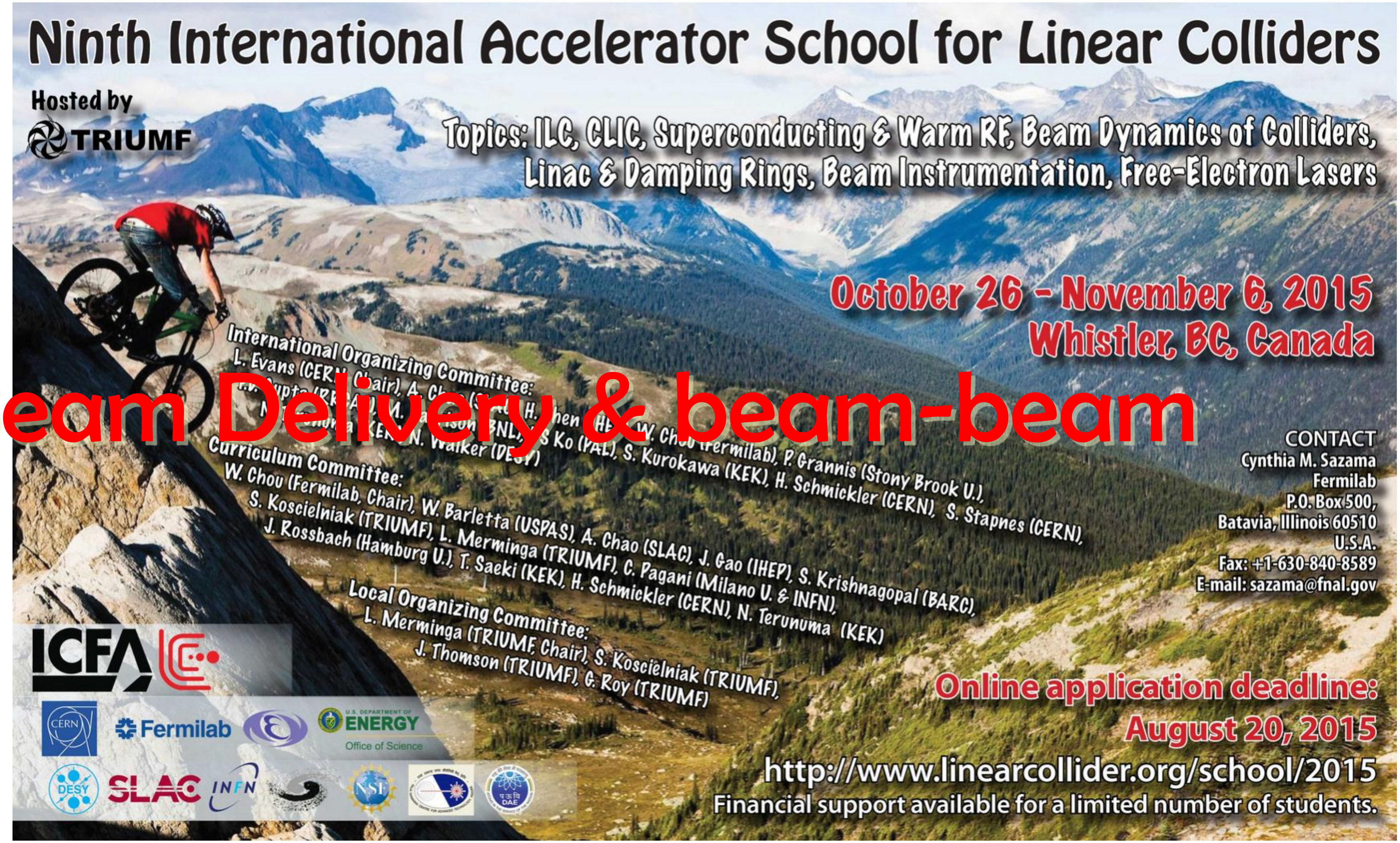
Accelerator Lecture A4 – PART 1 & 2



Beam Delivery & beam-beam

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Linear Collider – two main challenges

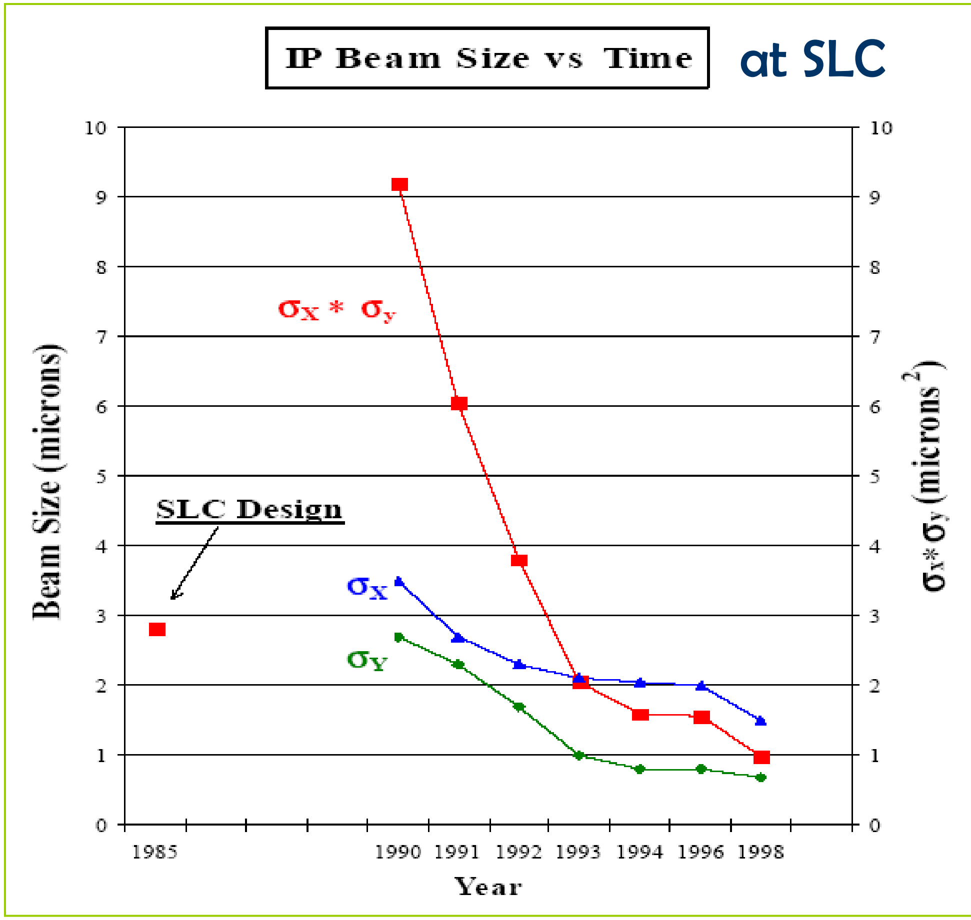
- **Energy** – need to reach at least 500 GeV CM

- **Luminosity** – need to reach 10^34 level

The Luminosity Challenge

- Must jump by a Factor of 10000 in Luminosity !!! (from what is achieved in the only so far linear collider SLC)

- Many improvements, to ensure this : generation of smaller emittances, their better preservation, …



- Including better focusing, dealing with beam-beam, safely removing beams after collision and better stability

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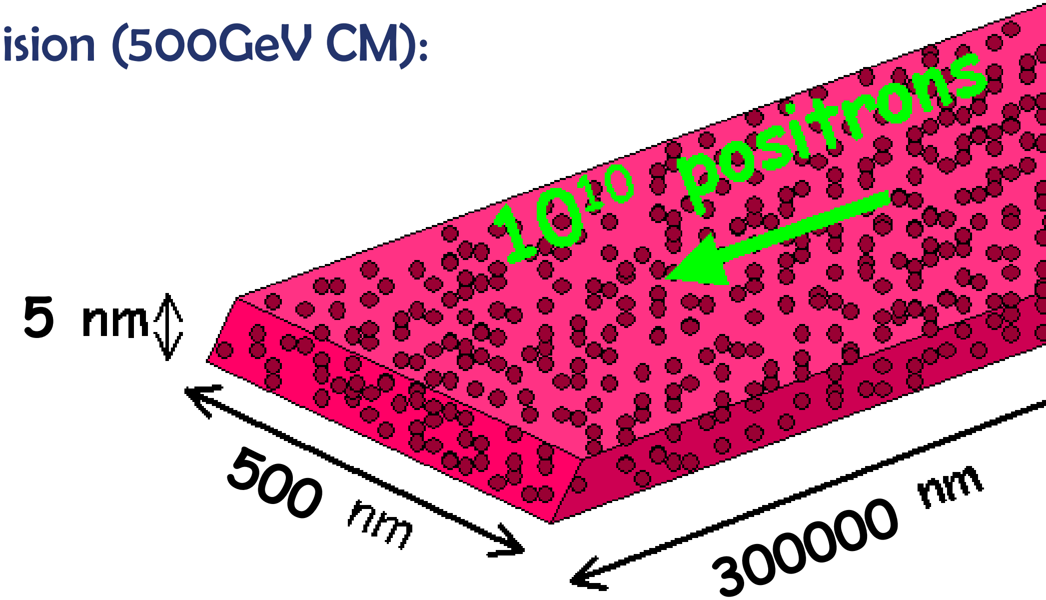
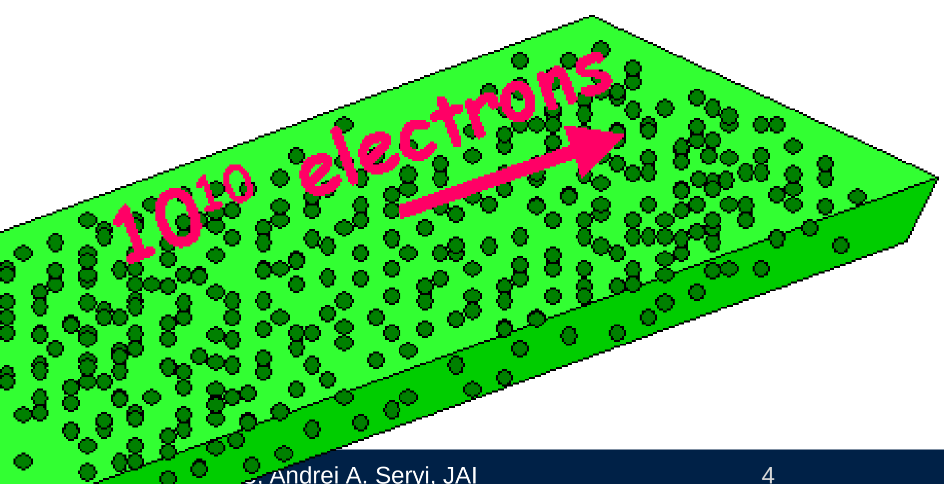
How to get Luminosity

- To increase probability of direct e^+e^- collisions (luminosity) and birth of new particles, beam sizes at IP must be very small
- E.g., ILC beam sizes just before collision (500GeV CM):
  500 * 5 * 300000 nanometers
  (x y z)

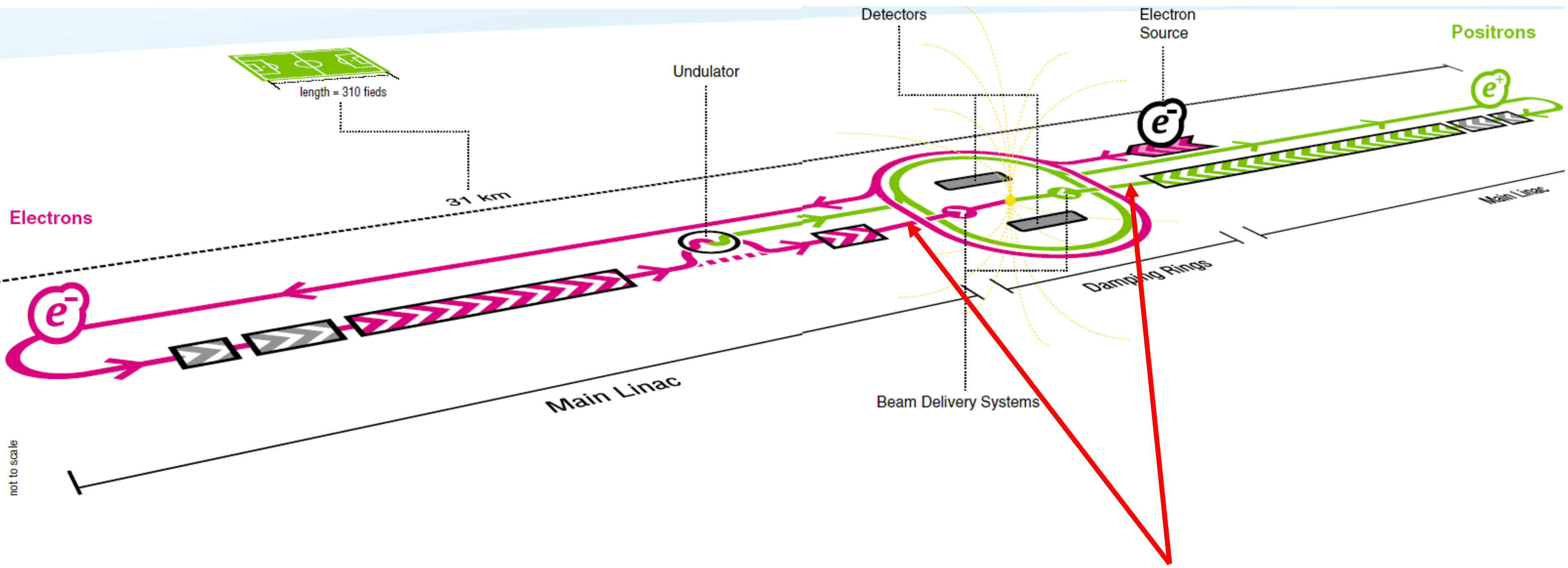
<u>Vertical size is smallest</u>





$$L = \frac{f_{rep}}{4\pi} \frac{n_b N^2}{\sigma_x \sigma_y} H_D$$

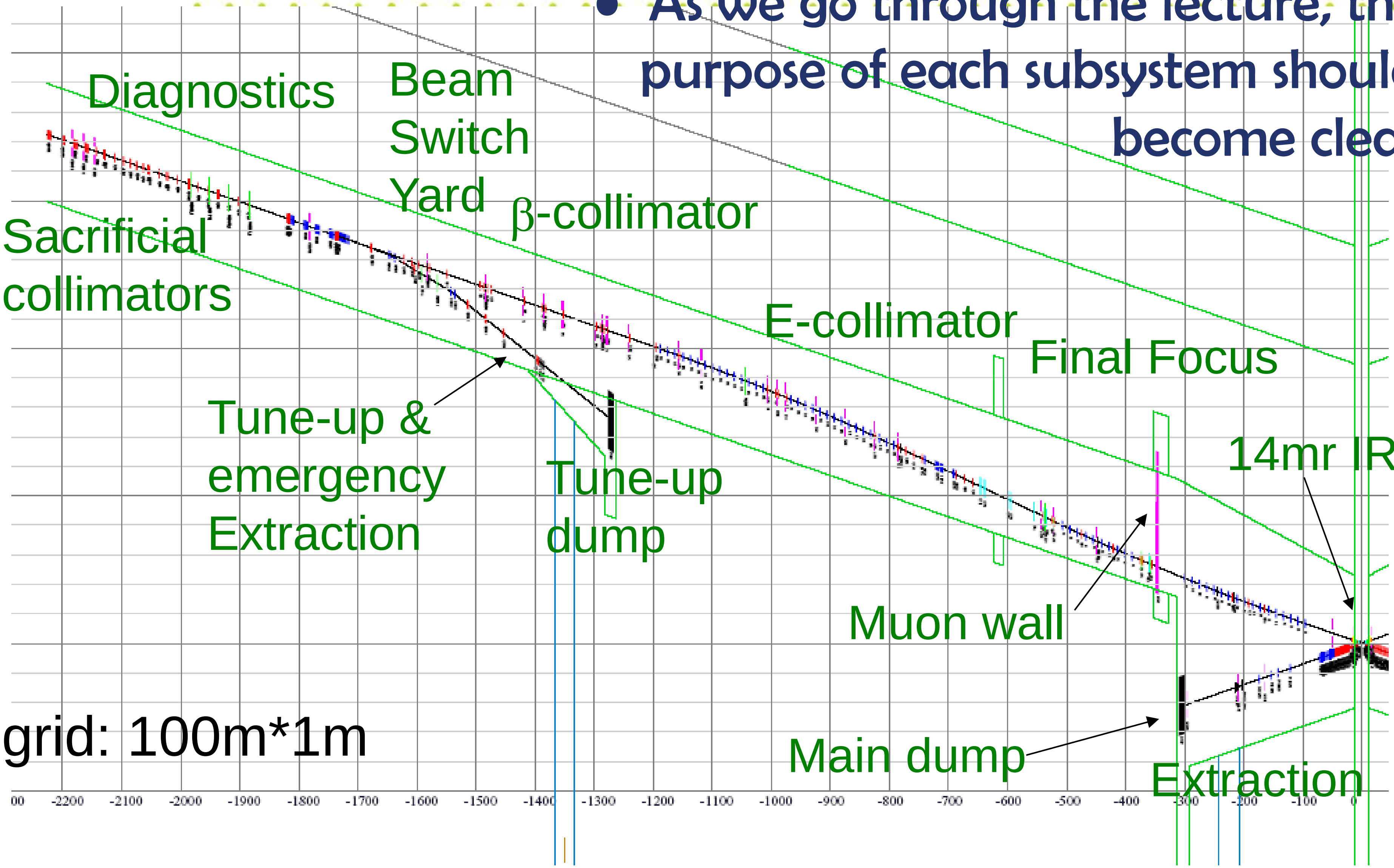
BDS: from end of linac to IP, to dumps



Beam Delivery System (BDS)

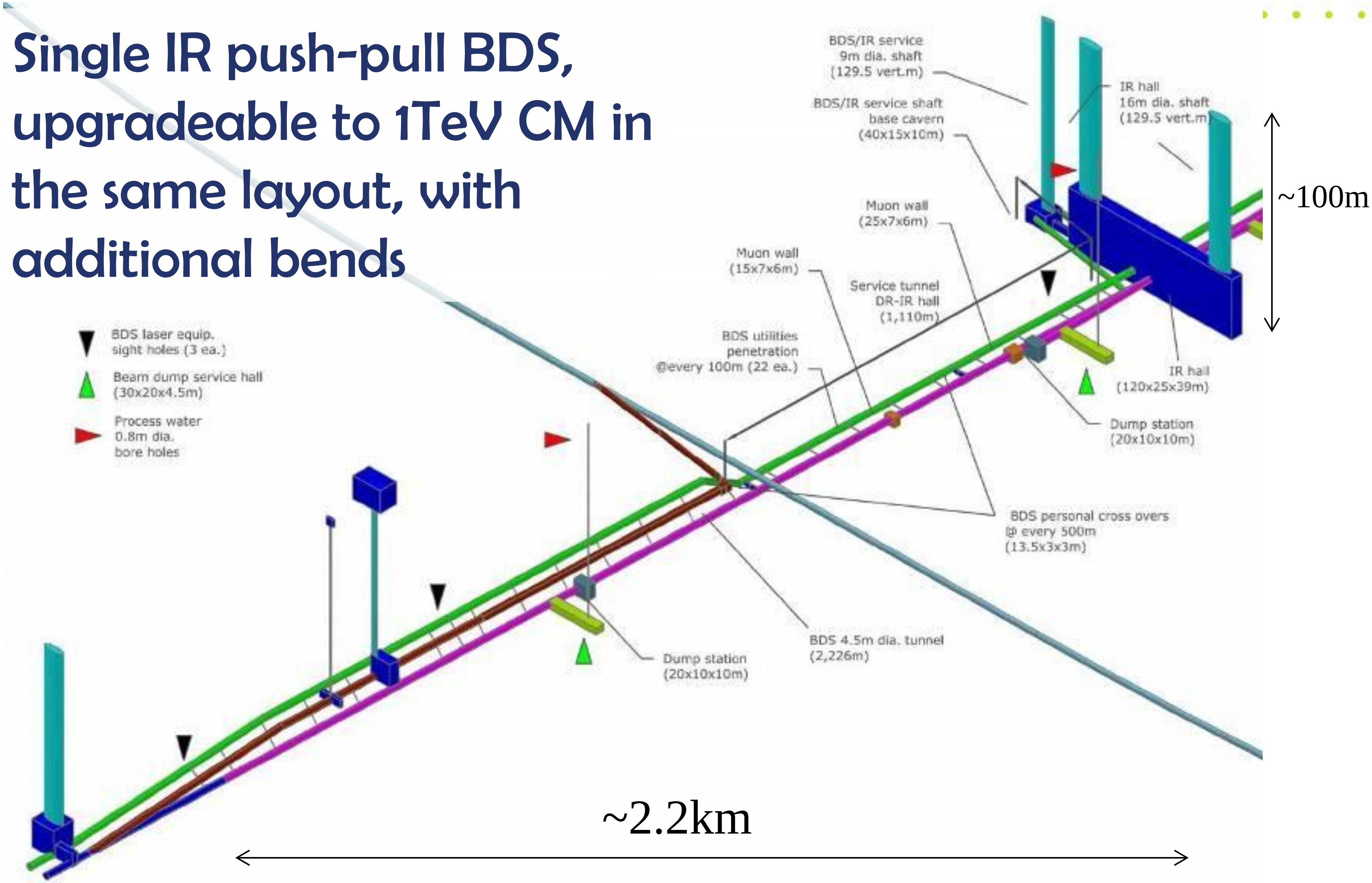
Beam Delivery subsystems

- As we go through the lecture, the purpose of each subsystem should become clear



Layout of Beam Delivery tunnels

- Single IR push-pull BDS, upgradeable to 1TeV CM in the same layout, with additional bends



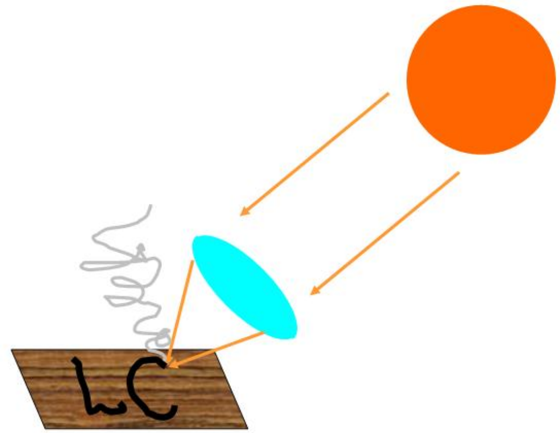
Beam Delivery System challenges

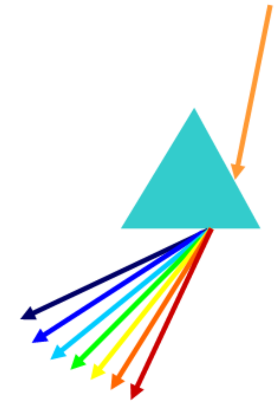
- measure the linac beam and match it into the final focus
- remove any large amplitude particles (beam-halo) from the linac to minimize background in the detectors
- measure and monitor the key physics parameters such as energy and polarization before and after the collisions
- ensure that the extremely small beams collide optimally at the IP
- protect the beamline and detector against mis-steered beams from the main linacs and safely extract them to beam dump
- provide possibility for two detectors to utilize single IP with efficient and rapid switch-over

Parameters of ILC BDS

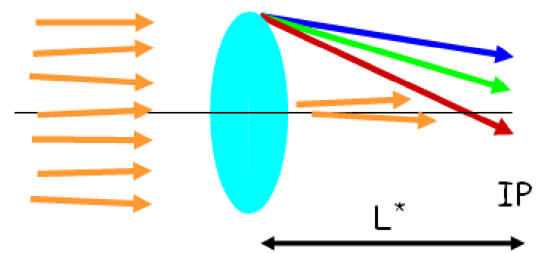
Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	655/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	31/14
Nominal beta-function at IP, β^*, x/y	mm	21/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.162/18.5
Nominal bunch population, N		2×10^{10}
Max beam power at main and tune-up dumps	MW	18
Preferred entrance train to train jitter	σ	< 0.5
Preferred entrance bunch to bunch jitter	σ	< 0.1
Typical nominal collimation depth, x/y		8–10/60
Vacuum pressure level, near/far from IP	nTorr	1/50

Factor driving BDS design

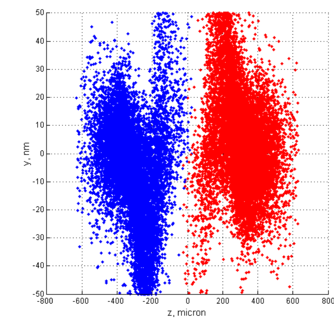




- Strong focusing
- Chromaticity



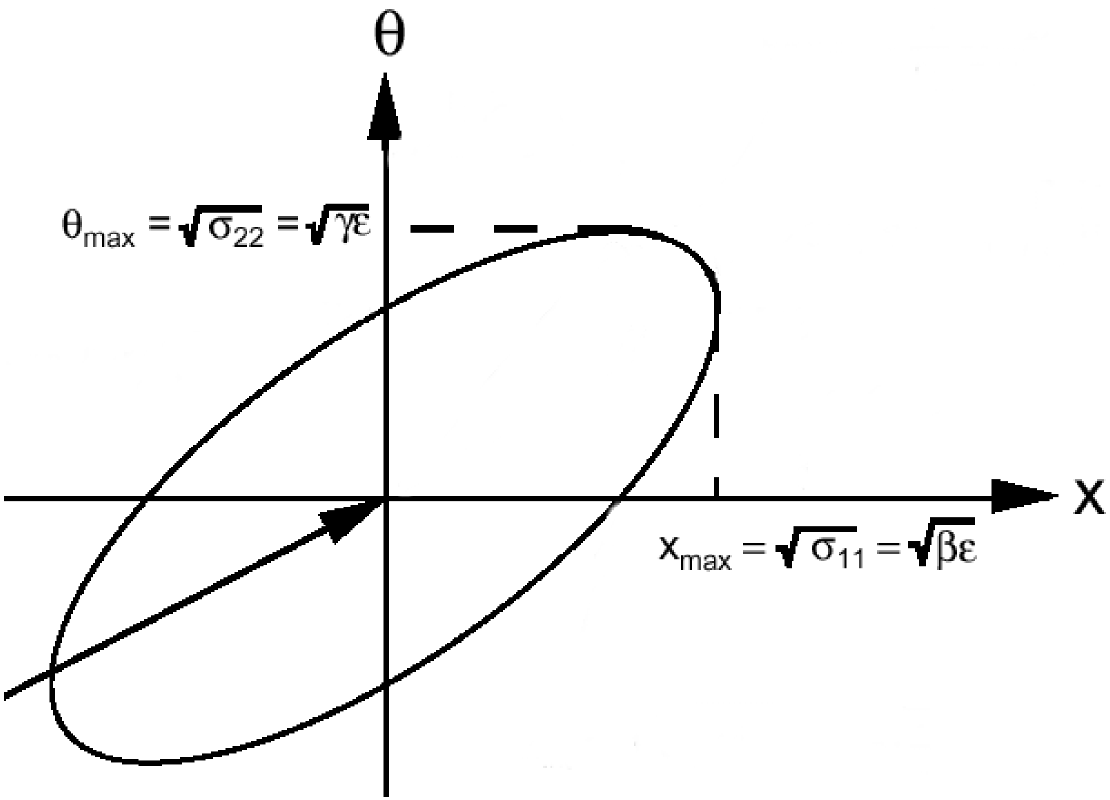
- Beam-beam effects



- Synchrotron radiation
  - let's consider some of this in more details

Recall couple of definitions

- Beta function β characterize optics
- Emittance ε is phase space volume of the beam
- Beam size: $(\varepsilon\ \beta)^{1/2}$
- Divergence: $(\varepsilon/\beta)^{1/2}$



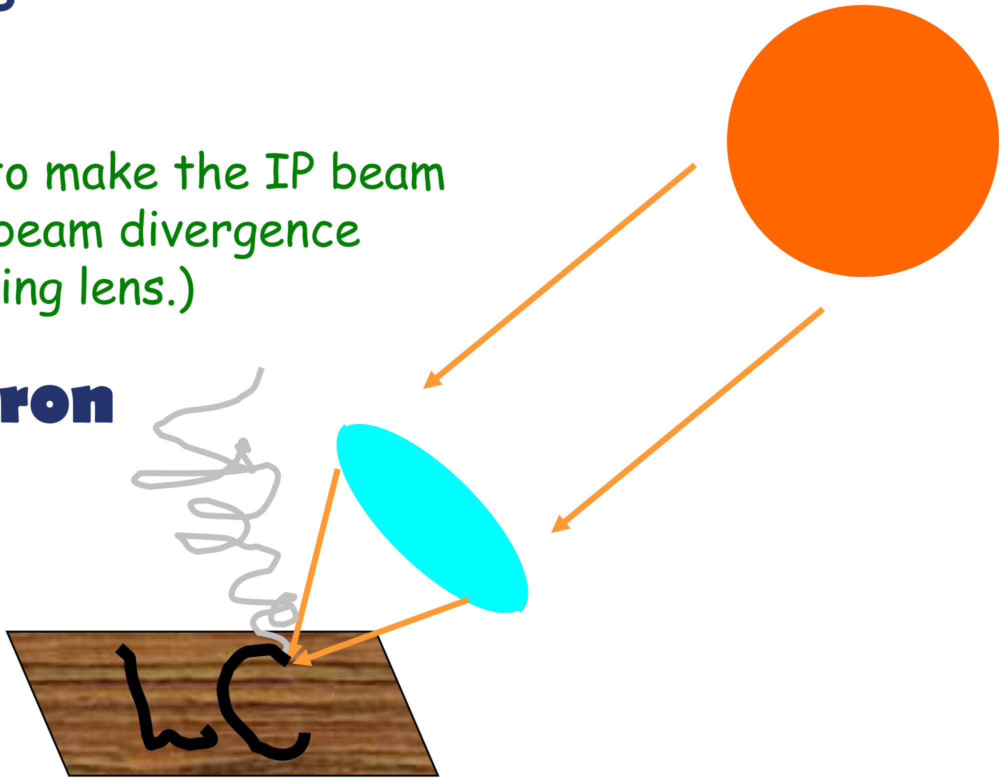
- Focusing makes the beam ellipse rotate with "betatron frequency"
- Phase of ellipse is called "betatron phase"

How to focus the beam to a smallest spot?

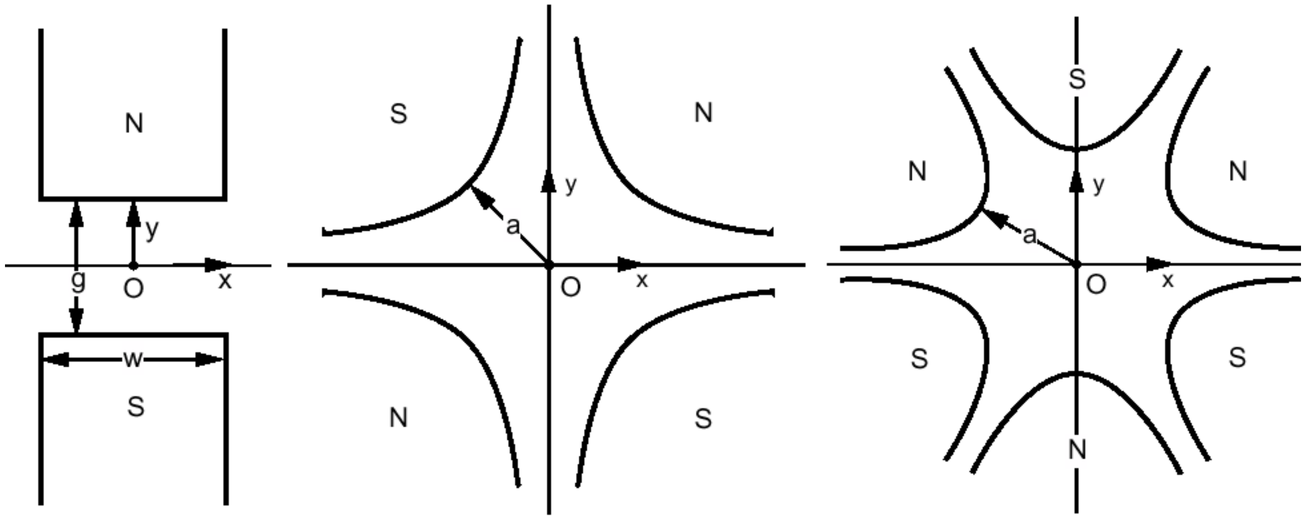
- If you ever played with a lens trying to burn a picture on a wood under bright sun, then you know that one needs a strong and big lens

(The emittance ε is constant, so, to make the IP beam size $(\varepsilon\ \beta)^{1/2}$ small, you need large beam divergence at the IP $(\varepsilon\ /\ \beta)^{1/2}$ i.e. short-focusing lens.)

- It is very similar for **electron** or **positron** beams
- But one have to use **magnets**



What we use to handle the beam



DIPOLE QUADRUPOLE SEXTUPOLE

Etc…

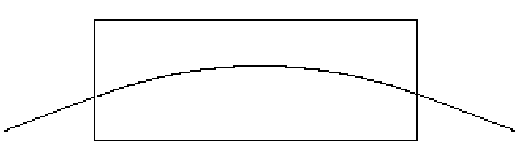
Just bend the trajectory

Focus in one plane, defocus in another:

$$x' = x' + G\,x$$
$$y' = y' - G\,y$$

Second order effect:

$$x' = x' + S\,(x^2 - y^2)$$
$$y' = y' - S\,2xy$$



Here x is transverse coordinate, x' is angle

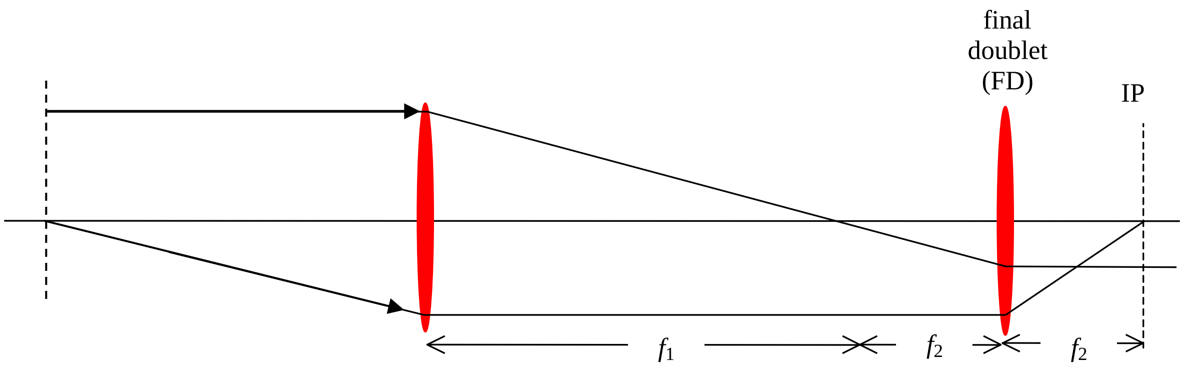
Optics building block: telescope

Essential part of final focus is final telescope. It "demagnify" the incoming beam ellipse to a smaller size. Matrix transformation of such telescope is diagonal:

$$R_{X,Y} = \begin{pmatrix} -1/M_{X,Y} & 0 \\ 0 & -M_{X,Y} \end{pmatrix}$$

A minimal number of quadrupoles, to construct a telescope with arbitrary demagnification factors, is four.

If there would be no energy spread in the beam, a telescope could serve as your final focus (or two telescopes chained together).



f_1 $\qquad f_2\ (=L^*)$

Use telescope optics to demagnify beam by factor $m = f1/f2 = f1/L^*$

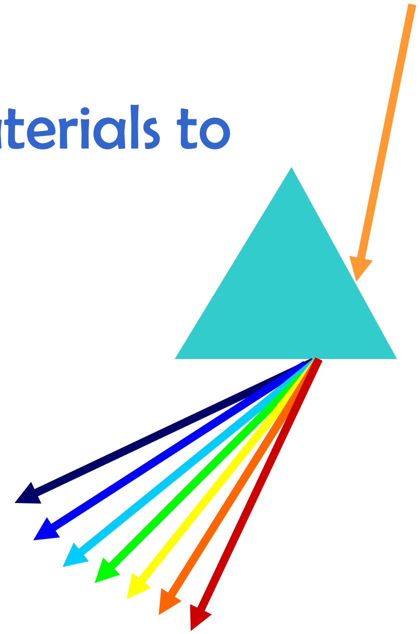
Matrix formalism for beam transport:

$$x_i^{out} = R_{ij}\ x_j^{in}$$

$$x_i = \begin{pmatrix} x \\ x' \\ y \\ y' \\ \Delta l \\ \delta \end{pmatrix}$$

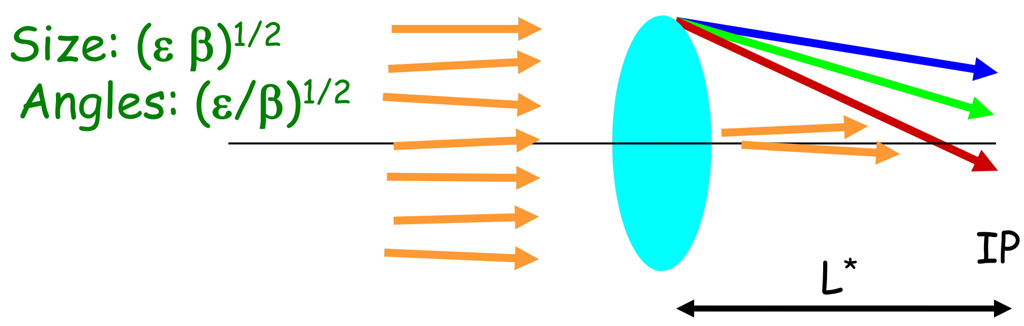
Why nonlinear elements

- As sun **light** contains different colors, **electron beam** has energy spread and get dispersed and distorted => **chromatic aberrations**
- For **light**, one uses lenses made from different materials to compensate chromatic aberrations



- Chromatic compensation for particle beams is done with **nonlinear** magnets
  - Problem: Nonlinear elements create **geometric** aberrations
- The **task** of **Final Focus system** (FF) is to focus the beam to required size and compensate aberrations

How to focus to a smallest size and how big is chromaticity in FF?



Size at IP:
$L^*\,(\varepsilon/\beta)^{1/2}$
$+\ (\varepsilon\,\beta)^{1/2}\,\sigma_E$

Beta at IP:
$L^*\,(\varepsilon/\beta)^{1/2} = (\varepsilon\,\beta^*)^{1/2}$
$\Rightarrow\ \beta^* = L^{*2}/\beta$

Chromatic dilution:
$(\varepsilon\,\beta)^{1/2}\,\sigma_E\,/\,(\varepsilon\,\beta^*)^{1/2}$
$= \sigma_E\ L^*/\beta^*$

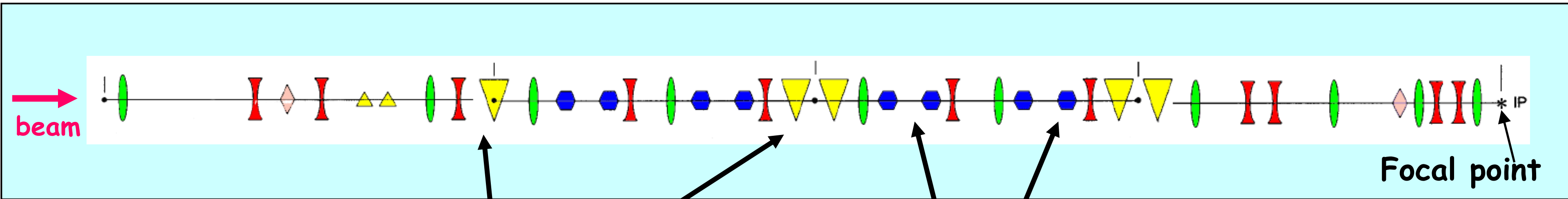
- The final lens need to be the strongest
  - (two lenses for both x and y => "Final Doublet" or FD)
- FD determines chromaticity of FF
- Chromatic dilution of the beam size is $\Delta\sigma/\sigma \sim \sigma_E\, L^*/\beta^*$

Typical:
σ_E -- energy spread in the beam ~ 0.002-0.01
L^* -- distance from FD to IP ~ 3 - 5 m
β^* -- beta function in IP ~ 0.4 - 0.1 mm

- For typical parameters, $\Delta\sigma/\sigma \sim$ 15-500 too big !
- => Chromaticity of FF need to be compensated

Example of traditional Final Focus

Sequence of elements in ~100m long Final Focus Test Beam



Dipoles. They bend trajectory, but also disperse the beam so that x depend on energy offset δ

Sextupoles. Their kick will contain energy dependent focusing

$$x' \Rightarrow S\,(x+\delta)^2 \Rightarrow 2S\,x\,\delta + ..$$

$$y' \Rightarrow -S\,2(x+\delta)y \Rightarrow -2S\,y\,\delta + ..$$

that can be used to arrange chromatic correction

Necessity to compensate chromaticity is a major driving factor of FF design

Terms x^2 are geometric aberrations and need to be compensated also

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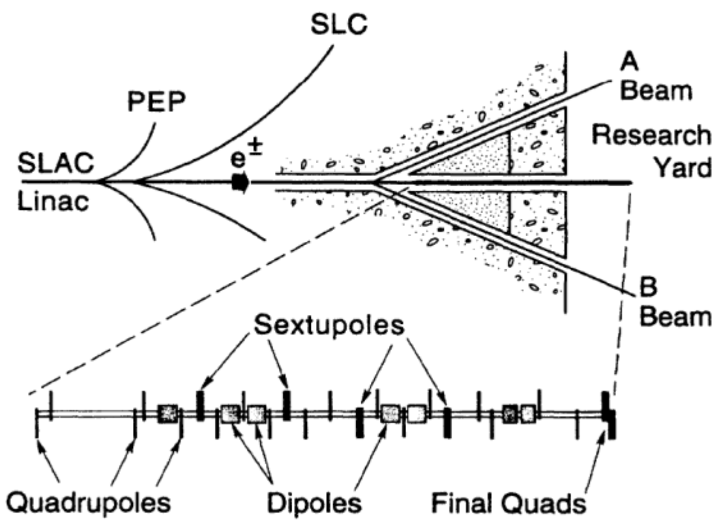
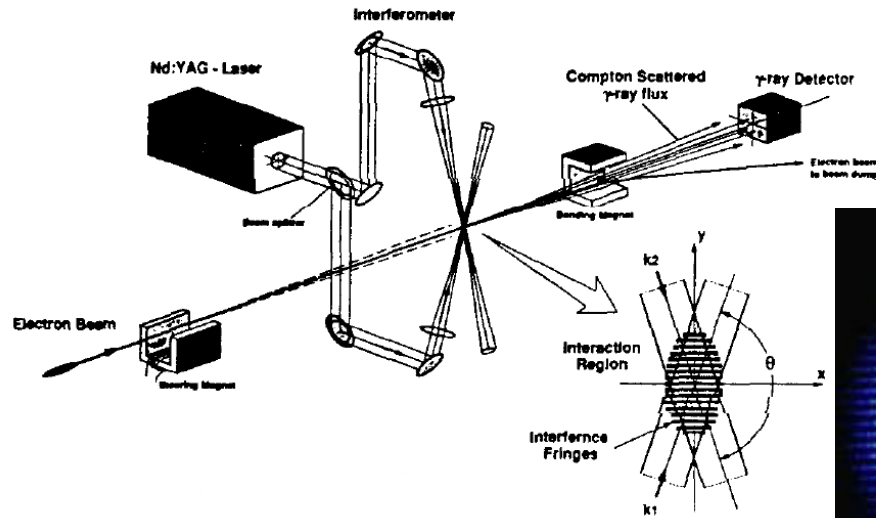
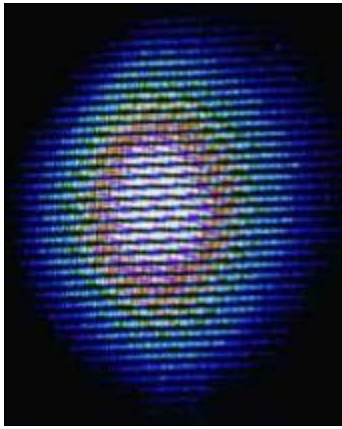
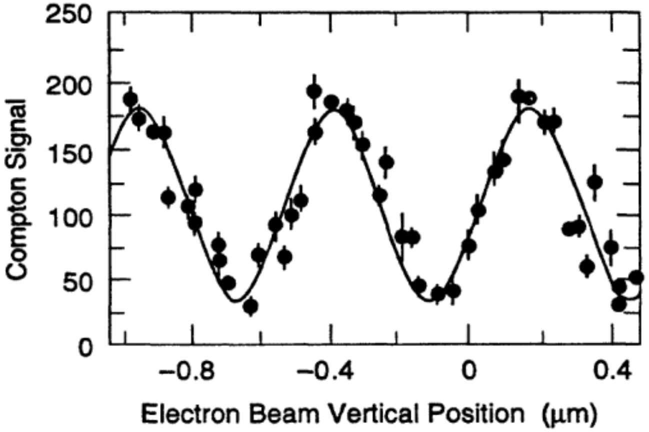
Final Focus Test Beam



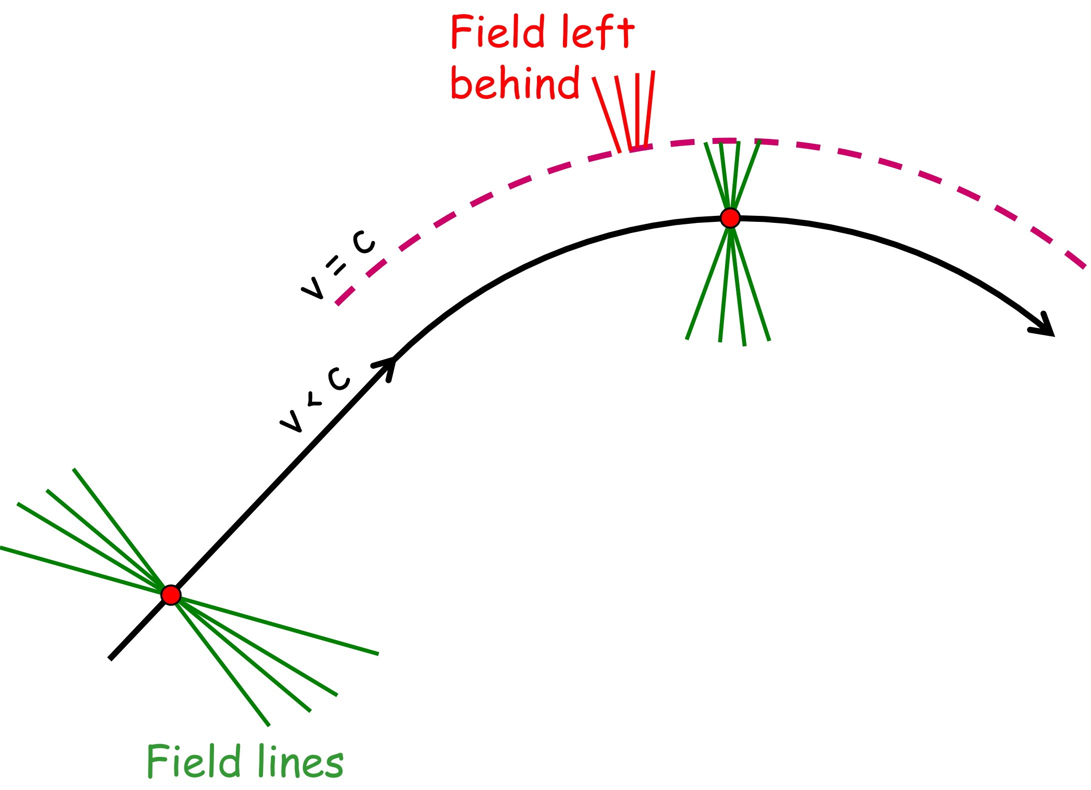




Achieved ~70nm vertical beam size



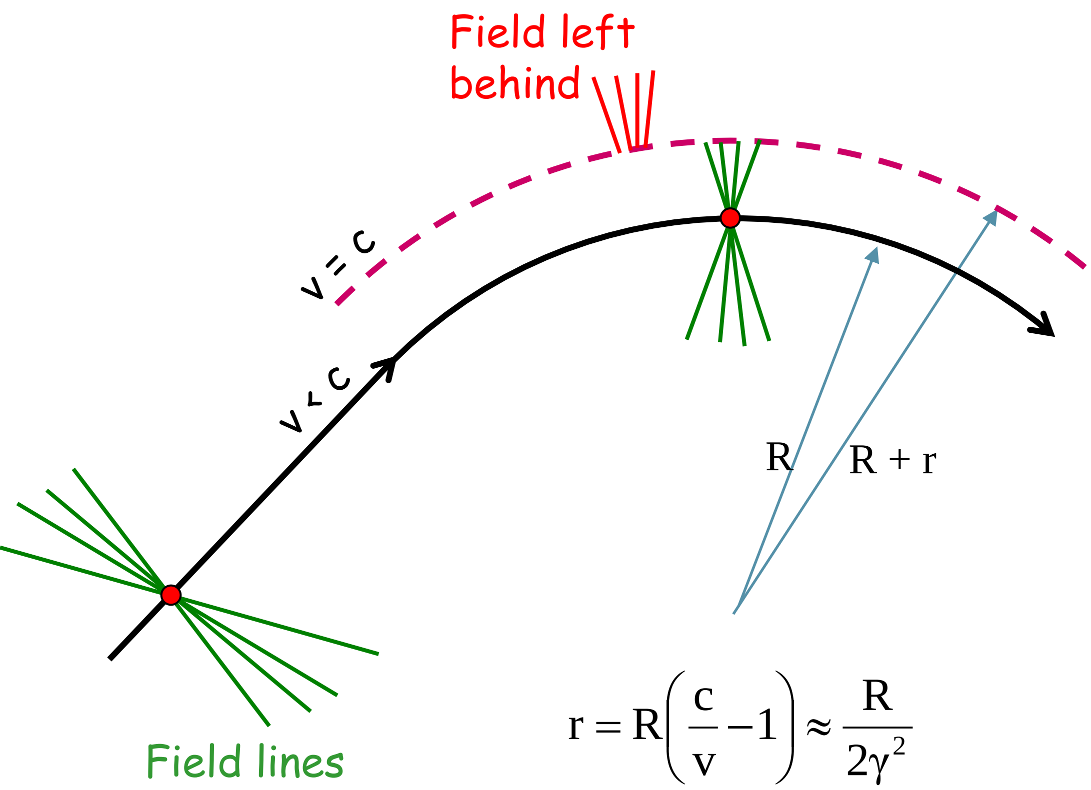
Synchrotron Radiation in FF magnets



- Bends are needed for compensation of chromaticity
- SR causes increase of energy spread which may perturb compensation of chromaticity
- Bends need to be long and weak, especially at high energy
- SR in FD quads is also harmful (Oide effect) and may limit the achievable beam size

Energy spread caused by SR in bends and quads is also a major driving factor of FF design

Let's estimate SR power



$$r = R\left(\frac{c}{v} - 1\right) \approx \frac{R}{2\gamma^2}$$

Energy in the field left behind (radiated !):

$$W \approx \int E^2 \, dV$$

The field $E \approx \frac{e}{r^2}$ the volume $V \approx r^2 \, dS$

Energy loss per unit length:

$$\frac{dW}{dS} \approx E^2 r^2 \approx \left(\frac{e}{r^2}\right)^2 r^2$$

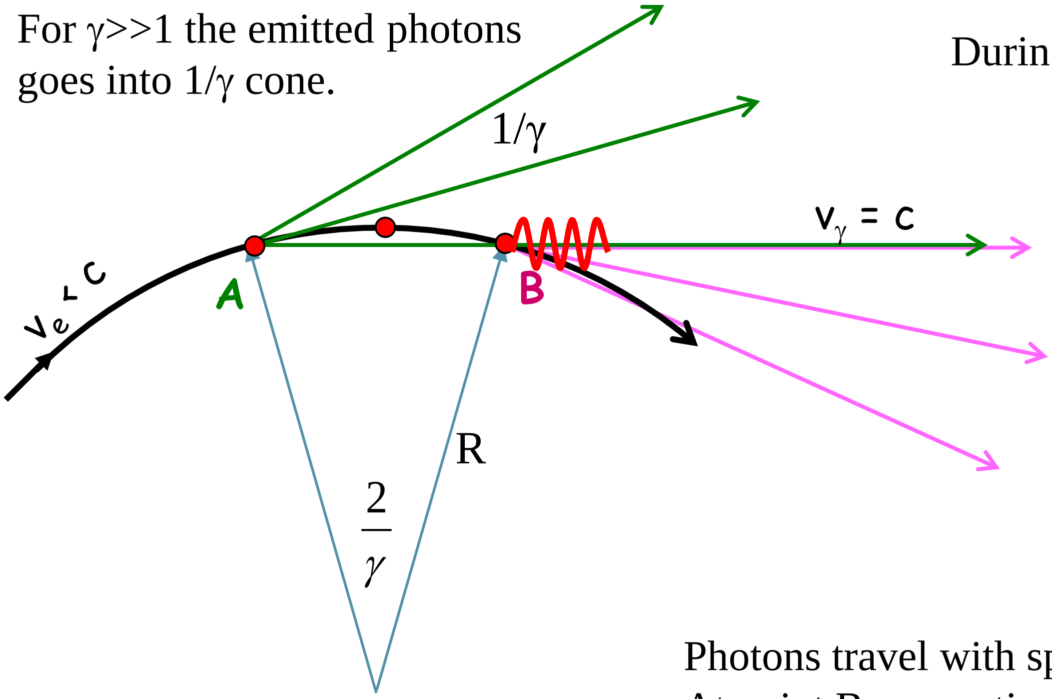
Substitute $r \approx \frac{R}{2\gamma^2}$ and get an estimate:

$$\boxed{\frac{dW}{dS} \approx \frac{e^2\gamma^4}{R^2}}$$

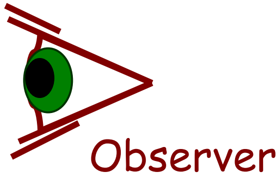
Compare with exact formula: $\frac{dW}{dS} = \frac{2}{3}\frac{e^2\gamma^4}{R^2}$

Let's estimate typical frequency of SR photons

For γ>>1 the emitted photons goes into $1/\gamma$ cone.



During what time Δt the observer will see the photons?



Photons emitted during travel along the $2R/\gamma$ arc will be observed.

Photons travel with speed c, while particles with v.
At point B, separation between photons and particles is

$$dS \approx \frac{2R}{\gamma}\left(1-\frac{v}{c}\right)$$

Therefore, observer will see photons during $\Delta t \approx \frac{dS}{c} \approx \frac{2R}{c\gamma}(1-\beta) \approx \frac{R}{c\gamma^3}$

Estimation of characteristic frequency $\boxed{\omega_c \approx \frac{1}{\Delta t} \approx \frac{c\gamma^3}{R}}$

Compare with exact formula: $\omega_c = \frac{3}{2}\frac{c\gamma^3}{R}$

Let's estimate energy spread growth due to SR

We estimated the rate of energy loss : $\frac{dW}{dS} \approx \frac{e^2 \gamma^4}{R^2}$ And the characteristic frequency $\omega_c \approx \frac{c\gamma^3}{R}$

The photon energy $\varepsilon_c = \hbar\omega_c \approx \frac{\gamma^3 \hbar c}{R} = \frac{\gamma^3}{R}\lambda_e mc^2$ where $r_e = \frac{e^2}{mc^2}$ $\alpha = \frac{e^2}{\hbar c}$ $\lambda_e = \frac{r_e}{\alpha}$

Number of photons emitted per unit length $\frac{dN}{dS} \approx \frac{1}{\varepsilon_c}\frac{dW}{dS} \approx \frac{\alpha\gamma}{R}$ (per angle θ : $N \approx \alpha\gamma\theta$)

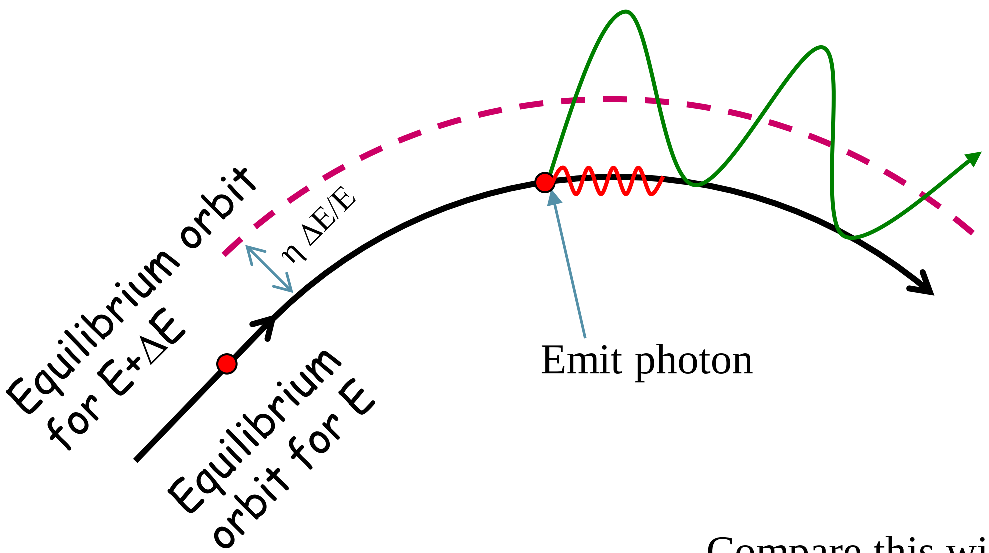
The energy spread $\Delta E/E$ will grow due to statistical fluctuations ($\sqrt{N}$) of the number of emitted photons :

$$\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \varepsilon_c^2 \frac{dN}{dS}\frac{1}{\left(\gamma mc^2\right)^2}$$

Which gives: $\boxed{\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \frac{r_e \lambda_e \gamma^5}{R^3}}$

Compare with exact formula: $\frac{d\left((\Delta E/E)^2\right)}{dS} = \frac{55}{24\sqrt{3}}\frac{r_e \lambda_e \gamma^5}{R^3}$

Let's estimate emittance growth rate due to SR



Dispersion function η shows how equilibrium orbit shifts when energy changes

When a photon is emitted, the particle starts to oscillate around new equilibrium orbit

Amplitude of oscillation is $\Delta x \approx \eta\, \Delta E/E$

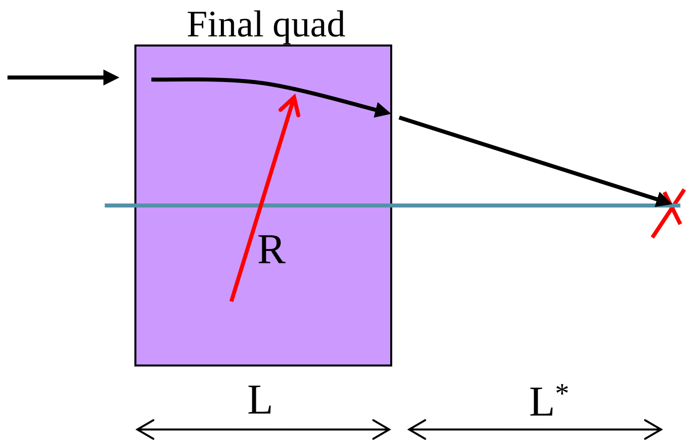
Compare this with betatron beam size: $\sigma_x = (\varepsilon_x\, \beta_x)^{1/2}$

And write emittance growth: $\Delta\varepsilon_x \approx \dfrac{\Delta x^2}{\beta}$

Resulting estimation for emittance growth: $$\frac{d\varepsilon_x}{dS} \approx \frac{\eta^2}{\beta_x}\,\frac{d\left((\Delta E/E)^2\right)}{dS} \approx \boxed{\frac{\eta^2}{\beta_x}\,\frac{r_e\,\lambda_e\,\gamma^5}{R^3}}$$

Compare with exact formula (which also takes into account the derivatives): $$\frac{d\varepsilon_x}{dS} = \boxed{\underbrace{\frac{\left(\eta^2 + (\beta_x\eta' - \beta_x'\eta/2)^2\right)}{\beta_x}}_{=\mathcal{H}}}\;\frac{55}{24\sqrt{3}}\,\frac{r_e\,\lambda_e\,\gamma^5}{R^3}$$

Let's apply SR formulae to estimate Oide effect (SR in FD)



IP divergence:

$$\theta^* = \sqrt{\varepsilon/\beta^*}$$

IP size:

$$\sigma^* = \sqrt{\varepsilon\,\beta^*}$$

Energy spread obtained in the quad:

$$\left(\frac{\Delta E}{E}\right)^2 \approx \frac{r_e\,\lambda_e\,\gamma^5\,L}{R^3}$$

Radius of curvature of the trajectory: $R = L/\theta^*$

Growth of the IP beam size: $\sigma^2 \approx \sigma_0^2 + \left(L^*\,\theta^*\right)^2 \left(\frac{\Delta E}{E}\right)^2$

Which gives $\sigma^2 \approx \varepsilon\beta^* + C_1 \left(\frac{L^*}{L}\right)^2 r_e\,\lambda_e\,\gamma^5 \left(\frac{\varepsilon}{\beta^*}\right)^{5/2}$ (where C_1 is ~ 7 (depend on FD params.))

This achieve minimum possible value:

$$\sigma_{min} \approx 1.35\,C_1^{1/7} \left(\frac{L^*}{L}\right)^{2/7} \left(r_e\,\lambda_e\right)^{1/7} \left(\gamma\varepsilon\right)^{5/7}$$

When beta* is:

$$\beta_{optimal} \approx 1.29\,C_1^{2/7} \left(\frac{L^*}{L}\right)^{4/7} \left(r_e\,\lambda_e\right)^{2/7} \gamma \left(\gamma\varepsilon\right)^{3/7}$$

Note that beam distribution at IP will be non-Gaussian. Usually need to use tracking to estimate impact on luminosity. Note also that optimal β may be smaller than the σ_z (i.e cannot be used).

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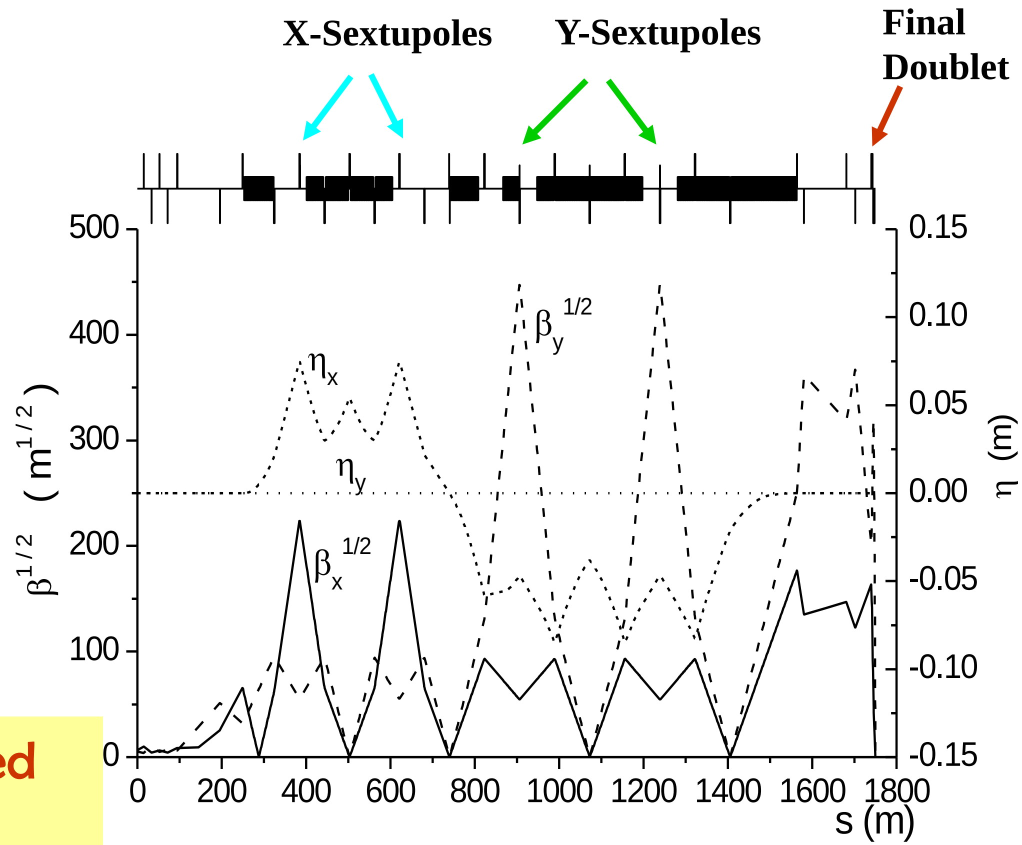
FF with non-local chromaticity compensation

- Chromaticity is compensated by sextupoles in dedicated sections
- Geometrical aberrations are canceled by using sextupoles in pairs with M= -I

Chromaticity arise at FD but pre-compensated 1000m upstream

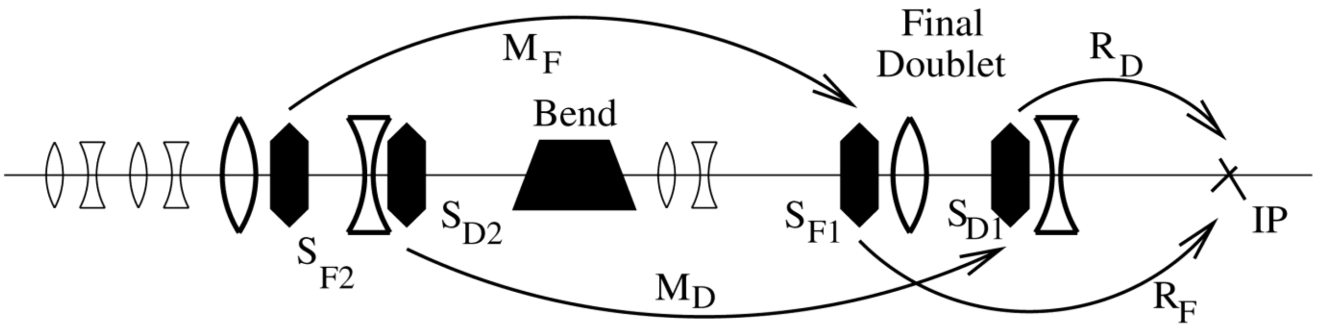


Traditional FF

Problems:

- Chromaticity <u>not locally</u> compensated
  - Compensation of aberrations is not ideal since M ≠ -I for off energy particles
  - Large aberrations for beam tails
  - ...

FF with local chromatic correction



- Chromaticity is cancelled <u>locally</u> by two sextupoles interleaved with FD, a bend upstream generates dispersion across FD

- Geometric aberrations of the FD sextupoles are cancelled by two more sextupoles placed in phase with them and upstream of the bend

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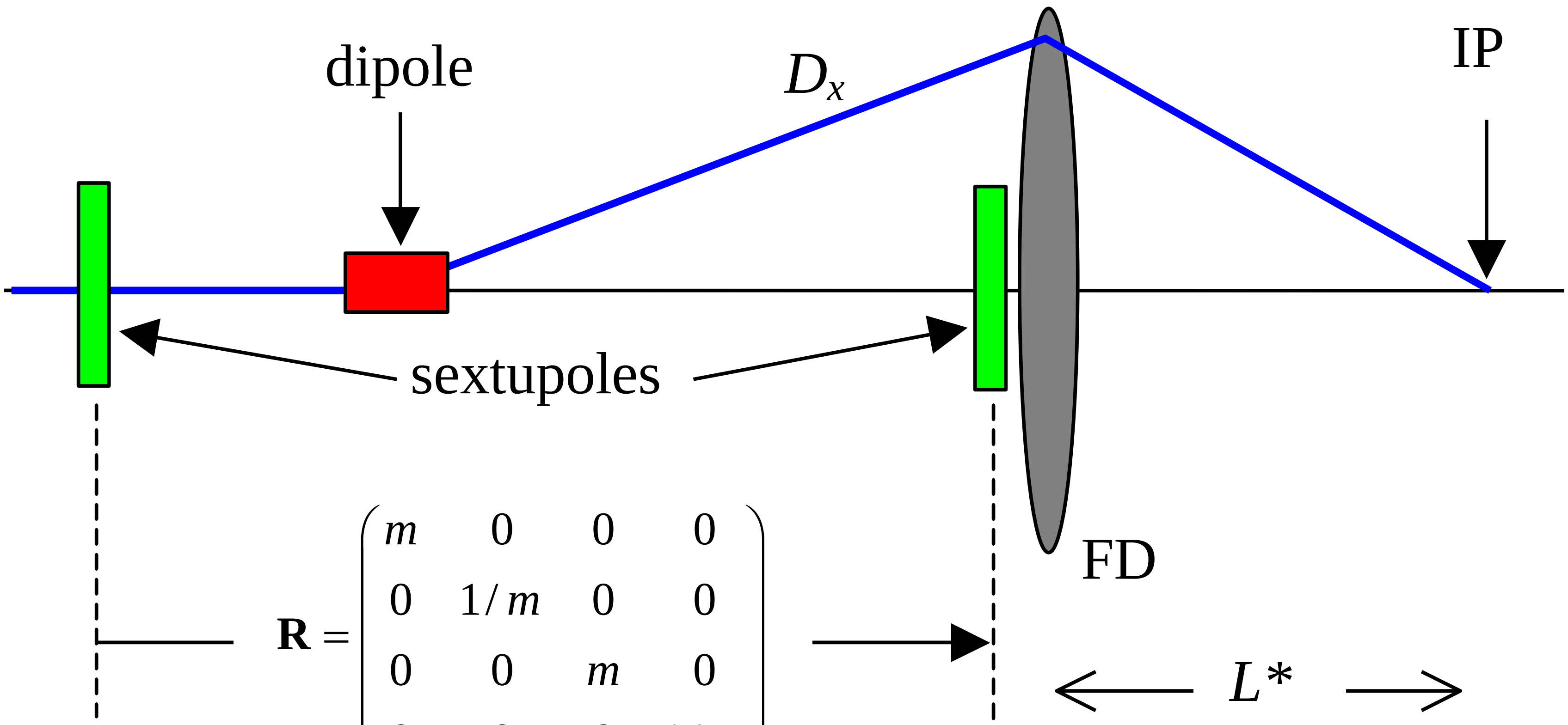
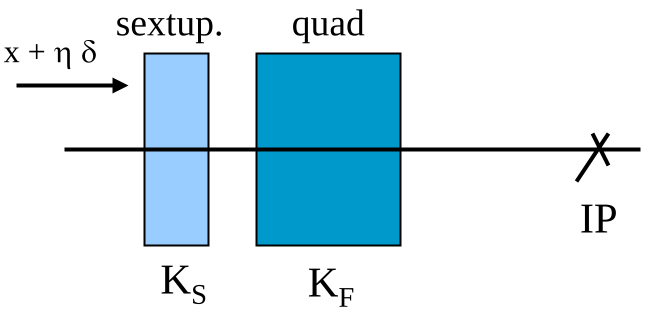
Local chromatic correction



$$\mathbf{R} = \begin{pmatrix} m & 0 & 0 & 0 \\ 0 & 1/m & 0 & 0 \\ 0 & 0 & m & 0 \\ 0 & 0 & 0 & 1/m \end{pmatrix}$$

- The value of dispersion in FD is usually chosen so that it does not increase the beam size in FD by more than 10-20% for typical beam energy spread

Chromatic correction in FD



- Straightforward in Y plane
- a bit tricky in X plane:

Quad: $$\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) \Rightarrow K_F(-\delta x - \eta\delta^2)$$

chromaticity

Second order dispersion

Sextupole: $$\Delta x' = \frac{K_S}{2}(x+\eta\delta)^2 \Rightarrow K_S\eta\left(\delta x + \frac{\eta\delta^2}{2}\right)$$

If we require $K_S\eta = K_F$ to cancel FD chromaticity, then half of the **second order dispersion** remains.

$$\Delta x' = \frac{K_F}{(1+\delta)}(x+\eta\delta) + \frac{K_{\beta\text{-match}}}{(1+\delta)}x \Rightarrow 2K_F\left(-\delta x - \frac{\eta\delta^2}{2}\right)$$

$$K_{\beta\text{-match}} = K_F \qquad K_S = \frac{2K_F}{\eta}$$

Solution:
The β-matching section produces as much X chromaticity as the FD, so the X sextupoles run twice stronger and cancel the **second order dispersion** as well.

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Definitions of chromaticity
1st : TRANSPORT

Storage Rings: chromaticity defined as a change of the betatron tunes versus energy.

In single path beamlines, it is more convenient to use other definitions.

$$x_i = \begin{pmatrix} x \\ x' \\ y \\ y' \\ \Delta l \\ \delta \end{pmatrix} \qquad\qquad x_i^{out} = R_{ij}\ x_j^{in}$$

The second, third, and so on terms are included in a similar manner:

$$x_i^{out} = R_{ij}\ x_j^{in} + T_{ijk}\ x_j^{in}\ x_k^{in} + U_{ijkn}\ x_j^{in}\ x_k^{in}\ x_n^{in} + \ldots$$

In FF design, we usually call ‘chromaticity’ the second order elements T_{126} and T_{346}. All other high order terms are just ‘aberrations’, purely chromatic (as T_{166}, which is second order dispersion), or chromo-geometric (as U_{32446}).

Definitions of chromaticity

2nd : W functions

Lets assume that betatron motion without energy offset is described by twiss functions $\boldsymbol{\alpha}_1$ and $\boldsymbol{\beta}_1$ and with energy offset $\boldsymbol{\delta}$ by functions $\boldsymbol{\alpha}_2$ and $\boldsymbol{\beta}_2$

Let's define chromatic function **W** (for each plane) as $W = (i\,A + B)/2$ where $i = \sqrt{-1}$

And where: $B = \dfrac{\beta_2 - \beta_1}{\delta\,(\beta_2 \cdot \beta_1)^{1/2}} \approx \dfrac{\Delta\beta}{\delta\;\beta}$ and $A = \dfrac{\alpha_2\beta_1 - \alpha_1\beta_2}{\delta\,(\beta_2 \cdot \beta_1)^{1/2}} \approx \dfrac{\Delta\alpha}{\delta} - \dfrac{\alpha}{\beta}\dfrac{\Delta\beta}{\delta}$

Using familiar formulae $\dfrac{d\beta}{ds} = -2\alpha$ and $\dfrac{d\alpha}{ds} = K \cdot \beta - \dfrac{(1+\alpha^2)}{\beta}$ where $K = \dfrac{e}{pc}\dfrac{dB_y}{dx}$

And introducing $\Delta K = \dfrac{K(\delta(- K(0)}{\delta} \approx -K$ we obtain the equation for **W** evolution:

Can you show this? →

$$\frac{dW}{ds} = \frac{2i}{\beta} W + \frac{i}{2}\beta\,\Delta K$$

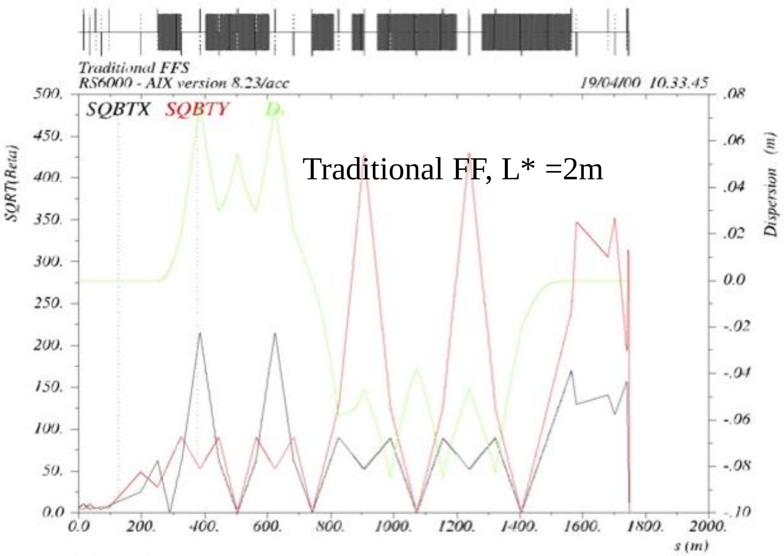
knowing that the betatron phase is $\dfrac{d\Phi}{ds} = \dfrac{1}{\beta}$

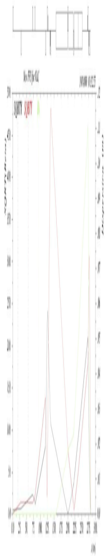
can see that if **ΔK**=0, then **W** rotates with double betatron frequency and stays constant in amplitude. In quadrupoles or sextupoles, only imaginary part changes.

Show that if in a final defocusing lens α=0, then it gives $\Delta W = L^*/(2\beta^*)$

Show that if T_{346} is zeroed at the IP, the W_y is also zero. Use approximation $\Delta R_{34} = T_{346}{}^*\delta$, use $R_{34} = (\beta\beta_0)^{1/2}\sin(\Delta\Phi)$, and the twiss equation for $d\alpha/d\Phi$.

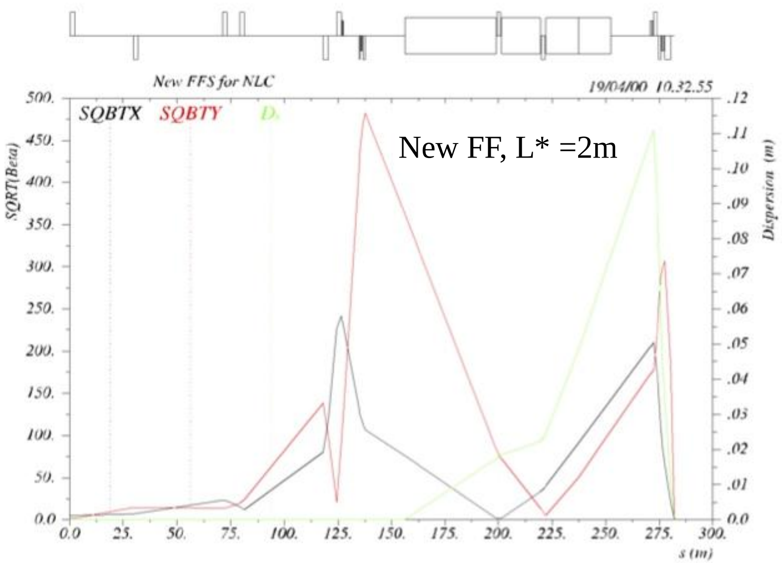
Compare FF designs



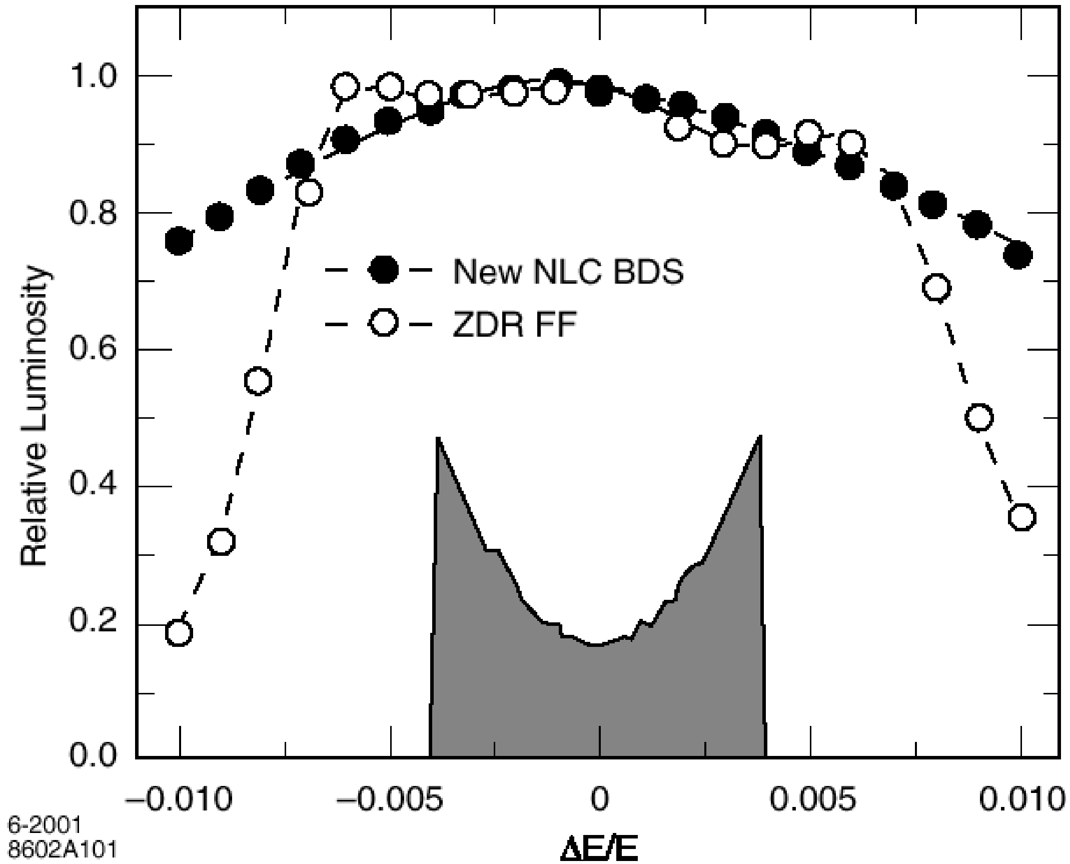


FF with local chromaticity compensation with the same performance can be ~300m long, i.e. 6 times shorter

Moreover, its necessary length scales only as $E^{2/5}$ with energy! One can design multi-TeV FF in under a km!



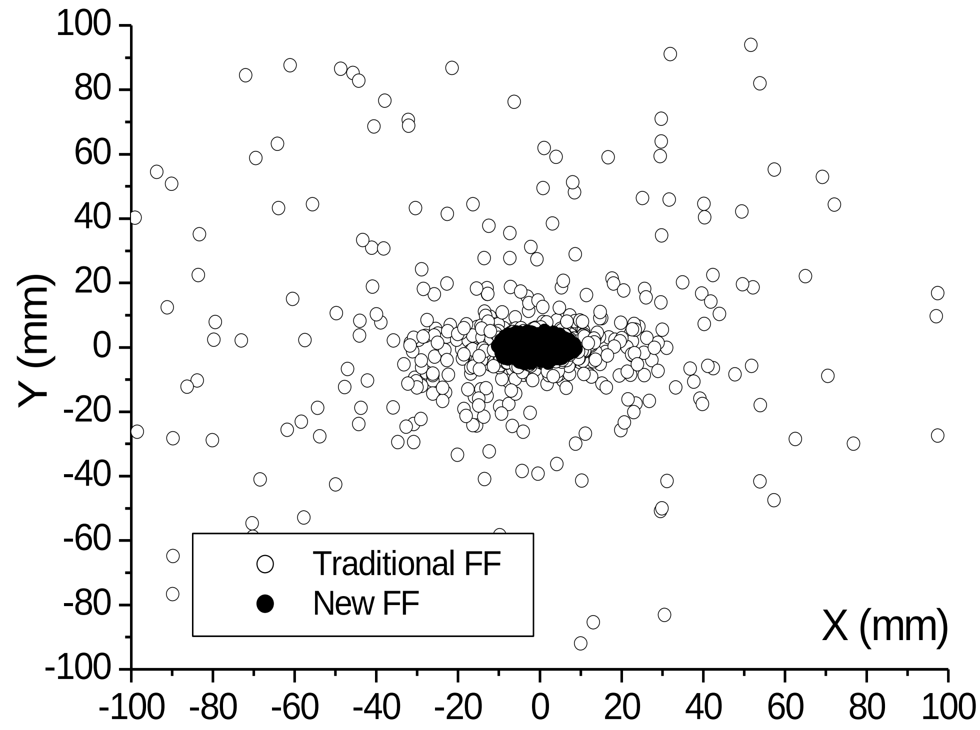
IP bandwidth

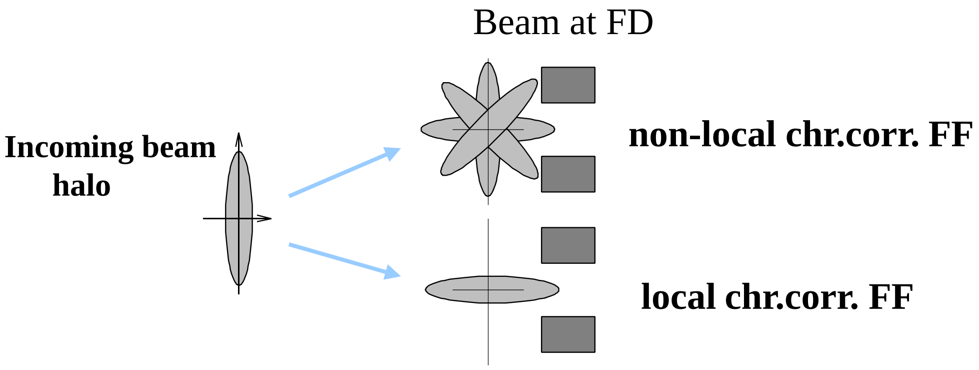


Bandwidth of FF with local chromaticity correction can be better than for system with non-local correction

Aberrations & halo generation in FF

- FF with non-local chr. corr. generate beam tails due to aberrations and it does not preserve betatron phase of halo particles
- FF with local chr. corr. has much less aberrations and it does not mix phases particles





Halo beam at the FD entrance. Incoming beam is ~ 100 times larger than nominal beam

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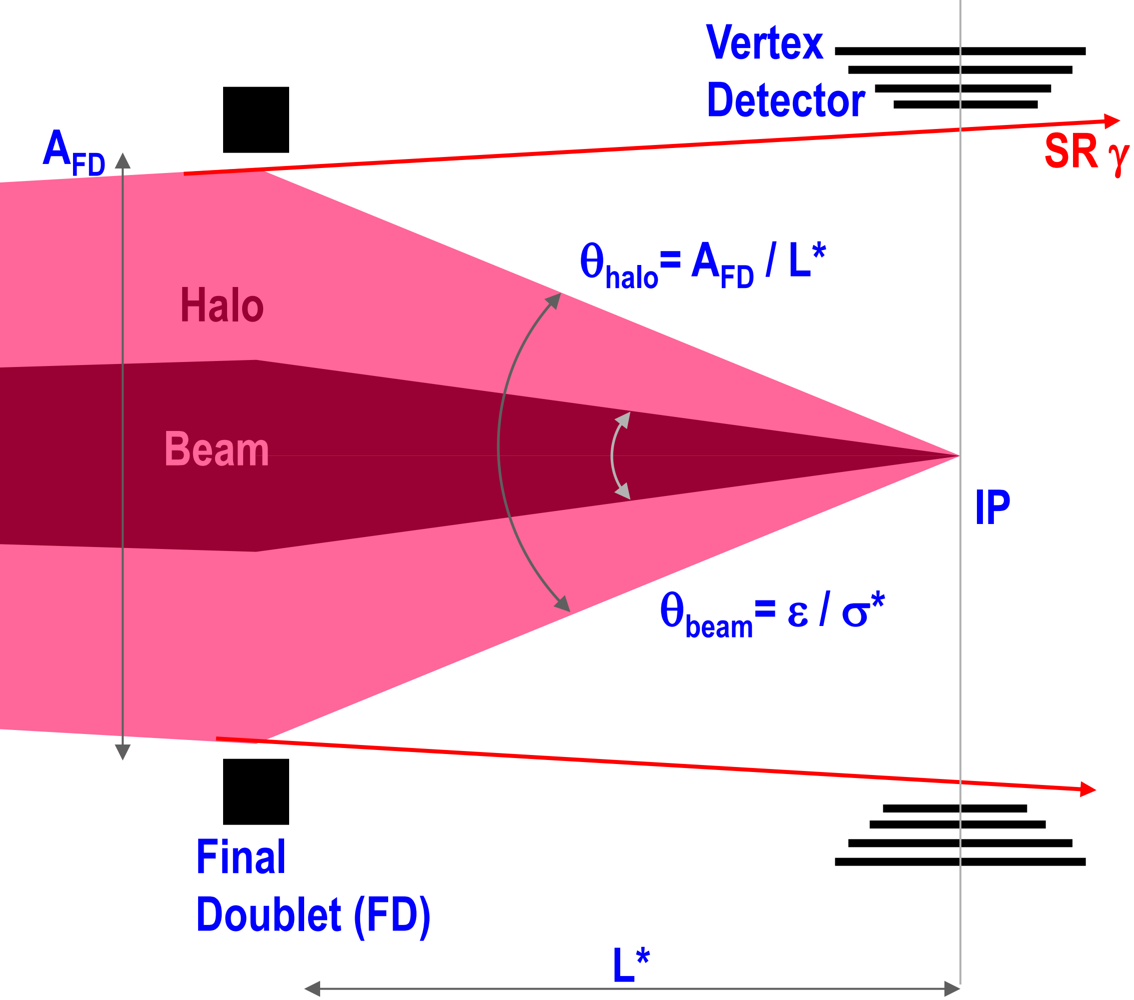
Beam halo & collimation

- Even if final focus does not generate beam halo itself, the halo may come from upstream and need to be collimated



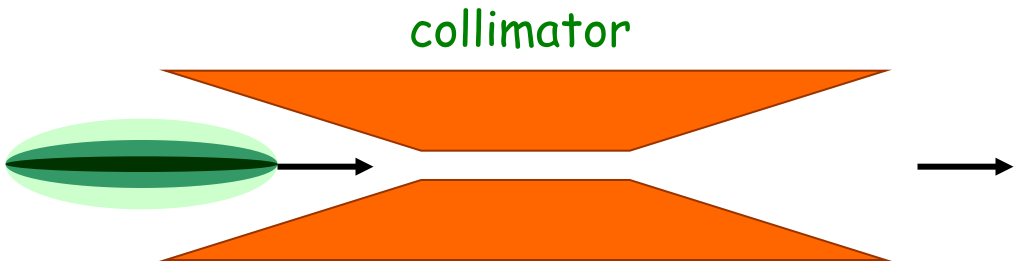
- Halo must be collimated upstream in such a way that SR γ & halo e^{+-} do not touch VX and FD
- => VX aperture needs to be somewhat larger than FD aperture
- Exit aperture is larger than FD or VX aperture
- Beam convergence depend on parameters, the halo convergence is fixed for given geometry

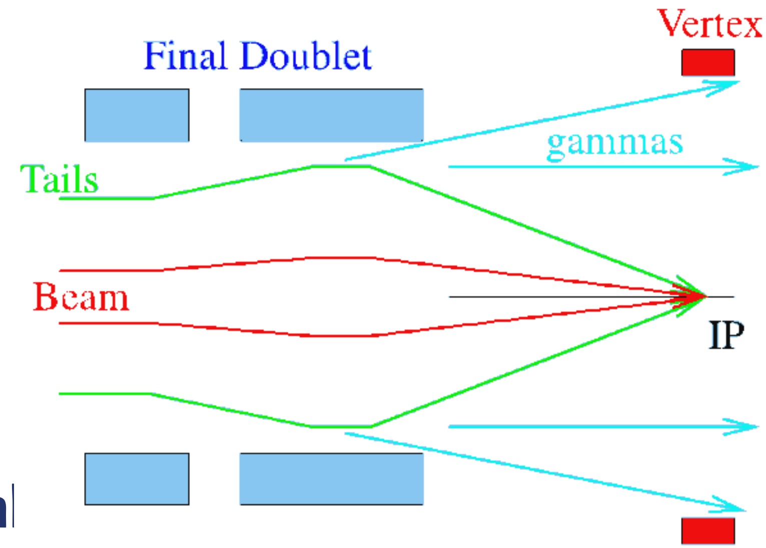
=> $\theta_{halo}/\theta_{beam}$ (collimation depth) becomes tighter with larger L* or smaller IP beam size

- Tighter collimation => MPS issues, collimation wake-fields, higher muon flux from collimators, etc.

More details on collimation

- Collimators has to be placed far from IP, to minimize background
- Ratio of beam/halo size at FD and collimator (placed in "FD phase") remains

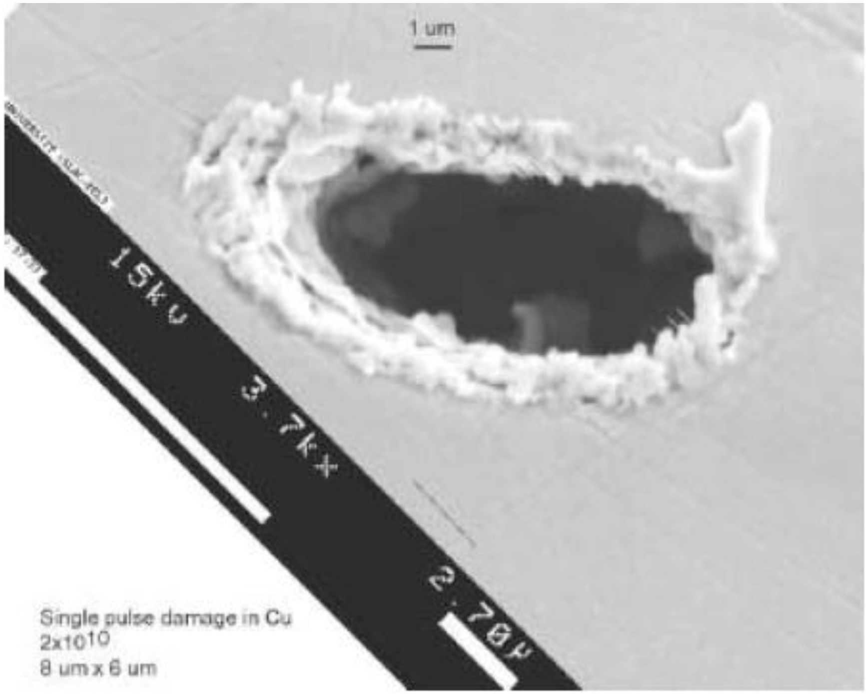




- Collimation depth (esp. in x) can be onl
- It is not unlikely that not only halo (1e-3 – 1e-6 of the beam) but full errant bunch(s) would hit the collimator

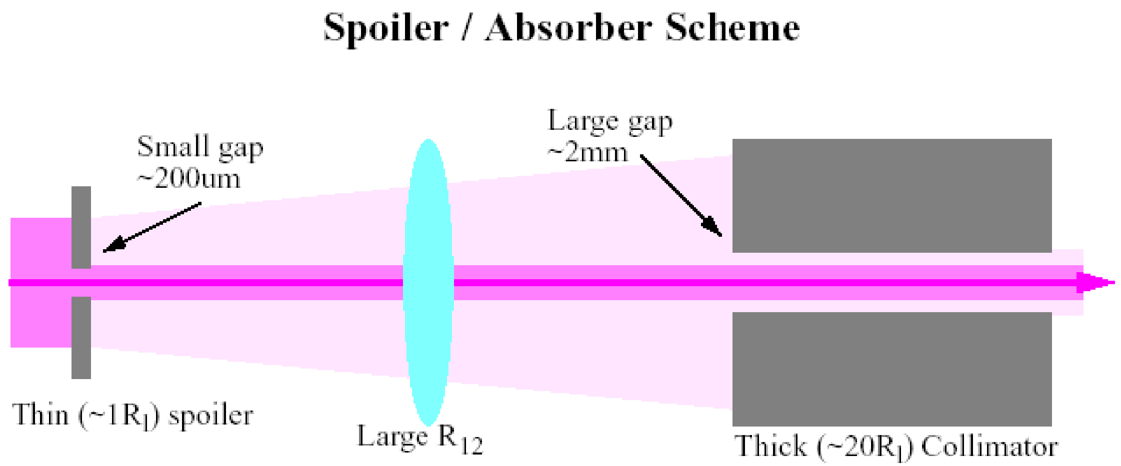
MPS and collimation design

- The beam is very small => single bunch can punch a hole => the need for MPS (machine protection system)
- Damage may be due to
  - electromagnetic shower damage (need several radiation lengths to develop)
  - direct ionization loss (~1.5MeV/g/cm^2 for most materials)
- Mitigation of collimator damage
  - using spoiler-absorber pairs
    - thin (0.5-1 rl) spoiler followed by thick (~20rl) absorber
  - increase of beam size at spoilers
  - MPS divert the beam to emergency extraction as soon as possible



Picture from beam damage experiment at FFTB. The beam was 30GeV, 3-20x10^9 e-, 1mm bunch length, s~45-200um^2. Test sample is Cu, 1.4mm thick. Damage was observed for densities > 7x10^{14}e-/cm^2. Picture is for 6x10^{15}e-/cm^2

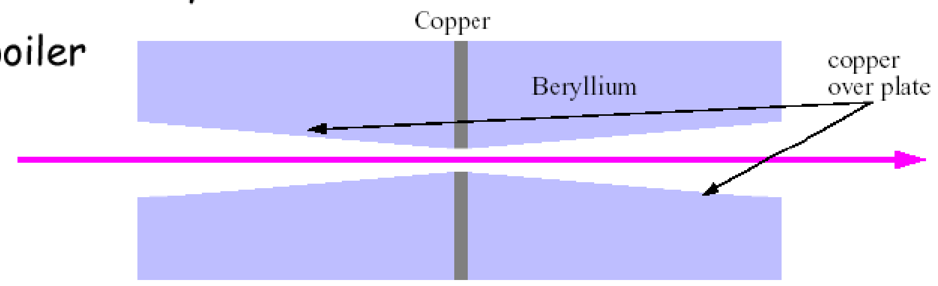
Spoiler-Absorber & spoiler design

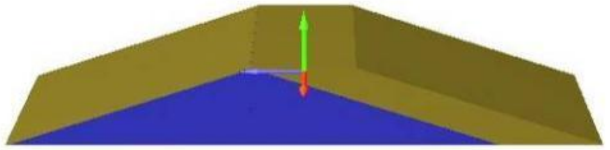


Thin spoiler increases beam divergence and size at the thick absorber already sufficiently large. Absorber is away from the beam and contributes much less to wakefields.

Tapered low resistivity surface for wakefields

Thin hi-Z spoiler





Recently considered design: 0.6 Xo of Ti alloy leading taper (gold), graphite (blue), 1 mm thick layer of Ti alloy

Need the spoiler thickness increase rapidly, but need that surface to increase gradually, to minimize wakefields. The radiation length for Cu is 1.4cm and for Be is 35cm. So, Be is invisible to beam in terms of losses. Thin one micron coating over Be provides smooth surface for wakes.

Spoiler damage

Spoiler material properties and temperature rise due to a <u>single bunch</u> of 1.25×10^{10} electrons within a beam spot with $\sigma_x = \sigma_y = 3.16$ μm.

	Be	C	Al	Ti	Cu	Fe
	35.7	21.7	9.0	3.7	1.4	1.8
Radiation Length (cm)						
dE/dx_{min} (MeV cm^{-1})	3.1	3.6	4.4	7.2	12.8	11.6
Specific Heat, C_p (J cm^{-3} °C^{-1})	3.3	1.9	2.5	2.4	3.5	3.8
Meltng Point, T_{melt} (°C)	1280	3600	660	1800	1080	1530
Stress Limit, T_{stress} (°C)	150	2500	140	770	180	135
Temperature Rise, ΔT (°C)	2350	4740	4403	7506	9150	7637
$\Delta T / T_{melt}$	1.8	1.3	6.7	4.2	8.5	5.0
$\Delta T / 4T_{stress}$	3.9	0.36	7.9	2.4	12.7	14.1

Temperature rise for thin spoilers (ignoring shower buildup and increase of specific heat with temperature):

$$\Delta T = \frac{0.393N}{\pi\sigma_x\sigma_y}\frac{dE/dx_{min}}{C_p}$$

The stress limit based on tensile strength, modulus of elasticity and coefficient of thermal expansion. Sudden T rise create local stresses. When ΔT exceed stress limit, micro-fractures can develop. If ΔT exceeds $4T_{stress}$, the shock wave may cause material to delaminate. Thus, allowed ΔT is either the melting point or four time stress limit at which the material will fail catastrophically.

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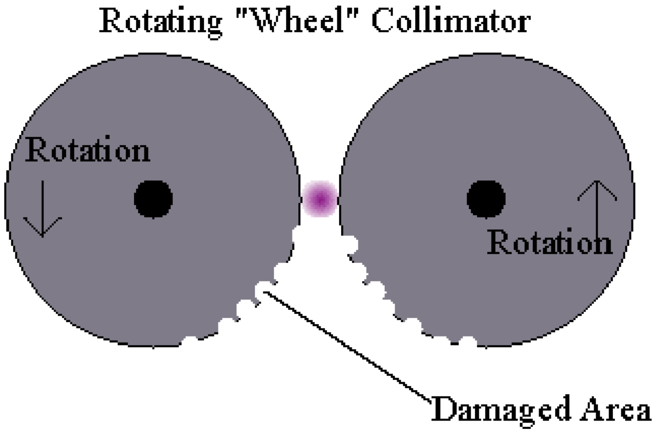
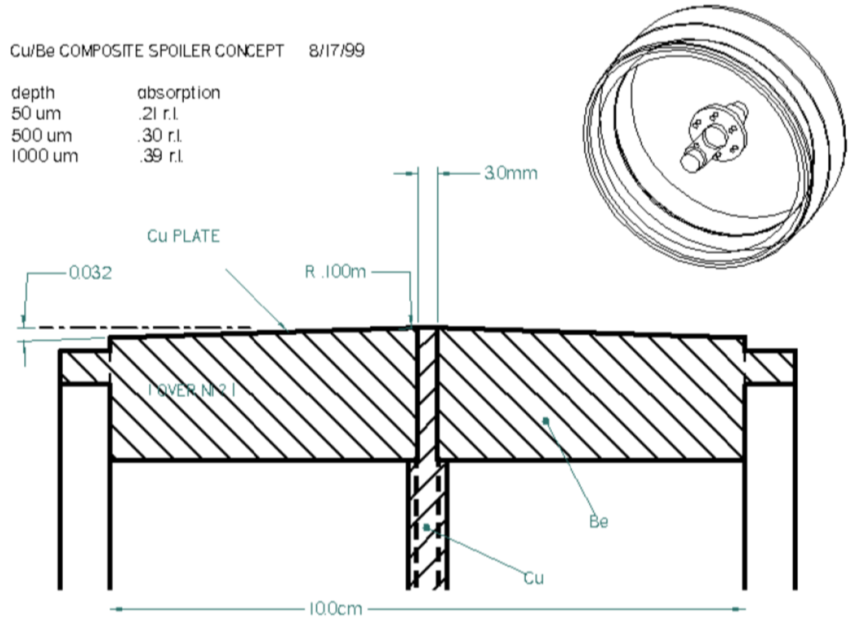
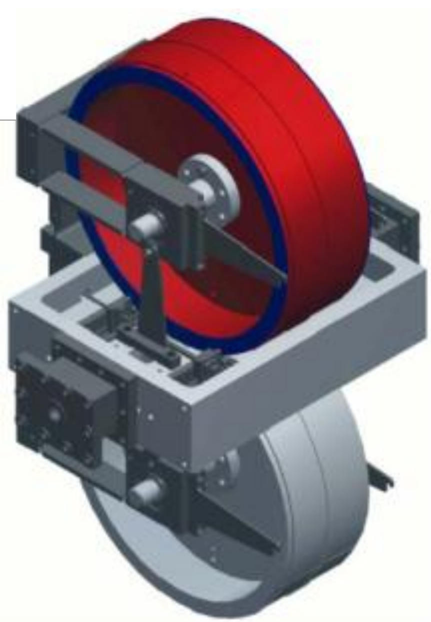
Survivable and consumable spoilers

- A critical parameter is number of bunches #N that MPS will let through to the spoiler before sending the rest of the train to emergency extraction
- If it is practical to increase the beam size at spoilers so that spoilers survive #N bunches, then they are survivable
- Otherwise, spoilers must be consumable or renewable

Renewable spoilers





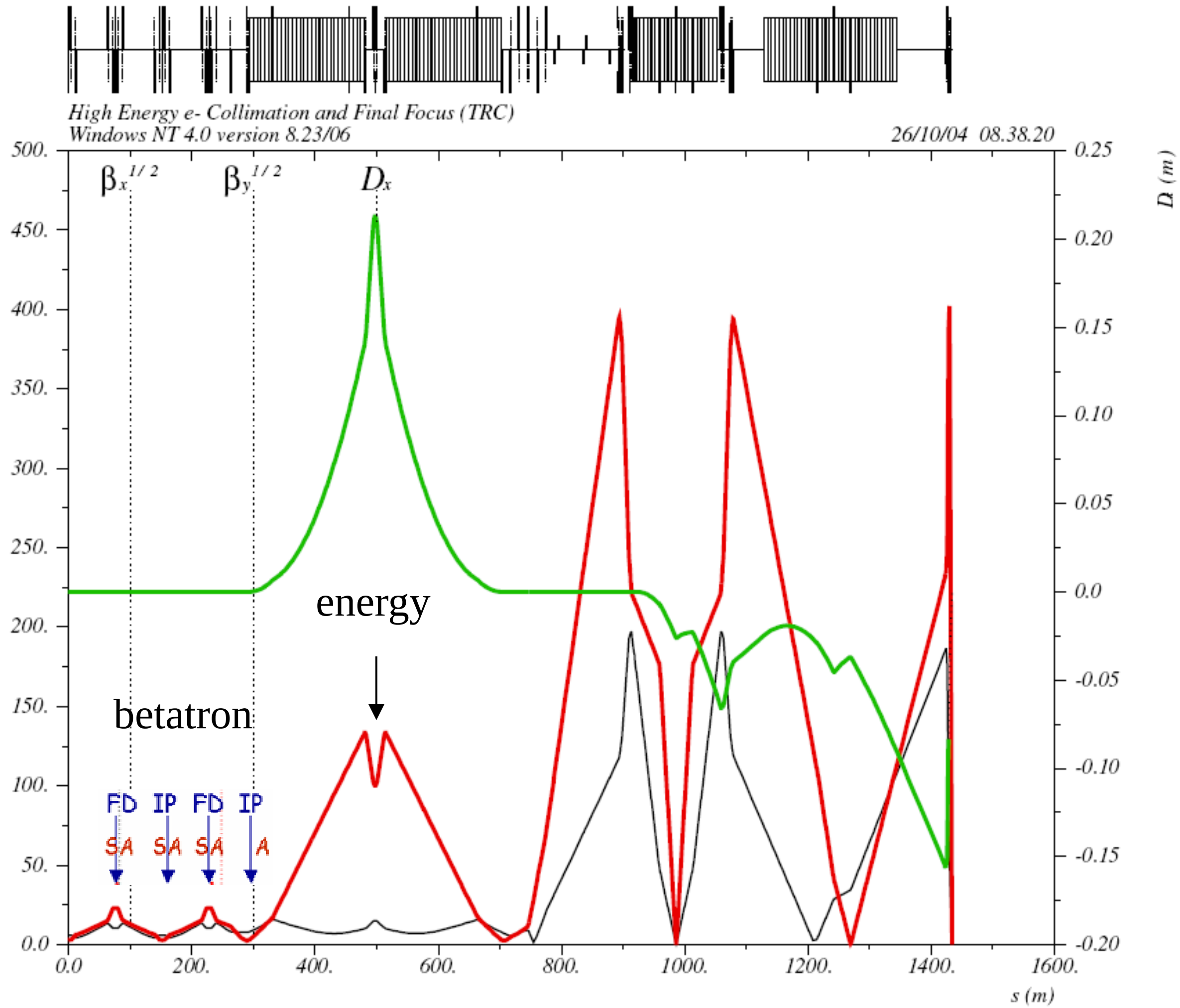


This design was essential for NLC, where short inter-bunch spacing made it impractical to use survivable spoilers.

This concept is now being applied to LHC collimator system.

BDS with renewable spoilers

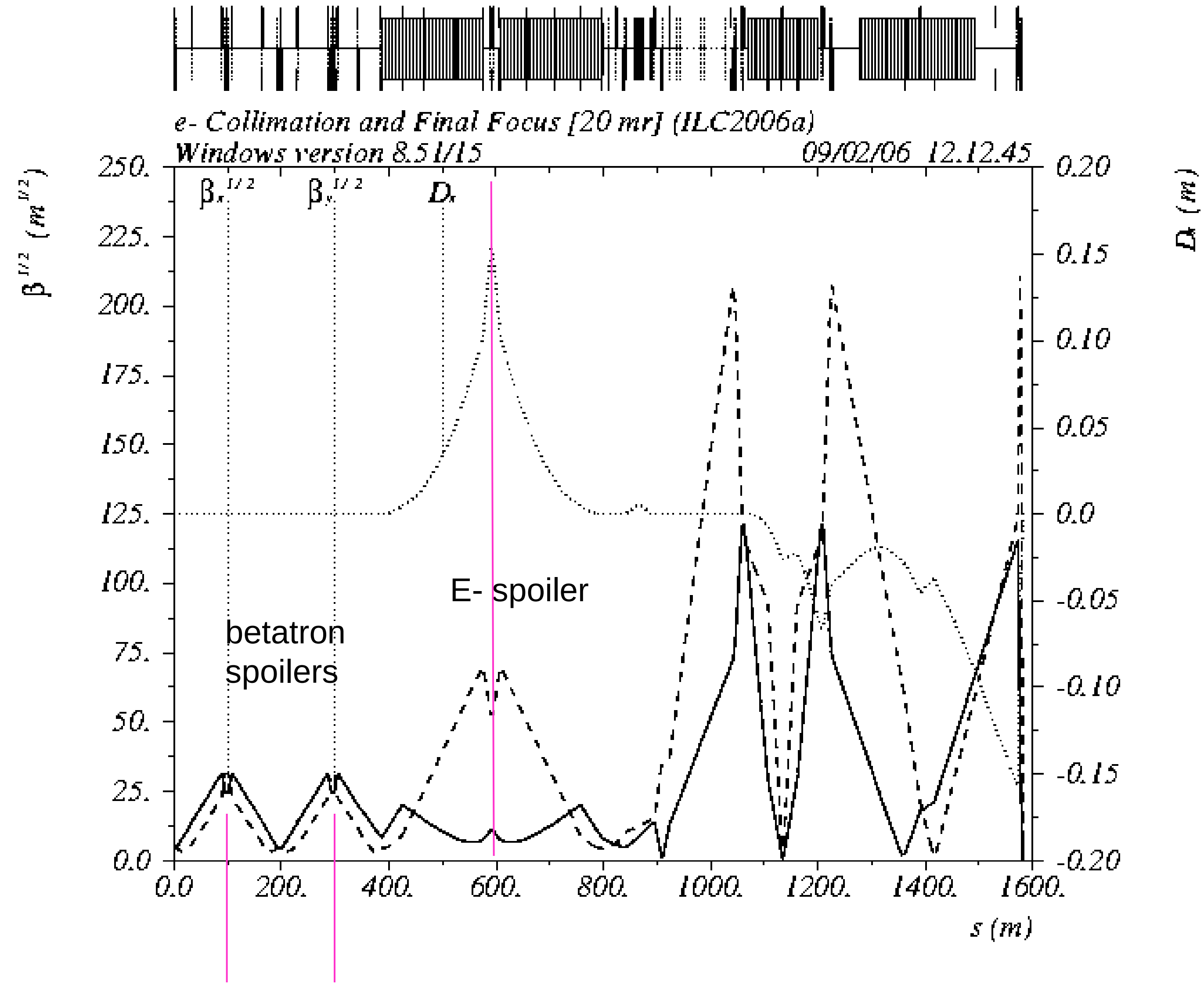
- Location of spoiler and absorbers is shown
- Collimators were placed both at FD betatron phase and at IP phase
- Two spoilers per FD and IP phase
- Energy collimator is placed in the region with large dispersion
- Secondary clean-up collimators located in FF part
- Tail folding octupoles (see below) are included



- Beam Delivery System Optics, an earlier version with consumable spoilers

ILC FF & Collimation

- Betatron spoilers survive up to two bunches
- E-spoiler survive several bunches
- One spoiler per FD or IP phase



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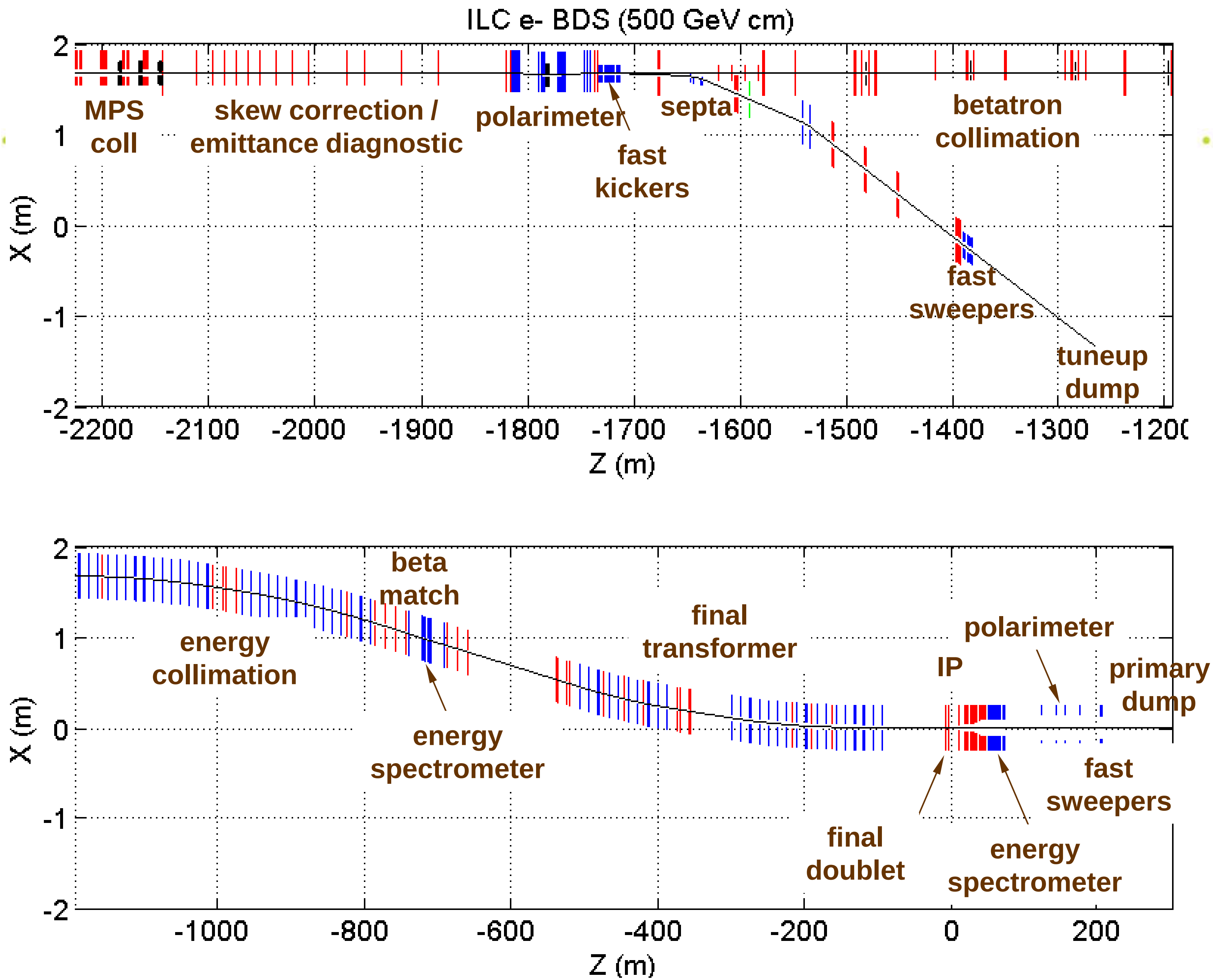
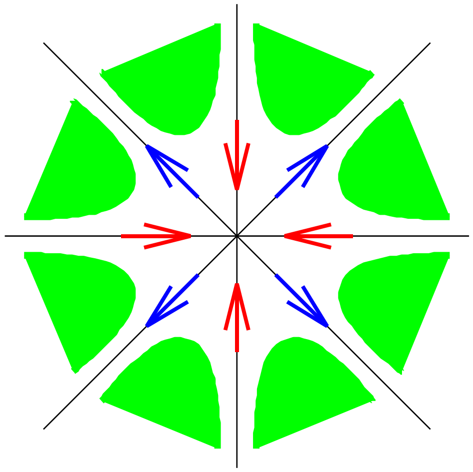

ILC e- BDS (500 GeV cm)
MPS coll
skew correction / emittance diagnostic
polarimeter
fast kickers
septa
betatron collimation
fast sweepers
tuneup dump
X (m)
Z (m)
energy collimation
beta match
energy spectrometer
final transformer
IP
polarimeter
primary dump
fast sweepers
final doublet
energy spectrometer
X (m)
Z (m)

Nonlinear handling of beam tails in ILC BDS

- **Can we ameliorate the incoming beam tails to relax the required collimation depth?**
- One wants to **focus beam tails** but not to change the core of the beam
  - use **nonlinear** elements
- **Several** nonlinear elements needs to be **combined** to provide **focusing in all directions**
  - (analogy with **strong focusing by FODO**)
- **Octupole Doublets (OD)** can be used for **nonlinear tail folding** in ILC FF



Single octupole focus in planes and defocus on diagonals.

An octupole doublet can focus in all directions !

Strong focusing by octupoles

- **Two octupoles** of different sign separated by **drift** provide **focusing in all directions for parallel beam:**

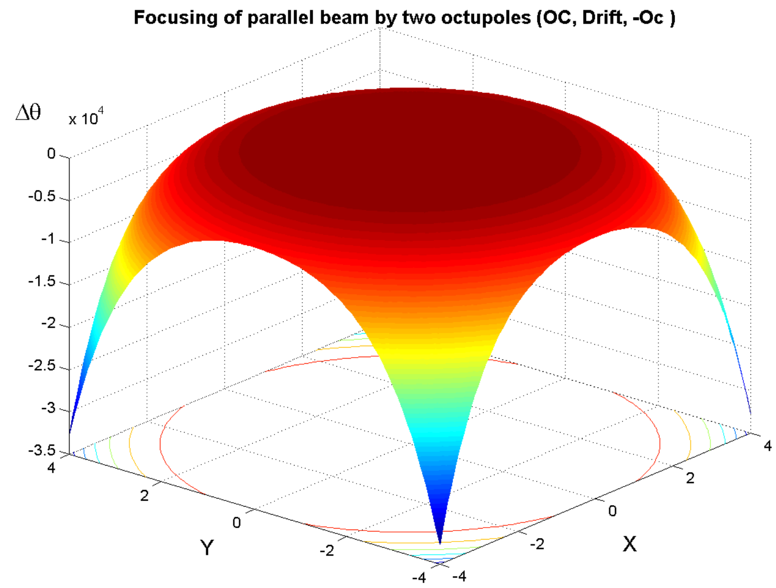
$$\Delta\theta = \alpha r^3 e^{-i3\varphi} - \left(\alpha r^3 e^{i3\varphi}\left(1+\alpha r^2 L e^{-i4\varphi}\right)^3\right)^*$$

$$x + iy = re^{i\varphi}$$

$$\Delta\theta \approx -3\alpha^2 r^5 e^{i\varphi} - 3\alpha^3 r^7 L^2 e^{i5\varphi}$$

Focusing in <u>all directions</u>

Next nonlinear term focusing – defocusing depends on φ

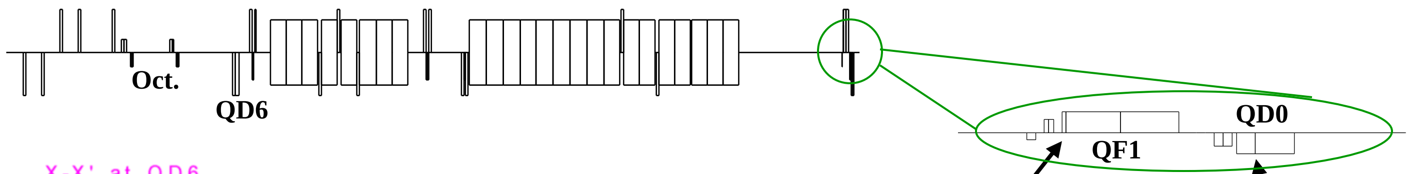


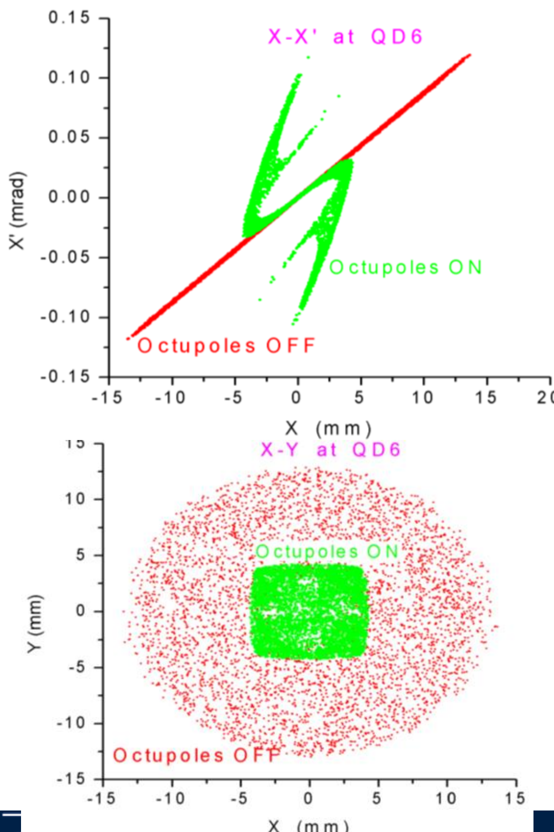
Effect of octupole doublet (Oc,Drift,-Oc) on parallel beam, ΔΘ(x,y).

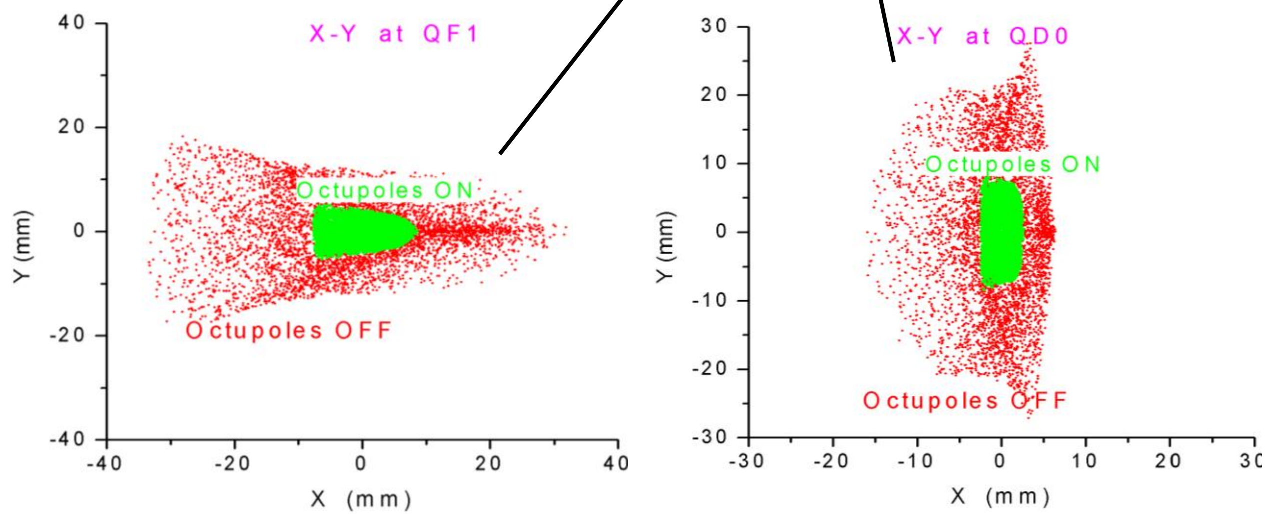
- For this to work, the beam should have **small angles**, i.e. it should be parallel or **diverging**

Tail folding in ILC FF

- **Two octupole doublets give tail folding by ~ 4 times in terms of beam size in FD**
- **This can lead to relaxing collimation requirements by ~ a factor of 4**

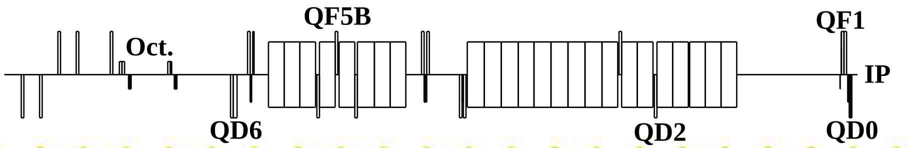


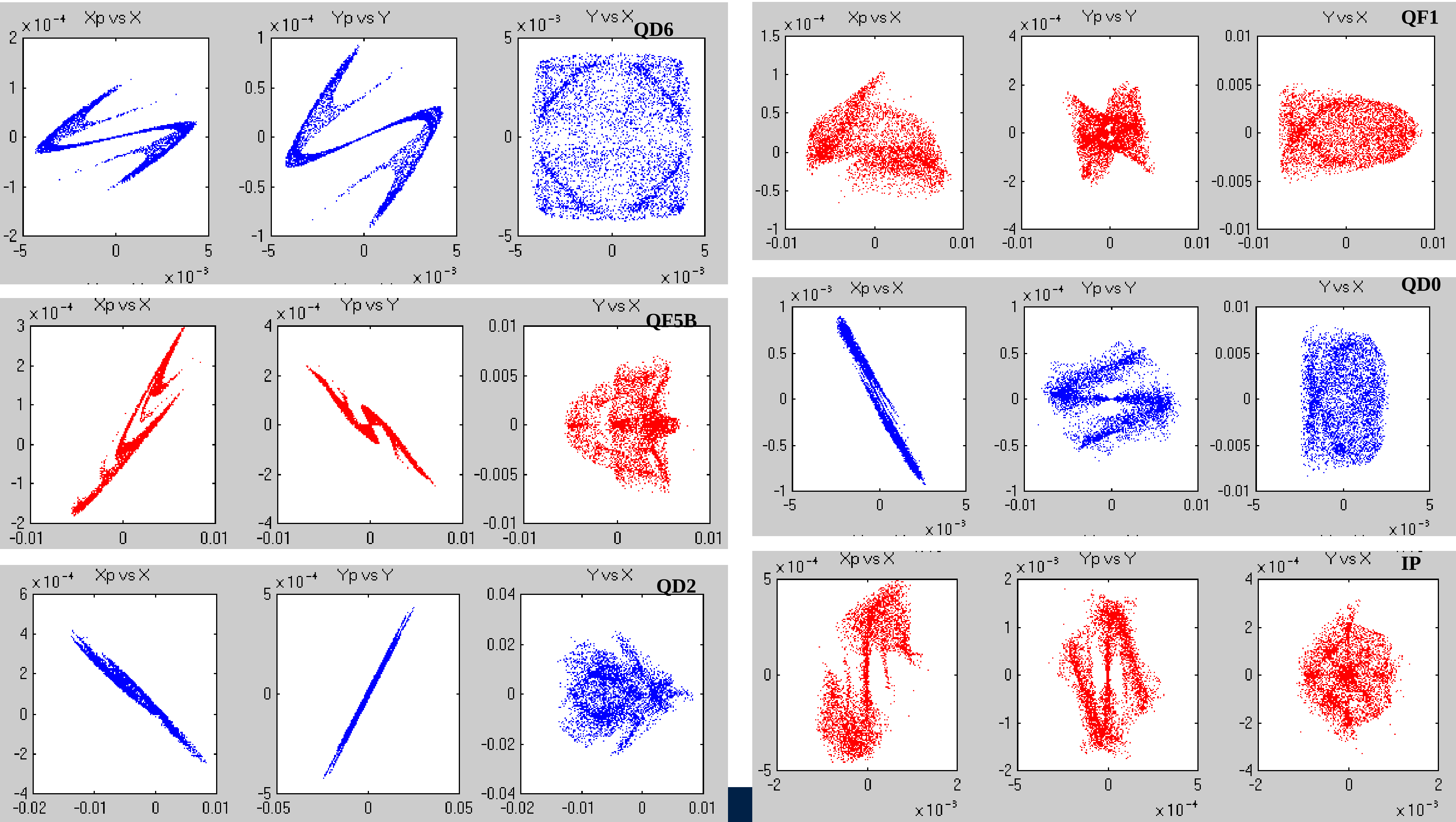




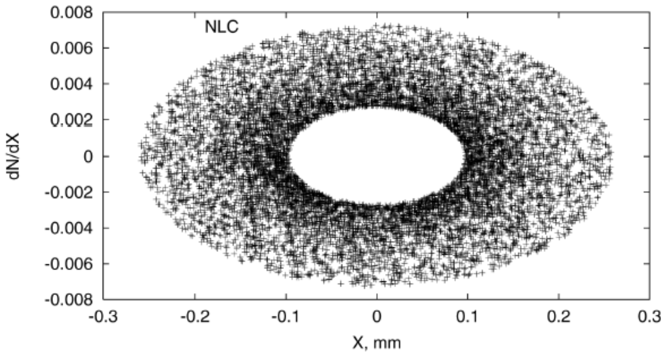
Tail folding by means of two octupole doublets in the ILC final focus
Input beam has (x,x',y,y') = (14μm,1.2mrad,0.63μm,5.2mrad) in IP units (flat distribution, half width) and ±2% energy spread,
that corresponds approximately to N_σ=(65,65,230,230) sigmas with respect to the nominal beam

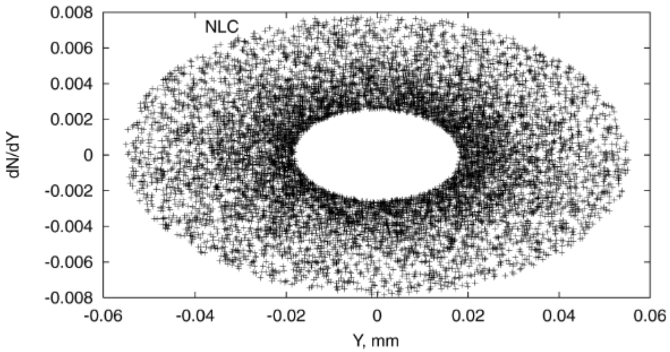
Tail folding
or Origami Zoo

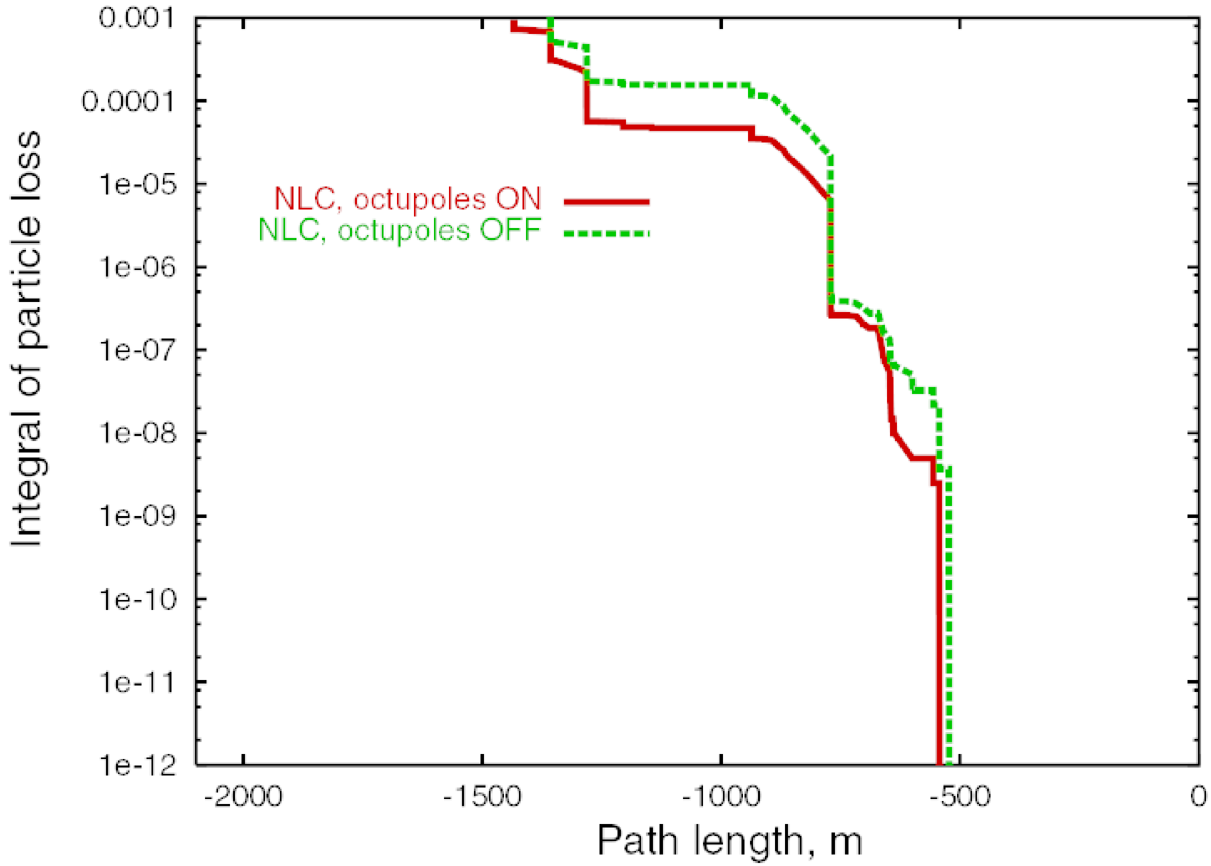




Halo collimation







Assumed halo sizes. Halo population is 0.001 of the main beam.

Assuming 0.001 halo, beam losses along the beamline behave nicely, and SR photon losses occur only on dedicated masks

Smallest gaps are +-0.6mm with tail folding Octupoles and +-0.2mm without them.

Collimator wakes

- Effect from offset of the beam at the collimator:

$$\Delta y' = K\, y$$

- Assume that beam jitter is a fixed fraction of the beam size

$$\frac{\Delta y'}{\sigma_{y'}} = K \frac{\sigma_y}{\sigma_{y'}} \frac{y}{\sigma_y}$$

- Jitter amplification factor

$$A_\beta = K \frac{\sigma_y}{\sigma_{y'}}$$

For locations with α=0 => $A_\beta = K\,\beta$

- If jitter is fraction of size in all planes, and y & y' not correlated , the fractional incoming jitter increases by

$$\sqrt{1 + A_\beta^2}$$

Following P.Tenenbaum, LCC-101 and G.Stupakov, PAC2001

Wakes for tapered collimators

- Rectangular collimators

3.1 r/h | 0.37 | $\sqrt{\alpha r/\sigma_z}$

$$K = \frac{\sqrt{\pi}}{2}\frac{N r_e}{\gamma}\frac{\alpha h}{\sigma_z r^2}$$

$$K = 2.7\frac{N r_e}{\gamma}\sqrt{\frac{\alpha}{\sigma_z r^3}}$$

$$K = \frac{N r_e}{\gamma}\frac{1}{r^2}$$

- where α is tapering angle, r is half gap, h is half width

Following P.Tenenbaum, LCC-101 and G.Stupakov, PAC2001

Wakes for tapered collimators

- Circular collimators

$$2\sqrt{\pi}$$

$$\alpha\, r / \sigma_z$$

$$K = \frac{N\, r_e}{\gamma} \frac{\alpha}{\sqrt{\pi}\, \sigma_z\, r}$$

inductive regime (smooth transition)

$$K = \frac{N\, r_e}{\gamma} \frac{2}{r^2}$$

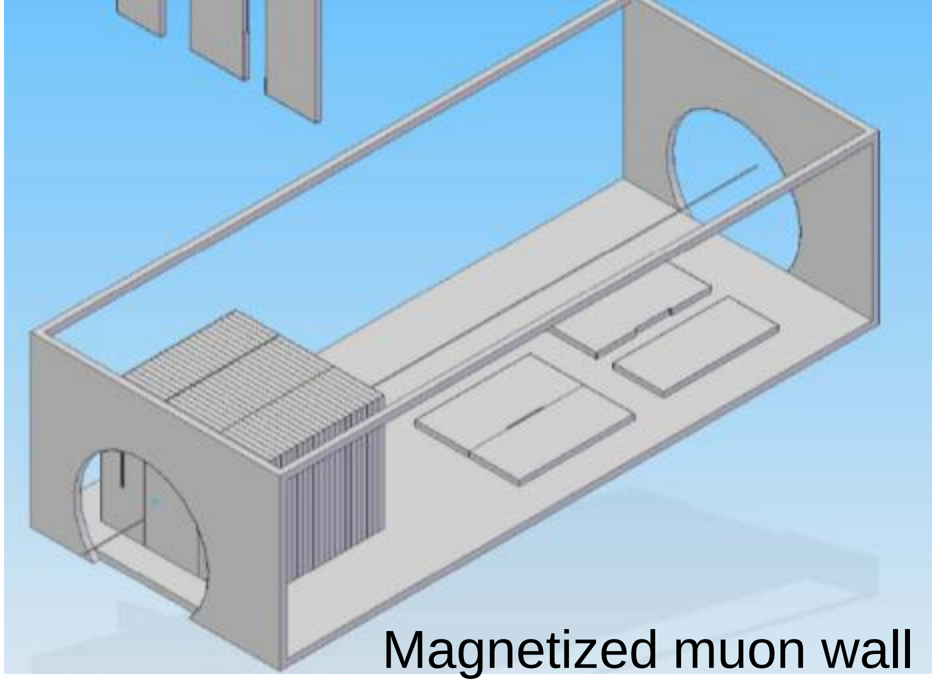
diffractive regime (sudden transition)

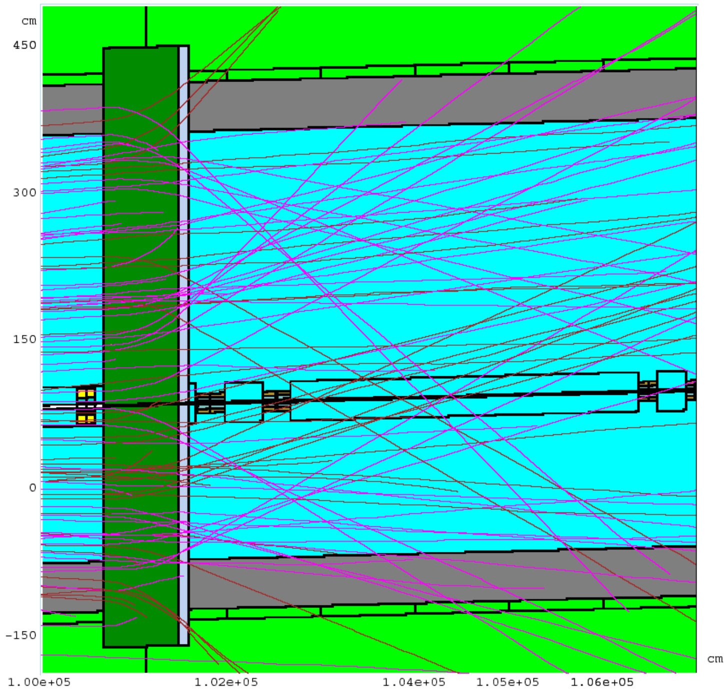
- where α is tapering angle, r is half gap

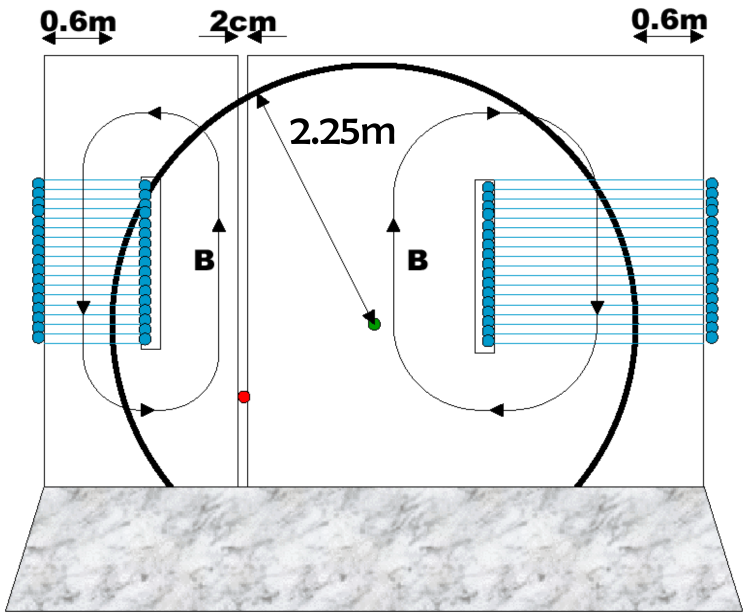
Following P.Tenenbaum, LCC-101 and G.Stupakov, PAC2001

Dealing with muons in BDS

- Muons are produced during collimation
- Muon walls, installed ~300m from IP, reduce muon background in the detectors


Magnetized muon wall





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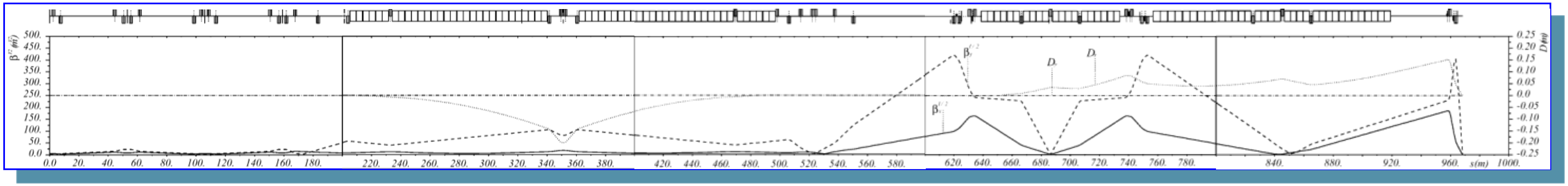
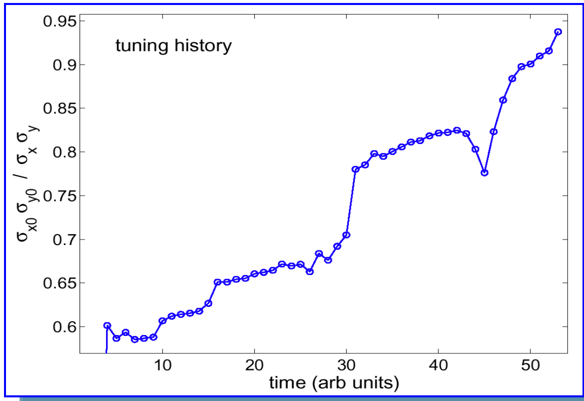
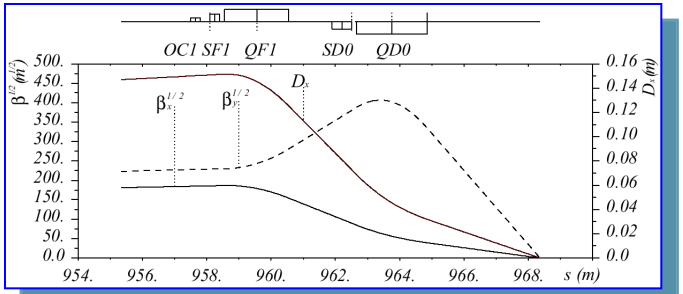
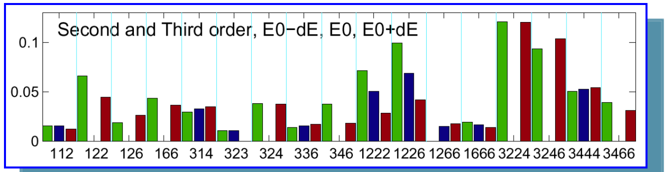
BDS design methods & examples

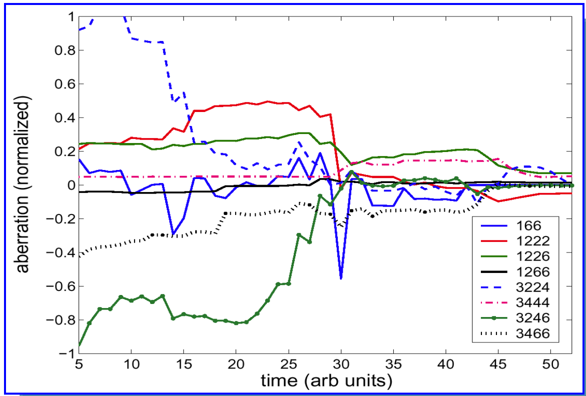


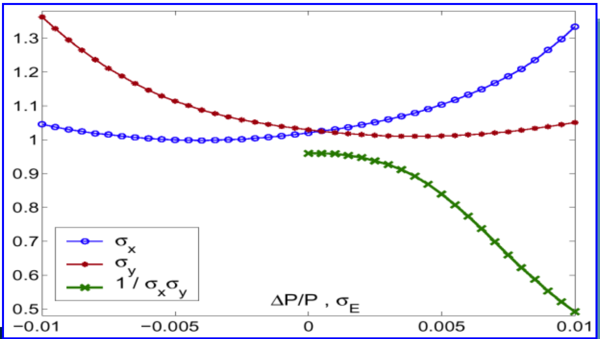


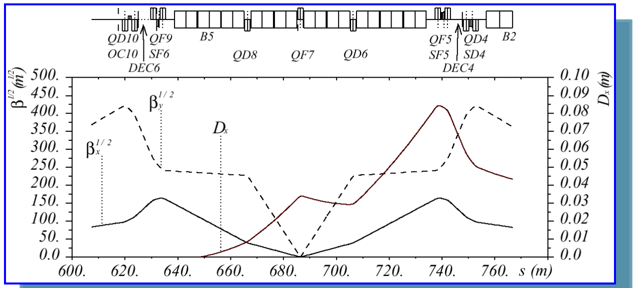
Example of a 2nd IR BDS optics for ILC; design history; location of design knobs







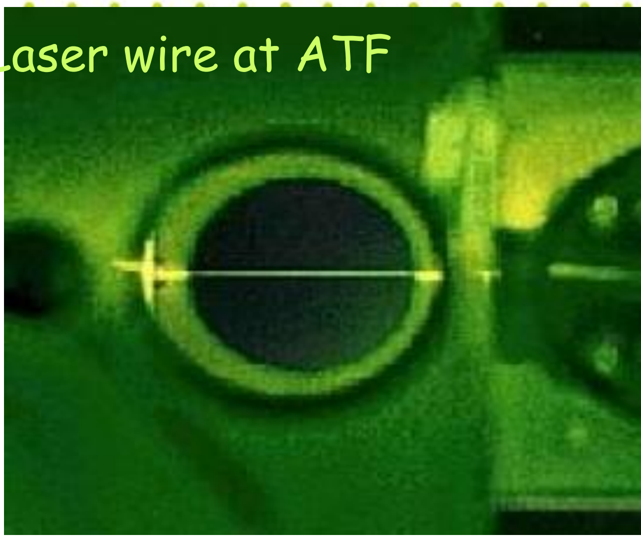




In a practical situation …

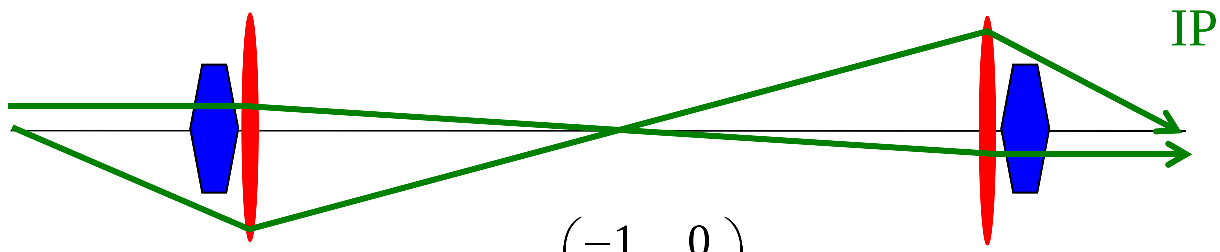
- While **designing** the FF, one has a **total control**
- When the system is built, one has just limited number of observable parameters (measured orbit position, beam size measured in several locations)
- The system, however, may initially have **errors** (errors of strength of the elements, transverse misalignments) and initial aberrations may be large
- **Tuning** of FF is done by optimization of "**knobs**" (strength, position of group of elements) chosen to affect some particular aberrations
- Experience in SLC FF and FFTB, and simulations with new FF give confidence that this is possible

Laser wire at ATF

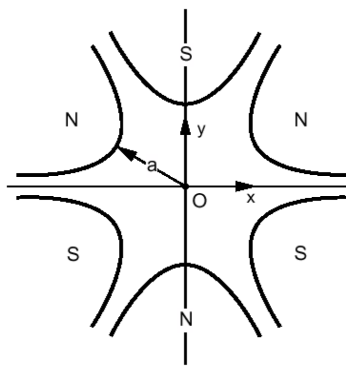


Laser wire will be a tool for tuning and diagnostic of FF

Sextupole knobs for BDS tuning



$$R_{X,Y} = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix}$$



SEXTUPOLE

Second order effect:

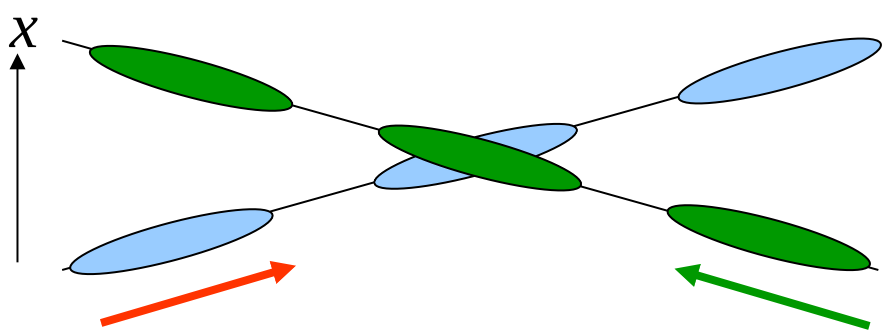
$x' = x' + S\,(x^2 - y^2)$

$y' = y' - S\,2xy$

- Combining offsets of sextupoles (symmetrical or anti-symmetrical in X or Y), one can produce the following corrections at the IP
  - waist shift
  - coupling
  - dispersion

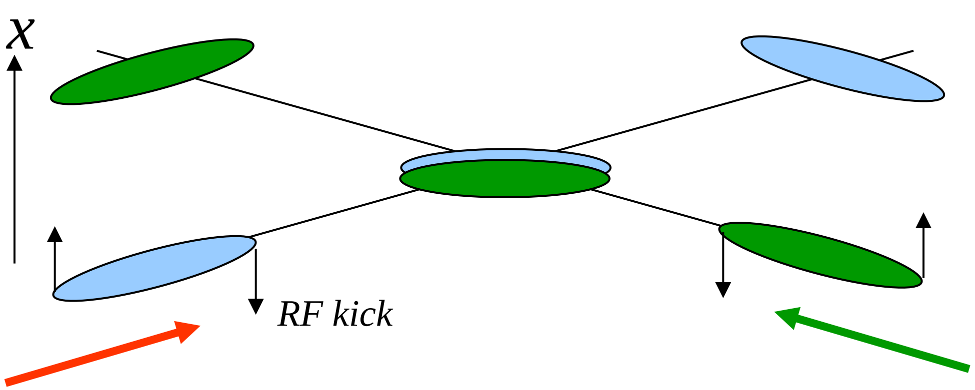
To create these knobs, sextupole placed on movers

Crab crossing

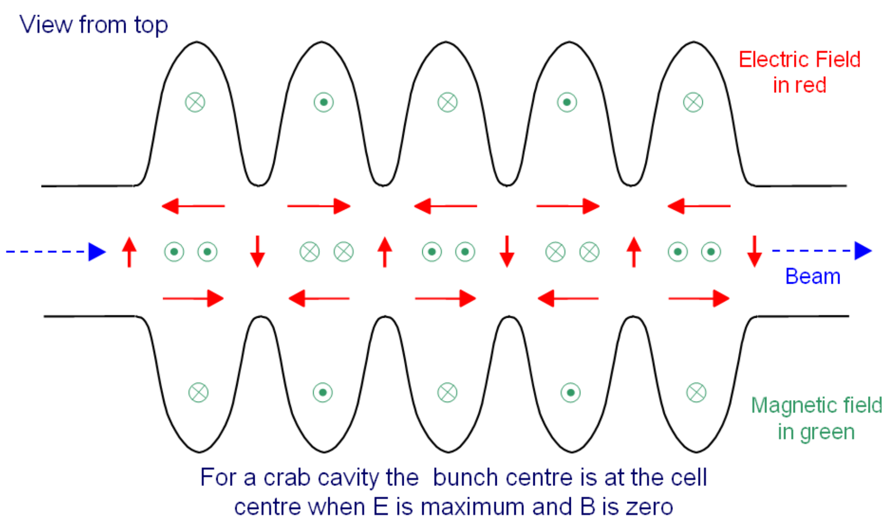


With crossing angle θ_c, the projected x-size is $(\sigma_x^2+\theta_c^2\sigma_z^2)^{0.5} \sim\theta_c\sigma_z \sim 4\mu m$

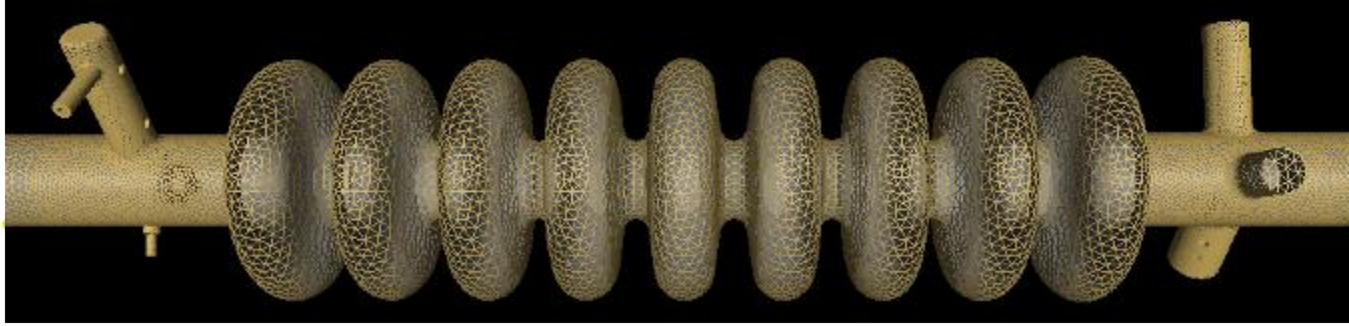
→ several time reduction in *L* without corrections



Use transverse (crab) RF cavity to 'tilt' the bunch at IP



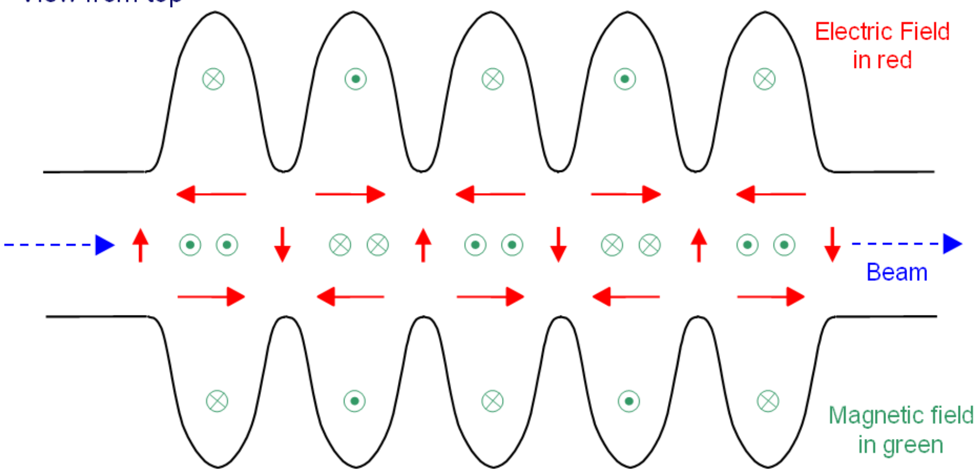
Crab cavity design



FNAL 3.9GHz 9-cell cavity in Opega3p. *K.Ko, et al*

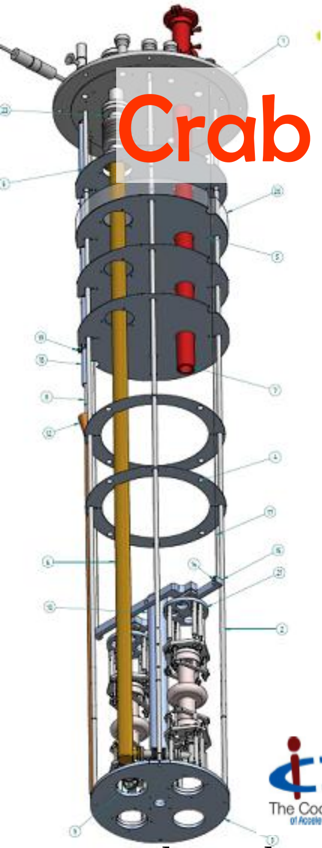
- Prototypes of crab cavity built at FNAL and 3d RF models
- Design & prototypes been done by UK-FNAL-SLAC collaboration

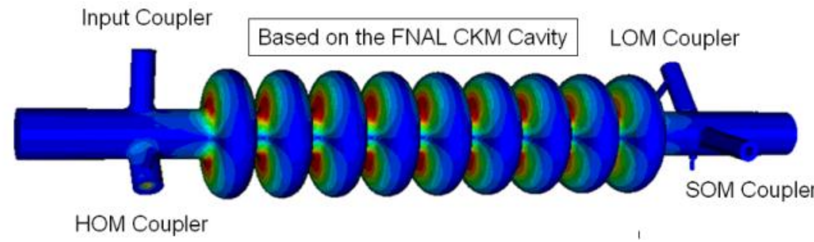
3.9GHz cavity achieved 7.5 MV/m (FNAL)

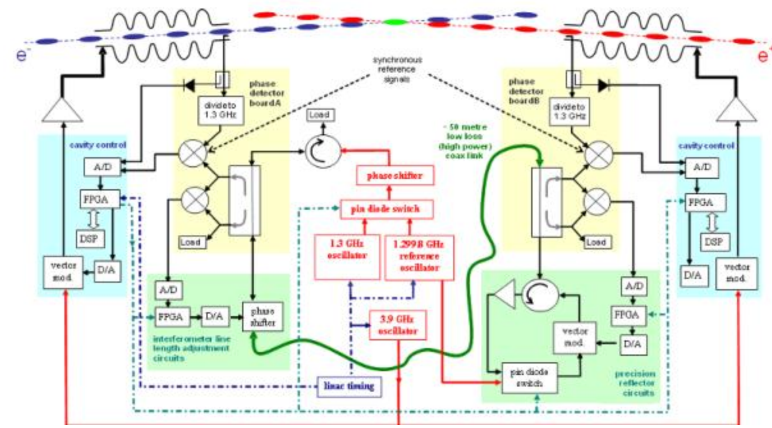


TM110 Dipole mode cavity

Crab cavity





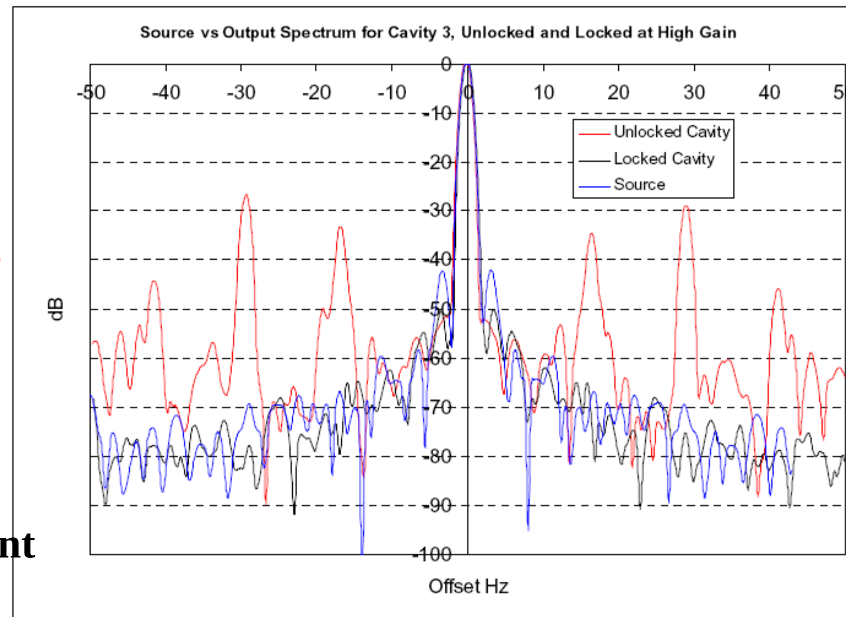


Cavities limited in gradient to 1 MV/m (~40kV/cell) – shielding implications.

The Cockcroft Institute of Accelerator Science and Technology

ASTeC

SLAC ACD



Independent phase lock achieved for both cavities:

– **Unlocked => 10º r.m.s.**

– **Locked => 0.135º r.m.s.**

• Performance limited by:

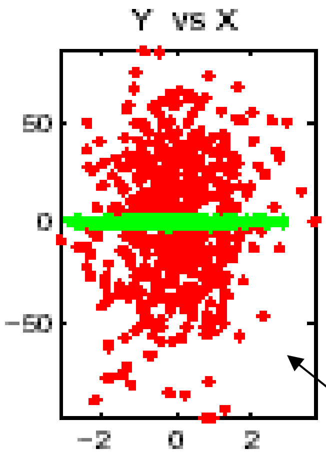
– **Source noise (dominant); ADC noise; Measurement noise; – Cavity frequency drift; Microphonics**

• Improvements being made; new tests being prepared

P.McIntosh at al

Imperial College London
Royal Holloway University of London
University of Oxford

IR coupling compensation

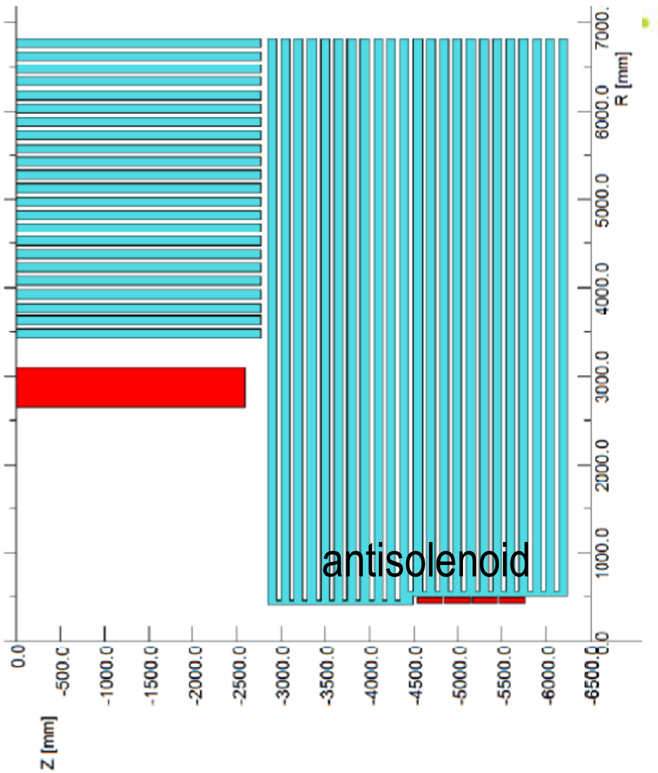


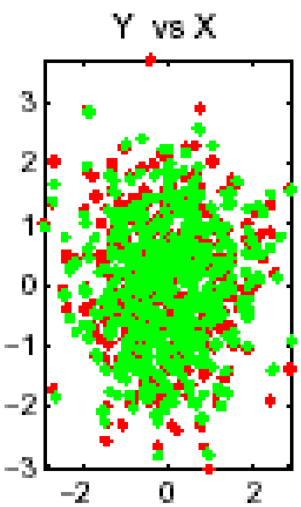
When detector solenoid overlaps QD0, coupling between y & x' and y & E causes large (30 – 190 times) increase of IP size (green=detector solenoid OFF, red=ON)

without compensation

$\sigma_y / \sigma_y(0)=32$

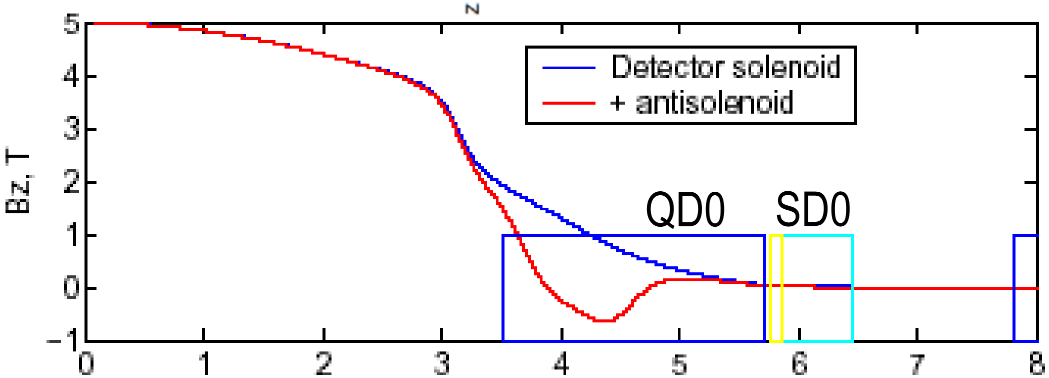
Even though traditional use of skew quads could reduce the effect, the local compensation of the fringe field (with a little skew tuning) is the most efficient way to ensure correction over wide range of beam energies



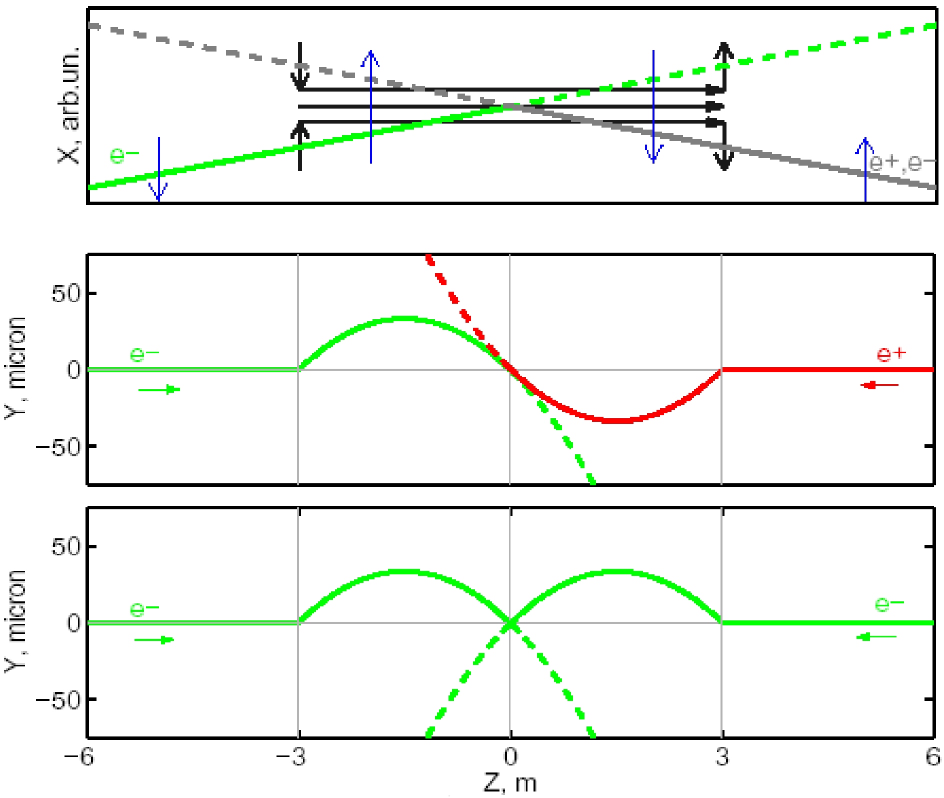


with compensation by antisolenoid

$\sigma_y / \sigma_y(0)<1.01$



Beam orbits near IR



- With a crossing angle, when beams cross solenoid field, vertical orbit arise
- For e+e- the orbit is anti-symmetrical and beams still collide head-on...

(ignore the effect of additional kicks shown by blue lines for the moment)

Orbits in the detector solenoid

Let us consider detector solenoid with sharp edges, as on the previous slide. In the case without compensation, the vertical deflection is caused by the edge kick

$$\Theta = \theta_c B_0 L / (2 B\rho)$$

which occurs when the beam enters the solenoid off axis at $\theta_c L$, and also by the kick linearly distributed in the body of the solenoid. Here θ_c is half of the crossing angle, L is the half-length of the detector solenoid, B_0 is the solenoid field, and $B\rho$ = pc/e is the magnetic rigidity of the beam.

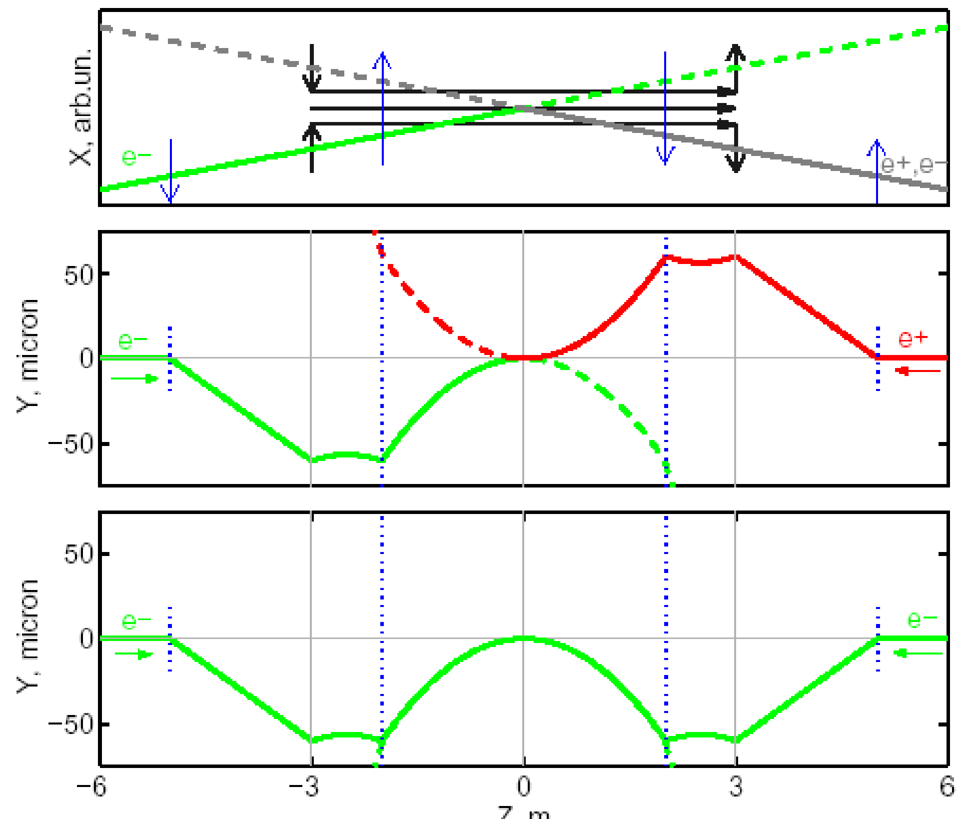
The body kick integrated from the solenoid entrance to the IP is equal to -2Θ, which is twice the edge kick, and since the body kick has half the lever arm, the resulting vertical offset at the IP cancels exactly.

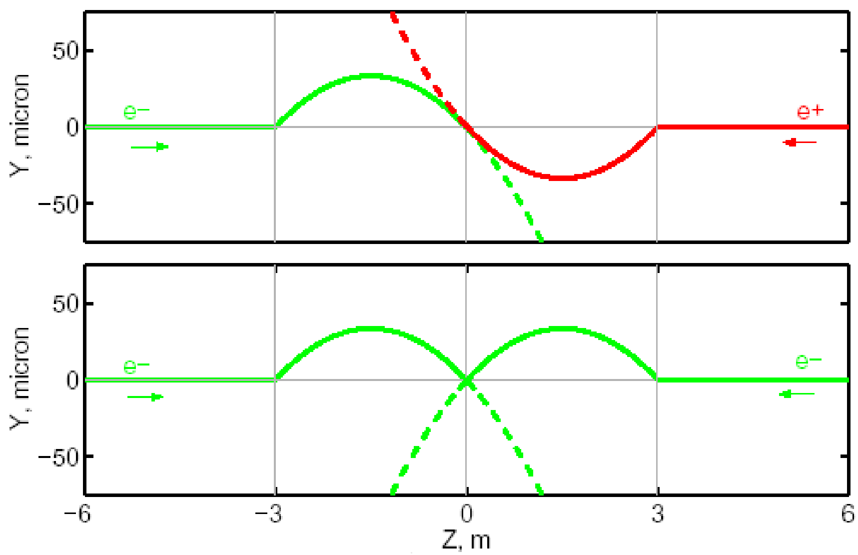
The remaining vertical angle at the IP is nonzero and equals $-\Theta$. The maximal deviation of the vertical orbit before the collision is $\Theta L/4$.

The vertical angle of the extracted beam, which passes through the entire solenoid, is -2Θ and the vertical offset at the exit is $-3\Theta L$.

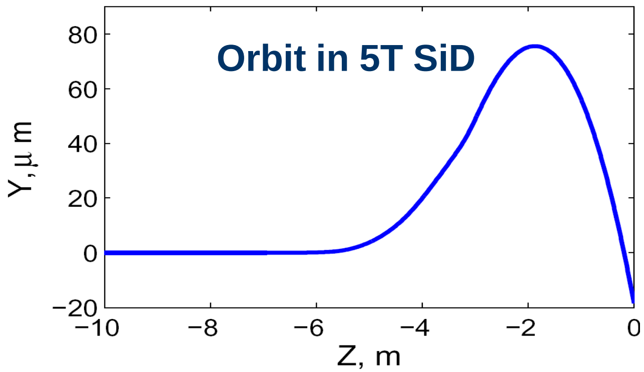
Detector Integrated Dipole

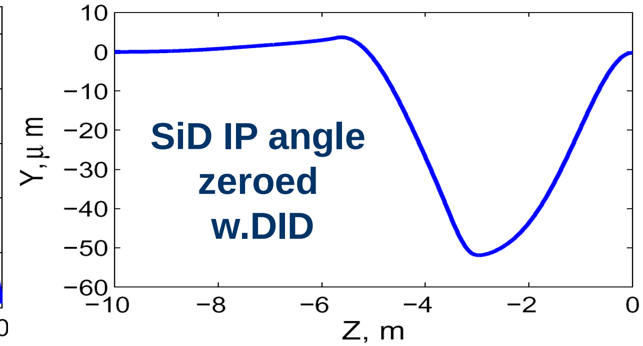
- With a crossing angle, when beams cross solenoid field, vertical orbit arise
- For e+e- the orbit is anti-symmetrical and beams still collide head-on
- If the vertical angle is undesirable (to preserve spin orientation or the e-e- luminosity), it can be compensated locally with DID
- Alternatively, negative polarity of DID may be useful to reduce angular spread of beam-beam pairs (anti-DID)





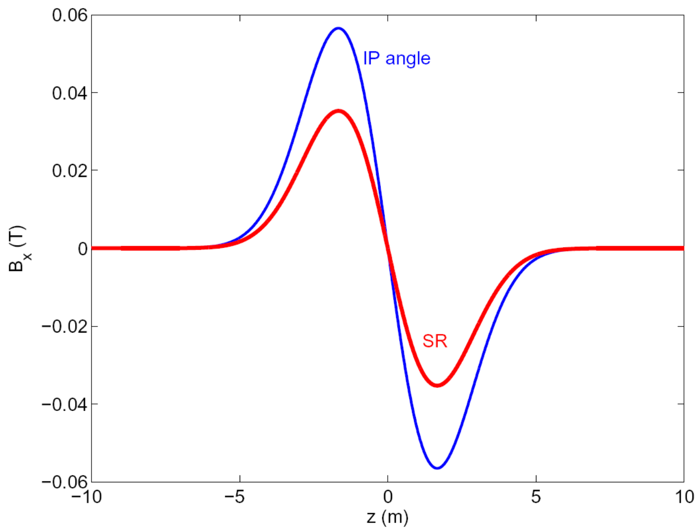
Use of DID or anti-DID

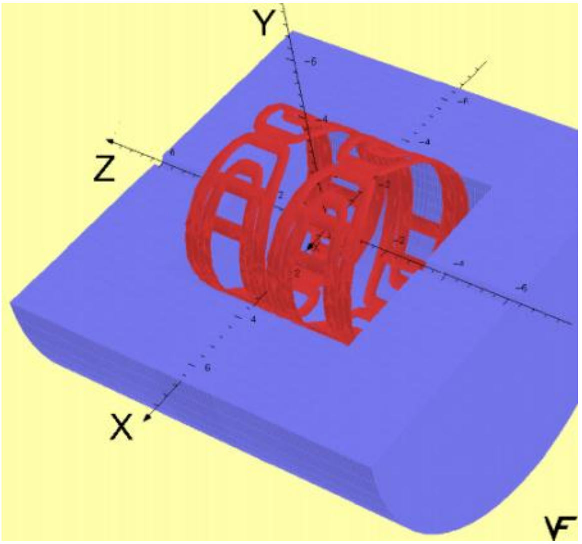




DID case

DID field shape and scheme

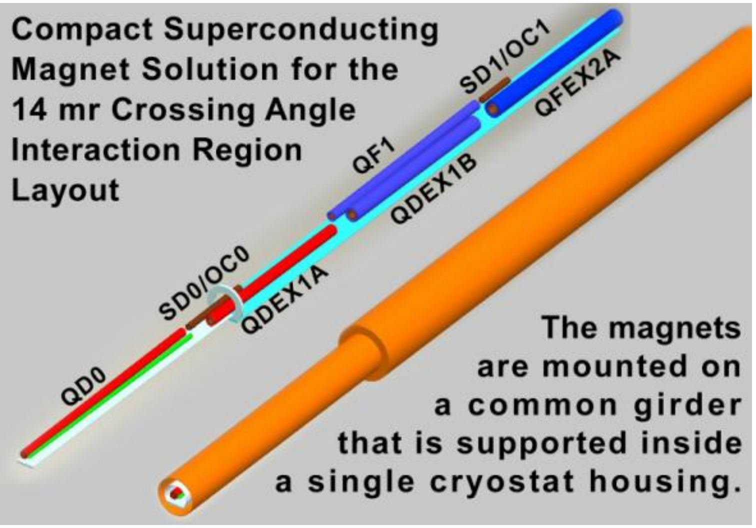


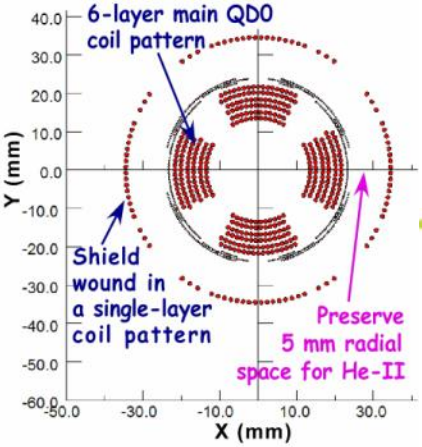


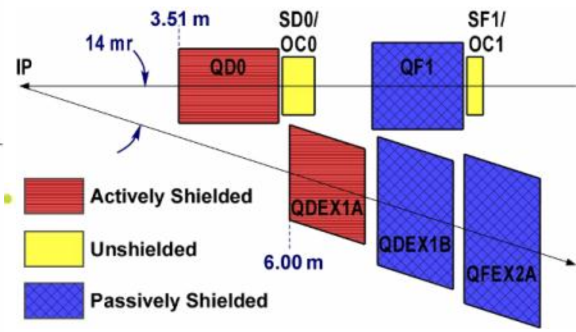
- The negative polarity of DID is also possible (called anti-DID)

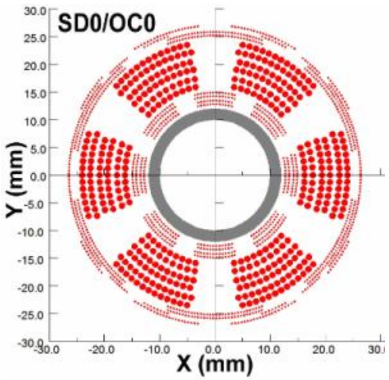
- In this case the vertical angle at the IP is somewhat increased, but the background conditions due to low energy pairs (see below) and are improved

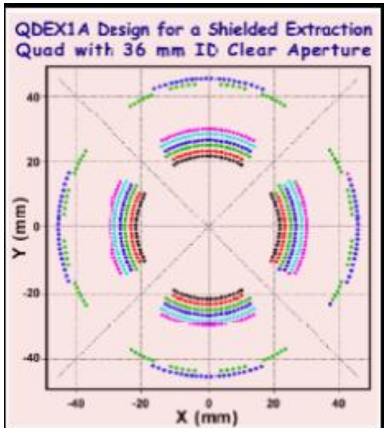
14 mrad IR

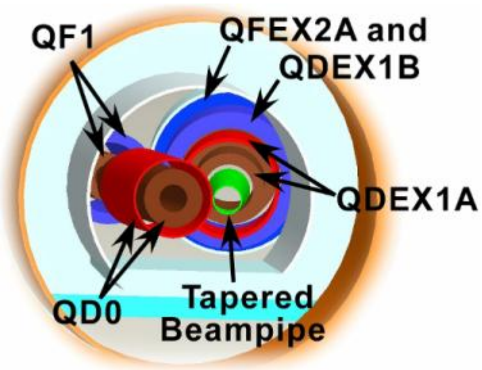


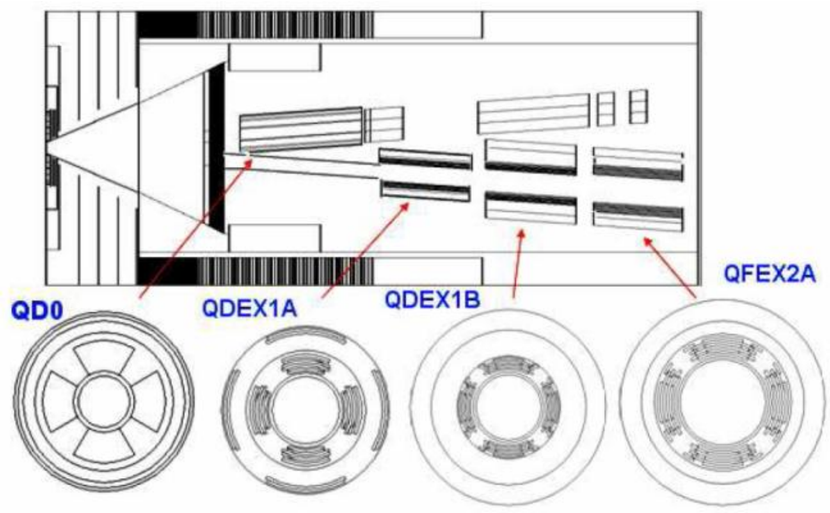


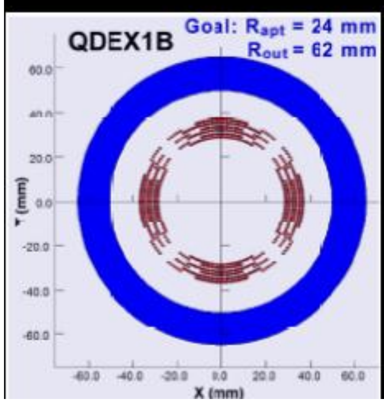






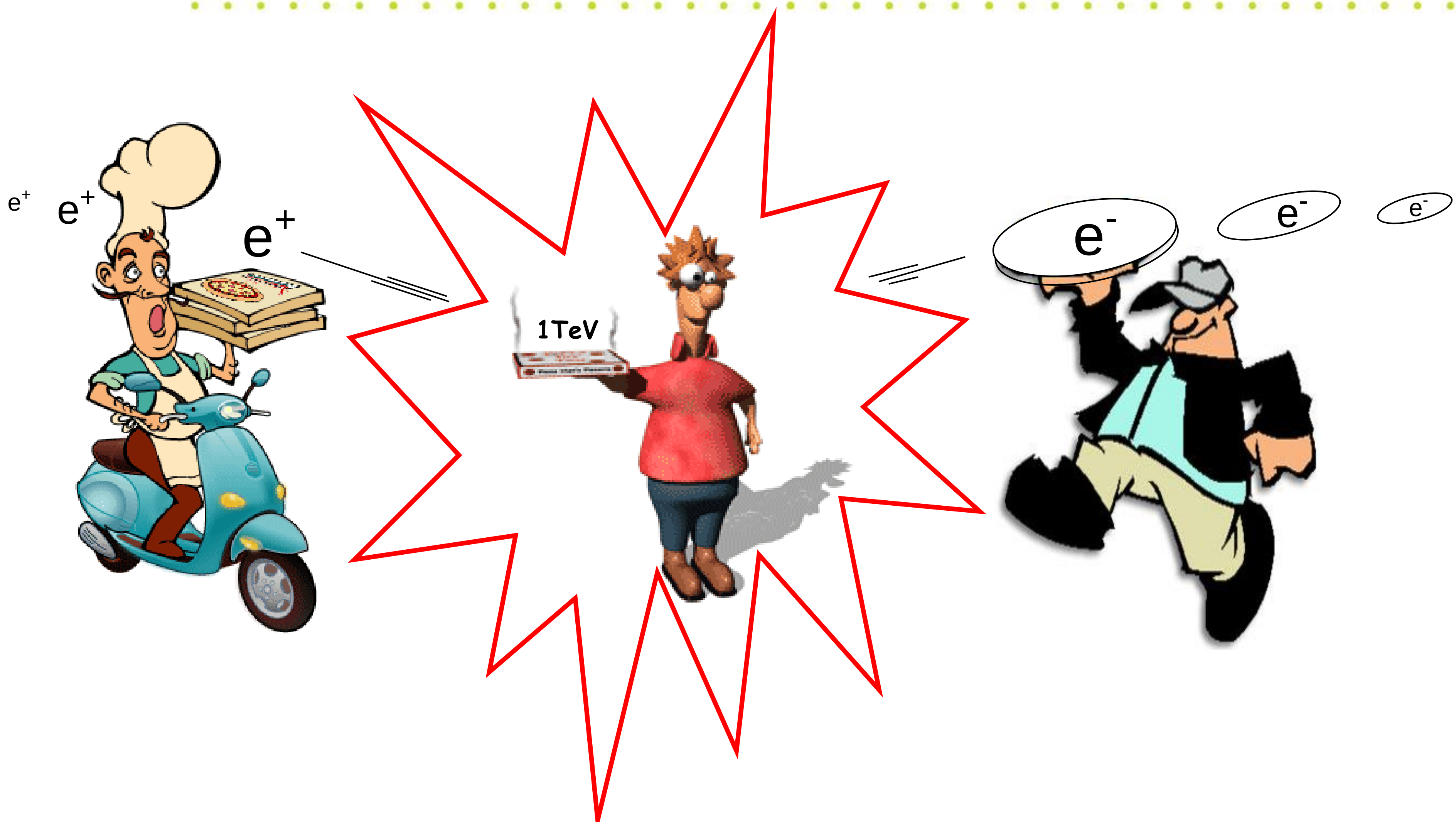






Royal Holloway University of London
UNIVERSITY OF OXFORD

Beam Delivered…



Beam-beam effects

Useful digression

- Creating a linear collider require solving many challenges
- We will now take a useful detour
- And will discuss how to invent…
- … in science
- After that we will come back to beam-beam
- And will return to inventiveness again at the end

How to invent more efficiently?

Forbes

Haydn Shaughnessy, Contributor
I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

What Makes Samsung Such An Innovative Company?

What was that magic bullet?
…wait a few slides…

But it was [redacted] that became the bedrock of innovation at Samsung. And it was introduced at Samsung by [redacted] whom Samsung had hired into its Seoul Labs in the early 2000s.

In 2003 [redacted] led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over $100 million. [redacted] is now an obligatory skill set if you want to advance within Samsung.

How to invent – evolution of the methods

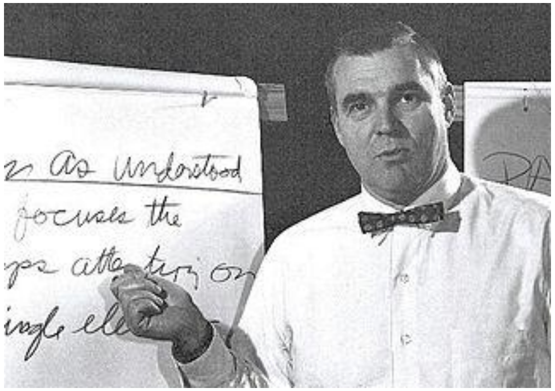
- **Brute-force or exhaustive search**
  - consider any possible ideas
- **Brainstorming**
  - psychological method which helps to solve problems and to invent
  - The main feature of brainstorming – separate the process of idea generation from the process of their critical analysis
  - The method of brainstorming did not meet expectations
    - the absence of feedback, which is the power of the method, is simultaneously its handicap, as feedback is needed for development and adjusting of an idea

Alex Osborn (1888 – 1966)

The author of brainstorming Alex Osborn introduced the method around 1950s

How to invent – evolution of the methods

- **Synectics – improved Brainstorming**
- **Features of Synectics:**
  - **Permanent groups for problem solving**
    - **whose members with time become less sensitive to critics and more efficient in problem solving**
  - **Emphasis on the importance to see familiar behind unknown and vice versa**
    - **which should help to solve a new and unfamiliar problem with known methods**
  - **Importance of a fresh view at a problem**
  - **Use of <u>analogies</u> to generate fresh view**
    - **direct (any analogy, e.g. from nature);**
    - **empathic (attempting to look at the problem identifying yourself with the object);**
    - **symbolic (finding a short symbolic description of the problem and the object);**
    - **metaphorical (describing the problem in terms of fairy-tales and legends);**



Attempting to improve brainstorming, George Prince (on the photo) and William Gordon introduced the method of Synectics

Synectics – use of analogies

– Use of <u>analogies</u> to generate fresh view

- …
- empathic (attempting to look at the problem identifying yourself with the object);
- …
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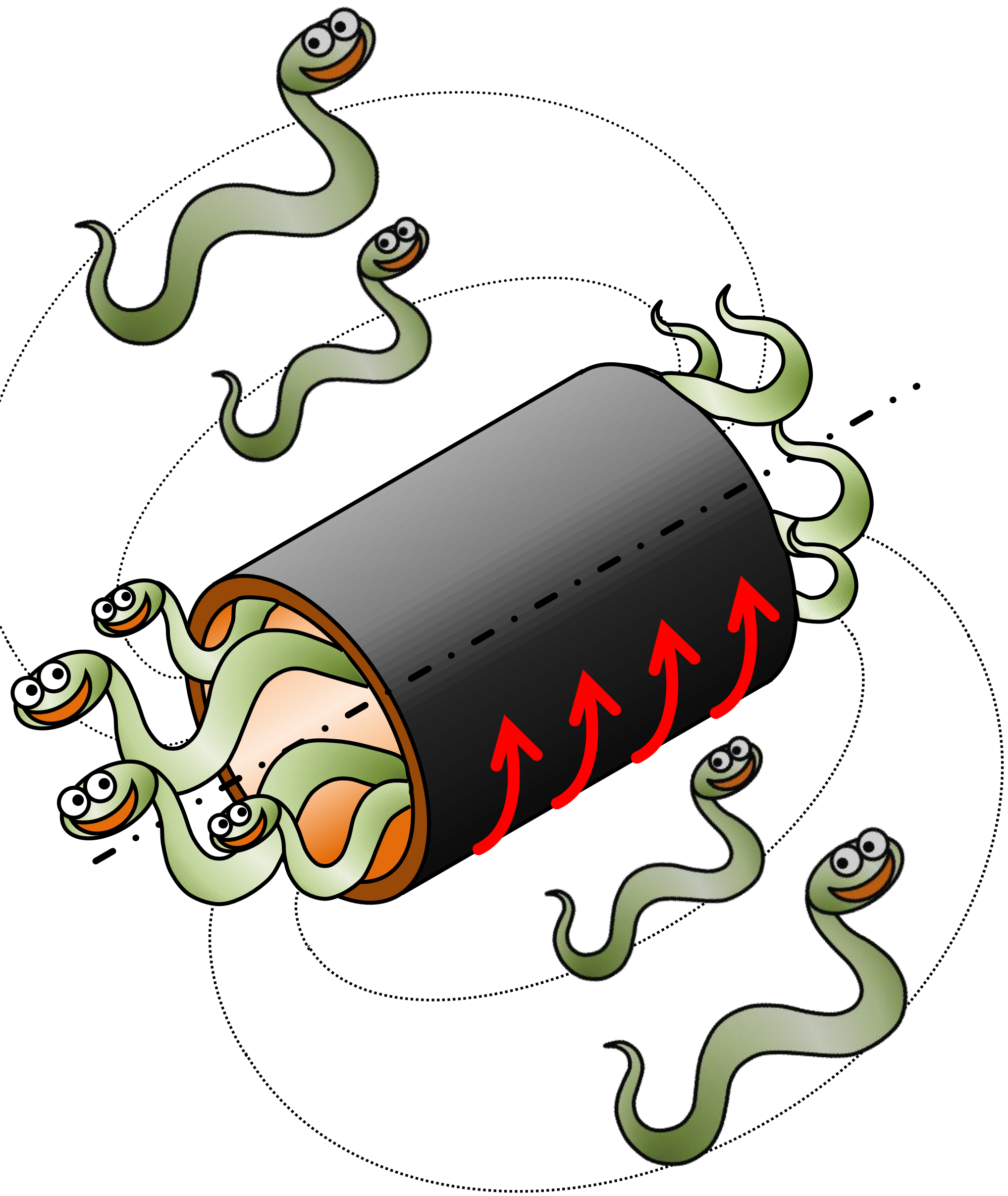


How to contain the magnetic flux?

How to invent – evolution of the methods

- **Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search**

How to invent – evolution of the methods

- **Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search**
  - **Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a natural and universal formula "the action has to happen itself"**

How to invent – evolution of the methods

- Synectics is the limit of what can be achieved, maintaining the brute force method of exhaustive search
  - Indeed, why one would employ analogies and metaphors and irrational factors in order to come to a **natural and universal formula "the action has to happen itself"**
  - **One should aim at such formula in any invention, armed with precise identification of physical contradiction – essence of TRIZ**

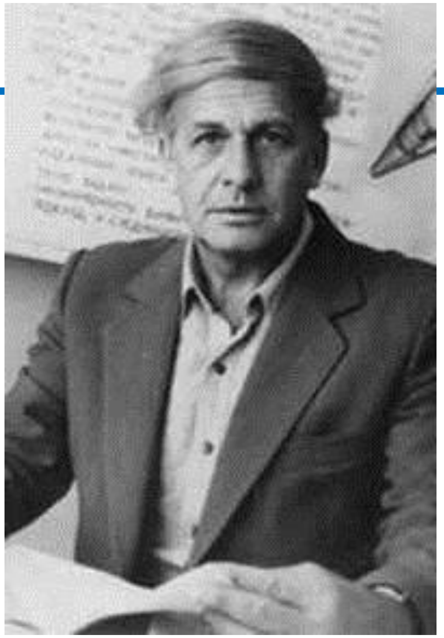
Illustration by Sasha Seraia

How to invent – TRIZ

- **TRIZ –** ***T****eoria* ***R****eshenia* ***I****zobretatelskikh* ***Z****adach*

= Theory of Inventive Problem Solving

- **Developed by Genrikh Altshuller in SU**
  - **Work in patent office in 1946**
  - **Analysed 200000 patents, discovered patterns and identified what makes a patent successful**
  - **Formulated TRIZ in 1956-1985**



Genrikh Altshuller (aka Altov)1926-1998

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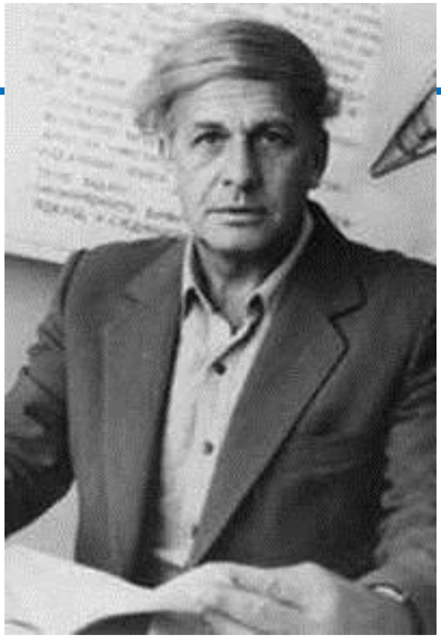

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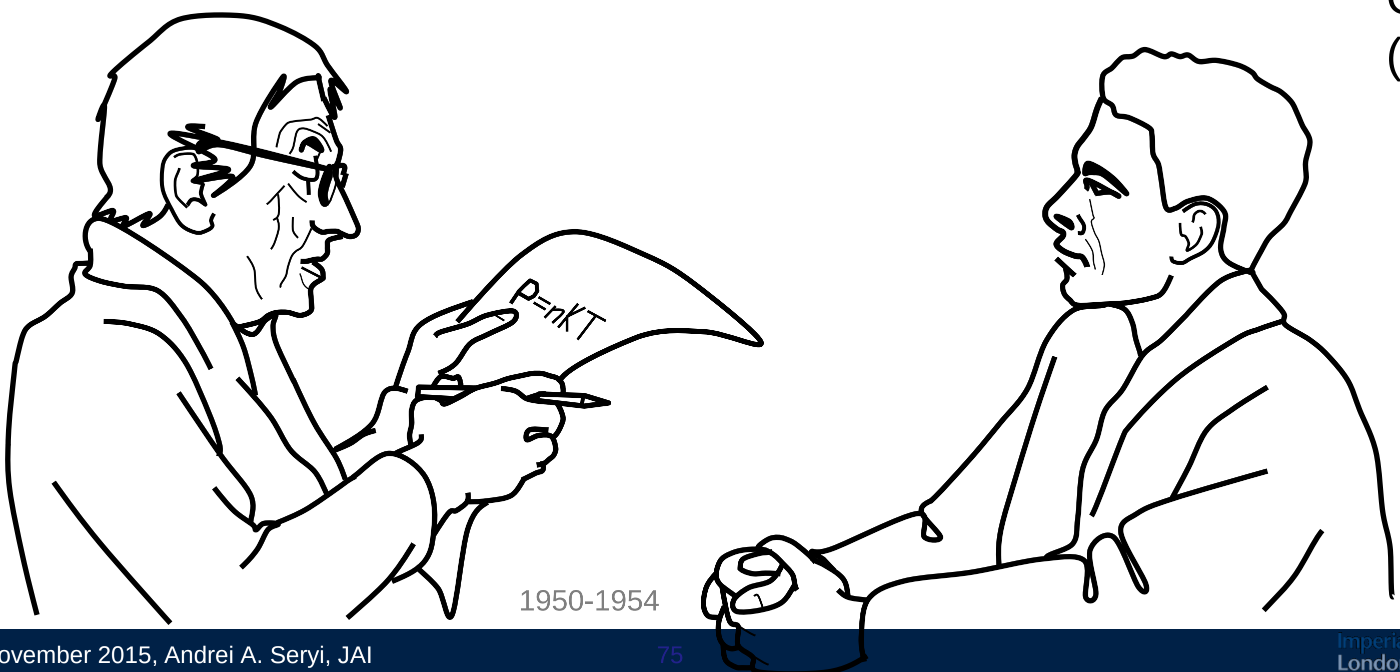
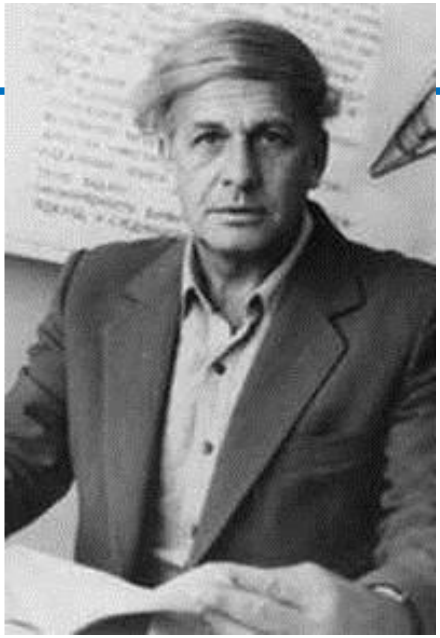


1950-1954

How to invent – TRIZ



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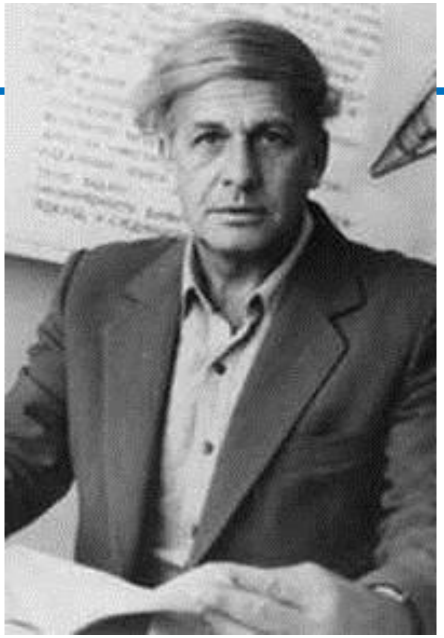
How to invent – TRIZ



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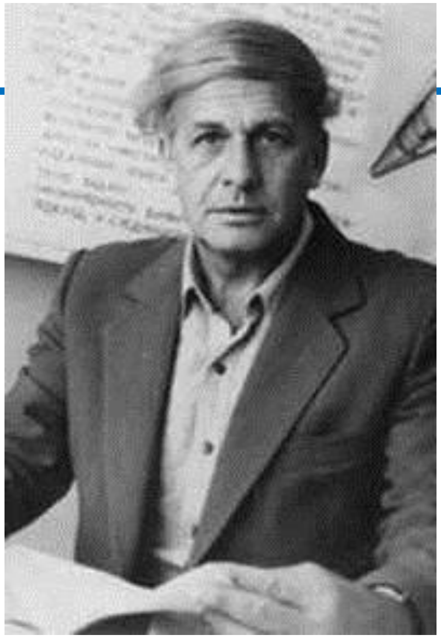

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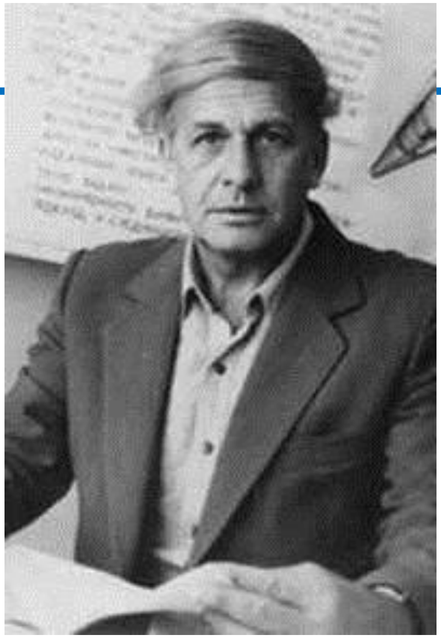

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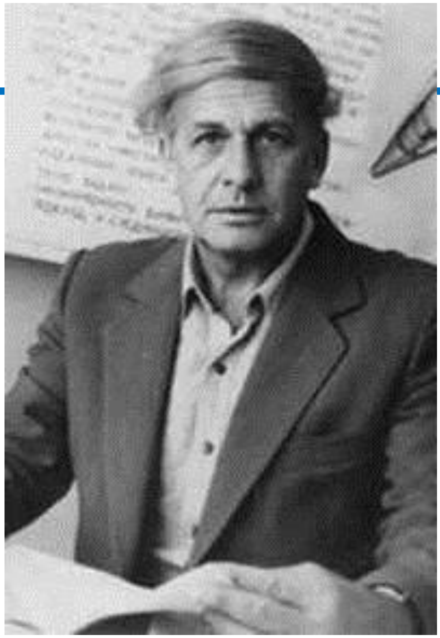

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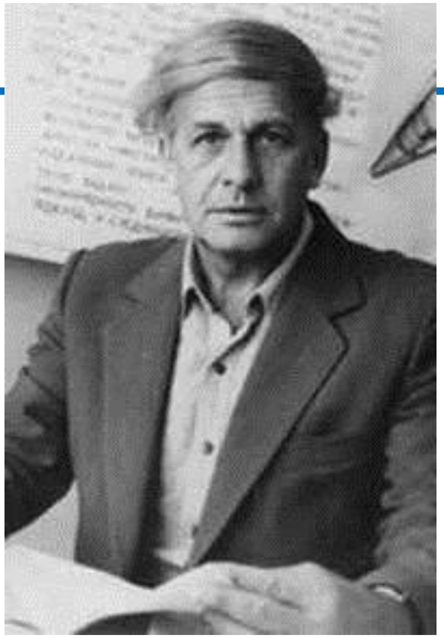
How to invent – TRIZ



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How to invent more efficiently?

Forbes

Haydn Shaughnessy, Contributor
I write about enterprise innovation.

TECH | 3/07/2013 @ 6:32AM | 72,570 views

What Makes Samsung Such An Innovative Company?

Why are we interested in this in relation to science?
…wait a few more slides…

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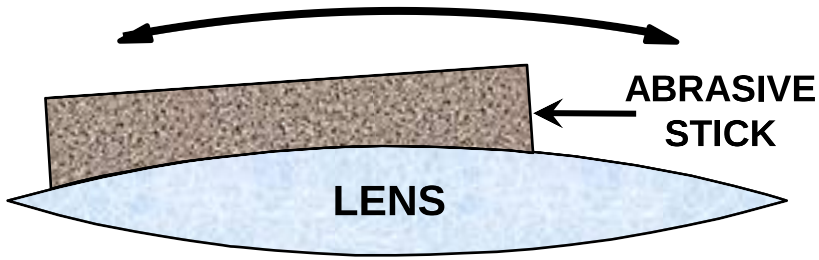
In 2003 TRIZ led to 50 new patents for Samsung and in 2004 one project alone, a DVD pick-up innovation, saved Samsung over $100 million. TRIZ is now an obligatory skill set if you want to advance within Samsung.

TRIZ in action - example



Problem: Lens polished – heat generated. Heat degrades optical properties. Existing cooling methods ineffective, as cannot achieve uniform cooling at each abrasive particle

To be improved: SPEED, What gets worse: TEMPERATURE

Has anyone else solved such contradiction?

1) Define the problem in terms of generic Contradiction parameters

TRIZ Generic Problem

TRIZ Generic Solution

3) Translate generic Inventive Principles into specific solution

Specific Problem

2) Use Contradiction Matrix to obtain relevant Inventive Principles

Specific Solution

Example: following J.Scanlan, School of Engineering Sciences, Univ. of Southampton

Elements of TRIZ contradiction matrix

1. Weight of moving object
2. Weight of stationary object
3. Length of moving object
4. Length of stationary object
5. Area of moving object
6. Area of stationary object
7. Volume of moving object
8. Volume of stationary object
9. Speed
10. Force (Intensity)
11. Stress or pressure
12. Shape
13. Stability of the object
14. Strength
15. Durability of moving object
16. Durability of non moving object
17. Temperature
18. Illumination intensity
19. Use of energy by moving object
20. Use of energy by stationary object
21. Power
22. Loss of Energy
23. Loss of substance
24. Loss of Information
25. Loss of Time
26. Quantity of substance/the
27. Reliability
28. Measurement accuracy
29. Manufacturing precision
30. Object-affected harmful
31. Object-generated harmful
32. Ease of manufacture
33. Ease of operation
34. Ease of repair
35. Adaptability or versatility
36. Device complexity
37. Difficulty of detecting
38. Extent of automation
39. Productivity

Only 39 Matrix parameters!!!

TRIZ Inventive Principles

1. Segmentation
2. Taking out
3. Local quality
4. Asymmetry
5. Merging
6. Universality
7. Russian dolls
8. Anti-weight
9. Preliminary anti-action
10. Preliminary action
11. Beforehand cushioning
12. Equipotentiality
13. "The other way round"
14. Spheroidality - Curvature
15. Dynamics
16. Partial or excessive actions
17. Another dimension
18. Mechanical vibration
19. Periodic action
20. Continuity of useful action
21. Skipping
22. Blessing in disguise
23. Feedback
24. Intermediary
25. Self-service
26. Copying
27. Cheap short-lived objects
28. Mechanics substitution
29. Pneumatics and hydraulics
30. Flexible shells and thin films
31. Porous materials
32. Colour changes
33. Homogeneity
34. Discarding and recovering
35. Parameter changes
36. Phase transitions
37. Thermal expansion
38. Strong oxidants
39. Inert atmosphere
40. Composite materials

Only 40 Principles !!!

TRIZ Principles and Contradiction matrix

For our example with the lens:

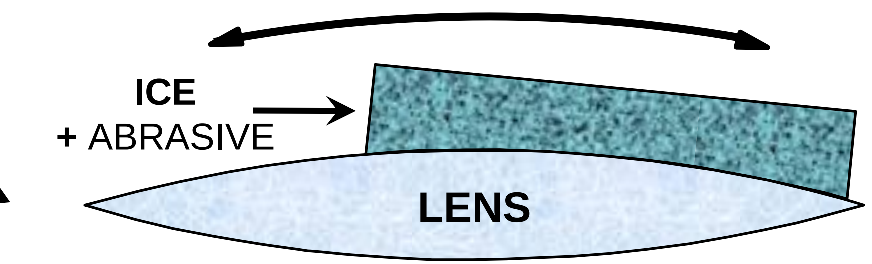
Parameter that deteriorates / **Improving Parameter**

	…	9. Speed	…	17. Temperature	…
…					
9. Speed				2, 28, 30, 36	
…					
17. Temperature					
…					

Suggested Principles that have solved similar Contradictions before

TRIZ in action - example

- **Perform lookup* of TRIZ Matrix for this contradiction:**
  - **Improving 9: SPEED without damaging 17: TEMPERATURE**
- **Find Principles to solve this contradiction:**
  - **2. Taking out**
  - **28. Mechanics substitution**
  - **30. Flexible shells and thin films**
  - **36. Phase transitions**
    - **Use phenomena occurring during phase transitions (e.g. volume changes, loss or absorption of heat, etc.).**



Abrasive + Ice - Inventive Principle ‘Phase Transition’

*) E.g. at http://www.triz40.com/

TRIZ => Science

- **TRIZ was created for engineering**
- **But the method is universal and can be applied to science!**
  - **In particular to Accelerator Science, but not only**
- **Examples given in the following slides show the applicability of TRIZ principles to a variety of areas**

TRIZ => Science

- **TRIZ was created for engineering**
- **But the method is universal and can be applied to science!**
  - **In particular to Accelerator Science, but not only**
- **Examples given in the following slides show the applicability of TRIZ principles to a variety of areas**

- **Looking at the world "through the prism of TRIZ" allows us to rethink the familiar things**

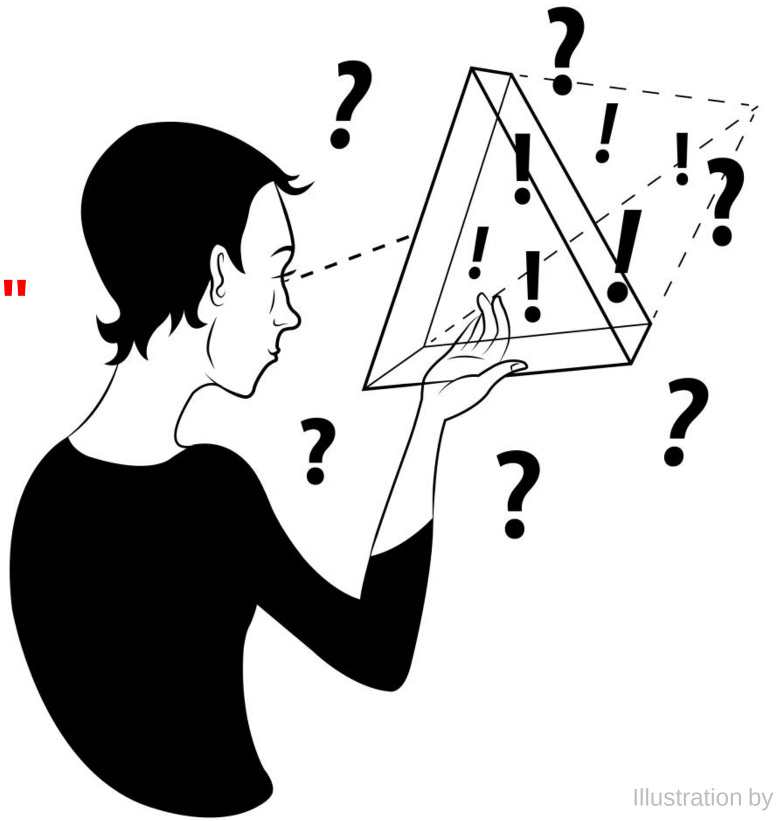


Illustration by Sasha Seraia

TRIZ Inventive Principles

1. Segm
2. Takir
3. Loca
4. Asym
5. Merg
6. Unive
7. Russian dolls
8. Anti-weight
9. Preliminary anti-action
10. Preliminary action
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12. Equipotentiality
13. "The other way round"
14. Spheroidality - C vature
15. Dynamics
16. Partial or exces
17. A
18. N
19. F
20. C

27. Cheap short-lived objects
28. Mechanics substitution
29. Pneumatics and hydraulics
32. Colour changes
33. Homogeneity
34. Discarding and recovering
35. Parameter changes
36. Phase transitions

Let's select a couple of principles and try to see if we can recognize them in well-known and familiar things

7. The principle of "Russian dolls"

13. The principle of "The other way round" (or the principle of anti-system)

The principle of "Russian dolls"

Could you give an example of using the principle of "Russian dolls" in everyday life?

The principle of “Russian dolls”

The principle of "Russian dolls"

And what about an example of the application of the principle of "Russian dolls", for instance ... in philology?

The principle of “Russian dolls”

“This is the house that Jack built”

This is the house that Jack built.

This is the malt
That lay in the house that Jack built.

This is the rat,
That ate the malt
That lay in the house that Jack built.

This is the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

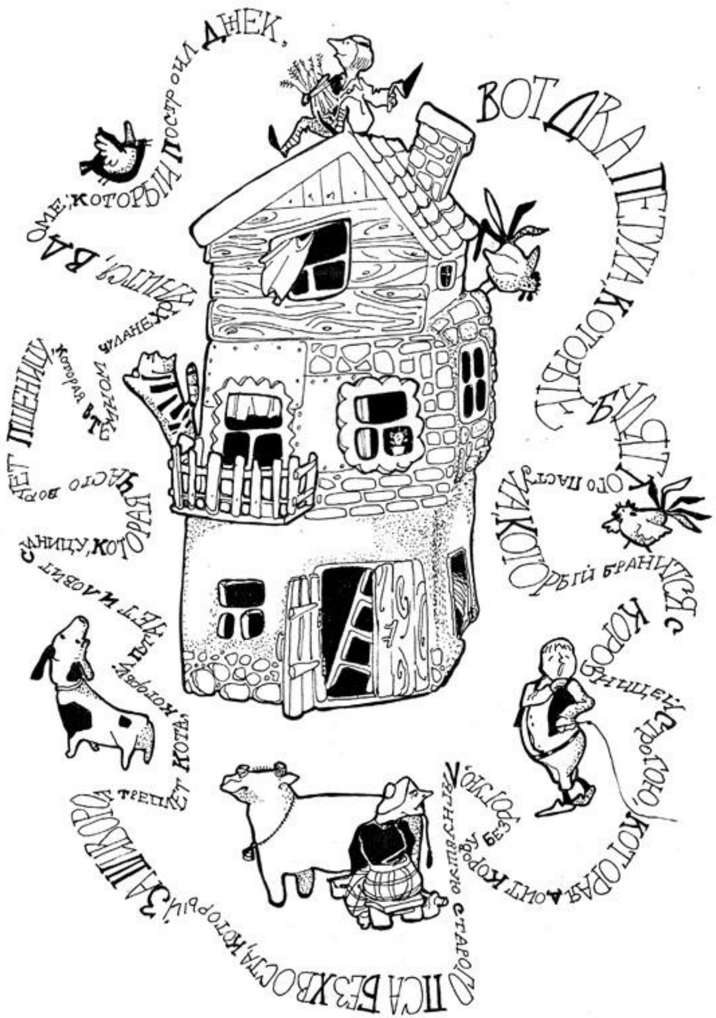

Illustration by Olga Rubtsova (Atroshenko)

This is the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

This is the farmer sowing his corn,
That kept the cock that crowed in the morn,
That waked the priest all shaven and shorn,
That married the man all tattered and torn,
That kissed the maiden all forlorn,
That milked the cow with the crumpled horn,
That tossed the dog,
That worried the cat,
That killed the rat,
That ate the malt
That lay in the house that Jack built.

Mother Goose Rhymes

The principle of “Russian dolls”

“This is the house that Jack built”

This is the house that Jack built.

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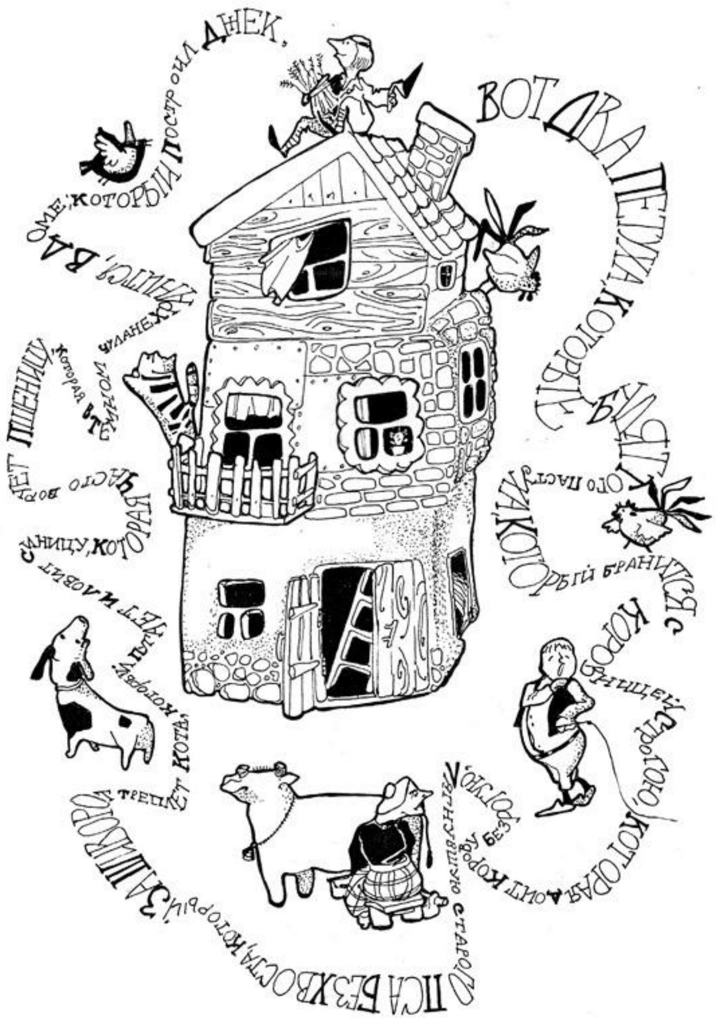

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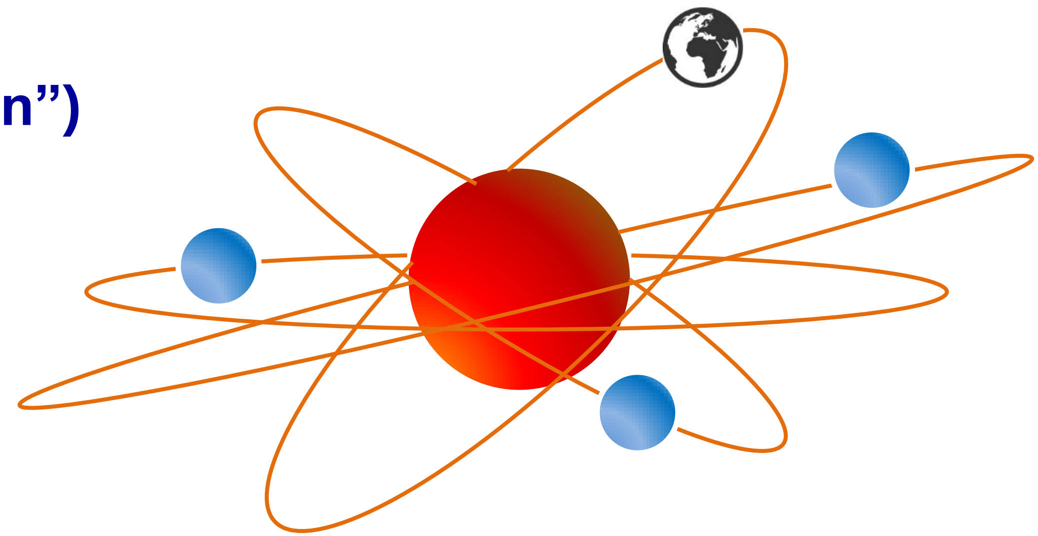
Mother Goose Rhymes

Is there any example of this principle in science fiction?

The principle of "Russian dolls"

Valery Bryusov – 1920 poem
"Atom" ("The World of Electron")



Быть может, эти электроны
Миры, где пять материков,
Искусства, знанья, войны, троны
И память сорока веков!

Ещё, быть может, каждый атом —
Вселенная, где сто планет;
Там — всё, что здесь, в объёме сжатом,
Но также то, чего здесь нет.

…

The principle of “Russian dolls”

Valery Bryusov – 1920 poem
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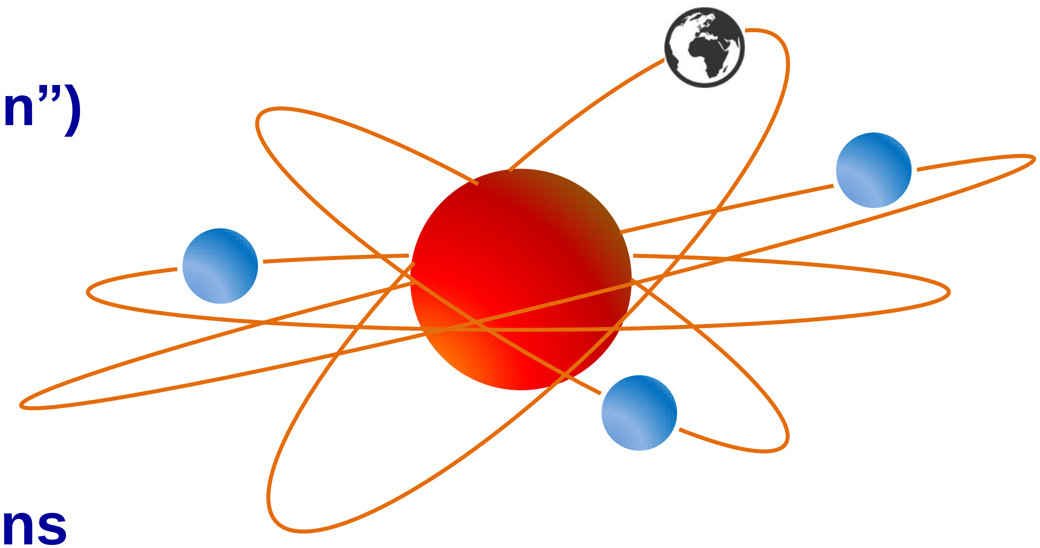


Can you imagine that electrons
Are planets circling their Suns?
Space exploration, wars, elections
And hundreds of computer tongues
…

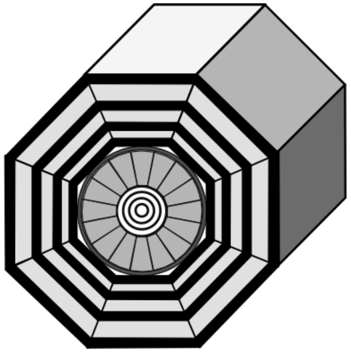
Remake-translation by A.Seryi

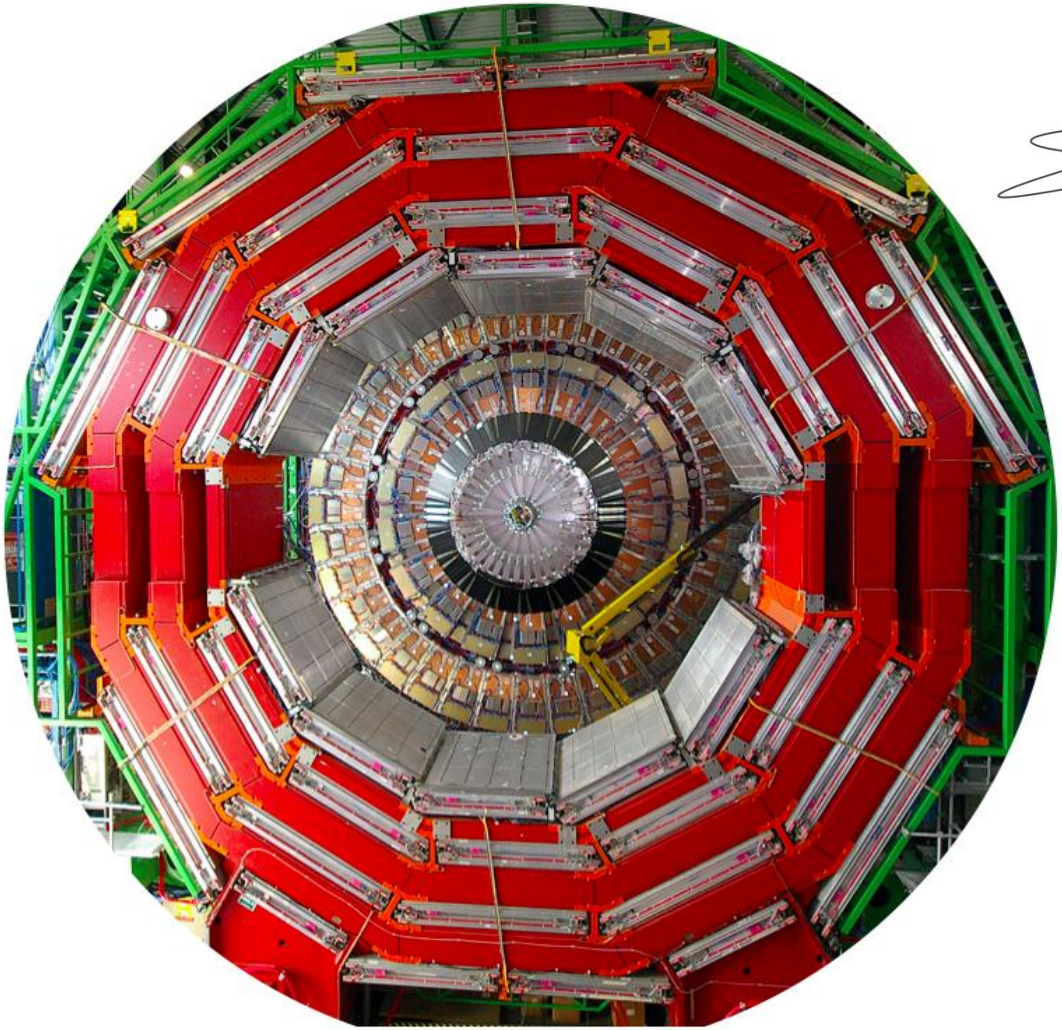
Быть может, эти электроны
Миры, где пять материков,
Искусства, знанья, войны, троны
И память сорока веков!

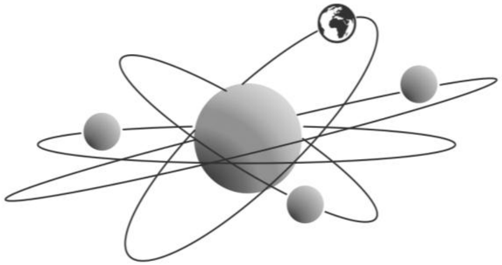
Ещё, быть может, каждый атом —
Вселенная, где сто планет;
Там — всё, что здесь, в объёме сжатом,
Но также то, чего здесь нет.

…

Is there world inside of an electron?

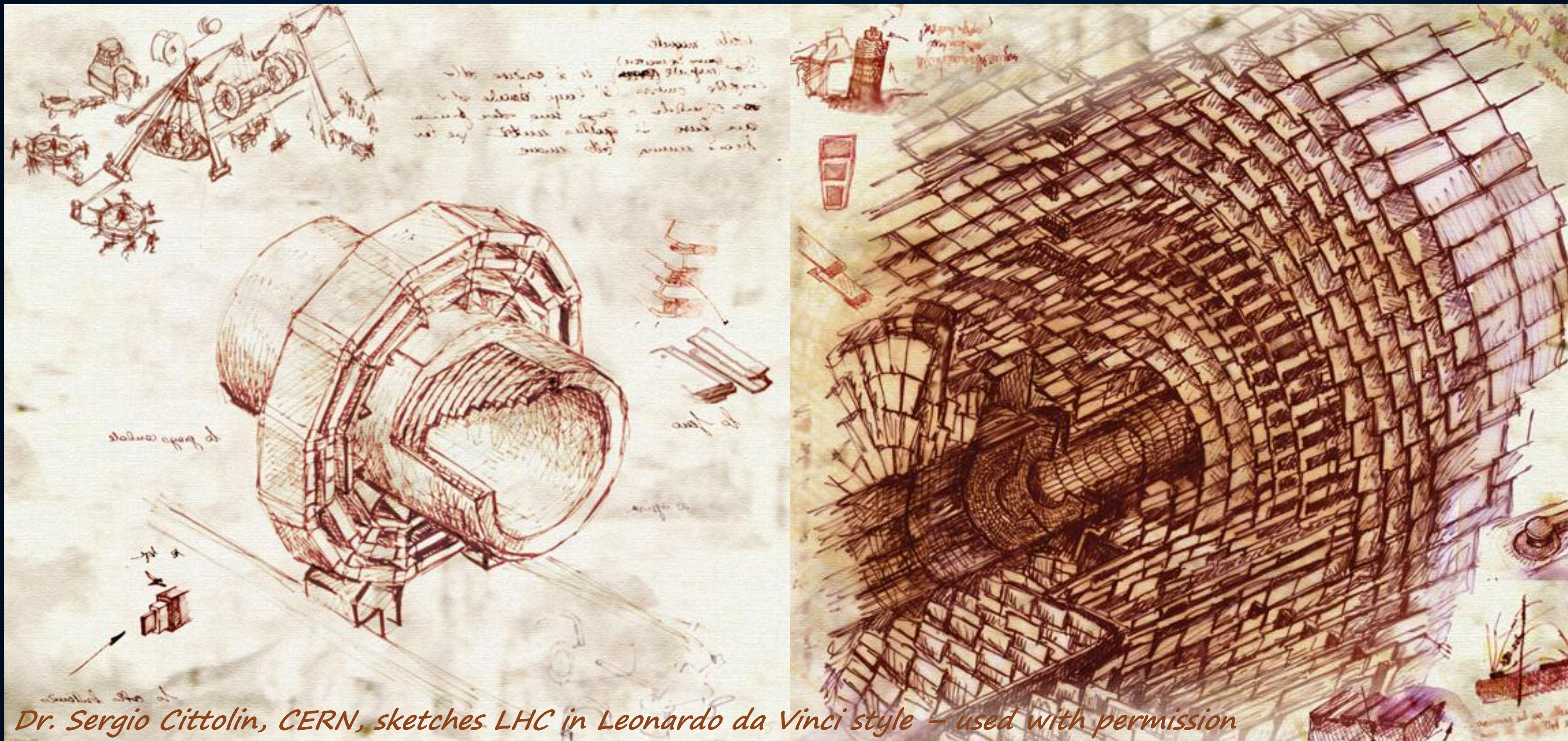






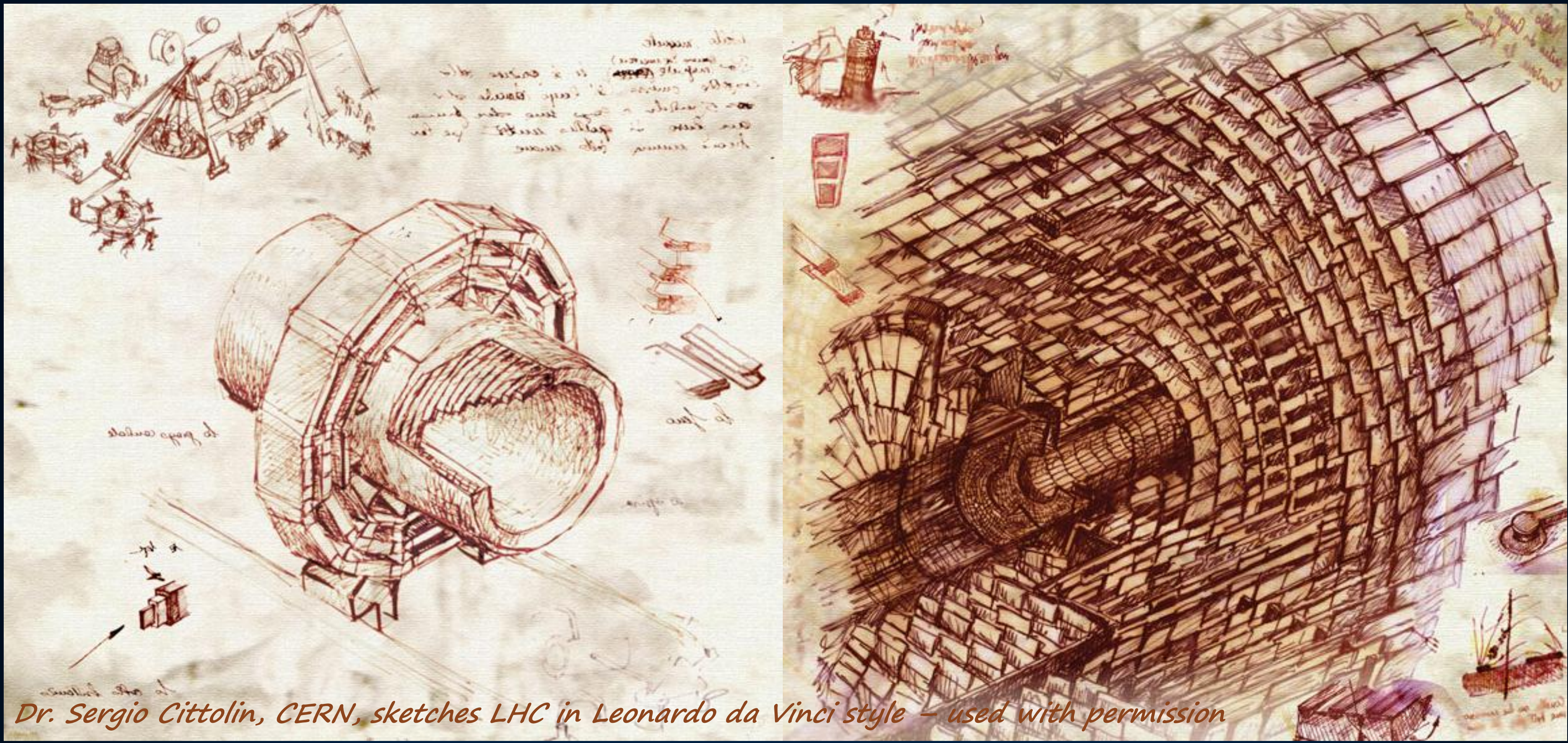
Accelerators and detectors can help to understand whether there is a world inside of an electron

The detectors are arranged just as “Russian dolls”



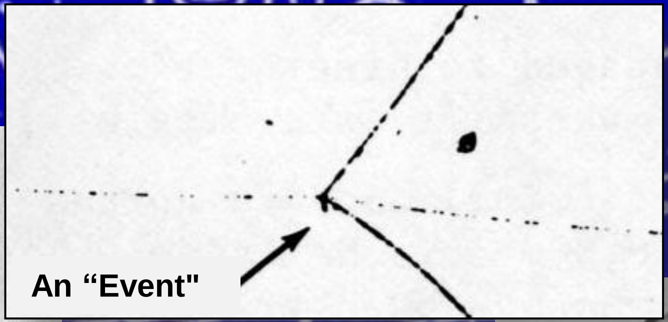
Dr. Sergio Cittolin, CERN, sketches LHC in Leonardo da Vinci style – used with permission

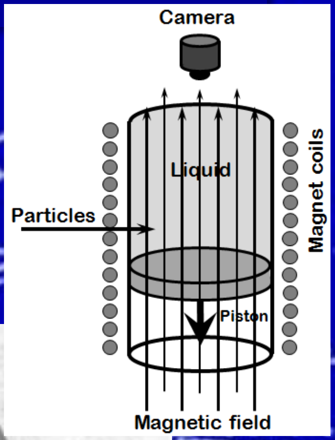
The detectors are arranged just as “Russian dolls”

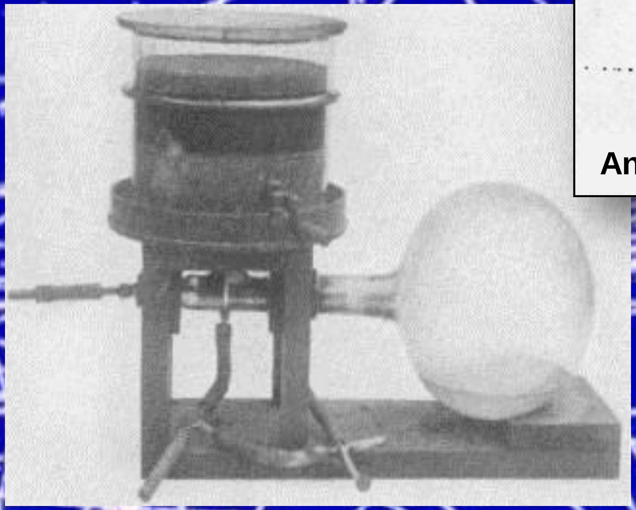


And what were the ones of the first particle detectors?

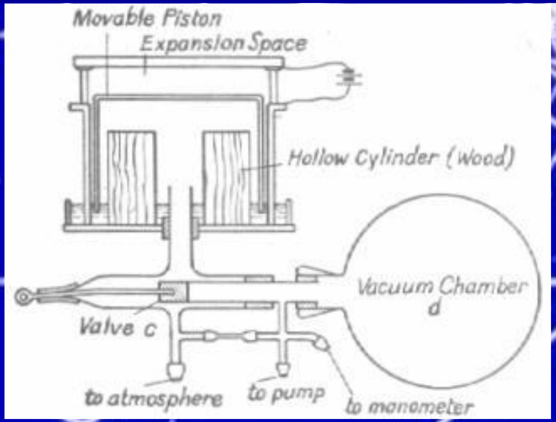
Cloud and bubble chambers







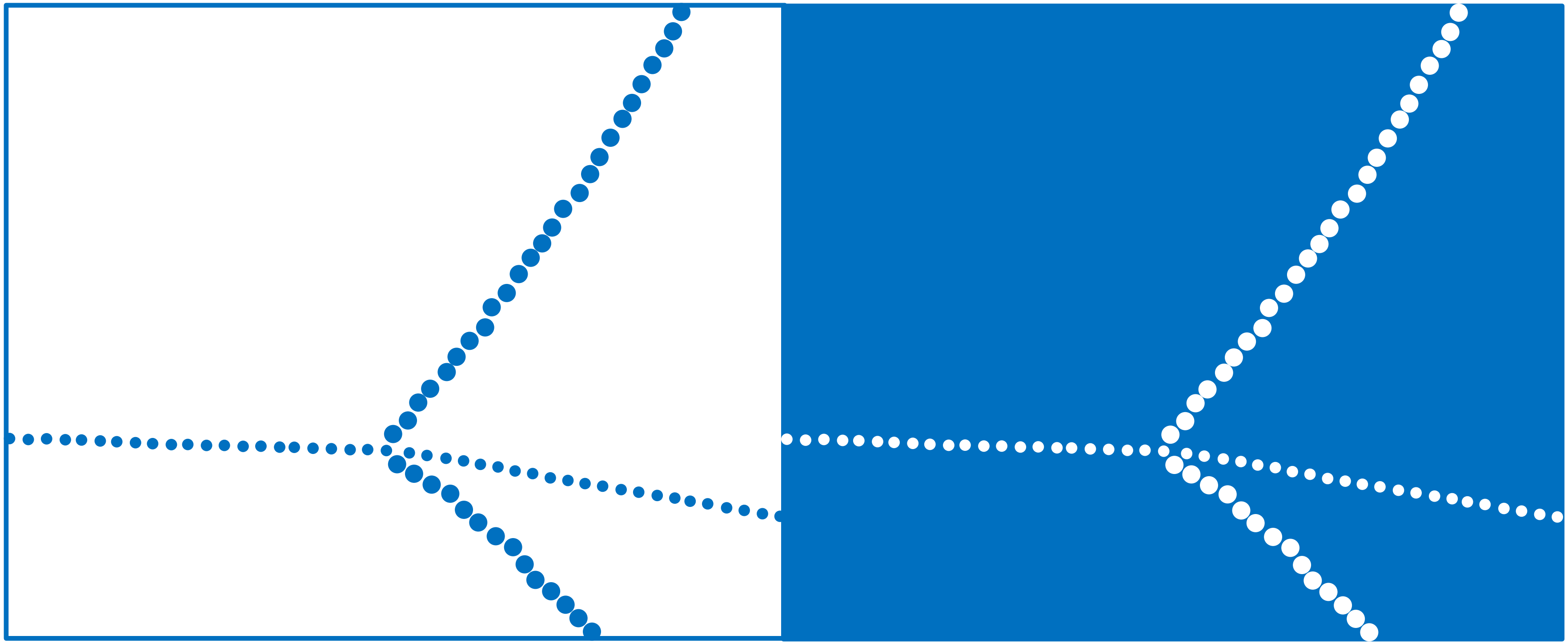
Wilson’s Cloud chamber (invented in 1911)



Bubble Chamber (invented in 1952 by D. Glaser – Nobel prize 1960)

On the photo Bubble chamber being installed near Fermilab

Cloud and bubble chambers



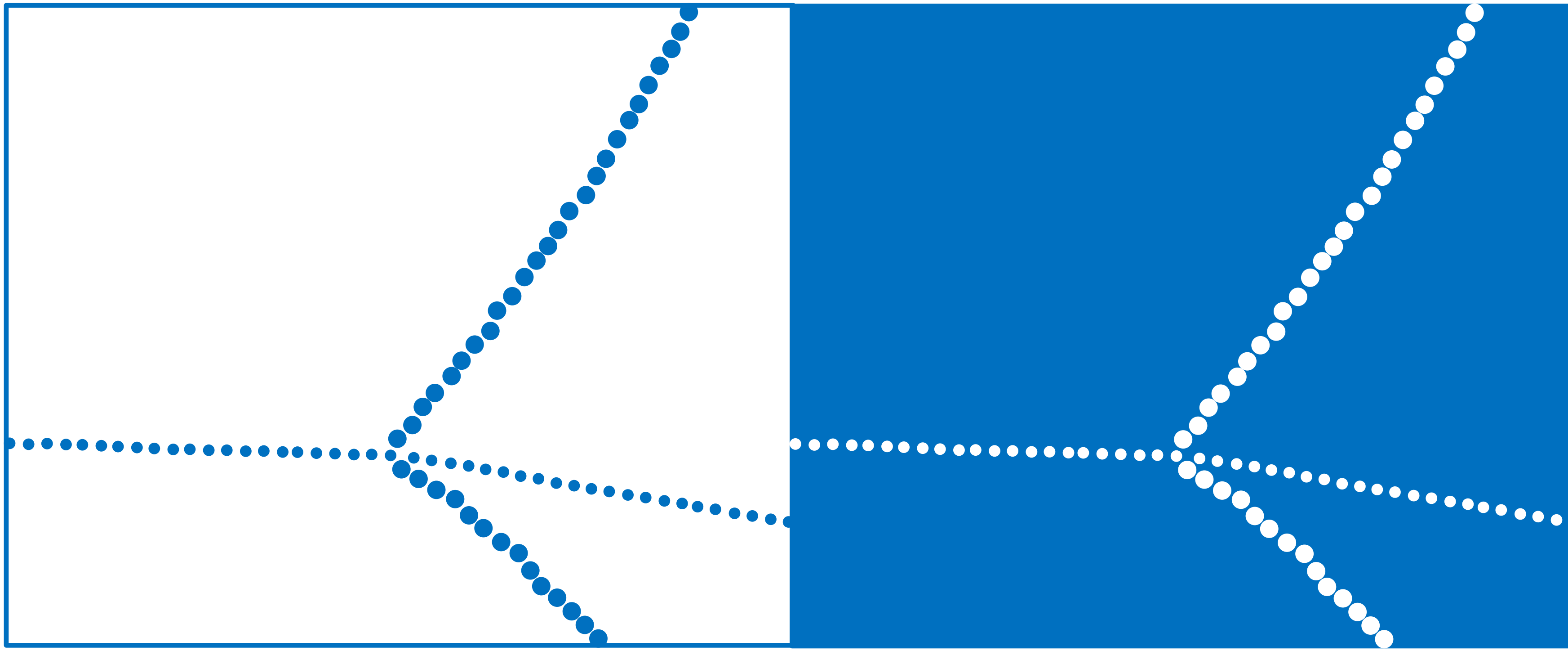
Wilson's Cloud chamber invented in 1911

Glaser's Bubble chamber, invented in 1952

Bubbles of liquid in gas

Bubbles of gas in liquid

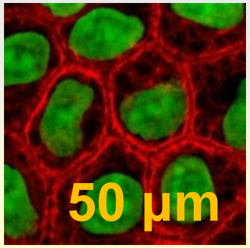
Cloud and bubble chambers



Wilson's Cloud chamber, **invented in 1911** ***Glaser's Bubble chamber***, **invented in 1952**

Cloud chamber and bubble chamber are often mentioned in the TRIZ books with the question - would the invention of the bubble chamber take almost half-a-century if the principle of anti-system had been used?

The structure of matter…



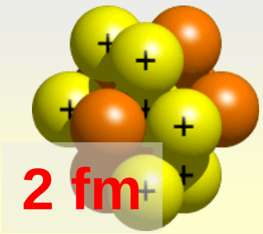
Extra magnification?

CELLS
Twenty
per mm

Microscope

x 25 thousand

DNA
Five hundred
thousand
per mm



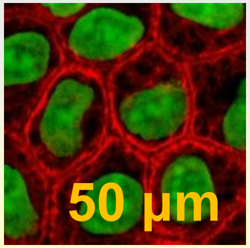
x 1 million

Nucleus
Five hundred
billion
per mm

x 2 thousand

Quarks
More than one
million billion
per mm

…use particles



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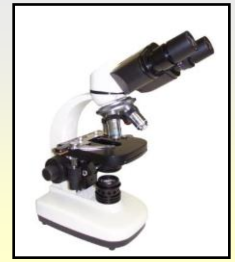

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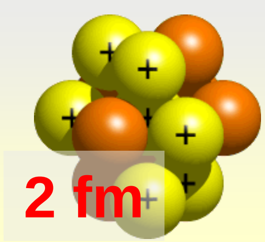

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Particles & their wave properties

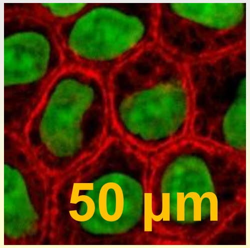
Wavelength corresponding to the particle:

$$\lambda = h/p$$

De Broglie Wavelength — Planck Constant — Momentum

See small? Use particles and increase their energy

…use particle accelerators



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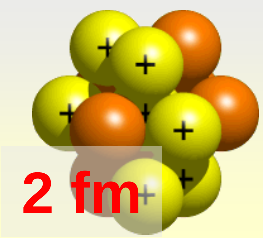
Electron microscope



x 1 million

Nucleus
Five hundred
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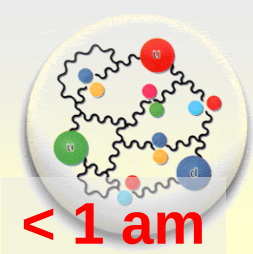
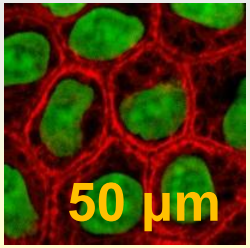
Particle Accelerators



x 2 thousand

Quarks
More than one
million billion
per mm

Chemistry Nobel 2014 & inventive principles?



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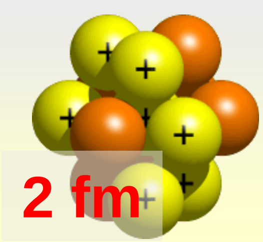
Electron microscope



x 1 million

Nucleus
Five hundred billion per mm

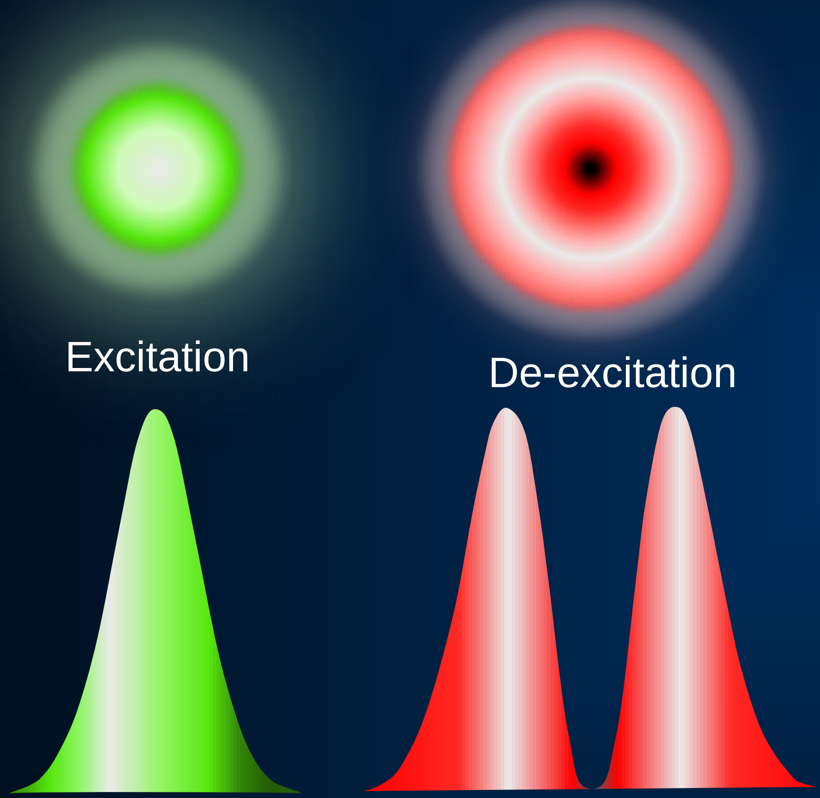
Particle Accelerators

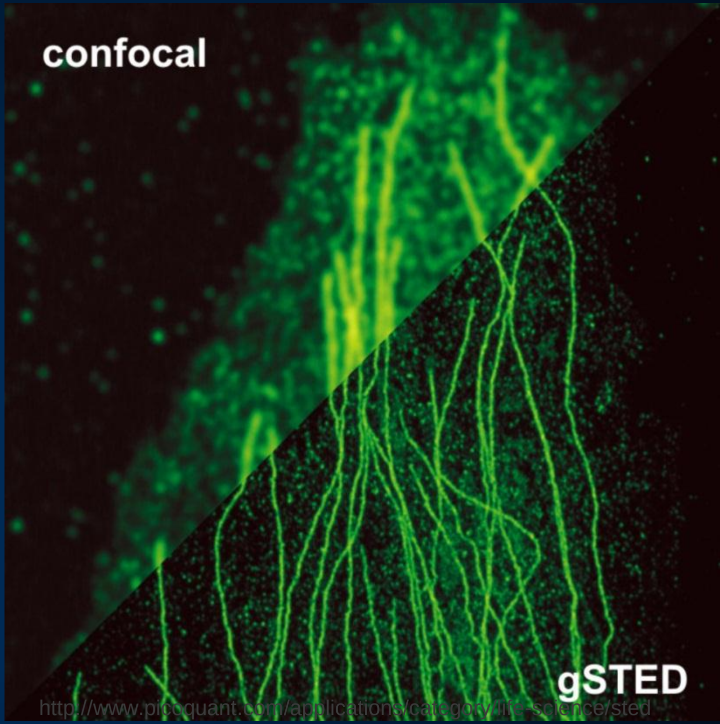
x 2 thousand

Quarks
More than one million billion per mm

Chemistry Nobel 2014 …

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell

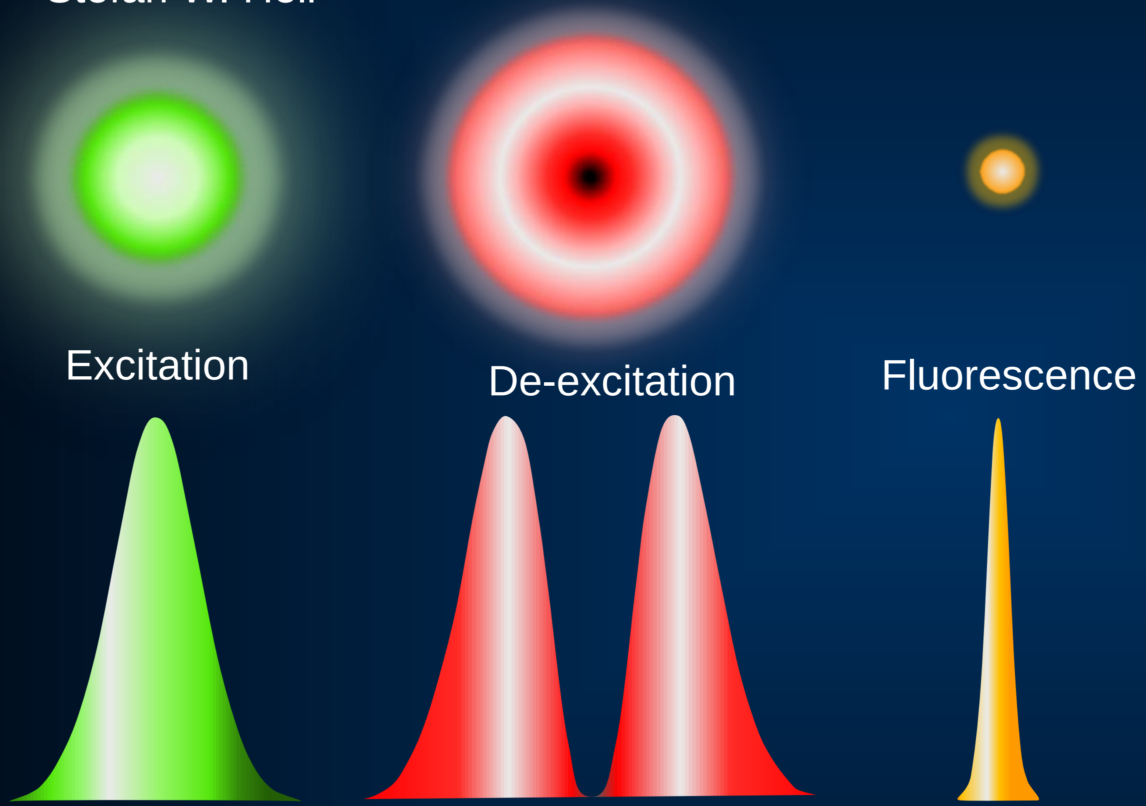


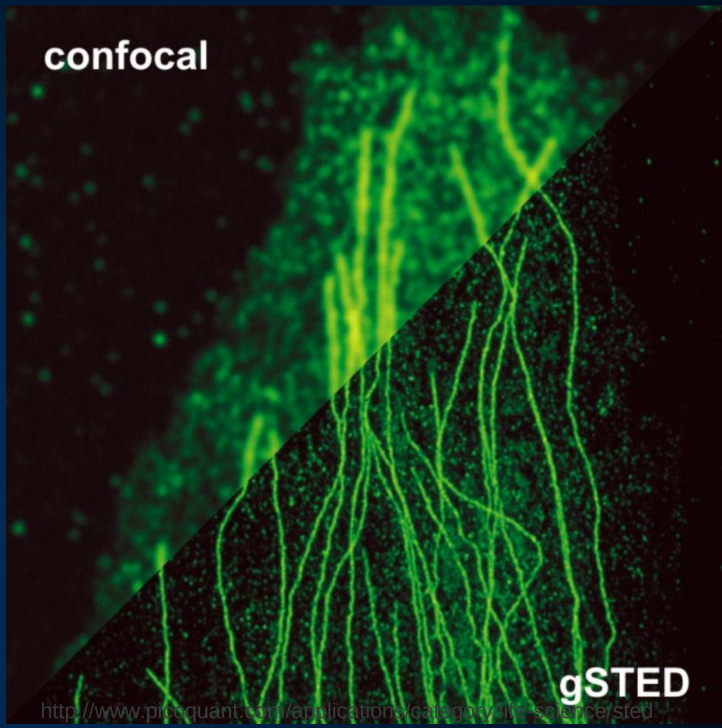


(gated) STED image of Tubulin vs standard confocal image

Chemistry Nobel 2014 & inventive principles

Stimulated Emission Depletion microscopy (STED)
Stefan W. Hell

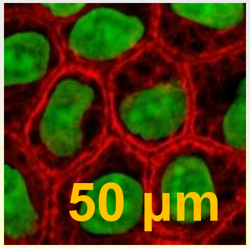




(gated) STED image of Tubulin vs standard confocal image

From the perspective of the theory of inventive problem solving this is an illustration of the use of the principle of system and anti-system

Colliders & principles of TRIZ



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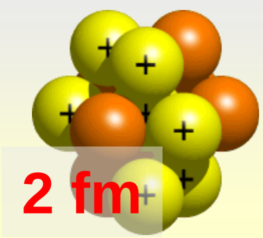
Electron microscope



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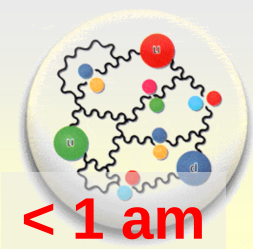
Nucleus
Five hundred billion per mm

Particle Accelerators

& Colliders



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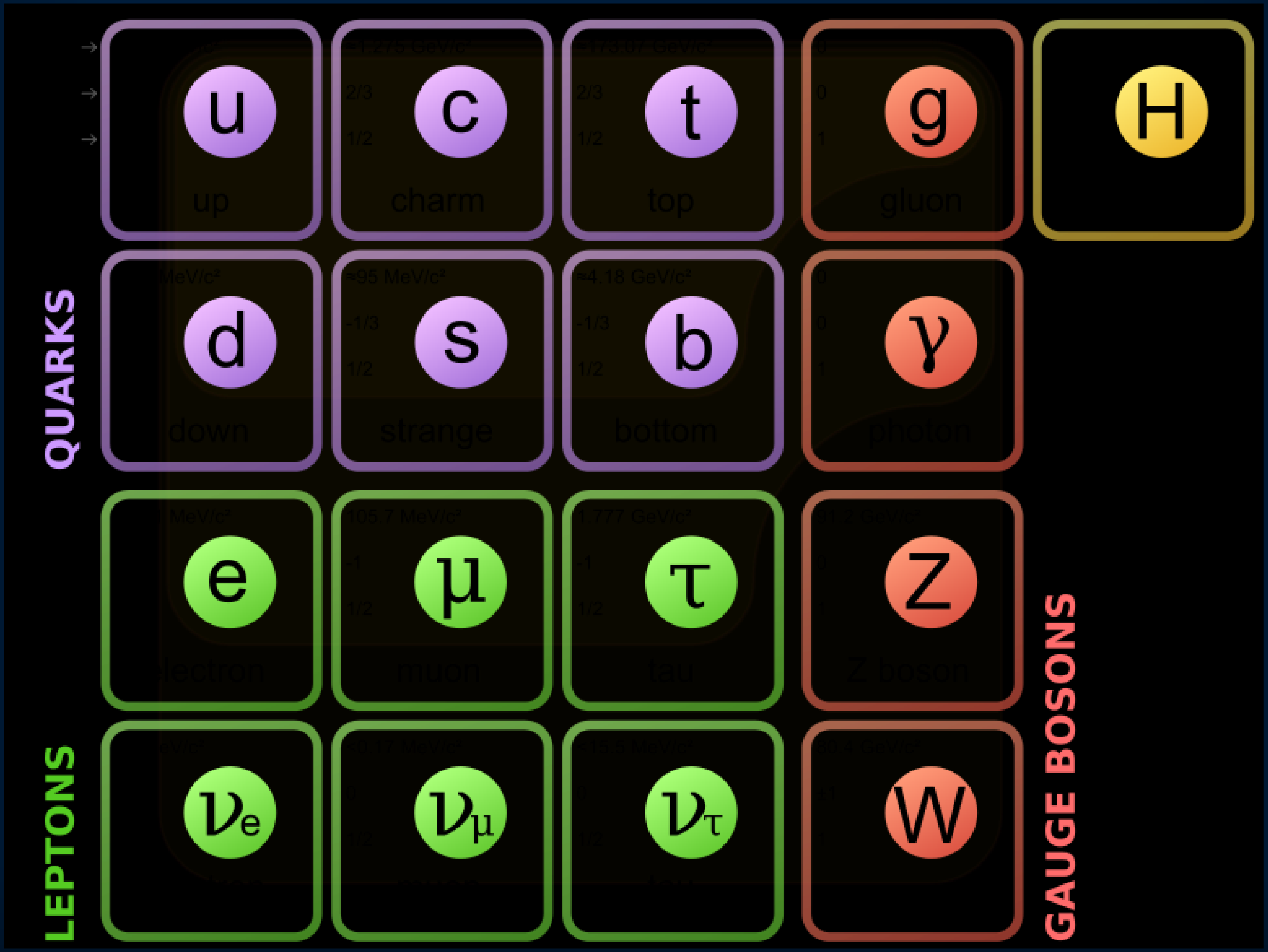
Discovery 2012, Nobel Prize in Physics 2013

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".*

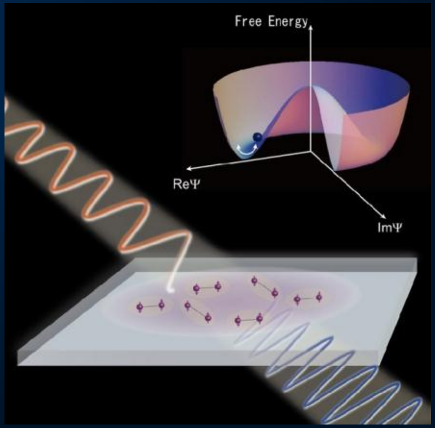
Standard Model Particle Physics



Higgs and Superconductivity

"The recent discovery of the Higgs boson has created a lot of excitement … the theoretical proposal of the Higgs mechanism was actually inspired by ideas from condensed matter physics … In 1958, Anderson discussed the appearance of a coherent excited state in superconducting condensates with spontaneously broken symmetry... *On page 1145 of this issue, Matsunaga et al. report direct observation of the Higgs mode in the conventional superconductor niobium nitride (NbN) excited by intense electric field transients*."

Particle physics in a superconductor,
A Pashkin & A Leitenstorfer Science 345, 1121 (2014)



Higgs and Superconductivity

"The recent discovery of the Higgs boson has created a lot of excitement … the theoretical proposal of the Higgs mechanism was actually inspired by ideas from condensed matter physics … In 1958, Anderson discussed the appearance of a coherent excited state in superconducting condensates with spontaneously broken symmetry... *On page 1145 of this issue, Matsunaga et al. report direct observation of the Higgs mode in the conventional superconductor niobium nitride (NbN) excited by intense electric field transients*."

Particle physics in a superconductor, A Pashkin & A Leitenstorfer Science 345, 1121 (2014)

This shows us that a general conclusion of TRIZ

"The same Problems and Solutions appear again and again but in different disciplines"

is applicable to science too

(Tentative) end of the PART 1

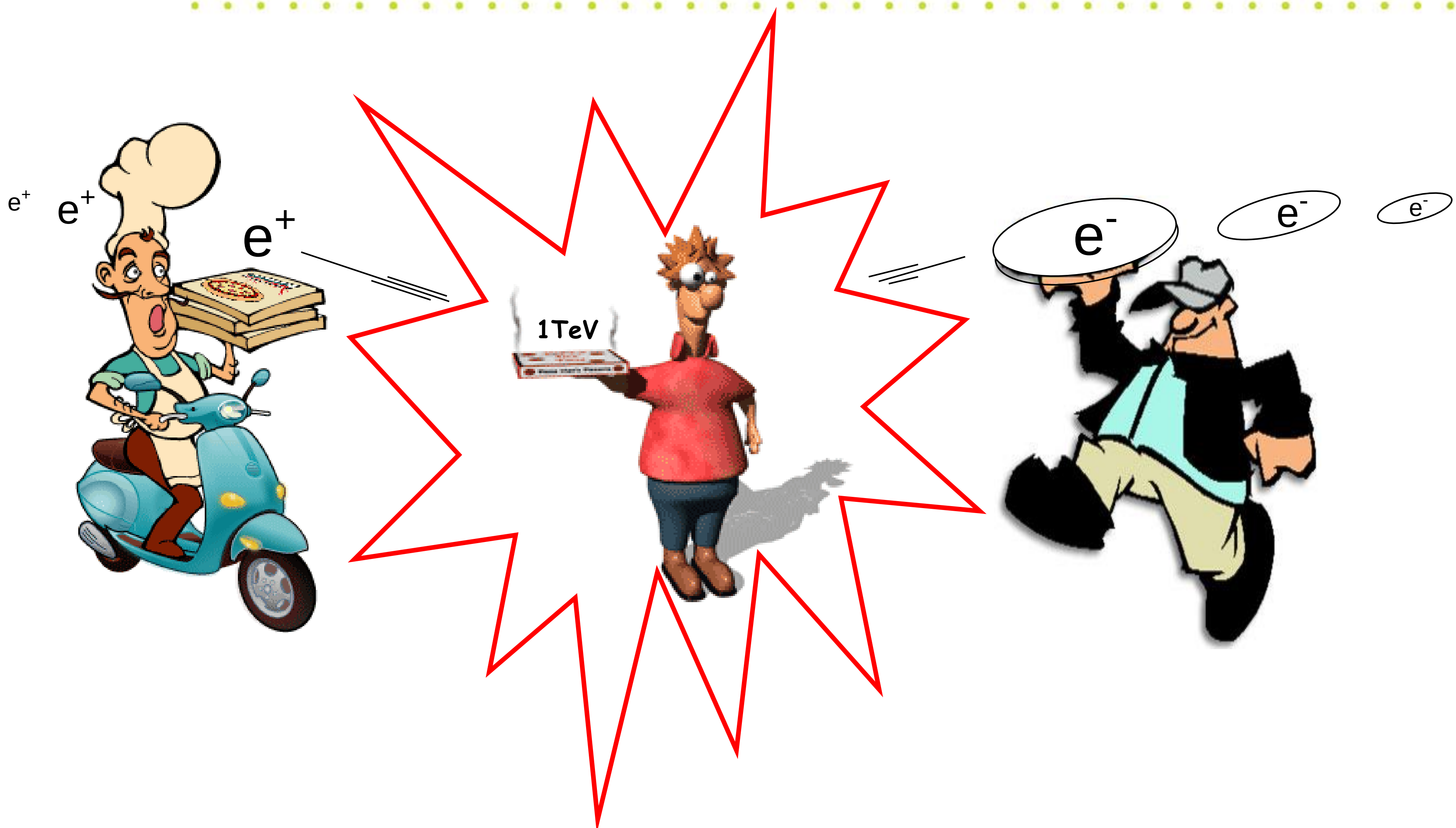
In the next lecture :

- We will carry on, starting from discussion of beam-beam effects…

- Many thanks to colleagues whose slides, results or photos were used in this lecture, namely Tom Markiewicz, Nikolai Mokhov, Daniel Schulte, Mauro Pivi, Nobu Toge, Brett Parker, Nick Walker, Timergali Khabibouline, Kwok Ko, Cherrill Spencer, Lew Keller, Sayed Rokni, Alberto Fasso, Joe Frisch, Yuri Nosochkov, Mark Woodley, Takashi Maruyama, Eric Torrence, Karsten Busser, Graeme Burt, Glen White, Phil Burrows, Tochiaki Tauchi, Junji Urakawa, Nobuhiro Terunuma and many other

Thanks to you for attention!

Beam Delivered...

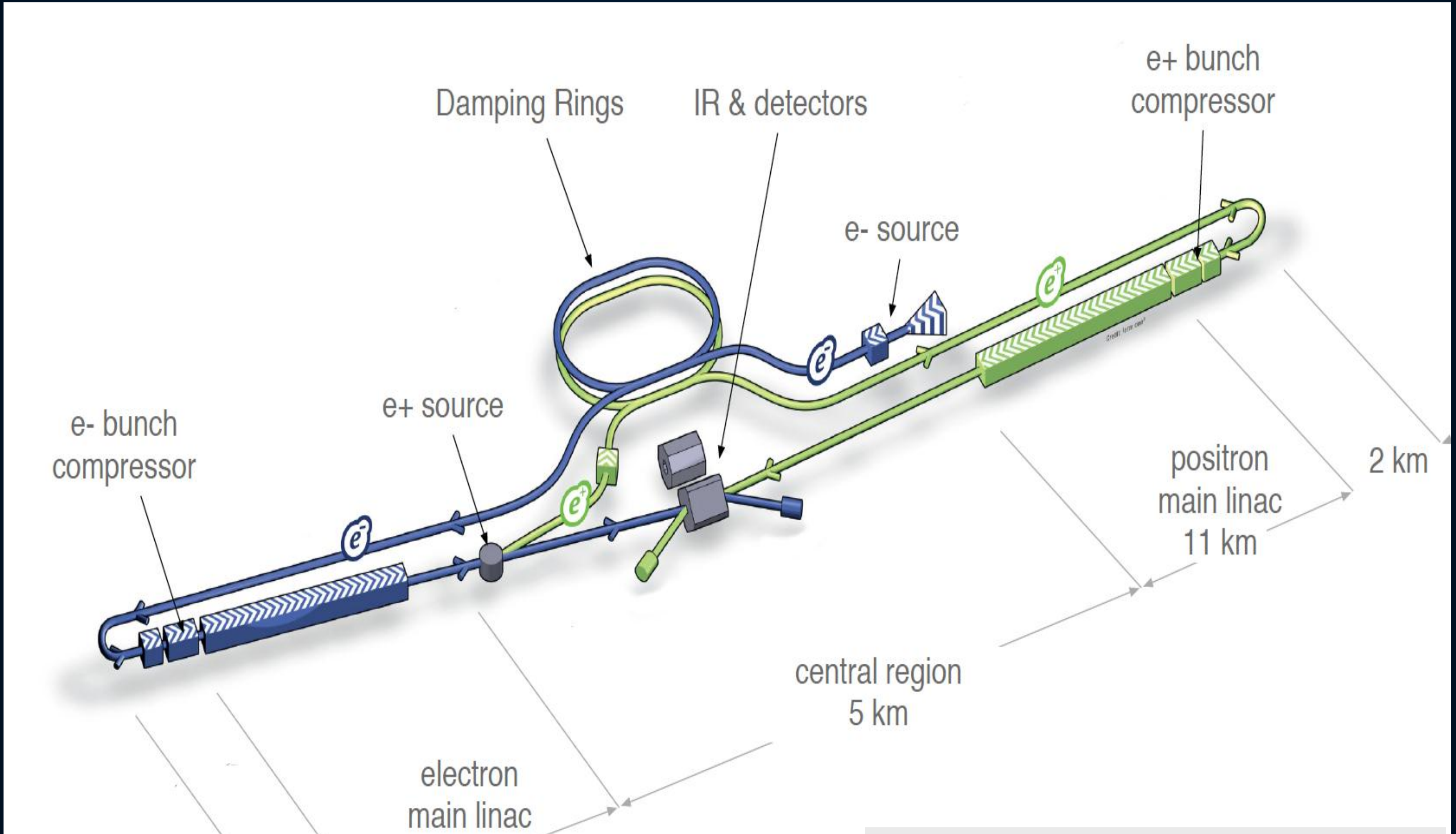


Beam-beam effects

Before we proceed with beam-beam effects…

- Let’s look at some examples of TRIZ-like inventions in the Interaction Region of ILC

International Linear Collider ILC



ILC e^{+}e^{-} Linear Collider

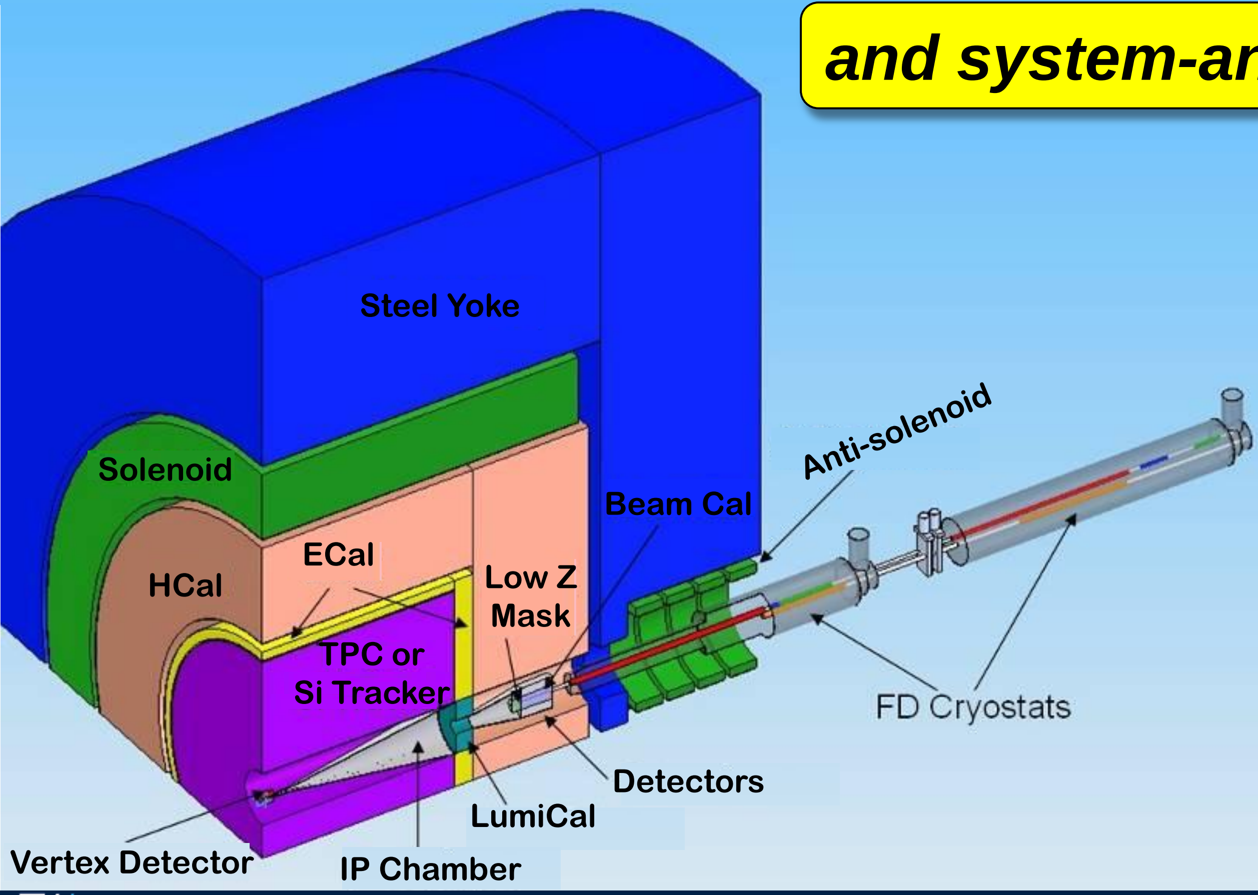
Energy **250 GeV x 250 GeV**

ILC Interaction Region…

has many examples of TRIZ-like inventions ..

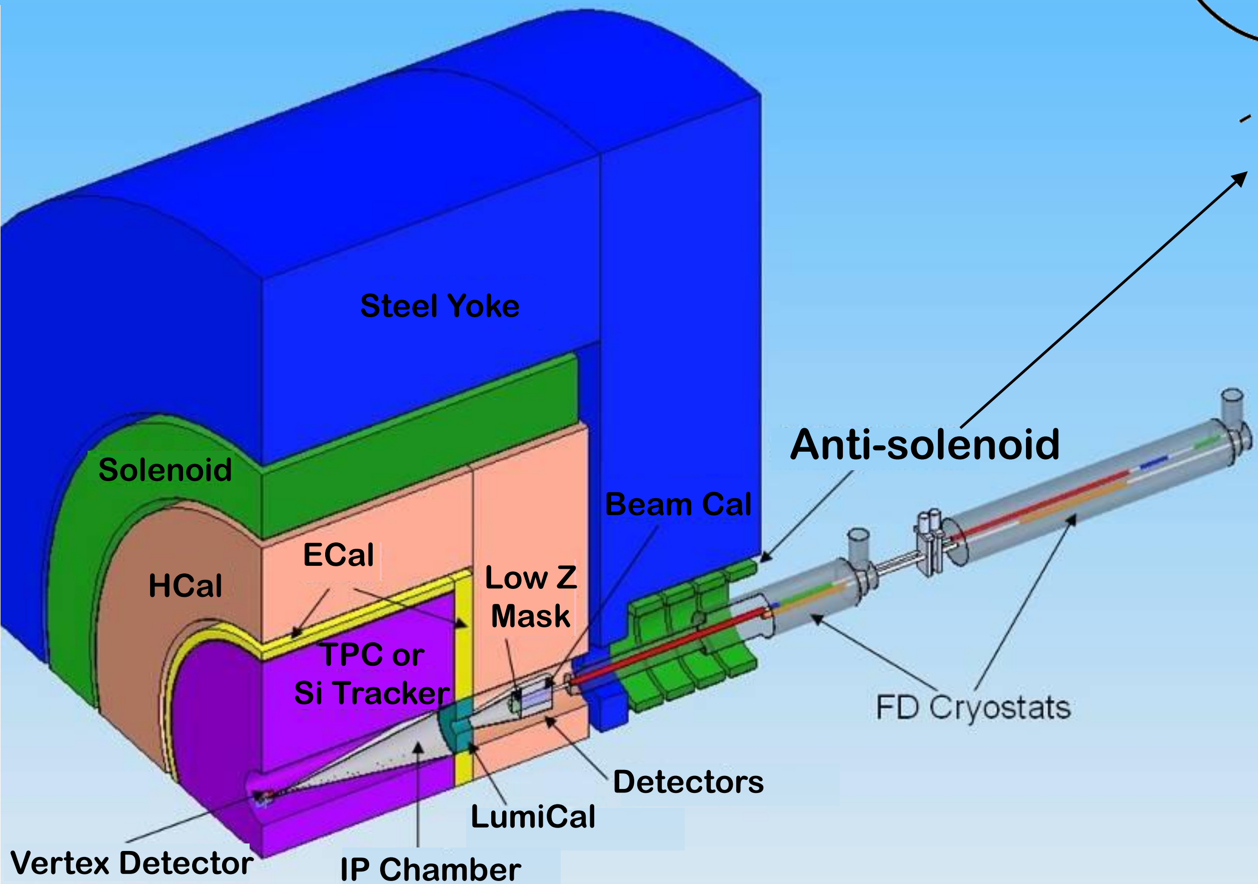
with Russian dolls…

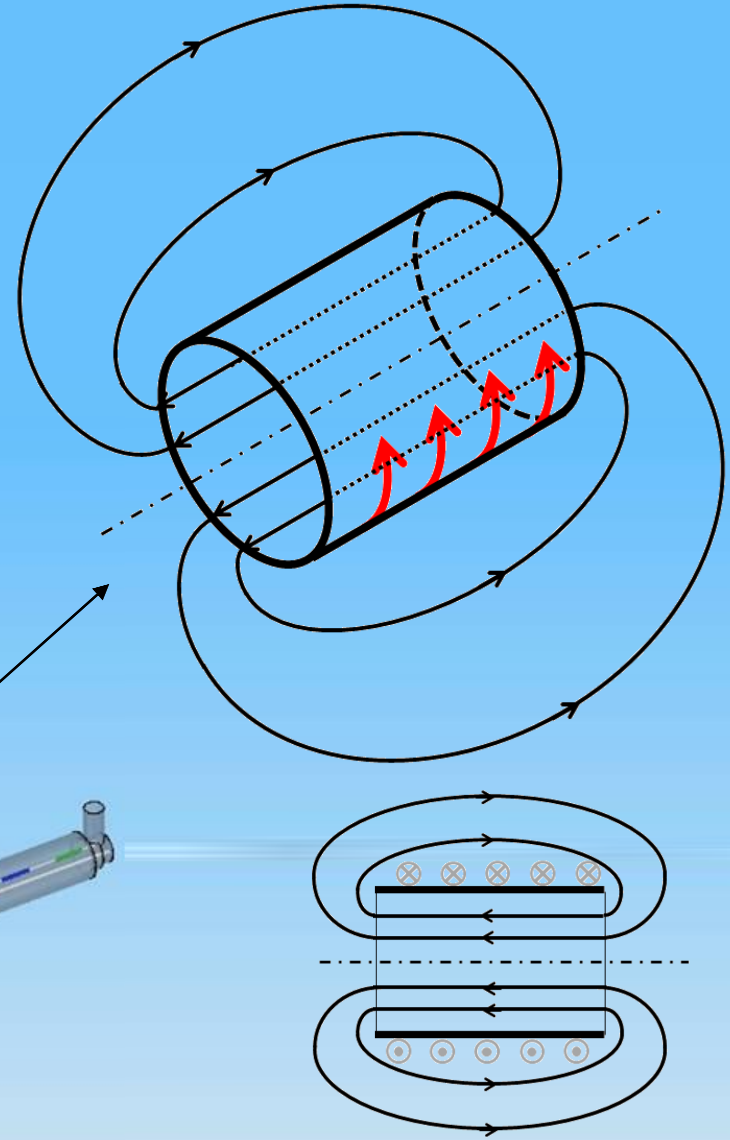
and system-antisystem principles



ILC Interaction Region…

Anti-solenoid is needed, but it would be pulled into the main solenoid with humongous force





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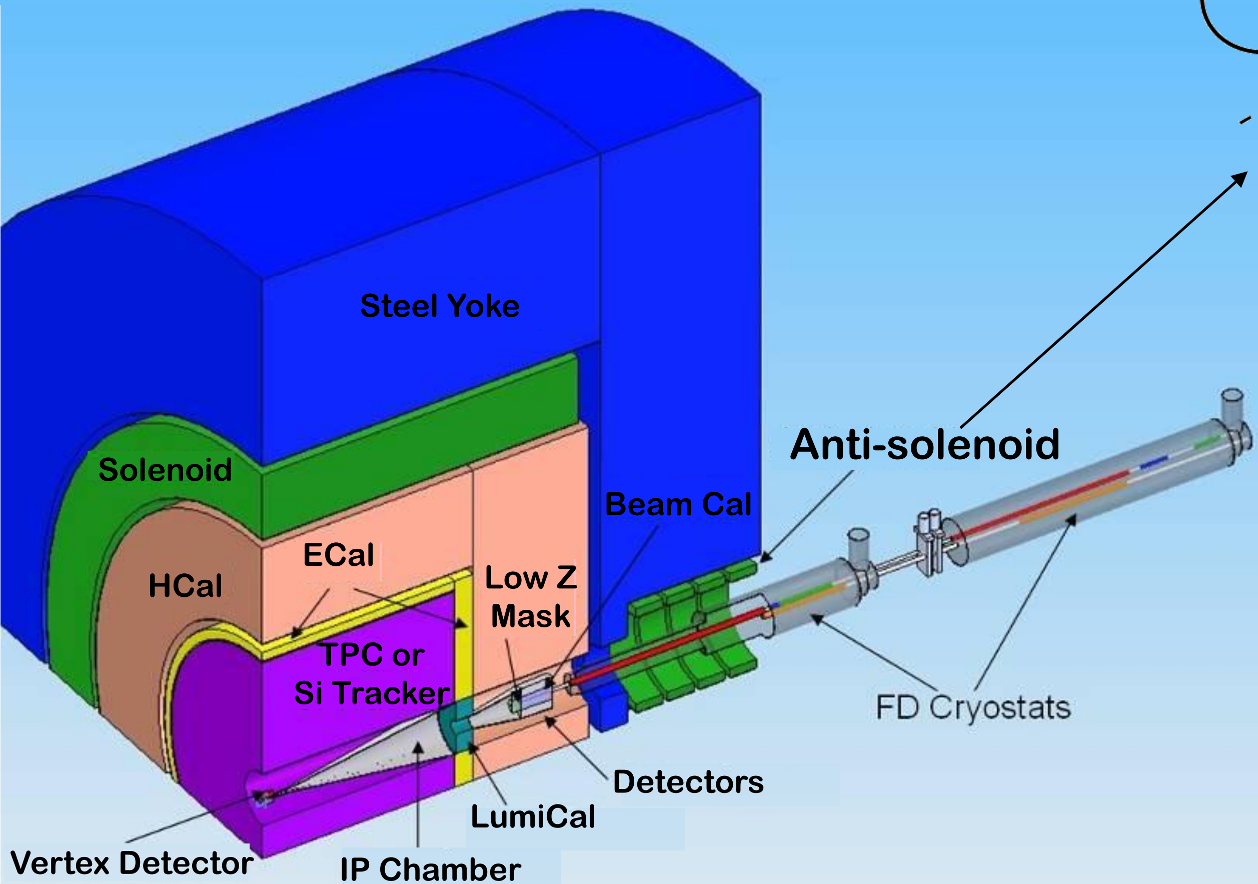
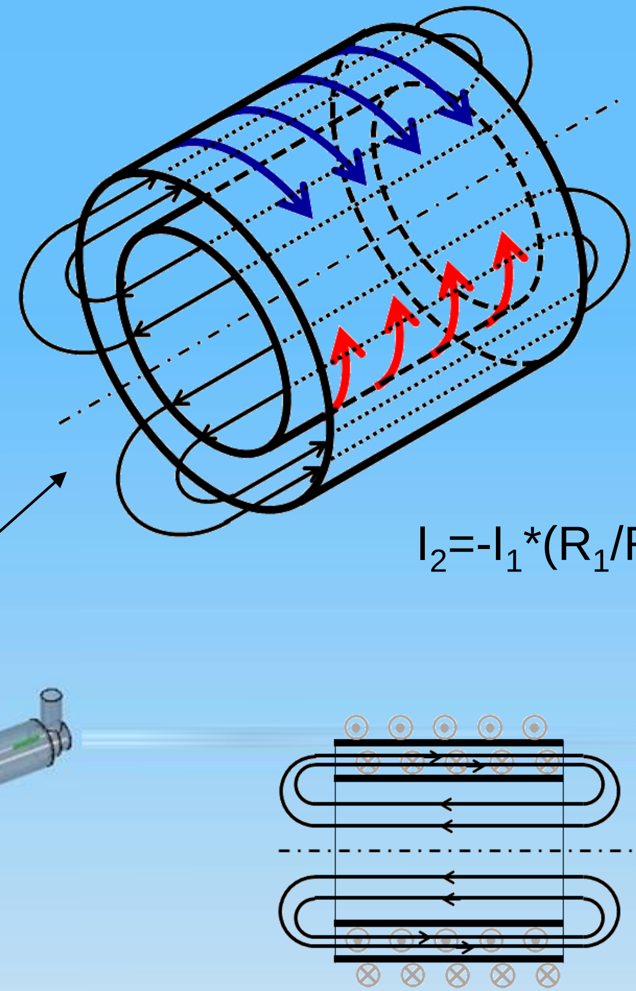
ILC Interaction Region…

Dual anti-solenoid is used, to cancel its external field – this makes it force-neutral



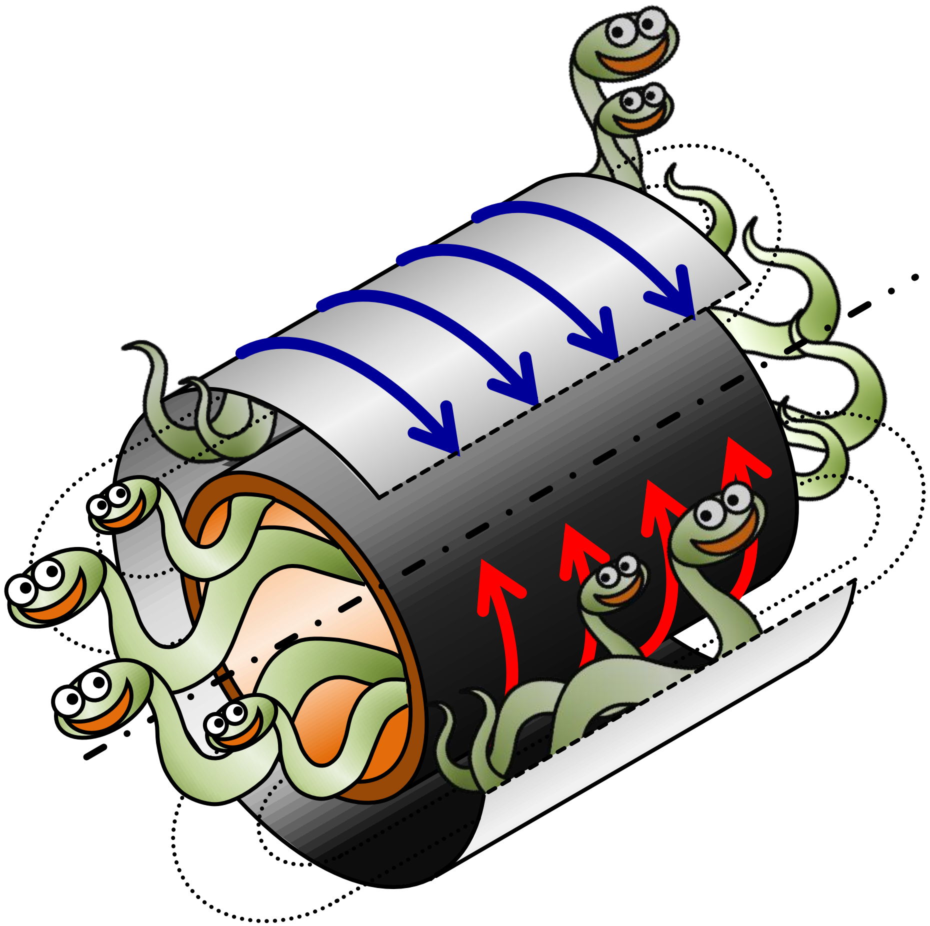


This is Russian doll & system – anti-system!

Recall synectics – use of analogies

– **Use of analogies to generate fresh view**

  - …
  - **empathic (attempting to look at the problem identifying yourself with the object);**
  - …
  - **metaphorical (describing the problem in terms of fairy-tales and legends);**

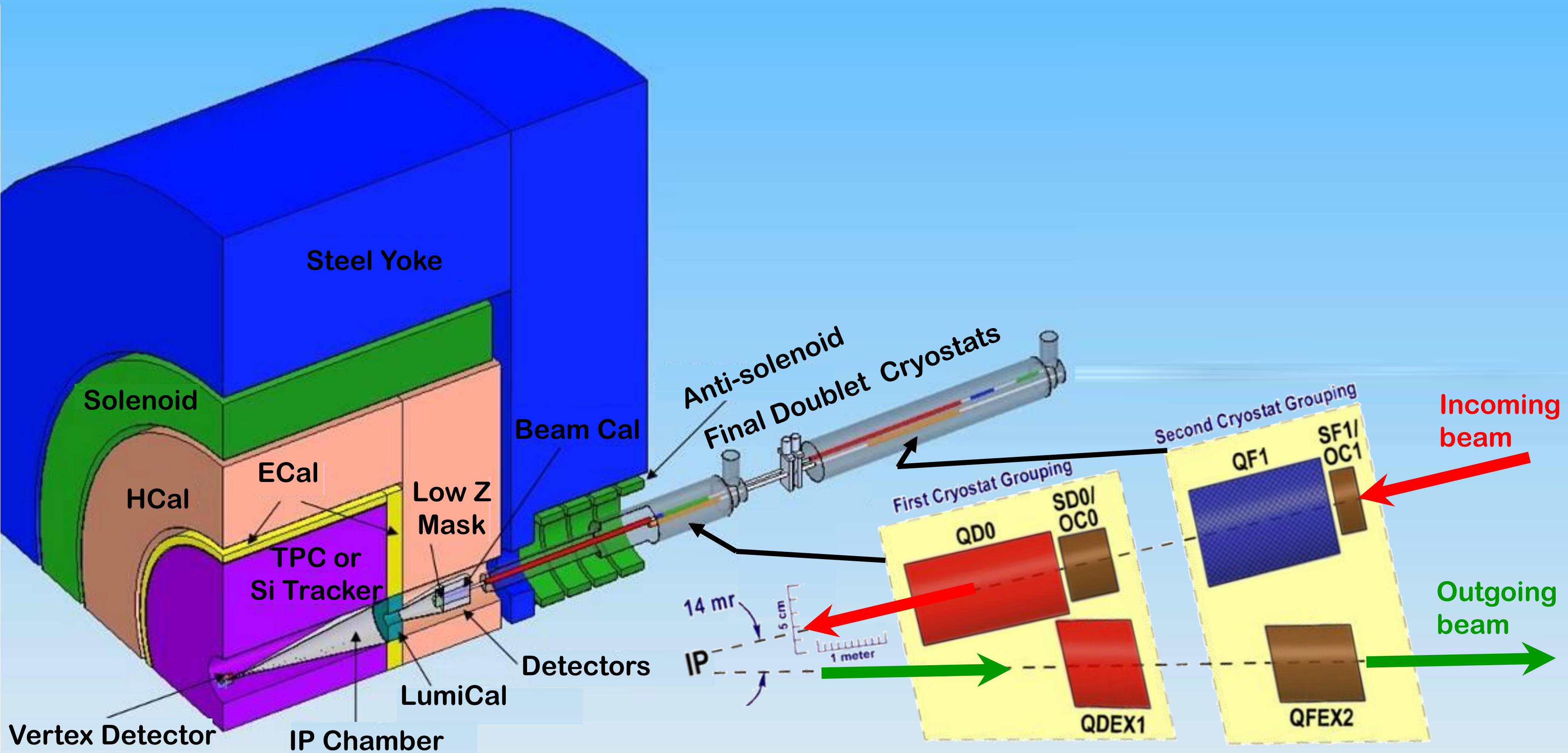


How to contain the magnetic flux?

You see how much more logical the TRIZ approach is

ILC Interaction Region…

Focusing quads are located just few cm away from each other, and their external field will affect the other beam

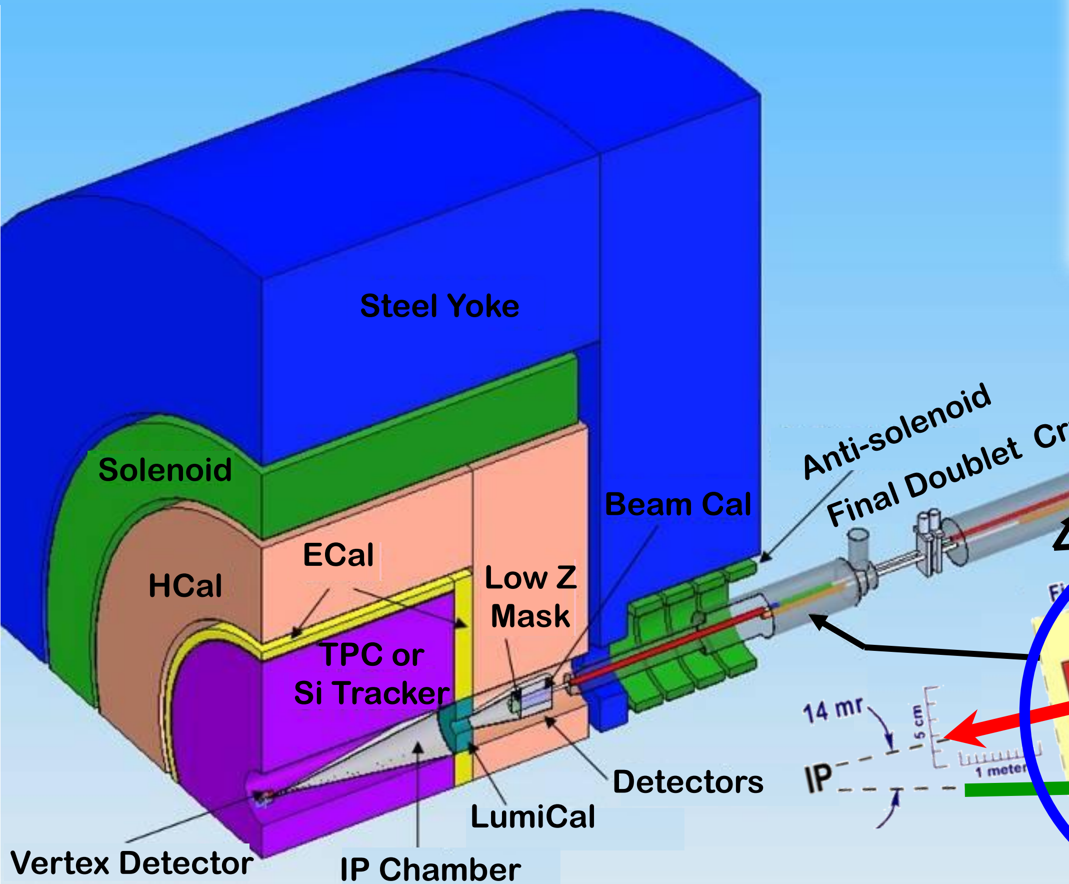


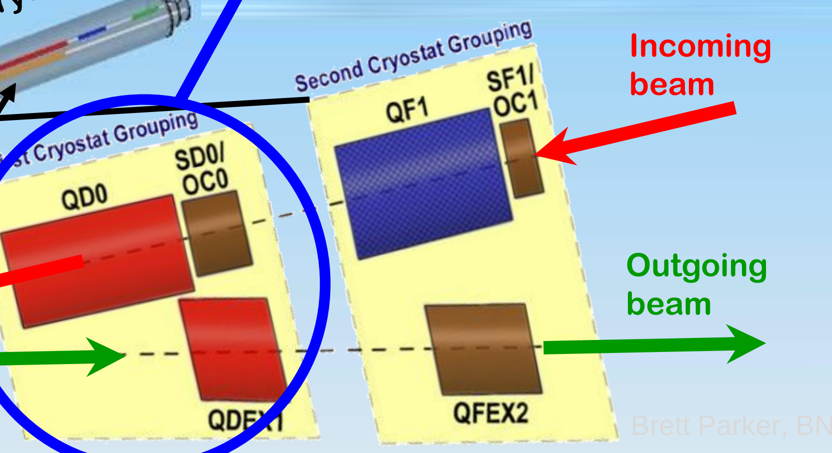
ILC Interaction Region…

Cross-talk of focusing quads is avoided by use of active shielding by a winding of opposite polarity

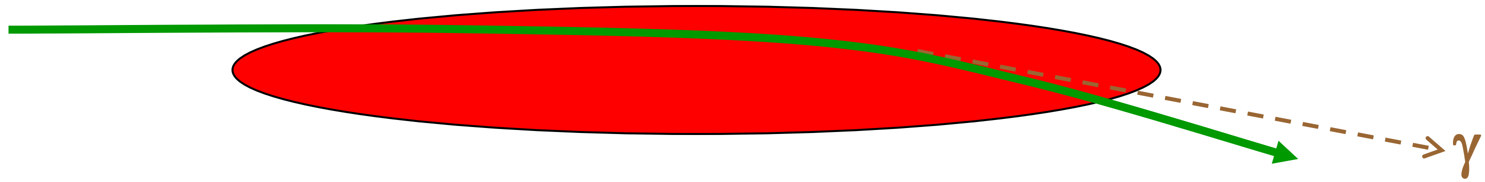
Actively shielded quad

Russian doll & system-antisystem





Beam-beam interactions



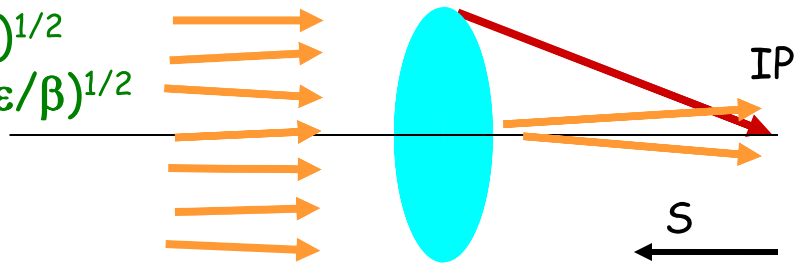
- Transverse fields of ultra-relativistic bunch
  - focus the incoming beam (electric and magnetic force add)
  - reduction of beam cross-section leads to more luminosity
    - H_D - the luminosity enhancement factor
  - bending of the trajectories leads to emission of beamstrahlung

Parameters of ILC BDS

Length (linac exit to IP distance)/side	m	2226
Length of main (tune-up) extraction line	m	300 (467)
Max Energy/beam (with more magnets)	GeV	250 (500)
Distance from IP to first quad, L*	m	3.5-(4.5)
Crossing angle at the IP	mrad	14
Nominal beam size at IP, σ^*, x/y	nm	655/5.7
Nominal beam divergence at IP, θ^*, x/y	μrad	31/14
Nominal beta-function at IP, β^*, x/y	mm	21/0.4
Nominal bunch length, σ_z	μm	300
Nominal disruption parameters, x/y		0.162/18.5
Nominal bunch population, N		2×10^{10}
Max beam power at main and tune-up dumps	MW	18
Preferred entrance train to train jitter	σ	< 0.5
Preferred entrance bunch to bunch jitter	σ	< 0.1
Typical nominal collimation depth, x/y		8–10/60
Vacuum pressure level, near/far from IP	nTorr	1/50

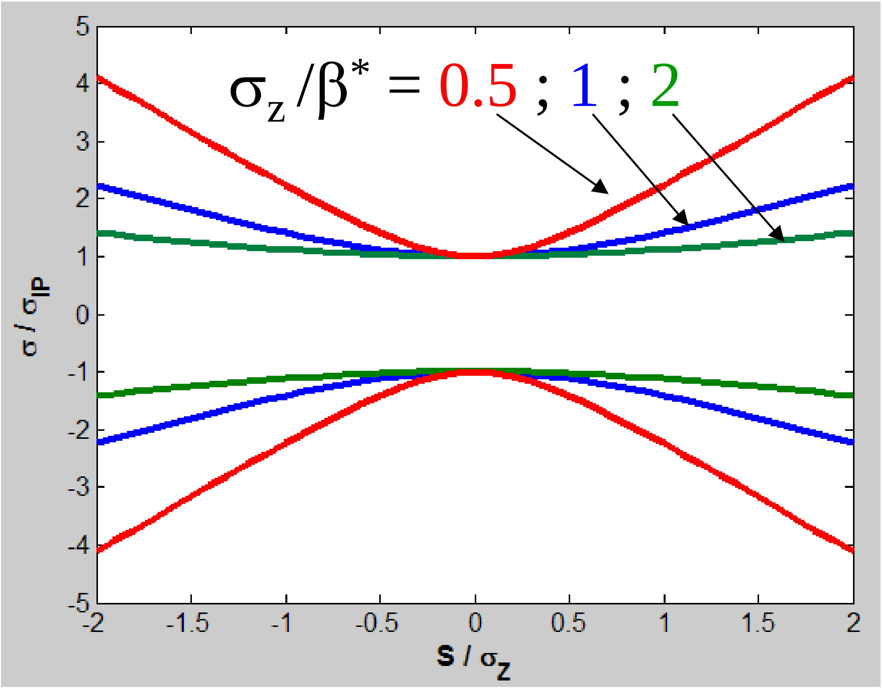
Hour-glass effect

Size: $(\varepsilon\, \beta)^{1/2}$
Angles: $(\varepsilon/\beta)^{1/2}$



Size at IP: $L^* (\varepsilon/\beta)^{1/2}$

Beta at IP:
$L^* (\varepsilon/\beta)^{1/2} = (\varepsilon\, \beta^*)^{1/2}$
$\Rightarrow \quad \beta^* = L^{*2}/\beta$

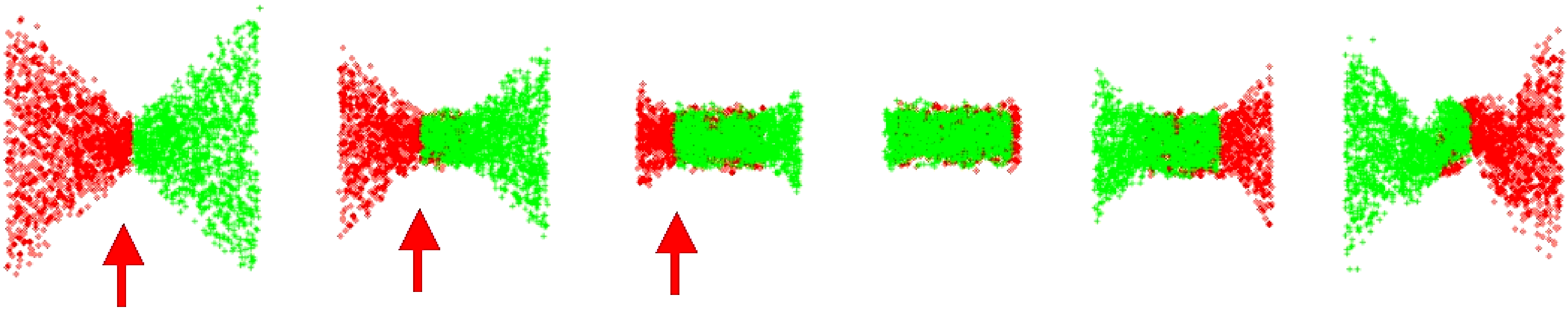


Behavior of beta-function along the final drift:

$(\beta)^{1/2} = (\beta^* + S^2/\beta^*)^{1/2}$

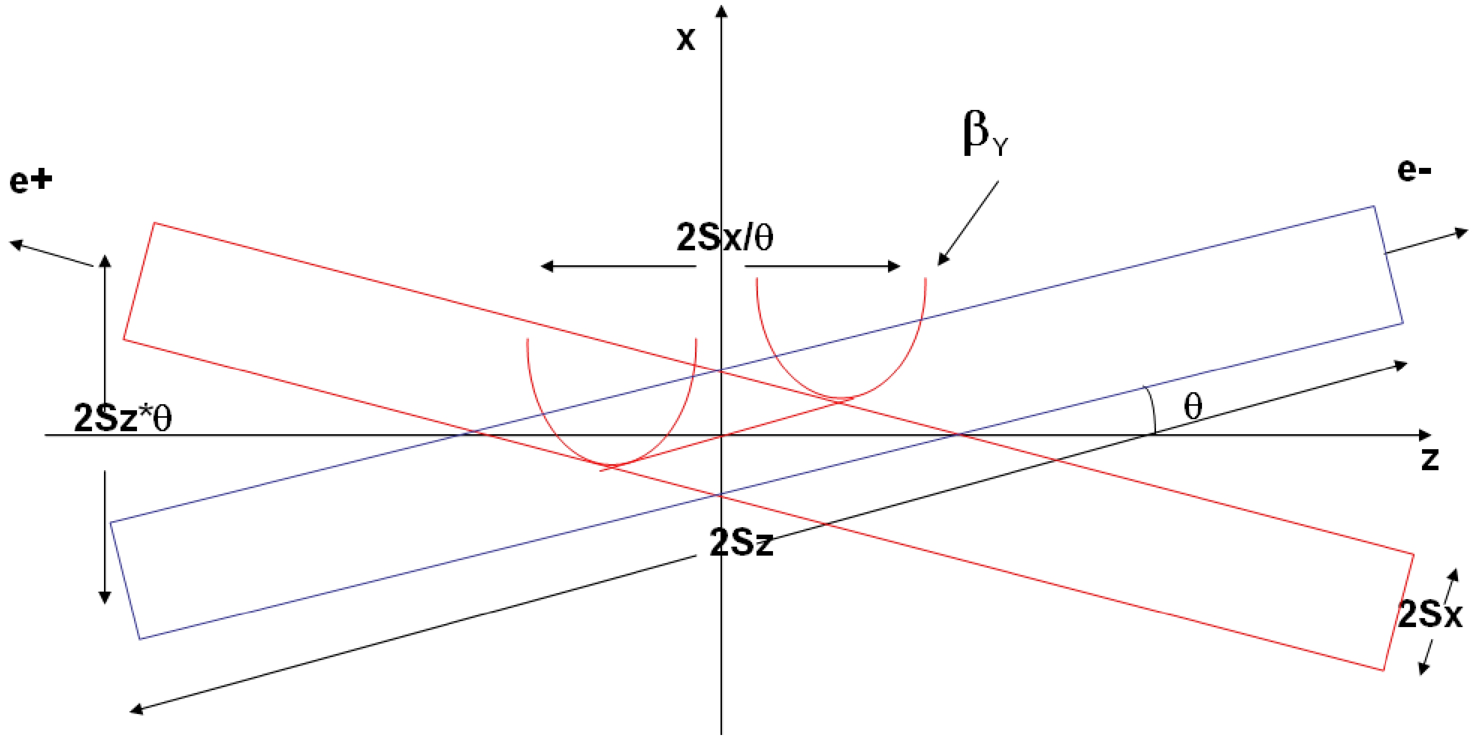
Reduction of β^* below σ_z does not give further decrease of effective beam size (<u>usually</u>)

Beam-beam: Travelling focus



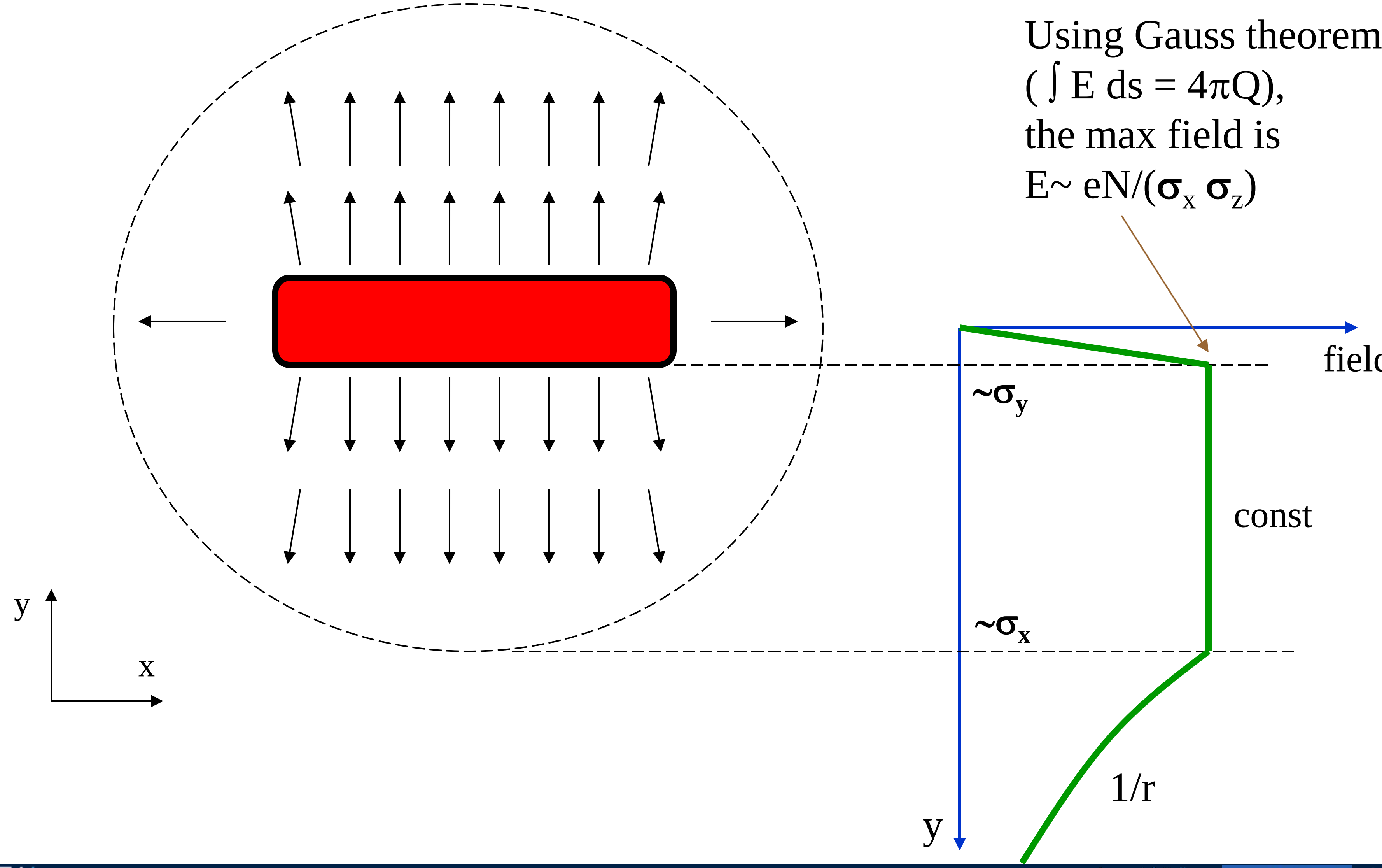
- Suggested by V.Balakin – idea is to use beam-beam forces for additional focusing of the beam – allows some gain of luminosity or overcome somewhat the hour-glass effect
- Figure shows simulation of traveling focus. The arrows show the position of the focus point during collision
- So far not yet used experimentally

Beam-beam: Crabbed-waist



- Suggested by P.Raimondi for Super-B factory
- Vertical waist has to be a function of X. In this case coupling produced by beam-beam is eliminated
- Experimentally verified at DAFNE

Fields of flat bunch, qualitatively



Using Gauss theorem
($\int E\, ds = 4\pi Q$),
the max field is
$E \sim eN/(\boldsymbol{\sigma}_x\, \boldsymbol{\sigma}_z)$

Disruption parameter

- For Gaussian transverse beam distribution, and for particle near the axis, the beam kick results in the final particle angle:

$$\Delta x' = \frac{dx}{dz} = -\frac{2Nr_e}{\gamma\sigma_x\left(\sigma_x+\sigma_y\right)}\cdot x \qquad \Delta y' = \frac{dy}{dz} = -\frac{2Nr_e}{\gamma\sigma_y\left(\sigma_x+\sigma_y\right)}\cdot y$$

- "Disruption parameter" – characterize focusing strength of the field of the bunch ($D_y \sim \sigma_z/f_{beam}$)

$$D_x = \frac{2Nr_e\sigma_z}{\gamma\sigma_x(\sigma_x+\sigma_y)} \qquad D_y = \frac{2Nr_e\sigma_z}{\gamma\sigma_y(\sigma_x+\sigma_y)}$$

- D << 1 – bunch acts as a thin lens
- D >> 1 – particle oscillate in the field of other bunch
  - If D is bigger than ~20, instability may take place

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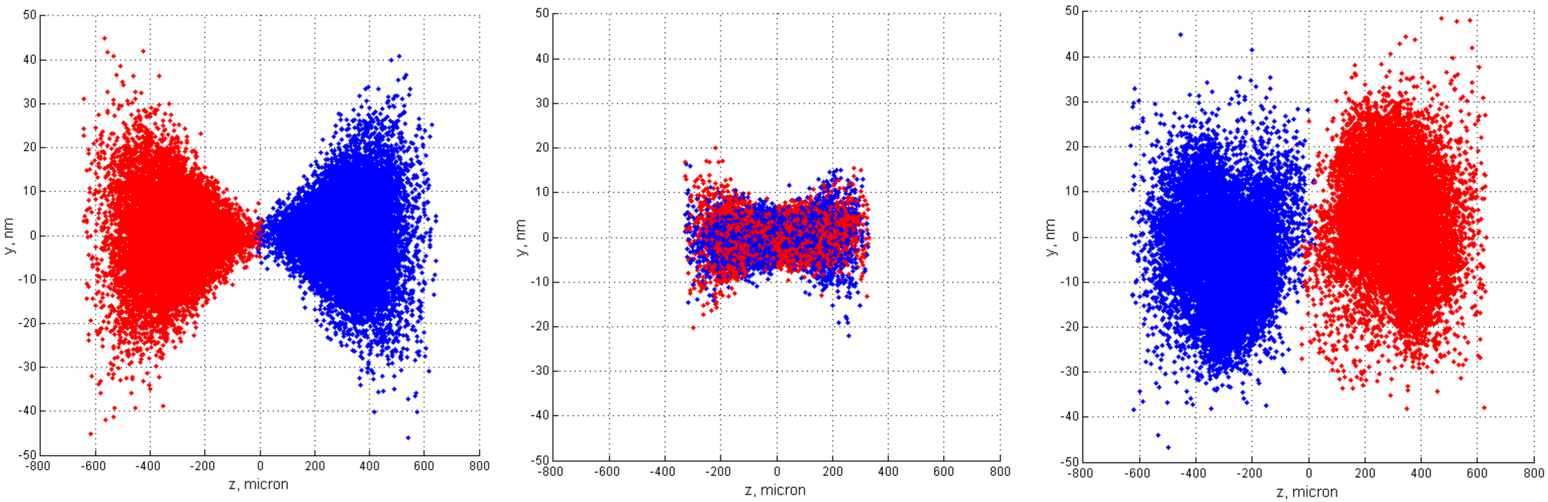
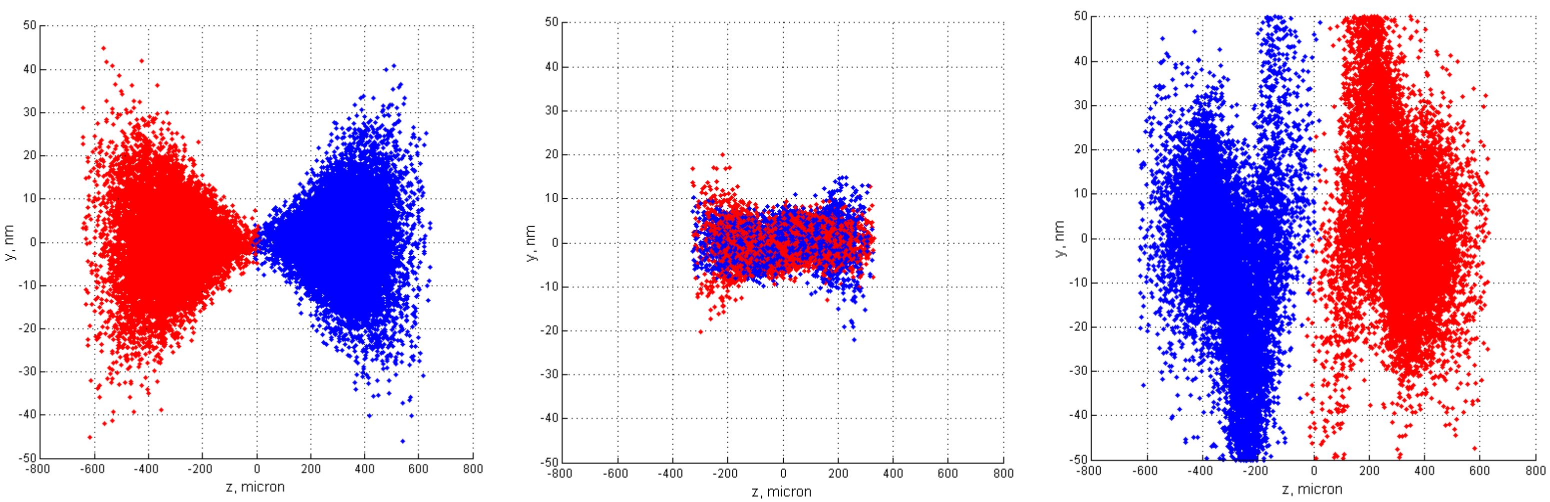
Beam-beam effects
H_D and instability

$$D_y = \frac{2r_e}{\gamma}\frac{N\sigma_z}{\sigma_x\sigma_y}$$



D_y~12



Nx2
D_y~24

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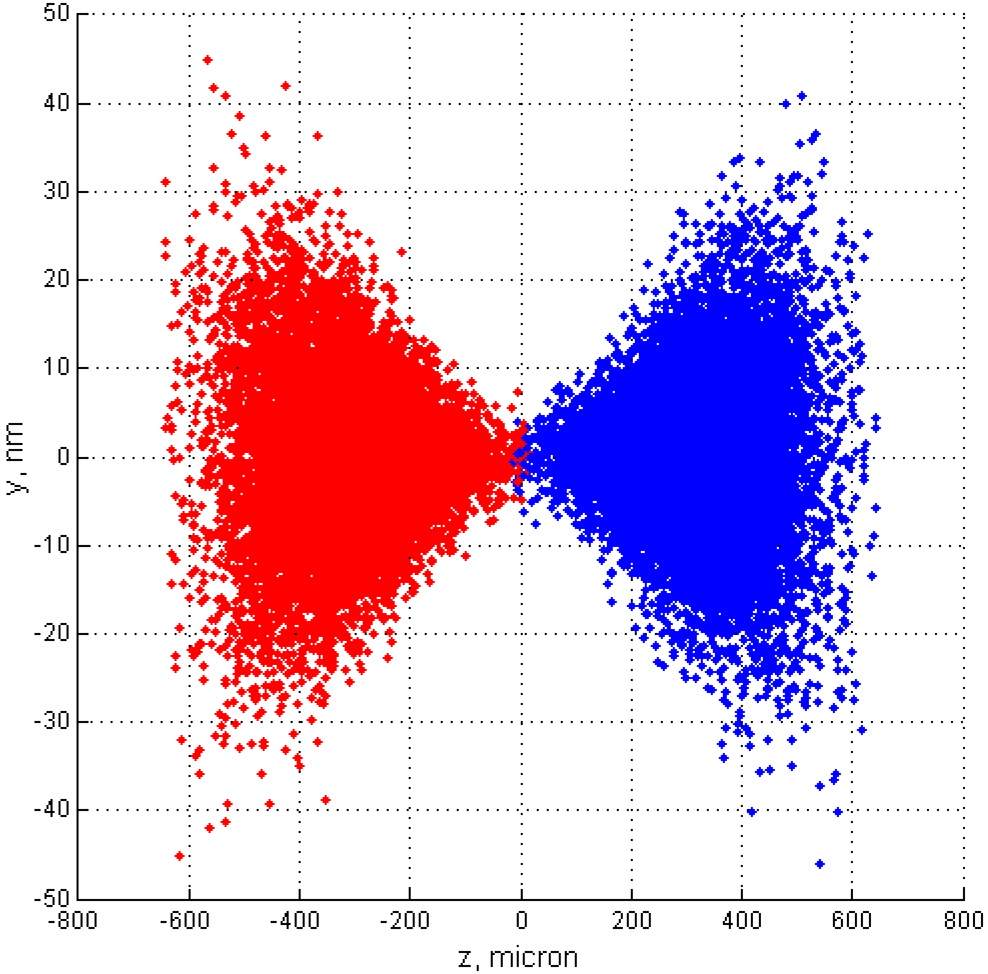
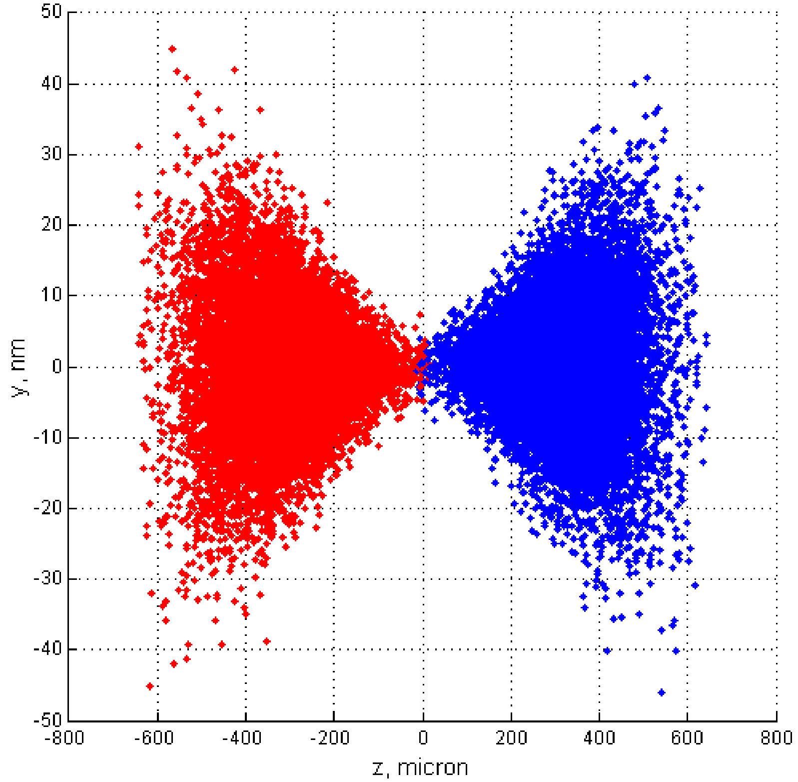
Beam-beam effects
H_D and instability



LC parameters
D_y~12

Luminosity enhancement
H_D ~ 1.4

Not much of an instability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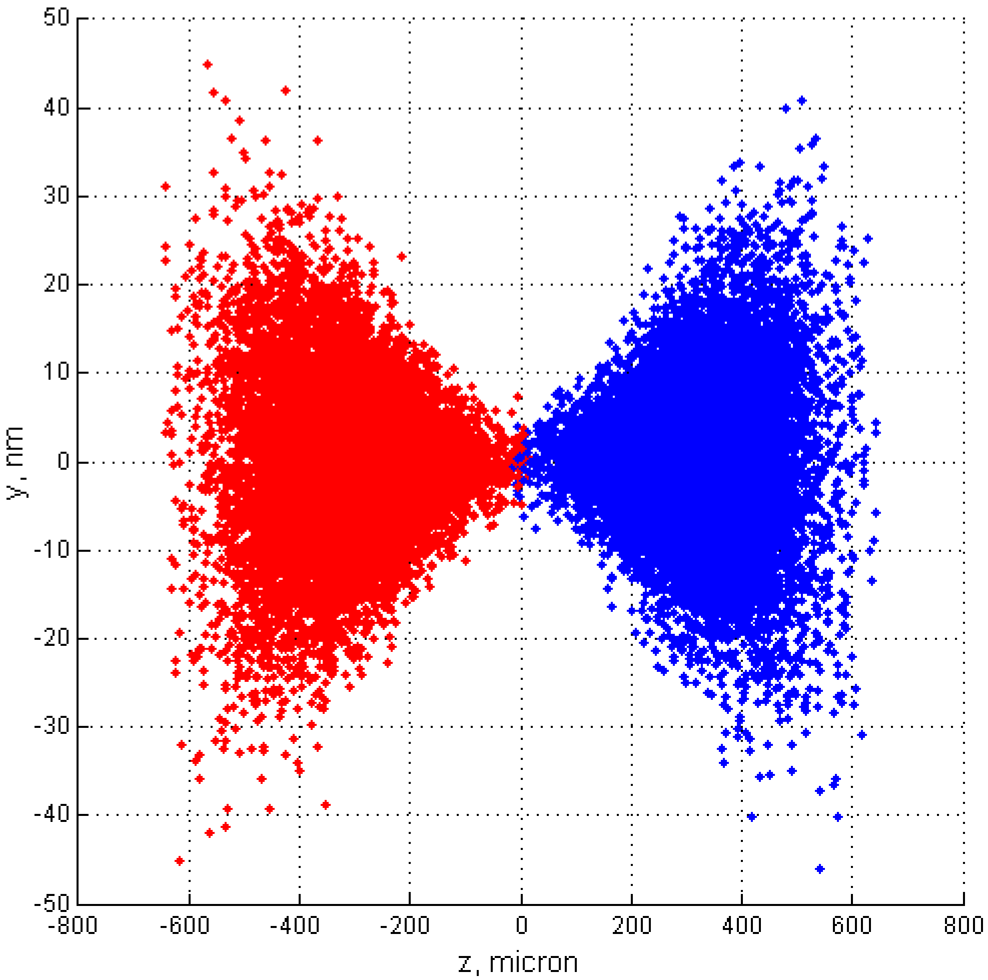
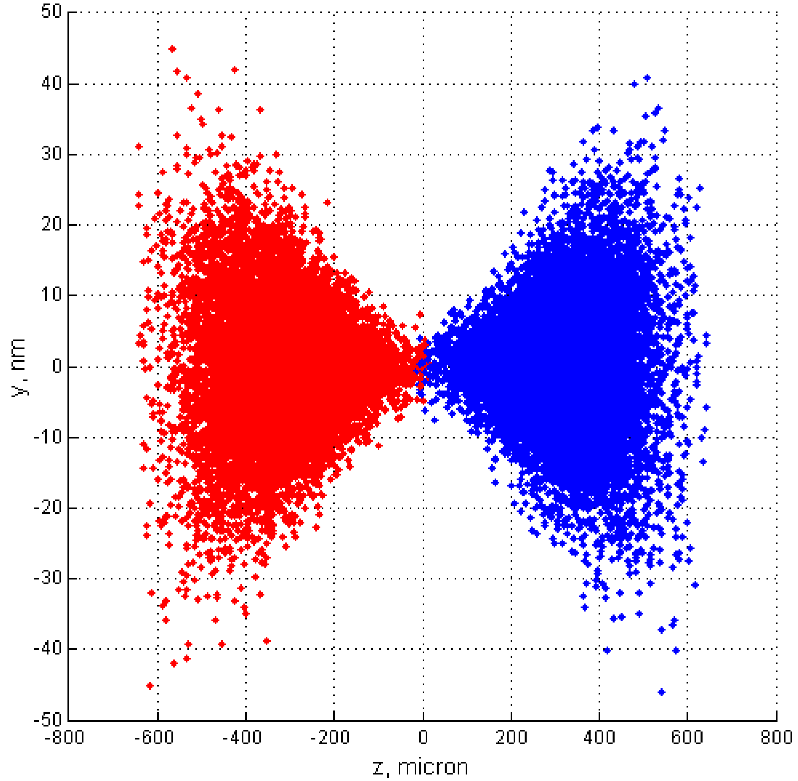
Beam-beam effects
H_D and instability



Nx2
D_y~24

Beam-beam instability is clearly pronounced

Luminosity enhancement is compromised by higher sensitivity to initial offsets



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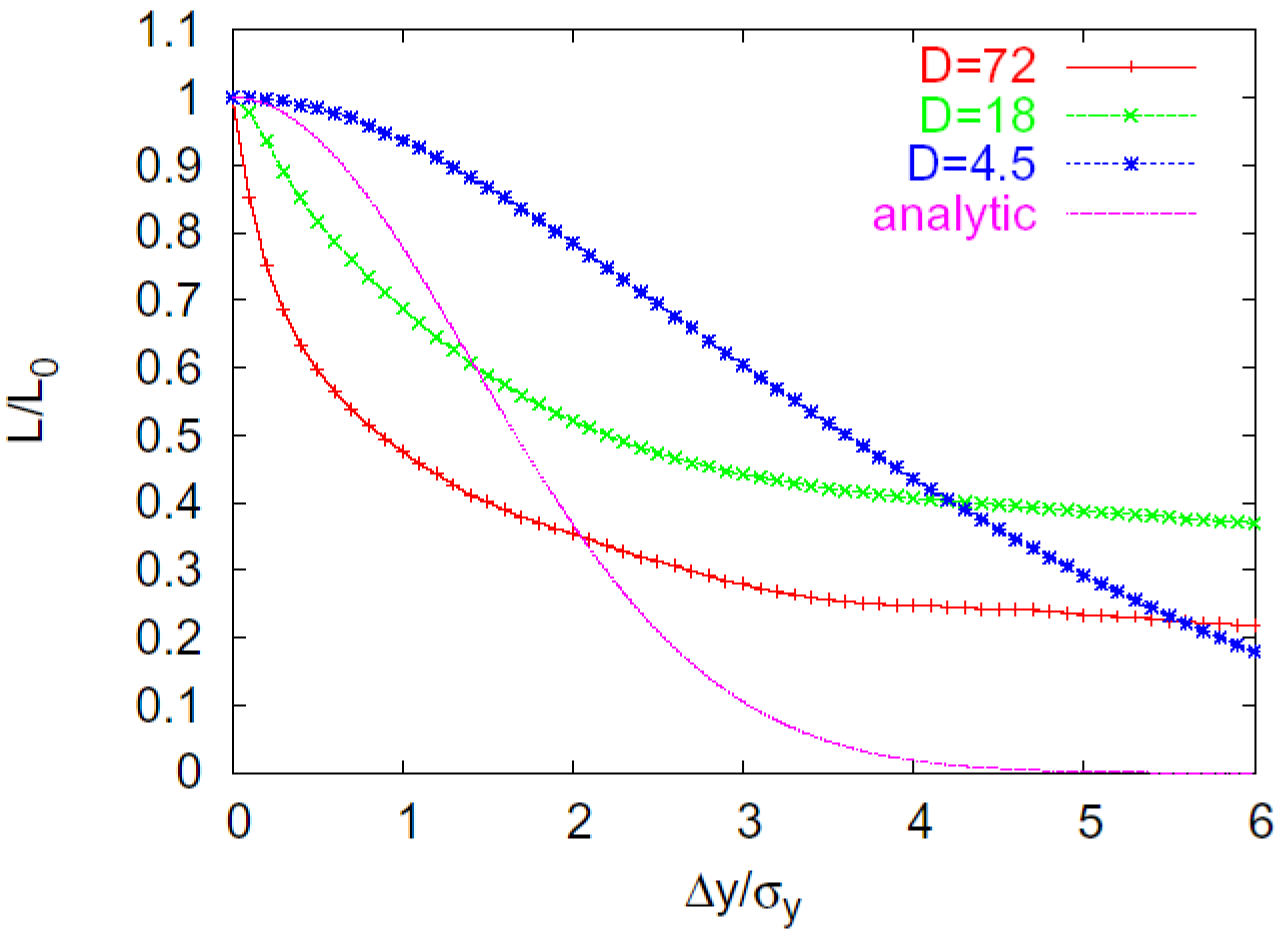
Sensitivity to offset at IP



- Luminosity (normalized) versus offset at IP for different disruption parameters

Beamstrahlung

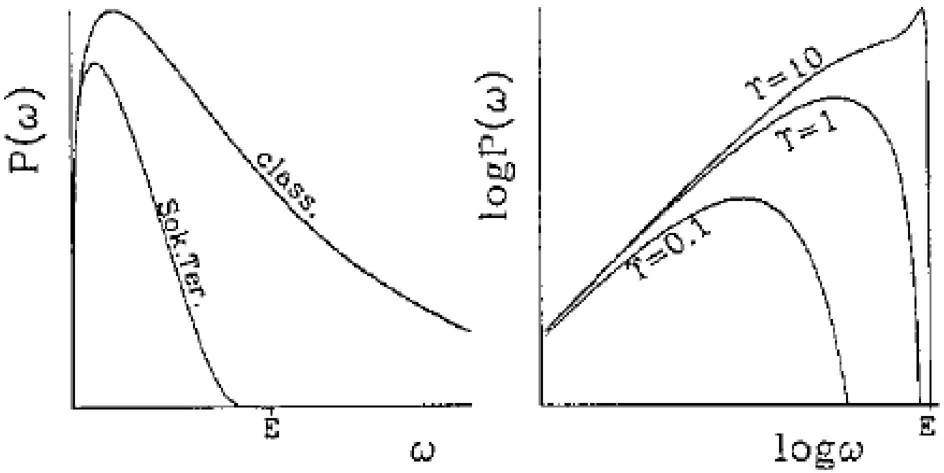
- Synchrotron radiation in field of opposite bunch
- Estimate R of curvature as R ~ $\sigma_z^2/(D_y\sigma_y)$
- Using formulas derived earlier, estimate ω_c and find that $h\omega_c/E \sim \gamma N r_e^2/(\alpha\sigma_x\sigma_z)$ and call it "Upsilon"

More accurate formula:
$$\Upsilon_{avg} \approx \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha\sigma_z\left(\sigma_x+\sigma_y\right)}$$

- The energy loss also can be estimated from earlier derived formulas: dE/E ~ $\gamma r_e^3 N^2 / (\sigma_z \sigma_x^2)$
  - This estimation is very close to exact one
- Number of γ per electron estimated $n_{\gamma/e} \sim \alpha r_e N/\sigma_x$
  - which is usually around one γ per e

Classical and quantum regime

- The "upsilon" parameter, when it is <<1, has meaning of ratio of photon energy to beam energy
- When Upsilon become ~1 and larger, the classical regime of synchrotron radiation is not applicable, and quantum SR formulas of Sokolov-Ternov should be used.
- Spectrum of SR change …



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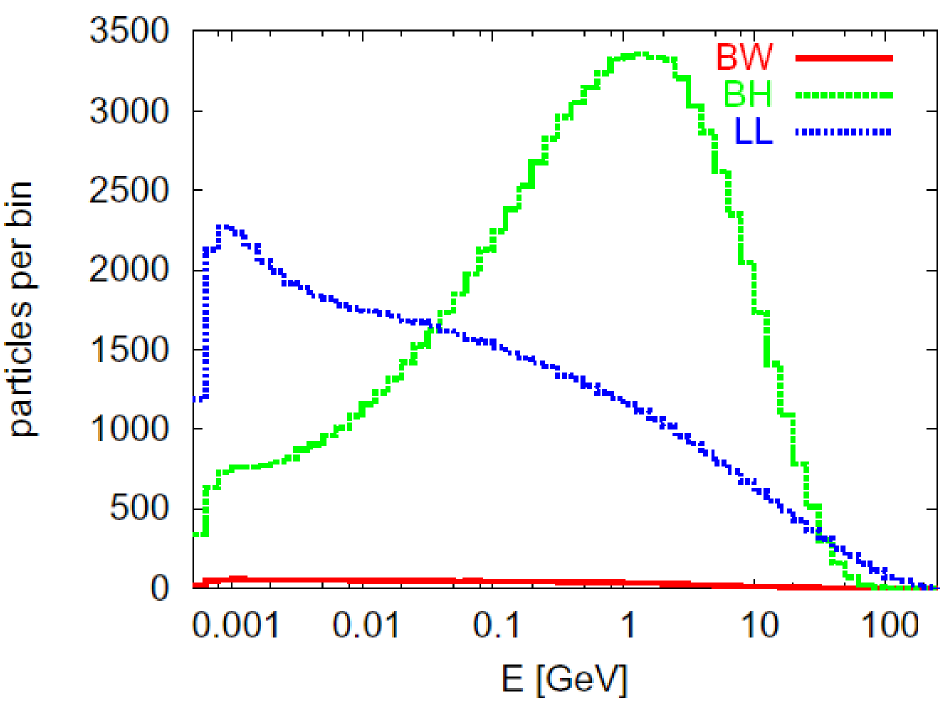
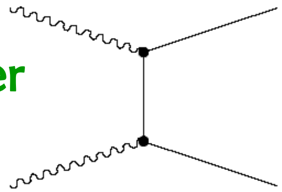
Incoherent* production of pairs

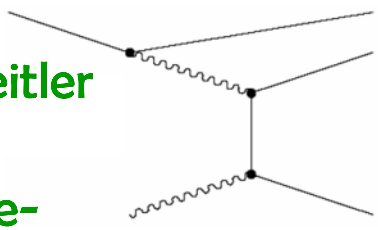
- Beamstrahling photons, particles of beams or virtual photons interact, and create e+e- pairs



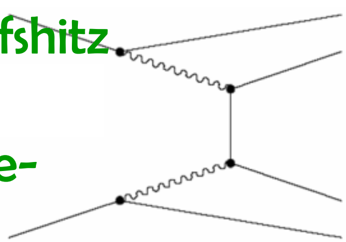
Breit-Wheeler process
$\gamma\gamma \rightarrow$ e+e-



Bethe-Heitler process
$e\gamma \rightarrow$ ee+e-



Landau-Lifshitz process
ee $\rightarrow$ eee+e-



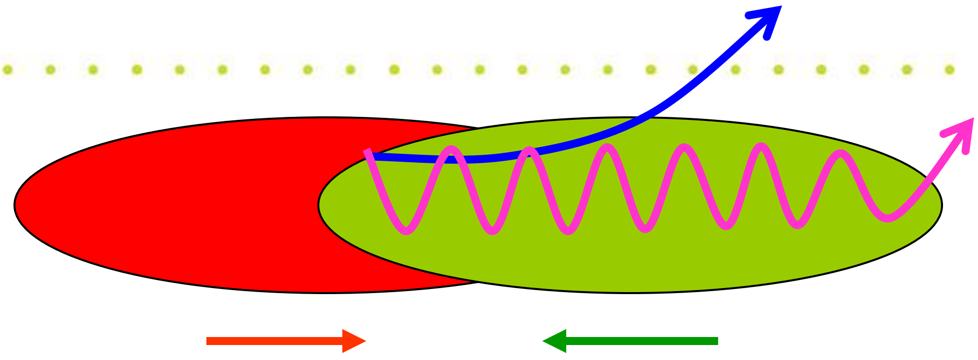
*) Coherent pairs are generated by photon in the field of opposite bunch. It is negligible for ILC parameters.

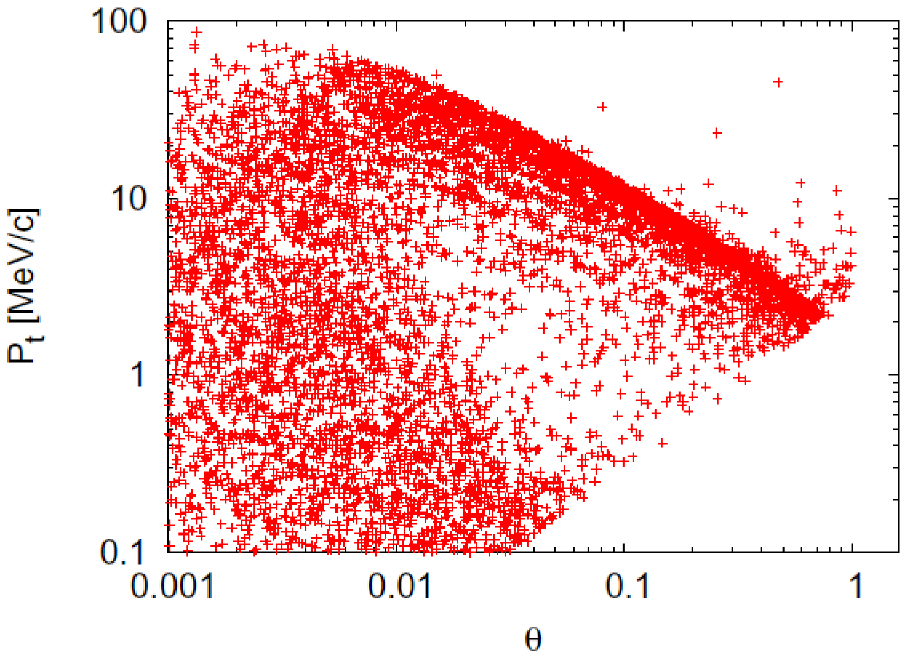
Deflection of pairs by beam

- Pairs are affected by the beam (focused or defocused)
- Deflection angle and P_t correlate
- Max angle estimated as (where ϵ is fractional energy):

$$\theta_m = \sqrt{4 \frac{\ln\left(\frac{D}{\epsilon}+1\right) D\sigma_x^2}{\sqrt{3}\epsilon\sigma_z^2}}$$

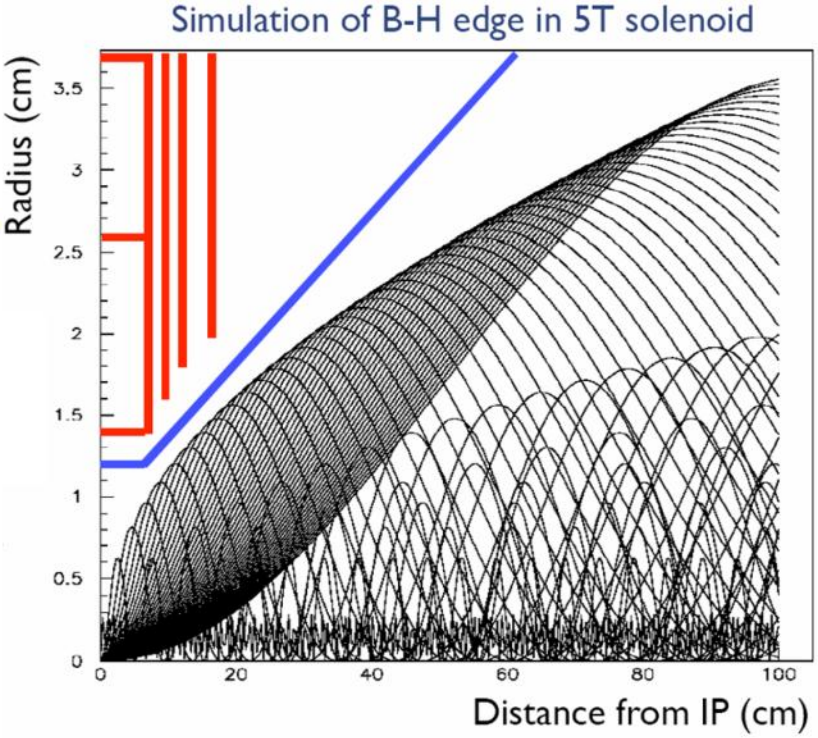
- Bethe-Heitler pairs have hard edge, Landau-Lifshitz pairs are outside

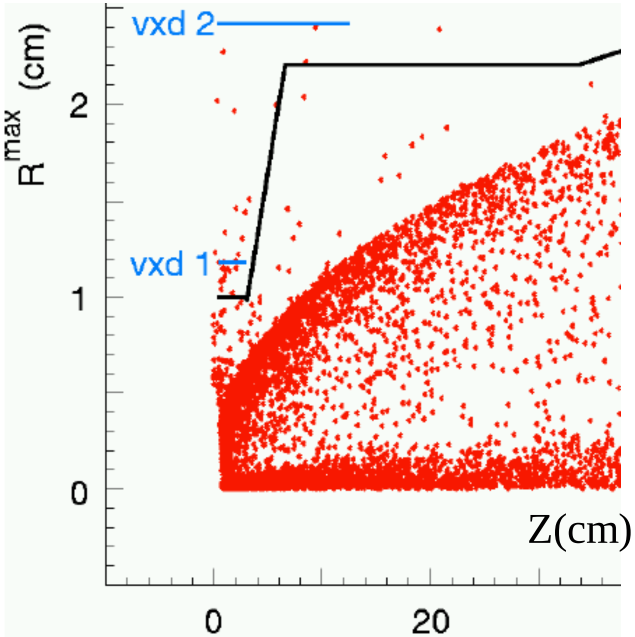




Deflection of pairs by detector solenoid

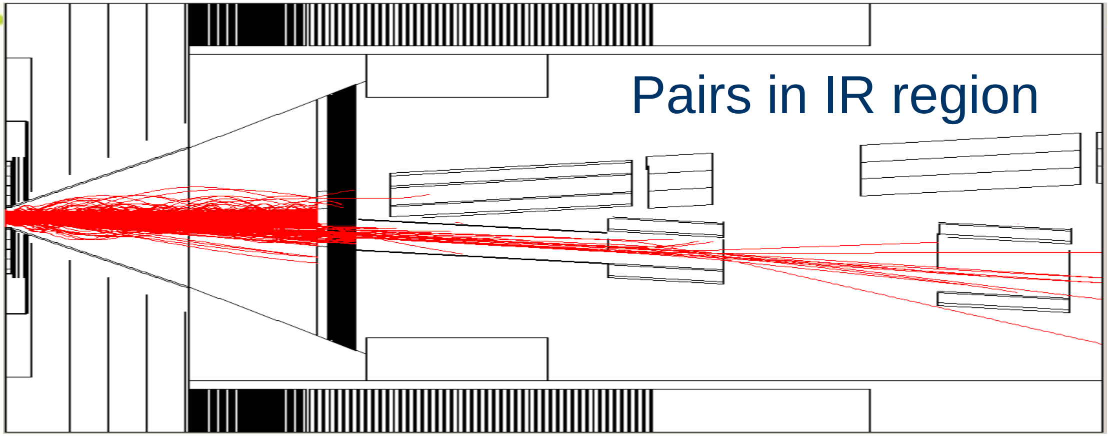
- Pairs are curled by the solenoid field of detector
- Geometry of vertex detector and vacuum chamber chosen in such a way that most of pairs (B-H) do not hit the apertures
- Only small number (L-L) of pairs would hit the VX apertures

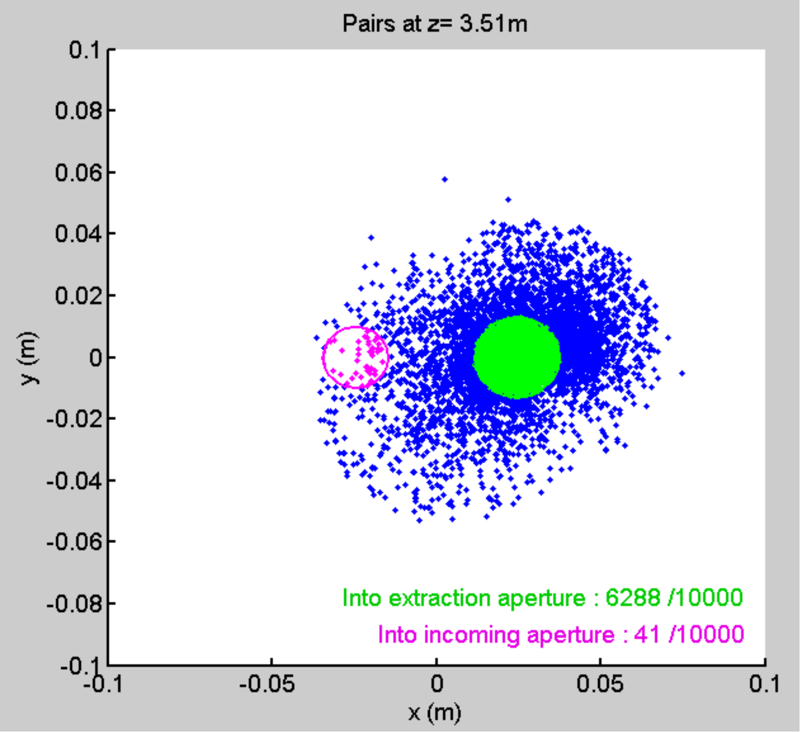


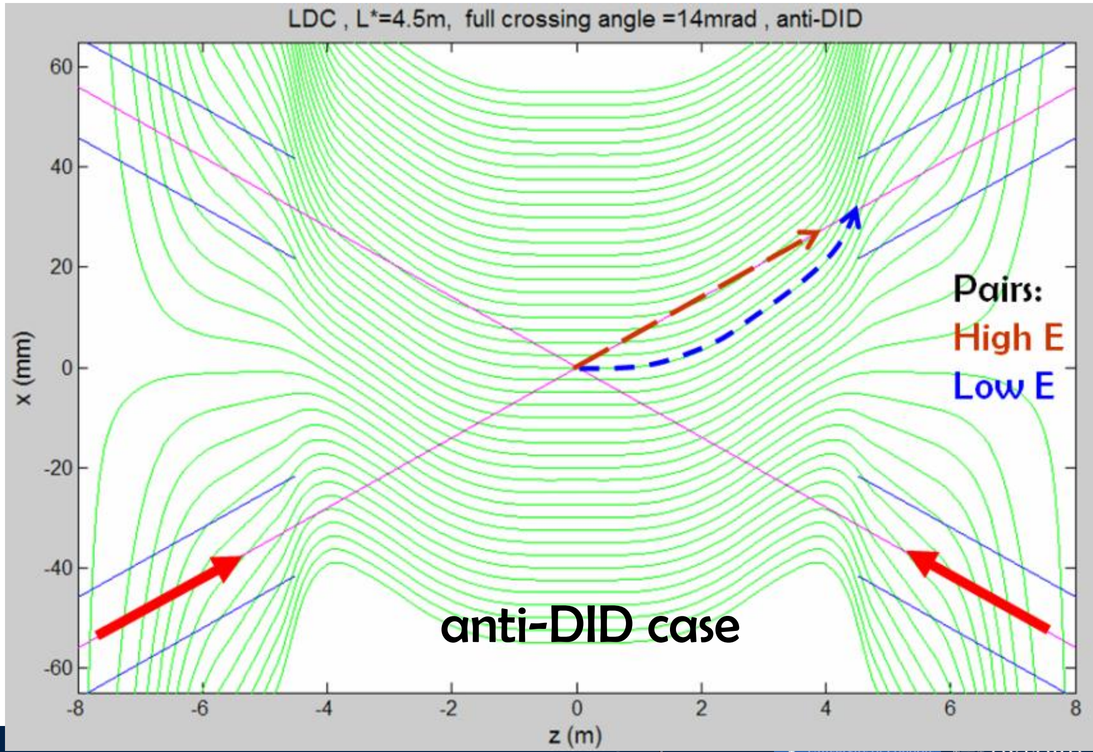


Use of anti-DID to direct pairs

Anti-DID field can be used to direct most of pairs into extraction hole and thus improve somewhat the background conditions







Overview of beam-beam parameters (D_y, δ_E , Υ)

$$\mathrm{Lumi} \sim H_D \frac{N^2}{\sigma_x \sigma_y}$$

- Luminosity per bunch crossing. H_D – luminosity enhancement

$$D_y \sim \frac{N \sigma_z}{\gamma \sigma_x \sigma_y}$$

- "Disruption" – characterize focusing strength of the field of the bunch ($D_y \sim \sigma_z / f_{beam}$)

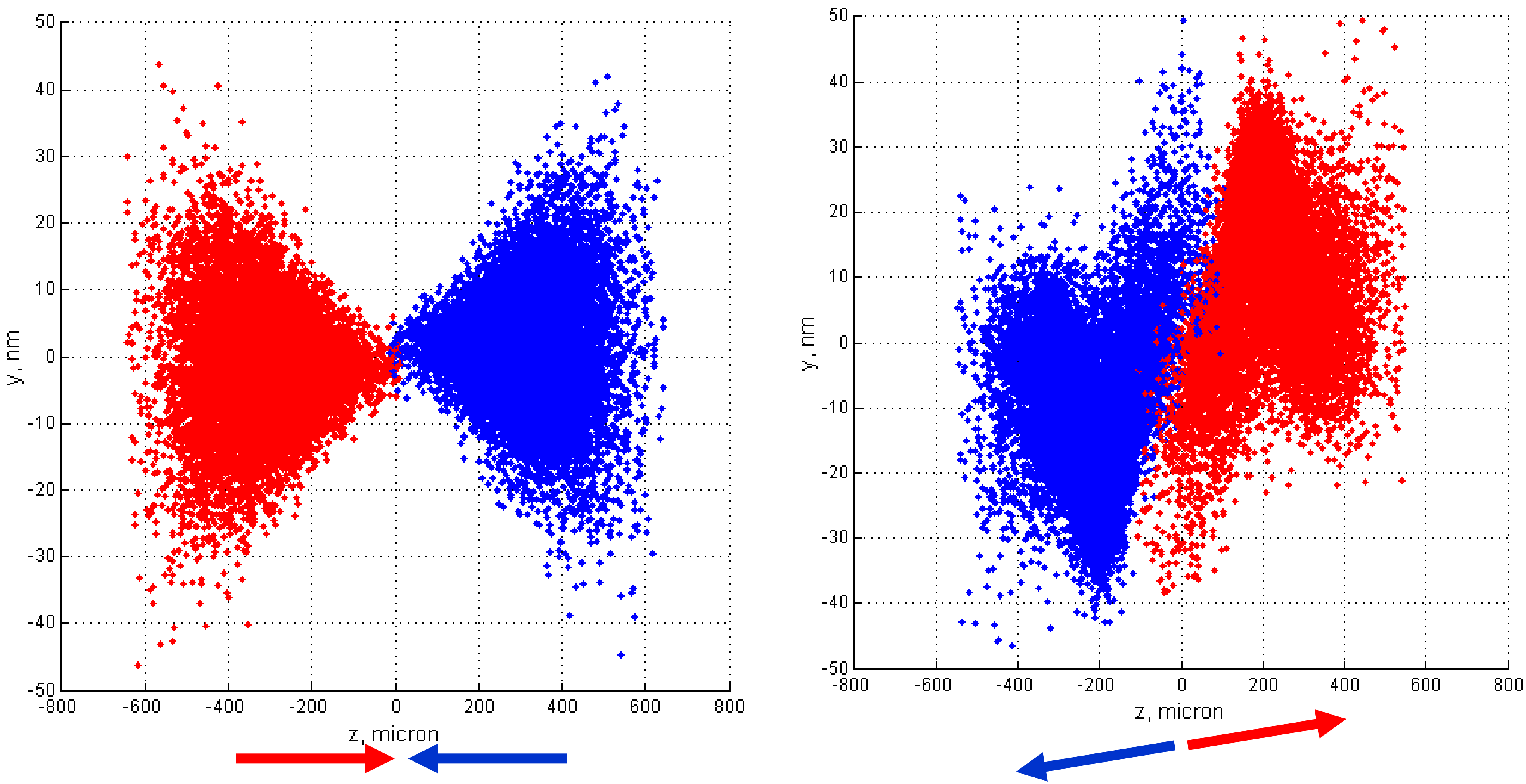
$$\delta_E \sim \frac{N^2 \gamma}{\sigma_x^2 \sigma_z}$$

- Energy loss during beam-beam collision due to synchrotron radiation

$$\Upsilon \sim \frac{N \gamma}{\sigma_x \sigma_z}$$

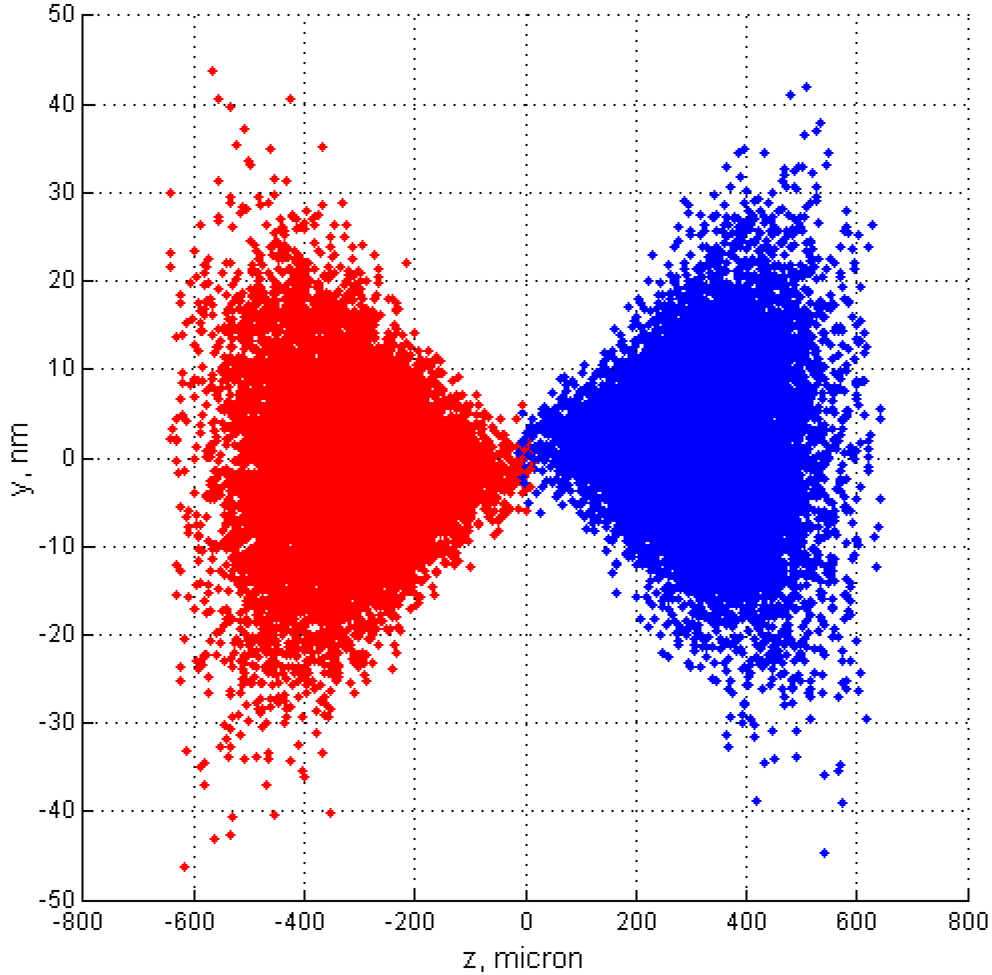
- Ratio of critical photon energy to beam energy (classic or quantum regime)

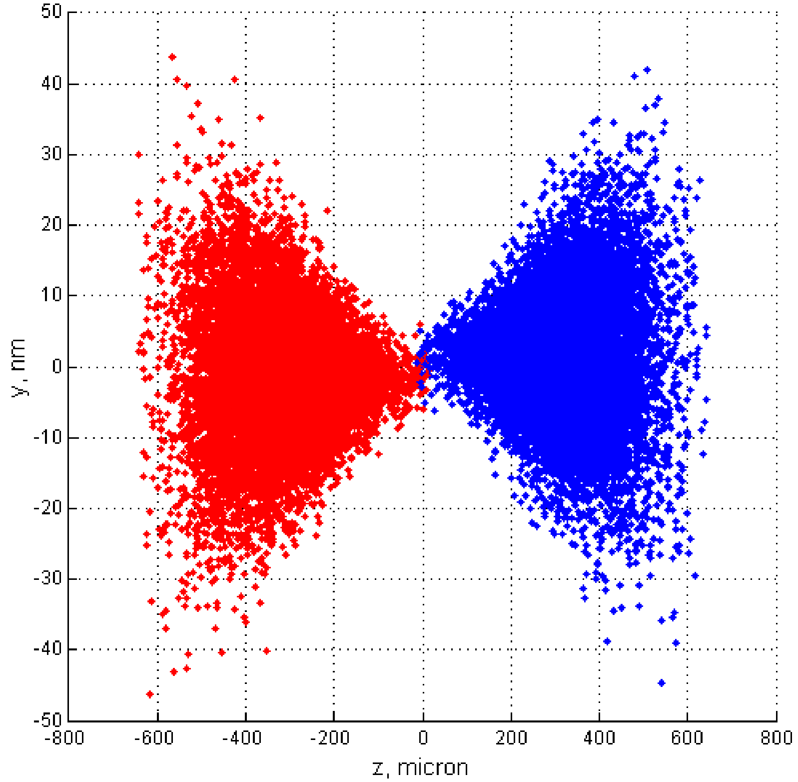
Beam-beam deflection



Sub nm offsets at IP cause large well detectable offsets (micron scale) of the beam a few meters downstream

Beam-beam deflection allow to control collisions





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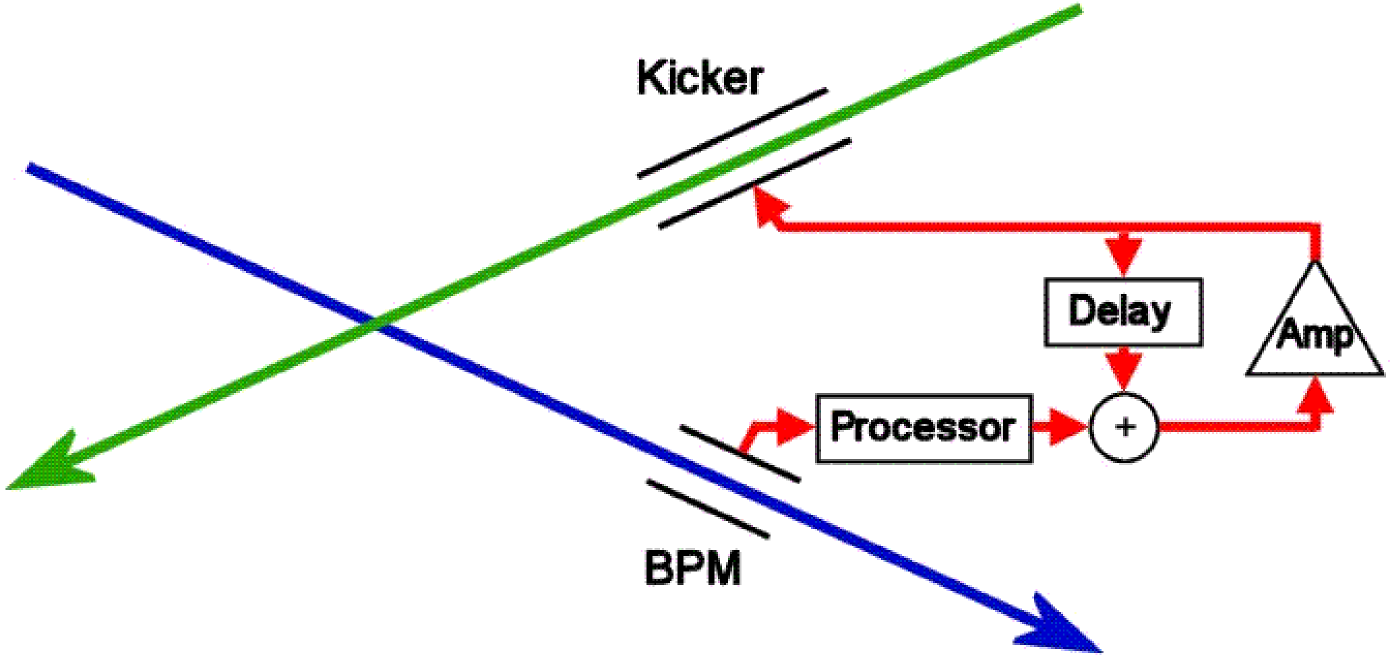
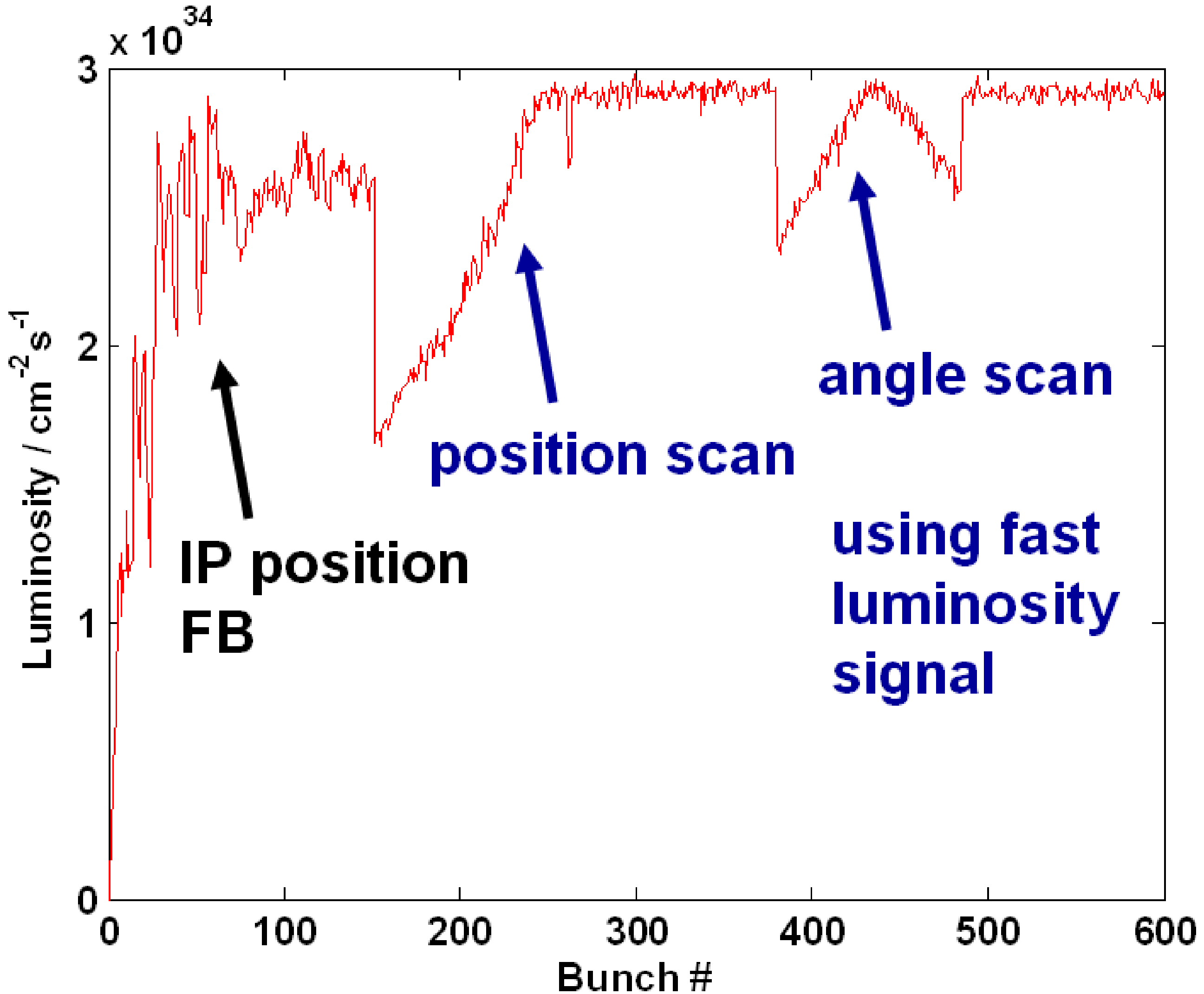
Beam-Beam orbit feedback



use strong beam-beam kick to keep beams colliding

ILC intratrain simulation

ILC intratrain feedback (IP position and angle optimization), simulated with realistic errors in the linac and “banana” bunches.



[Glen White]

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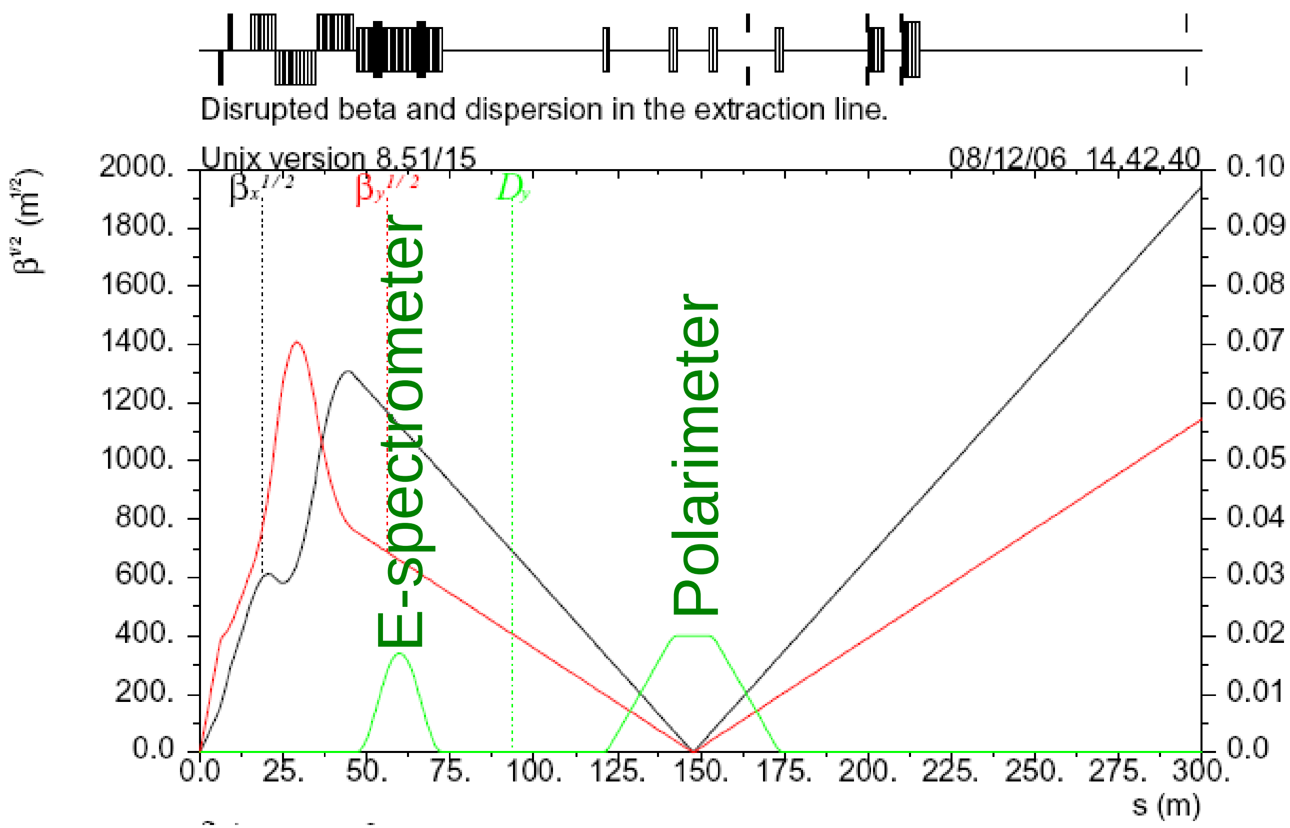
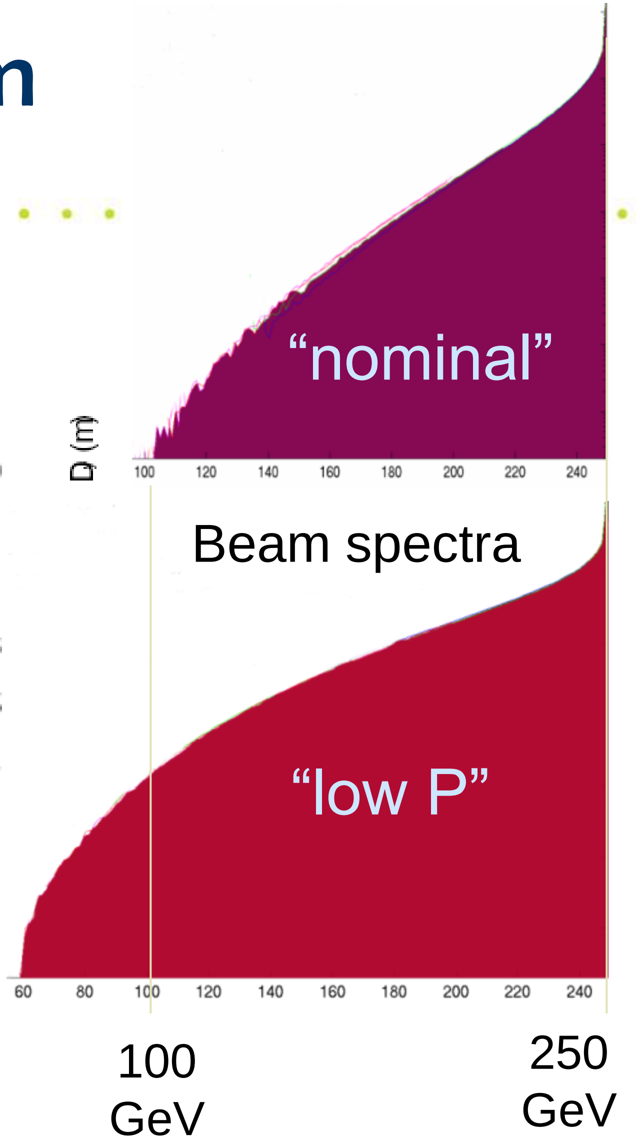
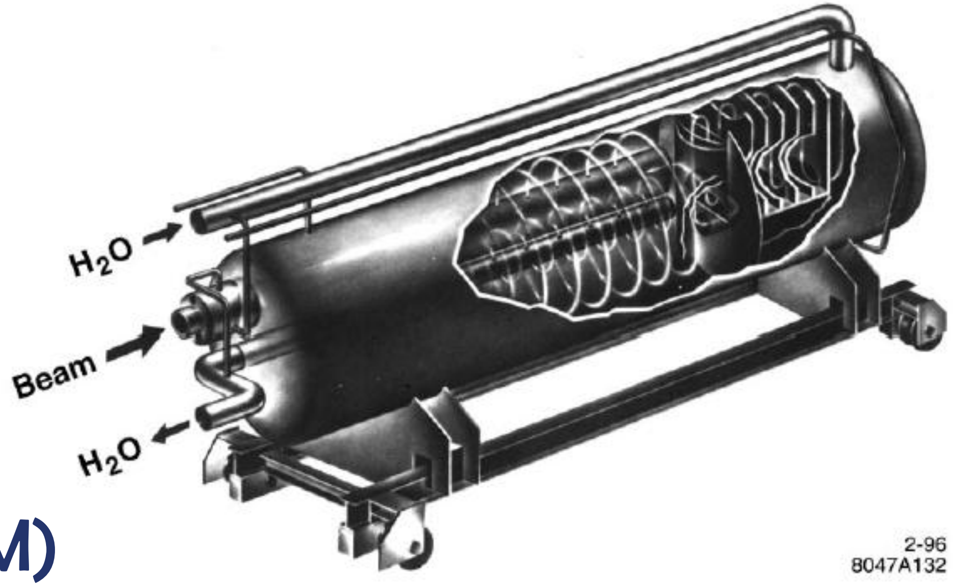
Optics for outgoing beam





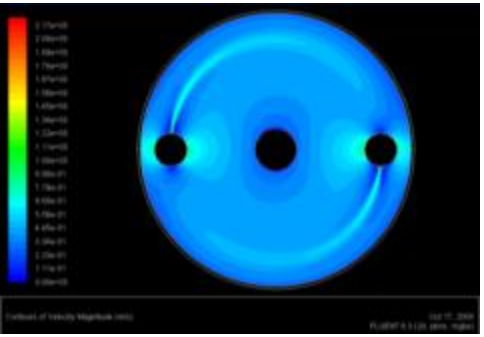
Extraction optics need to handle the beam with ~60% energy spread, and provides energy and polarization diagnostics

Beam dump



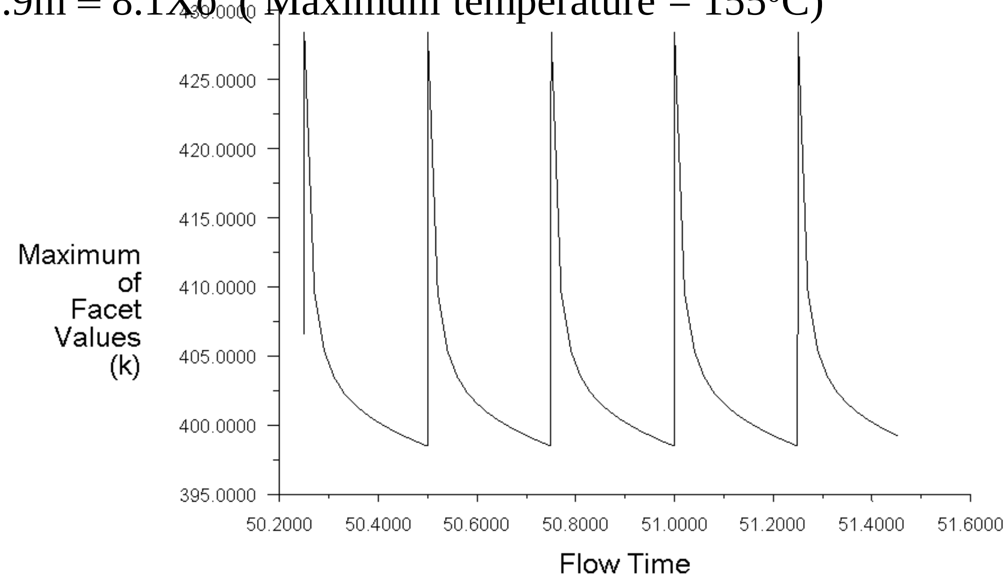
- 17MW power (for 1TeV CM)
- Rastering of the beam on 30cm double window
- 6.5m water vessel; ~1m/s flow
- 10atm pressure to prevent boiling
- Three loop water system
- Catalytic H_2-O_2 recombiner
- Filters for 7Be
- Shielding 0.5m Fe & 1.5m concrete

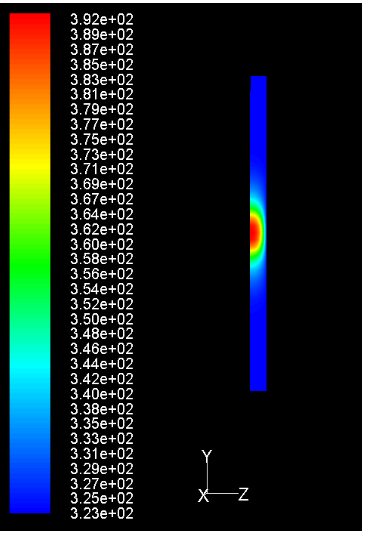
Beam dump design updates



Velocity contours (inlet velocity: 2.17m/s, mass flux: 19kg/m/s)

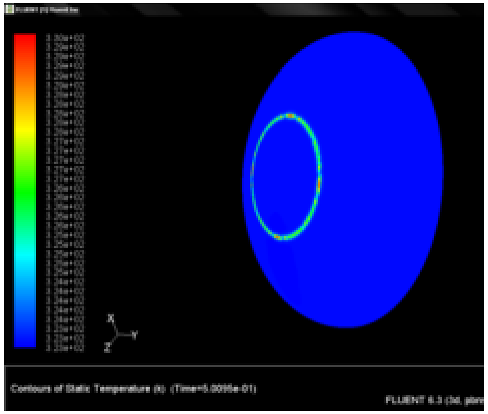
Maximum temperature variation as a function of time at z = 2.9m ≡ 8.1Xo. (Maximum temperature = 155^{0}C)





Temperature distribution across the cross-section of the End plate

Window temperature distribution just when the beam train completes energy deposition. (Max temp : 57^{0}C)

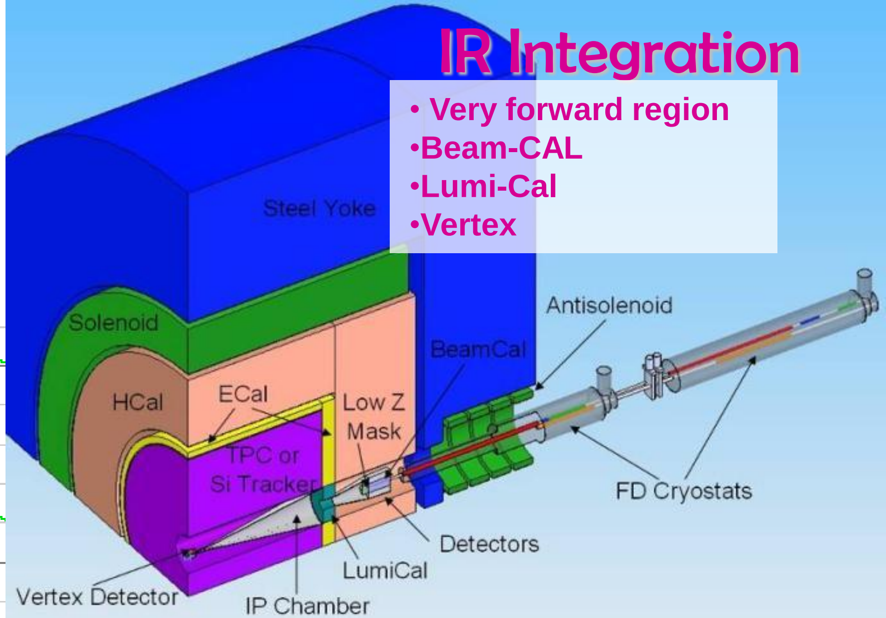


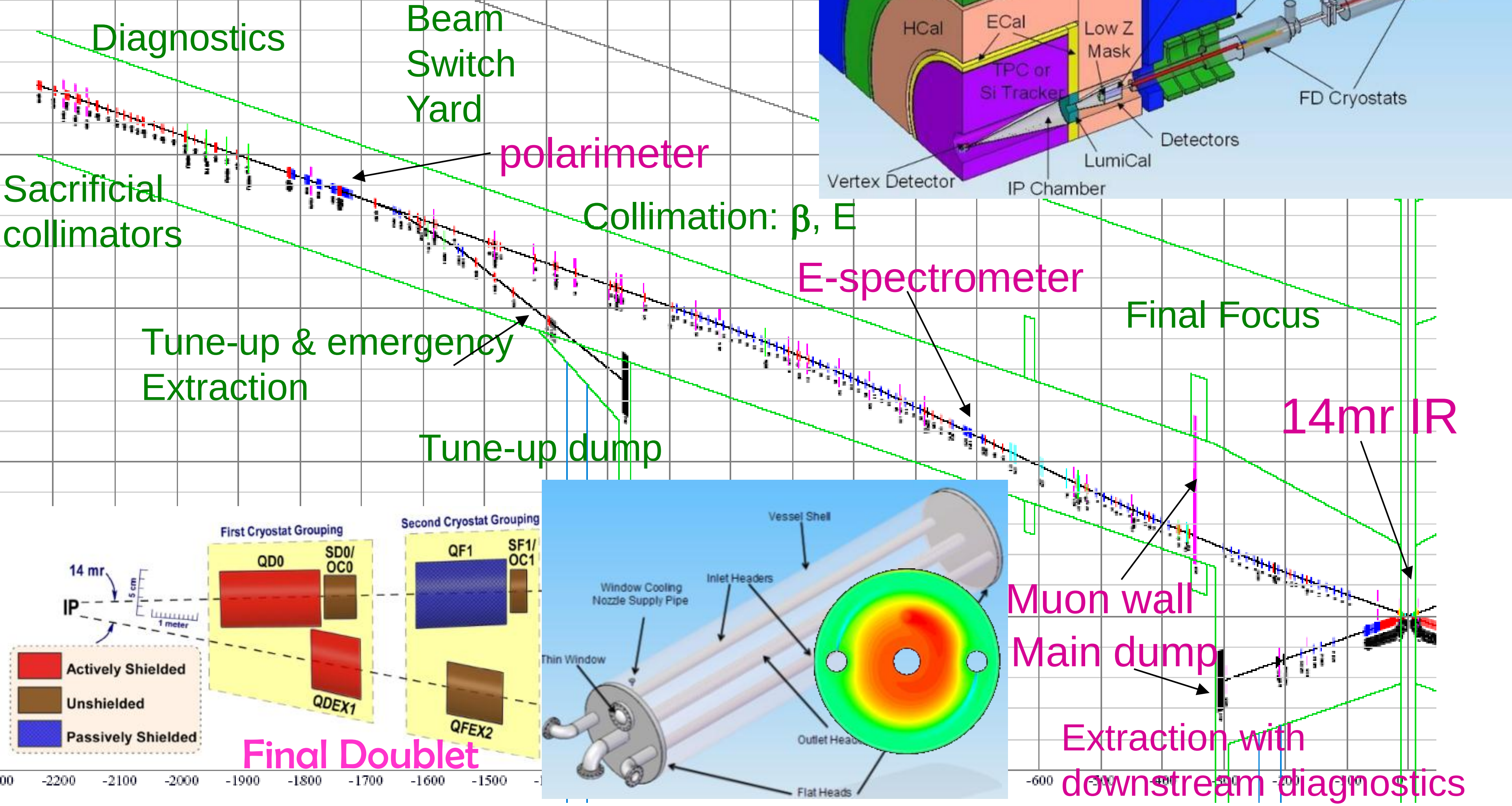
D. Walz , J. Amann, et al, SLAC
P. Satyamurthy, P. Rai, V. Tiwari, K. Kulkarni, BARC, Mumbai, India

From IPAC10 paper

Beam Delivery & MDI elements

1TeV CM, single IR, two detectors, push-pull





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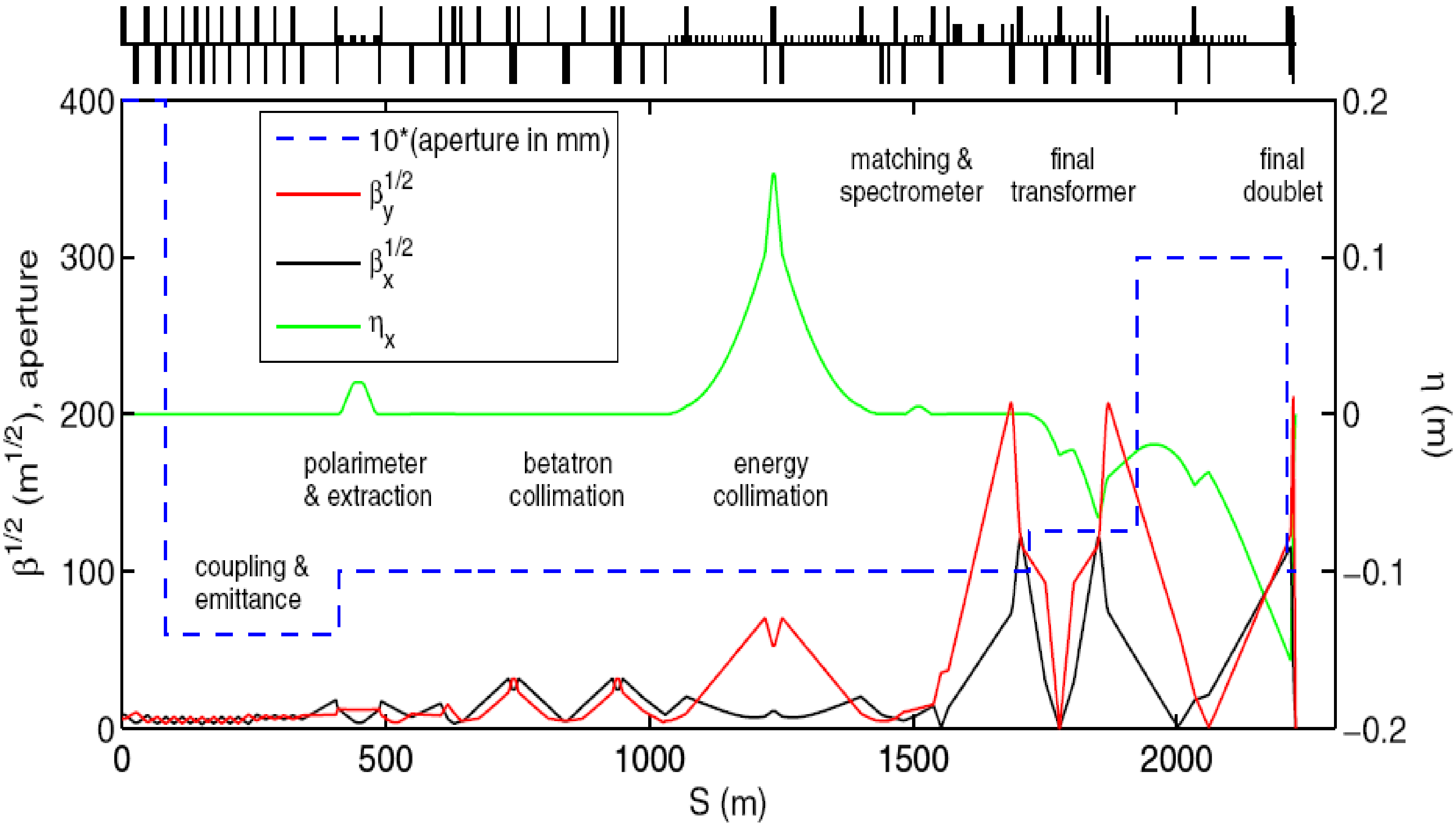
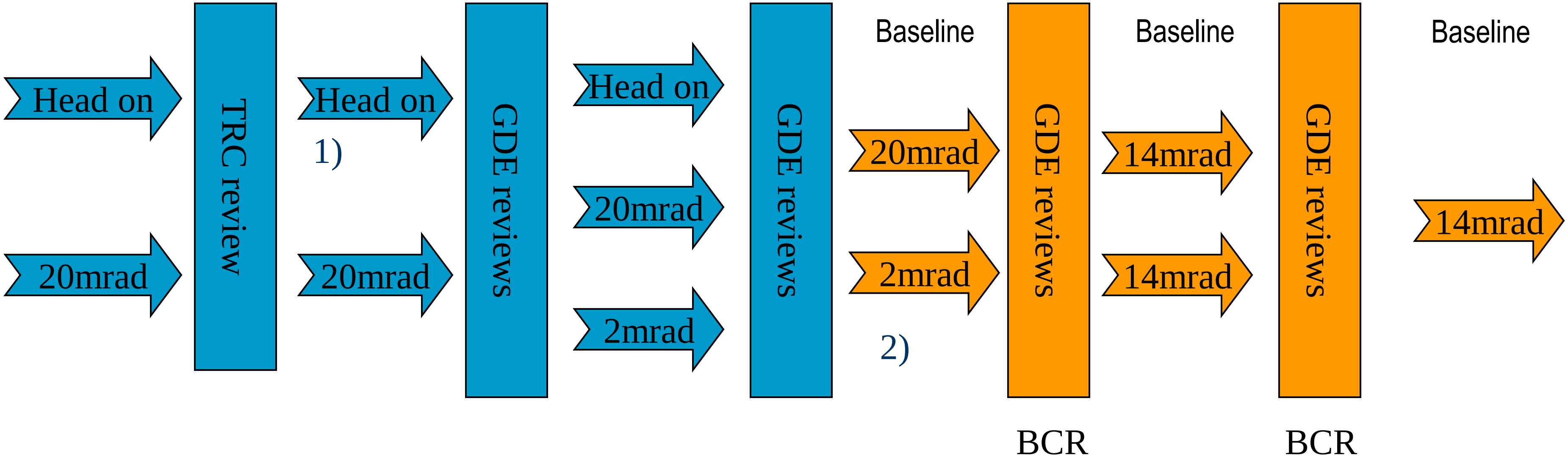
ILC BDS Optical Functions



BDS & MDI Configuration Evolution

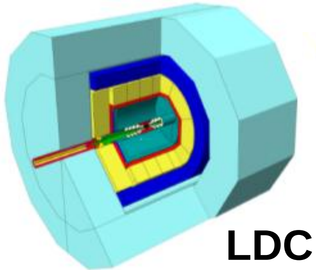


- **Evolution of BDS MDI configuration**
  - Head on; small crossing angle; large crossing angle

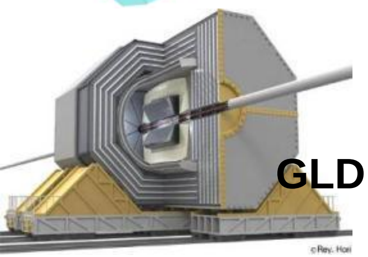
- MDI & Detector performance were the major criteria for selection of more optimal configuration at every review or decision point

1) Found unforeseen losses of beamstrahlung photons on extraction septum blade
2) Identified issues with losses of extracted beam, and its SR; realized cost non-effectiveness of the design

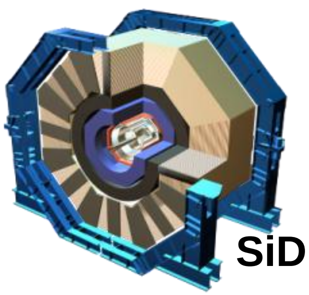
Evolution of ILC Detectors



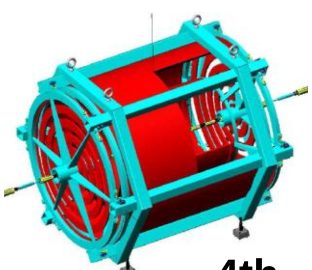
LDC



GLD



SiD



4th

LDC

GLD

Merged to ILD design

ILD

SiD

4th

Thorough evaluation of performance, validation of the concepts

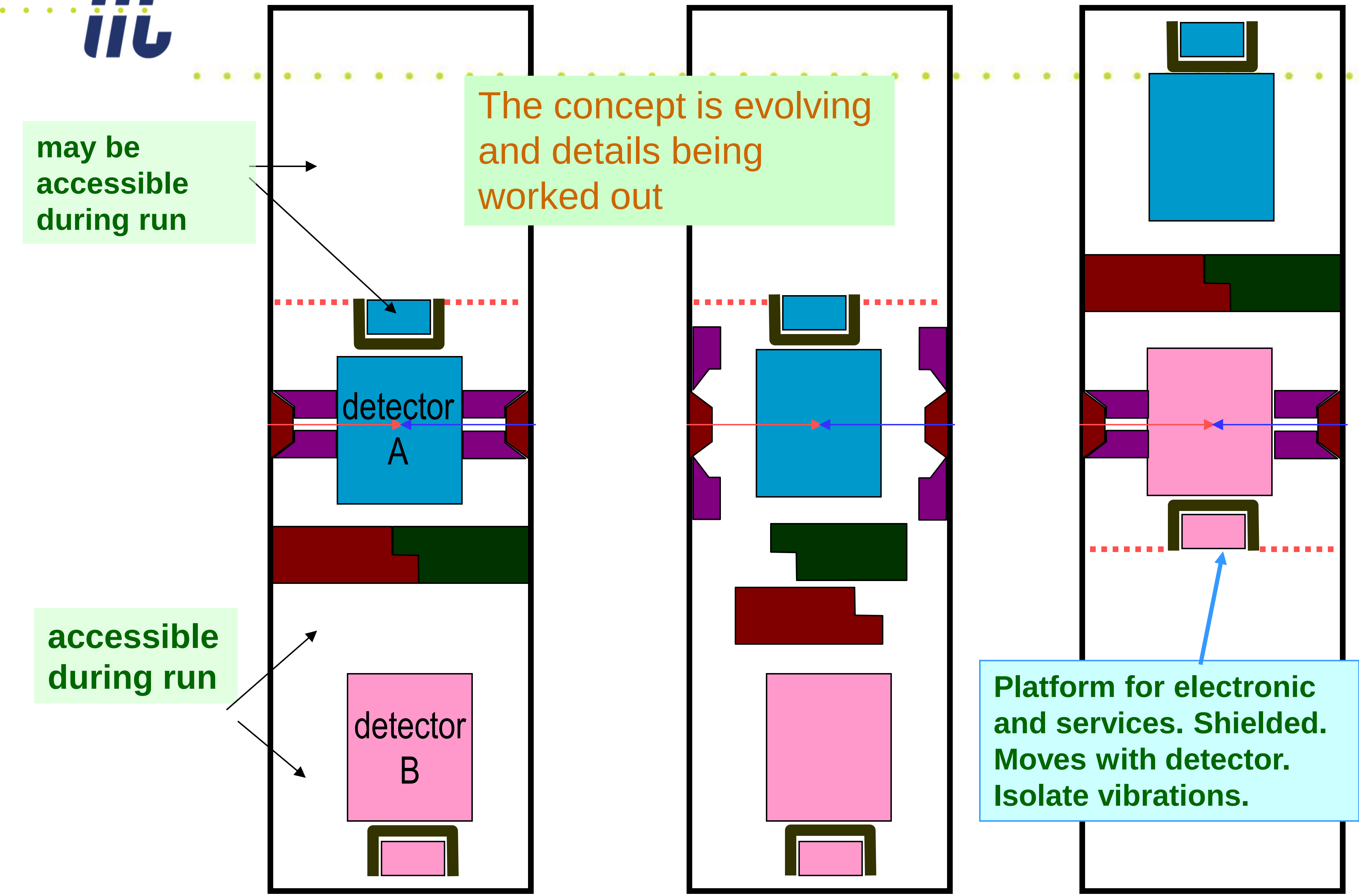
ILD validated

Technical design of detectors and R&D for critical sub-systems

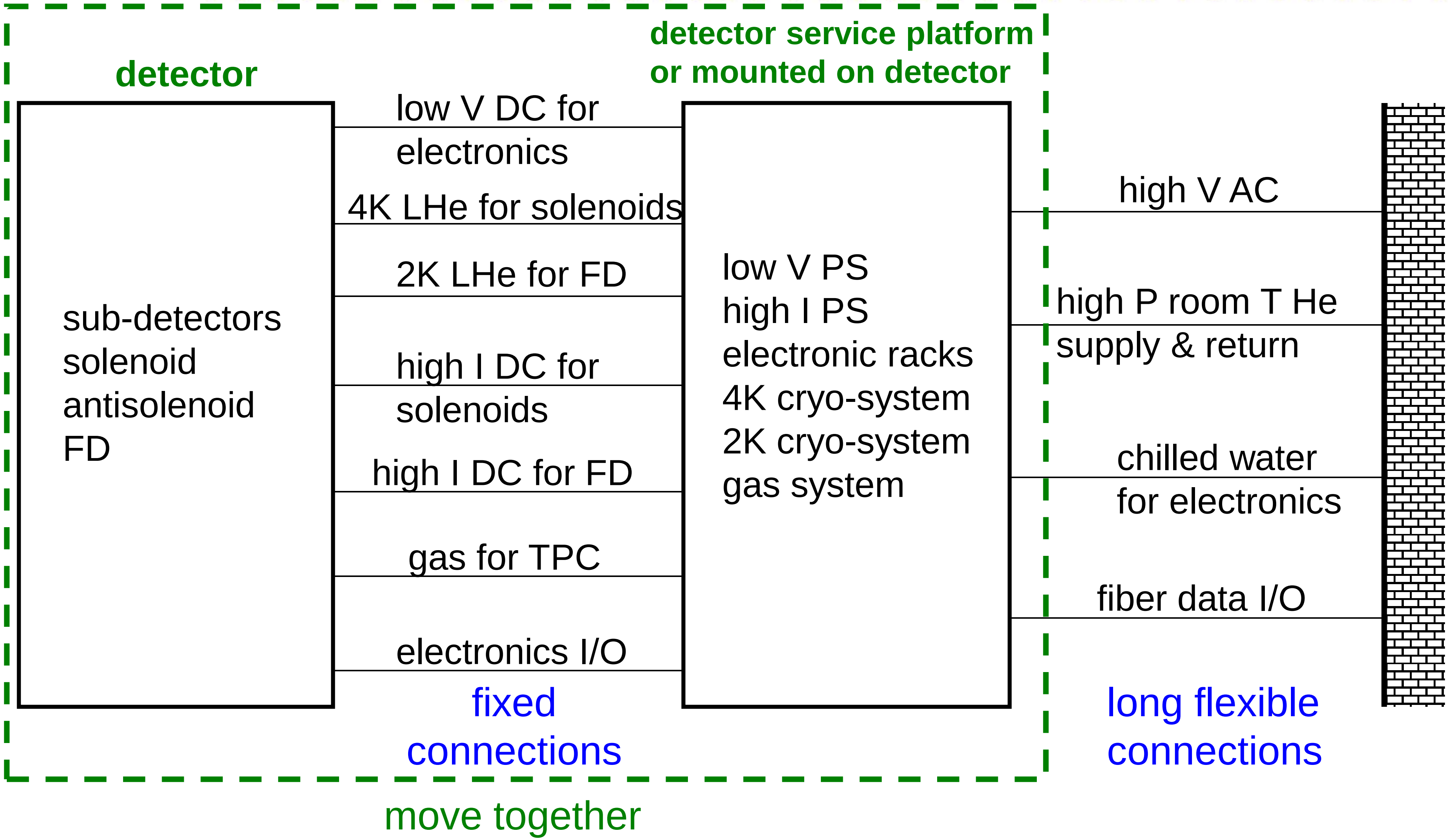
SiD validated

- **Evolution, self-review and selection process are essential for meeting the challenging detector requirements motivated by physics**
  - Triggerless event collection (software event selection)
  - Extremely precise vertexing
  - Vertex, tracker, calorimeters integrated for optimal jet reconstruction

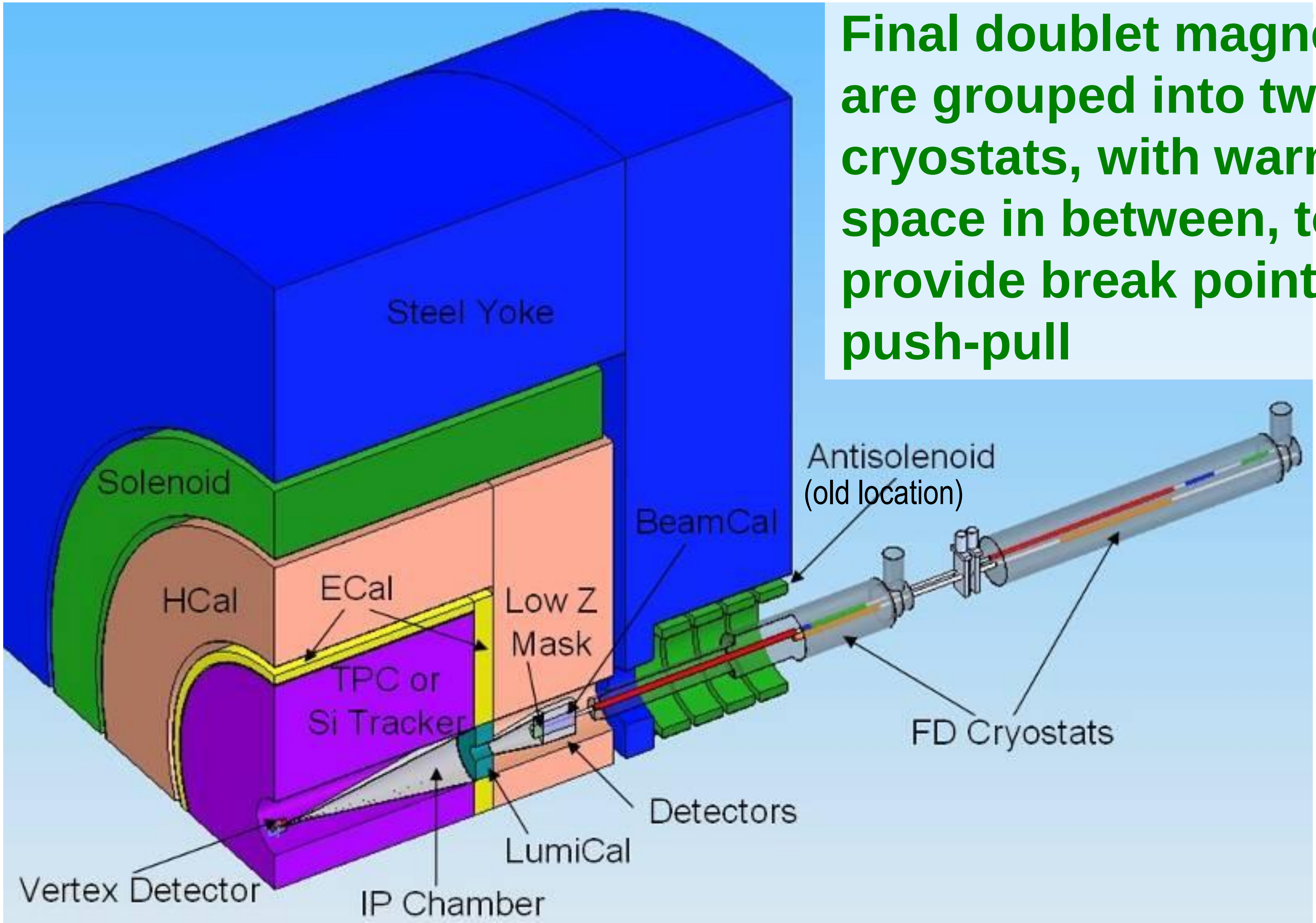
Concept of single IR with two detectors



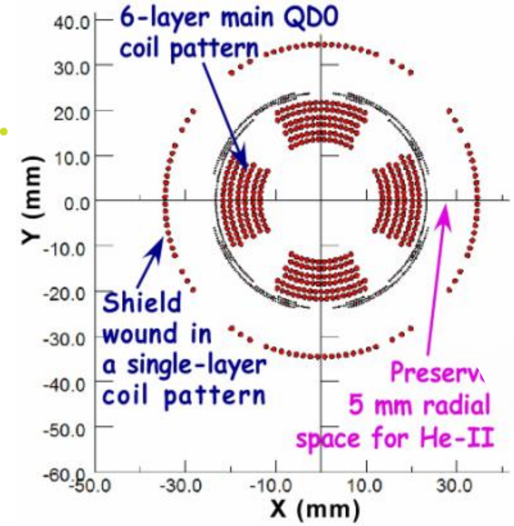
Concept of detector systems connections



IR integration

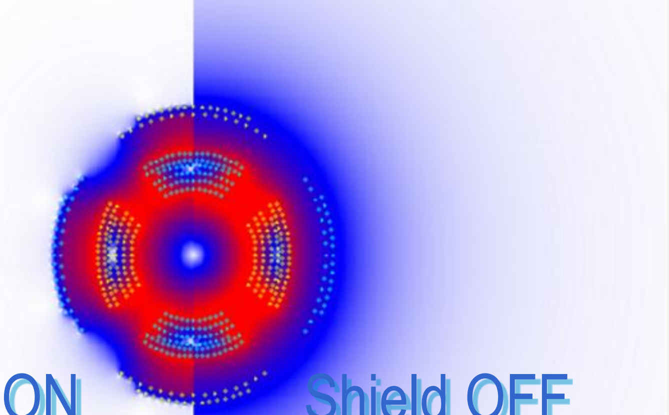


Final doublet magnets are grouped into two cryostats, with warm space in between, to provide break point for push-pull

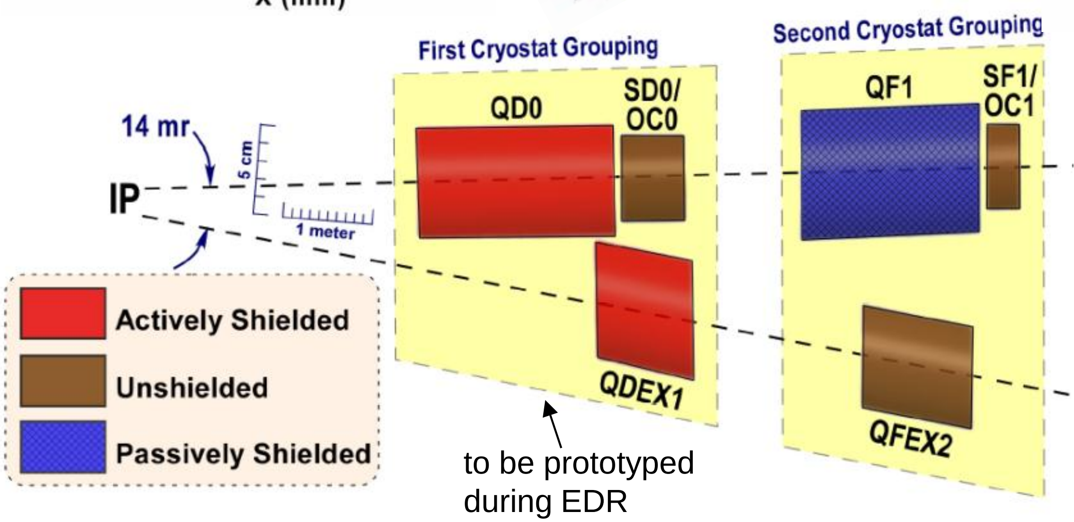


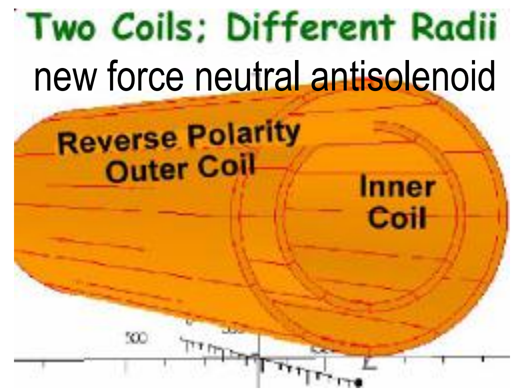
Actively shielded QD0

BNL



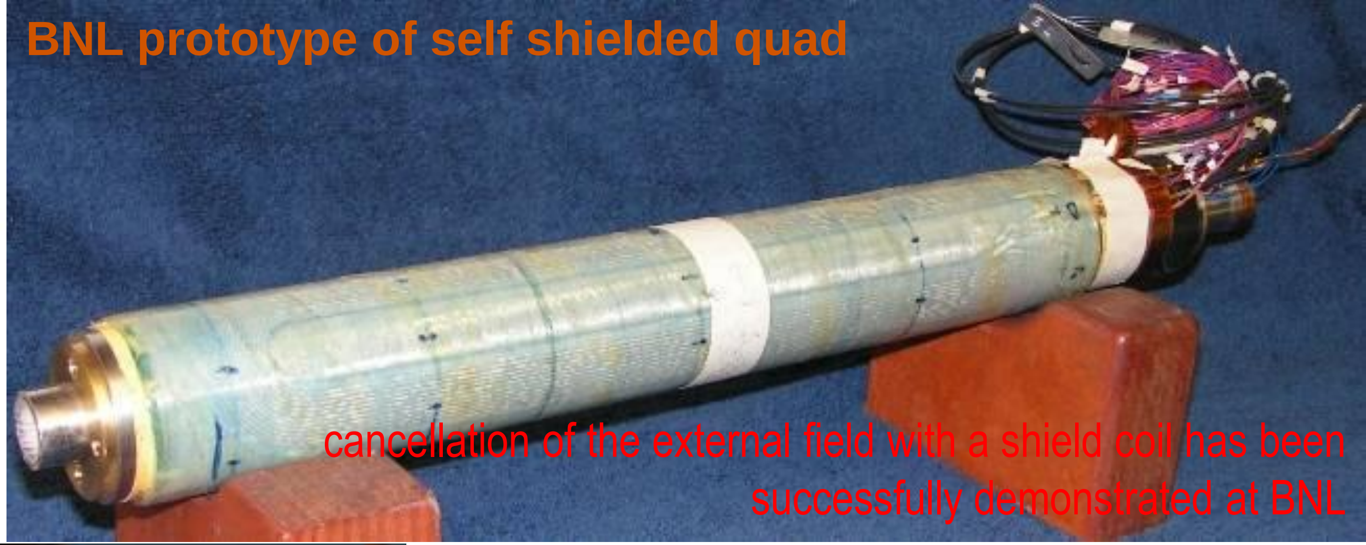
Intensity of color represents value of magnetic field.

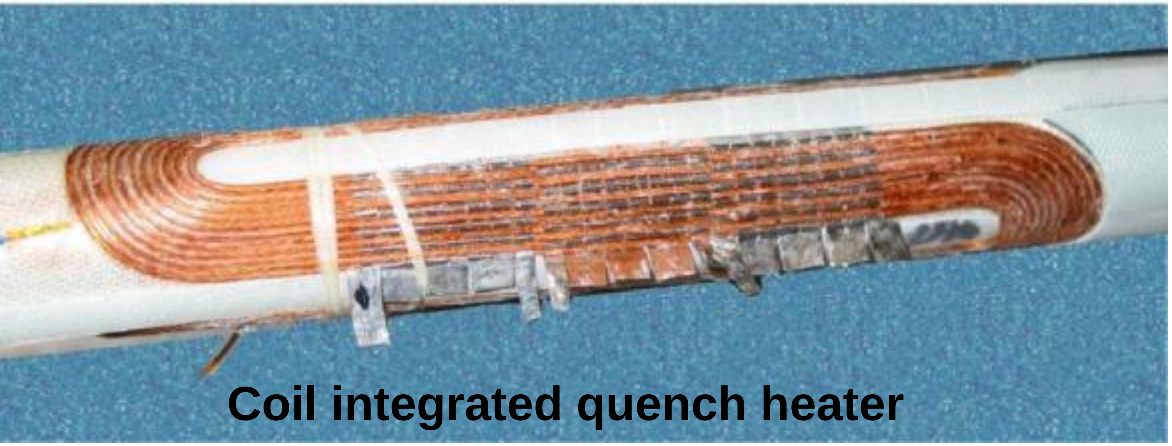


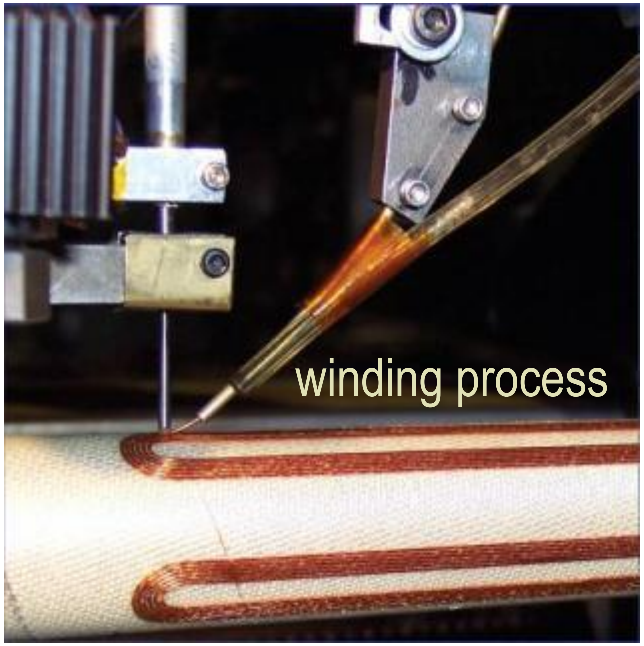


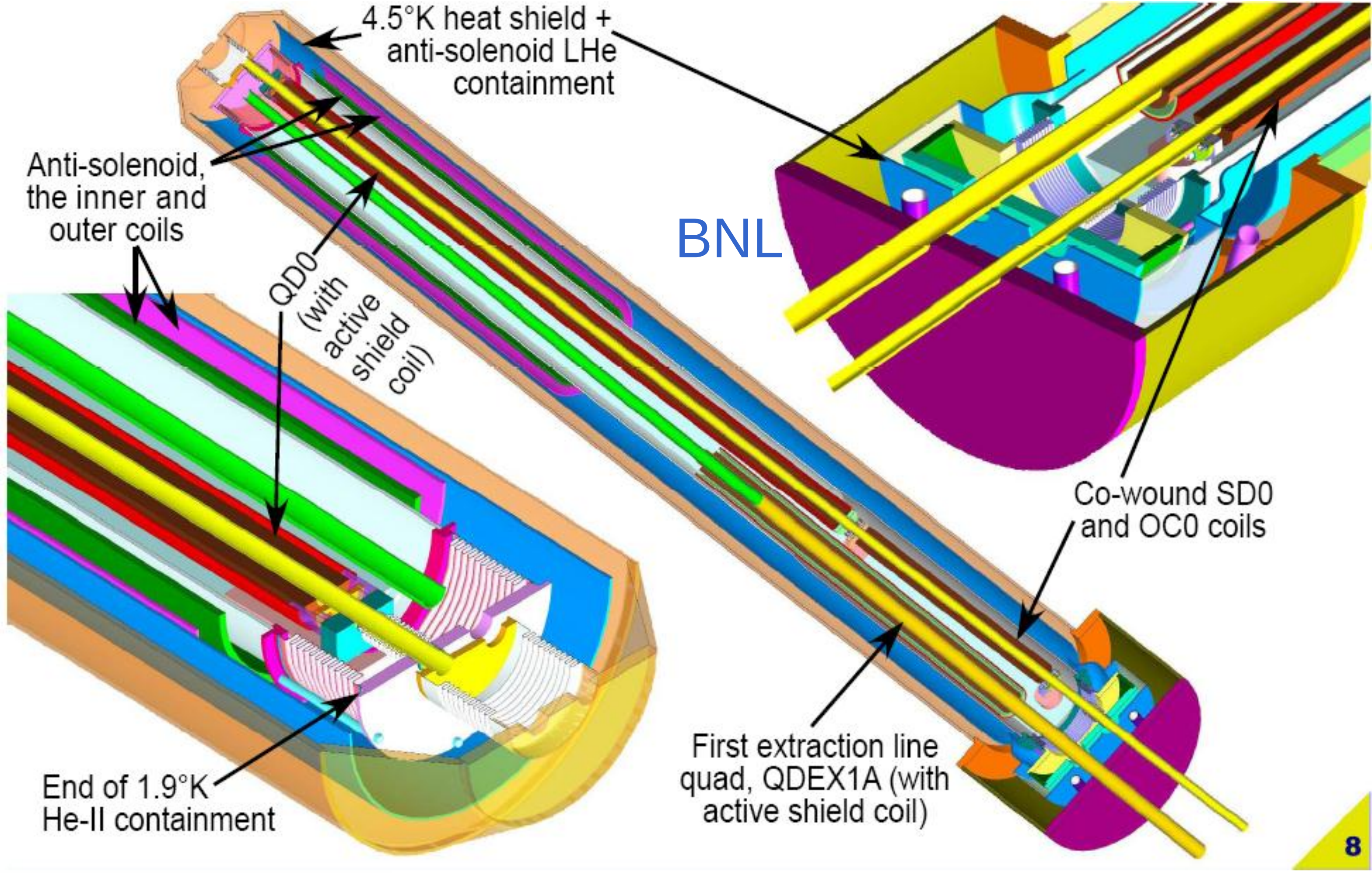
- Interaction region uses compact self-shielding SC magnets
- Independent adjustment of in- & out-going beamlines
- Force-neutral anti-solenoid for local coupling correction

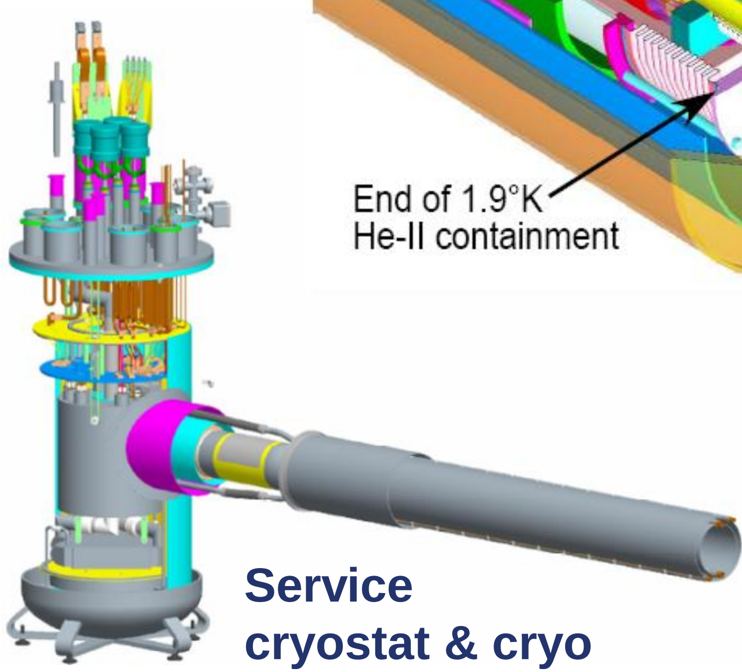
IR magnets prototypes at BNL







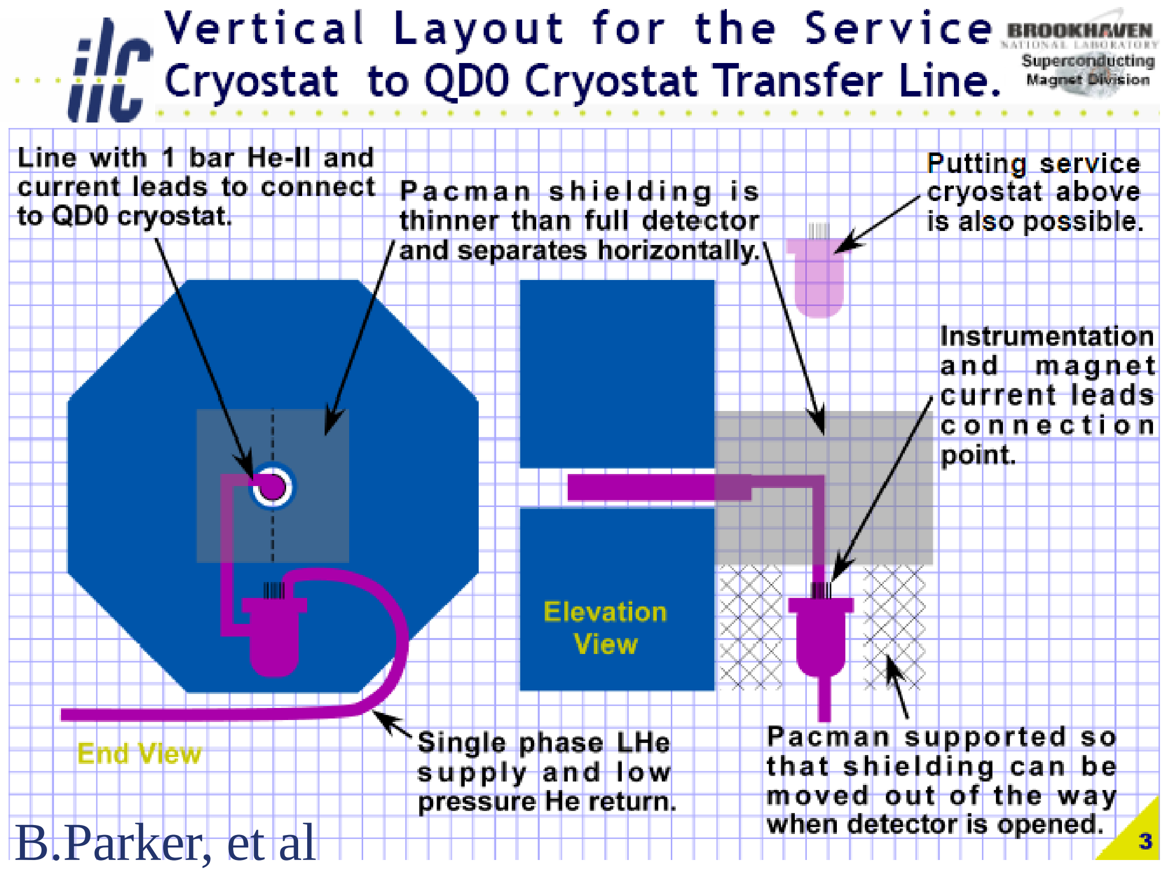


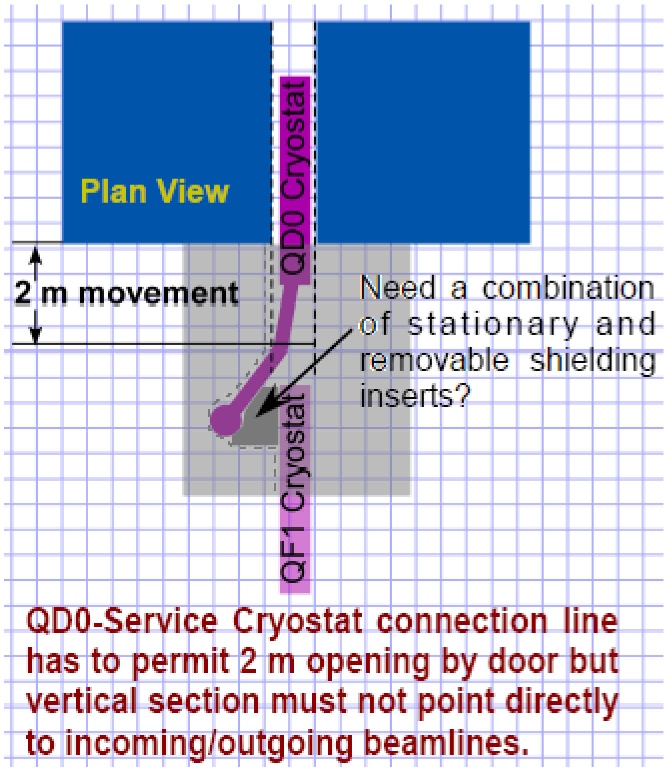


Service cryostat & cryo connections

- **Detailed engineering design of IR magnets and their integration has started**

Present concept of cryo connection





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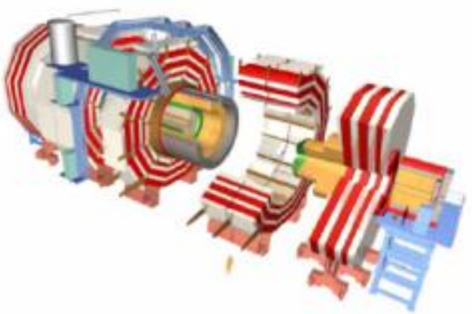
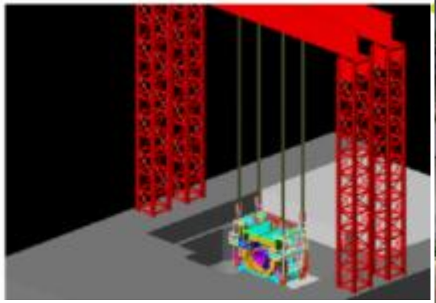
Detector assembly

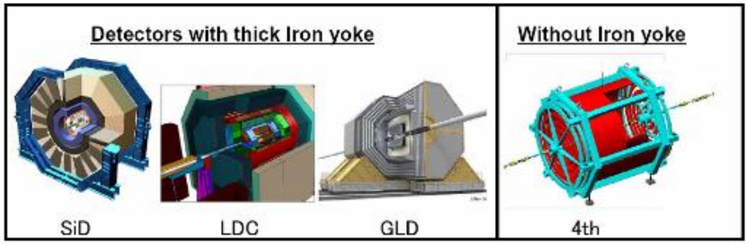


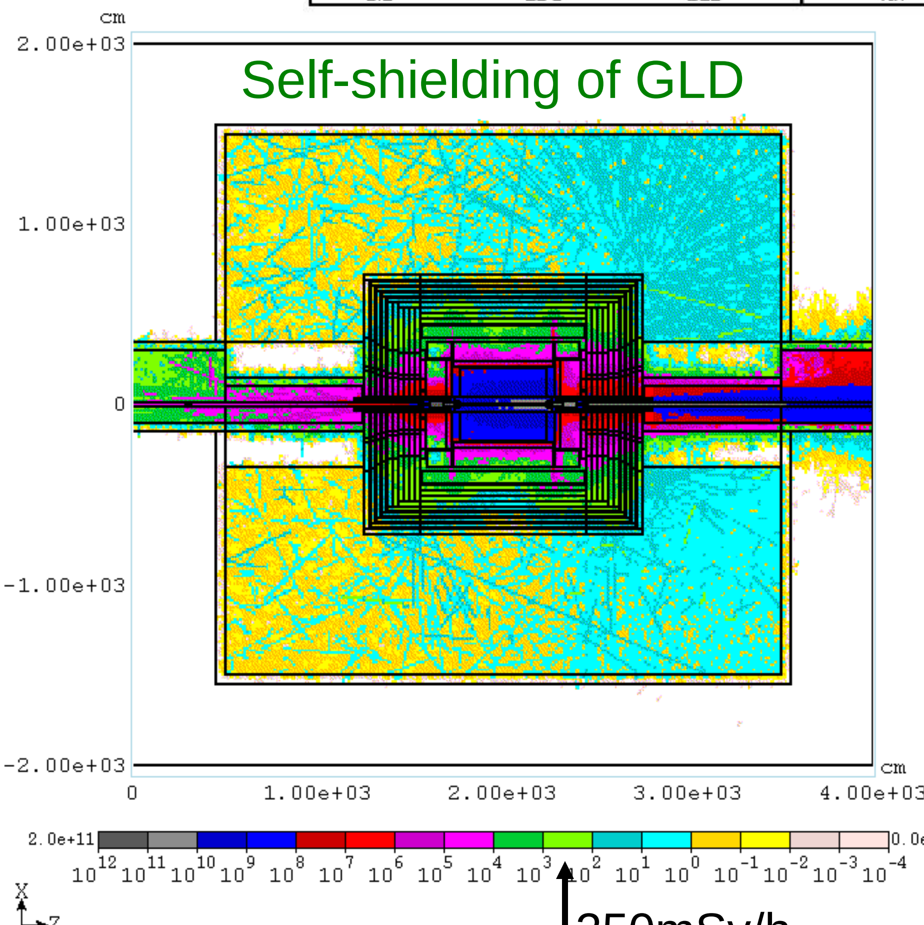


- CMS detector assembled on surface in parallel with underground work, lowered down with rented crane
- Adopted this method for ILC, to save 2-2.5 years that allows to fit into 7 years of construction

photos courtesy CERN colleagues

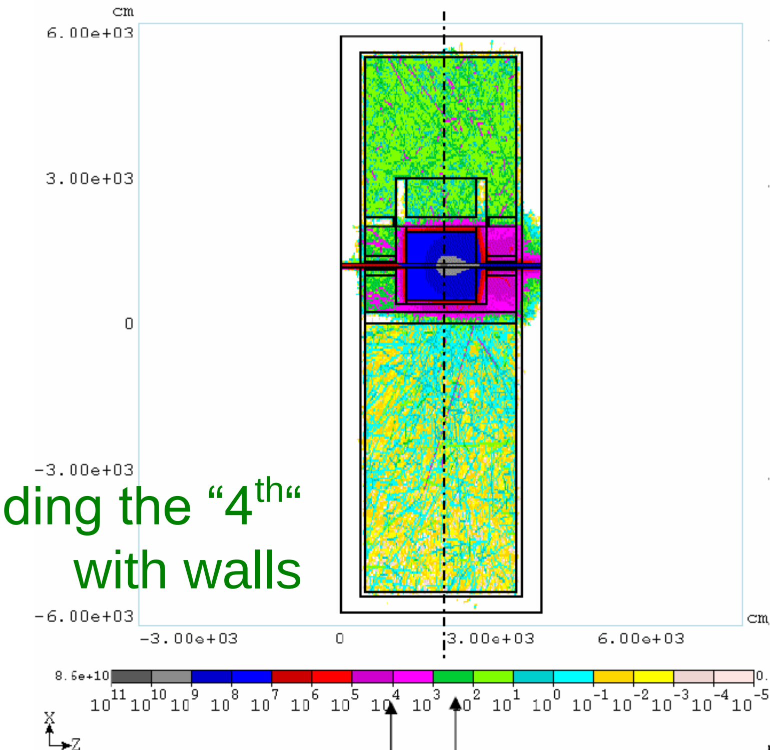
Shielding the IR hall



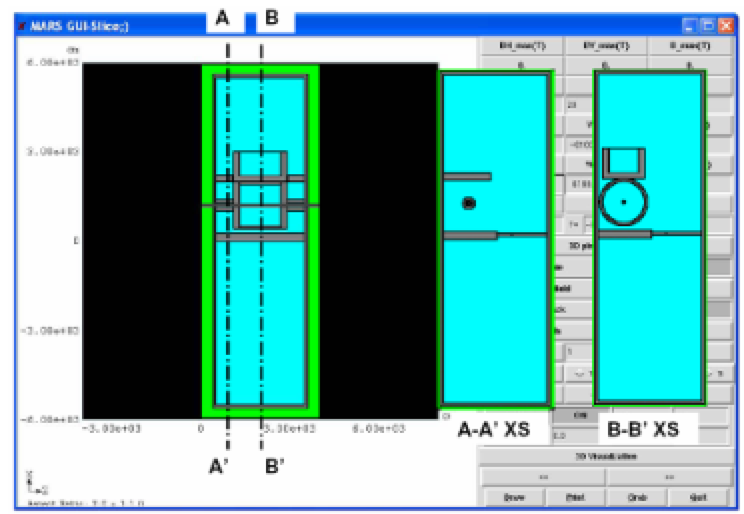


250mSv/h

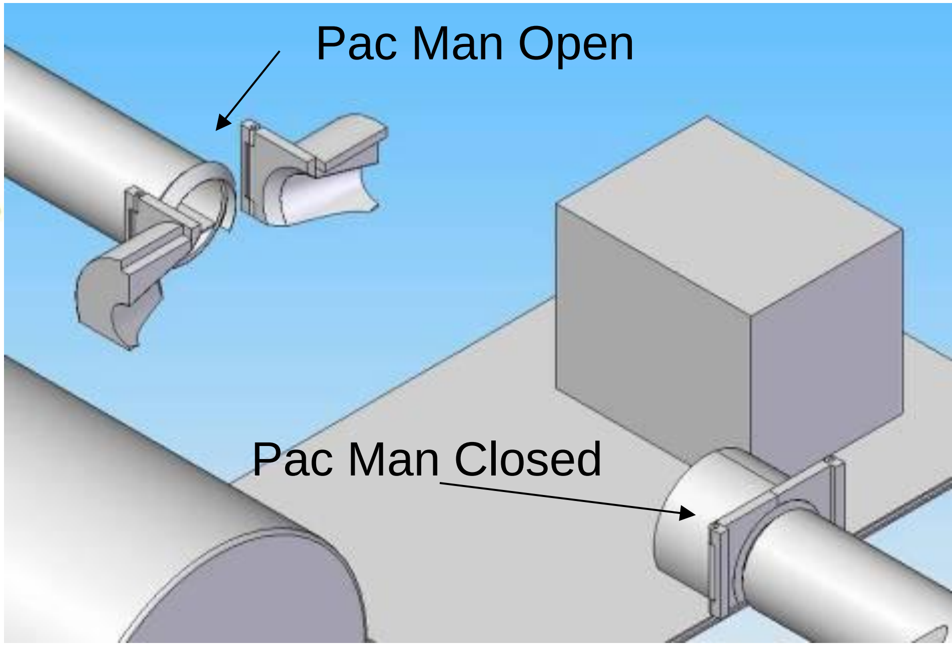
Shielding the "4th" with walls

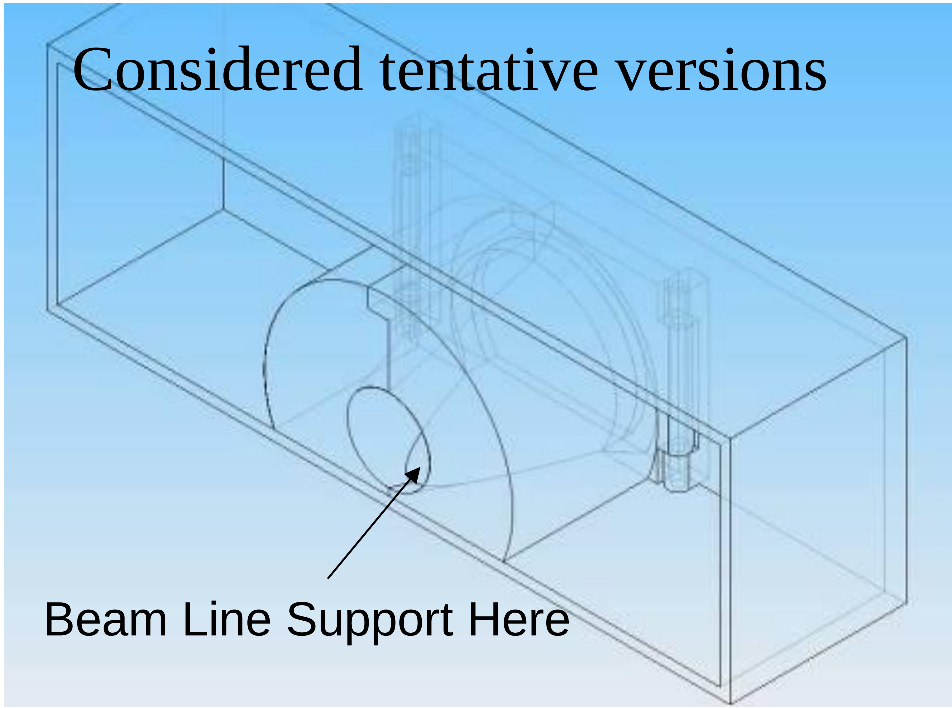


25rem/h@18MW



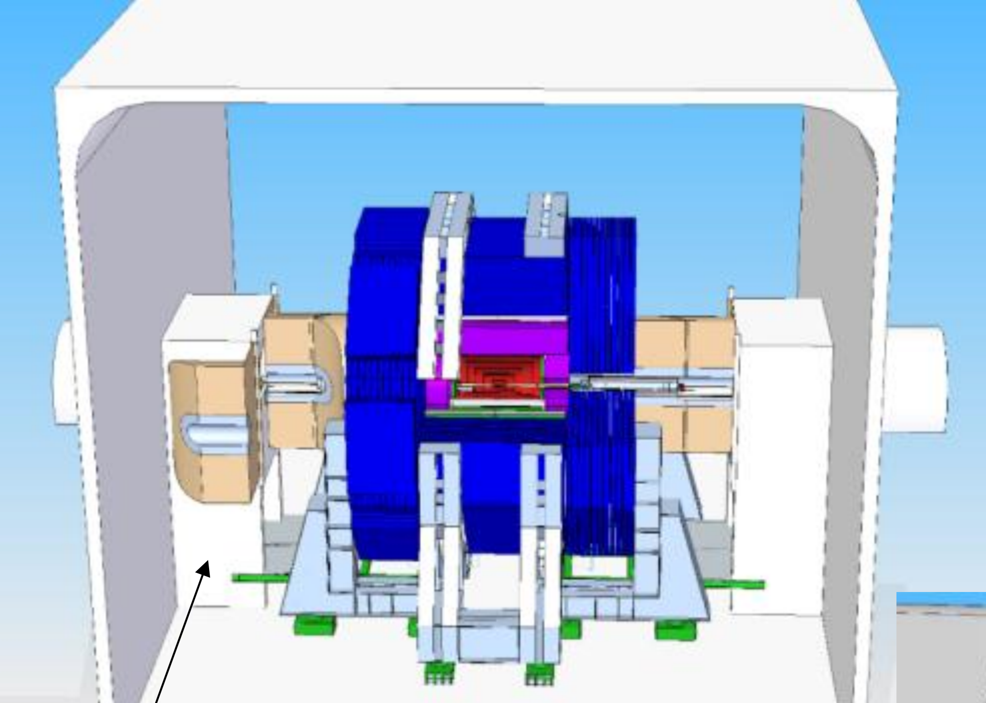
Pacman design



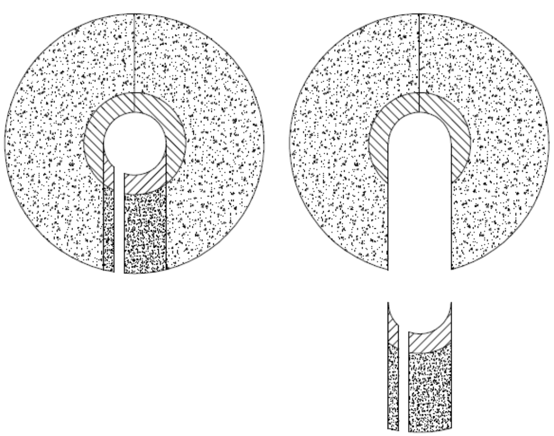


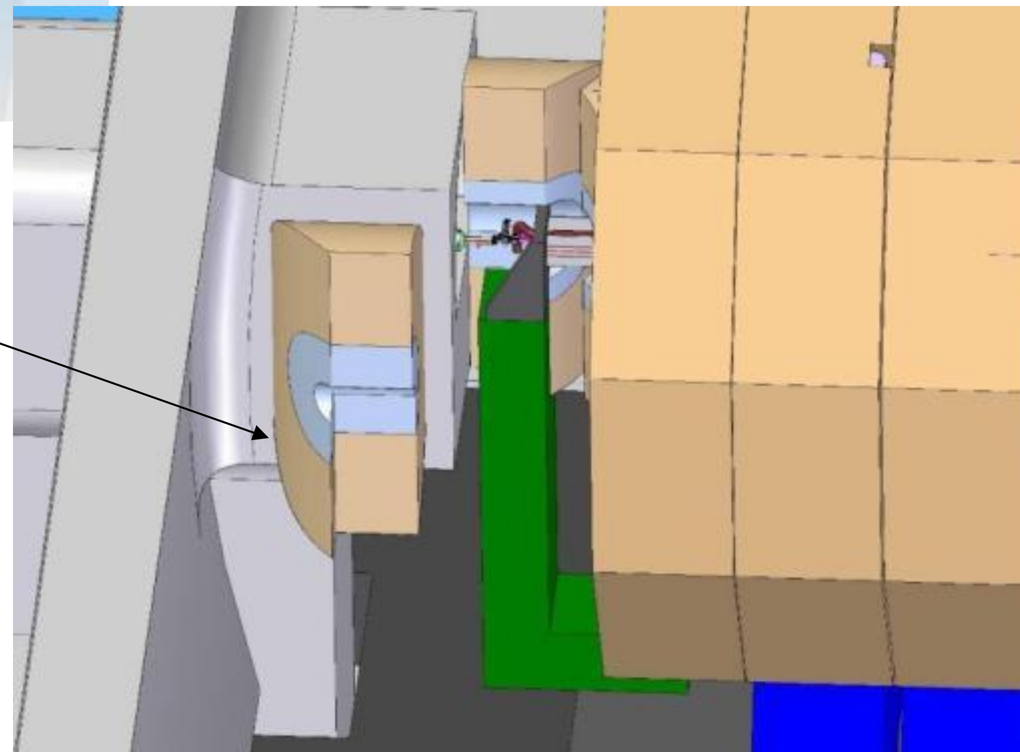
John Amann

Example of system where initially different designs converged on a single compatible solution:
CMS-Inspired Hinged PacMan
w/ Cut-outs for ILD Pillar and Plugs



SiD ILD

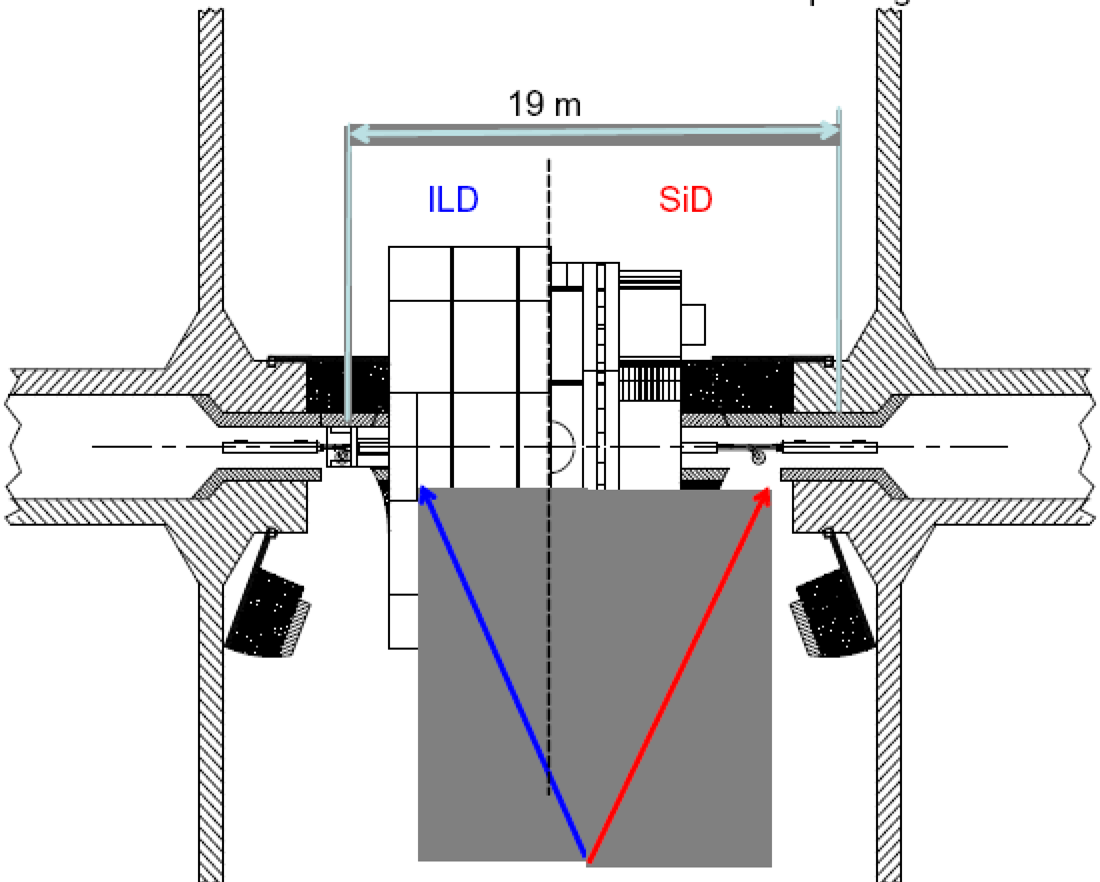




M.Oriunno, H.Yamaoka, A.Herve, et. al

Pacman compatible with SiD

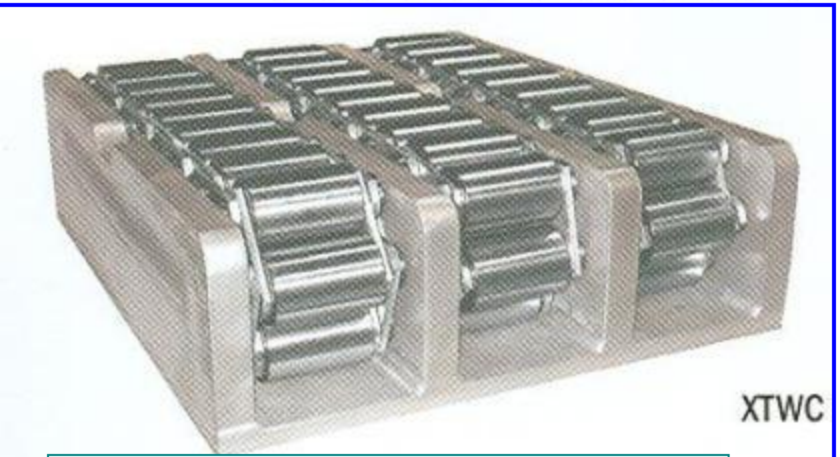
Pacmen closed: Modified to allow ILD opening



Interface pieces born by each experiment

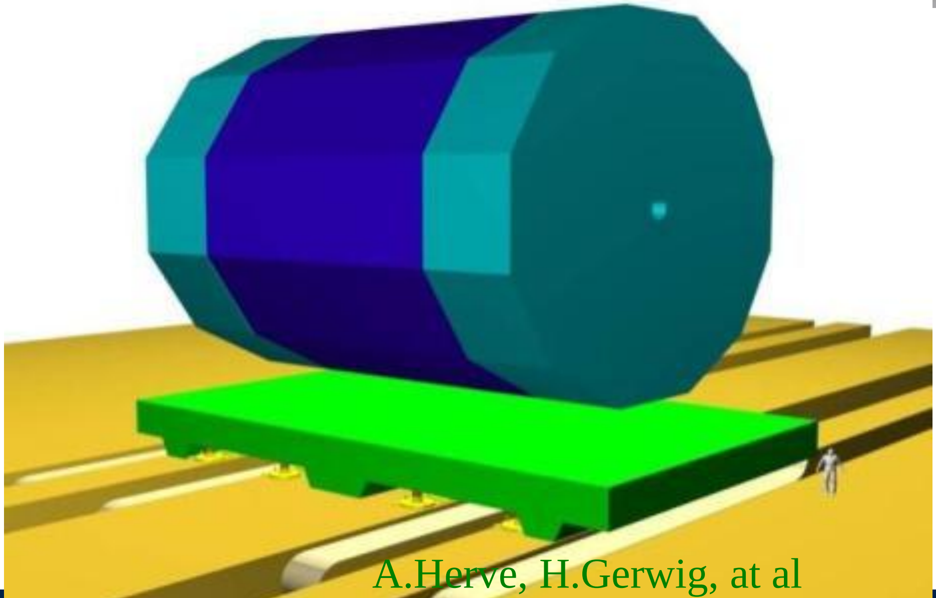
From A. Hervé, K. Sinram, M. Oriunno

Moving the detector



5000 ton Hilman roller module

Air-pads at CMS – move 2000k pieces

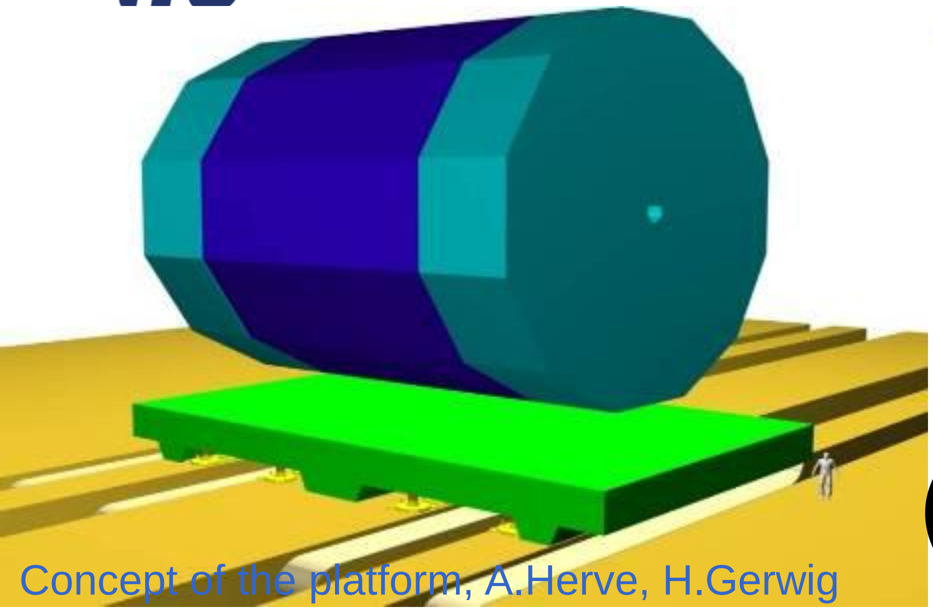


Is detector (compatible with on-surface assembly) rigid enough itself to avoid distortions during move?

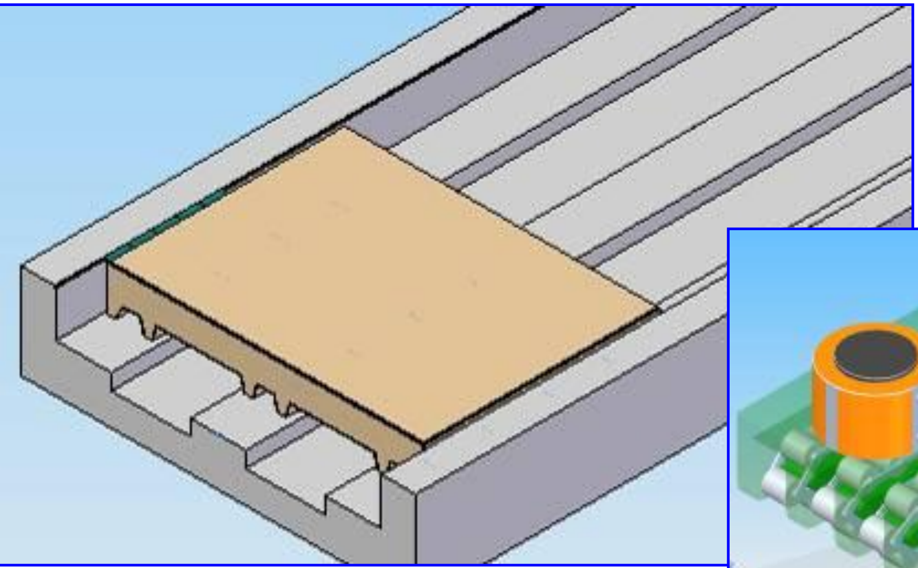
Concept of the platform to move ILC detector

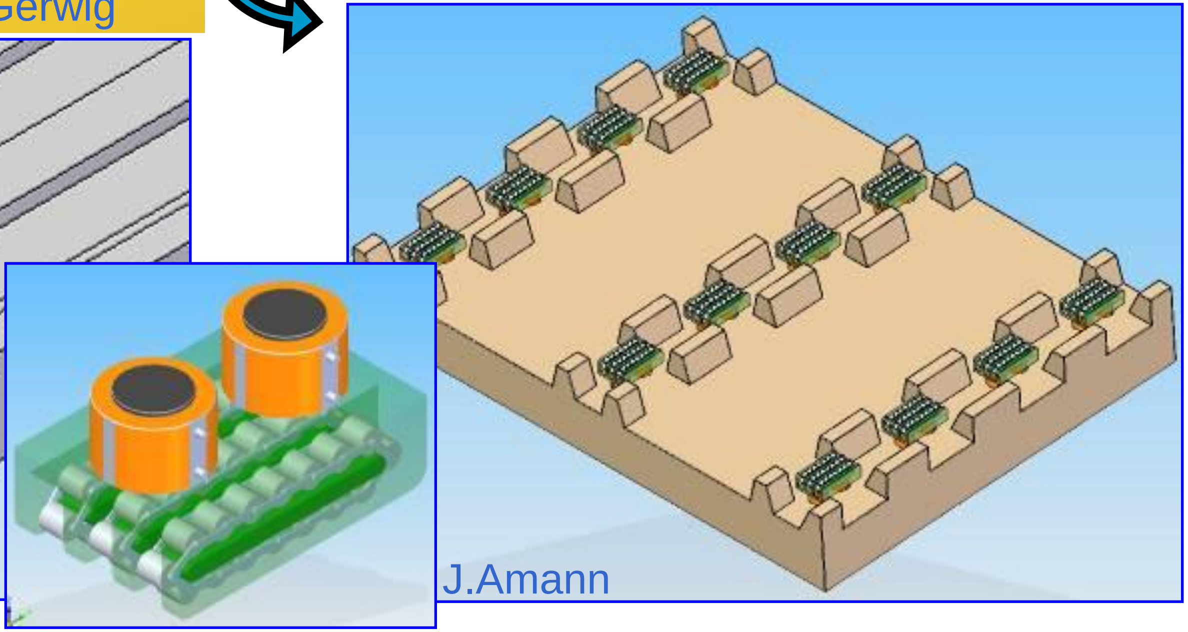
A.Herve, H.Gerwig, at al

Moving the detector



Concept of the platform, A.Herve, H.Gerwig

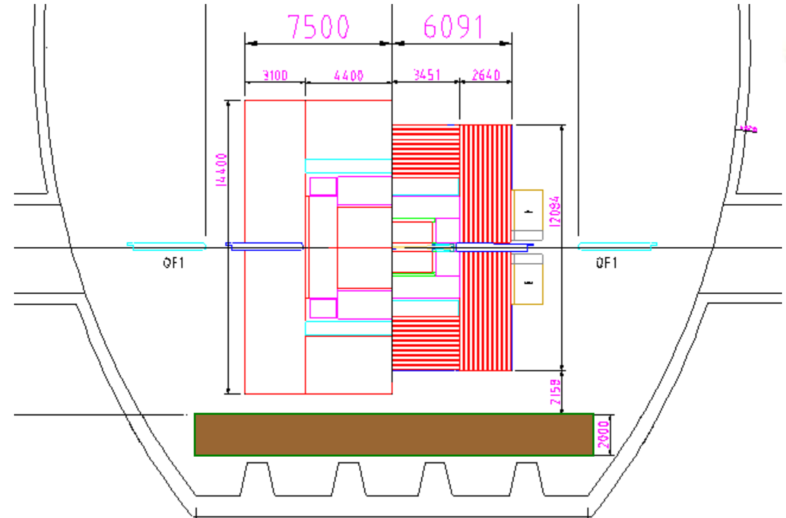


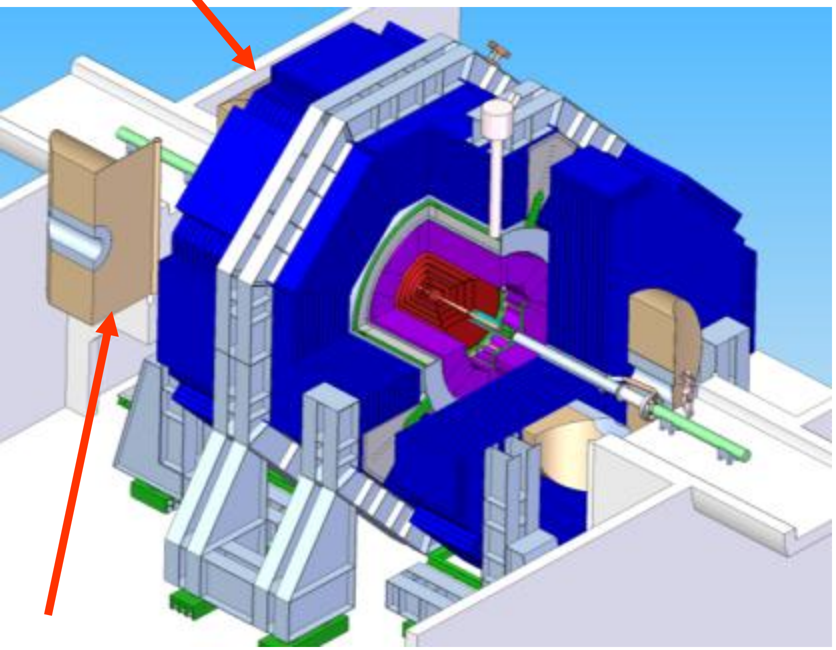


J.Amann

Example of MDI issues: moving detectors

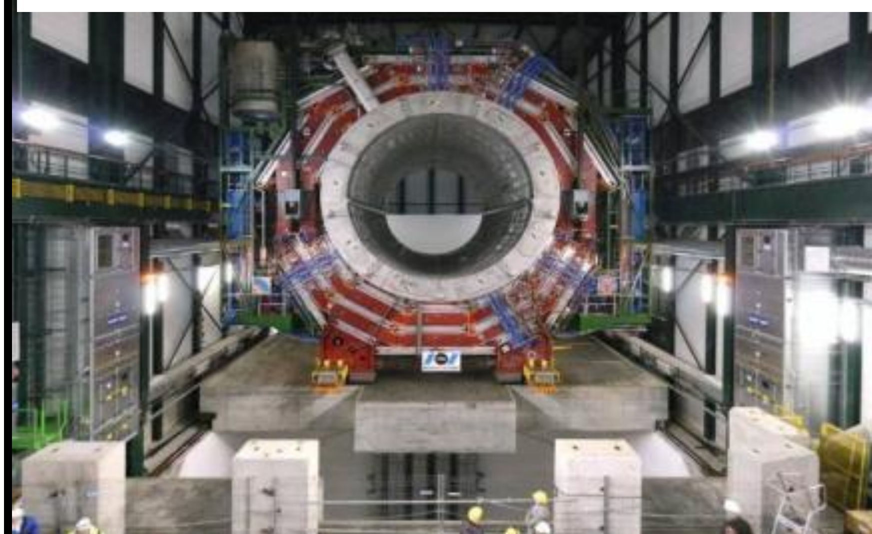
Detector motion system with
or without an intermediate platform



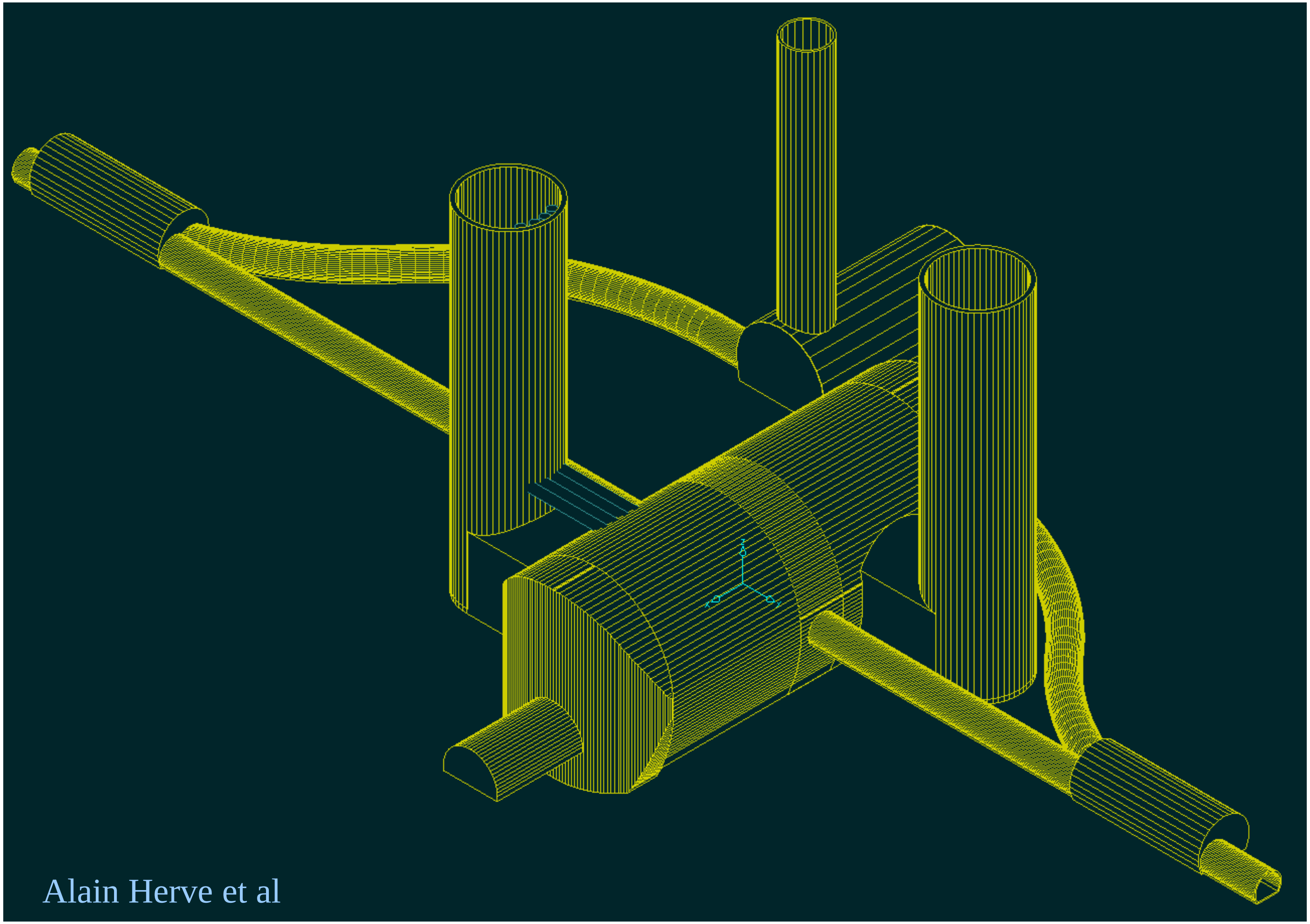


Detector and beamline shielding elements

CMS platform – proof of principle for ILC



Configuration of IR tunnels and halls



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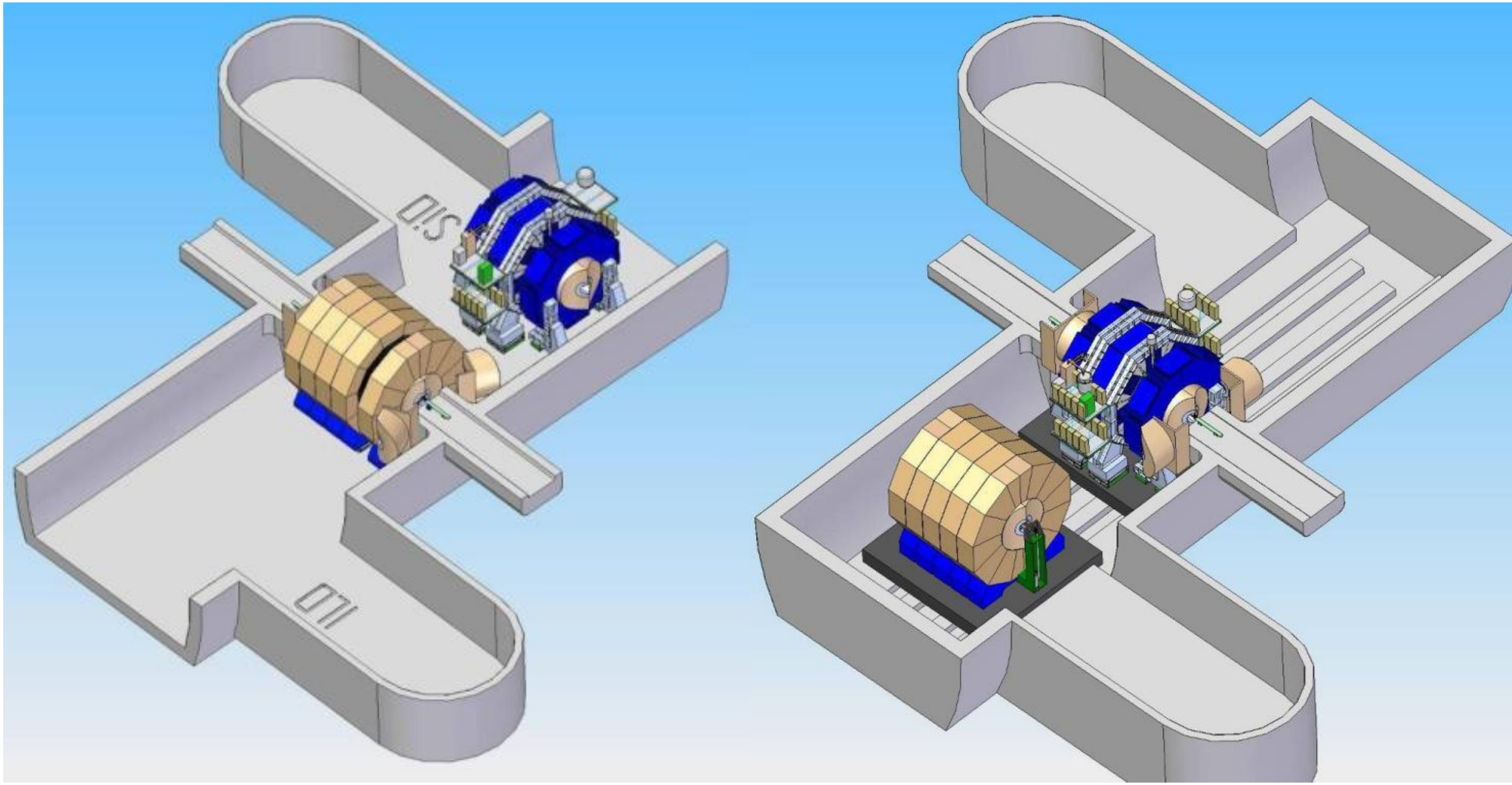
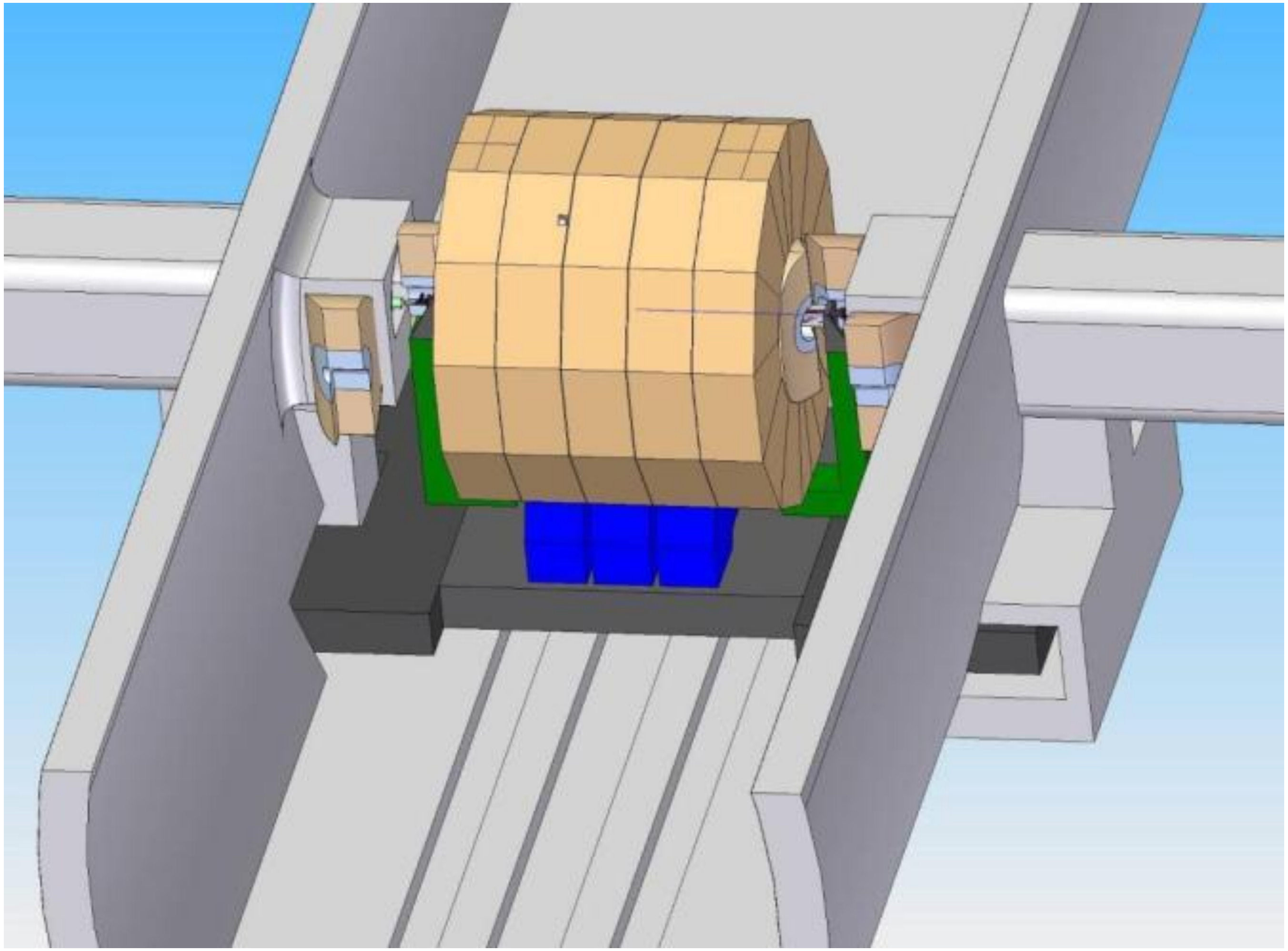
All detectors without / with platform

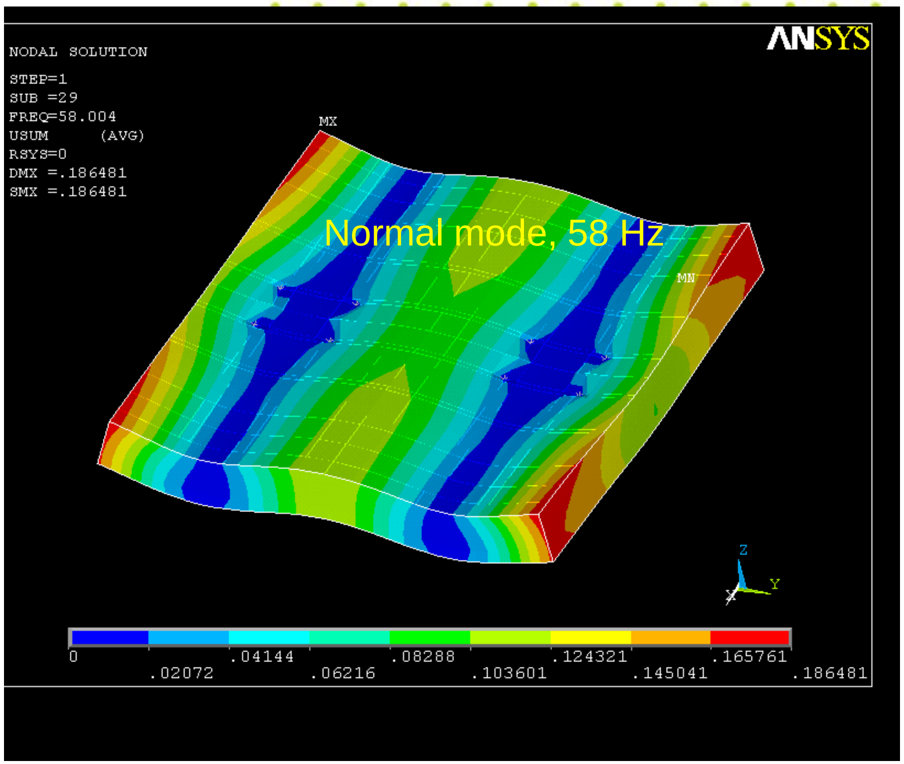


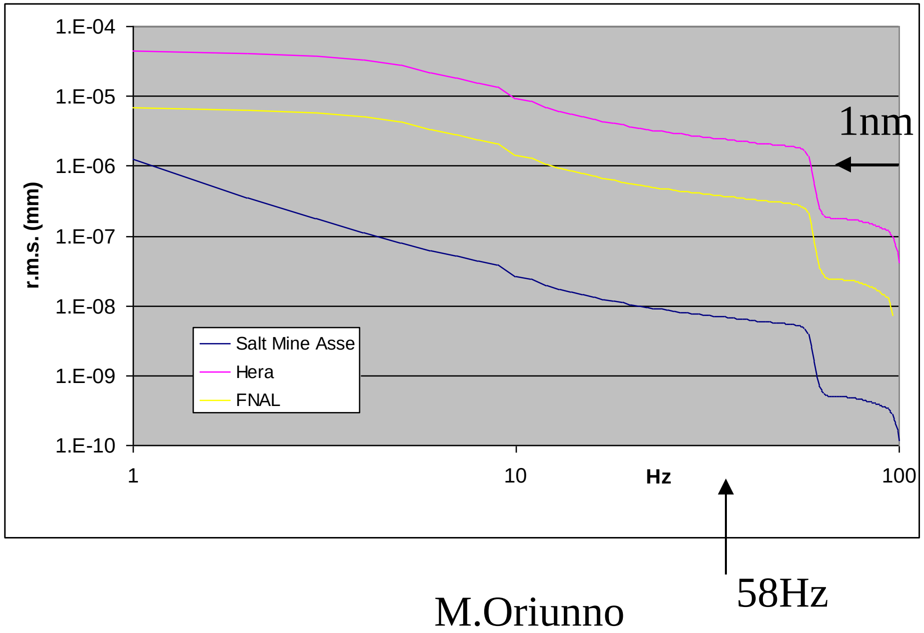
Half Platform w/ Pocket Storage



A.Herve, M.Oriunno, K,Sinram, T.Markiewicz, et al

Preliminary
ANSYS analysis of Platform





- First look of platform stability look rather promising: resonance frequencies are rather large (e.g. 58Hz) and additional vibration is only several nm

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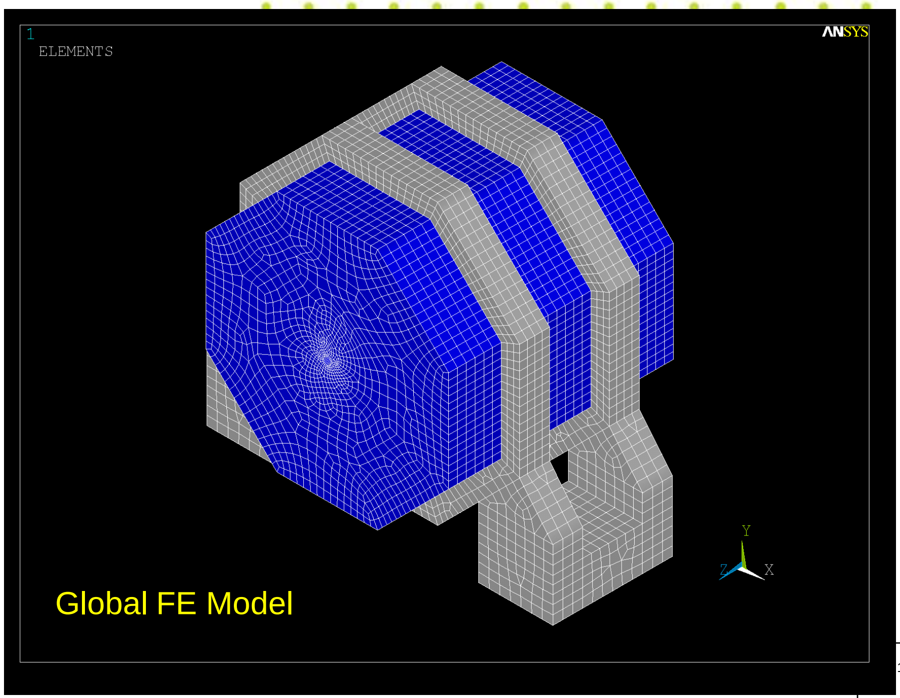
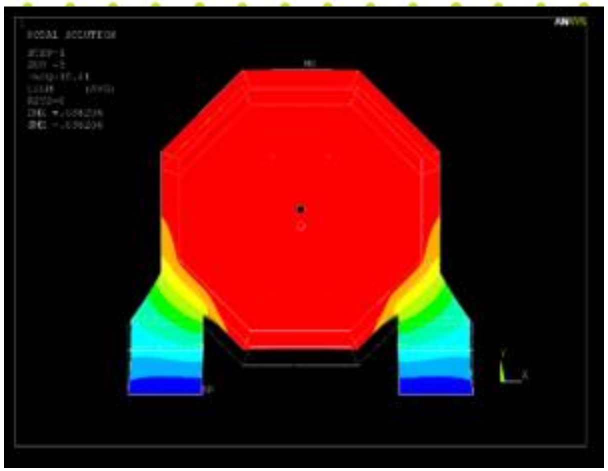
Detector stability analysis (SiD)

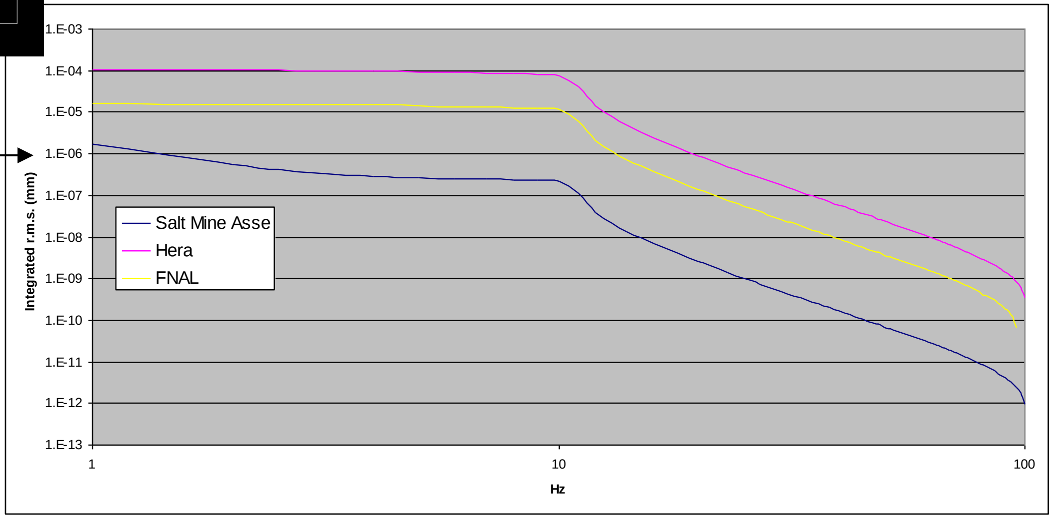




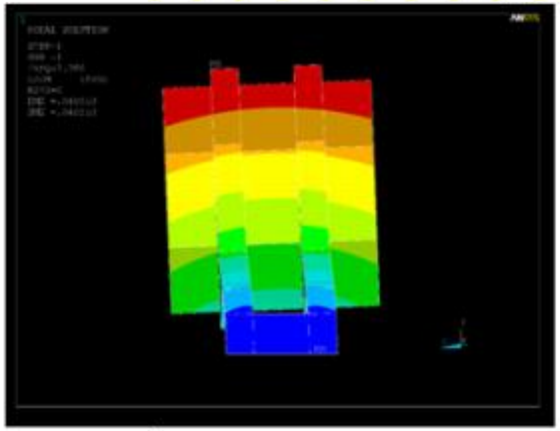
First vertical motion mode, 10.42 Hz

- First analysis shows possibilities for optimization
  - e.g. tolerance to fringe field => detector mass => resonance frequency

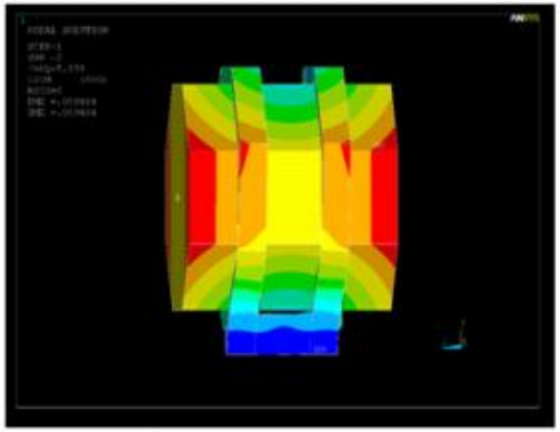
1nm



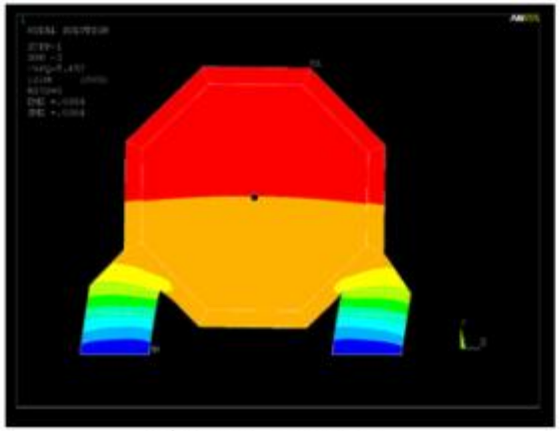
Free vibration modes of SiD



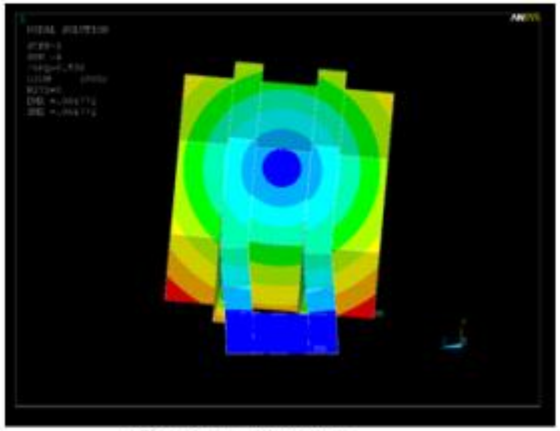
1st Mode, 2.38 Hz



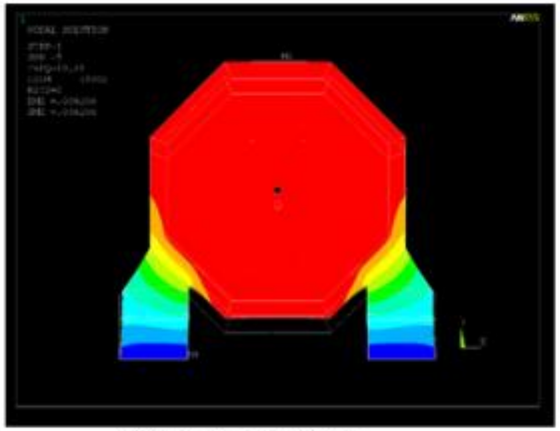
2nd Mode, 5.15 Hz



3rd Mode, 5.45 Hz

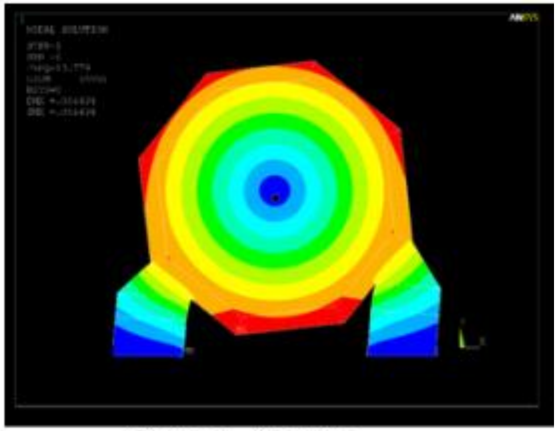


4th Mode, 6.53 Hz



5th Mode, 10.42 Hz

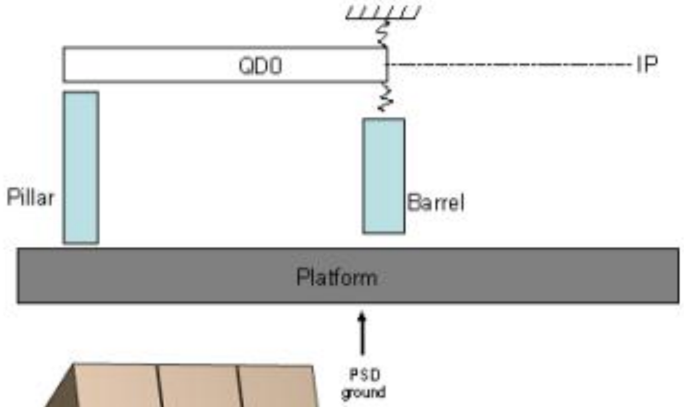
Vertical motion

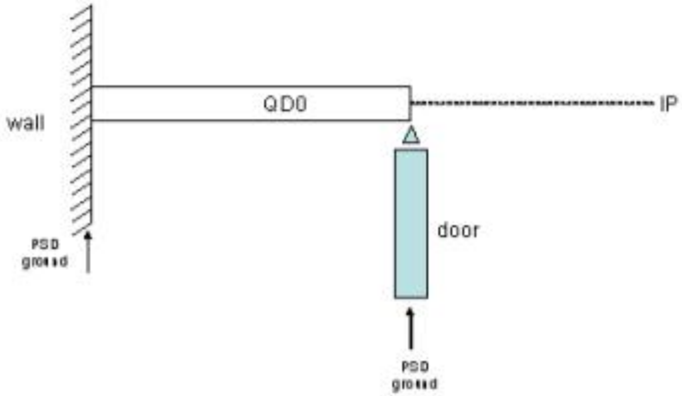


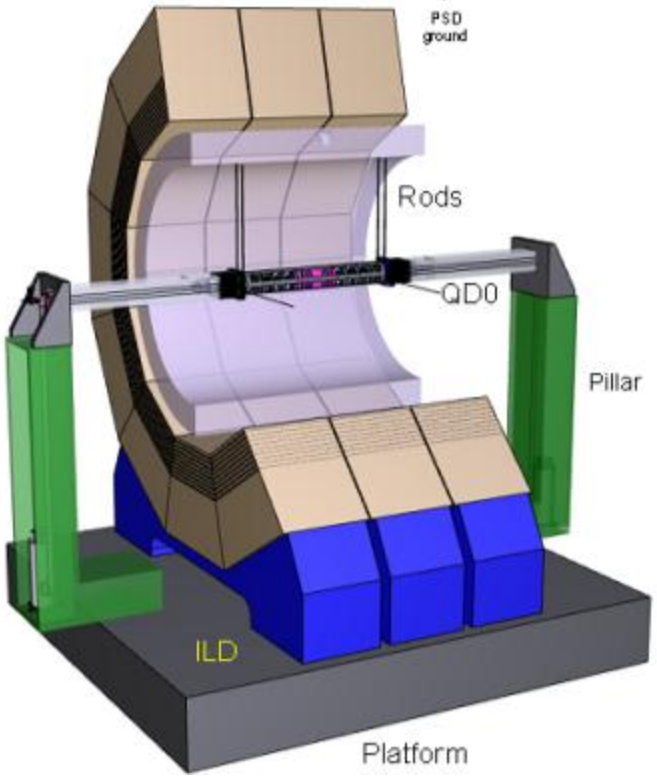
6th Mode, 13.7 Hz

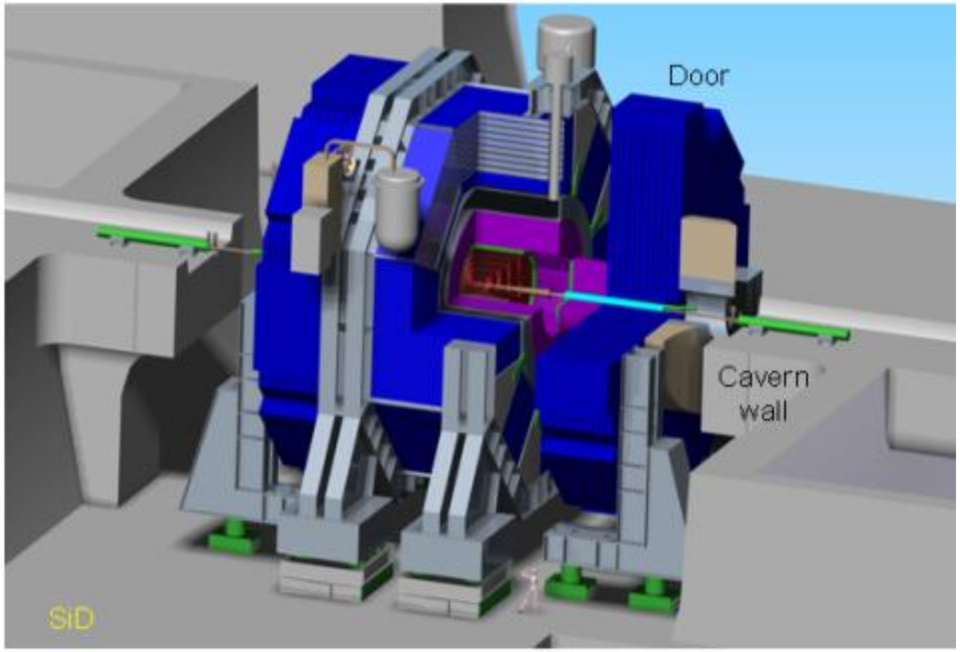
M.Oriunno

QD0 supports in ILD and SiD







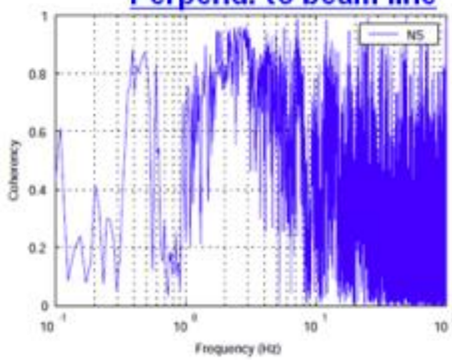


Stability studies at BELLE

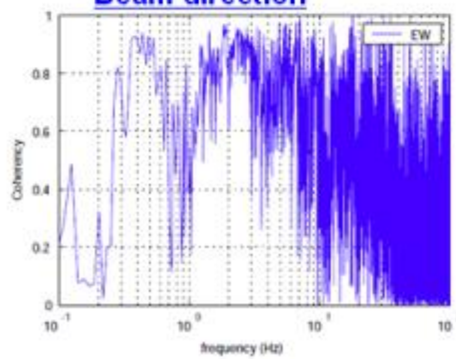
Measurement: B

How is the coherency between the tunnel and floor?

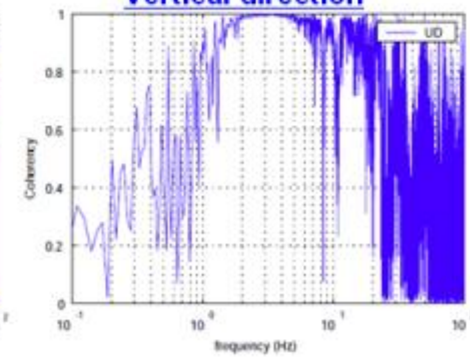
Perpend. to beam line

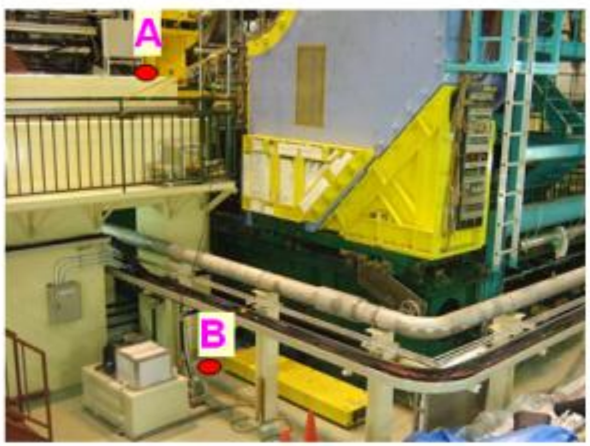


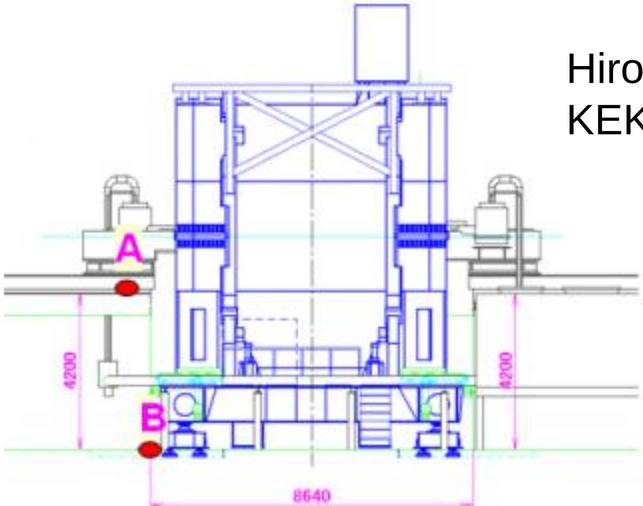
Beam direction



Vertical direction







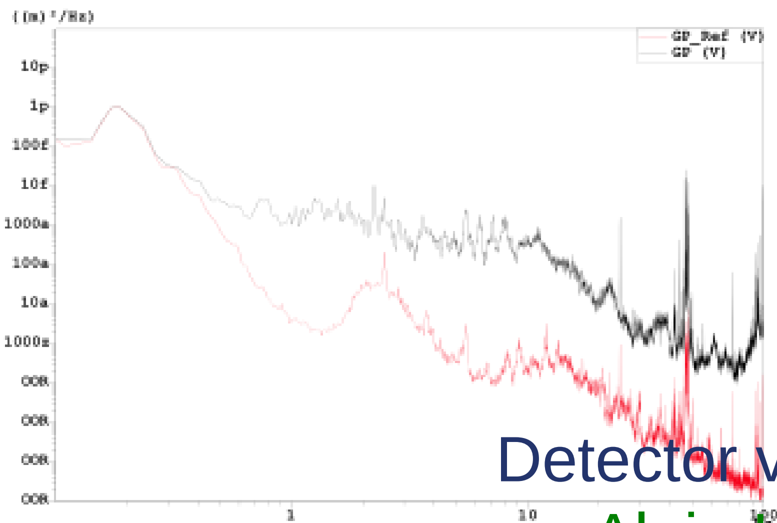
Hiroshi Yamaoka, KEK

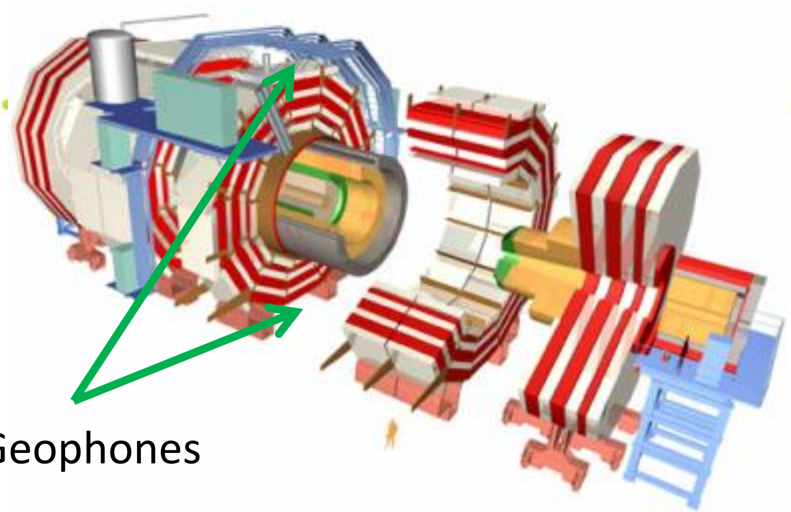
- Horizontal dir.: 0.~Hz, ~3Hz
- Vertical dir.: 1 ~ 20Hz

16

CMS top of Yoke measurement

PSD of the signals Vertical direction





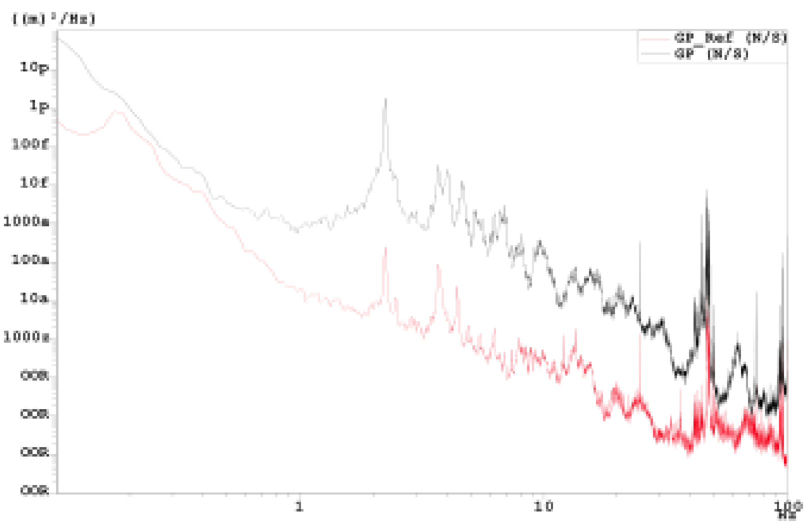
Geophones

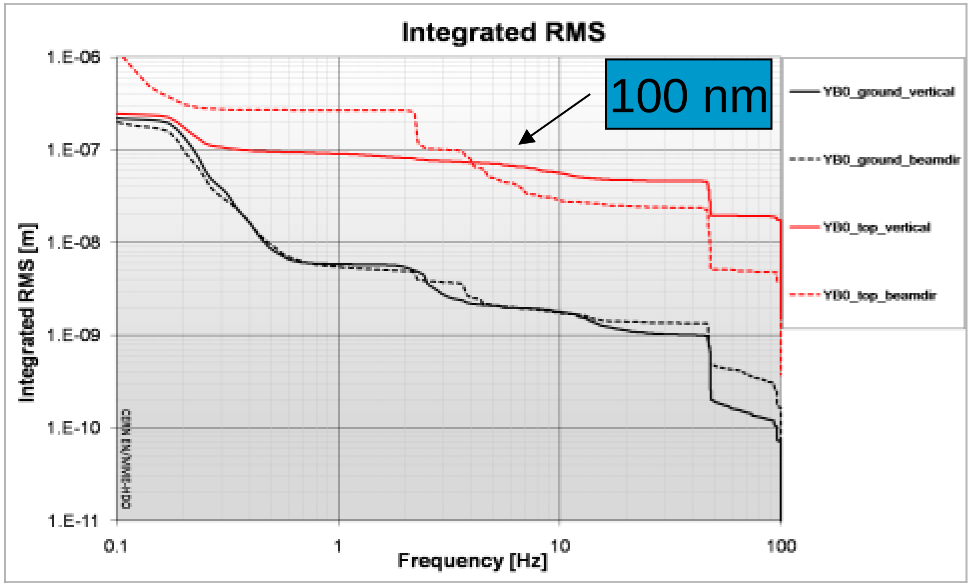
Detector vibrations and QD0 support

Alain Herve (ETH Zurich)

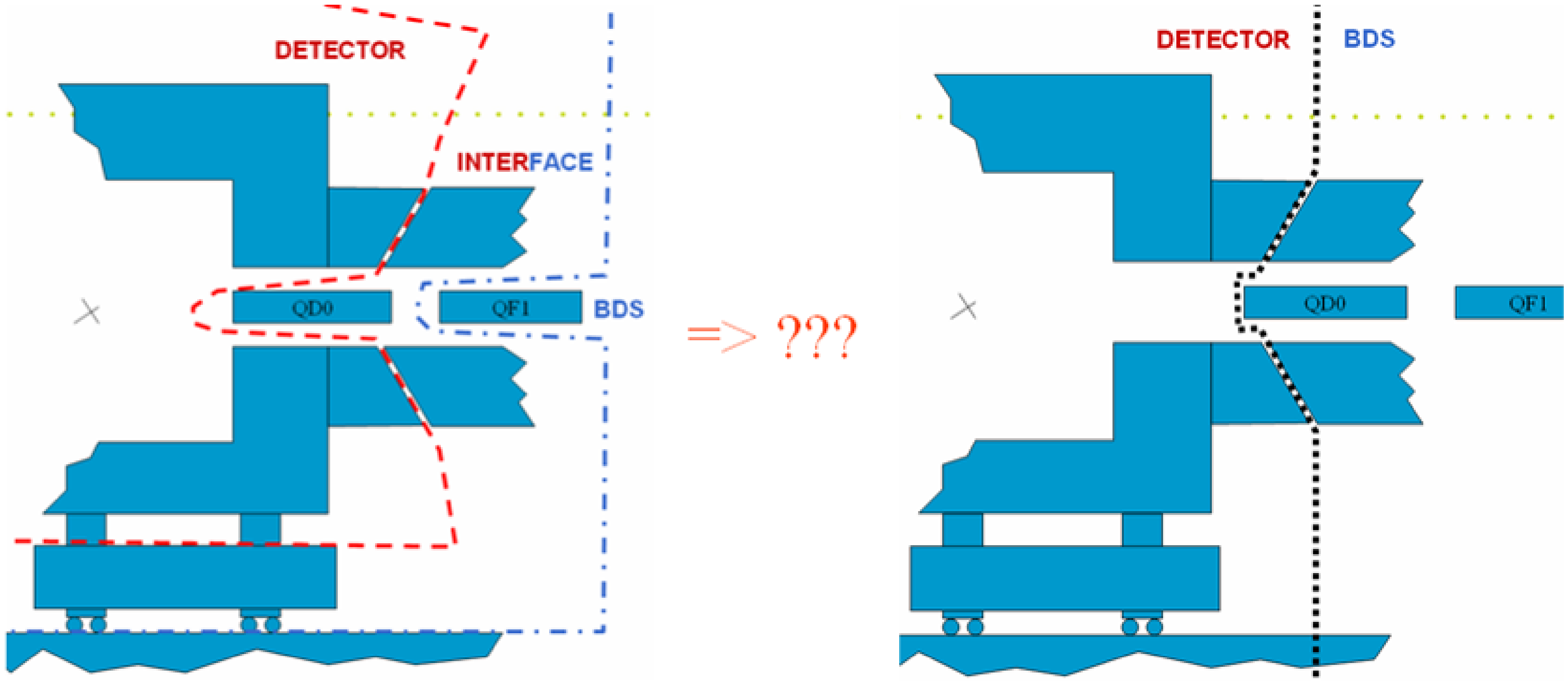
Cooling system OFF

PSD of the signals Beam direction





Longer L* → Simplified MDI?



- If doubled L* is feasible and acceptable then the MDI may be simplified tremendously
  - » and cost is reduced – do not need two extra sets of QD0
- An option of later upgrade for shorter L* may always be considered
- Has to be studied further

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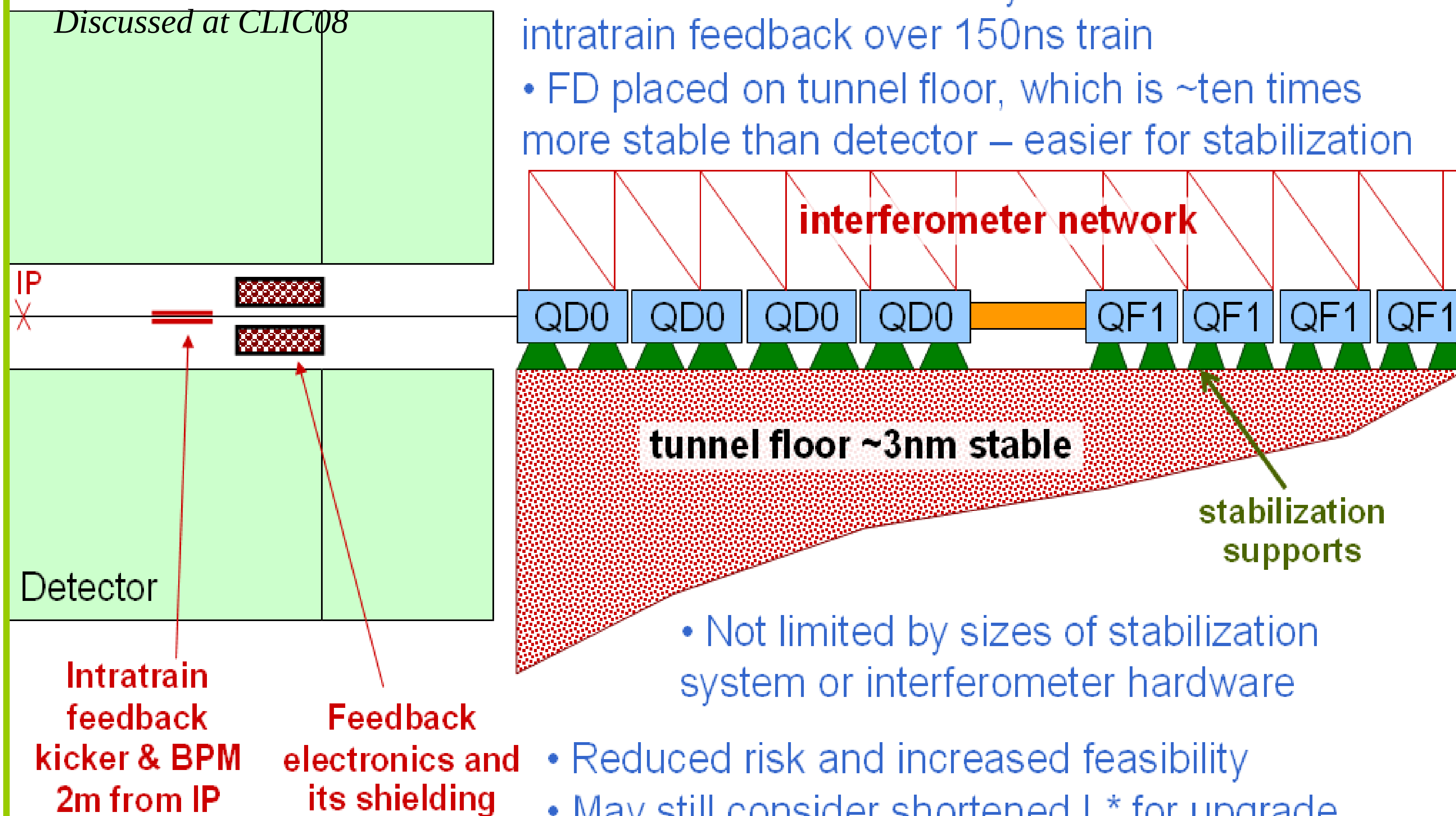
Doubled L* perhaps **necessary** for CLIC, where the FD stability requirement is ~0.1 nm

- Slower than 1/L* dependence of Lum => ↑L*
- Reduced feedback latency – several iteration of intratrain feedback over 150ns train
- FD placed on tunnel floor, which is ~ten times more stable than detector – easier for stabilization



- Not limited by sizes of stabilization system or interferometer hardware
- Reduced risk and increased feasibility
- May still consider shortened L* for upgrade

CLIC BDS & L*

FFS WITH L*=6M

In [12] it was proposed to use a longer L* to ease the QD0 stabilization challenge by supporting the FD on the tunnel. The initial lattice featured a L*=8m with about 30% lower luminosity than the current design and tighter pre-alignment tolerances to guarantee a successful tuning [2]. In the meantime the CLIC experiments have proposed to reduce the length of the detector to 6 m [13]. Consequently a new FFS has been designed with an L*=6m by scaling the old CLIC FFS with L*=4.3 m [14]. This lattice currently features IP spot sizes of $\sigma_x = 60.8$ nm and $\sigma_y = 1.9$ nm. Table 1 shows the total and energy peak luminosities for the different available FFS systems. Luminosity clearly decreases as L* increases. The L*=6 m case has a 16% lower peak luminosity than the nominal one (L*=3.5 m). Figure 5 displays the luminosity versus relative energy offset for all the FFS designs, showing a similar energy bandwidth in all cases.

L* $[m]$	Total luminosity $[10^{34} cm^{-2} s^{-1}]$	Peak luminosity $[10^{34} cm^{-2} s^{-1}]$
3.5	6.9	2.5
4.3	6.4	2.4
6	5.0	2.1
8	4.0	1.7

Table 1: Total and Peak luminosities for different L* lattices.

[12] A. Seryi, "Near IR FF design including FD and longer L* issues", CLIC08.

[13] CLIC09 Workshop, 12-16 October 2009, CERN , http://indico.cern.ch/conferenceDisplay.py?confId=45580

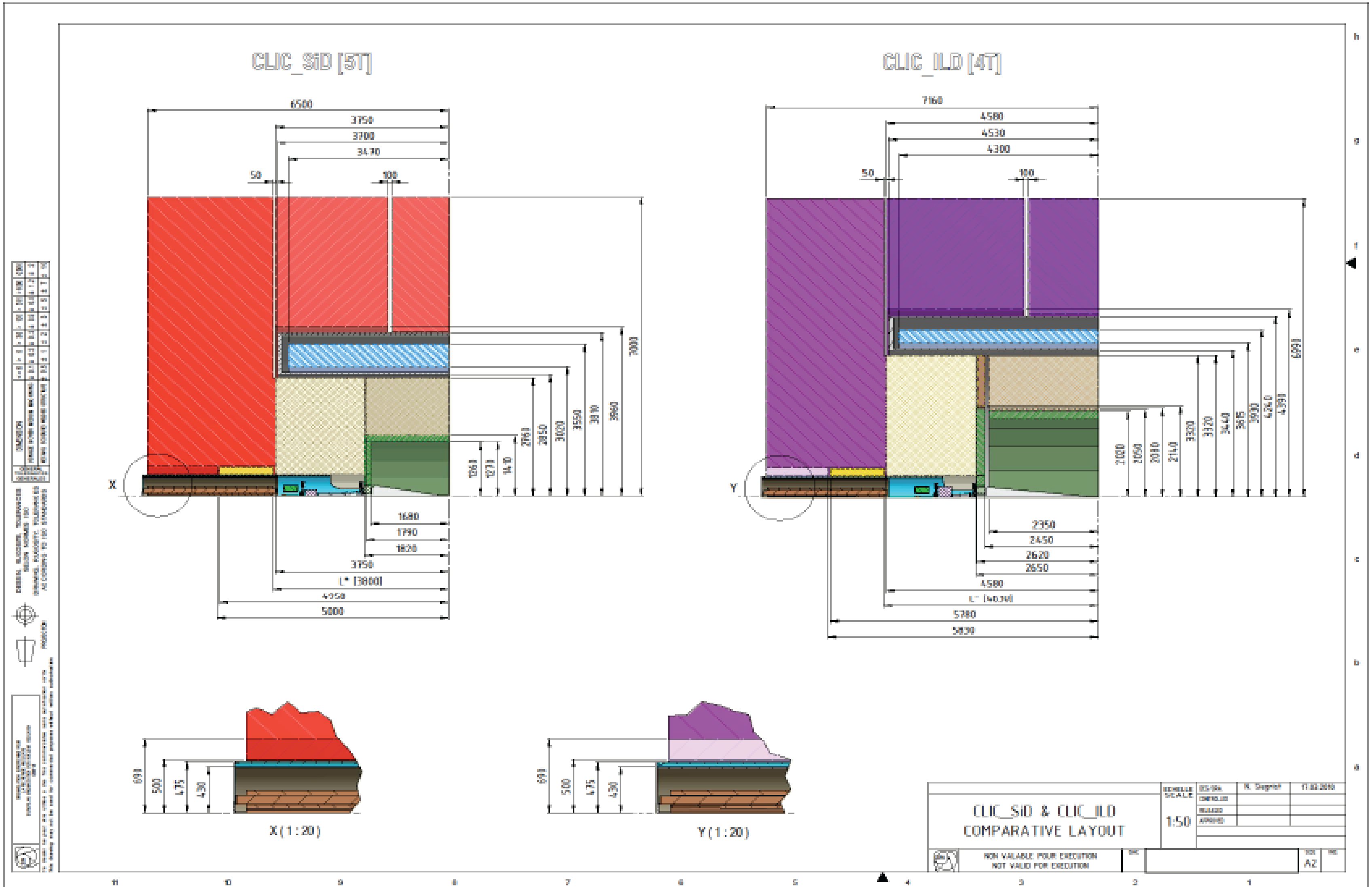
[14] http://clicr.web.cern.ch/CLICr/

The CLIC Beam Delivery System towards the Conceptual Design Report

IPAC10

D. Angal-Kalinin, B. Bolzon, B. Dalena, L. Fernandez, F. Jackson, A. Jeremie, B. Parker
J. Resta López, G. Rumolo, D. Schulte, A. Seryi, J. Snuverink, R. Tomás and G. Zamudio

CLIC detector comparison



March 28, 10 H. Gerwig - LCWS10/ILC10 5

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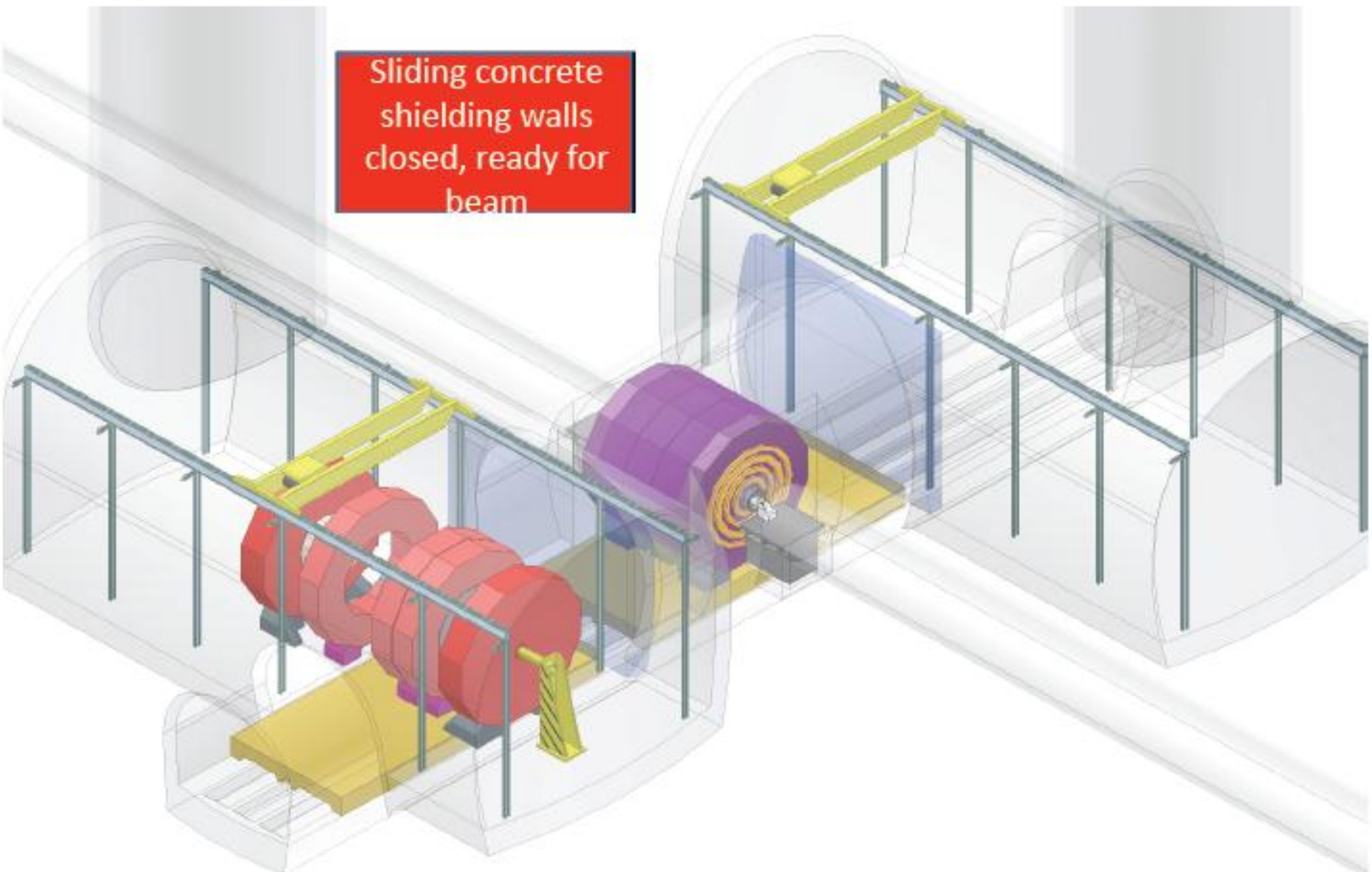
New concept of CLIC push-pull

Experiment 2 sliding on IP, shielding walls closed



March 28, 10 H. Gerwig - LCWS10/ILC10 28

New Low P parameter set

	Nom. RDR	Low P RDR	new Low P
Case ID	**1**	**2**	**3**
E CM (GeV)	500	500	500
N	2.0E+10	2.0E+10	2.0E+10
n_b	2625	1320	1320
F (Hz)	5	5	5
P_b (MW)	**10.5**	**5.3**	$\boxed{\mathbf{5.3}}$
$\gamma\varepsilon_X$ (m)	1.0E-05	1.0E-05	1.0E-05
$\gamma\varepsilon_Y$ (m)	4.0E-08	3.6E-08	3.6E-08
βx (m)	2.0E-02	1.1E-02	1.1E-02
βy (m)	4.0E-04	2.0E-04	2.0E-04
Travelling focus	No	No	**Yes**
Z-distribution *	Gauss	Gauss	Gauss
σ_x (m)	6.39E-07	4.74E-07	4.74E-07
σ_y (m)	5.7E-09	3.8E-09	3.8E-09
σ_z (m)	3.0E-04	2.0E-04	$\boxed{\text{3.0E-04}}$
Guinea-Pig $\delta E/E$	**0.023**	**0.045**	$\boxed{\mathbf{0.036}}$
Guinea-Pig L ($cm^{-2}s^{-1}$)	**2.02E+34**	**1.86E+34**	**1.92E+34**
Guinea-Pig Lumi in 1%	1.50E+34	1.09E+34	1.18E+34

*for flat z distribution the full bunch length is σ_z*2*$3^{1/2}$

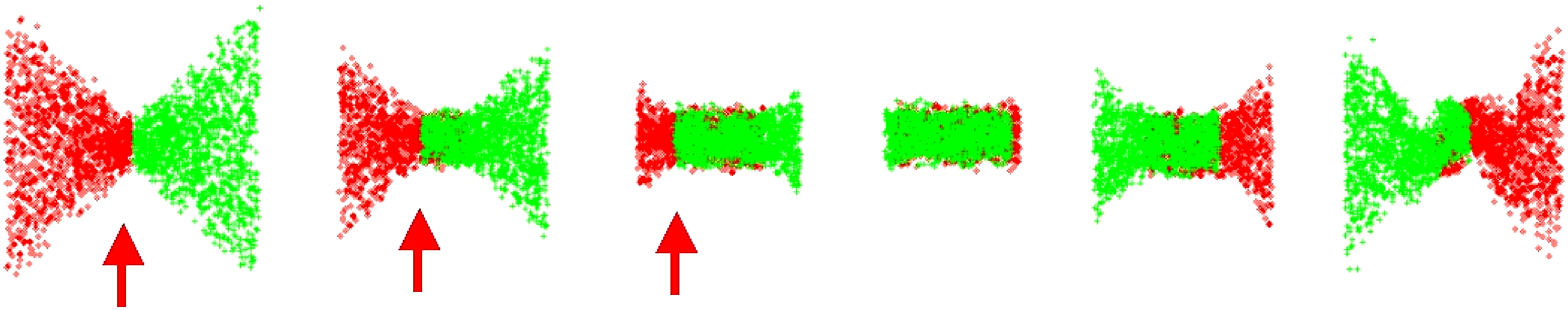
Travelling focus allows to lengthen the bunch

Thus, beamstrahlung energy spread is reduced

Focusing during collision is aided by focusing of the opposite bunch

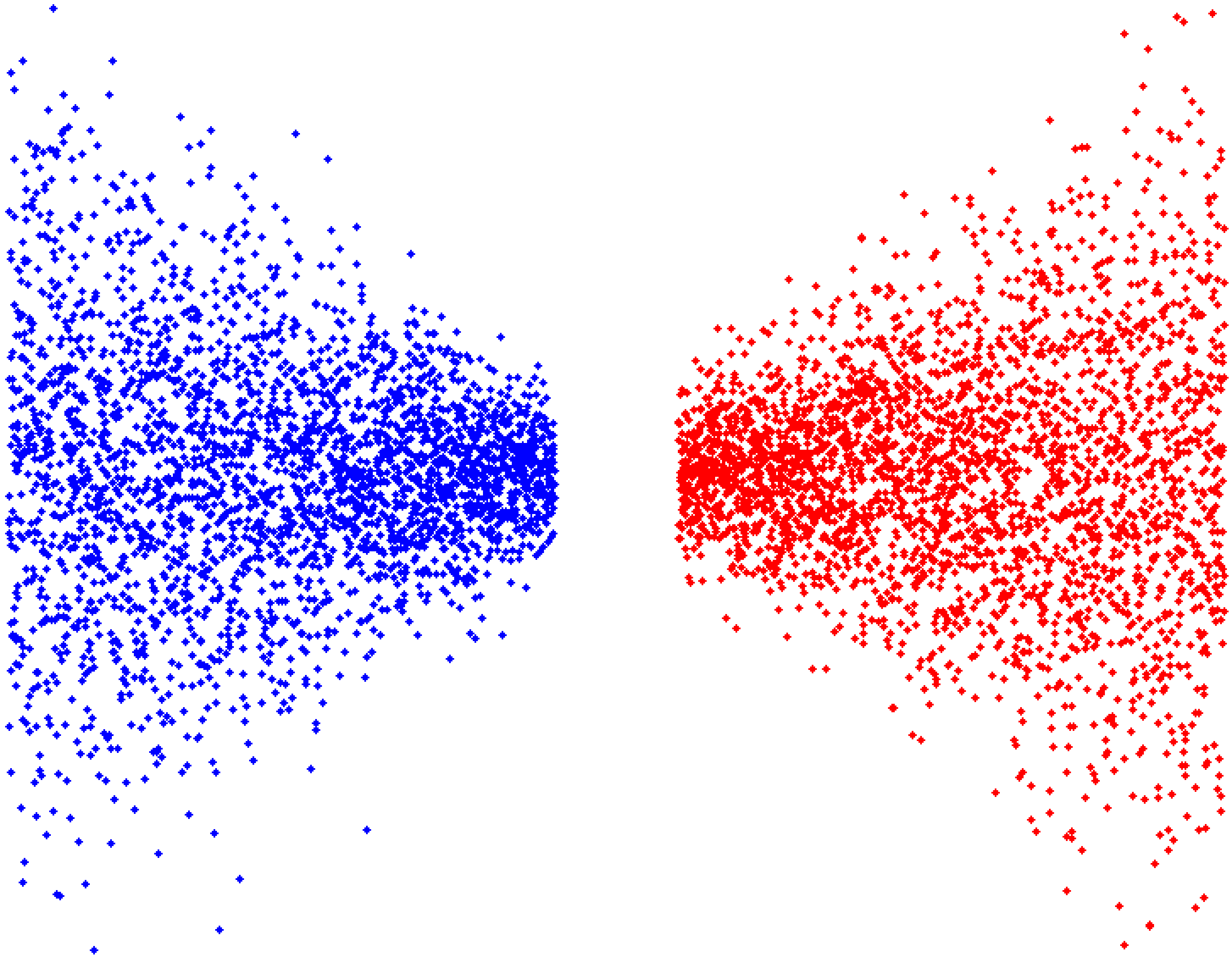
Focal point during collision moves to coincide with the head of the opposite bunch

Beam-beam: Travelling focus

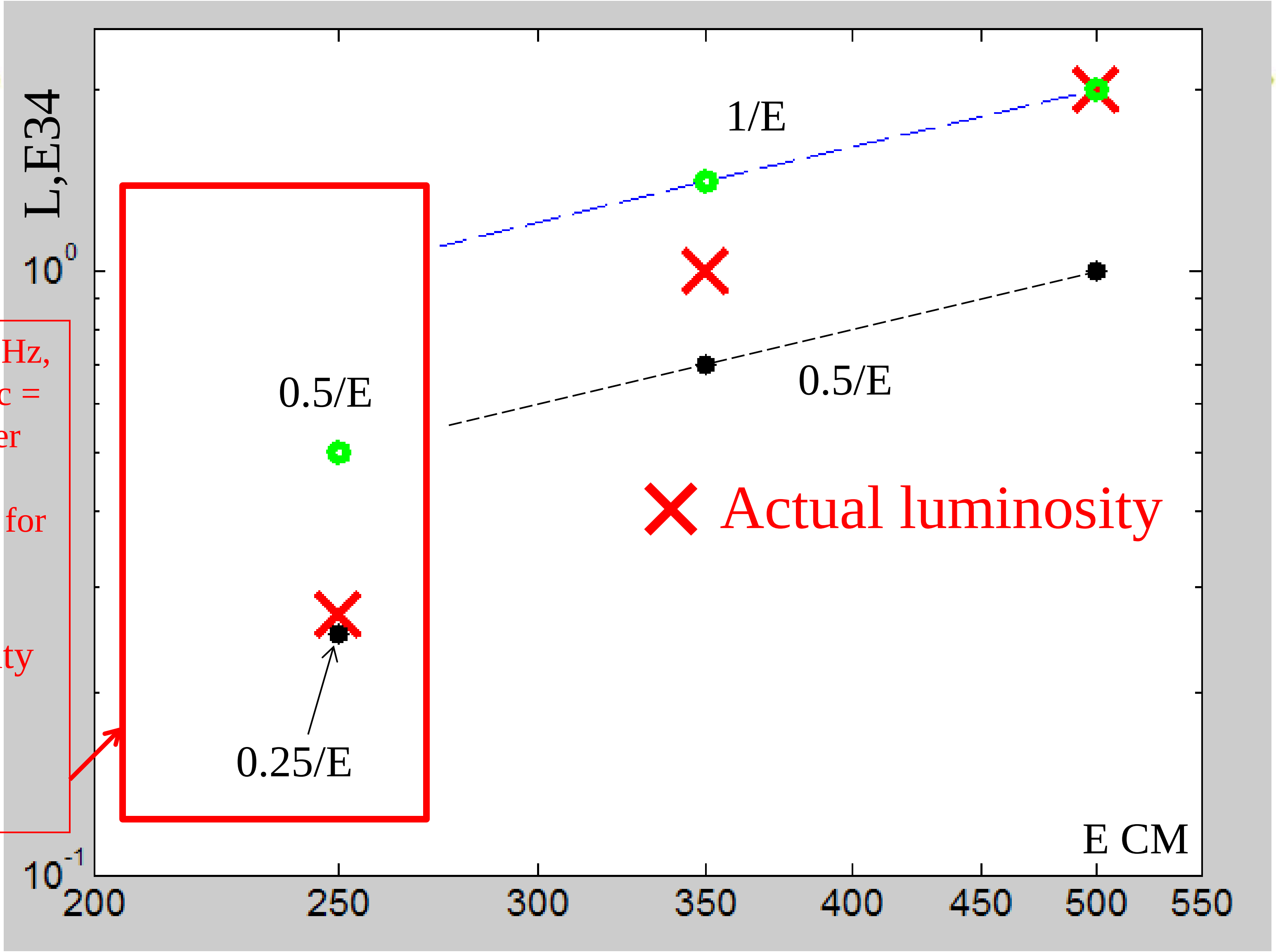


- Suggested by V.Balakin in ~1991 – idea is to use beam-beam forces for additional focusing of the beam – allows some gain of luminosity or overcome somewhat the hour-glass effect
- Figure shows simulation of traveling focus. The arrows show the position of the focus point during collision
- So far not yet used experimentally

Collision with travelling focus



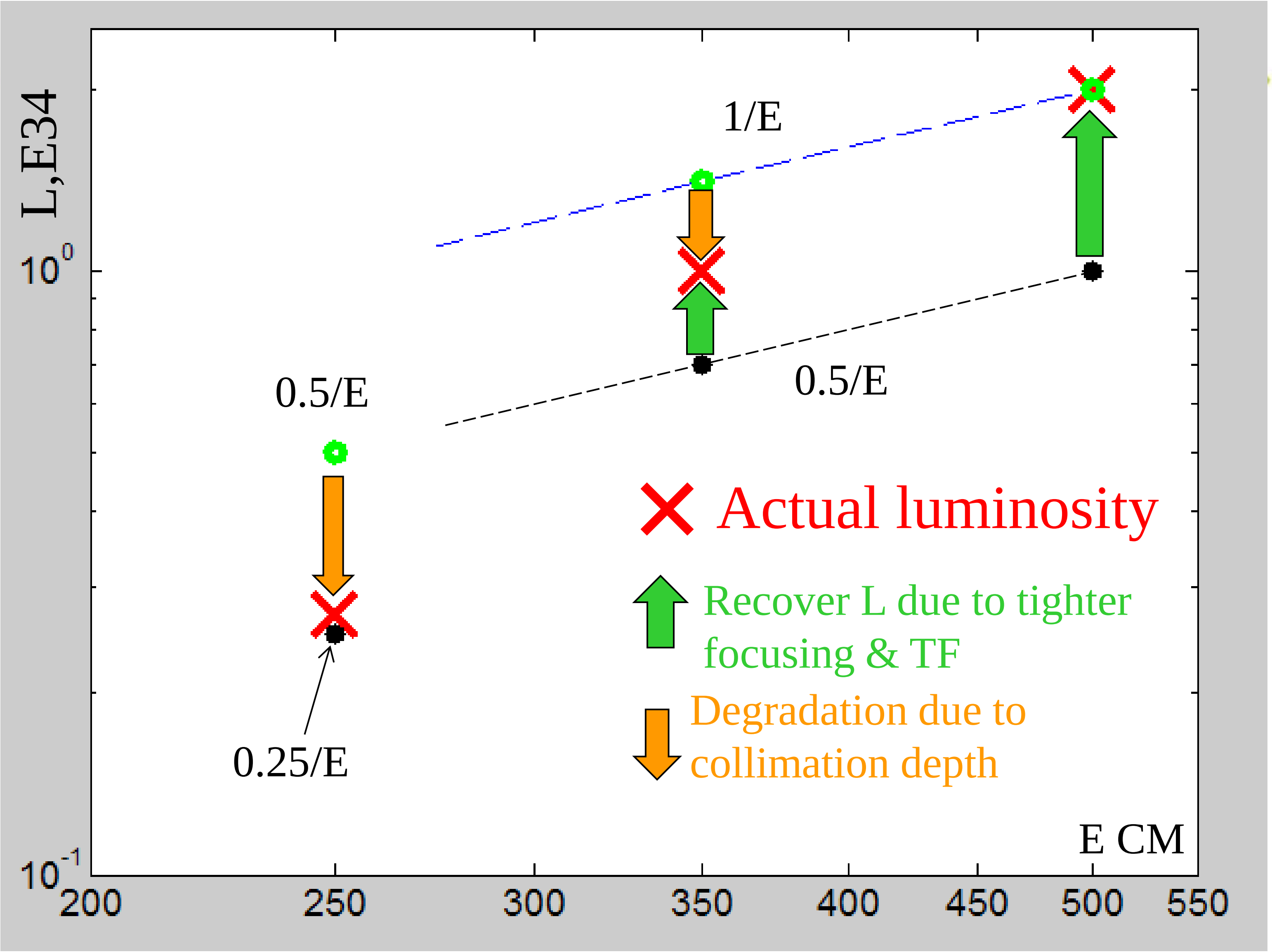
SB2009 Lumi



Rate at IP = 2.5Hz, Rate in the linac = 5Hz (every other pulse is at 150GeV/beam, for e+ production)

Low luminosity at this energy reduces the physics reach

SB2009 Lumi



L,E34
1/E
0.5/E
0.5/E
0.25/E
Actual luminosity
Recover L due to tighter focusing & TF
Degradation due to collimation depth
E CM
10^0
10^{-1}
200
250
300
350
400
450
500
550

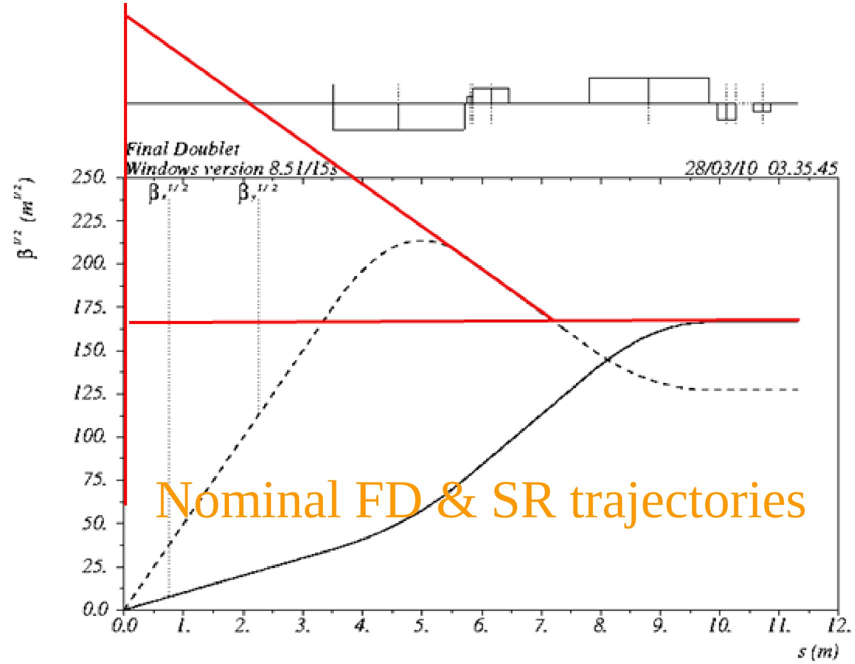
- The travelling focus can be created in two ways.
- The first way is to have small uncompensated chromaticity and coherent E-z energy shift $\delta E/\delta z$ along the bunch. One has to satisfy $\delta E\ k\ L^*_{eff} = \sigma_z$ where k is the relative uncompensated chromaticity. The δE needs to be 2-3 times the incoherent spread in the bunch. Thus, the following set may be used: δE=0.3%, k=1.5%, L^*_{eff} =6m.
- It is clear that additional energy spread affect the physics. Therefore, second method is considered:

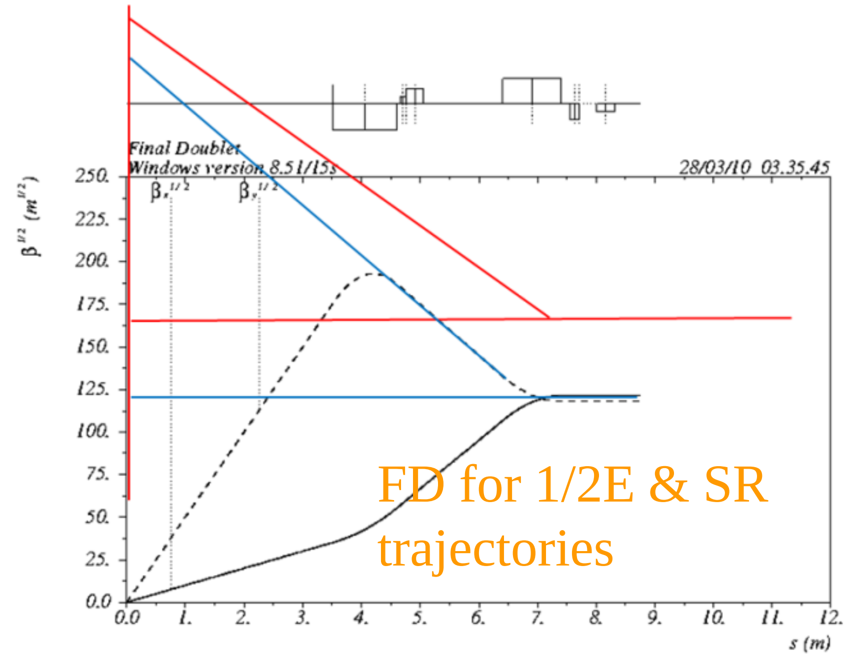
- The second way to create a travelling focus is to use a transverse deflecting cavity giving a z-x correlation in one of the FF sextupoles and thus a z-correlated focusing
- The cavity would be located about 100m upstream of the final doublet, at the $\pi/2$ betatron phase from the FD
- The needed strength of the travelling focus cavity can be compared to the strength of the normal crab cavity (which is located just upstream of the FD):
  - $U_{trav.cav.}/U_{crab.cav.} = \eta_{FD}\, R_{12}^{cc} / (L^{*}_{eff}\, \theta_c\, R_{12}^{trav})$.
  - Here η_{FD} is dispersion in the FD, θ_c full crossing angle, R_{12}^{trav} and R_{12}^{cc} are transfer matrix elements from travelling focus transverse cavity to FD, and from the crab cavity to IP correspondingly.
- For typical parameters η_{FD} =0.15m, θ_c =14mrad. R_{12}^{cc} =10m, R_{12}^{trav} =100m, L^{*}_{eff} =6m one can conclude that the needed strength of the travelling focus transverse cavity is about 20% of the nominal crab cavity.

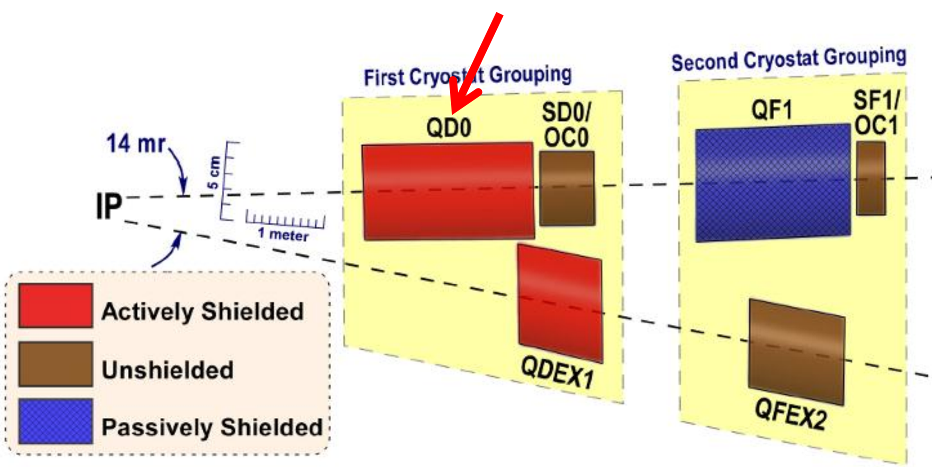
FD for low E

FD optimized for lower energy will allow increasing the collimation depth by ~10% in Y and by ~30% in X (Very tentative!)

- One option would be to have a separate FD optimized for lower E, and then exchange it before going to nominal E
- Other option to be studied is to build a universal FD, that can be reconfigured for lower E configuration (may require splitting QD0 coil and placing sextupoles in the middle)







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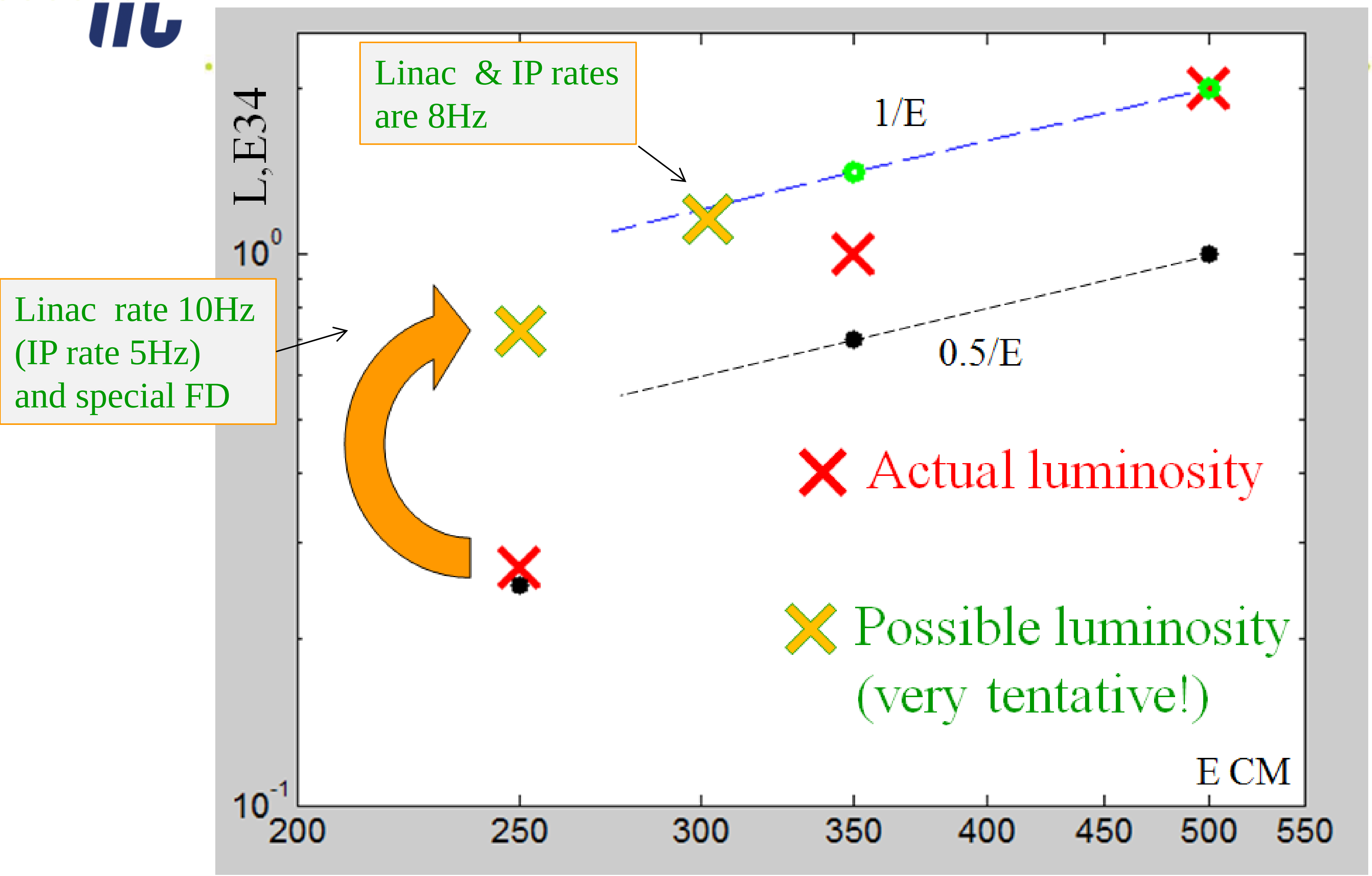
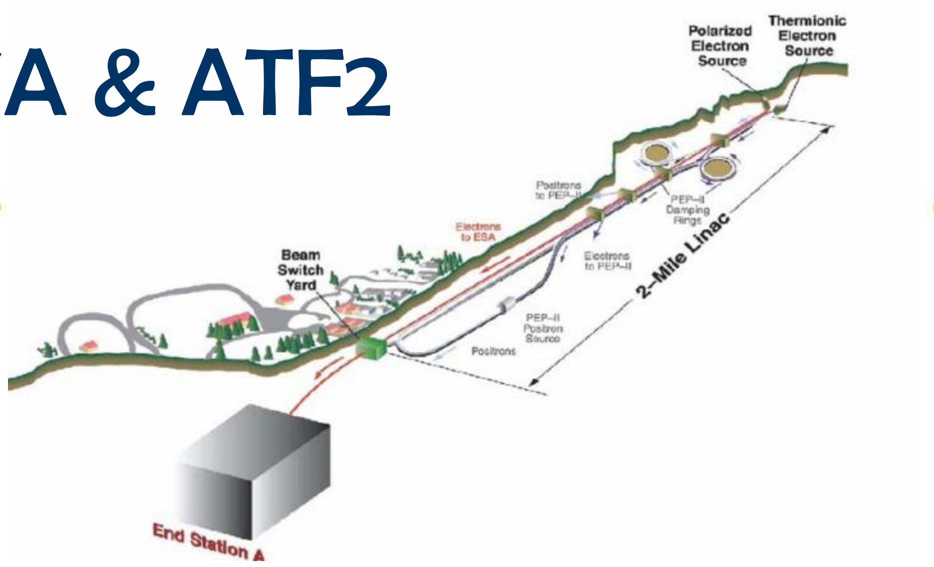
SB2009 Lumi

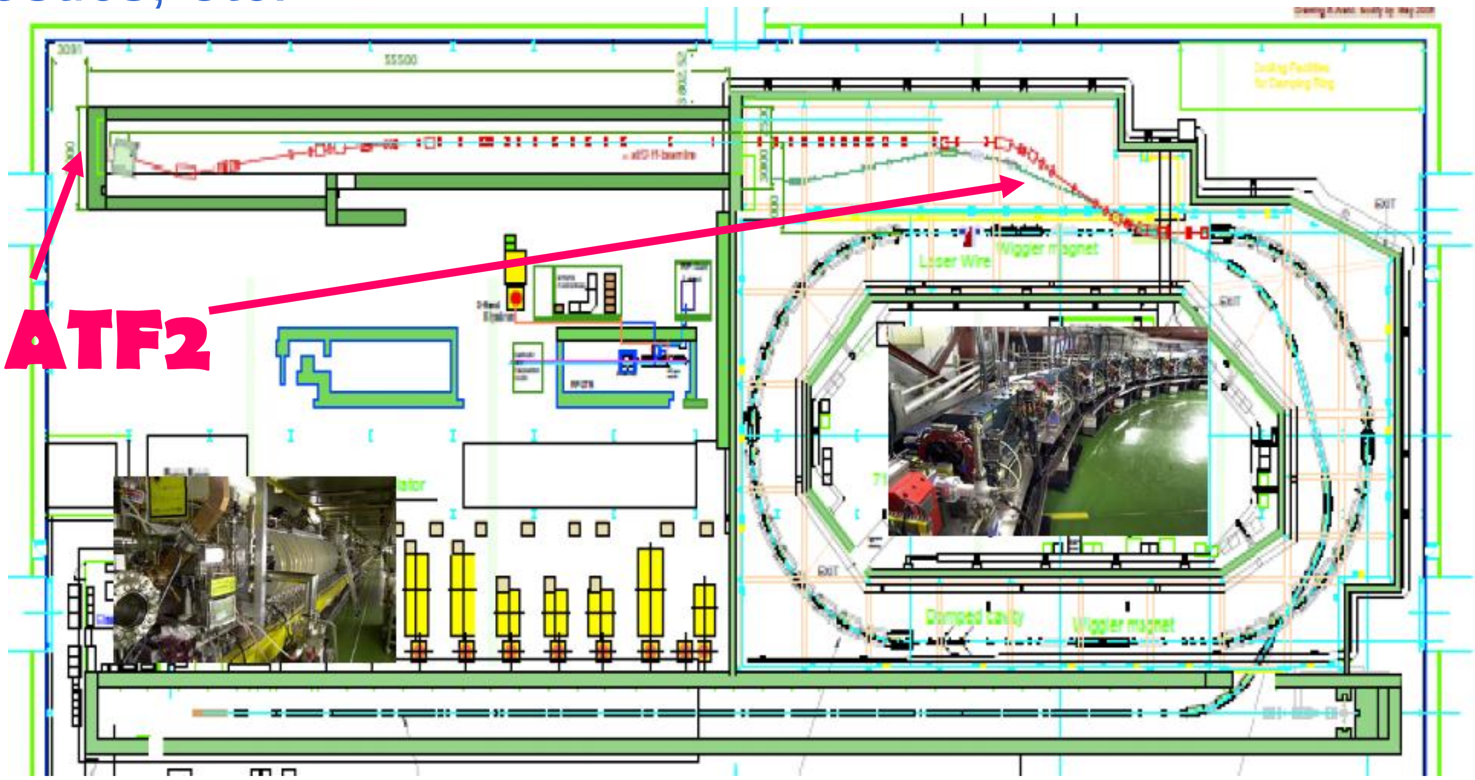

Linac & IP rates are 8Hz
Linac rate 10Hz (IP rate 5Hz) and special FD
1/E
0.5/E
Actual luminosity
Possible luminosity (very tentative!)
L, E34
10^0
10^{-1}
E CM
200
250
300
350
400
450
500
550

Test facilities: ESA & ATF2

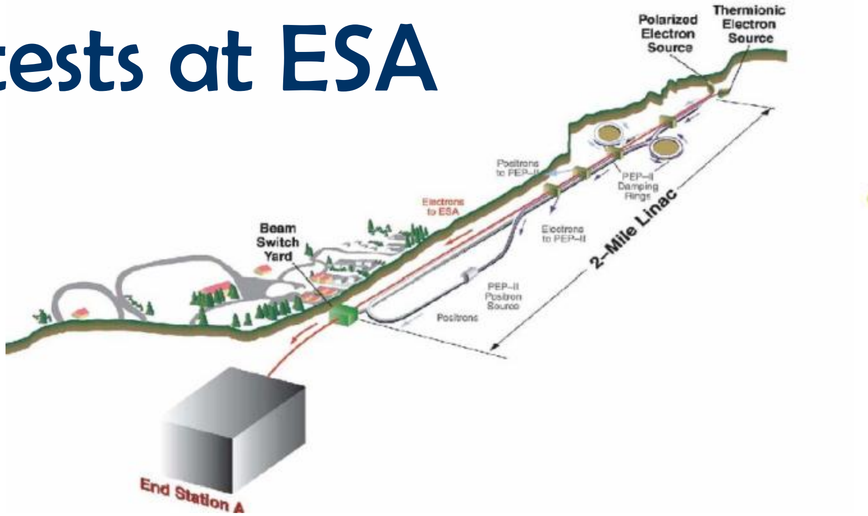
ESA: machine-detector tests; energy spectrometer; collimator wake-fields, etc.

ATF2: prototype FF, develop tuning, diagnostics, etc.

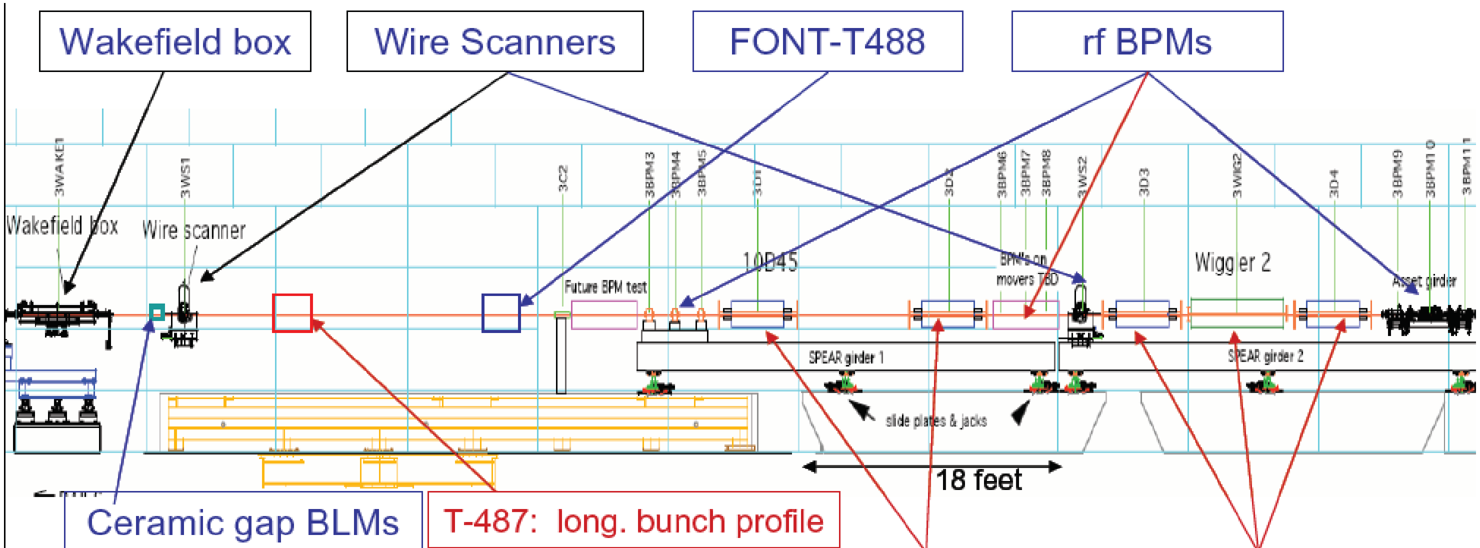




BDS beam tests at ESA



Study:
BPM energy spectrometer
Synch Stripe energy spectrometer
Collimator design, wakefields
IP BPMs/kickers—background studies
EMI (electro-magnetic interference)
Bunch length diagnostics



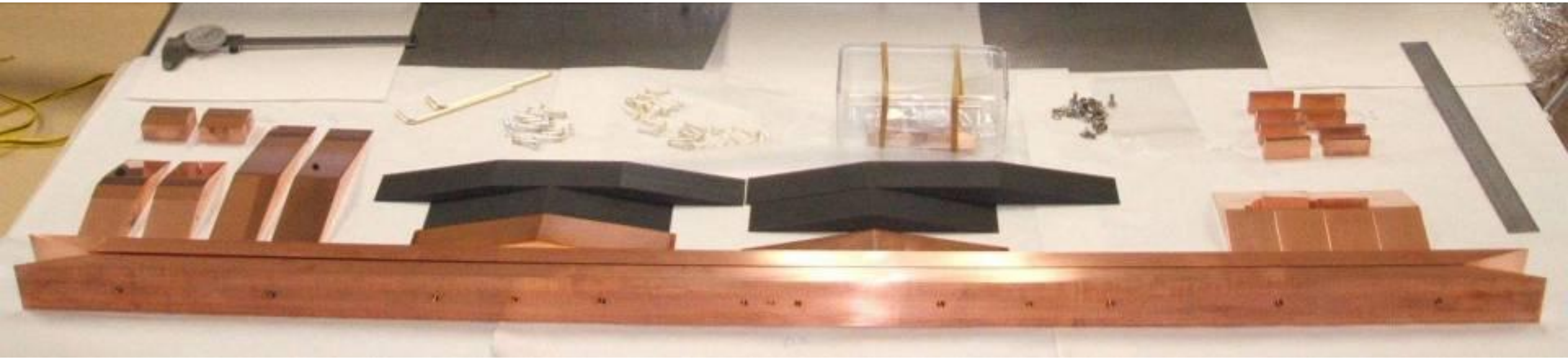
Upstream (not shown)

4 rf BPMs for incoming trajectory
Ceramic gap w/ rf diode detectors (16GHz, 23GHz, and 100GHz) and 2 EMI antennas

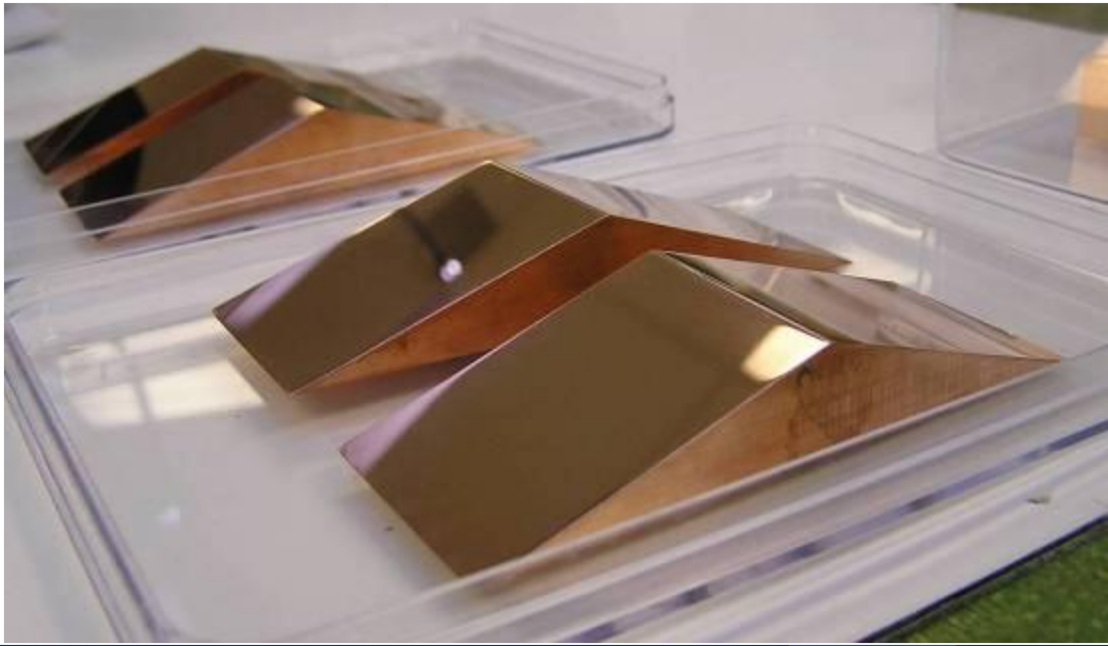
Downstream (not shown)

Ceramic gap for EMI studies
T475 Detector for Wiggler SR stripe

Collimator Wakefield study at ESA



- Spoilers of different shape investigated at ESA (N.Watson et al)
- Theory, 3d modeling and measurements are so far within a factor of ~2 agreement



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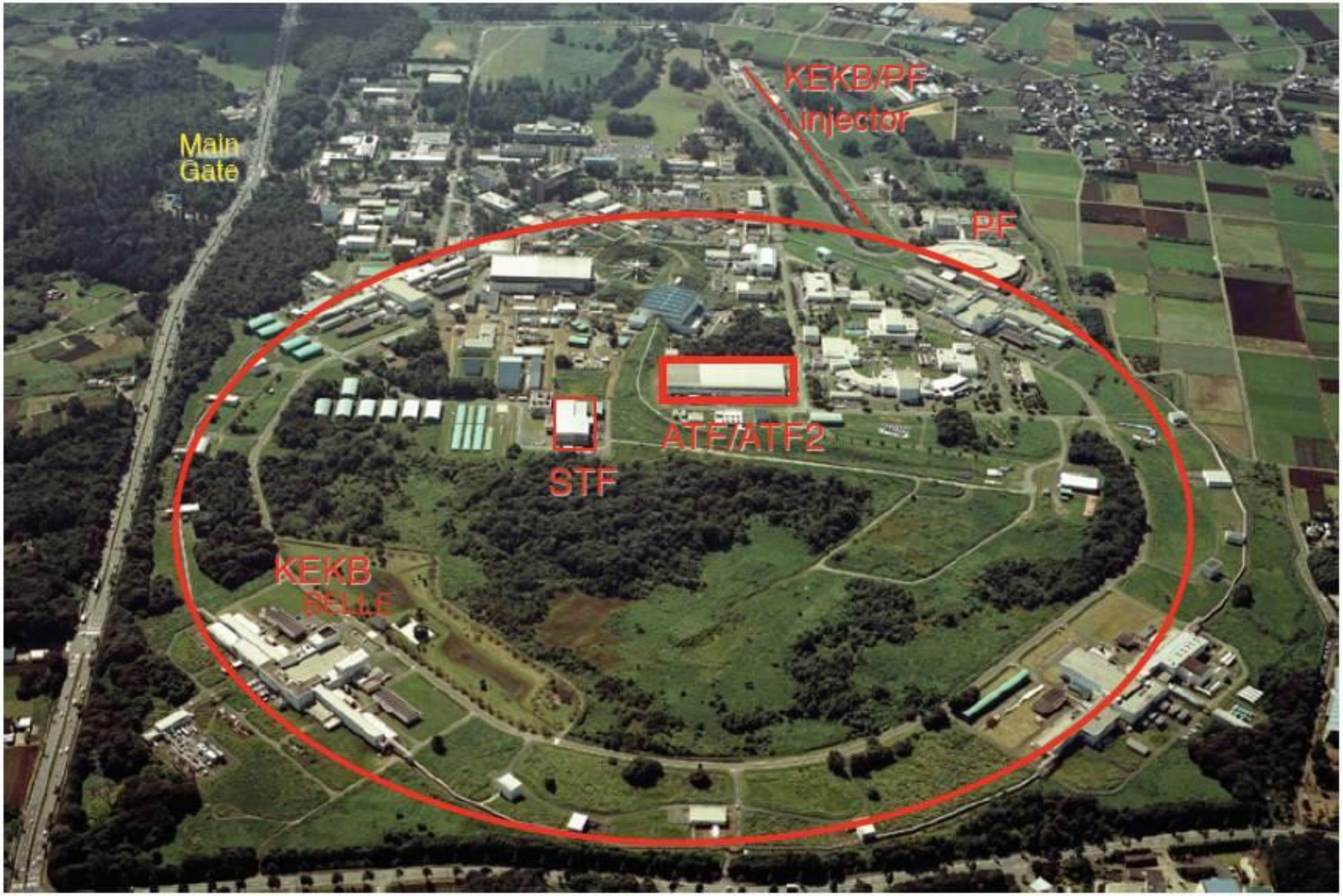
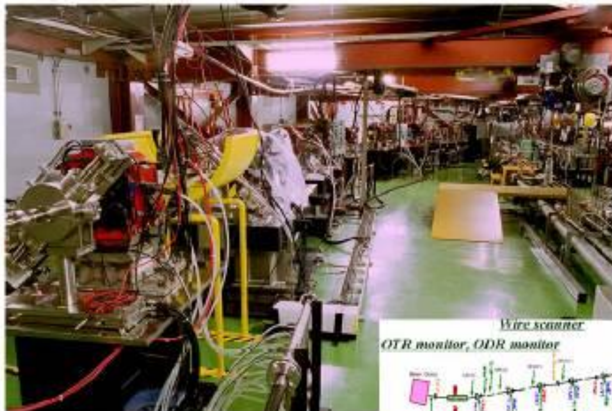
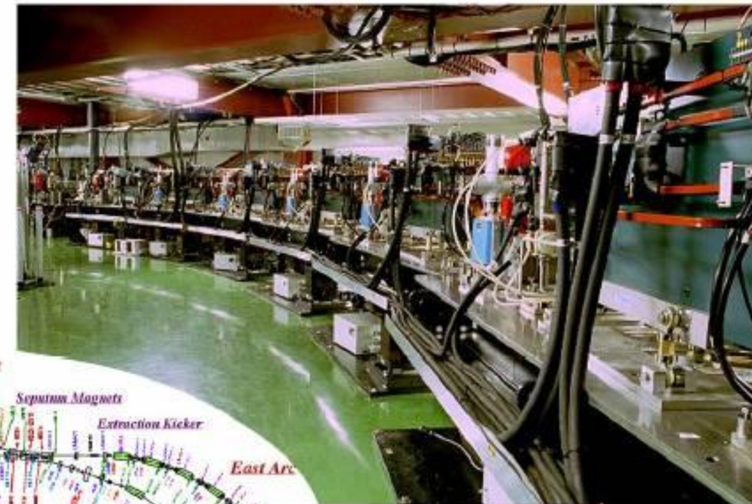


KEKB/PF
injector
Main
Gate
PF
ATF/ATF2
STF
KEKB
BELLE

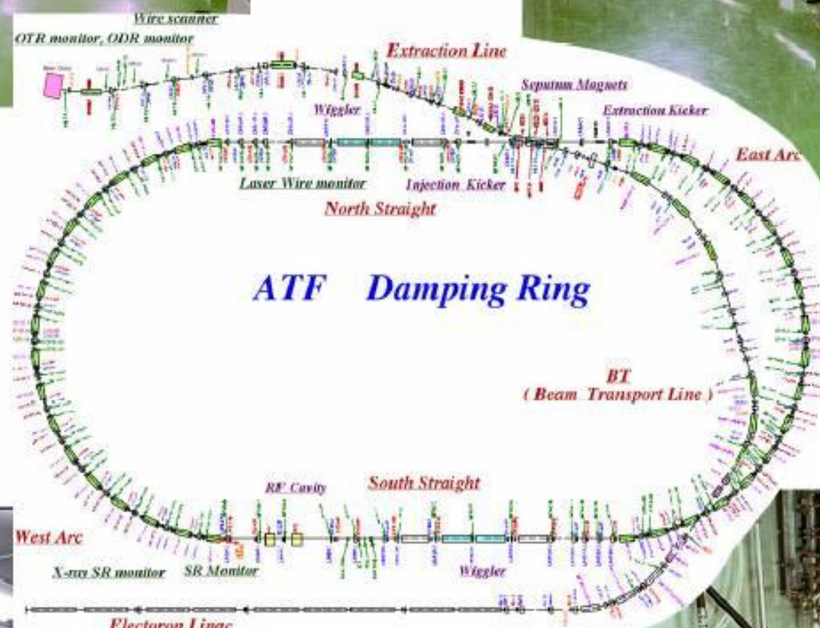
ATF and ATF2



Extraction Line

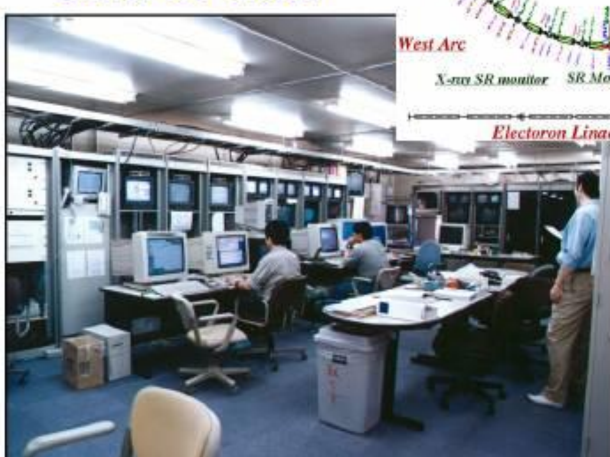


Damping Ring

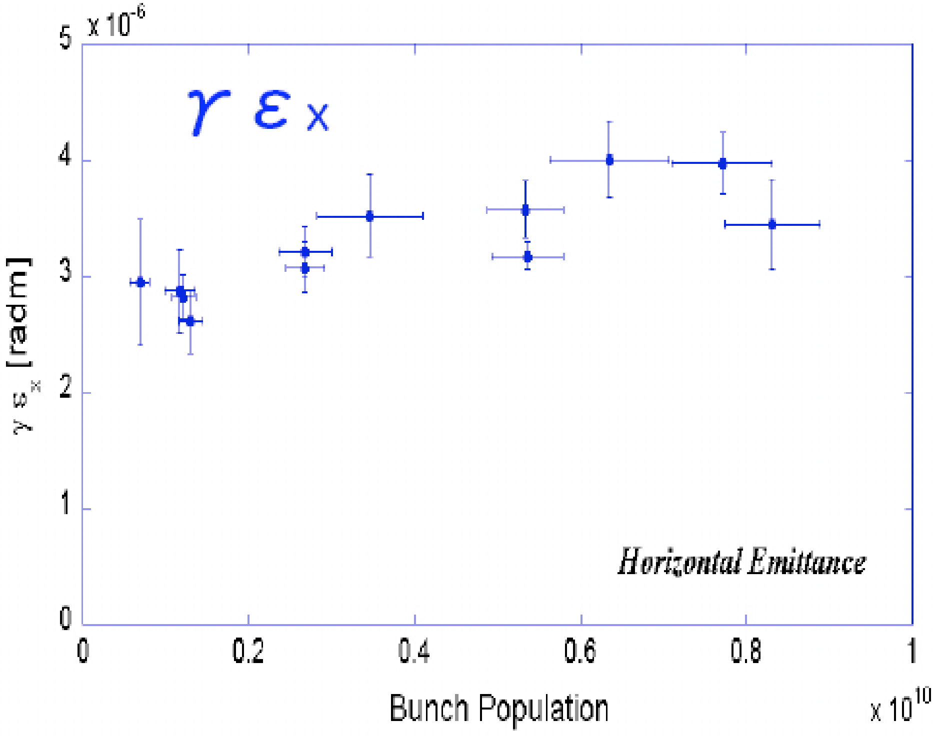


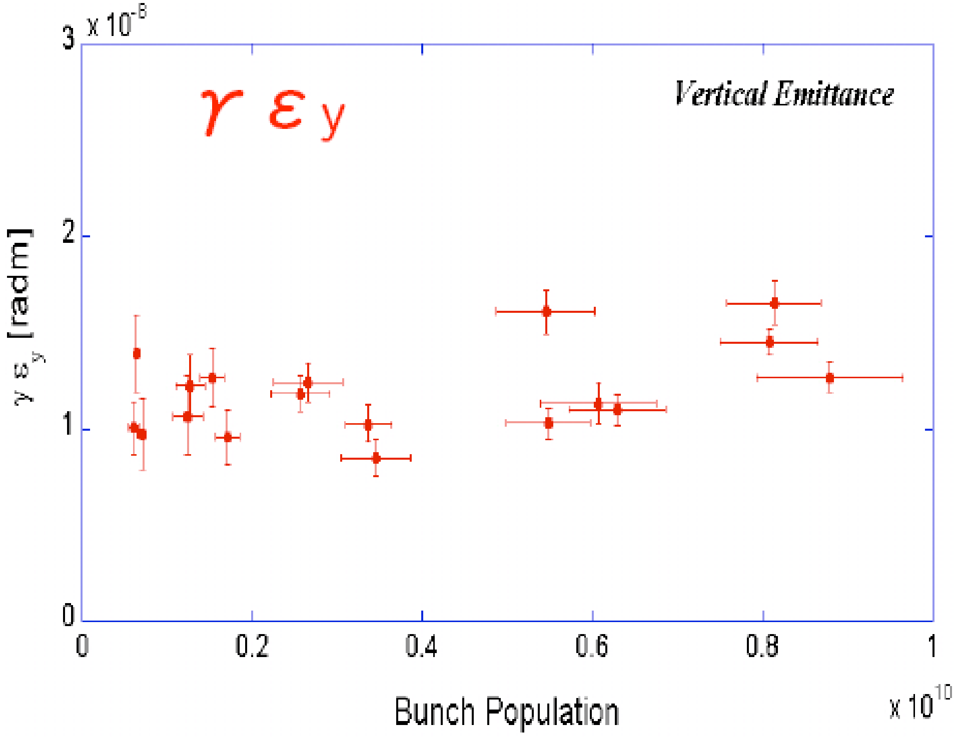
Linac

Control Room



Low emittance in ATF





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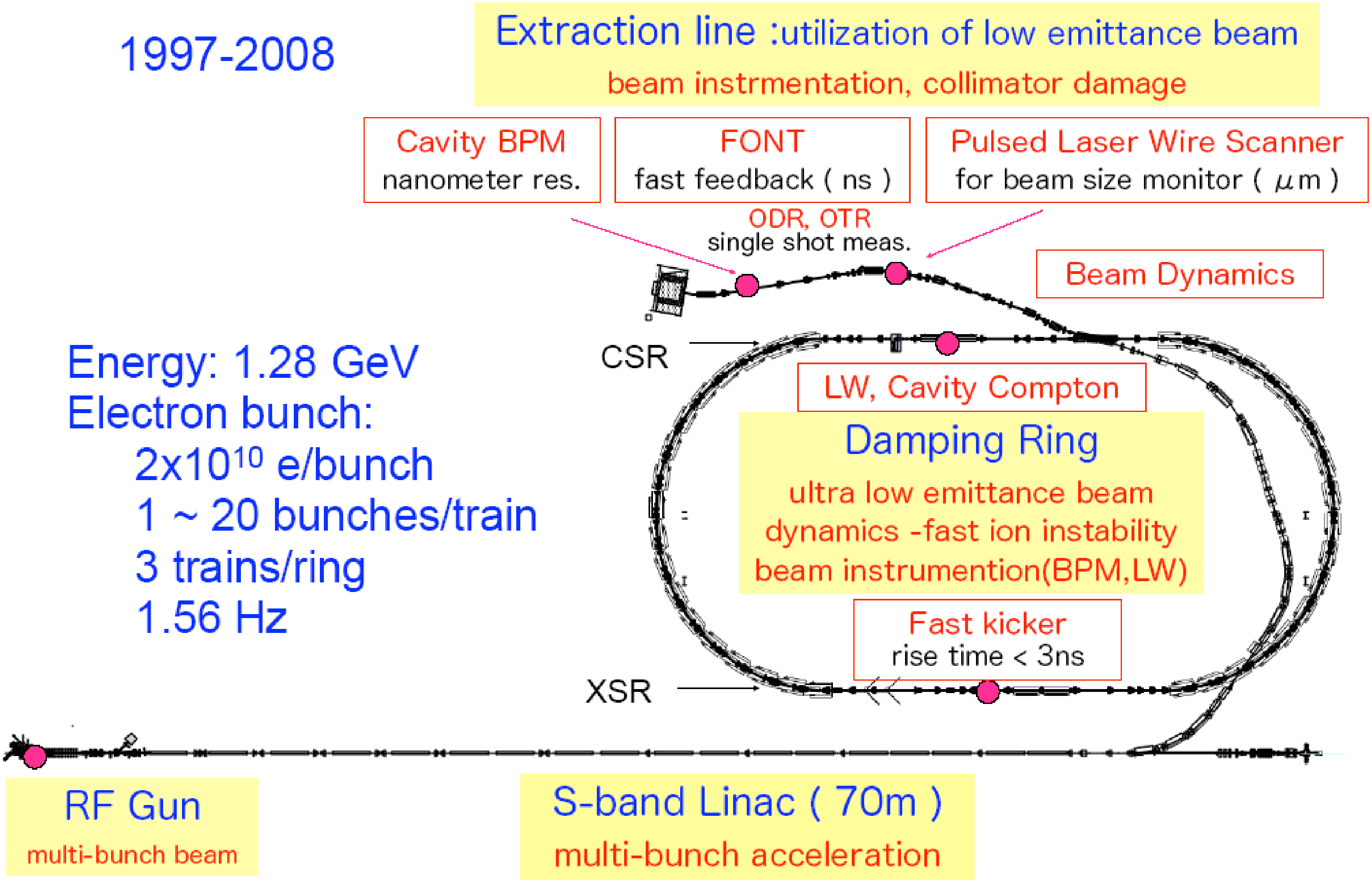
Accelerator Test Facility, KEK

1997-2008

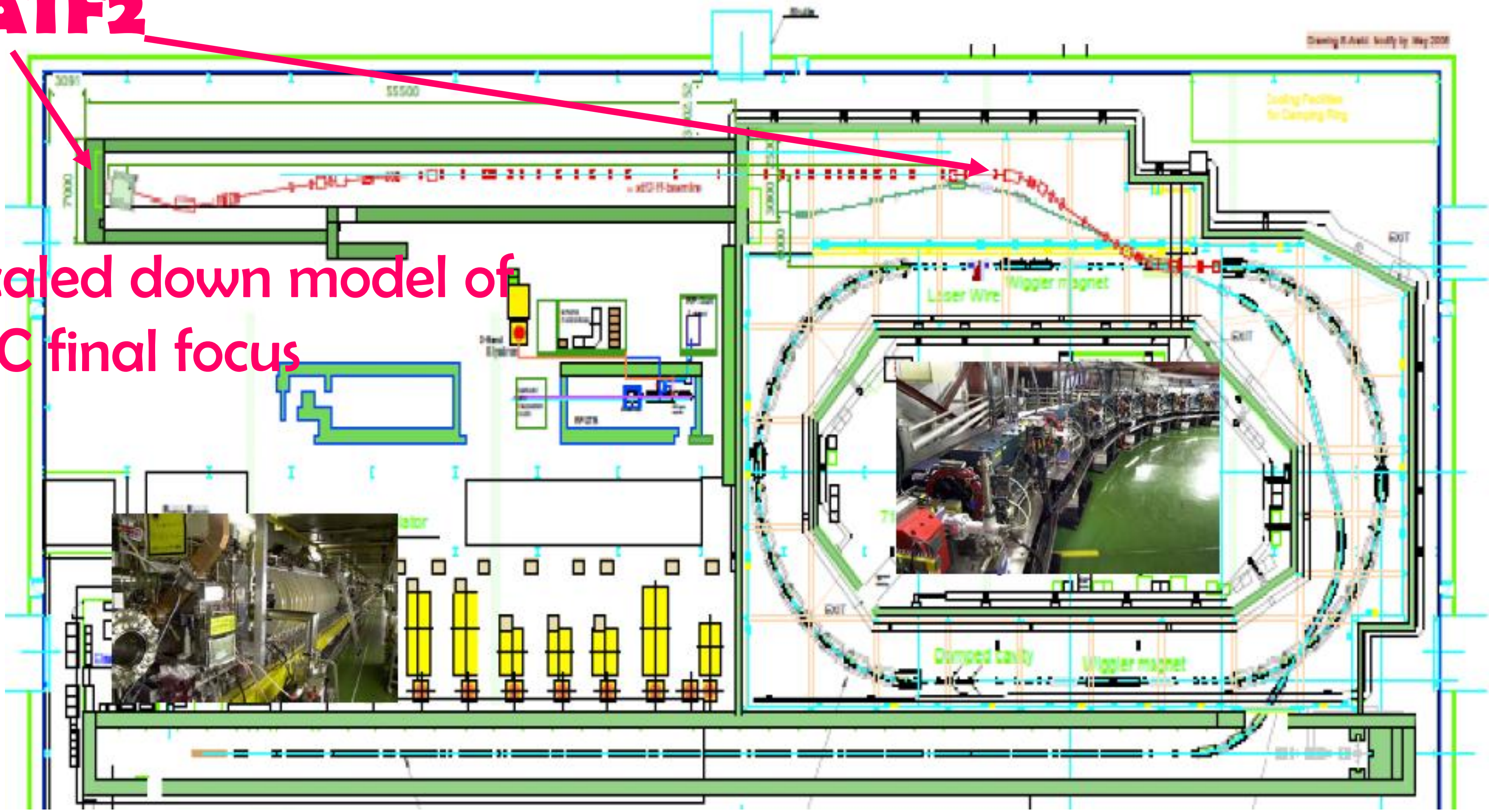
Energy: 1.28 GeV
Electron bunch:
- 2×10^{10} e/bunch
- 1 ~ 20 bunches/train
- 3 trains/ring
- 1.56 Hz



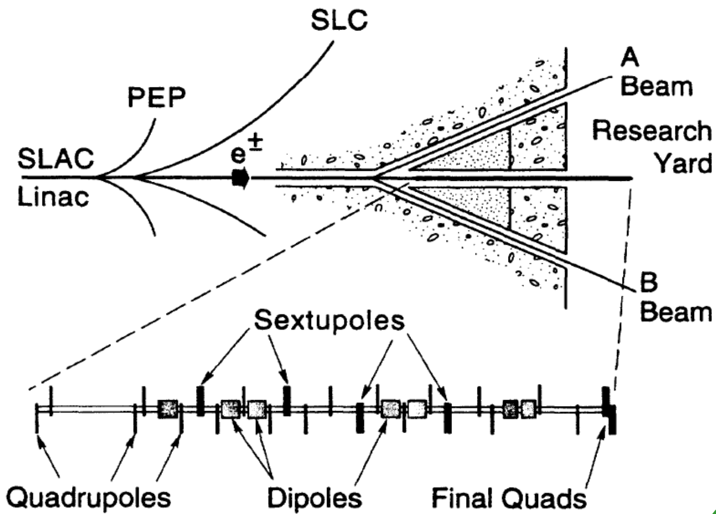
ATF
Accelerator Test Facility at KEK

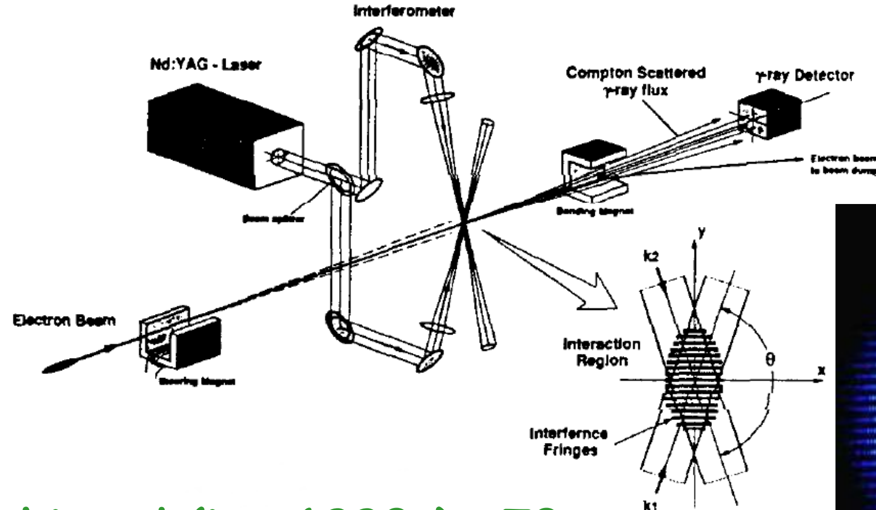
ATF2

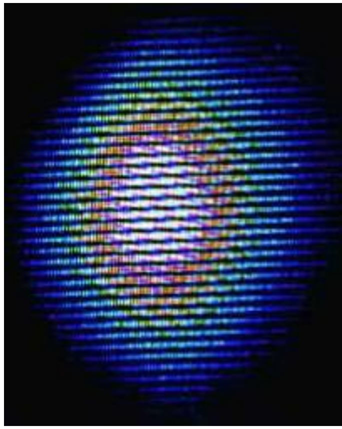
Scaled down model of ILC final focus



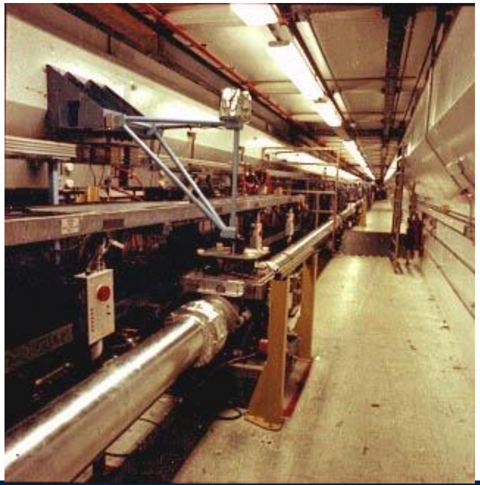
Final Focus Test Beam –
optics with traditional non-local chromaticity compensation

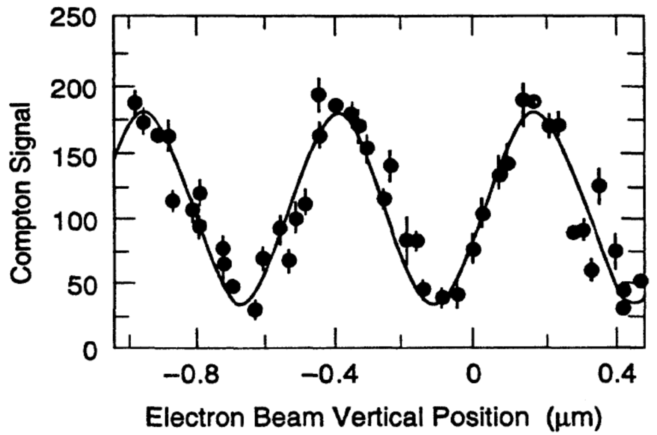






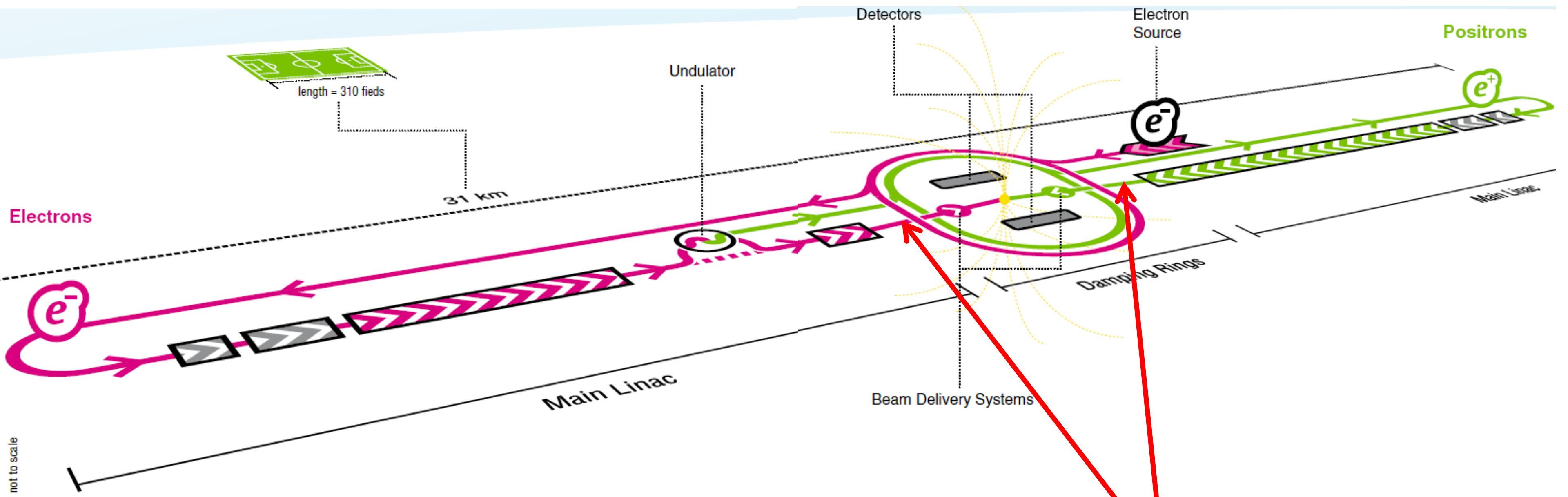
Achieved (in ~1990s) ~70nm vertical beam size





ILC BDS: from end of linac to IP

International Linear Collider

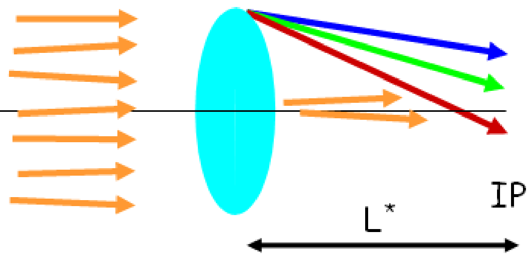


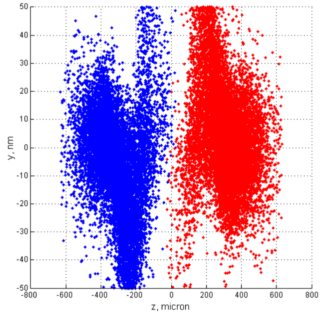
Beam Delivery System (BDS)

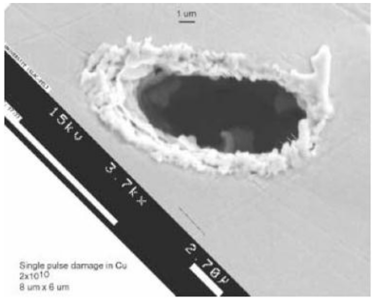
BDS includes:
Final Focus (FF), Collimation System, Diagnostic Section, Extraction line, etc.

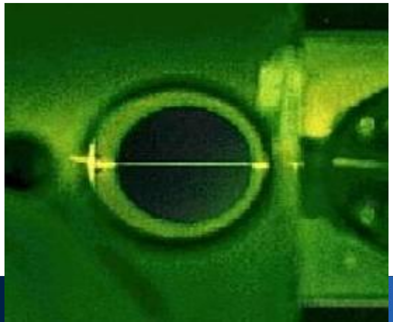
Factors driving design of BDS

- Final Doublet chromaticity
  - local compensation of chromaticity
- Beam-beam effects
  - background, IR and extraction design
- SR emittance growth in BDS bends
  - weak and long
- Halo collimation
  - survivability of spoilers
- Beam diagnostics
  - measurable size at laser wires
- ...



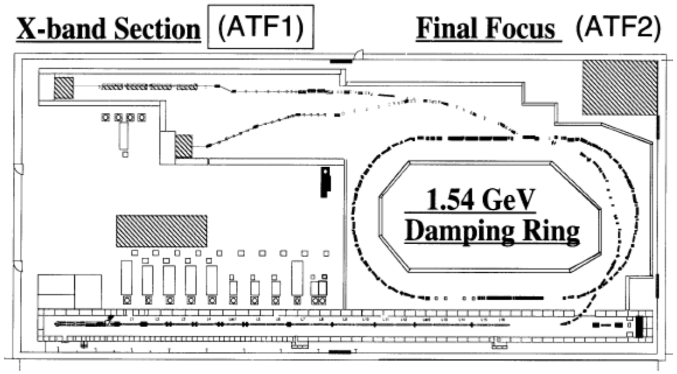






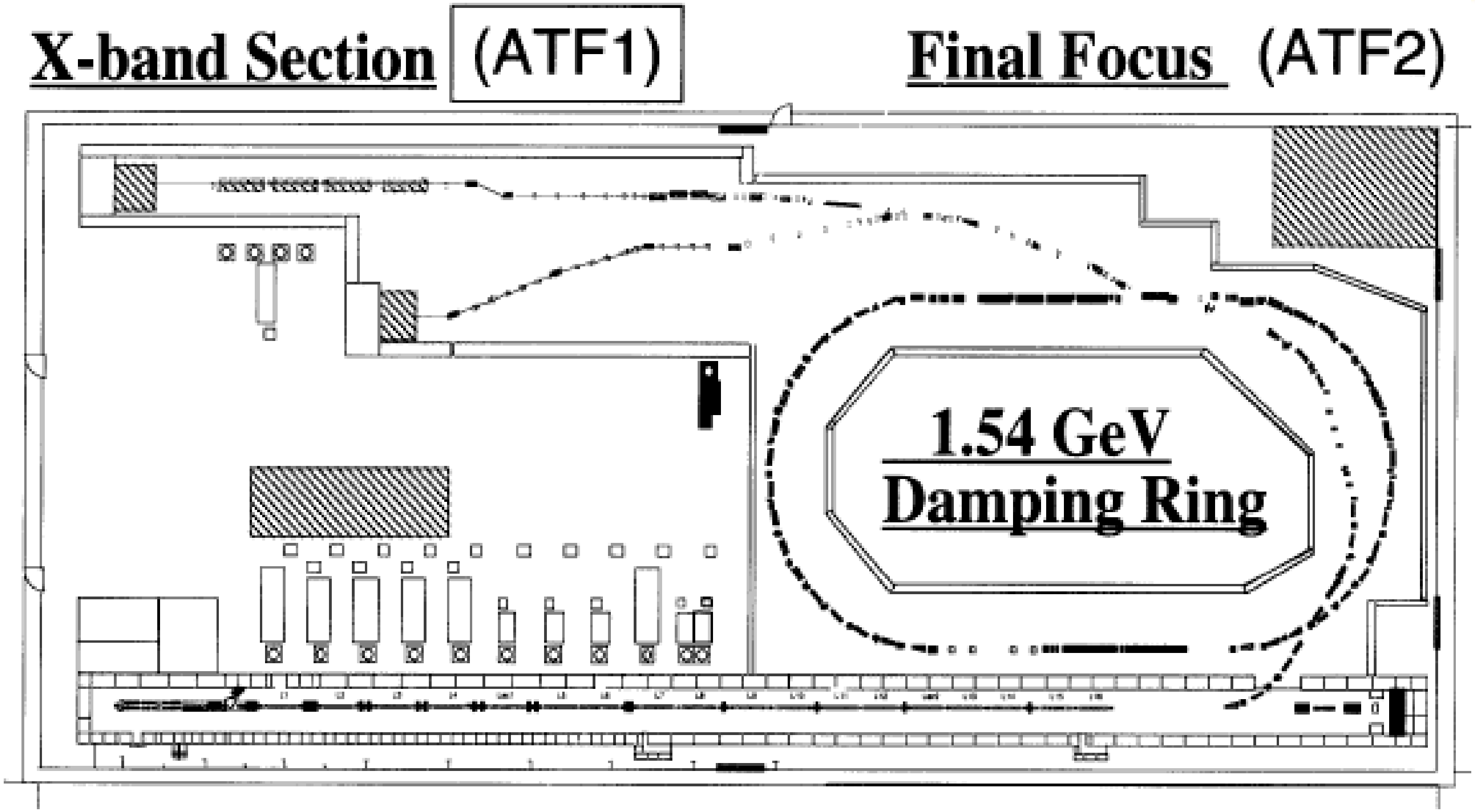
ATF2

- The idea of a new test facility at ATF, to prototype the **advanced final focus, for linear collider**, was conceived in **2002** at Nanobeam workshop in Lausanne
- Idea evolved, and has now been realized in iron and concrete



Early scheme presented by Junji Urakawa

- ATF2 goals
  - prototype ILC Final Focus system
  - develop FF tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs)
  - learn achieving ~37nm size & ~nm stability reliably
- ATF2 final goal – help to ensure collisions of nanometer beams, i.e. luminosity of ILC



Early scheme as presented by
Junji Urakawa at Nanobeam 2002

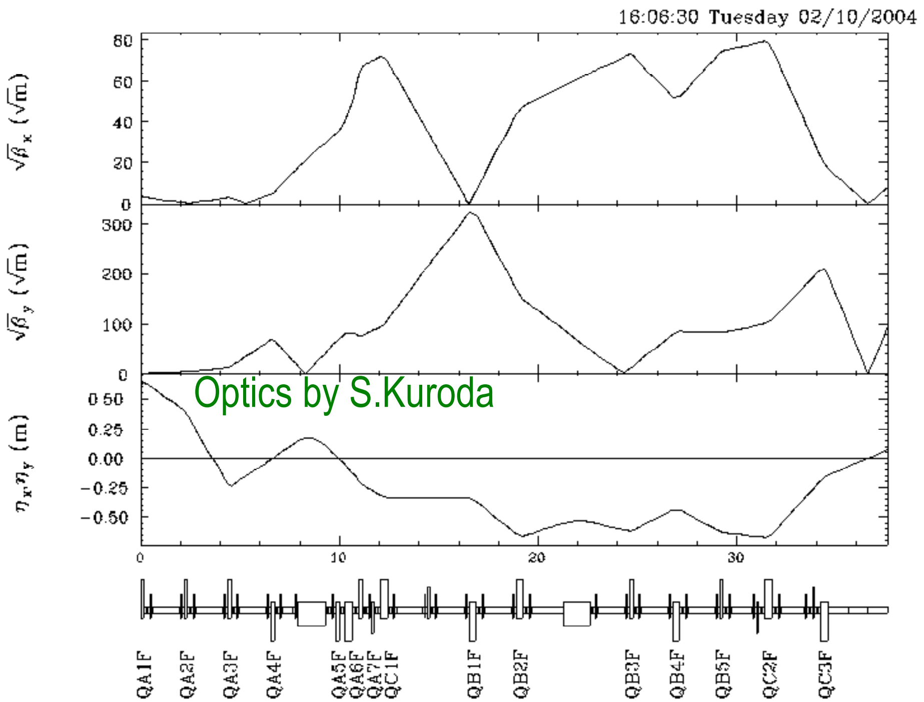
ATF2 major milestones

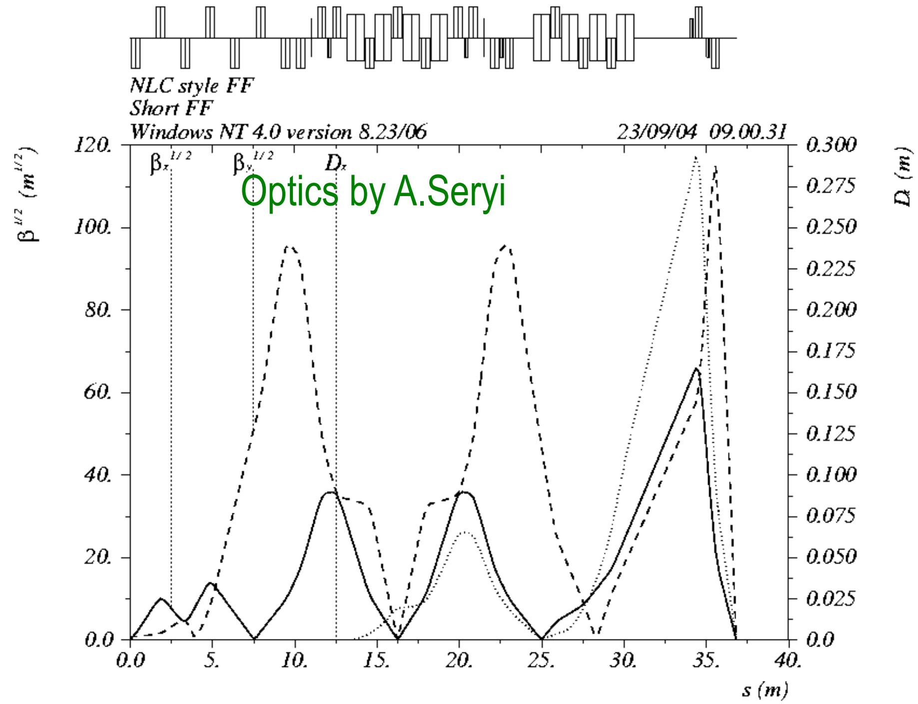
- September 2002, Nanobeam workshop, Lausanne
  - idea of new Final Focus test facility at ATF
- January 2005, SLAC, first ATF2 workshop
  - compared two optics versions, selected ILC-like design
  - stated the need to document the Proposal
- May 2005, ATF2 mtg at KEK
  - collaboration organization & MOU, task sharing, 1st version of schedule (commissioning start range: 02.2007-02.2008)
- August 2005
  - ATF2 Proposal, Vol.1 (technical description) released

ATF2 Proposal: 110 authors, 25 institutions

- February 2006, SLAC, 1st ATF2 Project Meeting
  - ATF2 Proposal, Vol.2 (organization, cost & contributions) released
- May 2006, KEK, 2nd ATF2 Project Meeting …
  - detailed design & role sharing
- … May 2008, BINP Novosibirsk, 6th ATF2 Project Meeting
  - Review of construction status and commissioning readiness
- … *To date: 14 ATF2 Project Meetings*

Optics considered for ATF2 in 2005



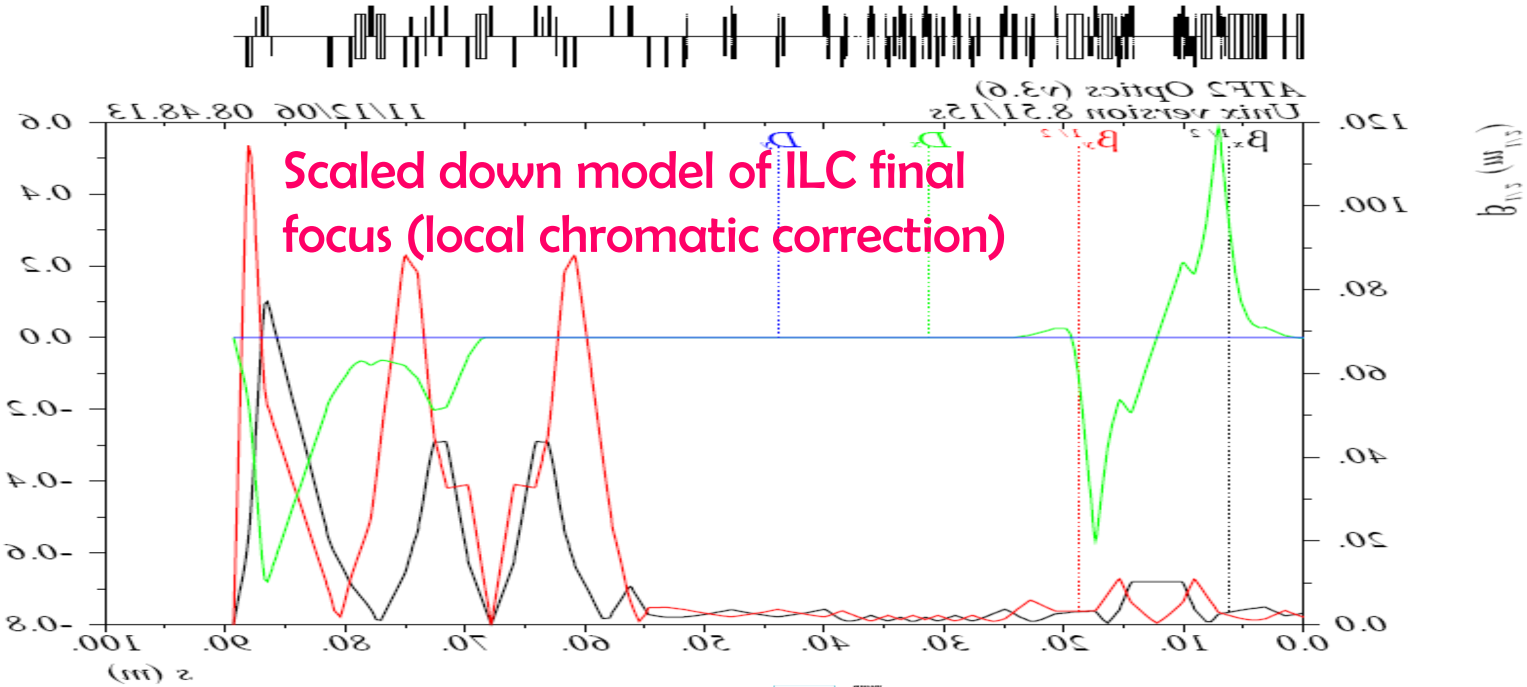


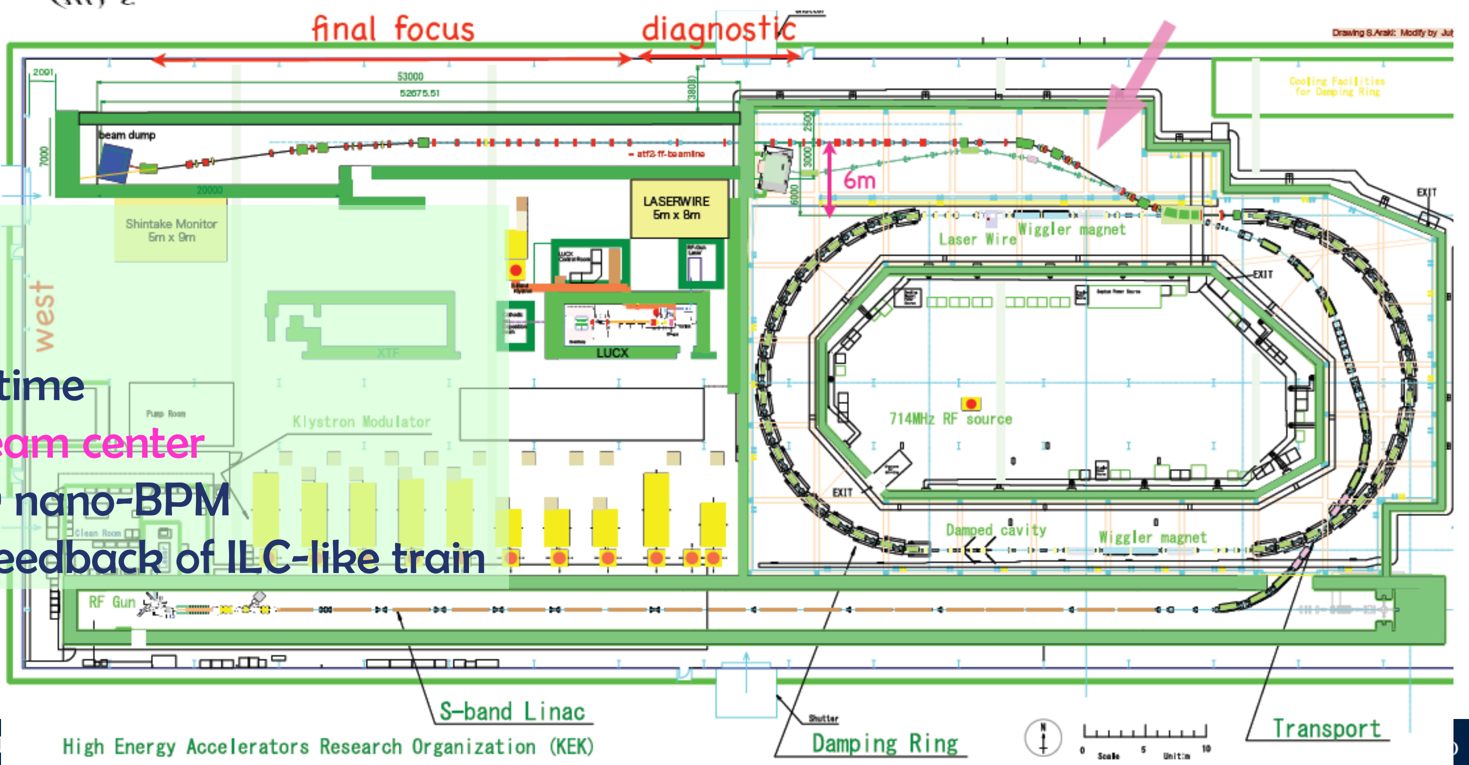
Optics with L*=1m, and IP β_x=4mm, β_y=0.1mm (same Y chromaticity as present ILC parameters)

Parameters used

$\gamma\varepsilon_x$=3e-6 m , $\gamma\varepsilon_y$=3e-8 m, E=1.54 GeV

ATF2 – model of ILC BDS

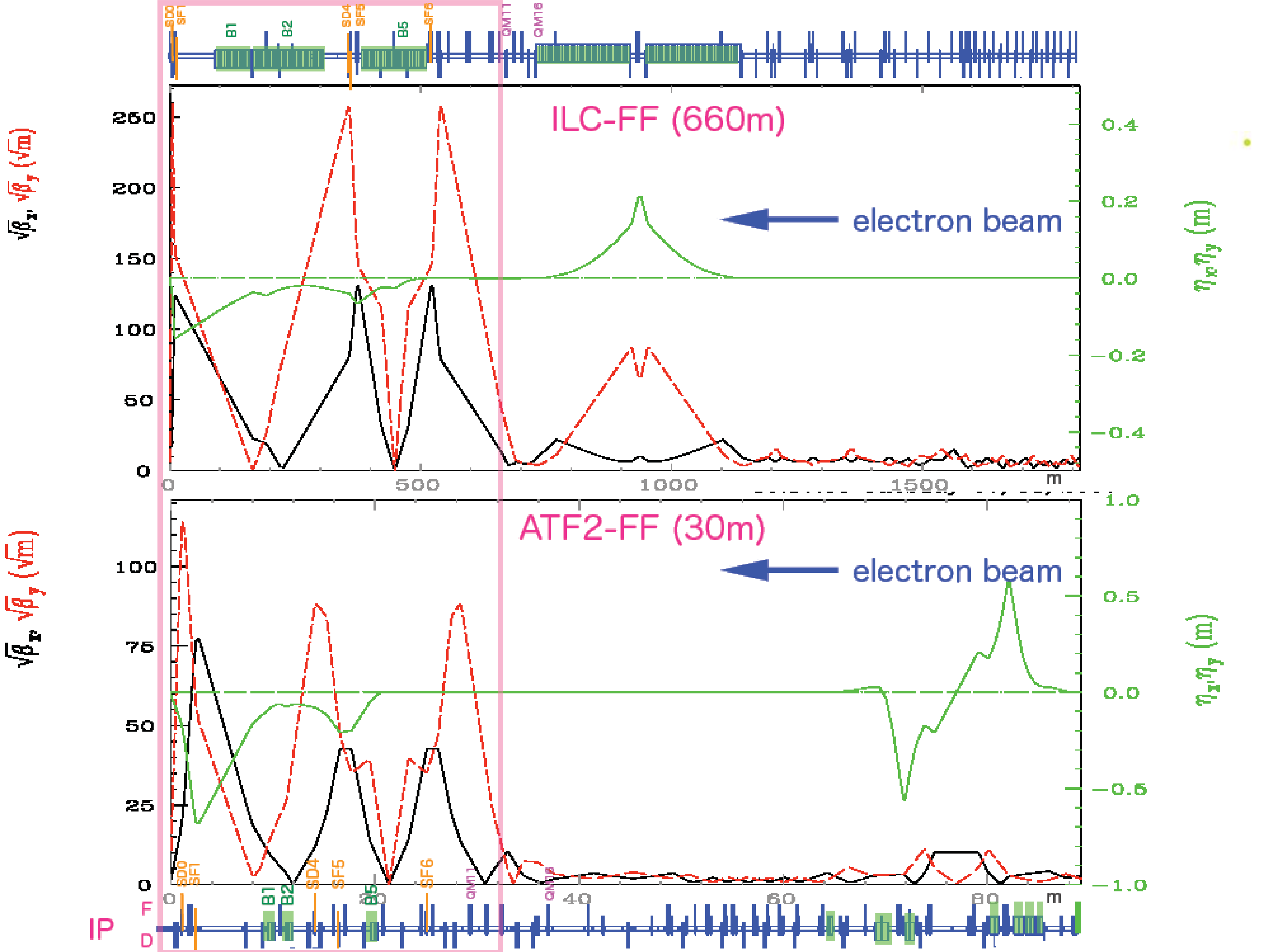




ATF2 goals

(A) Small beam size
- Obtain σ_y ~ 35nm
- Maintain for long time

(B) Stabilization of beam center
- Down to < 2nm by nano-BPM
- Bunch-to-bunch feedback of ILC-like train

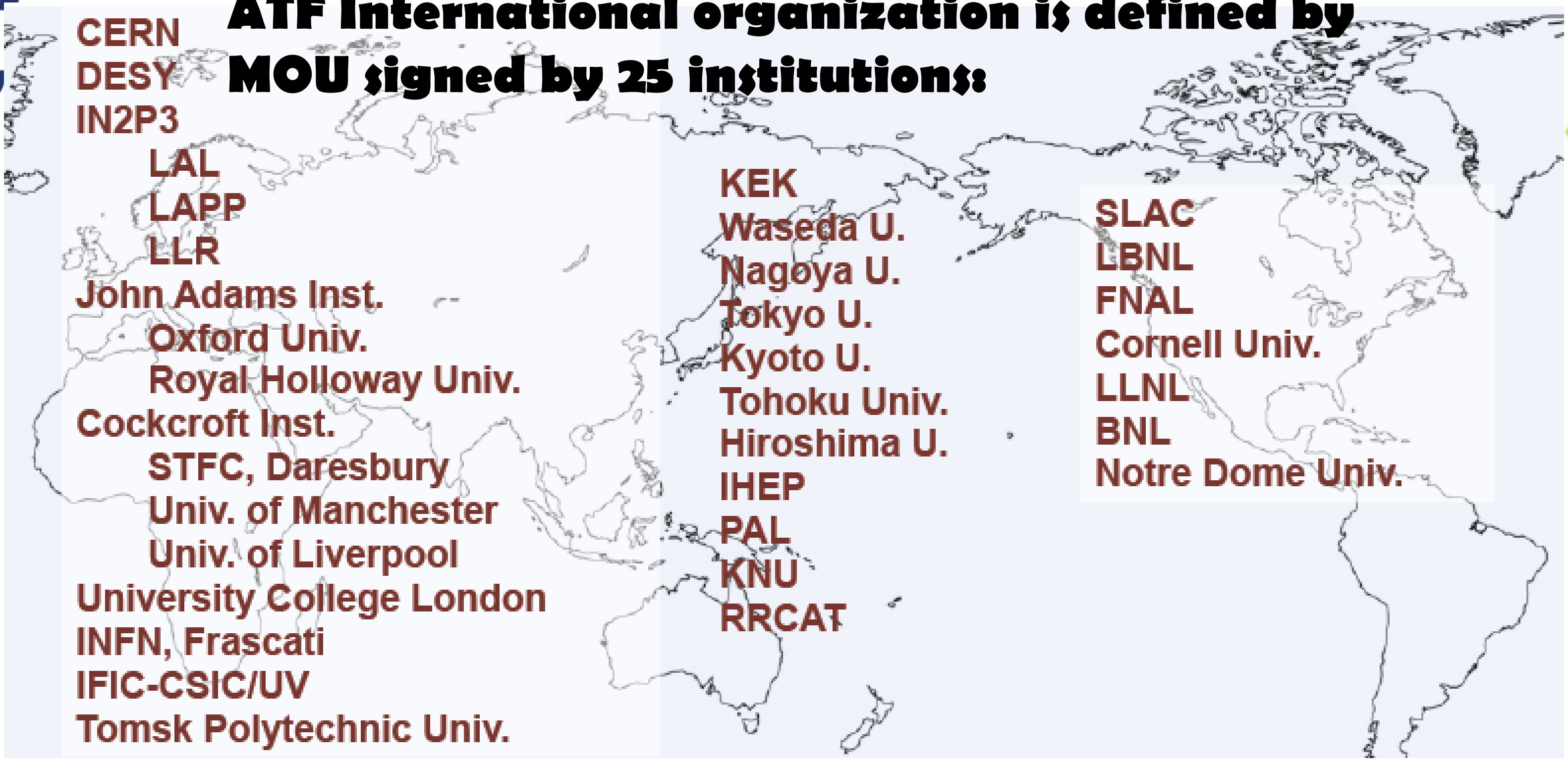


ILC-FF (660m)
electron beam
ATF2-FF (30m)
electron beam
SD0
SF1
B1
B2
SD4
SF5
B5
SF6
QM11
QM16
IP
F
D
m

ATF2 & ILC parameters

Parameters	ATF2	ILC
Beam Energy, GeV	1.3	250
L*, m	1	3.5-4.2
$\gamma\varepsilon_{x/y}$, m*rad	3E-6 / 3E-8	1E-5 / 4E-8
IP $\beta_{x/y}$, mm	4 / 0.1	21 / 0.4
IP η', rad	0.14	0.094
σ_E, %	~0.1	~0.1
Chromaticity	~1E4	~1E4
$n_{bunches}$	1-3 (goal A)	~3000
$n_{bunches}$	3-30 (goal B)	~3000
N_{bunch}	1-2E10	2E10
IP σ_y, nm	37	5

ATF International organization is defined by MOU signed by 25 institutions:



CERN
DESY
IN2P3
- LAL
- LAPP
- LLR

John Adams Inst.
- Oxford Univ.
- Royal Holloway Univ.

Cockcroft Inst.
- STFC, Daresbury
- Univ. of Manchester
- Univ. of Liverpool

University College London
INFN, Frascati
IFIC-CSIC/UV
Tomsk Polytechnic Univ.

KEK
Waseda U.
Nagoya U.
Tokyo U.
Kyoto U.
Tohoku Univ.
Hiroshima U.
IHEP
PAL
KNU
RRCAT

SLAC
LBNL
FNAL
Cornell Univ.
LLNL
BNL
Notre Dome Univ.

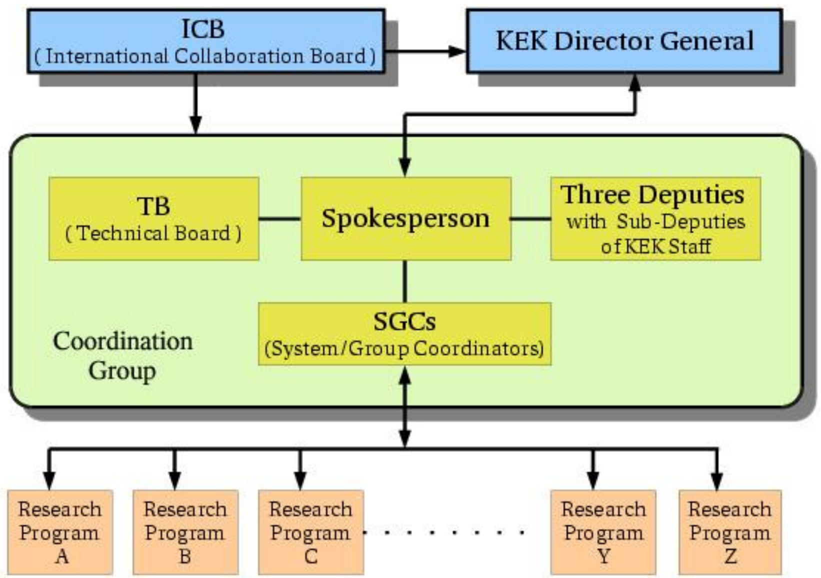
MOU: Mission of ATF/ATF2 is three-fold:

- ATF, to establish the technologies associated with producing the electron beams with the quality required for ILC and provide such beams to ATF2 in a stable and reliable manner.
- ATF2, to use the beams extracted from ATF at a test final focus beamline which is similar to what is envisaged at ILC. The goal is to demonstrate the beam focusing technologies that are consistent with ILC requirements. For this purpose, ATF2 aims to focus the beam down to a few tens of nm (rms) with a beam centroid stability within a few nm for a prolonged period of time.
- Both the ATF and ATF2, to serve the mission of providing the young scientists and engineers with training opportunities of participating in R&D programs for advanced accelerator technologies.

http://atf.kek.jp/

ICB: decision making body for executive matters related to the ATF collaboration (chair: Ewan Paterson, SLAC)

ATF International Collaboration



TB: assist the Spokesperson in formulating the ATF Annual Activity Plan, including the budget and beamtime allocation and assist the ICB in assessing scientific progress. (co-chairs: A.Wolski, CI, E.Elsen, DESY)

Spokesperson:
direct and coordinate the work required at ATF/ATF2 in accordance with the ATF Annual Activity Plan, report the progress to ICB and the progress and the matters related to KEK budget to director of KEK
(Junji Urakawa, KEK):

Org. snapshot ~2010

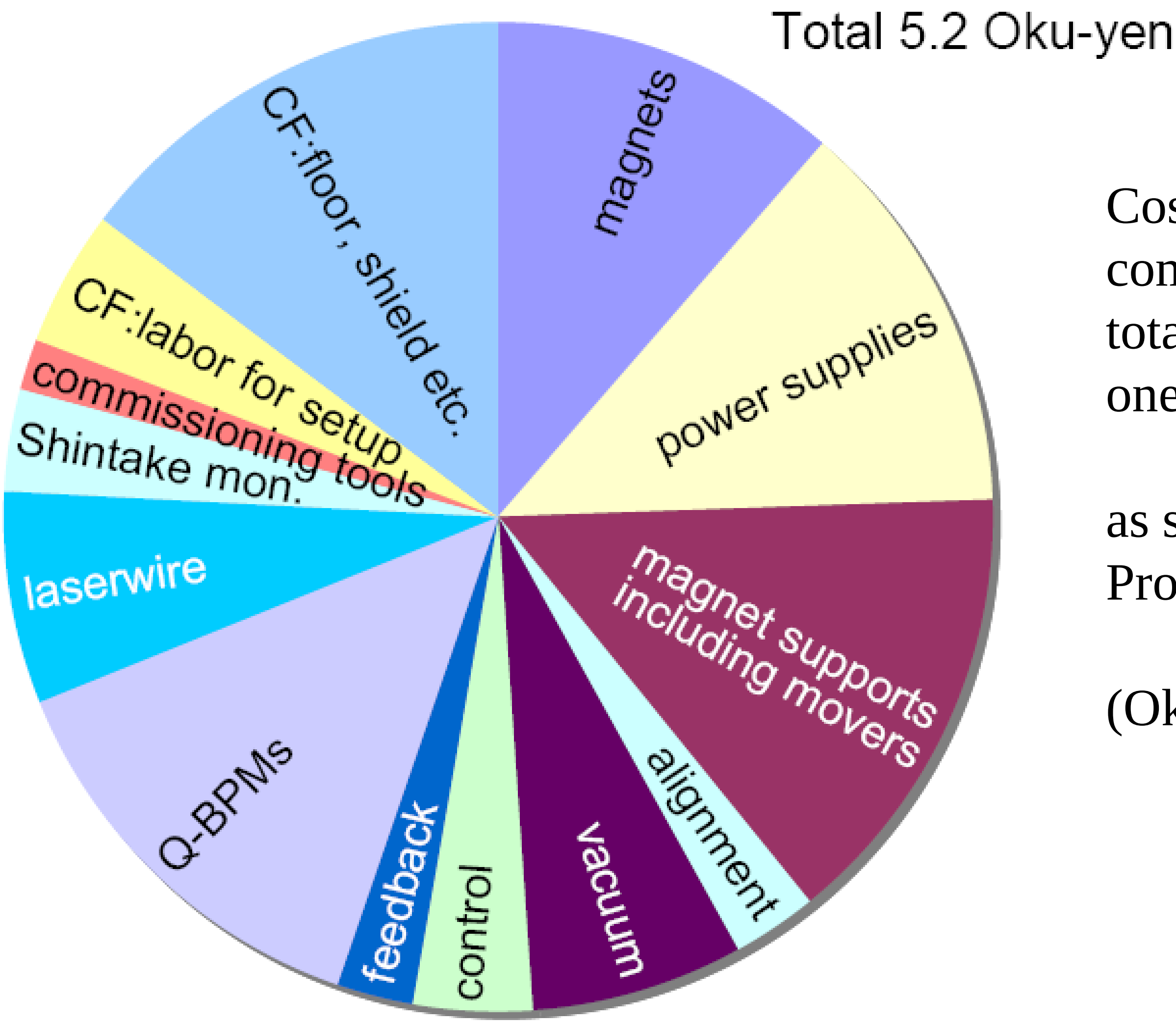
Deputies of Spokesperson: carry out tasks in the areas of

- Beam operation (Shigeru Kuroda, KEK)

- Hardware maintenance (Nobuhiro Terunuma, KEK)

- Design, construction and commissioning of ATF2 (Andrei Seryi, SLAC)

ATF2 cost



Cost distribution of the components normalized by the total cost, where the in-kind ones are also included

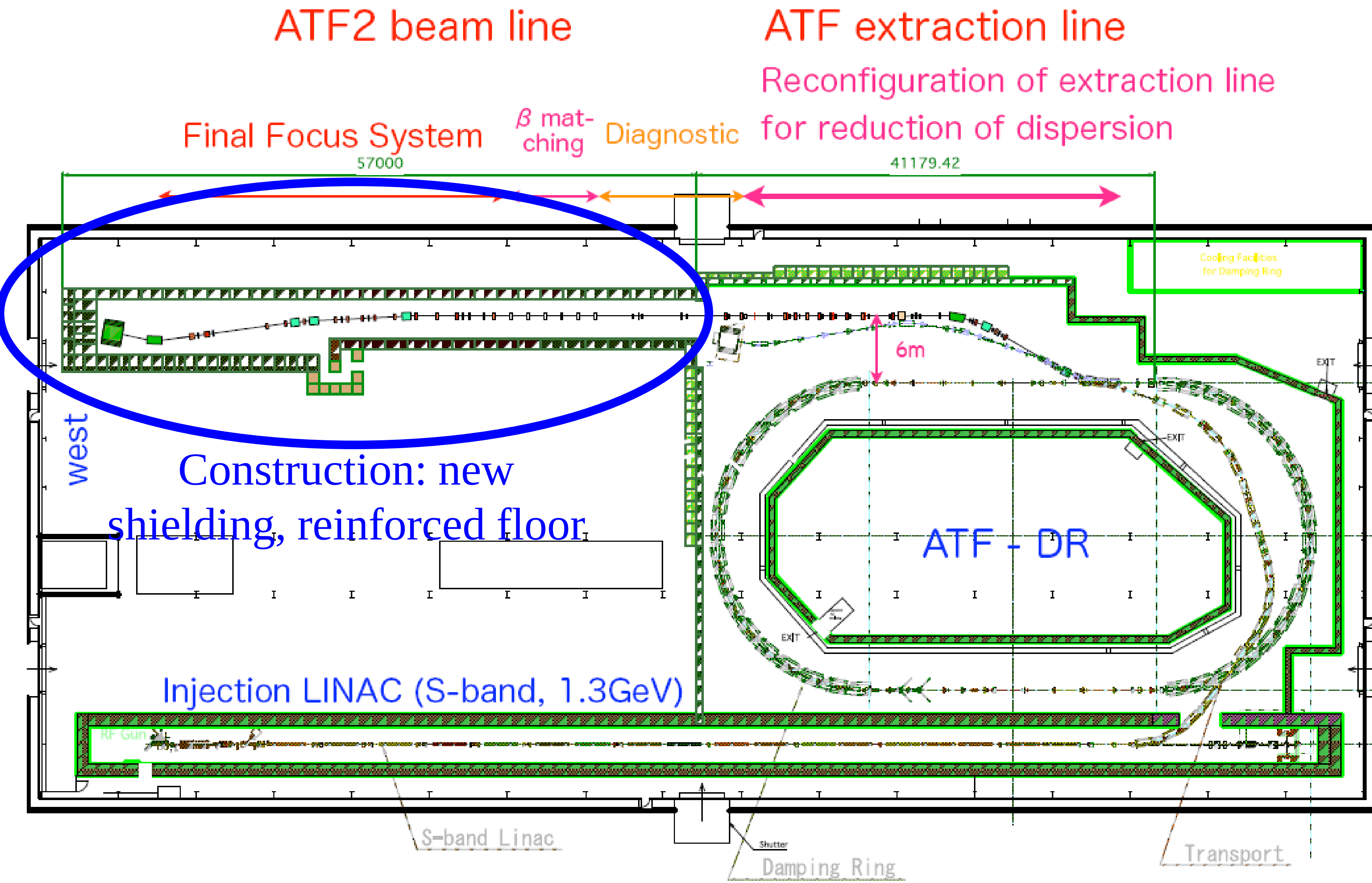
as seen in mid 2005 (from ATF2 Proposal, Volume 2)

(Oku-yen is 100*1E6 yen)

Japanese Fiscal year	JFY2005												JFY2006												JFY2007											
	2005									2006												2007												2008		
Activity	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
Beam operation	ATF							ATF				ATF							ATF					ATF											ATF2	
Conventional Facilities																								preparation			floor			utility				shield		
Magnets							24-Q						test					5-Q, Bends (7), 6,8poles						test			Final doublet					test				
Magnet Support								support (44)										movers																		
Alignment																																				
Power supplies							prototype									production											test									
QBPM						prototype				prodction-1				production-2					test at KEK																	
IP-BPM							prototype						test						support system							production										
Shintake monitor (BSM)					modification to the half wavelength ; i.e. 532nm with precise phase control																										test at KEK					
Laserwire								R&D at ATF-extraction																				production								
Other instrumentation																																				
Feedforward & FONT4/5								R&D and production																							test at KEK					
Vacuum																																				
Cable plant																																				
Control system																																				
Installation																																				
Funding Process								JFY2006							call for UK fund					JFY2007												JFY2008				

Outline of the ATF2 time schedule, as seen in mid 2005 (from ATF2 Proposal, Volume 2)

Layout & civil construction



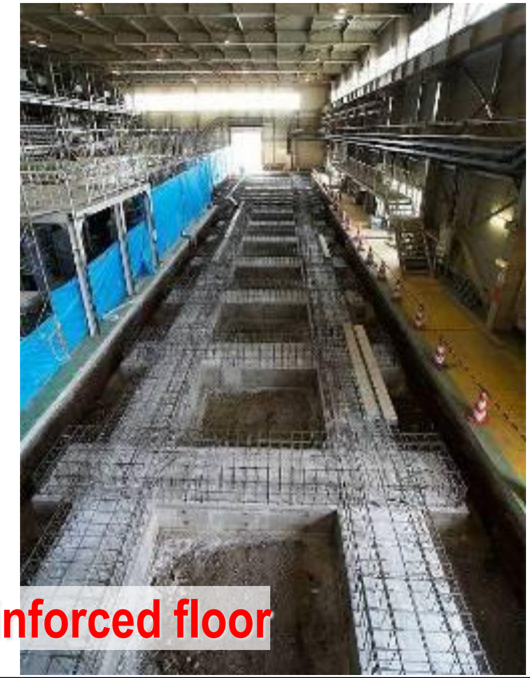
JAI Imperial College London Royal Holloway University of London University of Oxford

ATF2 construction in 2007 Aug – Dec


Assembly hall before construction


Assembly hall emptied for construction

Photos:
Nobu Toge



Construction of reinforced floor


Construction of shielding

ATF2 floor piles

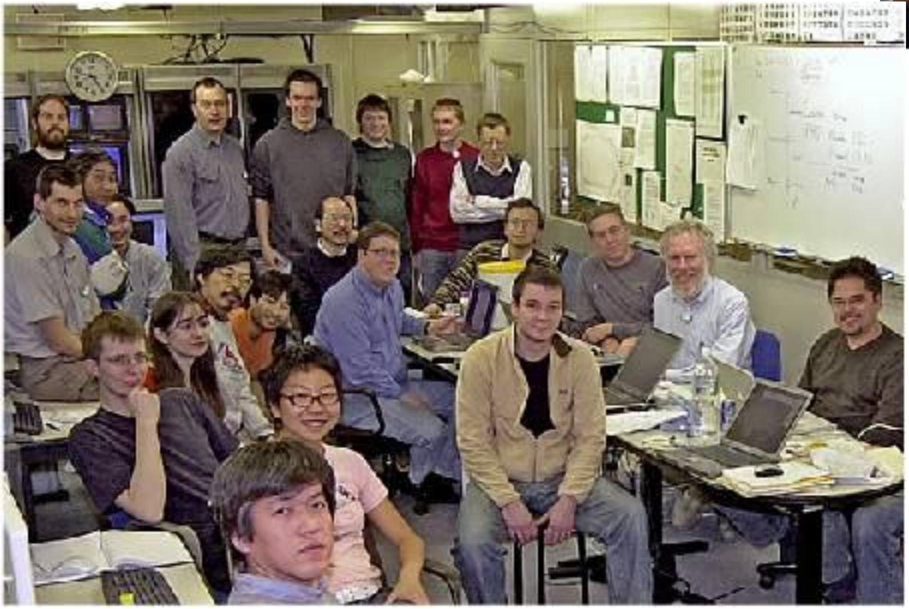
~ 13m x 38 sets

ATF2 floor base structure

Finalizing the ATF2 floor

ATF collaboration & ATF2 facility

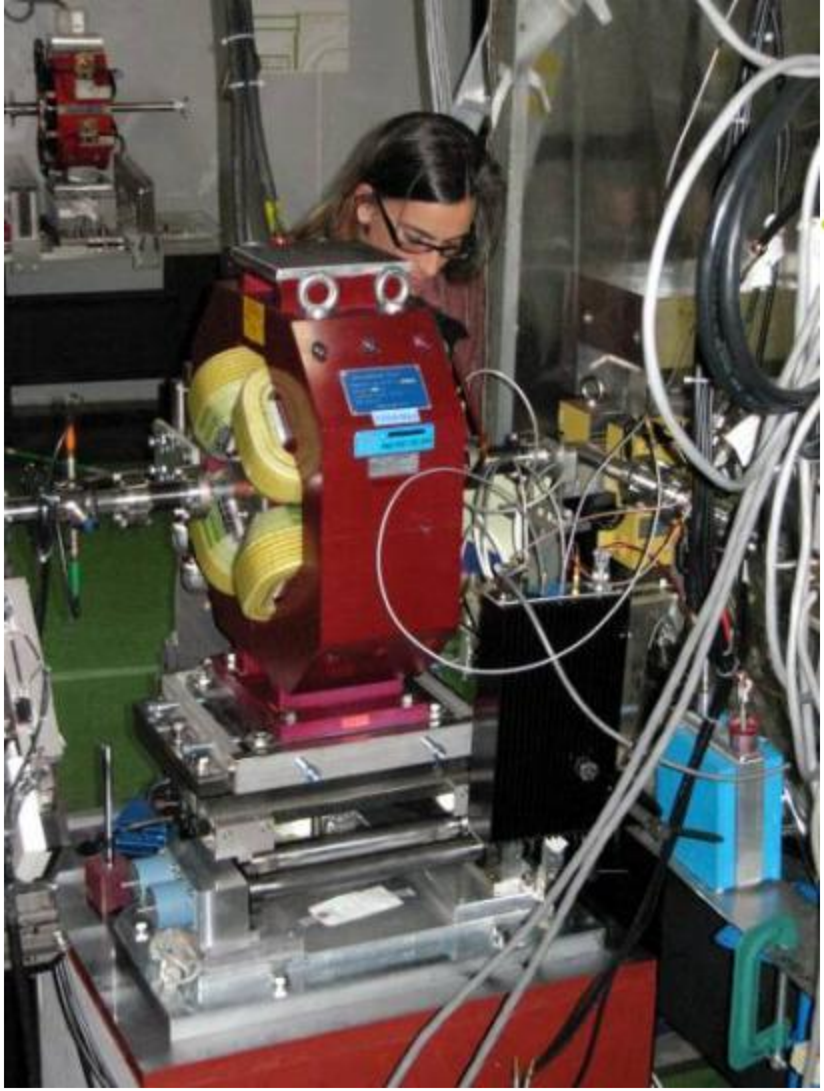
- ATF2 will prototype FF,
- help development tuning methods, instrumentation (laser wires, fast feedback, submicron resolution BPMs),
- help to learn achieving small size & stability reliably,



- ATF2 is one of central elements of BDS EDR work, as it will address a large fraction of BDS technical cost risk.
- **Constructed as ILC model, with in-kind contribution from partners and host country providing civil construction**

ATF & ATF2

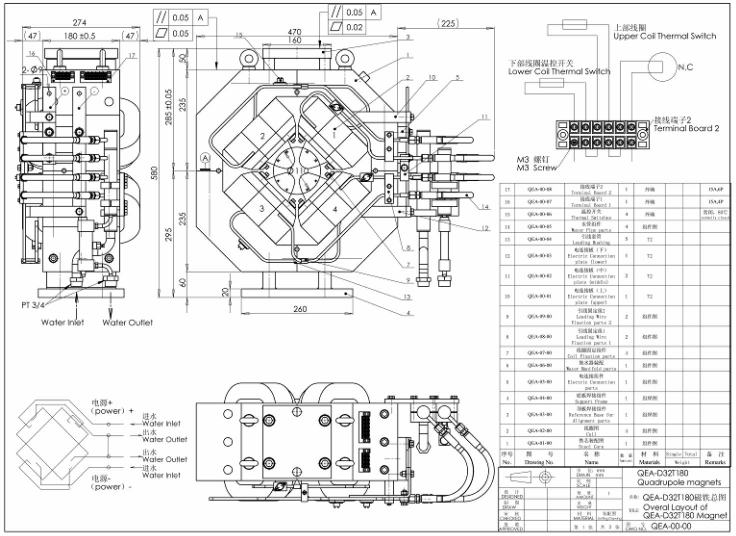
J.Nelson (at SLAC) and T.Smith (at KEK) during recent "remote participation" shift. Top monitors show ATF control system data. The shift focused on BBA, performed with new BPM electronics installed at ATF by Fermilab colleagues.



T.Smith is commissioning the cavity BPM electronics and the magnet mover system at ATF beamline

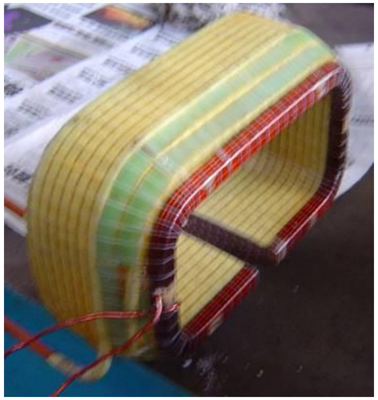
Power Supplies and Magnet system

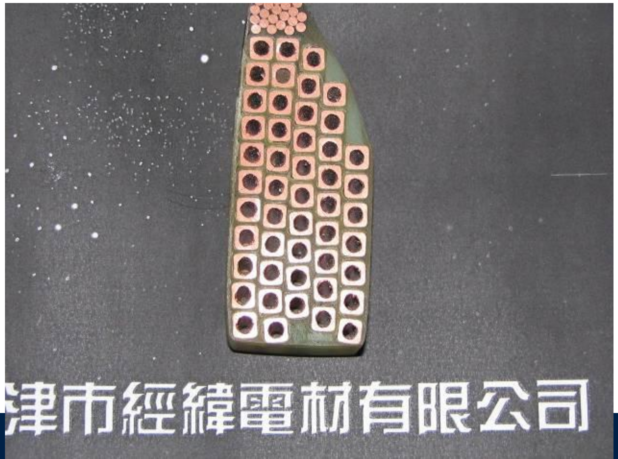
SLAC-built High Availability Power Supplies installed, connected and tested at ATF2

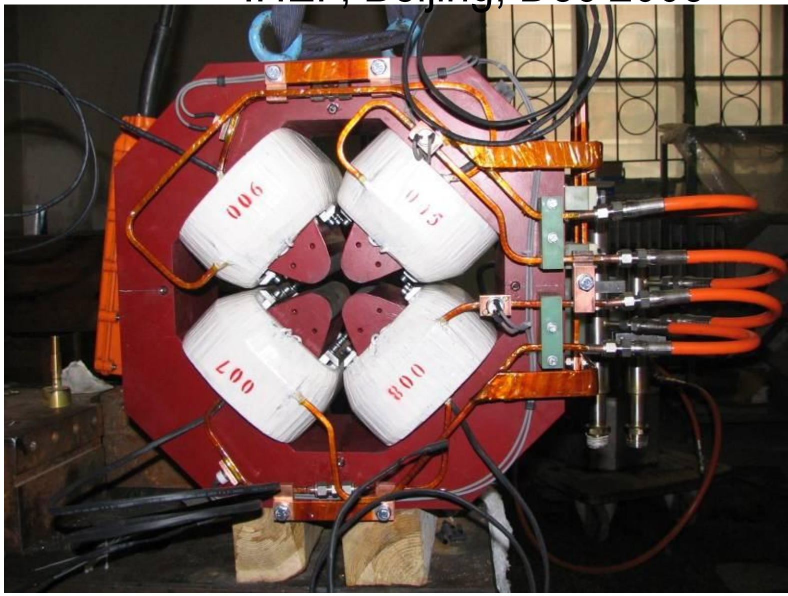


C.Spencer (SLAC) at IHEP, Beijing, Dec 2005

Beamline quads: SLAC / IHEP design, QC / production, measurements

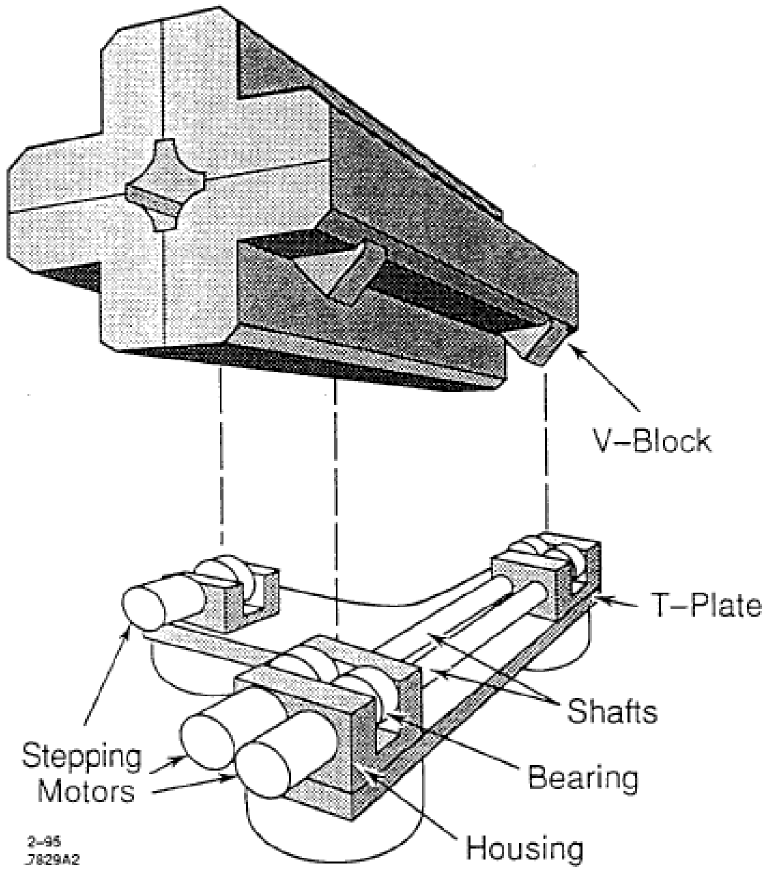


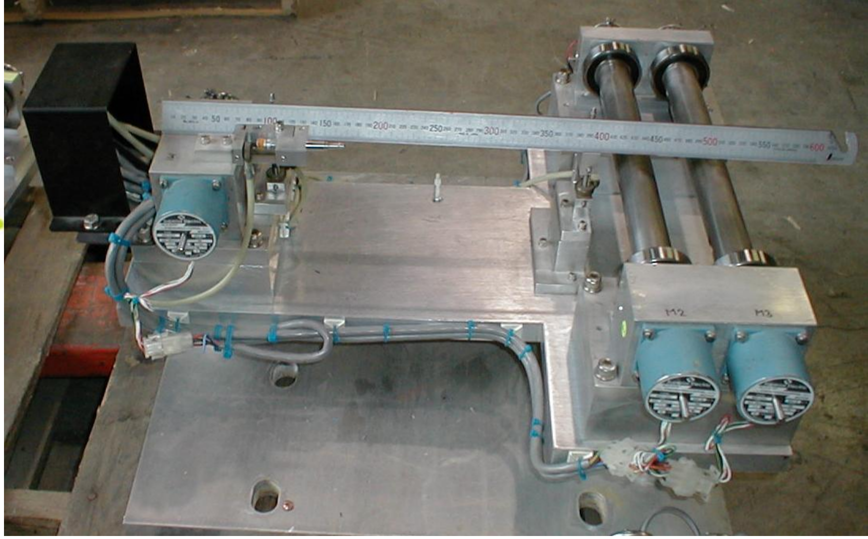




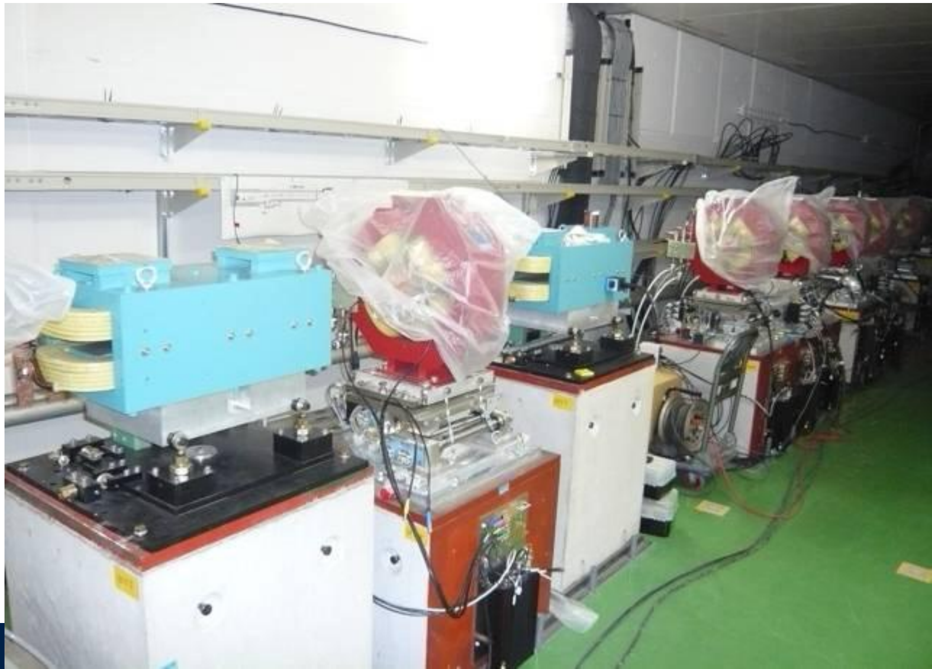
First ATF2 quad, Jan 2006

Beamline movers





- FFTB cam movers were refurbished and used for all and magnets of ATF2 (except bends)



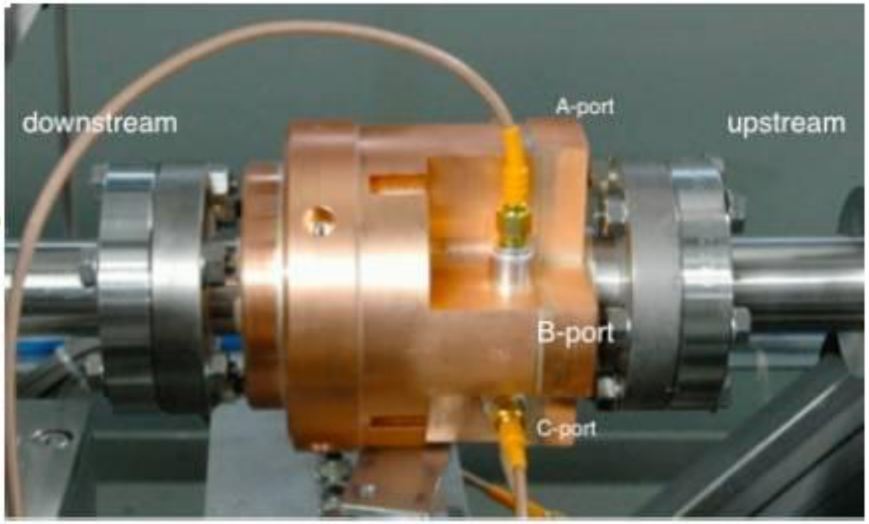
ATF2 construction – January 2008

The last regular quadrupole is going to the destination

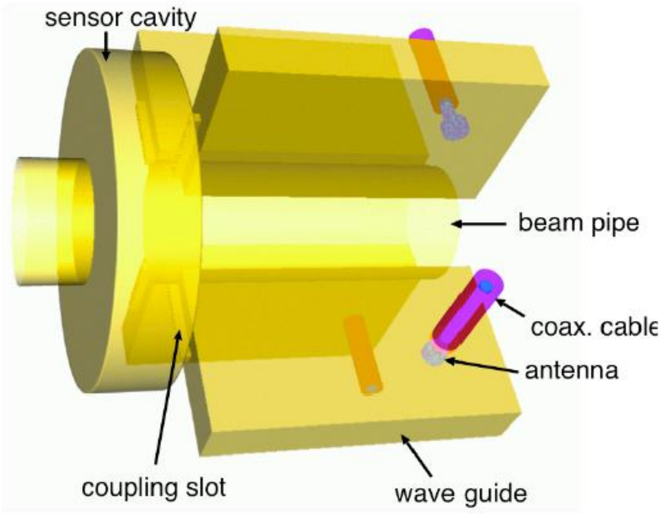
~20 sets of supports, movers & quads were installed in January. R.Sugahara et al

Cavity BPMs

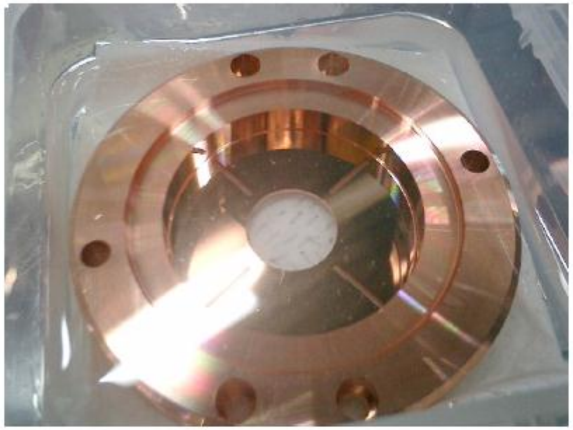
ATF2 beamline magnets equipped with cavity BPMs



Prototype at PAL



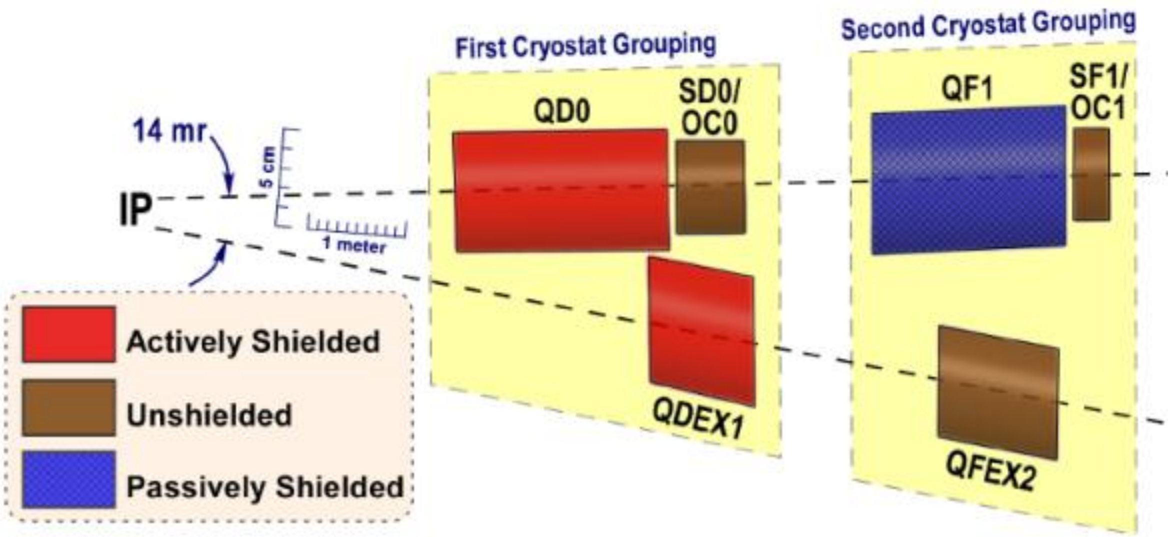
C-band
Sub 100 nanometer resolution
Large dynamic range >500um



Cavity BPMs

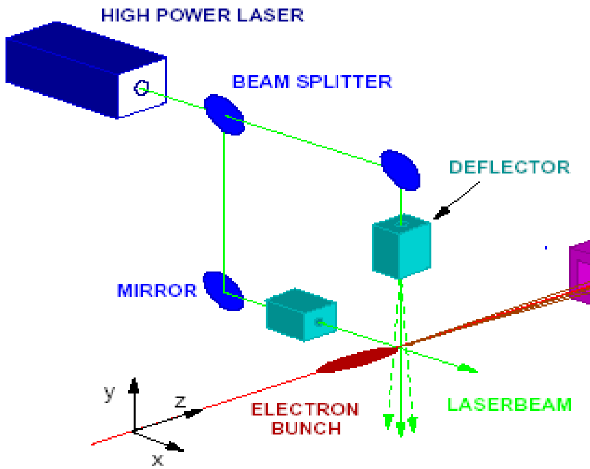
Cavity BPMs and SLAC front-end electronics modules provide sub-micron resolution of beam position

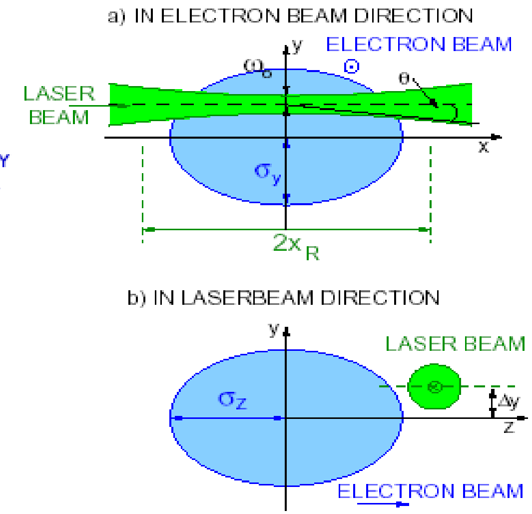
ATF2 final doublet



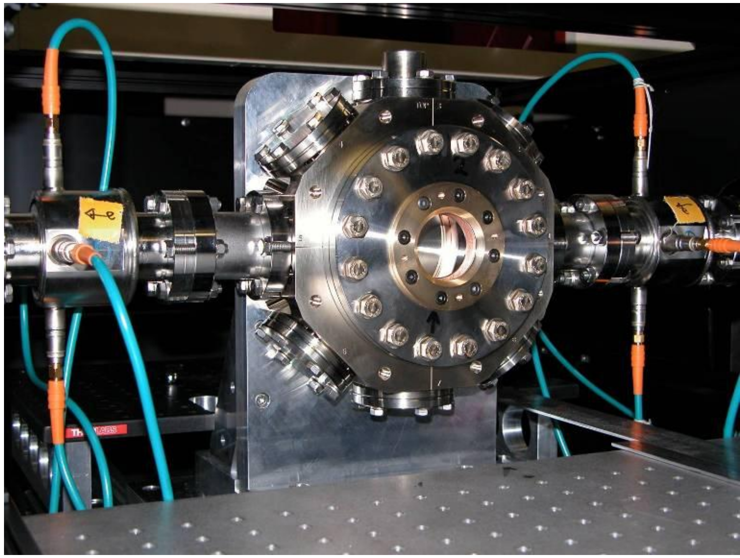
ILC Final Doublet layout

Laser wires





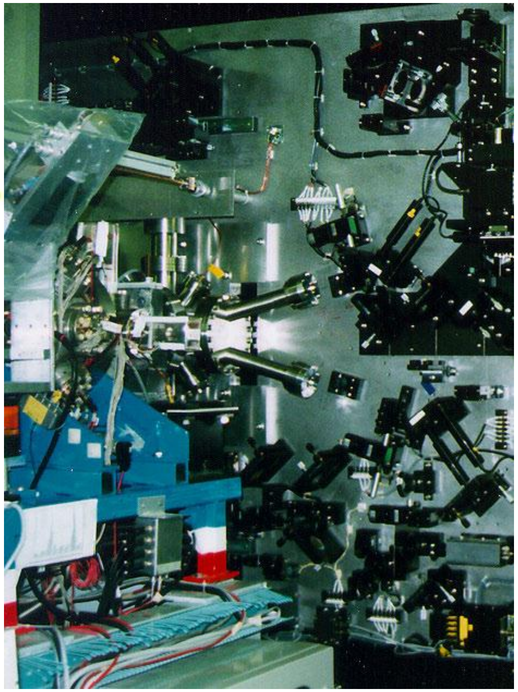
- Goal: non-destructive diagnostics for ILC
- (ATF2 is tuned with carbon wires and OTRs)
- Studies in ATF extraction line
- Aim to measure 1 μm spot beam
- Aim at 150ns intra-train scan
- Located at ATF2 in a place with μm spot
- Presently achieved resolution ~1μm



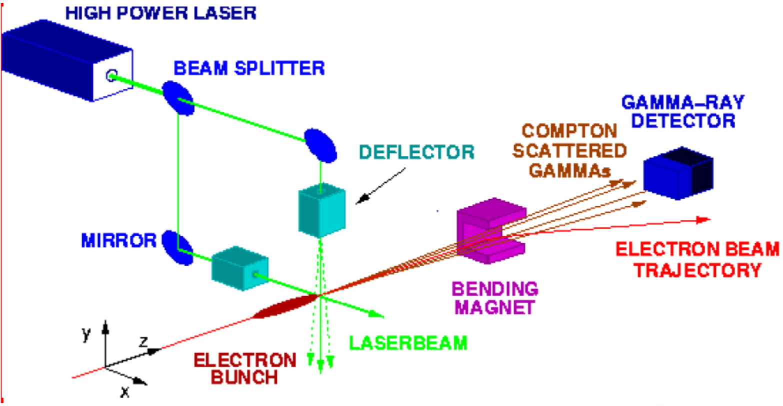
Laser wire chamber at ATF, JAI

Advanced beam instrumentation at ATF2

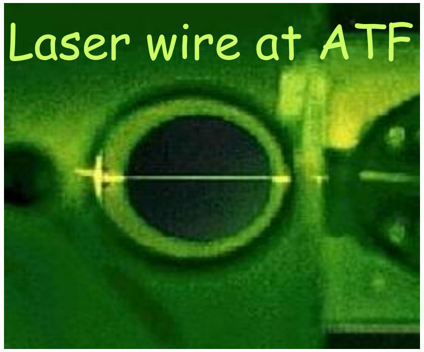
- BSM to confirm 35nm beam size
- nano-BPM at IP to see the nm stability
- Laser-wire to tune the beam
- Cavity BPMs to measure the orbit
- Movers, active stabilization, alignment system
- Intratrain feedback, Kickers to produce ILC-like train

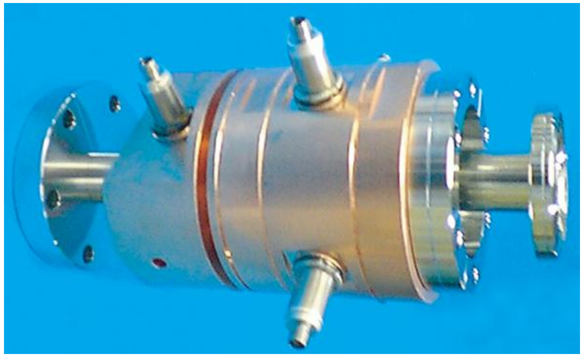


IP Beam-size monitor (BSM) (Tokyo U./KEK, SLAC, UK)



Laser-wire beam-size Monitor (UK group)





Cavity BPMs, for use with Q magnets with 100nm resolution (PAL, SLAC, KEK)

Cavity BPMs with 2nm resolution, for use at the IP (KEK)

Magnets and Instrumentation at ATF2

22 Quadrupoles(Q), 5 Sextupoles(S), 3 Bends(B) in downstream of QM16

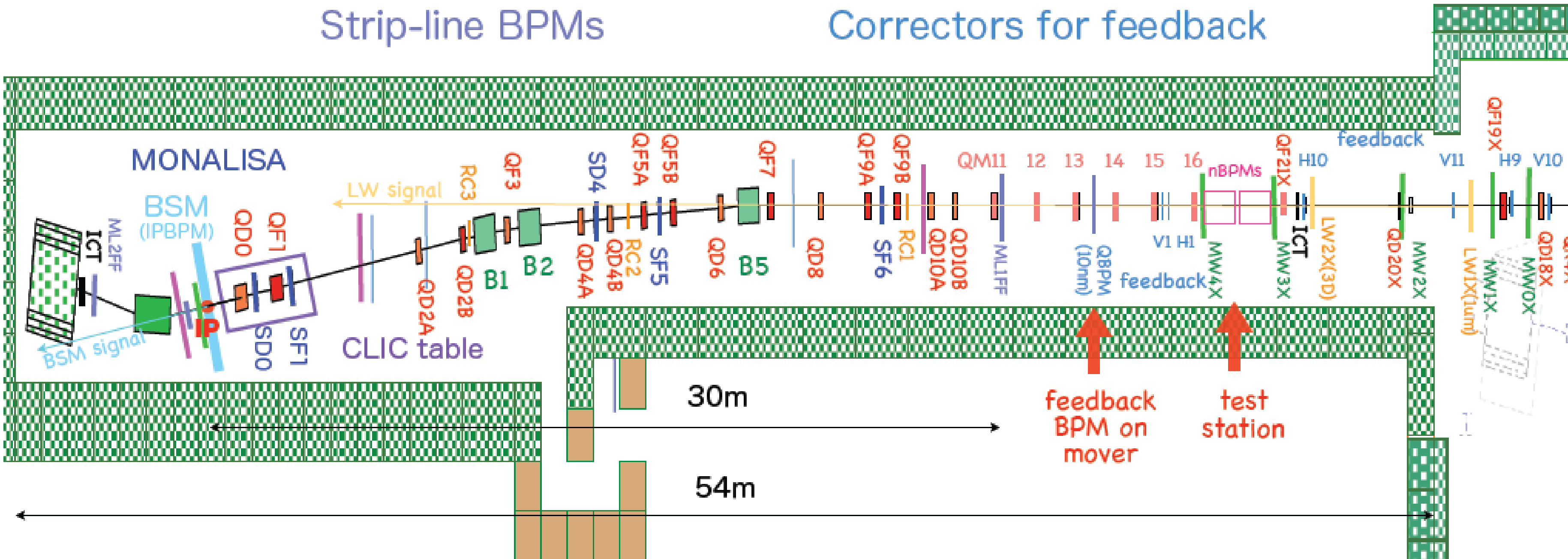
All Q- and S-magnets have cavity-type beam position monitors(QBPM, 100nm).

3 Screen Monitors

5 Wire Scanners, Laserwires

Strip-line BPMs

Correctors for feedback



Shintake Monitor (beam size monitor, BSM with laser interferometer)

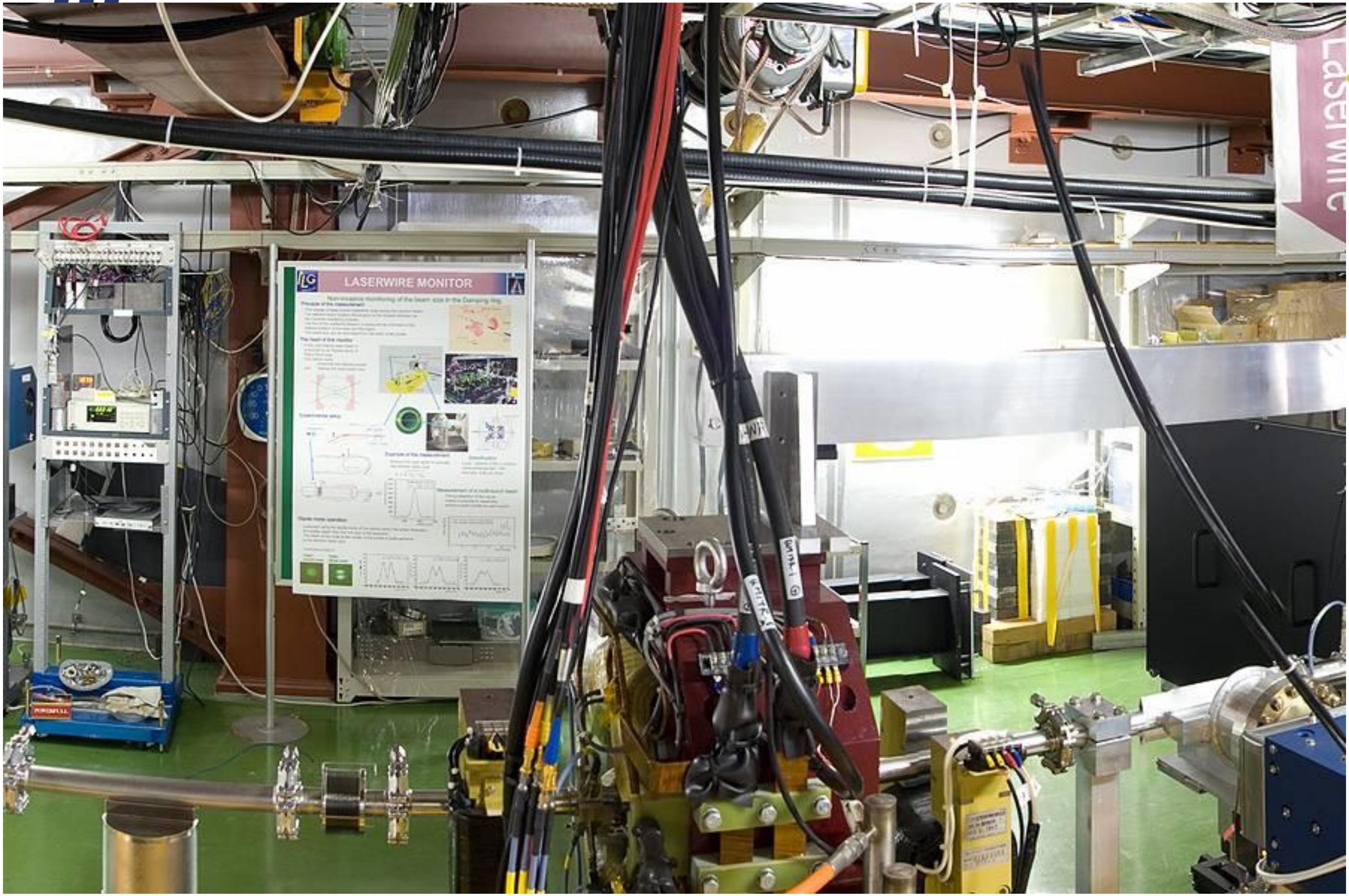
MONALISA (nanometer alignment monitor with laser interferometer)

Laserwire (beam size monitor with laser beam for 1 μm beam size, 3 axies)

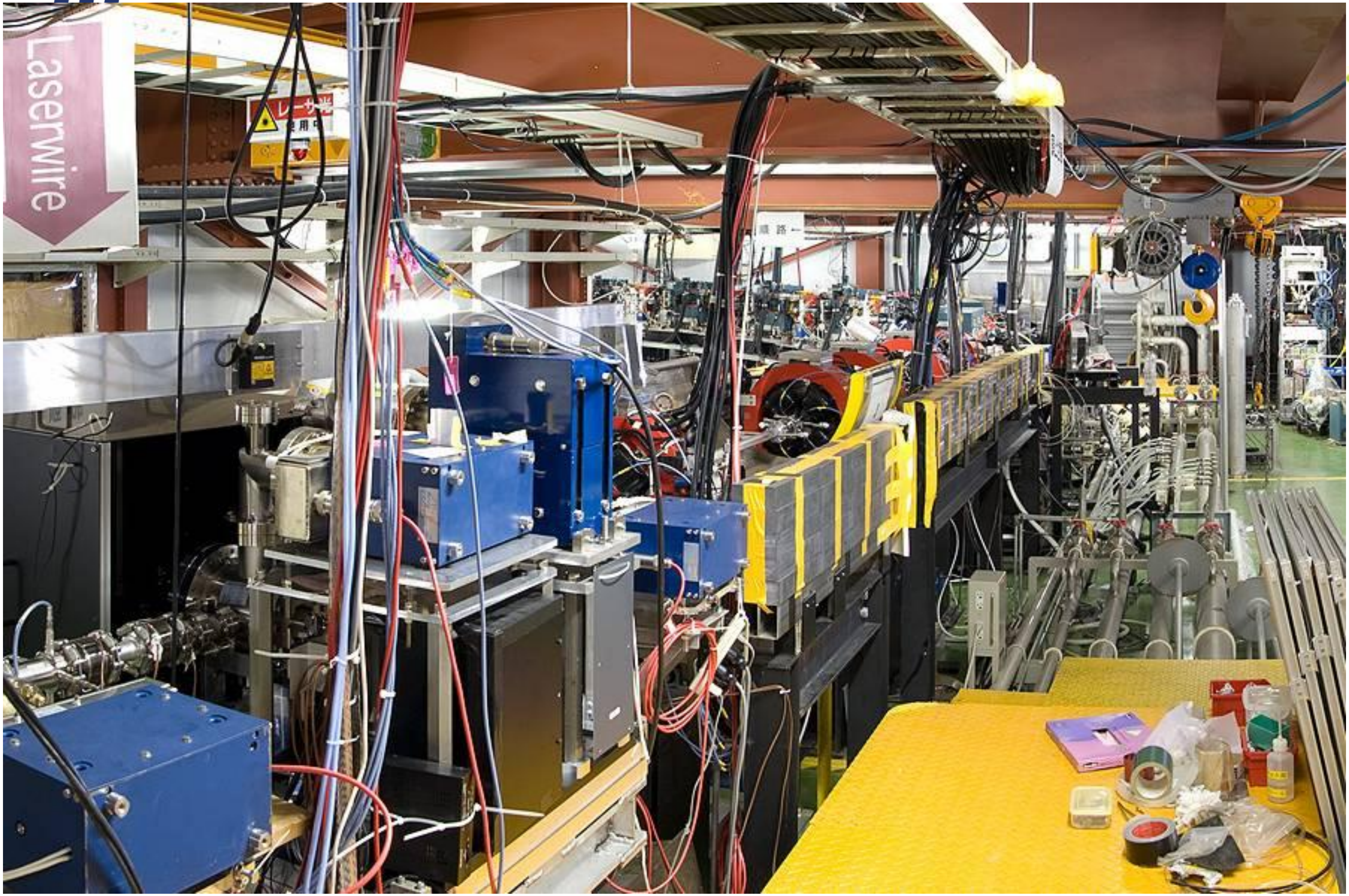
IP intra-train feedback system with latency of less than 150ns (FONT)

Magnet movers for Beam Based Alignment (BBA)

High Available Power Supply (HA-PS) system for magnets



Panoramic photo of ATF beamlines, N.Toge



Panoramic photo of ATF beamlines, N.Toge

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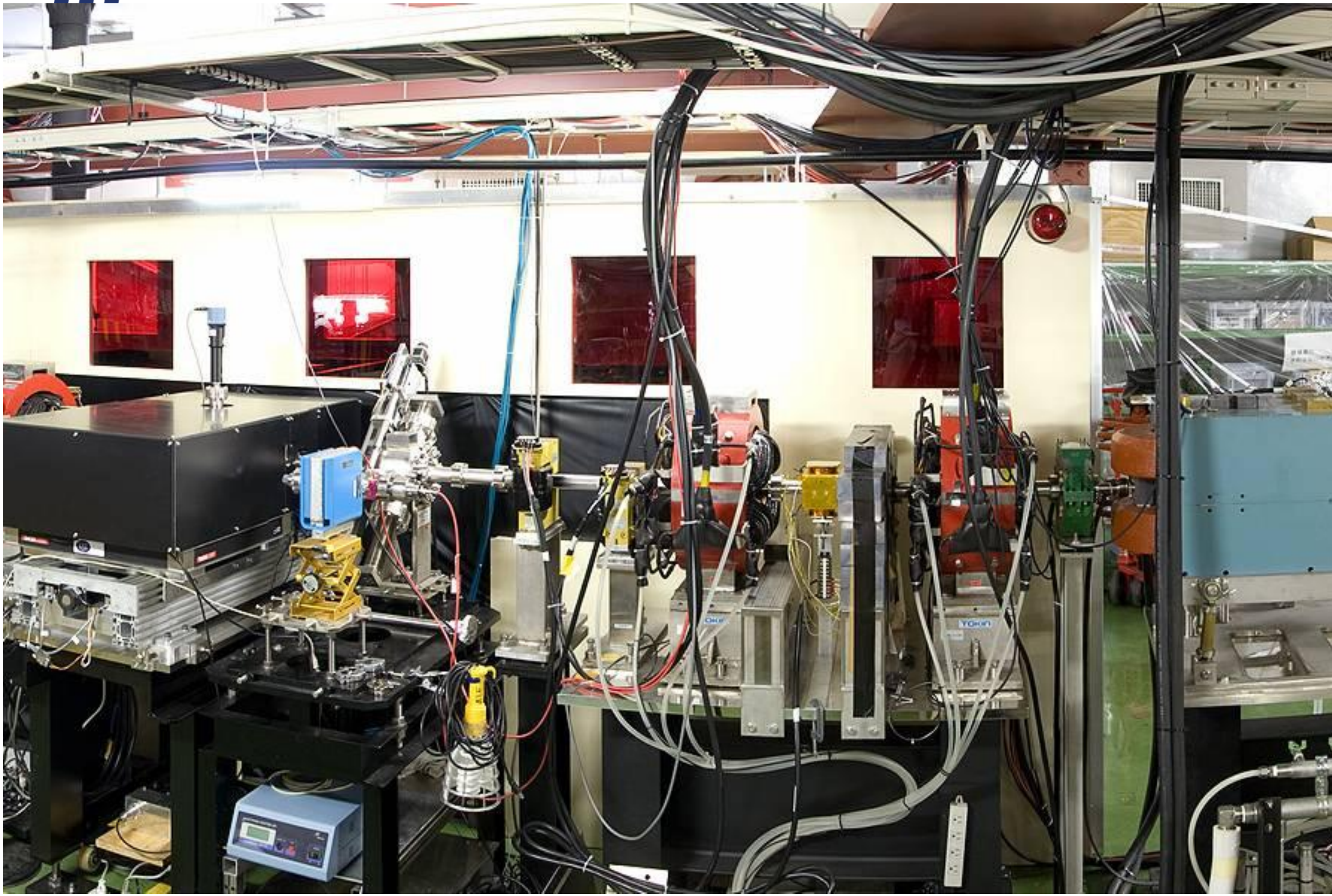

Panoramic photo of ATF beamlines, N.Toge

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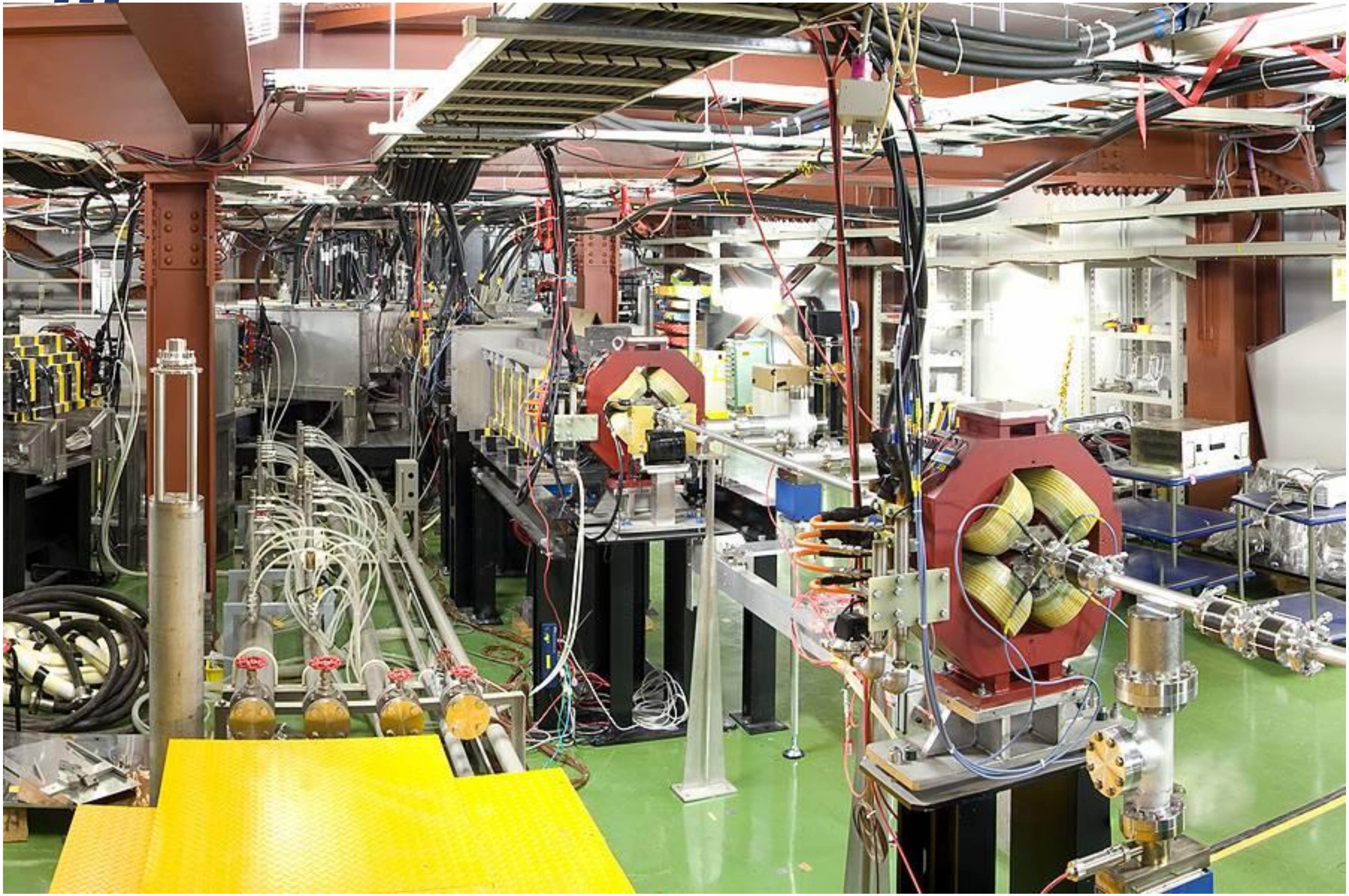


Panoramic photo of ATF beamlines, N.Toge

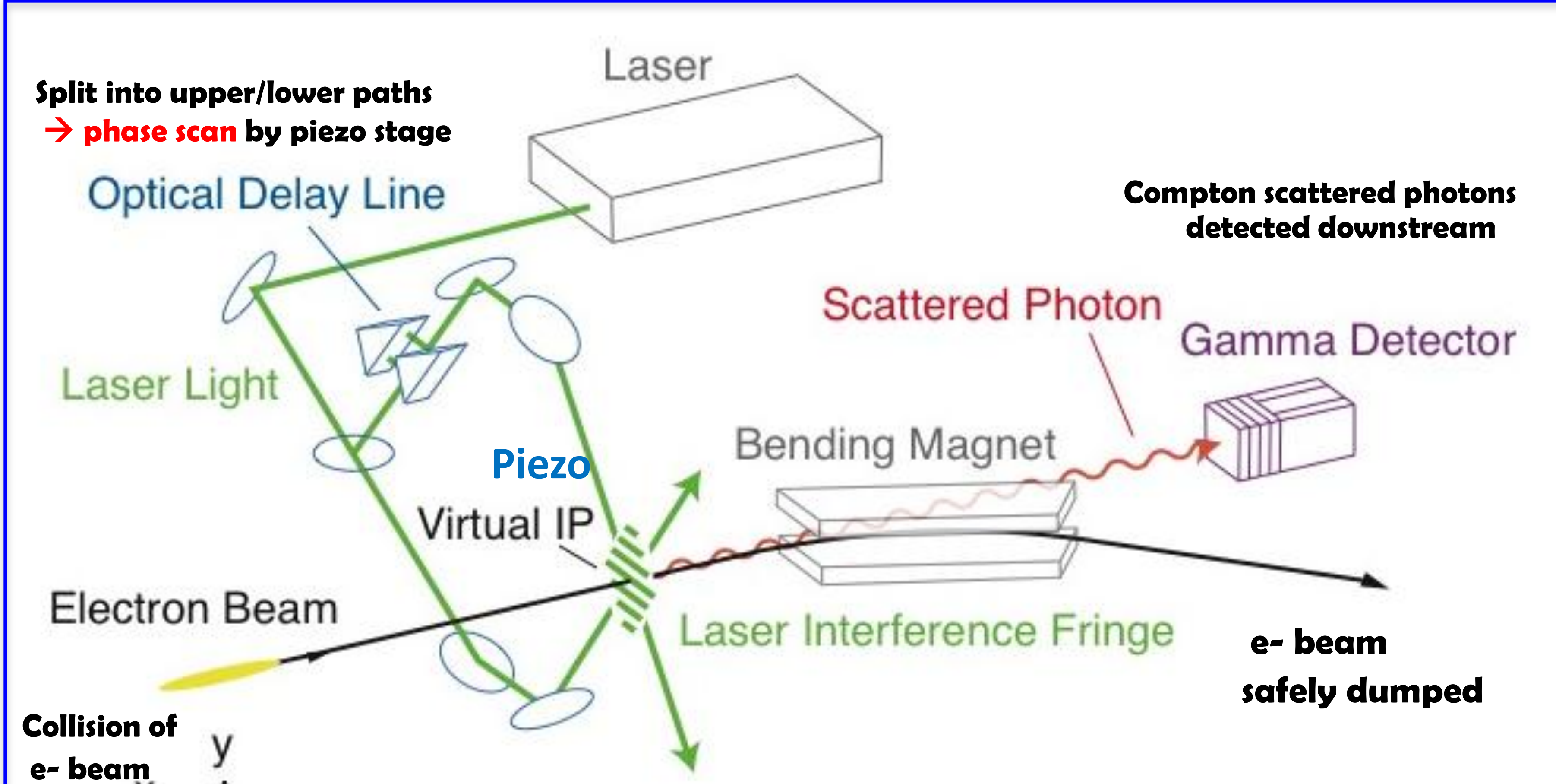
Panoramic photo of ATF beamlines, N.Toge

Beam Size Monitor

- Use **laser interference fringes** as target for e- beam

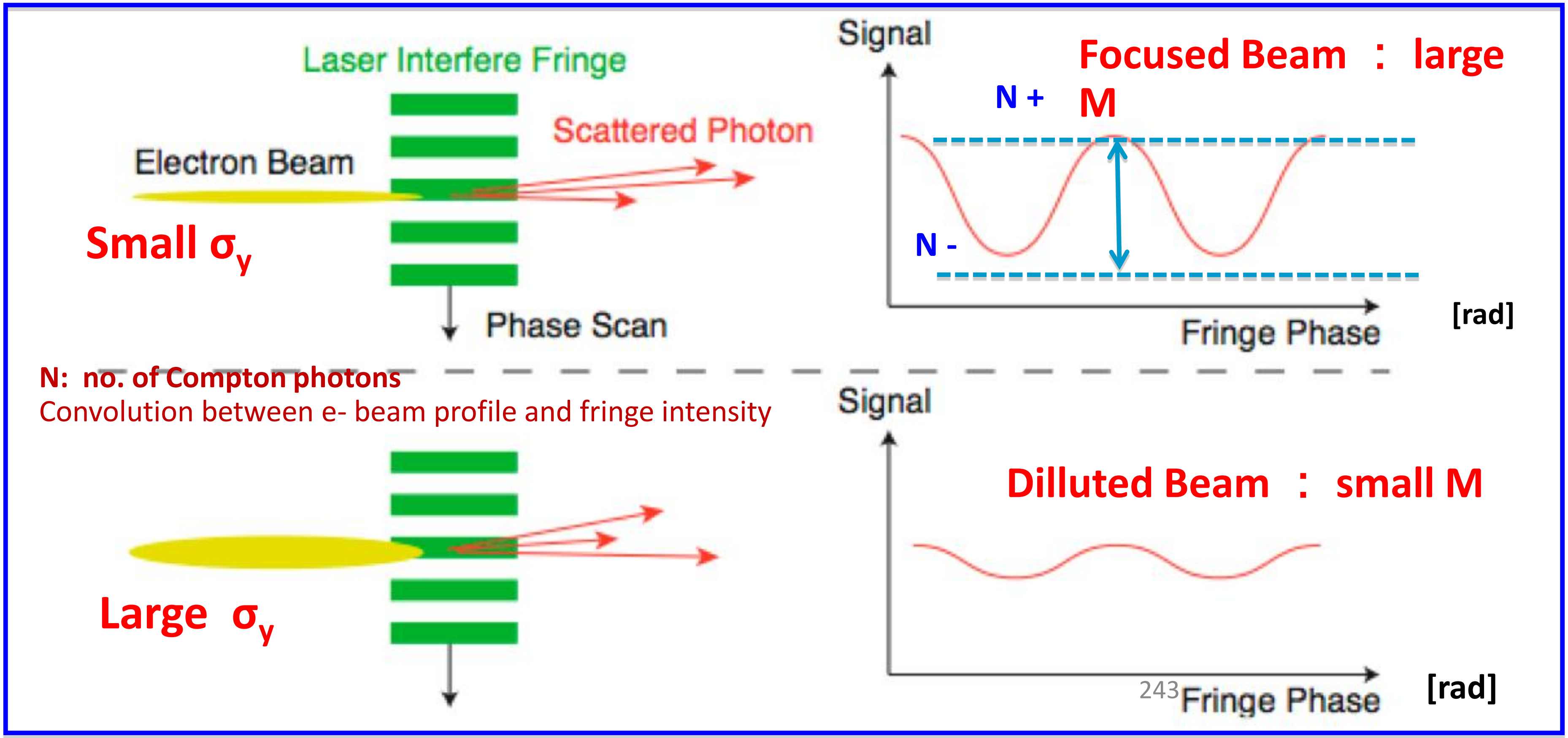
The only device able to measure σ_y < 100 nm !!

- Crucial for ATF2 beam tuning and realization of ILC



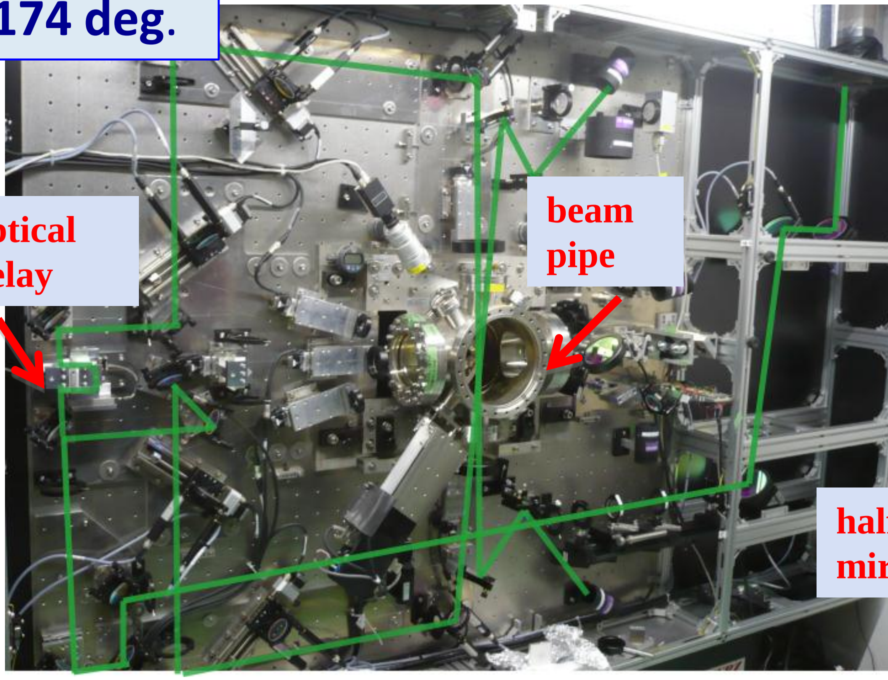
Jacqueline Yan, et al
University of Tokyo

Detector measures signal **Modulation Depth “M”**



Jacqueline Yan, et al
University of Tokyo

174 deg.



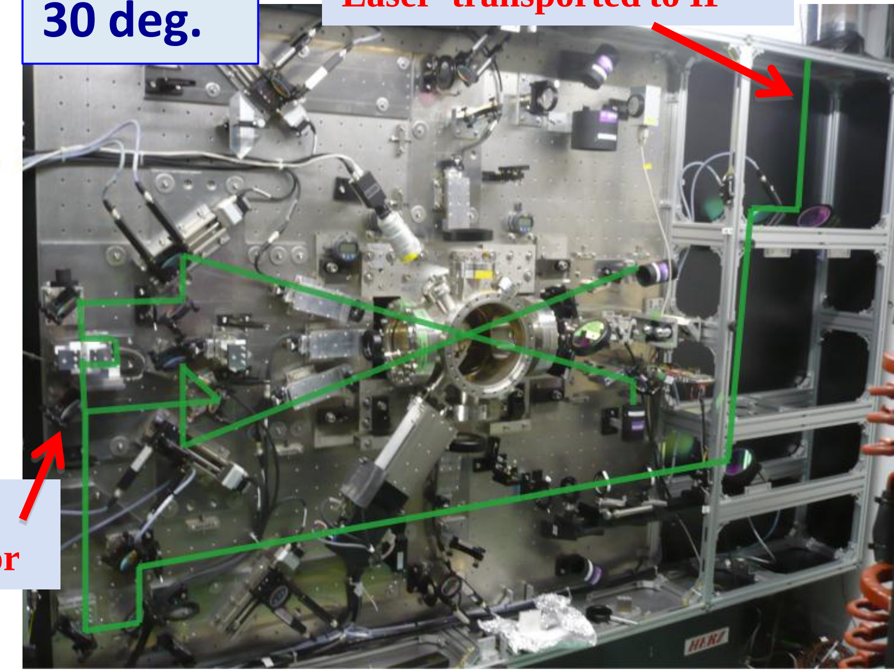
optical delay

beam pipe

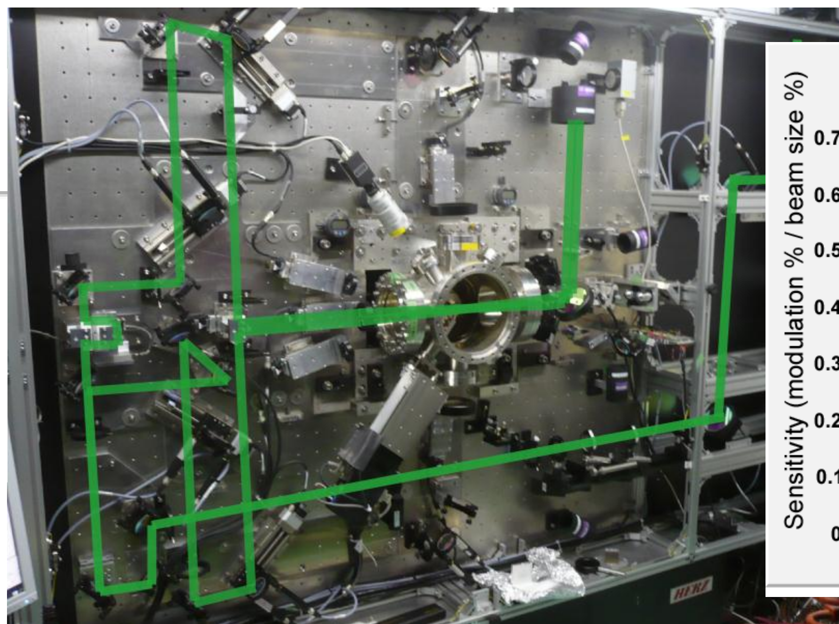
half mirror

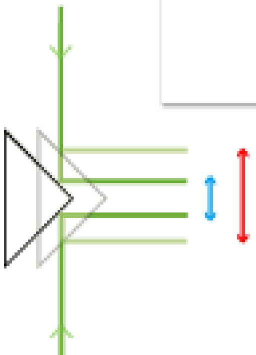
30 deg.

Laser transported to IP

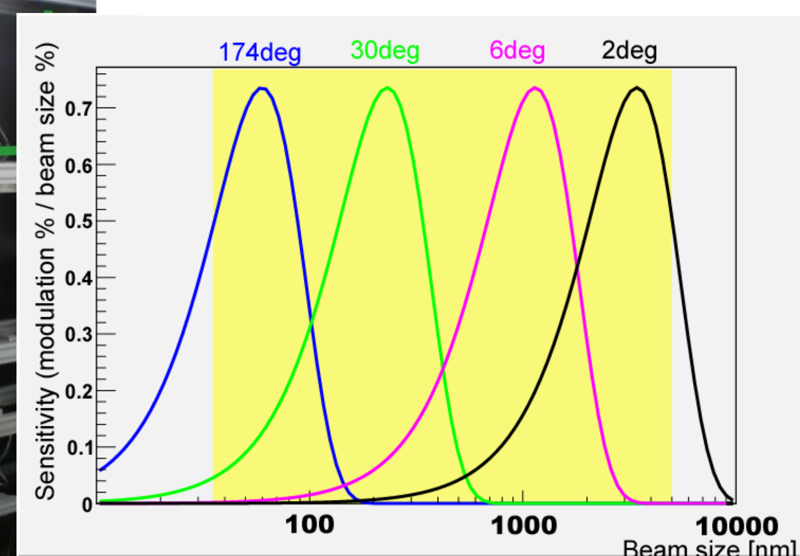


2 - 8 deg

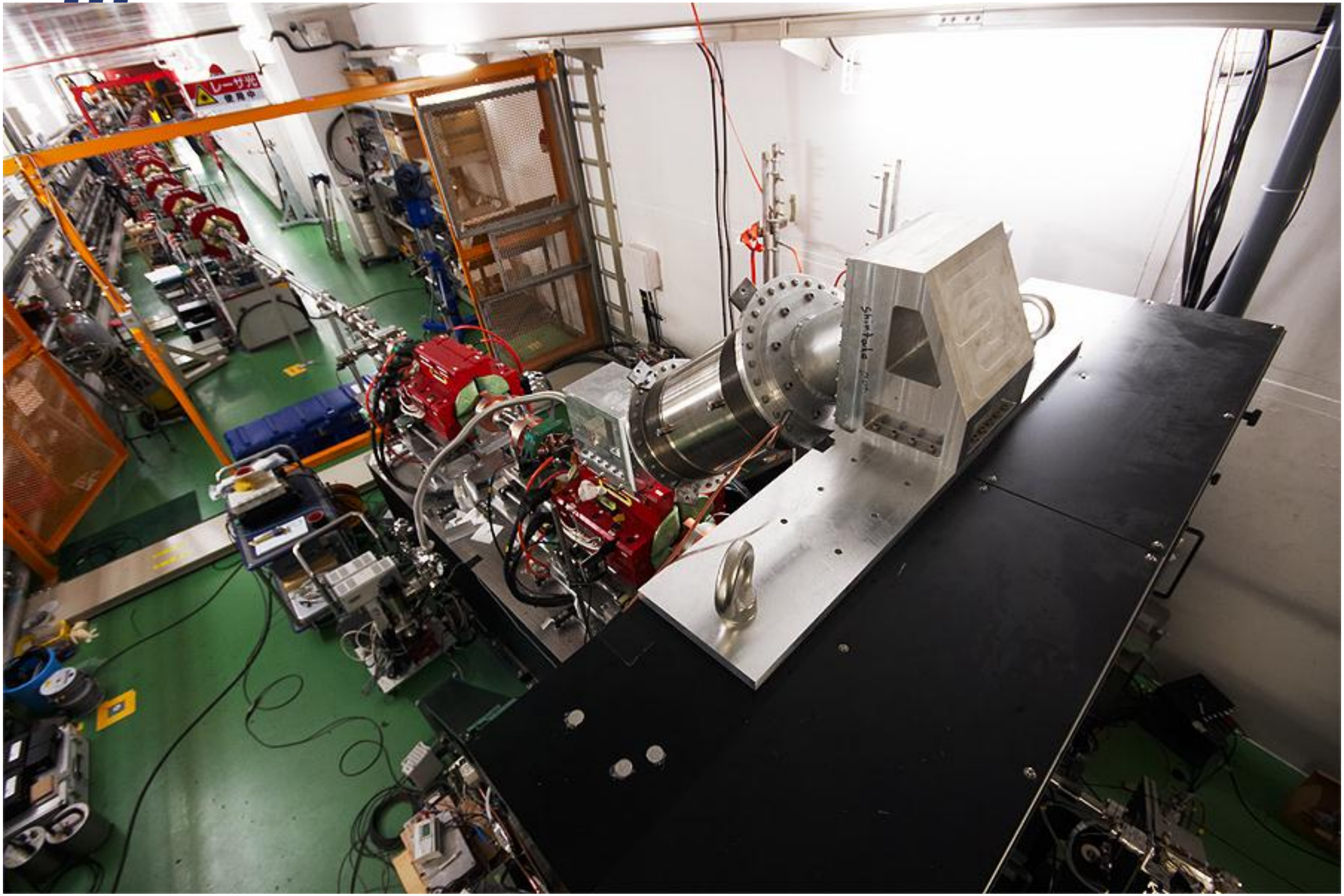




Crossing angle continuously adjustable by prism

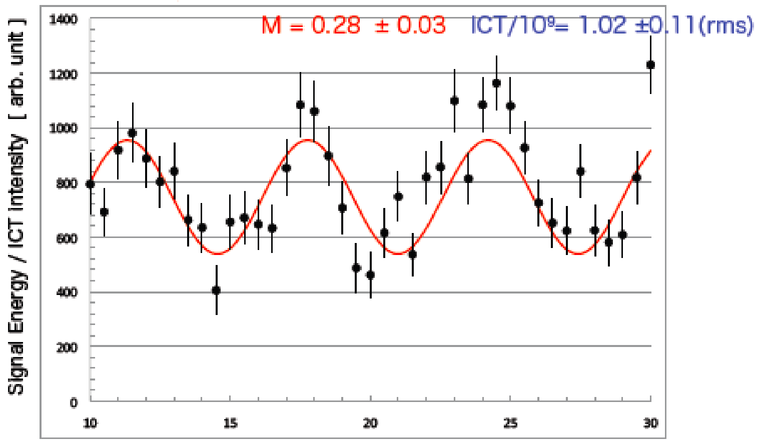


Imperial College London
Royal Holloway University of London
UNIVERSITY OF OXFORD


レーザ光
使用中

ATF2 results – December 2012

Preliminary ATF2@KEK meas121221_183019



Phase [rad] at 174 degree mode
266nm/pitch

FFTB@SLAC

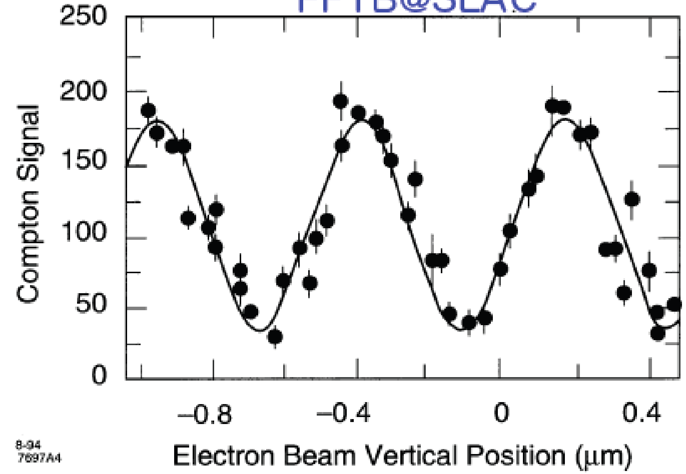
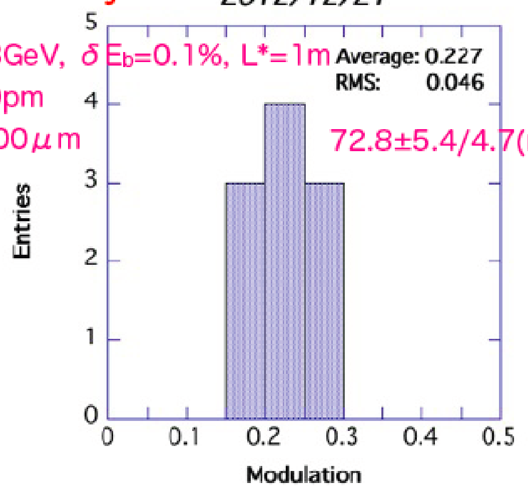


Figure 5.6: Laser-Compton beam size measurement performed in May of 1994. The measured size is 77±7 nanometers.

Slide: T.Tauchi

Preliminary

Both assumes no modulation reduction



rms of laser size = 17/12um

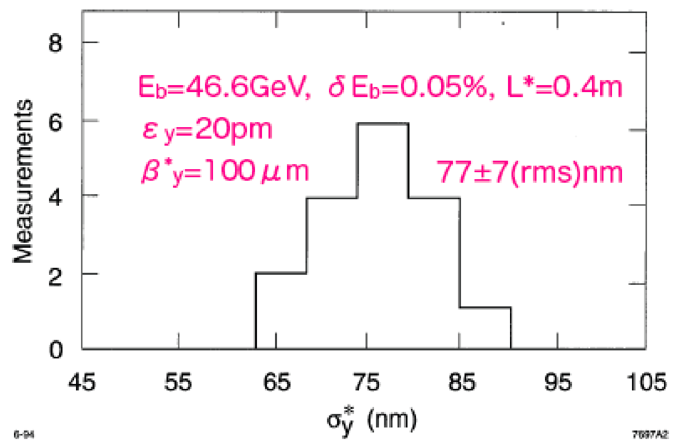
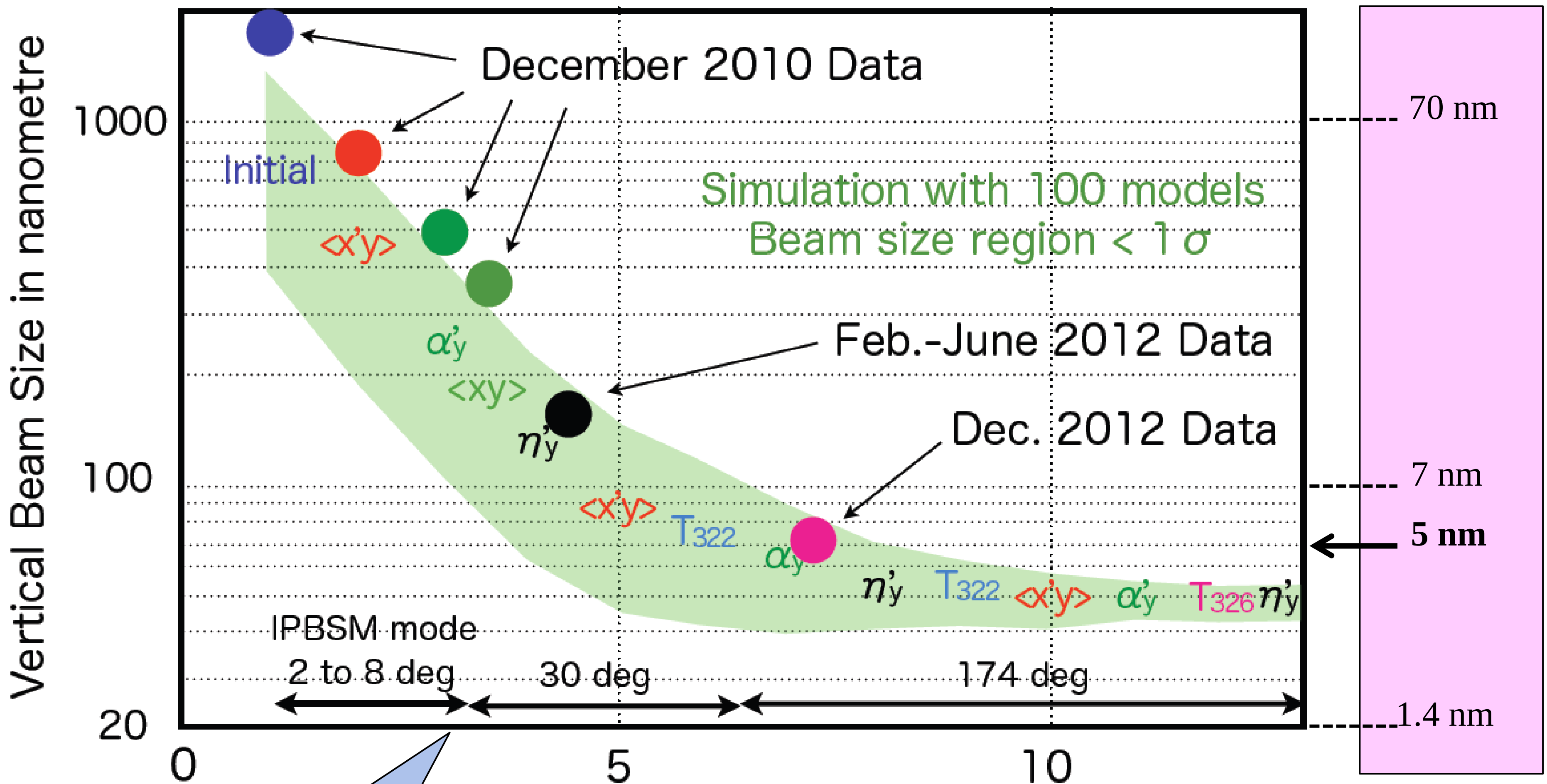


Figure 5.7: Histogram of measurements made during the last 3 hours of the May, 1994 FFTB run. Average size measured was 77 nm, with an RMS of 7 nm.

rms of laser size = 50um -> M reduction of 10%

2013年 1月 7日 月曜日

ATF2 results & scaling to 250GeV/beam



ATF2 results at 1.26 GeV/ beam

Rescaled to 250 GeV/beam

ATF2 review by ILC GDE, Apr 2013:

ATF2 review: General statements

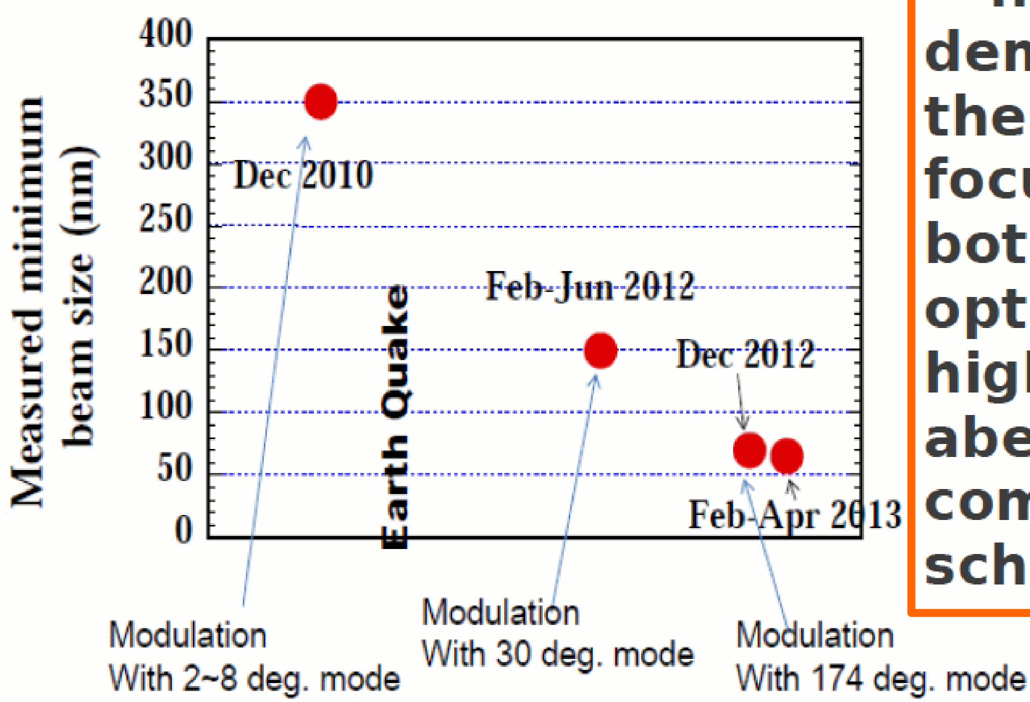
"...The extensive upgrades and improvements to the machine itself, including critical sub-systems such as the **IPBSM**, together with the **organized approach to shifts and personnel training**, have resulted in significant gains in terms of understanding and characterizing the accelerator, resulting in a best-recorded beam size of **64 nm.**"

ATF2 review by ILC GDE, Apr 2013:

Goal 1: 37 nm

- Reached 64 nm
- Tuning from ~3000 nm
- Suppression of aberrations confirmed to about ~90%
- Bunch charge ~10^9 e-!!
- **"...successful demonstration of the compact final focus optics and both the linear optics tuning and high-order aberration compensation schemes involved"**

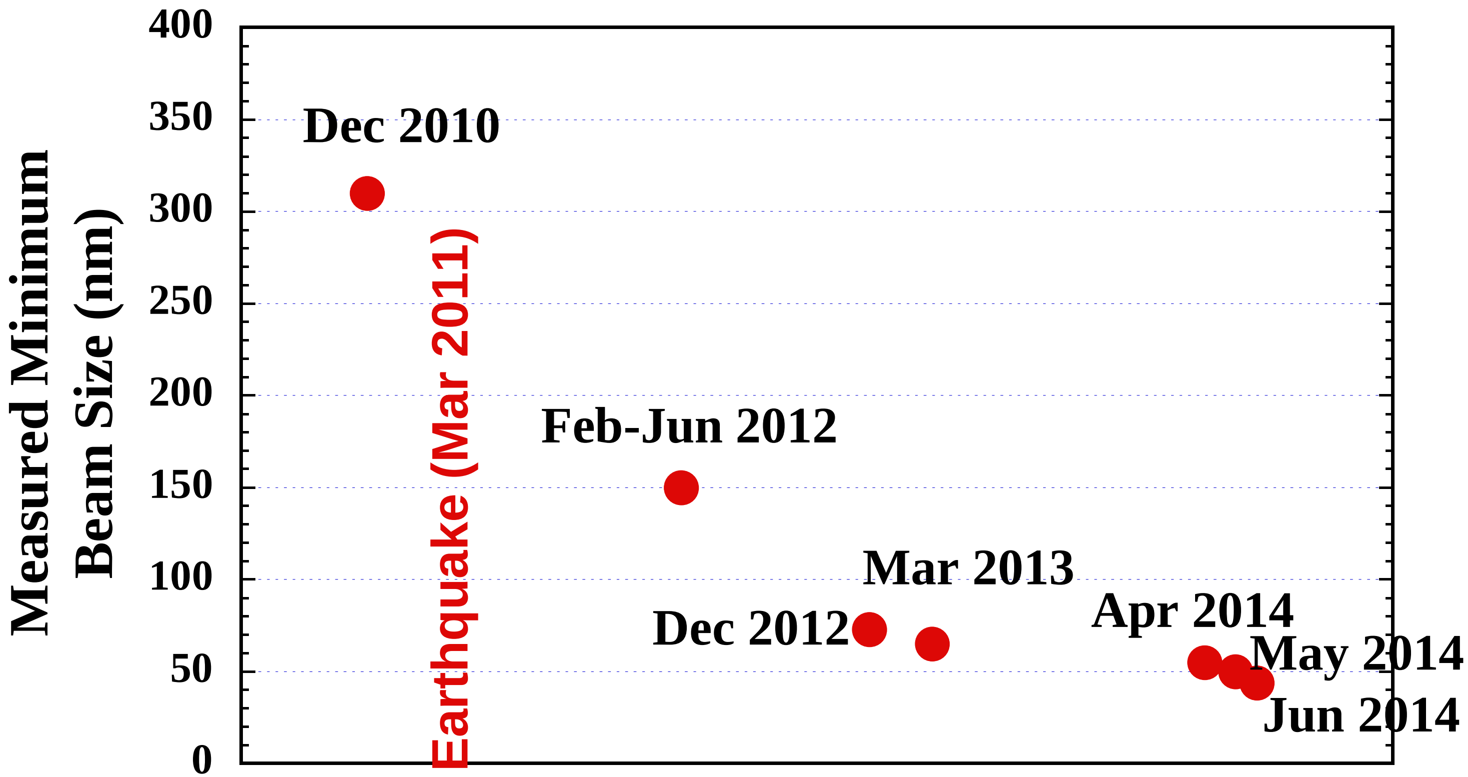
Kubo



History of measured beam size

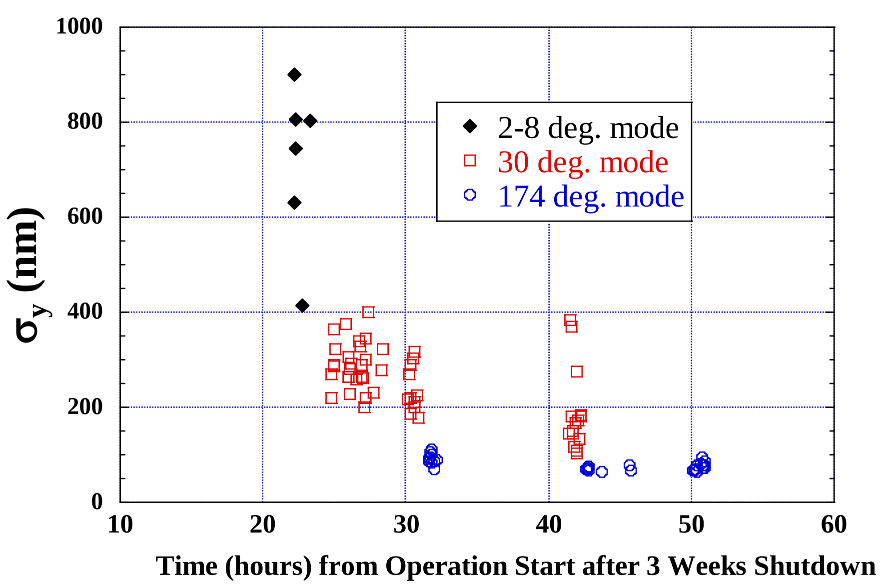
Presented in IPAC14

History of measured minimum beam size



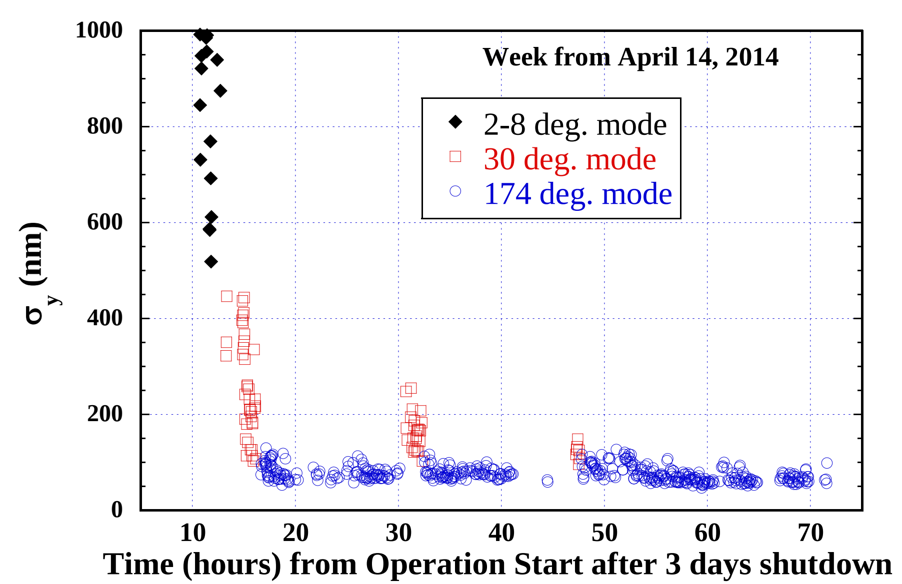
Presented in IPAC14

Beam Size Tuning
after 3 weeks shutdown
Small beam (~60 nm) observed
~32 hours from operation start
~10 hours of IP beam size tuning



Week 2014 April 7

Beam Size Tuning
after 3 days shutdown
Small beam (~60 nm) observed
~16 hours from operation start
~8 hours of IP beam size tuning

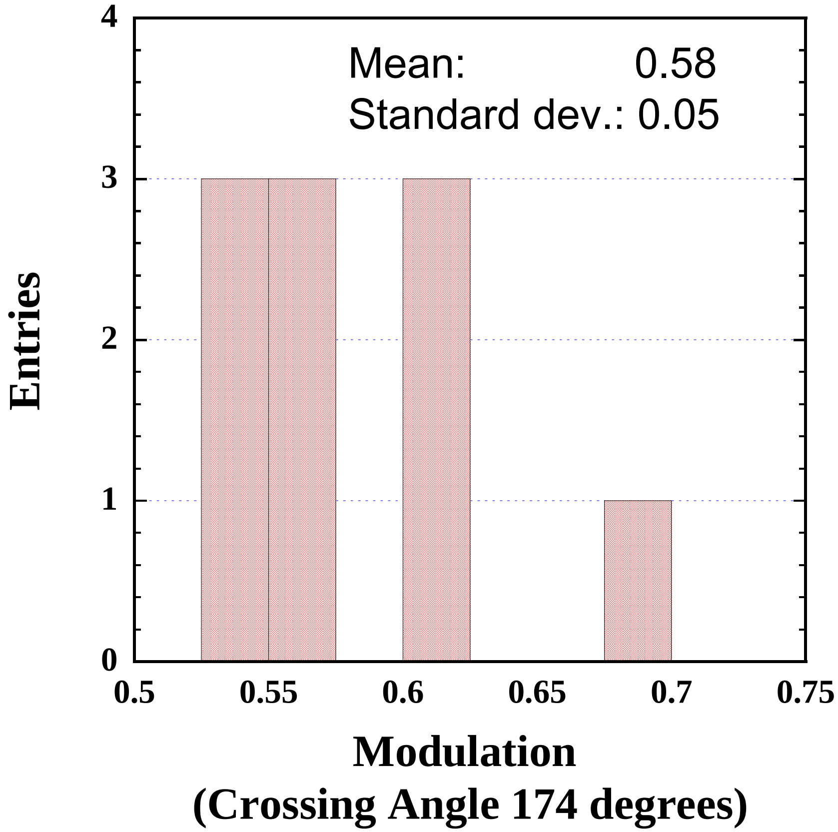


Week 2014 April 14

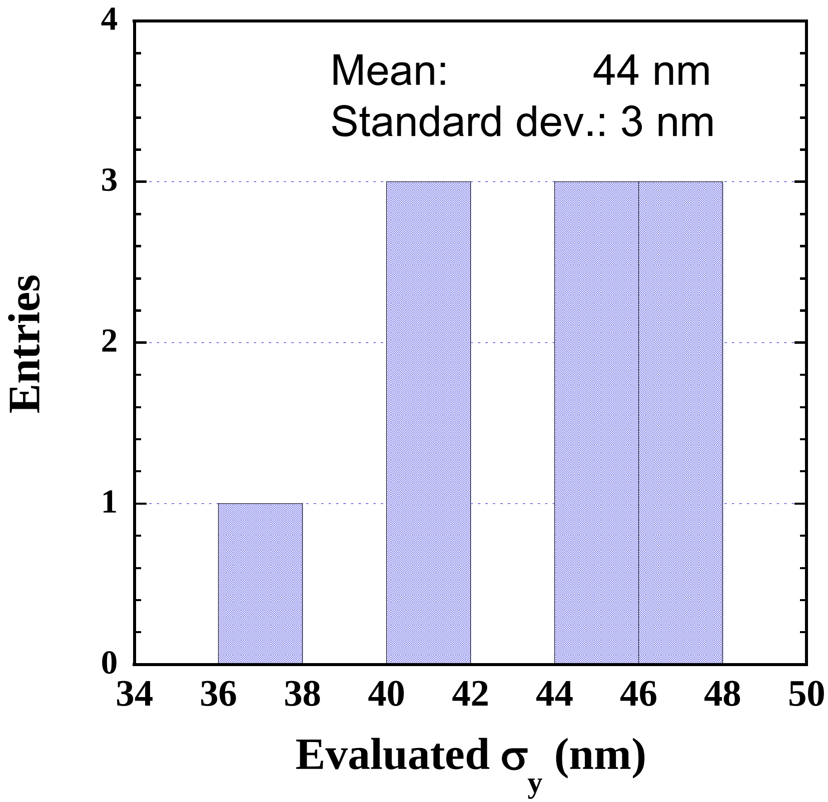
Data of Last Week before summer 2014

Presented in IPAC14

IPBSM Modulation
(174 degree Crossing angle)



Beam Size Evaluated from Modulation
(no systematic error assumed)



Bunch charge ~ 0.16 nC

summary of FF development

- Final Focus with local chromatic correction works in theory and in practice
- The ATF/ATF2 international collaboration successfully demonstrated operation of ILC-like final focus system
- The ATF2 project was realized as ILC-like international project, with in-kind contributions
- The ATF2 is a great training and advanced accelerator research facility

Thanks to all colleagues in the ATF Collaboration!

Ph.D. thesis at ATF2 (as of May 2010)

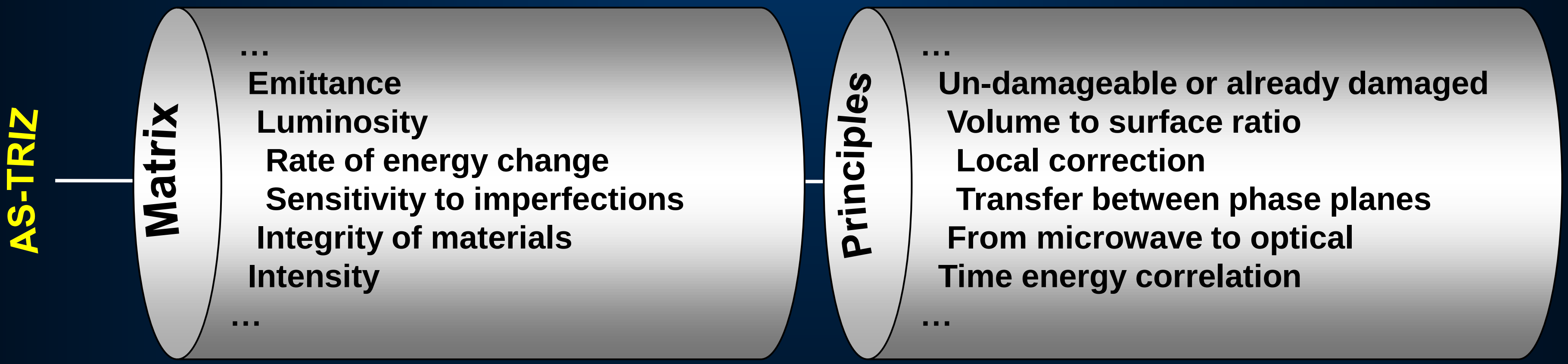
Year	university	country	Name	title
2007.11.12	Université de Savoie	France	Benoit Bolson	Etude des vibrations et de la stabilisation a l'echelle sous-nanometrique des doublets finaux d'un collisionneur lineaire
2007.12.21	University of Tokyo	Japan	Taikan Suehara	Development of a Nanometer Beam Size Monitor for ILC/ATF2
2009.4.14	Royal Holloway, University of London	UK	Lawrence Deacon	A Micron-Scale Laser-Based Beam Profile Monitor for the International Linear Collider
2010.6.8	UNIVERSITAT DE VALÈNCIA	Spain	María del Carmen Alabau Pons	Optics Studies and Performance Optimization for a Future Linear Collider: Final Focus System for the e-e- Option (ILC) and Damping Ring Extraction Line (ATF)
2010.5.8	IHEP CAS	China	Sha Bai	ATF2 Optics System Optimization and Experiment Study
2010.6.11	Université Paris-Sud 11	France	Yves Renier	Implementation and Validation of the Linear Collider Final Focus Prototype ATF2 at KEK (Japan)
	Oxford university	UK		FONT studies
2011.12.1	University of Tokyo	Japan	Masahiro Oroku	Beam Tuning with the Nanometer Beam Size Monitor at ATF2
2011.12.1	Kyungpook National University	Korea	Youngim Kim	IPBPM and BBA
2011.12.1	University of Manchester	UK	Anthony Scarfe	Tuning and alignment of ATF2 and ILC
2012.2.xx	University of Tohoku	Japan	Taisuke Okamoto	cavity-type tilt monitor of beam orbit for ILC
2012.12.1	Kyungpook National University	Korea	Siwon Jang	IPBPM and BBA
2012.12.1	CERN	Spain	Eduardo Marin Lacoma	Ultra Low Beta Optics
	Oxford university	UK		FONT studies
	ICIF, Valencia university	Spain	Javier Alabau-Gonzalvo	emittance, coupling measuremwnts with multiple OTR system

TRIZ for Accelerator Science => AS-TRIZ

- TRIZ Contradiction Matrix and Inventive Principles are suitable for engineering disciplines
- To be applicable to Accelerator Science, TRIZ may need to be re-interpreted and extended (extension called AS-TRIZ)

TRIZ for Accelerator Science => AS-TRIZ

- TRIZ Contradiction Matrix and Inventive Principles are suitable for engineering disciplines
- To be applicable to Accelerator Science, TRIZ may need to be re-interpreted and extended (extension called Accelerating Science TRIZ or AS-TRIZ)
  - AS-TRIZ Principles and Contradiction Matrix are being developed



TRIZ for Accelerator Science => AS-TRIZ

In order to understand, how TRIZ works,

we are trying to build AS-TRIZ,

going through the same steps of

invention analysis that were made

during creation of TRIZ.

AS-TRIZ

Matr

Rate of energy change
Sensitivity to imperfections
Integrity of materials
Intensity
…

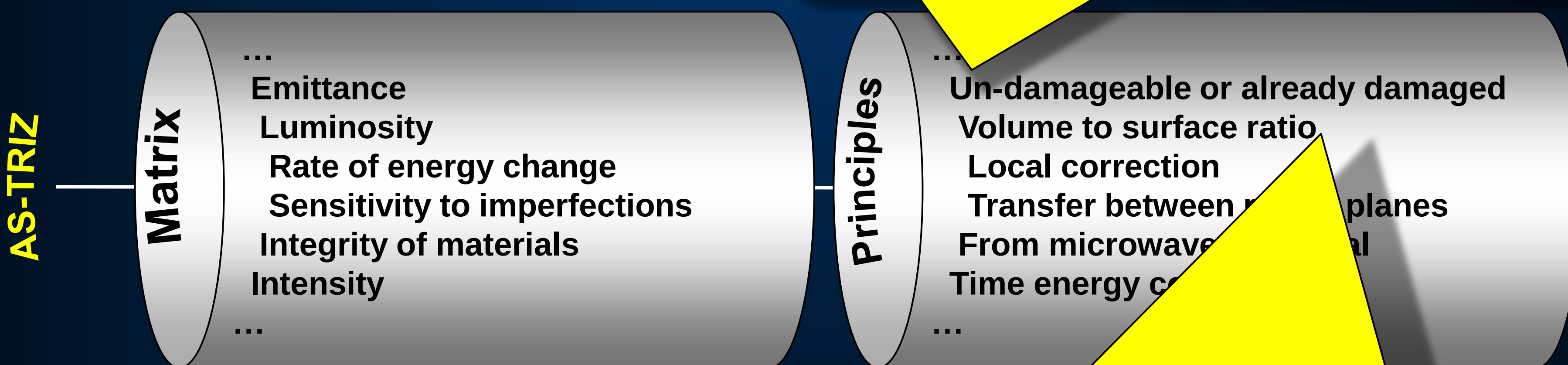
Princi

Local correction
Transfer between phase planes
From microwave to optical
Time energy correlation
…

And from the list of the AS-TRIZ principles we shall consider here this pair

- suitable for engineering disciplines
- To be applicable to Accelerator Science, TRIZ may need to be re-interpreted and extend
  Accelerating Science TRIZ o
  - AS-TRIZ Principles and Contra

3. Using un-damageable or already damaged materials

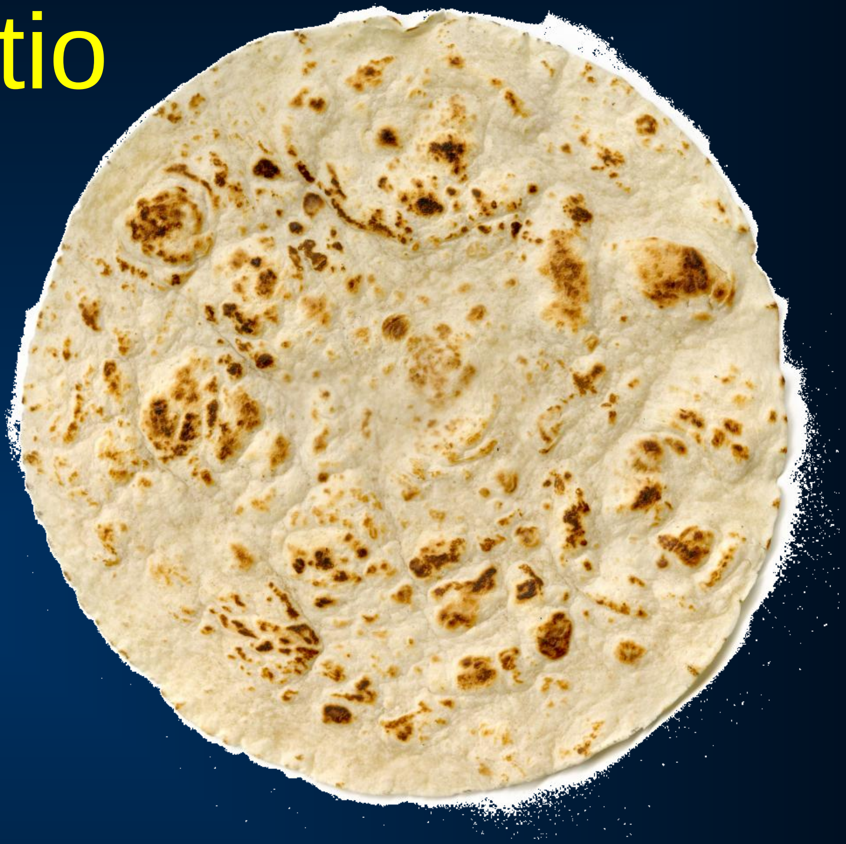


4. Changing of volume to surface ratio

The principle of changing the volume to surface ratio

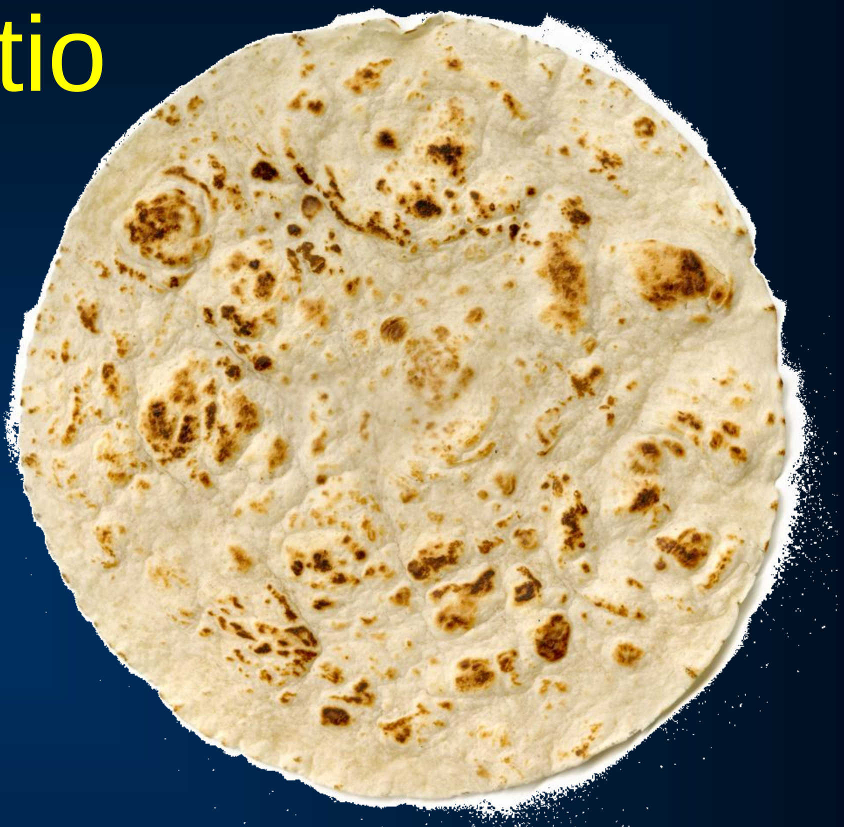
The same volume,
but different surface area

The principle of changing the volume to surface ratio



The same volume,
but different surface area

The principle of changing the volume to surface ratio



The same volume,
but different surface area

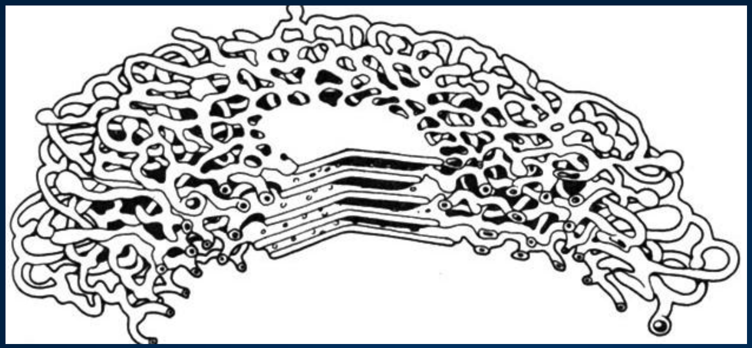
The same principle is used in linear colliders, where "pancakes" are collided instead of "buns"

The principle of changing the volume to surface ratio – an example

The same volume, but different surface area and the different amount of information ☺

And could we suggest an example illustrating this principle, for instance, in biology?

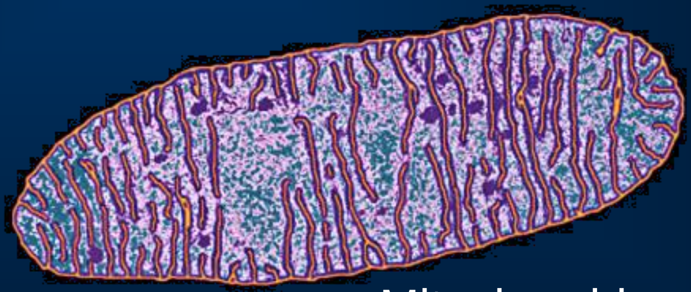
The principle of changing the volume to surface ratio – examples



Golgi Apparatus

Brain

Algae

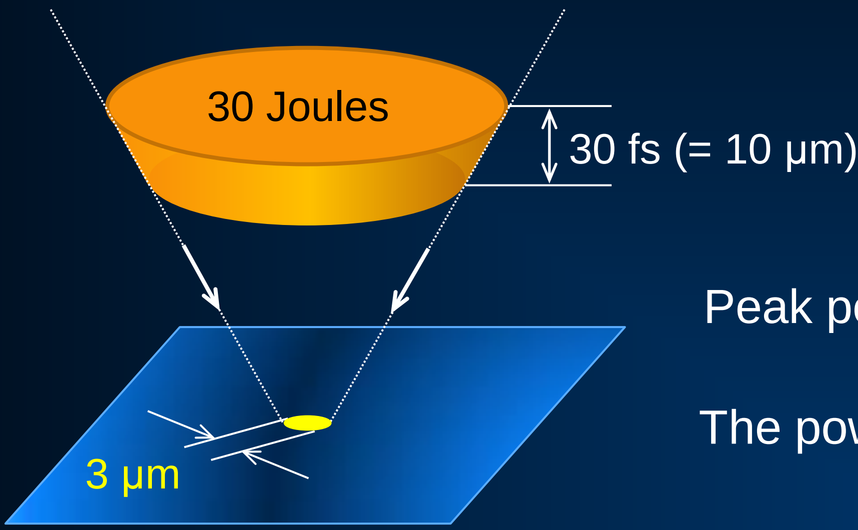


Mitochondria

Keeping the same volume but increasing the surface area to enhance the functionality

Contemporary high-power lasers

... are impressive

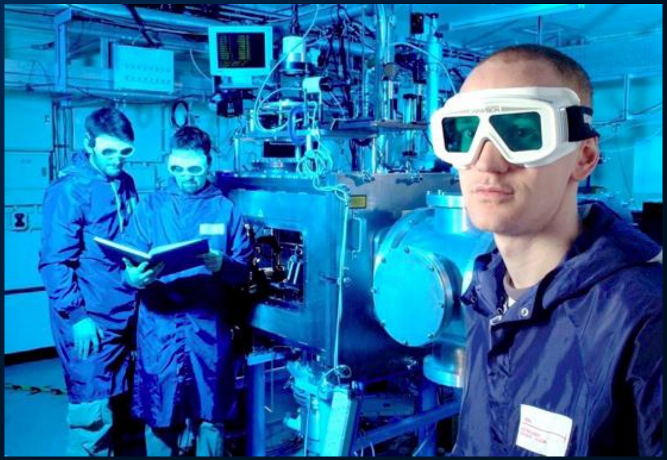


Peak power 10^{15} W

The power density at the focus is 10^{22} W/cm^2

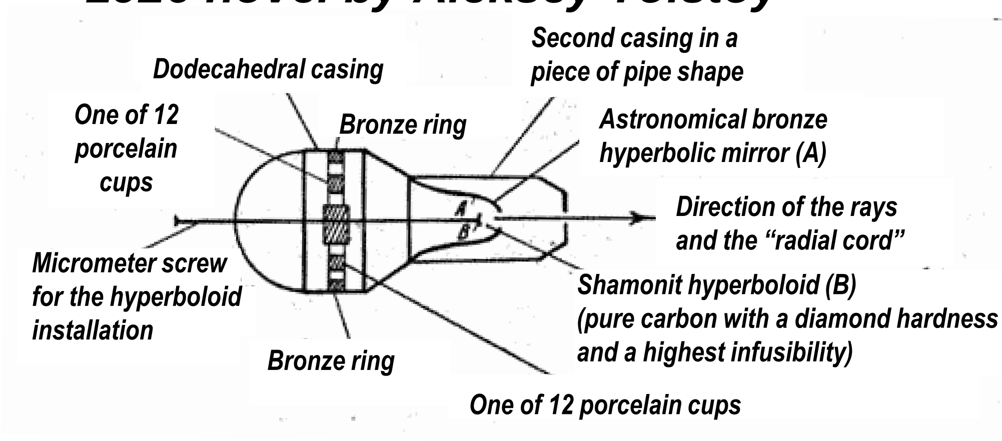
Laser of this power instantly ionizes any substance

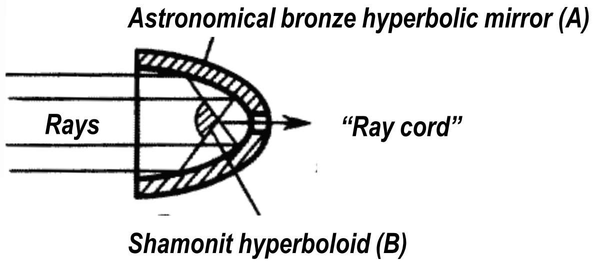
Electrons carried along by the field of such a laser instantly become relativistic...

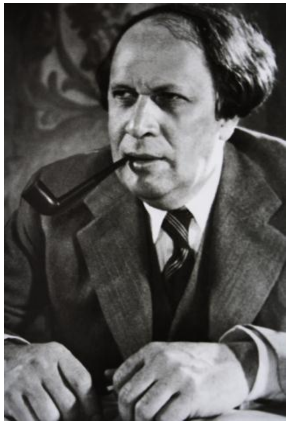


“The Hyperboloid of Engineer Garin”

1926 novel by Aleksey Tolstoy







Aleksey Tolstoy

“The Hyperboloid of Engineer Garin”

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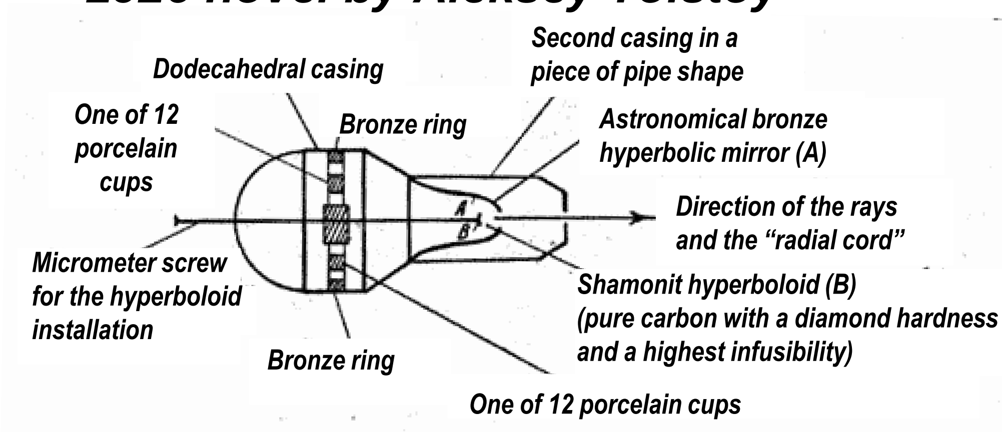
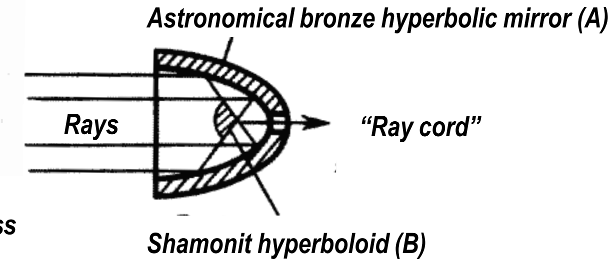




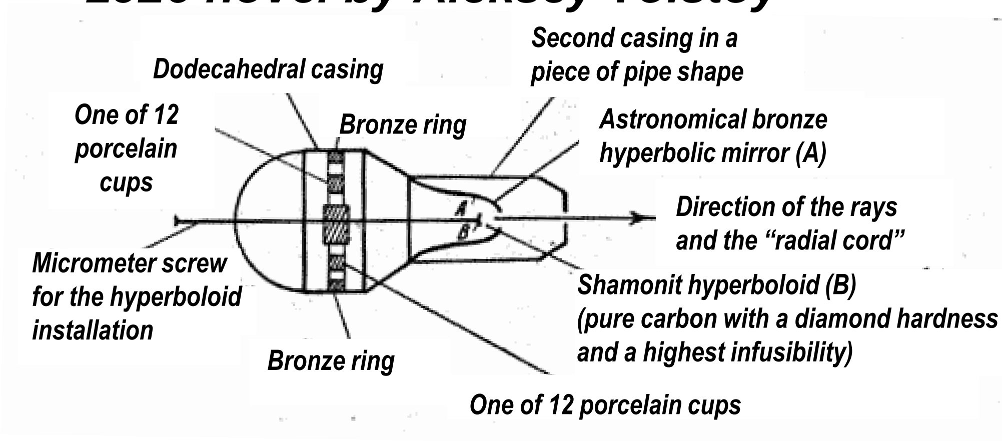
Aleksey Tolstoy

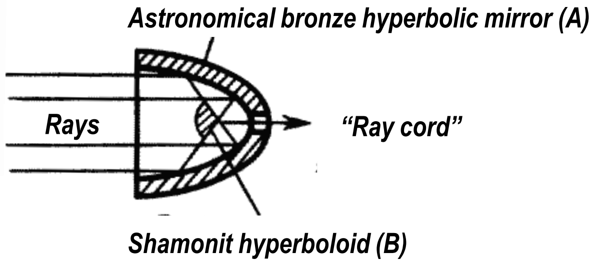
From Tolstoy’s novel:

“…Can you imagine what opportunities are opening now? Nothing in the nature can withstand the power of the ray cord - buildings, forts, dreadnoughts, airships, rocks, mountains, the earth's crust - everything could be penetrated, destroyed, cleaved with my beam.” Garin suddenly broke off and lifted his head, listening ... ”Three cars and eight people,” he said in a whisper, “they came after us”…

“The Hyperboloid of Engineer Garin”

1926 novel by Aleksey Tolstoy





Aleksey Tolstoy

… and laser

C.Townes N.Basov A. Prokhorov

Nobel Prize in 1964 for the research that led to the development of lasers

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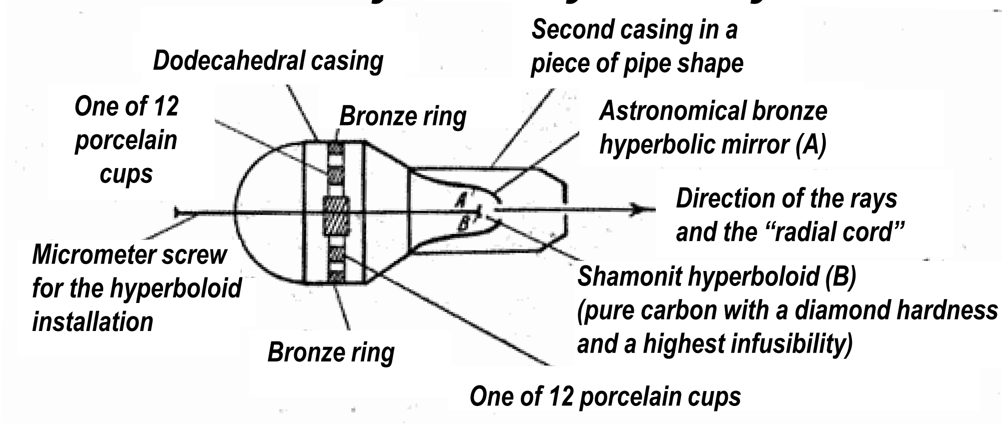

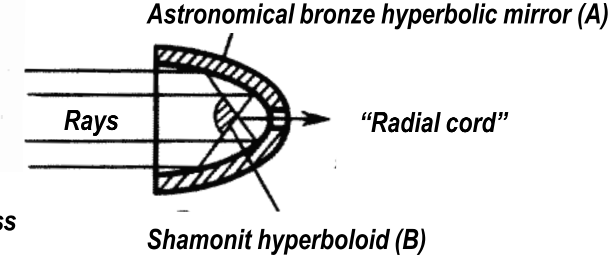

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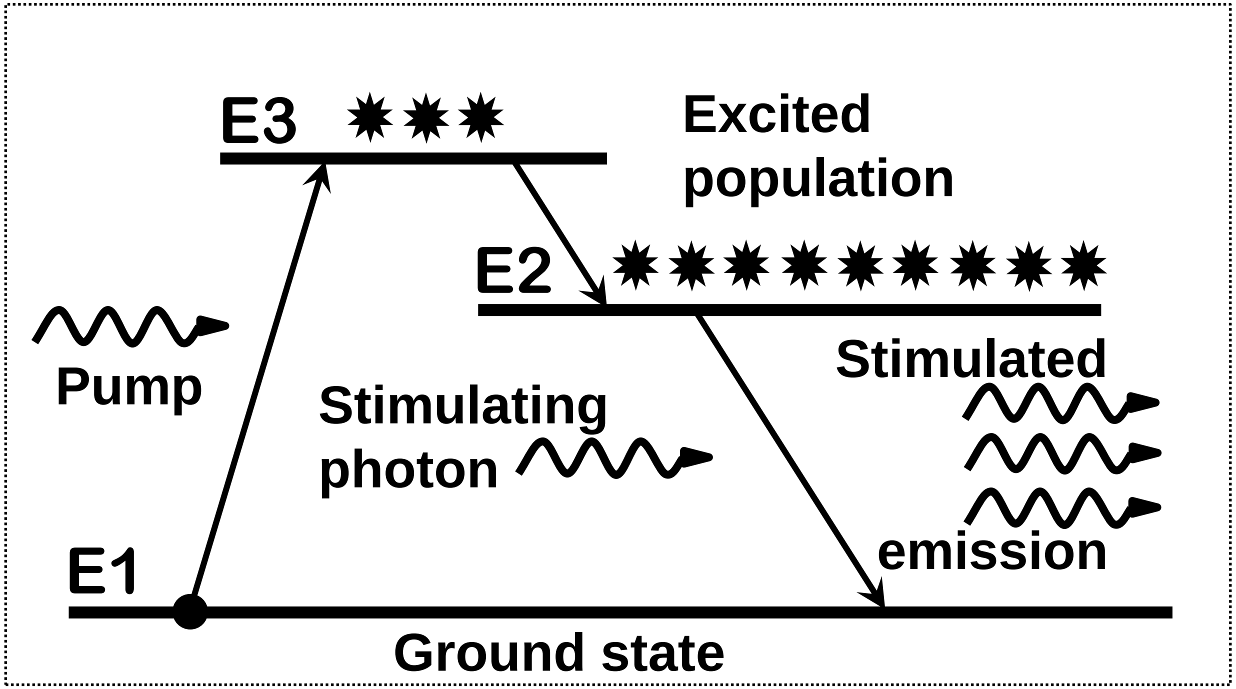

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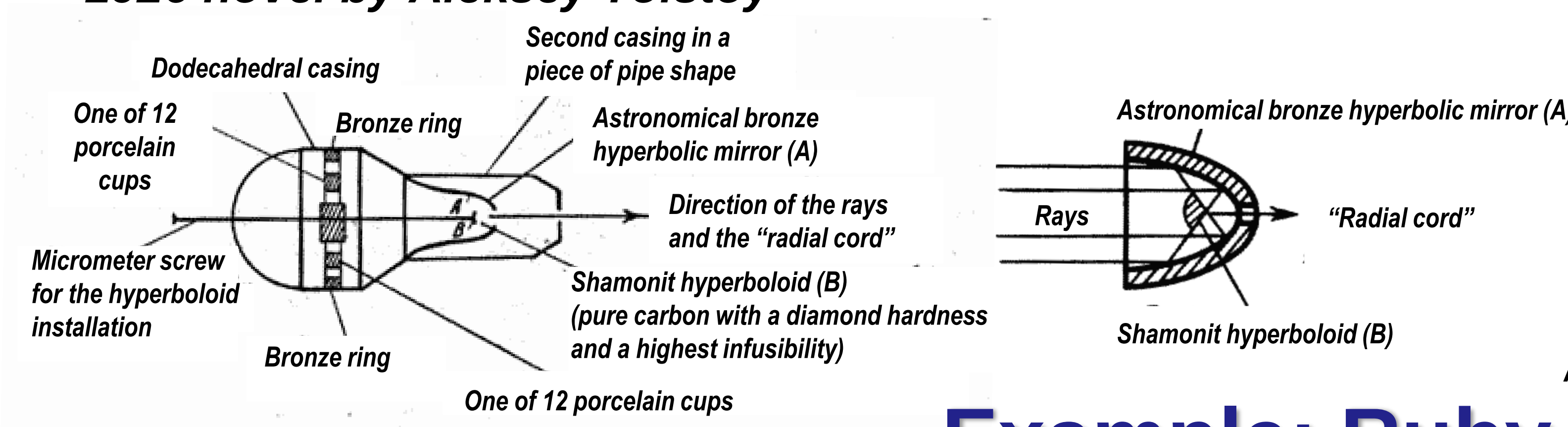
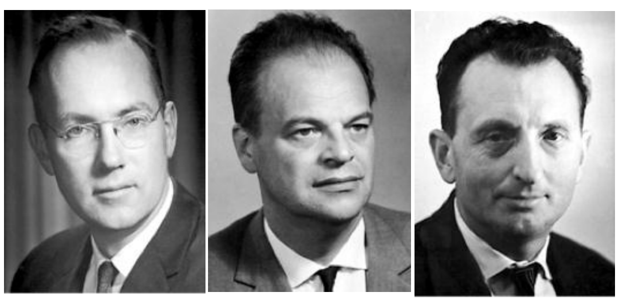


Aleksey Tolstoy

Example: Ruby laser



C.Townes N.Basov A. Prokhorov

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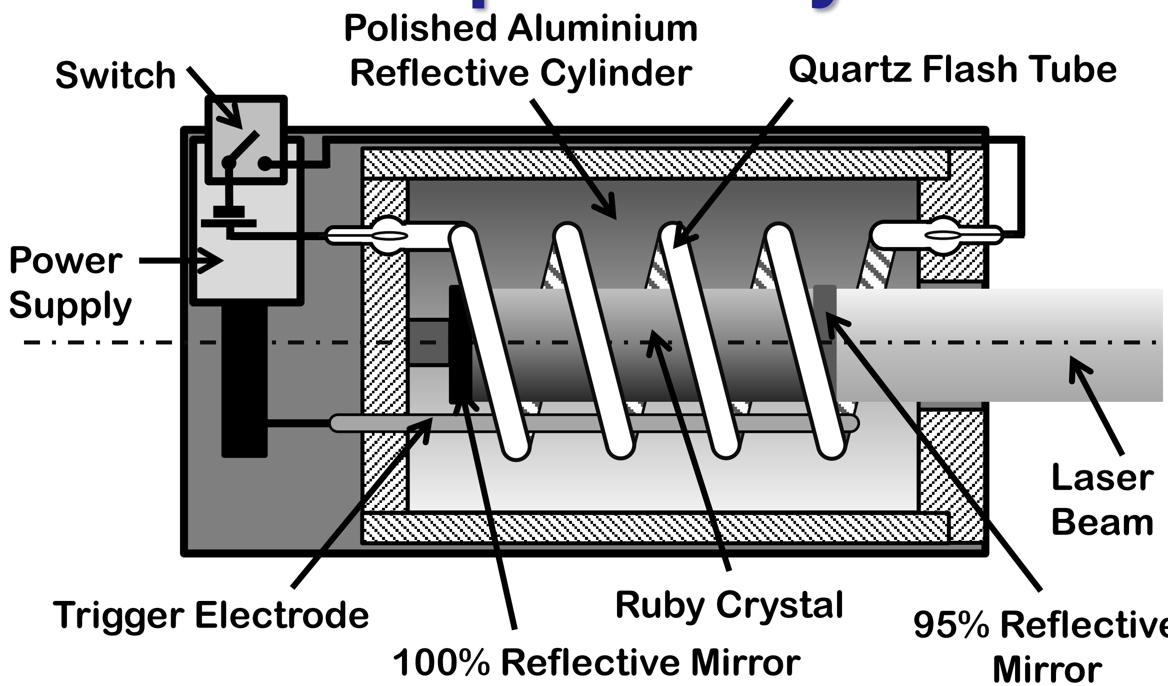

Problem of high-power lasers - active medium T°

Problem:

As intensity of the laser light increase, it takes much more time for active medium to cool down and be ready for next use

Contradiction:

To be improved: INTENSITY

What gets worse: REP RATE

Problem of high-power lasers - active medium T°

Problem:

As intensity of the laser light increase, it takes much more time for active medium to cool down and be ready for next use

Contradiction:

To be improved: INTENSITY

What gets worse: REP RATE

- **A general principle which can solve this can be taken from nature or AS-TRIZ:**
  - **4: Volume to surface ratio – change it to alter the characteristics such as cooling rate, fields of the object, etc**

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As intensity of the laser light increase, it takes much more time for active medium to cool down and be ready for next use

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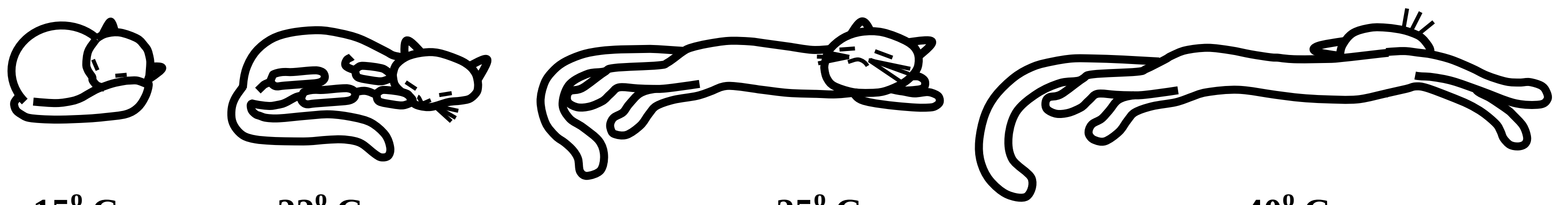

15^o C 22^o C 25^o C 40^o C

The cat intuitively knows the inventive principle of surface to volume ratio

Problem of high-power lasers - active medium T°

Problem:
As intensity of the laser light increase, it takes much more time for active medium to cool down and be ready for next use

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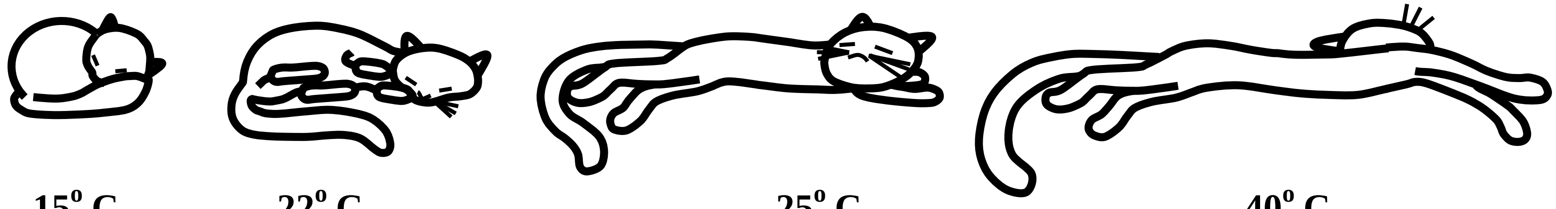
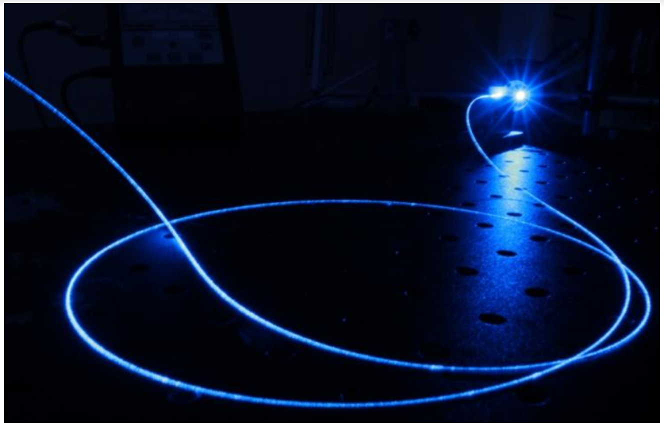


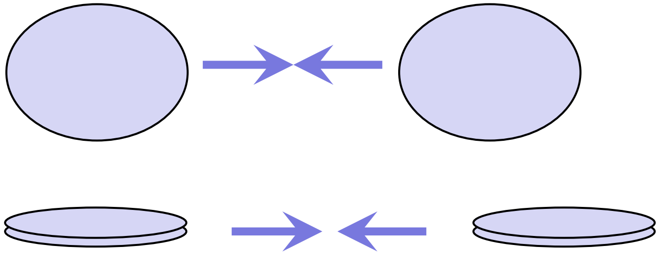
The cat intuitively knows the inventive principle of surface to volume ratio

- **Fiber lasers use the principle of a large surface to volume ratio**
  - **The possibility of high power, high repetition rate, high efficiency**

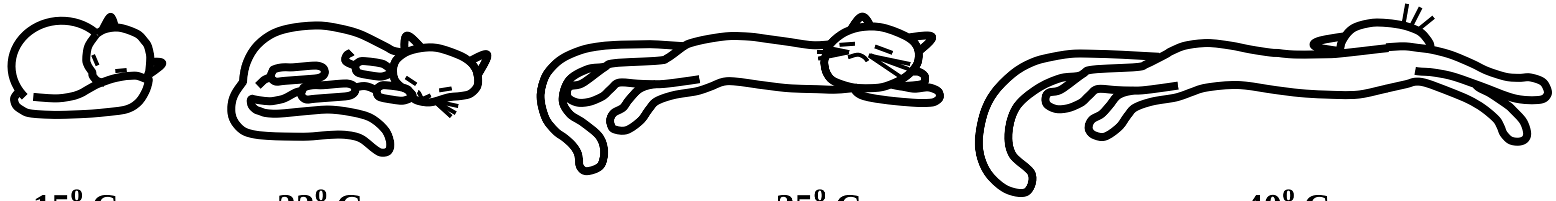


So, you just saw that

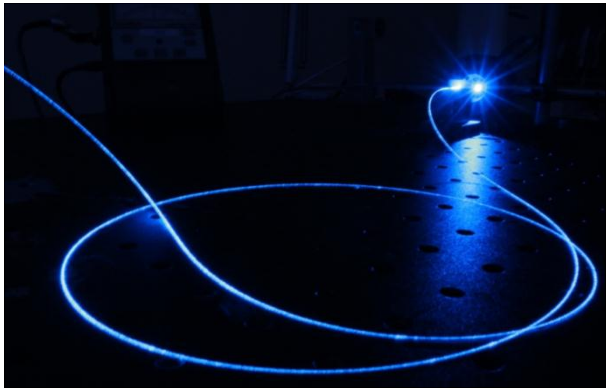
colliding beams…



cats…



The cat intuitively knows the inventive principle of surface to volume ratio



and fibre lasers…

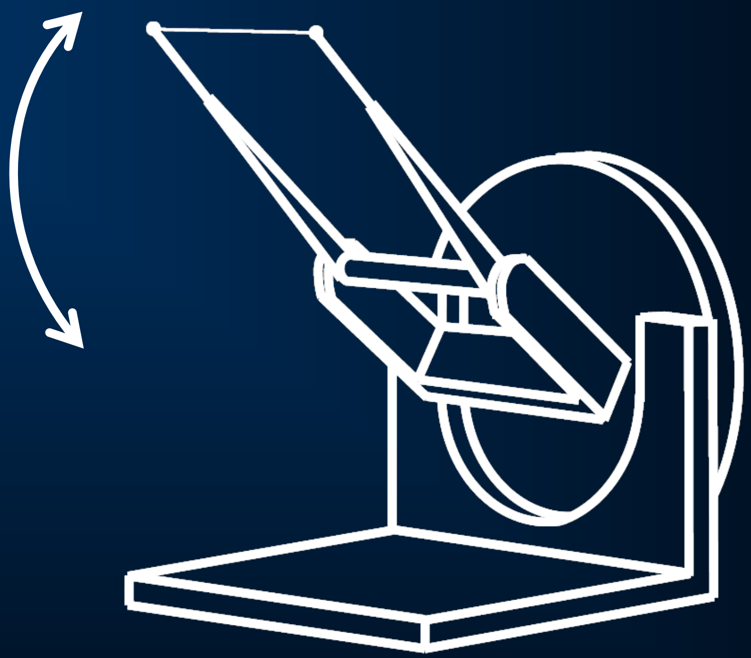
…are <u>connected via TRIZ inventive principles!</u>

Imperial College London
Royal Holloway University of London
UNIVERSITY OF OXFORD

Lasers and beam diagnostics

Lasers are often used to measure parameters of the beams in accelerators

But traditionally "simple" mechanical devices have been used

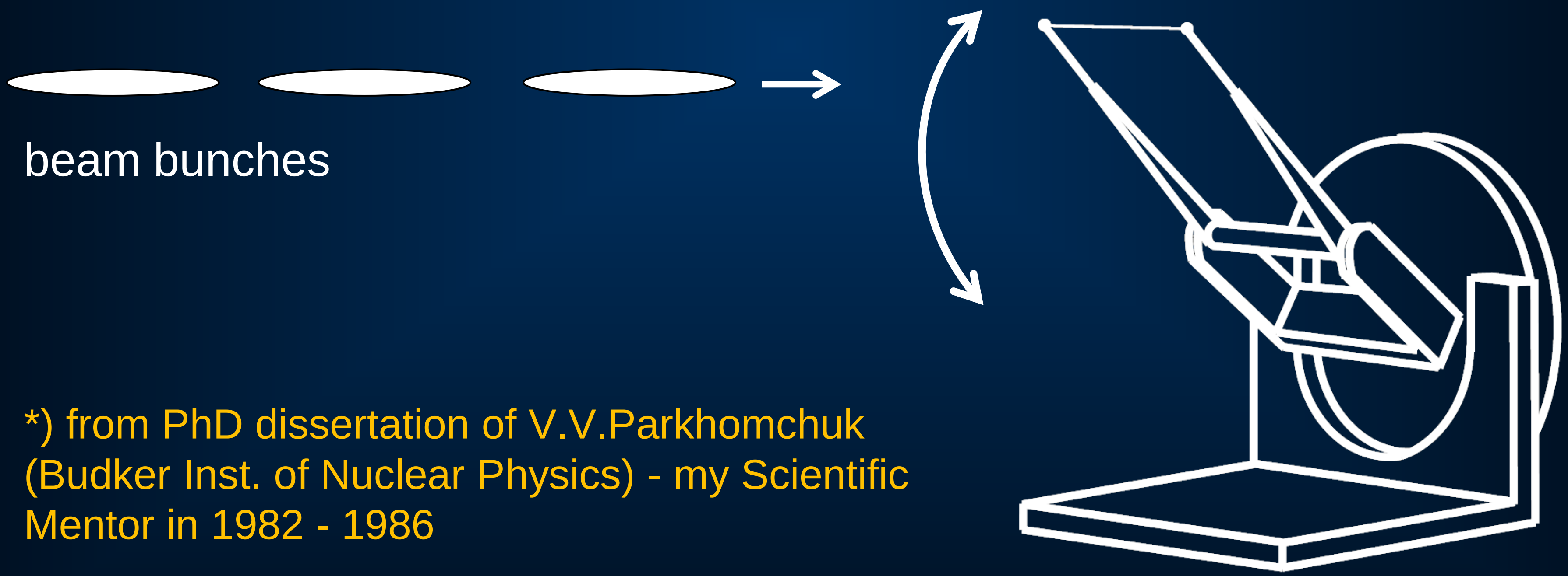


Wires for the beam profile monitor should be very thin ...

Romantic methods in physics

Sometimes thin wires for beam diagnostics were made ...

*"... With a romantic crossbow shooting method * ..."*



*) from PhD dissertation of V.V.Parkhomchuk (Budker Inst. of Nuclear Physics) - my Scientific Mentor in 1982 - 1986

Romantic methods in physics

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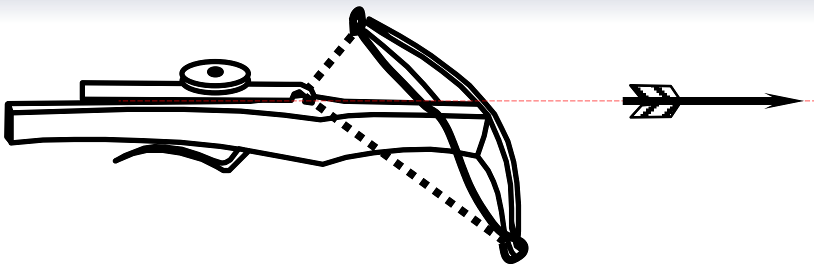


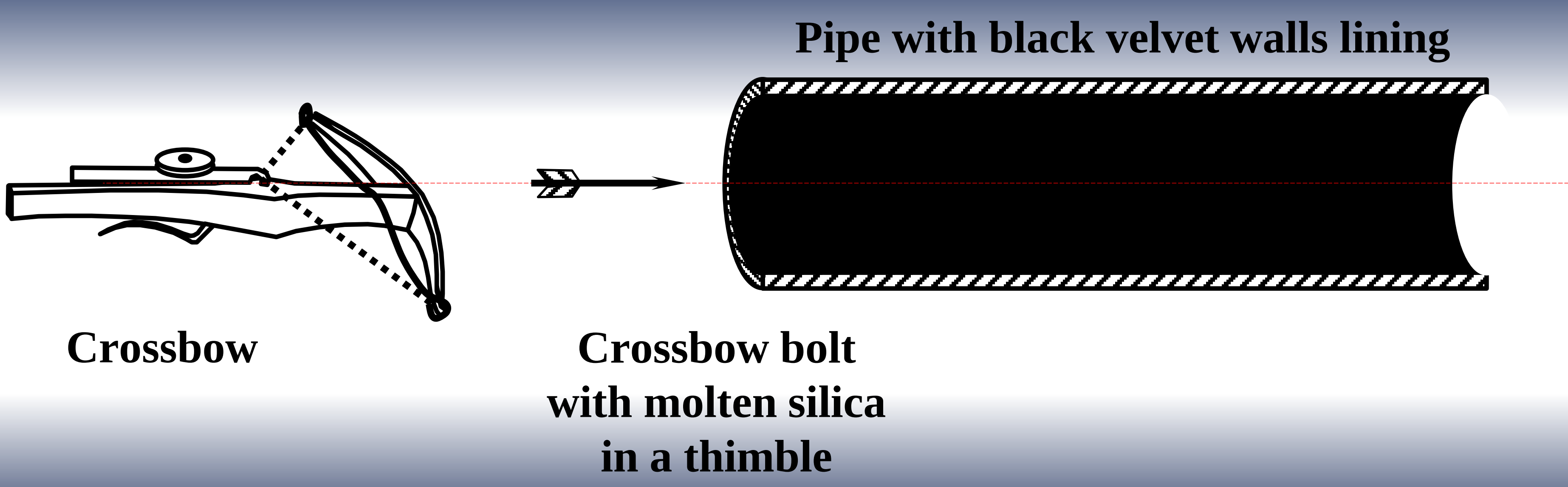
Crossbow

Crossbow bolt with molten silica in a thimble

Romantic methods in physics

Sometimes thin wires for beam diagnostics were made ...

*"... With a romantic crossbow shooting method * ..."*



Romantic methods in physics

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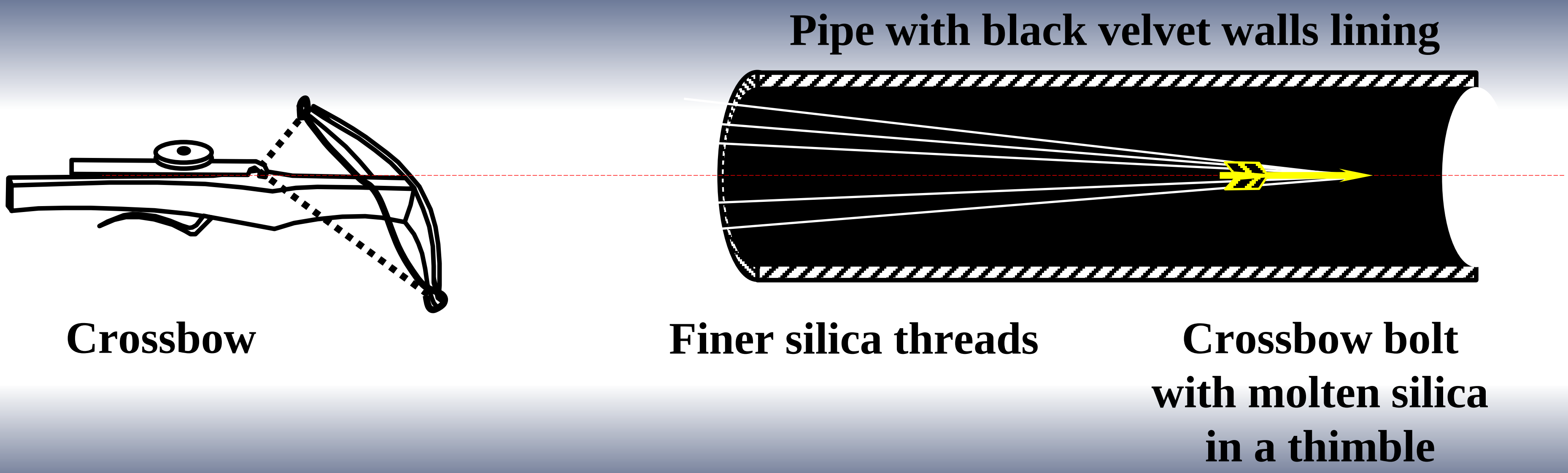
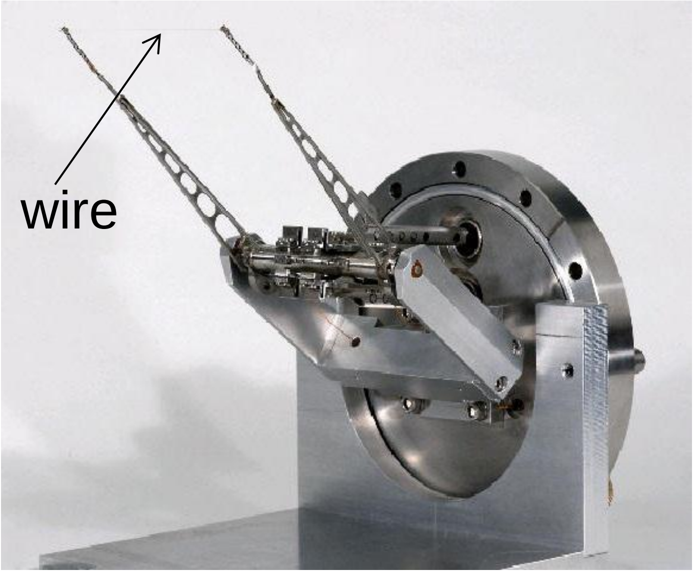


And yet, how laser can help here?



Beam profile monitor with tungsten or carbon wire

Problem:

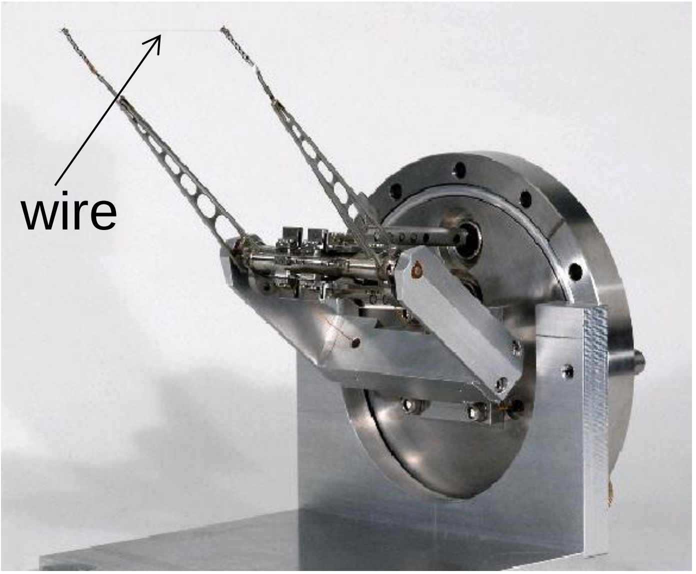
As intensity of the beam increase, the wire get damaged after a single use

Contradiction:

To be improved: INTENSITY

What gets worse: INTEGRITY

And yet, how laser can help here?



Beam profile monitor with tungsten or carbon wire

Problem:

As intensity of the beam increase, the wire get damaged after a single use

Contradiction:

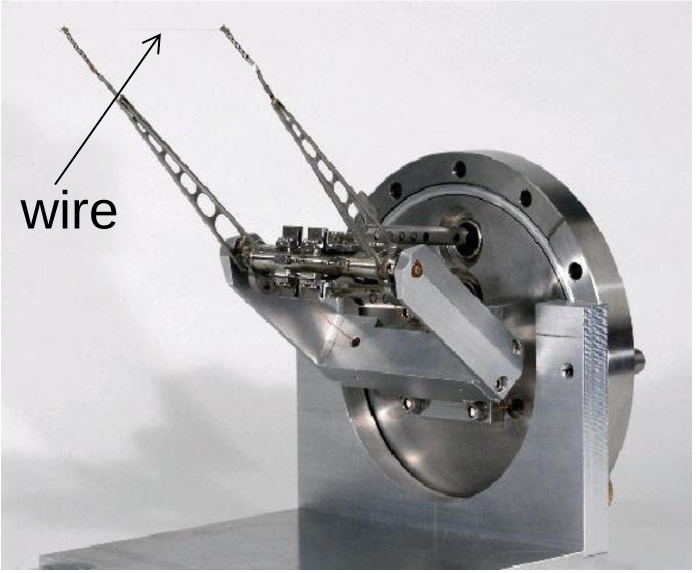
To be improved: INTENSITY

What gets worse: INTEGRITY

We look at the AS-TRIZ matrix:

Improving Parameter	Parameter that deteriorates			
	…	…	**9. Integrity**	…
…				
6. Intensity			**3, …**	
…				

And yet, how laser can help here?



Beam profile monitor with tungsten or carbon wire

Problem:

As intensity of the beam increase, the wire get damaged after a single use

Contradiction:

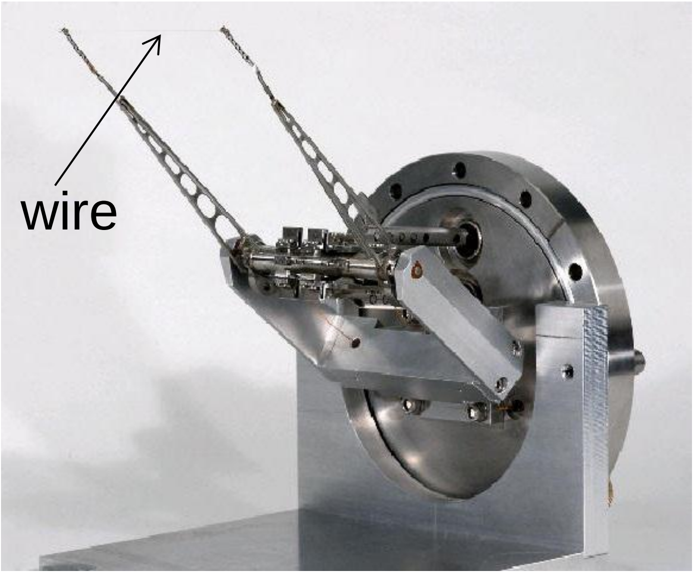
To be improved: INTENSITY

What gets worse: INTEGRITY

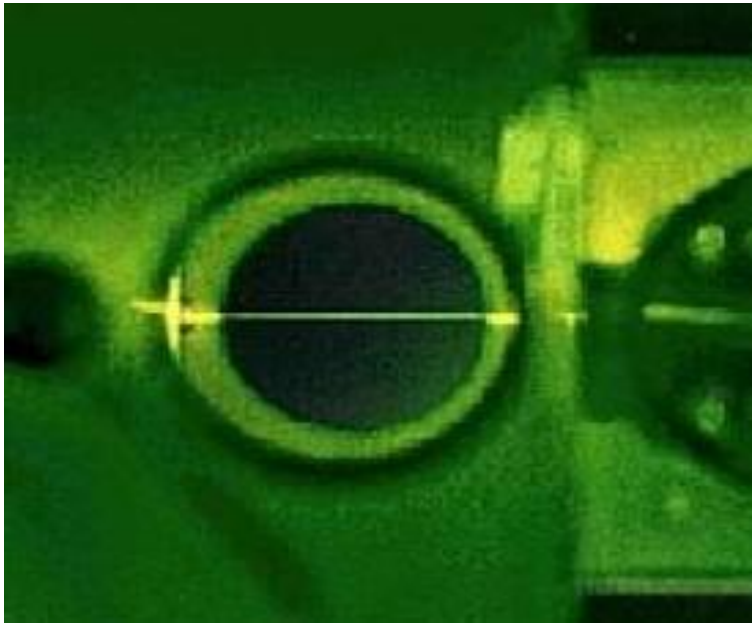
And select one of the inventive principles of emerging AS-TRIZ:

- **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

Indestructible laser wire!



Beam profile monitor with tungsten or carbon wire



Beam profile monitor with laser beam as the “wire”

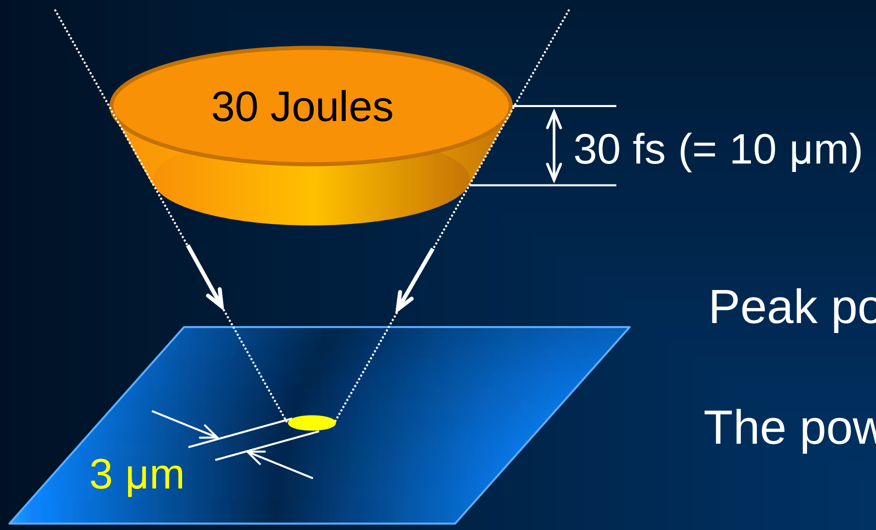
Solution:

Then we apply this AS-TRIZ inventive principle:

- **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already “damaged” (e.g. plasma)**

Contemporary high-power lasers

... are impressive



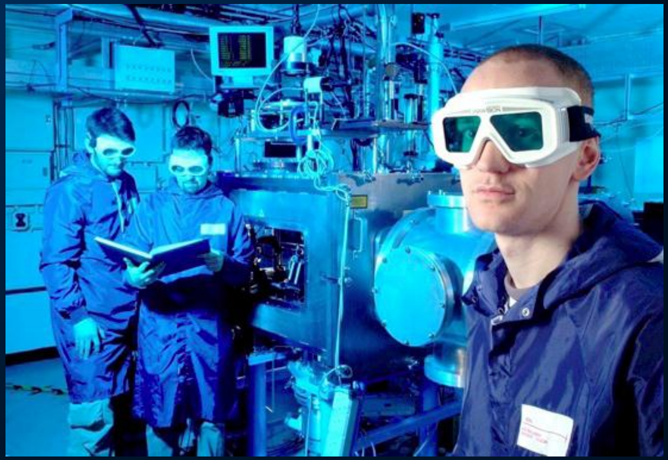
Peak power 10^{15} W

The power density at the focus is 10^{22} W/cm^2

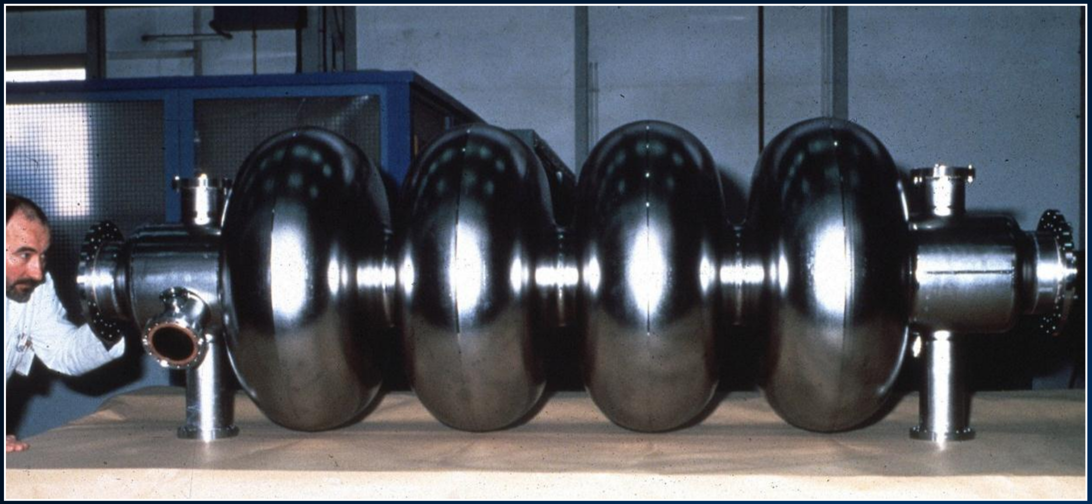
Laser of this power instantly ionizes any substance

Electrons carried along by the field of such a laser instantly become relativistic...

…although conventional resonators usually used for such acceleration



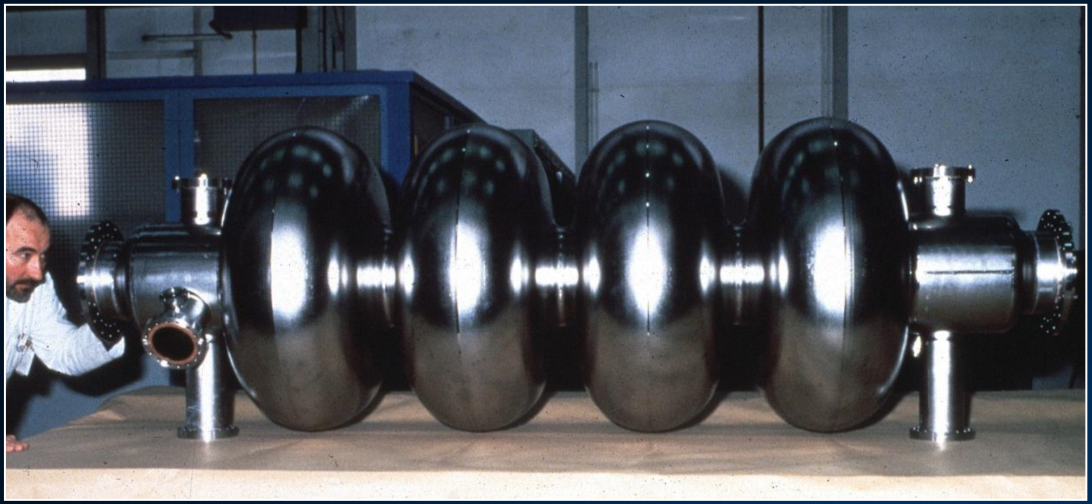
Resonators for particle acceleration



Superconducting Nb accelerating structures

Conventional, Cu

Limits of resonators for acceleration



Superconducting Nb accelerating structures

Conventional, Cu

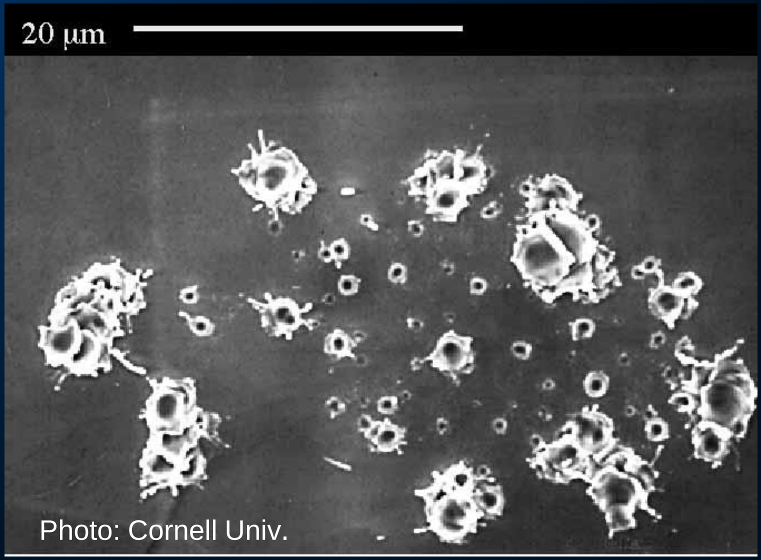
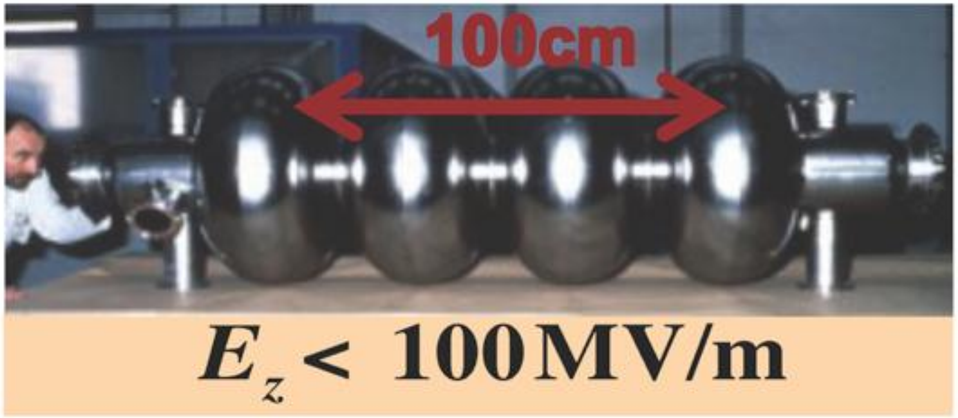


Photo: Cornell Univ.

Problem:
As rate of E change (accelerating gradient) increases, the surface of cavities get damaged by occasional breakdowns

Lasers and particle acceleration



Accelerating structure, metal (normal conductive or super-conductive)

Problem:

As rate of E change (accelerating gradient) increase, the surface of cavities get damaged by occasional breakdowns

Contradiction:

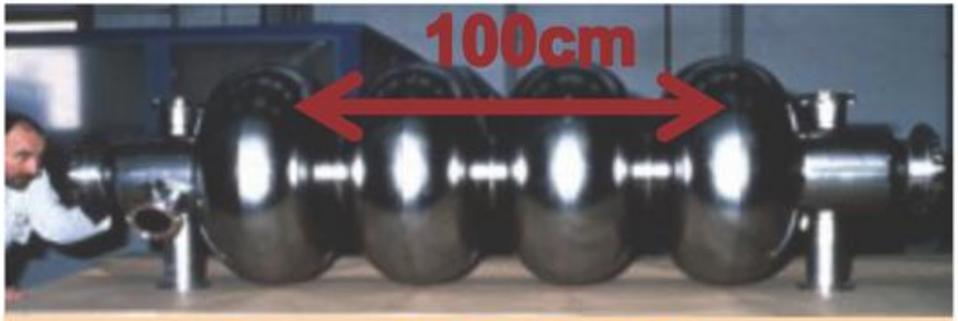
To be improved: Rate of E change

What gets worse: INTEGRITY

Select one of the inventive principles of emerging AS-TRIZ:

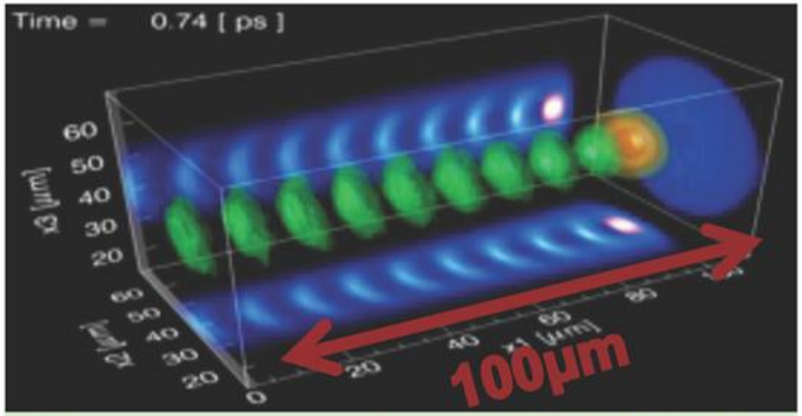
- **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already "damaged" (e.g. plasma)**

Lasers and particle acceleration



$$E_z < 100\,\mathrm{MV/m}$$

Accelerating structure, metal (normal conductive or super-conductive)



$$E_z = m_e c\omega_p / e \approx 100\,\mathrm{GV/m}$$

“Accelerating structure” produced on-the-fly in plasma by laser pulse

Solution:

Then apply this inventive AS-TRIZ principle:

- **3: Replace material that can be damaged with other media, which either cannot be damaged (light) or already “damaged” (e.g. plasma)**

More info on these subjects…

The book, "Unifying Physics of Accelerators, Lasers and Plasma" (by A.Seryi), published by CRC Press / Taylor & Francis in August 2015

This book includes detailed descriptions of the topic discussed in this lecture – the theory of inventive problem solving in application to science and the method of Accelerating Science TRIZ (AS-TRIZ), and uses this method throughout the book in applications to accelerators, lasers and plasma

The book is suitable for students of various levels between senior undergraduate and graduate students… and could also be useful for anyone interested in scientific innovations

http://www.crcpress.com/product/isbn/9781482240580


BEAM
DELIVERY
ILC
ILC
ERMC
ELK RIVER MACHINE CO.
Thanks to Bill Barletta for the picture

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Thanks to you for attention!