Second International Accelerator School for Linear Colliders

Lecture 1: Introduction and Overview

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Course Content

Lecture:

1. Introduction and overview (Nick Walker, DESY)
2. Sources & bunch compressors (Masao Kuriki, KEK)
3. Damping Rings (Andy Wolski, CI)
4. Linac (Peter Tenenbaum, SLAC)
5. Low-Level and High-Power RF (Stefan Simrock, DESY)
6. Superconducting RF (Kenji Saito, KEK)
7. Beam Delivery System and Beam-Beam (Andrei Seryi, SLAC)
8. Instrumentation and Controls (Marc Ross, FNAL)
9. Operations (Marc Ross, FNAL)
10. Compact Linear Collider, CLIC (Frank Tecker, CERN)
11. Conventional Facilties (Atsushi Enomoto, KEK)
12. Physics and Detectors (Jim Brau, Univ. of Oregon)

This Lecture

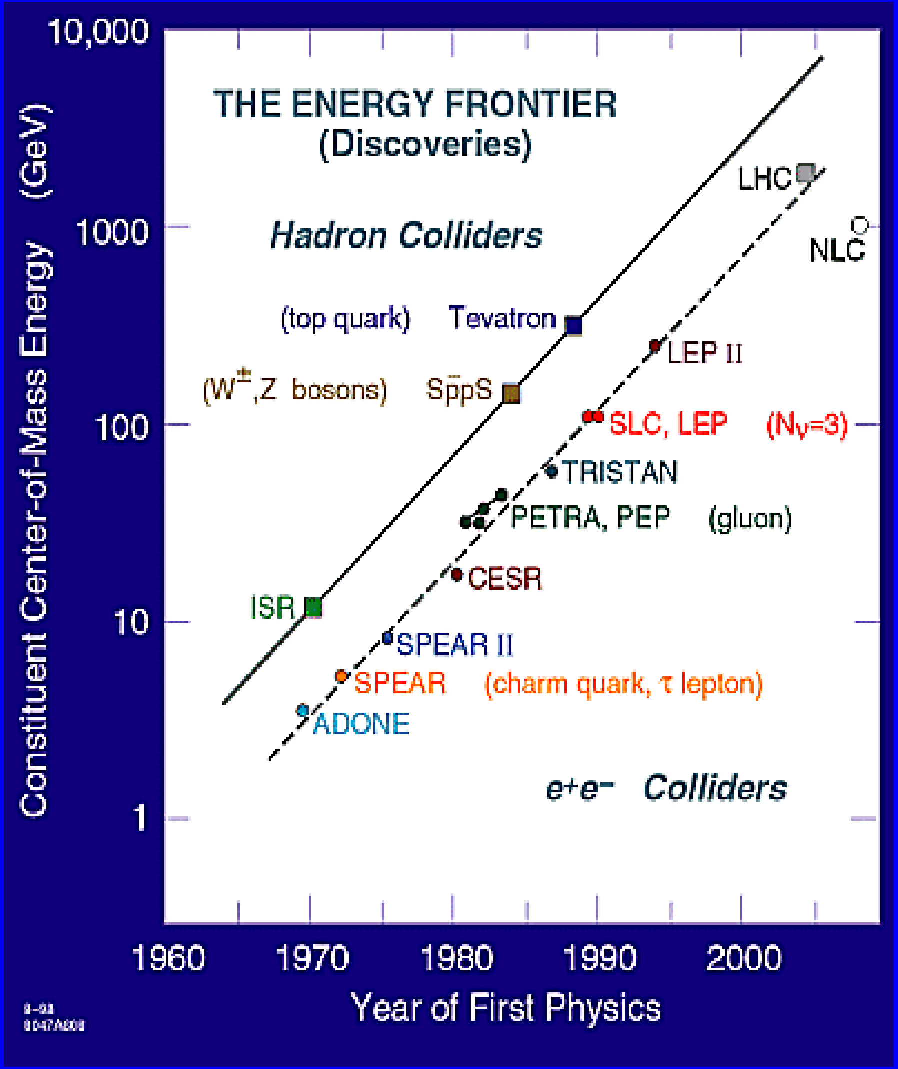
- Why LC and not super-LEP?
- The Luminosity Problem
  - general scaling laws for linear colliders
- A introduction to the linear collider sub-systems and key parameters:
  - main accelerator (linac)
  - sources
  - damping rings
  - bunch compression
  - final focus

We will be fast!

But you will here it all again in detail over the next two weeks

during the lecture, we will introduce (revise) some important basic accelerator physics concepts that we will need in the remainder of the course.

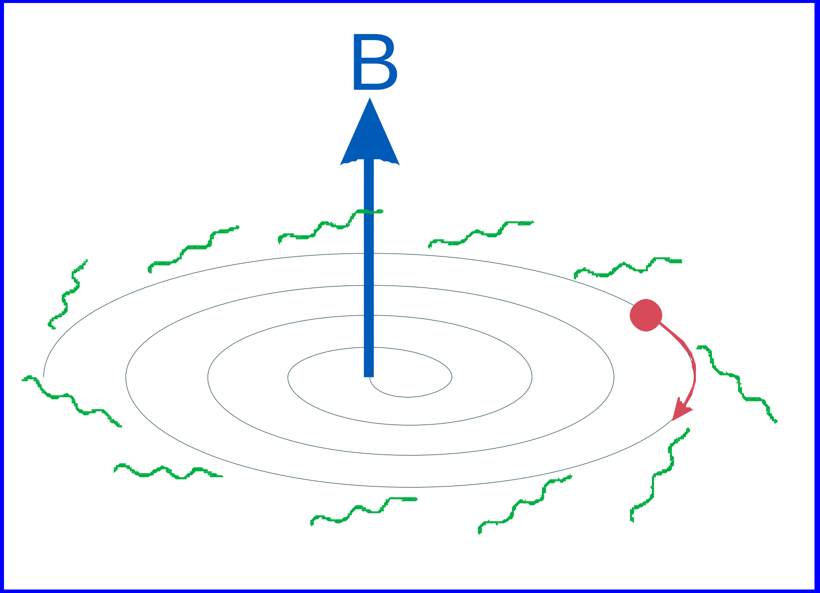
Energy Frontier e^+e^- Colliders



LEP at CERN, CH
E_{cm} = 180 GeV
P_{RF} = 30 MW

Why a Linear Collider?

Synchrotron Radiation from an electron in a magnetic field:



$$P_\gamma = \frac{e^2 c^2}{2\pi} C_\gamma E^2 B^2$$

Energy loss per turn of a machine with an average bending radius ρ:

$$\Delta E / rev = \frac{C_\gamma E^4}{\rho}$$

Energy loss must be replaced by RF system

Cost Scaling $$

- Linear Costs: (tunnel, magnets etc)

$$\$_{lin} \propto \rho$$

- RF costs:

$$\$_{RF} \propto \Delta E \propto E^4/\rho$$

- Optimum at

$$\$_{lin} = \$_{RF}$$

Thus optimised cost ($\$_{lin}+\$_{RF}$) scales as E^2

The Bottom Line $$$

		LEP-II	Super-LEP	Hyper-LEP
E_{cm}	GeV	180	500	2000
L	km	27		
ΔE	GeV	1.5		
$\$_{tot}$	10^9 SF	2		

The Bottom Line $$$

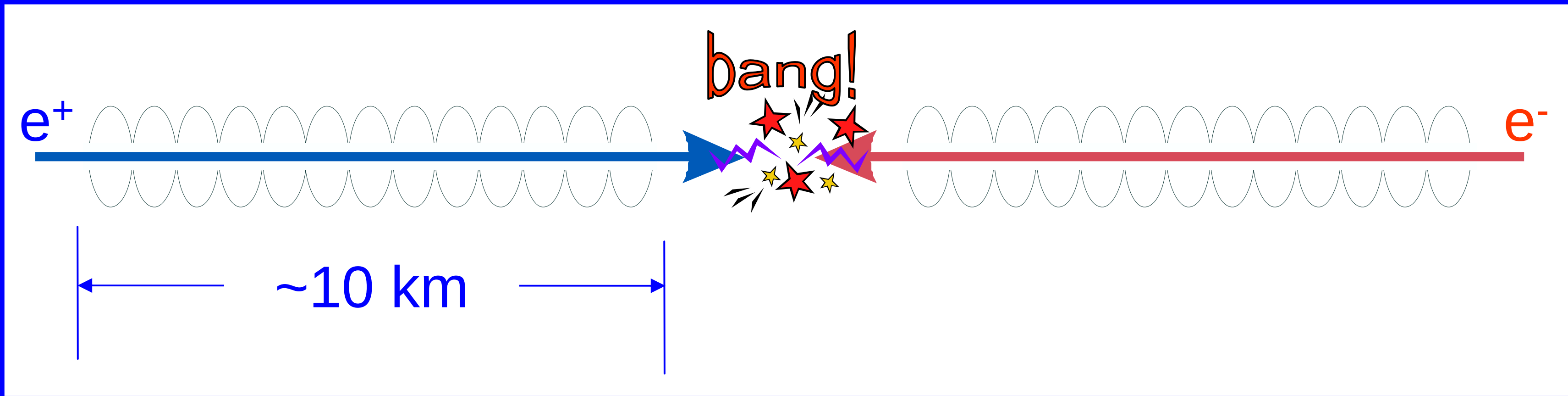
		LEP-II	Super-LEP	Hyper-LEP
E_{cm}	GeV	180	500	2000
L	km	27	200	
ΔE	GeV	1.5	12	
$\$_{tot}$	10^9 SF	2	15	

The Bottom Line $$$

		LEP-II	Super-LEP	Hyper-LEP
E_{cm}	GeV	180	500	2000
L	km	27	200	3200
ΔE	GeV	1.5	12	240
$\$_{tot}$	10^9 SF	2	15	240

solution: Linear Collider

No Bends, but *lots* of RF!



- long *linac* constructed of many RF accelerating structures
- Gradient ~30 MV/m

Note: for LC, $\$_{tot} \propto E$

A Little History

A Possible Apparatus for Electron-Clashing Experiments (*).

M. Tigner

Laboratory of Nuclear Studies. Cornell University - Ithaca, N.Y.

M. Tigner,
Nuovo Cimento **37** (1965) 1228

“While the storage ring concept for providing clashing-beam experiments ([1]) is very elegant in concept it seems worth-while at the present juncture to investigate other methods which, while less elegant and superficially more complex may prove more tractable.”

A Little History (1988-2003)

- SLC (SLAC, 1988-98)
- NLCTA (SLAC, 1997-)
- TTF (DESY, 1994-, now FLASH)
- ATF (KEK, 1997-)
- FFTB (SLAC, 1992-1997)
- SBTF (DESY, 1994-1998)
- CLIC CTF1,2,3 (CERN, 1994-)

- ILCTA (FNAL, 2007-)
- STF (KEK, 2006-)
- ATF-II (KEK, 2007-)

Nearly ~20 Years of Linear Collider R&D

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ILC relevant

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Nearly ~20 Years of Linear Collider R&D

ILC SCRF relevant

Past and Future

	SLC	ILC	
E_{cm}	100	500 (1000)	GeV
P_{beam}	0.04	10 (20)	MW
σ^*_y	500 (≈50)	3–5	nm
$\delta E/E_{\mathrm{bs}}$	0.03	~3	%
L	0.0003	~2	10^{34} cm^{-2}s^{-1}

generally quoted as ‘proof of principle’

but we have a very long way to go!

The *Luminosity* Issue

Collider luminosity (cm^{-2} s^{-1}) is approximately given by

$$L = \frac{n_b N^2 f_{rep}}{A} H_D$$

where:

N_b = bunches / train
N = particles per bunch
f_{rep} = repetition frequency
A = beam cross-section at IP
H_D = beam-beam enhancement factor

For *Gaussian* beam distribution:

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

The *Luminosity* Issue: RF Power

Introduce the centre of mass energy, E_{cm}:

$$L = \frac{\left(E_{cm} n_b N f_{rep}\right) N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

$$\begin{aligned} n_b N f_{rep} E_{cm} &= P_{beams} \\ &= \eta_{RF \to beam} P_{RF} \end{aligned}$$

η_{RF} is RF to beam power efficiency.

Luminosity is proportional to the *RF power* for a given E_{cm}

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

The *Luminosity* Issue: RF Power

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

Some rough ILC numbers:

$$\left.\begin{array}{ll} E_{cm} & = 500\ \mathrm{GeV} \\ N & = 2\times 10^{10} \\ n_b & = 3000 \\ f_{rep} & = 5\ \mathrm{Hz} \end{array}\right\} \quad P_{beams} \sim 2\times 10\ \mathrm{MW}$$

Need to include efficiencies:

RF→beam: ~ 60% (SCRF)

Wall plug →RF: ~ 50%

Linac average AC power ~70 MW just to accelerate beams and <u>achieve luminosity</u>

The *Luminosity* Issues: storage ring *vs* LC

LEP $f_{rep} = 44$ kHz

ILC $f_{rep} = 5$ Hz
(power limited)

$$L = \frac{\eta_{RF} P_{RF} N}{4\pi \sigma_x \sigma_y E_{cm}} H_D$$

$\Rightarrow$ factor 8800 in L already lost!

Must push very hard on beam cross-section at collision:

LEP: $\sigma_x \sigma_y \approx 130 \times 6\ \mu\text{m}^2$

ILC: $\sigma_x \sigma_y \approx 500 \times (3\text{-}5)\ \text{nm}^2$

factor of 10^6 gain!
Needed to obtain high luminosity of a few 10^{34} cm^{-2}s^{-1}

The *Luminosity* Issue: intense beams at IP

$$L = \frac{1}{4\pi E_{cm}} \left(\eta_{RF} P_{RF} \right) \left(\frac{N}{\sigma_x \sigma_y} H_D \right)$$

SCRF:

- efficiency
- available power

Beam-Beam effects:

- beamstrahlung
- disruption

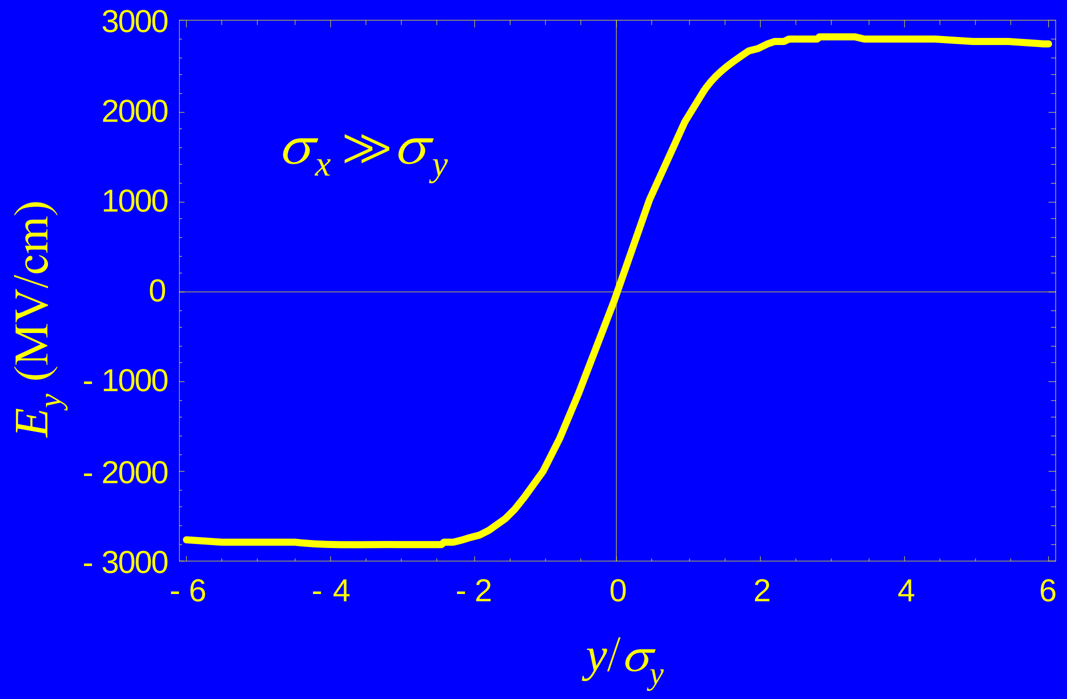
Strong focusing

- optical aberrations
- stability issues and tolerances

The *Luminosity* Issue: Beam-Beam

see lecture 7 on beam-beam

- strong mutual focusing of beams (pinch) gives rise to luminosity enhancement H_D
- As $e^{\pm}$ pass through intense field of opposing beam, they radiate hard photons [beamstrahlung] and loose energy
- Interaction of *beamstrahlung* photons with intense field causes copious $e^{+}e^{-}$ pair production [background]



The *Luminosity* Issue: Beam-Beam

see lecture 7 on beam-beam

beam-beam characterised by *Disruption Parameter:*

$$D_{x,y} = \frac{2 r_e N \sigma_z}{\gamma \sigma_{x,y}\left(\sigma_x + \sigma_y\right)} \approx \frac{\sigma_z}{f_{beam}}$$

σ_z = bunch length,

f_{beam} = *focal length* of beam-lens

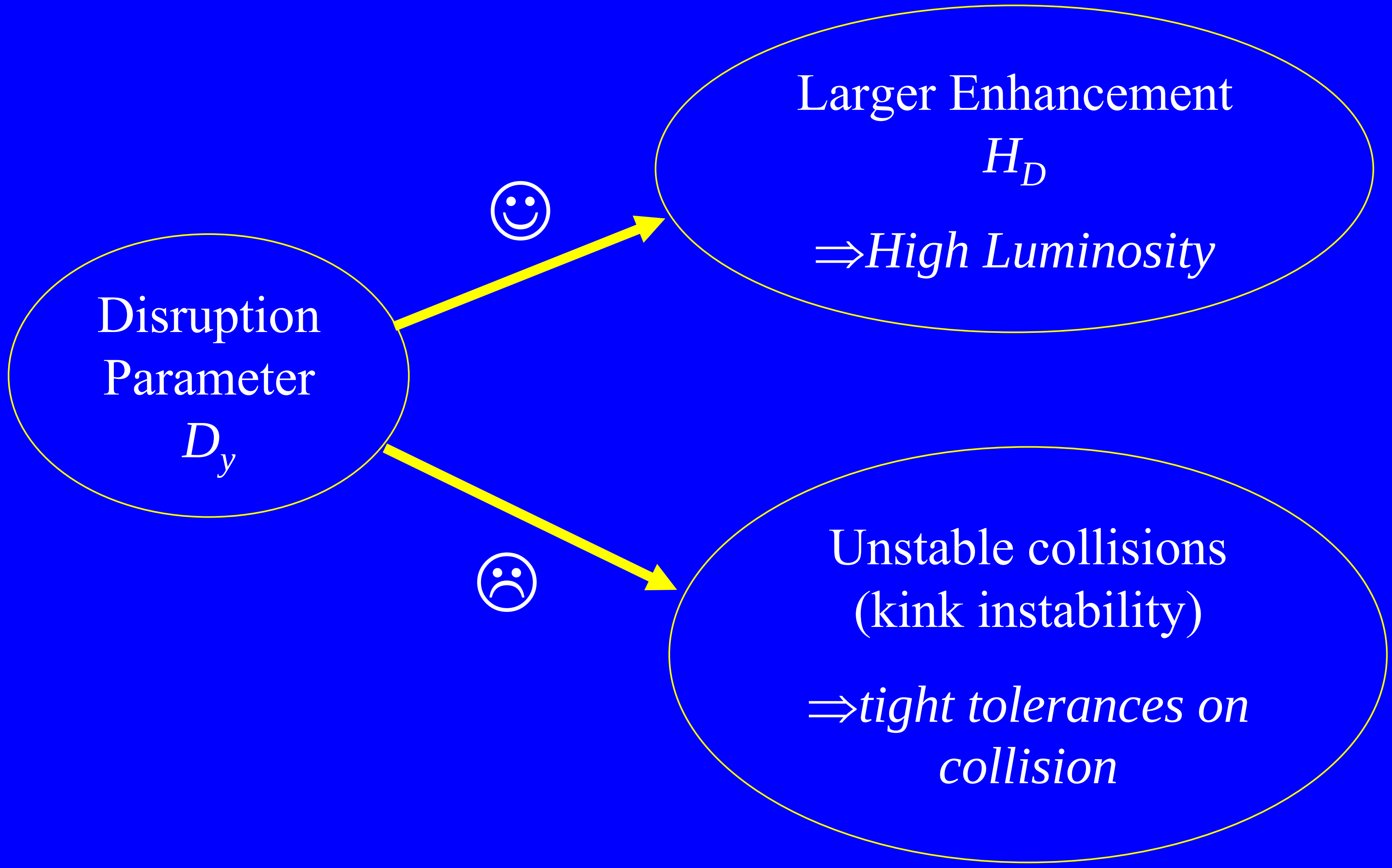
for storage rings, $f_{beam} \gg \sigma_z$ and $D_{x,y} \ll 1$

For ILC, $D_y \approx 10$ hence $f_{beam} < \sigma_z$

Enhancement factor (typically H_D ~ 1.5-2):

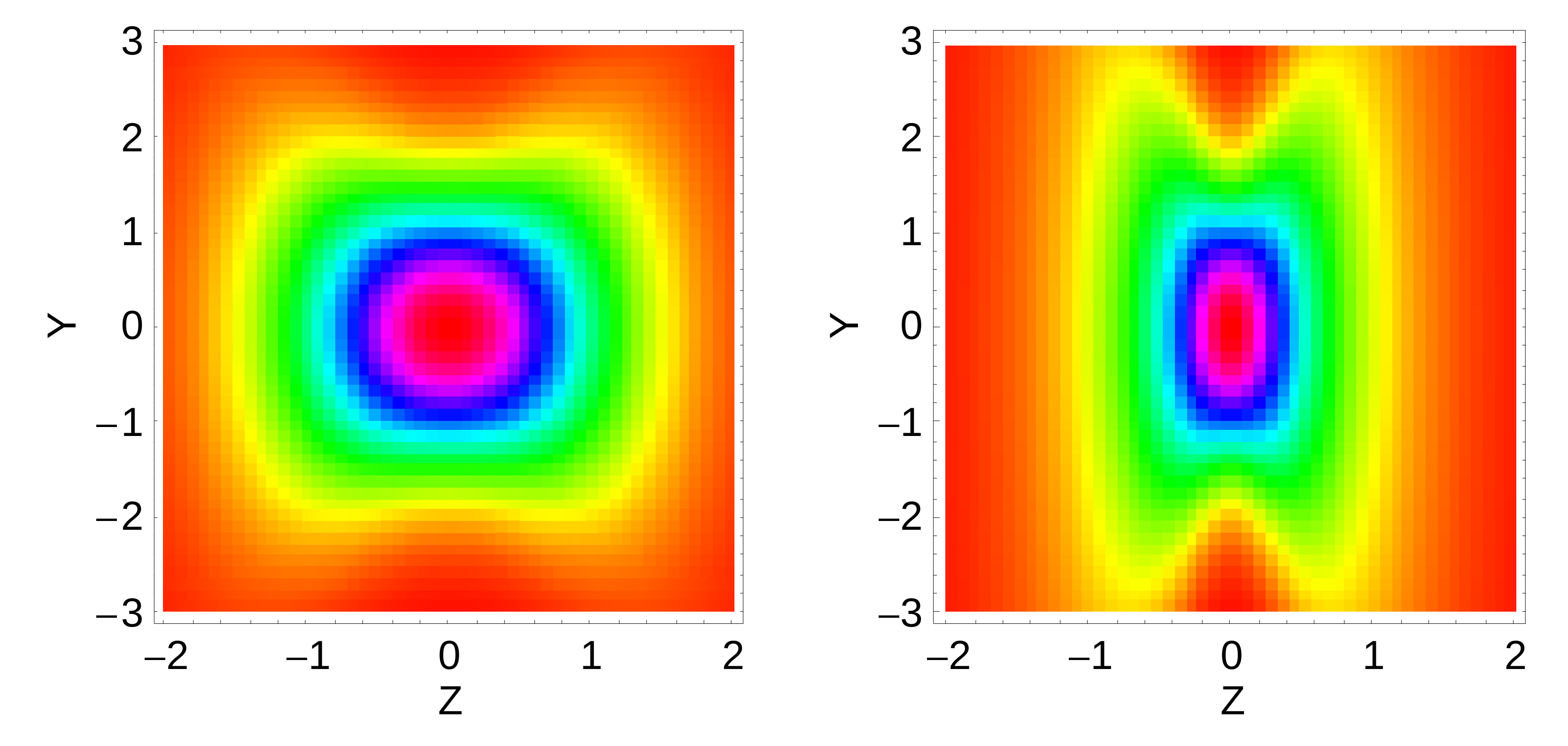
$$H_{Dx,y} = 1 + D_{x,y}^{1/4}\left(\frac{D_{x,y}^3}{1 + D_{x,y}^3}\right)\left[\ln\left(\sqrt{D_{x,y}} + 1\right) + 2\ln\underbrace{\left(\frac{0.8\beta_{x,y}}{\sigma_z}\right)}_{\text{'hour glass' effect}}\right]$$

The *Luminosity* Issue: Beam-Beam



The *Luminosity* Issue: Hour-Glass

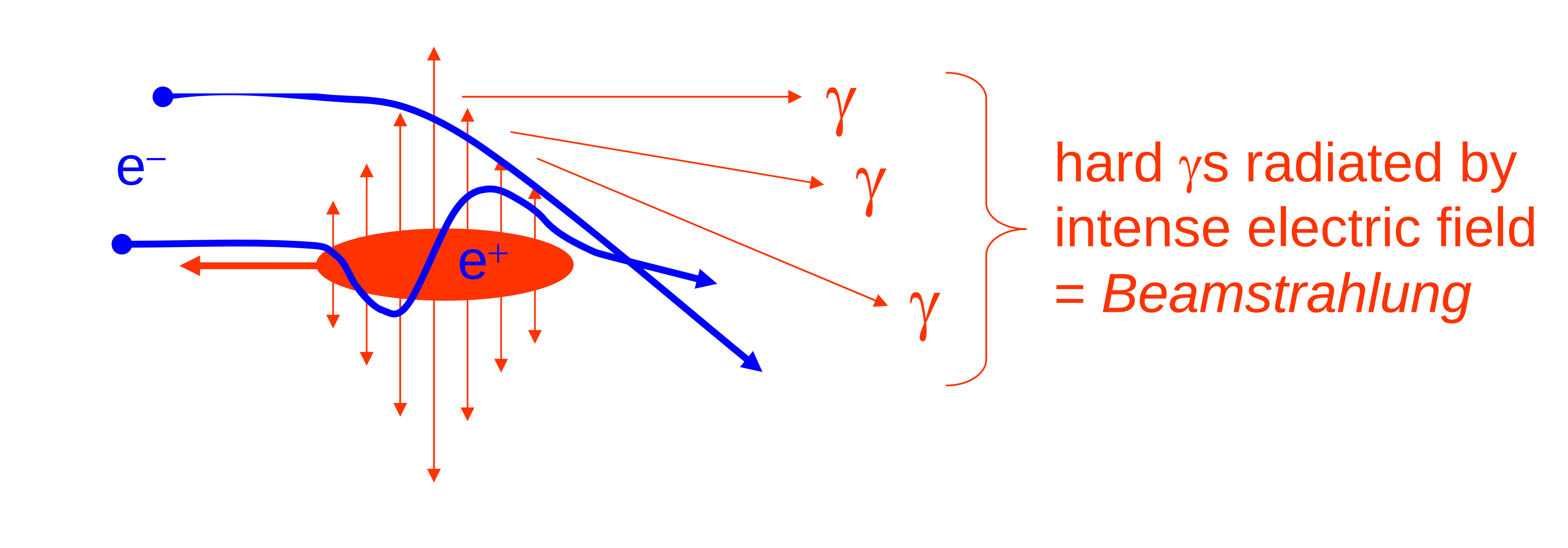
see lecture 7 on beam-beam

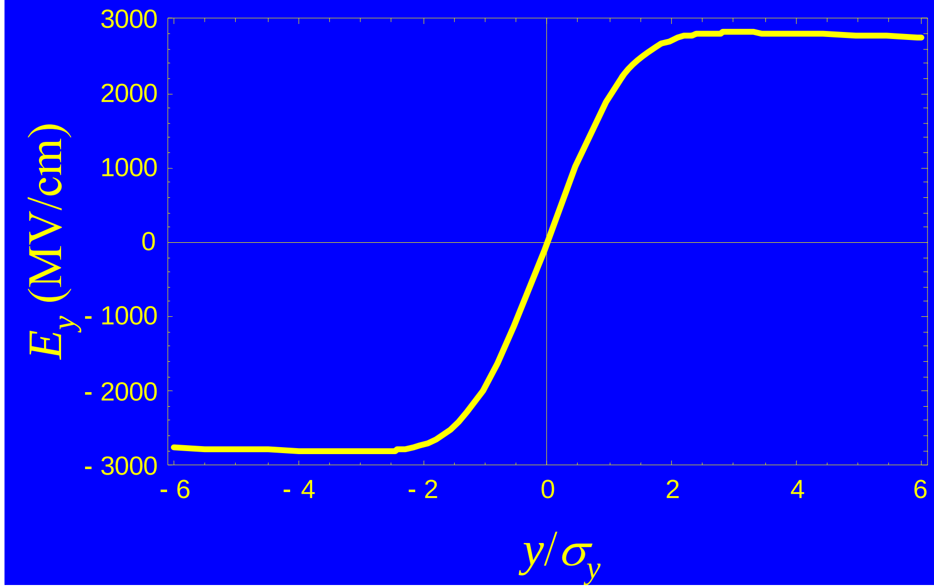


β = "depth of focus"

reasonable lower limit for β is bunch length σ_z

The *Luminosity* Issue: Beamstrahlung





Gives rise to

- average energy loss

- increase in RMS energy spread

in the beams.

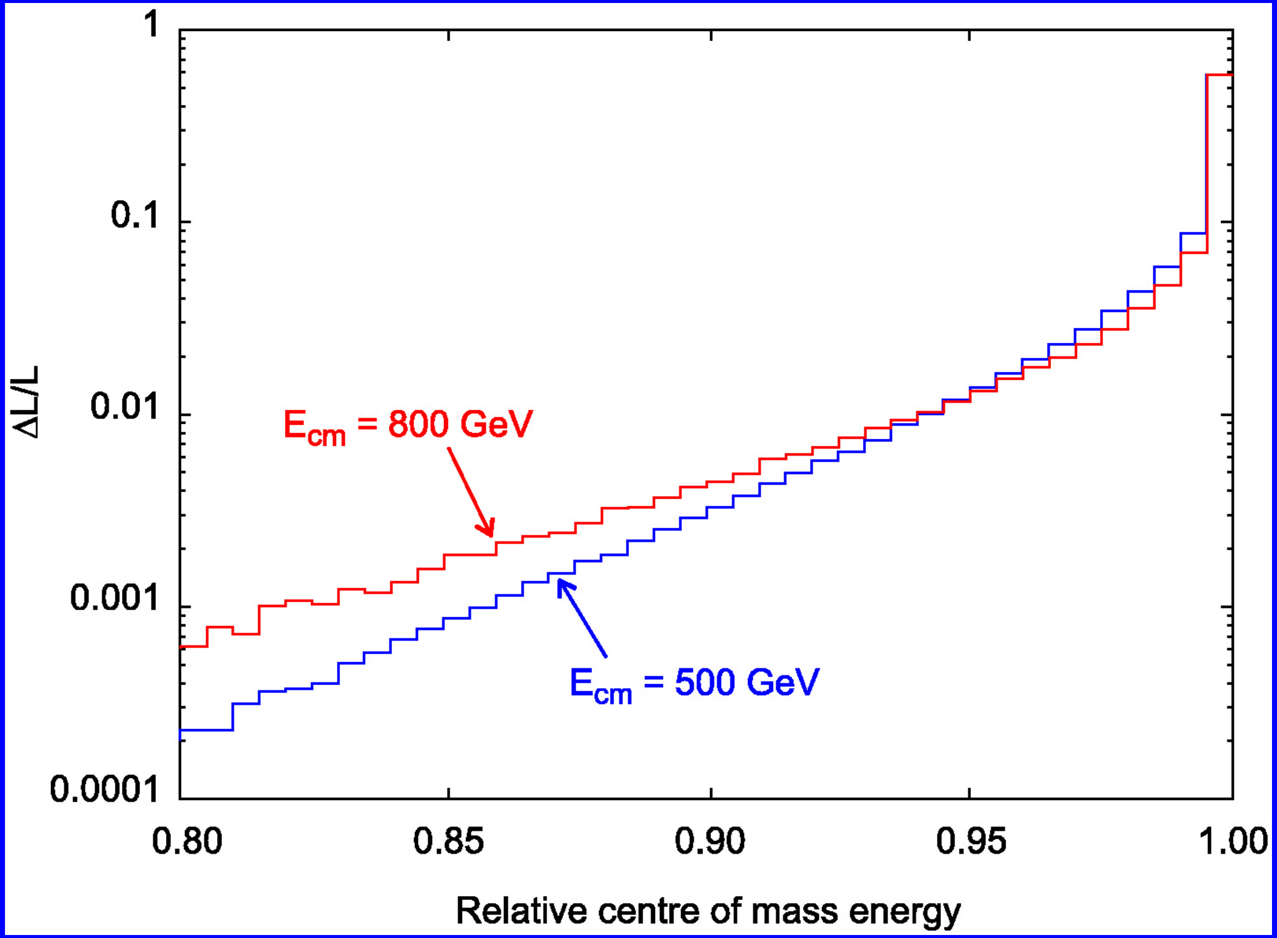
Beamstrahlung

Most important parameter is Υ

$$\Upsilon = \frac{2}{3}\frac{\hbar\omega_c}{E} = \frac{\lambda_e \gamma^2}{\rho} = \gamma \frac{2B}{B_s} = \frac{e}{m_0^2}\sqrt{\left|\left(F_{\mu\nu} p^\nu\right)^2\right|}$$

ω_c	critical photon frequency
λ_e	Compton wavelength
ρ	local bending radius
B	beam magnetic field
B_s	Schwinger's critical field (= 4.4 GTesla)
$F_{\mu\nu}$	em field tensor
p^ν	electron 4-momentum

The *Luminosity* Issue: Beamstrahlung



Example taken from the TESLA Technical Design Report

Emission of high-energy photons causes a degradation in the *luminosity spectrum*

Characteristic long low-energy tail

The *Luminosity* Issue: Beamstrahlung

see lecture 7 on beam-beam

RMS relative energy loss $$\delta_{BS} \approx 0.86 \frac{e r_e^2}{2 m_0 c^2} \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{(\sigma_x + \sigma_y)^2}$$

we would like to make $\sigma_x \sigma_y$ small to maximise luminosity

BUT keep $(\sigma_x + \sigma_y)$ large to reduce δ_{SB}.

Trick: use "flat beams" with $\sigma_x \gg \sigma_y$ $$\delta_{BS} \propto \left(\frac{E_{cm}}{\sigma_z} \right) \frac{N^2}{\sigma_x^2}$$

Now we set σ_x to fix δ_{SB}, and make σ_y as small as possible to achieve high luminosity.

For ILC, $\delta_{SB} \sim 2.4\%$

The *Luminosity* Issue: Beamstrahlung

Returning to our L scaling law, and ignoring H_D

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \left(\frac{N}{\sigma_x} \right) \frac{1}{\sigma_y}$$

From flat-beam beamstrahlung $$\frac{N}{\sigma_x} \propto \sqrt{\frac{\sigma_z \delta_{BS}}{E_{cm}}}$$

hence $$\boxed{L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS} \sigma_z}}{\sigma_y}}$$

The *Luminosity* Issue: story so far

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS}\sigma_z}}{\sigma_y}$$

For high Luminosity we need:

- high RF-beam conversion efficiency η_{RF}
- high RF power P_{RF}
- small vertical beam size σ_y
- large bunch length σ_z (will come back to this one)
- could also allow higher beamstrahlung δ_{BS} if willing to live with the consequences

Next question: *how to make a small* σ_y

The *Luminosity* Issue: A final scaling law?

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \frac{\sqrt{\delta_{BS}\sigma_z}}{\sigma_y} \qquad \sigma_y = \sqrt{\frac{\beta_y \varepsilon_{n,y}}{\gamma}}$$

where $\varepsilon_{n,y}$ is the normalised vertical emittance, and β_y is the vertical β-function at the IP. Substituting:

$$L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}^{3/2}} \sqrt{\frac{\delta_{BS}\gamma}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}} \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} \sqrt{\frac{\sigma_z}{\beta_y}}$$

hour glass constraint

β_y is the same 'depth of focus' β for hour-glass effect. Hence $\beta_y \geq \sigma_z$

The *Luminosity* Issue: A final scaling law?

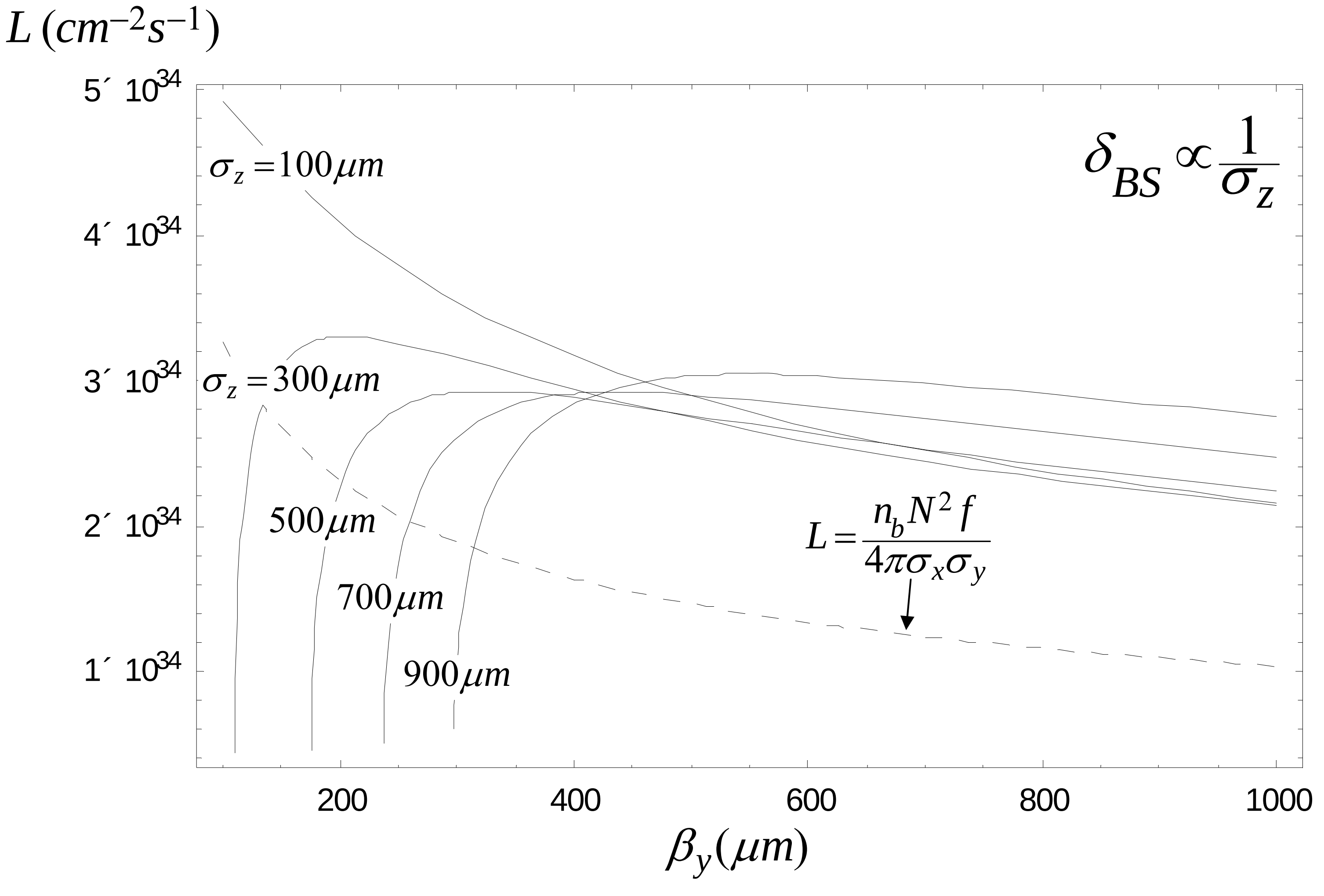
$$\boxed{L \propto \frac{\eta_{RF} P_{RF}}{E_{cm}} \sqrt{\frac{\delta_{BS}}{\varepsilon_{n,y}}} H_D} \qquad \beta_y \approx \sigma_z$$

- high RF-beam conversion efficiency η_{RF}
- high RF power P_{RF}
- small normalised vertical emittance $\varepsilon_{n,y}$
- strong focusing at IP (small β_y and hence <u>small</u> σ_z)
- could also allow higher beamstrahlung δ_{BS} if willing to live with the consequences

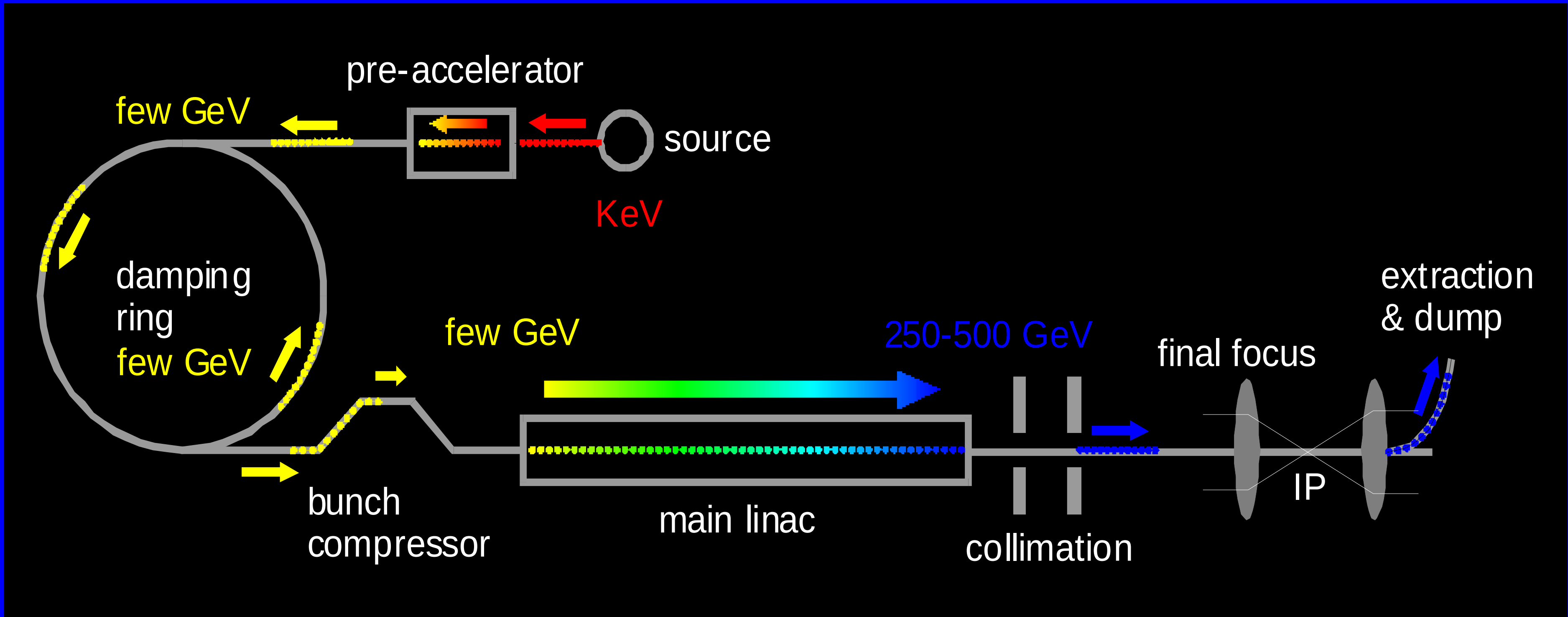
Above result is for the <u>low</u> beamstrahlung regime where $\delta_{BS} \sim$ few %

Slightly different result for <u>high</u> beamstrahlung regime

Luminosity as a function of β_y

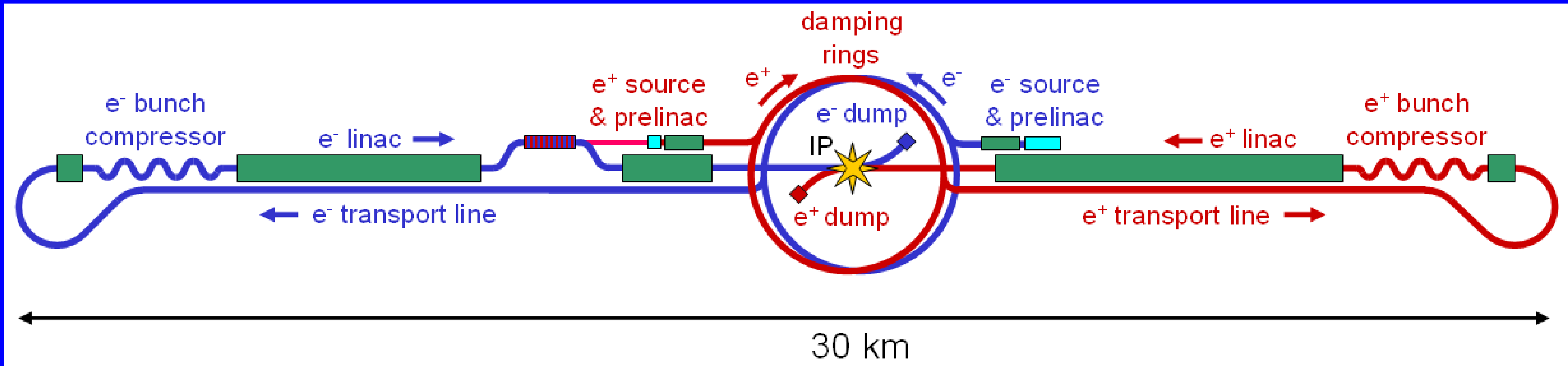


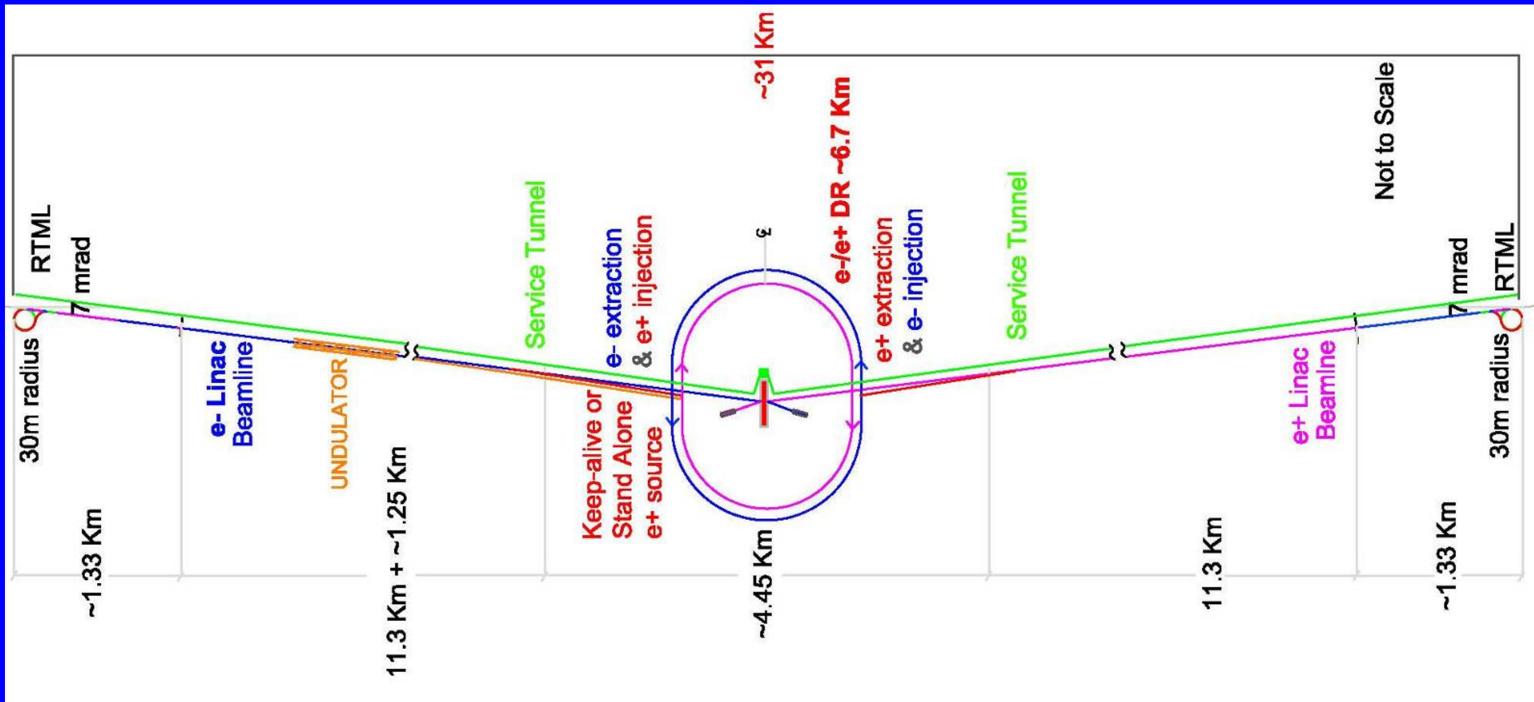
The ‘Generic’ Linear Collider



Each sub-system pushes the state-of-the-art in accelerator design

The ILC Footprint

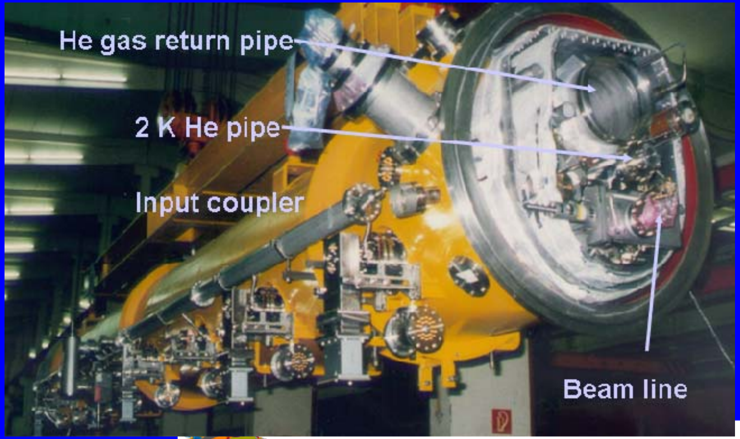




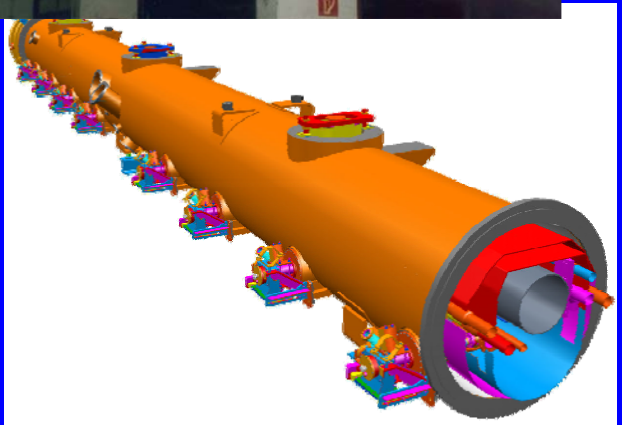
Superconducting RF Linac Technology

"TESLA" 9-cell 1.3GHz SCRF niobium cavity

TTF type-III cryomodule being installed at FLASH, DESY



Type-III TTF cryomodule



Type-IV ILC cryomodule, containing 9 nine-cell cavities

Superconducting RF Linac Technology

Multibeam Klystrons
(RF Power Source)

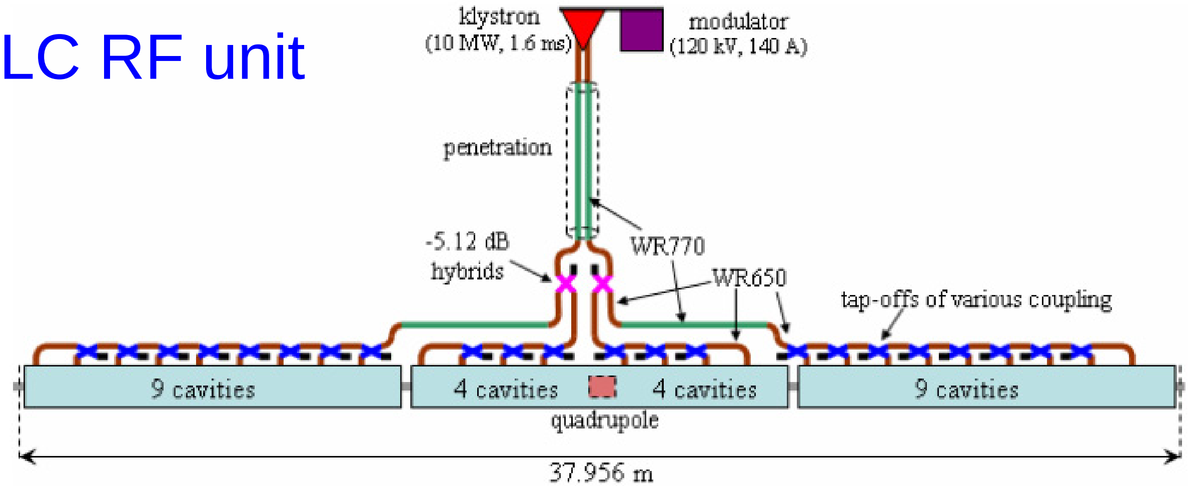
10MW MBK

1.5ms pulse

65% efficiency

see lecture 5 on
LL and HP RF

ILC RF unit



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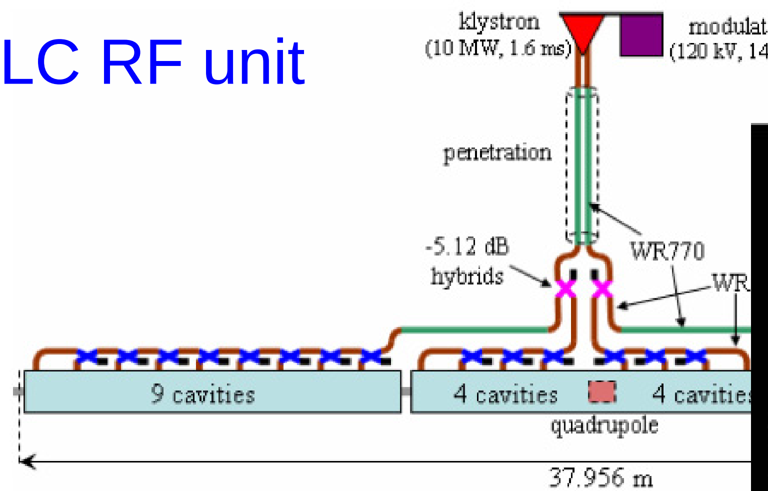
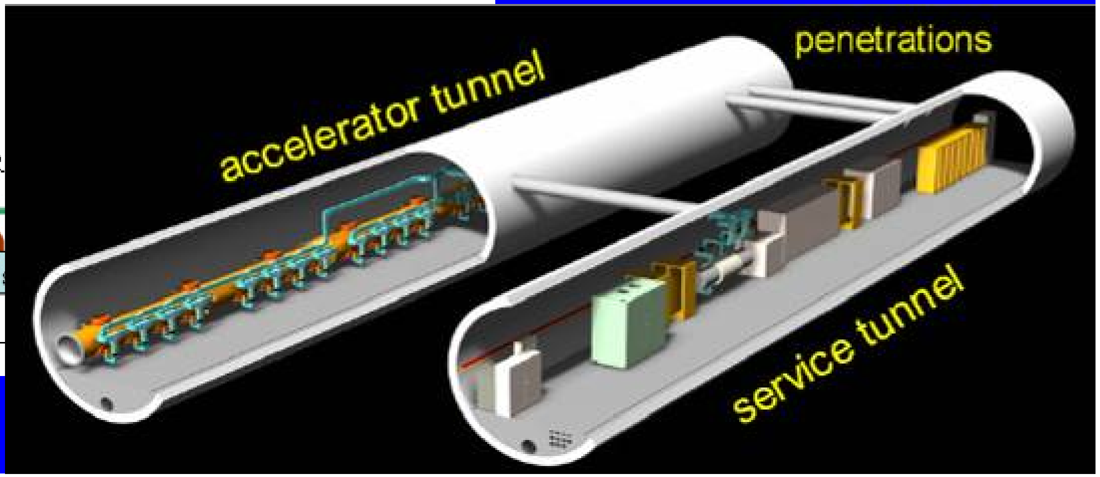
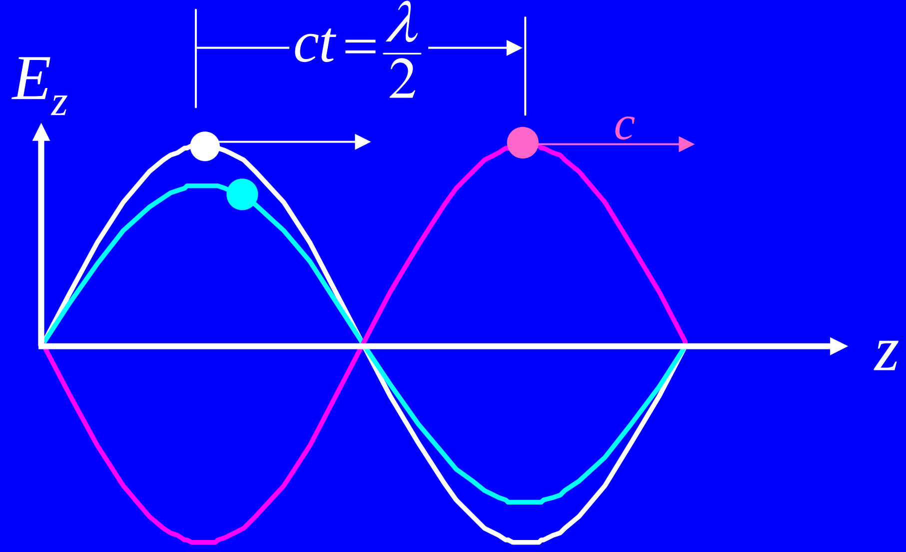




The Linear Accelerator (LINAC)

see lectures 4 on linac



standing wave cavity:

bunch sees field:

$$E_z = E_0 \sin(\omega t + \phi)\sin(kz)$$
$$= E_0 \sin(kz + \phi)\sin(kz)$$

- *only* consider relativistic electrons ($v \approx c$)
- Thus there is no longitudinal dynamics ($e^{\pm}$ do not move long. relative to the other electrons)
- No space charge effects

RF Cavity Basics: Figures of Merit

see lectures 4 on linac

- Power lost in cavity P_{cav}
- Shunt impedance r_s

$$\left.\begin{array}{l}\\ \\ \end{array}\right\} \quad V_{cav}^2 \equiv r_s P_{cav} \qquad E_z = \sqrt{P_{RF} R_s}$$

- Quality factor Q_0: $$Q_0 \equiv 2\pi \frac{\text{stored energy}}{\text{energy lost per cycle}} = \frac{\omega_0 U_{cav}}{P_{cav}}$$

- *R-over-Q* $$r_s / Q_0 = \frac{V_{cav}^2}{2\omega_0 U_{cav}}$$

r_s/Q_0 is a constant for a given cavity geometry independent of surface resistance

RF Cavity Basics: Fill Time

see lectures 4 on linac

Characteristic 'charging' time:

$$\boxed{\tau = \frac{2Q_0}{\omega_0}}$$

time required to (dis)charge cavity voltage to 1/*e* of peak value.

Often referred to as the cavity *fill time*.

True fill time for a pulsed linac is defined slightly differently as we will see.

RF Cavity Basics: Some Numbers

see lectures 4 on linac

f_{RF} = 1.3 GHz		S.C. Nb (2K)	Cu
Q_0		5×10^{9}	2×10^{4}
R/Q		1 kΩ	
R_0		5×10^{12} Ω	2×10^{7} Ω
P_{cav} (5 MV)	*cw!*	5 W	1.25 MW
P_{cav} (30 MV)	*cw!*	180 W	45 MW
τ_{fill}		1.2 s	5 μs

RF Cavity Basics: Some Numbers

see lectures 4 on linac

$f_{\mathrm{RF}} = 1.3$ GHz		S.C. Nb (2K)	Cu
Q_0		5×10^9	2×10^4
R/Q		1 kΩ	
R_0		$5\times10^{12}\ \Omega$	$2\times10^7\ \Omega$
P_{cav} (5 MV)	*cw!*	5 W	1.25 MW
P_{cav} (30 MV)	*cw!*	180 W	
τ_{fill}		1.2 s	

Very high Q_0: the great advantage of s.c. RF

RF Cavity Basics: Some Numbers

see lectures 4 on linac

f_{RF} = 1.3 GHz		S.C. Nb (2K)	Cu
			2×10^4
			2×10^7 Ω
P_{cav} (5 MV)	*cw!*	5 W	1.25 MW
P_{cav} (30 MV)	*cw!*	180 W	45 MW
τ_{fill}		1.2 s	5 µs

- very small power loss in cavity walls
- all supplied power goes into accelerating the beam
- very high RF-to-beam transfer efficiency
- (for AC power, must include cooling power)

RF Cavity Basics: Some Numbers

see lectures 4 on linac

f_{RF} = 1.3 GHz		S.C. Nb (2K)	Cu
Q_0			
R/Q			
R_0			
P_{cav} (5 MV)			
P_{cav} (30 MV)	*cw!*	125 W	31 MW
τ_{fill}		1.2 s	5 μs

- for high-energy higher gradient linacs (X-FEL, ILC), *cw* operation not an option due to load on cryogenics
- pulsed operation generally required
- numbers now represent peak power
- $P_{cav} = P_{pk} \times$duty cycle
- (Cu linacs generally use <u>very</u> short pulses!)

RF Cavity Basics: Some Numbers

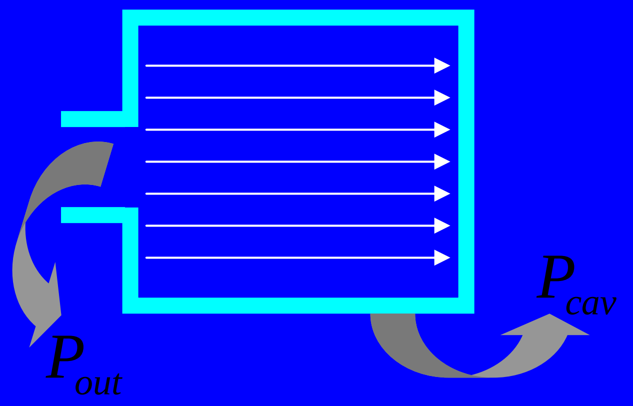
see lectures 4 on linac

f_{RF} = 1.3 GHz	S.C. Nb (2K)	Cu
Q_0	5×10^9	2×10^4
R/Q	1 kΩ	
R_0		
P_{cav} (5 MV)		
P_{cav} (30 MV)		
τ_{fill}	1.2 s	5 µs

- High Q of cavity requires very long charging time!!
- OK for *cw* operation, but clearly doesn't work for pulsed linacs like ILC

RF Cavity Basics: Power Coupling

- calculated ‘fill time’ was
1.2 seconds!
- this is time needed for field to decay to *V/e* *for a closed cavity* (i.e. only power loss to s.c. walls).
- however, we need a ‘hole’ (*coupler*) in the cavity to get the power in, and
- this hole allows the energy *in* the cavity to leak out (⇒ reflected power)



$$V(t) = V_{\max}\left[1 - \exp(-\omega_0 t / 2Q_L)\right]$$

$$Q_L \approx Q_0 / \beta$$

- *Effectively reduces Q of cavity seen by generator, and shortens fill-time*

$$\beta = \frac{\text{External generator (klystron) power}}{\text{Power lost in cavity walls}}$$

RF Cavity Basics: Power Coupling

$$\beta = \frac{P_{for}}{P_{cav}} = \frac{i_{beam} V_{acc}}{(V_{acc}^2 / r_s)} = \left(\frac{i_{beam}}{V_{acc}}\right)\left(\frac{r_s}{Q_0}\right) Q_0$$

(nearly) all power goes into beam:

9mA × 30 MV = 270 kW

cavity wall losses (SCRF):

~125 W (*nb* efficiency = 99.95%)

$$\boxed{Q_L = \frac{Q_0}{\beta} = \left[\left(\frac{i_{beam}}{V_{acc}}\right)\left(\frac{r_s}{Q_0}\right)\right]^{-1}}$$

'beam' impedance

R over Q (cavity geometry)

Cavity material surface preparation

Pulsed Operation

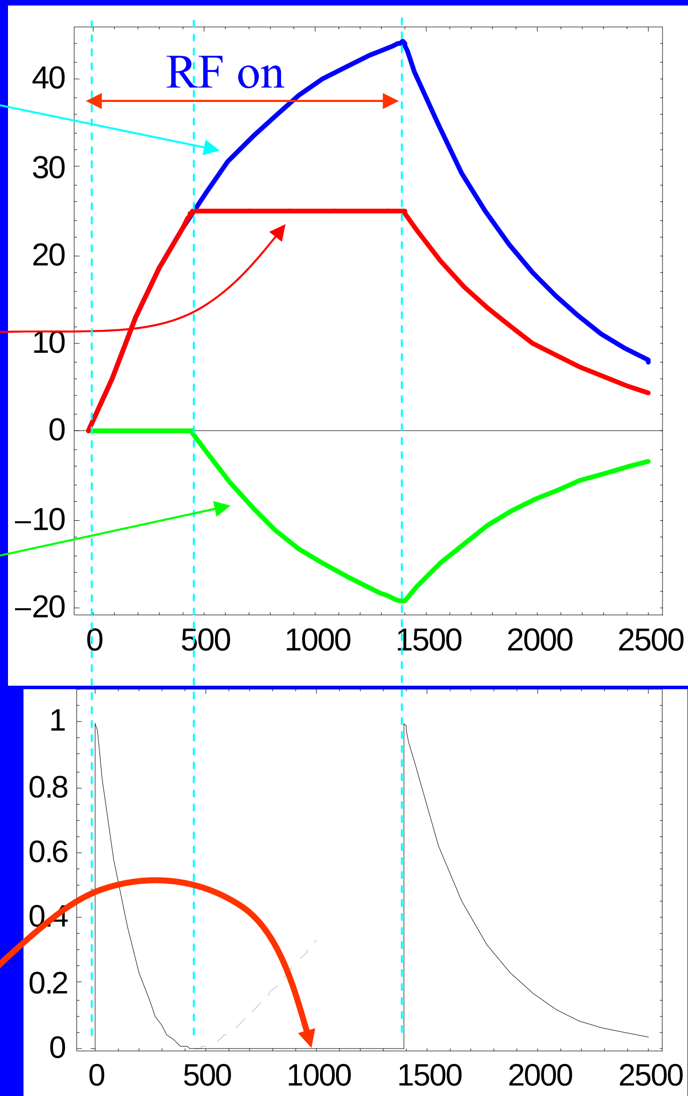
see lectures 4
on linac

- After t_{fill}, beam is introduced
- exponentials cancel and beam sees constant accelerating voltage V_{acc}= 25 MV
- Power is reflected before and after pulse

generator voltage

cavity voltage

beam induced voltage



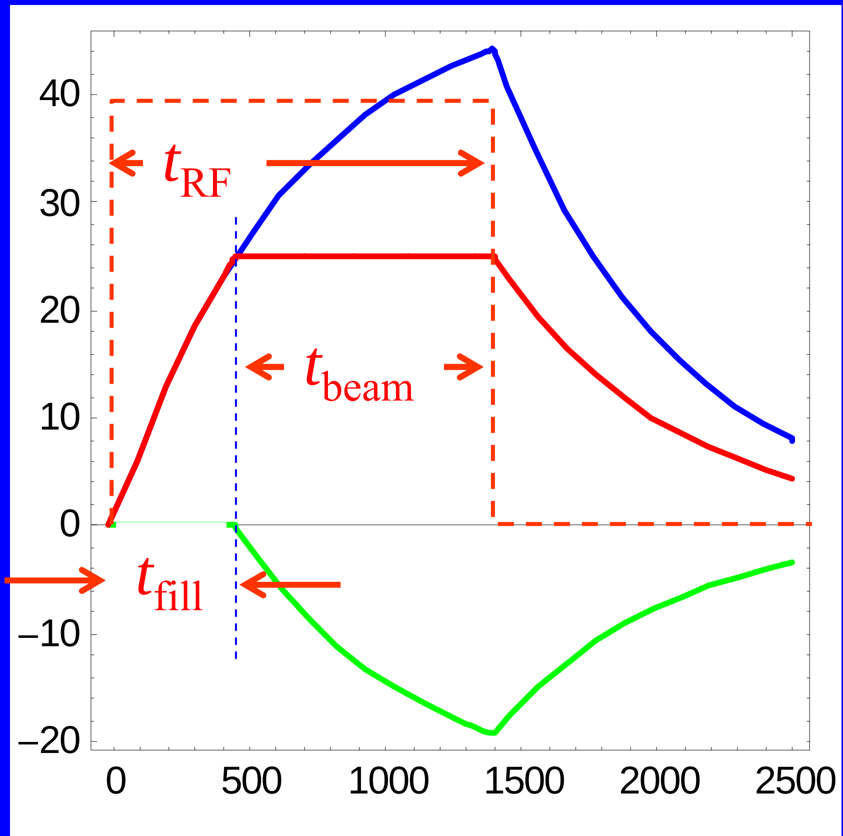
reflected power:

$P_{ref} \, / \, P_{for}$

$t/\mu s$

Cavity parameters adjusted so that *no* RF power is reflected during beam pulse (*matched condition)*

Pulsed RF→Beam Efficiency



$$\eta = \frac{t_{beam}}{t_{RF}} = \frac{t_{beam}}{t_{fill} + t_{beam}}$$

$$V_{max} = 2V_{acc}$$

$$t_{fill} = \ln(2)\tau_{fill}$$

ILC RF Parameters (putting it all together)

- bunch charge N = $2\times10^{10}e$ = 3.2 nC
- # bunches n_b = 2625
- bunch spacing t_b = 370 ns
- i_{beam} = 3.2nC / 370ns ≈ 9 mA
- beam pulse length = 2625 × 370ns = 970 μs
- Acc. voltage/cav V_{acc} = 31.5 MV
- Beam power/cav = 9mA × 31.5 MV = 284 kW
- # cavities per klystron = 26
- P_{klys} = 26 × 284 kW = 7.4 MW
- ΔE per klystron = 26 × 31.5 MeV = 820 MeV
- # klystrons / linac = (250-5) GeV / 820 MeV ≈ 300

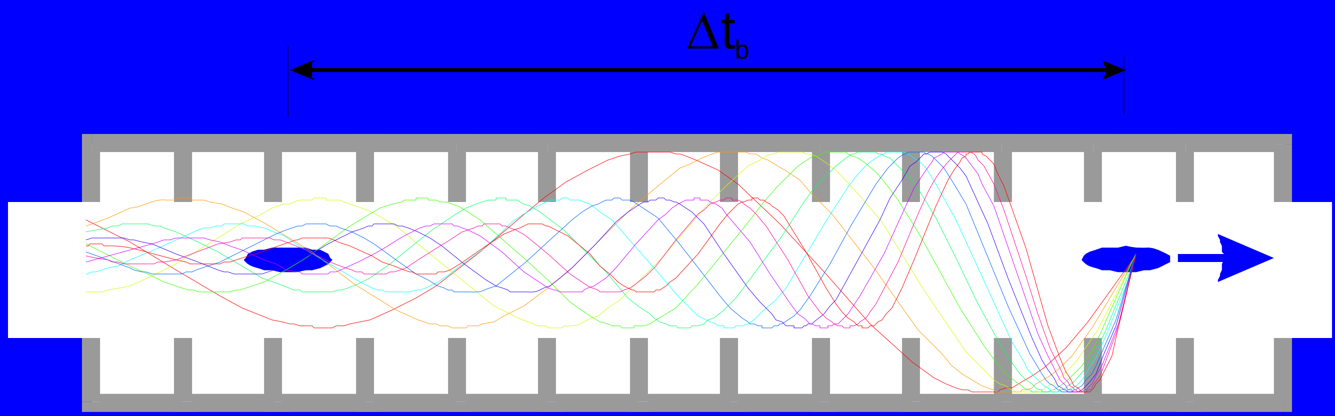
ILC RF Parameters (putting it all together)

- Q_0 = 5×10^9
- r/Q = $1\ \mathrm{k}\Omega$
- Coupler coeff. β = $(9\mathrm{mA} / 31.5\mathrm{MV}) \times 1\mathrm{k}\Omega \times (5\times10^9) = 1429$
- Q_L = $5\times10^9 / 1429 = 3.5\times10^6$
- cav. time const. τ_{fill} = $2\times(3.5\times10^6)/(2\pi\times1.3\mathrm{GHz}) = 857\ \mu\mathrm{s}$
- cav. fill time = $\ln(2) \times 857\ \mu\mathrm{s} = 594\ \mu\mathrm{s}$
- RF pulse length = $594\ \mu\mathrm{s} + 970\ \mu\mathrm{s} = 1.45\ \mathrm{ms}$
- RF→beam Efficiency = $970\ \mu\mathrm{s} / 1.45\ \mathrm{ms} = 59\%$

- Cavity wall (cryo) losses = $284\ \mathrm{kW} / 1429 = 200\ \mathrm{W}$ (peak)
- Average cryo losses $\approx 7800\times200\mathrm{W}\times(1\mathrm{ms}\times5\mathrm{Hz}) = 7.8\ \mathrm{kW}$

typical cryoplant efficiencies ~ 0.1%

LINAC beam dynamics:
Transverse Wakes - The Emittance Killer!



$$V(\omega,t) = I(\omega,t)Z(\omega,t)$$

Bunch current also generates transverse deflecting modes when bunches are not on cavity axis

Fields build up resonantly: latter bunches are kicked transversely

$\Rightarrow$ multi- and single-bunch beam breakup (MBBU, SBBU)

Transverse HOMs

wake is sum over modes: $W_{\perp}(t) = \sum_n \frac{2k_n c}{\omega_n} e^{-\omega_n t/2Q_n} \sin(\omega_n t)$

k_n is the *loss parameter* (units *V/pC/m*^{2}) for the n^{th} mode

Transverse kick of j^{th} bunch after traversing one cavity:

$$\Delta y'_j = \sum_{i=1}^{j-1} \frac{y_i q_i}{E_i} \frac{2k_i c}{\omega_n} e^{-\omega_n i\Delta t/2Q_n} \sin\left(\omega_i i \Delta t_b\right)$$

where y_i, q_i, and $E_{i,}$ are the offset *wrt* the cavity axis, the charge and the energy of the i^{th} bunch respectively.

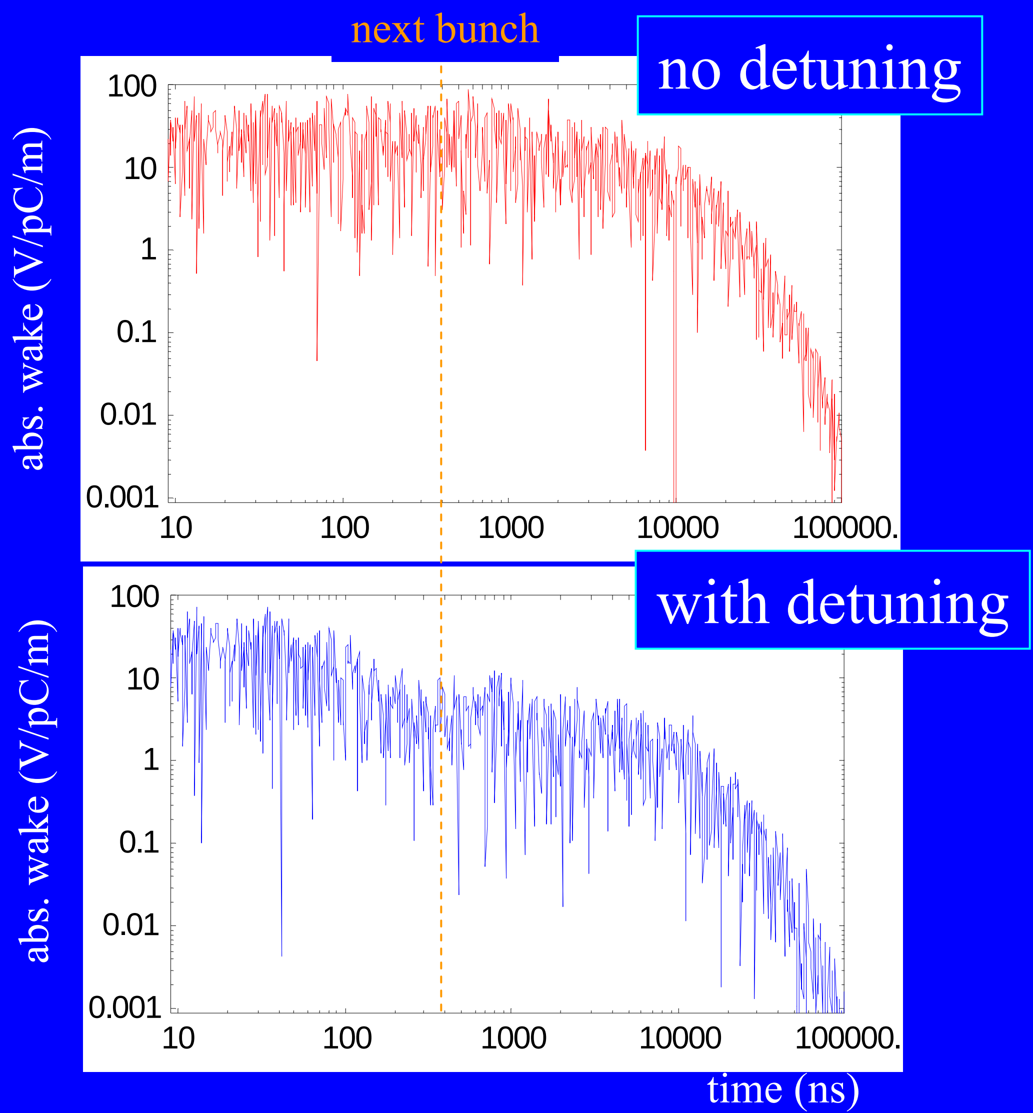
Detuning

HOMs cane be randomly detuned by a small amount.

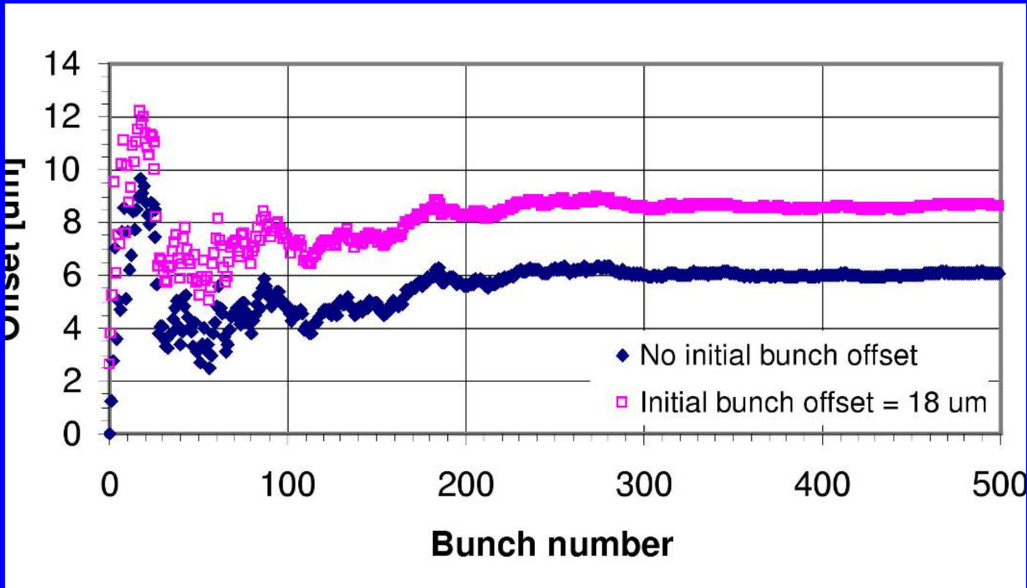
Over several cavities, wake ‘decoheres’.

Effect of random 0.1% detuning
(averaged over 36 cavities).

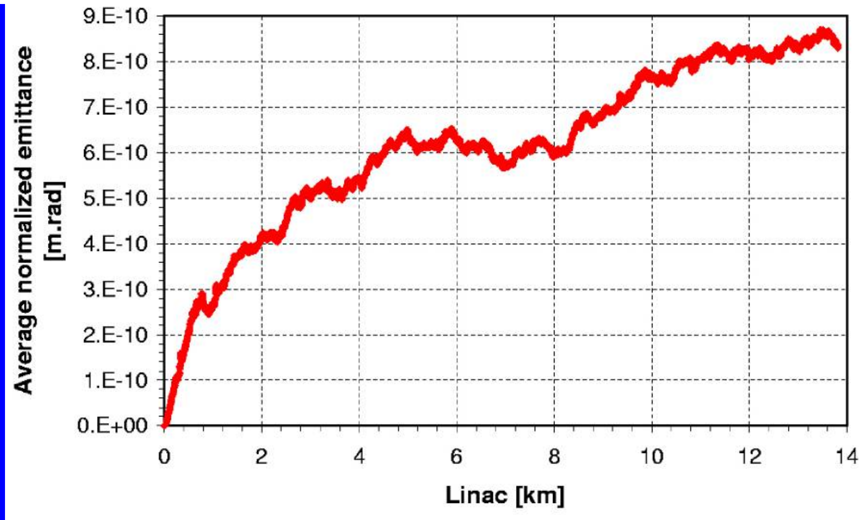
Still require HOM dampers



Effect of Emittance

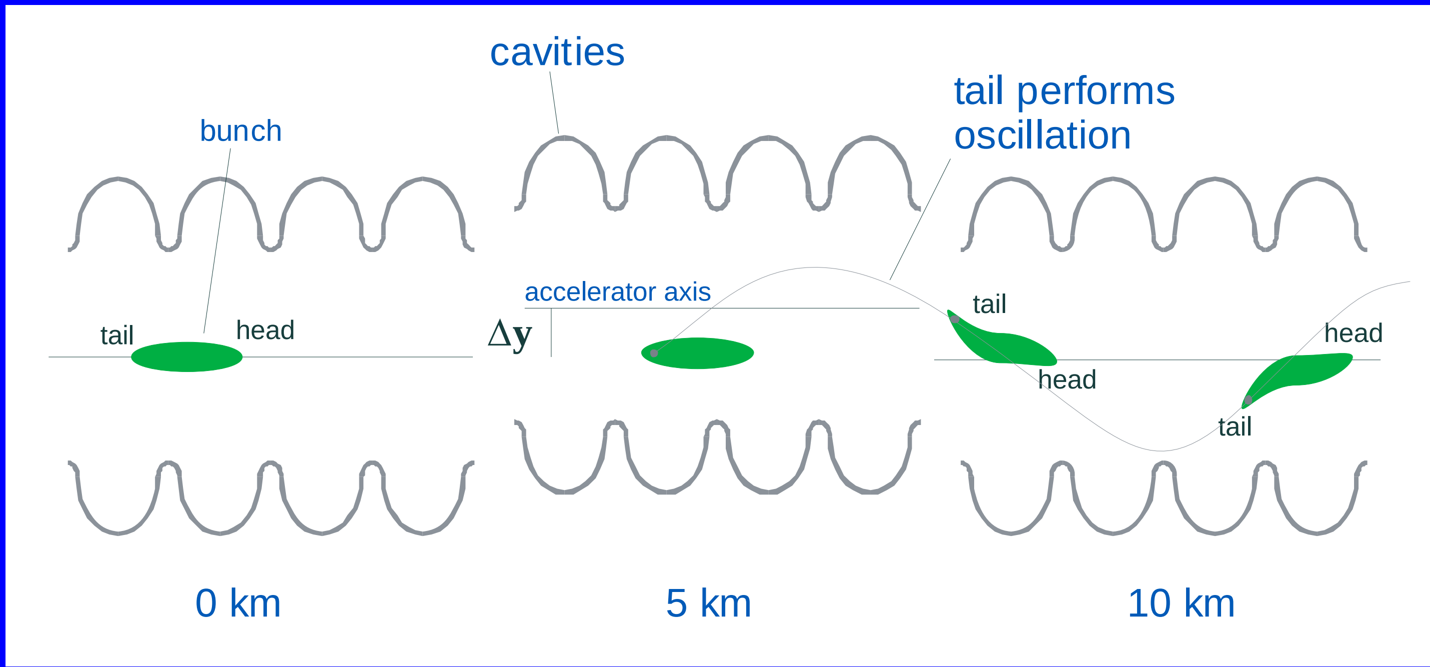


vertical beam offset along bunch train ($n_b = 2920$)



Multibunch emittance growth for cavities with 500µm RMS misalignment

Wakefields (alignment tolerances)



$$\delta Y_{\mathrm{RMS}} \propto \frac{1}{N W_{\perp}} \sqrt{\frac{E_z}{\beta}} \propto \frac{f^{-3}}{N} \sqrt{\frac{E_z}{\beta}}$$

higher frequency = stronger wakefields

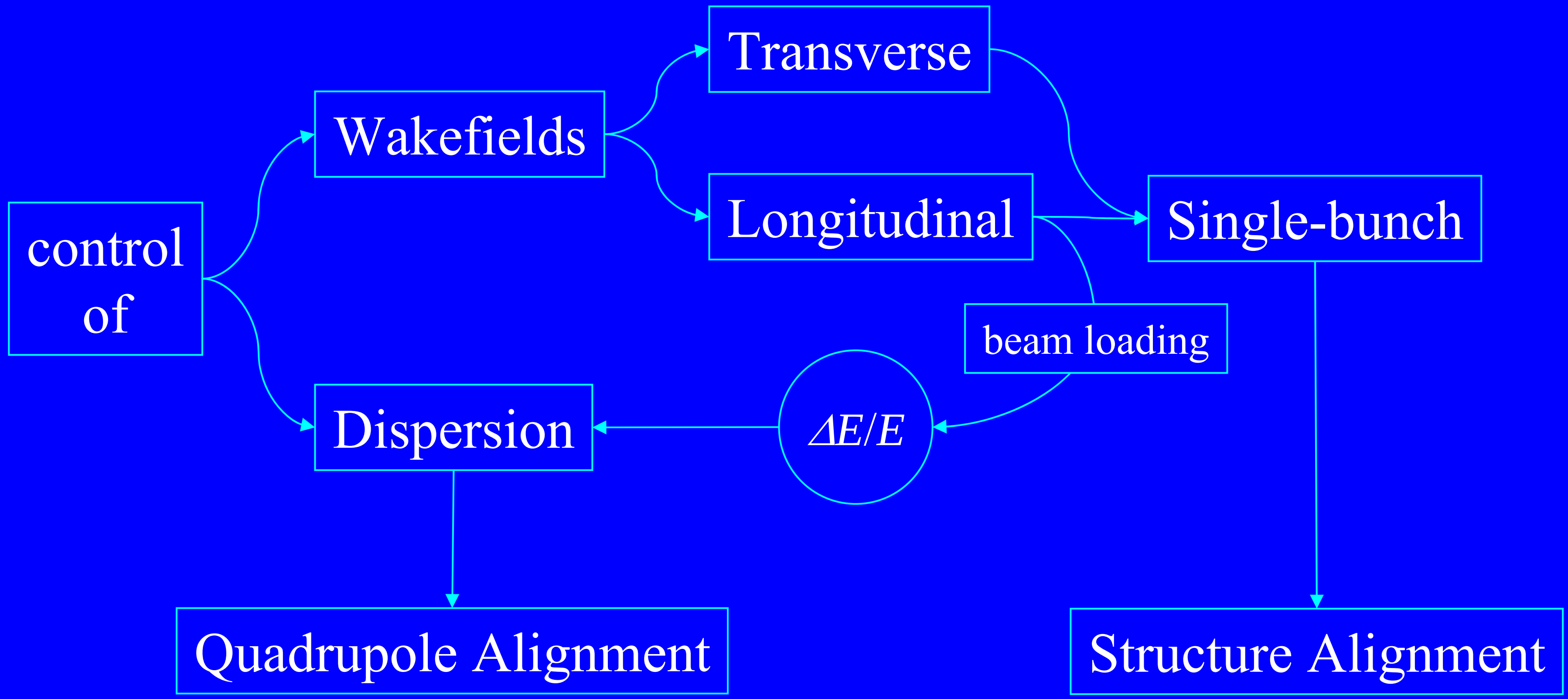
-higher gradients

-stronger focusing (smaller β)

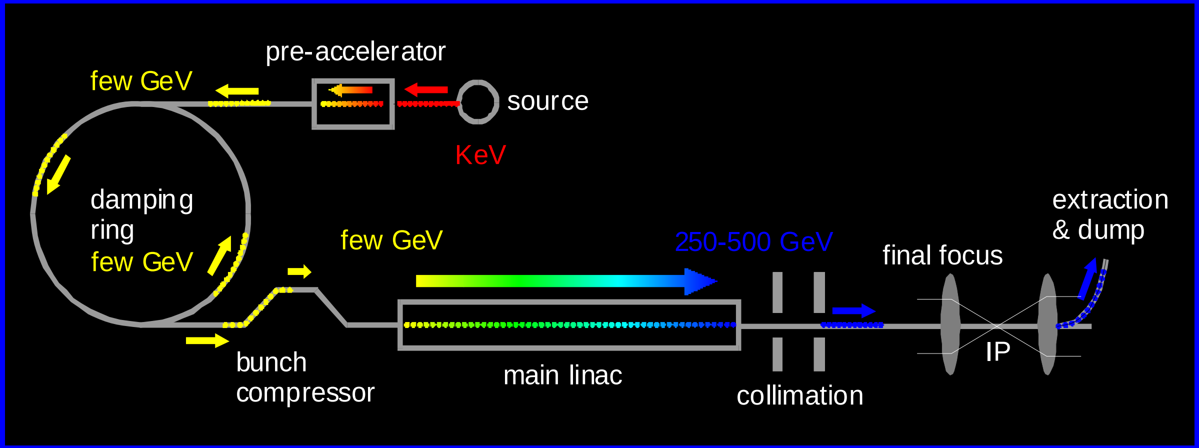
-smaller bunch charge

Wakefields and Beam Dynamics

The preservation of (RMS) Emittance!



The LINAC is only one part



Need to understand how to:

- Produce the electron charge?
- Produce the positron charge?
- Make small emittance beams?
- Focus the beams down to ~nm at the IP?

e^+e^- Sources

Requirements:

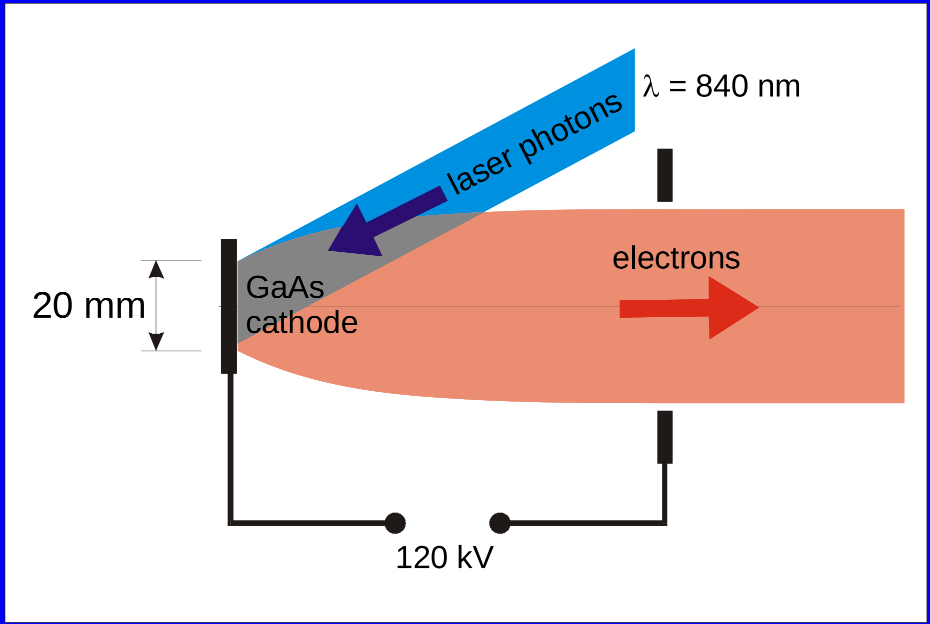
- produce long bunch trains of high charge bunches — 2625 @ 5 Hz, few nC
- with small emittances — $\varepsilon_{nx,y} \sim 10^{-6}, 10^{-8}$ m
- and *spin* polarisation (needed for physics) — mandatory for e^-, nice for e^+

Remember L scaling: $L \propto \frac{n_b N^2}{\sqrt{\varepsilon_n}}$

e^- Source: DC Gun

see lectures 2 on sources

- laser-driven photo injector
- circ. polarised photons on GaAs cathode
  → long. polarised e^-
- laser pulse modulated to give required time structure
- <u>very</u> high vacuum requirements for GaAs ($<10^{-11}$ mbar)
- beam quality is dominated by <u>*space charge*</u> (note $v \sim 0.2c$)



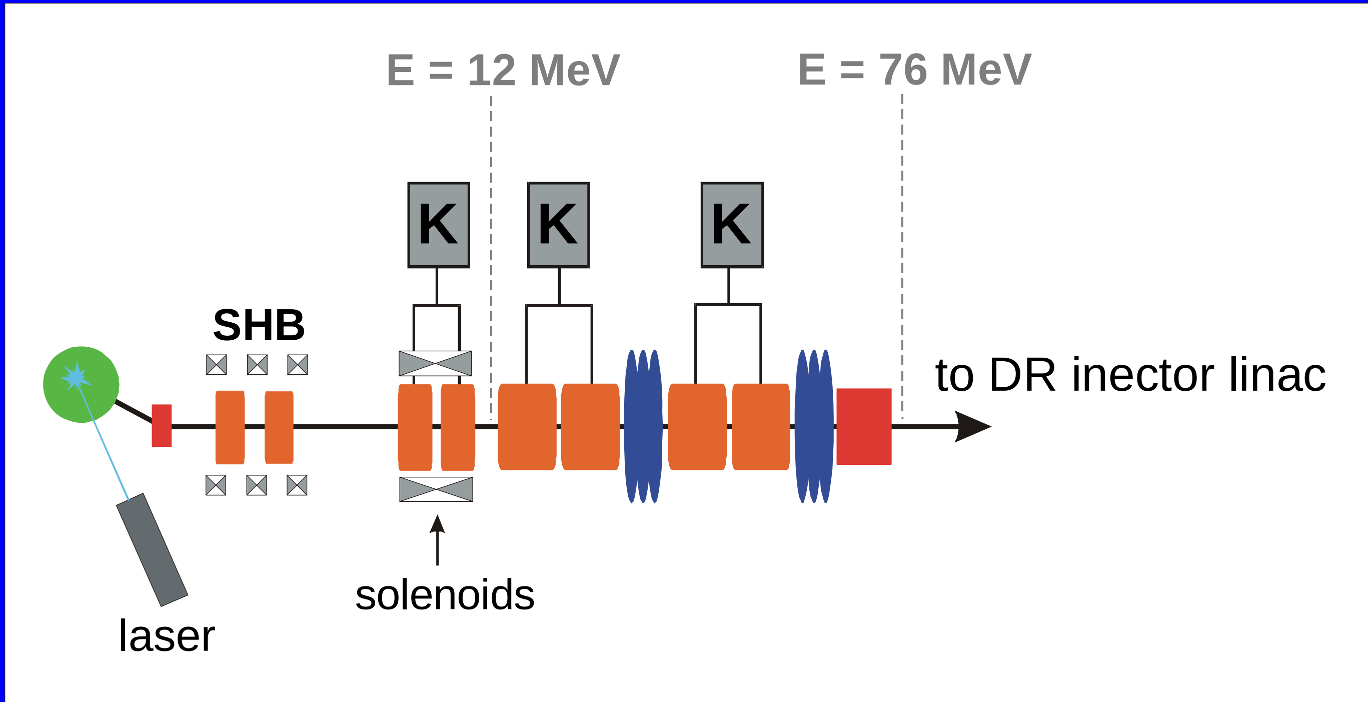
$$\varepsilon_n \approx 10^{-5} m$$

factor 10 in x plane

factor ~500 in y plane

e^- Source: pre-acceleration

see lectures 2 on sources



SHB = sub-harmonic buncher. Typical bunch length from gun is ~ns (too long for electron linac with $f \sim 1.3$ GHz, need tens of ps)

High-brightness RF guns as used in light sources would be significantly better, but vacuum conditions are generally to poor for polarised gun (cathodes)

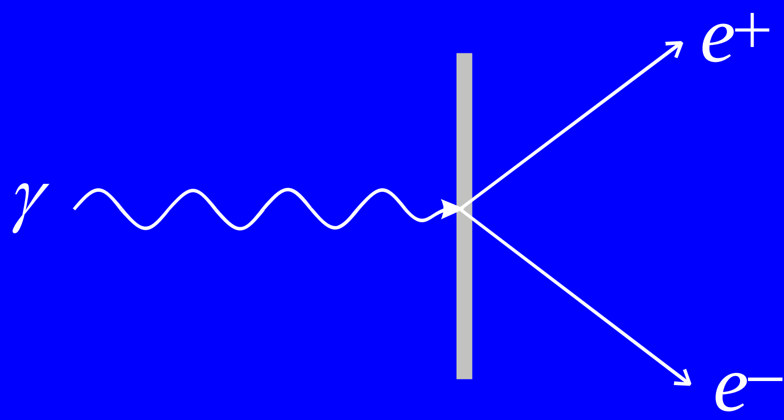
SC RF is an option – but remains an R&D project

e^+ Source

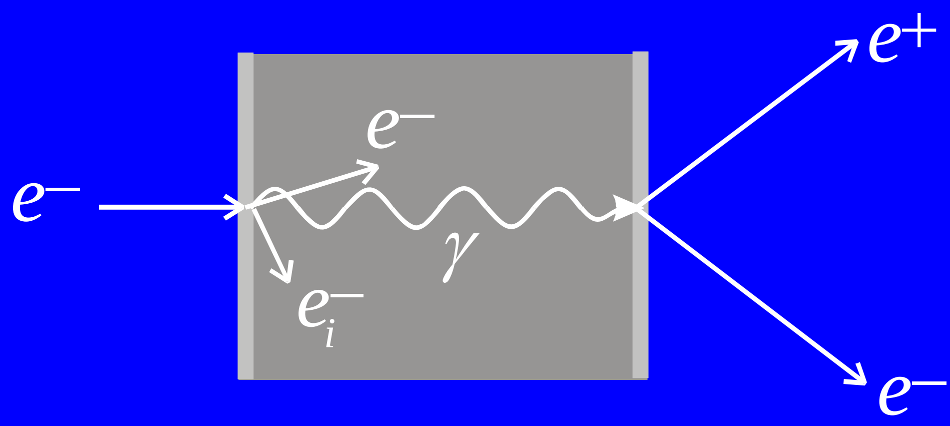
see lectures 2 on sources

Making a 9mA e$^+$ beam is a major challenge for the ILC

Photon conversion to $e^\pm$ pairs in target material

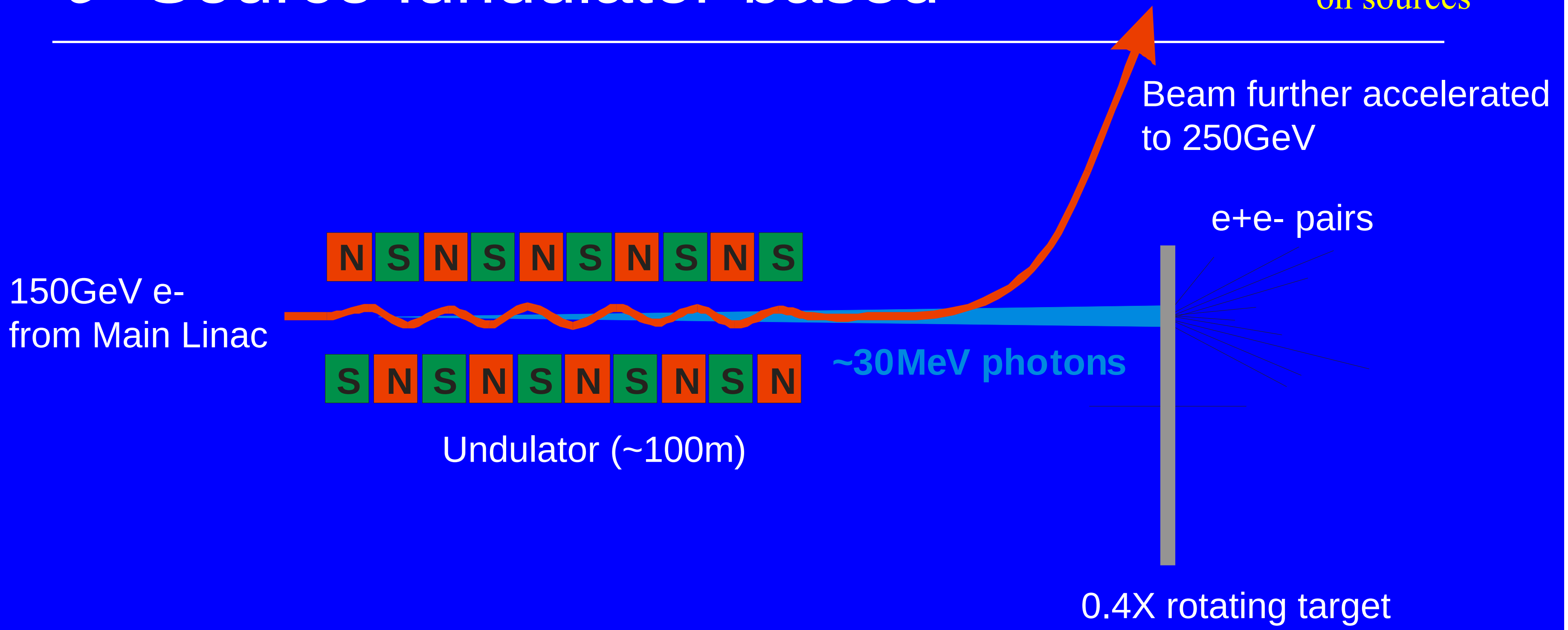


Standard method is e^- beam on 'thick' target (EM-shower)



e^+ Source :undulator-based

see lectures 2
on sources



- SR radiation from undulator generates photons ~ 30 MeV
- no need for 'thick' target to generate shower $0.4X_0$
- thin target reduces multiple-Coulomb scattering: hence better emittance (but still much bigger than needed) 10^{-2} m
- less power deposited in target (no need for mult. systems) 5 kW
- Achilles heel: needs initial electron energy > 150 GeV!
- Other possibilities to generate high-energy photons: Compton scattering of laser beams

Damping Rings

see lecture 3 on Damping Rings

- (storage) ring in which the bunch train is stored for T_{store} ~200 ms (5Hz rep. rate)
- emittances are reduced via the interplay of synchrotron radiation and RF acceleration

initial emittance
(~0.01m for e^+)

$$\varepsilon_f = \varepsilon_{eq} + (\varepsilon_i - \varepsilon_{eq}) e^{-2T/\tau_D}$$

final emittance

equilibrium emittance

damping time

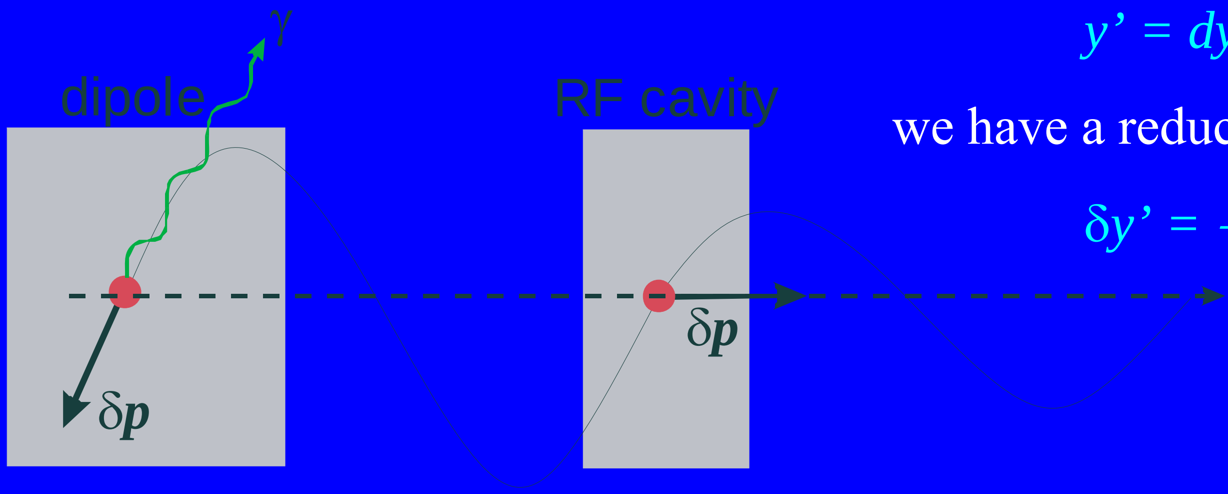
~15 *e*-foldings are required to damp the positron beam ($e^{-15} \sim 1.7\times10^{-7}$)

$\Rightarrow \tau_D \sim 25$ ms

Damping Rings: transverse damping

see lecture 3 on Damping Rings

y' not changed by photon *(or is it?)*



δp replaced by RF such that $\Delta p_z = \delta p$.

since (adiabatic damping again)

$$y' = dy/ds = p_y/p_z,$$

we have a reduction in amplitude:

$$\delta y' = -\delta p \; y'$$

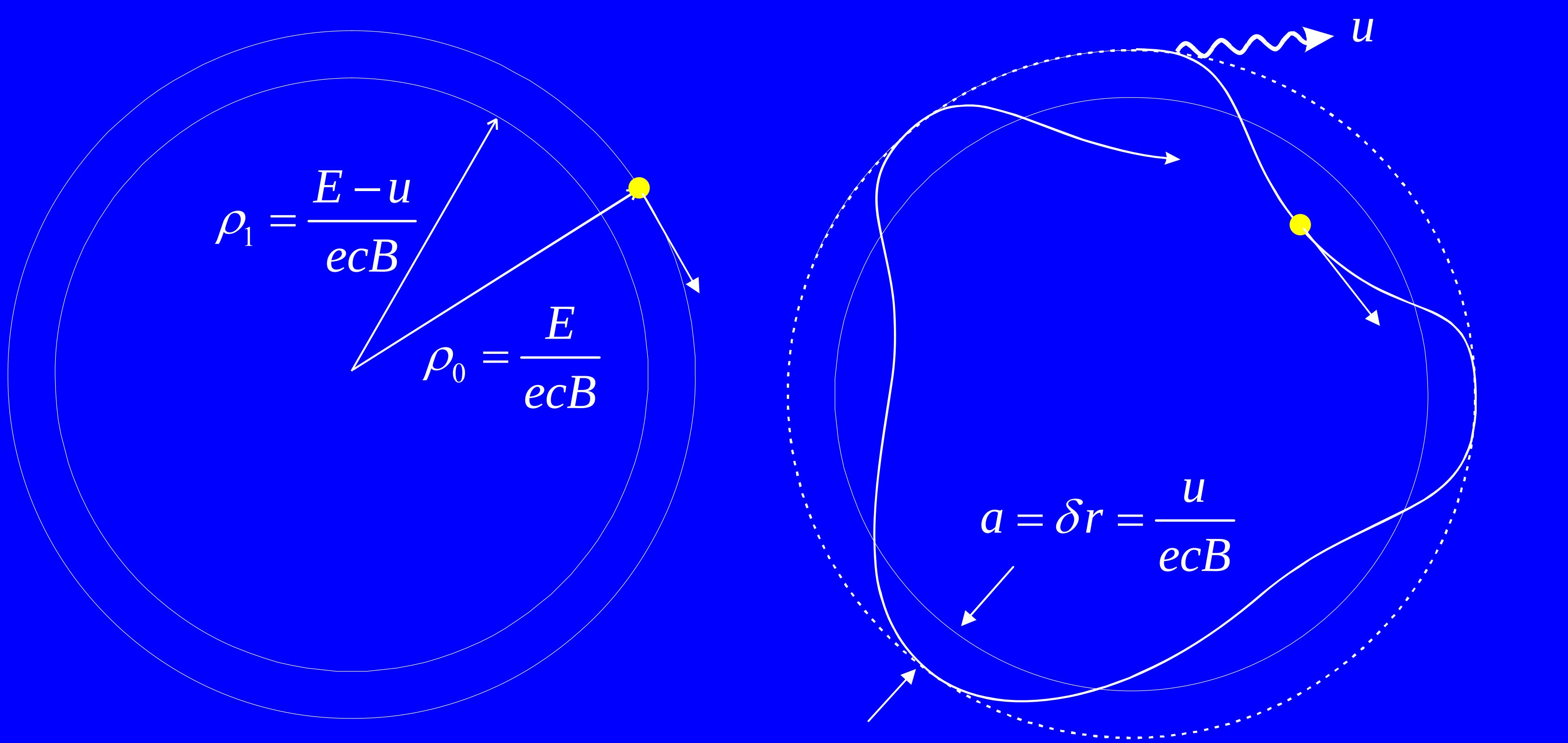
Must take average over all β-phases:

$$\tau_D \approx \frac{2E}{\langle P_\gamma \rangle} \quad \text{where} \quad \langle P_\gamma \rangle = \frac{c\,C_\gamma}{2\pi}\frac{E^4}{\rho^2} \quad \text{and hence} \quad \boxed{\tau_D \propto \frac{\rho^2}{E^3}}$$

LEP: $E \sim 90$ GeV, $P_\gamma \sim 15000$ GeV/s, $\tau_D \sim 12$ ms

Damping Rings: Anti-Damping

see lecture 3 on Damping Rings



particle now performs β-oscillation about new closed orbit $\rho_1 \Rightarrow$ increase in emittance

$$\frac{d\varepsilon_x}{dt} = Q$$

Equilibrium achieved when

$$\frac{d\varepsilon_x}{dt} = 0 = Q - \frac{2}{\tau_d}\varepsilon_x$$

Damping Rings: transverse damping

see lecture 3 on Damping Rings

$$\tau_D \propto \frac{\rho^2}{E^3}$$ suggests high-energy and small ring. But

required RF power: $$P_{RF} \propto \frac{E^4}{\rho^2} \times n_b N$$

equilibrium emittance: $$\varepsilon_{n,x} \propto \frac{E^2}{\rho}$$

Approximate ILC numbers:

- Take $E = 5$ GeV
- $\rho \approx 1000$ m $\Rightarrow B_{bend} = 0.017$ T
- $\langle P_\gamma \rangle = 2.6$ GeV/s [55 kV/turn]
- hence $\tau_D \approx$ 4 s -- 25 ms required!!!
  Increase $\langle P_\gamma \rangle$ by ×80 using *wiggler magnets*

Remember: $8\times\tau_D$ needed to reduce e^+ vertical emittance.

Store time set by f_{rep}:

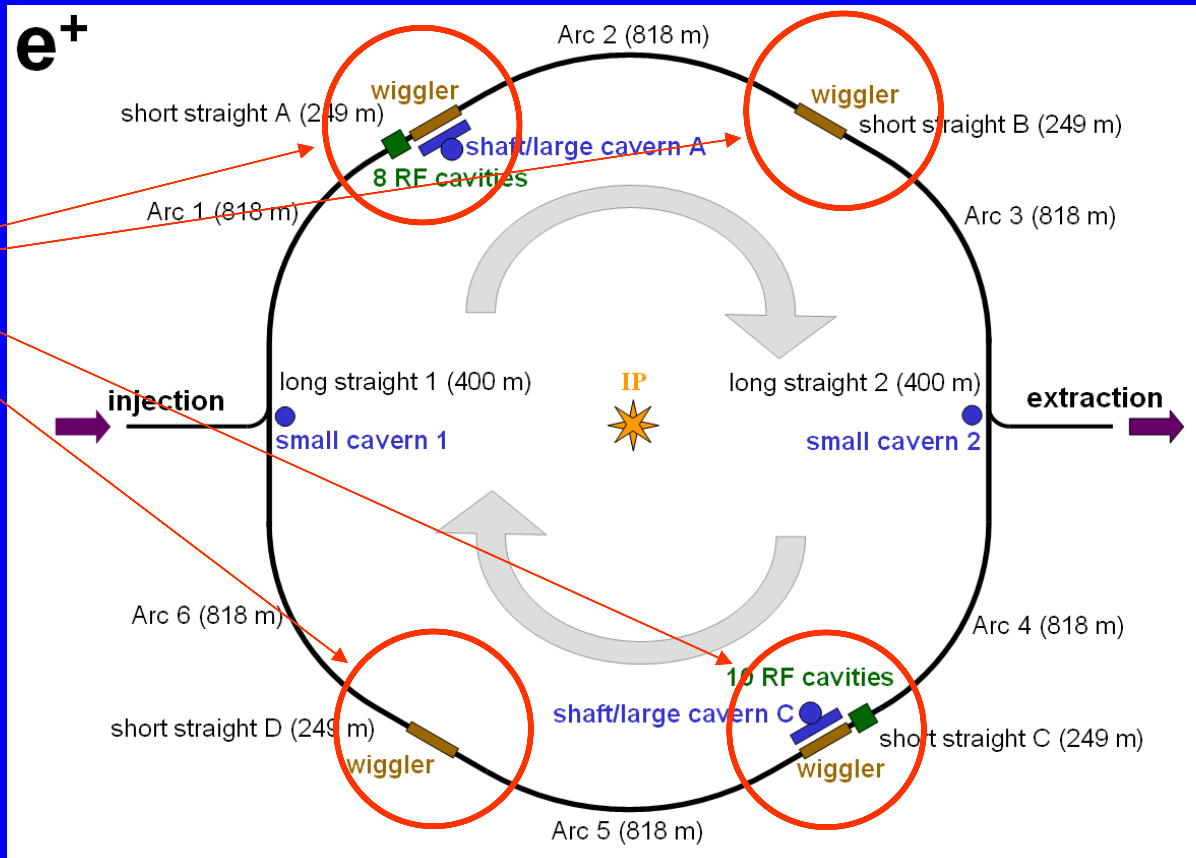
$$t_s \approx n_{train} / f_{rep}$$

radius:

$$\rho = \frac{n_{train} n_b \Delta t_b c}{2\pi}$$

ILC Damping Ring

Damping dominated by wiggler insertions



Damping Rings: limits on vertical emittance

see lecture 3 on Damping Rings

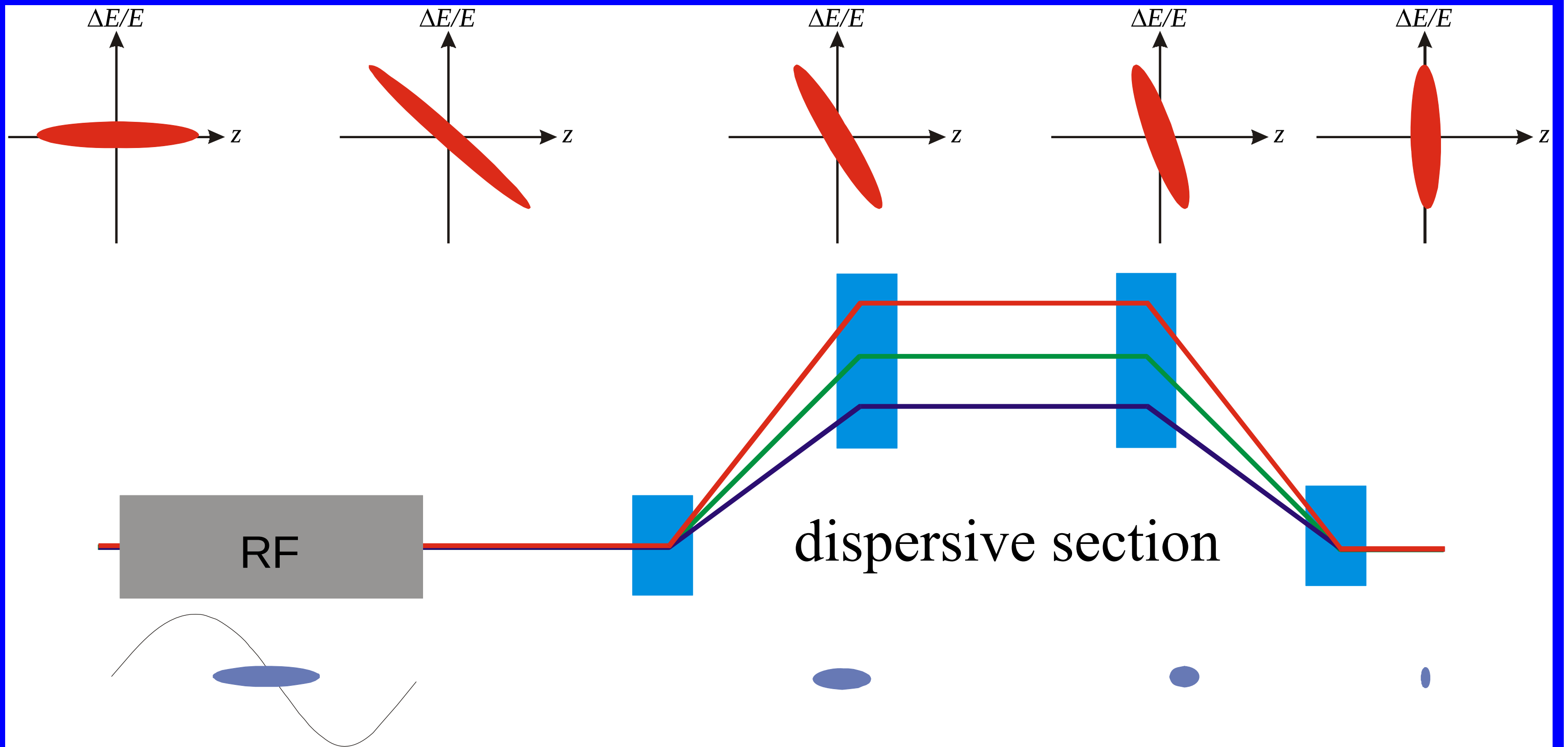
- Horizontal emittance defined by magnet lattice
- theoretical vertical emittance limited by
  - space charge
  - intra-beam scattering (IBS)
  - photon opening angle
- In practice, ε_y limited by magnet alignment errors [cross plane coupling, dispersion]
- typical vertical alignment tolerance: $\Delta y \approx 30\ \mu\text{m}$
  $\Rightarrow$ requires beam-based alignment techniques!

Bunch Compression

see lecture 2
on Bunch Compression

- bunch length from Damping Ring ~ 9 mm
- required at IP 200-300 μm

long.
phase
space



The linear bunch compressor

see lecture 2

initial (uncorrelated) momentum spread:	δ_u
initial bunch length	$\sigma_{z,0}$
compression ratio	$F_c = \sigma_{z,0} / \sigma_z$
beam energy	E
RF induced (correlated) momentum spread:	δ_c
RF voltage	V_{RF}
RF wavelength	$\lambda_{RF} = 2\pi / k_{RF}$
longitudinal dispersion:	R_{56}

conservation of longitudinal emittance (*nb* valid for $F_c >> 1$)

$$\delta_c \approx \delta_u F_c$$

RF cavity

$$\delta_c \approx \frac{k_{RF} V_{RF} \sigma_{z,0}}{E} \Leftrightarrow V_{RF} \approx \frac{E \delta_c}{k_{RF} \sigma_{z,0}} \approx \frac{E}{k_{RF}} \left(\frac{\delta_u}{\sigma_{z,0}} \right) F_c$$

The linear bunch compressor

see lecture 2

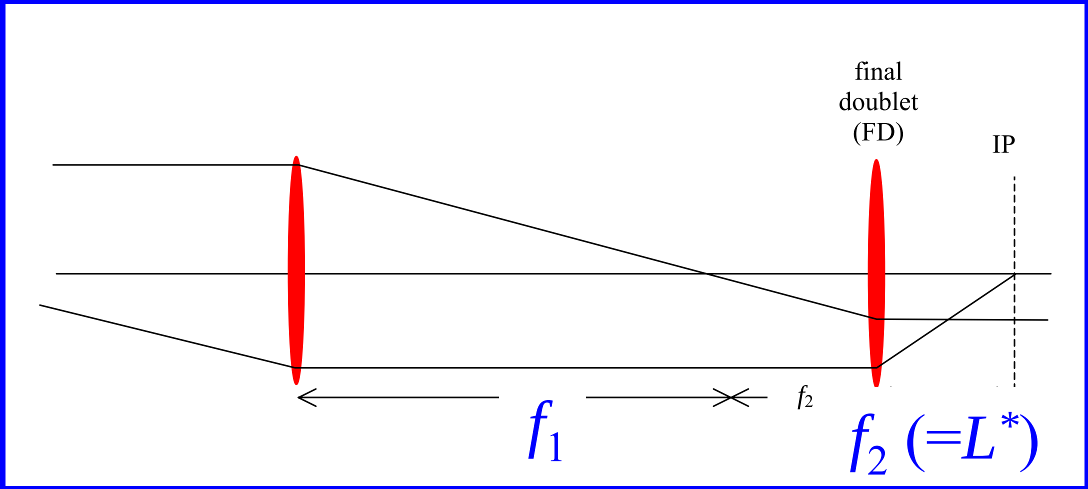
chicane (dispersive section)

$$\Delta z \approx R_{56}\delta \qquad R_{56} = -\frac{\langle \delta z \rangle}{\delta^2} = -\frac{\delta_c \sigma_{z,0}}{F^2 \delta_u^2} = \frac{k_{RF} V_{RF}}{E}\left(\frac{\sigma_{z,0}}{\delta_u}\right)^2 \frac{1}{F^2}$$

$$\left.\begin{aligned} \sigma_{z,0} &= 9\,\mathrm{mm} \\ \delta_{\mathrm{u}} &= 0.13\% \\ \sigma_z &= 300\,\mu\mathrm{m} \Rightarrow F_c = 30 \\ f_{RF} &= 1.3\,\mathrm{GHz} \Rightarrow k_{RF} = 27.2\,\mathrm{m}^{-1} \\ E &= 5\,\mathrm{GeV} \end{aligned}\right\} \qquad \begin{aligned} \delta &\approx 4\% \\ V_{RF} &\approx 800\,\mathrm{MV} \\ \left|R_{56}\right| &\approx 0.24\,\mathrm{m} \end{aligned}$$

Large resulting energy spread (4%) may cause beam dynamics problems in Main Linac: solution – 2 stage compressor with acceleration.

Final Focusing



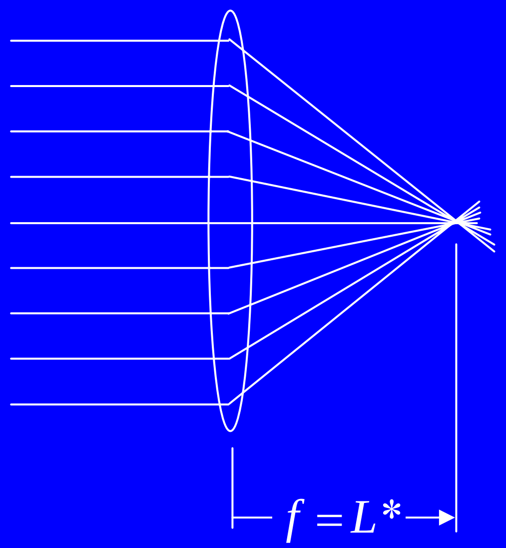
Use telescope optics to demagnify beam by factor $m = f_1/f_2 = f_1/L^*$

Need typically $m = 300$

putting $L^* = 2\text{m} \Rightarrow f_1 = 600\text{m}$

Final Focusing

see lecture 7



$$L^* \approx 2-4\ \mathrm{m}$$

$$\sigma_y = \sqrt{\varepsilon_{n,y}\beta_y / \gamma}$$

$$\sigma_y \approx 3-5\,\mathrm{nm} \Rightarrow \beta_y \approx 200-300\ \mu\mathrm{m}$$

remember $\beta_y \sim \sigma_z$

at final lens $\beta_y \sim 100$ km

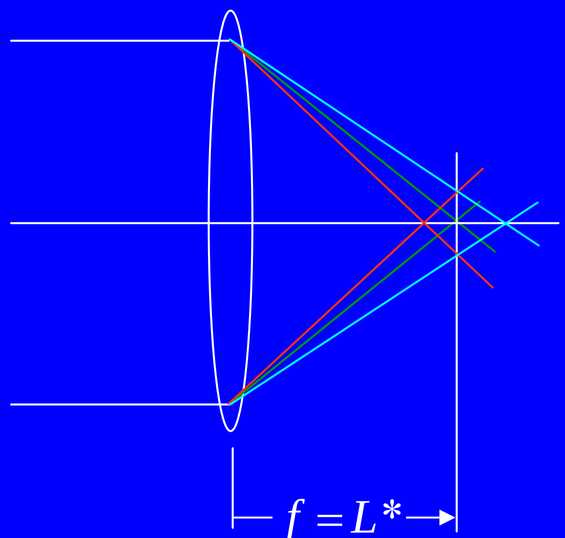
short f requires very strong fields (gradient): $dB/dr \sim 250$ T/m
pole tip field $B(r = 1\mathrm{cm}) \sim 2.5$ T

normalised quadrupole strength: $K_1 = \dfrac{1}{B\rho}\dfrac{B_o}{r_0}$

where $B\rho$ = *magnetic rigidity* = $P/e \sim 3.3356\, P$ [GeV/c]

Final Focusing: chromaticity

see lecture 7



for a *thin-lens* of length *l*: $$\frac{1}{f} \approx K_1 l$$

$$\Delta y'_{quad} \approx -K_1 l\, y_{quad} \frac{\delta}{1+\delta} \approx -K_1 l\, y_{quad}\, \delta$$

$$\Delta y_{IP} \approx f\, \Delta y'_{quad} = y_{quad} \delta$$

$$\left\langle \Delta y_{IP}^2 \right\rangle = \left\langle y_{quad}^2 \right\rangle \left\langle \delta^2 \right\rangle = \beta_{quad} \varepsilon_y \delta_{\mathrm{rms}}^2$$

for $\delta_{\mathrm{rms}} \sim 0.3\%$ $$\sqrt{\left\langle \Delta y_{IP}^2 \right\rangle} \approx 20 - 40\ \mathrm{nm}$$

more general: $$\left\langle \Delta y_{IP}^2 \right\rangle = \xi_y \delta_{\mathrm{rms}}^2$$

ξ is chromaticity $$\xi_y = \int K_1(s) \beta(s) ds$$

chromaticity must be corrected using sextupole magnets

Final Focusing: chromatic correction

see lecture 7

magnetic multipole expansion:

$$B_y(x) = B\rho\left(\frac{1}{\rho} + K_1 x + \frac{1}{2}K_2 x^2 + \frac{1}{3!}K_3 x^3 \ldots\right)$$

dipole quadrupole sextupole octupole

2nd-order kick: $$\Delta y' = \begin{cases} -k_1 y\delta & \text{quadrupole} \\ -k_2 xy & \text{sextupole} \end{cases} \qquad k_n \equiv \int_0^l K_n ds$$

introduce horizontal dispersion D_x

$$x \to x + D_x\delta$$

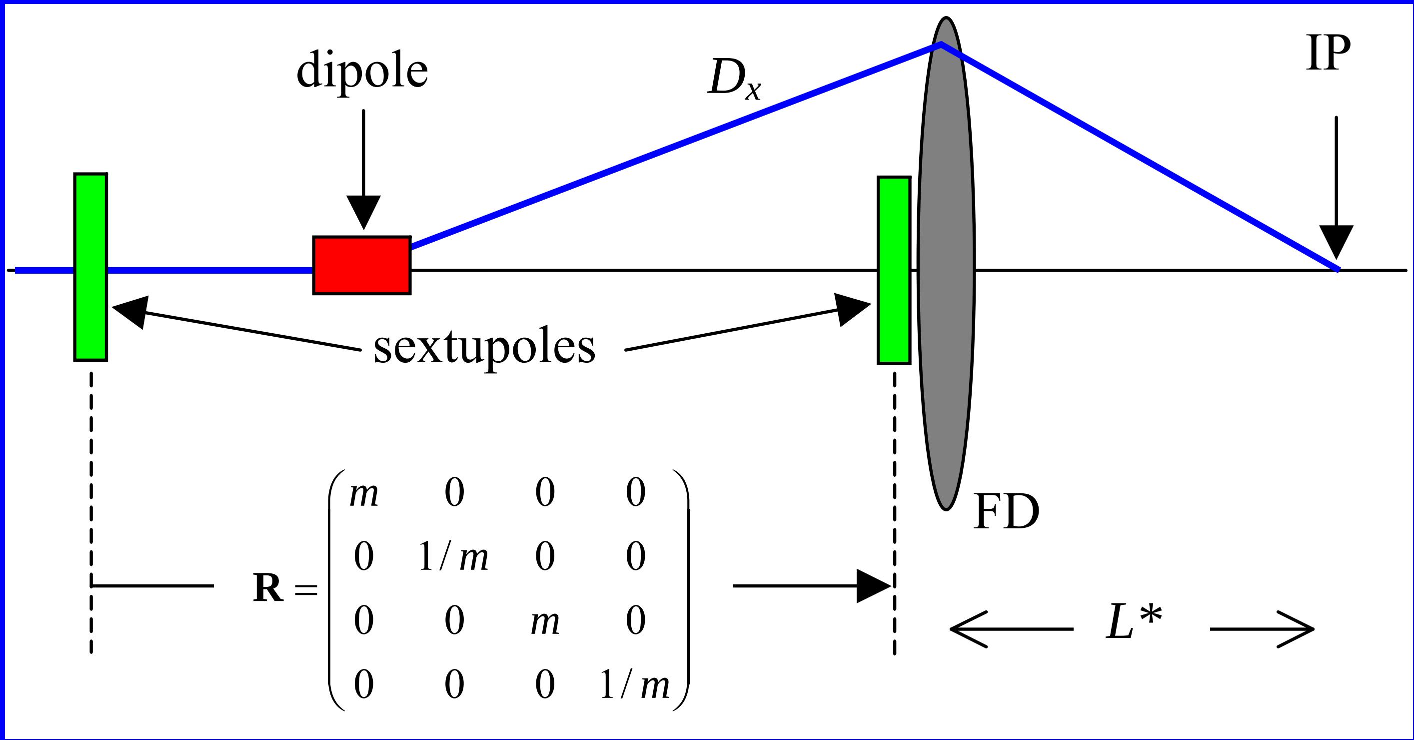
$$\Delta y' = \underbrace{-k_2 xy}_{geometric} - \underbrace{k_2 D_x y\delta}_{chromaticity}$$

chromatic correction when $k_2 = -\dfrac{D_x}{k_1}$

need also to cancel geometric (xy) term! (second sextupole)

Final Focusing: chromatic correction

see lecture 7



Final Focusing: Fundamental limits

Already mentioned that $\beta_y \geq \sigma_z$

At high-energies, additional limits set by so-called *Oide Effect*: synchrotron radiation in the final focusing quadrupoles leads to a beamsize growth at the IP

$$\left.\begin{aligned} &\text{minimum beam size:} \quad \sigma \approx 1.83\left(r_e \lambda\!\!\!^{-}_e F\right)^{1/7} \varepsilon_n^{5/7} \\ &\text{occurs when} \quad \beta \approx 2.39\left(r_e \lambda\!\!\!^{-}_e F\right)^{2/7} \varepsilon_n^{3/7} \end{aligned}\right\} \textit{independent of } E!$$

F is a function of the focusing optics: typically $F \sim 7$ (minimum value ~0.1)

Stability

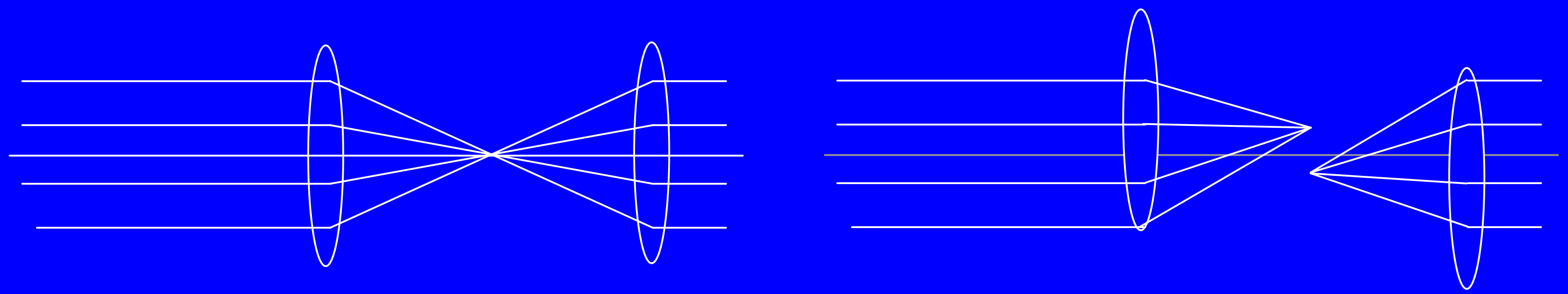
- Tiny (emittance) beams
- Tight component tolerances
  - Field quality
  - Alignment
- Vibration and Ground Motion issues
- Active stabilisation
- Feedback systems

Linear Collider will be "Fly By Wire"

Stability: some numbers

- Cavity alignment (RMS): ~ 500 μm
- Linac magnets: ~100 nm
- FFS magnets: 10-100 nm
- Final "lens": ~ nm !!!

parallel-to-point focusing:



LINAC quadrupole stability

$$y^* = \sum_{i=1}^{N_Q} k_{Q,i} \Delta Y_i g_i = k_Q \sum_{i=1}^{N_Q} \Delta Y_i g_i$$

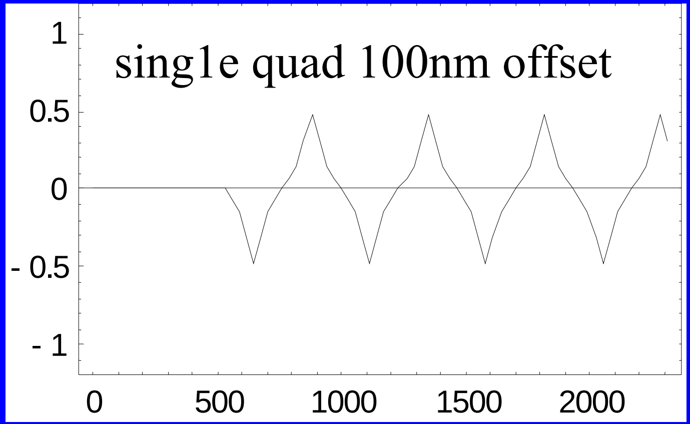
$$g_i = \sqrt{\frac{\gamma_i}{\gamma^*}} \sqrt{\beta_i \beta^*} \sin(\Delta\phi_i)$$

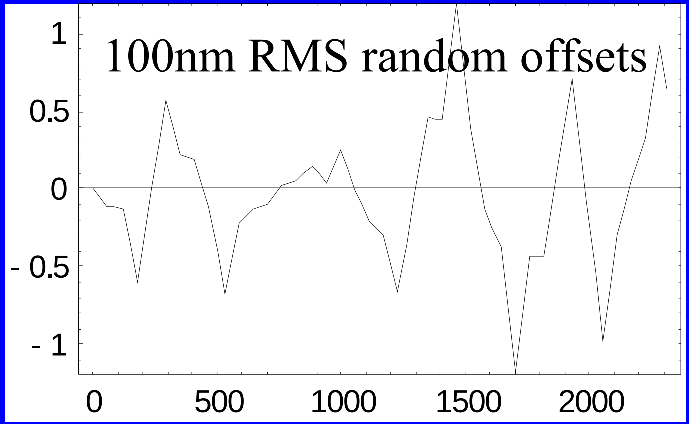
for uncorrelated offsets

$$\langle y^{*2} \rangle = \frac{\beta^* \langle \Delta Y^2 \rangle}{\gamma^*} \sum_{i=1}^{N_Q} \gamma_i k_{Q,i}^2 \beta_i \sin^2(\Delta\phi_{ij})$$

Dividing by $\sigma_y^{*2} = \beta^* \varepsilon_{y,n} / \gamma^*$
and taking average values:

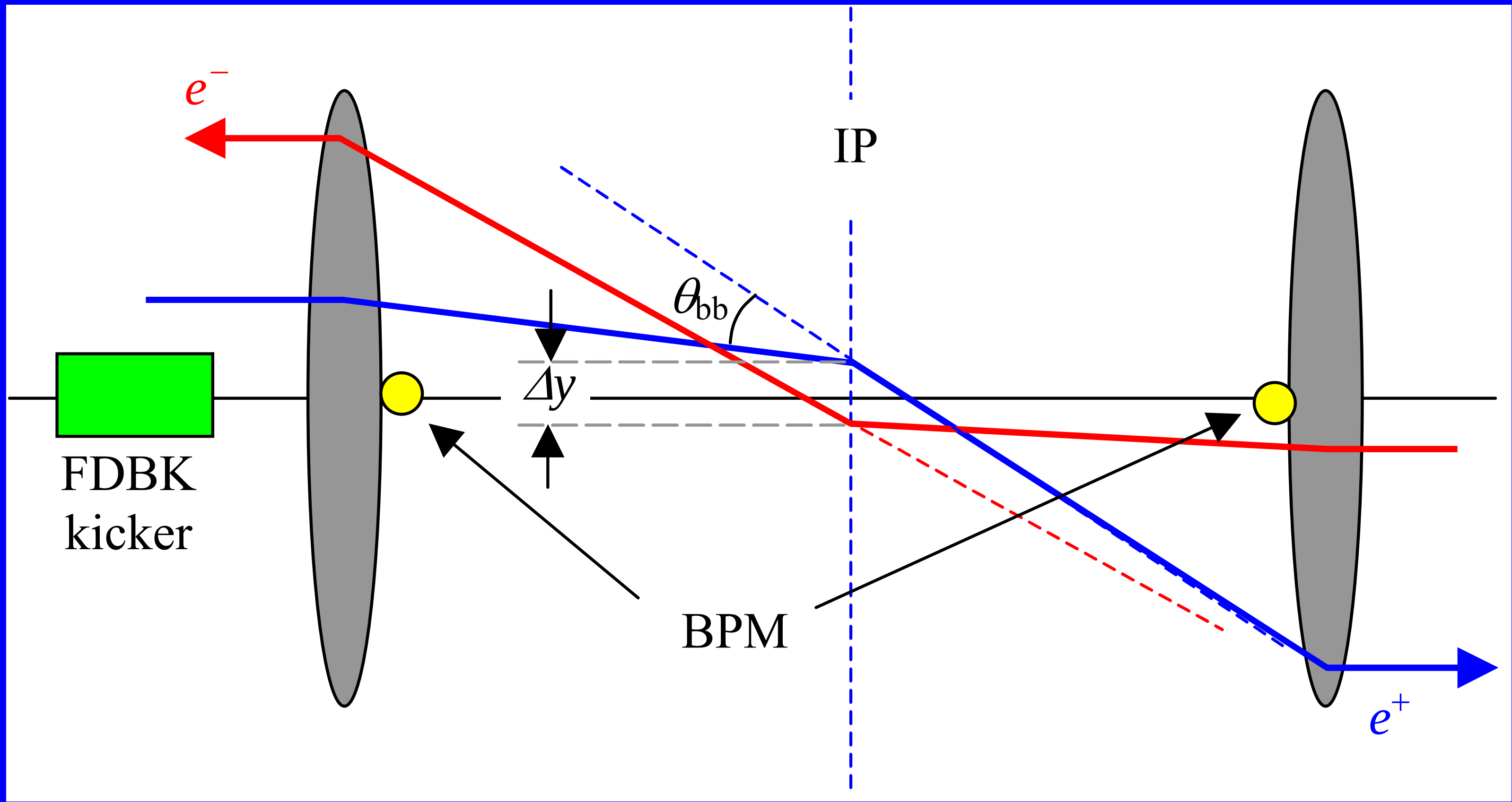
$$\frac{\langle y_j^2 \rangle}{\sigma_y^{*2}} \approx \frac{N_Q k_Q^2 \overline{\beta}\, \overline{\gamma}}{2\varepsilon_{y,n}} \sigma_{\Delta Y}^2 \leq 0.3^2$$





take $N_Q = 400$, $\varepsilon_y \sim 6\times10^{-14}$ m, $\beta \sim 100$ m, $k_1 \sim 0.03$ m^{-1} $\Rightarrow \sim 25$ nm

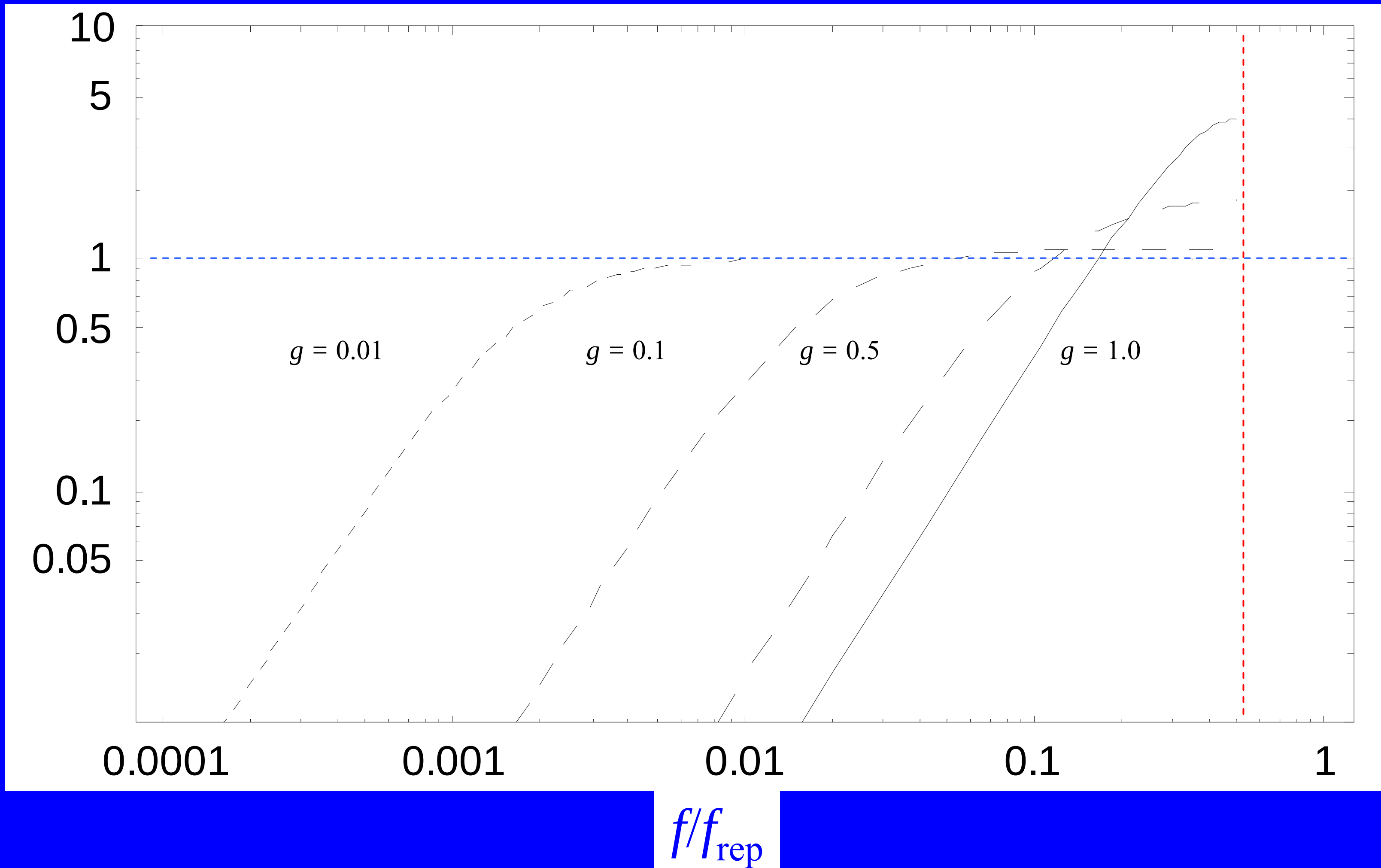
Beam-Beam orbit feedback



use strong beam-beam kick to keep beams colliding

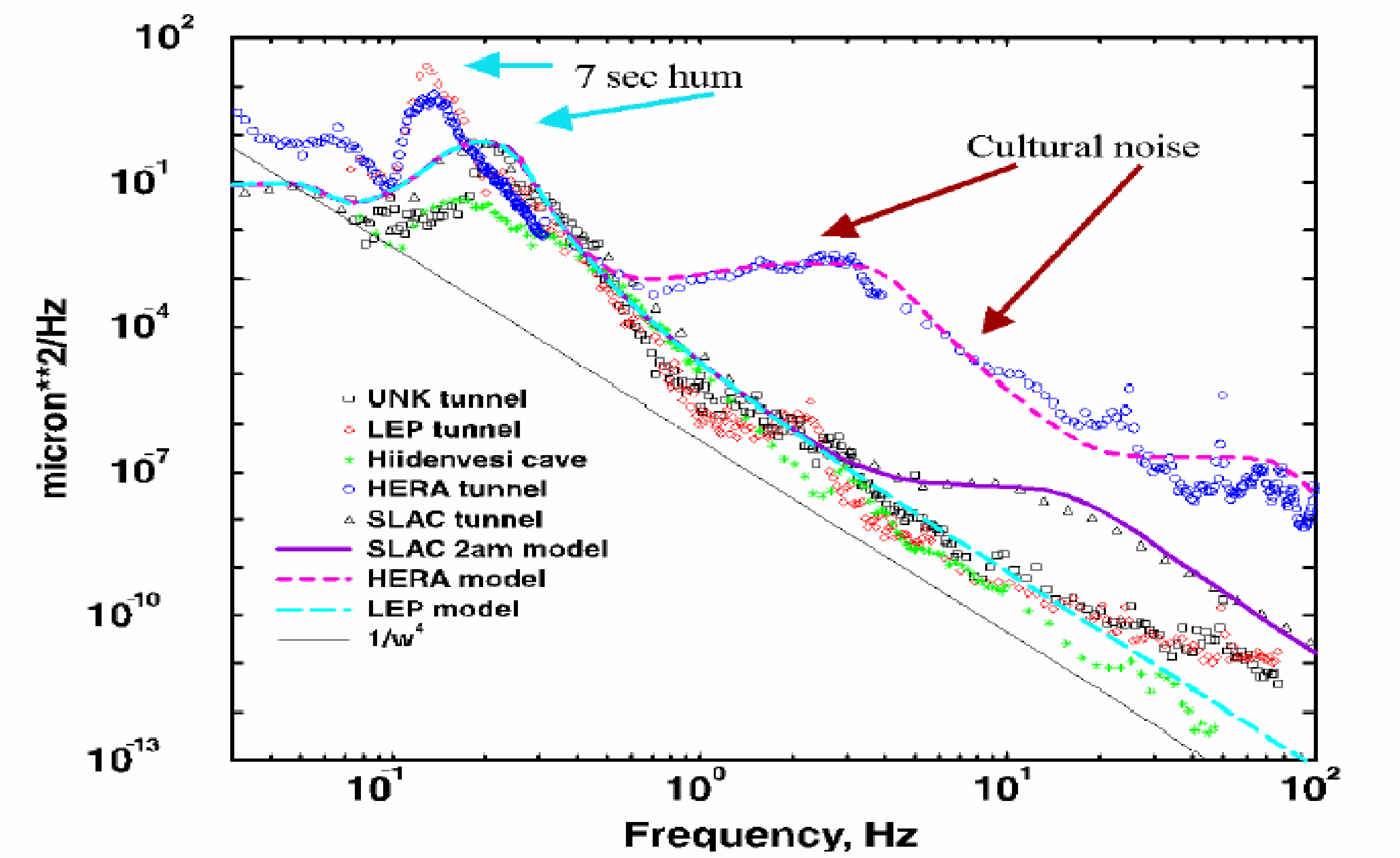
Generally, orbit control (feedback) will be used extensively in LC

Beam based feedback: bandwidth



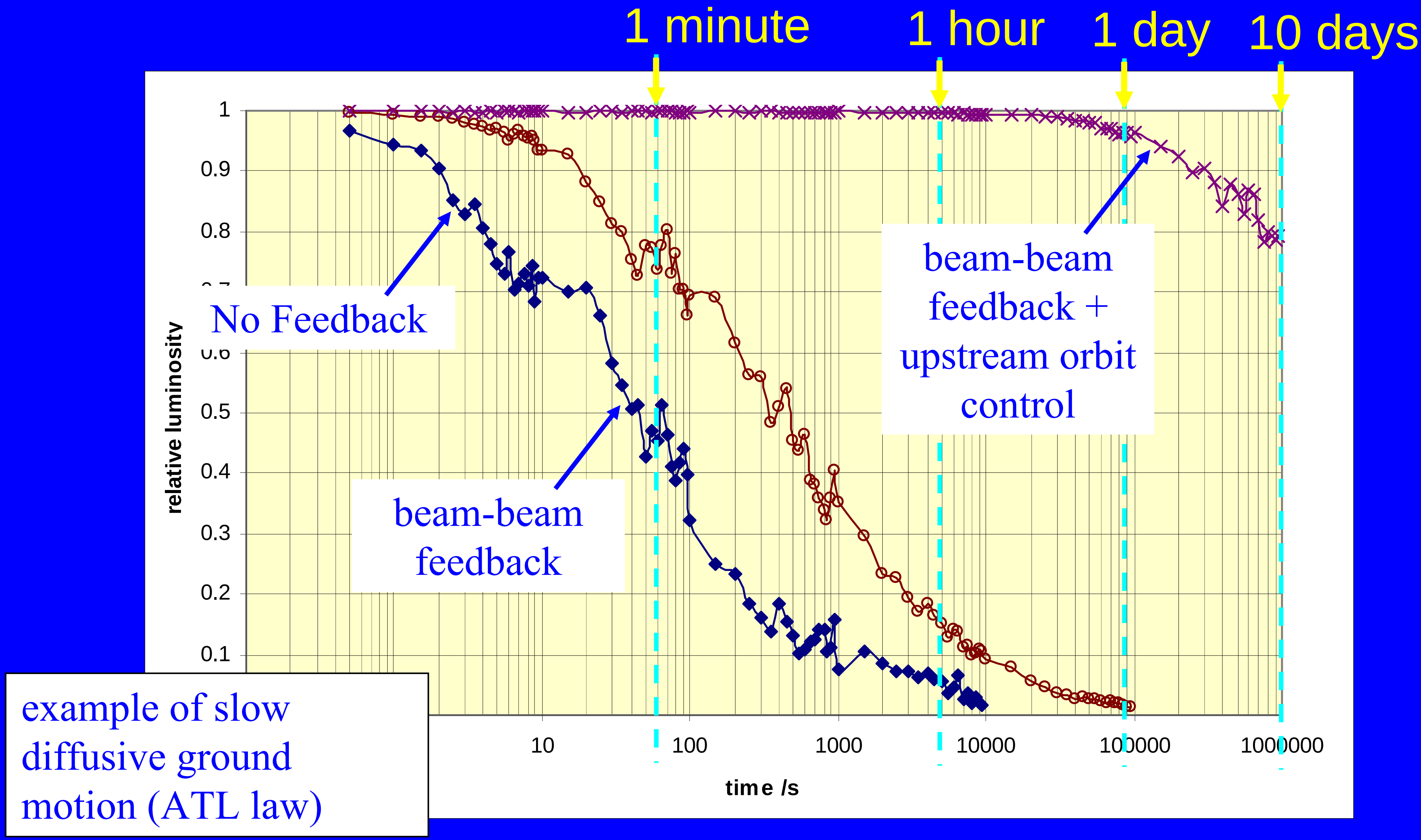
Good rule of thumb: attenuate noise with $f<f_{rep}/20$

Ground motion spectra



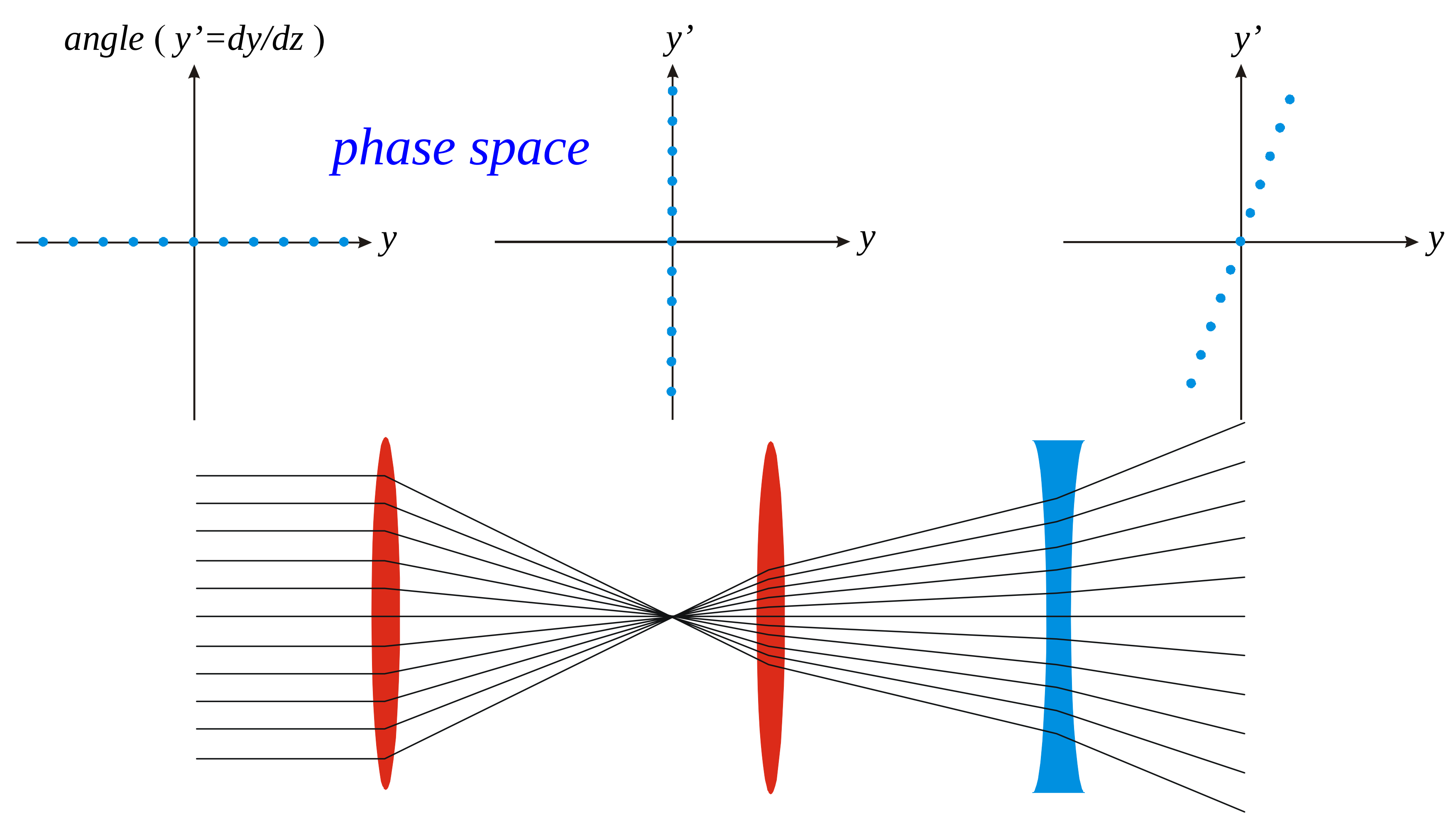
Long Term Stability

understanding of ground motion and vibration spectrum important



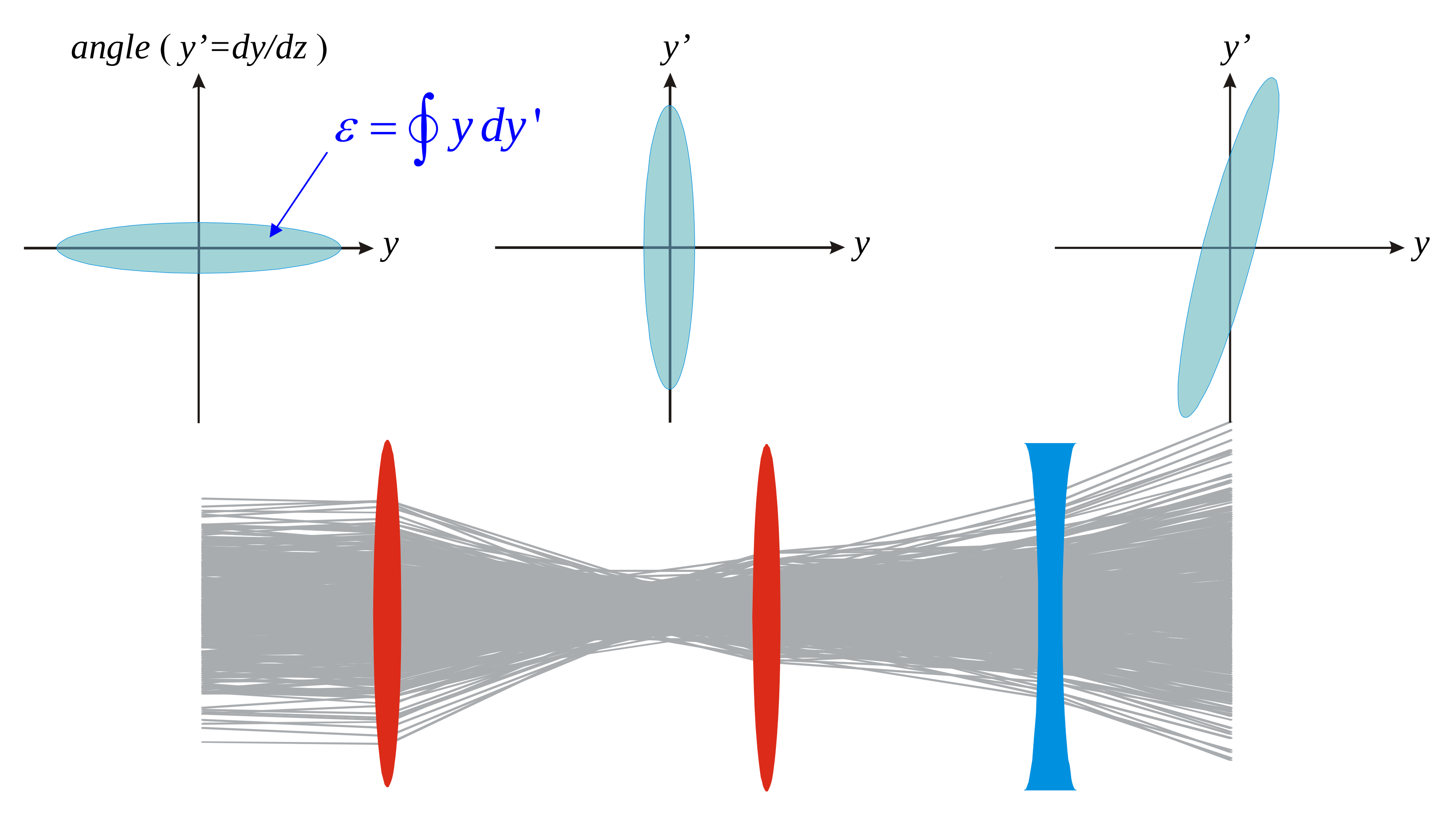
Here Endeth the First Lecture

Basic Optics 1: Phase Space and Emittance



Electron optics analogous to light optics
(quadrupole magnets instead of lenses)

Basic Optics 1: Phase Space and Emittance

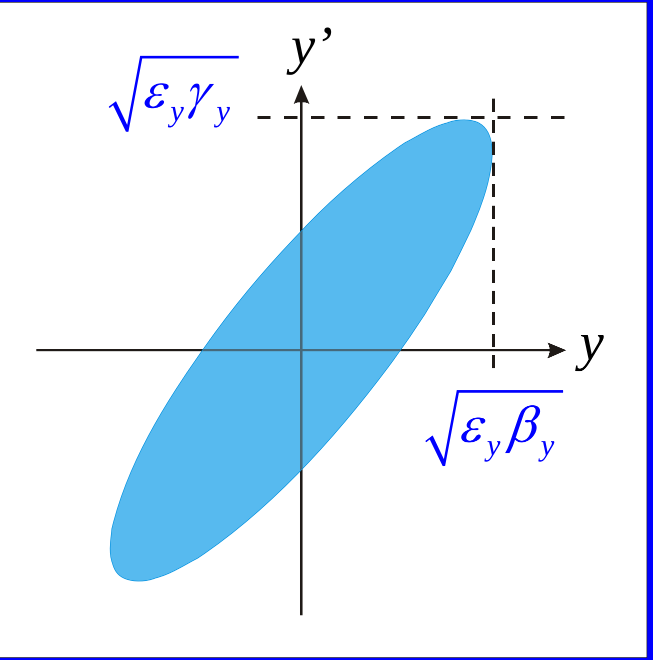


particle trajectories map out an area in the phase plane.
Integral over *y-y'* space is the *emittance*, which is a constant

Basic Optics 2: RMS Emittance

Take statistical *2nd-order moments* of phase space coordinates

$$\underbrace{\begin{pmatrix} \langle y^2 \rangle & \langle yy' \rangle \\ \langle yy' \rangle & \langle y'^2 \rangle \end{pmatrix}}_{\det = \varepsilon_y^2} = \underbrace{\begin{pmatrix} \beta_y & -\alpha_y \\ -\alpha_y & (1+\alpha_y^2)/\beta_y \end{pmatrix}}_{\det = 1} \varepsilon_y$$



define $\quad \varepsilon_y = \sqrt{\langle y^2 \rangle \langle y'^2 \rangle - \langle yy' \rangle^2}$

$$\frac{(1+\alpha_y^2)}{\beta_y} y^2 + 2\alpha_y yy' + \beta_y y'^2 = \varepsilon_y$$

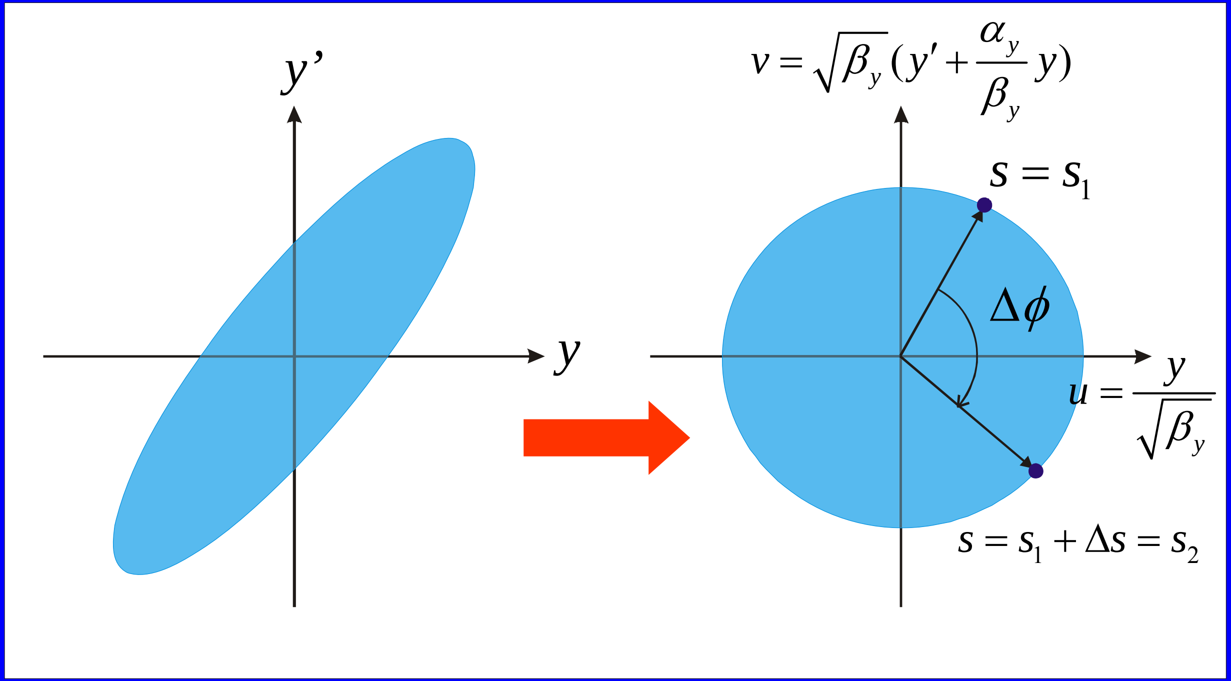
equation of an ellipse which bounds one standard deviation of the bivariate distribution

RMS emittance is conserved by linear optics.

Basic Optics 3: Phase Advance

The parameters $\beta = \beta(s)$ and $\alpha = \alpha(s)$ are functions of the magnetic lattice (optics). s is the distance along the system (magnetic axis).

At any point $s=s_1$, we can transform the phase space <u>ellipse</u> into a <u>circle</u> (*floquet transformation*)



phase advance

$$\Delta\phi(s_1, s_2) = \int_{s_1}^{s_2} \frac{ds}{\beta_y(s)}$$

note also:

$$\alpha_y(s) = -\beta_y'(s)$$

$$y(s) = a_y \sqrt{\beta_y(s)} \cos\left(\phi_y(s) + \phi_y(0)\right)$$

'betatron' oscillation

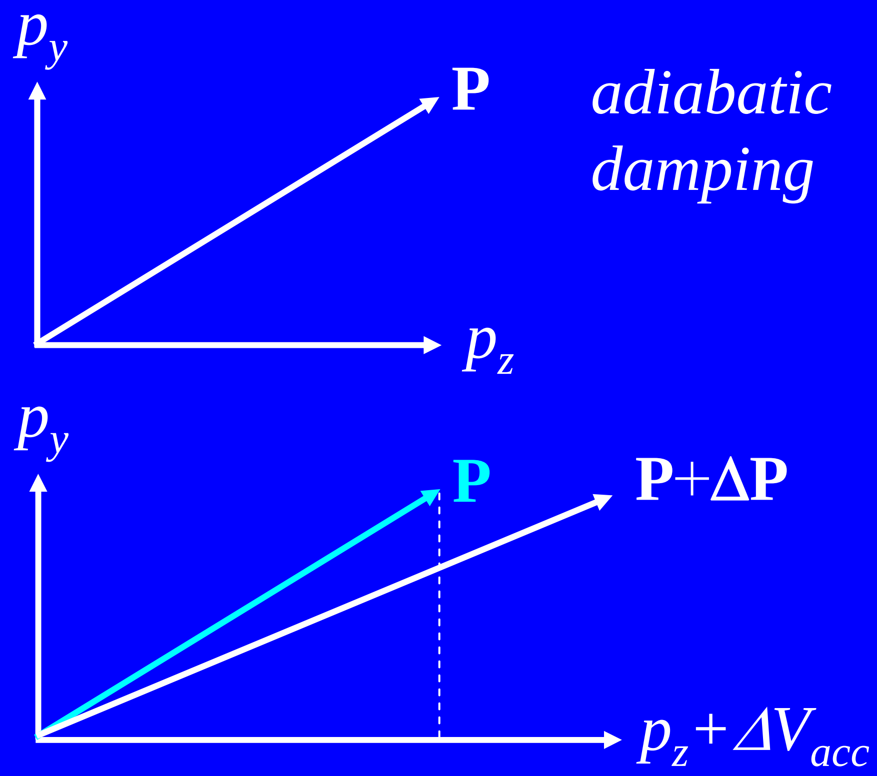
Basic Optics 4: Emittance and Acceleration

high-energy (relativistic) optics is based on very small angle approximations.

Hence we assume $p_z \gg p_y$ and thus

$$p_z \approx |\mathbf{P}|$$

$$y' = \frac{dy}{dz} \approx \frac{p_y}{p_z} \approx \frac{p_y}{|\mathbf{P}|}$$



adiabatic damping

hence for ultra-relativistic beams $y' \propto \frac{1}{\gamma}$ $\quad \gamma = E/m$

$$\gamma y' = const.$$

$$\Rightarrow \gamma\varepsilon_y = const. \quad \equiv \text{\underline{normalised} emittance}$$