ILC
International Linear Collider

9th Int. School for Linear Colliders at Whistler, Canada

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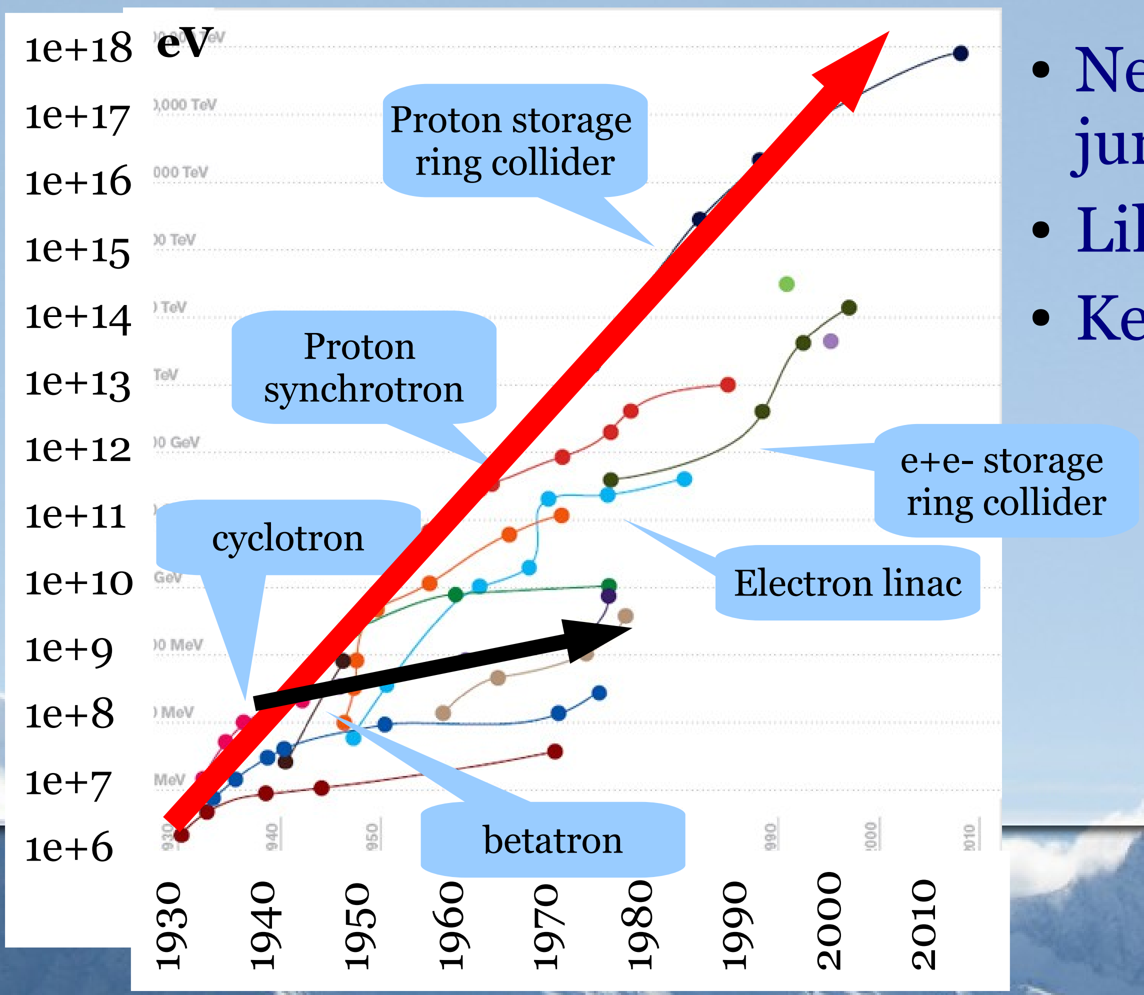
1. Future Colliders
2. ILC physics motivations
3. ILC Accelerator Overview
4. ILC, the global project

1. **Future Colliders**
2. **ILC physics motivations**
3. **ILC Accelerator Overview**
4. **ILC, the global project**

Livingston Plot :
Moor's law in Accelerator

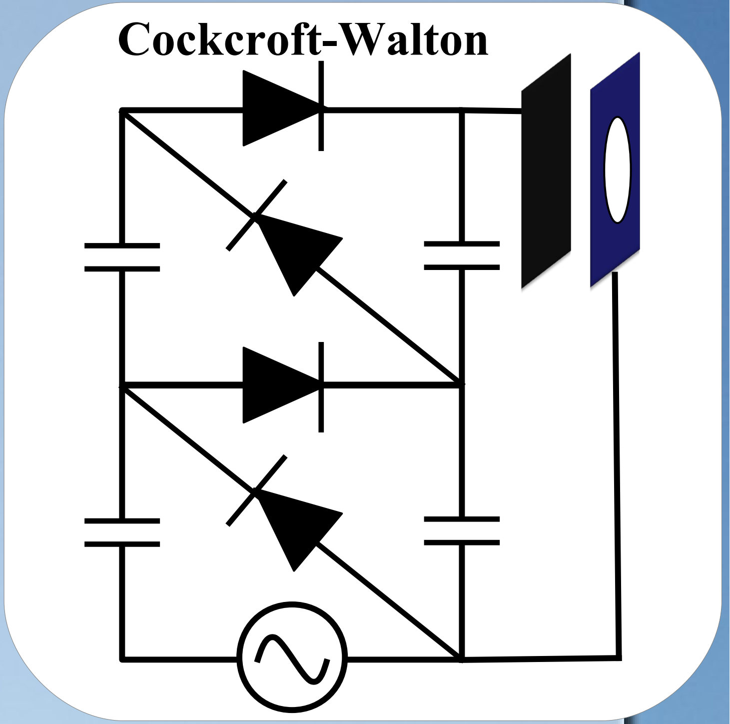


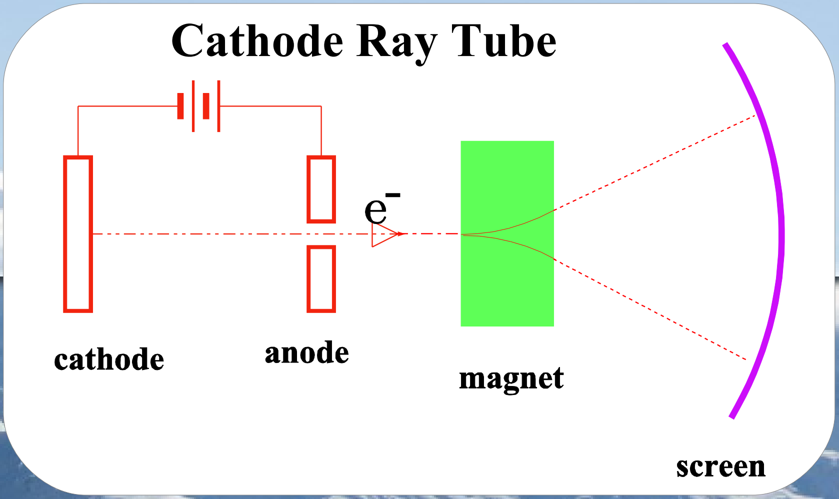
From Symmetry Magazine

- New inventions give a large jump.
- Like a multi-stage rocket.
- Keep the innovation!

Static Accelerator

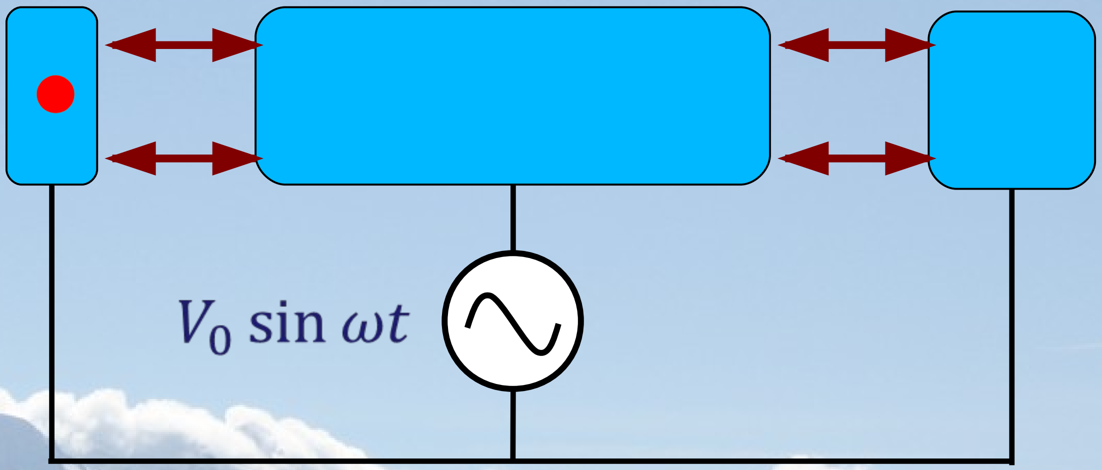
- First accelerator was DC type.
- It still shares the largest population in the world.
- It is simple, but the highest energy is limited by surface breakdown.
- The practical limit is 1~2 MeV.

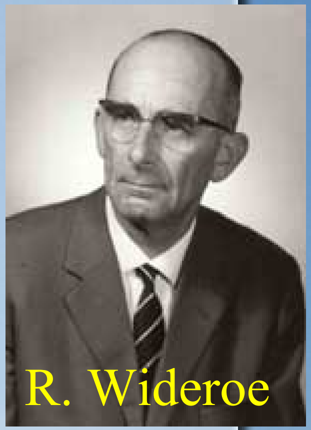




A big invention: RF accelerator

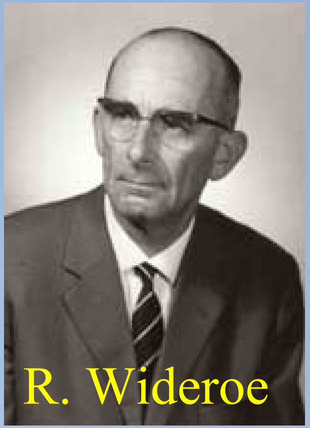
- R. Wideroe invent the principle of AC acceleration (RF acceleration). That is the biggest invention in accelerator.
- In principle, there is no limit on the energy by the repeatable acceleration.

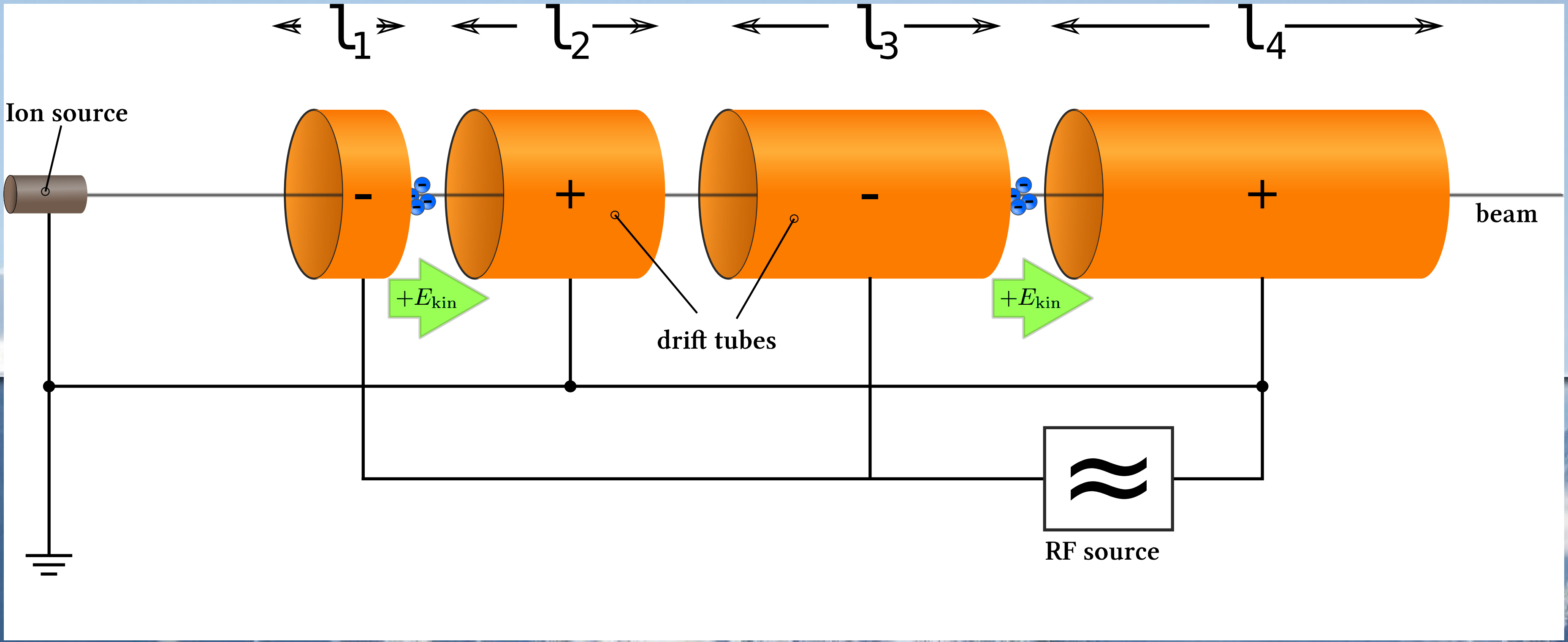




Wideroe-Linac: the first RF linac

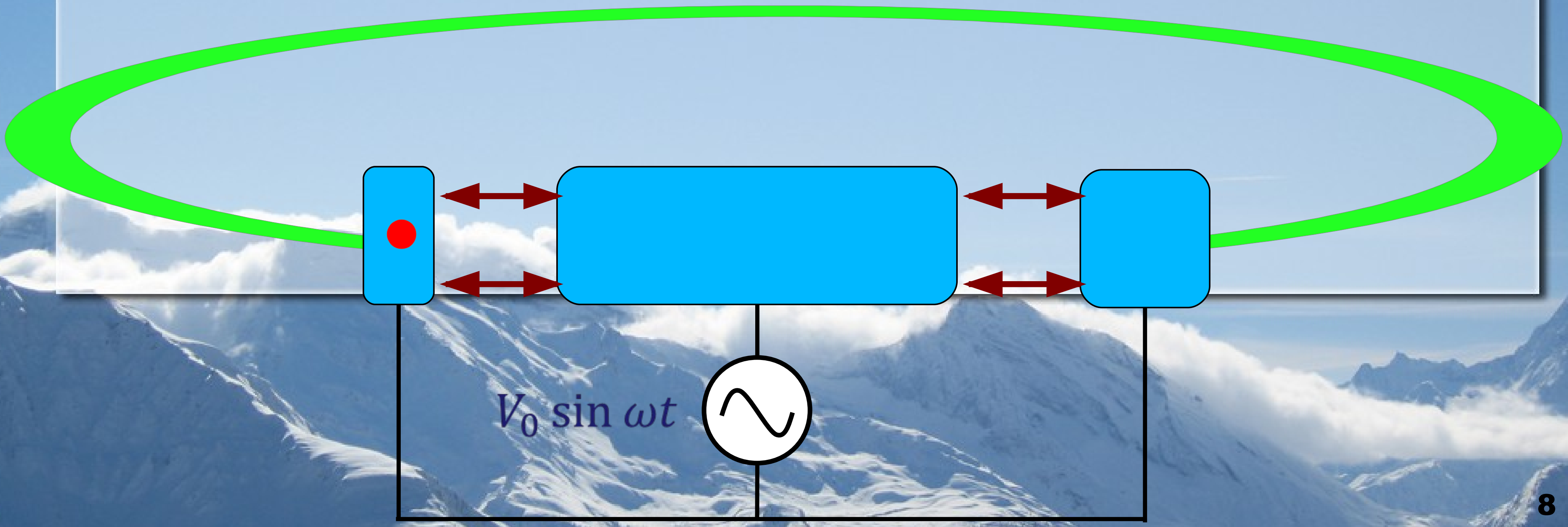
- The first repeatable acceleration.
- The phase advance to the next electrode is p.
- $E_{kin}=eN_{gap}V_{RF}$; The highest energy depends on number of electrode and voltage.
- l=v/2f. : The velocity and the electrode length have to be matched.





Wideroe is also initiator of Ring accelerator

- Install the Wideroe's RF cavity to a circular orbit = Synchrotron.
- The highest energy accelerator is still Proton Synchrotron (LHC).



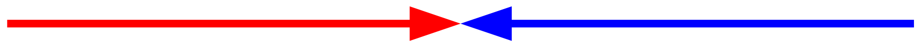
What is Collider?

- The Center of Mass energy depends on the frame, even the beam energy is same.
- It has a big advantage to reach higher energy (E>2m).
- Collider : The highest CME with a beam energy.

Fixed target

$$E_{CME} = \sqrt{2mE}$$

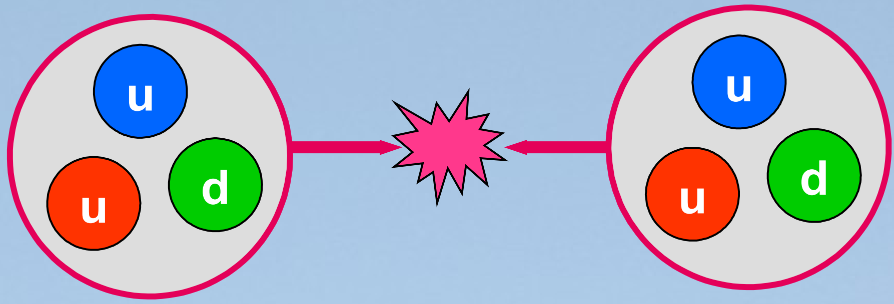
Collider

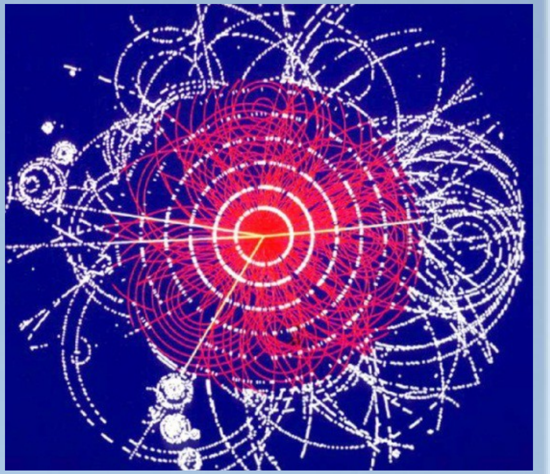


$$E_{CME} = 2E$$

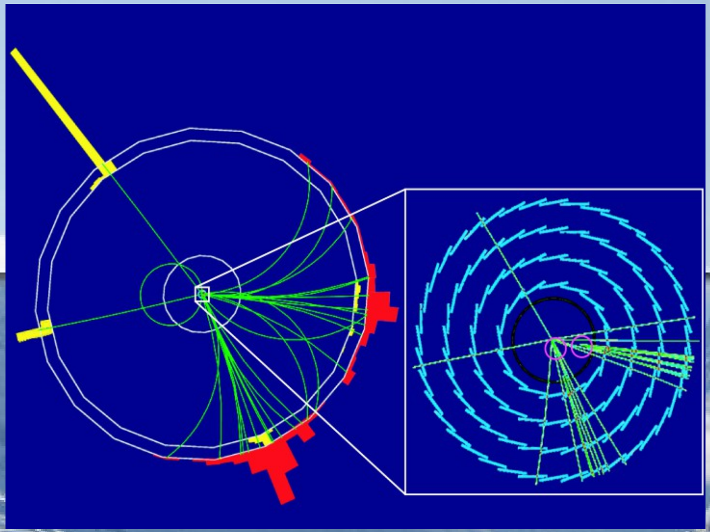
Hadron Collider and Lepton Collider

Proton (Hadron) Collider





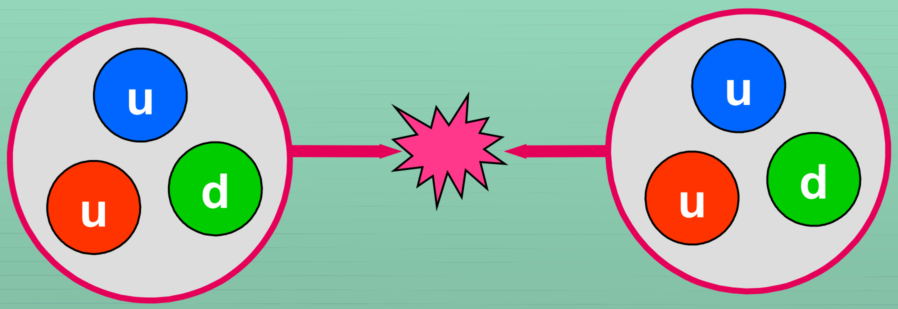
Lepton Collider

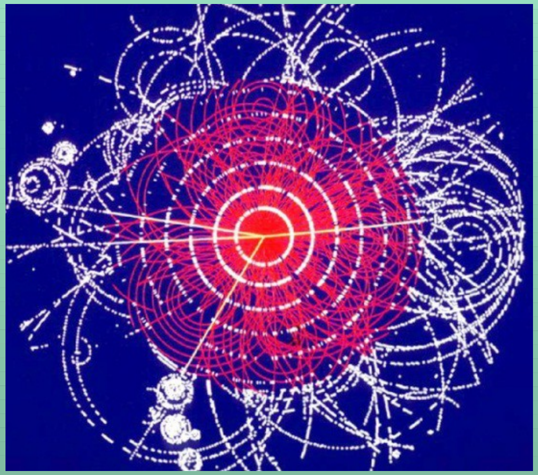


Hadron Collider

- Proton is a composite particle.
- Actual collision is made by partons (quarks and gluons).
- Each collisions have different initial states (energy) which we do not know.
- Interaction is complicated.
- Potential energy reach is very high.

Hadron Collider

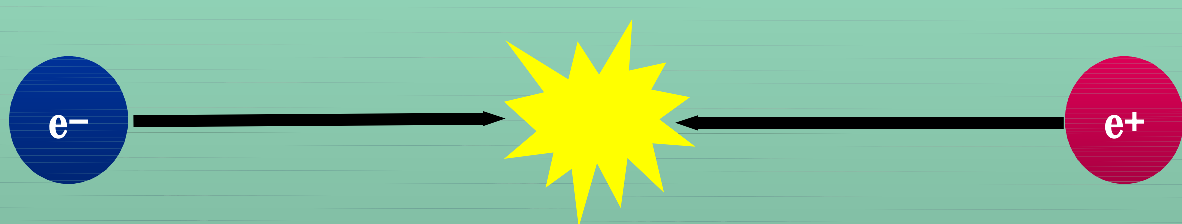


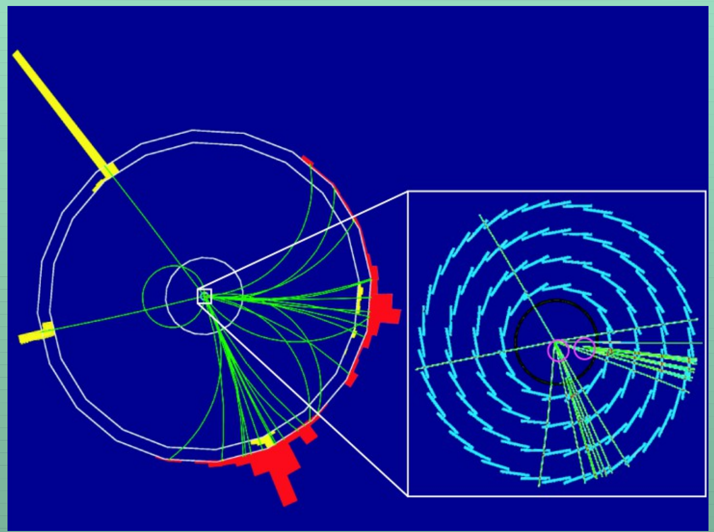


Lepton Collider

- Lepton is an elementary particle.
- Each collisions have same initial states. Full reconstruction of the event is possible.
- Interaction is simple.
- No energy reach beyond CME (Center of Mass Energy).

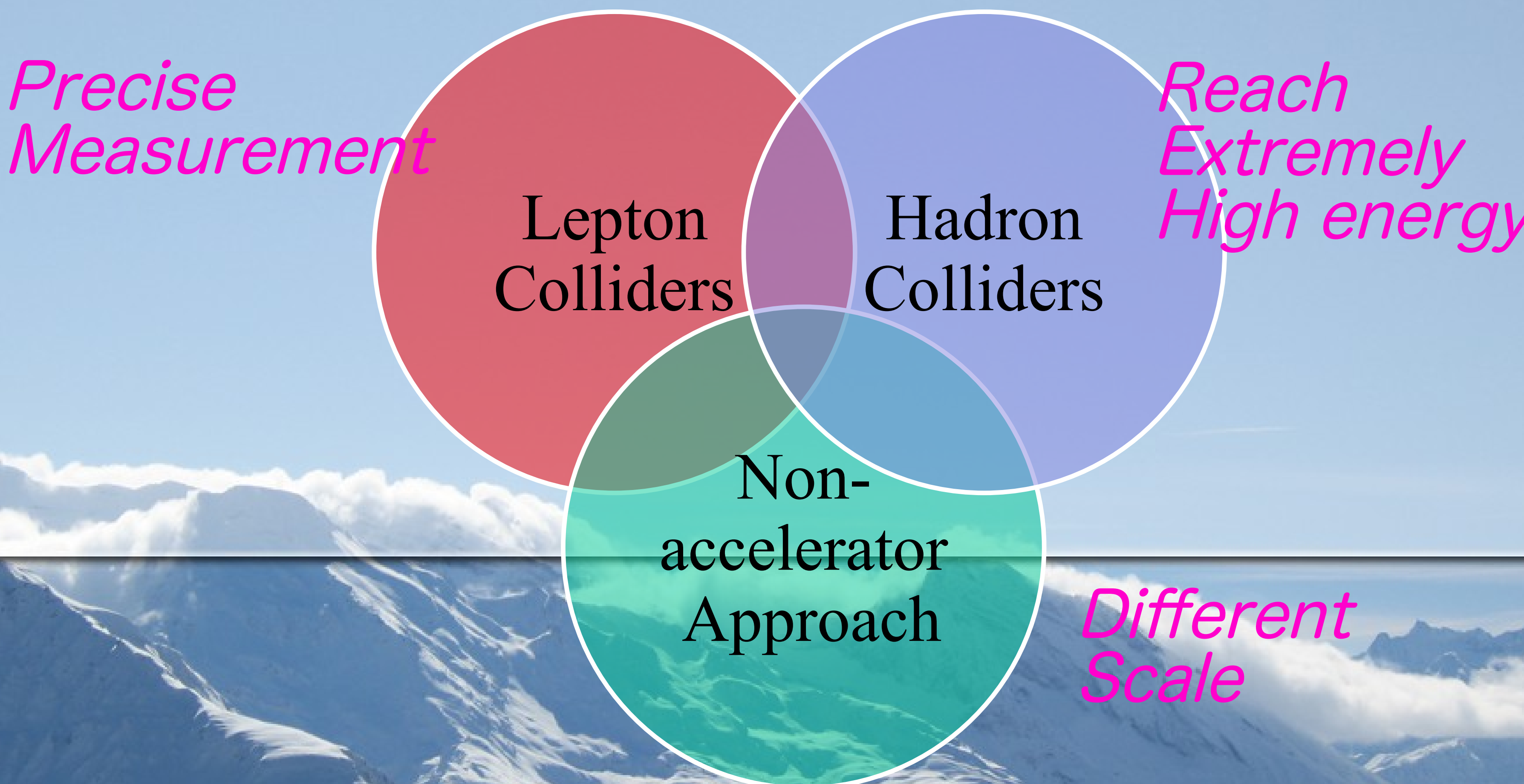
Lepton Collider





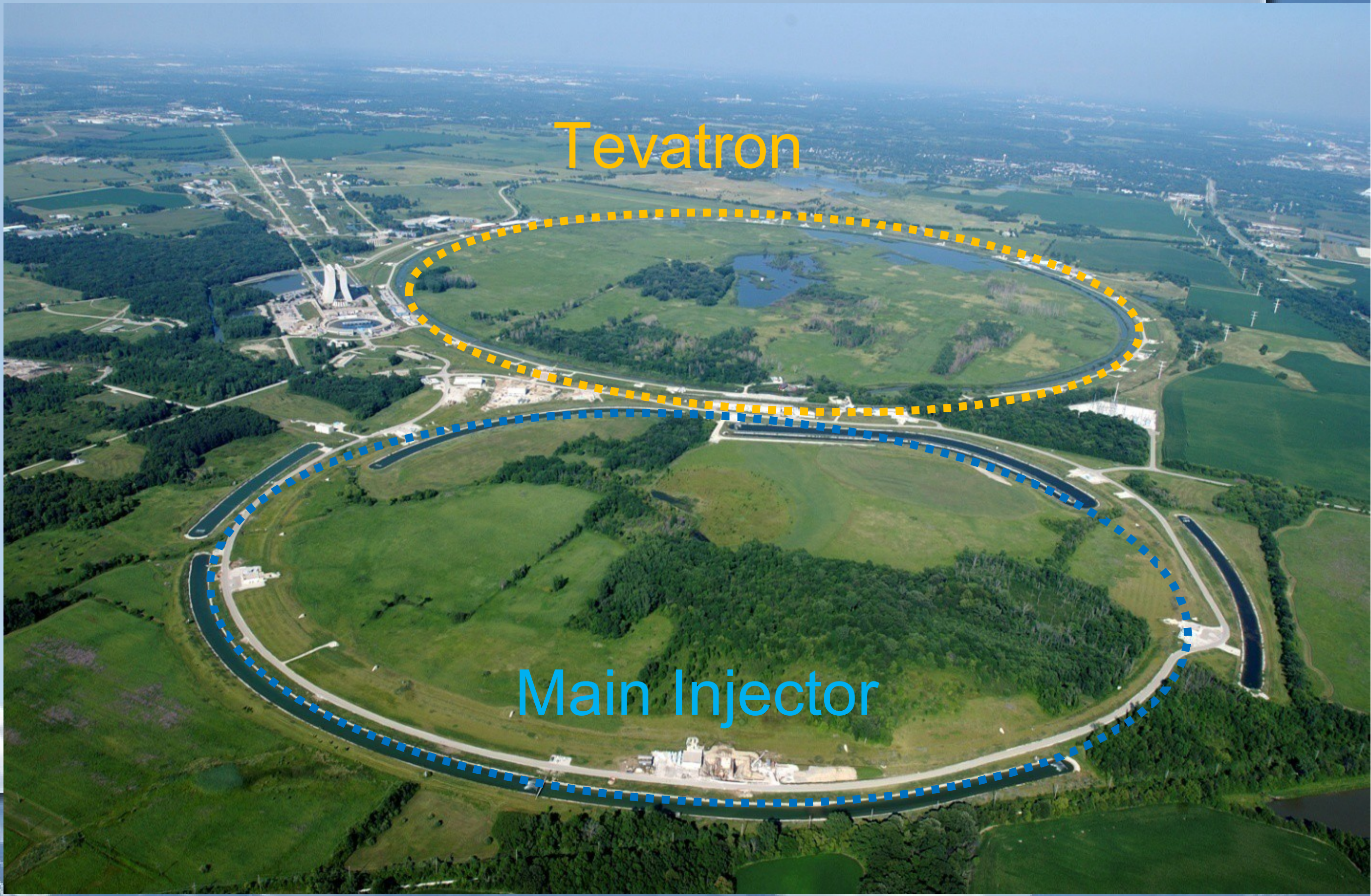
Lepton Colliders and Hadron Colliders

Both colliders are inseparable and important.

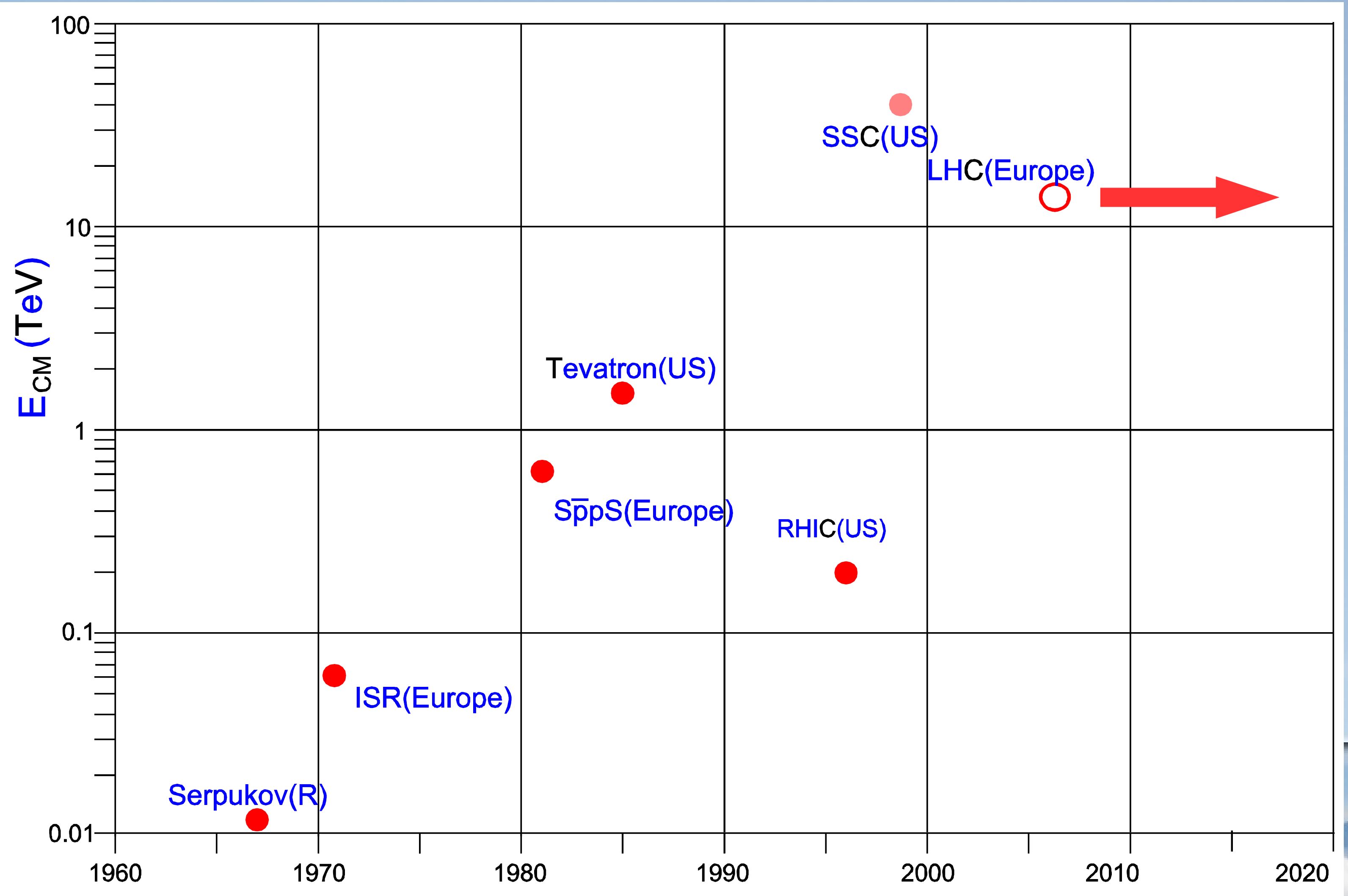


Era of Huge Ring Colliders: Tevatron

- FNAL
- Proton-antiproton
- circumference 6.3km
- up to ~1TeV
- Completed in 1983
- Superconducting magnet 4.2Tesla
- 1995 Top Quark
- 2009 shutdown



Evolution of Proton/Antiproton Colliders



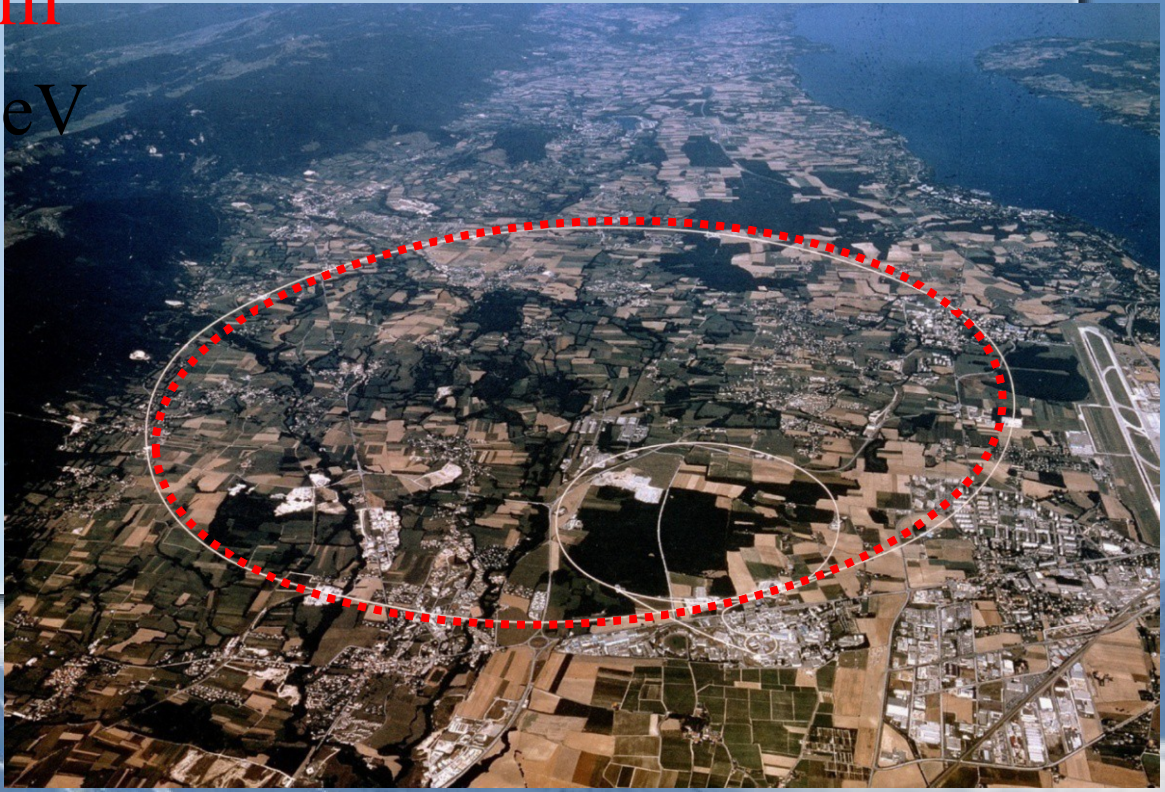
Era of Huge Ring Colliders: LEP

LEP (Large Electron-Positron Collider)

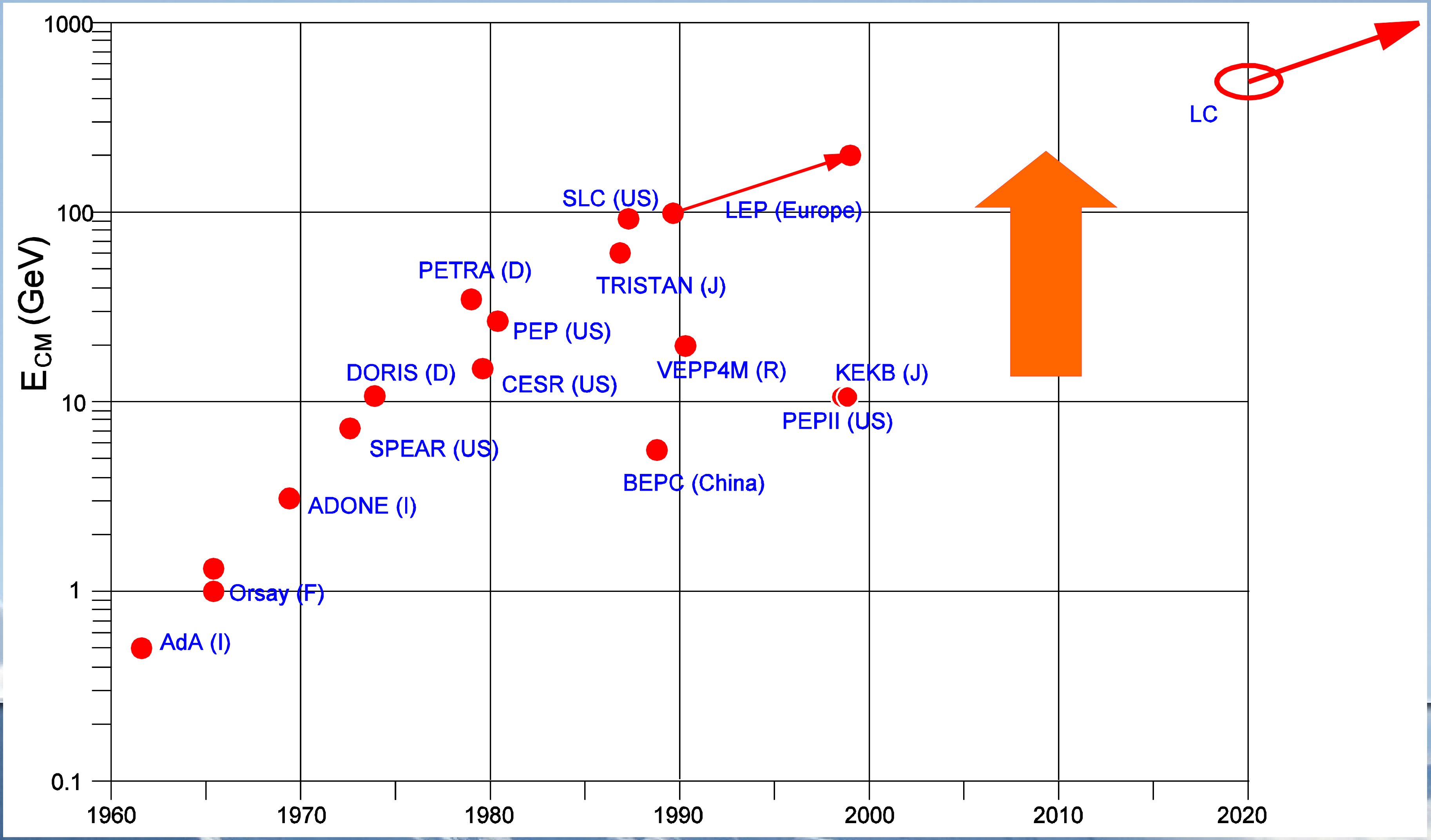
CERN

Construction started in 1983, operation in 1989

- circumference 27km
  - First target Z^0 at 92GeV
  - Final beam energy 104.5GeV
  - end in 2000

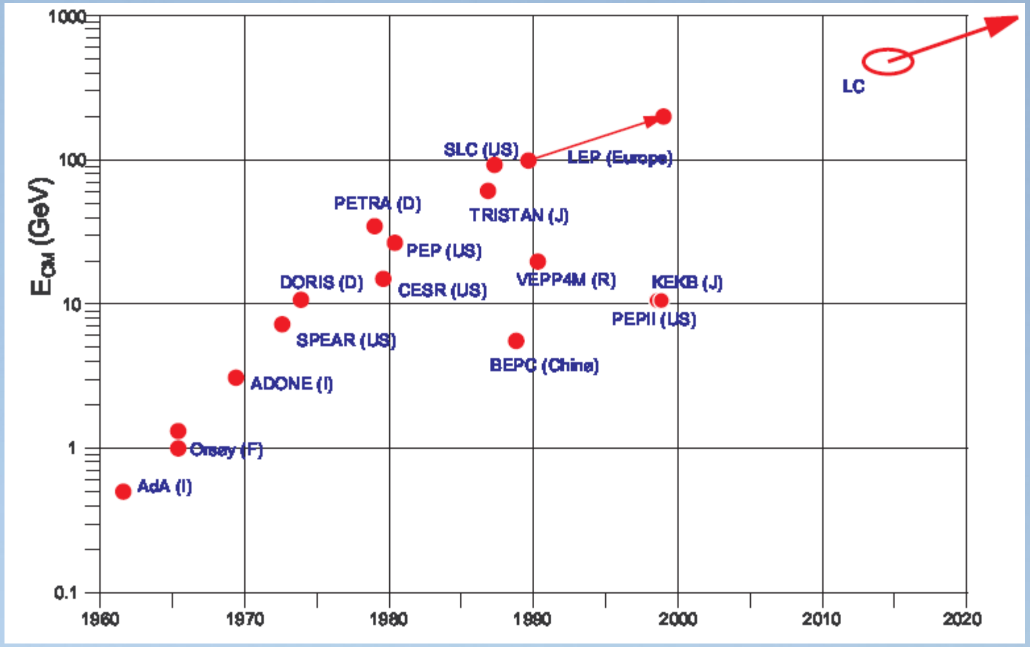


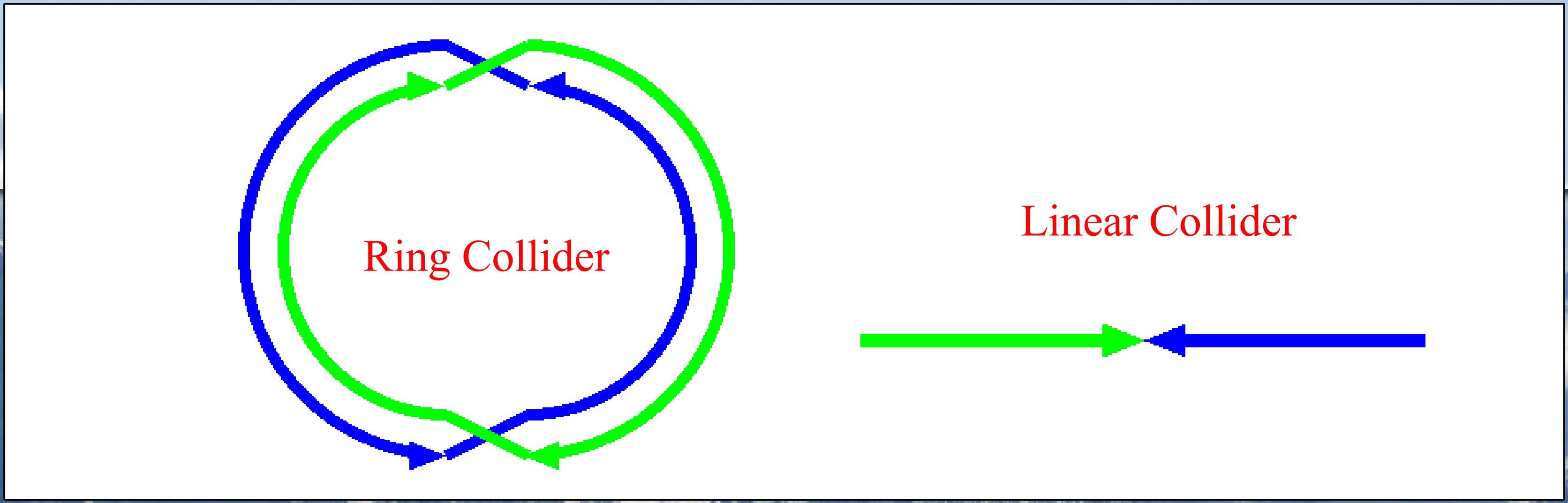
Evolution of Electron-Positron Colliders



Many Ring Colliders
and a Linear Collider

- History of collider is history of high energy physics in the last half of 20th century.
- They are ring colliders except one (SLC).
- The reason is a key issue of this lecture.





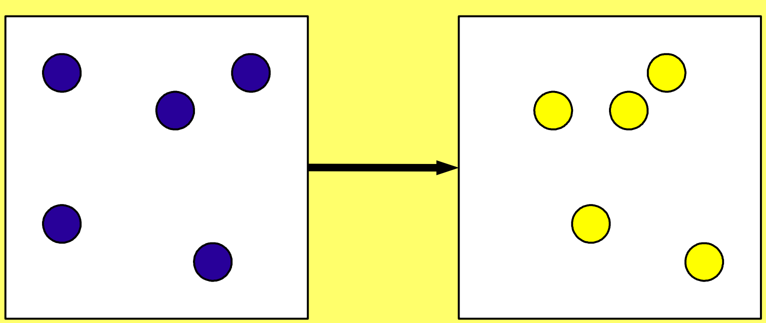
Luminosity Is essential for Colliders

- Event rate ＝ Performance of Collider

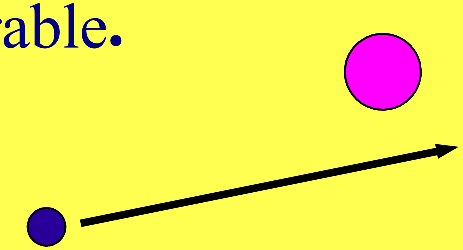
$$N[s^{-1}]=L[cm^{-2}]\times\sigma[cm^{2}]$$

L: Luminosity, particle density rate.
Operable.

$$L=\frac{f\,N^2}{4\pi\sigma_x\sigma_y}$$

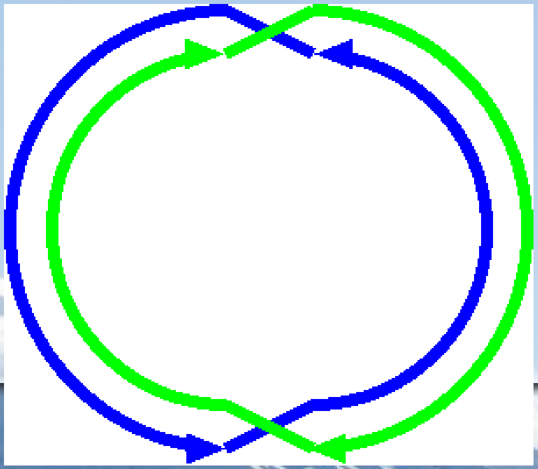


σ cross section.
Effective area for interaction. Not operable.



Why Ring Collider?

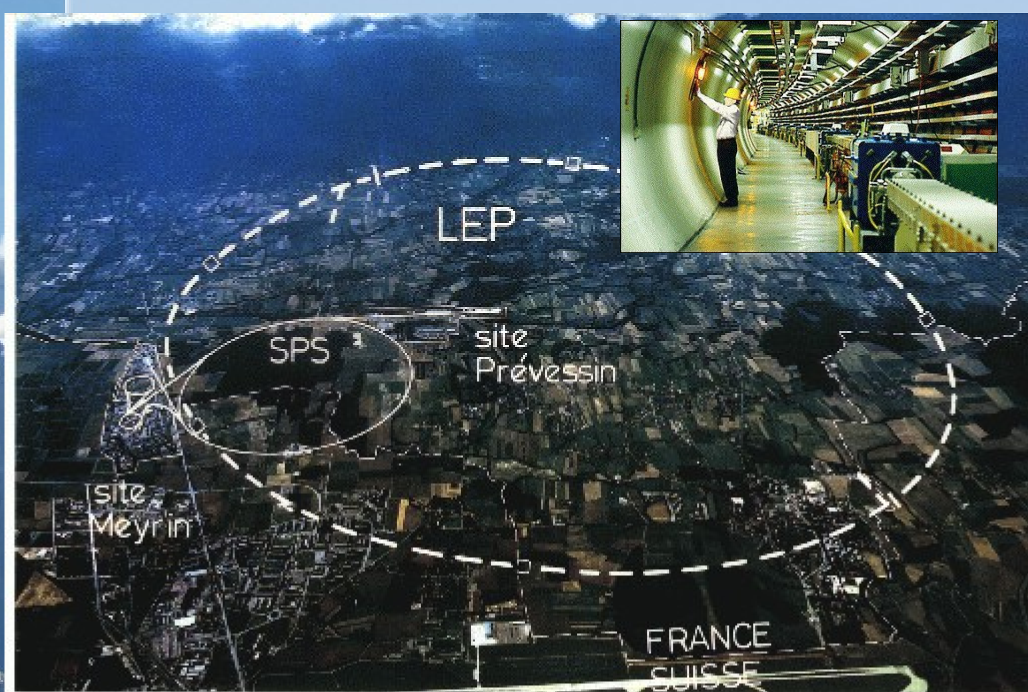
- All colliders ever built are ring colliders except SLC.
- The same bunch beam cycles many times in the orbit, the crossing rate can be very large.
- A large luminosity can be easily obtained because of high *f*.



$$L = \frac{f N^2}{4 \pi \sigma_x \sigma_y}$$

LEP accelerator

- Circumference 27km. It was at CERN, Geneva, Swiss.
- Operation started in 1989. The energy was 45 GeV x 45 GeV at Z^0.
- The operation ended in 2000. Maximum energy was 104 GeV x 104 GeV.
- LHC is now placed in this tunnel.



Keep Going?

- Ring hadron colliders and lepton colliders have been constructed.
- SM of particle physics has been established by many experiments at these facilities.
- Can we keep this way in this 21st century?
- If we have to change our strategy, why?

Synchrotron Radiation

- Why LEP stopped the operation at CME 209GeV? The was very close to see the 125GeV Higgs. （Z^0H production threshold energy is 215 GeV).
- 209GeV was the maximum energy which was possible with LEP.
- The reason ：Synchrotron Radiation

$$P[turn^{-1}] = \frac{4\pi}{3} e^2 \frac{\beta^4 \gamma^4}{\rho}$$

- 2GeV of 104 GeV is lost per turn. Huge power is required to recover this loss.

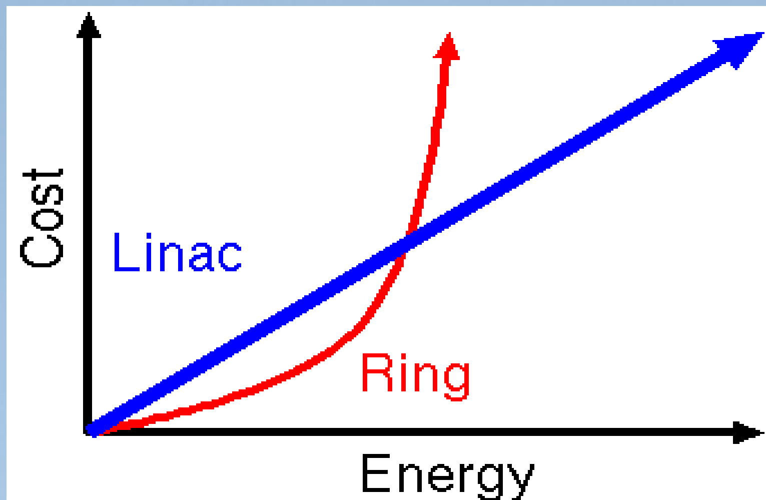
Synchrotron Radiation

- Huge energy loss by the synchrotron radiation is a big obstacle for e+e- ring colliders.
  - We have to consider another way for higher e+e- collider.
- The Synchrotron radiation is much less for proton
- Thanks for the heavy mass of proton, proton collider energy is not currently limited by SR. Actual limitation is B field.
- That is also true for muon colliders. In case of muon collider, cooling method and its short life are the biggest issue.

Brake!

- Due to the huge energy loss by SR, lepton (e+e-) ring collider is not realistic above 100 – 150 GeV beam energy.
- Required power to maintain the circulated beam is increased as fourth order of the beam energy.
- Construction and operation cost is dominated by this recover power. It is also proportional to 4^{th} order of the beam energy.
- Lepton Ring collider is now in dead-end. We have to find another way.
- That is Linear Collider.

Ring collider and Linear collider



not at all

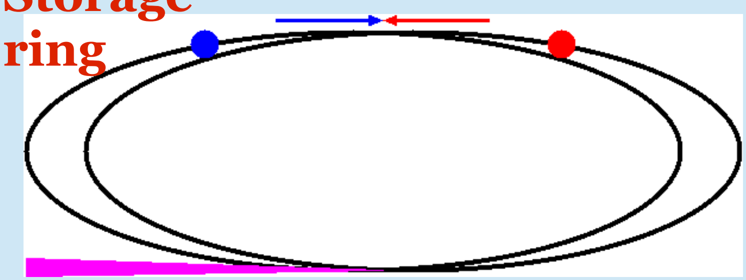
Energy loss

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

Huge loss
at high energy

LINAC

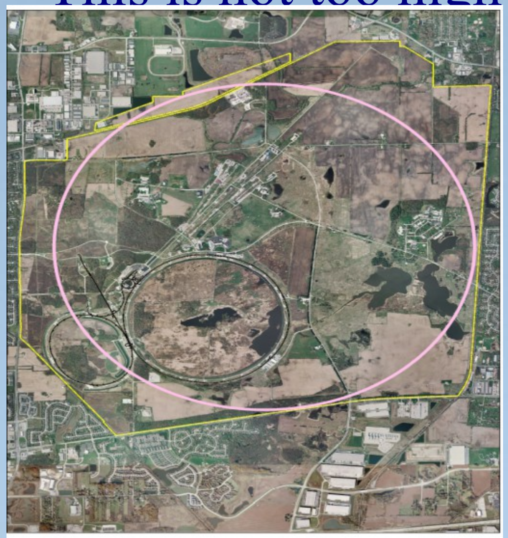
Storage ring



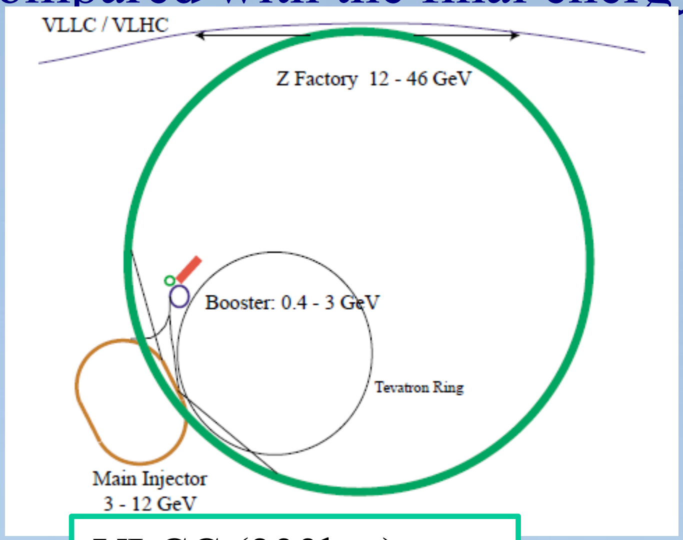
Revival of e+e- Ring Colliders ?

To create Higgs by e+e- → ZH requires E_{CM}~240GeV

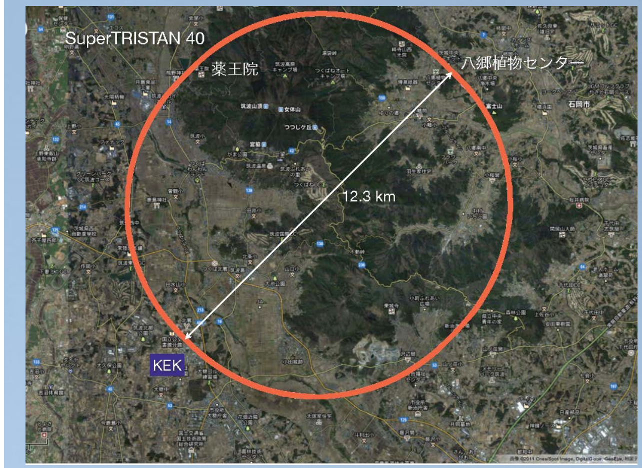
This is not too high compared with the final energy 209GeV at LEP



FNAL site filler (16km)



VLCC (233km)



SuperTRISTAN (40km, 60km)

pp collider

e^- e^+ Higgs Factory

CHF (China) (50km, 70km)

LEP3 (27km), TLEP (80km)

Synchrotron Radiation Loss

$$U = 0.088 \frac{E^4[\mathrm{GeV}]}{\rho[\mathrm{m}]} \quad [\mathrm{MeV}]$$

- This (almost) determines RF voltage per turn
  - ~7GeV in LEP tunnel
  - Still possible owing to the improvement of superconducting cavity technology
- But, the required electric power is huge! Real limitation comes from the wall-plug.
- US power consumption : 400GW.

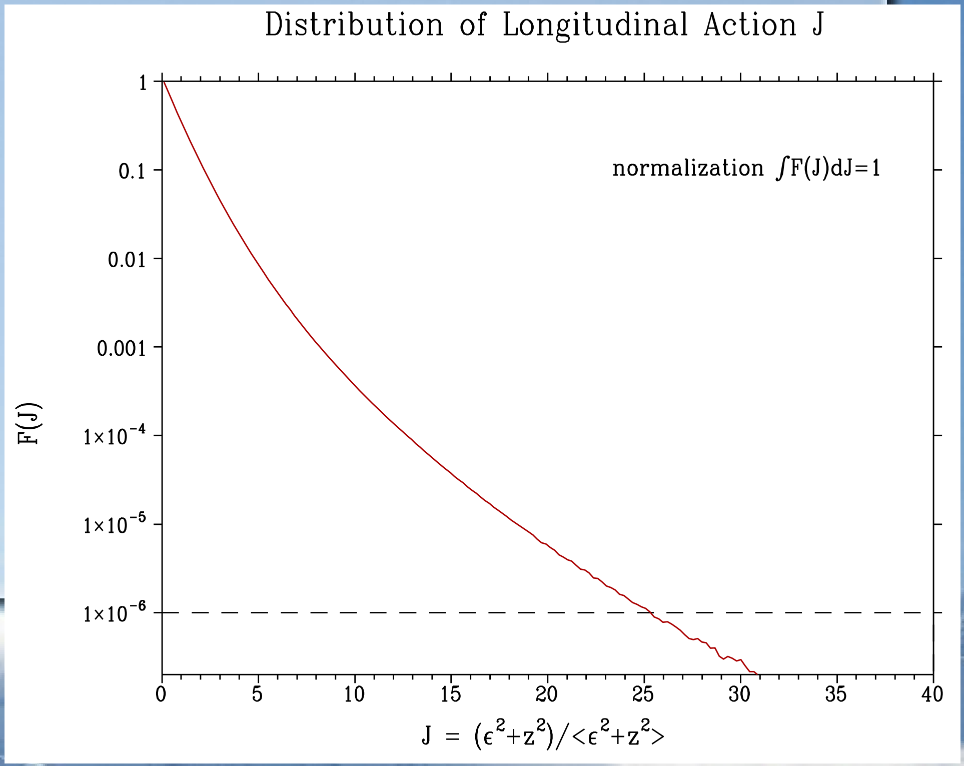
Beamstrahlung of e^+e^- Ring Colliders

Beamstrahlung causes significant energy loss

$$\Upsilon_{max} \approx \frac{2Nr_e^2\gamma}{\alpha\sigma_z(\sigma_x+\sigma_y)}$$

$$\frac{dW}{d\omega} \propto \exp\left[-\frac{2\omega}{3\Upsilon(E_e-\omega)}\right]$$

- Particles with large energy loss will be lost.
- Short beam lifetime.
- Hence, ring colliders are much more fragile than LCs.

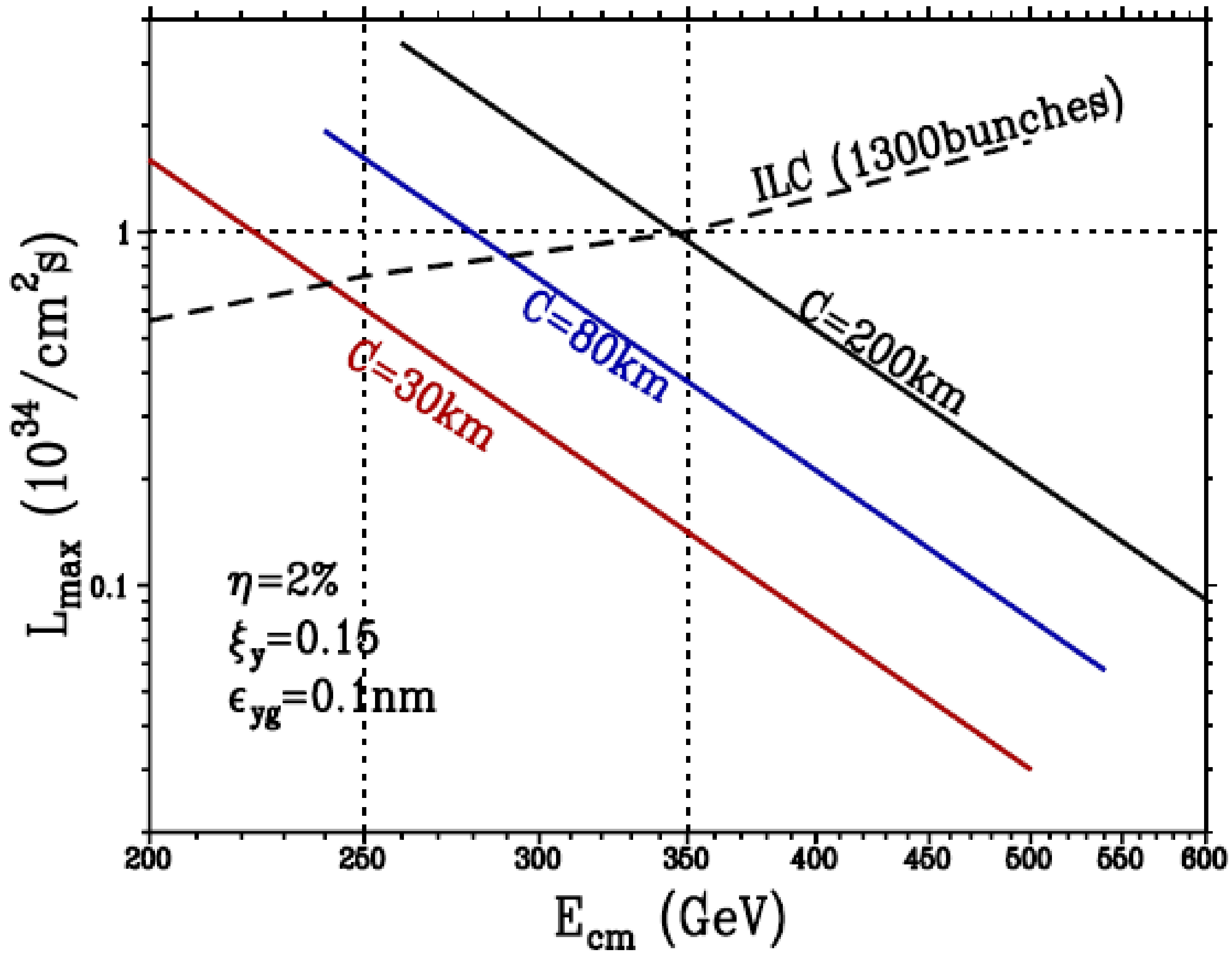


Luminosity vs. Energy

- Key parameters: momentum band width, vertical emittance, beam-beam tune-shift
- If e+e- at >~350GeV, there is no possibility at all.

example with

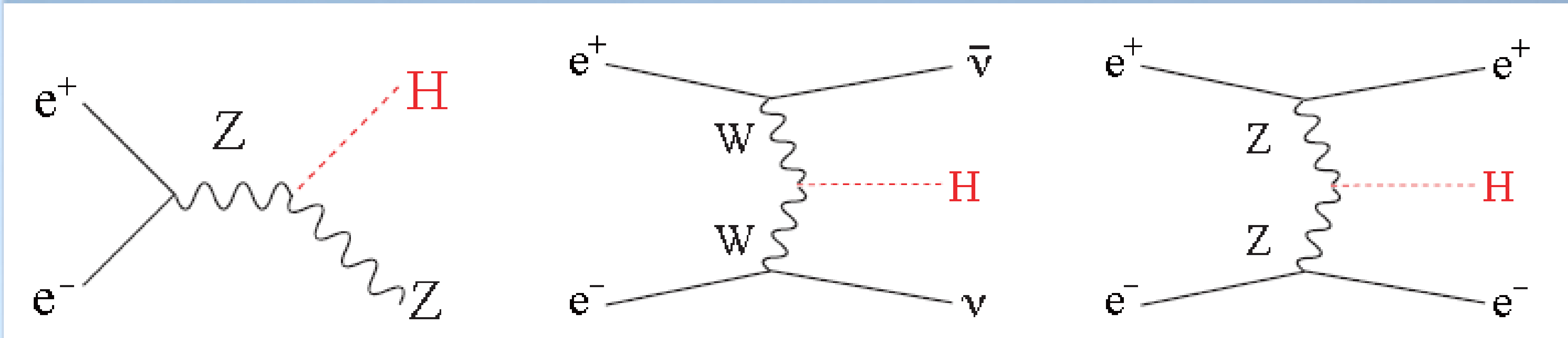
- η=2%
- ξ_y=0.15
- ε_{gy}=0.1nm

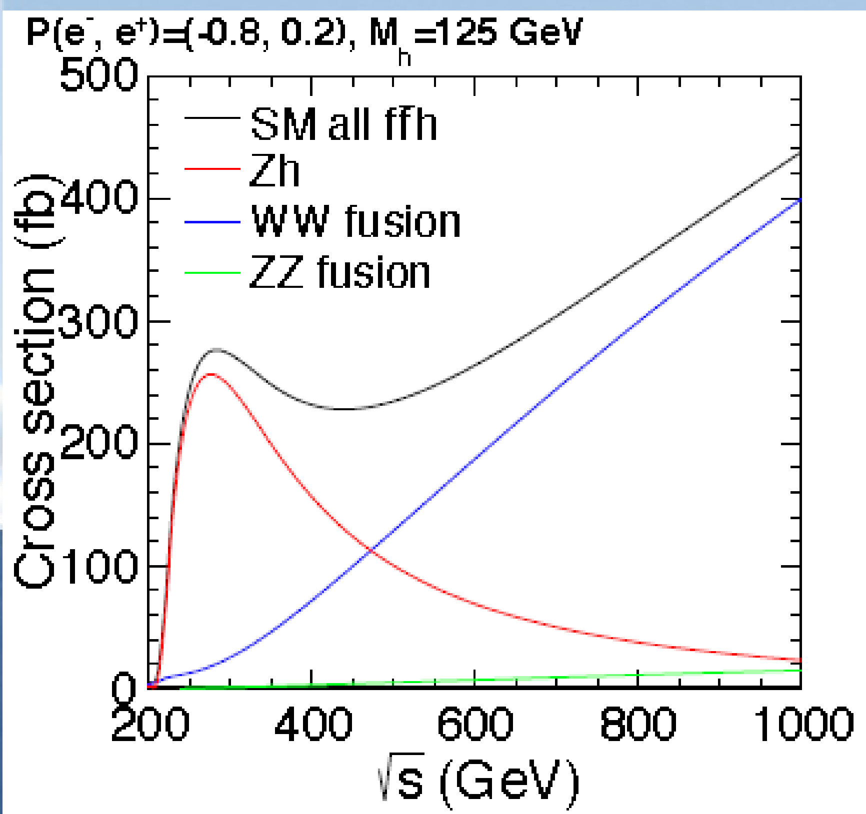


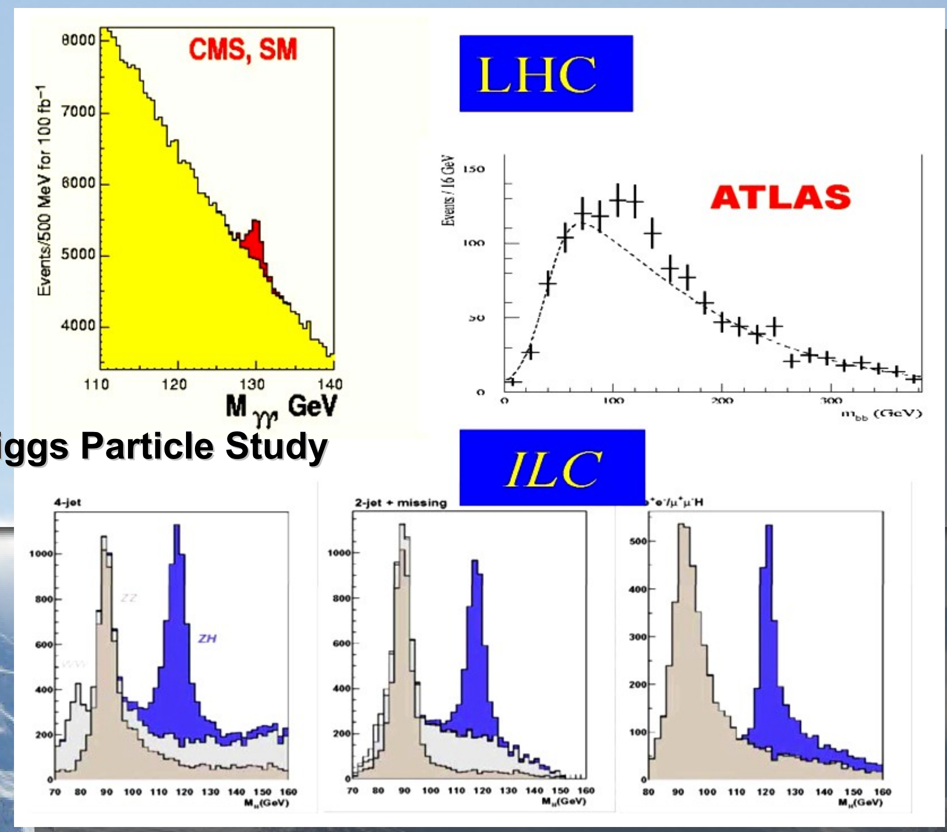
1. Future Colliders
2. **ILC physics motivations**
3. ILC Accelerator Overview
4. ILC, the global project


Internationa Linear Collider
CME - 250-500 GeV

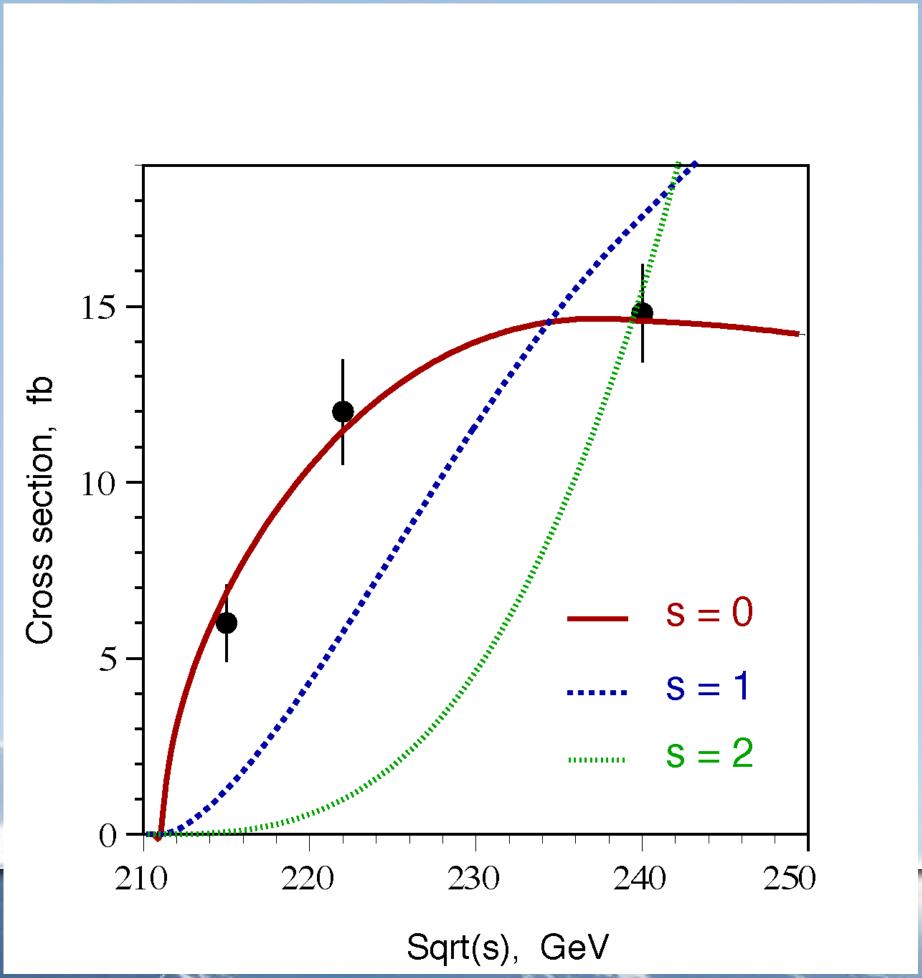
LC as Higgs factory







ILC: Is it really the Higgs ?

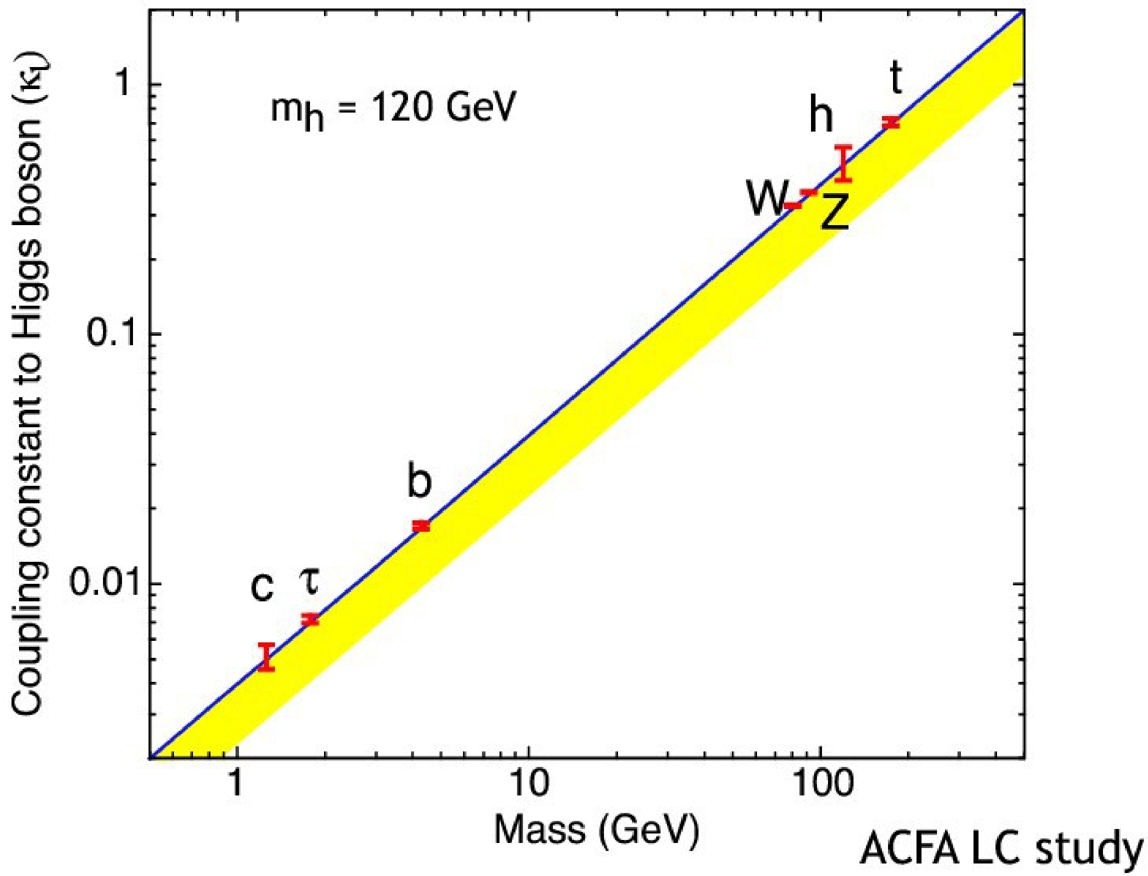


Measure the quantum numbers. The Higgs must have spin zero !

The linear collider will measure the spin of any Higgs it can produce by measuring the energy dependence from threshold

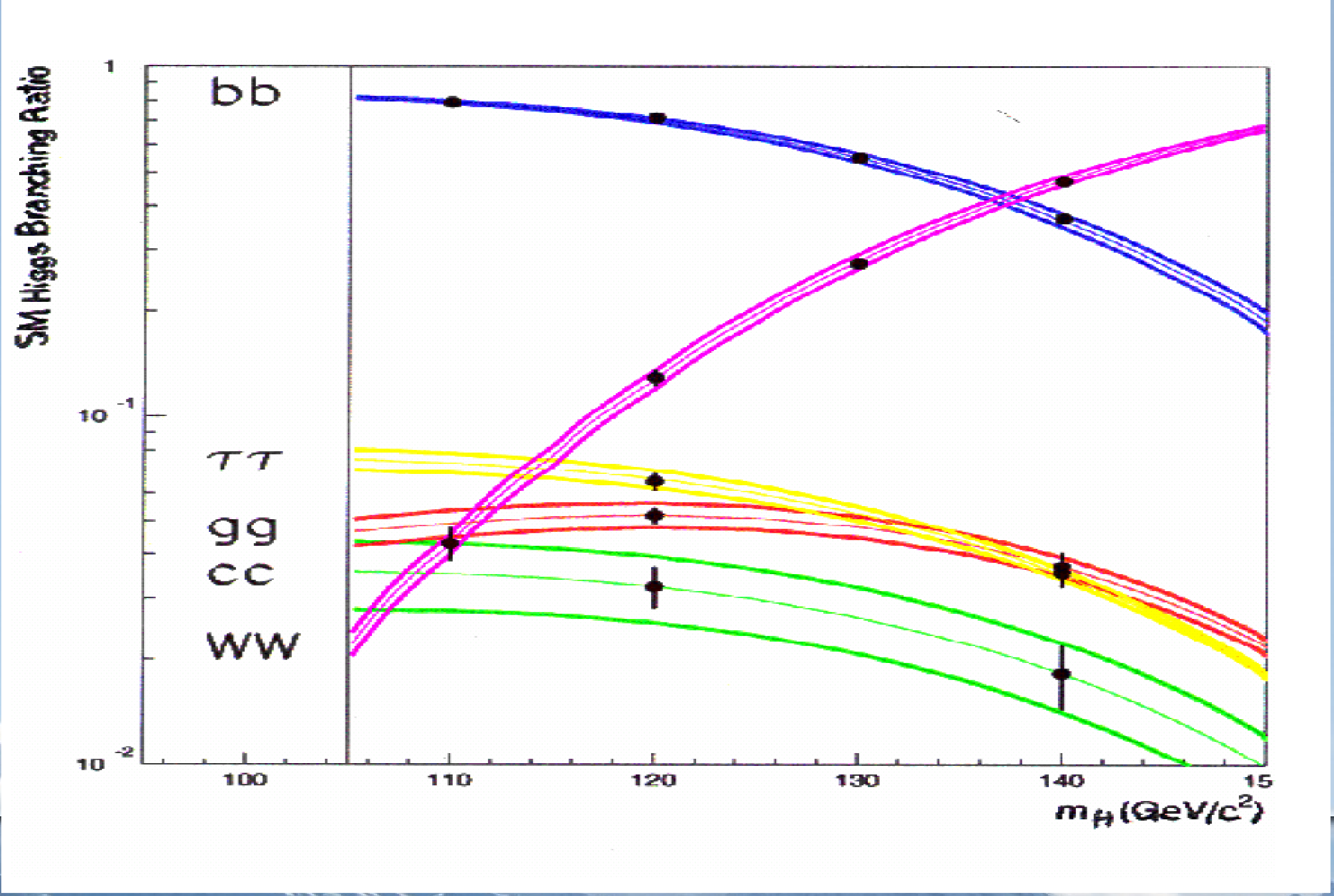
What can we learn from the Higgs?

Precision measurements of Higgs coupling



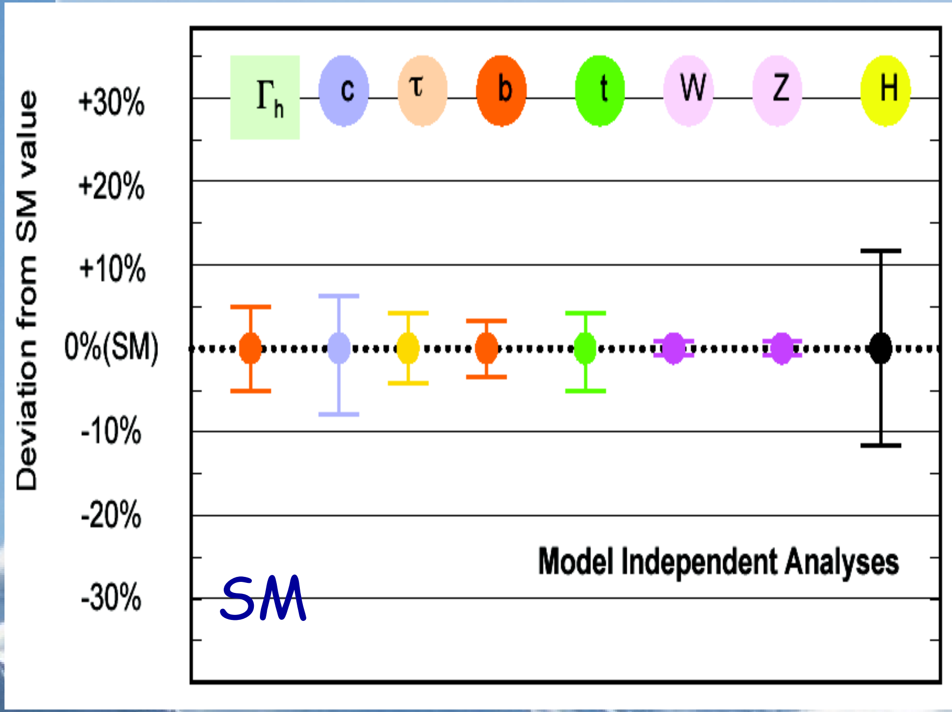
Higgs Coupling strength is proportional to Mass

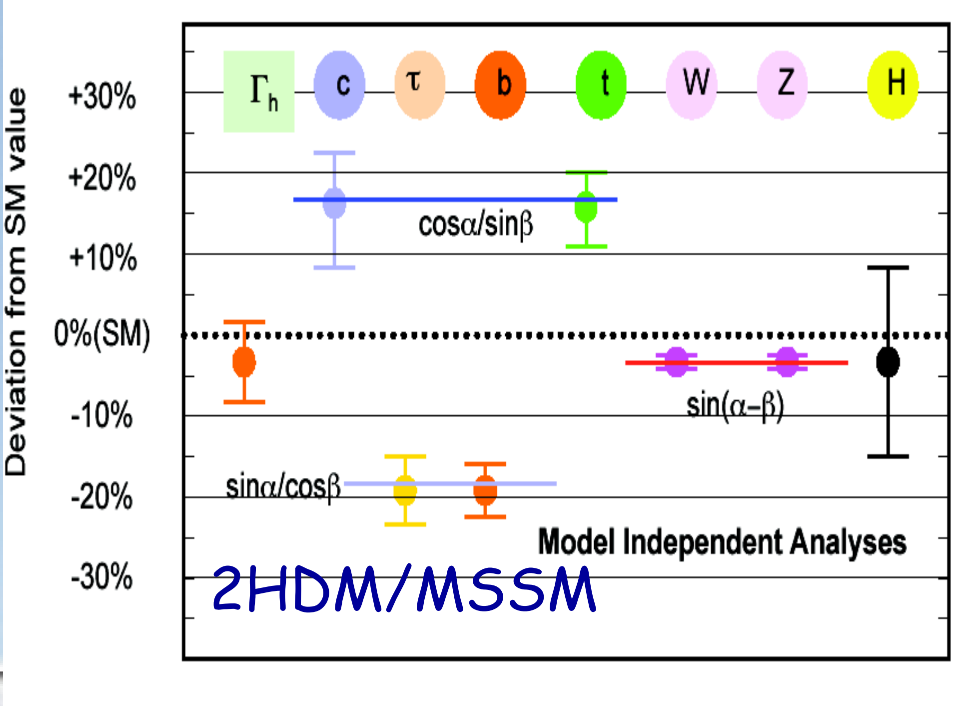
Higgs Branching Ratios



e^+e^- : Studying the Higgs

determine the underlying model

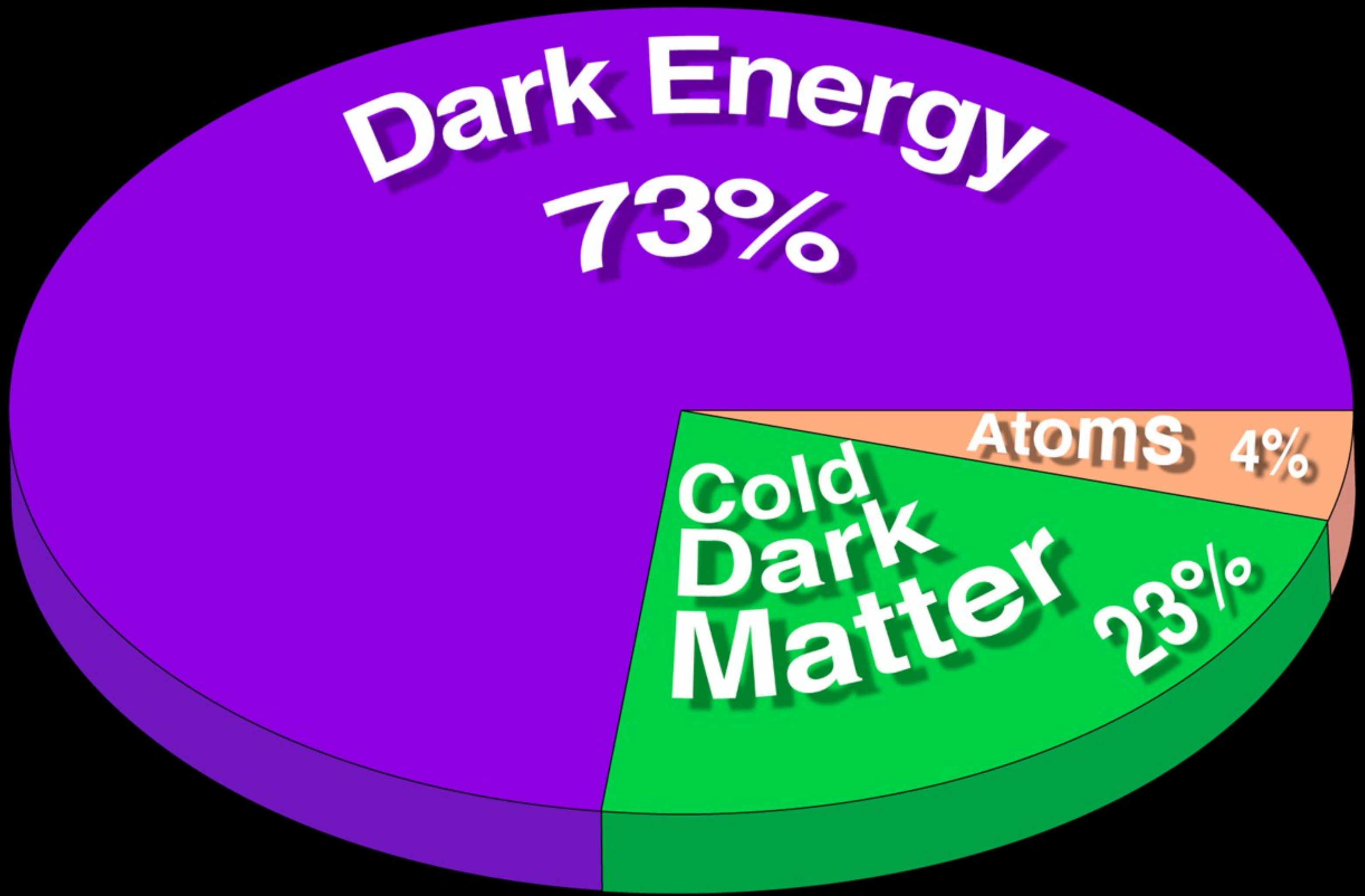




Yamashita et al

Zivkovic et al

Universe is ruled by Darkforce!



Supersymmetry

LHC is suitable for colored particle search .

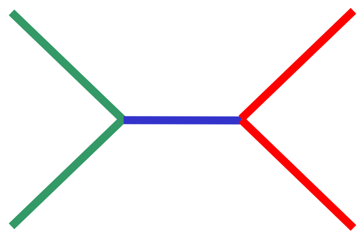
LSP (Lightest Supersymmetry Particle)
Is a candidate of Dark Matter.

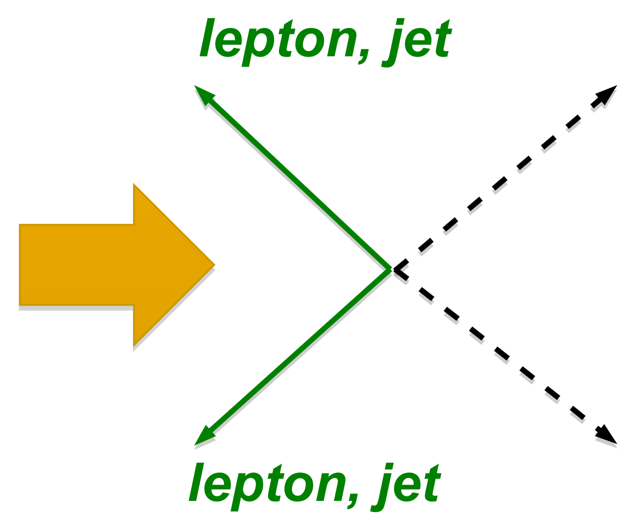
ILC can look also colorless particle.

ILC : A New Particle Factory

SUSY

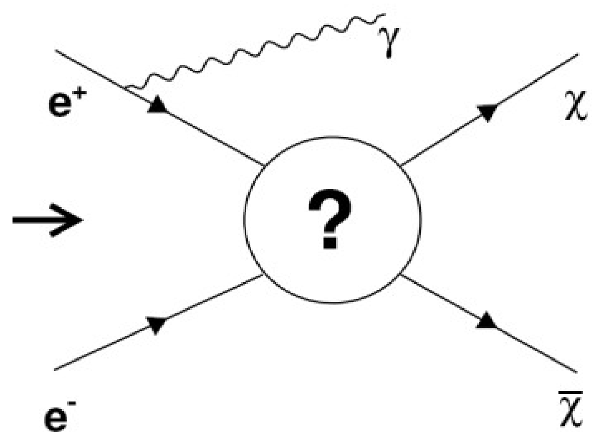
$$
\begin{aligned}
e^+e^- &\to \tilde{e}_R\tilde{e}_R,\ \tilde{e}_L\tilde{e}_L,\ \tilde{e}_R\tilde{e}_L,\ \tilde{\nu}_e\bar{\tilde{\nu}}_e \\
e^+e^- &\to \tilde{\mu}_R\tilde{\mu}_R,\ \tilde{\mu}_L\tilde{\mu}_L,\ \tilde{\nu}_\mu\bar{\tilde{\nu}}_\mu \\
e^+e^- &\to \tilde{\tau}_1\tilde{\tau}_1,\ \tilde{\tau}_2\tilde{\tau}_2,\ \tilde{\tau}_1\tilde{\tau}_2,\ \tilde{\nu}_\tau\bar{\tilde{\nu}}_\tau \\
e^+e^- &\to \tilde{\chi}_1^+\tilde{\chi}_1^-,\ \tilde{\chi}_1^+\tilde{\chi}_2^-,\ \tilde{\chi}_1^0\tilde{\chi}_2^0
\end{aligned}
$$

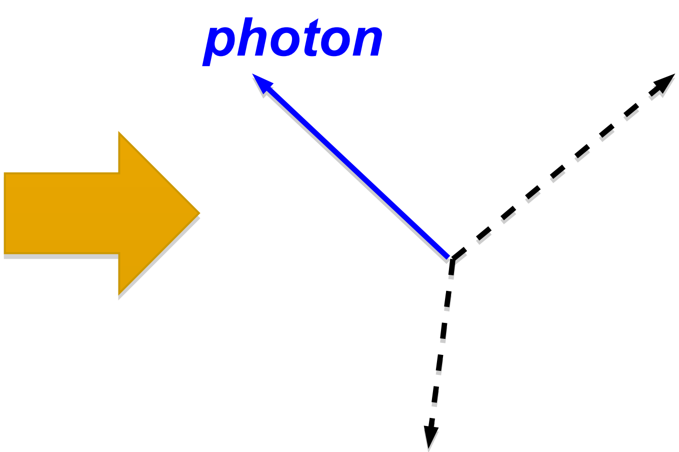




Direct search for new particles!

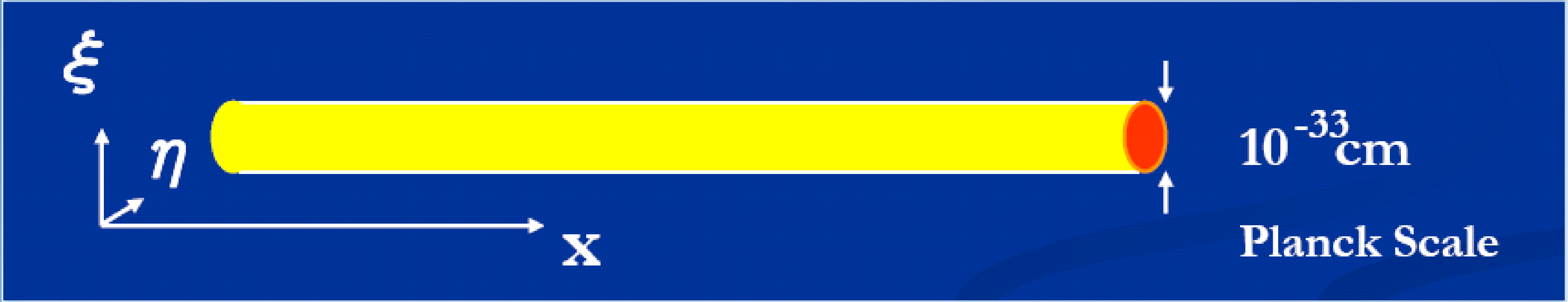
Dark Matter
Pair Creation





Superstring Theory
extra dimensions

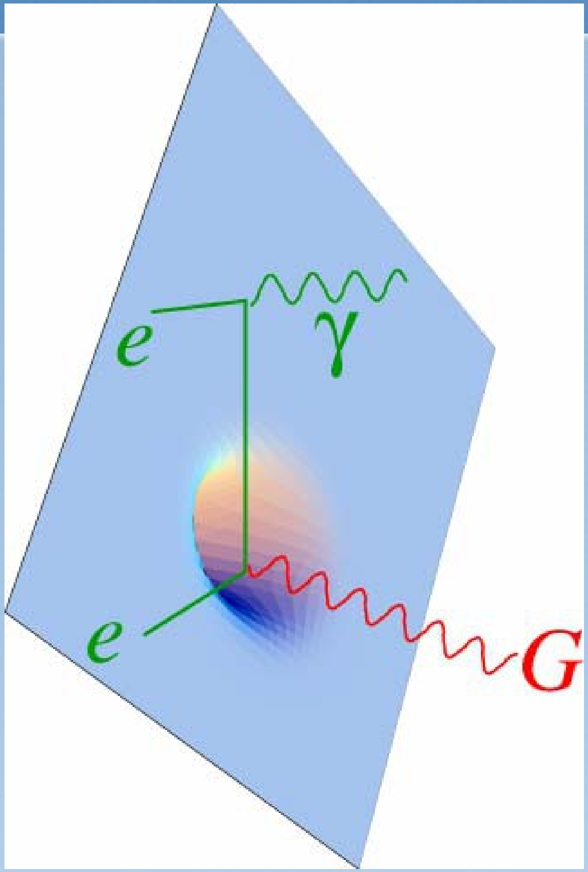
In addition to the 3+1 dimensional space-time, extra space-dimensions exist, presumably curled into a small space size.



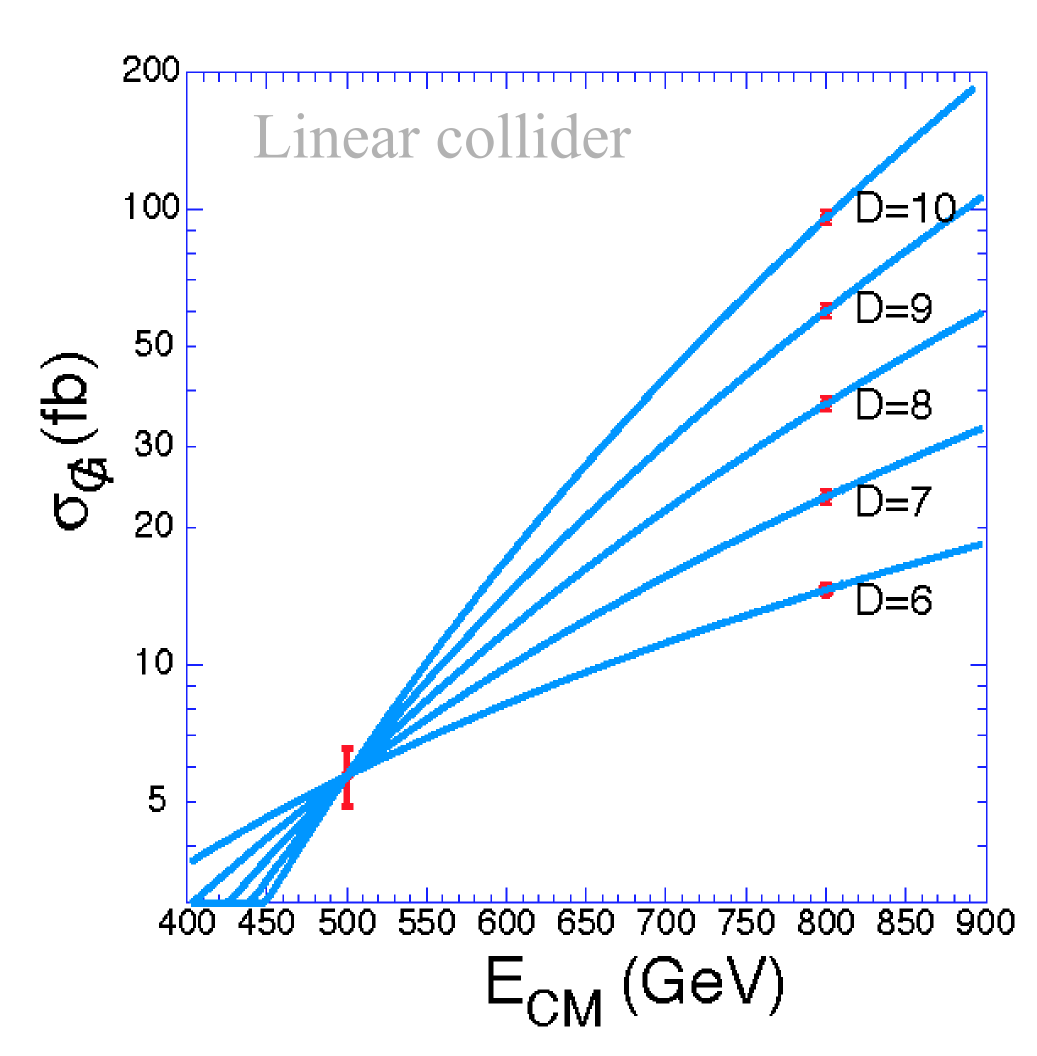
Internal quantum numbers of elementary particles are determined by the geometrical structure of the extra dimensions

Kaluza-Klein - Bosonic partners

Direct production from extra dimensions ?

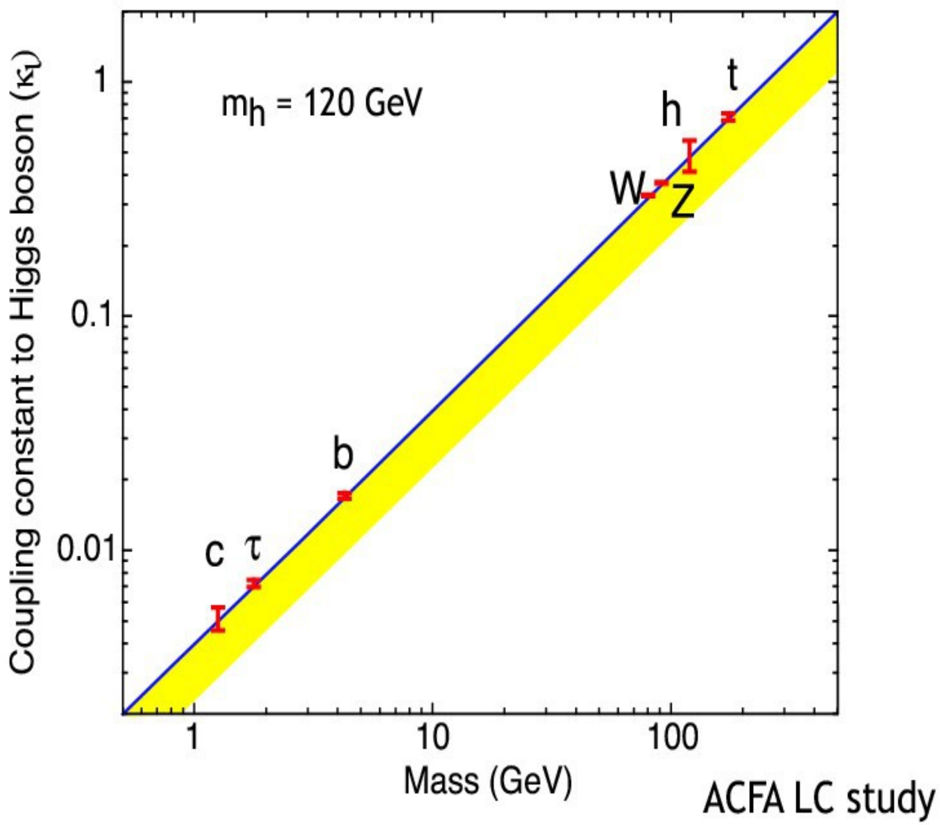


Total dimensions can be mapped by studying the emission of gravitons into the extra dimensions.



Extra dimensions and the Higgs?

Precision measurements of Higgs coupling can reveal extra dimensions in nature



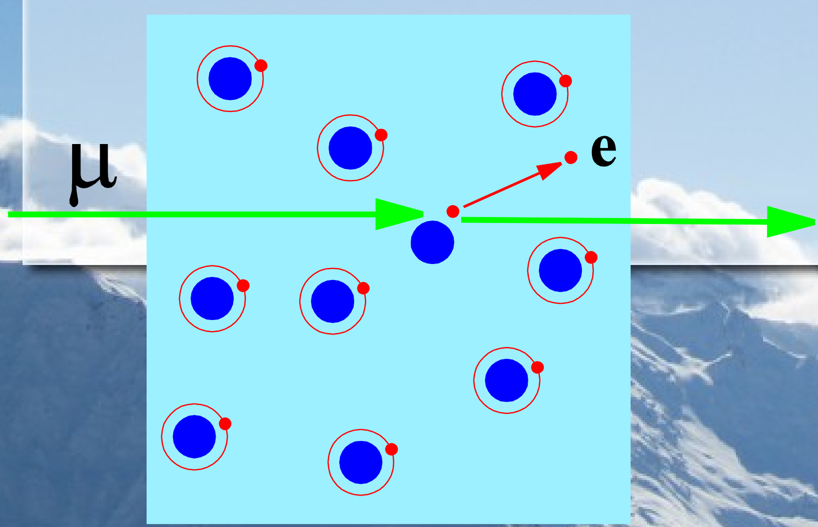
- **Straight blue line gives the standard model predictions.**
- **Range of predictions in models with extra dimensions -- yellow band, (at most 30% below the Standard Model**
- **The red error bars indicate the level of precision attainable at the ILC for each particle**

Target for each energy range

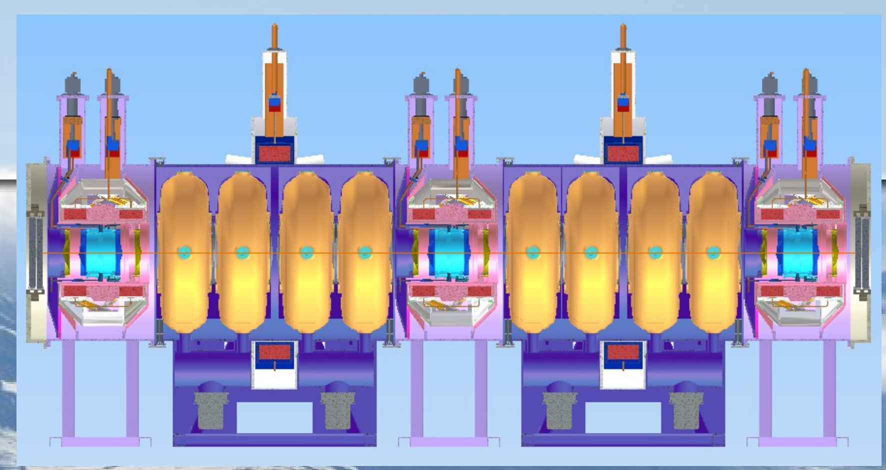
Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision EW
160 GeV	$e^+e^- \to WW$	ultra-precision Wmass
250 GeV	$e^+e^- \to Zh$	precision Higgs coupling
350-450 GeV	$e^+e^- \to tt$ $e^+e^- \to WW$ $e^+e^- \to \nu\nu h$	top quark mass and coupling precision W coupling precision Higgs coupling
500 GeV	$e^+e^- \to ff$ $e^+e^- \to tth$ $e^+e^- \to Zhh$ $e^+e^- \to \chi\chi$ $e^+e^- \to AH, H^+H^-$	precision search for Z' Higgs coupling to top Higgs self coupling search for super-symmetry search for extended Higgs sector
1000GeV		*and more.*

Muon Collider

- Properties of muons are quite similar to electron/positron, but heavier mass (200 times of e-mass). SR is not serious.
- I^{+}I^{-} collider is much cleaner than e+e- (beamstrahlung negligible)
  - except the problem of background from muon decay
- But muons do not exist naturally
- “Ionization cooling” invented by Skrinsky-Parkhomchuk 1981, Neuffer 1983

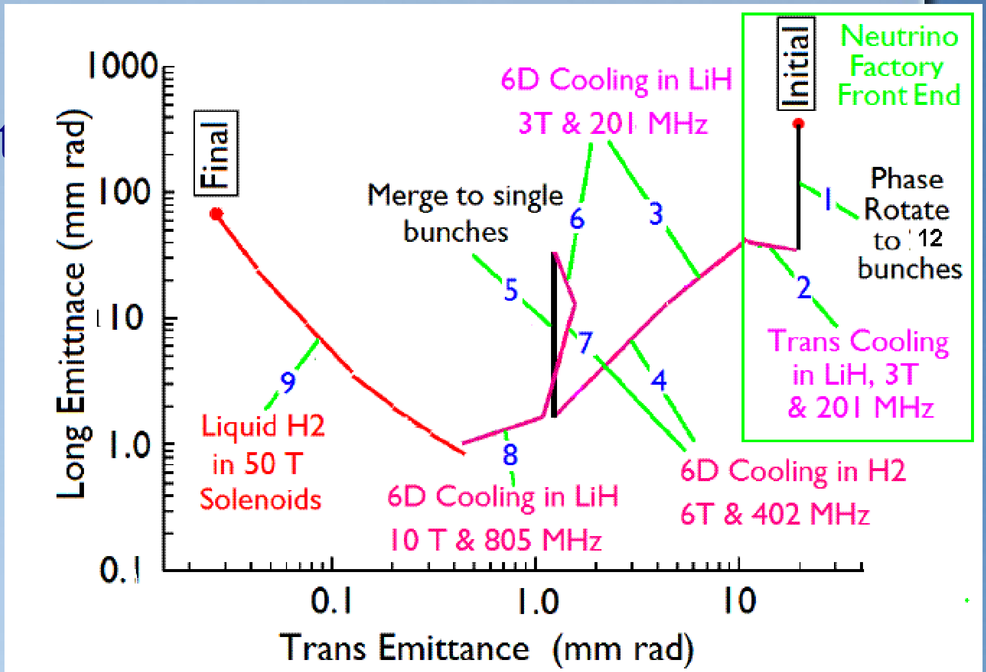


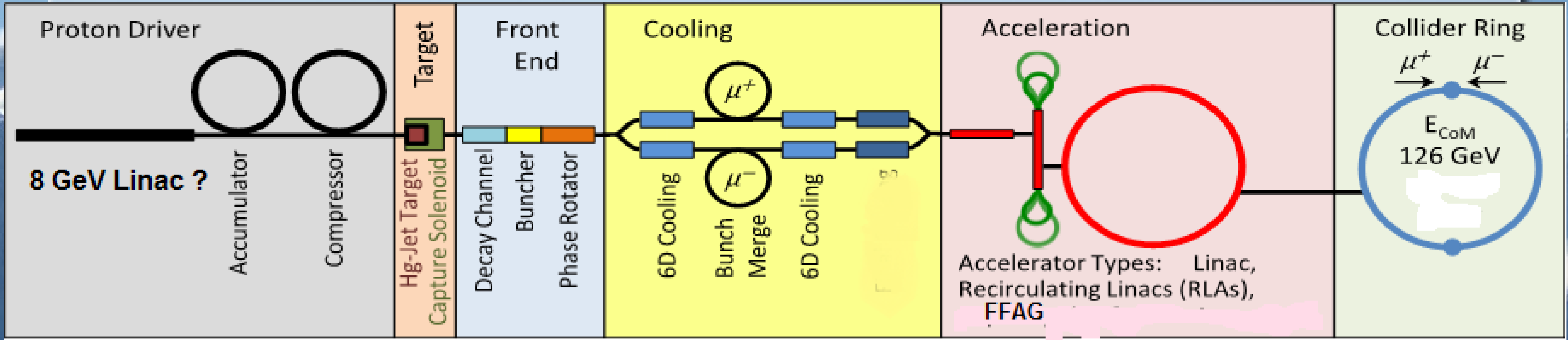
Ionization cooling test at MICE



Create and Cool Muon Beam

- Can be created by hadron collision
- Muons decay within 2I s in the rest frame; must be accelerated quickly
- Staging
  - Higgs factory at E_{cm}=126GeV
  - Neutrino factory
  - TeV muon collider

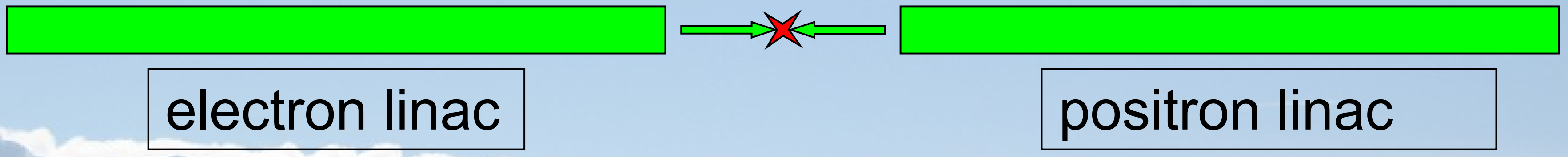




1. **Future Colliders**
2. **ILC physics motivations**
3. **ILC Accelerator Overview**
4. **ILC, the global project**

Electron-Positron Linear Collider

- The linear collider is designed based on a totally different strategy than that for a ring collider.
- Electron and positron will be accelerated by linac. Because only one path topology, the issues are
  - Acceleration gradient: accelerator should be reasonable length.
  - Enough Luminosity



Linear Collider Concept

- In Linear collider, the beam current can not be too high.
- Instead, the beam spot size at interaction point should be small enough to achieve an enough luminosity.
- The beam density could be extremely high at IP. A strong beam-beam effect which degrade the luminosity is concerned.
  - Beamstrahlung : Synchrotron radiation with magnetic field induced by the collision partner.
  - Disruption: Coulomb scattering with the collision partner.
- In linear collider, the limitation associated to the beam-beam effect is much easier than that for the ring collider.

It can not be too large because of the electricity.

$$L = \frac{f N^2}{4\pi \sigma_x \sigma_y}$$

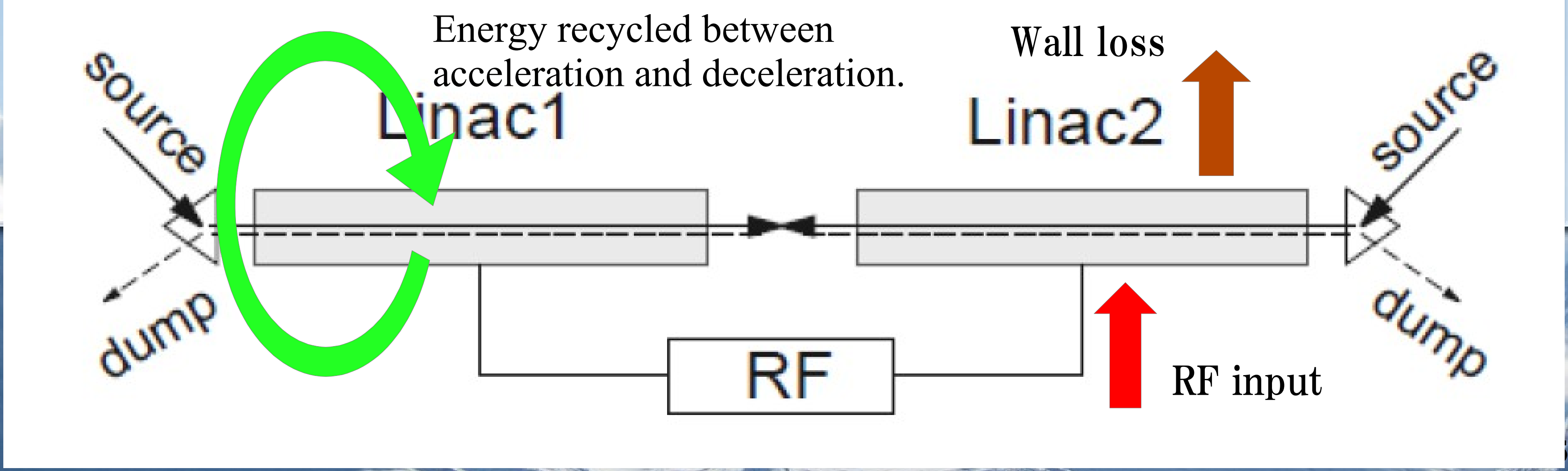
Minimize the beam size.
LC is strong for the beam-beam effect.

Advantage, Disadvantage, and Issue

- Advantage
  - No energy loss by Synchrotron radiation.
  - Strong against the beam-beam effect.
  - Electron and Positron can be polarized.
- Disadvantage and Issue
  - Beam power can not be too high (Beam passes IP only once).
  - A high gradient is required, otherwise the linac could be larger than the earth.

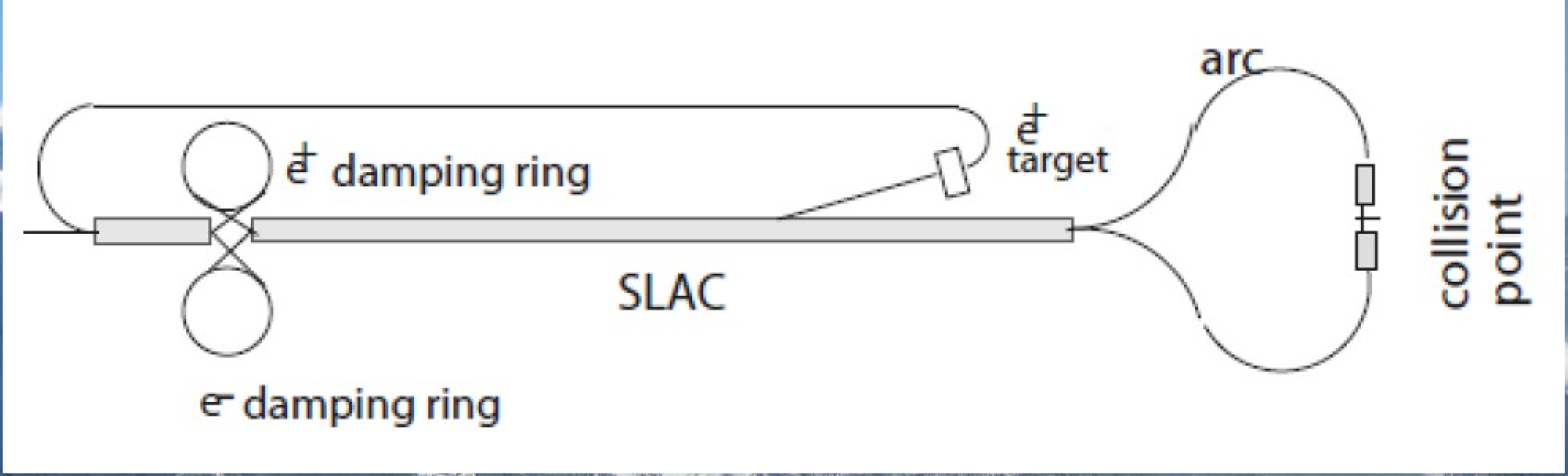
LC in History

- Proposed by M. Tigner in 1965.
- To save the electricity, the beam energy is recovered and re-used to accelerate the new beam.
- The ERL(Energy Recovery Linac) is seriously considered as the next generation light source.



SLC(SLAC Linear Collider)

- This is the first linear collider in the world.
- Electron and positron are accelerated by one linac on opposite phase.
- After the acceleration, the beam goes to IP through the arc.



Let us make it!

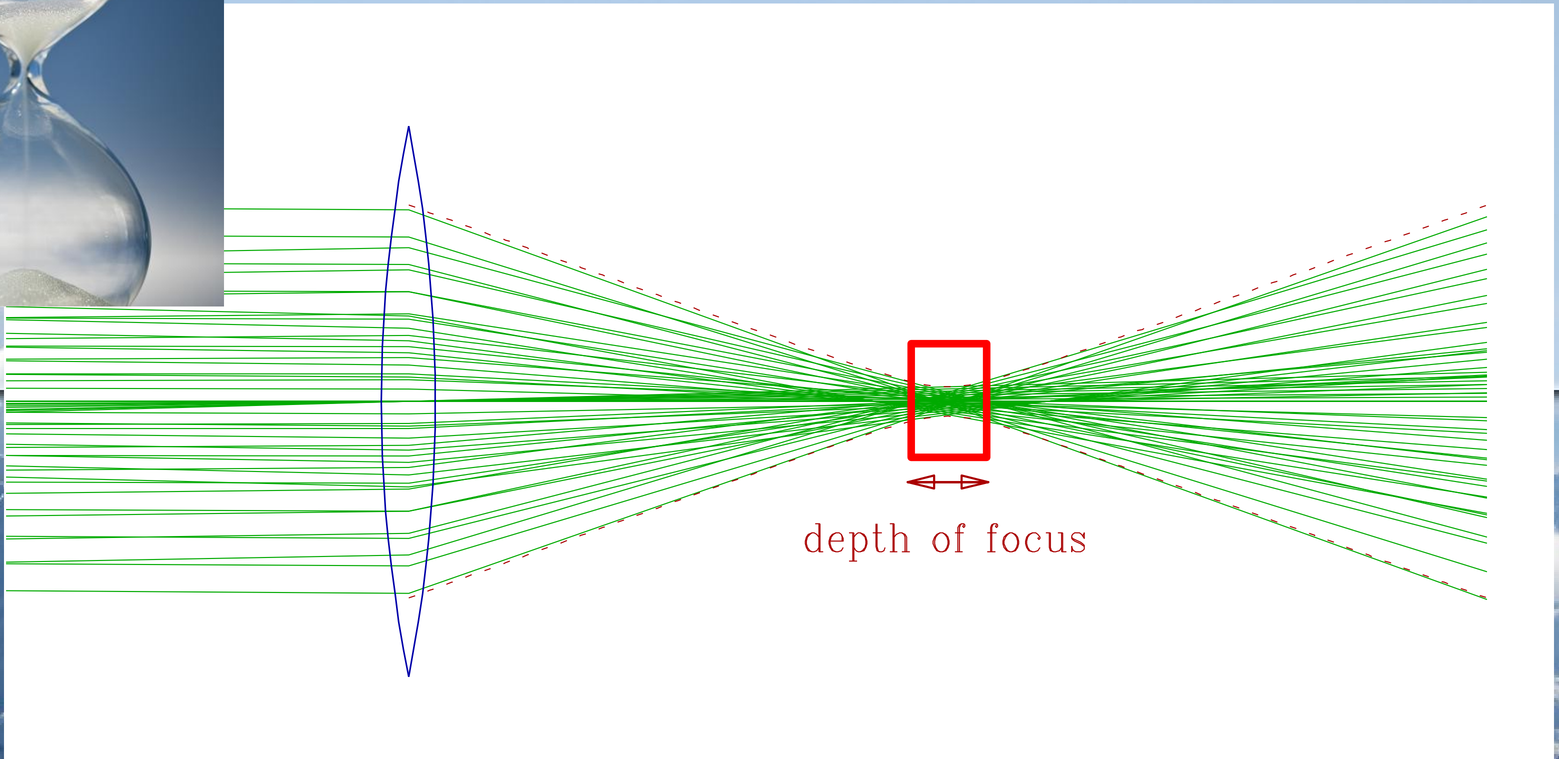
How can we realize the large luminosity with LC.

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

- f: Beam repetition rate (5Hz)
- n_b:number of bunches in a pulse(1300)
- N:number of particles in a bunch.($2\mathrm{x}10^{10}$)
- σ_x,σ_y:Transverse beam size at IP(6nm, 500nm)
- H_D:Enhancement factor(1.5)
- L:1-2e+34 $cm^{-2}s^{-1}$ (requirement)

Beam Focusing

- Need a strong focusing to get the small spot on IP.
- The beam size is finite (could not be zero) and the small beam size is kept only in the depth of focus. (Hour glass effect)
- Too strong focusing makes the depth short, which is not efficient for luminosity.



To obtain the proper focusing length, we have to understand the beam optics

The phase space, x and x'=dx/ds.

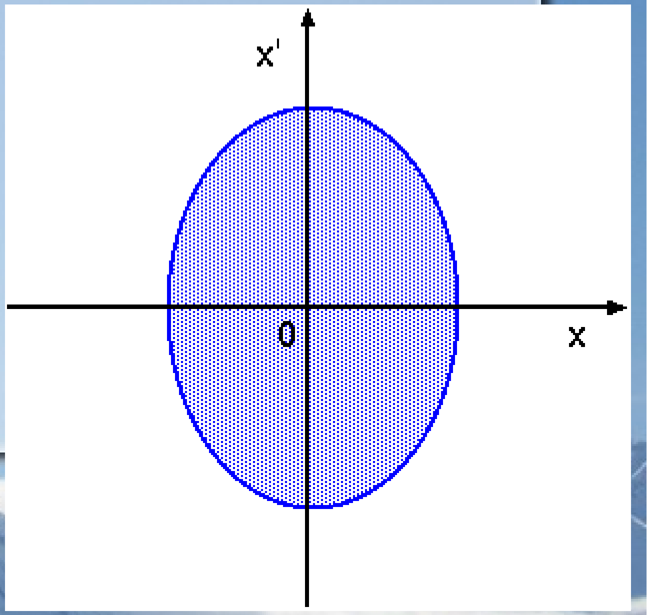
$$x' = \frac{dx}{ds} = \frac{v_x}{v_s} = \frac{p_x}{p_s} \sim \frac{p_x}{p}$$

Emittance (RMS) is given as

$$\epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$

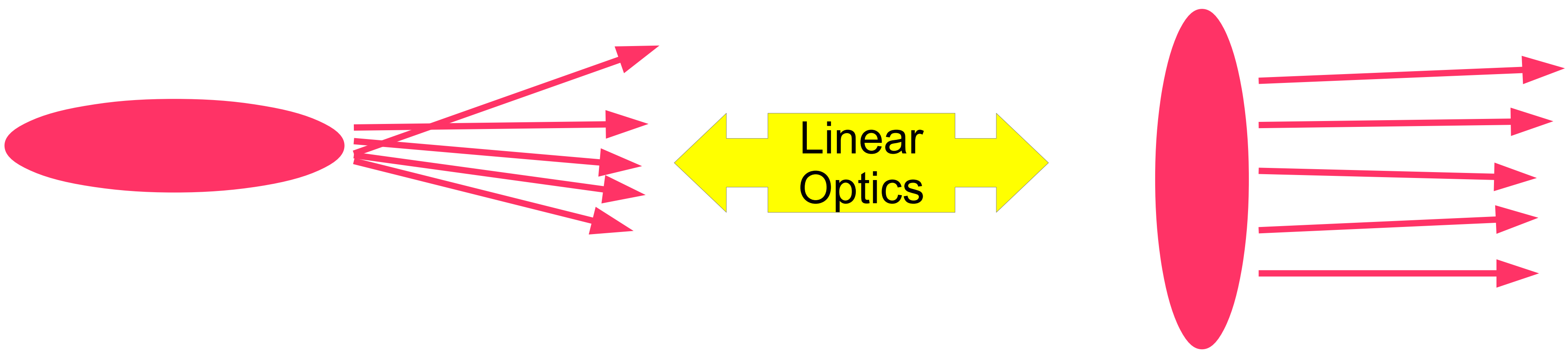
The emittance is area occupied by the beam particlesin the phase space. No correlation case,

$$\epsilon_x = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle}$$



To obtain the proper focusing length, we have to understand the beam optics

- Emittance shows the quality of the beam.
- The shape of the beam depends on the optics, but the emittance is invariant in the frame of the linear optics.
- Beam optics determine Beta function ∩(s) which express the geometrical beam size at the position.



$\beta_{x,y}$ *small*

$$\sigma_{x,y} = \sqrt{\beta_{x,y}\varepsilon_{x,y}}$$

$\beta_{x,y}$ *large*

Now, you should understand the beam focusing.

- Beam size at position *s*

$$\sigma_y(s)=\sqrt{\beta_y(s)\varepsilon_y}$$

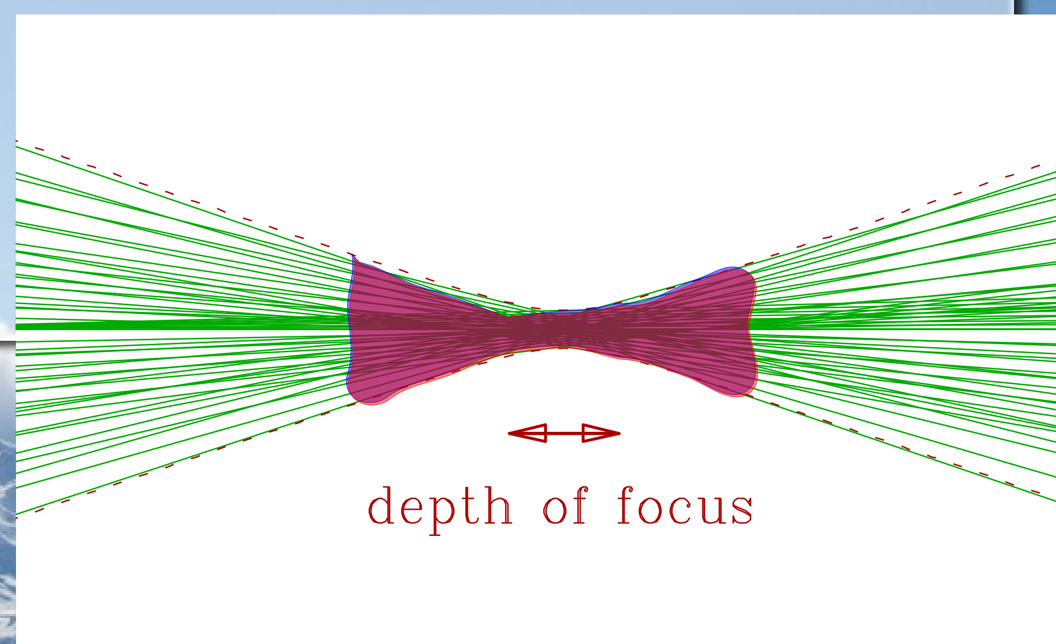
- Beta function near focal point

$$\beta_y(s)=\beta_y^*+\frac{s^2}{\beta_y^*}$$

- Beam size near the focal point, Depth of focus=$\cap_y$

$$\sigma_y(s)=\sqrt{\beta_y^*\varepsilon_y}\sqrt{1+\frac{s^2}{(\beta_y^*)^2}}$$

- If Q_z(Bunch length)>$\cap_y$, only a part of the bunch has large luminosity and the average over the whole bunch is smaller.



Now, you should understand the beam focusing.

- Beam size at position *s*

$$\sigma_y(s)=\sqrt{\beta_y(s)\varepsilon_y(s)}$$

- Beta function near focal point

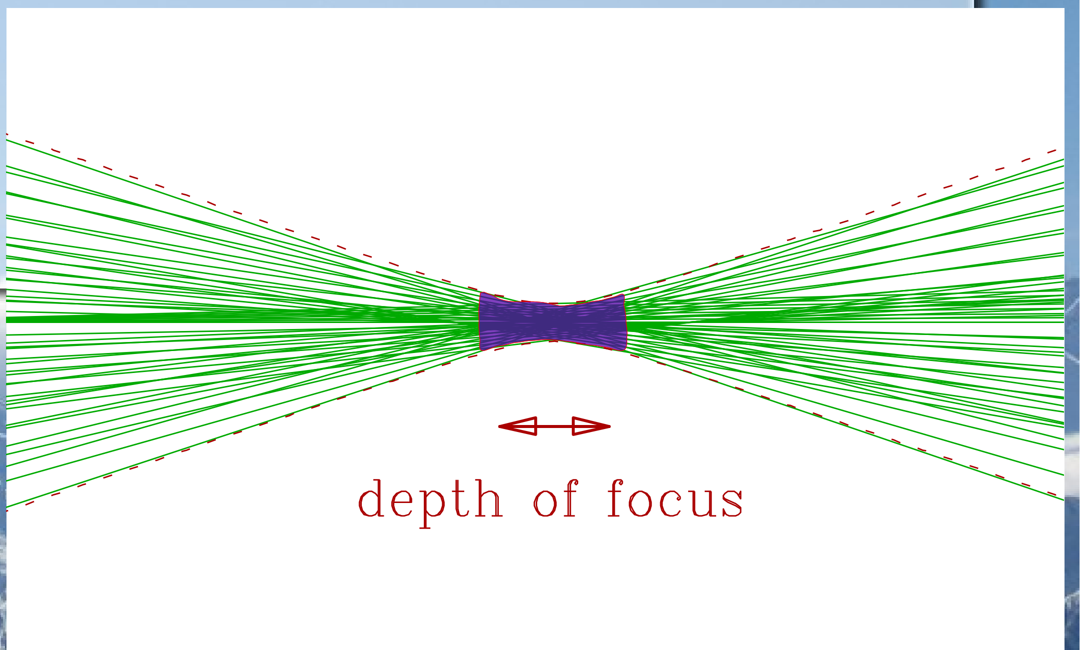
$$\beta_y(s)=\beta_y^*+\frac{s^2}{\beta_y^*}$$

- Beam size near the focal point,
  Depth of focus=∩y

$$\sigma_y(s)=\sqrt{\beta_y^*\varepsilon_y}\sqrt{1+\frac{s^2}{(\beta_y^*)^2}}$$

- If Ωz(Bunch length)=∩y,
  the whole bunch is contained
  in the focused region.
  The luminosity is maximized.

Ωz=∩y



Disruption

- The beam size is also affected by Coulomb interaction between beams.

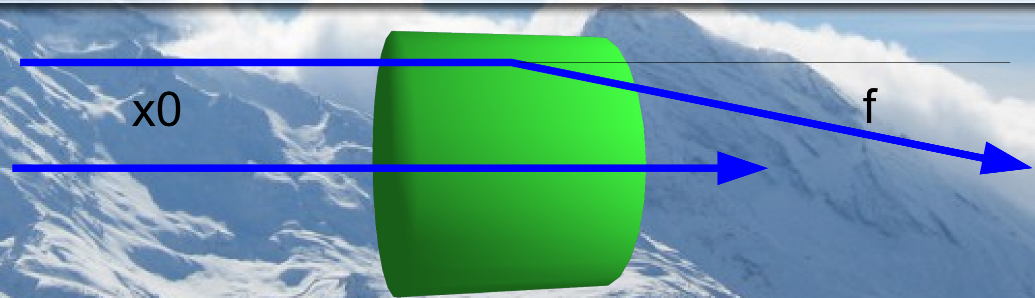
$$\ddot{x} + K_x x = 0, \qquad \ddot{y} + K_y = 0$$

- Assuming Gaussian shape beam and parallel particle, the focusing by Coulomb force is

$$\frac{dx}{dt} \sim -\frac{2\mathrm{Nr}_e}{\gamma} \frac{x_0}{\sigma_x(\sigma_x + \sigma_y)} = \frac{-x_0}{f}$$

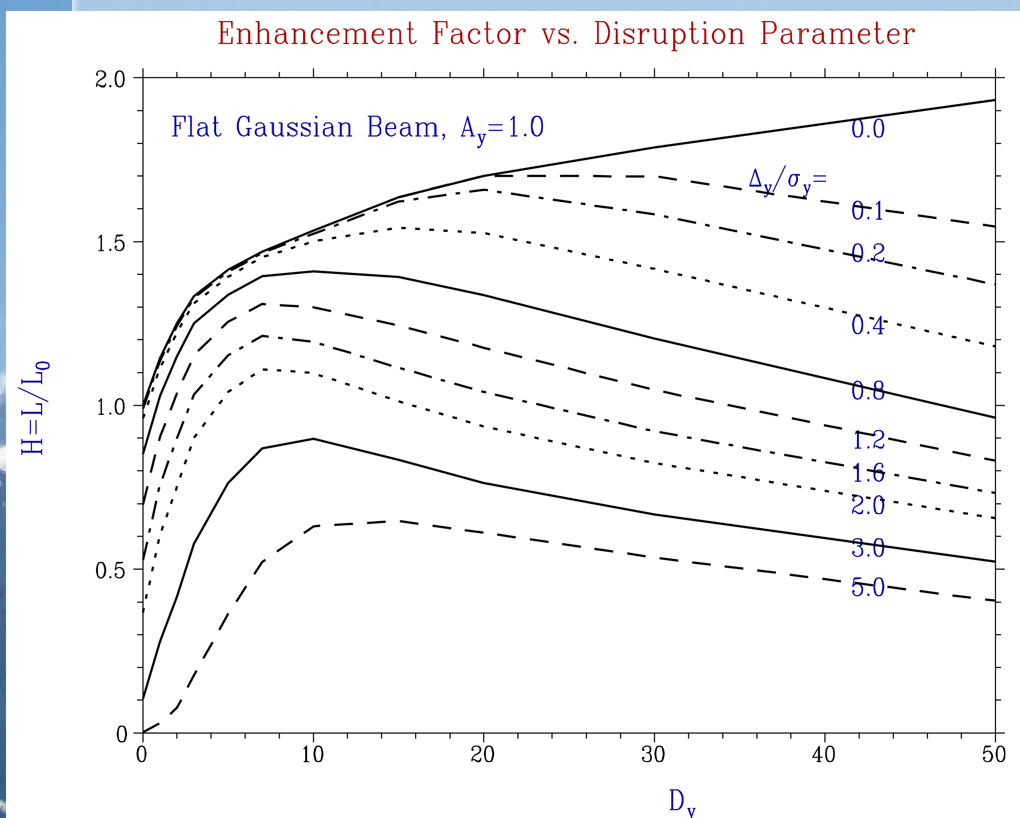
- Disruption parameter：σ_z over f, focusing strength

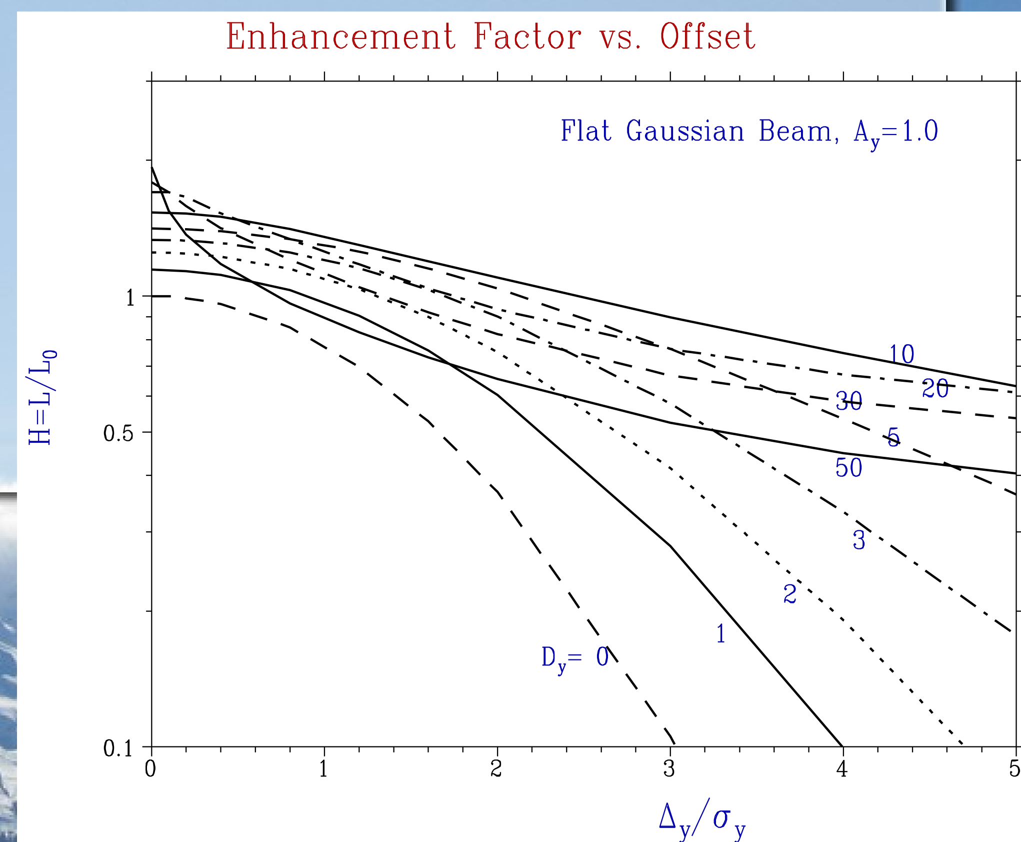
$$D_{x,y} \equiv \frac{\sigma_z}{f_{x(y)}} = \frac{2\mathrm{Nr}_e}{\gamma} \frac{\sigma_z}{\sigma_{x,y}(\sigma_x + \sigma_y)}$$



Luminosity Enhancement

- Due to the attractive Coulomb force between electron and positron, Luminosity is enhanced by the Disruption.
- With a beam offset, the luminosity is degraded by the over focusing.
- Assuming **Delta$_y$/sigma$_y$=0.5**, the design is D_x=0.5, D_y=25.





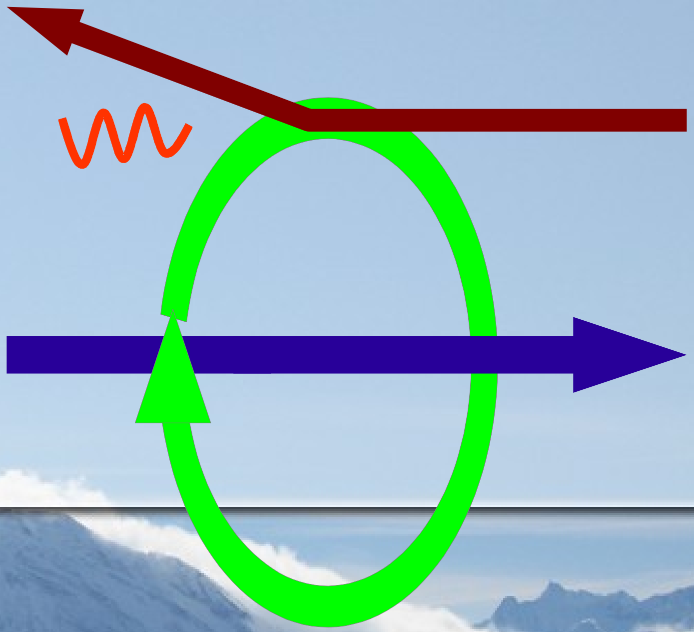
Beamstrahlung

- Synchrotron radiation with magnetic field induced by the collision partner.
- The field up to several kT with a short buch and small spot.
- Due to the radiation, effective energy spread is increased.
- Critical energy

$$\Upsilon \equiv \frac{2}{3}\frac{\hbar\omega_c}{E} = \gamma\frac{2B}{B_c} \qquad B_c = \frac{m^2}{e} \sim 4.4\,\mathrm{GT}$$

- For the whole beam

$$\Upsilon_{average} = \frac{5}{6}\frac{N r_e^2 \gamma}{\alpha\sigma_z(\sigma_x+\sigma_y)}$$



Beamstrahlung

Number of emitted photons per electron

$$n_\gamma \sim 1.08 \frac{2 N r_e \alpha}{\sigma_x + \sigma_y} U_0(\Upsilon)$$

$$U_0(\Upsilon) \sim \frac{1}{\sqrt{1+\Upsilon^{2/3}}}$$

Energy Spread by the Beamstrahlung

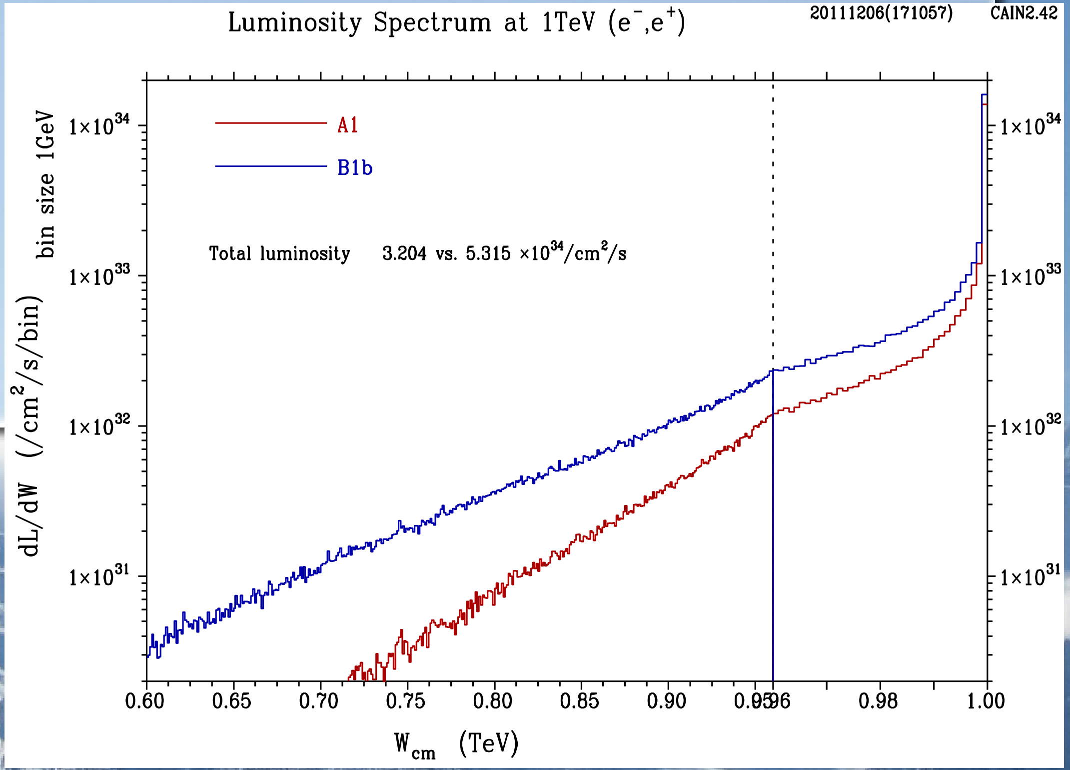
$$\delta_E = \langle -\frac{\Delta E}{E} \rangle \sim 0.209 \frac{N^2 r_e^3 \gamma}{\sigma_z} \left(\frac{2}{\sigma_x + \sigma_y} \right)^2 U_1(\Upsilon)$$

$$U_1(\Upsilon) \sim \frac{1}{[1+(1.5\,\Upsilon)^{2/3}]^2}$$

σ_x, σ_y, and σ_z can not be too small.

Flat Beam

- If Q_x>>Q_y, magnetic field depends only on Q_x. $$B=\frac{\mu_0 I}{2\pi r}\sim\frac{\mu_0 eN}{2\pi\sigma_x\sigma_z/c}$$
- Because Luminosity ö $1/(Q_x Q_y)$ both sizes do not have to be small. $$\delta_E=\langle-\frac{\Delta E}{E}\rangle\sim 0.209\frac{N^2 r_e^3\gamma}{\sigma_z}\left(\frac{2}{\sigma_x+\sigma_y}\right)^2 U_1(\Upsilon)$$
- The flat beam compensates Beamstrahlung and enhances Luminosity.
- In LC prameter, ∫BS~1%.



Flat Beam Concept

- Damping Ring (explained later), the vertical emittance (⌡$_y$) is naturally smaller than the horizontal emittance (⌡$_x$) .
- **By minimizing** the vertical emittance (⌡$_y$)**, Luminosity can be maximized and Beamstrahlung is compensated.**
- Due to the hour glass effect, $\cap_y^*$ ~Ω$_z$ (must not too small).
- Disruption in vertical direction becomes large. To keep Luminosity and obtain bonus (enhancement), the beam offset has to be small, ∞⌡ΘΣ$_y$=0.5 . (Fine beam control)

Luminosity Scaling

- P_{beam}: Beam power
- P_{wall}: Wall plug power

$$P_{beam} = eE\, f\, n_b N = \eta P_{wall}$$

- Γ:efficiency
- Beam size

$$\sigma_{x,y} = \sqrt{\frac{\epsilon_{x,y}\beta_{x,y}}{\gamma}}$$

- Energy spread by Beamstrahlung

$$\delta_{BS} \sim \frac{N^2 E}{\sigma_x^2 \sigma_z}$$

$$L = \frac{P_{beam}}{eE}\sqrt{\frac{\delta_{BS}}{\epsilon_y}}\sqrt{\frac{\sigma_z}{\beta_y}} \sim \frac{\eta P_{wall}}{eE}\sqrt{\frac{\delta_{BS}}{\epsilon_y}}$$

Luminosity Scaling

- P_{beam}: Beam power
- P_{wall}: Wall plug power $\quad P_{beam} = eE\, f\, n_b N = \eta P_{wall}$
- Γ:efficiency
- Beam size $\quad \sigma_{x,y} = \sqrt{\frac{\epsilon_{x,y}\beta_{x,y}}{\gamma}}$
- Energy spread by Beamstrahlung $\quad \delta_{BS} \sim \frac{N^2 E}{\sigma_x^2 \sigma_z}$

Normalized Luminosity

$$\frac{L}{P_{wall}} \sim \frac{\eta}{eE}\sqrt{\frac{\delta_{BS}}{\epsilon_y}}$$

Normalized Luminosity
Voices from Nature

Improve efficiency

Accept large δ_{BS}

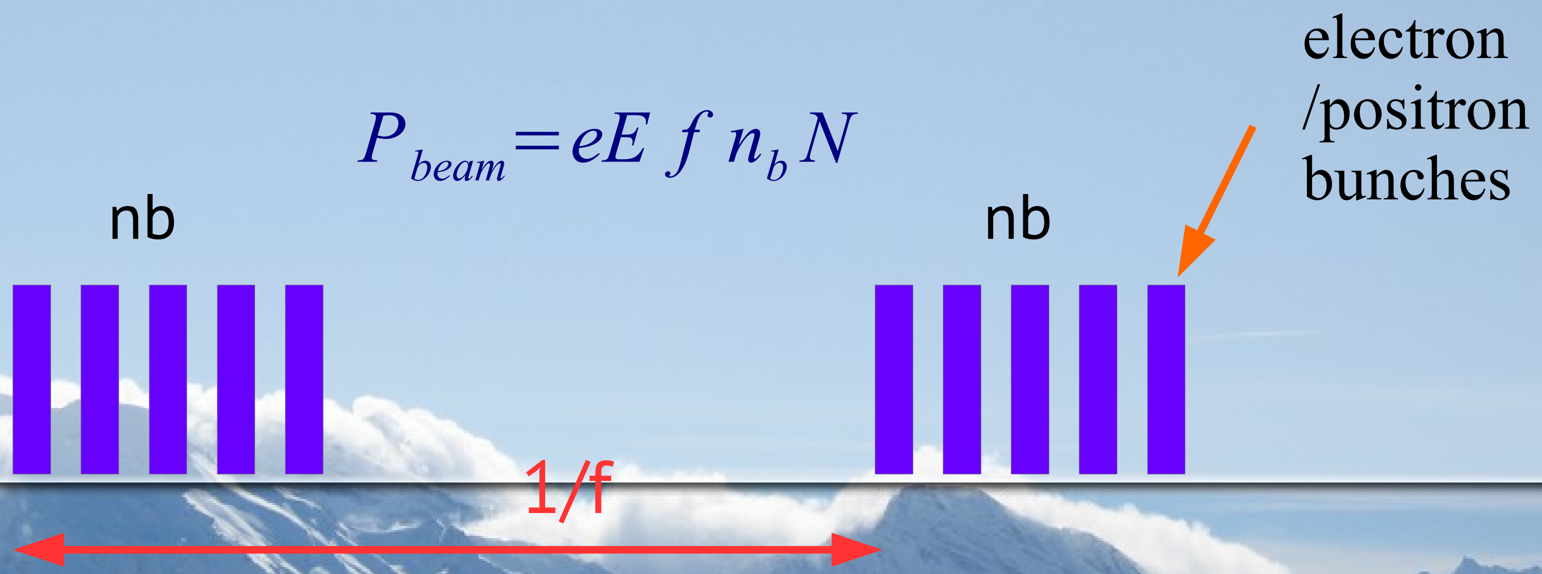
$$\frac{L}{P_{wall}} \sim \frac{\eta}{eE}\sqrt{\frac{\delta_{BS}}{\epsilon_y}}$$

Minimize ϵ_y

Beam Format

- Luminosity determines the average and peak current.
- The beam format is determined by accelerator configuration.

$$P_{beam} = eE\,f\,n_b\,N$$



Pulse structure and Efficiency

- Super-conducting accelerator
  - Resistivity is quite small (not zero).
  - Temperature must be very low ~2K.
  - Standing wave structure with zero group velocity.
  - It takes a long time store the electric power in the cavity.

Standing Wave Structure

- Standing wave with zero group velocity.
- Superimpose of two opposite traveling wave.
- RF power is fed by build up. A large fraction of RF power is reflected during the build up time.
- Once RF power is fed to the cavity and the power is balanced between the input power, wall loss, and beam loading, the field becomes constant.

Standing Wave Structure

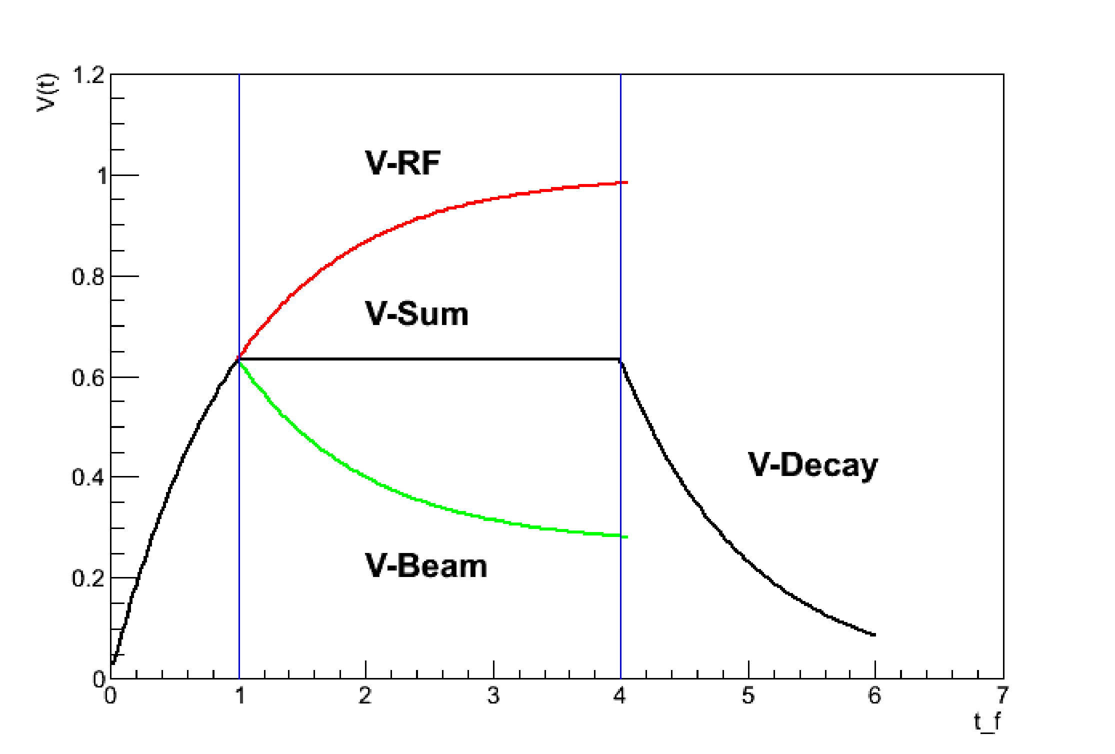
- RF build up (input RF) and the beam loading (energy consumption by the beam acceleration) have the same time constant, T_0.
- If balance, the field is flat.

Input RF

$$V(t)=\frac{2\sqrt{\beta P_0 r L}}{1+\beta}\left(1-e^{\frac{-t}{T_0}}\right)-\frac{IrL}{1+\beta}\left(1-e^{\frac{-t-t_b}{T_0}}\right)$$

Beam loading

$$T_0=\frac{Q}{\omega(1+\beta)}$$



SC vs NC

Electricity for NC structure

$$P = \frac{V^2}{(R/Q)Q} + I_{Beam} V ,$$

Q ~10^4

Electricity for SC structure

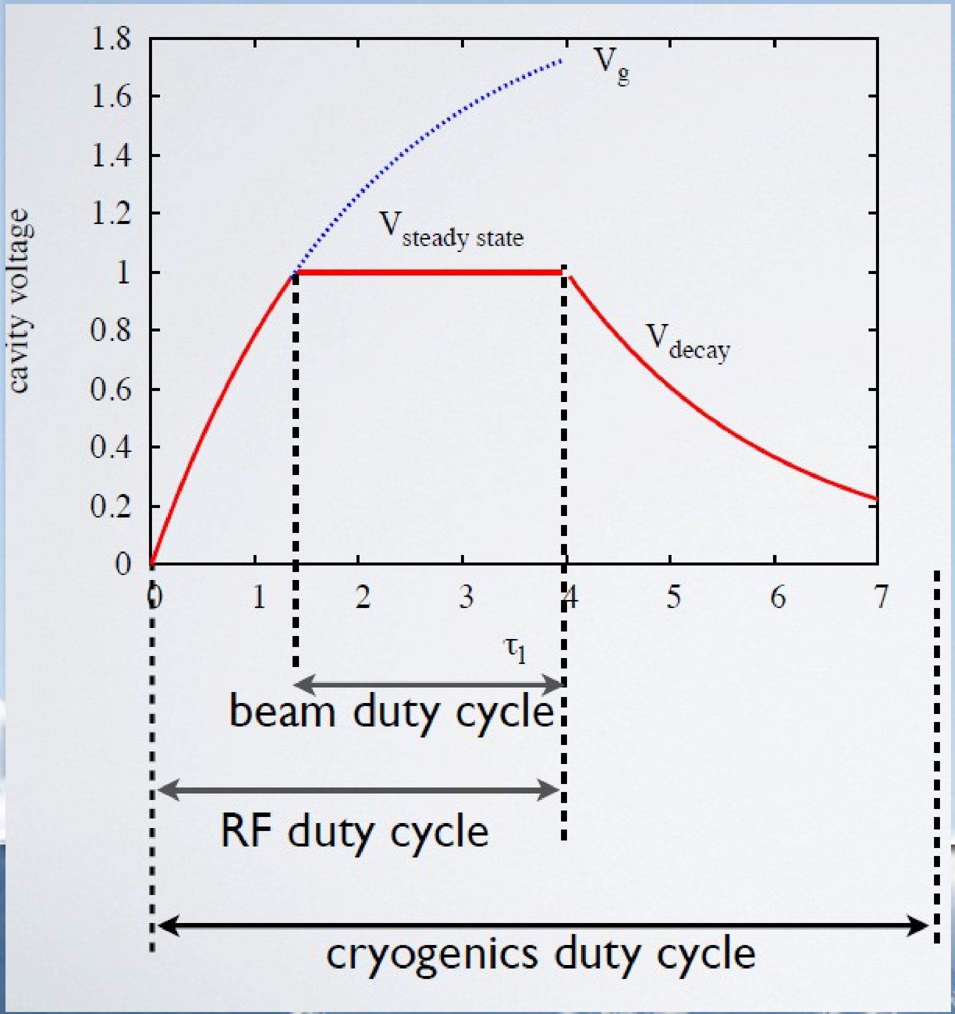
$$P = \frac{V^2}{(R/Q)Q_0} + I_{Beam} V \sim I_{Beam} V ,$$

Q_0 ~10^{10}

SC has extremely high efficiency,
but the build up time is quite long.

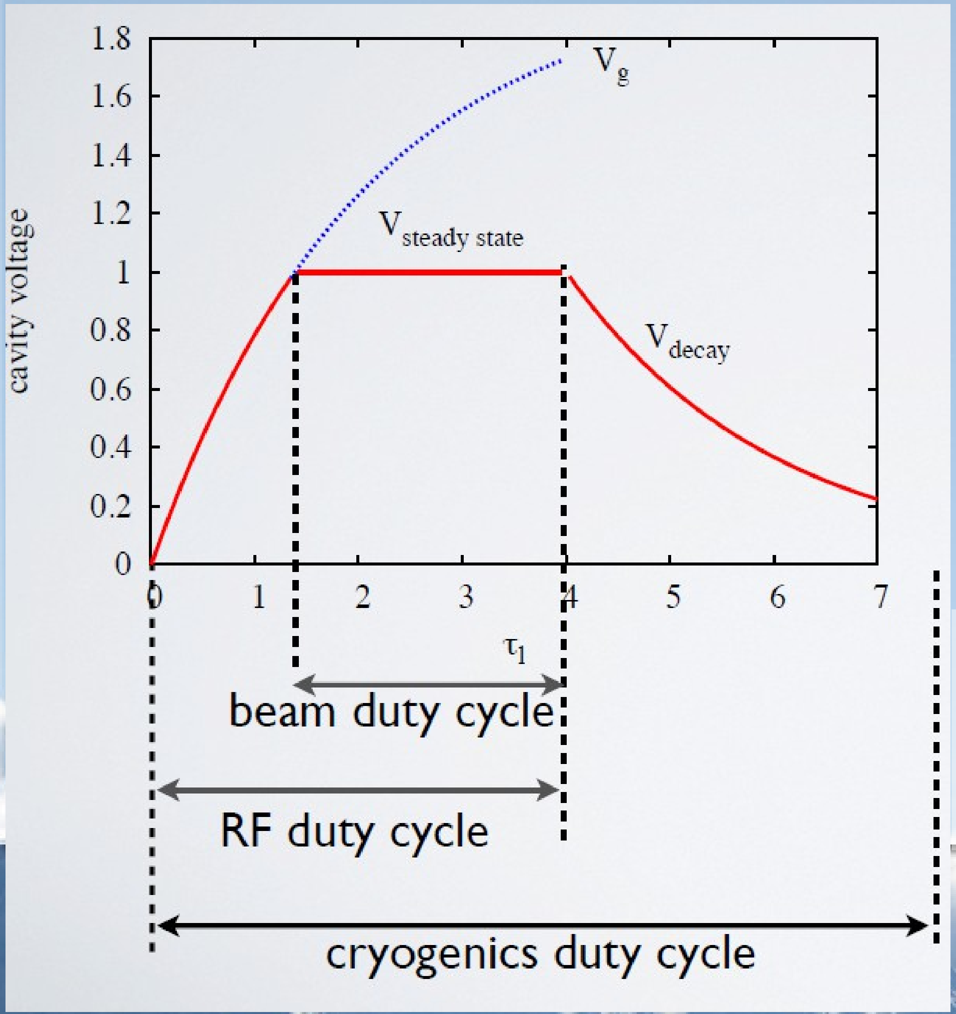
$$T_0 = \frac{Q_L}{\omega} = \frac{Q_0}{\omega(1+\beta)} ,$$

SC operation cycle



- High efficiency=Long build up.
- RF pulse should be longer than the beam pulse.
- Cryogenic cycle has to be also longer than the beam pulse.

SC operation cycle



RF period

$$t_{RF} = 1.39\,\tau + t_{beam}\,,$$

Cryogenic period

$$t_{cryo} = 1.55\,\tau + t_{beam}$$

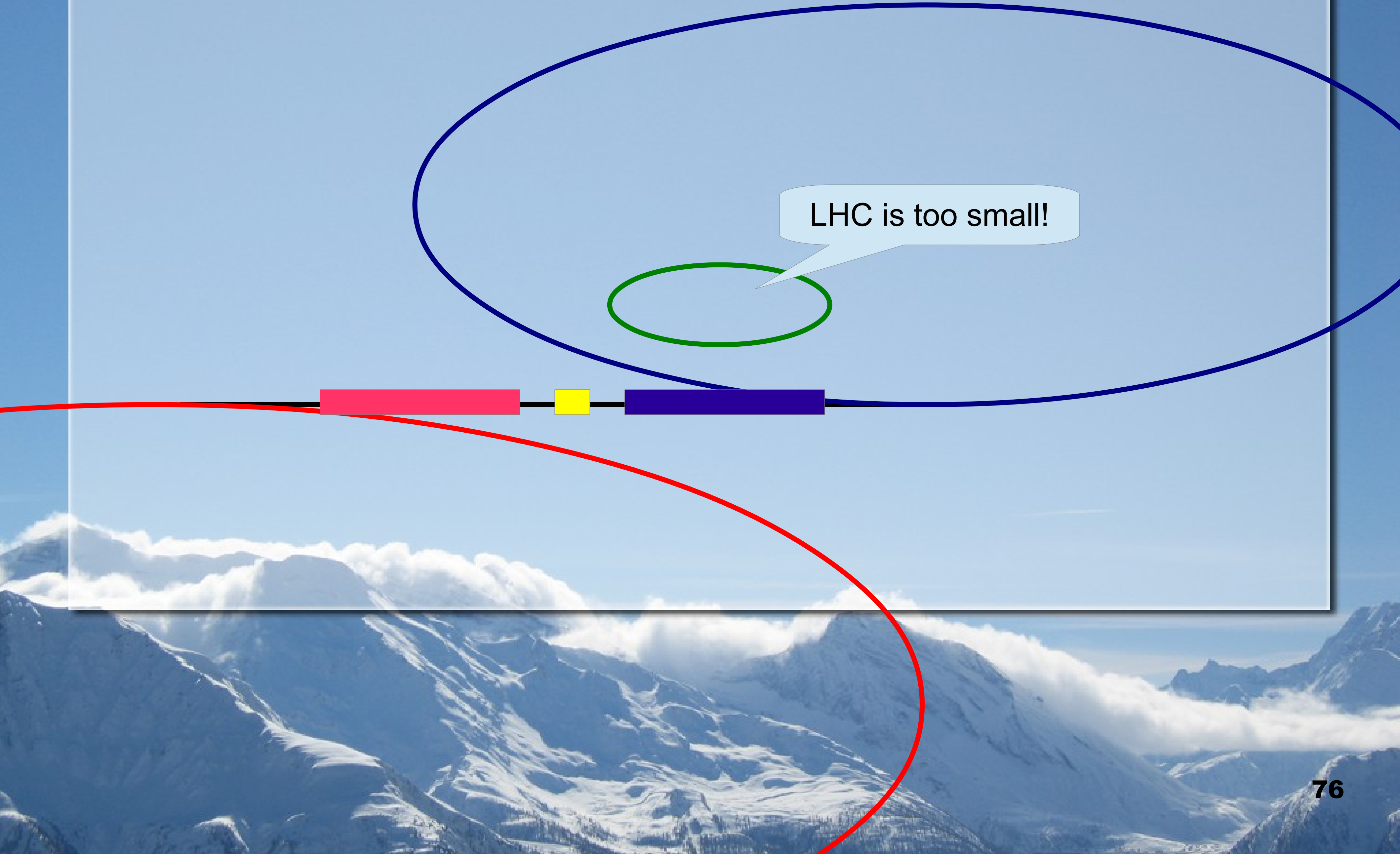
$$\frac{t_{cryo}}{t_{beam}} = \frac{1.55\,\tau + t_{beam}}{t_{beam}}$$

For better efficiency, t_{beam} should be as large as possible, because the cryogenic power is dominant.

How To Fix T_{beam}?

- t_{beam} should be as large as possible. t_{beam} should be at least longer than T_0=0.5ms for ILC cavity.
- There is a practical limitation on t_{beam}.
  - For the extremely low emittance at IP, the beam has to be stored in DR for ~several 100 ms.
  - t_{beam}c(velocity of light)＝C_{DR} (DR circumference)： For t_{beam}=0.5ms, C_{DR} is 150km.

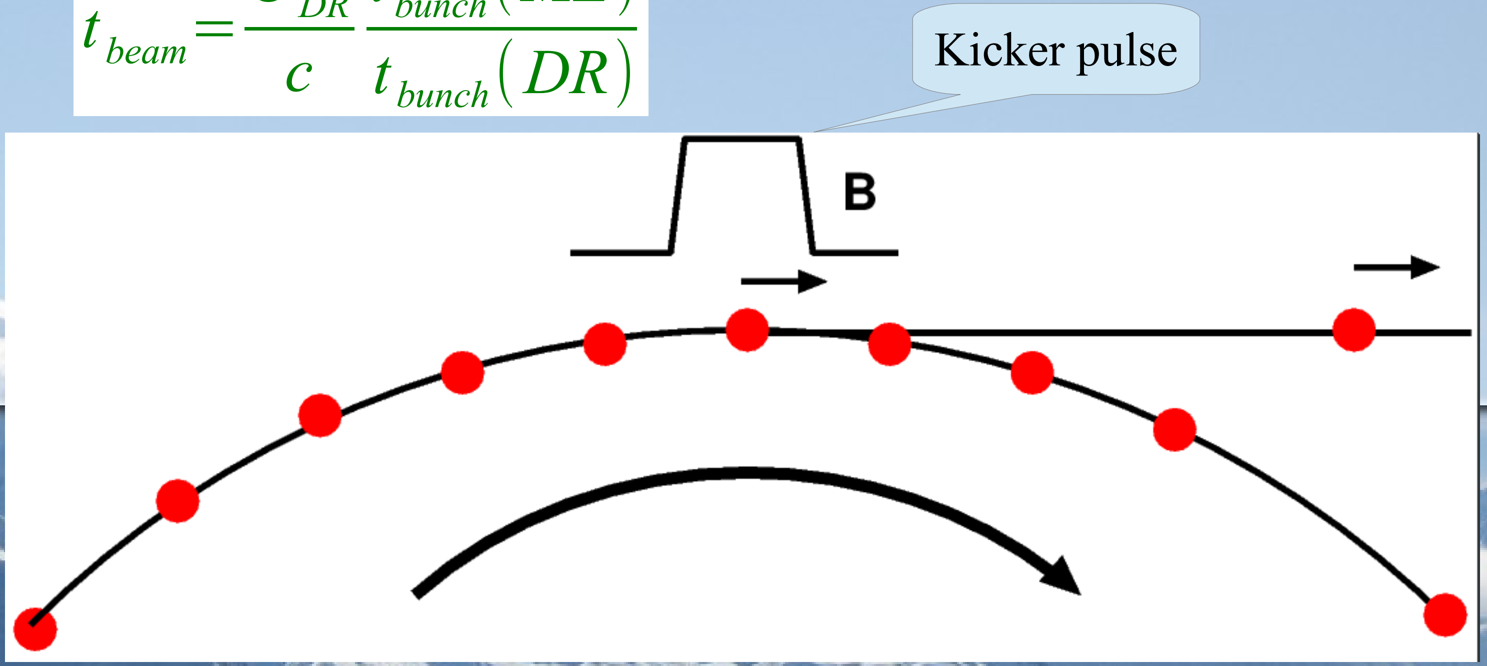
Stupid Linear Collider



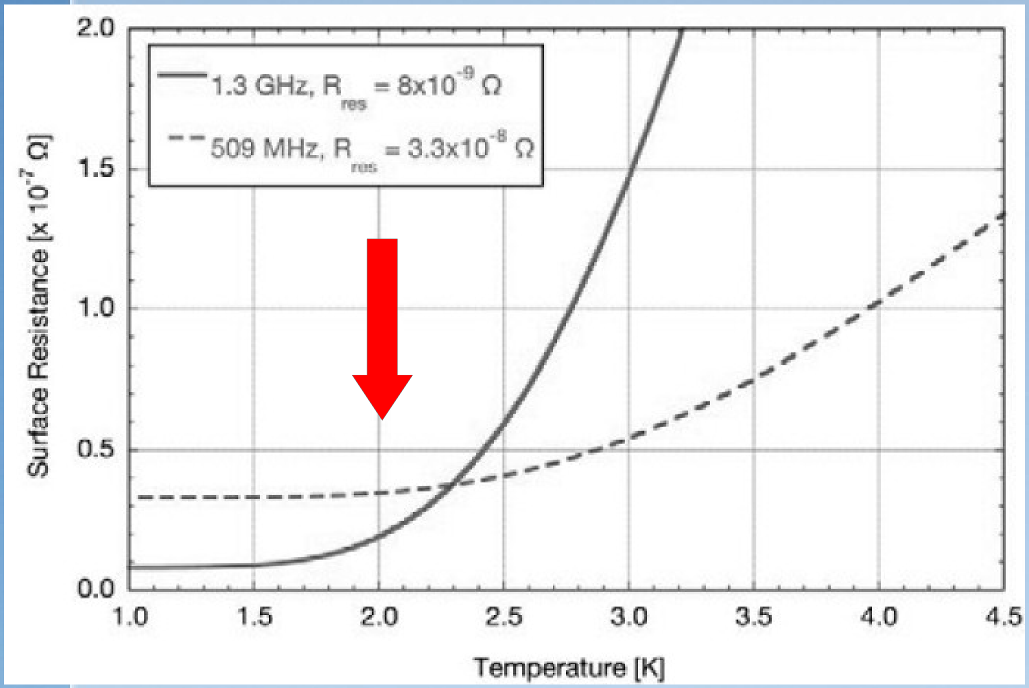
DR Circumferrence

- 0.5ms> t_{beam} makes C>150km.
- Bunches are stored in DR with shorter separation than that in ML.
- t_{bunch}(ML) = 500ns, t_{bunch}(DR)=6ns, comression ratio is 85 and C_{DR} is 3.1km. (Now, it becomes realistic)
- t_{beam} is determined with C_{DR} and t_{bunch}(DR).
- t_{bunch}(DR) is limited by ability of the injection/extraction kicker.

$$t_{beam}=\frac{C_{DR}}{c}\frac{t_{bunch}(ML)}{t_{bunch}(DR)}$$



Operation Temperature



- RF resistance of SC is not zero.
- It is less at lower temperature, but small gain <2.0K.
- On the other hand, cryogenic efficiency is rapidly decreased at low temperature.
- LC~2.0K

cryogenic efficiency

Temp.	Carnot eff	Refrig. eff	Combined eff	Room temp. W/W
70K	30. 43%	20%	6. 09%	16
4. 5K	1. 52%	20%	0. 30%	328
1. 8K	0. 60%	10%	0. 06%	1657

$$\eta_{Carnot} = \frac{T_C}{T_0 - T_C}$$

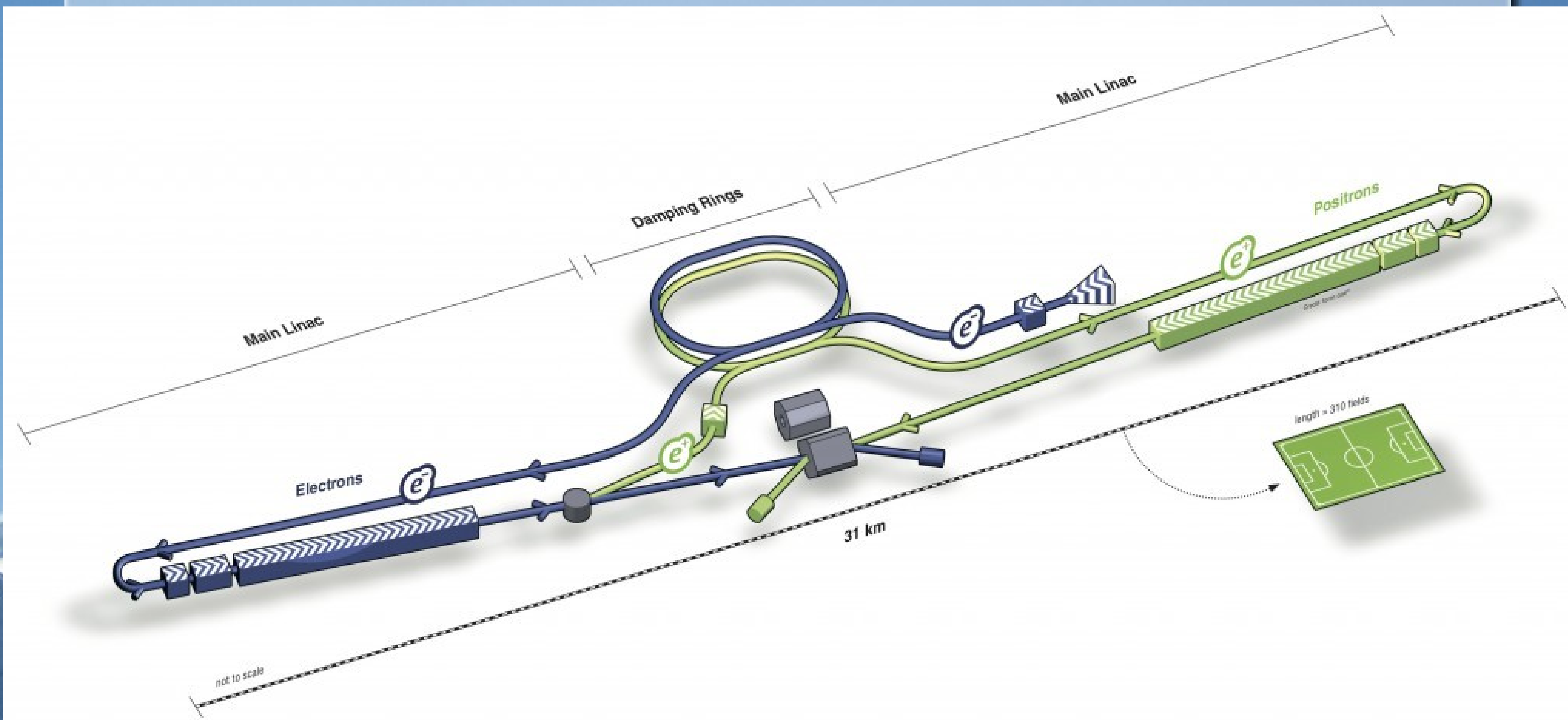
Beam Parameter Summary

Parameterby	Unit	500GeV	Luminosity Upgrade	ECM upgrade 1TeV
ECM	GeV	500	500	1000
f_{rep}	Hz	5	5	4
# of bunches		1312	2625	2450
# of Parciles in Bunch	$x10^{10}$	2	2	1.74
t_{bunch}(ML)	ns	554	366	366
Average beam current in a pulse	mA	5.8	8.8	7.6
Accelerator Gradient	MV/m	31.5	31.5	38.2
Beam power	MW	10.5	21.0	27.2
Wall plug power	MW	163	204	300
Bunch length	mm	0.3	0.3	0.25
Vertical emittance	mm.mrad	10	10	10
Horizontal emittance	mm.mrad	0.035	0.035	0.030
∩∫IŒ$_x$	mm	11	11	26
∩∫IŒ$_y$	mm	0.48	0.48	0.25
Luminosity	$10^{34}cm^{-2}.s^{-1}$	1.8	3.6	3.0
Luminosity in 1% dE/L	%	58.3	87.1	59.2

Up to this point

- You must (I believe) understand the concept of LC.
- Next, I try to explain LC based on each components (sub-systems).

I try to explain why ILC shape is like this.



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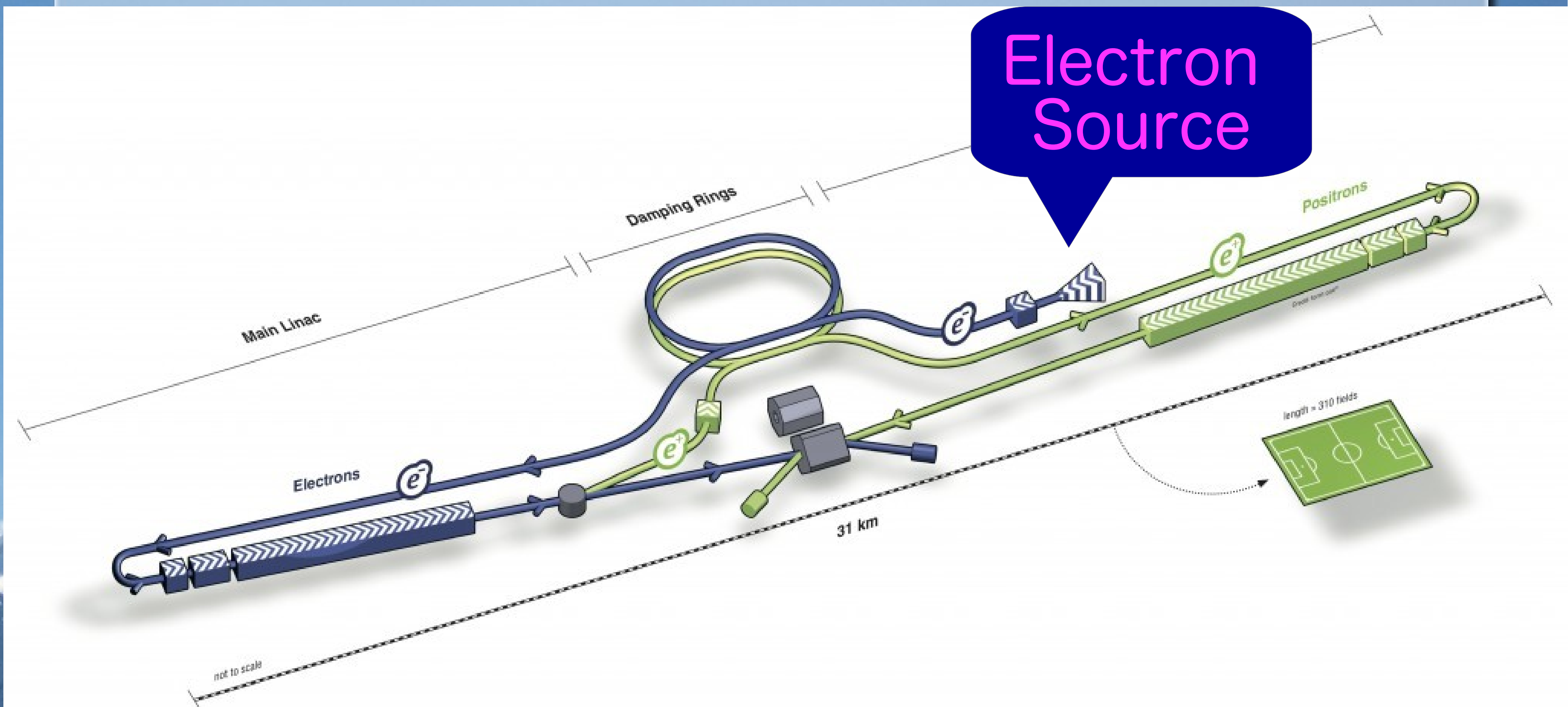
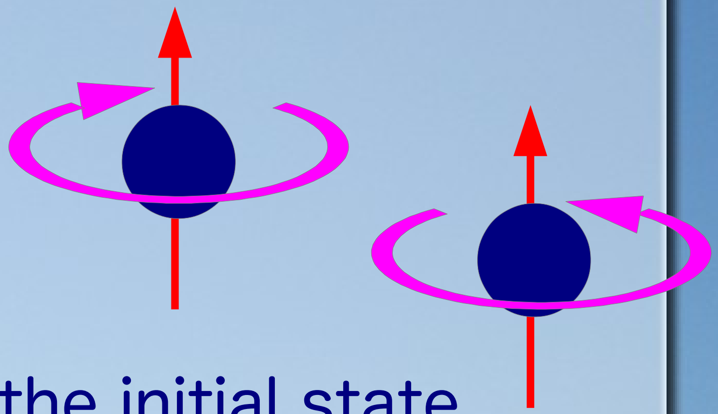

Electron Source
Positrons
Damping Rings
Main Linac
Electrons
31 km
length = 310 fields
not to scale

Electron Injector

- Electron/Positron are spin ½ fermion with two eigen states.
- In SU(2)xU(1) gauge theory(Standard model of particle physics), these two eigen states are different particle.

$$l_L \equiv \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix} \qquad I_W = \frac{1}{2}, \quad Y_W = -1$$

$$e_R \qquad I_W = 0, \quad Y_W = -2$$



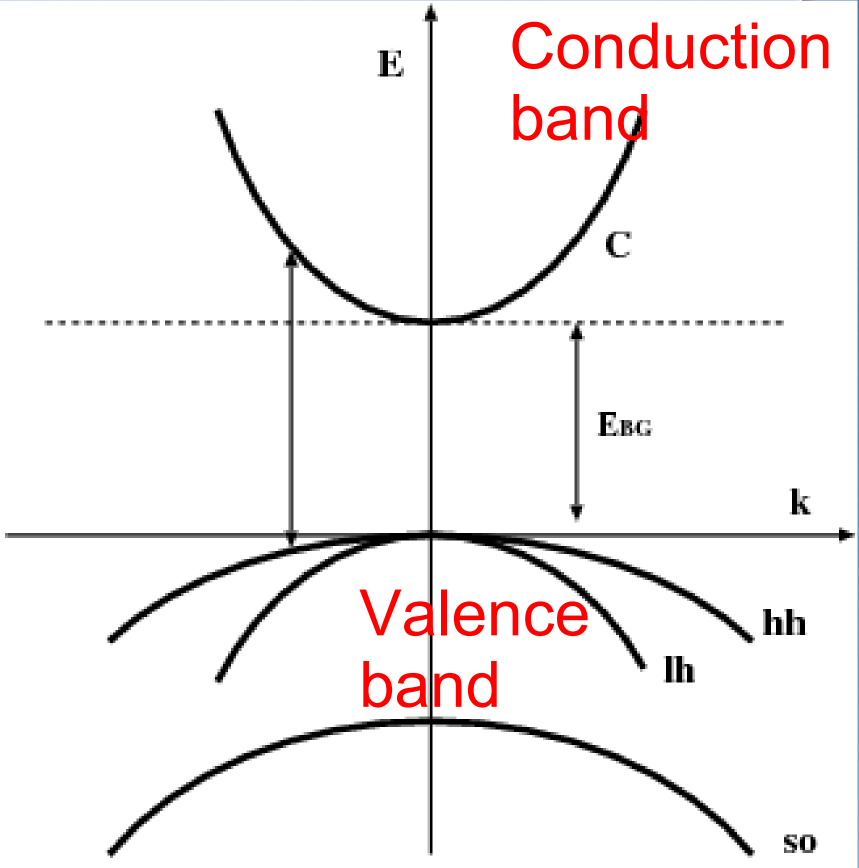
- Only one spin eigen state：define the initial state.

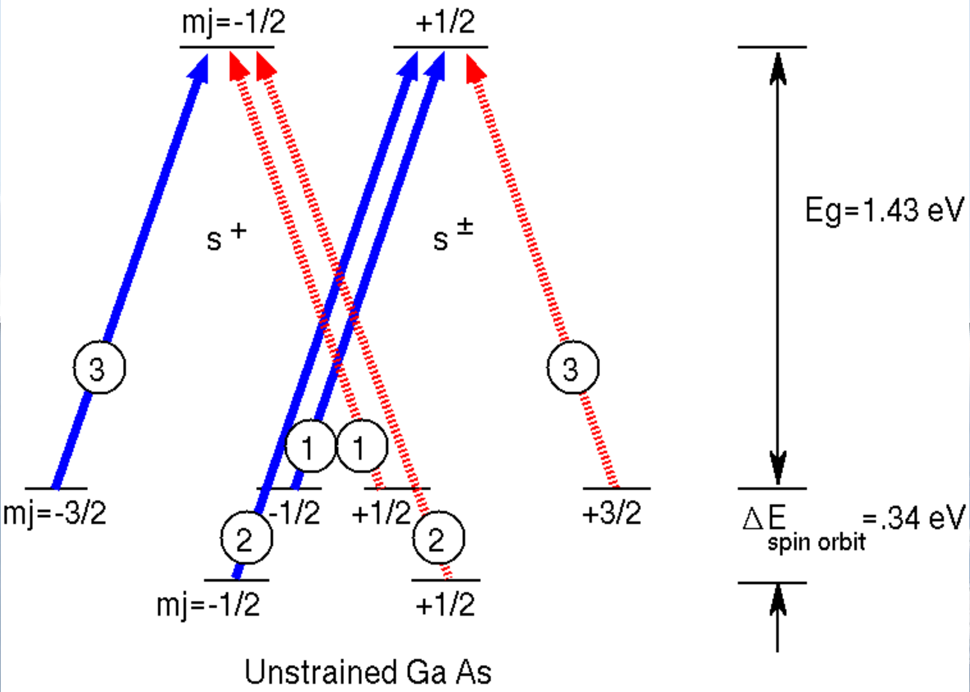
Beam polarization P
(ideally 1.0)

$$P \equiv \frac{N_R - N_L}{N_R + N_L}$$

Polarized Electron from GaAs

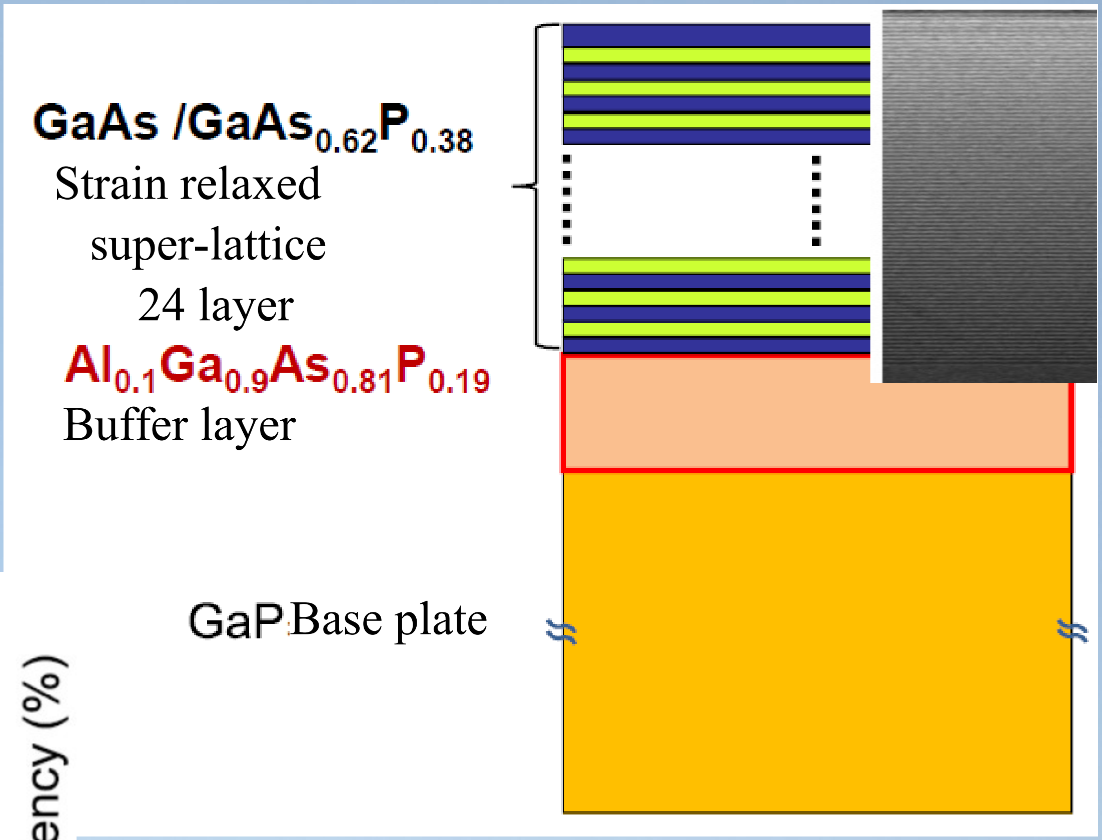
- Polarized electron : Photo-electron from GaAs cathode.
- Spin dependent transition probability by circularly polarized laser.
- Up to 50% with degeneration, ideally up to 100% breaking the degeneration.

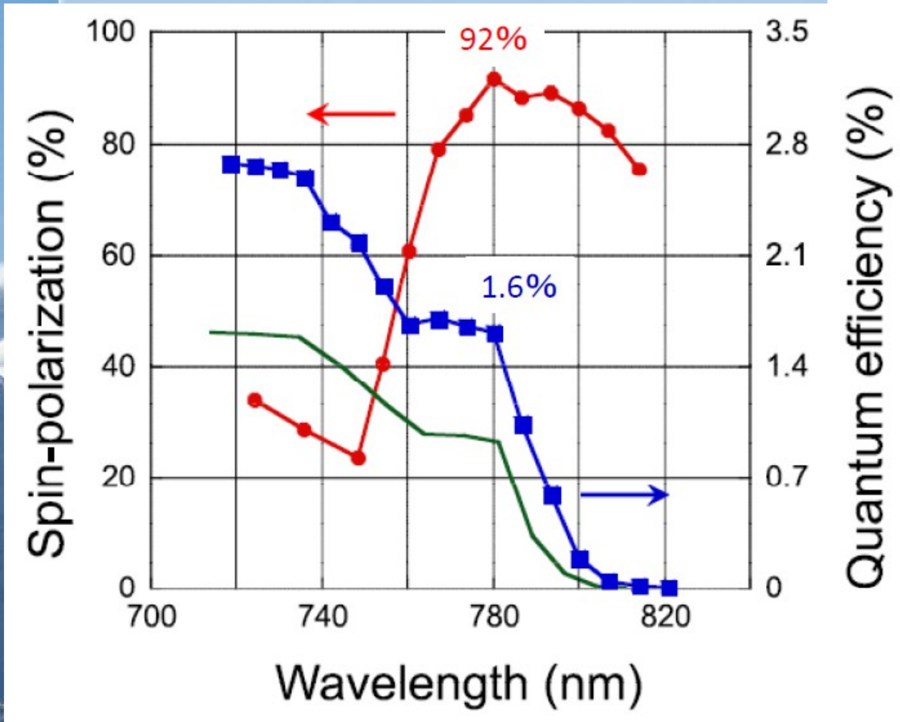




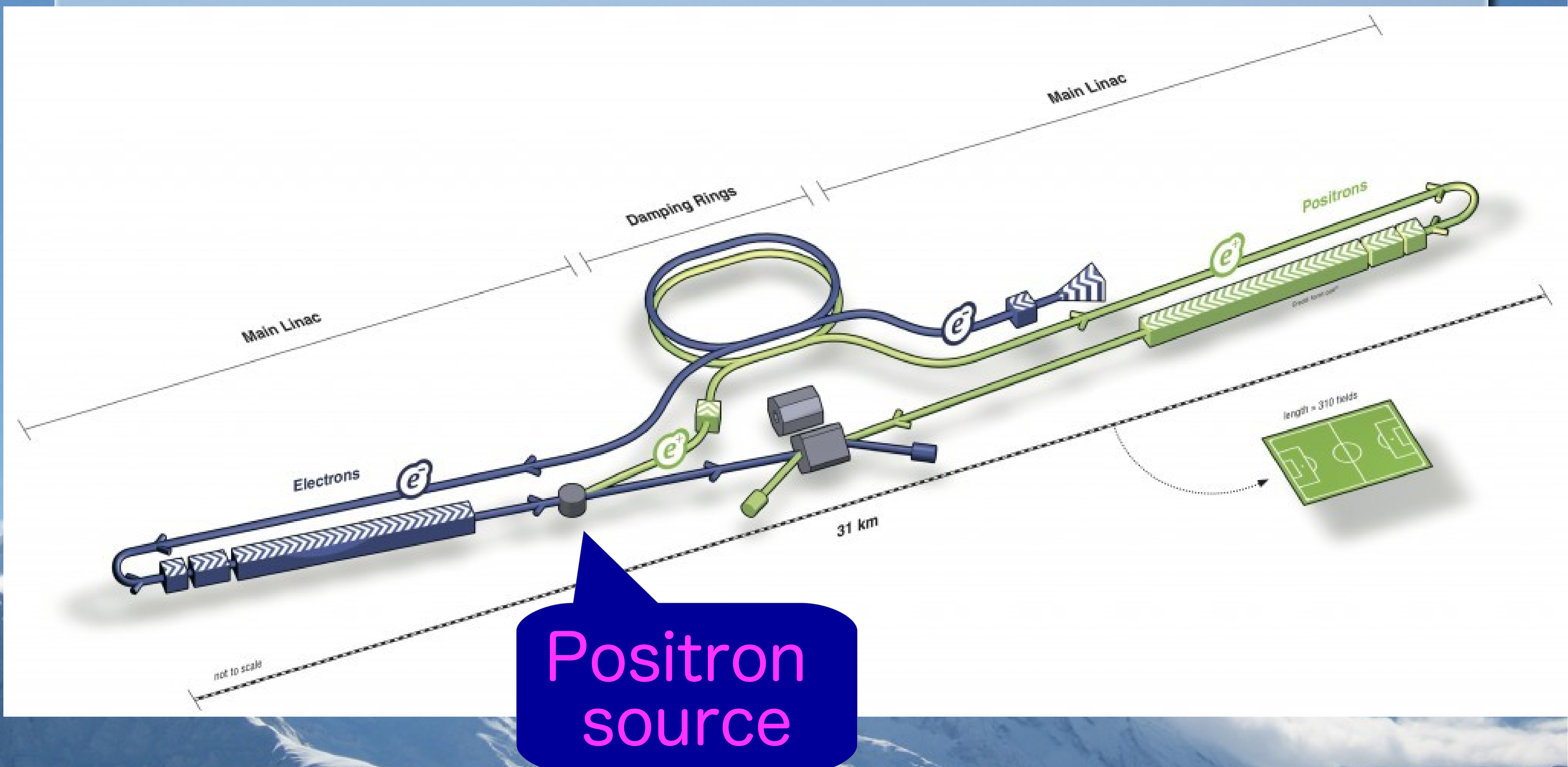
Polarized Electron from GaAs

- Super-lattice structure to break the degeneration.
- It is achieved by GaAs/GaAsP Super-lattice Crystal.



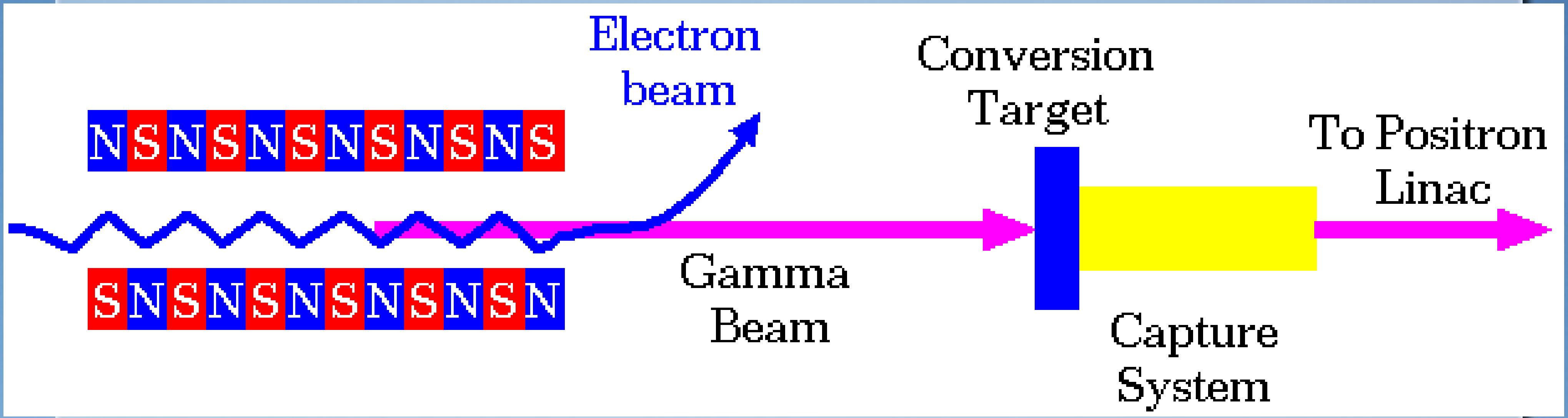


- 92% polarization, 1.6% QE


Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km
not to scale
length = 310 fields
Positron
source

86

ILC Positron Source
(Undulator Radiation method)



- Positron is generated by gamma from Undulator radiation with 250GeV electron beam.
- The electron beam is "recycled" for the collision.
- Generated positron is once stored in DR and used for the next collision.
- To avoid this operation complexity, other methods is considered.

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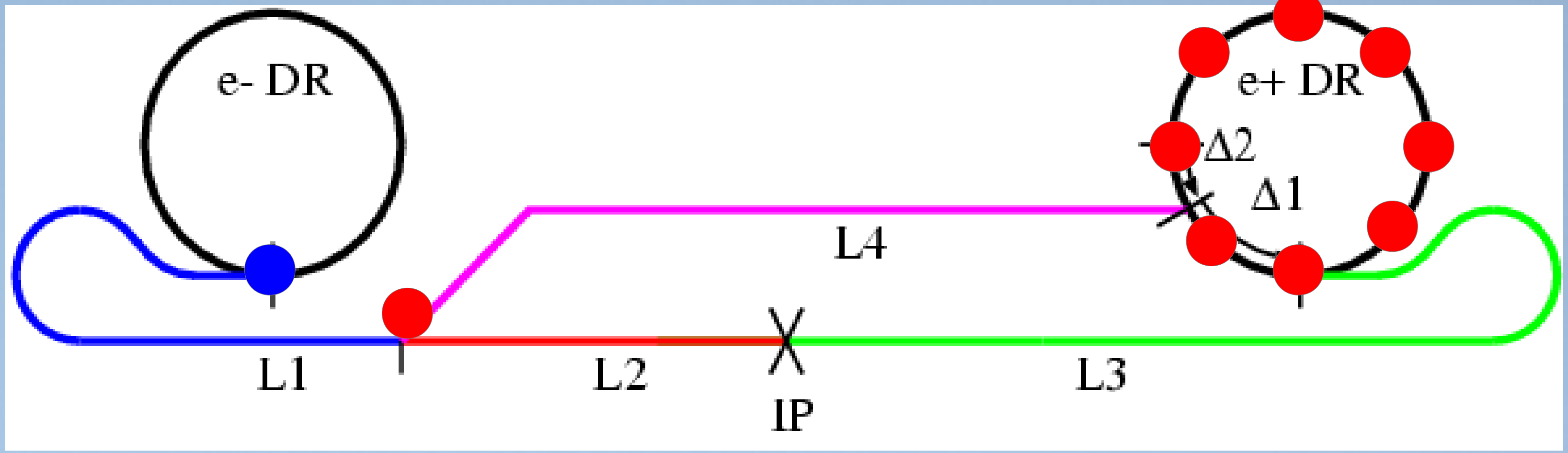
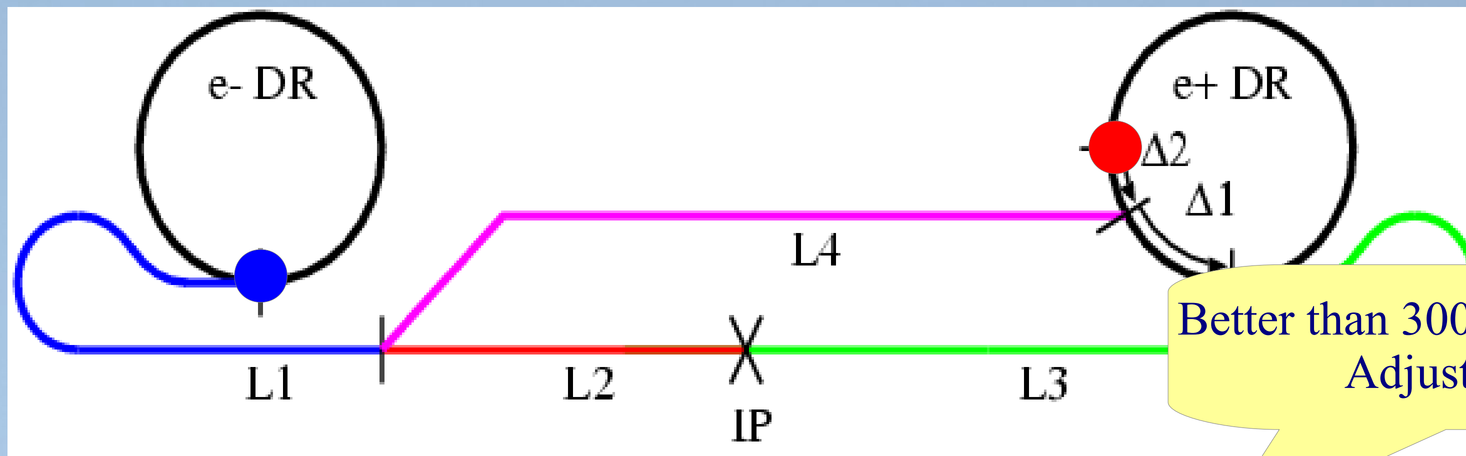
Path Length Condition



- Positrons is generated with electrons.
- Generated positrons have to wait in DR for 200ms until next collision.
- Positron generation and collision are performed simultaneously and many DR buckets are shared with positron bunch who waits the collision.
- Vacant buckets should be prepared for the newly generated positron bunches.
- One idea: the newly generated positron bunch will be in a bucket where a positron bunch who collided with the electron bunch who generates the new positron bunch, were in.

Path-length condition:
Self-reproduction + collision



Better than 300um (bunch length)
Adjusted by ∞2.

- Collision condition: $L_1+L_2=\Delta_1+\Delta_2+L_{3,}$
- Self-reproduction condition: $L_1+L_4=\Delta_2+nC_{DR},$

$$L_3+L_4+\Delta_1=L_2+nC_{DR},$$

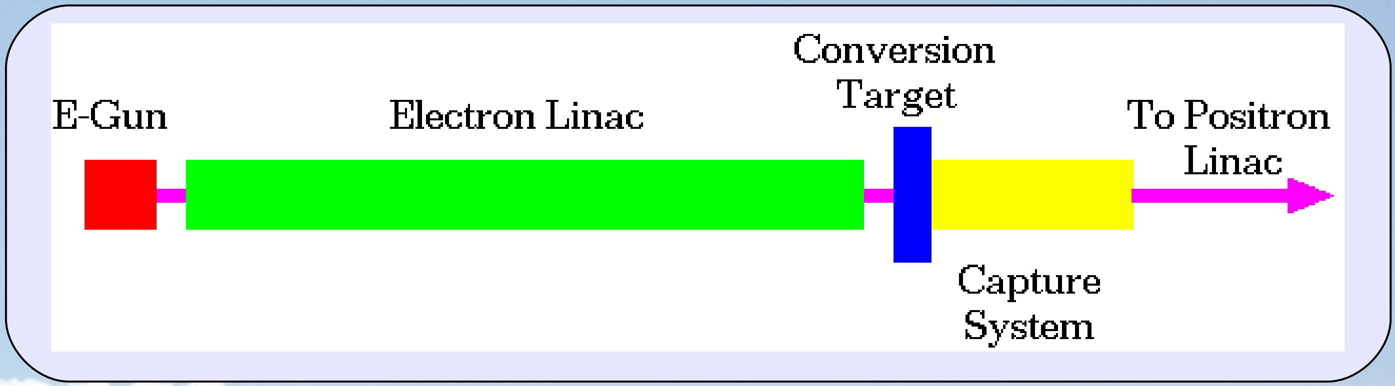
Better than RF bucket height (5m
Adjusted by physical length.

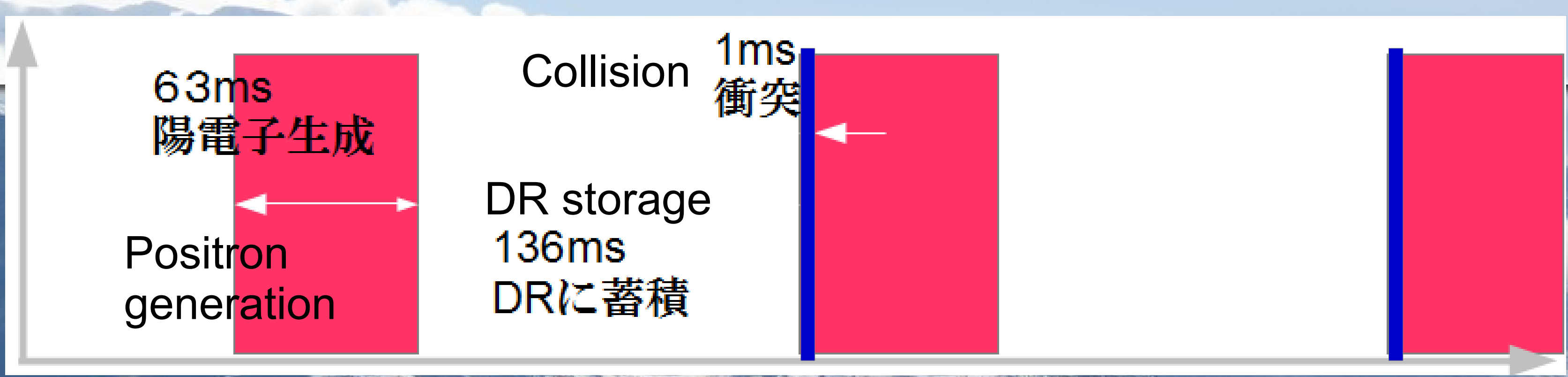
Physical path length has to be adjusted.

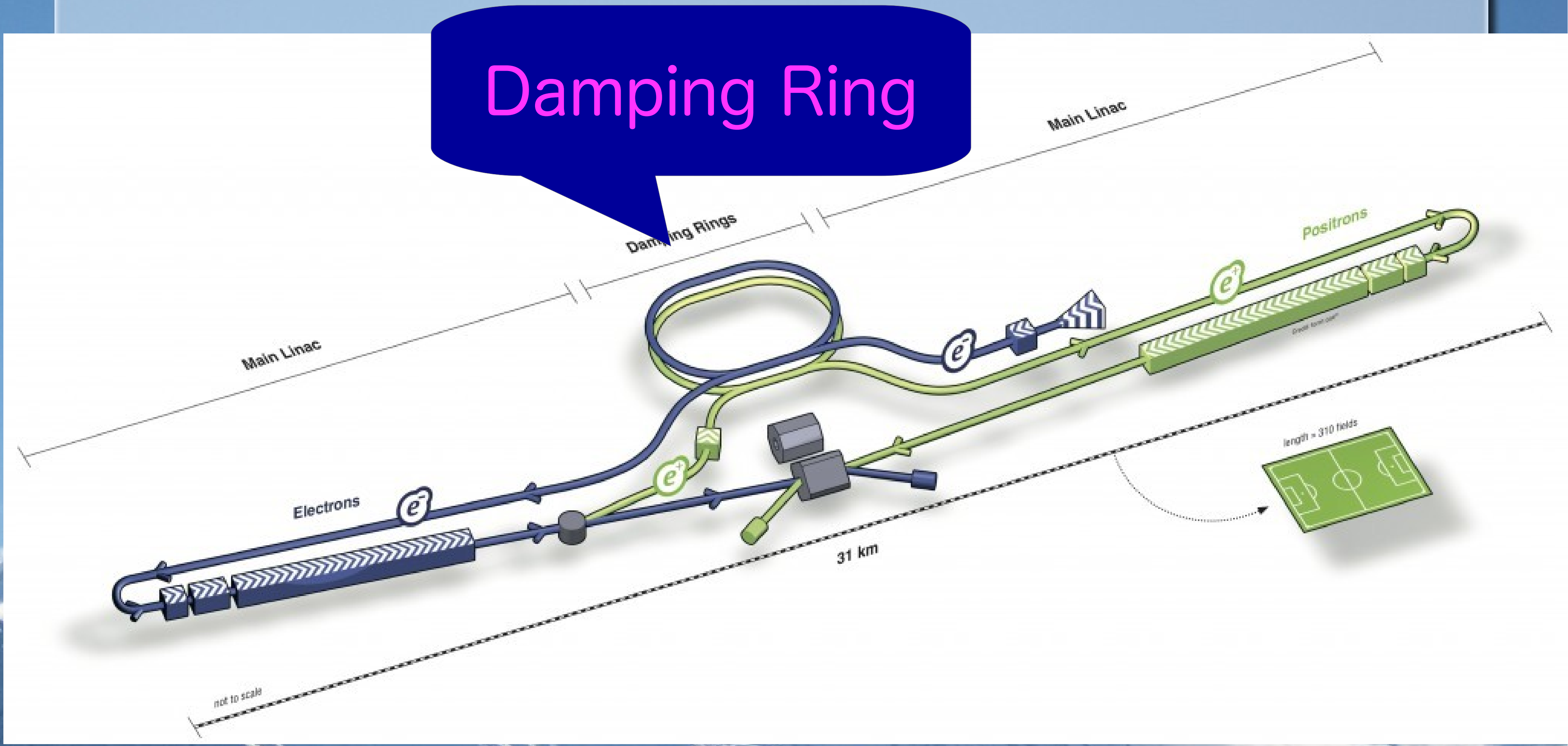
Physical Adjustment

Electron Beam Driven Method

- It is a technical backup as a conventional method.
- 6 GeV electron beam impinges on W-Re target.
- To avoid possible target destruction by the heavy thermal heat load on the target, positron beam is generated in 64 ms instead of 1ms.



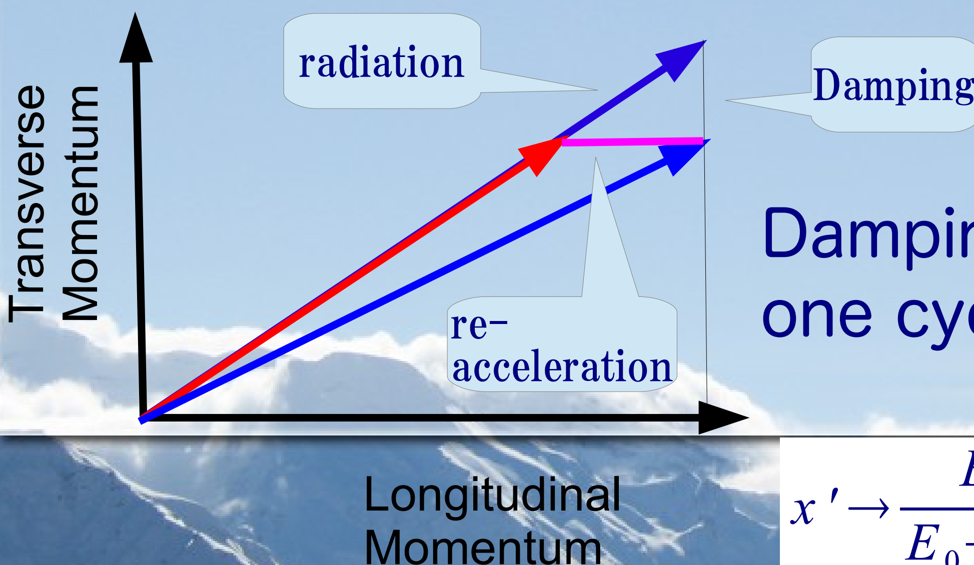



Damping Ring
Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km
not to scale
length = 310 fields

92

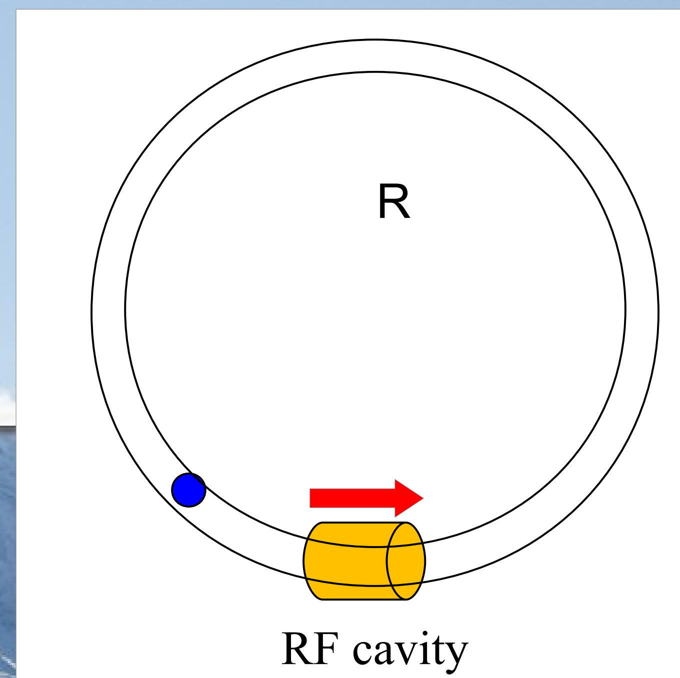
Radiation Damping

- To realize extremely small spot size at IP, we need also extremely small emittance too.
- It is made by radiation damping in a storage ring.
- Synchrotron radiation decreases both transverse and longitudinal momentum.
- The longitudinal momentum is kept by re-acceleration.
- The transverse momentum is damped by many cycles.



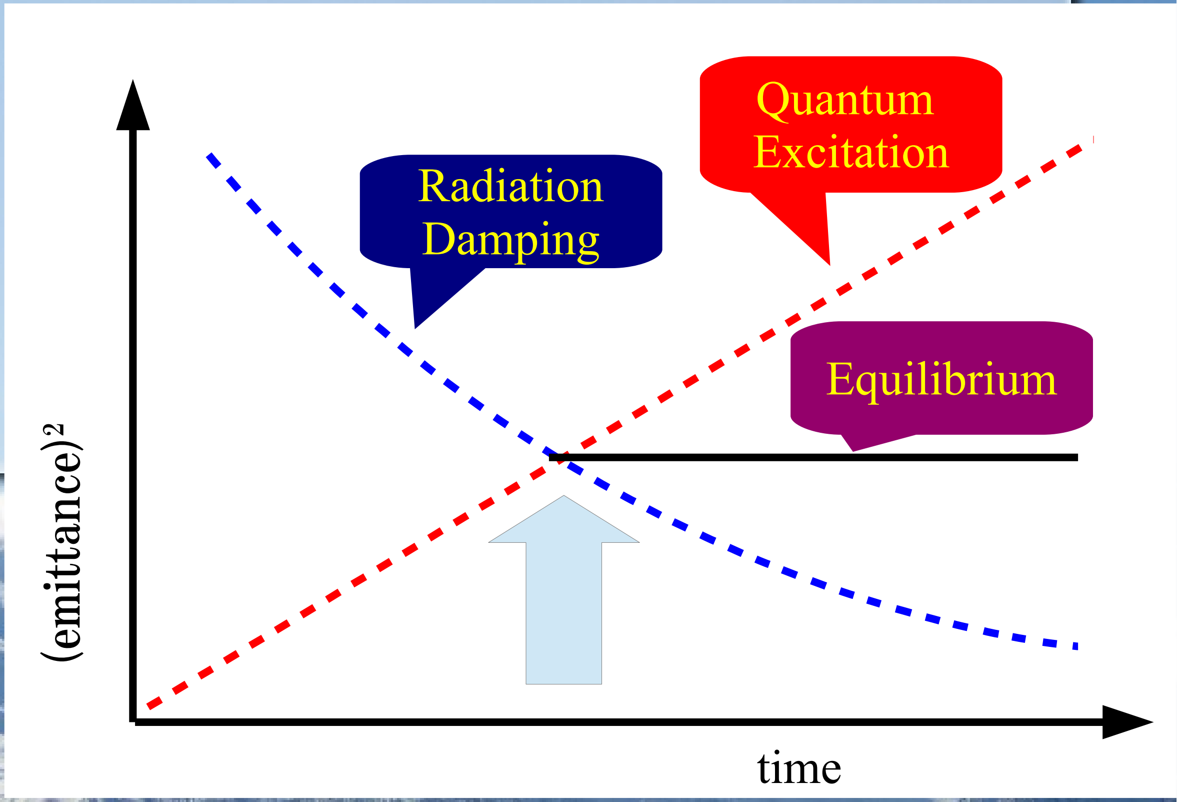
Damping by one cycle

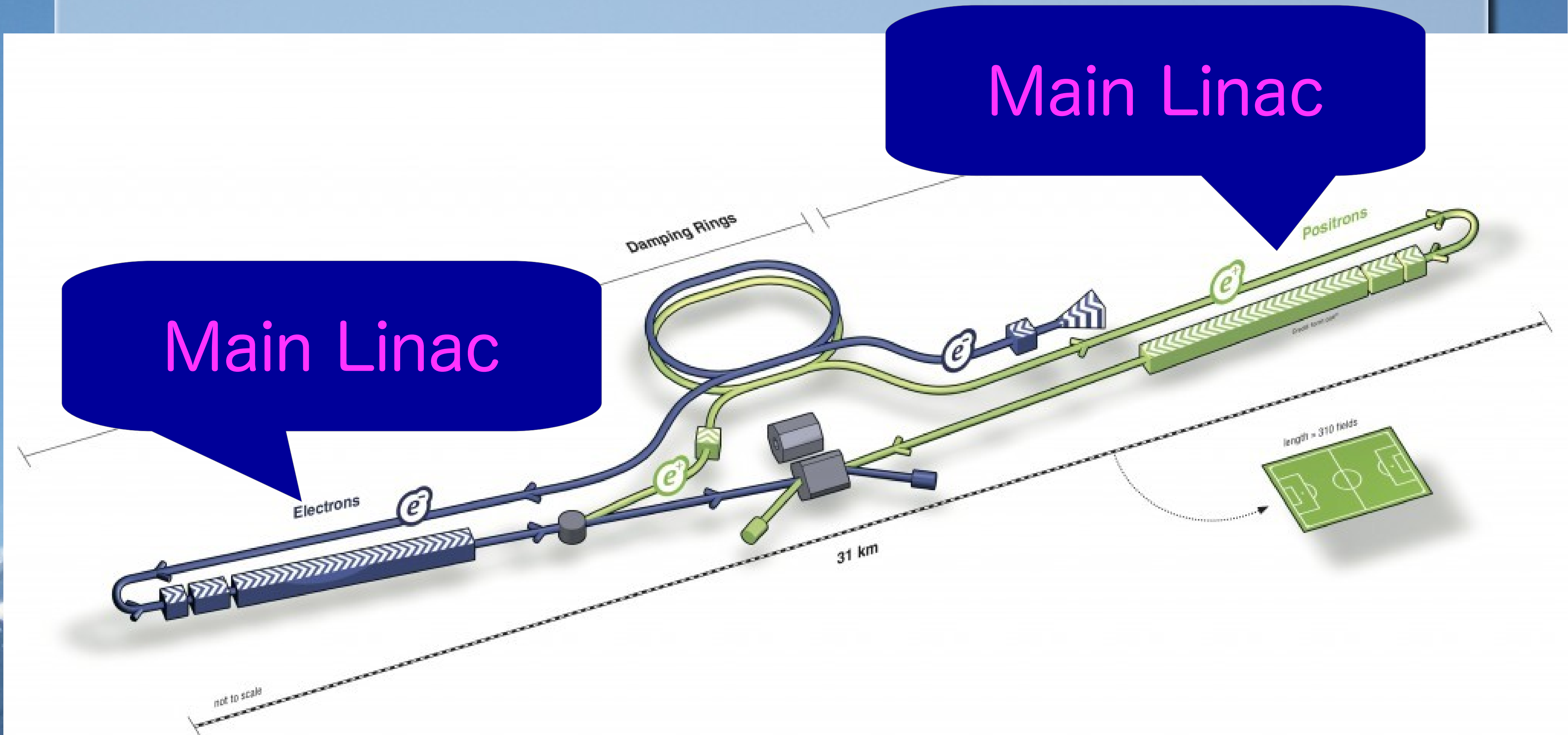
$$x' \rightarrow \frac{E_0}{E_0+U_0} x'$$



Equilibrium Emittance

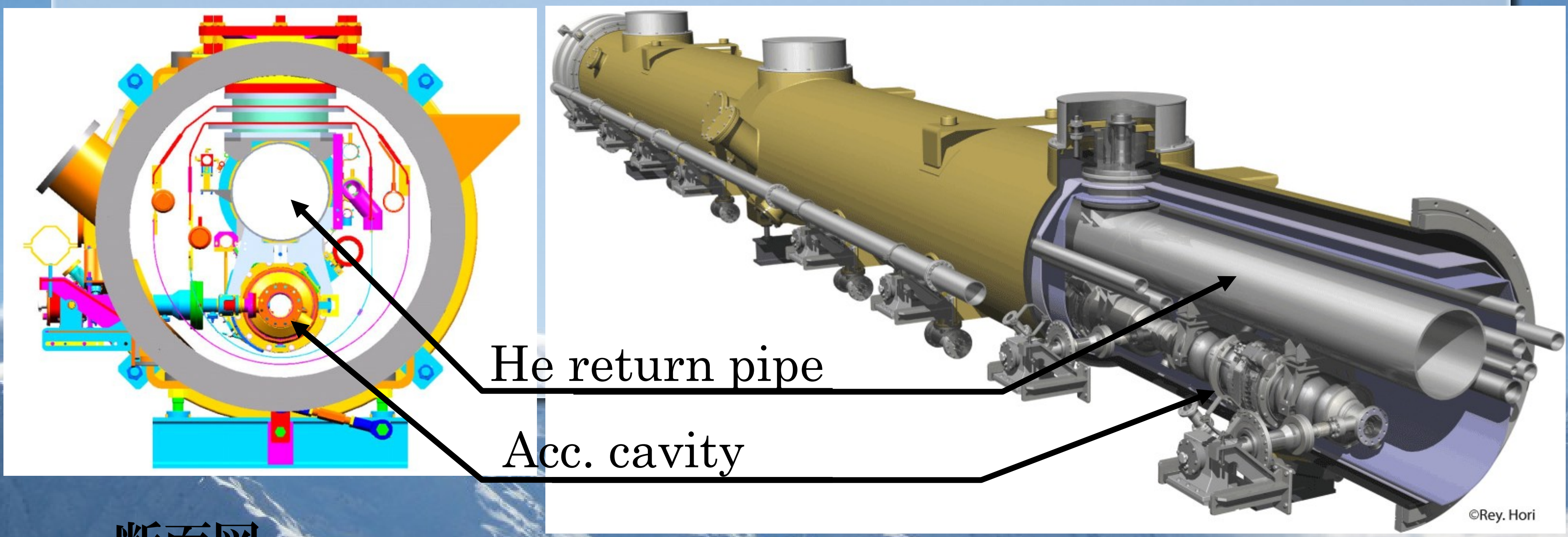
- Emittance can not be damped down to zero. There is a limit.
- Quantum excitation increases the transverse momentum.
- Quantum excitation is a random walk in the phase-space. Deviation is linearly increased by time.
- Equilibrium state is a balance between the Quantum excitation and Radiation damping.
- The Quantum excitation is only in horizontal plane. That is why the vertical emittance can be extremely small.
- That is convenient for LC.




Main Linac
Main Linac
Damping Rings
Positrons
Electrons
31 km
not to scale

ILC Main Linac

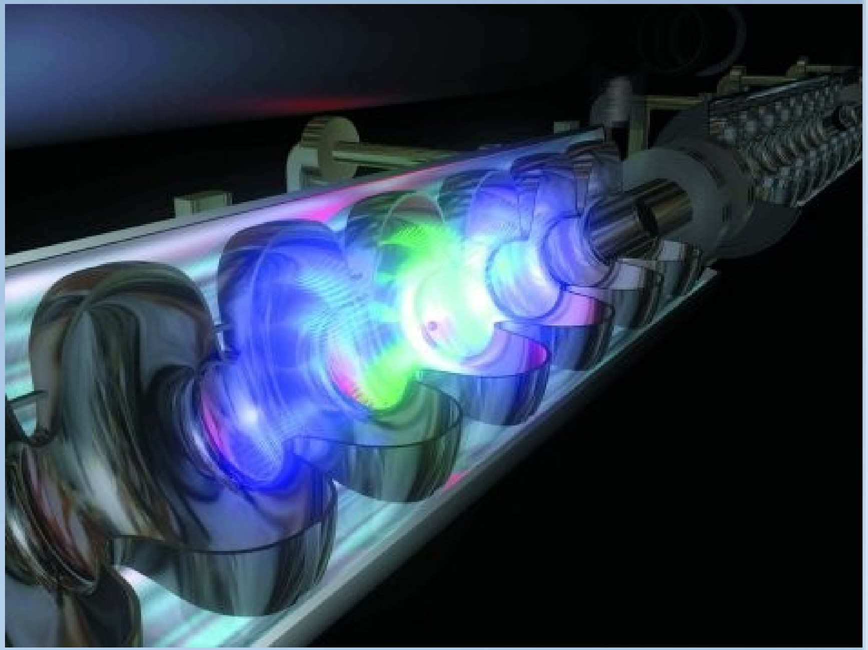
- RF cavity made with Nb cooled by super-fluid He.
- In a cryogenic tank (cryostat), He is pumped.
- In a cryostat, 8 or 9 cavities are accommodated.
- The basic performance is confirmed.

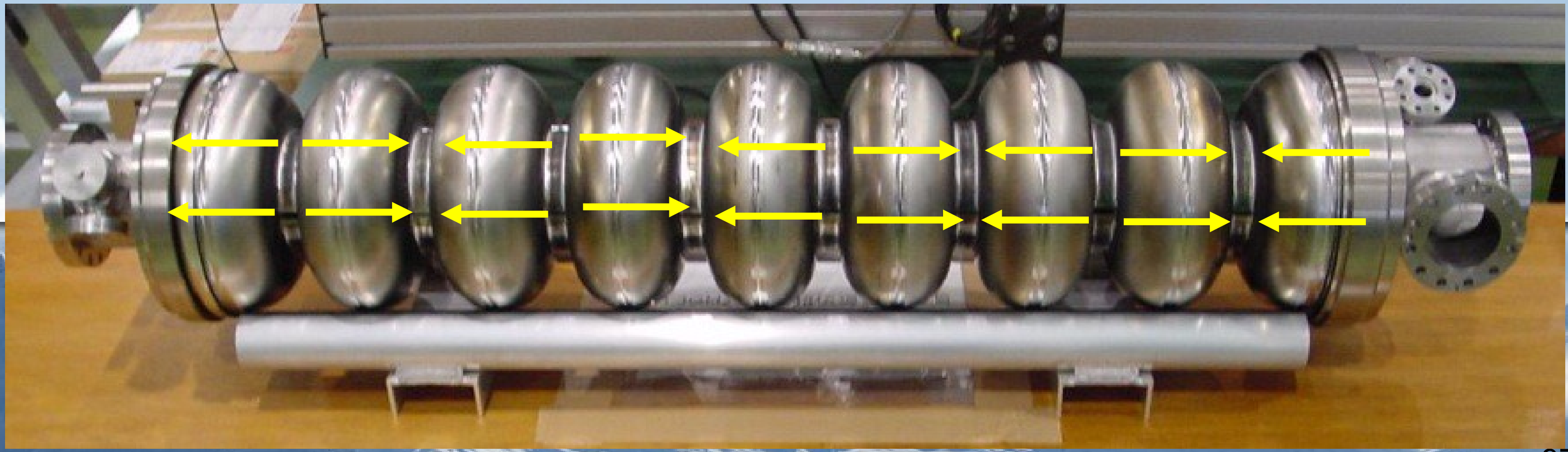


断面図

ILC Cavity

- Based on TESLA cavity developed in DESY, Germany.
- 1.2m, 9 cells.
- Accelerator gradient：31.5MV/m.
- Standing wave (pi-mode).
- Electro-polishing technique for the high gradient.





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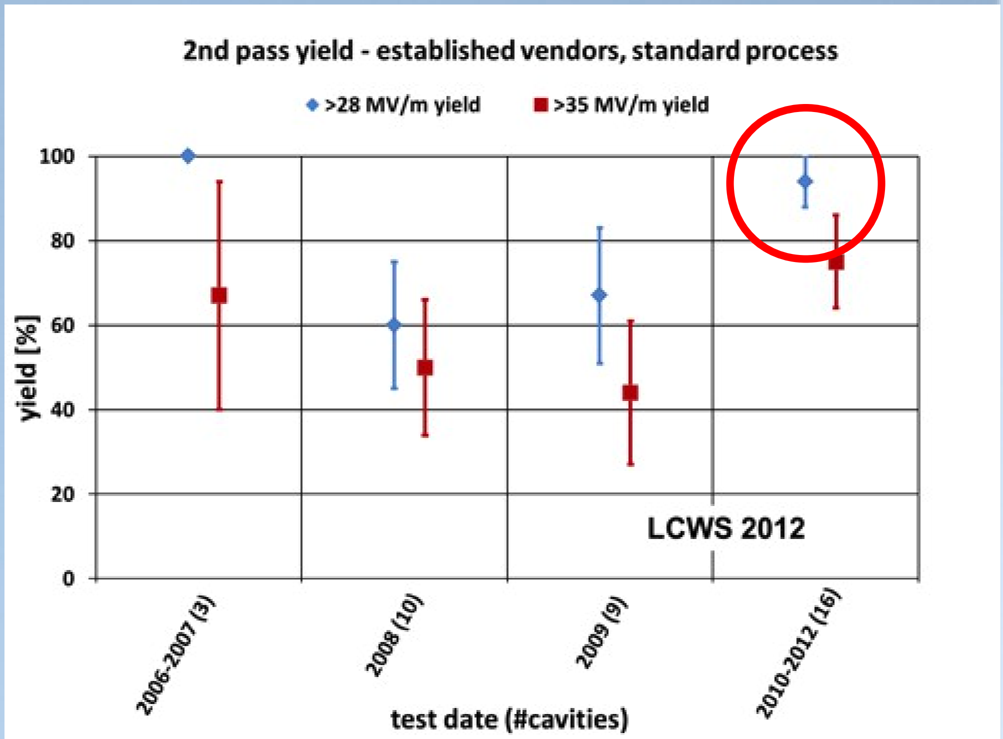
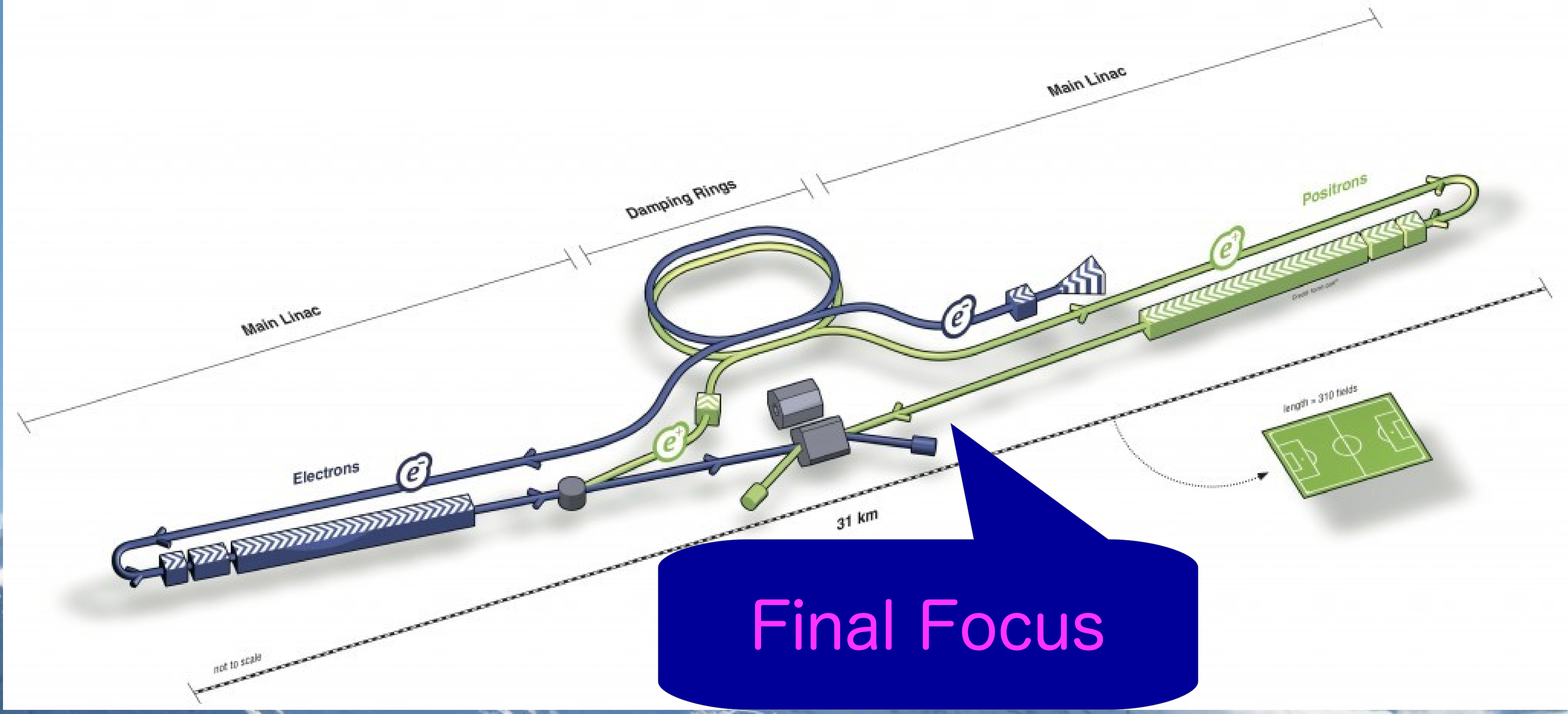
Fabrication / Insutorialization

Production yield:
94 % @ > 28 MV/m,
Average gradient:
37.1 MV/m
Design average gradient:
35 MV/m



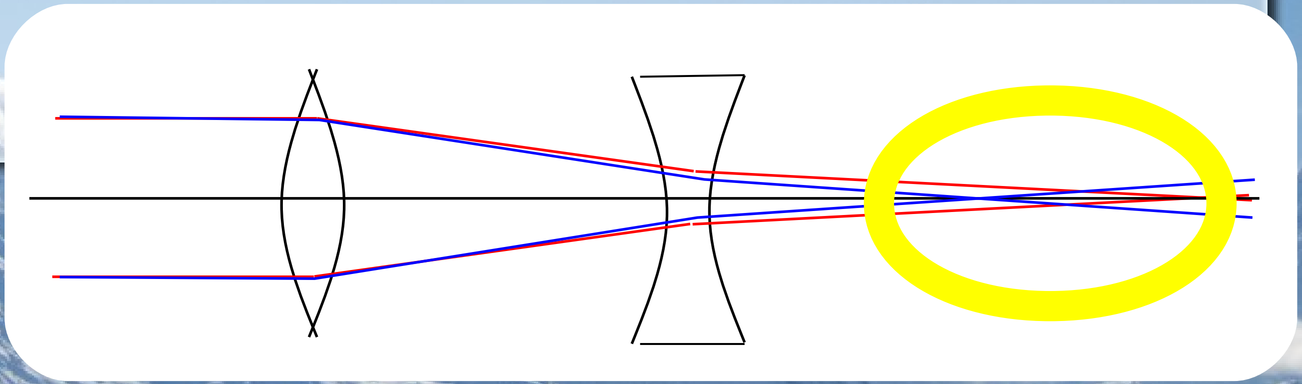
It is ready for production!


Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km
length ≈ 310 fields
not to scale
Final Focus

Final Focus System

- The beam is focused down to 5.7nm (vertical direction).
- Correction for chromatic aberration is the key.
- Chromatic aberration correction is made by non-linear optics.
  - Light optics : achromatic lens
  - Beam optics : Sextupole magnet

wikipedia

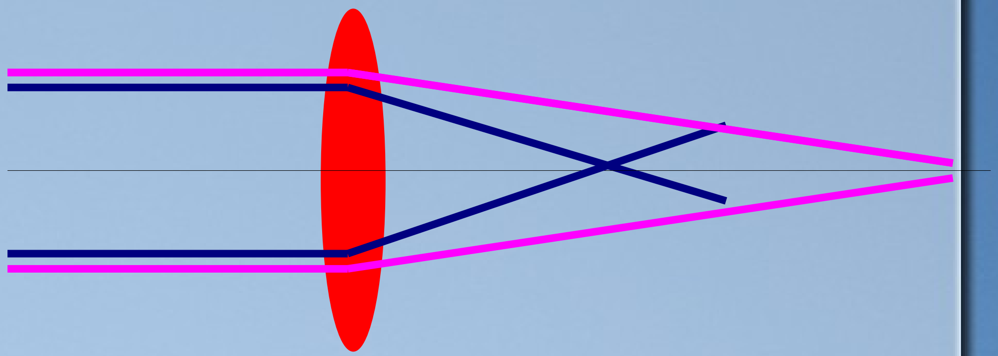


Chromatic Aberration

Focus by Quadrupole.

$$\frac{dx'}{ds} = -g\,x$$

$$g \equiv \frac{e\,G\,L}{p_0}$$



depends on p_0

$$dg = \frac{d\,g}{dp}\Delta\,p = \frac{-g}{p_0}\Delta\,p \sim -g\,\delta$$

$$\frac{dx'}{ds} = -g(1-\delta)x$$

Focal length depends on the color!
(Beam energy)

Chromatic Correction

- Sextupole magnet is placed where there is a dispersion(*).

$$\frac{dx'}{ds}=\frac{-eH}{p_0}\left[\left(\eta_x\delta+x_\beta\right)^2-y^2\right]\sim\frac{-2\mathrm{eH}}{p_0}\eta_x\delta\,x_\beta$$

It is proportional to the energy deviation.

(Neglect higher order)

- By combining Sextupole and Quadrupole,

$$\frac{dx'}{ds}=-g\left(1-\delta\right)x_\beta-\frac{2\mathrm{eH}}{p_0}\eta_x\delta\,x_\beta=-g\,x_\beta$$

No chromatic term

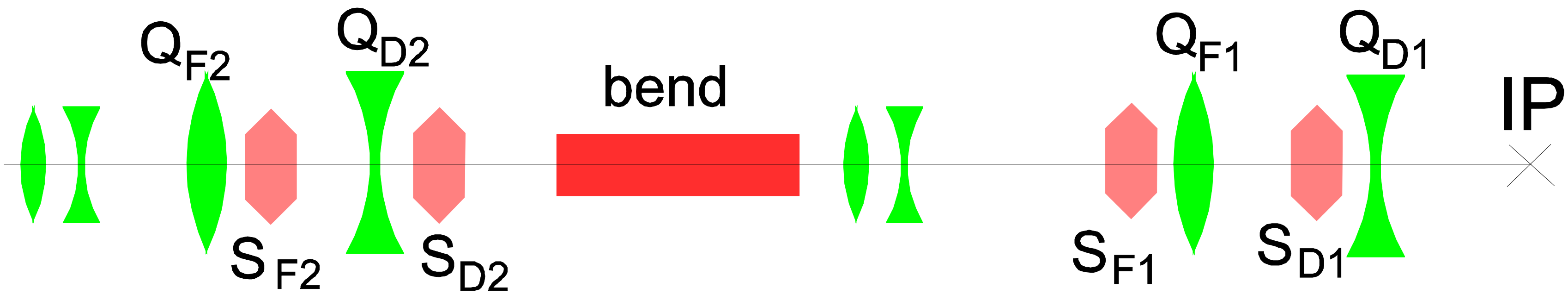
correction condition

$$g=\frac{2\mathrm{eH}}{p_0}\eta_x$$

(*) dispersion is a coefficient of position shift to energy deviation.

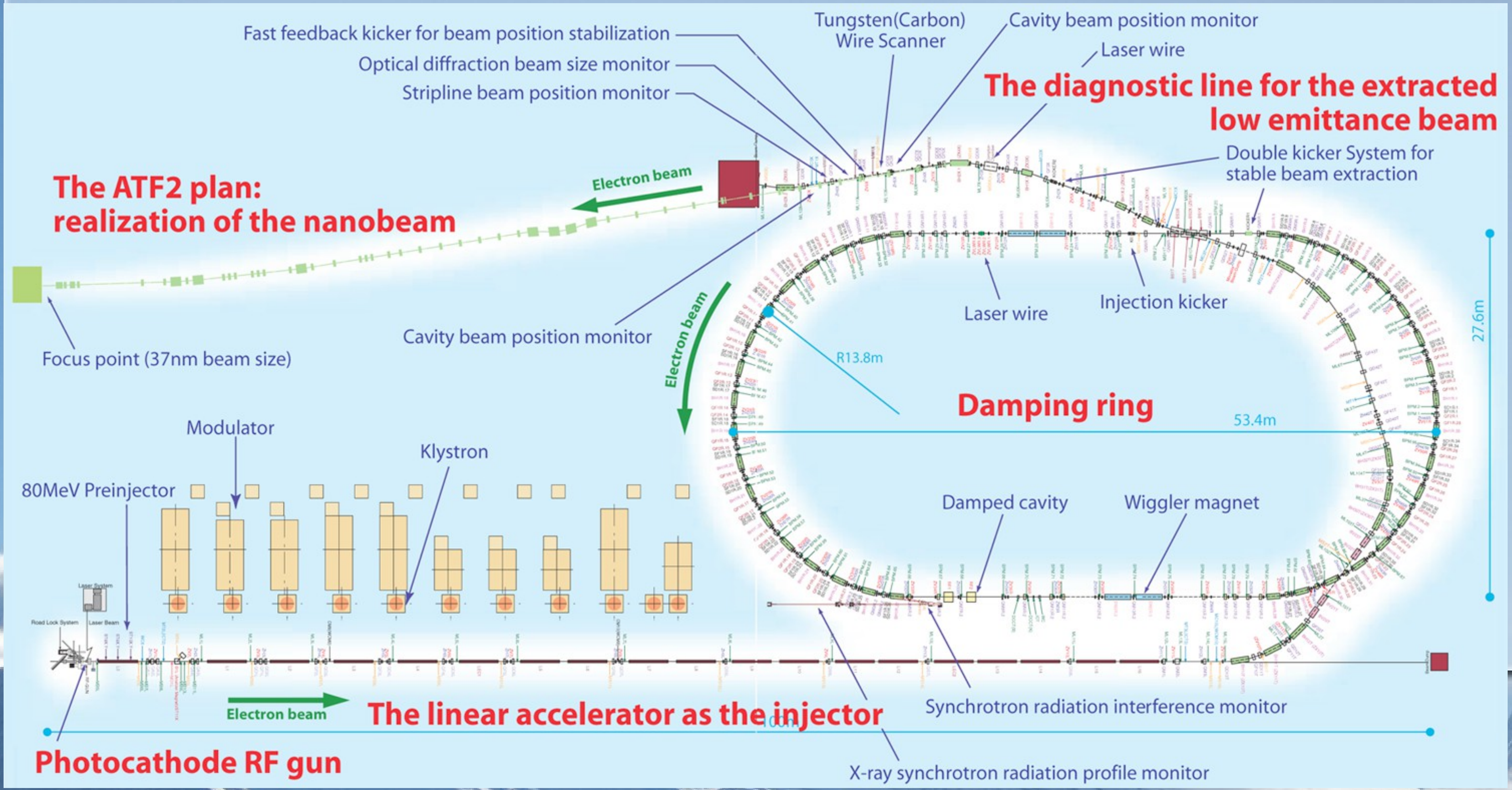
Local Chromaticity Correction

- In the ILC design, Quadrupole (Q_{F1} and Q_{D1}) and Sextupole (S_{F1} and S_{D1}) magnets are placed where there is a finite dispersion in, to correct the chromatic aberration.

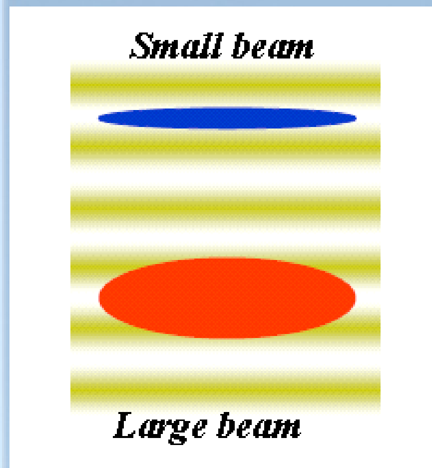


- S_{D2} and S_{F2} cancel the non-linearity made by S_{F1} and S_{D1}.
- This method is called as local choromaticity Correction.
- It is common for ATF2 which is a test facility to demonstrate the final focus design.

Final Focus Test (ATF2)

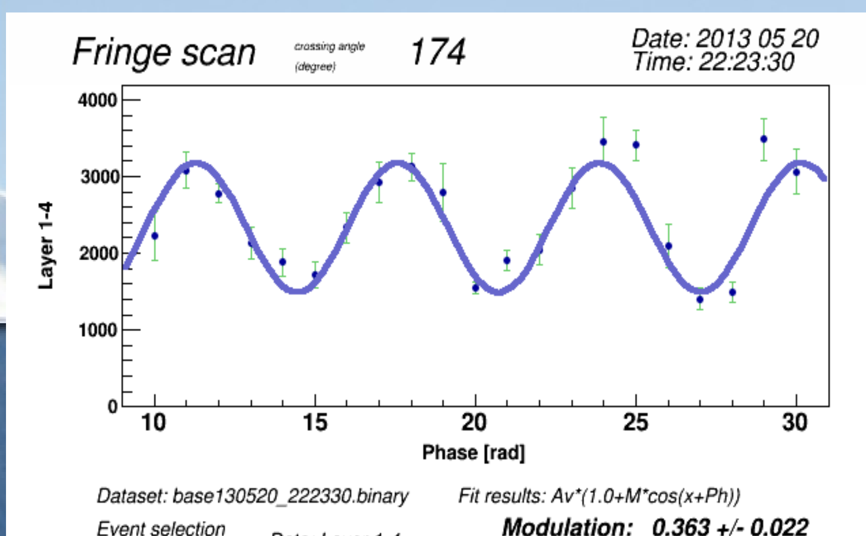


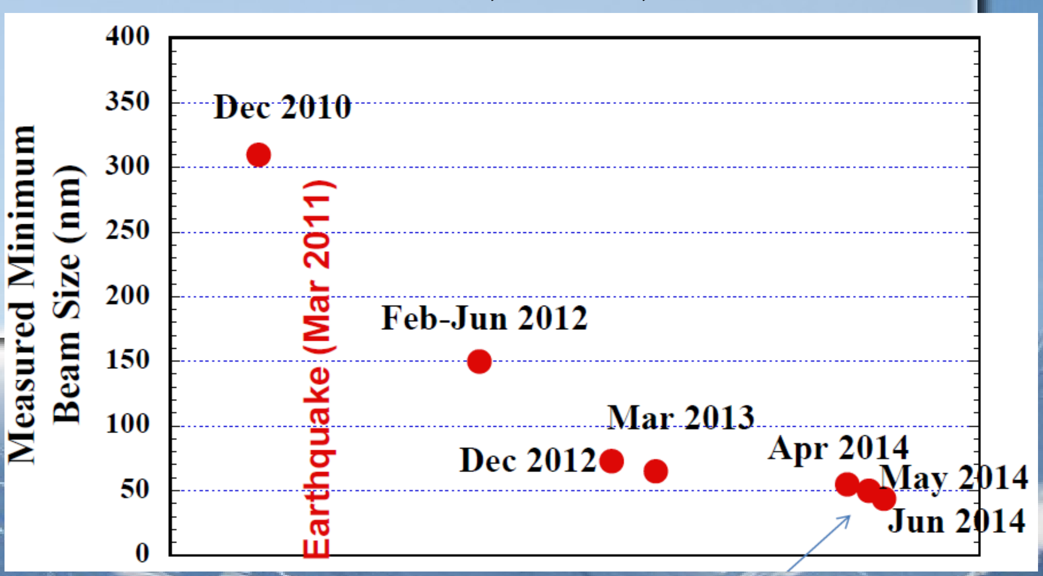
We are approaching!



- Generation of Extremely small beam and its measurement is carried out at KEK-ATF.
- 45nm had been confirmed.
- 37nm in ATF2 (1.3 GeV) is equivalent to 5.7nm in ILC (250) .

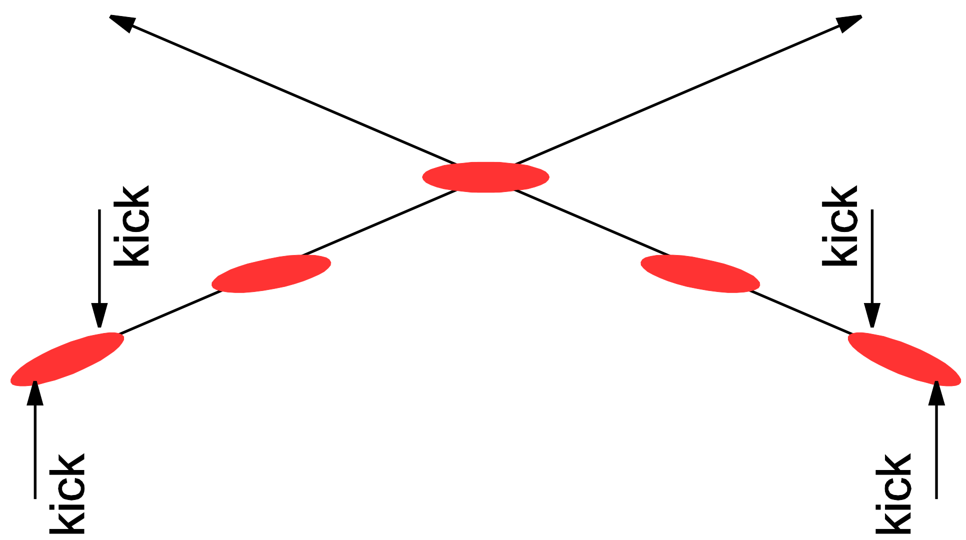
K. Kubo, weza01, IPAC14

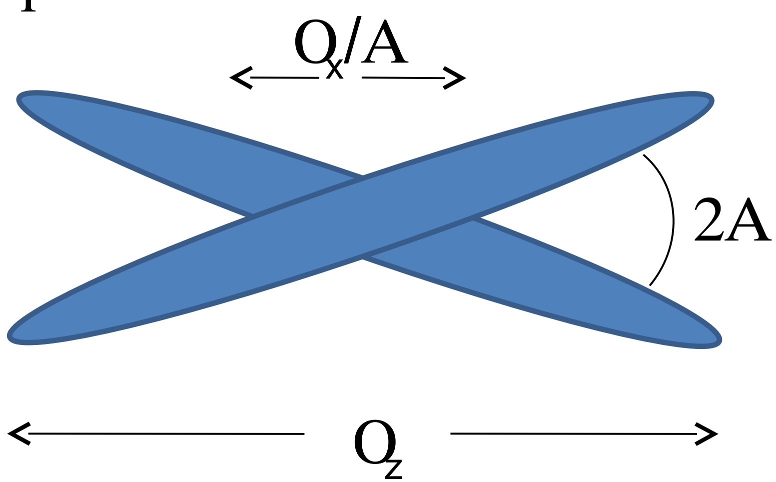




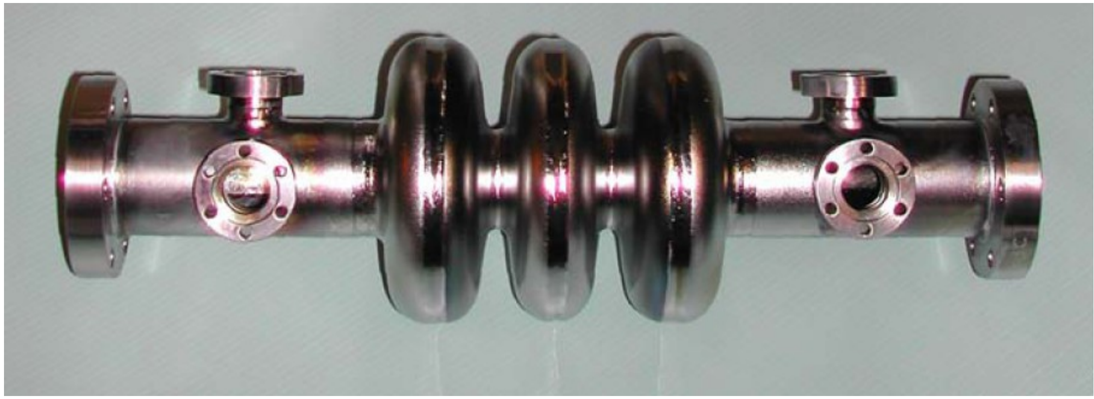
Crab Crossing

- To avoid too much backround to detector, crossing angle is 14mm in ILC.
- Because 14mrad >> s_x / s_z , geometrical overlap becomes small and luminosity is much decreased.
- Crab crossing recovers the luminosity loss.
- The cavity is 13.4 m from IP.
- A very fine timing adjustment is required.



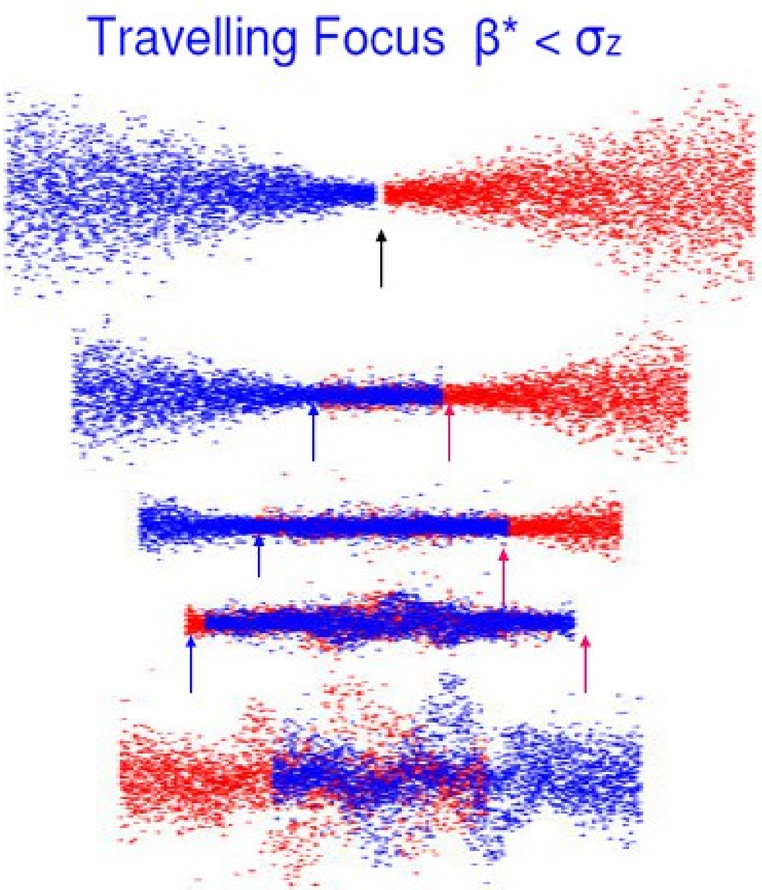


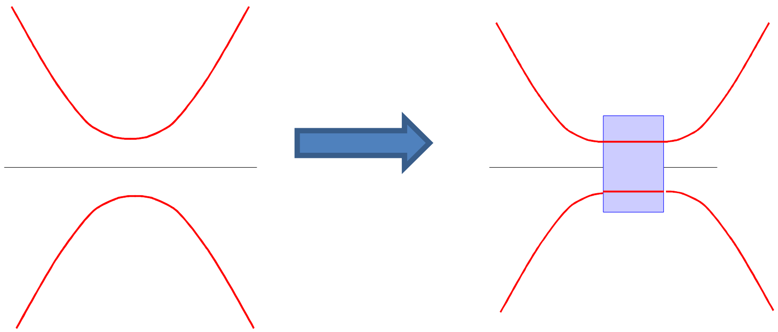
A prototype of Crab cavity

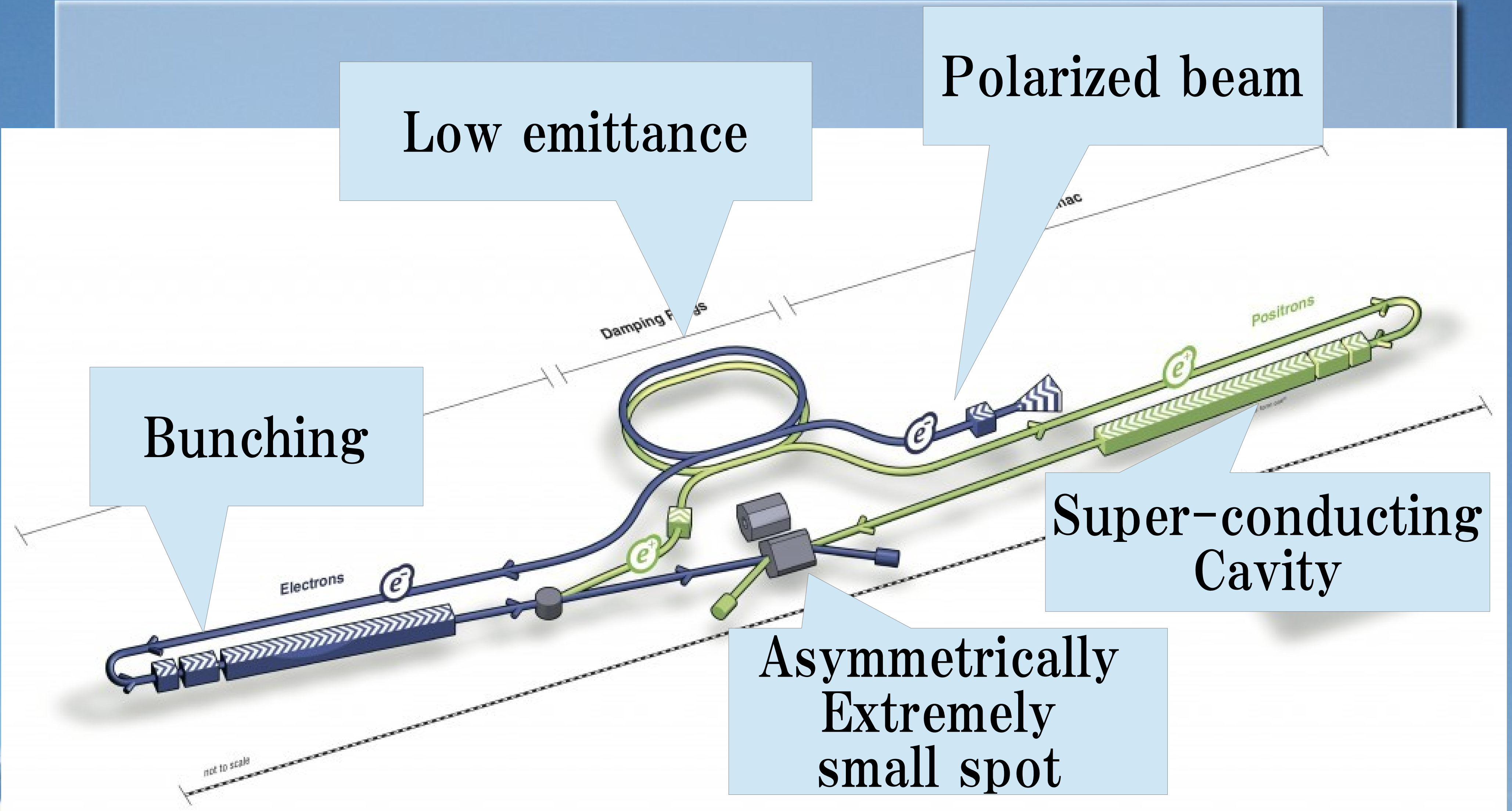


Traveling Focus

- In a conventional focusing, $\sigma_y \ll \sigma_z$ is not effective by hour-glass effect.
- If another focusing force near IP, the luminosity is enhanced even with $\sigma_y \ll \sigma_z$
- Collision partner provides the focusing force.
- Need a large D_y.
- To keep the focusing force over the whole bunch,
  - The focal point is the head of the bunch and moving forward (Traveling Focus).
- Idea
  - Crab cavity + Sextupole magnet.
    - It is sensitive to error on crab cavity.
  - Energy slope + chromaticity.
    - Energy spread becomes large and sub-effects on the CMS energy spread and chromaticity correction could be serious.







High Luminosity with low beam power

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ILC: High energy collision with Low Power

- ILC beam power

$$P_{beam} = 250\,GeV \times 10\,mA \times 1\mathrm{ms} \times 5\,Hz \times 2 = 25\,MW$$

- LEP beam power

$$P_{beam} = 45\,GeV \times 3\,mA \times 2 = 270\,MW$$

- ILC is a low power collider making the high energy collision.
- The luminosity is optimized (maximized) in the strong beam-beam effect regime.
- In case of ring collider (LEP), the beam-beam effect should not be too large to maintain the beam circulation.

ILC Wall Plug Power

Main Linacs 73 MW — **Total 163 MW** — **Sub-Systems 90 MW**

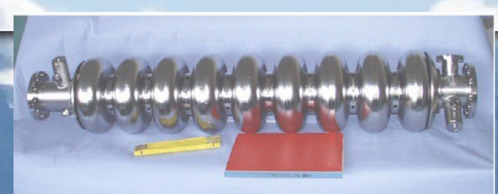
RF
35 MW

78%

65%

Cryogenics:
38 MW

60%



Injectors

Damping rings

BDS

Auxiliaries

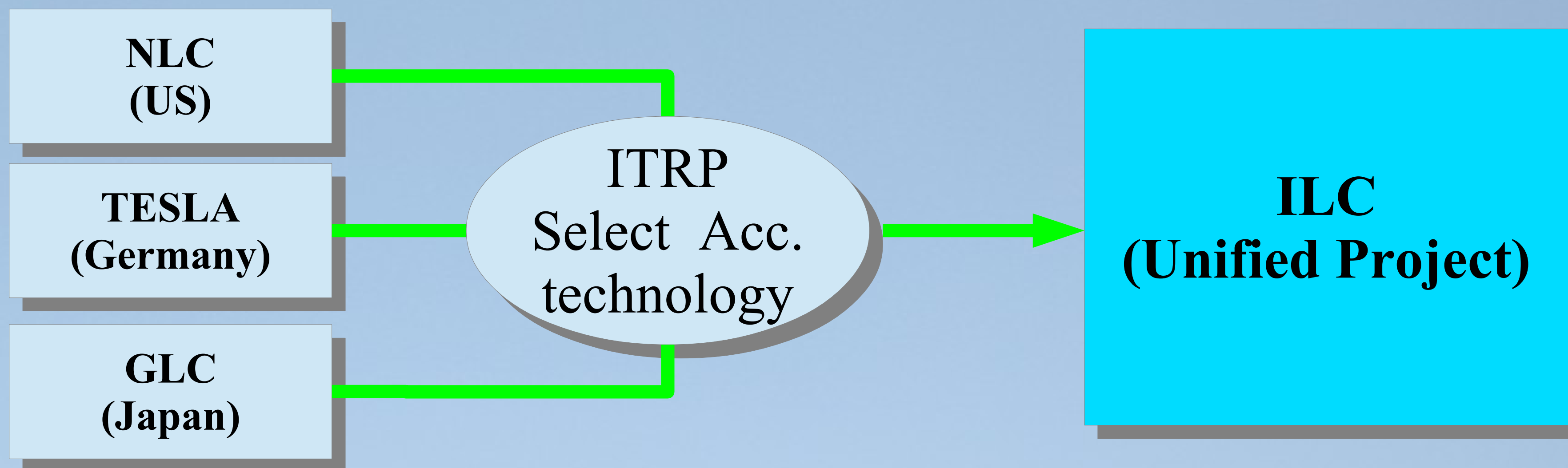
Beam Power
10.5 MW

1. **Future Colliders**
2. **ILC physics motivations**
3. **ILC Accelerator Overview**
4. **ILC, the global project**

ILC, The first global project in Asia.

Evolution of LCs

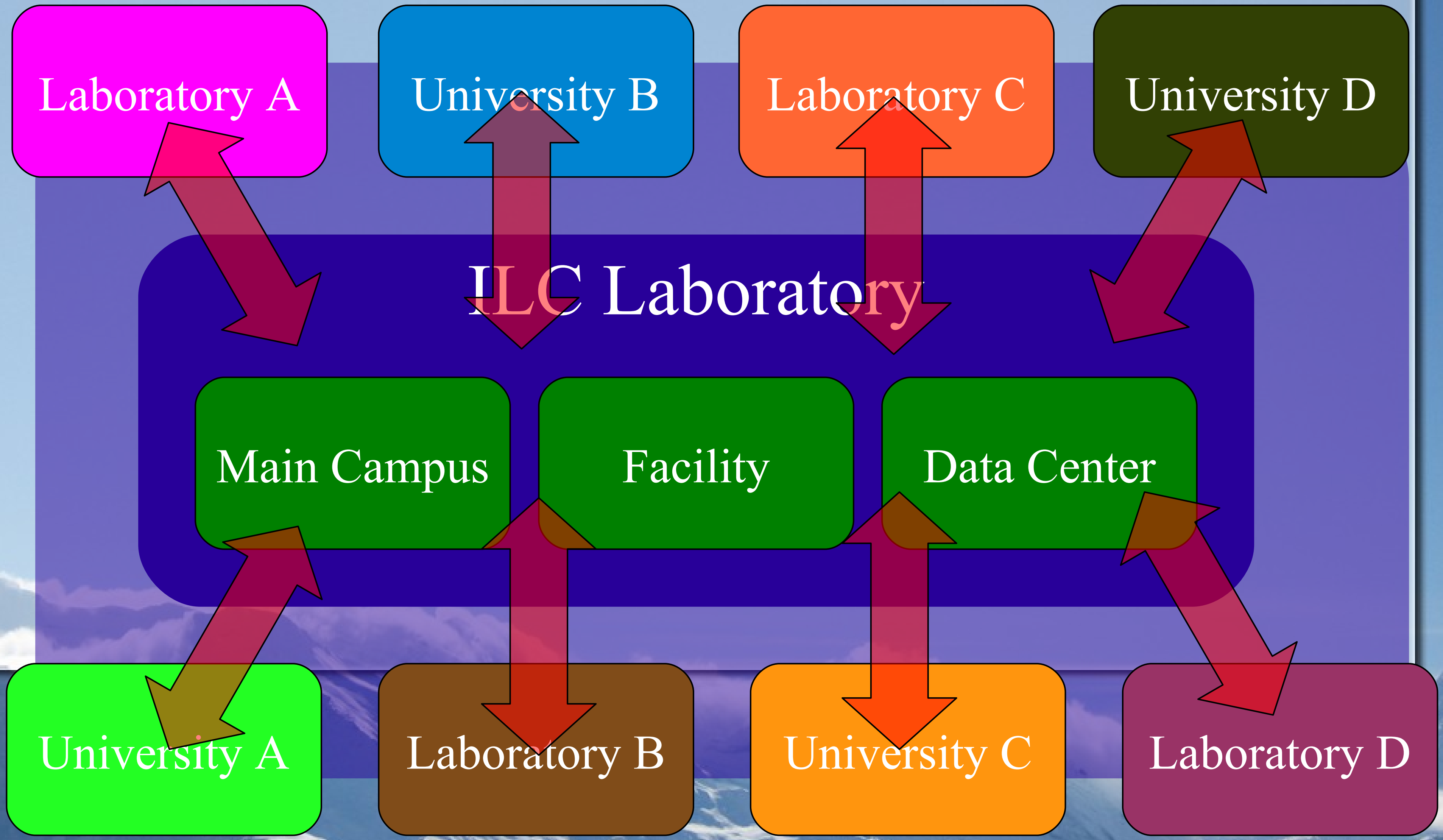
Next future collider



Next next future collider

In 2013, ILC TDR is published!

Multilateral Lab



Japan will host ILC (?)

- Japan Association of High Energy Physicists supports ILC as the next future project.
- Japanese government is very active for accelerator research.
- Science council of Japan made a positive statement for ILC scientific value and recommended investigations for social conditions (technical maturity, man-power and financial budget,etc.).
- A wise-man committee has been formed under MEXT (Ministry of Education, Science, Culture, and Sports) and summarize the report in JPY 2015 (2016 Spring).
- In their interim report, the official decision for the project will be in 2017 after LHC run2.

Japanese HEP Society

- Japanese society (Japan Association of High Energy Physicists) made recommedations concerning large-scale projects, which comprise the core fo future high energy physics research in Japan.
  - Should a new particle such as a Higgs boson with a mass below approximately 1 TeV be confirmed at LHC, Japan should take the leadership role in an early realization of an e+e- linear collider.
- Japanese society (http://www.jahep.org/) proposes a staging approach of LC.
  - Physics studies shall start with a precision study of the "Higgs Boson", and then evolve into studies of the top quark, "dark matter" particles, and Higgs selfcouplings, by upgrading the accelerator.

from a report of subcomittee for future projects of high energy physics.

Japanese Candidate Site

The ILC site evaluation committee of Japan has assessed the two candidate sites based on technical and socio-environmental criteria and unanimously concluded as follows:

The Kitakami site is evaluated to be the best domestic candidate site for the ILC.

Social conditions

- "Japan should contribute to innovation on advanced accelerator technology" (In the policy speech of the prime minister).
- 150 diet members form ILC promotion alliance. **ILC議員連盟**
- Advanced Accelerator Science and Technology Association (AAA) is formed by companies, labs, and universities.

LCC director Lyn Evans hands over the ILC TDR to the prime ministor Abe.

Science Council of Japan
日本学術会議

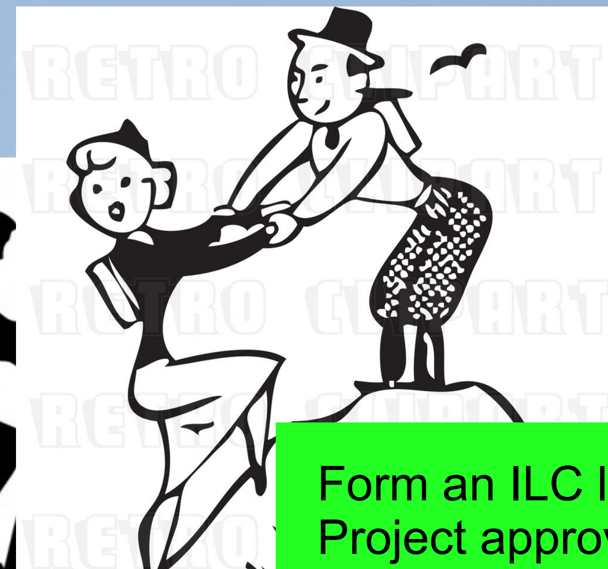
- A report of a series of special session for ILC is published in September 2013.
- ***Science of ILC is significant.***
- ***For the official bid by Japanese goverment, various issues on monetary budget sharing, human resources for detector and accelerator constructions, etc. should be well investigated within several years.***
- ***Budget for this investigation should be funded by Japanese government.***

Translation by the presenter. It is not official

STEPs to ILC

For each steps,
supports from various countries, organizations, societies, are helpful and necessary.

This is a nature of international projects.



Form an ILC lab.
Project approval

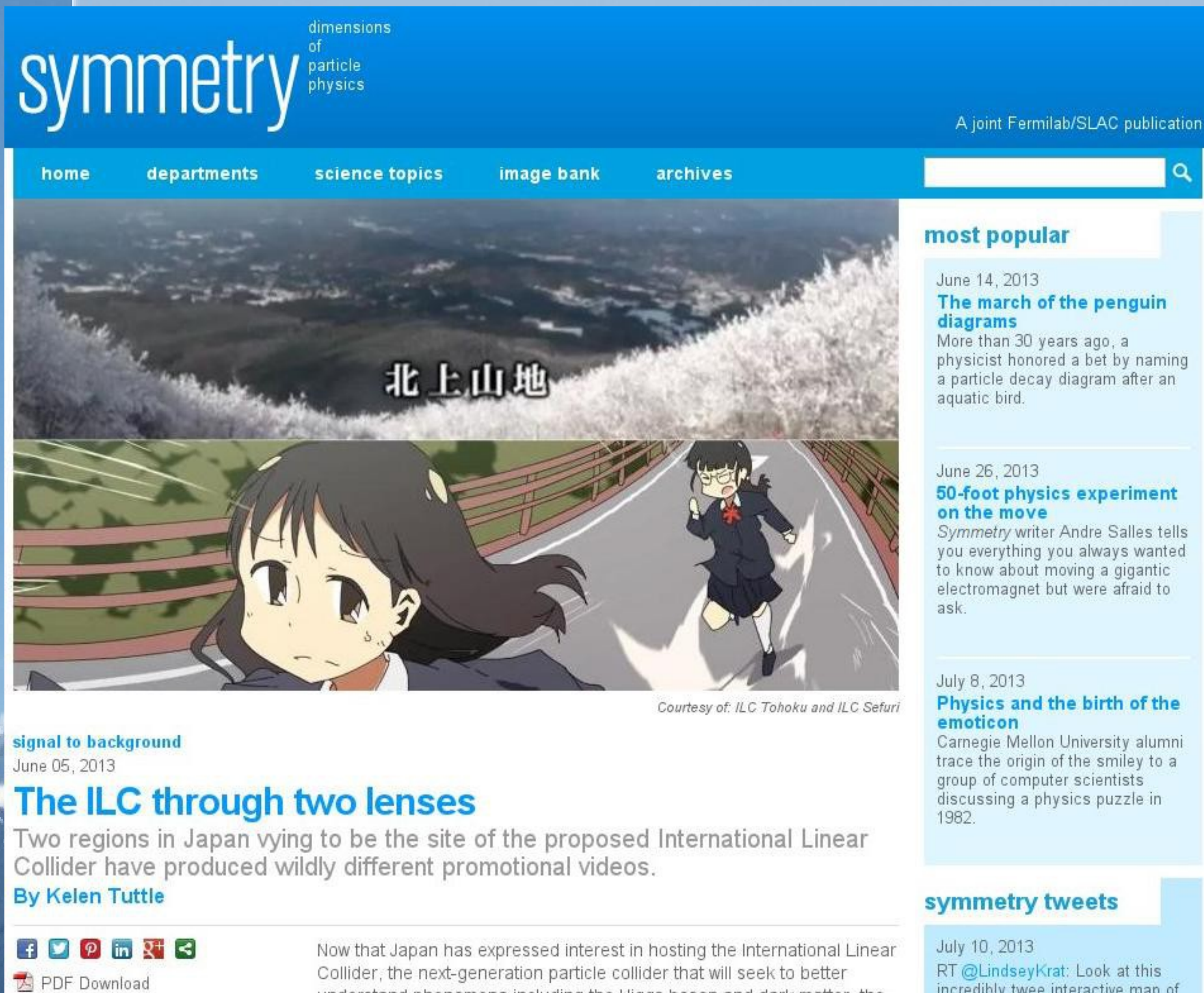
Negotiation between Governments, Pre-ILC lab.

Recognition of Scientific Value by Academic Authority

R&D
Technical Design Report

Form ILC
(World Unified Project)

Japanese Candidate Site



symmetry dimensions of particle physics

A joint Fermilab/SLAC publication

home departments science topics image bank archives

Courtesy of: ILC Tohoku and ILC Sefuri

signal to background

June 05, 2013

The ILC through two lenses

Two regions in Japan vying to be the site of the proposed International Linear Collider have produced wildly different promotional videos.

By Kelen Tuttle

PDF Download

Now that Japan has expressed interest in hosting the International Linear Collider, the next-generation particle collider that will seek to better understand phenomena including the Higgs boson and dark matter, the

most popular

June 14, 2013
The march of the penguin diagrams
More than 30 years ago, a physicist honored a bet by naming a particle decay diagram after an aquatic bird.

June 26, 2013
50-foot physics experiment on the move
Symmetry writer Andre Salles tells you everything you always wanted to know about moving a gigantic electromagnet but were afraid to ask.

July 8, 2013
Physics and the birth of the emoticon
Carnegie Mellon University alumni trace the origin of the smiley to a group of computer scientists discussing a physics puzzle in 1982.

symmetry tweets

July 10, 2013
RT @LindseyKrat: Look at this incredibly twee interactive map of

Kitakami site

Sefuri site

Message from the world

European Strategy for Particle Physics

There is a strong scientific case for **an electron-positron collider, complementary to the LHC**, that can study the properties of the Higgs boson and other particles with unprecedented precision and whose energy can be upgraded …... **The initiative of the Japanese particle physics community to host the ILC in Japan is most welcome, and European groups are eager to participate.** Europe looks forward to a proposal from Japan to discuss a possible participation”.

A lepton collider: a decisive asset…

..if

- can be decided/built soon
- It might start at 250 Gev, but it should be upgradable to 500 GeV, with a possible extension to 1 TeV c.m.

Best candidate: ILC

- Mature design
- TDR delivered
- Japanese community has submitted to the government a request to host it.

Japan should put something on the table and then CERN will come.

Message from the world

HEPAP Facilities sub-panel:

Measuring Higgs properties and searching for Beyond the Standard Model effects are of primary scientific significance. **The LHC … upgrades and the 500 GeV ILC in Japan can address these questions in complementary** fashions and are absolutely central to progress in high energy physics. …. **e+e-collider at $\sqrt{s}$=500 GeV in Japan is only lepton collider ready for construction in next decade**.... Should an agreement be reached the US particle physics community would be **eager to participate in both the accelerator and detector construction.**

Snowmass Energy Frontier WG
Chip Brock

bottom line

This Higgs Boson changes everything.

We're obligated to understand it using all tools.

Host Nation

- We need to think more broadly
  - CERN was founded on the ashes of war by a set of visionary physicists
    - And today, we are beneficiaries of their foresight

est. 1954

Science for peace!

Host Nation

- So perhaps today, at the dawn of the Asian century, the world needs Japan, China, Korea, India, Vietnam all collaborating on a peaceful endeavor

Summary

- Hadron collider and lepton collider are inseparable partner in the physics.
- Next e+ e- collider has to be Linear collider.
- Rich physics for the Linear collider.
- Accelerator design is ready for construction.
- ILC could be the first global project in Asia. We hope that Japan announces host ILC soon.