e^+e^- Linear Collider

<u>Disclaimer</u>

This talk was lifted from an earlier version of a lecture by N.Walker

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DESY Summer Student Lecture
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Disclaimer II

Talk is largely based on TESLA design which meanwhile evolved into the design of the

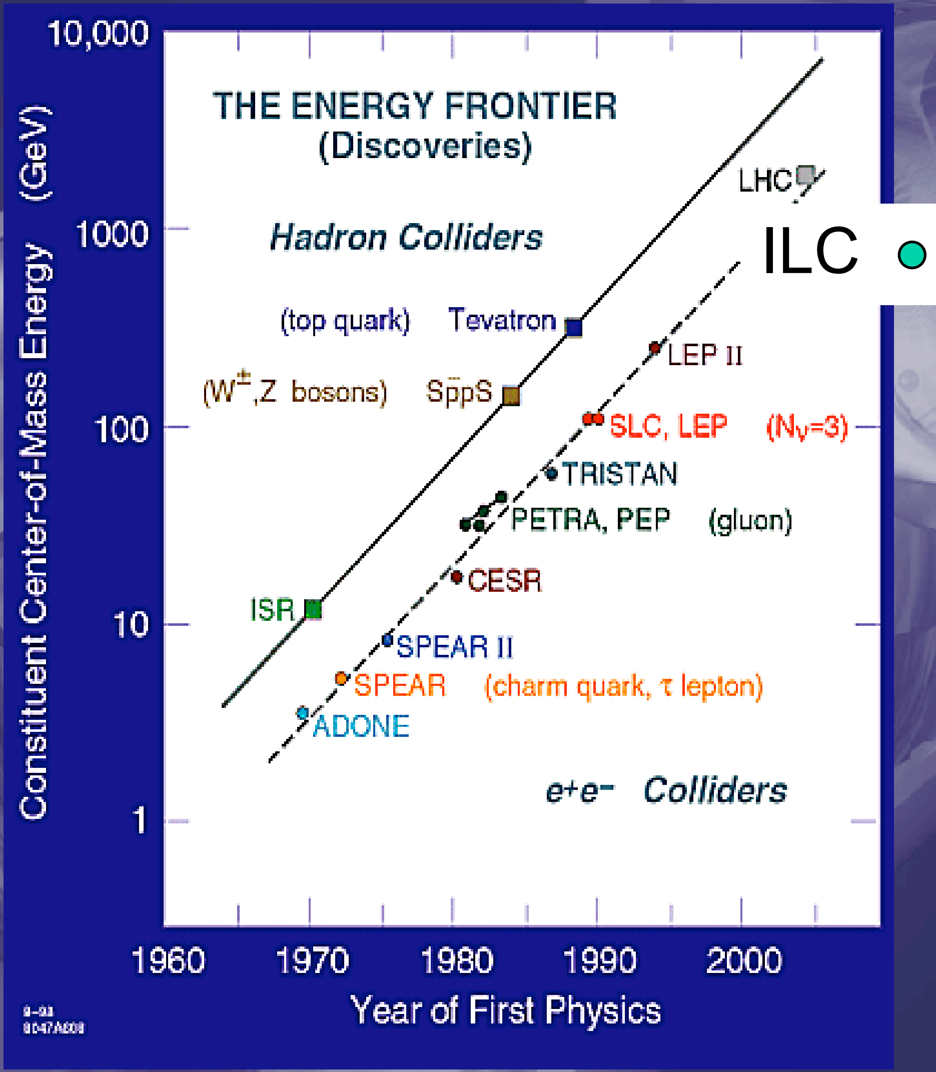
International Linear Collider (ILC)

some reference will be made to the specifics of the ILC (The TESLA numbers are only indicative of the foreseen ILC performance).

The TESLA Linear Collider

- Technical Design Report (TDR) published in March 2001
- 500 GeV LC based on SCRF technology
- Chosen as the basis for the International Linear Collider

Energy Frontier e^+e^- Colliders



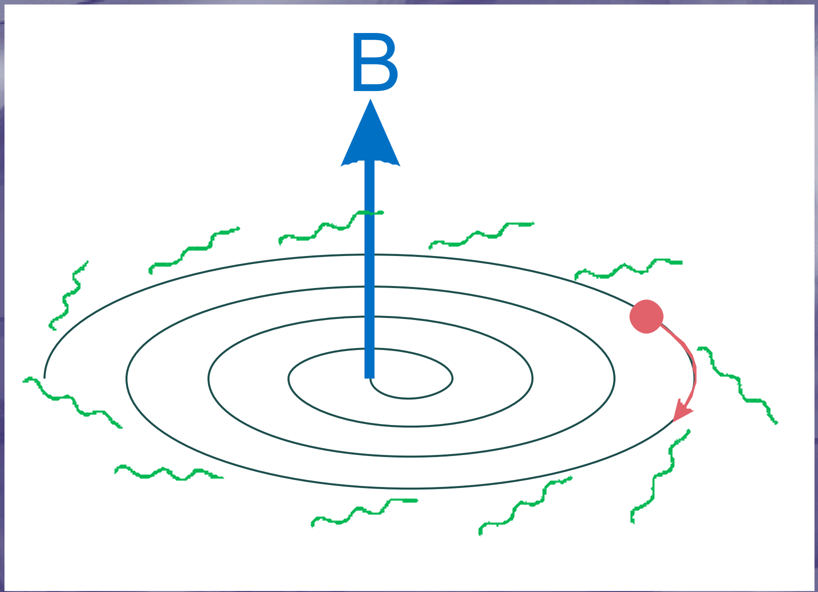
LEP at CERN, CH

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 $$$

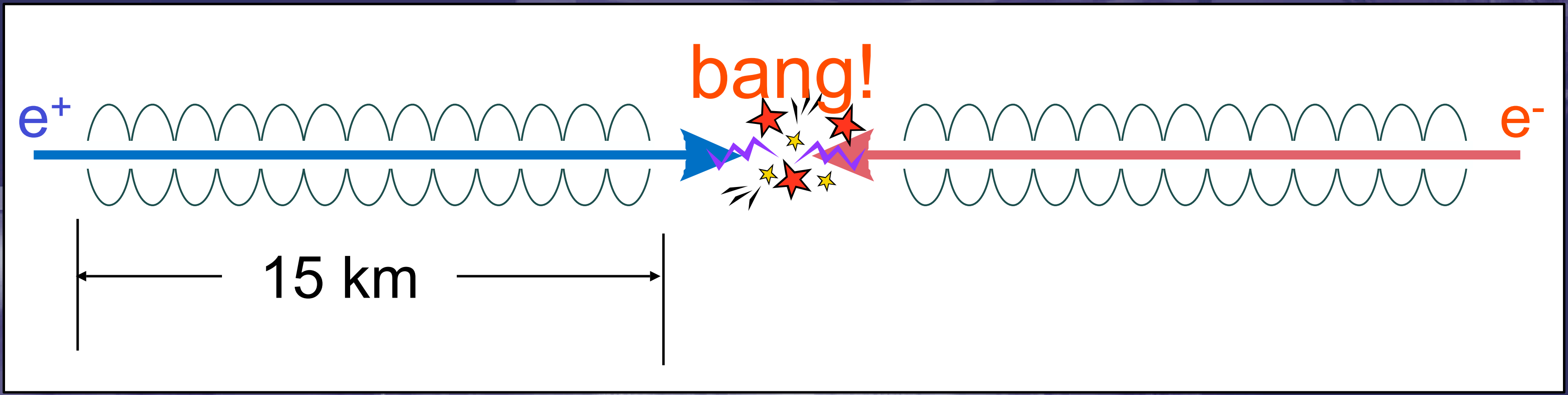
		LEP-II	Super-LEP	Hyper-LEP
E_{cm}	GeV	180	500	2000
L	km	27	200	
Δ_E	GeV	1.5	12	
$\$_{tot}$	10^9 SF	2	15	

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!



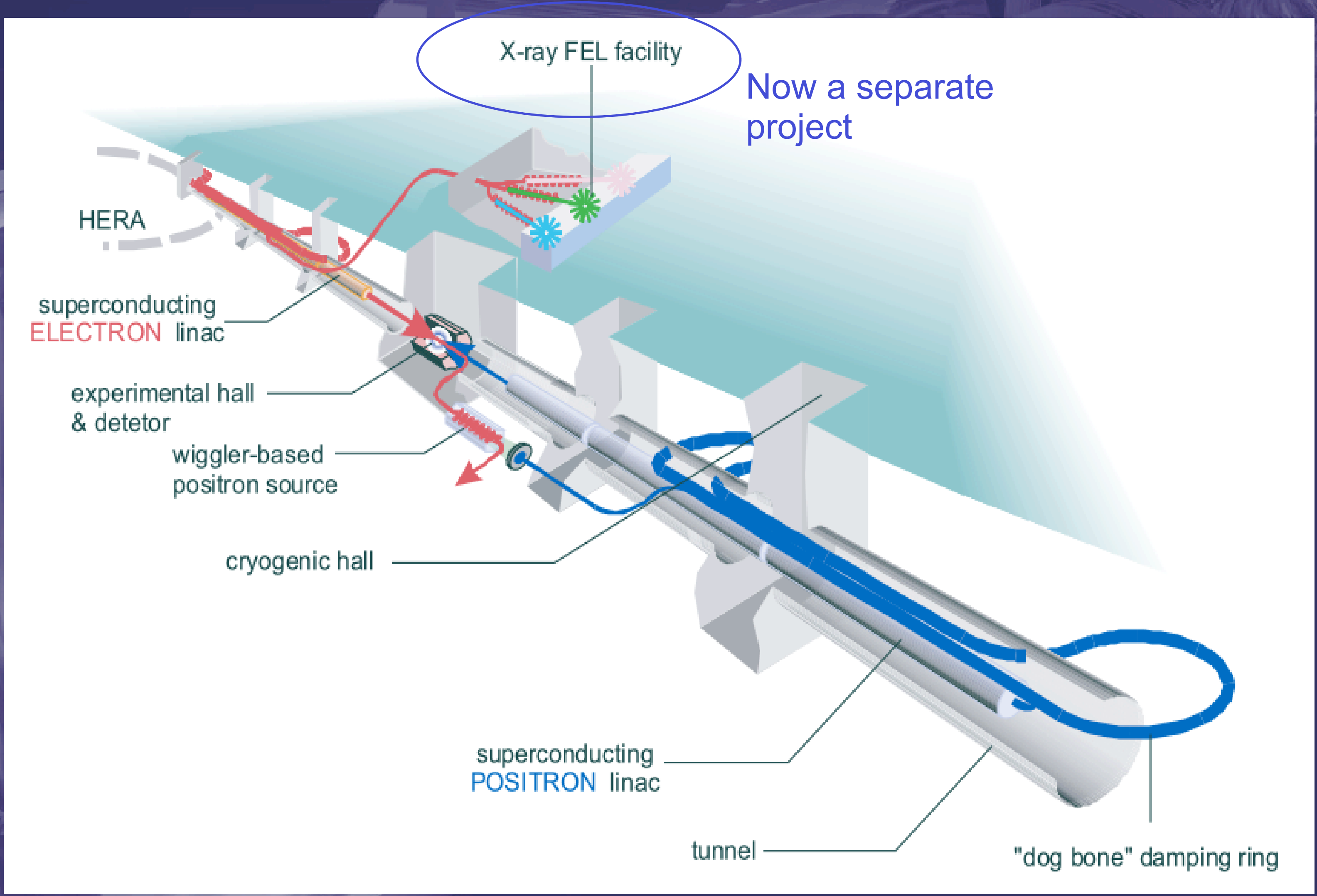
For a E_{cm} = 1 TeV machine:

Effective gradient G = 500 GV / 15 km

= 34 MV/m

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

The TESLA linear collider



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 (1988-2006)

- SLC (SLAC, 1988-98)
- NLCTA (SLAC, 1991-)
- TTF (DESY, 1994-2006)
- ATF (KEK, 1991-)
- FFTB (SLAC, 1992-1995)
- SBTF (DESY, 1994-1998)
- CLIC CTF1,2,3 (CERN, 1994-)
- FLASH (DESY, 2006-)

Over 18 Years of Linear Collider R&D

The *Luminosity* Issue

No. bunches in bunch train

particles per bunch

repetition rate

Beam-beam enhancement factor (pinch effect)

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

beam cross-section at Interaction Point (IP)

LEP f_{rep} = 40 kHz

LC f_{rep} = 5–200 Hz!

LEP: 130×6 μm²

LC: 550×5 nm²

The *Luminosity* Issue

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

Requirements for Next Generation LC:

$L \geq 10^{34}$ cm^{-2} s^{-1}

$E_{cm} = 0.5$ - 1 TeV

The *Luminosity* Issue

$$L = \frac{1}{4\pi E_{cm}} \overbrace{(E_{cm} f_{\mathrm{rep}} n_b N)}^{P_{beam}} \frac{N}{\sigma_x^*} \frac{1}{\sigma_y^*} \times H_D$$

Requirements for Next Generation LC:

$L \geq 10^{34}\ \mathrm{cm^{-2}\ s^{-1}}$

$E_{\mathrm{cm}} = 0.5$ - 1 TeV

The *Luminosity* Issue

Efficiency

$$L = \frac{1}{4\pi} \frac{\eta P_{RF}}{E_{cm}} \frac{N}{\sigma_x^*} \frac{1}{\sigma_y^*} \times H_D$$

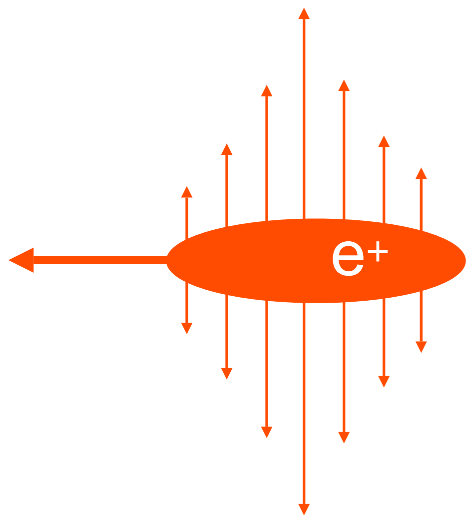
Beamstrahlung (energy loss δE/E)

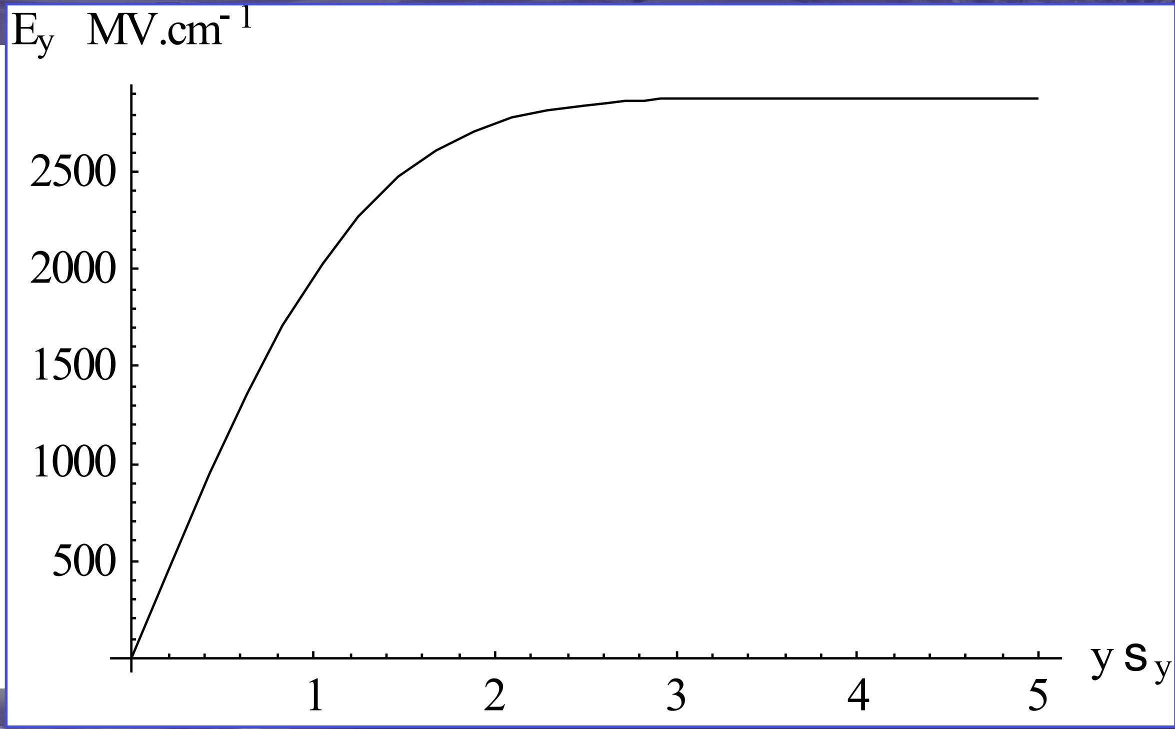
Requirements for Next Generation LC:

$L \geq 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

$E_{\mathrm{cm}} = 0.5 - 1\ \mathrm{TeV}$

Beamstrahlung

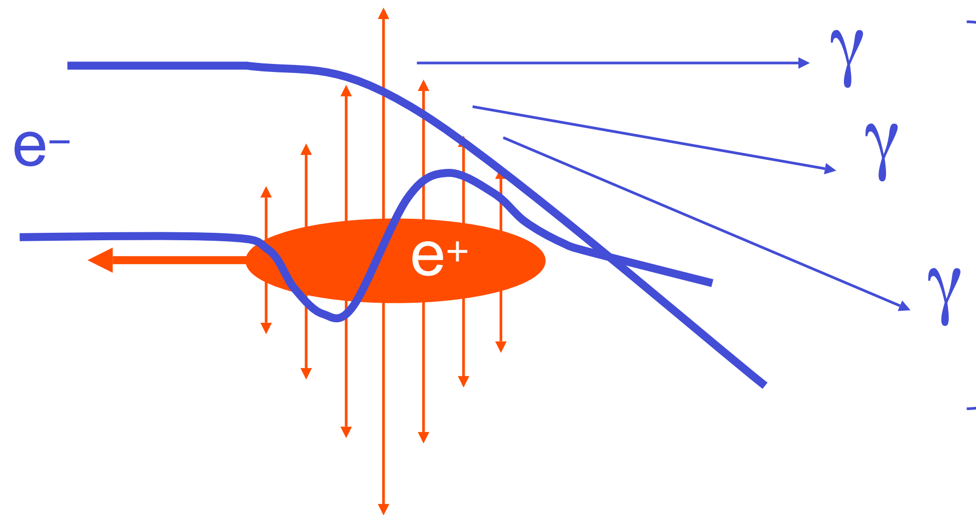




RMS Energy Loss for a flat beam

$(\sigma_x » \sigma_y)$

Beamstrahlung



hard γs radiated by intense electric field of approaching beam = Beamstrahlung

RMS Energy Loss for a flat beam ($\sigma_x \gg \sigma_y$)

$$\delta_{BS} \propto \frac{E_{cm}}{\sigma_z}\left(\frac{N}{\sigma_x}\right)^2$$

Luminosity re-visited

IP focusing & Emittance

$\sigma_y^* = \sqrt{\beta_y^* \varepsilon_y}$

$$L \propto \frac{\eta P_{RF}}{E_{cm}^{3/2}} \left(\frac{\delta_{BS}}{\sigma_z}\right)^{1/2} \frac{1}{\sigma_y^*} \times H_D$$

Requirements for Next Generation LC:

$L \geq 10^{34}$ cm^{-2} s^{-1}

$E_{cm} = 0.5$ - 1 TeV

Emittance and Strong Focusing

$$\sigma_y^* = \sqrt{\frac{\varepsilon_y \beta_y^*}{\gamma}}$$

$$\sigma_y^* \propto \sqrt{\frac{\varepsilon_y \beta_y^*}{E_{cm}}}$$

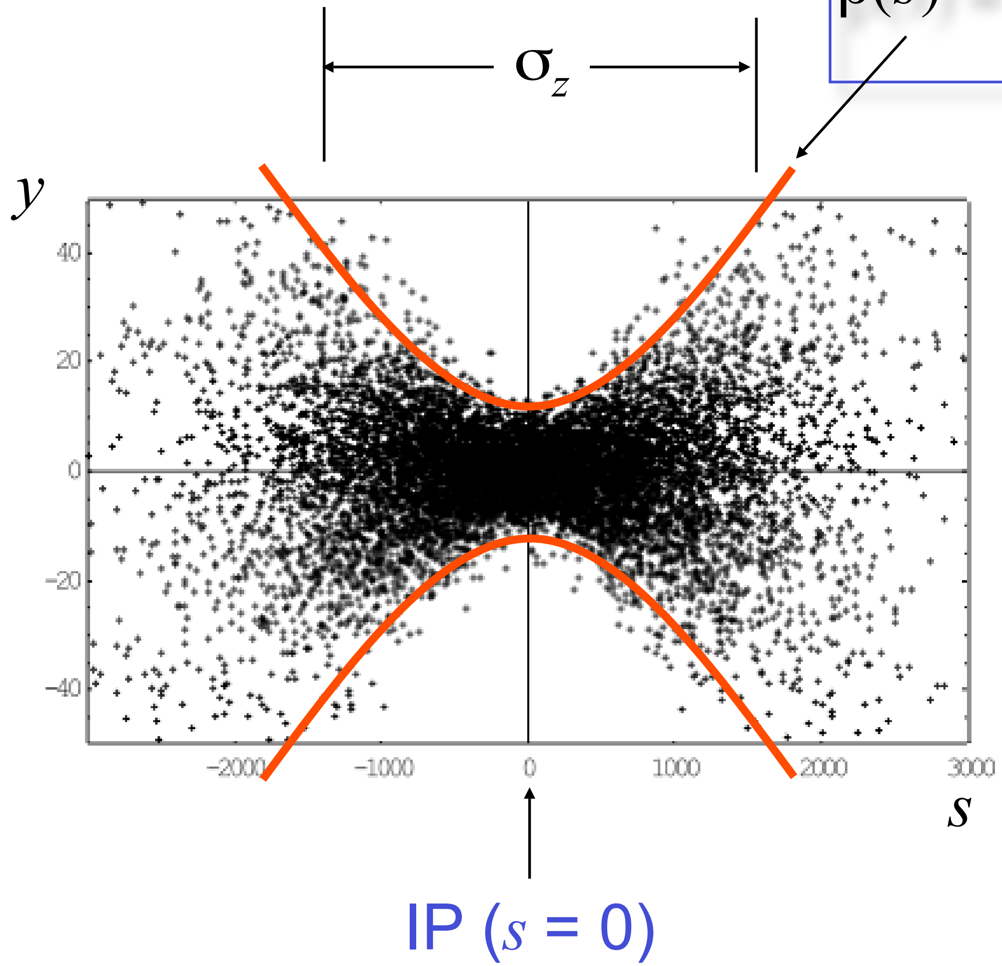
σ_y^* = 5 nm

ε_y = 3×10^{-8}m

β_y^* = 0.4 mm

Limit on β^*

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}, \qquad \beta^* = \beta(s=0)$$



β^* = "depth of focus"

reasonable lower limit for β^* is bunch length σ_z

Thus set $\beta^* = \sigma_z$

Final Luminosity Scaling Law

$$L \propto \frac{\eta P_{RF}}{E_{cm}} \left(\frac{\delta_{BS}}{\epsilon_y}\right)^{1/2}$$

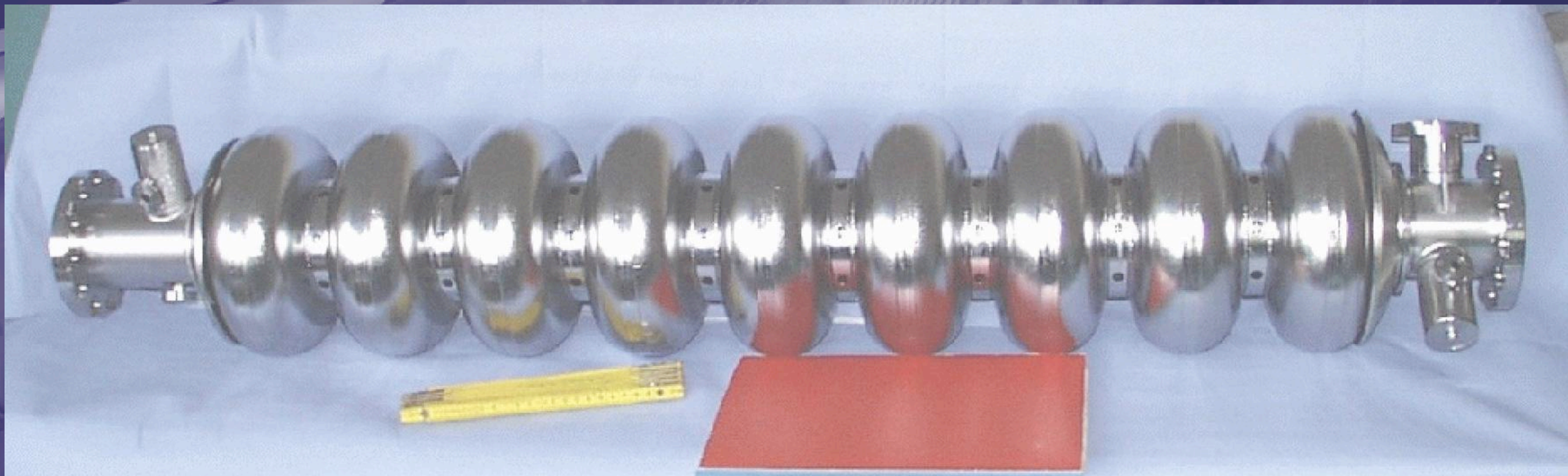
$$L \propto \frac{\eta P_{RF}}{E_{cm}} \left(\frac{\delta_{BS}}{\epsilon_y}\right)^{1/2}$$

- High Beam Power
- Small IP vertical beam size

Superconducting RF Technology

- High current (n_b N)
- High efficiency ($P_{RF} \rightarrow P_{beam}$)
- Small emittance ε_y
- Strong focusing (small β^*_y)

TESLA superconducting 9-cell Niobium cavity



operated at 2°K

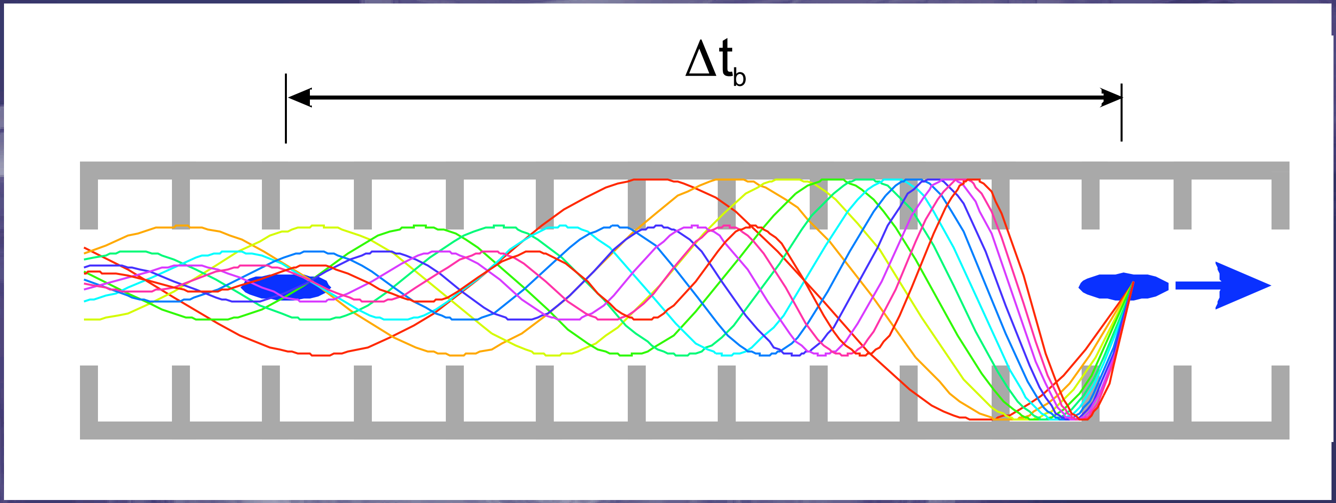
The Superconducting Advantage

- Low RF losses in resonator walls
  ($Q_0 \approx 10^{10}$ compared to Cu $\approx 10^4$)
  - high efficiency $\eta_{AC \rightarrow beam}$
  - long beam pulses (many bunches) → low RF peak power
  - large bunch spacing allowing feedback correction within bunch train.

The Superconducting Advantage

- Low-frequency accelerating structures 1.3 GHz (for Cu 6-30 GHz)
  - very small *wakefields*
  - relaxed alignment tolerances
  - high beam stability

Wakefields

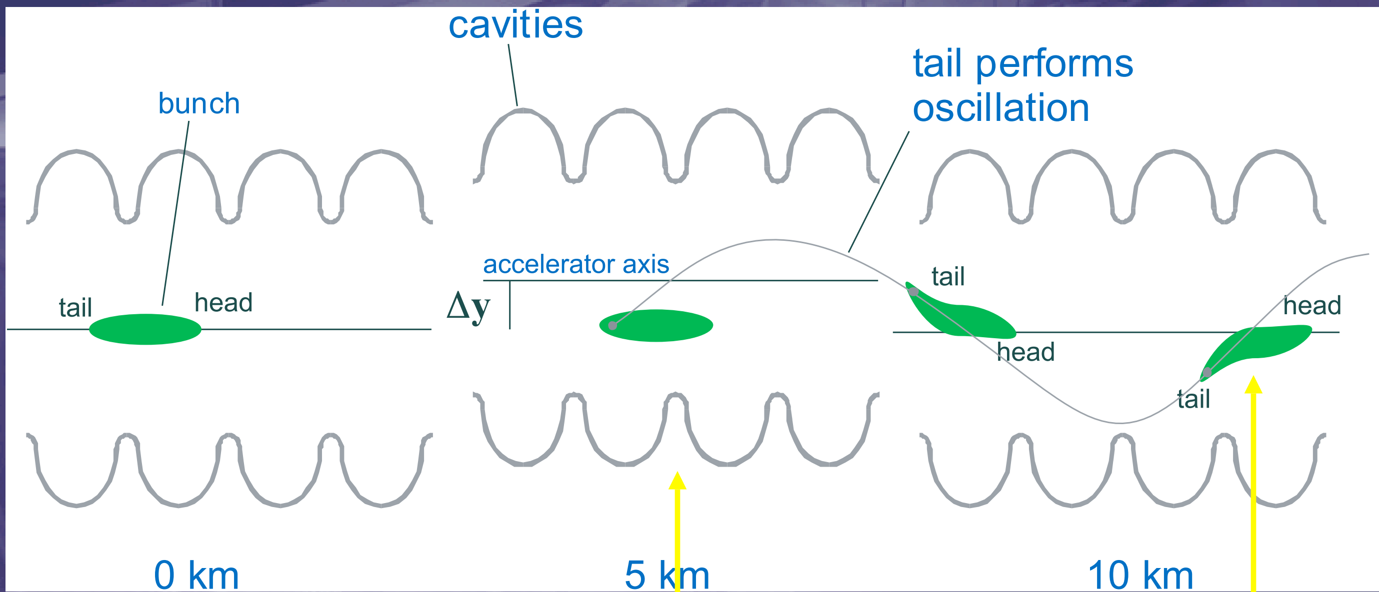


Just Ohm's Law: $V(\omega,t) = I(\omega,t)Z(\omega,t)$

The TESLA concept:

"Put a large current through a low impedance"

Wakefields (alignment tolerances)

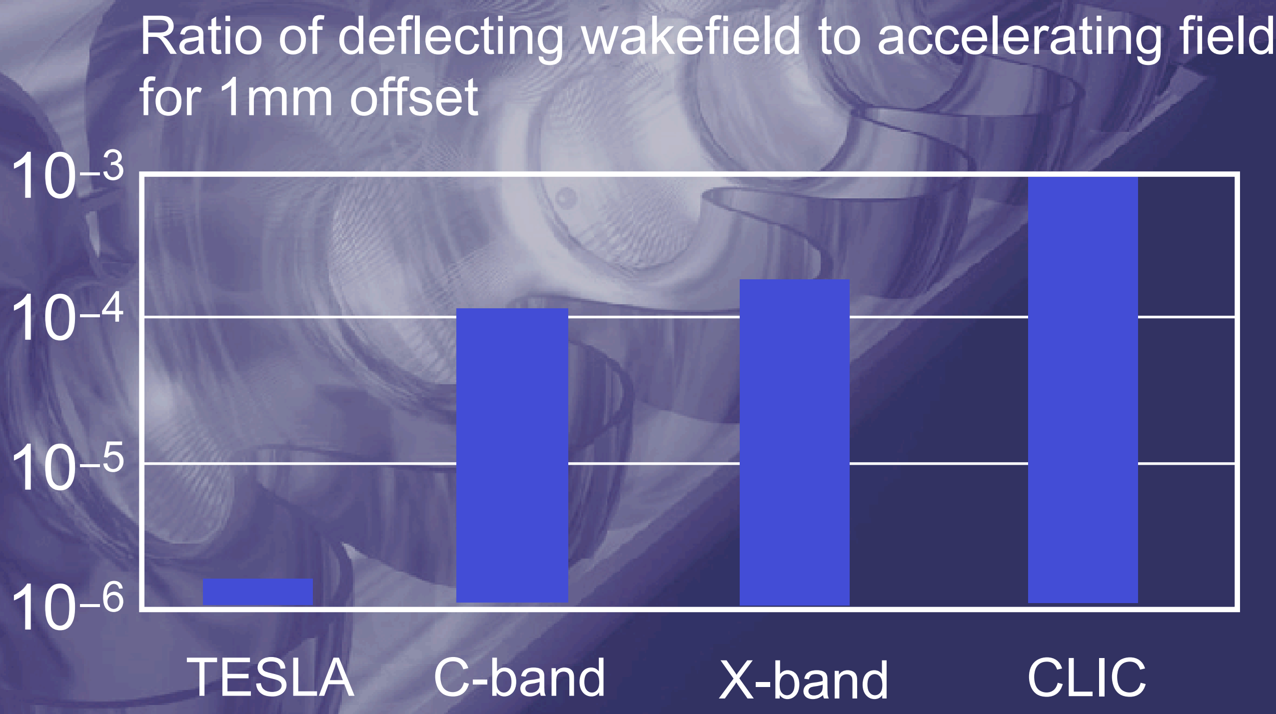


Misplaced cavity

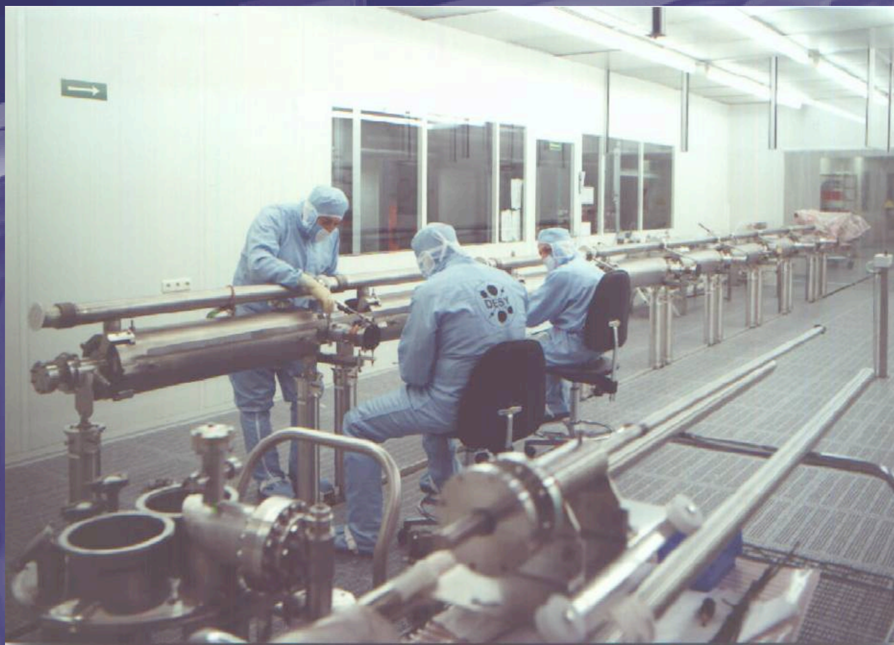
"Banana"

Wakefields (alignment tolerances)

Transverse Wakefield Kick $\propto f^3$



The TESLA Test Facility (TTF)



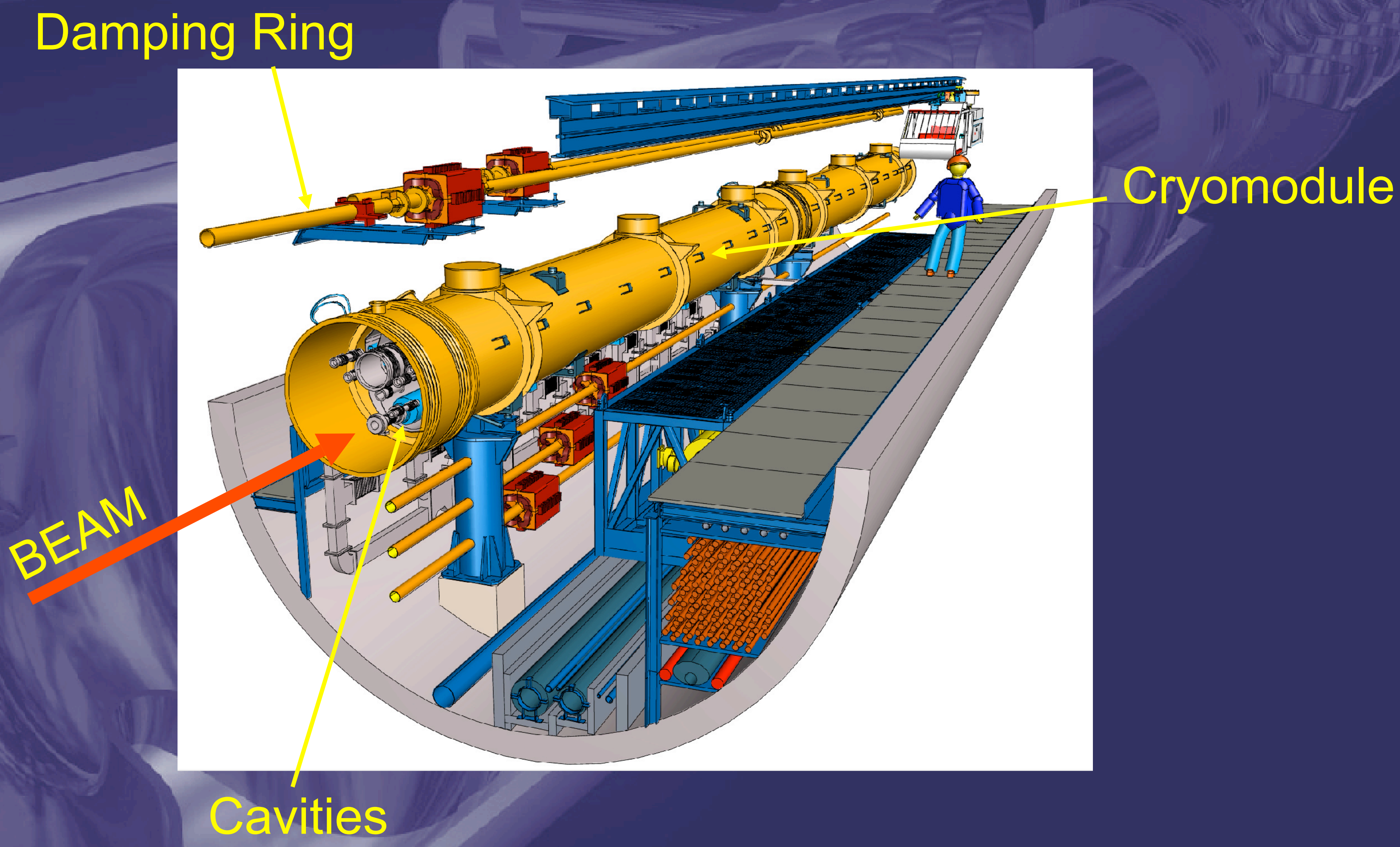
Cavity strings are prepared and assembled in ultra-clean room environment at TTF

The TESLA Test Facility (TTF)

TTF Test Linac constructed from completed Cryomodules

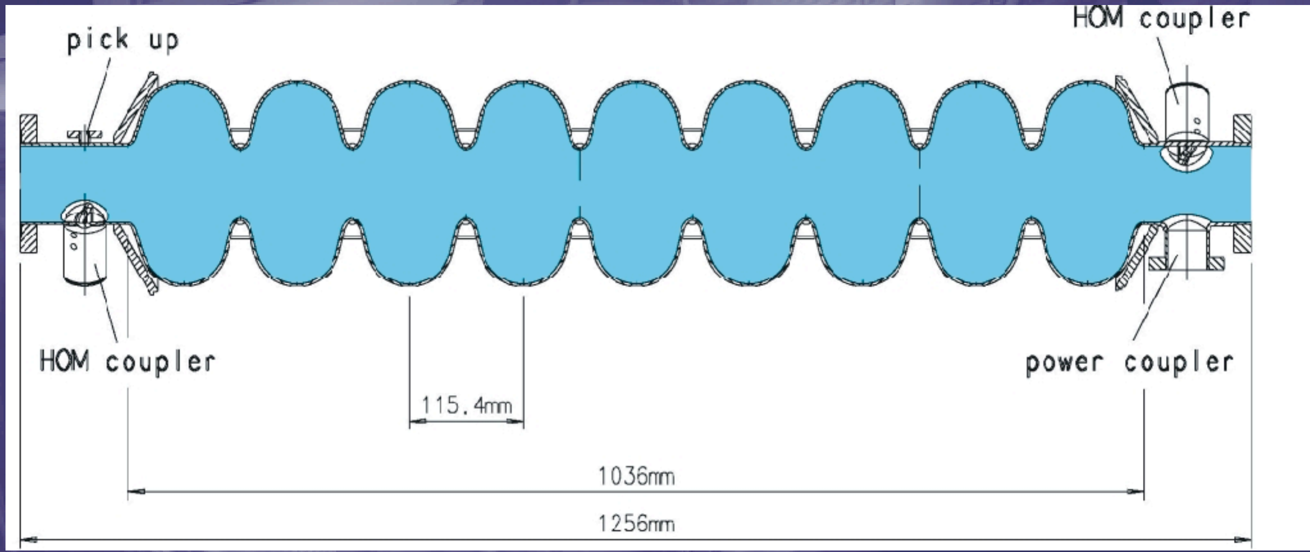
now user facility: FLASH

The TESLA Linac



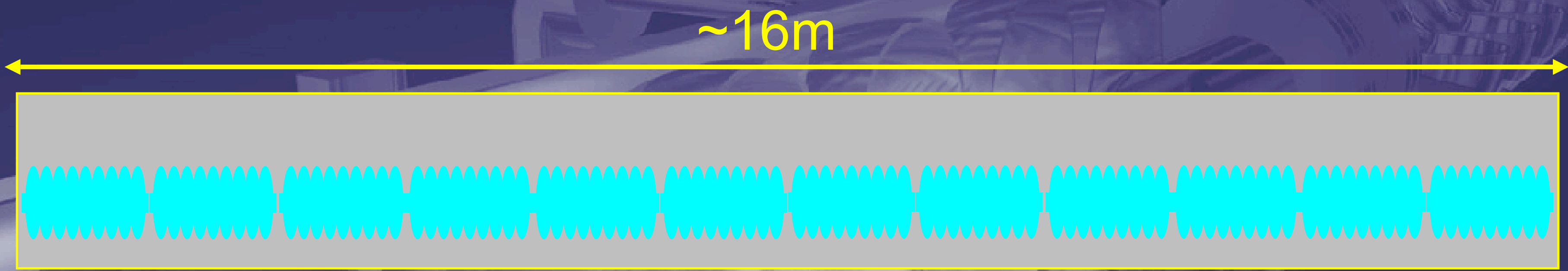
The TESLA Linac

~1m



1 9-cell 1.3GHz Niobium Cavity

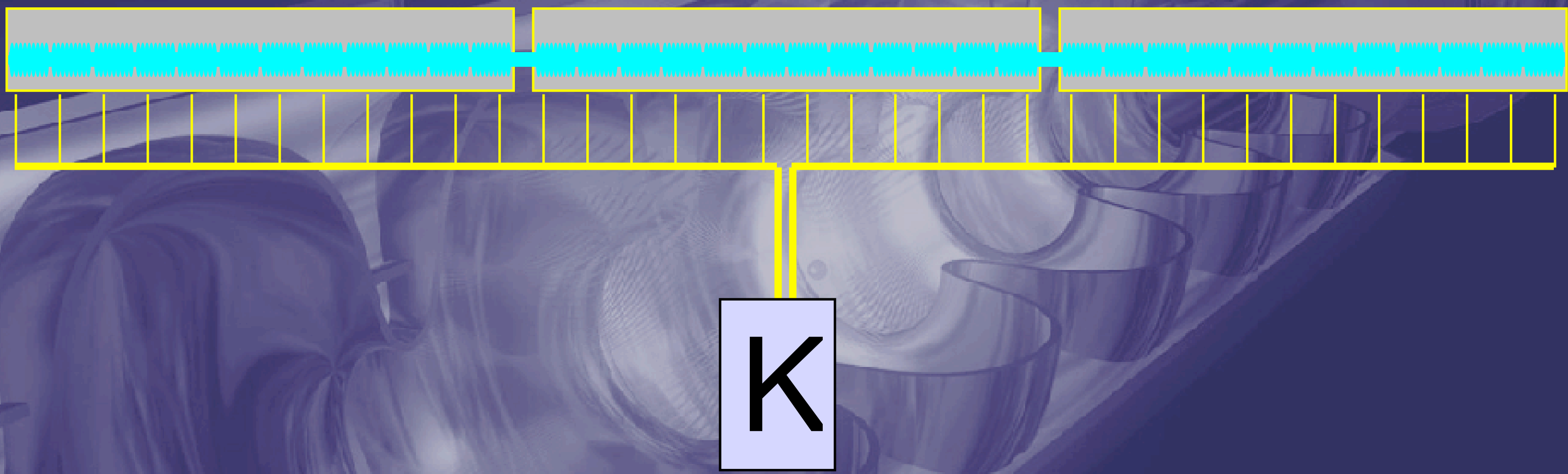
The TESLA Linac



12 9-cell 1.3GHz Niobium Cavity

1 Cryomodule

The TESLA Linac

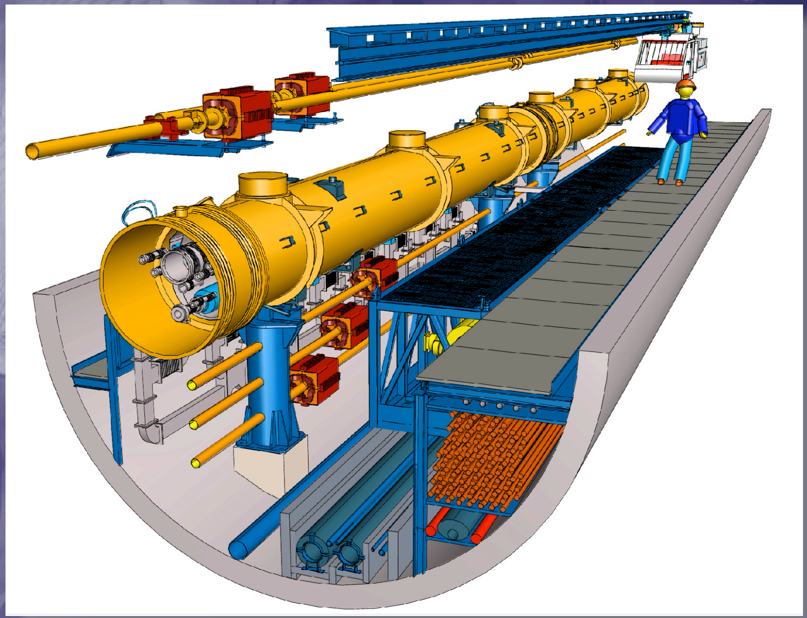


36 9-cell 1.3GHz Niobium Cavity
3 Cryomodule
1 10MW Multi-Beam Klystron

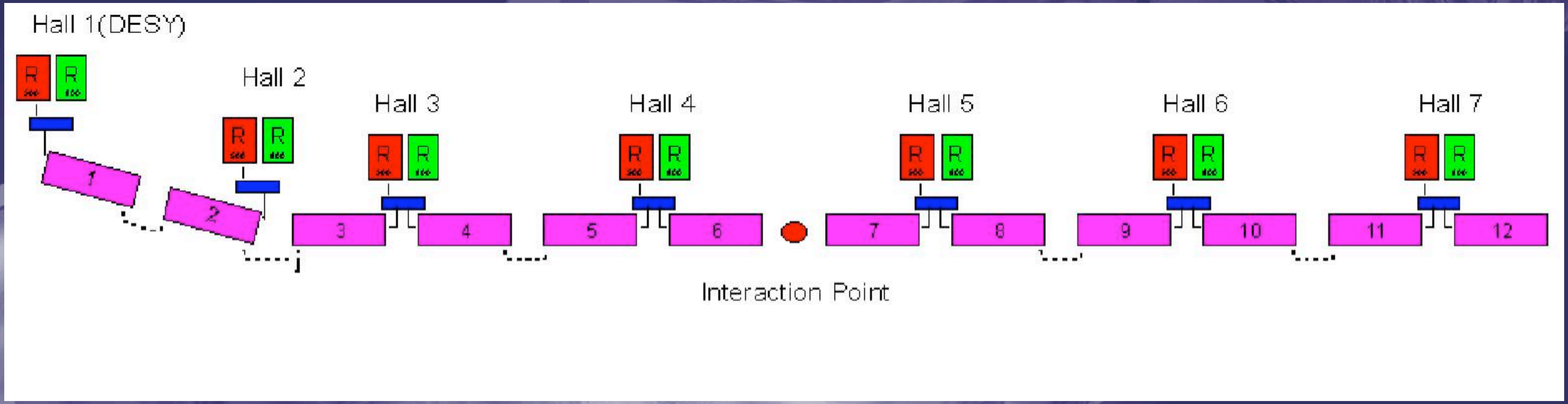
The TESLA Linac

Per Linac (E_{cm} = 500 GeV):

- 10,296 Cavities
- 858 Cryomodules
- 286 Klystrons
- Gradient: 23.4 MV/m
  (inc. 2% overhead)
- LENGTH 14.4km
  (fill factor: 74%)

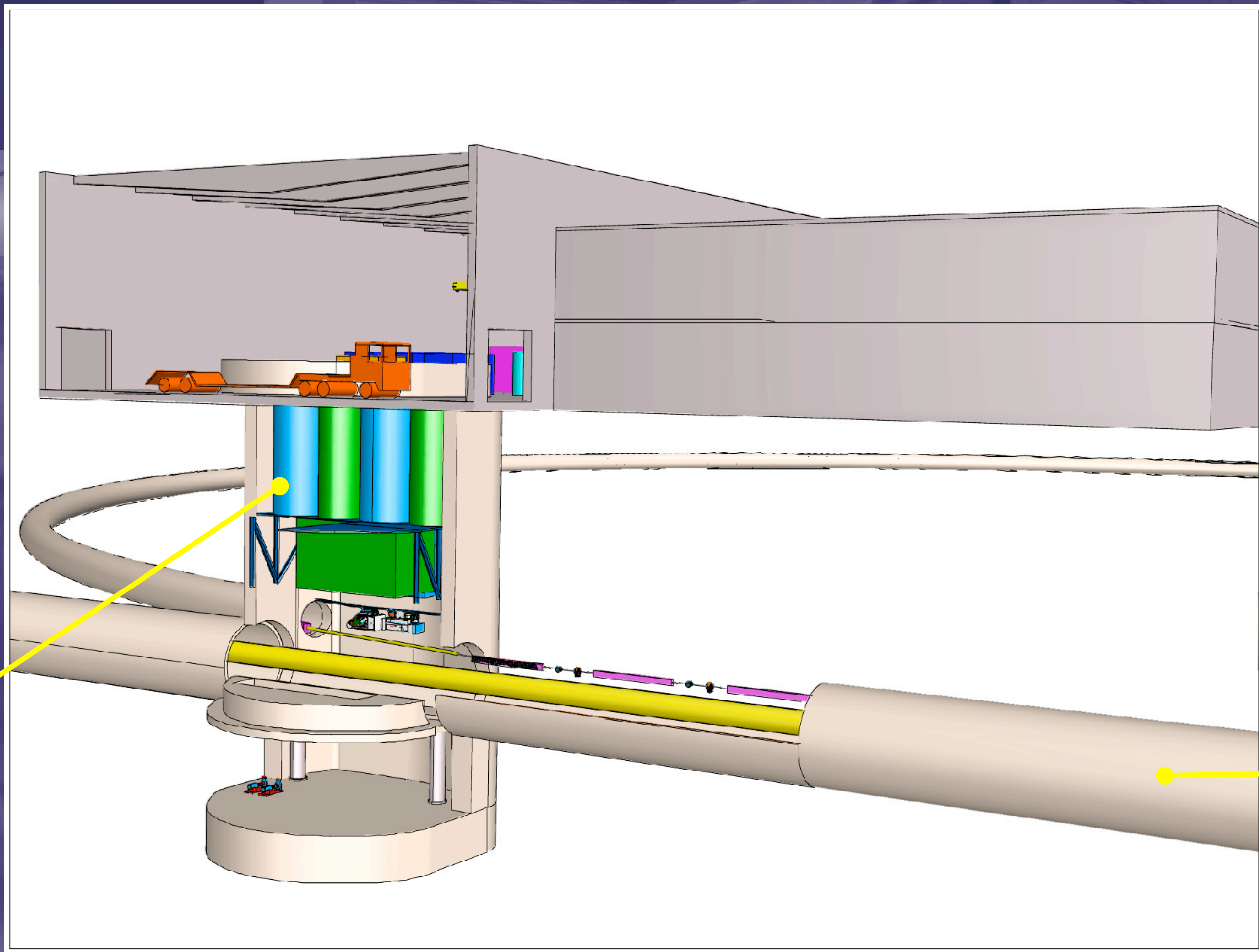


Cryoplants



- Each linac divided into 6 *Cryo-units* (~140 cryomodules)
- 7 refrigeration (liquid He) plants housed in 7 surface halls (~5km)

Cryohalls



Refrigerators

LINAC tunnel

10MW Multibeam Klystron

Design power and pulse length (1.5ms) at 65% efficiency reached at TTF

The Thomson TH1801 multibeam klystron

10MW Multibeam Klystron

Design power and pulse length (1.5ms) at 65% efficiency reached at TTF

The Thomson TH1801 cathode

The LINAC is only one part of a linear collider!

The SC linac can:

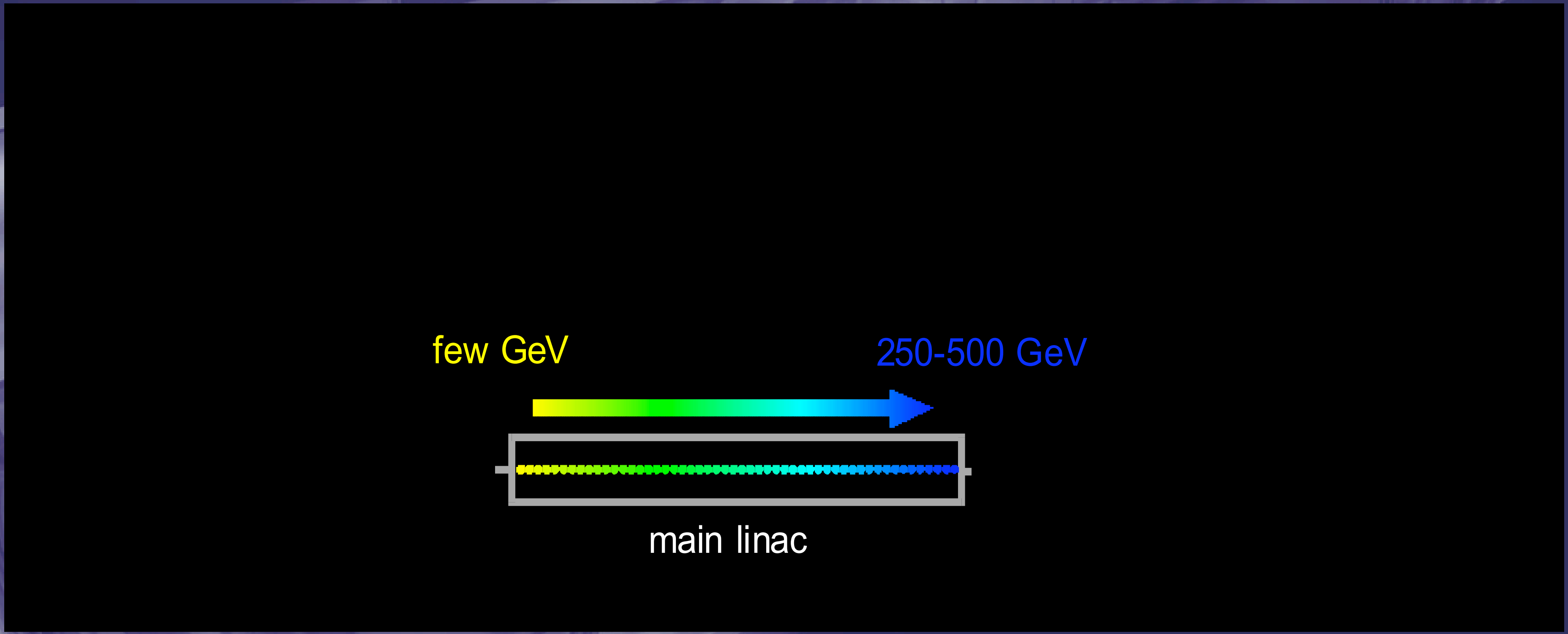
- Efficiently accelerate a high charge to high energies
  (high RF→beam power transfer efficiency)
- Preserve the required small bunch volumes (small emittance) because of low <u>wakefields</u>
- Has relatively relaxed tolerances

The LINAC is only one part of a linear collider!

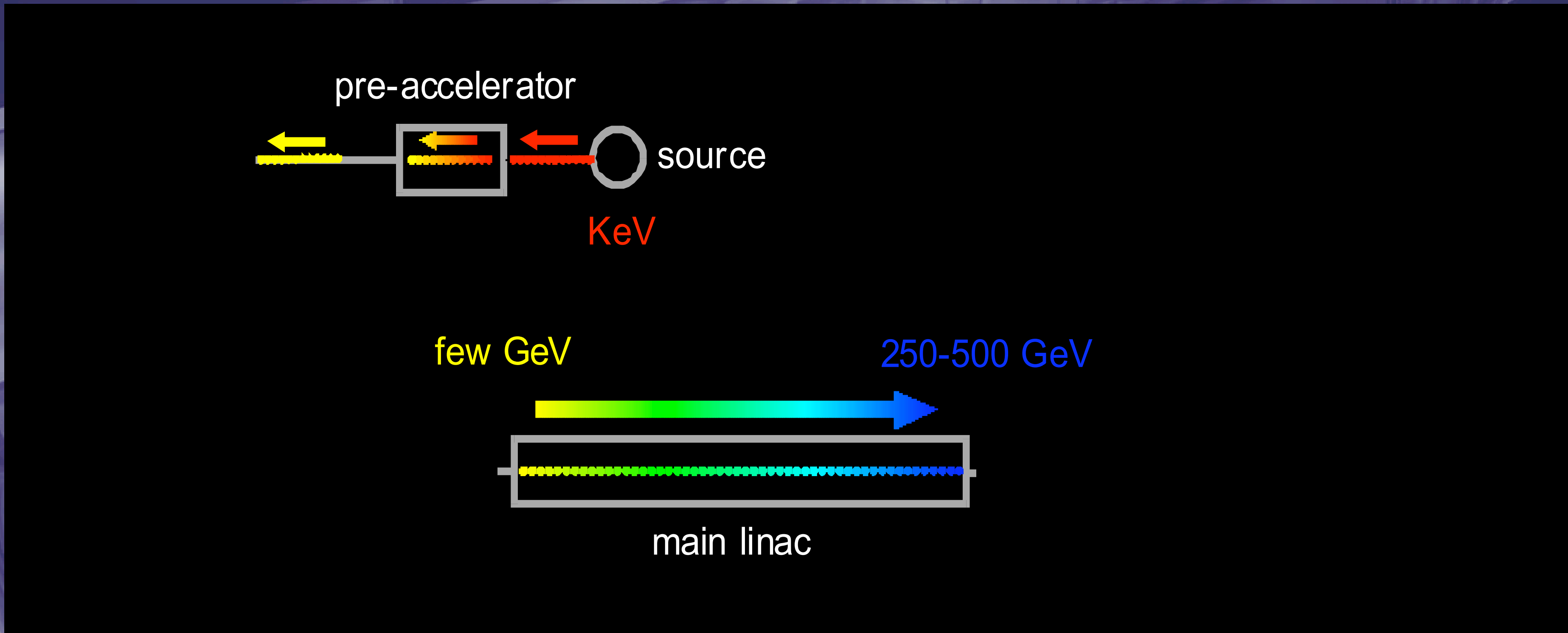
BUT how do we:

- Produce the electron charge?
- Produce the positron charge?
- Make small emittance beams?
- Focus the beam down to 5nm at the IP?

The LINAC is only one part of a linear collider!



The LINAC is only one part of a linear collider!



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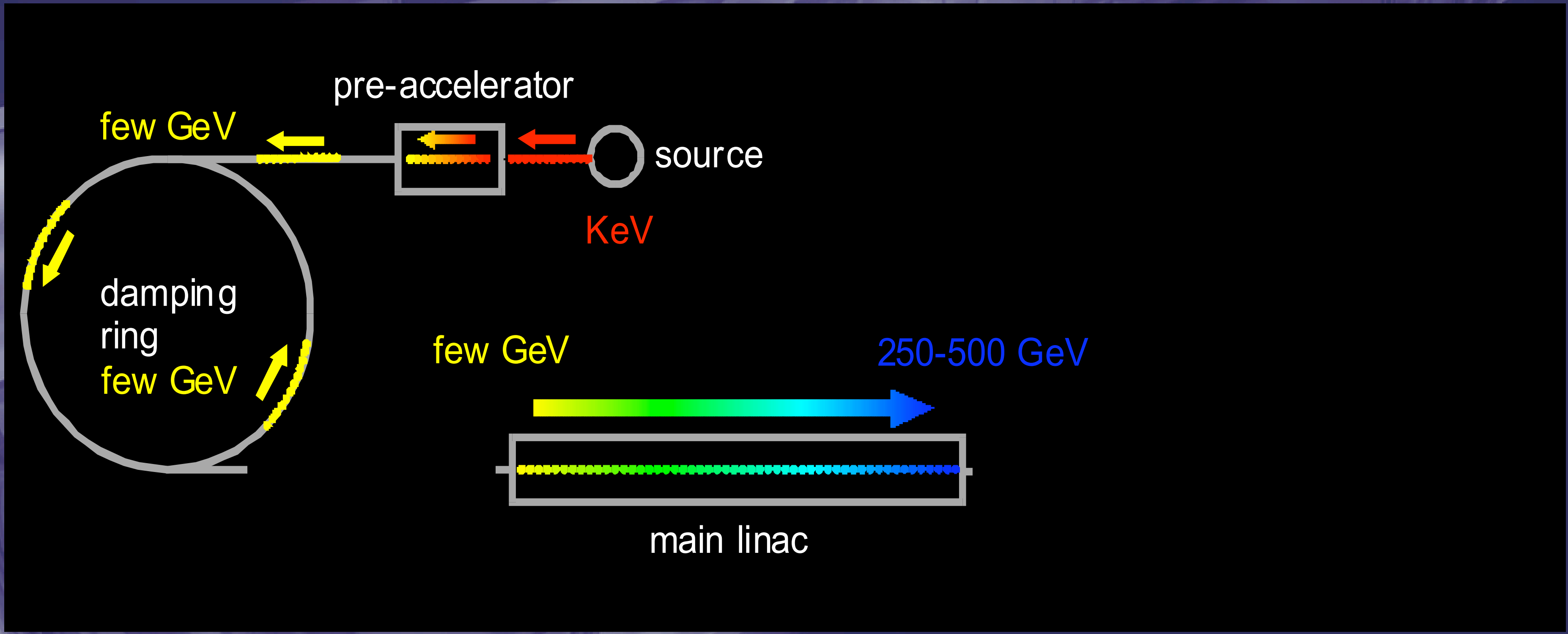

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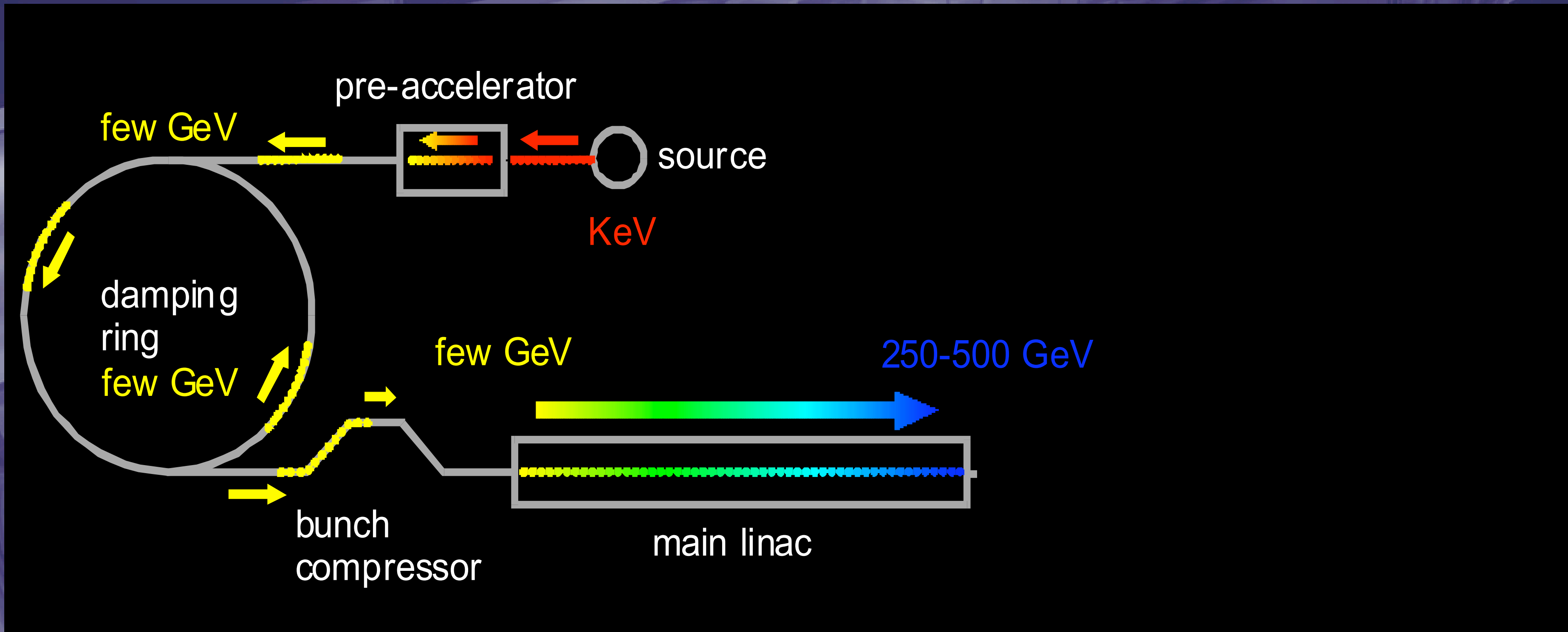
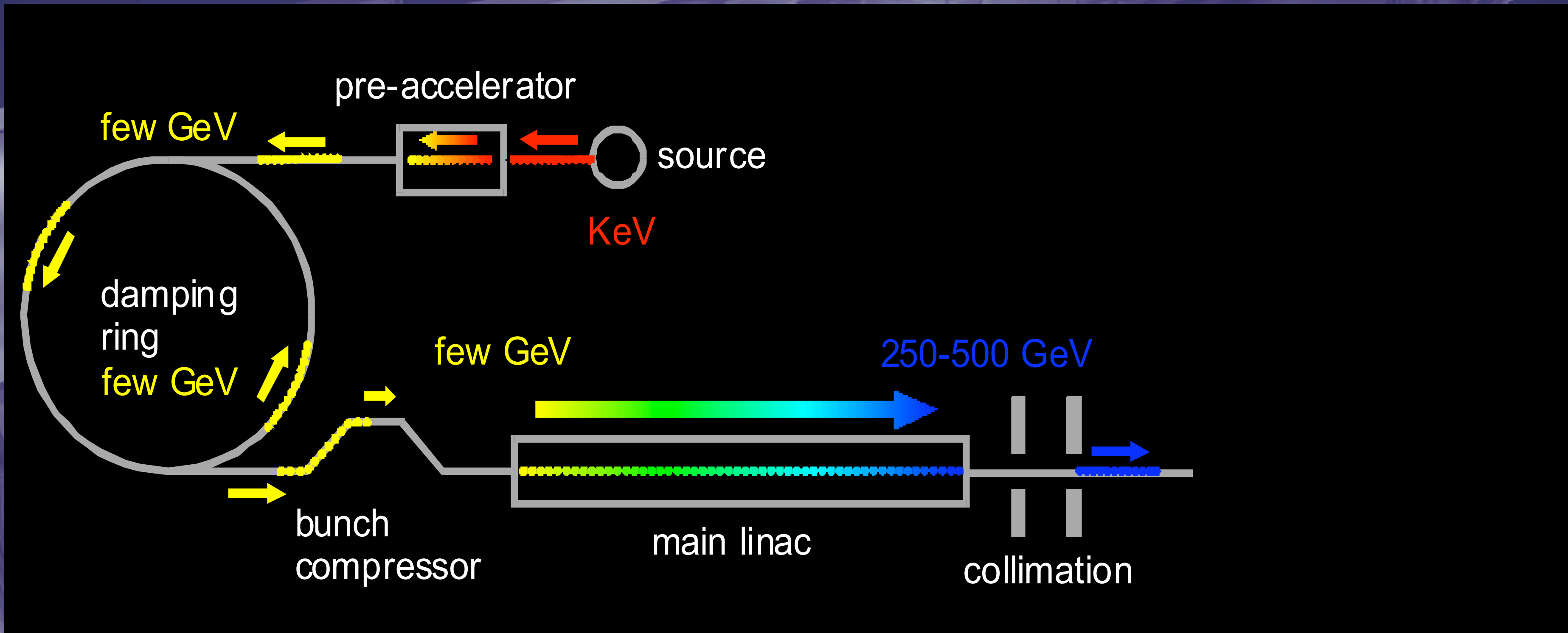


The LINAC is only one part of a linear collider!



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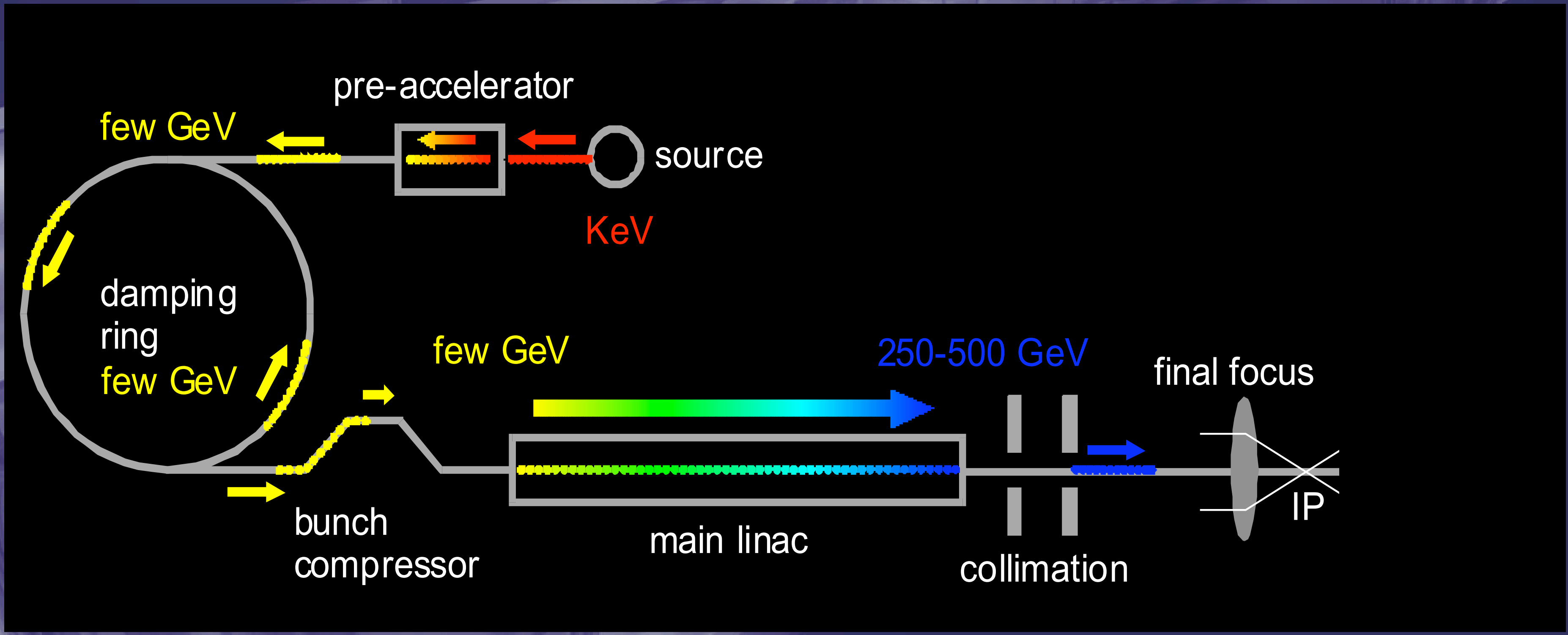
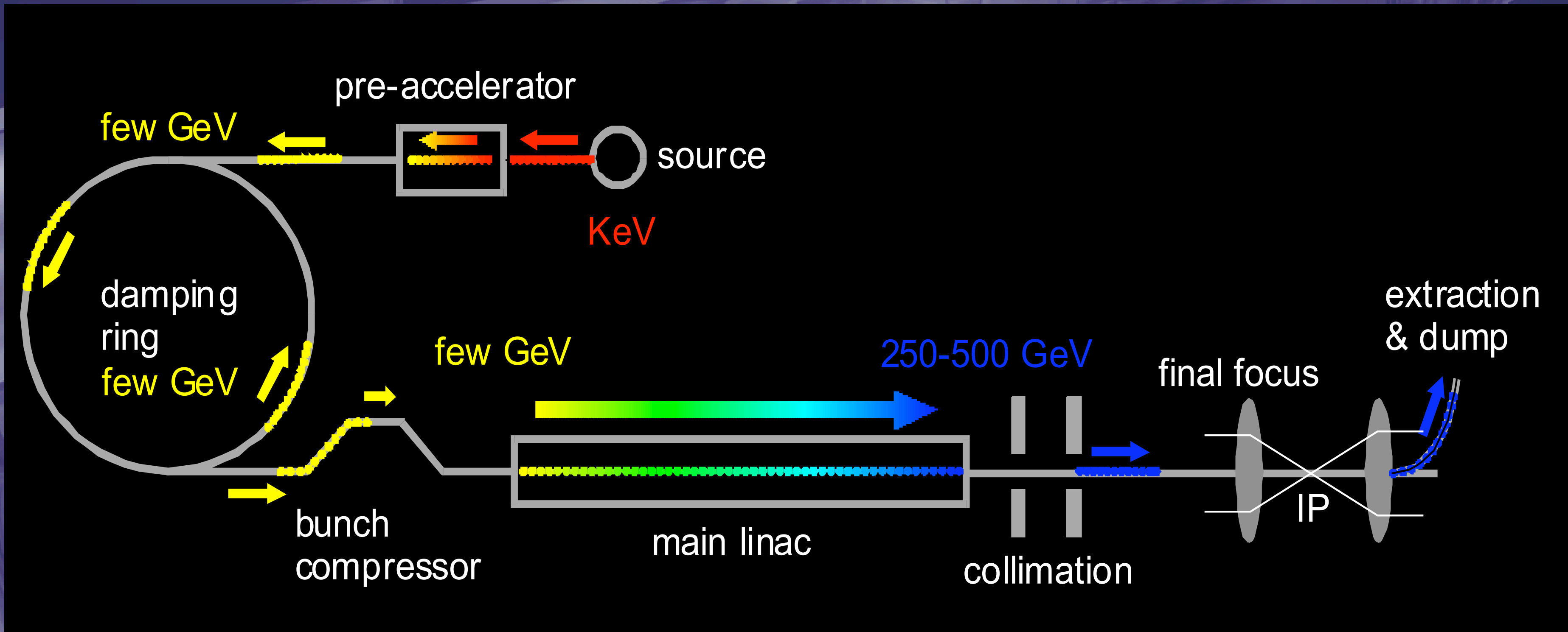
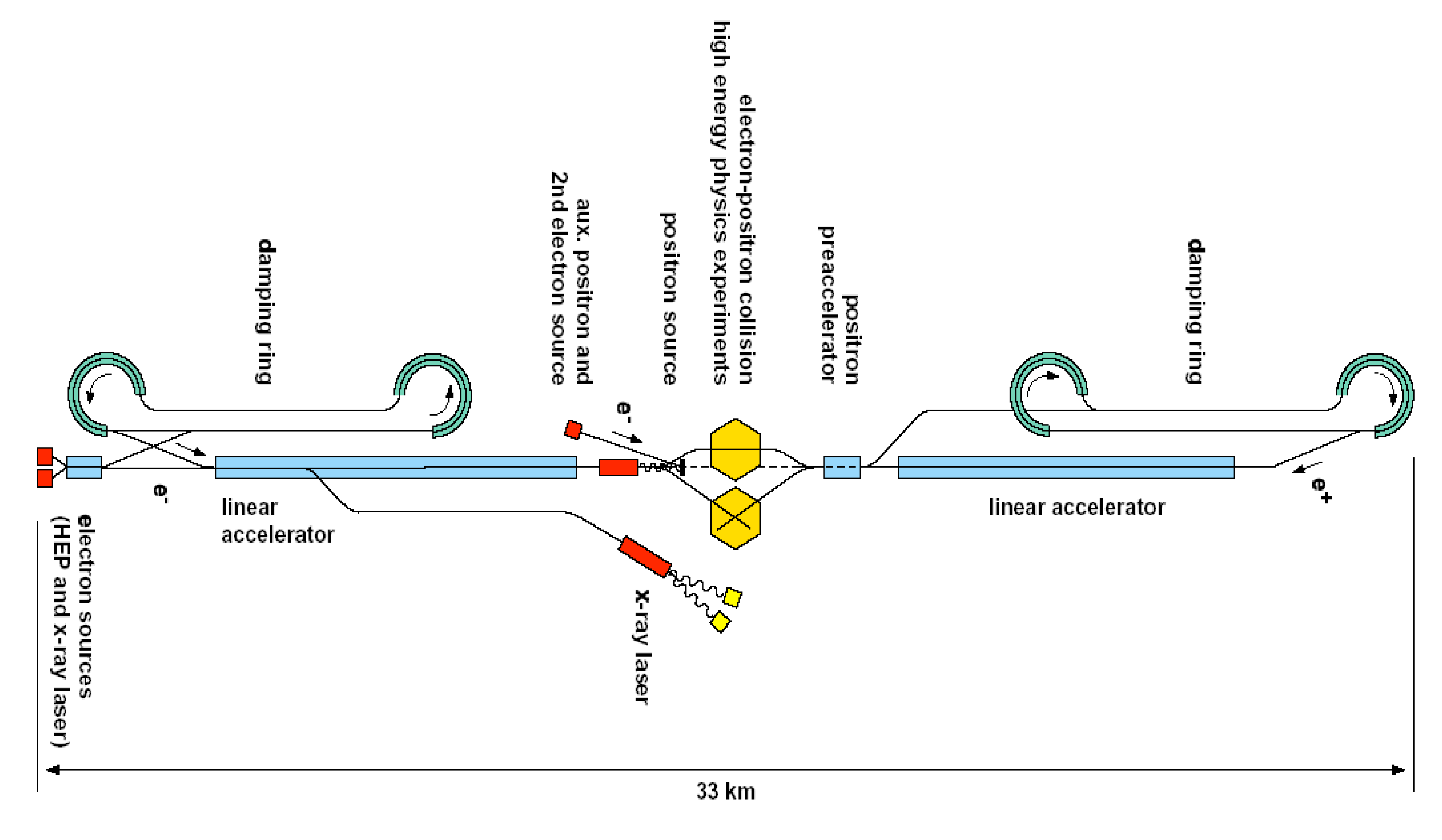


The LINAC is only one part of a linear collider!

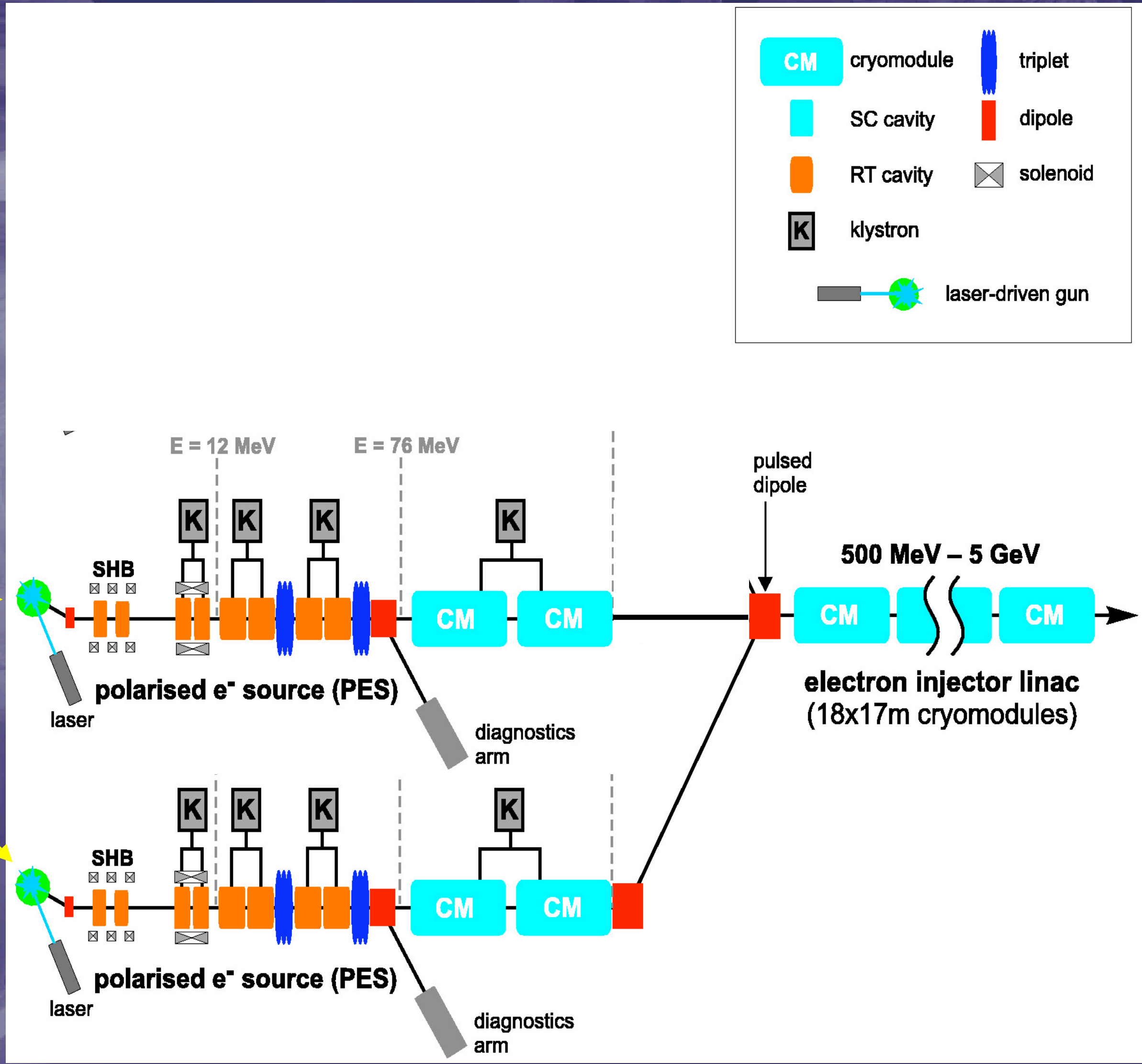


Machine Overview (TESLA)

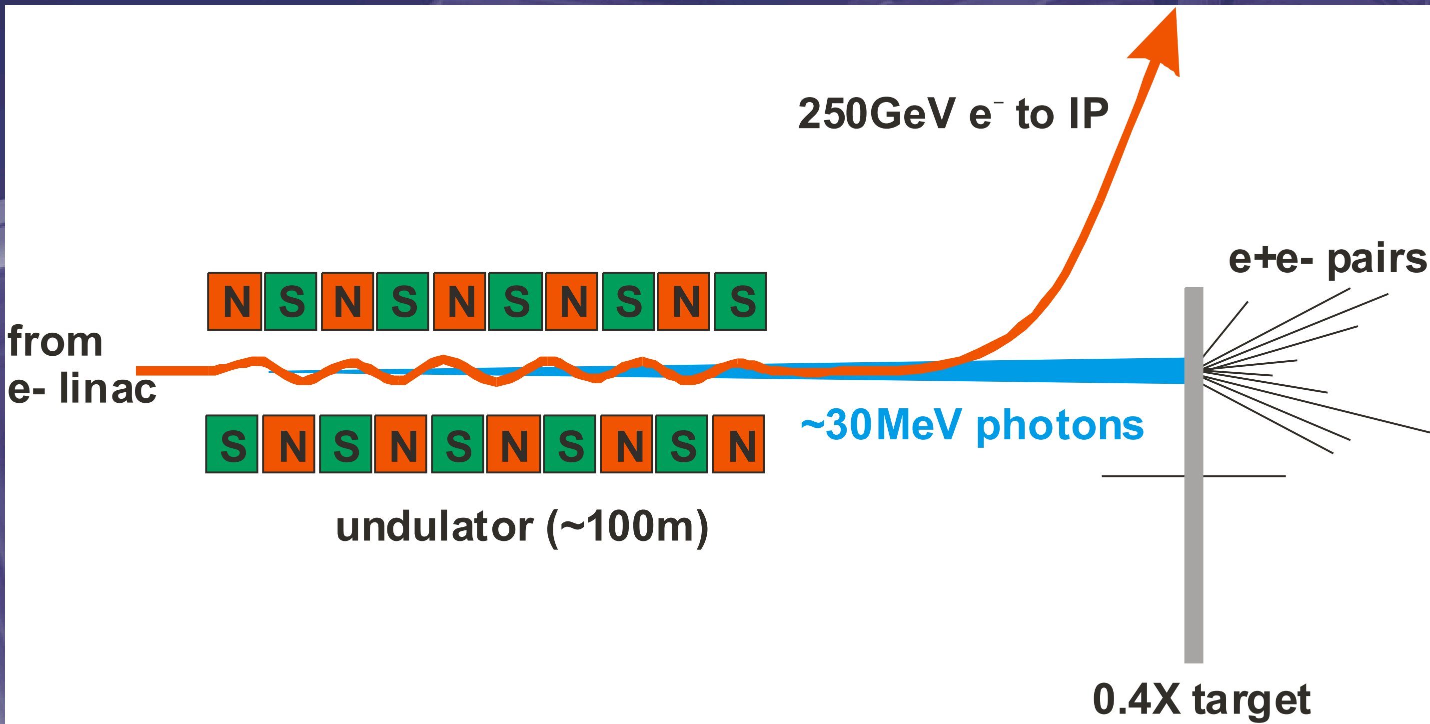


Electron Sources

Laser-driven photo-injectors



Positron Source



Replacing planar undulator with HELICAL undulator gives possibility of POLARISED POSITRONS

Small Emittances

- Require normalised emittances of

$$\gamma\varepsilon_x = 10^{-5}\ \mathrm{m}$$
$$\gamma\varepsilon_y = 3\times10^{-8}\ \mathrm{m}$$

- Thermionic guns ($\varepsilon \sim 10^{-5}$) and state-of-the-art RF guns ($\varepsilon \sim 10^{-6}$) not good enough

⇒ Emittance Damping Ring required

Damping Rings

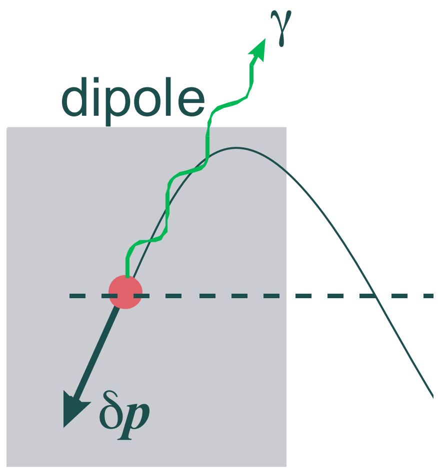
- ring in which the bunch train is stored for T ~200 ms
- $\varepsilon_{x,y}$ is damped down due to synchrotron radiation effects:

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

- final emittance: ε_f
- equilibrium emittance: ε_{eq}
- initial emittance: ε_i (~0.01m for e^+)
- damping time: τ_D ~ 28 ms

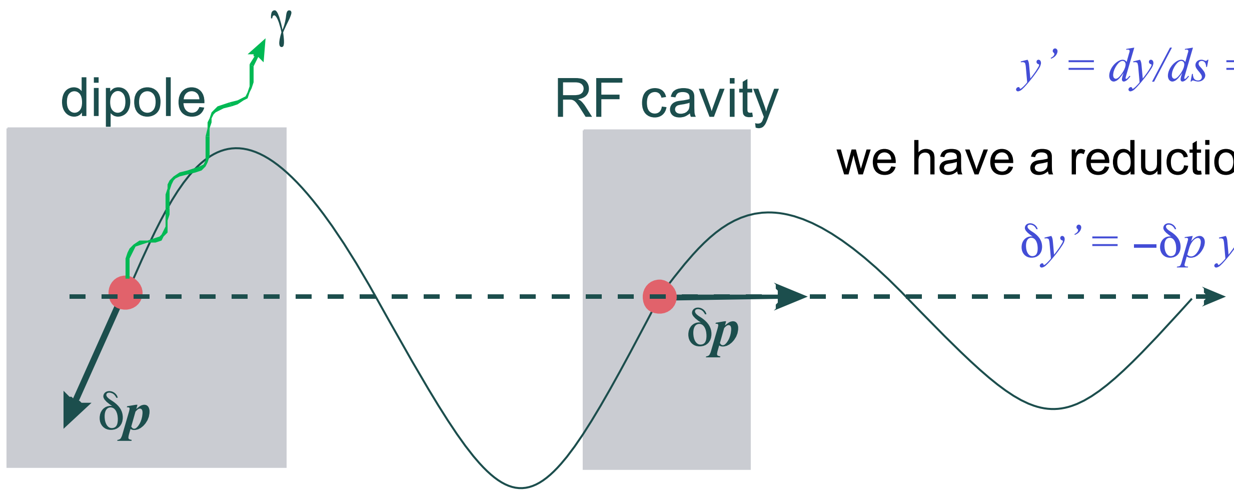
How β-damping works

y' not changed
by photon



How β-damping works

y' not changed by photon



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

since

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

we have a reduction in amplitude:

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

Must take average over all β-phases:

$$\tau_D \approx \frac{2E}{\langle P_\gamma \rangle} \quad \text{where} \quad \langle P_\gamma \rangle \propto \frac{E^4}{\rho^2} \quad \text{and hence} \quad \tau_D \propto \frac{\rho^2}{E^3}$$

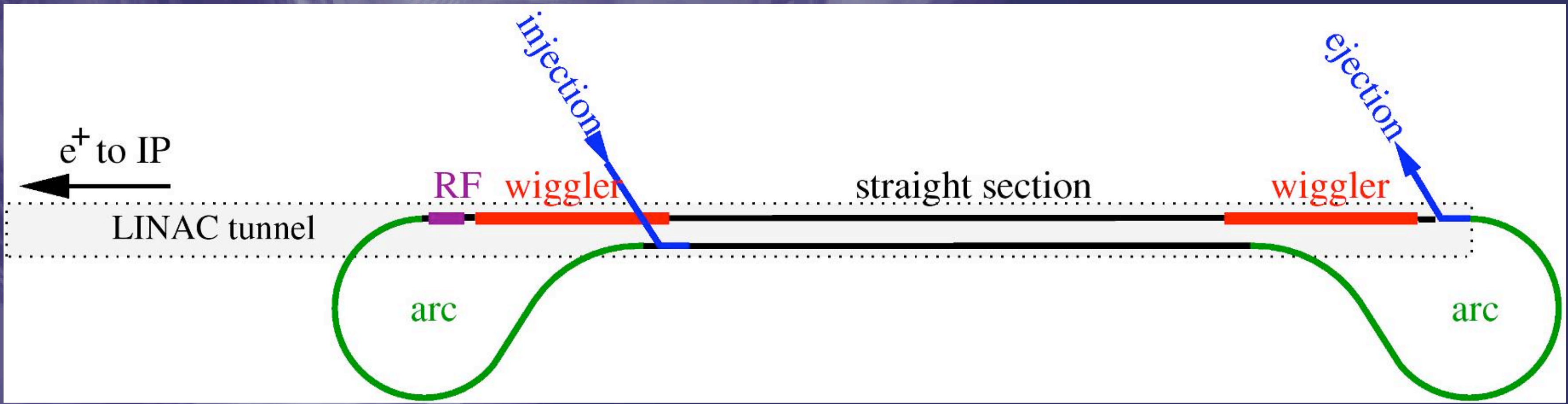
LEP: E_{cm} ~ 135 GeV, P_γ ~ 4.7×10^3 GeV/s, τ_D ~ 28 ms

Damping Rings for LC

- Typically $E \approx$ 3-5 GeV
- B_{bend} = 0.2 T $\Rightarrow \rho \approx$ 50-80 m
- $<P_\gamma>$ = 240 GeV/s [330 kV/turn]
- hence $\tau_D \approx$ 28 ms
- Note: $\varepsilon_{eq} \propto E^2/\rho$

TESLA Damping Rings

- Long pulse: 950ms × c = 285km!!
- Compress bunch train into 18km "ring"
- Minimum circumference set by speed of ejection/injection kicker (~20ns)
- Unique "dog-bone" design: 90% of 'circumference' in linac tunnel.

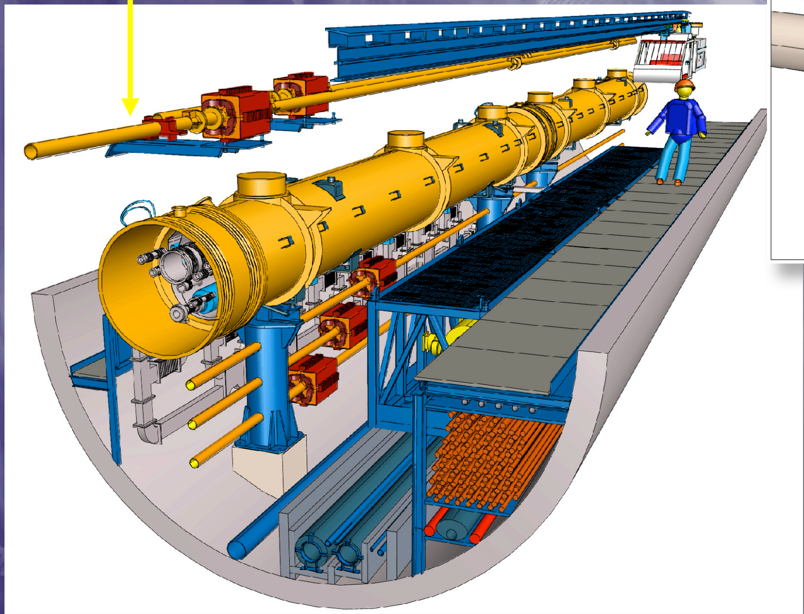


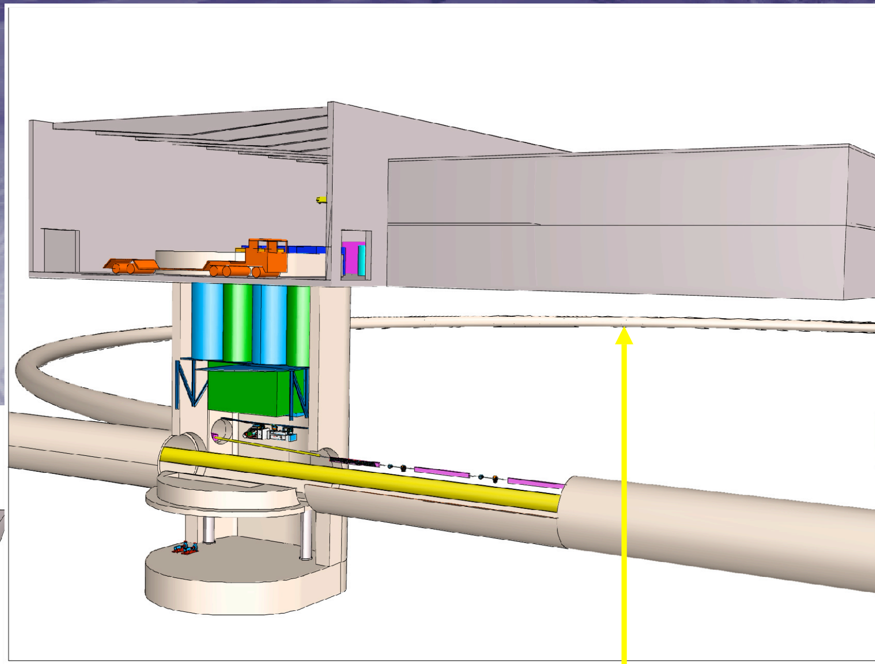
Limits on ε_{eq}

- Horizontal emittance defined by lattice (presence of dispersion in x-plane leads to so-called anti-damping):
- theoretical vertical emittance limited by
  - space charge
  - intra-beam scattering (IBS)
- In practice, ε_y limited by magnet alignment errors [cross plane coupling]
- typical vertical alignment tolerance: $\Delta y \approx 30$ μm
  $\Rightarrow$ requires beam-based alignment techniques!

Damping Rings

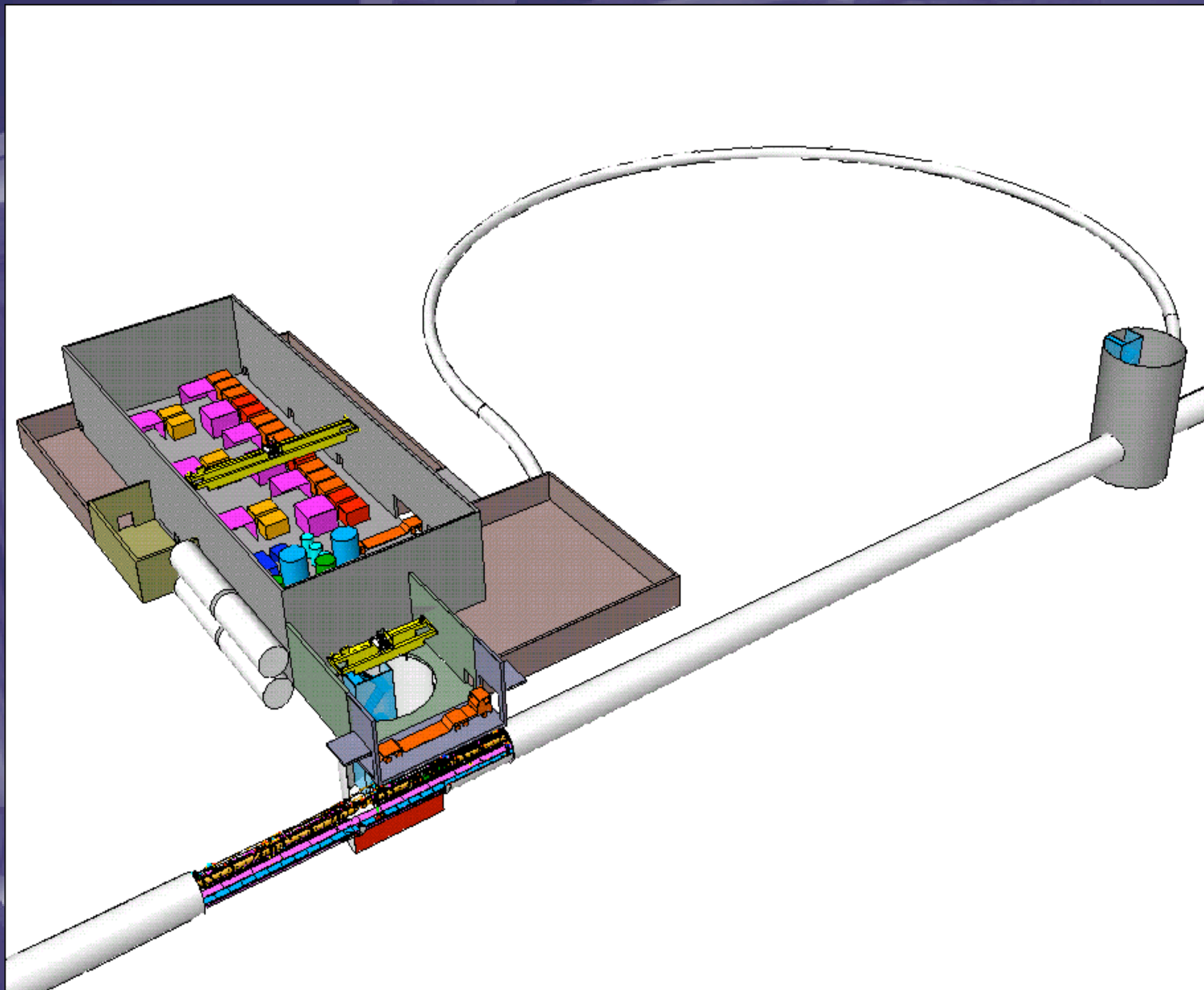
Dogbone Straight Sections





Dogbone Arc Tunnel

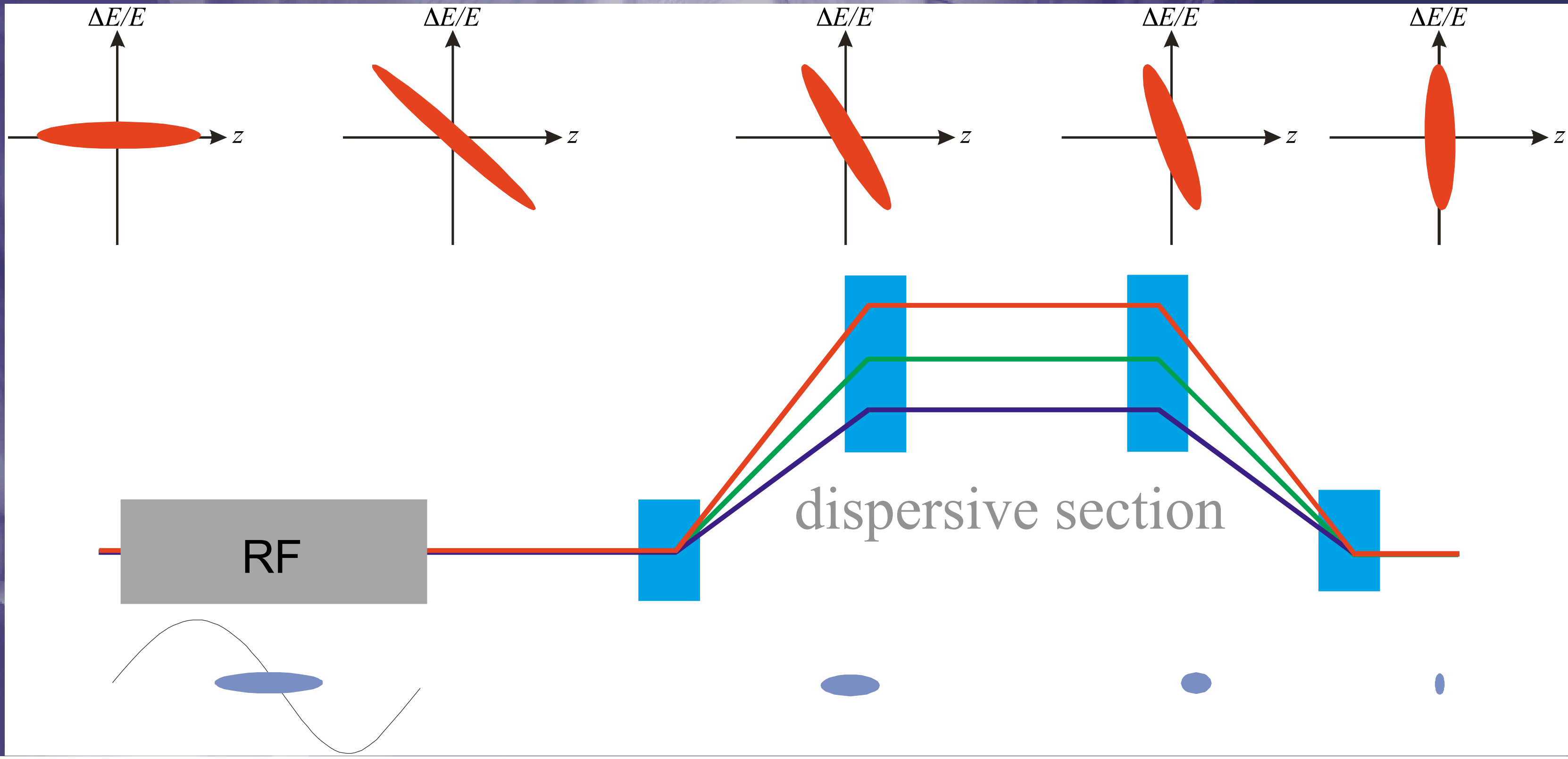
Cryohall and “dogbone” tunnel



Bunch Compression

- bunch length from ring ~ few mm
- required at IP 100-300 μm

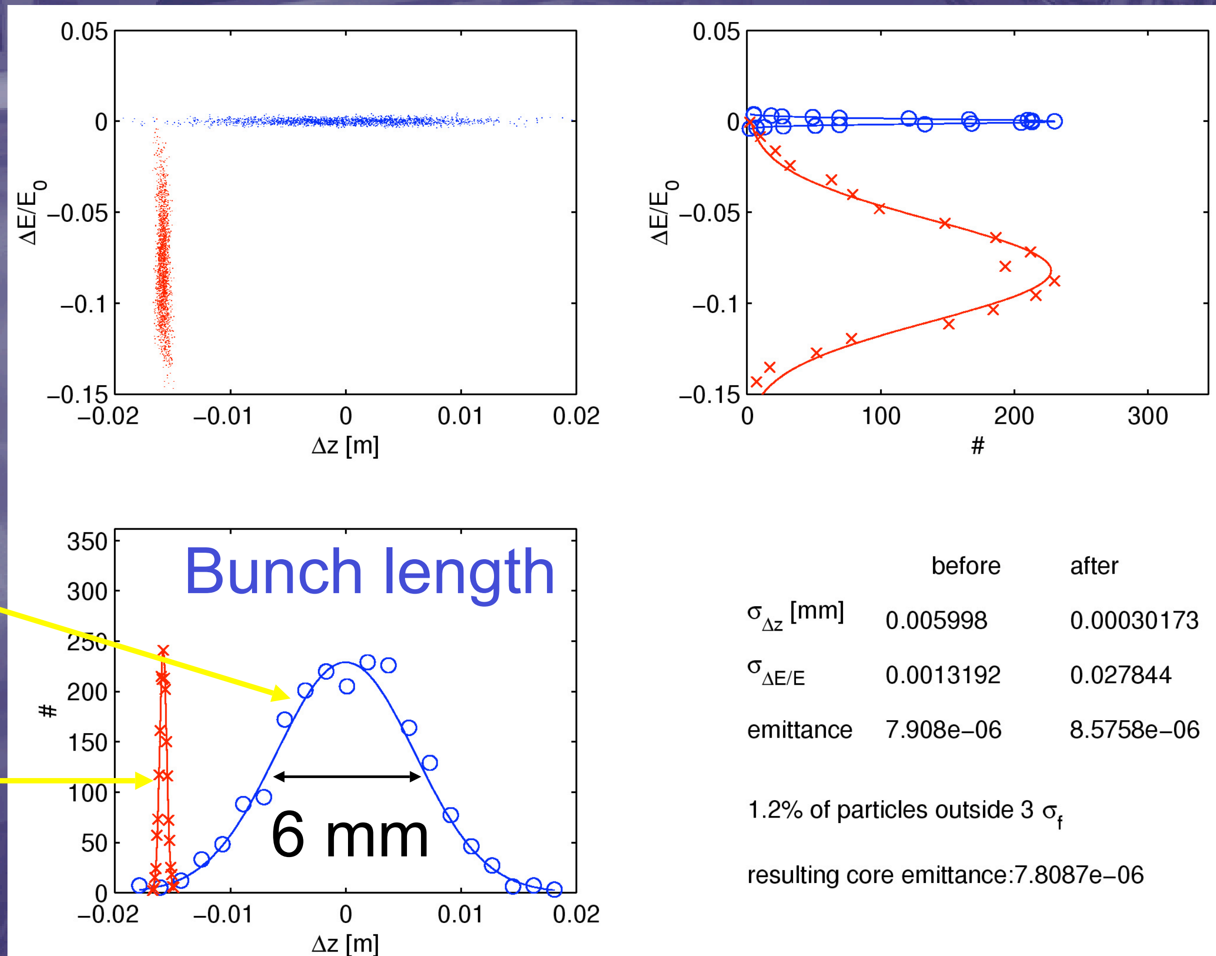
longitu-
dinal
phase
space



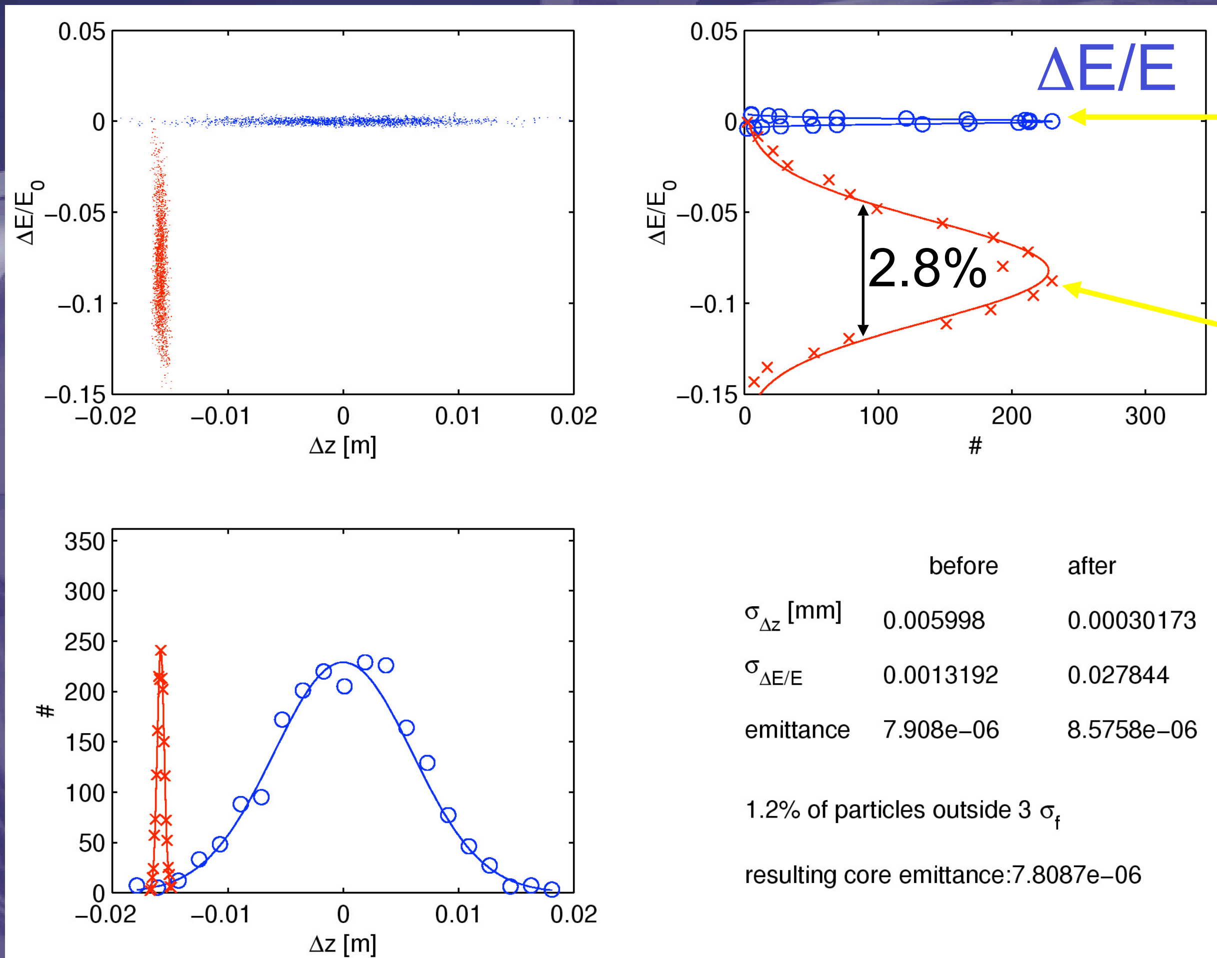
Bunch Compression

Damping ring

After compression
(300 μm)



Bunch Compression



Damping ring (~ppm)

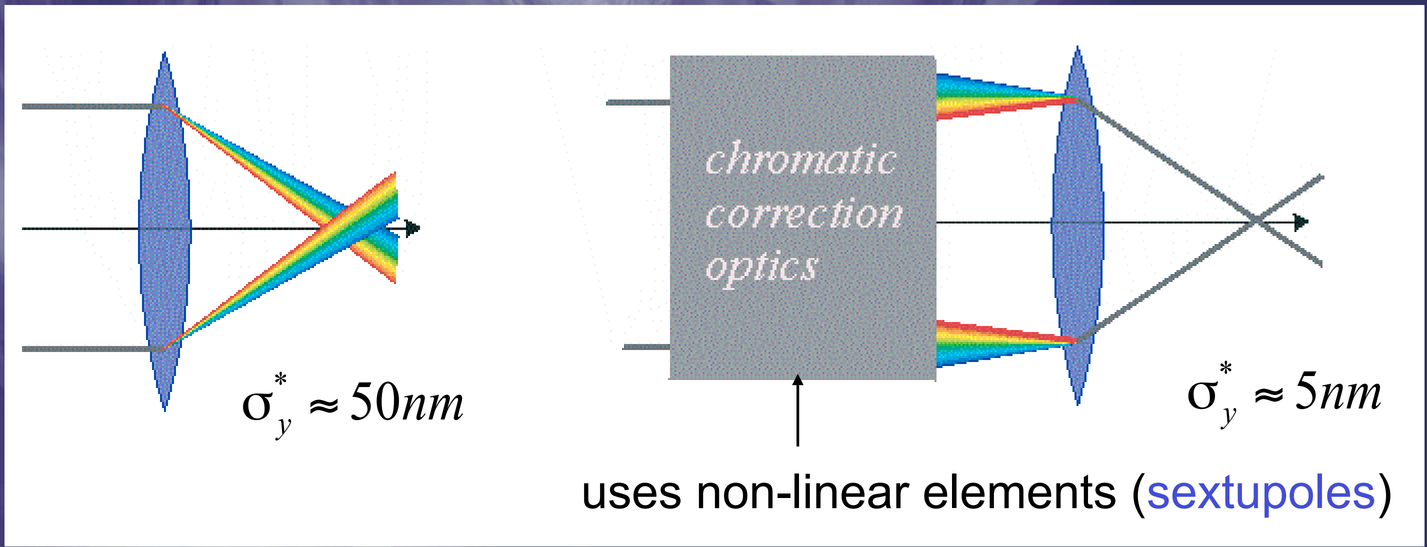
After compression

5 GeV: 2.8%

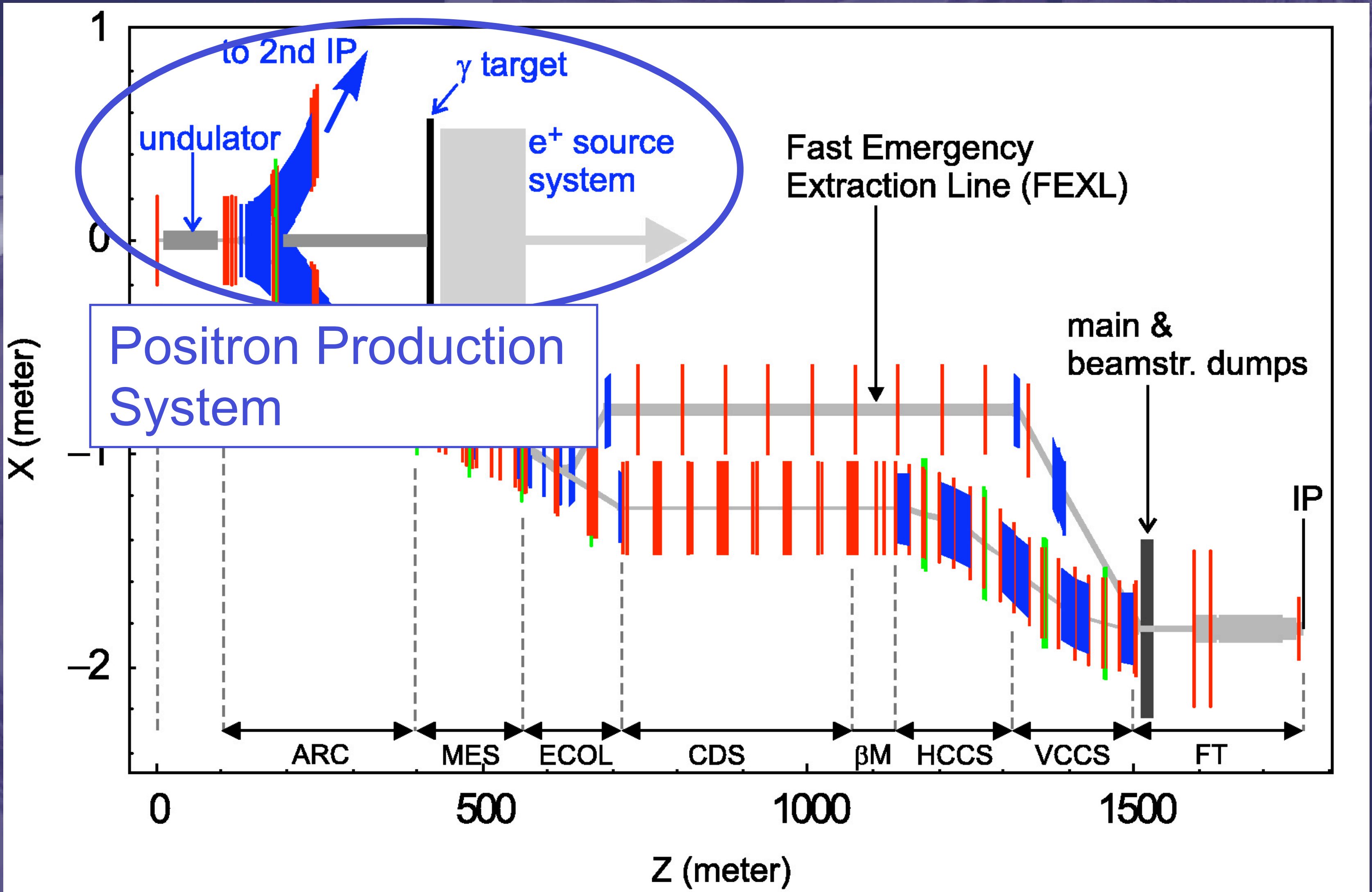
250 GeV: 0.6‰

Final Focus System for small β*

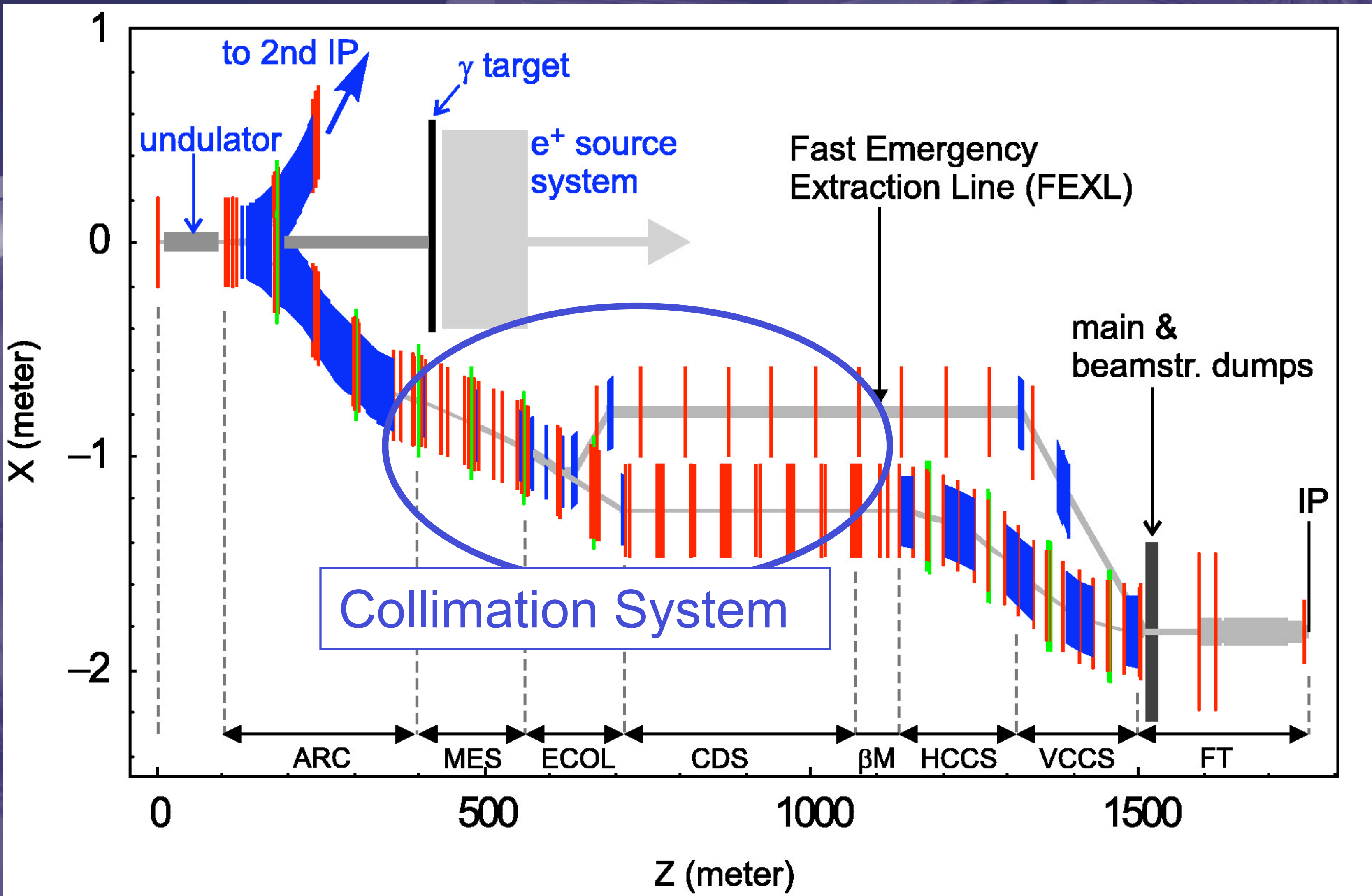
- Optical telescope required to strongly demagnify the beam ($M_x \approx$ 1/100, $M_y \approx$ 1/500)
- Strong focusing leads to unacceptable chromatic aberrations [non-linear optics]
- Require 2nd-order optical correction



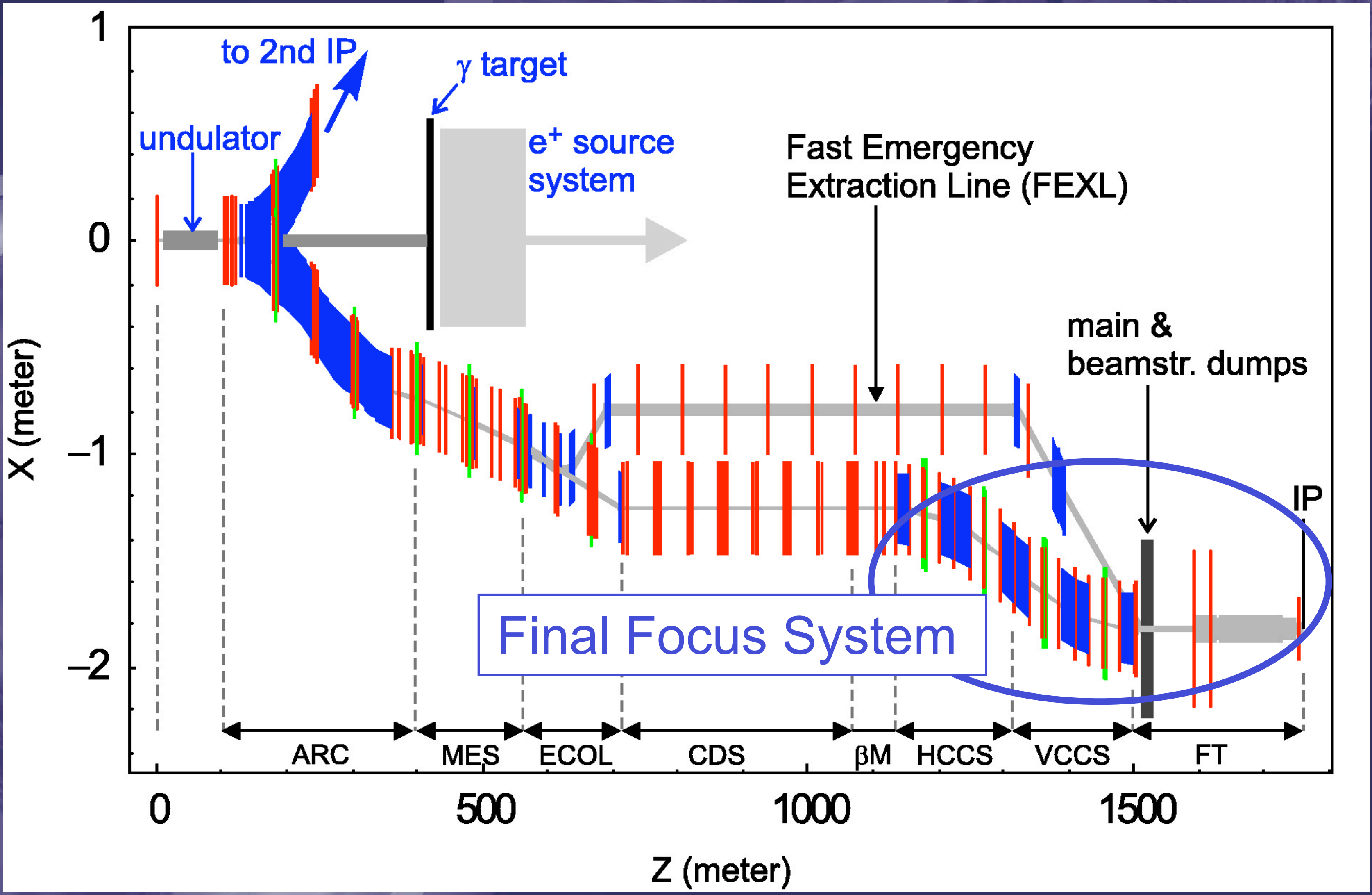
Beam Delivery System



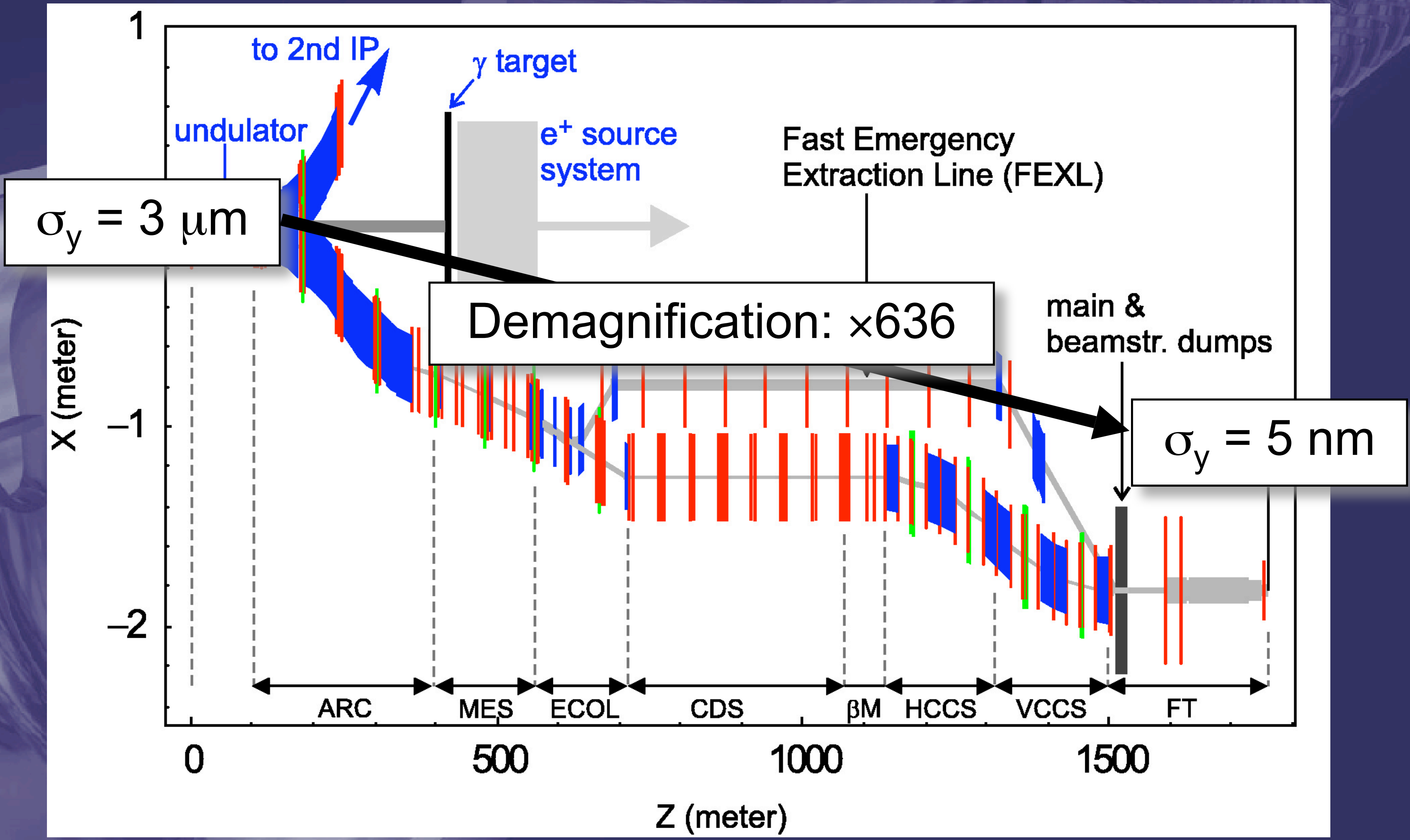
Beam Delivery System



Beam Delivery System



Beam Delivery System



Stability

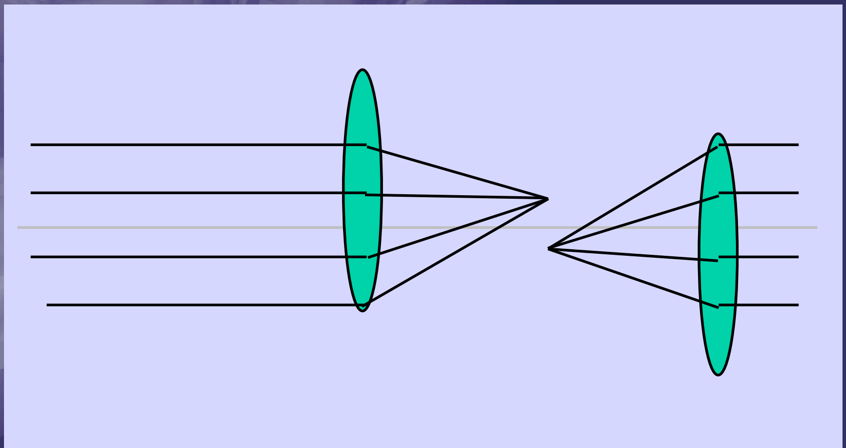
- Tiny (emittance) beams
- Tight component tolerances
  - Field quality
  - Alignment
- Vibration and Ground Motion issues
- Active stabilisation
- Feedback systems

Linear Collider will be “Fly By Wire”

Stability: some numbers

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

Parallel-to-
Point focusing

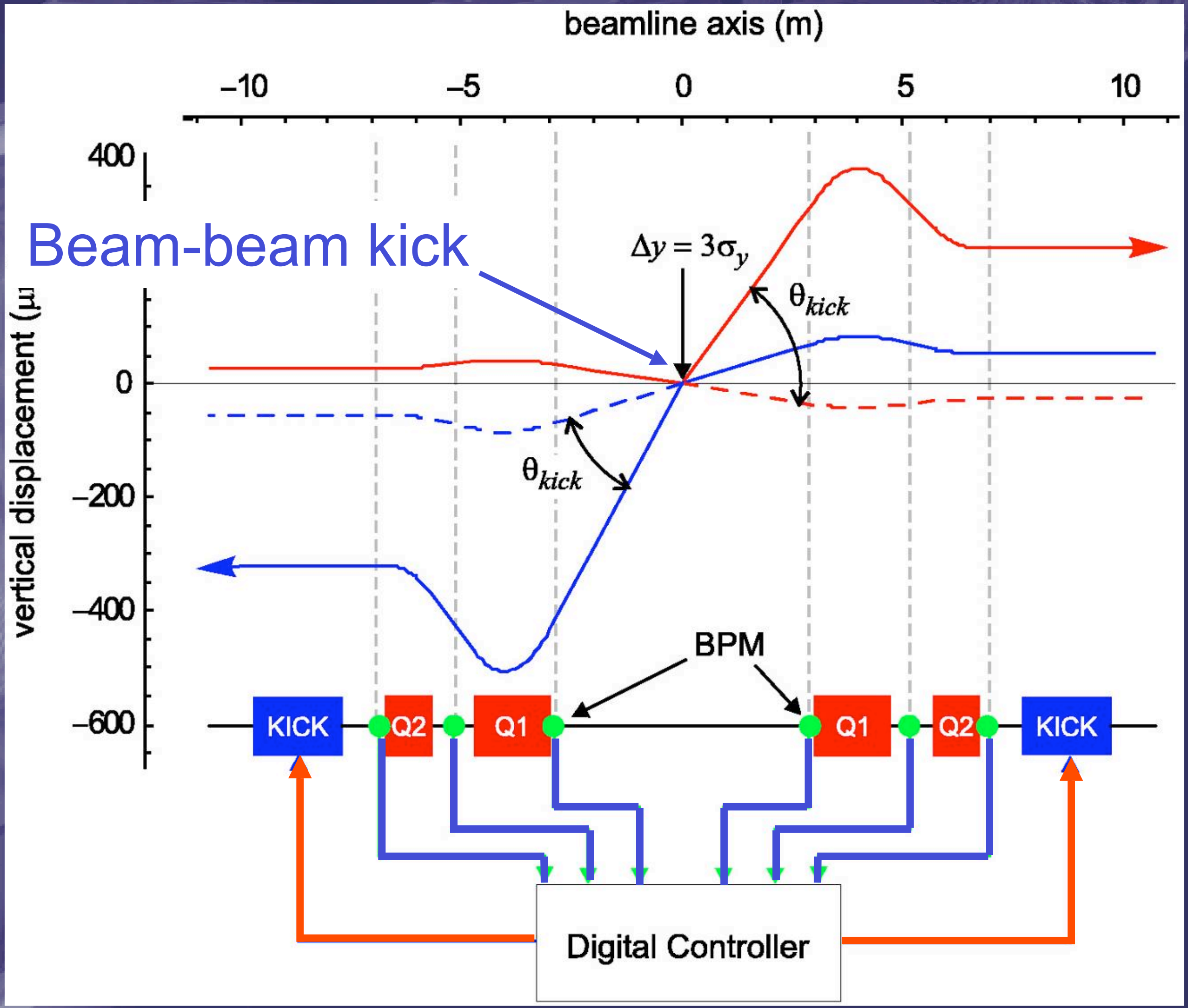


IP Fast (orbit) Feedback

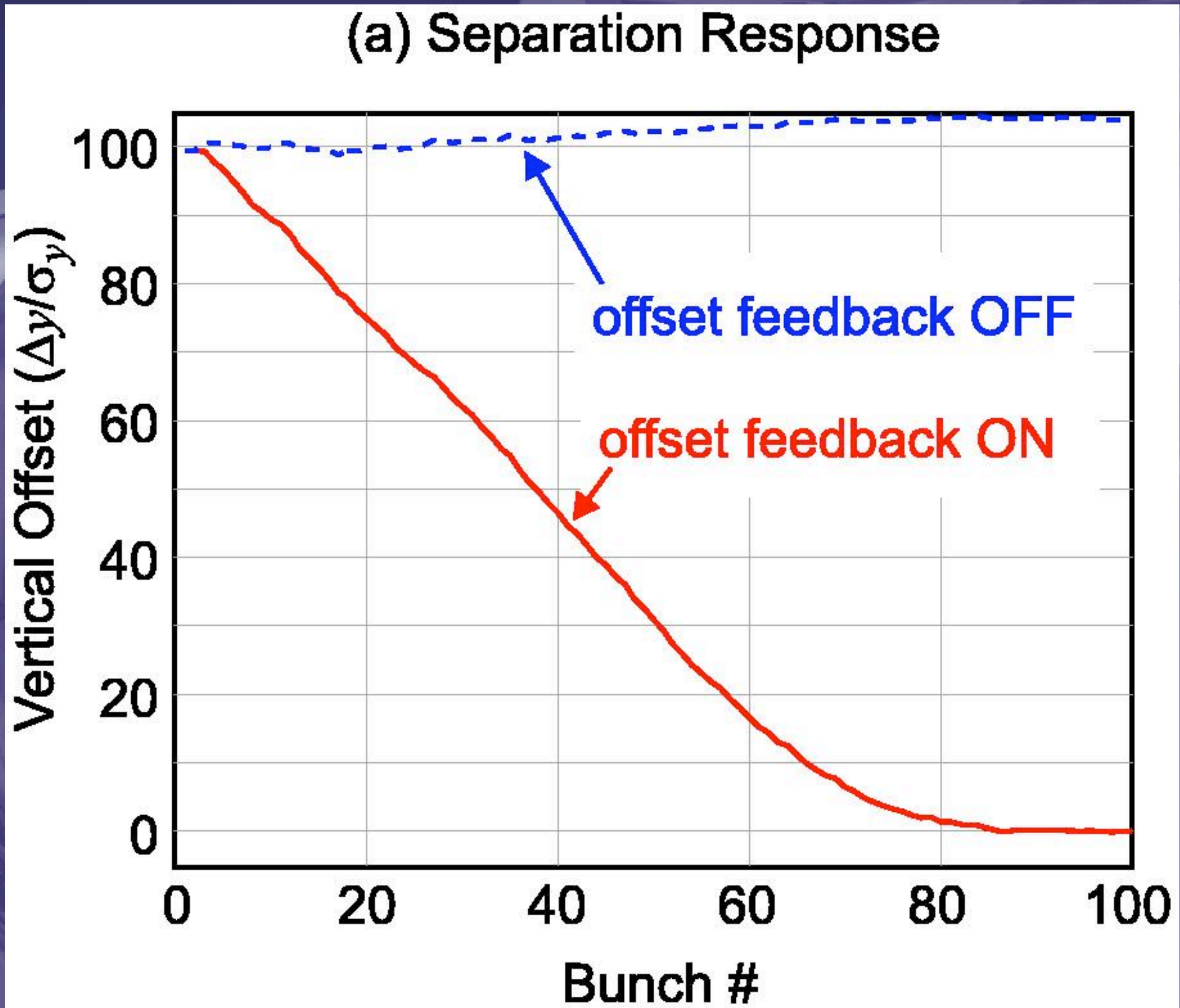
Long bunch train:

2820 bunches

t_b = 337 ns



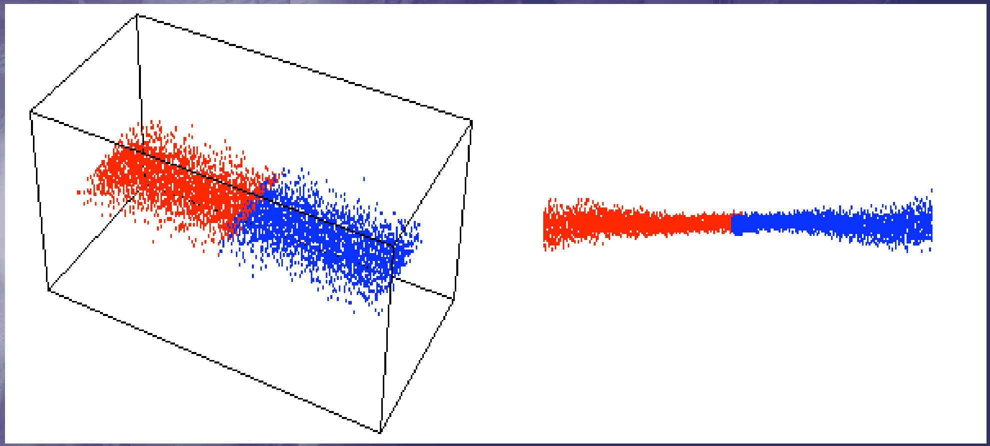
IP Fast (orbit) Feedback



Systems successfully tested at TTF

‘Banana’ Effect : Beam-Beam Simulation

- Instability driven by vertical beam profile distortion
- Strong for high disruption
- Distortion caused by transverse wakefields and quad offset – only a few percent emittance growth
- Tuning can remove static part

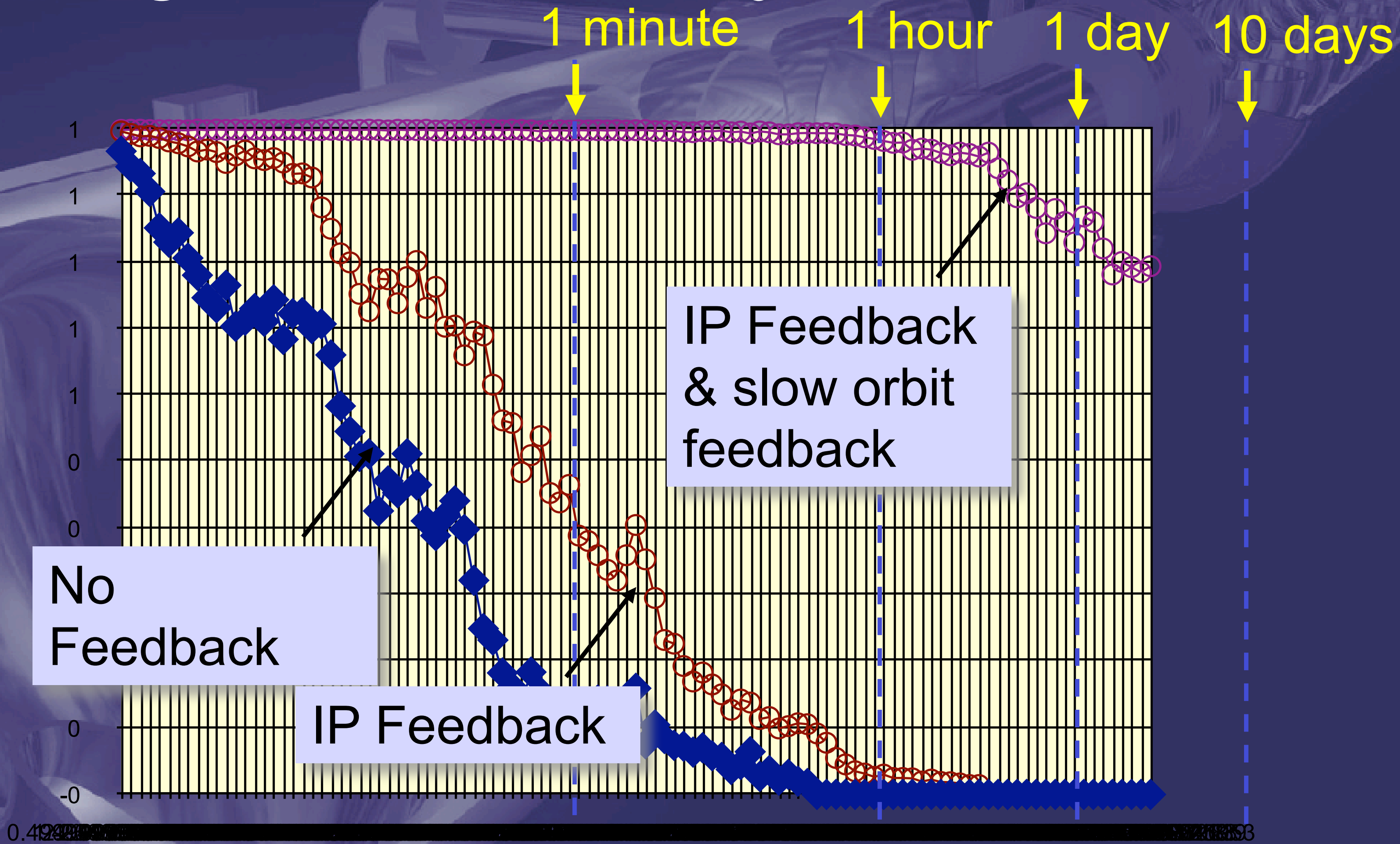


Nominal TESLA Beam Parameters +

y-z correlation (equivalent to few % projected emittance growth)

Beam centroids head on

Long Term Stability



Damping ring to IP Simulations

Gaussian bunch from DR

Ideal machine

Change of bunch compressor phase by ±2.5 deg (powerful knob at the SLC)

This is just an example what we intend to study

Timeline

- 1995 SLAC produced X-Band design report (ZDR)
- 2001 TESLA TDR Published
- US Snowmass HEP Workshop: World-Wide Consensus
- 2003 KEK (Japan) X-Band GLC TDR Published
- 2004 International Technology Recommendation Panel Decision (X-Band or TESLA?) → SCRF
  - 1st ILC Workshop, KEK Japan, November 2004
- 2005 Formation of 'Global Design Initiative' and 'Regional Design Teams', Baseline defined
  - 2nd ILC Workshop, Snowmass Colorado, USA, August 2005
- 2006 Reference Design Report
- 2007-2008 International TDR with full costs
- 2008+ Site selection, start of construction
- 2015++ Begin e^+e^- physics

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