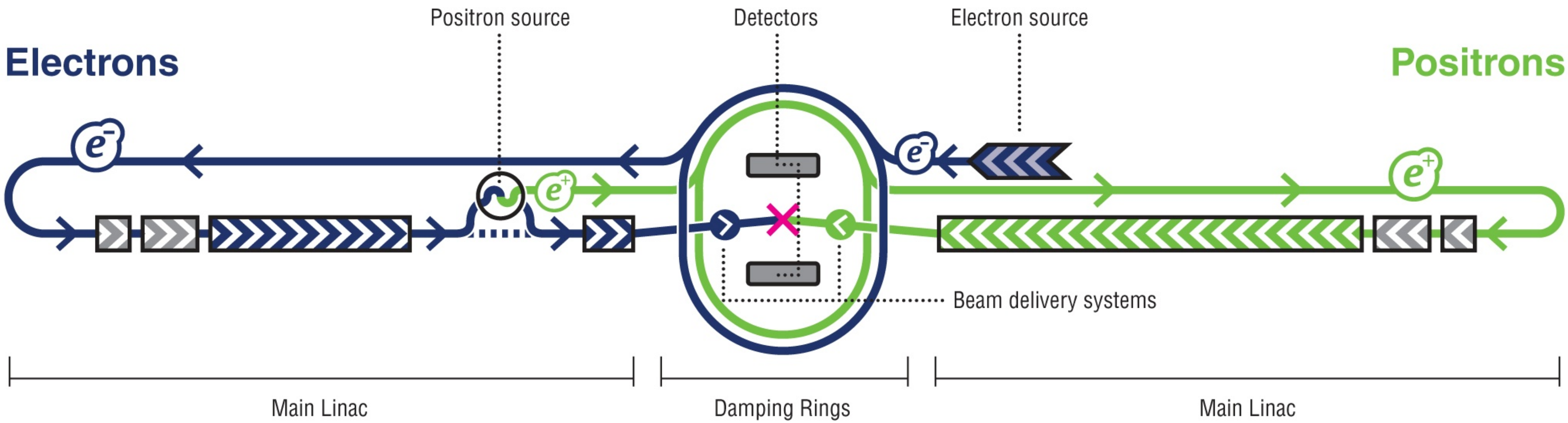
Accelerator Physics of the International Linear Collider



Shane Koscielniak

TRIUMF & U. Victoria

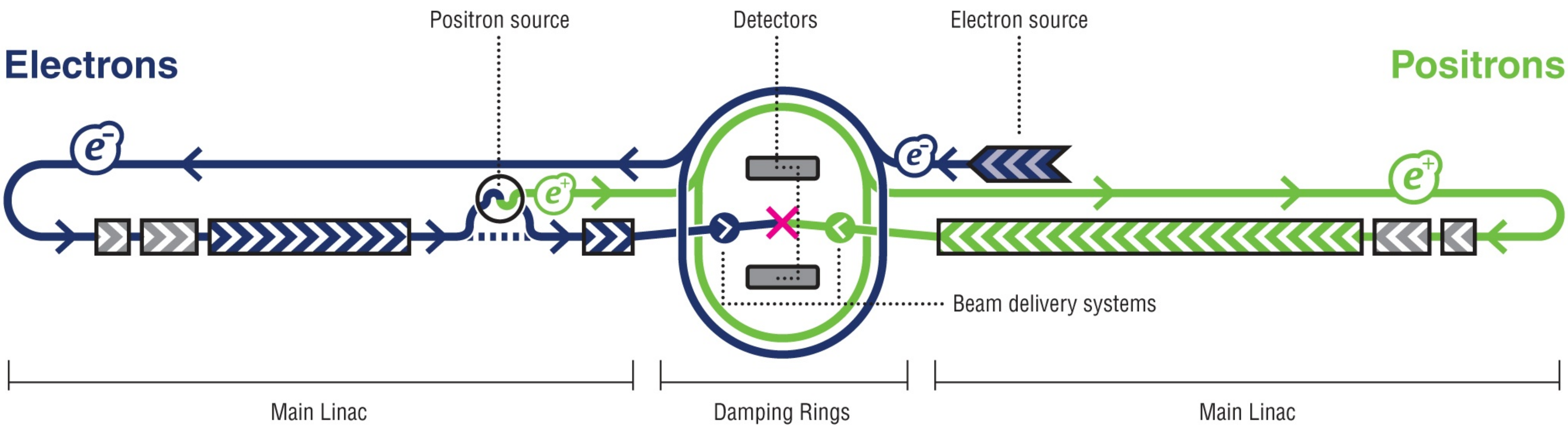
Outline – of two talks

- **ILC motivation**
  - Higgs particle
  - Cyclic versus linear acceleration
  - Synchrotron radiation
- **Particle accelerator basics**
  - Emittance
  - Lattice functions
  - Synchrotron radiation
- **ILC – the machine**
  - e+,e- sources
  - Damping rings
  - Ring to Main Linac
  - Main Linac
  - Superconducting cavities
  - Beam delivery system
  - Detectors
- **Electron Linac Project at TRIUMF**

Lecture #1

Lecture #2

International Linear Collider (ILC) Reference Design

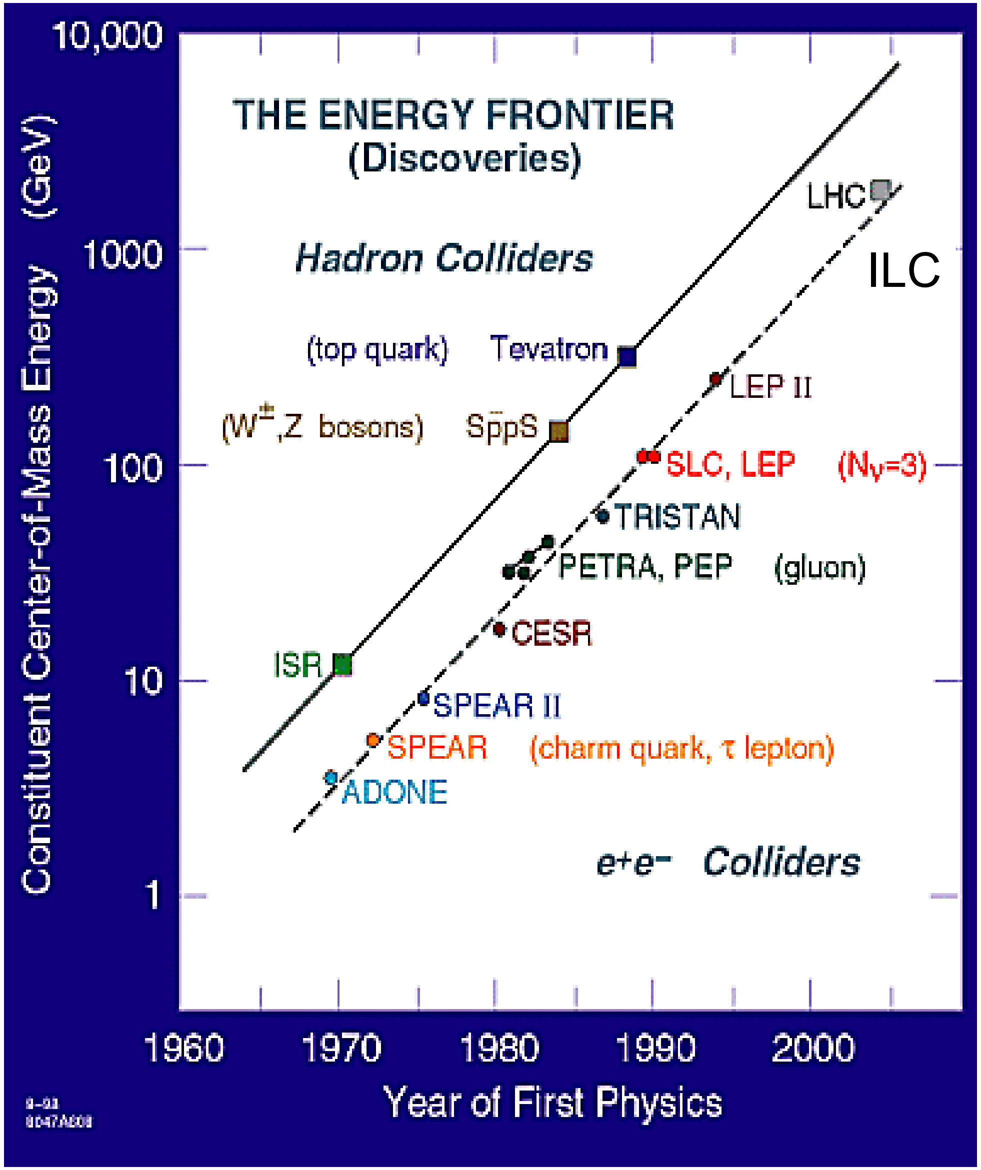


This is the frontier High-Energy Physics (HEP) instrument after 2020

The ILC will collide electrons and positrons (e- & e+) at centre of mass energy 500 GeV (500×10^9 eV)

Although this is an electron accelerator, its design is very much shaped by properties of (i.e. interaction with) photons!

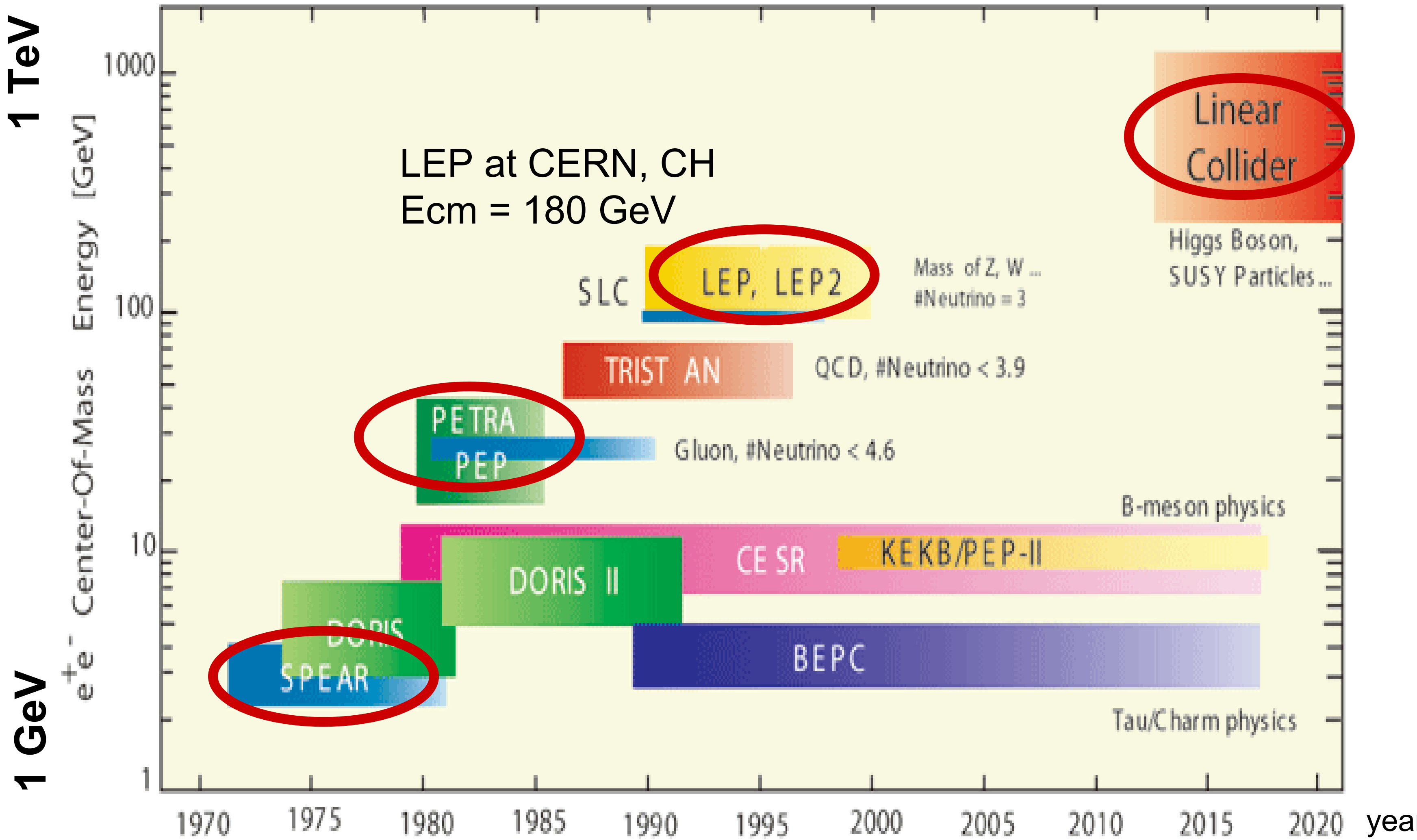
Frontier Colliders



- There are the Hadron colliders at the energy frontier, SPPS at CERN confirming electroweak model, Tevatron at Fermilab, Chicago, doing top and bottom physics -and soon the LHC.
- And then there is the precision frontier: the lepton colliders. Most recently the linear collider at SLAC, SLC, the LEP ring at CERN, and hopefully the ILC.

Four Generations of e+e- Colliders

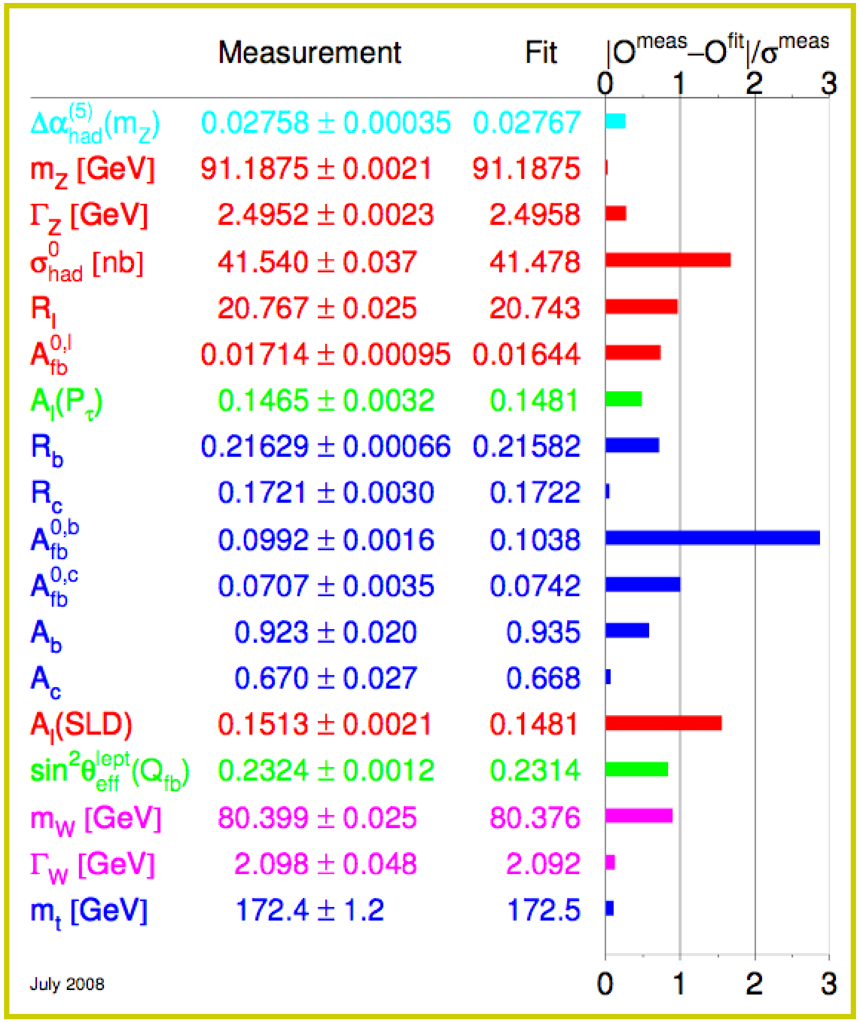
The Energy Frontier



Some of the fundamental physics uncovered or confirmed by the lepton colliders. Very important was pinning down the number of generations of quarks and leptons as only 3. Also precision mass measurements and coupling ratios on W, Z and B.

Precision measurements

A brief look at the physics motivation for LHC and ILC. Here is a comparison of measurements against values fitted from parameters of the Standard Model. The values of the masses are consistent with a light Higgs particle.



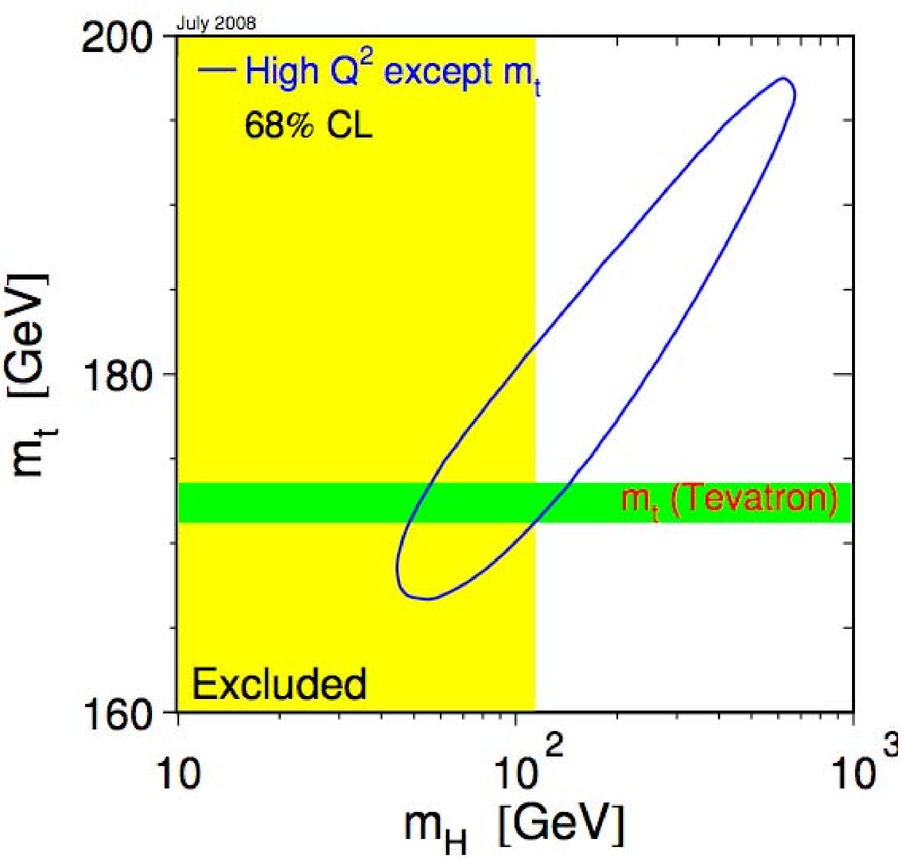
$$\text{Ideally, } \frac{(\text{meaurement})-(\text{model fit})}{(\text{experimental error})}<1$$

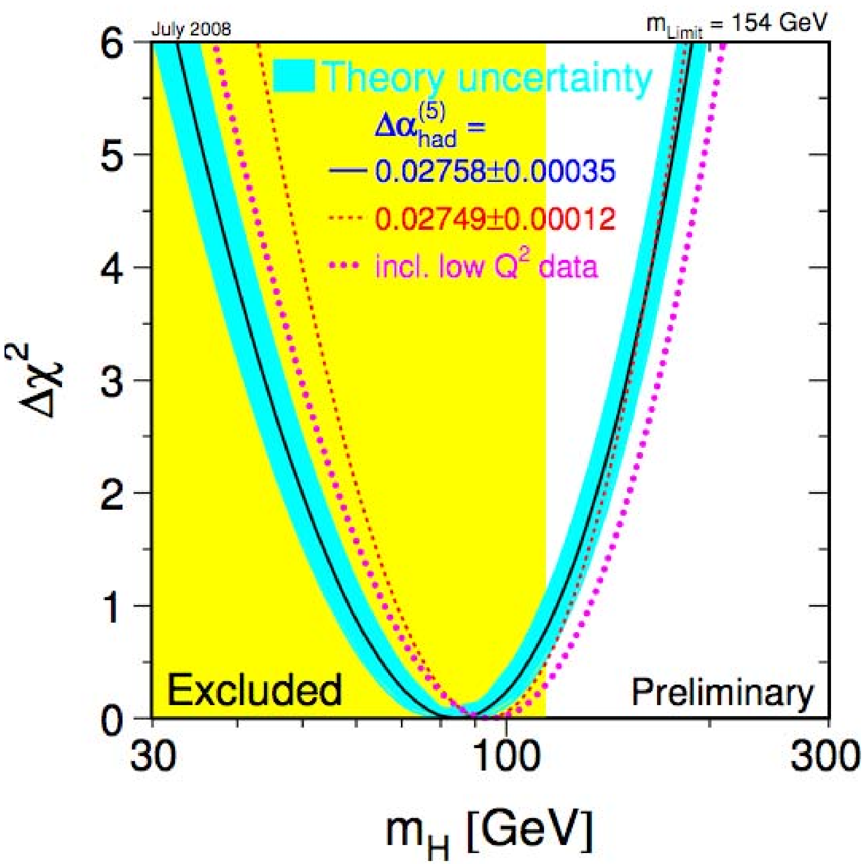
"A host of precision measurements, from laboratories around the world, are completely consistent with the Standard Model …"

- They point to a light Higgs particle
  - Well within reach of the LHC
  - And also the ILC …

Jonathan Bagger
Johns Hopkins University

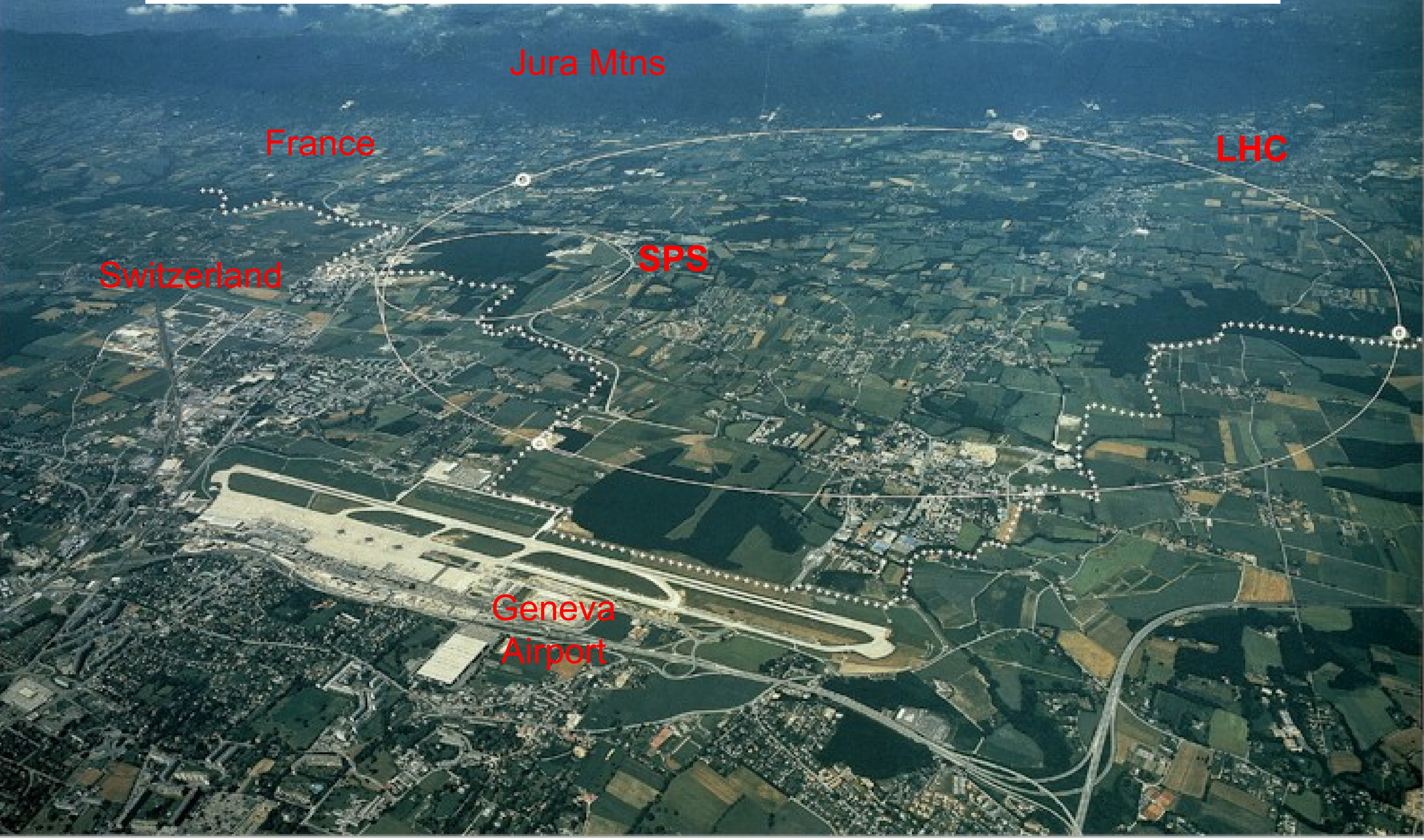
The evidence for a light Higgs particle





Areas excluded by previous experimental searches are shown in yellow.

Here is the site of three notable circular colliders SPPS, LEP and LHC which occupies the former LEP tunnel. LHC Repairs and retrofits should be complete June 2009; beams in collision late Oct 2009.



CERN Geneva – the LHC (former LEP) and SPS tunnels & Swiss-French border

Exploring the Terascale - *the tools*

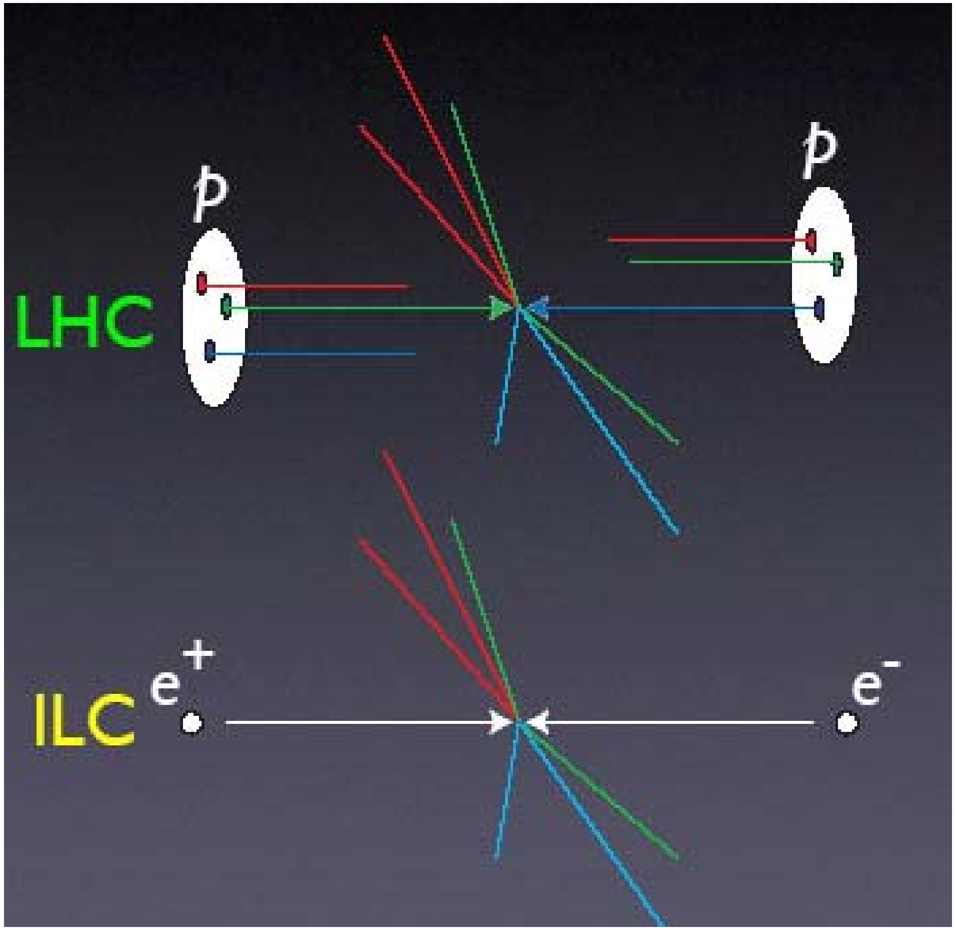
- The LHC
  - It will lead the way and has large energy reach
  - Quark-quark, quark-gluon and gluon-gluon collisions at 0.5 - 5 TeV
  - Broadband initial state

- The ILC
  - A second view with high precision
  - Electron-positron collisions with fixed energies, adjustable between 0.1 and 1.0 TeV
  - Well defined initial state
- Together, these are our tools for the terascale

Precision Physics at the Terascale - the advantages of electrons as a physics probe

In contrast to protons which are composite objects that share the collision energy between their constituent quarks in a variety of ways

- e+,e- elementary particles
- well-defined
  - energy,
  - angular momentum
- uses full Centre of Mass energy
- produces particles democratically
- can mostly fully reconstruct events



Barry Barish

LCWS DESY, 30-May-07

ILC Physics Goals

- E_{cm} adjustable from 200 – 500 GeV
- Luminosity → $\int L dt$ = 500 fb^{-1} in 4 years
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarization of at least 80%
- The machine must be upgradeable to 1 TeV

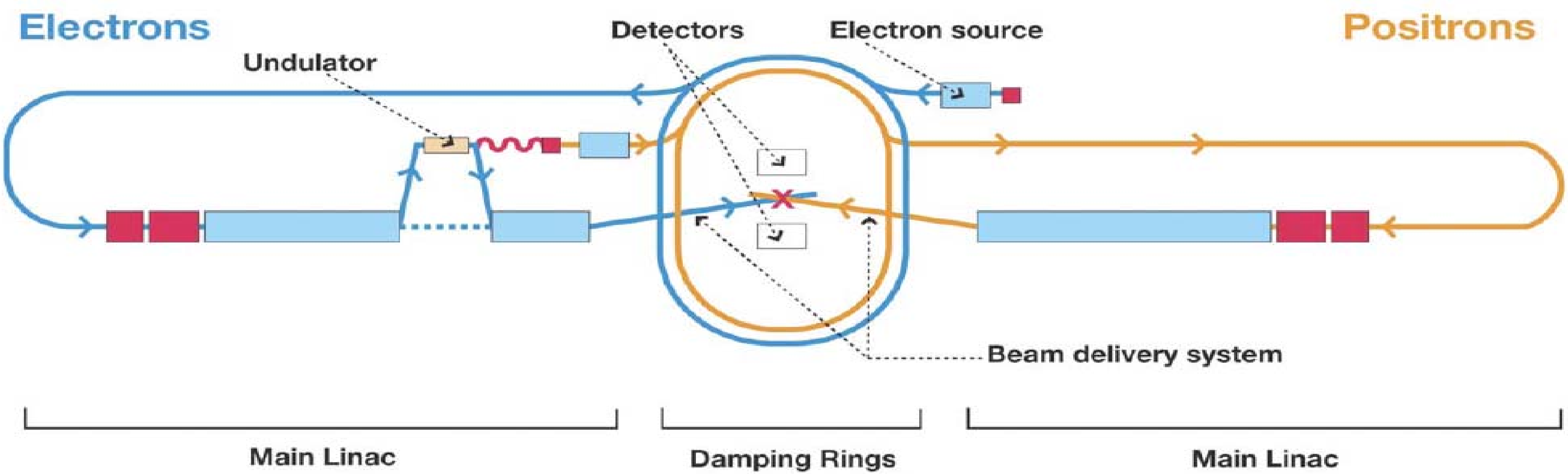
The Reference Design meets the goals of the ICFA- ILCSC parameters study

A Vision of the Future

Reference Design Report to ILC

Barry Barish

LCWS DESY 30-May-07



Enter the ILC, two opposing 250 GeV linacs. We take a more detailed look later. And we shall need to introduce some accelerator physics basics to do that.

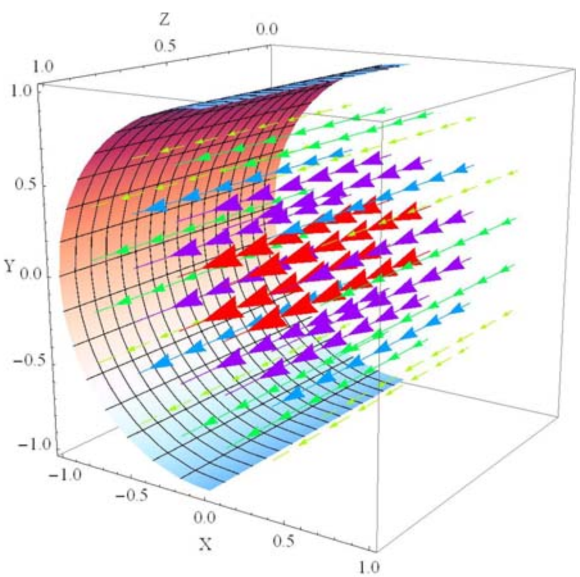
Particle Acceleration

By definition, particle accelerators transfer energy from an electrical field to kinetic energy of the particle.

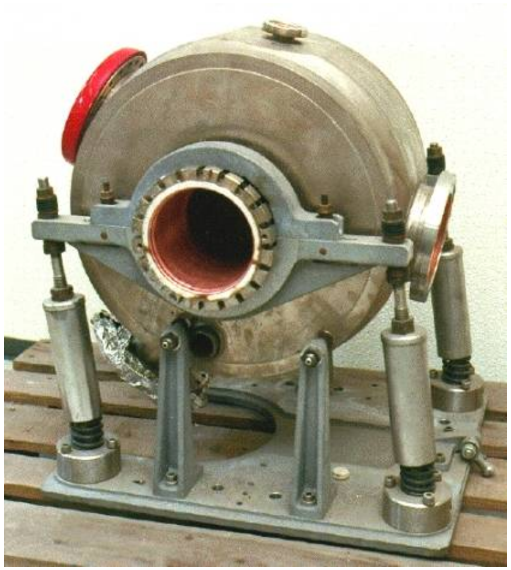
The EM fields are stored in cavity resonators.

Why use cavity resonators?

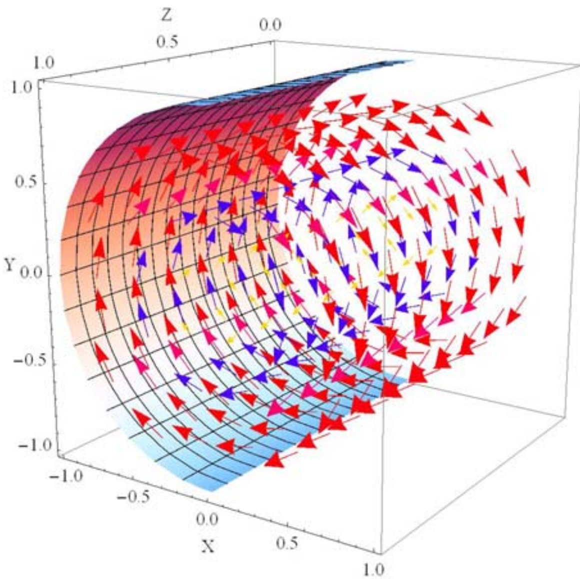
- Resonator response can amplify external excitation
- Mode excitation gives specific/reproducible electric field shape &time dependence.
- EM field points in the correct/desired direction!



Electric vector field



TM-010 mode of cylindrical resonator



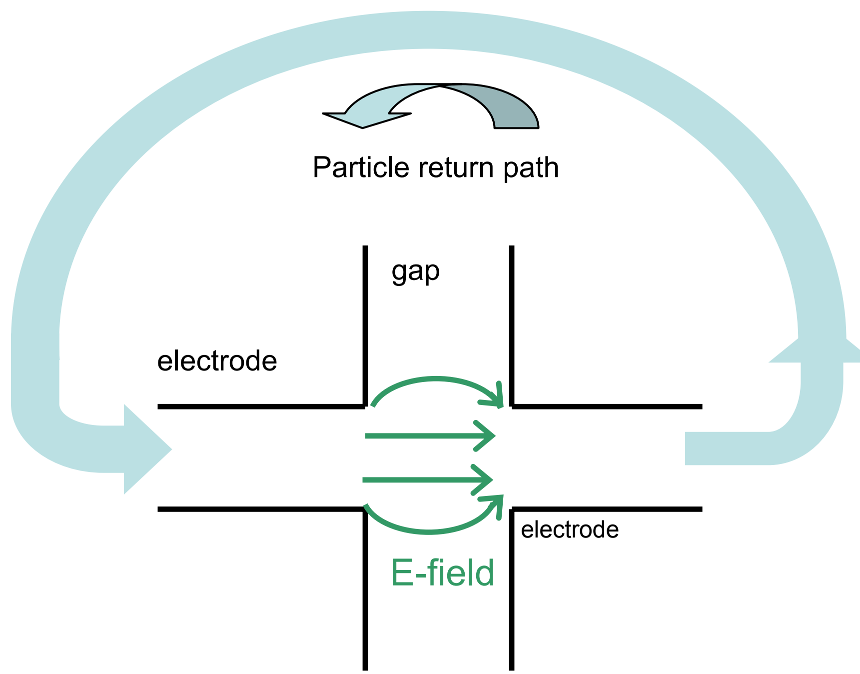
Magnetic vector field

Circular accelerators, such as cyclotrons & synchrotrons (e.g. LEP and LHC) **employ cyclic acceleration**

Setting up the electric field has $ cost of hardware to create that field. More efficient if the field can be re-used by multiple passages through the same field. This is principle of *cyclic acceleration* – and can result in large cost savings.

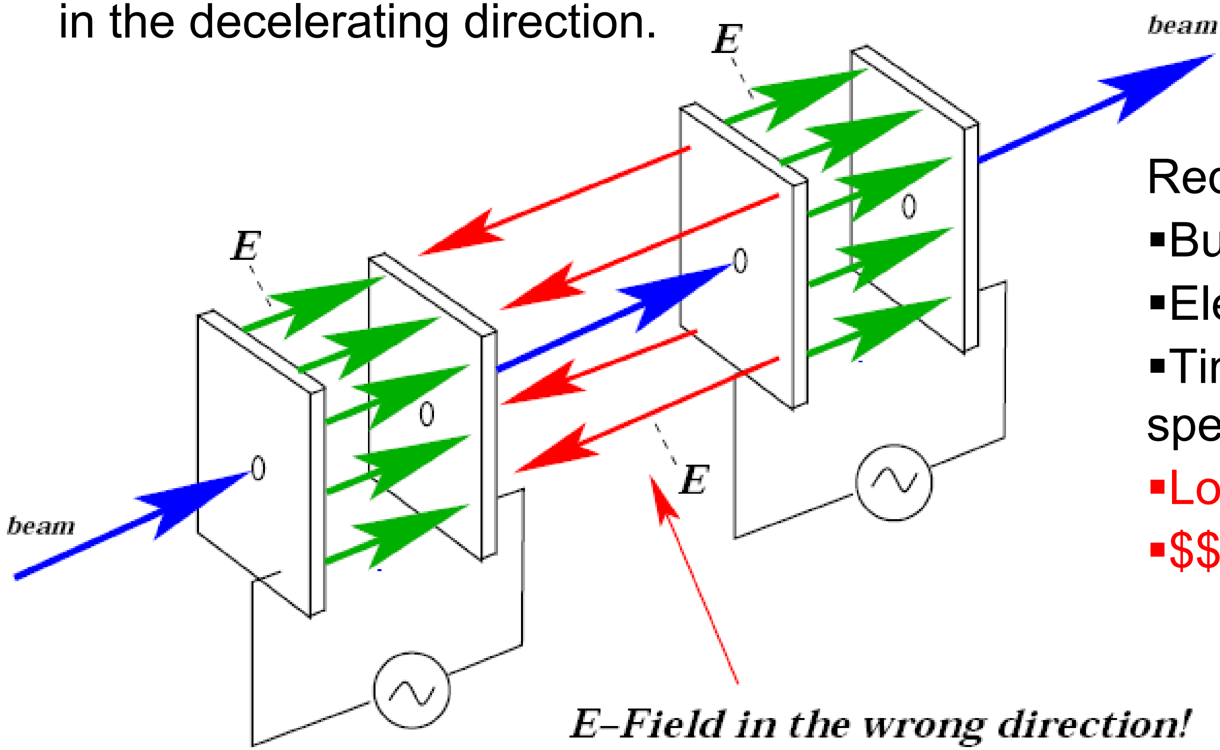
Equip the accelerating gap with a return path - a series of bending and focusing magnets called "magnetic lattice"

Cost savings arise because RF acceleration systems are much more expensive than DC magnets.



Linear Accelerators employ multiple accelerating gaps, many cavities.

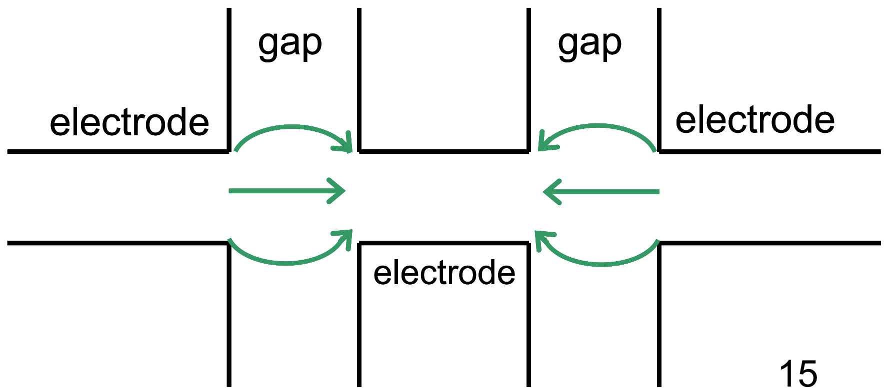
The particle must be protected from the AC electric field when field polarity is in the decelerating direction.



Requires:

- Bunched Beam
- Electrical Shielding
- Timing between particle speed and RF oscillation
- Long accelerator structure
- $$

In the case of multiple gaps with common electrodes excited from a single RF source, the transit time between gaps must be (n+ ½) RF periods.



So Why a Linear Collider?

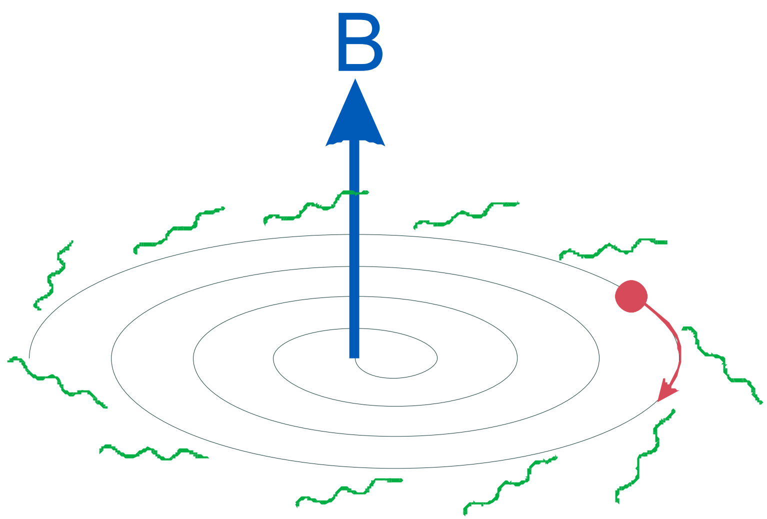
(linear collider = two opposing linear accelerators)

Particle energy

Magnetic field

Synchrotron Radiation Power from an electron in a magnetic field:

$$\boxed{P_\gamma \propto E^2 B^2}$$

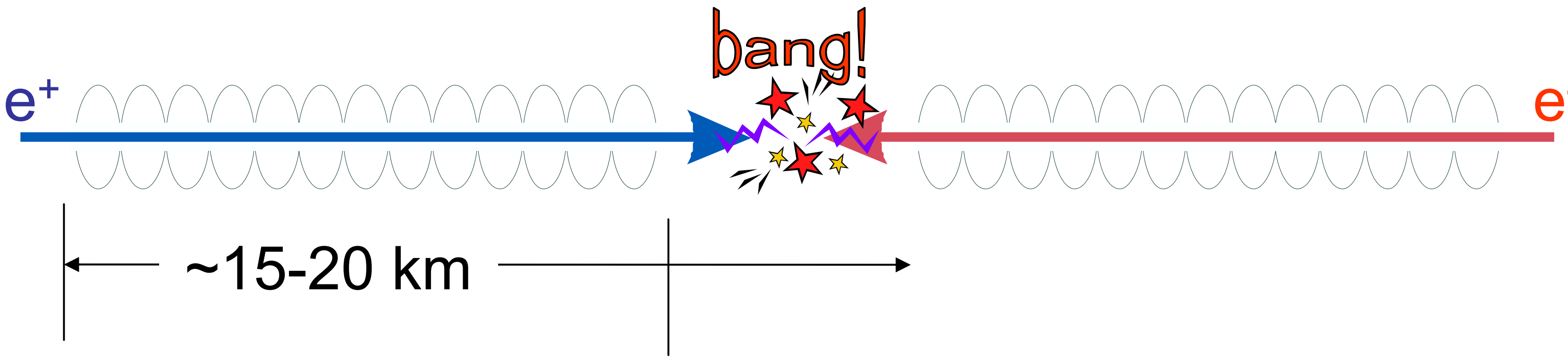


Energy loss per turn of a machine with an average bending radius ρ:

$$\boxed{\frac{\Delta E}{\text{turn}} \propto \frac{E^4}{\rho}}$$

Energy loss must be replaced by RF acceleration system cost scaling \$ $\propto E_{cm}{}^2$

Solution: Linear Collider
No Bends, but *lots* of RF acceleration!



For a E_{cm} = 1 TeV machine:

Effective electric field gradient
G = 500 GV / 15 km

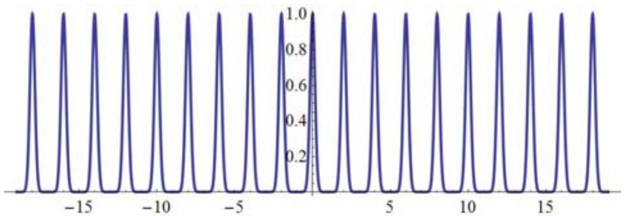
= 34 MV/m

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

The *Luminosity* Issue

Luminosity is the number of particles per unit area per unit time. Combined with scattering cross-sections for sub-atomic processes it is a measure of the number of collisions.

One bunch train



 # bunches in bunch train

particles per bunch

Train repetition rate

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

beam cross-section at Interaction Point (IP)

Beam-beam enhancement factor (pinch effect)

The *Luminosity* Issue

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

In a circular machine such as LEP train repetition rate is revolution frequency around the ring – relatively high.

In linear machine, rep rate is how quickly you can afford to pulse the machine.

BOTTOM line: you have to compensate by using beams of much smaller cross-section in ILC

LEP f_{rep} = 40 kHz

ILC f_{rep} = 5 Hz!

LEP: 130×6 μm^2

ILC: 550×5 nm^2

SUMMARY

Because of dramatic energy loss via synchrotron radiation, no choice but to use linear accelerator.

However, luminosity of collisions depends on having smallest possible beams collide head on.

Cannot make beams with sufficiently small transverse size without deliberately exciting some (limited) synchrotron radiation!

Particle Accelerator Basics

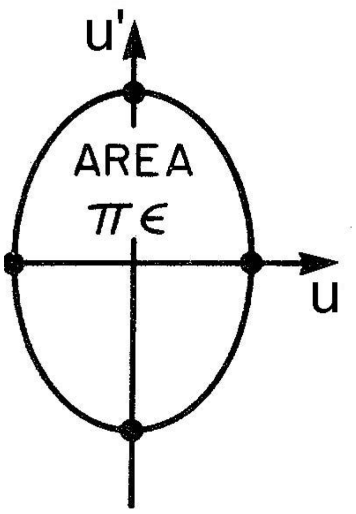
- Emittance
- Lattice functions
- Synchrotron radiation

Emittance

Emittance characterizes the particle beam. Never interested in single electrons, always a population or ensemble. For a system whose dynamics can be derived from a Hamiltonian/Lagrangian, the volume occupied in the 6D space of position and conjugate momentum is a constant.

In the absence of coupling between degrees of freedom, volume maybe written as the product of the areas occupied in the three orthogonal subspaces.

The area in each plane is an **"invariant emittance".**



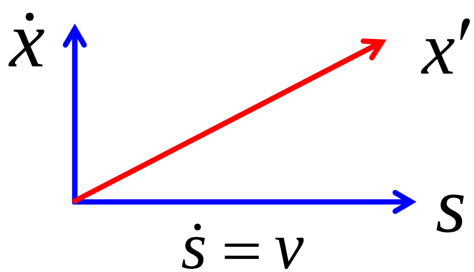
Invariant vs geometric emittance

Strictly speaking, invariant emittance refers to the space formed by the coordinates and their canonically conjugate **momenta**

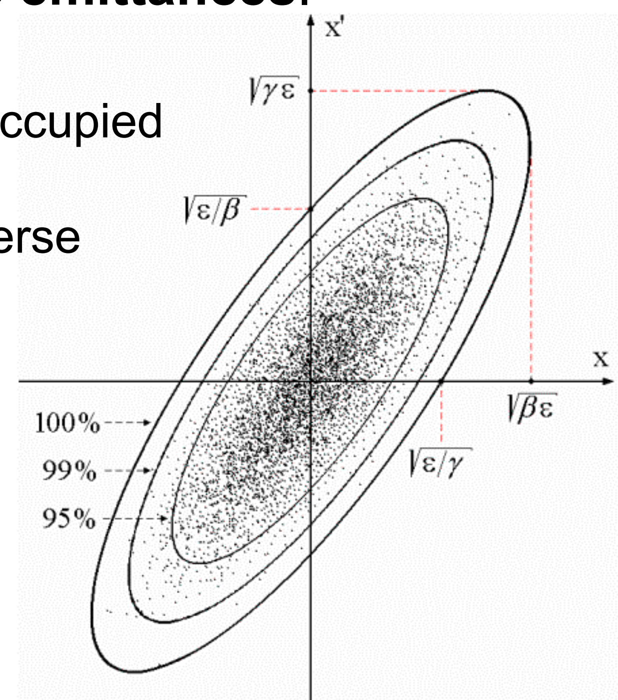
$$p_x \equiv \frac{\partial L}{\partial \dot{x}}$$, etc., where *L* is the Lagrangian

i.e. the space of (x, p_x, y, p_y, z, p_z) - or perhaps (*t*, *E*) longitudinally.

But in situations where the energy *E* = *constant*, the coordinate-divergence space (x, x', y, y', dz, dp_z/p) is a valid phase space. The areas in (x, x') and (y, y') are the **geometric emittances**.



Area occupied in one transverse plane



$$\text{Divergence} \equiv dx/ds \equiv x'$$

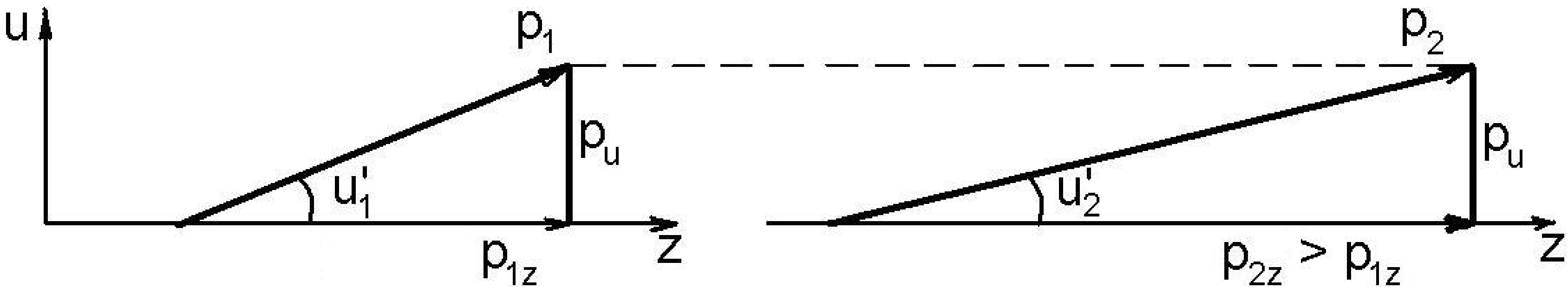
$$\dot{x} = \frac{dx}{dt} = \frac{dx}{ds}\frac{ds}{dt} = x'v$$

ADIABATIC DAMPING

The "geometric" emittance ε is usually quoted in displacement-divergence *(u-u')* units such as mm-mrad

- but conserved quantity has units of displacement-momentum *(u-p_u)*.

No problem at fixed energy, but where there is acceleration, the increased forward velocity reduces the divergence.



This phenomena, where the beam transverse dimensions can be made smaller simply by longitudinal acceleration is called "Adiabatic Damping" – it's a useful effect!

What we measure in the laboratory is geometric emittance. This is normalized to a constant value by multiplying by relativistic kinematic $\beta\gamma$

Invariant emittance= Normalized emittance= $\beta\gamma$ ×geometric emittance

Magnet Structure & Lattice functions

Almost invariably, particles are accelerated by AC electric fields and are guided by DC (or slowly ramped) magnetic fields.

Typically there is a reference particle: this is defined to travel along the "axis" of the accelerator, and to receive precisely the correct amount of acceleration.

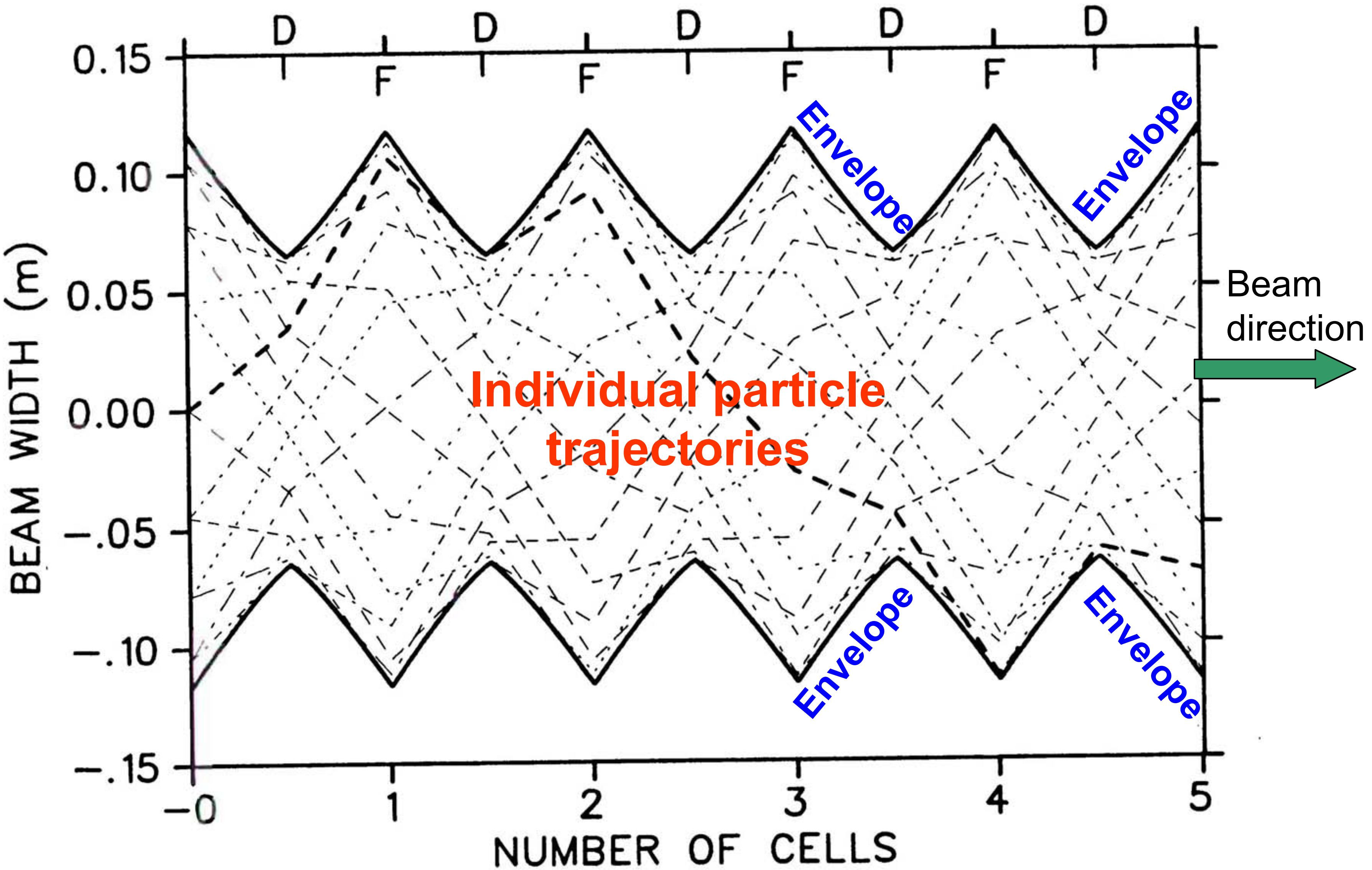
But we have to treat entire particle beam: this includes off-axis particles and particles having the wrong longitudinal momentum.

A system of magnetic elements called the "lattice" provides transverse restoring forces for off-axis particles that bring them back toward the reference axis.

In a linear accelerator, the axis is straight.

In a circular accelerator, the reference "axis" is curved.

The beam is a bundle of individual rays that oscillate transversely within an envelope that reflects the periodicity of the magnetic elements.



Alternating focusing in a F0D0 lattice – provided by quadrupoles with alternating polarity

Lattice functions – the machine description

Lattice functions provide a beam-independent description of the transverse focusing properties of the particle accelerator.

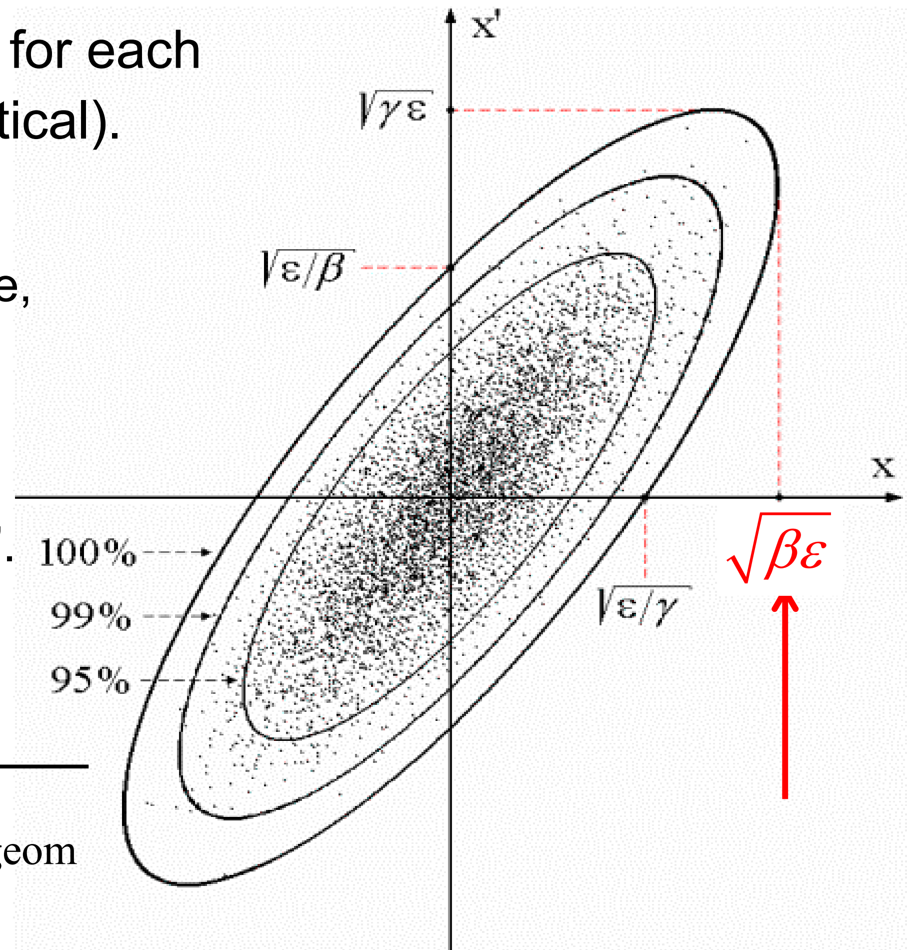
Given a sequence of linear magnetic elements (dipoles, quadrupoles), four lattice functions (α,β,γ,η) may always be computed for each transverse plane (horizontal & vertical).

The beta function β(s): Essentially, if somebody tells you the beam emittance, this function allows you to immediately calculate the maximum particle displacements.

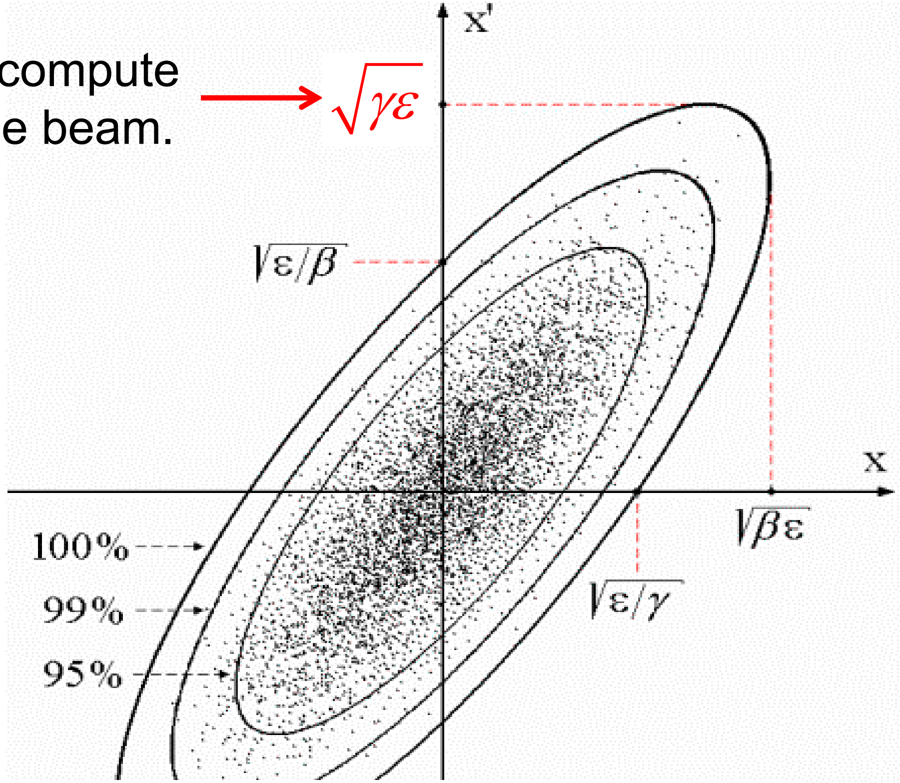
i.e. transverse size or "beam envelope".

You have to plug in the geometric emittance ε for the particular beam.

$$\text{Envelope } \Delta x(s) = \pm\sqrt{\beta(s)\,\varepsilon_{\text{geom}}}$$



The gamma function $\gamma(s)$: this allows you to compute the maximum divergence of particles with the beam.



The alpha function $\alpha(s)$: Essentially this tells you whether the beam envelope is converging toward the axis or diverging away from it.

$$\alpha(s) = -\frac{1}{2}\frac{d\beta}{ds}$$

Conservation of area implies the identity $(\beta\gamma - \alpha^2) = 1$

The previous three functions assume particles have the reference longitudinal momentum.

The fourth function is **dispersion** $\eta(s)$. This tell you the additional displacement and divergence off axis for an "off-momentum" particle.

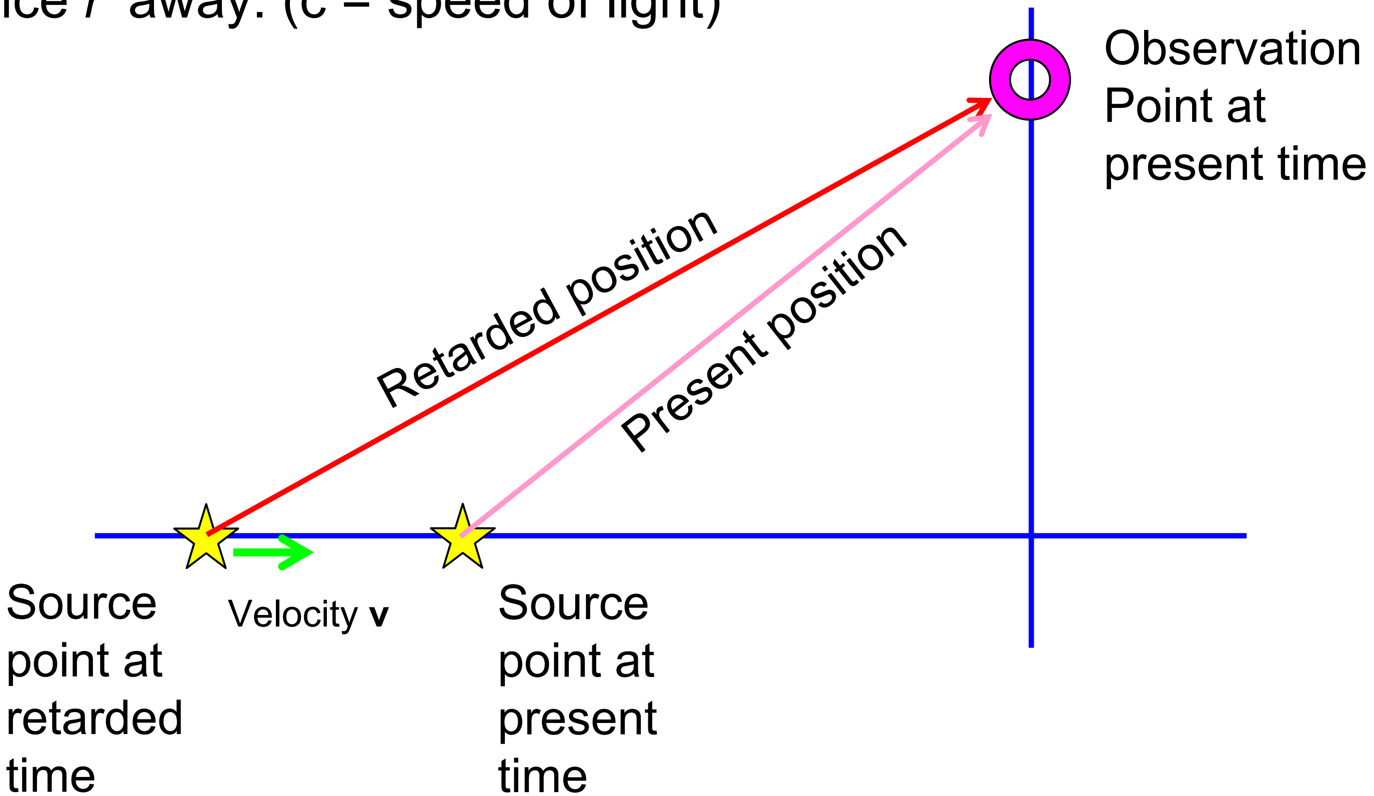
$$\Delta x = \eta(s)\frac{\Delta p_z}{p_z} \qquad \Delta x' = \eta'(s)\frac{\Delta p_z}{p_z}$$

The source of dispersion is bending magnets: different momenta have different bending radii

Synchrotron Radiation – from accelerated charges

EM fields travel at the speed of the light. The concept of retarded fields takes account of field propagation time.

Suppose we have an observation point and a source point. We know both their locations at time *t*. But the field at the observation point at time t, was emitted by the source at a retarded time $t' = t - r'/c$ when it was a retarded distance r' away. (c = speed of light)



Synchrotron Radiation – from accelerated charges

It is customary to write the E and B fields in terms of retarded times and distances, and drop the primes.

$$\frac{4\pi\varepsilon_0 s^3}{q}\mathbf{E} = \frac{\mathbf{r}_u}{\gamma^2} + \frac{1}{c^2}\left[\mathbf{r}\times\left(\mathbf{r}_u \times \frac{d}{dt}\mathbf{v}\right)\right] \quad \text{and} \quad \mathbf{B} = \frac{\mathbf{r}\times\mathbf{E}}{rc} \quad \text{where} \quad \frac{1}{\gamma^2} = \left(1-\frac{v^2}{c^2}\right)$$

All quantities are retarded

$$\mathbf{r}_u \equiv \left(\mathbf{r} - \frac{\mathbf{v}r}{c}\right) \quad \text{and} \quad s = r - (\mathbf{v}\cdot\mathbf{r})/c$$

When d**v**/dt=0, fields fall of as $1/R^2$ - like Coulomb field

When d**v**/dt ≠ 0, get additional radiation field – falls of as 1/R

The *minimalist* definition of E.M. radiation is a non-zero value for the Poynting vector **S = E×B** which gives energy flow per unit surface.

$$S = \left(\frac{e}{4\pi\varepsilon_0}\right)^2 \frac{r}{\varepsilon_0 s^5 c^3}\left[\mathbf{r}\times\left(\mathbf{r}_u \times \dot{\mathbf{v}}\right)\right]^2$$

Synchrotron radiation continued

Poynting vector
$$S=\left(\frac{e}{4\pi\varepsilon_0}\right)^2\frac{r}{\varepsilon_0 s^5 c^3}\left[\mathbf{r}\times\left(\mathbf{r}_u\times\dot{\mathbf{v}}\right)\right]^2$$

Integrating this flux over a sphere centred on the charge gives the synchrotron radiation power:

$$-P_\gamma=\frac{2}{3}\frac{e^2}{4\pi\varepsilon_0}\frac{\gamma^2}{m_0^2c^3}\left[\left(\frac{d\mathbf{p}}{dt}\right)^2-\left(\frac{1}{c}\frac{dE}{dt}\right)^2\right]$$

$\mathbf{p}=\text{momentum}$

The Lorentz force $\dfrac{d\mathbf{p}}{dt}=e\left(\mathbf{v}\times\mathbf{B}\right)\equiv\mathbf{F}$ implies d**p**/dt is perpendicular to **v** and $\dfrac{dE}{dt}=\mathbf{F}\cdot\mathbf{v}=0$

Hence the instantaneous radiation power is
$$-P_\gamma=\frac{2}{3}\frac{e^4}{4\pi\varepsilon_0}\frac{\left|\mathbf{p}\times\mathbf{B}\right|^2}{m_0^4c^3}$$

Inverse quartic dependence on particle mass explains why synchrotron radiation so much worse for electrons than protons.

$$m_p\approx 2000\times m_e$$

Synchrotron radiation continued

We may use the relation **p**/ρ = e**B**, where ρ is the local bending radius to eliminate the magnetic field strength **B**.

$$-P_\gamma = \frac{ec}{6\pi\varepsilon_0}\frac{1}{\rho^2}(\beta\gamma)^4 = 0.2878 \times \frac{1}{\rho^2\left(\text{metre}^2\right)}(\beta\gamma)^4 \ \text{eV/sec}$$

If we assume constant bending radius, then the energy loss per turn (per particle) is

$$E_\gamma = P_\gamma \times \frac{2\pi\rho}{v} = \frac{e}{3\varepsilon_0}\frac{\beta^3\gamma^4}{\rho} = 6\times10^{-9}\,\frac{\beta^3\gamma^4}{\rho\left(\text{metre}\right)} \ \text{eV}$$

Comparison of synchrotron radiation at two HEP colliders

Machine	particle	Energy GeV	gamma x10^3	Bend radius km	B-field Tesla	Radiation power GeV/sec	Energy loss per turn MeV
LHC	proton	7000	7.46	2.78	8.4	0.115	0.0067
LEP	electron	50	97848	1.191	0.14	18590	464

LEP= Large Electron Positron Collider. 28 km ring at CERN. Performed precision experiments on W± and Z_0 bosons

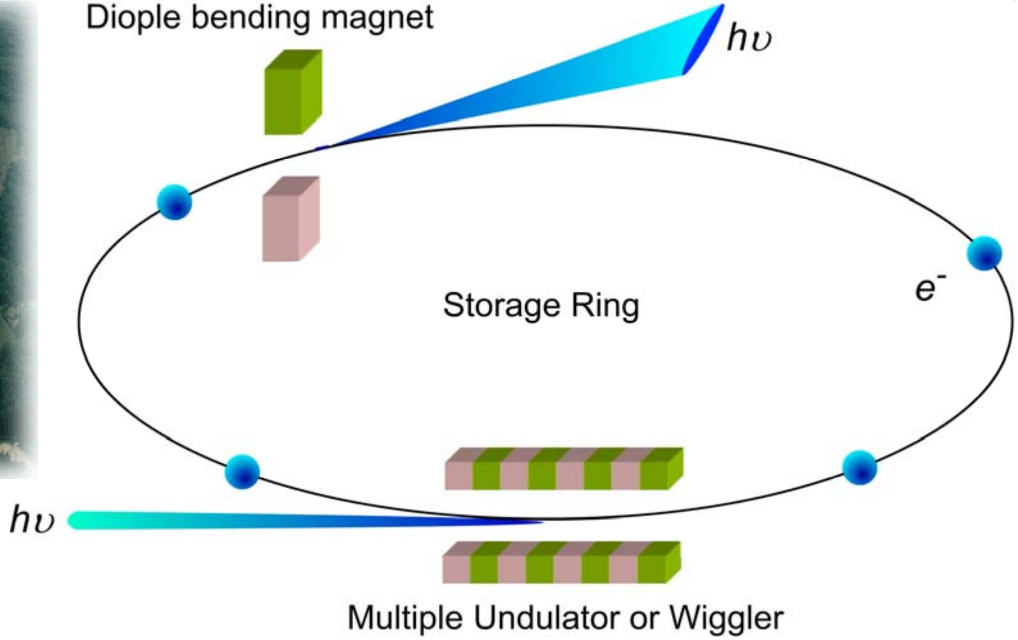
LHC= Large Hadron Collider. 28 km at CERN, will discover Higgs particle or…

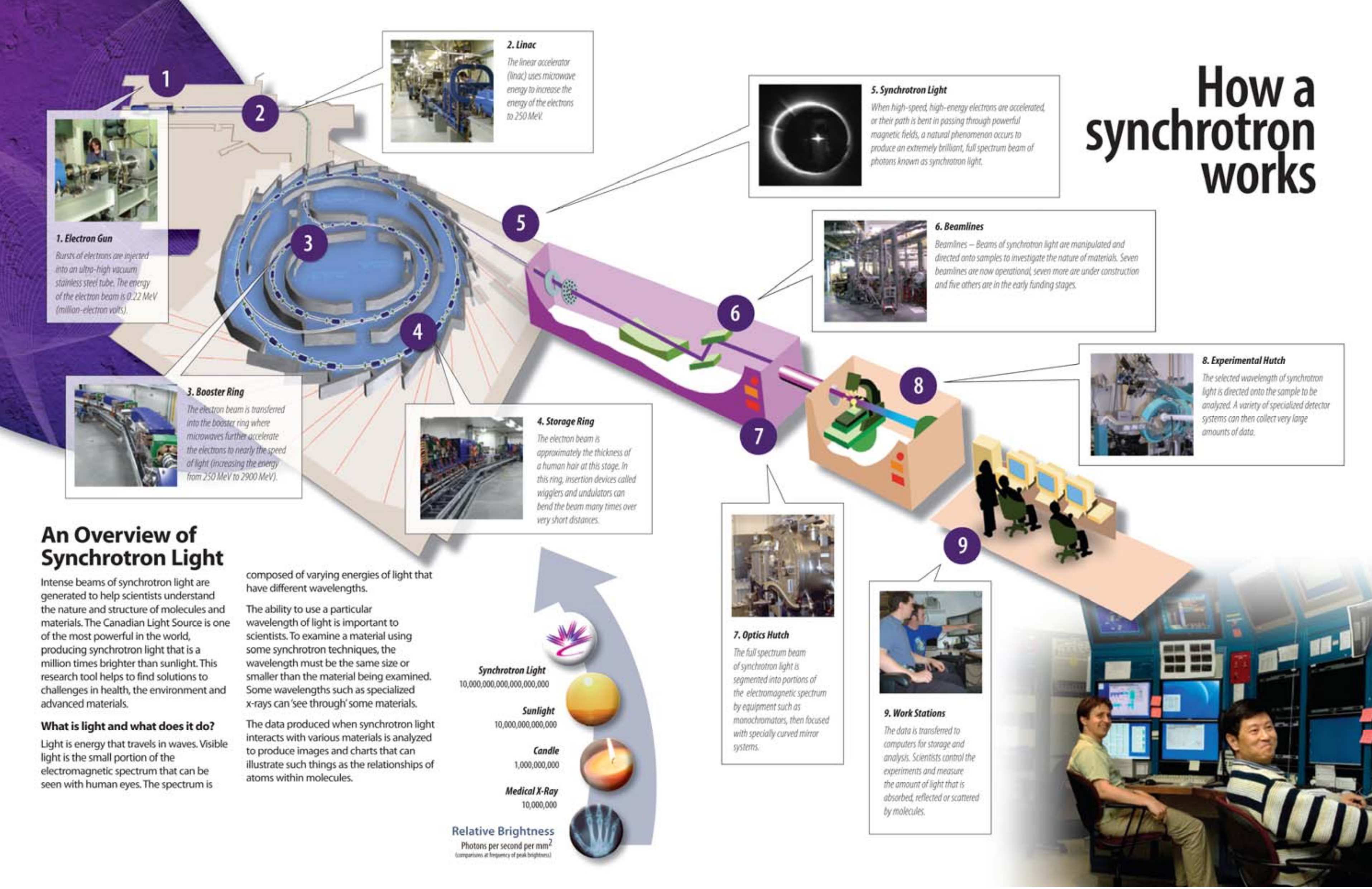
ILC energy is 250 GeV in each beam, synchrotron radiation losses would be unimaginable in a circular collider

Synchrotron light sources

There are very few high-energy colliders world-wide, but there are many light-sources. The light is very brilliant, is tunable and is used for a variety of diffraction experiments for the determination of structures in chemistry, materials science (e.g. semiconductors, alloys), biology (e.g. proteins, cells, bone structure), etc.

Most dedicated light sources operate in regime 1-3 GeV with rings of modest size, 100 metre radius. But three 6-8 GeV rings exist across the globe (APS USA, ESRF France, SPRING8 Japan).

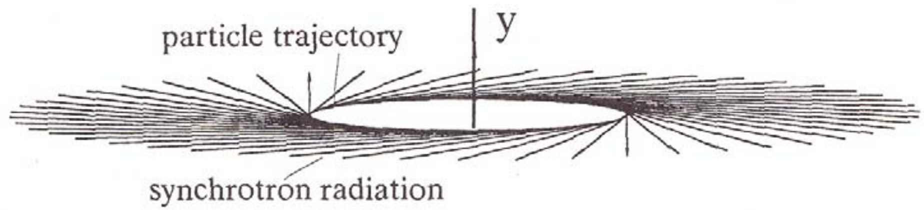




THE CANADIAN LIGHT SOURCE IN SASKATOON

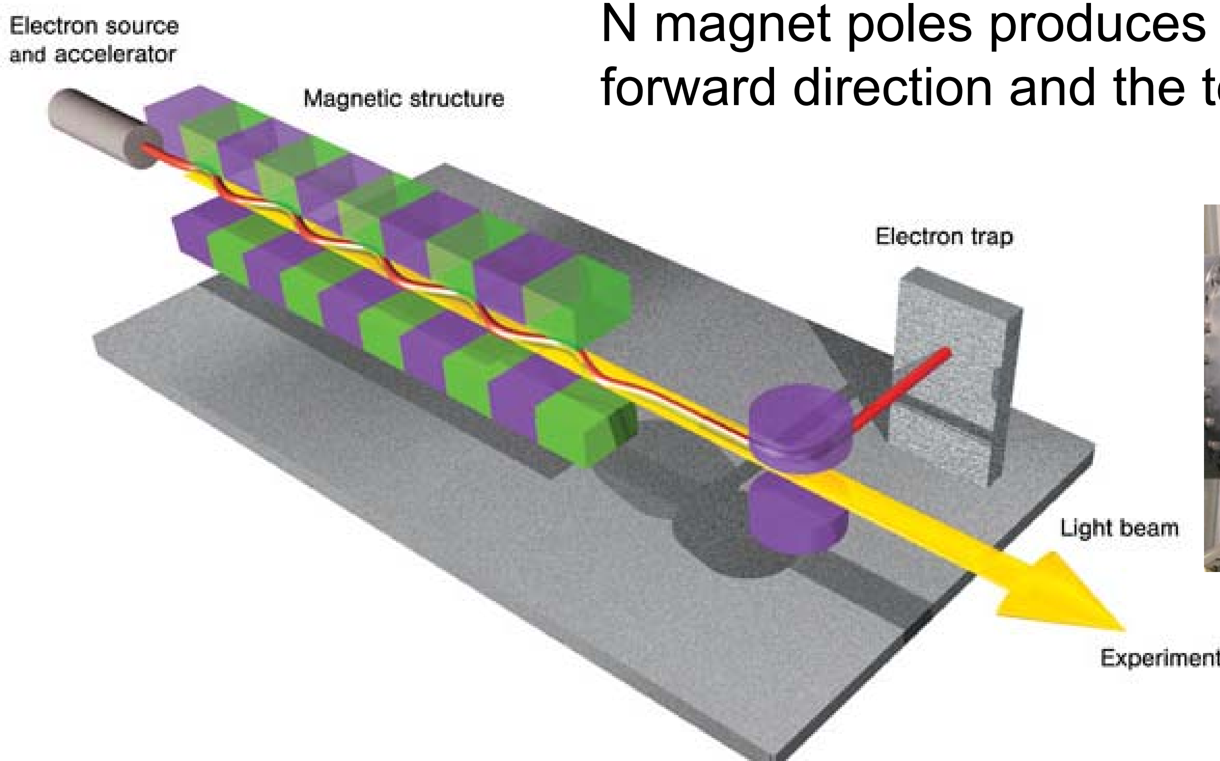
250-MeV electron linac + 2.9-GeV booster synchrotron + storage ring

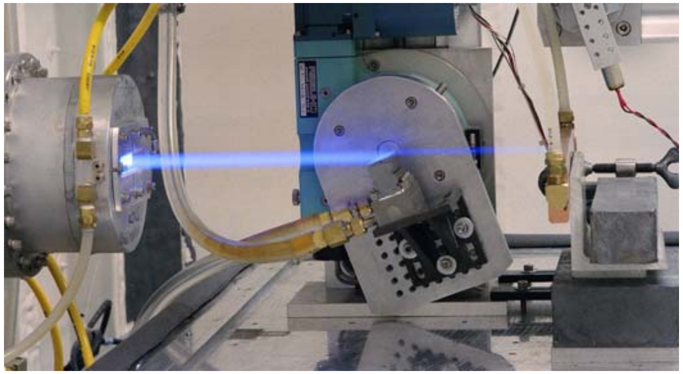
Bending Magnet Radiation: appears as a horizontal swath with a vertical opening angle $\pm 1/\gamma$



Wiggler/Undulator magnet radiation

Consider series of equal and opposite poles, bending in alternate directions – with no net bend. Each of the N magnet poles produces a fan of radiation in the forward direction and the total flux is N times larger.

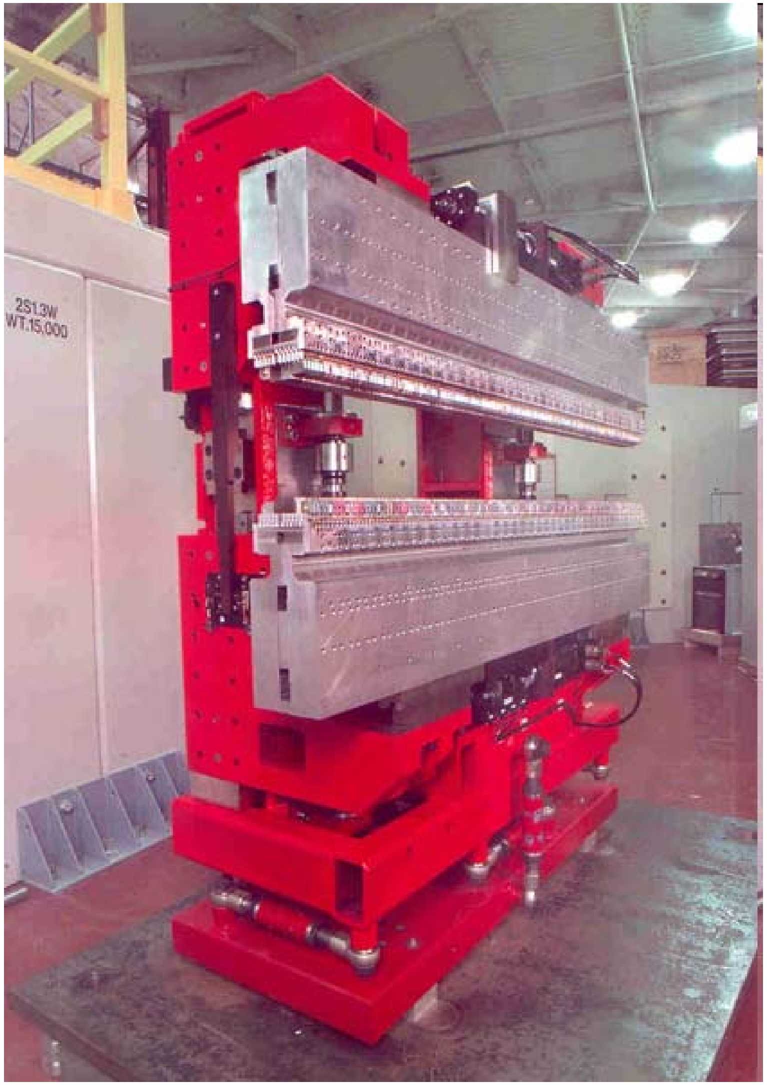




Light beam at National Synchrotron Light Source, Brookhaven National Lab

Wiggler/Undulator magnet radiation

Undulator at Advanced Light Source, Berkley CA



Vertical field $B_y = B_0 \sin\left(2\pi z / \lambda_p\right)$ $\lambda_{\mathbf{p}} = \text{wiggler period}$

Deflection angle per half pole $\theta = \dfrac{B_0}{p}\dfrac{\lambda_p}{2\pi}$

Strength parameter $K = \gamma\theta$

If K»1, device is strong: a "**wiggler**". Get periodic interchange of longitudinal and transverse momentum

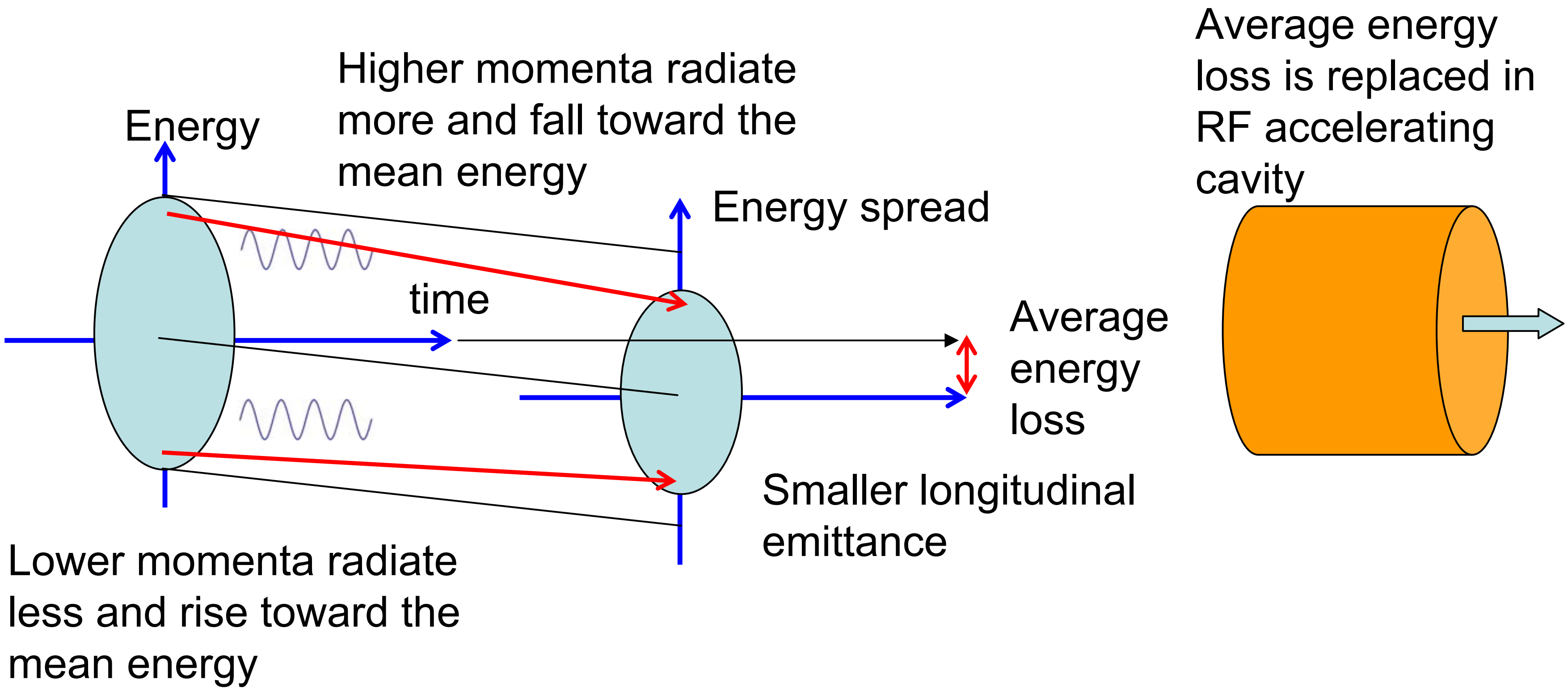
If K≤1, device is weak: an "**undulato**r". The deflection angle «1 Hence, purely transverse oscillation with period of magnet structure, and an approx monochromatic radiation spectrum.

Wavelength of radiation: $\lambda_\gamma = \dfrac{\lambda_p}{2\gamma^2}\left[1 + K^2/2\right]$

Photon energy $E_\gamma\left(\text{eV}\right) = 950\dfrac{E^2\left(\text{GeV}^2\right)}{\lambda_p\left(\text{cm}\right)\left(1 + K^2/2\right)}$

Beam emittance damping by synchrotron radiation emission

So far we have learnt that synchrotron radiation leads to beam energy loss. But there is another effect that is also relevant to ILC – it leads to smaller emittances. Let us start with the longitudinal effect.



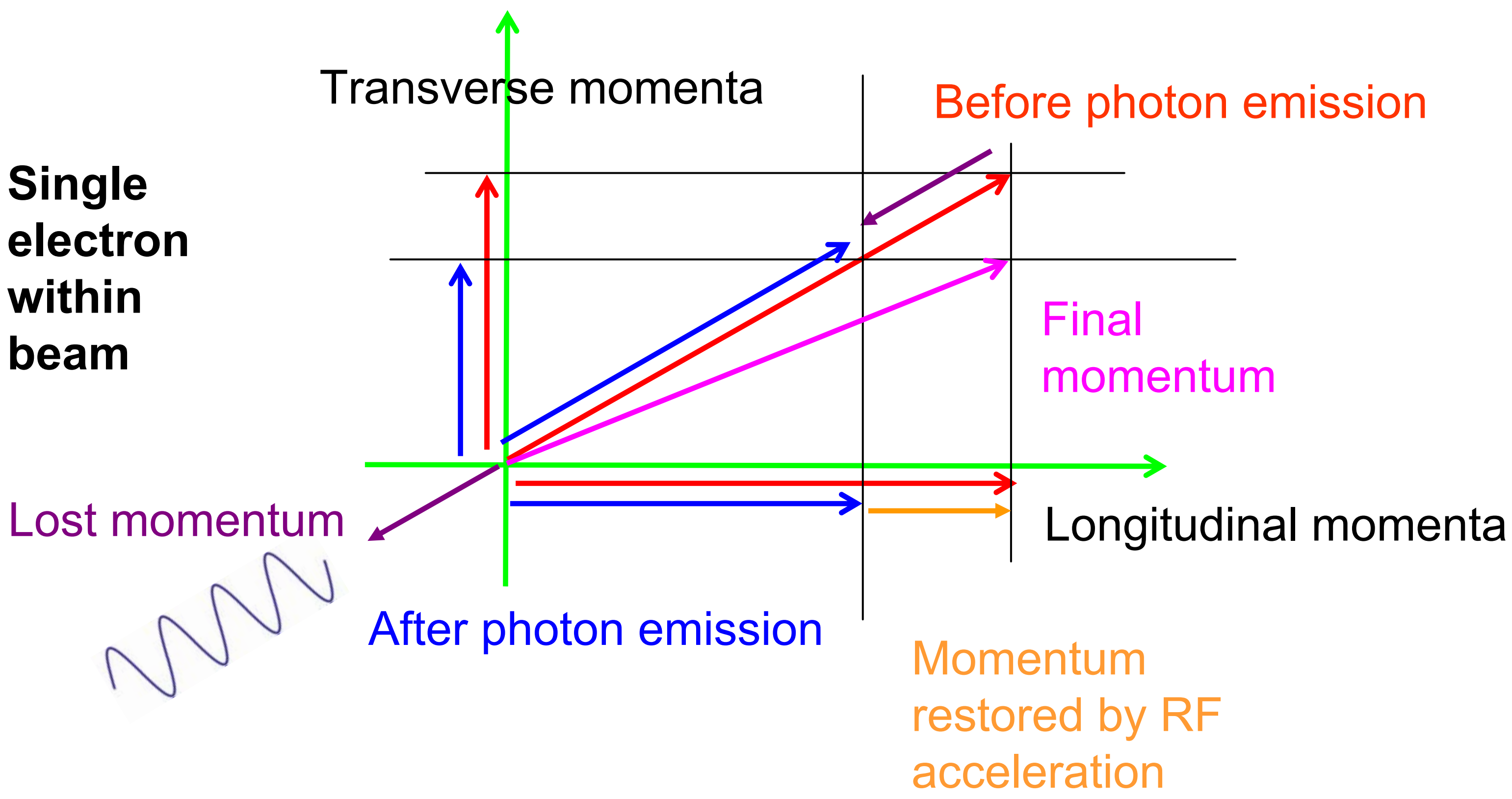
Returning to the ***Luminosity Issue***, this is a mechanism that can be used to make smaller sized electron beams

Transverse effect of synchrotron radiation

Similar to adiabatic damping.

Transverse momentum is reduced by emission of photon, and is not replaced by the RF cavity. But acceleration restores the longitudinal momentum, and so the beam divergence is reduced.

Single electron within beam



Limitations to emittance damping

Wrinkle: when longitudinal momentum changes, particle is instantaneously on wrong dispersed orbit.

$$\Delta x = \eta(s)\frac{\Delta p_z}{p_z}$$

It is in disequilibrium and so starts a transverse oscillation.

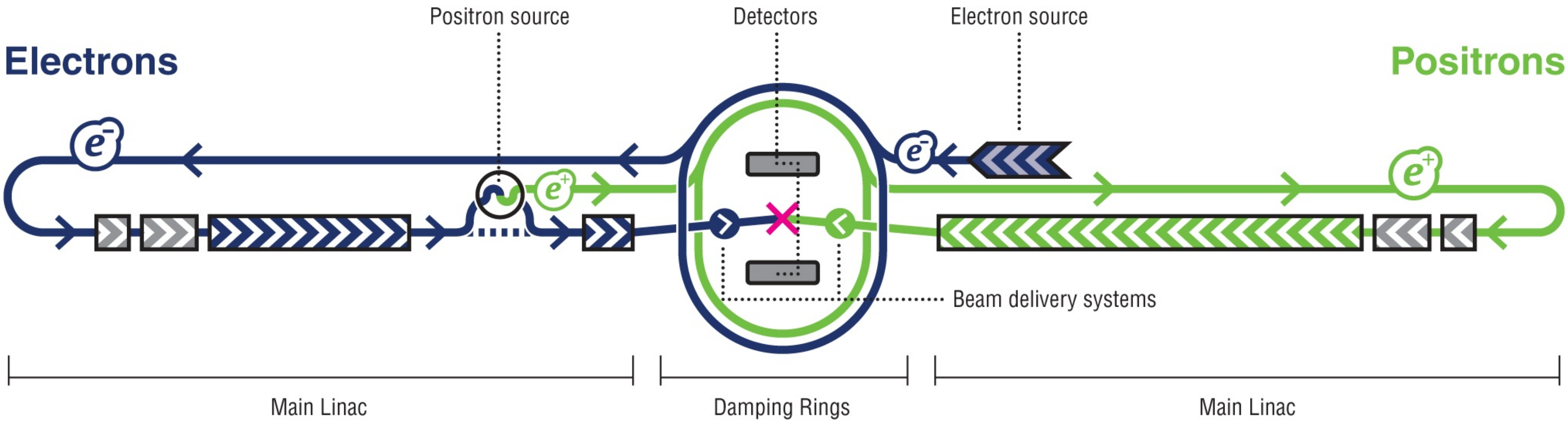
Hence there is a limitation on transverse damping.

Indeed 3 degrees of freedom are coupled and total amount of damping is shared between horizontal, vertical and longitudinal plane – according to partion functions that depend on precise optics of the magnetic lattice.

The other wrinkle: photo-emission is a quantum process: statistical fluctuations will tend to increase the emittance and energy spread. Hence damping down to very small emittances eventually encounters a fundamental limitation.

SKIP

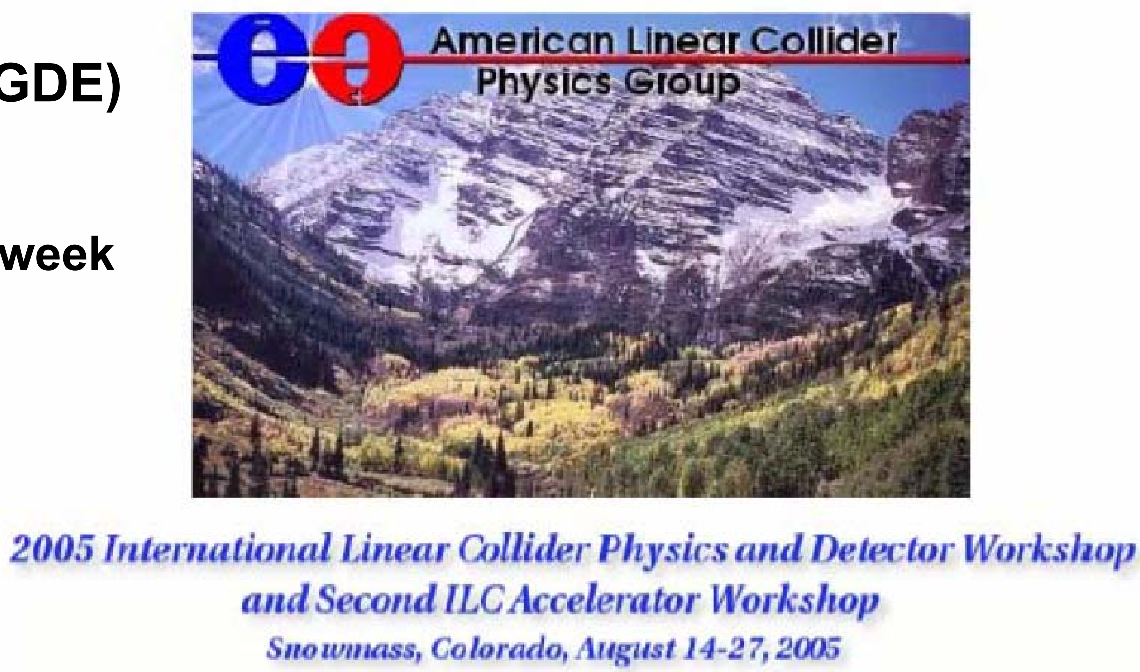
Back to the ILC – how did it all start?



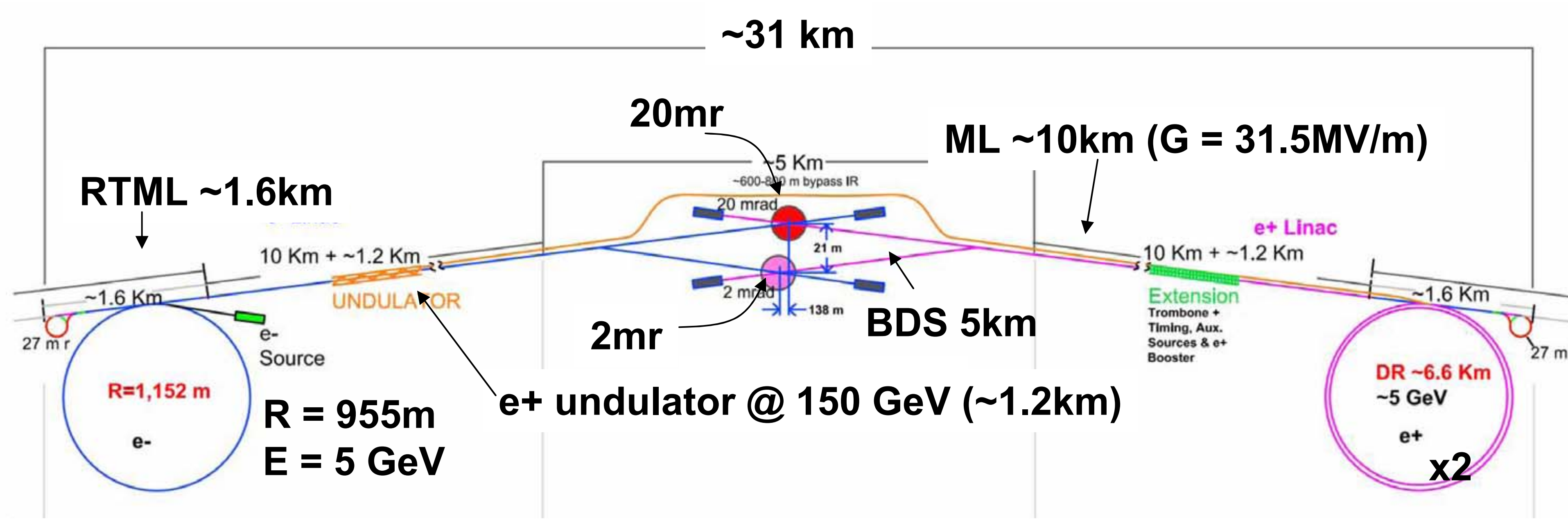
ILC Global Design Effort (GDE) Began at Snowmass 2005

670 Scientists attended two week workshop at Snowmass

GDE formed.
Members:
Americas 22
Europe 24
Asia 16



The Baseline Machine (500GeV) **January 2006**



not to scale

RTML = Ring To Main Linac

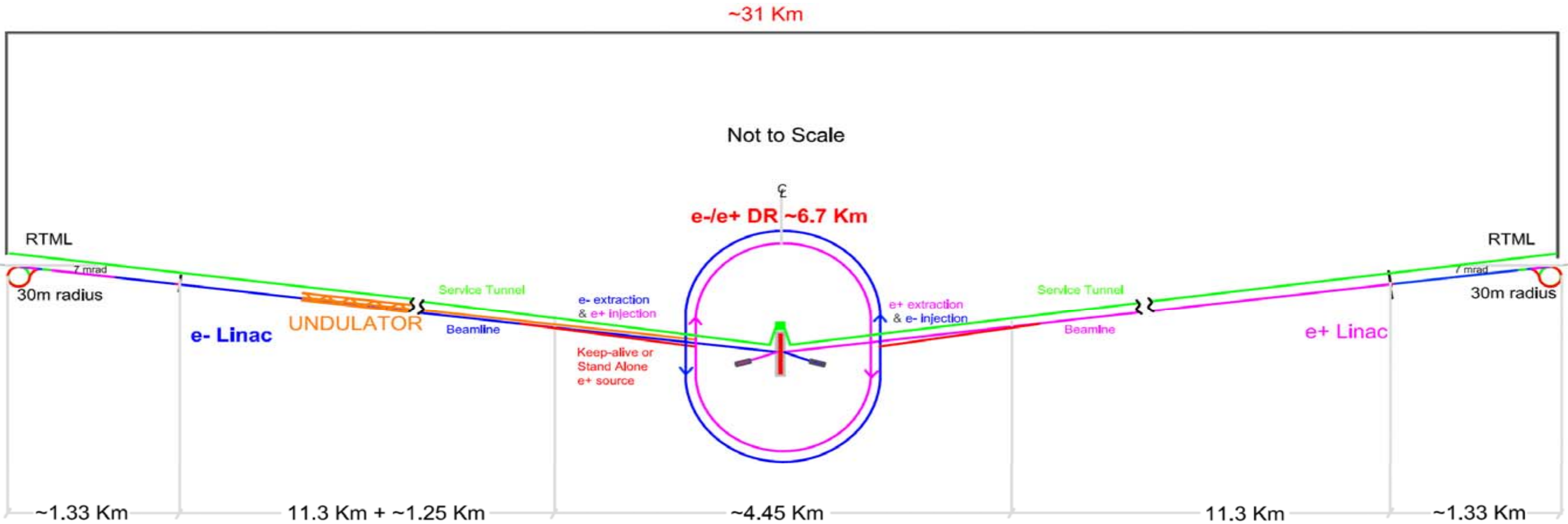
ML = Main Linac

BDS = Beam Delivery System

This is the baseline machine as it appeared in 2006. You will notice damping rings at either end, and two experimental regions at the centre.

ILC Reference Design – Feb 2007

- 11km SC linacs operating at 31.5 MV/m for 500 GeV
- Centralized injector
  - Circular damping rings for electrons and positrons
  - Undulator-based positron source
- Single Interaction Region with 14 mrad crossing angle
- Dual tunnel configuration for safety and availability



Schematic Layout of the 500 GeV Machine

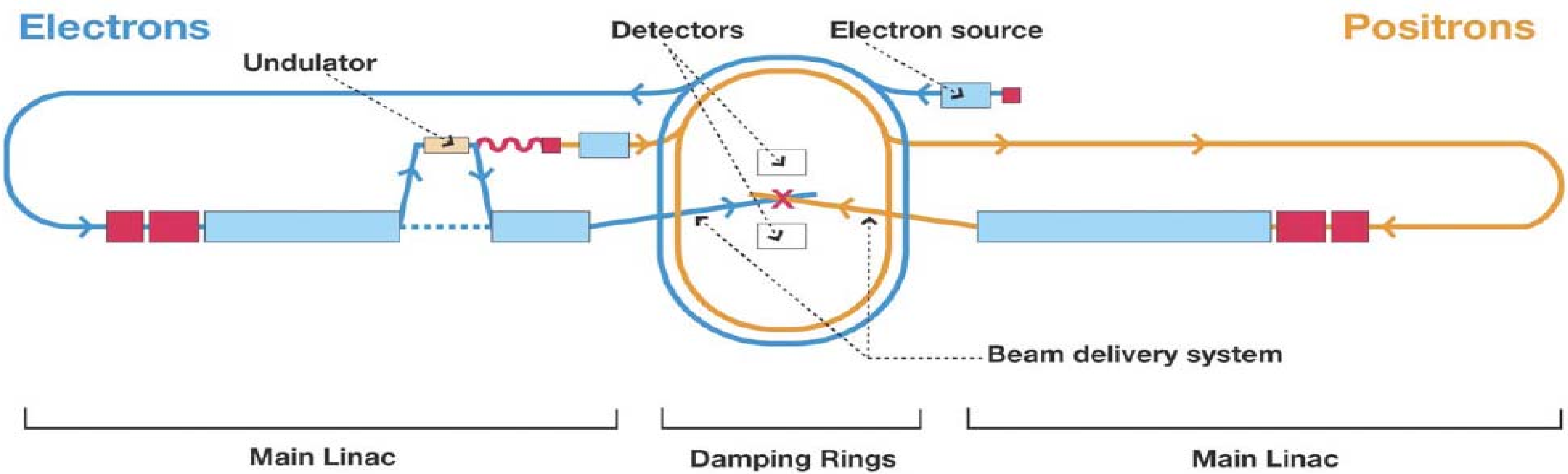
ILC Reference Design Report Parameters

Max. Center-of-mass energy	500	GeV
Peak Luminosity	$\sim 2\times10^{34}$	$1/cm^2s$
Beam Current	9.0	mA
Repetition rate	5	Hz
Average accelerating gradient	31.5	MV/m
Beam pulse length	0.95	ms
Total Site Length	31	km
Total AC Power Consumption	~230	MW

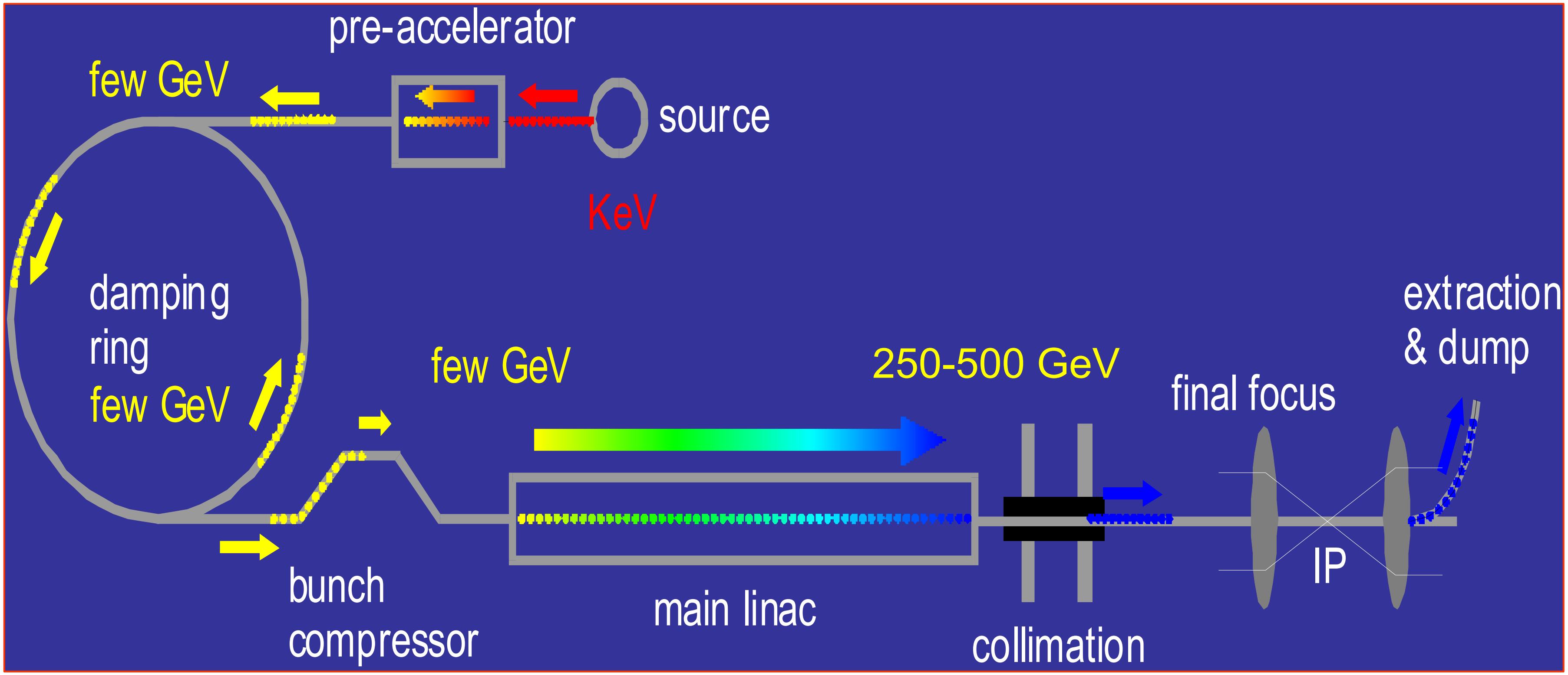
This is the specification to which the machine must be designed.

A Vision of the Future

RDR to ILC, May 2007 –B. Barish

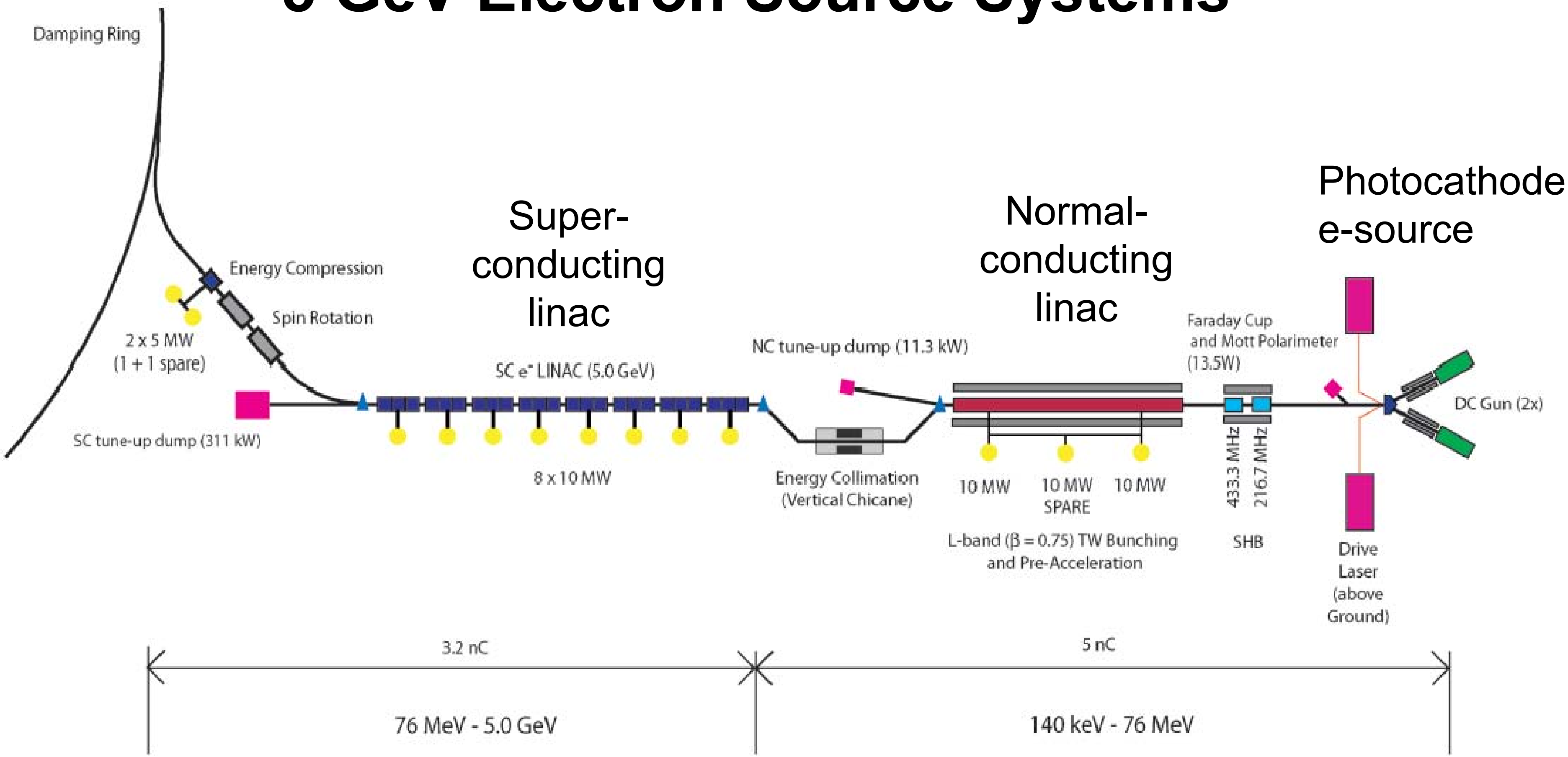


Let us look at one half of this machine and the energy scales involved



Now let us examine the components of this machine starting at the e+,e- sources and finishing at the High Energy Physics detectors

5 GeV Electron Source Systems



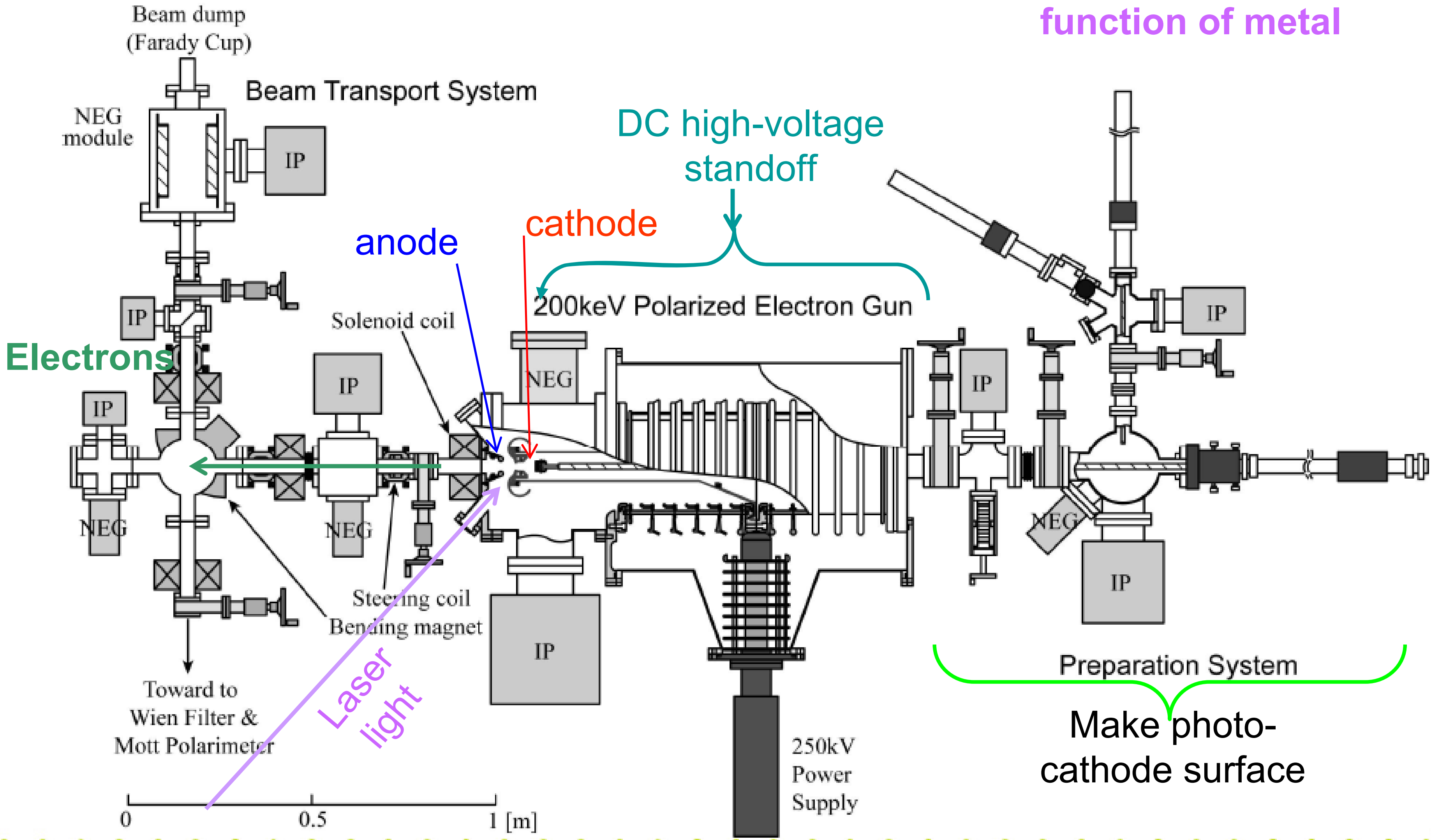
ILC polarized Electron Source Parameters

Parameter	Symbol	Value	Unit
Electrons per bunch (at gun exit)	n_e	$3*10^{10}$	Number
Electrons per bunch (at DR injection)	n_e	$2*10^{10}$	Number
Number of bunches	N_e	~ 3000	Number
bunch repetition rate	$F_{\mu b}$	3	MHz
bunch train repetition rate	F_{mb}	5	Hz
bunch length at source	Δt	2	ns
Peak current in bunch at source	I_{avg}	3.2	A
Energy stability	S	< 5	% rms
Polarization	Pe	80 (min)	%
Photocathode Quantum Efficiency	QE	0.5	%
Drive laser wavelength	λ	780-810 (tunable)	nm
single bunch laser energy	E	5	μJ

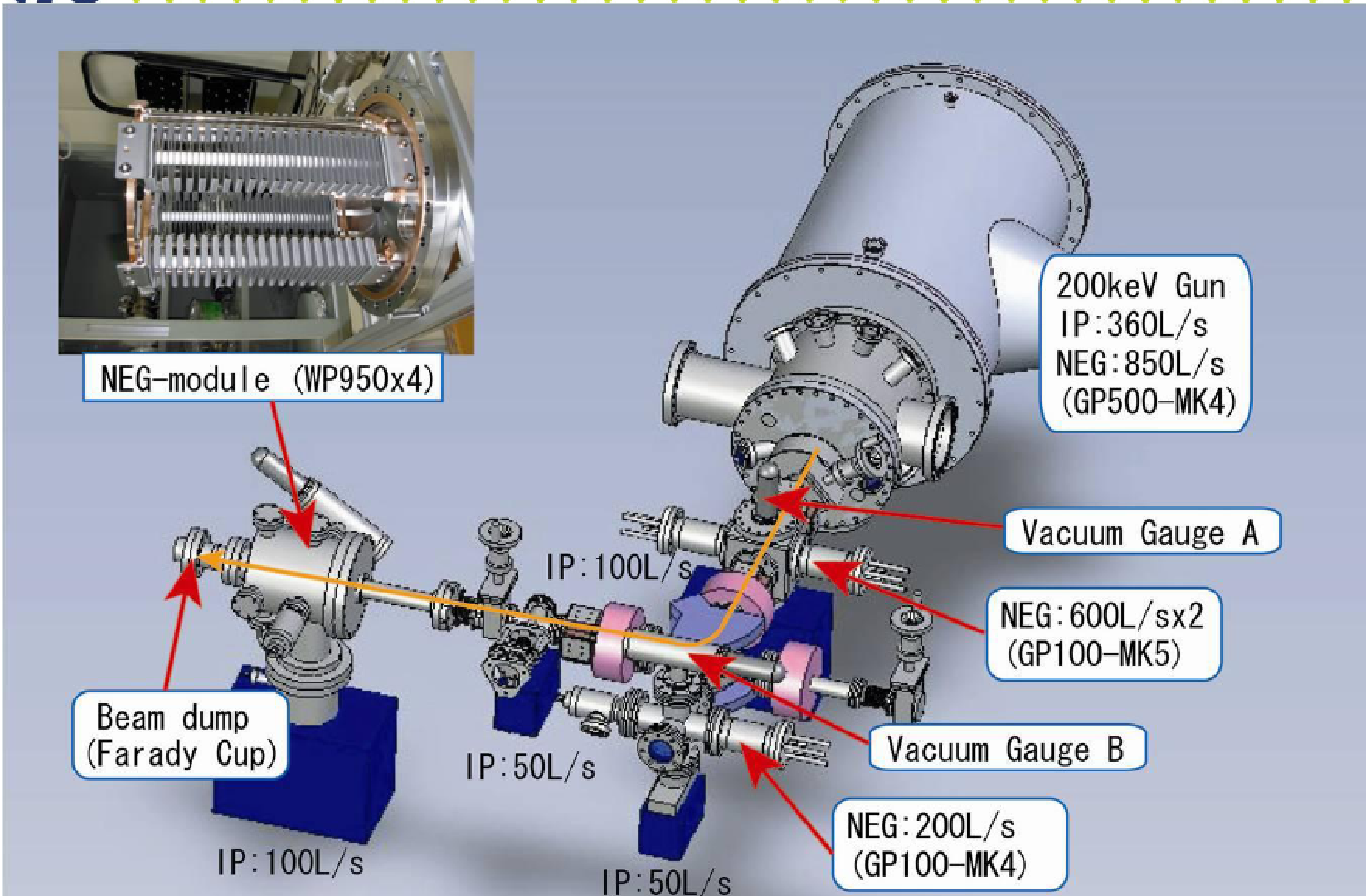
A. Brachmann, J. Sheppard, F. Zhou - SLAC National Accelerator Lab
M. Poelker- Jlab LCWS 2008

200keV Polarized electron source at Nagoya University

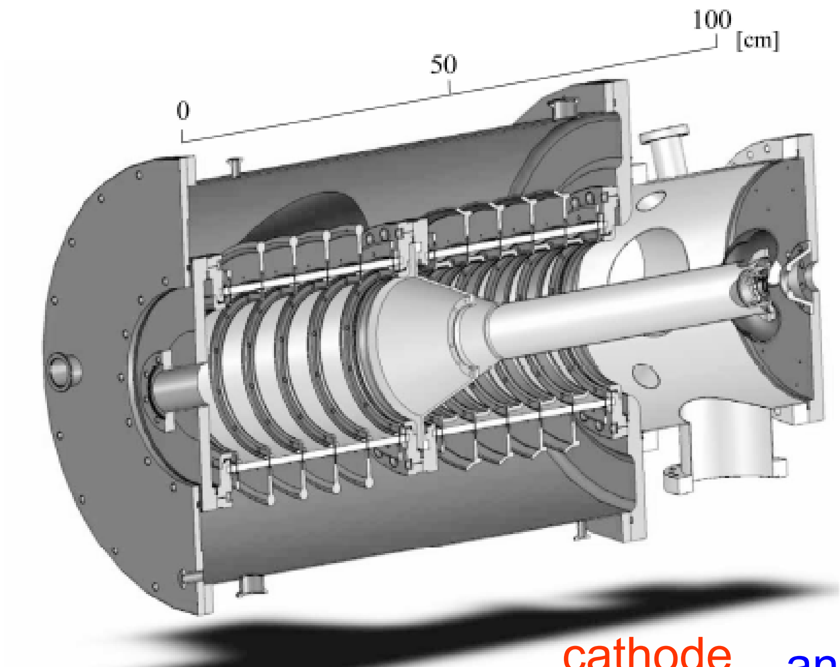
Laser shines with photon energy > work function of metal

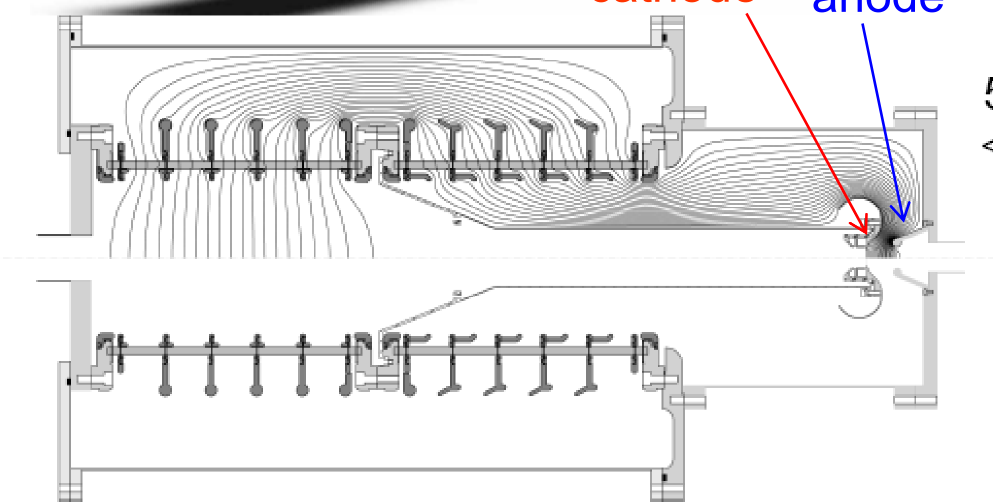


Beam transport & Vacuum system



200keV gun basic performance





Base pressure: 2×10^{-9} Pa

200 baking for >100 hours

360 L/s IP, 850 L/s NEG

Maximum field gradient (200kV):

7.8MV/m (Cathode)

3.0MV/m (Photocathode)

Electrode

Cathode: Molybdenum (>99.6%)

Anode: Titanium (JIS-grad 2)

Finishing: electro-buff polishing

Ceramic

Dividing five segments w/ guard rings.

(to avoid field concentration)

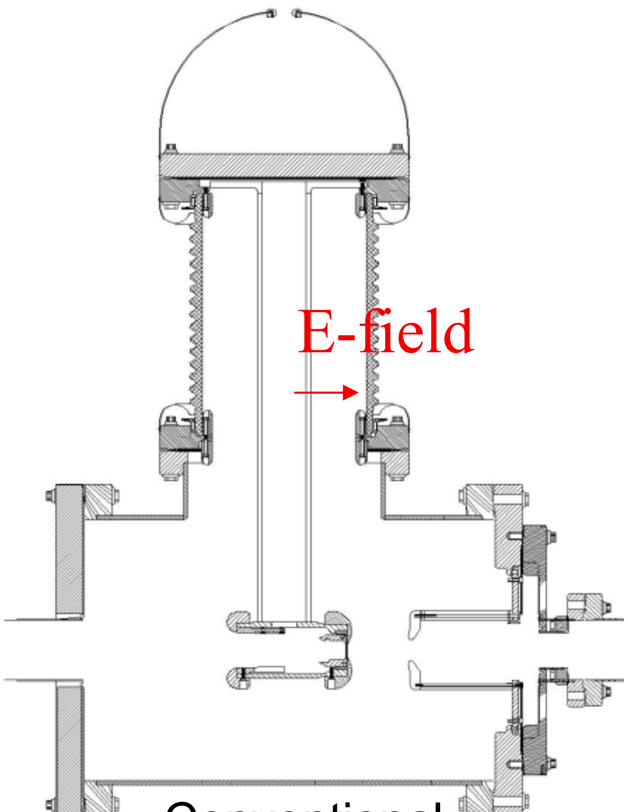
500MΩ connection for each

<0.3MV/m for each segment at the junctions

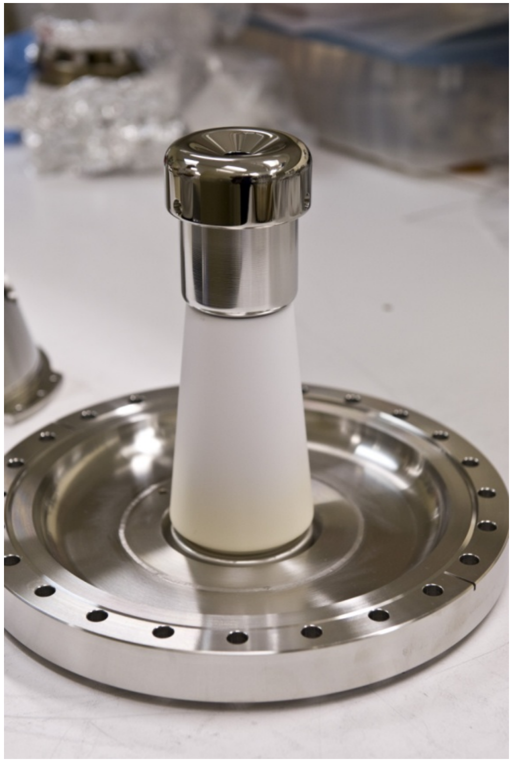
Alternative DC Gun Development at Jefferson laboratory

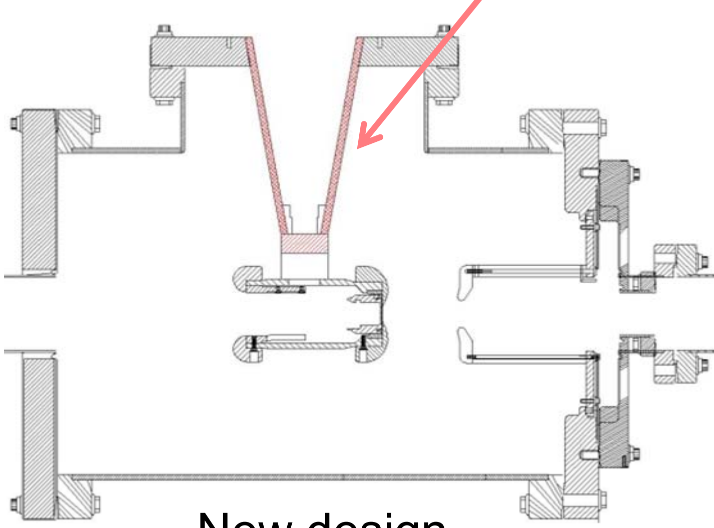
Currently developing a 200kV gun **SKIP**

- **Joint with ILC (CEBAF synergy)**
- **Inverted ceramic insulator**
  - **medical x-ray technology, no exposed HV, no SF6, field emission not likely to accumulate on insulator**



Conventional design

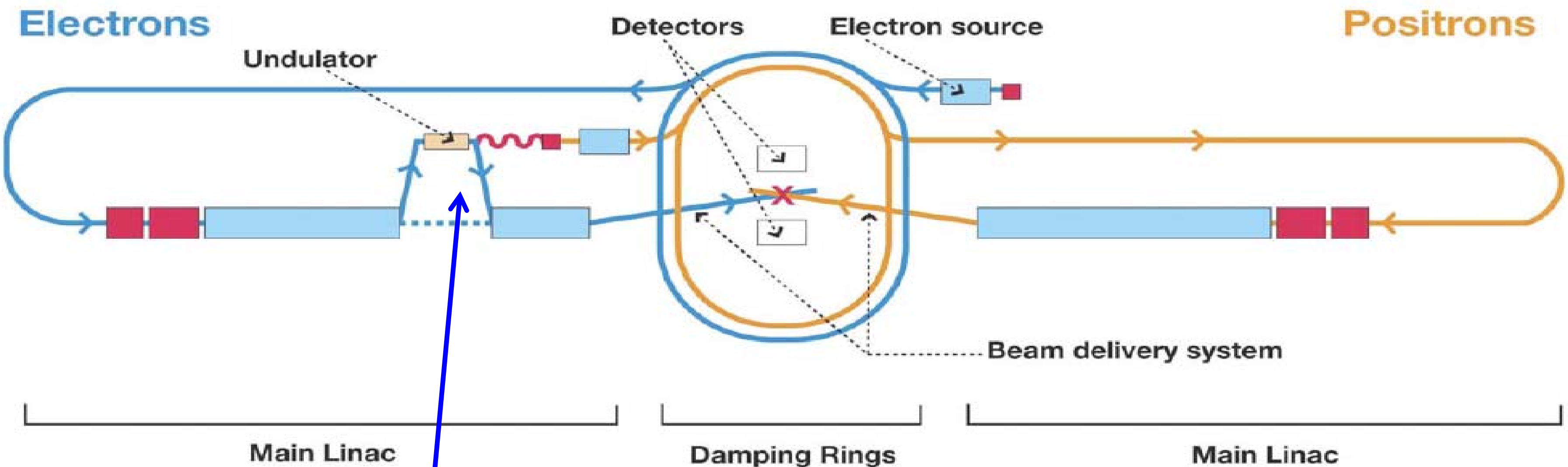




New design concept

A Vision of the Future

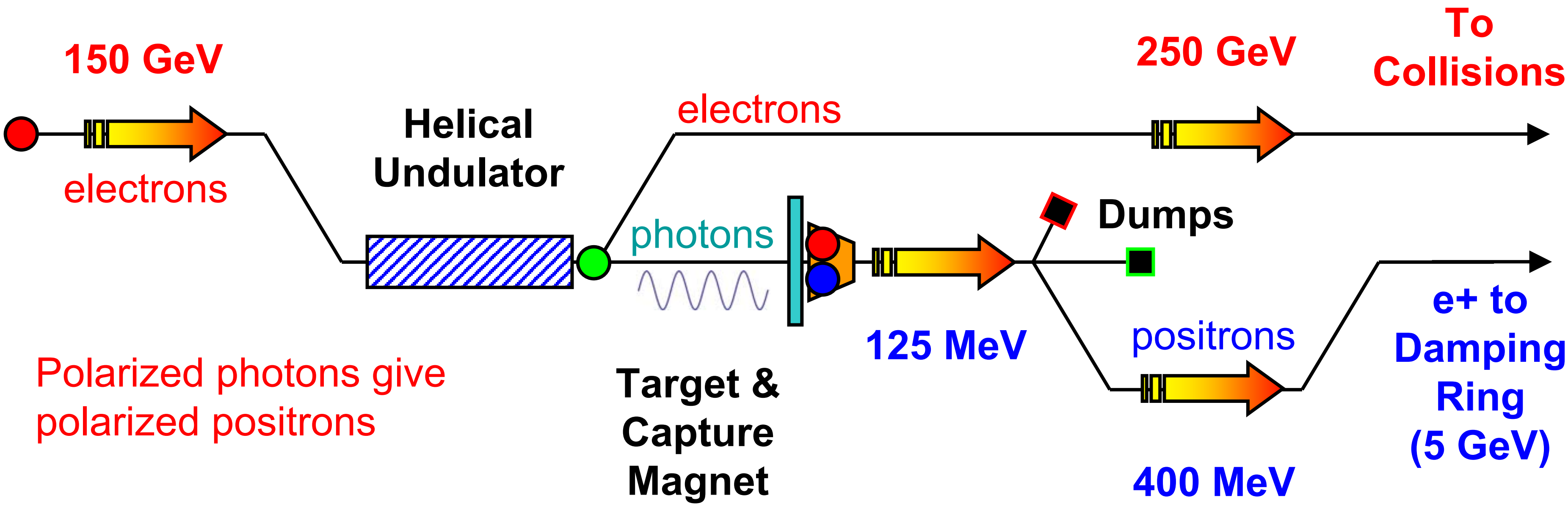
RDR to ILC



Positron Source

Positron Source Layout

Jim Clarke
ASTeC & Cockcroft Institute
Daresbury Laboratory



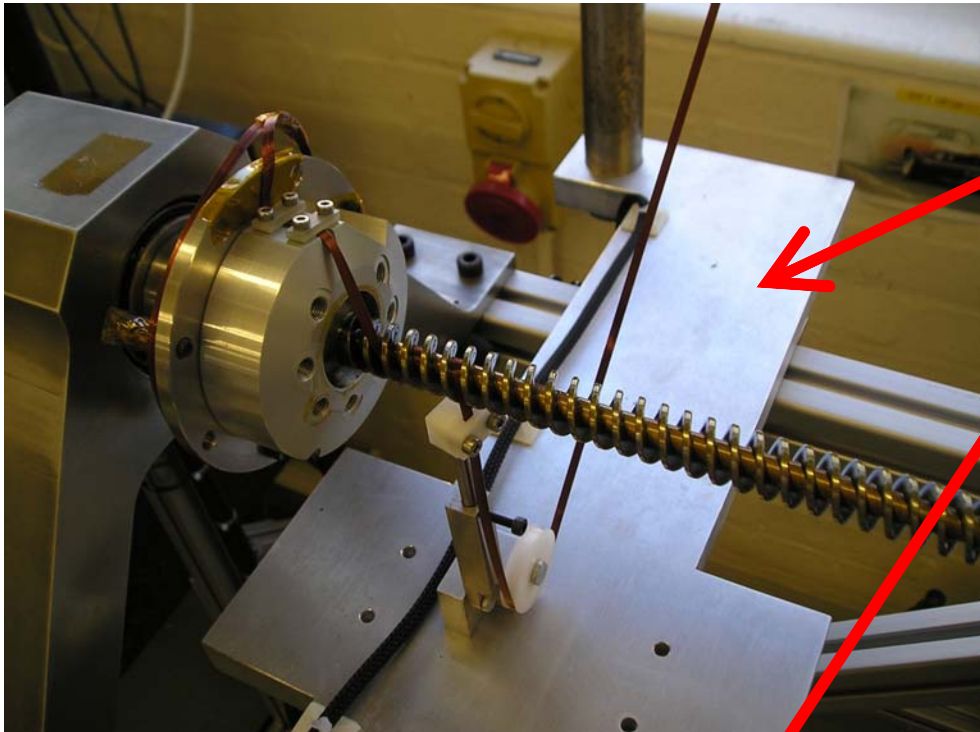
- **10MeV+ photon beam** generated in helical undulator by **150 GeV electrons**
- Photon beam travels ~400 m beyond undulator and then generates e^+e^- pairs in **titanium alloy target**
- Positrons captured and accelerated to 125 MeV
- Any electrons and remaining photons are then separated and dumped
- Positrons further accelerated to **400 MeV and transported for ~5km**
- Accelerated to 5 GeV and **injected into Damping Ring**

Undulator Details

Undulator Parameters	Symbol	Value	Units
Undulator period	λ	1.15	cm
Undulator strength	K	0.92	
Undulator type		helical	
Active undulator length	L_u	147	m
Field on axis	B	0.86	T
Beam aperture		5.85	mm
Photon energy (1^{st} harmonic cutoff)	E_{c10}	10.06	MeV
Photon beam power	P_γ	131	kW

You should recognize the undulator parameters from slide # 36

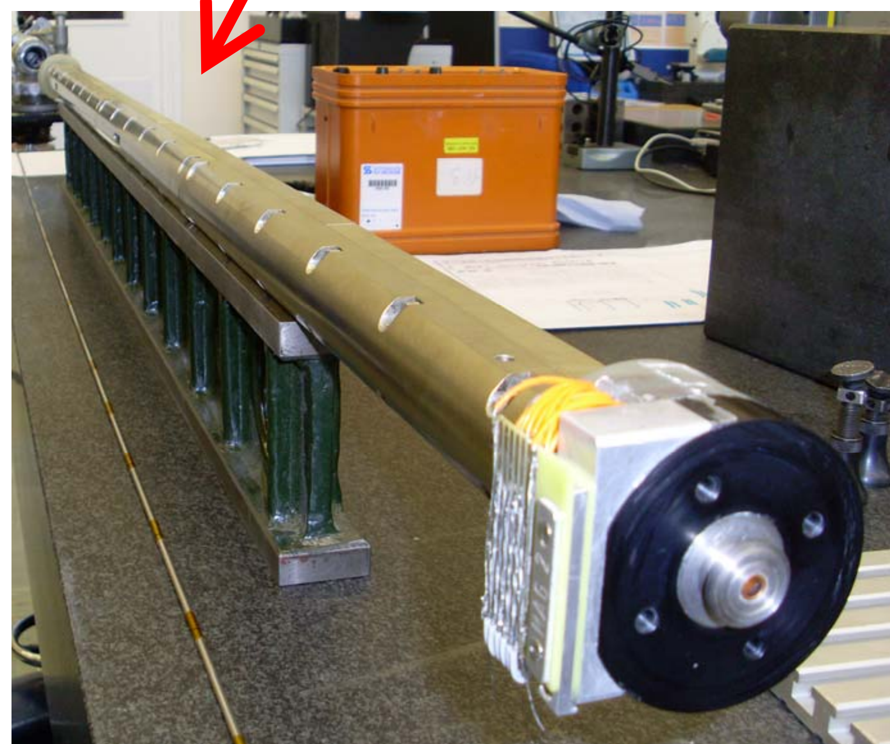
Short Prototype 1.75m Undulator - fabrication at Daresbury UK



Winding

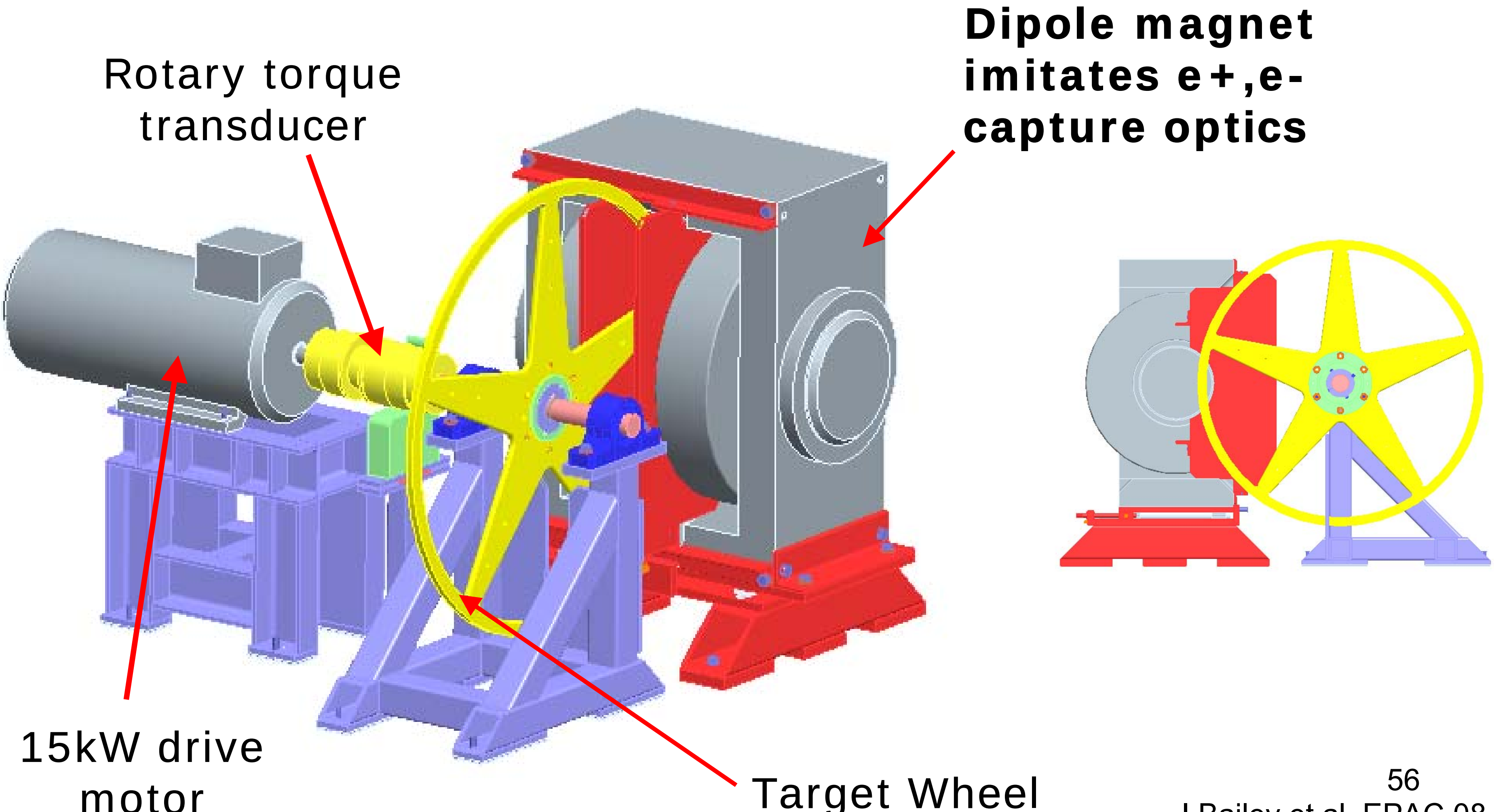
Potted and in one half of steel yoke

Complete magnet



Photons from the undulator strike Ti target → e+,e- pair production

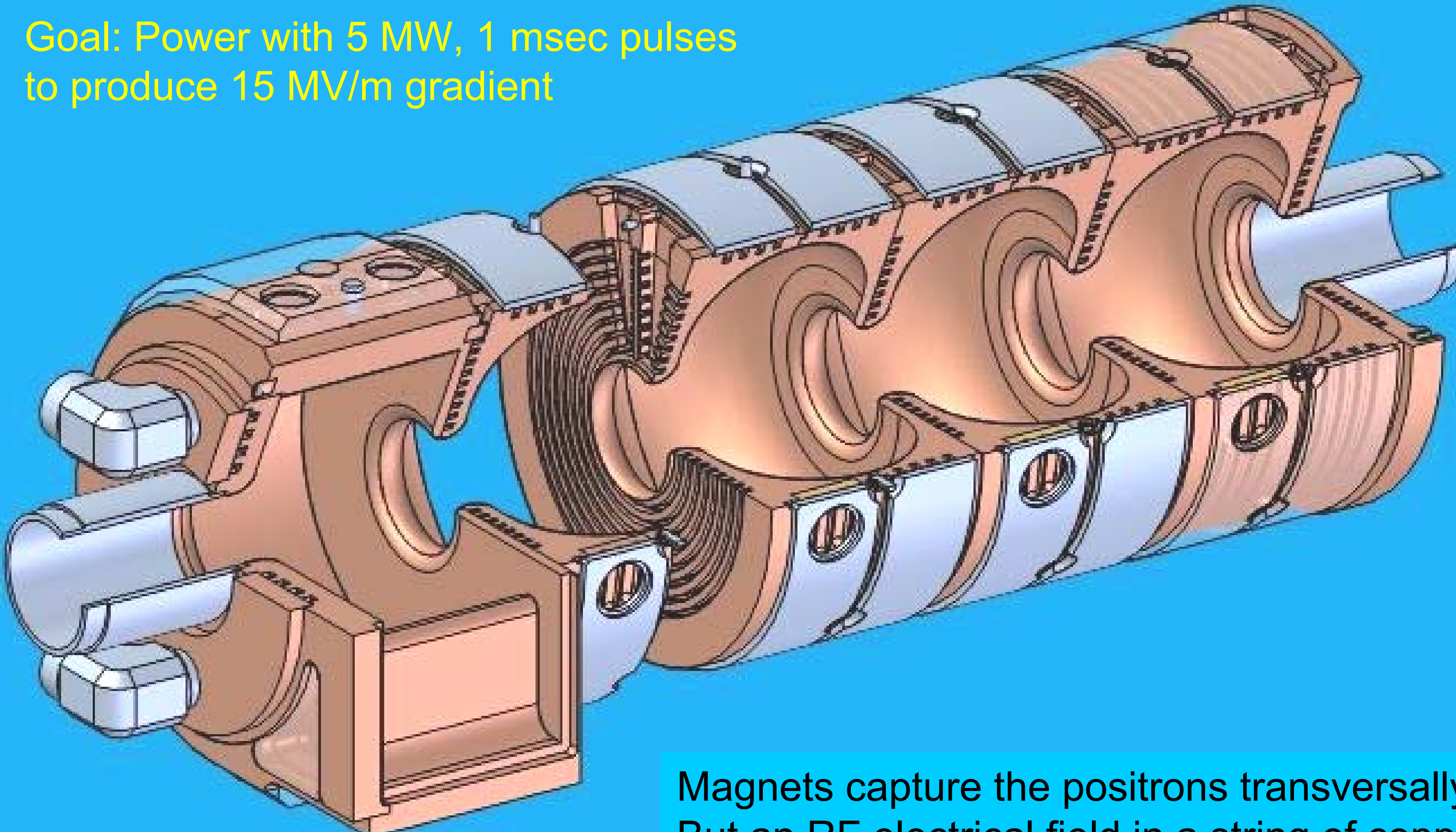
Experiment initiated at Cockcroft Institute/Daresbury Laboratory to monitor *eddy current* effects and *mechanical stability* of full size wheel at design velocity



I Bailey et al, EPAC 08

ILC Positron Capture Cavity Prototype

Goal: Power with 5 MW, 1 msec pulses
to produce 15 MV/m gradient



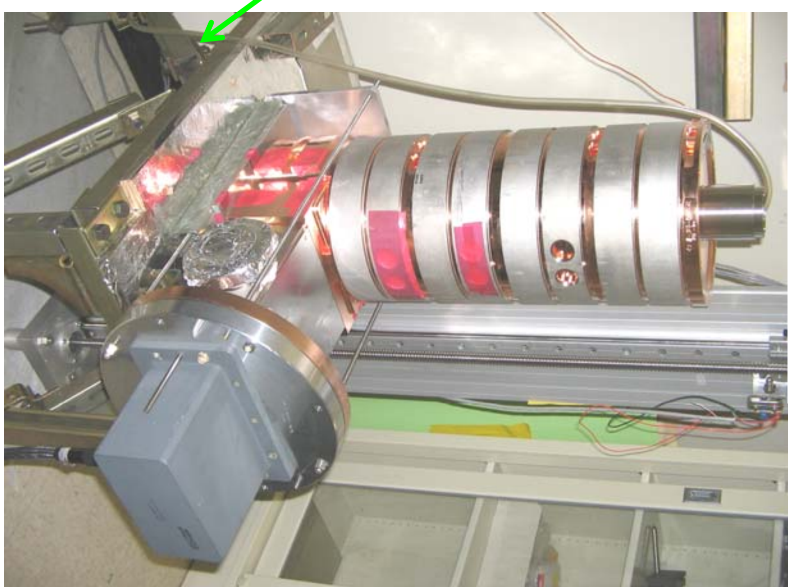
Magnets capture the positrons transversally. But an RF electrical field in a string of copper cavity resonators captures the positrons in energy-time space.

ILC Positron Capture Cavity Prototype

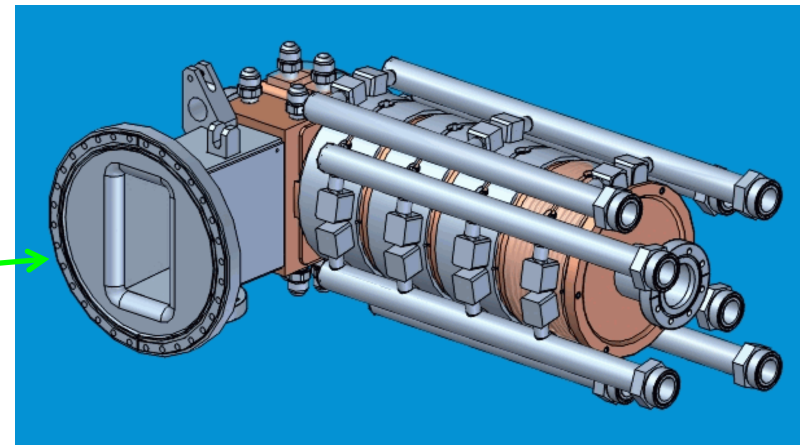
C. Adolphsen &
C. Nantista - SLAC

SKIP

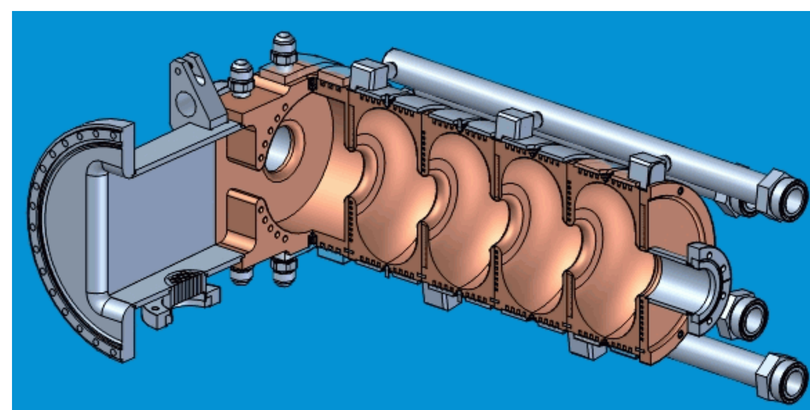
RF power in



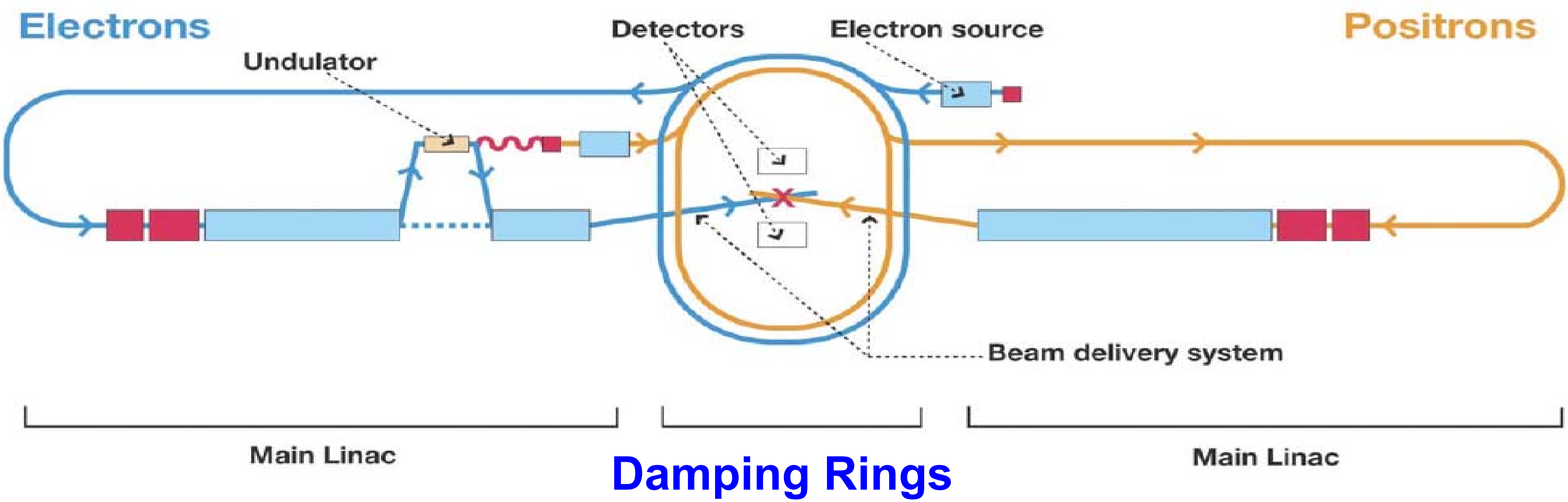
SLAC Standing Wave Accelerator CAD model



Section View



A Vision of the Future
RDR to ILC



Purpose of the damping rings is two fold.

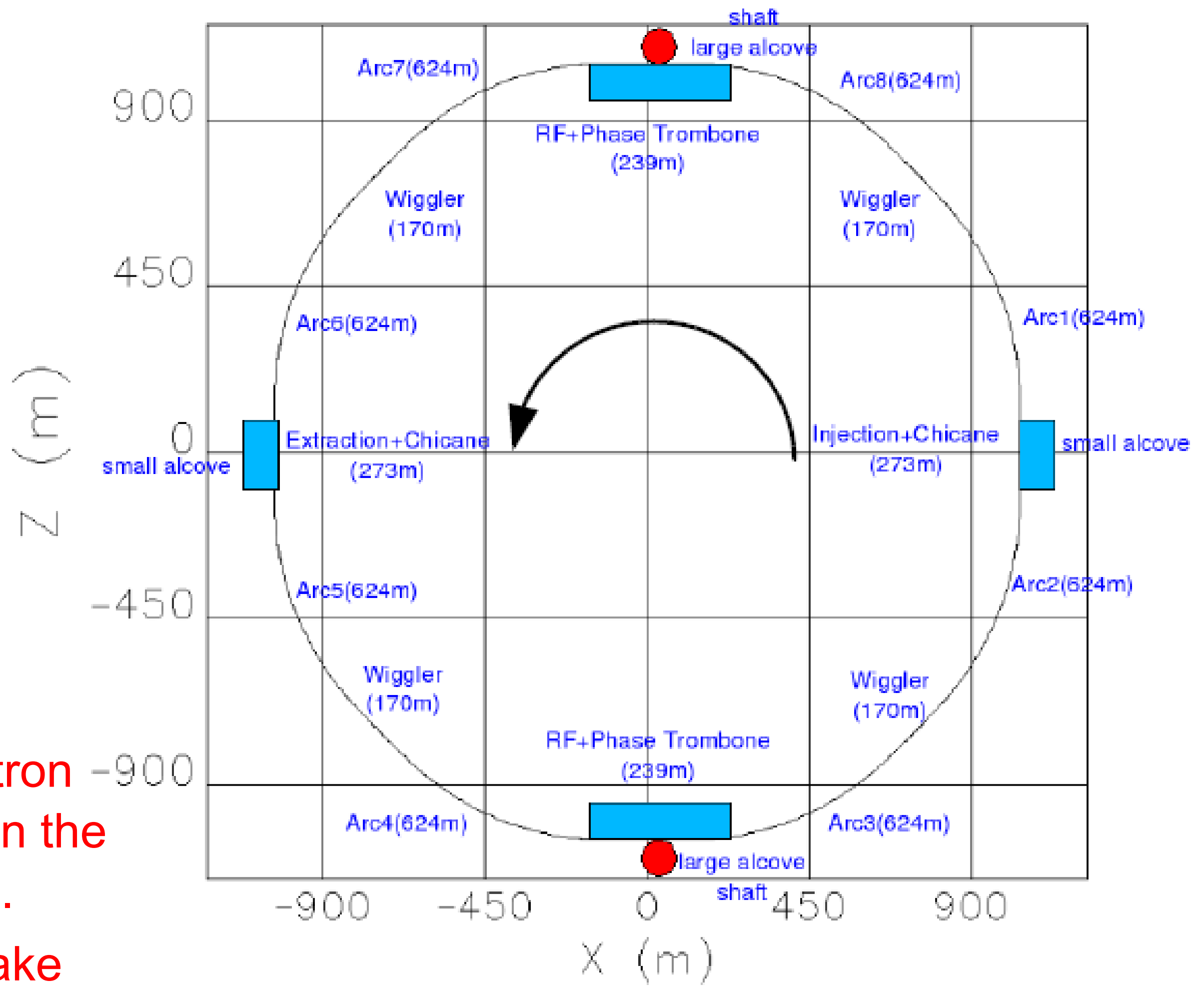
1st, through deliberate excitation of synchrotron radiation in wigglers to reduce the transverse emittance to nano-metre level.

2nd, Accumulate and compress the bunch train.
Initially long pulse: 950ms $\times$ c = 285km!! Has to be compressed into 6 km "ring" by interleaving. Original 3 MHz bunch train $\rightarrow$ GHz bunch train

Damping Ring Lattice Design: Louis Emery, Aimin Xiao; Argonne National Laboratory

ILC 2007 WS, DESY, Germany, May 31st 2007

- Positron and electron rings on top of each other
- Beams are counter-rotating
- Injection and extraction lines on each side would be in same tunnel
- SC RF cavities from different rings don't interfere with each other

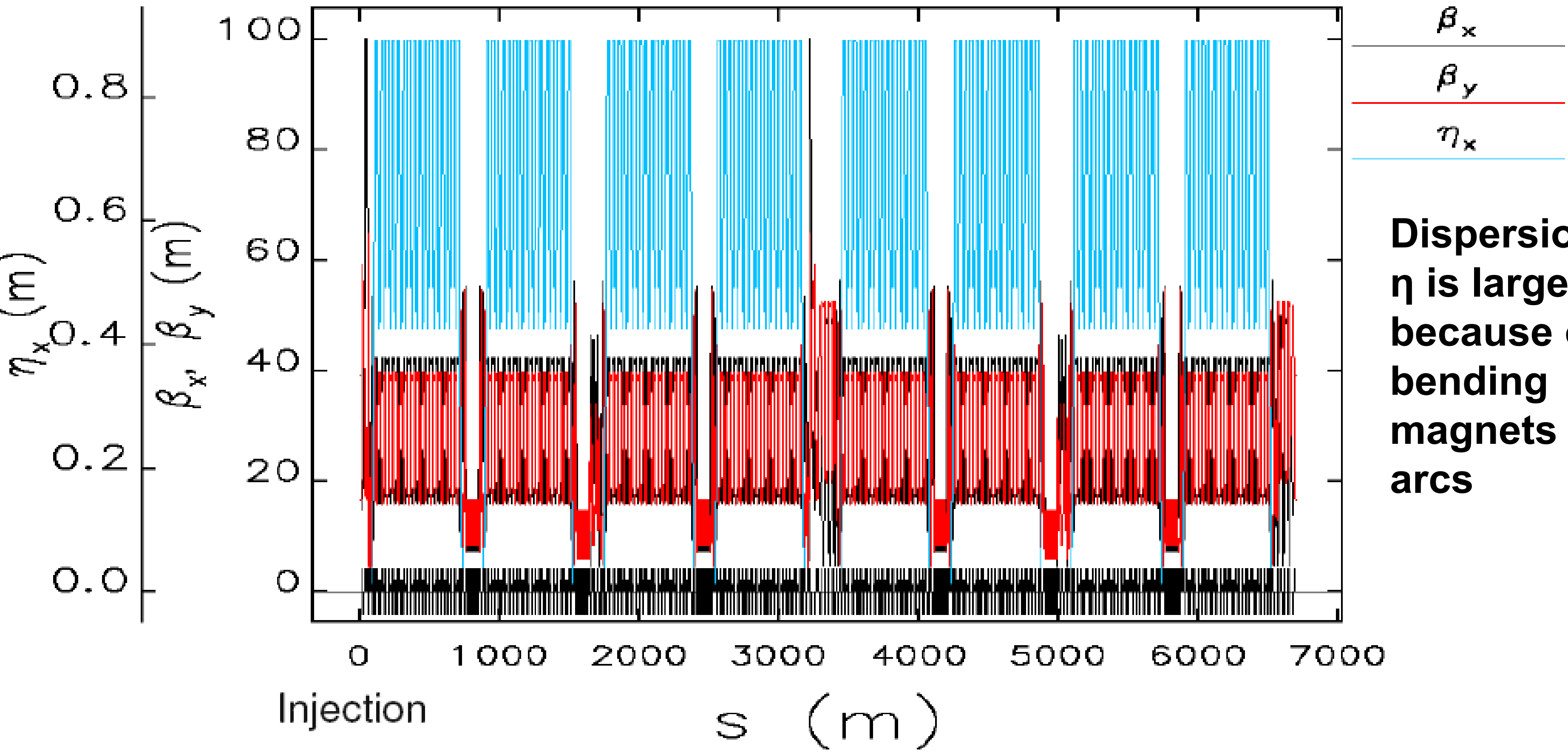


OCS8 Ring Layout

- Emittance damping via synchrotron radiation from bending magnets in the 8 arcs and wigglers in 4 straights.
- Cavities for reacceleration to make up beam energy loss in 2 straights.
- Injection and extraction in 2 straights.

OCS8, Eight Arcs

Lattice functions enable you to calculate beam size from equilibrium emittance



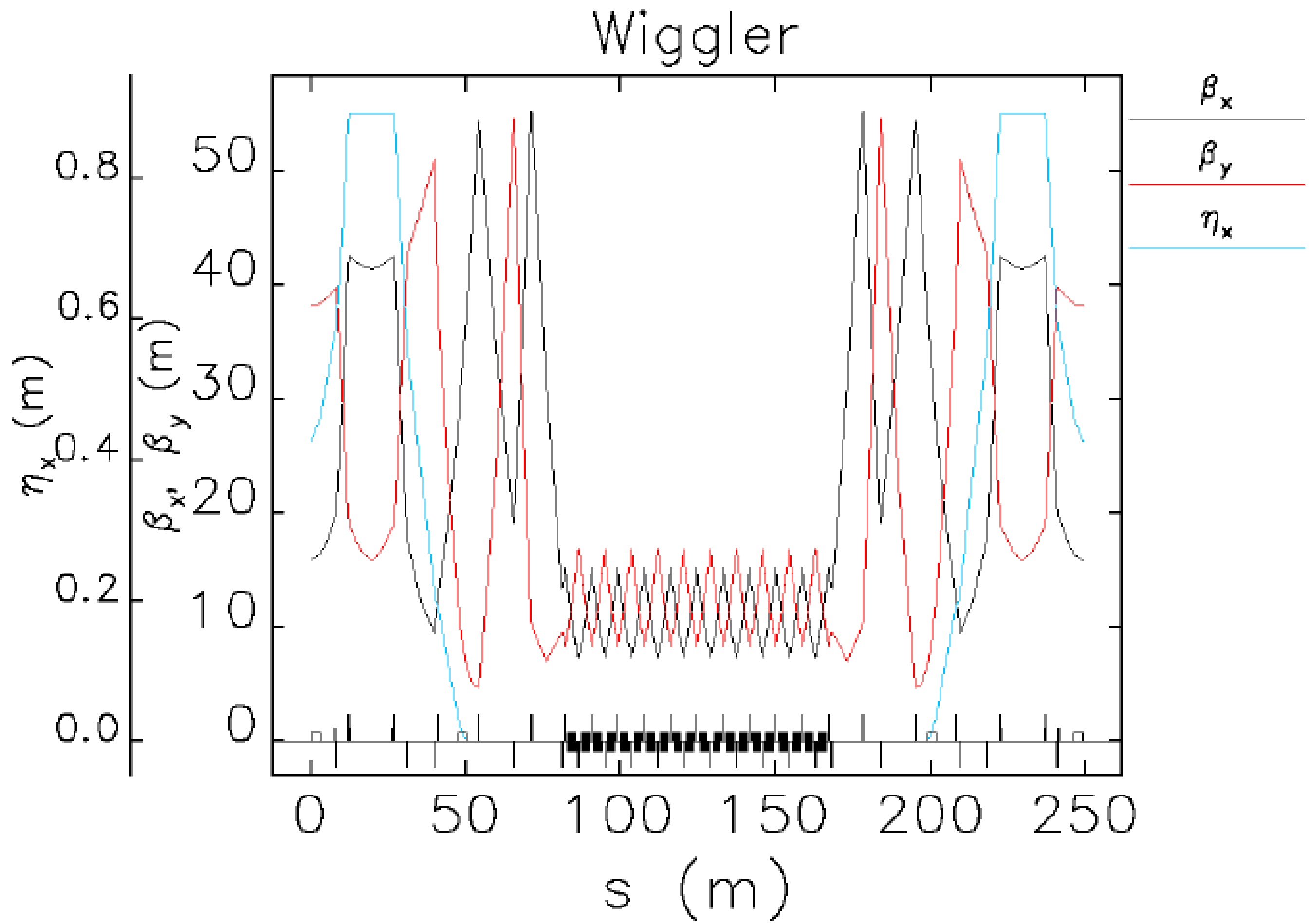
Dispersion η is large because of bending magnets in arcs

OCS8 (March 2007): 6.6 km circumference, 8 arcs, 4 long straight sections to separate wigglers from rf sections, combined injection/extraction straight section

Wiggler Section

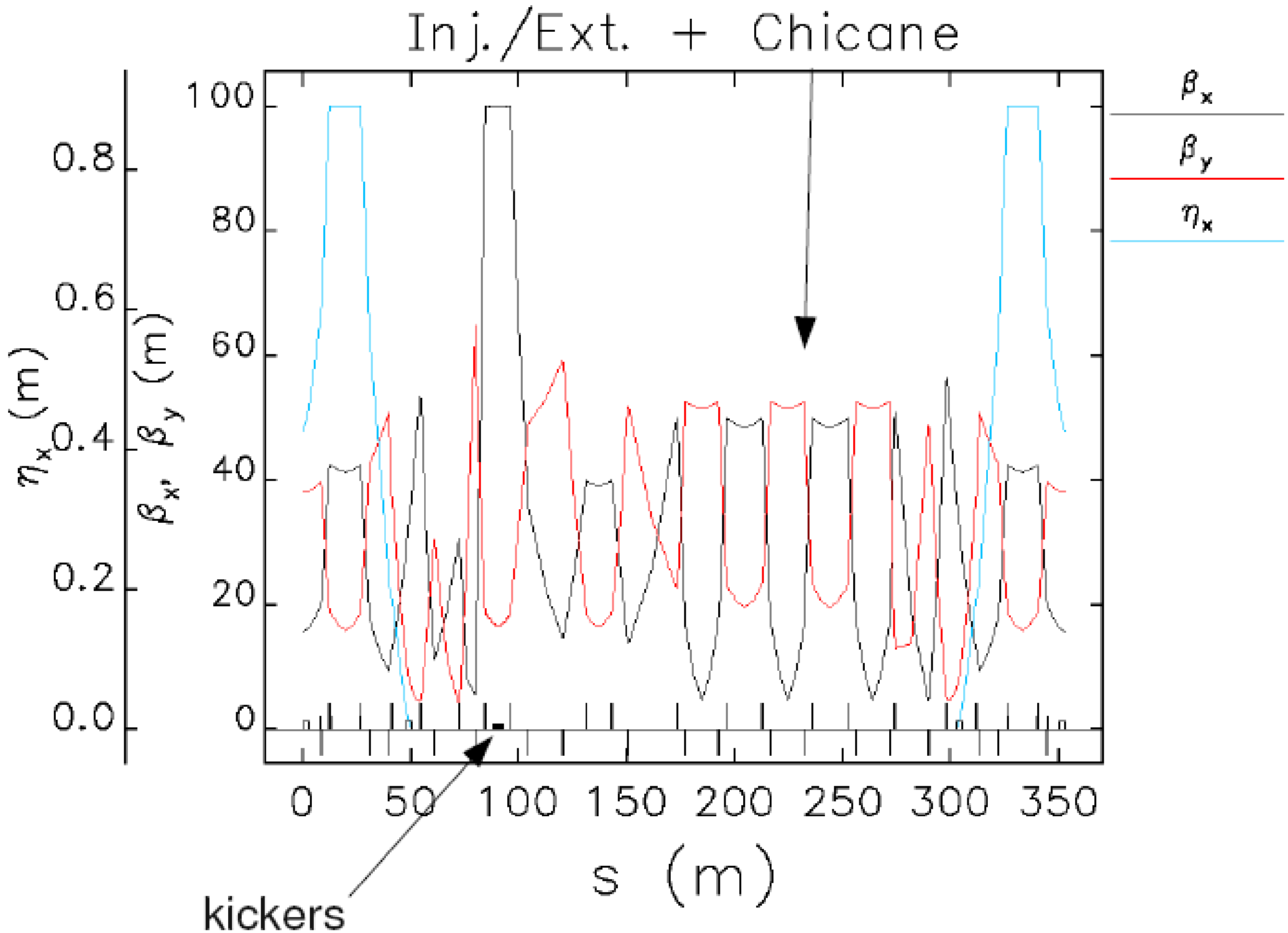
ILC 2007 WS, DESY, Germany, May 31st 2007

Used to promote synchrotron radiation to speed up emittance damping



Injection or Extraction plus Chicane

SKIP



Overview of Damping Ring Status November 2008 – ILCWS08

- **Lattice design**
  - Reactivated racetrack design for cost savings & phase tuning
- **Low-emittance tuning**
  - **ILC damping rings are specified to operate with 2 pm vertical emittance (geometric).**
  - Swiss Light Source has recently achieved 3 pm.
  - Studies planned/ongoing at Accelerator Test Facility, KEK, Japan
- **Electron cloud and vacuum system**
  - Cornell program/CesrTestAccelerator
  - SLAC/PEP program
  - KEK/ATF program

SKIP

Reminder of beam and optical parameters at the interaction point – maximize luminosity!

		Nom. RDR	Low P RDR	new Low P
E_{CM} (GeV)		500	500	500
Particles per bunch, N ($\times 10^{10}$)		2.0	2.0	2.0
Bunches per pulse, n_b		2625	1320	1320
Pulse repetition rate (Hz)		5	5	5
Peak beam power, P_b (MW)		10.5	5.3	5.3
$\gamma\varepsilon_x$ (mm)	Invariant	10	10	10
$\gamma\varepsilon_y$ (nm)	emittance	40	36	36
β_x (cm)	Lattice beta-	2.0	1.1	1.1
β_y (mm)	function value	0.4	0.2	0.2
Traveling focus		No	No	Yes
σ_x (nm)	nano-meter	640	474	474
σ_y (nm)	beam size	5.7	3.8	3.8
σ_z (mm)		300	200	300
Beamstrahlung* dE/E		0.023	0.045	0.036
Luminosity* ($\times 10^{34}$ cm^{-2}s^{-1})		2.0	1.7	1.9

Reminder: $\sigma = \sqrt{\beta\varepsilon}$

N.J. Walker, PAC Meeting, October 2008

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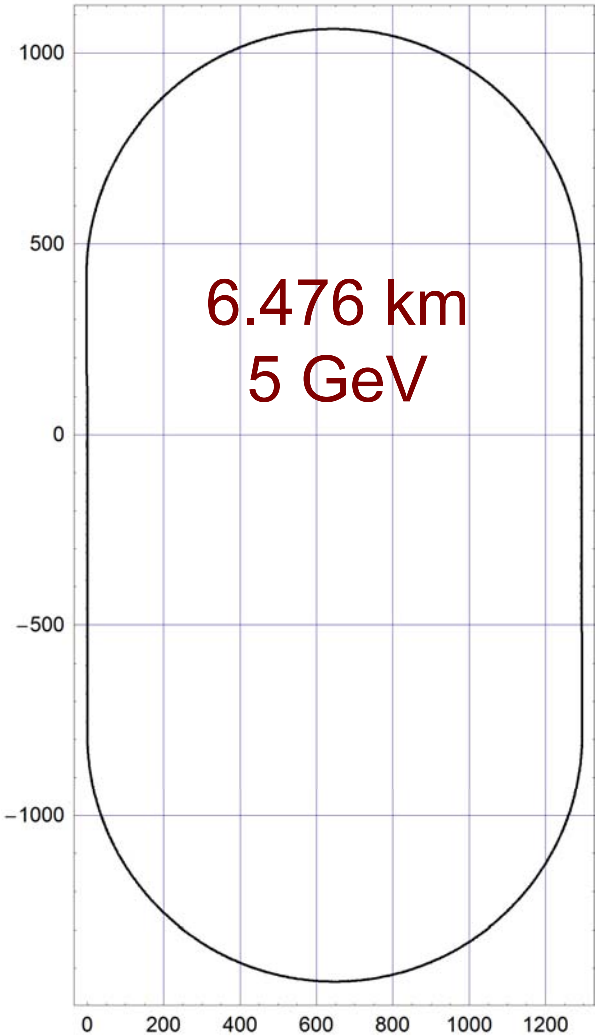
SKIP

Damping Rings Design 20 November 2008



A. Wolski, Global Design Effort

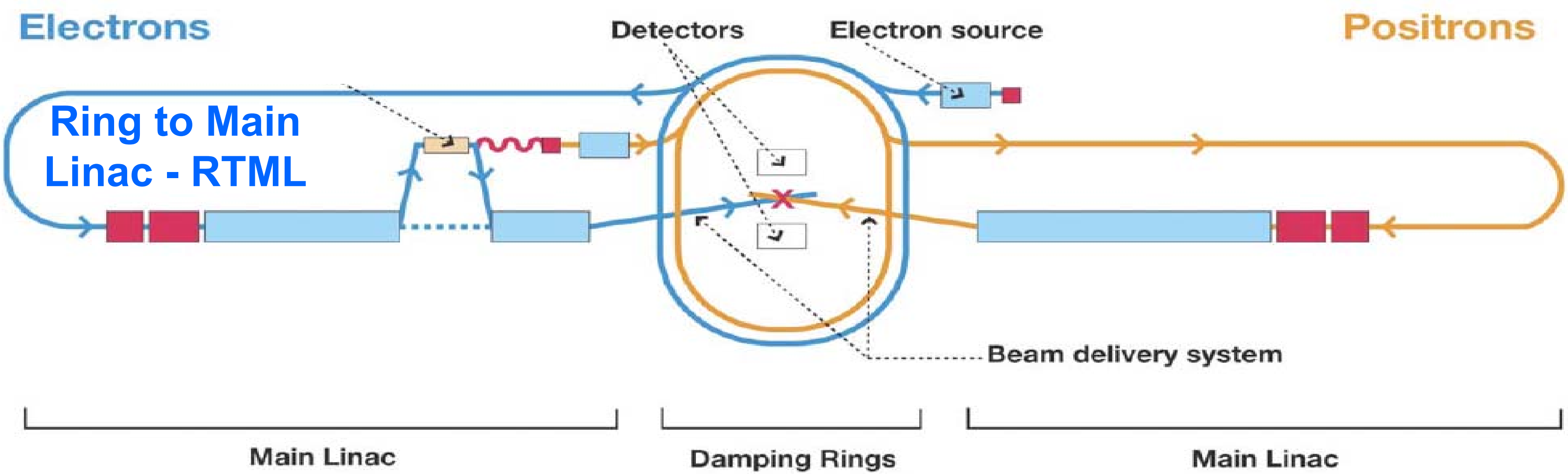
Present baseline: DCO lattice

- Arcs consist of a total of 192 FODO cells
- Flexibility in tuning momentum compaction factor, given by phase advance per arc cell:
  - 72° phase advance: $\alpha_p=2.8\times10^{-4}$
  - 90° phase advance: $\alpha_p=1.7\times10^{-4}$
  - 100° phase advance: $\alpha_p=1.3\times10^{-4}$
- No changes in dipole strengths needed for different working points.
- Racetrack structure has two similar straights containing:
  - injection and extraction in opposite straights
  - phase trombones
  - circumference chicanes
  - rf cavities
  - "doglegs" to separate wiggler from rf and other systems
  - wiggler

SKIP

A Vision of the Future

RDR to ILC



Barry Barish

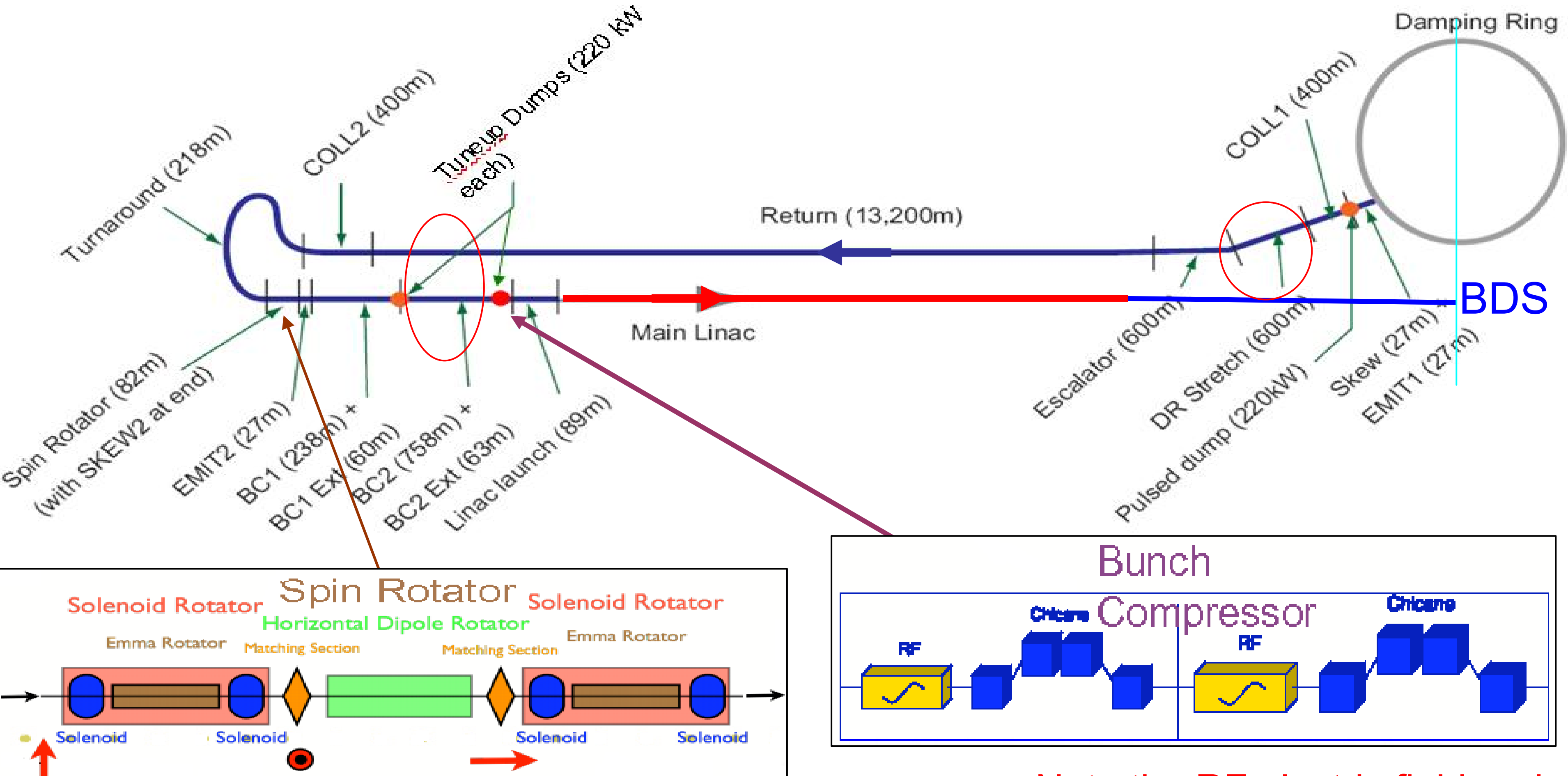
LCWS DESY

30-May-07

RTML Schematic

Nikolay Solyak

Note: e- and e+ RTMLs have minor differences in Return line (undulator in e- linac side) and Escalator (DR's at different elevations); they are otherwise identical.



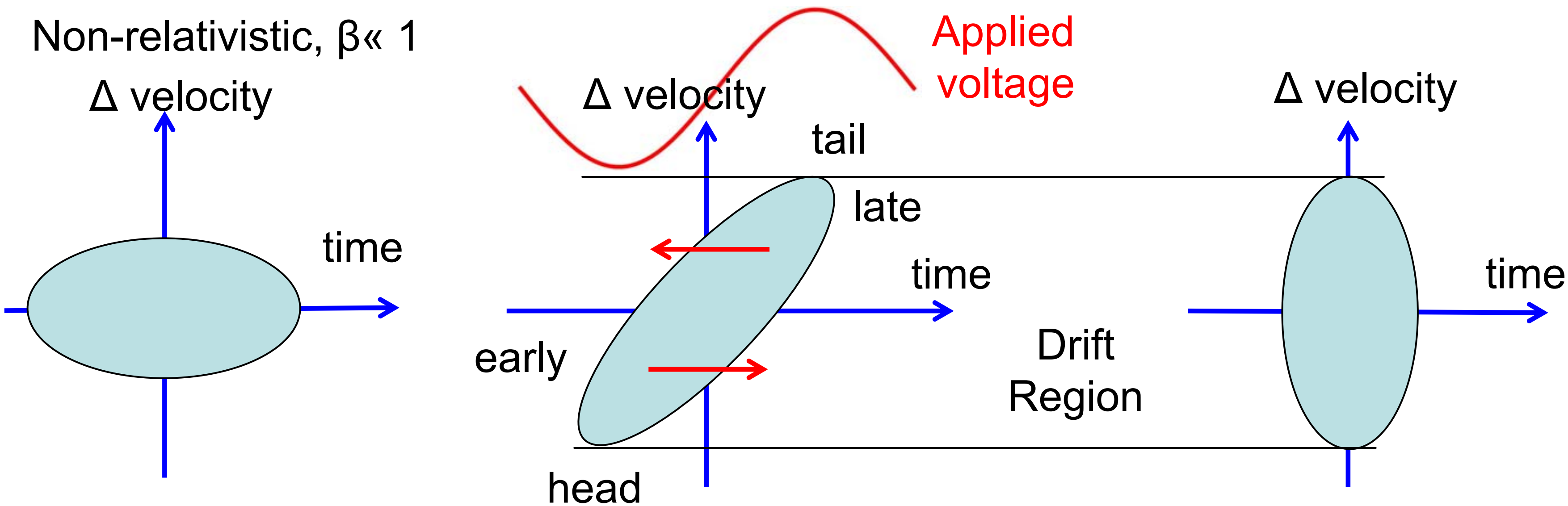
The RTML performs two manipulations to prepare the bunches for the collision point. Because beam rigidity is much lower, its easier to do here rather than after M Linac.

Note the RF electric field and the magnetic chicane.

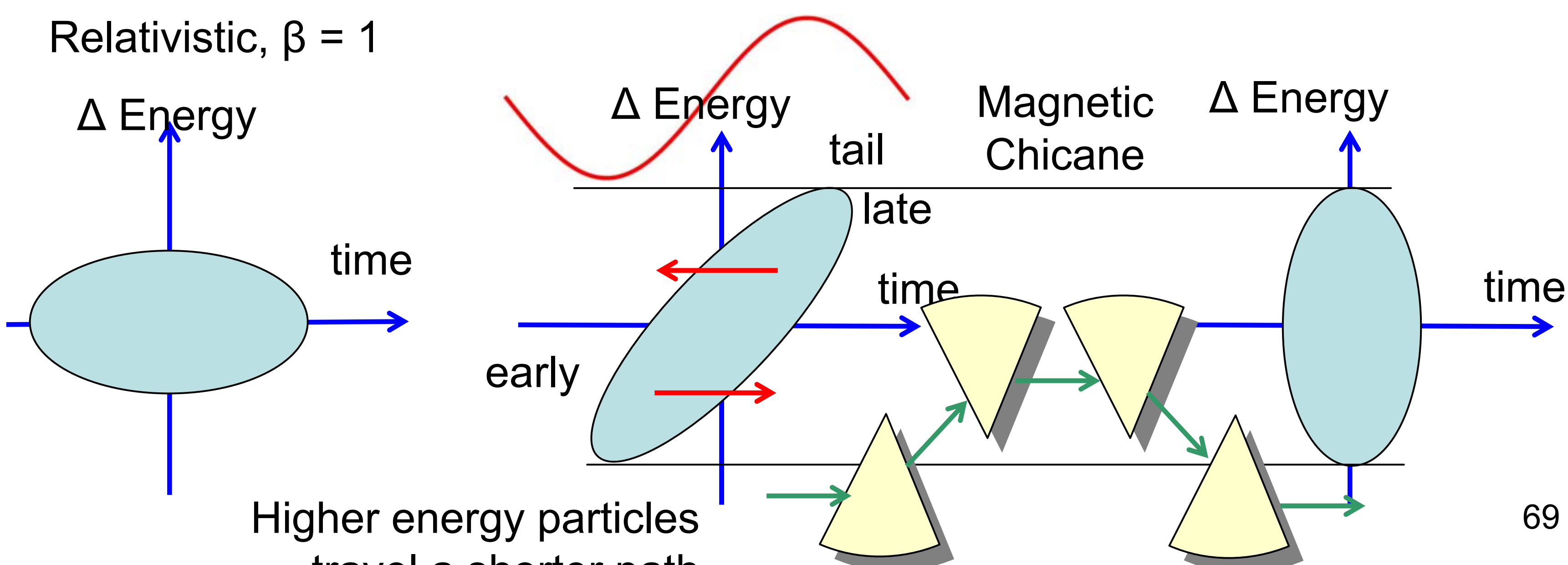
Bunch Compression –i.e. how to shorten the bunch length.

Impose correlation between velocity (or energy) and time along bunch

Non-relativistic, β« 1

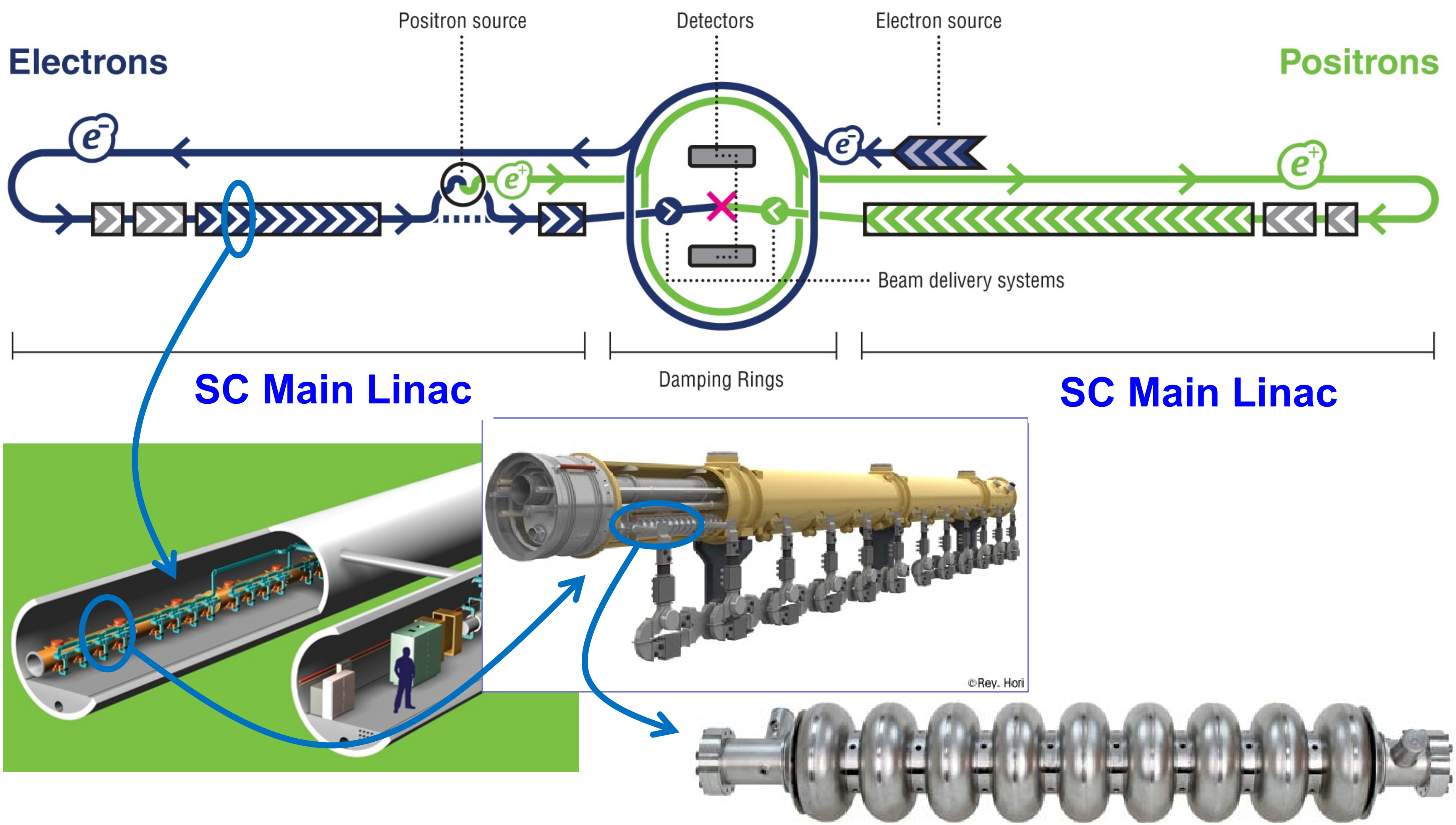


Relativistic, β = 1



Higher energy particles travel a shorter path

ILC Reference Design



Now its time to look at the 250 GeV main linacs. Each linac is housed in a 11 km tunnel. Each linac is composed of a strings of cryomodules at liquid helium temperature, and each cryomodule contains many super-conducting electric cavities.

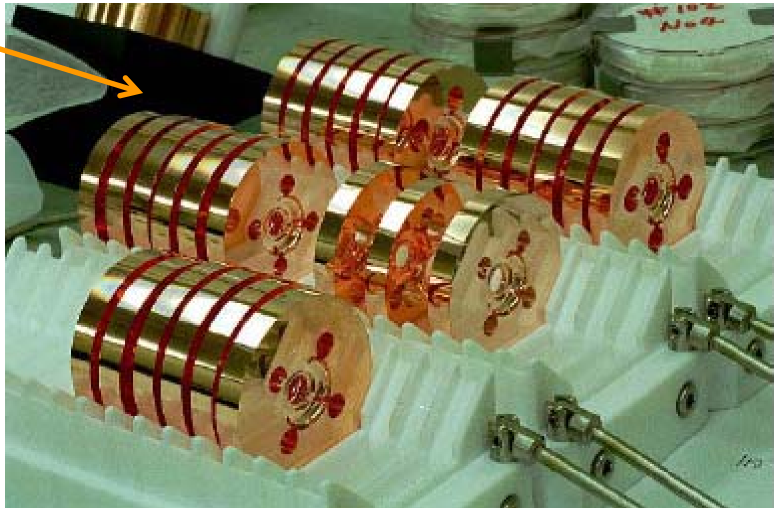
70

Why are Superconducting RF (SCRF) cavities used for acceleration?

- Low RF losses in resonator walls ($Q_0 \approx 10^{10}$ compared to NC, $Q_0 \approx 10^4$)
- high efficiency transfer of wall-plug power to particle beam
- long beam pulses (many bunches) $\rightarrow$ low RF peak power
- large bunch spacing allowing feedback correction within bunch train.

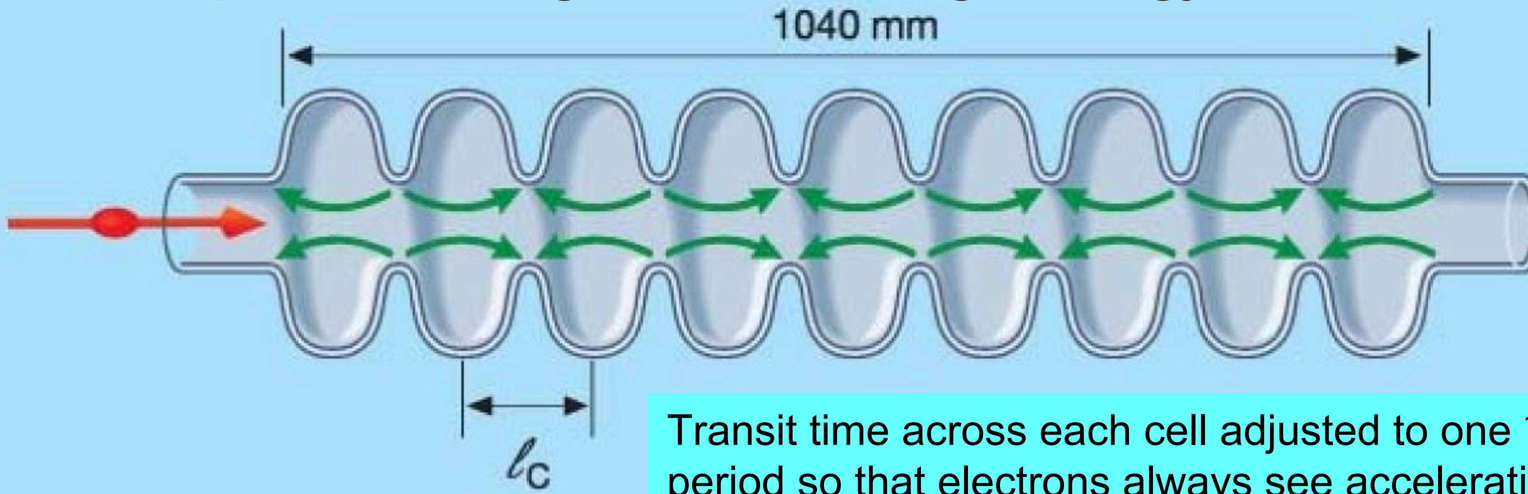
- Low-frequency accelerating structures
- 1.3 GHz for Nb, c.f. 6-30 GHz for Cu
- very small wakefields
- relaxed alignment tolerances
- high beam stability

KEK & SLAC



Quality factor, Q, is number of oscillations for E-field to fall to 1/e of its initial value

Superconducting cavities for High-Energy Electrons

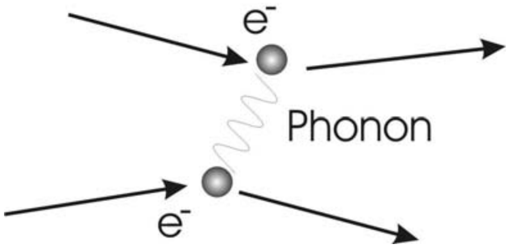


Transit time across each cell adjusted to one ½ RF period so that electrons always see accelerating field.

Nine-Cell 1.3GHz Niobium Cavity developed by the TESLA collaboration at DESY (Deutsches Elektronisches Synchrotron) Hamburg, Germany

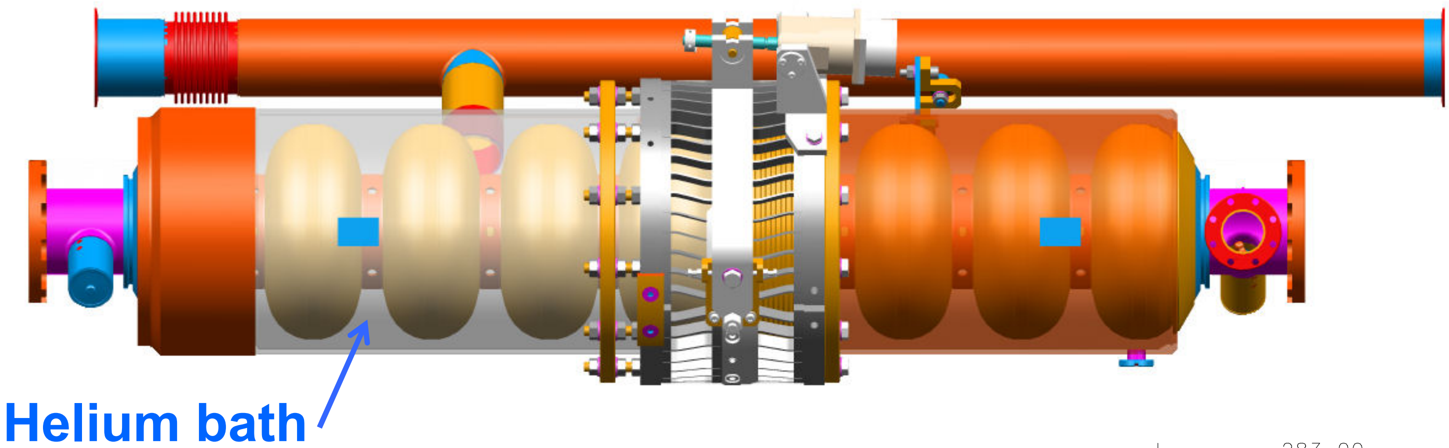
Reduction of cost by factor of 20 over 10 years of R&D!

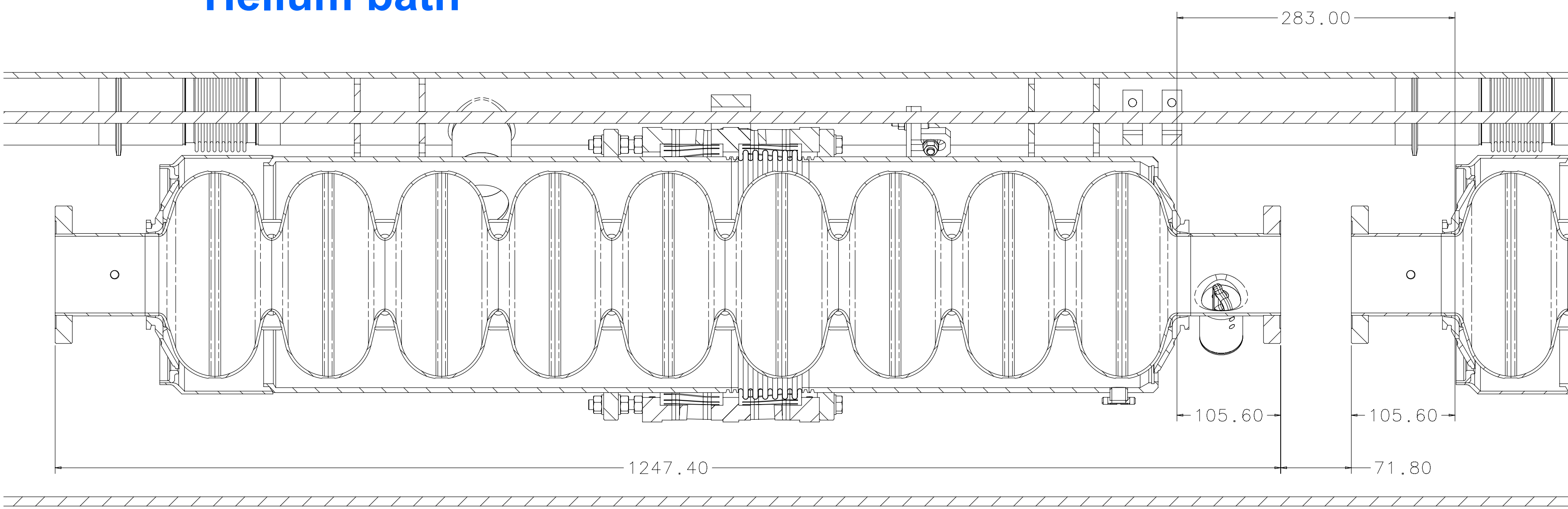
When Nb is cooled below 4 kelvin, it passes into SC state: electrical currents are carried by “super-carriers” which are lossless and collisionless.



The carriers are quasi-particles: electron pairs bound together via exchange of phonons – “Cooper pairs”. The pairs behave as bosons (not fermions) and condense into a common ground state.

The Nb cavities are cooled by liquid Helium bath at 2 kelvin. The He bath is isolated from room temperature by a vacuum enclosure. Several cavities are assembled into a cryomodule.

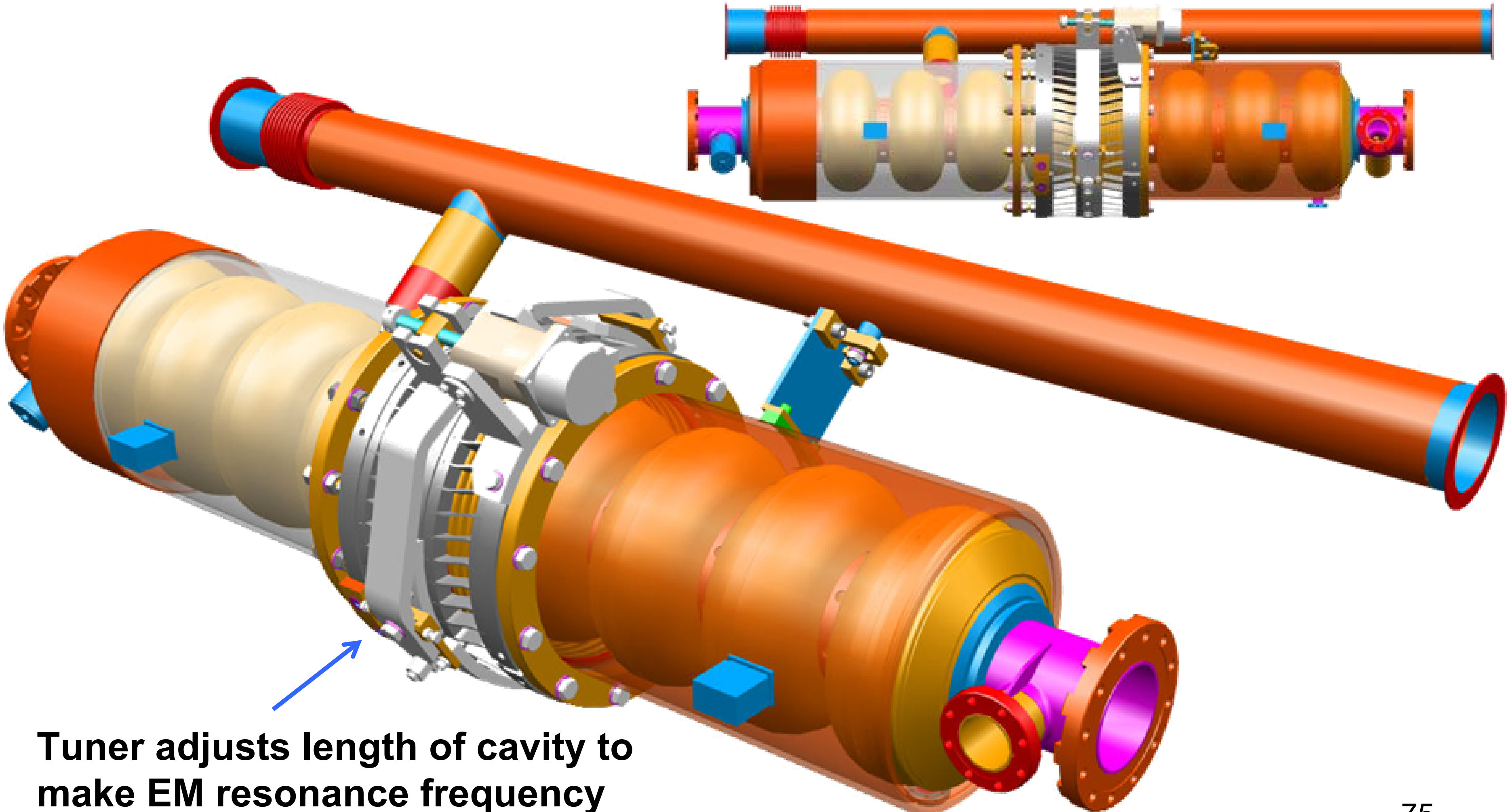




Cavity Dimensions (mm)

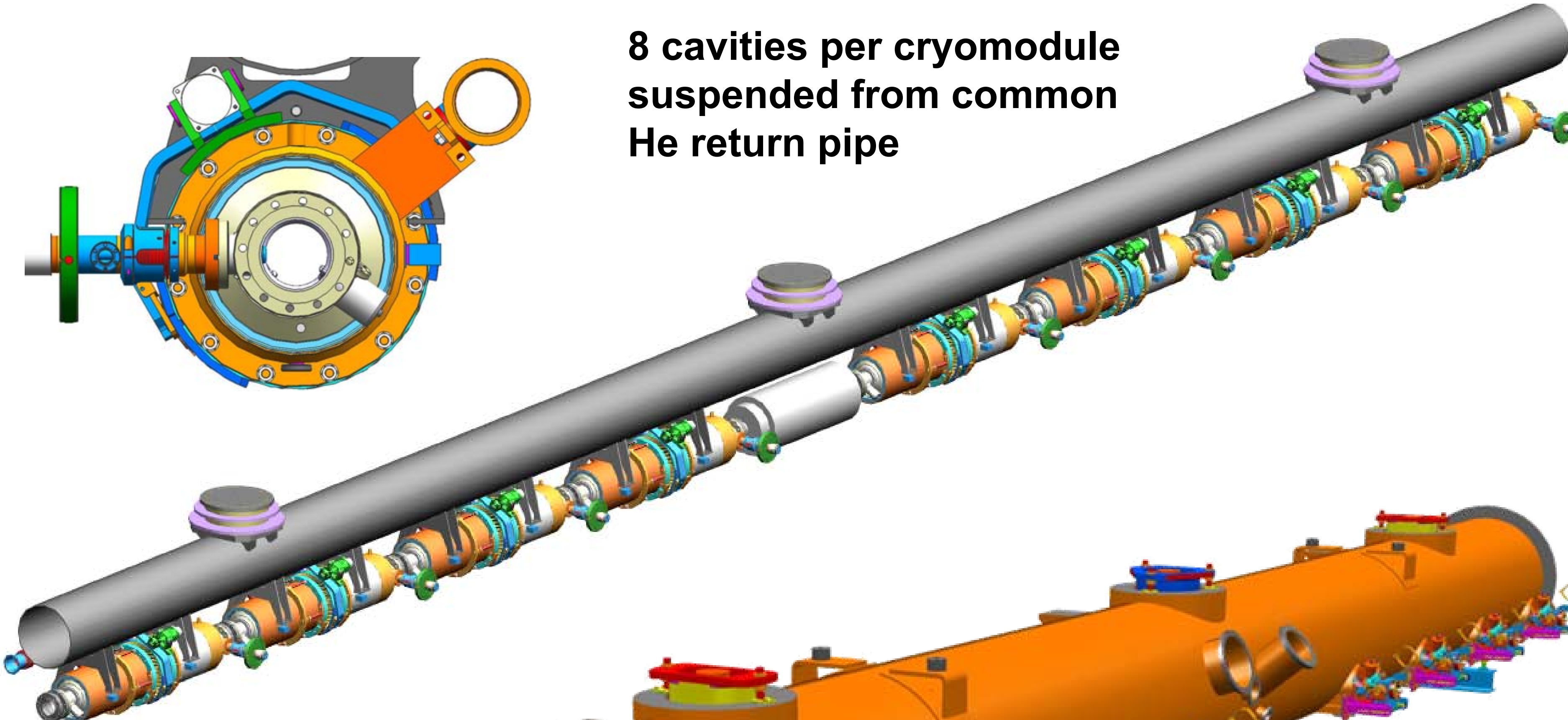
T4CM Proposed Cavity with Bladetuner

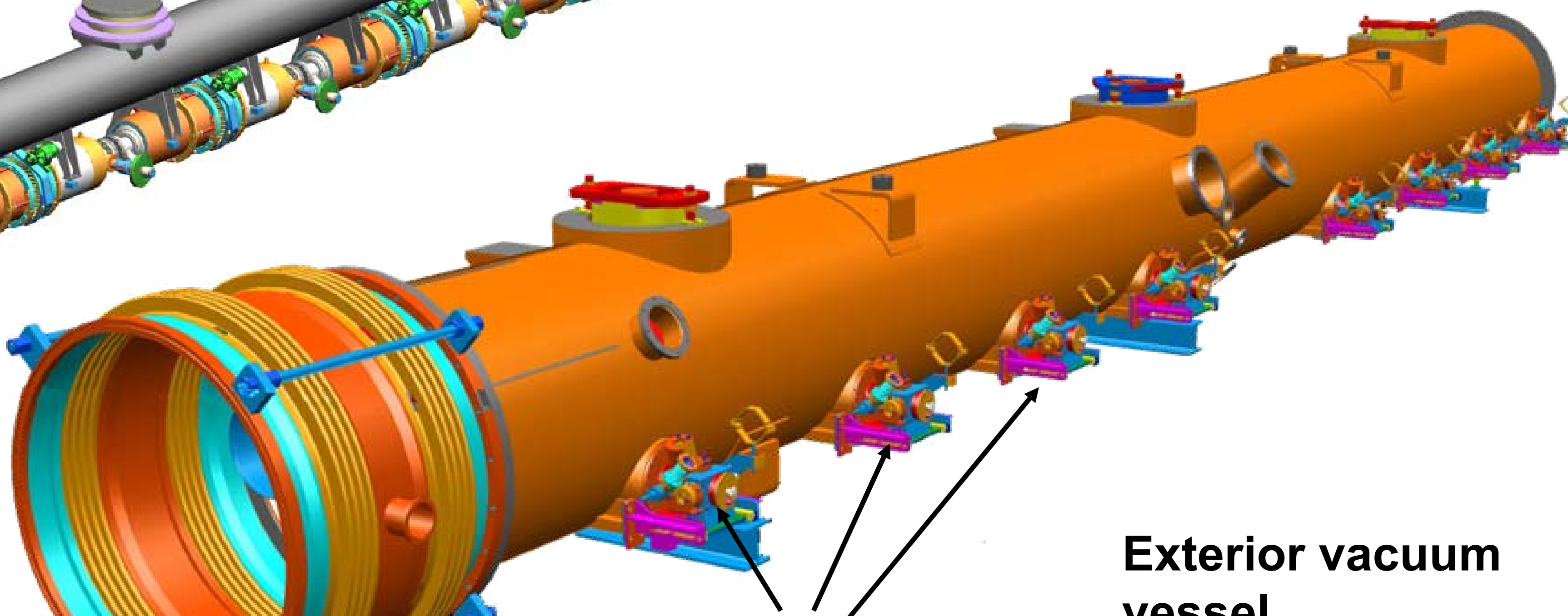
from D. Mitchell presentation



Tuner adjusts length of cavity to make EM resonance frequency precisely equal 1.3 GHz

8 cavities per cryomodule
suspended from common
He return pipe



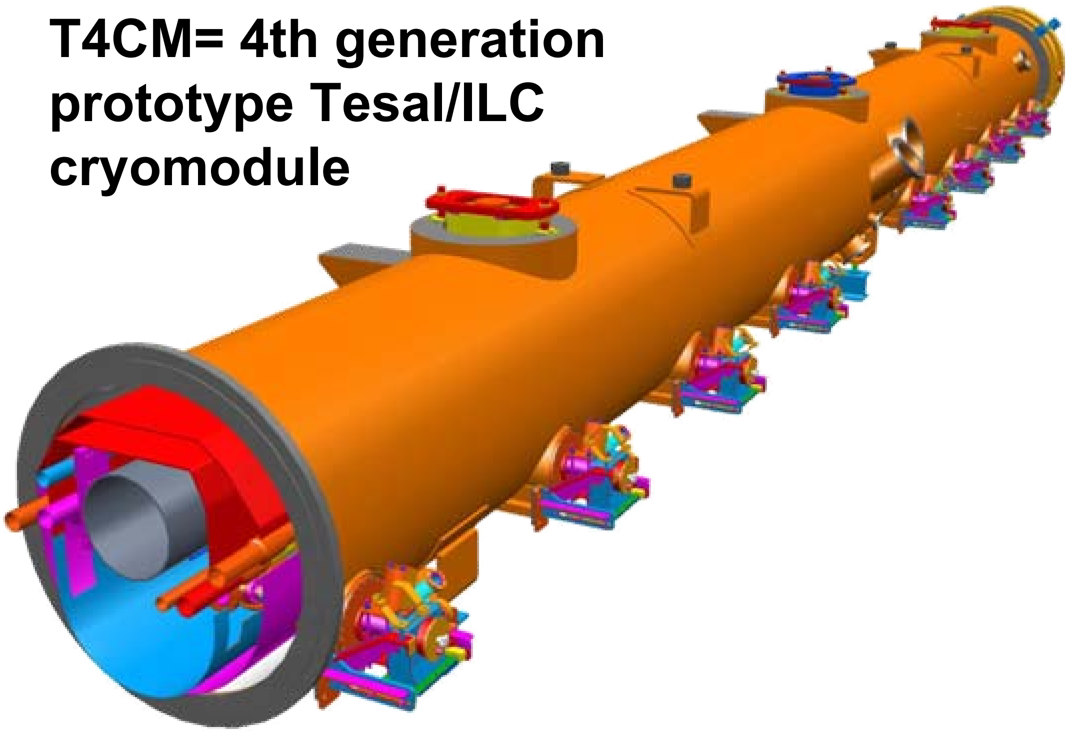


Exterior vacuum
vessel

Ports for RF
power input

Cryomodules

T4CM= 4th generation prototype Tesal/ILC cryomodule



Partial assembly showing vacuum vessel, He return pipe, and 2 layers of heat shields

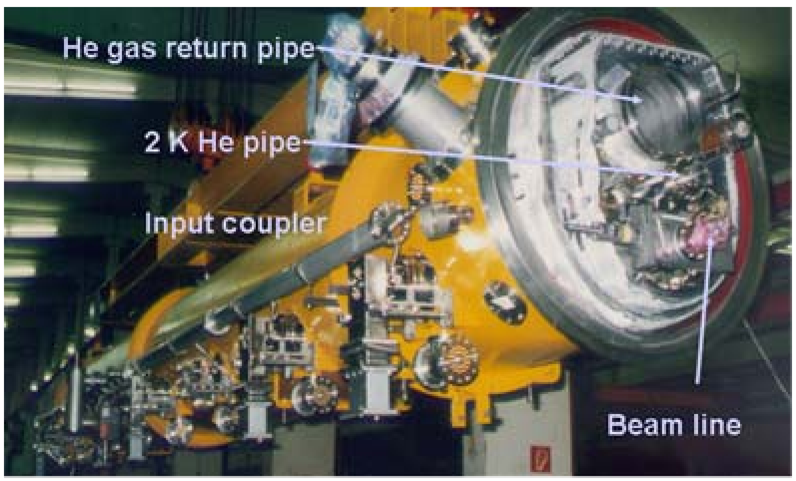
DESY-TESLA cryomodule

SKIP

Cryomodule Variants

cryomodule variants
- number of cavities
- intercavity spacing
- quadrupole position

	TTF	ILC
# cavities	8	12?
spacing	$3\lambda/2$	$\lambda/2$?
quad loc.	end	centre?



Tesla Test Facility CM already 3rd generation

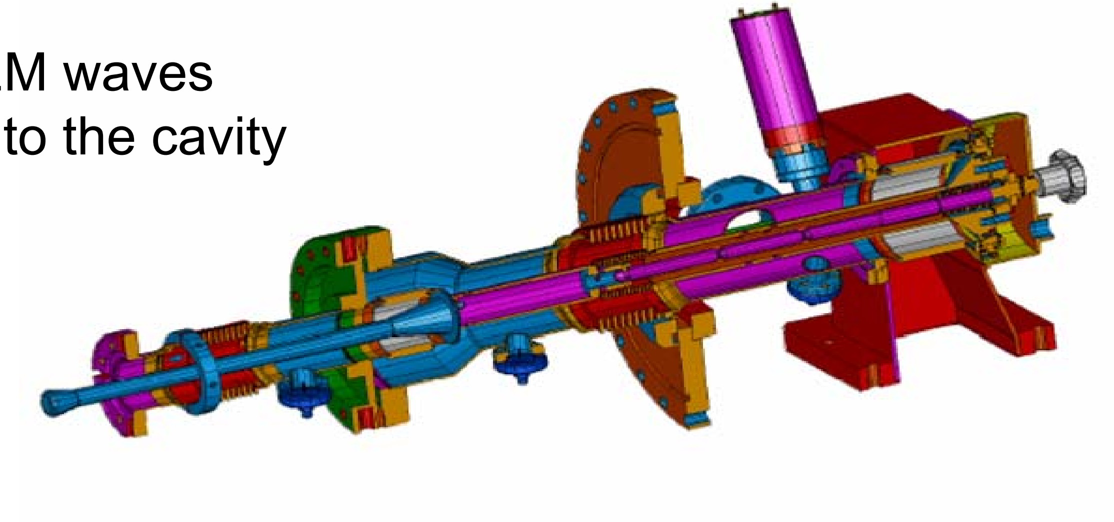
Main emphasis is on
- industrialisation
- reliability
- cost optimisation

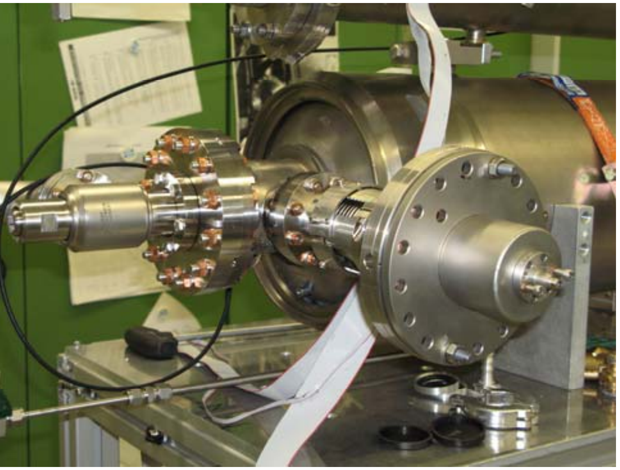
XFEL, X-ray Free-electron Laser at DESY

Auxiliaries – Input coupler

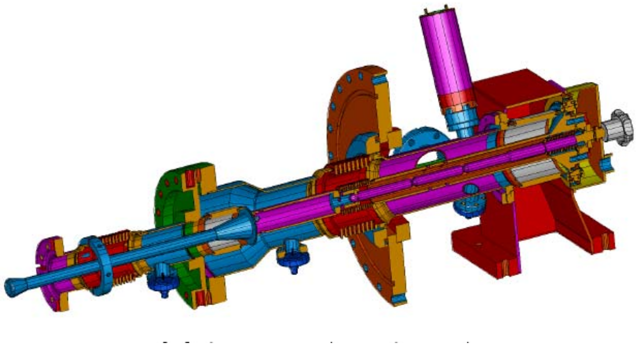
This brings the 1.3 GHz EM waves from RF power generator to the cavity

High peak-power, ≈ 300 kW, moderate average power ≈ 12 kW

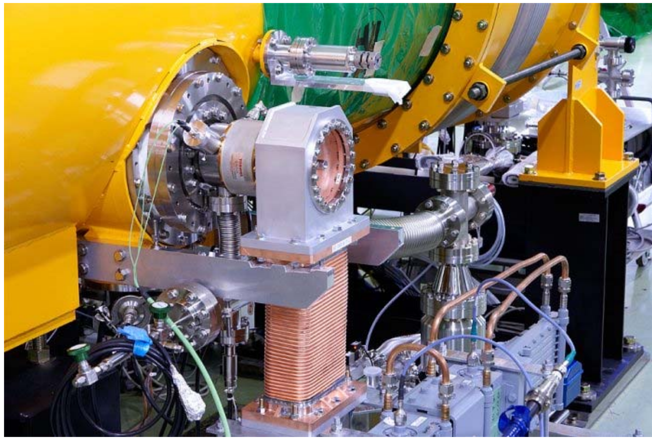




DESY-XFEL prototype cavity and “cold” end of coupler at 2K



TESLA-Test-Facility version 3 of original Saclay SCRF coupler

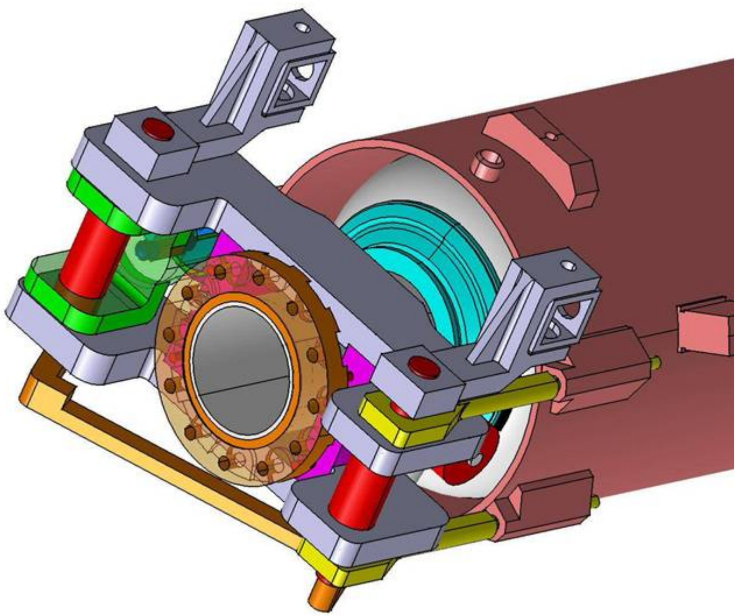


KEK-STF prototype cryomodule and “warm” end of coupler at 300 K

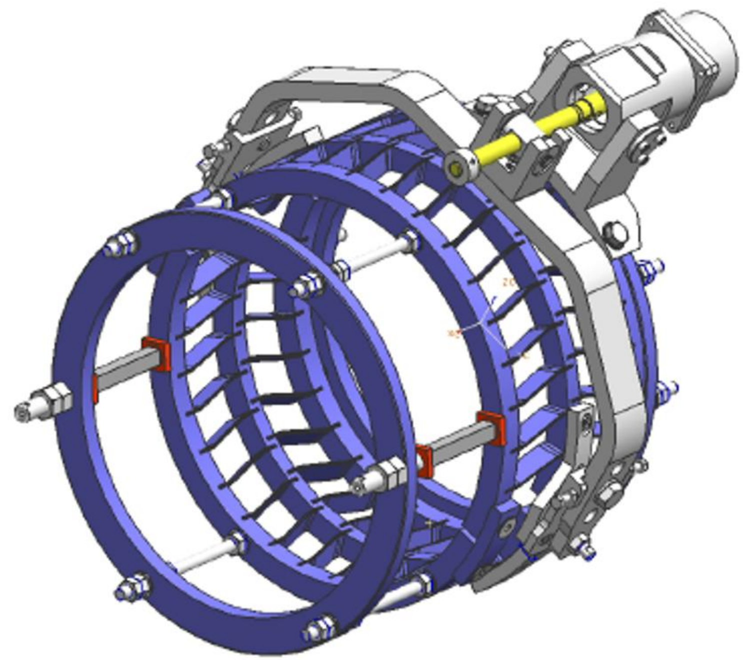
Auxiliaries - tuner candidates

SC cavity has very narrow resonance width « 1Hz.
But the RF is 1.3×10^9 Hz.

Have to very carefully adjust cavity length to make EM resonance frequency equal to the drive frequency

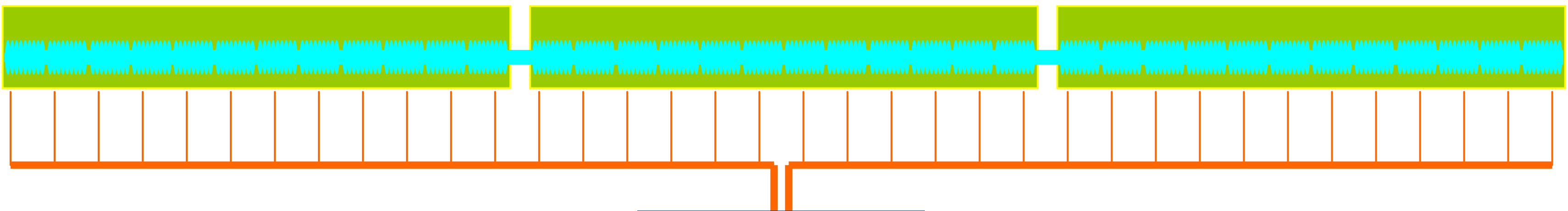


SACLAY tuner (type III)

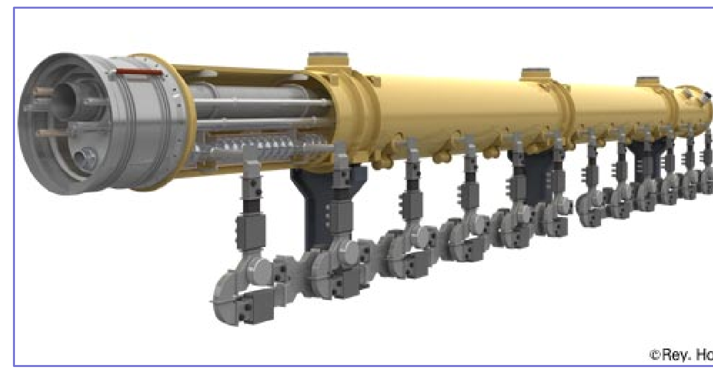


INFN blade tuner

Main Linac – RF power sources & distribution



10MW klystron



36 9-cell 1.3GHz Niobium Cavity

3 Cryomodule

1 10MW Multi-Beam Klystron

Power Flow

Main Linac – the big picture
RF power and cryogenic refrigeration groupings

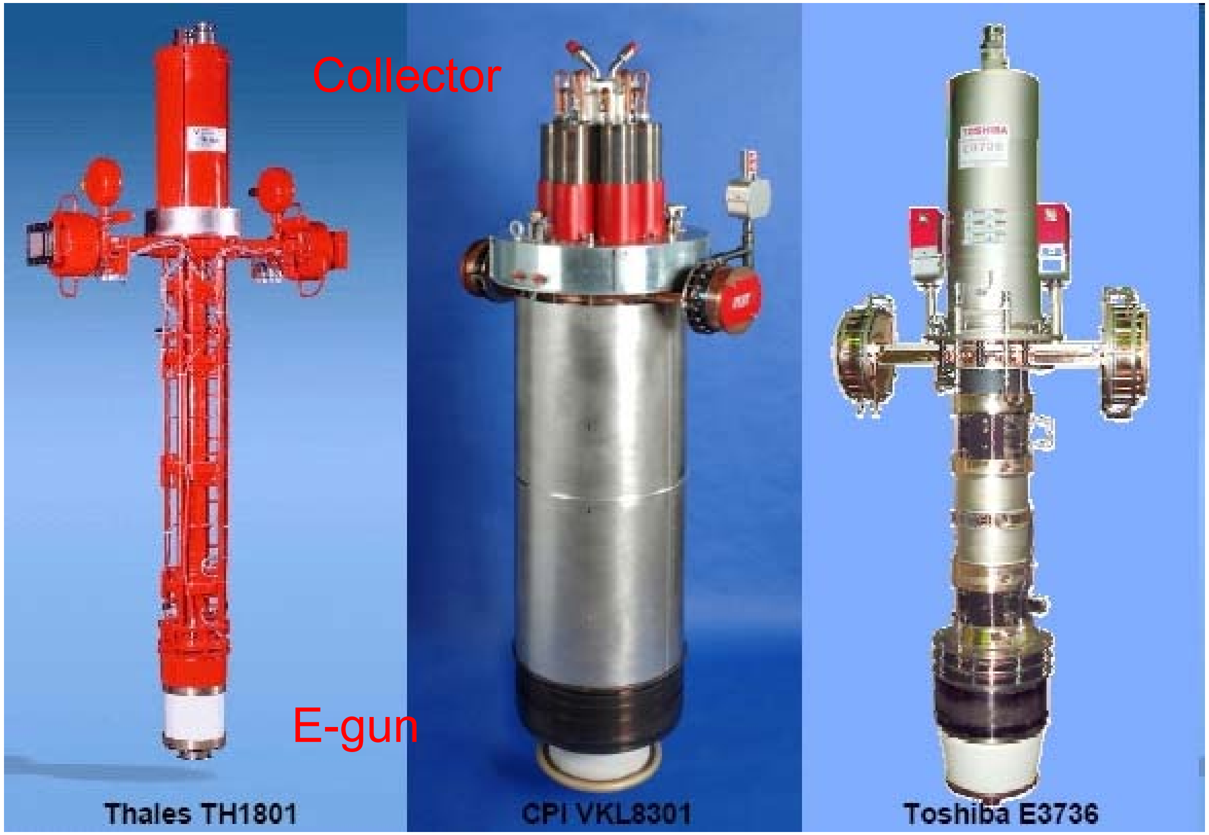
Layer above = Cryogenic grouping

Previous slide

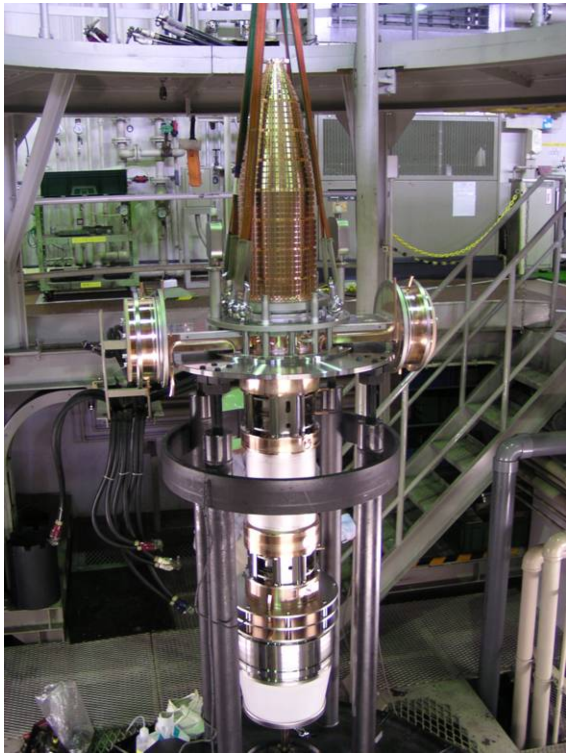
Subdivision	Length (m)	Number
Cavities (9 cells + ends)	1.326	14,560
Cryomodule (9 cavities or 8 cavities + quad)	12.652	1,680
RF unit (3 cryomodules)	37.956	560
Cryo-string of 4 RF units (3 RF units)	154.3 (116.4)	71 (6)
Cryogenic unit with 10 to 16 strings	1,546 to 2,472	10
Electron (positron) linac	10,917 (10,770)	1 (1)

SKIP

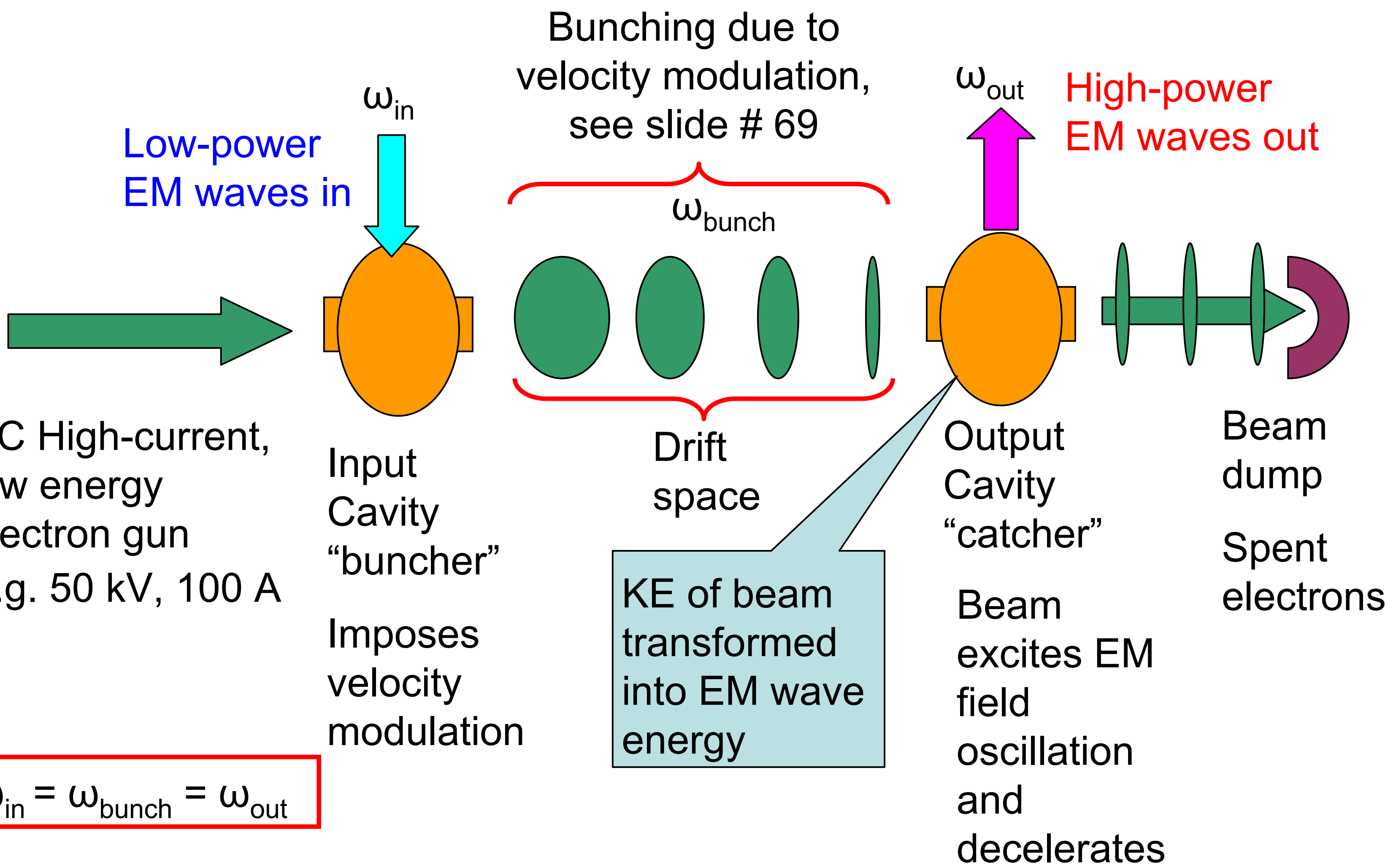
Multibeam Klystrons: 10MW, 1.4ms pulse, 5 Hz rep rate, duty factor = 1%
Need 650 for 500 GeV
Need additional 650 for 1 TeV upgrade



Toshiba klystron undressed



What is a klystron RF power generator? An EM-wave generator.



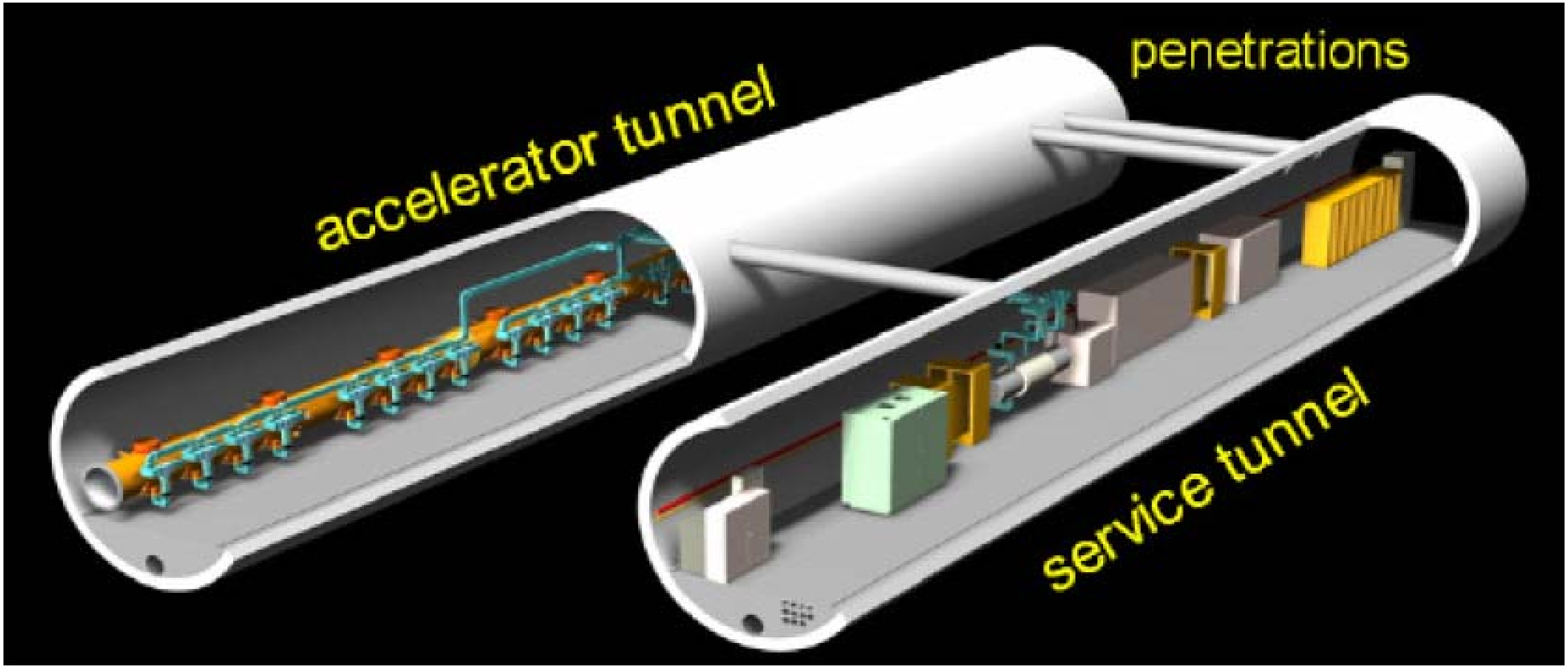
$\boxed{\omega_{in} = \omega_{bunch} = \omega_{out}}$

Klystron = RF system in miniature.

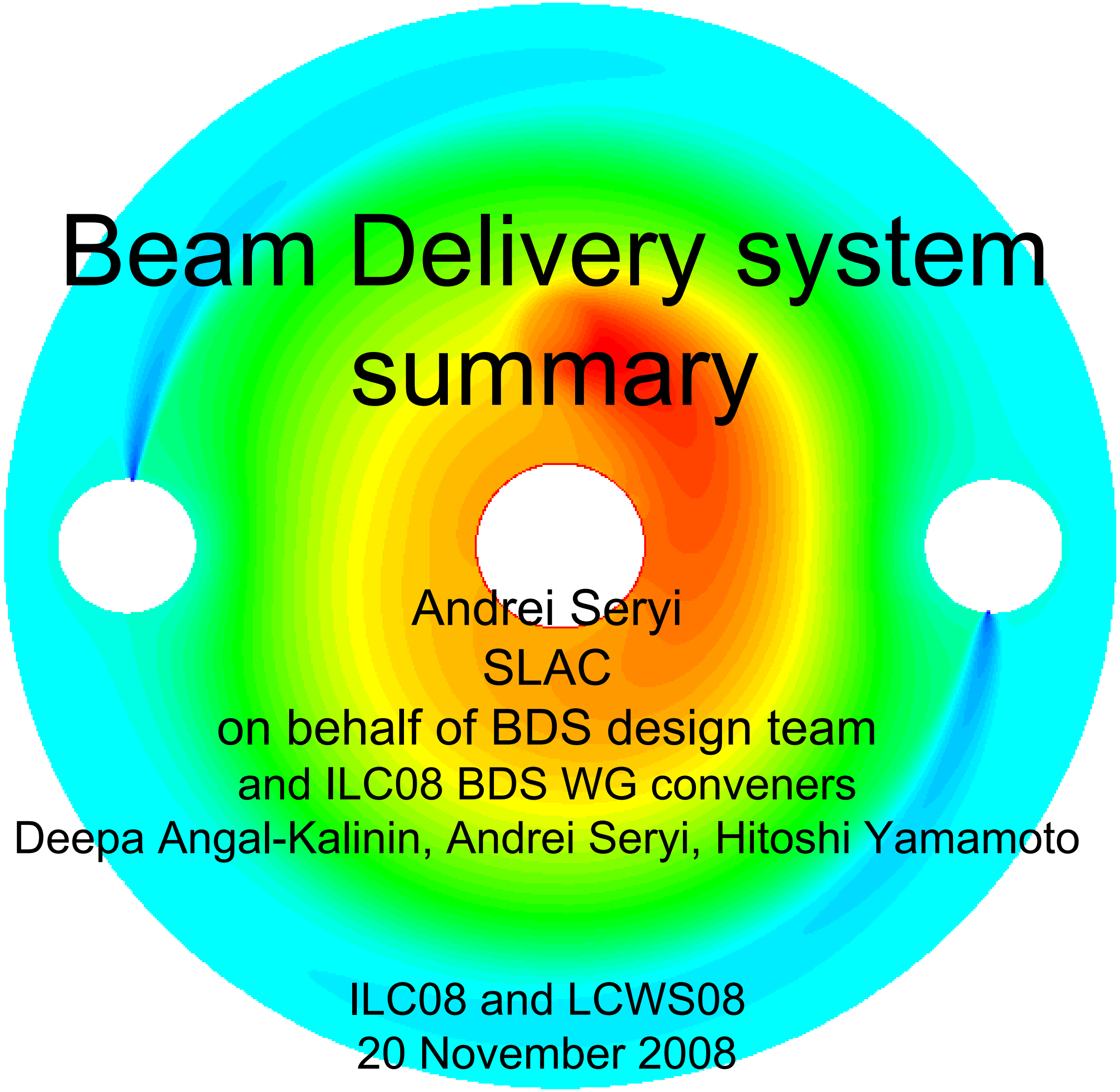
Power output end = reverse of "particle accelerator"

Main Linac Double Tunnel

SKIP



- Three RF/cable penetrations every rf unit
- Safety crossovers every 500 m
- 34 kV power distribution



Beam Delivery system summary

Andrei Seryi
SLAC
on behalf of BDS design team
and ILC08 BDS WG conveners
Deepa Angal-Kalinin, Andrei Seryi, Hitoshi Yamamoto

ILC08 and LCWS08
20 November 2008

Endview illustration of water-tank type beam dump with double header is from Satyamurthy Polepalle et al (BARC-SLAC)

Beam Delivery System Functionality

- Focus and collide *nanobeams* at the interaction point (IP)
- Remove (collimate) the beam halo to reduce detector background
- Provide beam diagnostics for the upstream machine (linac)

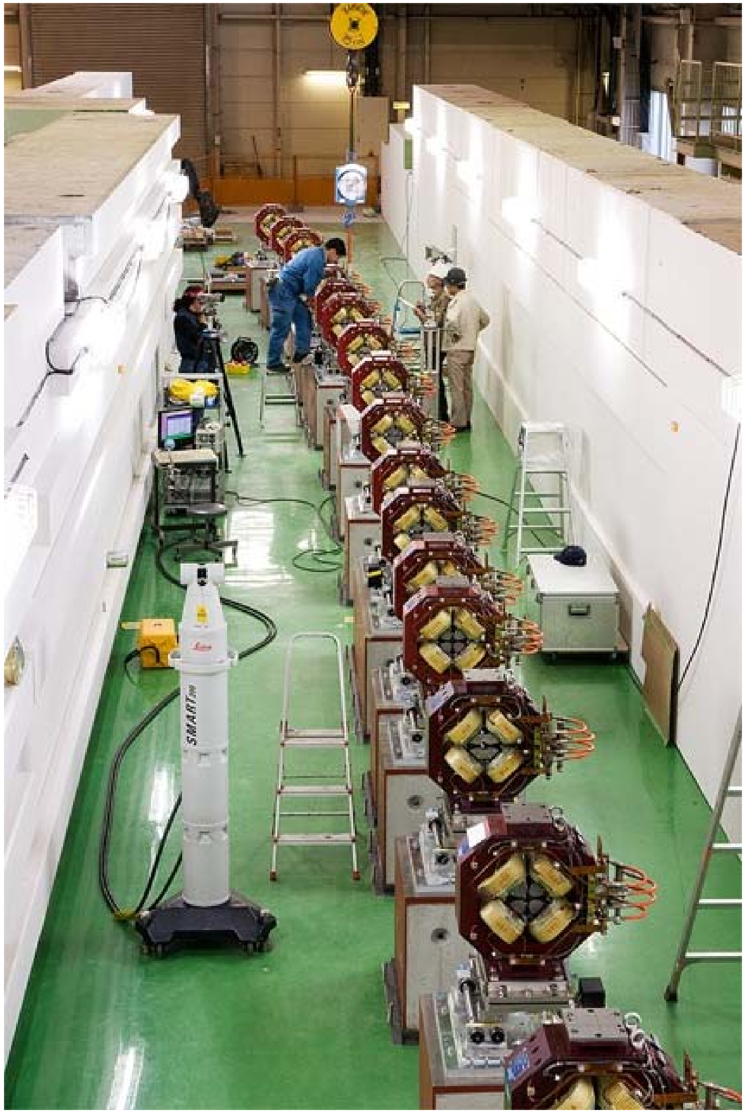
Each one of these is a challenge!

- Final Focus Systems (FFS) need to provide very strong focusing of the beams
- Correction of chromatic and geometric aberrations becomes principle design challenge
- A consequence: systems have extremely tight alignment (*vibration*) tolerances

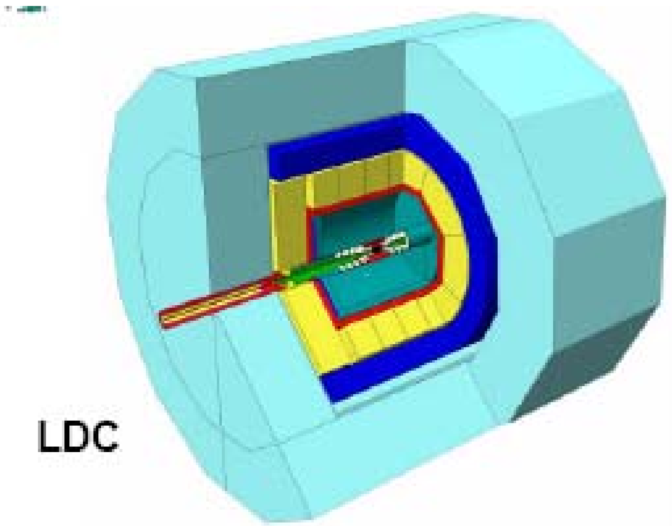
stabilisation techniques by active feedbacks are a must!

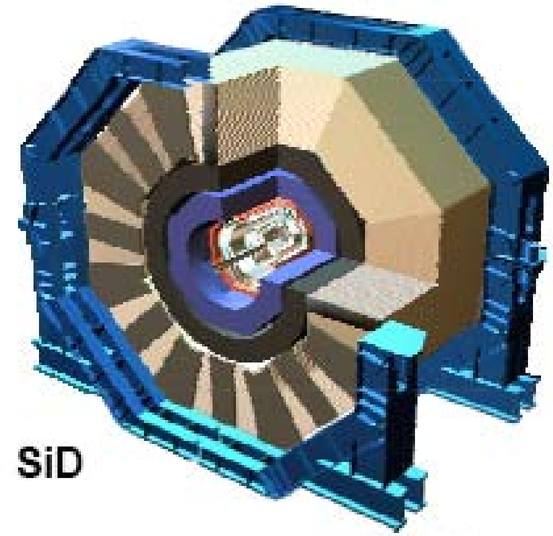
- Beam delivery system studies
  - Demonstrate ~ 50 nm beam spot by 2010
  - Stabilize final focus by 2012
- Broad international collaboration (mini-ILC) for equipment, commissioning and R&D program

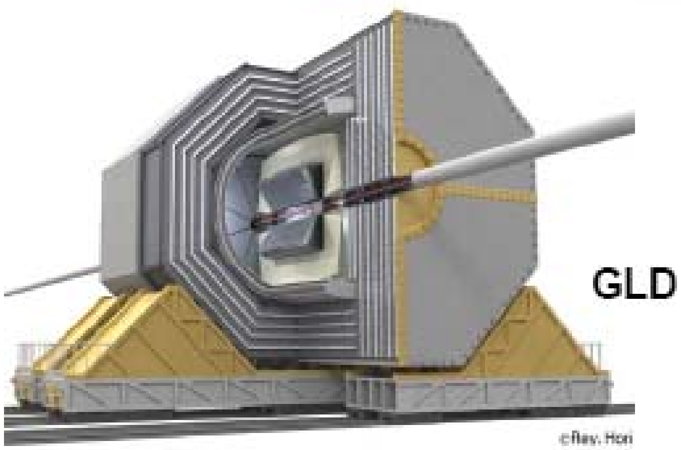
KEK-ATF2 Beam Line vacuum pipe connected in October 2008

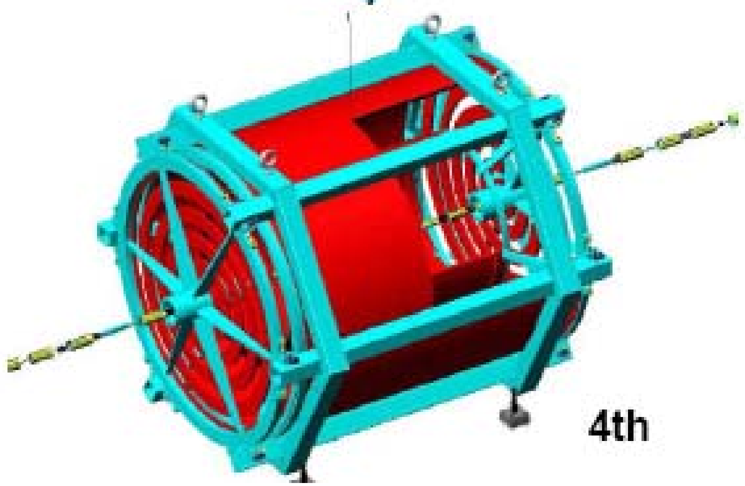


Detector Concepts Report



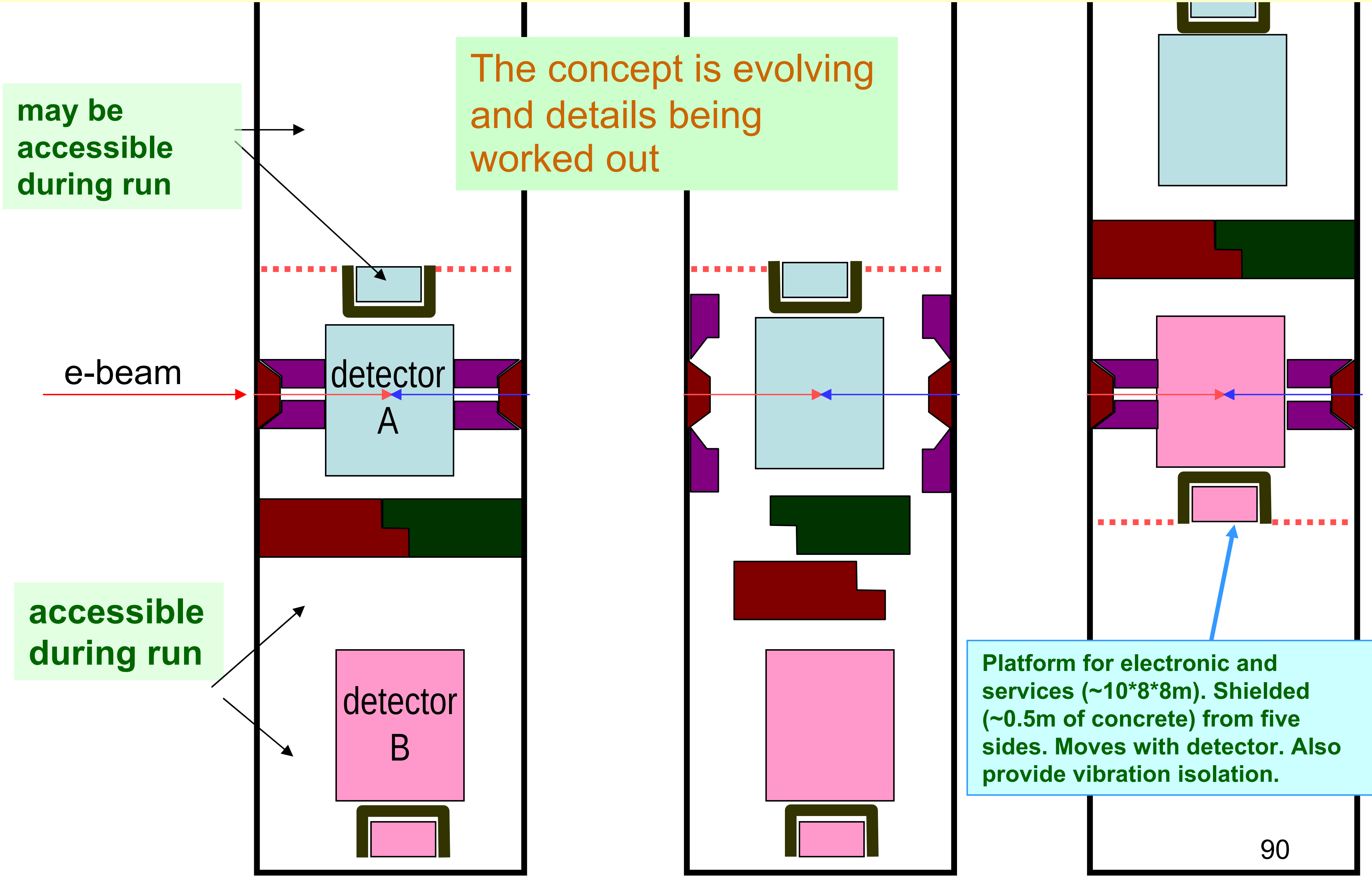






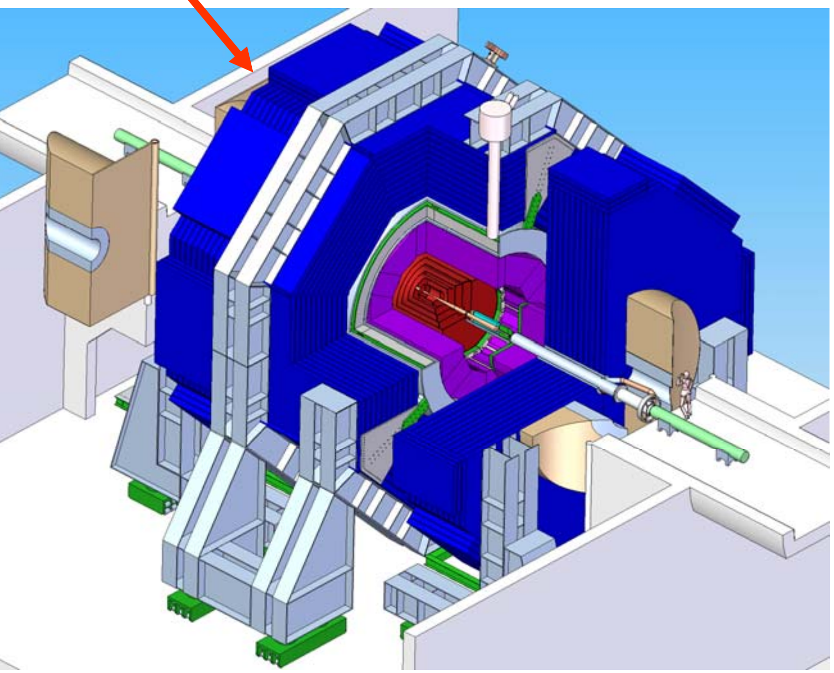
There are 4 competing detector concepts. Two will be chosen.

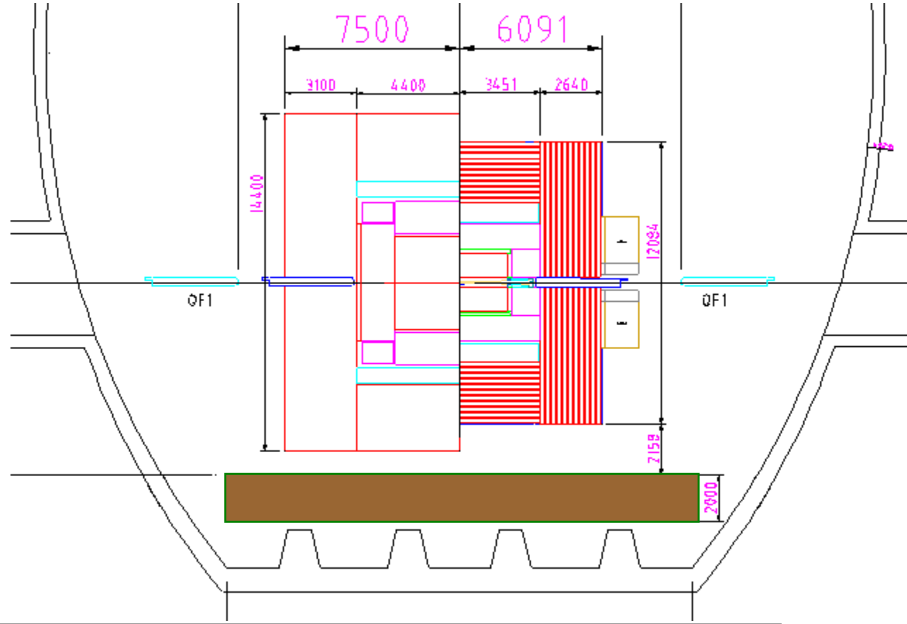
Push-Pull Concept for two detectors

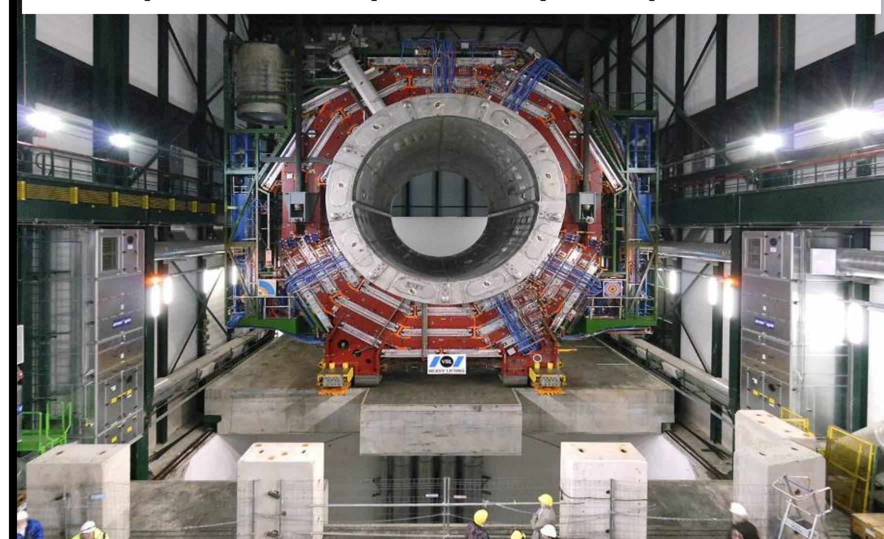


Hot Issue: Machine Detector Interface (MDI), examples

Detector motion system with or without an intermediate platform



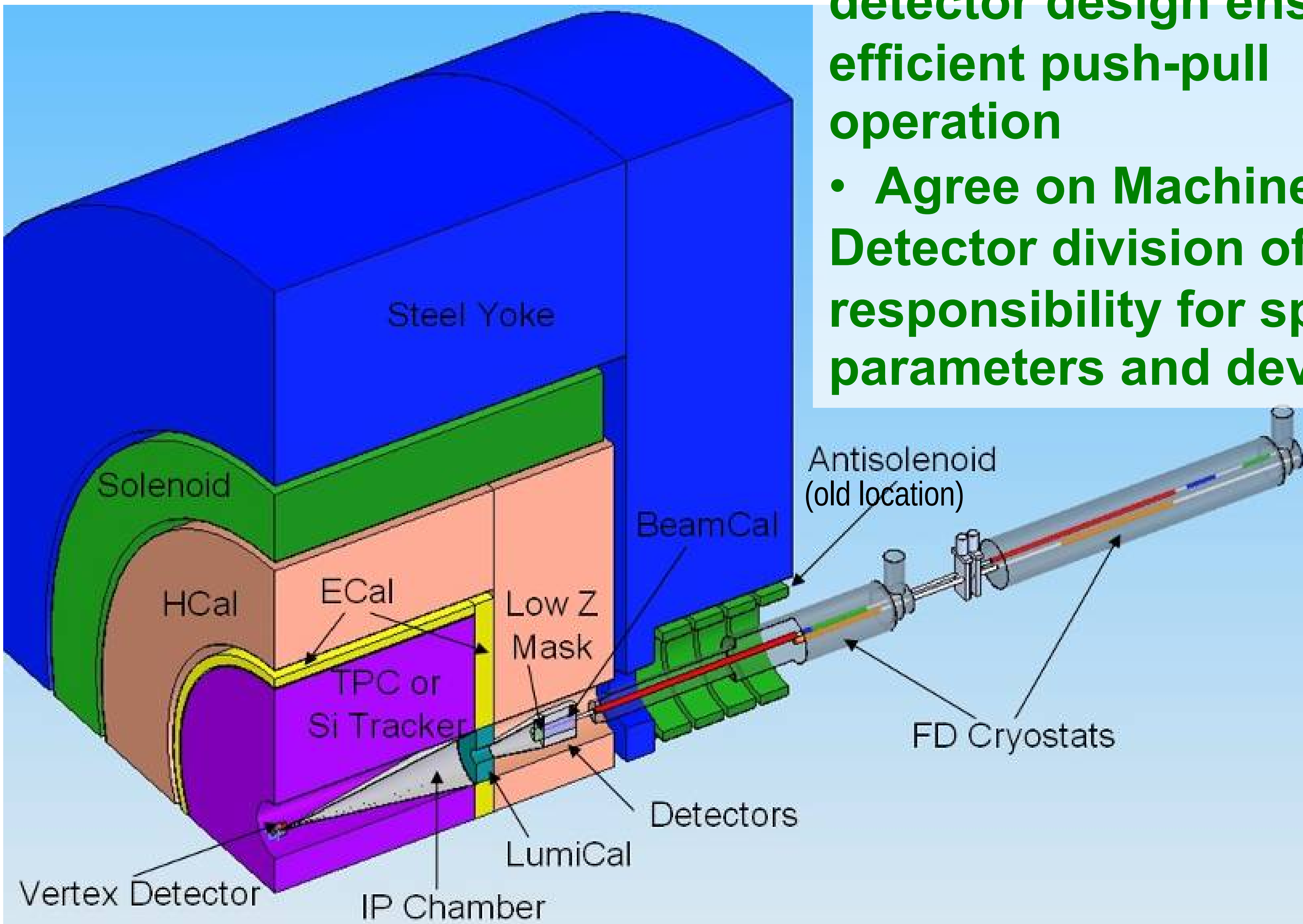




CMS platform – proof of principle for ILC

- Working assumption: use platform
- As detector design develops, a feasible and cost effective solution without a platform might be found

Interaction Region - integration



Challenges:

- **Optimize IR and detector design ensuring efficient push-pull operation**
- **Agree on Machine-Detector division of responsibility for space, parameters and devices**