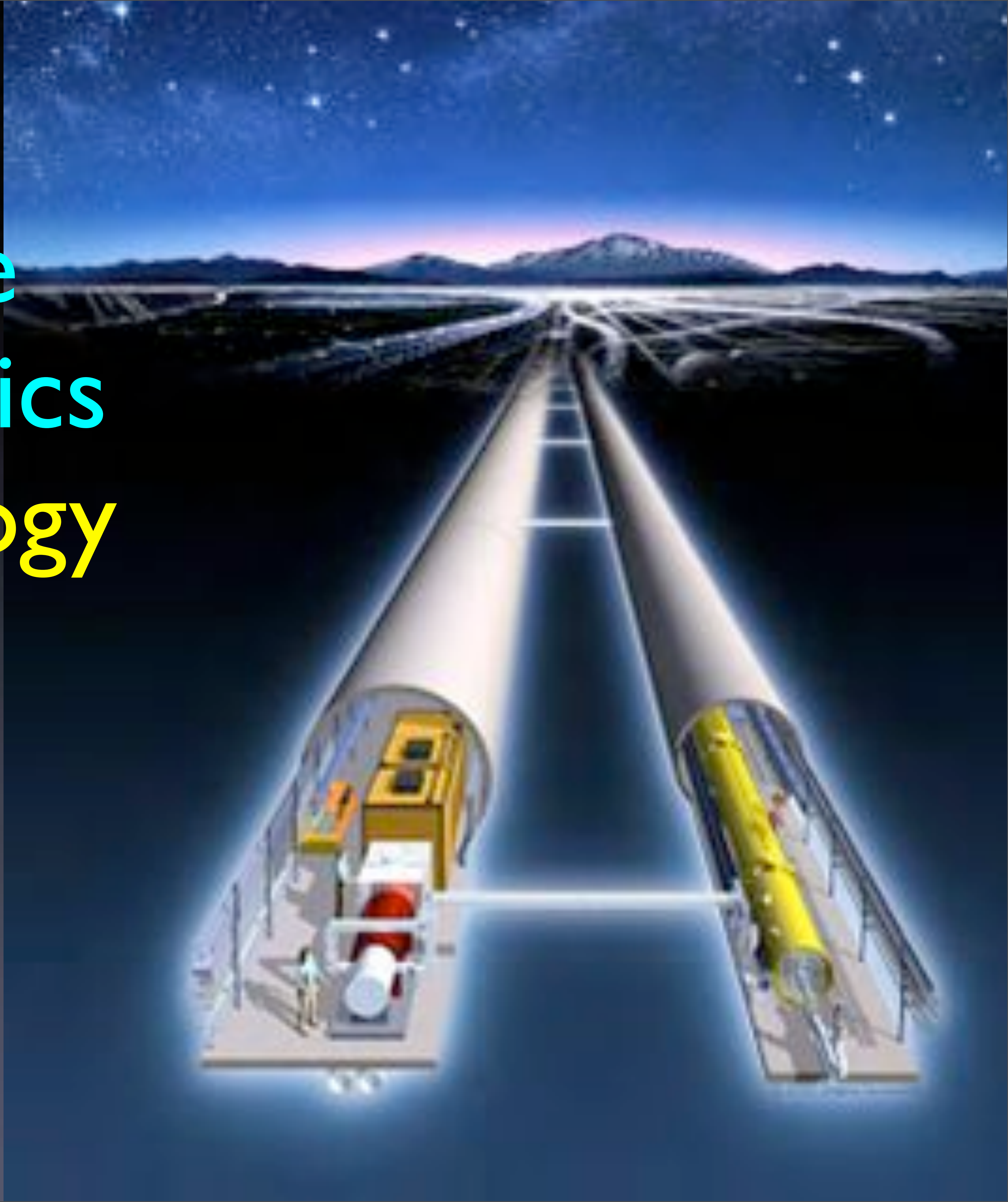
Linear Accelerators

E.Elsen

- Case for Terascale Accelerators (H. Murayama @ TILC 08)
- Longitudinal Phase Space
- Introducing the ILC

ILC, Future Particle Physics and Cosmology

Hitoshi Murayama
(IPMU Tokyo & Berkeley)
TILC08, March 3, 2008



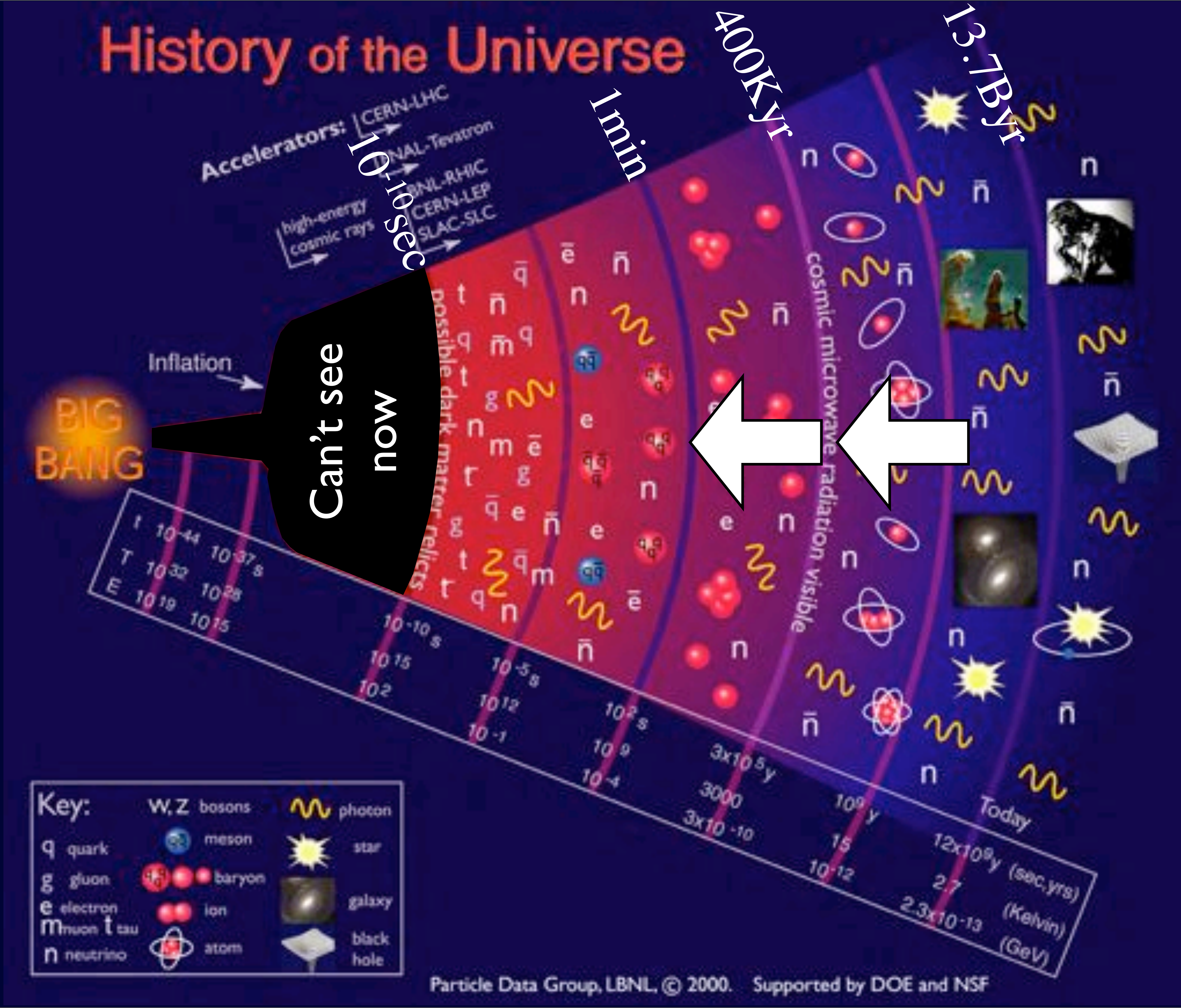
Particle Physics and Cosmology

To understand physics at the largest scale:
Universe
we need to understand the smallest scale:
elementary particles

Questions of the New Millennium

- What is the Universe made of?
- How did it come to be?
- Why do we exist?

Moving from philosophy to physics


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
Can't see now
10-10sec
1min
400Kyr
13.7Byr
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec, yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
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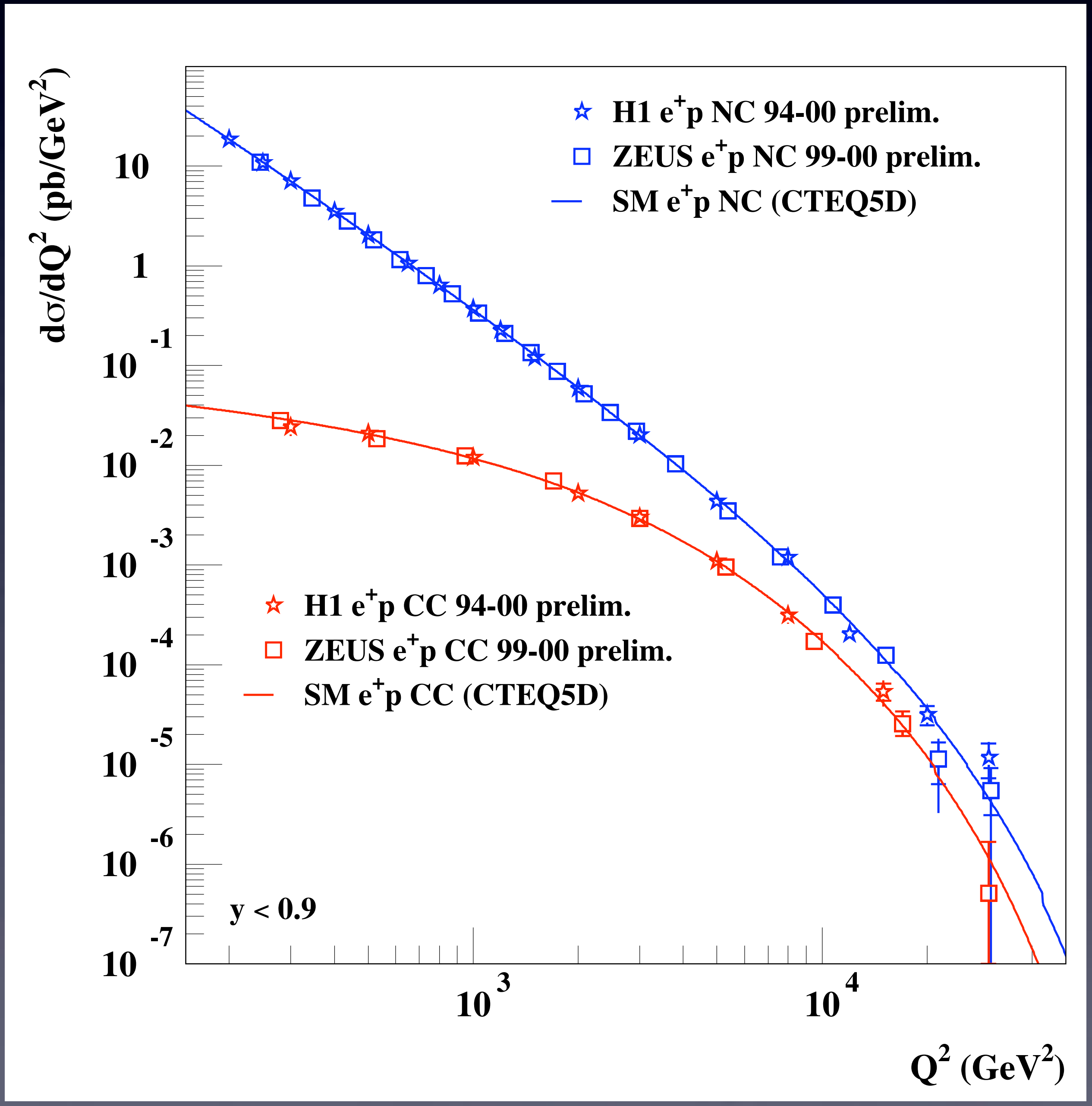
Just about to achieve a new layer of unification

HERA ep collider



- Unification of electromagnetic and weak forces

$\Rightarrow$ electroweak theory

- Long-term goal since '60s
- We are getting there!
- The main missing link: Dark Field

Terascale: rich physics?

- *Dark Matter*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(\mathrm{TeV})^2}{\sigma_{ann}}$$

- *Fermi (Dark Field) scale*

$G_F^{-1/2}=0.3\mathrm{TeV}$

- *Dark Energy*

$\rho_\Lambda \sim (2\mathrm{meV})^4$ *vs* $(\mathrm{TeV})^2/M_{Pl} \sim 0.5\mathrm{meV}$

- *Neutrino*

$(\Delta m^2_{LMA})^{1/2} \sim 7\mathrm{meV}$ *vs* $(\mathrm{TeV})^2/M_{Pl} \sim 0.5\mathrm{meV}$

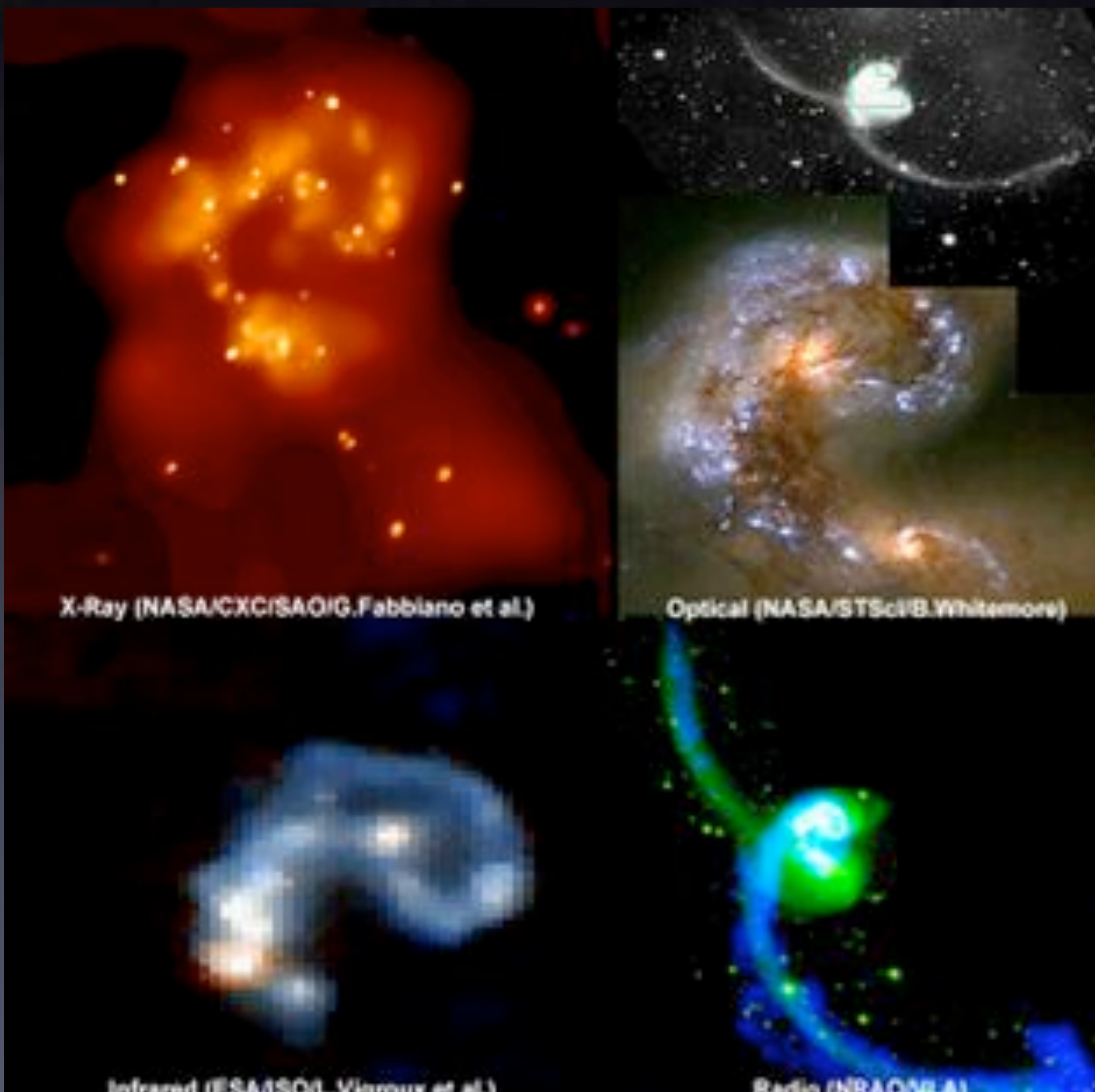
Terascale physics likely to be rich

We are now getting there!

IPMU

BERKELEY CENTER FOR THEORETICAL PHYSICS

Multiple Wavebands in Astronomy



Colliding galaxies!

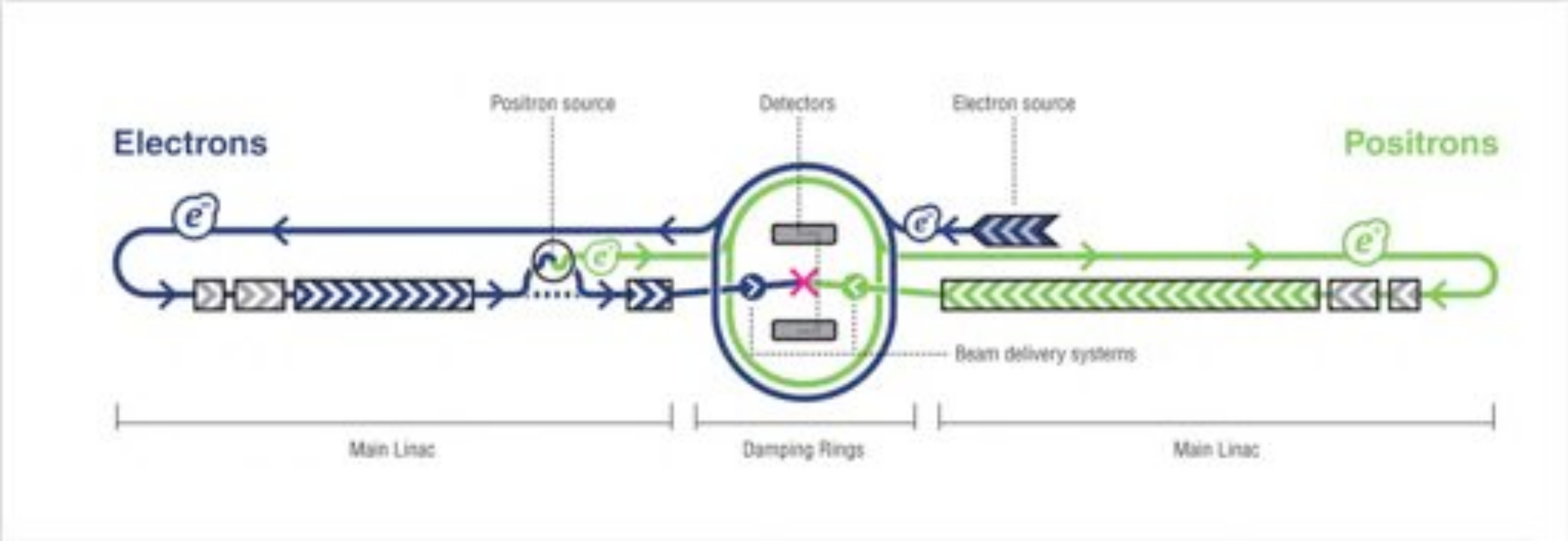
Telescopes vs Accelerators

purpose	need	telescopes	accelerators
probe deeper	better resolution	better mirrors, CCD	higher energy
better image	better exposure	larger telescopes, more time	more powerful beams (luminosity)
full understanding	multiple probes	visible, radio, X-ray, infrared, UV, gamma	protons, electrons, neutrinos

Large Hadron Collider (LHC)

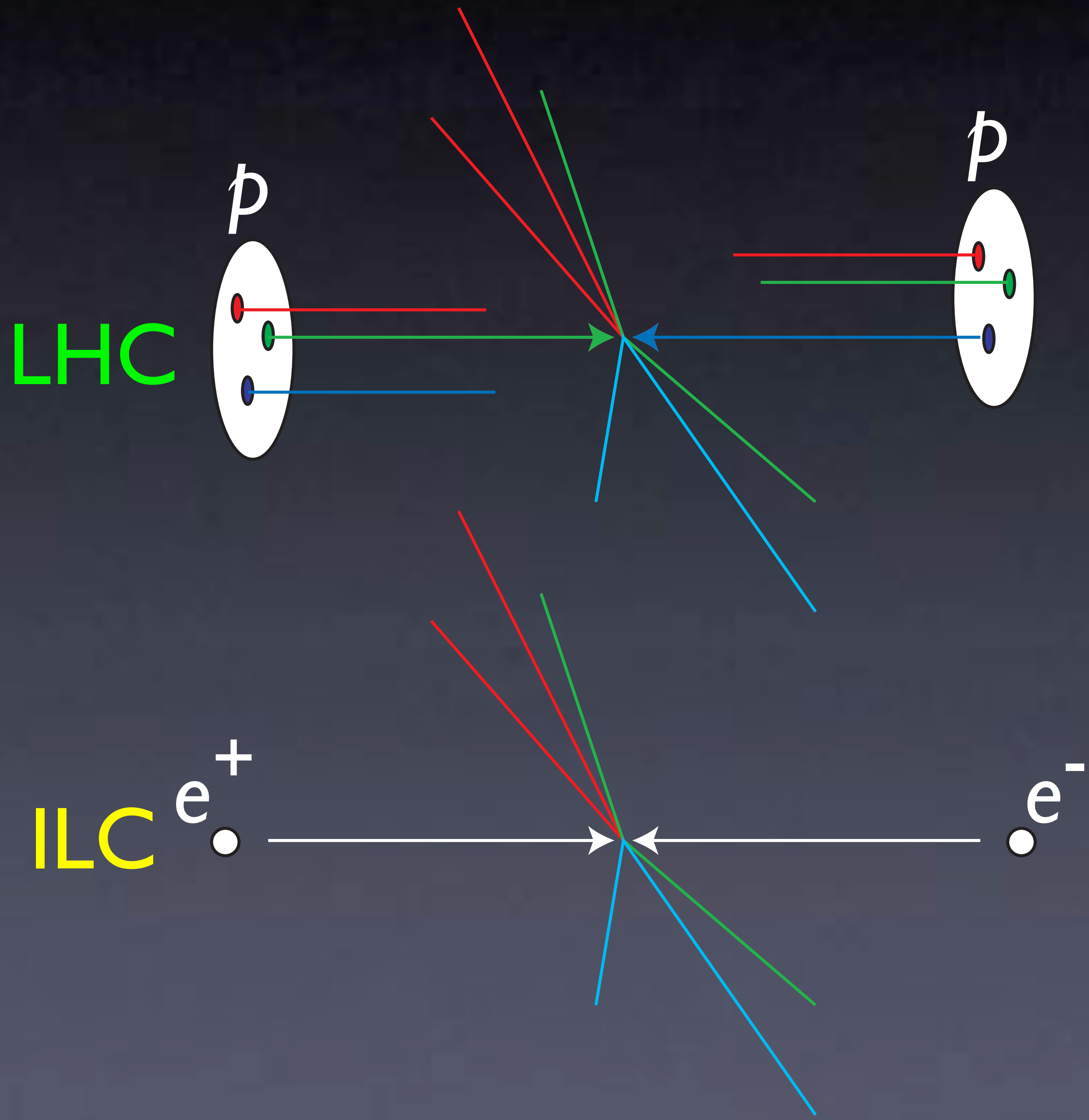
ILC

- electron position collider at 0.5-1 TeV
- about 20 miles long
- super-high-tech: nanometer beams



ILC

- elementary particles
- well-defined energy, angular momentum
- uses its full energy
- can produce particles democratically
- can capture nearly full information



LHC vs ILC

(oversimplified)

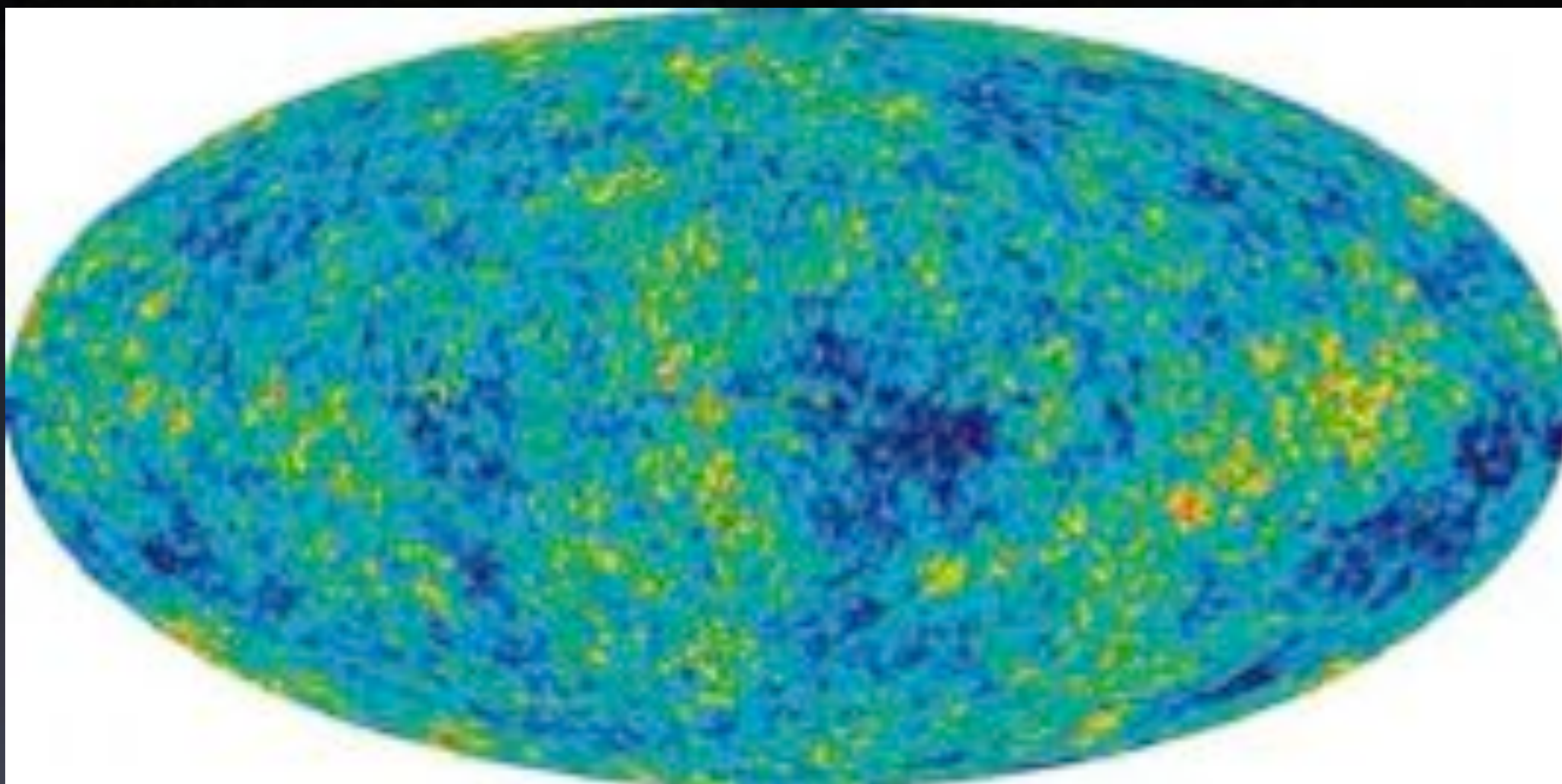
total energy	14TeV	0.5-1 TeV
usable energy	a fraction	full
beam	proton (composite)	electron (point-like)
signal rate	high	low
noise rate	very high	low
analysis	specific modes	nearly all modes
events	lose info along the beams	capture the whole
status	under construction	needs to finish design

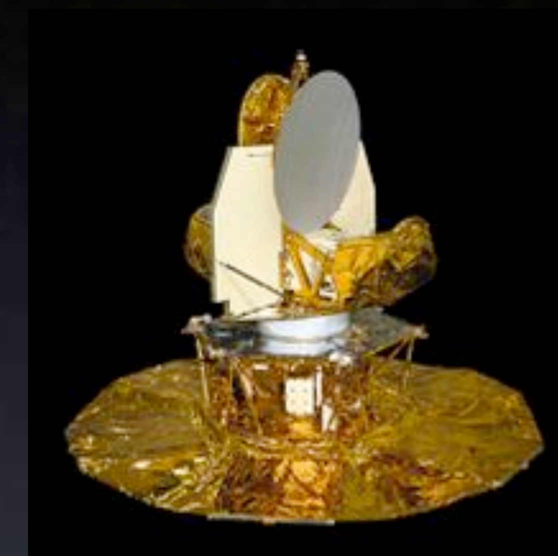
Dark Matter

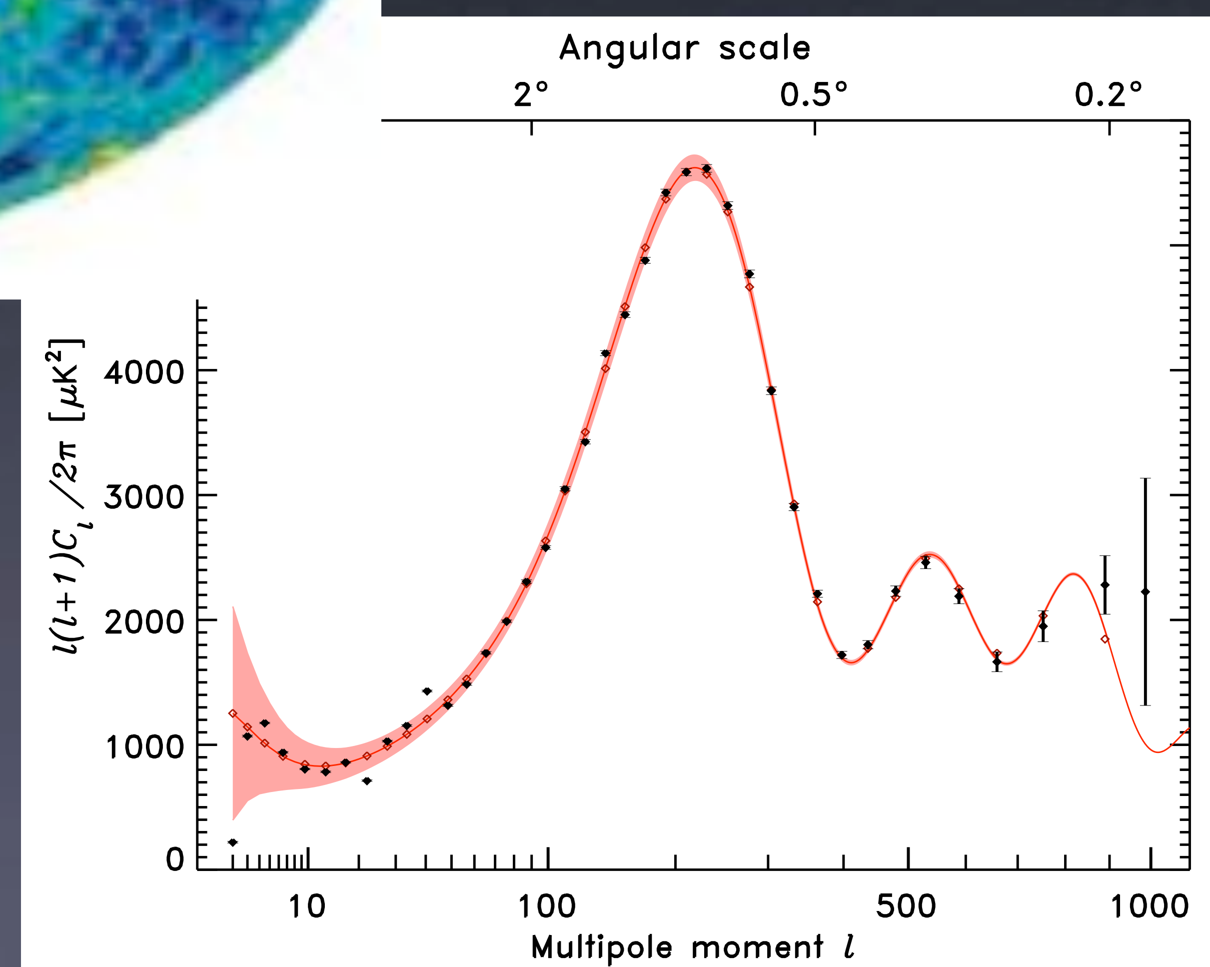
You don't want to be there

You don’t want to be there

Cosmological scales







$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

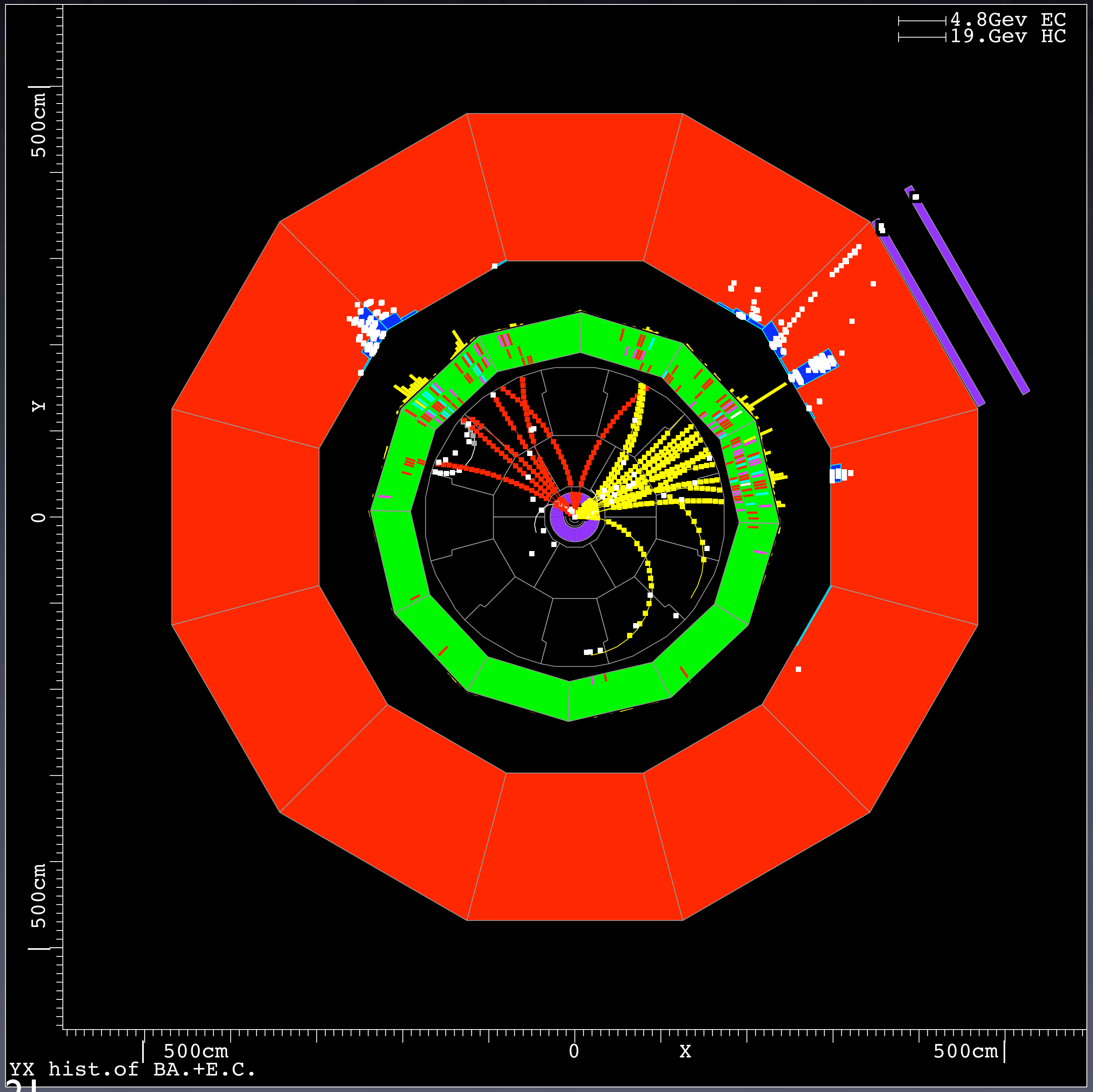
Producing Dark Matter in the laboratory

- Mimic Big Bang in the lab
- Hope to create invisible Dark Matter particles
- Look for events where energy and momenta are unbalanced

“missing energy” E_{miss}

- Something is escaping the detector

⇒Dark Matter!?



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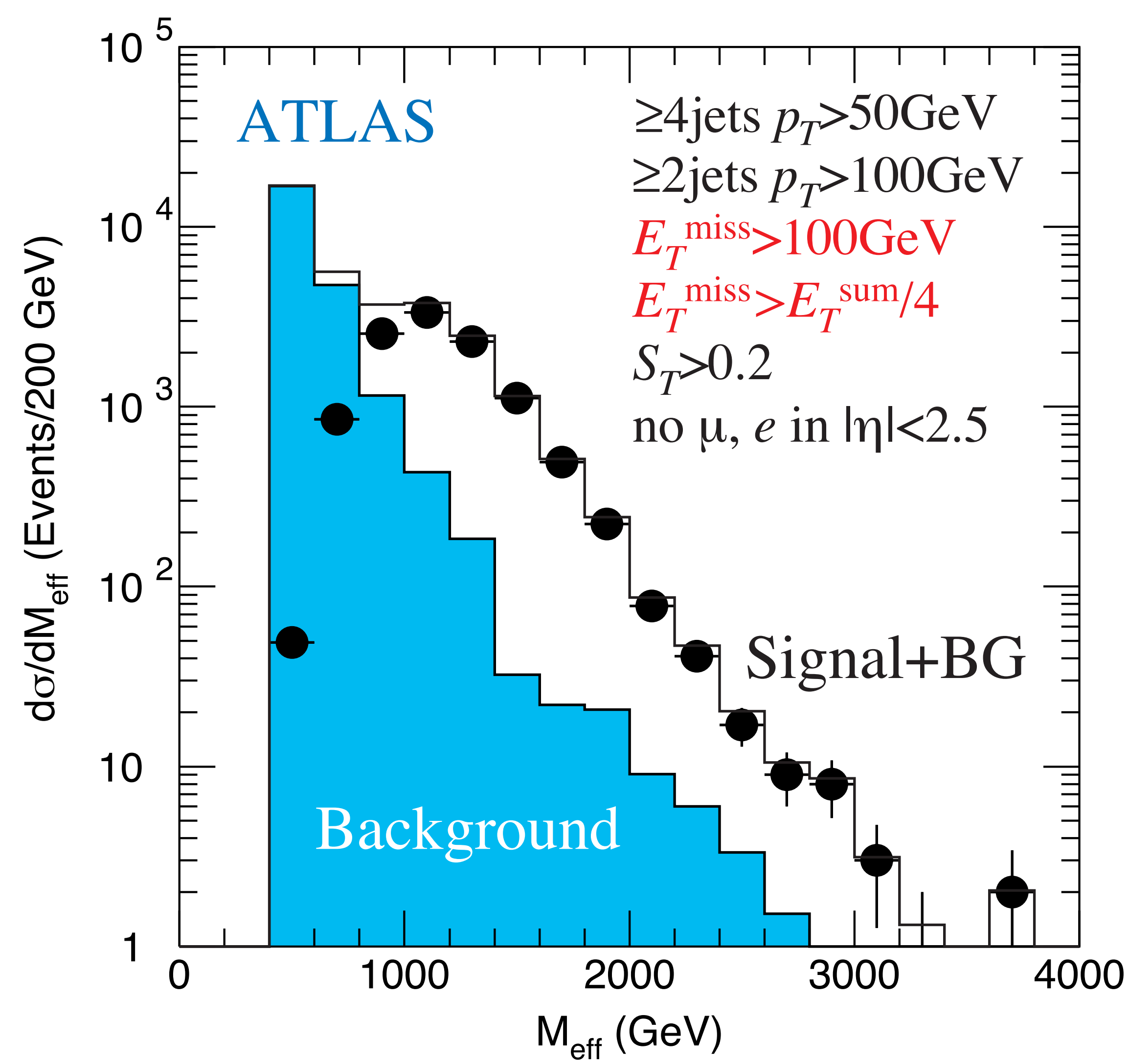
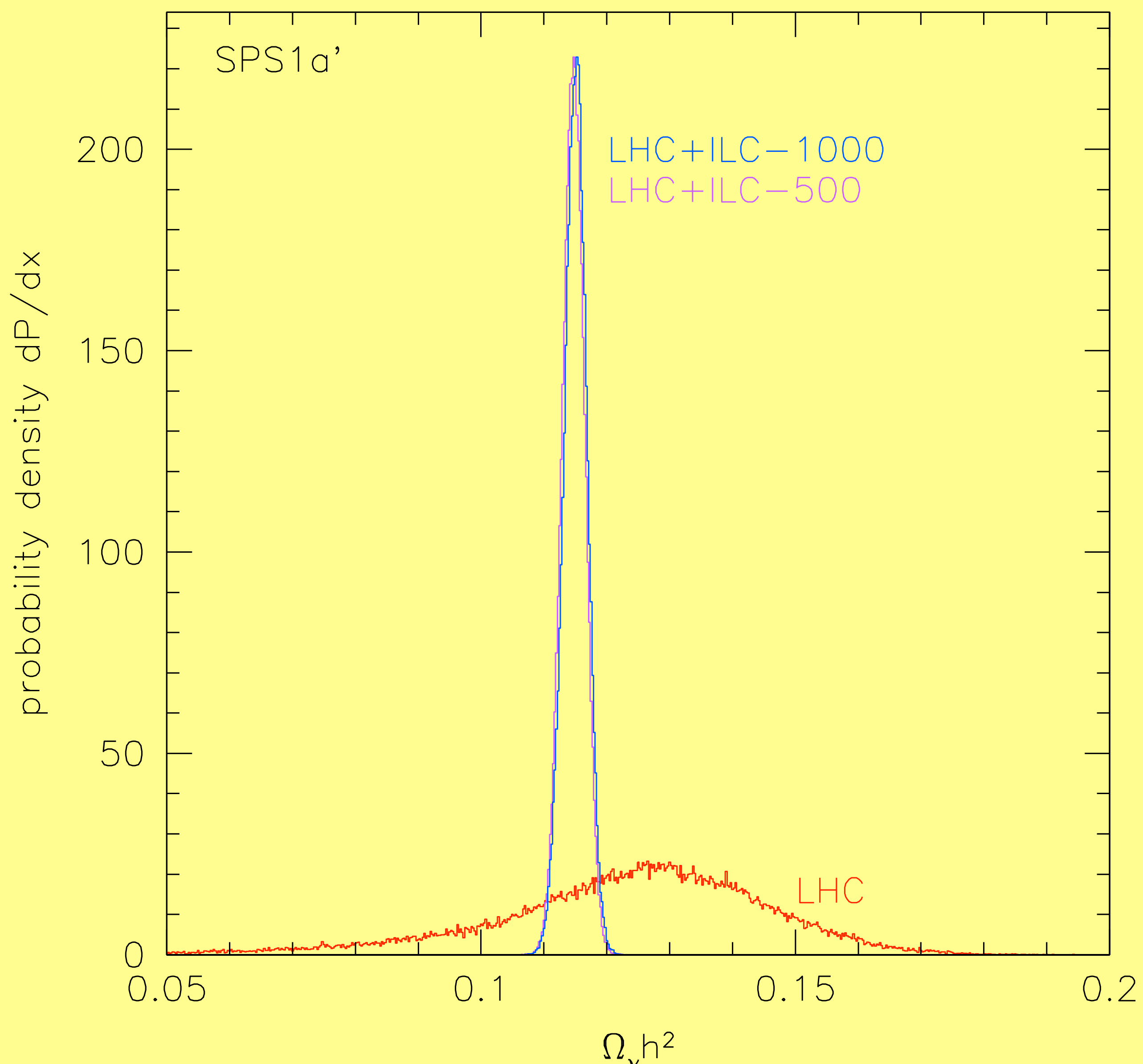
Supersymmetric Dark Matter



Measure the Universe with colliders



case study

Baltz, et al, hep-ph/0602187

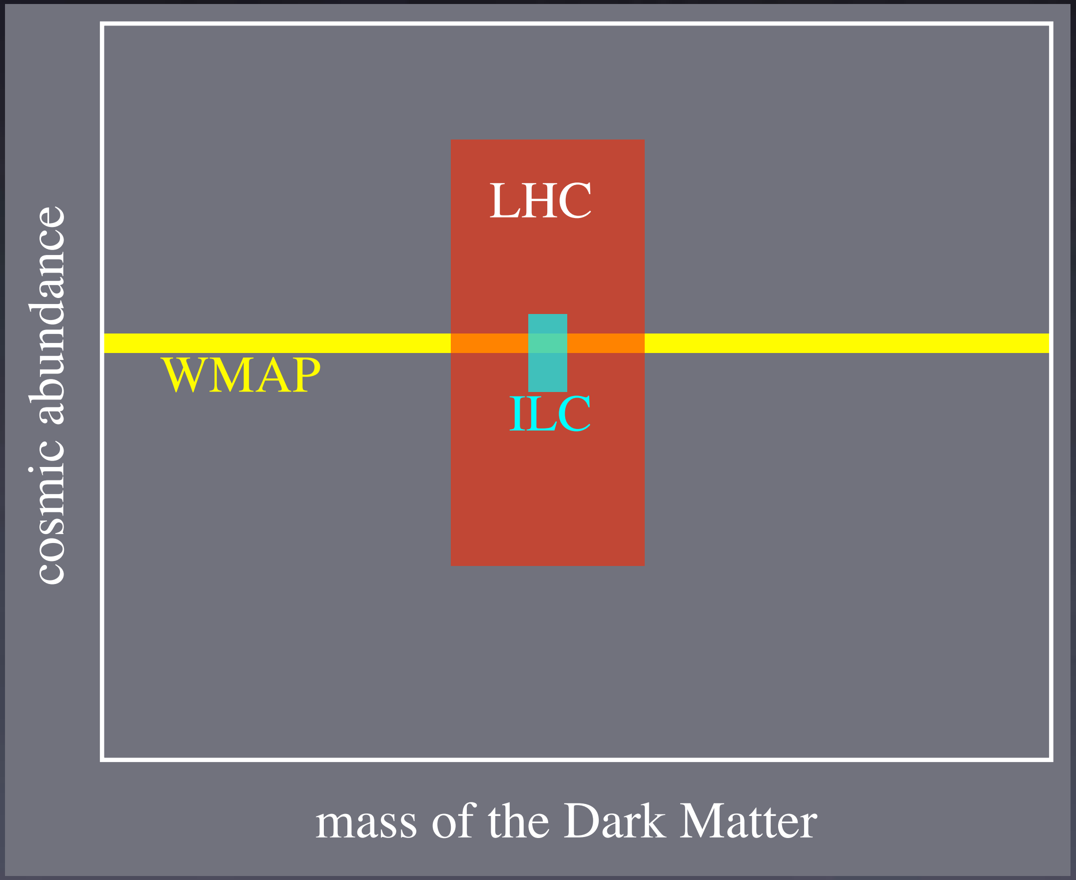
- With LHC & ILC data, we can calculate how much dark matter there *should* be
- Does that agree with the way the Universe *is*?

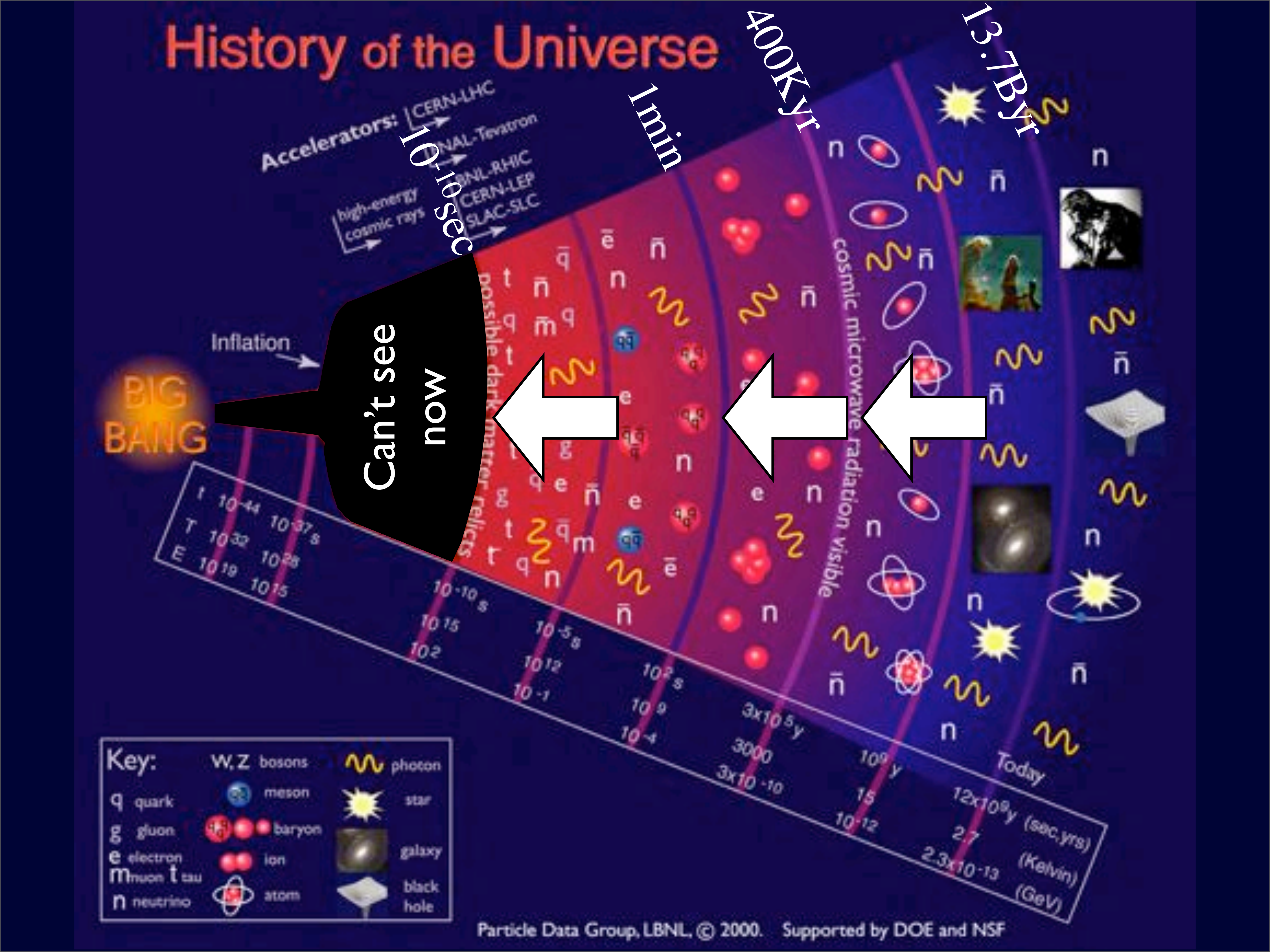
Dark Matter Concordance

- cosmological measurement of dark matter
  - abundance $\propto \sigma_{ann}^{-1}$
- detection experiments
  - scattering cross section
- production at colliders
  - mass, couplings
  - can calculate cross sections
- If they agree with each other:

$\Longrightarrow$ Will know *what Dark Matter is*

$\Longrightarrow$ Will understand universe back to t~10^{-10} sec

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Today
Key:
W,Z bosons
photon
q quark
meson
star
g gluon
baryon
e electron
ion
galaxy
m muon t tau
n neutrino
atom
black hole
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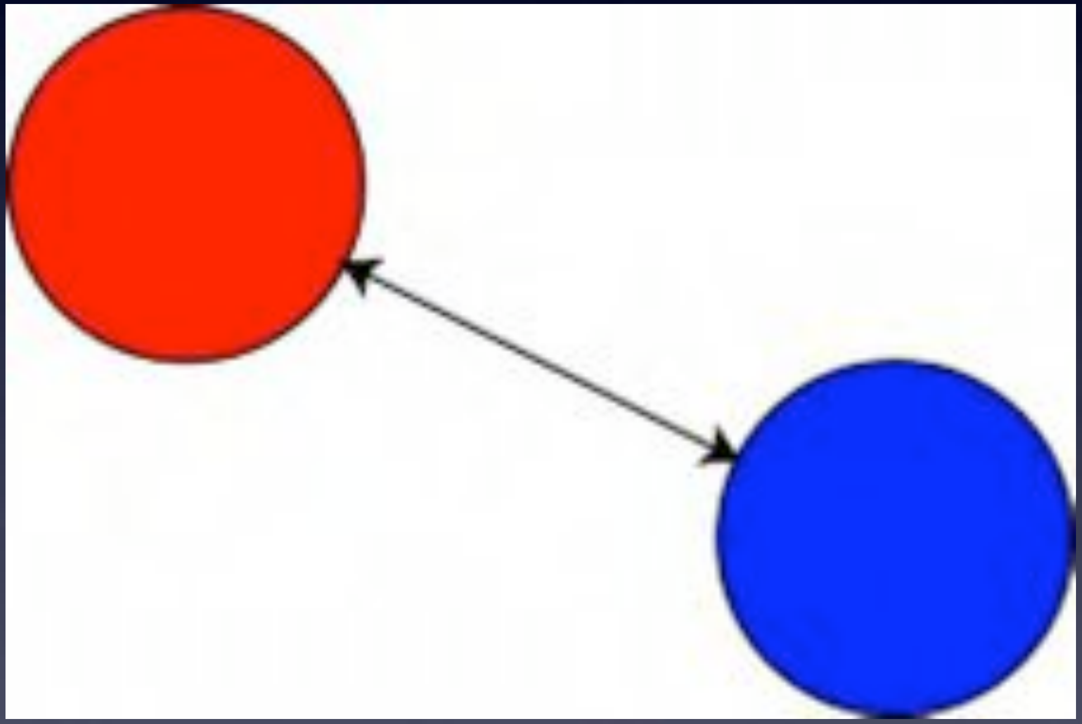
Dark Field
=Cosmic Superconductor

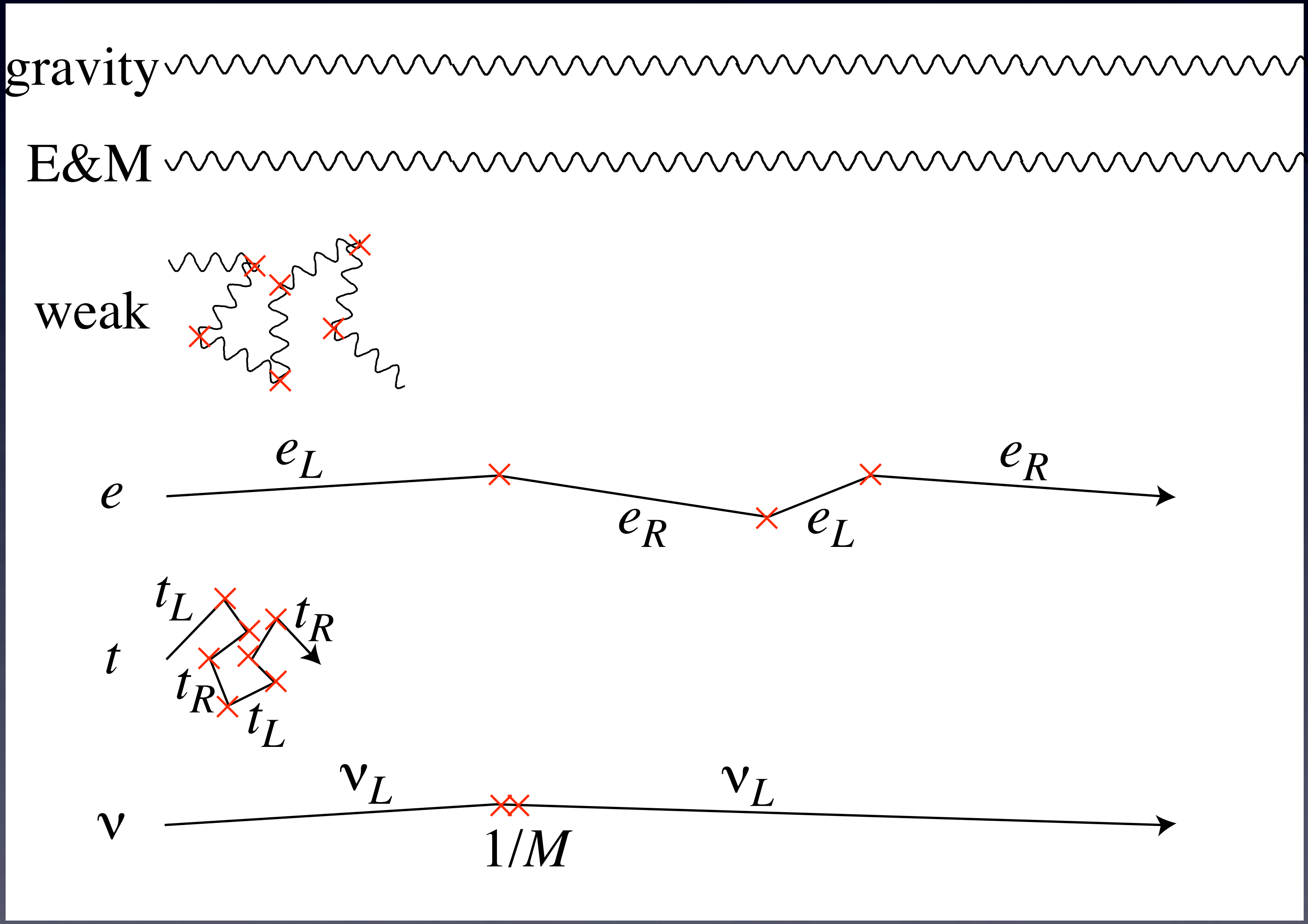
Mystery of the weak force

- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer
- We know the energy scale: ~0.3 TeV



We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??



Cosmic Superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"

  $\Rightarrow$ Magnetic field is short-ranged!

- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Doesn't have enough energy (gap) to break up Cooper pairs

That's the stage where we are!

We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
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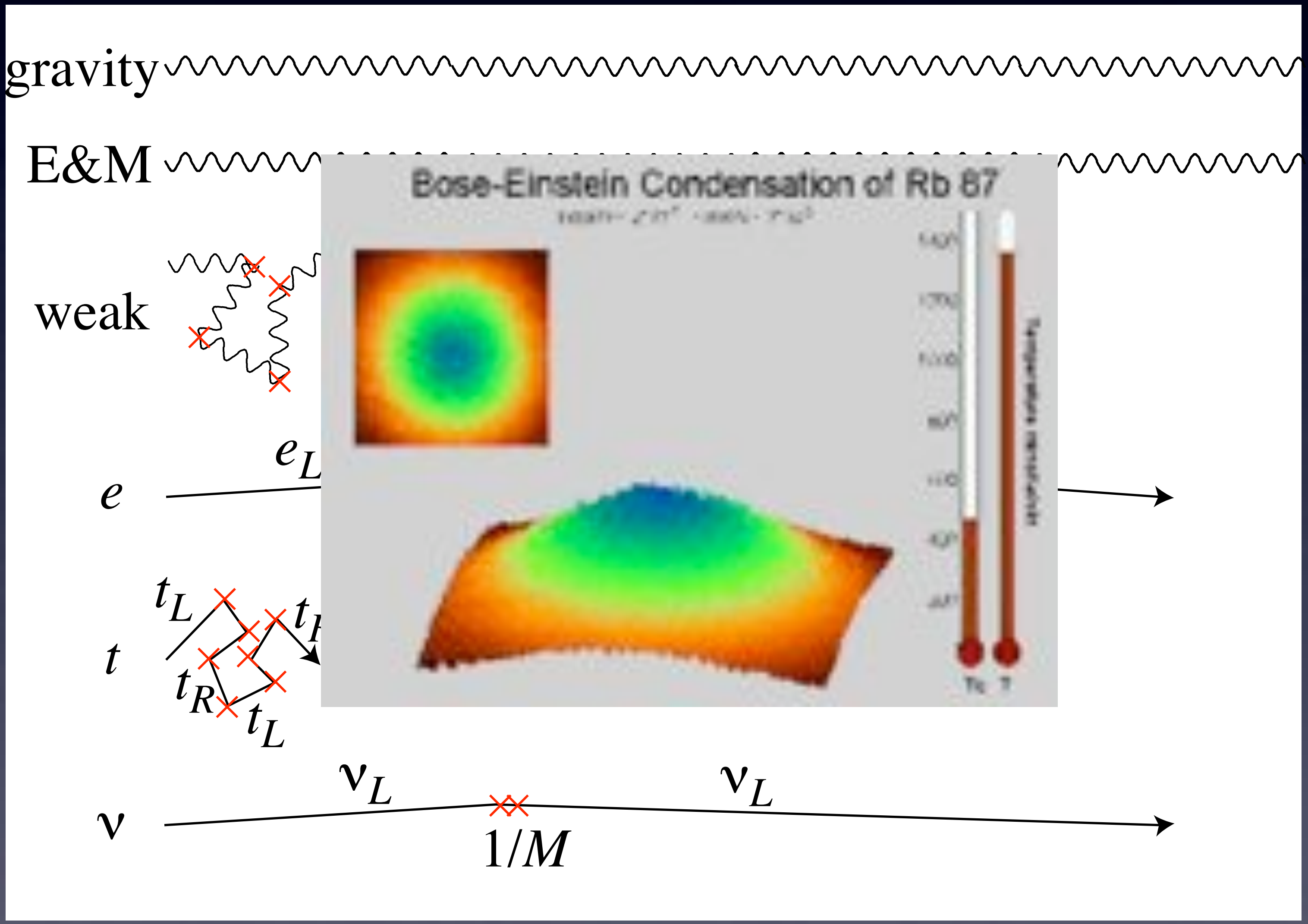


Break

Intermittence

The longitudinal Phase Space
(in circular accelerators)

completing the lectures on
Introduction to Accelerator Physics

4.3. Longitudinal Beam Dynamics

4.3.1. Equation of Motion in Phase Space

From the discussion of the momentum compaction (chapter 4.3.7.) we have obtained for the relative variation of the travel time $\Delta T / T_0$ and the angular revolution frequency $\Delta\omega / \omega_0$:

$$\frac{\Delta T}{T_0} = -\frac{\Delta\omega}{\omega_0} = -\left(\frac{1}{\gamma^2} - \alpha_c\right)\frac{\Delta p}{p_0} = -\eta \cdot \frac{\Delta p}{p_0}$$

The revolution frequency ω_0 is linked to the RF frequency ω_{RF} by the number h of circulating bunches, which is called the **harmonic number**. Using this relation we obtain for the phase shift $\Delta\varphi = \varphi - \varphi_0$ with respect to a reference particle (with reference phase φ_0):

$$\Delta\varphi = \omega_{RF} \cdot \Delta T = h \cdot \omega_0 \cdot \Delta T$$

The phase shift per revolution can be linked to the relative momentum deviation by using the η-parameter:

$$\left(\Delta\varphi\right)_{rev} = -\eta\, h\, \omega_0\, T_0 \frac{\Delta p}{p_0} = -2\pi\, h\, \eta \frac{\Delta p}{p_0}$$

and may be expressed in terms of the relative energy deviation using

$$E^2 = m_0^2 c^4 + p^2 c^2 \;\Rightarrow\; 2E \cdot dE = 2\, p\, c^2 \cdot dp \;\Rightarrow\; dE = \beta\, c \cdot dp \;\Rightarrow\; \frac{dE}{E} = \beta^2 \frac{dp}{p}$$

which gives:

$$\left(\Delta\varphi\right)_{rev} = -\frac{2\pi\, h\, \eta}{\beta^2} \frac{\Delta E}{E_0}$$

So far, we have expressed the phase shift $\left(\Delta\varphi\right)_{rev}$ per revolution in terms of $\Delta E = E - E_0$. In order to relate this to the energy gain per turn produced by acceleration, we first have to divide by the revolution time T_0 to get the change of the phase shift per unit time $\Delta\dot{\varphi}$:

$$\frac{d}{dt}\Delta\varphi = \frac{(\Delta\varphi)_{rev}}{T_0} = -\frac{2\pi h\eta}{\beta^2 T_0 E_0}\cdot \Delta E$$

We then have to built the second derivative to express this variation in terms of the energy gain $(\Delta E)_{rev}$ per turn

accelerating voltage — radiation loss — $U(\varphi(t)) = U_0 \sin\varphi(t)$

$$(\Delta E)_{rev} = eU(\varphi) - W(E) = eU_0 \sin\varphi - W(E)$$

where $W(E)$ represents the radiation losses per turn due to synchrotron radiation and $U(\varphi)$ is the acceleration voltage for a given phase φ. The energy gain per turn $(\Delta E)_{rev}$ is linked to the energy deviation ΔE with respect to the reference particle by

$$\frac{d}{dt}\Delta E = \frac{1}{T_0}\cdot(\Delta E)_{rev}$$

This gives

$$\frac{d^2\Delta\varphi}{dt^2} + \frac{2\pi h\eta}{\beta^2 T_0 E_0}\cdot\frac{d\,\Delta E}{dt} = 0$$

and we finally obtain

$$\frac{d^2\Delta\varphi}{dt^2} + \frac{2\pi h\eta}{\beta^2 T_0^2 E_0}\cdot\left[eU_0\sin\left(\varphi_0+\Delta\varphi\right)-W(E)\right] = 0$$

This term may have either sign...

4.3.2. Small Oscillation Amplitudes

For small deviations $\Delta\varphi$ from the synchronous phase we can expand the acceleration voltage into a Taylor series and get

$$\frac{d}{dt}\Delta E = \frac{\Delta E}{T_0} \approx \frac{1}{T_0}\left\{eU(\varphi_0) + e\frac{dU(\varphi_0)}{d\varphi}\cdot\Delta\varphi - W\left(E_0\right) - \frac{dW\left(E_0\right)}{dE}\cdot\Delta E\right\}$$

$$\frac{d}{dt}\Delta\varphi \sim \Delta E$$

At equilibrium we have $eU(\varphi_0)=W(E_0)$ and obtain the phase equation

$$\frac{d^2\Delta\varphi}{dt^2} + 2\cdot\underbrace{\left(\frac{1}{2T_0}\cdot\frac{dW(E_0)}{dE}\right)}_{=\alpha_S}\cdot\frac{d\Delta\varphi}{dt} + \underbrace{\left(\frac{2\pi h\eta e}{\beta^2 T_0^2 E_0}\cdot U_0\cos\varphi_0\right)}_{=\Omega_S^2}\cdot\Delta\varphi = 0$$

Particles orbiting in a circular accelerator therefore perform longitudinal oscillations with the angular frequency Ω_S, which are called **synchrotron oscillations**. These phase oscillations are damped or antidamped depending on the sign of the damping decrement α_S. For small oscillation amplitudes the movement can be described by a damped harmonic oscillator. In most cases we find the damping time much longer than the phase oscillation period

$$\tau_S = \frac{1}{\alpha_S} \ll \frac{2\pi}{\Omega_S} = \frac{1}{Q_S}$$

and the synchrotron tune Q_S, defined by the number of longitudinal oscillations per turn, much smaller than the transverse tunes Q_X, Q_Z.

The oscillations are stable for a real angular frequency Ω_S and therefore for a positive product $\eta \cdot \cos\varphi_0$. From $\eta = 1/\gamma^2 - 1/\gamma_{tr}^2$ and the equilibrium condition $eU_0 \sin\varphi_0 = W(E_0) > 0$ we derive the condition for stable phase focusing:

$$0 < \varphi_0 < \frac{\pi}{2} \qquad \text{for} \qquad \gamma < \gamma_{tr}$$

$$\frac{\pi}{2} < \varphi_0 < \pi \qquad \text{for} \qquad \gamma > \gamma_{tr}$$

Neglecting the small damping term the equation of motion reads

$$\frac{d^2\,\Delta\varphi}{dt^2} + \Omega_S^2 \cdot \Delta\varphi = 0$$

and is solved by a harmonic oscillation

$$\Delta\varphi = \widehat{\Delta\varphi} \cdot \cos\left(\Omega_S t + \phi\right)$$

Building the first derivative and relating $\Delta\dot{\varphi}$ to the relative energy deviation $\Delta E / E_0$,

we obtain for the amplitude $\widehat{\Delta\varphi}$ of the oscillation

$$\Delta\dot{\varphi} = -\Omega_S \cdot \widehat{\Delta\varphi} \cdot \sin\left(\Omega_S t + \phi\right) = -\frac{2\pi h \eta}{\beta^2 T_0} \cdot \frac{\Delta E}{E_0} = \eta\,\omega_{RF} \cdot \frac{\Delta p}{p_0}$$

$$\Rightarrow \qquad \widehat{\Delta\varphi} = \frac{\eta\,\omega_{RF}}{\beta^2\,\Omega_S}\cdot\left(\frac{\Delta E}{E_0}\right)_{\max} = \frac{\eta\,\omega_{RF}}{\Omega_S}\cdot\left(\frac{\Delta p}{p_0}\right)_{\max}$$

All particles of a beam perform incoherent phase oscillations about a common reference point and generate thereby the appearance of a steady longitudinal distribution of particles which we call a particle bunch.

The total bunch length l_b can be determined from the maximum longitudinal excursion of particles from the bunch center and is twice the amplitude of the phase variation.:

$$\frac{l_b}{2} = \frac{\lambda_{RF}}{2\pi}\cdot\widehat{\Delta\varphi} = \frac{c}{h\,\omega_0}\cdot\widehat{\Delta\varphi}$$

Using the equation derived above, this gives

$$l_b = 2\cdot\frac{c\sqrt{2\pi}}{\beta\,\omega_0}\cdot\sqrt{\frac{\eta\,E_0}{h\,e\,U_0\cos\varphi_0}}\cdot\left(\frac{\Delta E}{E_0}\right)$$

4.3.3. Large Amplitude Oscillations

We will ignore the small damping term for the following discussions. This allows us to rewrite the equation of motion (without any further approximation) to

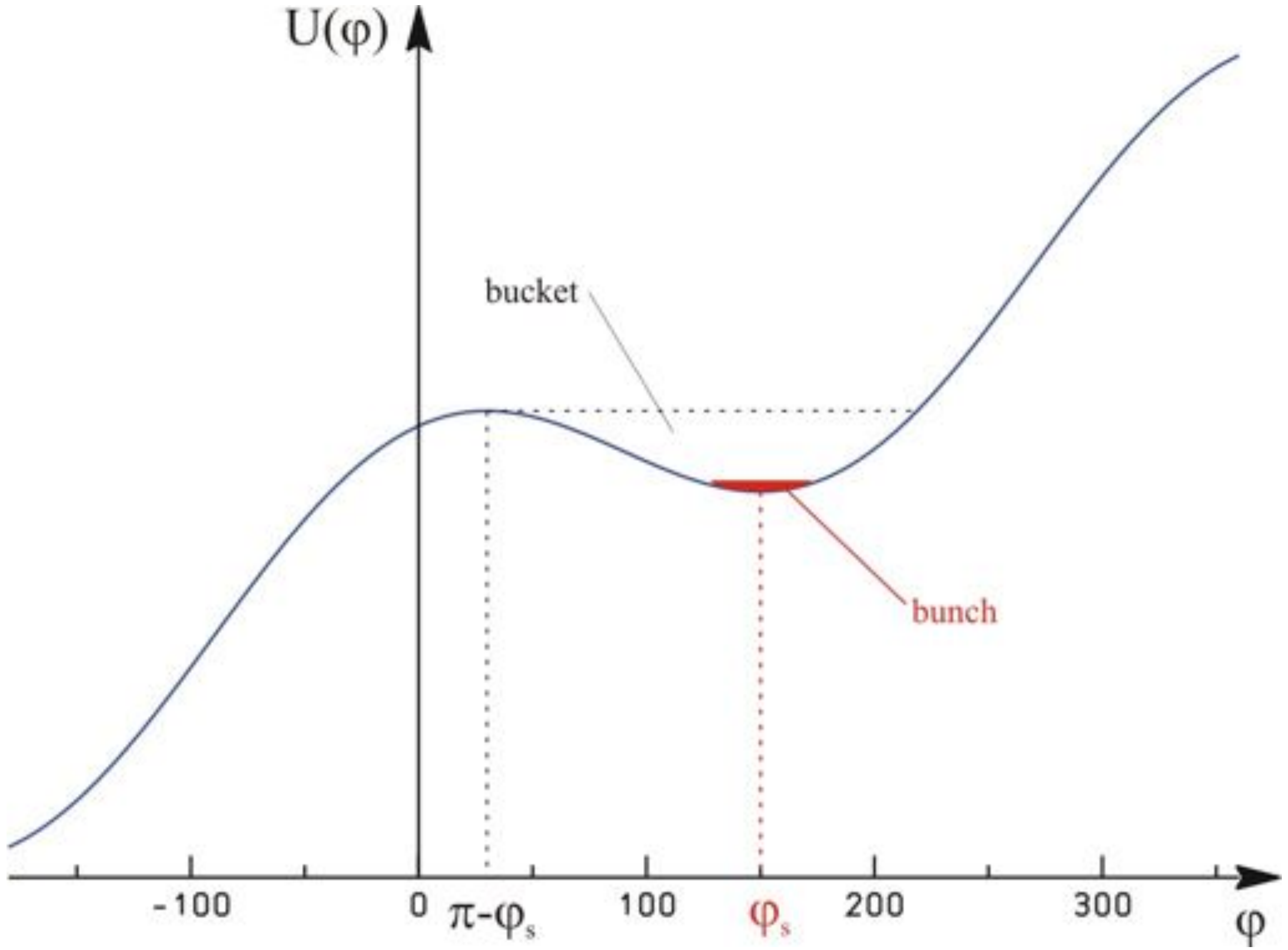
$$\ddot{\varphi} + \frac{\Omega_S^2}{\cos\varphi_0}\left[\sin\varphi - \sin\varphi_0\right] = 0$$

with the synchrotron frequency Ω_S defined above and $\varphi = \varphi_0 + \Delta\varphi$.

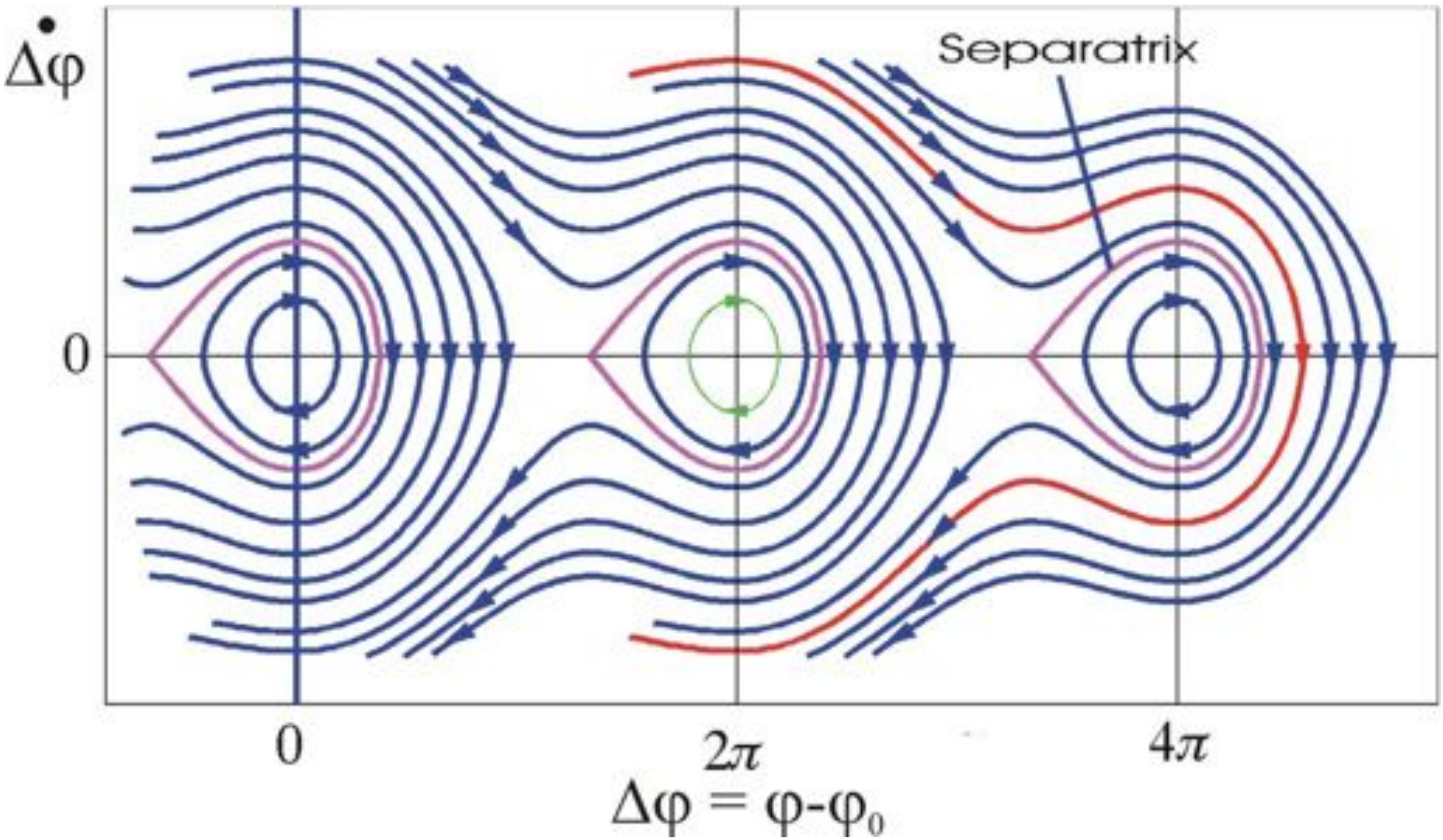
This can easily be integrated to the potential equation

$$\underbrace{\frac{\dot{\varphi}^2}{2}}_{\text{kinetic energy}} + \underbrace{\left\{ -\frac{\Omega_S^2}{\cos\varphi_0}\left[\cos\varphi + \varphi\sin\varphi_0\right] \right\}}_{\text{potential energy}} = \text{const.}$$

The potential energy function corresponds to the sum of a linear function and a sinusoidal one. An oscillation can only take place if the particle is trapped in the potential well:



$\varphi_1^{max} = \pi - \varphi_0$ is an extreme elongation corresponding to a stable motion. The corresponding curve in phase space is called separatrix and the area delimited by this curve is called the RF bucket. Part of this area is filled with particles, forming the bunch.

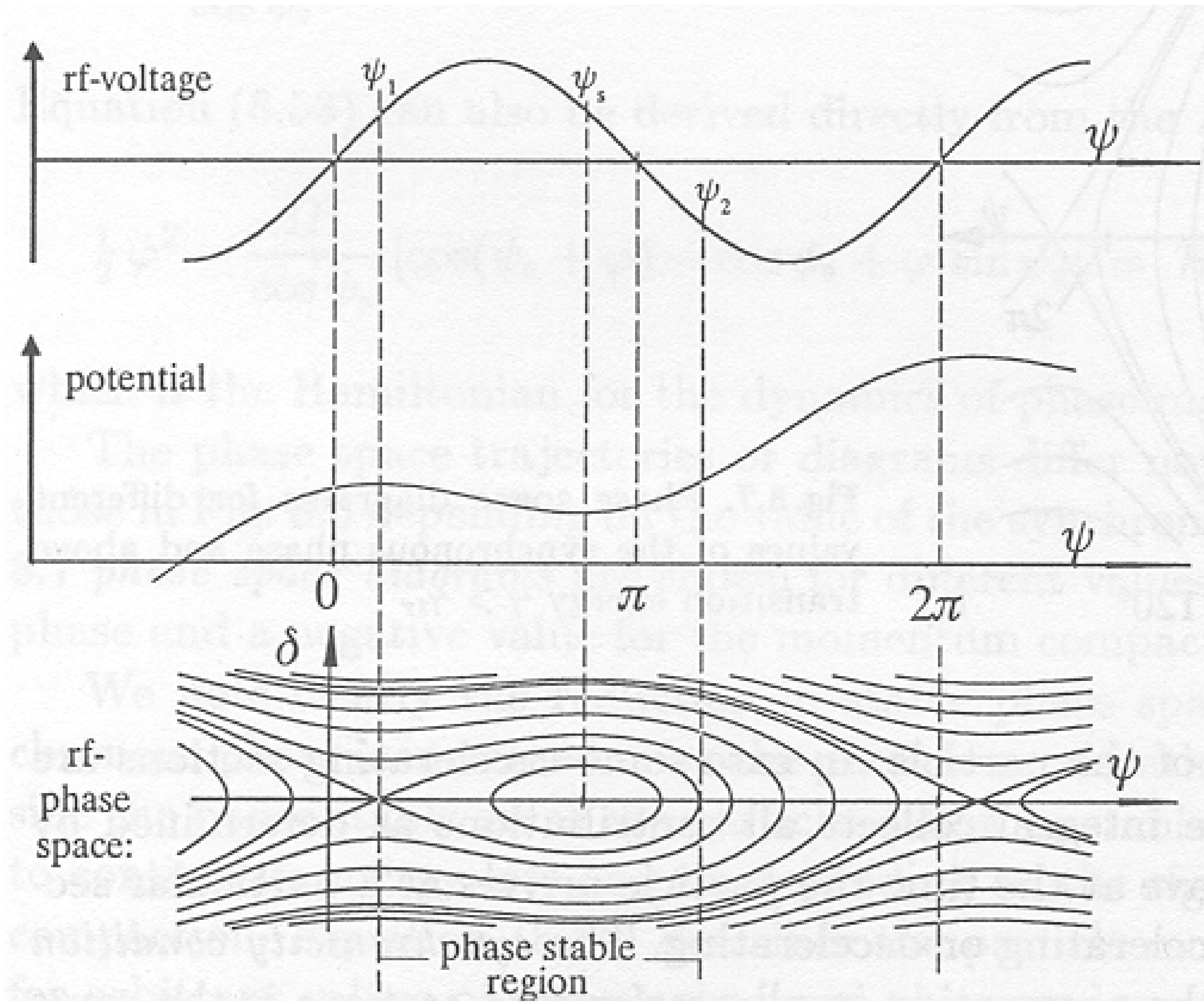


The equation of the separatrix is

$$\frac{\dot{\varphi}^2}{2} - \frac{\Omega_S^2}{\cos\varphi_0}\left[\cos\varphi + \varphi \cdot \sin\varphi_0\right] = -\frac{\Omega_S^2}{\cos\varphi_0}\left[\cos(\pi - \varphi_0) + (\pi - \varphi_0) \cdot \sin\varphi_0\right]$$

The other extreme elongation $\varphi_2^{\max}$ (second value for which $\dot{\varphi} = 0$), is such that

$$\cos\varphi_2^{\max} + \varphi_2^{\max} \cdot \sin\varphi_0 \;=\; \cos\left(\pi - \varphi_0\right) + \left(\pi - \varphi_0\right) \cdot \sin\varphi_0$$



From the equation of motion it is also seen that $\dot{\varphi}$ reaches a maximum when $\ddot{\varphi} = 0$ corresponding to $\varphi = \varphi_0$. This gives the maximum stable values of $\dot{\varphi}$ and the maximum energy spread $\Delta E_{\max}$, which is called the **RF acceptance**:

$$\dot{\varphi}^2_{\max} = 2\Omega_S^2 \left[2 - (\pi - 2\varphi_0) \cdot \tan\varphi_0 \right]$$

$$\left(\frac{\Delta E}{E_0} \right)_{\max} = \pm \beta \sqrt{ \frac{eU_0}{\pi h \eta E_0} \cdot \left[2\cos\varphi_0 - (\pi - 2\varphi_0) \cdot \sin\varphi_0 \right] }$$

In accelerator physics one usually defines an **over voltage factor** q by

$$q = \frac{\text{maximum RF voltage}}{\text{desired energy gain}} = \frac{eU_0}{eU_0 \sin\varphi_0} = \frac{1}{\sin\varphi_0}$$

Using this factor, we can rewrite the RF acceptance to

$$\left(\frac{\Delta E}{E_0}\right)_{\max} = \beta\sqrt{\frac{2eU_0\sin\varphi_0}{\pi h\eta E_0}\cdot\left(\sqrt{q^2-1}-\operatorname{arc}\cos\frac{1}{q}\right)} \leq \beta\sqrt{\frac{2eU_0}{\pi h\eta E_0}}$$

Using $\eta=\left(\gamma^{-2}-\alpha_C\right)$, $\alpha_C \approx 1/Q_x^{\,2}$ and $\omega_{RF} = h\cdot\omega_0$ we finally note the important scaling:

$$\boxed{\left(\frac{\Delta E}{E_0}\right)_{\max} \sim \frac{1}{\sqrt{\omega_{RF}}}}, \qquad \boxed{\left(\frac{\Delta E}{E_0}\right)_{\max} \overset{\gamma\gg1}{\sim} Q_S}, \qquad \boxed{\left(\frac{\Delta E}{E_0}\right)_{\max} \sim \sqrt{\frac{eU_0\sin\varphi_0}{E_0}}}$$

Break

Introducing the ILC

ILC Parameters

an initial physics wish list

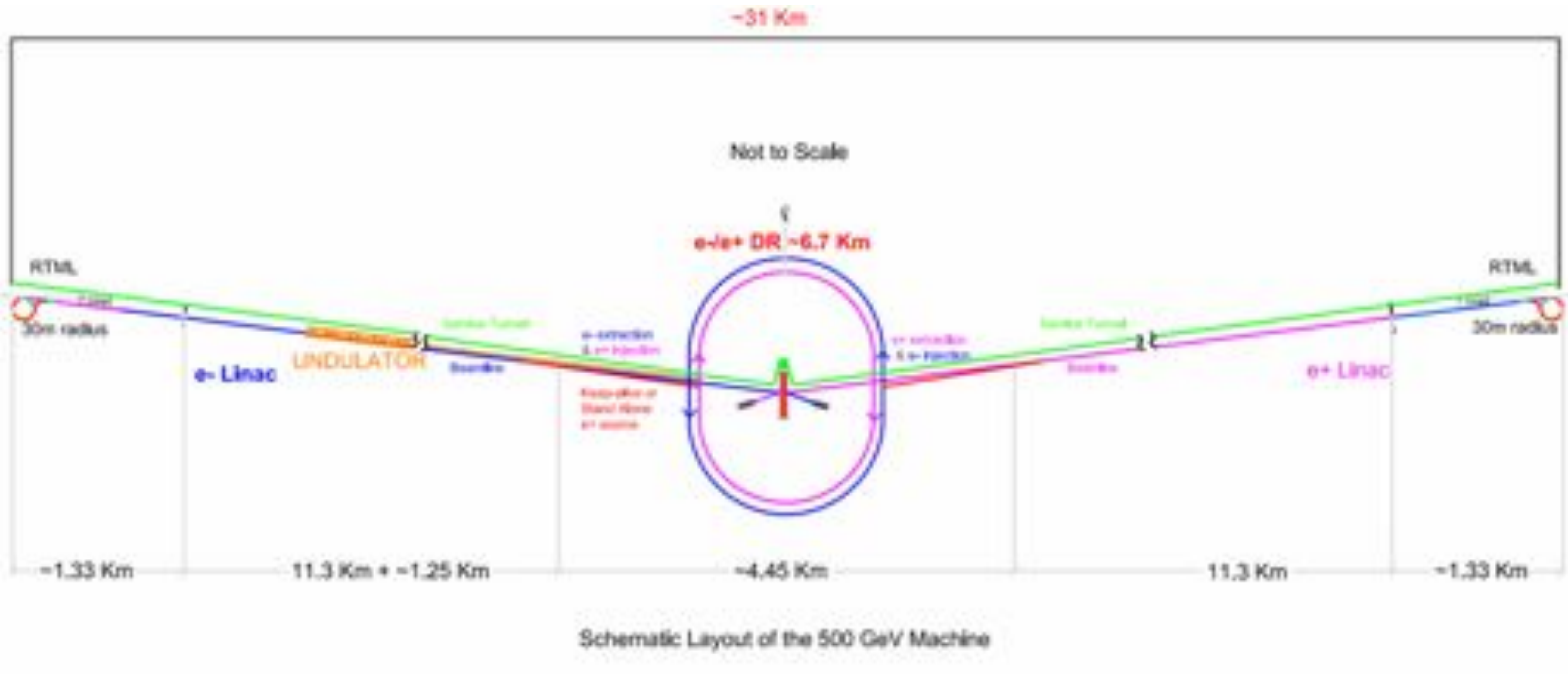
- E_{cm} adjustable from 200 – 500 GeV
- Luminosity $\int L dt$ = 500 fb^{-1} in 4 years
  (corresponds to 2×10^{34} cm^{-2}s^{-1} with a start-up profile)
- Ability to scan between 200 and 500 GeV
- Energy stability and precision below 0.1%
- Electron polarisation of at least 80%
- The machine must be upgradeable to 1 TeV!

e^+e^-–Collider

- Circular colliders are prohibitive above ~200 GeV
- Linear colliders
  - low emittance source (damping ring)
  - acceleration
    - Einstein helps: $\varepsilon \rightarrow \varepsilon / \gamma$
  - focussing & collision

Overall Layout

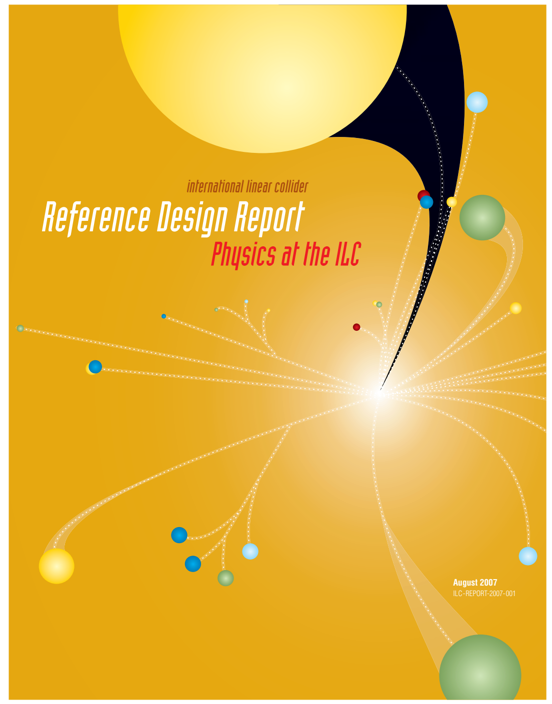
1st Stage: 500 GeV

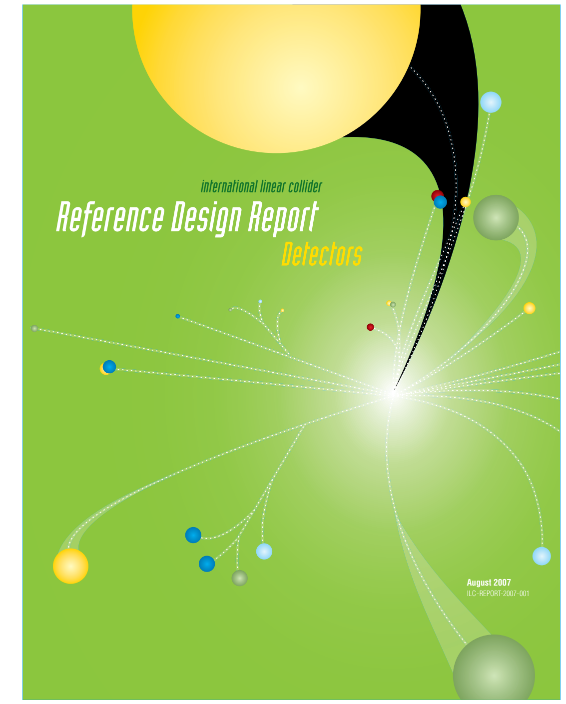


Basic Parameters

Max. Centre-of-mass energy	500	GeV
Peak Luminosity	$\sim 2 \times 10^{34}$	$cm^{-2}s^{-1}$
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

ILC Reference Design Report





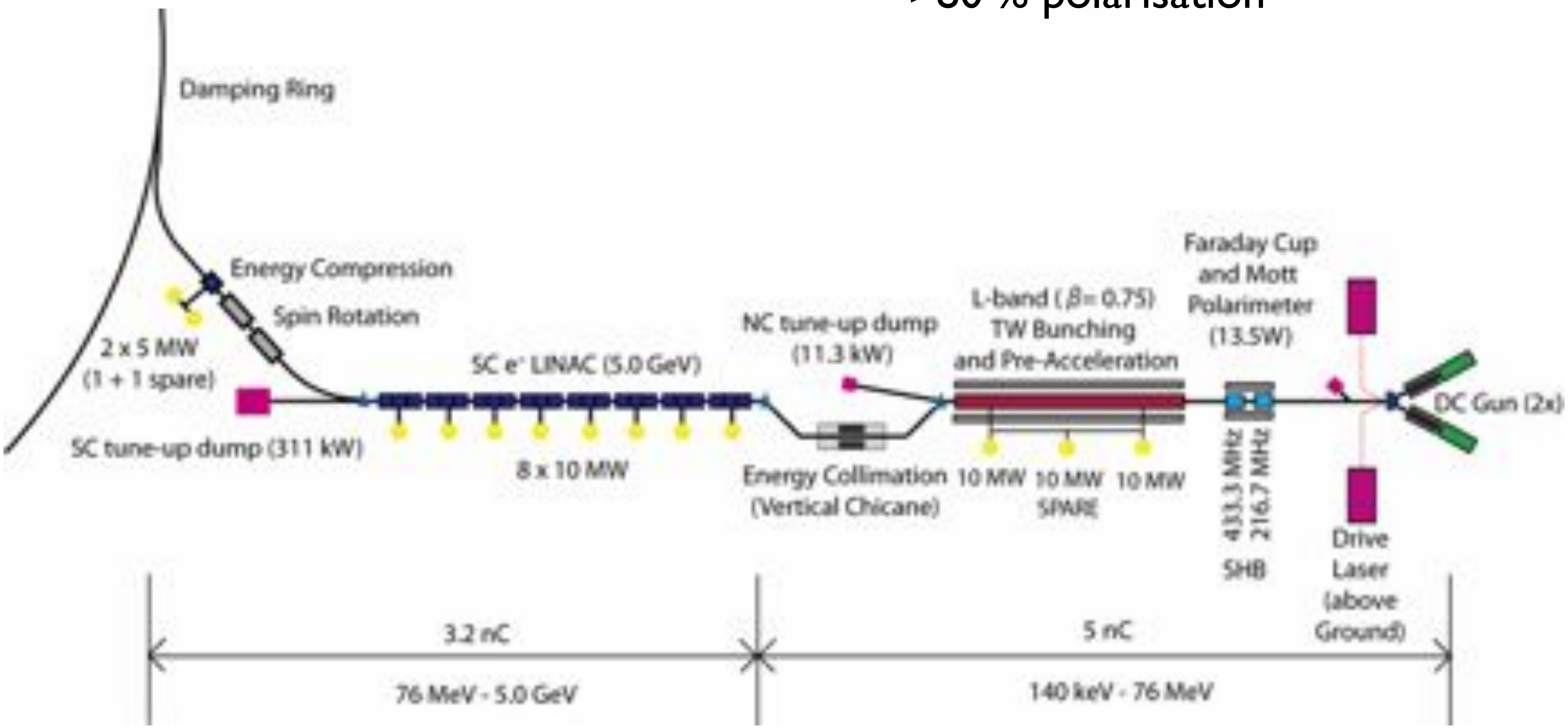
~700 Contributors from 84 Institutes

available from http://www.linearcollider.org

The RDR is not a full engineering design - it is conceptual; some aspects require R&D. It forms reliable basis for detailed engineering design & costing.

Electron Source System

- ~2600 bunches, ~1 ms, 2×10^{10} at DR
- >80 % polarisation



Positron Source

- 3 possible positron generation schemes have been proposed

  A) Standard method: a few GeV electron on target

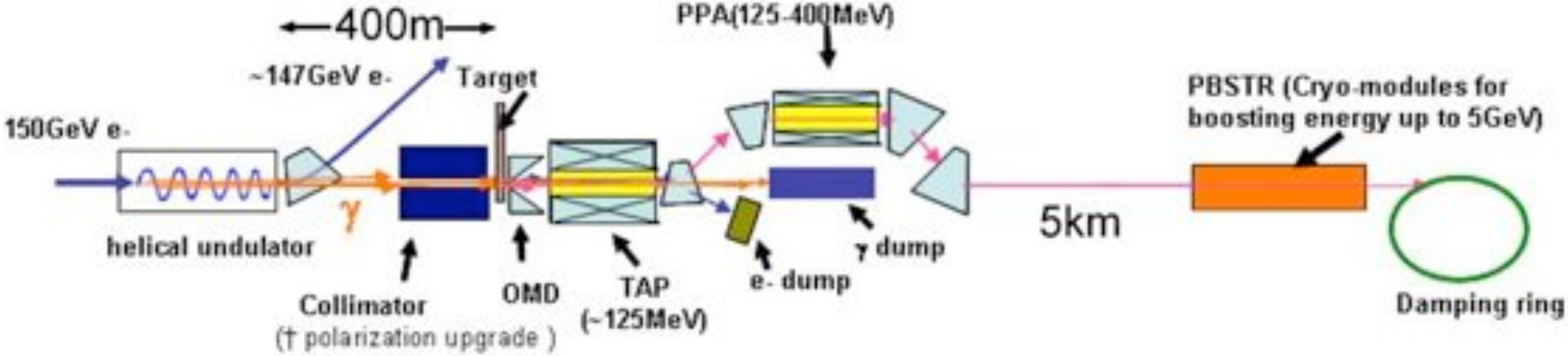
  B) Undulator scheme: use photons from >100 GeV electron through undulator

  C) Compton scheme: use photons from a few GeV electron through laser-Compton scattering

- Scheme B) has been selected as the baseline
  - C) is immature
  - Cost saving by A) is not significant. Physics descoping (no positron polarisation)

Positron Source

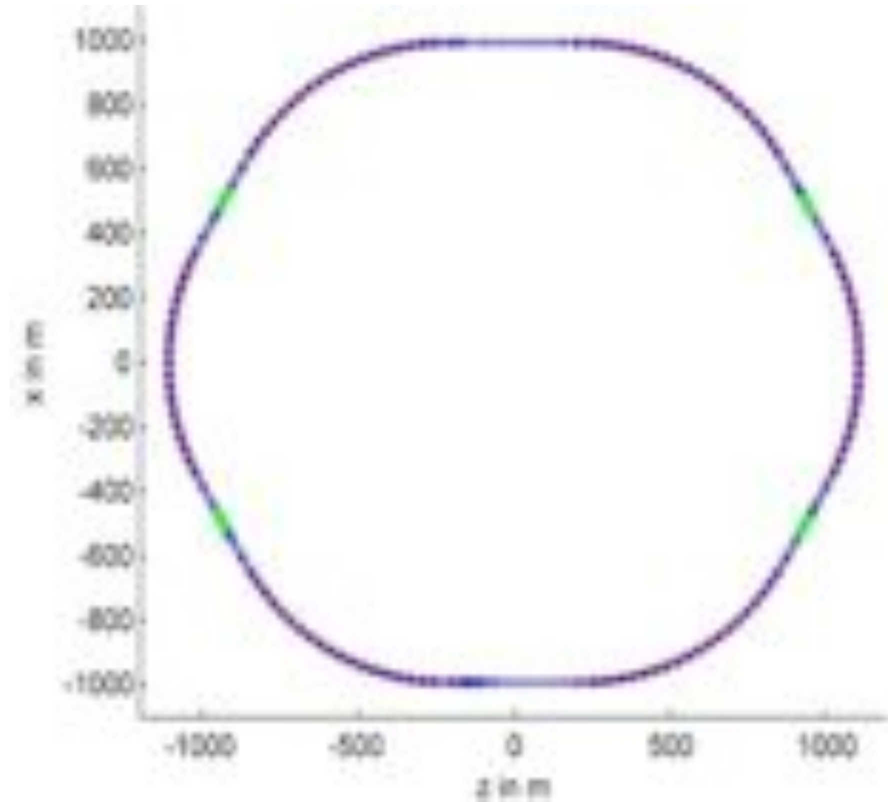
- Undulator scheme - Baseline
  - Electron beam at 150 GeV



  - Undulator
    - Helical, superconducting
    - length 147 m (longer for polarised e^+)
    - K = 0.92, λ = 1.15 cm, (B = 0.86 T)
  - Needs 'keep-alive source' for commissioning
    - 10 % intensity
    - Share 5 GeV linac

Damping Ring Issues

- Injection/extraction kickers
- Instabilities
  - Electron-cloud, Fast Ion, …
- Dynamic aperture
- Tuning for low emittance

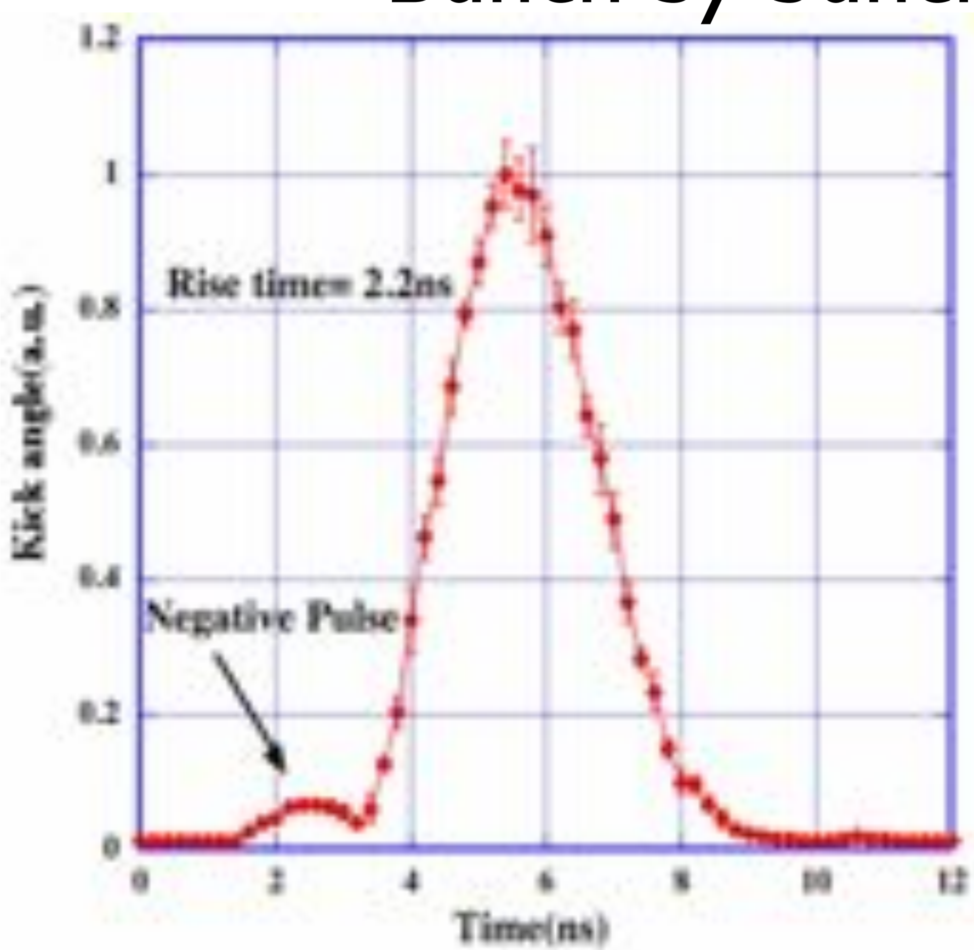


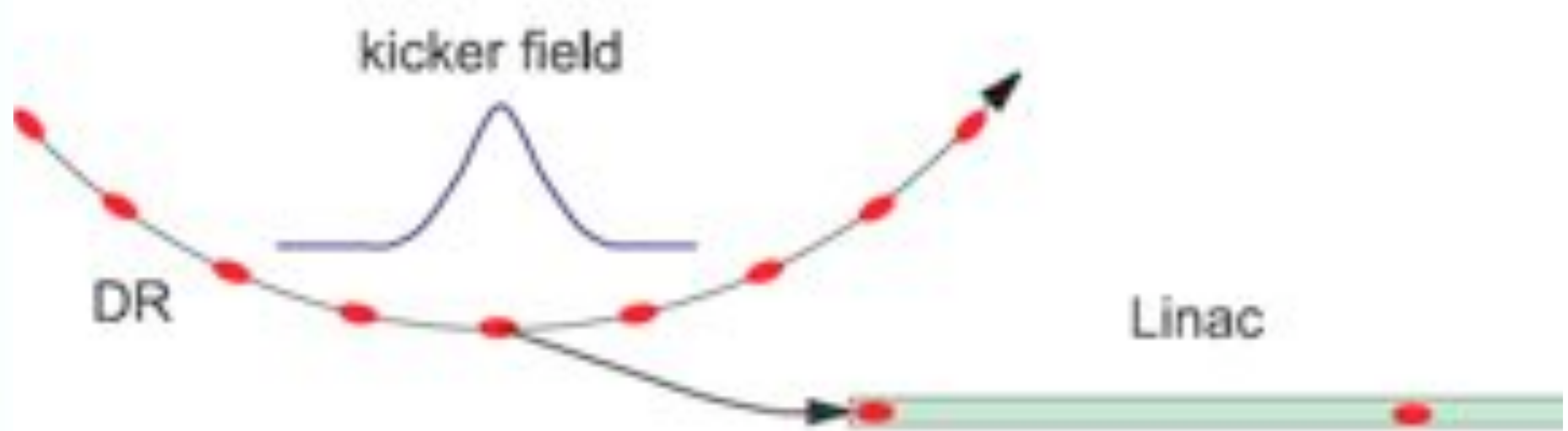
Considerable R&D underway

- Machines available for tests
  - KEK-ATF
  - KEKB, CESR, (HERA needs injection path)

Kicker System

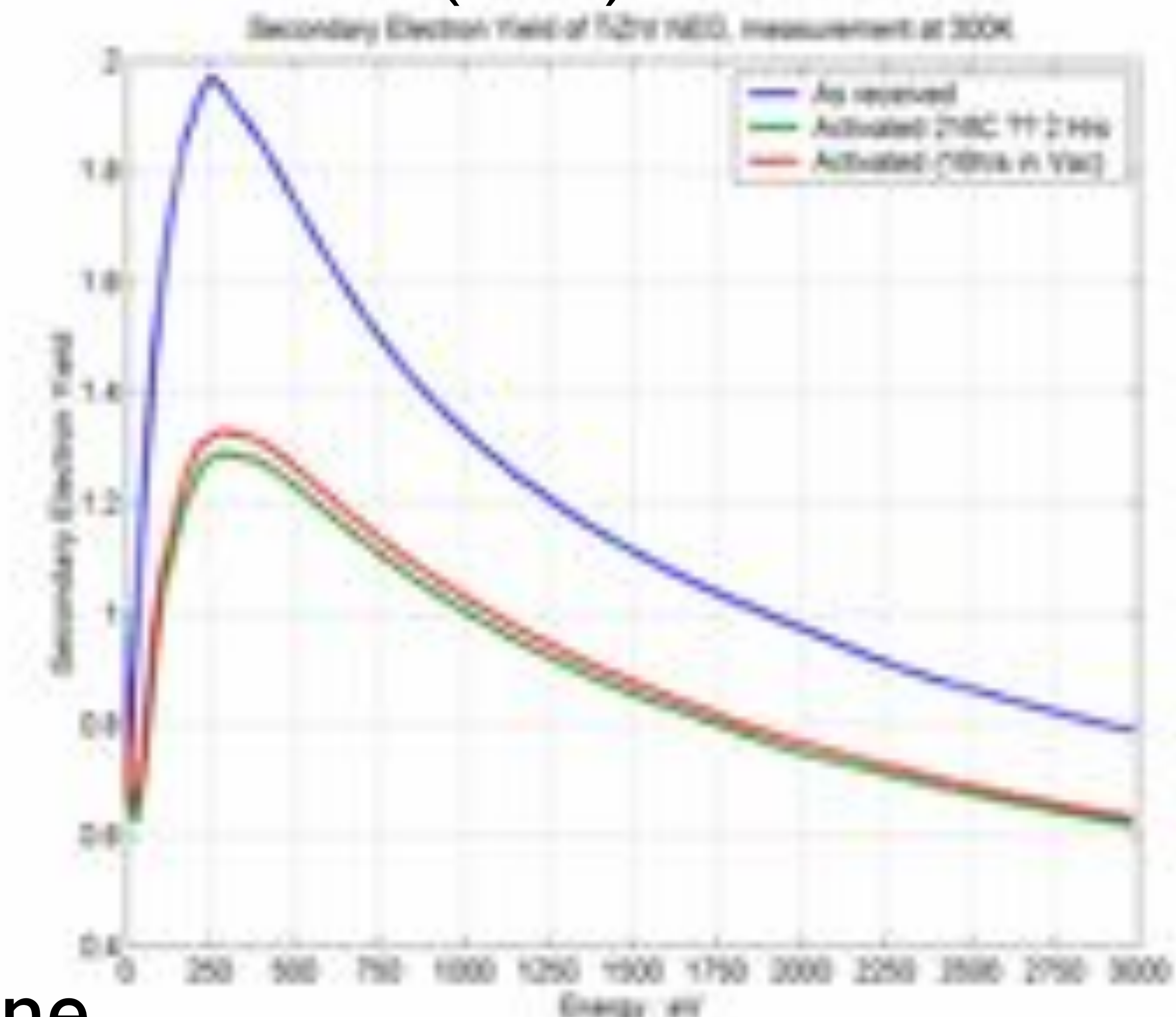
- Number of bunches ~3000 (6000 desirable)
- 300 ns interval in linac; total length for 1 ms train → 300 km
- Store compactly in DR (6 km circumference → ~6 ns bunch to bunch)
- Bunch by bunch extraction in 300 ns intervals





Electron Cloud

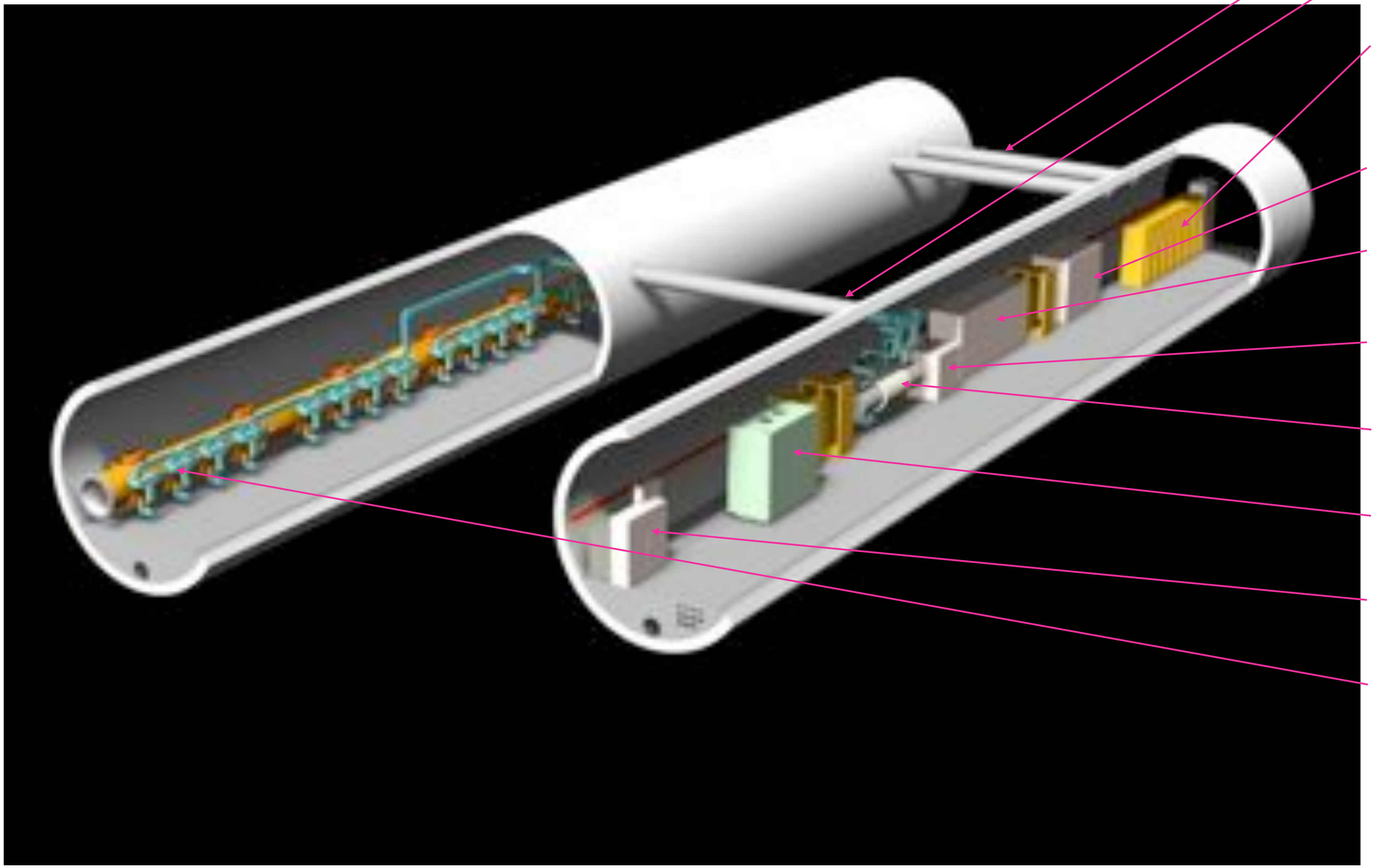
- Secondary electrons attracted by positron beam cause an instability
- Maximum of Secondary Electron Yield (SEY) should be < 1.1
- Possible cures
  - Coating with NEG
  - Solenoids in free field region
    - Grooves on chamber wall
    - Clearing electrode



- Confident enough to baseline single e^+ damping ring

Main Linac Layout

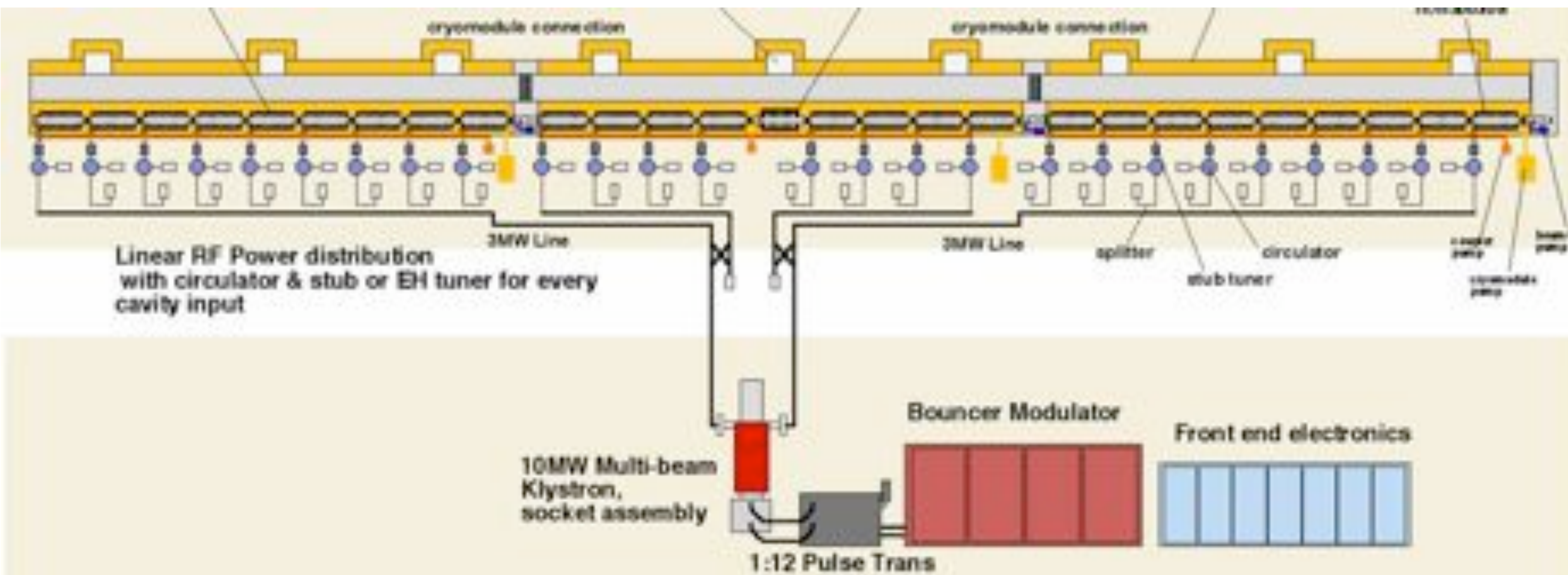
- 2 tunnels diameter 4.5 m



Dwg: J. Liebfritz

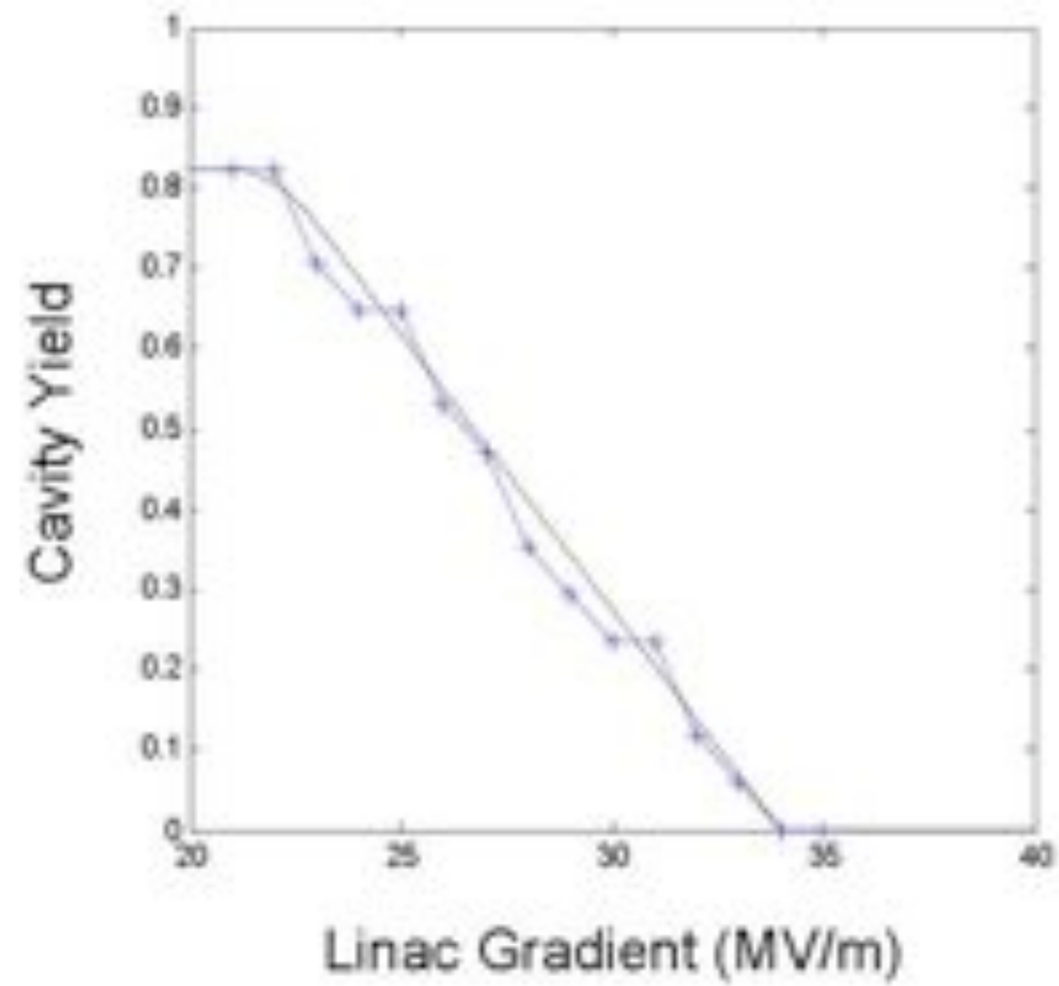
Main Linac RF Unit Overview

- Bouncer type modulator
- Multibeam klystron (10 MW, 1.6 ms)
- 3 Cryostats (9+8+9 = 26 cavities)
- 1 Quadrupole at the centre



Cavities

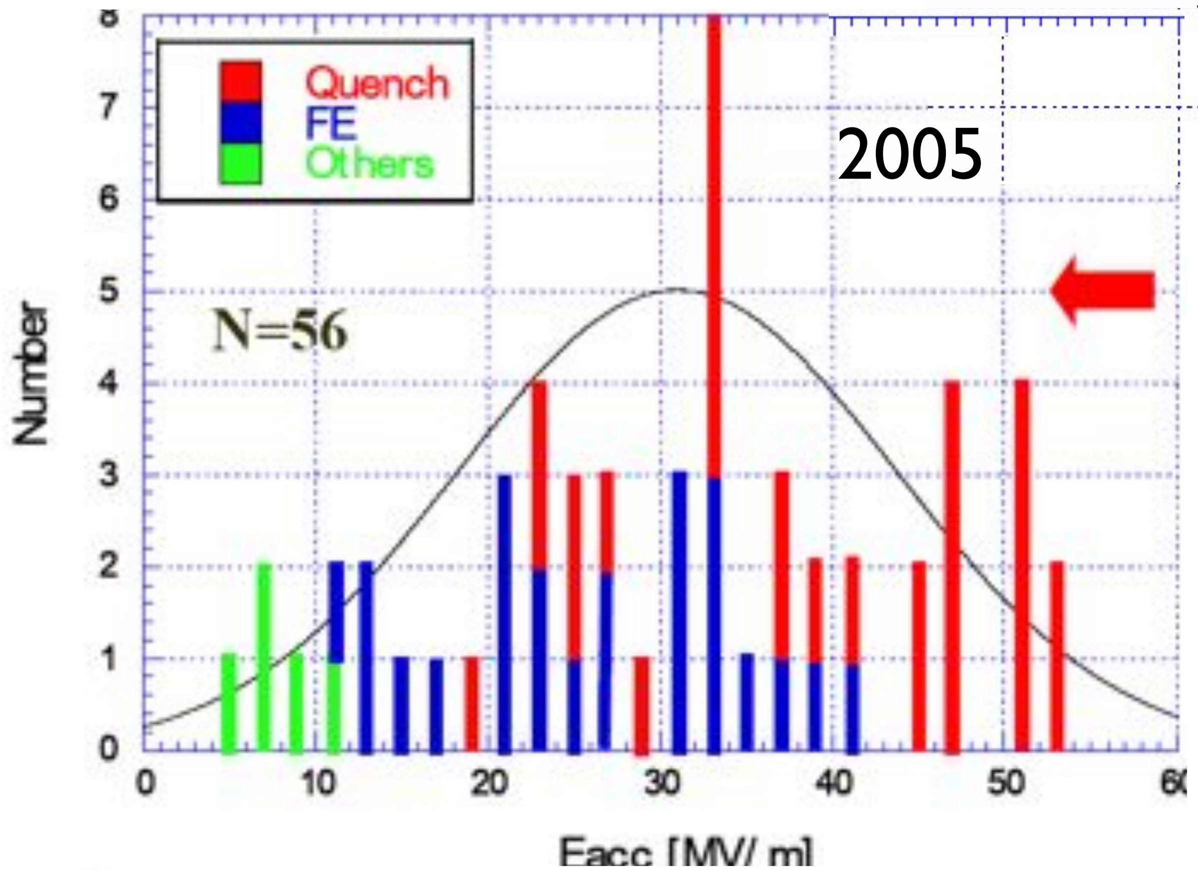
- Baseline: TESLA-type 1.3 GHz
  - Identical to XFEL cavities
    - Only beam-tubes shortened
- Accelerating gradient
  - Vertical test
    - >35 MV/m, $Q>0.8\times10^{10}$
  - Average gradient in cryomodule
    - 31.5 MV/m, $Q>1\times10^{10}$
- With the presently available technology
  - Average gradient lower than 31.5 MV/m
  - Spread of gradient large
- If uniform distribution in
  22<G<34 MV/m, average 28 MV/m
  Cost increase ~7% w.r.t 31.5 MV/m

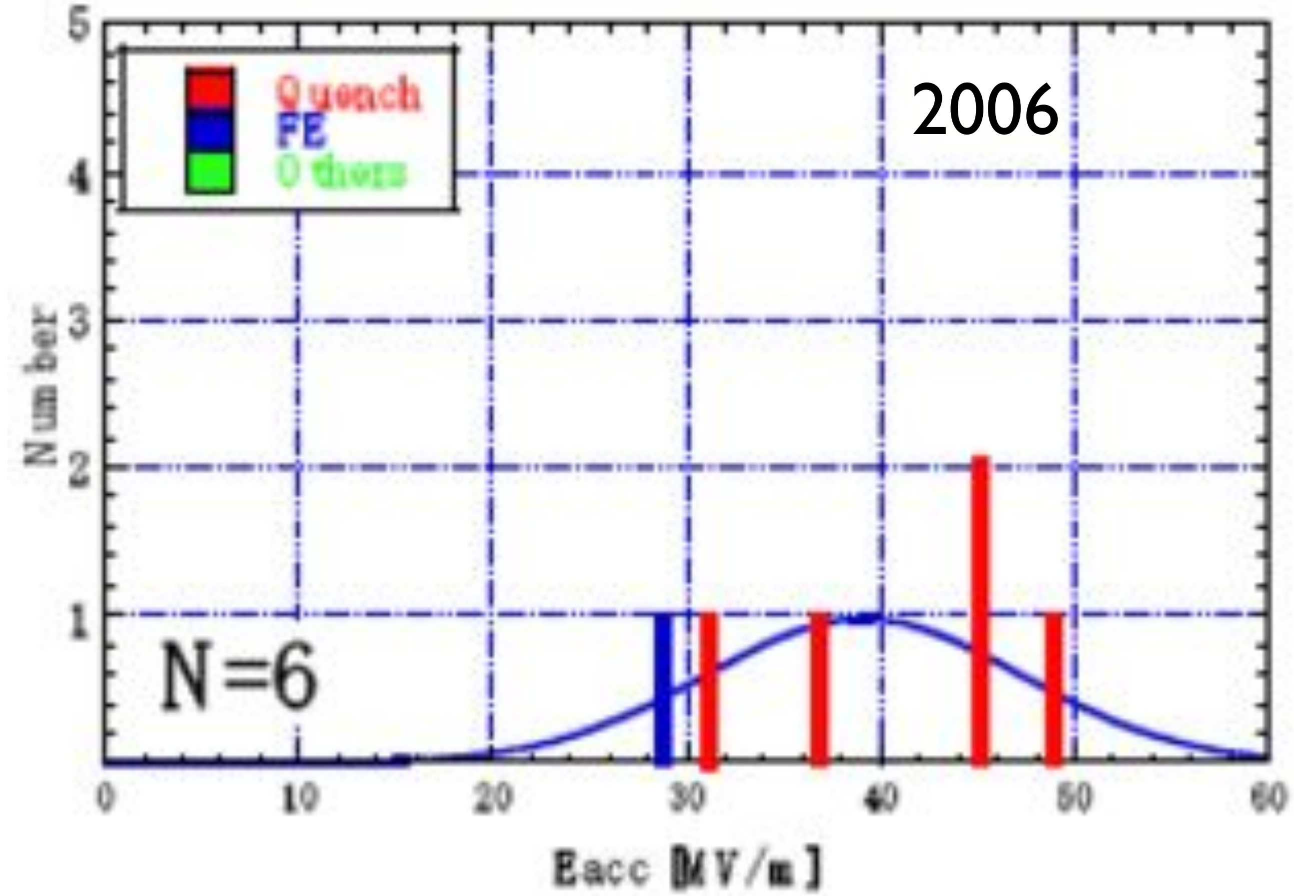


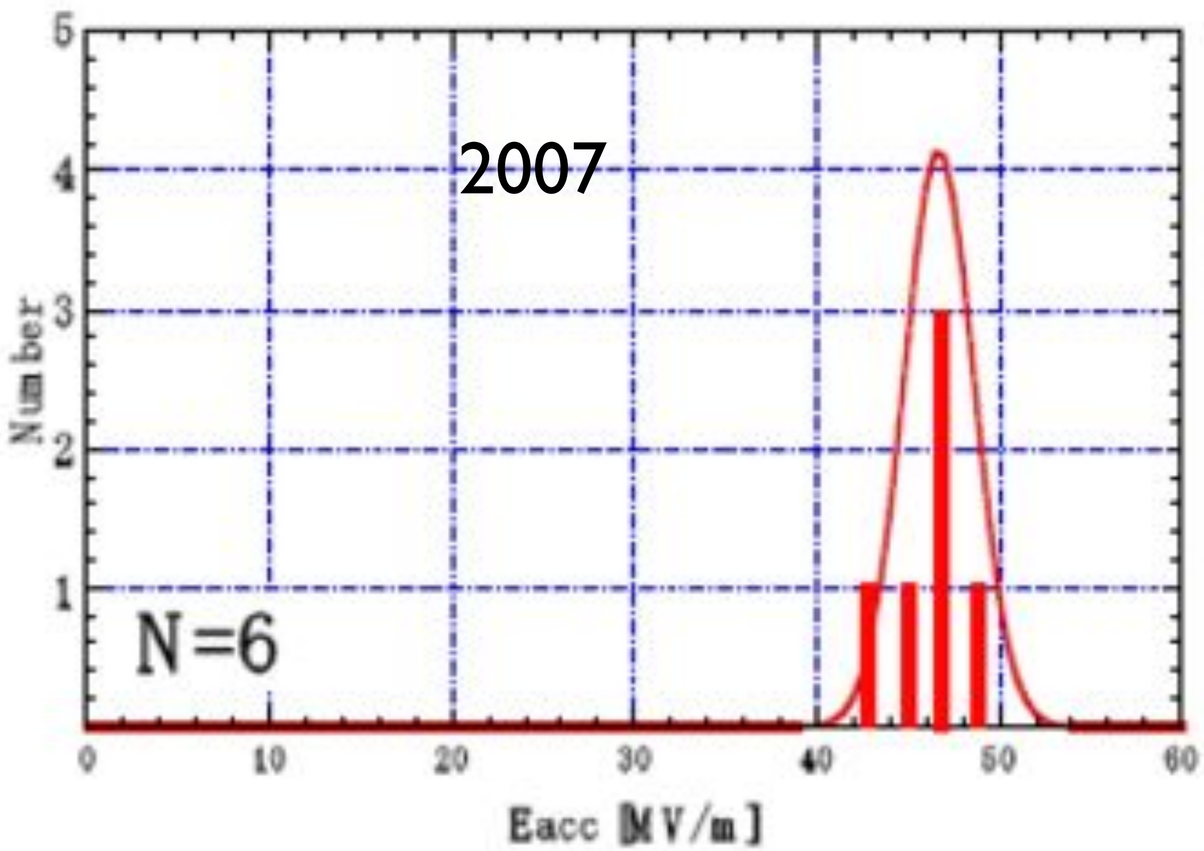
High Gradient Reproducibility: S0 S1 Program

- Task Force has been created and R&D program set up
- S0: establish 35 MV/m in low power tests
  - Single-cell program
    - optimise final surface preparation (e.g. short electro-polishing, alcohol rinse, ultrasound degrease)
  - Tight-loop process
    - repeated surface treatment with small number of cavities including exchange of cavities among Asia-US-Europe in 2007
  - Production-like process
    - Many cavities with the same recipe
    - Large data set is (will be) available from the XFEL project
      - experience with TTF and FLASH
      - pre-production runs
        - includes industrialisation e.g. electro-polishing in industry
- Time line
  - Establish high yield well before EDR
- S1: Establishing 31.5 MV/m operational in accelerator modules

Current status







KEK single cell results:

2005 – learning

2006 – standard recipe

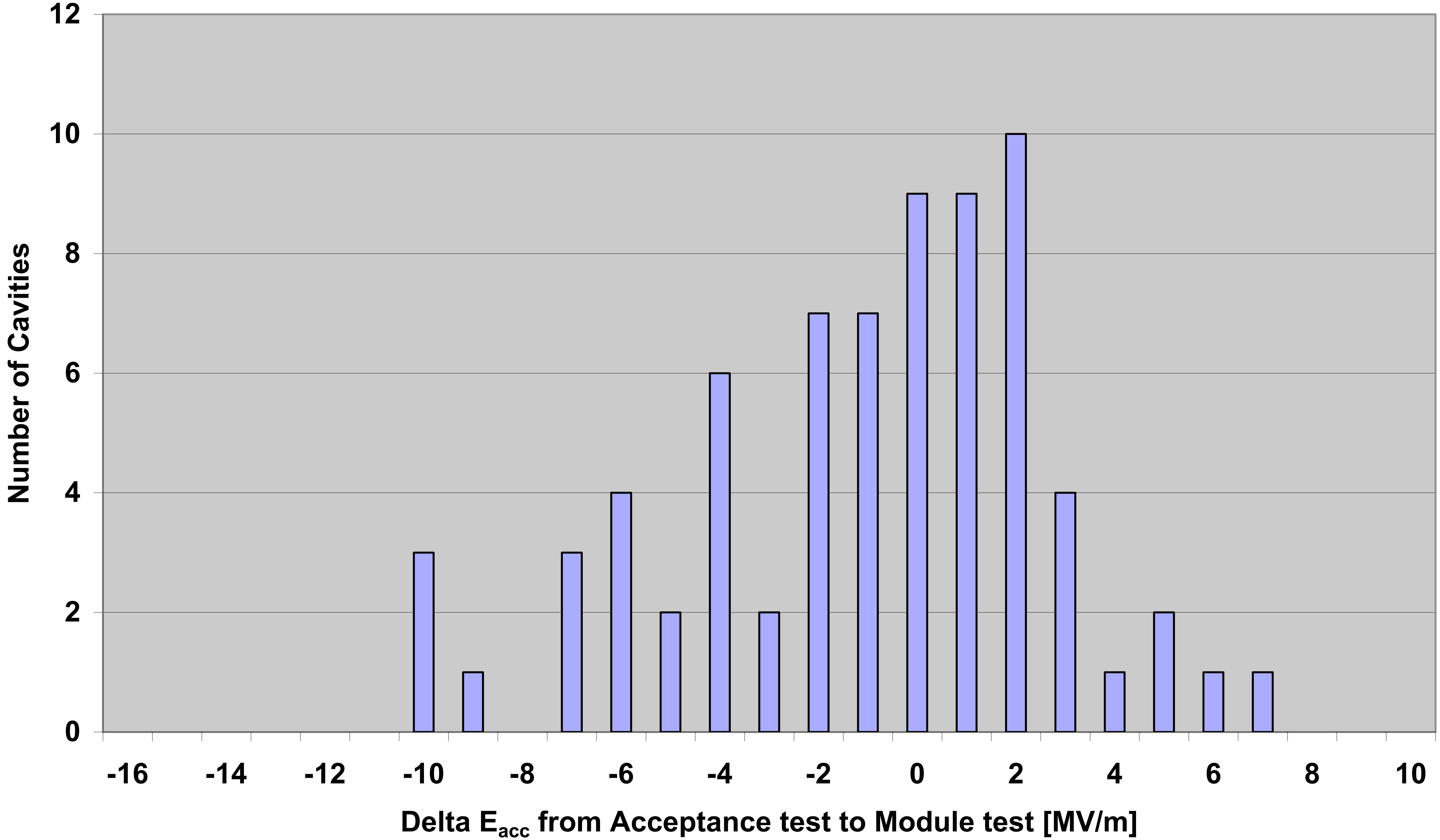
2007 – add final 3 μm fresh acid EP

Note: multi-cells harder than single cells

Module Test – Goal

- Intermediate goal
  - Achieve 31.5 MV/m average operational accelerating gradient in a single cryomodule as a proof-of-principle. In case of cavities performing below the average, this could be achieved by tweaking the RF distribution accordingly.
  - Auxiliary systems like fast tuners should be operational.
- Final goal
  - Achieve > 31.5 MeV/m operational gradient in 3 cryomodules.
  - The cavities accepted in the low power test should achieve 35 MV/m at $Q_0 = 10^{10}$ with a yield as described above (80% after first test, 95% after re-preparation).
  - It does not need to be the final cryomodule design

S1 RF Performance: Compare Acceptance Test with Module Operational Accelerating Gradient

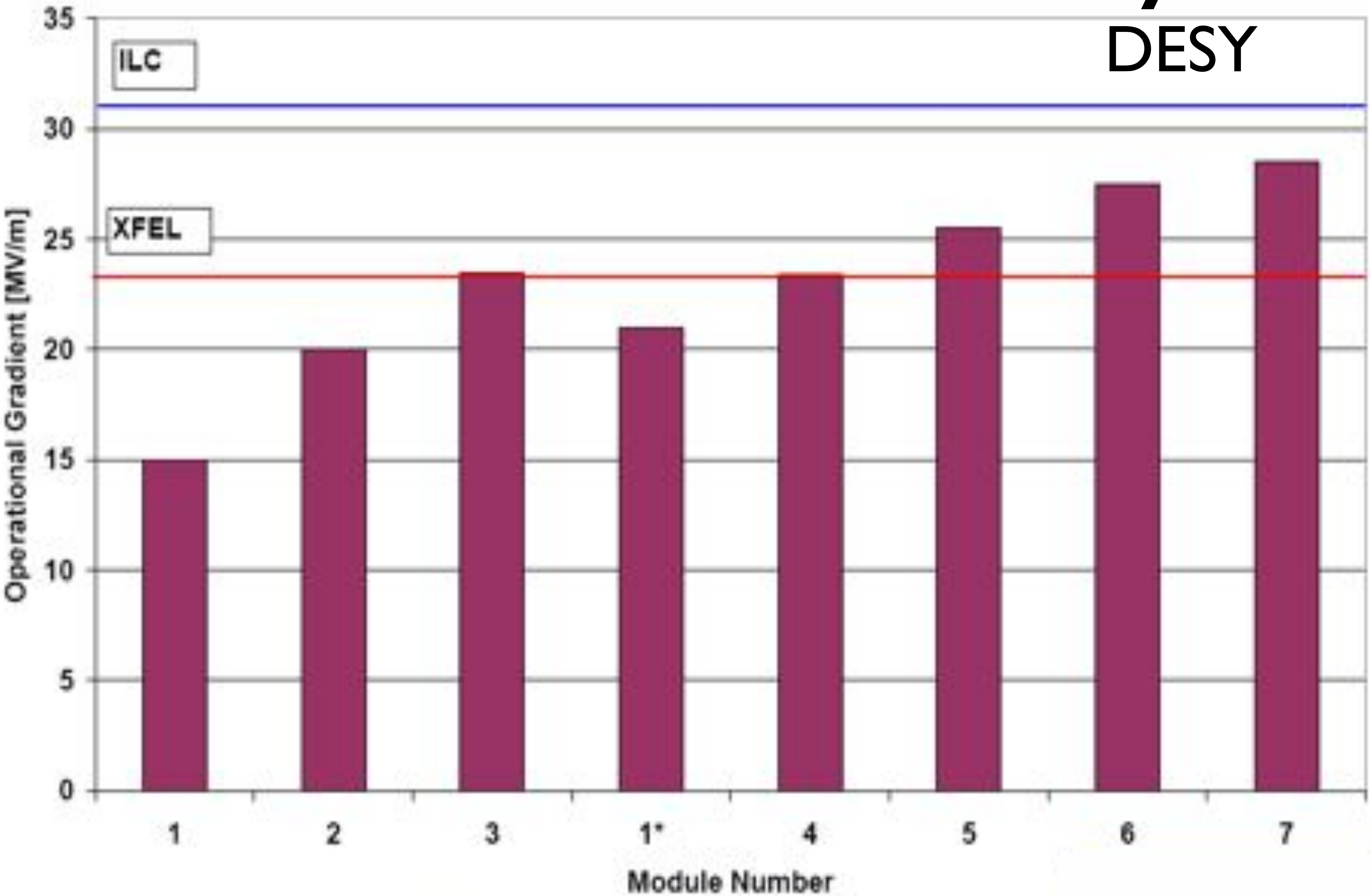


- This is the main motivation for S1
- Improvement on assembly procedures needed
  - Addressed in studies with industry also

XFEL assets: Module Test at DESY

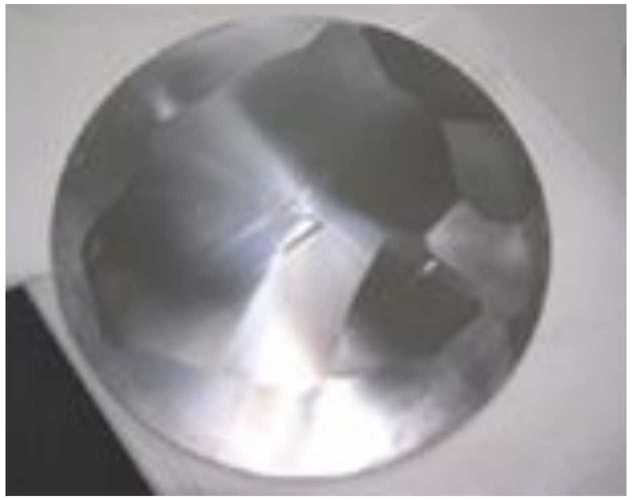
- High gradient modules have been assembled
  - For installation in FLASH
- Test in dedicated test stand possible e.g.
  - Cavity performance
  - Thermal cycles
  - Heat loads
  - Coupler conditioning
  - Fast tuner performance
  - (LLRF tests)
- Part of the ongoing preparatory work for XFEL

Module Test History



Alternatives:

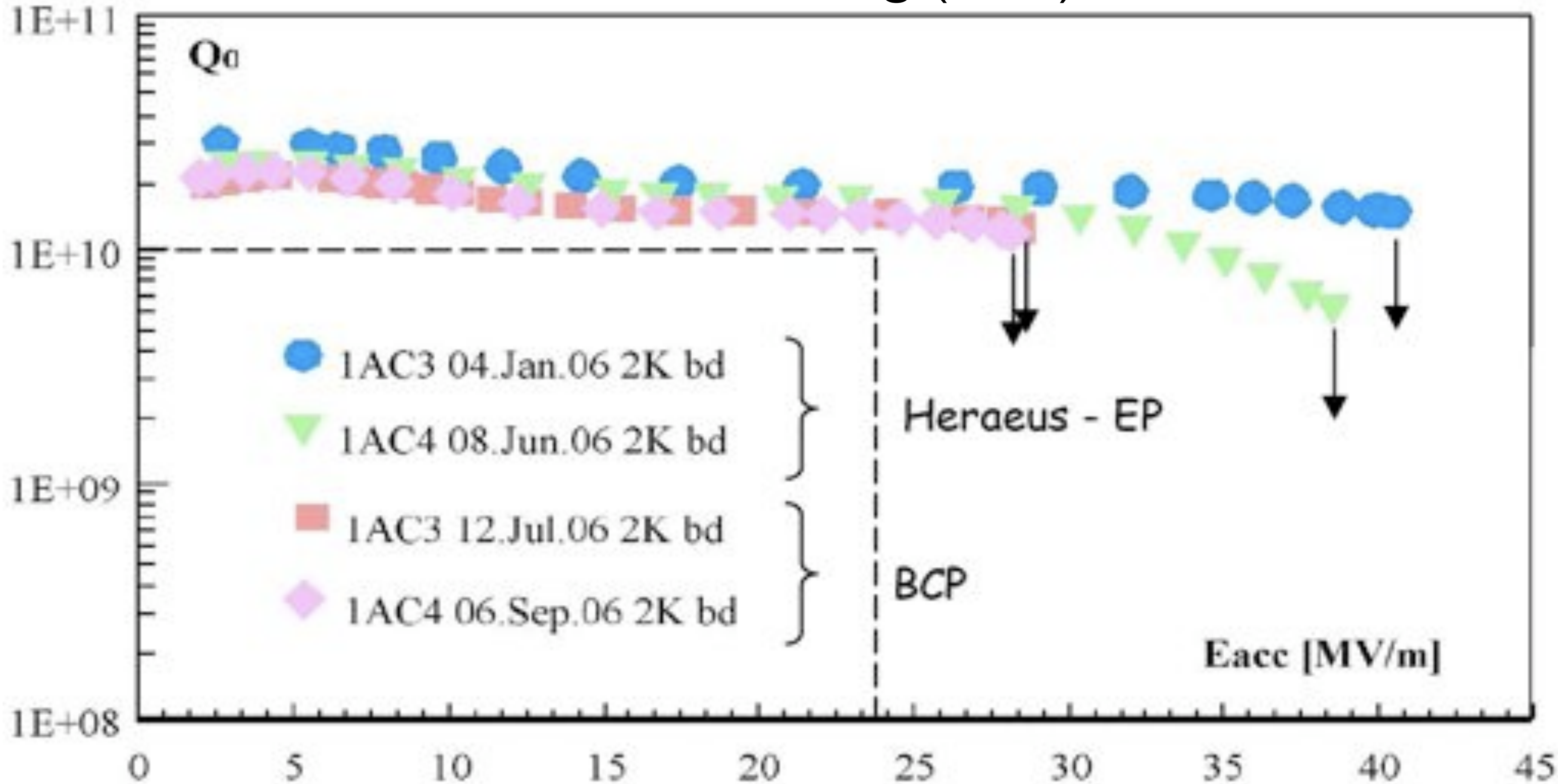
- LL-type cavity
  - Lower maximum magnetic field at same accelerating gradient
    - Potentially higher gradient > 40 MV/m
  - Under development at KEK and JLab
    - Single-cell test successful with max. over 50MV/m
    - But 9-cell cavities are still poor with max. 29MV/m without HOMs



- Nb material:Large grain
  - Started at JLab
  - Single-cells
    - comparable performance to standard material
  - Full nine-cells fabricated XFEL preparation phase
    - so far only etched (BCP)
    - EP underway

Large Grain Material

- Electro-polishing (EP)
- Buffered Chemical Processing (BCP)



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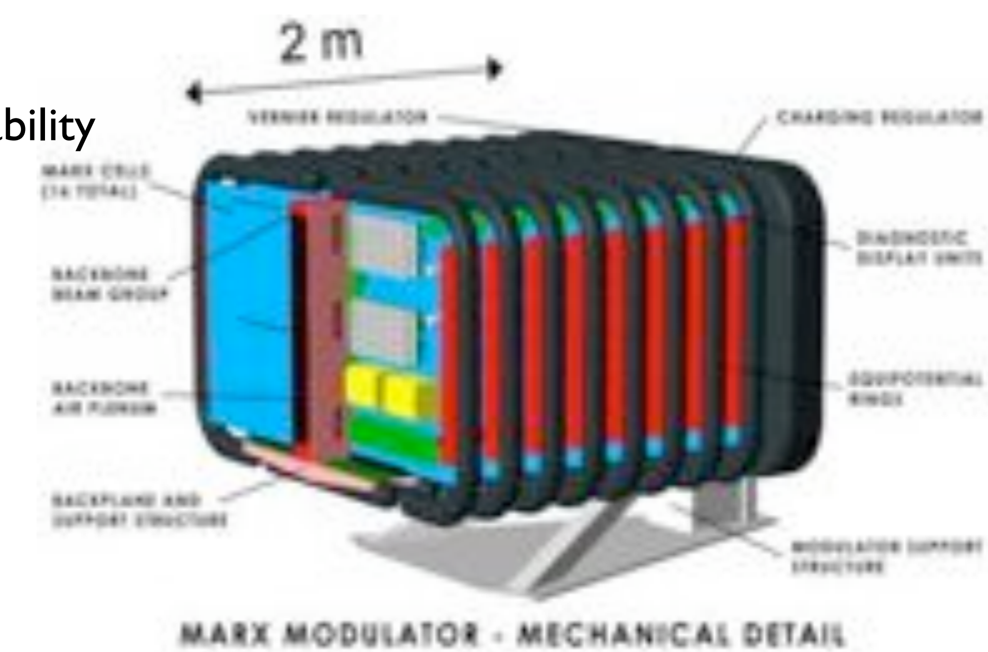
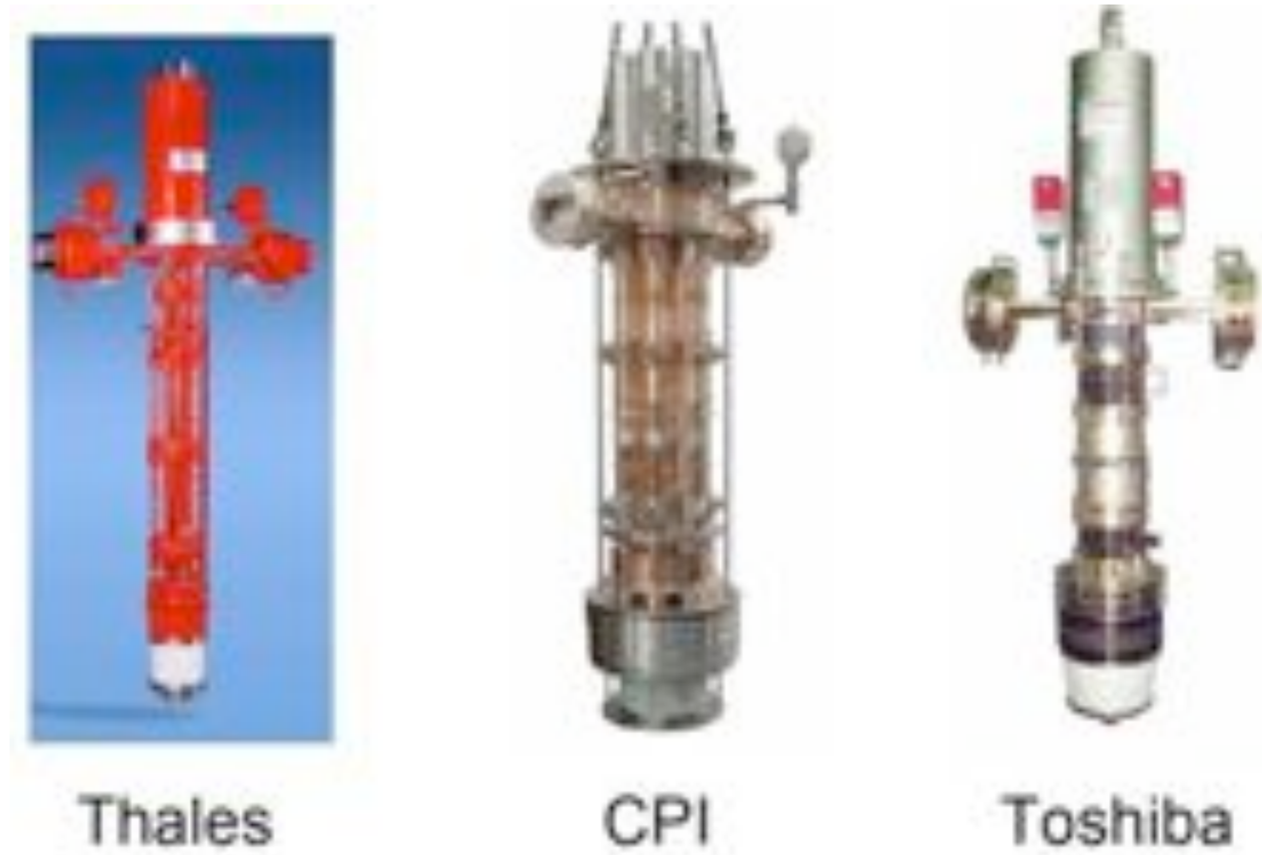
Modulator

- Baseline
    - Bouncer-type modulator
        - Design at FNAL
            - Has been working for >10 years at TTF at DESY
            - No major technical issues
            - XFEL choice
    - Design improvements (within XFEL industrialisation)
        - More cost-efficient design under way
        - Redundancy of internal components for higher availability
- Alternative:
    - Marx Modulator
        - Under development at SLAC
        - Smaller size
        - No step-up transformer
        - Potentially high cost saving



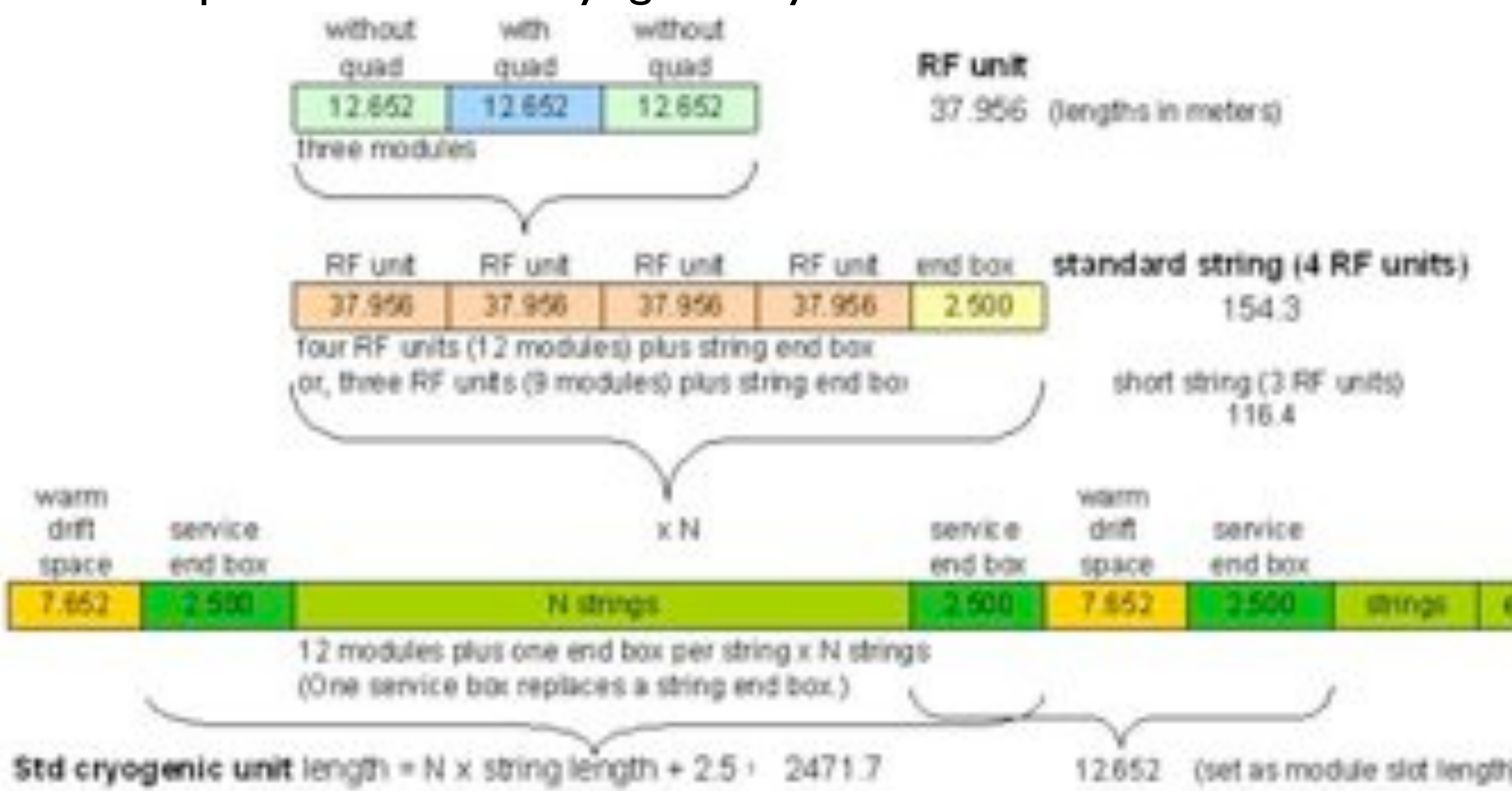
Klystrons



- Requirements:
  - 10 MW
  - 1.6 ms
  - 5 Hz
  - lifetime for full power >40000 hrs
- Baseline solution: Multi-beam klystron
  - Use multiple beams of low charge
  - Lower space-charge effects
  - Lower voltage (120 kV)
  - Higher efficiency (~65 %)
- Prototypes from 3 manufacturers for the European XFEL (higher repetition rate: 10 Hz)
  - Thales and Toshiba MBKs being successfully tested at DESY at full spec
    - for > 1000 hrs
    - Several klystrons under varying operating conditions at FLASH, PITZ and test stand
- Horizontally mounted klystron needed for small tunnel diameter (first tests at Toshiba)
  - XFEL develops this with industry
- More lifetime testing going on (eventually also at SLAC)
  - At DESY all tubes now in operation show no sign of degradation

Cryogenics System

- 1 cryogenic plant covers 2.5km linac length.
  - Installed power ~4.5MW
- Total 10 plants
  - installed power ~45MW
  - comparable to LHC cryogenics system



Beam Delivery System (BDS)

- From main linac exit to IP (Interaction Point) and to the beam dump

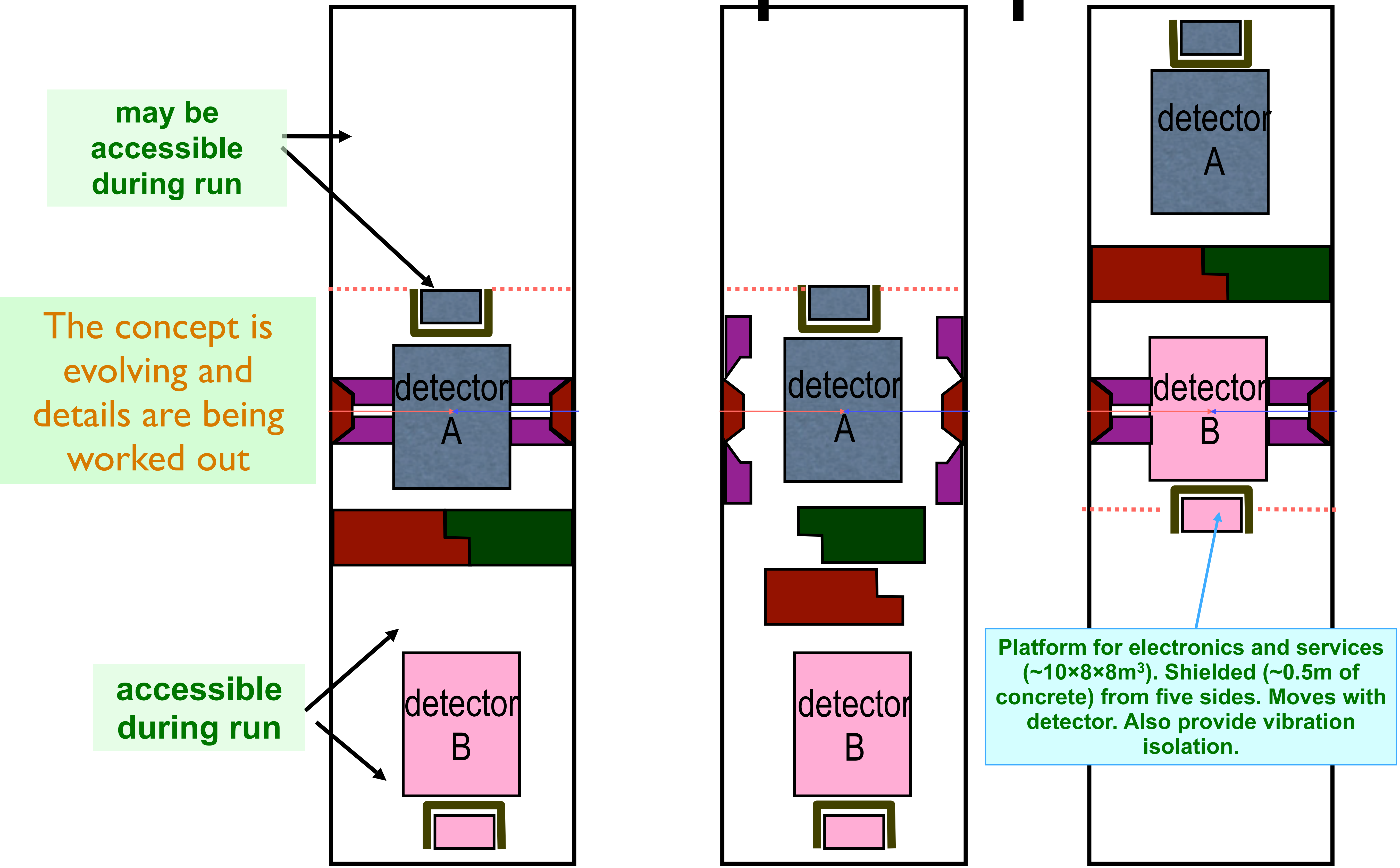
- Roles of BDS
  - Focus the beam to the desired spot size for collision
  - Remove beam-halo to minimise the background events
  - Protect the beam-line and detectors against mis-steered beam
  - Diagnostics of the linac beam
  - Safely dump the spent beams

Single IR with Push-Pull Detectors

- Large cost savings compared with 2 IR
  - ~200 M$ compared with 2 IR with crossing angles 14 + 14 mrad - much more if one

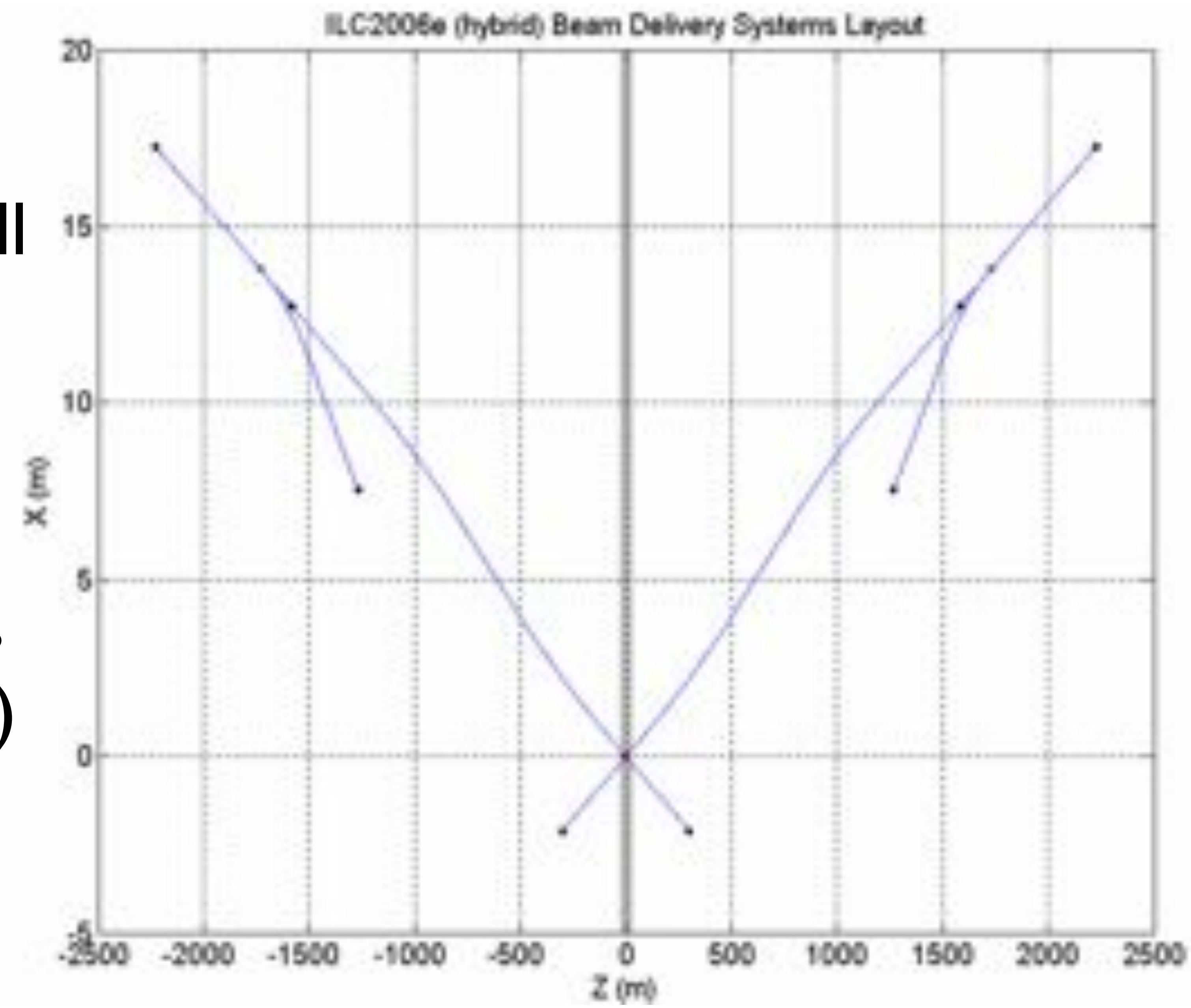
    IR has “small angle” crossing.
- Push-pull detectors
  - Task force from WWS and GDE formed
  - Conclusion is
    - No show-stoppers
    - But need careful design and R&D works
    - 2IR should be left as an 'Alternative'

IR Hall for push-pull

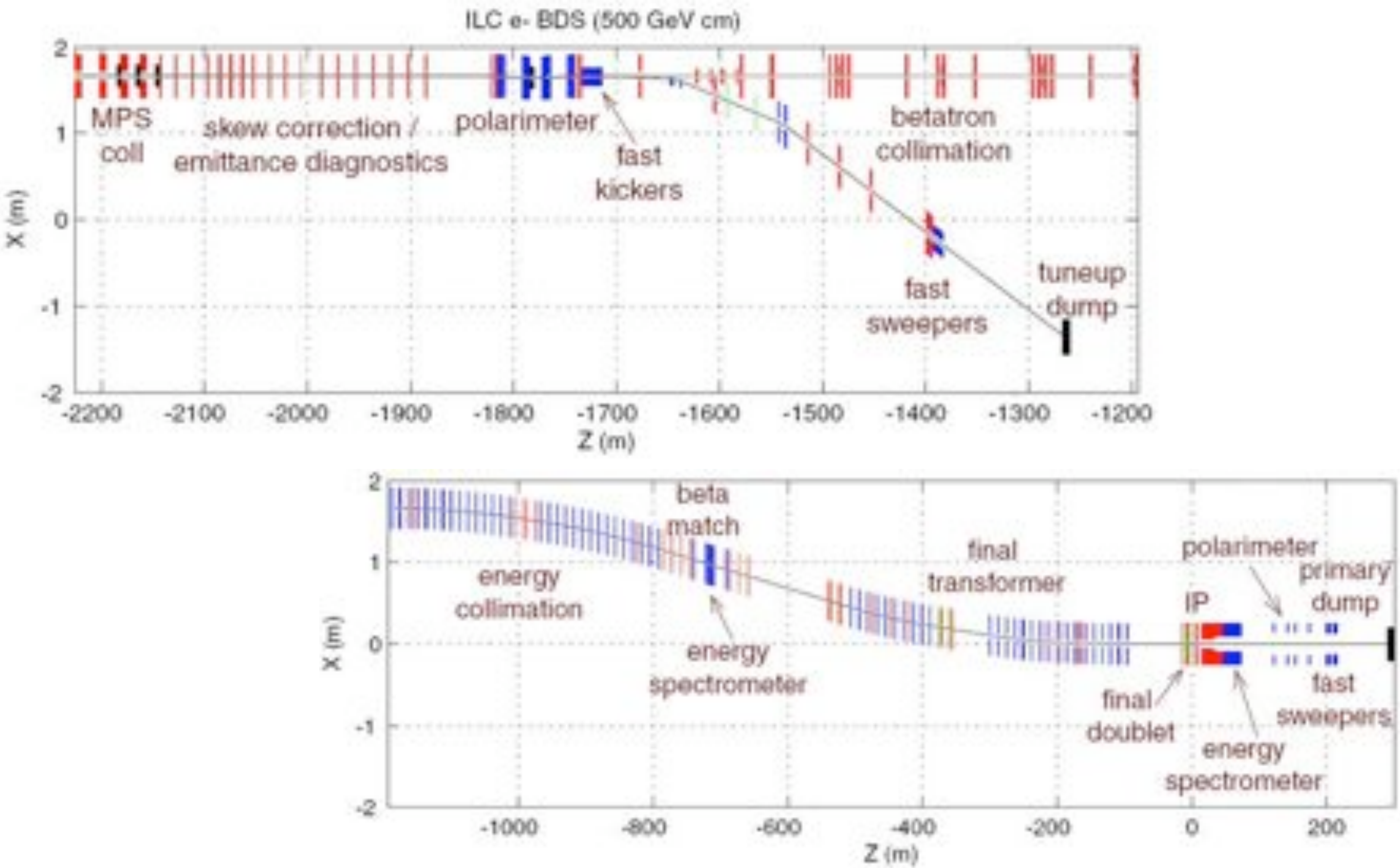


BDS (Beam Delivery System)

- Single IR and push-pull detector
- Total length 4.45 km
- 1 TeV upgrade by inserting components (no geometry change)

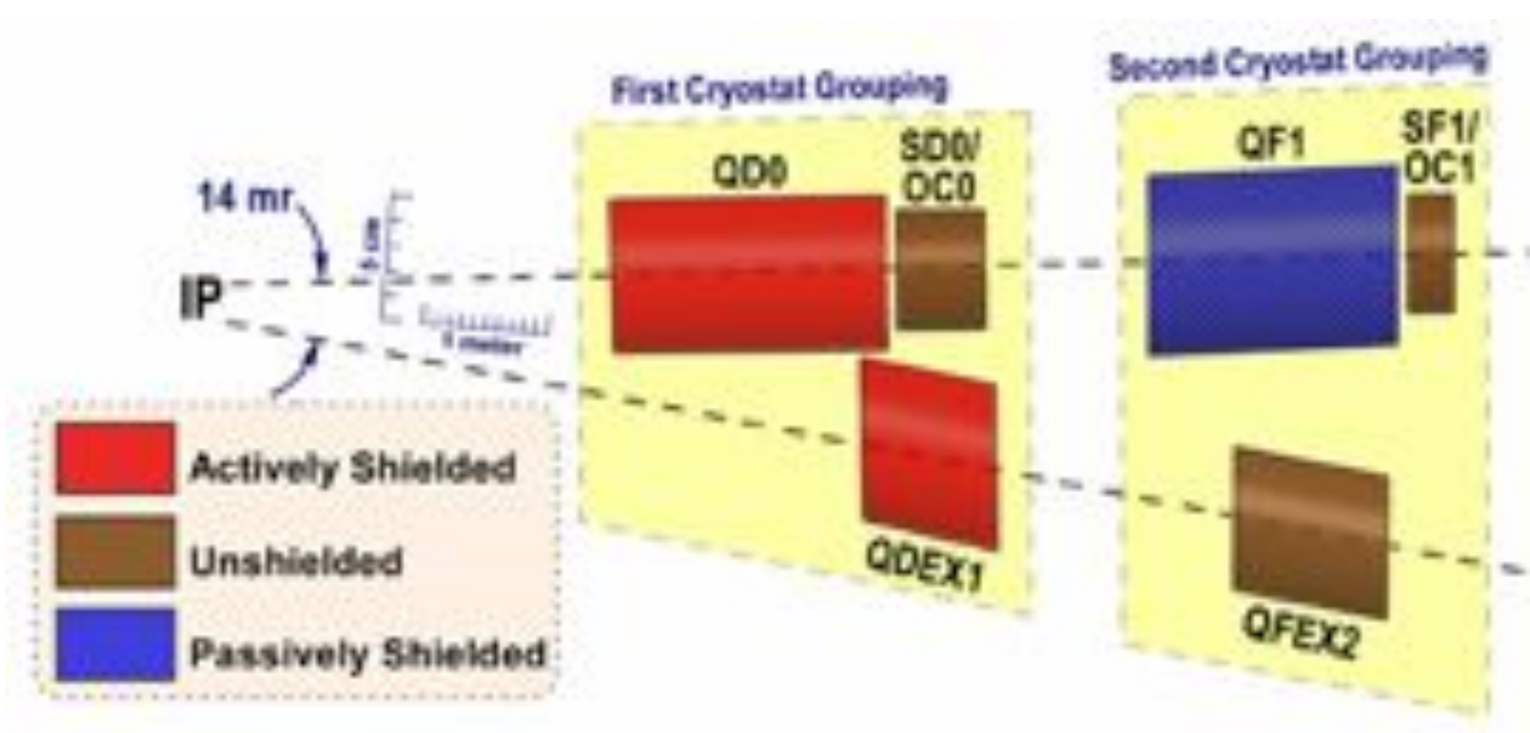


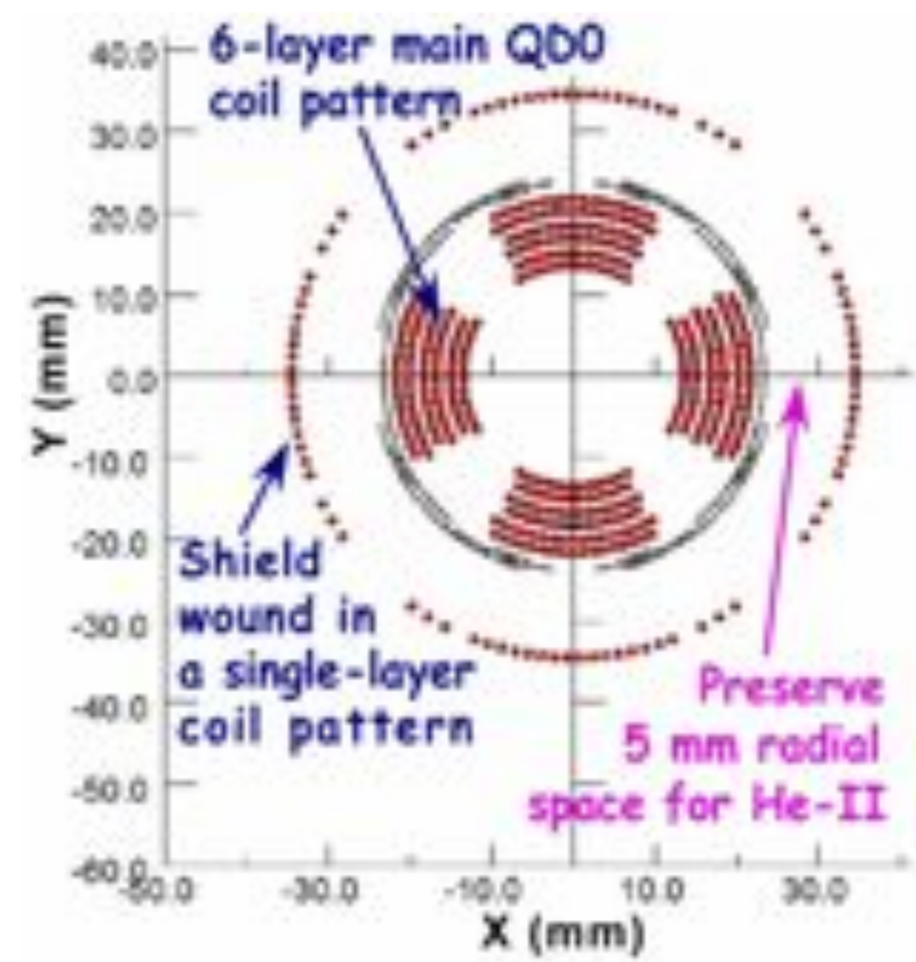
BDS Layout


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

Interaction Region

- Crossing angle 14 mrad
- Final quadrupole magnets
  - Superconducting (QD0 in detector magnetic field)
  - Out-going beam goes outside





Crab Crossing

- Large crossing angle 14 mrad
- Need to deflect head and tail oppositely
- Crab cavity
  - 3.9 GHz SC
  - phase tolerance ~60 fs
  - prototype fabricated