

Experimental particle. physics

esipap...
European School of Instrumentation
in Particle & Astroparticle Physics

2. a few things about
particle accelerators

why?

a small hint...

$$E = mc^2$$

Aren't natural radioactive processes enough?
What about cosmic rays?

Why accelerating and colliding particles?

Aren't natural radioactive processes enough? What about cosmic rays?

High energy

$$E = mc^2$$

- Probe smaller scale
- Produce heavier particles

Large number of collisions

$$N = \mathcal{L} \cdot \sigma$$

- Detect rare processes
- Precision measurements

Luminosity

Number of events
in unit of time

$$N = \mathcal{L} \cdot \sigma$$

$[\text{t}^{-1}]$

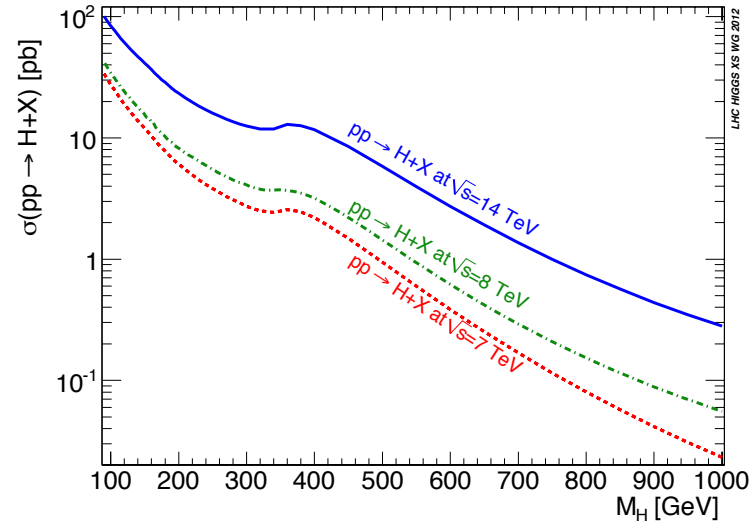
?

$[\text{L}^{-2} \text{t}^{-1}]$

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

$[\text{L}^2]$

$\sigma(\text{pp} \rightarrow \text{H}+\text{X}) \sim 20 \text{ pb}$



In a collider ring...

$$\mathcal{L} = \frac{1}{4\pi} \frac{fkN_1N_2}{\sigma_x\sigma_y}$$

Current

Beam sizes (RMS)

What particle to accelerate and collide?

- **Stable (charged) particle**

- ✓ Electron/positron

- ✓ Proton/antiproton



what particle should we use?

- **Secondary beams of charged or neutral particles**

- ✓ (Anti)neutrinos

- ✓ Muons

- ✓ Photons

- ✓ Charged pions

- ✓ Kaons

- ✓ ...

Particle accelerations for dummies

(non-relativistic)
Lorentz Force

$$\vec{F}_L = q \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

time variation of
kinetic energy

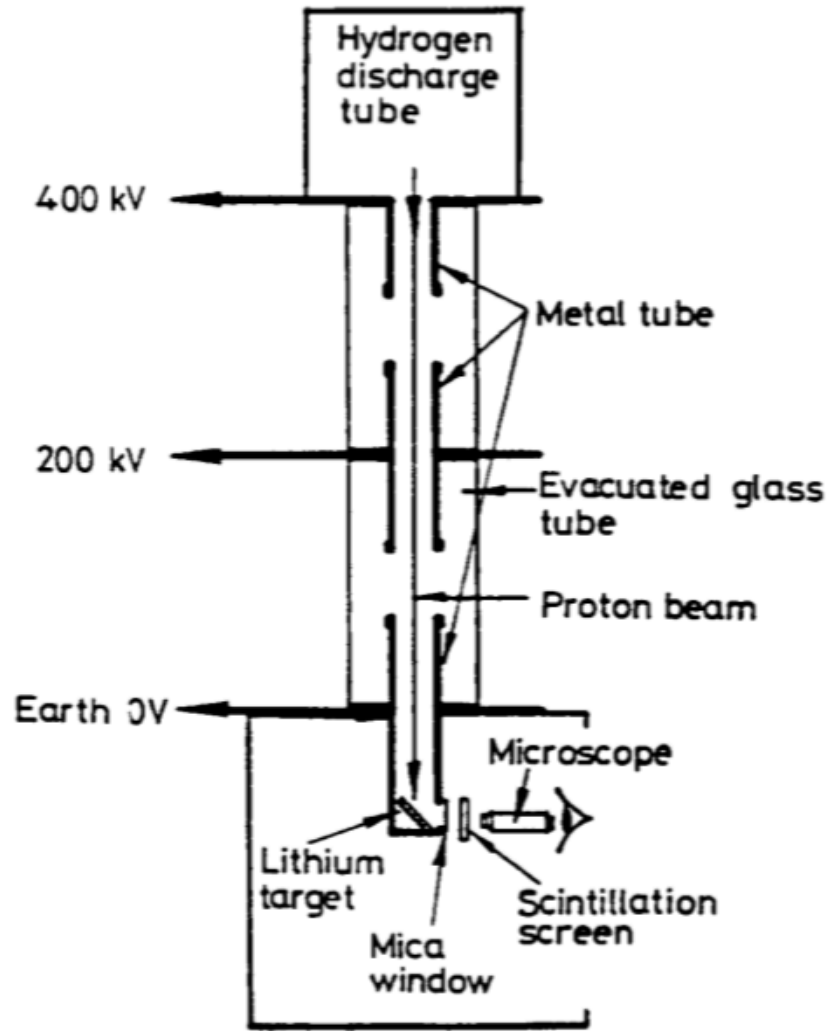
$$\frac{dE_{\text{kin}}}{dt} = \vec{F}_L \cdot \vec{v} = q\vec{v} \cdot \vec{E}$$

- Only longitudinal component of electrical field matters
- Time-varying electrical field to change energy
- (Static) magnetic field cannot change particle momentum...
- ... but can be used to bend its trajectory!

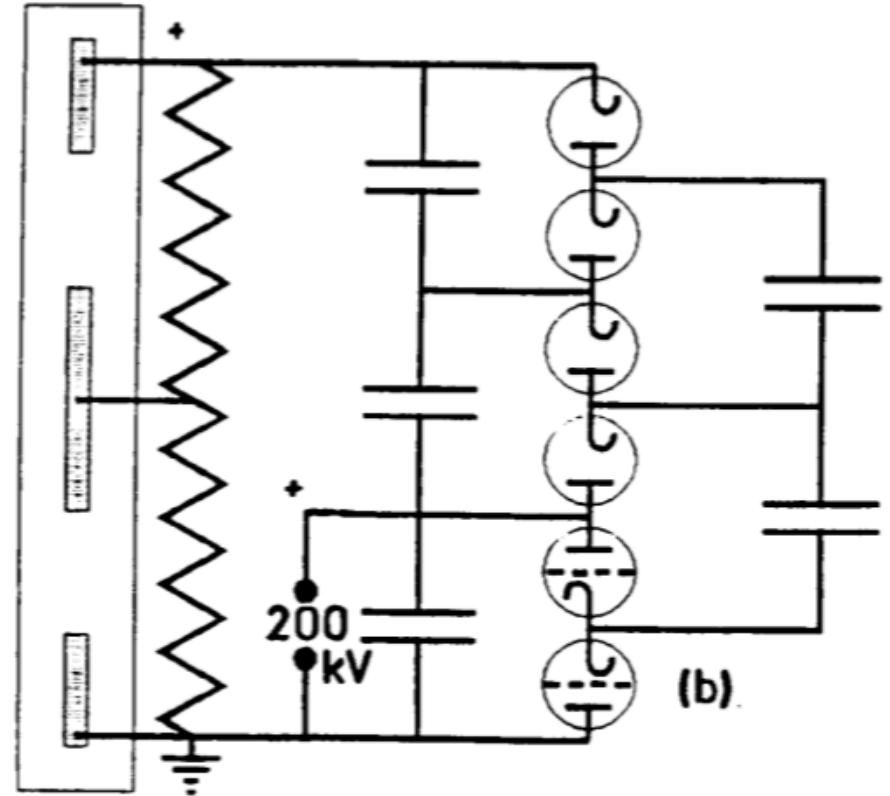
A brief history of particle accelerators – part I

| | | |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------|
| 1895 | Lenard. Electron scattering on gases (Nobel Prize). | < 100 keV electrons. Wimshurst-type machines. |
| 1913 | Franck and Hertz excited electron shells by electron bombardment. | |
| 1906 | Rutherford bombards mica sheet with natural alphas and develops the theory of atomic scattering. | Natural alpha particles of several MeV |
| 1911 | Rutherford publishes theory of atomic structure. | |
| 1919 | Rutherford induces a nuclear reaction with natural alphas. | |
| | ... Rutherford believes he needs a source of many MeV to continue research on the nucleus. This is far beyond the electrostatic machines then existing, but ... | |
| 1928 | Gamov predicts tunnelling and perhaps 500 keV would suffice ... | |
| 1928 | Cockcroft & Walton start designing an 800 kV generator encouraged by Rutherford. | |
| 1932 | Generator reaches 700 kV and Cockcroft & Walton split lithium atom with only 400 keV protons. They received the Nobel Prize in 1951. | |

Cockcroft and Walton's apparatus

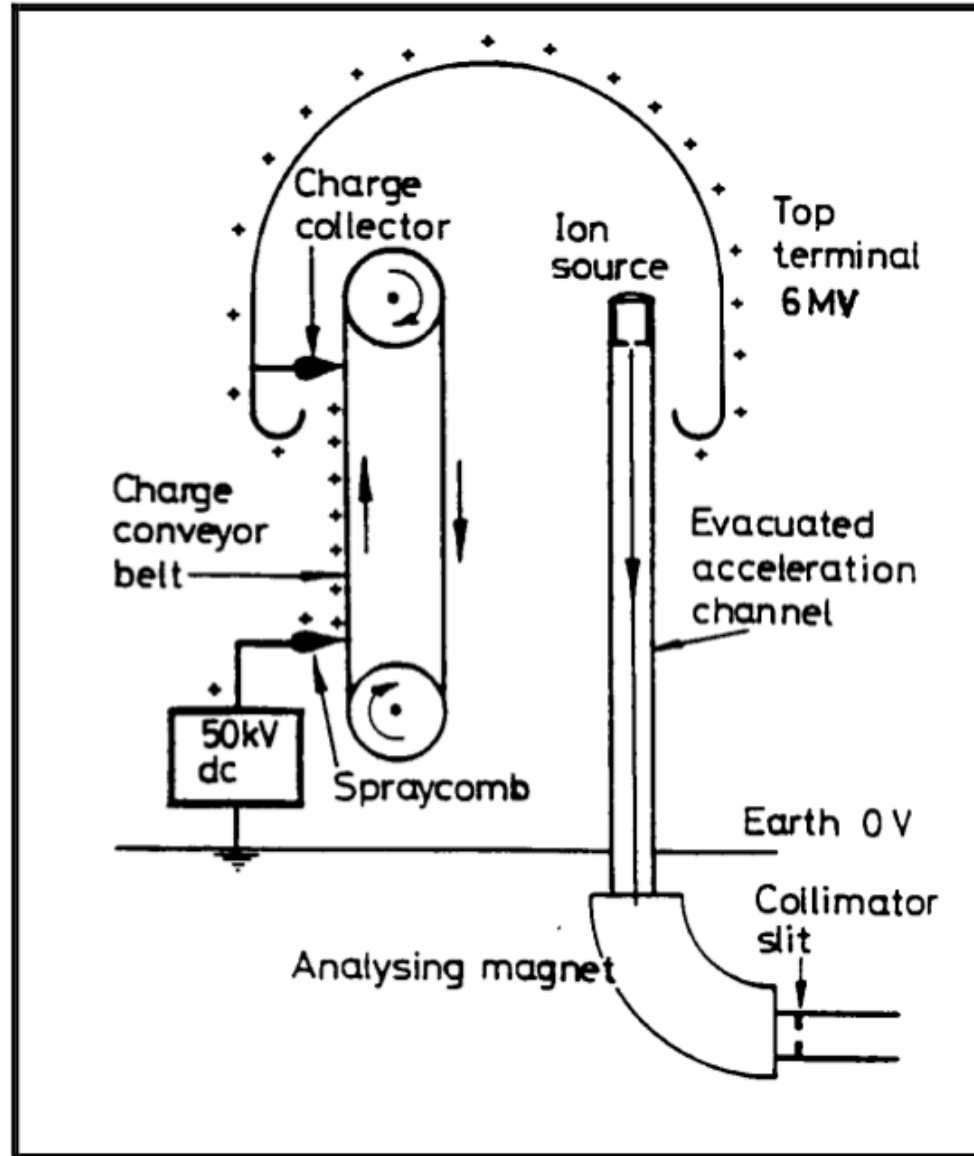


(a) Accelerating column

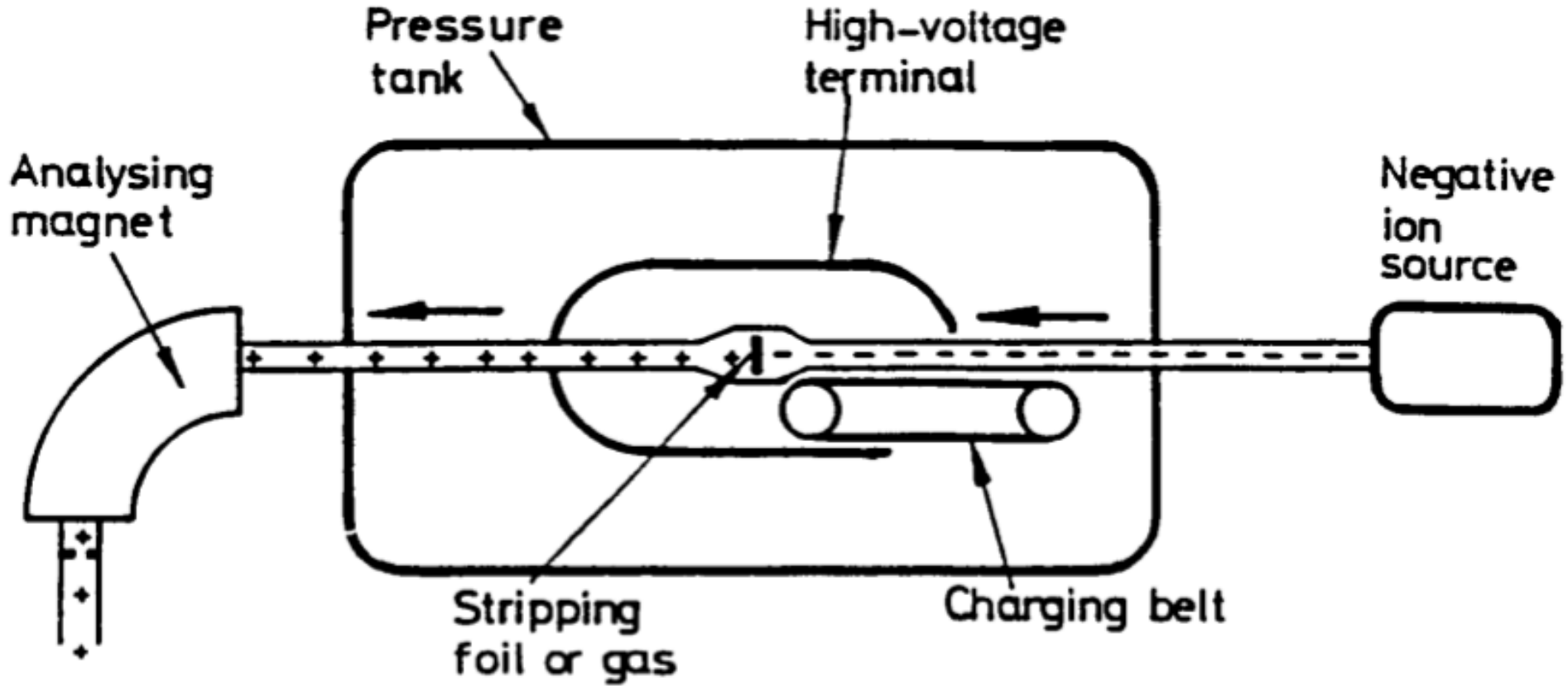


(b) DC generator

Van de Graaff electrostatic generator



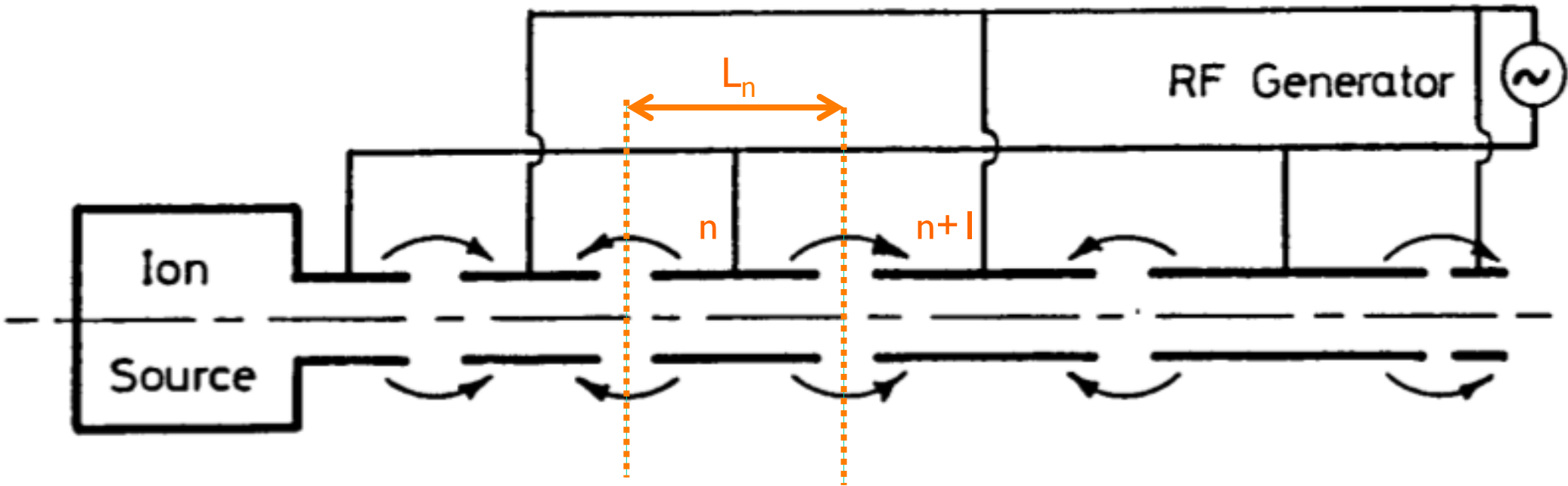
Two-stage Tandem accelerator



A brief history of particle accelerators – part 2

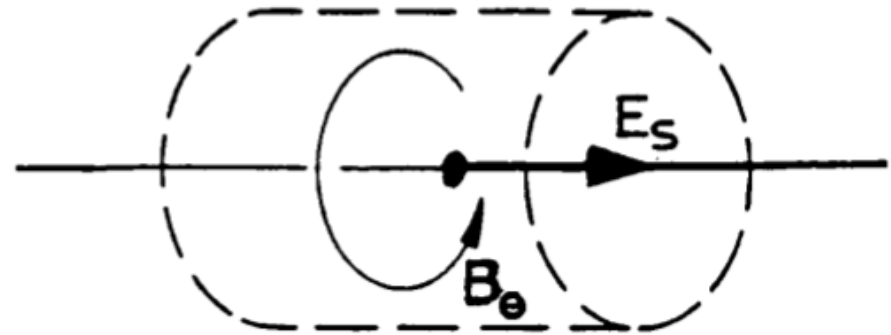
- | | |
|------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1924 | Ising proposes time-varying fields across drift tubes. This is "resonant acceleration", which can achieve energies above that given by the highest voltage in the system. |
| 1928 | Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions. |
| 1929 | Lawrence, inspired by Wideröe and Ising, conceives the cyclotron. |
| 1931 | Livingston demonstrates the cyclotron by accelerating hydrogen ions to 80 keV. |
| 1932 | Lawrence's cyclotron produces 1.25 MeV protons and he also splits the atom just a few weeks after Cockcroft and Walton (Lawrence received the Nobel Prize in 1939). |

RF linear accelerator (LINAC)



$$L_n = k \frac{v_n}{c} \frac{\lambda}{2}$$

Where: $k=1, L < \lambda$



LINAC length

Total LINAC length

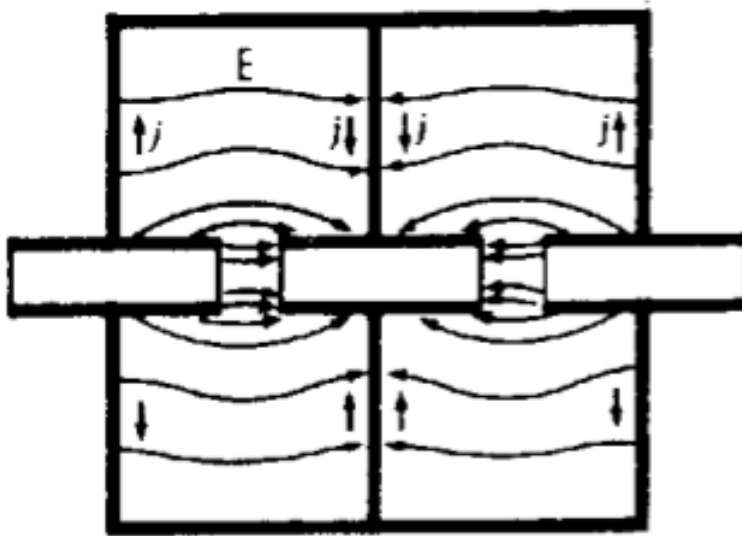
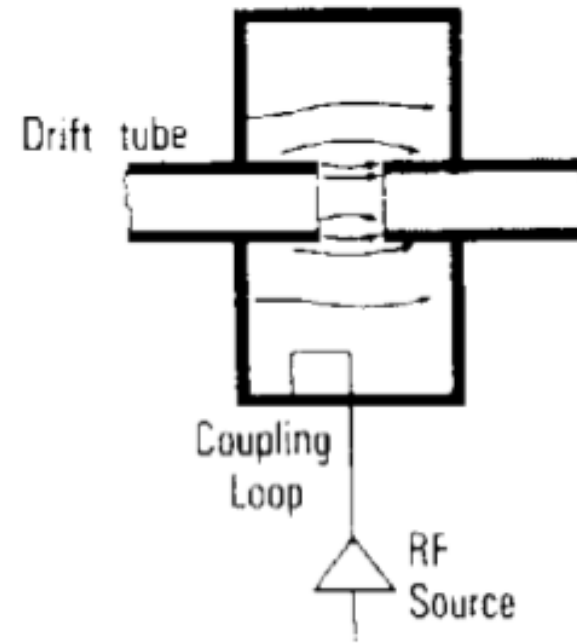
$$L = \frac{k}{\Delta E} \sqrt{\frac{E^3}{Amc^2}} \frac{\lambda}{2}$$

energy gain per gap ion atomic number final particle energy

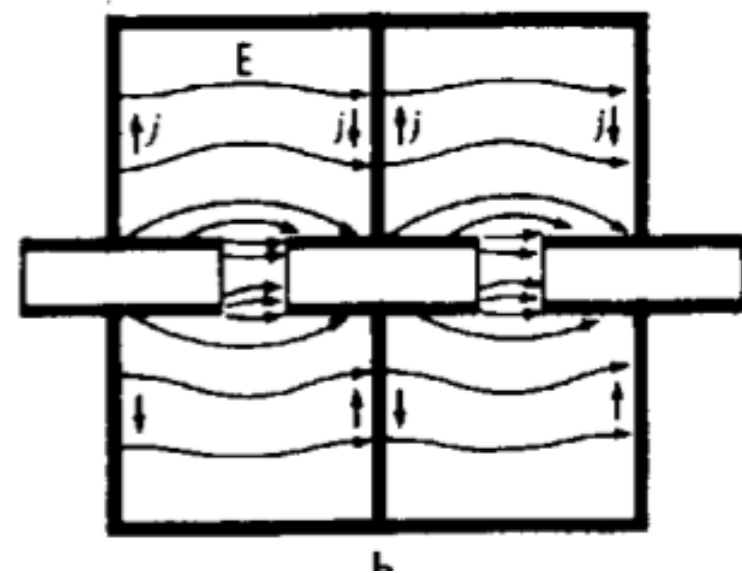
- Example: proton ($A=1$) with $K = 1$ MeV ($\beta = 4.6 \cdot 10^{-2}$) if $\nu_{RF} = 7$ MHz will travel about 1m in half a RF cycle
- Total LINAC length increases dramatically with increasing speed
- A possible solution would be to increase ν_{RF}
- ... but at very high ν_{RF} open tube structure radiates too much energy!

RF cavities

- The problem can be solved by closing the structure as a **cavity**...
- Cavities can be joined
- Choosing $k=2$ currents on walls cancel, and walls can be eliminated

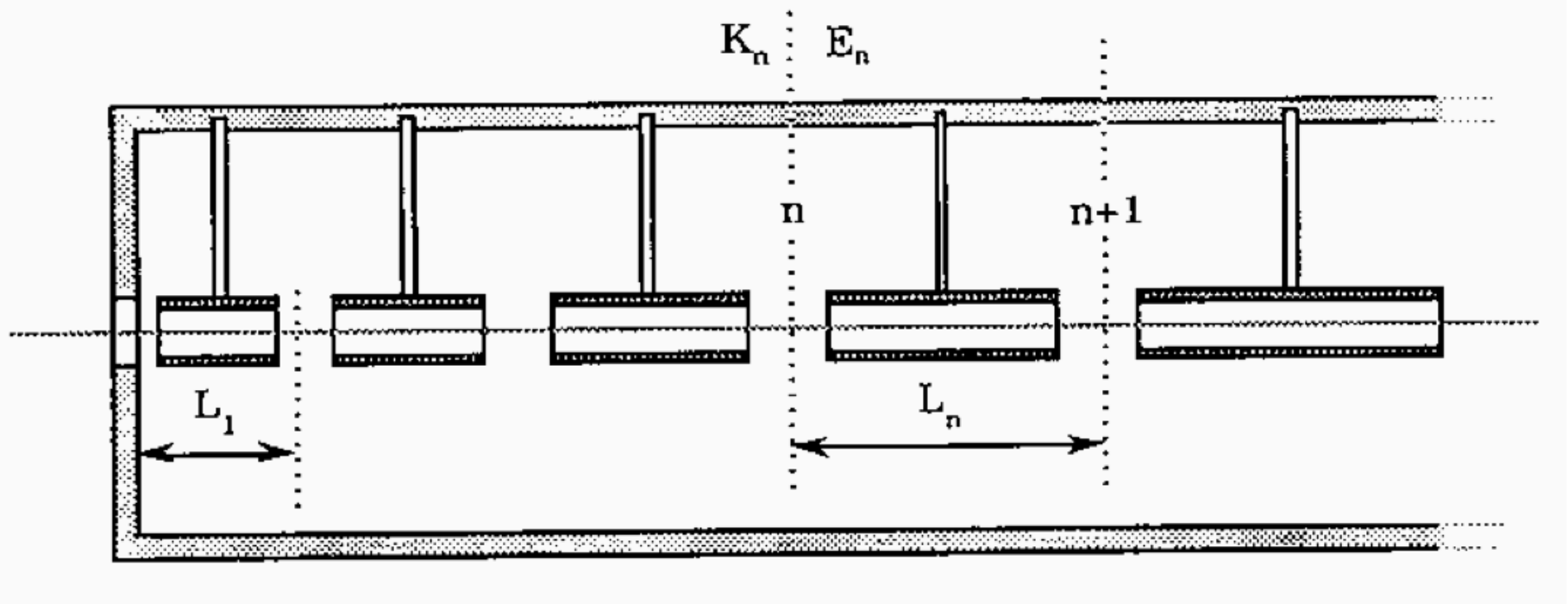


$k=1$



$k=2$

Alvarez structure



$$k = 2, v_{RF} \sim 100 \text{ MHz}, \lambda < L$$

protons $\beta \sim 1$ for $E \sim 10 \text{ GeV}$

electrons $\beta \sim 1$ for $E \sim 10 \text{ MeV}$

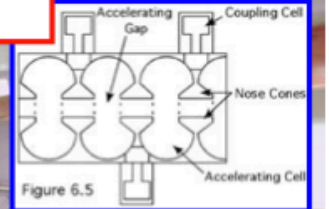
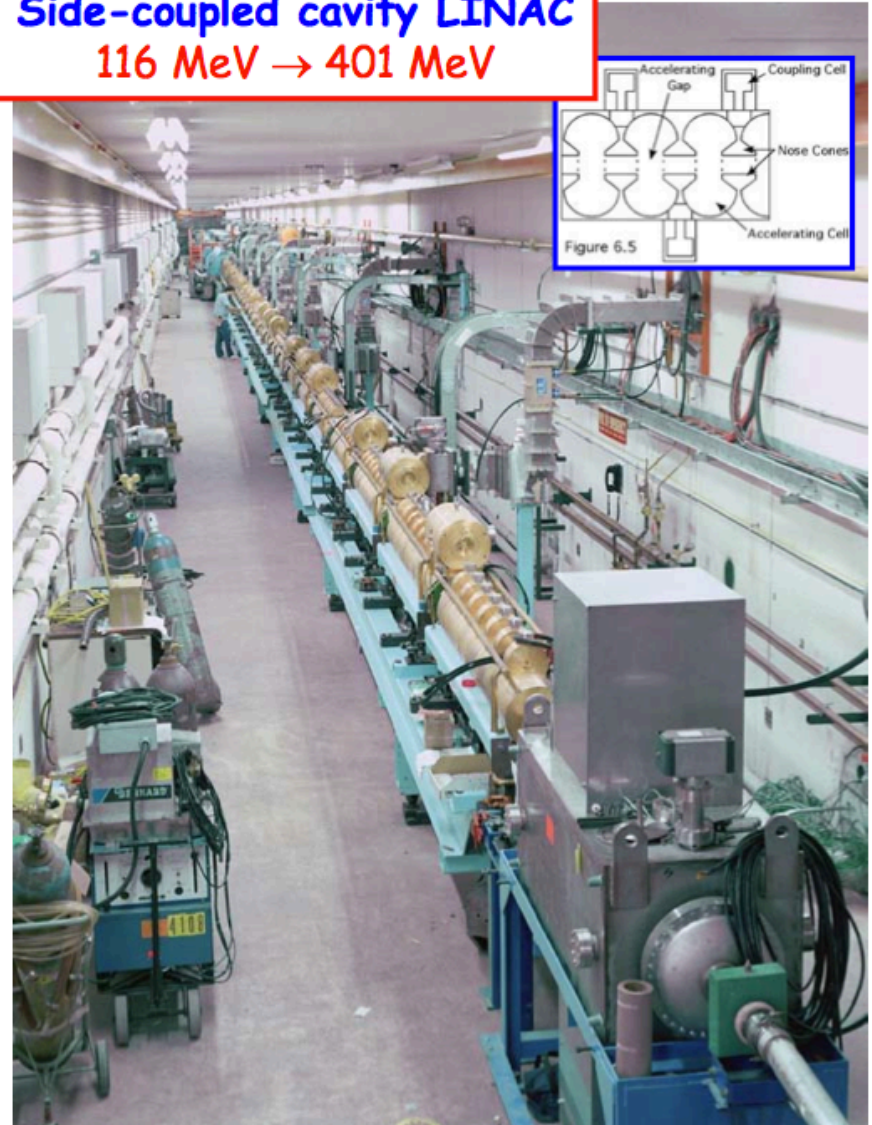
already at those energies $v \sim c \rightarrow$ drift tube length can stay constant!

Example: Fermilab LINAC

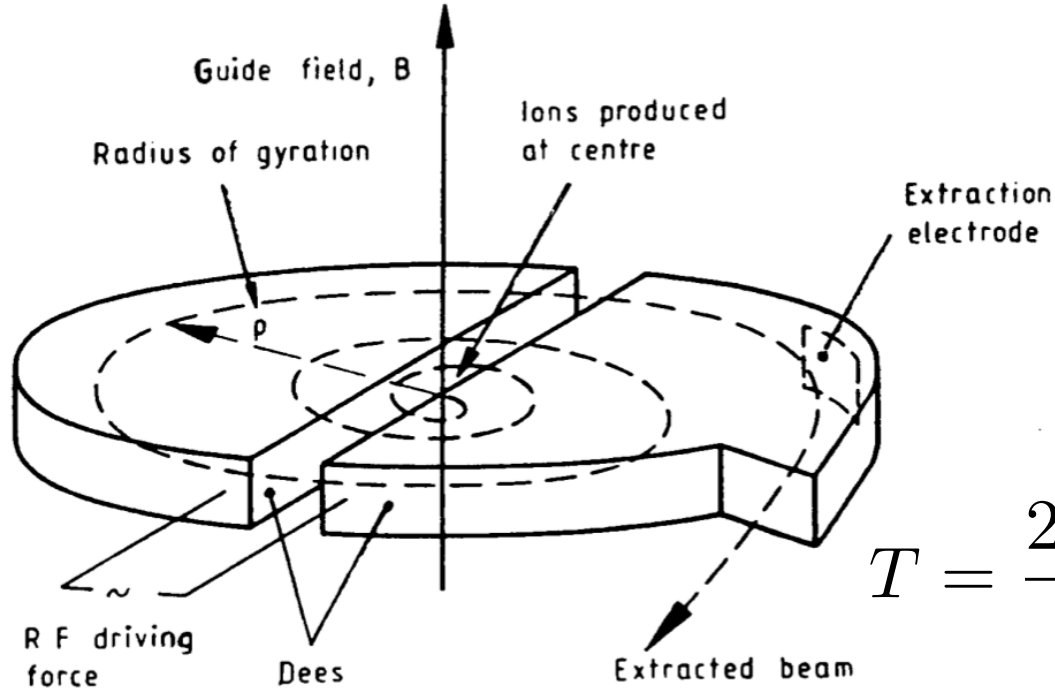


Drift tube (Alvarez) LINAC
750 keV → 116 MeV

Side-coupled cavity LINAC
116 MeV → 401 MeV



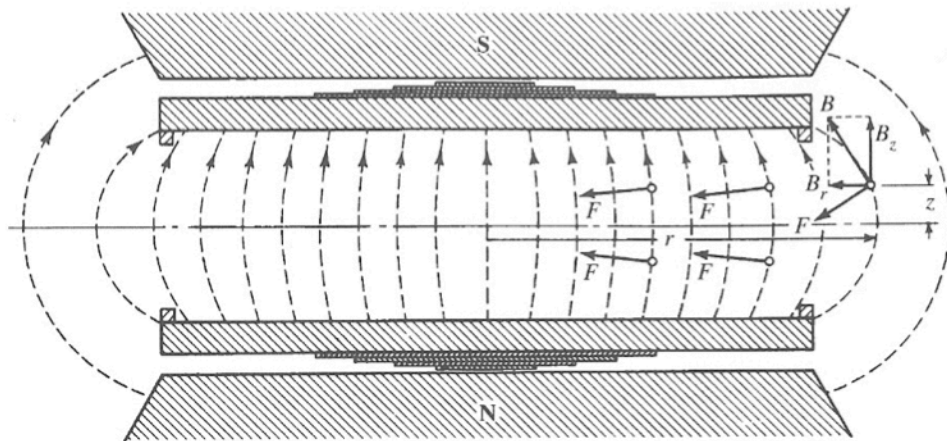
(Syncro) Cyclotron



$$p = m\gamma\beta$$

$$p = eBR$$

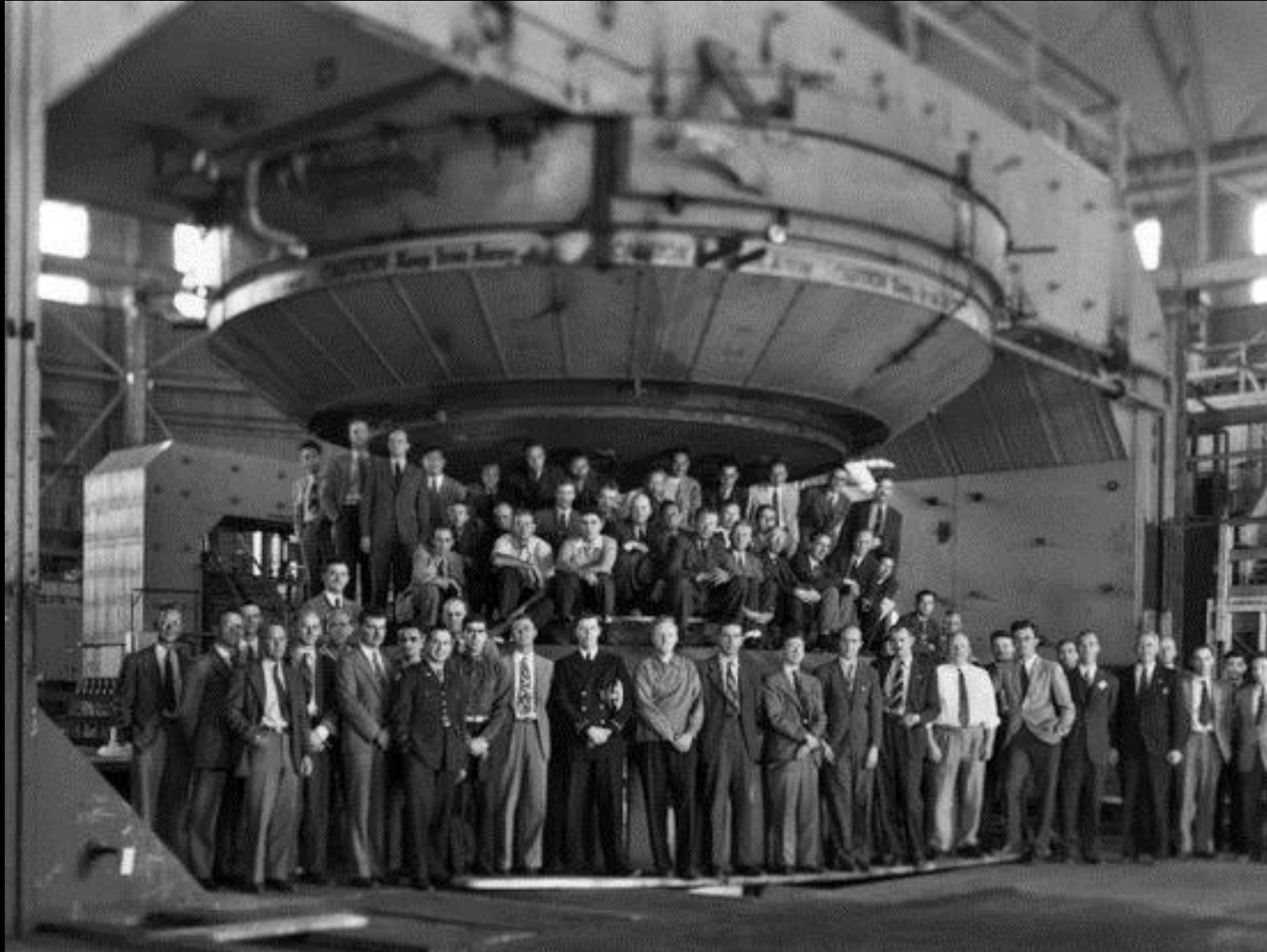
$$T = \frac{2\pi R}{v} = \frac{2\pi R}{\beta c} = \frac{\pi p}{eB\beta c} = \gamma \frac{\pi m}{eB}$$



for relativistic particle **cyclotron frequency** should be adjusted to speed/energy (**synchro-cyclotron**)

weak focusing

Berkeley syncro-cyclotron (p, $E = 340$ MeV)

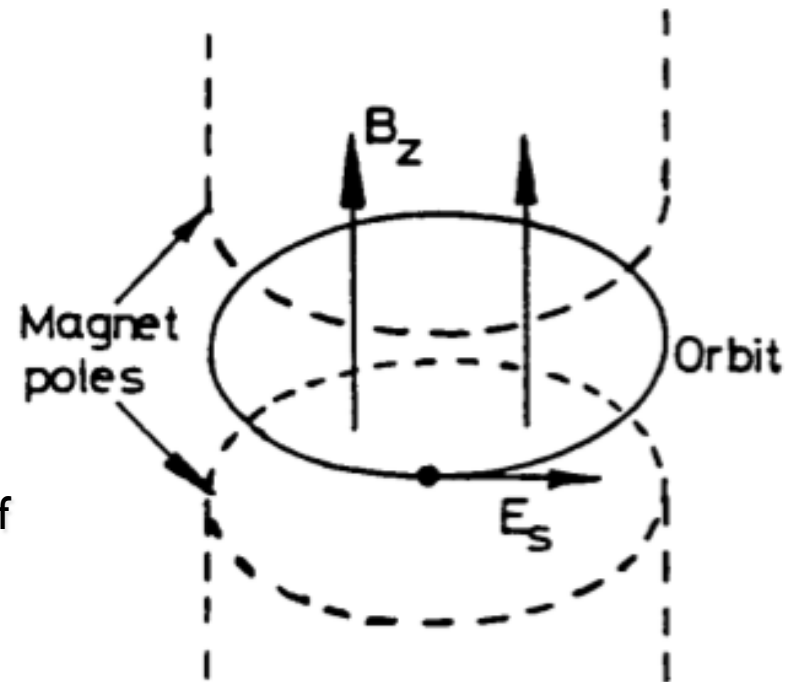
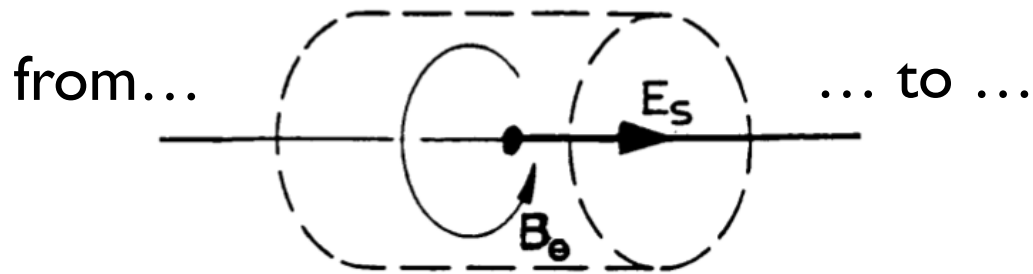


A brief history of particle accelerators – part 3

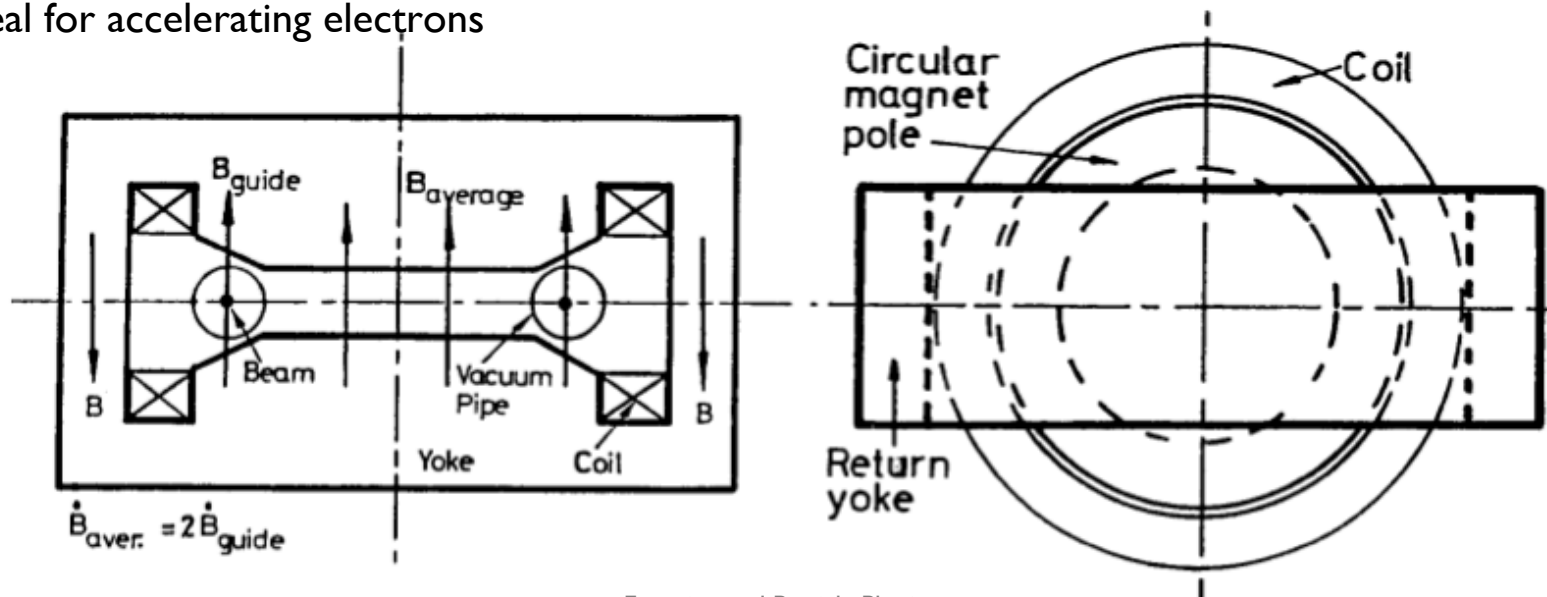
(or as varying magnetic fields could also be used to accelerate particles)

- 1923 Wideröe, a young Norwegian student, draws in his laboratory notebook the design of the betatron with the well-known 2-to-1 rule. Two years later he adds the condition for radial stability **but does not publish.**
- 1927 Later in Aachen Wideröe makes a model betatron, but it does not work. Discouraged he changes course and builds the linear accelerator mentioned in Table 2.
- 1940 Kerst re-invents the betatron and builds the first working machine for 2.2 MeV electrons.
- 1950 Kerst builds the world's largest betatron of 300 MeV.

Betatron acceleration

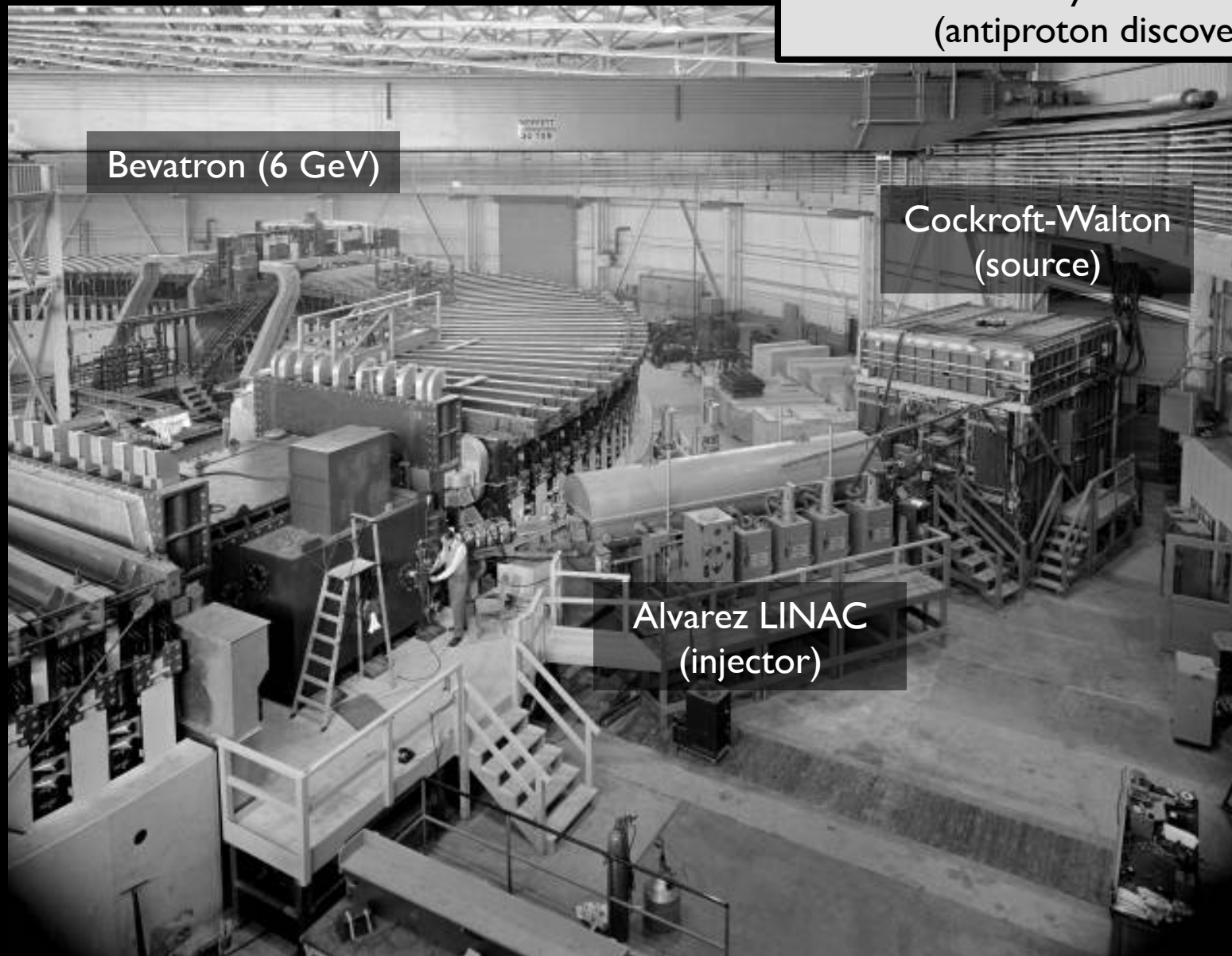


- Trick is to arrange magnetic field increase in vicinity of beam to correspond to increase of particle energy
 - ✓ beam stays on the same orbit (“2-to-1 rule”)
- Betatrons insensitive to relativistic effects
 - ✓ ideal for accelerating electrons



Accelerators work together!

Lawrence Berkeley National Laboratory
(antiproton discovery)



Bevatron (6 GeV)

Cockroft-Walton
(source)

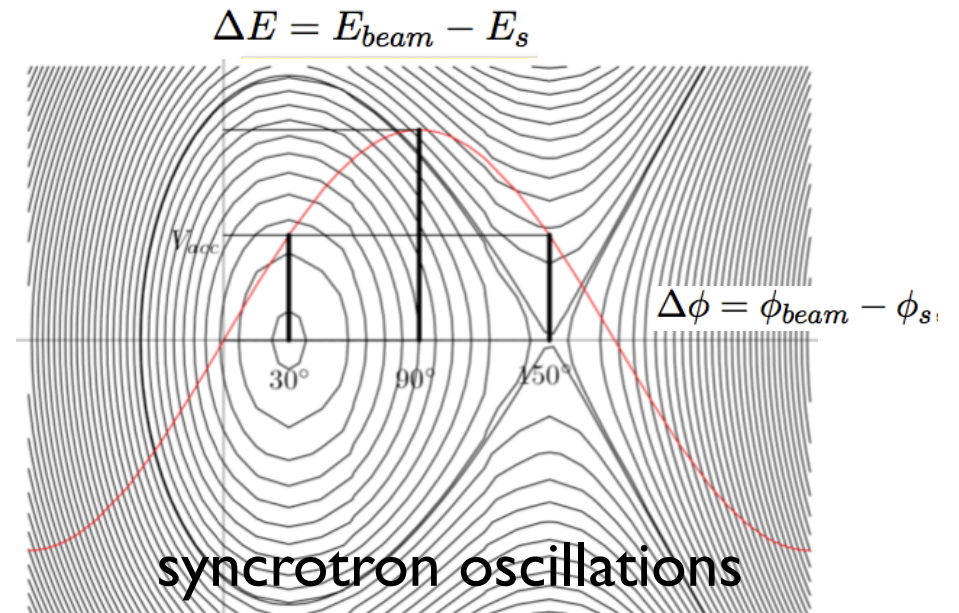
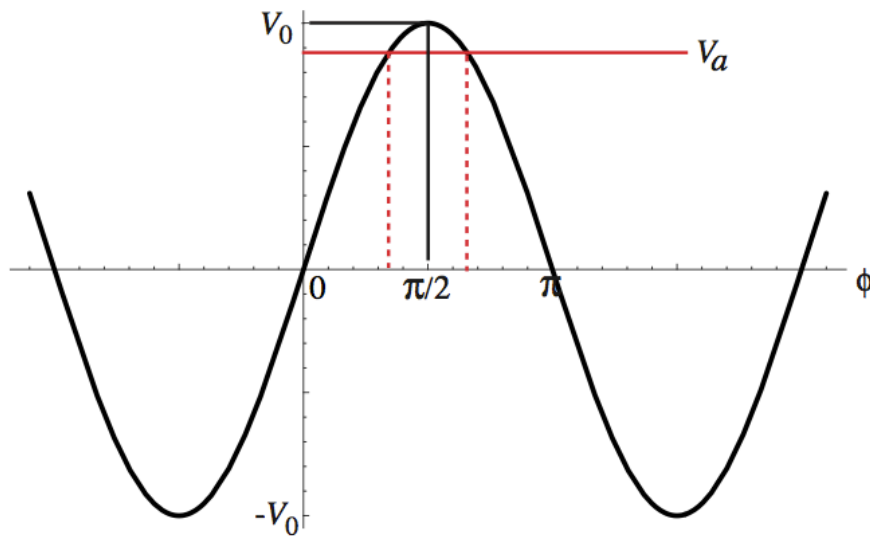
Alvarez LINAC
(injector)

The road toward synchrotrons

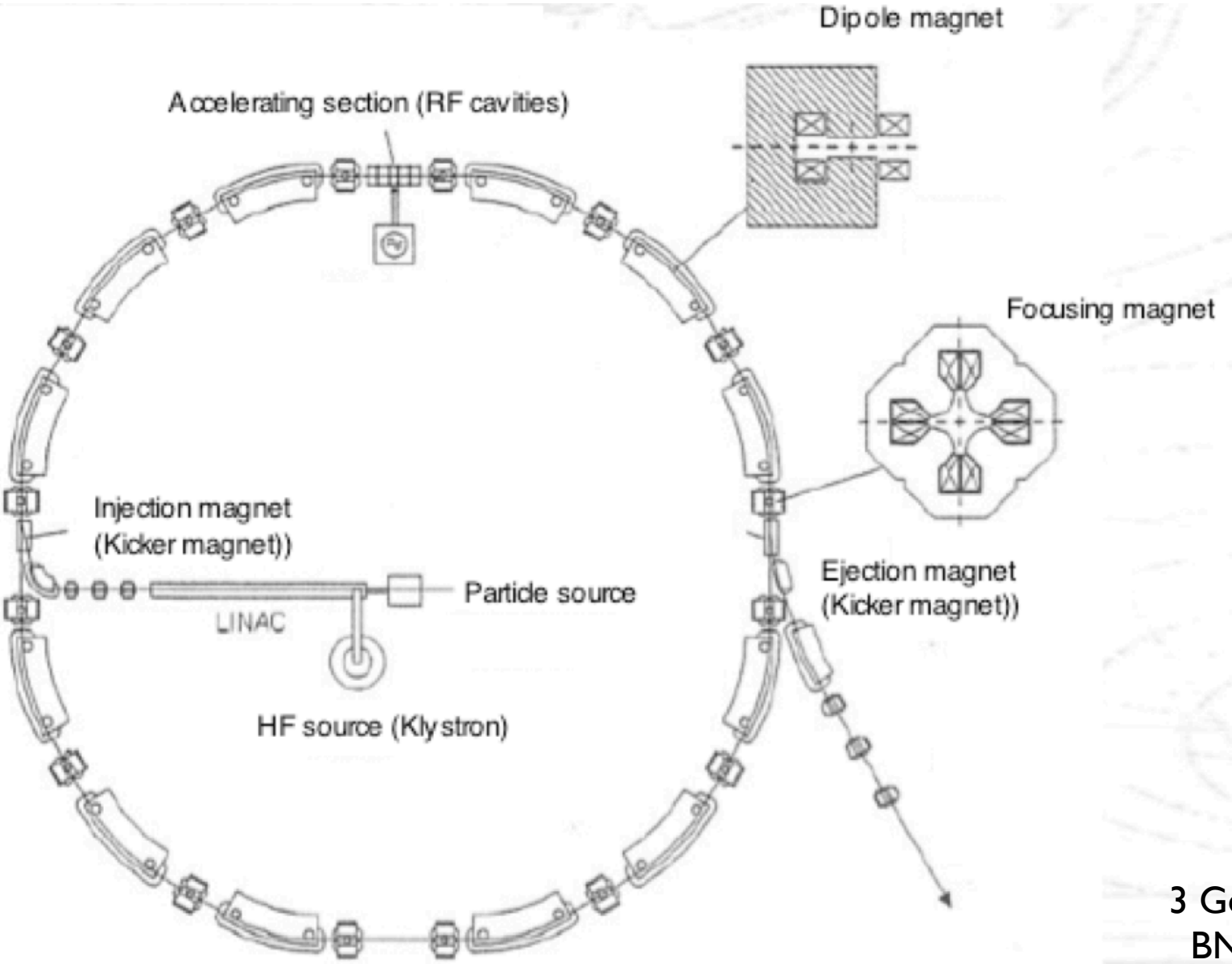
- Problems in RF acceleration in the 1940s...
 - ✓ Linacs
 - poor RF sources; electron tube technology was yet in its infancy
 - ✓ Cyclotrons
 - relativistic effects → asynchronous RF
 - ✓ Betatrons
 - intensity of trapped beam depends critically on the injected beam's positions and angles
 - analysis of particle transverse oscillations led to theory of **betatron oscillations**
- Advancements during WW2
 - ✓ High power microwave tubes for the radars were put to practical use
 - magnetrons and klystrons
 - ✓ Discovery of the **phase stability principle** in RF acceleration
 - Vladimir Veksler (1944) and Edwin M. McMillan (1945)
 - cyclotron → synchrocyclotron → synchrotron

Phase stability

- Particles of different energies have differences in velocity and in orbit length
 - ✓ particles may be asynchronous wrt RF frequency
- RF field have however a restoring force at a certain phase, around which asynchronous particles be captured in **bunches**
- The phenomenon enables a stable, continuous acceleration of the whole particles in a bunch to high energies: circular accelerators based on this principle are called “synchrotron”
 - ✓ Principle is also applicable to linacs, particularly in low energy range, to bunch continuous beams emitted from a source and to lead bunches to downstream accelerator sections

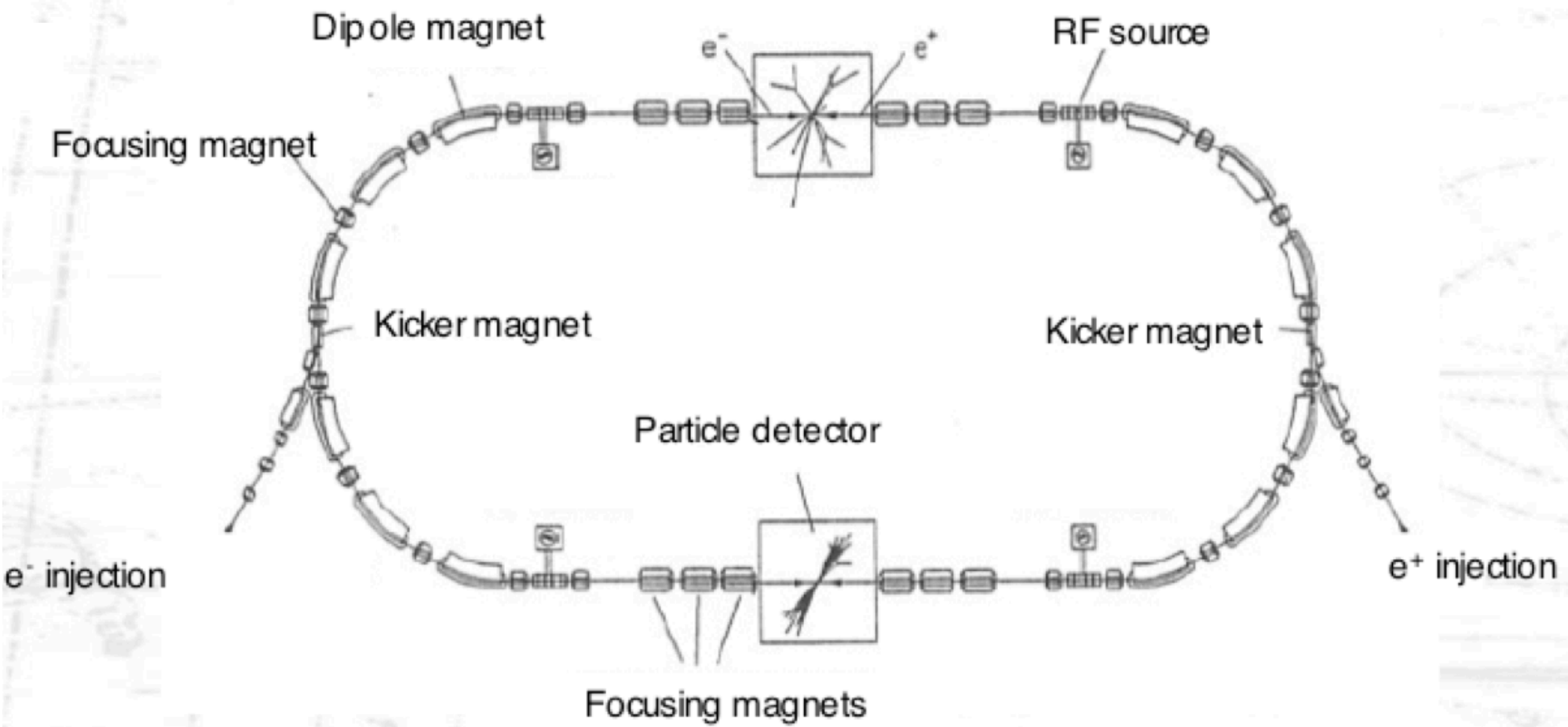


Synchrotron

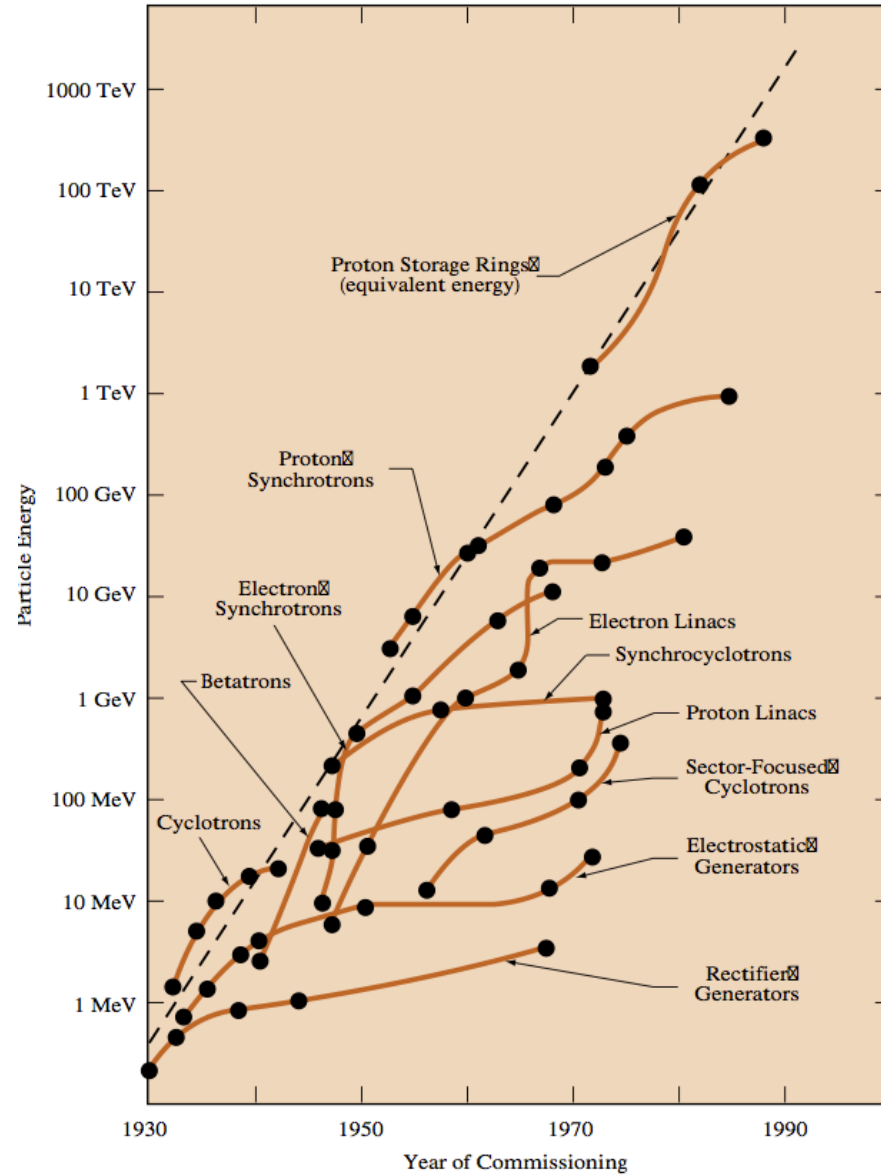


3 GeV protons
BNL ~ 1950

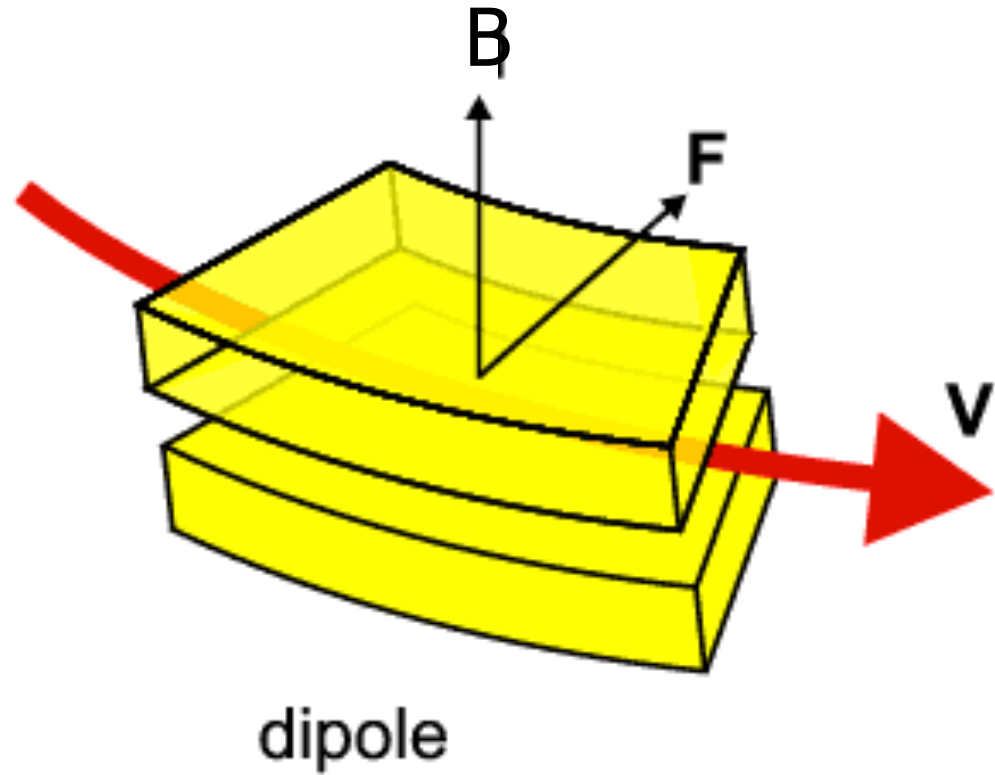
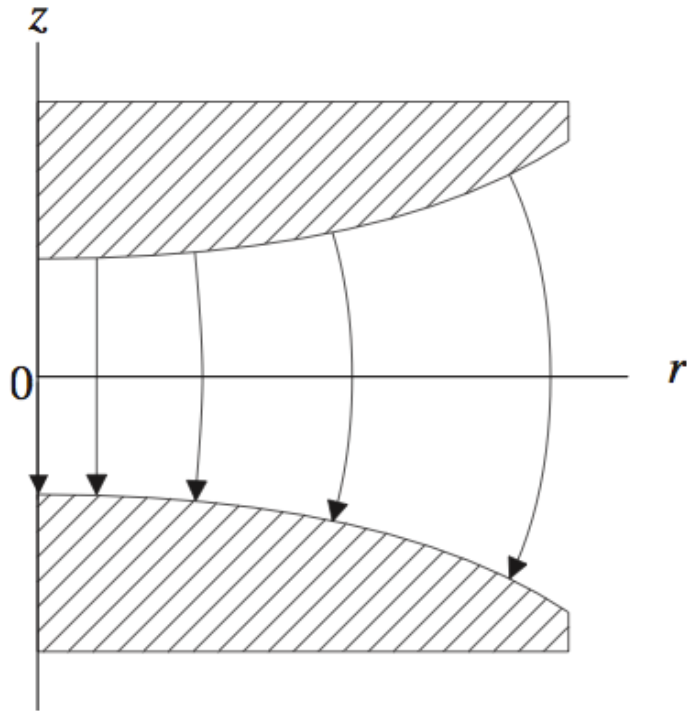
Storage rings



Livingstone chart

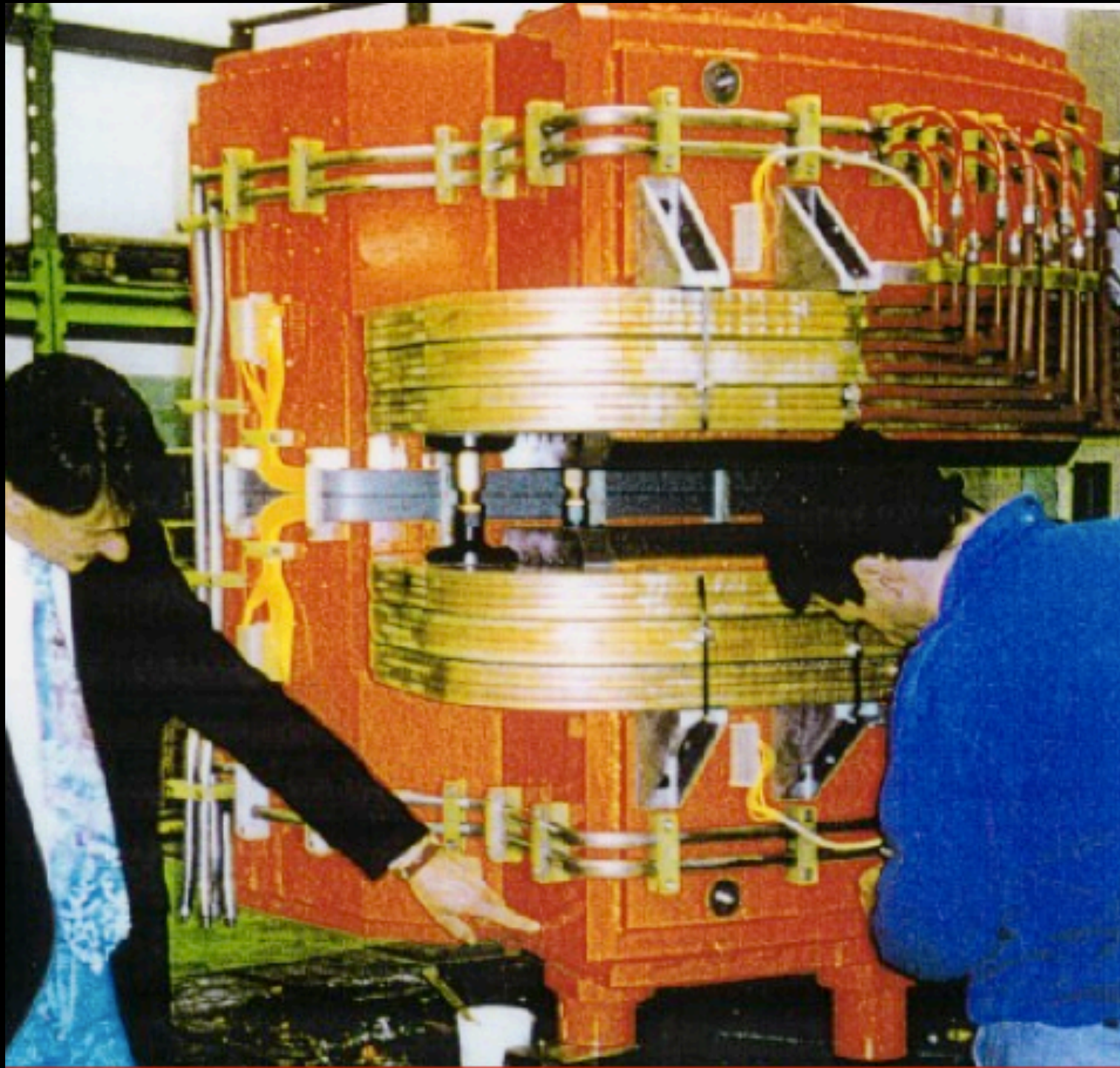


Bending: dipoles



$$\begin{aligned} B_x &= 0 \\ B_y &= B \\ B_z &= 0 \end{aligned}$$

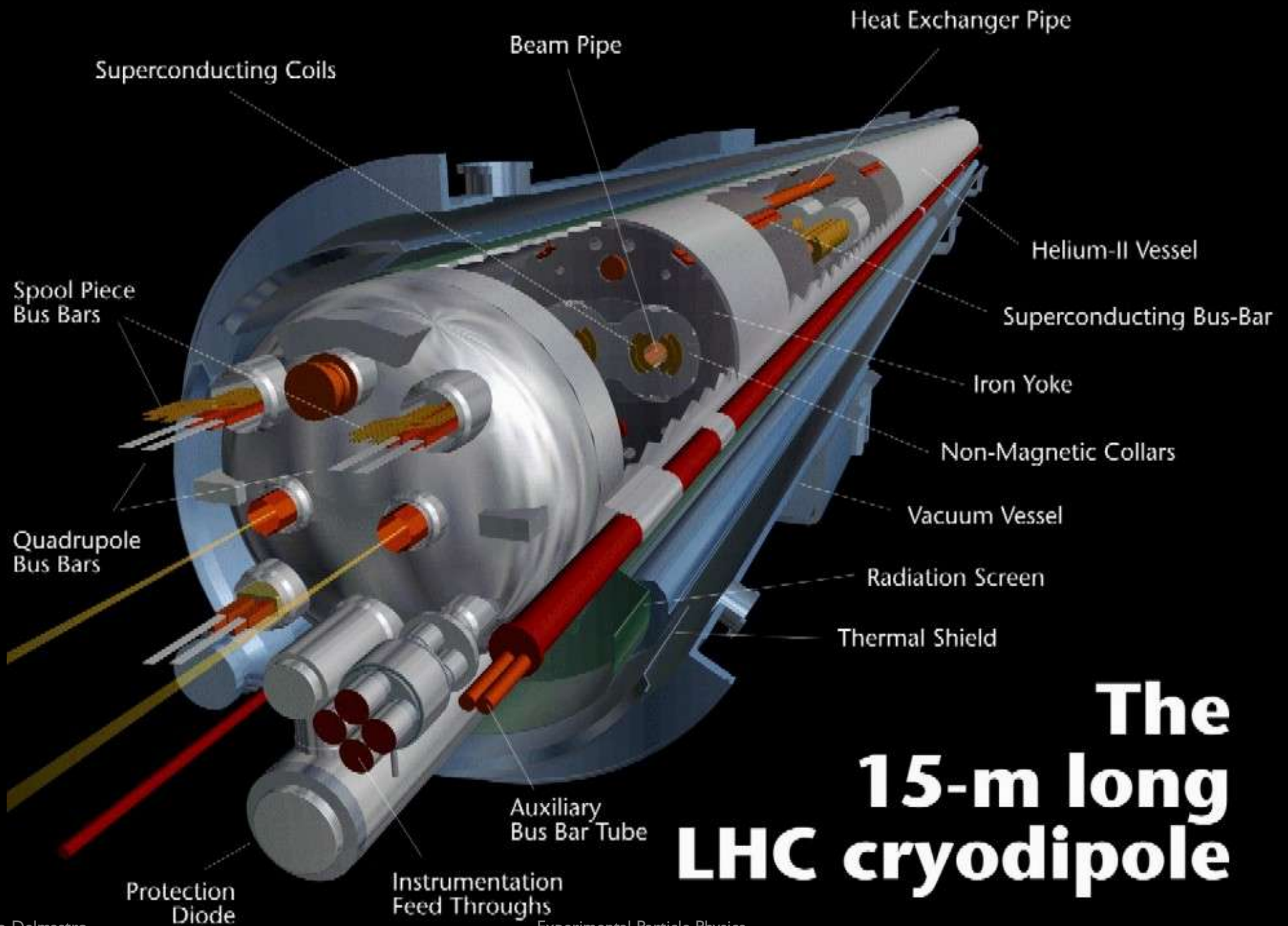
$$\frac{1}{R} [\text{m}^{-1}] = 0.3 \frac{B[\text{T}]}{E[\text{GeV}]}$$





1136

21R8
BG

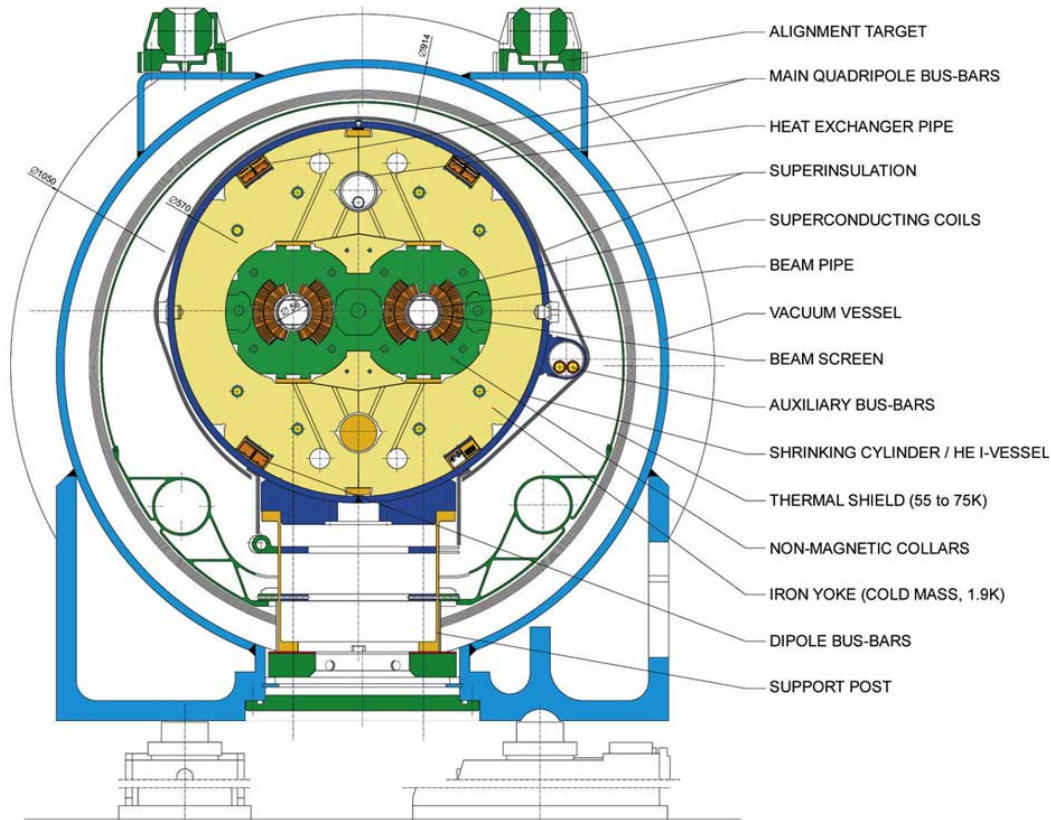


The 15-m long LHC cryodipole

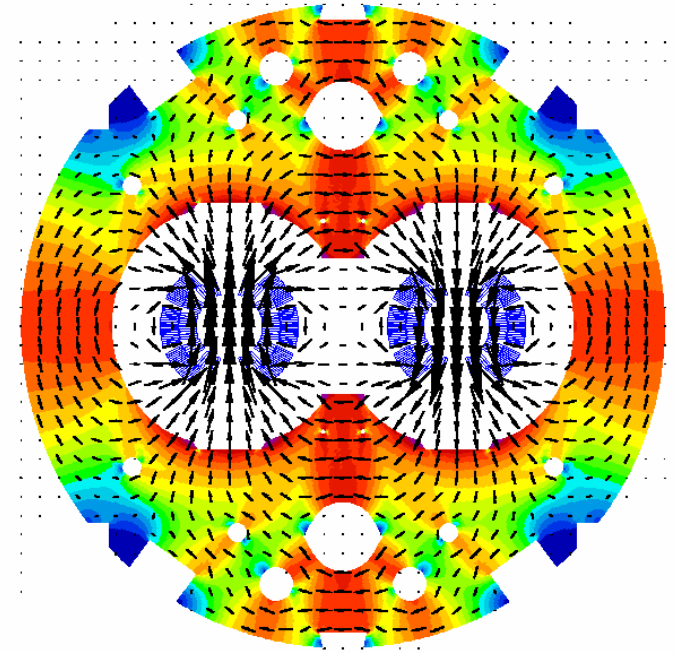
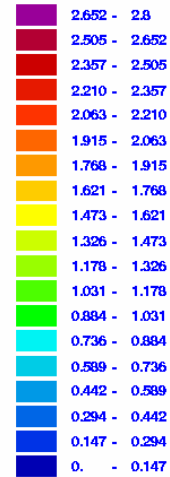
LHC dipoles

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DT/MM - HE 107 - 30 04 1999



$|B_{tot}|$ (T)



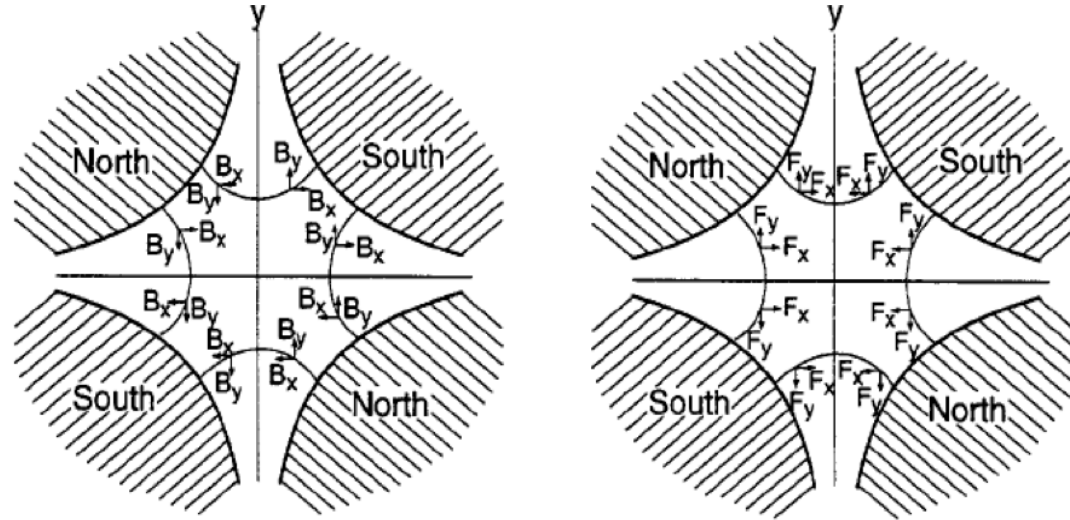
Focusing (defocusing): quadrupoles

$$B_x = -g \times x$$

$$B_y = -g \times y$$

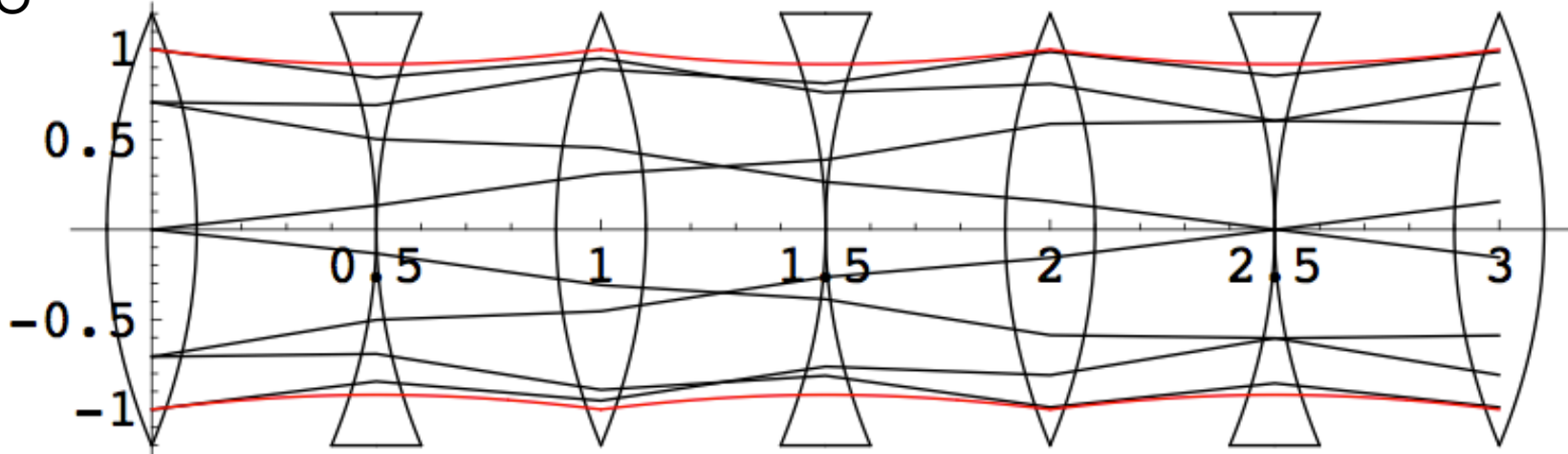
$$B_z = 0$$

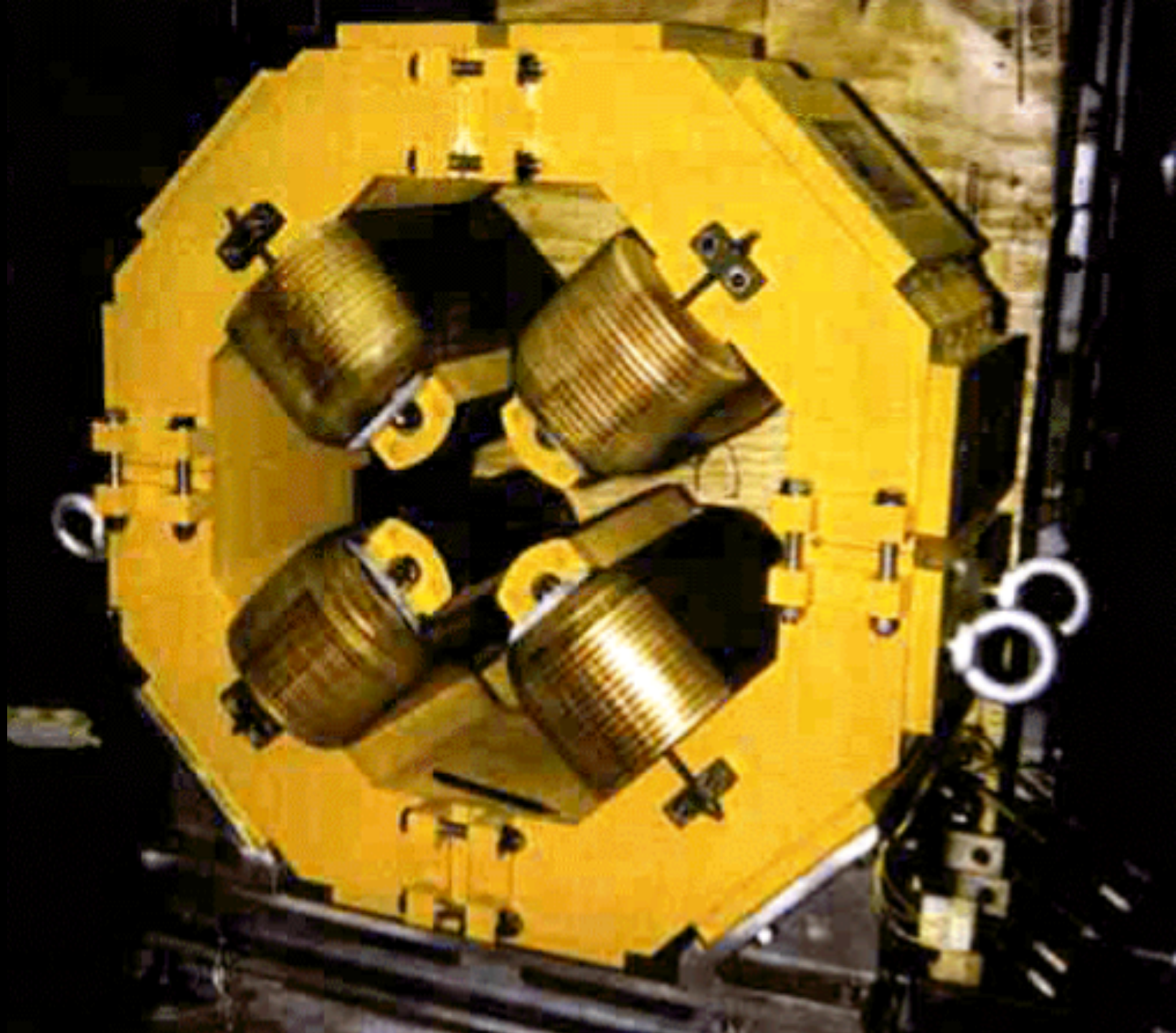
$g[\text{T/n}] = \text{field gradient}$



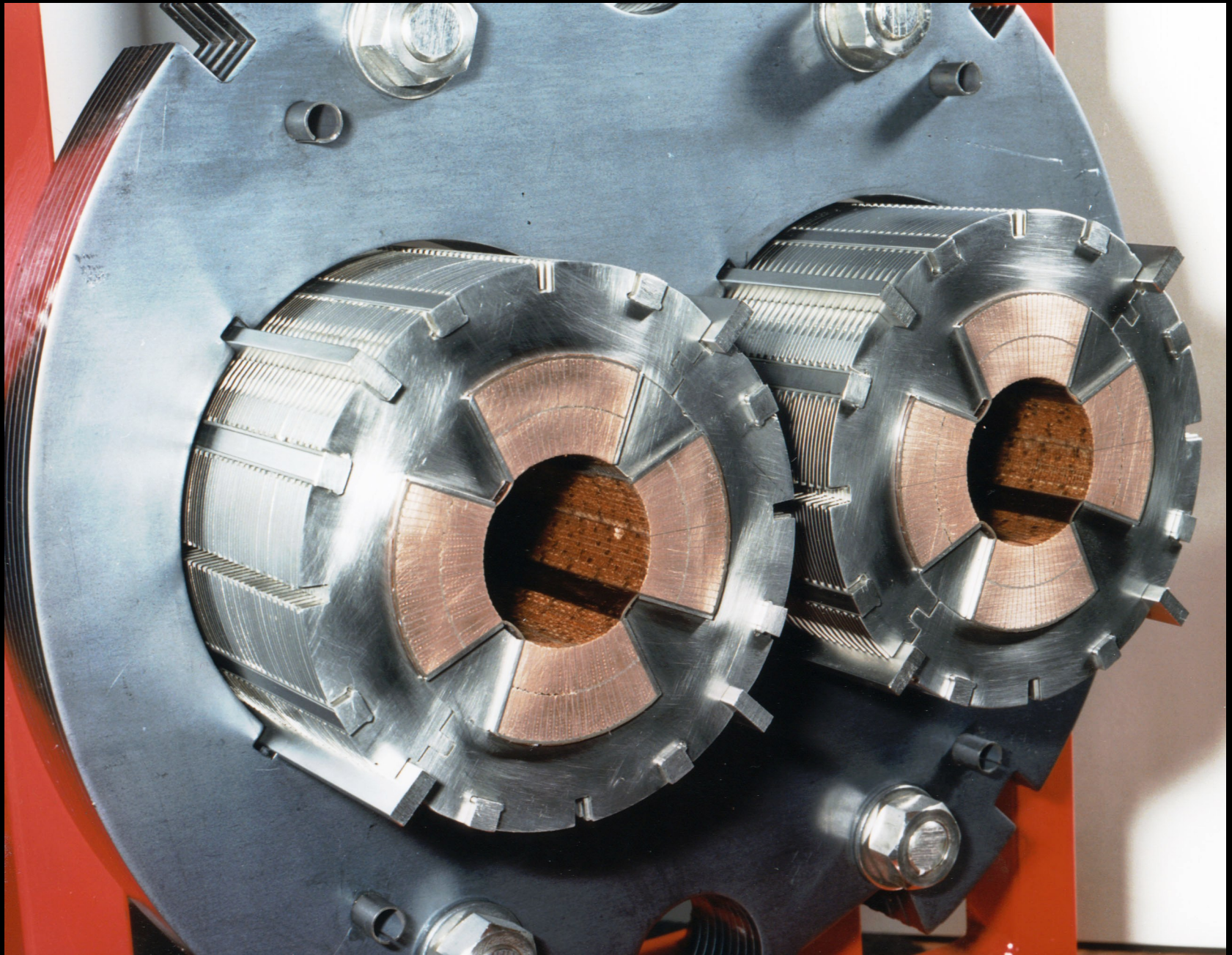
Focusing in one direction, defocusing in the other

FO-DO
array

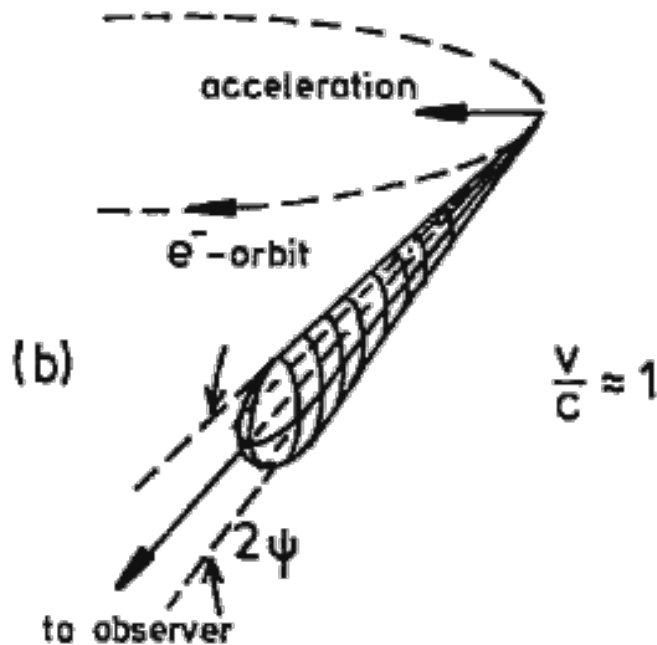
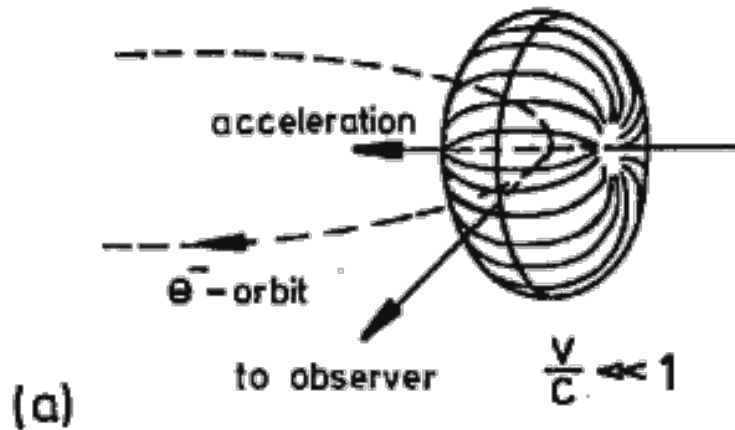








Synchrotron radiation



energy lost per revolution

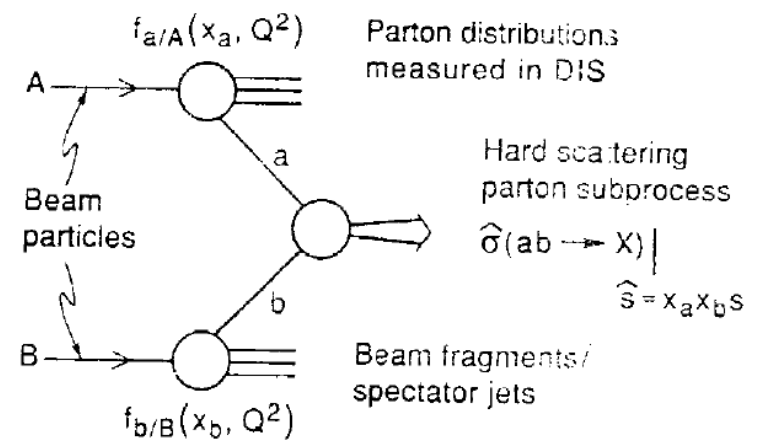
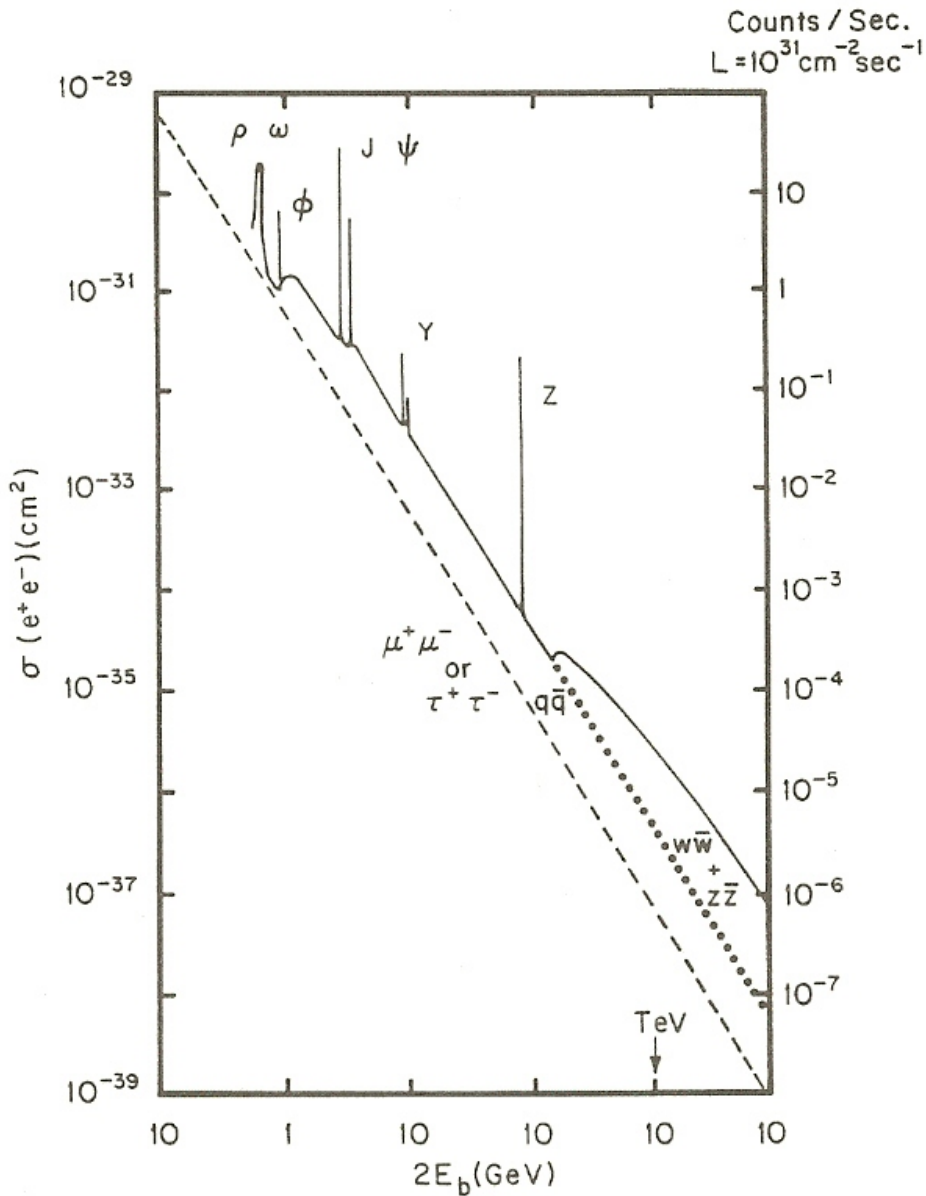
$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^3 \beta^3 \gamma^4}{R} \right)$$

electrons vs. protons

$$\frac{\Delta E_e}{\Delta E_p} \simeq \left(\frac{m_p}{m_e} \right)^4$$

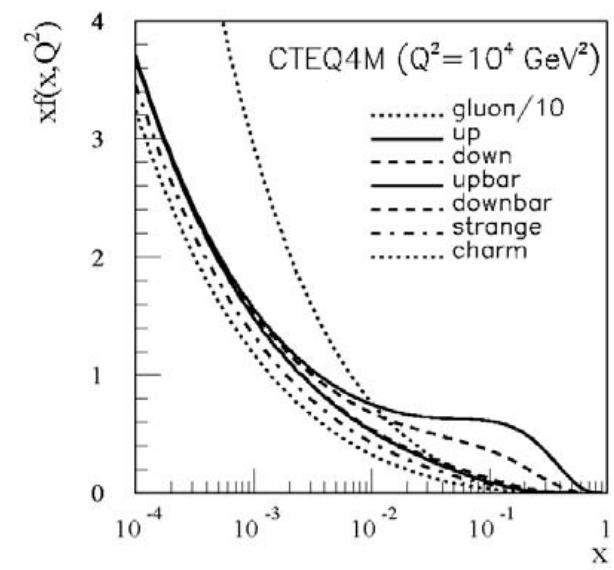
It's easier to accelerate protons to higher energies, but protons are fundamentals...

e^+e^- vs. hadron collider

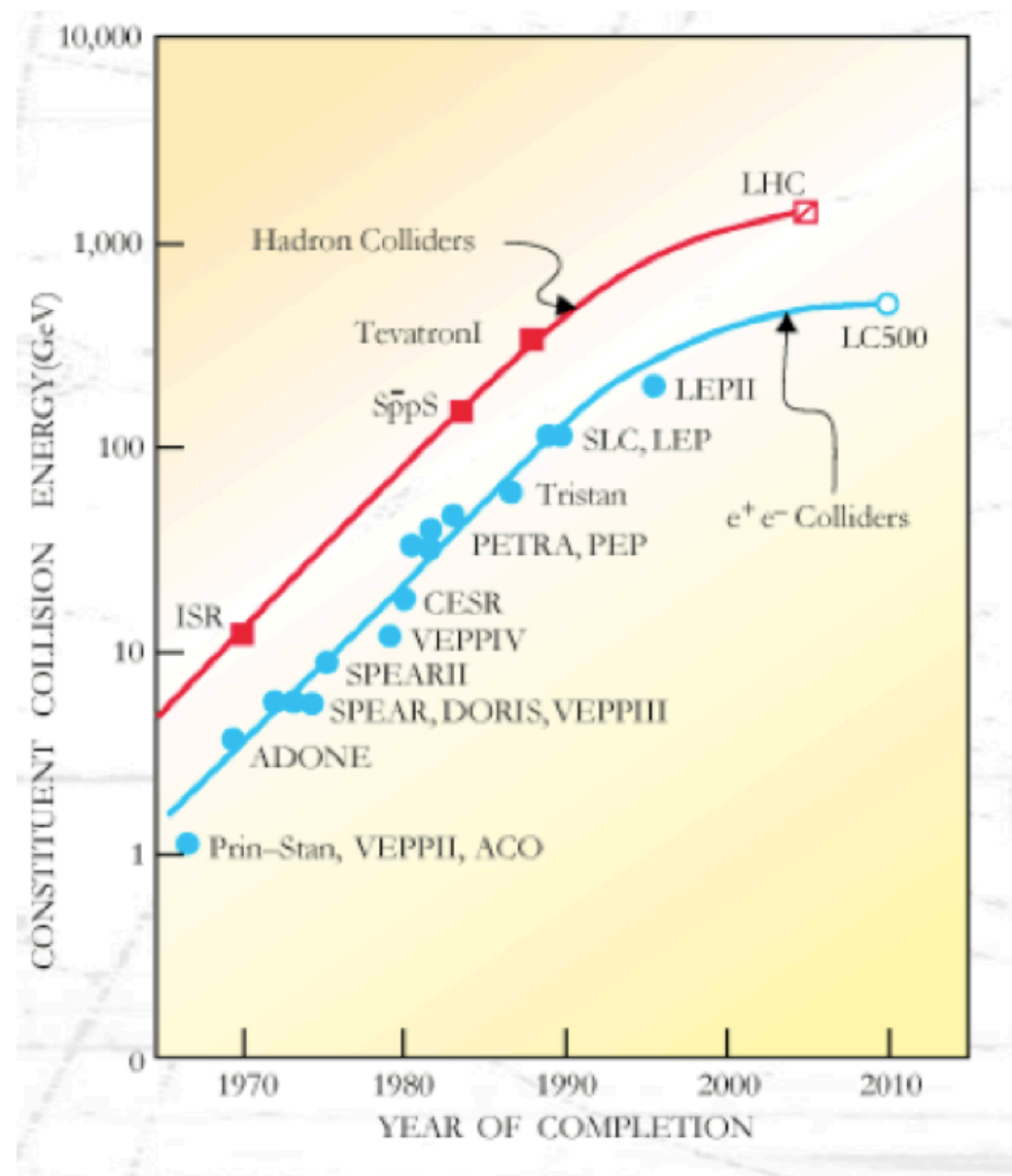


$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

$$\sigma = \sum_{a,b} \int dx_a dx_b f_a(x, Q^2) f_b(x, Q^2) \hat{\sigma}_{ab}(x_a, x_b)$$



e^+e^- vs. hadron collider



↕ 5-10

Accelerators around the world (past and present)

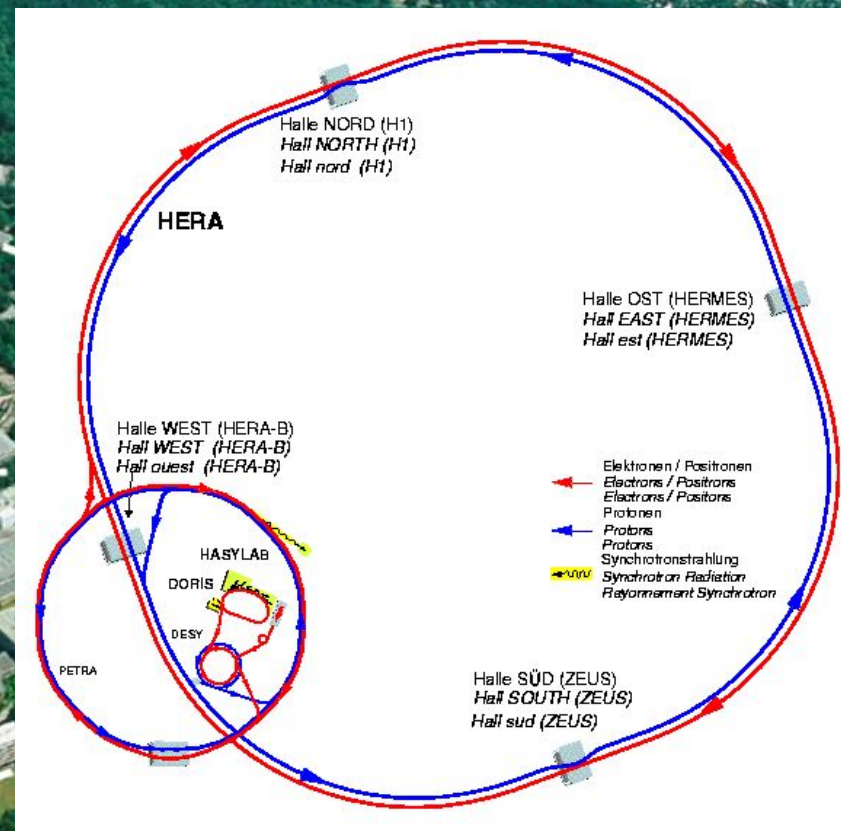
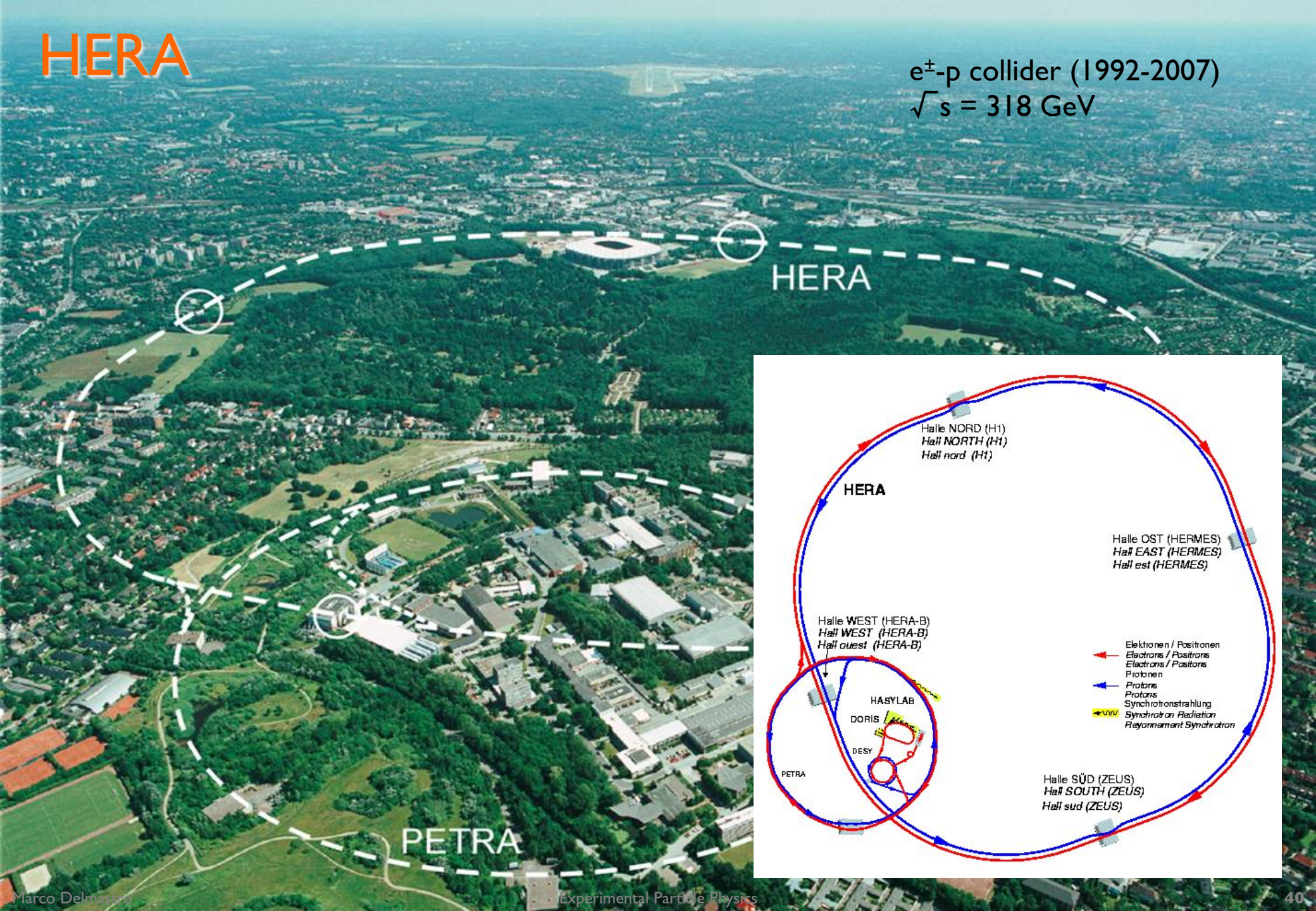
Political Map of the World



802373 (R00350) 4-95

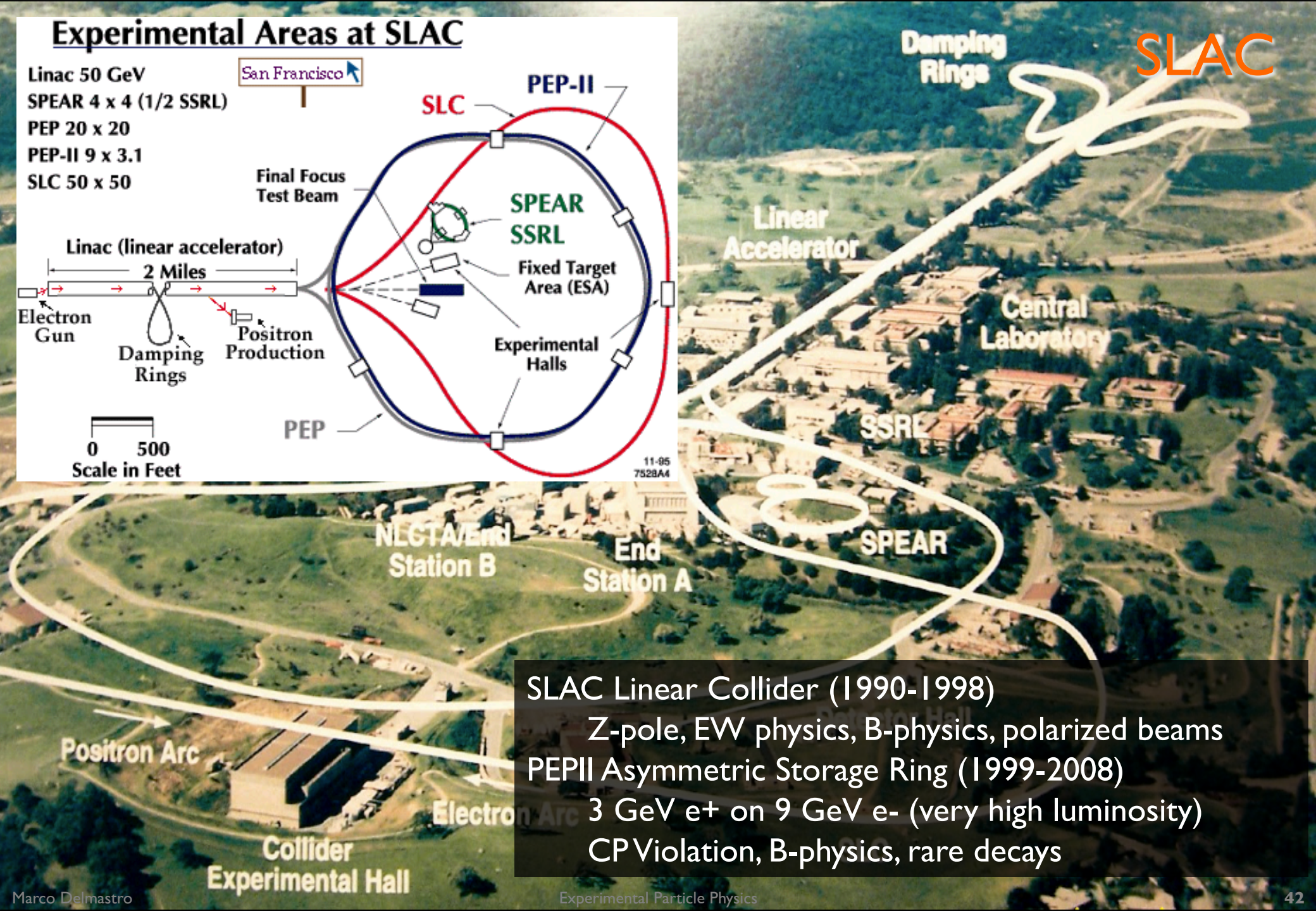
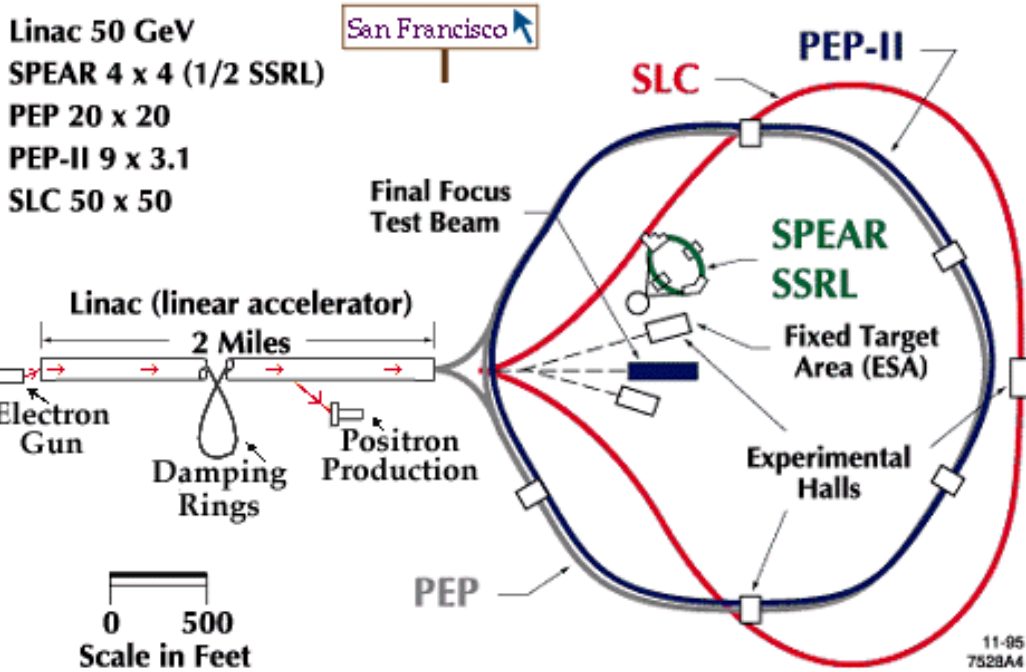
HERA

e^+p collider (1992-2007)
 $\sqrt{s} = 318 \text{ GeV}$



Experimental Areas at SLAC

Linac 50 GeV
 SPEAR 4 x 4 (1/2 SSRL)
 PEP 20 x 20
 PEP-II 9 x 3.1
 SLC 50 x 50



SLAC Linear Collider (1990-1998)
 Z-pole, EW physics, B-physics, polarized beams
 PEP-II Asymmetric Storage Ring (1999-2008)
 3 GeV e⁺ on 9 GeV e⁻ (very high luminosity)
 CP Violation, B-physics, rare decays

RHIC

(PHOBOS)
10:00 o'clock

Jet Target
12:00 o'clock

AnDy
2:00 o'clock

PHENIX
8:00 o'clock

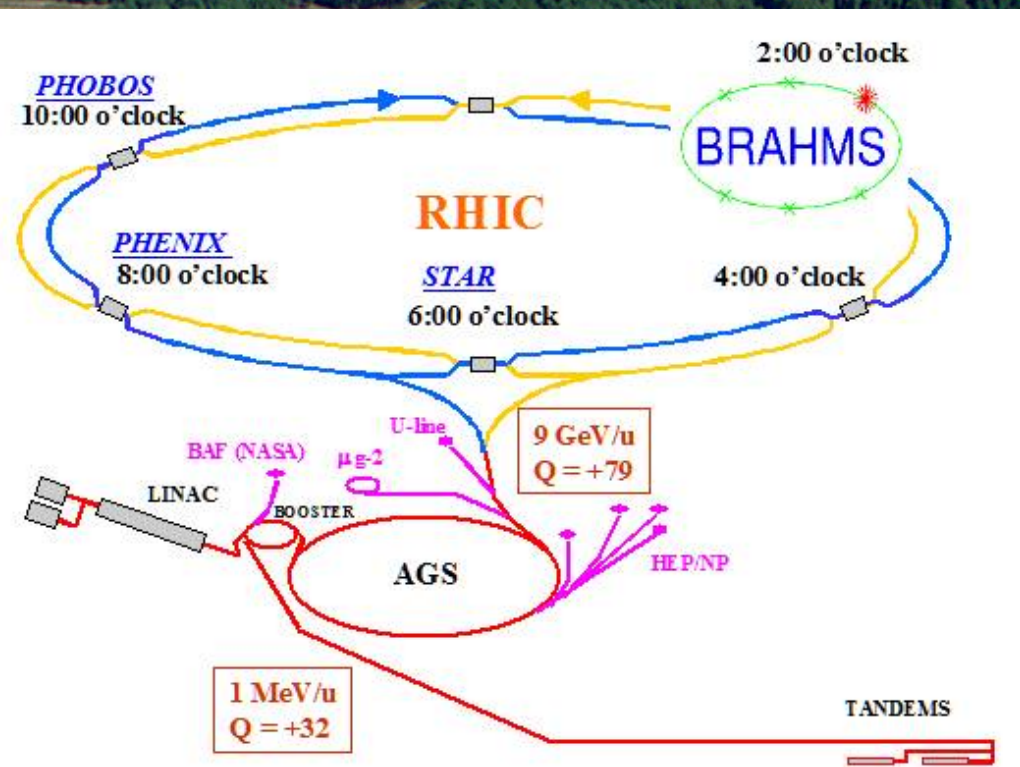
RF
4:00 o'clock

STAR
6:00 o'clock

LINAC
EBIS
Booster

NSRL

AGS



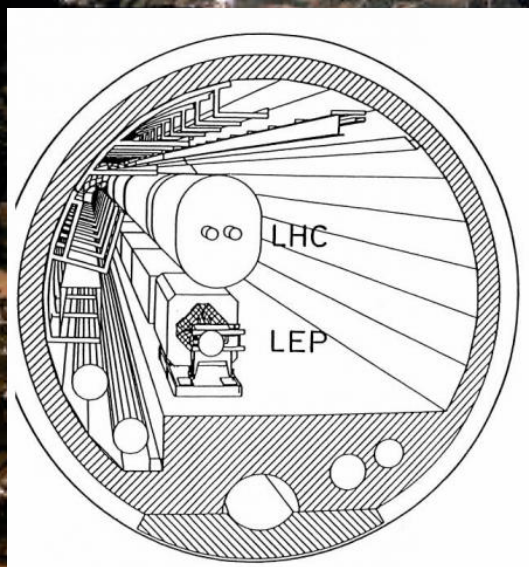
Heavy ions (BNL, 2000-present)

LEP

e^+e^- collider (1998-2000)

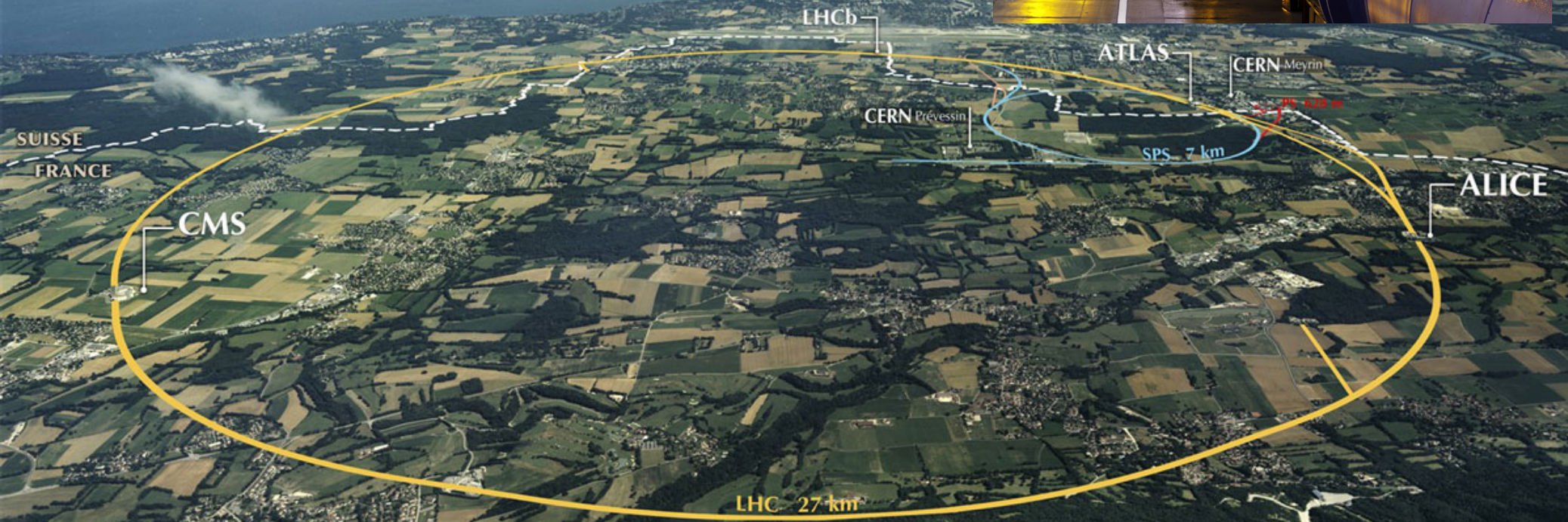
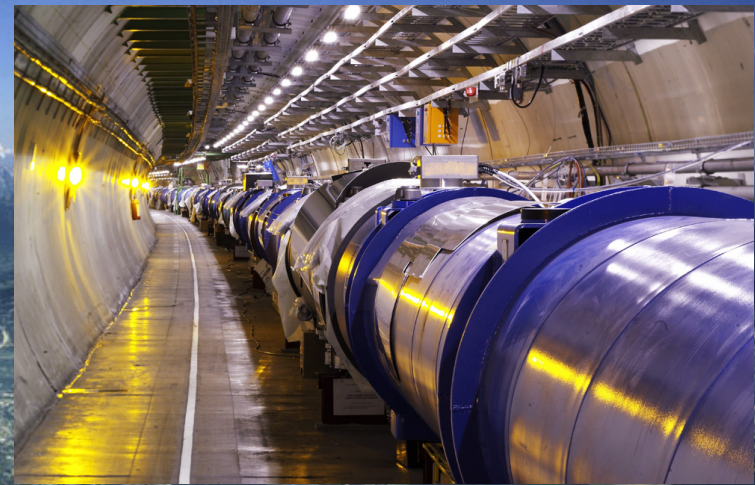
$\sqrt{s} = 91 \text{ GeV}$ (LEP)

$\sqrt{s} \sim 200 \text{ GeV}$ (LEP2)

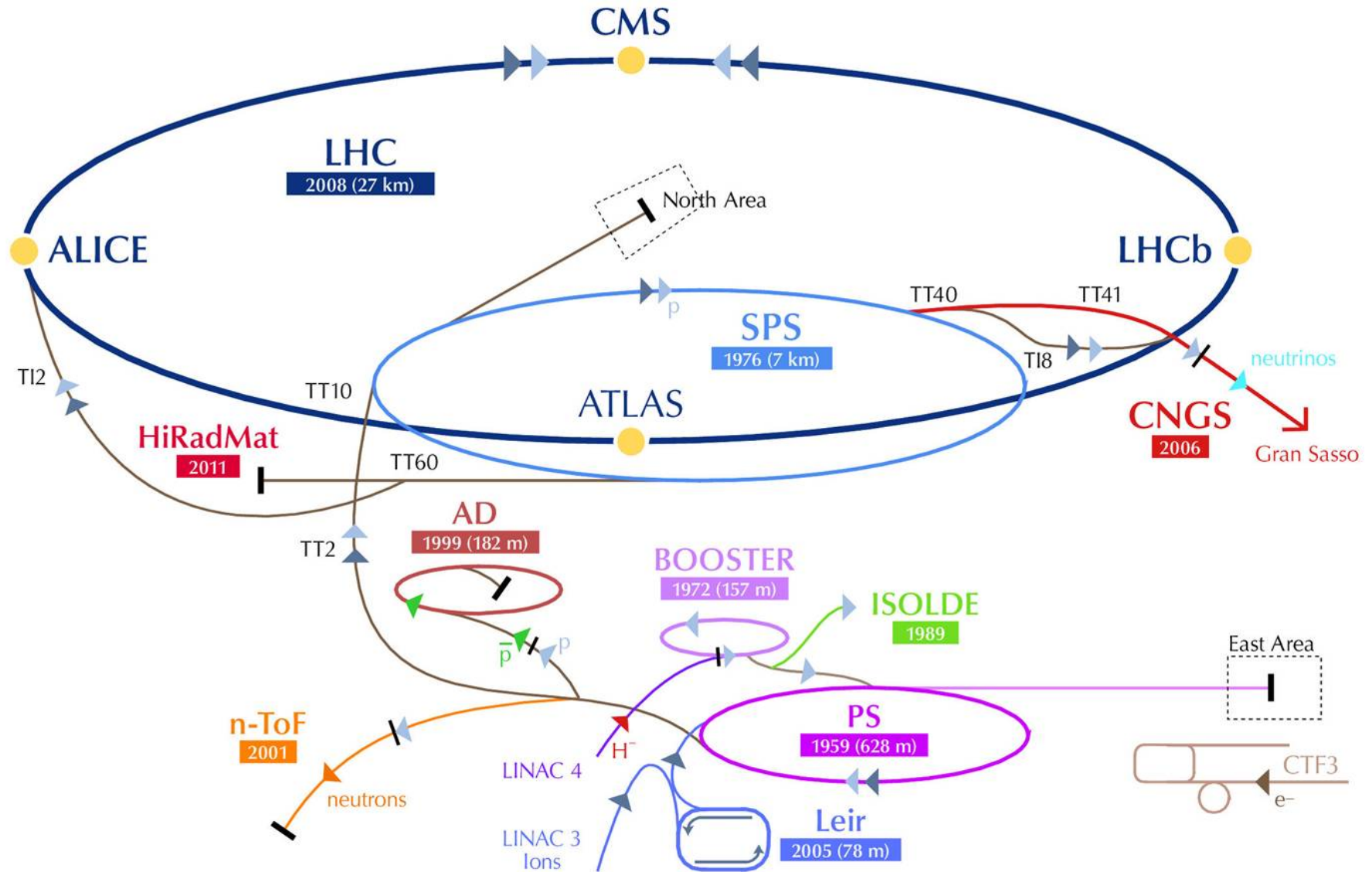


LHC

pp collider (2008-present)
 $\sqrt{s} = 7-14 \text{ GeV}$

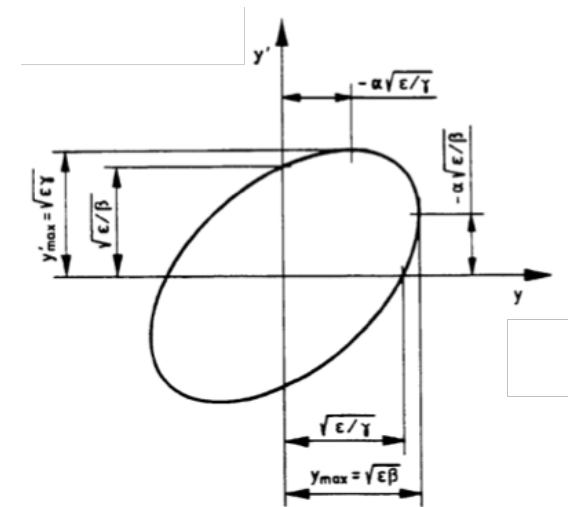
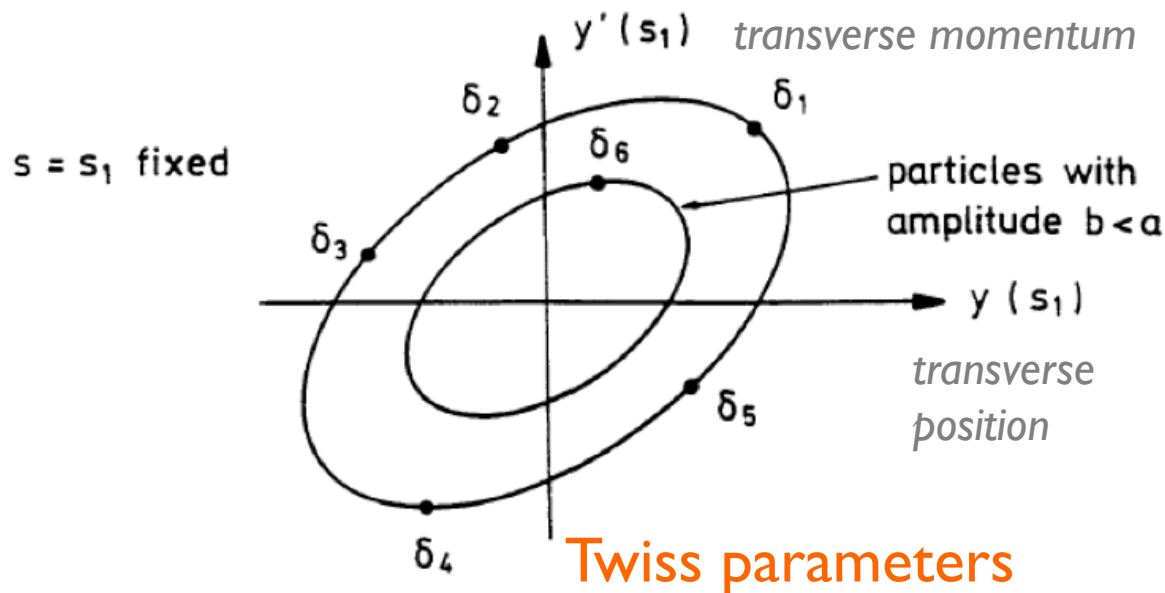


CERN accelerator complex



Beam emittance

- Beam size and distribution of particle momenta evolve during motion in collider ring
- Each particle position in *phase space* sits in ellipse of **constant area**
 - ✓ From beam motion equation and Liouville theorem...



$$\gamma y^2 + 2\alpha yy' + \beta y'^2 = \text{const} = \epsilon$$

Beam dimensions

position along beam directions

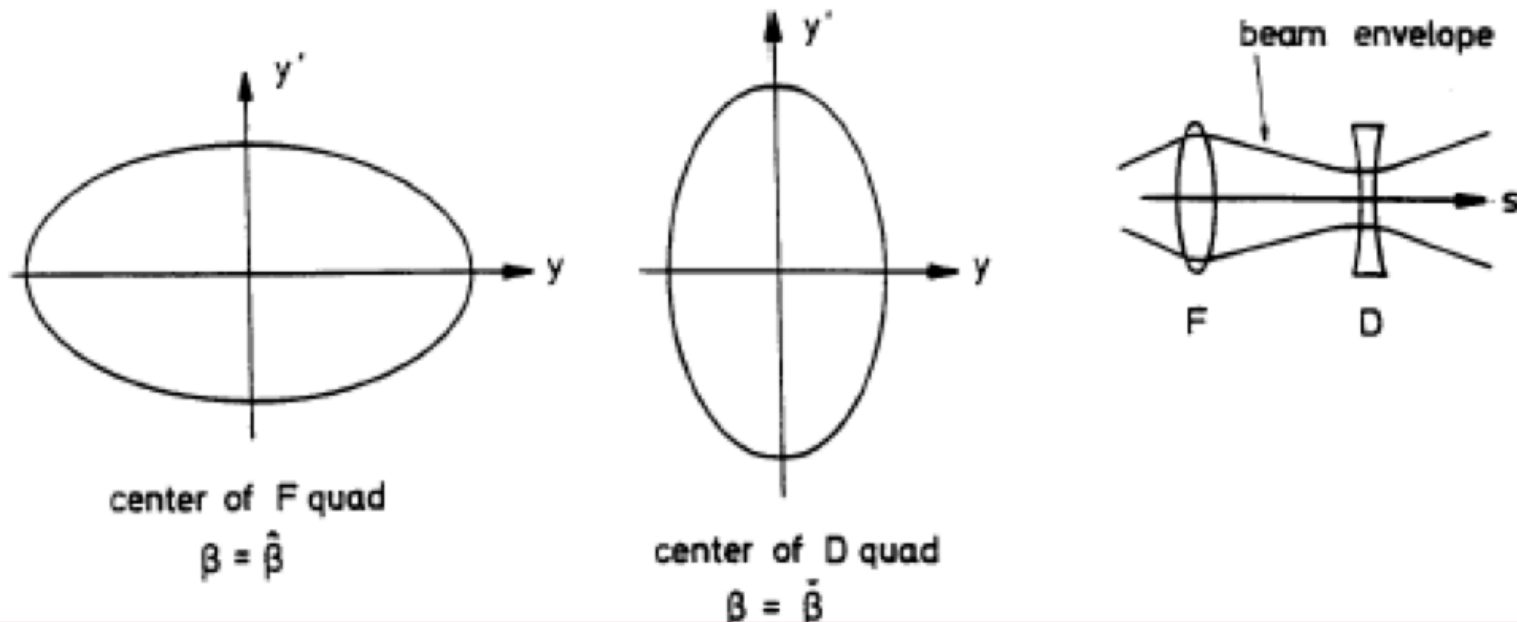
Gaussian width (RMS)
in transverse direction

$$\sigma(z) = \sqrt{\underbrace{\epsilon}_{\text{emittance}} \underbrace{\beta(z)}_{\text{Twiss parameter (amplitude function)}}}$$

emittance Twiss parameter (amplitude function)

“Beta star” at interaction point, often adjusted to be minimum

$$\beta^* = \beta(z_0)$$



Improvements to luminosity?

increase number
of bunches?

increase number particle
per bunch?

$$\mathcal{L} = \frac{1}{4\pi} \frac{f k N_1 N_2}{\sqrt{\epsilon_x \beta_x^* \epsilon_y \beta_y^*}}$$

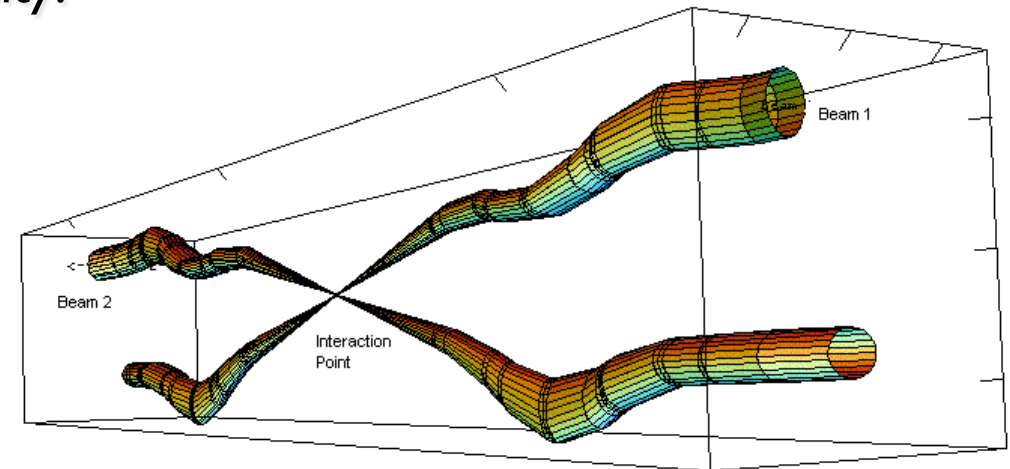
decrease emittance!

decrease beta star!

Crossing angle

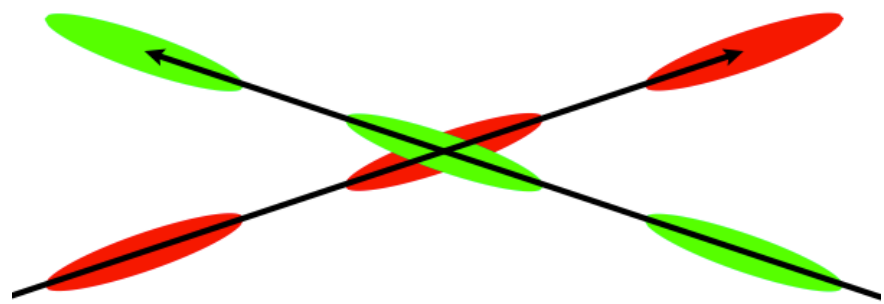
- To avoid parasitic encounters, beams with close bunches often cross at an angle
 - ✓ LHC beams cross at an angle of 300 microradian (bunch spacing 25 ns)
- Crossing angle has an impact on luminosity!

$$\frac{L}{L_0} = \frac{1}{\sqrt{1 + \left(\frac{\sigma_z}{\sigma_x} \tan \frac{\theta_c}{2}\right)^2}}$$

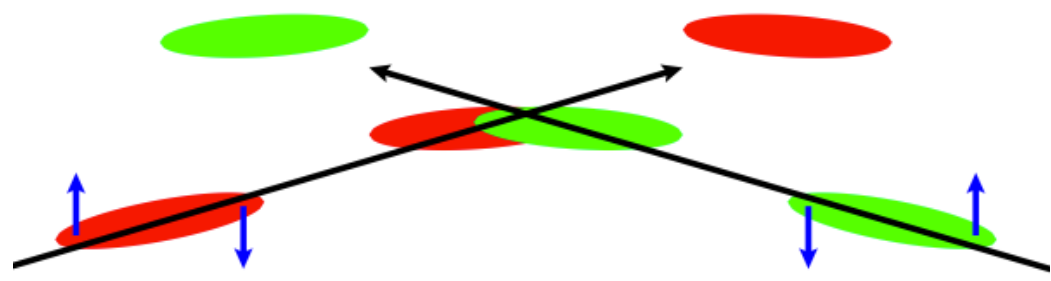


Relative beam sizes around IP1 (Atlas) in collision

with crossing angle

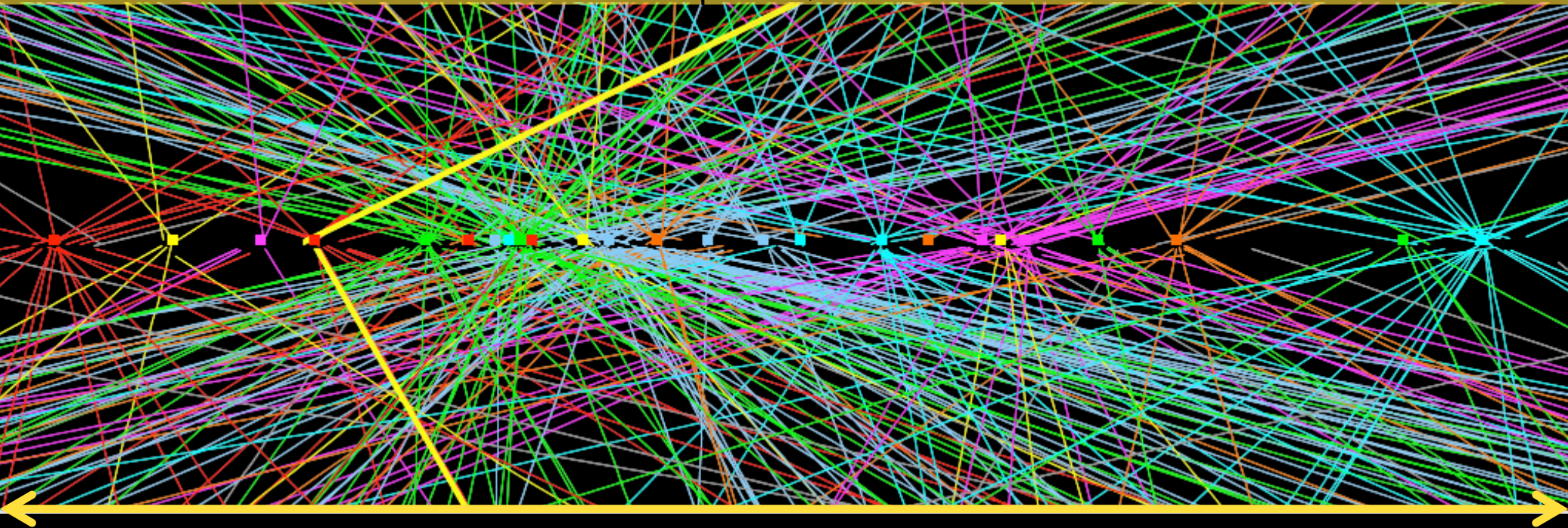


“crab” crossing



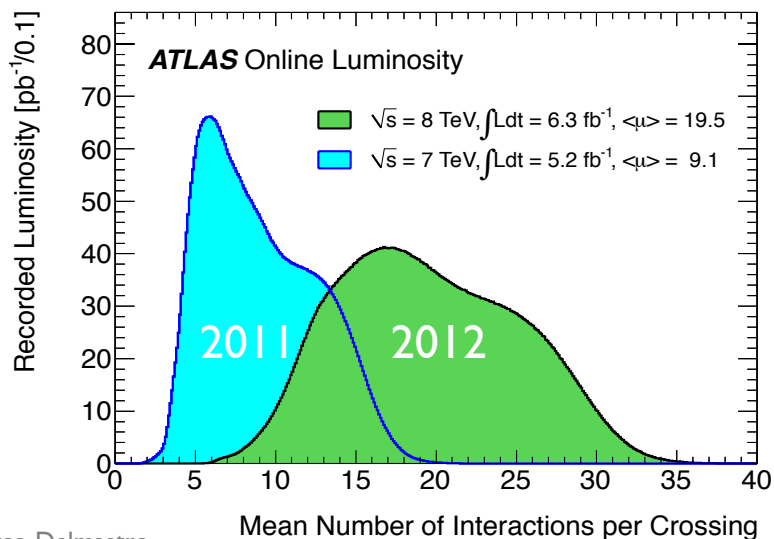
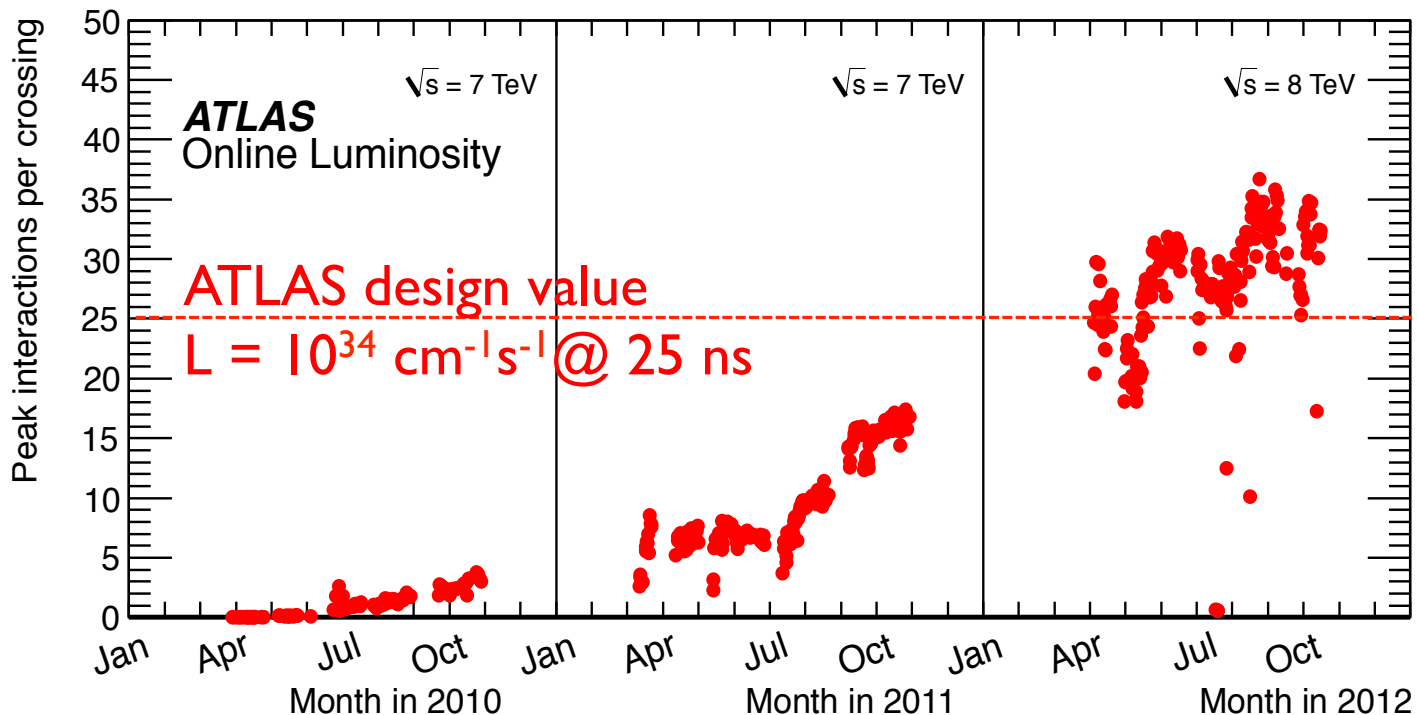
$Z \rightarrow \mu\mu$ event with 25 reconstructed vertices

April 15th, 2012



~5 cm

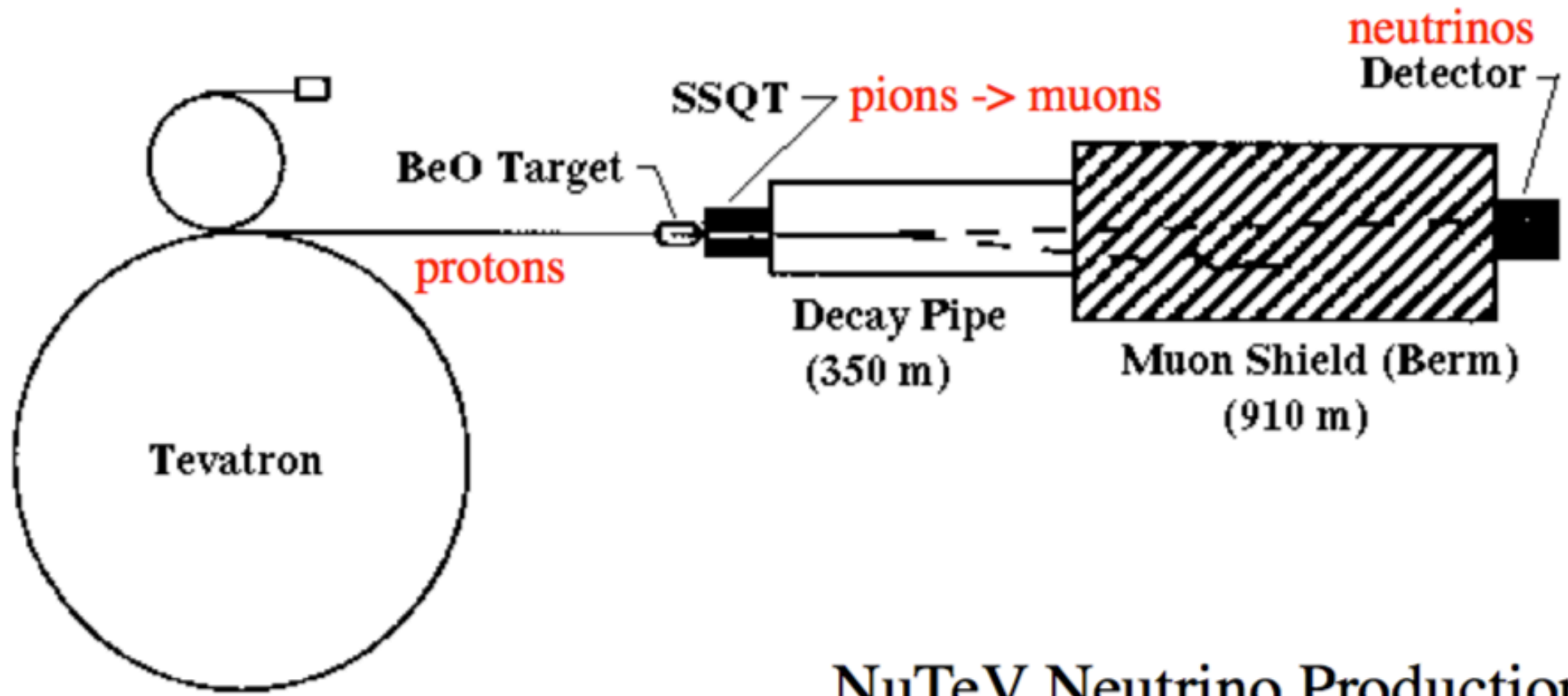
Pileup!



Running with 50 ns bunch spacing (instead of 25 ns)
 → double pile-up for same luminosity!

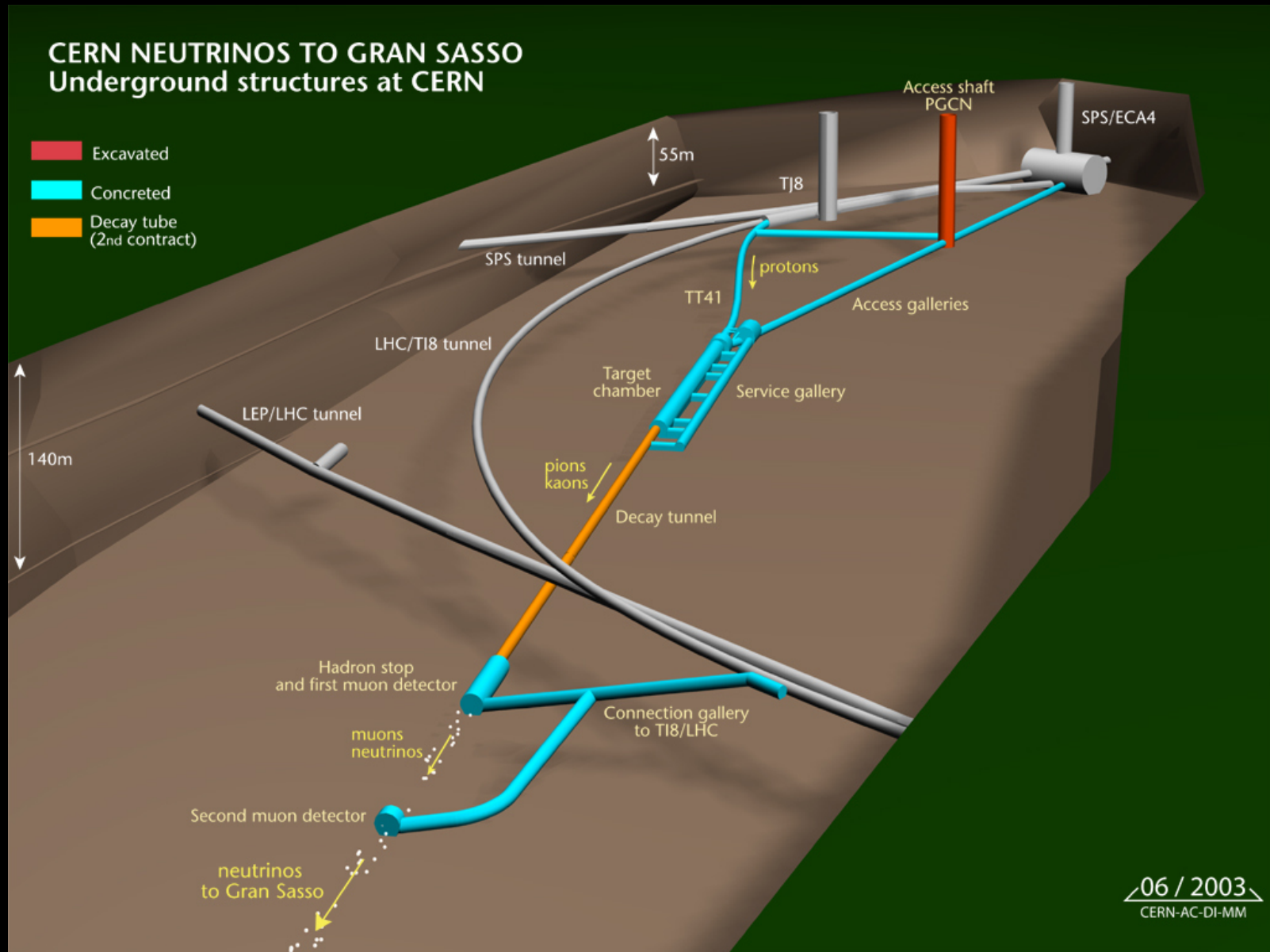
- Pileup-robust fast triggers
- Pileup-optimized reconstruction and identification
- Precise modeling of in-time/out-of-time pile-up in MC

Production of secondary beams

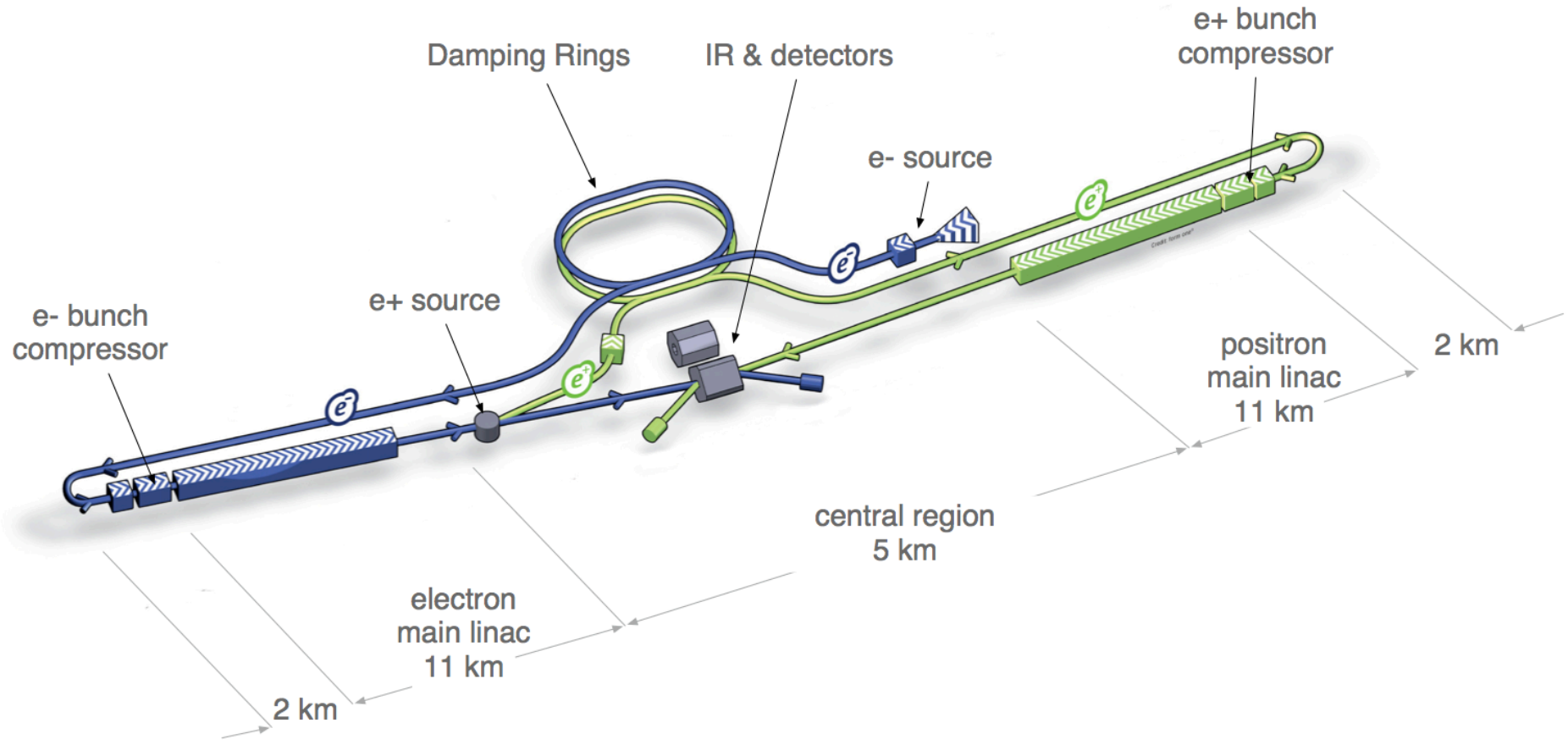


NuTeV Neutrino Production

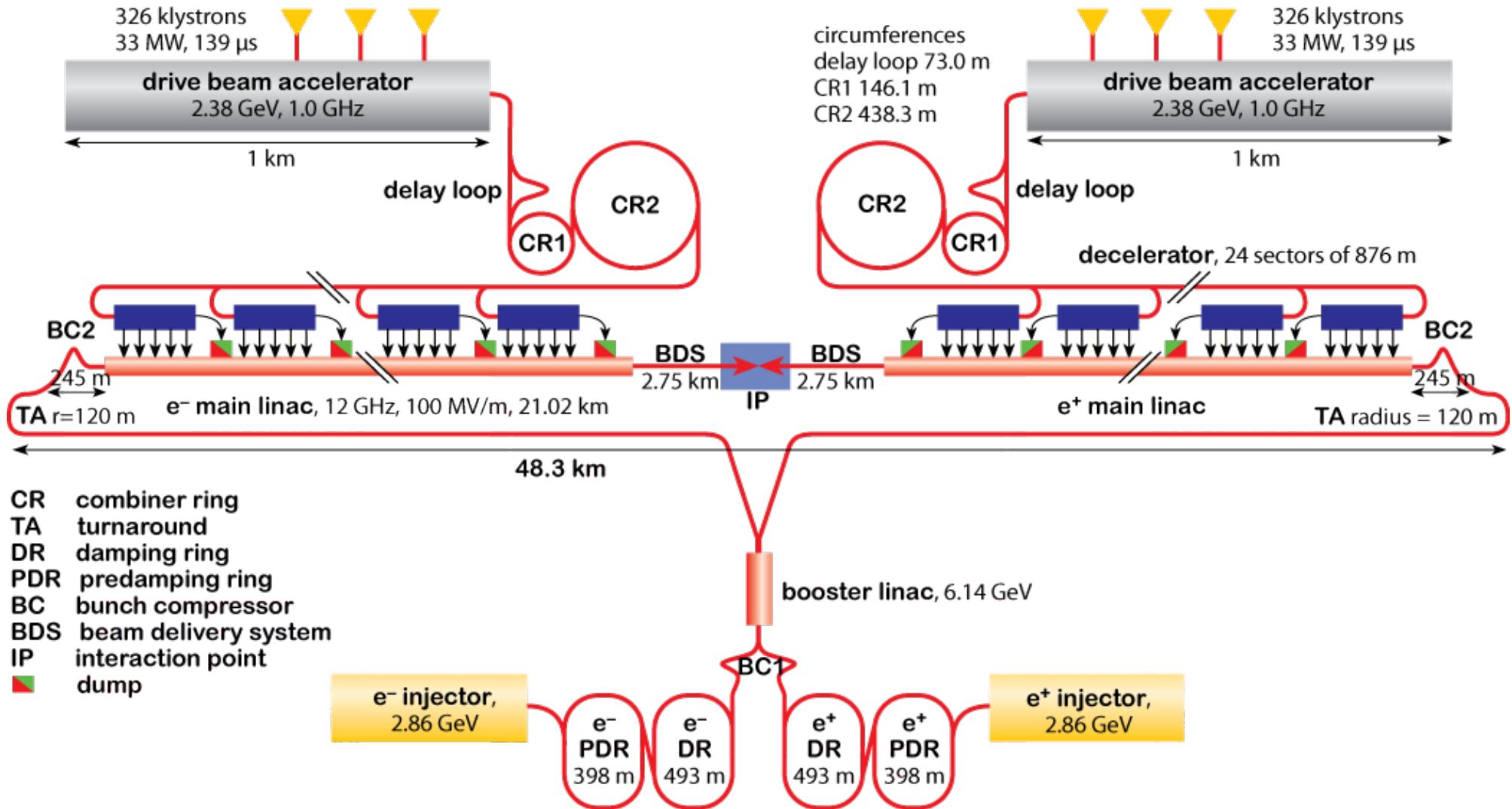
Production of secondary beams



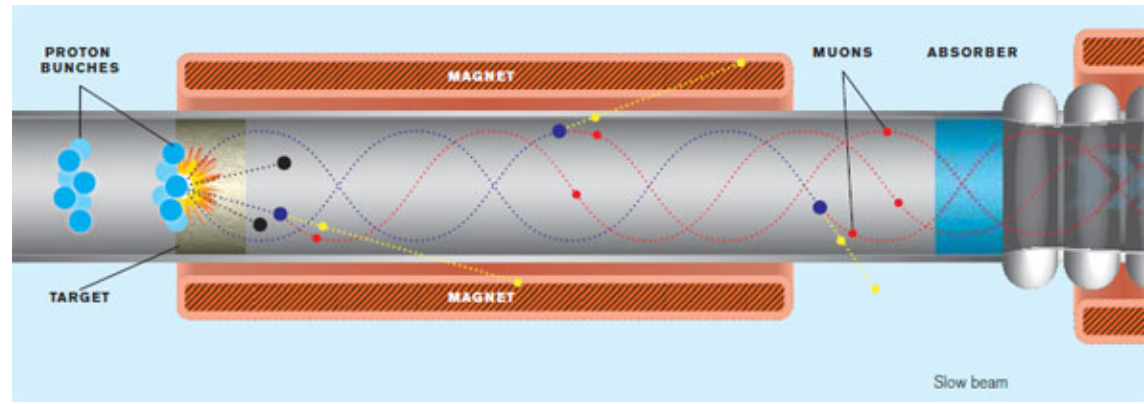
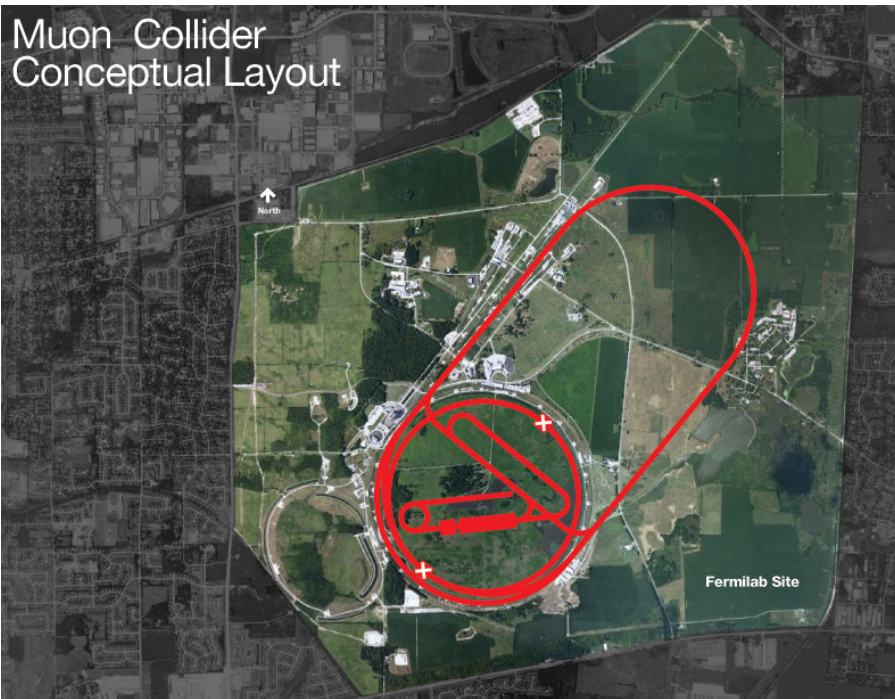
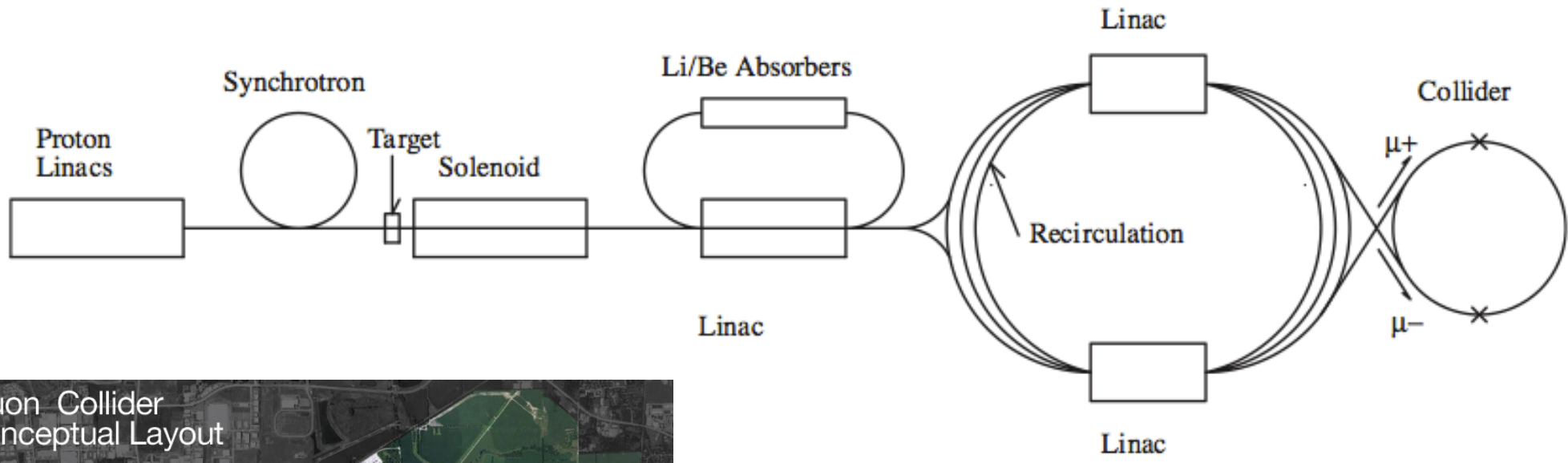
Future colliders? ILC



Future colliders? CLIC



Future colliders? Muon collider





Muon collider
d=2km



ILC
l=30km



CLIC
l=50km



LHC
d=8.4km

