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

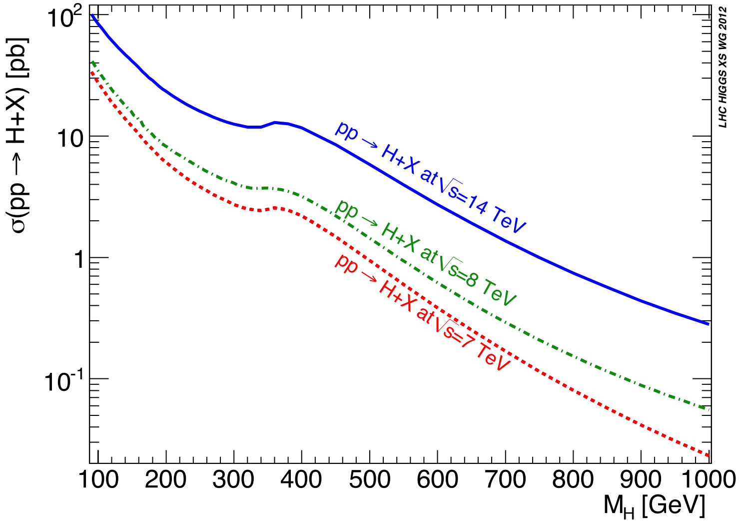
Luminosity

Number of events
in unit of time

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

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

? $10^{34}\ \mathrm{cm}^{-2}\, \mathrm{s}^{-1}$ σ(pp → H+X) ~ 20 pb



In a collider ring…

$$\mathcal{L} = \frac{1}{4\pi} \frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

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

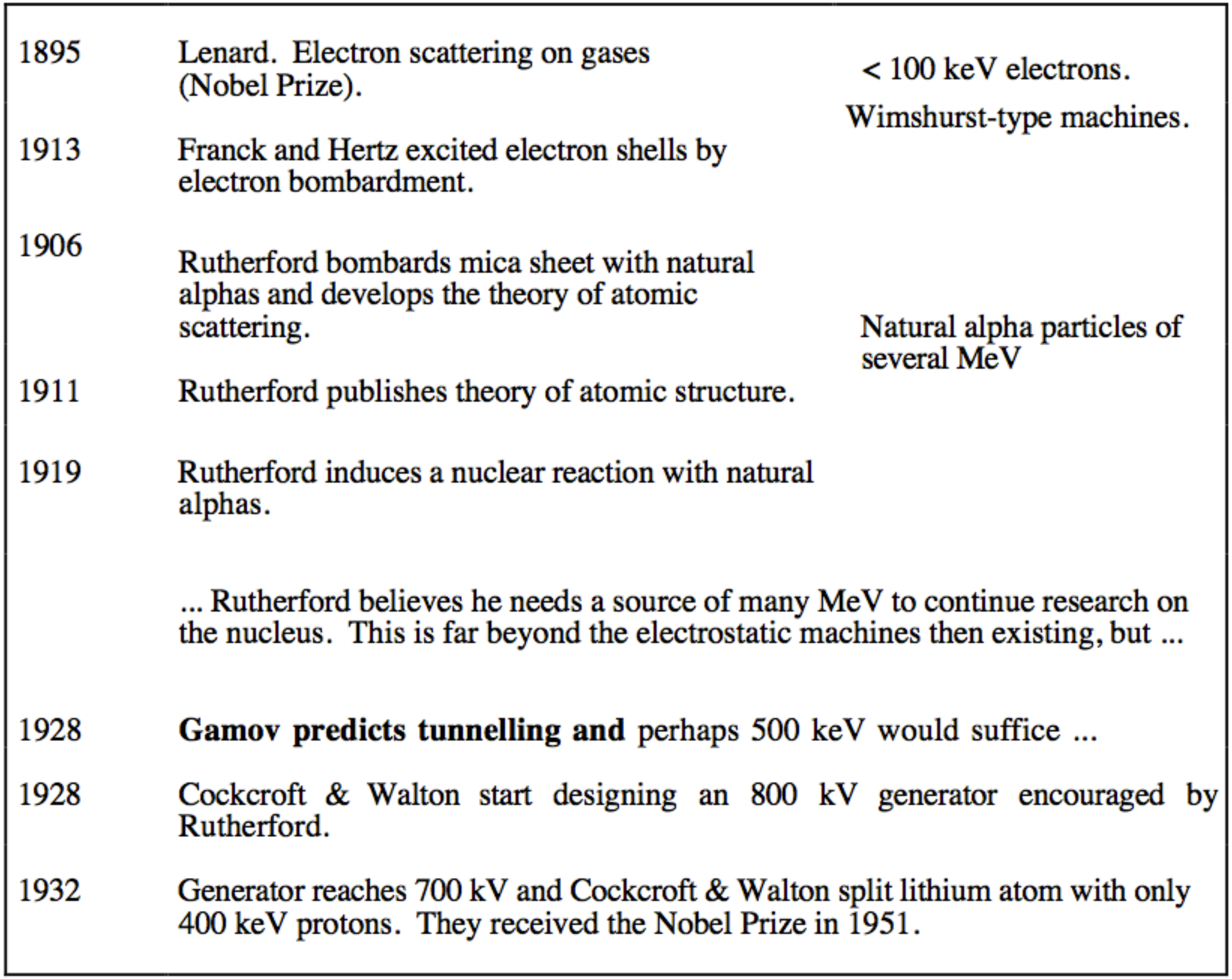
$$\vec{F}_L = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

time variation of
kinetic energy

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

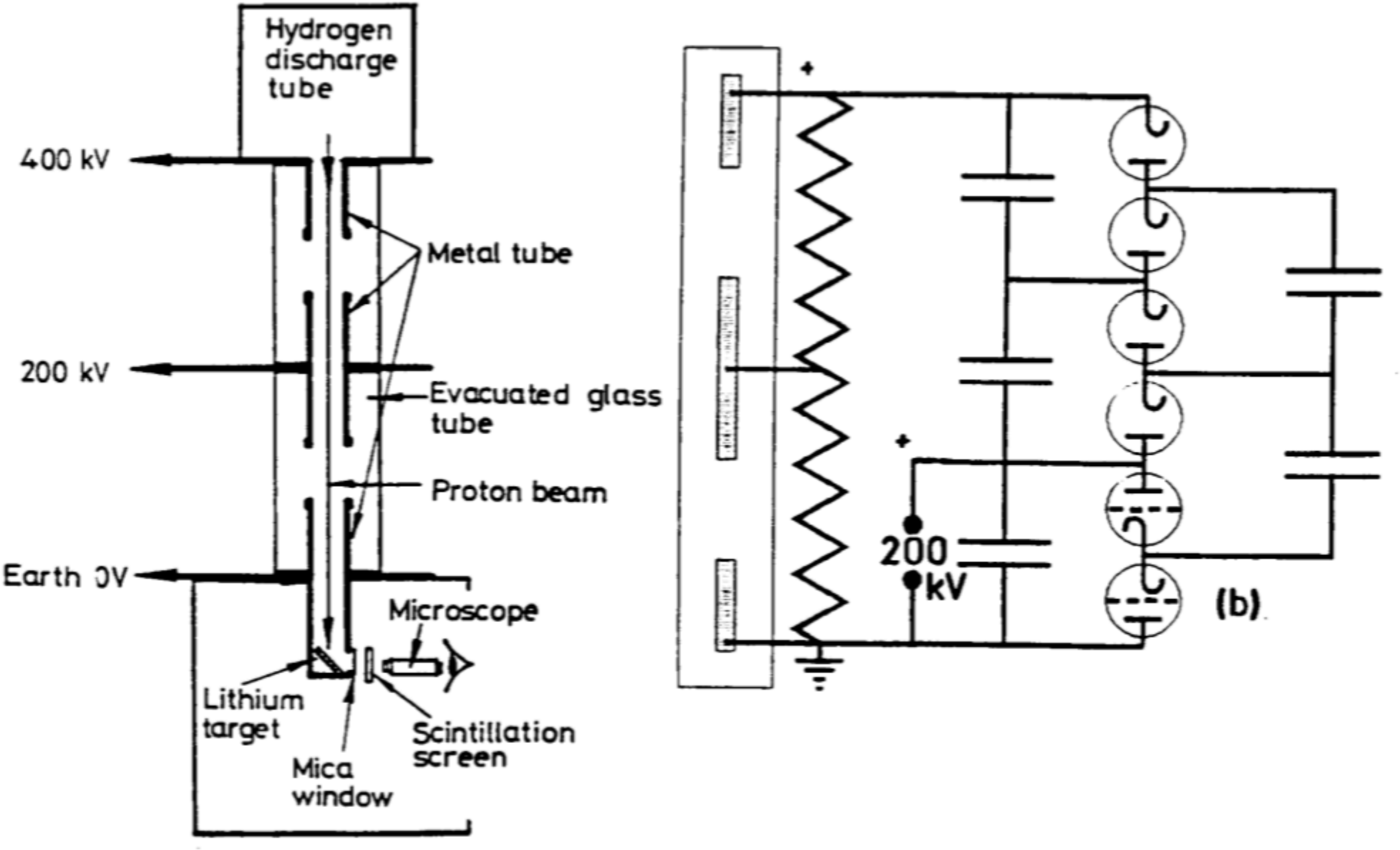
- Only longitudinal component of electrical field matters
- Time-varying electrical field to change energy
- (Static) magnetic field cannot change particle momentum…
- … but can be used to bend its trajectory!

A brief history of particle accelerators – part 1



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.	

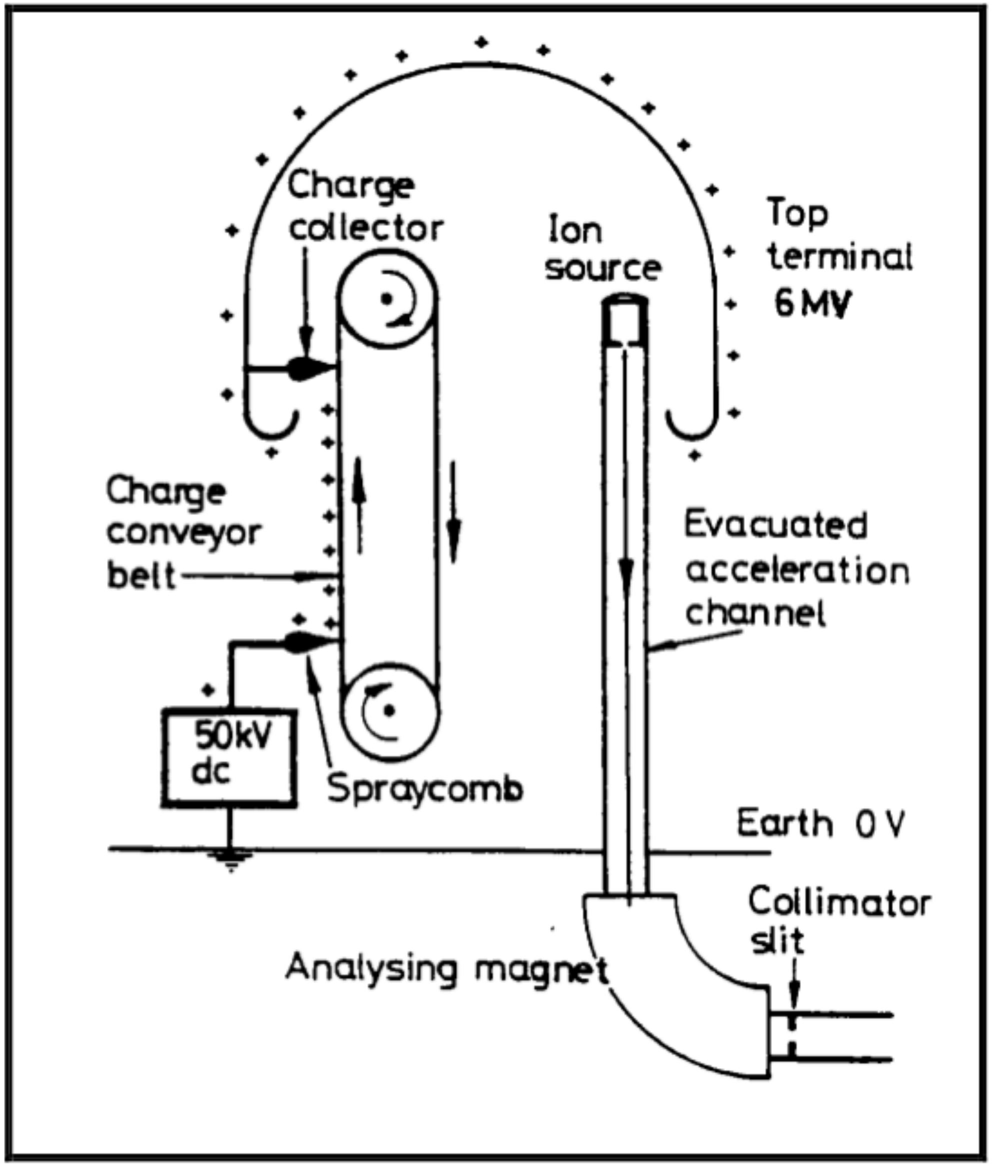
Cockcroft and Walton's apparatus



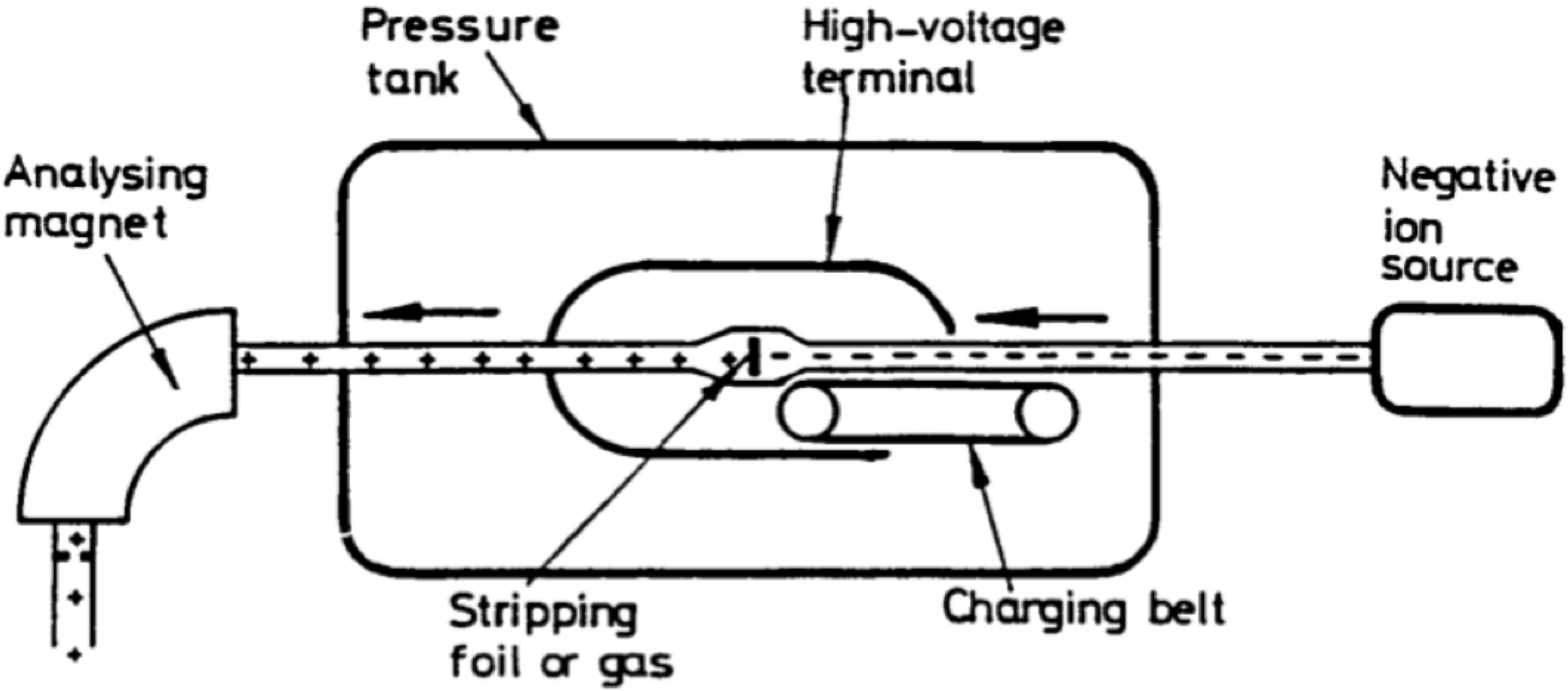
(a) Accelerating column

(b) DC generator

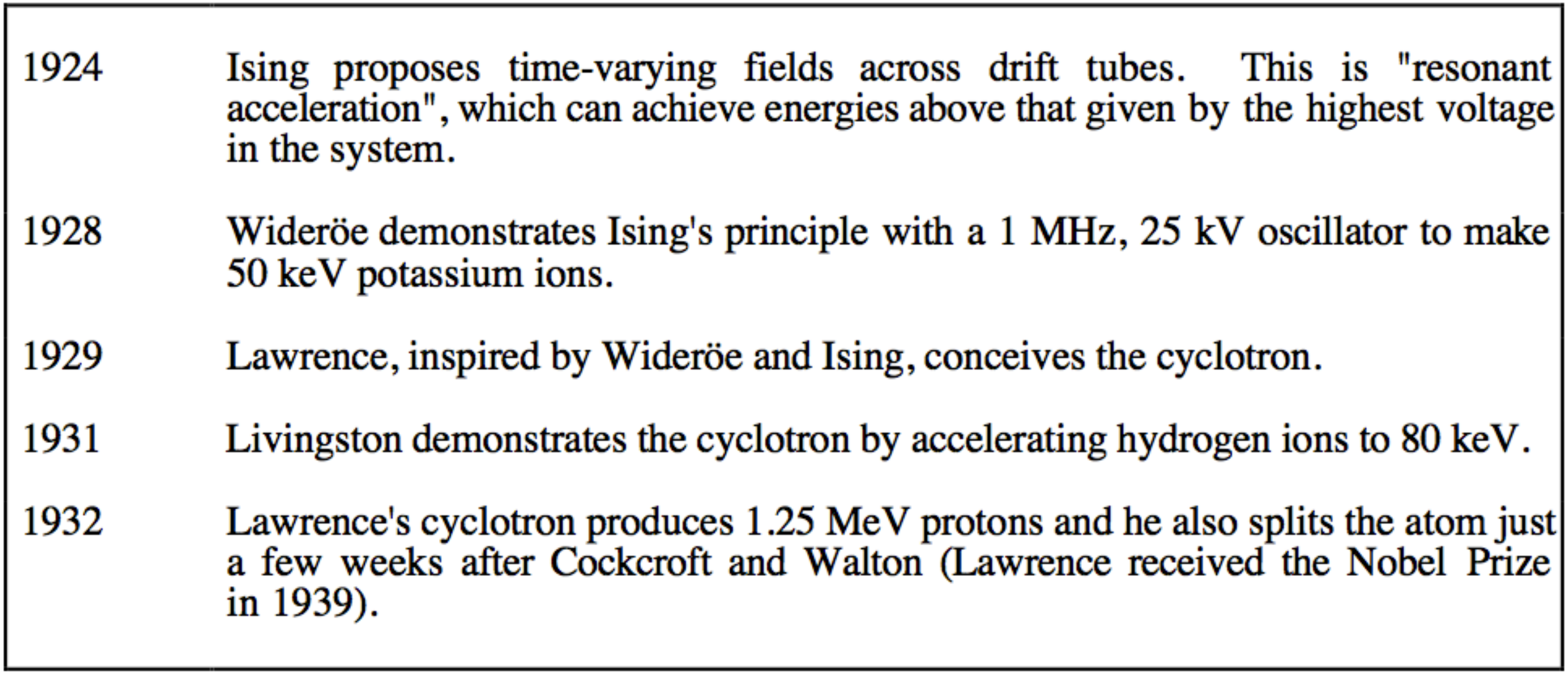
Van de Graaff electrostatic generator



Two-stage Tandem accelerator

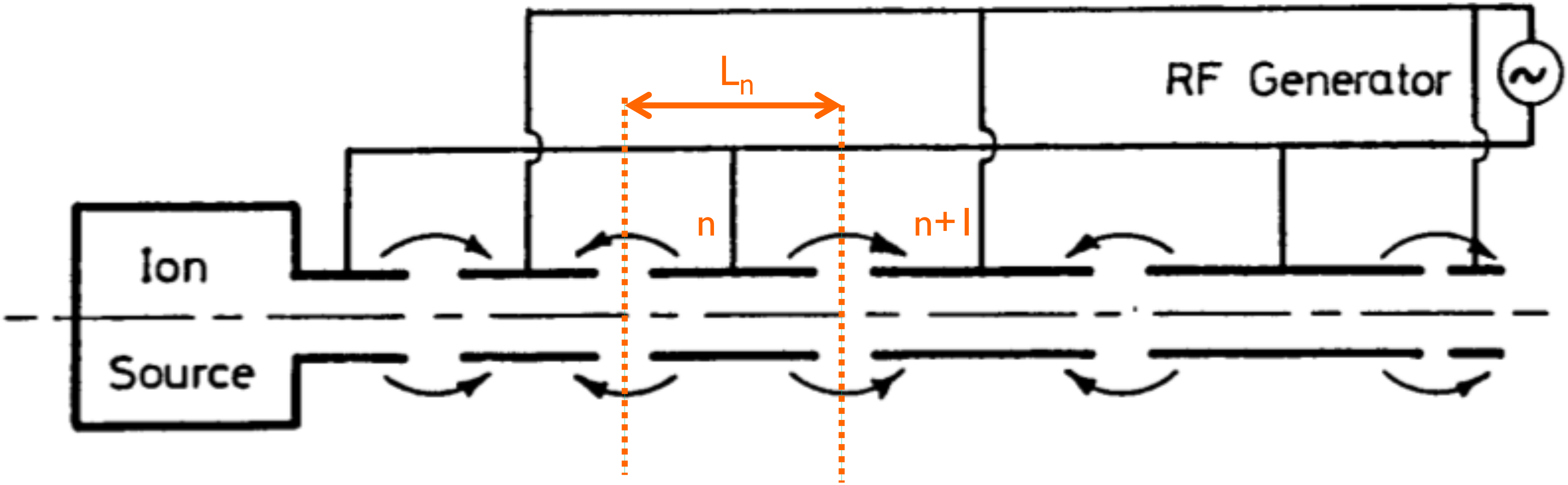


A brief history of particle accelerators – part 2

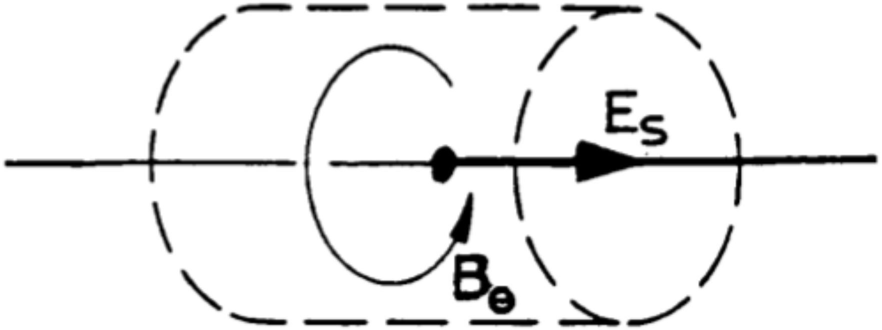


1924	Ising proposes time-varying fields across drift tubes. This is "resonant acceleration", which can achieve energies above that given by the highest voltage in the system.
1928	Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions.
1929	Lawrence, inspired 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)



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



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

LINAC lenght

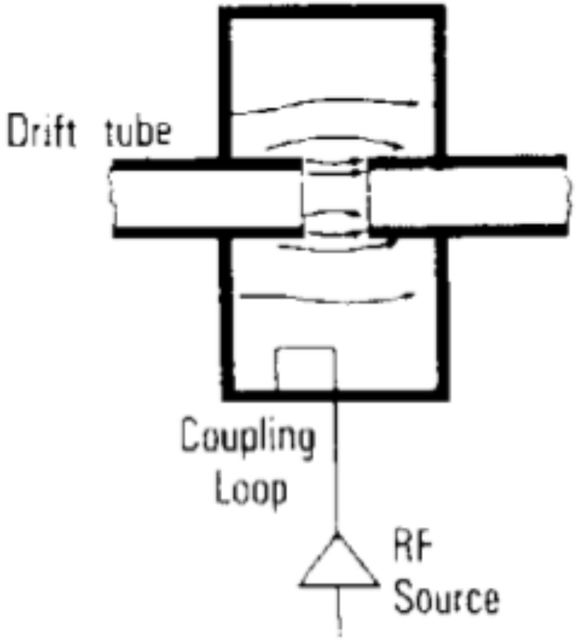
Total LINAC length

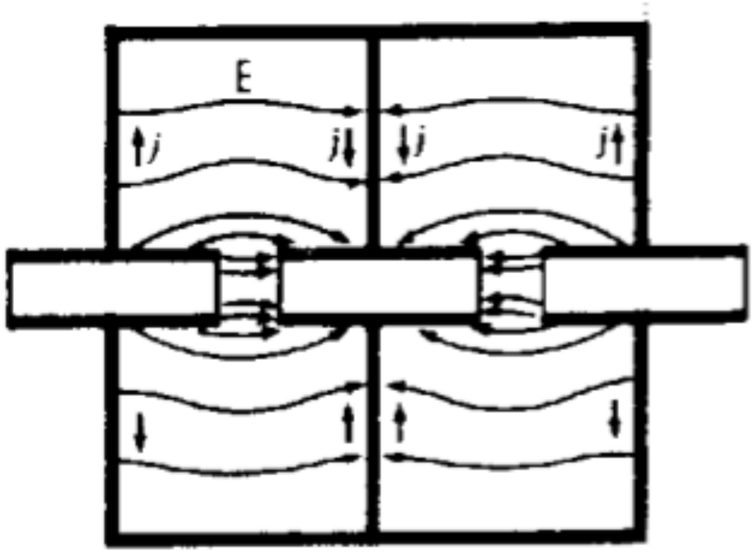
$$L = \frac{k}{\underbrace{\Delta E}_{\text{energy gain per gap}}} \sqrt{\frac{\overbrace{E^3}^{\text{final particle energy}}}{\underbrace{A}_{\text{ion atomic number}} mc^2}}\,\frac{\lambda}{2}$$

- Example: proton (A=1) with E = 1 MeV ($\beta = 4.6\ 10^{-2}$) 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!

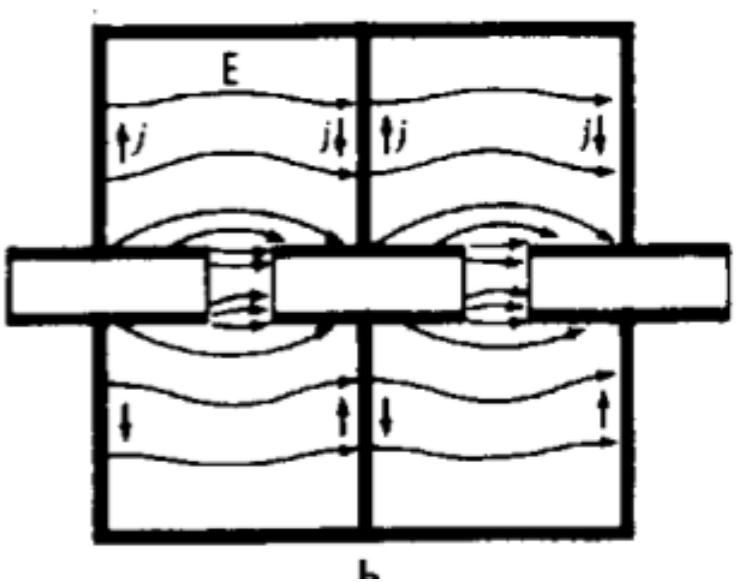
RF cavities

- 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 eliminated



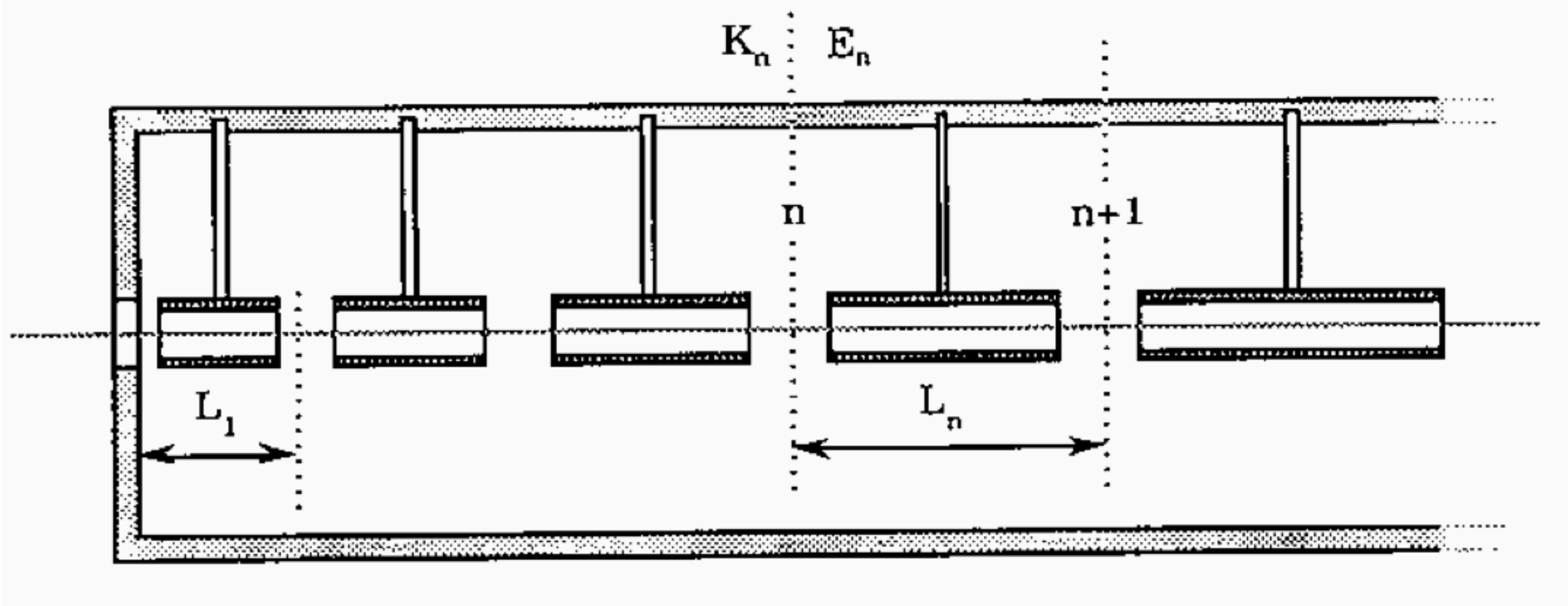


k=1



k=2

Alvarez structure



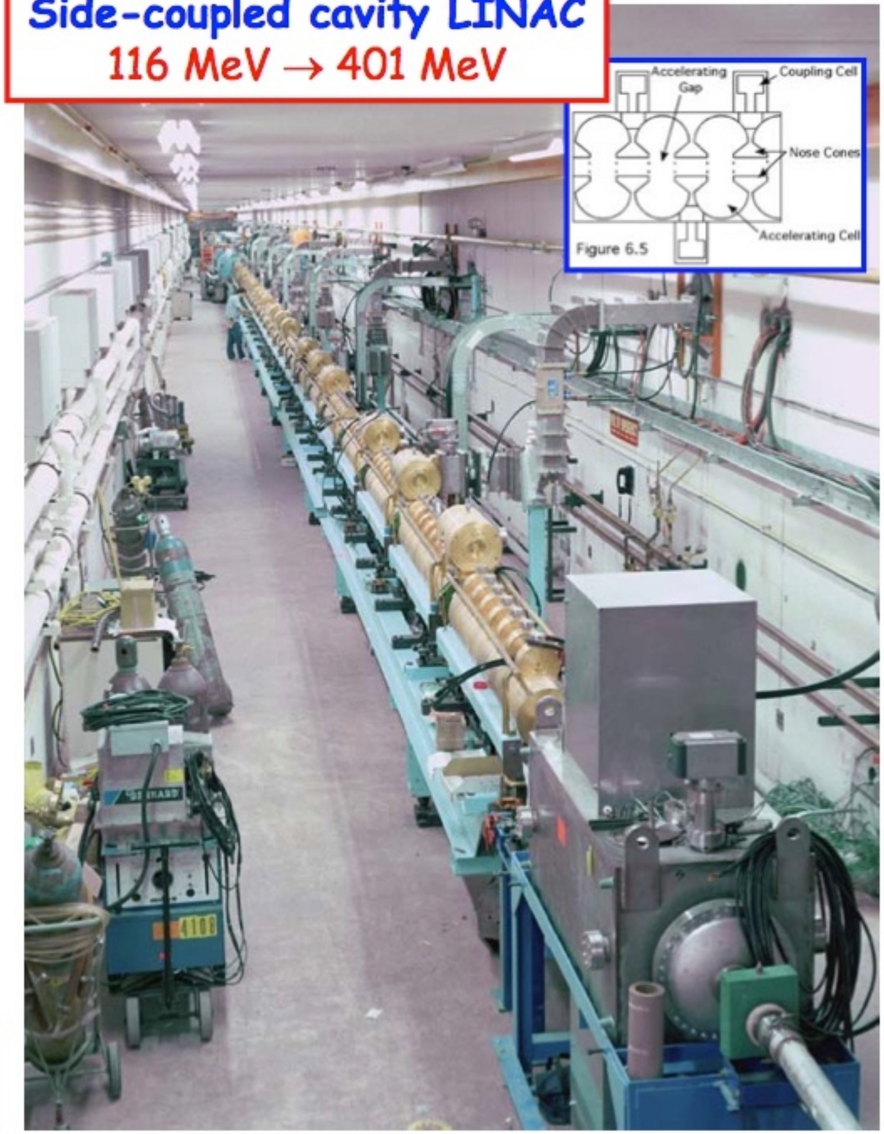
$k = 2$, ν_{RF} ~100 MHz , $\lambda < L$

protons β ~ 1 for E ~ 10 GeV electrons β ~ 1 for E ~ 10 MeV

already at those energies v~c → drift tube length can stay constant!

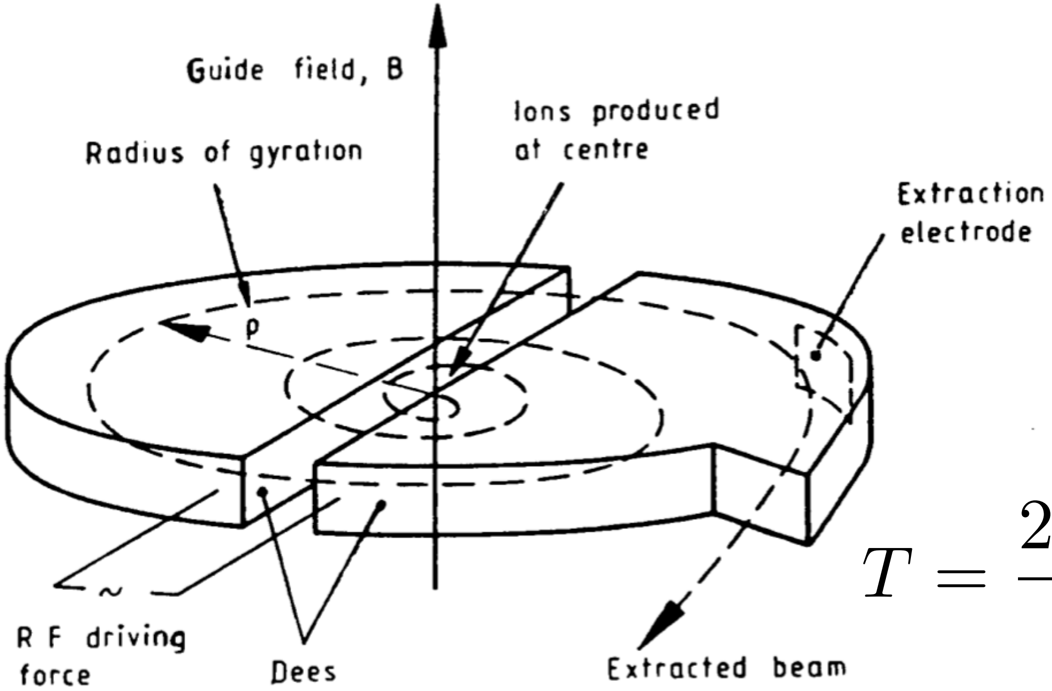
Example: Fermilab LINAC

Drift tube (Alvarez) LINAC
750 keV → 116 MeV



Side-coupled cavity LINAC
116 MeV → 401 MeV

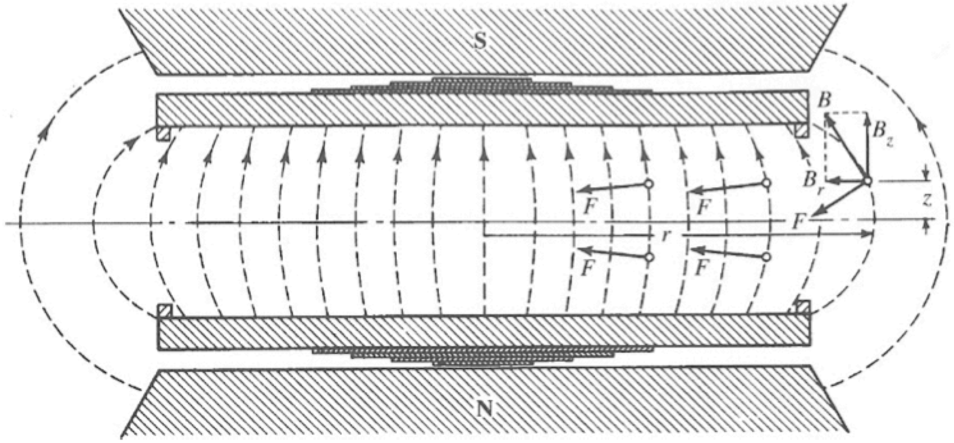
(Syncro) Cyclotron



$$p = m\gamma\beta$$

$$p = eBR$$

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



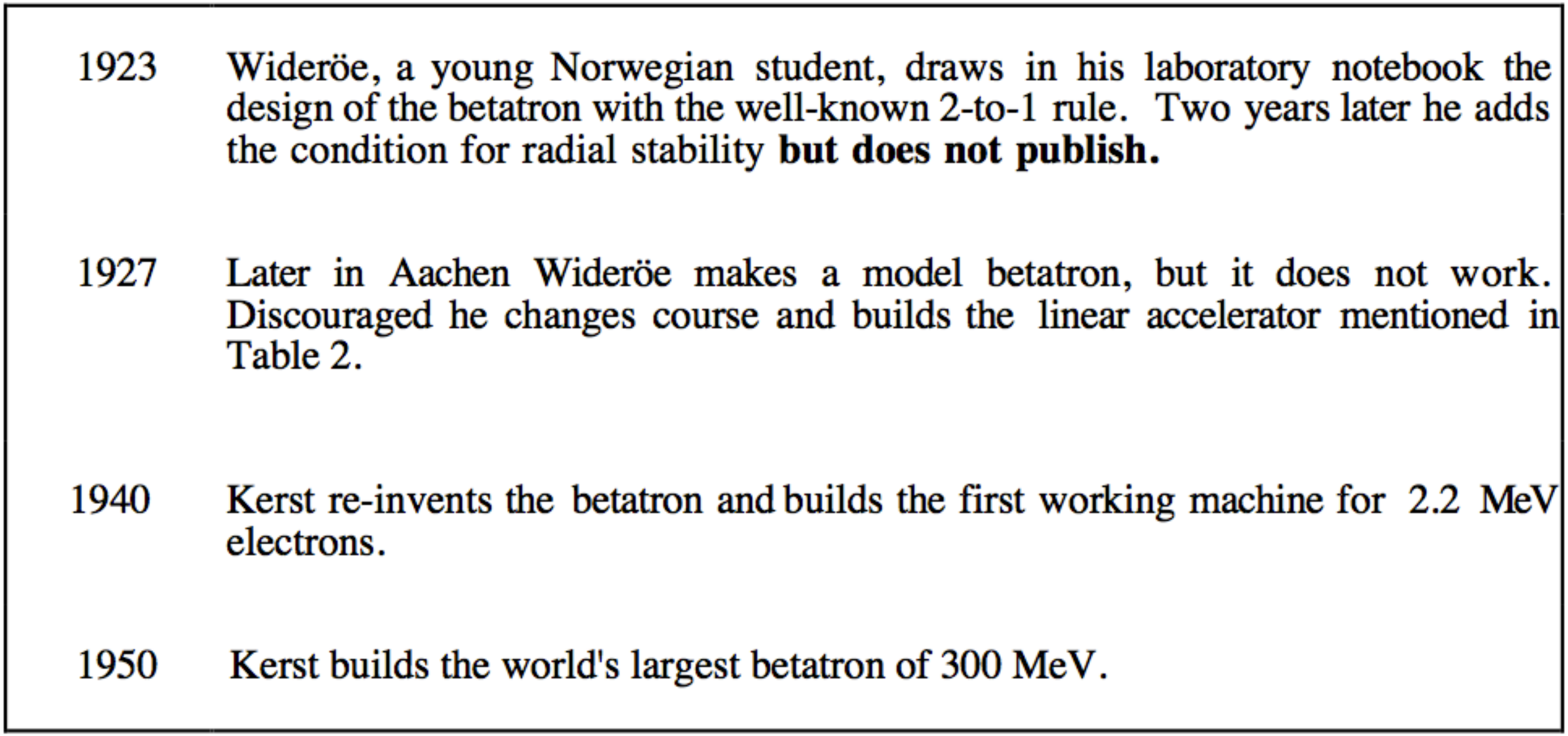
for relativistic particle cyclotron frequency should be adjusted to speed/emergy (syncro-cyclotron)

weak focusing

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

A brief history of particle accelerators – part 3

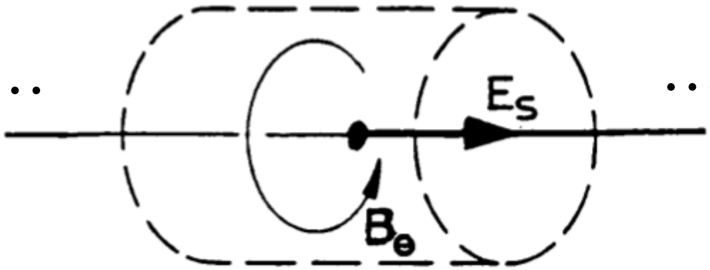
(or as varying magnetic fields could also be used to accelerate particles)



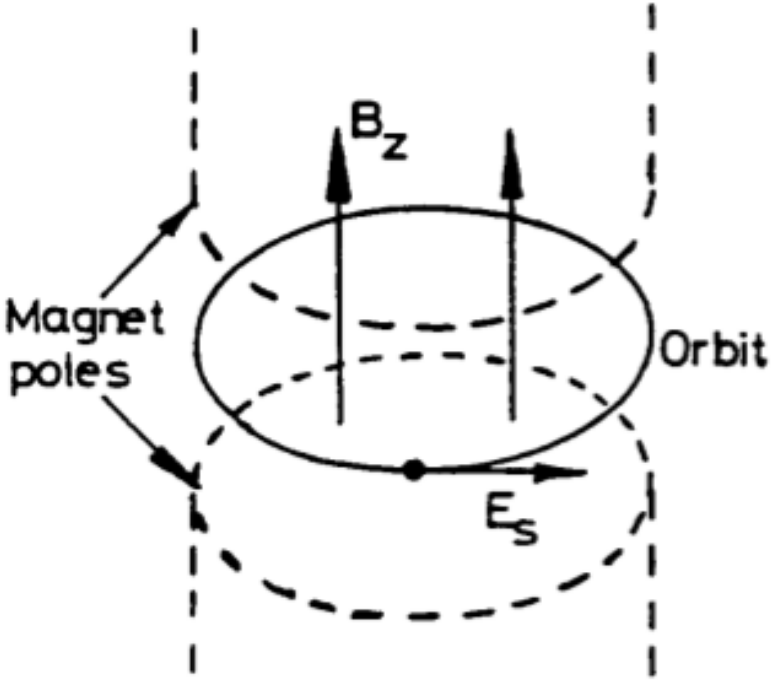
1923	Wideröe, a young Norwegian student, draws in his laboratory notebook the design of the betatron with the well-known 2-to-1 rule. Two years later he adds the condition for radial stability **but does not publish.**
1927	Later in Aachen Wideröe makes a model betatron, but it does not work. Discouraged 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

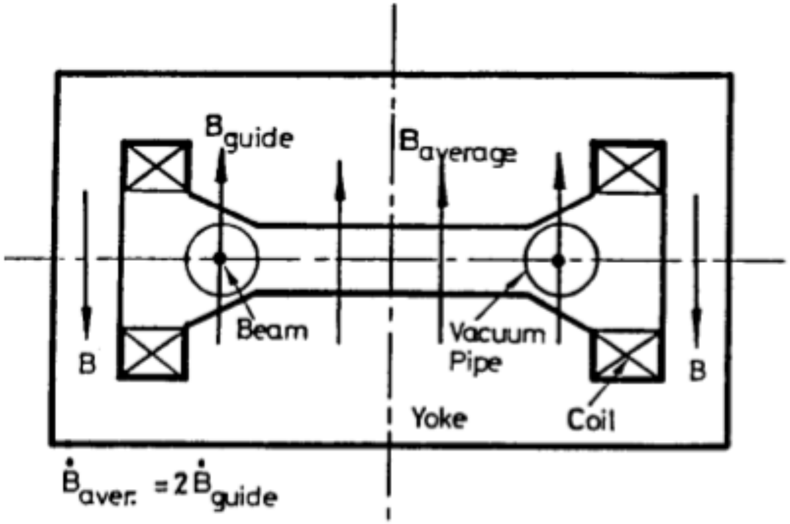
from…

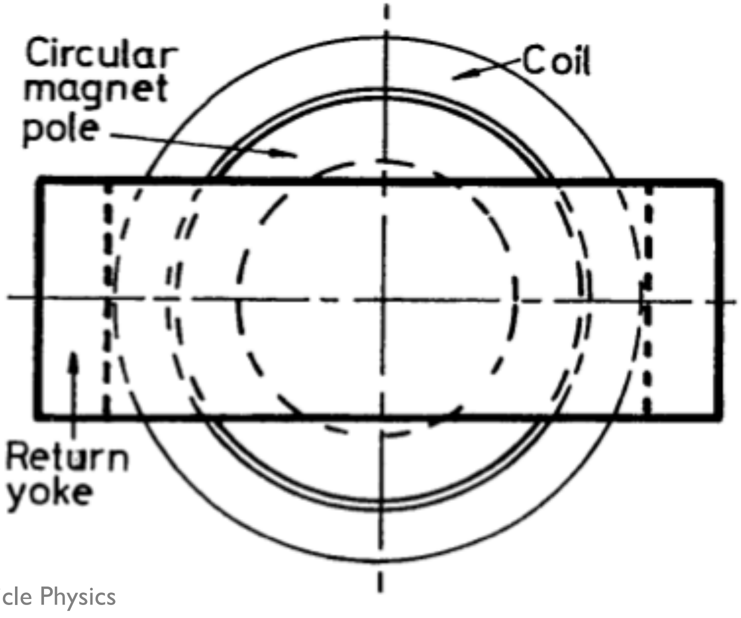


… to …



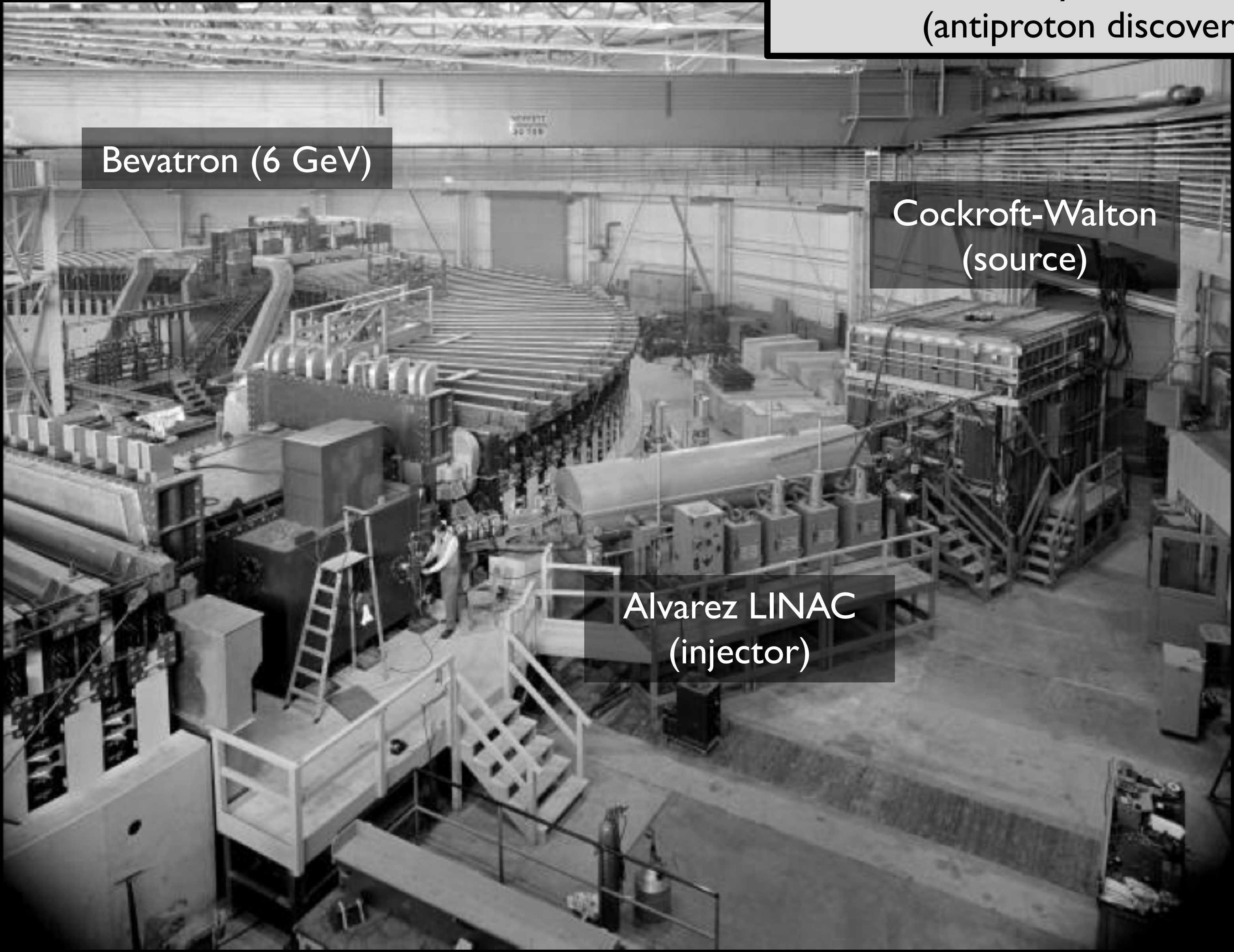
- Trick is to arrange magnetic field increase in vicinity of beam to correspond to increase of particle energy
  - ✓ beam stays on the same orbit (“2-to-1 rule”)
- Betatrons insensitive to relativistic effects
  - ✓ ideal for accelerating electrons





Accelerators work together!

Lawrence Berkeley National Laboratory
(antiproton discovery)



Bevatron (6 GeV)

Cockroft-Walton
(source)

Alvarez LINAC
(injector)

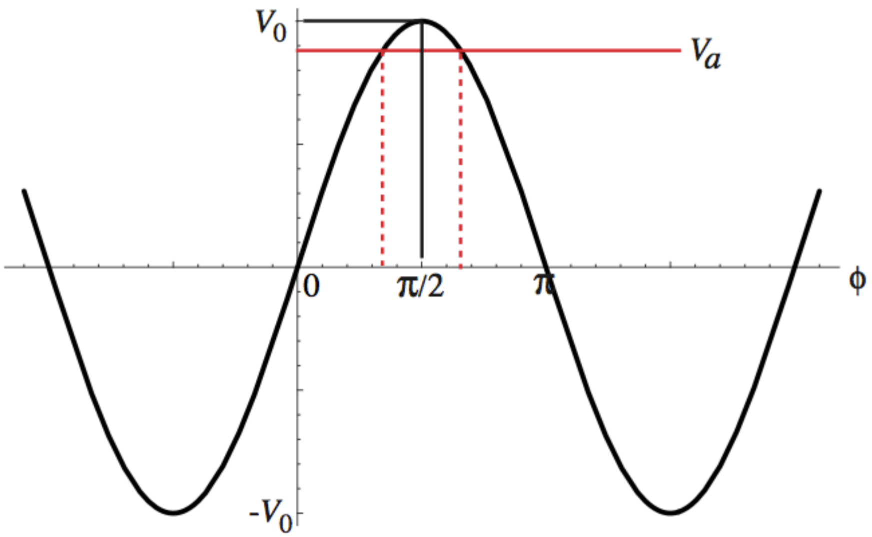
The road toward syncrotrons

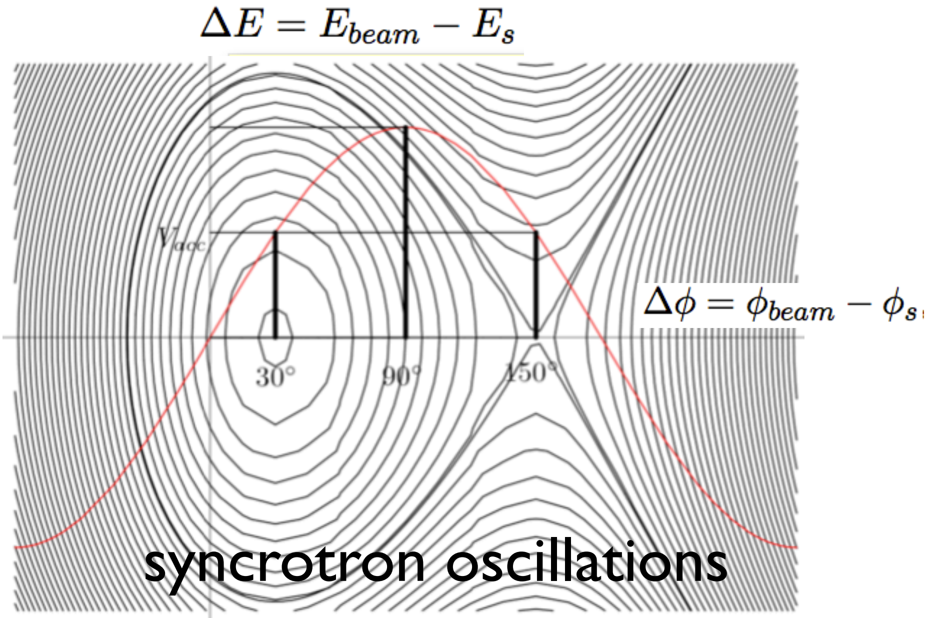
- Problems in RF acceleration in the 1940s…
  - ✓ Linacs
    - poor RF sources; electron tube technology was yet in its infancy
  - ✓ Cyclotrons
    - relativistic effects → asynchronous RF
  - ✓ Betatrons
    - intensity of trapped beam depends critically on the injected beam's positions and angles
    - 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

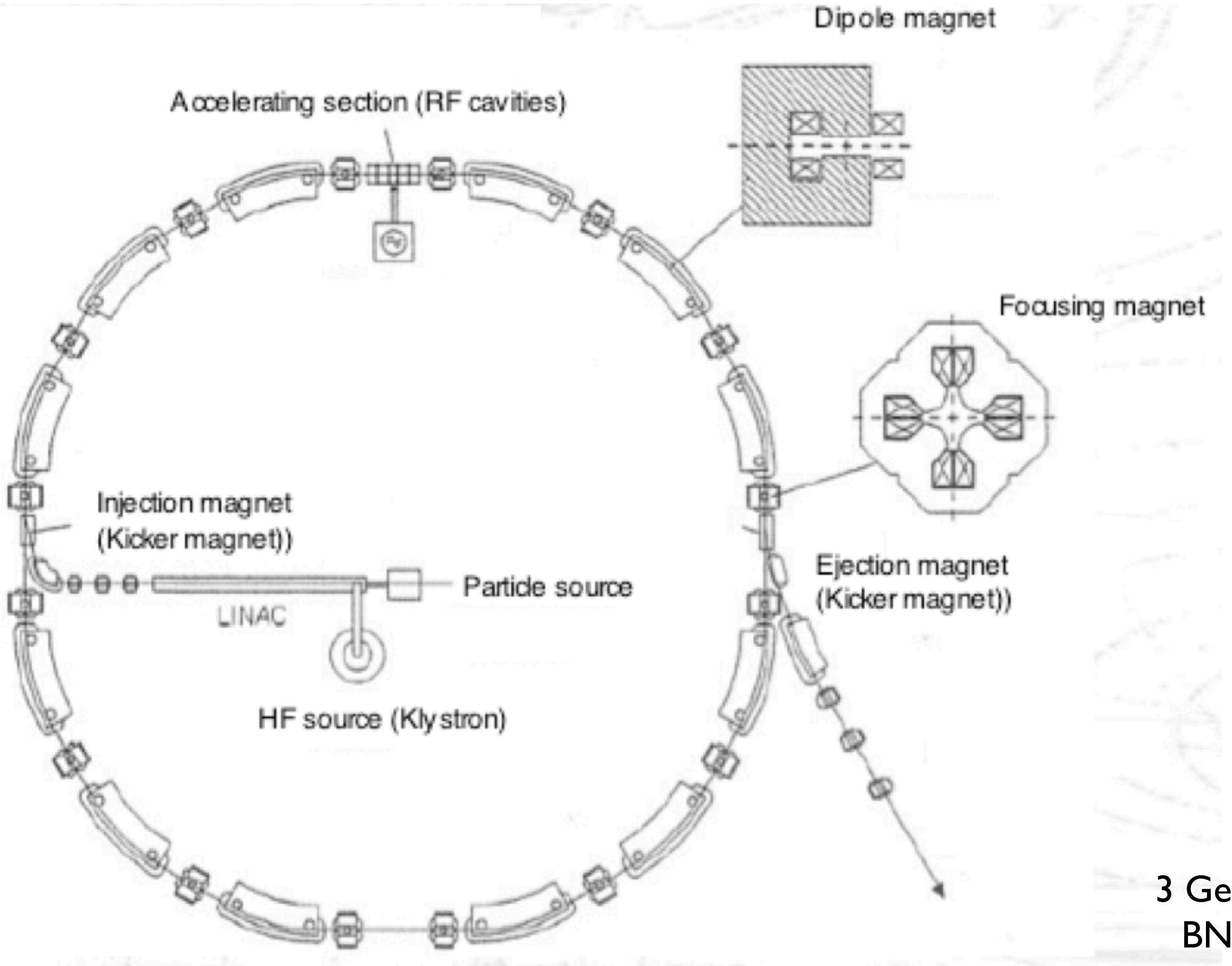
- Particles of different energies have differences in velocity and in orbit length
  - particles may be asynchronous wrt RF frequency
- RF field have however a restoring force at a certain phase, around which asynchronous particles be captured in bunches
- The phenomenon enables a stable, continuous 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





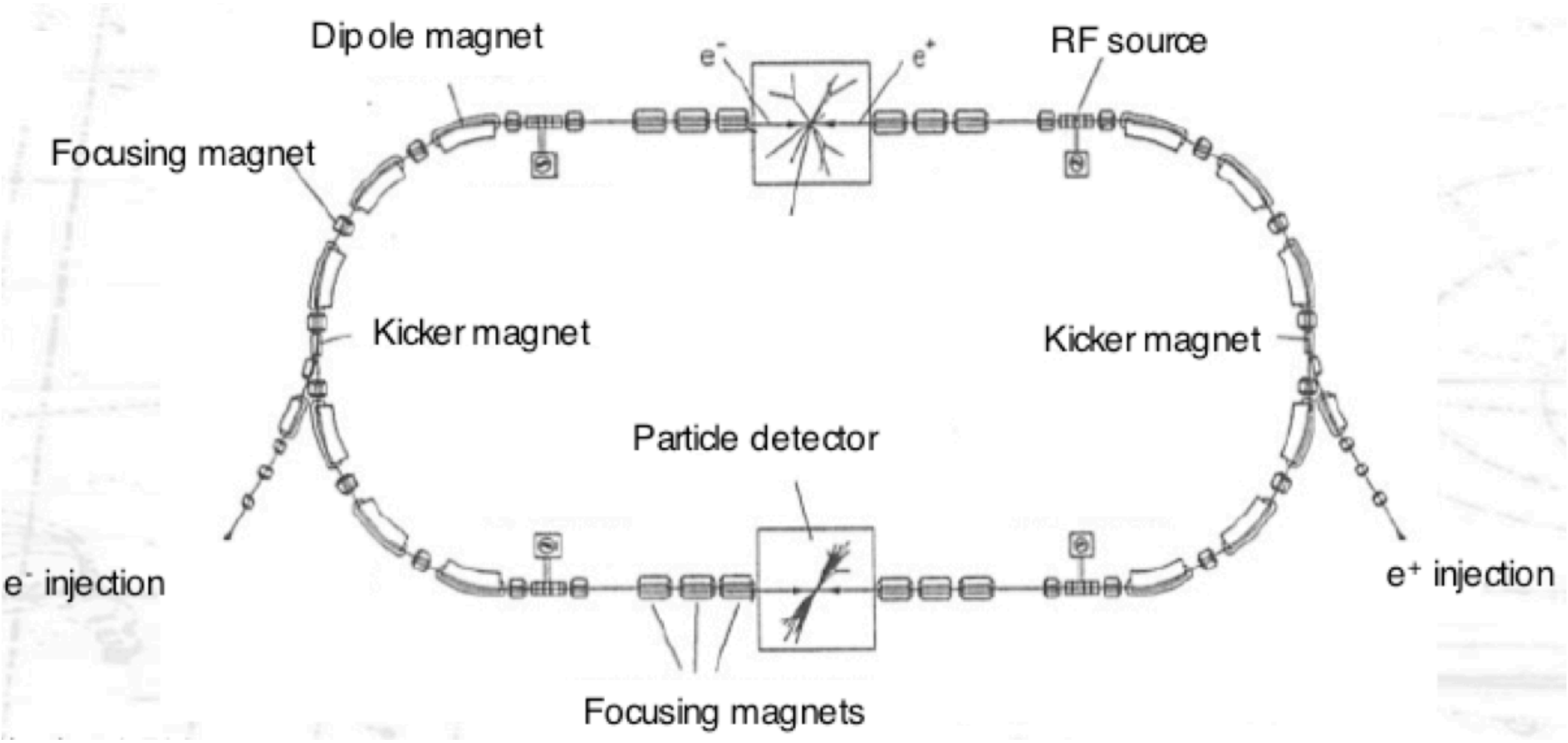
syncrotron oscillations

Syncrotron

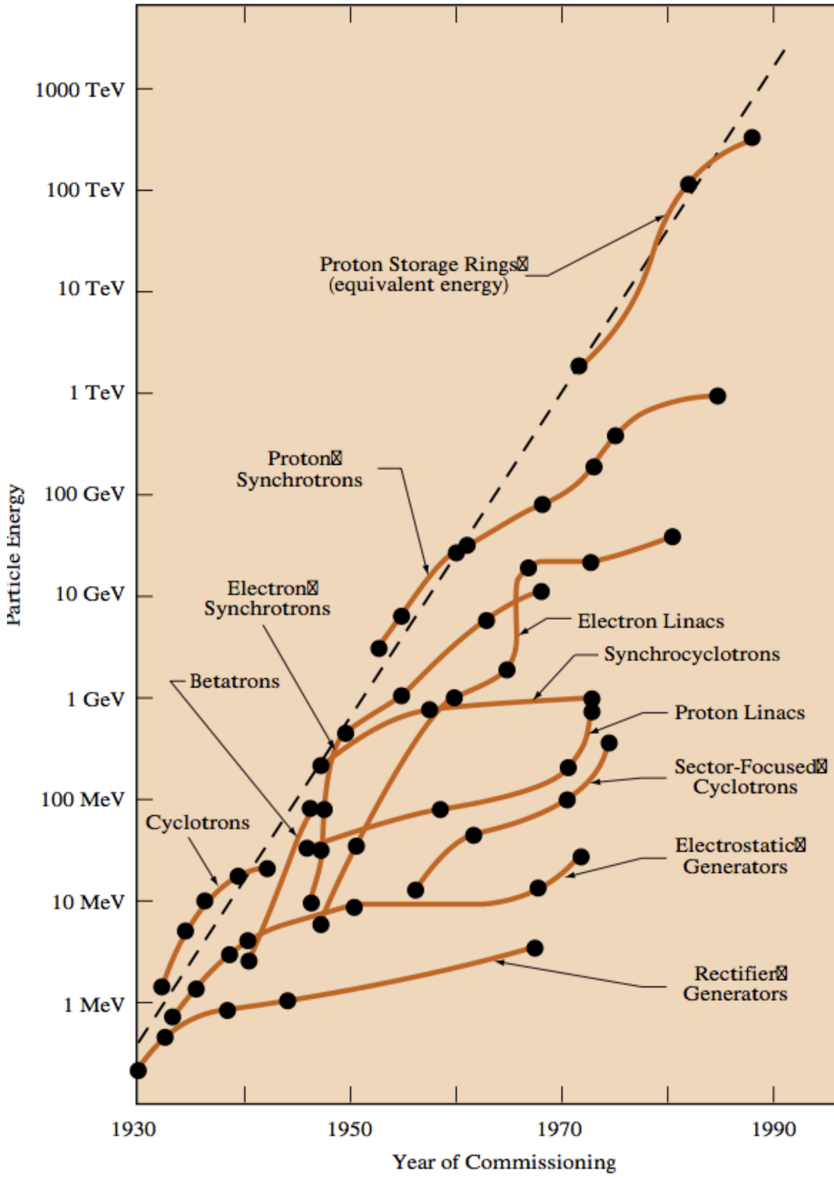


3 GeV protons
BNL ~ 1950

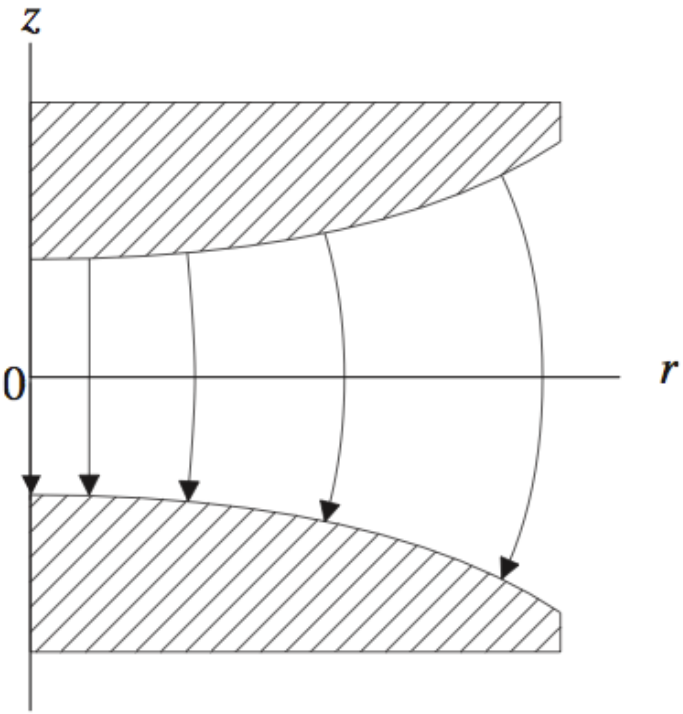
Storage rings

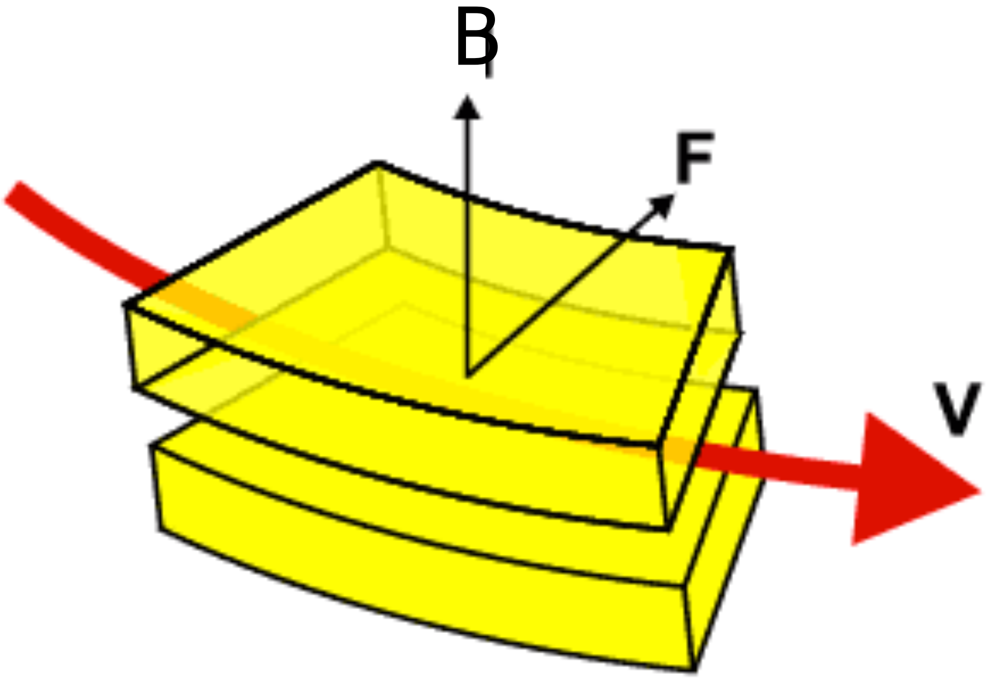


Livingstone chart



Bending: dipoles

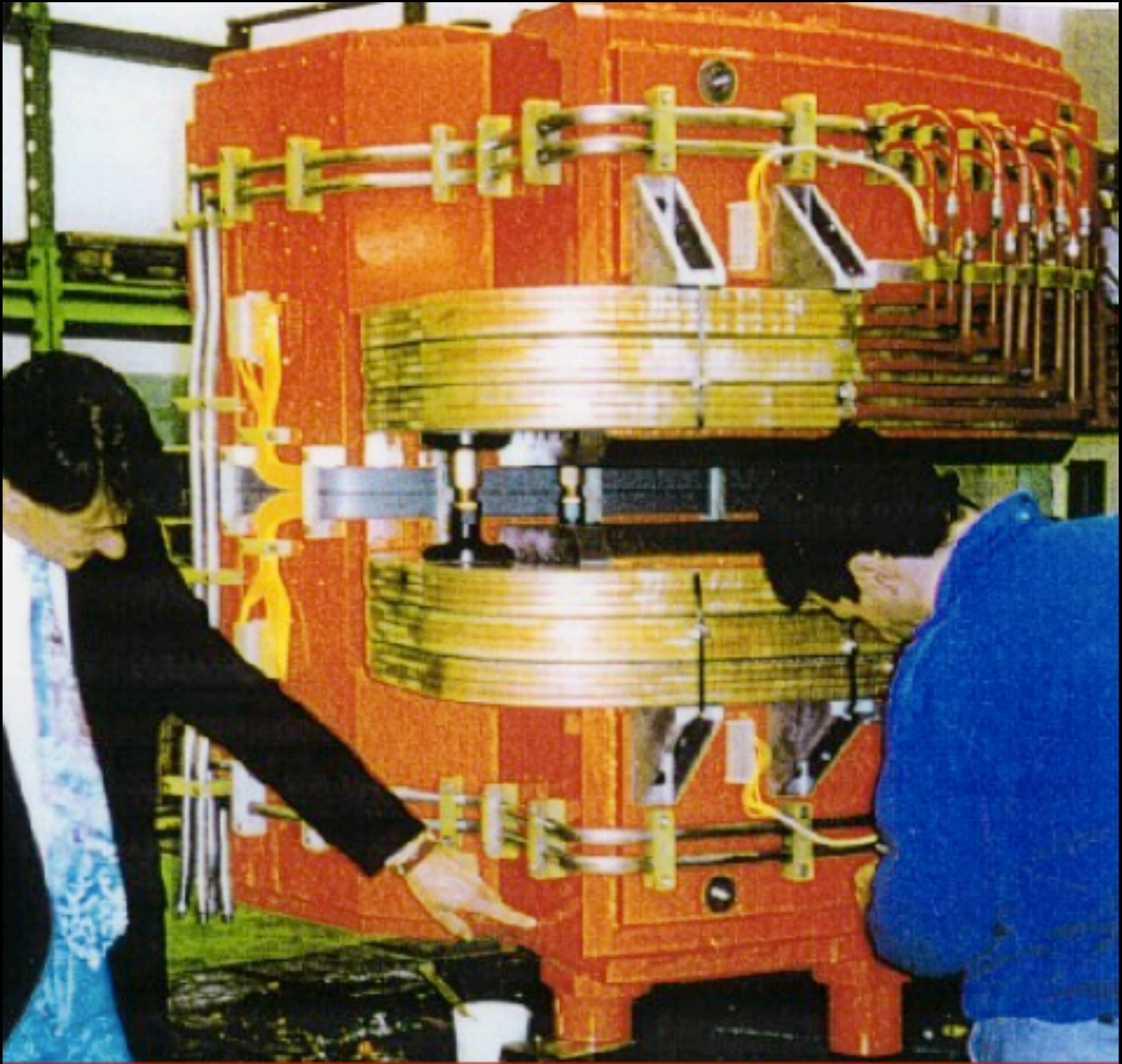


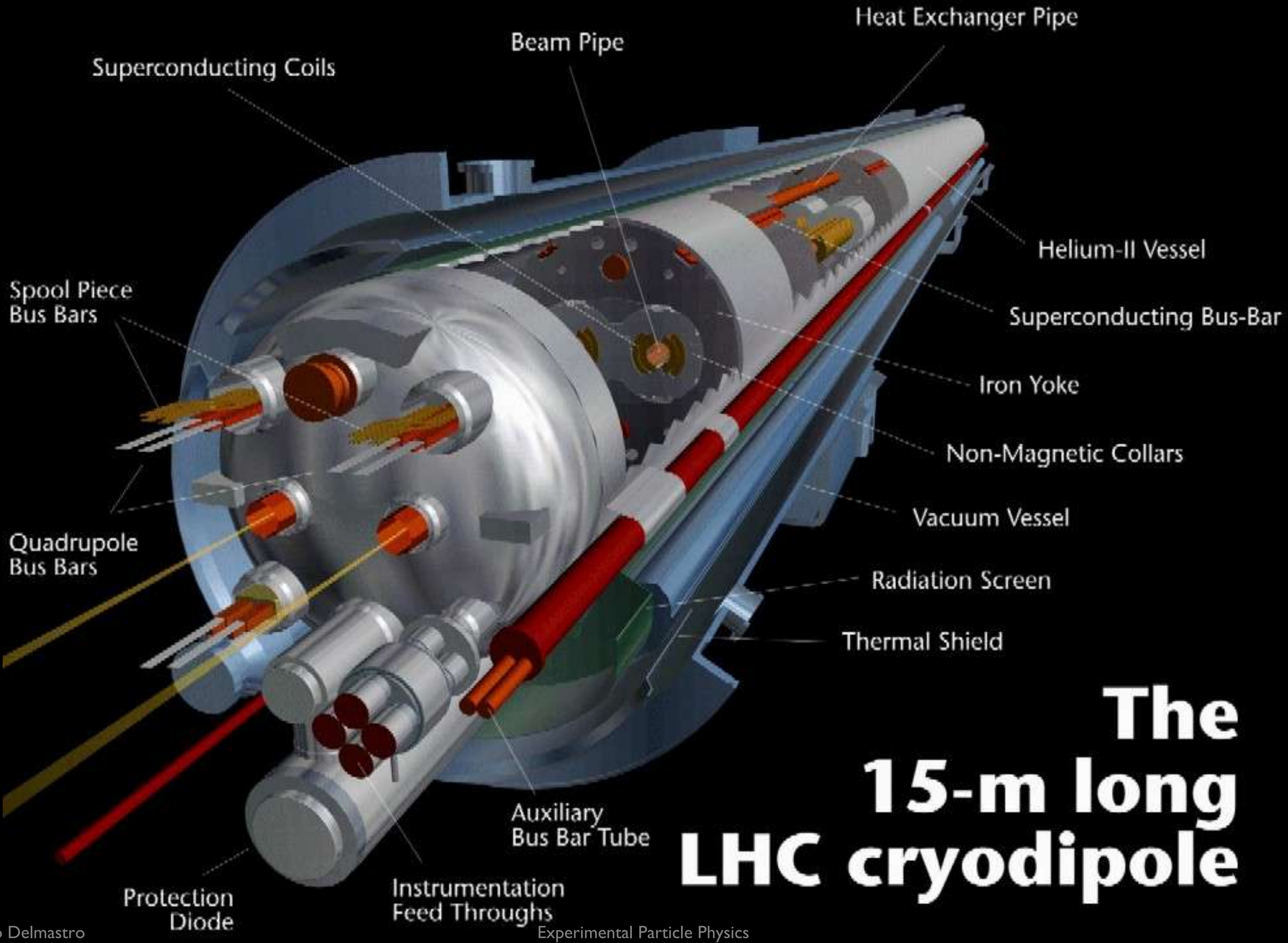


dipole

$B_x = 0$
$B_y = B$
$B_z = 0$

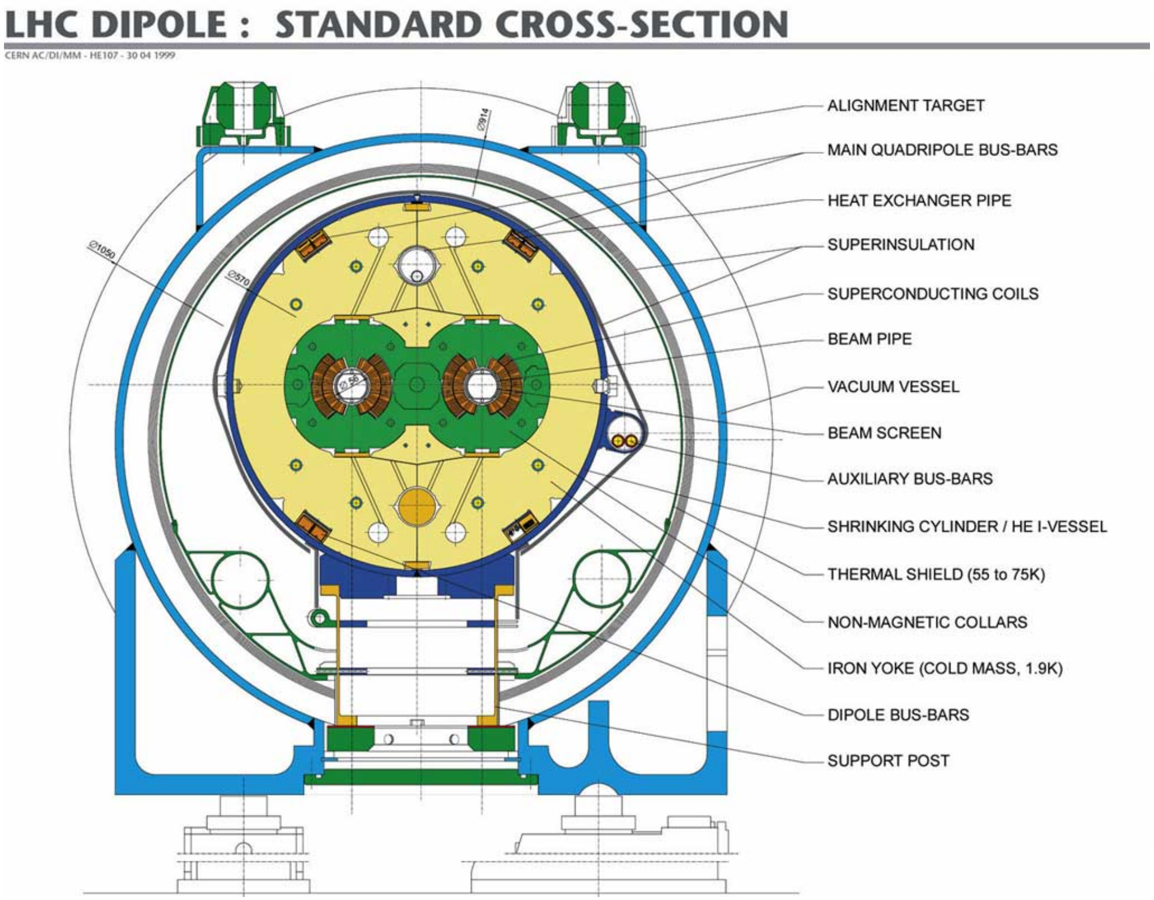
$$\frac{1}{R}[\mathrm{m}^{-1}] = 0.3\frac{B[\mathrm{T}]}{E[\mathrm{GeV}]}$$

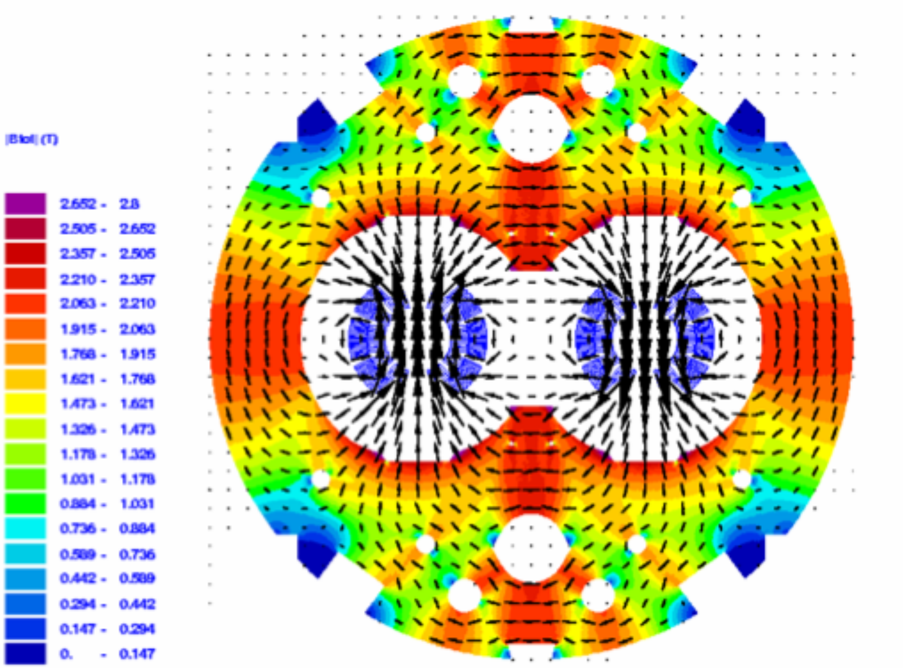




The 15-m long LHC cryodipole

LHC dipoles


LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
Ø914
Ø1050
Ø570
Ø56
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 75K)
NON-MAGNETIC COLLARS
IRON YOKE (COLD MASS, 1.9K)
DIPOLE BUS-BARS
SUPPORT POST


|Btot| (T)
2.652 - 2.8
2.505 - 2.652
2.357 - 2.505
2.210 - 2.357
2.063 - 2.210
1.915 - 2.063
1.768 - 1.915
1.621 - 1.768
1.473 - 1.621
1.326 - 1.473
1.178 - 1.326
1.031 - 1.178
0.884 - 1.031
0.736 - 0.884
0.589 - 0.736
0.442 - 0.589
0.294 - 0.442
0.147 - 0.294
0. - 0.147

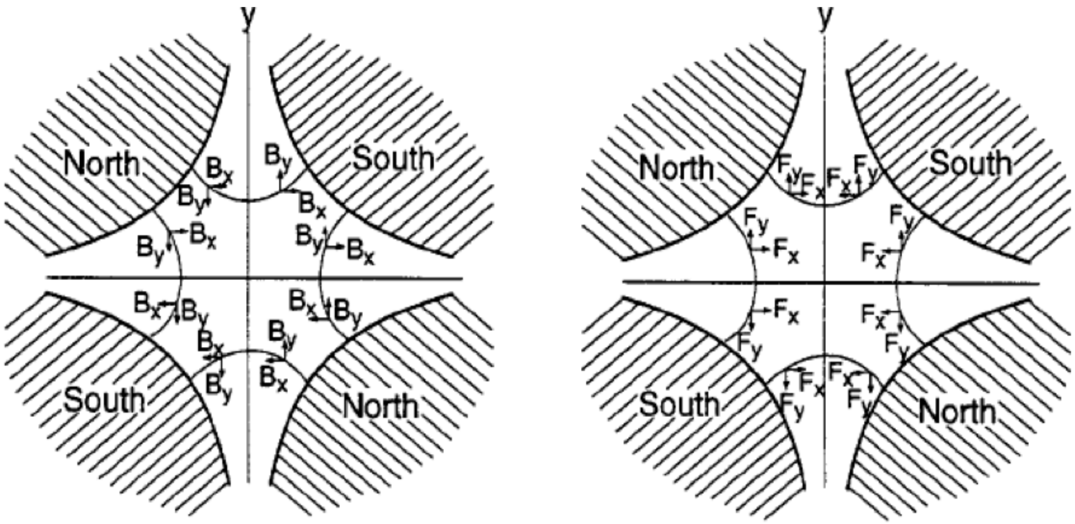
Focusing (defocusing): quadrupoles

B_x = -g x x

B_y = -g x y

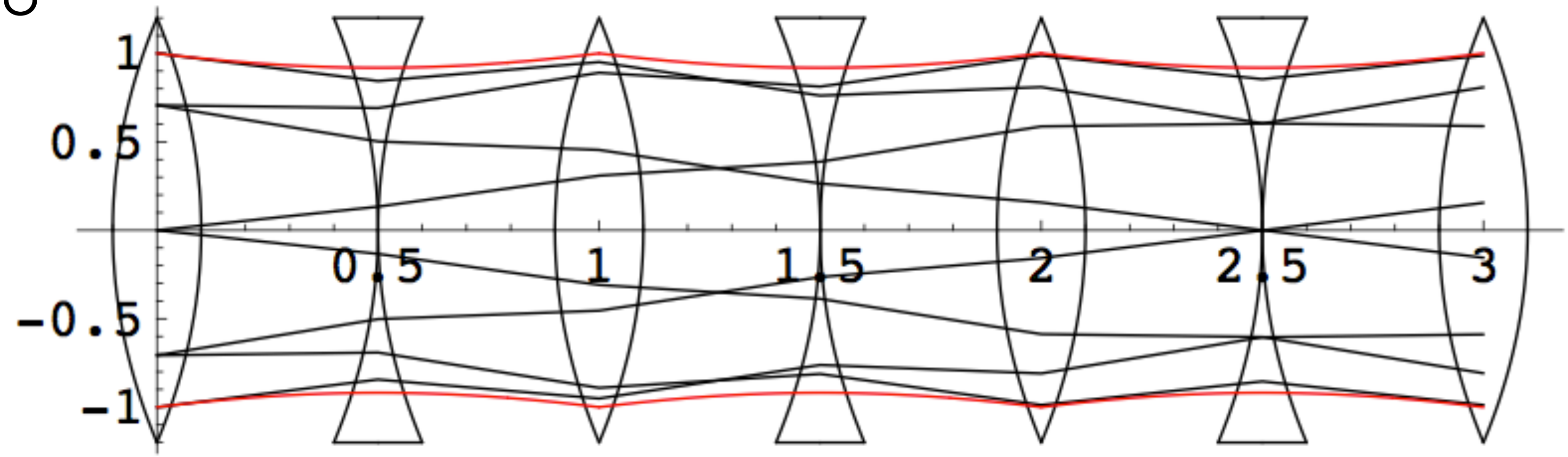
B_z = 0

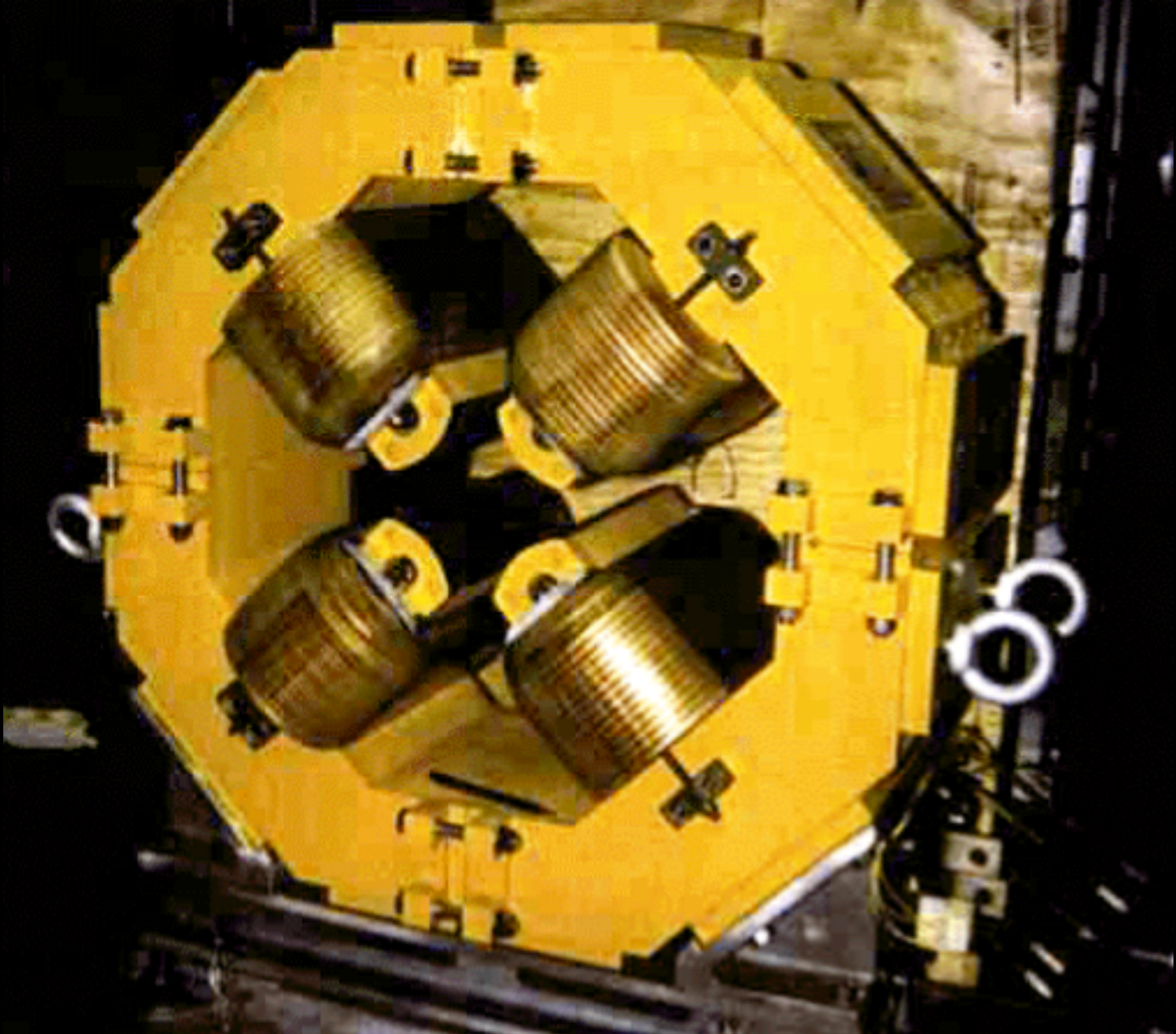
g[T/n] = field gradient



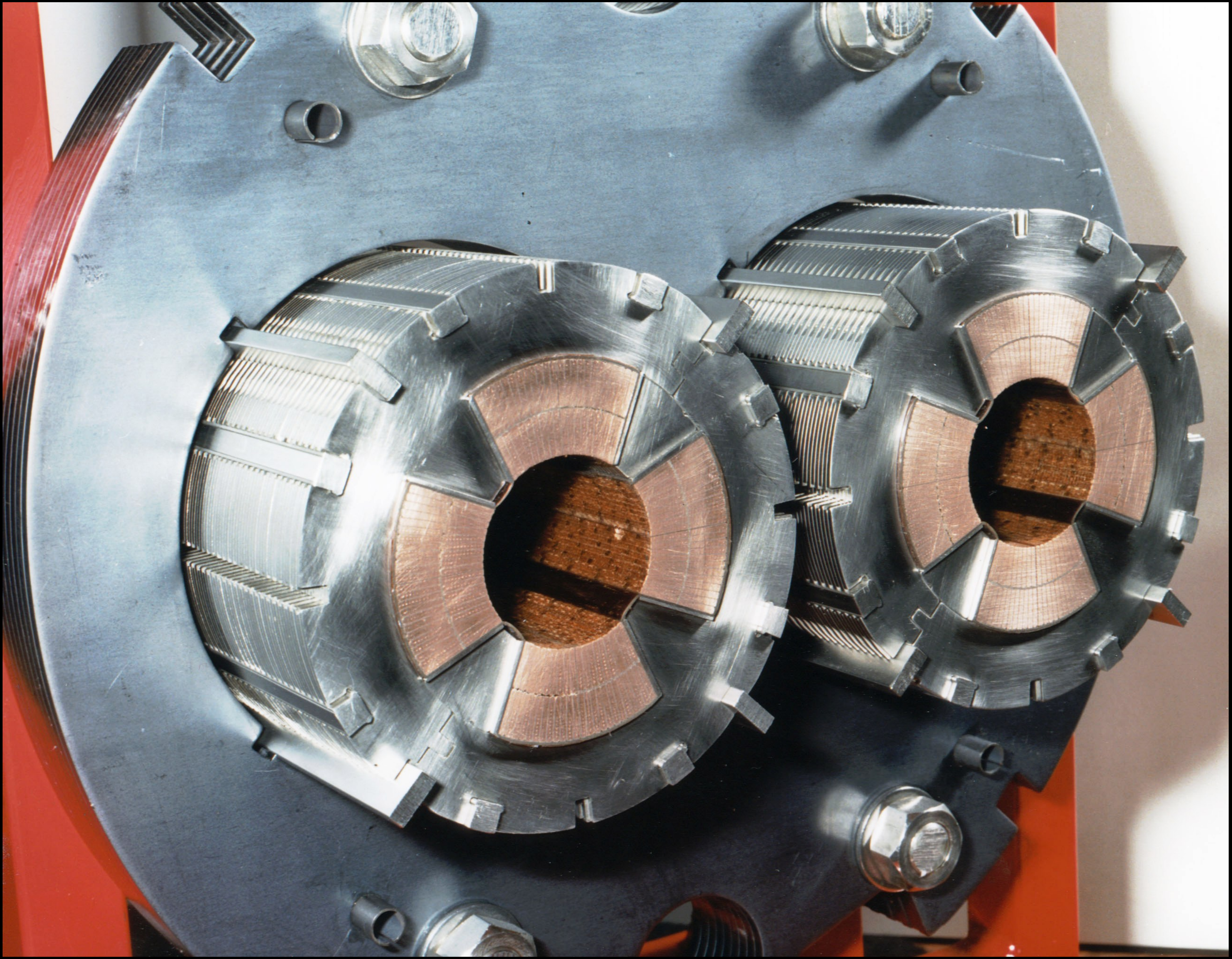
Focusing in one direction, defocusing in the other

FO-DO array

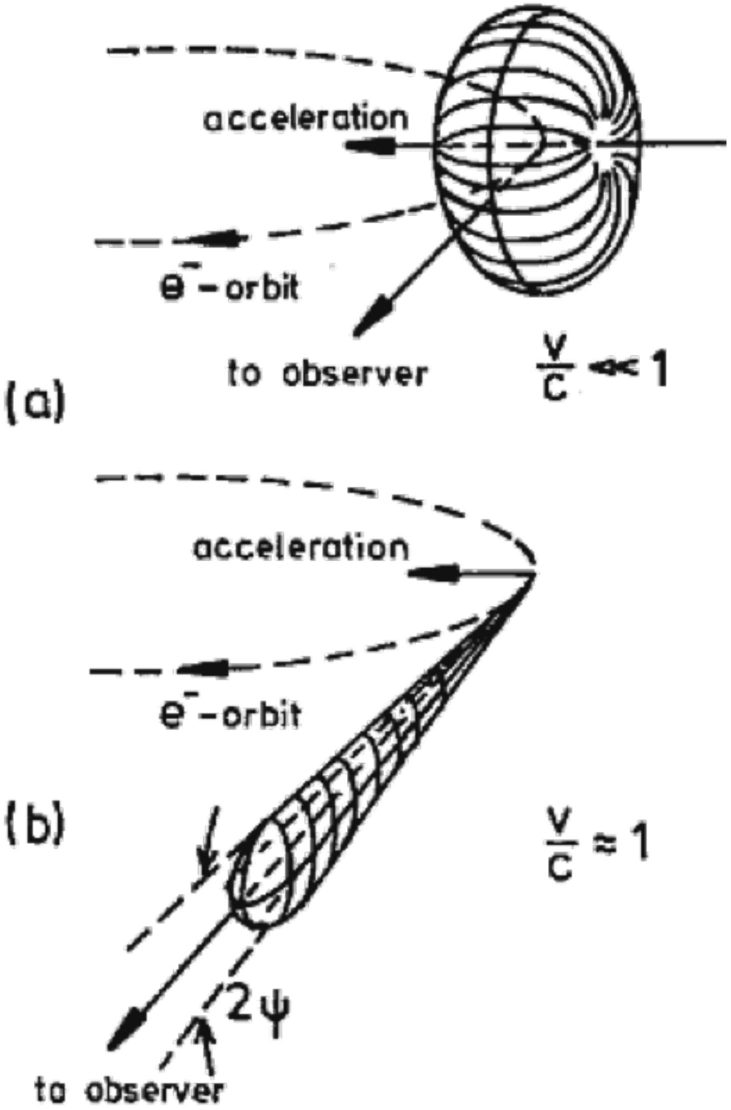





Fermilab



Syncrotron radiation



energy lost per revolution

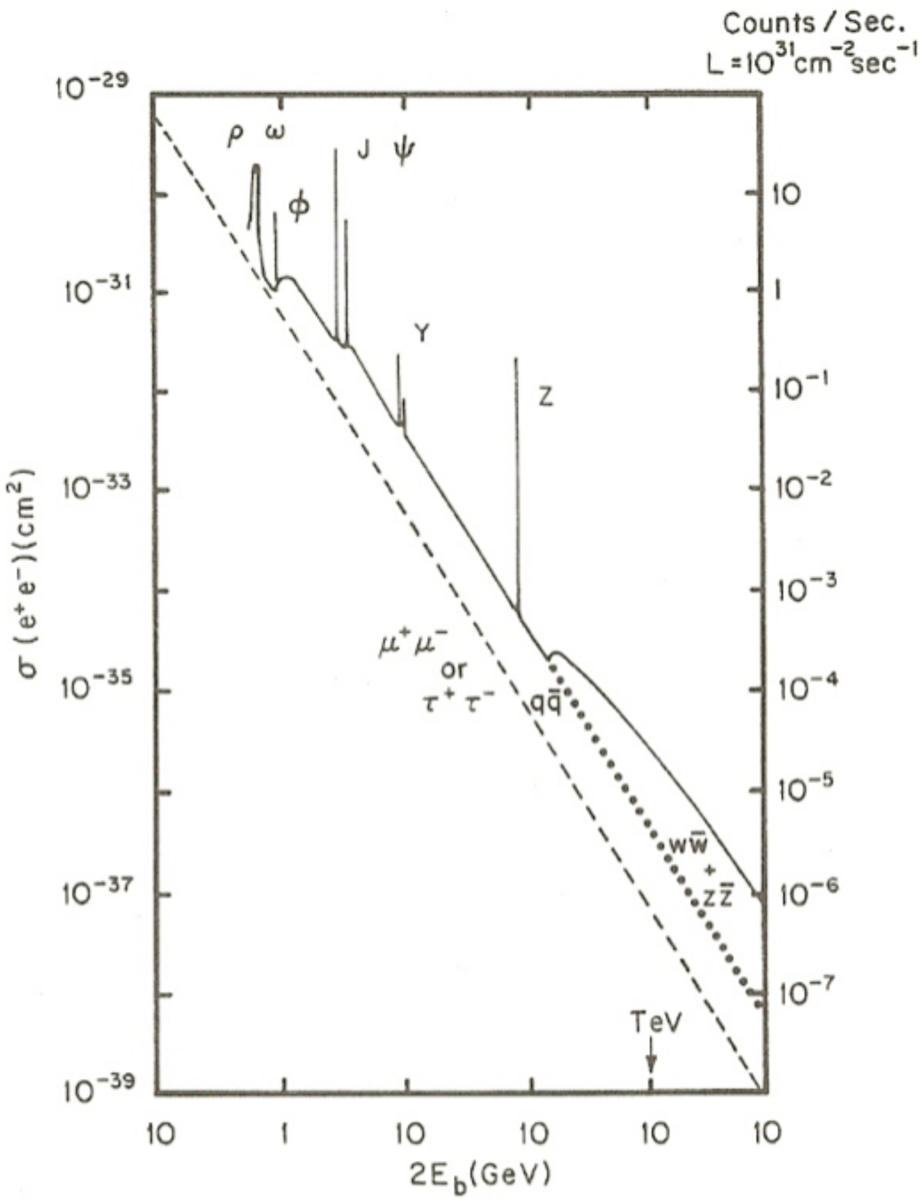
$$\Delta E = \frac{4\pi}{3} \frac{1}{4\pi\epsilon_0} \left(\frac{e^2 \beta^3 \gamma^4}{R} \right)$$

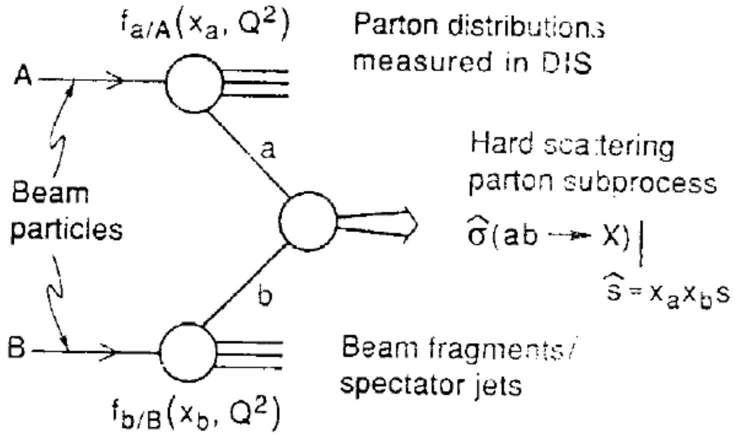
electrons vs. protons

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

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

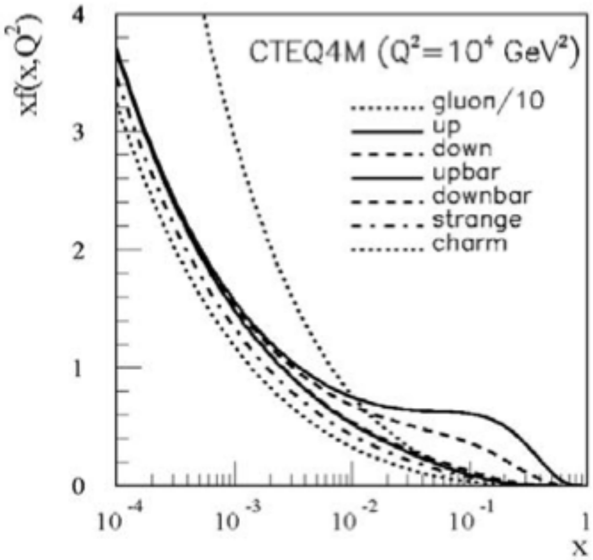
e^+-e^- vs. hadron collider



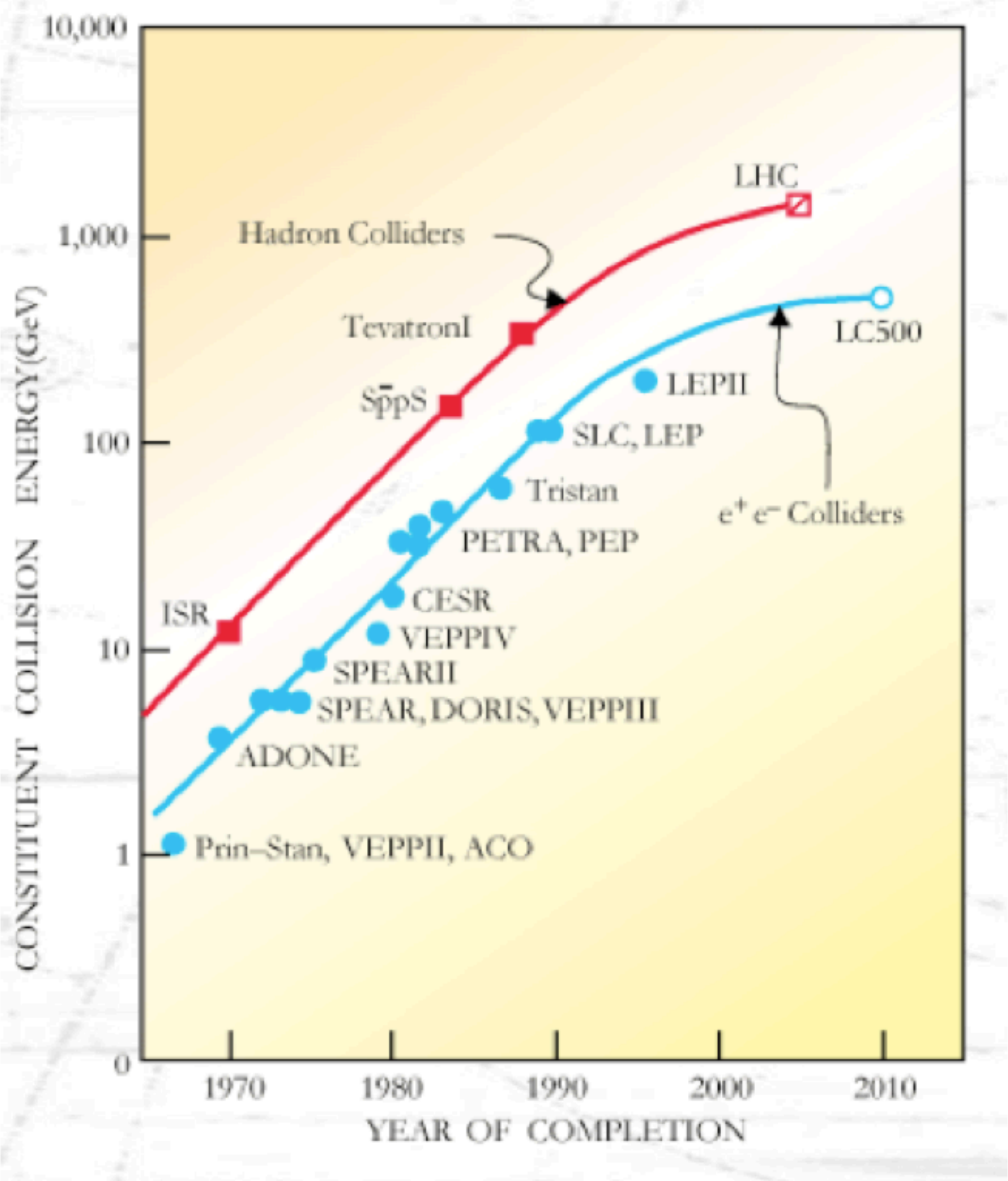


$$\sqrt{\hat{s}} = \sqrt{x_a x_b s}$$

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



e^+-e^- vs. hadron collider

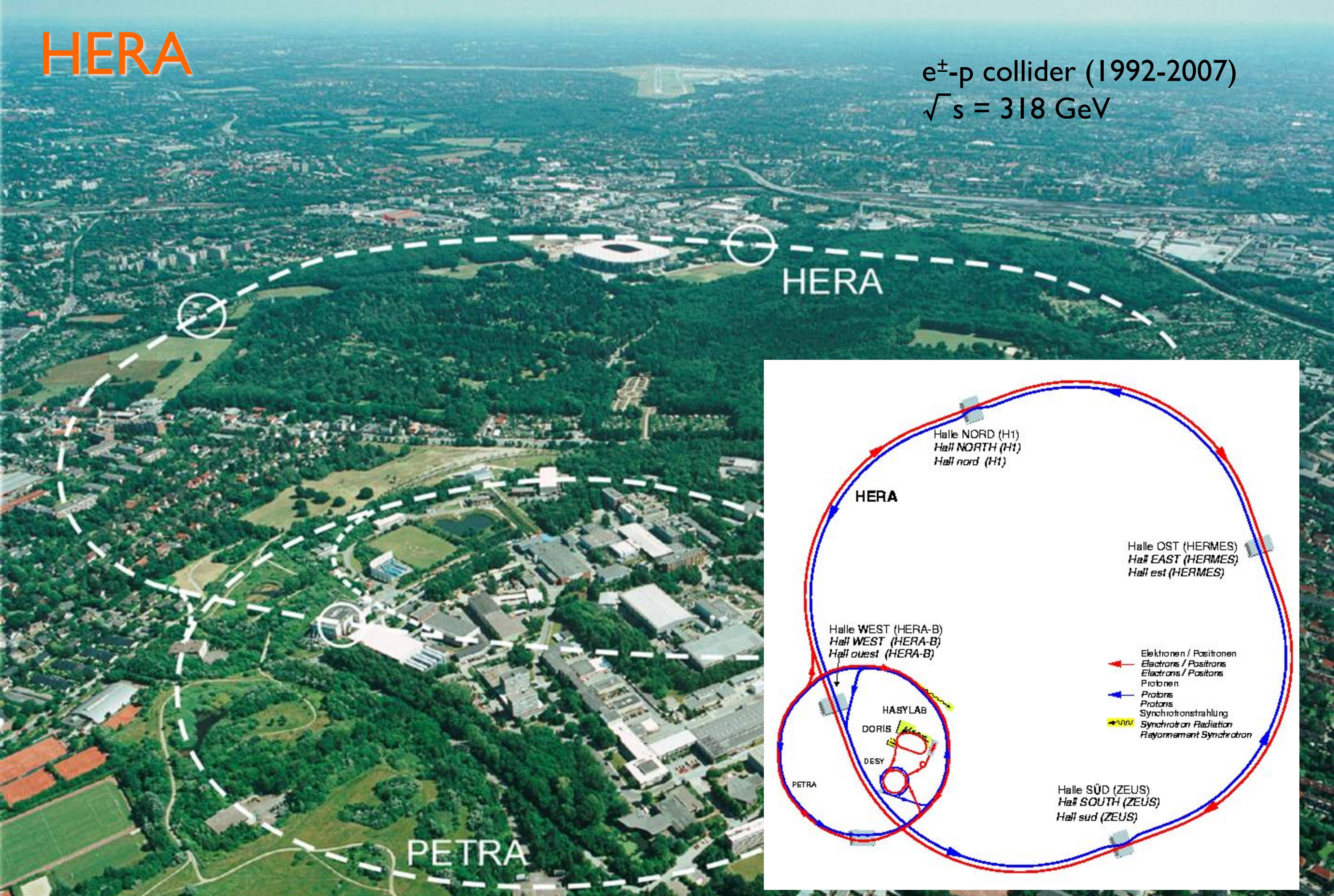



5-10

Accelerators around the world (past and present)

HERA

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

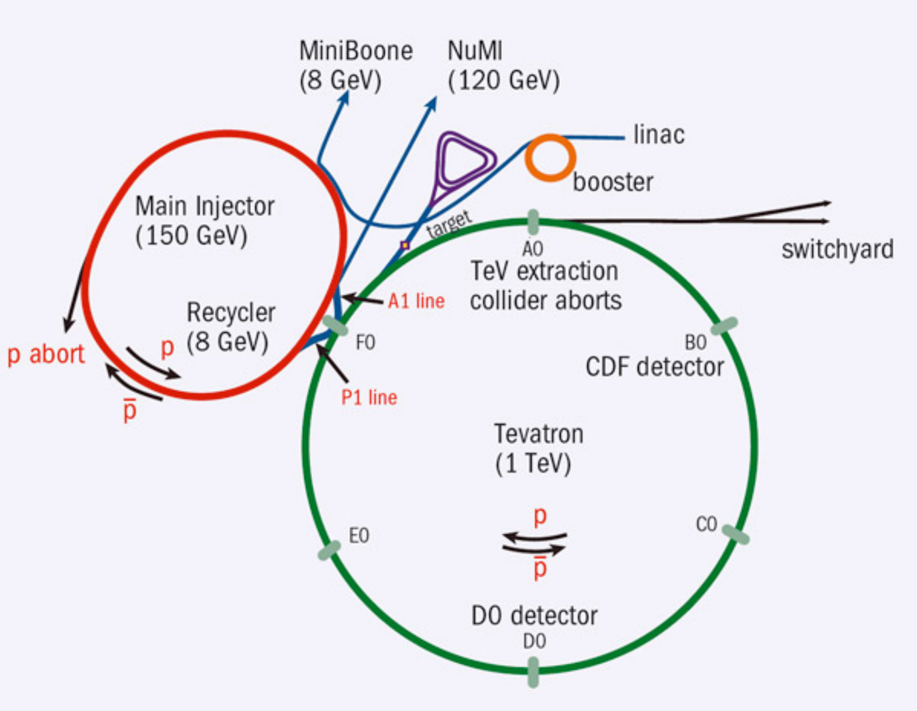


Tevatron

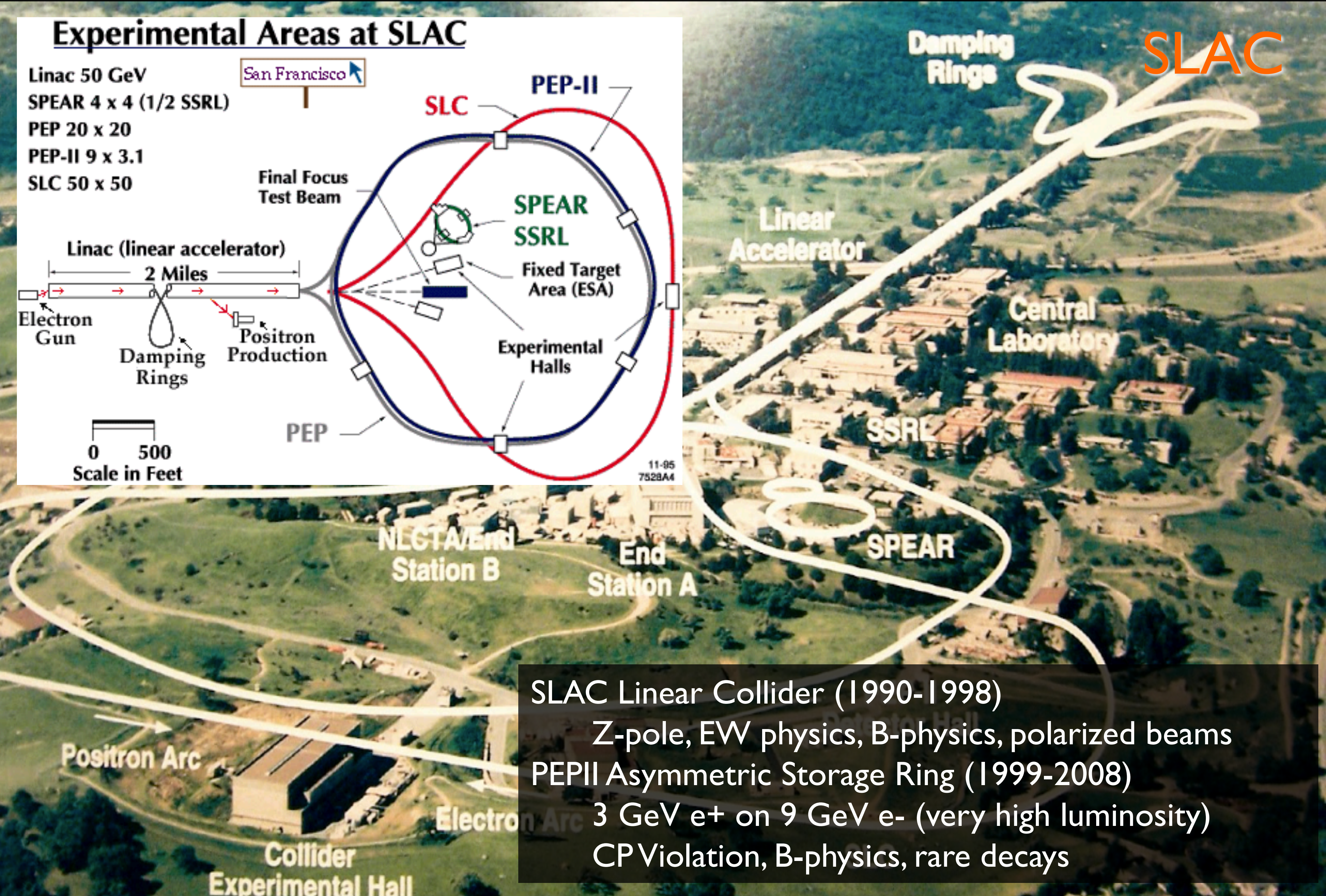
$p\bar{p}$ collider (1983-2011)

$\sqrt{s}$ = 1.96 TeV

CDF-D0
- top quark discovery
- Higgs search
- new physics



SLAC



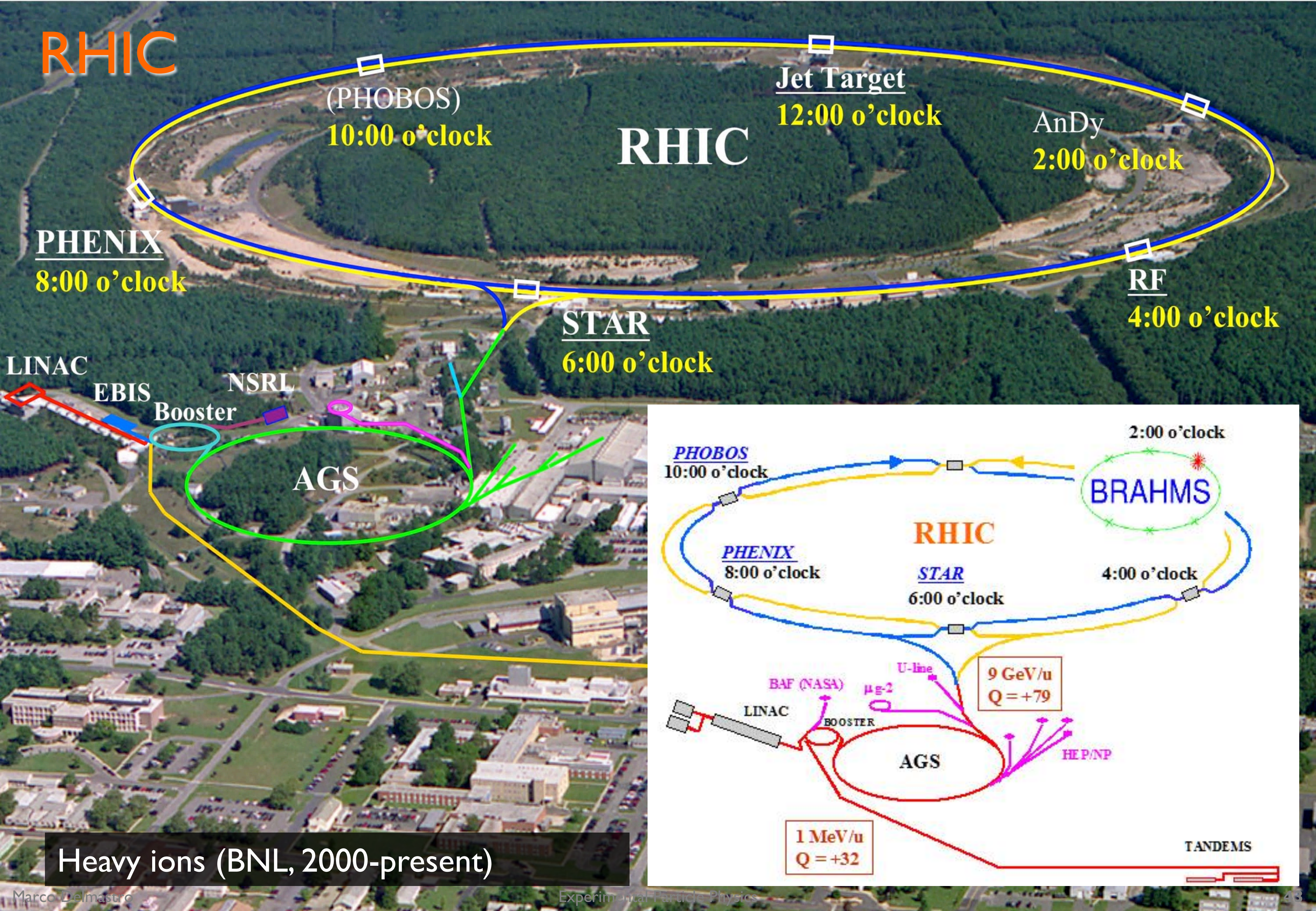
SLAC Linear Collider (1990-1998)

- Z-pole, EW physics, B-physics, polarized beams

PEPII Asymmetric Storage Ring (1999-2008)

- 3 GeV e+ on 9 GeV e- (very high luminosity)
- CP Violation, B-physics, rare decays

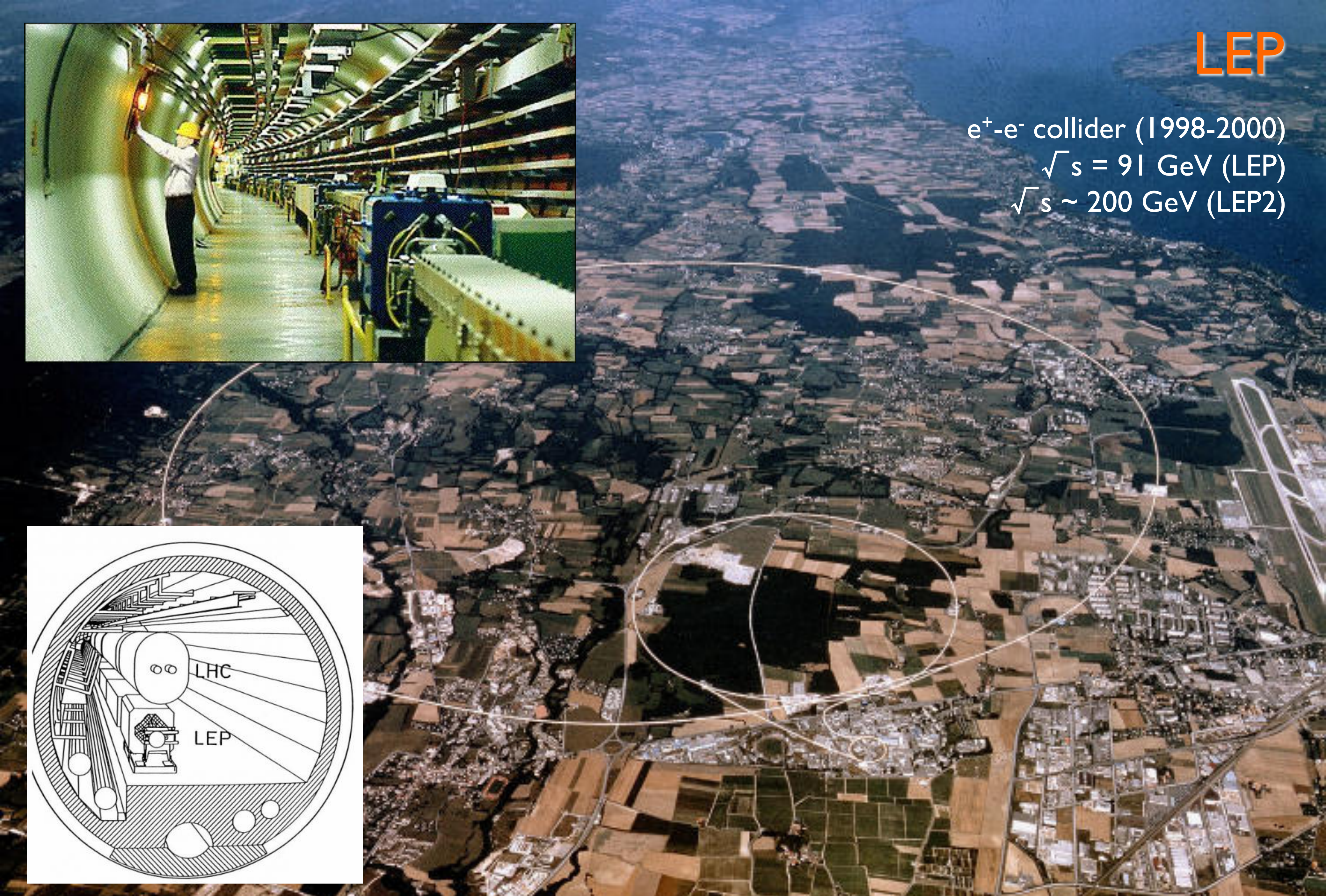
RHIC



Heavy ions (BNL, 2000-present)

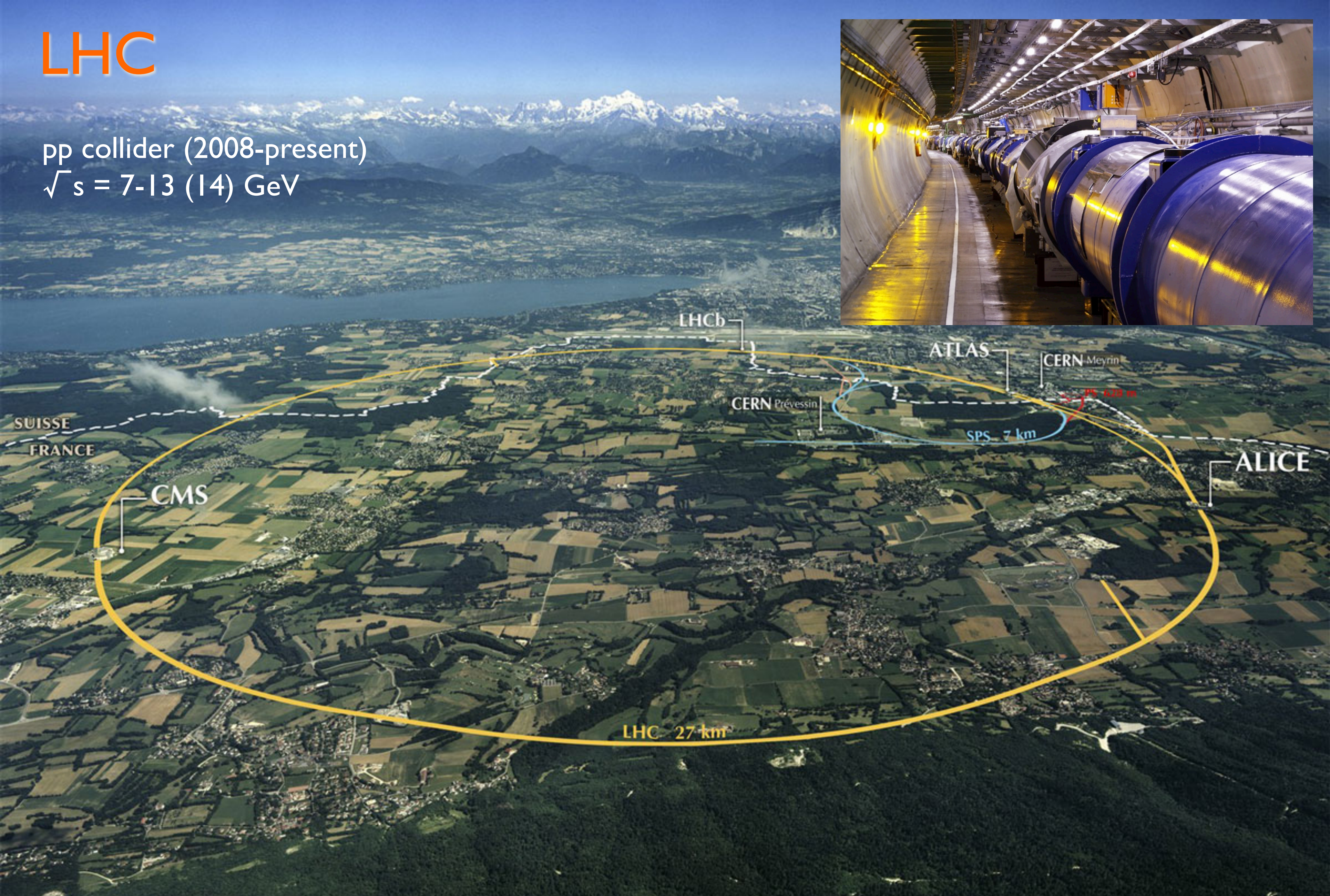
LEP

e$^+$-e$^-$ collider (1998-2000)
$\sqrt{s}$ = 91 GeV (LEP)
$\sqrt{s}$ ~ 200 GeV (LEP2)

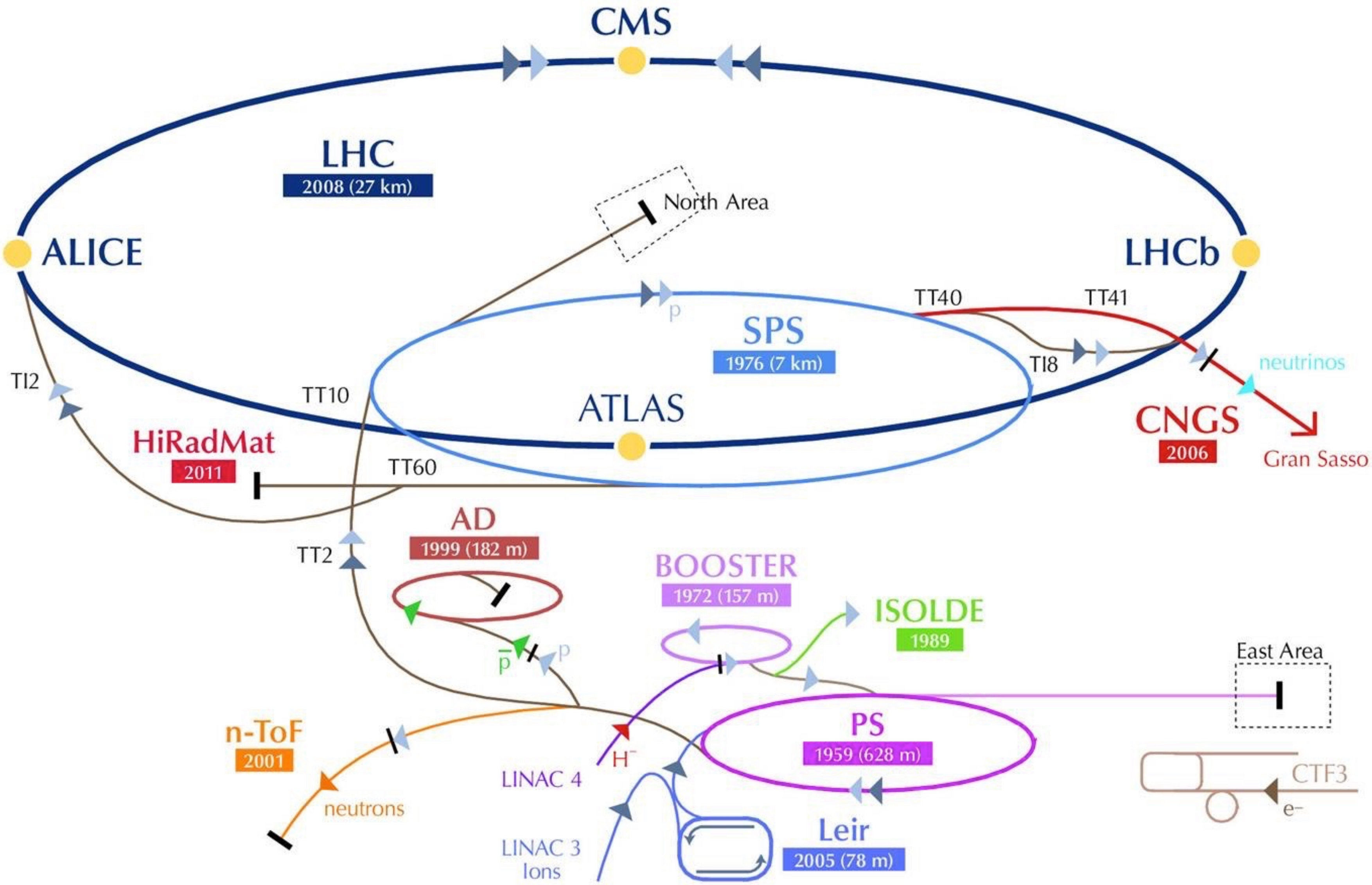


LHC

pp collider (2008-present)
$\sqrt{s}$ = 7-13 (14) GeV

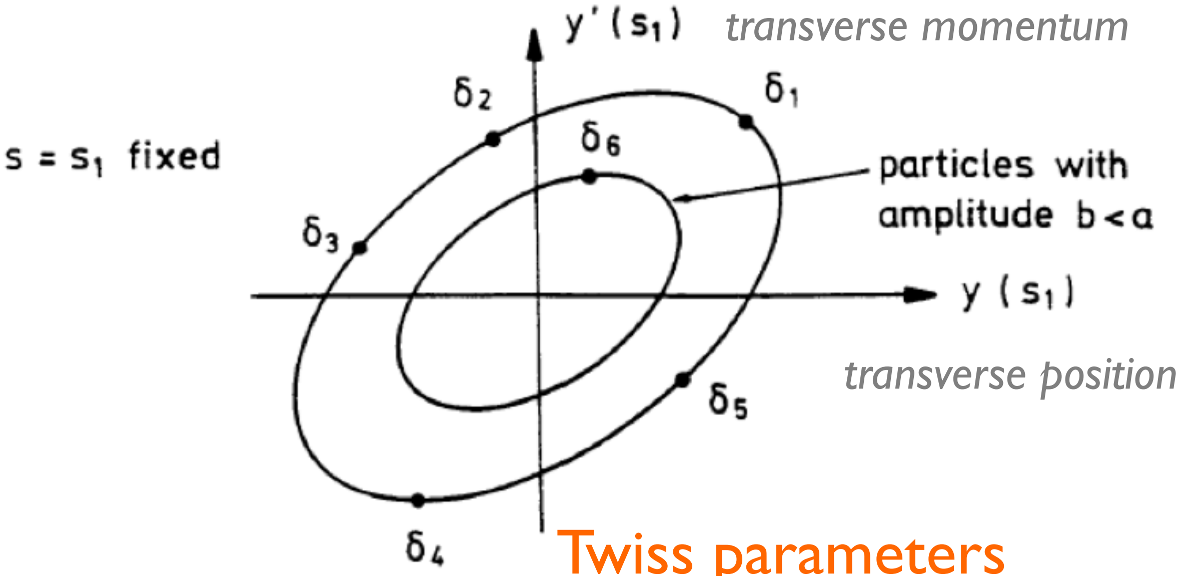


CERN accelerator complex



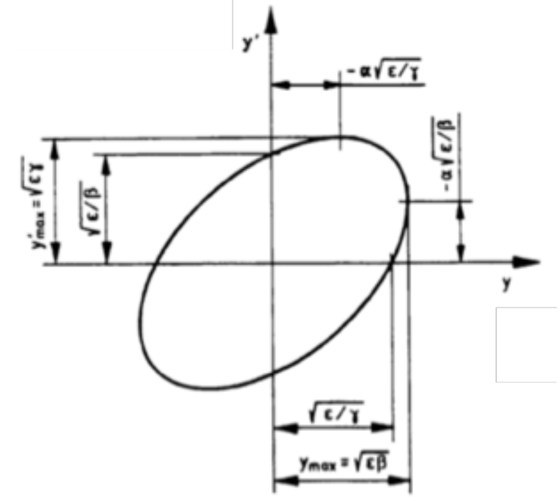
Beam emittance

- 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…



transverse momentum

transverse position



$$\gamma\, y^2 + 2\overbrace{\alpha}^{\text{Twiss parameters}}\, y\, y' + \overbrace{\beta}\, y'^2 = const = \overbrace{\varepsilon}^{\text{Emittance}}$$

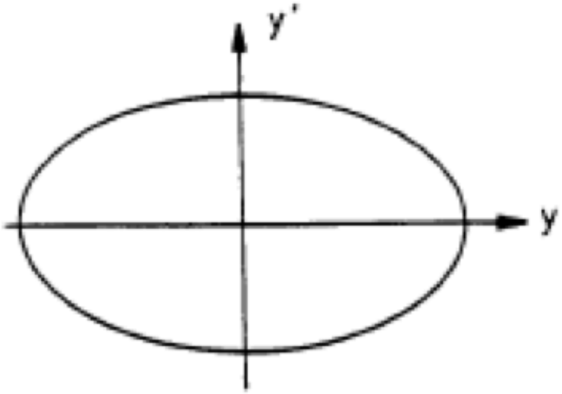
Beam dimensions

Gaussian width (RMS) in transverse direction

$$\sigma\overbrace{(z)}^{\text{position along beam directions}} = \sqrt{\underbrace{\varepsilon}_{\text{emittance}}\underbrace{\beta(z)}_{\text{Twiss parameter (amplitude function)}}}$$

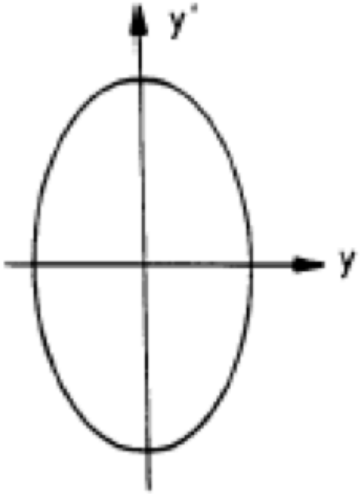
“Beta star” at interaction point, often adjusted to be minimum

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



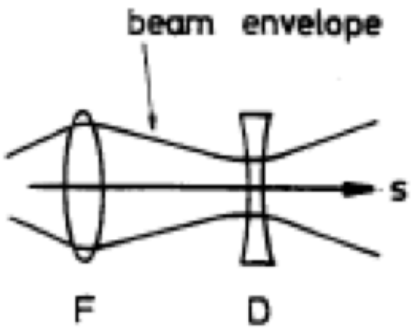
center of F quad

$\beta = \hat{\beta}$



center of D quad

$\beta = \check{\beta}$



Improvements to luminosity?

increase number
of bunches?

increase number particle
per bunch?

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

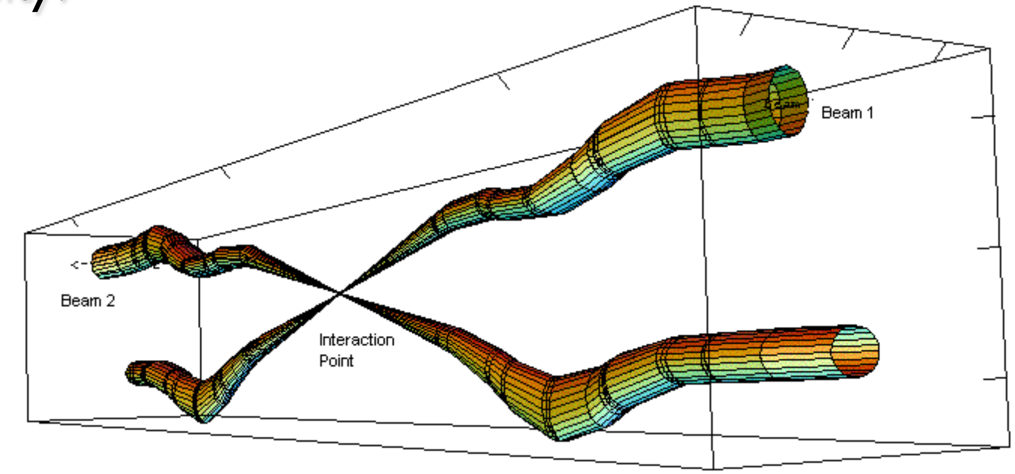
decrease emittance!

decrease beta star!

Crossing angle

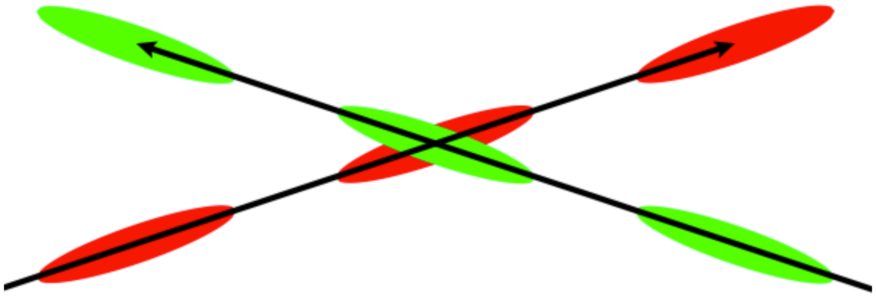
- To avoid parasitic encounters, beams with close bunches often cross at an angle
  - ✓ LHC beams cross at an angle of 300 microradian (bunch spacing 25 ns)
- Crossing angle has an impact on luminosity!

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

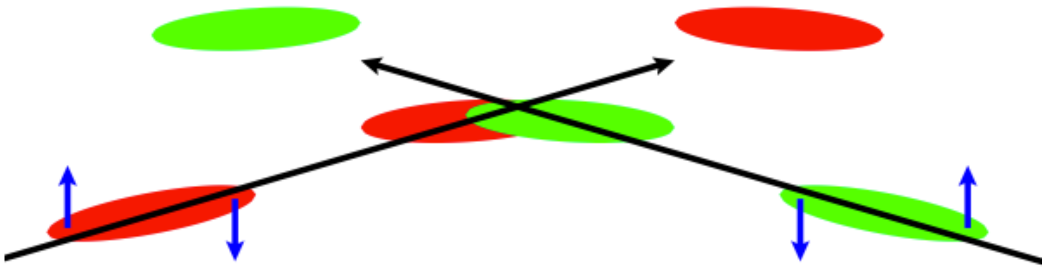


Relative beam sizes around IP1 (Atlas) in collision

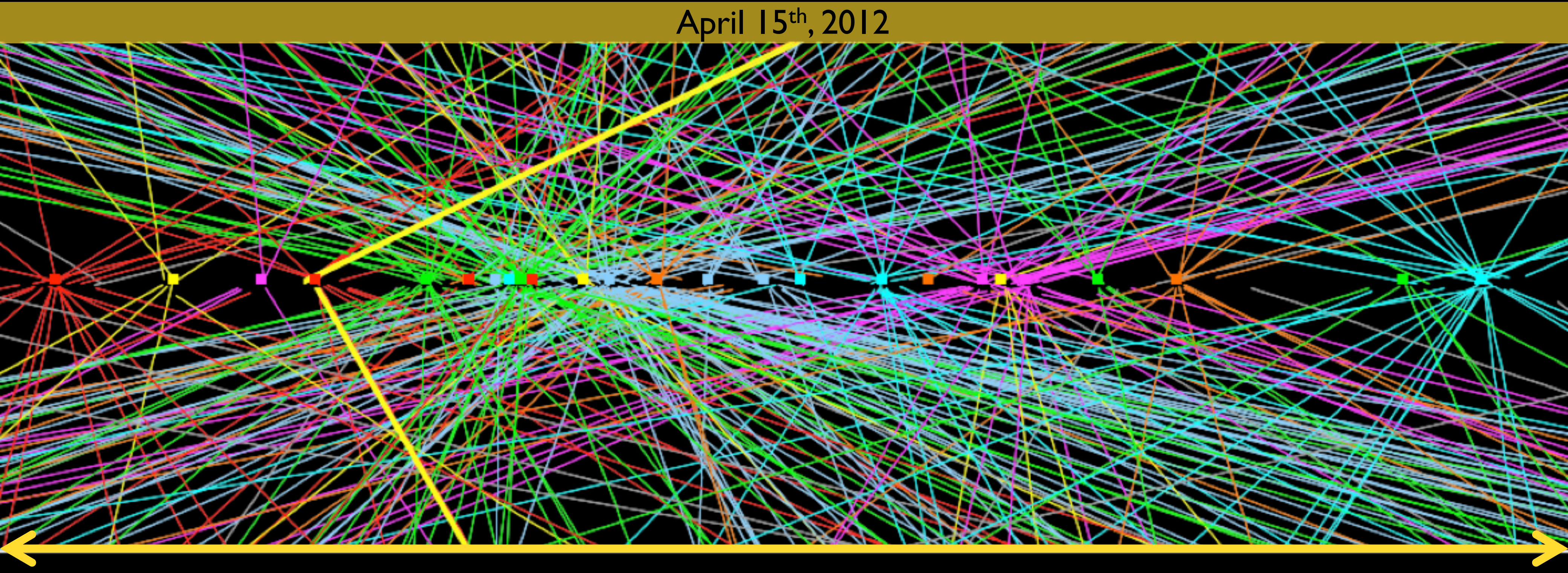
with crossing angle



“crab” crossing



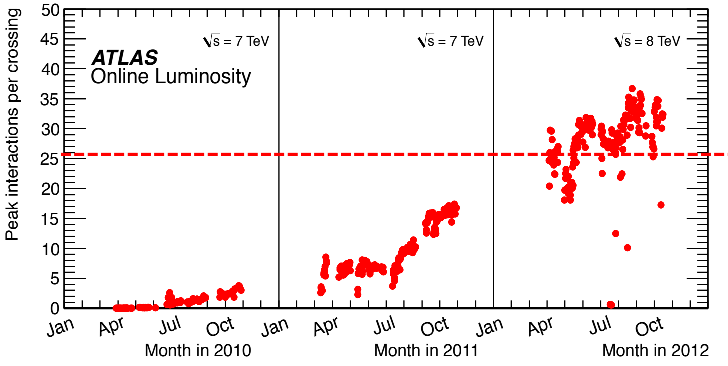
Z→μμ event with 25 reconstructed vertices

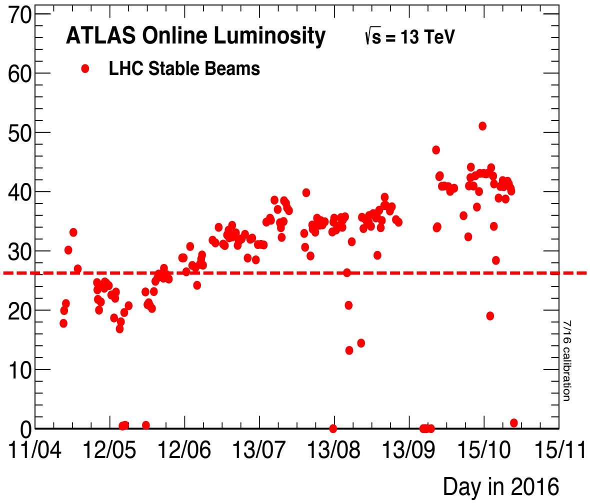


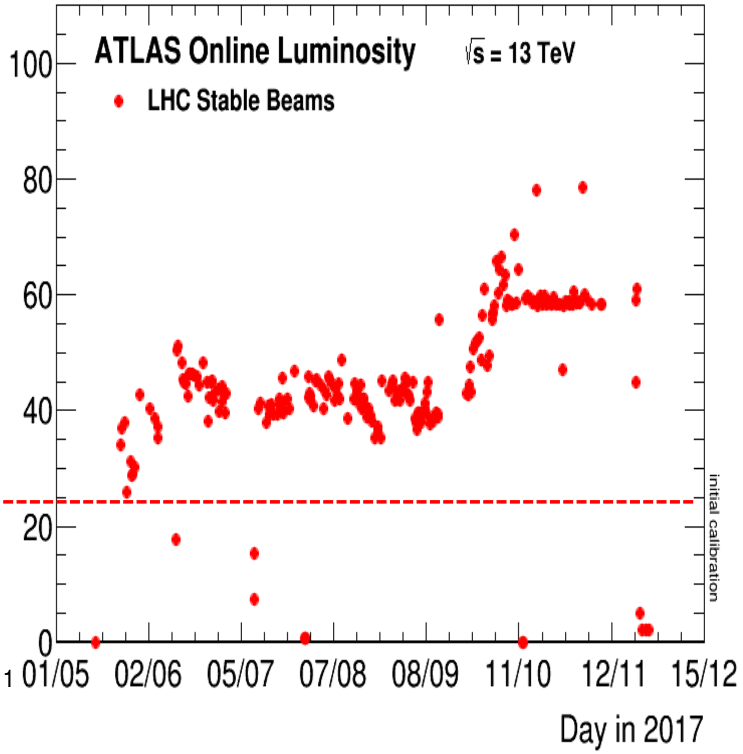
~5 cm

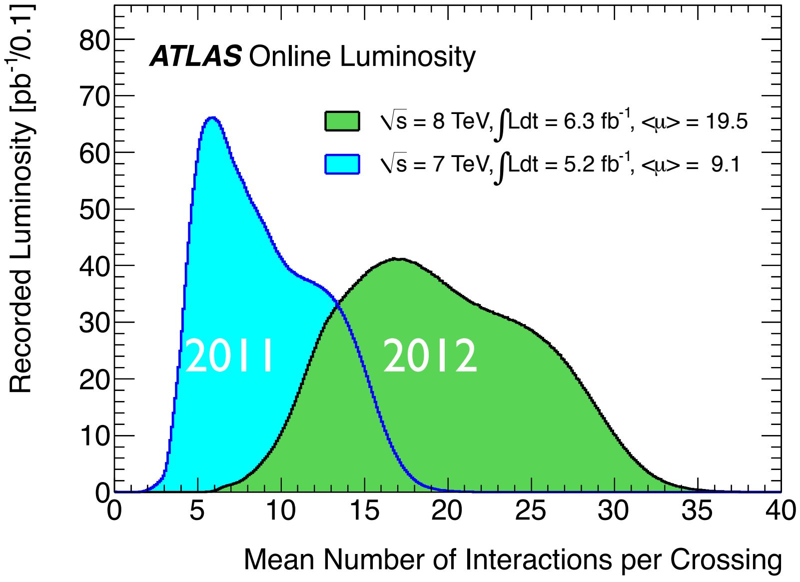
Pileup!

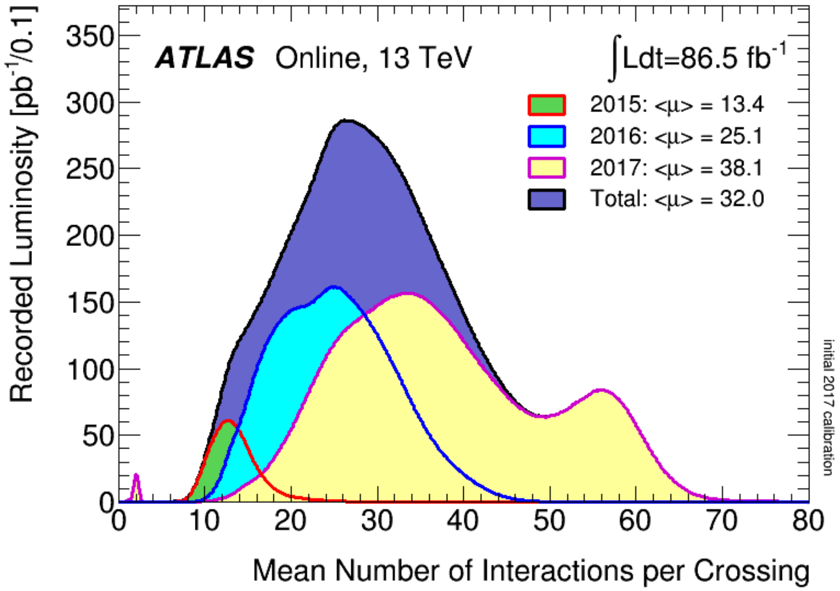
ATLAS design value
$L = 10^{34}\ \mathrm{cm^{-1}s^{-1}}$@ 25 ns



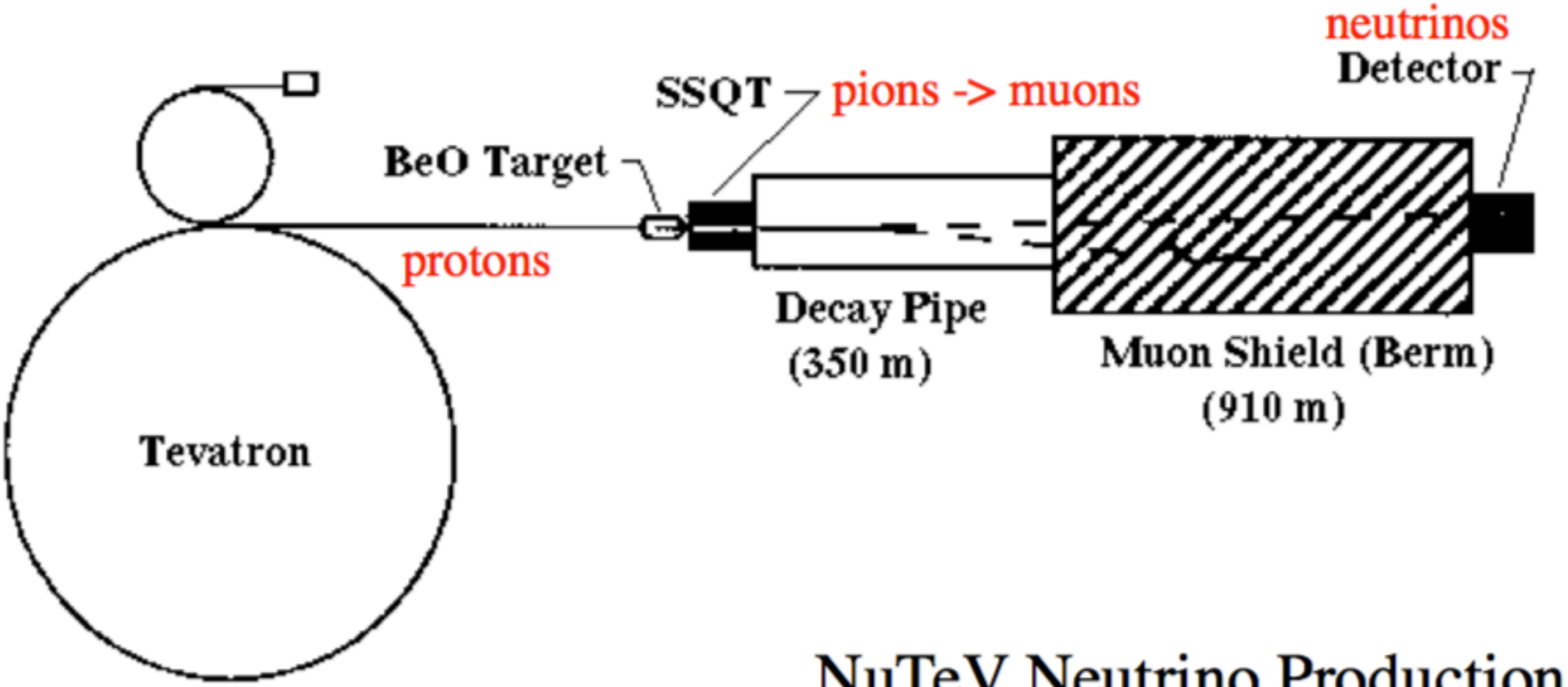






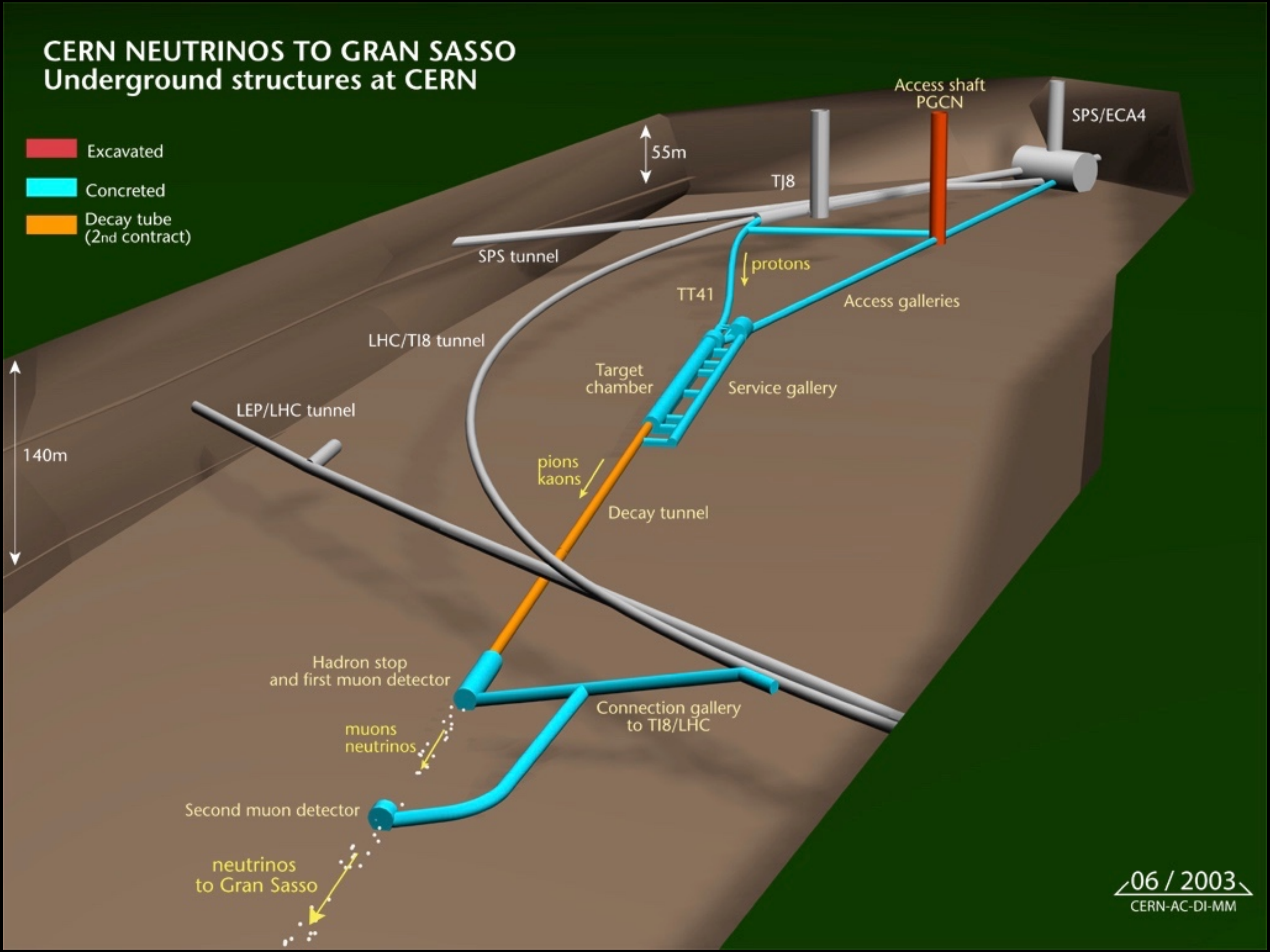


Production of secondary beams

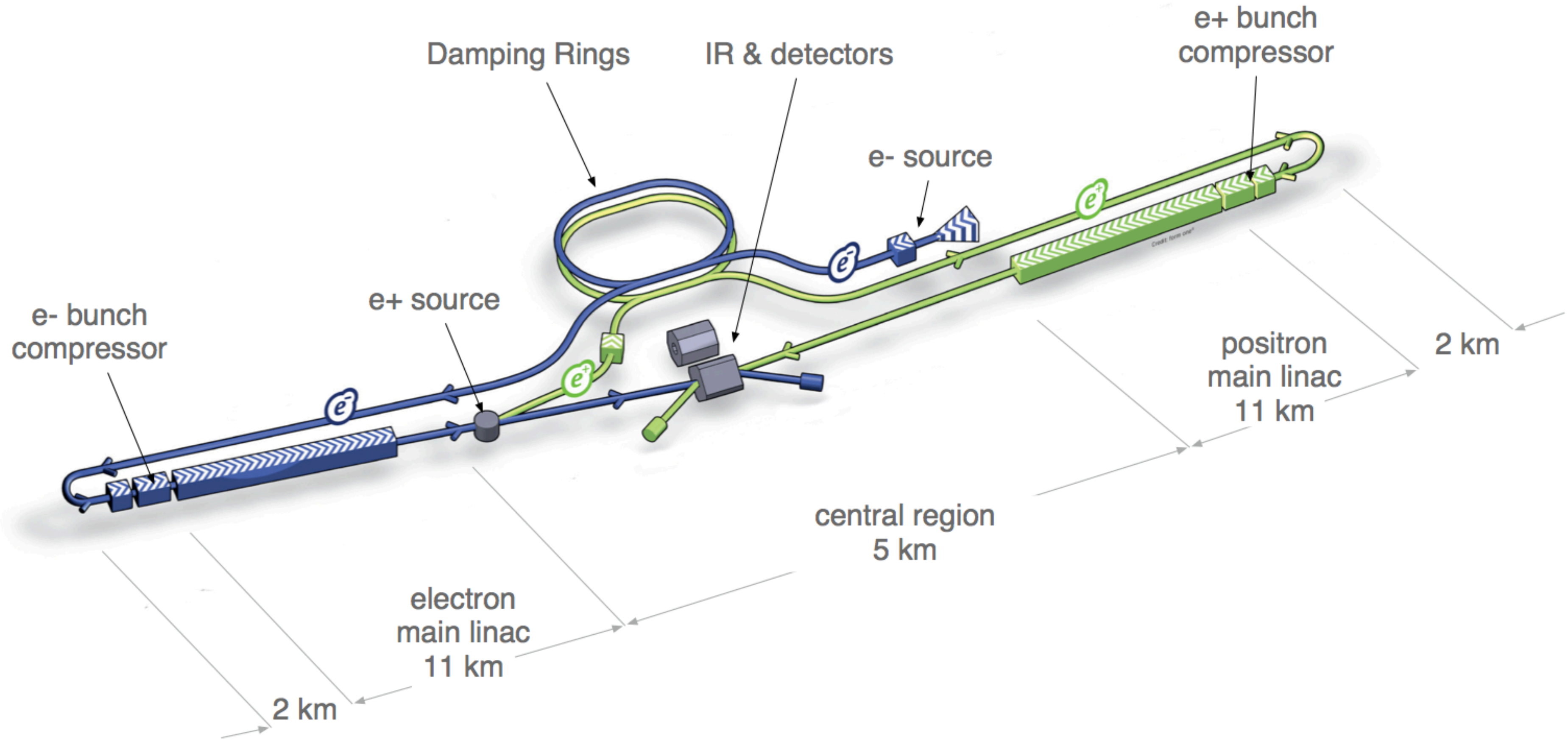


NuTeV Neutrino Production

Production of secondary beams



Future colliders? ILC



Damping Rings

IR & detectors

e+ bunch compressor

e- source

e- bunch compressor

e+ source

positron main linac 11 km

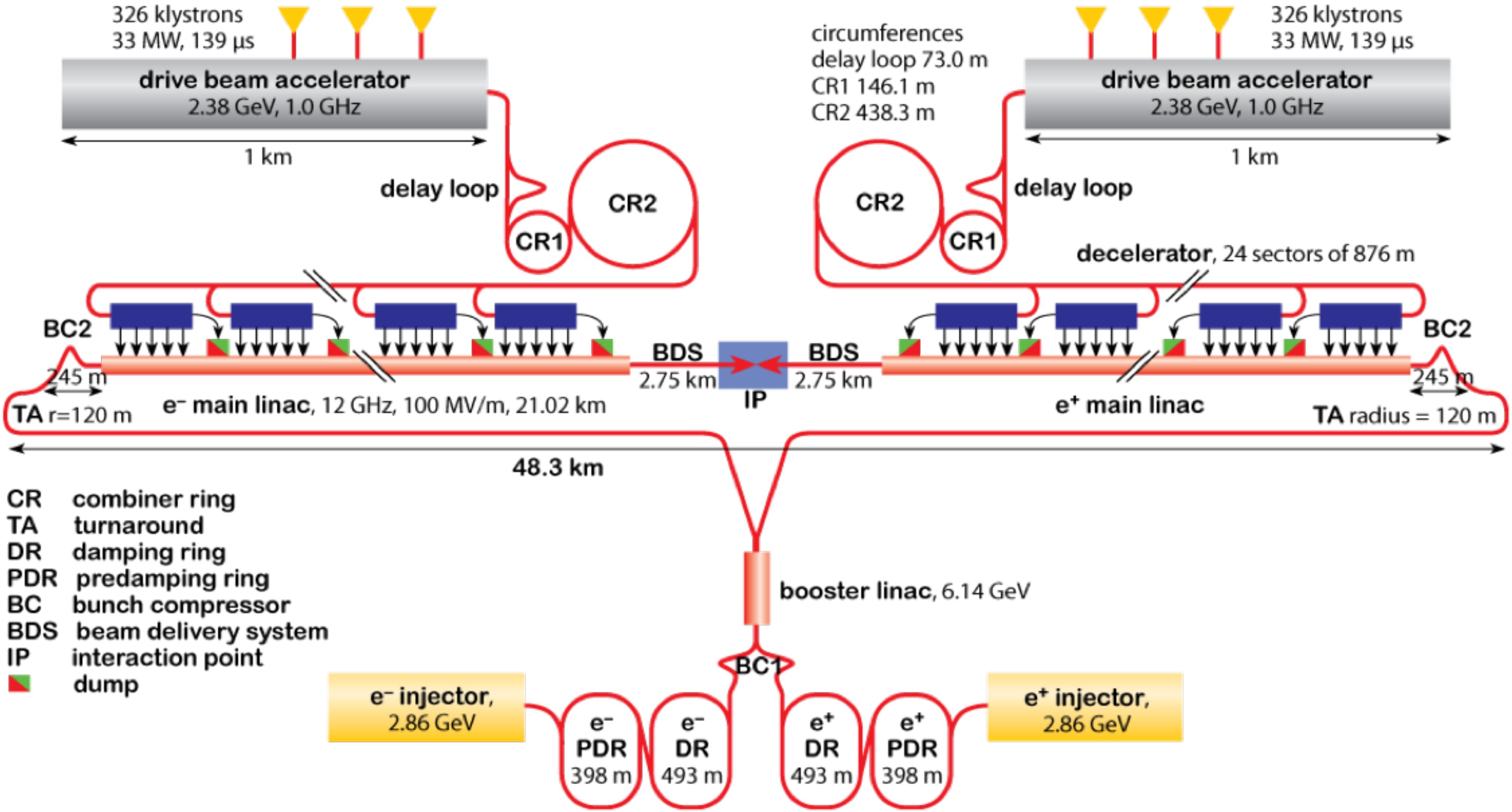
2 km

central region 5 km

electron main linac 11 km

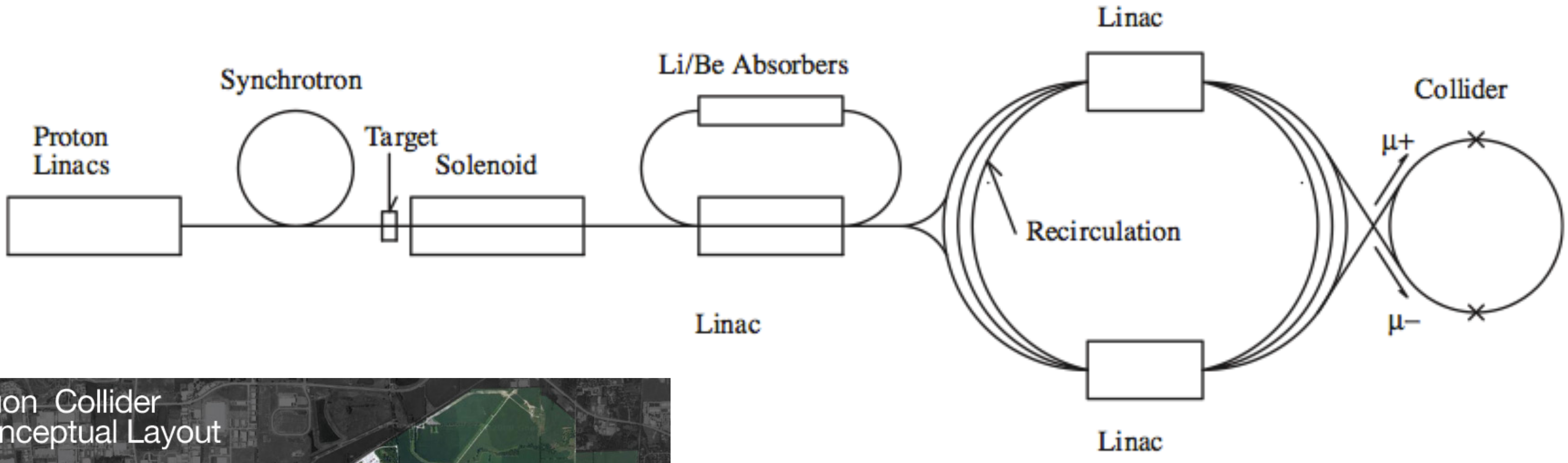
2 km

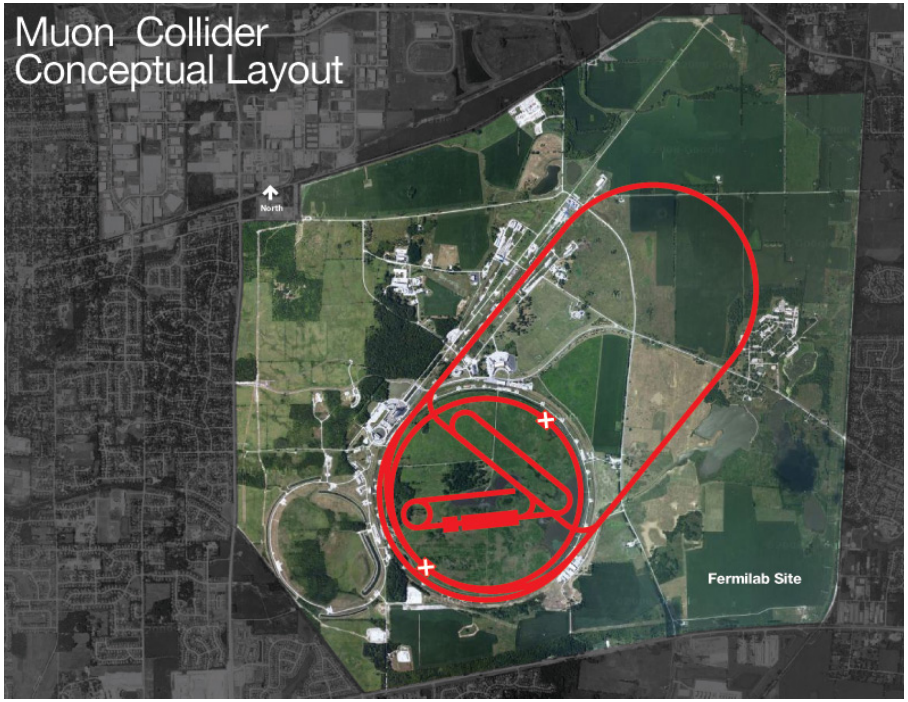
Future colliders? CLIC

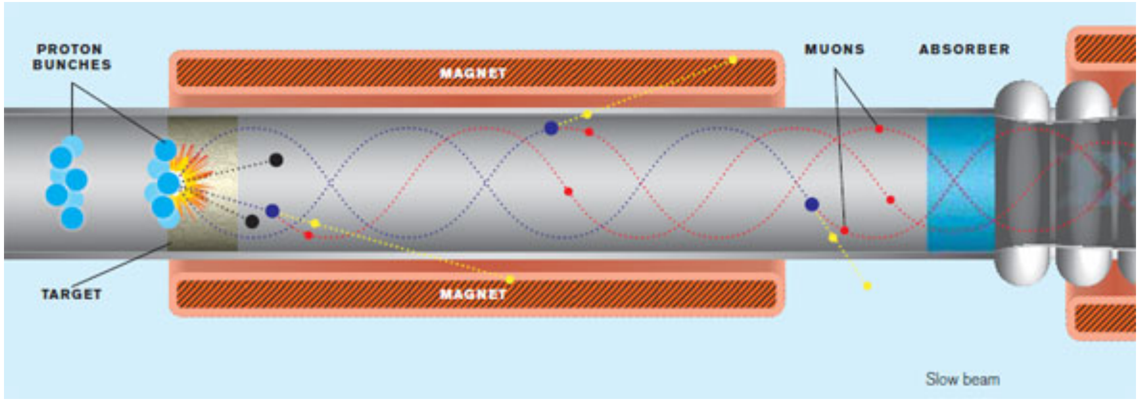


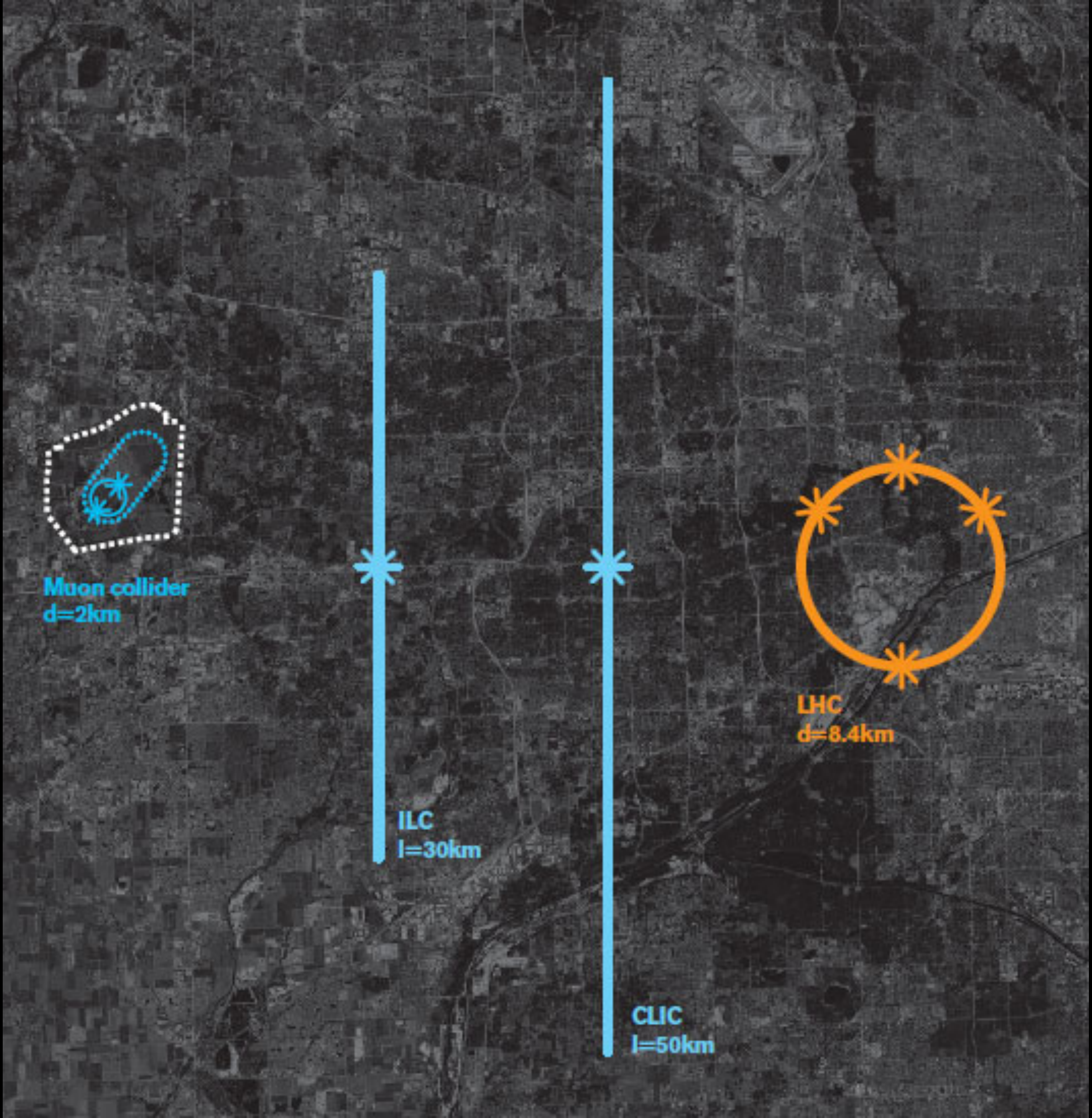
CR	combiner ring
TA	turnaround
DR	damping ring
PDR	predamping ring
BC	bunch compressor
BDS	beam delivery system
IP	interaction point
🟥	dump

Future colliders? Muon collider

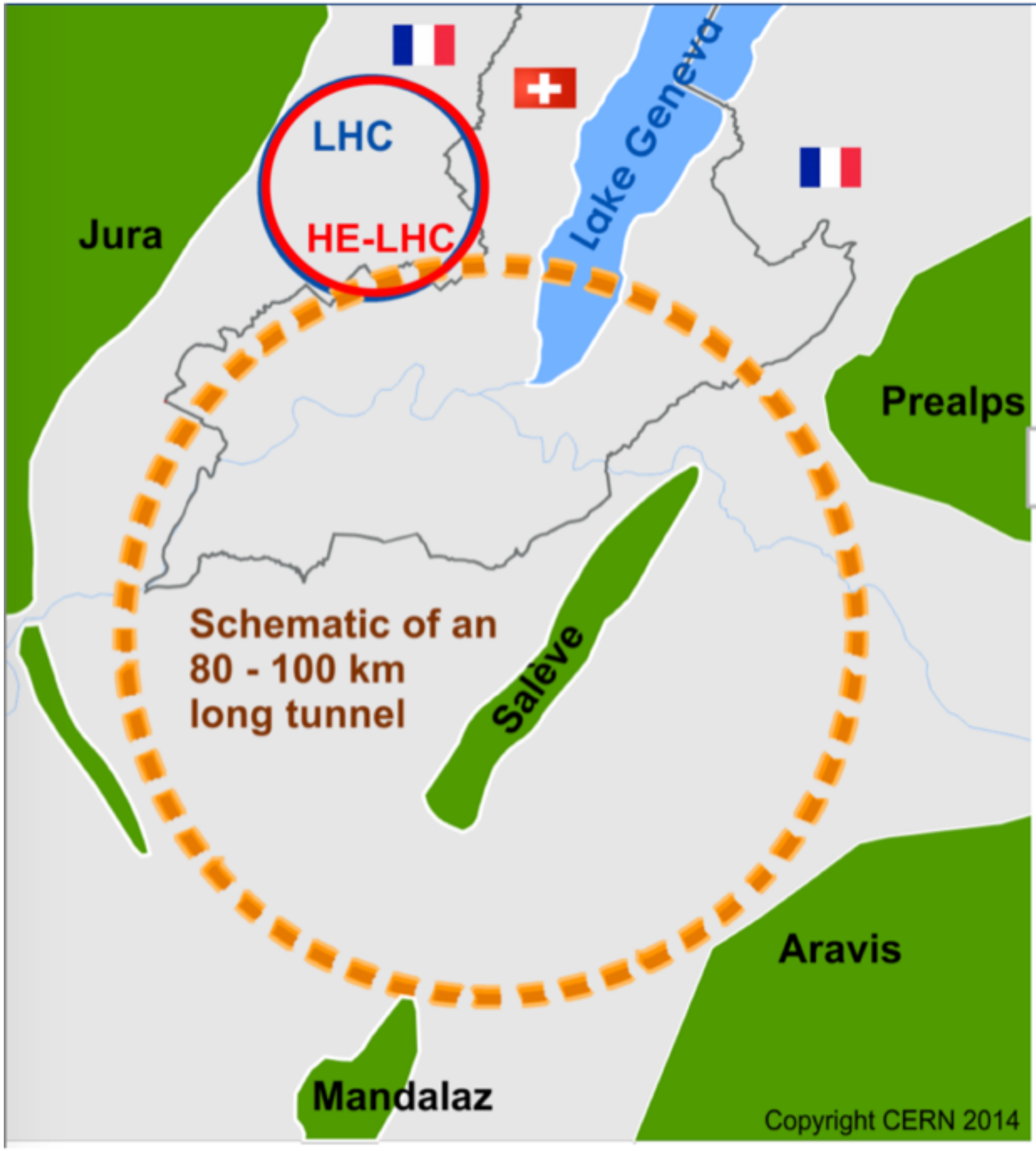







Muon collider
d=2km
ILC
l=30km
CLIC
l=50km
LHC
d=8.4km

Future Circular Collider (FCC)



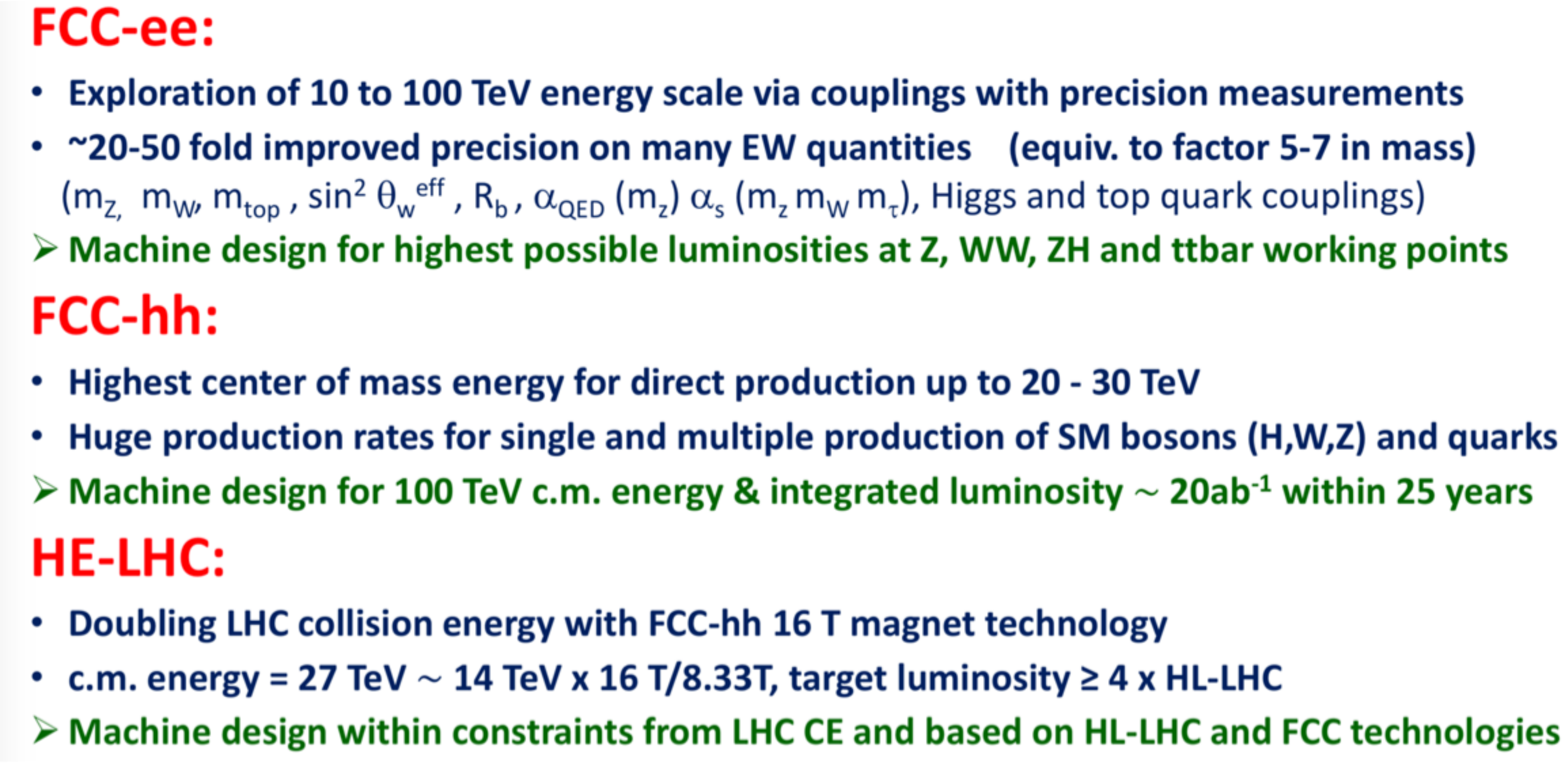
International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **~100 km tunnel infrastructure** in Geneva area, site specific
- **e^+e^- collider (*FCC-ee*),** as potential first step
- **HE-LHC** with *FCC-hh* technology
- ***p-e* (*FCC-he*) option,** IP integration, e^- from ERL

Future Circular Collider (FCC)



FCC-ee:

- **Exploration of 10 to 100 TeV energy scale via couplings with precision measurements**
- **~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass)** ($m_{Z,}$ m_W, m_{top}, $\sin^2 \theta_w^{eff}$, R_b, α_{QED} (m_z) α_s (m_z m_W m_τ), Higgs and top quark couplings)

➢ **Machine design for highest possible luminosities at Z, WW, ZH and ttbar working points**

FCC-hh:

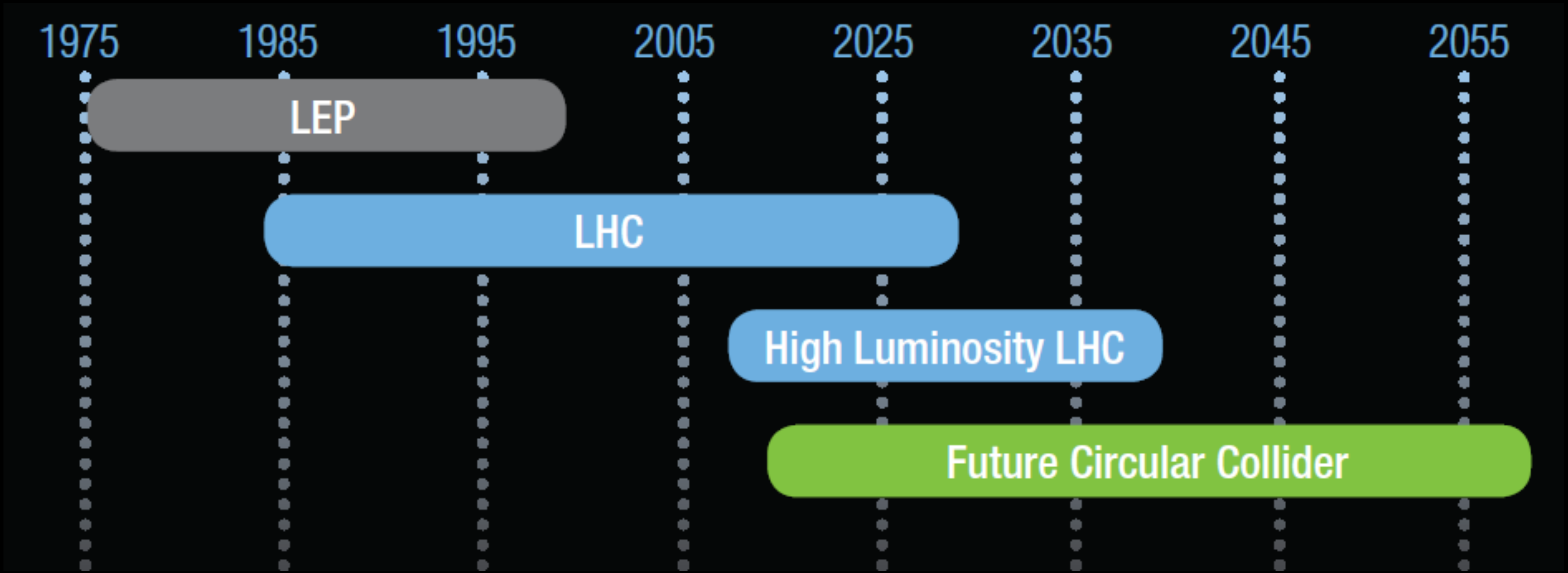
- **Highest center of mass energy for direct production up to 20 - 30 TeV**
- **Huge production rates for single and multiple production of SM bosons (H,W,Z) and quarks**

➢ **Machine design for 100 TeV c.m. energy & integrated luminosity ~ 20ab^{-1} within 25 years**

HE-LHC:

- **Doubling LHC collision energy with FCC-hh 16 T magnet technology**
- **c.m. energy = 27 TeV ~ 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC**

➢ **Machine design within constraints from LHC CE and based on HL-LHC and FCC technologies**


1975
1985
1995
2005
2025
2035
2045
2055
LEP
LHC
High Luminosity LHC
Future Circular Collider