Experimental particle physics

European School of Instrumentation
in Particle & Astroparticle Physics

2.

a few things about particle accelerators

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

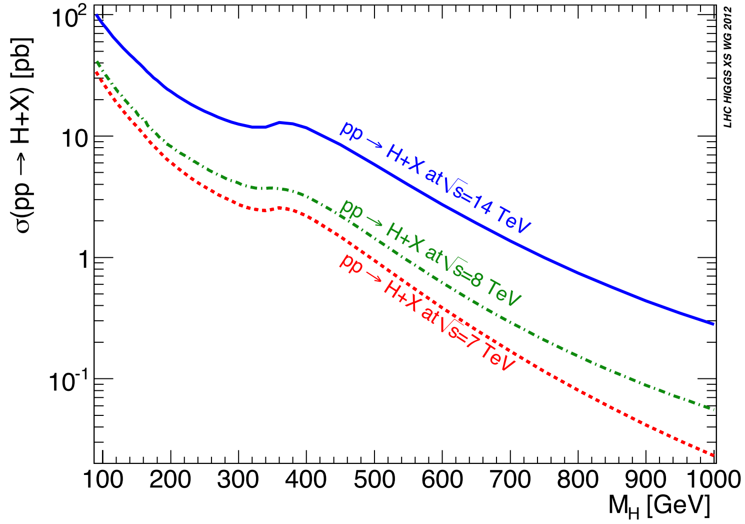
Number of events
in unit of time

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

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

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

$\sigma(pp \to H+X) \sim 20$ 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

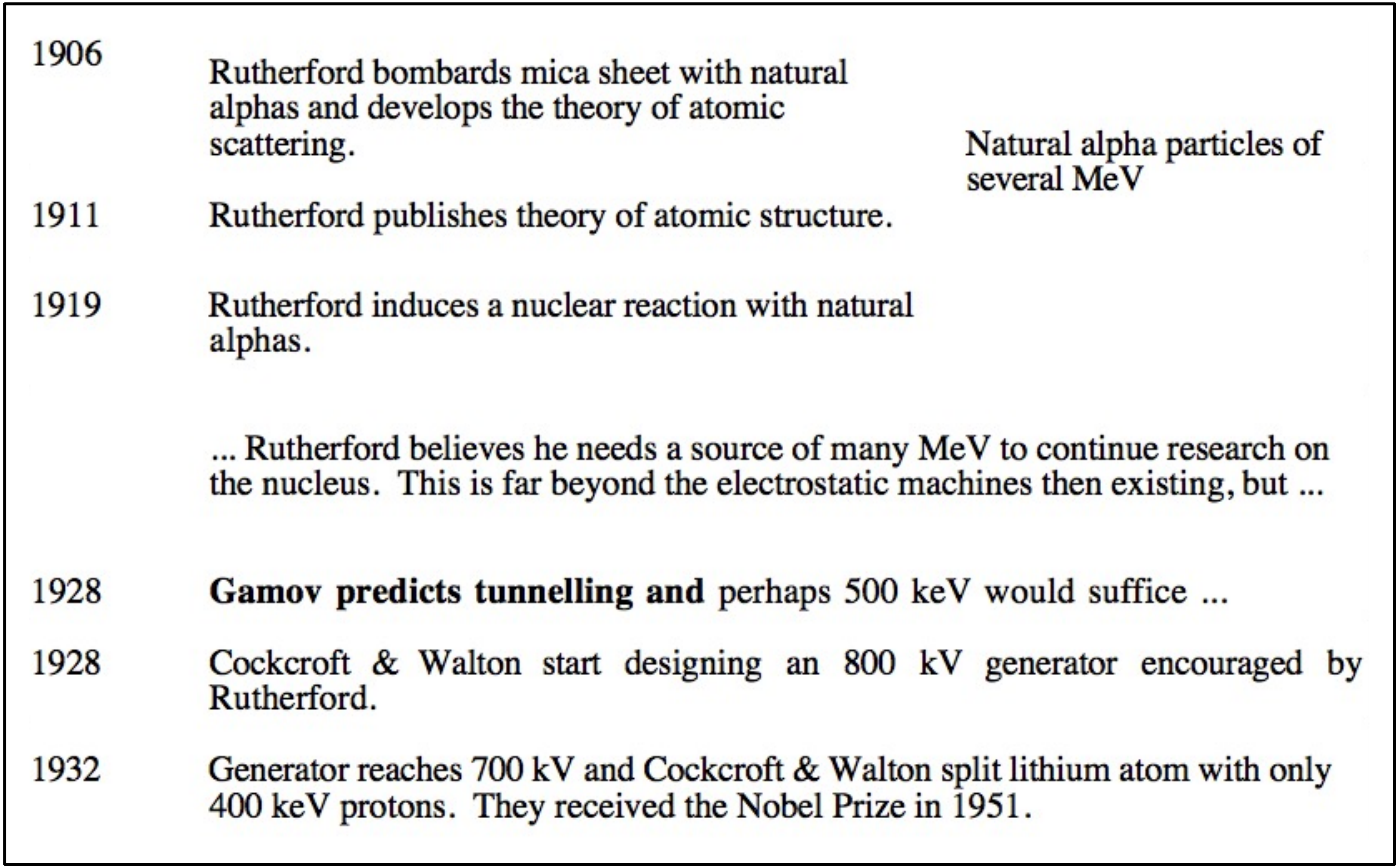
$$\vec{F}_L = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

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

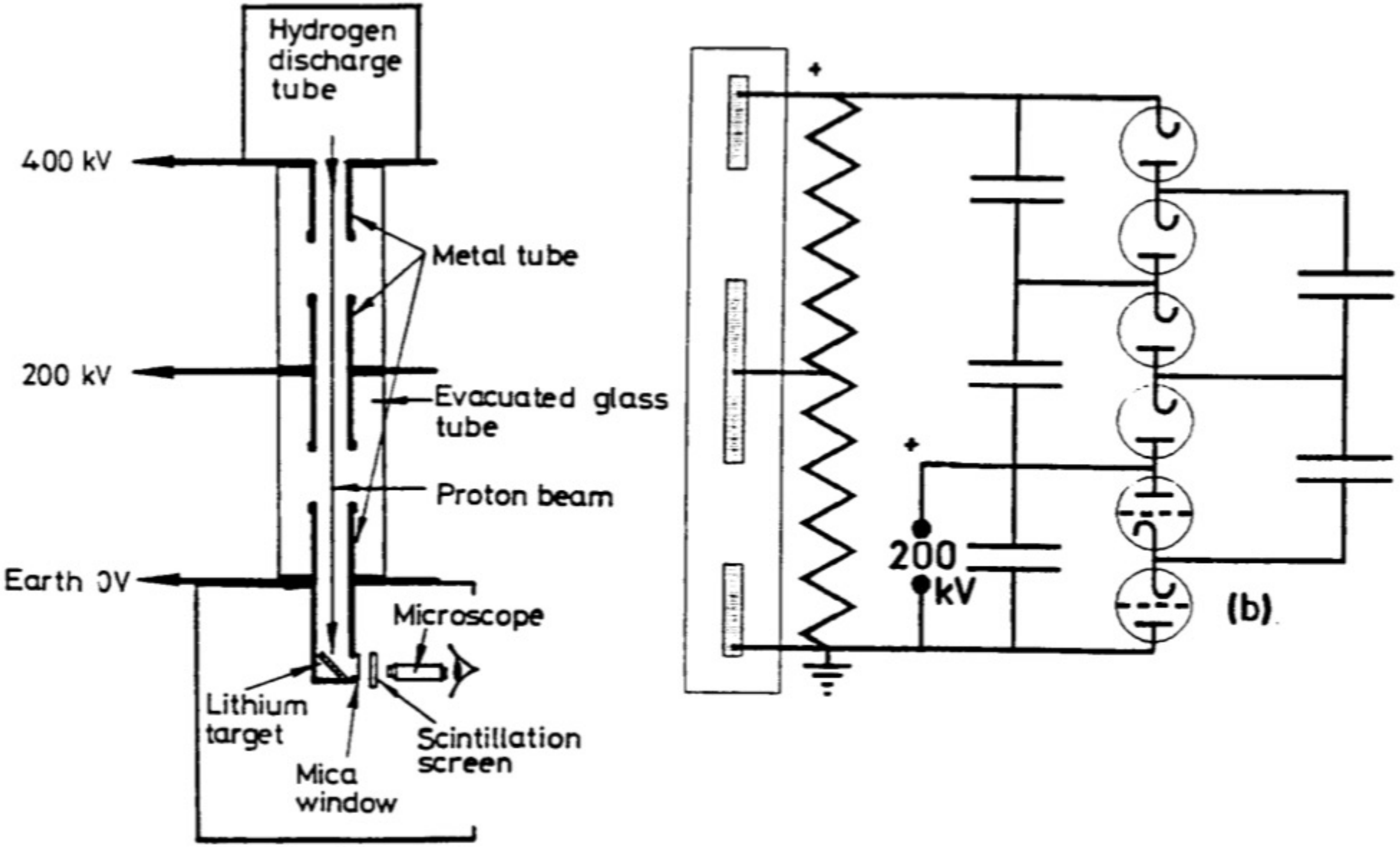


1906	Rutherford bombards mica sheet with natural alphas and develops the theory of atomic scattering.
1911	Rutherford publishes theory of atomic structure.
1919	Rutherford induces a nuclear reaction with natural alphas.
	... Rutherford believes he needs a source of many MeV to continue research on the 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.

Natural alpha particles of several MeV

(inspired by "A brief history and review of accelerators" by P.J Bryant https://cds.cern.ch/record/261062/)

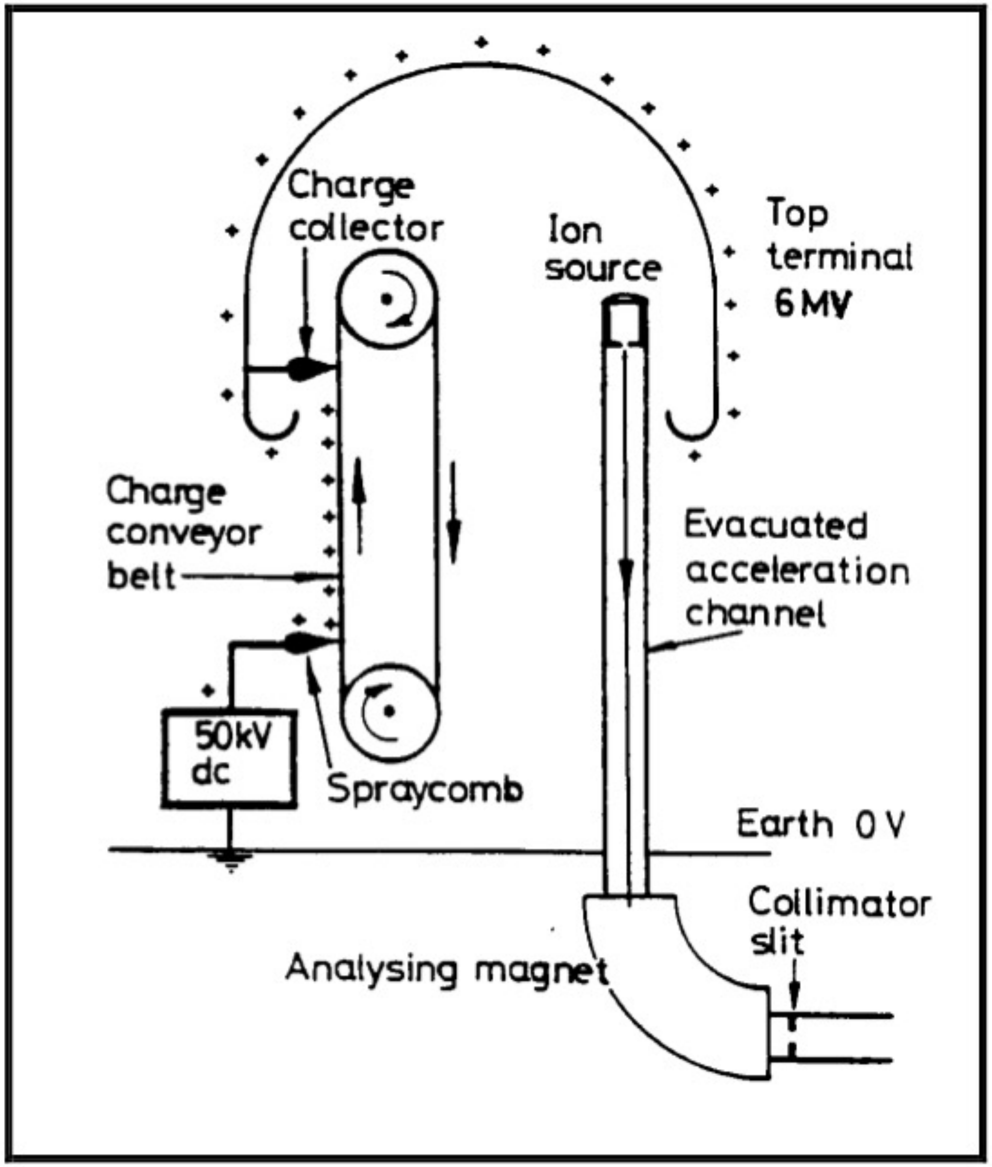
Cockcroft and Walton's apparatus



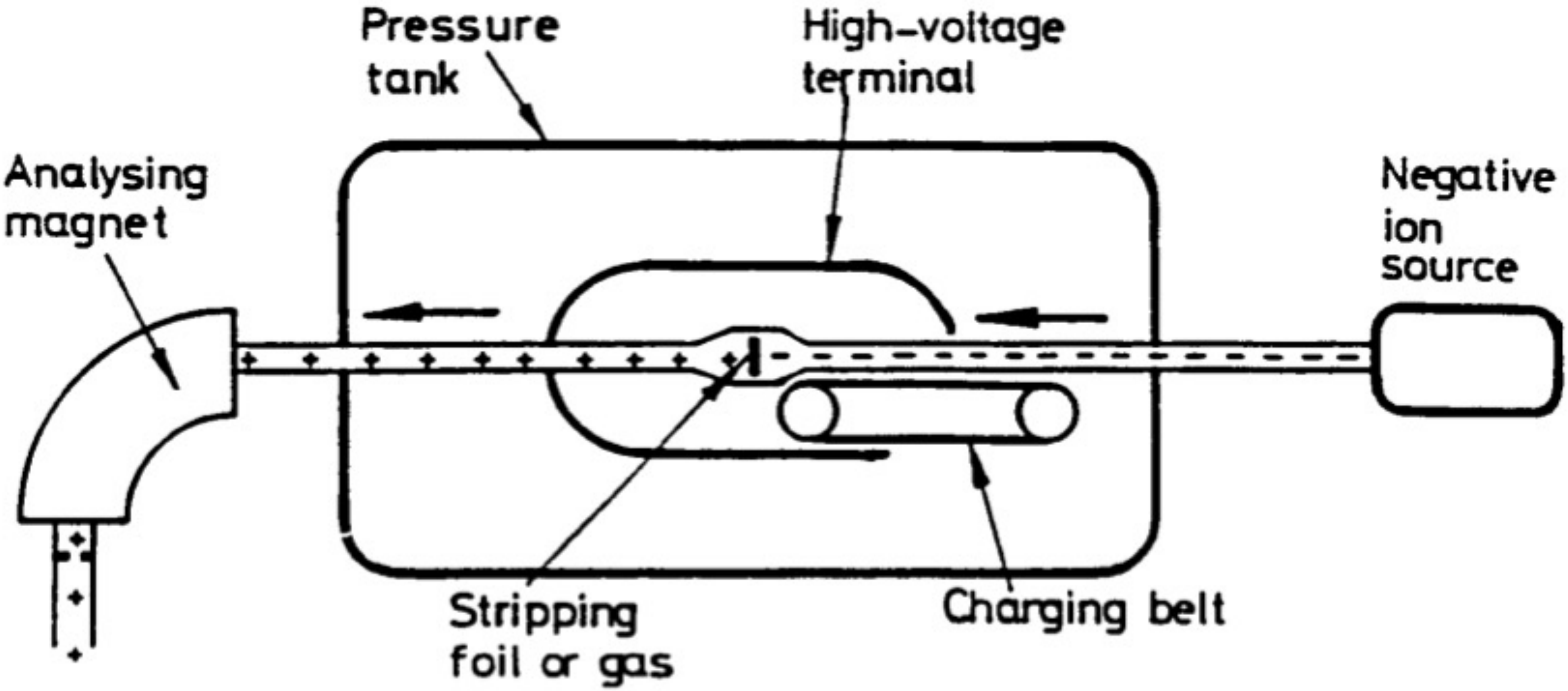
(a) Accelerating column

(b) DC generator

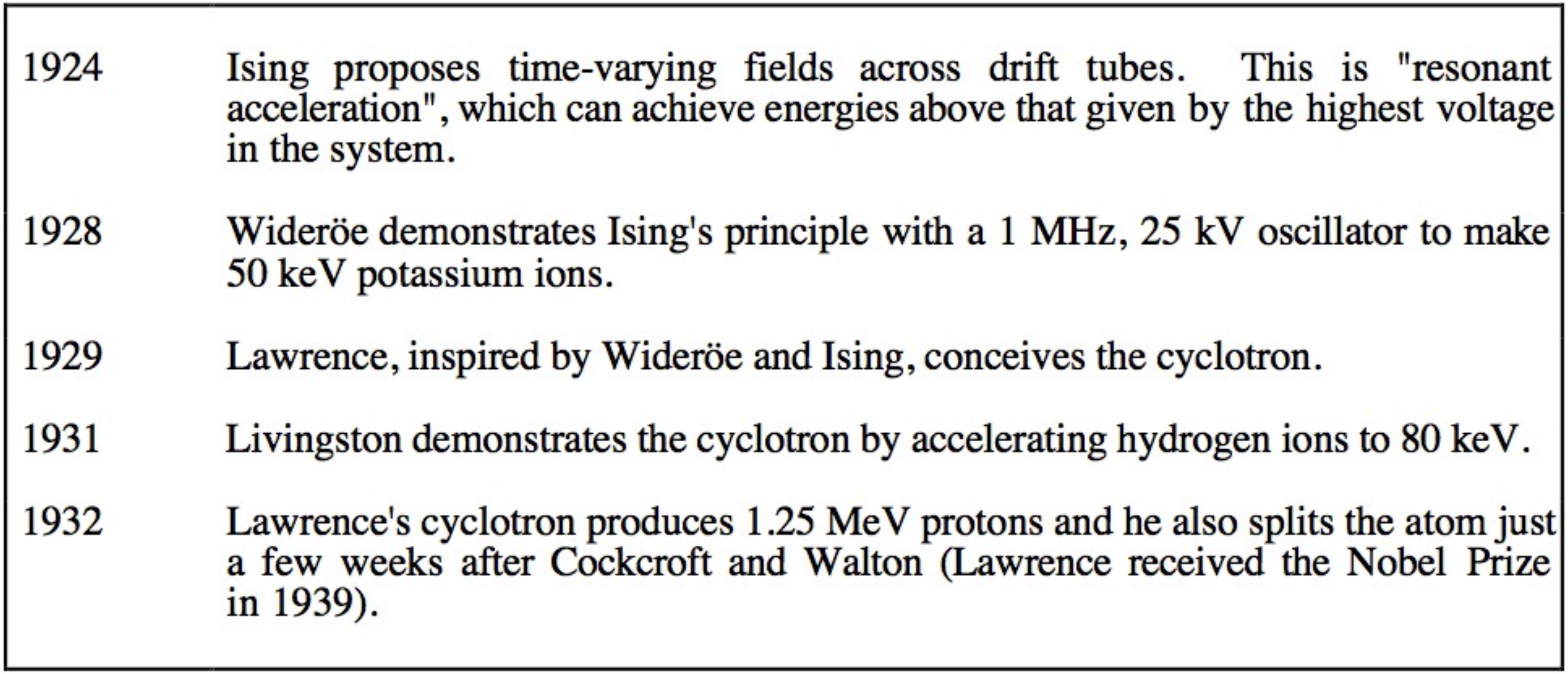
Van de Graaff electrostatic generator



Two-stage Tandem accelerator

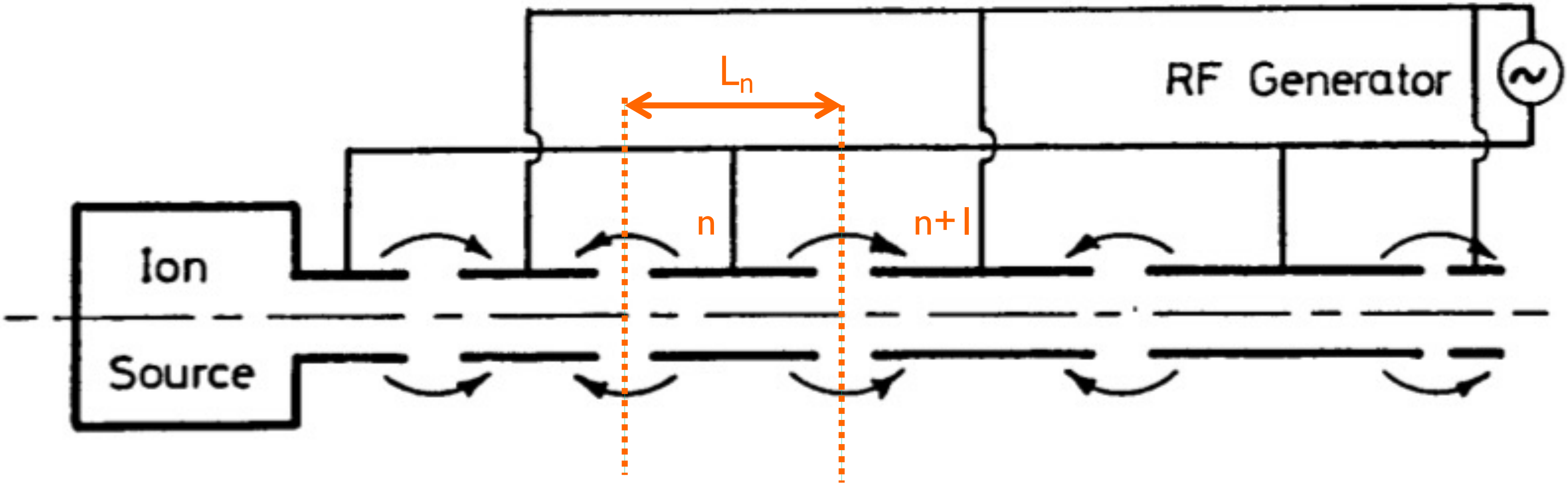


A brief history of particle accelerators – part 2

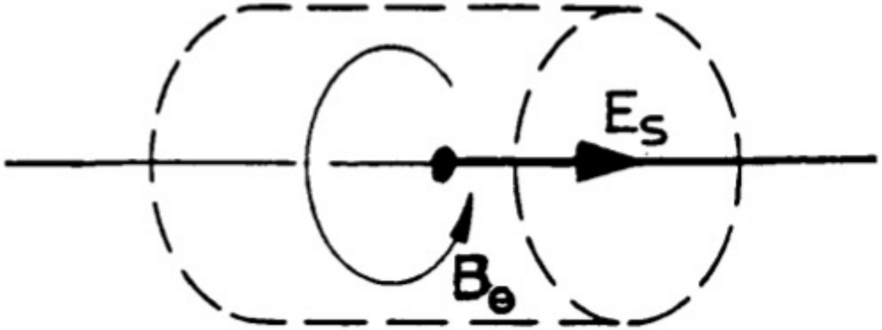


1924	Ising proposes time-varying fields across drift tubes. This is "resonant acceleration", which can achieve energies above that given by the highest voltage in the system.
1928	Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions.
1929	Lawrence, inspired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

LINAC lenght

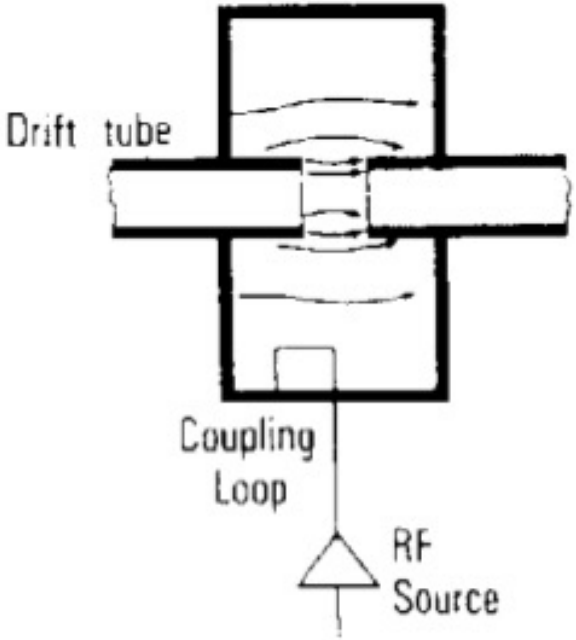
Total LINAC length

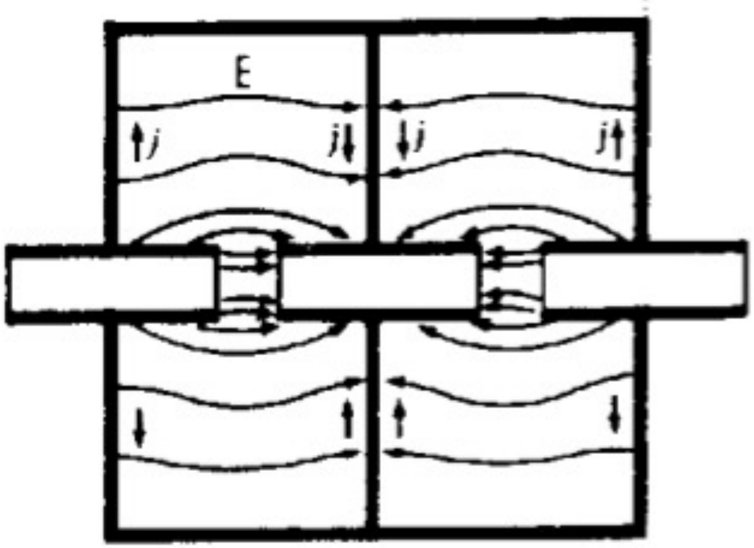
$$L = \frac{k}{\underbrace{\Delta E}_{\text{energy gain per gap}}} \sqrt{\frac{\overbrace{E^3}^{\text{final particle energy}}}{\underbrace{A}_{\text{ion atomic number}} mc^2}} \, \frac{\lambda}{2}$$

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

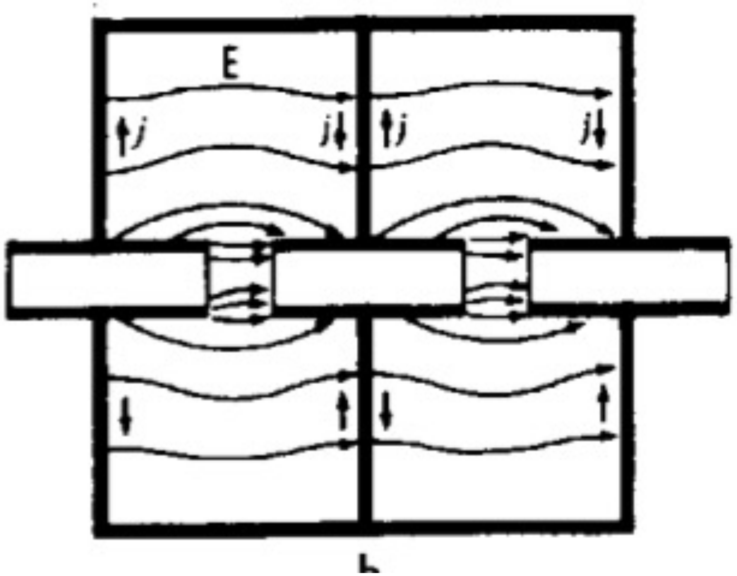
RF cavities

- 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



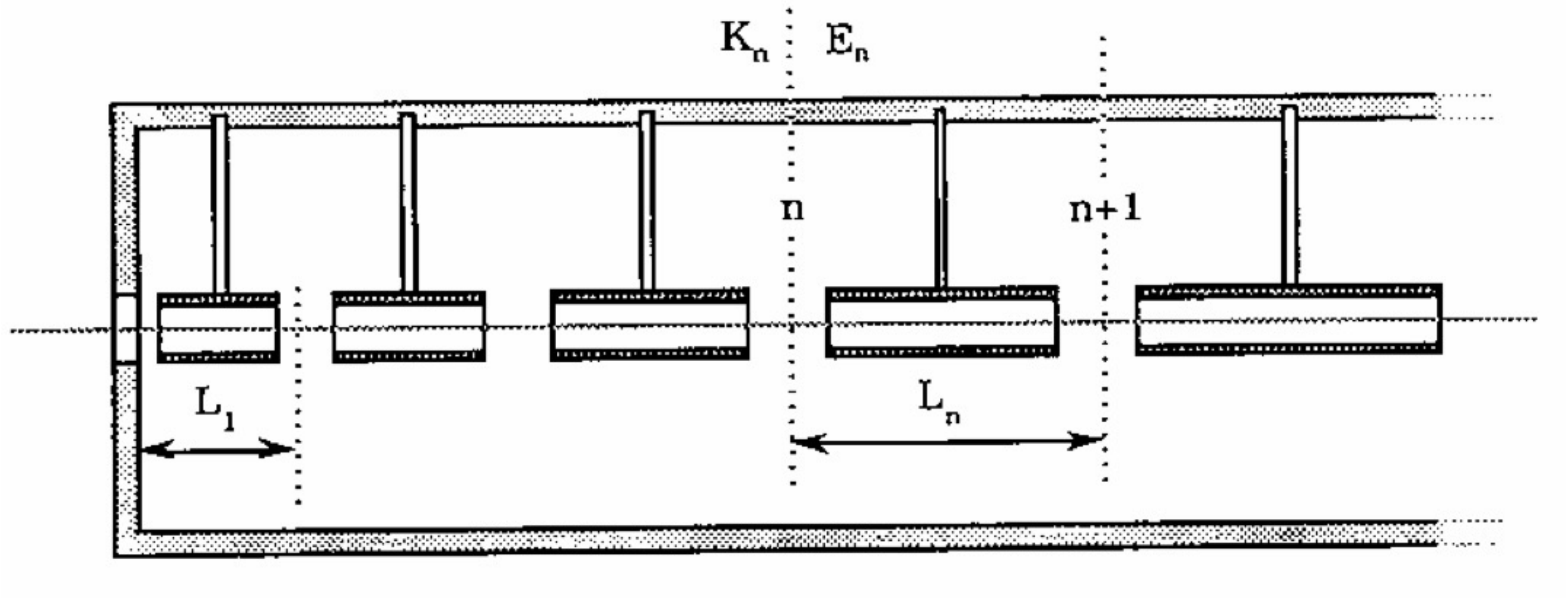


k=1



k=2

Alvarez structure



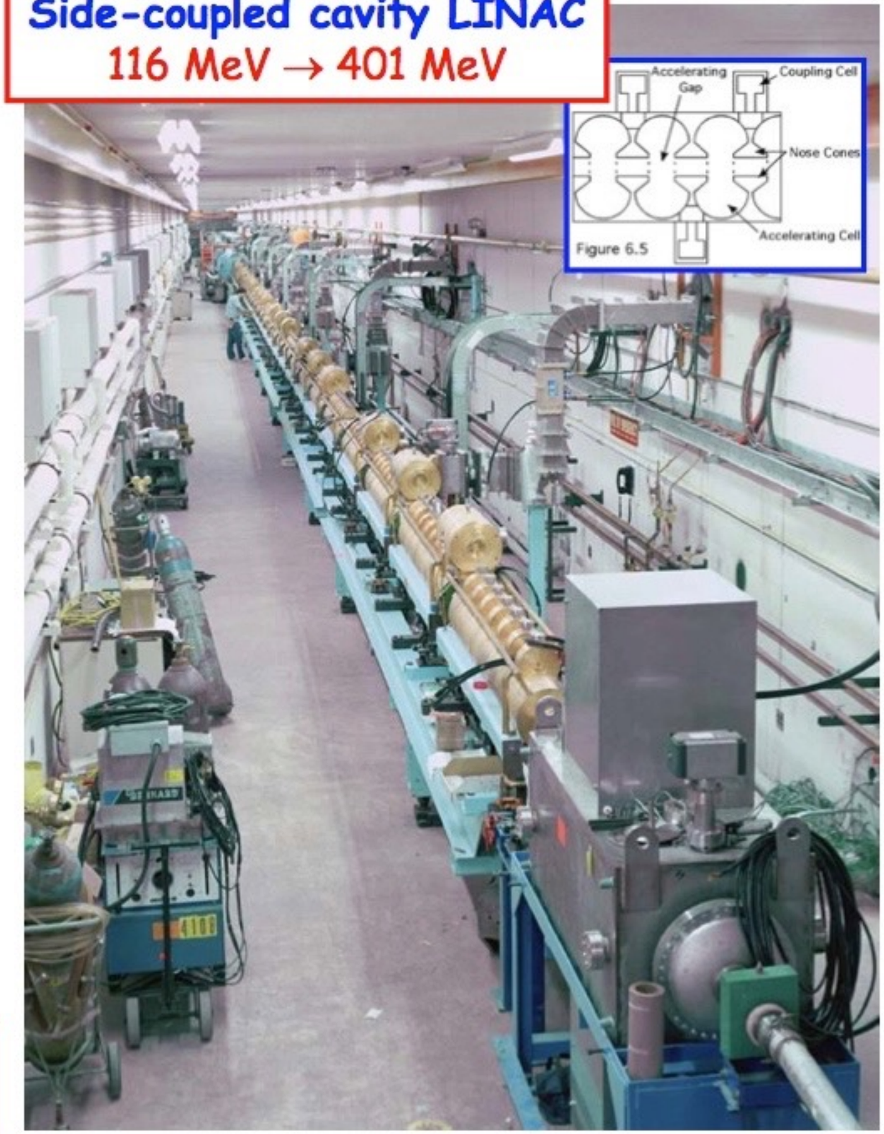
$k = 2$, ν_{RF} ~100 MHz , $\lambda < L$

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!

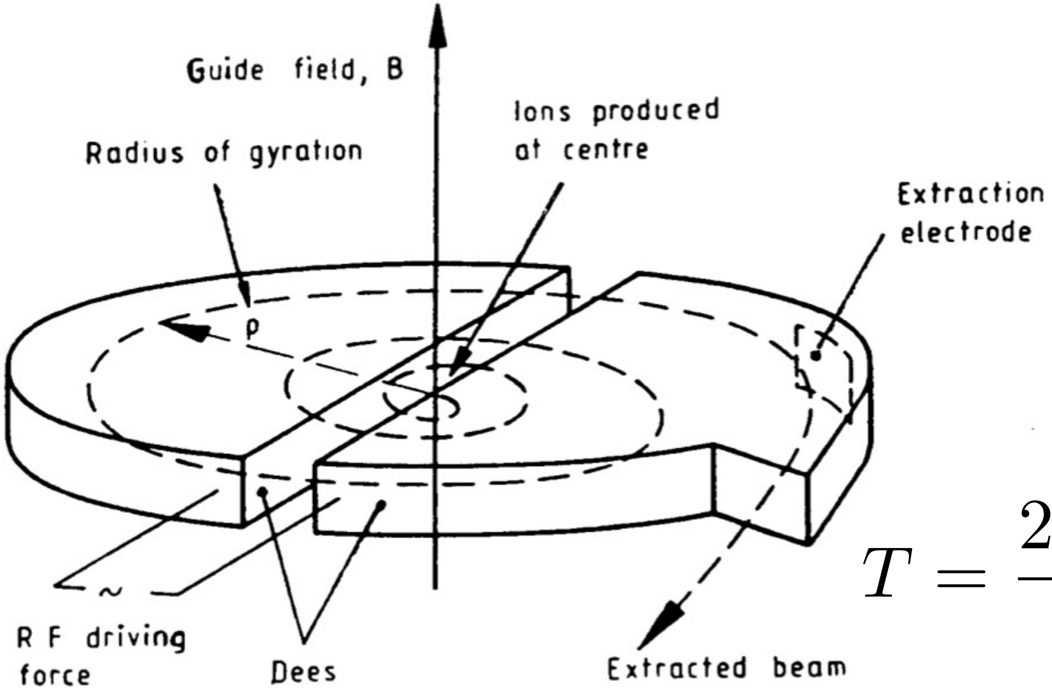
Example: Fermilab LINAC

Drift tube (Alvarez) LINAC
750 keV → 116 MeV



Side-coupled cavity LINAC
116 MeV → 401 MeV

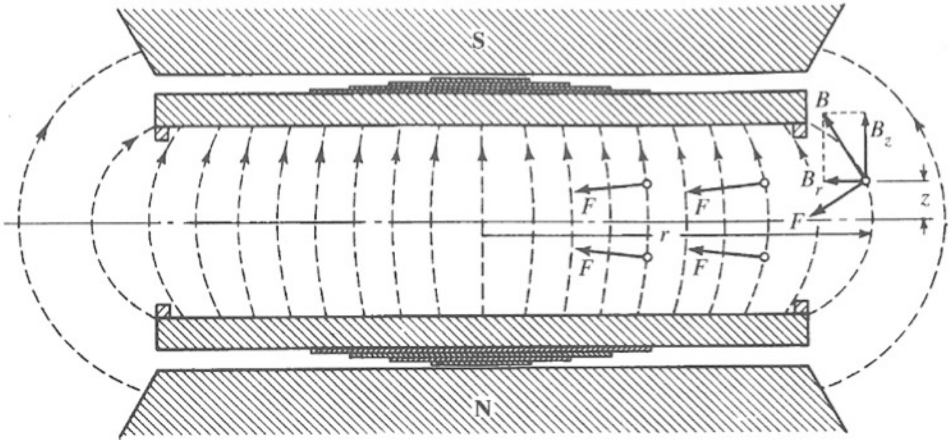
(Syncro) Cyclotron



$$p = m\gamma\beta$$

$$p = eBR$$

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



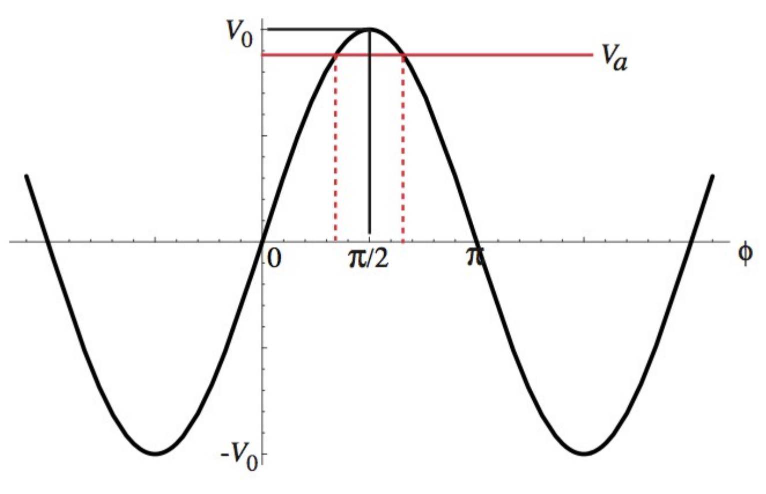
for relativistic particle cyclotron frequency should be adjusted to speed/energy (syncro-cyclotron)

weak focusing

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

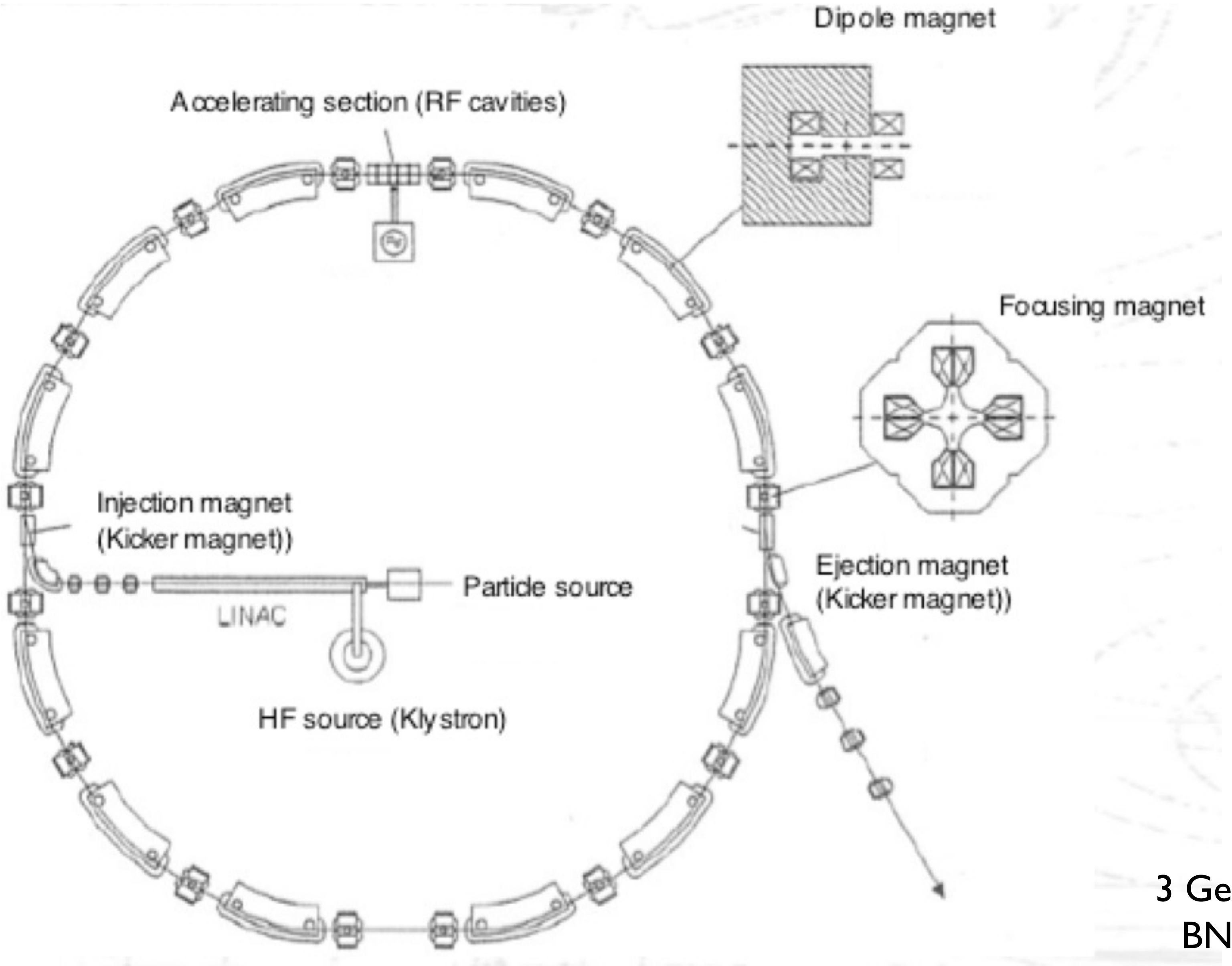
The road toward syncrotrons

- Problems in RF acceleration in the 1940s…
  - ✓ Linacs
    - Poor RF sources; electron tube technology was yet in its infancy
  - ✓ Cyclotrons
    - Relativistic effects → asynchronous RF
- 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
    - Veksler (1944) and McMillan (1945)
  - ✓ **Cyclotron → synchrocyclotron → synchrotron**



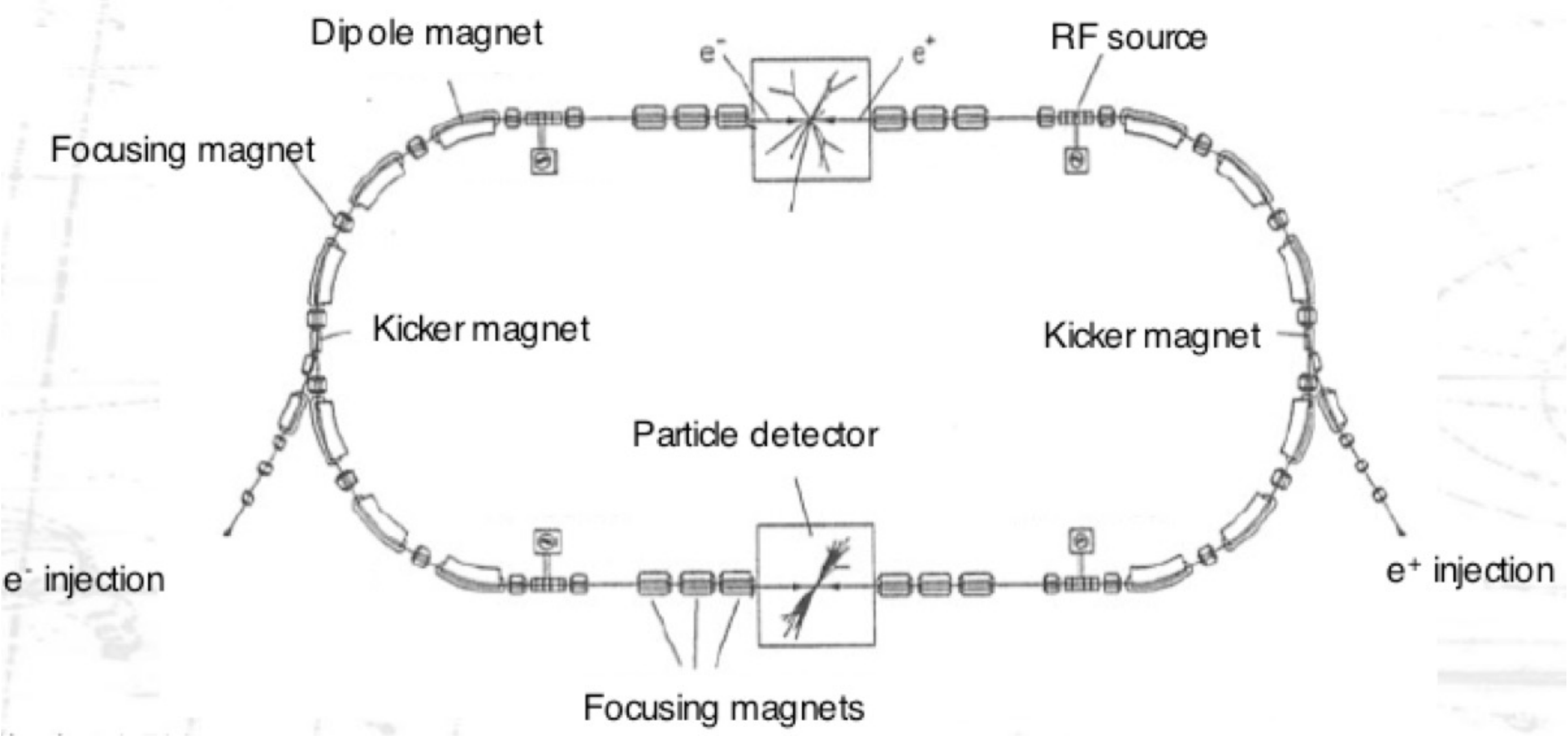
- Particles of different energies have differences in velocity and in orbit length
  - ✓ particles may be asynchronous wrt RF frequency
- RF field have however a restoring force at a certain phase, around which asynchronous particles be captured in bunches

Syncrotron

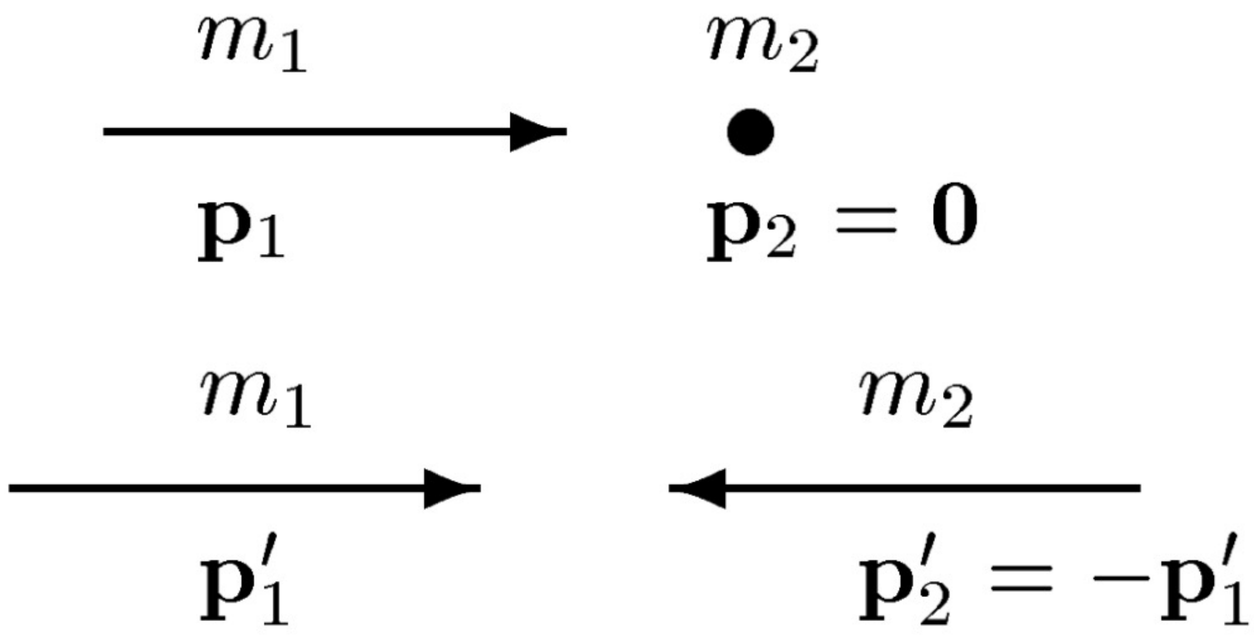


3 GeV protons
BNL ~ 1950

Storage rings



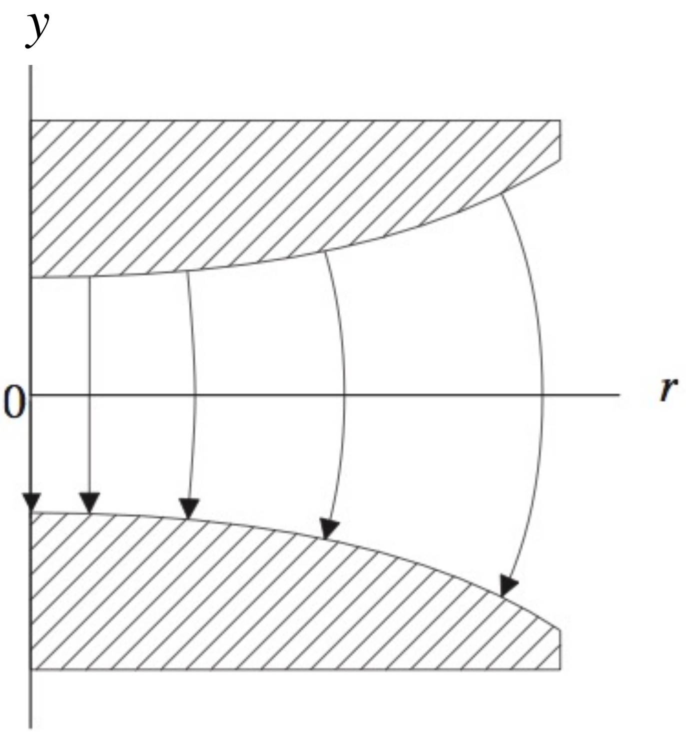
Fixed target vs. collider

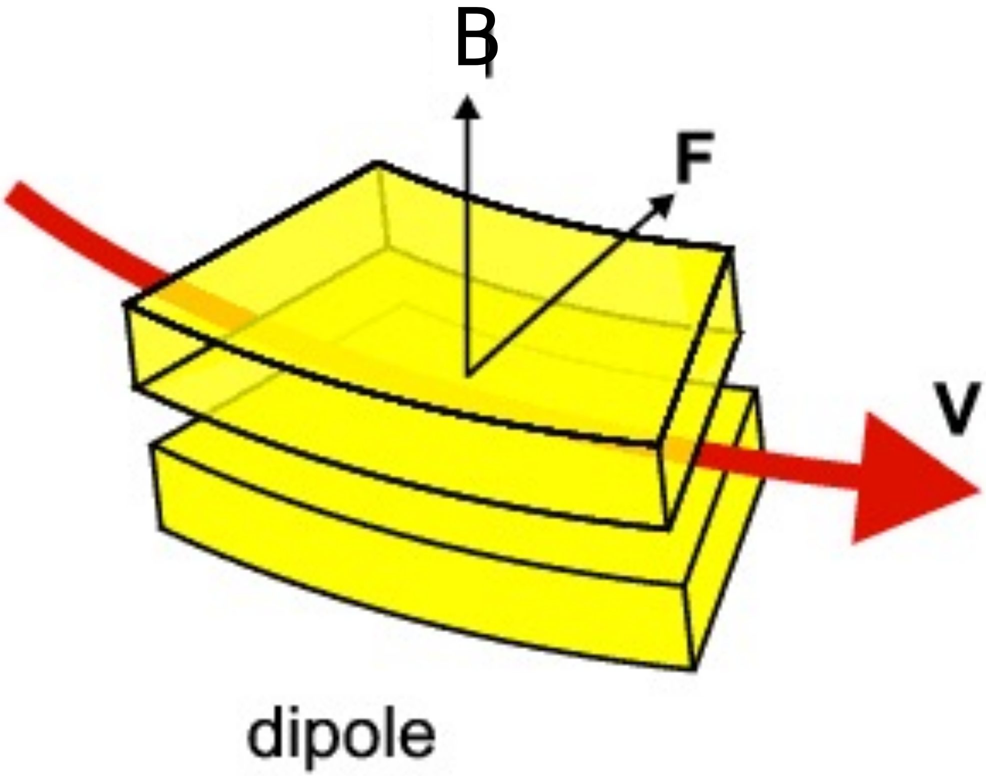


How much energy should a fixed target experiment have to equal the center of mass energy of two colliding beam?

$$E_{\text{fix}} = 2\frac{E_{\text{col}}^2}{m} - m$$

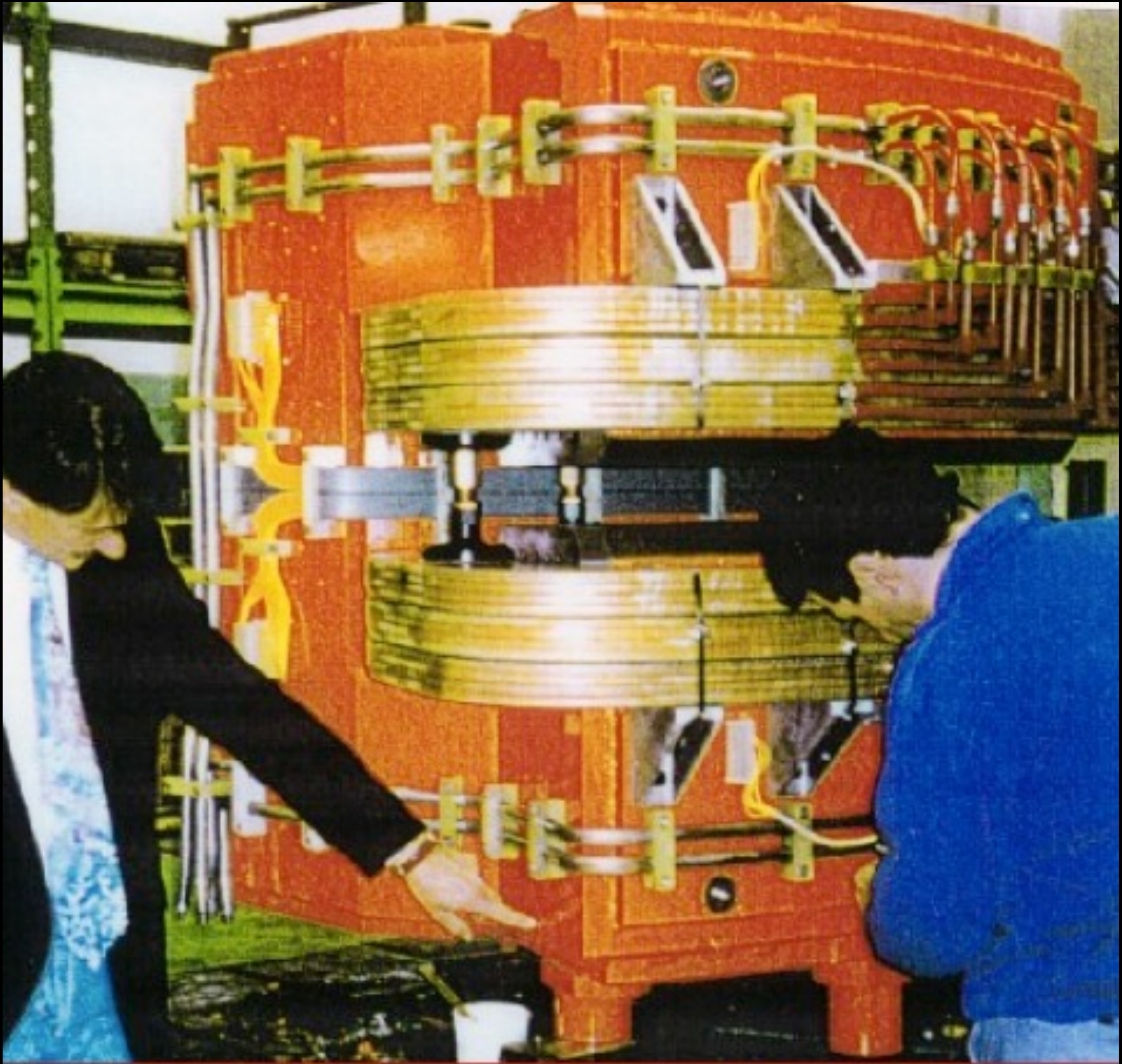
Bending: dipoles



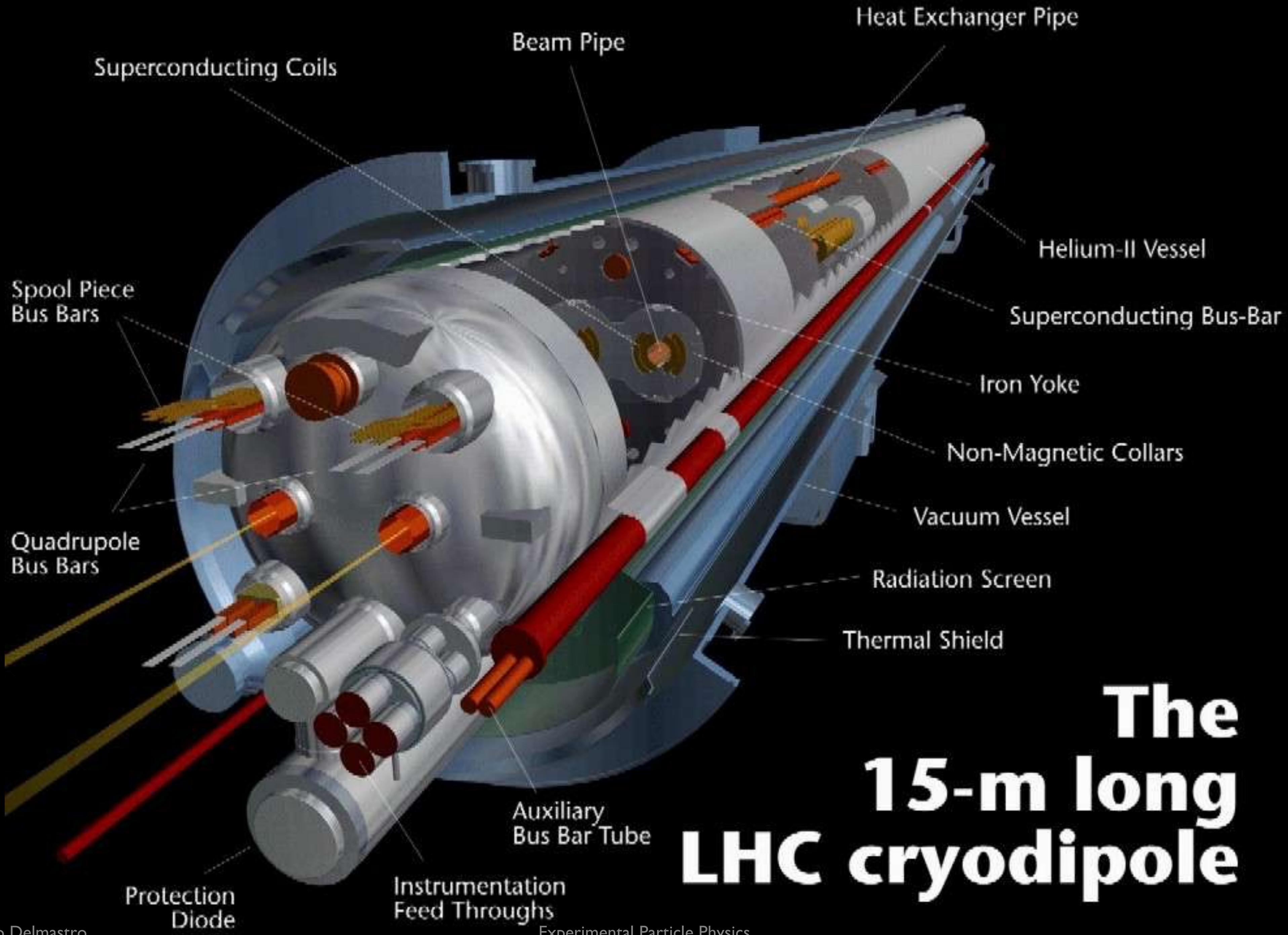


$B_x = 0$
$B_y = B$
$B_z = 0$

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

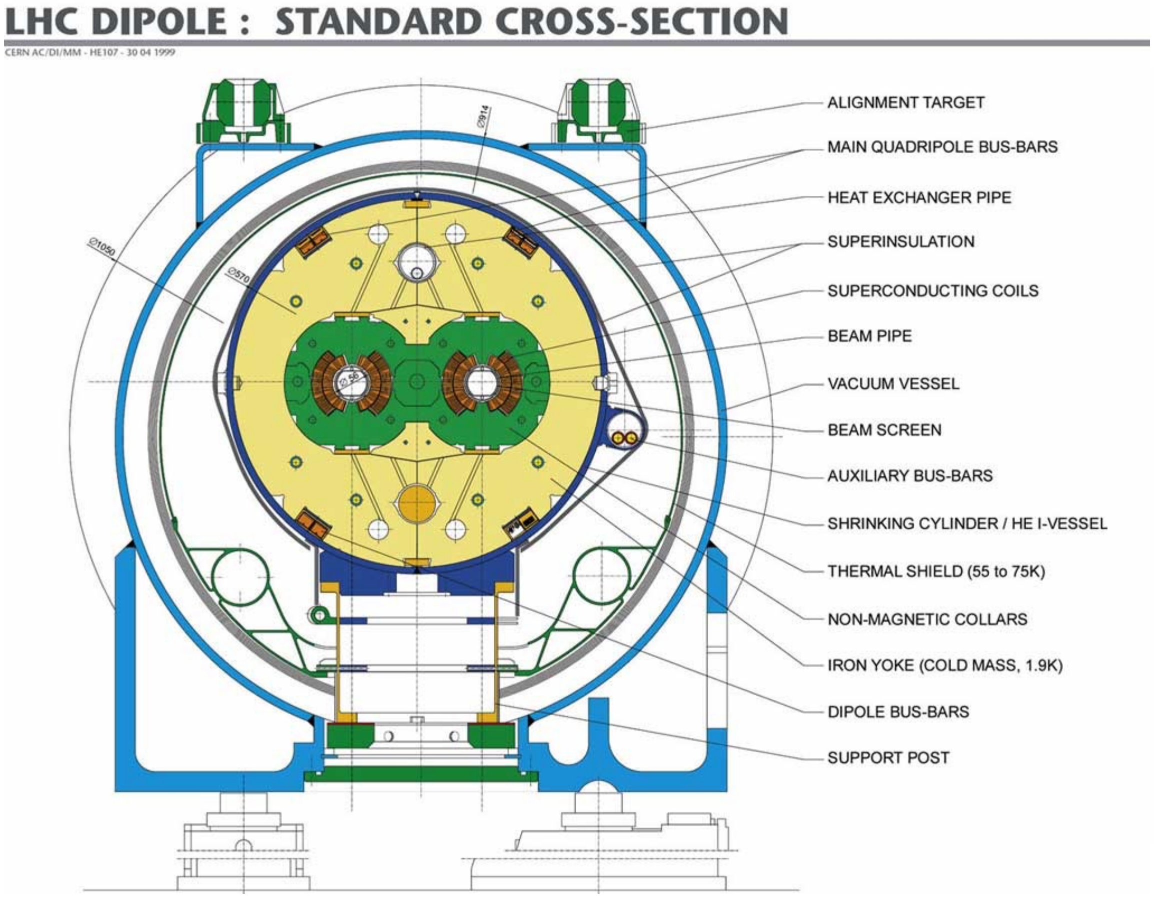


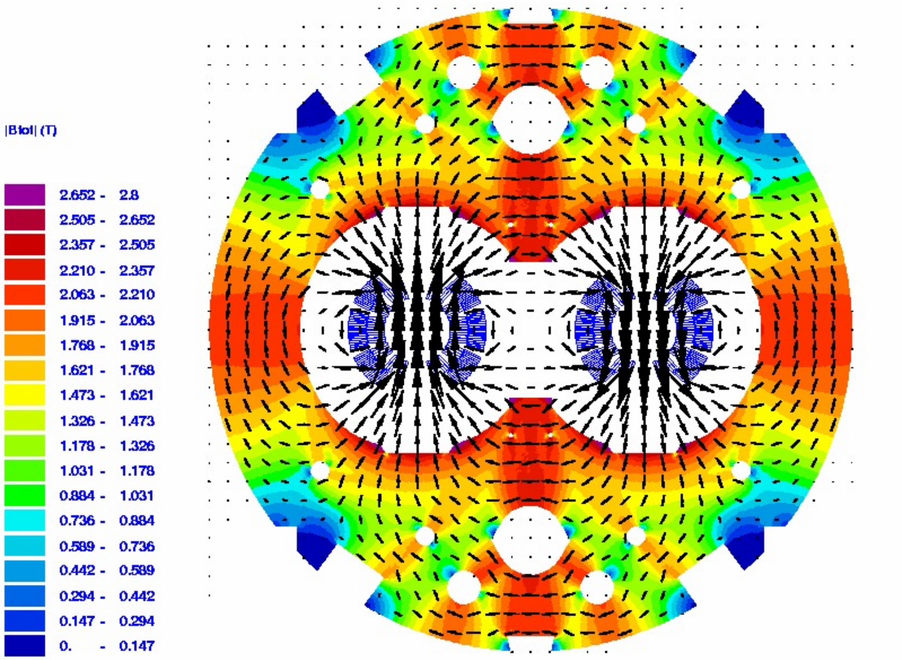

1136
21R8
BG
U



The 15-m long LHC cryodipole

LHC dipoles

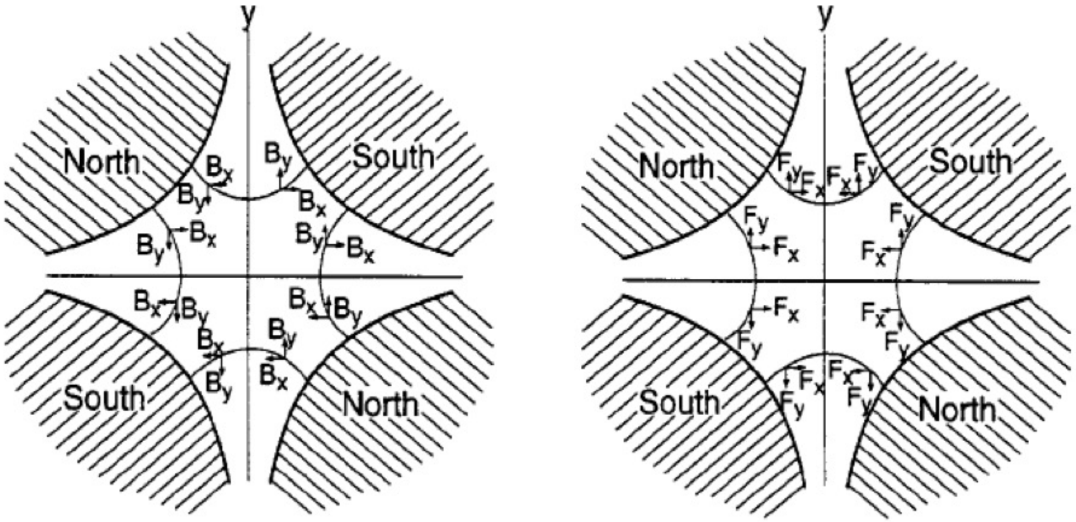

LHC DIPOLE : STANDARD CROSS-SECTION
CERN AC/DI/MM - HE107 - 30 04 1999
Ø914
Ø1050
Ø570
Ø56
ALIGNMENT TARGET
MAIN QUADRIPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
VACUUM VESSEL
BEAM SCREEN
AUXILIARY BUS-BARS
SHRINKING CYLINDER / HE I-VESSEL
THERMAL SHIELD (55 to 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

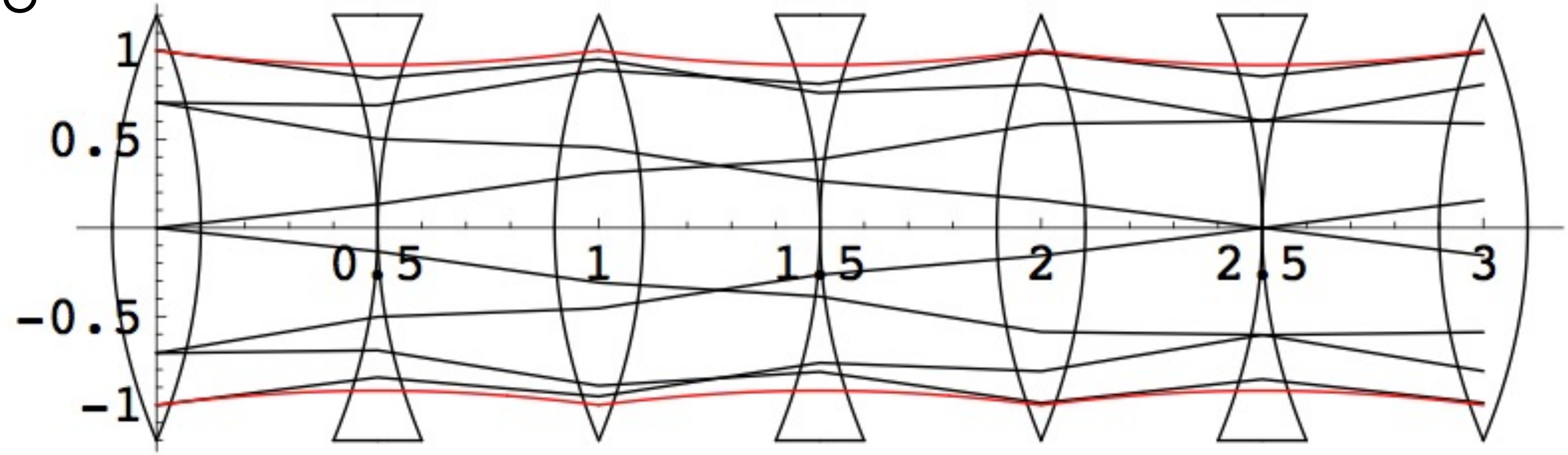
$B_x = -g \times x$
$B_y = -g \times y$
$B_z = 0$

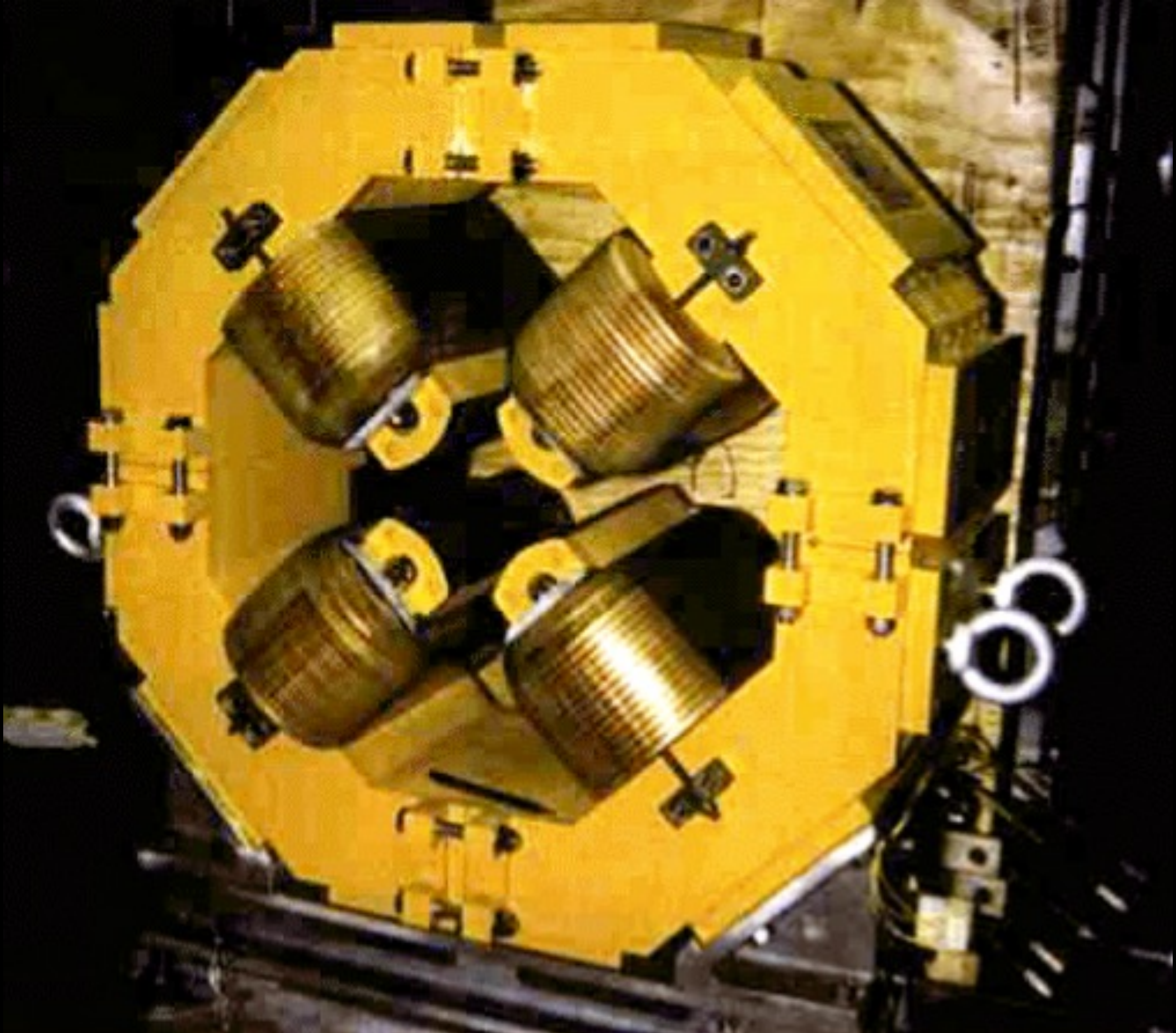
g[T/n] = field gradient



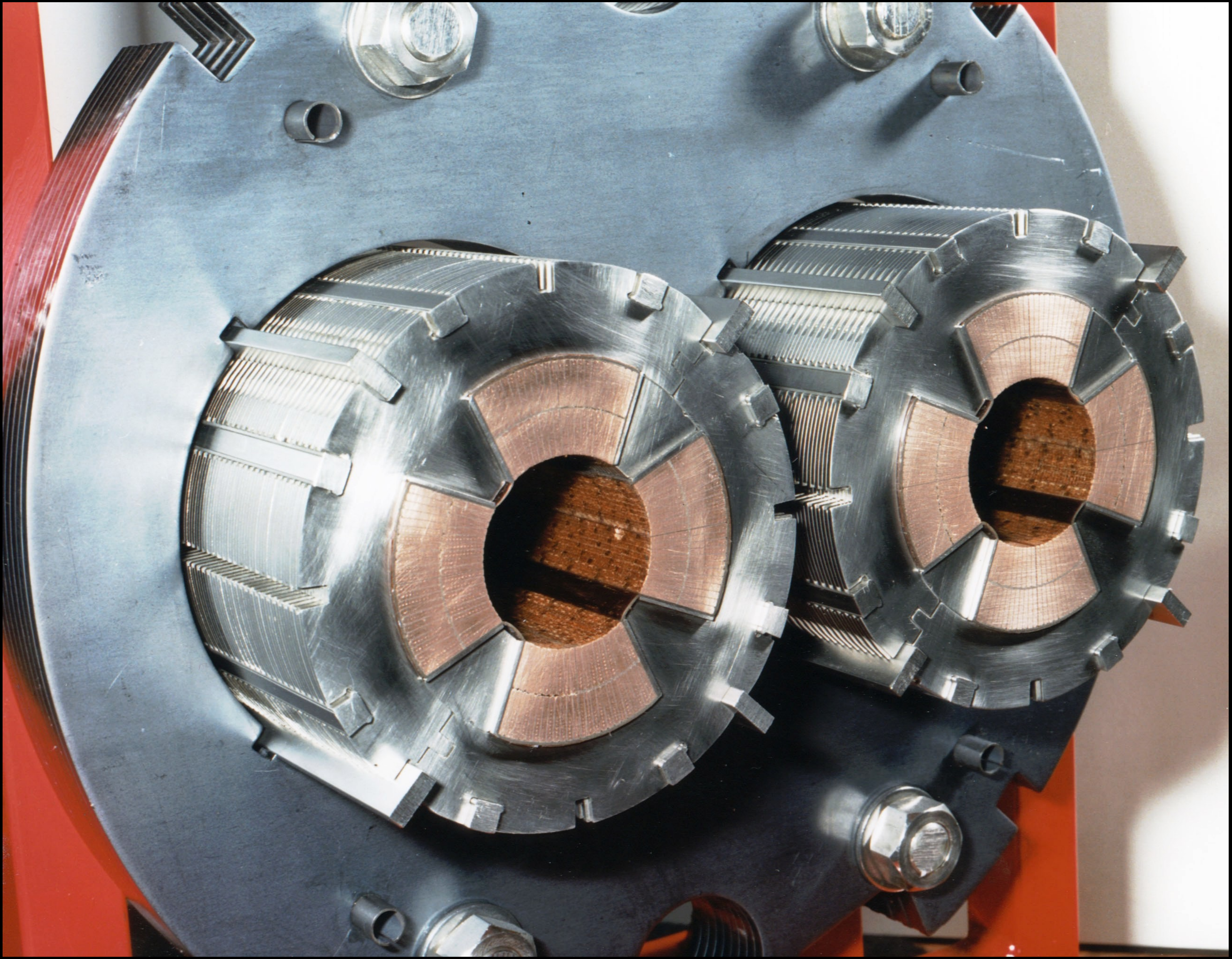
Focusing in one direction, defocusing in the other

FO-DO array

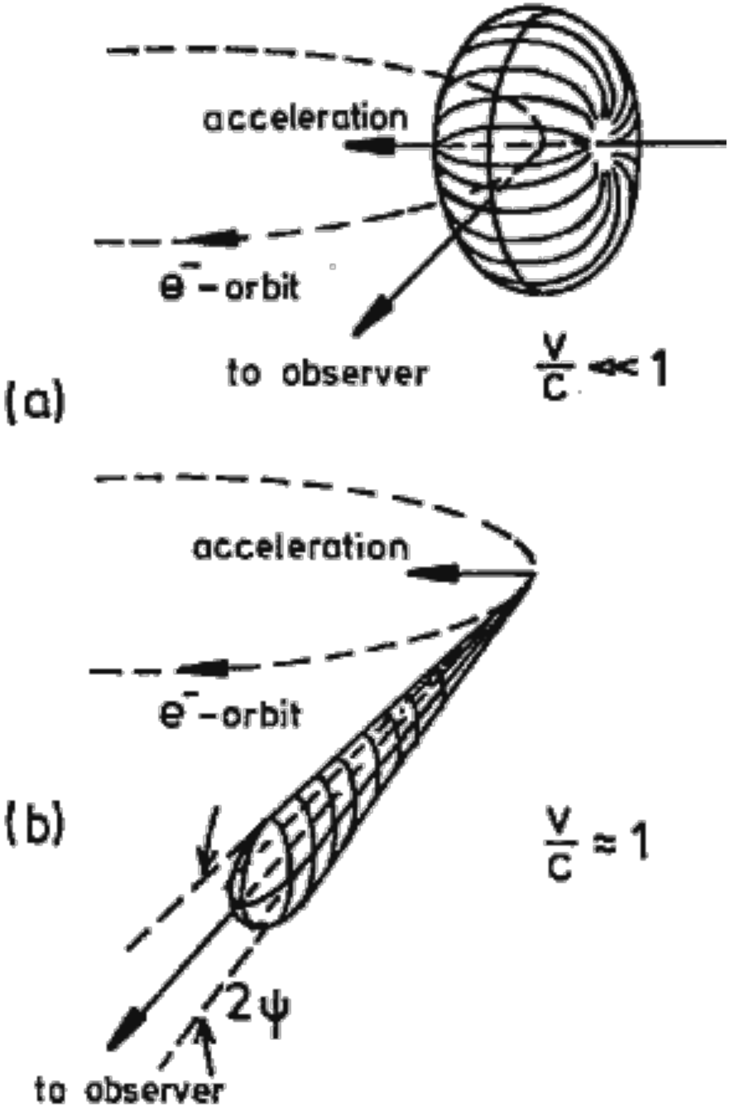





Fermilab



Syncrotron radiation



energy lost per revolution

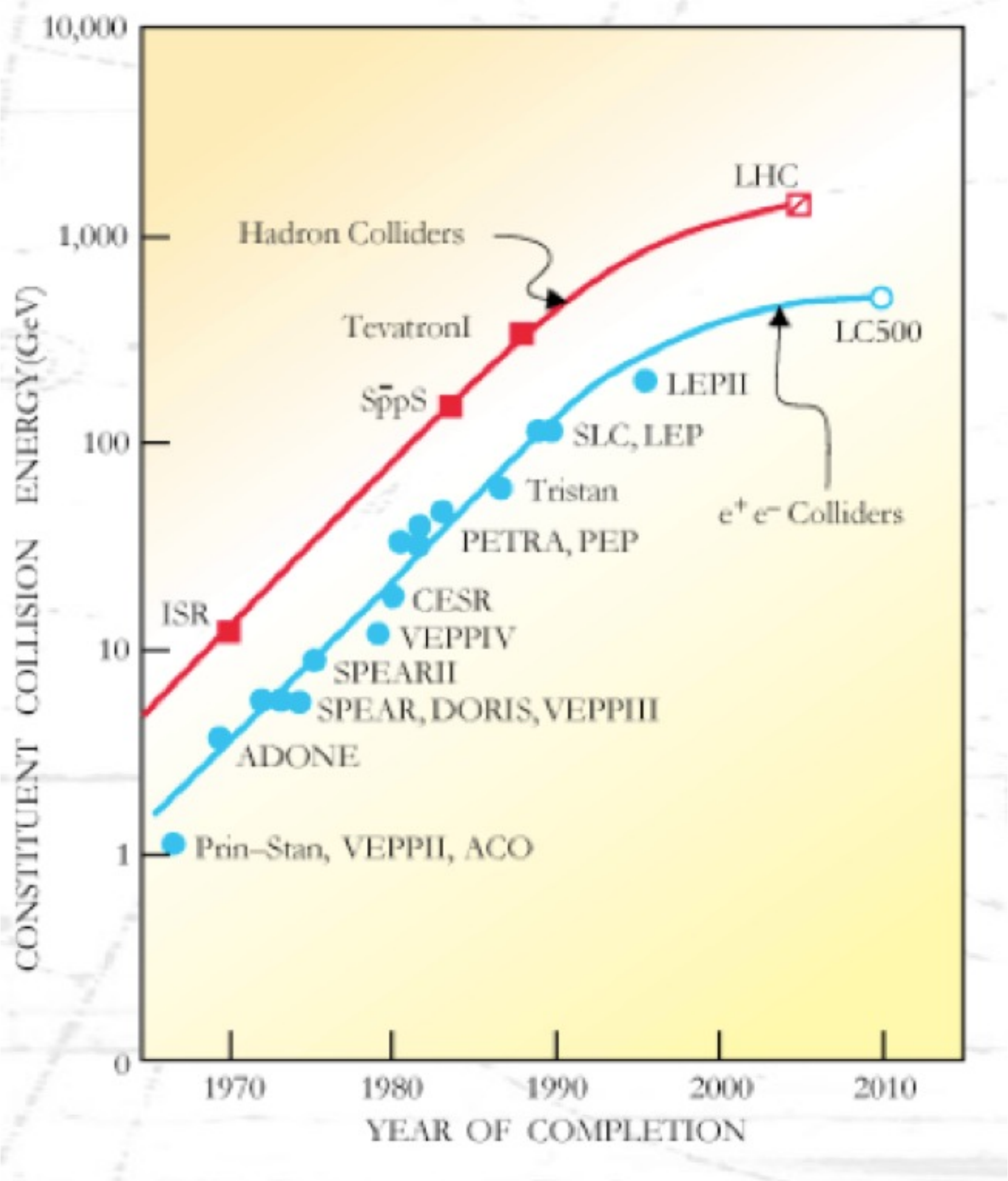
$$\Delta E = \frac{4\pi}{3}\frac{1}{4\pi\epsilon_0}\left(\frac{e^2\beta^3\gamma^4}{R}\right)$$

electrons vs. protons

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

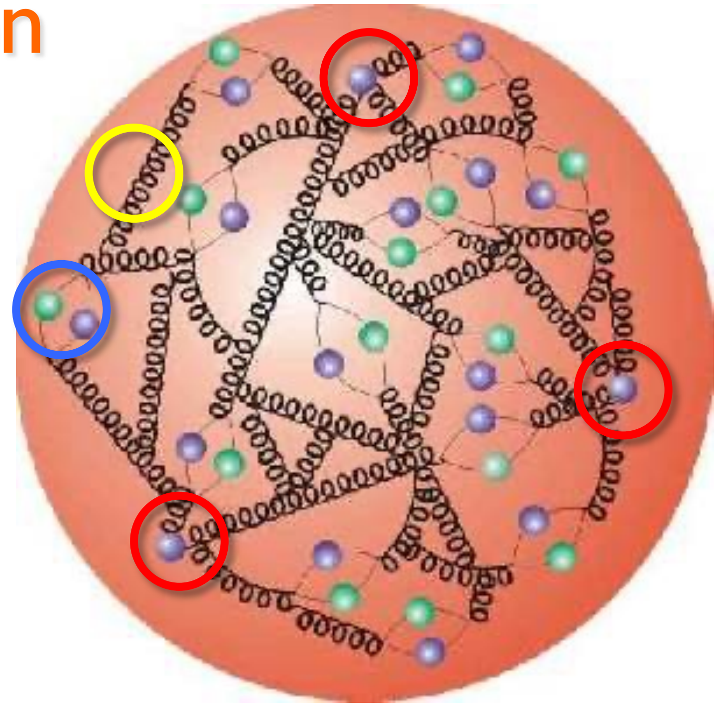
It’s easier to accelerate protons to higher energies, but protons are fundamentals…

e^+-e^- vs. hadron collider



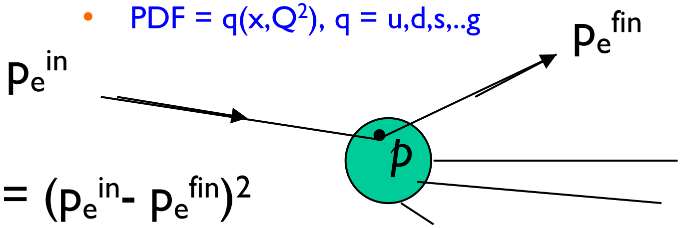
5-10

About the inner life of a proton



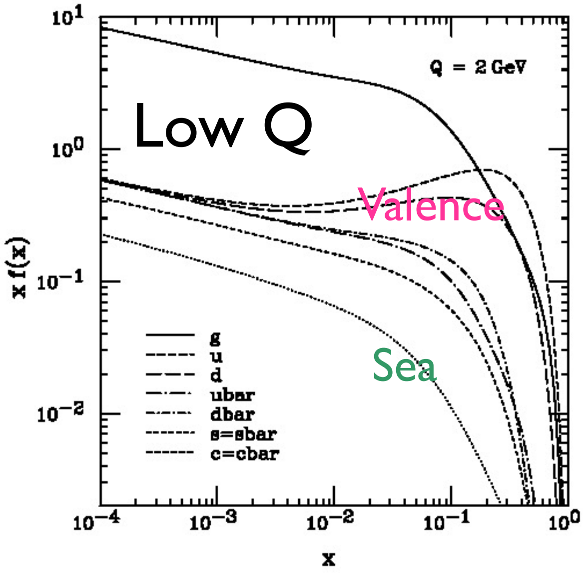
- ***p*rotons have substructures**
  - ✓ partons = quarks & gluons
  - ✓ 3 valence (colored) quarks bound by gluons ○
  - ✓ Gluons (colored) have self-interactions ○
  - ✓ Virtual quark pairs can pop-up (sea-quark) ○
  - ✓ *p* momentum shared among constituents
    - described by *p* structure functions

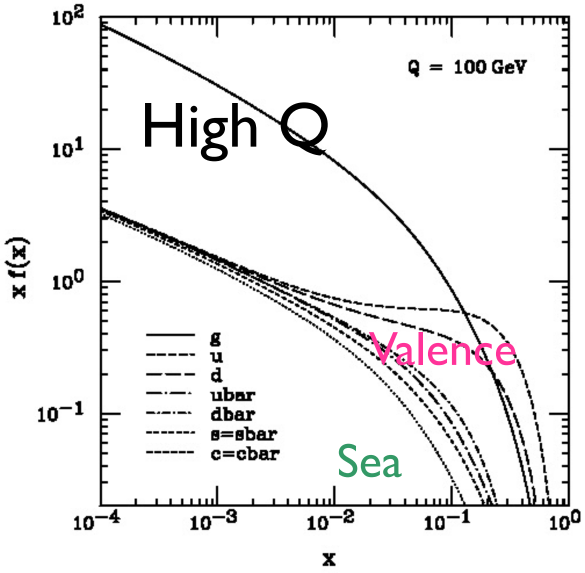
- **Parton energy not 'monochromatic'**
  - ✓ Parton Distribution Function
    - PDF = $q(x,Q^2)$, q = u,d,s,..g



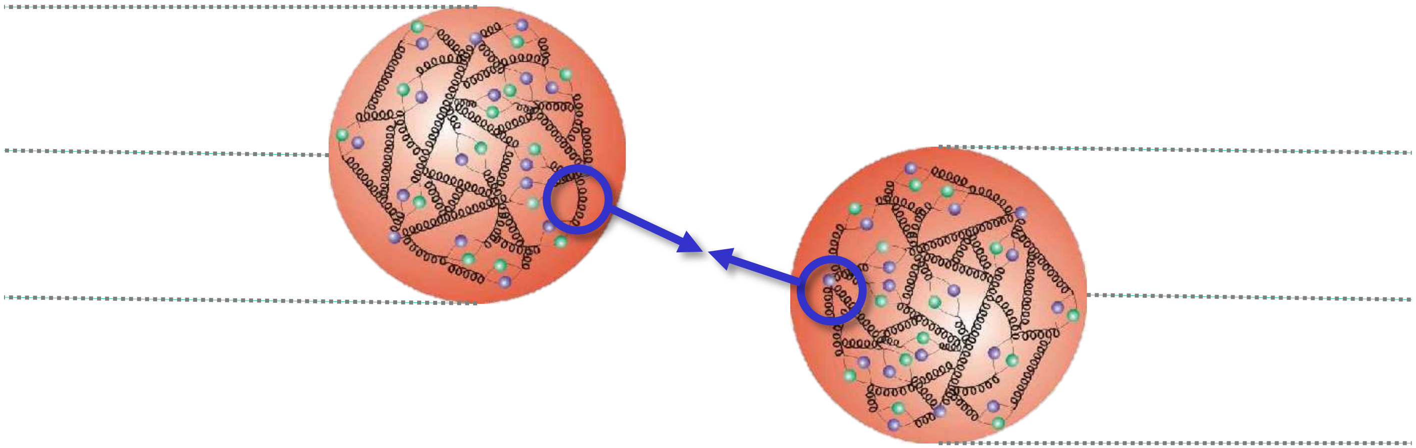
$Q^2 = (p_e^{in} - p_e^{fin})^2$

- **Kinematic variables**
  - ✓ Bjorken-x: fraction of the proton momentum carried by struck parton
    - $x = p_{parton}/p_{proton}$
  - ✓ Q^2 : 4-momentum² transfer



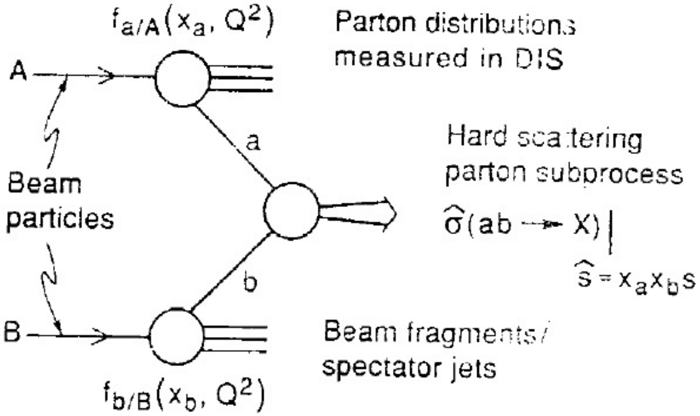


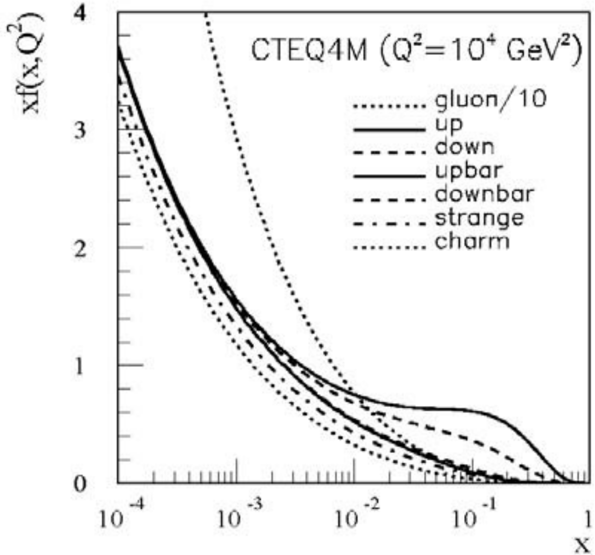
Cross sections at a proton-proton collider



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

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



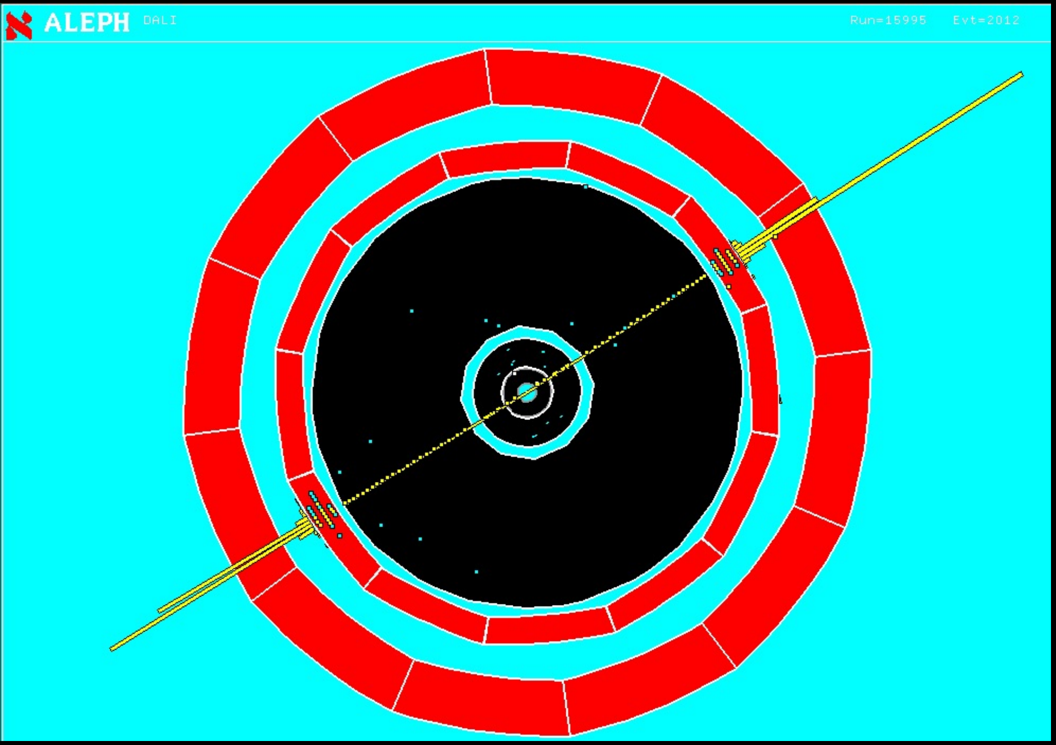


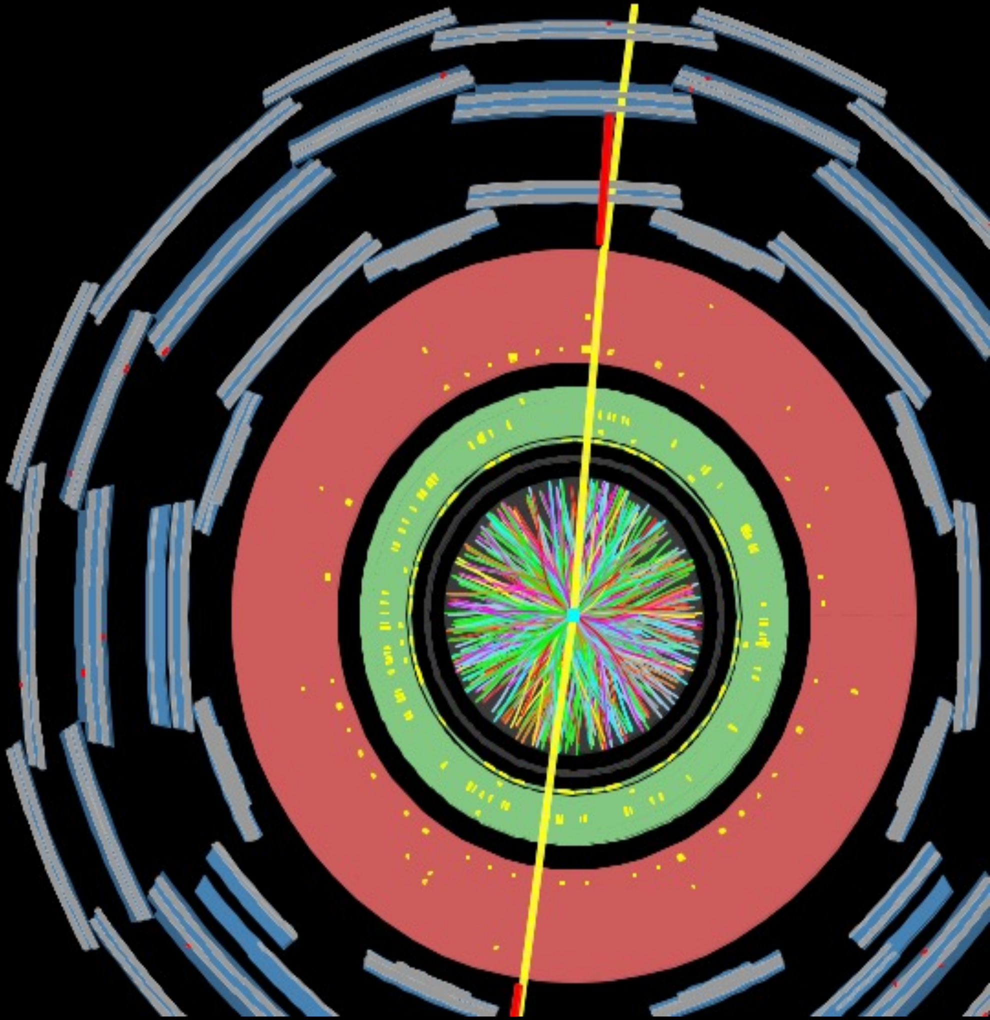
Example: to produce a particle with mass m = 100 GeV

$\sqrt{\hat{s}}$ = 100 GeV

$\sqrt{s}$ = 14 TeV → $x_a x_b$ = 0.007

A Z→e^+e^- event at LEP and ad LHC





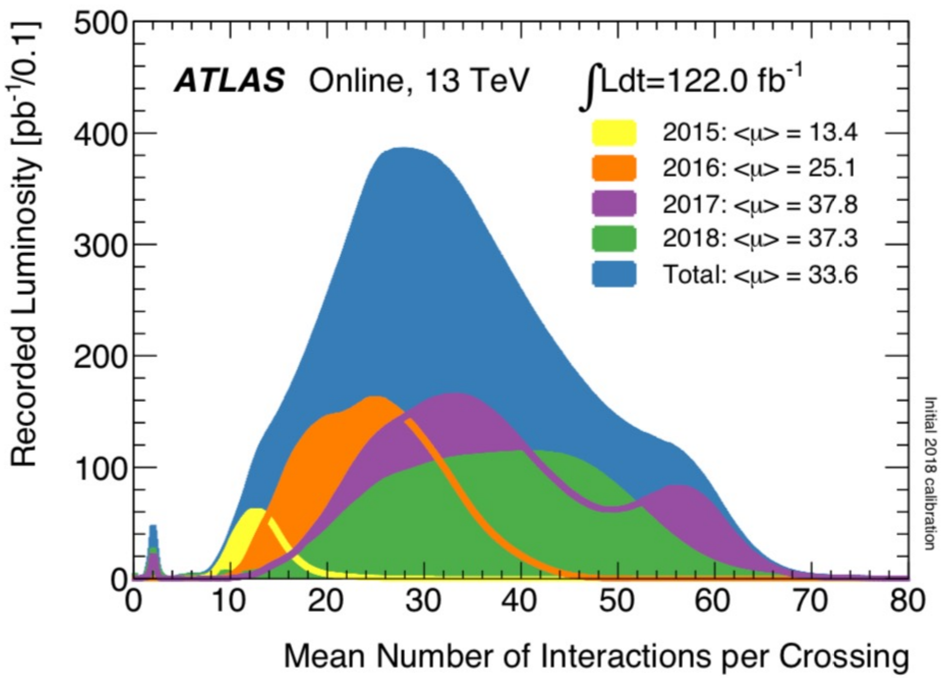
ALEPH @ LEP

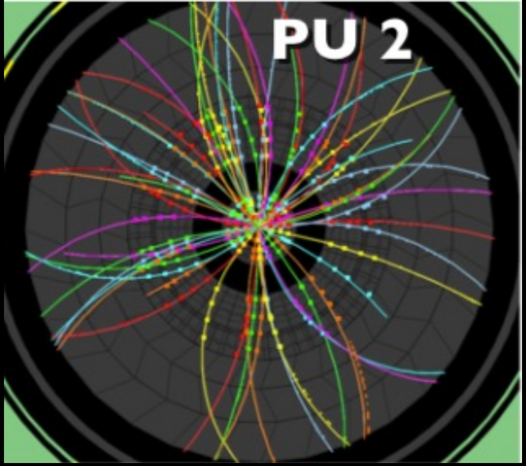
ATLAS @ LHC

Pile-Up

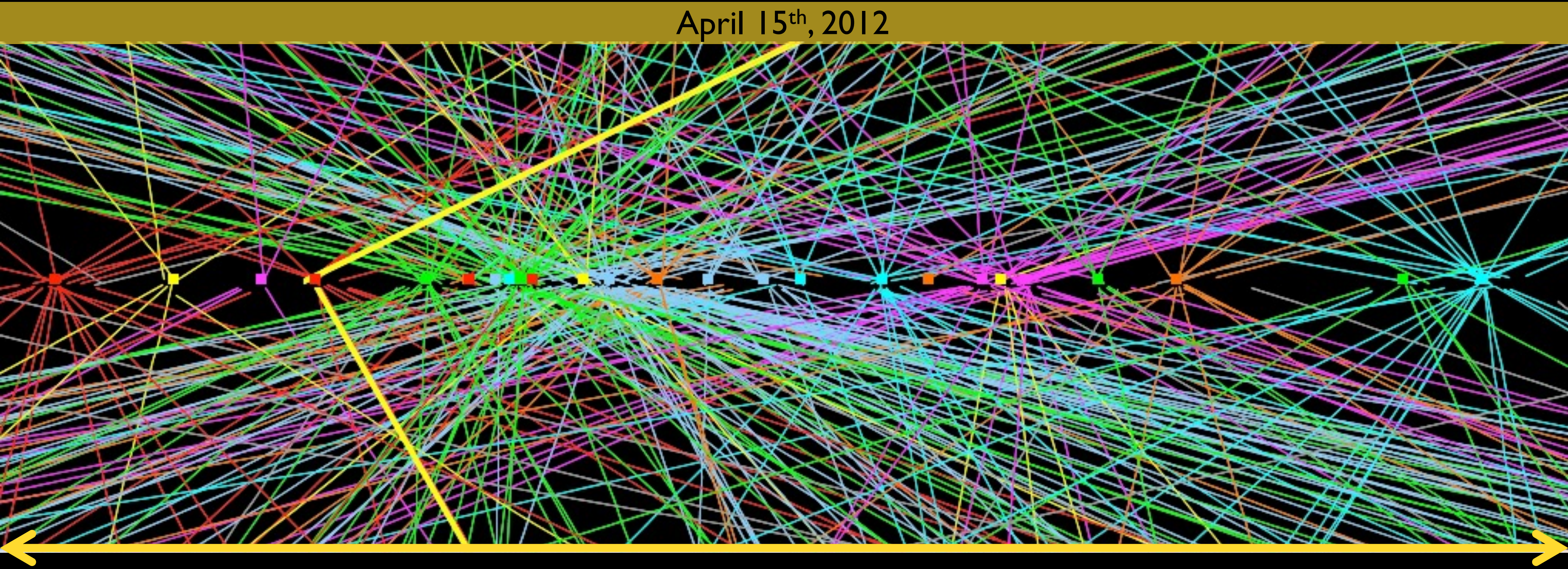
$$\mathcal{L} = \frac{1}{4\pi}\frac{f k N_1 N_2}{\sigma_x \sigma_y}$$

PU = number of inelastic interactions per beam bunch crossing



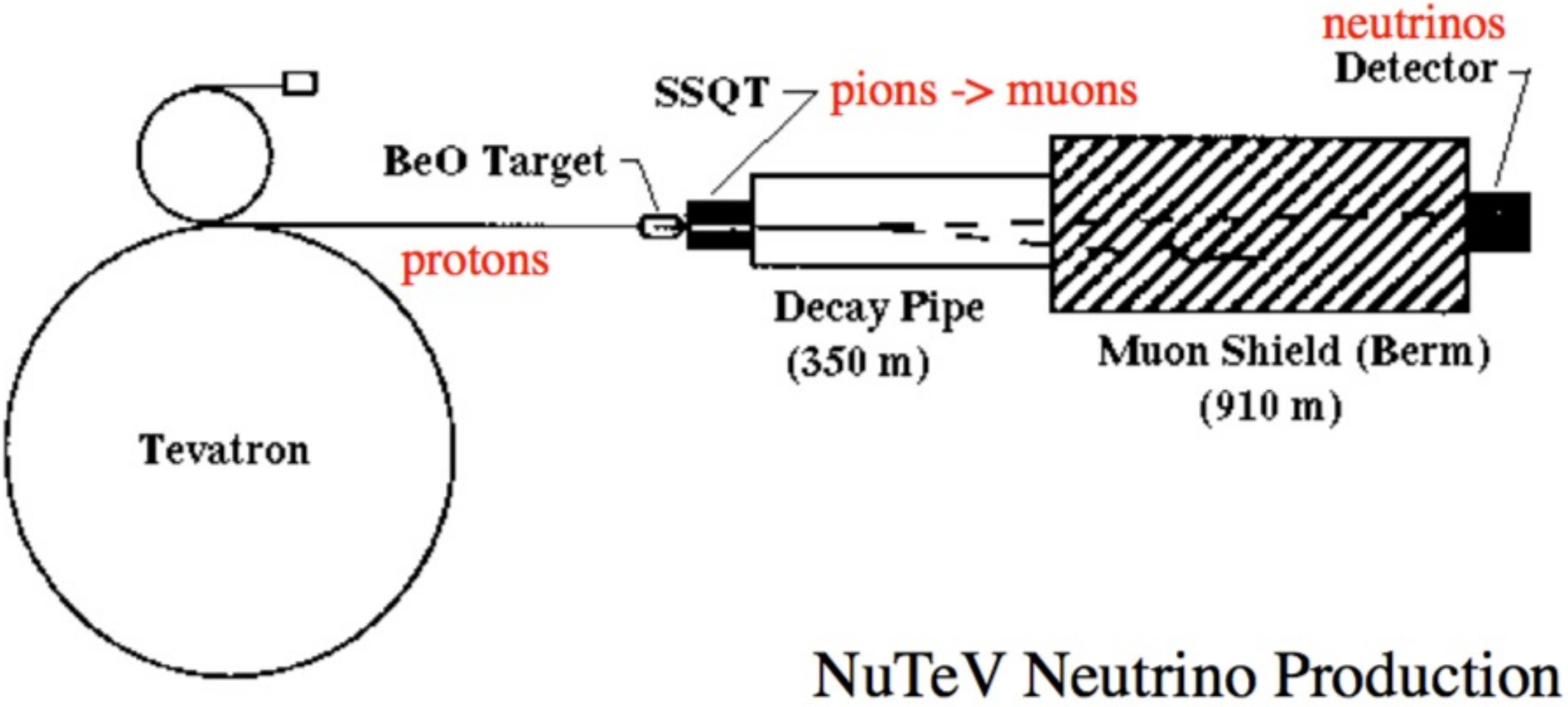


Z→μμ event with 25 reconstructed vertices

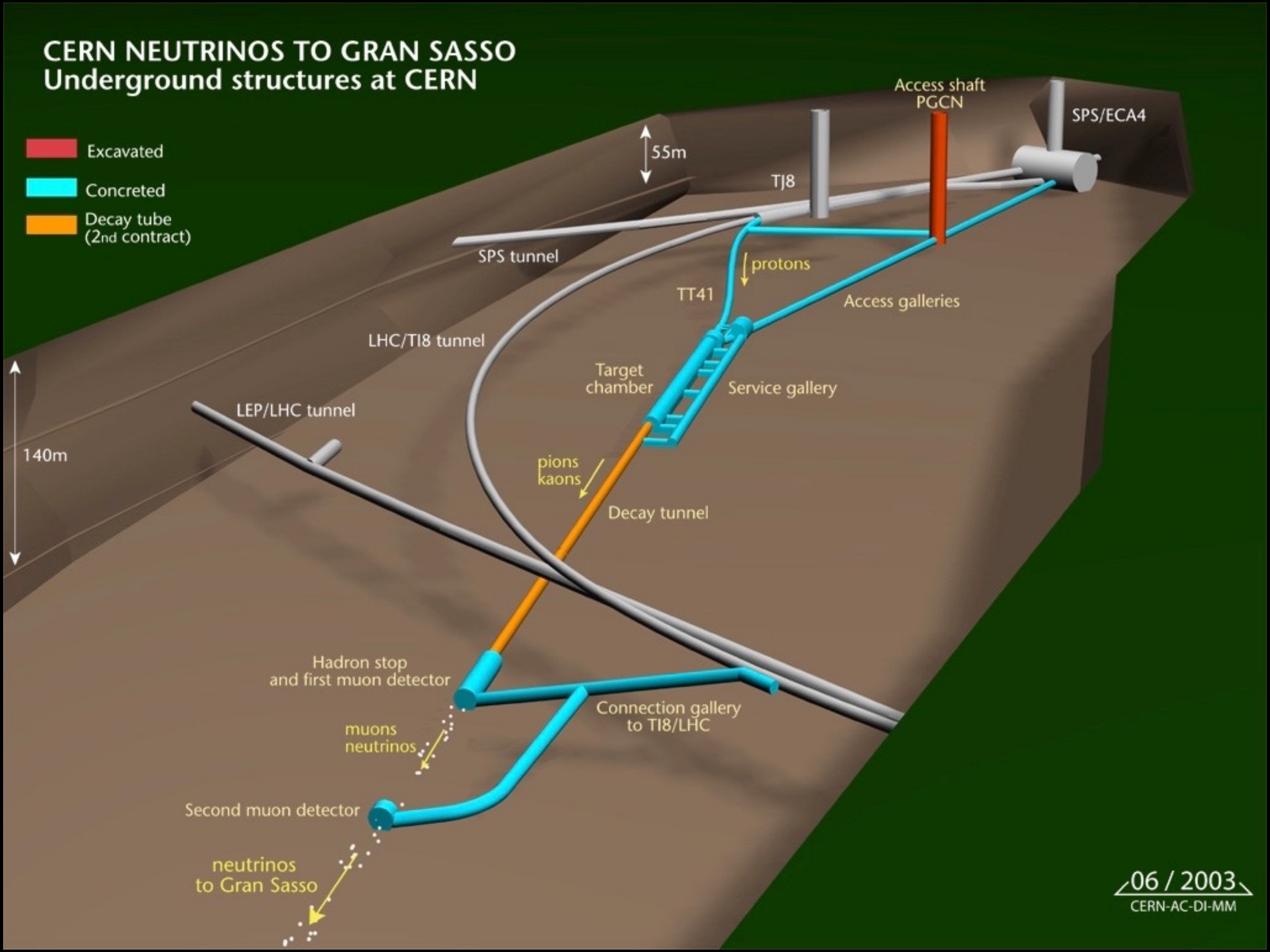


~5 cm

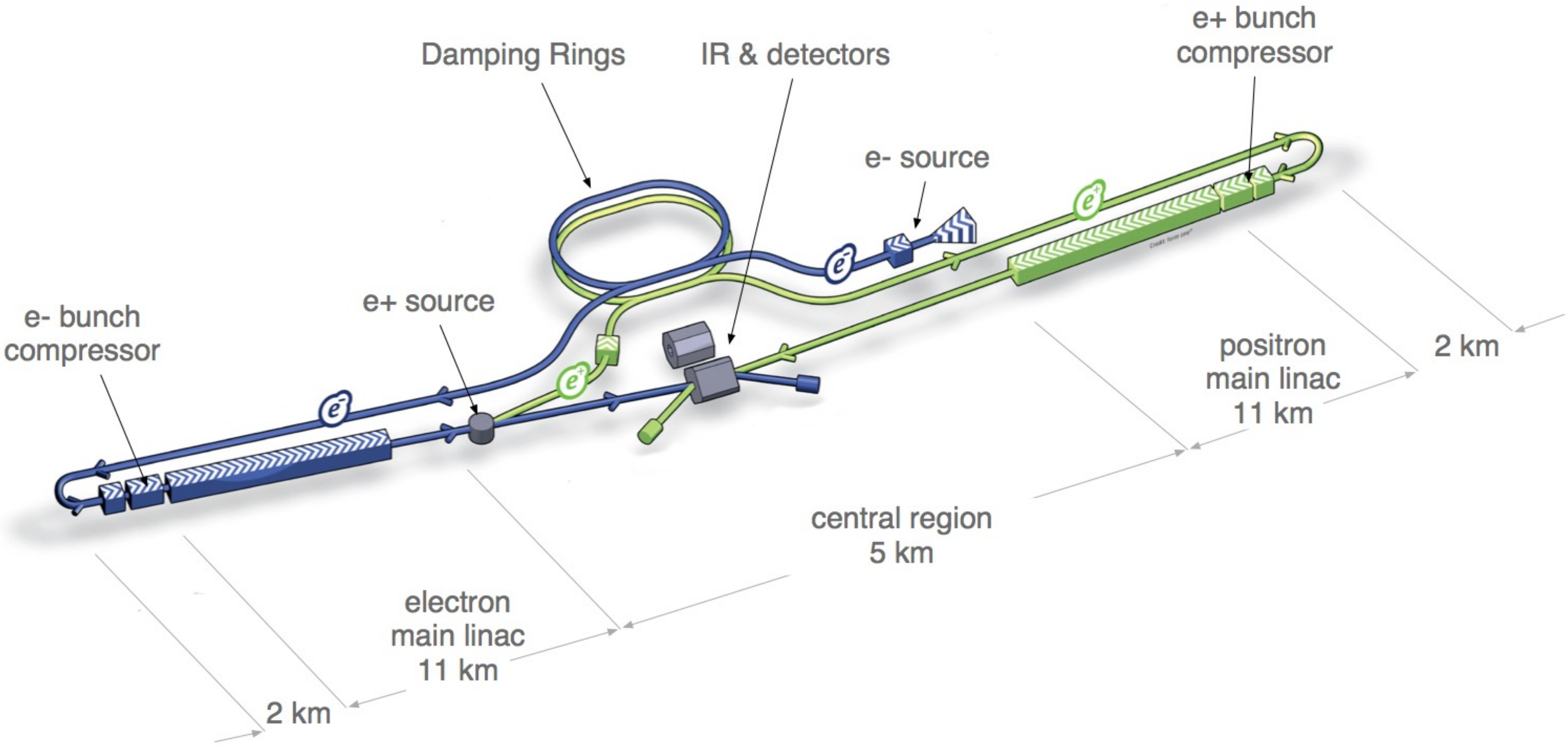
Production of secondary beams



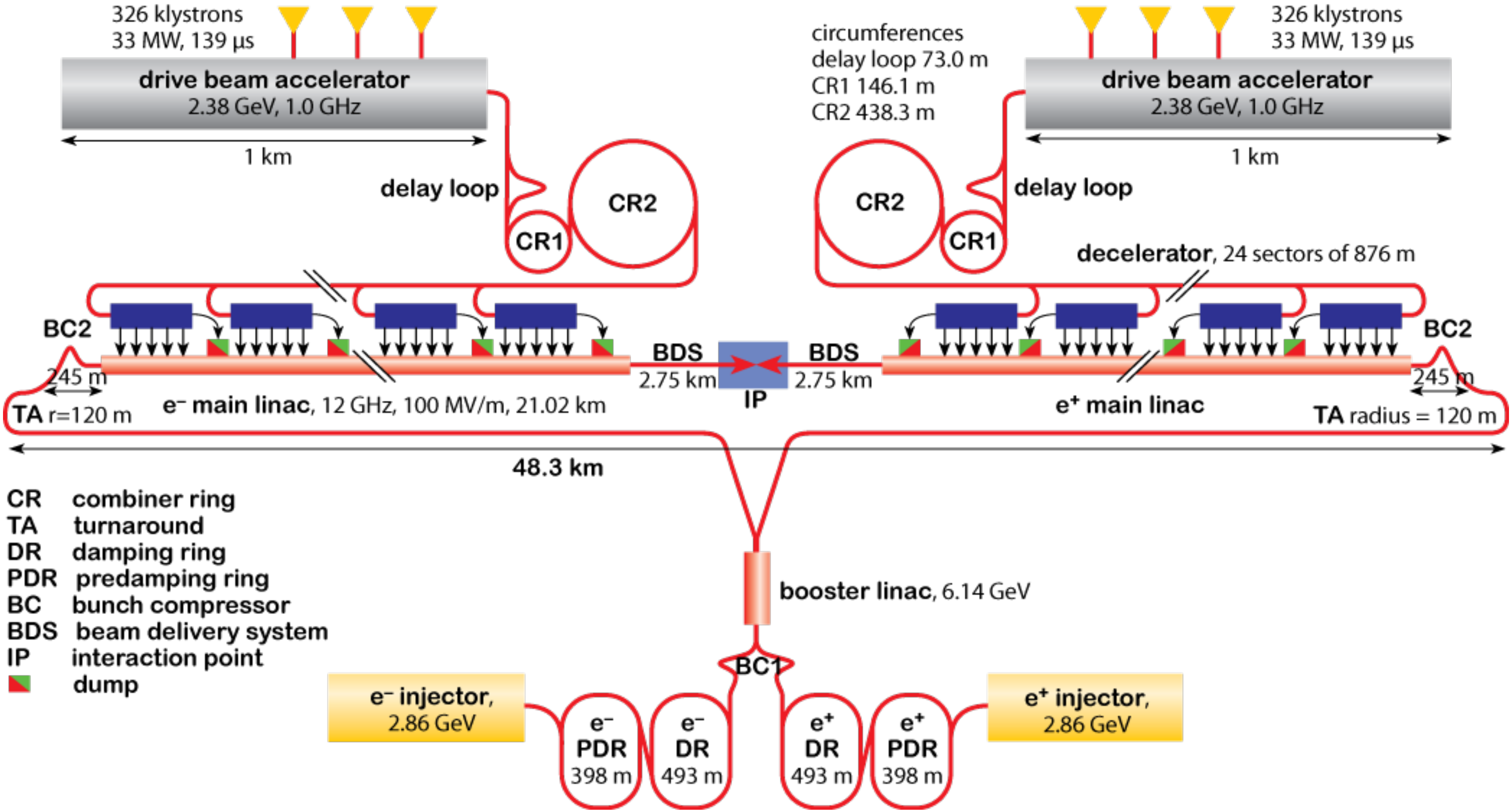
Production of secondary beams



Future colliders? ILC



Future colliders? CLIC



326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

delay loop

CR2

CR1

circumferences
delay loop 73.0 m
CR1 146.1 m
CR2 438.3 m

326 klystrons
33 MW, 139 μs

drive beam accelerator
2.38 GeV, 1.0 GHz

1 km

delay loop

CR2

CR1

decelerator, 24 sectors of 876 m

BC2

245 m

TA r=120 m

e⁻ main linac, 12 GHz, 100 MV/m, 21.02 km

BDS
2.75 km

IP

BDS
2.75 km

e⁺ main linac

BC2

245 m

TA radius = 120 m

48.3 km

booster linac, 6.14 GeV

BC1

e⁻ injector,
2.86 GeV

e⁻
PDR
398 m

e⁻
DR
493 m

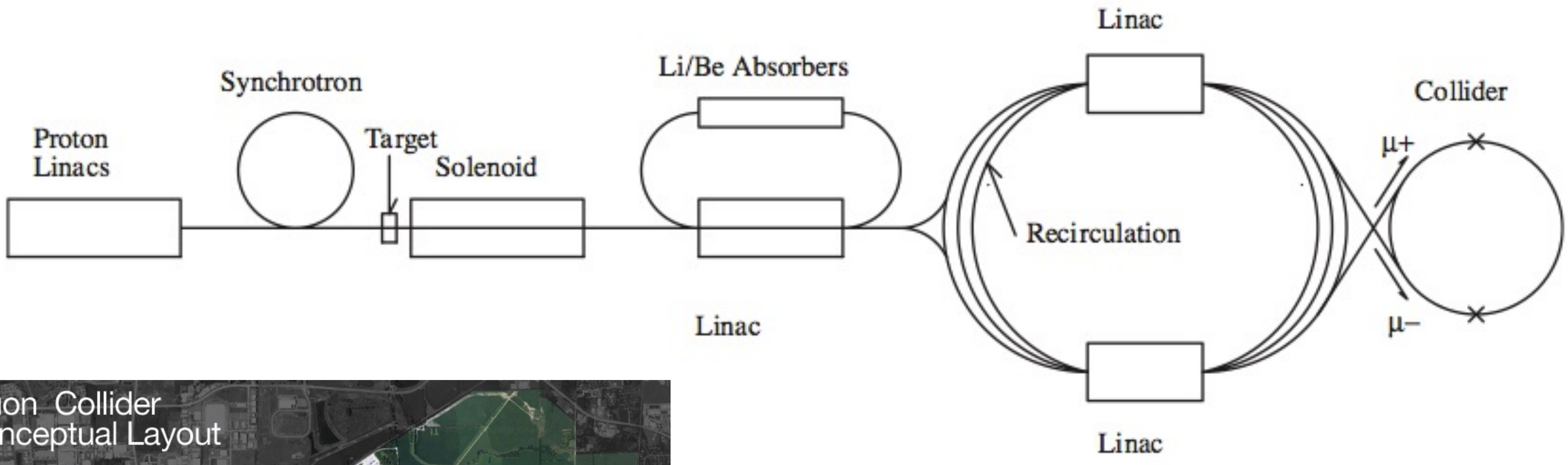
e⁺
DR
493 m

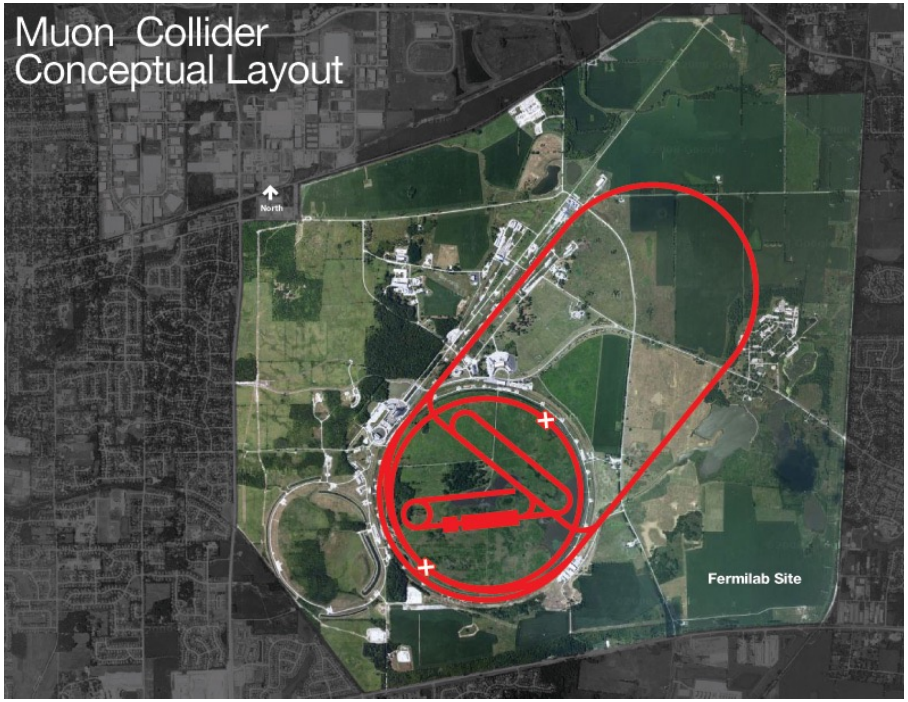
e⁺
PDR
398 m

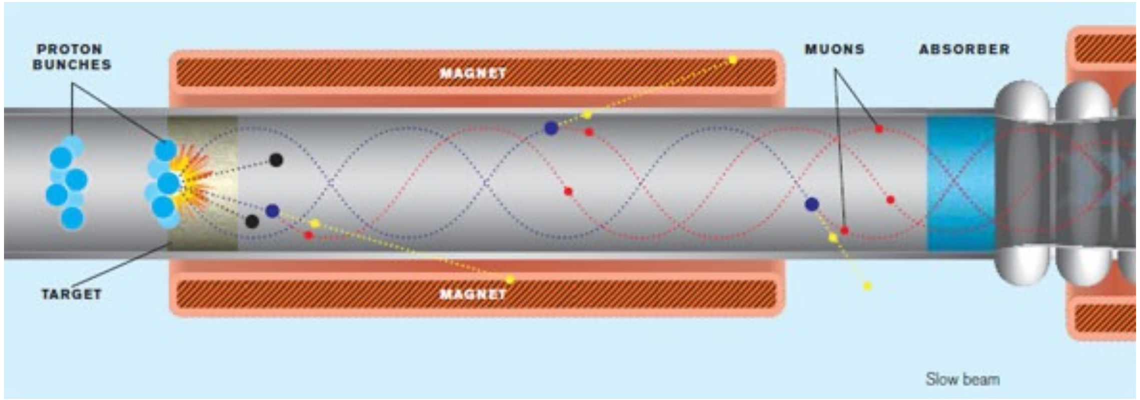
e⁺ injector,
2.86 GeV

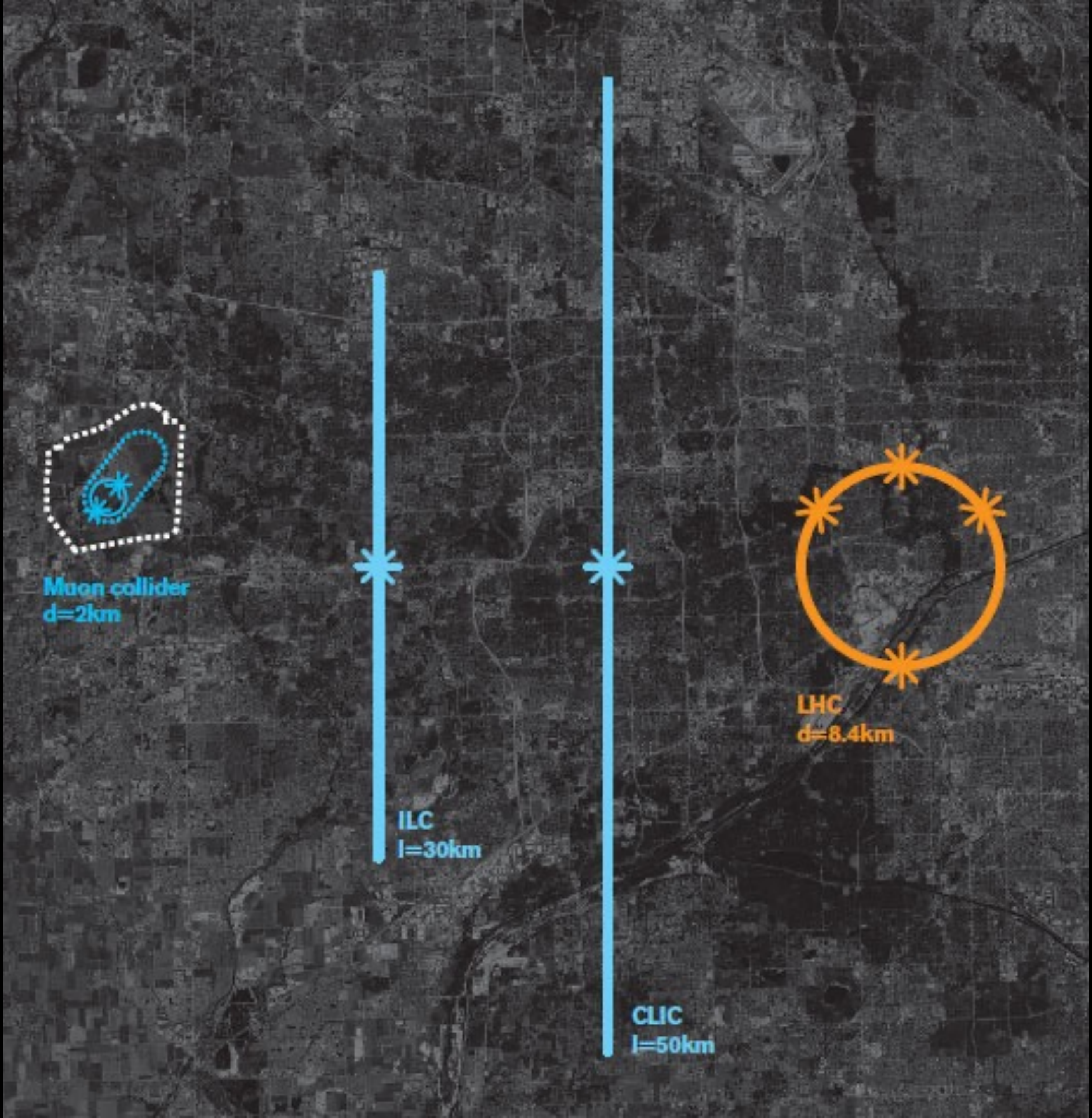
CR	**combiner ring**
TA	**turnaround**
DR	**damping ring**
PDR	**predamping ring**
BC	**bunch compressor**
BDS	**beam delivery system**
IP	**interaction point**
🟥	**dump**

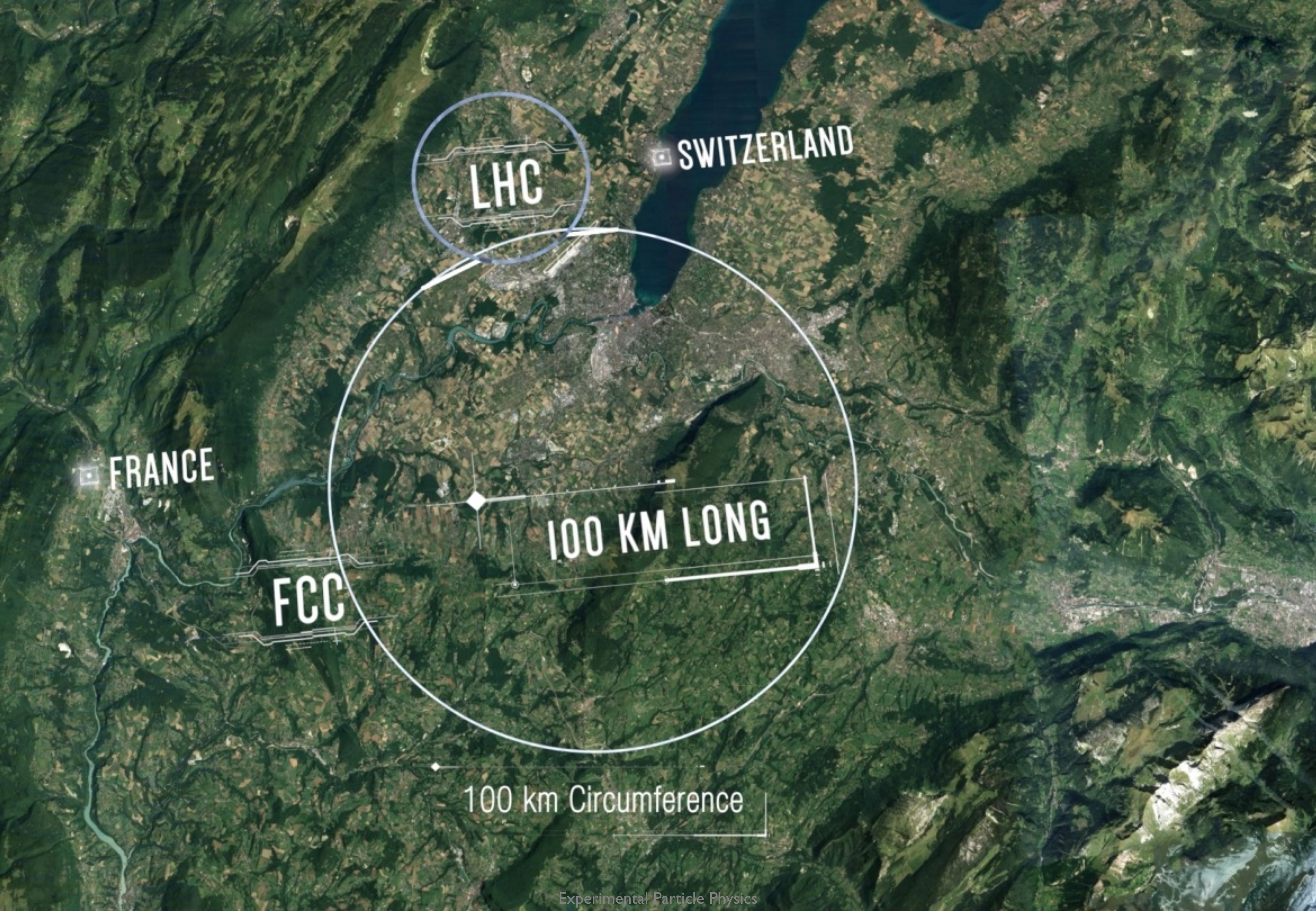
Future colliders? Muon collider





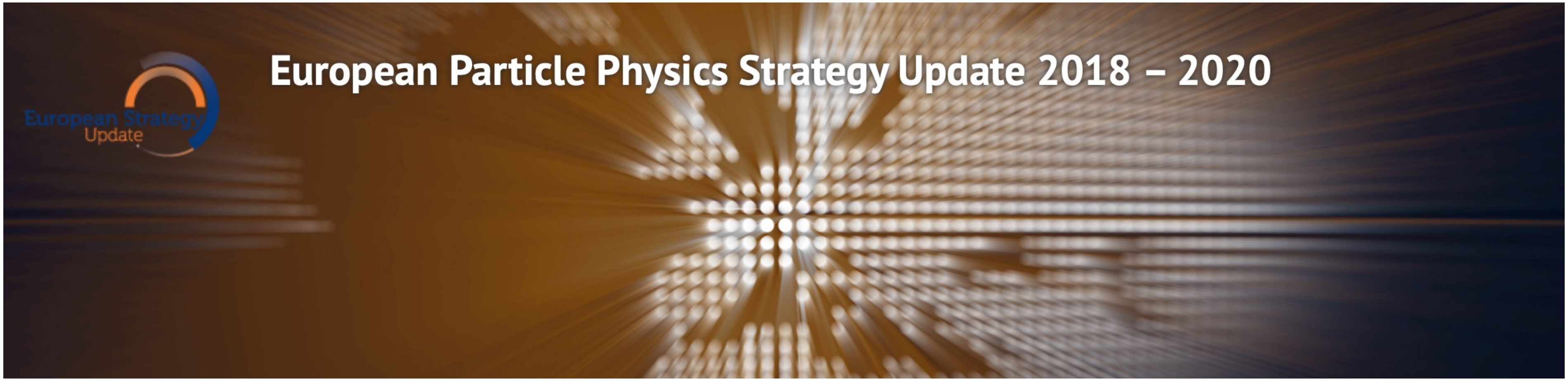



Muon collider
d=2km
ILC
l=30km
CLIC
l=50km
LHC
d=8.4km


SWITZERLAND
LHC
FRANCE
100 KM LONG
FCC
100 km Circumference

Get curious, inform yourself on the future!

- **European Strategy for Particle Physics**
  - ✓ http://europeanstrategyupdate.web.cern.ch



- **Physics Briefing Book : Input for the European Strategy for Particle Physics Update 2020**
  - ✓ https://arxiv.org/abs/1910.11775