Introduction to particle physics: Experimental part

Akcelerators

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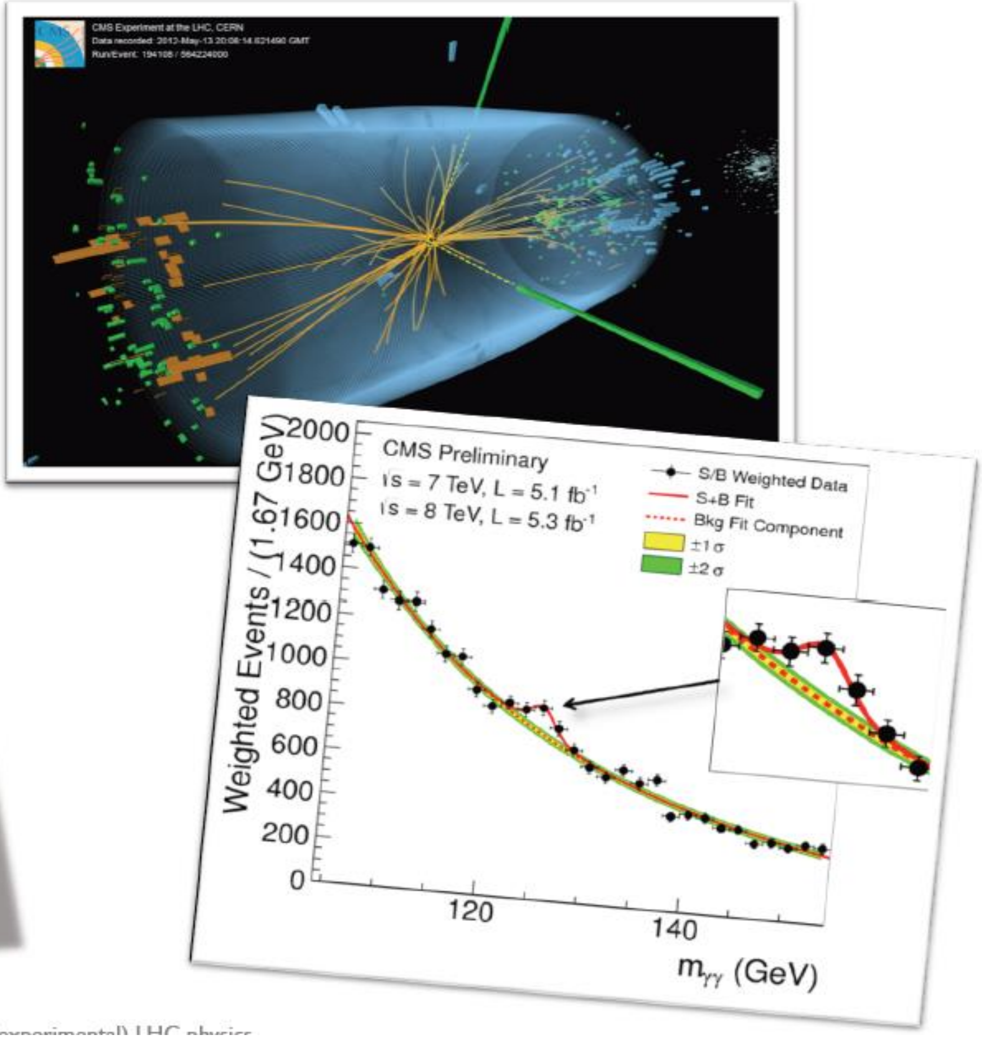
Experiment = probing theories with data



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

What particle to accelerate and collide

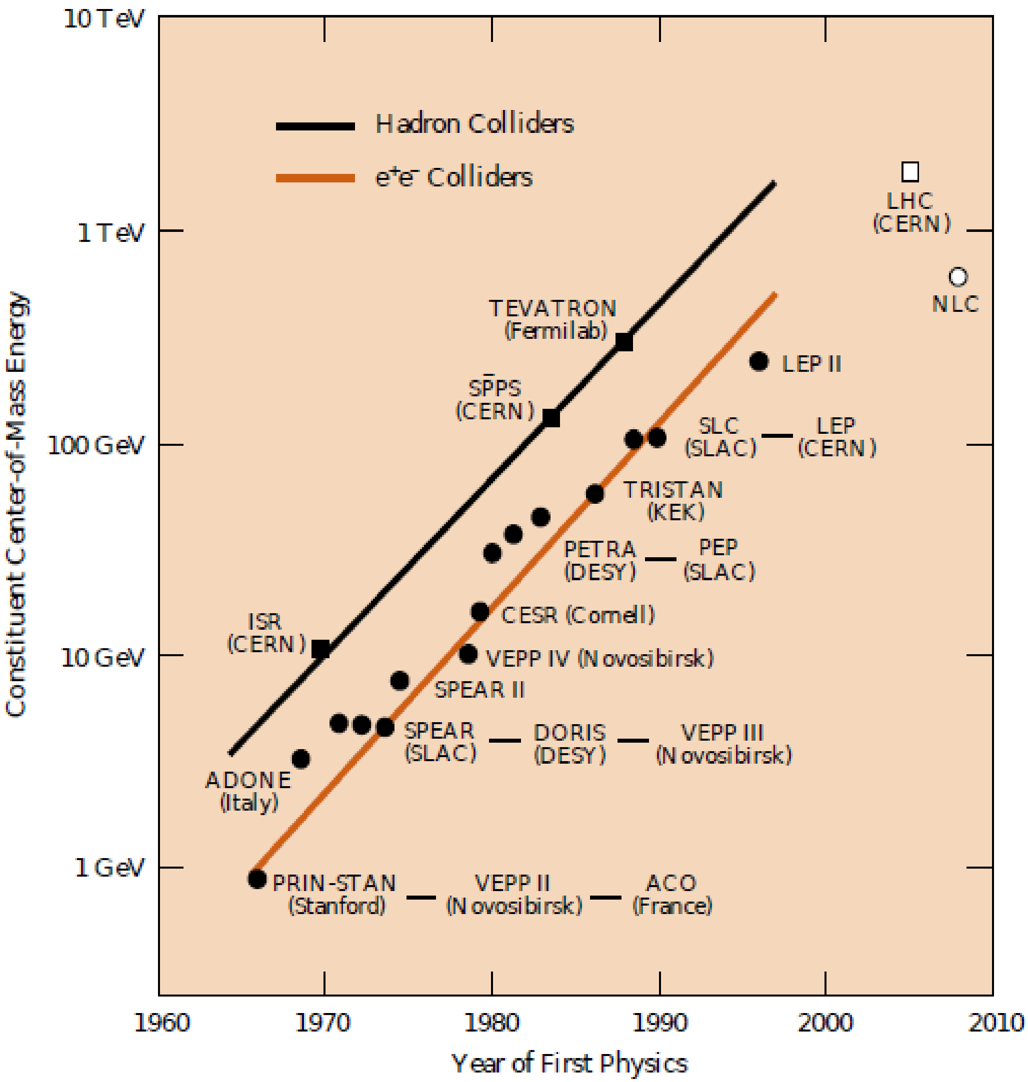
- **Stable (charged) particle**
  - ✓ Electron/positron
  - ✓ Proton/antiproton

what particle should we use?

- **Secondary beams of charged or neutral particles**
  - ✓ (Anti)neutrinos
  - ✓ Muons
  - ✓ Photons
  - ✓ Charged pions
  - ✓ Kaons
  - ✓ …

Energy frontier

- Historical progress has been like power law for most of the last 70 years
  - Vast majority of recent machines were synchrotrons
  - Notable exceptions
    - SLC
    - NLC/ILC

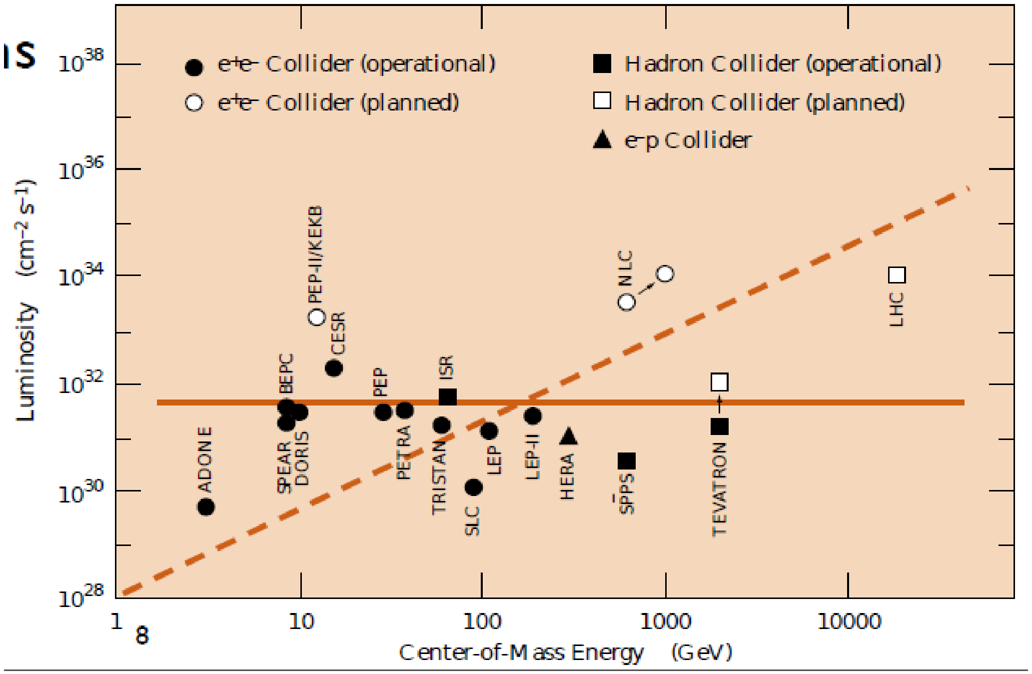


Luminosity frontier

- Need corresponding rise in luminosity (beam intensity)

$$\overset{\text{Number of events}}{N} = \underset{\text{Cross section}}{\sigma}\,\underset{\text{Integrated luminosity}}{L} = \sigma \int \overset{\text{Instantaneous luminosity}}{\mathcal{L}}\, dt$$

- High luminosity brings all the challenges for the detectors:
  - High event rates
  - Pile up
  - Beam –beam interactions
  - Beamstrahlung

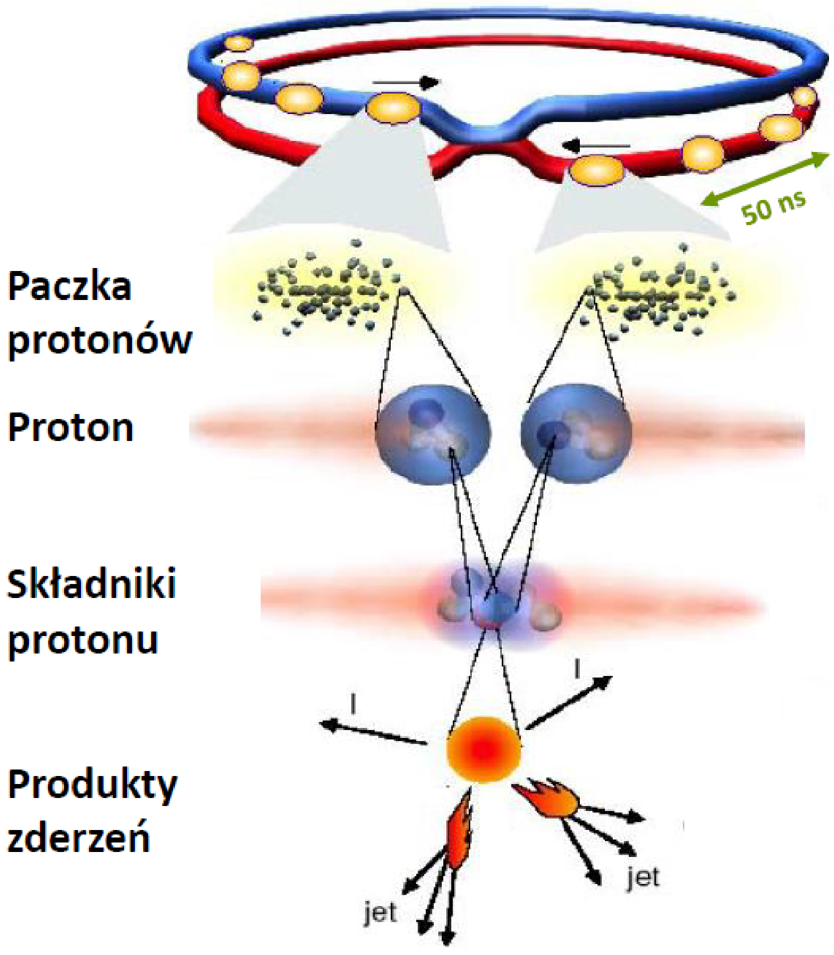


Designing a machine

- Particle species
  - Electron/positrons
  - Protons/antiprotons
  - Muons/antimuons
- Beam energy
- Spin
- Luminosity

- How do you produce antiparticles?
- Ones produced how ones keep them (muon collider)?
- Ones collided what ones does with spent beams?
- Accelerator and detector protection

Proton-proton collisions at LHC



Paczka protonów

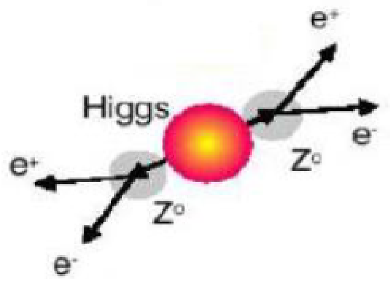
Proton

Składniki protonu

Produkty zderzeń

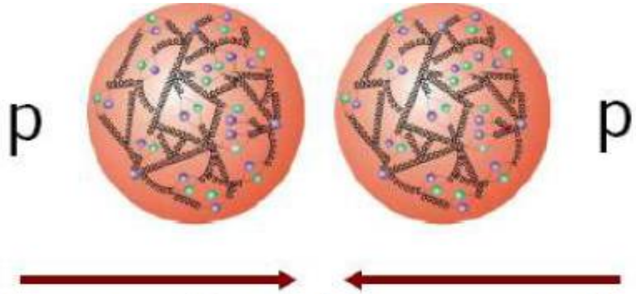
Proton-Proton	1380 paczek/wiązkę
Protonów/paczka	1.7 10^{11}
Energia wiązki	4 TeV

Każdy proton porusza się z prędkością bliską prędkości światła i niesie kinetyczną energię muchy w locie, okrąża pierścień akceleratora 1100 razy na sekundę.
Rozmiar poprzeczny wiązki: 16μm (4 razy mniejszy niż grubość ludzkiego włosa).
Każda z wiązek niesie energię pociągu TGV o dł. 200 m i jadącego z prędkością 155km/godz (360M Jula).



Takie zdarzenie pojawia się raz na 10 bilionów zderzeń

Complementarity between pp and ee machines



- Proton-(Anti-)Proton Colliders
  - Higher energy reach (limited by magnets)
  - Composite particles: unknown and different colliding constituents, energies in each collision
  - Confusing final states
- Discovery machines (W, Z, t)
- In some cases: precision measurements possible (W mass at the Tevatron)

- Electron-Positron-Colliders
  - Energy reach limited by RF
  - Point like particles, exactly definded initial system, quantum numbers, energy, spin polarisation possible
  - Hadronic final states with clear signatures
- Precision machines
- Discovery potential, but not at the energy frontier

Acceleration

Lorentz force law

$$\mathbf{F} = q\left(\underset{\substack{\uparrow\\\text{Electric field}}}{\mathbf{E}} + \underset{\substack{\uparrow\\\text{Velocity}}}{\mathbf{v}} \times \underset{\substack{\uparrow\\\text{Magnetic field}}}{\mathbf{B}}\right)$$

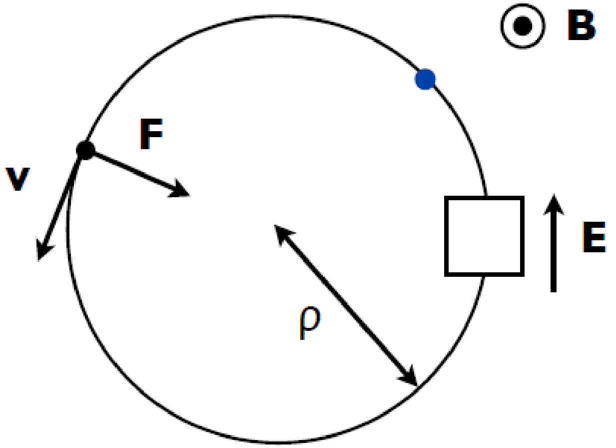
Energy change

$$\Delta E = \int_{\mathbf{r}_1}^{\mathbf{r}_2} \mathbf{F} \cdot d\mathbf{r}$$

- Electric field (either static or more commonly, time varying) to accelerate, or more appropriately, increase energy of beam
- Magnetic part of Lorentz force used to guide and focus
  - Dipole magnets: to bend
  - Quadrupole: to focus or defocus

Synchrotron

- Workhorse of modern particle physics
  - Huge legacy of discovery
  - Increase energy whilst synchronously increasing bending magnet strength
  - Stable storage of high beam current/power
- Magnetic field proportional to momentum



Velocity

$$qBv = \frac{m_0 v^2}{\rho}$$

Magnetic field

Bending radius

$$B\rho = p/q$$

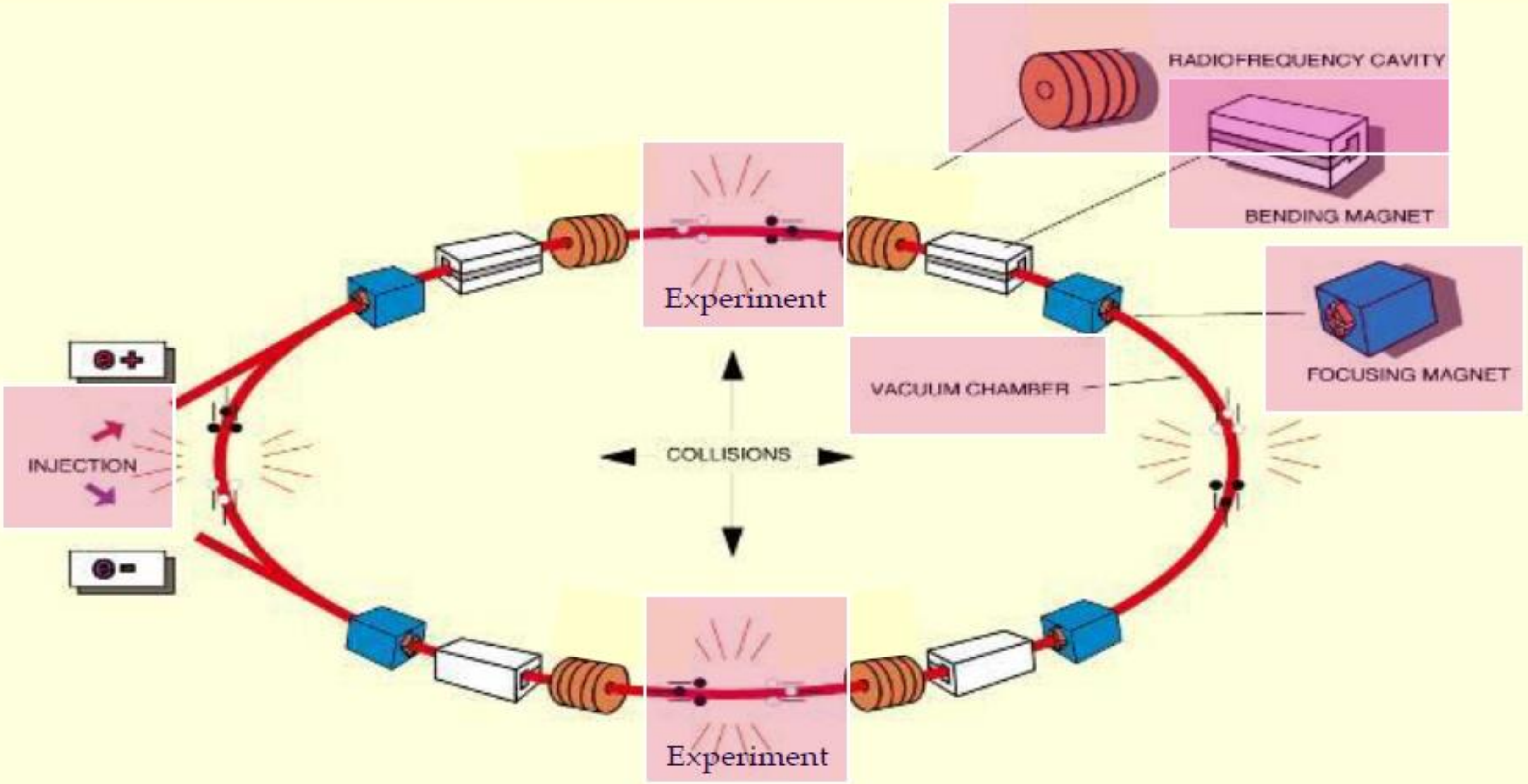
Momentum

Accelerator is much more than just….

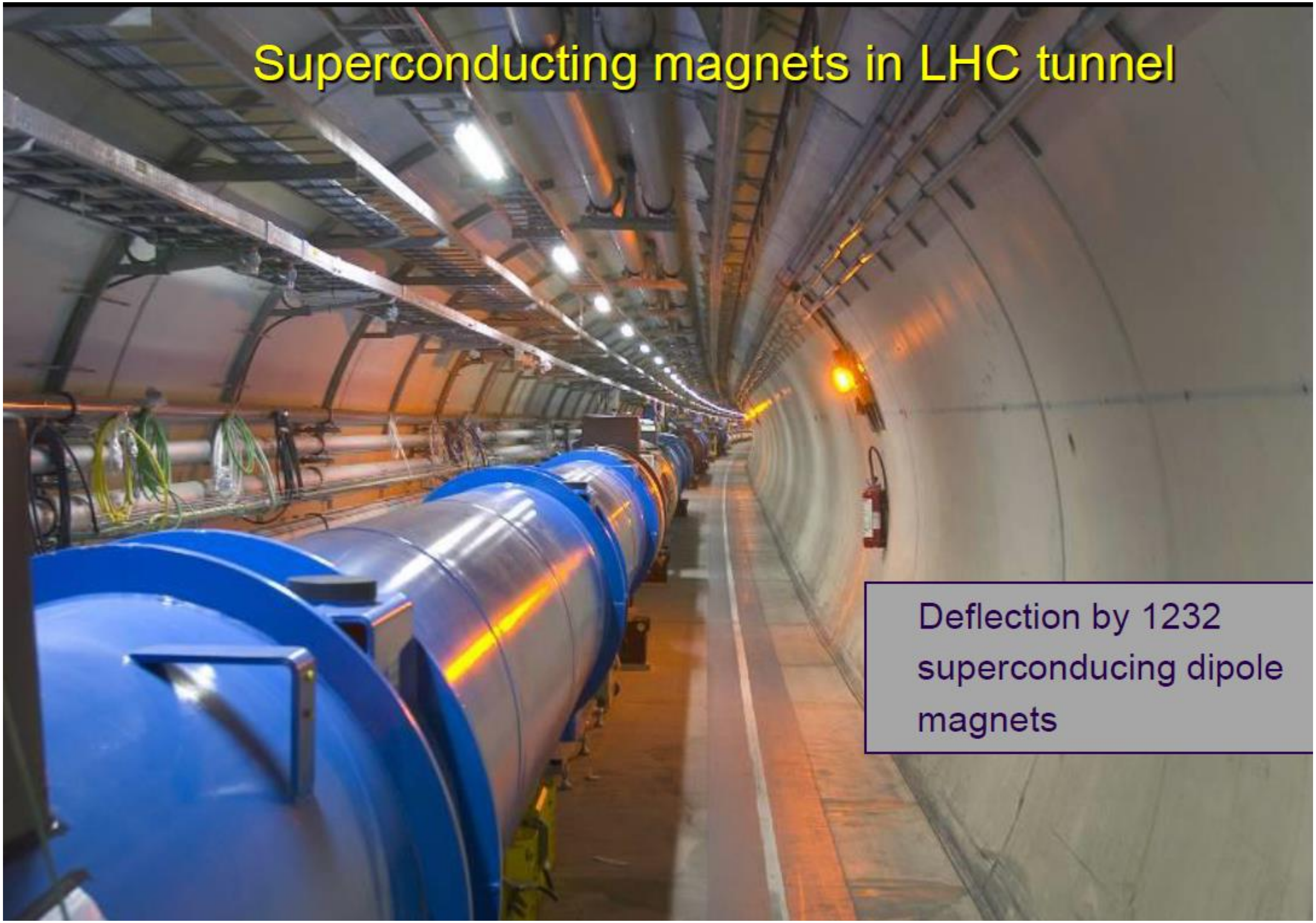
- Particle production
- Damping, cooling or preparation
- Injection and extraction
- Acceleration
- Collimation (betatron, energy etc.)
- Diagnostics and controls
- Machine (and detector protection)
- Beam delivery and luminosity production
- Technology spin off
  - Lower energy machines, medical applications, applied physics, materials, …..

Synchrotron + many passages in RF cavities

LHC **circular machine** with energy gain per turn ~0.5 MeV
acceleration from 450 GeV to 7 TeV will take about 20 minutes



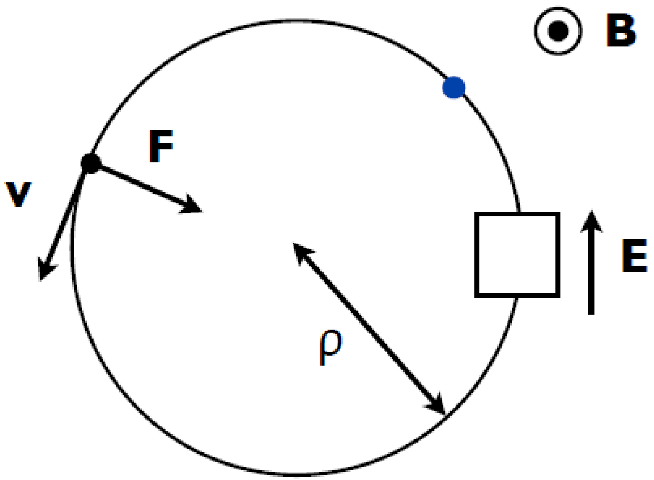
CERN AC - ES09

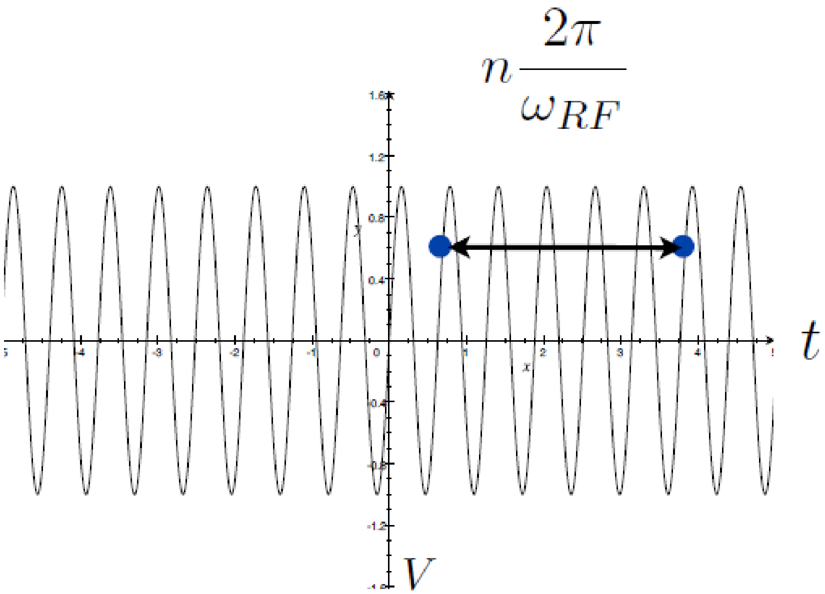


Superconducting magnets in LHC tunnel

Deflection by 1232 superconducing dipole magnets

Synchrotron





- Time varying electric field:

$$V(t) = V_0 \sin(\omega_{RF} t + \phi)$$

Angular frequency of accelerating field

- Particle gets a kick every revolution

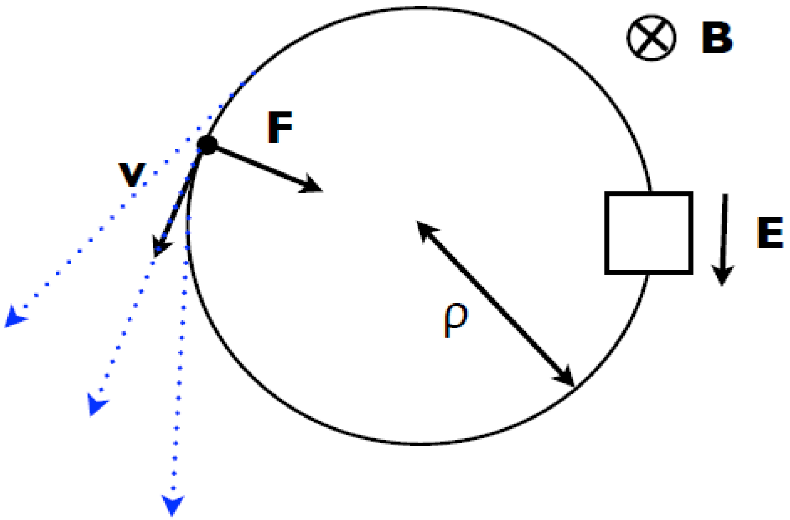
$$\frac{1}{f_{\text{ref}}} = n\frac{2\pi}{\omega_{\text{RF}}}$$

Revolution frequency

Integer

Synchrotron Radiation Limits

- Why not just build bigger LEP?
  - Reuse accelerating section every revolution of particle bunch
  - Power loss due to synchrotron radiation
  - LEP2 was practical limit for electron-positron synchrotron



Power

$$P = \frac{1}{4\pi\epsilon_0}\frac{e^2 v^4}{c^3 \rho^2}\gamma^4$$

Beam energy

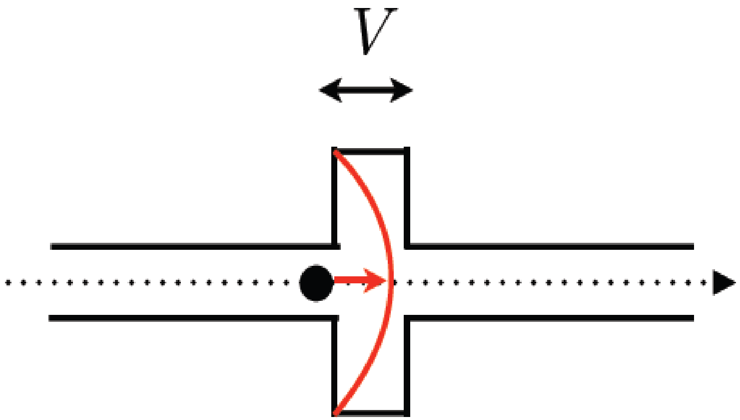
Energy loss per turn

$$W = 8.85 \times 10^{-5} E^4/\rho$$

Magnetic radius

Absolute Limits on Acceleration

- Need to create large on axis electric fields
  - Accelerating structures:
    - Superconducting (~35 MV/m)
    - Normal conducting (~100 MV/m)
- Beyond these values there is high voltage breakdown



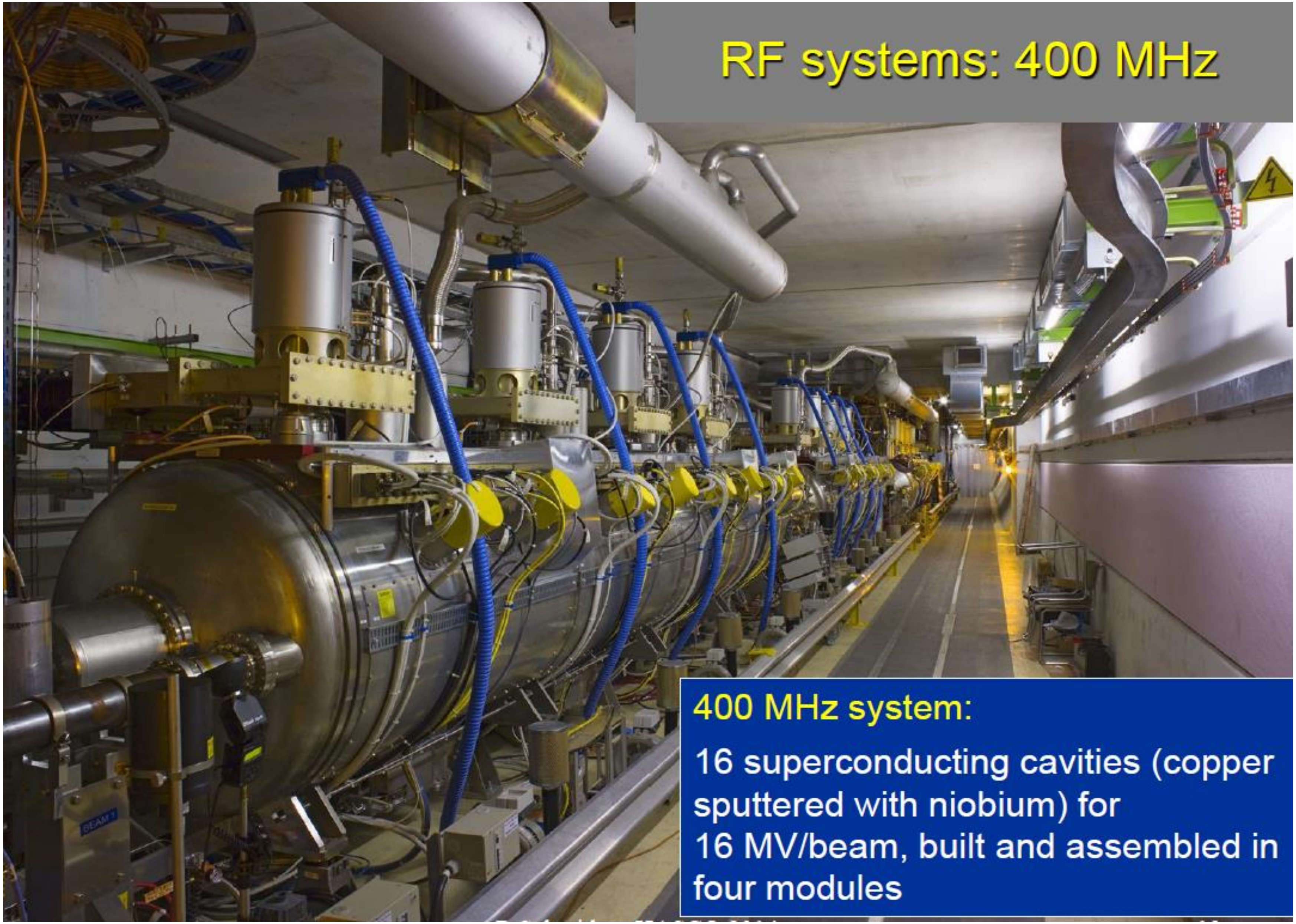
Machine length [m]

Beam energy [MeV]

$$S = \frac{E}{q\, dV/ds}$$

Accelerating gradient [MV/m]

RF systems: 400 MHz

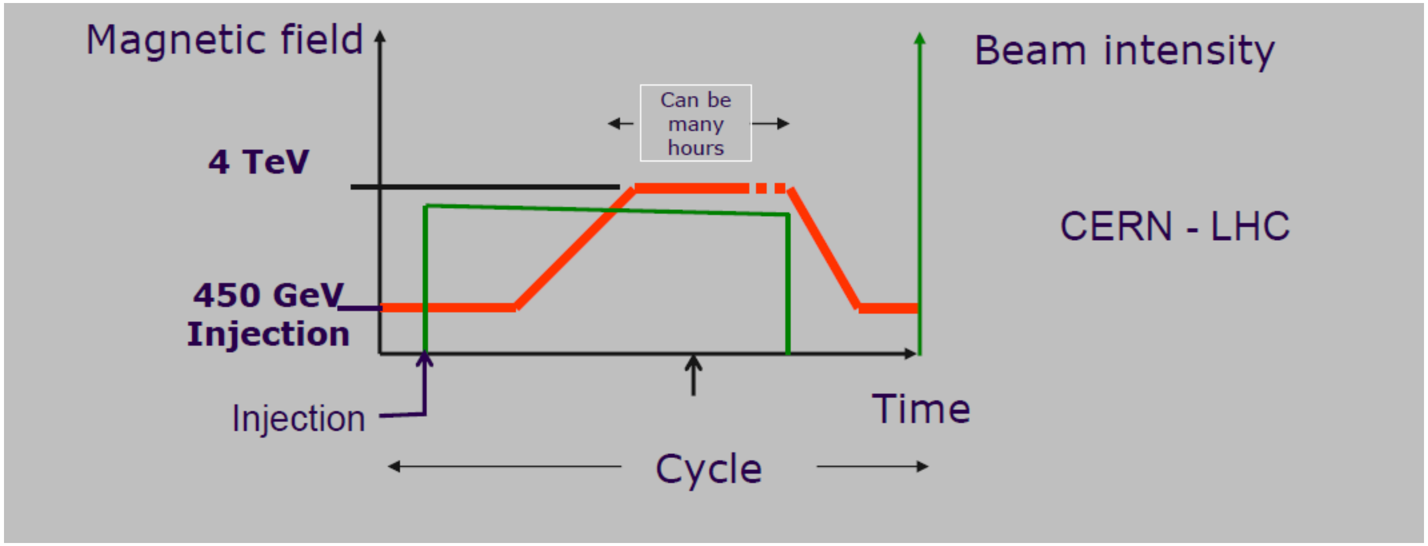


400 MHz system:

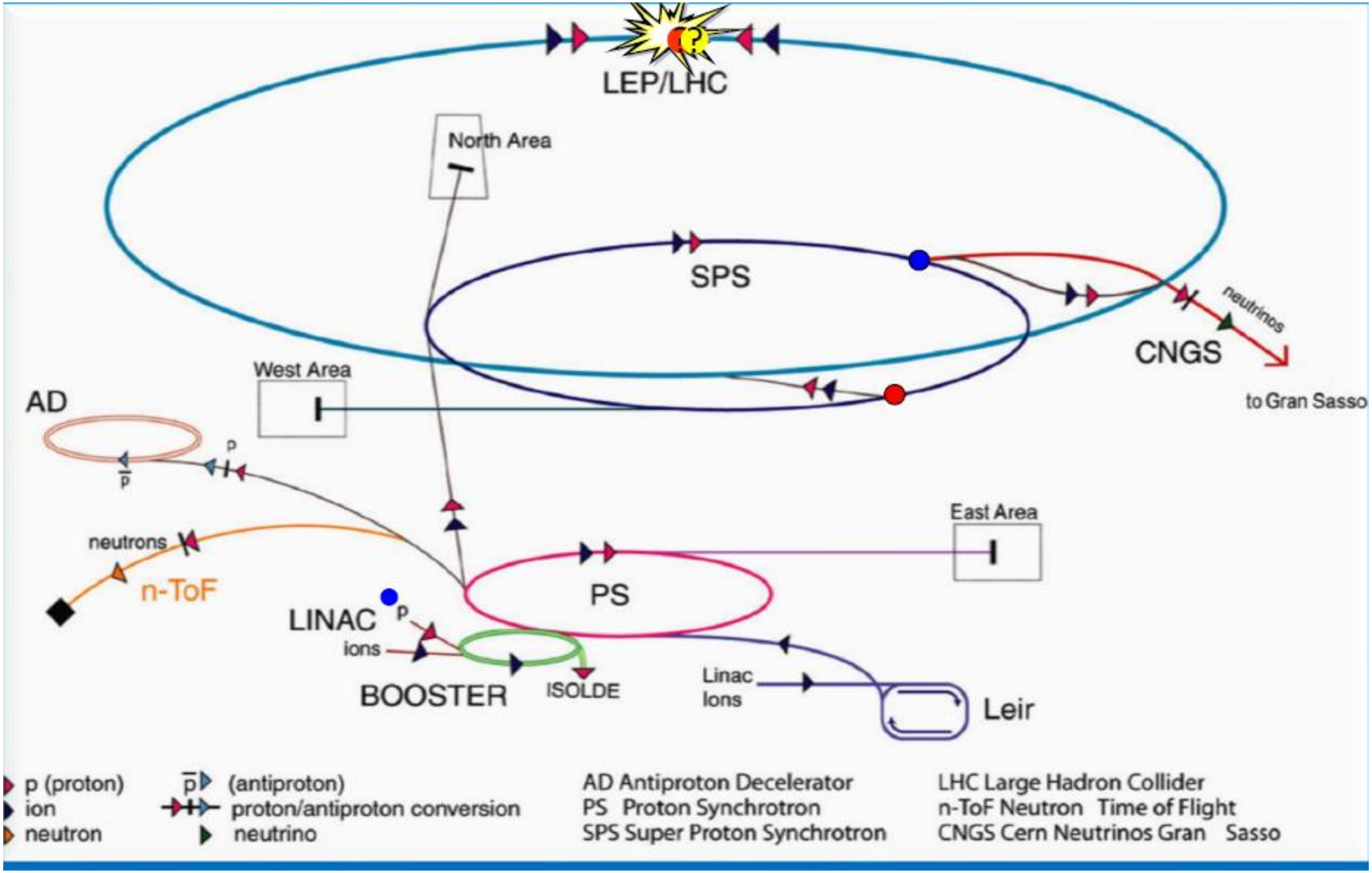
16 superconducting cavities (copper sputtered with niobium) for 16 MV/beam, built and assembled in four modules

Principle of a synchrotron

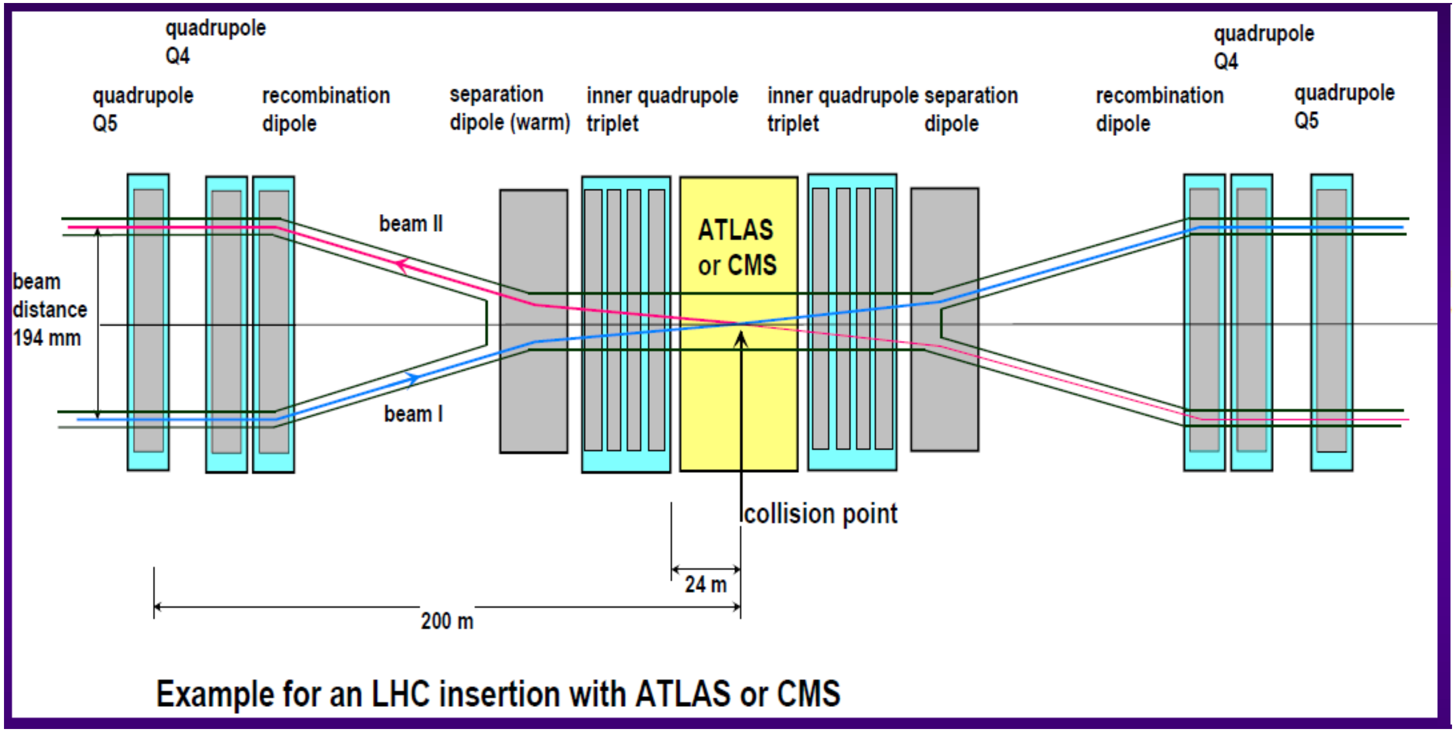
- Injection at low energy
- Ramping of magnetic field and acceleration by RF field. Beams are accelerated in bunches
- Operation (collisions) at top energy



CERN accelerator complex



Experimental long straight section



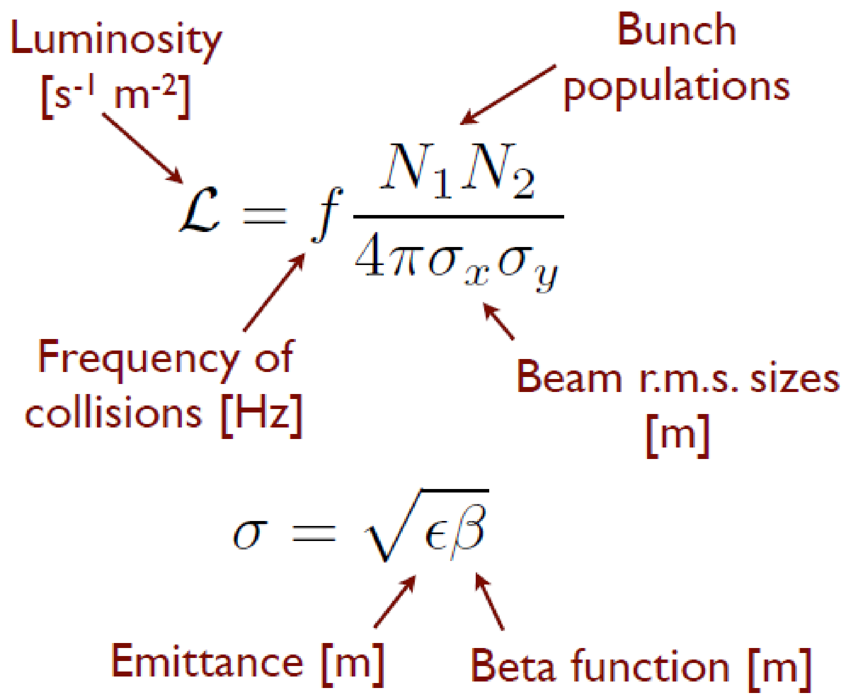
Example for an LHC insertion with ATLAS or CMS

The 2 LHC beams are brought together to collide in common region. Over ~260m the beams circulate in one vacum chamber with „parasitic" encounters.

The crossing angle of about 300μrad

Luminosity

- What luminosity is required for measurement?
  - Need some knowledge of x-section
- Simple relationship between number of particles, frequency of collision and beam sizes



Luminosity [s^{-1} m^{-2}]

Bunch populations

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

Frequency of collisions [Hz]

Beam r.m.s. sizes [m]

$$\sigma = \sqrt{\epsilon\beta}$$

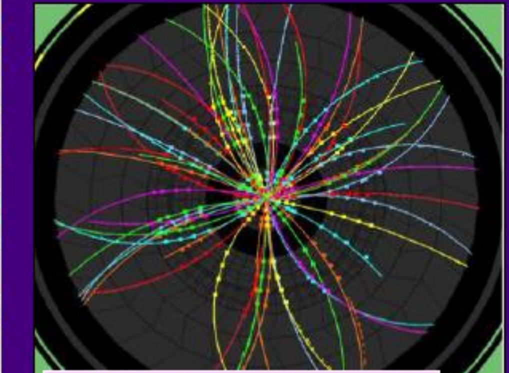
Emittance [m]

Beta function [m]

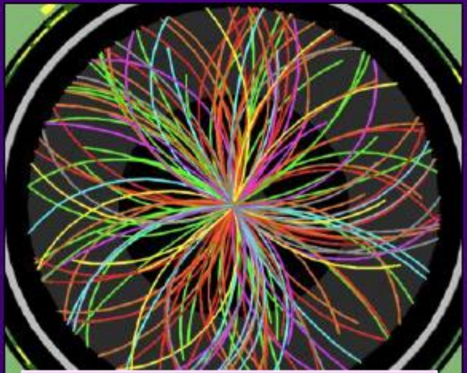
$$\mathcal{L} = f \frac{N_1 N_2}{4\pi\sqrt{\epsilon_x\beta_x^*\epsilon_y\beta_y^*}}$$

⇒ With the parameters of 2012 for each bunch crossing there are up to ~35 interactions (lower luminosity, less number of bunches)

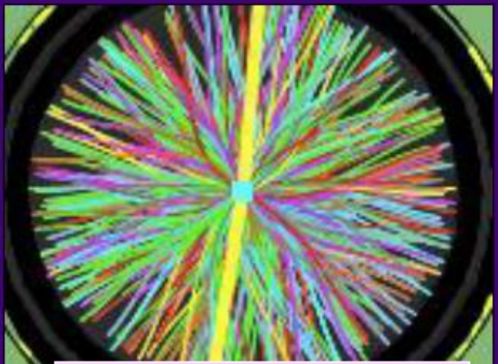
⇒ 'Hats off' to ALTAS & CMS for handling this pile-up !!



2010: ~ 2 events/x-ing



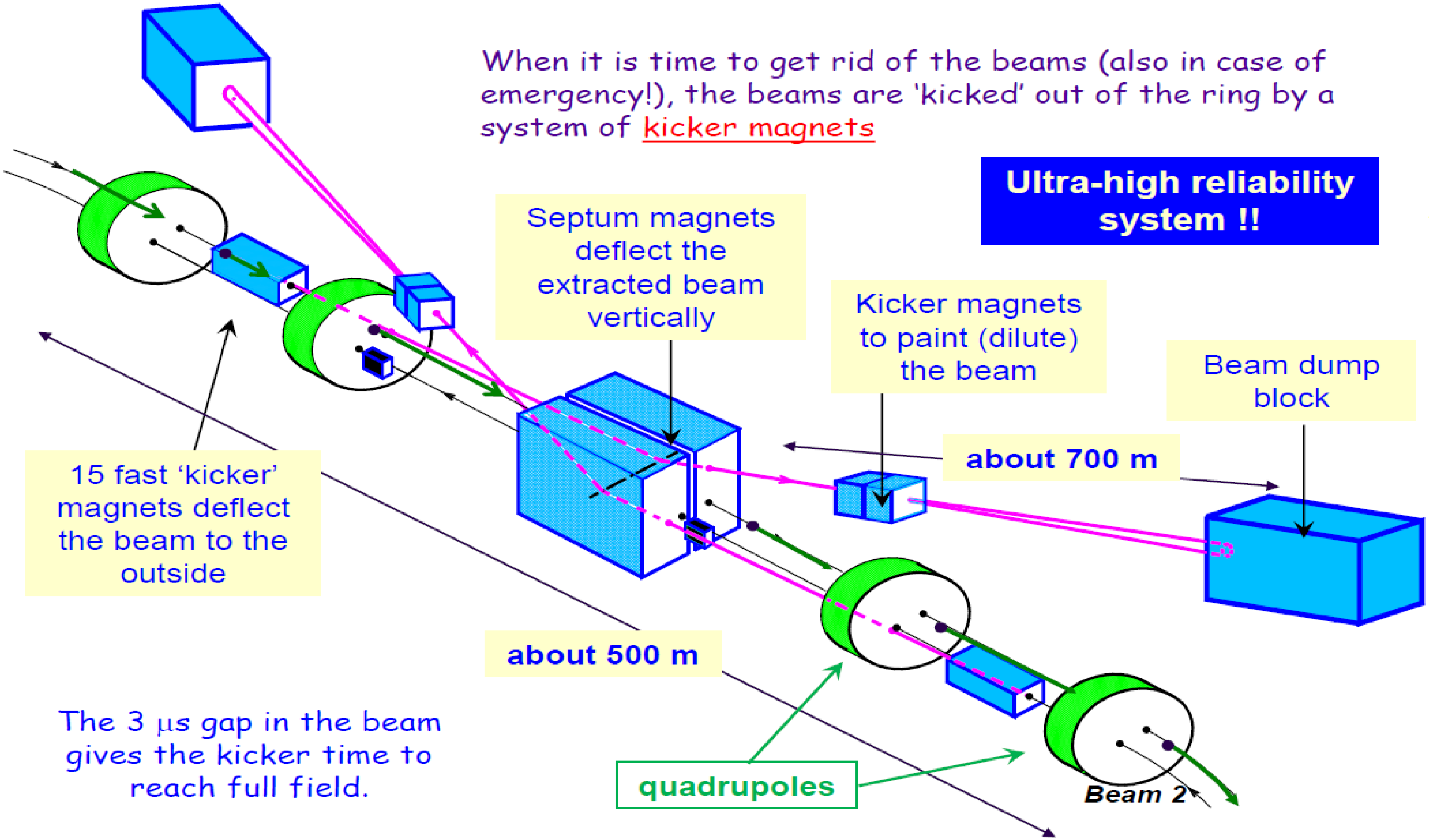
2011: ~ 10 events/x-ing



2012: ~ 20 events/x-ing

Layout of beam system dump

When it is time to get rid of the beams (also in case of emergency!), the beams are 'kicked' out of the ring by a system of kicker magnets



Ultra-high reliability system !!

Septum magnets deflect the extracted beam vertically

Kicker magnets to paint (dilute) the beam

Beam dump block

about 700 m

15 fast 'kicker' magnets deflect the beam to the outside

about 500 m

quadrupoles

The 3 μs gap in the beam gives the kicker time to reach full field.

Dump line

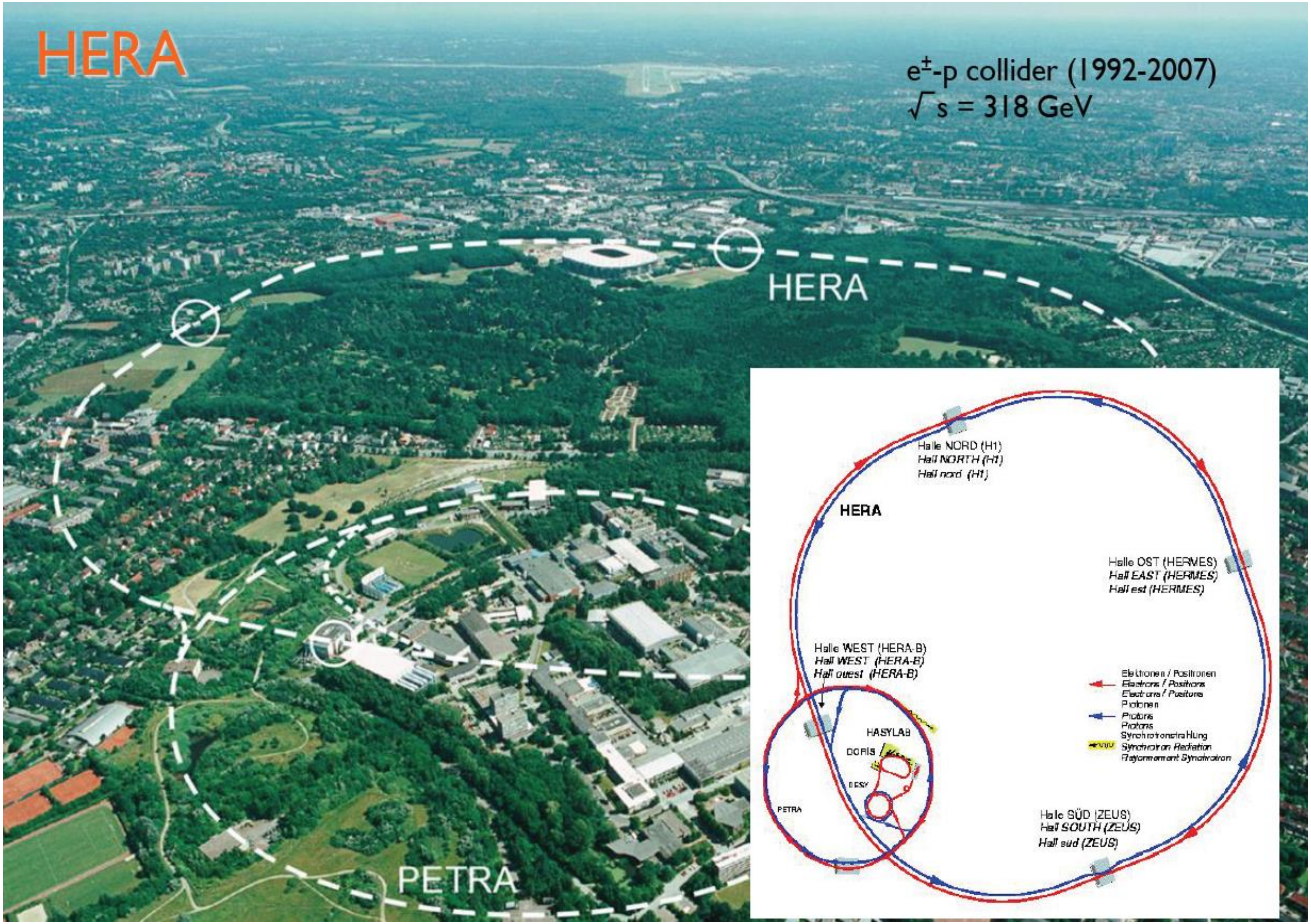
Beam Loss Monitors

- Ionization chambers to detect beam losses:
  - Reaction time ~ ½ turn (40 μs)
  - Very large dynamic range (> 10^6)
- There are **~3600 chambers** distributed over the ring to detect abnormal beam losses and if necessary trigger a beam abort !
- Very important beam instrumentation!

Accelerators around the world (past and present)

HERA

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



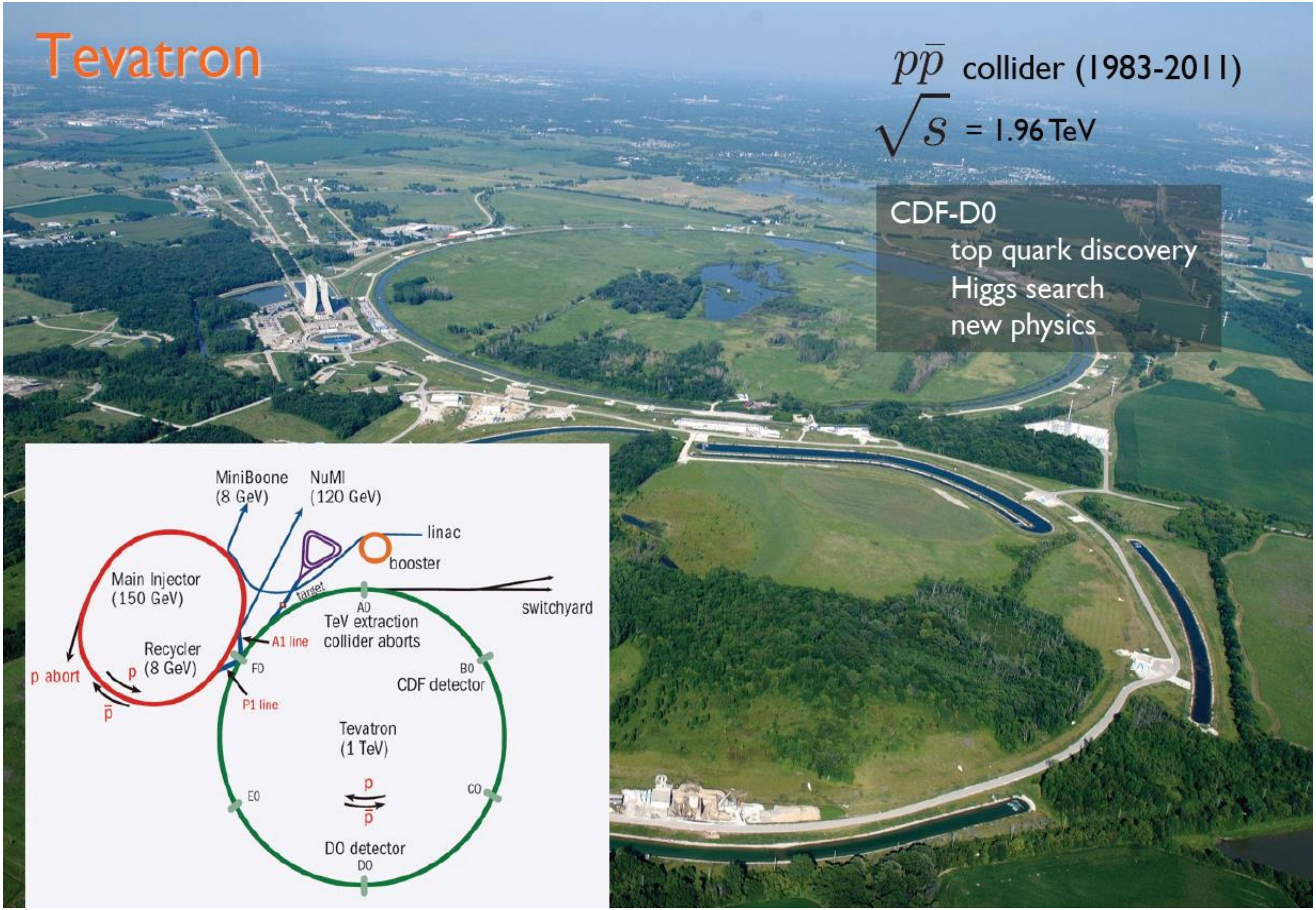
Tevatron

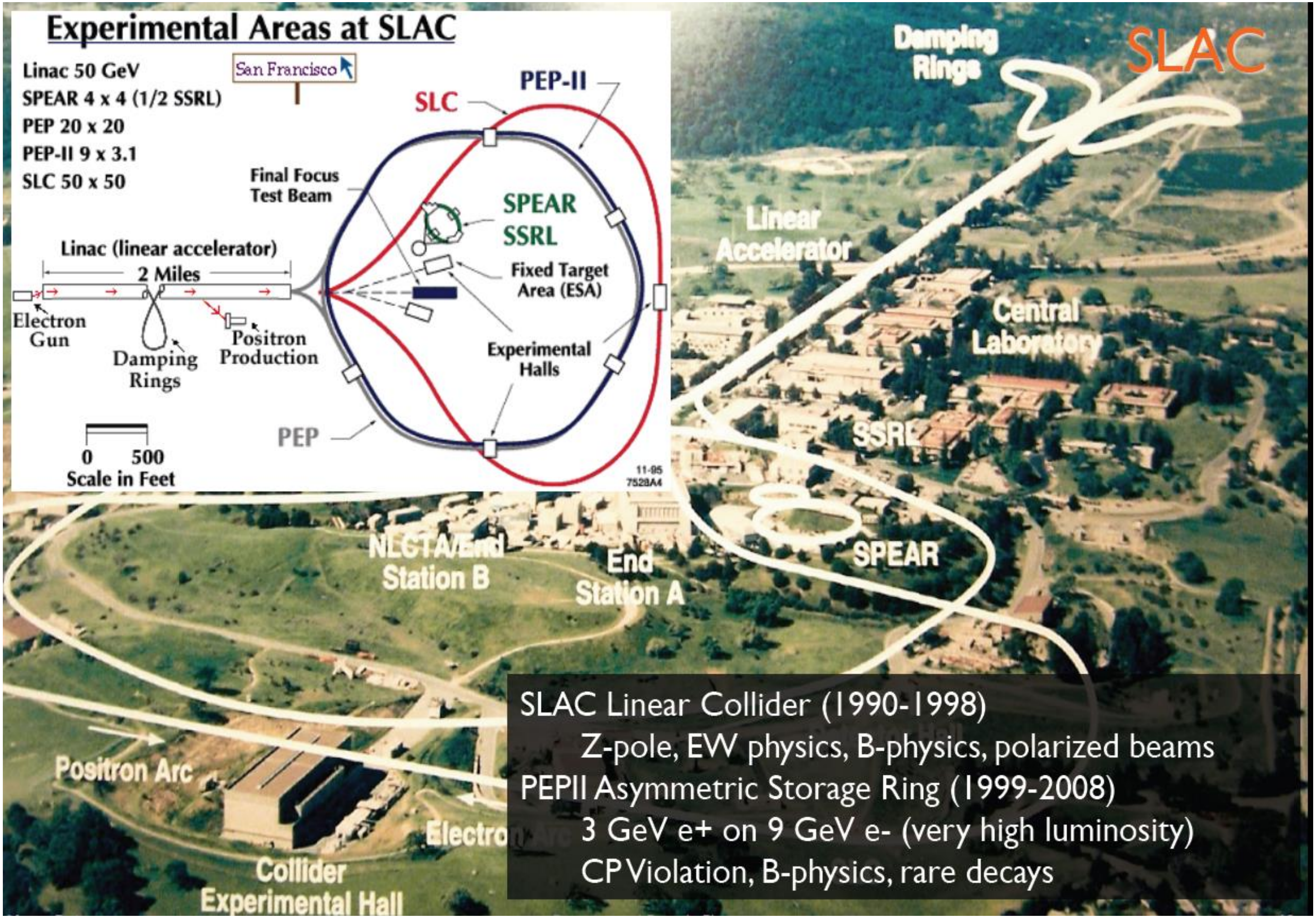
$p\bar{p}$ collider (1983-2011)

$\sqrt{s}$ = 1.96 TeV

CDF-D0

- top quark discovery
- Higgs search
- new physics





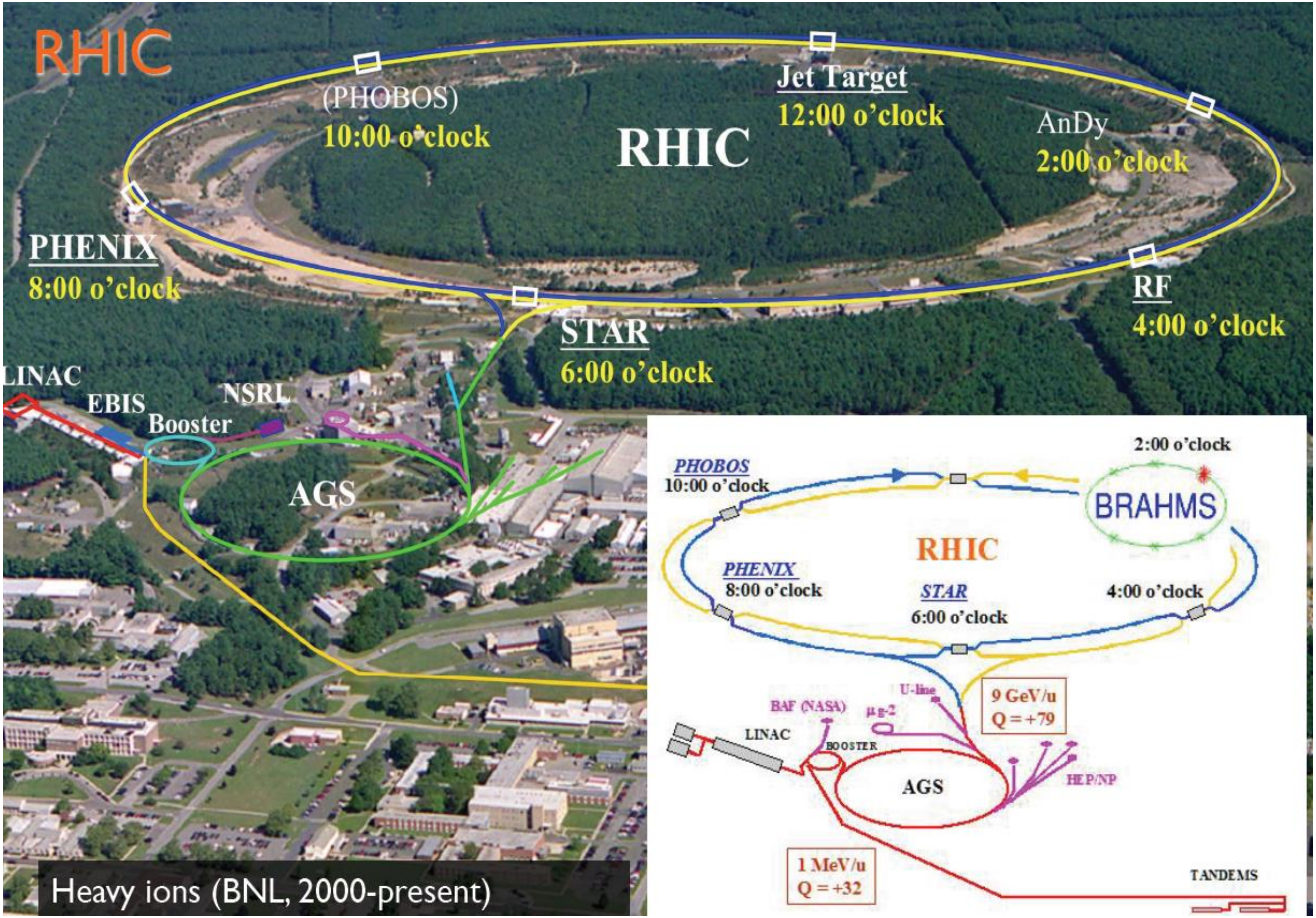
SLAC Linear Collider (1990-1998)

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

PEPII Asymmetric Storage Ring (1999-2008)

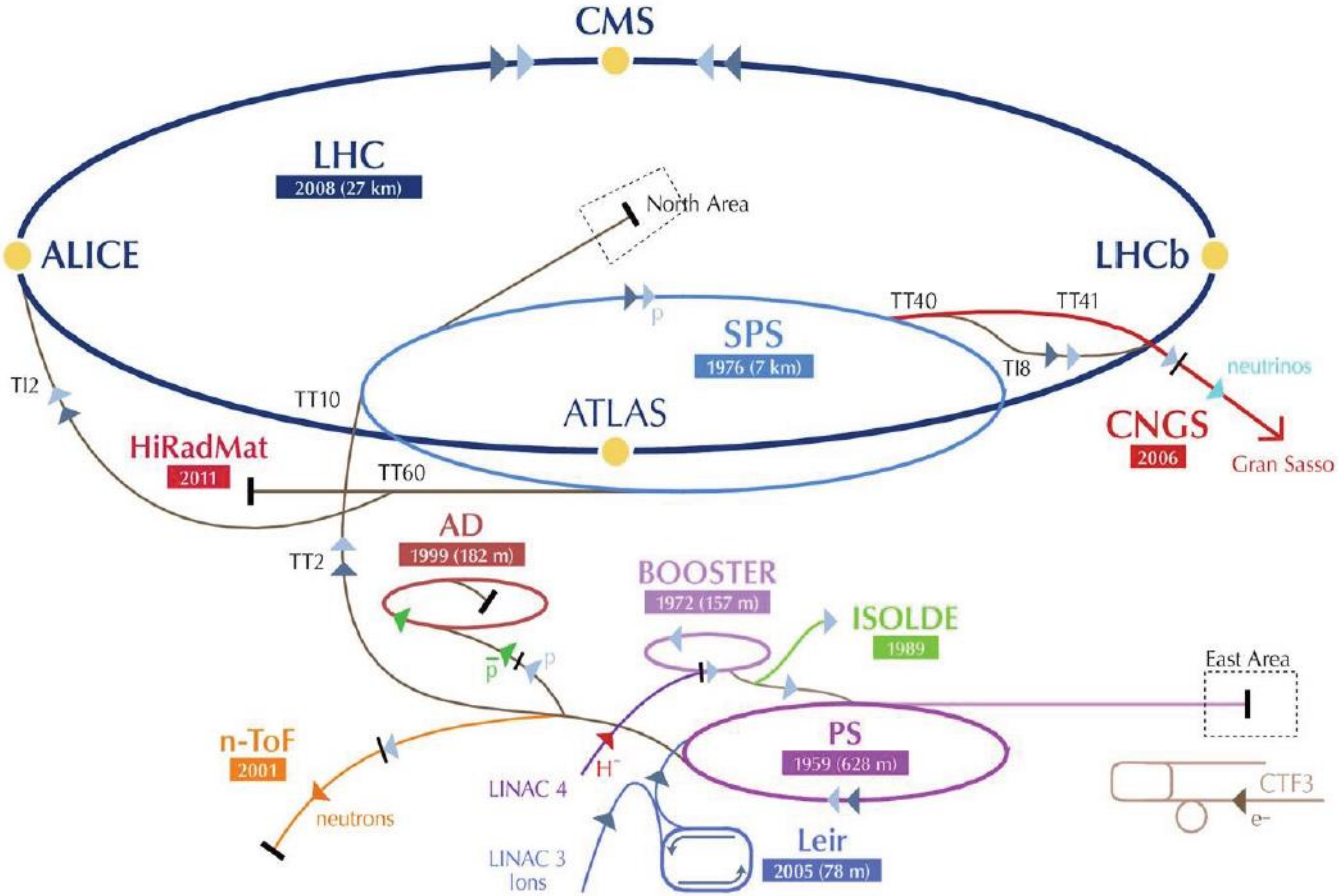
- 3 GeV e+ on 9 GeV e- (very high luminosity)
- CP Violation, B-physics, rare decays

RHIC

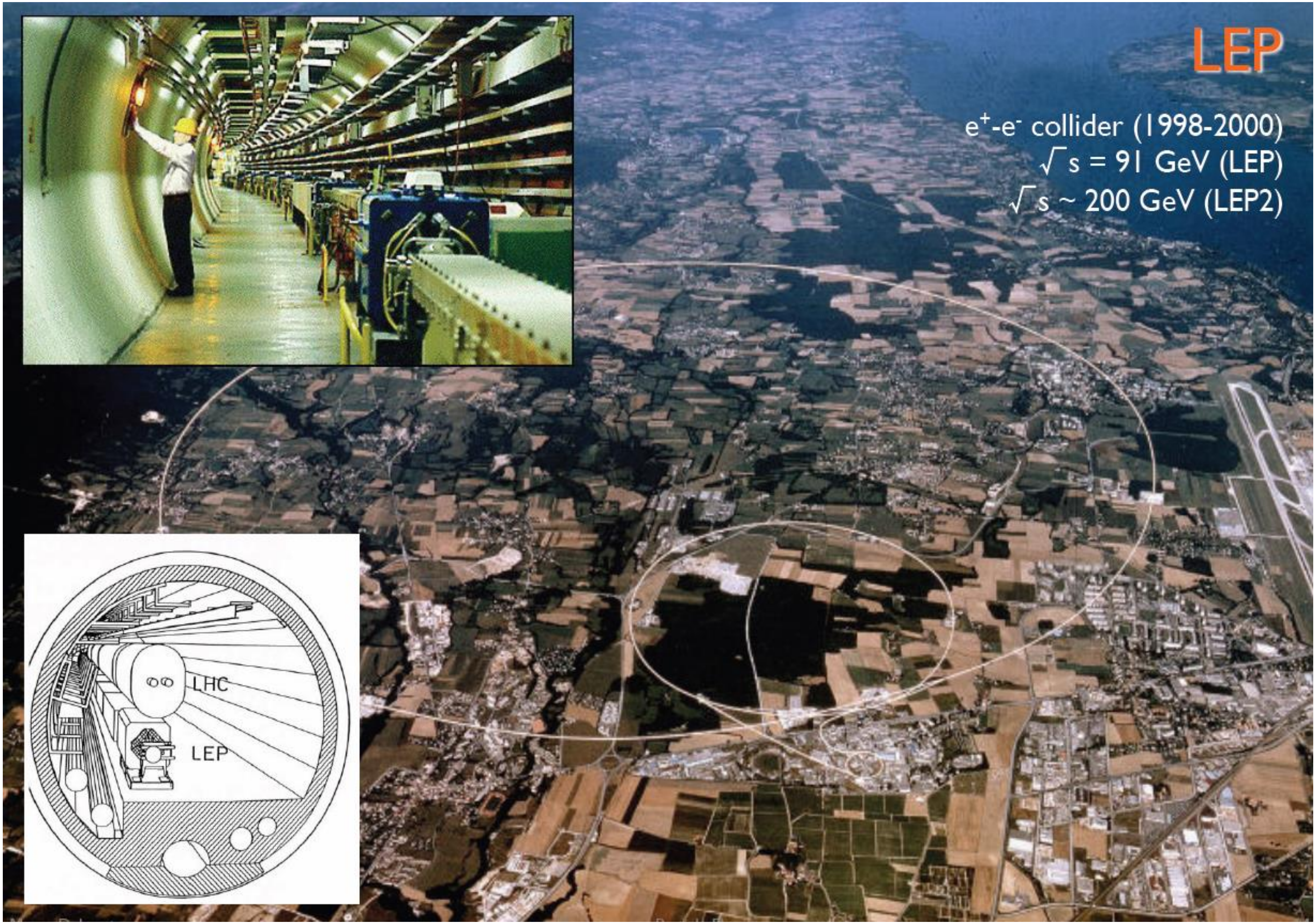


Heavy ions (BNL, 2000-present)

CERN accelerator complex

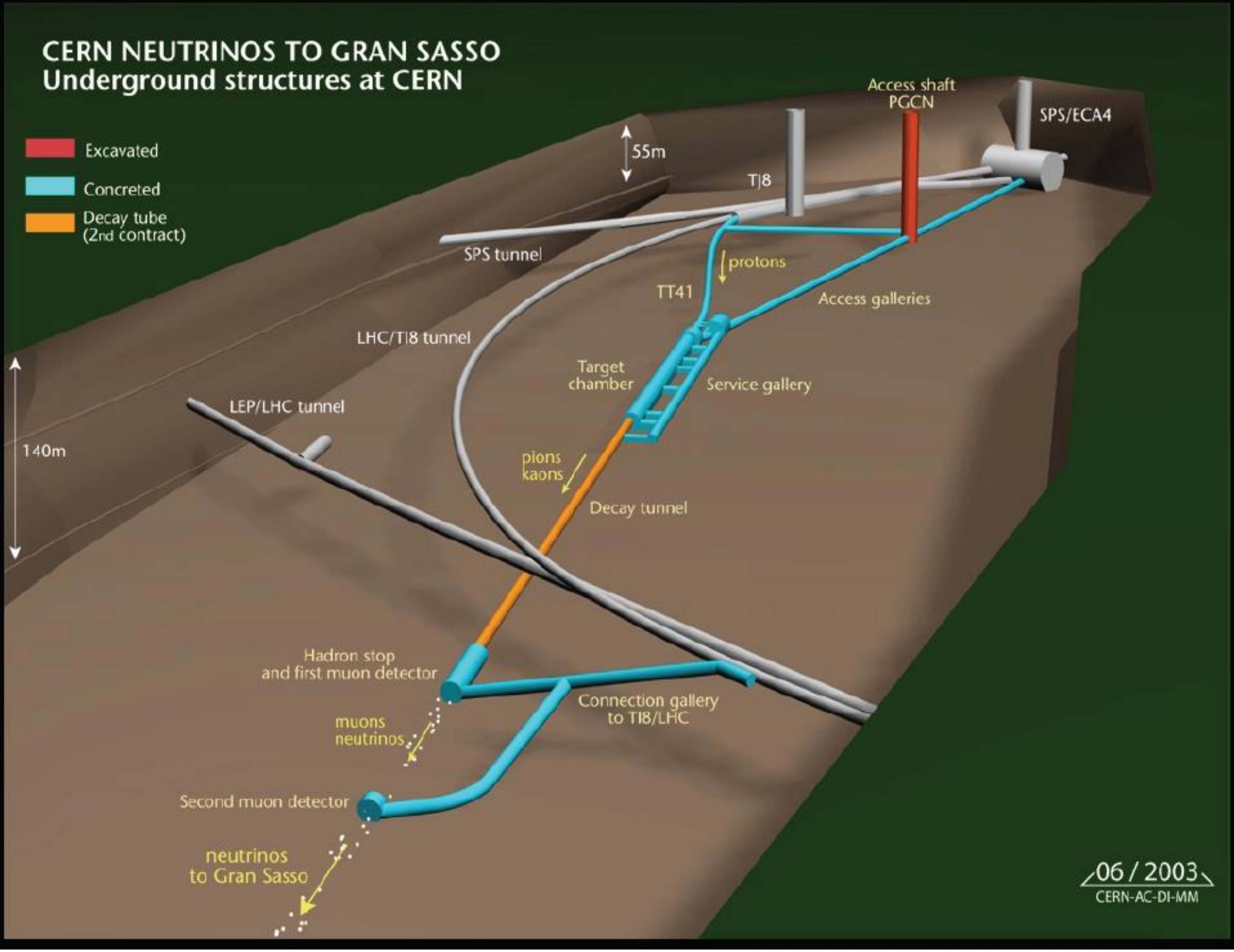


LEP



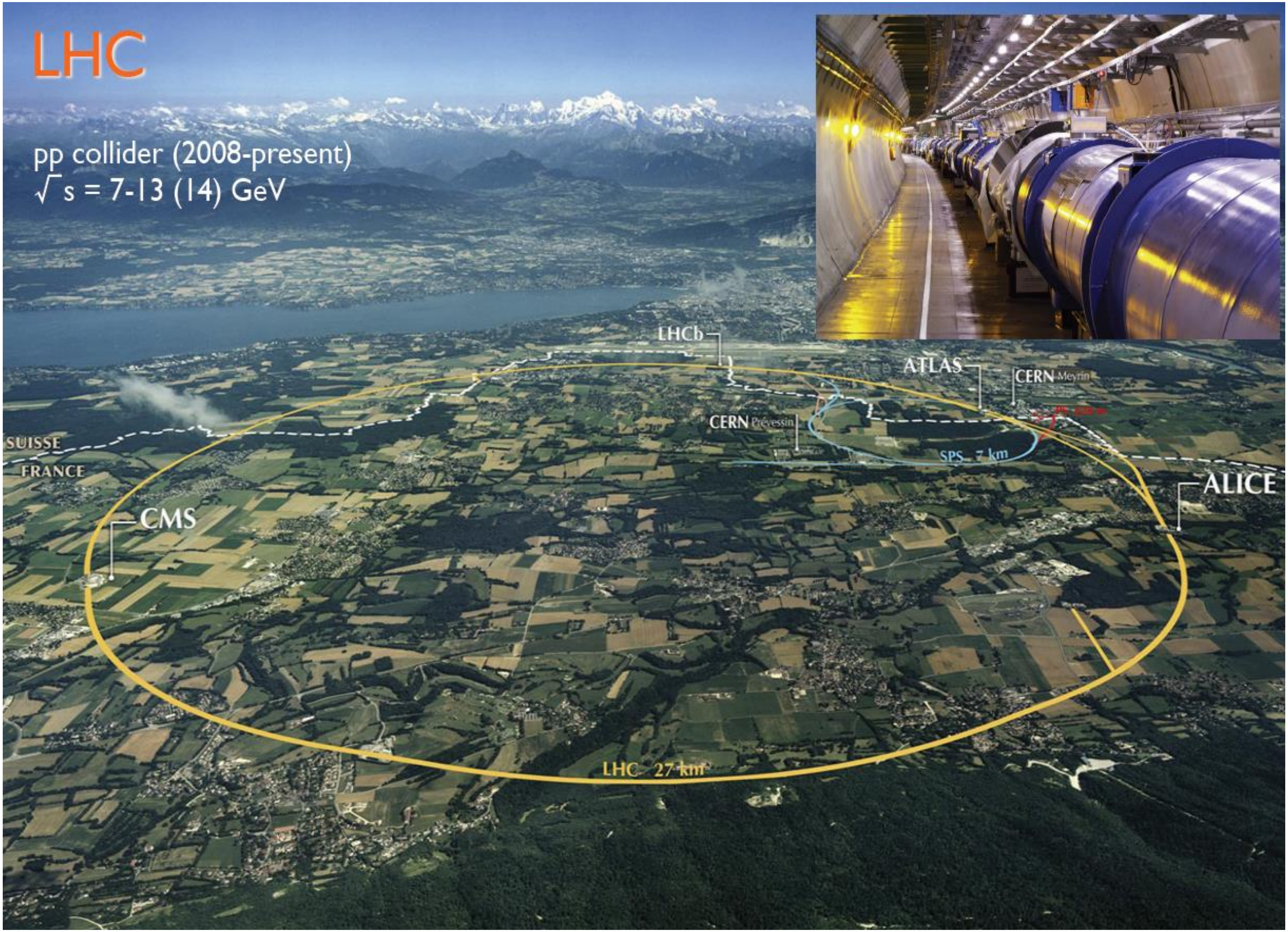
e^+-e^- collider (1998-2000)
$\sqrt{s}$ = 91 GeV (LEP)
$\sqrt{s}$ ~ 200 GeV (LEP2)

Production of secondary beams

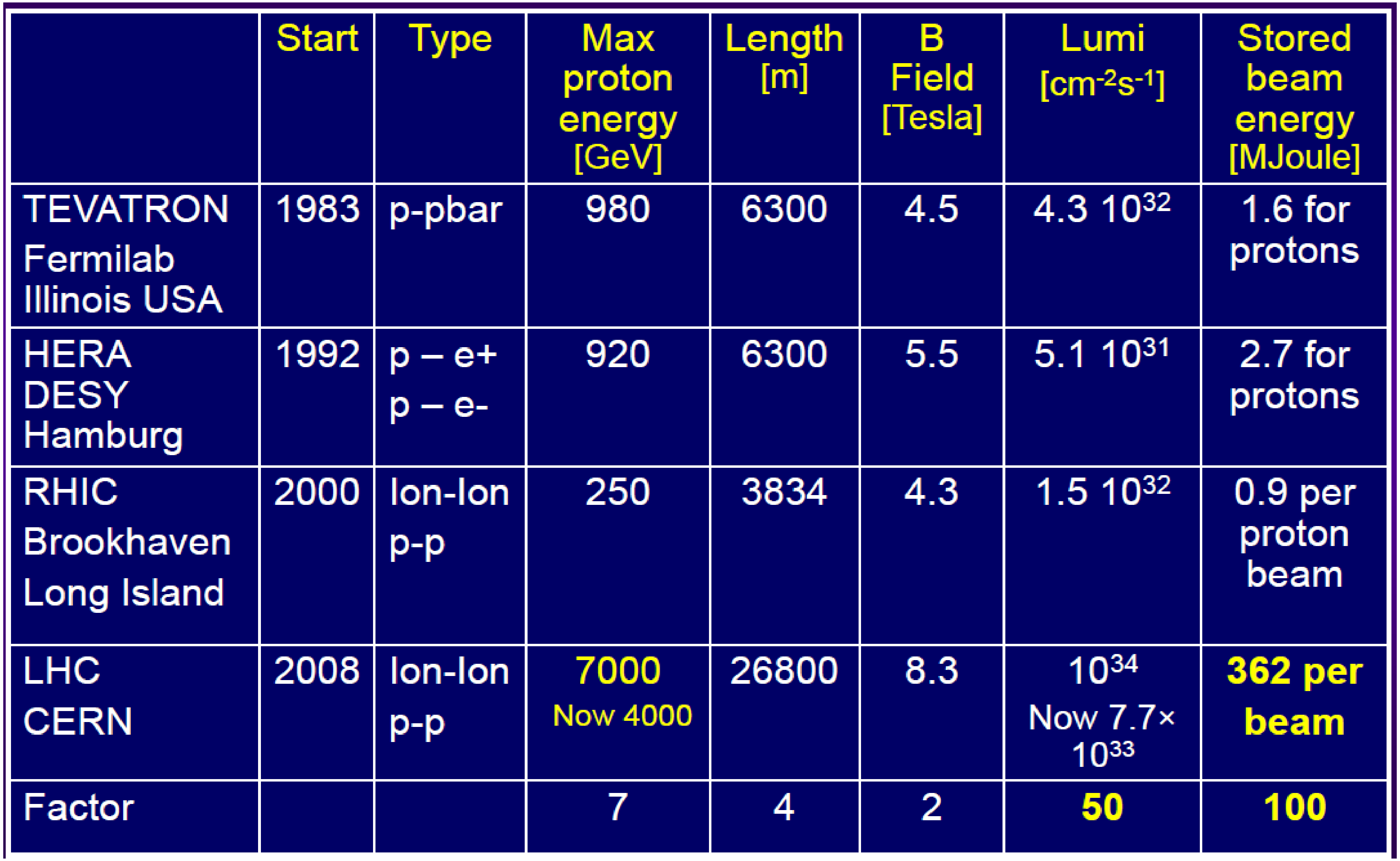


LHC

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

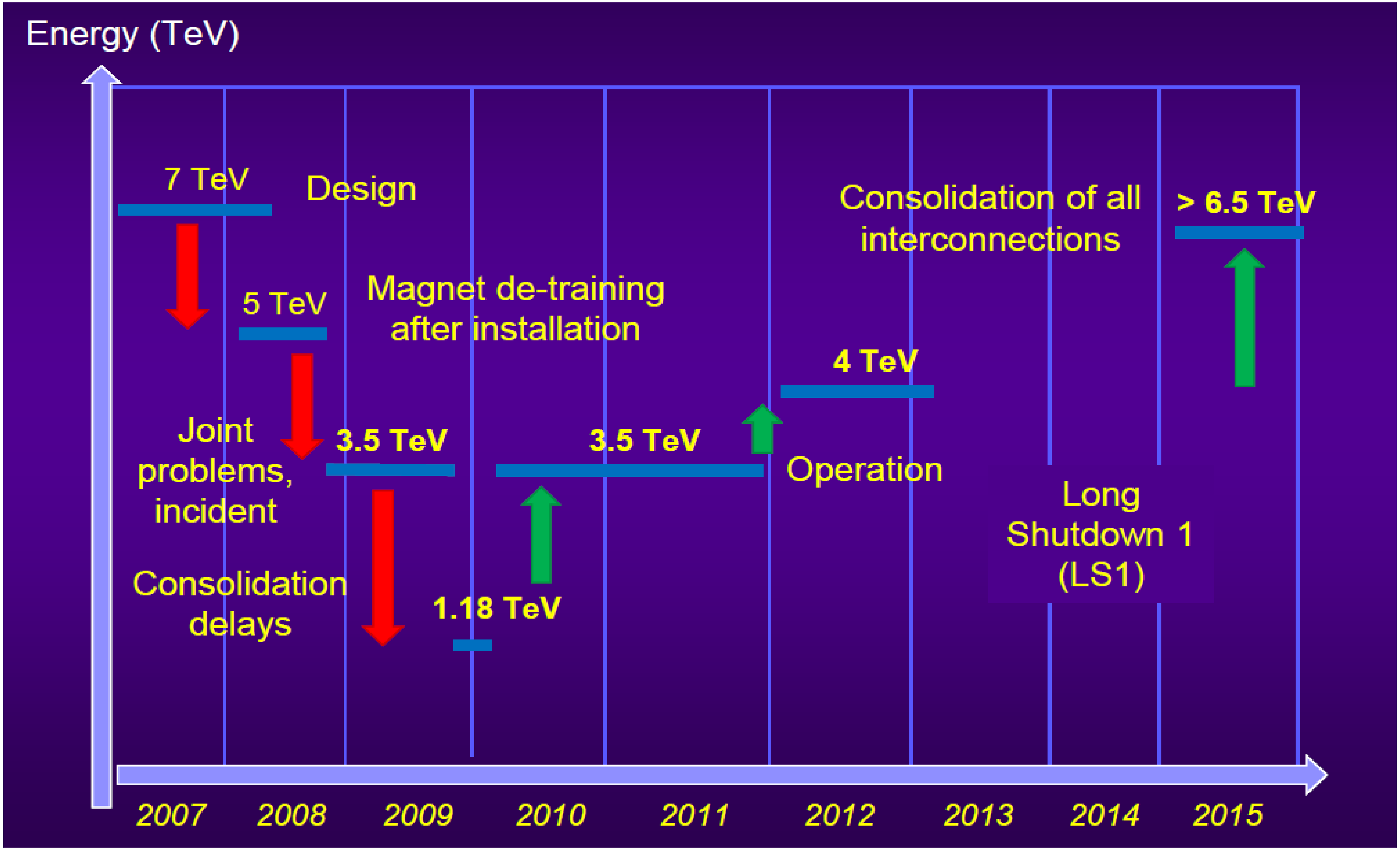


The LHC: just another collider?



	Start	Type	Max proton energy [GeV]	Length [m]	B Field [Tesla]	Lumi [cm^{-2}s^{-1}]	Stored beam energy [MJoule]
TEVATRON Fermilab Illinois USA	1983	p-pbar	980	6300	4.5	4.3 10^{32}	1.6 for protons
HERA DESY Hamburg	1992	p – e+ p – e-	920	6300	5.5	5.1 10^{31}	2.7 for protons
RHIC Brookhaven Long Island	2000	Ion-Ion p-p	250	3834	4.3	1.5 10^{32}	0.9 per proton beam
LHC CERN	2008	Ion-Ion p-p	7000 Now 4000	26800	8.3	10^{34} Now 7.7× 10^{33}	**362 per beam**
Factor			7	4	2	**50**	**100**

LHC energy evolution



Summary: 2010 - 2012

$$L = \frac{k N_b^{\,2} f \gamma}{4\pi \beta^* \varepsilon^*} F$$

Parameter	**2010**	**2011**	**2012**	**Nominal**
Energy [TeV]	3.5	3.5	**4.0**	7.0
N_b [10^{11} p/bunch]	1.2	1.45	**1.6**	1.15
k (no. bunches)	368	1380	**1380**	2808
Bunch spacing [ns]	150	75 / 50	**50**	25
Stored energy [MJ]	25	112	**140**	362
ε^* [μm]	2.4	2.4	**2.5**	3.75
β^* [m]	3.5	1.5 → 1	**0.6**	0.55
Crossing angle [μrad]	200	240	**290**	285
L [10^{34} cm^{-2}s^{-1}]	0.02	0.35	**0.76**	1.0
Beam-beam parameter/IP (ΔQ_{bb})	-0.0054	-0.0065	**-0.0069**	-0.0033
Average Pile-up @ beg. of fill	8	17	**38**	26

Improvements to luminosity

increase number
of bunches?

increase number particle
per bunch?

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

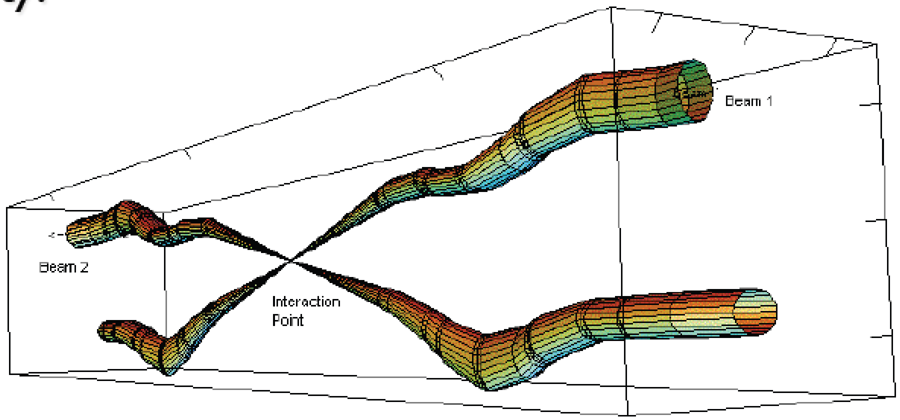
decrease emittance!

decrease beta star!

Crossing angle

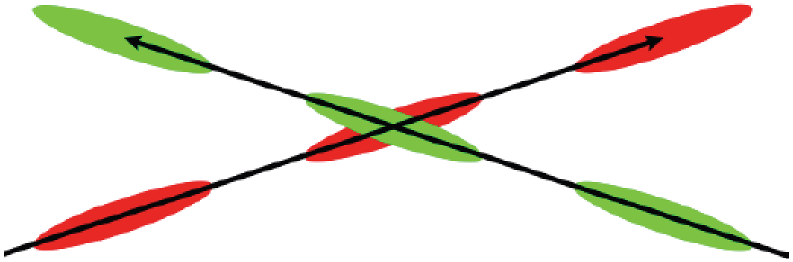
- To avoid parasitic encounters, beams with close bunches often cross at an angle
  - ✓ LHC beams cross at an angle of 300 microradian (bunch spacing 25 ns)
- Crossing angle has an impact on luminosity!

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

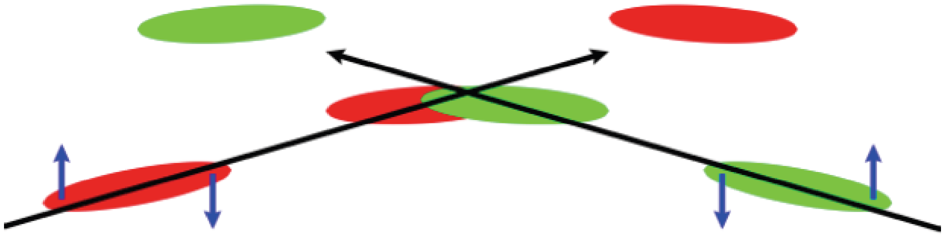


Relative beam sizes around IP1 (Atlas) in collision

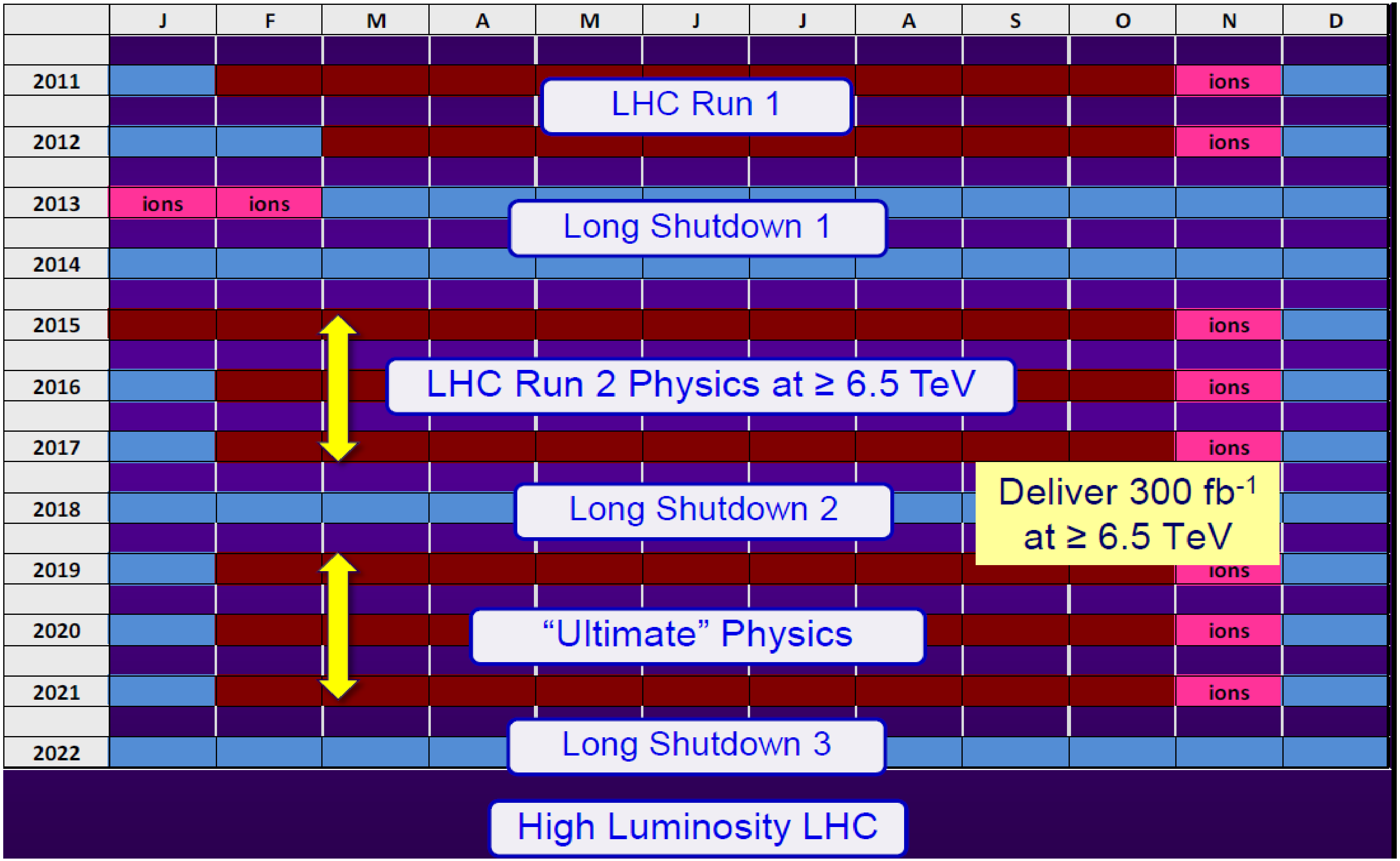
with crossing angle



“crab” crossing



The next years



	J	F	M	A	M	J	J	A	S	O	N	D
2011											ions	
2012											ions	
2013	ions	ions										
2014												
2015											ions	
2016											ions	
2017											ions	
2018												
2019											ions	
2020											ions	
2021											ions	
2022												

LHC Run 1

Long Shutdown 1

LHC Run 2 Physics at ≥ 6.5 TeV

Deliver 300 fb^{-1} at ≥ 6.5 TeV

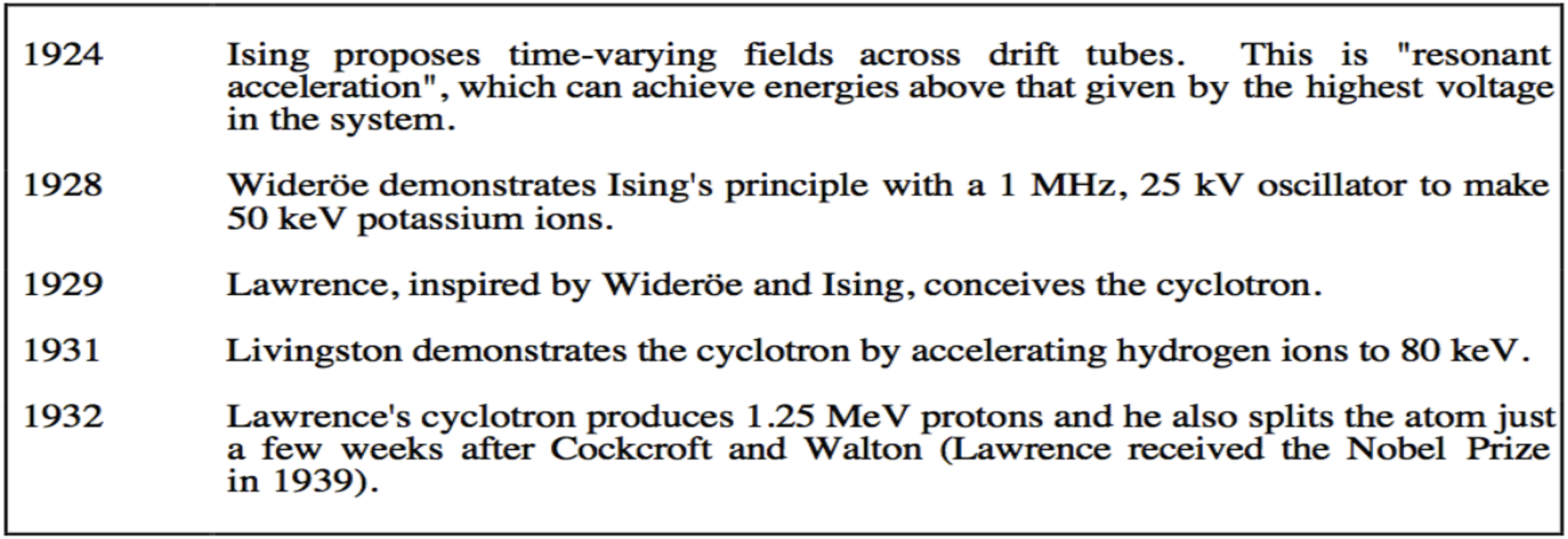
Long Shutdown 2

“Ultimate” Physics

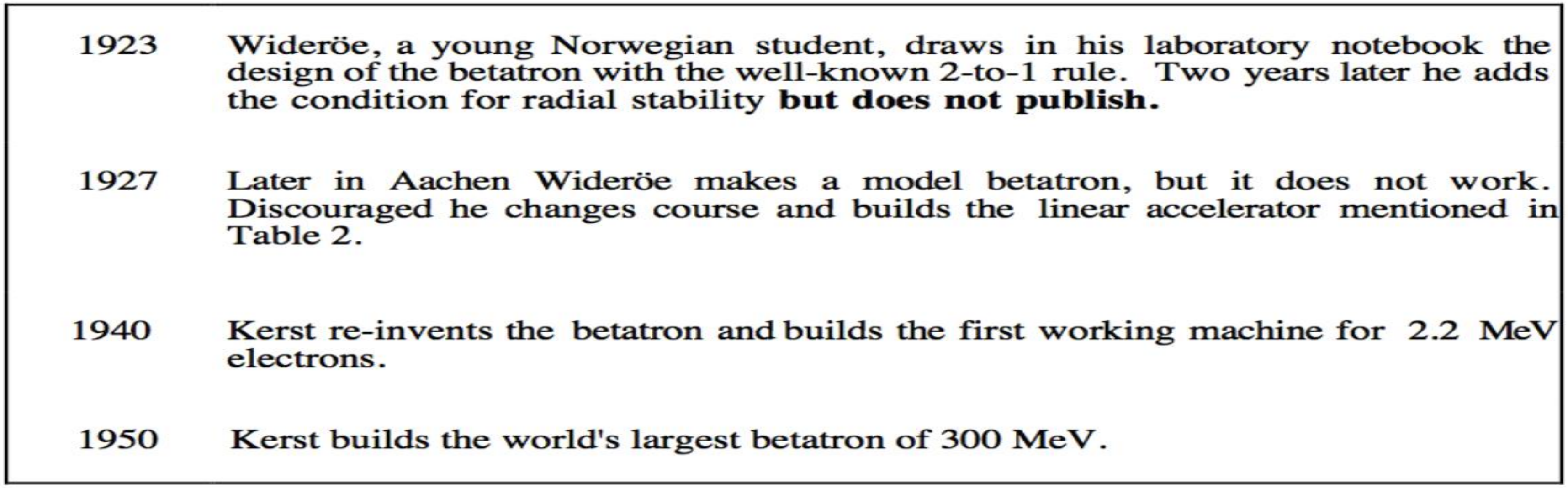
Long Shutdown 3

High Luminosity LHC

A biref history of particle accelerators

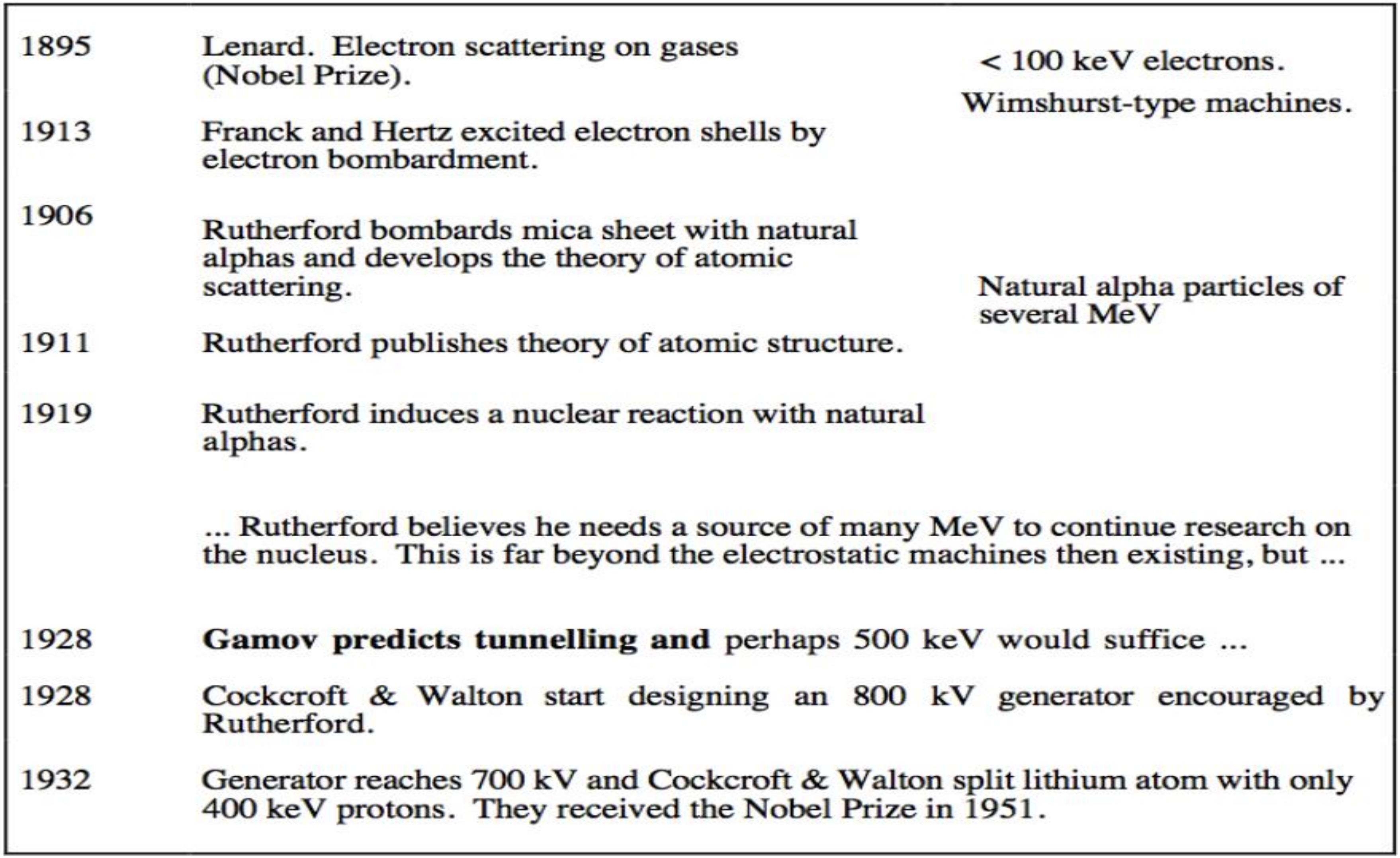


1924	Ising proposes time-varying fields across drift tubes. This is "resonant acceleration", which can achieve energies above that given by the highest voltage in the system.
1928	Wideröe demonstrates Ising's principle with a 1 MHz, 25 kV oscillator to make 50 keV potassium ions.
1929	Lawrence, inspired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



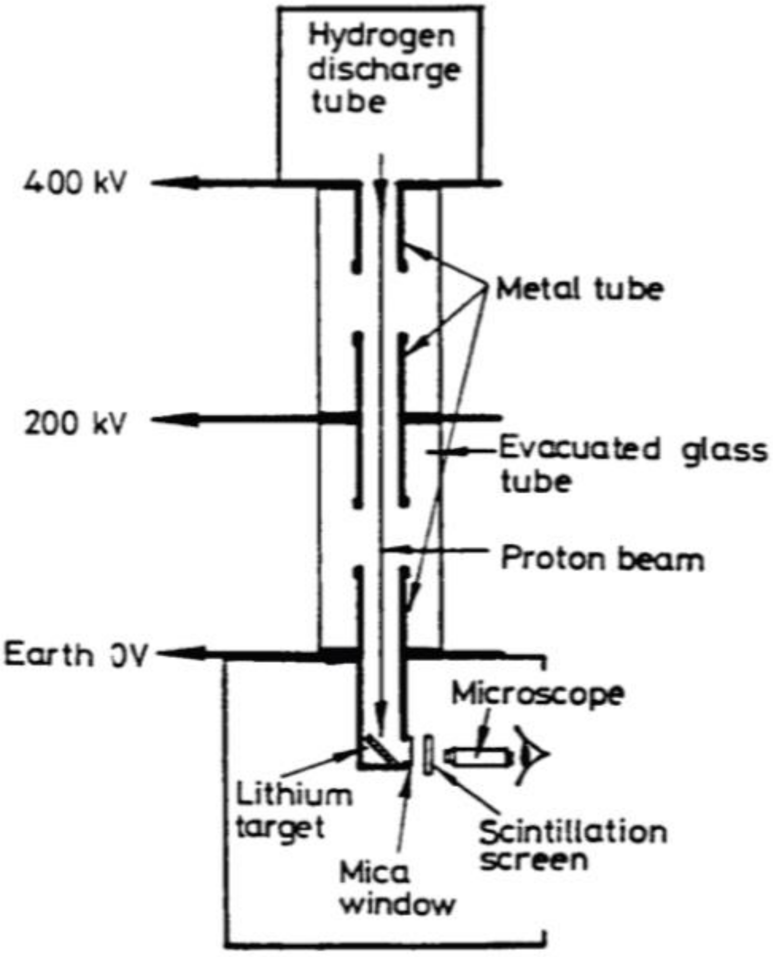
1923	Wideröe, a young Norwegian student, draws in his laboratory notebook the design of the betatron with the well-known 2-to-1 rule. Two years later he adds the condition for radial stability **but does not publish.**
1927	Later in Aachen Wideröe makes a model betatron, but it does not work. Discouraged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

A brief history of particle accelerators

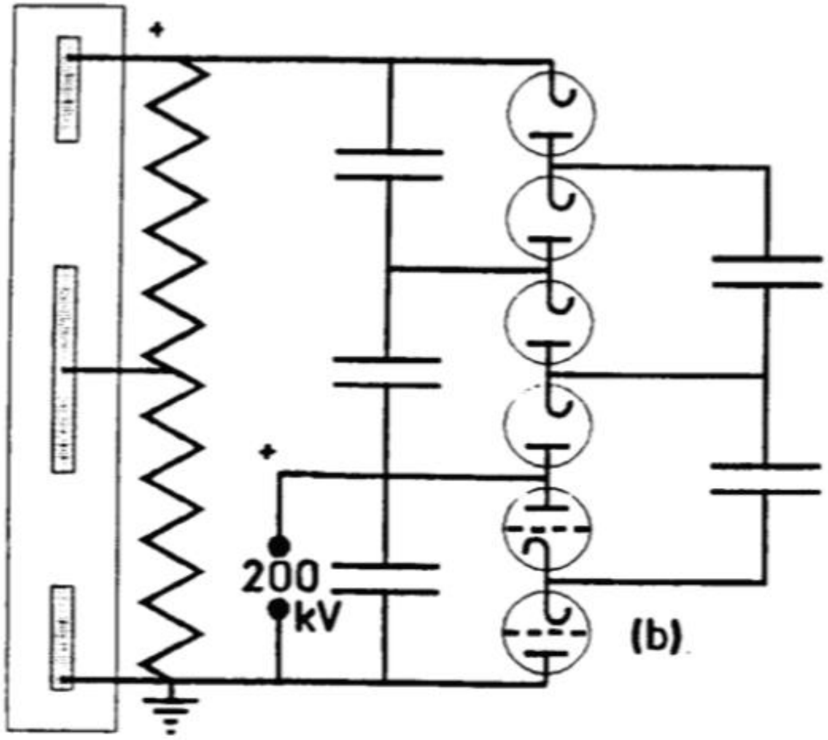


1895	Lenard. Electron scattering on gases (Nobel Prize).	< 100 keV electrons. Wimshurst-type machines.
1913	Franck and Hertz excited electron shells by electron bombardment.	
1906	Rutherford bombards mica sheet with natural alphas and develops the theory of atomic scattering.	Natural alpha particles 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

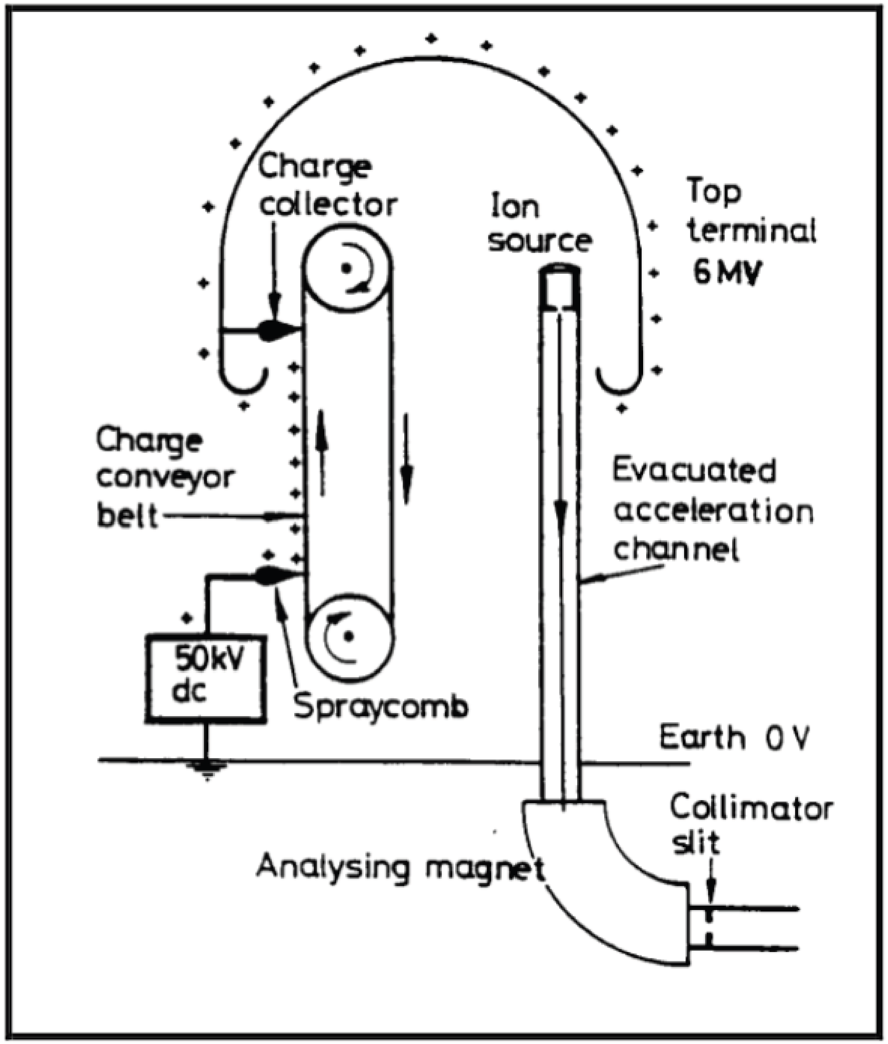


(a) Accelerating column



(b) DC generator

Van de Graaff electrostatic generator



Two-stage Tandem accelerator