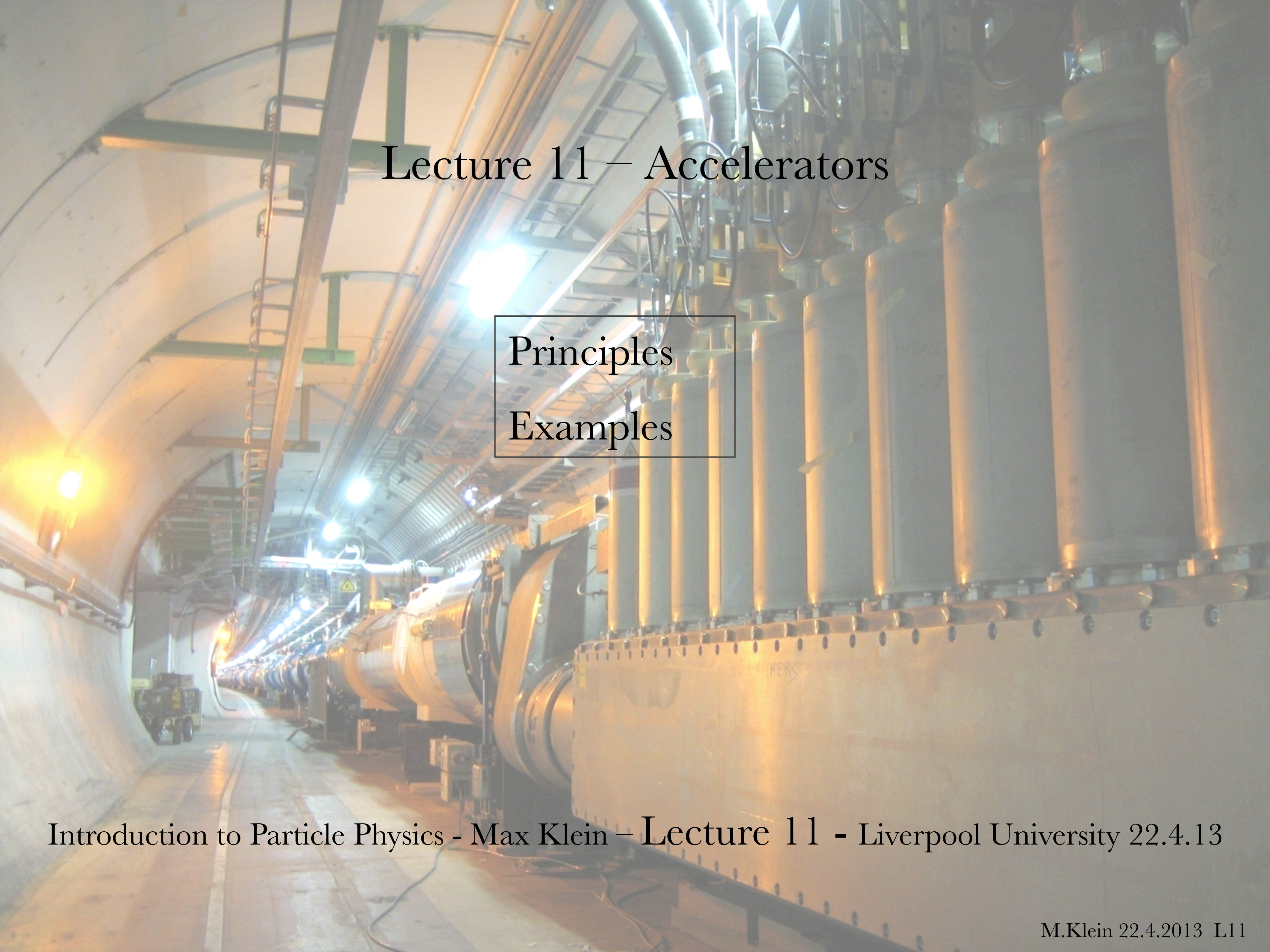

Lecture 11 – Accelerators

Principles

Examples

Introduction to Particle Physics - Max Klein – Lecture 11 - Liverpool University 22.4.13

References

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- H. Wiedemann, "*Particle accelerator physics, 1 : basic principles and linear beam dynamics*"- 2nd ed. , Springer, Berlin 1999.
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- J.B. Rosenzweig, "*Fundamentals of Beam Physics*," Oxford Univ. Press, 2003.
- A.W. Chao, M. Tigner, "*Handbook of accelerator physics and engineering*", World Scientific, Singapore,1999

From F.Zimmermann

Course Overview

25.2. Introduction and Basics

4.3. Quantum Numbers and Quarks, Gluons

11.3. Leptons,Photons, QED and Neutrinos,Weak Interactions

18.3. Strange and Heavy Quarks

Easter Break

15.4. Detectors, Tracking and Calorimeters

22.4. Accelerators and Revision

29.4. Higgs and HEP Outlook

Tutorials: 14.3., 21.3., two more: 25.4., 2.5.
Exam: Friday 24th of May, 2.30-4.00 pm 204

Electrostatic Accelerator

$$qV = \frac{m}{2}v^2 = \frac{p^2}{2m}$$

$$p = \sqrt{2mqV}$$

Momentum of particle of charge q and mass m after passage of a voltage difference. Limited by V.

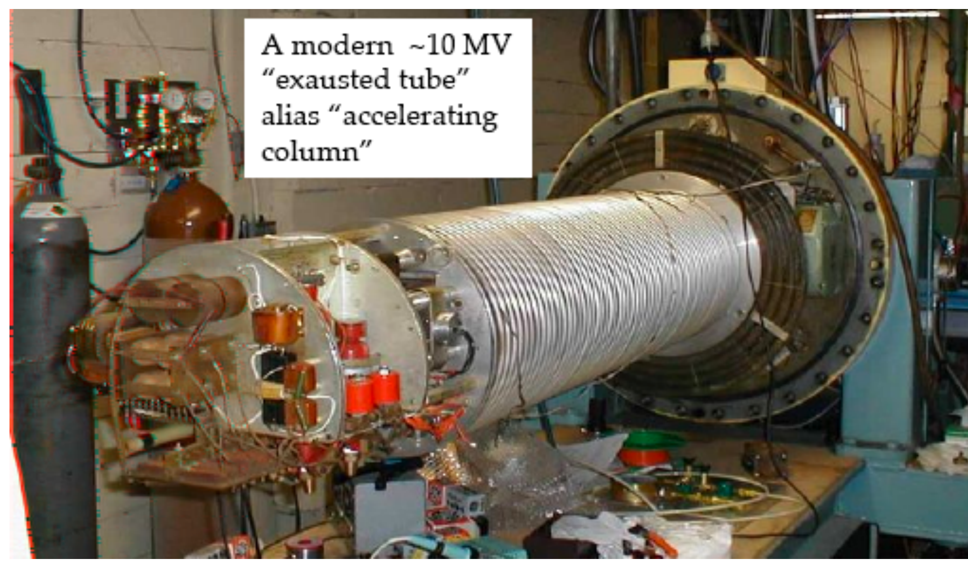
Van de Graaf
Cockcroft Walton
Tandem
Oscillographs, CRT TV sets..

Braun cathode ray tube (1897)

Karl Ferdinand Braun

"What we require is an apparatus to give us a potential of the order of 10 million volts which can be safely accomodated in a reasonably sized room and operated at a few kilowatts of power.
We require too an exausted (*evacuated*) tube capable of withstanding this voltage…….I see no reason why such requirements can not be made practical."

Rutherford 1930



Tazzari, Cern Acc School 2006

High Frequency Linear Accelerator

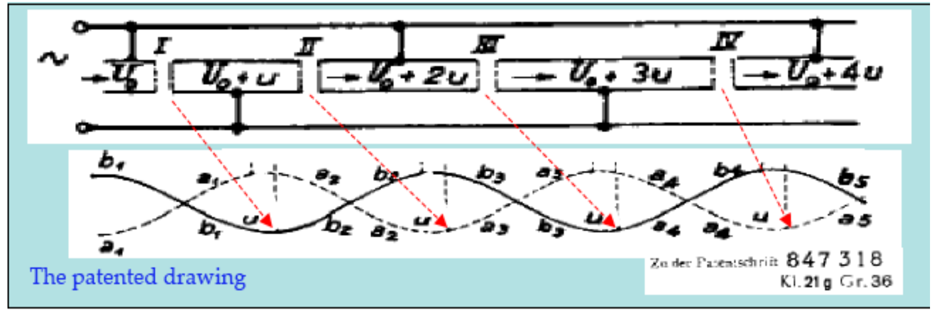
$$qNV = \frac{m}{2}v^2 = \frac{p^2}{2m}$$

$$p = \sqrt{2mqNV}$$

Passage through N times
a voltage difference V

Multiple acceleration
cf Laurence Nobel lecture:

Gustaf Ising, "Prinzip einer Methode zur Herstellung von Kanalstrahlen Hoher Voltzahl", Arkiv för Matematik, Astronomi och Fysik, Band 18 (1924)



R.Wideroe's sketch in: *"The Infancy of Particle Accelerators"*, DESY-Report 94-039.


1920

[note: V=u for RW!]

$$V : v_1 = \sqrt{2qV/m}$$

$$\Delta t = \frac{L_1}{v_1} = \frac{T}{2} = \frac{1}{2f}$$

$$f_1 = \frac{v_1}{2L_1} = \frac{1}{2L_1}\sqrt{2qV/m}$$

$$2V : v_2 = \sqrt{2} \cdot \sqrt{2qV/m} = \sqrt{2} \cdot v_1$$

$$f_2 = \frac{v_2}{2L_2} = \frac{v_1\sqrt{2}}{2L_2}$$

$$L_2 = \sqrt{2} \cdot L_1 \mapsto f_2 = f_1 = f$$

$$L_k = \sqrt{k} \cdot L_1, k = 1 \ldots N$$

Resonance condition:

Frequency = velocity/2L at each gap. As frequency is constant, length has to grow like √k.

For large v=cβ, frequency has to be very high to keep L small

Rolf Wideroe, 1902-1996
1927 (PhD)
[2 sections, 25kV, 50Hz]

$$\frac{mv^2}{r} = qvB$$

$$v = \frac{q}{m} rB$$

$$r = \frac{mv}{qB}$$

$$t = \frac{\pi r}{v} = \frac{\pi m}{qB} = \frac{T}{2} = \frac{1}{2f}$$

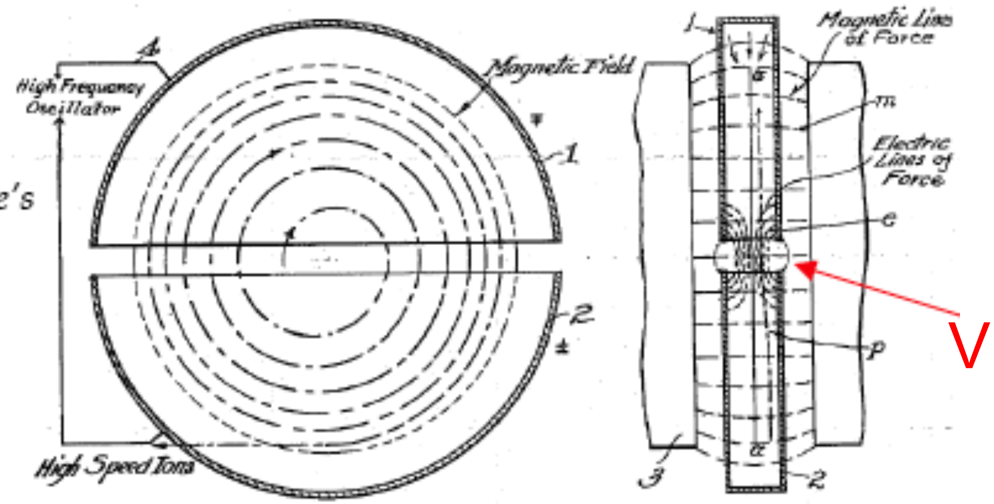
$$f = \frac{v}{2\pi r}$$

$$f = \frac{qB}{2\pi m}$$

Cyclotron [B=const, f=const, r varies]

Lawrence invents the cyclotron 1931 based on Wideroes linac.
Strong magnetic field to bend particles on a circle.
Alternating electric field (potential between two halves):
Each turn an energy qV is gained. The time per turn is
independent of the radius as r and v increase like √k with
the frequency resonance condition analogous to Wideroe's.

Lawrence's patent claim design.



$$E_{kin} = \frac{m}{2} v^2 = \frac{q^2}{2m} (rB)^2$$

Large radius and high mag field to achieve large energy. Needs constant mass, i.e. non relativistic conditions (Bethe E_p < 20 MeV..?)

Cyclotron [B=const, f=const, r varies]

$$\frac{mv^2}{r} = qvB$$

$$v = \frac{q}{m} rB$$

$$r = \frac{mv}{qB}$$

$$t = \frac{\pi r}{v} = \frac{\pi m}{qB} = \frac{T}{2} = \frac{1}{2f}$$

$$f = \frac{v}{2\pi r}$$

$$f = \frac{qB}{2\pi m}$$

$$E_{kin} = \frac{m}{2} v^2 = \frac{q^2}{2m} (rB)^2$$

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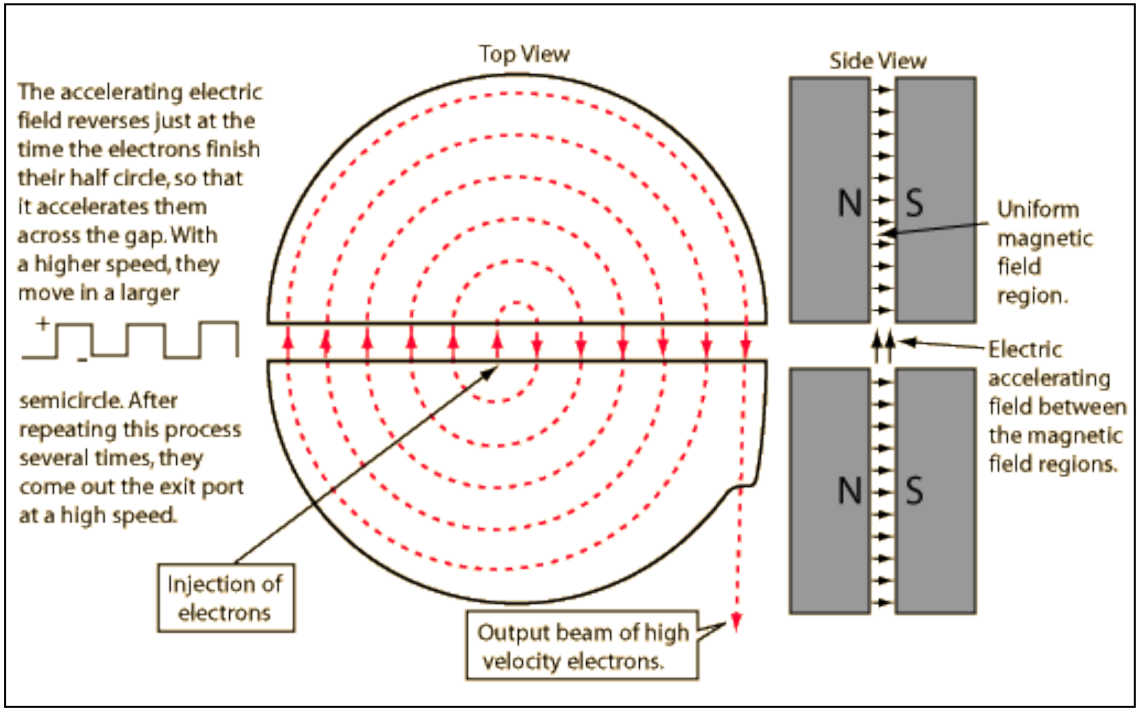
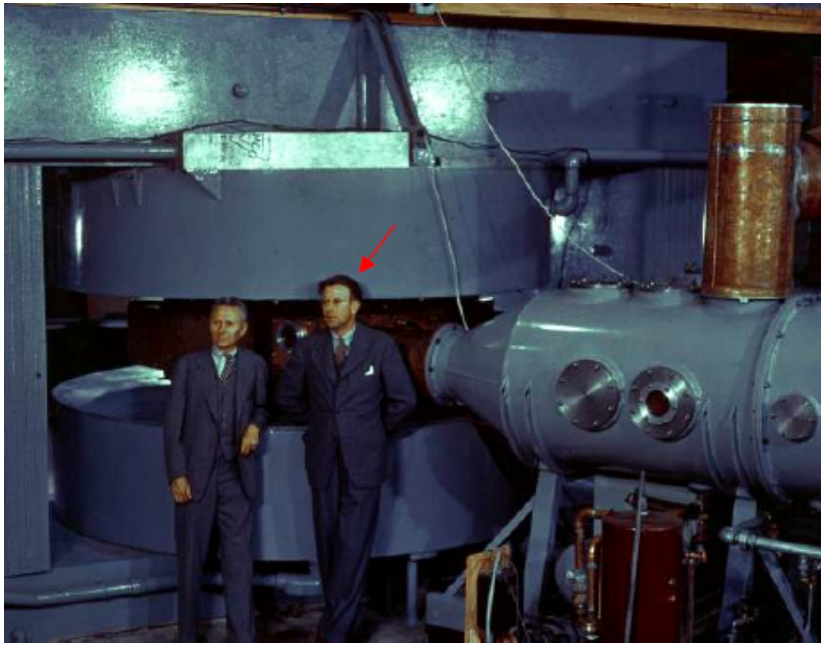


Large radius and high mag field to achieve large energy. Needs constant mass, i.e. non relativistic conditions (Bethe E_p < 20 MeV..?)

Cyclotron



4”
11”, 27” (1932)

60” - 8 MeV p - 220t magnet – 1938
[isotopes, plutonium during WWII..]

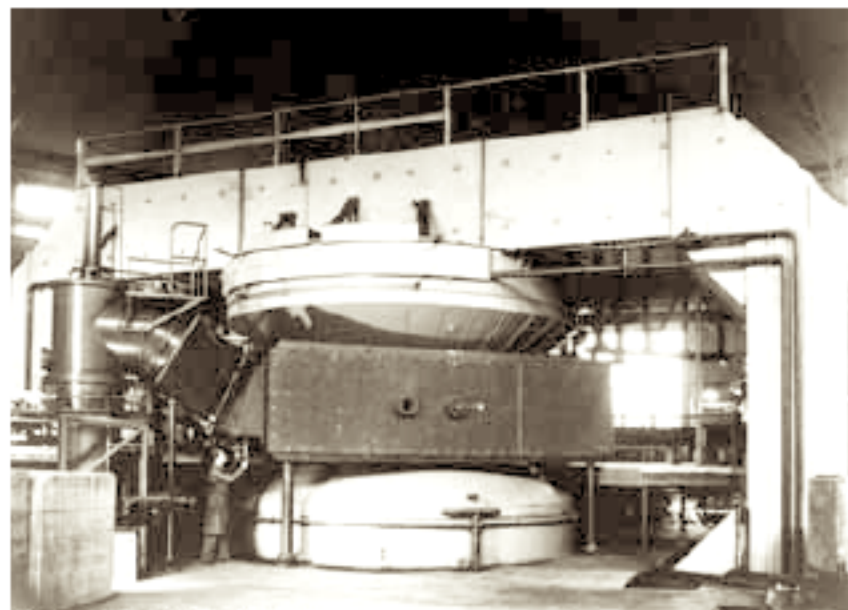
Phase stability: McMillan, Veksler 1945

“Fast: early arrival: less push
slow: late arrival: more push” (Koeth)

The machine was thus the first able to produce, identify and precisely investigate mesons (1948).

In 1950 it was upgraded to produce 350 MEV protons as well as 200 MeV deuterons and 400 MeV alpha particles.

184”



Tazzari, Cern Acc School 2006

Betatron [B varies, f=const, r=const]

Cyclotron: radius increases during acceleration ~√k
Betatron: radius constant but magnetic field increases with time [Kerst]

$$r = \frac{mv}{qB}$$

$$rot\vec{E} = -\frac{d\vec{B}}{dt}$$

$$V = \oint_s \vec{E}\,ds = \int_F rot\vec{E}\cdot d\vec{F} = -\frac{d}{dt}\int_F \vec{B}d\vec{F}$$

$$V = \pi r_0^2 \frac{d\langle B\rangle}{dt}$$

$$p = q\int E\,dt = q\int \frac{V}{2\pi r_0}dt$$

$$p = q\cdot r_0\cdot\langle B\rangle/2$$

Variable magnetic field induces electric field. This causes an accelerator voltage V. Particles are accelerated without an extra external voltage applied. The accelerator voltage V is proportional to the radius of the accelerator squared and the mean field. The generated momentum p is given as the product of r and B.

Stability requires that the mean field divided by 2 is equal to the field at r_0 (Wideroe stability criterion).

Synchrotron

[B varies, f varies, r=const]

$$r = \frac{mv}{qB}$$

$$p = qrB = 0.3Br$$ high field, large radius

$$LHC: 7TeV = 0.3 * 5.6T * 4.1km$$

$$m = \frac{m_0}{\sqrt{1-\beta^2}}, \beta = v/c$$

$$f = \frac{v}{2\pi r}$$

Cyclotron: radius changes with v, frequency is constant (for small β) and B is constant. Must fail in relativistic velocity range.

Betatron: keep radius constant and vary B field, but again fails in relativistic region.

The **synchrotron** cures deficits of cyclotron and betatron by adjusting the magnetic field to compensate for the relativistic rise of mass and the frequency to keep the radius constant.

$$B(v) = \frac{mv}{qr_0} = \frac{v}{qr_0}\frac{m_0}{\sqrt{1-\beta^2}}$$

$$v(B) = \frac{1}{\sqrt{\frac{1}{c^2} + (\frac{m_0}{qr_0 B})^2}}$$

$$f_k = \frac{v\sqrt{k}}{2\pi r_0}$$ k - accelerator elements * turns

$$f_k(B) = \frac{\sqrt{k}}{2\pi} \cdot \frac{1}{\sqrt{\left(\frac{r_0}{c}\right)^2 + \left(\frac{m_0}{qB}\right)^2}}$$

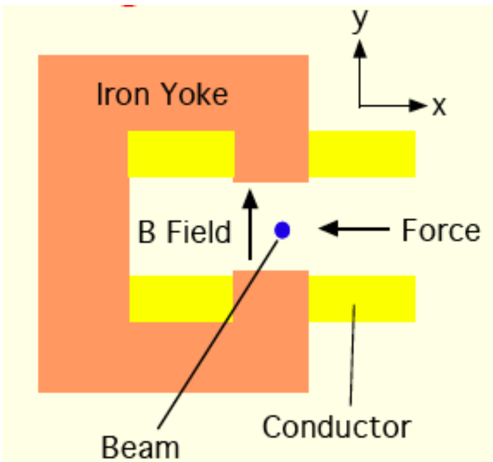
Orbit stabilisation required
"phase stability" Veksler, McMillan (1945)

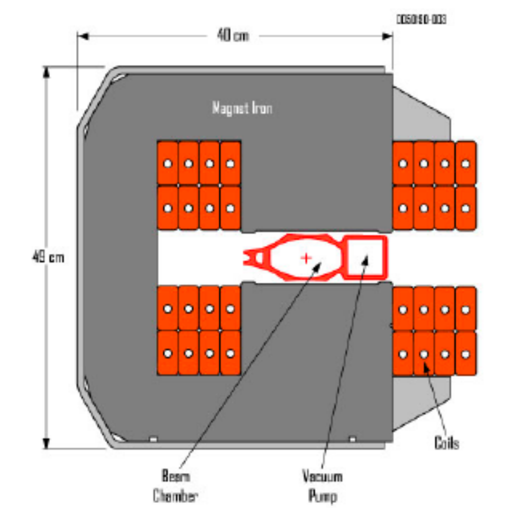
Bunched beam:
only particles at right moment are accelerated.

CERN: SPS: 400GeV, 4600 bunches, revolution frequency is 200 MHz from 2MW rf. 10^5 turns in 2s

Accelerator Elements

Dipole: keep beam on orbit

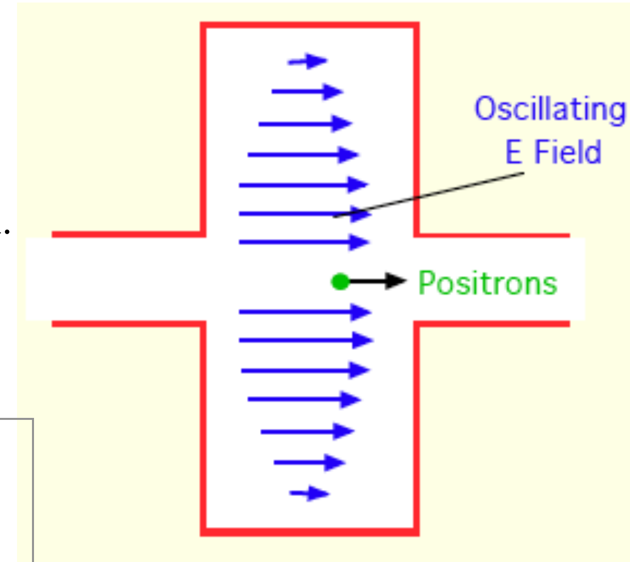


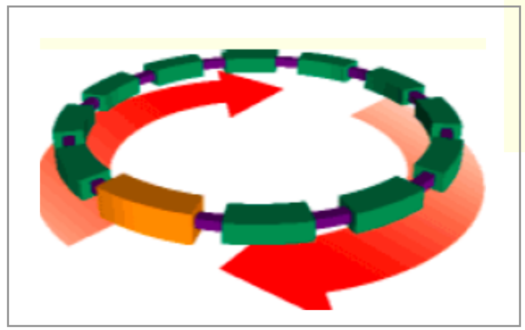


M.Billing, Cornell 07

Cavity: rf structure to develop large oscillating field. up to tens of MV/m.

“ride on crest of a wave”





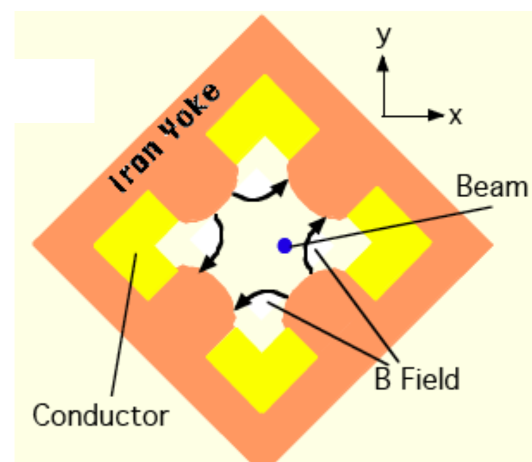
Quadrupole: focus/defocus

beam alternating in x/y plane

“strong focussing” principle

FODO lattice concept

[Christofilos 1950; Courant, Snyder 1952]



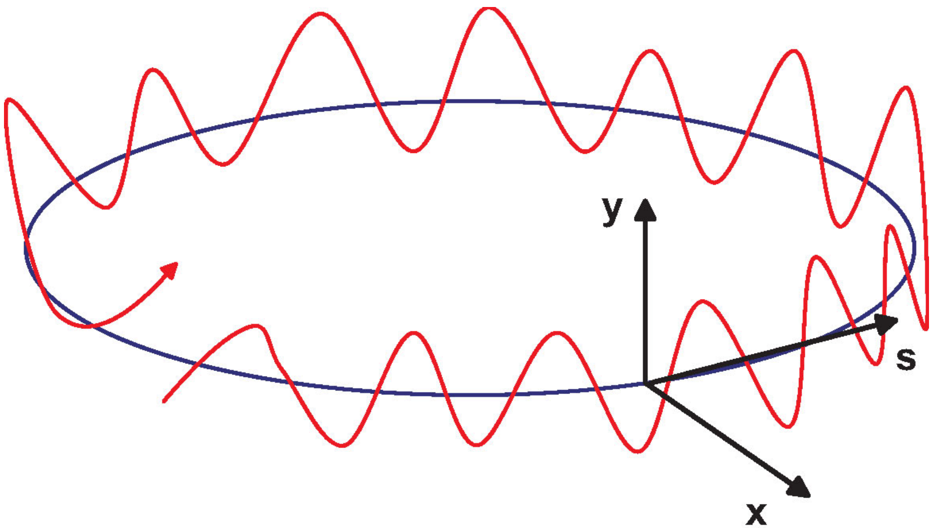
Beam Optics

Linear optics described by Hills equation $x'' + K(s)x = 0$ $\quad x' \equiv \frac{p_x}{p_s}$

Solution expressed in terms of "beta-function" $\quad K(s) = K(s+C)$

C = circumference

$$x(s) = A_0\sqrt{\beta(s)}\cos\left(\int_0^s \frac{ds'}{\beta(s')} + \phi_0\right)$$



Tune: number of oscillations per turn

$$Q = \frac{\phi_\beta(C)}{2\pi} = \frac{1}{2\pi}\oint_C \frac{ds}{\beta(s)}$$

F.Zimmermann

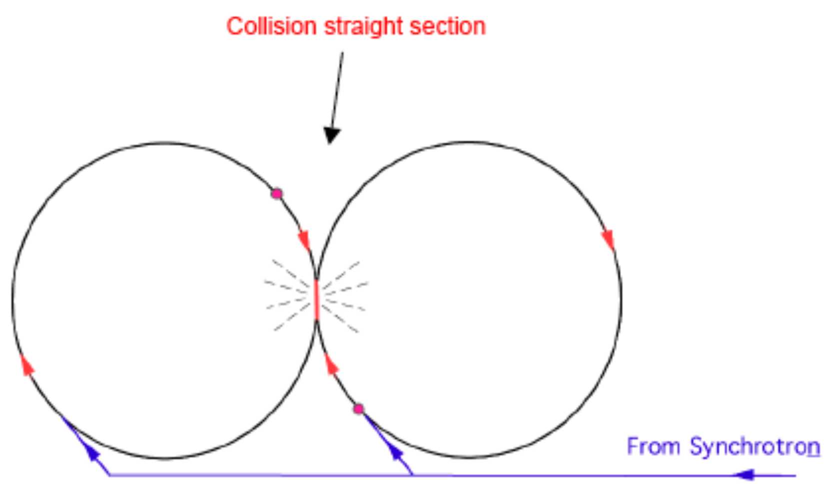
Storage Rings

D.W. Kerst et al *"The possibility of producing interactions in stationary coordinates by directing beams against each other has often been considered, but the intensities of beams so far available have made the idea impractical.*

.... accelerators offer the possibility of obtaining sufficiently intense beams so that it may ***now*** *be reasonable* ***to reconsider directing two beams*** *of approximately equal energy* ***at each other."***

D. W. Kerst et al., Phys. Rev. 102, 590 (1956).

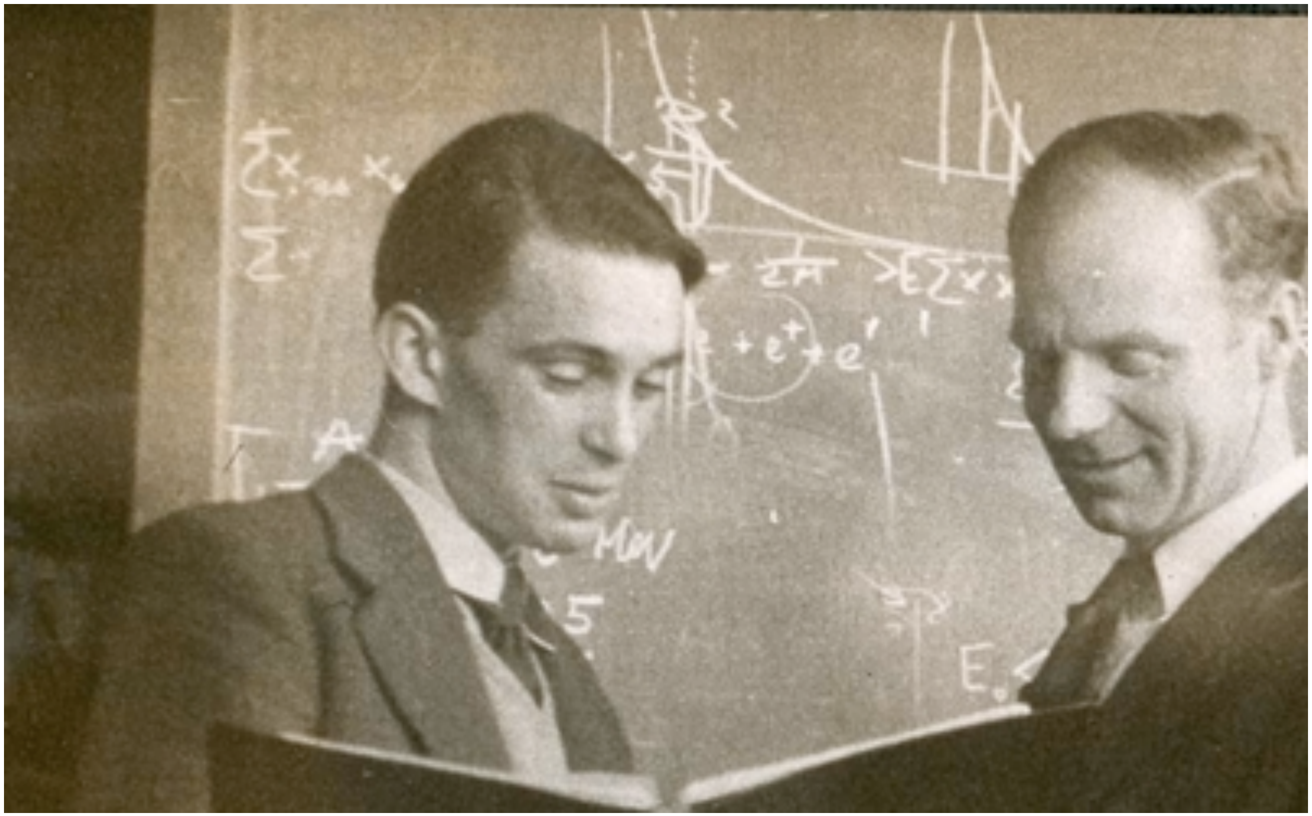
G. K. O'Neill, interested in p-p collisions, introduces the idea of injecting the beam extracted from a high energy proton synchrotron in two "**storage rings**" in which particles would be accumulated and stored for a long time. Typically in a figure-of-8 configuration they have a common section in which the two stored beams collide head-on.



Tazzari, Cern Acc School 2006

fixed target accelerator: s=2ME, collider: s=4E^2 : gain: 2E/M

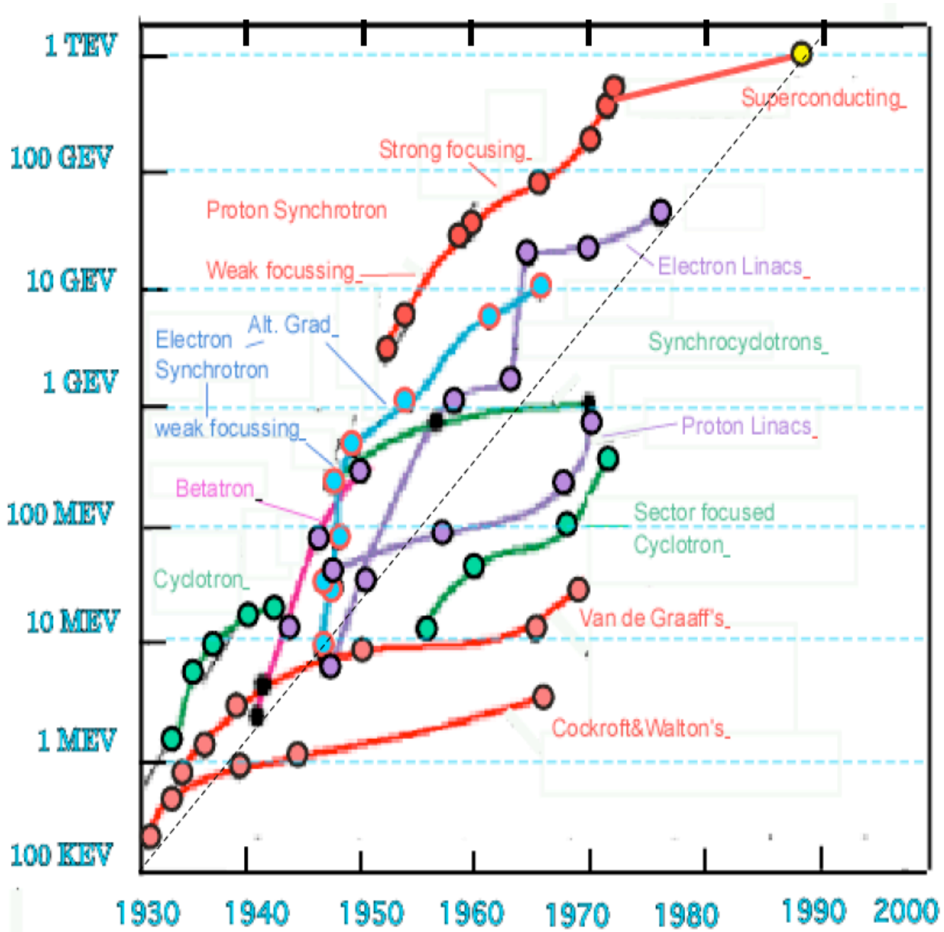
First e^+e^- storage ring ADA at Frascati: Bruno Touschek et al.

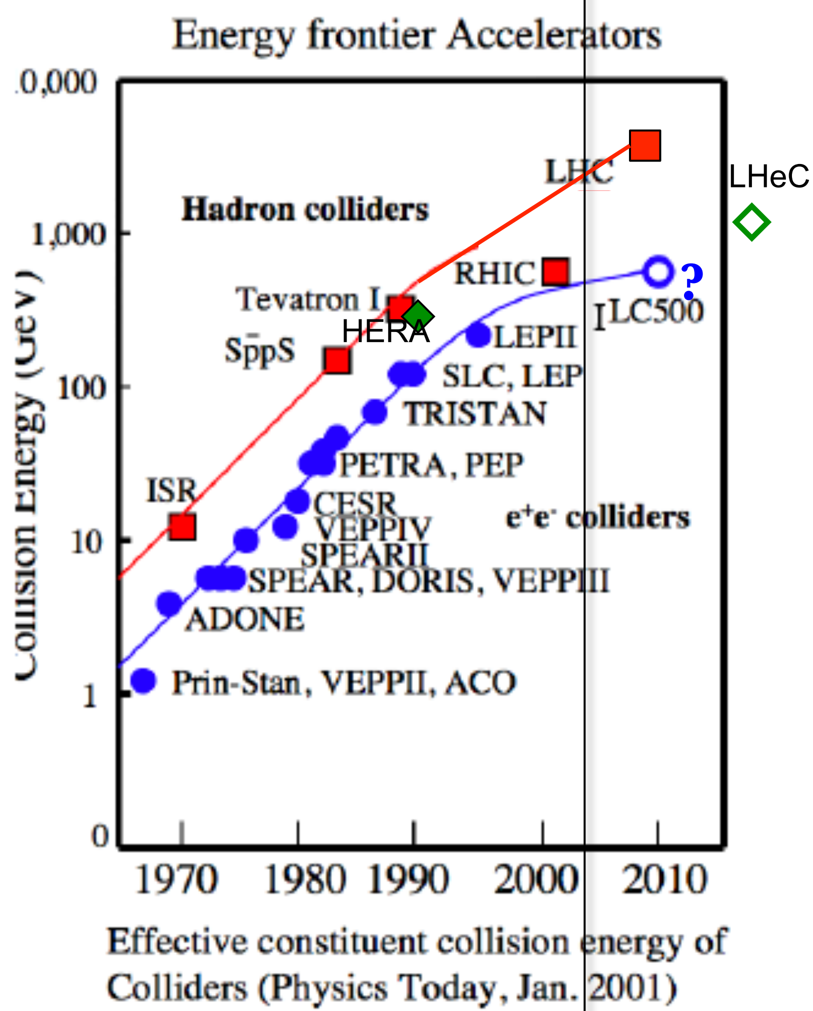


Bruno Touschek (1921-1978) Sam Currant (1912-1988)

Accelerator Development

Development up to 1990





pp, ep, e$^+$e$^-$

World Accelerators

The demands of particle physics for high energies and intensities have had a major impact on modern society

Accelerators running in the world

CATEGORY OF ACCELERATORS	NUMBER IN USE (*)	
High Energy acc. (E >1GeV)	~120	
Synchrotron radiation sources	>100	
Medical radioisotope production	~200	
Radiotherapy accelerators	> 7500	9000
Research acc. included biomedical research	~1000	
Acc. for industrial processing and research	~1500	
Ion implanters, surface modification	>7000	
TOTAL	> 17500	

(*) W. Maciszewski and W. Scharf: Int. J. of Radiation Oncology, 2004

Recent HEP Colliding Ring Machines

Planned: ep: LHeC, e^+e^-: ILC, CLIC
muon collider, photon collider
50TeV pp machine in ~100km tunnel
with associated e^+e^- and ep programme

HERA ep: built 1985-1991

6.2 km ring accelerator(s)

Superconducting p ring

Warm magnet e ring

Data delivery: 1992-2007

HERA and its Pre-Accelerator Chain

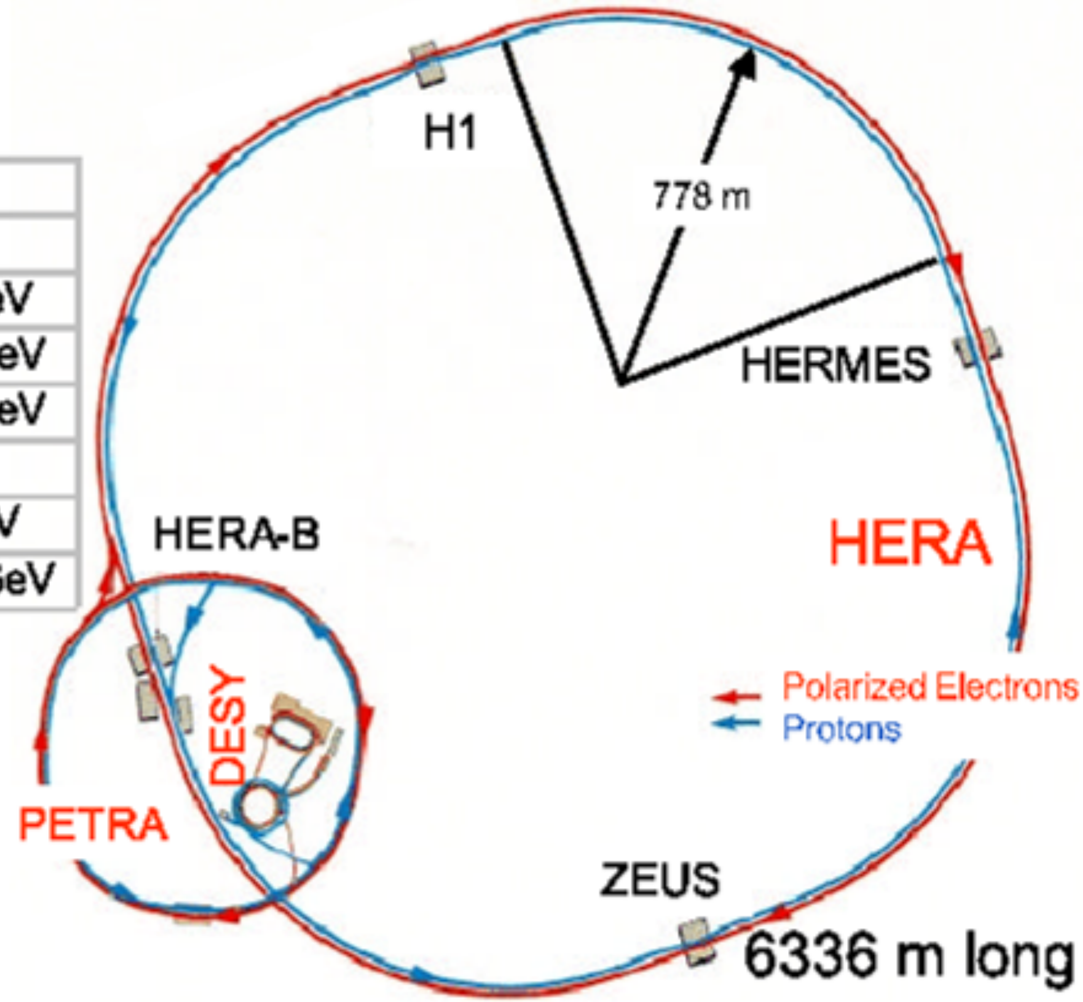
	Protons	Electrons	
20 keV	Source	Source	150 keV
750 keV	RFQ	Linac II	450 MeV
50 MeV	Linac III	Pia	450 MeV
8 GeV	DESY III	DESY II	7 GeV
40 GeV	PETRA	PETRA	12 GeV
920 GeV	HERA-p	HERA-e	27.5 GeV

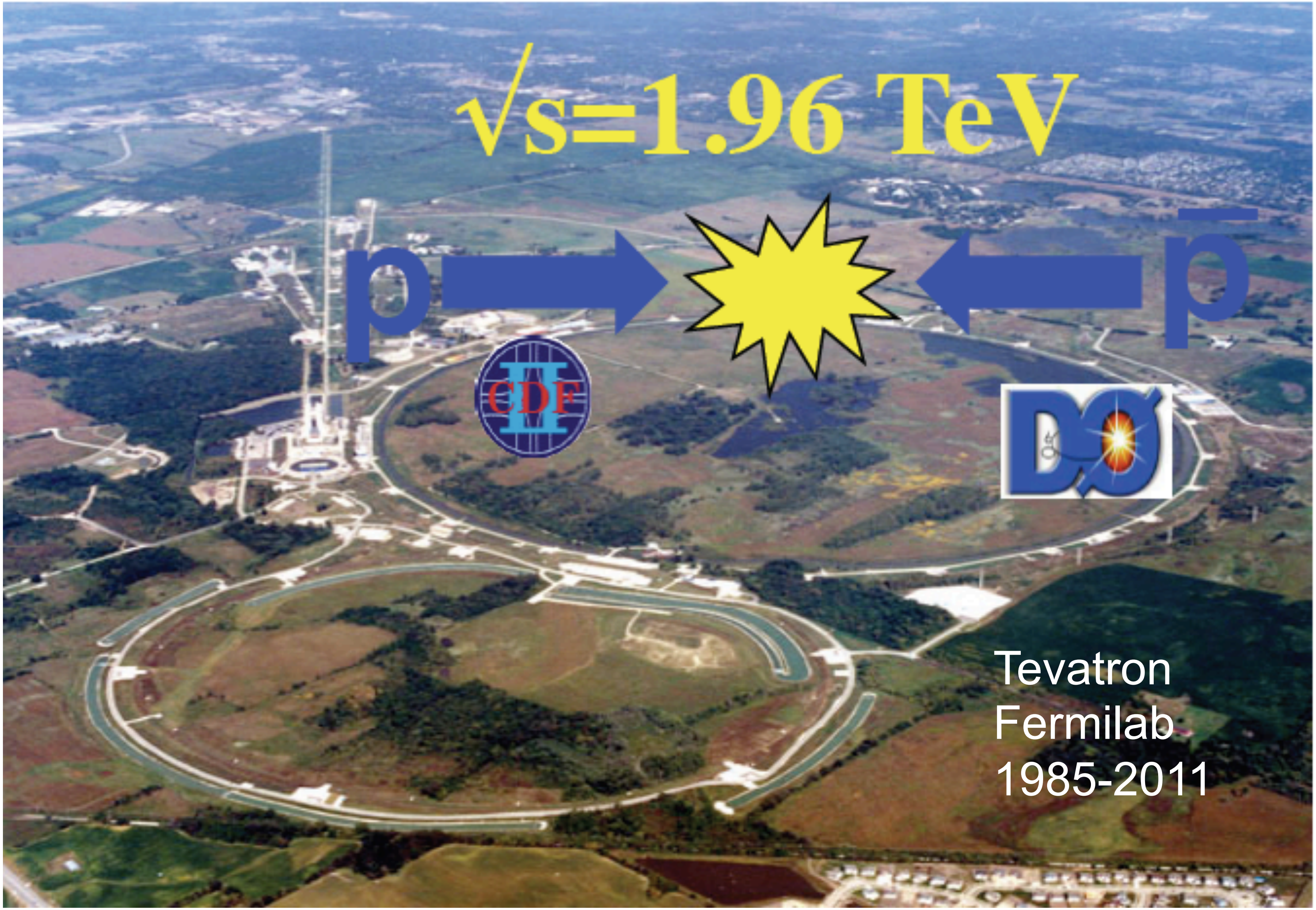
$E_e = 15..30 GeV, E_p = 400..1000 GeV$

$polarisation: P(e) = -0.5...0...+0.5$

$L_{spec} \approx 0.4...2 \cdot 10^{30} cm^{-2} s^{-1} mA^{-2}$

$I_e = 20...50 mA, I_p = 60...100 mA$

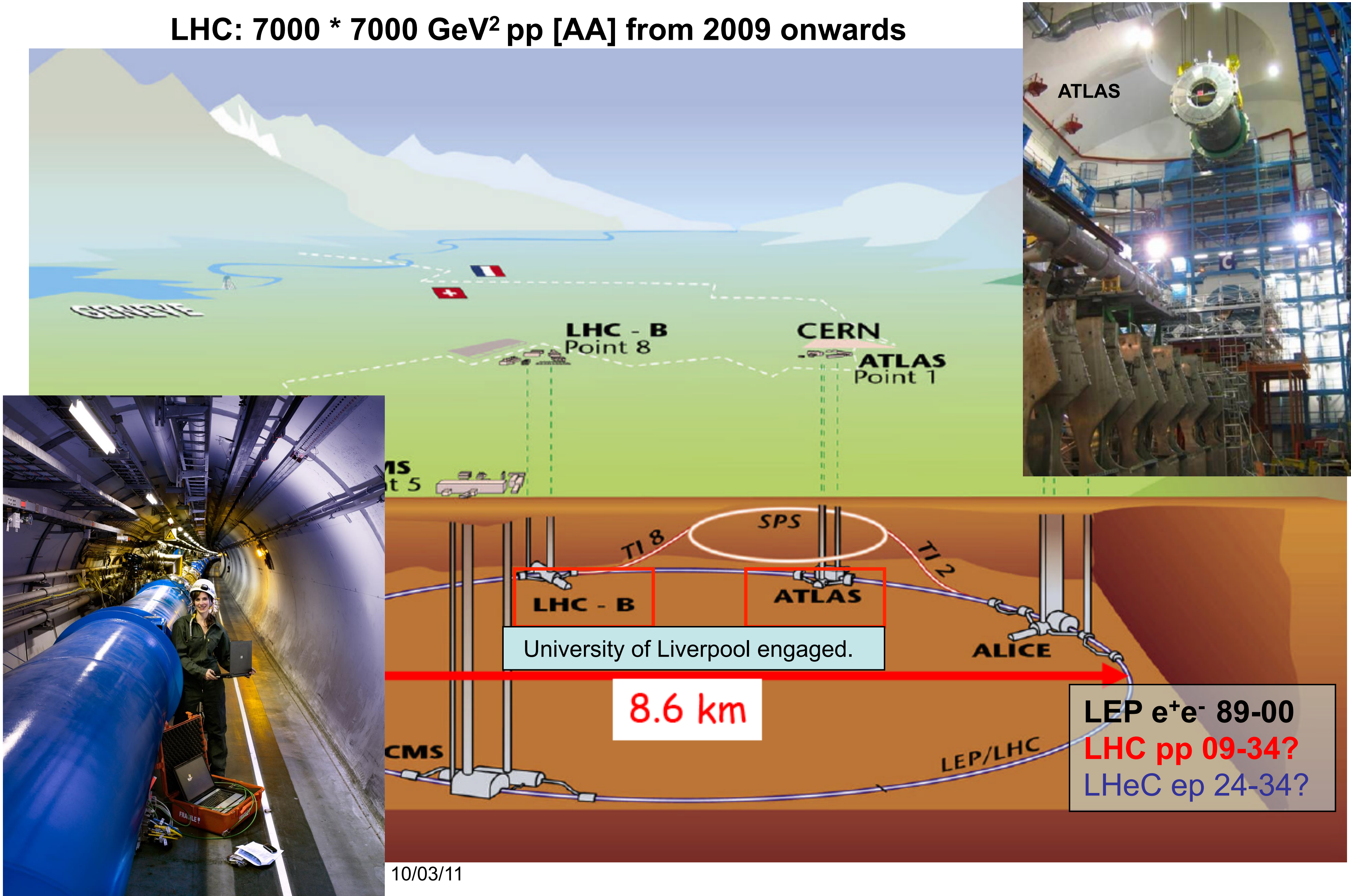




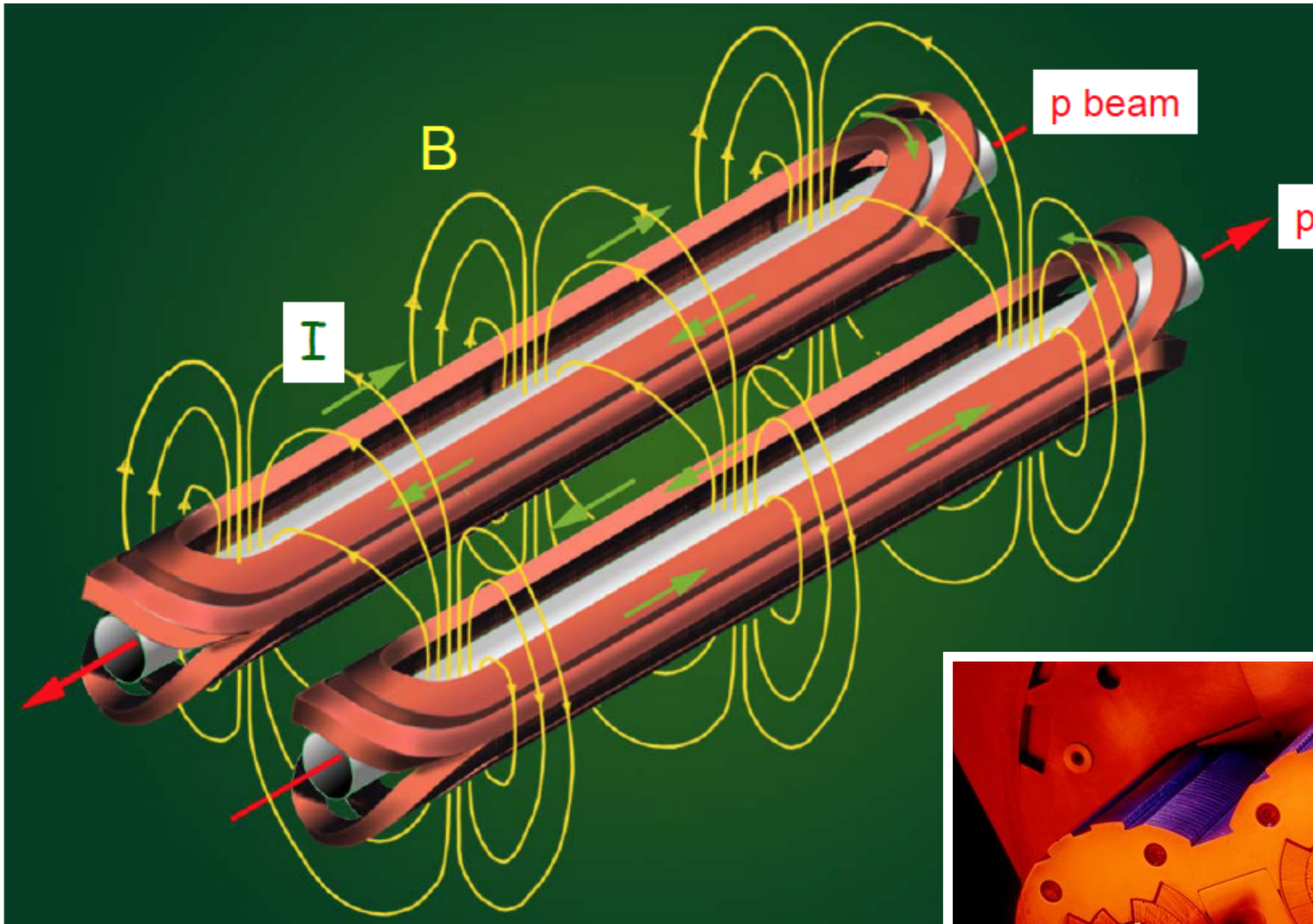
√s=1.96 TeV
p
p̄
CDF II
DØ
Tevatron
Fermilab
1985-2011

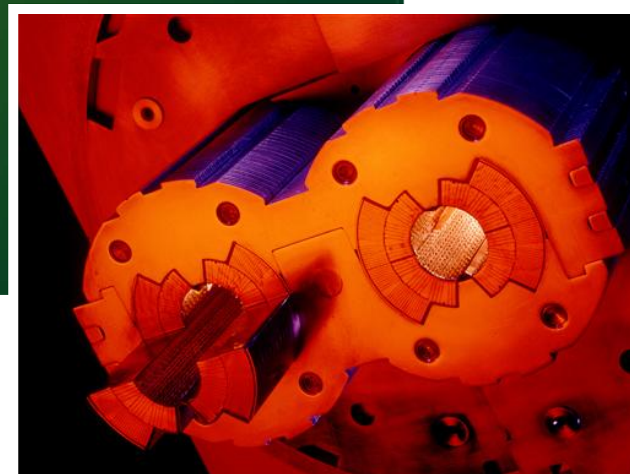
The Large Hadron Collider

LHC: 7000 * 7000 GeV^2 pp [AA] from 2009 onwards



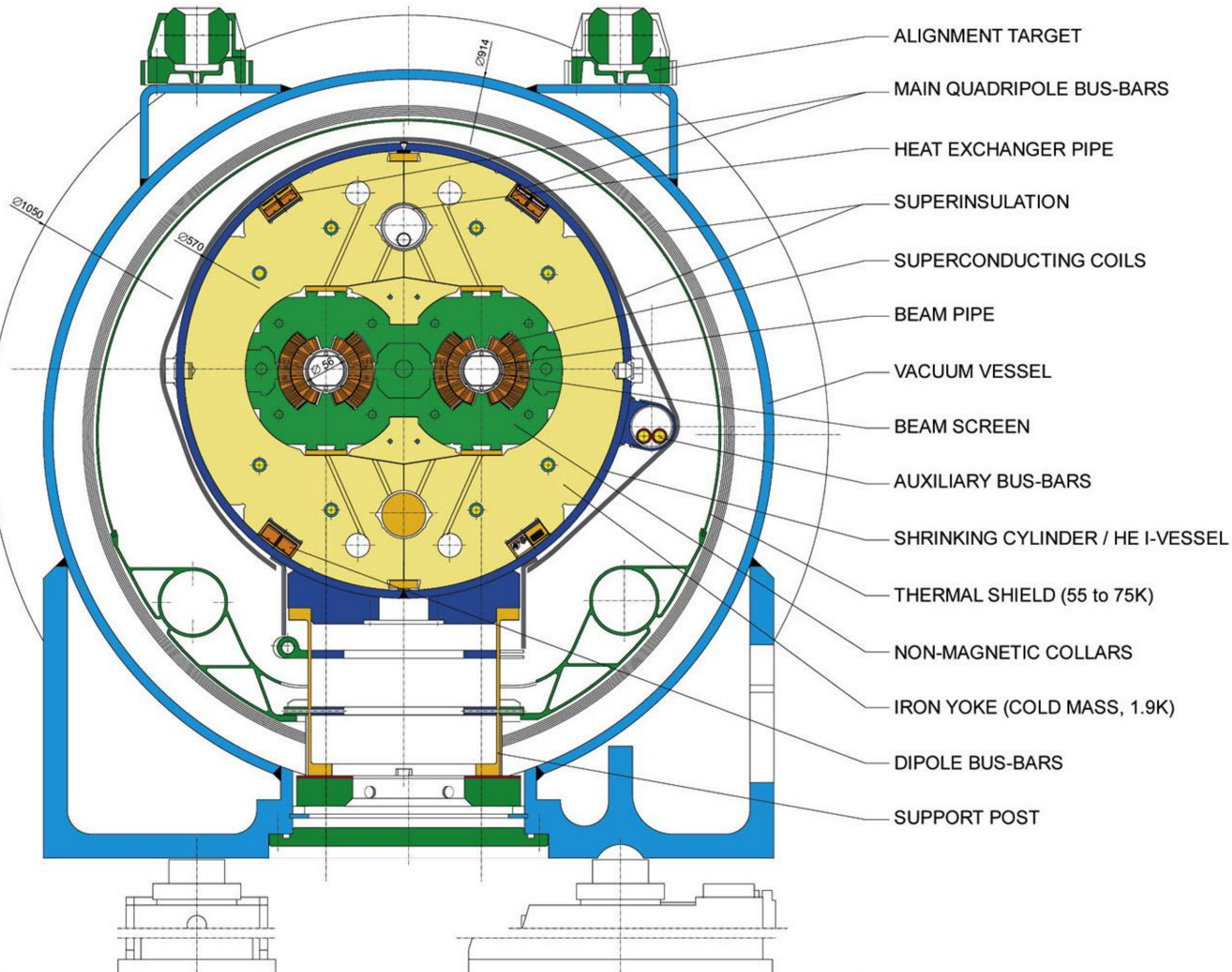
LHC 2-in-1 Dipole

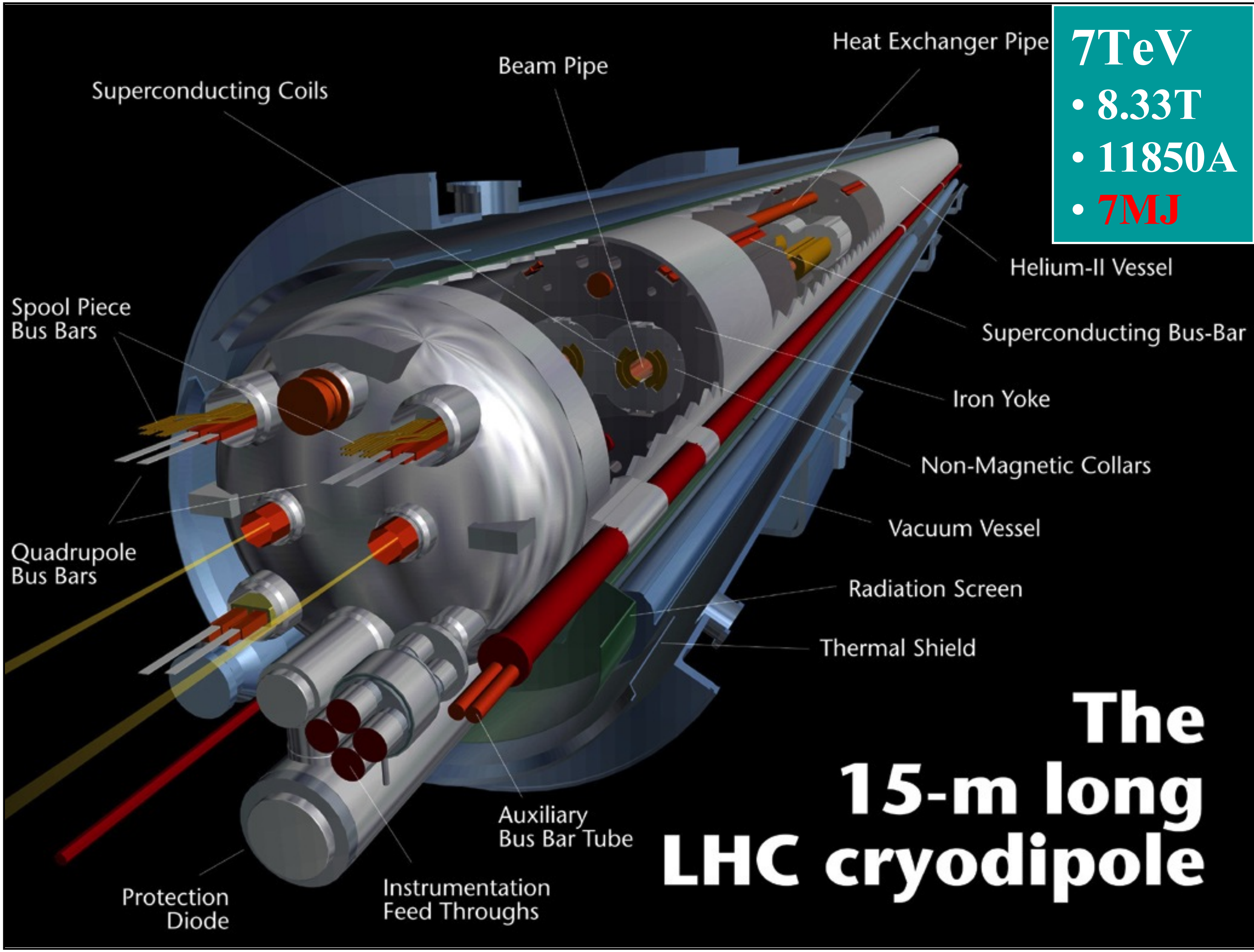




LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30 04 1999




7TeV
• 8.33T
• 11850A
• 7MJ
Heat Exchanger Pipe
Beam Pipe
Superconducting Coils
Helium-II Vessel
Spool Piece Bus Bars
Superconducting Bus-Bar
Iron Yoke
Non-Magnetic Collars
Vacuum Vessel
Quadrupole Bus Bars
Radiation Screen
Thermal Shield
The 15-m long LHC cryodipole
Auxiliary Bus Bar Tube
Instrumentation Feed Throughs
Protection Diode


LHC tunnel 2002
10 years from here to the Higgs boson …