Development of circular Accelerators

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Univ. of Liverpool and CERN

Outline

- With emphasis on circular accelerator developments in Europe & USA

- Pre-War efforts, WW II & consequences
- Birth of Big Laboratories

- Birth of synchrotrons

- USA and Europe [friendly competition ping-pong]

- Two ring hadron Colliders

- 'Cheap' one ring hadron Colliders [thanks to S van der Meer]

- The latest in Synchrotrons & Colliders

- *[Apologies for no electron machines]*

Some nomenclature for the uninitiated

- **Cyclotron**
  - Synchro-cyclotron
  - Isochronous cycloton
  - Calutron (Univ of Calif)
- **Betatron**
- **Synchroton**
  - Weak focusing **Cosmitron** to **Cosmotron** (BNL)
    - **Bevatron** (Berkeley)
  - Strong focusing

    AGS Alternating Gradient Synchrotron

Livingston Plots ~ energy progression by factor 10 every 6-8 yrs

from 1962 Livingston-Blewett Book

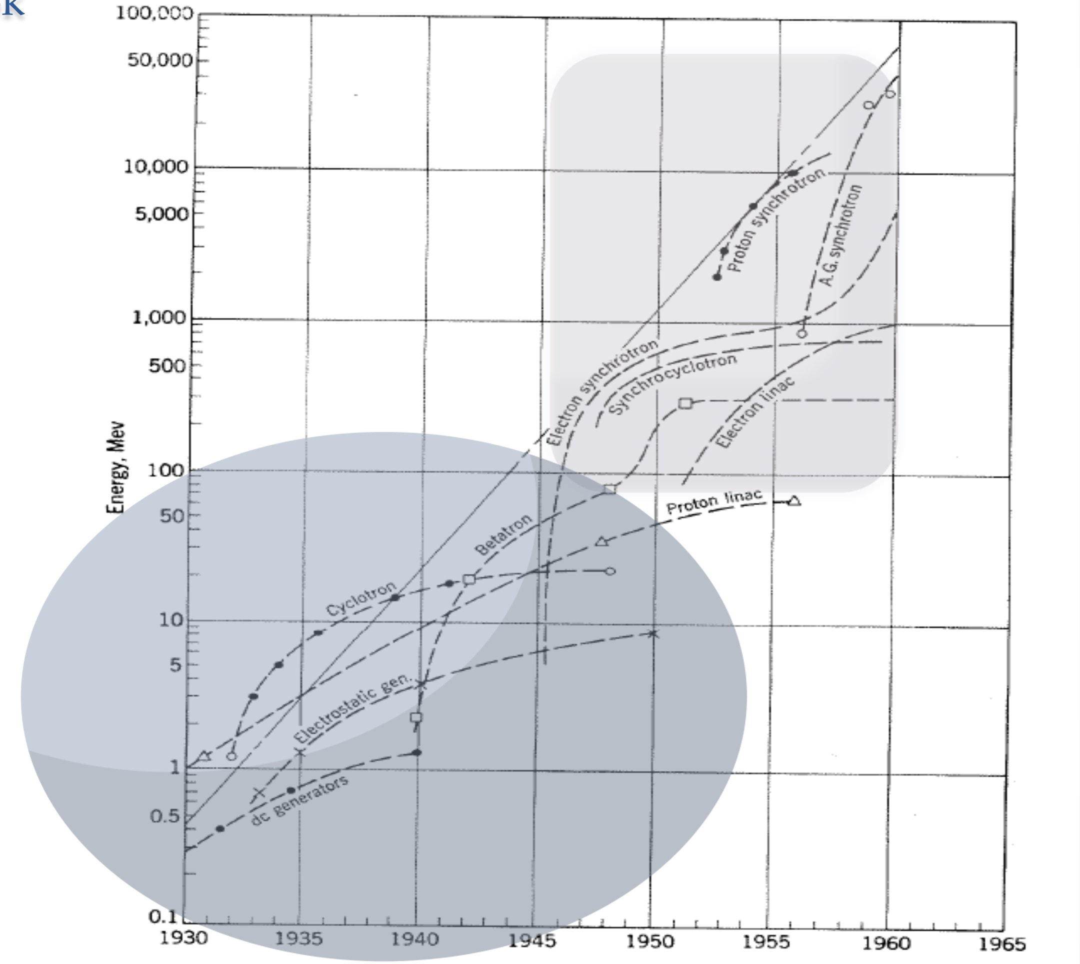
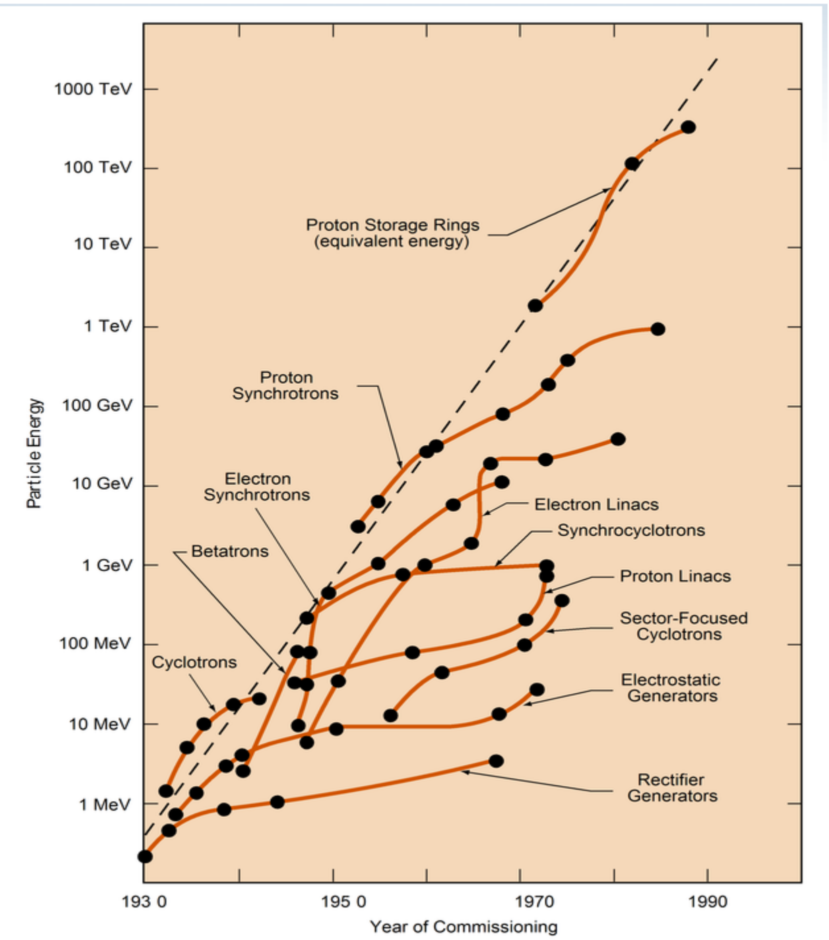


Fig. 1-1. Energies achieved by accelerators from 1930 to 1960. The linear envelope of the individual curves shows an average tenfold increase in energy every six years.

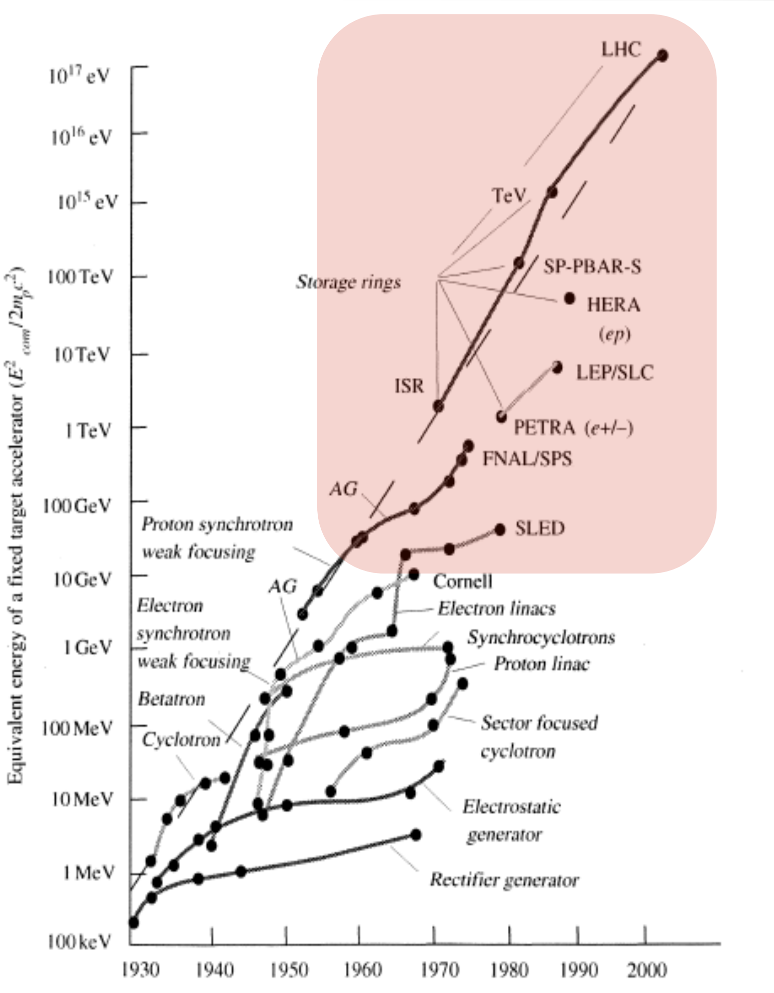
Livingston Plots ~ energy progression by factor 10 every 6-8 yrs

First plot by :M. Stanley Livingston, 1954

~1997 Panofsky



~2006 EJN Wilson Book

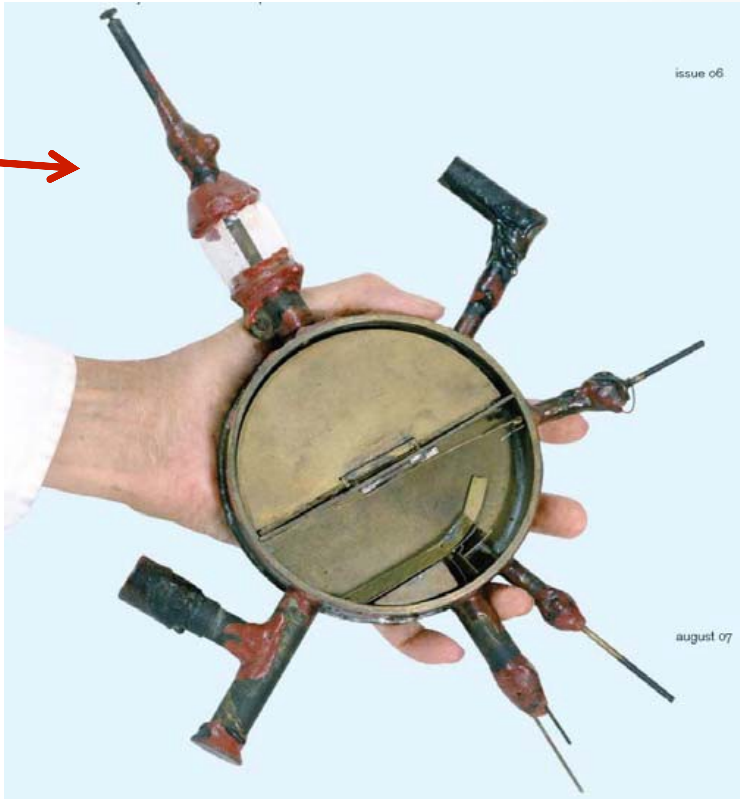


Cyclotrons : USA led the way

- Lawrence inspired from Wideroe paper in 1929: build a '**curled linac**'
- Practical Success In Jan. 1931: Lawrence and Livingstone's **4.5 inches** diameter device. This was followed by successive larger diameter devices, 9, 11, 27.5 ,37 and 60 inches cyclotrons in Berkeley, culminating in a ***184 inch cyclotron in 1946 with a 4000 tons magnet !***

British work in cyclotrons [~before & after the war]

- **Cambridge & Liverpool had 37.5 inch cyclotrons**
- **Birmingham 61.4 inch cyclotron**



[illegible] Berkeley cyclotron under construction

From Lawrence's Nobel Lecture 1951: to 'curl' the Linac

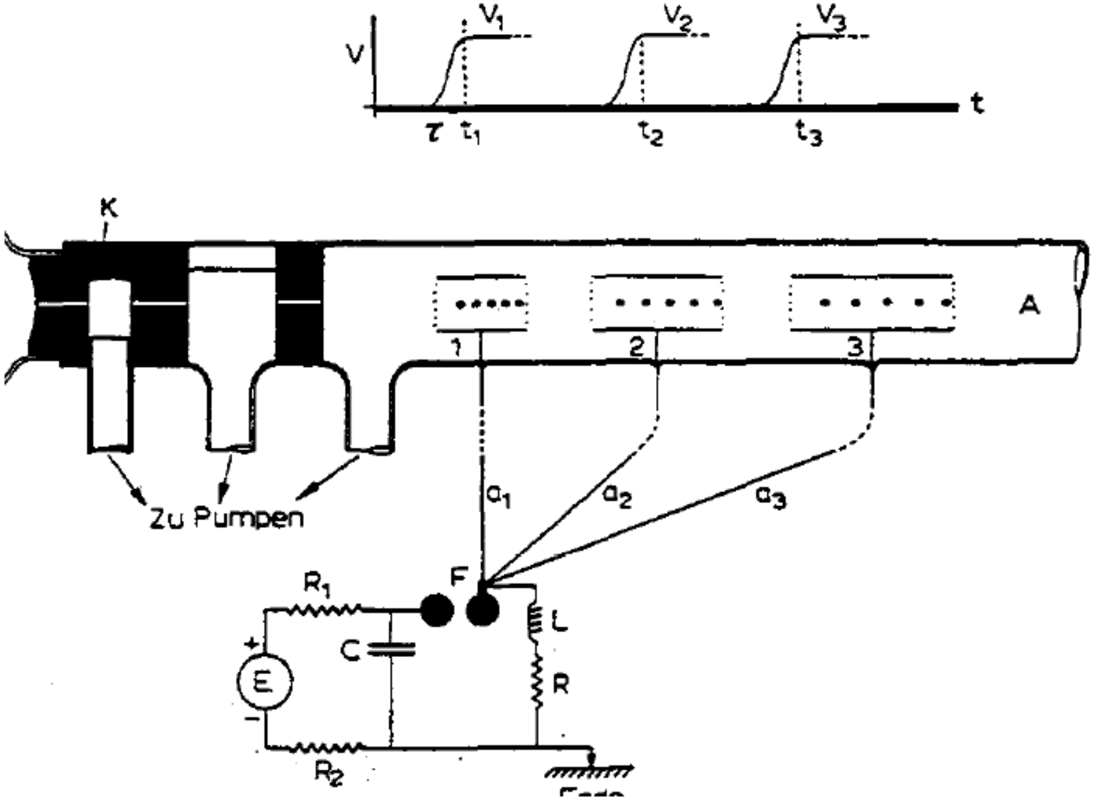
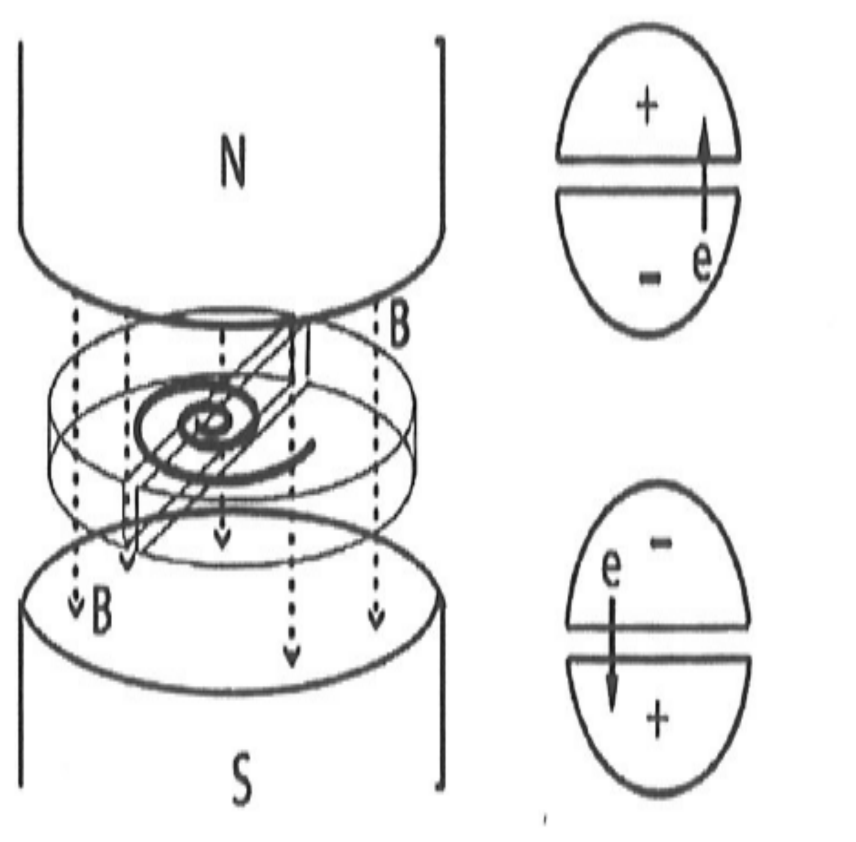


Fig. 1. Diagram of linear accelerator from Professor G. Ising's pioneer publication (1924) of the principle of multiple acceleration of ions.

Basic Principles of a Cyclotron

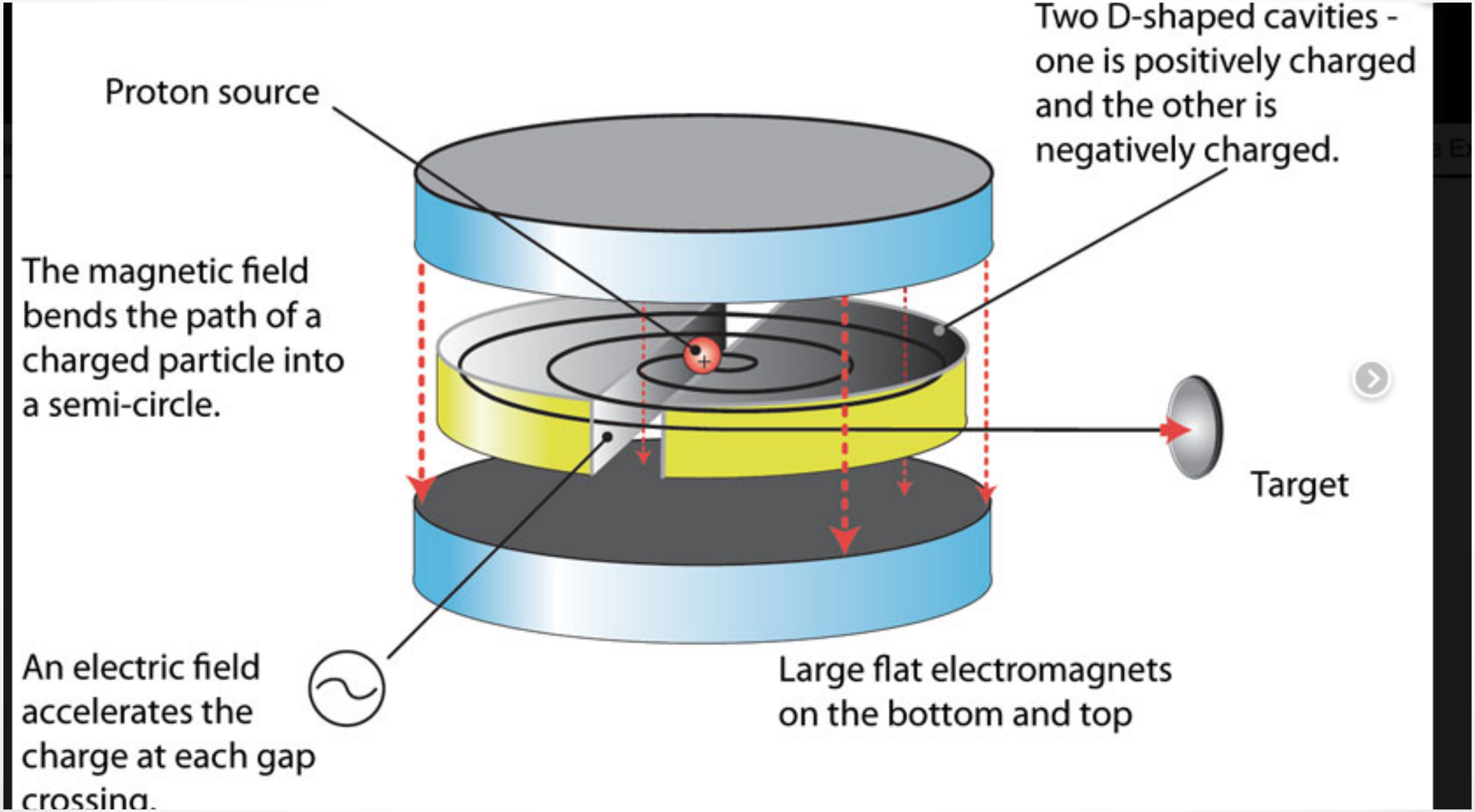


D-shaped chambers placed inside a vacuum chamber. D-shapes form the electrodes & the particle accelerated in the gap

Magnetic Field [B] bends the particles along a circular orbit and a fixed freq. alternating electric field applied across the two 'dees' accelerates the particles

Particles injected and spiral out to a larger radii with increasing velocity
[Orbital frequency independent of radius]

Energy limited by diameter & Field Strength of the Magnet



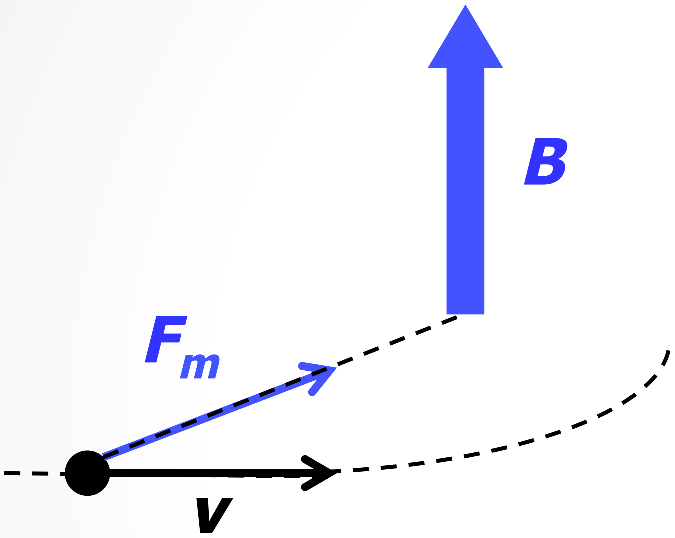
Two D-shaped cavities - one is positively charged and the other is negatively charged.

The magnetic field bends the path of a charged particle into a semi-circle.

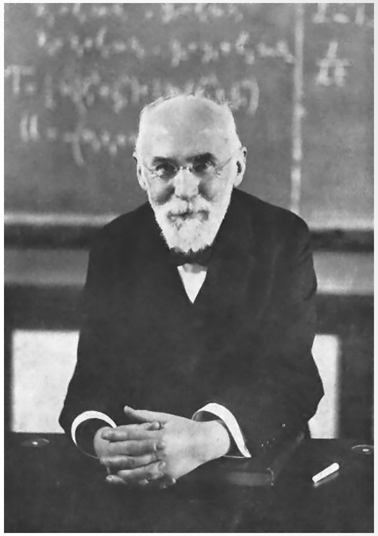
An electric field accelerates the charge at each gap crossing.

Large flat electromagnets on the bottom and top

Bending & focusing by a Magnetic Field




J.C. Maxwell

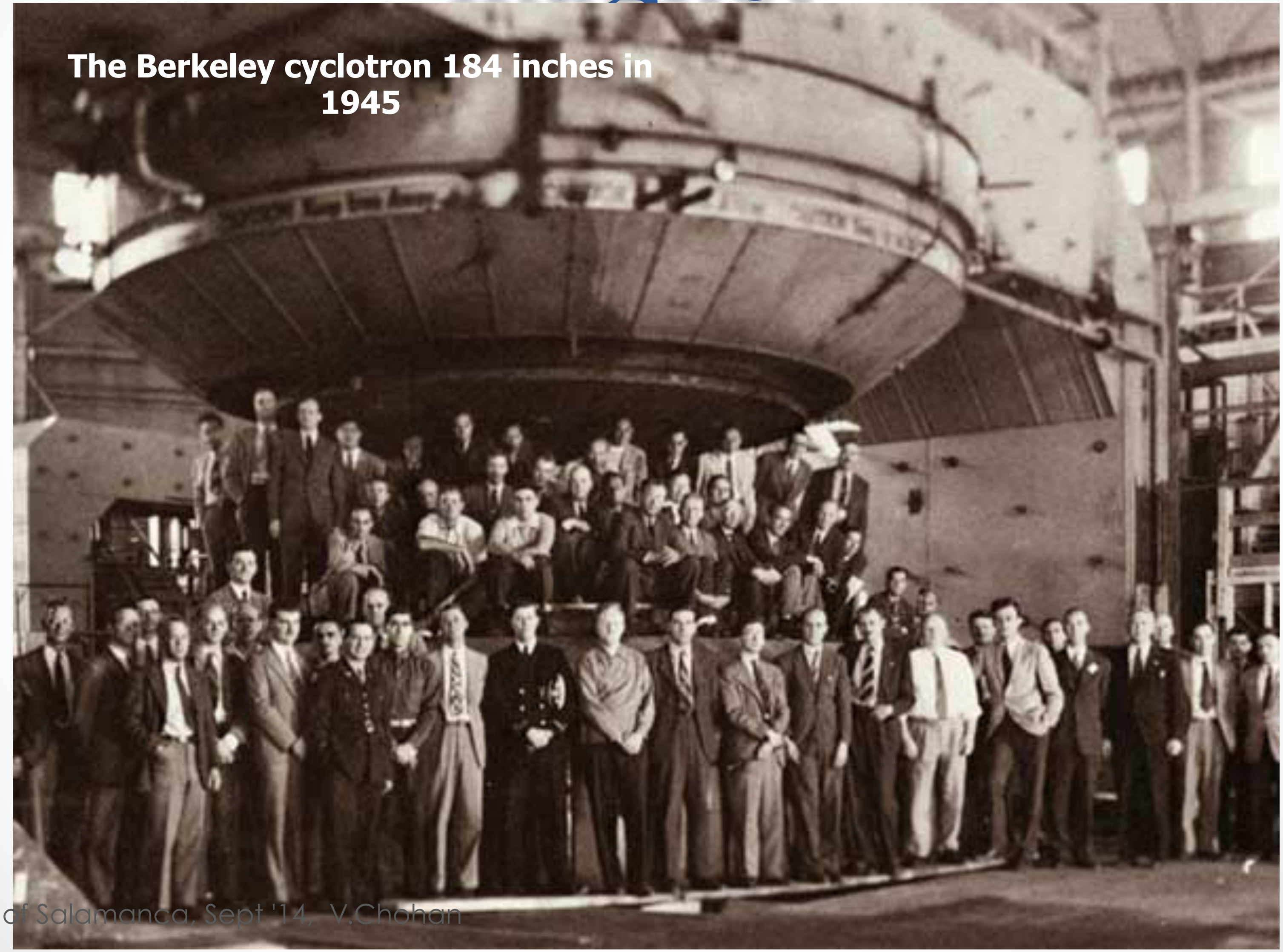

H.A. Lorentz

A charged particle is subjected to a force, *in presence of magnetic field:*

- <u>Orthogonal</u> to its velocity ***v*** and magnetic field ***B*** (centripetal force)
- <u>Proportional</u> to its electric charge and Magnetic Field ***B***

One cannot accelerate with a magnetic field but one can *bend or focus* the particles and hence construct circular accelerators
To limit the le diameter of the accelerator, one seeks to increase ***B***

Cyclotron with one big magnet



The Berkeley cyclotron 184 inches in 1945

Cyclotrons & War effort

- **the Liverpool and Cambridge cyclotrons were not completed until the middle of 1939**, each having taken about three years to build. Cambridge first 'had beam' in July and Liverpool's started in the September, but these events were overshadowed by the outbreak of war.

- **The overriding question in the minds of British senior government and the Service Chiefs was, 'is an atomic bomb feasible?'. The answer to this question depended on greater knowledge of all aspects of the uranium nucleus. One way to get information on, say, the nuclear capture cross sections of uranium, was to use a neutron-producing machine — that is, a cyclotron**

- Experimental work on uranium, fission and other nuclear studies relating to the information required in atomic bomb design continued on the **Liverpool cyclotron** until the **middle of 1943**

- *www.evolve360.co.uk/Data/10/Docs/09/09King.pdf*

Cyclotrons: Limits & drawbacks

- Cyclotrons were the physics machines in the 1930s and 1940s;
- The energy was limited by relativistic effects

difficulties in passing ~30 MeV mark when protons started getting relativistic

- Synchro-cyclotrons were the extension of cyclotrons

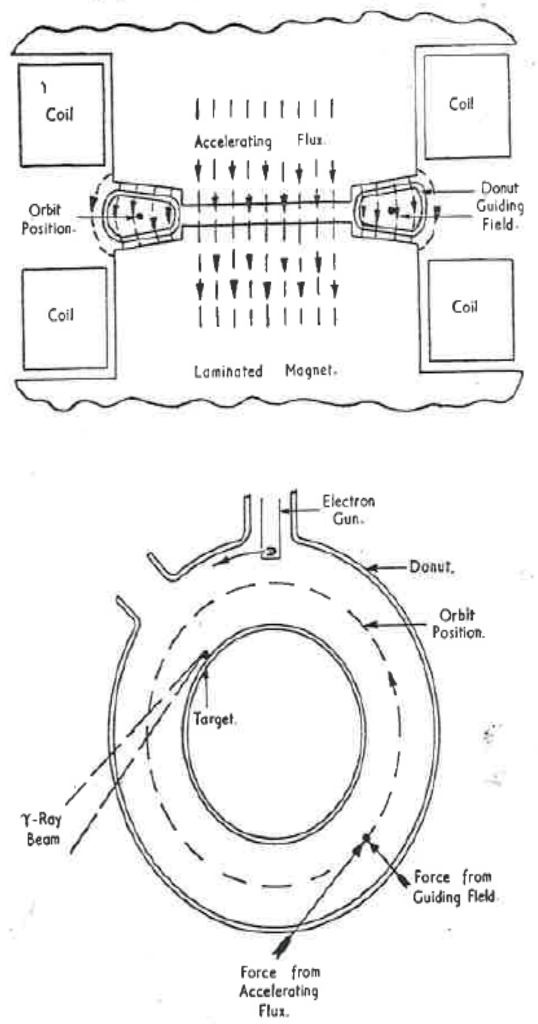
gradually changing or reducing the frequency of applied accelerating voltage to be synchronous with particle orbits

- The size or mass of the magnet was also a limitation;4000 tons for 184 inch Berkeley machine in 1946 or,
- 10000 tons for Gatchina /St Petersburg machine with 6 metres(240 in) diameter magnet

- Synchro-cyclotron was also used in the Manhattan project for enriching Uranium(Calutron)

Betatron ~1940

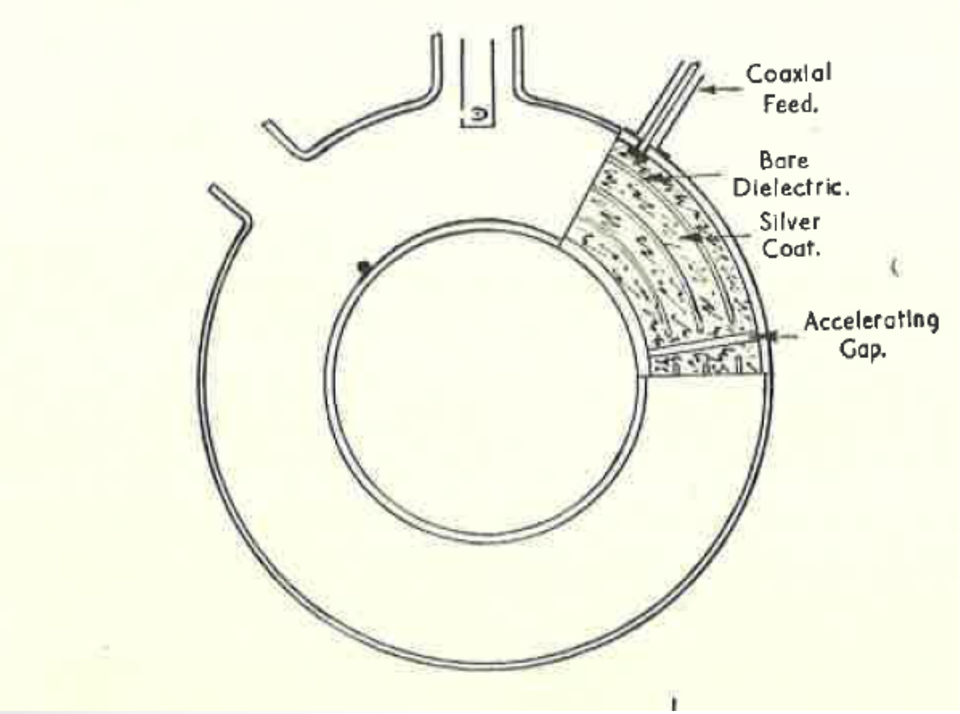
- **The Betatron**
- Betatrons used varying magnetic field to accelerate in a ‘donut’
- the name betatron does not tell us anything about how it works, but it is best thought of as a transformer, **with a ring of electrons as the secondary coil**. The alternating magnetic field used to make the electrons move in a circle is also the one used to accelerate them; the magnet must be carefully designed



bit of Betatron history & drawbacks

- **1923**:Widerøe, a Karlsruhe student, draws in his laboratory notebook the design of the **betatron** with the well-known 2-to-1 rule. He added the condition for radial stability 2 years later, but did not publish.
- **1927** in Aachen, Widerøe makes a model betatron, but it does not work. Discouraged, he changes course and *builds the world's first linac* .**His betatron is *'forgotten'* in his notes.**
- **1940**: Donald Kerst re-invents the betatron and built the first working machine for **2.2 MeV** electrons (University of Illinois), a **20 MeV** machine (**1942**), a **100 MeV** machine at General Electric and finally in,
- **1950**, Kerst built the world's largest betatron (**300 MeV**).
- After a brief spell of interest, they were rapidly overtaken by linacs and synchrotrons.
- Although robust and simple devices which were ideally suited for accelerating electrons, they were limited in energy by the size of the magnetic yoke.

Betatrons to Synchrotrons



- What was called the ***betatron started synchrotron*** with accelerating resonator incorporated in the 'donut'

- *[F.Goward, 1950 IOP paper]*

A bit of background…

UK

The idea of a pulsed magnet ring, fundamental to the synchrotron, appeared in a proposal by Oliphant in 1943 and was followed by the independent discovery of phase stability by Veksler in 1944 and McMillan in 1945.

UK
Later
USA

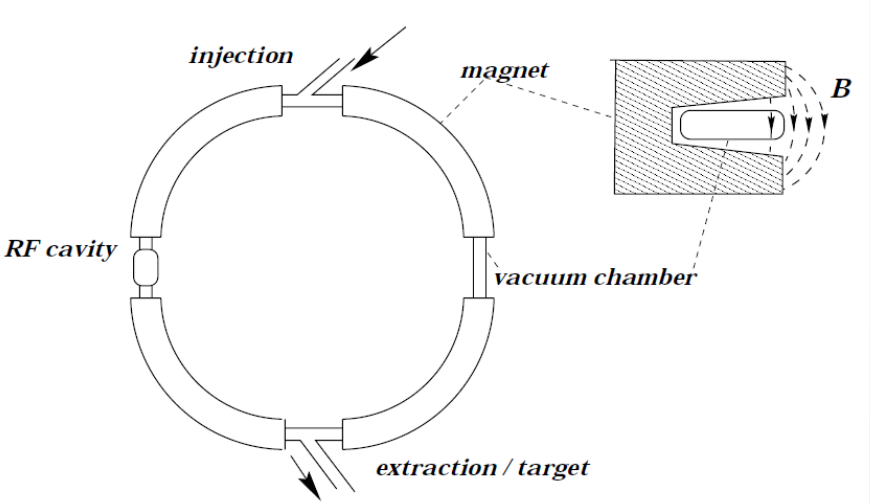
This opened the door to a demonstration of ***synchrotron acceleration to 8 MeV by Goward and Barnes*** *in a converted betatron at Woolwich Arsenal, UK. The event, which took place in August 1946, was followed only two months later by the operation of the General Electric Laboratory's 70 MeV machine at Schenectady, USA built by Elder, Gurewitsch, Langmuir and Pollock* .

The sixty years that follow have seen projects spanning almost six orders of magnitude in energy. The phenomenal success of the synchrotron principle was sustained by two other important discoveries, that of *alternating-gradient focusing and The use of colliding beams.*

Birth of Synchrotrons

- **Betatrons** used *varying magnetic field to accelerate in a 'donut'*

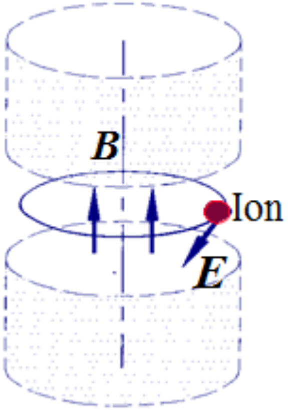
- **Synchrotrons** use *the ideas from both of Synchro-cyclotrons (varying RF Freq) and betatrons (varying the Field)*



Pictorial views….*[P.Bryant, O.Bruening]*

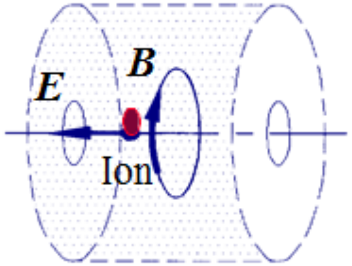
Energy Gain only due to E field
Trajectory Curvature due to B field

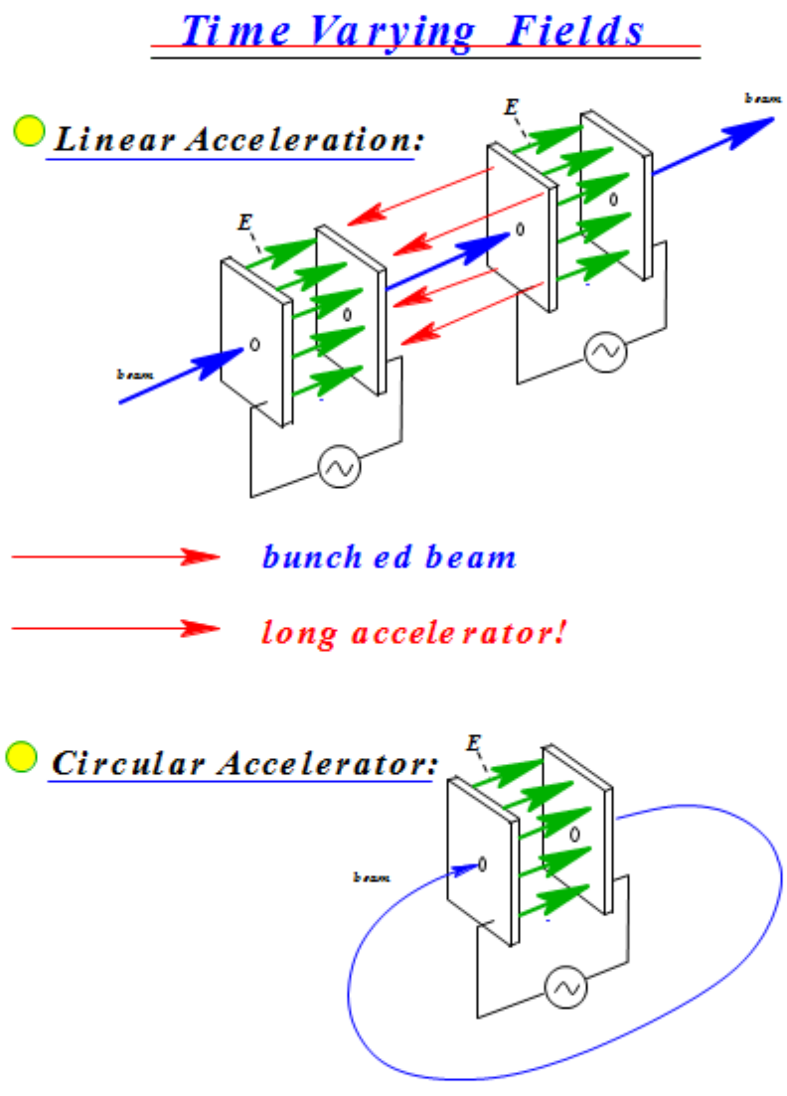
‘Betatron’ or ‘unbunched’ acceleration



‘Resonant’ or ‘bunched’ acceleration

- **Linear accelerator (linac).**
- **Synchrotron.**
- **Cyclotron (‘coiled’ linac).**





Time Varying Fields

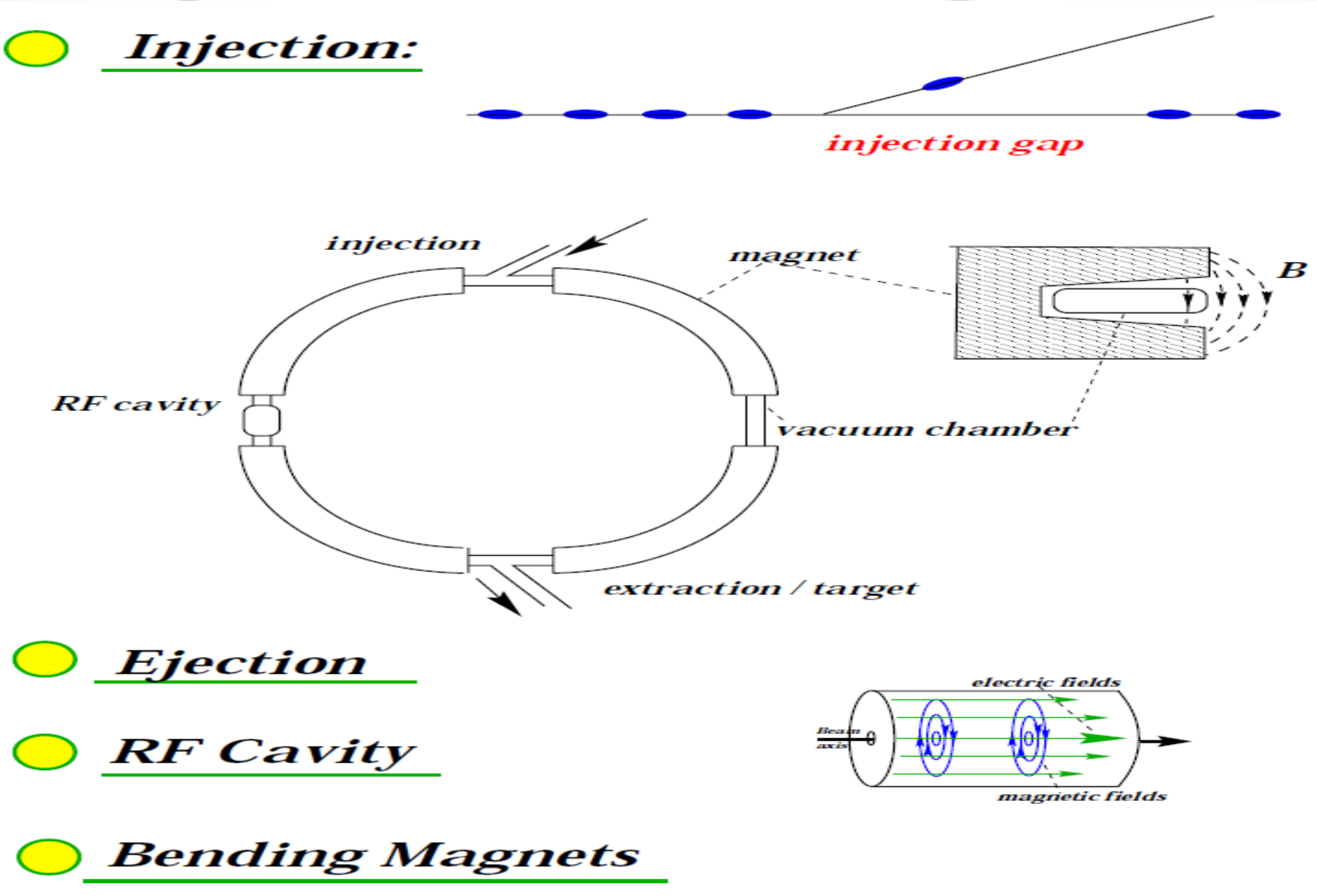
Linear Acceleration:

bunch ed beam

long accele rator!

Circular Accelerator:

Synchrotron requisites



- **Injection:**
- **Ejection**
- **RF Cavity**
- **Bending Magnets**

Some key dates: synchrotron development

Electrons

- 1946 :Synchrotron principle 4-8 MeV acceleration UK
  [F. Goward,D. Barnes *aug1946*] *Nature, 158 p413*
- 1947 :70 MeV electron synchrotron GEC N.York {Blewett]
- 1948 : 240 MeV Univ of Rochester [Sydney Barnes]
- 1949: 300 MeV Cornell [R. Wilson],
- 1949 300 MeV Lawrence Radiation Lab [Mcmillan]
  - 300 MeV machine at Univ of Glasgow

Protons

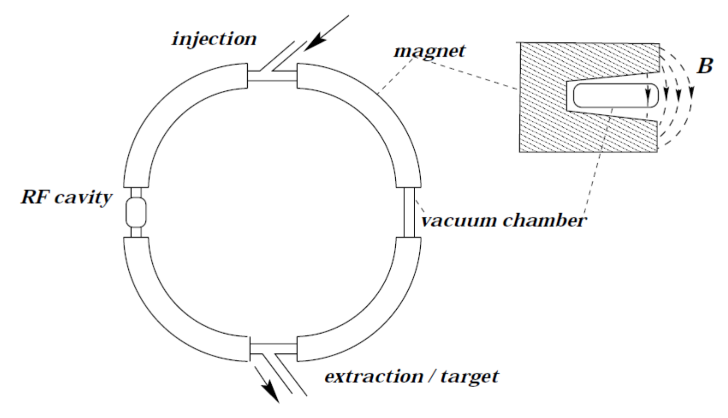
1.3 GeV machine at Birmingham

- **1952 3 GeV** protons machine @BNL : ambition to *Cosmic ray creation* *'Cosmitron'* became **Cosmotron**
- **1955 6 GeV** proton Berkeley machine called **Bevatron** [for billion eV machine]

Beginnings of Accelerator Laboratories

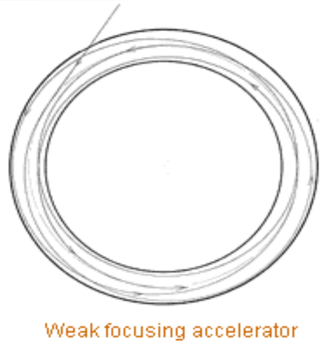
- 1946 in USA *{ east coast vs west coast rivalry }*
  - Just as the war ended, the US Atomic Energy Commission[AEC] was set up
  - East Coast Universities of Columbia, Cornell, Harvard, John Hopkins, Princeton, Pennsylvania, Rochester, Yale, MIT set up a non-profit corporation to create a large accelerator research facility :
  - Brookhaven National Laboratory [BNL] established in March 1947, under the supervision of AEC which also funded the construction of the first accelerator at BNL
  - AEC had agreed/decided at the same time that Berkeley , California would also build a GeV class accelerator
  - BNL chose to build the smaller 3 GeV machine while Berkeley decided on 6 GEV, so as to create the antiprotons
- 1949 in Europe *{destructions of war and pooling resources for the future}*
  - Cultural conference in Lausanne proposal to set up a European Research Centre[Louis de Broglie]
  - June 1950 UNESCO Confr in Florence & I.Rabi resolution for UNESCO ‘ to assist & encourage the formation of regional research laboratories…’
  - Feb 1952, 11 European countries signed an agreement establishing CERN and Geneva was chosen as a site for a particle physics laboratory in Oct 1952
  - Sept 1954 CERN’s FORMAL birth , after ratification by individual Governments

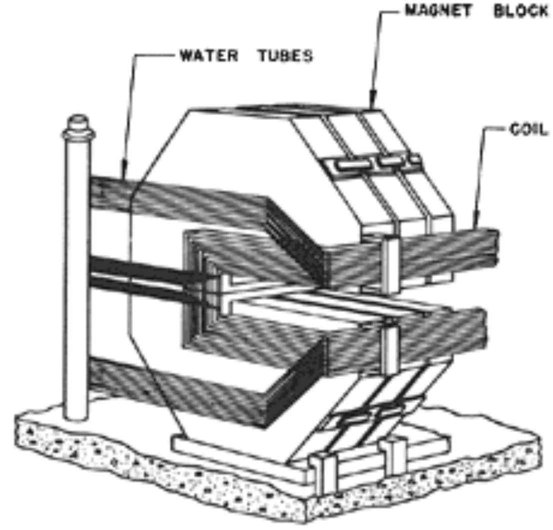
first 3 GeV proton sychrotron 'Weak-focusing'

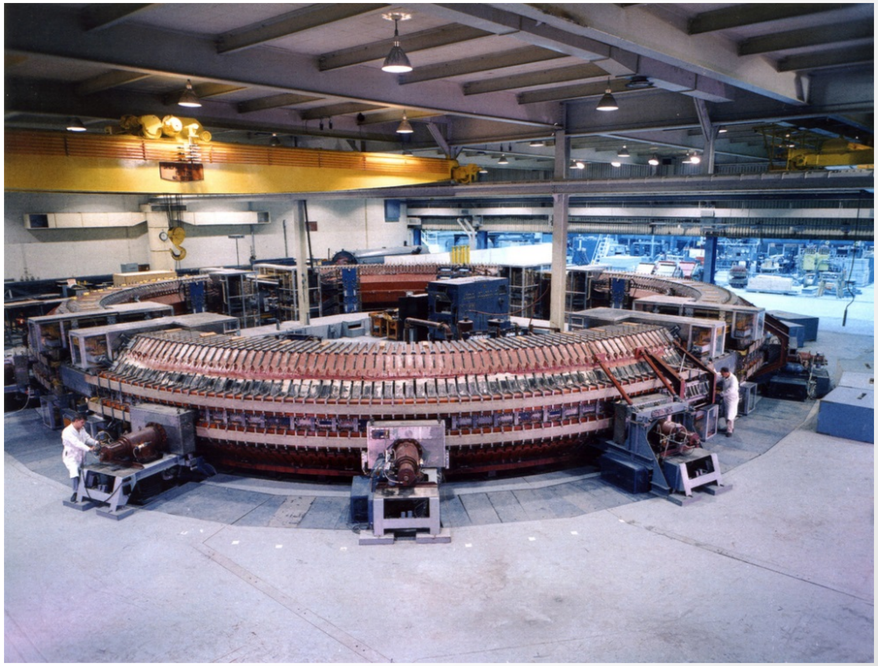


1952: Operation of the Cosmotron, 3.3 GeV proton synchrotron at Brookhaven: magnet gap height was : 22.5 cm. & pole length ~90 cm
Natural ring focusing

C shaped Magnets







Synchrotron (1952, 3 GeV, BNL)

New concept of circular accelerator. The magnetic field of the bending magnet varies with time.
As particles accelerate, the B field is increased proportionally.
The frequency of the RF cavity, used to accelerate the particles has also to change.

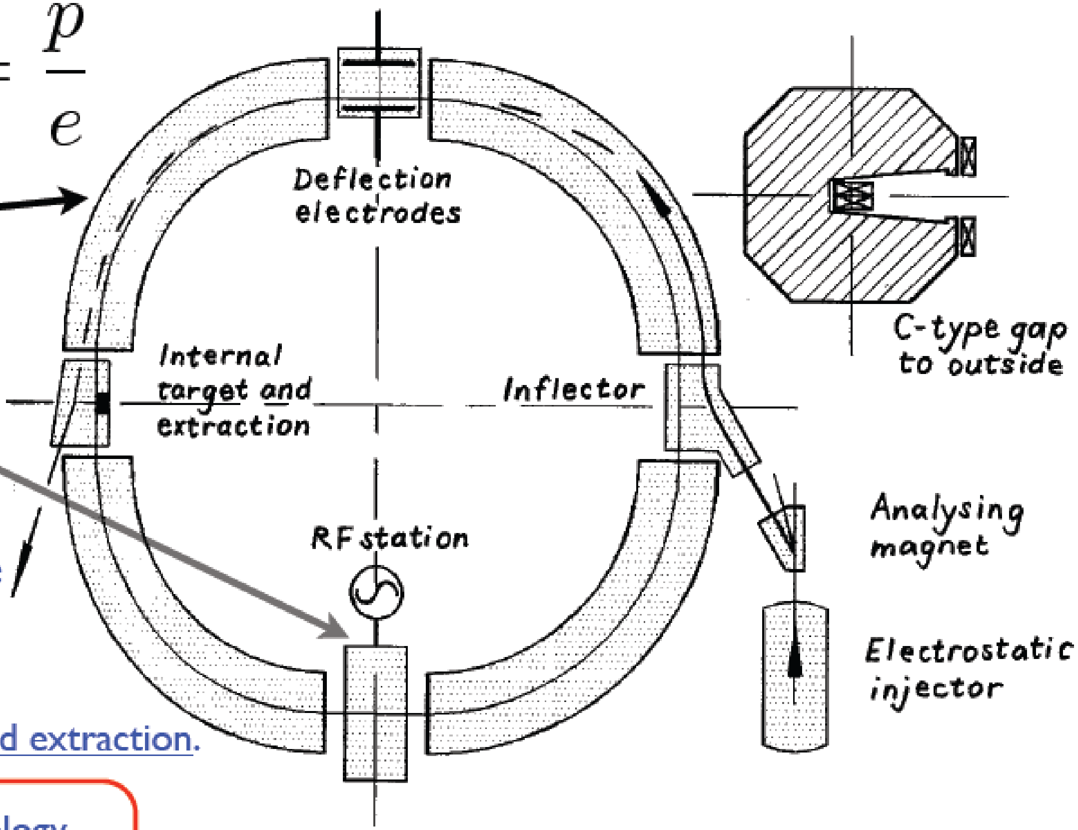
Particle rigidity: $B\rho = \frac{p}{e}$

B = B(t) magnetic field from the bending magnets

p = p(t) particle momentum varies by the RF cavity

e electric charge

ρ constant radius of curvature

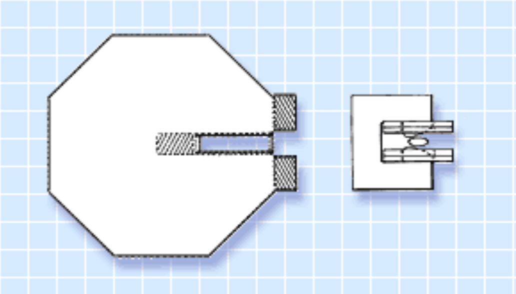


New magnetic elements for injection and extraction.

Bending strength limited by used technology to max ~ 1 T for room temperature conductors

Weak focusing machine: no quadrupoles yet
Strong focusing machine, using quadrupoles, were proposed in 1952

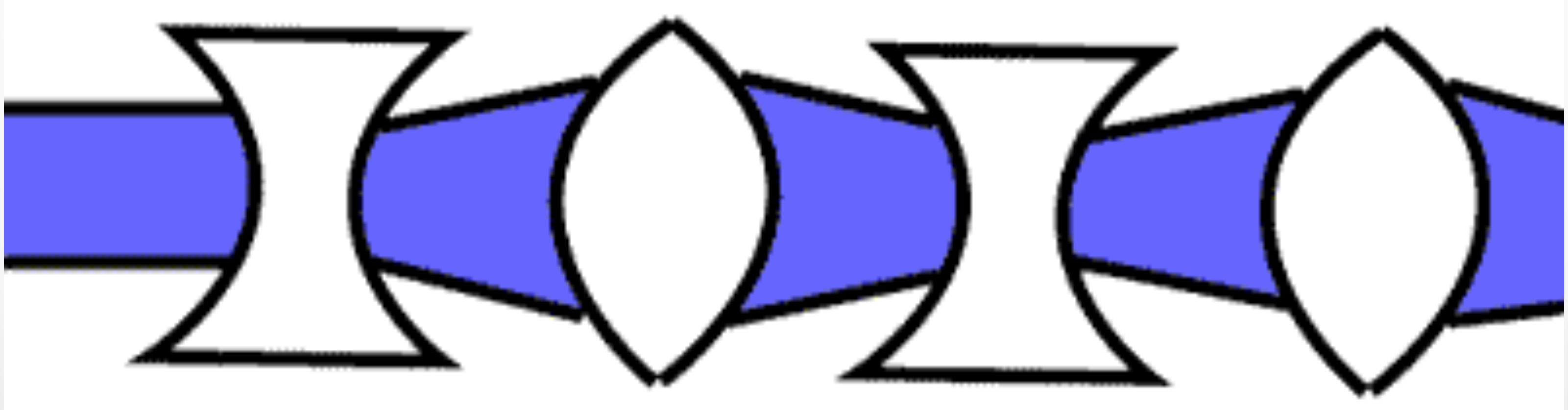
Invention of strong focusing



1952 Christofilos and Courant, Livingston & Snyder independently invent strong focusing

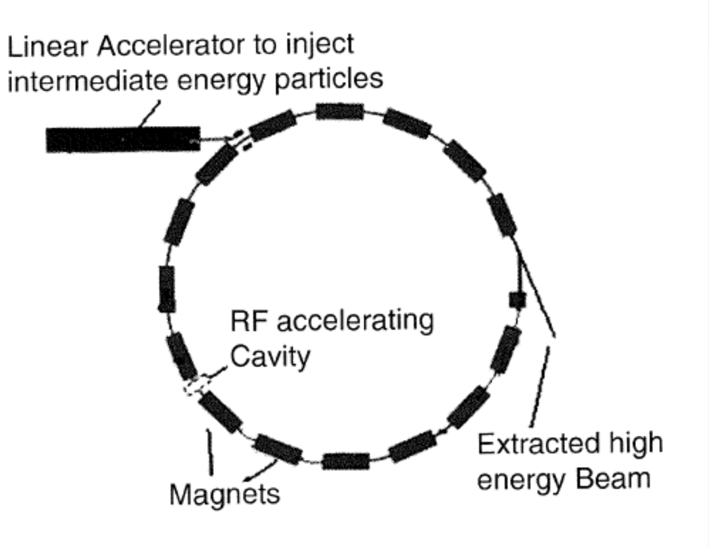
strong focusing: **small amplitudes small vacuum chamber** + **efficient magnets**

Strong focusing brings in the concept of separate-function lattices, reduces the aperture and makes it possible to customize the lattice



Birth of Alternating gradient Synchrotrons

- Betatrons used varying magnetic field to accelerate in a ‘donut’
- Synchrotrons use the ideas from both of Synchro-cyclotrons (varying RF Freq) and betatrons (varying the Field)



- Today‘s Synchrotrons: only strong focusing is used. Need for small magnets and poor field quality at lower field means that the low energy injection {~ 20-800MeV} is done via a Linac. Further staged synchrotrons to increase the final Energy [e.g. , see CERN’s complex]

Alternating gradient Synchrotron: Magnet Limits

- ***strong focusing:***
- **small amplitude**
- **small vacuum chamber**
- **efficient magnets**

- **<u>however, warm magnets start saturating at > 2 Tesla</u>**

[earth field ~ : 0.3 * 10E-4 Tesla]

- ***Rule of thumb :***

- **$B\rho \sim T/300$** **where**

B [Tesla],
T is in MeV
ρ =bending radius [Metres]

CERN 26 GeV PS : ~0.8 Tesla Magnet
CERN 450 GeV SPS : ~ 1.5 Tesla

- *LHC Example based on fact that 27 km LEP tunnel was existing [arcs about 23 km so,circle radius ~3500 metres]*

- LHC Main Bending

ρ =2803 m & T= 7 TeV requires **B ~ 8.4 Tesla** ***So had to go for superconducting magnets***

Conversely, Protons with T = 20 TeV , B = 6.8 T required a 87 km SSC tunnel

a large International Accelerator Infrastructure

[*with Impact beyond Science and Technology*]

CERN and 1952 era

- **The earlier 1930-40 years had seen successful , progressive development of synchro-cyclotrons in USA and UK**
- The electron synchrotrons were relatively new and the **proton synchrotron [cosmotron]** at BNL was the only state-of-the-art accelerator in the world

- In this climate and at the *1st Meeting of Provisional **CERN** Council in May 1952* , ***TWO Study Groups were set up to :***
  - ○ **design/build a Synchro-cyclotron** (Cornelis Bakker, Amsterdam)
  - ○ **design/build a European Cosmotron but with higher energy [10-20 GeV] like the one at BNL** (Odd Dahl, Bergen)

CERN's beginnings:1952

❖ ***Synchro-cyclotron***

- Work started in 1955 on the 600MeV SC, applying all the previous knowledge gained in the US and UK
- Unsurprisingly, the machine achieved its design goals straight away after commissioning in 1957
- Rare decays and beta decays of mesons were observed and quantified and contributed significantly to muon physics at that time

❖ ***Scaled up Cosmotron***

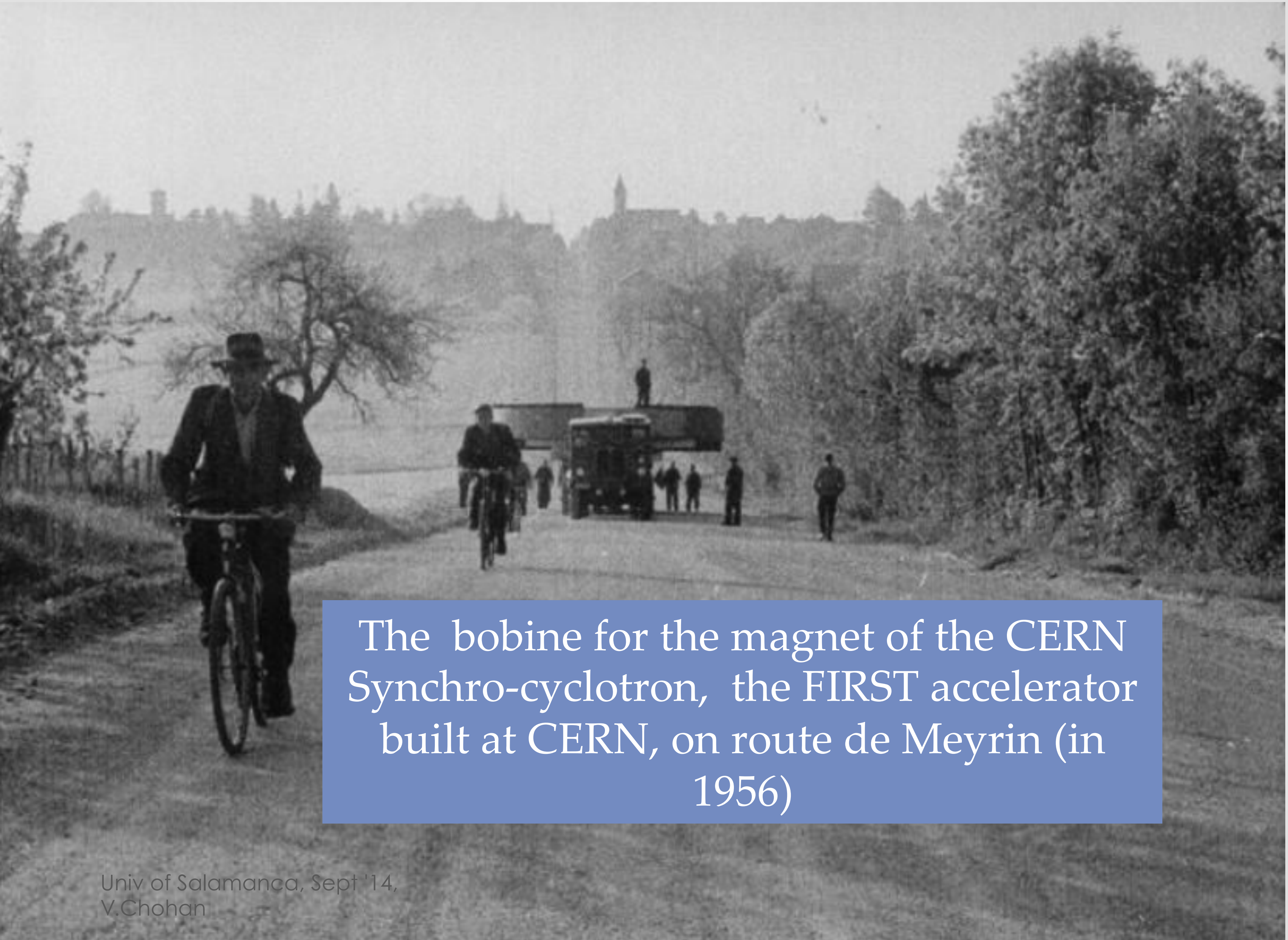
10-20 GeV like the 3 GeV one at BNL

- Goward, Dahl, Wideroe visited BNL in August 1952 and learned about the new principle for focusing: the Alternating-Gradient (AG)
  [attributed to :Christofilos-Courant-Livingston-schnyder]
- ***Council October 1952*** *decided on this new proposal and* **<u>abandon</u> the idea of scaled-up weak-focusing "Cosmotron"**

go for 30 GeV PS based on Alternating Gradient principle for ~ the same cost (~ 70 MCHF)

Subsequent work *meant trade-offs in:*

- size of vacuum chamber and magnets, i.e., cost
- sensitivity to B-field inhomogeneity and alignment errors
- Weight of magnets :

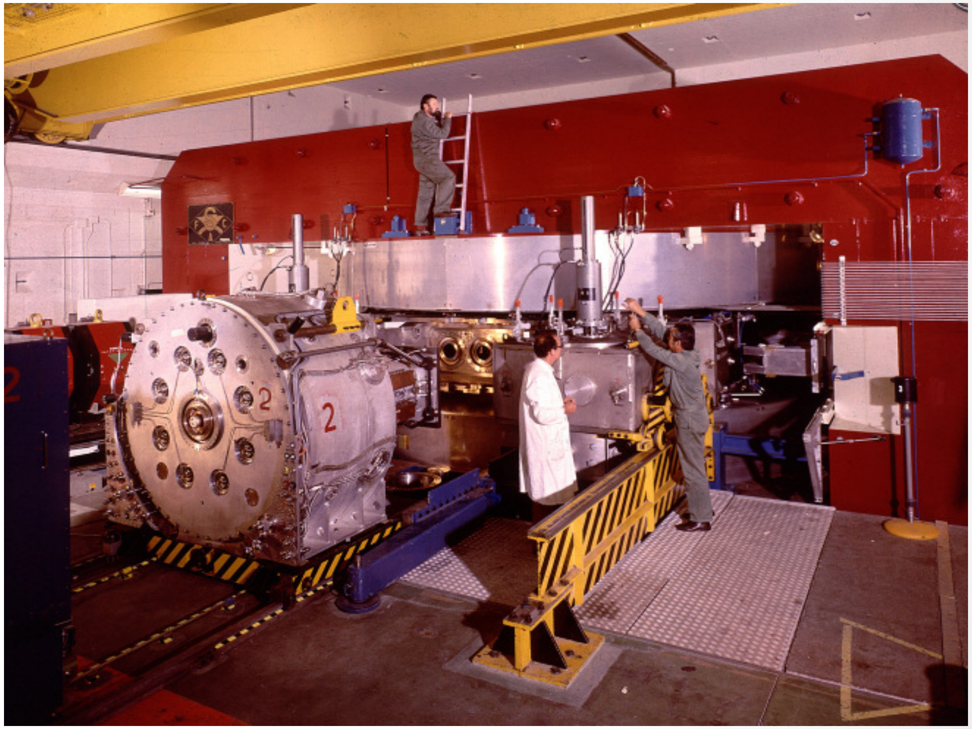


The bobine for the magnet of the CERN Synchro-cyclotron, the FIRST accelerator built at CERN, on route de Meyrin (in 1956)

CERN 600 MeV Synchro-cyclotron

- early start of meson physics
  training for accelerator technology

- SC Stop: end of 1990
  ISOLDE moved to CPS Booster (PSB) 1991

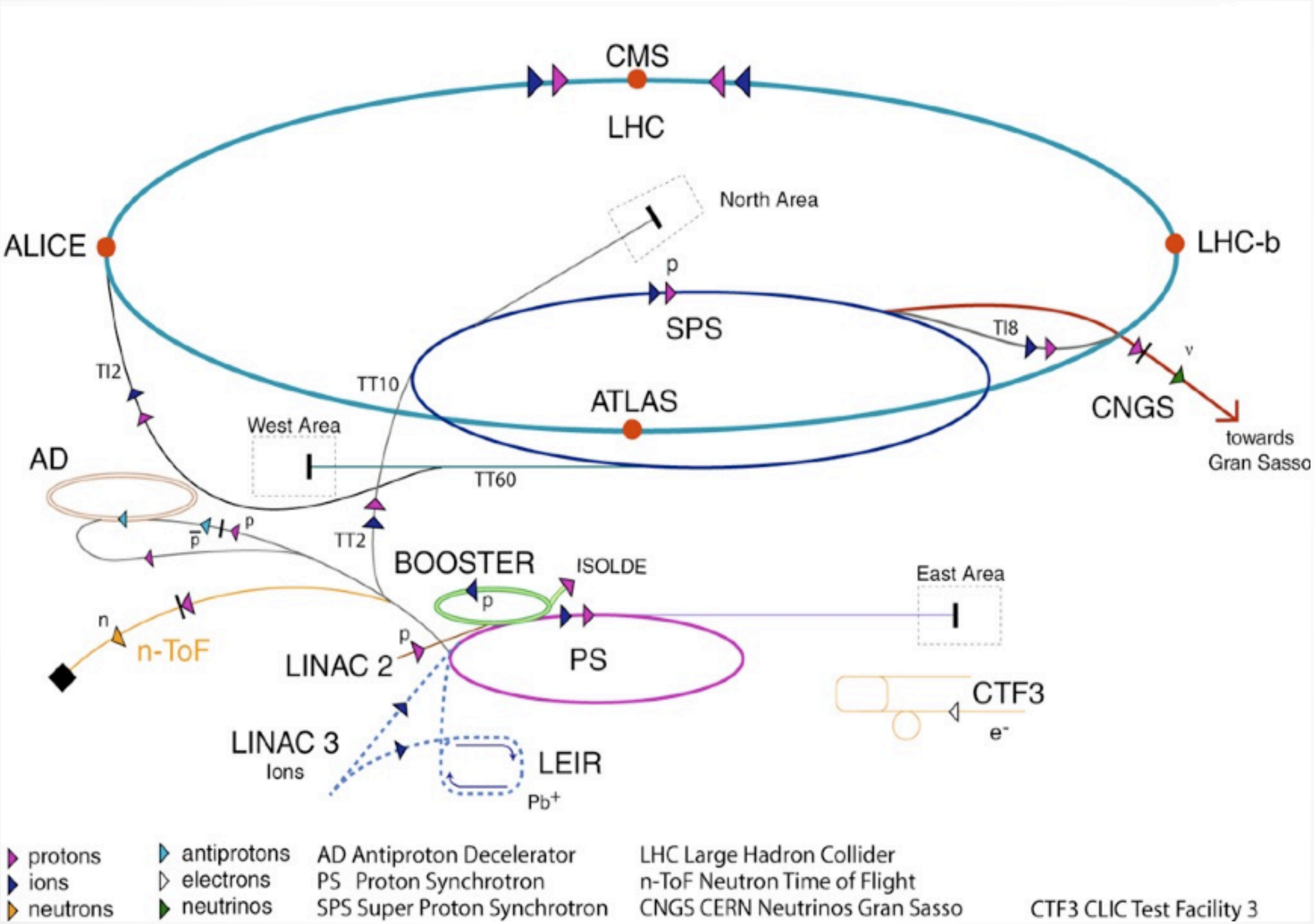


Comment: its progress was reassuring for Council and good physics was done

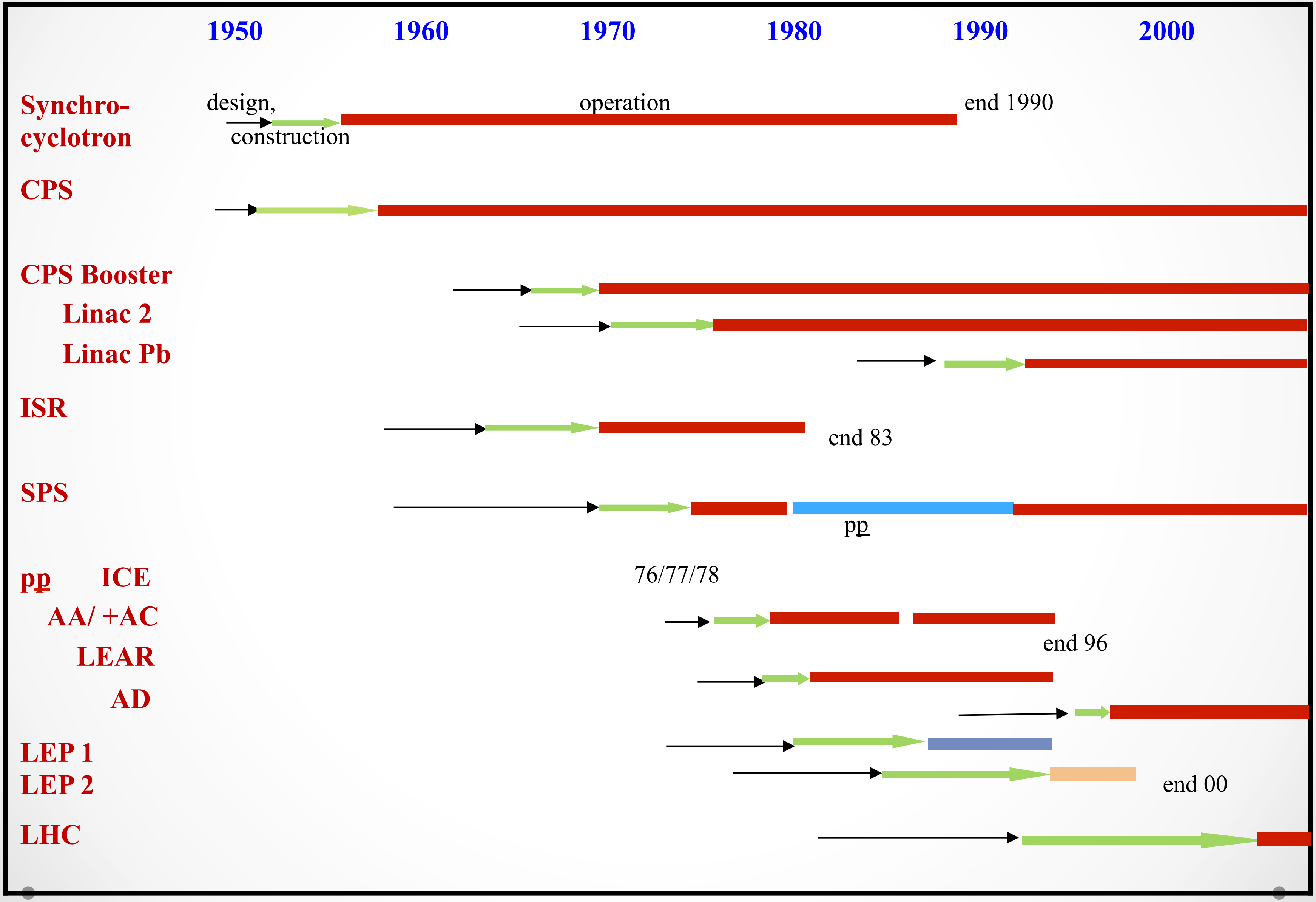
but tied physics community in the 50's

- disservice to PS experimental programme (which started only 1961 about 2 years after PS start-up)

CERN Accelerator Complex **today**



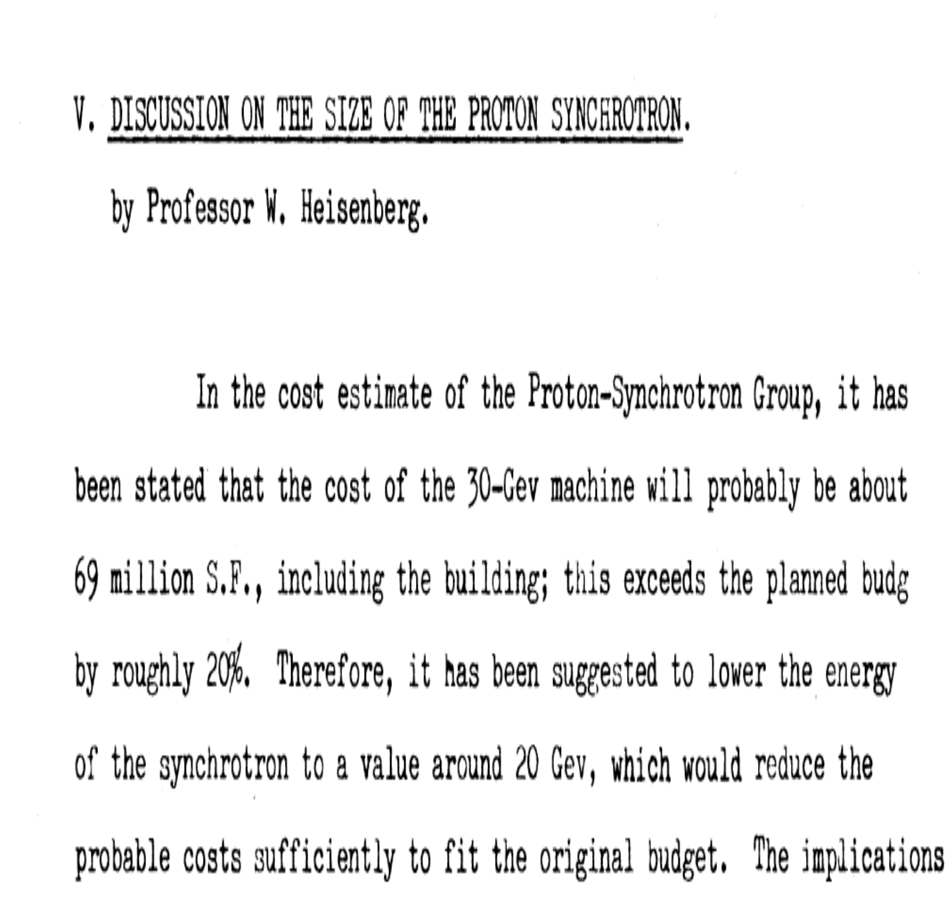
Evolution of CERN's Accelerators



CERN in 1955

Conference on the The CERN PS , oct 1953 ,

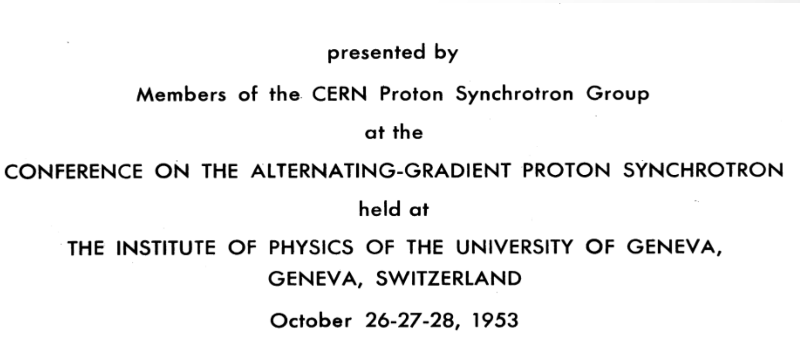
Uni of Geneva



V. DISCUSSION ON THE SIZE OF THE PROTON SYNCHROTRON.

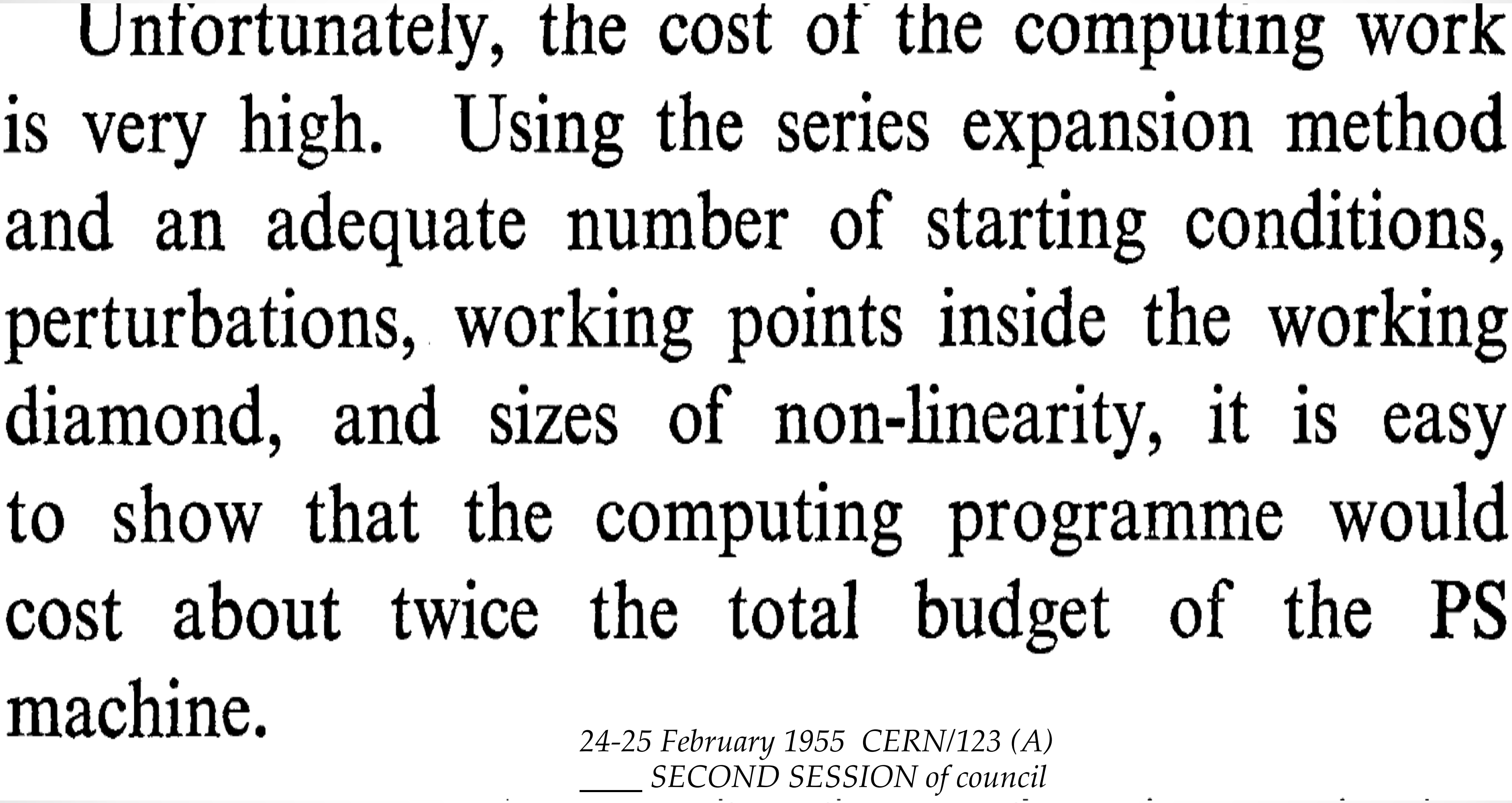
by Professor W. Heisenberg.

In the cost estimate of the Proton-Synchrotron Group, it has been stated that the cost of the 30-Gev machine will probably be about 69 million S.F., including the building; this exceeds the planned budg by roughly 20%. Therefore, it has been suggested to lower the energy of the synchrotron to a value around 20 Gev, which would reduce the probable costs sufficiently to fit the original budget. The implications



presented by
Members of the CERN Proton Synchrotron Group
at the
CONFERENCE ON THE ALTERNATING-GRADIENT PROTON SYNCHROTRON
held at
THE INSTITUTE OF PHYSICS OF THE UNIVERSITY OF GENEVA,
GENEVA, SWITZERLAND
October 26-27-28, 1953

Designing the PS : anxieties….



Unfortunately, the cost of the computing work is very high. Using the series expansion method and an adequate number of starting conditions, perturbations, working points inside the working diamond, and sizes of non-linearity, it is easy to show that the computing programme would cost about twice the total budget of the PS machine.

24-25 February 1955 CERN/123 (A)
____ SECOND SESSION of council
PS DIVISION PROGRESS REPORT
Geneva, February 9th, l955 Report by J .Adams

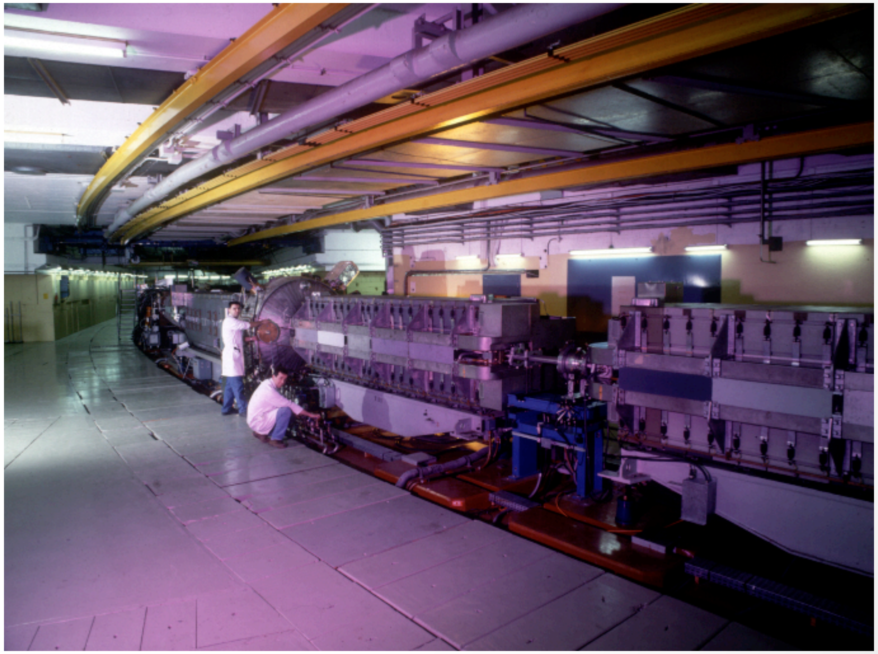
CERN 26 GeV Proton Synchrotron (CPS)

❖ ***Key Dates & Lessons***

- May 1954: ground breaking
- ***Design: AG combined function (dipole + quad),*** $2\pi R = 628$ ***m***
- Dec. 1959: first beam to 28 GeV
- Initial drama: no beam line equipment, only rudimentary detectors

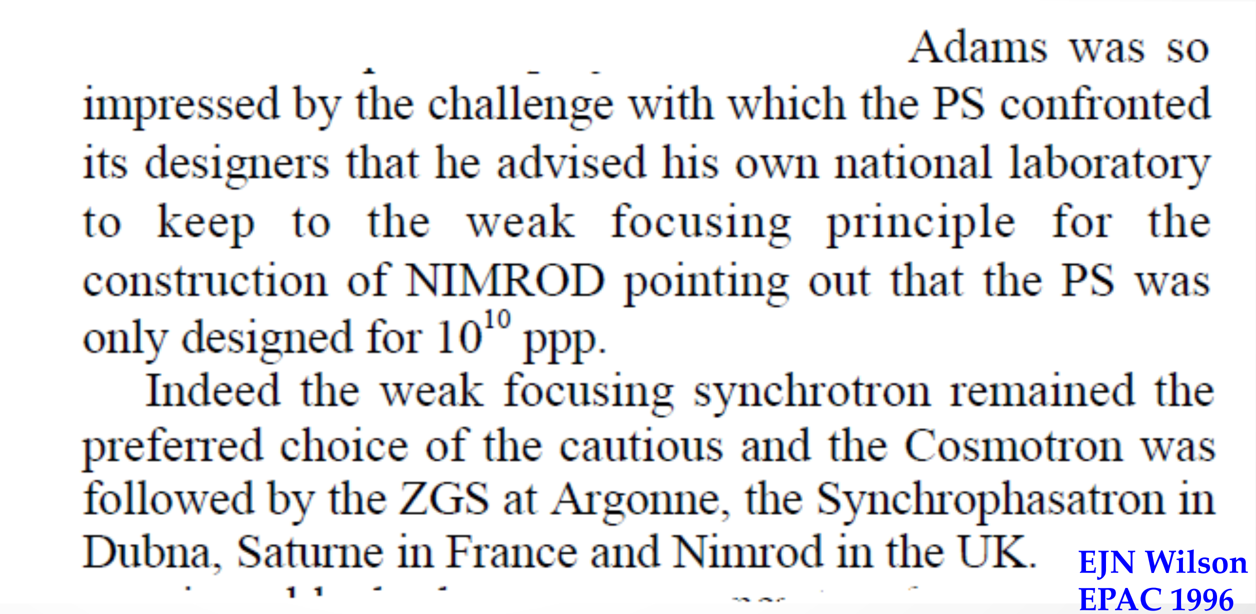
Lessons :

- beam physics with Alternating Gradient principle,
- producing precise magnets
- precise alignment system, geodesy
- rf control
- management of a large project in European/international context



The PS starting conditions: International Context

- *Choice of new focusing principle was a bold step*
- *"For awful gamble stands AG but if it works or not we'll see (R.Peierls)*
- *however if it works : CERN starts level with US and ahead*
- *Others did not trust AG: US: ZGS/ANL; UK: Nimrod/RAL; Russia:JINR*:



Adams was so impressed by the challenge with which the PS confronted its designers that he advised his own national laboratory to keep to the weak focusing principle for the construction of NIMROD pointing out that the PS was only designed for 10^{10} ppp.

Indeed the weak focusing synchrotron remained the preferred choice of the cautious and the Cosmotron was followed by the ZGS at Argonne, the Synchrophasatron in Dubna, Saturne in France and Nimrod in the UK.

EJN Wilson EPAC 1996

… after the PS

- At the beginning of the1960's a debate was raging about the next step for CERN. Opinions were sharply divided between a "large PS", a proton machine of 300 GeV energy or a much more ambitious colliding beam machine.

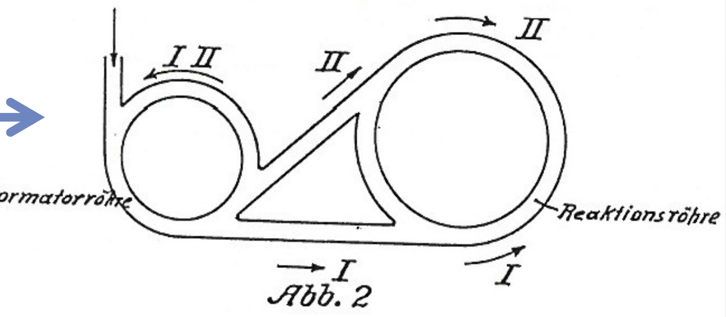
- In February 1964, 50 physicists from among Europe's best met at CERN. They decided to transform themselves into the European Committee for Future Accelerators (ECFA) under the chairmanship of Eduardo Amaldi.

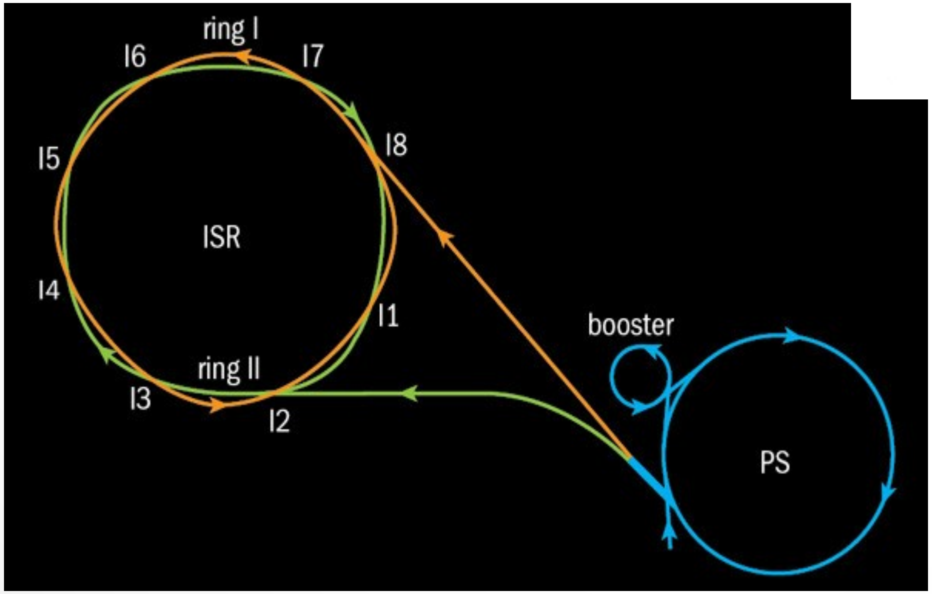
- It took another 2 years before a consensus was formed. In December 1965 the CERN Council approved the **construction of the ISR : a TWO-Ring 31 GeV per beam Collider**

Advent of Colliding beams

- Widerøe was indeed a pioneer and patented the idea of circular colliders **in 1943**
- Owing to the war, the patent was not published until 1953.
- **ISR was the first CERN project to use this principle.**

Wideroe's patent application cutting :

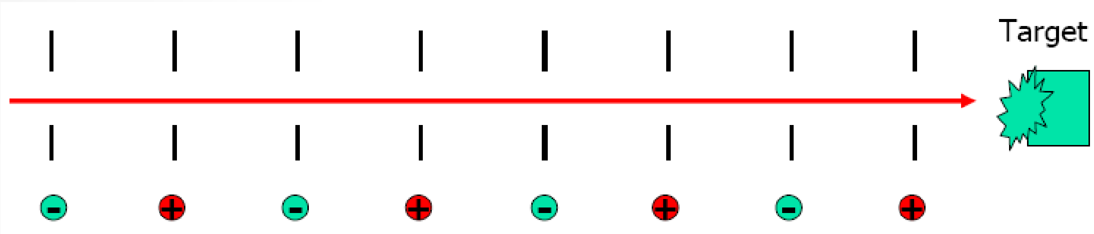




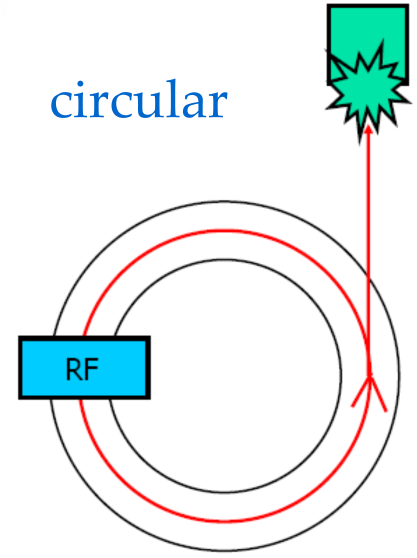
The CERN ISR layout.

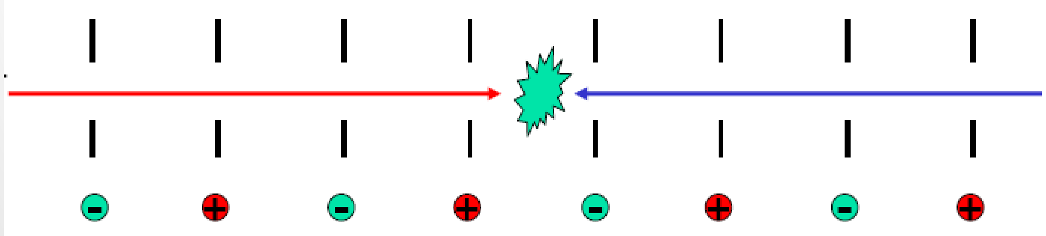
Accelerators and Colliders

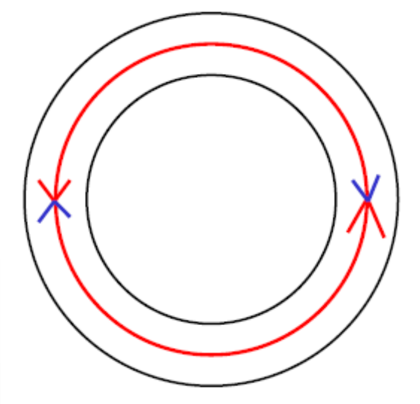
linear



circular

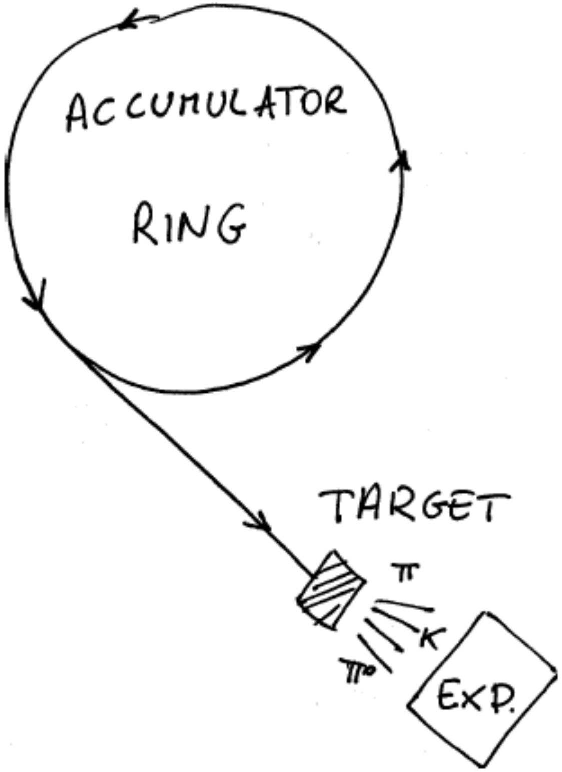




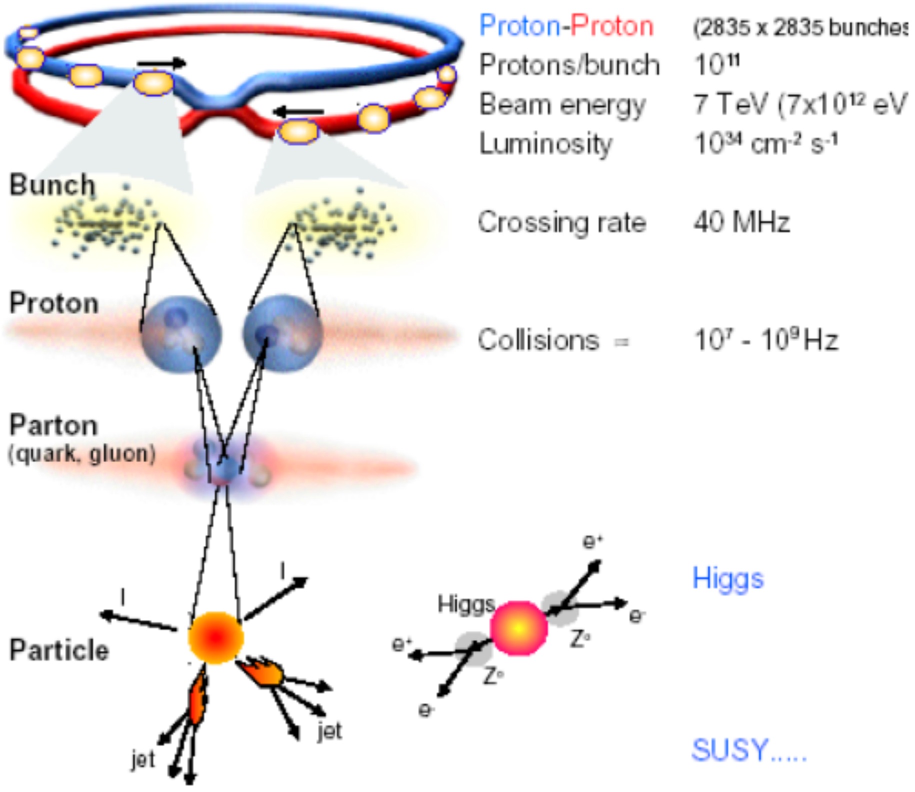


Different approaches: fixed target vs collider

Fixed target



Storage ring/ collider



Proton-Proton	(2835 x 2835 bunches
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

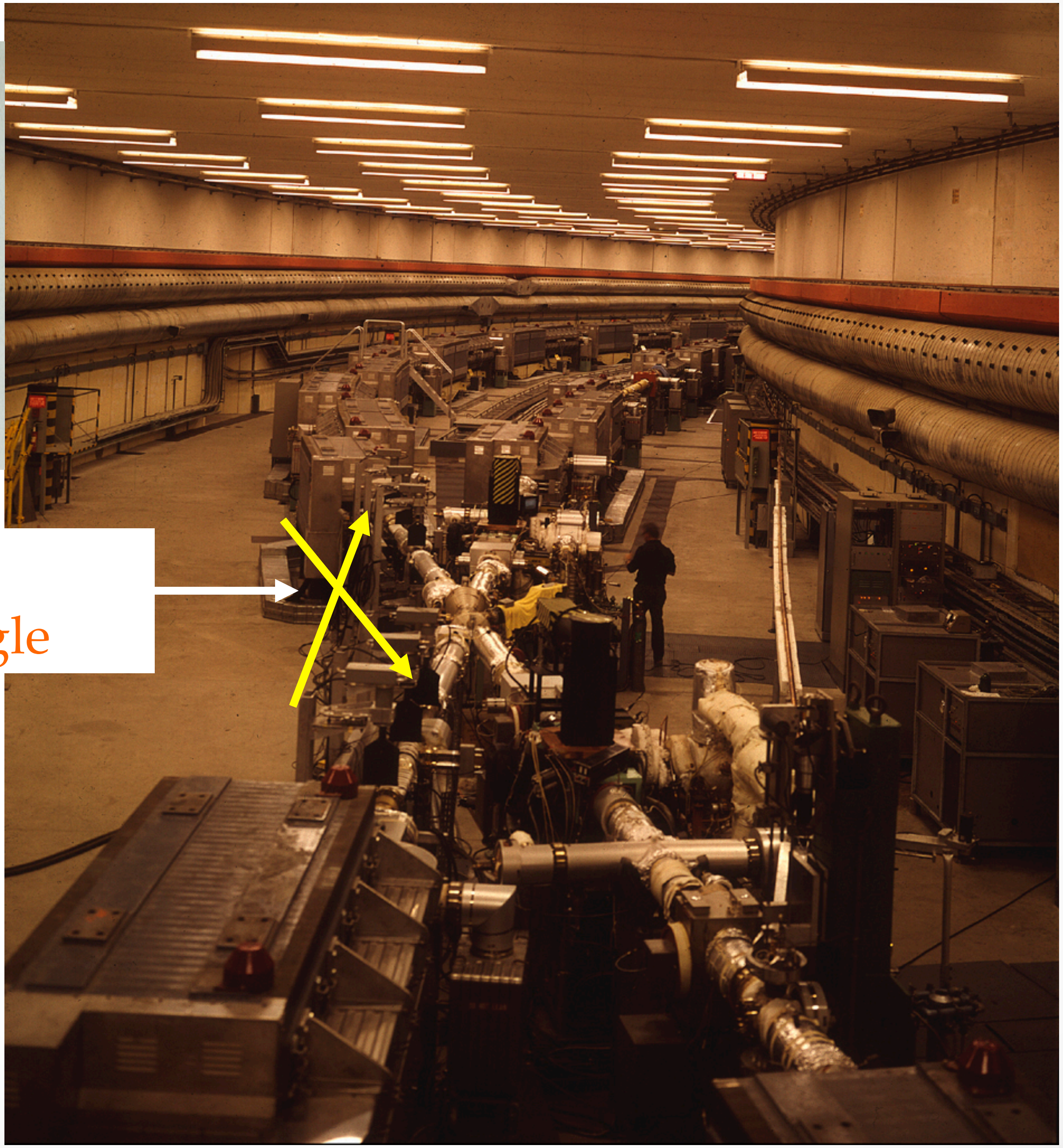
$$E_{CM} = \sqrt{2\left(E_{beam} mc^2 + m^2c^4\right)} \quad << \quad E_{CM} = 2\left(E_{beam} + mc^2\right)$$

Two intersecting Rings :ISR


Werner Heisenberg
1901 - 1976

inaugurated the
CERN Intersecting Storage Rings
on 16 October 1971

View of intersection point 5 in 1974



Interaction point
with crossing angle

Intersecting Storage Rings (ISR): the venture into hadron colliders

pp collider up to **31.4 GeV per beam**

2π R = 942 m, injection from CPS

- Combined-function lattice, large Δp/p
- 8 Intersection points (5 used for exp.)

- Constr.: **1966-70,**
- Operated:**1971-83**

L= 4 x 10^{30} to 1.4 x 10^{32} $cm^{-2}s^{-1}$,

Notable features:

- 40 A DC beam current per beam
- Ultra-high vacuum and ion clearing
- Low-impedance vacuum envelope
- High-stability of power supplies (10^{-7} ripple tolerance on dipoles)
- Superconducting low-β insertion

(L increased by 6.5)

but experiments not fully exploiting it.

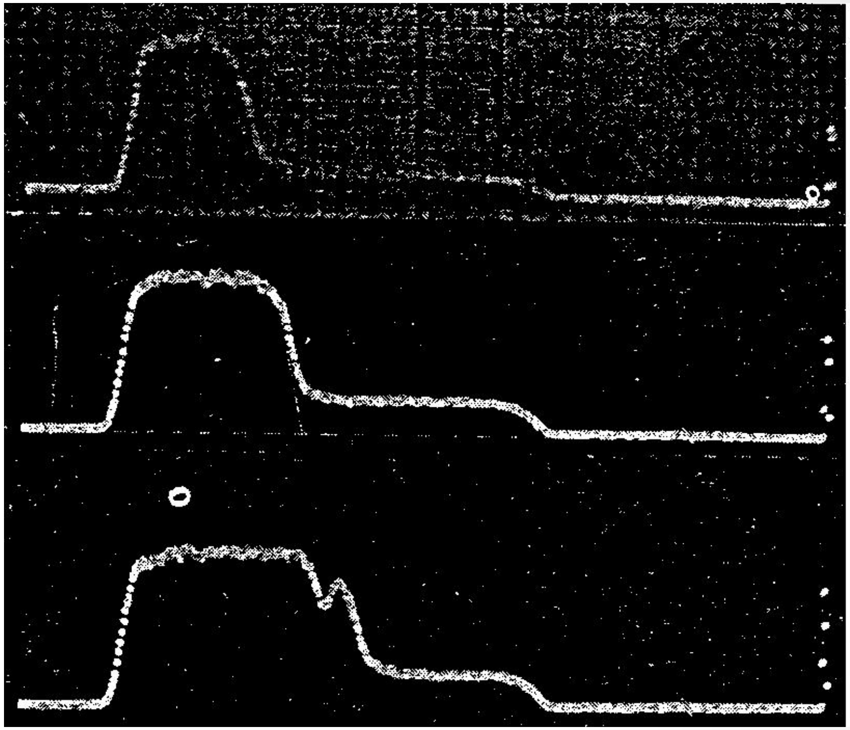
Selected ISR Achievements

Non-destructive beam diagnostics of coasting beams with Schottky noise

For monitoring particle distribution →

- **<p>, Δp, density f(p)**

- **extrema of betatron tunes in stack,**
  rms amplitude and tune
  at particular orbit
  by measuring fast and slow wave signals (n +- Q) f $_{\text{rev}}$

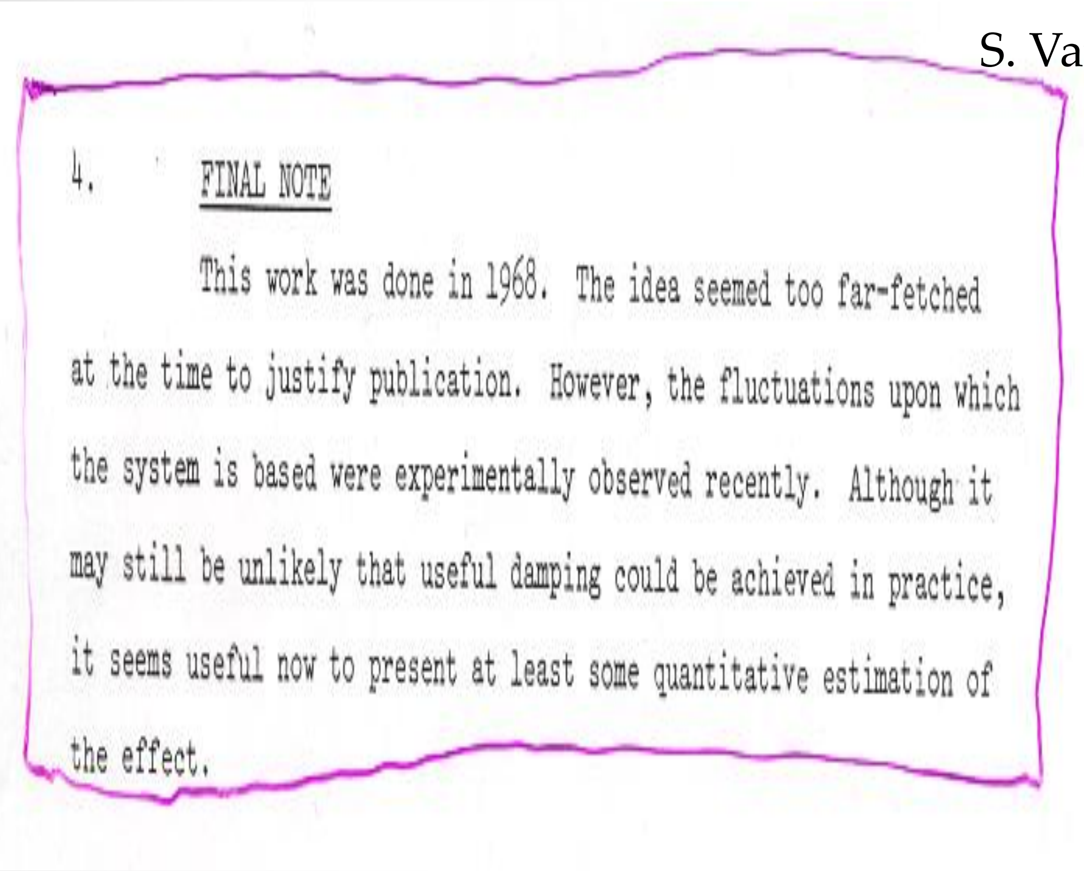


Example: Longitudinal Schottky scan
$(dN/dp)^{1/2} = f(p)$
at 10, 15, 19 A proton current

J.Borer et al., HEACC (1974) 53

Invention of Stochastic Cooling 1968

S. Van Der Meer CERN/ISR-PO/72-31



4. FINAL NOTE

This work was done in 1968. The idea seemed too far-fetched at the time to justify publication. However, the fluctuations upon which the system is based were experimentally observed recently. Although it may still be unlikely that useful damping could be achieved in practice, it seems useful now to present at least some quantitative estimation of the effect.

and experimental test 1972-3

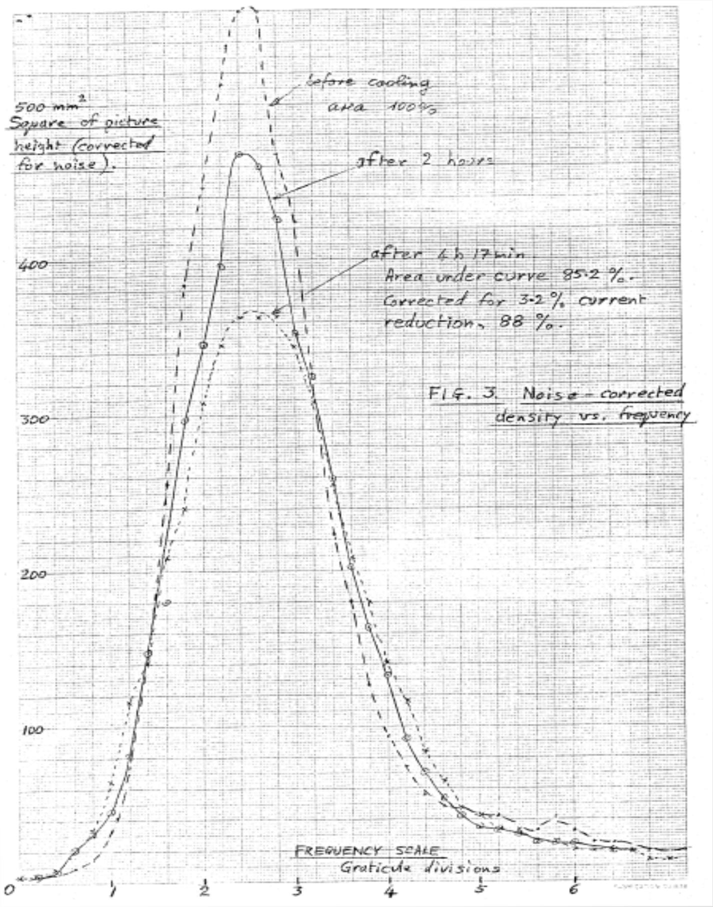
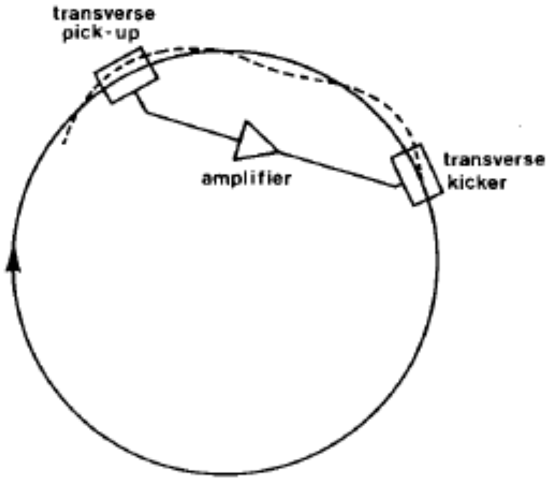


FIG. 3. Noise-corrected density vs. frequency

Stochastic cooling: Nobel Lecture S van der Meer 1984

- *…….Fortunately, there is a trick - and it consists of using the fact that particles are points in phase space with empty space in between. We may push each particle towards the centre of the distribution, squeezing the empty space outwards. The small-scale density is strictly conserved, but in a macroscopic sense the particle density increases. This process is called cooling because it reduces the movements of the particles with respect to each other….*

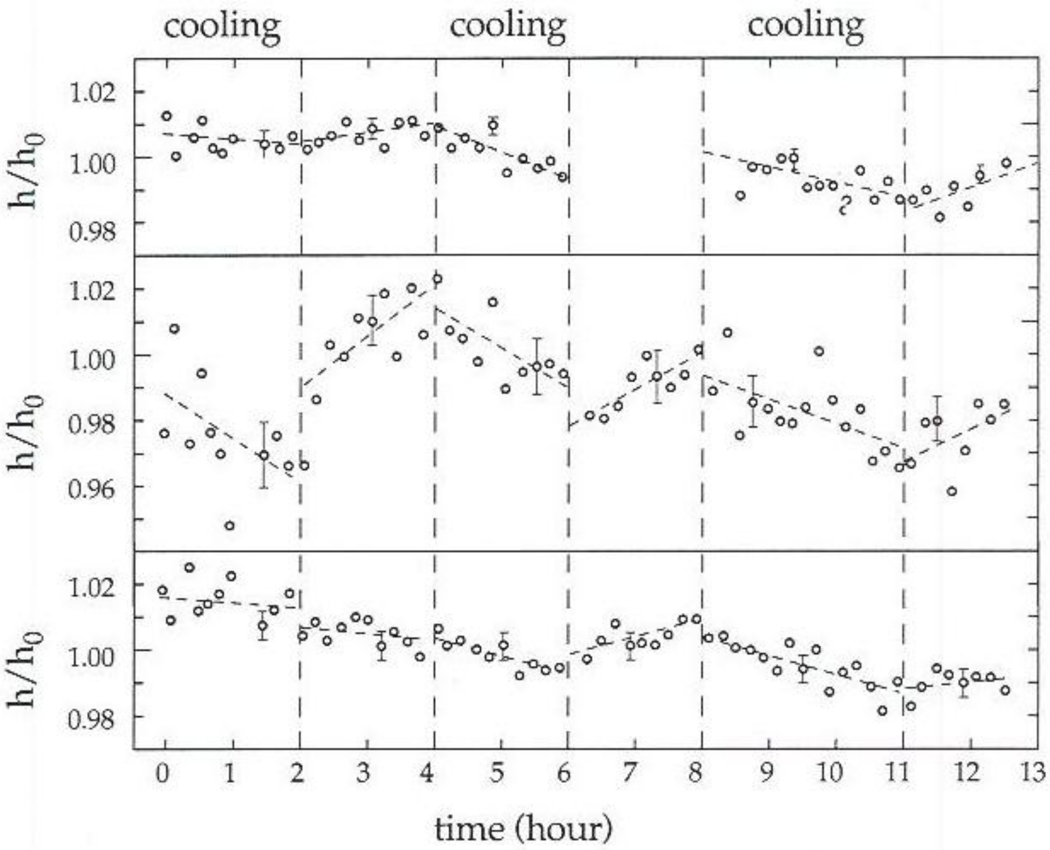
- **A stochastic cooling system therefore consists of a sensor (pick-up) that acquires electrical signals from the particles, and a so-called kicker that pushes the particles and that is excited by the amplified pick-up signals.**



Cooling of the horizontal betatron oscillation of a single particle

Stochastic cooling in the ISR (Schnell)

Thorndahl 1975

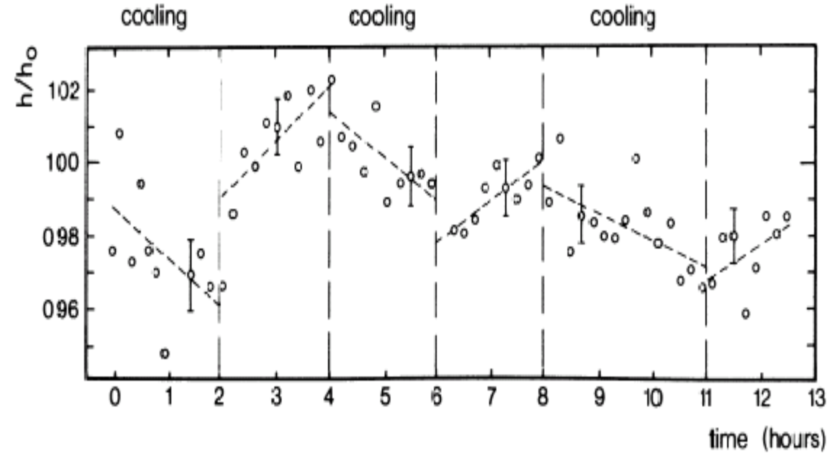


P.Bramham et al. NIM 125(1975) 201

Selected ISR Achievements

Resurrection of stochastic cooling and experimental test (theory: van der Meer 1968)

Measurement of relative effective beam height with cooling on and off

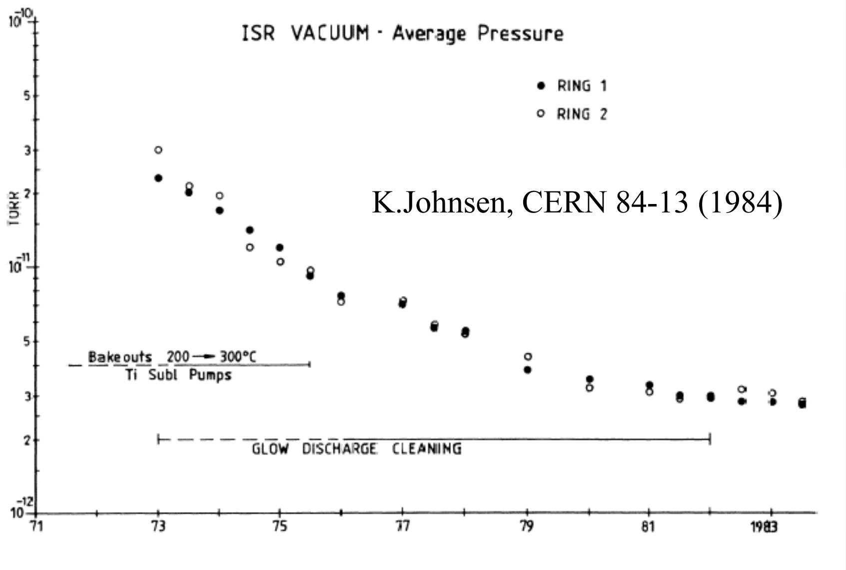


P.Bramham et al. NIM 125(1975) 201

Use in ISR: e.g. p beam kept for 345h

Ultra-high vacuum technology

Evolution of average pressure: design nTorr, at end pTorr

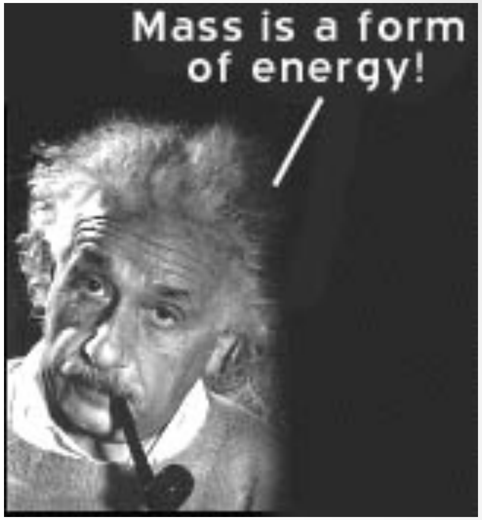


K.Johnsen, CERN 84-13 (1984)

Fig 5 The average pressure of the ISR vacuum for the years 1971-83

Result: physics runs up to 60 h, beam lifetime of about 3 to 4 months

When one accelerates a particle…



It does not necessarily go much faster

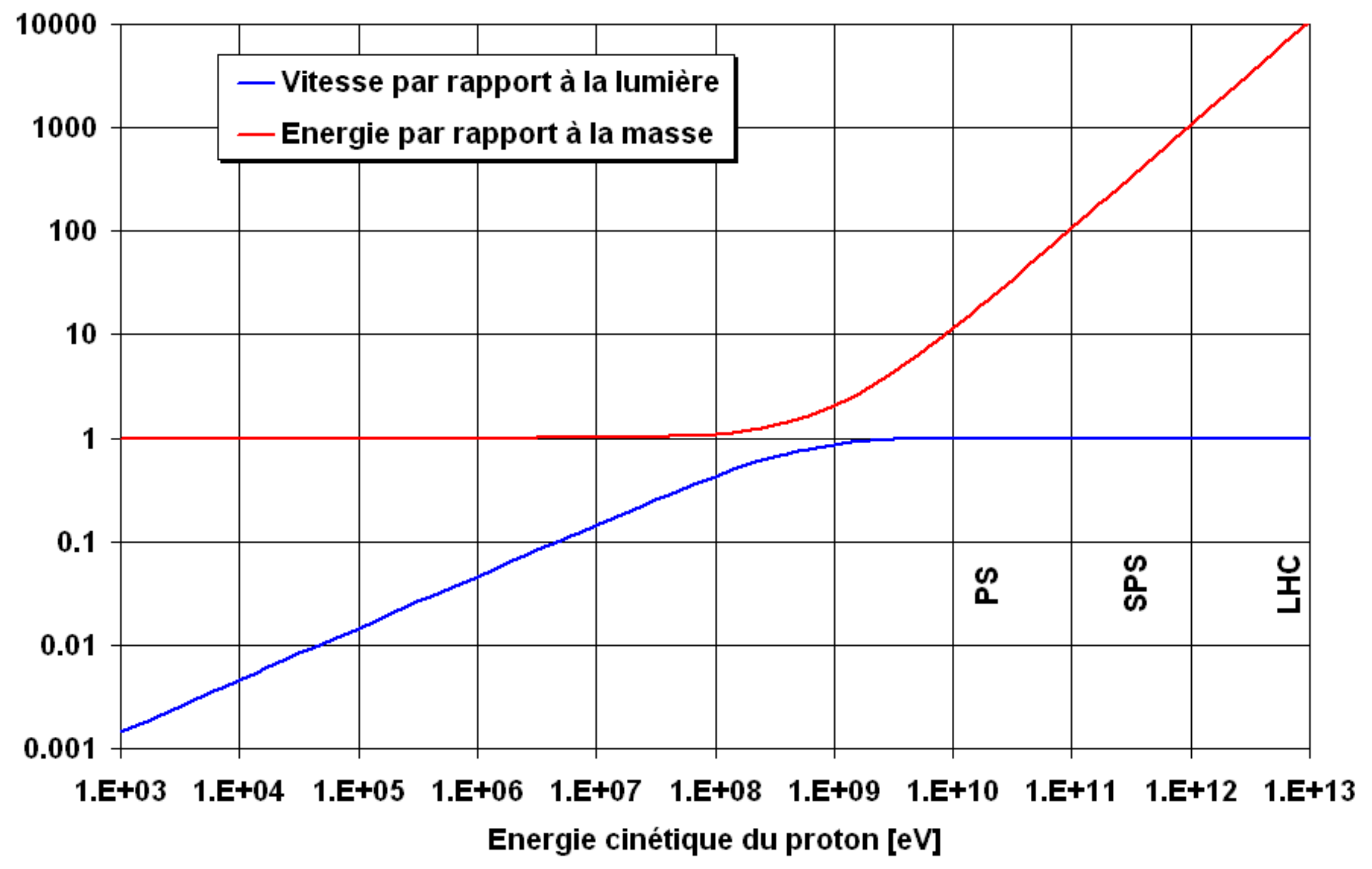
Its mass increases by relation

$$E = m c^2$$

In an interaction, it can transform its energy into massive particles

…one transforms energy into mass

Speed and Energy of a proton



2nd Generation Synchrotrons : FNAL & SPS

- USA takes the lead again: R. R. Wilson a pioneer with his great experience & maverick manner sets up **in 1967 Fermilab**, (Fermi National Accelerator Laboratory) at Batavia, Illinois, near Chicago;*!*

- By separating the functions of the combined focusing and bending magnets of the AGS & PS and using discrete Dipole and Quadrupole units, he could squeeze more bending power per metre in the lattice. ***Wilson kept his promise to complete the 200 GeV synchrotron in only 5 years*** .

- **The original main ring accelerator at Fermilab (6.86 km circum). was completed in June 1971.The beam energy reached the design value of 200 GeV by March 1972 and with upgrades reached 500 GeV by 1976.**

- At CERN, SPS construction {1971-76} process just about began when Fermilab already had started operating their Main Ring

World's first SC Synchrotron : @FNAL ; *doubling energy again*

- **In 1983, The highest energy Synchrotron leadership was still in the hands of US with the addition of a superconducting magnet ring below the Main Ring in the same tunnel Fermilab [Energy saver/Doubler project]**

- The Energy Saver has reached its primary design goal: accelerating protons to 500 GeV **in a ring of superconducting magnets. With the injection energy of 150 GeV from the old main ring**

- **1984** :The Energy Saver/Doubler achieved 800 GeV

- **1986:** Energy Saver/Doubler achieved **900 GeV**

Fermilab Energy Doubler

1983 :Main 'warm magnet' Ring above injects into the Superconducting ring below

CERN 450 GeV Super Proton Synchrotron (SPS)

❖ ***Key Dates , figures & Lessons***

- Concept: 300 GeV in early 60’s
- final Site {1970}:Prevessin near existing CERN
- use CERN PS as Injector
- Construction: 1971- 1976
- E= 450 GeV p, 158 GeV/u Pb (1986)
- N(p)= 4.5 x 10^{13} /cycle (4.5 x design)
- Neutrino beam to Gran Sasso
  - (732km, operation 2006
- LEP and LHC injector

- Separated function, classical magnets
- 2πR = 6912 m (11 x PS),
- 2 big experimental halls (West, North)

Lessons :

- deep tunneling
- direct powering from grid with
- reactive power compensation*)
- rf acceleration with TW structure
- computer control from start*)
- start experiments with accelerator

- **) at smaller scale already at PS Booster*

Search for the *next* step

after ISR and SPS

CERN Studies and Investigations : ***(1974 -78):***

- **CHEEP**: 27GeV *e-* ↔270 GeV *p*
  in SPS with new e- ring in SPS
- **LSR/SISR** : 400 GeV pp collider
- **MISR**: 60 GeV p storage ring (ISR magnets) ↔ SPS
- **SCISR**: 120 GeV sc p rings in ISR
- **US**: ISABELLE 400 GeV pp 1978-83 (stop)

Winners: (Decisions/First collisions)

- ***p-pbar in SPS (1978 / 1981)***
  medium-term: "quick and dirty"
- **e+e- in LEP *(1981/ 1989)***
  long-term: "flagship"

Single-ring Hadron Colliders

- The Invention of Stochastic Cooling, together with the ability to create and store sufficiently large number of antiprotons was the primordial ingredient to be able to *convert an existing fixed-target physics synchrotron into a Proton-antiproton Collider*

- **Europe pioneered the way with**

  SPS p-pbar collider :1981-91

- **Fermilab followed with the Energy-Saver becoming a p-pbar Collider called**

  Tevatron :1986-2011

The p-pbar Programme *"Collider on the cheap"* : convert SPS into a Collider at CERN

Needed the Antiproton Accumulator to create and store antiprotons: new elements in bold

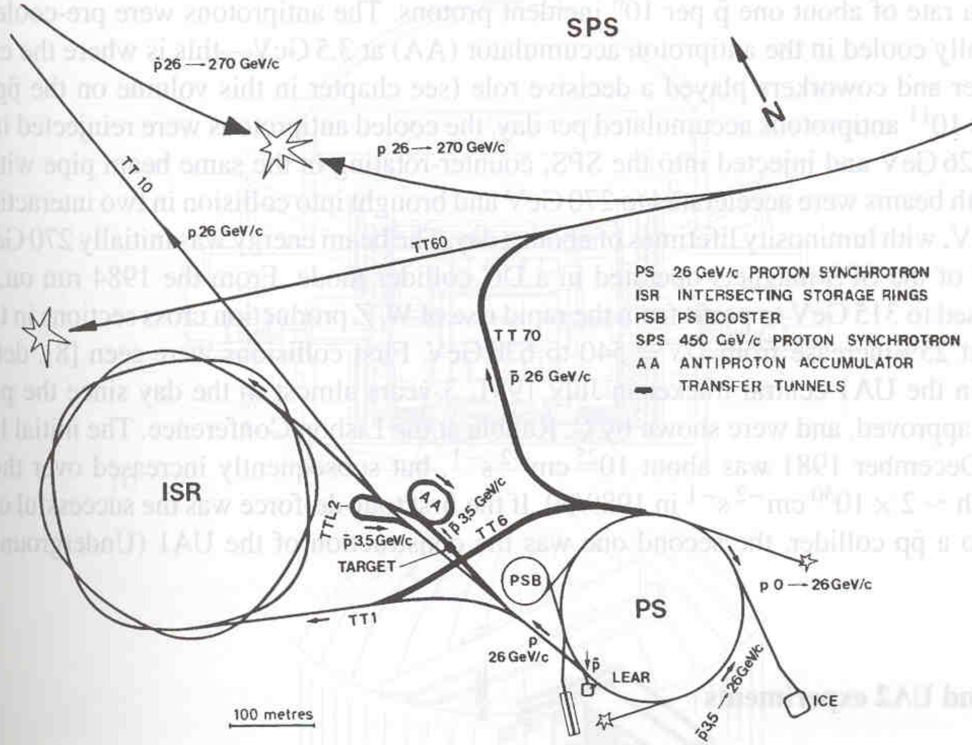
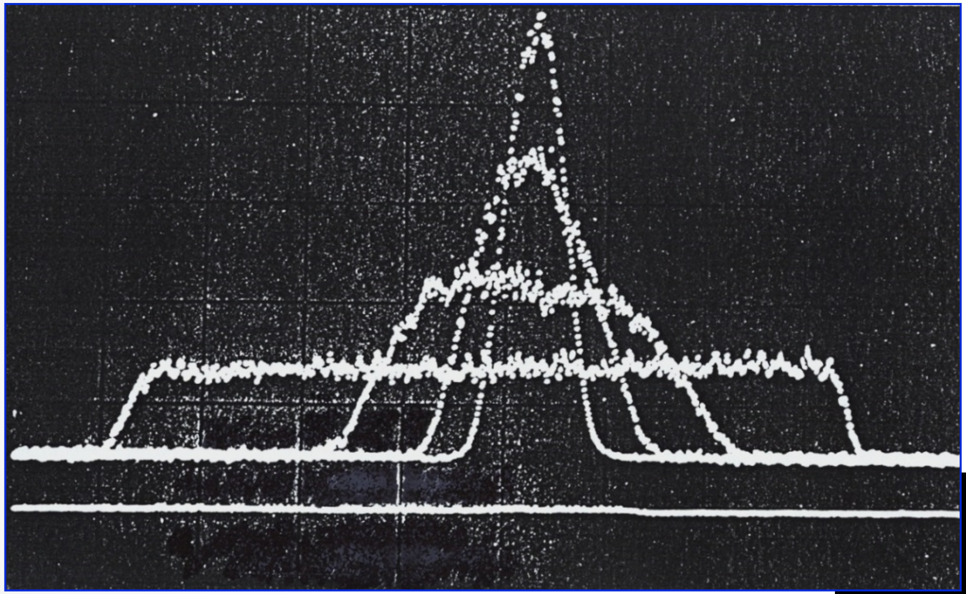


Fig. 1. The CERN proton–antiproton collider complex.

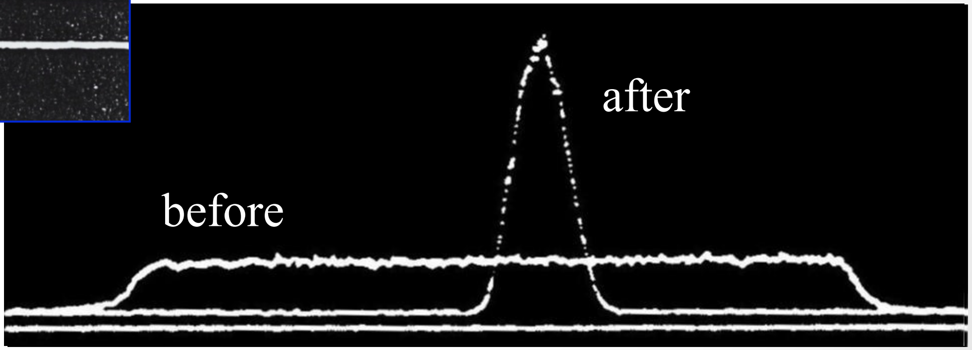
The AA proposal called for an overall increase in antiproton density from the production target to the stack core of over 1E9. However, the stochastic stacking process, which was prone to instabilities was an essential feature in the accumulation scheme;. The process involved simultaneous cooling in both transverse planes and increasing the longitudinal density by four orders of magnitude whilst moving the particles into the dense core, using a combination of filter and radial-pickup-based Palmer cooling techniques to avoid instabilities.

CERN ICE test ring demonstration in 1978 of stochastic Cooling lea



Schottky scan after 1, 2 and 4 min.

Signal height proportional to the square root of density and width proportional to Δ p/p



stochastic cooling in longitudinal phase space,
simultaneous cooling in all 3 dimensions

AA, AC and SPS era 1980-1991

- **Antiproton Accumulator (AA)**

3.5 GeV/c storage ring, $2\pi R=$ 157m
Built 1978-80 , stochastic cooling
for 3D precooling, stack cooled in AA
Overall gain of ≈ 6 in d<u>N</u>/dt

- **New beam transport lines, transfer tunnels TTL2, TT70**

- **SPS Modifications:**

Vacuum: 200 nTorr (des.)>> 2 nTorr
Low-β insertions for UA1 and UA2
RF modifications (TW,add 100 MHz)
Electrostatic deflectors for separating the 6 bunches/beam in 9 points

- **1987 Addition to increase pbar flux by factor 10 :Antiproton Collector Ring(AC)**

3.5 GeV/c storage ring, $2\pi R=182$m, constucted 1985-87

The Antiproton Accumulator

- Machine was constructed 1978-1980 as an "Experiment"

- The UA1 & UA2 were the first Large collaborations and the pioneering pre-cursors to large LEP Expts. & present LHC Expts.

- Machine Design was for 100π Transverse Acceptance 1.5 % in Δp

  Achieved only ~ 80 π in both transverse planes

- Copper Target & Magnetic Horn for pbar collection

  first target was tungsten but was soon replaced by Cu for better yields

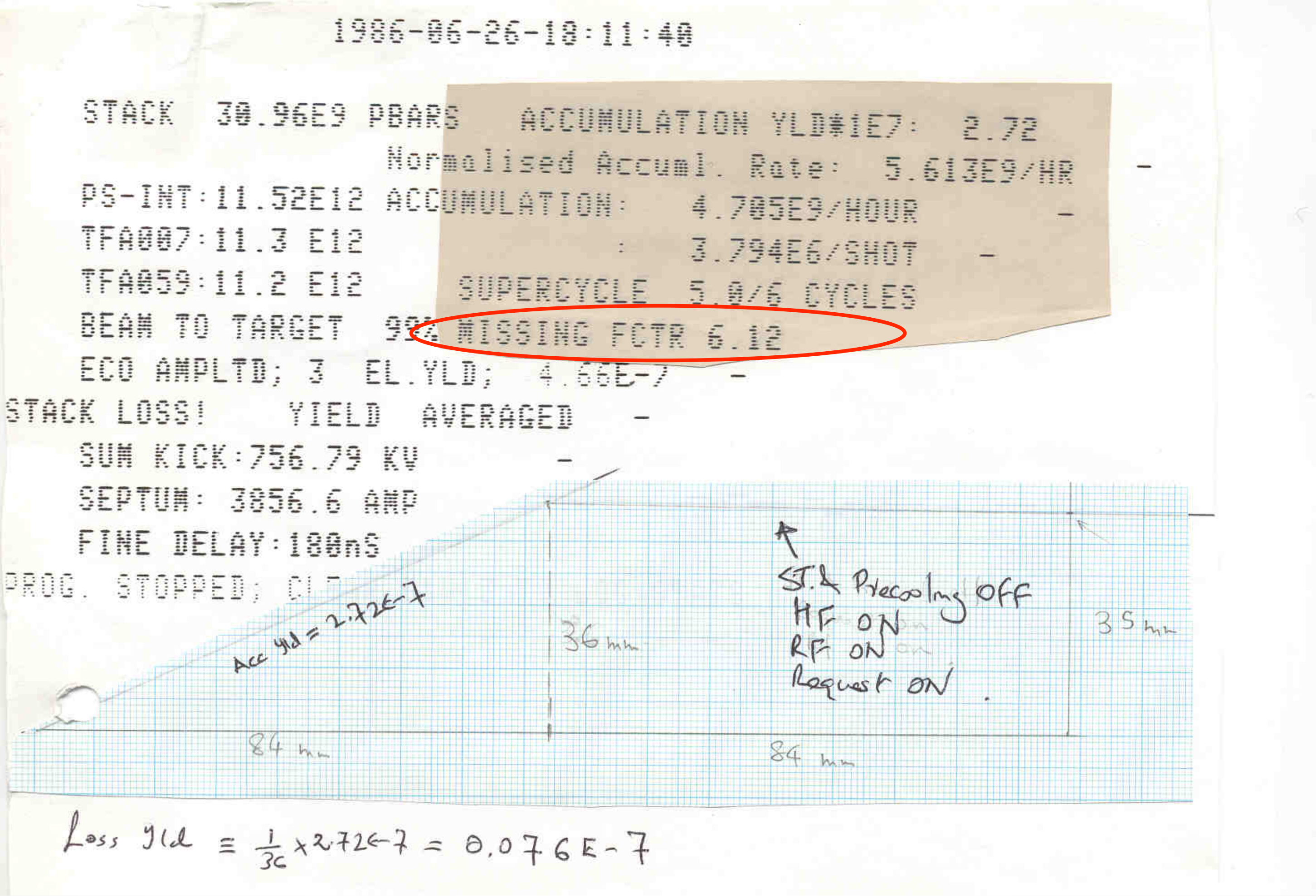
  Operational Yield (pbars per proton) on Inj Orbit ~ 5E-7

  Best Accum. Rate ~ 6 E9 /hr

- Several Stochastic cooling systems (pre-cooling, Stack tail & Core)& multi-functionality within same ring needing pulsed Shutters, interference of systems & limitations in stack Core size

Antiproton Accumulator: key to CERN p-pbar project

The AA before AC & the continued struggle for chasing the “ *Missing Factor* ” (1986)



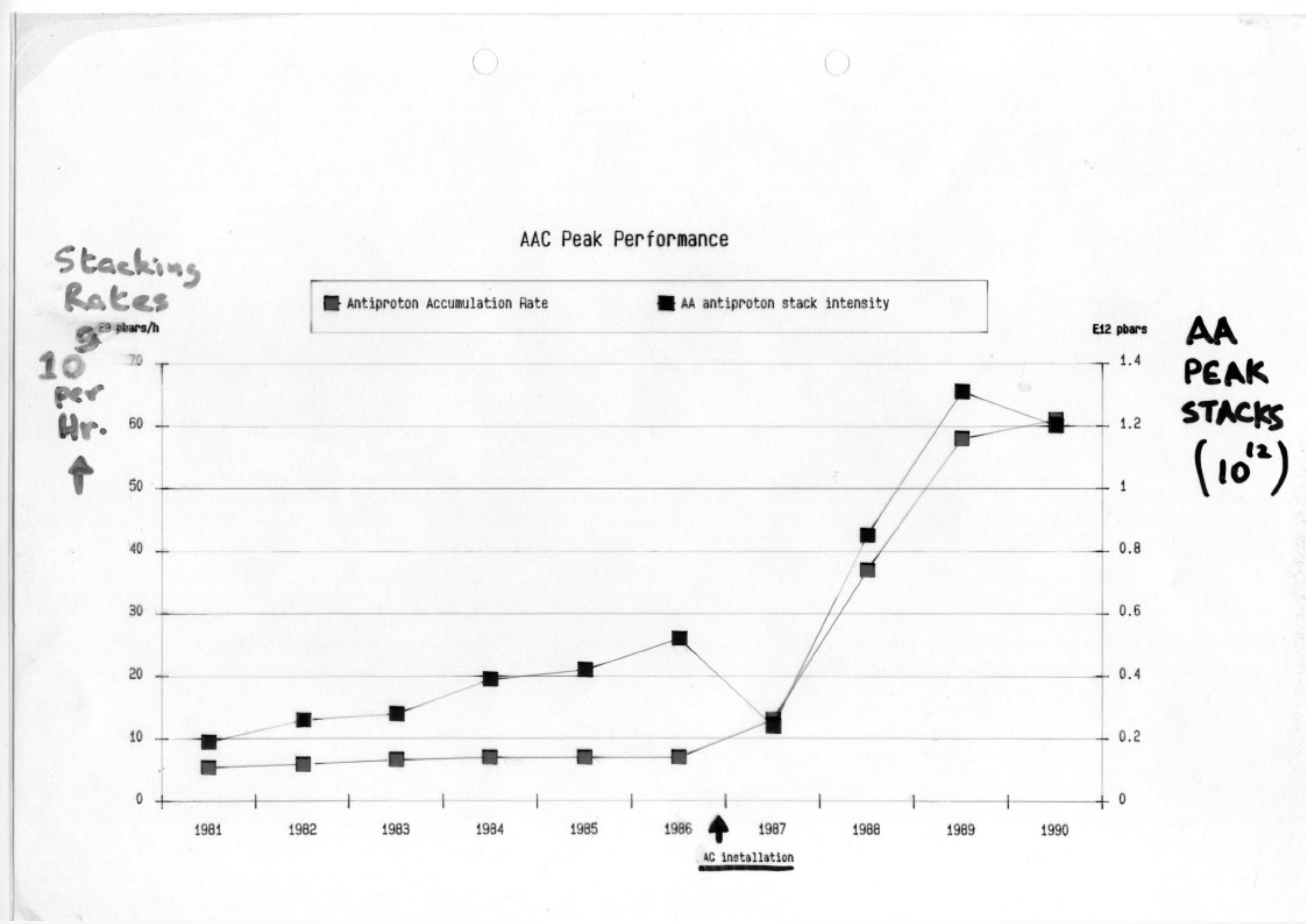
```
                1986-06-26-18:11:40

   STACK  30.96E9 PBARS  ACCUMULATION YLD*1E7:  2.72
                  Normalised Accuml. Rate:  5.613E9/HR   -
   PS-INT:11.52E12 ACCUMULATION:   4.705E9/HOUR          -
   TFA007:11.3 E12             :   3.794E6/SHOT    -
   TFA059:11.2 E12    SUPERCYCLE  5.0/6 CYCLES
   BEAM TO TARGET  99% MISSING FCTR 6.12
   ECO AMPLTD; 3  EL.YLD;  4.66E-7    -
STACK LOSS!    YIELD  AVERAGED   -
   SUM KICK:756.79 KV        -
   SEPTUM: 3856.6 AMP
   FINE DELAY:180nS
PROG. STOPPED; CL
```

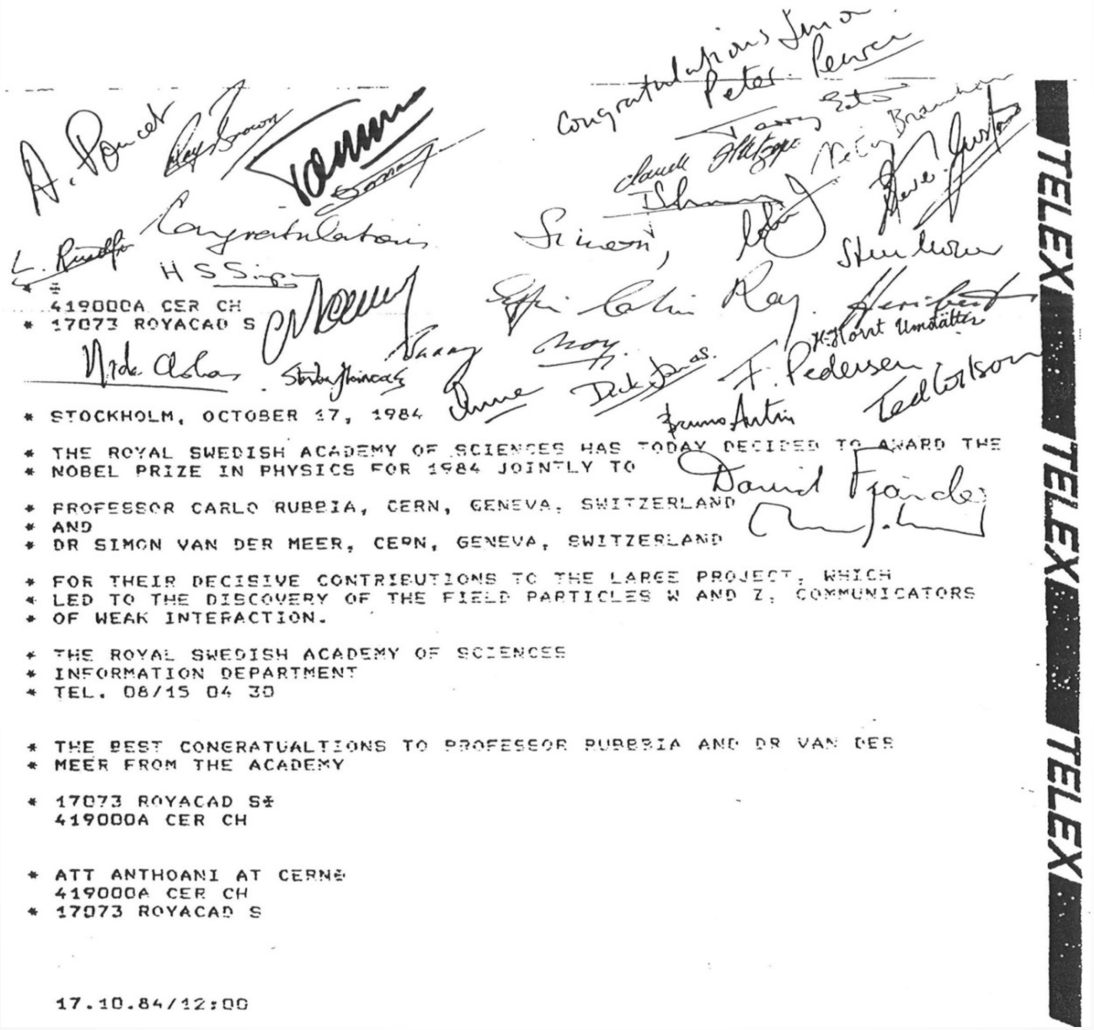
Loss yld $\equiv \frac{1}{36} \times 2.72E-7 = 0.076E-7$

From AA to [AA+AC] : 1981-1991

Stacking Rates & Peak Stacks



Discovery of the W & Z and Nobel Prize



A. Poncet

Congratulations

H S Singh

Congratulations Simon

Peter

Simon,

Steve

Colin

Ray

F. Pedersen

Ted Wilson

Bruno Autin

David

```
*
 419000A CER CH
* 17073 ROYACAD S

* STOCKHOLM, OCTOBER 17, 1984

* THE ROYAL SWEDISH ACADEMY OF SCIENCES HAS TODAY DECIDED TO AWARD THE
* NOBEL PRIZE IN PHYSICS FOR 1984 JOINTLY TO

* PROFESSOR CARLO RUBBIA, CERN, GENEVA, SWITZERLAND
* AND
* DR SIMON VAN DER MEER, CERN, GENEVA, SWITZERLAND

* FOR THEIR DECISIVE CONTRIBUTIONS TO THE LARGE PROJECT, WHICH
* LED TO THE DISCOVERY OF THE FIELD PARTICLES W AND Z, COMMUNICATORS
* OF WEAK INTERACTION.

* THE ROYAL SWEDISH ACADEMY OF SCIENCES
* INFORMATION DEPARTMENT
* TEL. 08/15 04 30

* THE BEST CONGRATUALTIONS TO PROFESSOR RUBBIA AND DR VAN DER
* MEER FROM THE ACADEMY

* 17073 ROYACAD S+
  419000A CER CH

* ATT ANTHOANI AT CERN+
  419000A CER CH
* 17073 ROYACAD S

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Quest for more antiprotons for the CERN Collider

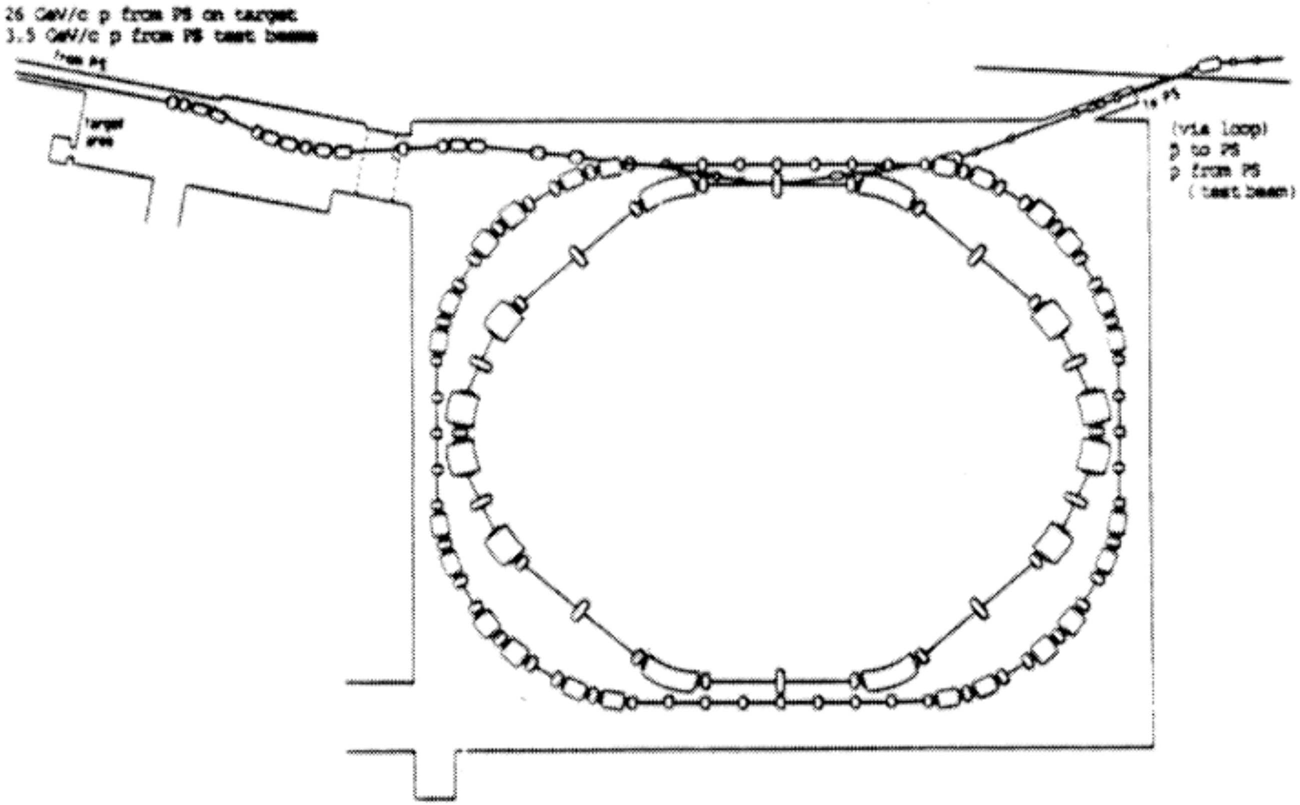


Fig. 1. General layout (magnetic elements only) of the Antiproton Accumulator Complex (AAC): outer ring - Antiproton Collector (AC), inner ring - Antiproton Accumulator (AA).

Towards the Design of the CERN AC Ring 1982-85 & [Dubuncher+Acuumulator] @ FNAL too !

Aim to Increase the Stacking Rate by a factor 10 and hence provide a bigger flux for the Collider Operation (*LEAR was only a 'parasitic' operation*)

How?

Have a Separate Ring(AC-Antiproton Collector) separate some functions (fast pre-collect , debunch & fast pre-cool) and use AA purely for Stack Core Accumulation

Energy Saver/Doubler becomes Tevatron@FNAL 1986

- **1986: The Energy Doubler/Saver working as fixed targert physics machine achieved 900 GeV**

- **1984-86 Construction of Debuncher/Accumulator pbar source**

- **Late 1986:** ***First p-pbar collsions @FNAL with 900 GeV on 900 GeV = 1.8 TeV total energy , hence the name change to Tevatron***

- ***Like the CERN p-pbar SPS Collider , the Tevatron had used the same idea as CERN to convert a single ring into a Collider with protons & antiprotons colliding in the same ring***

Fermilab's Pbar Source machines:AD & AA

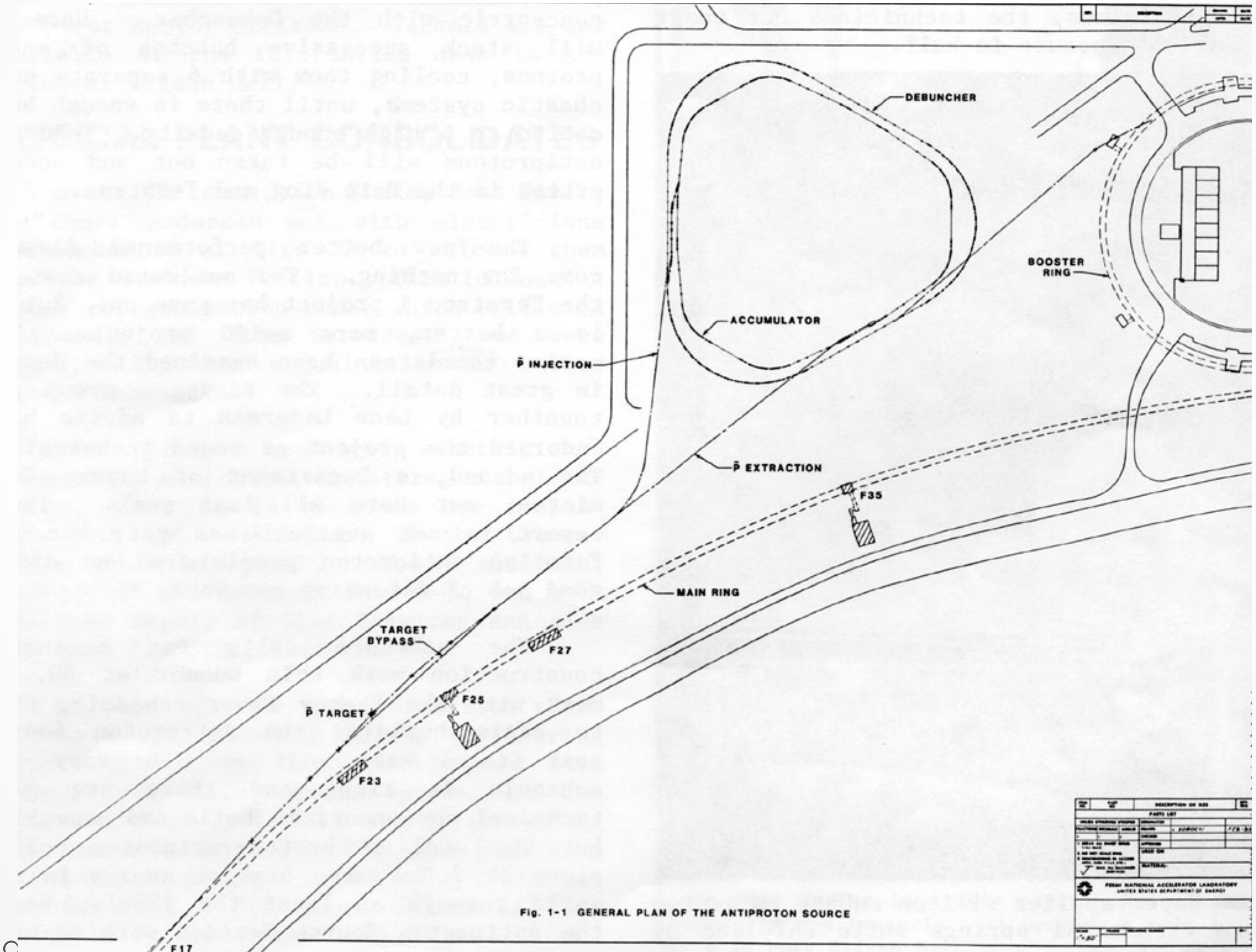
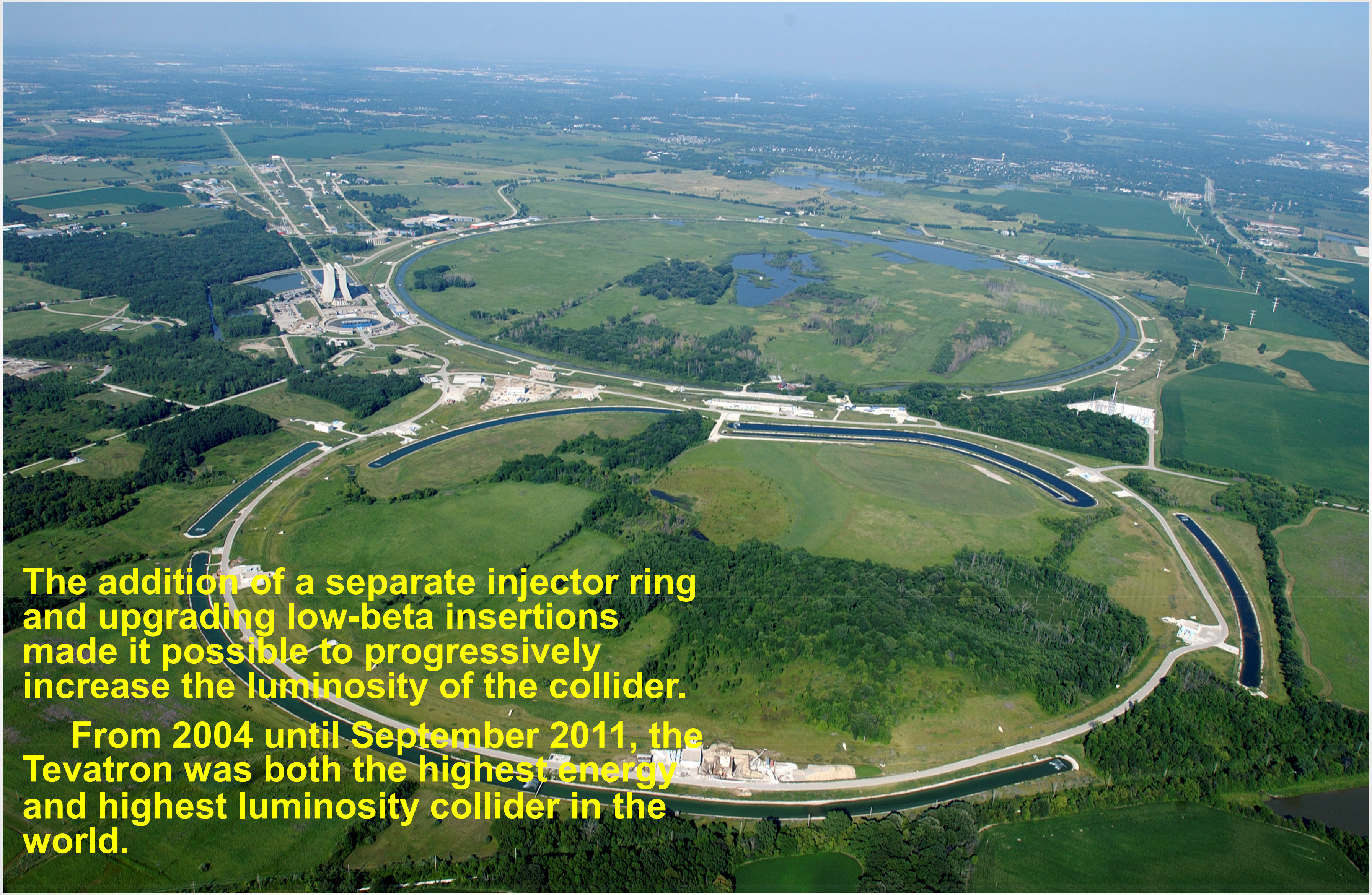


Fig. 1-1 GENERAL PLAN OF THE ANTIPROTON SOURCE

Pbar source & 7 km Tevatron from air

& finally, 1989/90 runs had shown that Top Quark limit was beyond the 315 GeV on 315 GeV collisions at SPS Collider & FNAL had an open field ; Top Quark was discovered in 1995 at the Tevatron

Fermilab and the Tevatron



The addition of a separate injector ring and upgrading low-beta insertions made it possible to progressively increase the luminosity of the collider.

From 2004 until September 2011, the Tevatron was both the highest energy and highest luminosity collider in the world.

Meanwhile …in the eighties

- CERN was also building the 27 km LEP tunnel and LEP machine with the idea of putting a p-p machine in the long run in the same tunnel

Large Electron Positron Ring (LEP)

Design : 1975 – 1981 with iterations

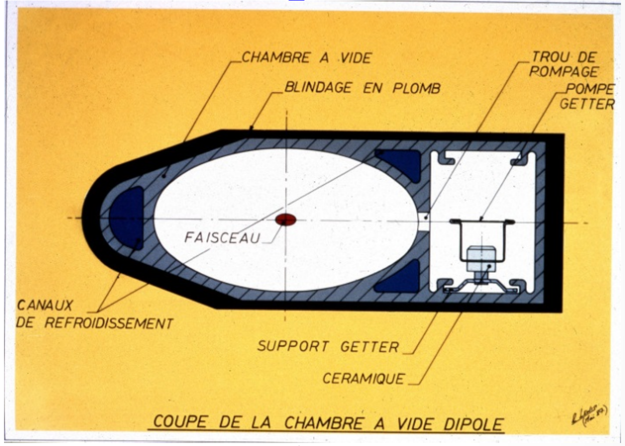
	1977	1978	1979	**1984**
E (GeV)	100	70	86	**55**
2πR (km)	52	22	31	**27**
Experim.	8	8	8	**4**
P_{rf} (MW)	109	74	96	**16**

Choice of site: PS/SPS as injector

Construction: 1982 – 1989

Operation: 89-95 (Z_0), 95-00($> Z_0$), 1997 W-threshold

Technical challenges: **Vacuum**:



Dipole magnets: low B > concrete-steel magnets (steel filling 27%) > B reproducible, cheap and rigid

RF system: 350 MHz Cu cavities 1.5 MV/m, storage cavities for $P_{rf}\downarrow$ by 1.4; 1 MW tubes. LEP 1 (Z_0): $V_{rf} = 0.4$ GV

The proper particle for the proper scope

Electrons (and positrons) are (so far) point like particles: no internal structure

The energy of the collider, namely two times the energy of the beam colliding is totally transferred into the collision

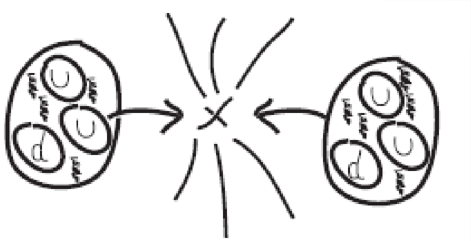
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

Pros: the energy can be precisely tuned to scan for example, a mass region

Precision measurement (LEP)

Cons: above a certain energy is no more convenient to use electron because of too high synchrotron radiation

Protons (and antiprotons) are formed by quarks (uud) kept together by gluons



The energy of each beam is carried by the proton constituents, and it is not the entire proton which collides, but one of his constituent

Ecoll < 2Eb

Pros: with a single energy possible to scan different processes at different energies

Discovery machine (LHC)

Cons:the energy available for the collision is lower than the accelerator energy and there is a large background

Limits of Electron Synchrotrons like the 27 km ring LEP

- Energy(RF) needed to compensate for synchrotron Radiation becomes too large ; more & more RF power

- Electron beam with p = 100 GeV/c in CERN’s 27 km LEP tunnel radiated 20 MW

- Each electron lost about 4GeV per turn, requiring many RF accelerating sections.

Late seventies, Eighties & Nineties and the next Highest energy frontier…

- **ISABELLE** (the **I**ntersecting **S**torage **A**ccelerator + "belle") was to be built at BNL. It was to be a 200+200 GeV proton-proton collider using Superconducting magnets. Construction began in 1978. However there were difficulties in SC magnet development **and the discovery of W & Z at CERN in 1983** did not help ; ISABELLE was **cancelled in July 1983**, Partly to avoid redundancy and partly in the hope of freeing resources for the SSC

- USA wanting to keep the lead after successes of the 'Energy Doubler 'had first proposed the **SSC as early as** 1983.The **SSC** was to be built in Texas with a circumference of 87.1 km and 20 TeV per beam (much bigger and more powerful than the present CERN LHC).

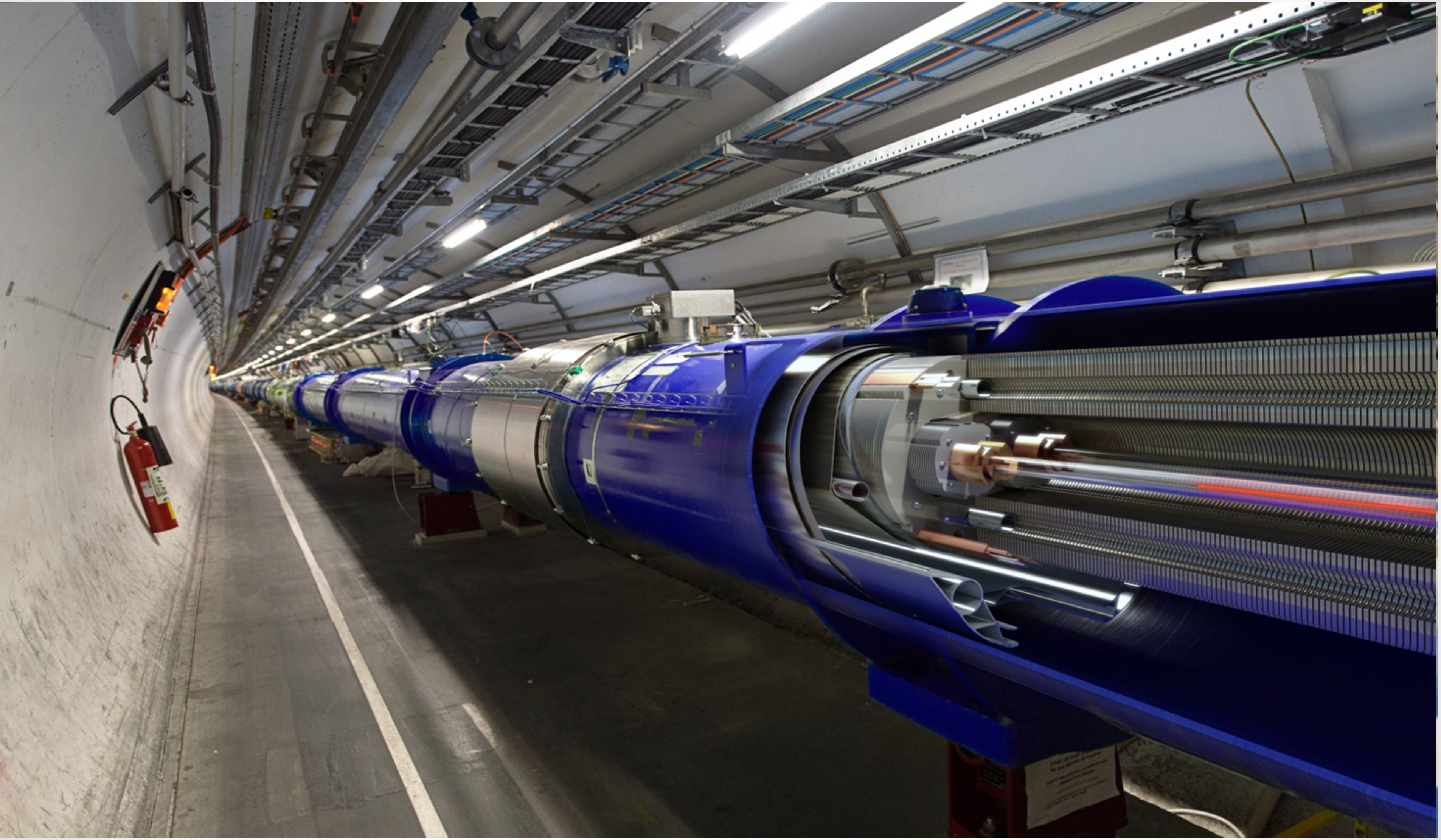
- CERN proposal (1984)was to build a SC Collider **(LHC)** in the existing 27 km LEP tunnel with ~9 Tesla main field giving 7 TeV per beam

- Despite the success of the Tevatron, difficulties were soon being experienced with the **SSC** (Superconducting Super Collider) that was intended as the next-generation, world-beating machine. Unfortunately, the cancellation of ISABELLE (July 1983) served more as a dangerous precedent for the **closure of the SSC**(1993)

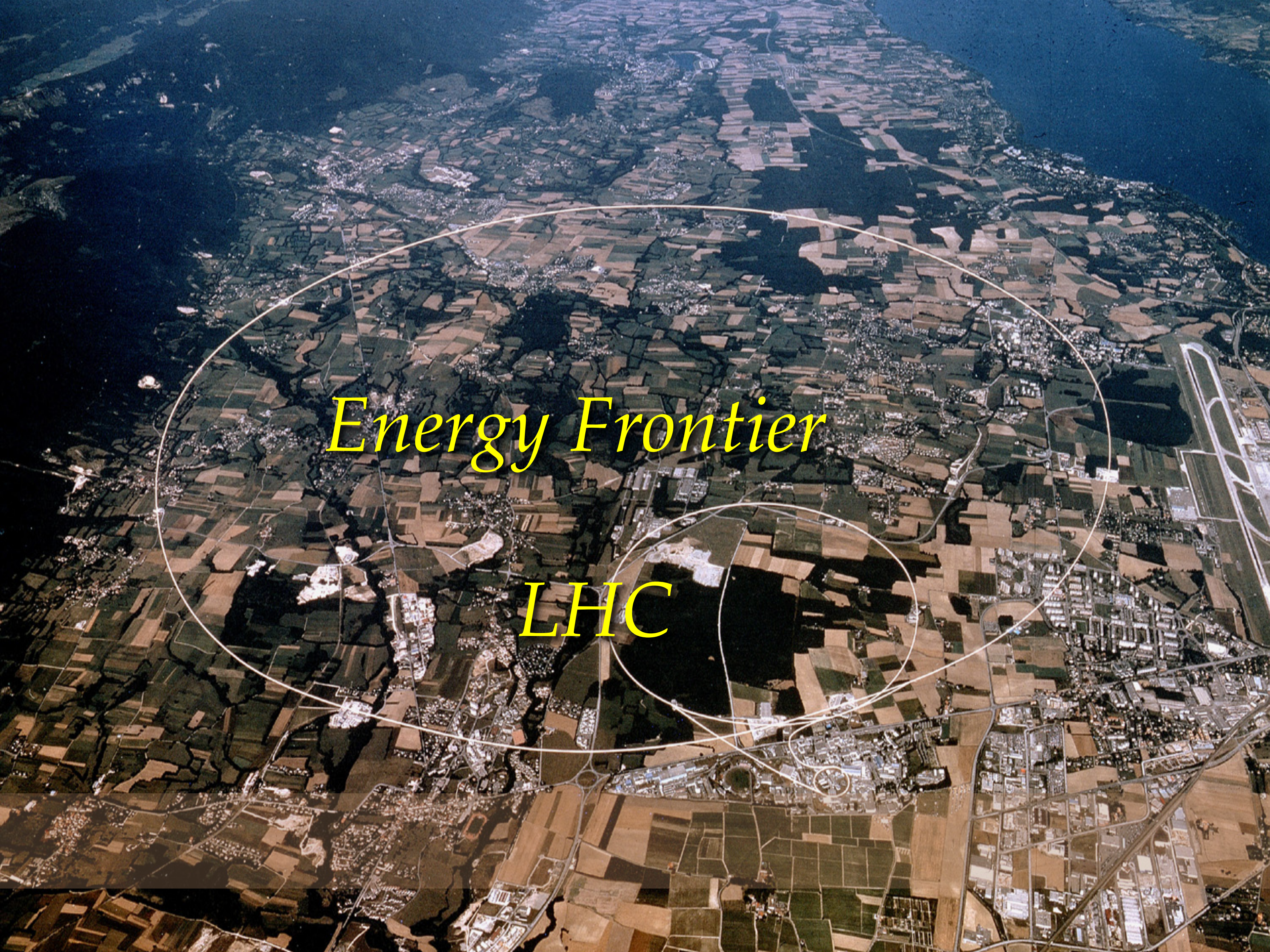
- **With the cancellation of the SSC in October 1993 and approval of LHC in 1994, CERN was now leading the world in the construction of the highest energy machine.**

- *Remark: The complications /scarcity of antiprotons meant that hadron colliders of next generation had to be 'proton-on-proton' as mentioned in LHC Pink Design Report **1991***

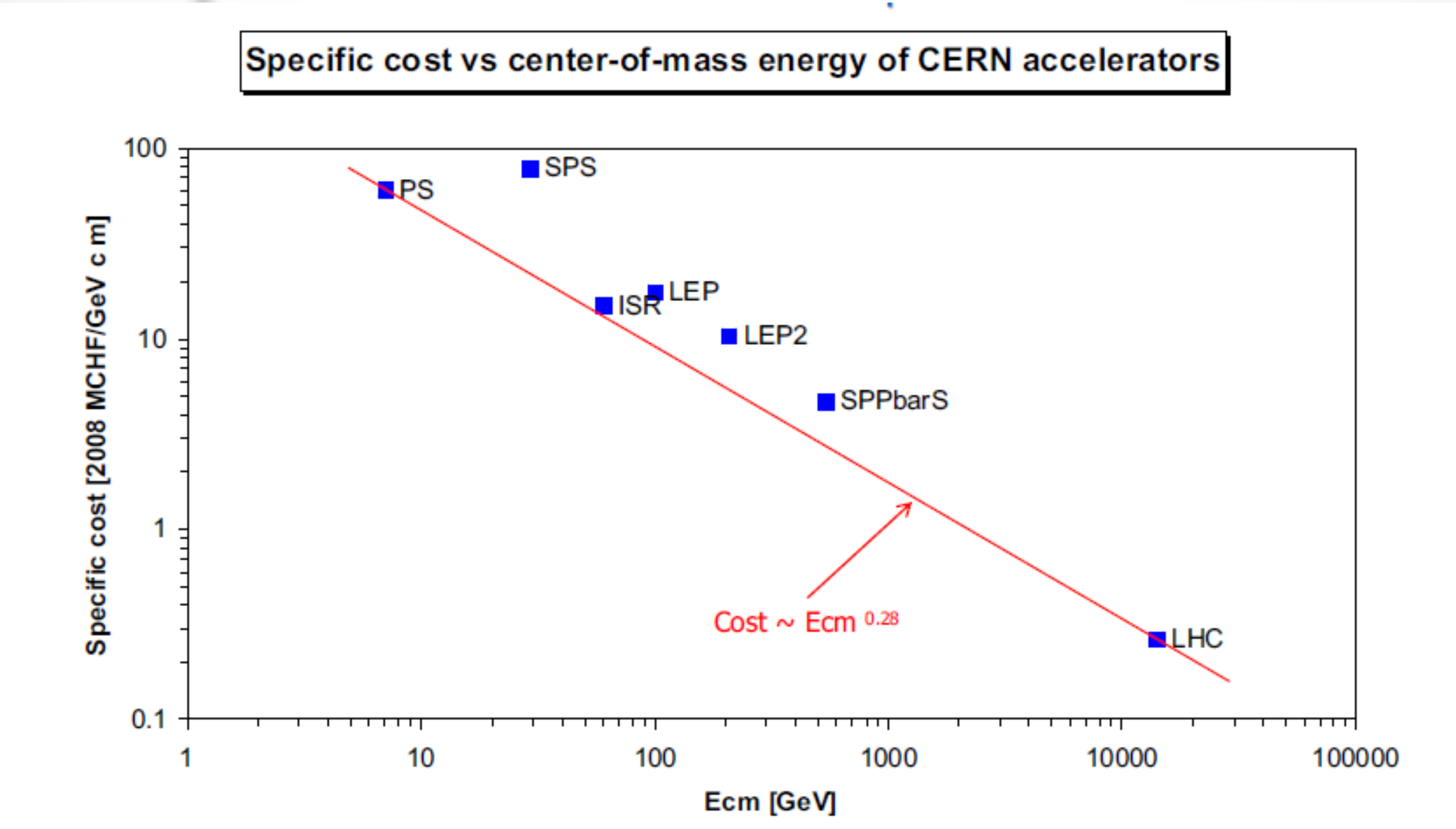
From LEP to LHC in the same tunnel… !



Energy Frontier



Sustained Decrease in specific costs *[Ph. Lebrun,2011]*



The long road to the LHC

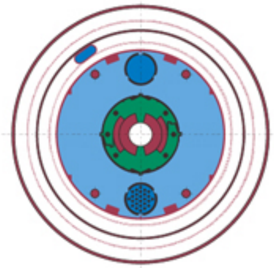
- It is generally accepted that the birth of the LHC was at the Lausanne Workshop in March 1984 where particle physicists and machine builders got together for the first time
- In reality, the seeds were sown much earlier.

- The word **Hadron** was used to imply ***either proton-proton or proton-antiproton collisions***

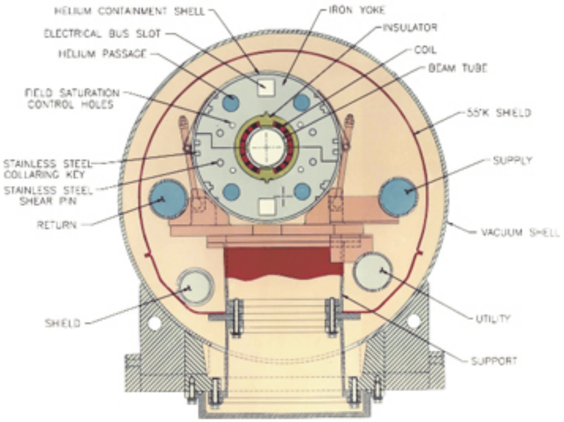
The dipole historical outlook

DIPOLE MAGNETS

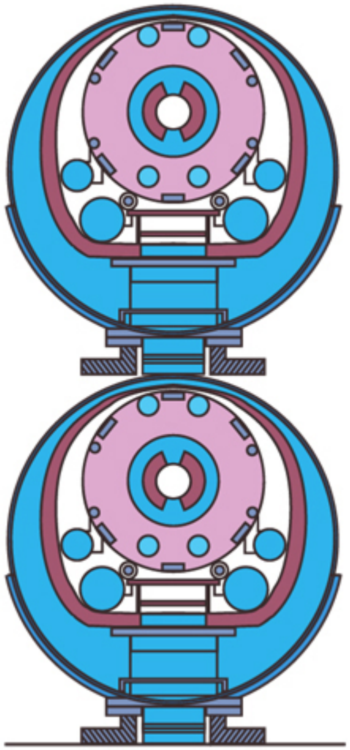
SSC :TWO-ring Collider



HERA
B = 4.7 T
BORE : 75 mm

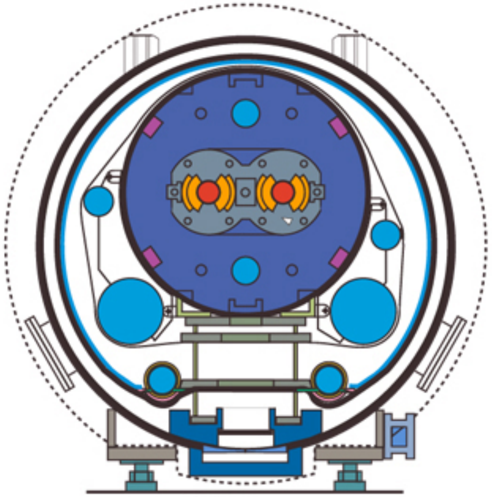


RHIC
B = 3.5 T
Bore : 80 mm



SSC
B = 6.6 T
Bore : 50-50 mm

TEVATRON
B = 4.5 T
Bore : 76 mm



LHC
B = 8.3 T
Bore : 56 mm

LHC:two-in-one machine

CERN AC - HE 109 RHIC 2001/09/20

Highest bending field in 27 km existing tunnel

- *LHC Example :*
- *based on fact that 27 km LEP tunnel was existing*
- *arcs about 23 km so, circle radius ~3500 metres*

With **B ~ 8.4 Tesla one could design a lattice with**
ρ =2803 m & giving **T= 7 TeV per beam**

8.4 Tesla meant superconducting magnets in 27 km tunnel

Conversely, Protons with T = 20 TeV , B = 6.8 T required a 87 km SSC tunnel

Large Hadron Collider (LHC): the 3rd generation synchrotron & collider

Parameters:

Proton beam energy: 7 TeV

$L = 1.0 \times 10^{34}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Pb ion beam energy : 2.8 TeV/u

$L = 1.0 \times 10^{27}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

Installed in LEP tunnel

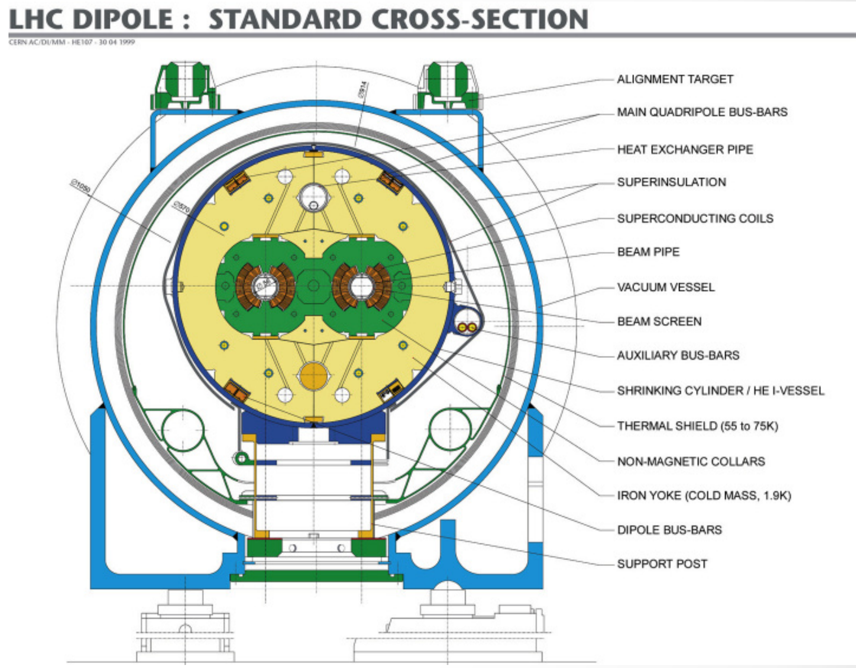
Chronology:

Design: 83 – 94
(considered since mid 70’s)

Approval:

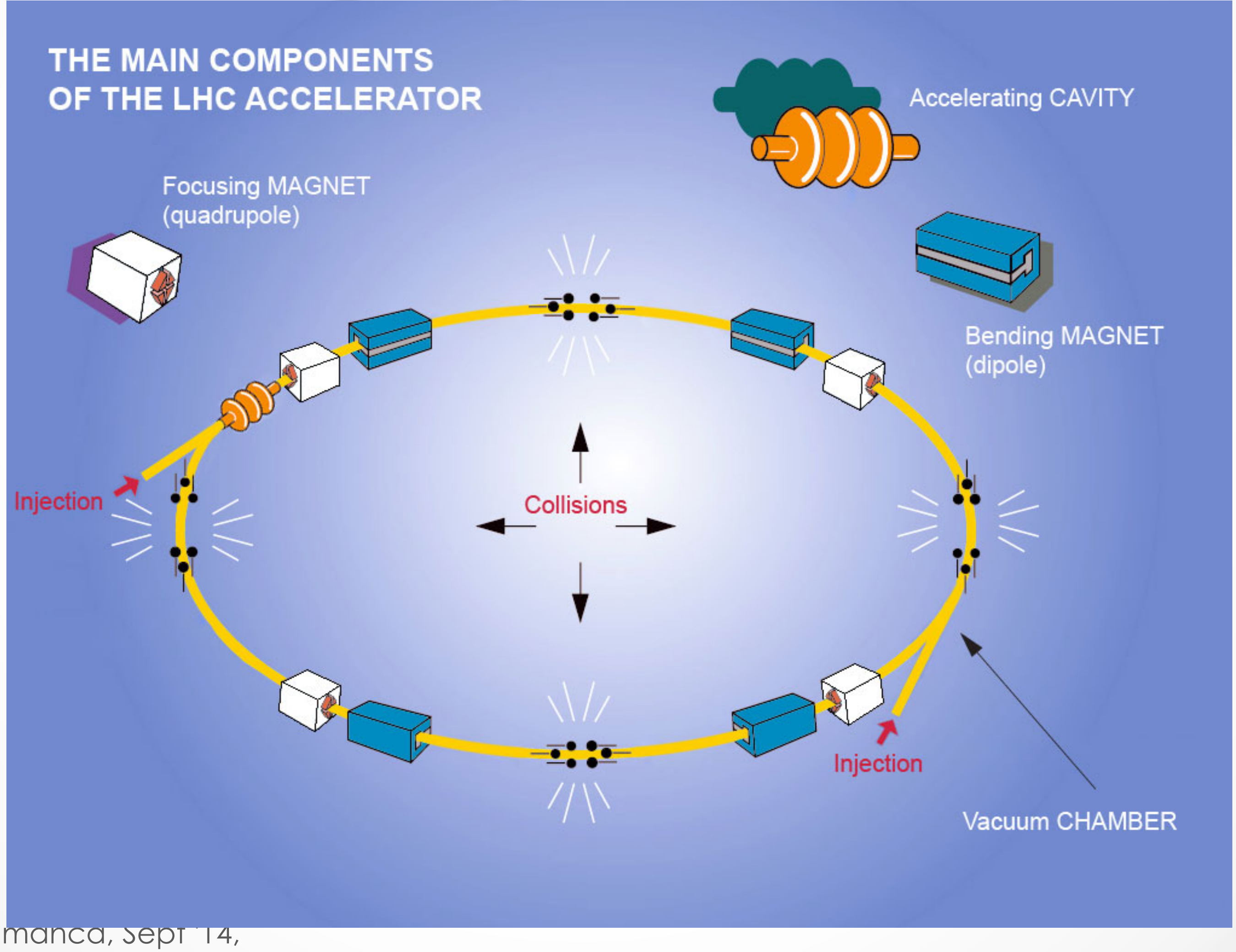
- 94 (two-stages 5 → 7TeV)
- 96 (single stage 7 TeV) with substantial NMS contributions

Operation: 2007 →

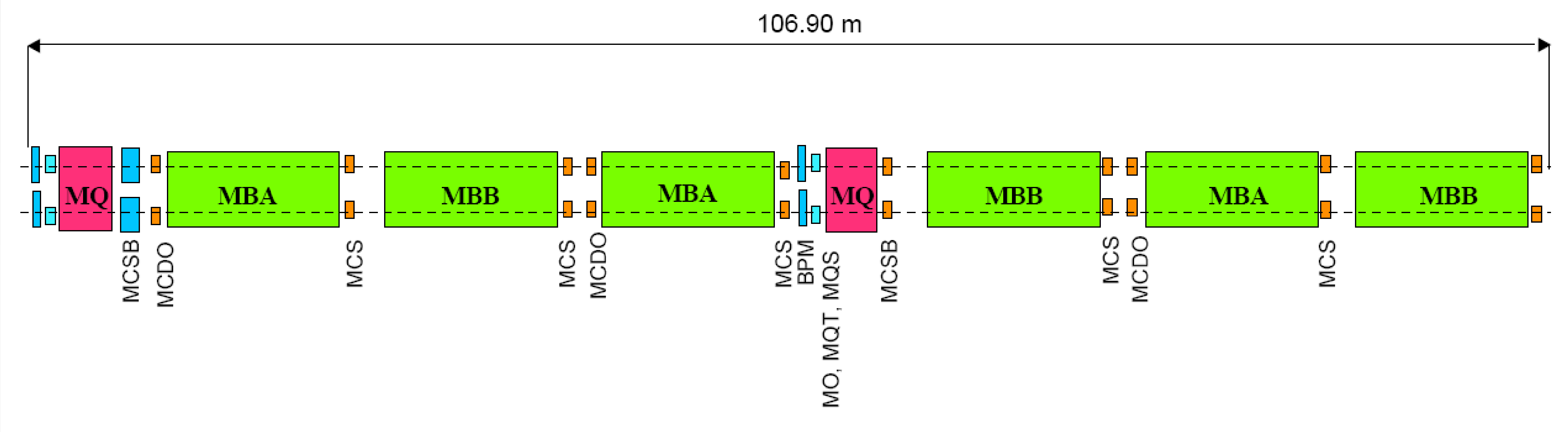


Dipole magnet: B = 8.3 T, 12 kA,
Nb-Ti sc 6-7μm filaments > cables,
1.9 K He II cooling, Δx = 194 mm b-b
cold mass: L = 16.5 m overall, 35 t

LHC main components like any synchrotron !



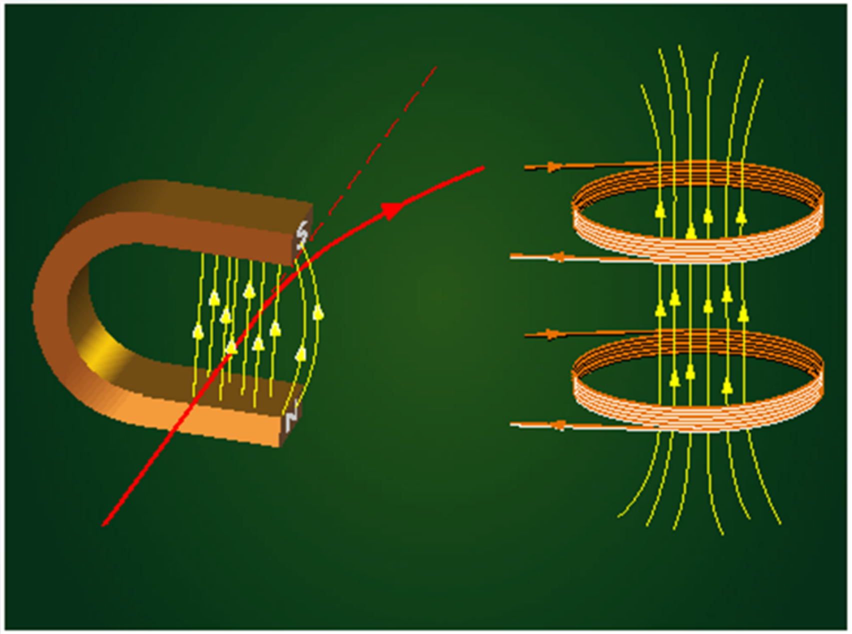
LHC arcs lattice ½ cell structure

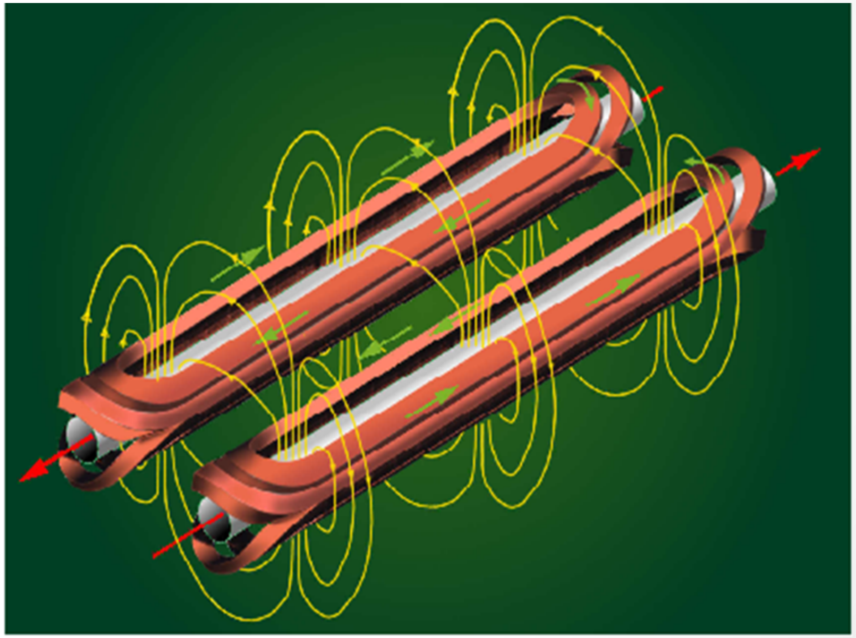


Particle bending in Accelerators

Cyclotrons, Synchrocyclotrons:
fill the magnetic volume with particle orbits

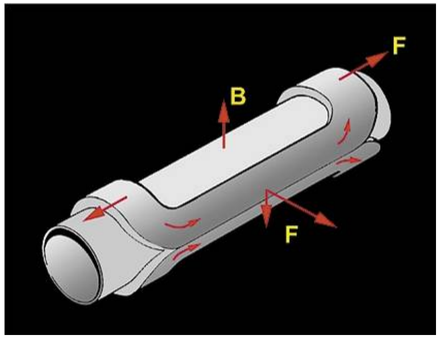
synchrotrons, colliders:
minimum field volume along the beam path

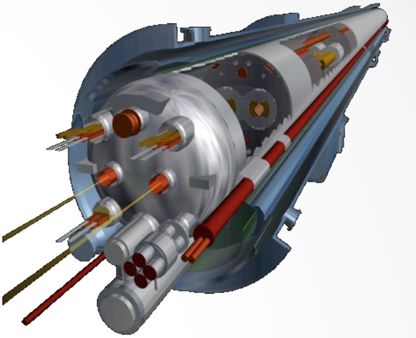




Accelerator magnets issues

- In iron dominated magnets the pole shape dictates field quality
- In superconducting magnets the conductor position dictates the accuracy of the field.
- Coils not self-supporting
- Beam will circulate 500 Millions times in the LHC ! Field accuracy: 10-100 ppm
- Necessity to have all dipoles equal in length within ~ 100 ppm (1.5 mm over 15 m of the LHC dipole length !)



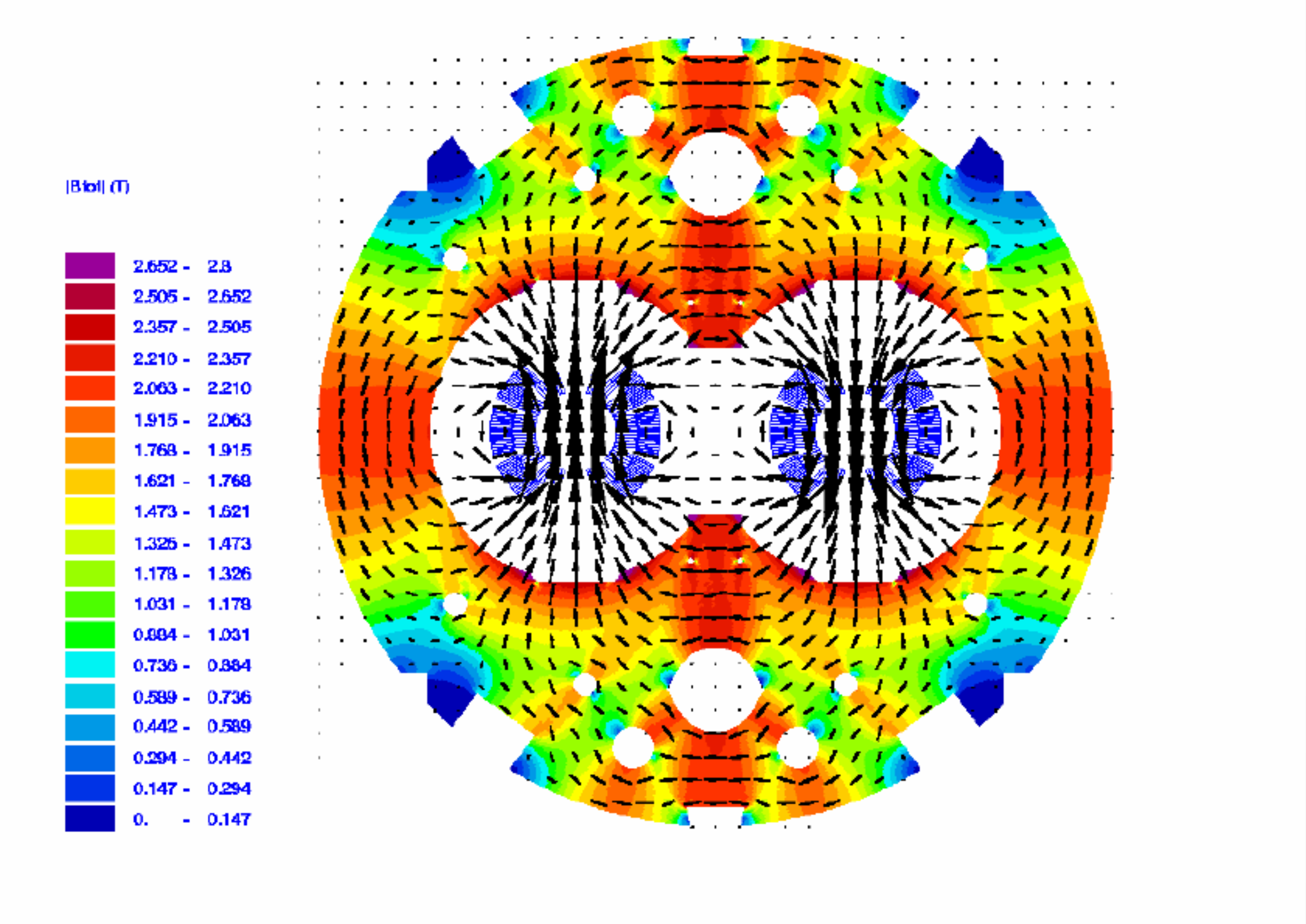


LHC main dipoles

- Quantity: 1232 dipoles ×15 m = 18.5 km
- Operated at same current: 154 circuits
- Extremely high current density: operation 85% of Ic (on load line), little stabilizer to increase J⇒ Training. BUT we cannot train them at long (it costs too much) and **they should not need re-training.**
- After the cool down the **worst magnet determines the energy of the accelerator !.**

Courtesy: L.Rossi

Dipole magnetic flux plot



LHC Challenges

- **Dipoles** : (similar problems for quads)

cable production,

quench protection W_{em}=7 MJ + low T > low heat capacity of cable ,

strong forces (2MN/m per coil quadrant)

- **Cryogenics**:

upgrade 4.5 > 1.9 K LEP refrigerators,

plants and cryo-lines for superfluid He,

deal with quenches : rapid cool-down

- **Vacuum**: for 100 h beam lifetime :

good pumping by 1.9 K cold tube protected from syn.rad 0.2 W/m by beam screen

- **Collimation and beam dumping**

Beam dynamics:

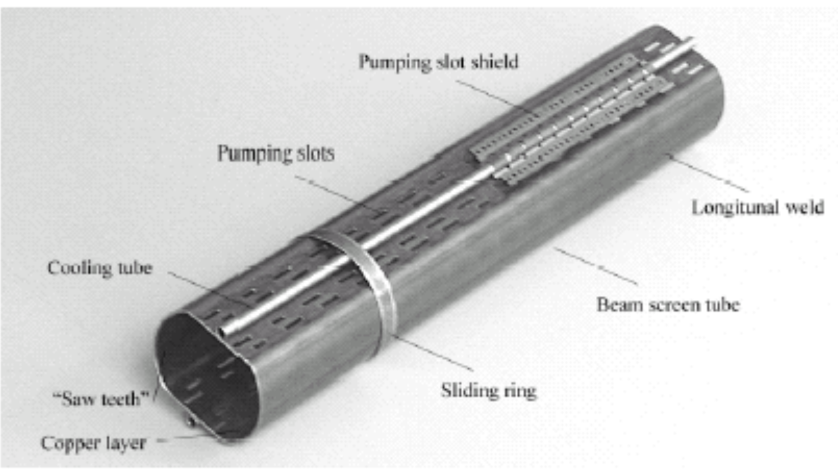
b-b effects in IP and 120 parasitic crossings near IP (2808 bunches)

electron-cloud effects: 25 ns bunch spacing + beam-induced multi-pactor > dense e-clouds >

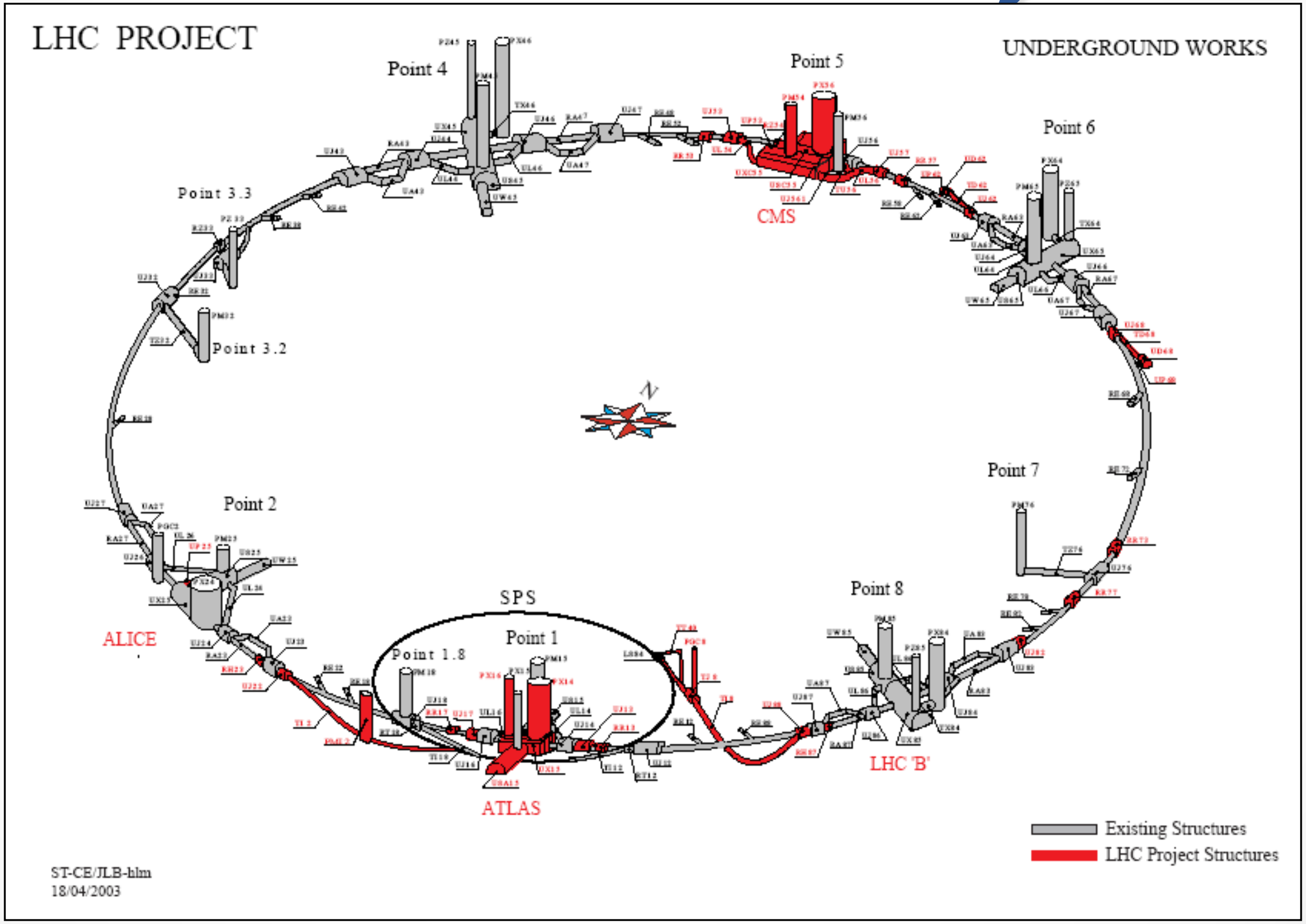
i) heat load on beam screen

ii) beam instabilities

Remedies: sawtooth in chamber, coating, scrubbing with beam.



LHC machine Layout

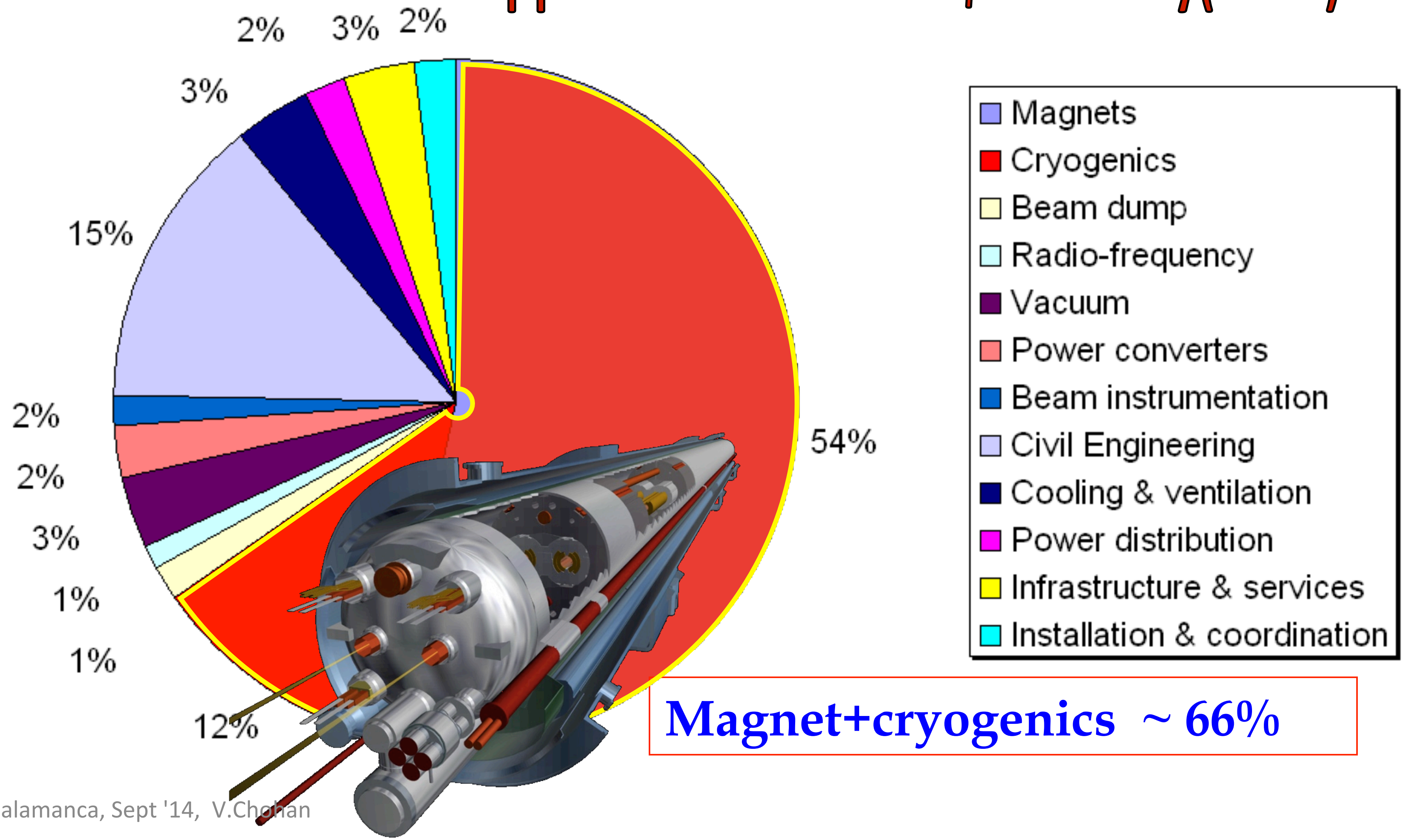


ST-CE/JLB-hlm
18/04/2003

Cost structure of only the LHC Accelerator part

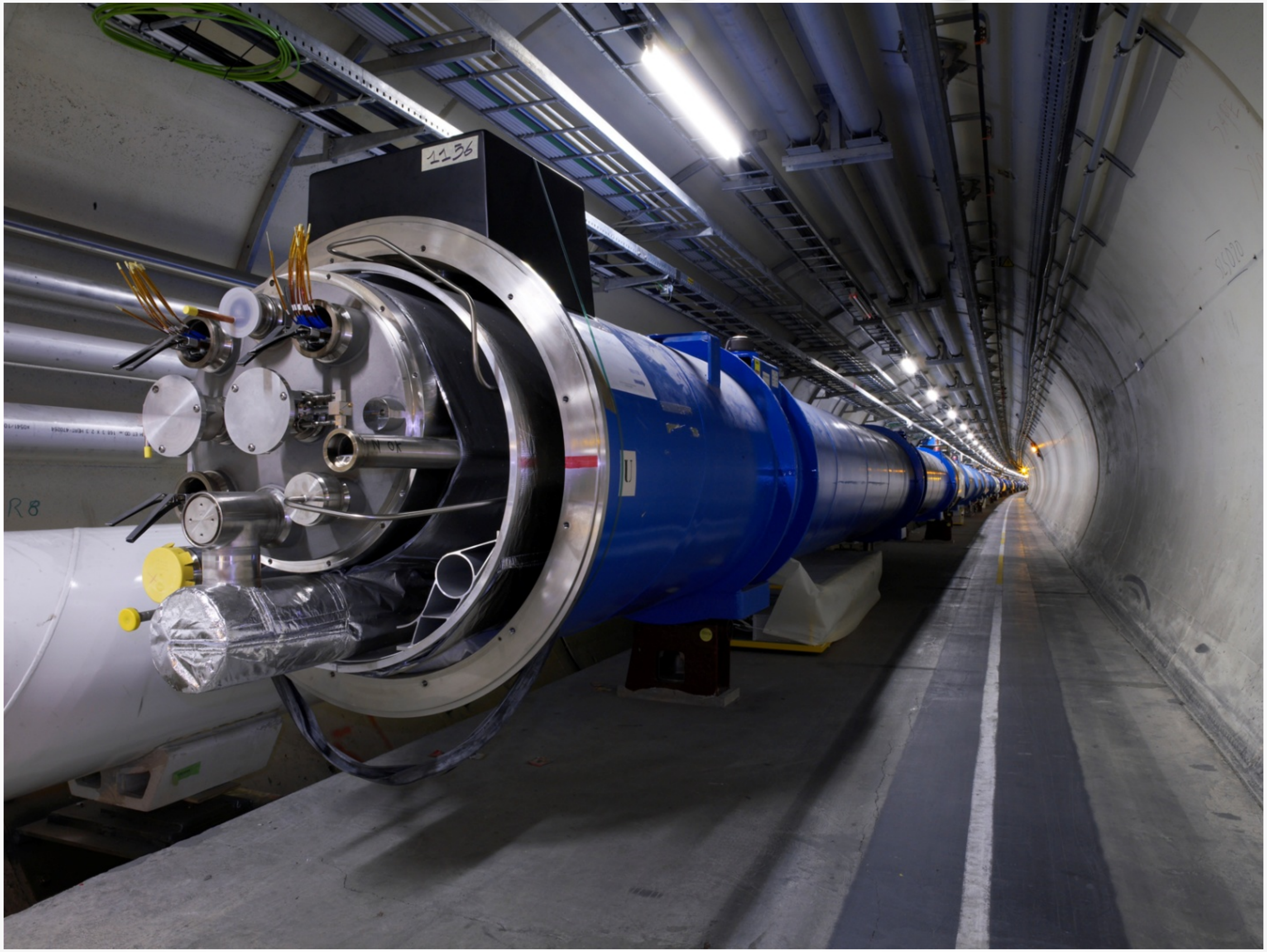
Total material cost ~: 3.3 BCHF

Approx 3.3 Billion US $ of today(2011)



Magnet+cryogenics ~ 66%

LHC Tunnel



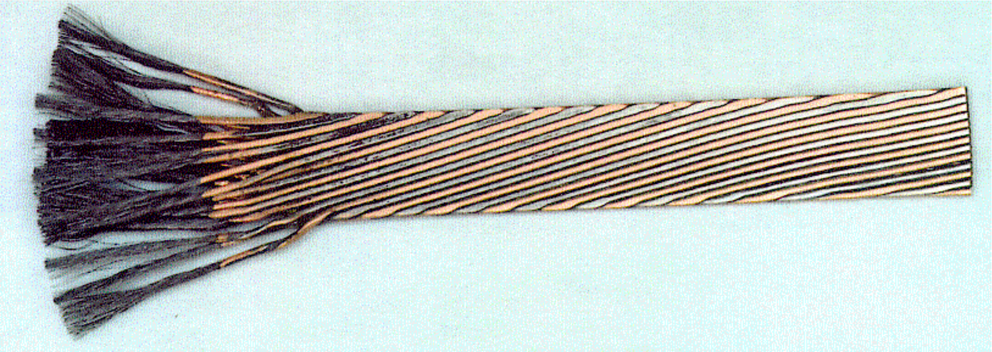
23 km of superconducting magnets

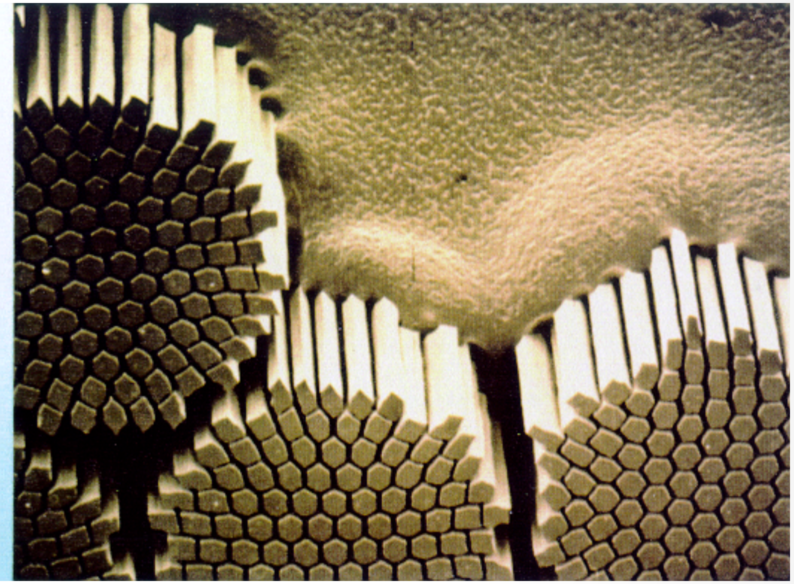
Dipole storage before installation

LHC Superconducting magnets

Type	Number	Function
MB	1232	Main dipoles
MQ	392	Arc quadrupoles
MBX/MBR	16	Separation & recombination dipoles
MSCB	376	Combined chromaticity & closed orbit correctors
MCS	2464	Sextupole correctors for persistent currents at injection
MCDO	1232	Octupole/decapole correctors for persistent currents at injection
MO	336	Landau damping octupoles
MQT/MQTL	248	Tuning quadrupoles
MCB	190	Orbit correction dipoles
MQM	86	Dispersion suppressor & matching section quadrupoles
MQY	24	Enlarged-aperture quadrupoles in insertions
MQX	32	Low-beta insertion quadrupoles

7000 km of superconducting cable Nb-Ti





…implying industrial production…

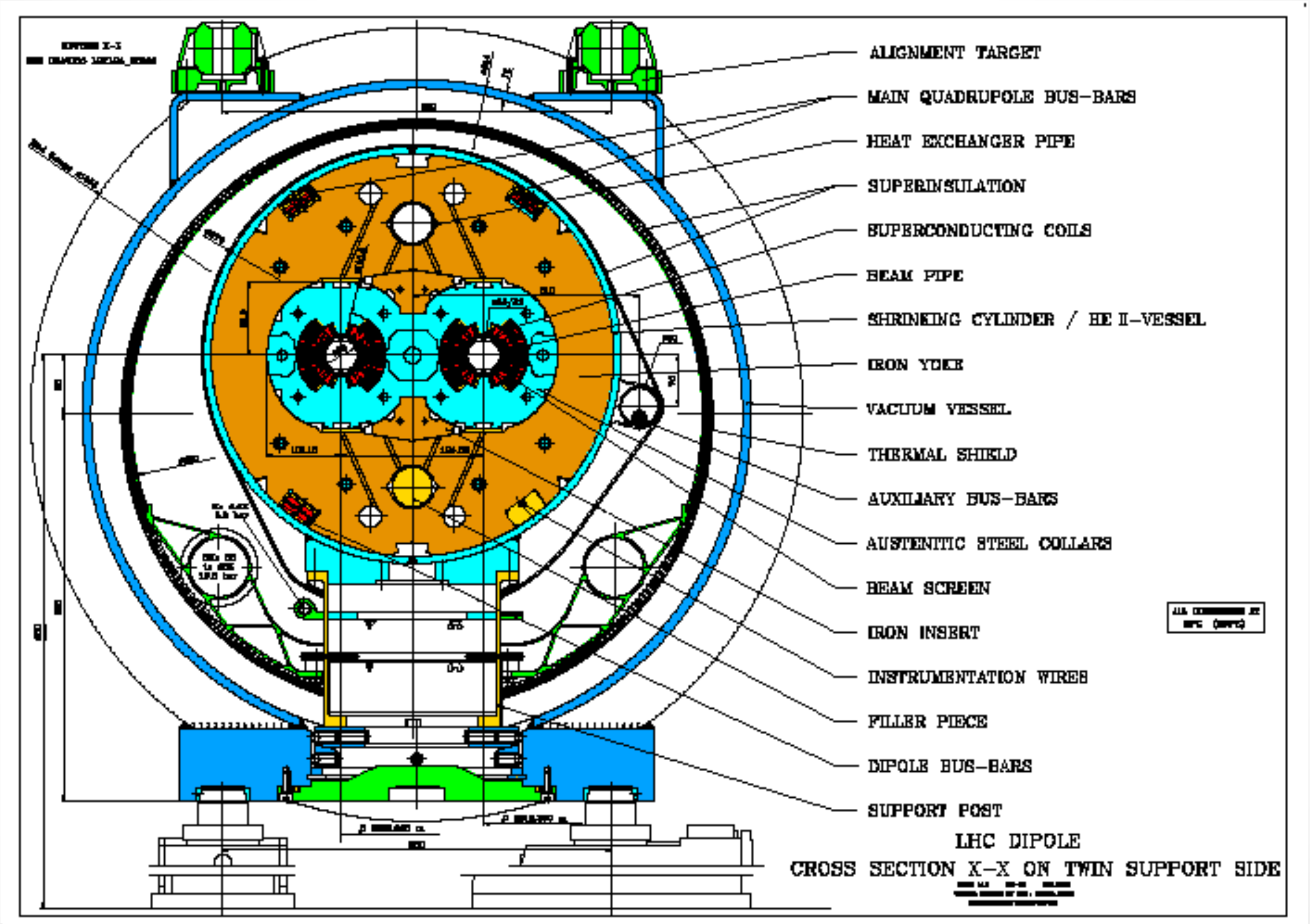
Industrial manufacturing of Dipoles

ALSTOM, NOELL, ANSALDO

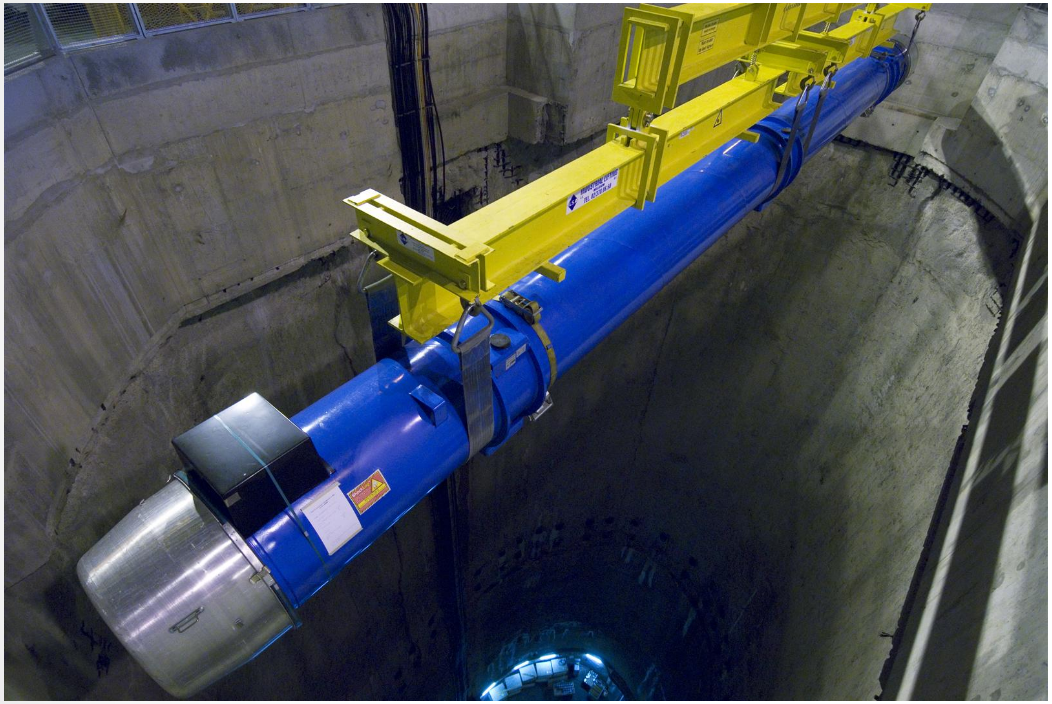
Magnet cryostating at CERN

Cryogenic magnet test benches

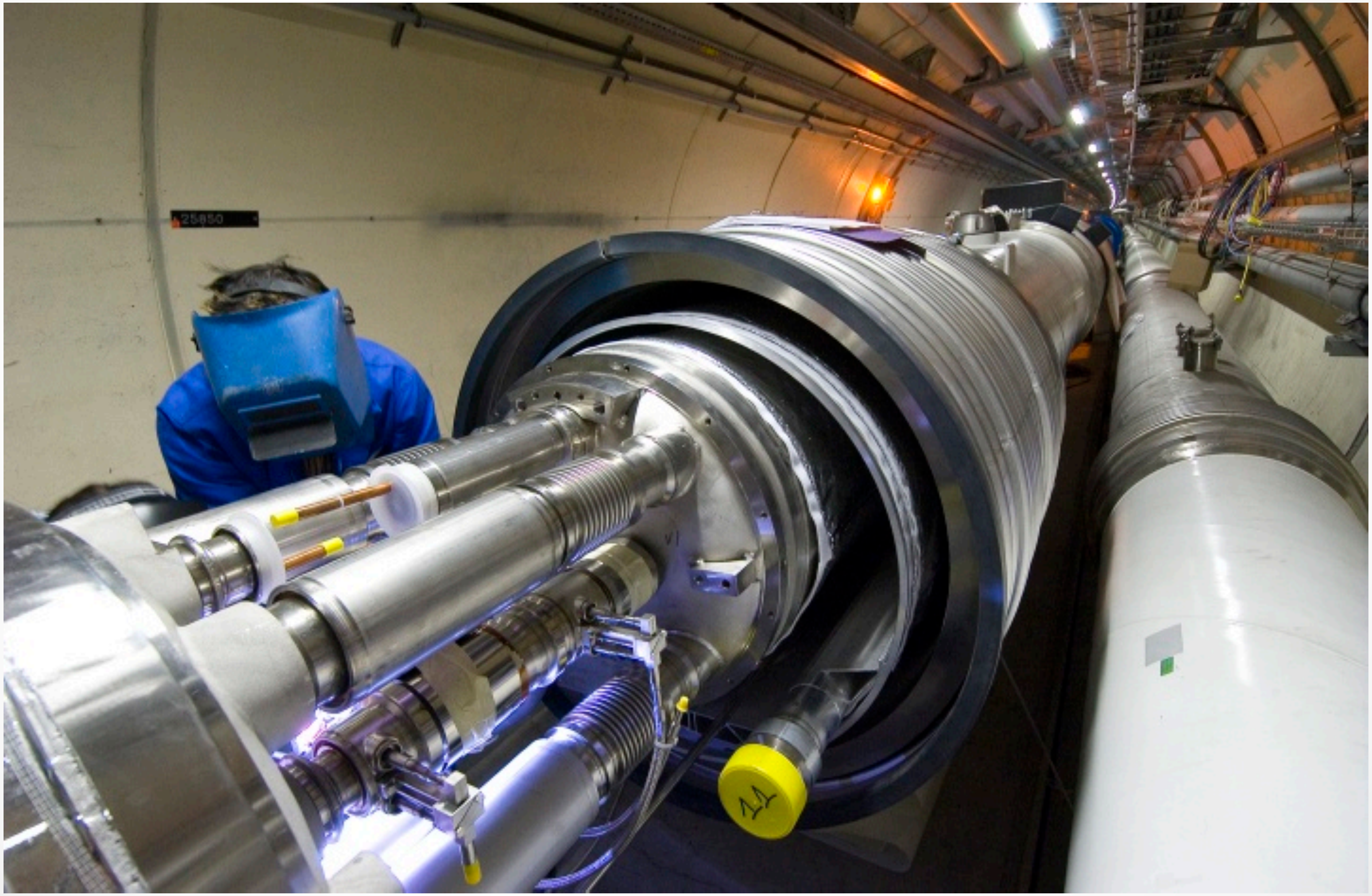
Cryodipole cross-section



Dipole descent into the tunnel

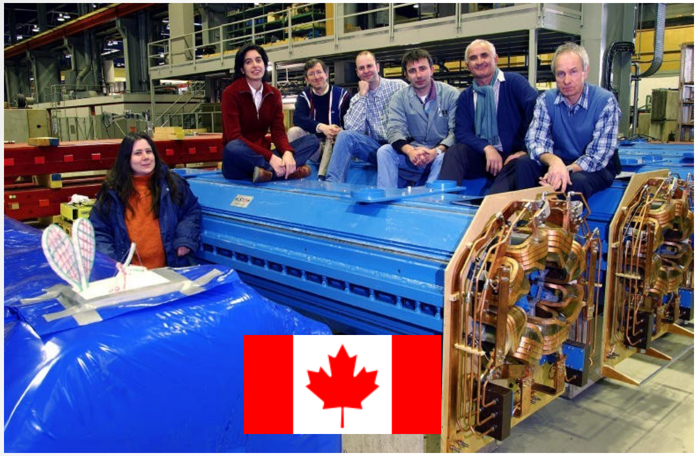


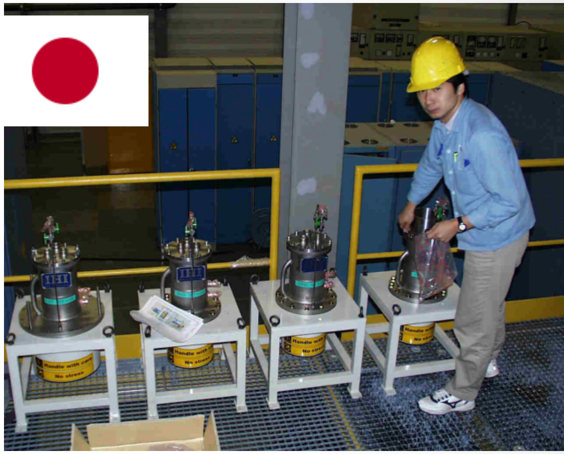
Dipole-Dipole Interconnect

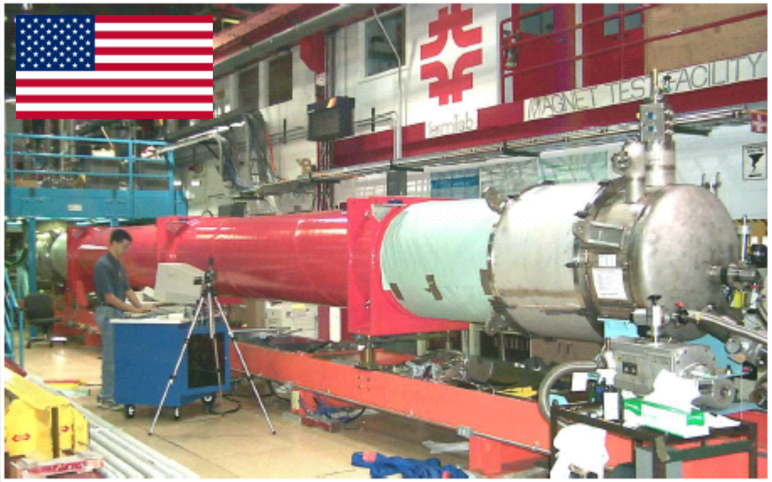


Interconnect Splices

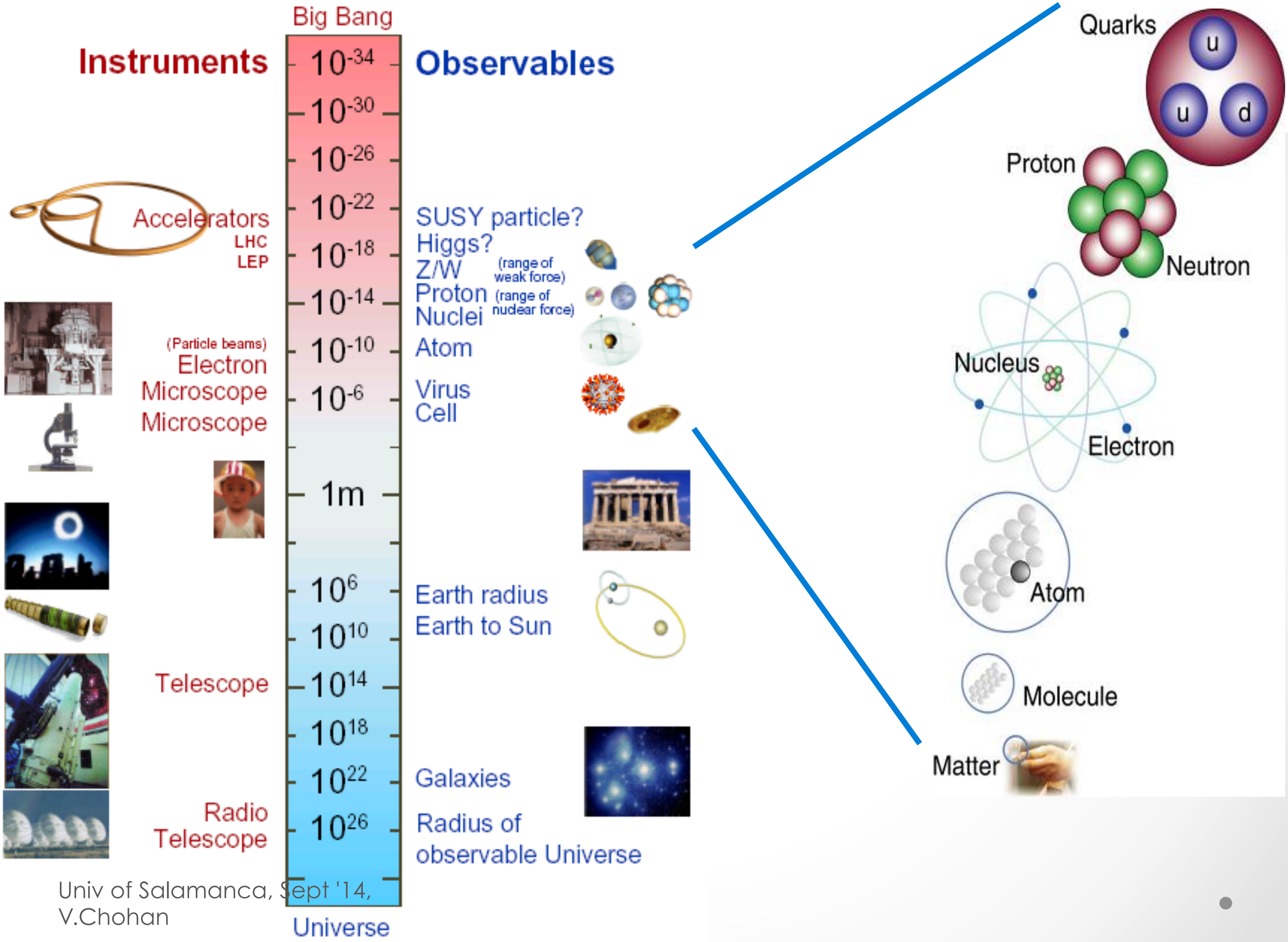
Key Contributors : a global project



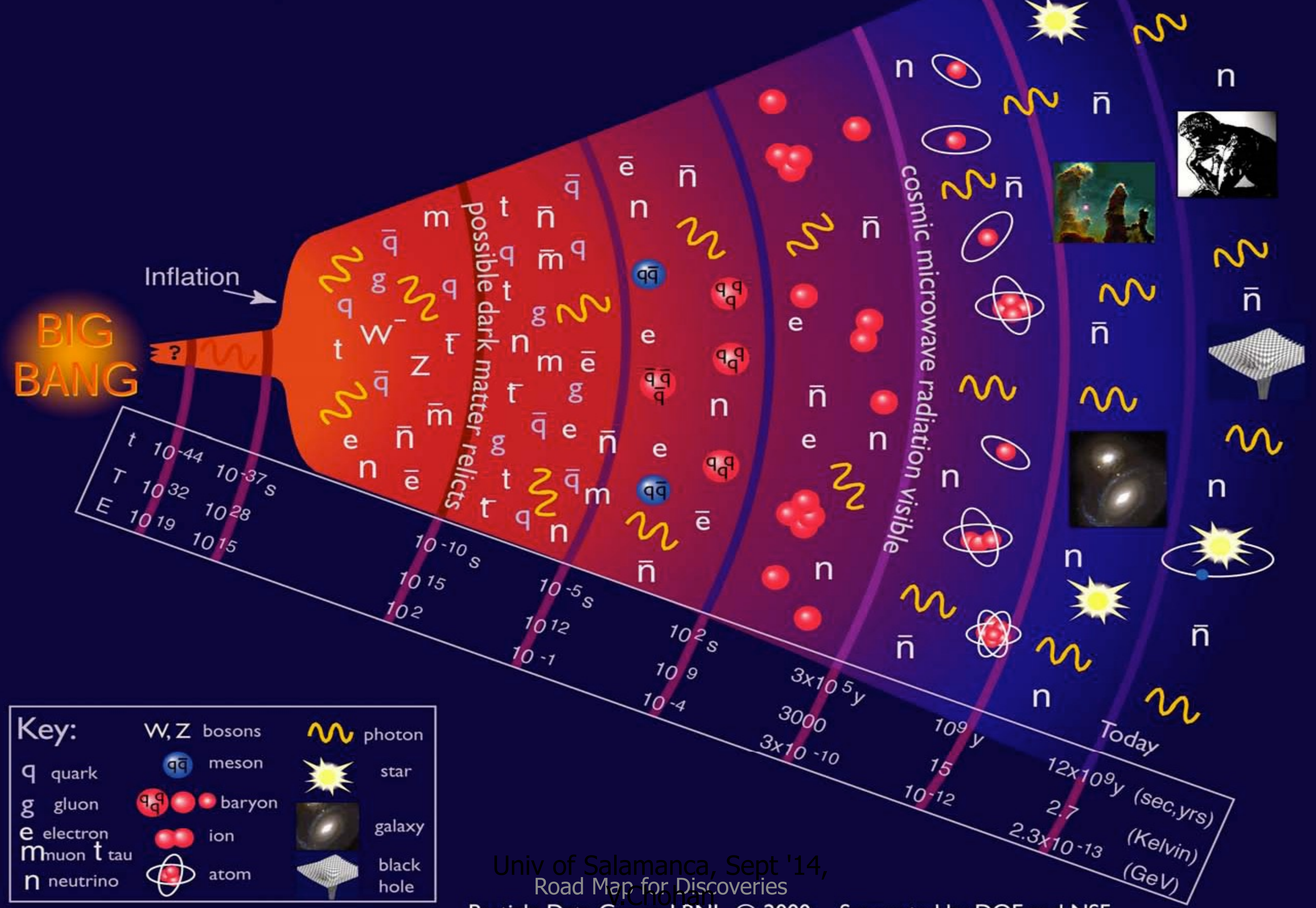




The size of things

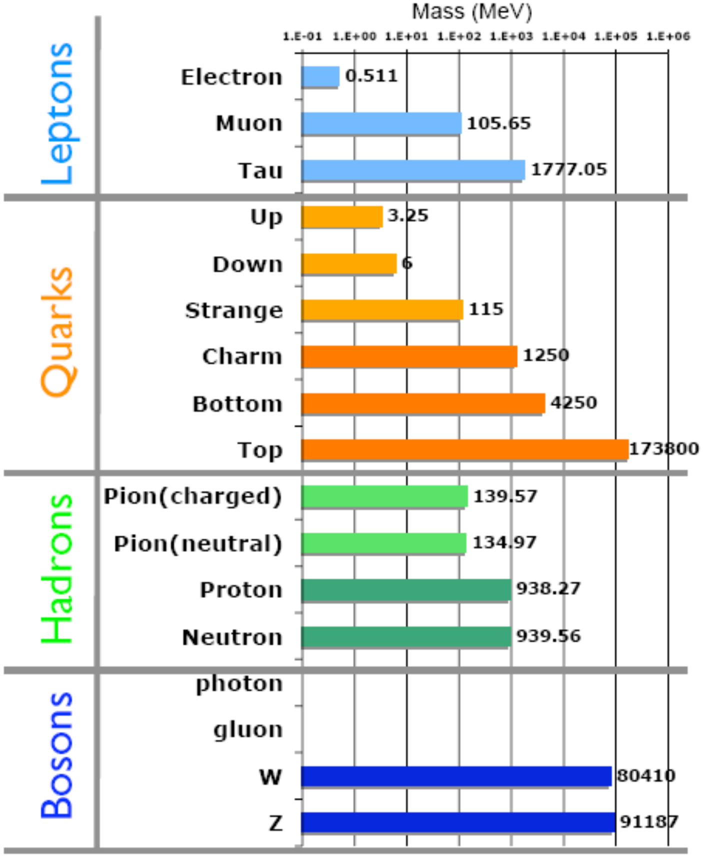


History of the Universe

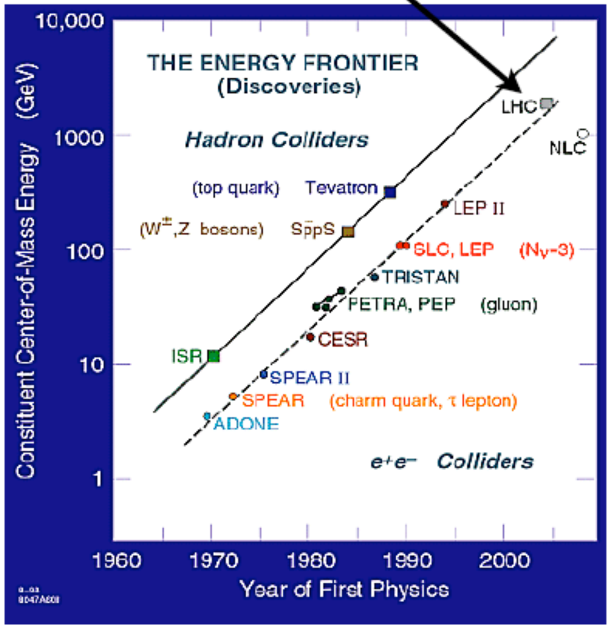


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

History/energy line vs discovery



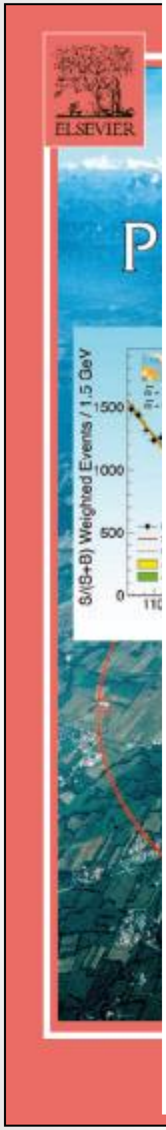
Higgs and super-symmetry ?
Or something else maybe

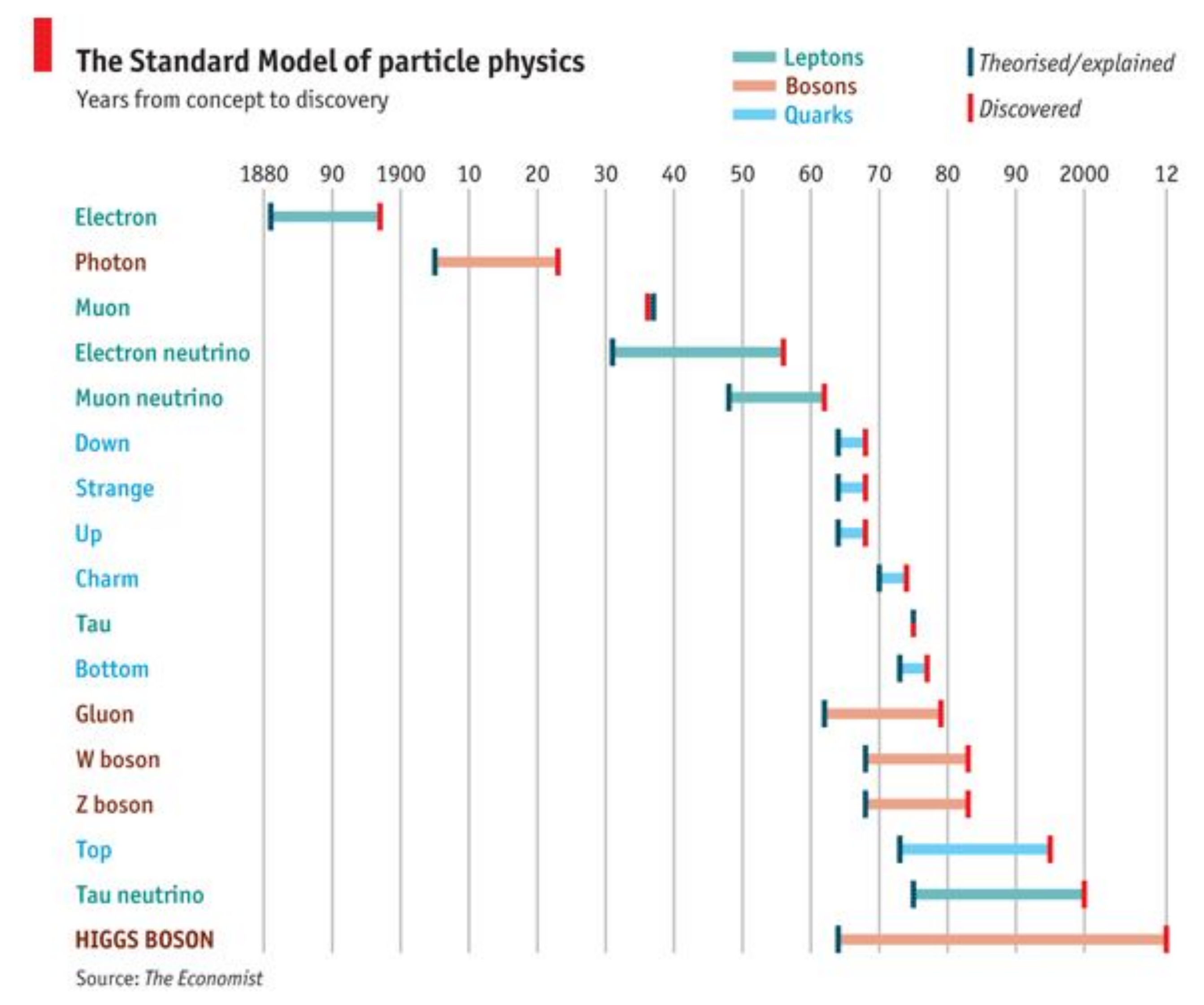


Behind the history plot is hidden the technological development required for each step

Obs: you can notice different particle species used in the different colliders electron-positrons and hadron colliders (either $\bar{p}$-p as Tevratron, p-p as LHC)

Higgs Discovery: highlight of year 2012

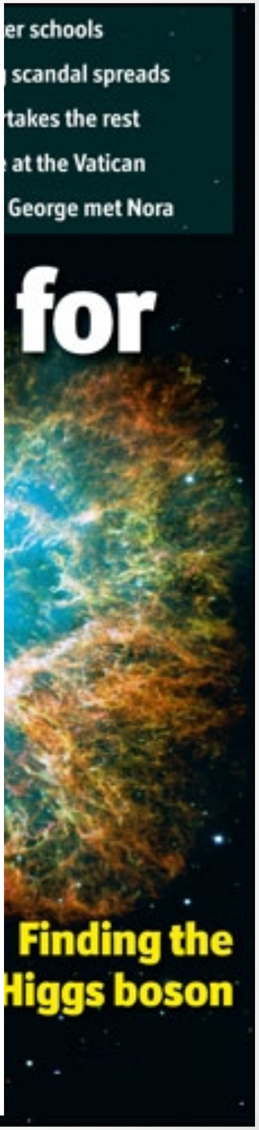




The Standard Model of particle physics

Years from concept to discovery

Source: *The Economist*



LHC and its 4 Experiments are projects of giant scale and international collaboration …

Where we are today…

- *All the currently used accelerating methods were known by the early 1940s and all the circular accelerators' [synchrotron] basic design techniques were known by the 1950s.*

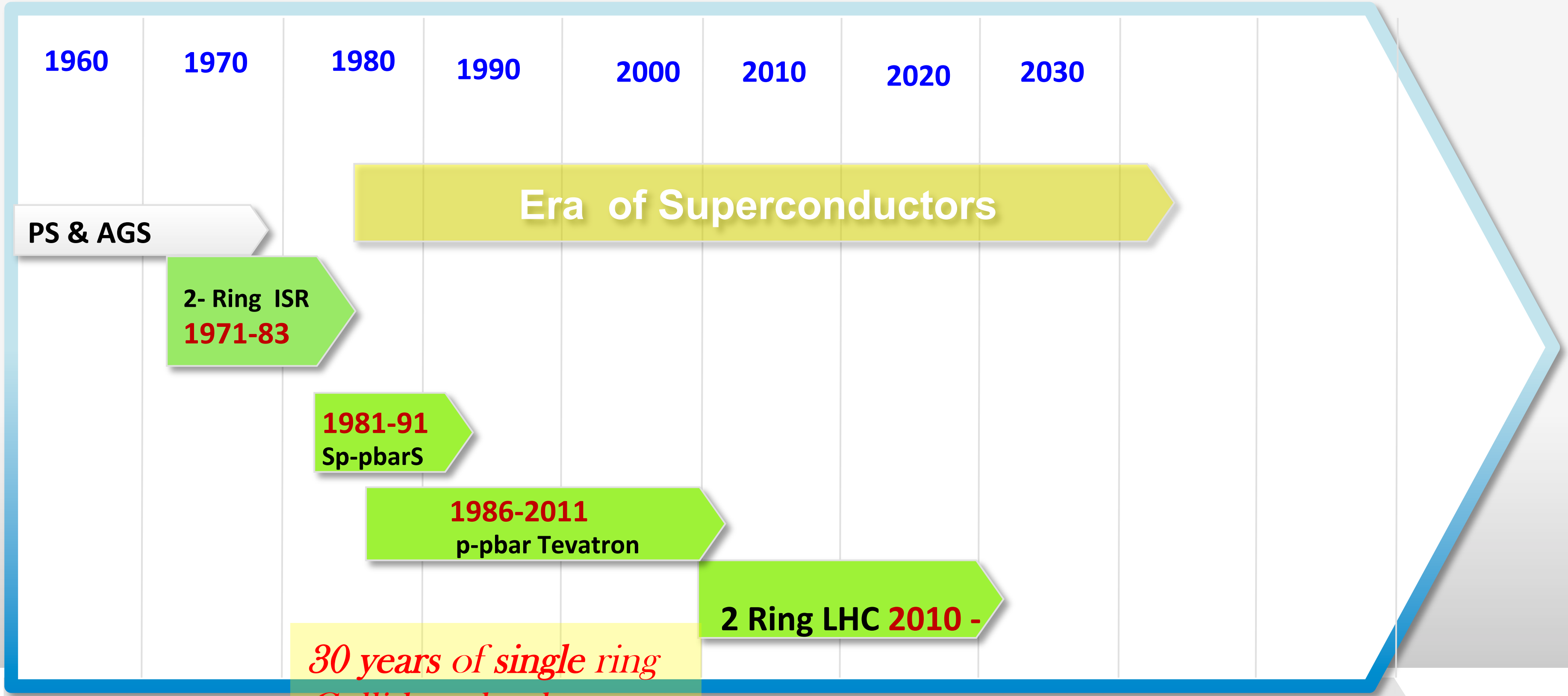
- *Advances in beam energy frontier, emittance and intensity has continued unabated since, thanks to the development of* **Colliders** *and technological progress in* ***superconductivity, new materials, electronics and computing***

- *Like immediately after the WW II, Governments have still continued to support joint-effort laboratories like CERN, funded by multiple countries, even at the expense of cutting country-centred facilities*

- *For large new projects, international collaborations have led the way, not only in physics experiments but also in accelerator development/construction*

TIMELINE : Hadron COLLIDERS as Energy Frontier Machines and Superconductivity

30 of Last ~40 Years p-pbar !



1960 1970 1980 1990 2000 2010 2020 2030

Era of Superconductors

PS & AGS

2- Ring ISR
1971-83

1981-91
Sp-pbarS

1986-2011
p-pbar Tevatron

2 Ring LHC 2010 -

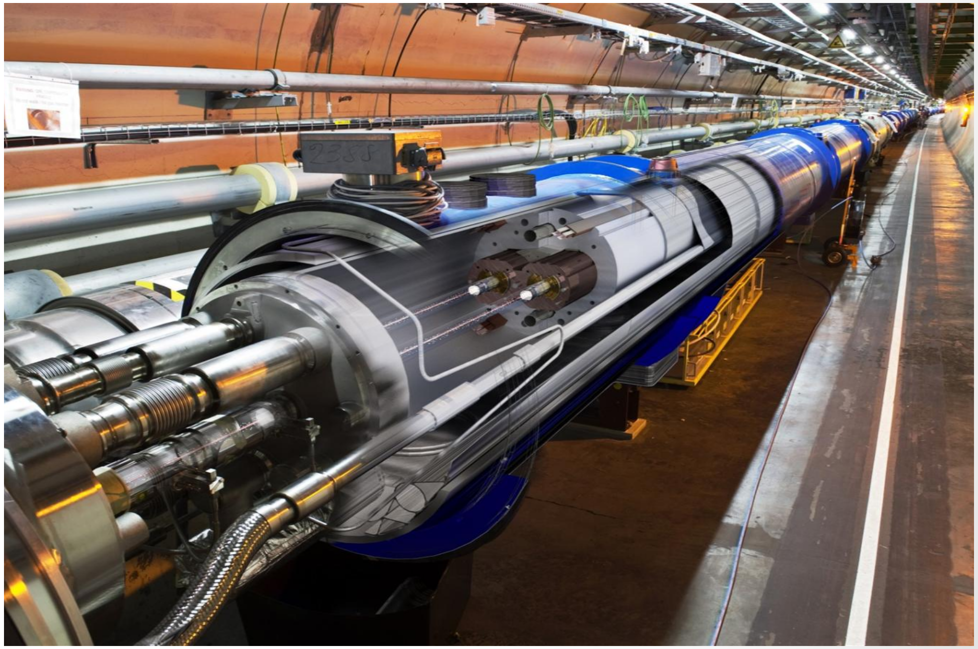
30 years of single ring Colliders thanks to Stochastic Cooling & Antiproton sources

Discovery of W , Z & Top Quark

Synchrotron: with several hundreds of discrete magnets

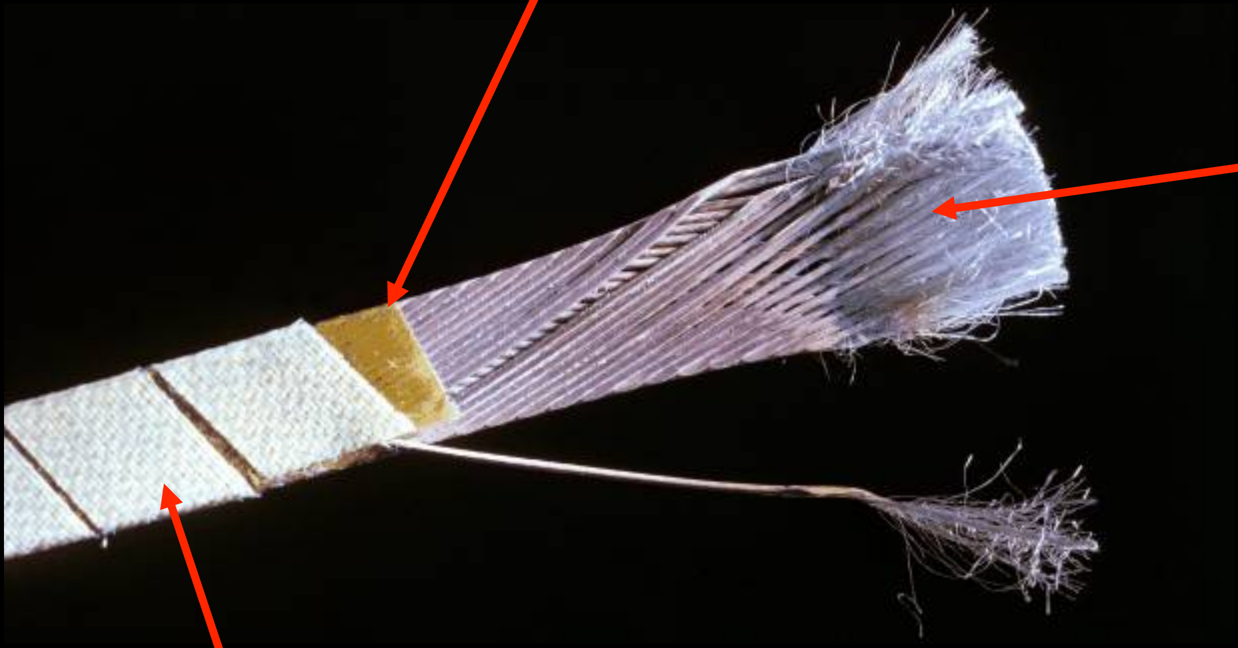
we are still doing the same as in fifties : *For achieving higher and higher energies, it is more economical to limit the volume of the magnetic field by circulating the particles in a small diameter vacuum pipe around which the Bending and focusing magnets are installed*

Classical magnets of CERN SPS ~ 7 km
1976



LHC~27 km with its superconducting magnets
2008

Tevatron: engineering of <Rutherford and insulation: buy SC by tons



Overlapping wrap of .001” kapton film for insulation

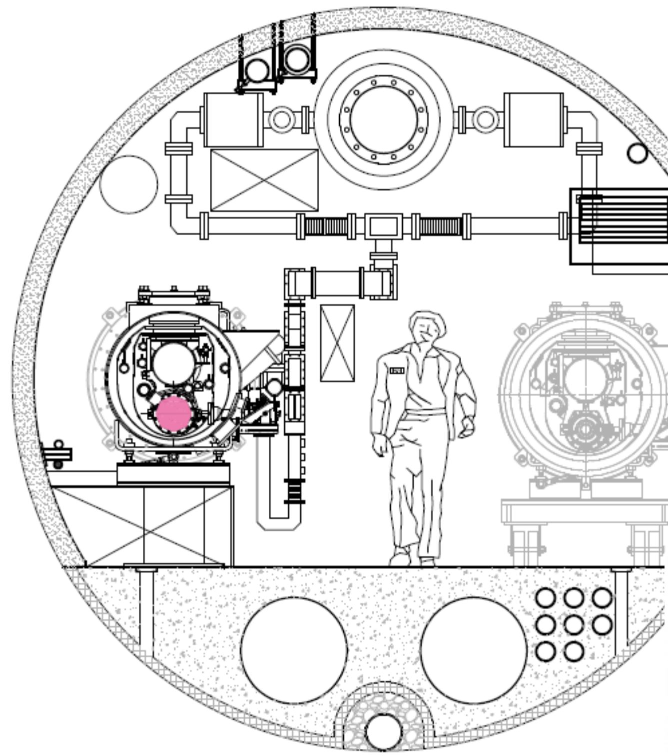
.023” strand with 2100, 8 micron NbTi filaments

Glass tape impregnated with uncured epoxy resin.

After the coil is wound, it is placed in a precision form and the epoxy is cured by heating.

After the LHC:

International Linear Collider (ILC)



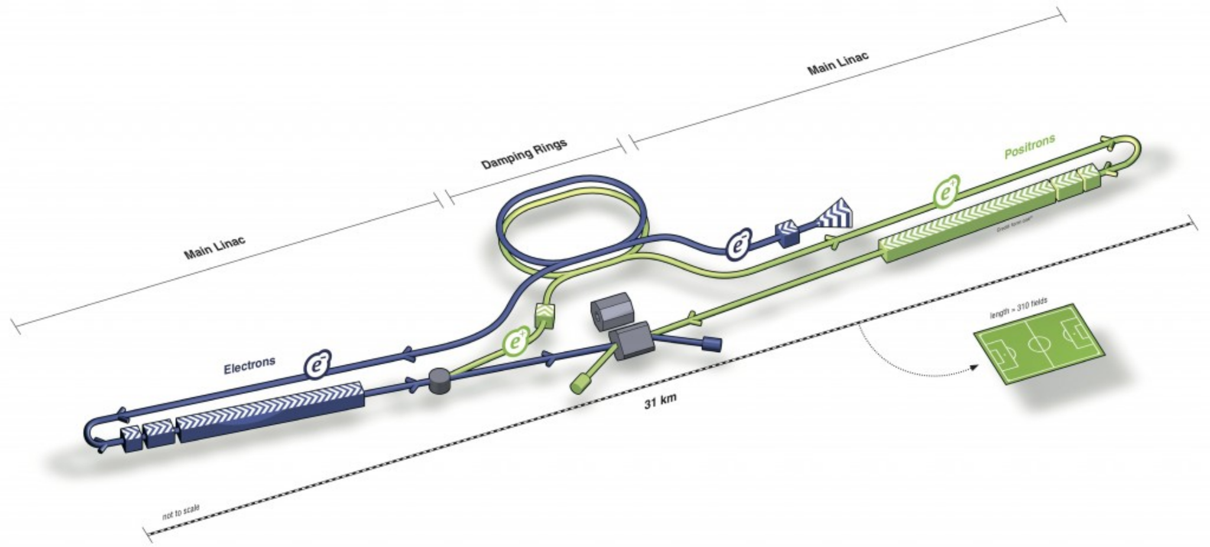
e+ e- Linear Collider (500 GeV)

Total Length 31 km

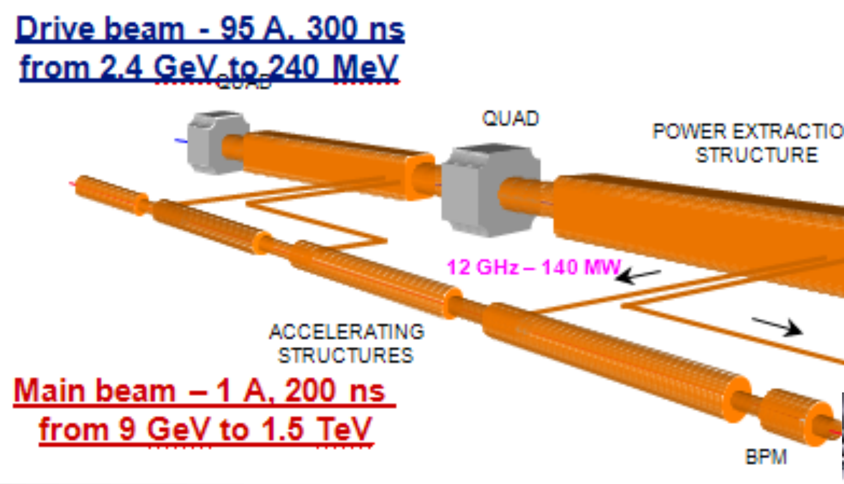
Key Technology required: superconducting RF cavities

International Collaboration

Implantation expectations: to be in Japan



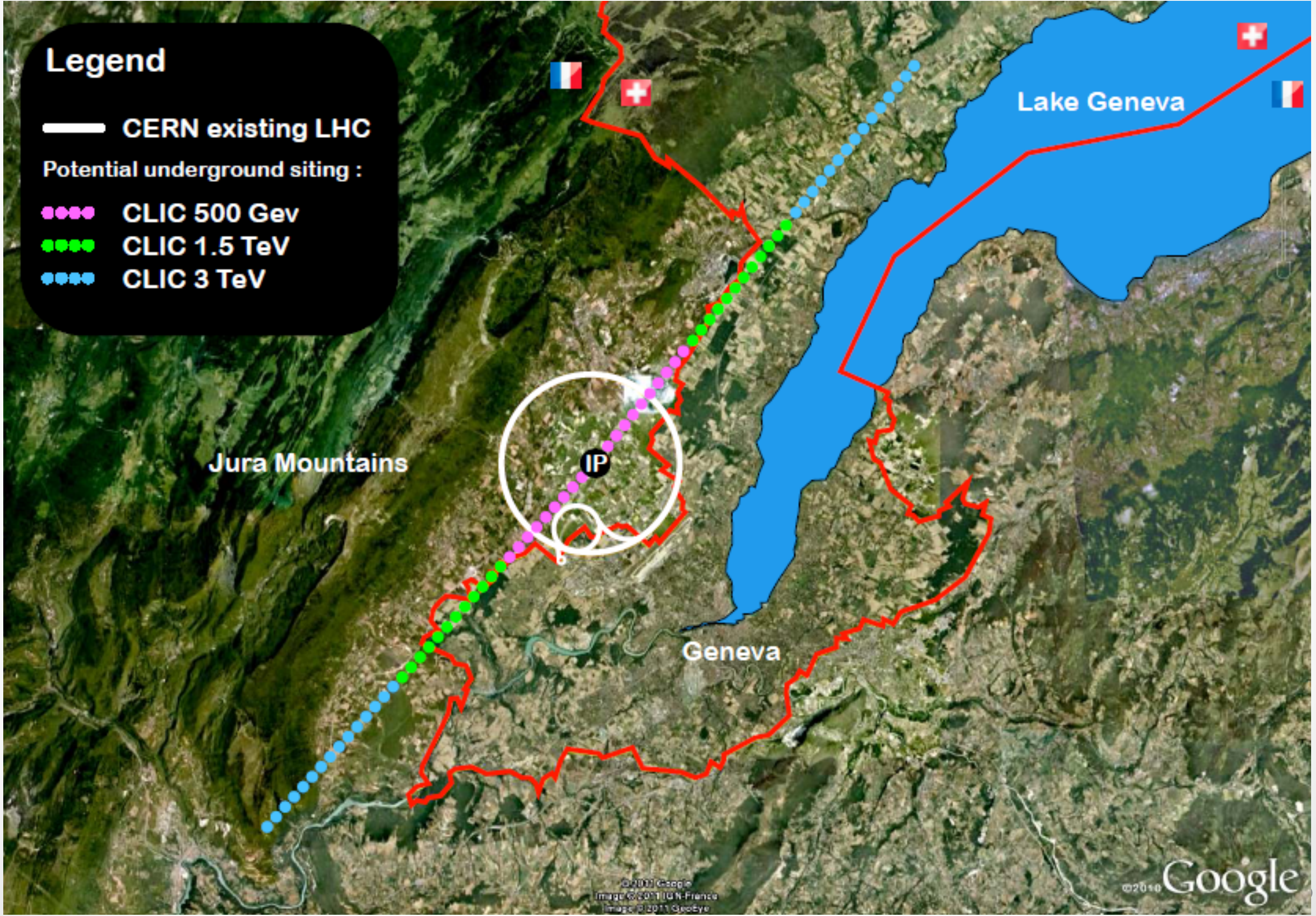
After the LHC:
Compact Linear Collider (CLIC)



- e+ e- Linear Collider (500 GeV upto 3 TeV)
- Key Technology required : Two beam technology >> Drive Beam & Main Beam
- International Collaboration lead by CERN

After the LHC:

Possible Implementation of CLIC @ CERN

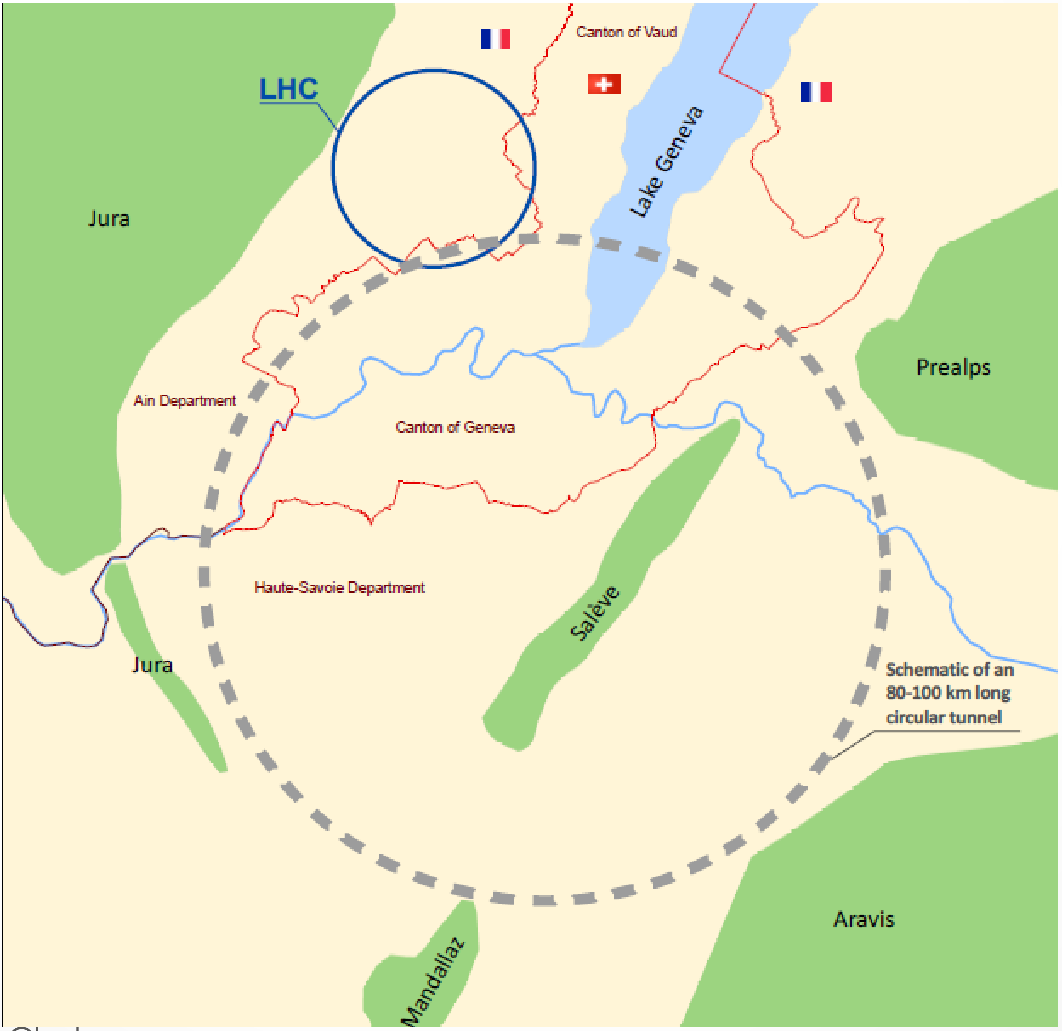


After the LHC:
Future Circular Colliders (FCC) study

Approx 4 x LHC Circumference

Approx twice strong , 15 Tesla Magnets

So 50 TeV on 50 TeV



Thank you

Acknowledgements

CERN Library and CDS are great resources for research for such a talk as well as

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I am grateful for the liberal availability & use of all the different resources mentioned