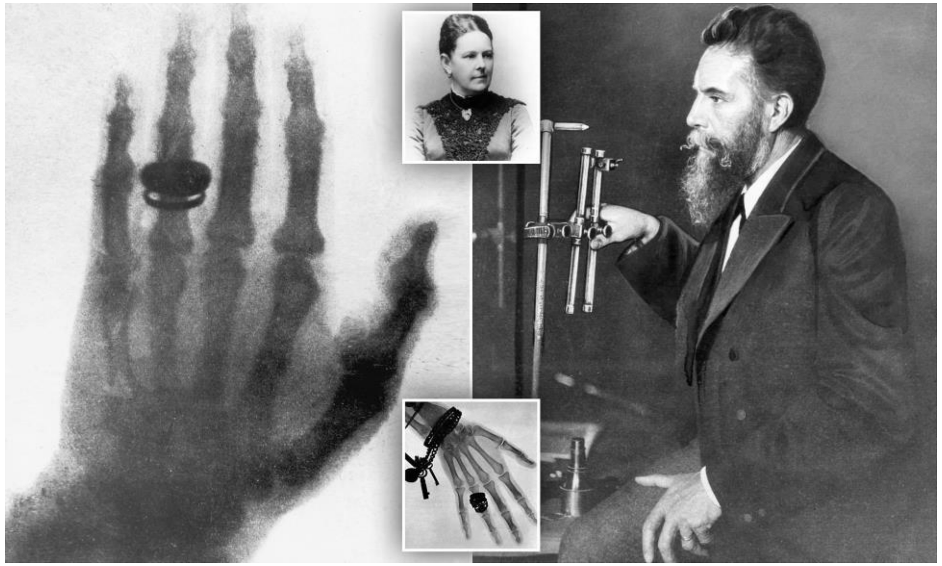
Particle Accelerators

Mike Lamont
International High School Teacher Programme
6th August 2024

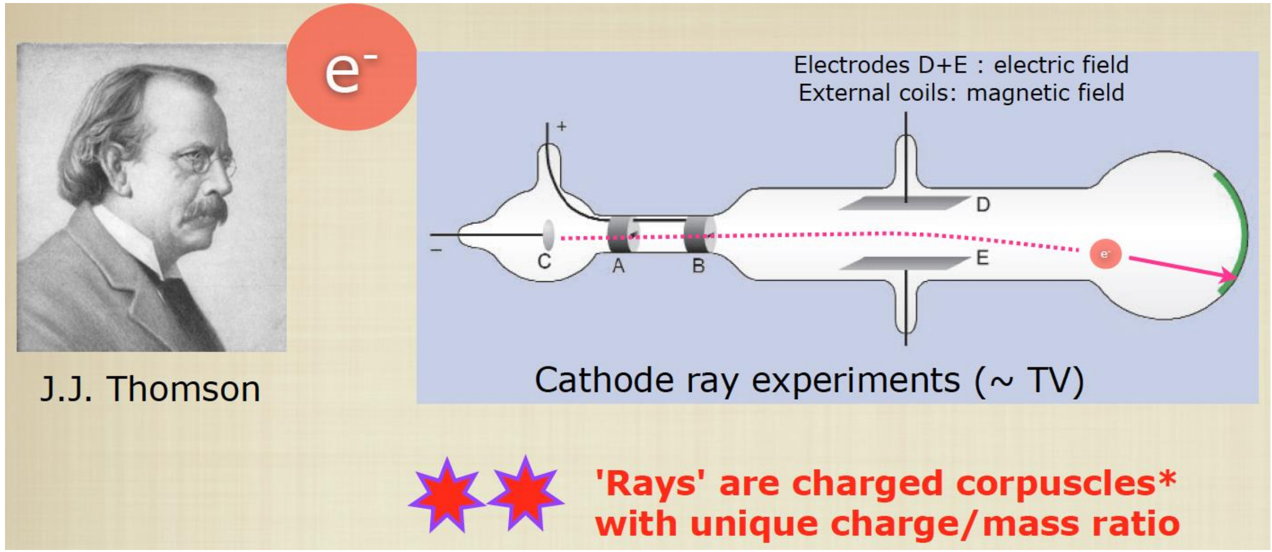
The First Historical Particle Accelerators

Nobel Laureate Wilhelm Conrad Röntgen

- “Cathode rays” emitted by a heated cathode impinging on an anode produced X-rays



First human X-ray of Röntgen's wife Bertha’s hand (1895)



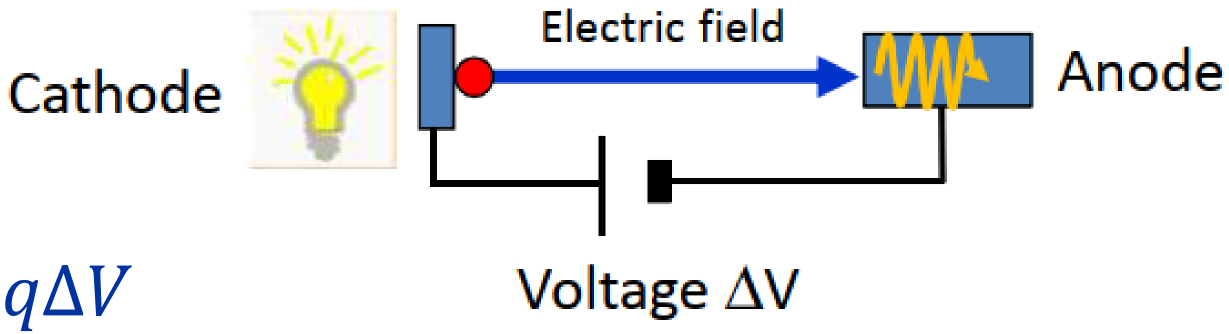
Nobel Laureate J.J. Thomson

- 1897 - Thomson showed cathode rays were composed of negatively charged particles (electrons)
- Calculated to be much smaller than atoms with a very large charge-to-mass ratio

Acceleration – The Simple Case

Wilhelm Conrad Röntgen's first historical particle accelerator

- Vacuum tube containing a cathode connected to negative pole of DC voltage generator
- Electrons emitted by the heated cathode were accelerated while flowing to the positive anode
- Collisions between these energetic electrons and the anode produced X-rays



$$\Delta E = q\Delta V$$

Particle energy usually expressed in electron-volt [eV]

1 eV ($1.6\text{x}10^{-19}$ J) equal to energy gained by an electron accelerated through an electrostatic potential of 1 volt

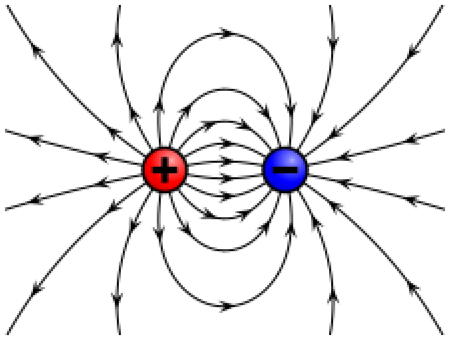
Maxwell's equations

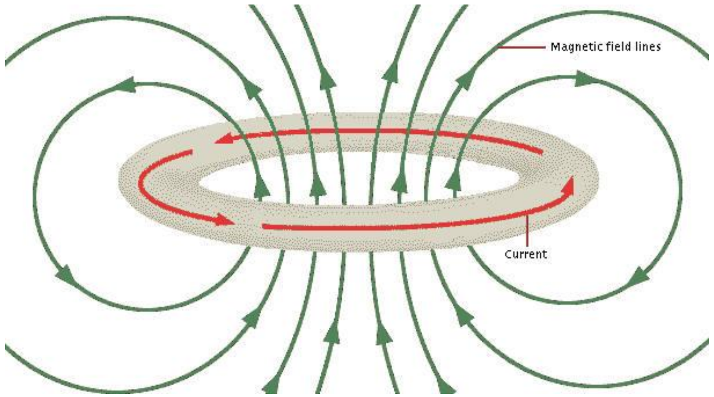
$$\nabla \cdot E = \frac{\rho}{\varepsilon_0}$$

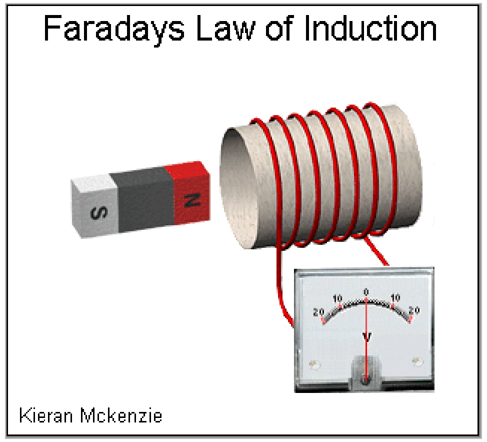
$$\nabla \cdot B = 0$$

$$\nabla \times E = -\frac{\partial B}{\partial t}$$

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \frac{\partial E}{\partial t}$$



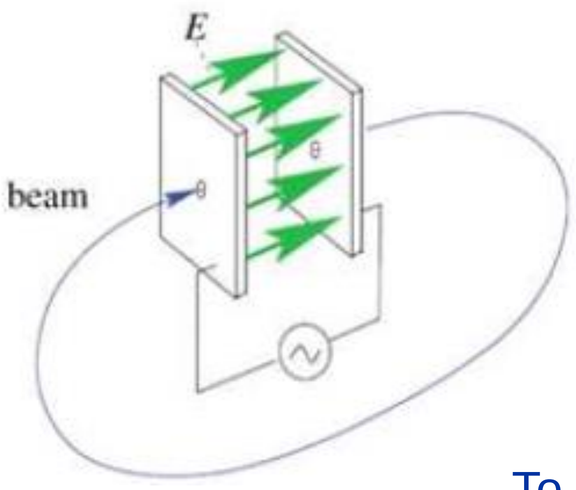




The Principles behind Particle Accelerators

Lorentz Force

- Particles accelerated via electric fields and bent or focused using magnetic fields

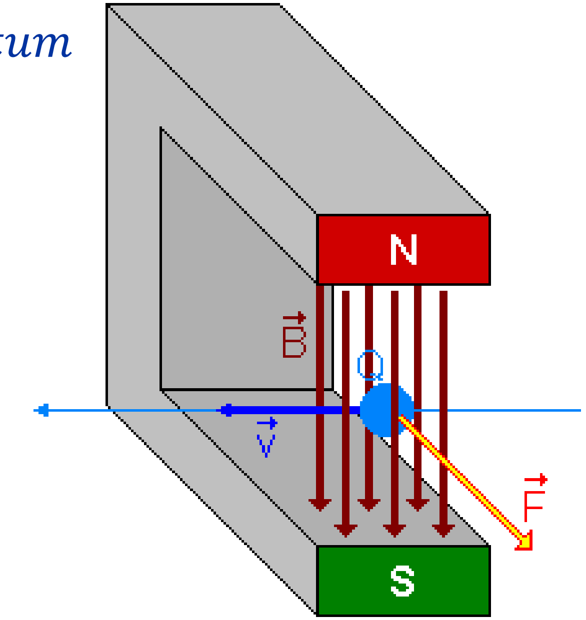


$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \vec{v} \times \vec{B}\right)$$

$\vec{p} =$ *momentum*
$\vec{v} =$ *velocity*
$q =$ *charge*

Acceleration
To accelerate we need a force in the direction of motion

Bending & Focusing
Perpendicular to motion
$\Rightarrow$ Change in momentum but no acceleration



Electric Field

Magnetic Field

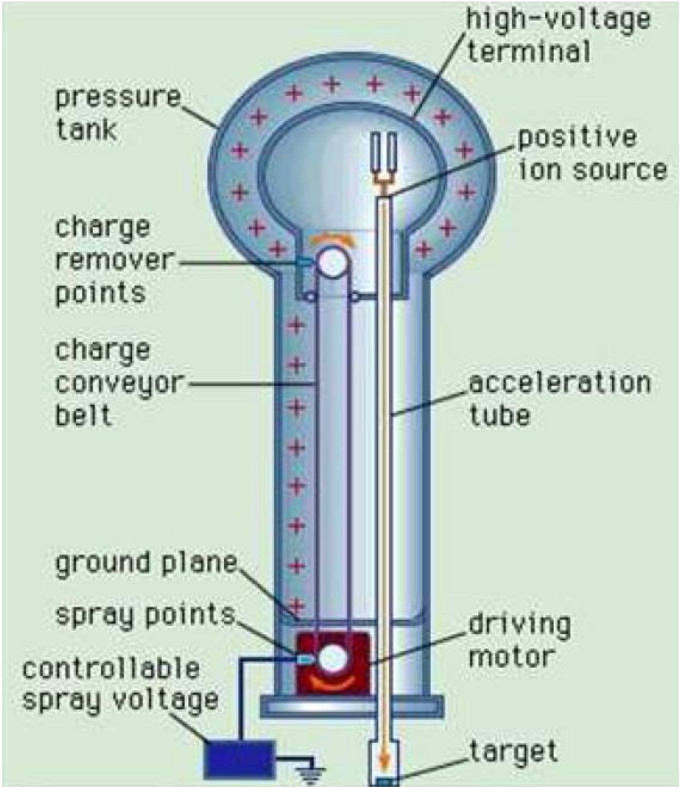
Electrostatic Accelerators

To increase achievable maximum energy

- **Cockcroft and Walton** built a cascade generator
- **Van de Graaff** built a generator with a dielectric belt transporting positive charges to an isolated electrode hosting an ion source
- In air versions reached 2-3 MV while later versions under isolating gas atmospheres reached up to 25 MV
- Main limitation: the breakdown at the charged terminal

Cockcroft–Walton generator in the London Science Museum - WikiMedia Commons

Cockcroft-Walton Cascade Generator



Van de Graaff Generator

1932 - first artificial nuclear disintegration in history - 1951 Nobel Prize in Physics for "Transmutation of atomic nuclei by artificially accelerated atomic particles"

Radio Frequency Linear Accelerators (LINACs)

- **To overcome the breakdown limitation Rolf Widerøe used a Radio Frequency (RF) generator originally proposed by Gustav Ising in 1924**
  - For his Thesis at Aachen University (1928) built the first radio frequency LINAC

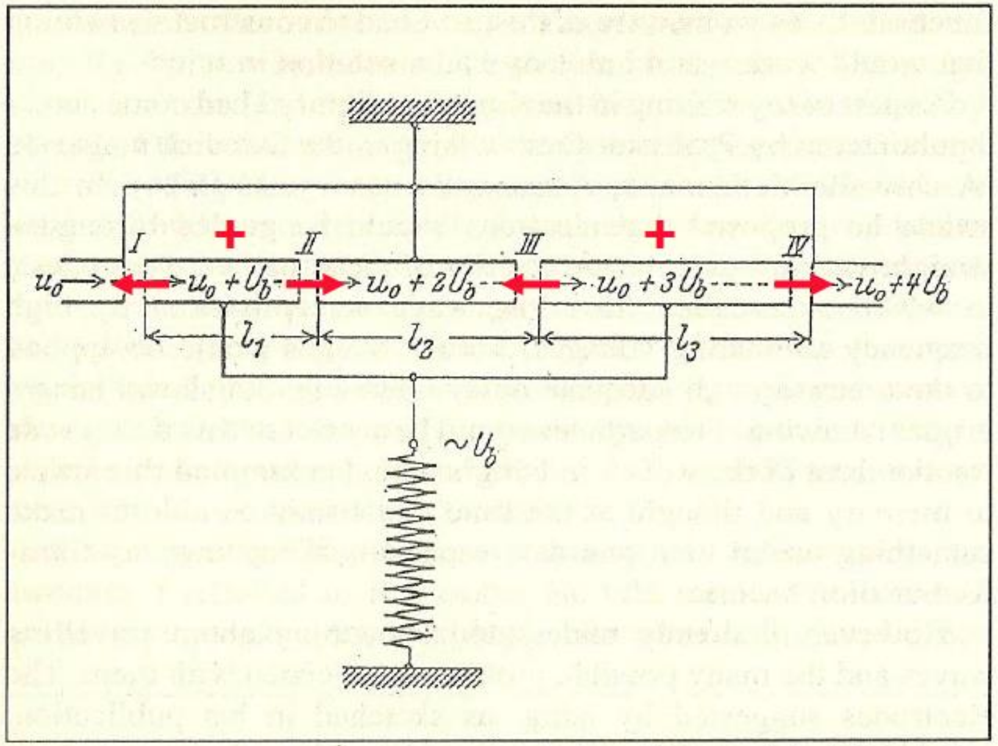
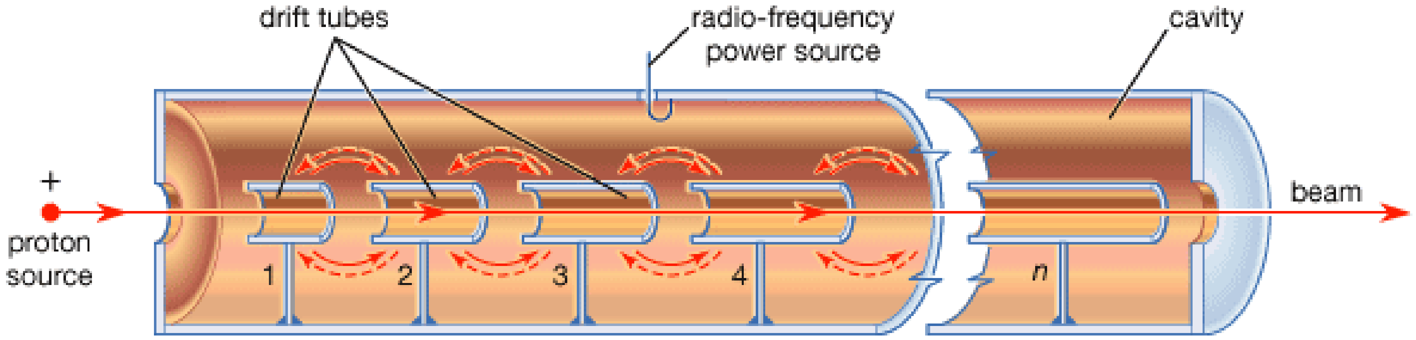


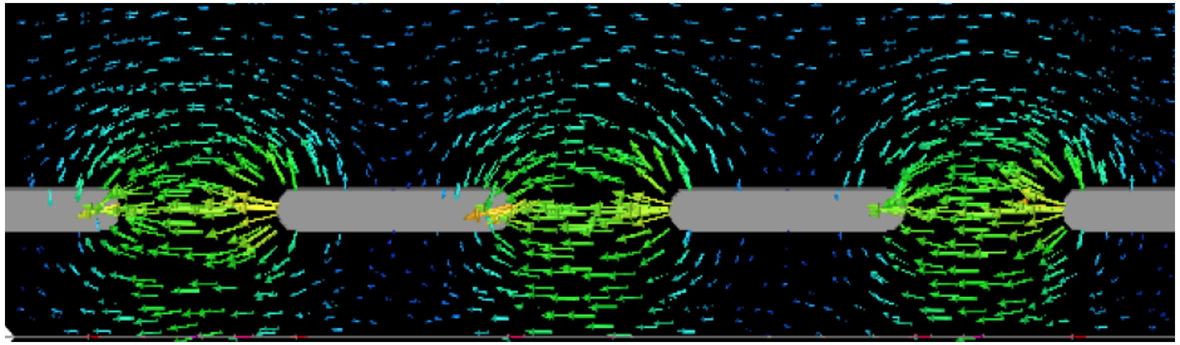
Fig. 3.5: The principle of the 'drift-tube' as illustrated in Wideröe's thesis [Wi28].

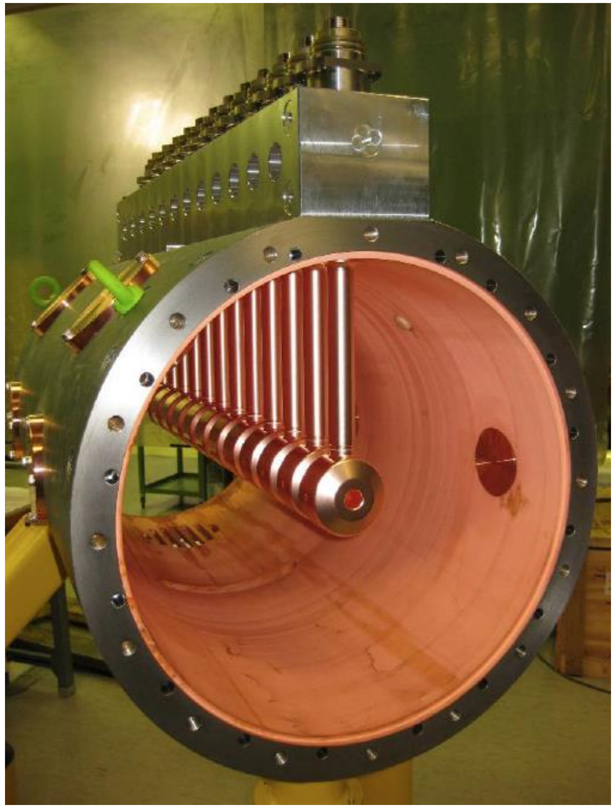
Rolf Widerøe 1928

Radio Frequency Linear Accelerators (LINACs)

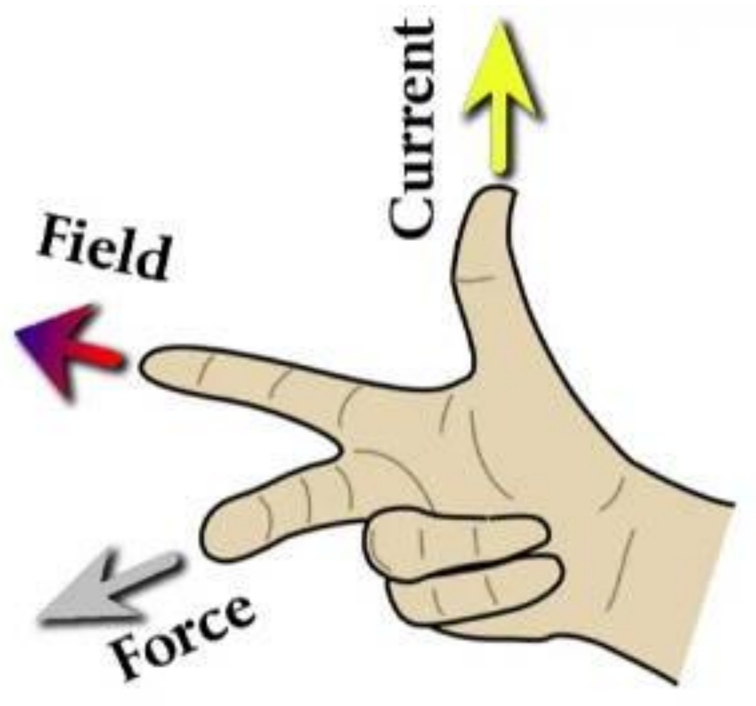
- **Drift Tube LINAC**
  - Particles accelerated by a sequence of gaps
  - Distance between gaps increases proportionally to the particle velocity, to keep synchronicity
  - Used in the range where velocity increases rapidly





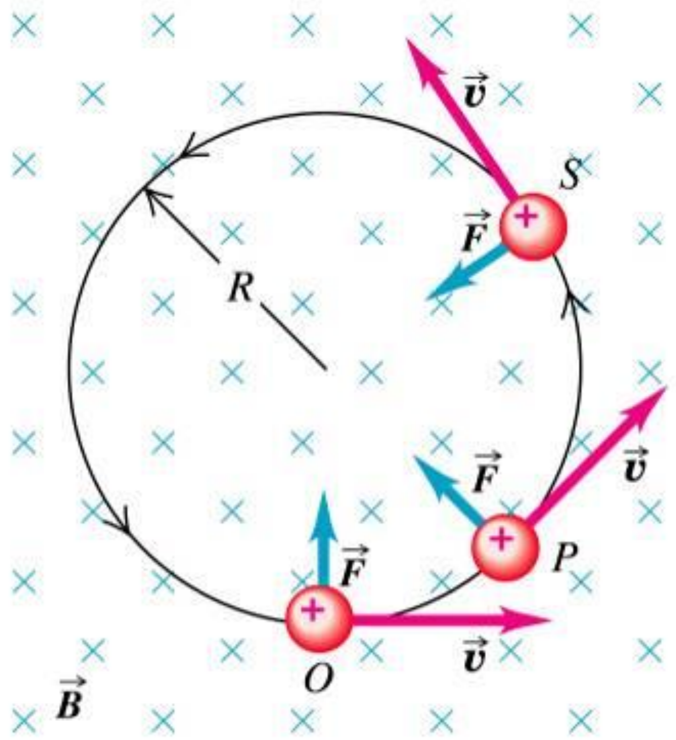


Circular Accelerators



$$\boldsymbol{F} = q\boldsymbol{v} \times \boldsymbol{B}$$

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



A moving charged particle will follow a circular path in a magnetic field

Circular Accelerators - Cyclotron

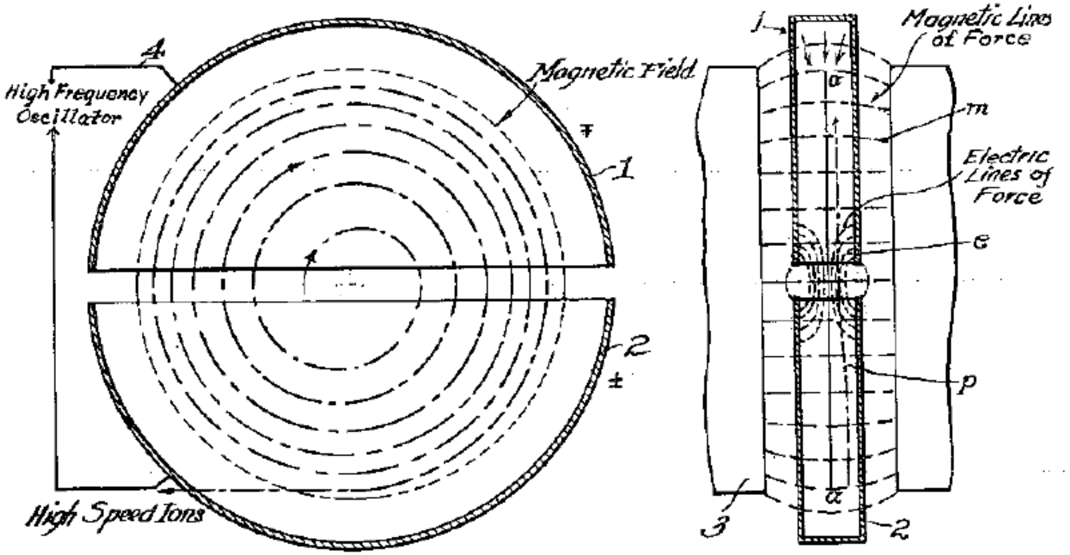


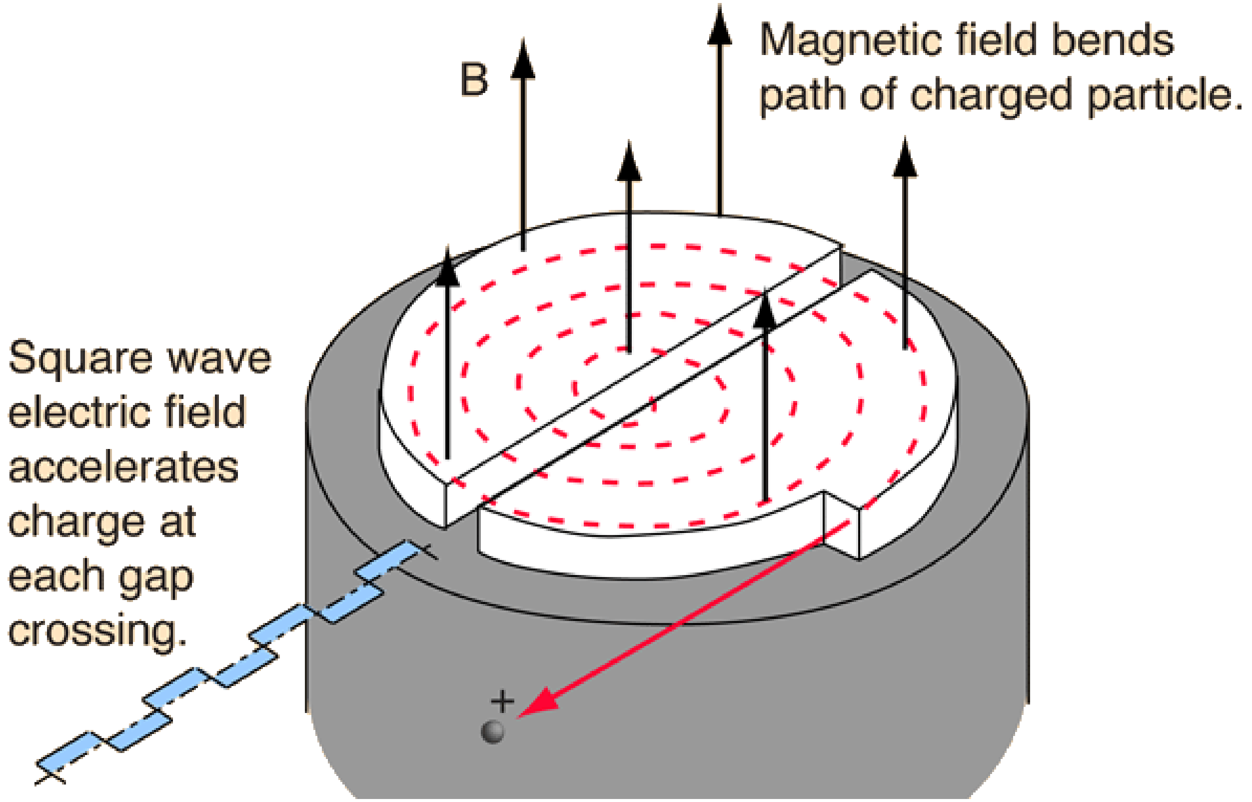
Figure 1: The cyclotron concept, from Lawrence's patent.

When Lawrence worked out the dynamics, he found an unexpectedly favourable result: for a particle with mass m, charge q, moving with velocity $\mathbf{v}$ normal to uniform magnetic induction $\mathbf{B}$, the Lorentz Force $\mathbf{F} = q\,\mathbf{v} \times \mathbf{B}$ produces a circular orbit, and

$$q\, \cancel{r}\omega B = m\, \cancel{r}\omega^2 = m\omega.$$

"r cancels r", as Lawrence explained excitedly to each of his students, so that the "cyclotron frequency" is independent of v and the orbits are "isochronous":

$$\omega = \frac{qB}{m}$$



The First Circular Accelerator

Lawrence and Livingston's 80 keV cyclotron (1930)

Ernest O. Lawrence

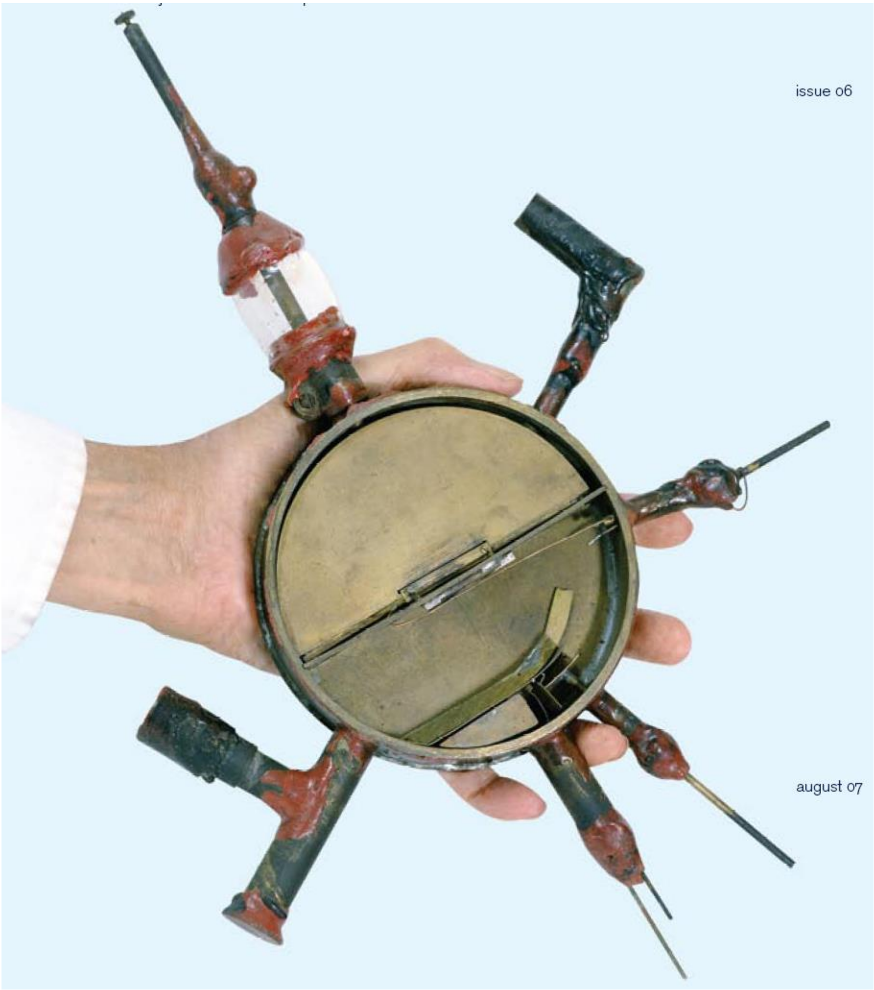
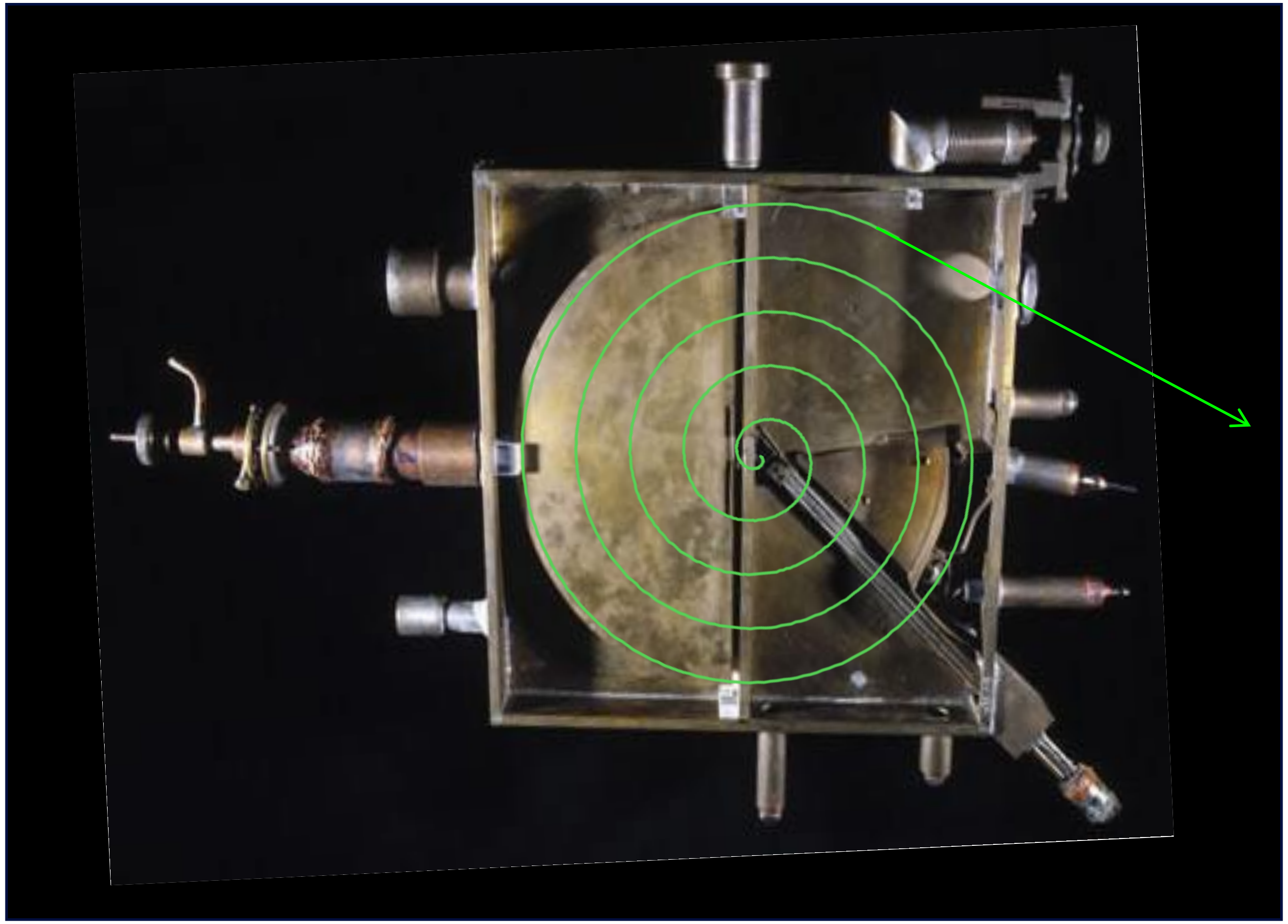


Figure 2: The 4-inch cyclotron vacuum chamber, showing the single dee, the deflector, and G. Seaborg's left hand.

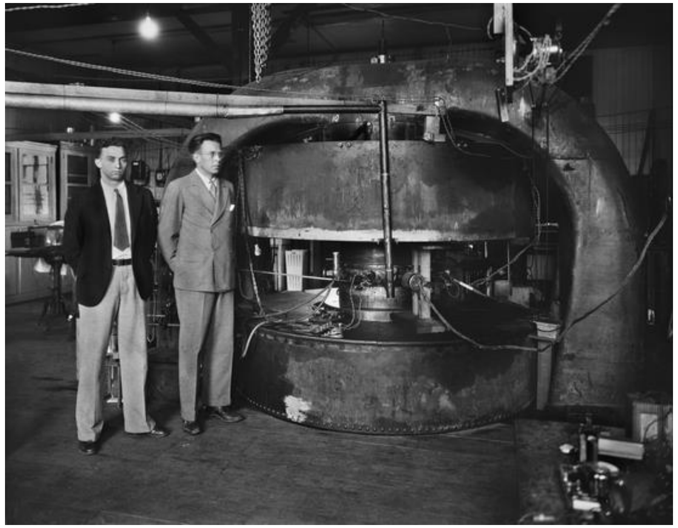
Cyclotron



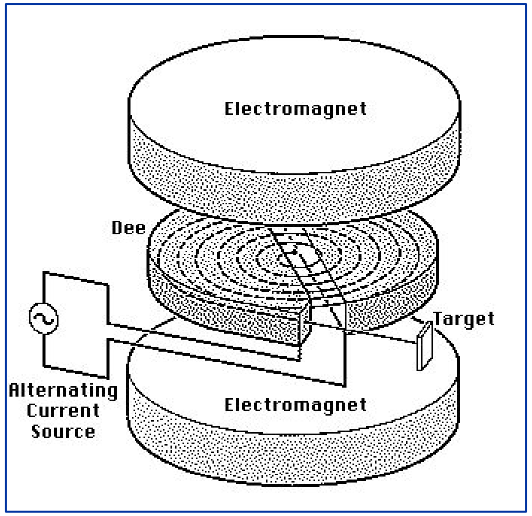
In what became a familiar style, Lawrence quickly moved to acquire larger and stronger magnets. First came the 11-inch (referring to the pole diameter), with which he and Livingston were able to achieve a world-record of 1.22-MeV protons in January 1932.

Circular Accelerators

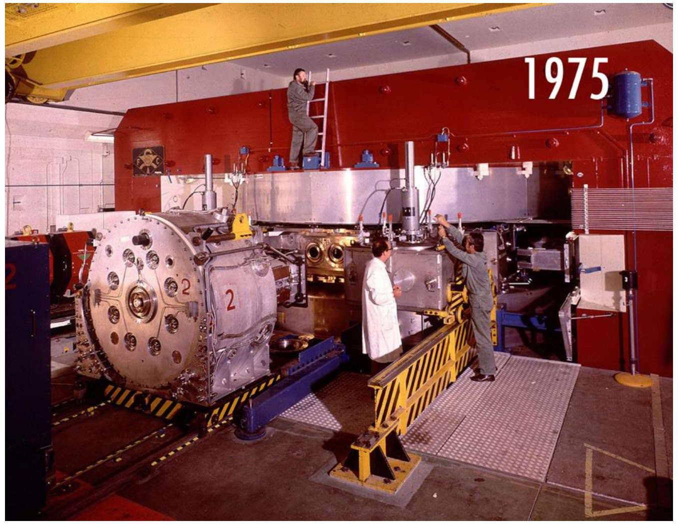
Cyclotron

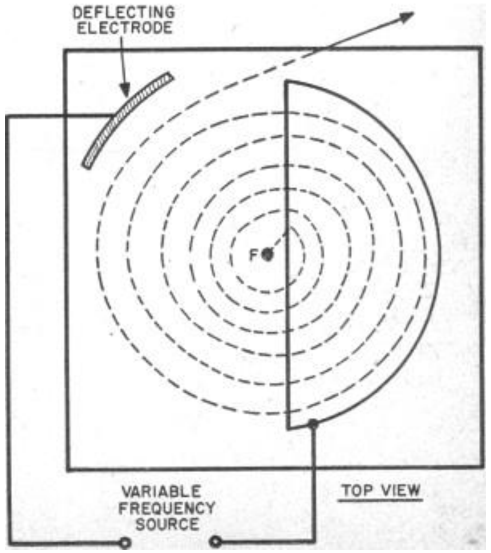


Livingston and Lawrence standing beside the 27 inch cyclotron, built in 1934



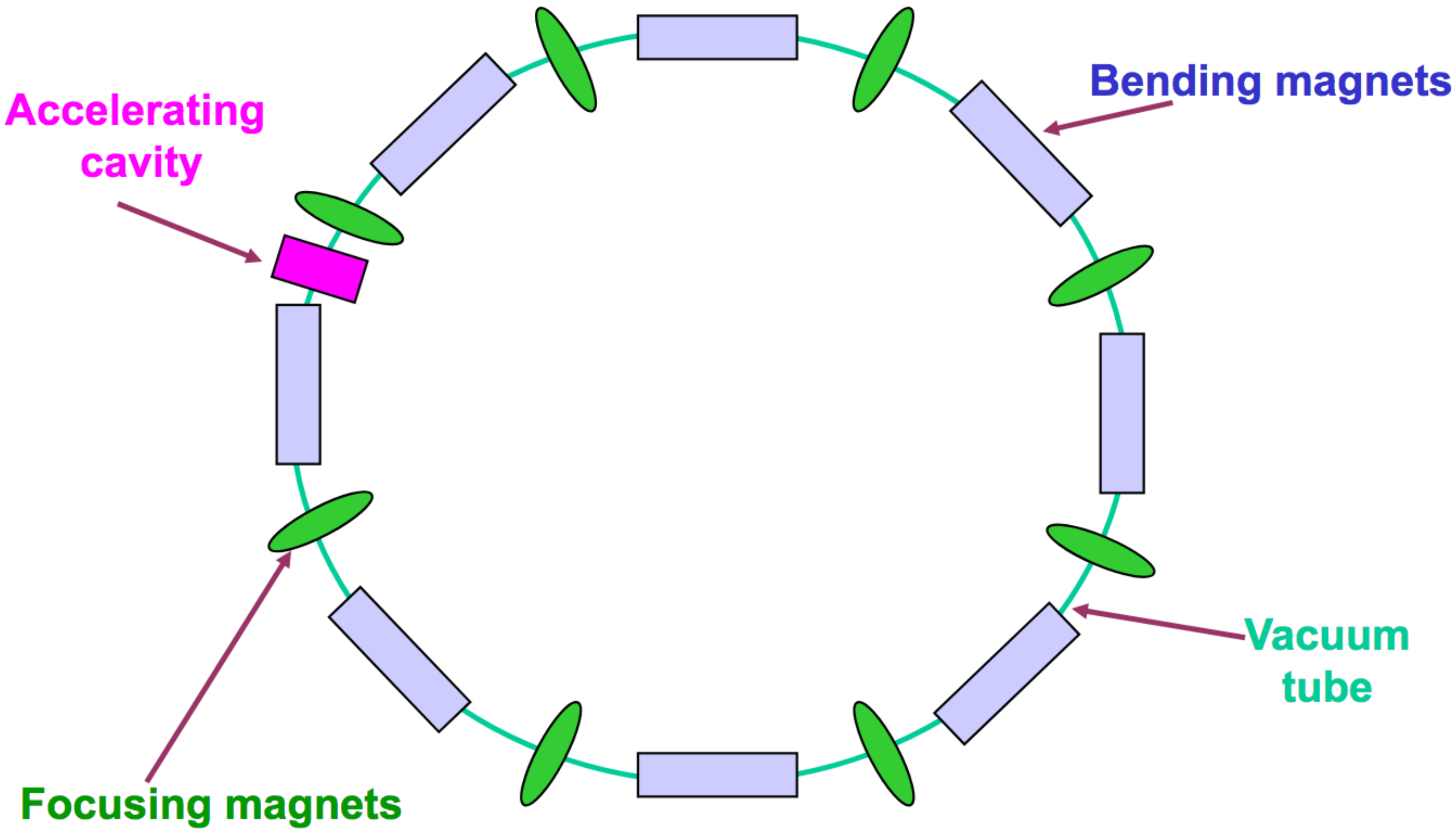
Synchro-Cyclotron



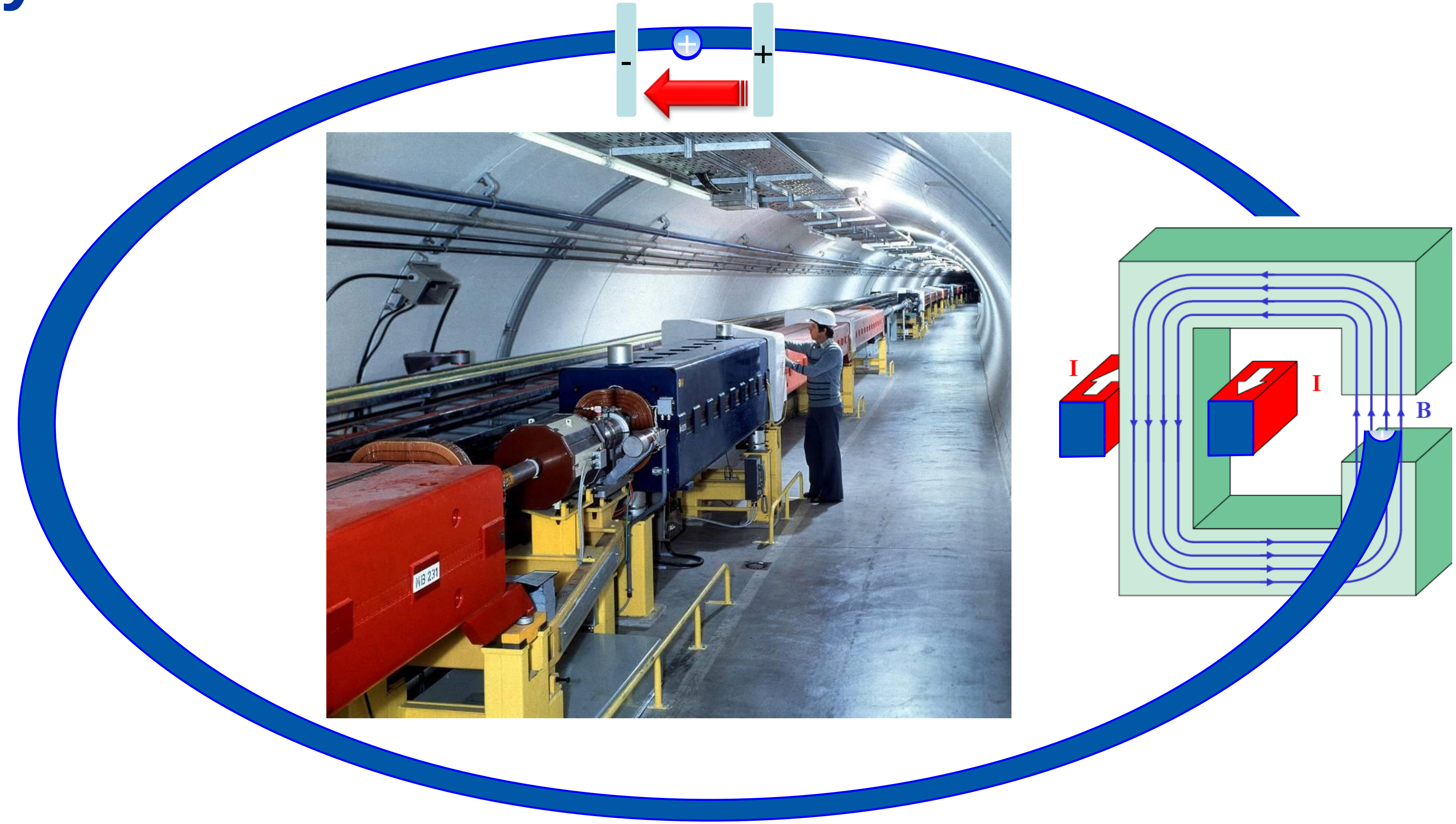


Circular Accelerators – The Synchrotron

The basic principle of the synchrotron is to maintain the accelerated particles at a constant orbital radius



The Synchrotron



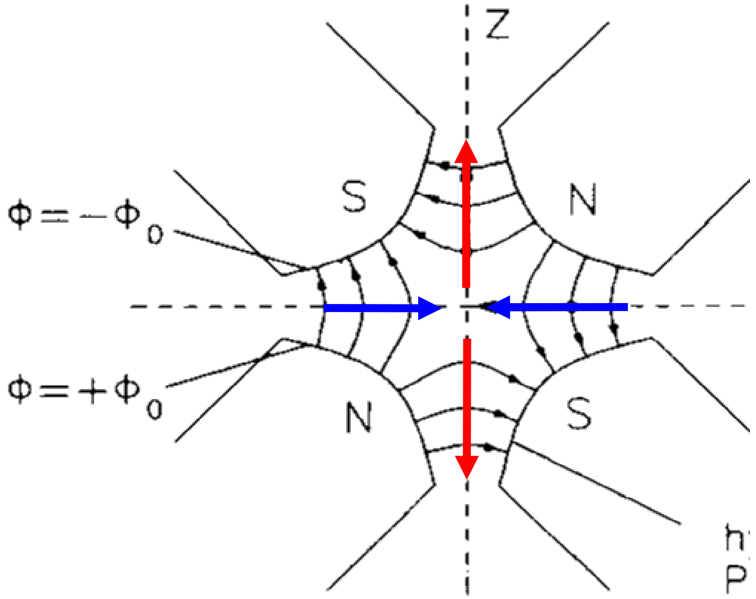
The magnetic field increases with energy so that the particle follows the same path

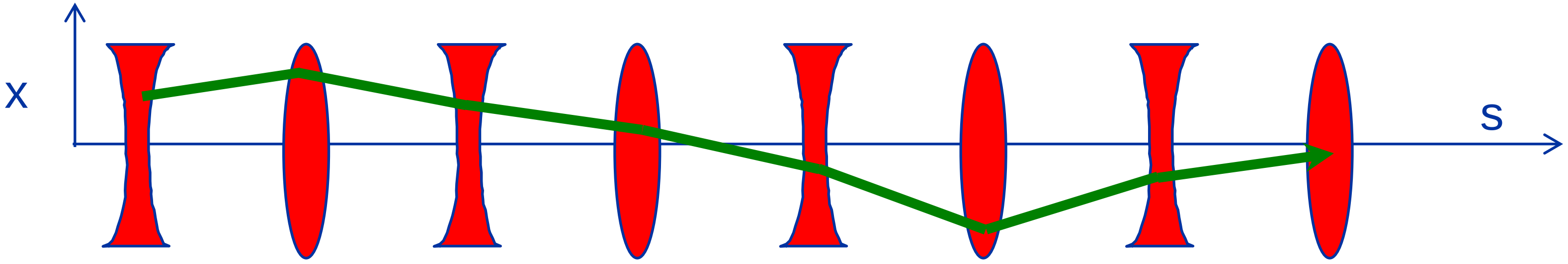
LHC tunnel

Video 1’22’’

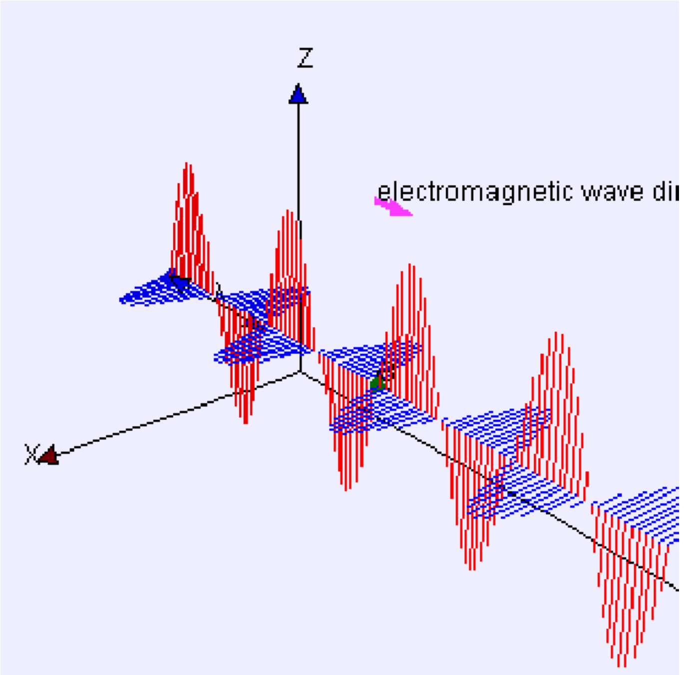
Quadrupole Magnets

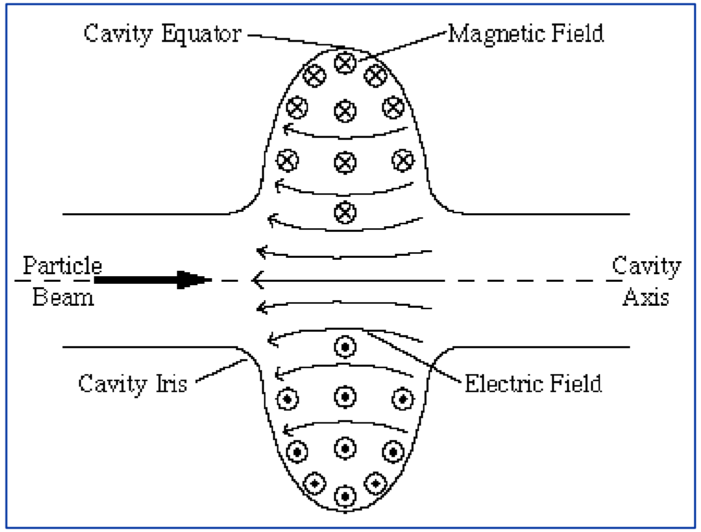
- **A quadrupole magnet will focus in one plane and de-focus in the other**
  - Convention: a "focusing" quadrupole focuses in the horizontal plane
- **A series of focusing and defocusing magnets can be used to constrain the charged particle in both planes**
- **A synchrotron is mostly regular cells of bending, focusing and defocusing magnets**
  - with some space left for beam acceleration, injection, extraction and sometimes an experiment

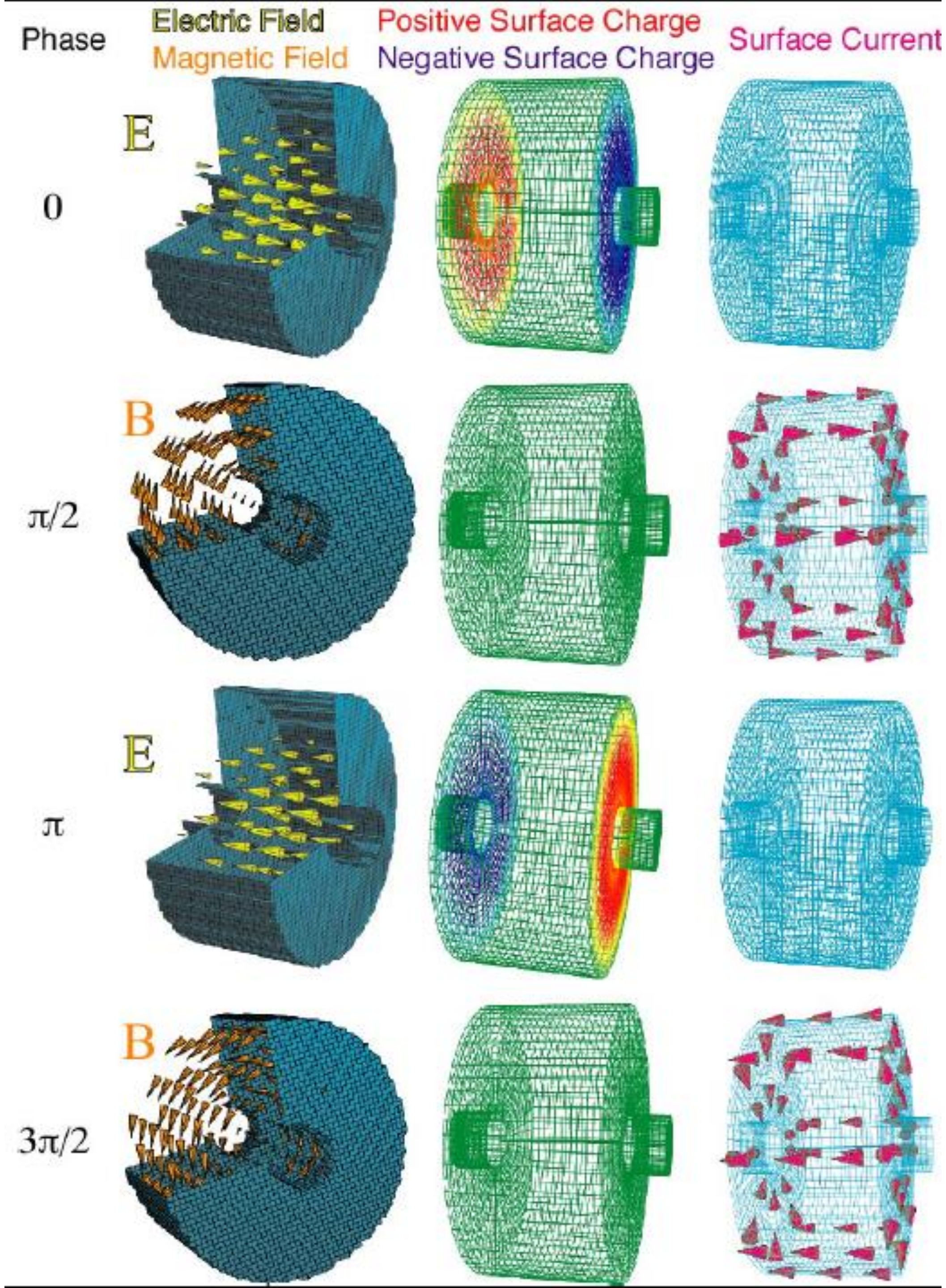




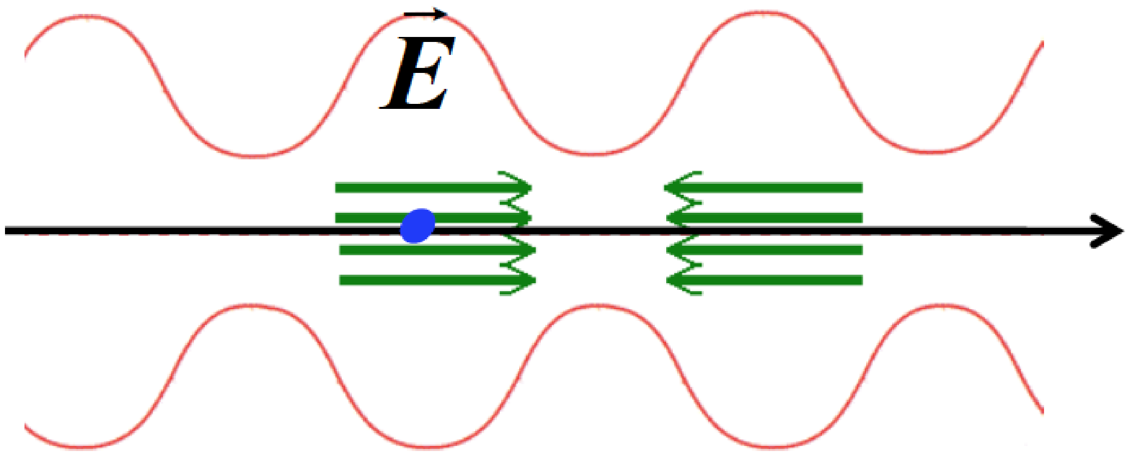
Radio Frequency (RF)



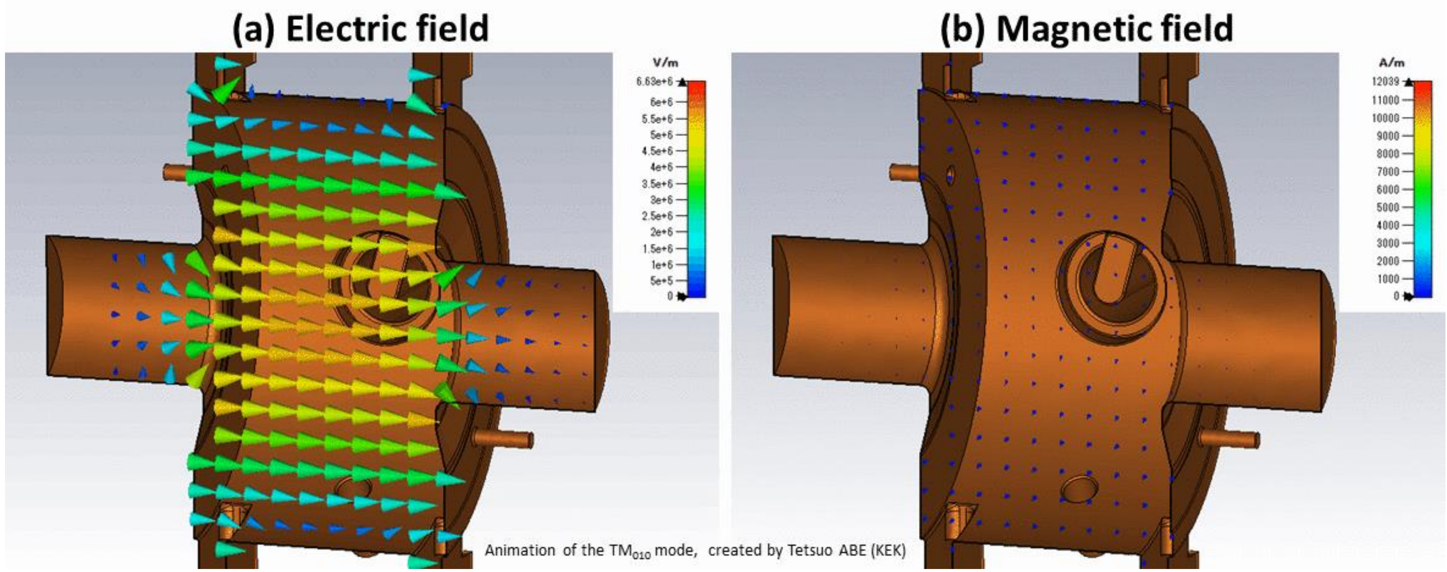




RF cavities



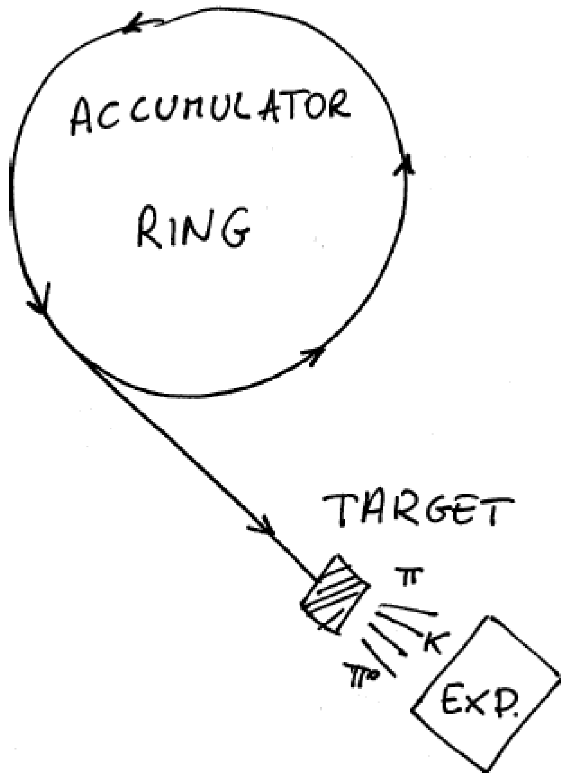
$\vec{E}$



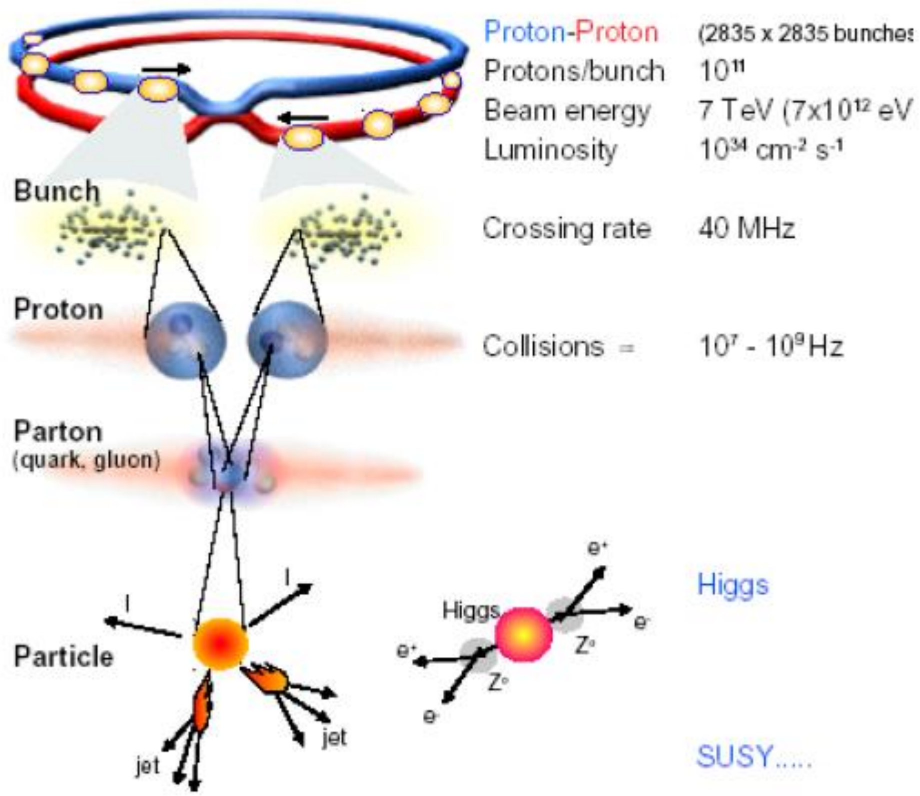
(a) Electric field
(b) Magnetic field
V/m
A/m
Animation of the TM_{010} mode, created by Tetsuo ABE (KEK)

Different Approaches: Fixed Target v Collider

Fixed Target



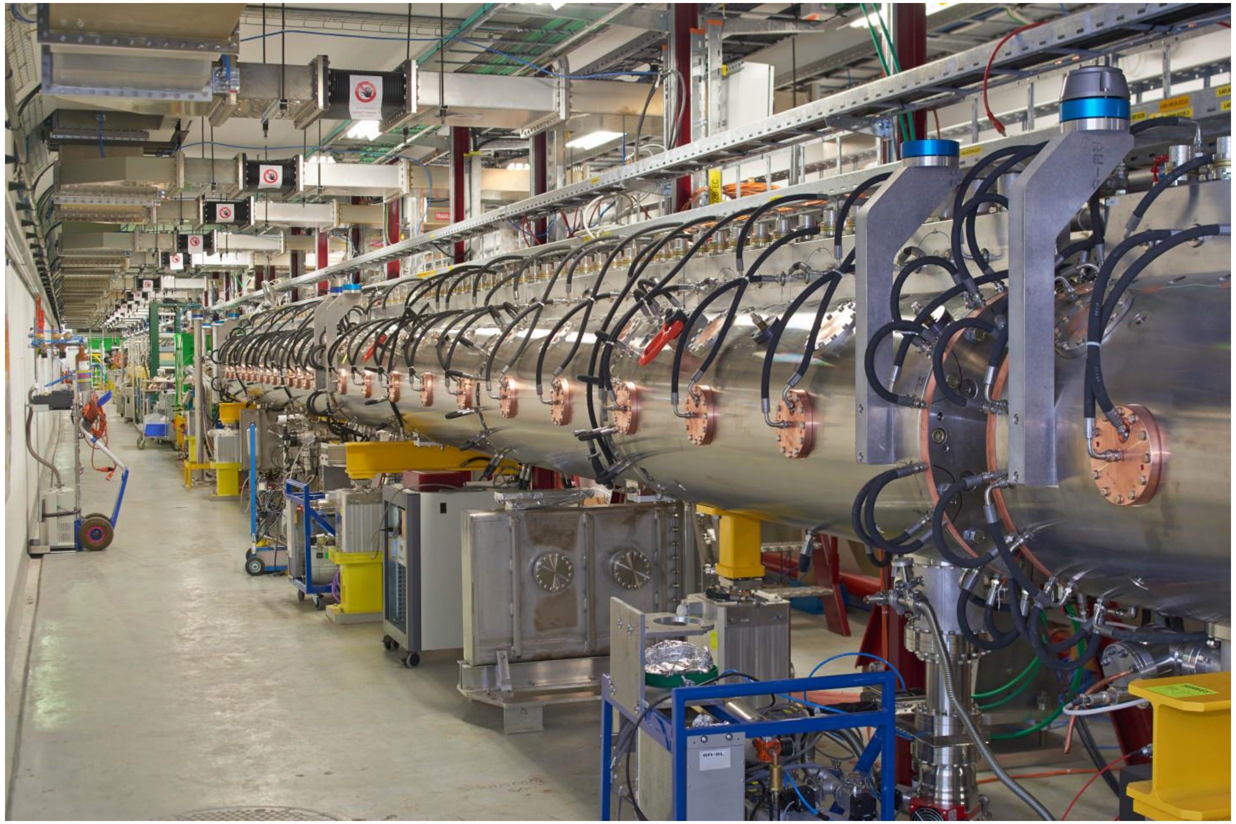
Storage Ring / Collider



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

Drift Tube LINACs at CERN

LINAC2 in service from 1978-2018
Accelerating tank 1 shown here
provided an energy gain of 10 MeV

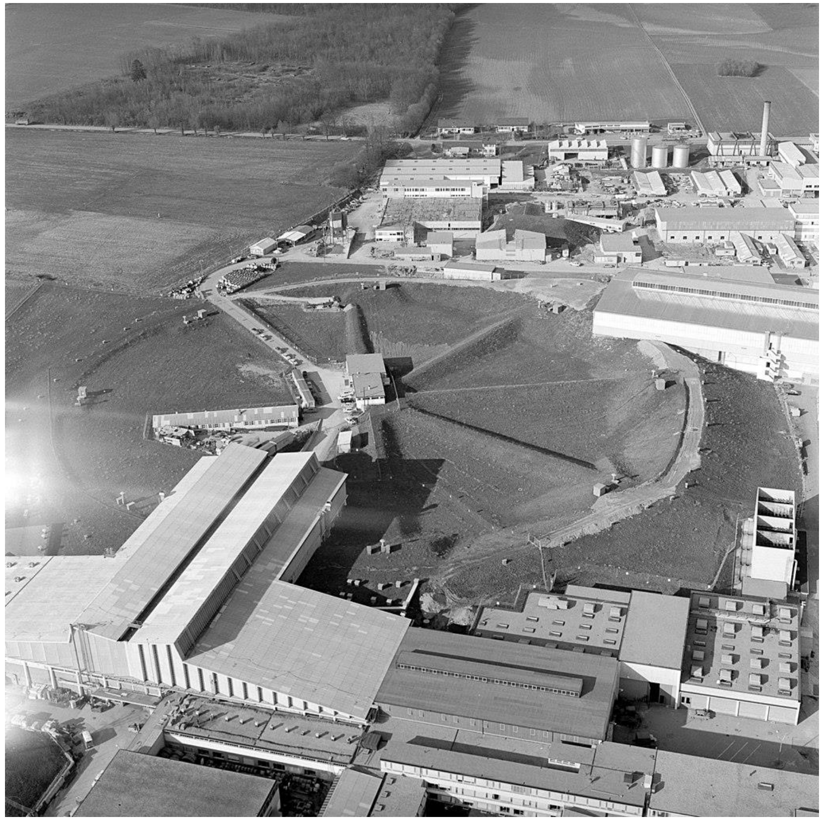


LINAC4 DTL modules providing
acceleration from 3 MeV to 50 MeV
on-line since 2020

The Proton Synchrotron (PS)

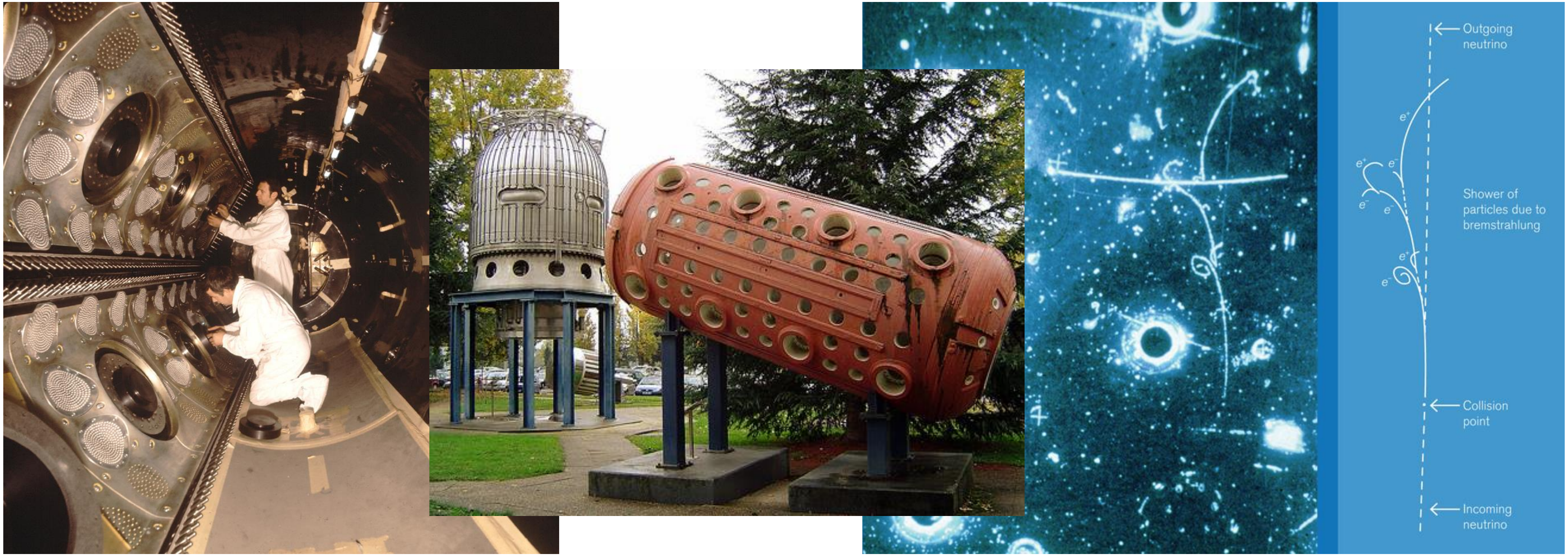
CERN's first synchrotron is still providing beams to the complex!

- **The PS first accelerated protons on 24 November 1959**
  - For a brief period it was the world's highest energy particle accelerator
  - Now accelerates beams up to an energy of 26 GeV
  - Over the years it has undergone many modifications
    - The intensity of its proton beam has increased a thousandfold



Gargamelle and the Proton Synchrotron

- **1974: discovery of weak neutral currents**
  - Gargamelle (freon) bubble chamber looking for neutrinos from collision with fixed target from the PS
  - Distinctive signatures of Z boson & neutrino interaction (weak interaction)
    - Only known mechanism for elastic scattering of neutrinos in matter



The Antiproton Accumulator (AA)

Built to provide antiprotons to the Super Proton Synchrotron (SPS)

- Antiprotons created by firing 26 GeV/c protons from the PS onto a target
- Stochastic cooling used to decrease momentum spread of emerging antiprotons
- Process repeated over a day to produce an intense antiproton beam that was ultimately transferred to the SPS

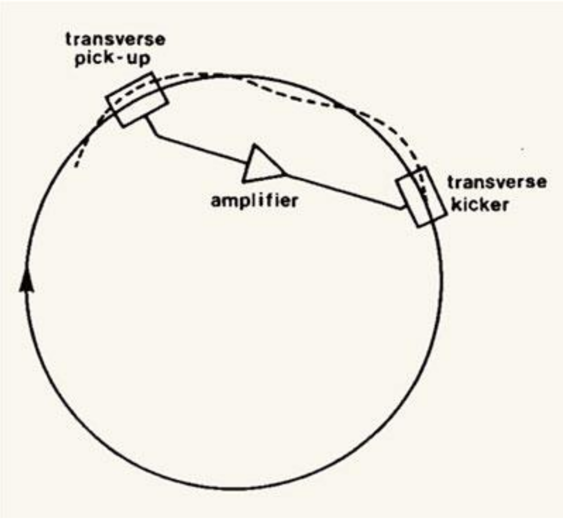

The control room of the anti-proton accumulator (AA) in 1981


Simon van der Meer in the Antiproton Accumulator Control Room, 1984

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.



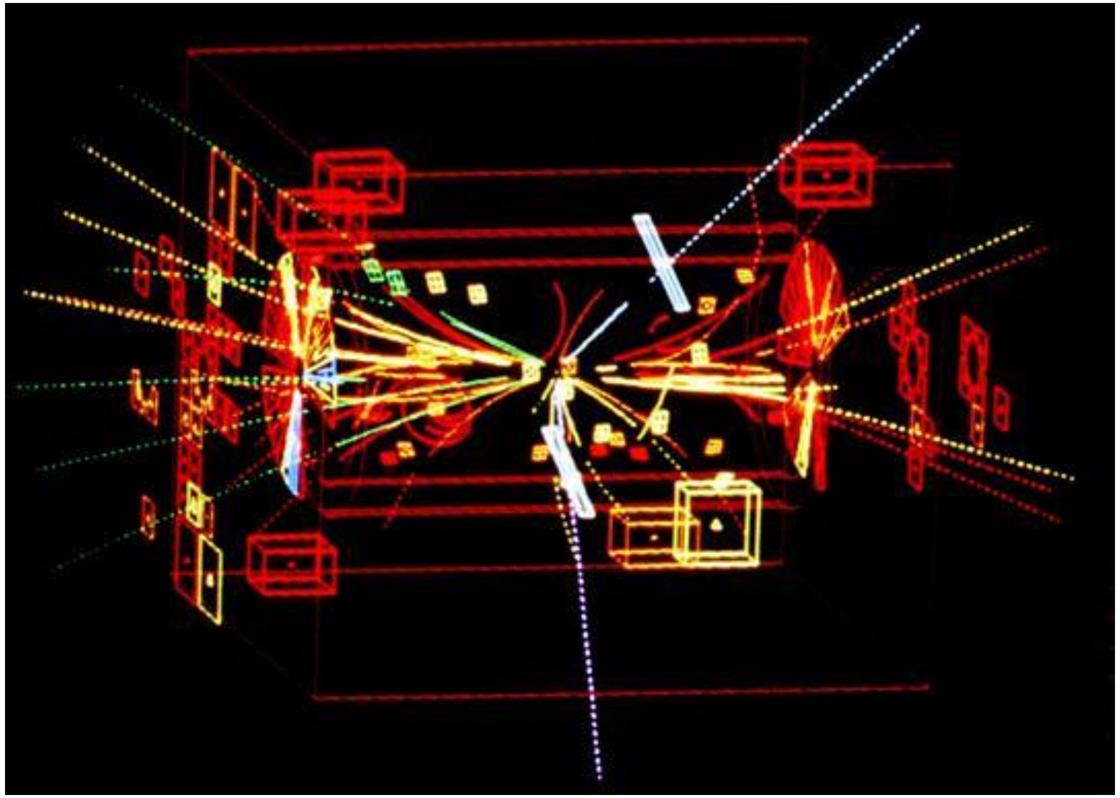
With a mild push from friends and colleagues, Simon finally published the first internal note on stochastic cooling in 1972

Essential technique to create the dense anti-proton beams required for proton-antiproton collisions

The Super Proton Synchrotron (SPS)

The 6.9 km SPS became the workhorse of CERN’s particle physics programme in 1976

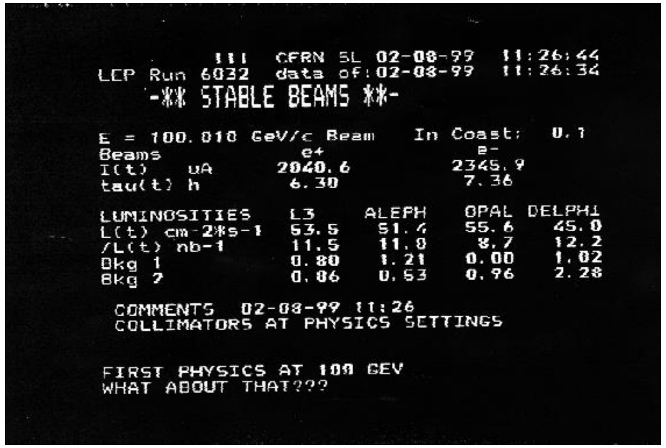
- Used for both fixed target experiments & from 1981 - 1991 as a hadron (proton–antiproton) collider
- Nobel-prize-winning discovery (C. Rubbia & S. van der Meer) of W^+, W^- and Z^0 particles in 1983

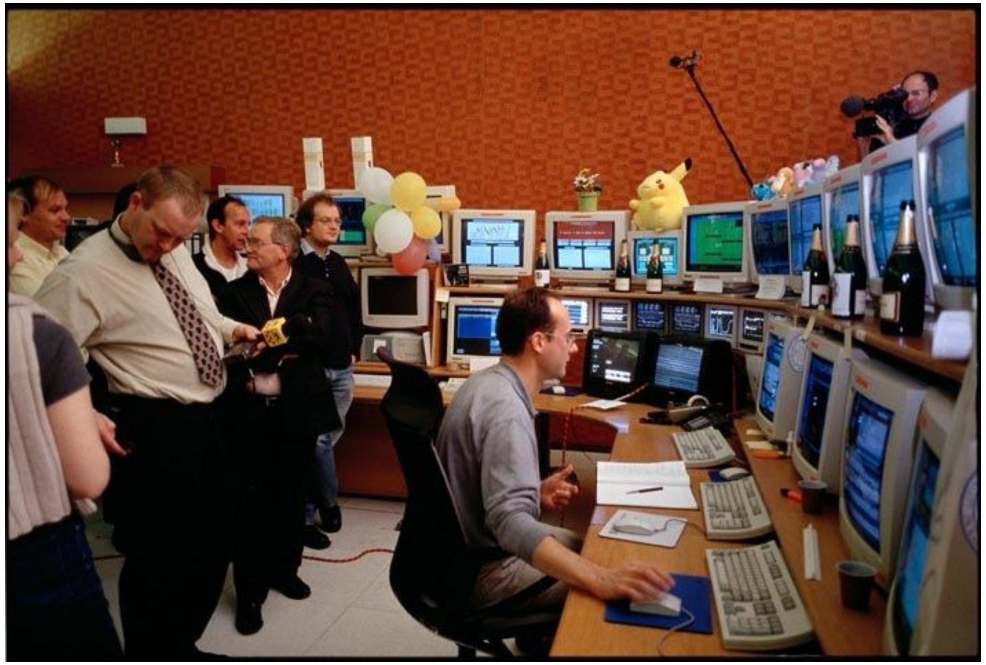


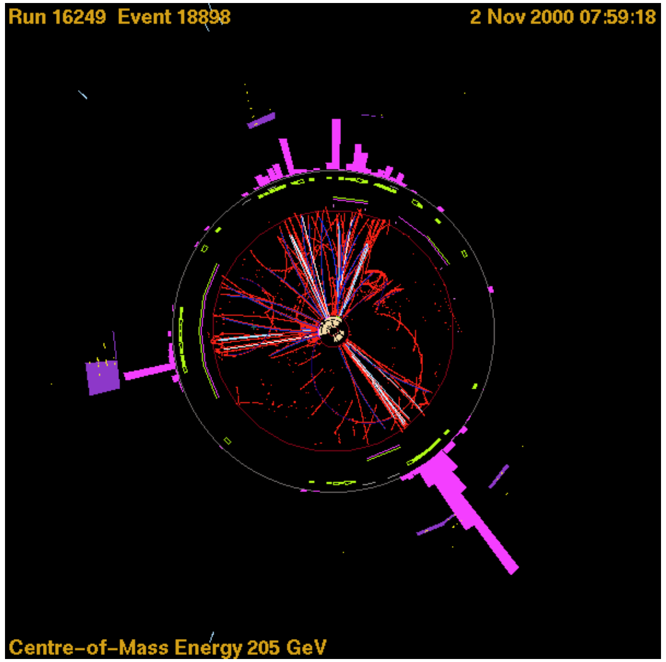
The Large Electron-Positron Collider (LEP)

27 km LEP built to do precision physics on the W and Z

- Largest electron-positron accelerator ever built (to date!)
- Operated 1989 - 2000
- Produced 18 million Zs and 80,000 Ws (1989-2000)





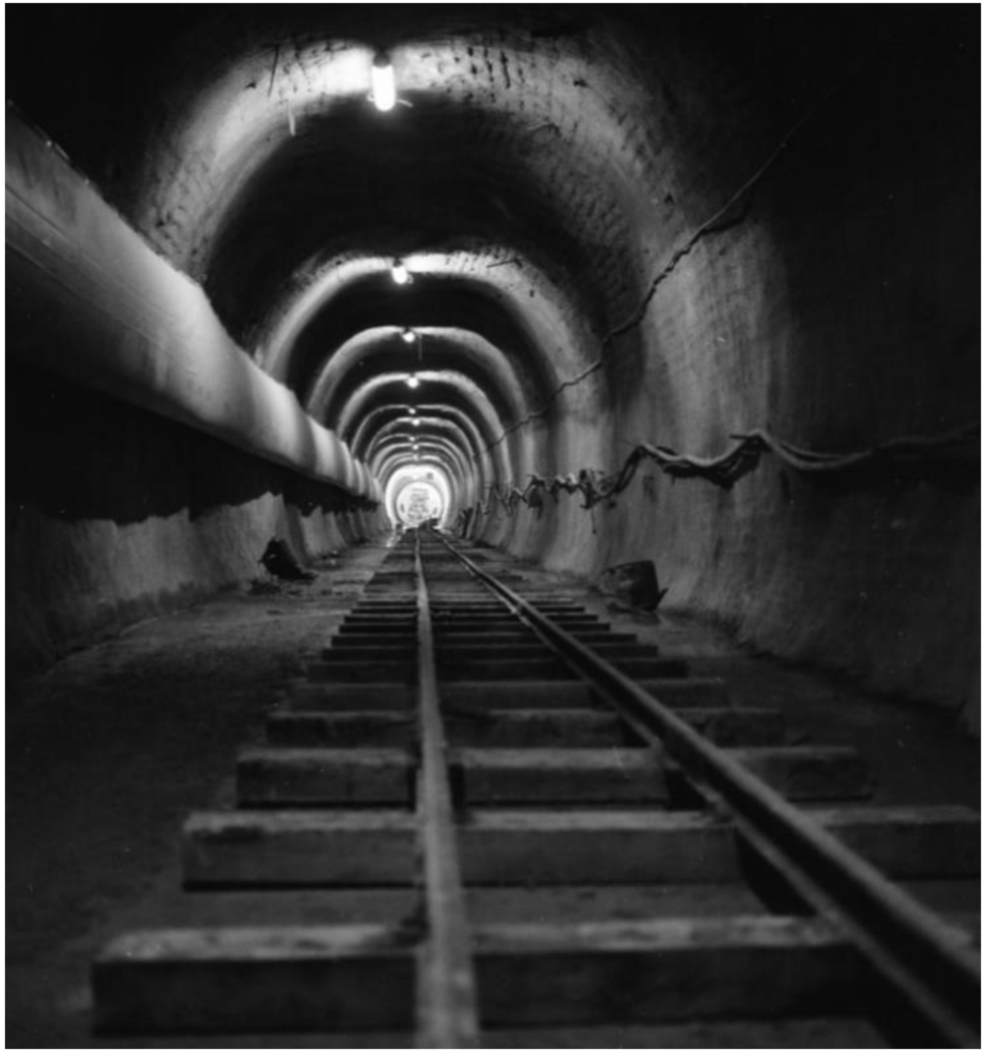


LEP/LHC tunnel named as one of the 50 most iconic tunnels in the world

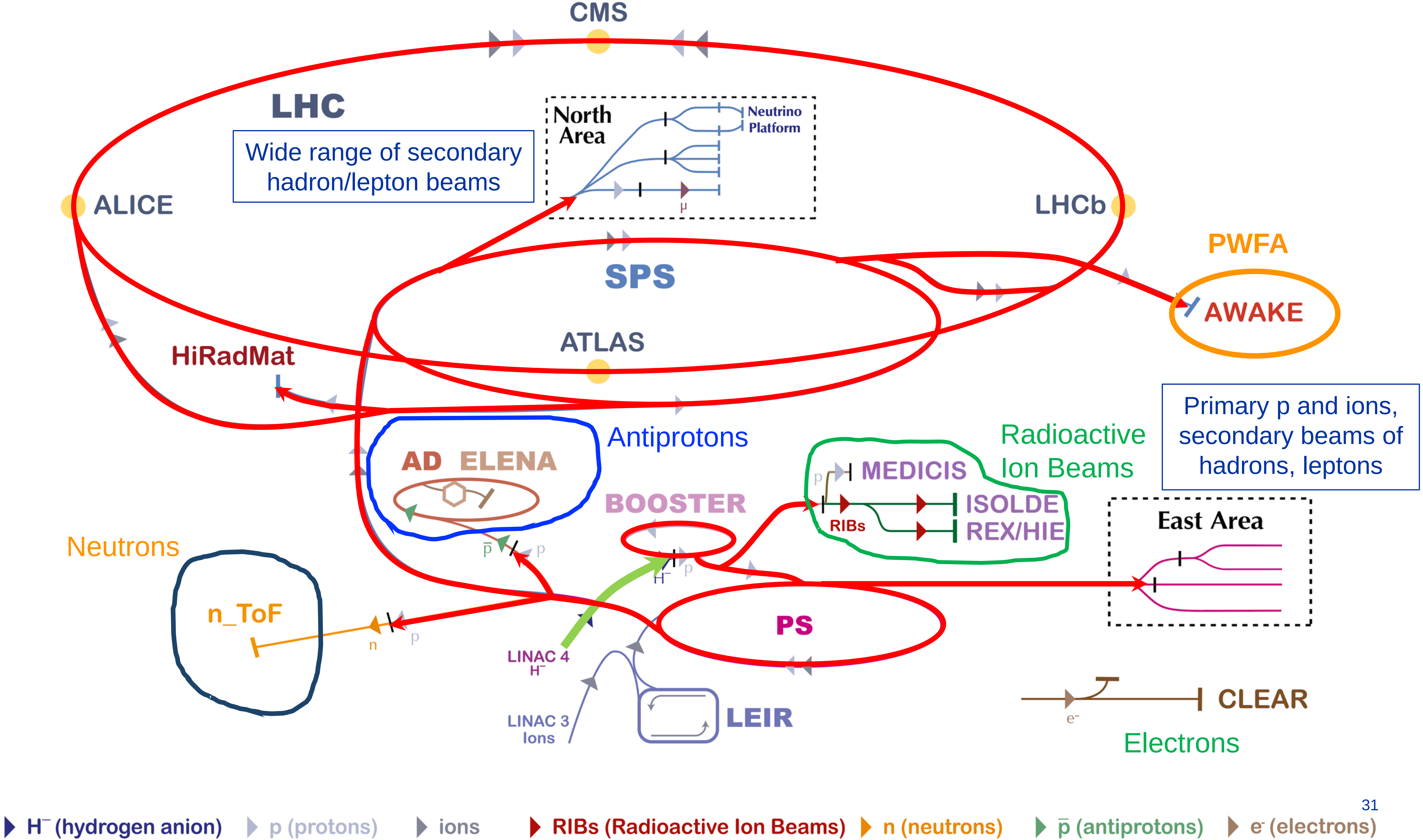
27-km LEP tunnel excavated between 1985 and 1988 using three tunnel boring machines

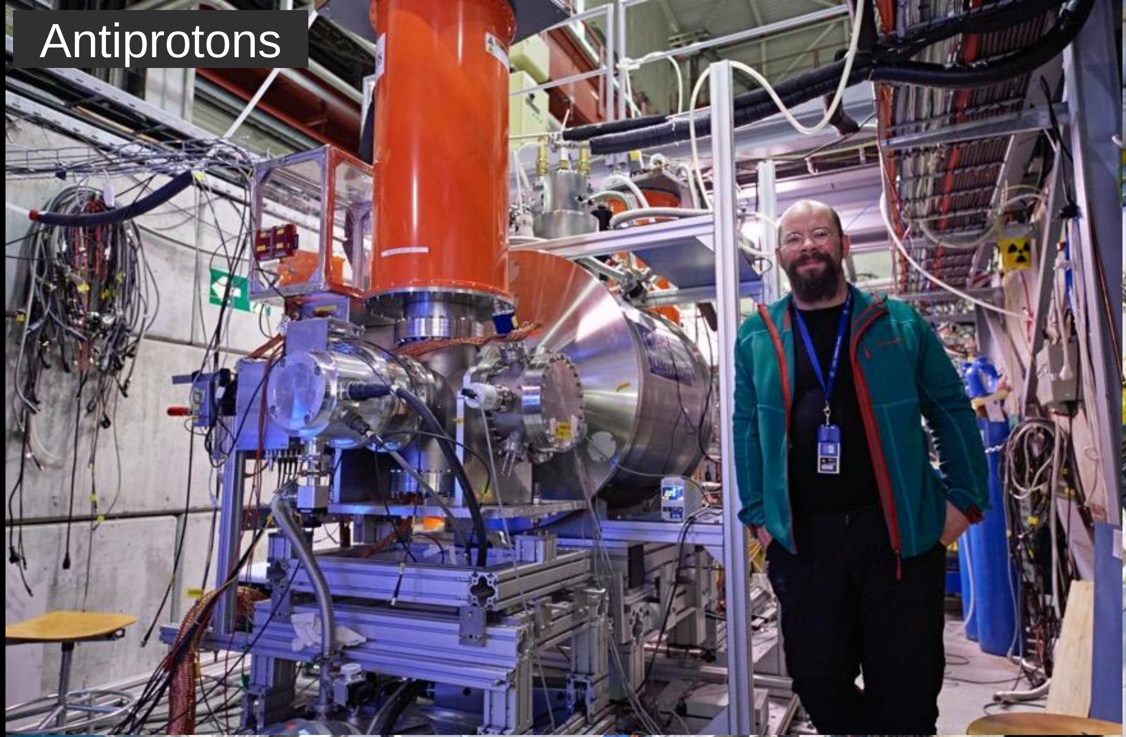
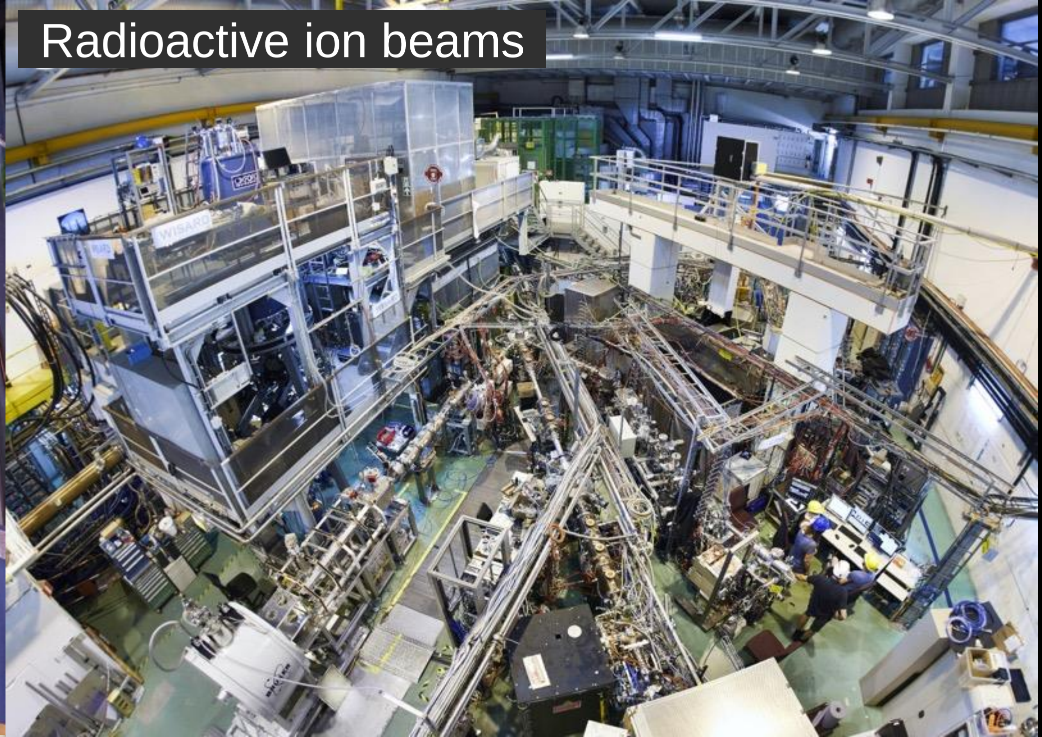
One of the "most remarkable feats of civil engineering" according to ITA (International Tunnelling and Underground Space Association*)

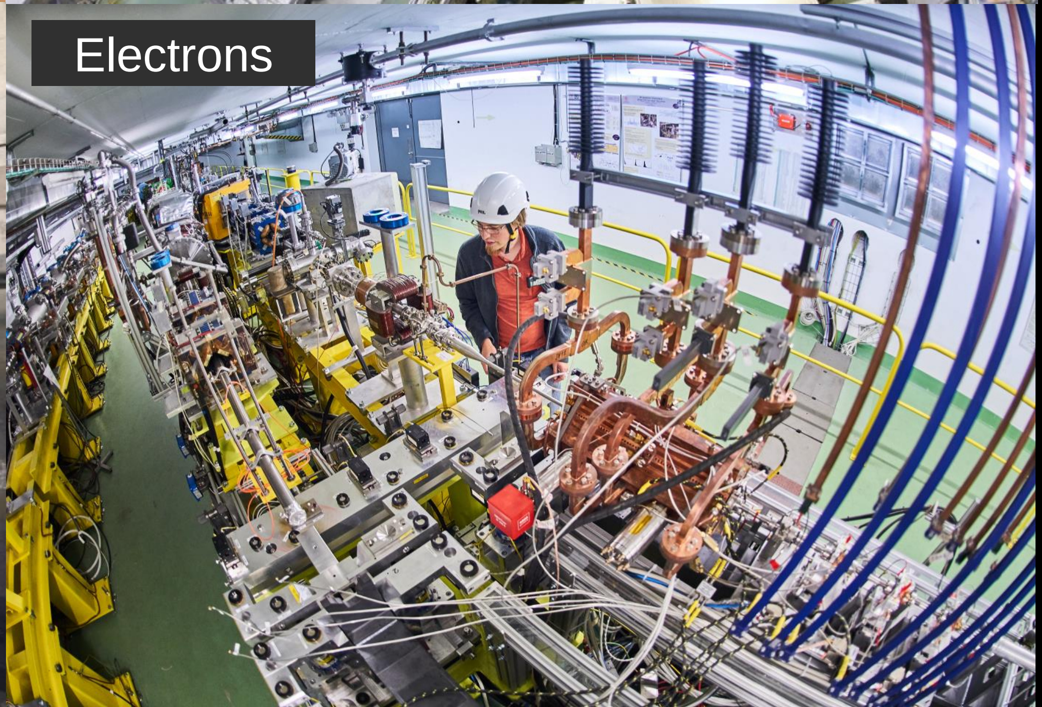
On the occasion of its 50th anniversary, ITA published a commemorative book listing the 50 most iconic tunnels in the world, including the LEP/LHC tunnel (list also includes the Gothard Base Tunnel and the Channel Tunnel)



* Founded in 1974 by the initiative of 19 Nations, ITA's mission is to lead, advocate and facilitate the development of sustainable and innovative solutions for increased, optimised, safe and equitable use of Underground Space.


CMS
LHC
Wide range of secondary hadron/lepton beams
North Area
Neutrino Platform
μ
ALICE
LHCb
PWFA
SPS
AWAKE
ATLAS
HiRadMat
Antiprotons
AD ELENA
p̄
p
Radioactive Ion Beams
Primary p and ions, secondary beams of hadrons, leptons
MEDICIS
ISOLDE
REX/HIE
RIBs
BOOSTER
H⁻
East Area
Neutrons
n_ToF
n
PS
LINAC 4
H⁻
LINAC 3
Ions
LEIR
CLEAR
e⁻
Electrons
H⁻ (hydrogen anion)
p (protons)
ions
RIBs (Radioactive Ion Beams)
n (neutrons)
p̄ (antiprotons)
e⁻ (electrons)


Antiprotons

Radioactive ion beams

Protons

Electrons

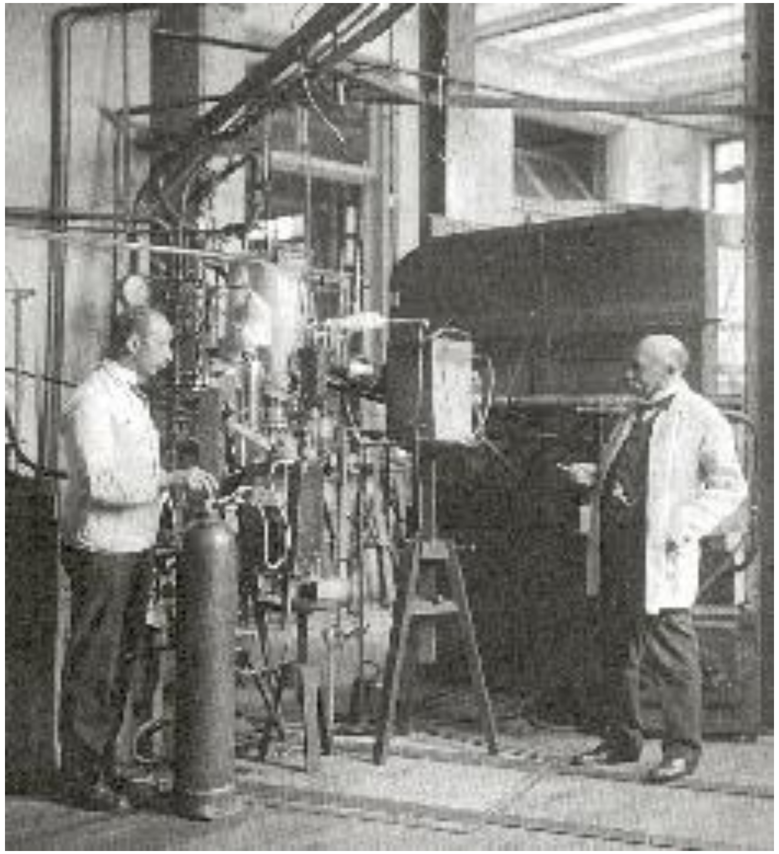
Liquid Helium

- **Helium first liquified at the physics laboratory of Leiden in the Netherlands**

Heike Kamerlingh Onnes

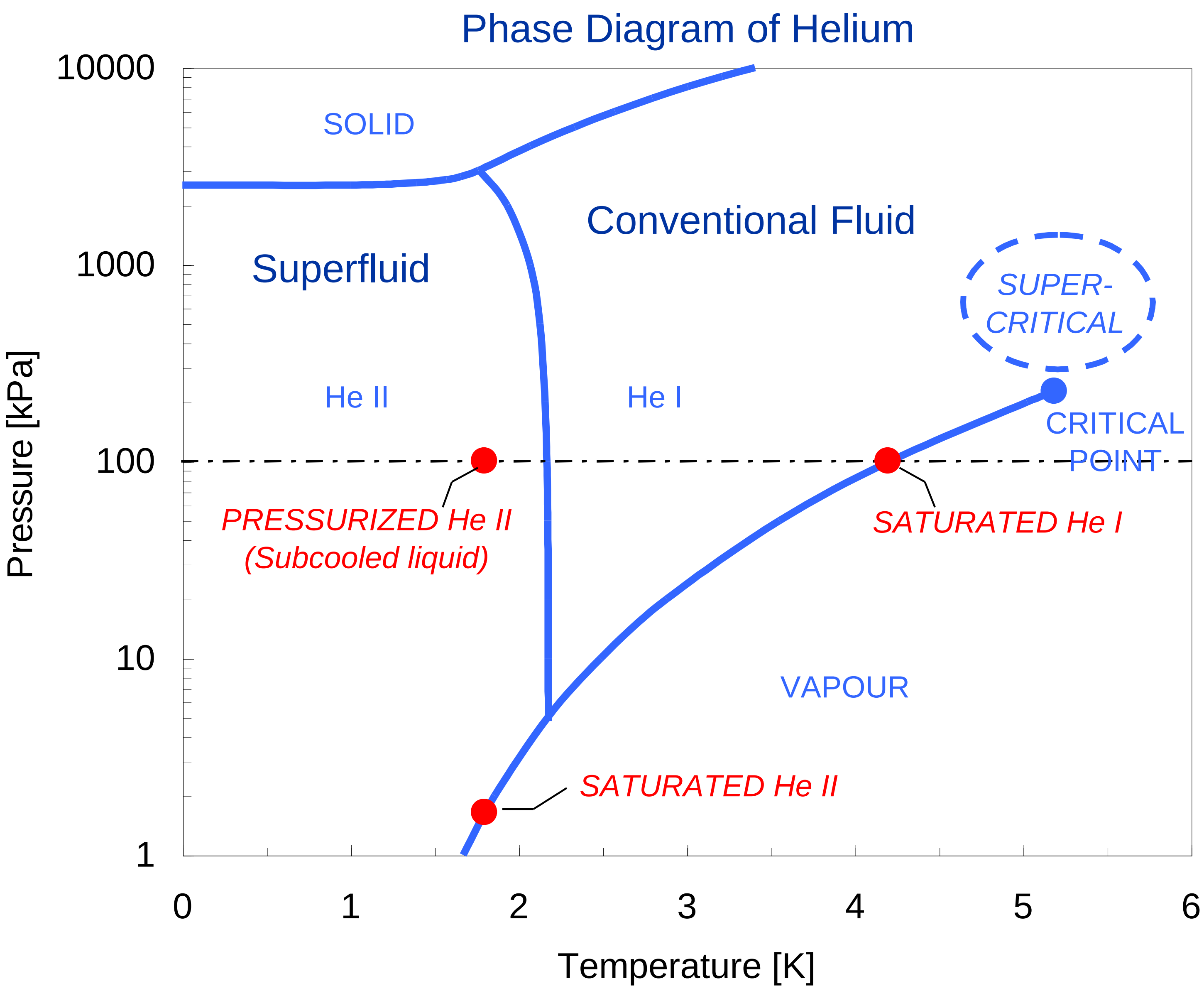
“Door meten tot weten”
To knowledge through measurement

10 July 1908



Liquid Helium

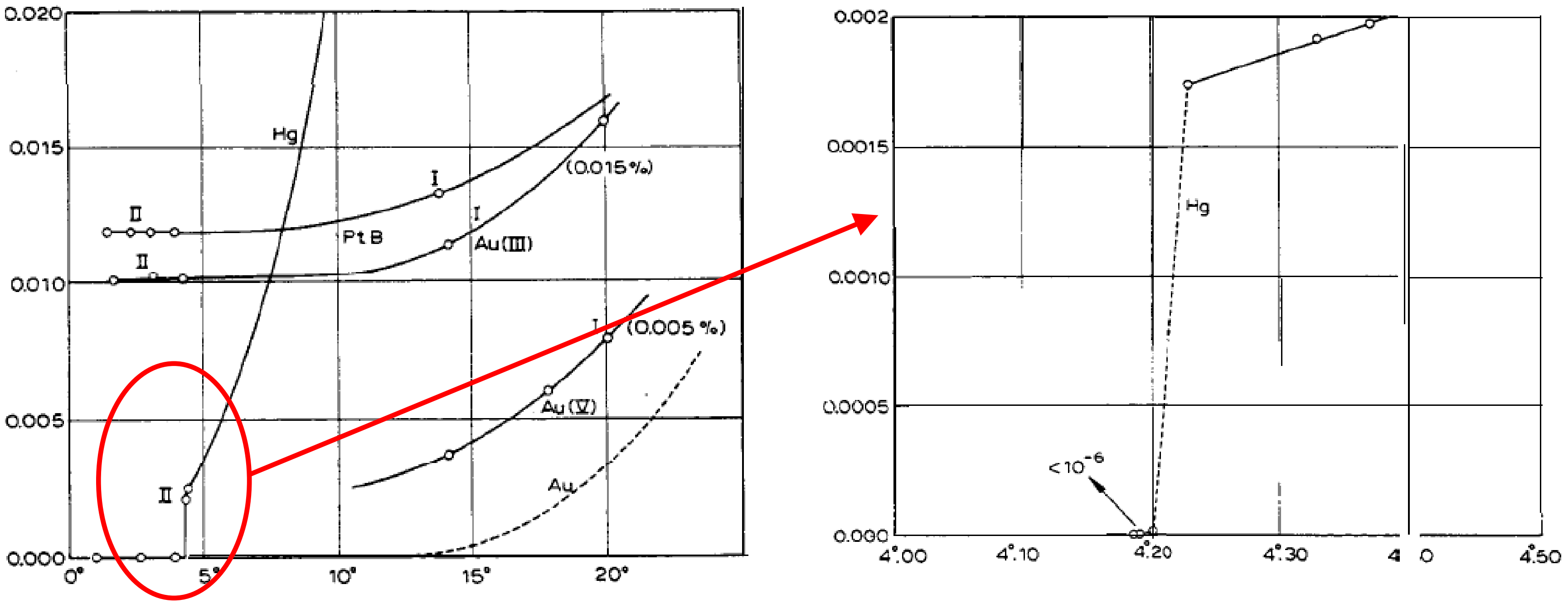
- **The remarkable properties of superfluid helium, He II**
  - Very high thermal conductivity (3000 times that of copper)
  - Very low coefficient of viscosity… can penetrate tiny cracks, deep inside the magnet coils to absorb any generated heat
  - Very high heat capacity…stablises small transient temperature fluctuations



Video 1’44’’

Superconductivity

On 8 April 1911, Kamerlingh Onnes found that at 4.2 K the resistance in a solid mercury wire immersed in liquid helium suddenly vanished

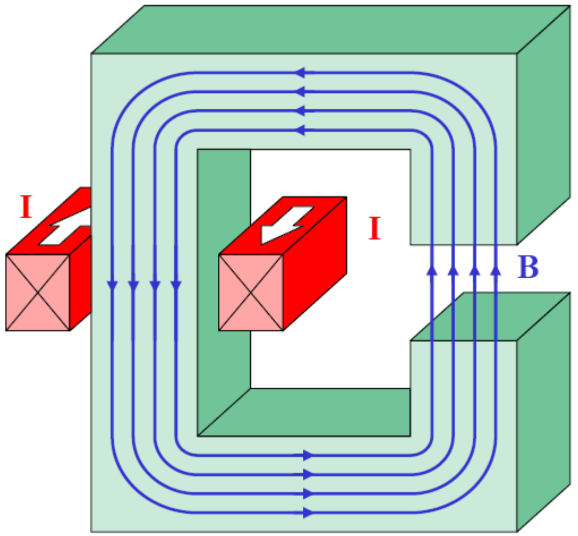


Thus the mercury at 4.2°K has entered a new state, which, owing to its particular electrical properties, can be called the state of superconductivity.

Why use superconductivity?

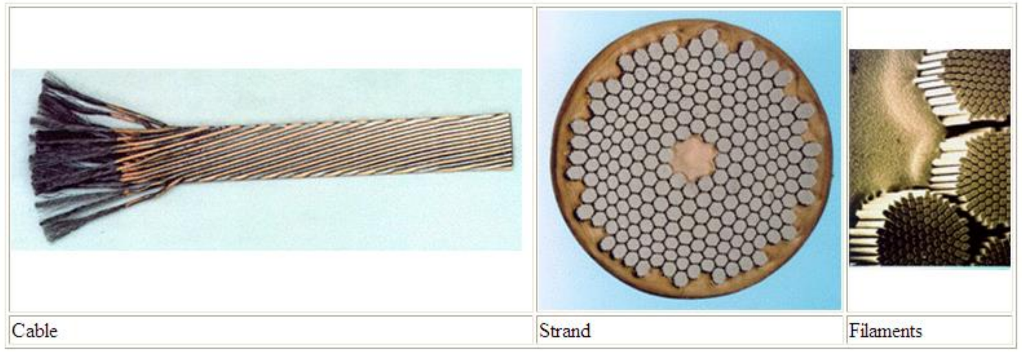
Iron Yoke Magnets

- Good to reduce current required
- Iron guides the magnetic field
- BUT – iron saturates at around 2 T (Tesla)
    - For an accelerator with fixed magnetic field
        - Increasing the energy = increasing the size

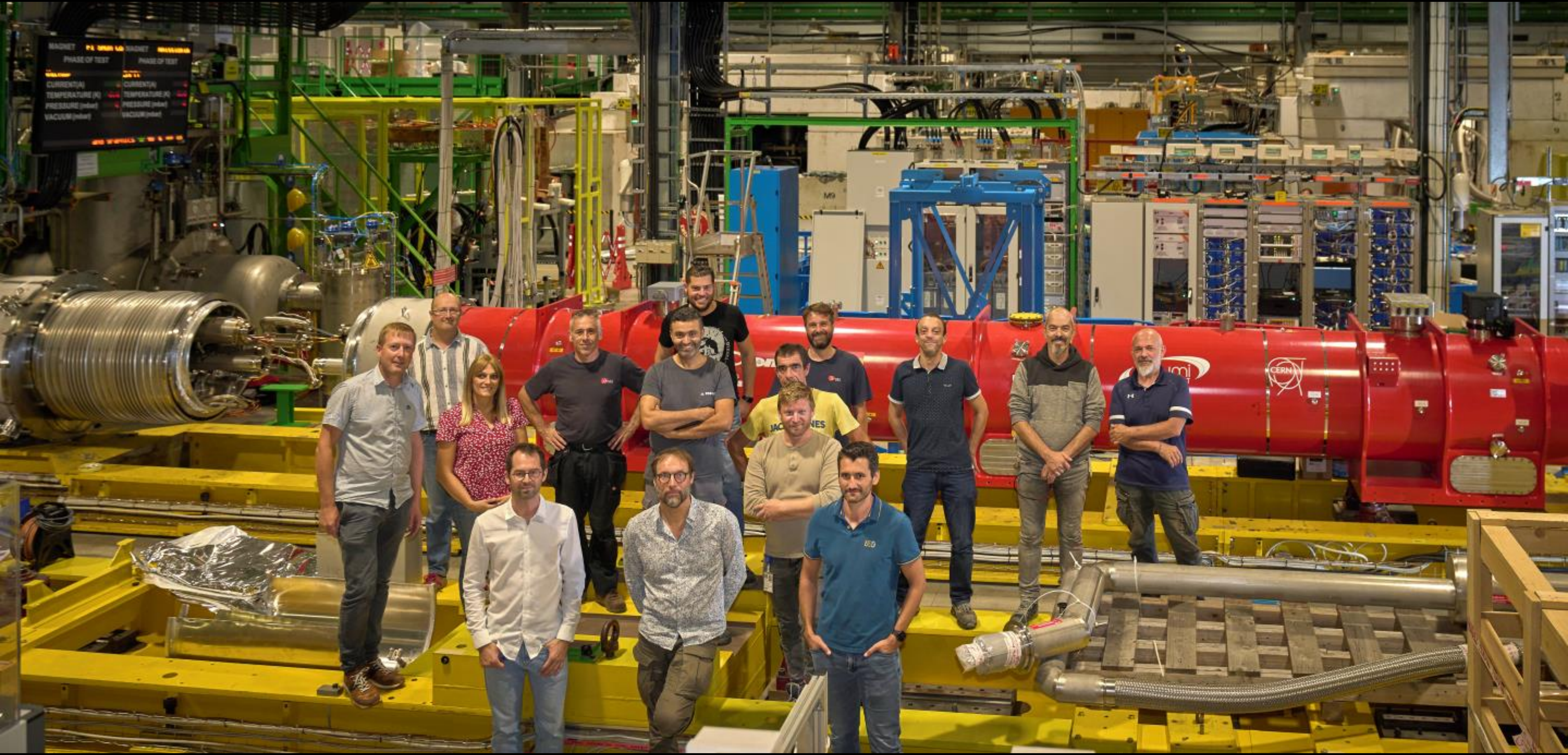


Superconducting Magnets

- Virtually lossless - no resistance!
    - Can carry very high currents to create high magnetic fields
        - **~8 T in LHC**
    - BUT the wire needs to be cooled to near absolute zero



CERN staff sitting on the first PS main magnet at the École de Physique 1955

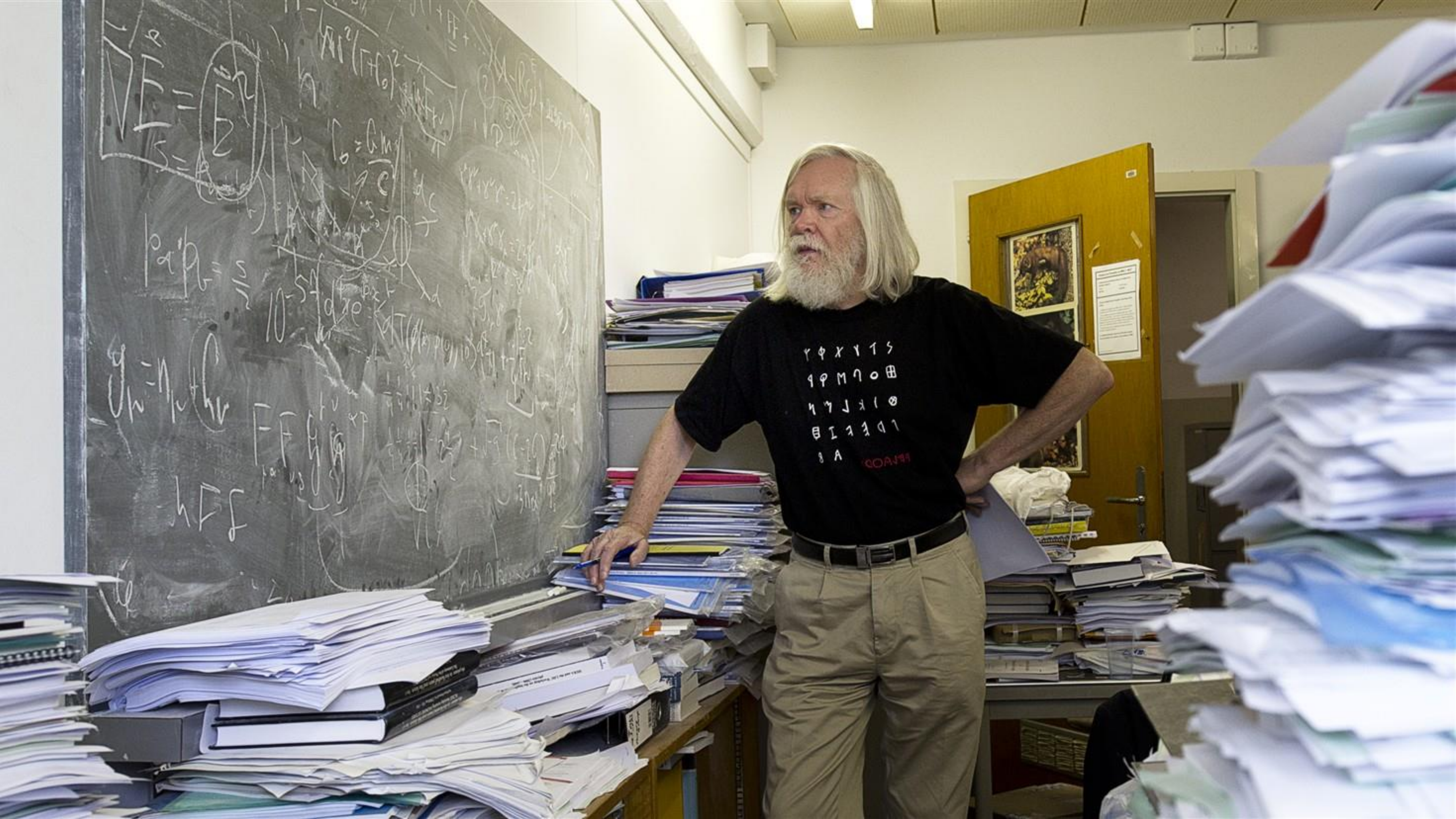


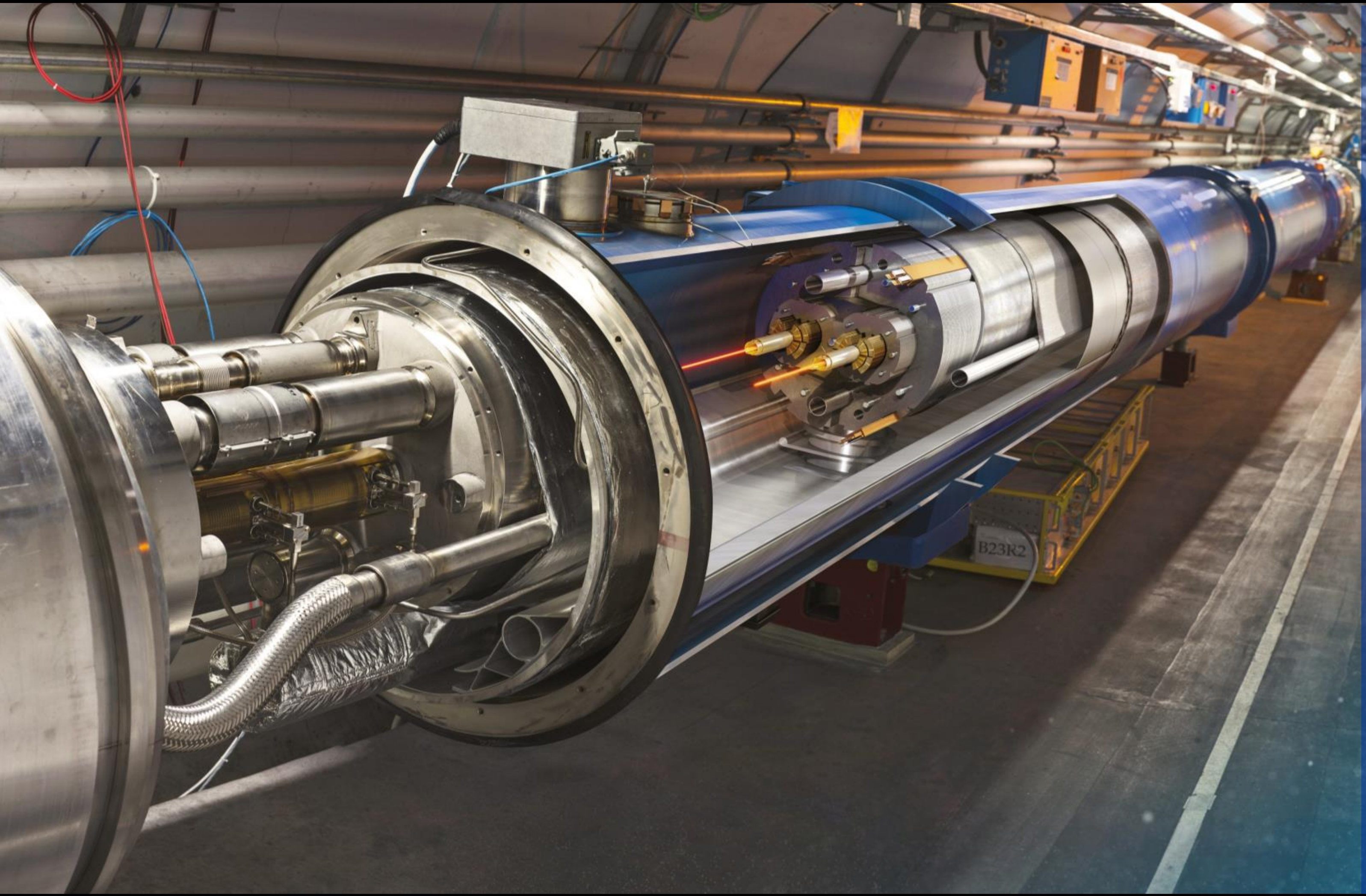
CERN staff in front of one of the first High Luminosity LHC quadrupoles 2023


Our goal is to understand the most fundamental particles and laws of the universe.

We kids ask
basic and deep questions
How did the Universe begin?
What is its fate?
What is made of?
What are the basic laws?
Why do we exist?
Where do we come from?
What can I do Daddy?

Thanks to Hitoshi Murayama

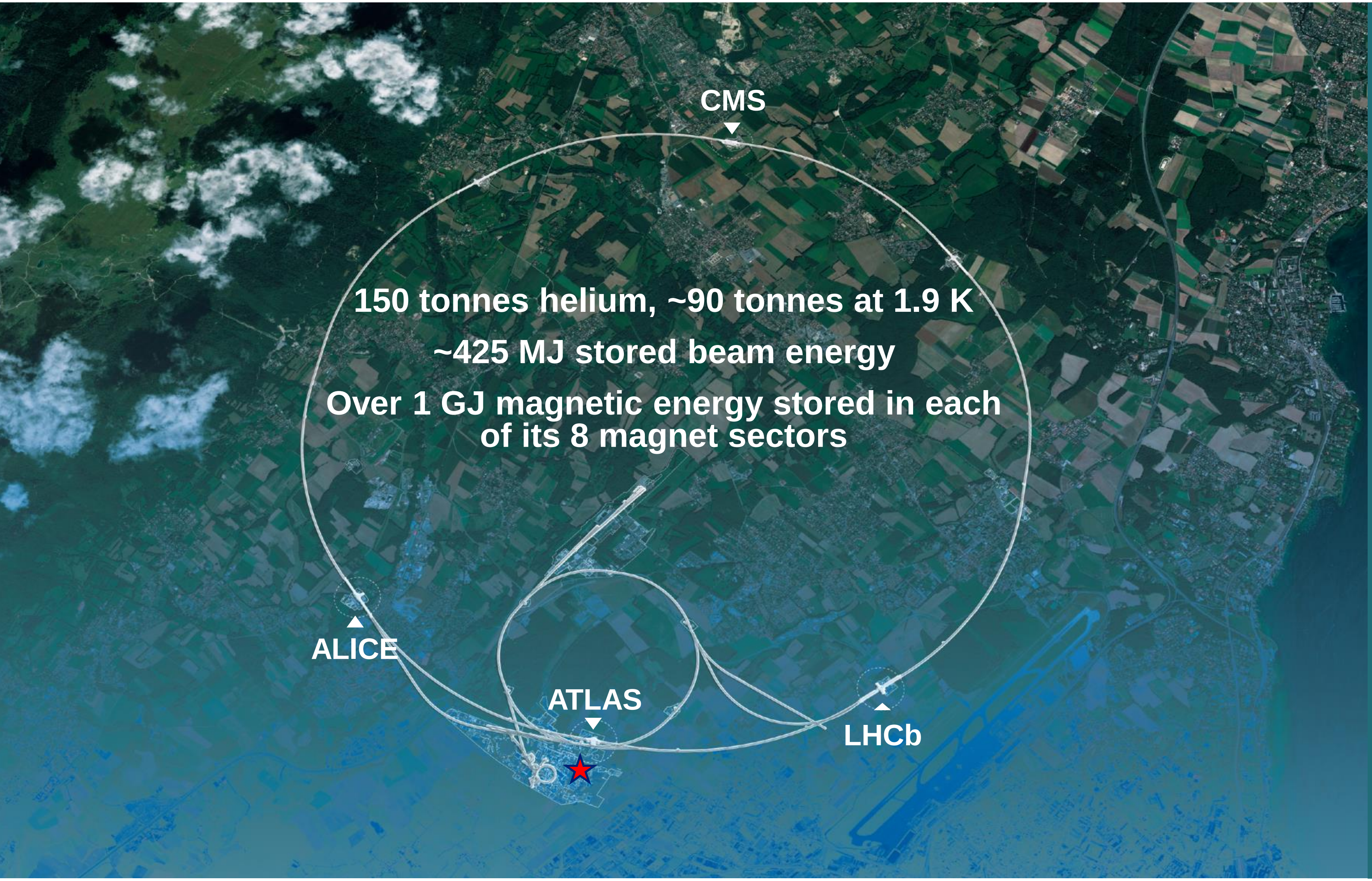


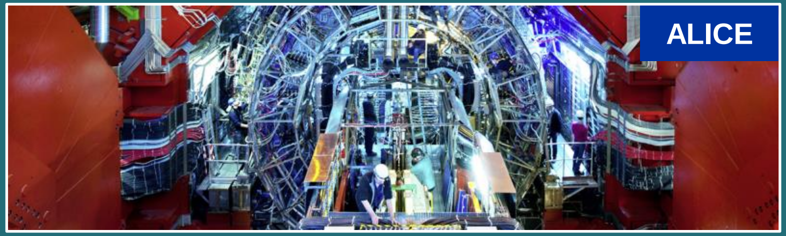


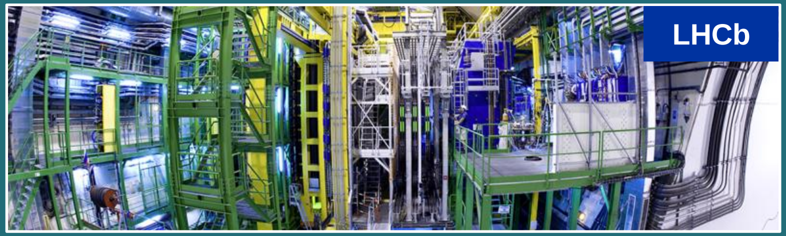
The Large Hadron Collider

- 27 km in circumference
- About 100 m underground
- 2 beams of trillions of protons travelling at 0.999999991 times the speed of light in opposite directions
- Superconducting radiofrequency system to accelerate the beams
- NbTi Superconducting magnets operating at - 271.3 °C to bend them in a circle
- Largest beam vacuum system worldwide
- Advanced powering, machine protection systems, beam diagnostics & control
- 4 large experiments

The LHC and its Detectors







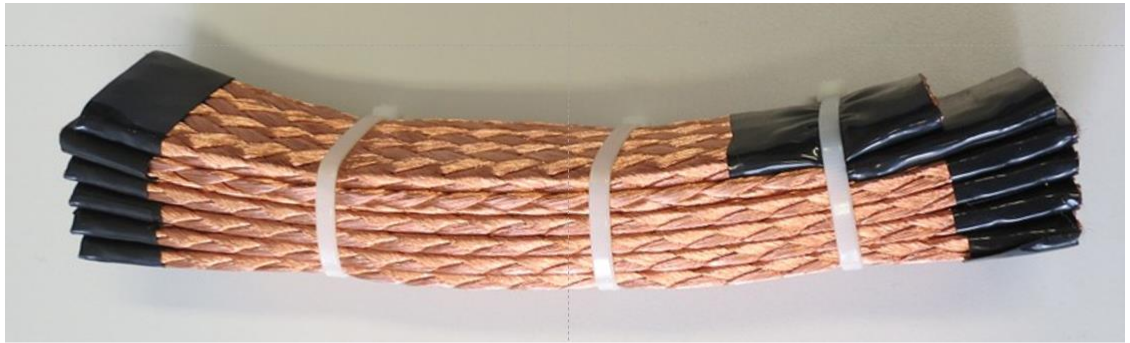
Announcement of Higgs discovery July 4th 2012

with a quadrillion collisions…

Why is the LHC Superconducting?

- A standard household power cable can carry 13 Amps of current
  - 13 Amps at Room Temperature

- A magnet strong enough for the LHC needs 13’000 Amps
  - 13’000 Amps at Room Temperature

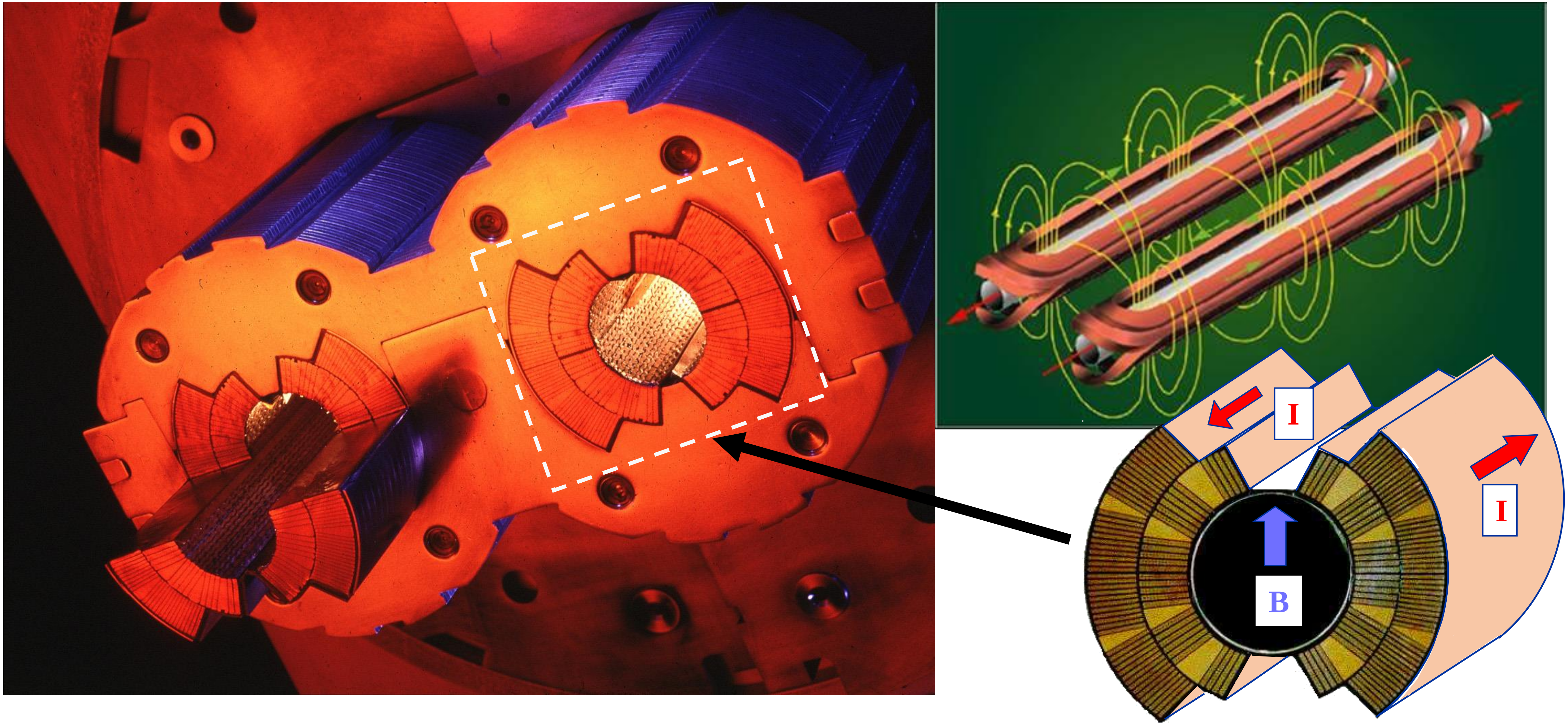


  - 13’000 Amps at -271 ºC

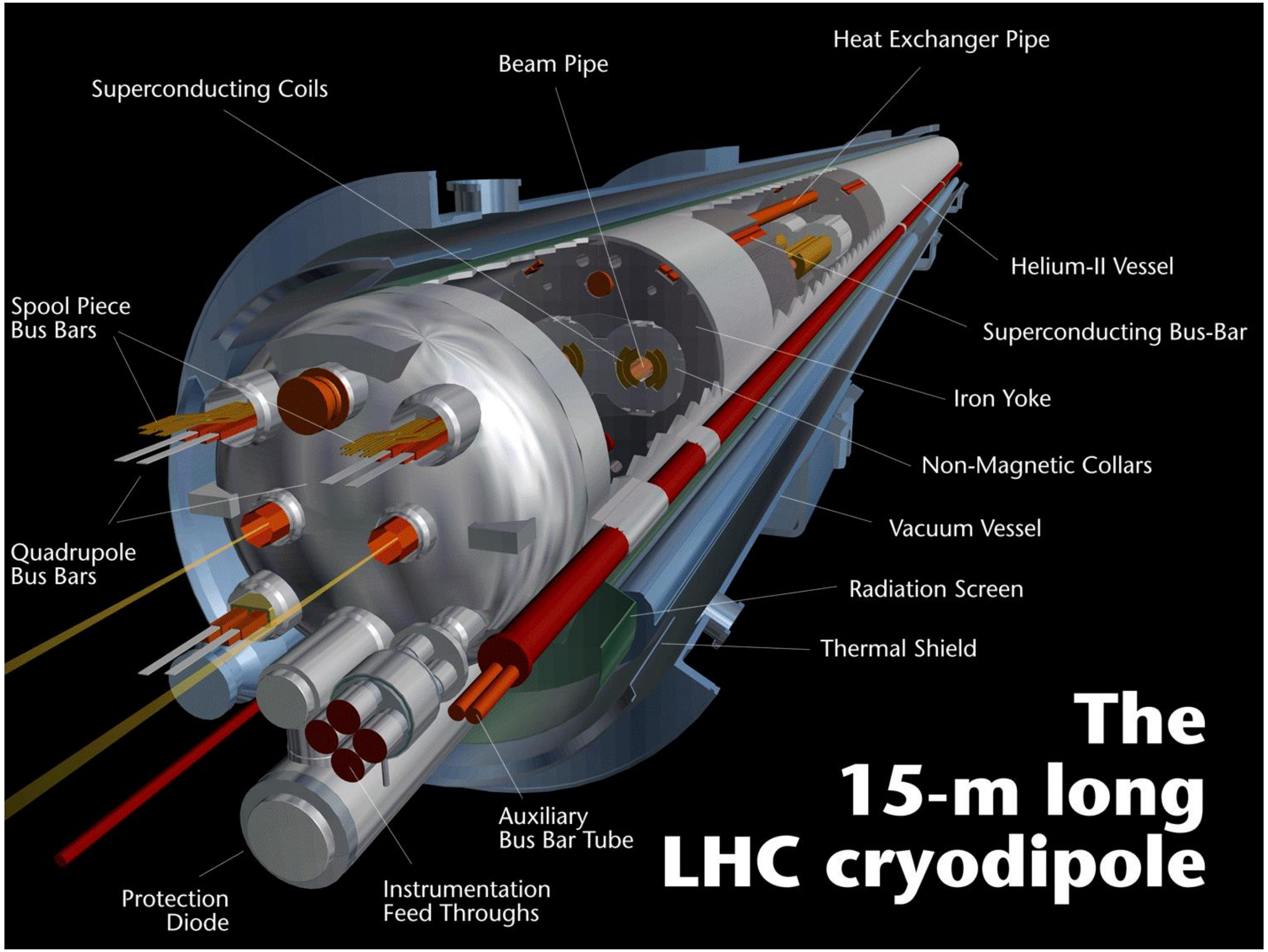
Scale

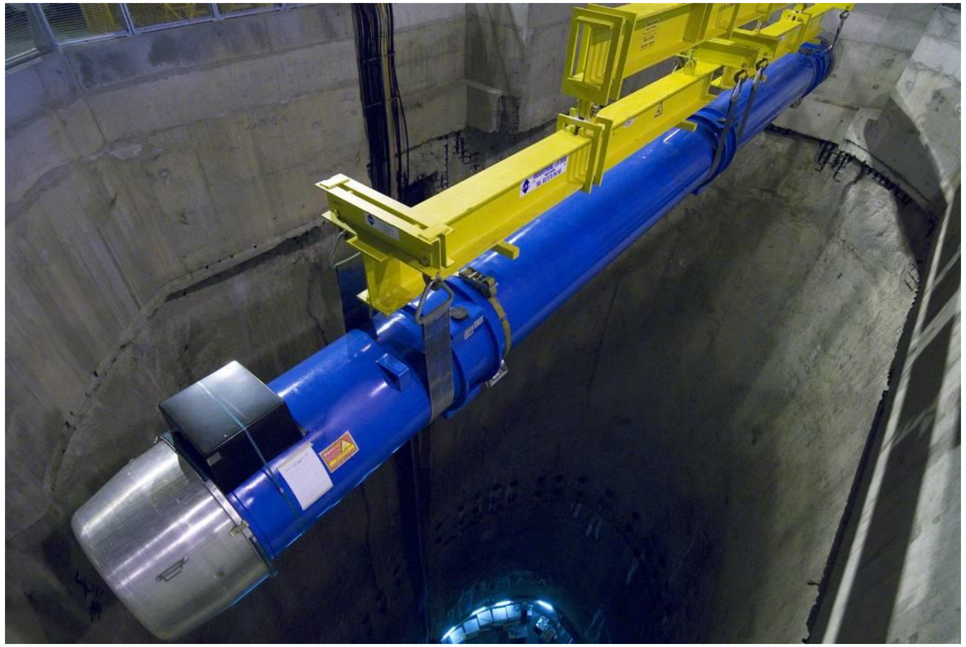
- Using superconducting cable operating at 1.9 Kelvin (-271 ºC) was the only way to produce magnets for the LHC

LHC Dipole Magnets



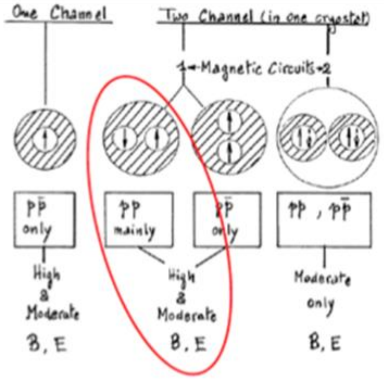
LHC Dipole Magnets





LHC Dipole Magnets – the long road to success

ECFA-CERN workshop



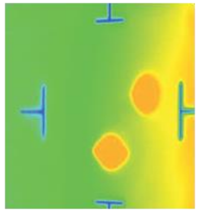
June 1994
first full scale prototype dipole

1994 project approved by council (1-in-2)

SSC cancelled

June 2007 First sector cold

April 2008
Last dipole down



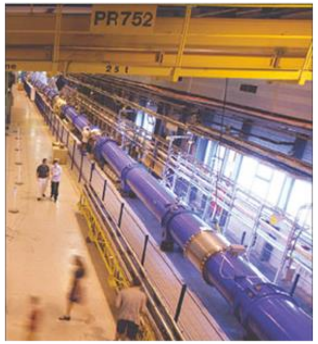
Main contracts signed

September 10, 2008
First Beam

84 | // | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10

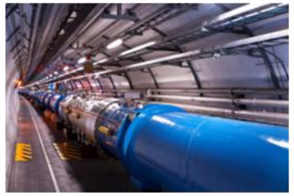
First set of twin 1 m prototypes
Over 9 T

2002 String 2



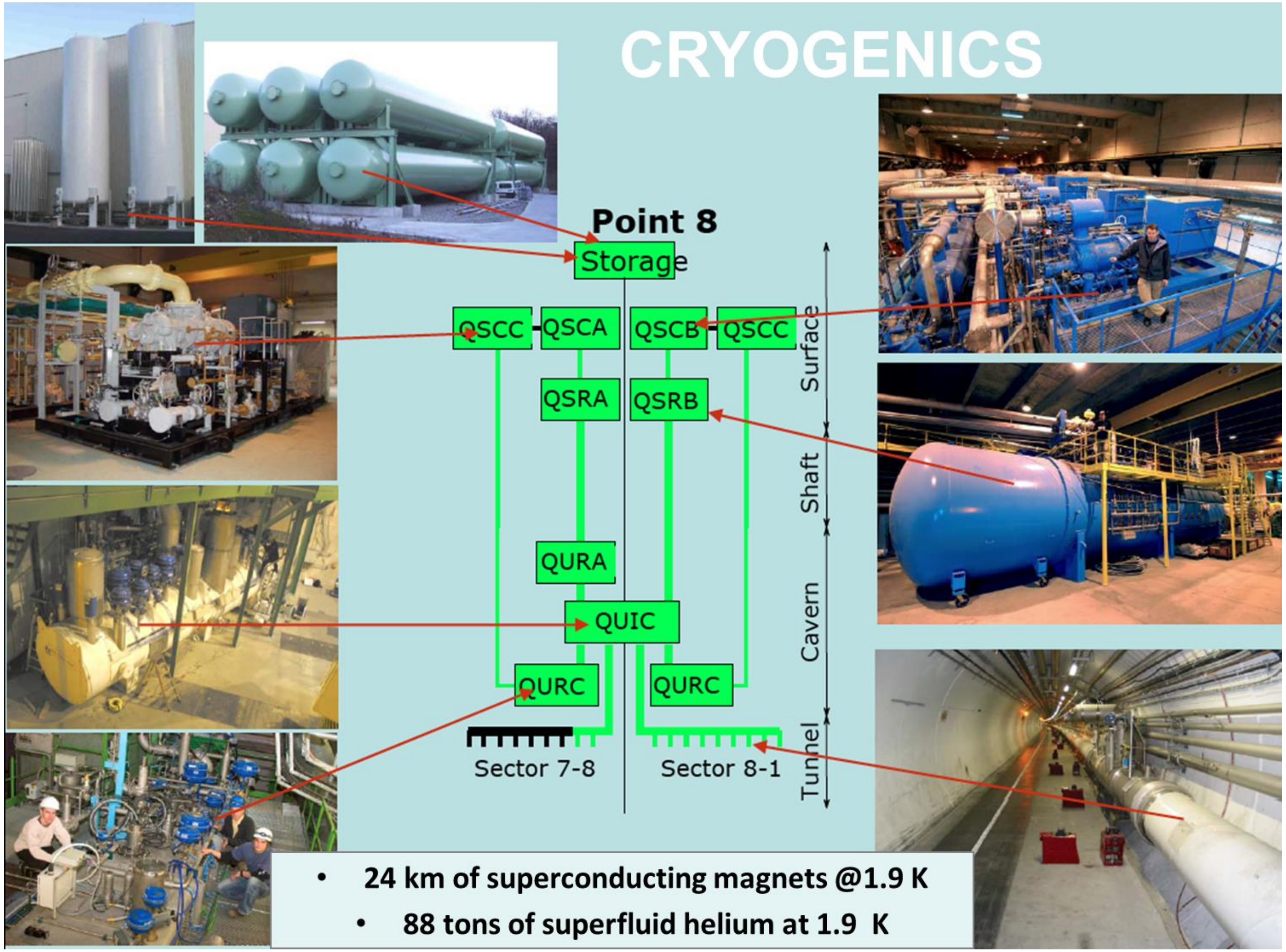
November 2006
1232 delivered

September 19, 2008
The incident



November 20, 2009
Run 1 begins

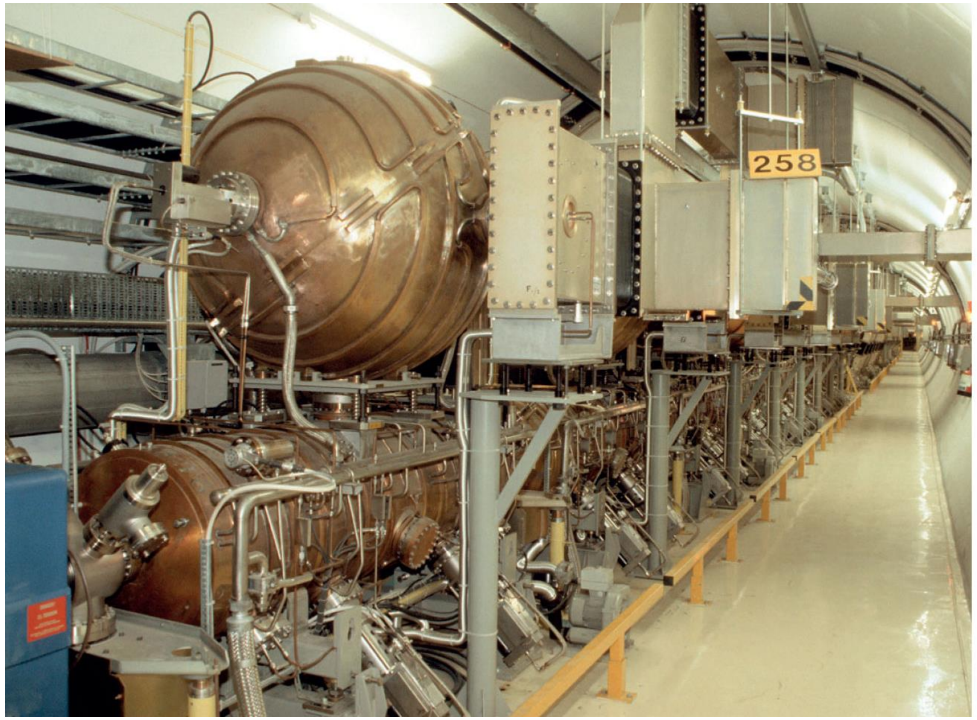
Cooling the Magnets

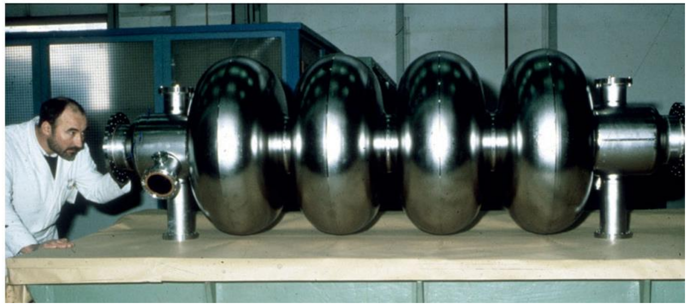


Superconducting Acceleration Cavities

Superconducting radio frequency (SRF)

- Ultra-low electrical resistivity of superconducting material allows an RF resonator to store energy with very low loss over a narrow bandwidth so that nearly all the RF power goes to the beam
- Copper cavities used to accelerate particles in LEP later replaced by superconducting niobium RF cavities to double the collider’s energy beyond the pair-production threshold for W bosons



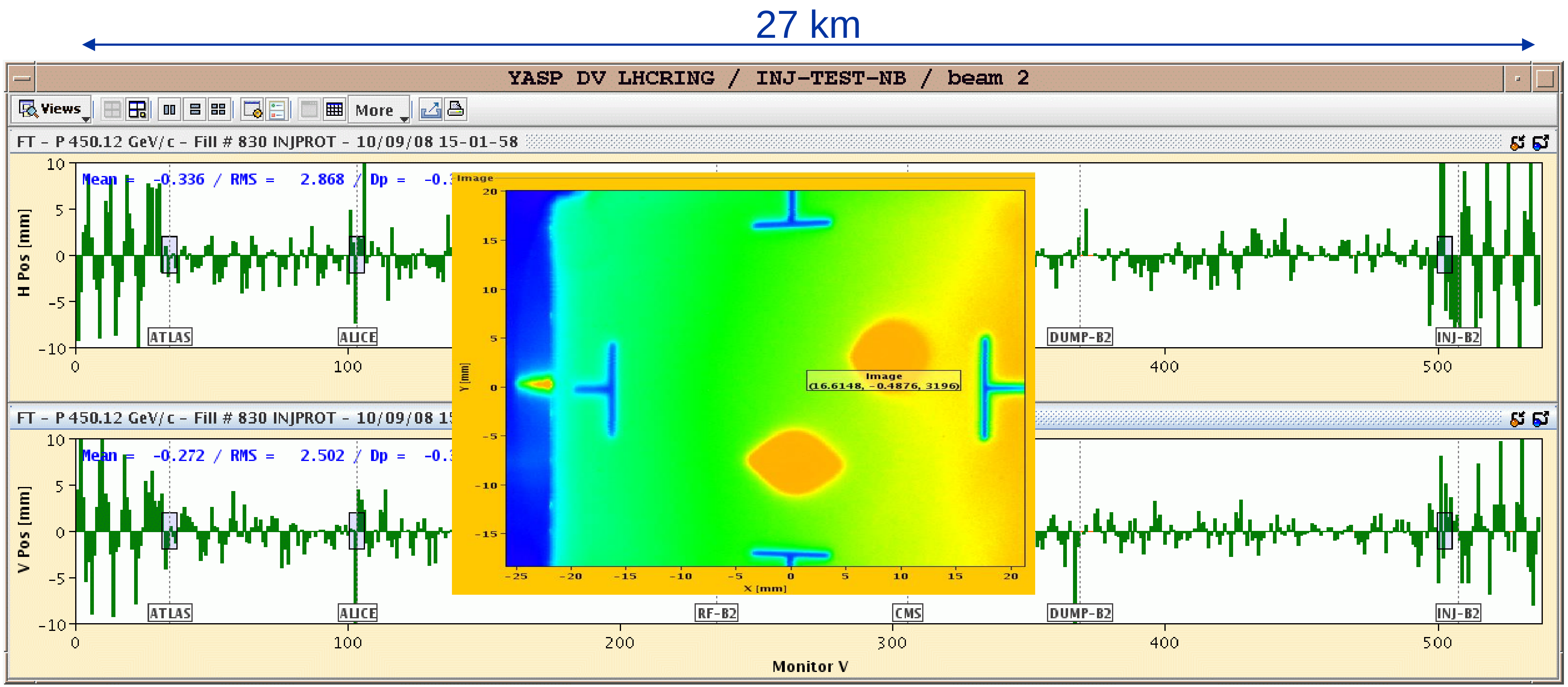


Acceleration in the LHC

- **The acceleration section of the LHC is only 30 m in length**
- **Contains 2 modules per beam, 4 cavities per module**
  - Providing up to 2 x 4 x 2 MV = 16 MV of accelerating gradient
- **It LHC takes ~30 minutes to reach top energy (~20 million turns)**
  - Driven by how fast the magnetic field can be ramped-up rather than the RF

Controlling the Beams

- **Beam Instrumentation - over 500 position monitors per beam**
  - Automatic feedback systems measure the beams & correct trajectories by adjusting magnetic field to keep them within 10 microns of desired position

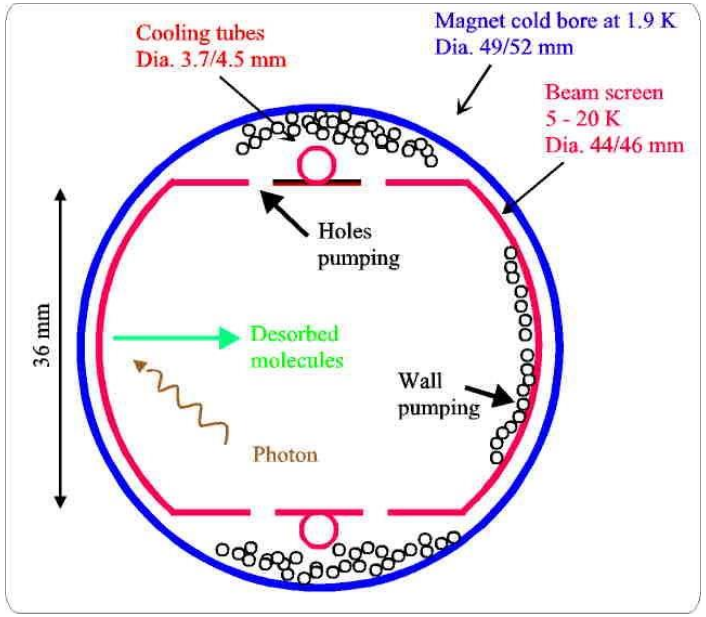


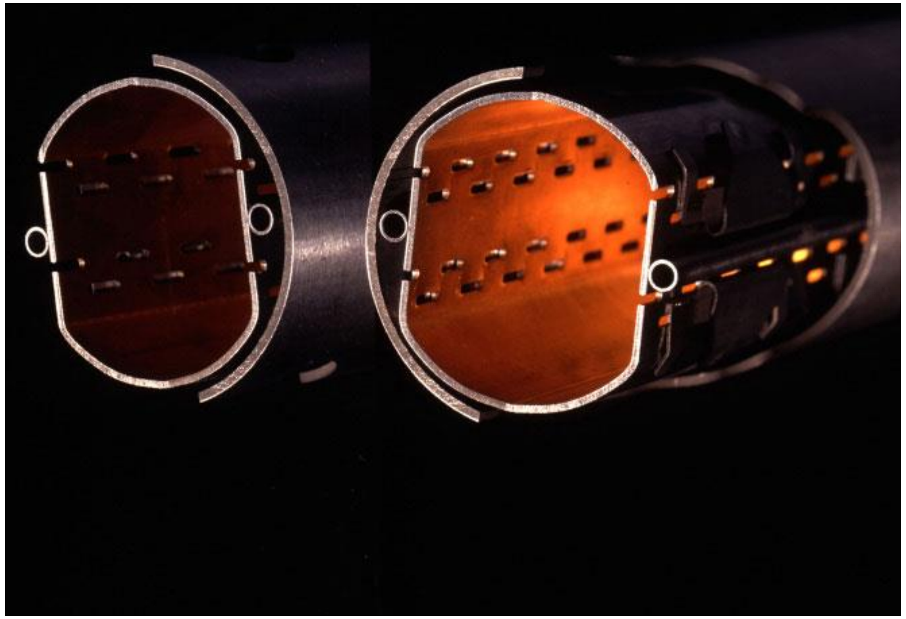
Controlling the Beams

- **Synchrotron light monitors**
  - The protons have such a high energy that they emit light when bent by the magnetic field
    - “synchrotron radiation”
  - Looking at this light allows us to measure the size of the individual proton bunches in the LHC

LHC Vacuum

Beam vacuum ~10^{-10} mbar (~3 million molecules/cm^3)

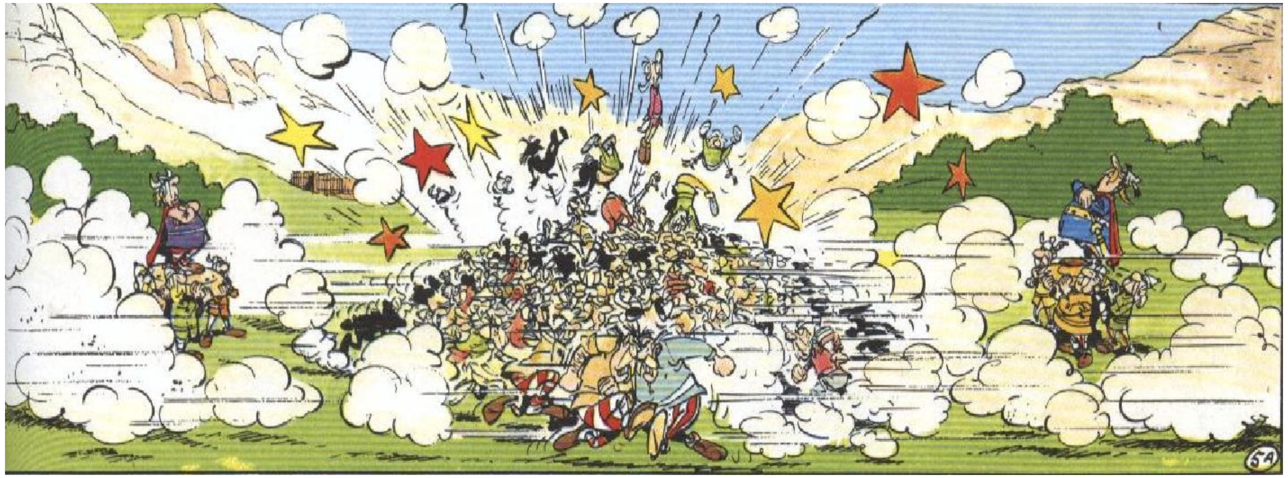


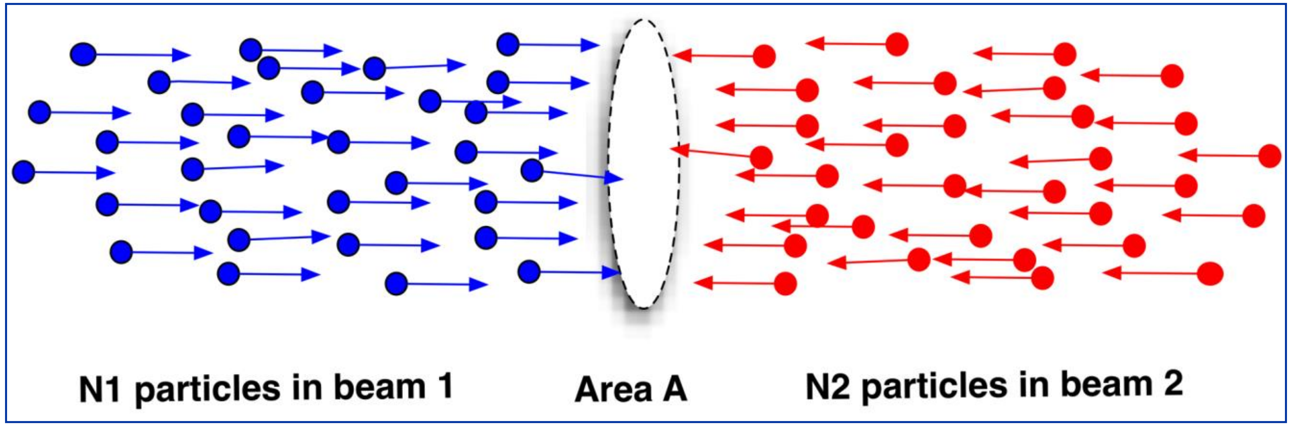


- **Cold**
  - Pumping is insured by cold surfaces for all gases except helium
  - Low initial pressures are required before cool-down and this is ensured by turbo molecular pumps
- **Warm**
  - Non-evaporable getter (NEG) provides most of the pumping capacity

Aim of the Game

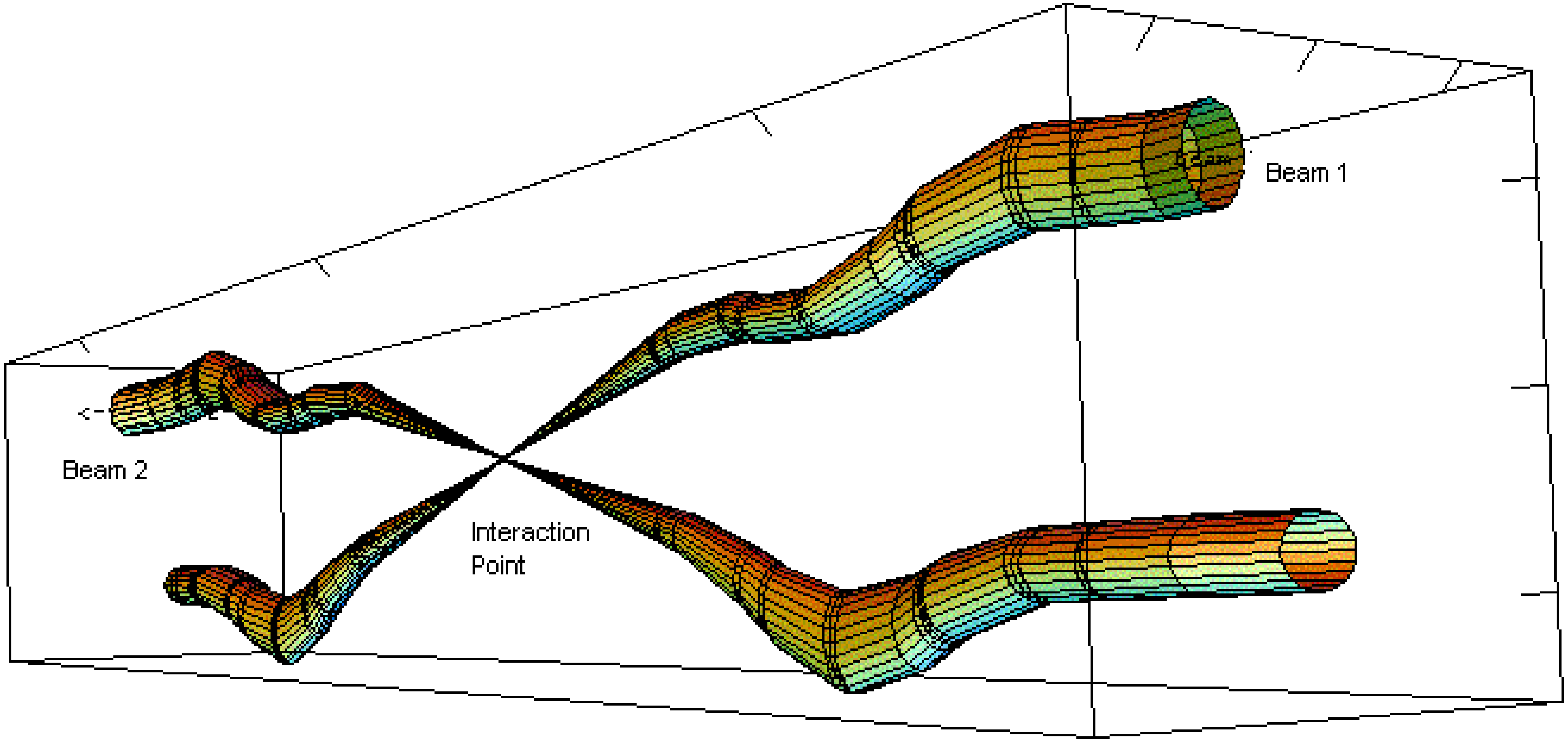
To deliver the maximum number of collisions at the maximum beam energy for maximum physics reach – LUMINOSITY Counts!





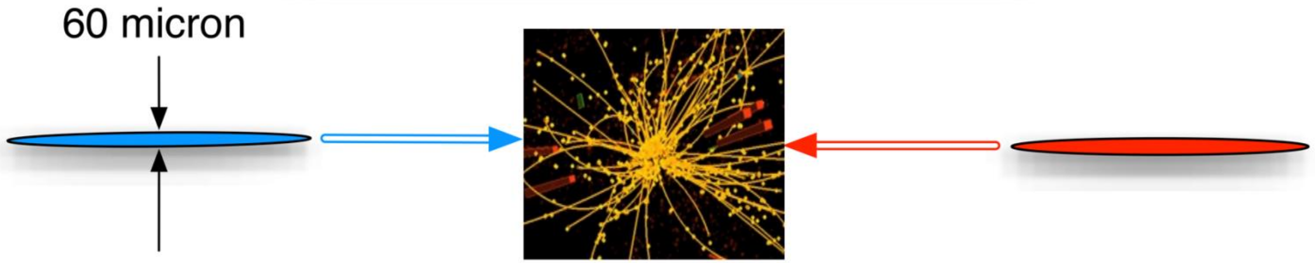
The Squeeze

- **Focusing the beams at the interaction point**



Collisions in the LHC

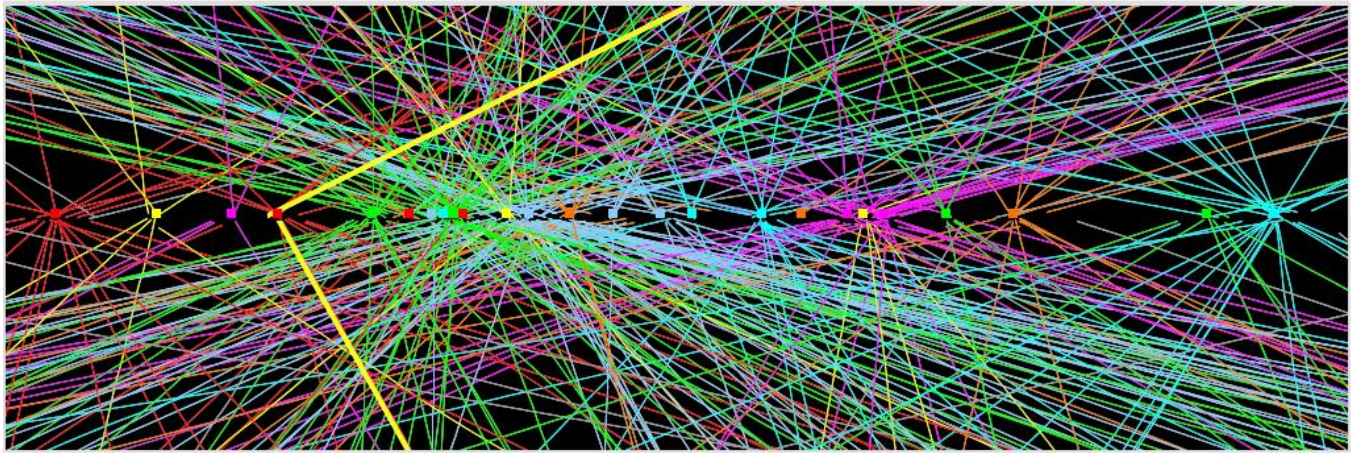
140,000,000,000 protons a bunch
~30 collide at each bunch crossing



~30 collisions per crossing
11,000 crossings per second per bunch
1380 bunches
~400 million collisions per second

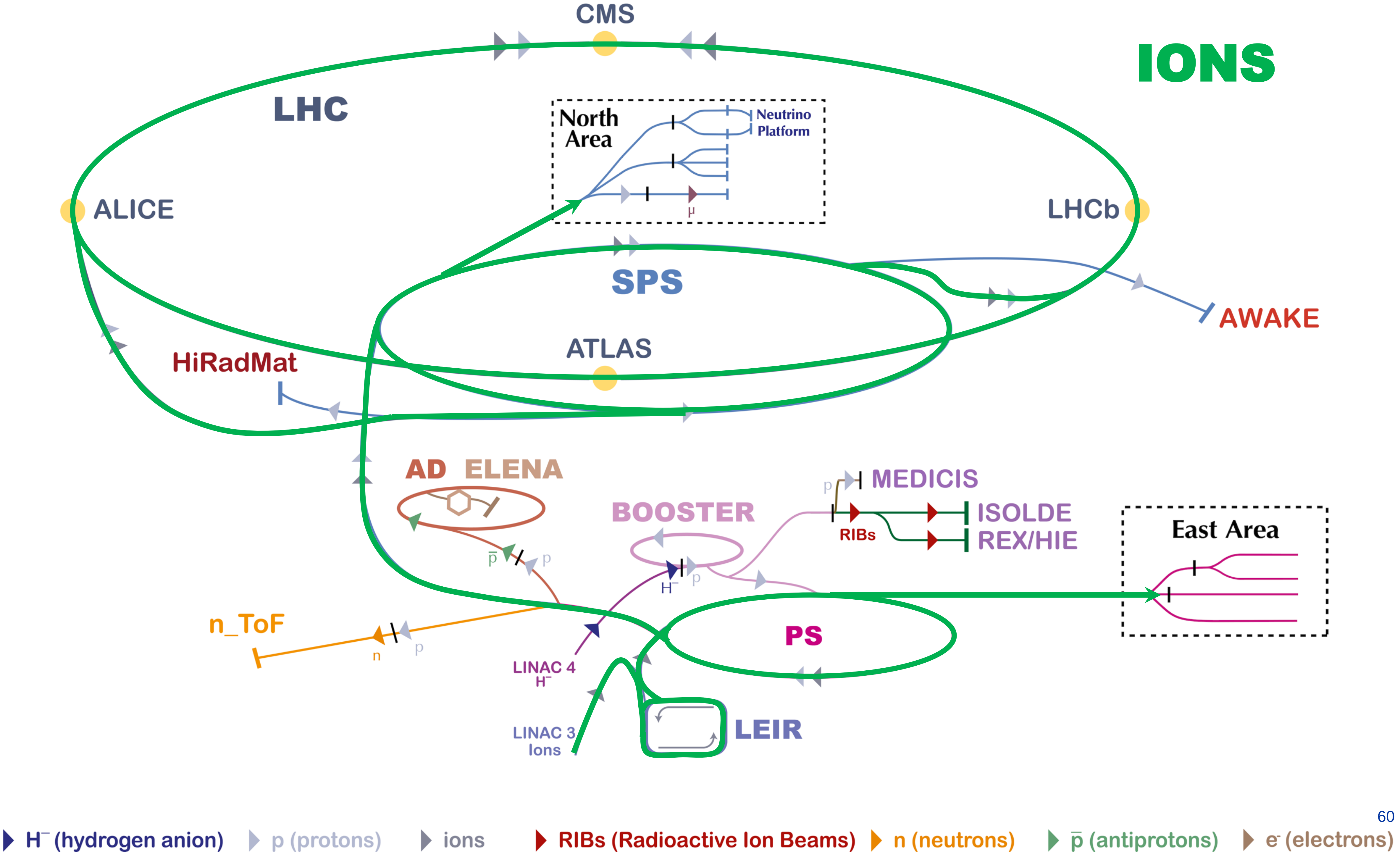
Now regularly operating with

- 1.6 x 10^{11} protons per bunch
- Over 2000 bunches
- Up to 65 collisions per bunch crossing
- 1.5 billion collisions per second



LHC Page 1

IONS



CMS
LHC
North Area
Neutrino Platform
μ
ALICE
LHCb
SPS
AWAKE
ATLAS
HiRadMat
AD
ELENA
BOOSTER
MEDICIS
ISOLDE
REX/HIE
RIBs
East Area
n_ToF
PS
LINAC 4
H⁻
LINAC 3
Ions
LEIR
H⁻ (hydrogen anion)
p (protons)
ions
RIBs (Radioactive Ion Beams)
n (neutrons)
p̄ (antiprotons)
e⁻ (electrons)

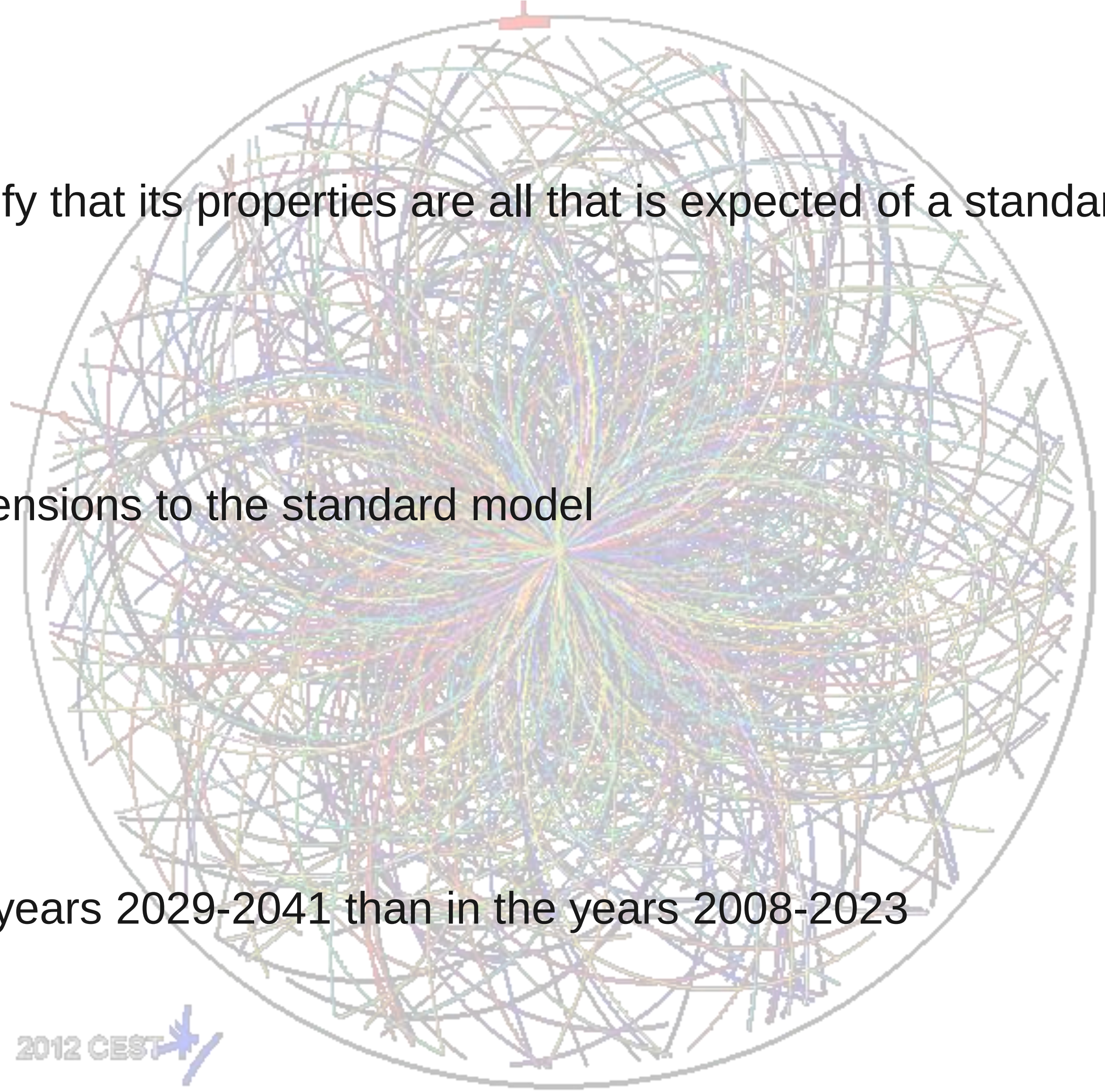

CERN

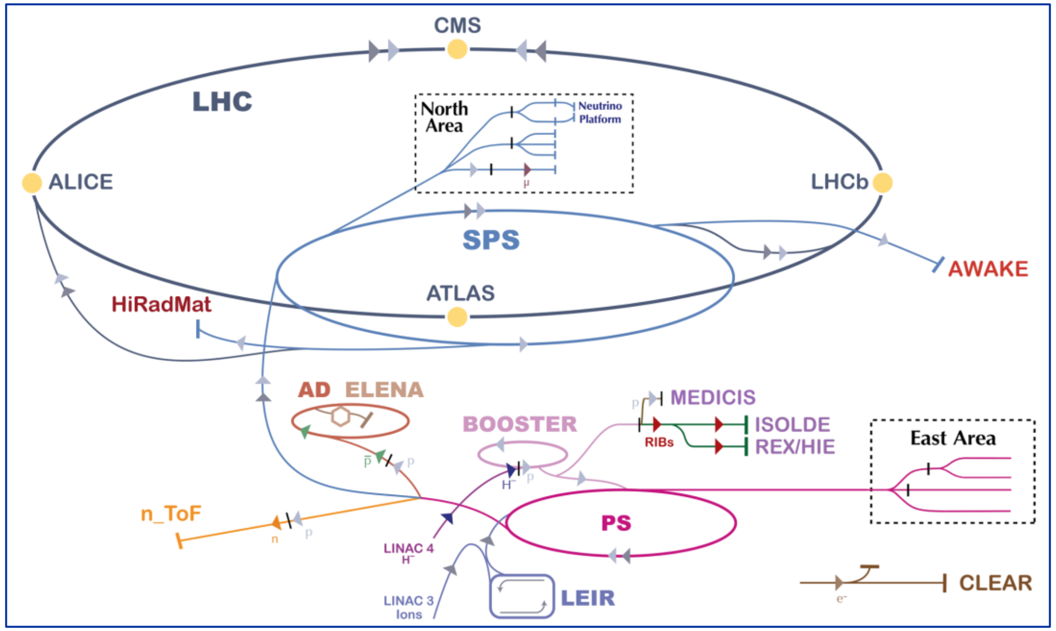
What next for the LHC?

- **Studying the Higgs particle in detail**
  - It will take time and much more data to verify that its properties are all that is expected of a standard model Higgs Boson, portal for new physics

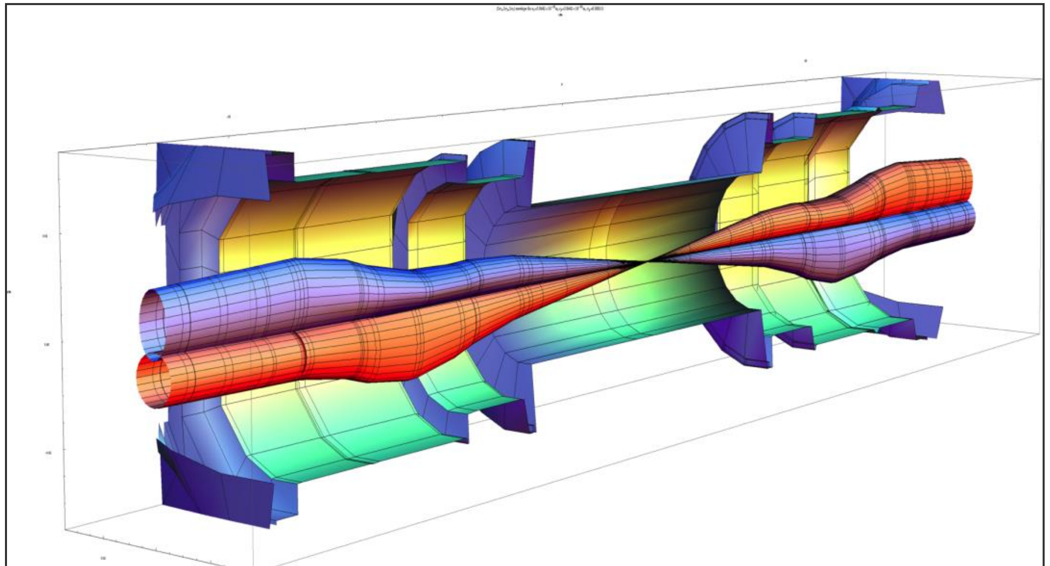
- **Looking for new physics**
  - Constraining theoretical alternatives or extensions to the standard model
  - All this relies on much more data

- **Upgrading to High Luminosity LHC**
  - Foreseen for 2026-28
  - Aim is to collect 10 times more data in the years 2029-2041 than in the years 2008-2023

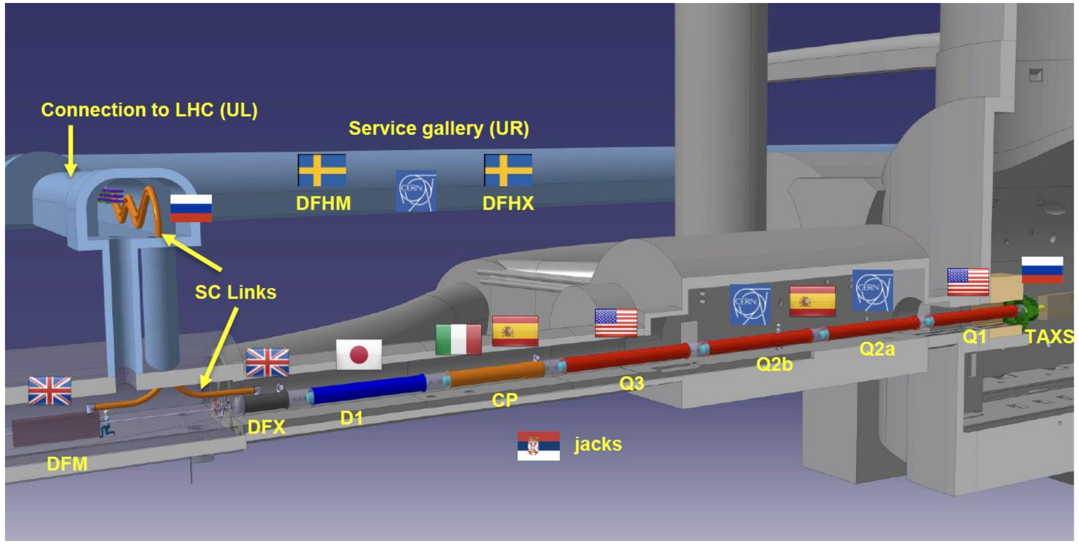


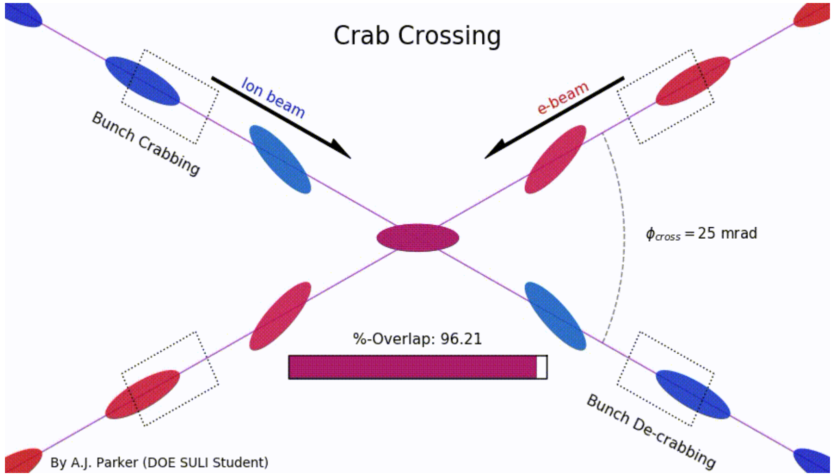


Injector upgrade (bunch population, emittance)



Interaction region upgrade (beta*)



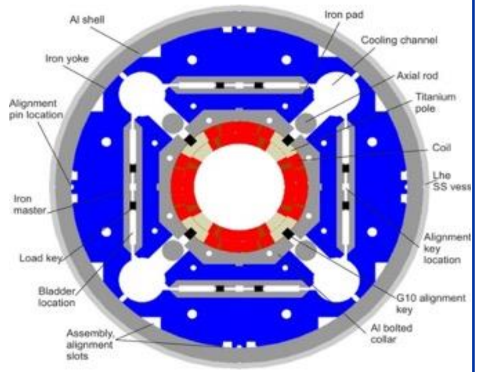


Crossing angle compensation (crab cavities)

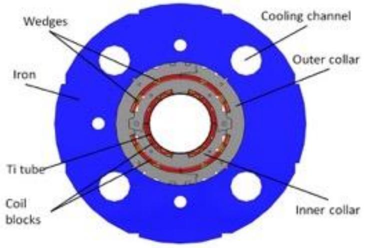
Operate in a high luminosity regime

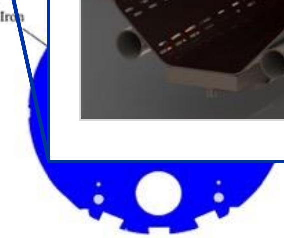
New wide-apertu

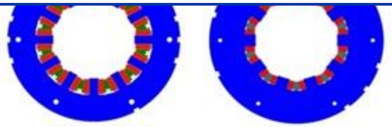
Final focus quadrupole (MQXF)



Dipole correctors

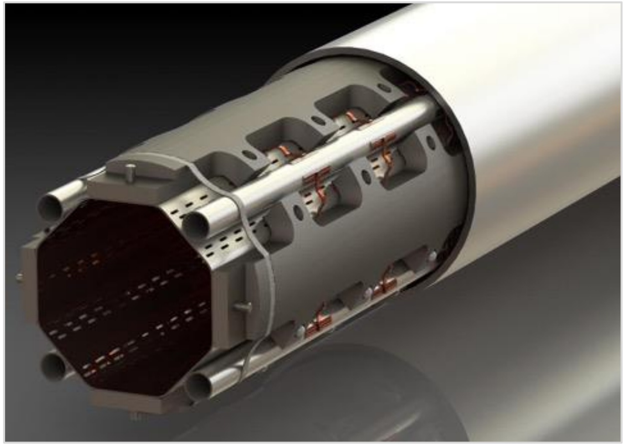






Final focus quadrupoles

- **Nb_3Sn technology** → Larger operational peak fields (~12 T)
- **Large aperture**: 150 mm
  - → Allows for **smaller beam size** at the experiments
  - → Allows introducing **tungsten shielding** to protect the magnet from radiation generated by collisions
- **Series production in progress**



CERN

US HL-LHC AUP

cea SACLAY

INFN

Ciemat
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

IHEP

HEP options – (some of) the tools of the trade

Hadron (protons, ions) colliders

- Messy collisions
- High luminosity
- High energy – good for discovery

Circular e+e- Colliders

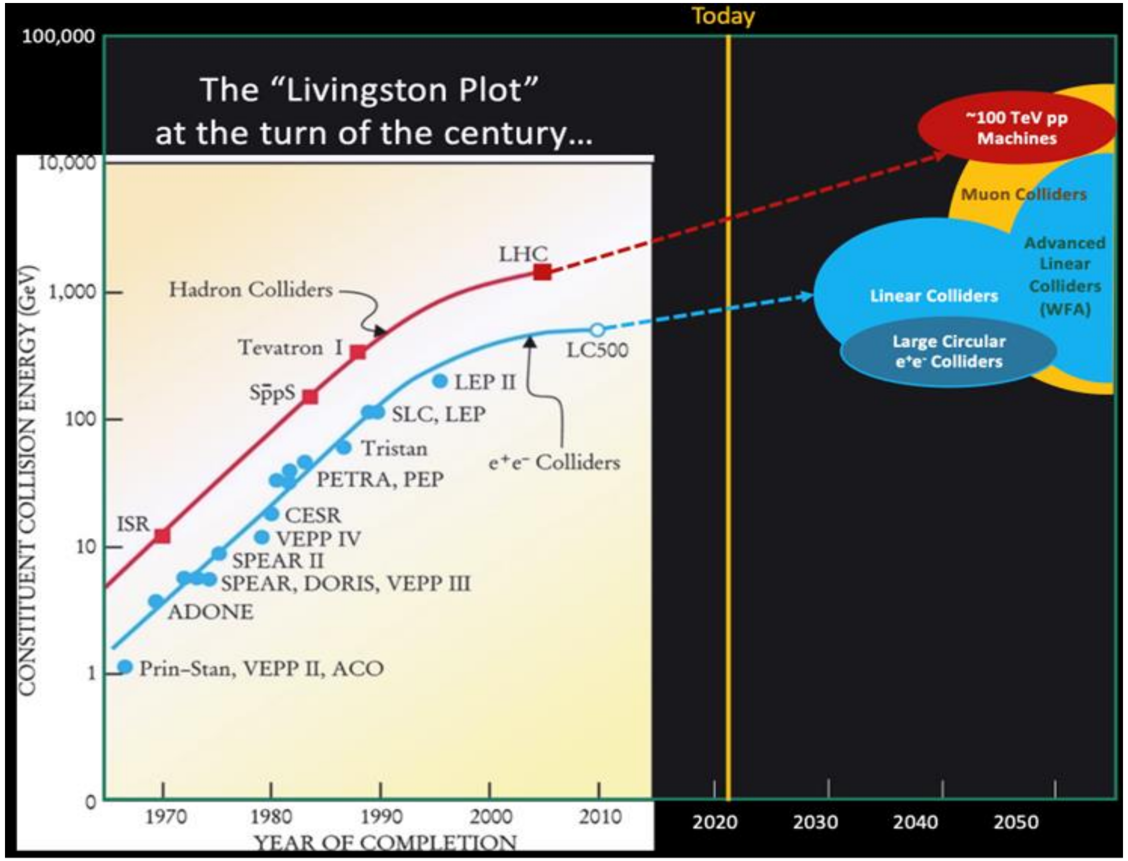
Reuse tunnel

- Clean collisions – good for precision
- Multi-pass – high luminosity
- Energy eventually limited by synchrotron radiation
- Multiple Interaction Points

Linear e+e- Colliders

Extend

- Insignificant synchrotron radiation
- 1 Interaction Point, 1 or 2 experiments
- Single pass, nanometre beam sizes at IP



M. Palmer, MT21

Future Options at CERN

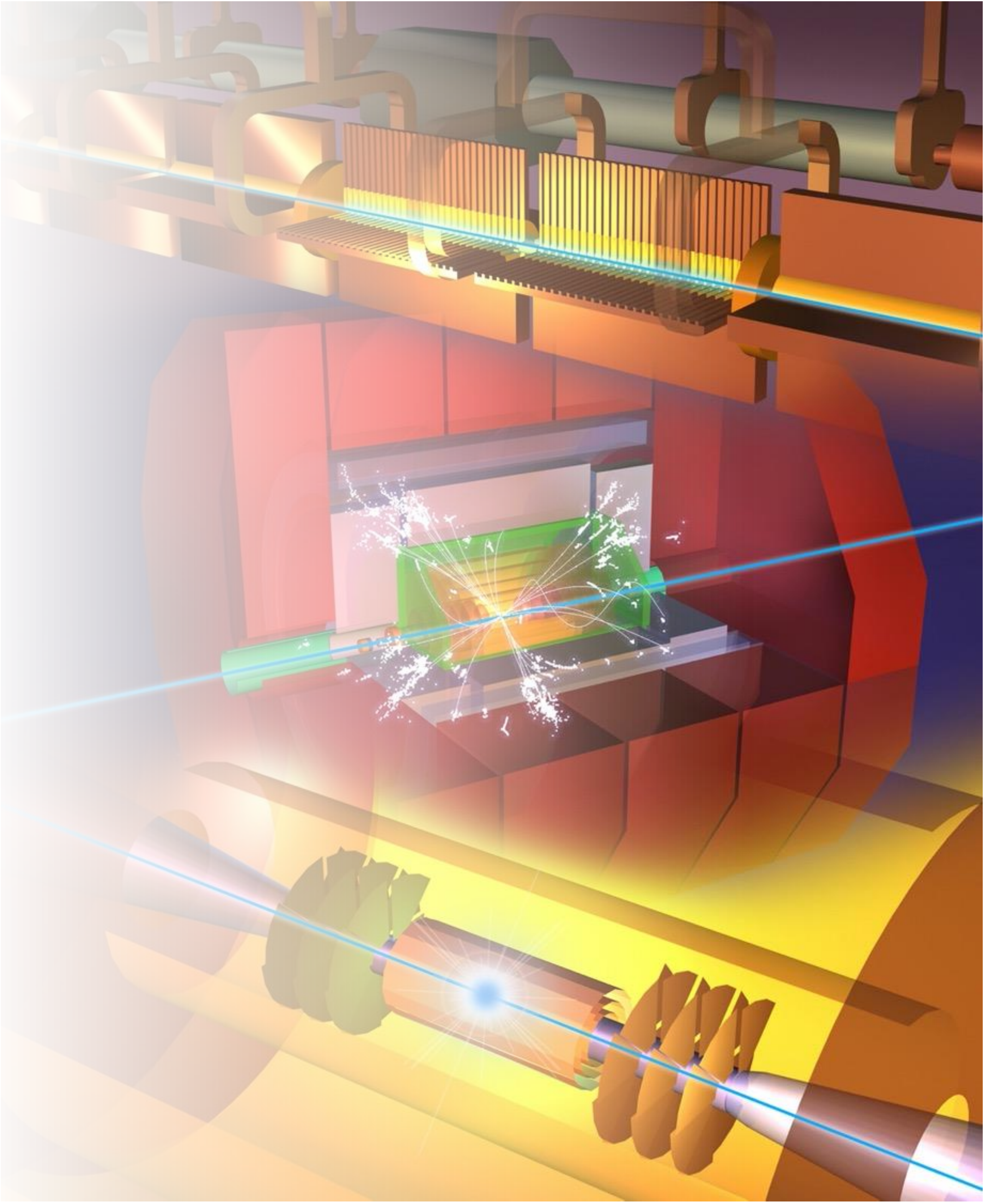
Within specified timeframe (start ops. ~2045)

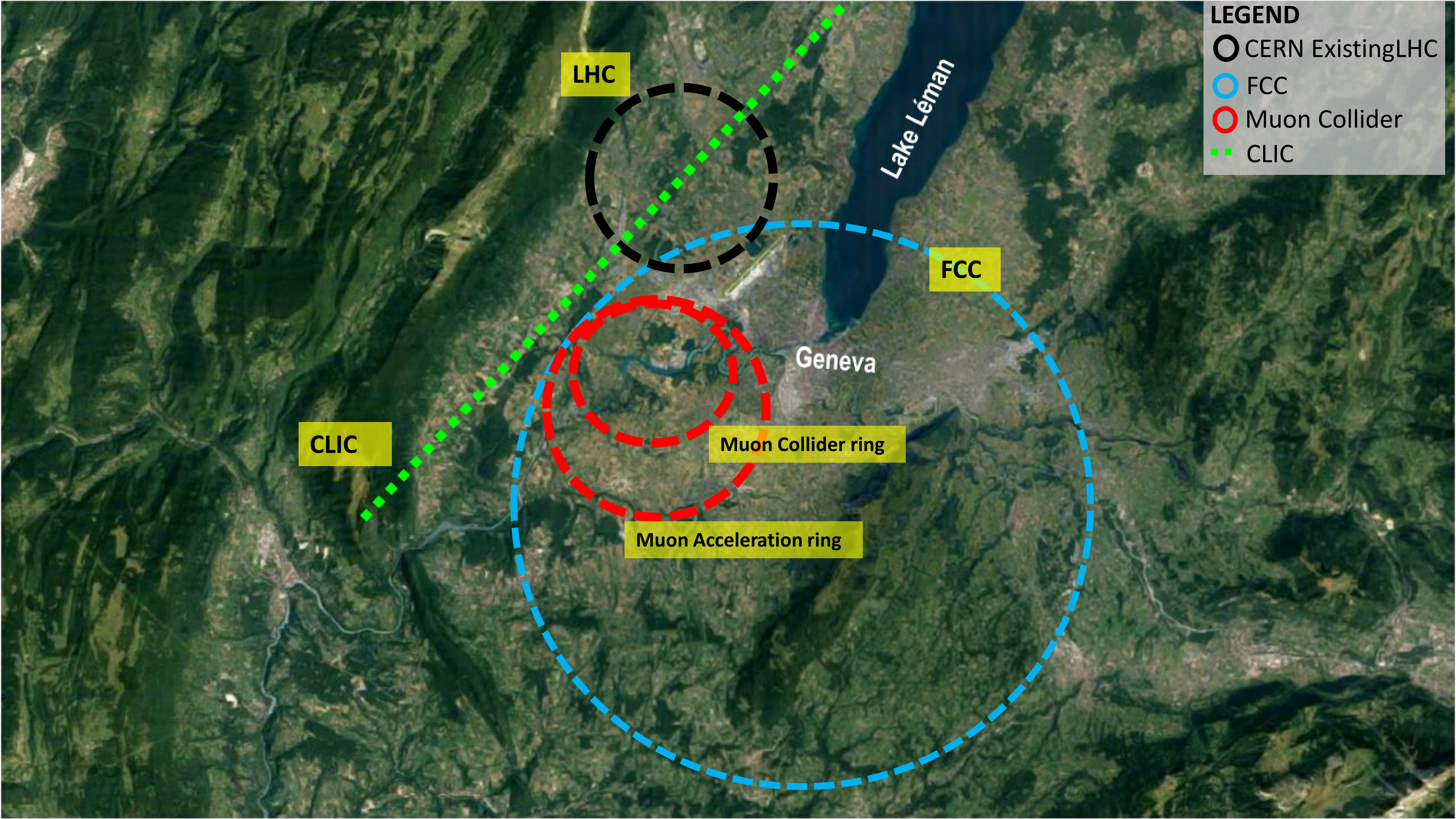
- FCC-ee
- CLIC

Outside specified timeframe

- FCC-hh - natural continuation of FCC programme
- Muon Collider

Options possibly in timeframe but not at CERN: ILC, CEPC



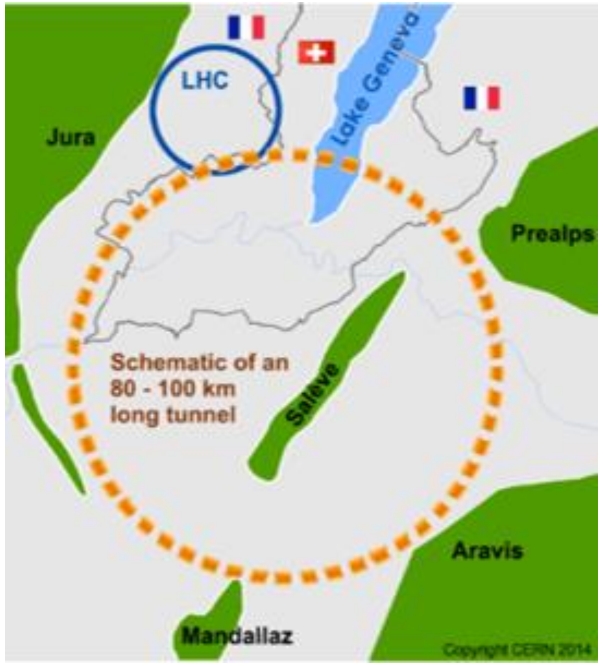

LEGEND
CERN ExistingLHC
FCC
Muon Collider
CLIC
LHC
Lake Léman
FCC
Geneva
CLIC
Muon Collider ring
Muon Acceleration ring

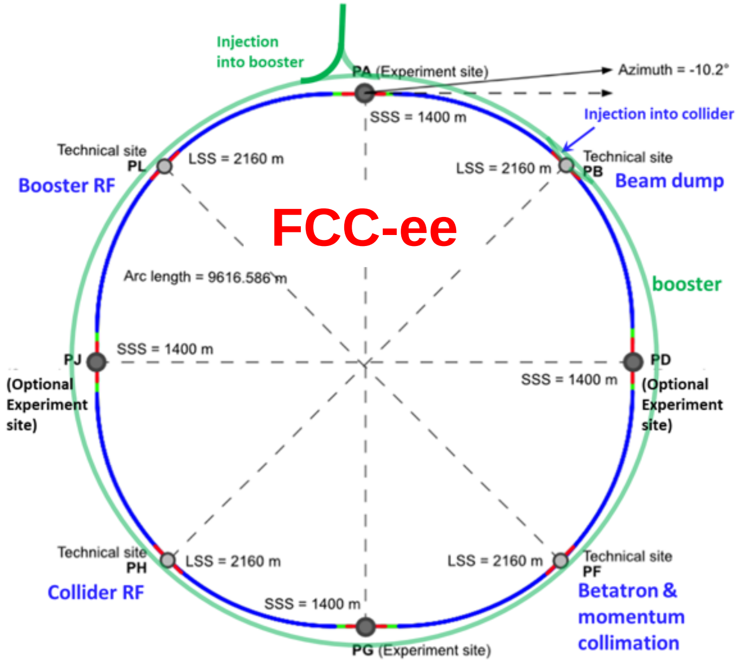

Switzerland
LHC
France
FCC
91 km circumference
LHC
PS
SPS
FCC

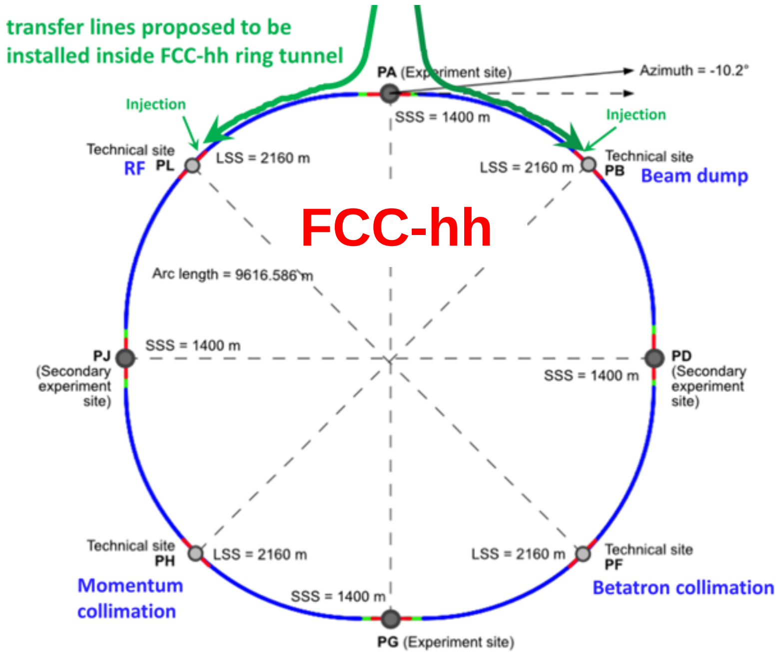
FCC integrated program: inspired by LEP- LHC

Comprehensive long-term program maximizing physics opportunities:

- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**







2020 - 2040 | **2045 - 2063** | **2070 - 2095**

Underground Civil Engineering Schematic

Tunnel Circumference: 90.7 km

Excavated vol: 6.2 Mm^3 (in the ground)

Access shafts: 12

Large experiment areas: 2

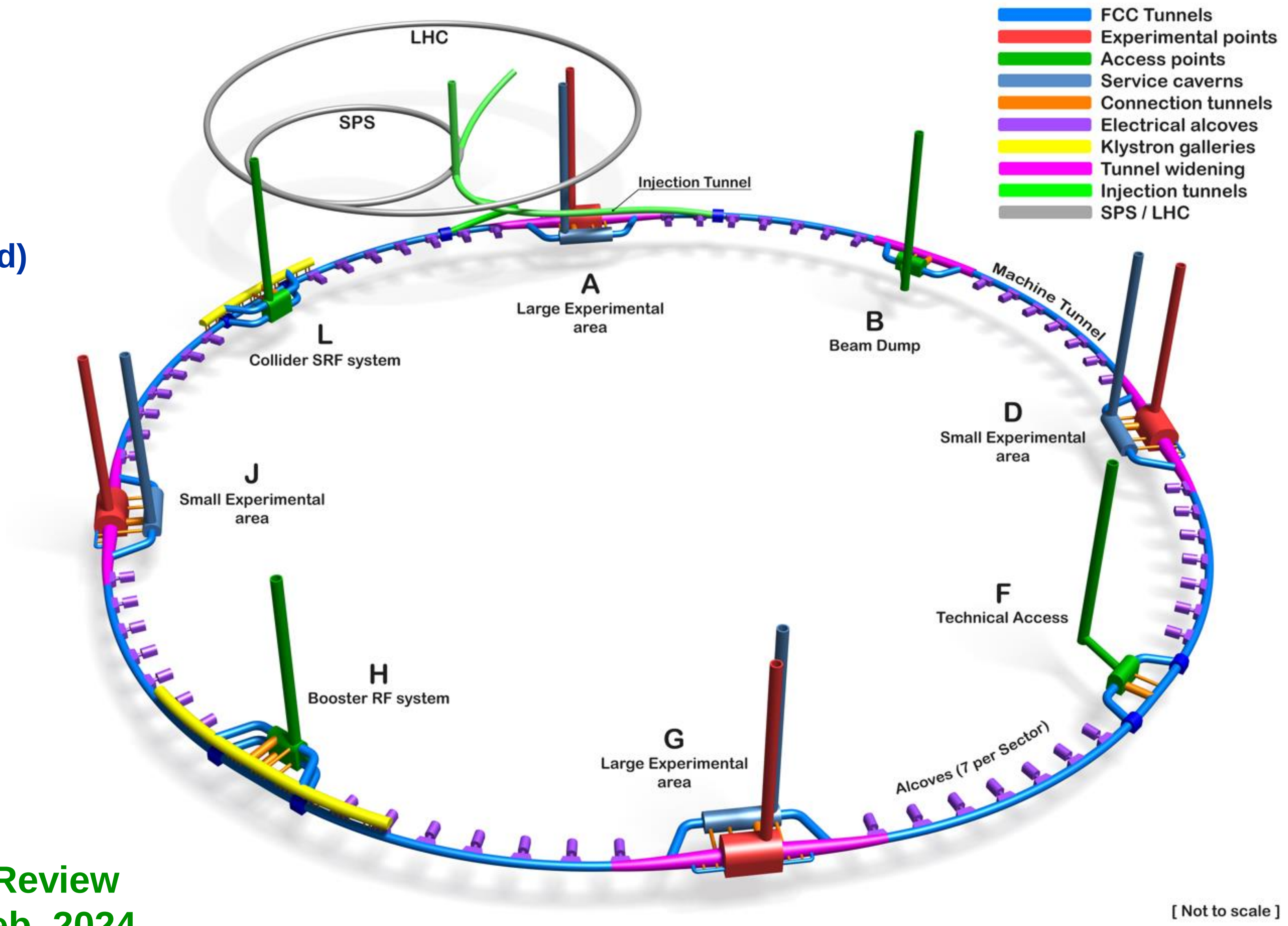
Small experiment areas: 2

Technical points: 4

Deepest shaft: 400 m

Average shaft depth: 243 m

FCC Feasibility Study Mid-Term Review well received by CERN Council Feb. 2024

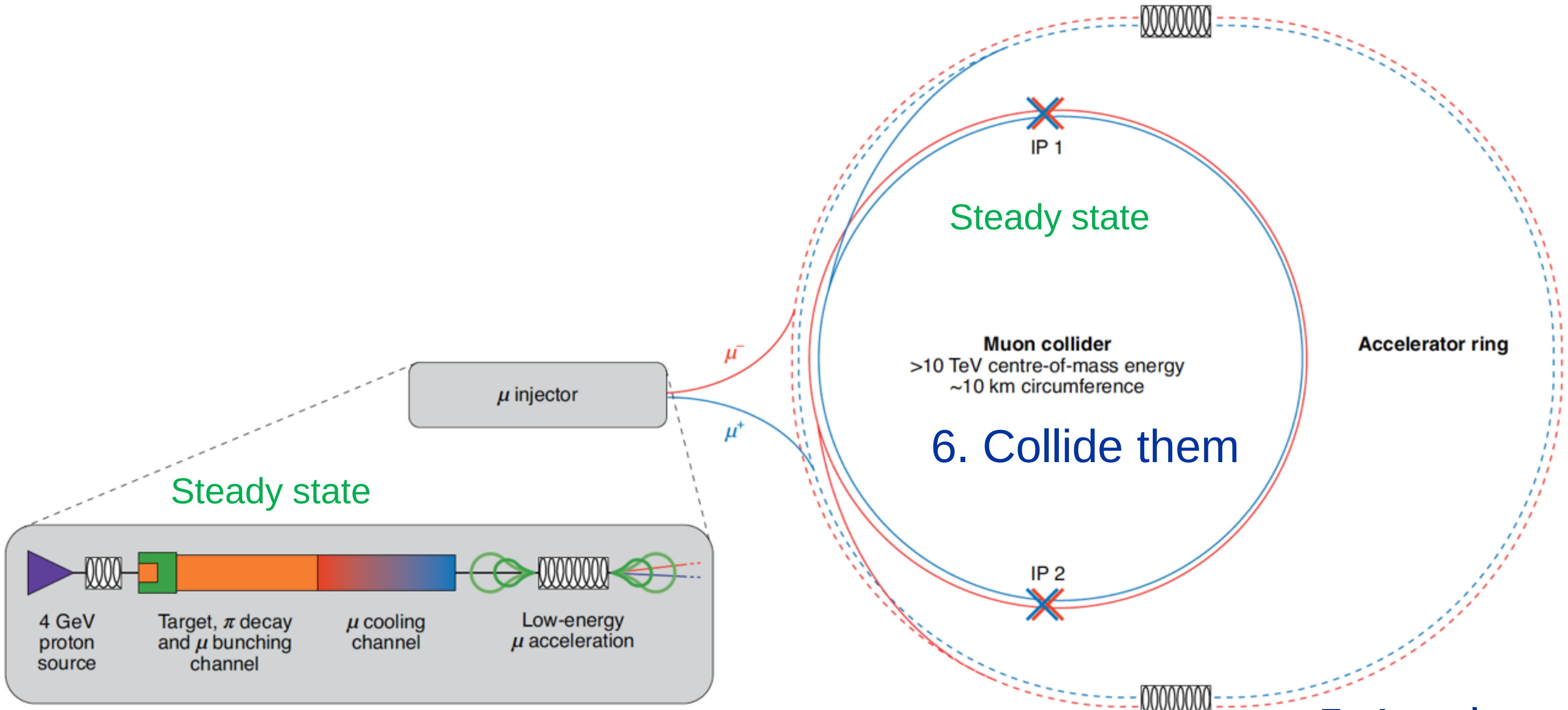


Muon Collider

Large mass (207 m_e) suppresses synchrotron radiation => circular collider
Fundamental particle yields clean collisions & requires less energy than protons
But lifetime at rest is only 2.2 μs (fortunately increases with energy)!

$\sqrt{s}$	$\int \mathcal{L}dt$
3 TeV	1 ab^{-1}
10 TeV	10 ab^{-1}
14 TeV	20 ab^{-1}

1. Produce muons



5. Accelerate them

2. Capture them

3. Cool them

4. Accelerate them

Pion (π) production:

Proton + carbon target→ $\pi^{+/-}$ + X

Pion decay:

$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu}$

$\pi^{-} \rightarrow \mu^{-} + \overline{\nu}_{\mu}$

(Lifetime: 26 nsec.)

Muon decay

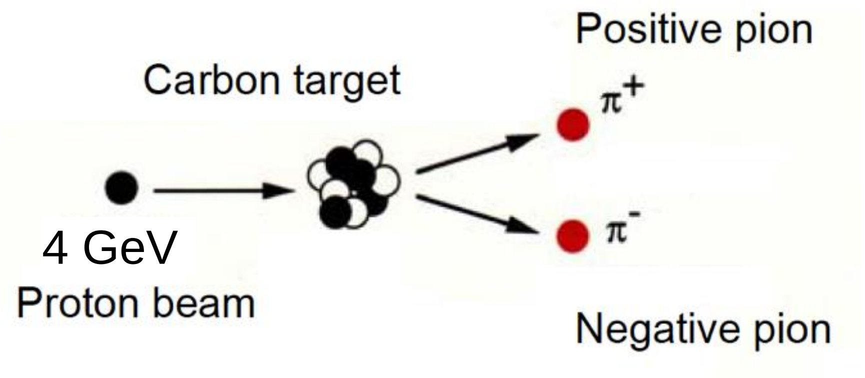
$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$

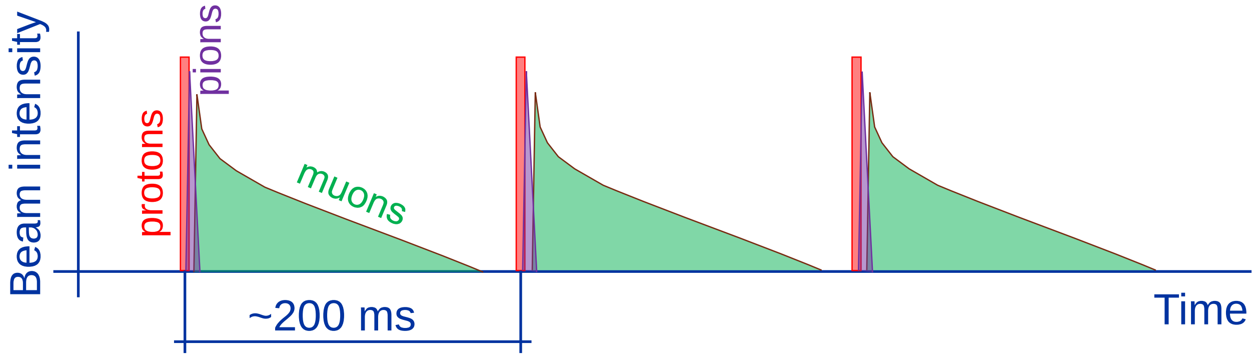
$\mu^{-} \rightarrow e^{-} + \overline{\nu}_{e} + \nu_{\mu}$

(Lifetime: 2.2 μsec.)

At 3 TeV – lifetime is 63 ms

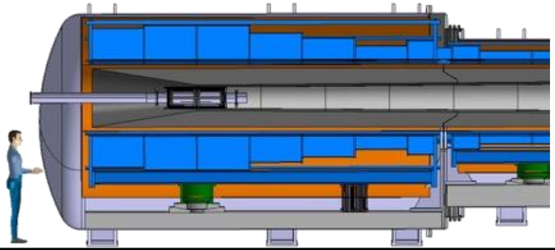
At 10 TeV - lifetime is 210 ms





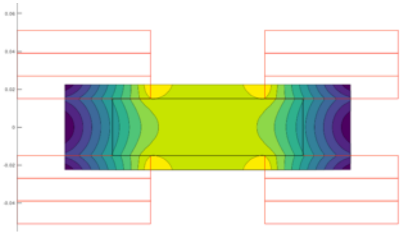
Muon Collider magnets

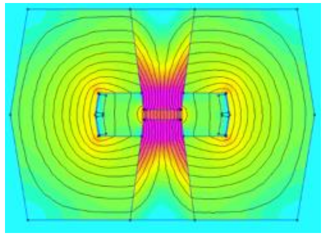
20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

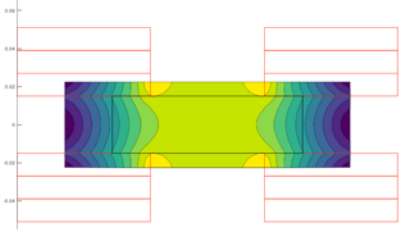


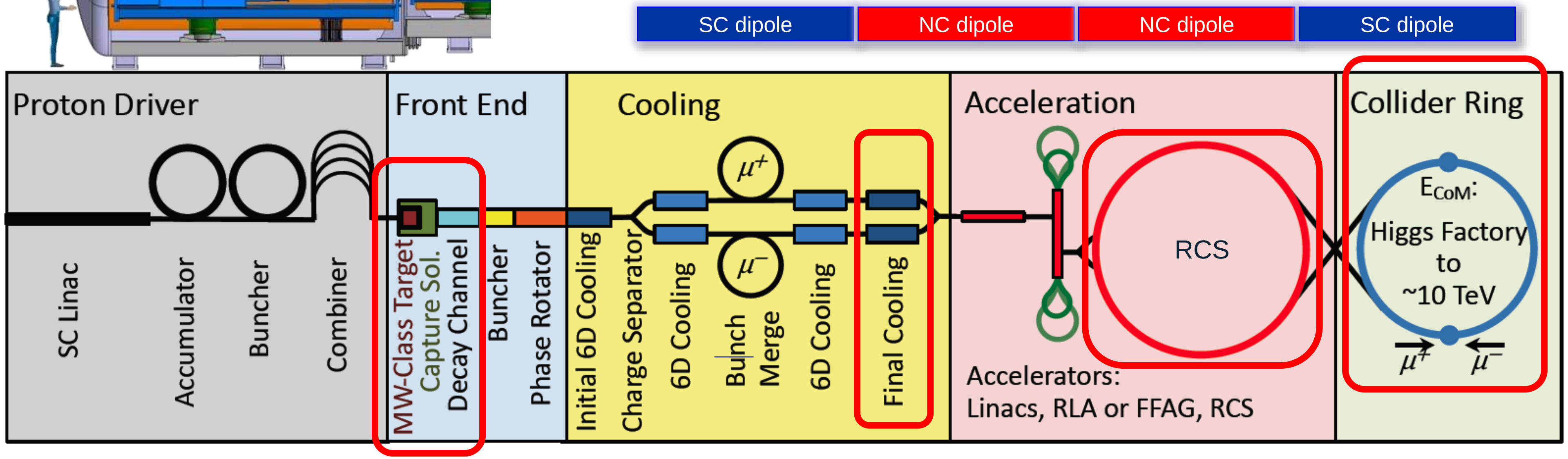
NC ±1.8 T, 400 Hz
100 mm x 30 mm

SC < 10T
100 mm x 30 mm

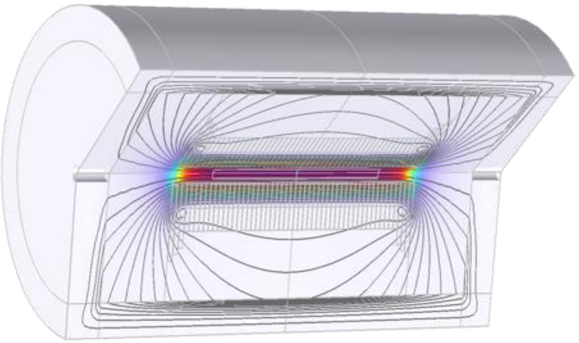




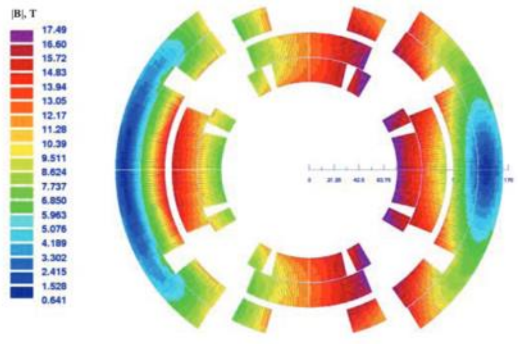




> 40 T, 60 mm

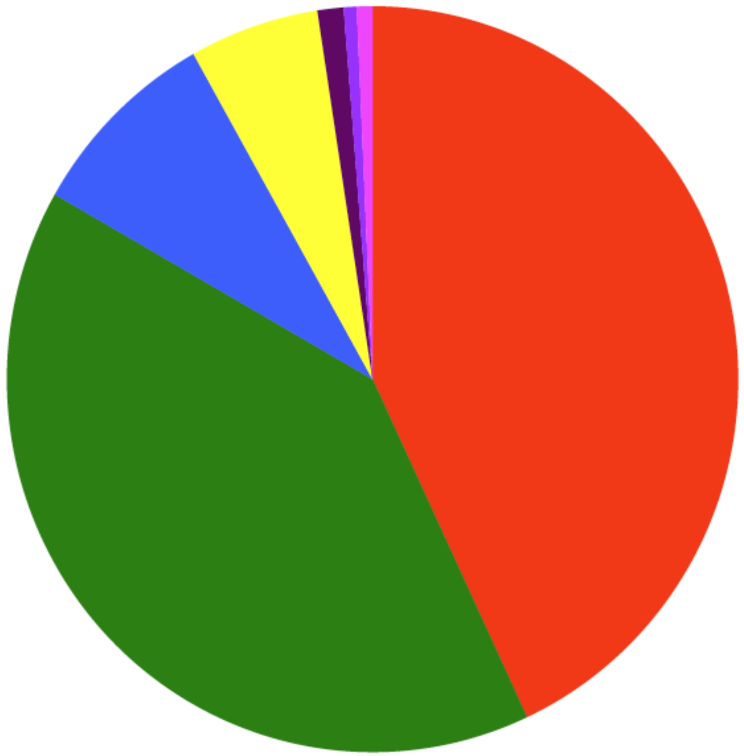


16 T peak, 160 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy



- *"A beam of particles is a very useful tool…"*

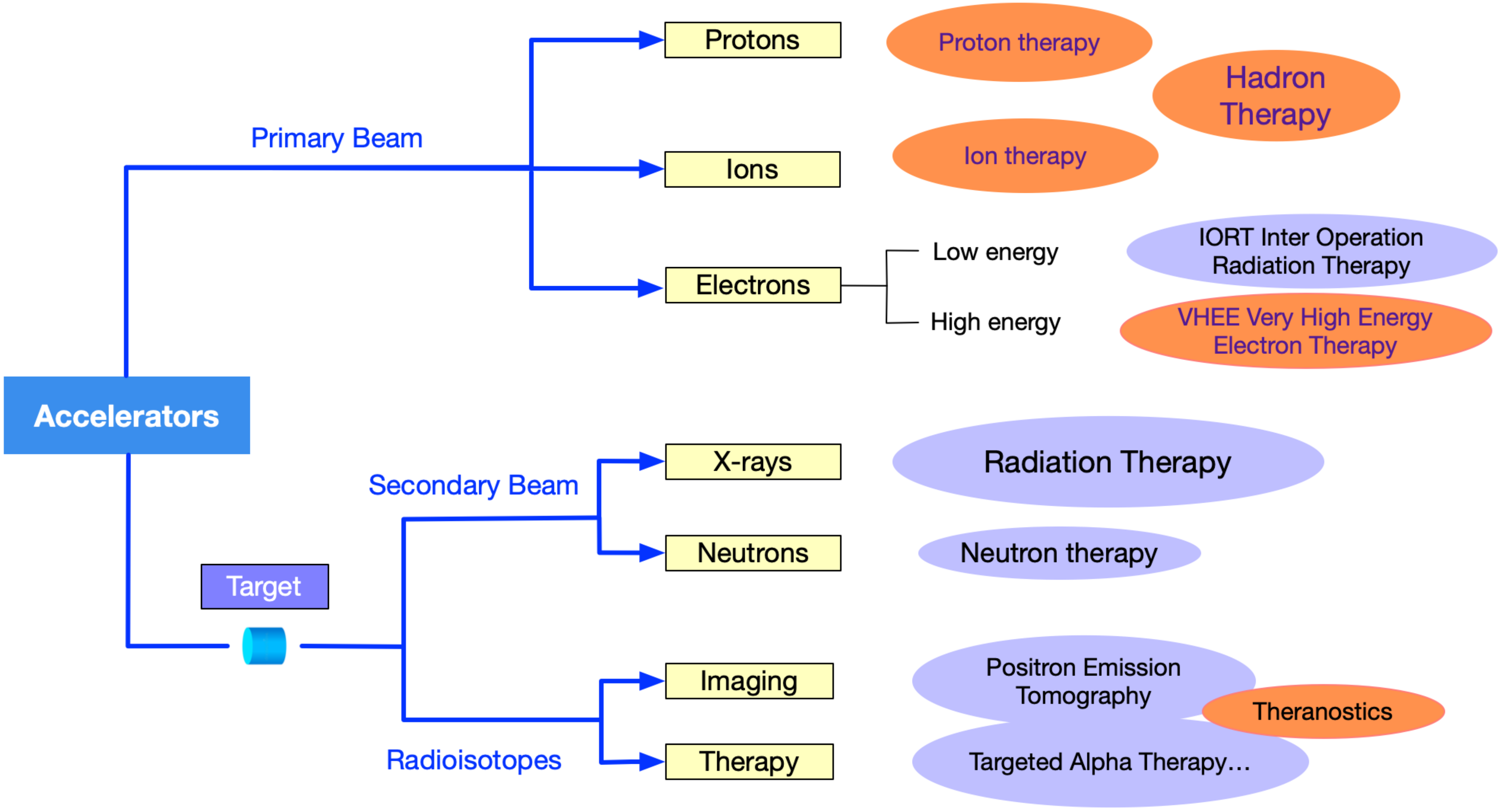
-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011



- Radiotherapy accelerators
- Ion implanters, surface & bulk modification
- Industrial processing and research
- Low energy accelerators for research
- Medical radioisotope production
- Synchrotron light sources
- High energy accelerators for research (E>1GeV)

There are roughly 35,000 accelerators in the world
(Above 1 MeV…)

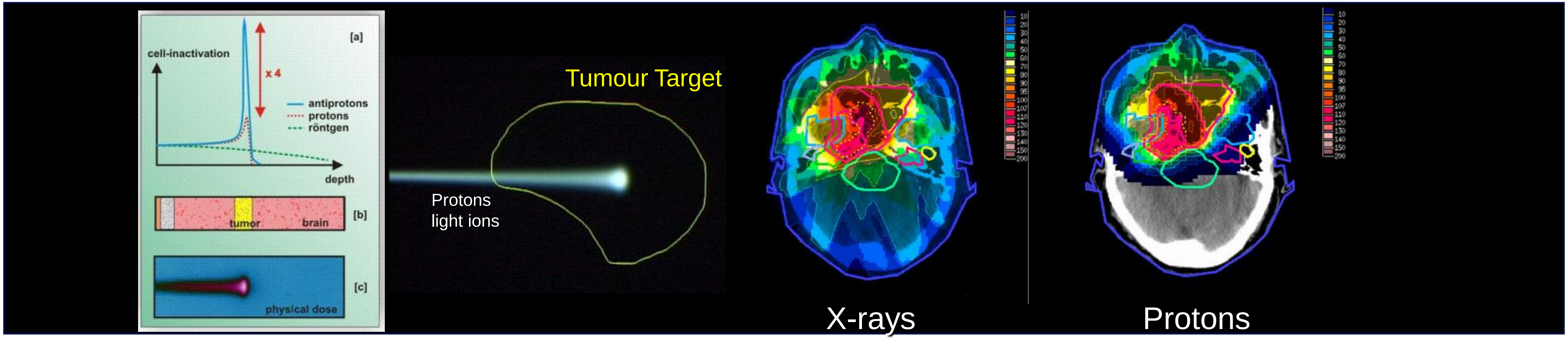
Accelerators versus Cancer



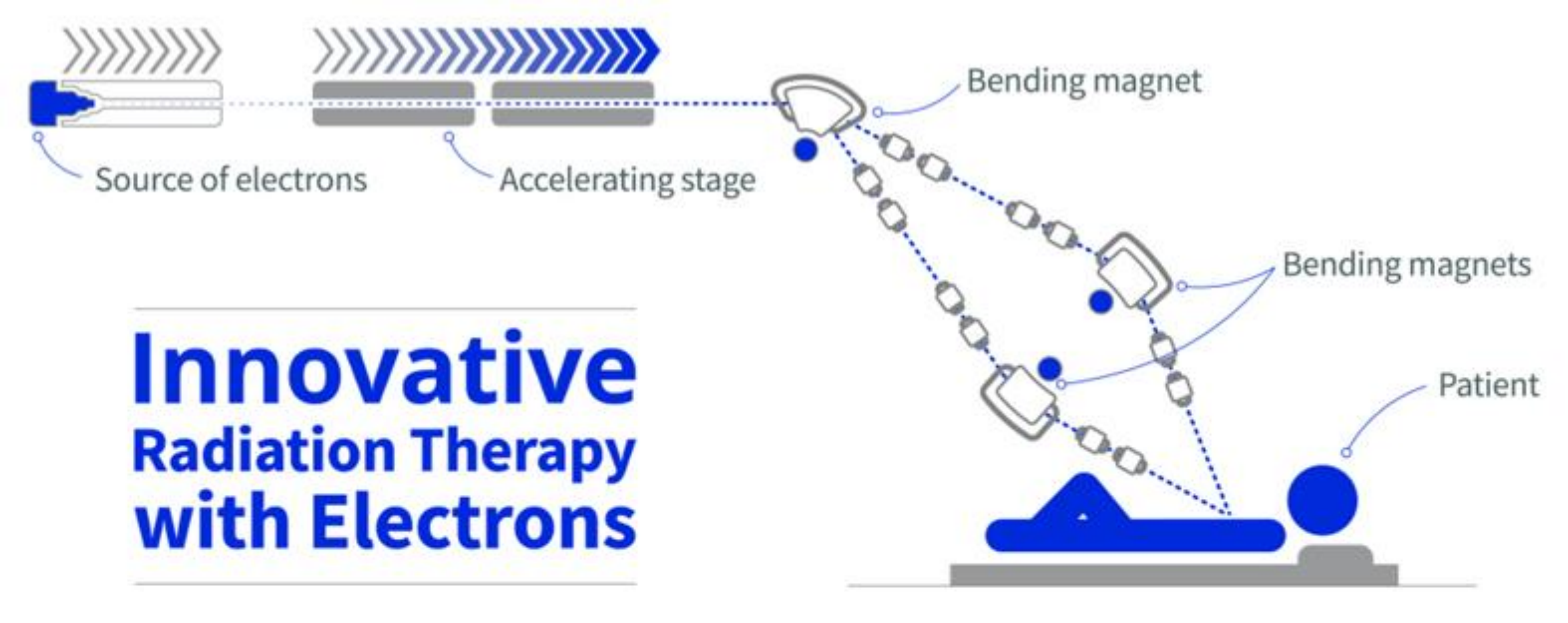
Medical Applications

- **Accelerating particle beams**
  - ~30’000 accelerators worldwide
  - ~17’000 used for medicine
- **Hadron Therapy**
  - >170’000 patients treated worldwide (81 facilities)
    - 16 facilities in Europe
  - >21’000 patients treated with carbon ions
    - Leadership in Ion Beam Therapy in Europe & Japan

National Hadron Therapy Centre (**CNAO**), Pavia, Italy



Very High Energy Electrons (VHEE)



Oncologists believe that ultrafast bursts of electrons damage tumours more than healthy tissue.
This is known as the “FLASH effect”.

That’s not Very High Energy Electrons…

Producing a high dose of electrons using a unique accelerator based on CLIC (Compact Linear Collider) technology.

Precisely controlled, intense electron beams
Compact high accelerating gradients

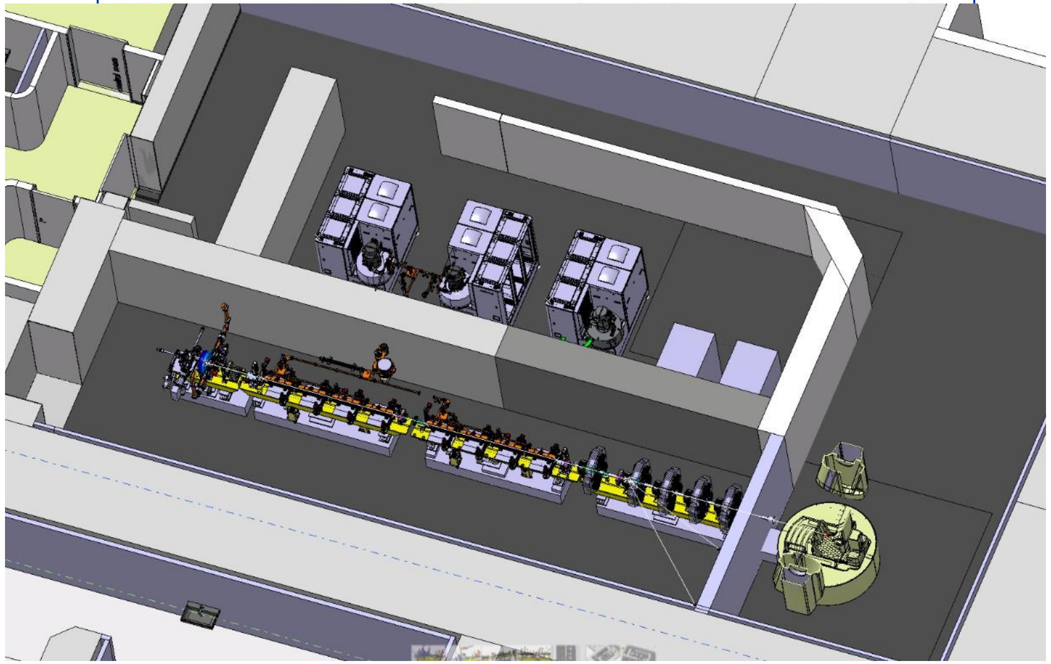
FLASH Therapy with VHEE

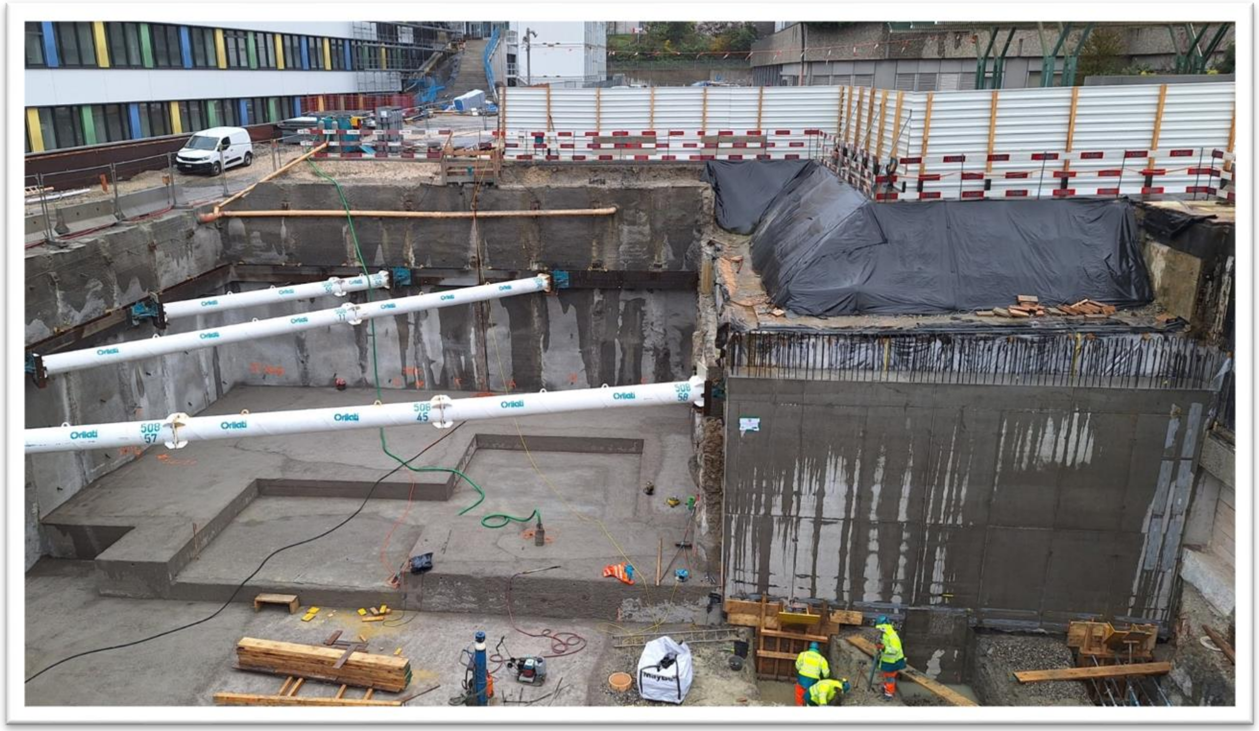
CHUV, CERN together with an industrial partner THERYQ (ALCEN group) in process of constructing facility for clinical trials – industrialization foreseen

CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

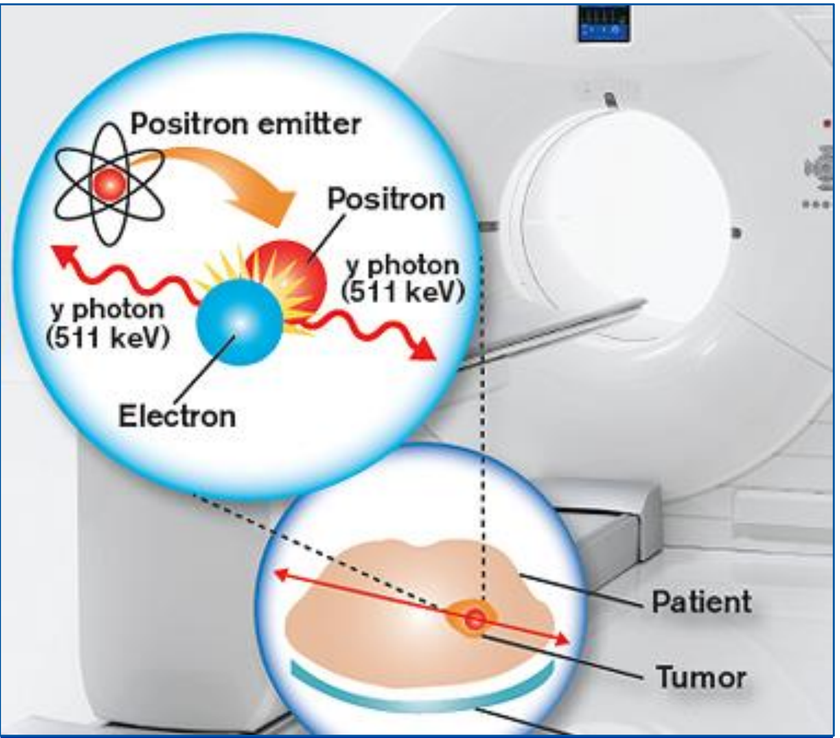
15 SEPTEMBER, 2020





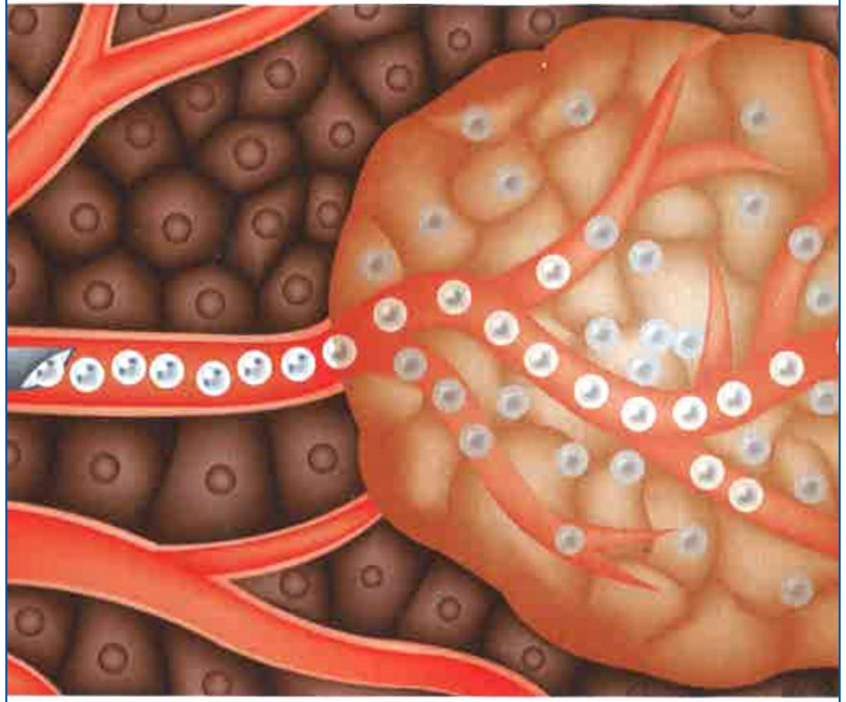
Bunker under construction in Lausanne, first clinical trials in 2027

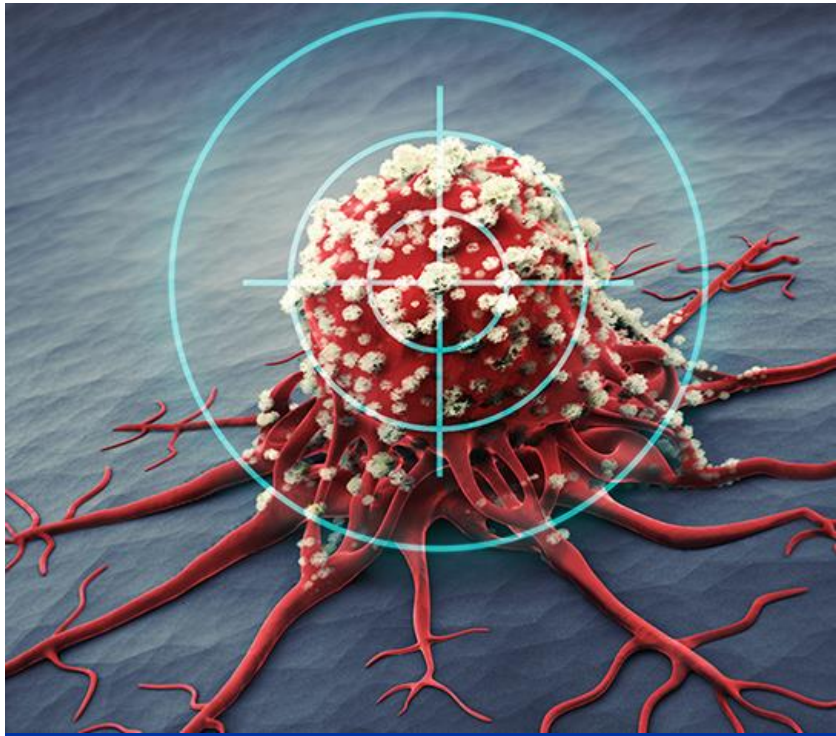
Use of medical radionuclides



Diagnostic, where the radioisotope allows doctors to visualize a tumour's precise location and contours within the body

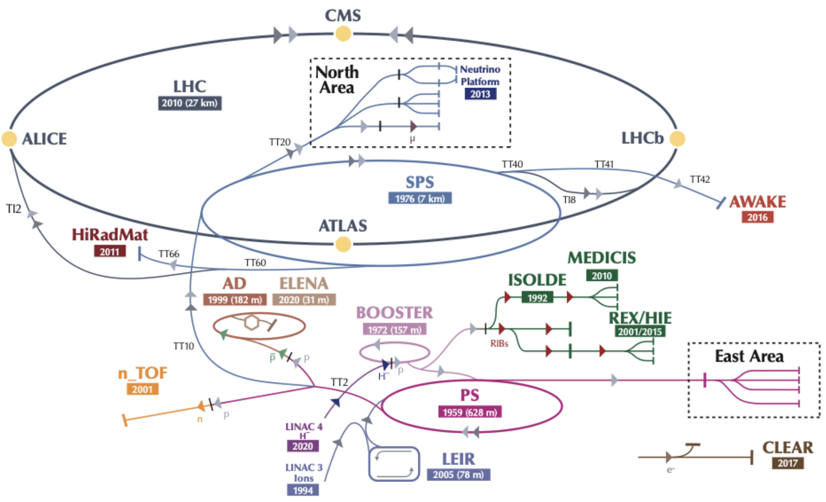
Therapeutic, where doctors use the radionuclide to deliver cancer-killing radiation directly to tumour cells



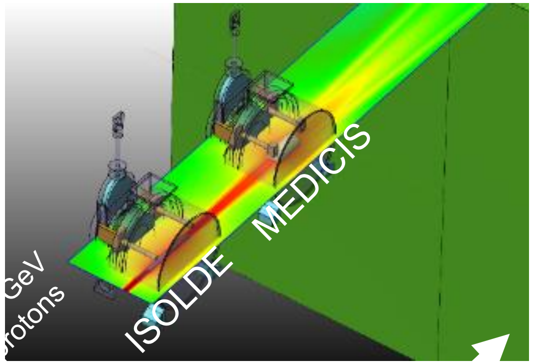


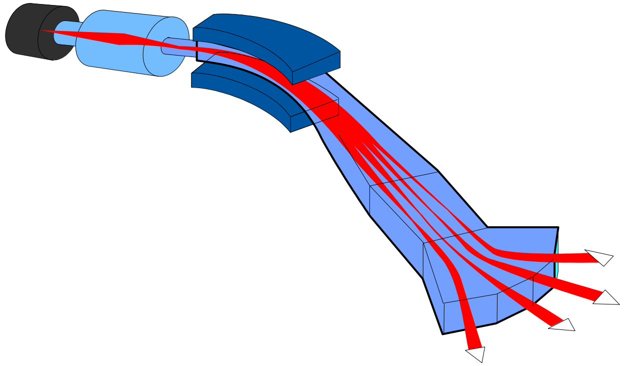
The **theragnostic** radionuclide agent allows a doctor to both visualize and treat a tumour simultaneously.

MEDICIS in one slide!



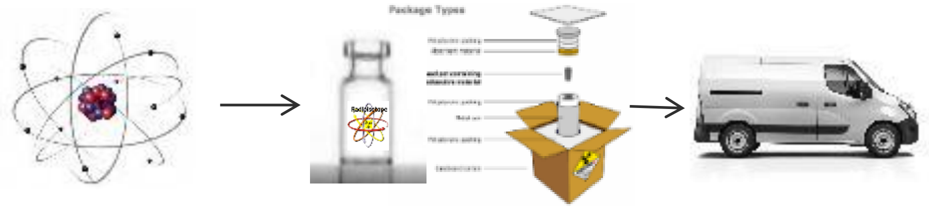
“Free” proton beam





The only dedicated medical isotope mass separation facility in Europe.

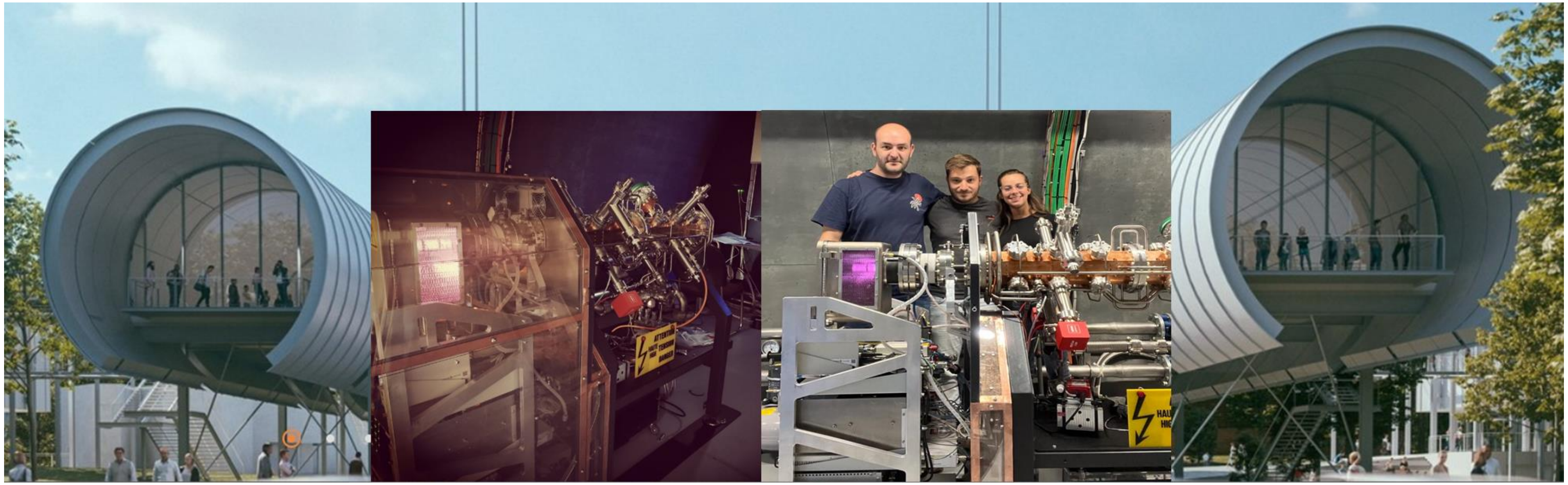
Non-conventional isotopes are collected by mass separation for novel medical applications



From CERN-MEDICIS to the lab/Hospital (Countries: BE, CH, FR, PK, PT, LV, UK)

Surface Science

- **Particle-induced X-ray emission (PIXE)**
  - Powerful, non-destructive elemental analysis technique
  - When exposed to particle beam, atomic interactions occur that give off EM radiation of X-ray wavelengths
  - Routinely by geologists, archaeologists, art conservators and others to help answer questions of provenance, dating and authenticity
- **CERN’s very own working PIXE accelerator, ELISA, can be seen in the Science Gateway**



Next time someone asks you what accelerators are for…

"A beam of the right particles with the right energy at the right intensity can shrink a tumor, produce cleaner energy, spot suspicious cargo, make a better radial tire, clean up dirty drinking water, map a protein, study a nuclear explosion, design a new drug, make a heat-resistant automotive cable, diagnose a disease, reduce nuclear waste, detect an art forgery, implant ions in a semiconductor, prospect for oil, date an archaeological find, package a Thanksgiving turkey or…

…discover the secrets of the universe."

-Accelerators for Americas Future Report, pp. 4, DoE, USA, 2011

Social Cost-Benefit Analysis of LHC and HL-LHC

Massimo Florio with Andreas Bastianin (2018)

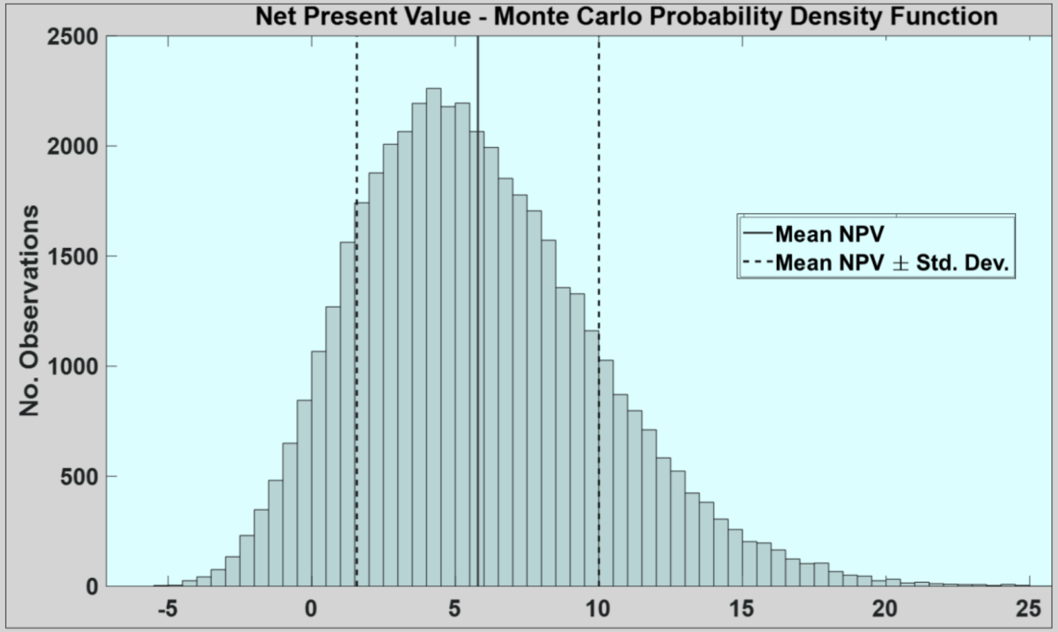
SUMMING UP: BENEFITS AND COSTS

STOCHASTIC NET PRESENT VALUE OF LHC + HIGH LUMINOSITY LHC

Benefits baseline	**25.7**
Scientific publications	0.6
Human capital	8.5
Technological spillovers	10.2
Cultural benefits	3.3
Public good value	3.1
Costs baseline	**22.3**
Net Present Value	**3.4**

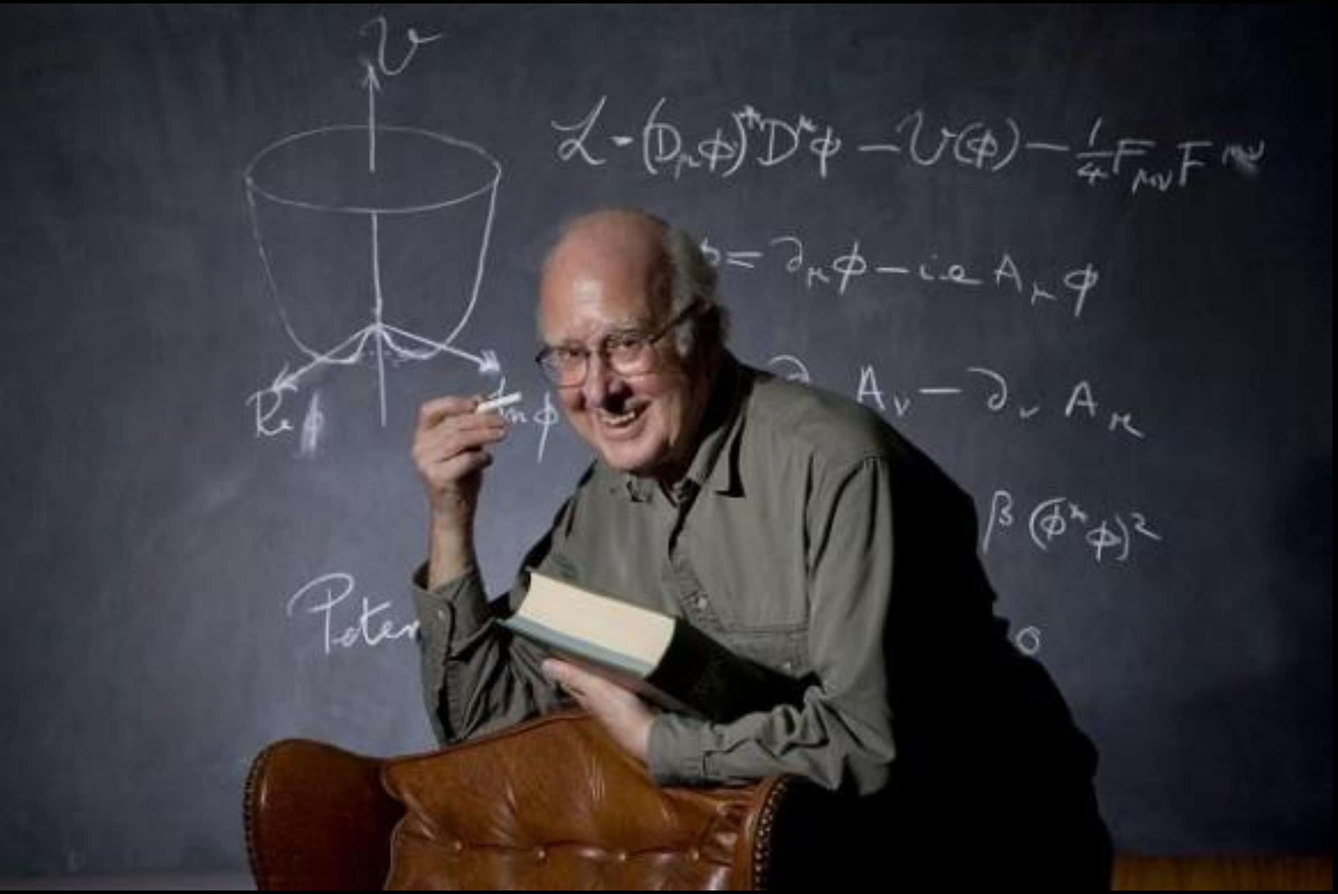
Source: Bastianin, Florio (2018)

Billion CHF 2016



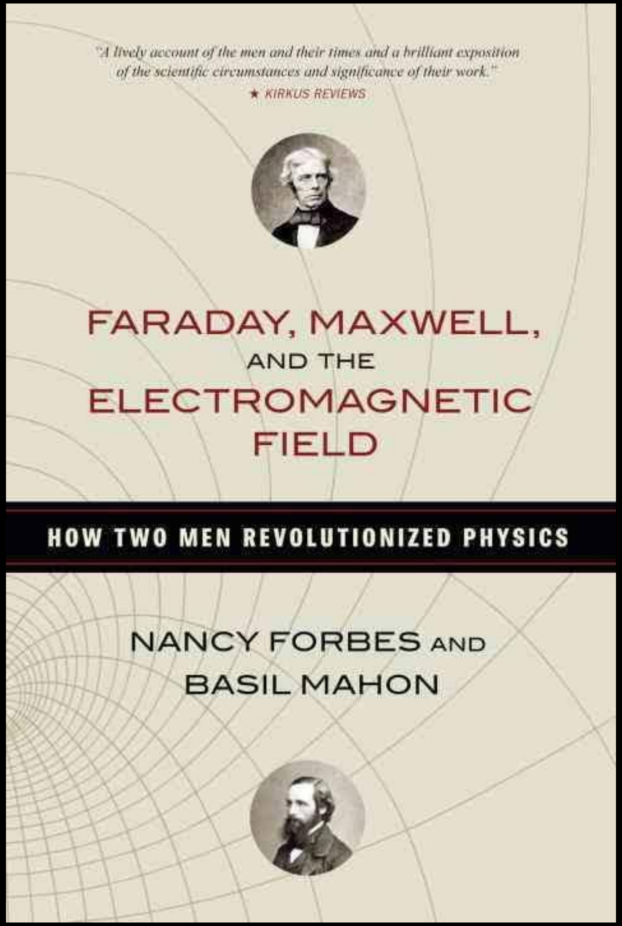
$$NPV = \left(PV_{B_u} + PV_{B_n}\right) - PV_c$$

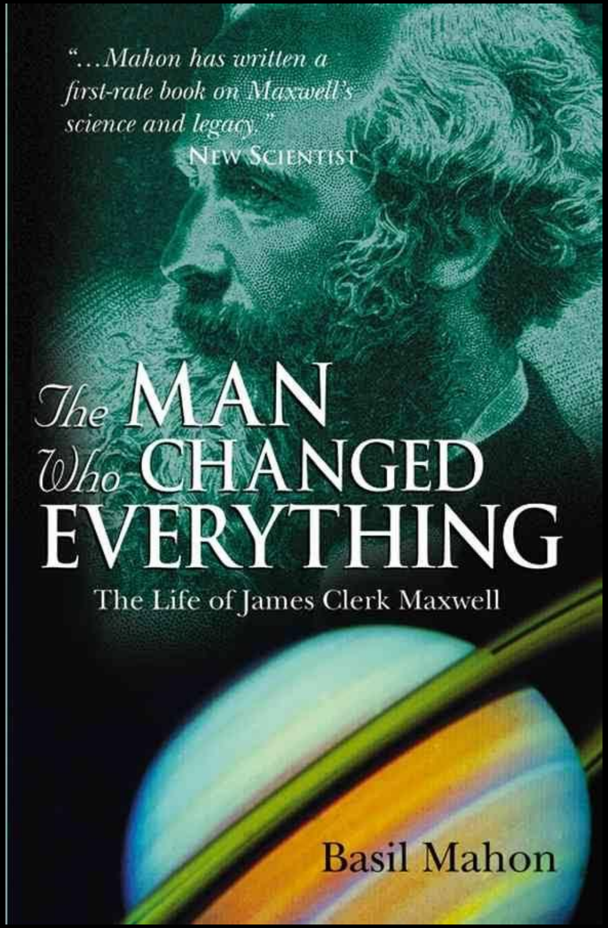
“The surprising finding is that a machine as costly as the LHC, entirely devoted to describe things for which we currently have no use, passes a cost-benefit test.”

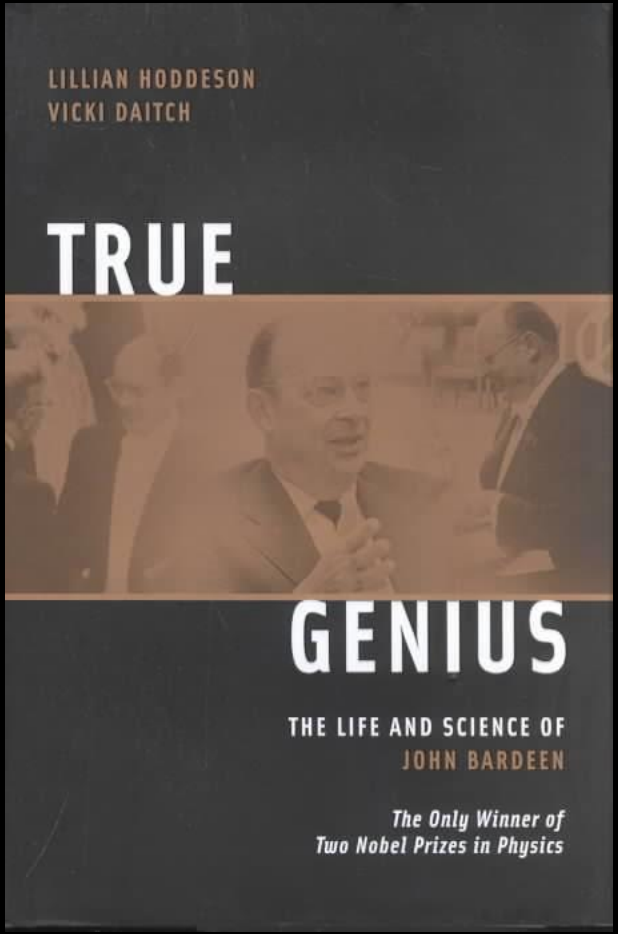


Physics is Beautiful and Useful!

Books


"A lively account of the men and their times and a brilliant exposition of the scientific circumstances and significance of their work."
★ KIRKUS REVIEWS
FARADAY, MAXWELL, AND THE ELECTROMAGNETIC FIELD
HOW TWO MEN REVOLUTIONIZED PHYSICS
NANCY FORBES AND BASIL MAHON


"...Mahon has written a first-rate book on Maxwell's science and legacy."
NEW SCIENTIST
The MAN Who CHANGED EVERYTHING
The Life of James Clerk Maxwell
Basil Mahon


LILLIAN HODDESON
VICKI DAITCH
TRUE GENIUS
THE LIFE AND SCIENCE OF JOHN BARDEEN
The Only Winner of Two Nobel Prizes in Physics