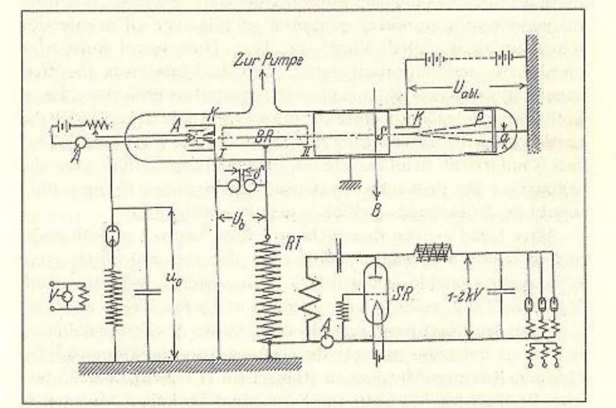
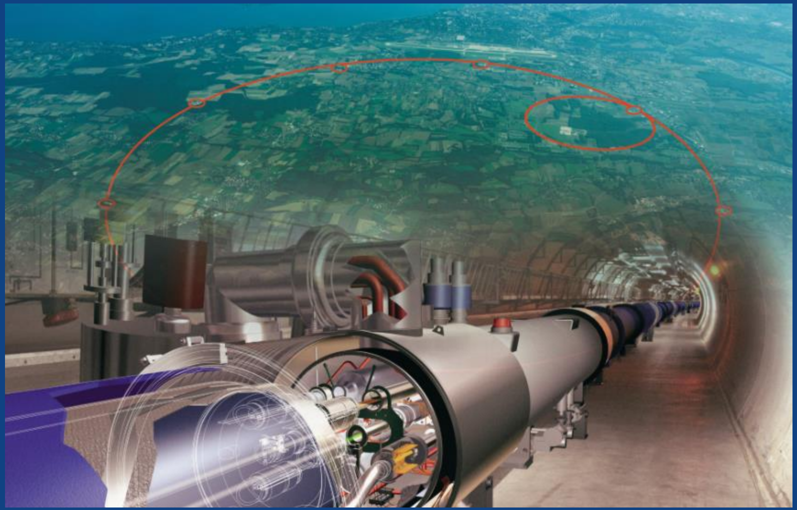
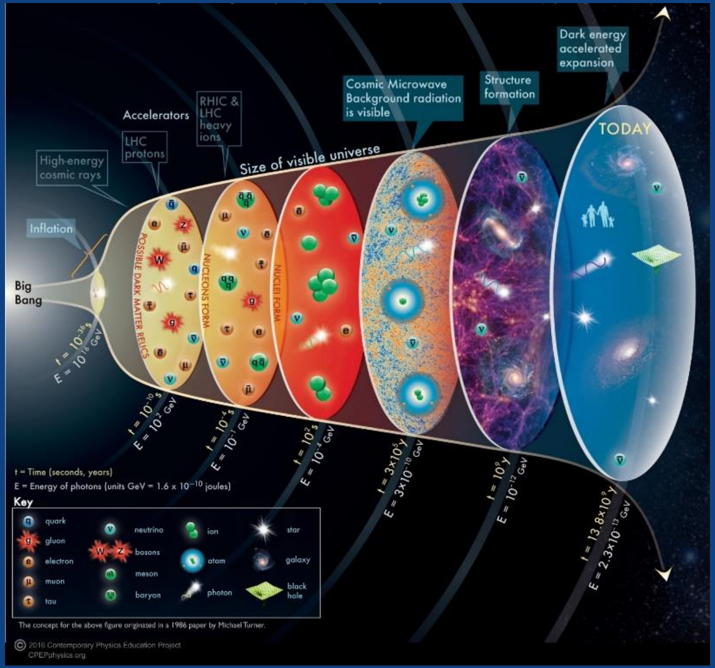
GENERAL INTRODUCTION TO ACCELERATORS

Frédérick Bordry







The concept for the above figure originated in a 1986 paper by Michael Turner.

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6th Summer School on INtelligent signal processing for FrontIEr Research and Industry

Particle accelerators: Motivation

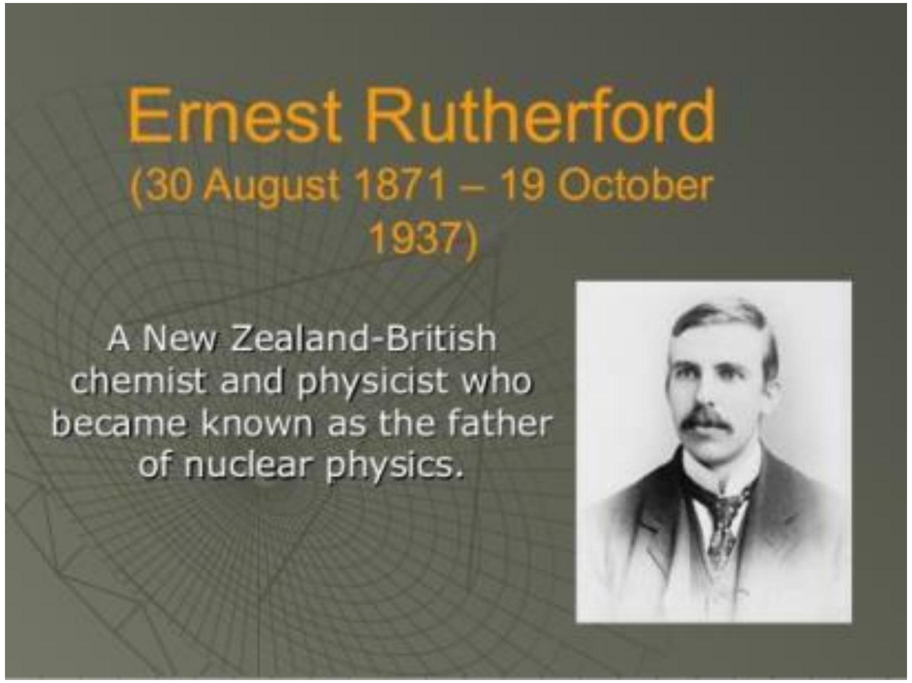
The first motivation was from **Ernest Rutherford** who desired to produce nuclear reactions with accelerated nucleons.

For many decades the motivation was to get to ever higher beam energies. At the same time, and especially when colliding beams became important, there was a desire to get to ever higher beam current.

In the last three decades there has been motivation from the many applications of accelerators, such as producing X-ray beams, medical needs, ion implantation, spallation sources, and on and on.

Lord Rutherford, in his inaugural presidential address to the Royal Society in London in 1928, said:

"I have long hoped for a source of positive particles more energetic than those emitted from natural radioactive substances".

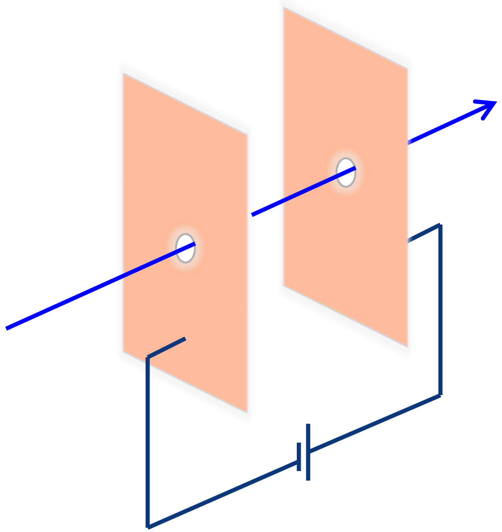


Ernest Rutherford

(30 August 1871 – 19 October 1937)

A New Zealand-British chemist and physicist who became known as the father of nuclear physics.

This was the start of a long quest for the production of high energy beams of particles in a very controlled way

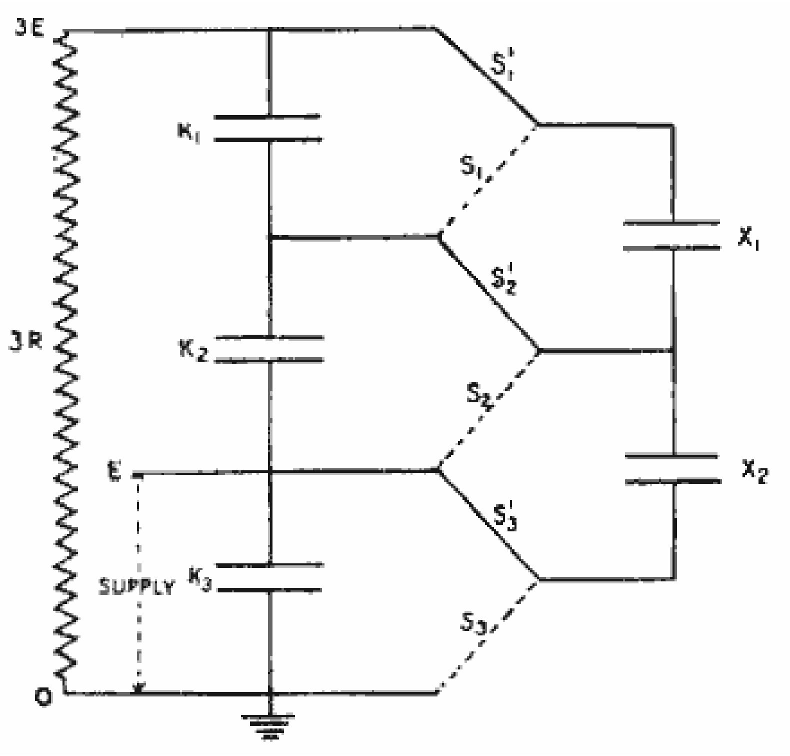


Energy gain

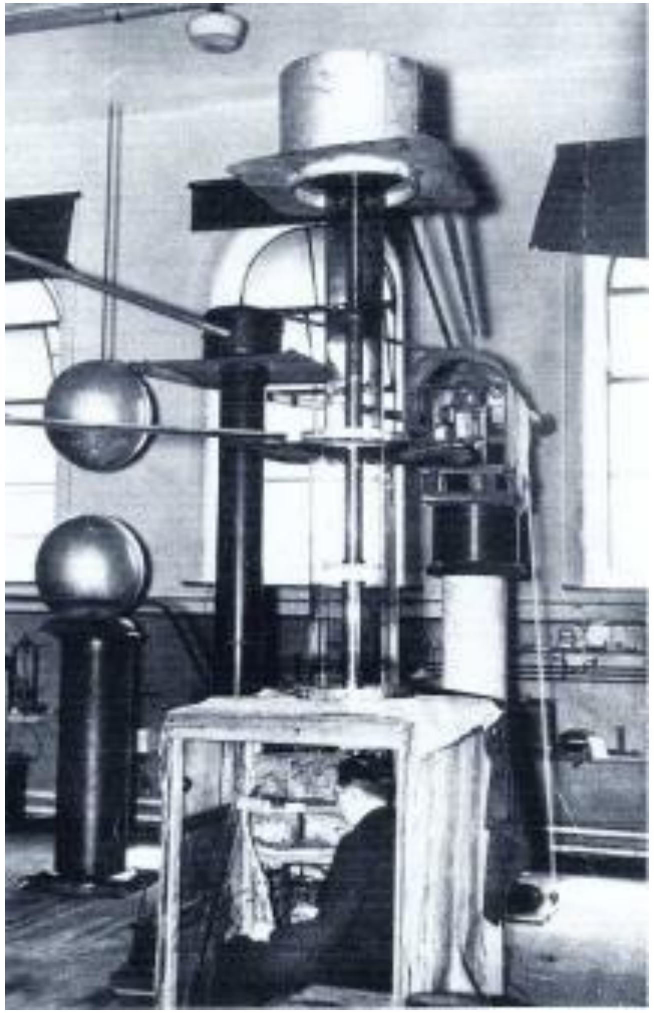
1 eV is the energy that an elementary charge gains when it is accelerated through a potential difference of 1 Volt

1 eV = $1.6\ 10^{-19}$ J

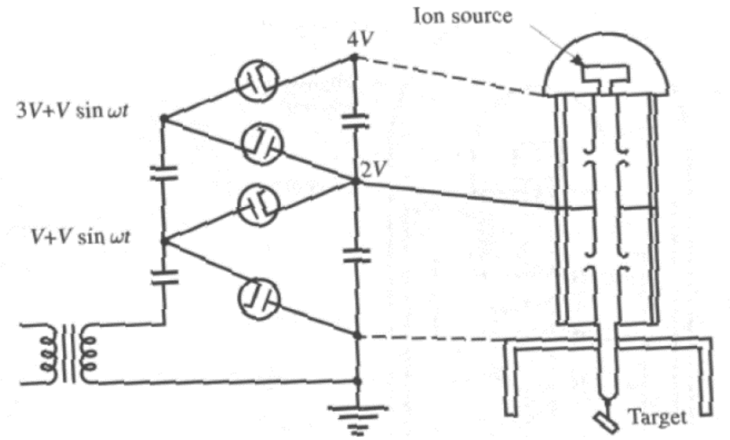
High "energy" physics

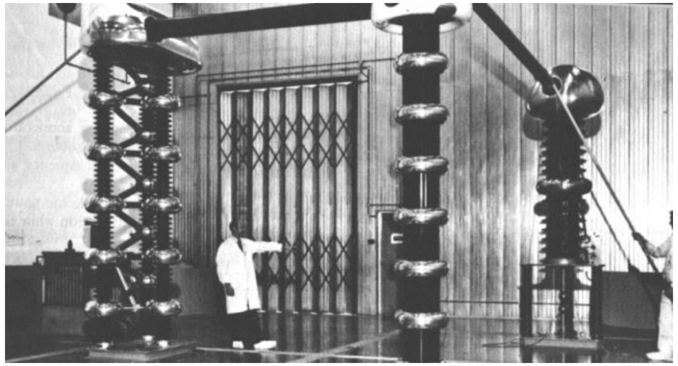


Schematic of Cockcroft and Walton's voltage multiplier. Opening and closing the switches S transfers charge from capacitor K3 through the capacitors X up to K1.



Electrostatic accelerators





- Static voltage accelerator
- Voltage multiplication by AC to DC conversion along the ladder
- Theoretical maximum voltage

  $V_{DC} = 2\,N\,V_{AC}$; N number of stages

- Accelerating voltage up to several hundred kV

  (160 - 700 keV)

First breaking of the atomic nucleus by Cockcroft & Walton (1932)
Nobel Prize 1951

J.D. Cockcroft

E.T.S. Walton

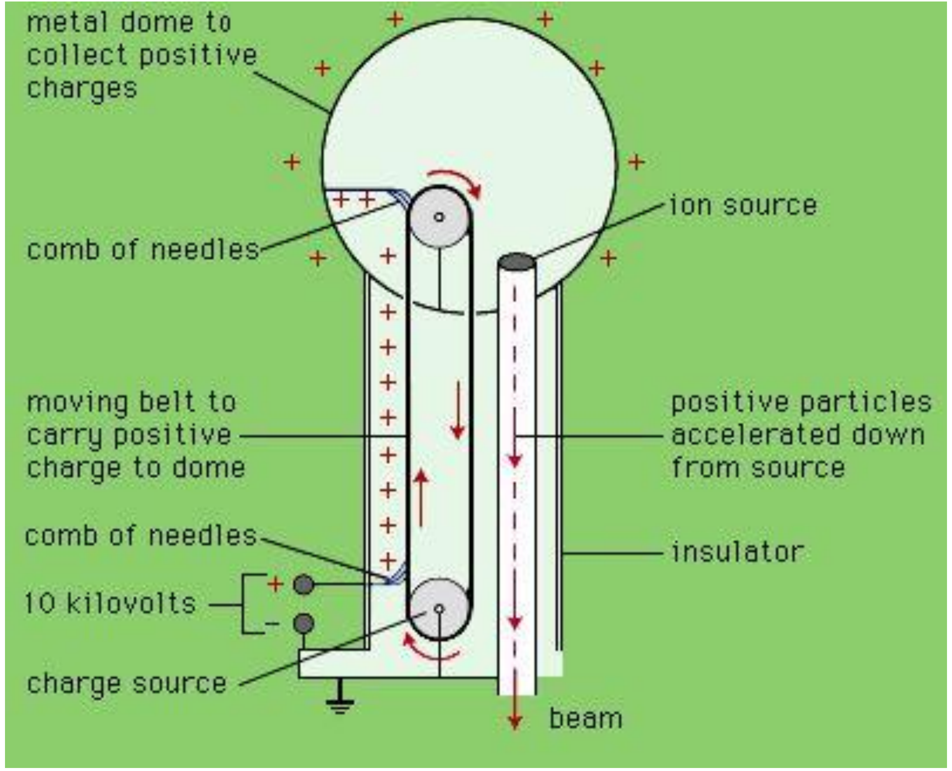
Shoot accelerated protons onto lithium target

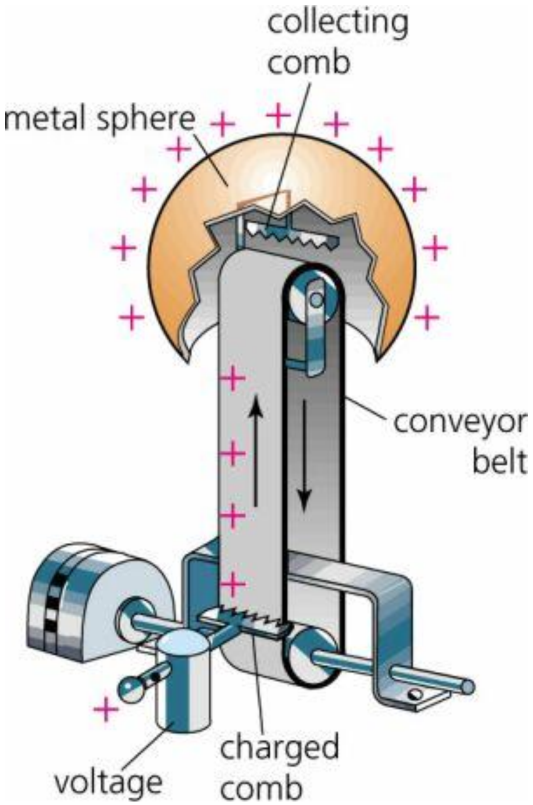
For incident energy above 125 keV

$$ {}^{7}_{3}Li + p \rightarrow {}^{8}_{4}Be \rightarrow {}^{4}_{2}He + {}^{4}_{2}He + 17.2\ MeV $$

Pushing this simple idea – high voltages

Van der Graaff

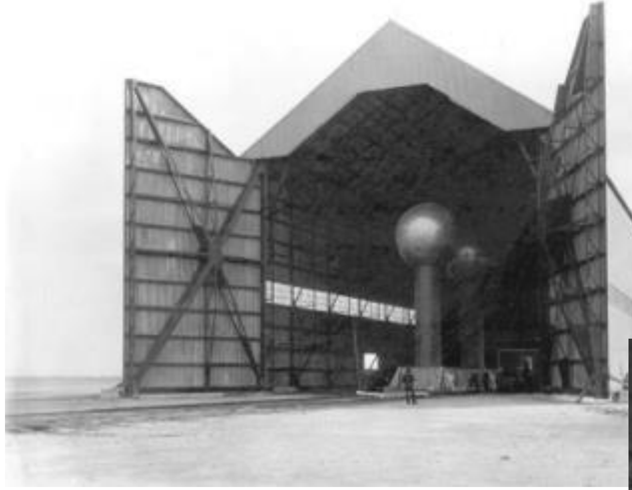


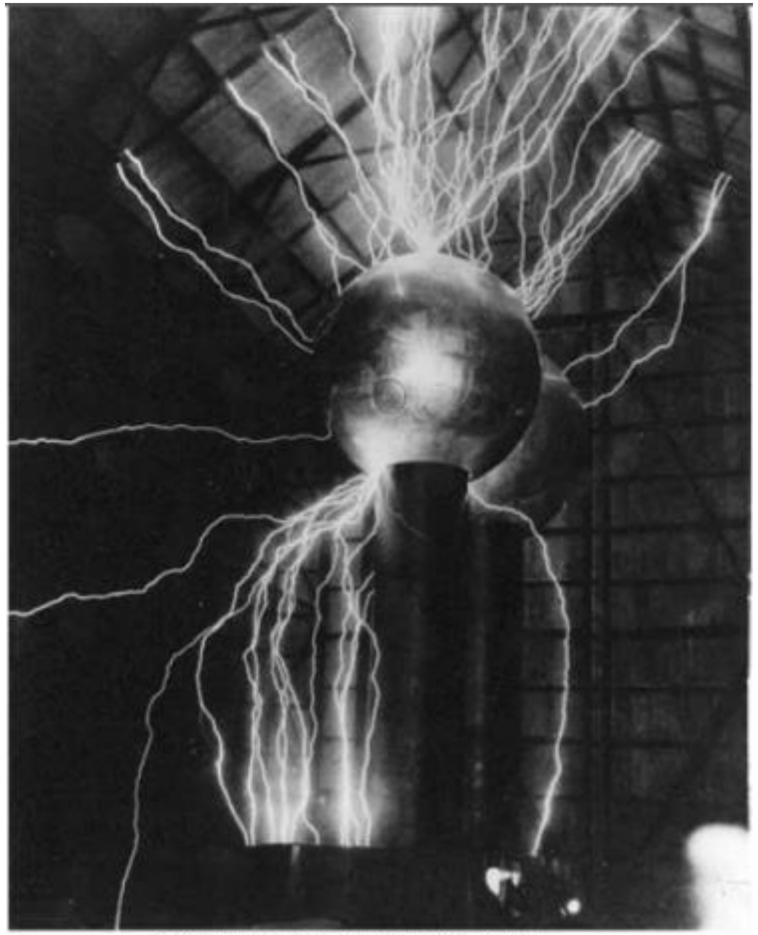


- Electric charges are transported mechanically on an insulating belt
- Stable, continuous beams, practical limit 10 - 15 MV

R.J. Van de Graaf

Van de Graaff's very large accelerator built at MIT's Round Hill Experiment Station in the early 1930s.





AT ROUND HILL SPARKING TO HANGAR (LONG EXPOSURE)

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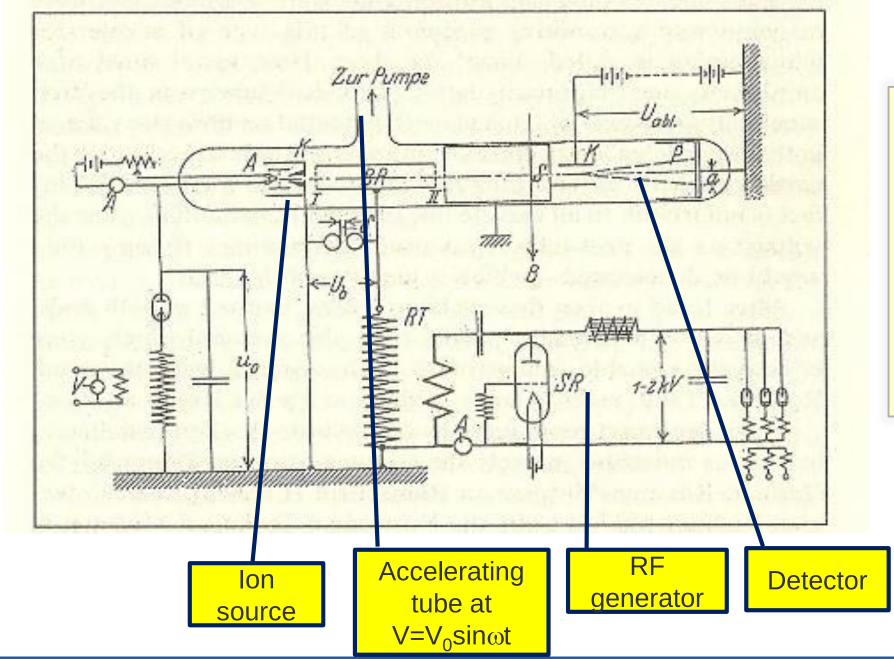
"Under normal operation, because the electrodes were very smooth and almost perfect spheres, Van de Graaff generators did not normally spark. However, the installation at Round Hill was in an open-air hanger, frequented by pigeons, and here we see the effect of pigeon droppings."

THE beginning of **modern accelerators** in 1928

A Norwegian student of **electrical engineering** at Karlsruhe and Aachen.The X-ray transformer that he had chosen for his PhD Thesis at Aachen University did not work, and he was forced to choose quickly another subject. Inspired by a 1924 paper by Ising (acceleration of particles using “voltage pulses”).

In 1928, Rolf Wideröe’s PhD thesis introduced the basic concept of modern particle accelerators, using periodic acceleration provided by electric field at Radio-Frequency (RF).

This was a major step from the previous DC (constant voltage) acceleration, limited to few MeV



Ion source

Accelerating tube at $V=V_0\sin\omega t$

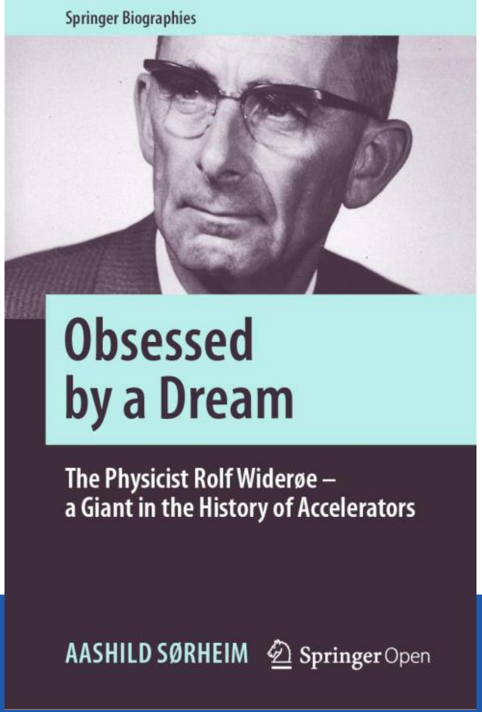
RF generator

Detector

Rolf Wideröe’s PhD thesis,
1928, University of Aachen

Acceleration of potassium ions 1+ with 25kV of RF at 1 MHz → 50 keV acceleration in a 88 cm long glass tube) “

at a cost of four to five hundred marks”, less than 2’000 € today!


Springer Biographies

Obsessed by a Dream

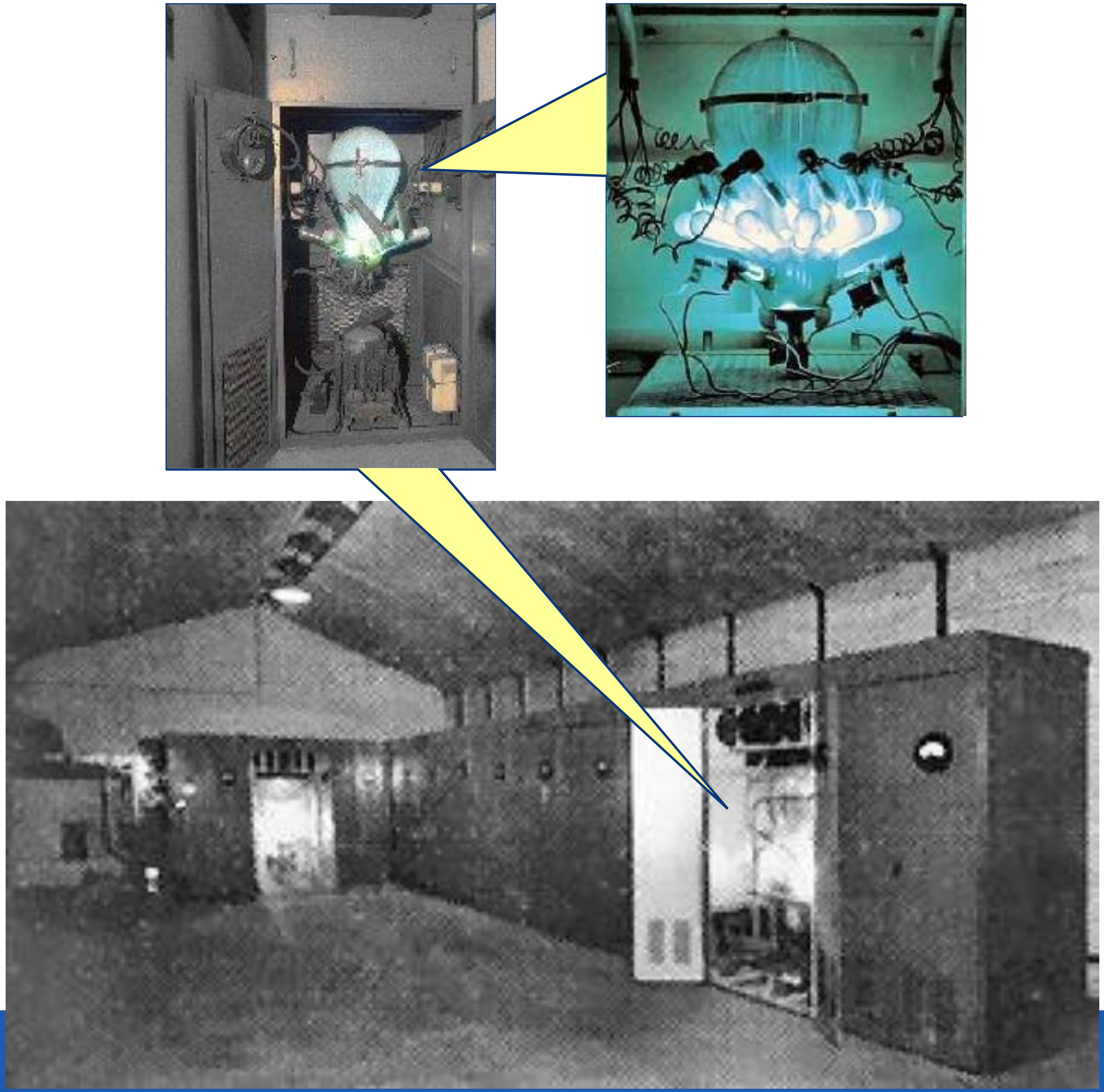
The Physicist Rolf Widerøe – a Giant in the History of Accelerators

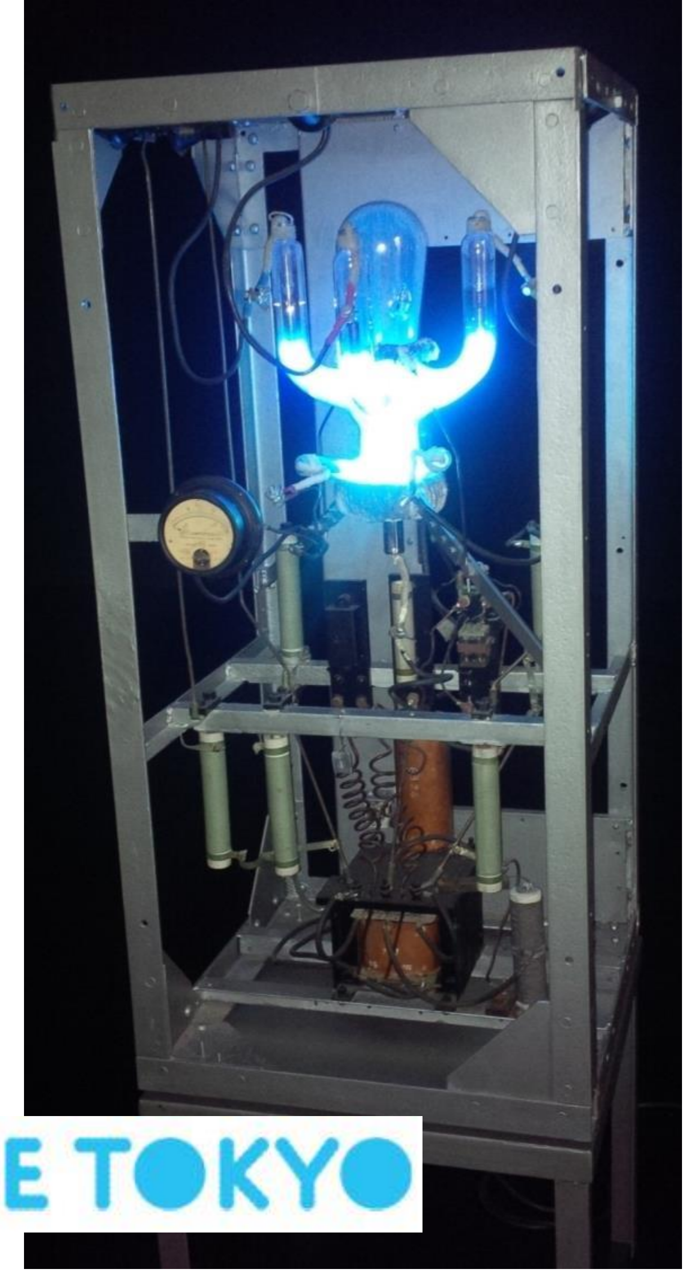
AASHILD SØRHEIM

Springer Open

Once upon a time…. not so far

This is a 6-phase device, 150A rating with grid control.
It measures 600mm high by 530mm diameter.



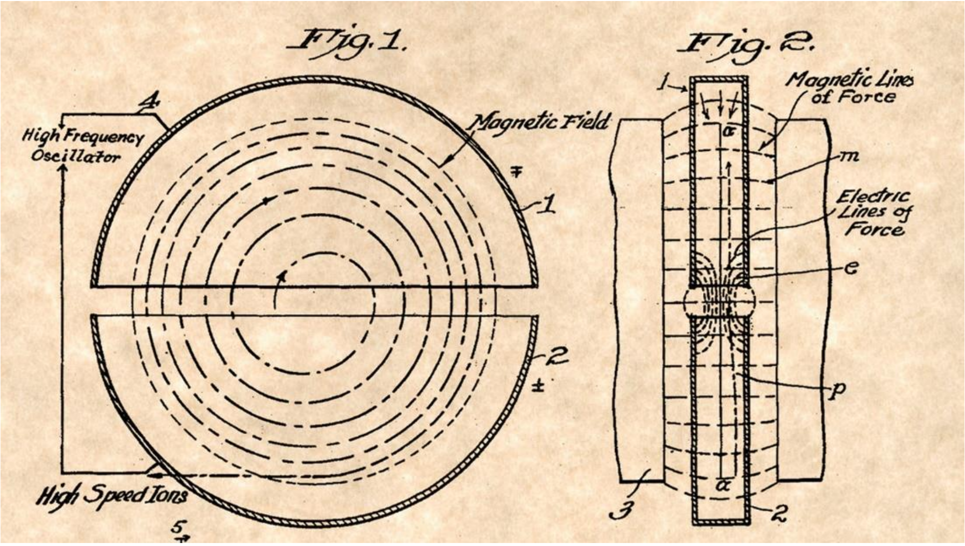


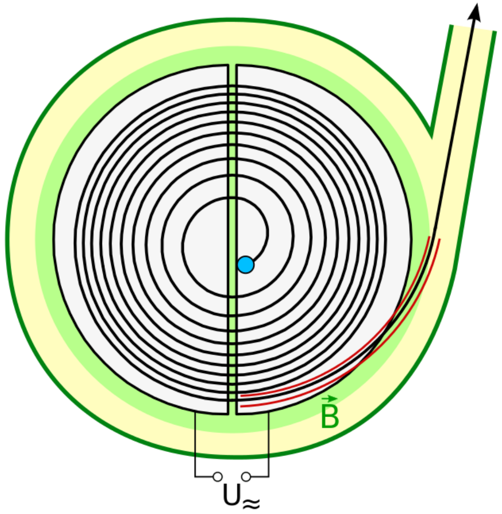
PALAIS DE TOKYO

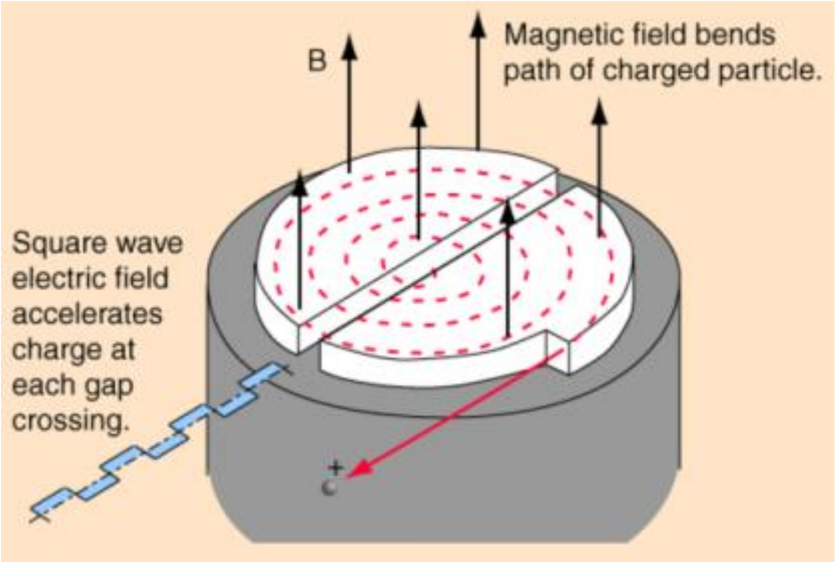
Cyclotron

- 1932: 1.2 MeV – 1940: 20 MeV (E.O. Lawrence, M.S. Livingston)
- Constant magnetic field
- Alternating voltage between the two D’s
- Increasing particle orbit radius

- Development lead to the synchro-cyclotron to cope with the relativistic effects.



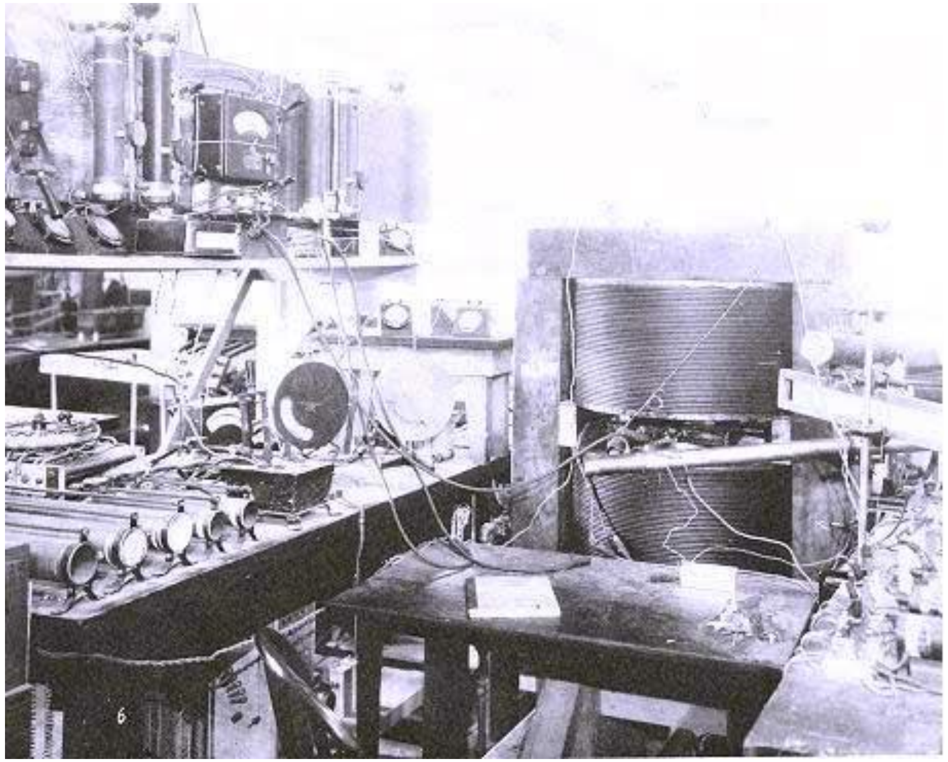




First cyclotrons

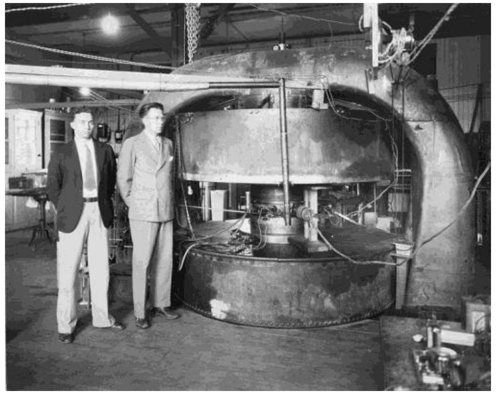
In 1939 Lawrence received the Nobel prize for his work.

4.5 inch Cyclotron: accelerates to 80 keV (January 1931)



11 inch cyclotron accelerates protons to 1 MeV (summer 1931)

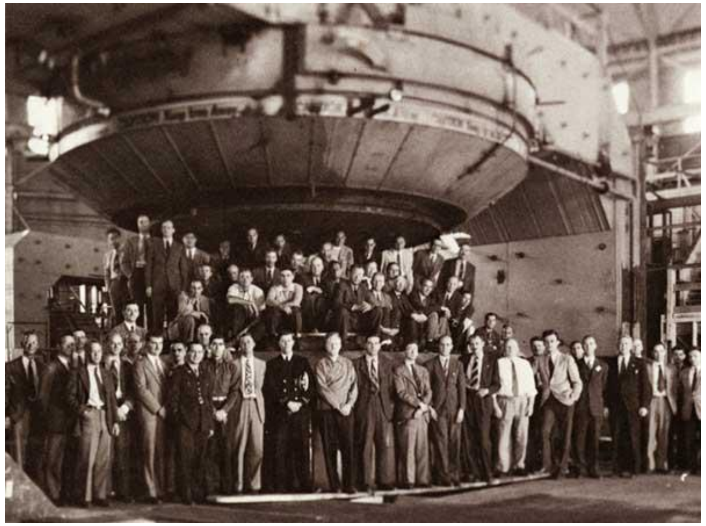
The escalation…



M. Stanley Livingston (L) and Ernest O. Lawrence in front of 27-inch cyclotron (70 cm) at the old Radiation Laboratory at the University of California, Berkeley.

Lawrence with the 37-inch cyclotron (94 cm), 1937. E.O. Lawrence was awarded the Nobel Prize in Physics in 1939. (Courtesy Lawrence Berkley National Laboratory)

60-inch cyclotron (1.5 m), 1939. This shows the cyclotron at the Lawrence Radiation Laboratory, Berkeley



Berkeley 184-inch cyclotron (4.7 m), 4000 tons magnet, >100 MeV protons (1946)

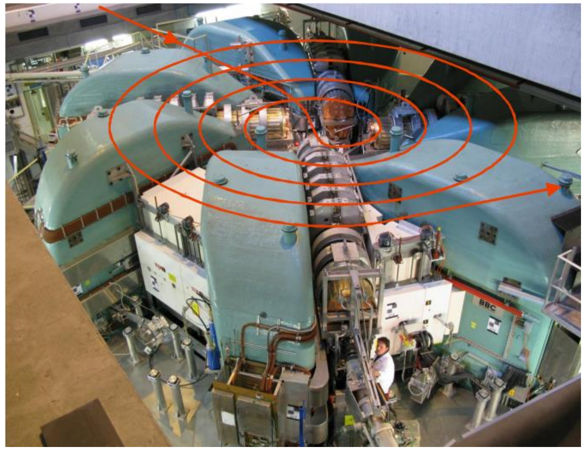
27 inch cyclotron, 80 tons magnet, 3.6 MeV (summer 1932)
37 inch cyclotron (1937)
60 inch cyclotron (1939)

Gatchina cyclotron, 10’000 tons magnet, 1 GeV protons (1957)

High-energy cyclotrons

TRIUMF 520 MeV proton cyclotron
(Vancouver, Canada)
18 m, In operation from 1974

Poles of the 600 MeV ion
superconducting cyclotron
(Catania, Italy)



590 MeV cyclotron
at the Paul Scherrer Institute
(Villigen, Switzerland).

1.4 MW Beam Power
(World Record!)
8 Magnets 250 tons
4 Cavities 900 kV
Extraction 99.99%

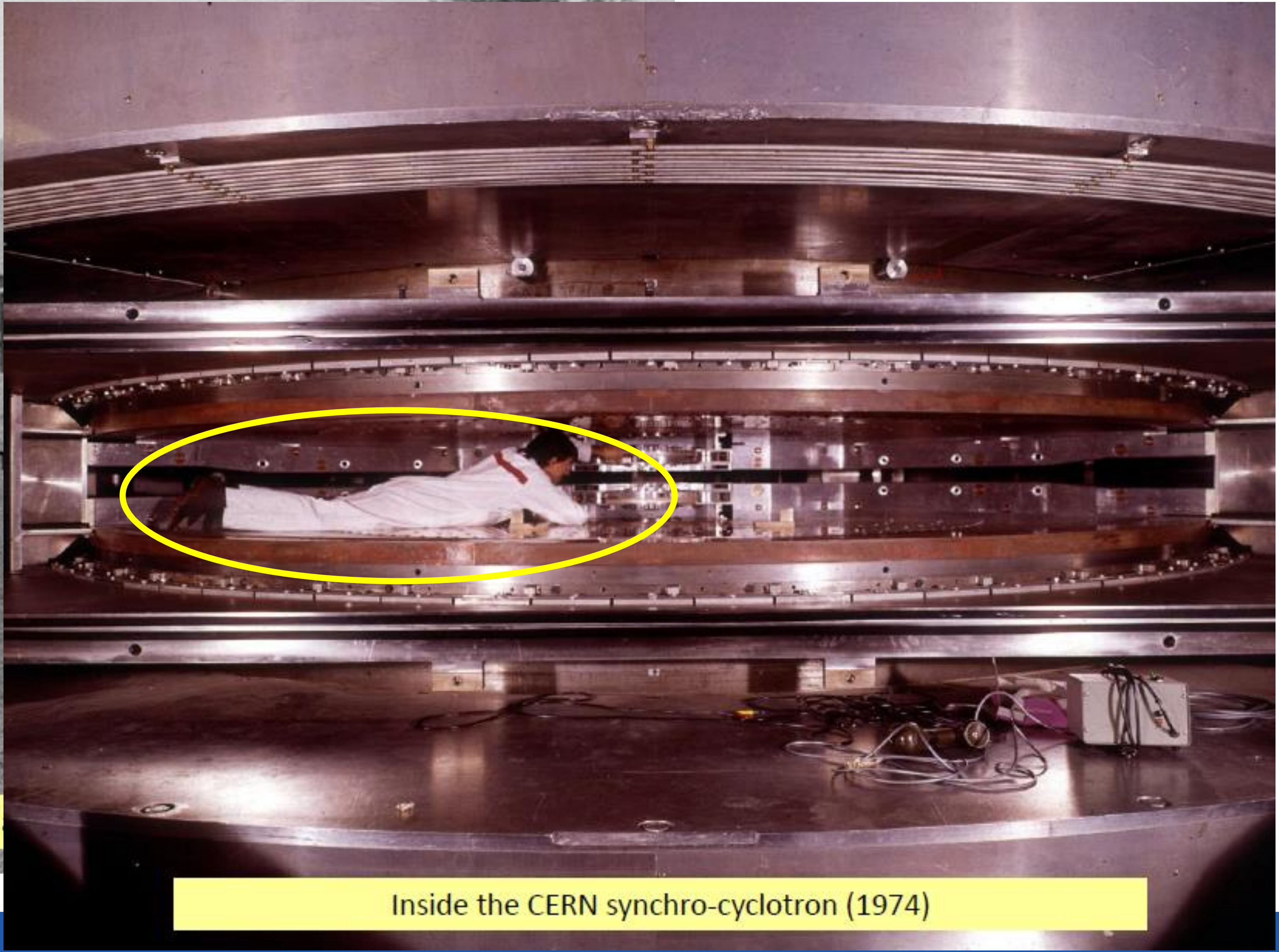
Cyclotrons face two types of limitation at higher energy

- **Loss of isochronism in the relativistic regime**
- **Large size of the magnet**

Possible solutions

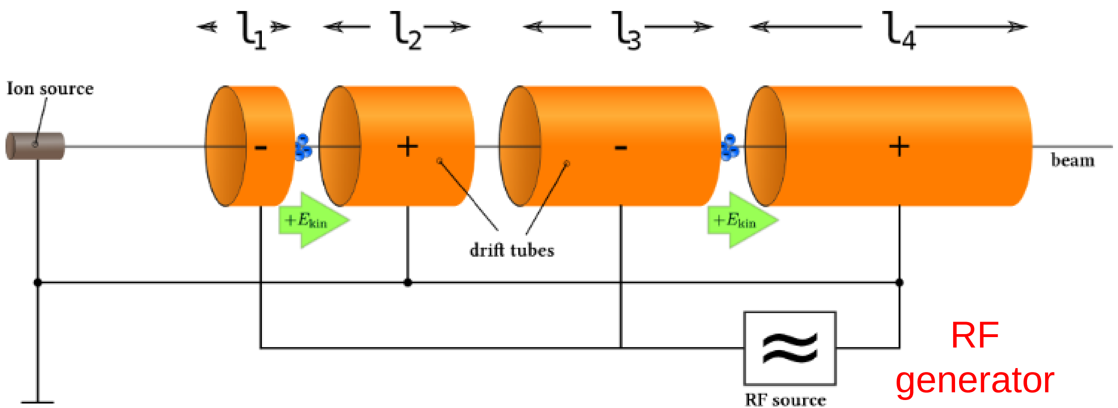
- **Synchro-cyclotrons**
- **Sectored magnet ⇒ isochronism and focussing**
- **Superconducting magnets ⇒ higher field ⇒ higher energy at given radius**

Coil for the CERN SC being transported



Inside the CERN synchro-cyclotron (1974)

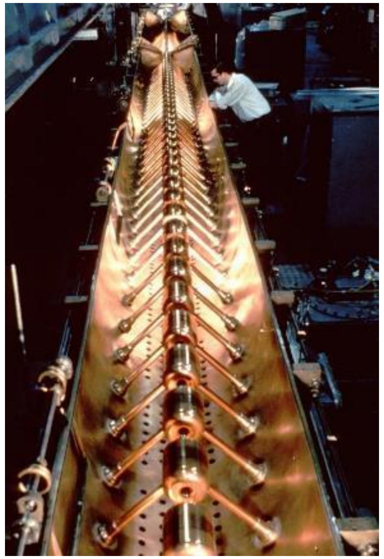
Linear Accelerator



RF generator with fixed frequency

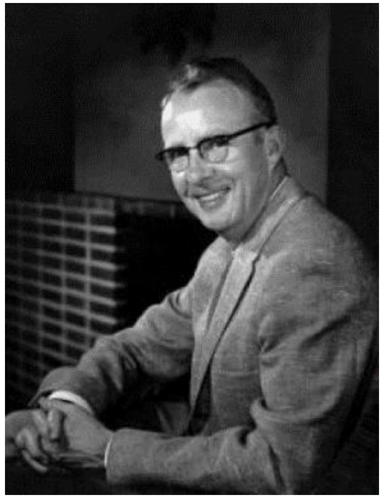
- Acceleration occurs in the gaps between the drift tubes
- First practical proton linac (200 MHz, 32 MeV) built by L. Alvarez at Berkeley in 1946
- As particle velocity increases, the drift tubes are longer ⇒ lost length
- Then increasing f_{RF} ⇒ increased power loss
- To limit the power loss, use a resonant cavity.

- The periodicity becomes regular as v => c.



- Many people involved: Wideroe, Sloan, Lawrence, Alvarez,….
- Main development took place between 1931 and 1946.
- Development was also helped by the progress made on high power high frequency power supplies for radar technology.
- Today still the first stage in many accelerator complexes.
- Limited by energy due to length and single pass.

First practical proton linac (200 MHz, 32 MeV) built by L. Alvarez at Berkeley in 1946

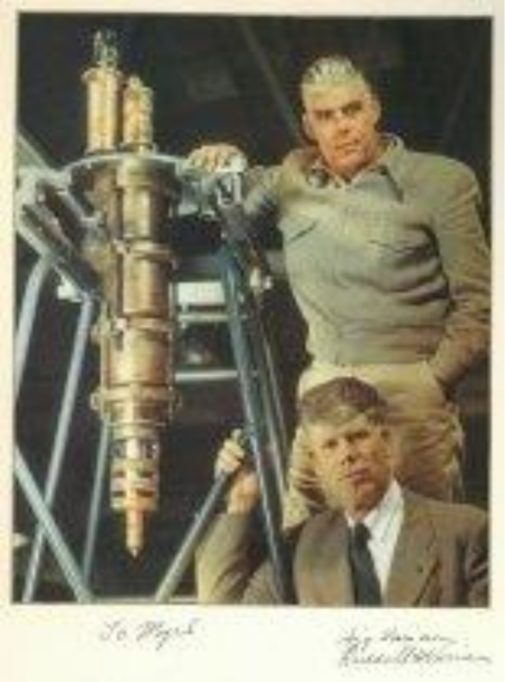


L. Alvarez

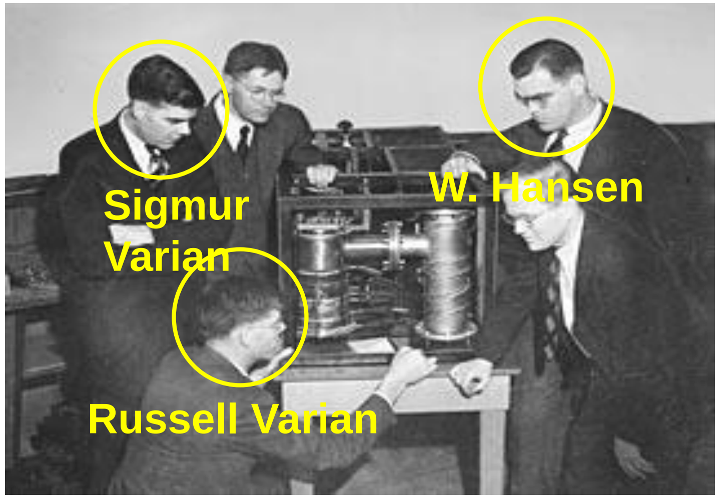
Electron Linac

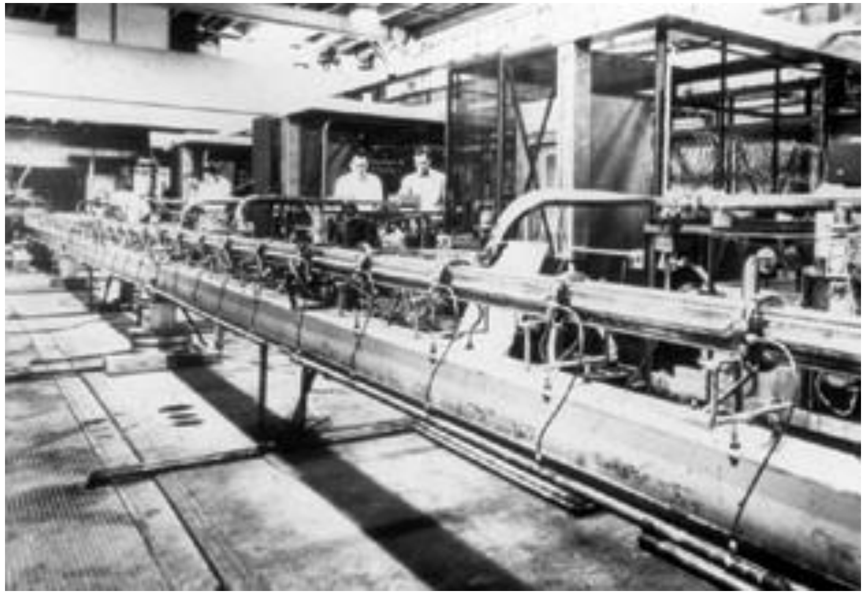
Thanks to the klystron development, large beam energy increase of electron linacs.

Mark I electron linac (6 MeV)



Sigmur and Russell Varian posing with klystron, 1953





Mark III electron linac (75 MeV)

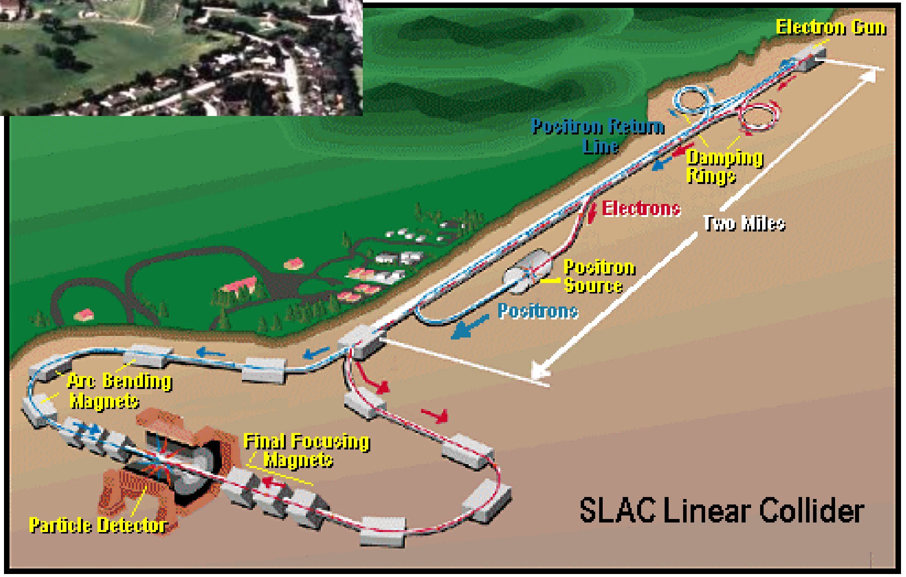
The real Beginning was *at SLAC*

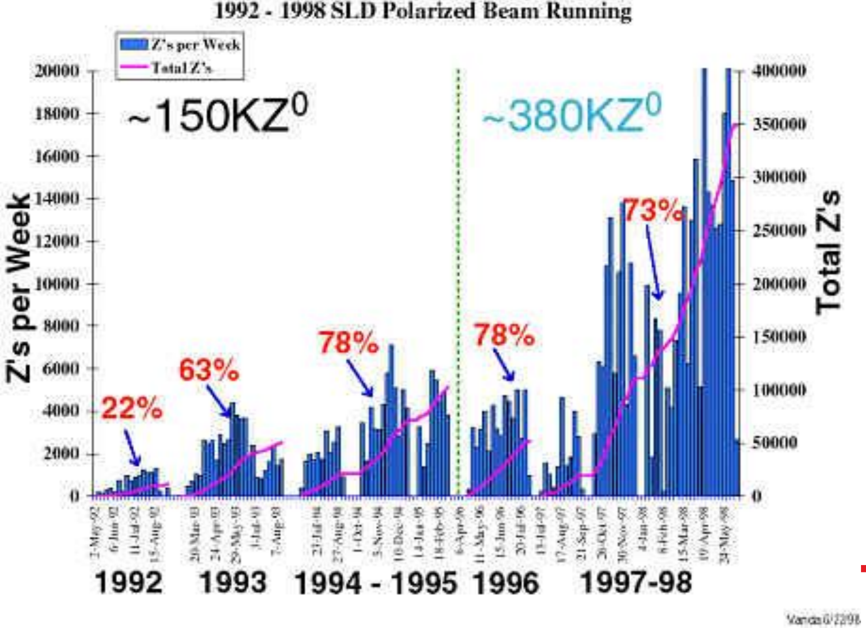
Burt Richter

SLAC Linear Collider (SLC)

1988-1998

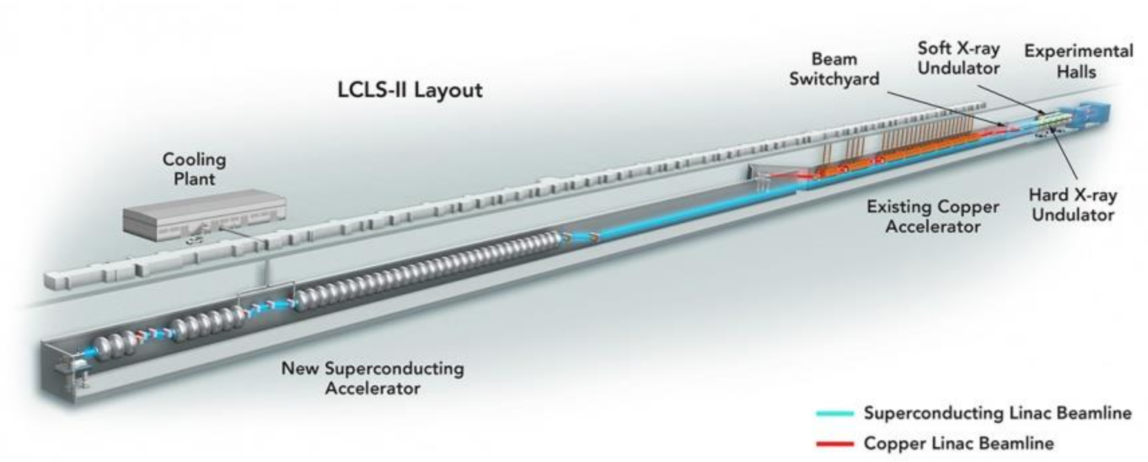
A proof of principle





Achieved $\sigma^x \times \sigma^y$ = 1/3 of design

LCLS II at SLAC



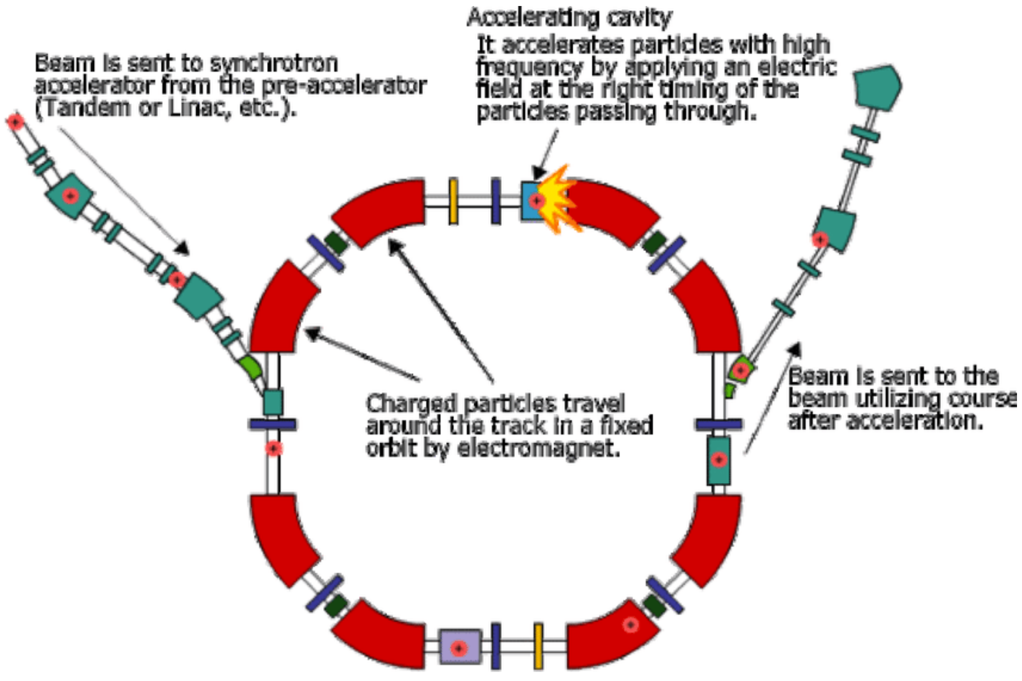
The LCLS-II project is to provide a major upgrade to LCLS (Linac Coherent Light Source) by adding two new X-ray laser beams. The new system will utilize the 500 m (1,600 ft) of existing tunnel to add a new superconducting accelerator at 4 GeV and two new sets of undulators that will increase the available energy range of LCLS. The advancement from the discoveries using this new capabilities may include new drugs, next-generation computers, and new materials.

Synchrotrons

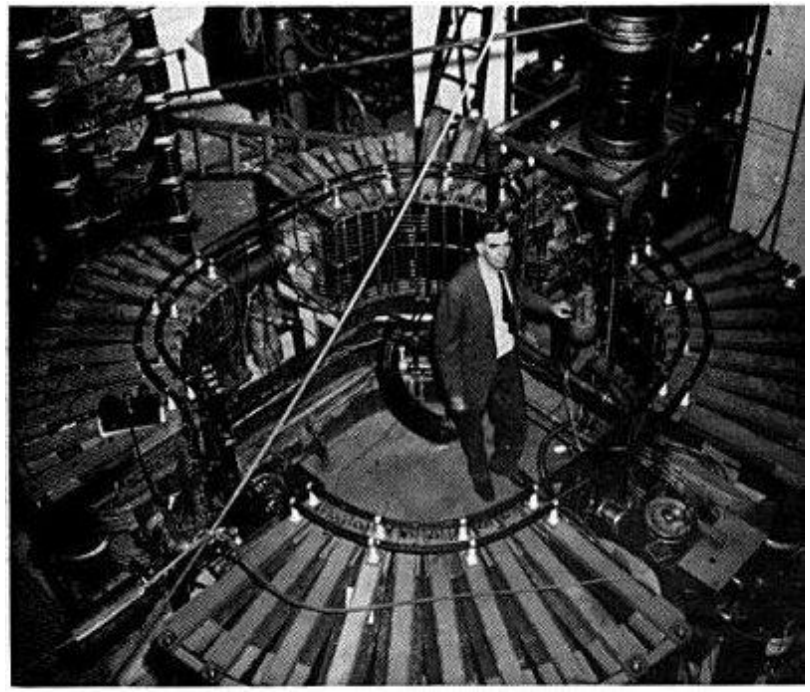
1943: M. Oliphant described his synchrotron invention in a memo to the UK Atomic Energy directorate

- Fixed radius for particle orbit
- Varying magnetic field and radio frequency
- Phase stability
- Important focusing of particle beams (Courant – Snyder)

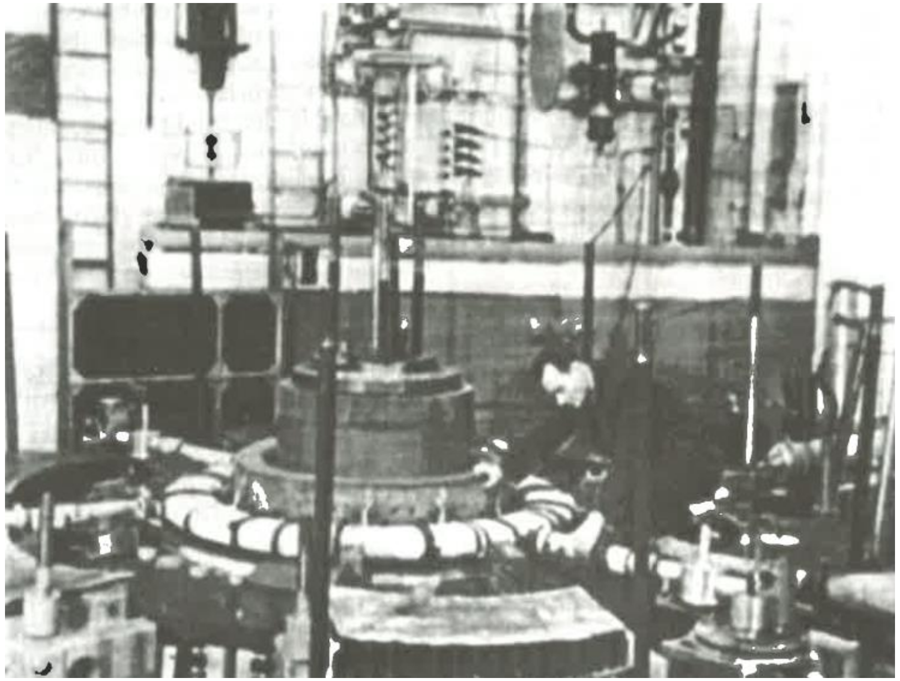
- 1959: CERN-PS and BNL-AGS
- Providing beam for fixed target physics
- Paved the way to colliders



Early Synchrotrons



300 MeV electron synchrotron
at University of Michigan (1949)

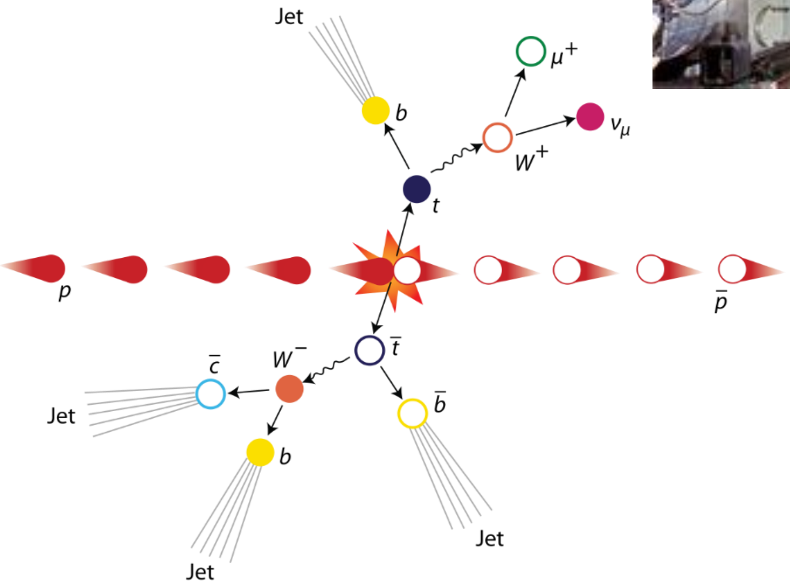


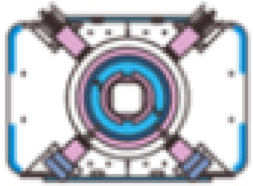
250 MeV electron synchrotron at
Lebedev Institute, Moscow (1949)

Cosmotron at Brookhaven
National Laboratory:
3.3 GeV in 1953

The TeVatron collider (6.28 km) at Fermilab

Colliding beams of protons and antiprotons accelerated at 980 GeV

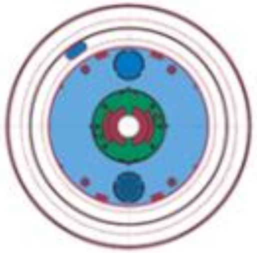




TEVATRON
B = 4.5 T
Bore : 76 mm

Discovery of the top quark, the heaviest particle (175 GeV)
CDF and D0 detectors at the TeVatron (1995)

HERA (Hadron-Elektron-Ringanlage) was a particle accelerator at DESY in Hamburg. It began operating in 1992. At HERA, electrons or positrons were collided with protons at a center of mass energy of 318 GeV. It was the only lepton-proton collider in the world while operating. Also, it was on the energy frontier in certain regions of the kinematic range. HERA was closed down on 30 June 2007



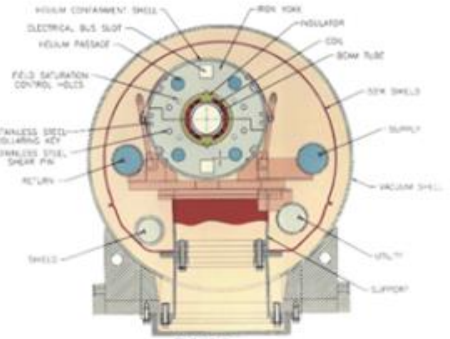
HERA
B = 4.7 T
BORE : 75 mm

	e^+ / e^-	p^+
Circumference L	6335.82 m	
Injection momentum $p_0 c$	12 GeV	40 GeV
Design momentum $p_N c$	30 GeV	820 GeV
Center of mass energy E_{cm}	314 GeV	
Number of bunches N	210	
Number of buckets N_B	220	
Average beam current I	58 mA	163 mA
Luminosity per IP $\mathcal{L}$	$1.5\ 10^{31}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	
Specific luminosity $\mathcal{L}_{sp}$	$3.3\ 10^{29}\ \mathrm{mA}^{-2}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	
Length of straight sections	4×361.4 m	

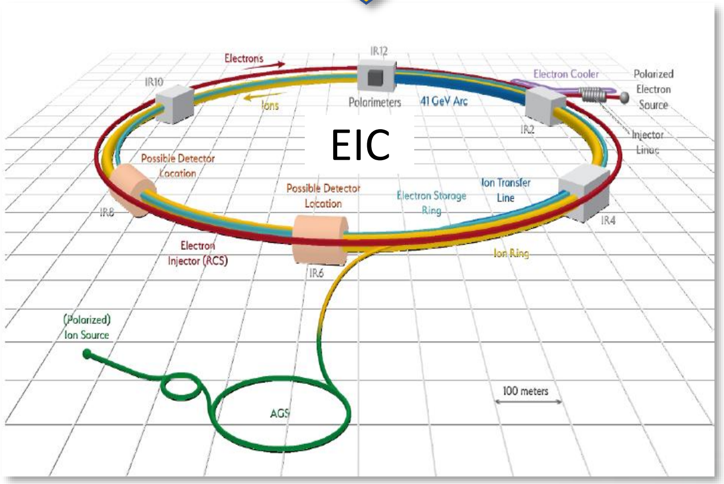
Electron-Ion Collider Concept

Design based on **existing** RHIC (Relativistic Heavy Ion Collider) ,
RHIC is well maintained, operating at its peak

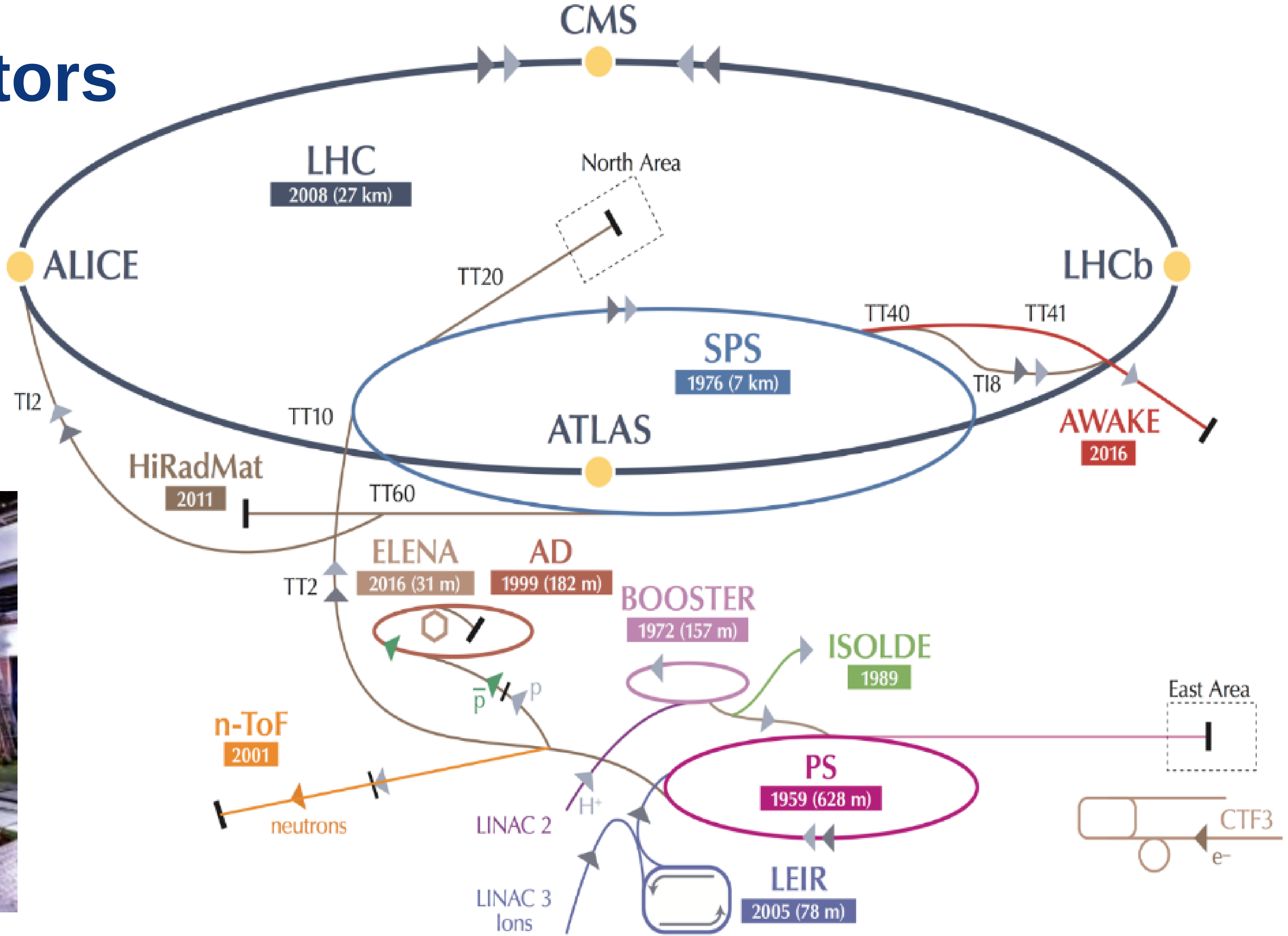
- **Hadron storage ring 40-275 GeV** (existing)
    - Many bunches
    - Bright beam emittance
    - Need strong cooling **or** frequent injections
- **Electron storage ring (2.5–18 GeV** (new))
    - Many bunches,
    - Large beam current (2.5 A) ➔ 10 MW S.R. power
- **Electron rapid cycling synchrotron** (new)
    - 1-2 Hz
    - Spin transparent due to high periodicity
- **High luminosity interaction region(s)** (new)
    - L = $10^{34} cm^{-2} s^{-1}$
    - Superconducting magnets
    - 25 mrad Crossing angle with crab cavities
    - Spin Rotators (longitudinal spin)
    - Forward hadron instrumentation



RHIC
B = 3.5 T
Bore : 80 mm



CERN accelerators



LHC (Large Hadron Collider)

1983	First studies for the LHC project
1988	First magnet model (feasibility)
1994	Approval of the LHC by the CERN Council
1996-1999	Series production industrialisation
1998	Declaration of Public Utility & Start of civil engineering
1998-2000	Placement of the main production contracts
2004	Start of the LHC installation
2005-2007	Magnets Installation in the tunnel
2006-2008	Hardware commissioning
2008-2009	Beam commissioning

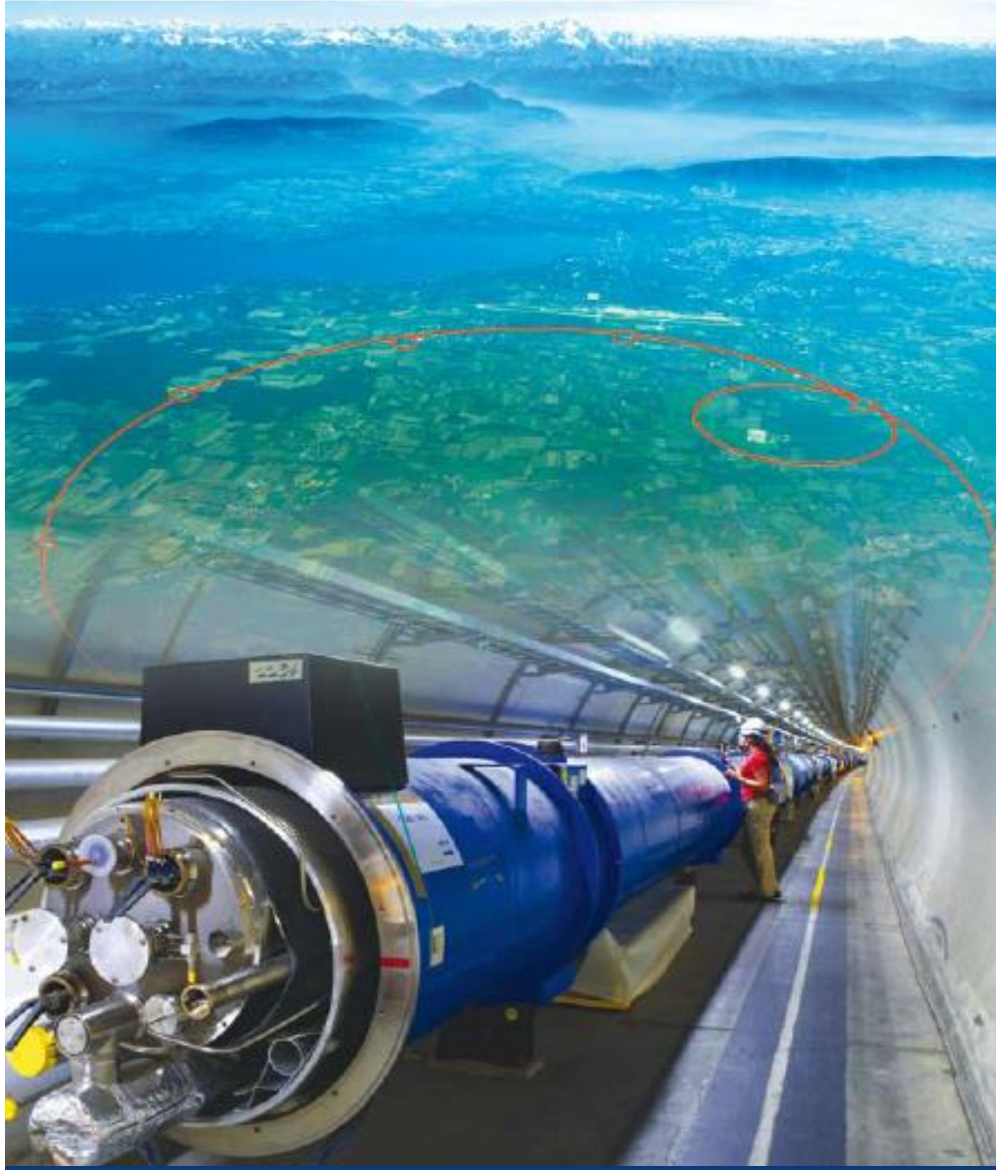
~ 25 years

2010-2037… Physics exploitation

2010 – 2012	Run 1 ;7 and 8 TeV
2015 – 2018	*Run 2 ; 13 TeV*
2021 – 2023	Run 3 (14 TeV)
2024 – 2025	HL-LHC installation
2026 – 2037…	HL-LHC operation

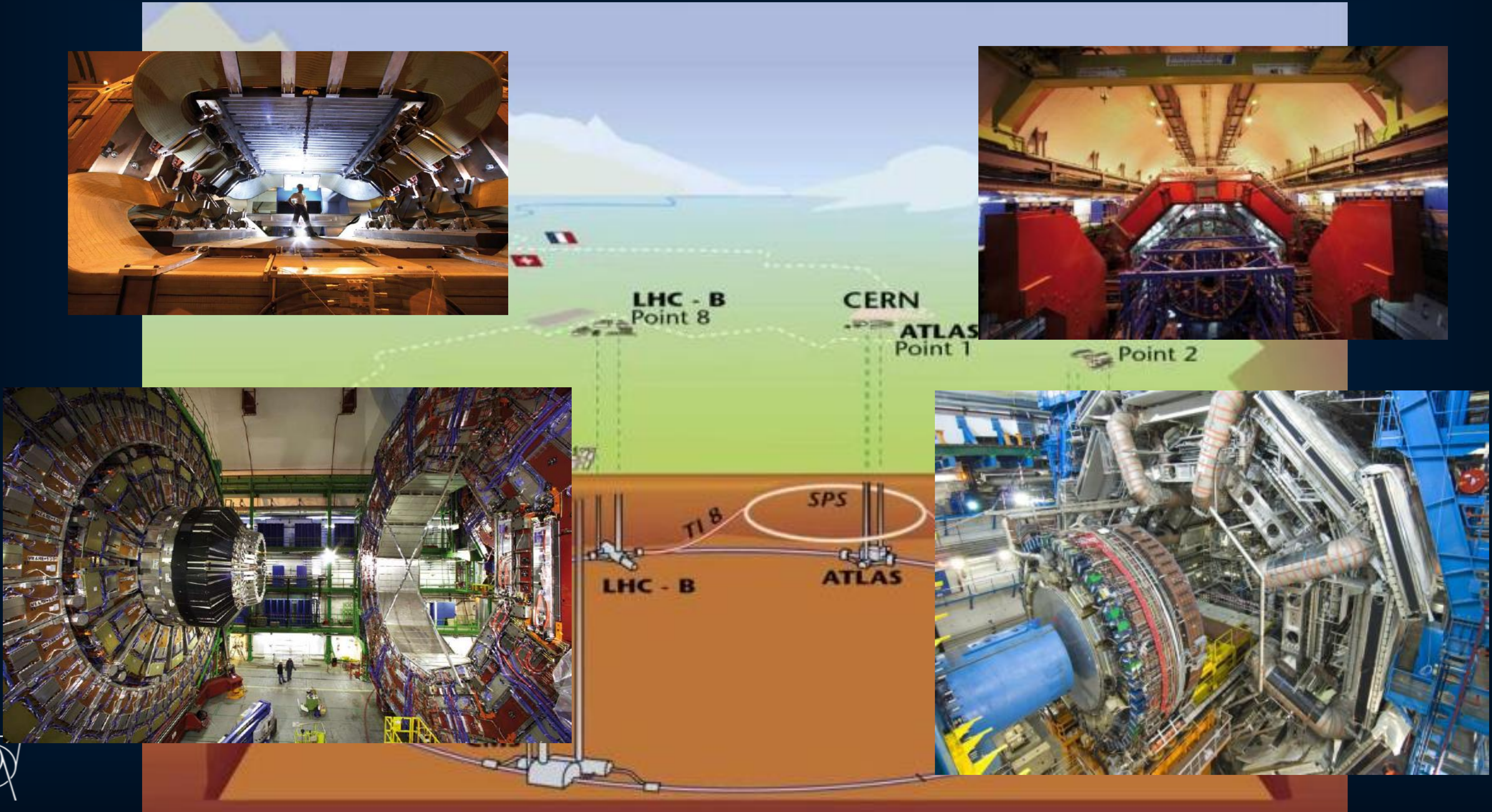
~ 30 years

HiLumi
HL-LHC PROJECT



A 27 km circumference collider…

LHC: an accelerator of 27 km with four main experiments

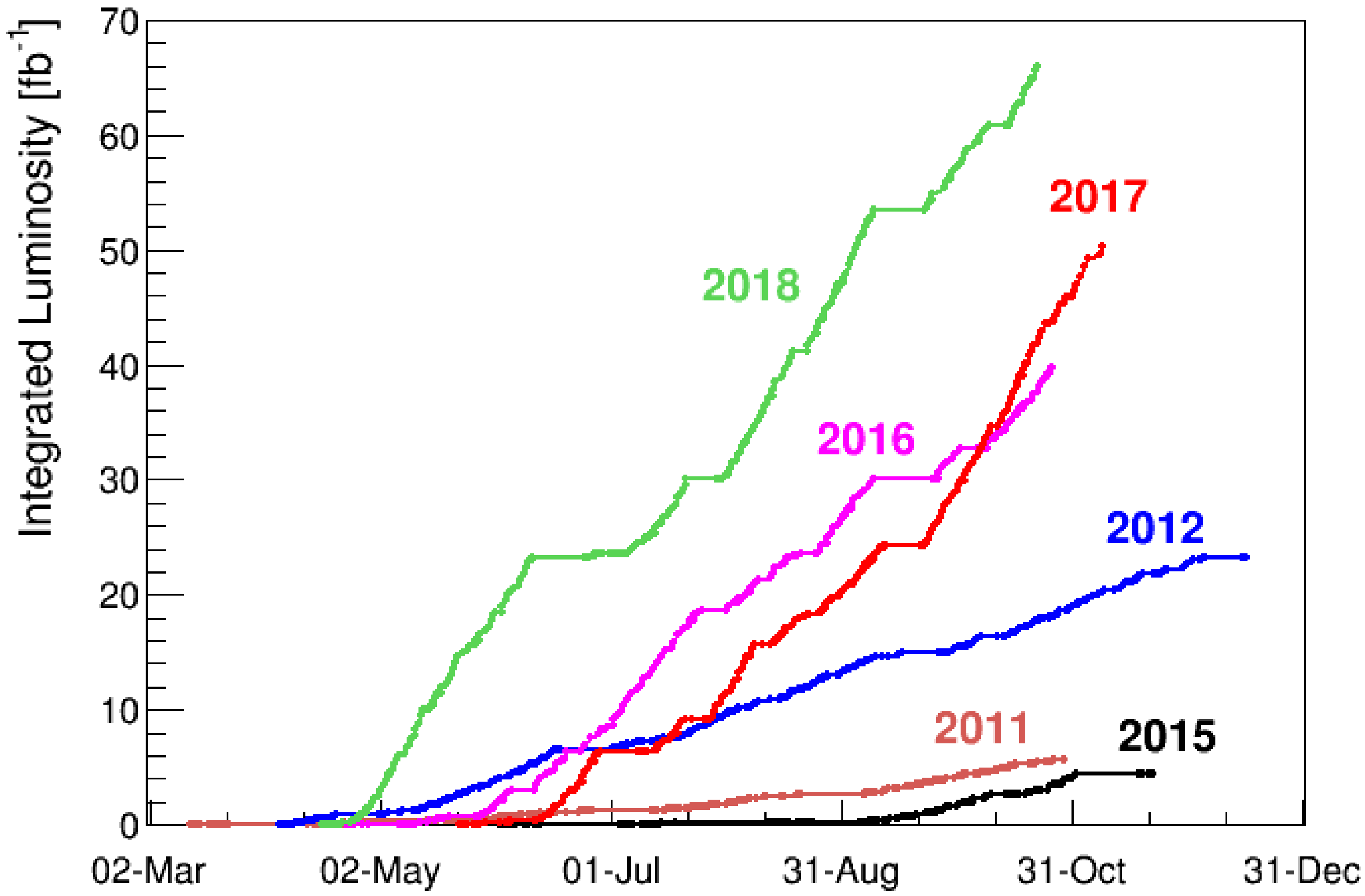


LHC: technological challenges

The specifications of many systems were beyond the state of the art. Long R&D programs with many institutes and industries worldwide.

- **The highest field accelerator magnets: 8.3 T** (1232 dipole magnets of 15 m)
- **The largest superconducting magnet system** (~10’000 magnets)
- **The largest 1.9 K cryogenics installation** (superfluid helium, 150 tons of LHe to cool 42’000 tons)
- **Ultra-high cryogenic vacuum for the particle beams** (10^{-13} atm, ten times lower than the Moon)
- **The highest currents controlled with high precision** (up to 13 kA)
- **The highest precision ever demanded from the power converters** (parts per million level)
- **A sophisticated and ultra-reliable magnet quench protection system**
  (Energy stored in the magnet system: ~10 Gjoule, in the beams > 700 MJ)

LHC: Run 1 and Run 2



Run 1 at 7 TeV:
2010, 2011
Run 1 at 8 TeV : 2012

Run 2 at 13 TeV:
2015, 2016, 2017, 2018

∑ (Run1 + Run2)
≈ 190 fb^{-1}

Energy management challenges

Energy stored in the magnet system: ~10 GJoule

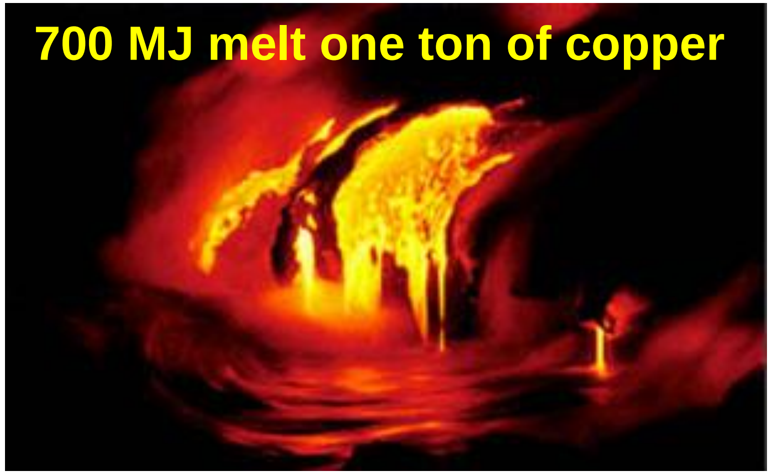

10 GJoule ≅ flying 700 km/h

560 tons


10 GJoule ≅ 55 km/h

88’000 tons

Energy stored in the two beams: 720 MJ *[6 10^{14} protons (1 ng of H+) at 7 TeV]*


700 MJ melt one ton of copper

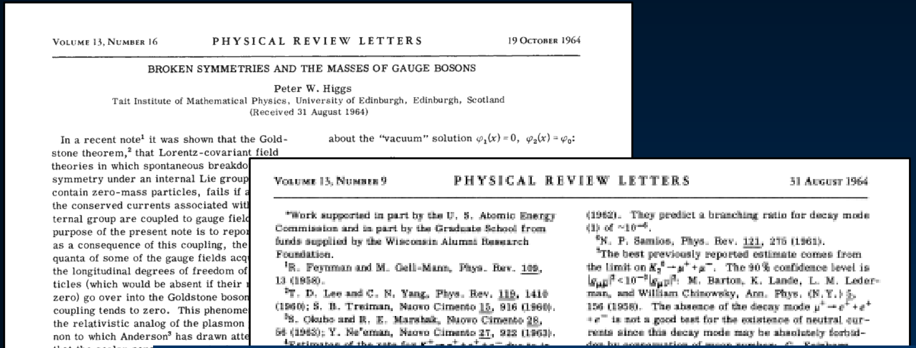
700 MJoule dissipated in 88 μs

$700.10^{6} / 88.10^{-6} \cong 8$ TW

World Electrical Installed Capacity ≅ 3.8 TW

1 electron volt = 1,602× 10^{-19} Joule
1 proton at 7 TeV = 1.1 x 10^{-12} Joule

From **individual** theoretical physicist **idea**….



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdo
symmetry under an internal Lie group
contain zero-mass particles, fails if a
the conserved currents associated wit
ternal group are coupled to gauge fiel
purpose of the present note is to repo
as a consequence of this coupling, the
quanta of some of the gauge fields acq
the longitudinal degrees of freedom of
ticles (which would be absent if their
zero) go over into the Goldstone boson
coupling tends to zero. This phenome
the relativistic analog of the plasmon
non to which Anderson[3] has drawn atte
that the scalar zero
conducting neutral
nal plasmon modes
is charged.

The simplest theo
havior is a gauge-i
used by Goldstone[2]
fields φ_1, φ_2 and a
through the Lagran

$L = -\frac{1}{2}(\nabla\varphi_1)^2 -$

where

about the "vacuum" solution $\varphi_1(x) = 0$, $\varphi_2(x) = \varphi_0$:

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

*Work supported in part by the U. S. Atomic Energy Commission and in part by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.

[1]R. Feynman and M. Gell-Mann, Phys. Rev. 109, 13 (1958).

[2]T. D. Lee and C. N. Yang, Phys. Rev. 119, 1410 (1960); S. B. Treiman, Nuovo Cimento 15, 916 (1960).

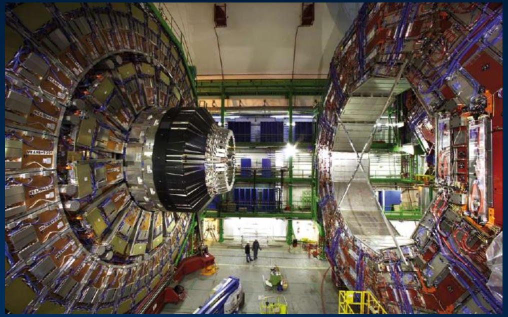
[3]S. Okubo and R. E. Marshak, Nuovo Cimento 28, 56 (1963); Y. Ne'eman, Nuovo Cimento 27, 922 (1963).

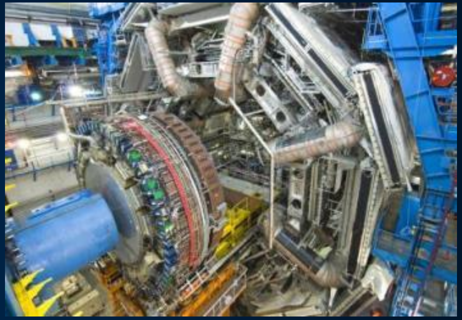
(1962). They predict a branching ratio for decay mode (1) of ~10^{-6}.

[5]N. P. Samios, Phys. Rev. 121, 275 (1961).

[6]The best previously reported estimate comes from the limit on $K_2^0 \to \mu^+ + \mu^-$. The 90 % confidence level is $|g_{\mu\mu}|^2 < 10^{-2}|g_{\mu\nu}|^2$: M. Barton, K. Lande, L. M. Lederman, and William Chinowsky, Ann. Phys. (N.Y.) 5, 156 (1958). The absence of the decay mode $\mu^+ \to e^+ + e^+ + e^-$ is not a good test for the existence of neutral currents since this decay mode may be absolutely forbidden by conservation of muon number.

…to **collective innovation** !





To design and construct this
many thousands of technicians,
engineers and physicists
from **many different disciplines**,
from **all over the world**

and respect

Discovery 2012, Nobel Prize in Physics 2013

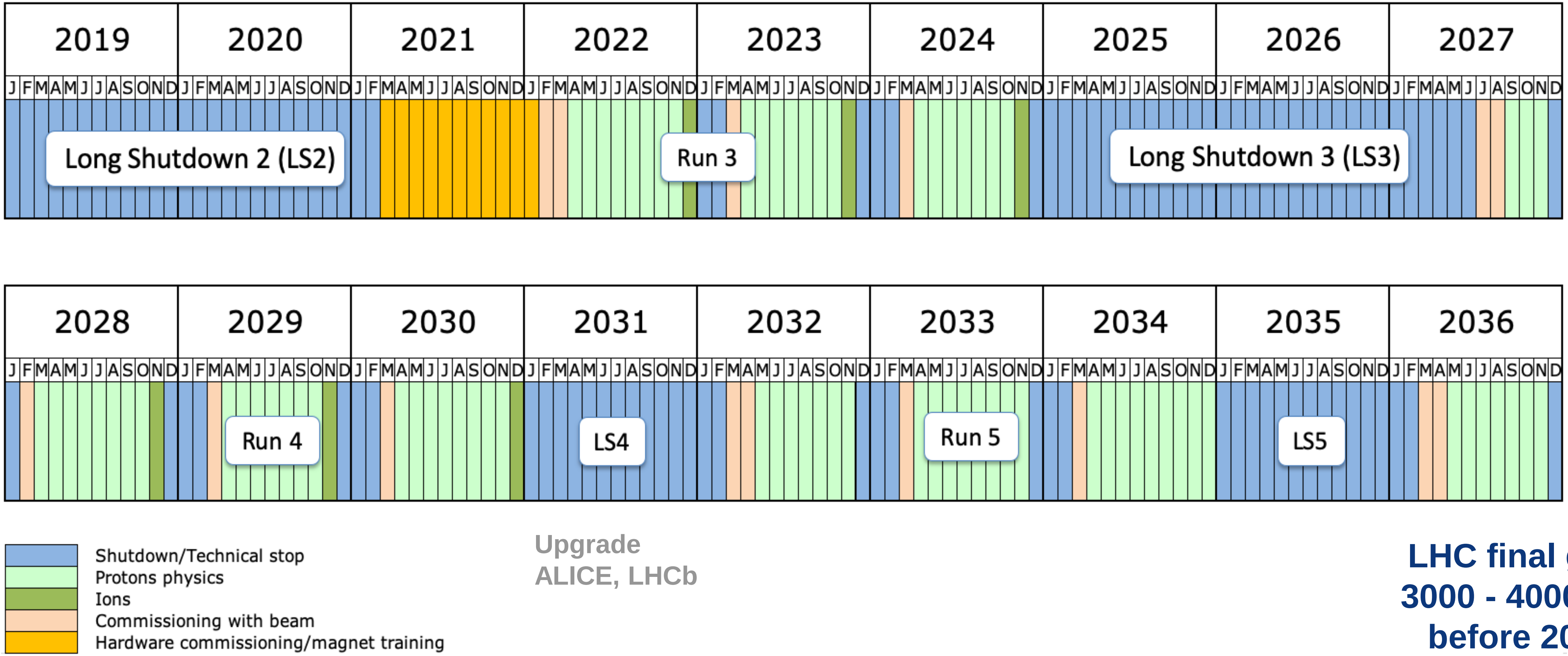
1964-2012

LHC schedule (until approx. 2040)

Phase I upgrade
ALICE, ATLAS, CMS, LHCb

Phase II upgrade
ATLAS, CMS

High-luminosity LHC

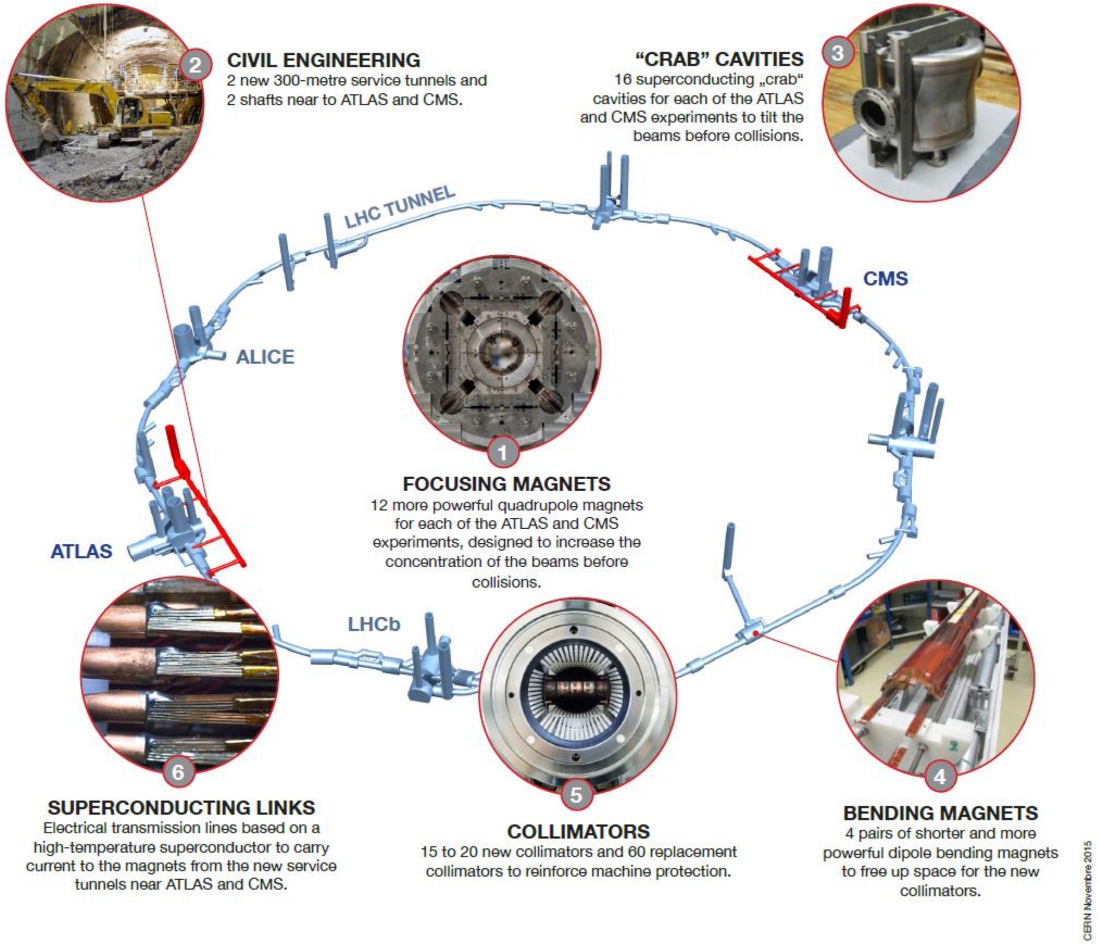


Upgrade
ALICE, LHCb

LHC final goal
3000 - 4000 fb^{-1}
before 2020

The HL-LHC Project

Total cost
Material: 950 MCHF
Personnel: ≈ 2000 FTE-years



CIVIL ENGINEERING
2 new 300-metre service tunnels and 2 shafts near to ATLAS and CMS.

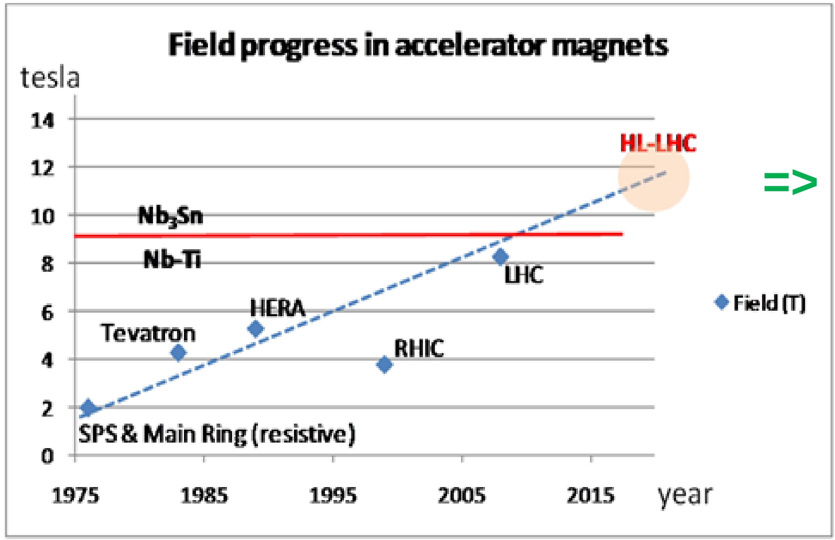
“CRAB” CAVITIES
16 superconducting „crab“ cavities for each of the ATLAS and CMS experiments to tilt the beams before collisions.

FOCUSING MAGNETS
12 more powerful quadrupole magnets for each of the ATLAS and CMS experiments, designed to increase the concentration of the beams before collisions.

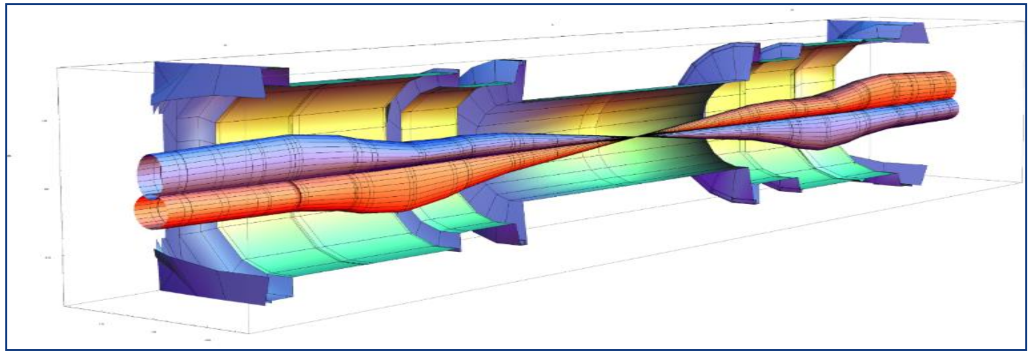
SUPERCONDUCTING LINKS
Electrical transmission lines based on a high-temperature superconductor to carry current to the magnets from the new service tunnels near ATLAS and CMS.

COLLIMATORS
15 to 20 new collimators and 60 replacement collimators to reinforce machine protection.

BENDING MAGNETS
4 pairs of shorter and more powerful dipole bending magnets to free up space for the new collimators.



=> Nb$_3$Sn technology



Major intervention on more than 1.2 km of the LHC

The Importance of Energy

New discoveries often follow the opening of a new energy regime:

Discovery of the electron	**1 eV**
Discovery of the nucleus	**5 MeV**
Discovery of pion and muon	**100 MeV**
Discovery of the kaon	**500 MeV**
Discovery of the proton substructure	**20 GeV**
Discovery of the top quark	**2 TeV**
Discovery of the BEH (Higgs) boson	**8 TeV**
Dark Matter (Supersymmetry,…) **Extra dimensions,** **Matter-antimatter asymmetry**	**13-14 TeV ?** **towards 100 TeV ?**

Lorentz force

Challenge *B* and *E* ↗

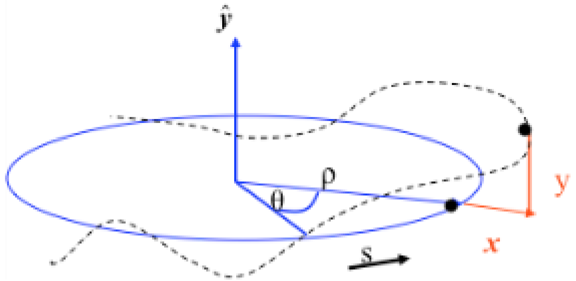
- Implicit in relativistic formulation of Maxwell’s equations
- Describes the force on a charged particle moving in an em field

$$\vec{f} = q(\vec{E} + \vec{v} \wedge \vec{B})$$

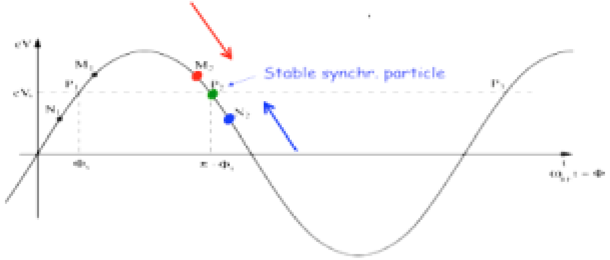
$$\vec{E} = 0 \qquad\qquad \vec{B} = 0$$

$$\vec{f} = q\,\vec{v} \wedge \vec{B} \qquad\qquad \vec{f} = q\,\vec{E}$$

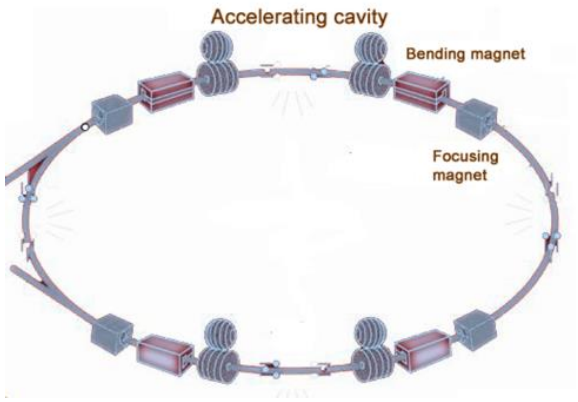
Transverse Beam Dynamics



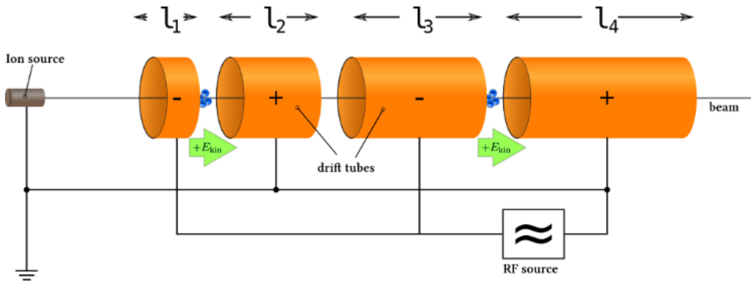
Longitudinal Beam Dynamics



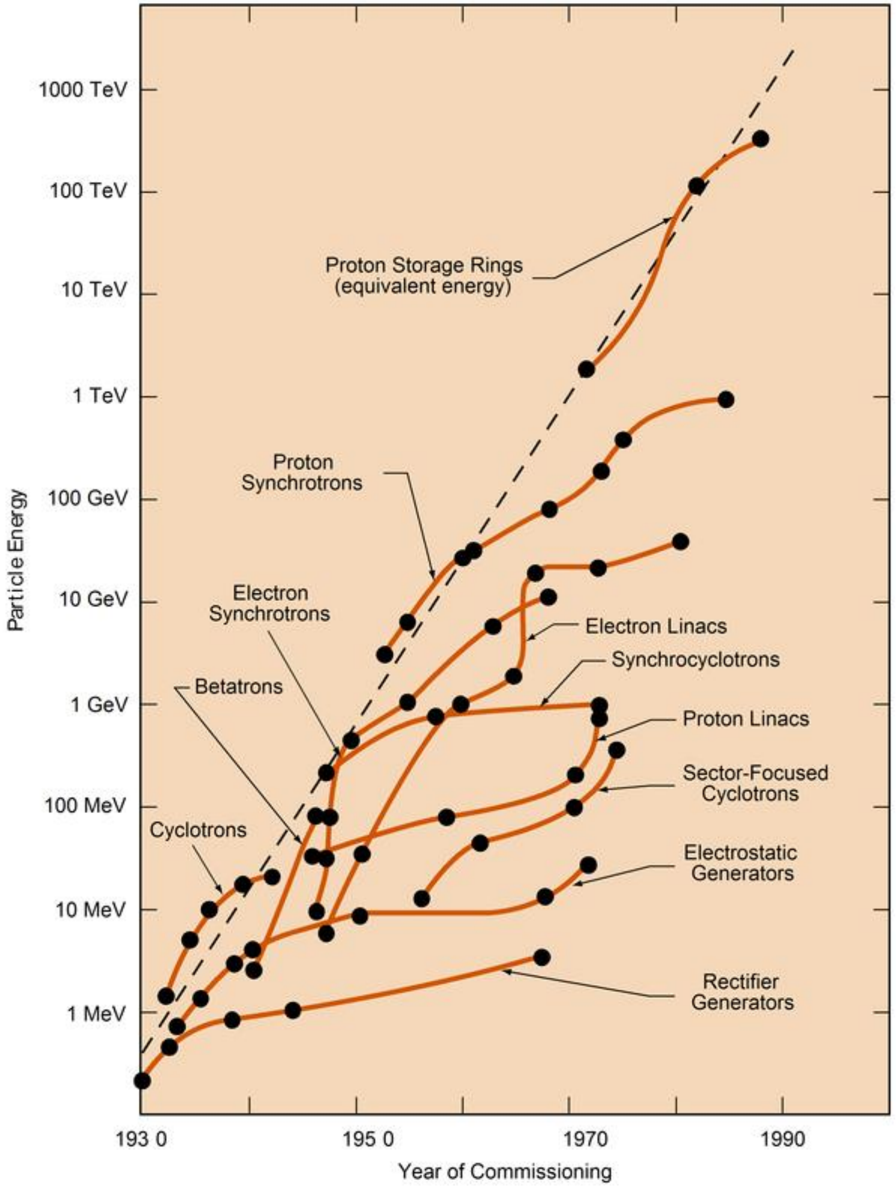
How to get higher energy or smaller accelerators ?



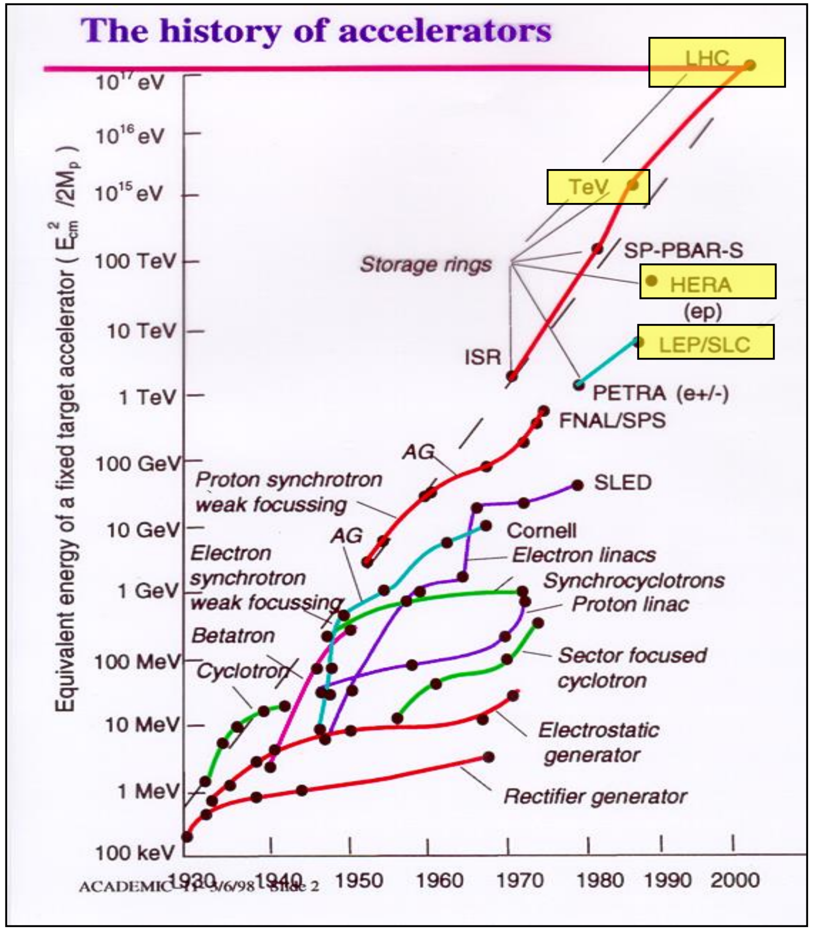
Synchrotrons: $p/q=B\rho$ (magnetic rigidity)
Need to maximise ***magnetic field***
Superconductivity is nowadays required,
The limitations is the critical current density
(Jc for superconducting magnets)



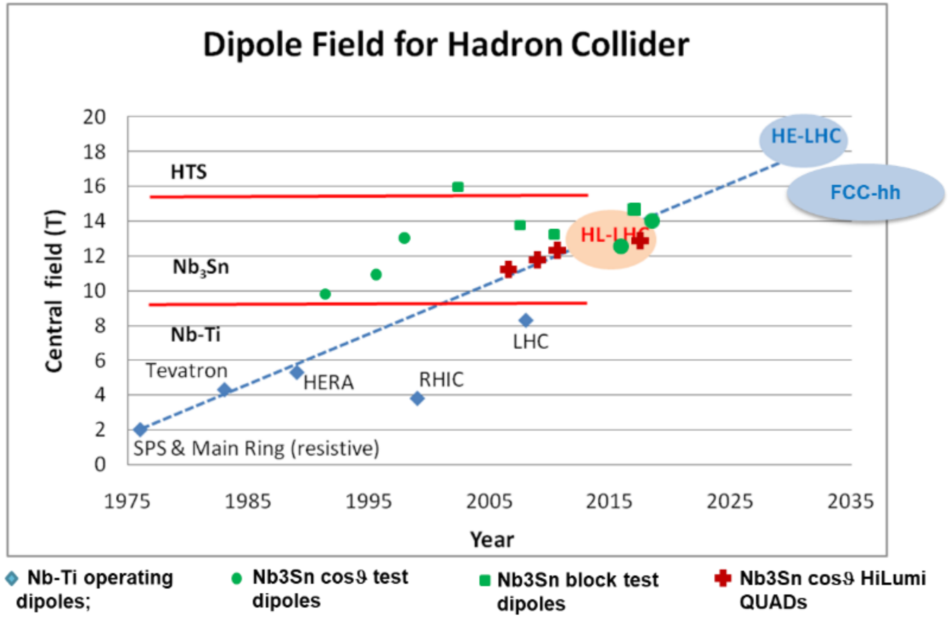
Linear accelerators: $W=E\ell$
Need to maximise ***electric field***
Limitations: arcing between electrodes, field emission, etc.
(and RF power, proportional to V^2 !)



- sustained exponential development for more than 80 years
- progress achieved through repeated jumps from saturating to emerging technologies
- superconductivity, key technology of high-energy machines since the 1980s



High Field Magnets: superconducting technologies



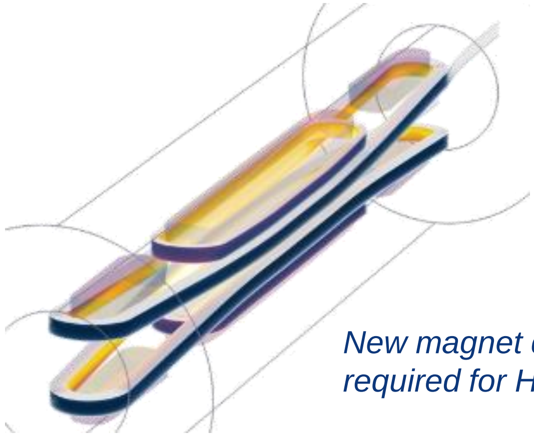
Three technologies under consideration

1. **NbTi** (Niobium Titanium as in the LHC): mature but limited to about 9T field.

2. **Nb$_3$Sn** (Niobium Tin) technology has seen a great boost in the past decade (factor 3 in J_C w/r to ITER) but is not yet used in an accelerator – The HL-LHC upgrade will be the first one.

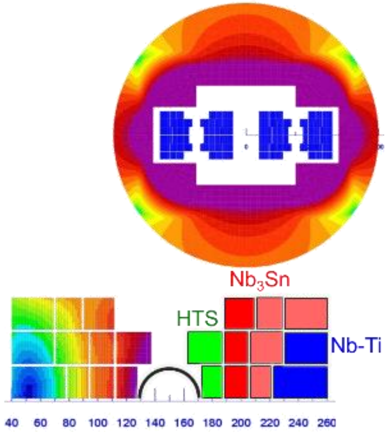
3. **HTS** (High-Temperature Superconductor) technology still in the experimental phase (Production quantities, homogeneity and cost need to evolve!) but can be a disruptive technology for future high-field magnets.

R&D towards a 20 T HTS dipole magnet, develop 10 kA cable.
REBCO (rare earth barium copper oxyde) deposition on stainless substrate, tape arranged in Roebel cables.
values of 900-1200 A/mm2 at 4.2 K , 18-20 T have been obtained



New magnet designs are required for HTS

layered structures with sections of different conductors



Cost optimized, graded winding

High Field Magnet roadmap for accelerators

The LHC High-Luminosity Upgrade is the **foundation** for **new HFM magnet technology** for accelerators, and provides an interesting opportunity for industry

- Nb_3Sn accelerator magnet development and production
- Production in 2018-2023
- First use ever of Nb_3Sn in a running accelerator ! **(8T to 12T)**

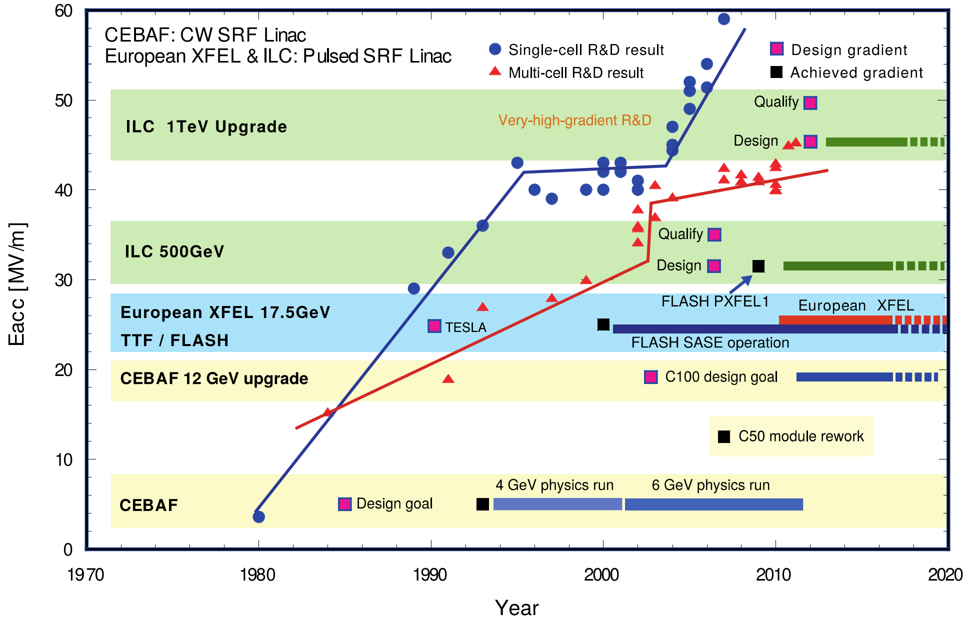
The **next step** is the development of magnets for high energy accelerator : **12T to 16T**
(SppC, FCC, HE-LHC,...)

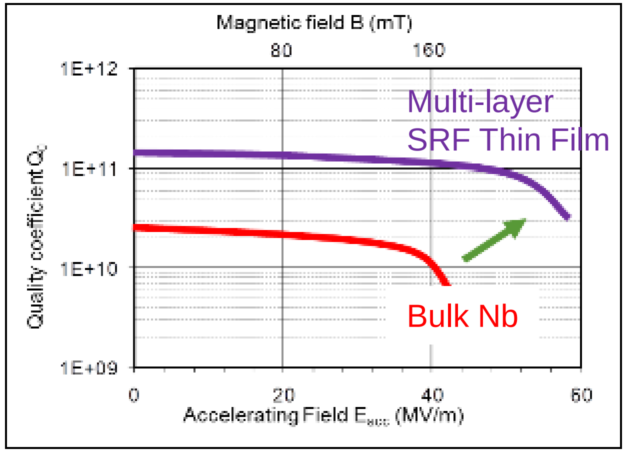
- Model activities are planned in European, US and China laboratories in 2018-2022
- Prototyping in industry (full length, ≈ 5-10 magnets), in 2023-2026
- **Performance (Jc), stress, stored energy management, field quality, and cost**
- This is the logical sequence of the HL-LHC production, profiting from Nb_3Sn technology established in laboratories and industry (Global Approach)

HTS is only in its infancy, but is the **disruptive HFM technology** of the further future

- HTS for special applications (energy distribution and current leads for SC magnets) and as option for the 20T (24T ?) programme (insert)
- Niche magnets for next accelerators (as final focussing magnets,…)
- Requires high-tech R&D, spanning from material science to electromechanical engineering, 5-10 years program defined
- More producers than Nb_3Sn: medical, energy (production and transport),… markets
- **HTS is the high-risk/high-return investment of the future**

The electric field frontier – superconducting cavities





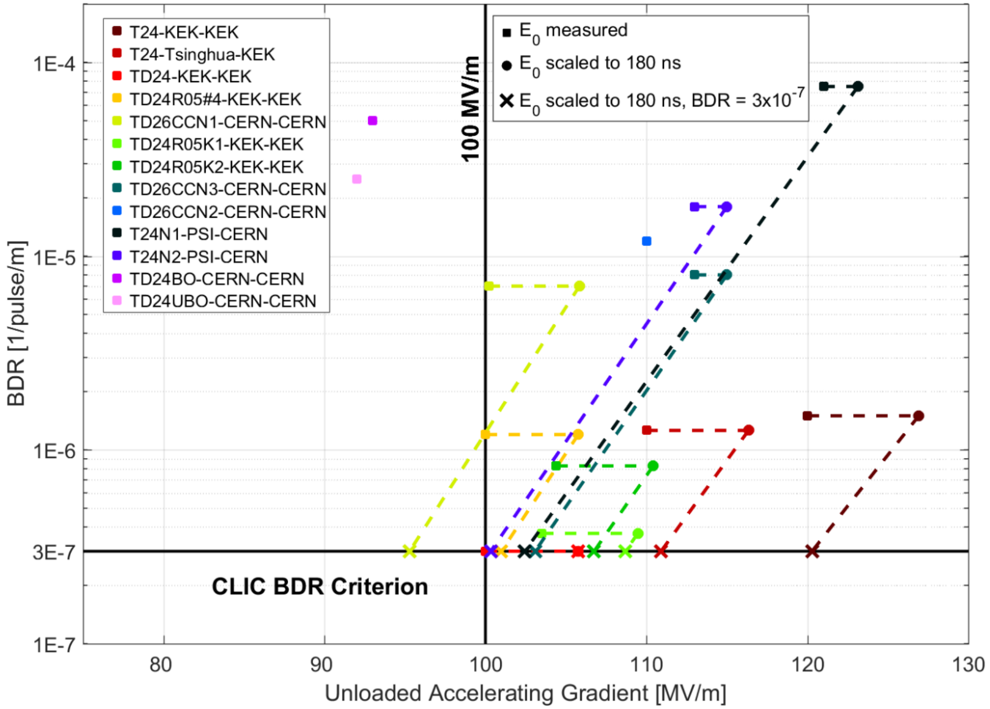
TRENDS:

- Nitrogen infusion process (FNAL) and other doping techniques: high Q operation, gradients ~45 MV/m
- Coating of Nb with a thin layer of Nb_3Sn (allows operation at larger T, improved cryogenic efficiency)
- Coating of Cu cavites with Nb by HiPIMS (High Power Impulse Magnetron Sputtering),

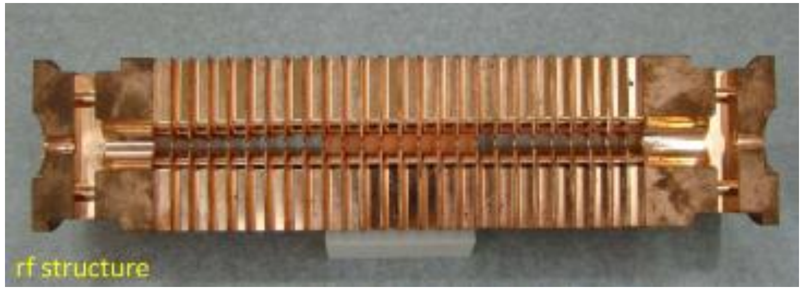
Long-term goal: 60 → 90 MV/m

Courtesy of Maurizio Vretenar

The electric field frontier – normal conducting cavities



Most advanced results by the Compact Linear Collider (CLIC) study based at CERN (X-band, 12 GHz)
Large international collaboration to understand the physics of breakdown phenomena.



Pulsed systems, characterised by a Break-Down Rate (BDR), pulses lost because of vacuum arcing in the structure

100 MV/m gradient can be achieved (and exceeded)

… but the power scales as the square of the gradient!
High gradient means smaller dimensions but higher power consumption.

Courtesy of Maurizio Vretenar

2020 Update of the European Strategy for Particle Physics (June 2020)


2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

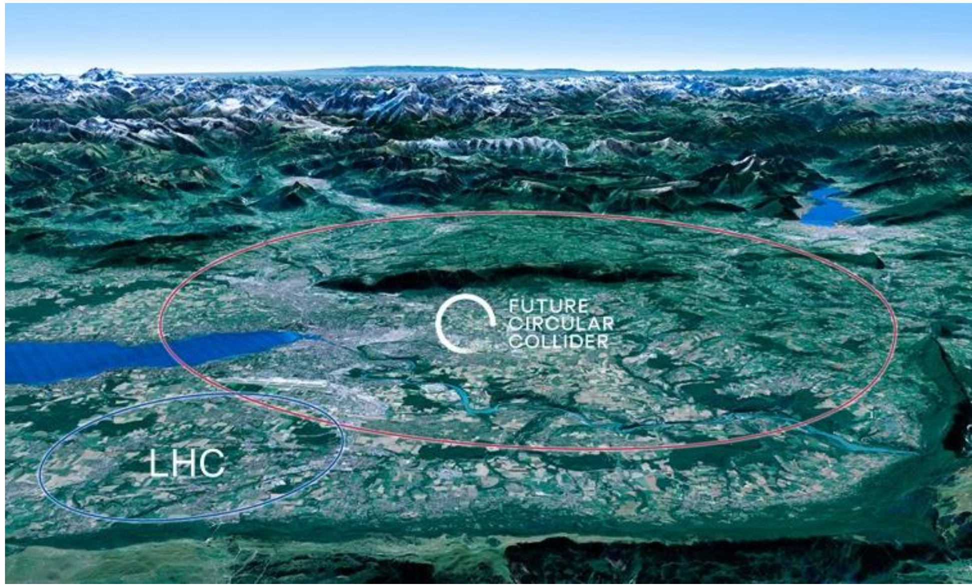

High-priority future initiatives

A. An electron-positron Higgs factory is the highest-priority next collider. For the longer term, the European particle physics community has the ambition to operate a proton-proton collider at the highest achievable energy. Accomplishing these compelling goals will require innovation and cutting-edge technology:

- the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors;

- Europe, together with its international partners, should investigate the technical and financial feasibility of a future hadron collider at CERN with a centre-of-mass energy of at least 100 TeV and with an electron-positron Higgs and electroweak factory as a possible first stage. Such a feasibility study of the colliders and related infrastructure should be established as a global endeavour and be completed on the timescale of the next Strategy update.

The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.



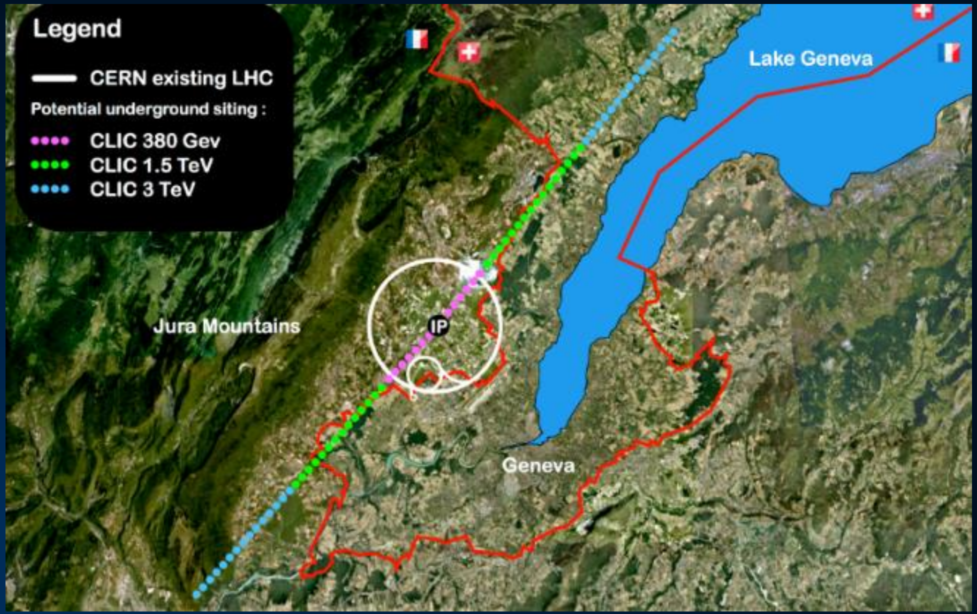
- Fully exploit LHC with the HL-LHC upgrade
- electron-positron Higgs and electroweak factory is the highest-priority next collider
- Investigate the technical and financial feasibility of a future energy-frontier 100 km collider at CERN (FCC)
- Continue supporting other projects around the world

Post LHC accelerator studies

Compact Linear Collider (CLIC)

Linear e^+e^- collider $\sqrt{s}$ up to 3 TeV

100 MV/m accelerating gradient
needed for compact (~50 km) machine
→ based on normal-conducting
accelerating structures and a
two-beam acceleration scheme



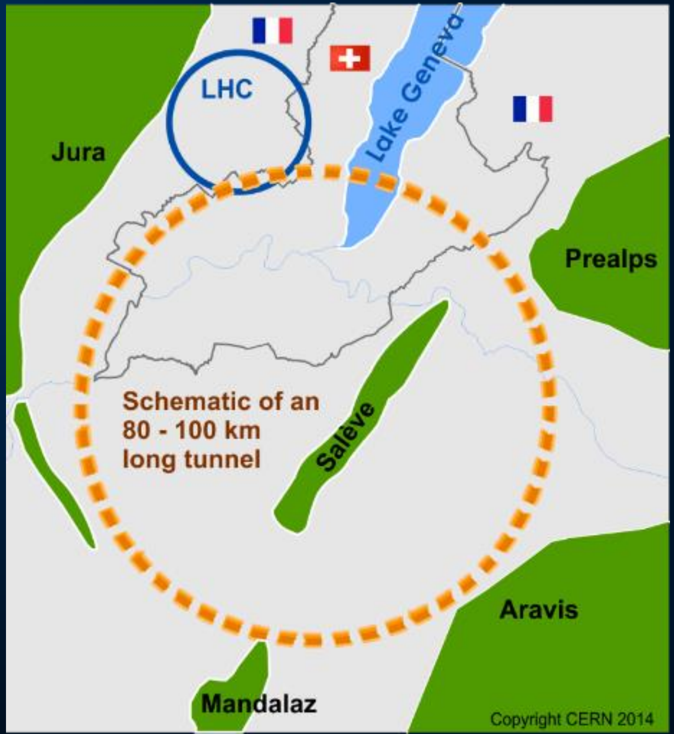
Future Circular Collider (FCC)

hh-collider (FCC-hh)
80-100 km tunnel infrastructure in Geneva area,

~16 T ⇒ 100 TeV *pp* in 100 km

- e+e- collider (FCC-ee) as potential 1st step

- HE-LHC in the present LHC tunnel with FCC-hh technology



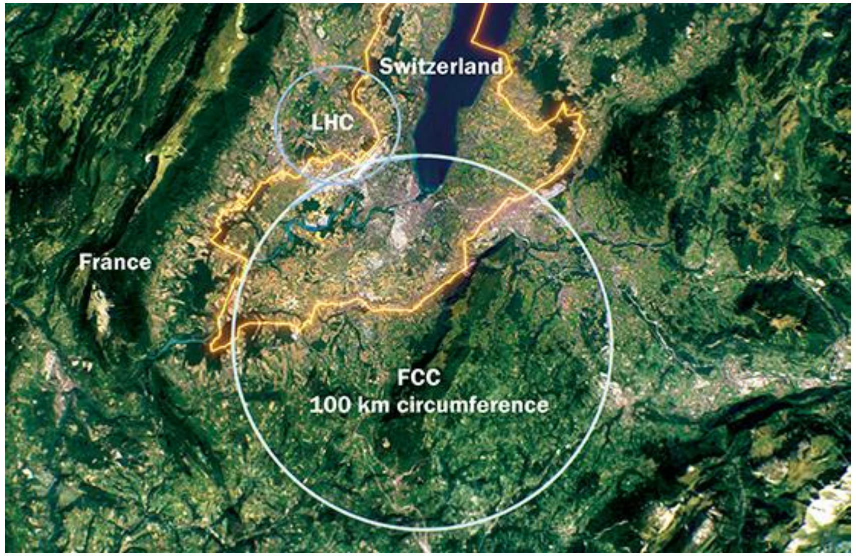
FCC Feasibility Study 2021-2025

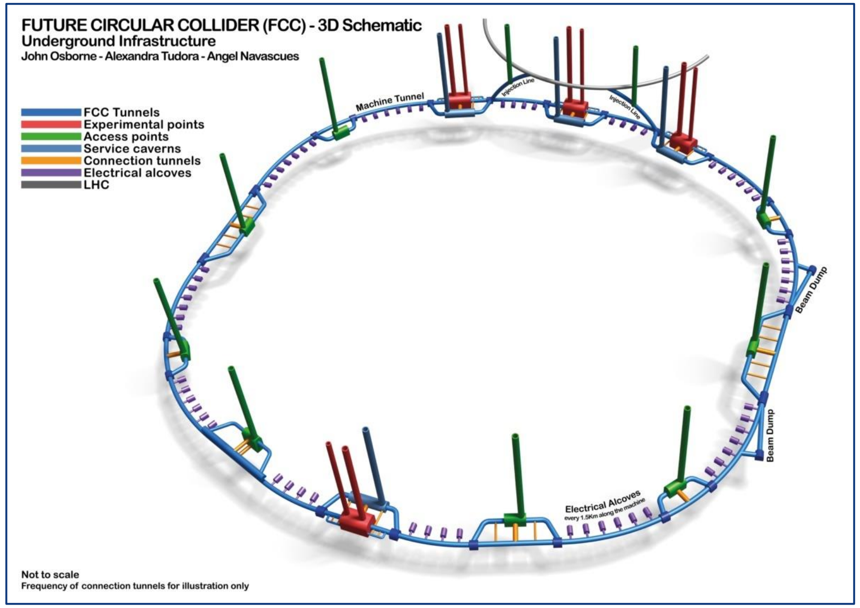
Tunnel: assess geological, technical, administrative, environmental feasibility → aim is to demonstrate there is no show-stopper for ~ 100 km ring in Geneva region

Technologies: superconducting high-field magnets and RF accelerating structures; high-efficiency power production; energy saving and other sustainable technologies

Funding: development of funding model for first-stage machine (tunnel and FCC-ee, total ~ 10 BCHF) and identification of substantial resources from outside CERN's budget

"Consensus building": gathering scientific, political, societal support → communication campaign targeting scientists, governmental and other authorities, industry, general public

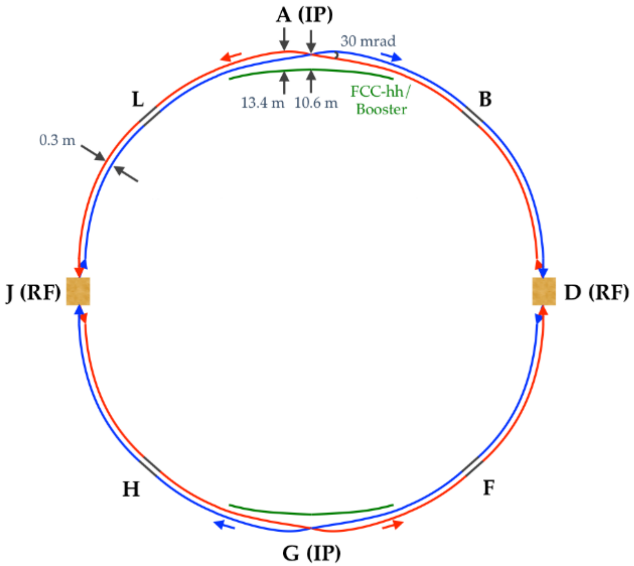




The FCC integrated program

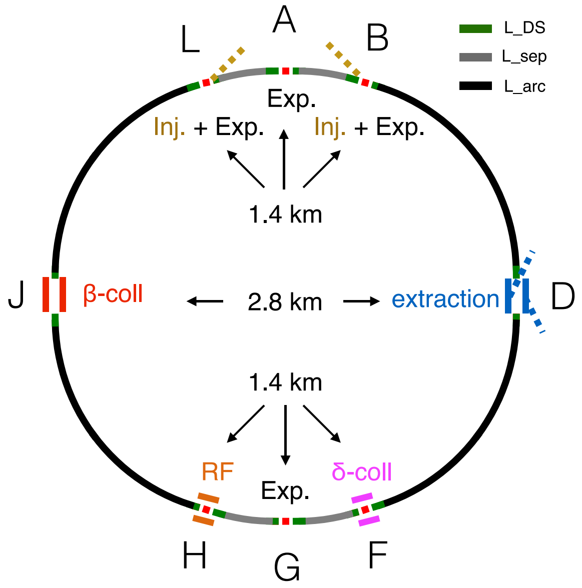
Comprehensive long-term program, maximizing physics opportunities

- Stage 1: **FCC-ee** as Higgs factory, electroweak and top factory at highest luminosities
- Stage 2: **FCC-hh** (~100 TeV) as natural continuation at energy frontier, with ion and eh options



FCC-ee (electron-positron collider)

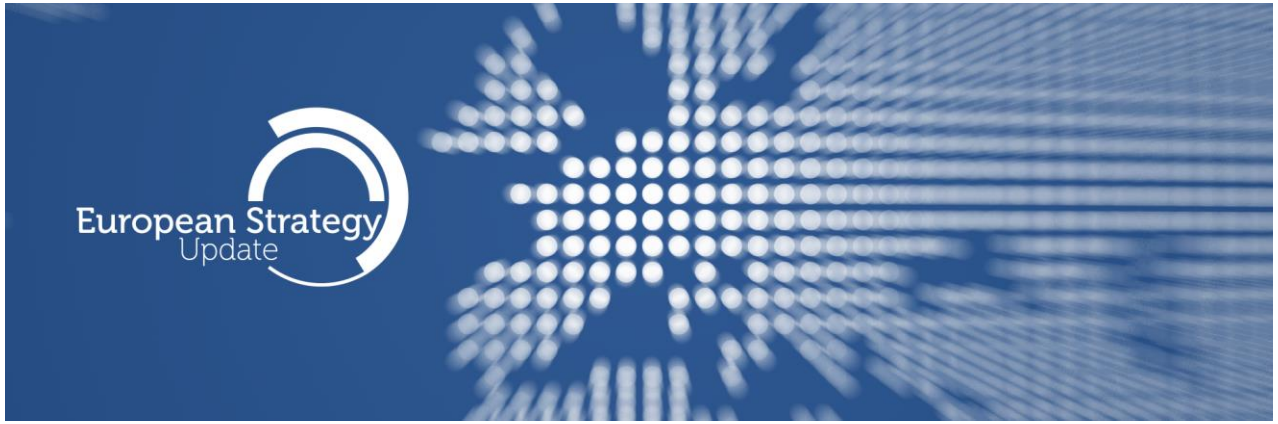
Warm magnets, superconducting radiofrequency cavities

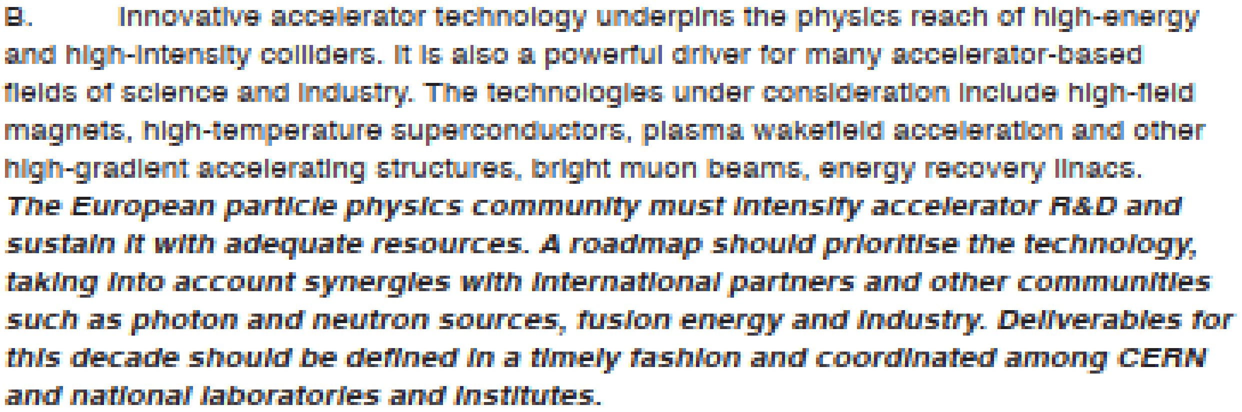


FCC-hh (proton-proton collider)

High-field superconducting magnets (Niobium and HTS ?)

Scientific priorities for the future: innovation




B. Innovative accelerator technology underpins the physics reach of high-energy and high-intensity colliders. It is also a powerful driver for many accelerator-based fields of science and industry. The technologies under consideration include high-field magnets, high-temperature superconductors, plasma wakefield acceleration and other high-gradient accelerating structures, bright muon beams, energy recovery linacs. *The European particle physics community must intensify accelerator R&D and sustain it with adequate resources. A roadmap should prioritise the technology, taking into account synergies with international partners and other communities such as photon and neutron sources, fusion energy and industry. Deliverables for this decade should be defined in a timely fashion and coordinated among CERN and national laboratories and institutes.*

Development of **innovative accelerator technology** as driver for **science and industry**.

In particular:

1. high-field magnets and high temperature superconductors
2. Plasma wakefield and other high-gradient acceleration
3. Muon beams
4. Energy recovery linacs

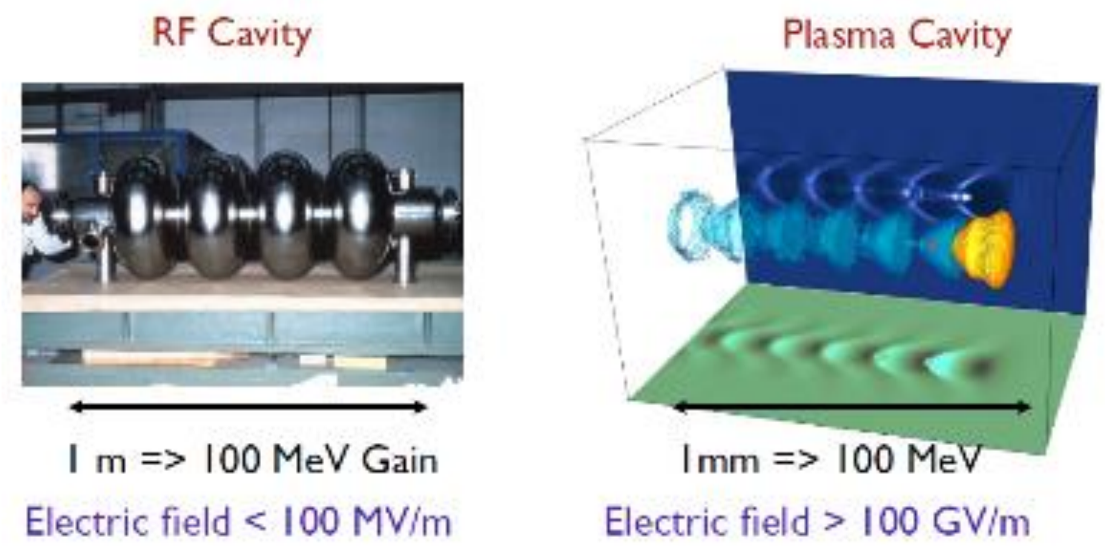
New acceleration techniques using lasers and plasmas

Accelerating field of today’s RF cavities or microwave technology is **limited to <100 MV/m**

Several tens of kilometers for future linear colliders

Plasma can sustain up to **three orders of magnitude much higher gradient**

SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient



V. Malka et al., Science **298**, 1596 (2002)

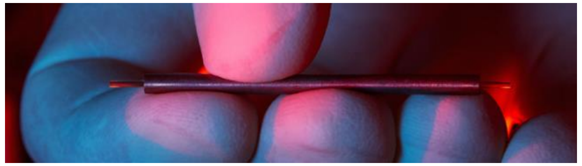
Lasers can produce huge transverse electric fields (TV/m !)

Can we convert the transverse fields into longitudinal and use them for acceleration?

(1) Micro/Nano-Accelerators

(2) Plasma Accelerators

Send THz Laser into Dielectric Waveguide (Micro-Accelerator)

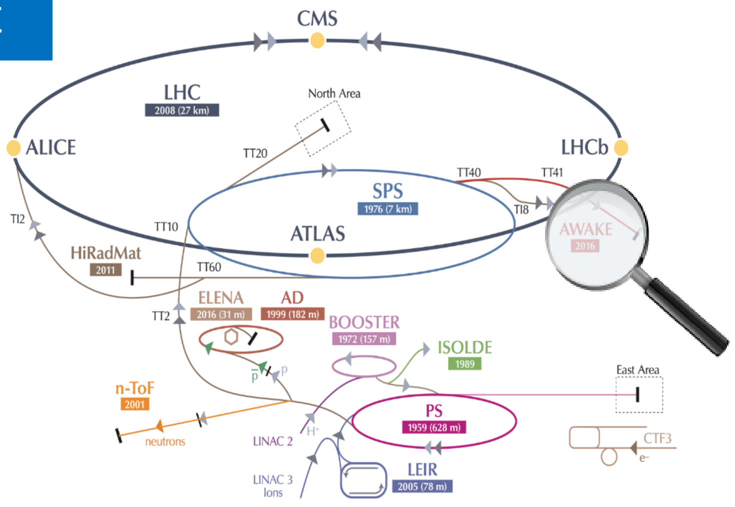


The «accelerator on a chip»

Use a plasma to convert the transverse electrical field of the laser (or the space charge force of a beam driver) into a longitudinal electrical field, by creating plasma waves.

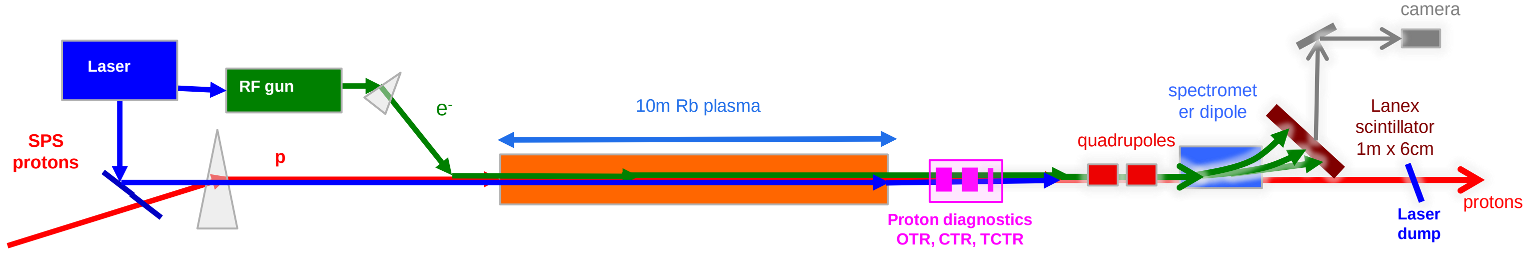
Courtesy of Maurizio Vretenar

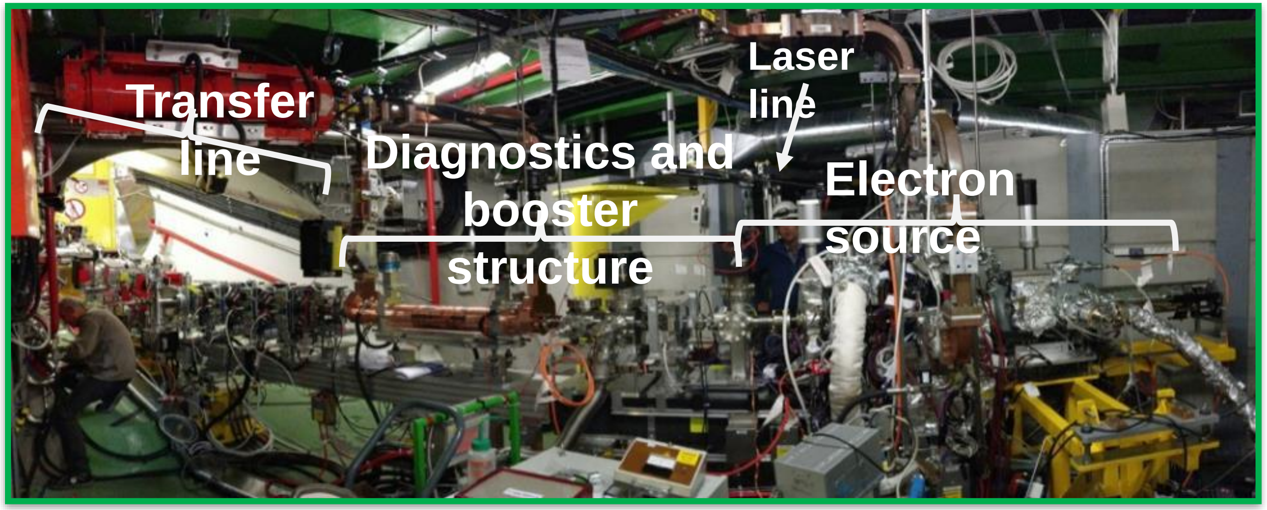
AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment



2017: 1st milestone reached! First demonstration of seeded self-modulation of a high energy proton bunch in plasma

2018: 2nd milestone: Inject electrons externally and accelerate to GeV level





Electron beam system and electron diagnostics installed in 2017, commissioning started end 2017, first run May 2018, run periods in July, August and October 2018.

AWAKE Accelerates Electrons!

AWAKE has for the first time demonstrated proton driven plasma wakefield acceleration of externally injected electrons.

- Electron acceleration up to 2 GeV in 10 m plasma has been observed.
  → average gradient of 200MV/m!
- AWAKE managed to reach all physics milestones within the foreseen timescale.

nature
International journal of science

LETTER

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https://doi.org/10.1038/s41586-018-0485-4

Acceleration of electrons in the plasma wakefield of a proton bunch

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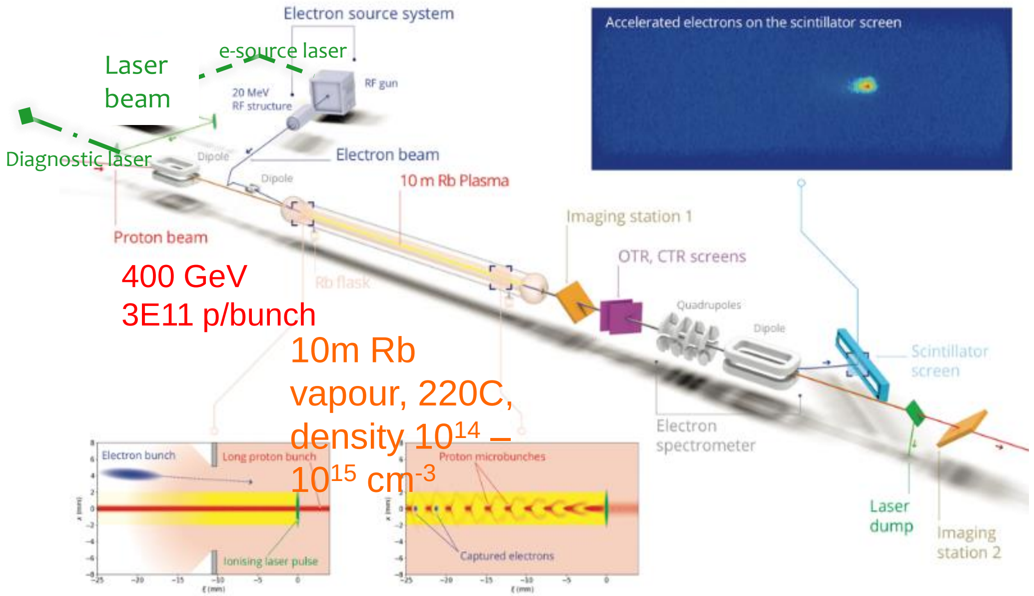
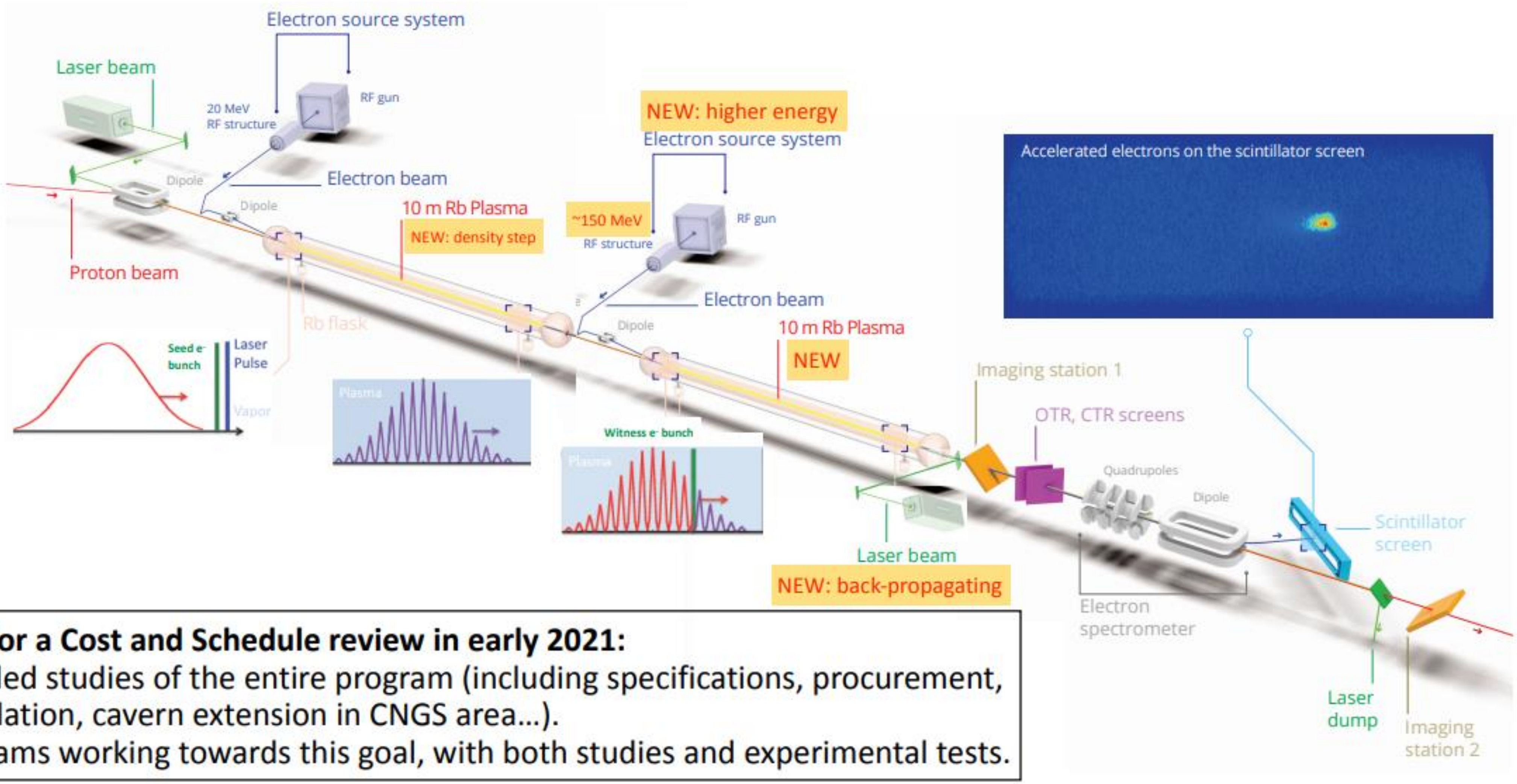


400 GeV
3E11 p/bunch

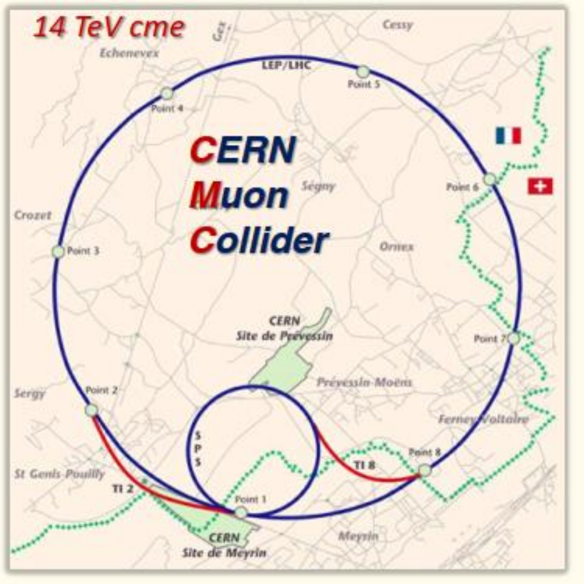
10m Rb vapour, 220C, density 10^{14} – 10^{15} cm^{-3}

AWAKE Phase 2 (2022-2024)

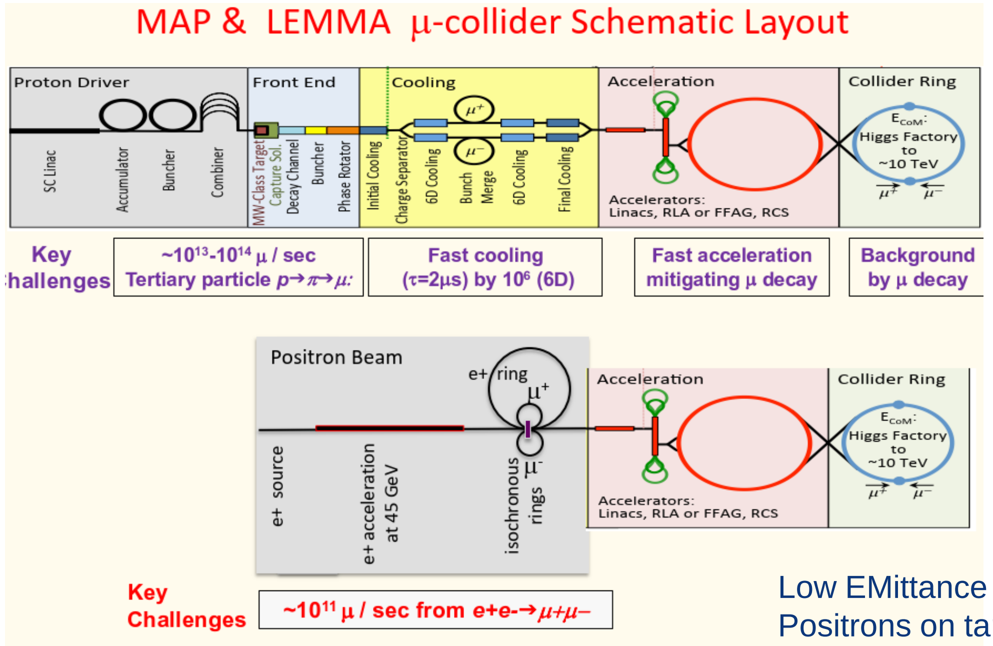


Aim for a Cost and Schedule review in early 2021:
Detailed studies of the entire program (including specifications, procurement, installation, cavern extension in CNGS area…).
All teams working towards this goal, with both studies and experimental tests.

Muon collider: other options for high energy



MOPMF072, IPAC18, V. Shiltzev, D. Neuffer



Low EMittance Muon Accelerator
Positrons on target, annihilation

Colliding muons:

Muons are leptons, **similar to electrons but heavier (207 times),** produced by pion decay or electron/positron annihilation, **have a lifetime of only 2.2 μs.**

- A $\mu^+\mu^-$ collider offers an ideal technology to extend lepton high energy frontier in the multi-TeV range:
  - No synchrotron radiation (limit of e^+e^- circular colliders)
  - No beamstrahlung (limit of e^+e^- linear colliders)
  - but muon lifetime is 2.2 μs (at rest)
- Best performances in terms of luminosity and power consumption

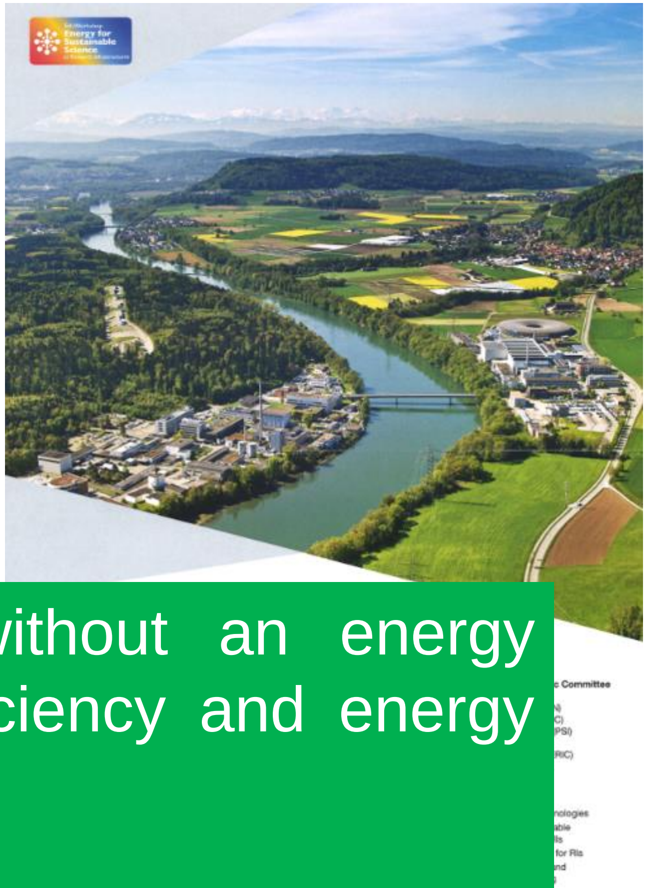
Critical components:

- Muon production complex (proton or positron beam, MAP or LEMMA)
- Muon acceleration complex
- Neutrino radiation

Excellent in term of power/luminosity, potential for cost savings
Many critical technical challenges requiring R&D

Courtesy of Maurizio Vretenar

From 2010, global thinking on “Energy at Research Infrastructures”



Energy Management

To share experience between representatives from various research laboratories **strategies, goals and institutional practice to advance environmental sustainability at their research facilities and research campus with particular emphasis on energy savings and energy efficiency measures**

There will be no future large-scale science project without an energy management component and an incentive for energy efficiency and energy recovery among the major objectives.

A selection of specific programs for consolidating existing infrastructures is a way to put into practice these good intentions, and to acquire expertise with proven references.

CERN

EUROPEAN SPALLATION SOURCE

ERF European Association of National Research Facilities Open to International Access

6th Workshop on Energy for Sustainable Science at Research Infrastructures on 17th and 18th March 2022 in Grenoble

Accelerators contributed to 26 Nobel Prizes in physics since 1939

1939 Ernest O. Lawrence
1951 John D. Cockcroft & Ernest Walton
1952 Felix Bloch
1957 Tsung-Dao Lee & Chen Ning Yang
1959 Emilio G. Segrè & Owen Chamberlain
1960 Donald A. Glaser
1961 Robert Hofstadter
1963 Maria Goeppert Mayer
1967 Hans A. Bethe
1968 Luis W. Alvarez
1976 Burton Richter & Samuel C.C. Ting
1979 Sheldon L. Glashow, Abdus Salam &
Steven Weinberg
1980 James W. Cronin & Val L. Fitch
1981 Kai M. Siegbahn

r
Simon van der Meer

an, Melvin Schwartz &

hi & Toshihide Maskawa
& Peter Higgs
Arthur B. MacDonald

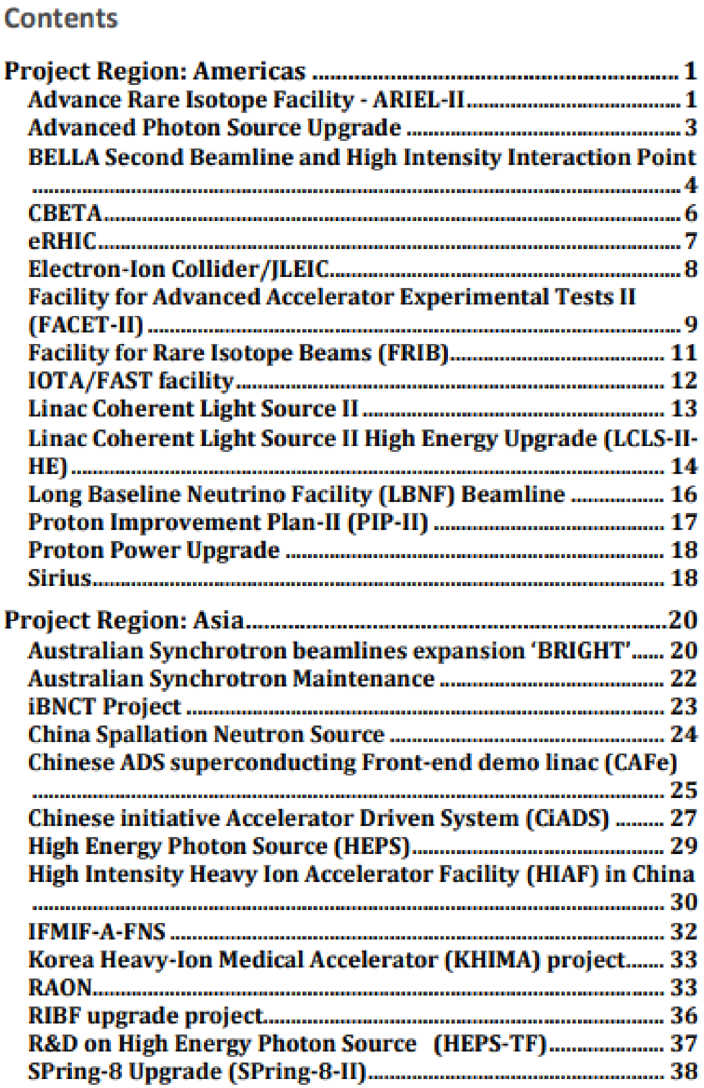
Steven Weinberg, one of the greatest theoretical physicists of all time, passed away on **23 July 2021,** aged 88. He revolutionised particle physics, quantum field theory and cosmology with conceptual breakthroughs which still form the foundation of our understanding of physical reality.

Particle accelerators: a successful and booming field !

The Tenth International Particle Accelerator Conference

PARTICLE ACCELERATOR PROJECTS & UPGRADES BOOKLET

19 - 24 May 2019
MCEC
Melbourne Australia



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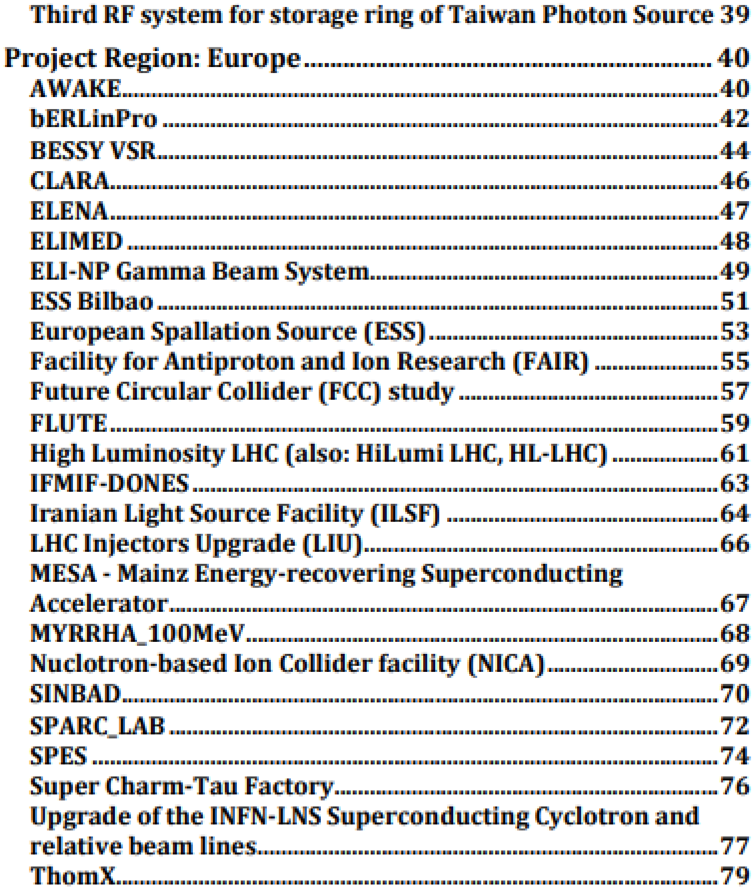
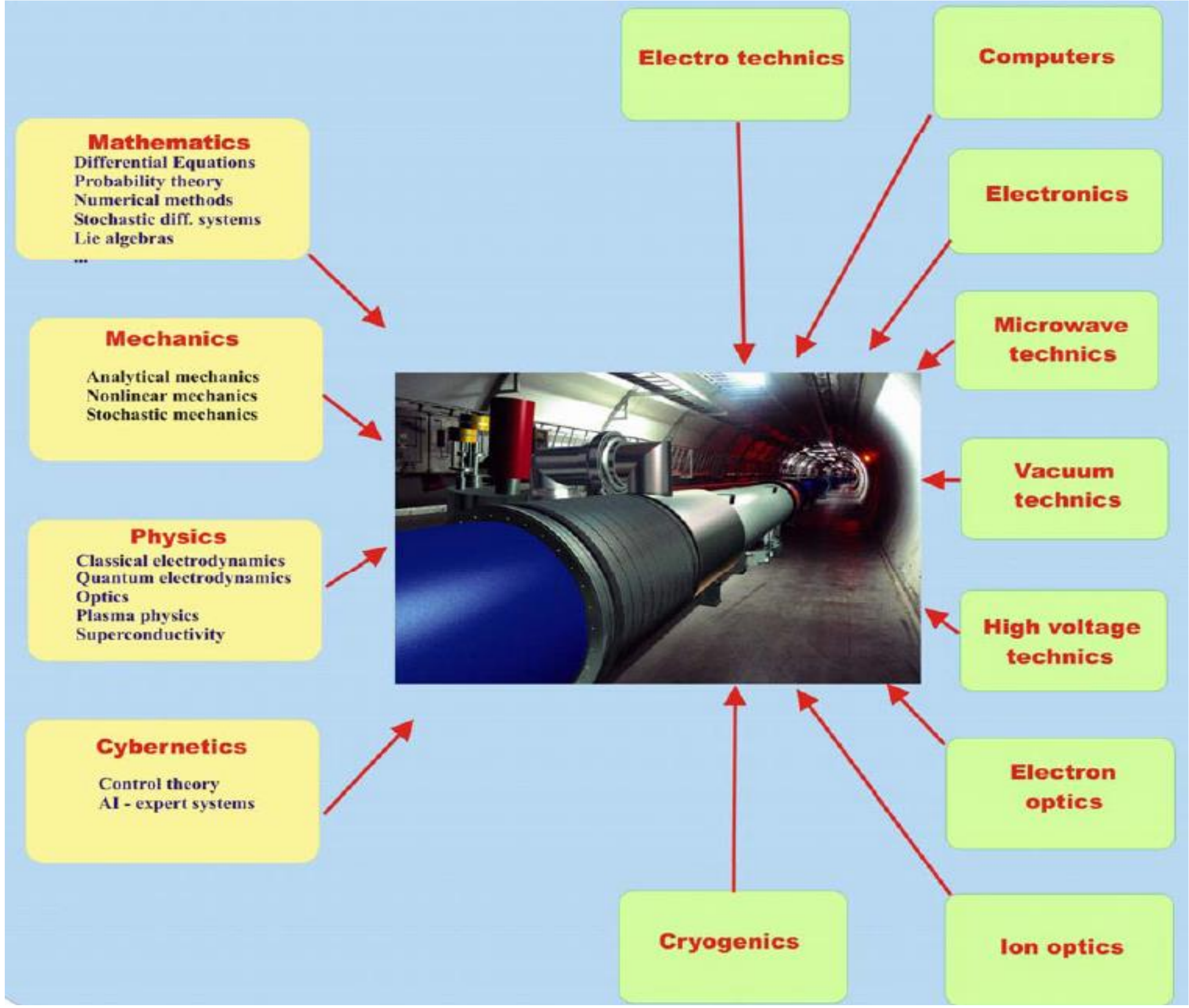


> 50 ongoing accelerator construction, upgrade projects and studies listed in the 2019 IPAC Conference

List of Technologies needed for building and operating particle accelerators



Electrical engineering
Electronics
Mechanical engineering
Beam-materials science
Computer engineering
Civil Engineering
Large scale simulations
……

A multidisciplinary domain !

High Energy Physics can offer interesting and challenging careers for skilled engineers and physicists

“Faster, Higher, Stronger - Together”

New Olympic motto

"The task of the mind is to produce future"

Paul Valéry

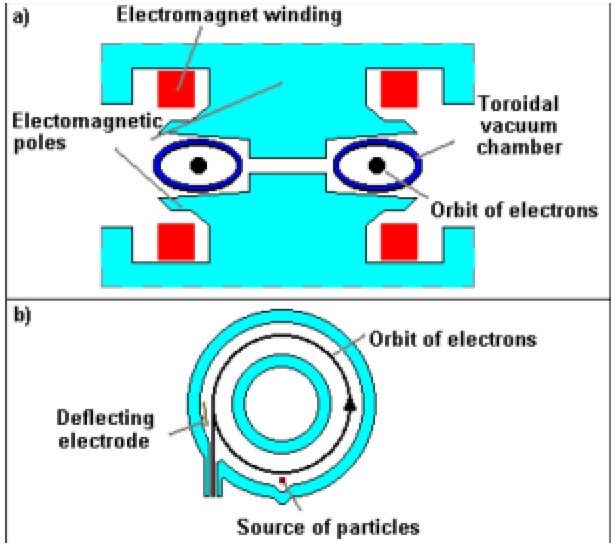
Muchas gracias por su atención.

Accelerating Science and Innovation

Betatron

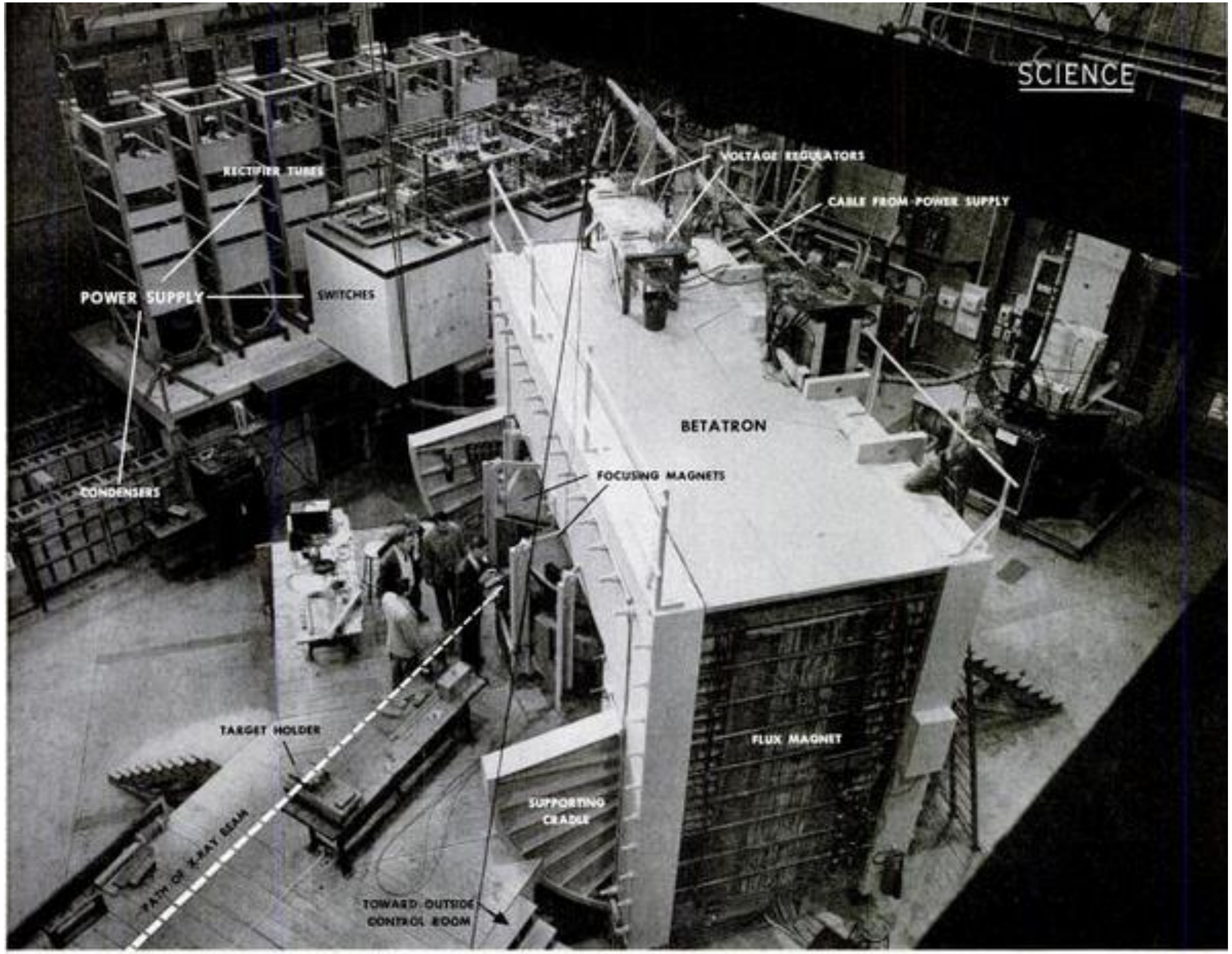
rheotron, inductron,
"*Ausserordentlichhochgeschwindigkeitelektronenentwickelndenschwerarbeitsbeigollitron*"
Extraordinaryhighspeedelectrondevelopingheavyworking

- 1940: Kerst 2.3 MeV and very quickly 300 MeV (initial idea Rolf Widerøe)
- It is actually a transformer with a beam of electrons as secondary winding.
- The magnetic field is used to bend the electrons in a circle, but also to accelerate them.
- A deflecting electrode is use to deflect the particle for extraction.



Courtesy Rende Steerenberg

300 MeV Betatron University of Illinois



PHYSICISTS RIG NEW BETATRON FOR FIRST EXPERIMENT IN SUNKEN RADIATION LABORATORY. NO ONE STAYS IN ROOM WHEN THE MACHINE IS TURNED ON