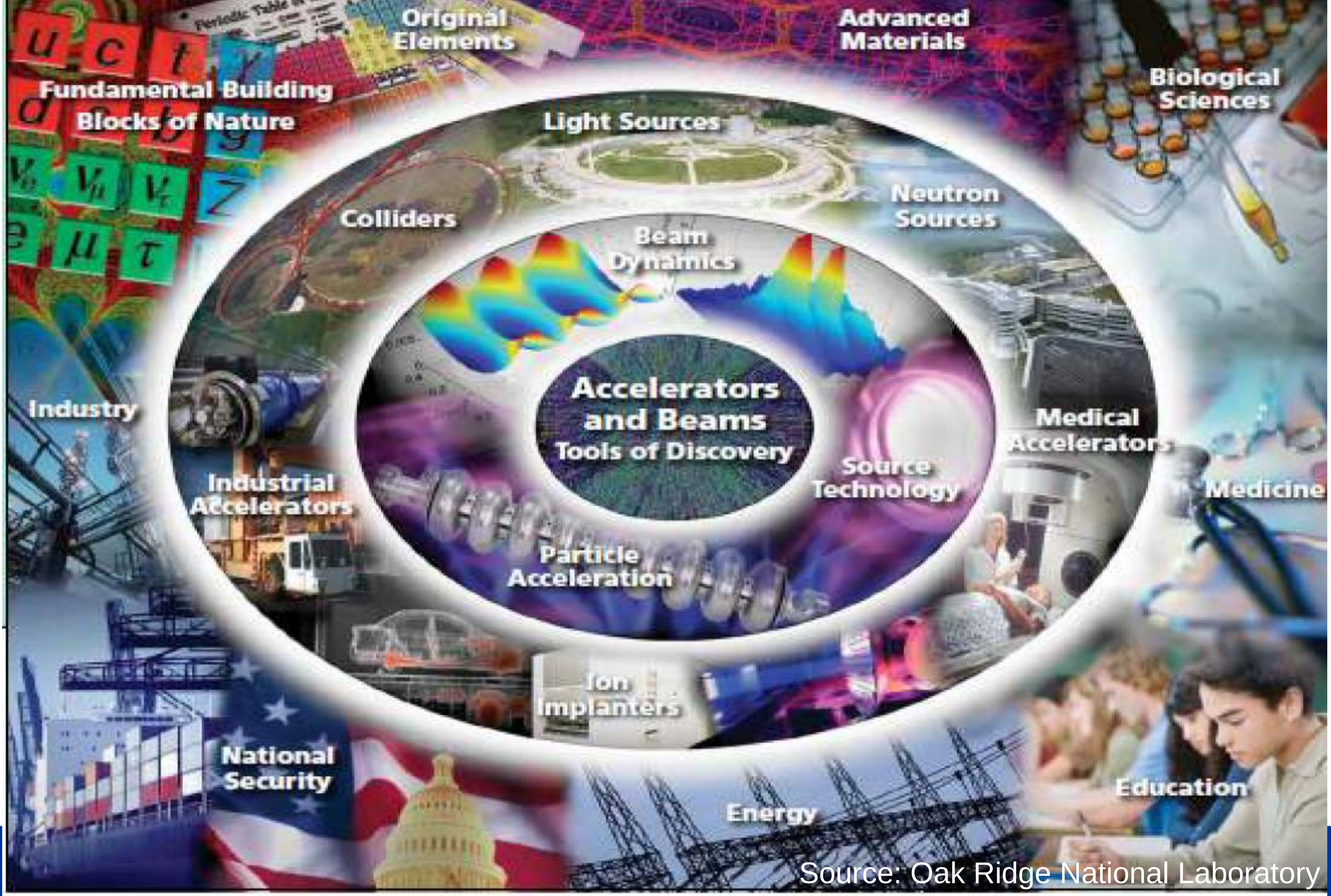
Accelerators for High Energy Physics

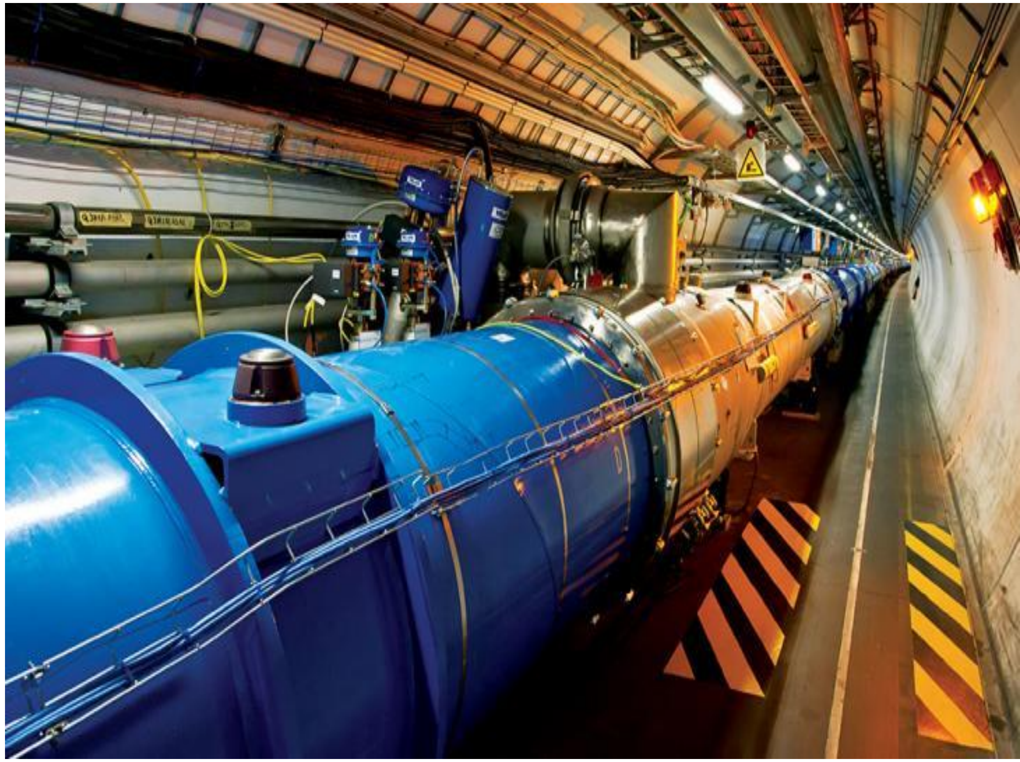
Isabel Bejar Alonso et al.


Original Elements
Advanced Materials
Fundamental Building Blocks of Nature
Biological Sciences
Light Sources
Neutron Sources
Colliders
Beam Dynamics
Accelerators and Beams
Tools of Discovery
Industry
Medical Accelerators
Source Technology
Medicine
Industrial Accelerators
Particle Acceleration
Ion Implanters
National Security
Education
Energy
Source: Oak Ridge National Laboratory

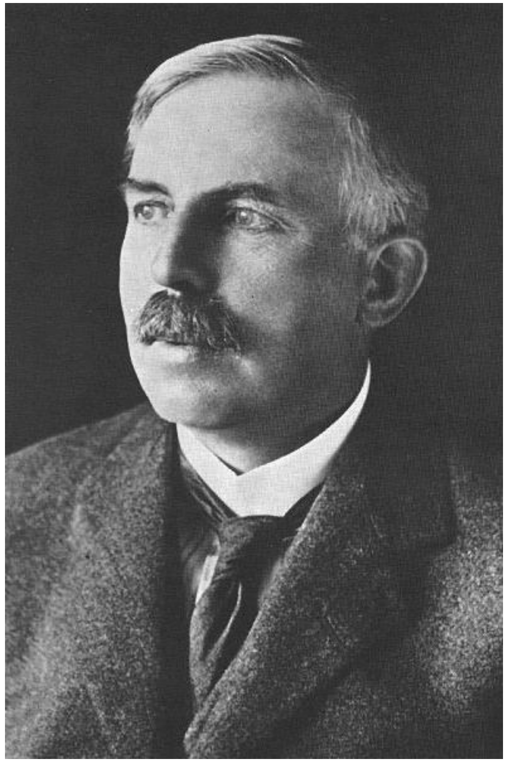
The history of accelerators

Once upon a time

The evolution of the research tools



Who started? (the electrostatic accelerators)

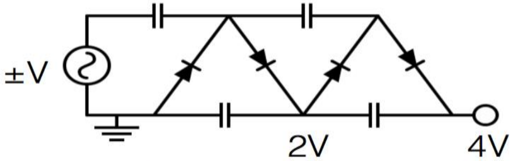


Sir Rutherford

Robert Jemison Van de Graaff

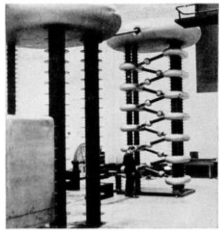
Walton and the machine used
to "split the atom"

Cavendish Lab, Cambridge



Voltage multiplier circuit

https://www.youtube.com/watch?v=ep3D_LC2UzU



1.2 MV 6 stage Cockcroft-Walton accelerator at Clarendon Lab, Oxford University in 1948.

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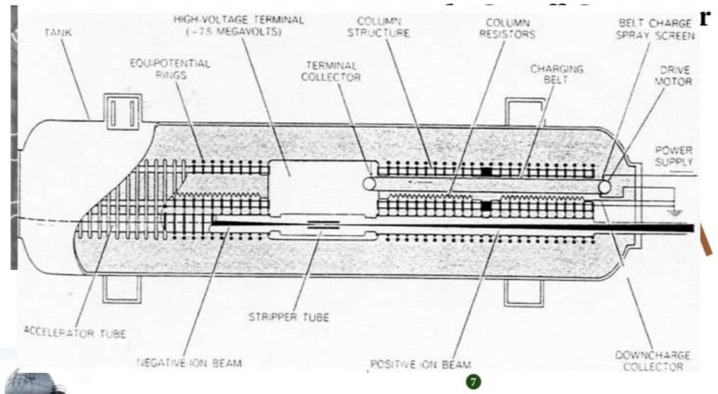
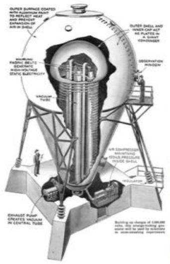
Robert Van de Graaff



1. hollow metal sphere
2. upper electrode
3. upper roller (for example an acrylic glass)
4. side of the belt with positive charges
5. opposite side of belt, with negative charges
6. lower roller (metal)
7. lower electrode (ground)
8. spherical device with negative charges
9. spark produced by the difference of potentials

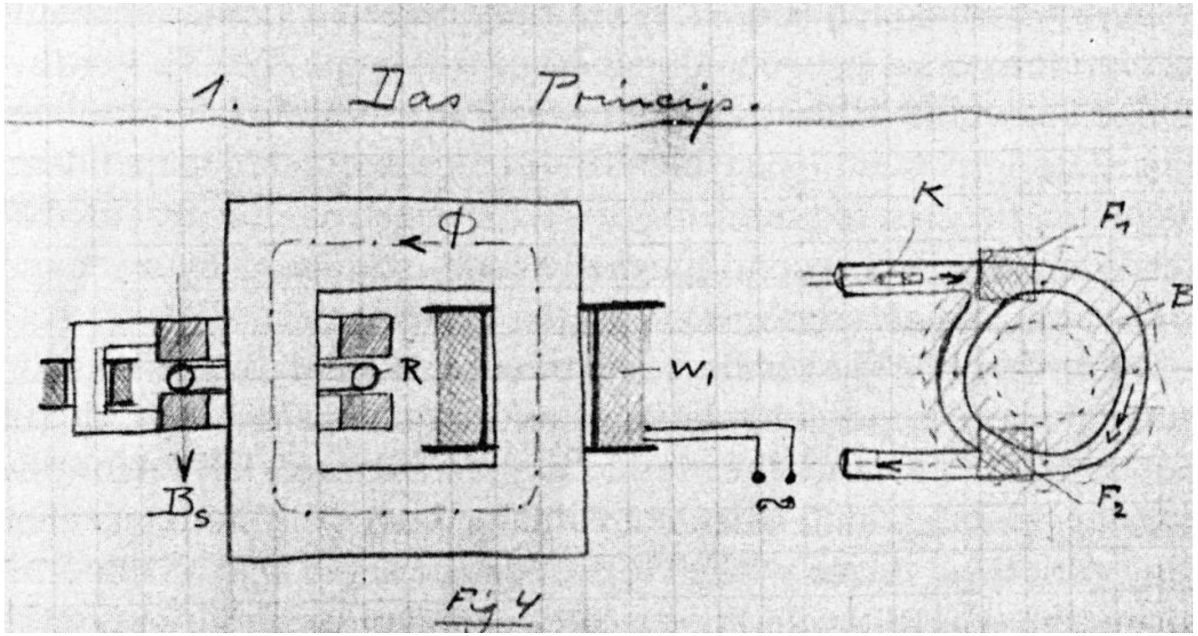


The Westinghouse atom smasher, 1937 11

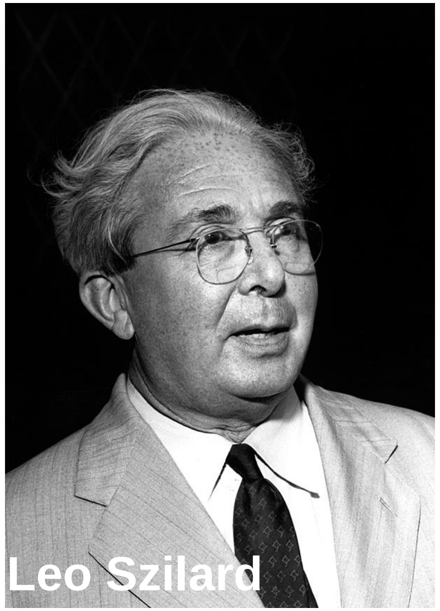
But nobody is unanimous (linac and betatron)

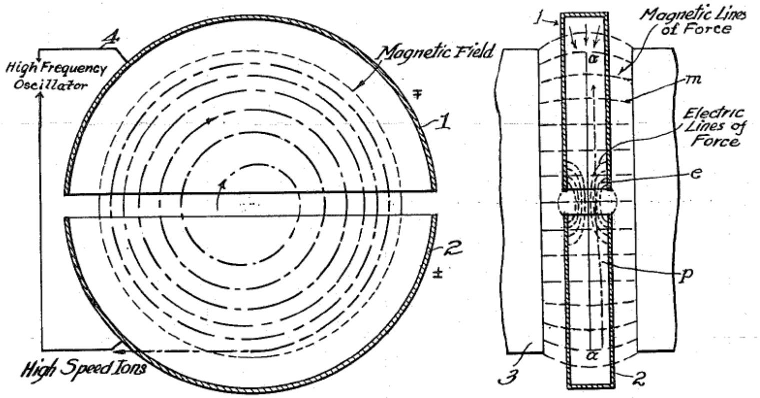
Rolf Widerøe

Gustaf Ising



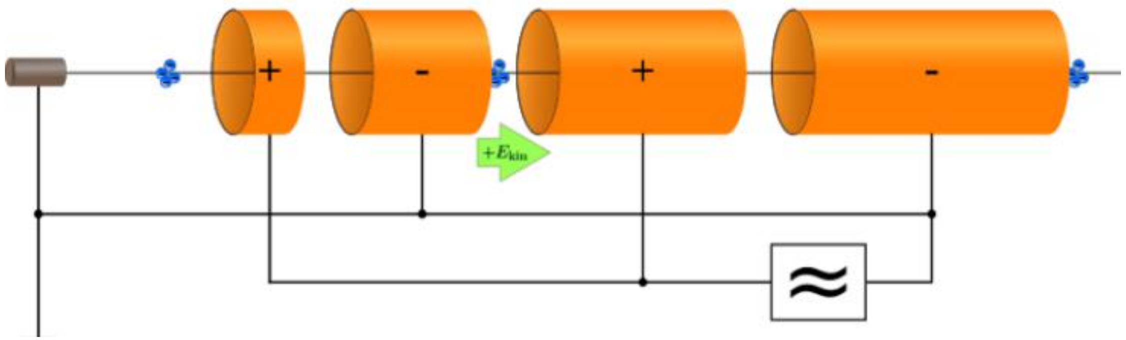
It was a bubbling period … (Cyclotron)





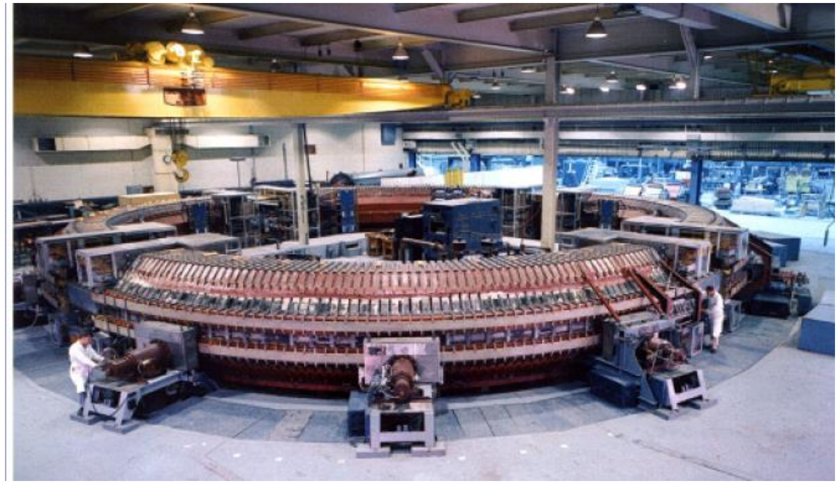
It was a bubbling period … (linacs the next step)

- Widerøe, Sloan, Lawrence, Alvarez,….
- The development of high-frequency power supplies for radar technology during WWII was fundamental.
- Good for high energy electrons, no synchrotron radiation and good beam quality & small spot size

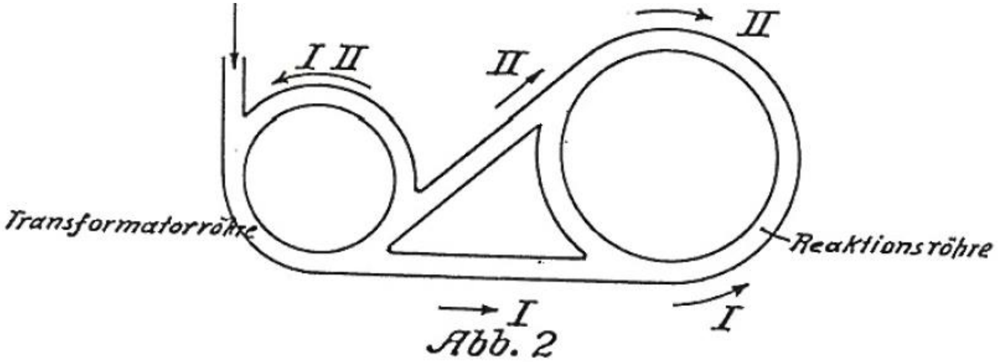


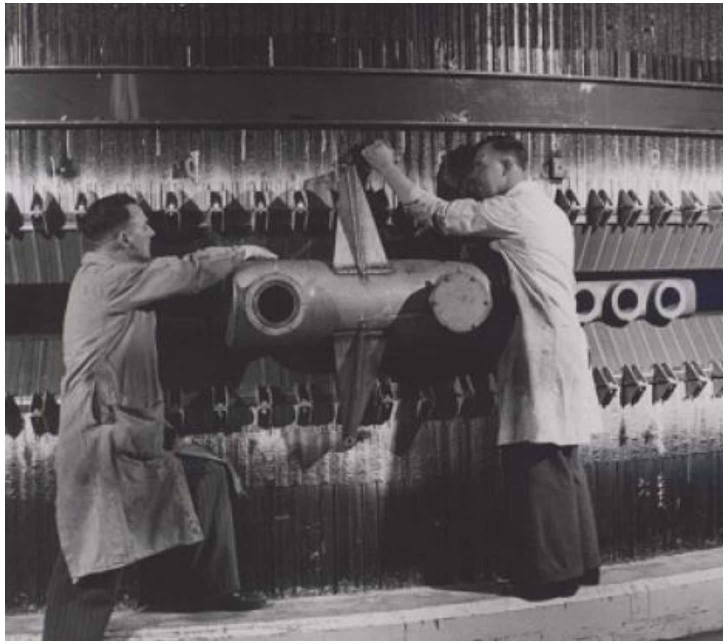
Even if they are limited by energy due to length and single pass several variants are studied for future discovery machines

The revolution of the Synchrotron

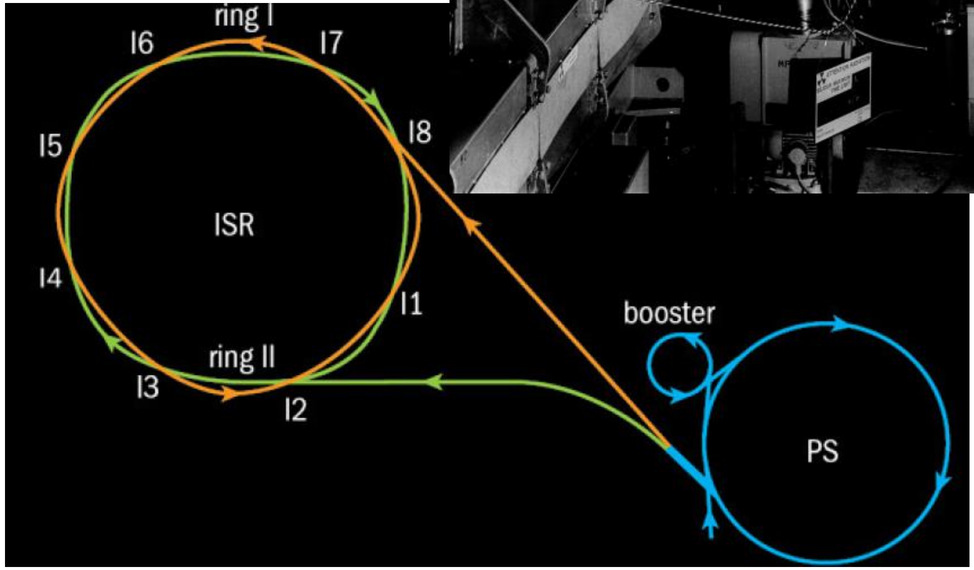


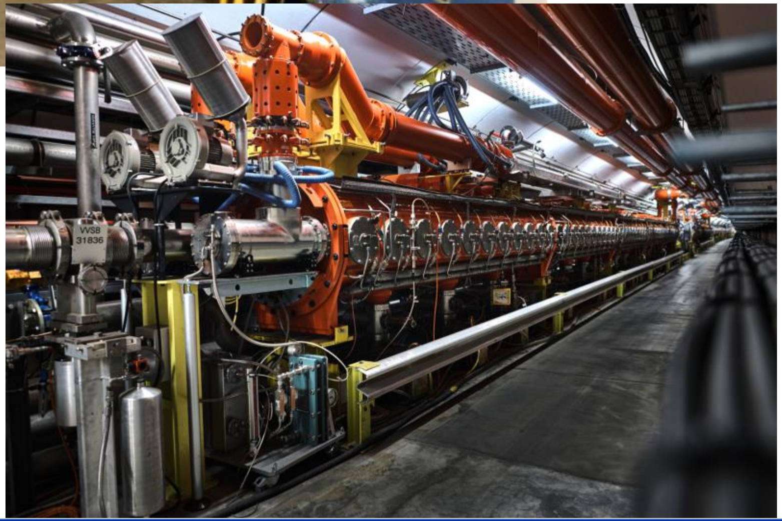
- In 1943, Widerøe is again a pioneer and patents circular colliders.
- 1944 McMillan and Veksler independently propose synchronous acceleration with phase stability.
- 1946 Goward and Barnes are first to make the synchrotron work in the UK.
- 1947 Oliphant and Hyde start a 1 GeV machine in Birmingham, UK, but an American group overtakes them and is first with the 3 GeV Cosmotron at BNL.



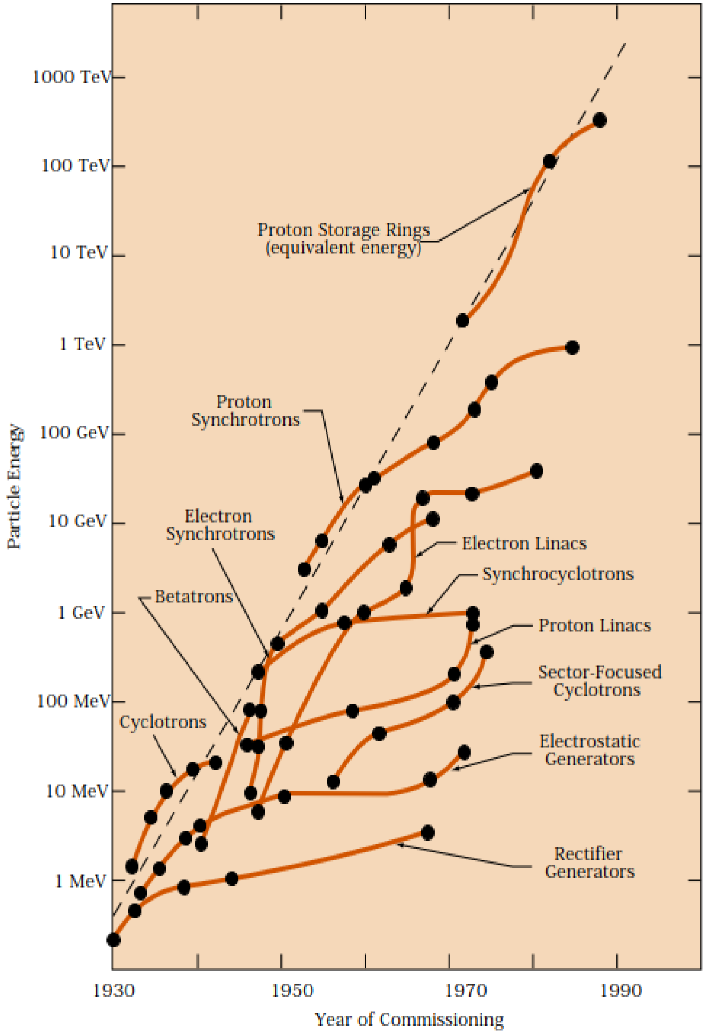


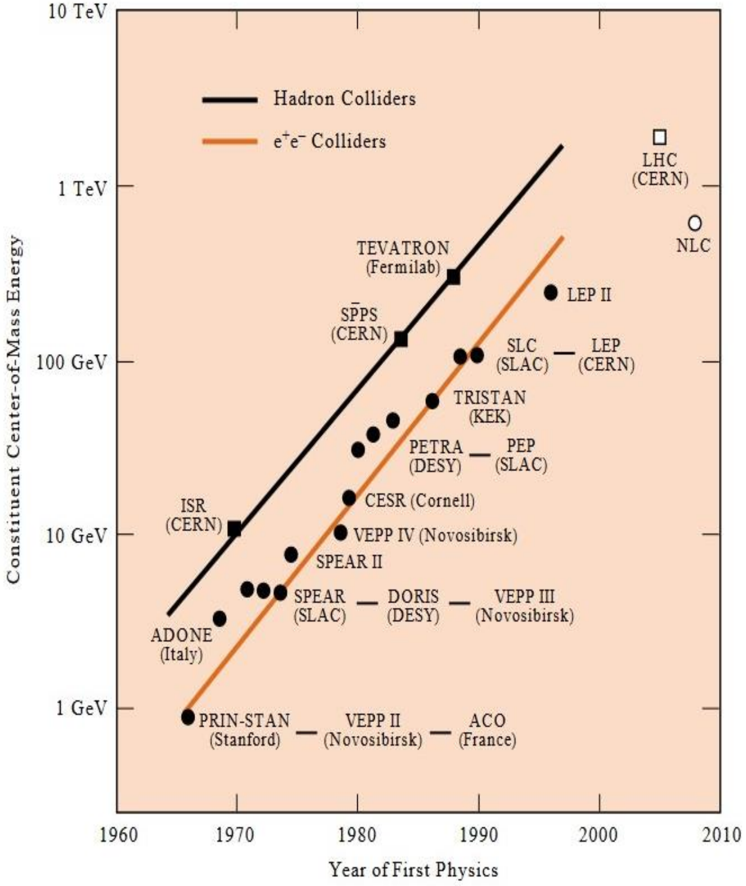
The revolution of the Synchrotron

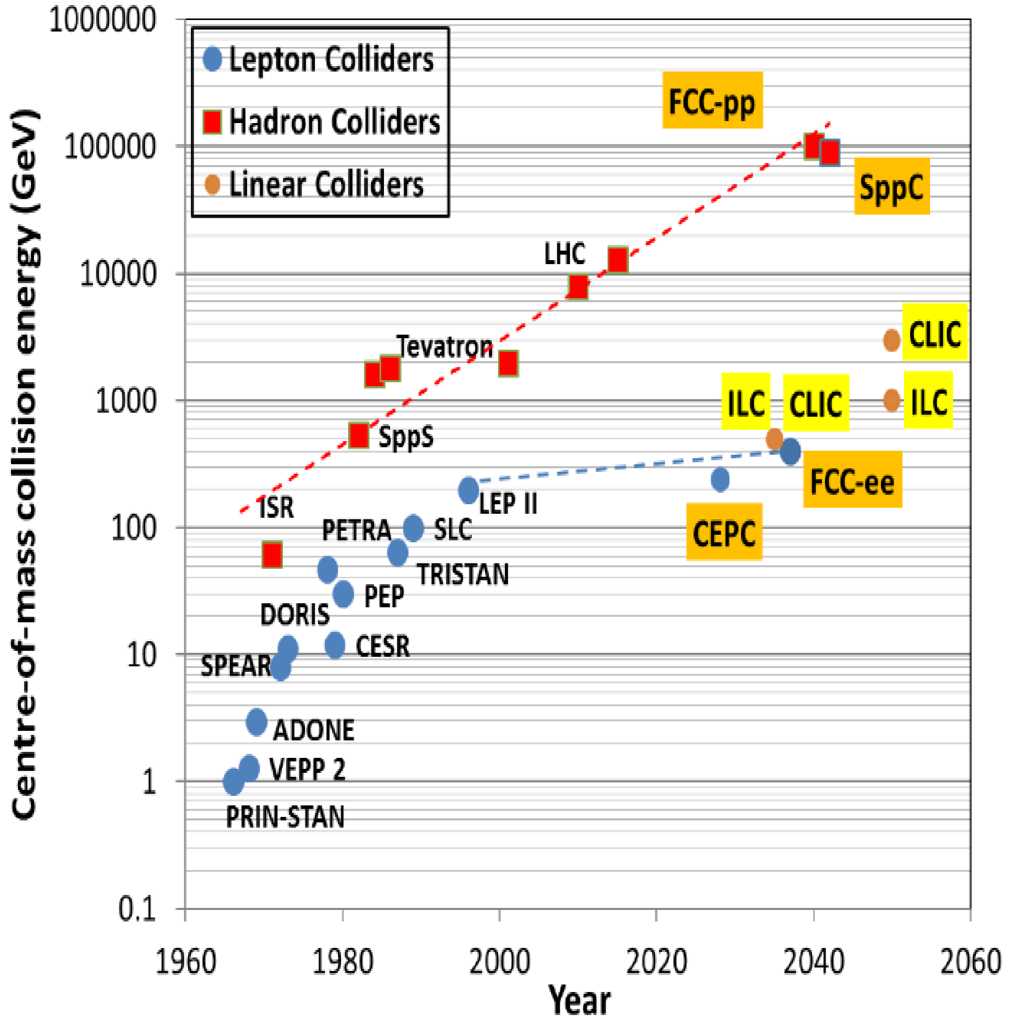




Energy is a key driver







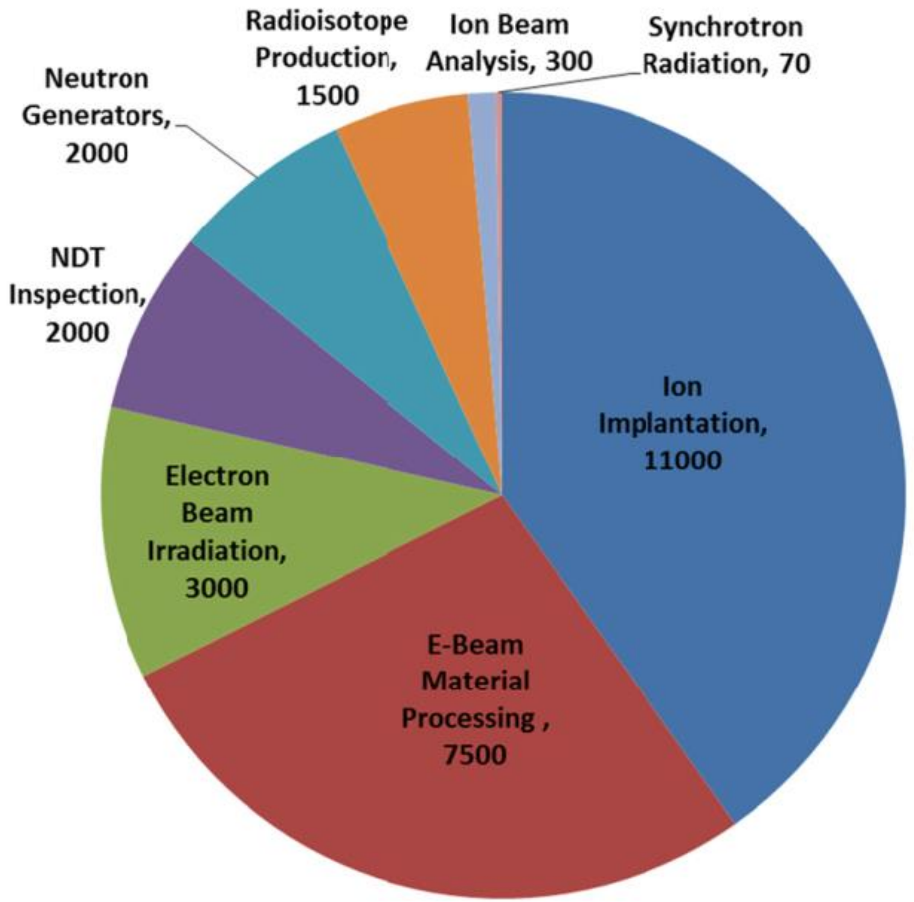
Accelerators only for HEP?

A key tool beyond HEP

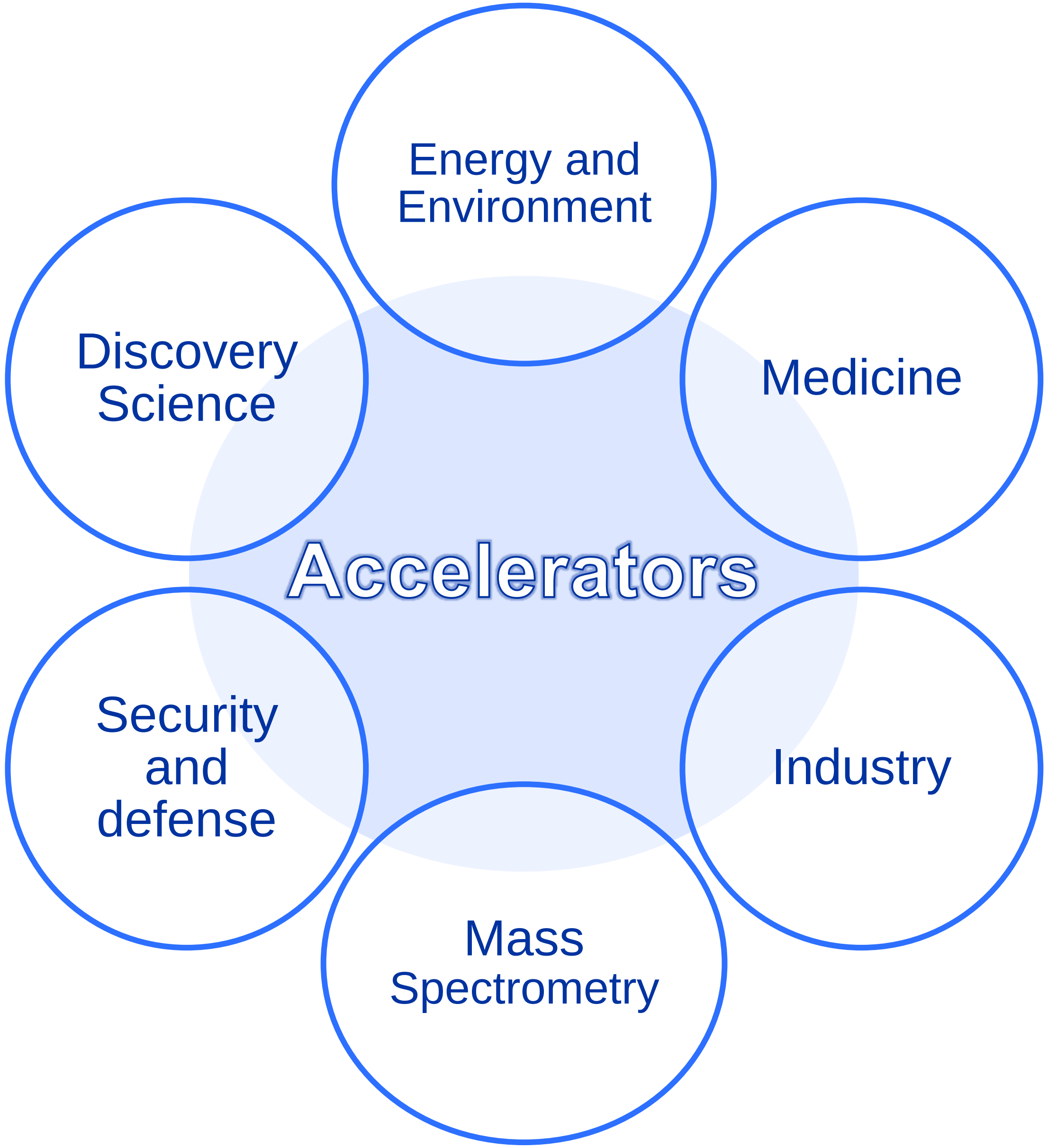
Accelerators – a tool not only for HEP

More than 27.000 charged particle beam accelerators have been built worldwide for use in industrial processes. This total does not include the 14.000 accelerators that have been produced for medical therapy with electrons, ions and X-rays. Around 30.000 of those are still in operation today.

A beam of the right particles with the right energy at the right intensity can shrink a tumour, 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 or discover the secrets of the universe.



Usages


Energy and Environment
Discovery Science
Medicine
Accelerators
Security and defense
Industry
Mass Spectrometry

Usages – Energy and Environment

Energy and Environment

Accelerators for power generation and nuclear waste transmutation

Accelerator-driven transmutation would use a high-power proton accelerator to generate neutrons in a dense metal target. Those neutrons interact with surrounding fuel material containing the chemically separated long-lived isotopes, transmuting them into more manageable isotopes.

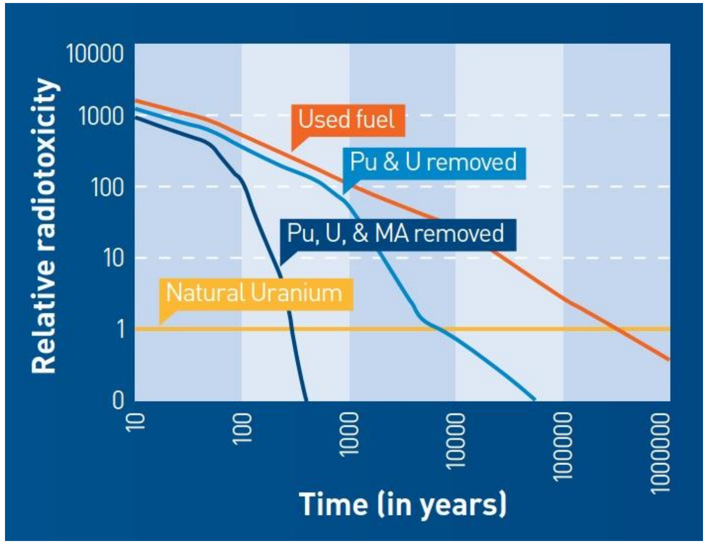
Sustainable energy and non proliferation: subcritical reactors

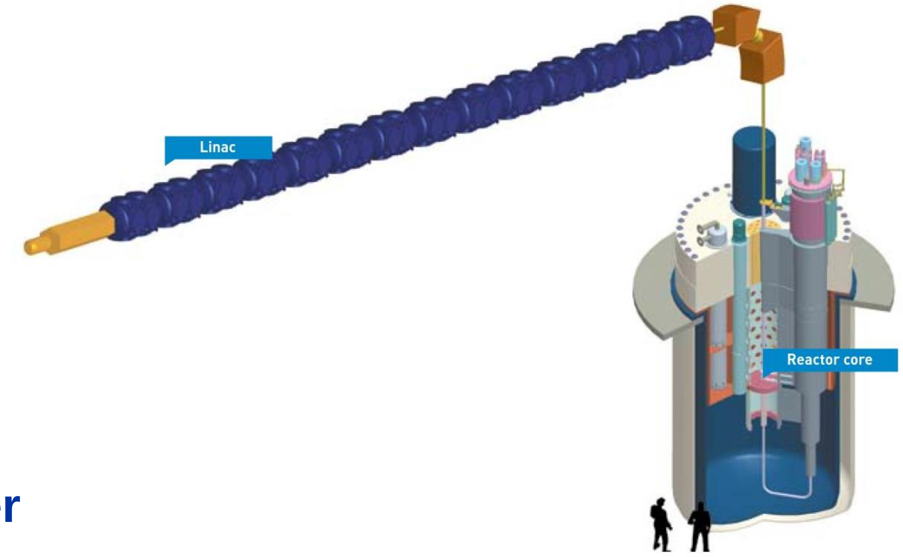
In an accelerator-driven subcritical thorium reactor, the neutrons produced by the proton beam hitting a spallation target breed ^{233}U and promote its fission. Such fission reactions can serve either for power generation or the destruction of actinides from the U/Pu fuel cycle.

Accelerators for developing materials for advanced nuclear power systems

Accelerators for materials irradiation require high-intensity, high-power continuous beams with high availability and low beam losses to allow hands-on maintenance with acceptable radiation exposure. Such accelerators have much in common with those used in other high-power applications, including spallation neutron sources and proton drivers for particle physics research.

Low-energy, high-power electron accelerators for clean air and water





Usages – Medicine

Medicine

Radioisotopes

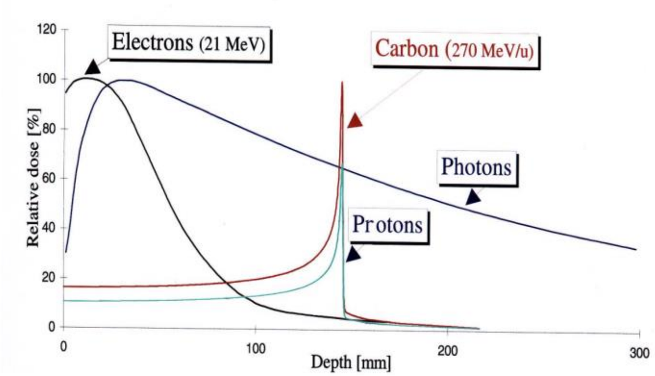
Radioisotopes have become vital components for scientific research and industry, with hundreds of applications in medicine, biology, physics, chemistry, agriculture, national security and environmental and materials science.
Accelerators are the tool to produce isotopes for PET, SPECT or Brachytherapy

X-ray therapy

The most widely employed radiation treatment uses high-energy photons, commonly referred to as x-rays, produced by an electron beam striking a heavy-metal target. S-band electron linacs of 5-30 MeV are the mainstay of radiation therapy powered by either a magnetron for lower-energy, or a klystron for higher-energy electrons.

Hadrontherapy

For deep-seated tumours and/or minimizing dose in surrounding healthy tissue use hadrons (protons, light ions).
Based on medium-energy cyclotrons and synchrotrons for hadron therapy with protons (250 MeV) or light ion beams (400 MeV/u 12C-ions)



Neutrons & X-Ray

Neutron and X-ray imaging are essential for studies of proteins and advanced materials.

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Usages – Industry

Industry

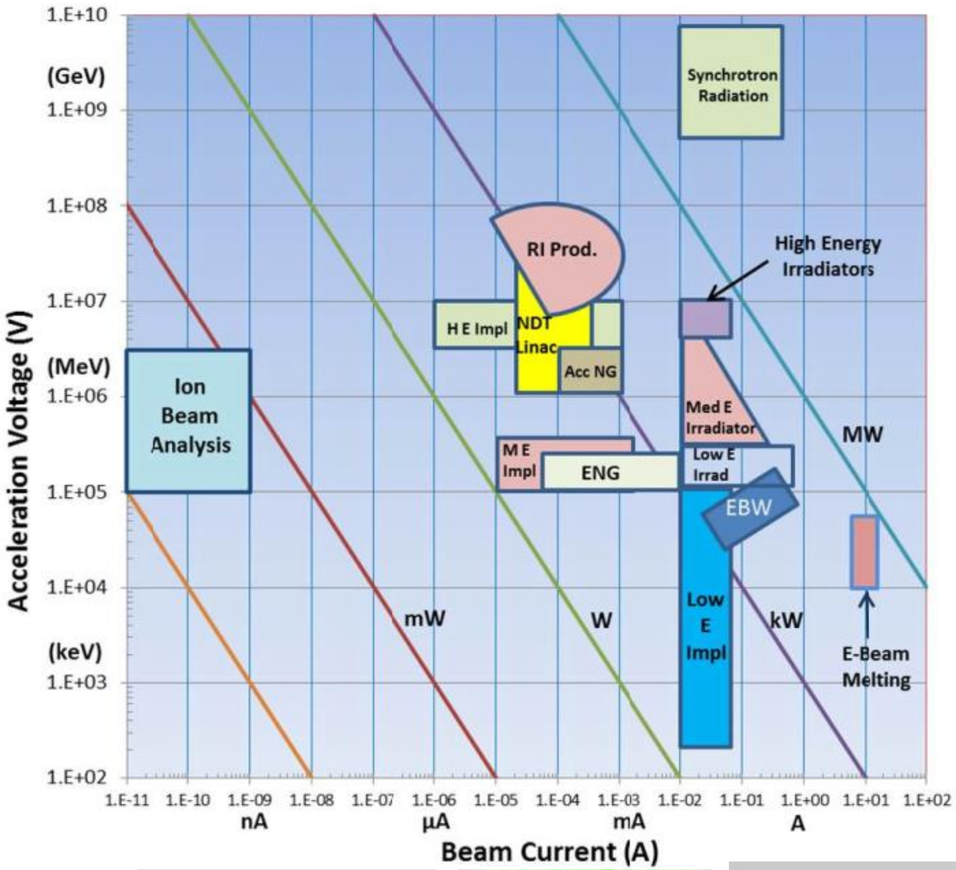
Electron beams

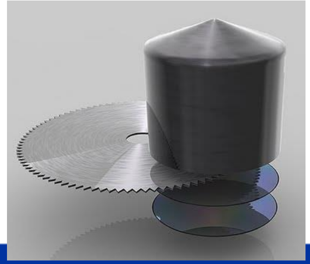
- Modification of polymers by cross-linking.
- Curing of inks, coatings and adhesives
- Manufacture of hydrogels for wound and burn treatment
- Sterilization of medical equipment
- Elimination of food-borne pathogens
- Metal coating
- Treatment of nitrogen and sulfur oxides
- Decontamination of wastewater and drinking water
- Ethanol production

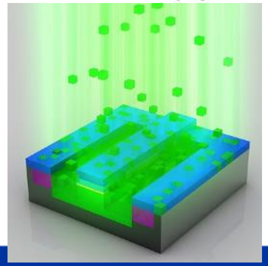
Ion beams

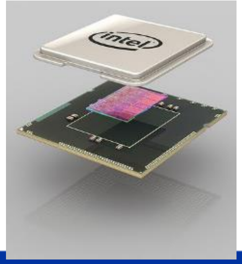
- Ion implantation (chips industry).
- Hardening of the surfaces of metals and ceramics for high-speed cutting tools and artificial human joints;
- Modification of the optical properties of materials
- Non-destructive elemental analysis

Synchrotron light sources, Neutron sources, SRF accelerators







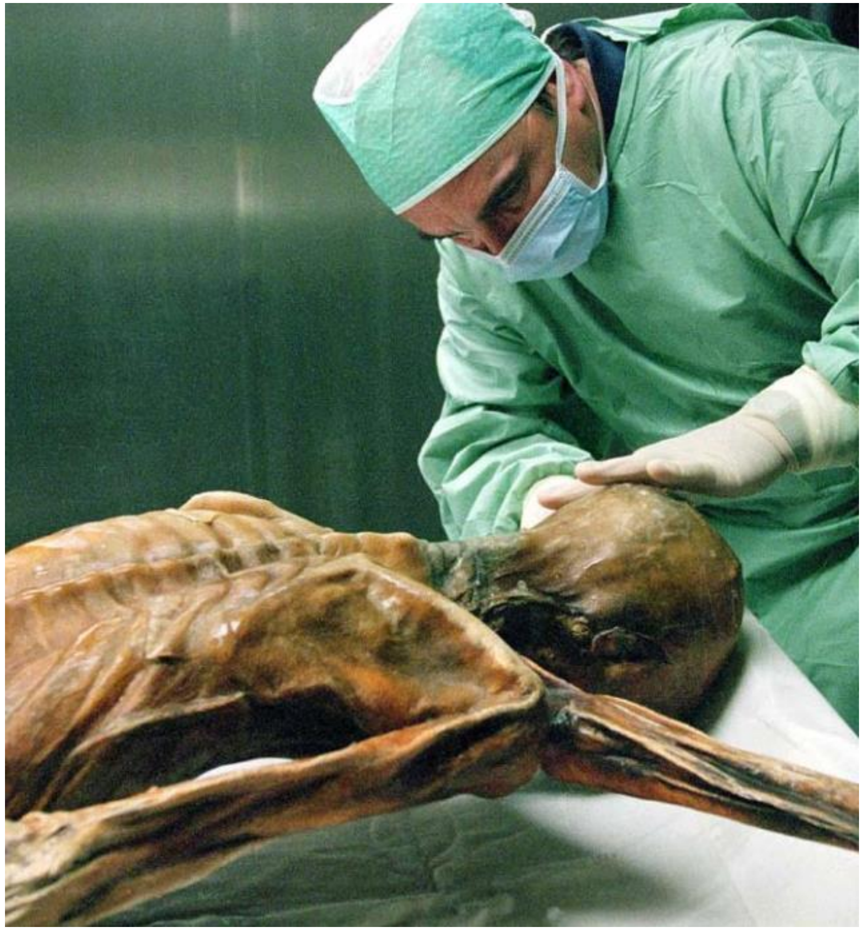


Mass Spectrometry

Usages – Mass Spectroscopy

Determining the exact ratio of a radioisotope to the stable isotope of the same element present in an artefact or other material allows researchers to determine its age and other critical properties. Accelerators have taken centre stage by virtue of their ability to make extremely precise measurements of long-lived radioisotopes at ultra-low concentrations.
Some of the usages:

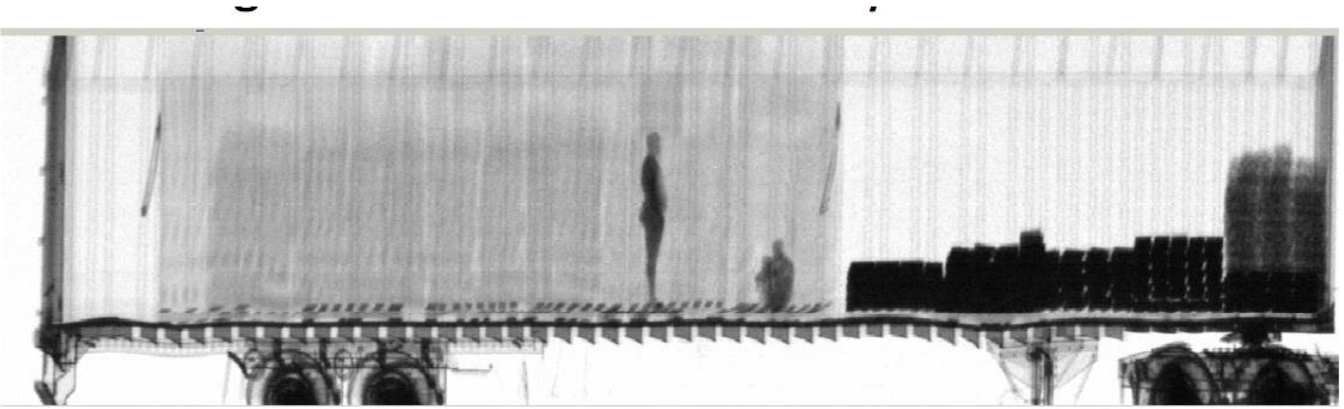
- studies of trace gases and the origin and transport of aerosols, exchanges between atmospheric layers;
- dating of ground waters and aquifers, global ocean circulation patterns,
- paleo-climatic studies in lake and ocean sediments;
- paleo-climatic studies of ice cores,
- variations of cosmic radiation, bomb peak identification;
- exposure and erosion dating of surface rocks, tectonic plate subduction and volcanic rock measurements;
- radionuclides in meteoritic and lunar samples;
- isotope ratios in presolar grains, supernova remnants on earth;
- nuclear safeguards, neutron fluxes,
- forensic and in vivo tracer studies of plants, animals, and humans, with medical and pharmaceutical applications.

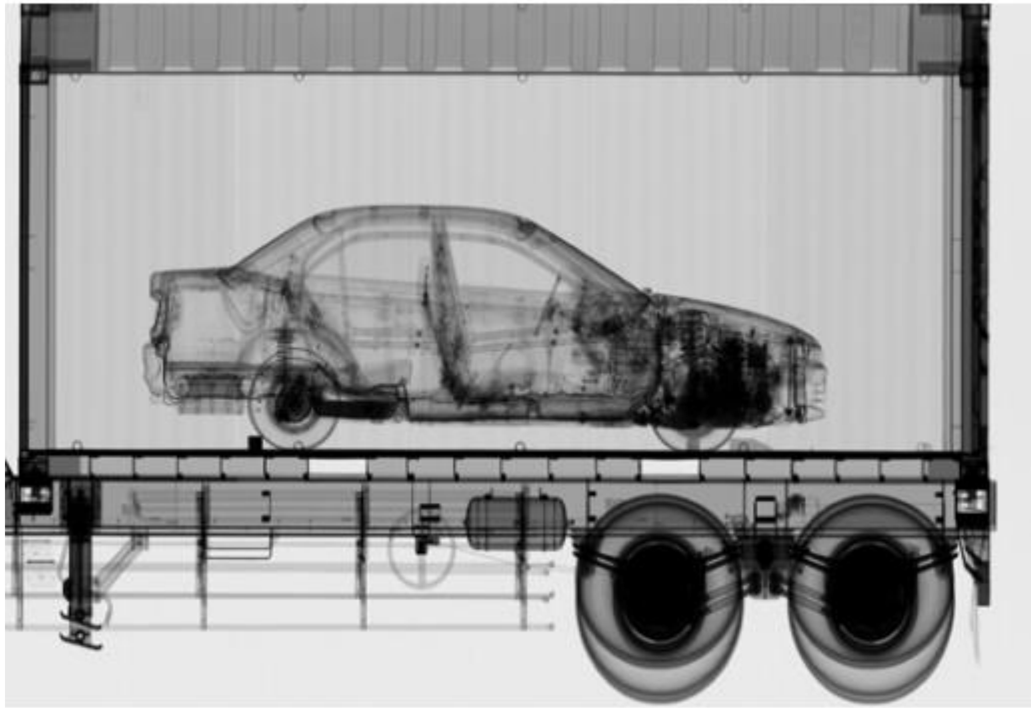


Usages – Security and defense

Security and defense

- Inspect nuclear fuels
- Cargo inspections
- Simulate systems for detecting special nuclear materials and by-products of nuclear fission.
- Nuclear forensics



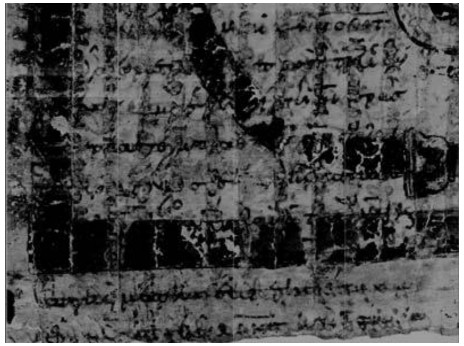


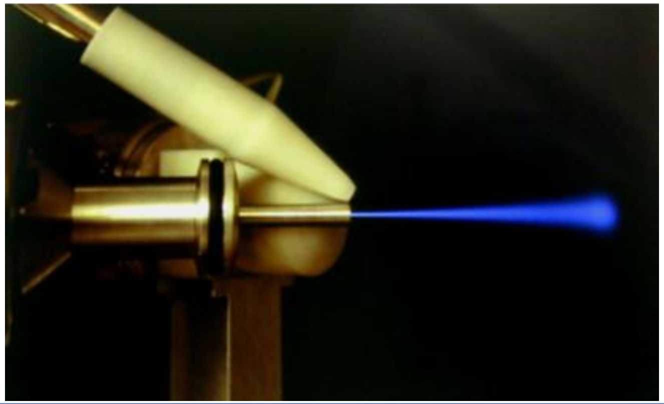
culture

Usages – Others

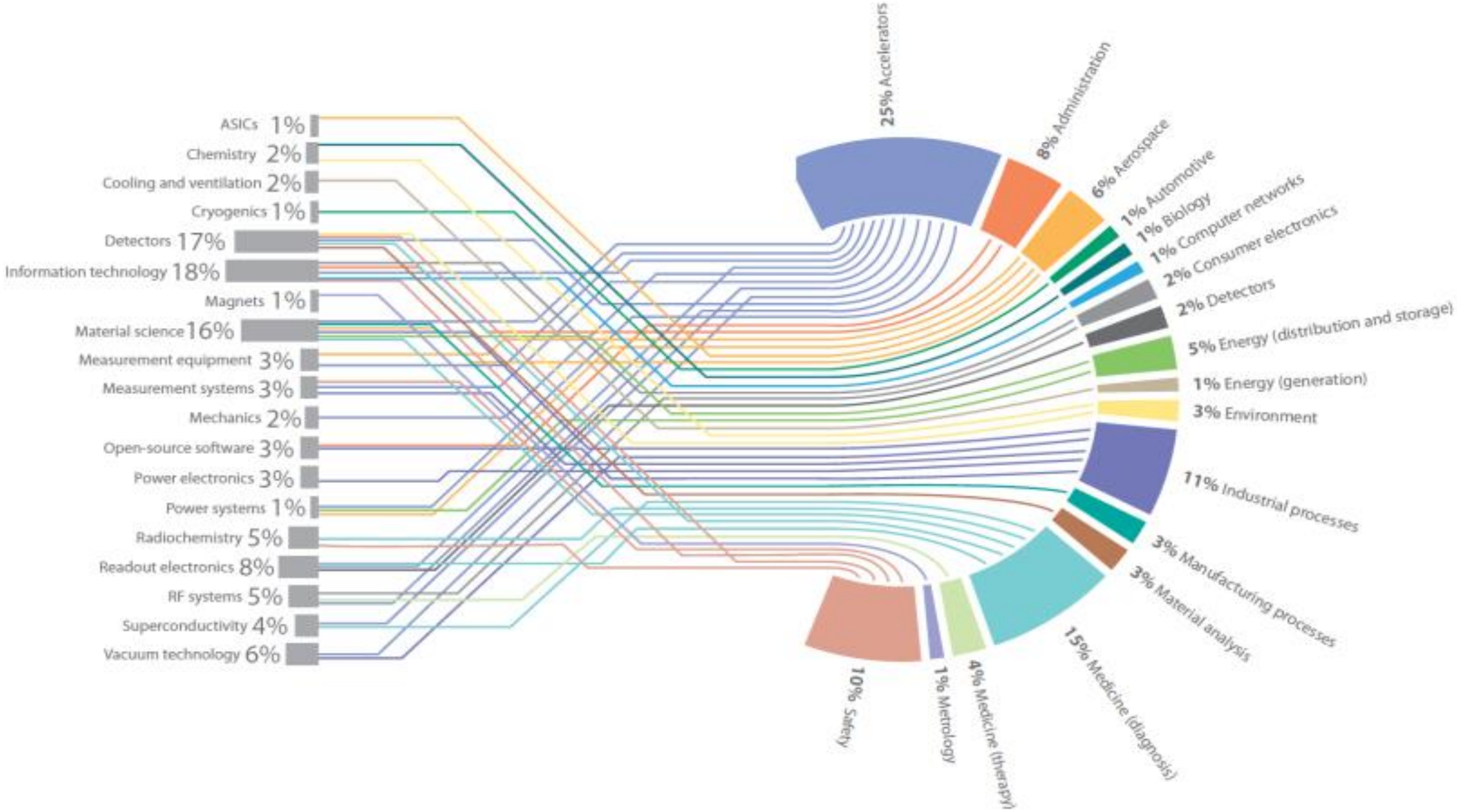
- Ion Beam Analysis (MeV) shows us the chemical composition of pigments used in paint
- Backscattered radiation can give detailed analysis of atoms present in surface.
- This allows art historians to compare them with paints available to artists like Leonardo da Vinci

A synchrotron X-ray beam at the SSRL facility illuminated an obscured work erased, written over and even painted over of the ancient mathematical genius Archimedes.

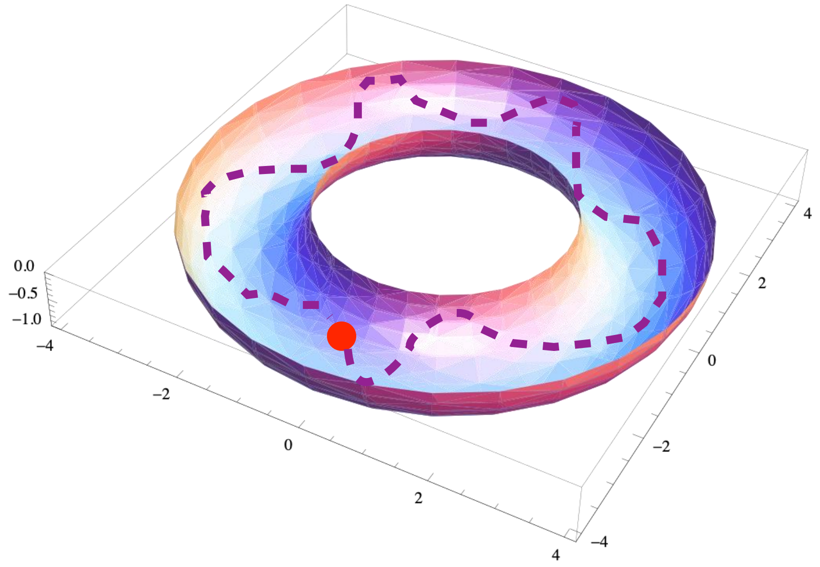




Technology Transfer & IP Management



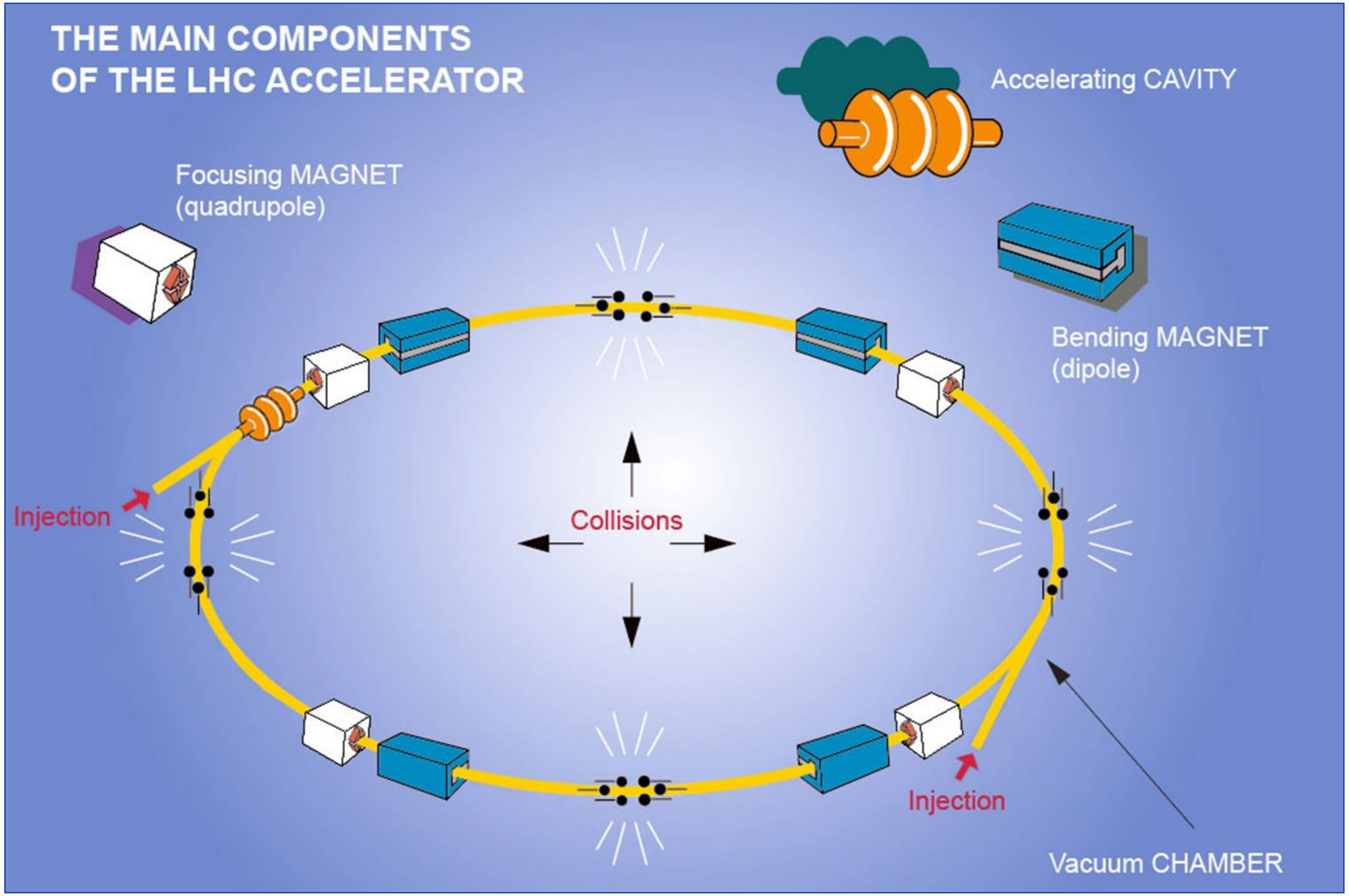
$$\overline{F(t)} = q\left(\overline{E(t)} + \overline{v(t)} \otimes \overline{B(t)}\right)$$



How does an accelerator work?

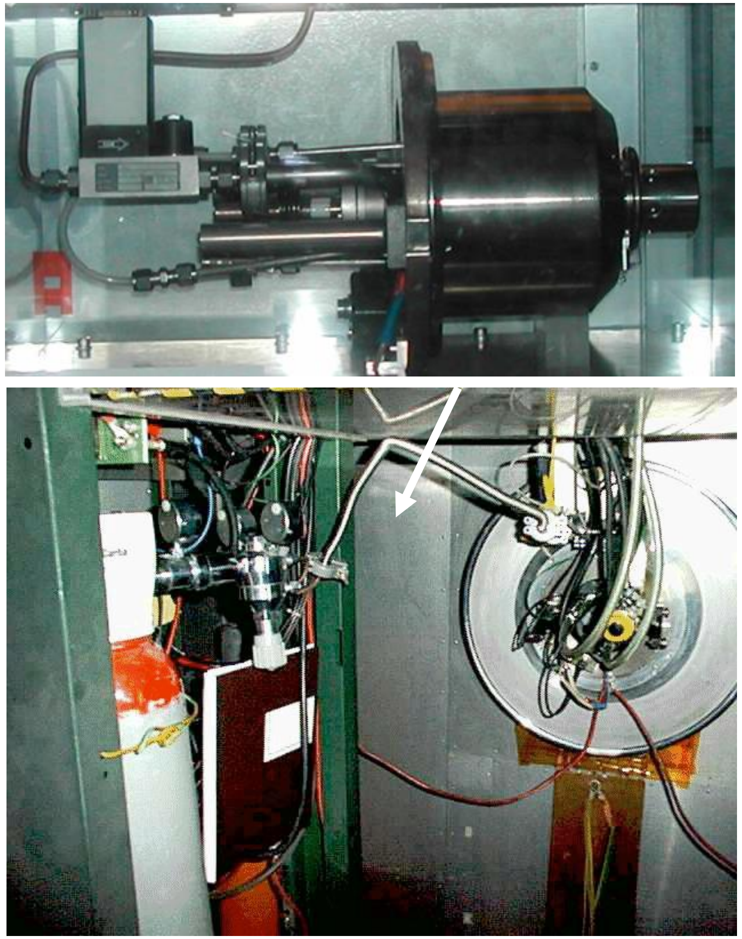
Main components

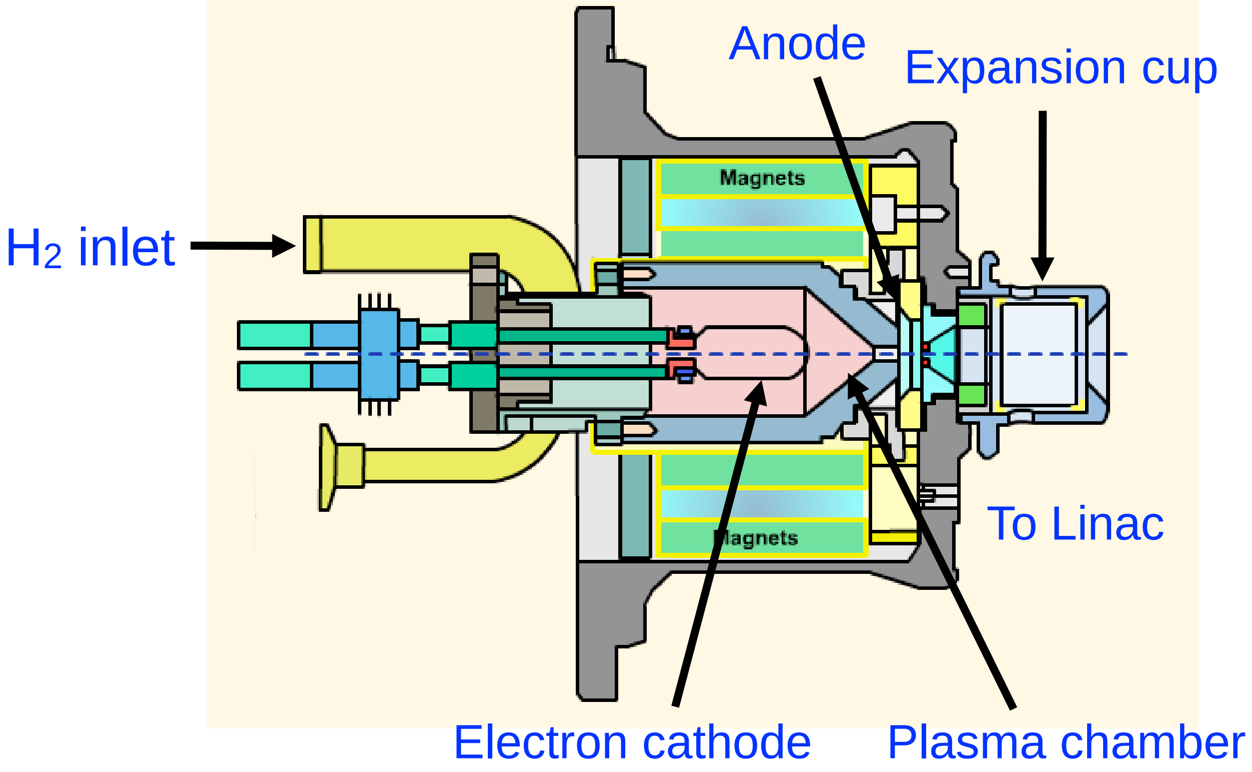
What are the components of an accelerator



How to get protons: duoplasmatron source

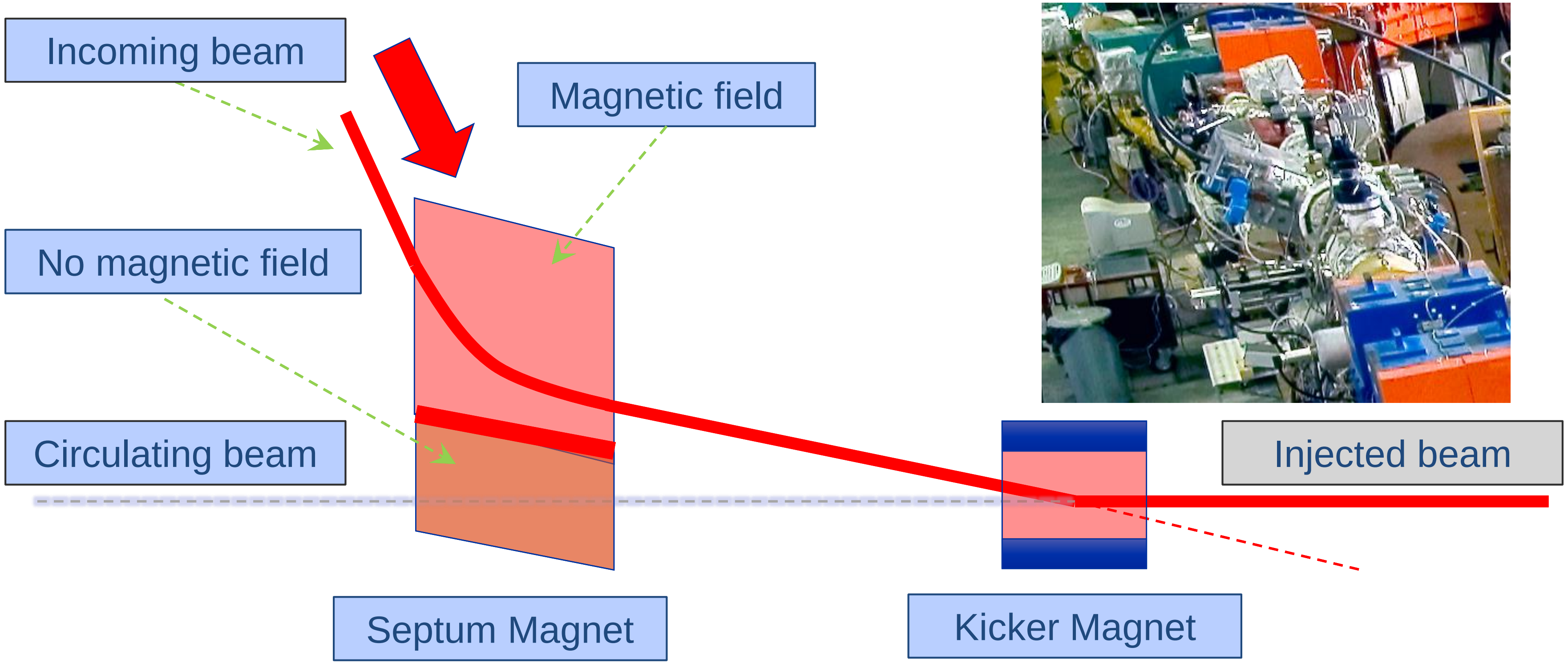
Protons are produced by the ionization of H_2 plasma enhanced by an electron beam





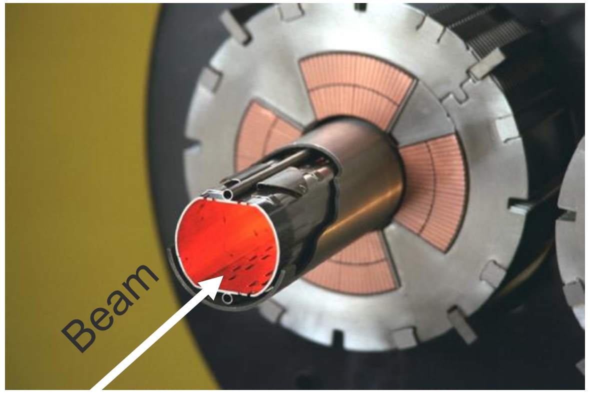
Proton exiting from the about 1 mm^2 hole have a speed of 1.4 % c, v ≈4000 km/s

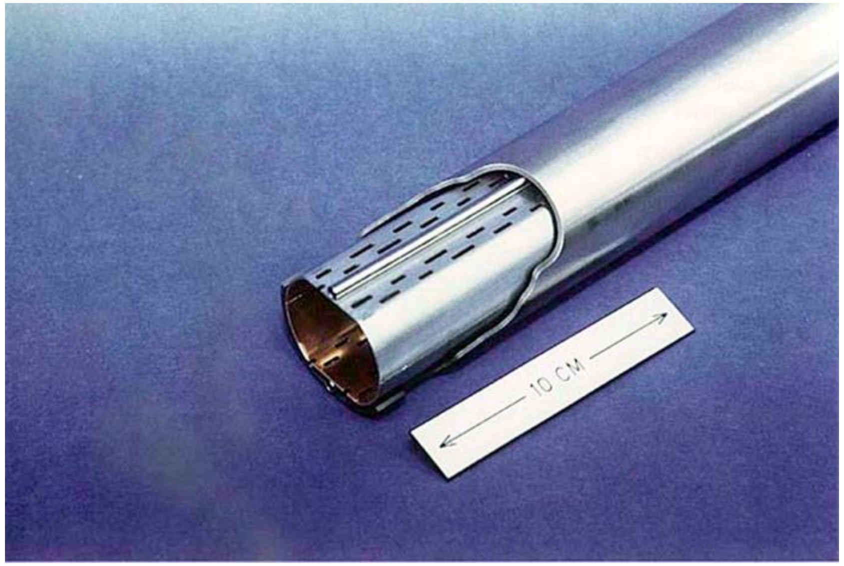
Injecting & Extracting Particles



Ultra vacuum

Beam screen to protect Superconducting magnets from Synchrotron radiation.



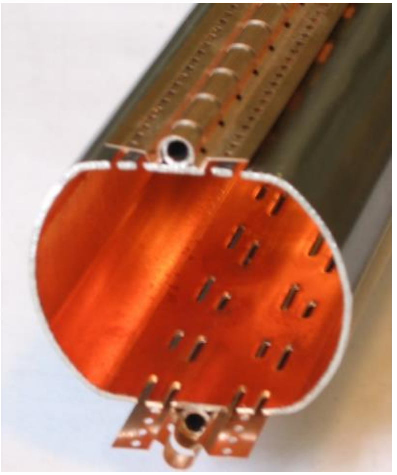


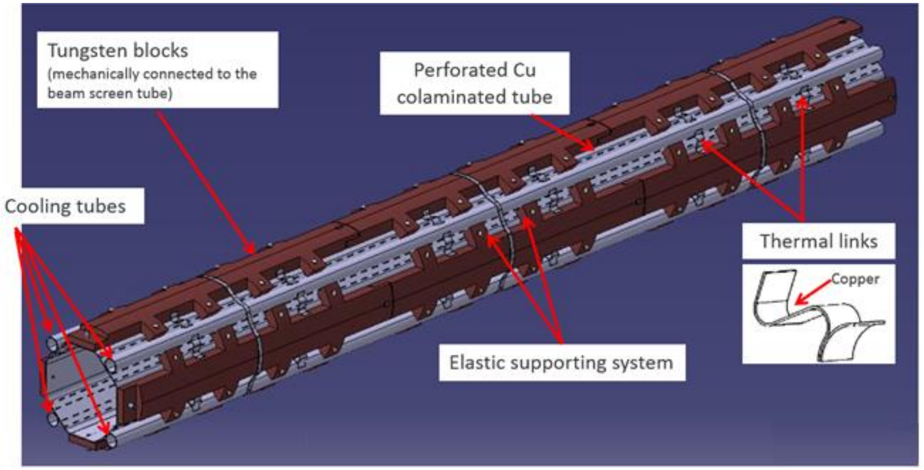
Atmosphere pressure = 750 Torr
Moon atmospheric pressure = 5 10^{-13} Torr

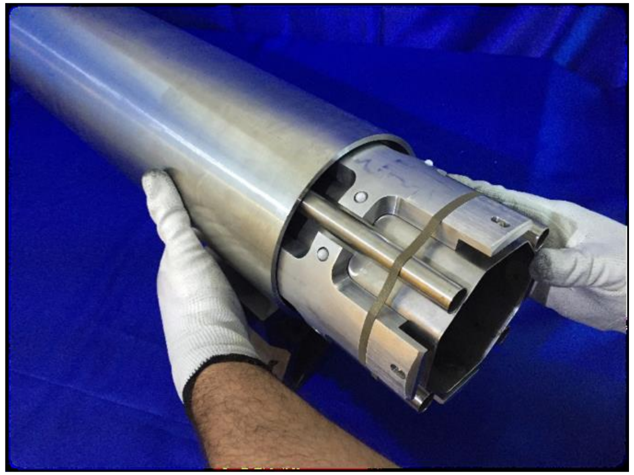
Vacuum required to avoid unwanted collision far from the IPs and decrease the Luminosity

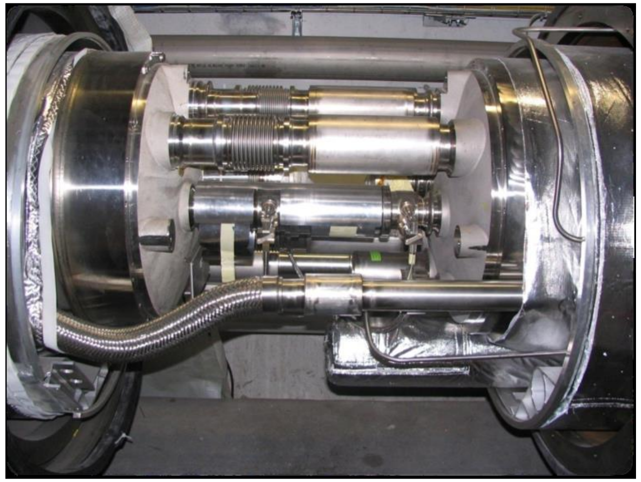
Typical vacuum: **10^{-13} Torr**
There is ~6500 m^3 of total pumped volume in the LHC, like pumping down a cathedral

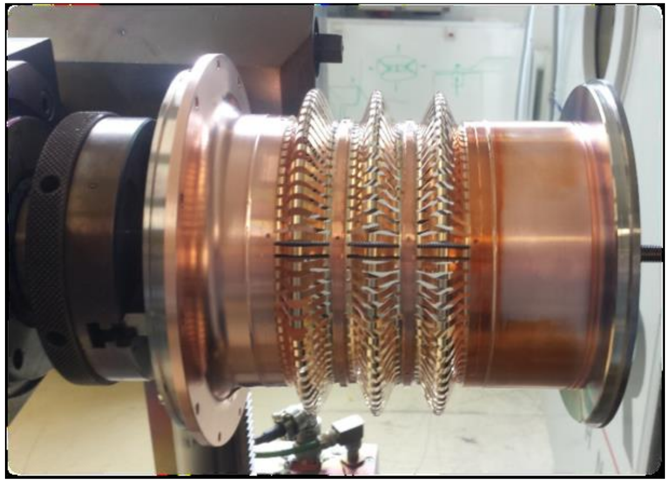
Ultra vacuum











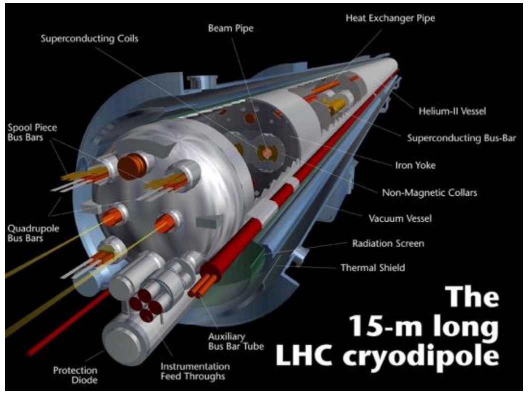
Magnet Systems

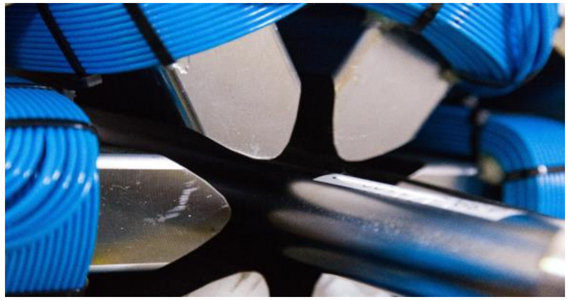
Dipole Magnets: Bend the beam trajectory

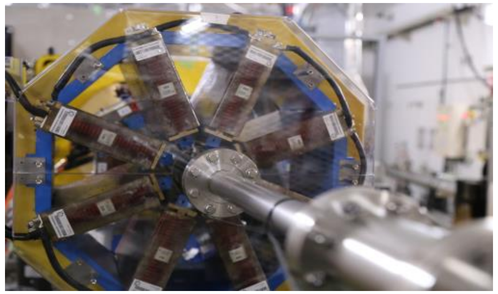
Quadrupole magnets: Focus/de-focus beam

Sextupole magnets: Correct chromaticity

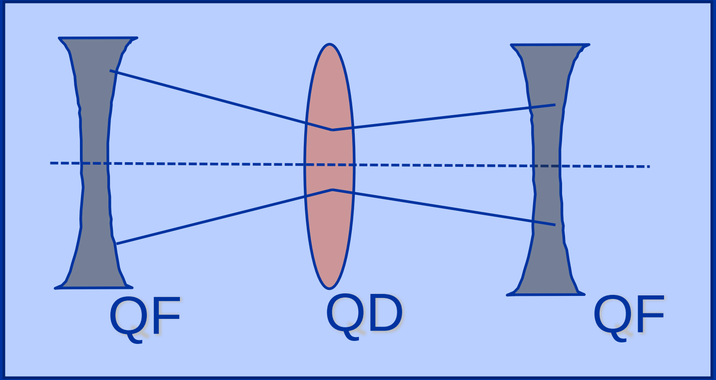
Octupole magnets: Change tune vs amplitude

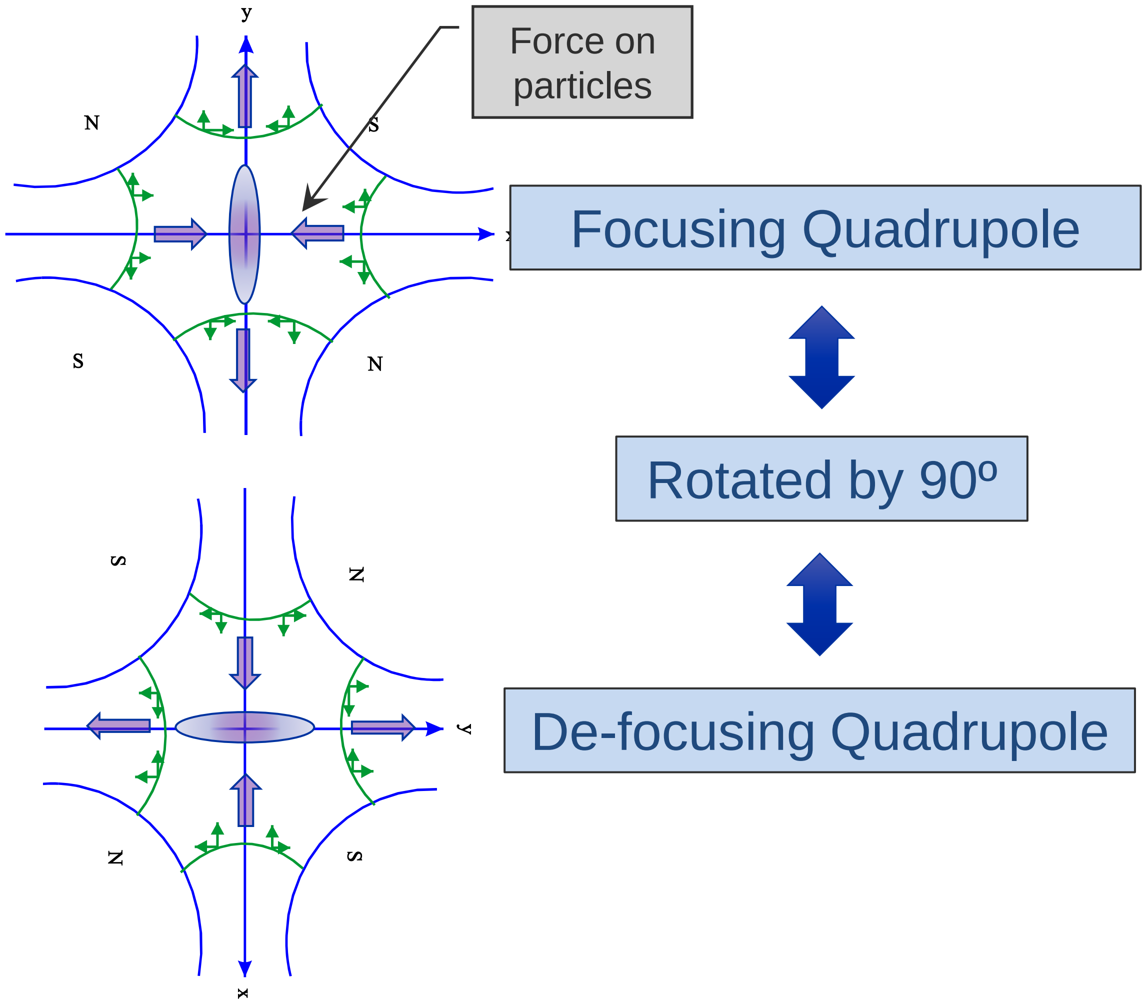






Focusing Particle Beams, a bit like a lens

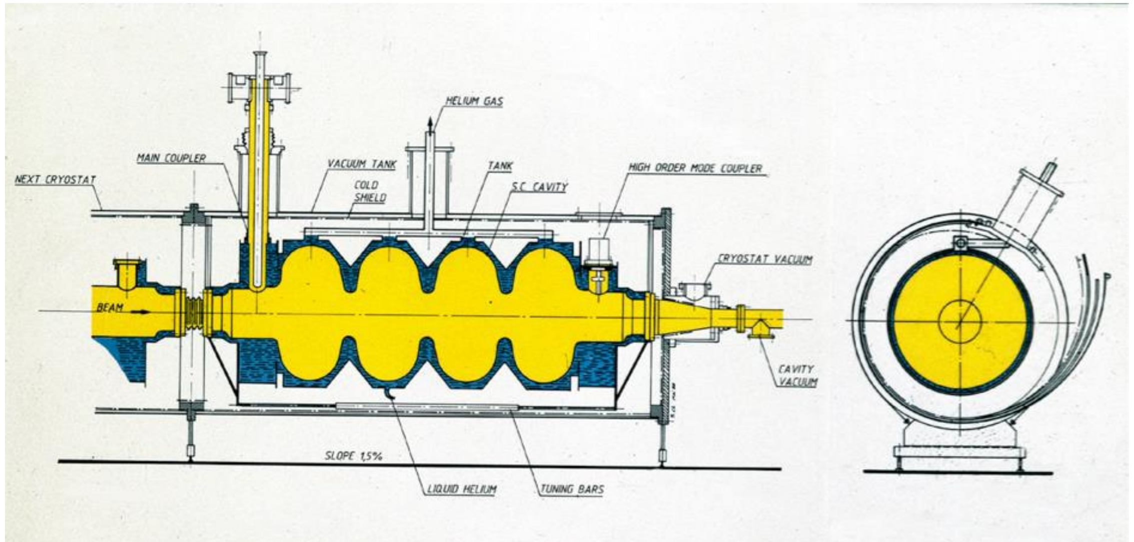




RF systems, LEP, LHC

Charged particles are accelerated by a longitudinal electric field

The electric field needs to alternate with a harmonic of the revolution frequency
A typical cavity can provide from few kV/m few MV/m



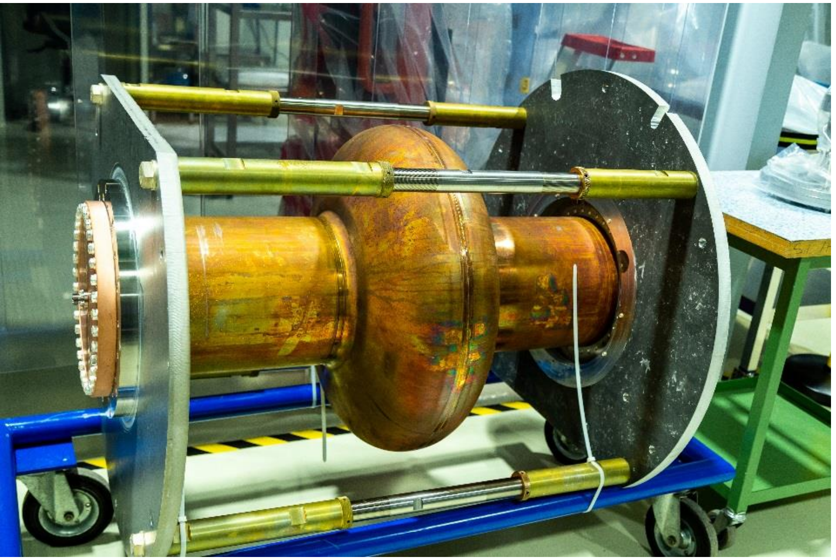
SUPERCONDUCTING CAVITY WITH ITS CRYOSTAT

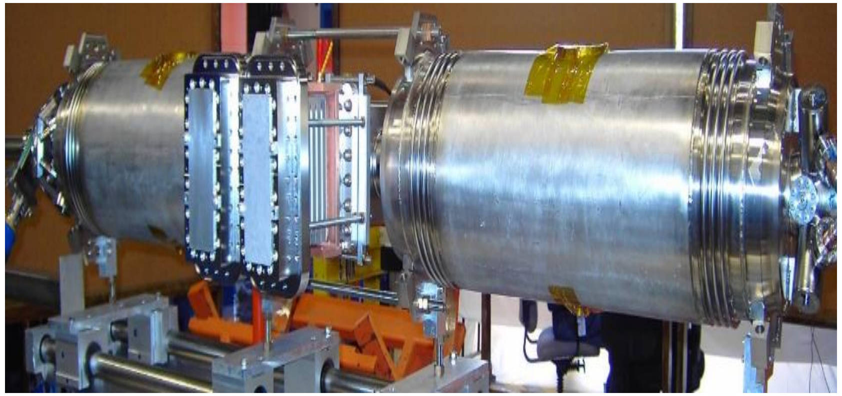
Example for LEP:

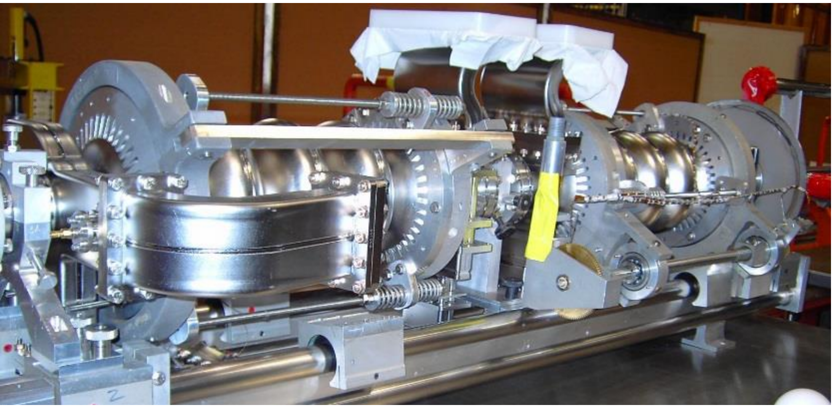
120 cavities (room temperature) at 352 MHz, provided over **300 MV circumferential voltage** (! that's why we do not bend with E fields...)

Then, the new superconducting RF provided **2000 MV circumferential voltage**

RF Cavities

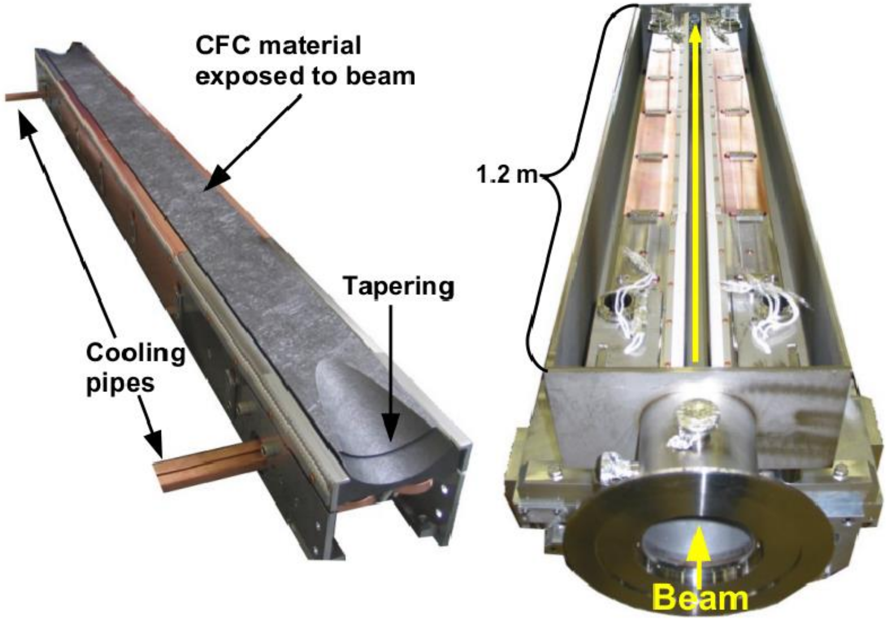


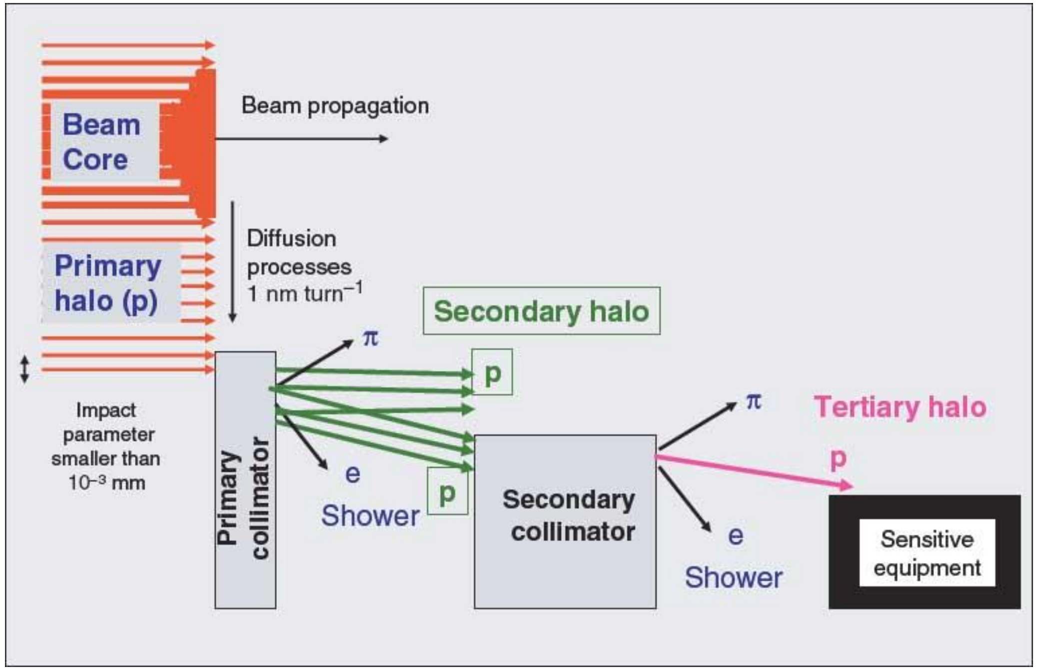




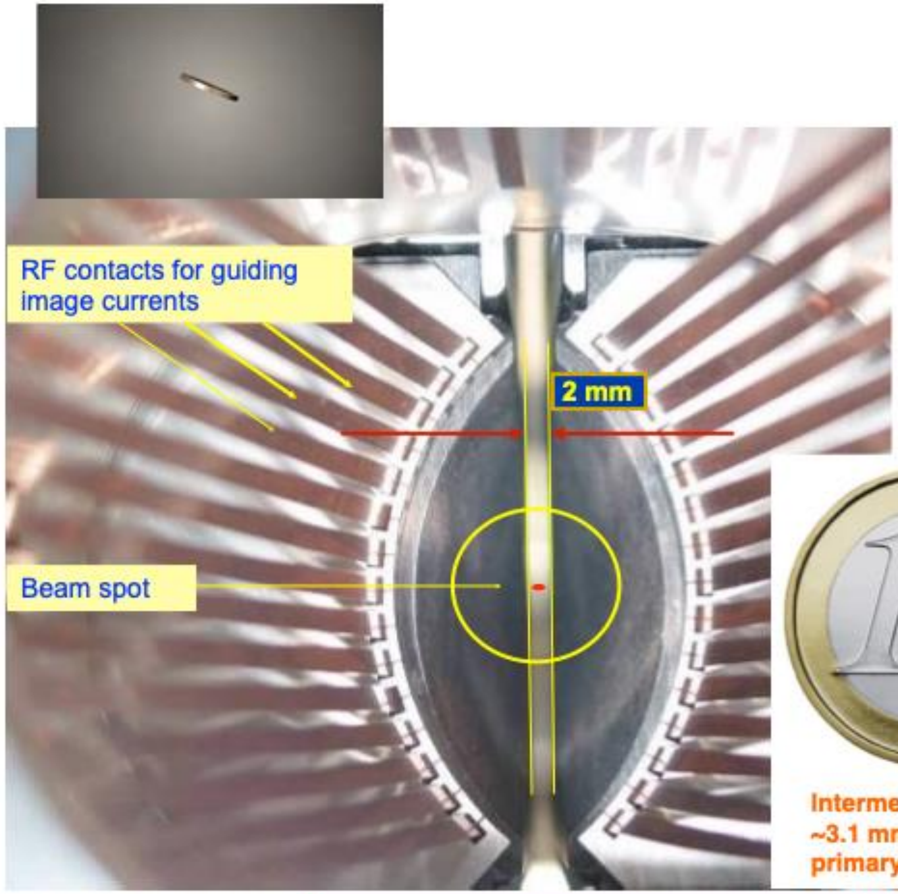
Collimation

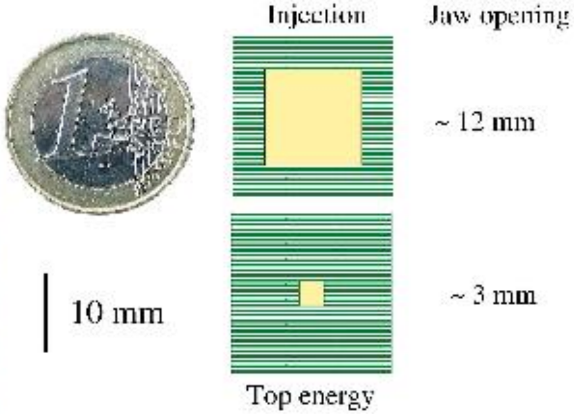
Some particles can deviate from the nominal trajectory perturbing the beam and potentially damaging the accelerator the collimation system cleans the beam from such particles

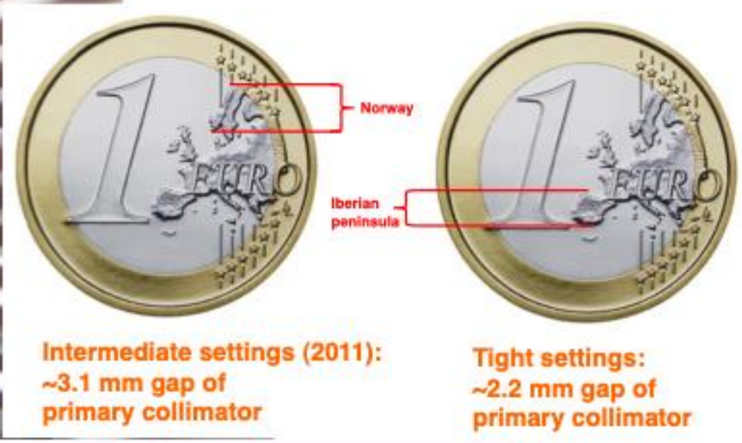


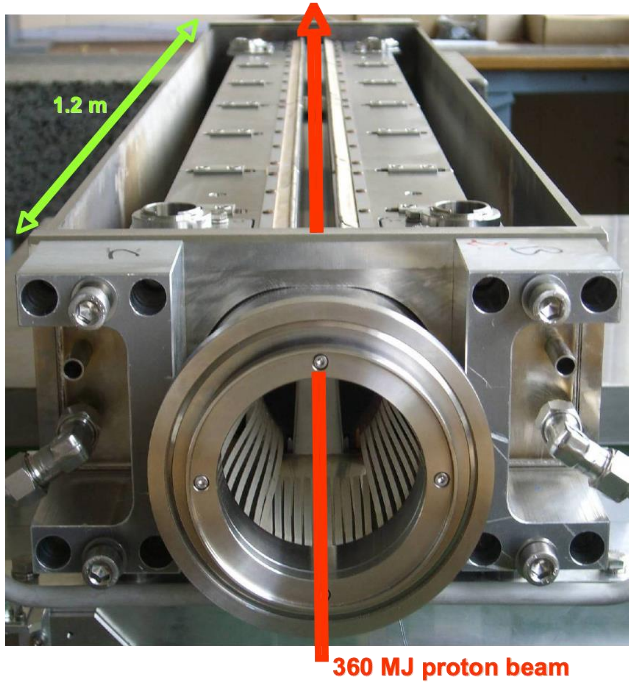


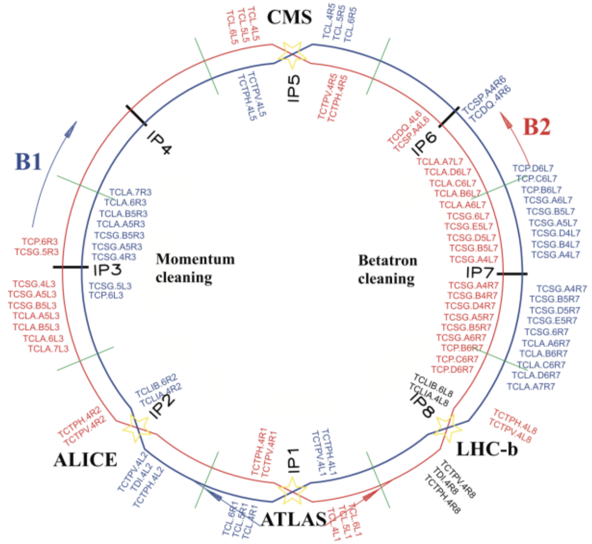
Collimation





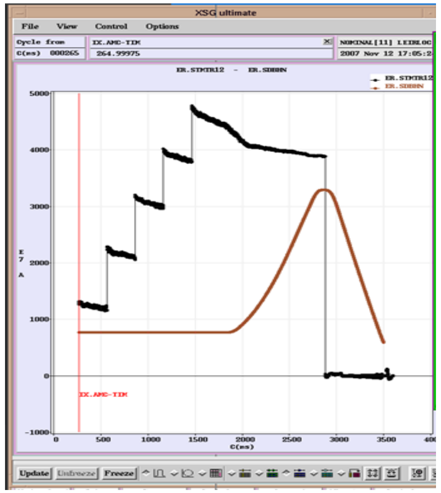




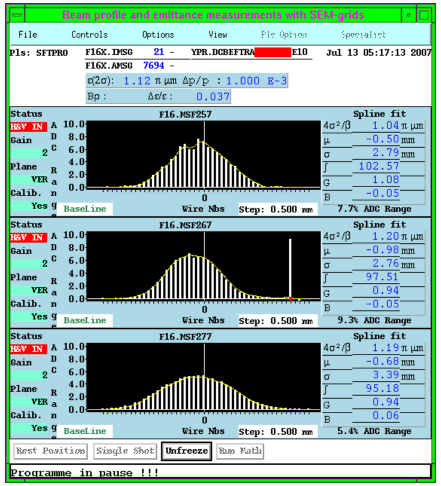


Precision required for collimator movements about 25 μm

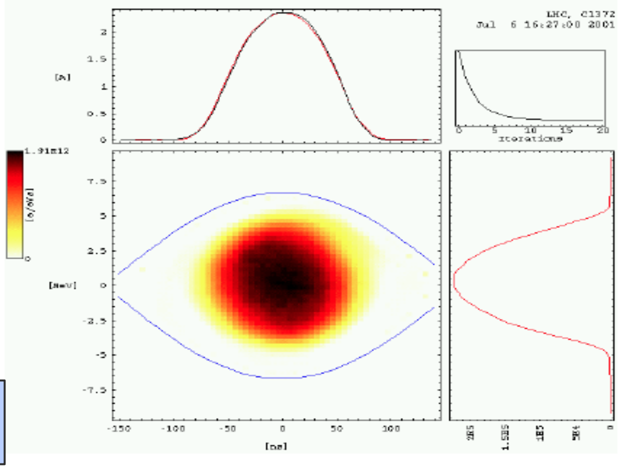
The Eyes of Operations



Beam intensity or current measurement



Transverse beam profile/size measurement



Longitudinal beam profile measurements

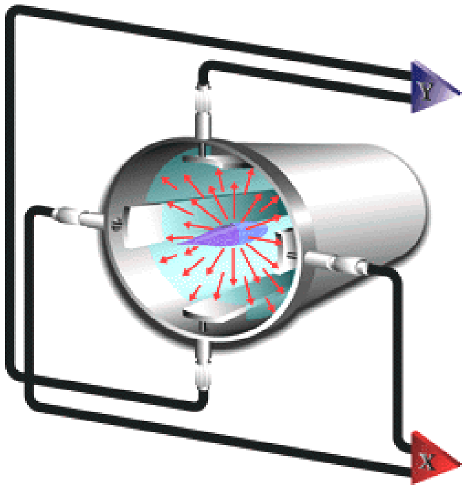
Measure the LHC luminosity, number of events per surface and time unit.

Any many more beam properties…..

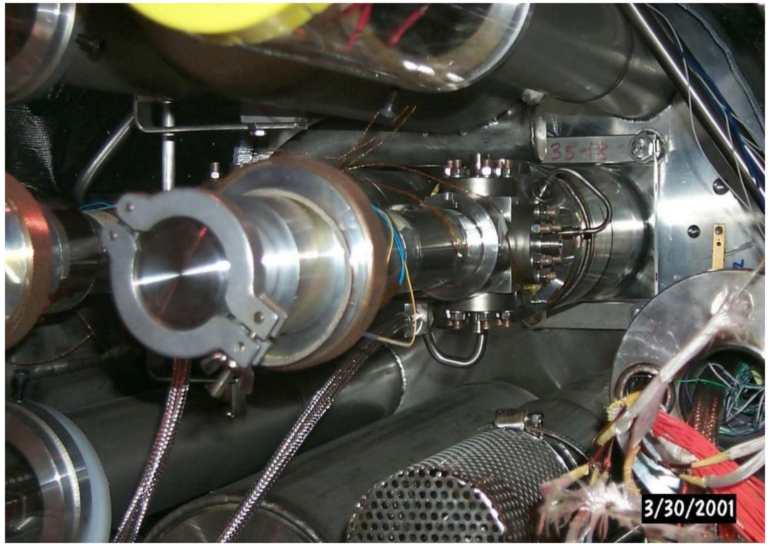
Beam Position Monitor (BPM)

The electric field from the beam induces a charge on the antennas

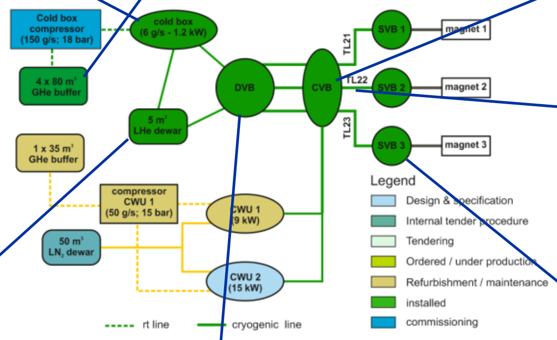
The charges on each antenna are measured, and one can then calculate the position of the beam inside the beamline



4 buttons pick-up the EM signal induced by the beam. One can infer the transverse position in both planes.



Cryogenics


Cold box compressor (150 g/s; 18 bar)
cold box (6 g/s - 1.2 kW)
4 x 80 m³ GHe buffer
5 m³ LHe dewar
1 x 35 m³ GHe buffer
compressor CWU 1 (50 g/s; 15 bar)
50 m³ LN₂ dewar
CWU 1 (9 kW)
CWU 2 (15 kW)
DVB
CVB
TL21
TL22
TL23
SVB 1
SVB 2
SVB 3
magnet 1
magnet 2
magnet 3
Legend
Design & specification
Internal tender procedure
Tendering
Ordered / under production
Refurbishment / maintenance
installed
commissioning
rt line
cryogenic line

Power and Stored Energy

1 eV = 1.6E-19 J, therefore 7 TeV = 1120 nJ

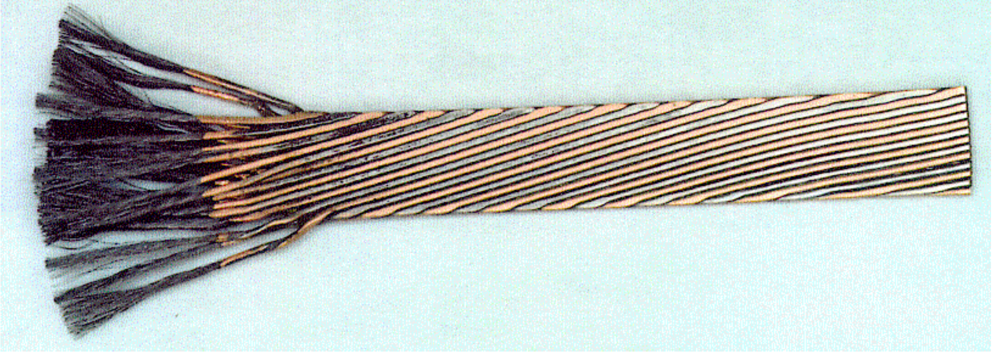
Since 3E14 protons, get 340 MJ

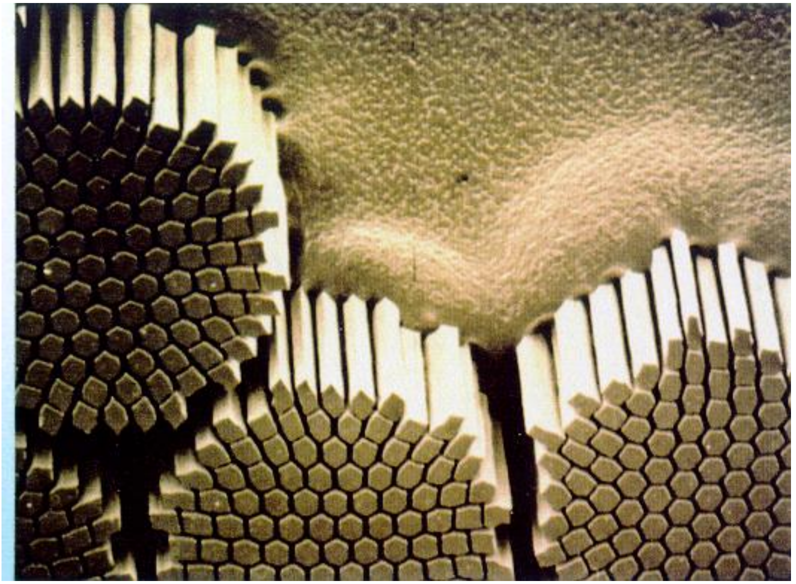
- Similar to Airbus 380 flying at 100kph

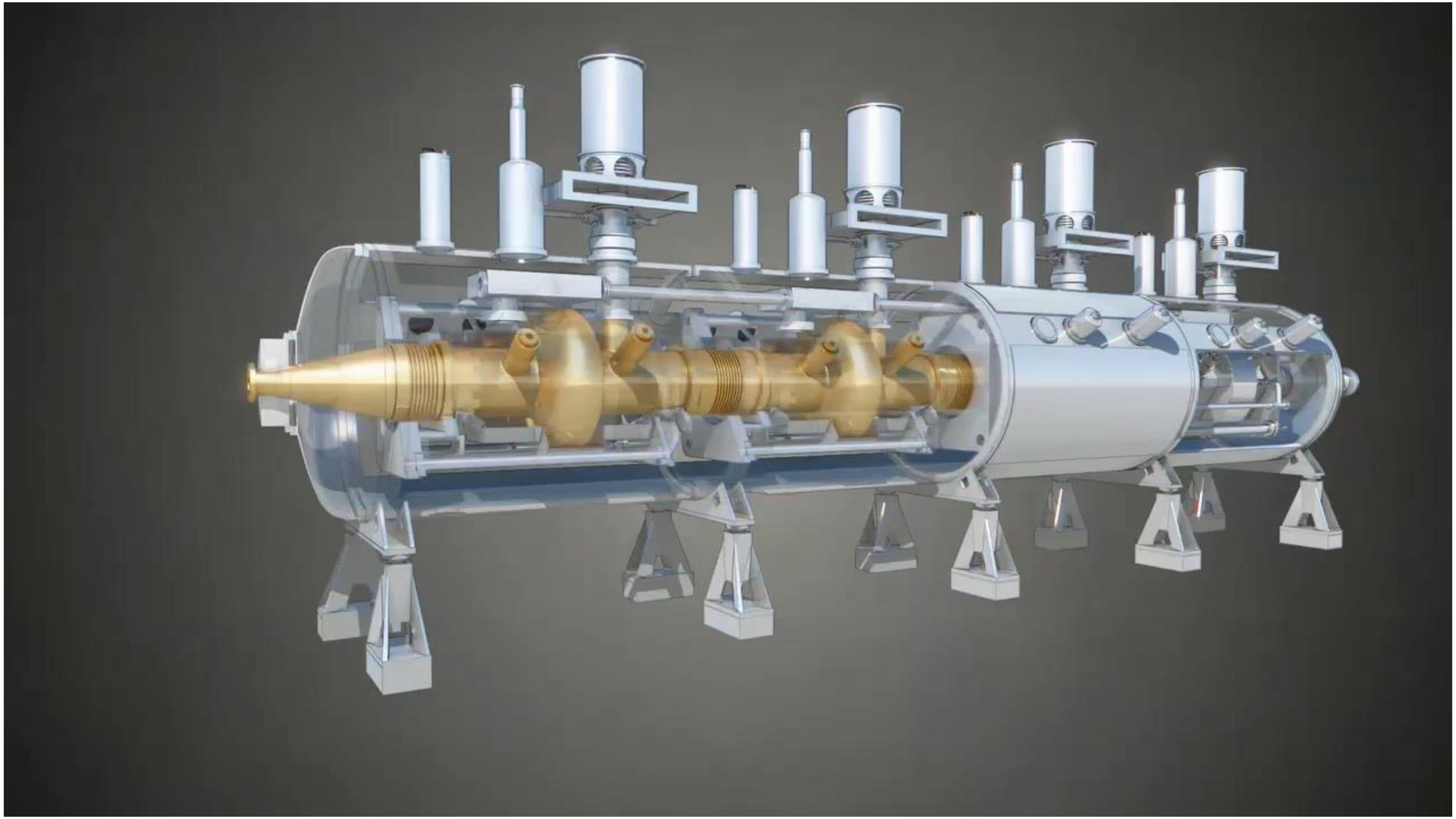
Power = Energy / Time

- 340 MJ / 90 microseconds = 4 Petawatts

Technology



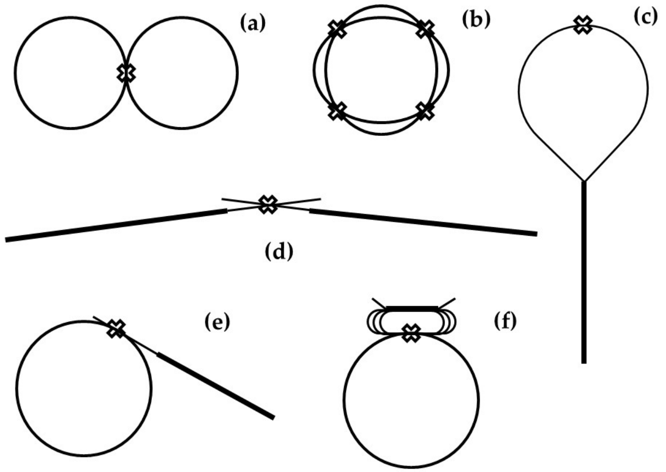


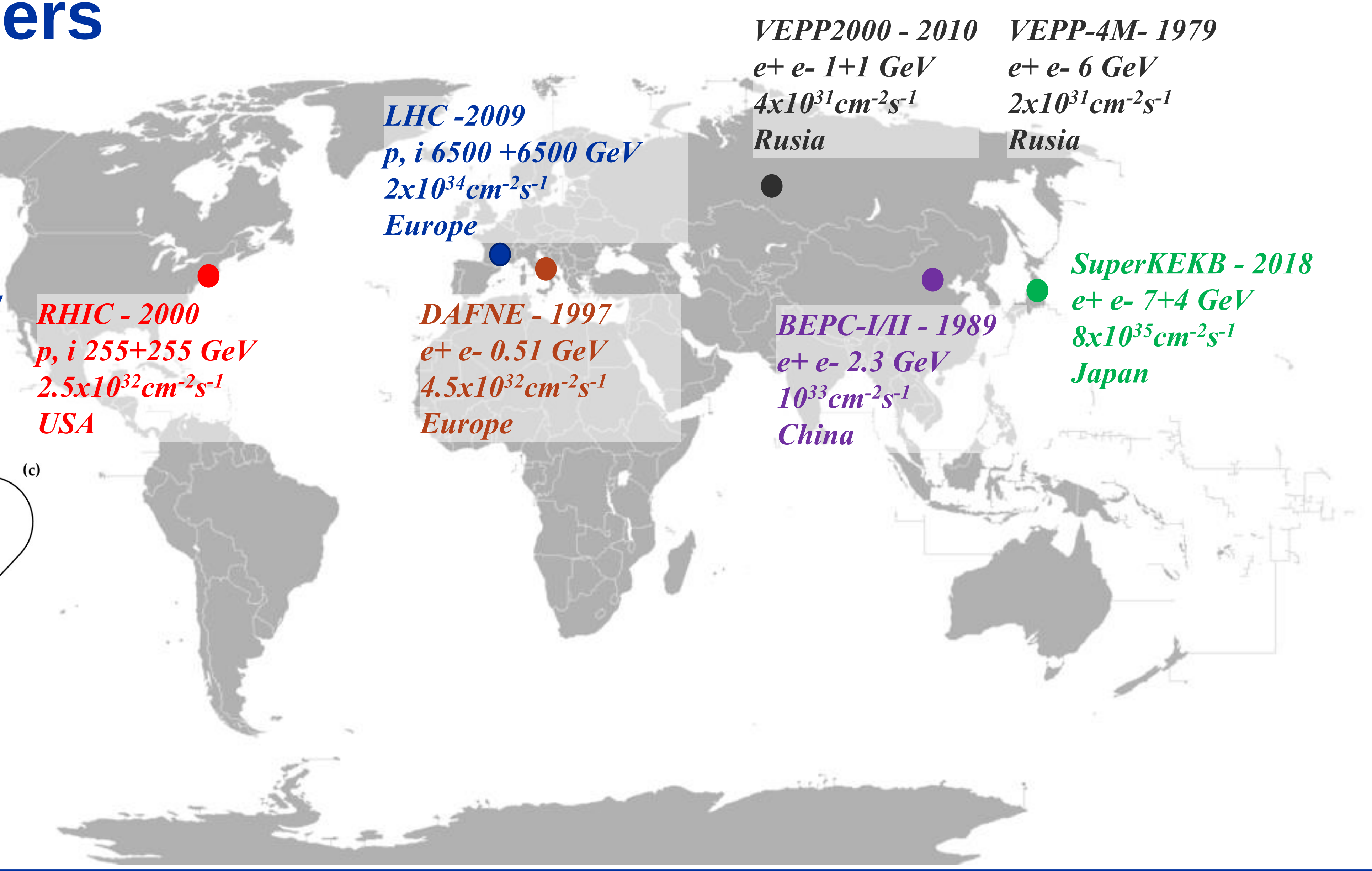


World colliders

$$E_{cme} = 2E_b$$

For E=7000 GeV
Ecm = 14000 GeV





24 (+1) Nobel Prizes in Physics that had direct contribution from accelerators

Year	Name	Accelerator-Science Contribution to Nobel Prize-Winning Research
1939	Ernest O. Lawrence	Cyclotron at Berkeley in 1929
1951	John D. Cockcroft and Ernest T.S. Walton	Linear positive-ion accelerator at Cavendish 1932
1952	Felix Bloch	Use cyclotron at Berkeley - Discovery of the magnetic moment of the neutron in 1940
1957	Tsung-Dao Lee and Chen Ning Yang	Use Bevatron at Lawrence Radiation Laboratory – Parity is not conserved in weak interactions 1956
1959	Emilio G. Segrè and Owen Chamberlain	Use Bevatron at Lawrence Radiation Laboratory – Discovery of the antiproton 1955
1960	Donald A. Glaser	Use of high-energy protons from Cosmotron at Brookhaven - Bubble chamber 1955
1961	Robert Hofstadter	Use of the SLAC linacelectron – Structure of nucleons 1959
1963	Maria Goeppert Mayer	Neutron beams University of Chicago cyclotron - Discoveries on high magic numbers 1948
1967	Hans A. Bethe	Analysis of nuclear reactions accelerated protons & other nuclei Discovered how energy is produced in stars 1939
1968	Luis W. Alvarez	Hydrogen bubble chamber and beams from Bevatron at the Lawrence Radiation Laboratory - resonance states
1976	Burton Richter and Samuel C.C. Ting	SPEAR collider at Stanford (Richter) and Brookhaven Alternating Gradient Synchrotron (Ting) – J/Ψ particle 1974
1979	Sheldon L. Glashow, Abdus Salam, and Steven Weinberg	Experiments on the bombardment of nuclei with neutrinos at CERN - prediction of weak neutral currents 1973

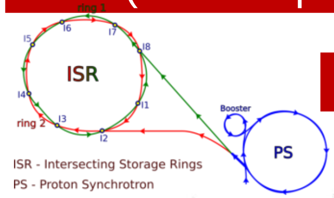
1980	James W. Cronin and Val L. Fitch	Brookhaven Alternating Gradient Synchrotron - CP (charge-parity) symmetry violation 1964
1981	Kai M. Siegbahn	Weak-focusing principle for betatrons 1944
1983	William A. Fowler	Analysis accelerator-based experiments – stellar-fusion processes 1957
1984	Carlo Rubbia and Simon van der Meer	SPS CERN Observed the intermediate vector bosons W and Z 1983
1986	Ernst Ruska	Magnetic optical system that provided large magnification - Electron microscope in 1933
1988	Leon M. Lederman, Melvin Schwartz, and Jack Steinberger	Brookhaven's Alternating Gradient Synchrotron – Muon neutrino 1962
1989	Wolfgang Paul	Paul's idea in the early 1950s of building ion traps grew out of accelerator physics
1990	Jerome I. Friedman, Henry W. Kendall, Richard E. Taylor	SLAC linac – Deep inelastic scattering of electrons on protons and bound neutrons 1974
1992	Georges Charpak	CERN multiwire proportional chambers 1970
1995	Martin L. Perl	Stanford's SPEAR collider Tau lepton 1975
2004	David J. Gross, Frank Wilczek, and H. David Politzer	SLAC linac on electron-proton scattering – Asymptotic freedom in the theory of strong interactions 1973
2008	Makoto Kobayashi Toshihide Maskawa	KEKB accelerator at KEK and the PEP II at SLAC – Theory of quark mixing 1973

A.Chao and E. Haussecker "*Impact of Accelerator Science on Physics Research*", published in ICFA Newsletter, Dec 2010; & submitted to the Physics in Perspective Journal, Dec 2010.

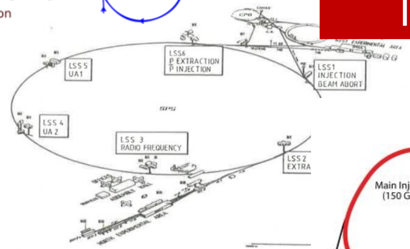
50 Years of Hadron Colliders (Since 1971)

1971 - 1981 → 1981 - 1991 → 1991 - 2001 → 2001 - 2011 → 2011 - 2023 → 2023 - 2031

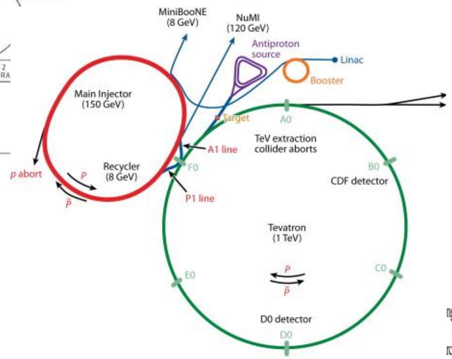
ISR (62 GeV p-p)



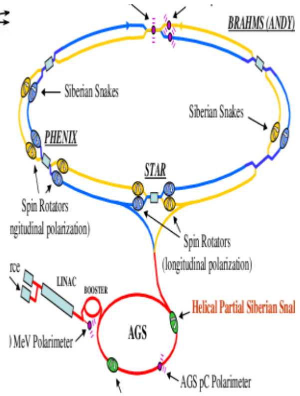
SppS (630 GeV proton-antiproton)



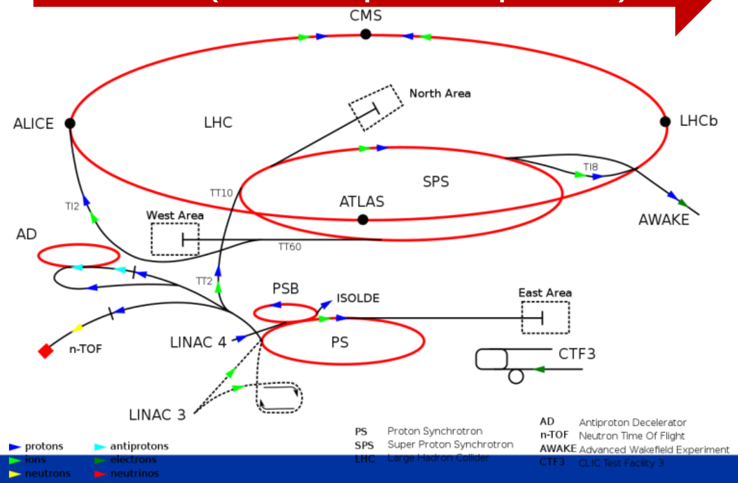
Tevatron (2 TeV proton-antiproton)



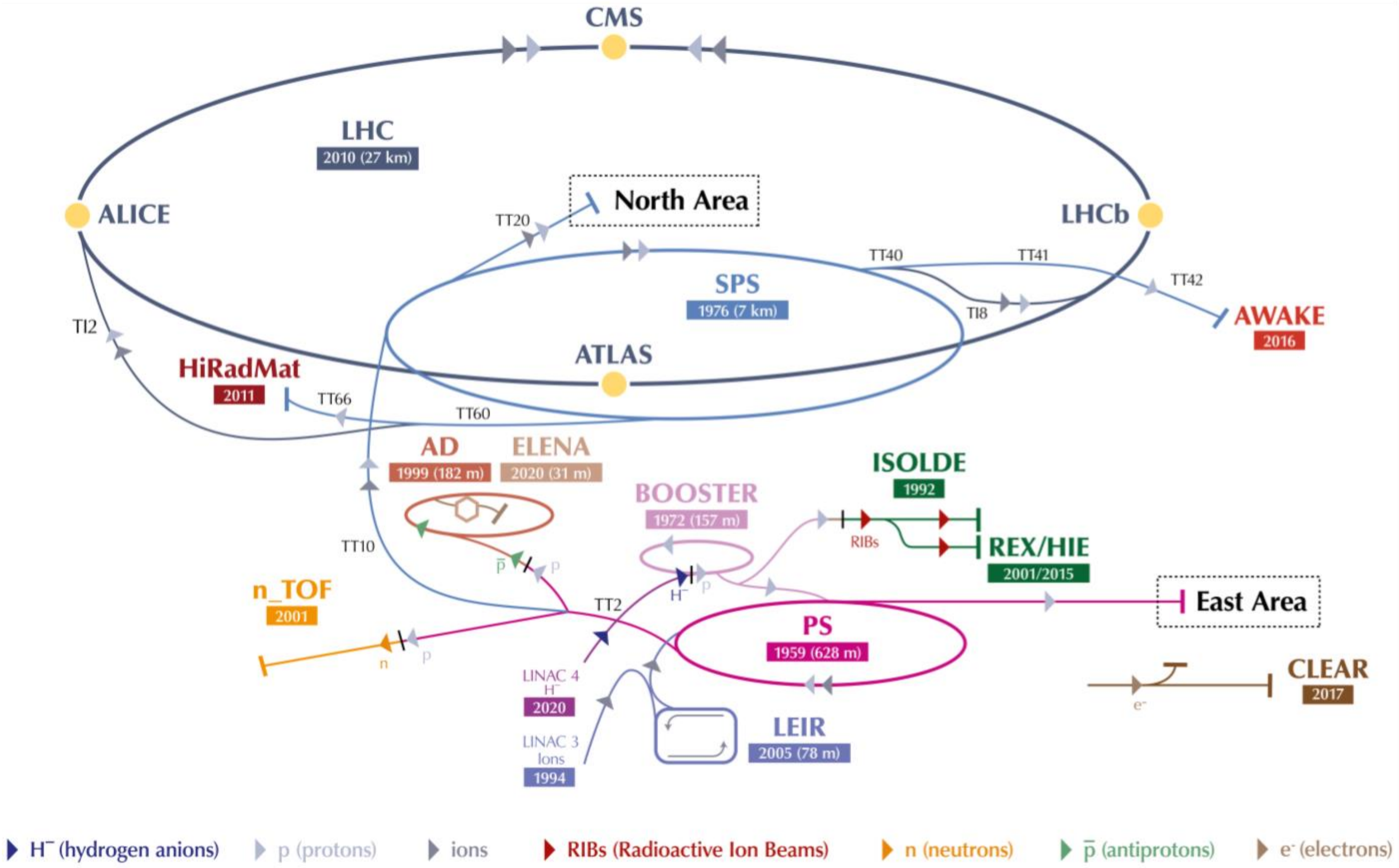
RHIC (ion-ion) → EIC (e-ion)



LHC (13 TeV proton-proton)



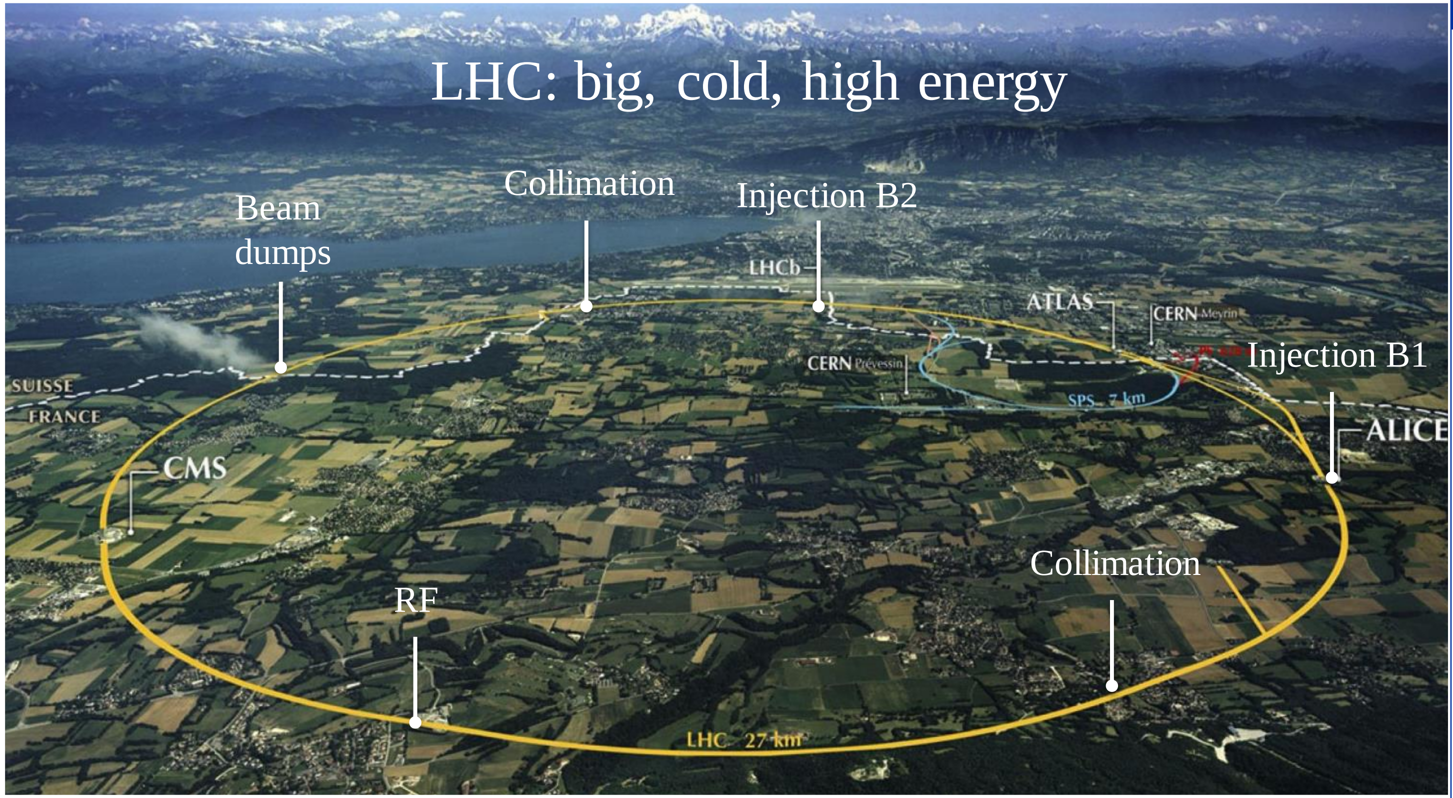
Together we are stronger



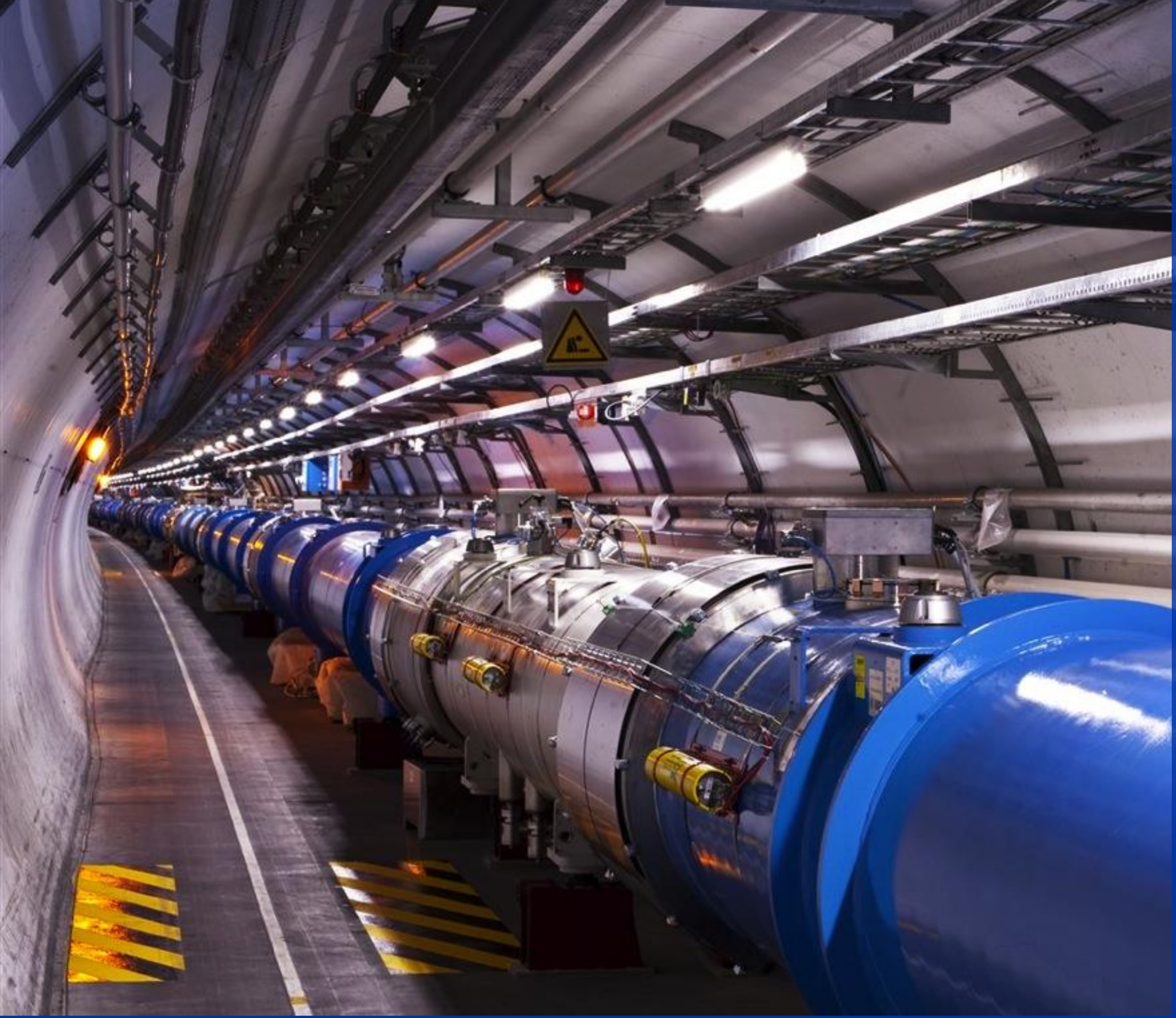
The Large Hadron Collider : the LHC

The largest machine and scientific instrument ever built by mankind

…. For the moment….



Quantity	Number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets Number of main dipoles Number of main quadrupoles	9593 1232 392
Nominal energy, protons Nominal energy, protons collisions	6.5 TeV (6.8 TeV) 13 TeV (13.6 TeV)
No. of protons	Some 10^{14}
Number of turns per second Number of collisions per second	11245 1 billion



LHC

- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality
- Main magnets use superconducting cables (Cu-clad Nb-Ti)
- 12’000 A provides a nominal field of 8.33 Tesla
- Operating in superfluid helium at 1.9K

LHC: Luminosity the Figure of Merit

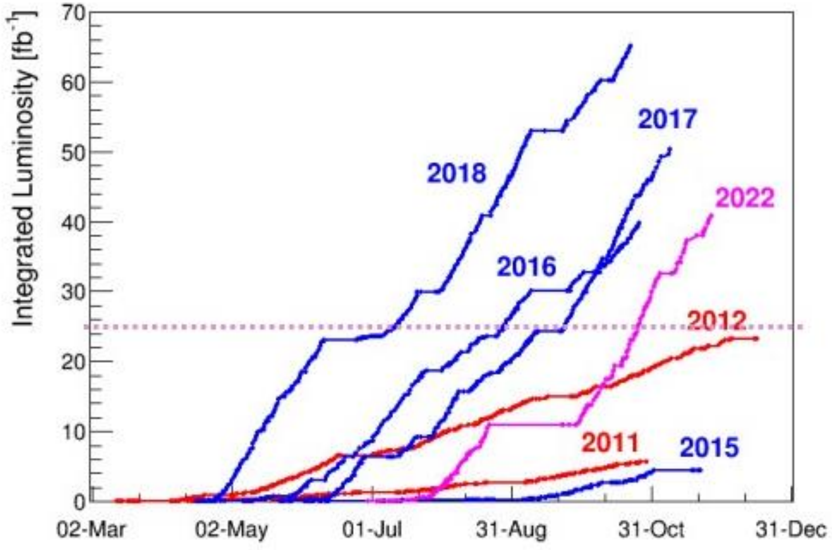
$$LUMINOSITY = \frac{N_{event/sec}}{\sigma_r} = \frac{N_1 N_2 f_{rev} n_b}{4\pi\sigma_x\sigma_y} F$$

Intensity per bunch

Number of bunches

Geometrical Correction factors

Beam dimensions



Maximise Luminosity:

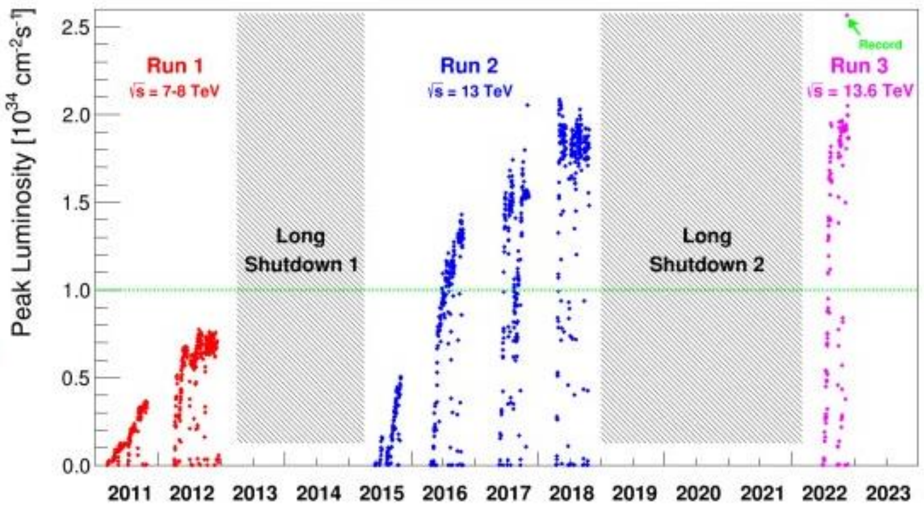
- Bunch intensity
- Transverse beam size
- Beam size at collision points (optics functions)
- Crossing angle
- Machine availability

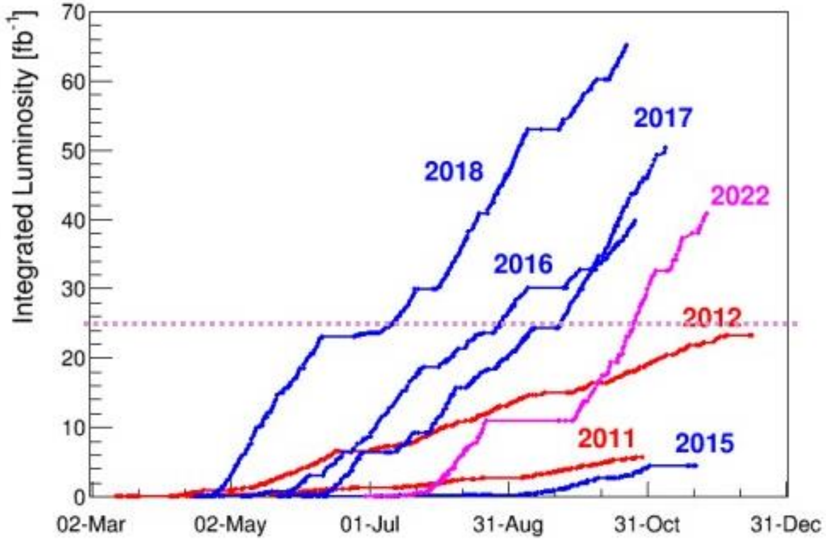
LHC performance

- First stable-beam collisions at 13.6 TeV on 5 July
- Very fast intensity ramp-up
  (high reproducibilty after a 3-year shutdown)

- Reached ~ $2x10^{34}$ cm^{-2} s^{-1} in physics operation (2 x design value), β*-leveled to ~ 50 pile-up evts/crossing in ATLAS and CMS.
  ~ 2.6 $x10^{34}$ cm^{-2} s^{-1} achieved during a cryo test.
  Main limitation: heat load (e^- cloud) in sector 7-8

- Integrated luminosity to ATLAS and CMS: ~ 40 fb^{-1} (target was 25 fb^{-1}).
  ~ 3 week stop in Sept due to RF problem and 2-weeks earlier start of YETS "compensated" by postponement of heavy-ion run

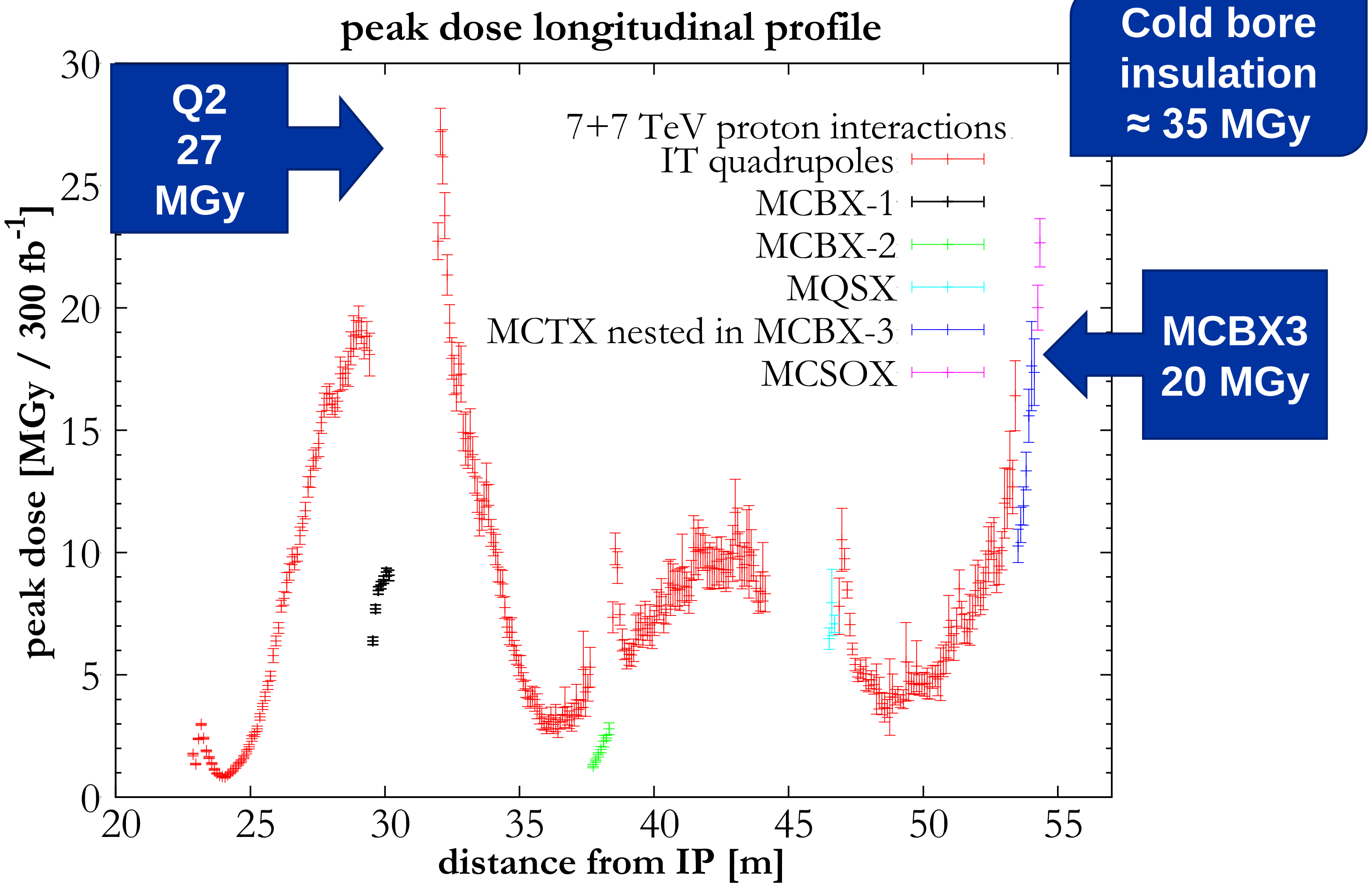




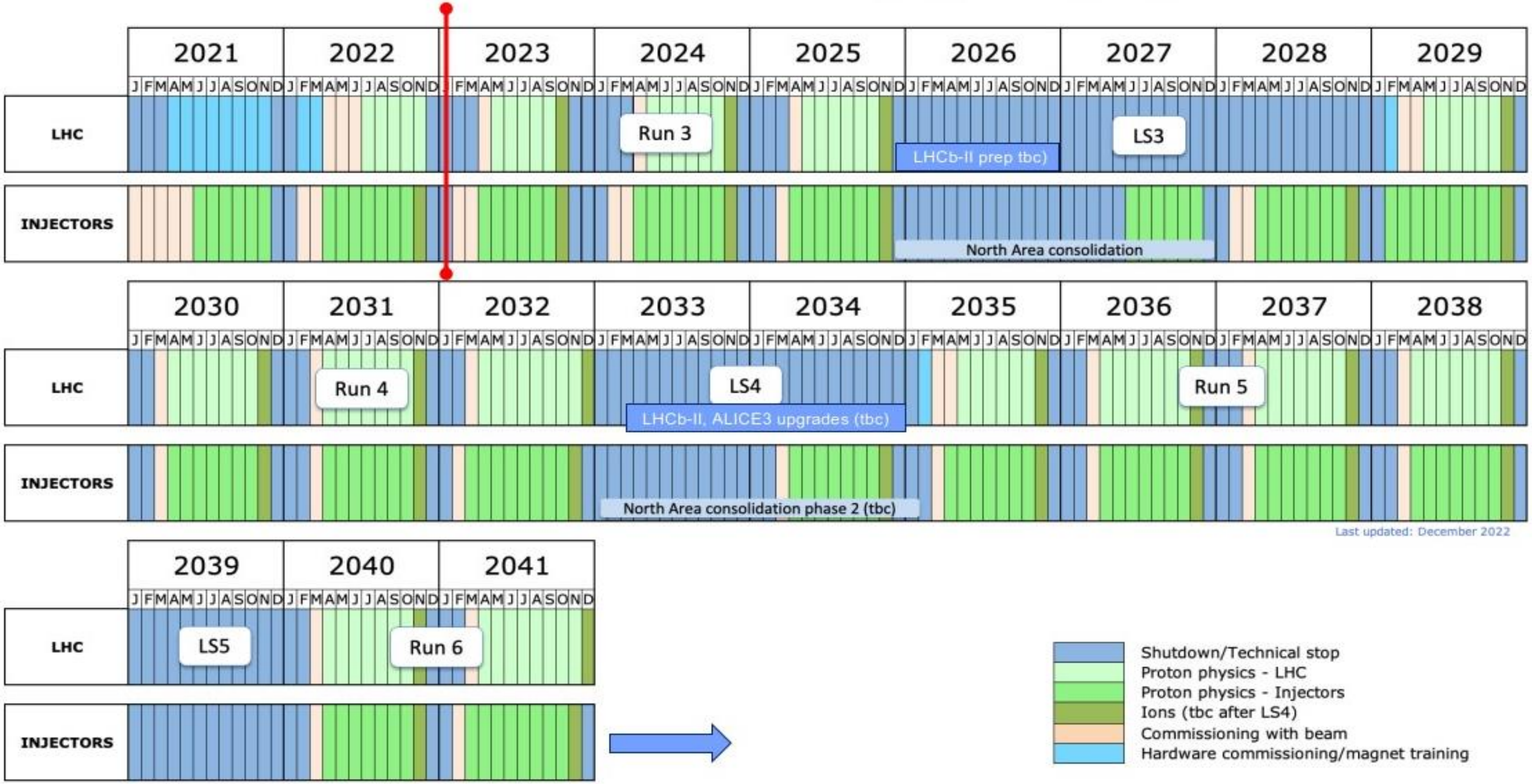
- Preliminary luminosity targets for 2023 (to be confirmed end of Jan):
  75 fb^{-1} ATLAS and CMS; 7 fb^{-1} LHCb; 3 nb^{-1} Pb-Pb ALICE
  Despite accelerator complex operation reduced by 20% in 2023 in response to European energy crisis.

- Luminosity targets for Run 3:
  250 fb^{-1} ATLAS and CMS, 25-30 fb^{-1} LHCb, 7 nb^{-1} Pb-Pb ALICE

HL-LHC technical bottleneck: Radiation damage to triplet magnets at 300 fb-1



LHC Physics programme



The future

How the strategy is decided

Drivers – The National or supranational strategies

U.S. Particle Physics

P5 (Particle Physics Projects Prioritization Panel)

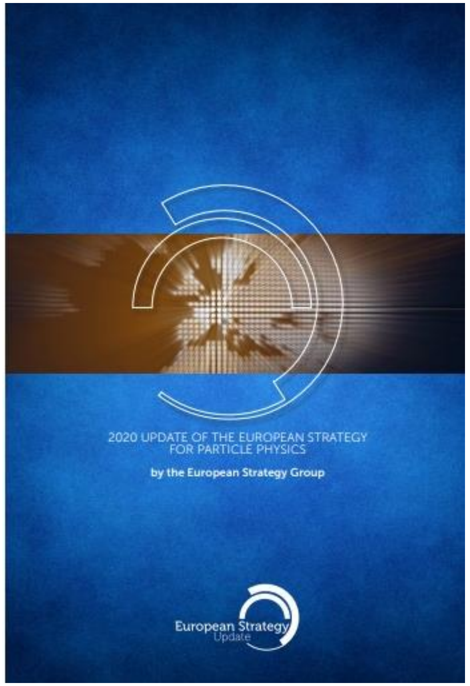
- **Reports to HEPAP (High-Energy Physics Advisory Panel) that advises High-Energy Physics of DOE Office of Science and Division of Physics of NSF.**
- **Hash out priorities for the next 10 years within a 20-year context.**

Starting this year
- **Town Halls (community)**
- **Closed Meetings (panel)**

European Strategy Update

Started in 2018 – report published in 2020

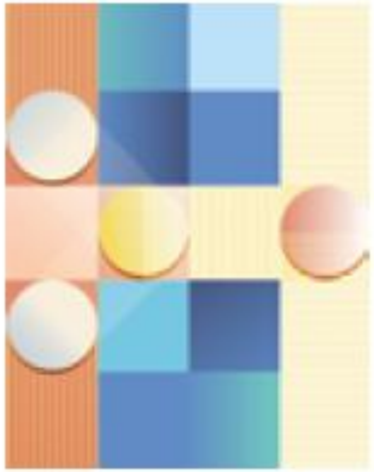
Equivalent consultation process



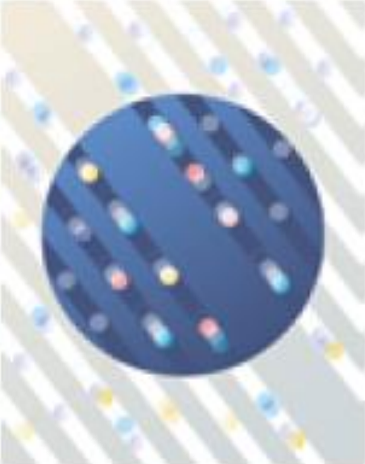
Drivers – P5 - USA

Five intertwined scientific Drivers were distilled from the results of a yearlong community-wide study:

- Use the Higgs boson as a new tool for discovery
- Pursue the physics associated with neutrino mass
- Identify the new physics of dark matter
- Understand cosmic acceleration: dark energy and inflation
- Explore the unknown: new particles, interactions, and physical principles

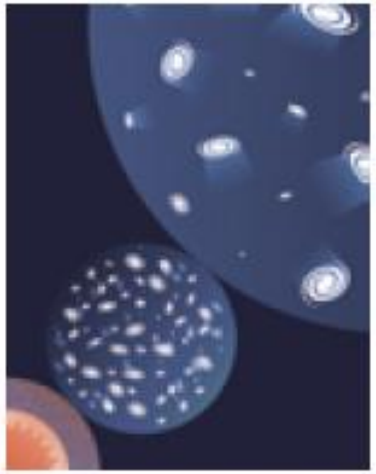


Higgs boson



Neutrino mass

Dark matter



Cosmic acceleration

Explore the unknown

Strategy USA (P5 – 2014)

High-priority future initiatives for EU

Three considerations:

- An electron-positron Higgs factory is the highest-priority next collider.

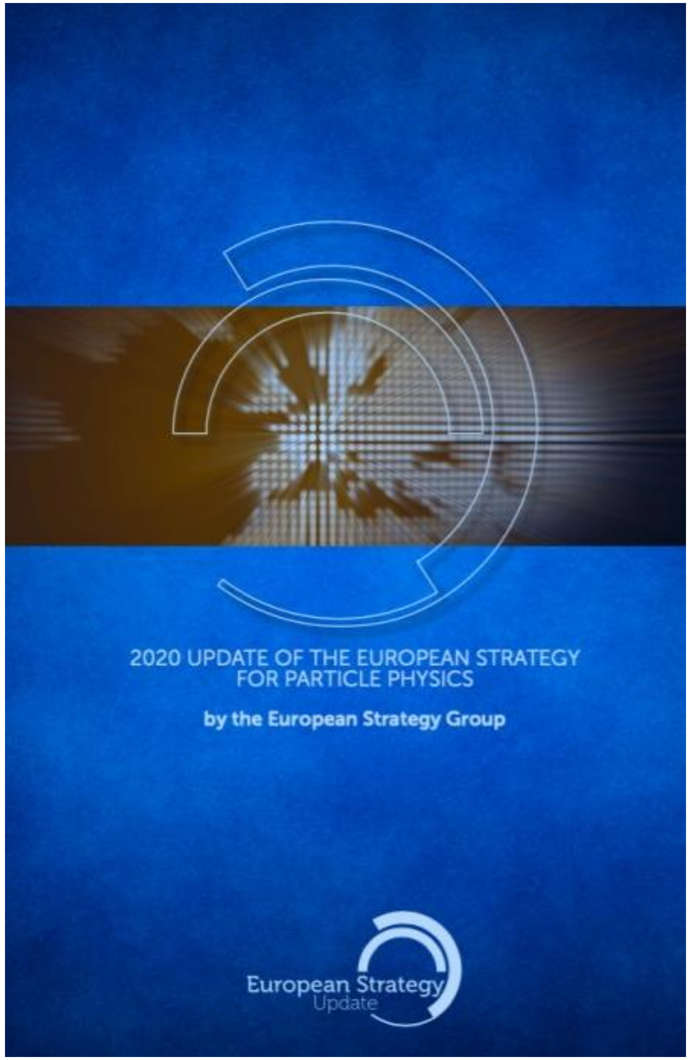
➔ Consensus on Higgs physics being the major the scientific driver for a new collider, technology ready for construction on a 15 years timescale

- For the longer term, the European particle physics community has the ambition to operate a proton- proton collider at the highest achievable energy.

➔ Exploring the energy frontier is the next logical step: preference given to the FCC project

- 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.

➔ Accelerator technologies need to be developed intensively to explore the potential of possible alternatives and continue to participate in accelerator technologies for other purposes and fields



High-priority future initiatives

Three recommendations:

- *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;*

➔ To realize a machine at the energy frontier, high filed magnets with at least 16T are mandatory and far from industrialisation, development of HTS magnets reaching higher fields should be pursued

- *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.*

➔ Feasibility study should be carried out before the next Strategy Update to allow for decision to be taken
  - technical feasibility, administrative implications and questions of implementation in the Geneva area including tunnelling and environmental impact)
  - financial feasibility for construction and operation, including additional resources from international partners and start establishing the global frame for the project.

- *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.*

High-priority future initiatives

Three recommendations (cont')d:

- *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.*

➔ Accelerator R&D should be carried out as a high priority and be a shared effort of CERN and the major national laboratories

➔ Establish an accelerator R&D roadmap on critical accelerator technologies established and coordinated among CERN and the National Laboratories:

plasma acceleration: compact facilities for applications, FELs and linear colliders

muon collider: international design study

ERL: R&D for high intensity, multi-turn energy recovery linacs

Reduction in **energy consumption**

Superconductive and normal conductive **high gradient accelerator structures** for LC and light sources

Other essential scientific activities

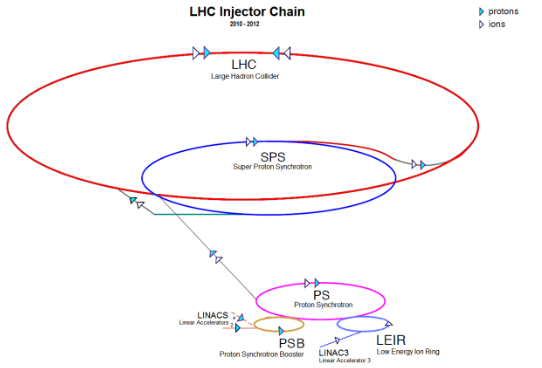
B/ *Europe should continue to vigorously support a broad programme of* ***theoretical research*** *covering the full spectrum of particle physics from abstract to phenomenological topics. The pursuit of new research directions should be encouraged and links with fields such as cosmology, astroparticle physics, and nuclear physics fostered. Both exploratory research and theoretical research with direct impact on experiments should be supported, including recognition for the activity of providing and developing computational tools.*

C/ ***Detector R&D programmes and associated infrastructures*** *should be supported at CERN, national institutes, laboratories and universities. Synergies between the needs of different scientific fields and industry should be identified and exploited to boost efficiency in the development process and increase opportunities for more technology transfer benefiting society at large. Collaborative platforms and consortia must be adequately supported to provide coherence in these R&D activities. The community should* ***define a global detector R&D roadmap*** *that should be used to support proposals at the European and national levels.*

D/ *The community must vigorously pursue common, coordinated R&D efforts in collaboration with other fields of science and industry to* ***develop software and computing infrastructures*** *that exploit recent advances in information technology and data science. Further development of internal policies on open data and data preservation should be encouraged, and an adequate level of resources invested in their implementation.*

Full exploitation of the LHC: LIU LHC Injector Upgrades

DONE!!!



LINAC4 – PS Booster:

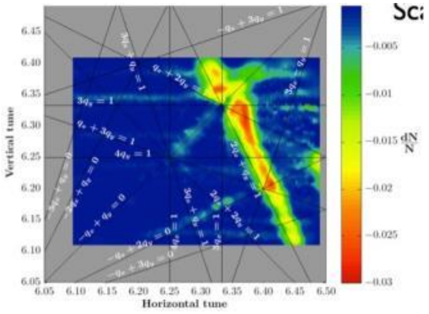
- H^- injection and increase of PSB injection energy from 50 MeV to 160 MeV, to increase PSB space charge threshold
- New RF cavity system, new main power converters
- Increase of extraction energy from 1.4 GeV to 2 GeV

PS:

- Increase of injection energy from 1.4 GeV to 2 GeV to increase PS space charge threshold
- Transverse resonance compensation
- New RF Longitudinal feedback system
- New RF beam manipulation scheme to increase beam brightness

SPS

- Electron Cloud mitigation – strong feedback system, or coating of the vacuum system
- Impedance reduction, improved feedbacks
- Large-scale modification to the main RF system

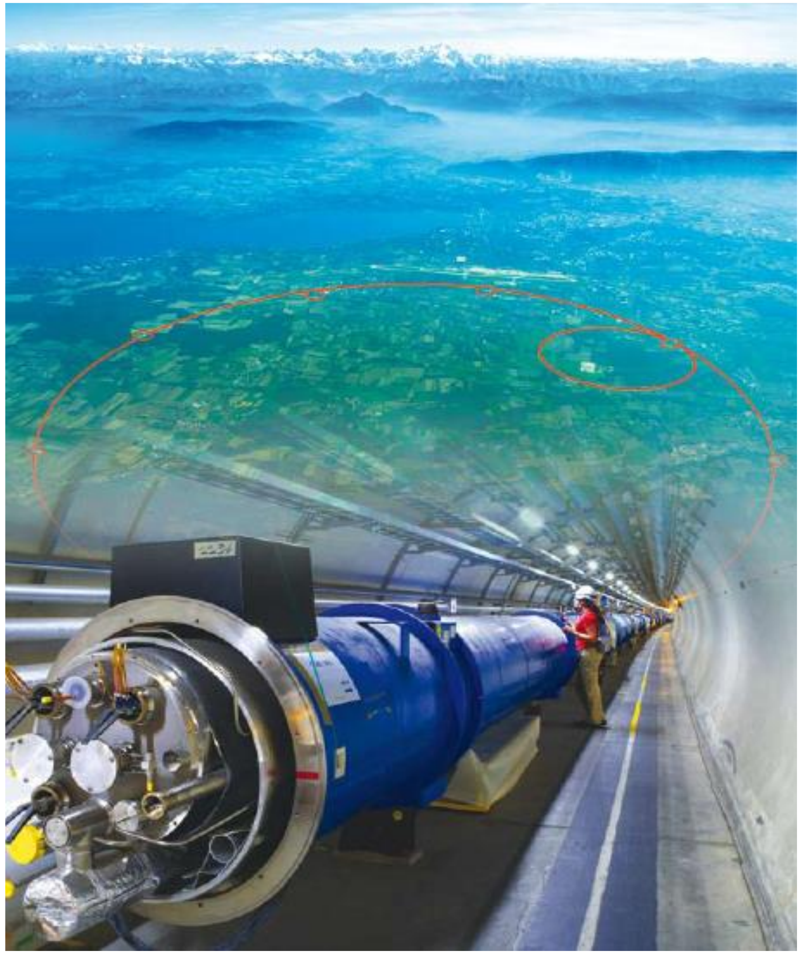


The future

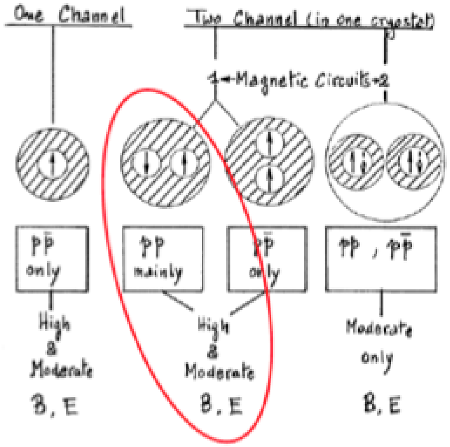
A not so simple long way

From concept to the full exploitation of the LHC

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 CE
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 and repair
2009-2041	Physics exploitation



ECFA-CERN workshop



June 1994
first full scale prototype dipole

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

June 2007 First sector cold

April 2008
Last dipole down

9T- 1m single bore

25 years

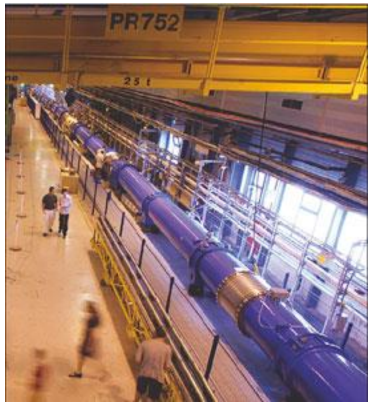
Main contracts signed

83 | 84 | // | 90 | 91 | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 00 | 01 | 02 | 03 | 04 | 05 | 06 | 07 | 08 | 09 | 10

Decision for Nb-Ti

9T -10 m prototype

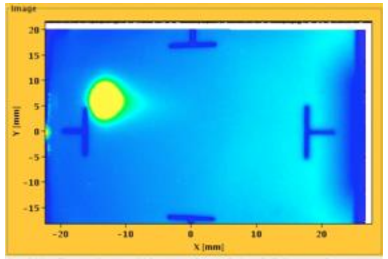
2002 String 2



November 2006
1232 delivered

September 10, 2008
First beams around

August 2008
First injection test



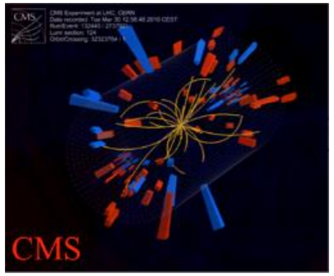
Sept. 10, 2008
First beams around

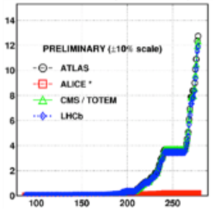
Sept. 19, 2008
Incident

Repair and Consolidation

November 29, 2009
Beam back

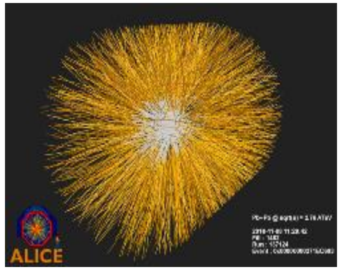
March 30, 2010
First collisions at 3.5 TeV





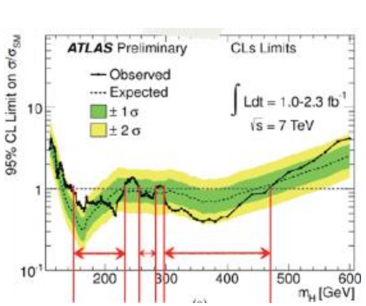
October 14, 2010
L= $1x10^{+32}$
248 bunches

November 2010
Pb^{82+} Ions



June 28 2011
1380 bunches

1380

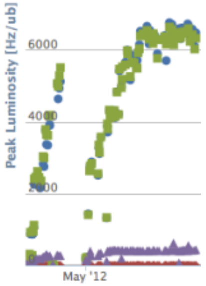


October, 2011
$3.5x10^{+33}$, 5.7 fb^{-1}

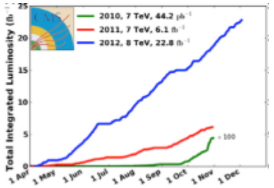
First Hints!!

November 2011
Second Ion Run

March 14th 2012
Restart
with Beam

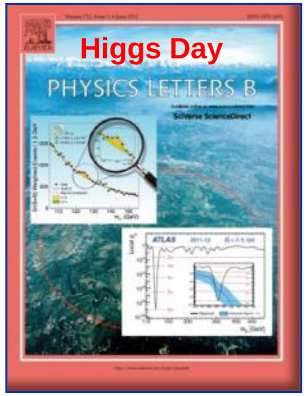


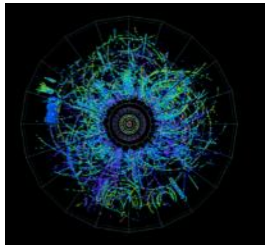
May 2012
Ramping
Performance



Nov. 2012
End of p^{+} Run 1

Higgs Day





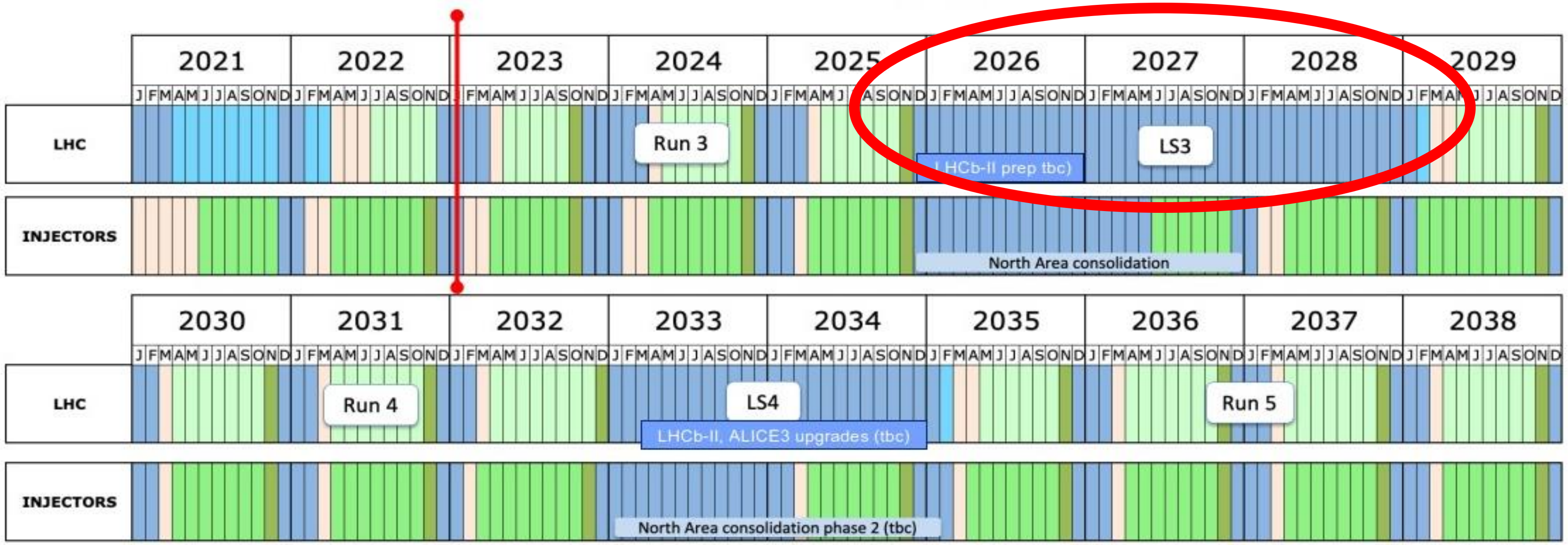
Feb. 2013
$p\text{-}Pb^{82+}$
New Operation
Mode

LS1

2008 | 2009 | 2010 | 2011 | 2012 | 2013


2015
2016
2017
2018
2019
2020
2021
Q1 Q2 Q3 Q4
LHC
Injectors
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
2032
2033
2034
2035
Run 2


2019
2020
2021
2022
2023
2025
2026
2027
J F M A M J J A S O N D
Long Shutdown 2 (LS2)
Run 3
Long Shutdown 3 (LS3)
2028
2029
2030
2031
2032
2033
2034
2035
2036
Run 4
LS4
Run 5
LS5
Shutdown/Technical stop
Protons physics
Ions
Commissioning with beam
Hardware commissioning/magnet training


2021
2022
2023
2024
2025
2026
2027
2028
2029
J F M A M J J A S O N D
LHC
Run 3
LHCb-II prep tbc)
LS3
INJECTORS
North Area consolidation
2030
2031
2032
2033
2034
2035
2036
2037
2038
Run 4
LS4
LHCb-II, ALICE3 upgrades (tbc)
Run 5
North Area consolidation phase 2 (tbc)

An Endeavour … and investment … the industry

Search this site | Search

HL-LHC Industry

Industry Relations and Procurement Website for the HL-LHC project

HiLumi HL-LHC PROJECT

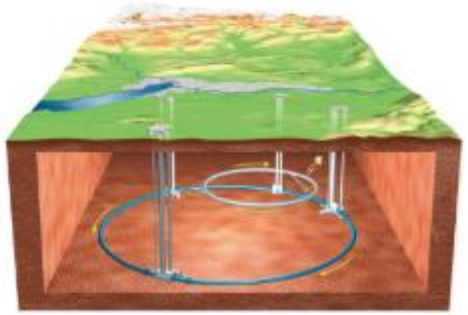
Home | General Info | Procurement Overview | Tendering | Acquisition Timeline | Events | Contact

Building the HL-LHC with the Industry

The HL-LHC Industry Website has been specially designed for all those firms that wish to participate in this ambitious project. We want to share all the relevant information related to the procurement that will be required to accomplish this major upgrade of the LHC.

The industry will have a crucial role and will be heavily involved within the HL-LHC Project since it will be the main source to provide the technologies and equipment that are required to successfully achieve the goals of this upgrade of the LHC.

The HL-LHC will collaborate with many types of industries and businesses to pursue its goals. Knowledge and technology to be developed during the HL-LHC project will make a lasting impact on society.



ILOS

ILOs Portal

HIGHLIGHTS

12 June 2017

BIG SCIENCE BUSINESS FORUM

Big Science Business Forum 2018

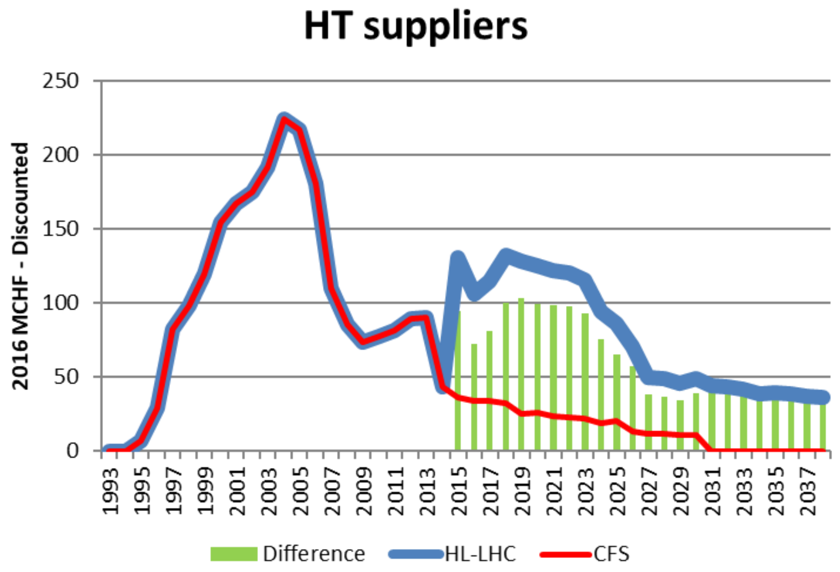
Big Science Business Forum 2018 will be the first one-stop-shop for European companies and other stakeholders to learn about Europe's Big Science organisations' future investments and procurements. CERN event will at thie major event that will be held at Copenhagen on 27 and 28 February 2018.

Read more

With a clear return to society

Anstudy from the university of Milan has evaluated that each Swiss Franc invested in the HL-LHC upgrade project pays back approximately 1.7 CHF in societal benefits.

- Technological or industrial spill overs
- Training (or human capital formation)
- Cultural effects for the public
- Academic publications and pre-prints for scientists



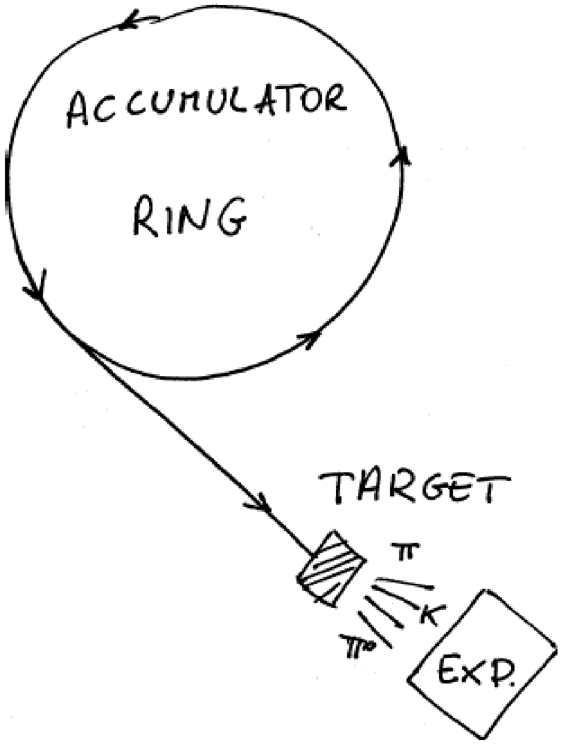
The future

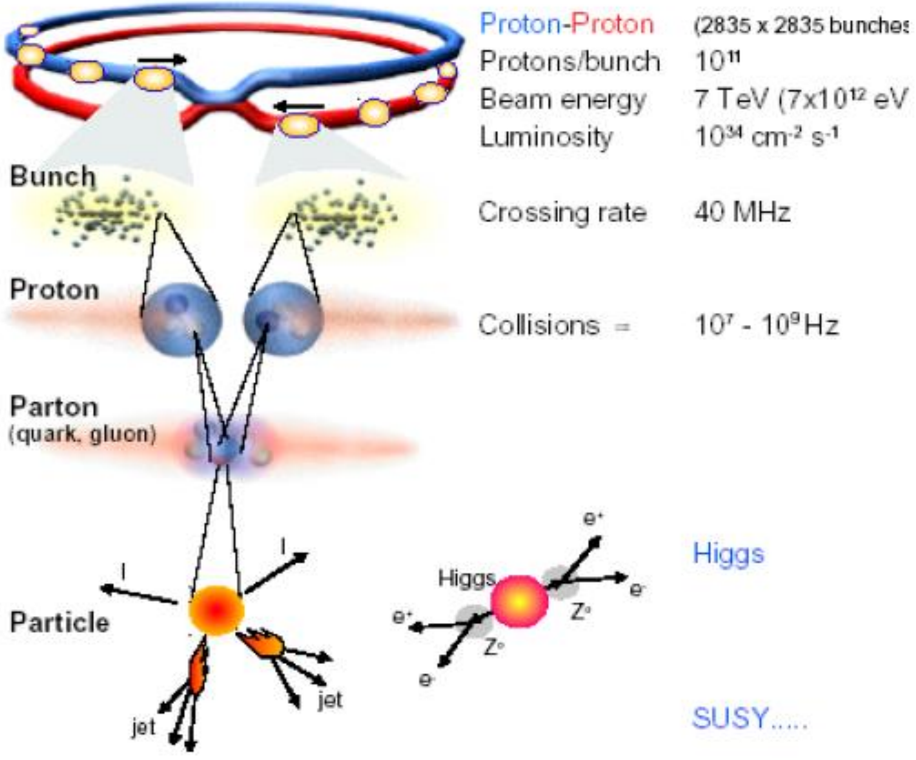
Which type of accelerator?

Coming back to the basic decision principles

Fixed

Collider





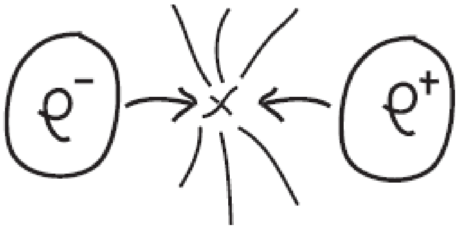
Much of the energy is lost in the target and only part is used to produce secondary particles

All energy will be available for particle production

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

And the right particle

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



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

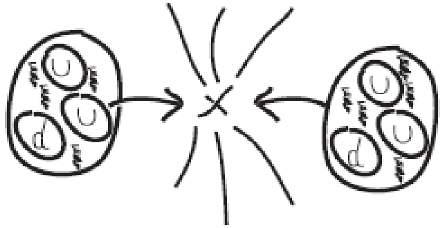
Ecoll= Eb1+ Eb2= 2Eb = 200 GeV (LEP)

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

Precision measurement (LEP)

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

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



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

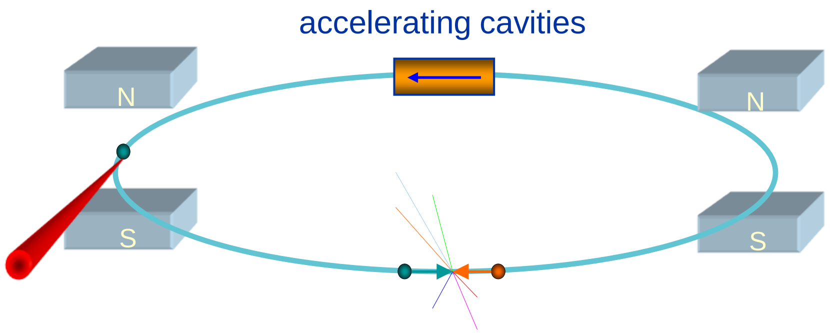
Ecoll < 2Eb

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

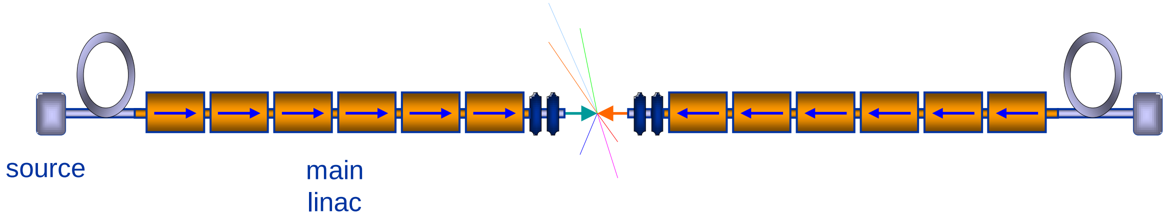
Discovery machine (LHC)

Cons: the energy available for the collision is lower than the accelerator energy

Circular versus Linear Collider



Circular Collider



Linear Collider

Many magnets, few cavities, stored beam

Higher energy → Stronger magnetic field

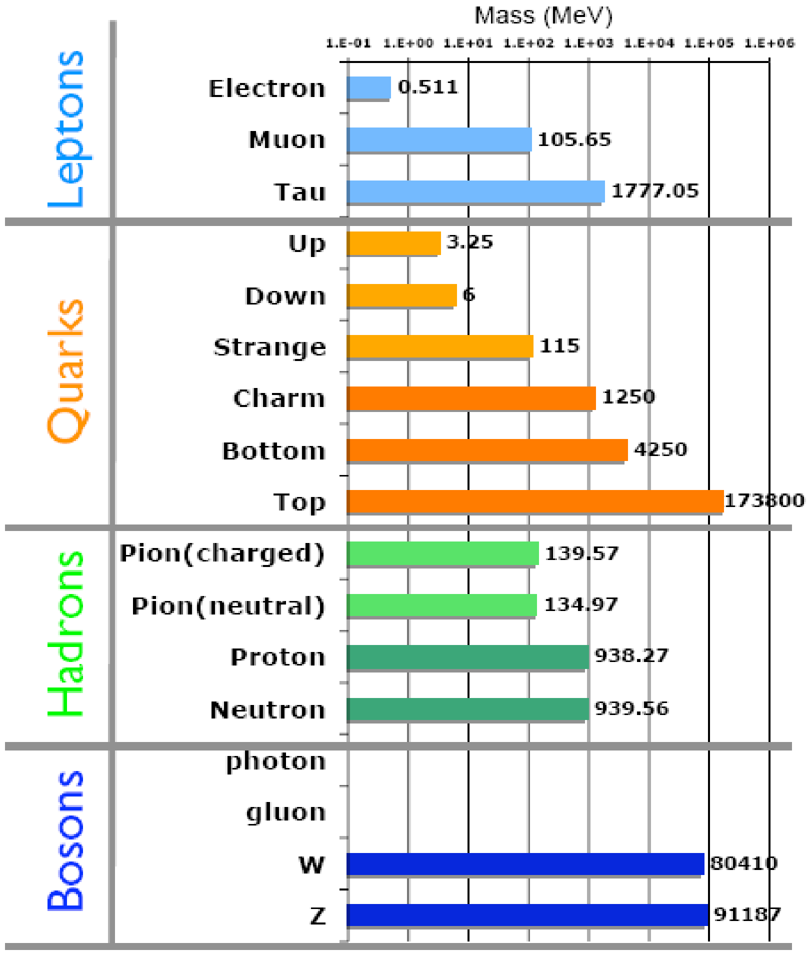
Higher synchrotron radiation losses (E^4/m^4R)

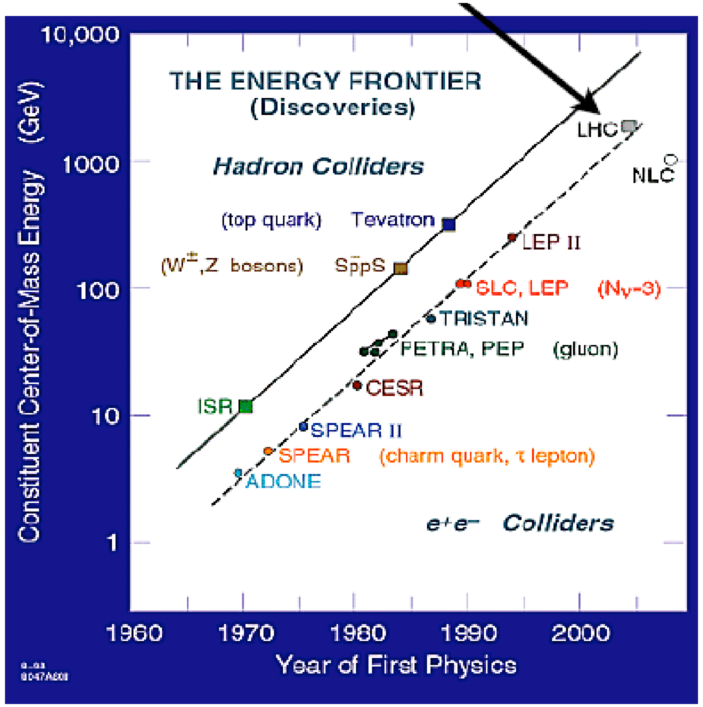
Few magnets, many cavities, single pass beam

Higher energy → Higher accelerating gradient

Higher luminosity → Higher beam power (high bunch repetition)

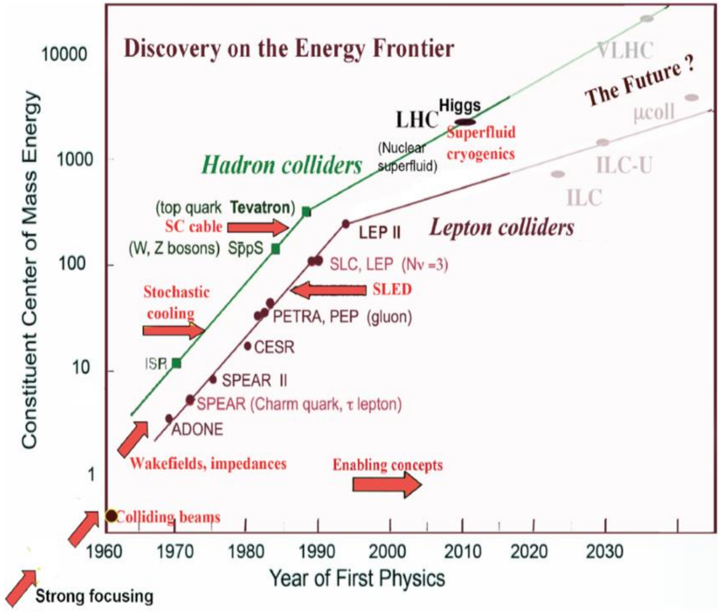
Finally, you have also to think the energy you are exploring

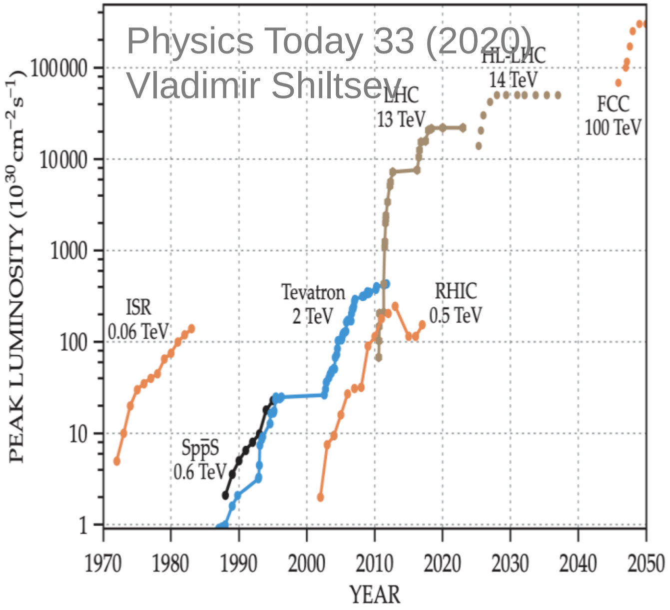


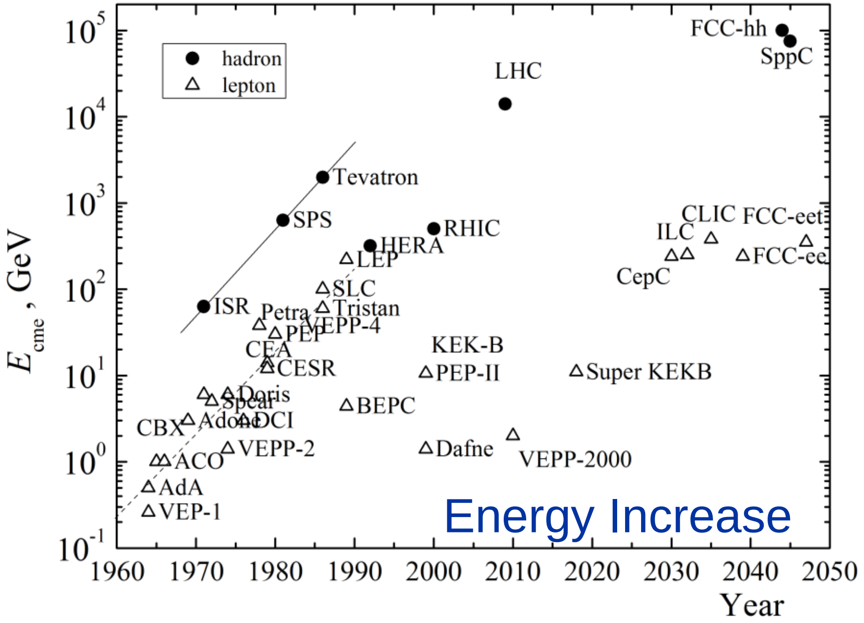


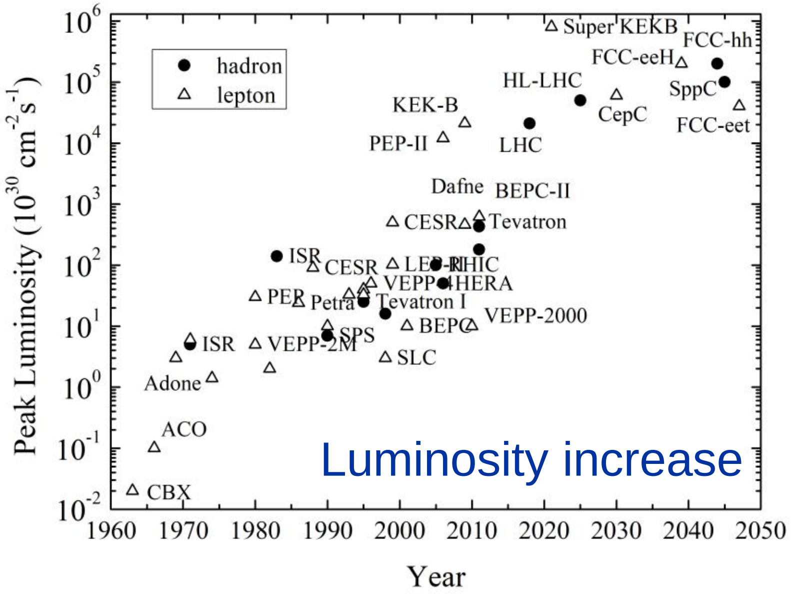
Behind the history plot is hidden the technological development required for each step

We built on previous experience







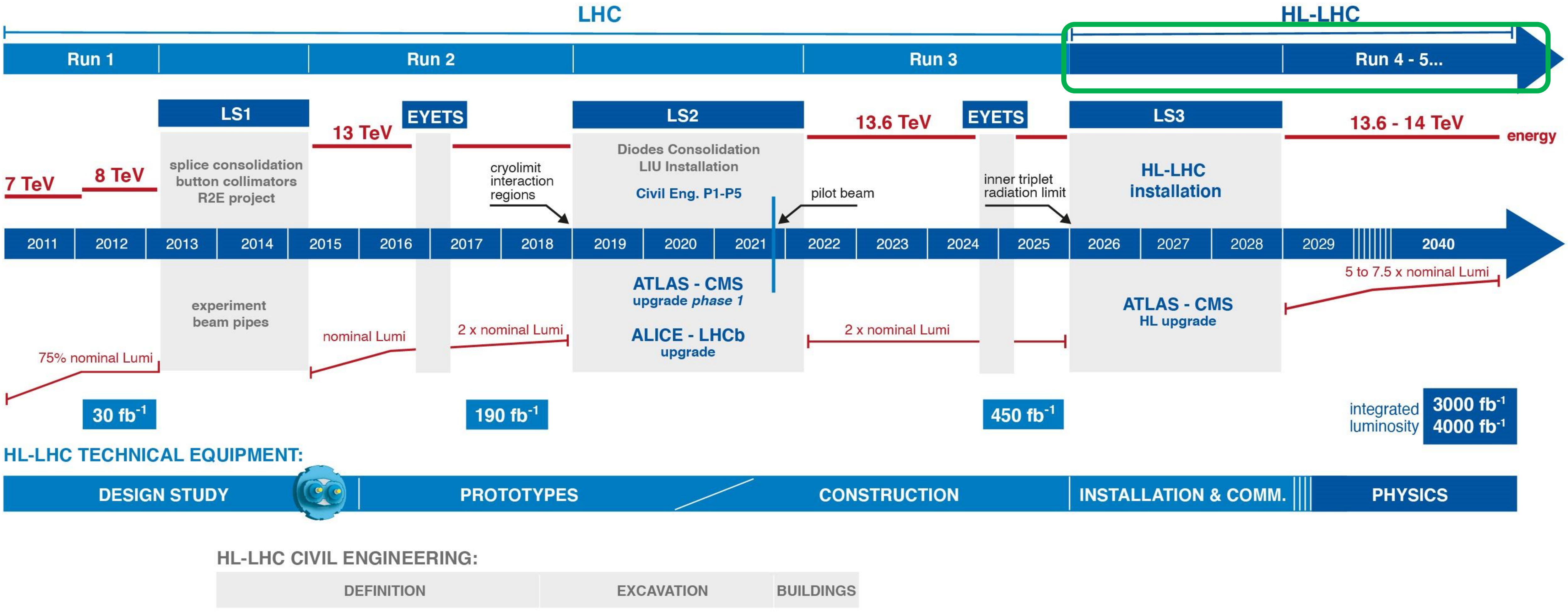


Each generation of accelerators has built on previous generations’ experience and discoveries

The future

HL-LHC

LHC / HL-LHC Plan



Global collaboration

BNL
Brookhaven National Laboratory

CEA
Commissariat à l'Énergie Atomique

CIEMAT
Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

CERN
Conseil Européen pour la Recherche Nucléaire

CI
Cockcroft Institute

SOTON
University of Southampton

UHUD

UNIUPP
Uppsala University

IHEP

USDOE
United States Department of Energy

STFC
Science & Technology Facilities Council

FNAL
Fermilab

INFN
Istituto Nazionale Fisica Nucleare

KEK
KEK Japan

ULAN
University of Lancaster

LBNL
Lawrence Berkeley National Laboratory

UNILIV
University of Liverpool

NCBJ

UNIMAN
University of Manchester

ODU

RHUL
Royal Holloway University

SLAC
National Accelerator Laboratory

Jefferson Lab

Joint Institute for Nuclear Research

Lapland University of Applied Sciences

National Centre for Nuclear Research

Old Dominion University

TRIUMF

JLAB
Jefferson Lab

JINR
Joint Institute for Nuclear Research

LAPIN AMK
Lapland University of Applied Sciences

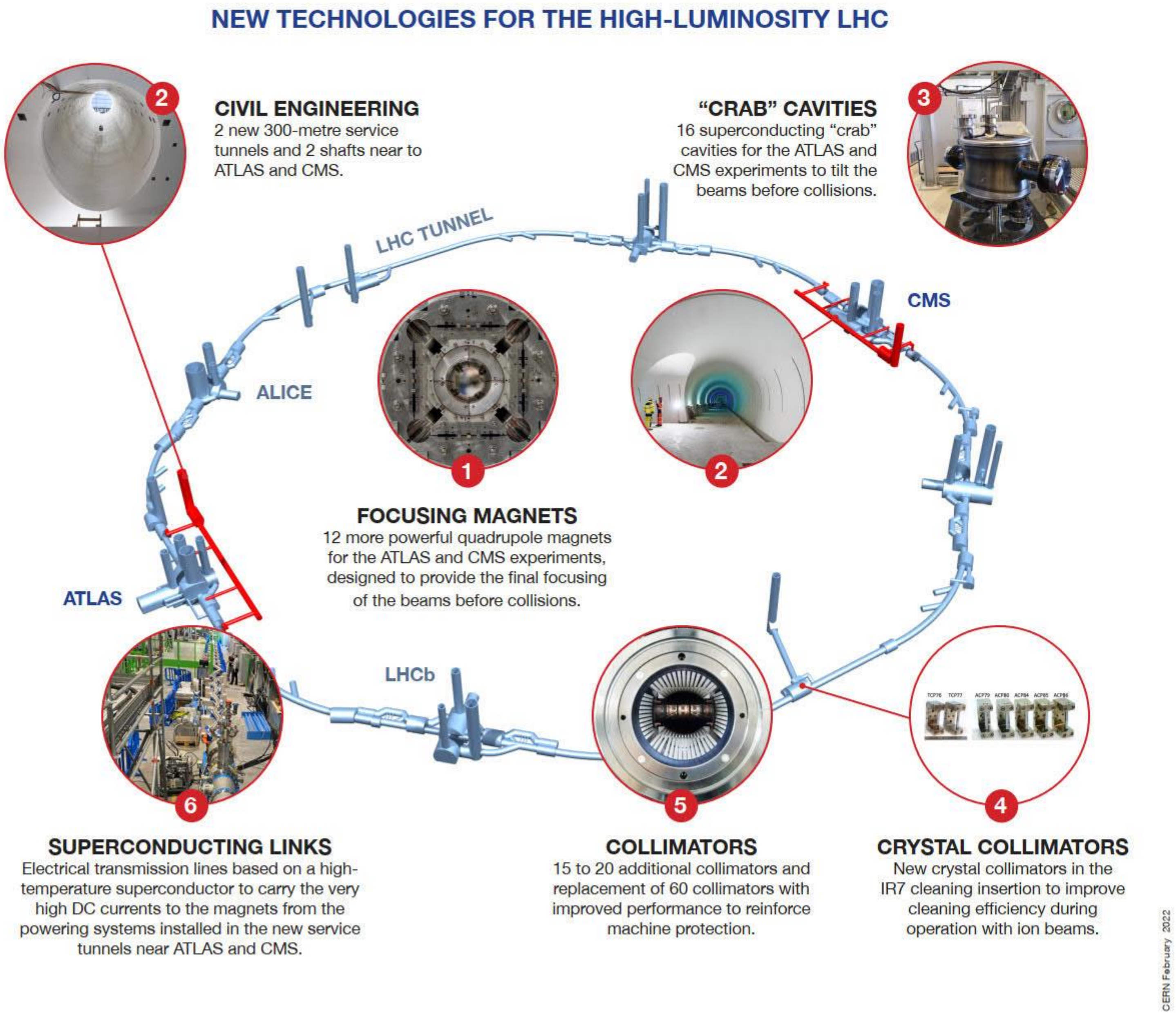
NCBJ
National Centre for Nuclear Research

ODU
Old Dominion University

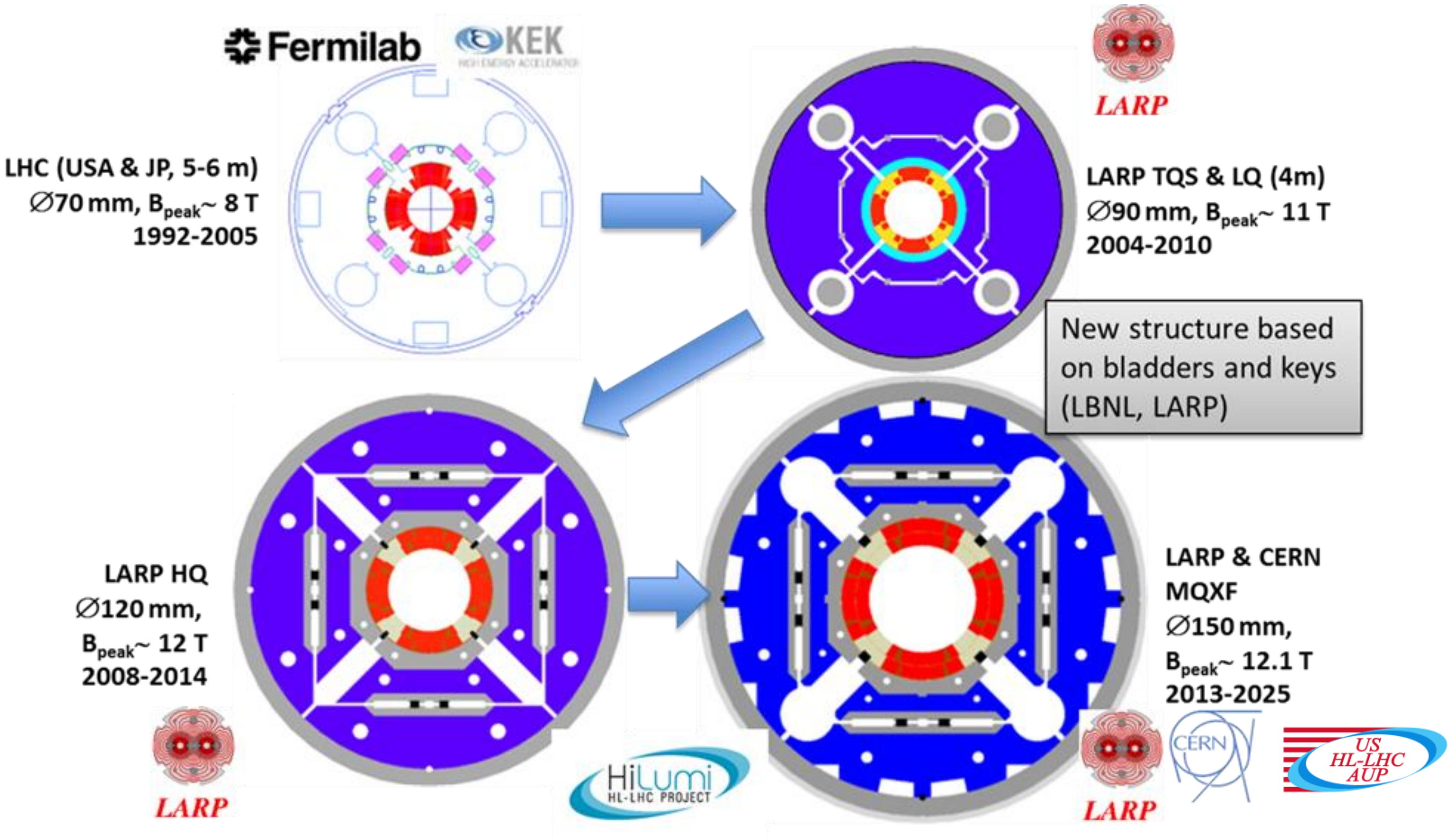
TRIUMF

No accelerator project has so many challenging novelties covering such a broad technology spectrum

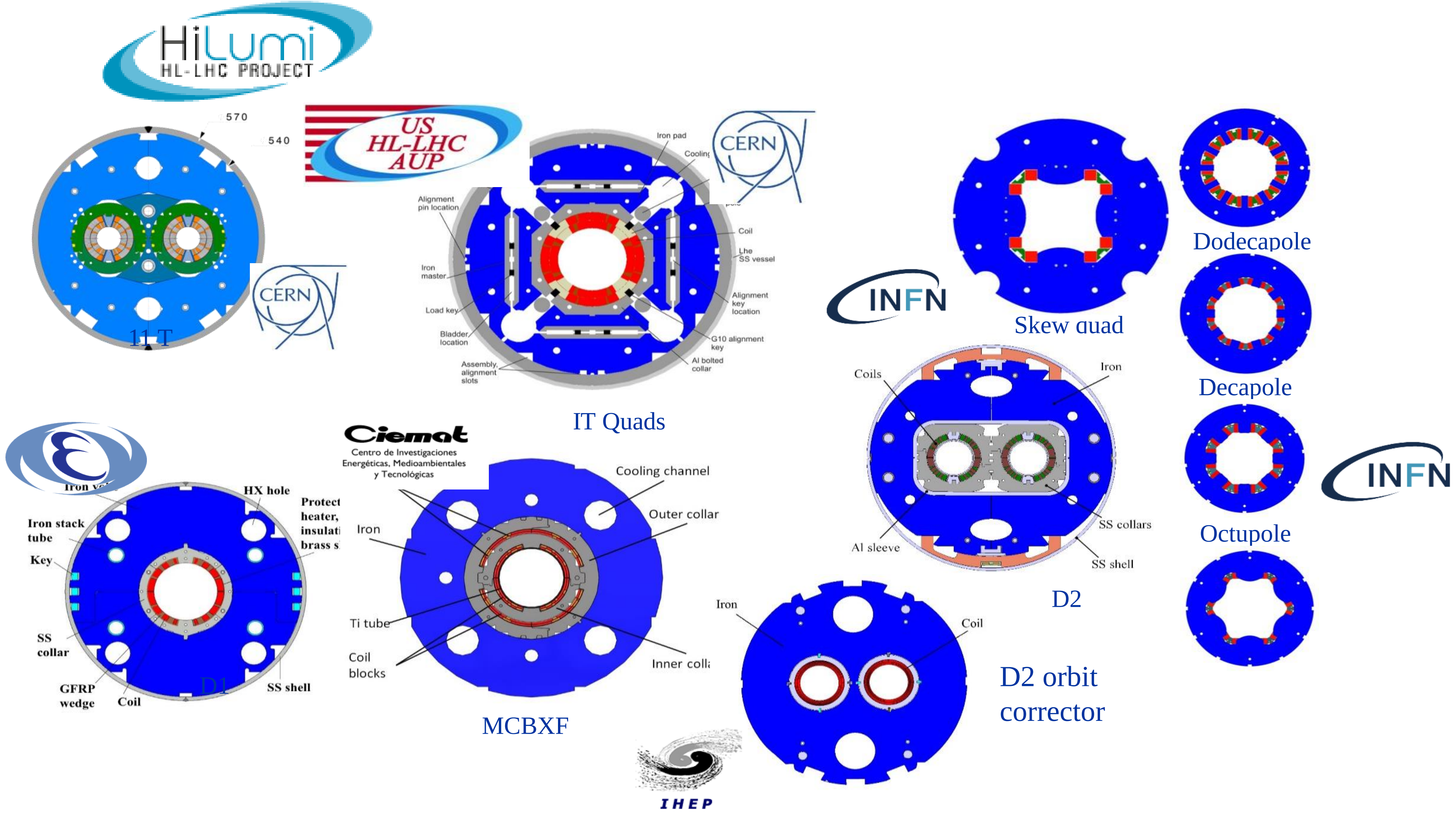
Technology intensive project!



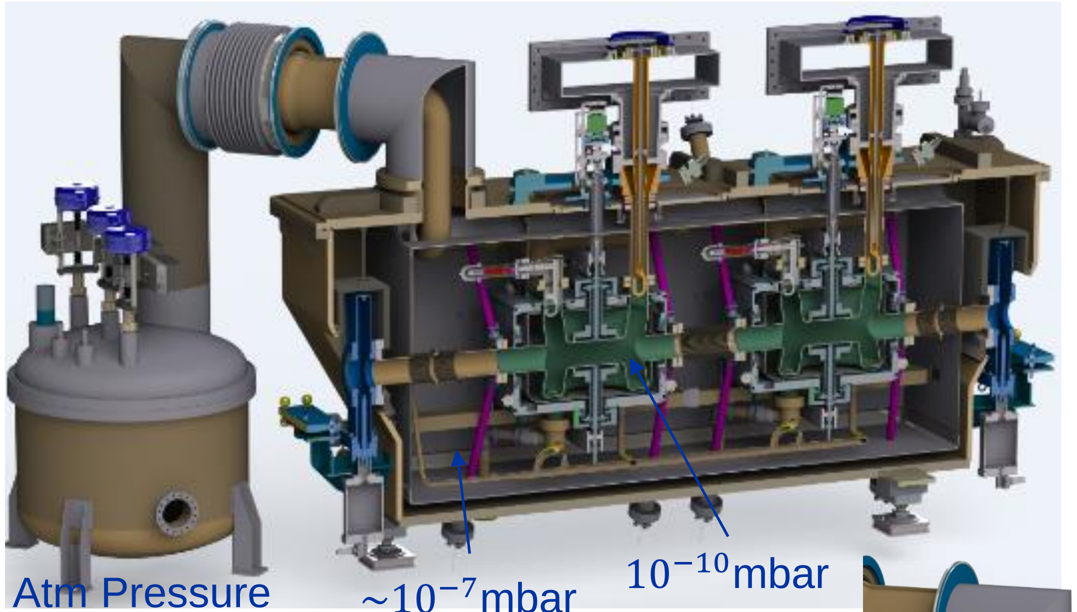
IT quadrupole. Increase in field but also in size wrt LHC. Very relevant also for FCC magnets



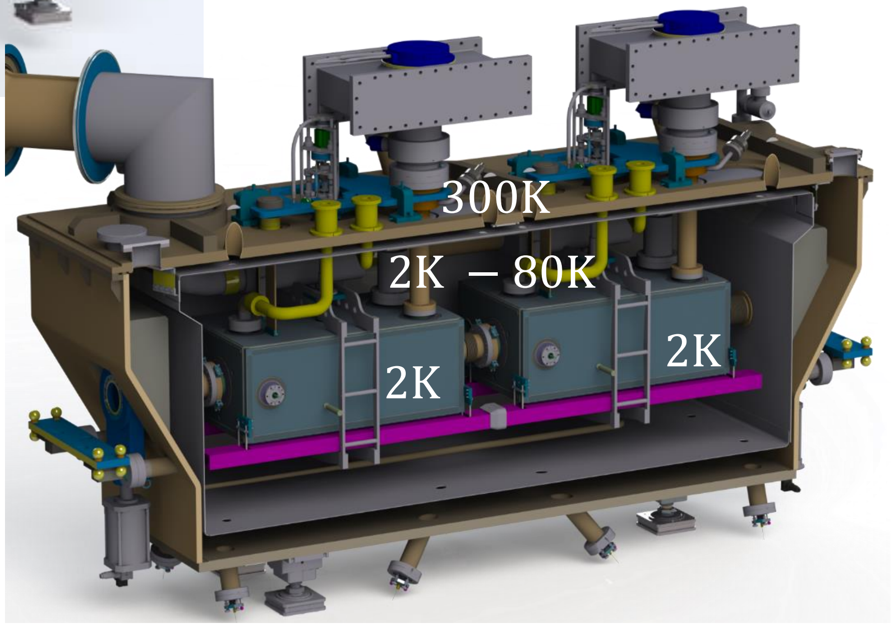
New generation of Magnets (~130)



Crab cavities

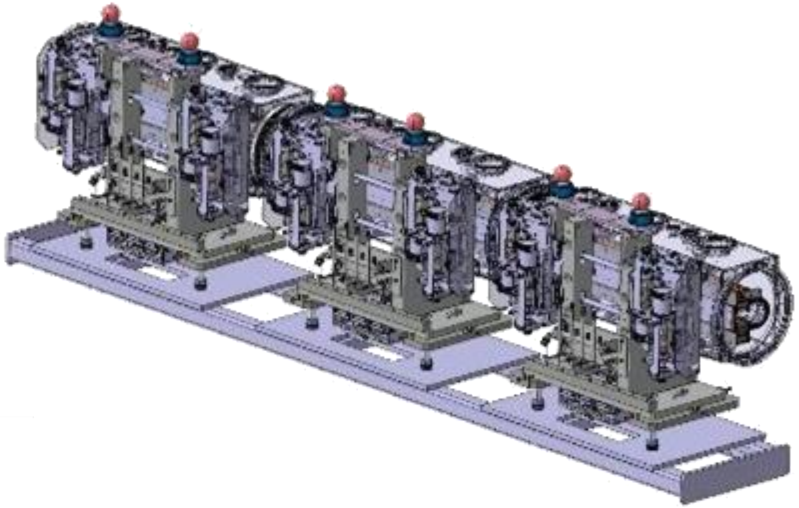


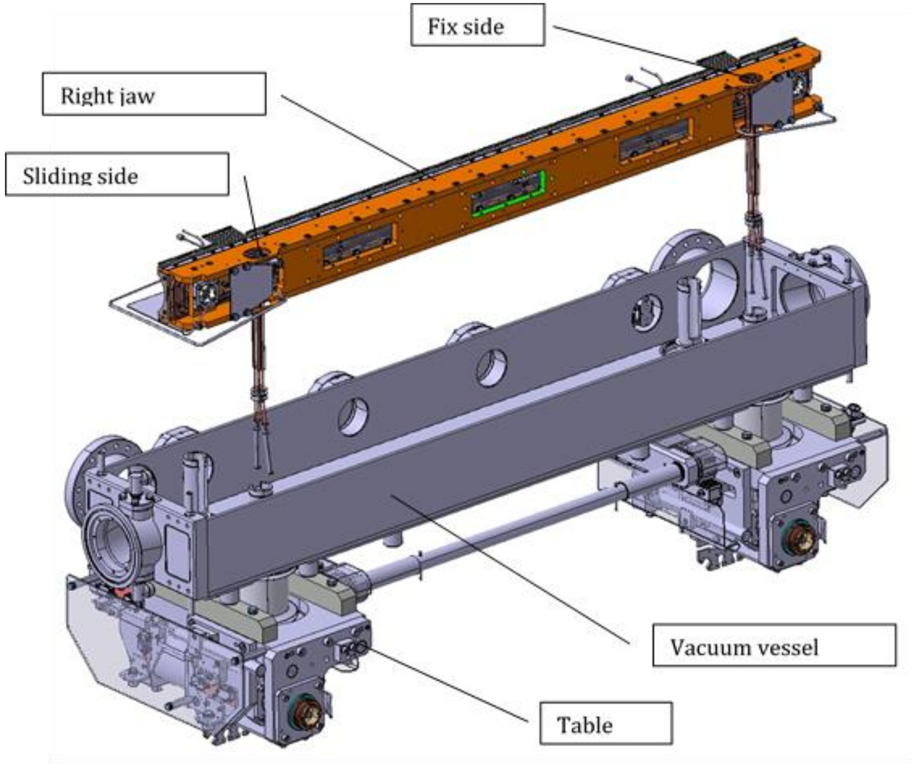
Crab cavities (DQW)
Vertical crossing for
ATLAS experiments

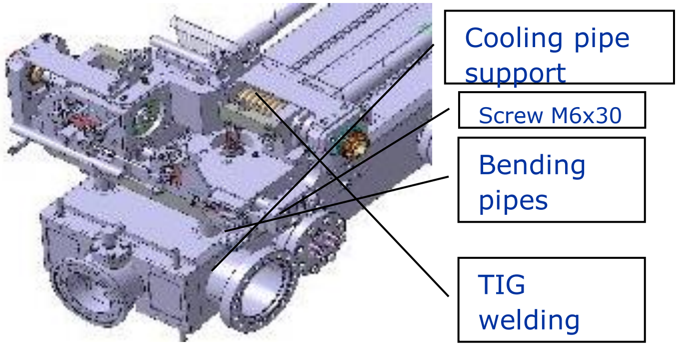


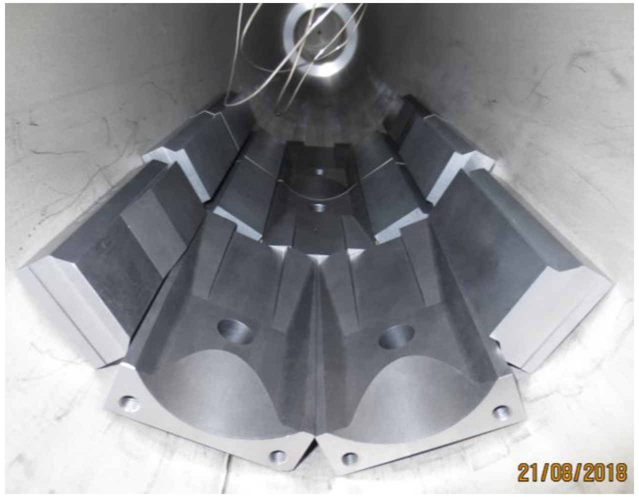
Crab cavities (RFD)
Horizontal crossing for
CMS experiment

Collimators



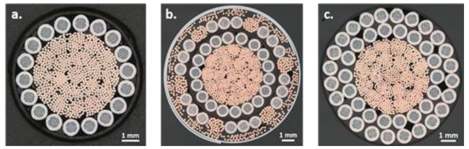


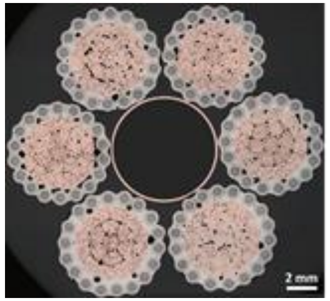




SC Links

20 kA **MgB_2 cable**





Ansaldo Superconduttori

No current degradation; thermal contraction and thermal loss management sucessful!

Power converters

- **PC Very high current:**

- [HL-LHC18kA-10V] ~ 6 units
- [HL-LHC14kA-08V] ~ 10 units

- **PC High current:**

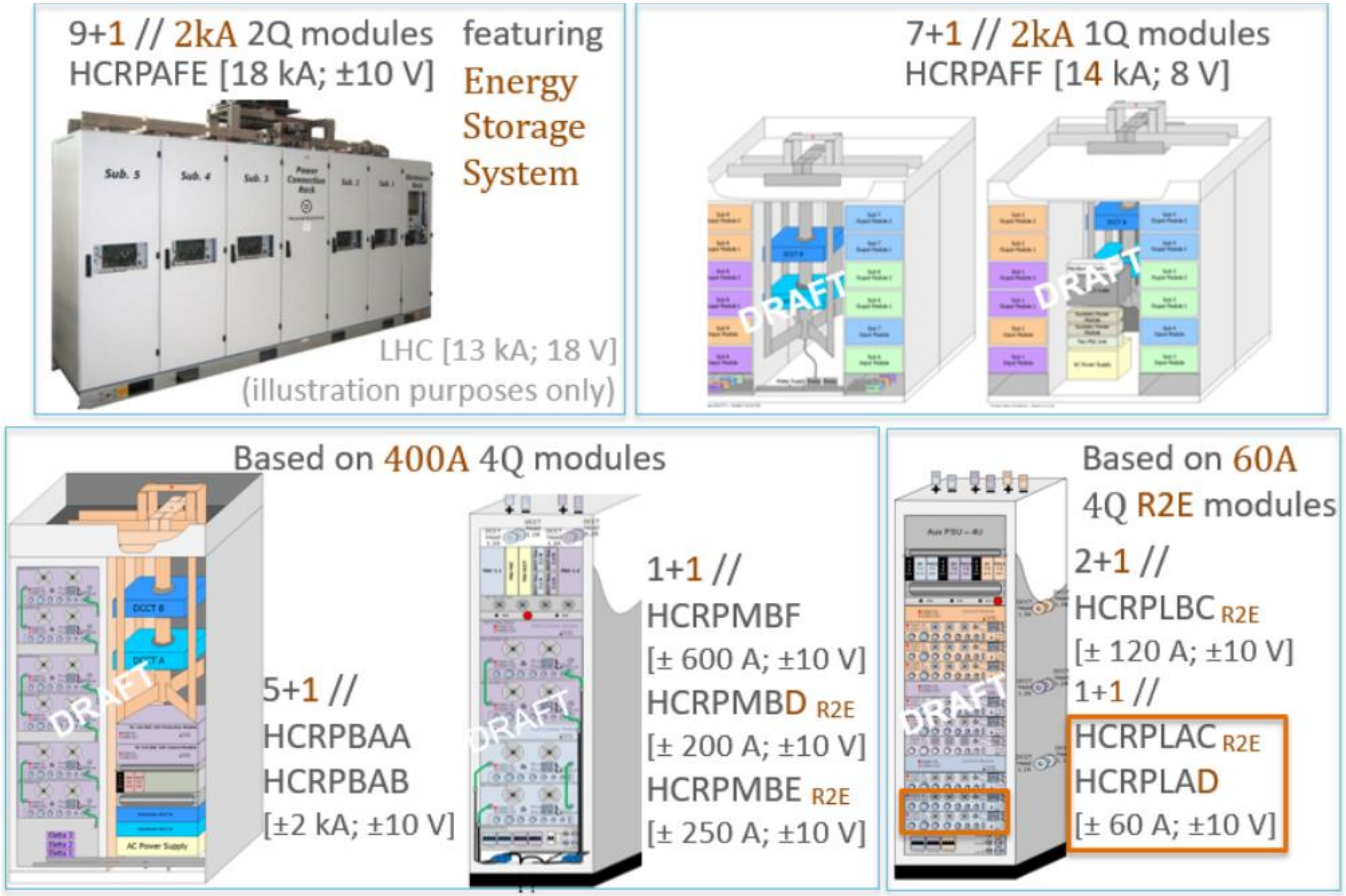
- [HL-LHC2kA-10V] ~ 37 units

- **PC Medium current:**

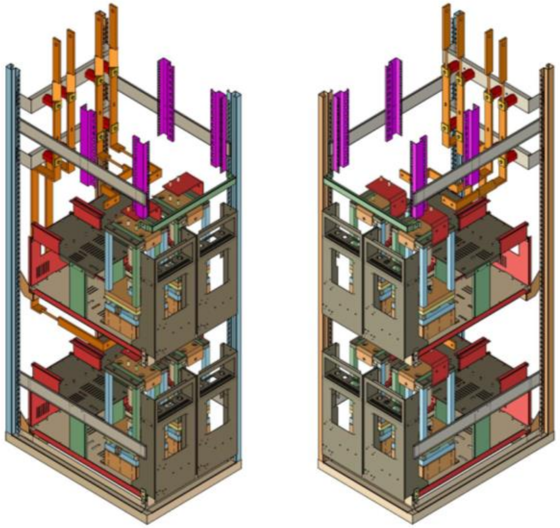
- [HL-LHC600A-10V] ~ 20 units

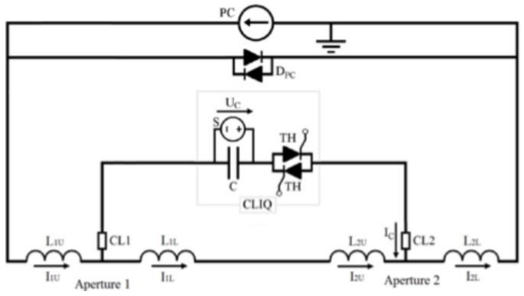
- **PC Low current:**

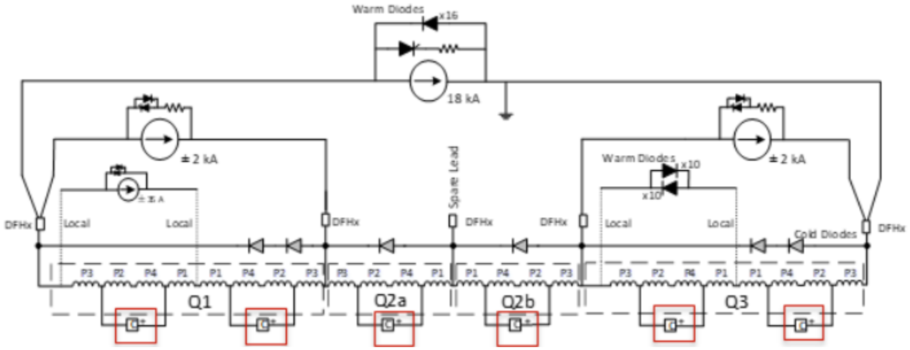
- [R2E-HL-LHC120A-10V] ~ 100 units
- [R2E-HL-LHC60A-10V] ~ 400 units



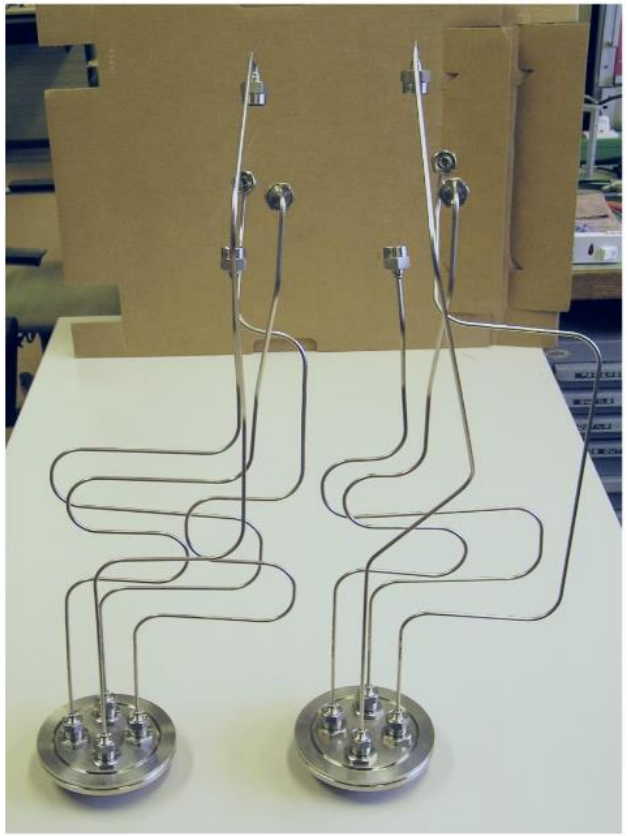
Energy extraction

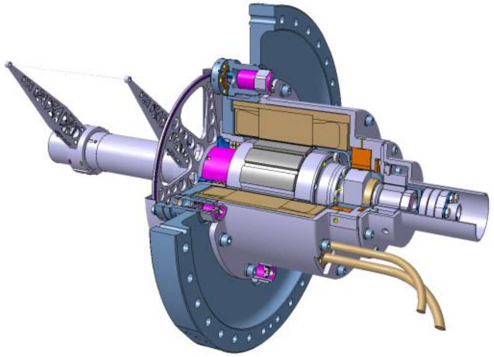


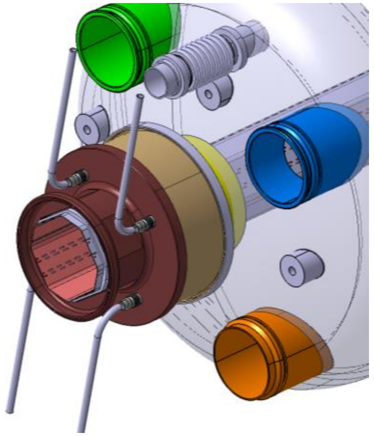


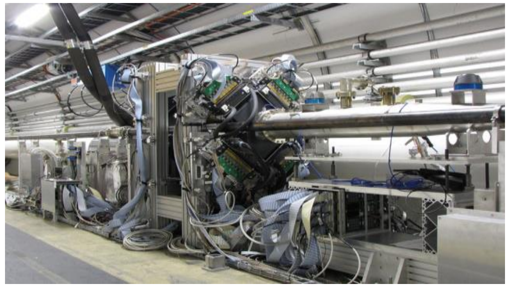


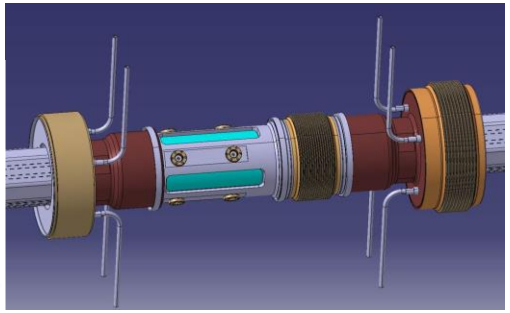
Beam Instrumentation

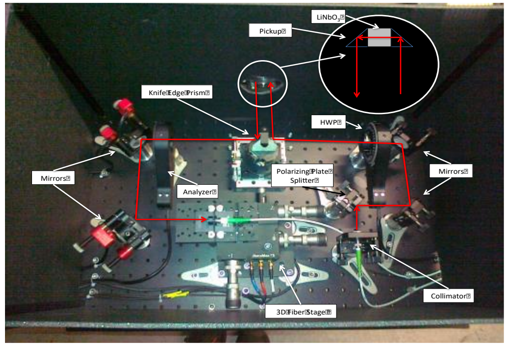


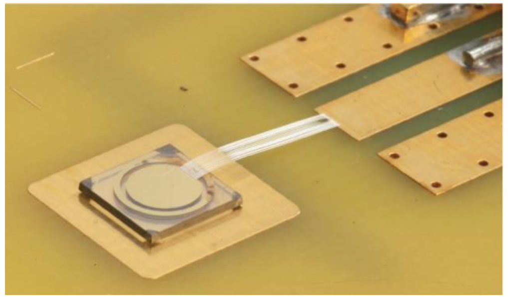


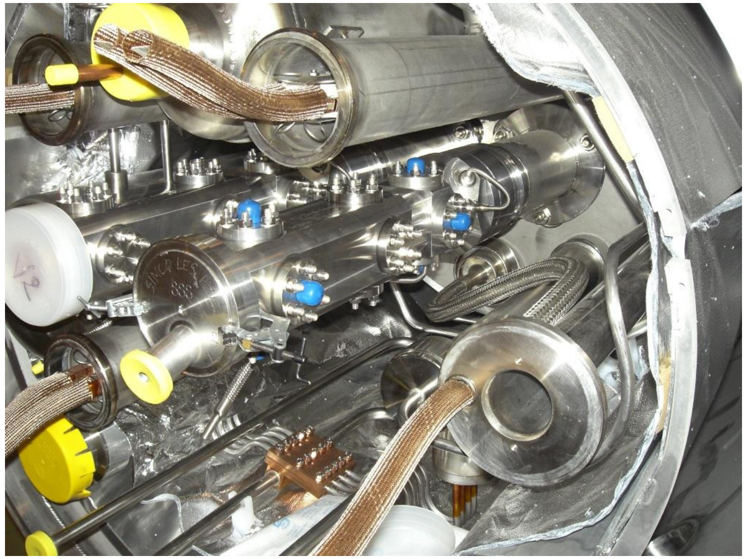


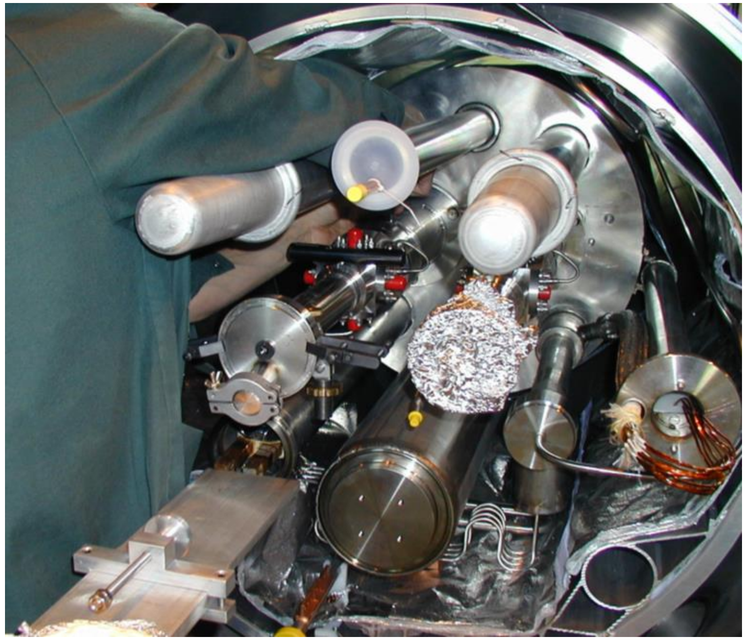




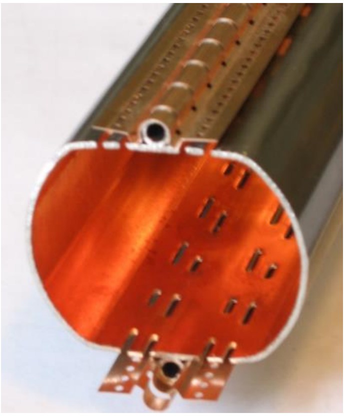


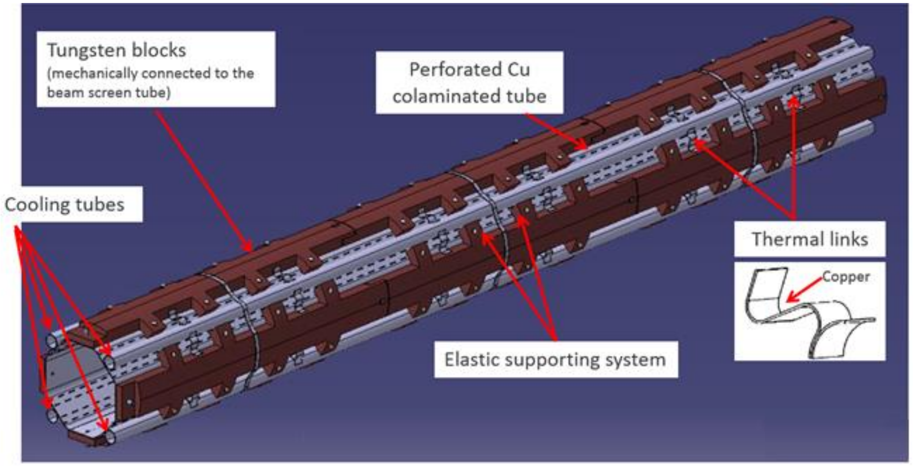


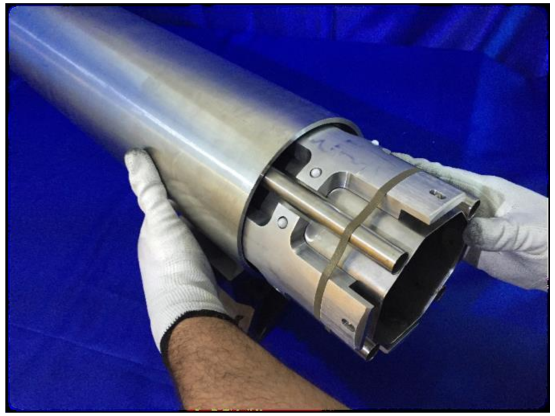




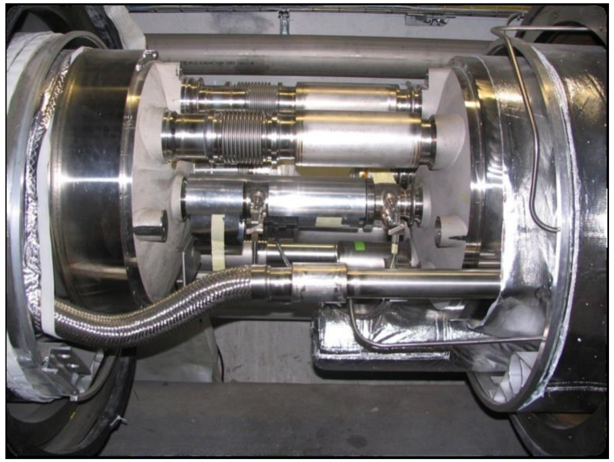
Ultra High Vacuum components and systems

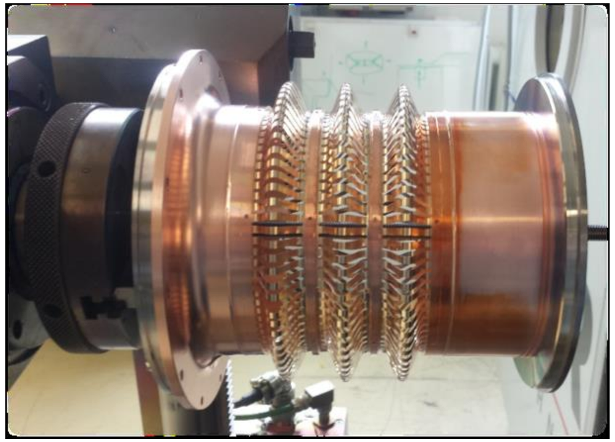




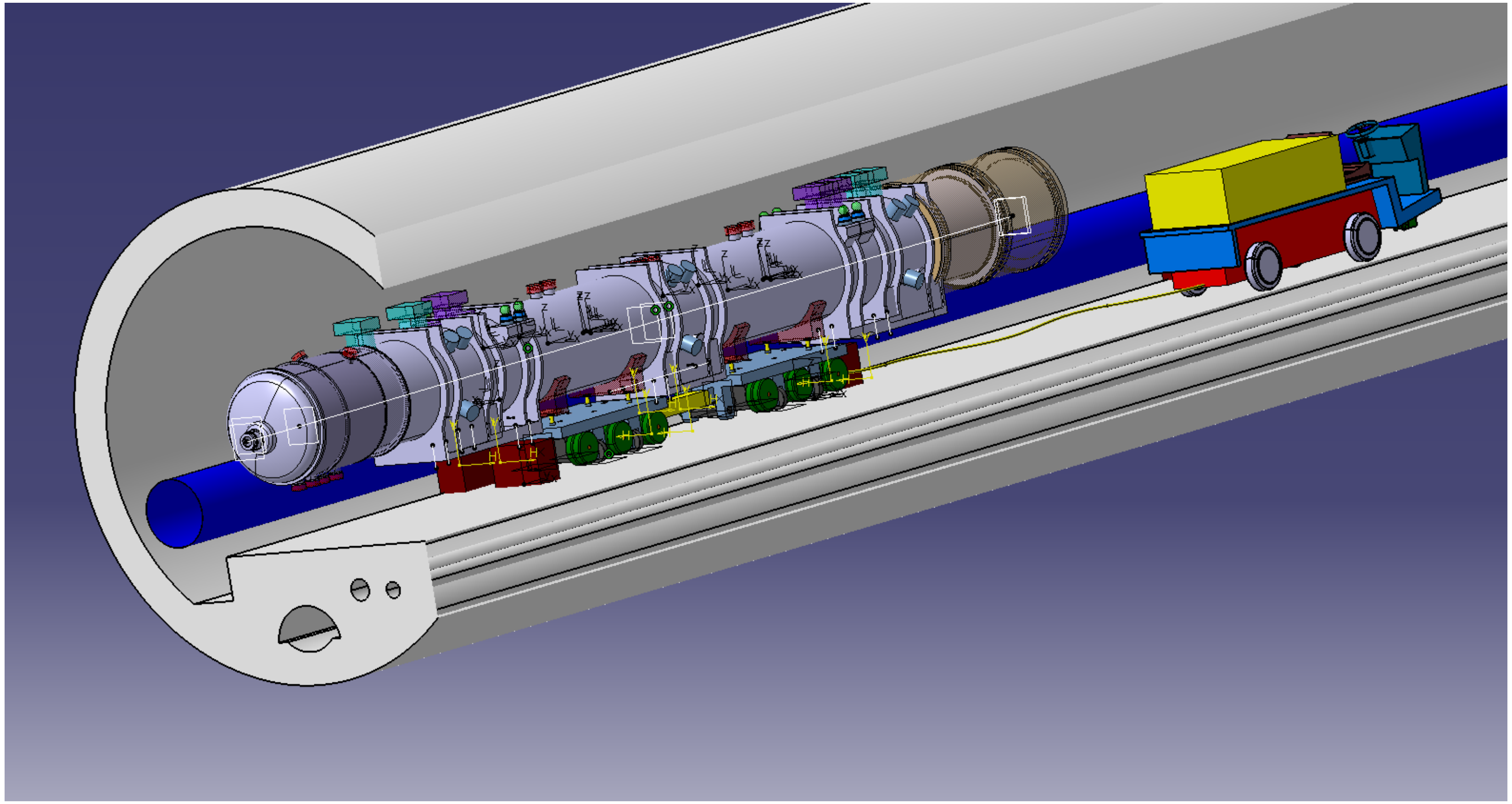


- New intercnnection, plug-in modules

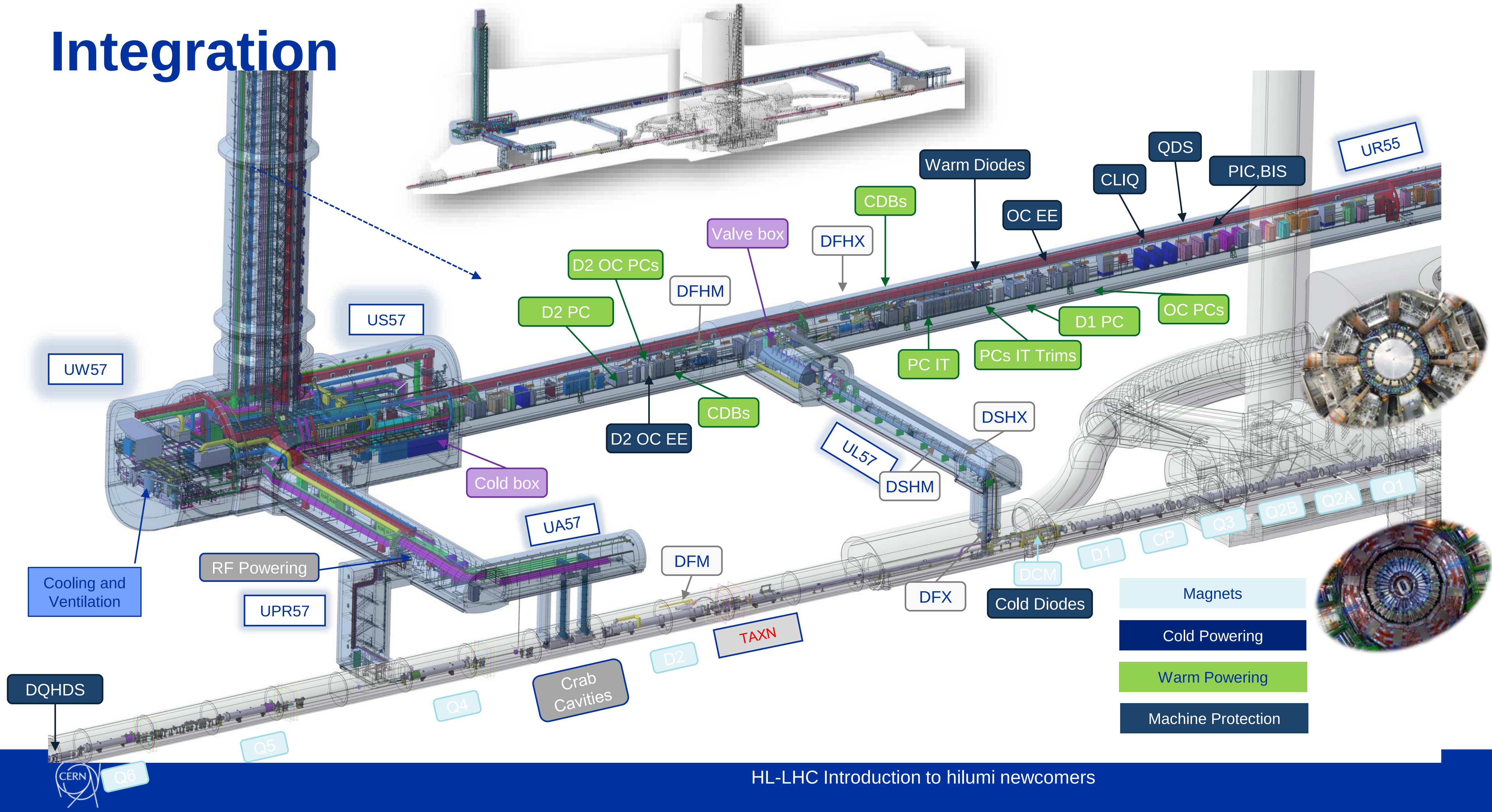




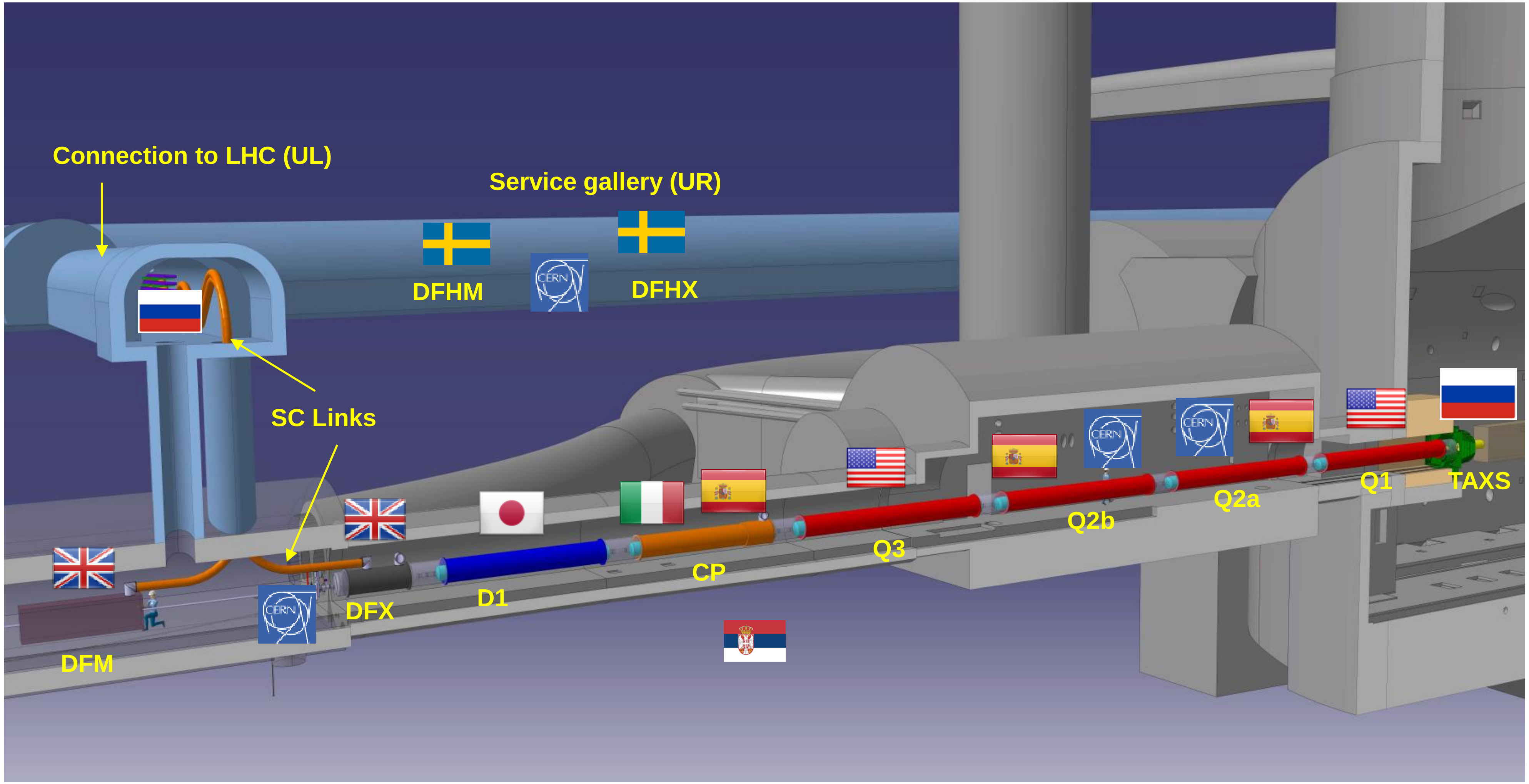
Machines to transport components



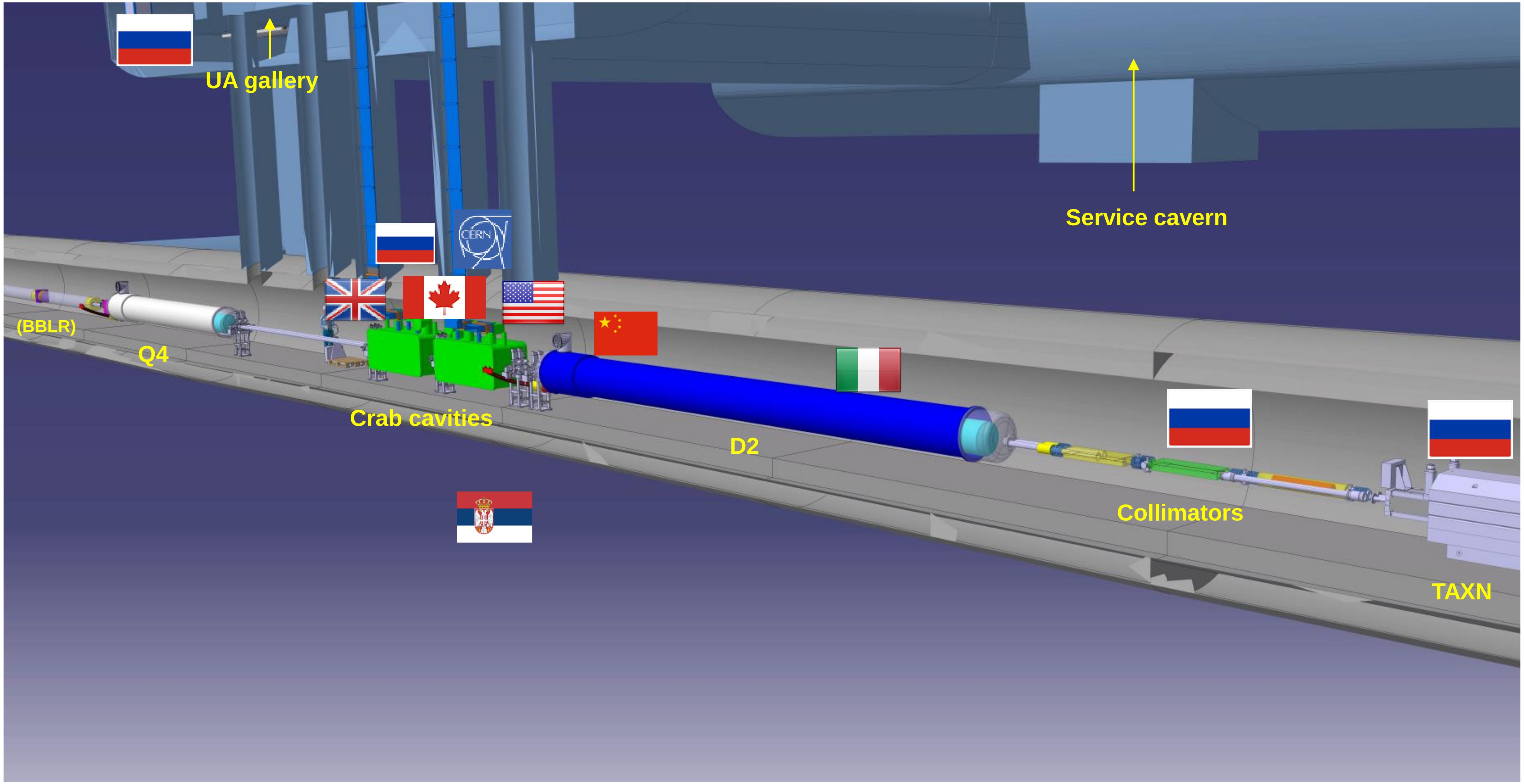
Integration



HL-LHC is a truly International Collaboration



The MS region with in-kind contributions



The future

FCC

CERN Scientific Priorities for the Future

- Implementation of the recommendations of the 2020 Update of the European Strategy for Particle Physics:

- Fully exploit the LHC & HL-LHC.

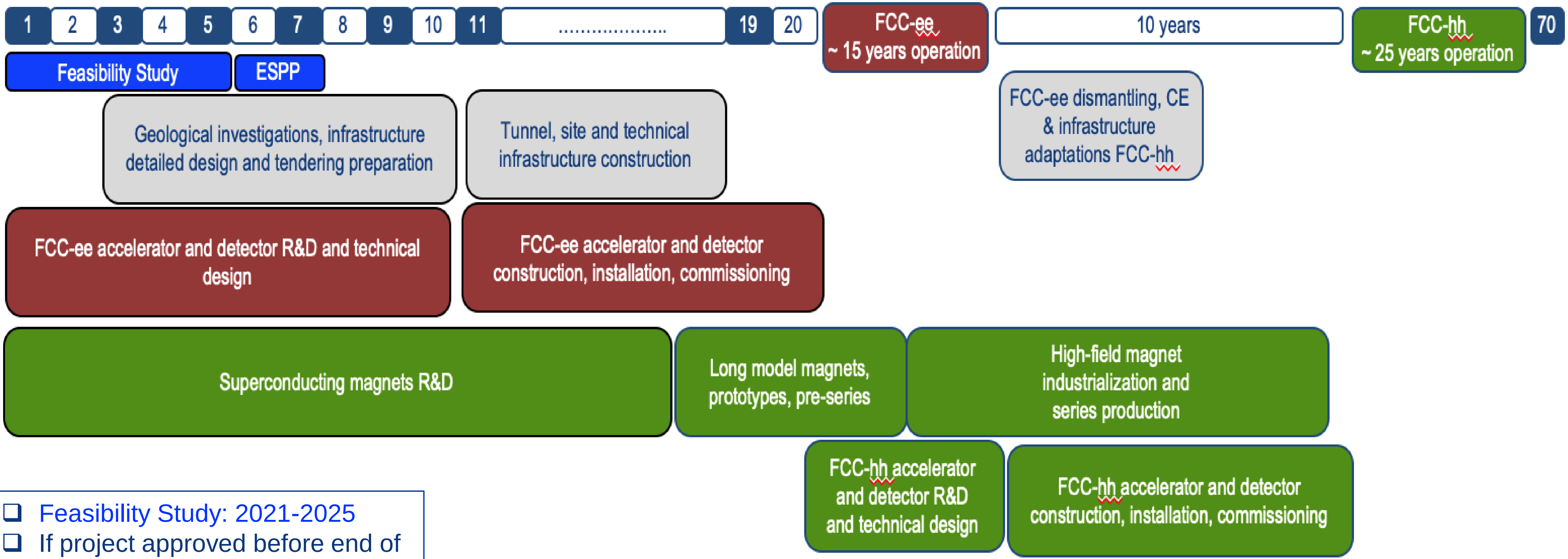
- Build a Higgs factory to further understand this unique particle.

- Investigate the technical and financial feasibility of a future energy-frontier 100 km collider at CERN.

- Ramp up relevant R&D.

- Continue supporting other projects around the world.

Technical timeline of FCC integrated programme



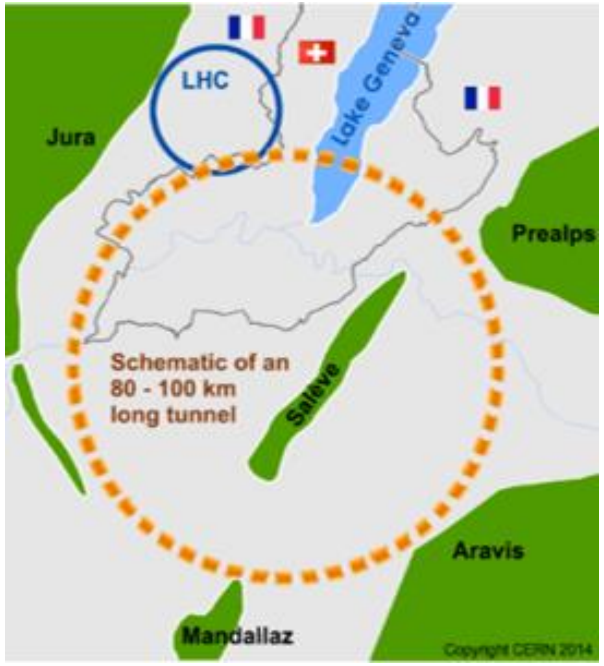
- Feasibility Study: 2021-2025
- If project approved before end of decade → construction can start beginning 2030s
- FCC-ee operation ~2045-2060
- FCC-hh operation 2070-2090++

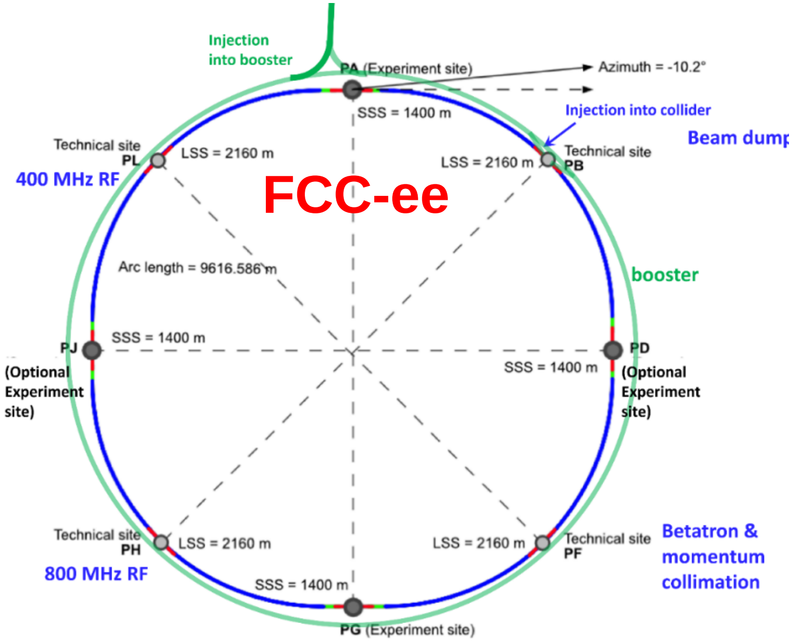
The FCC Integrated Programme

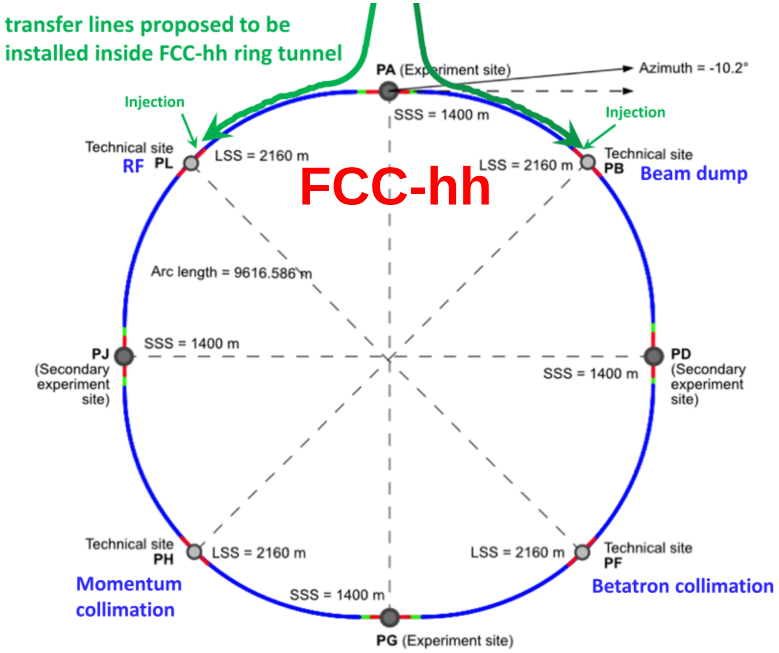
Inspired by Successful LEP – LHC Programmes at CERN

Comprehensive long-term programme maximising 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**
- Complementary physics
- Common civil engineering and technical infrastructures, building on and reusing CERN's existing infrastructure
- FCC integrated project allows seamless continuation of HEP after completion of the HL-LHC programme







2020 - 2040 | **2045 - 2060** | **2070 - 2090++**

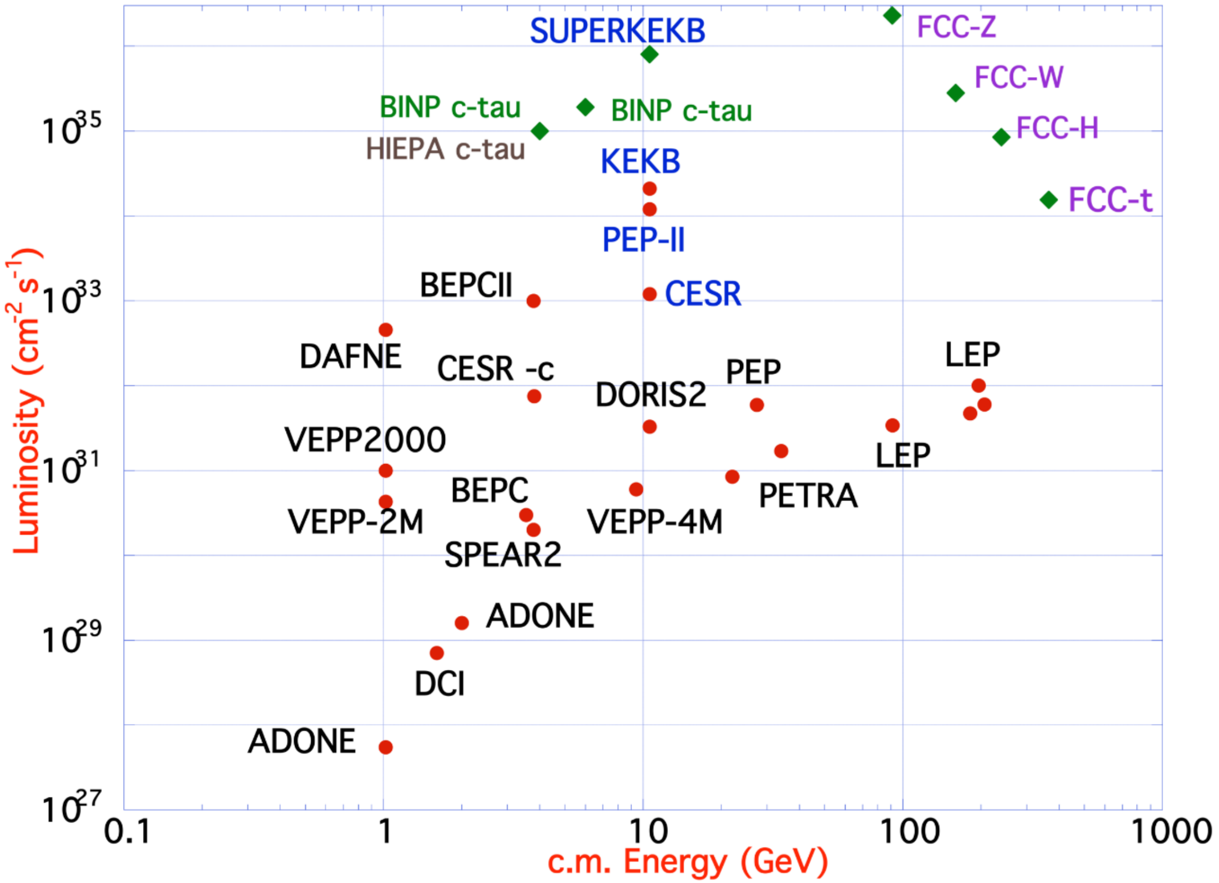
a similar two-stage project CEPC/SPPC is under study in China

FCC Feasibility Study (2021-205): high-level objectives

- demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- optimisation of the design of the colliders and their injector chains, supported by R&D to develop the needed key technologies;
- elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- consolidation of the physics case and detector concepts for both colliders.

Results will be summarised in a Feasibility Study Report to be released at end 2025

FCC-ee Design Concept
Based on lessons and techniques from past colliders



B-factories: **KEKB & PEP-II:**
- **double-ring lepton colliders,**
- **high beam currents,**
- **top-up injection**

DAFNE: crab waist, double ring

S-KEKB: low β_y*, crab waist

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

combining successful ingredients of several recent colliders → highest luminosities & energies

Parameters Stage 1: FCC-ee Collider

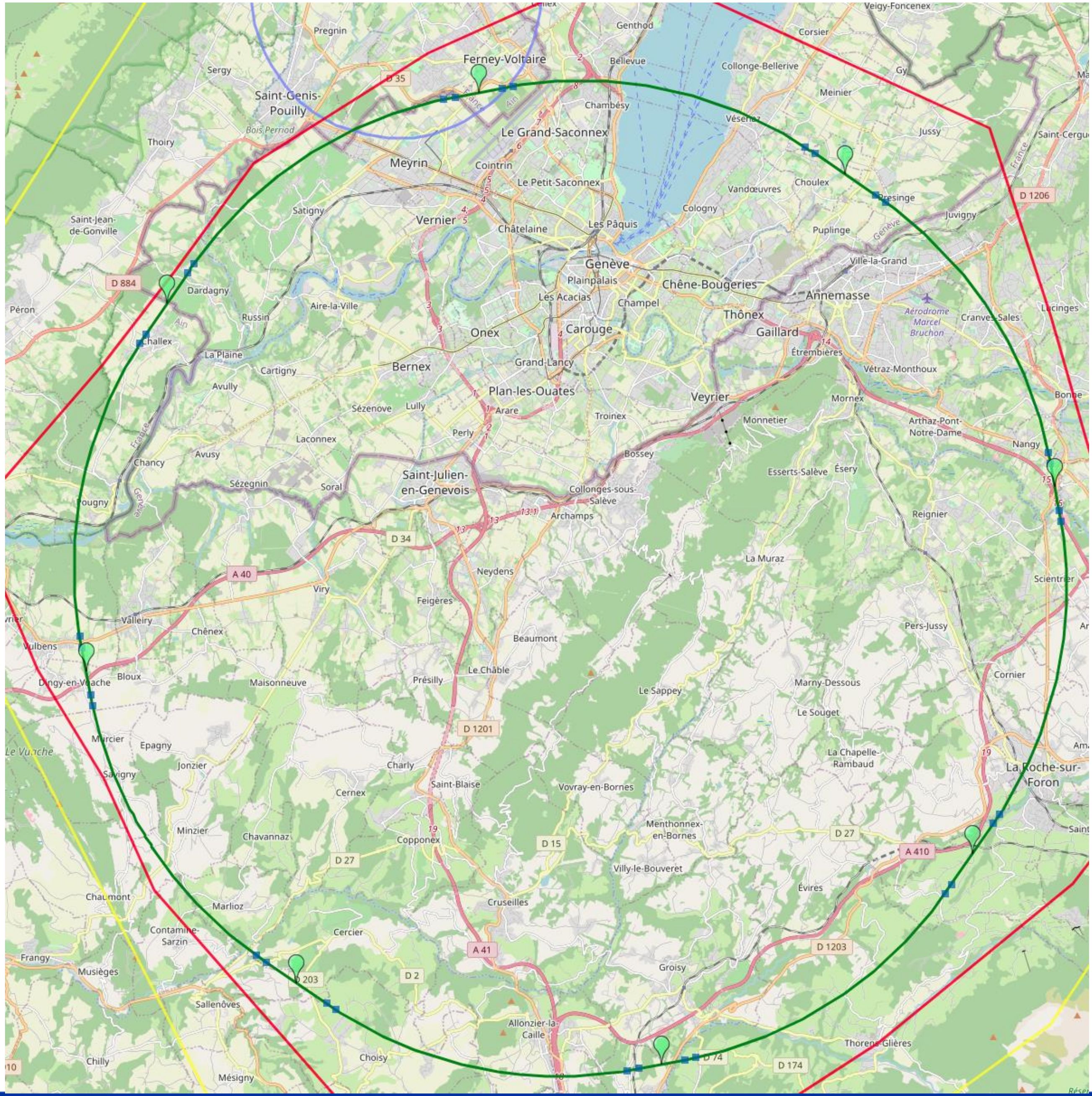
Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [mm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter x_x / x_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime rad Bhabha + BS [min]	19	18	6	9

Layout

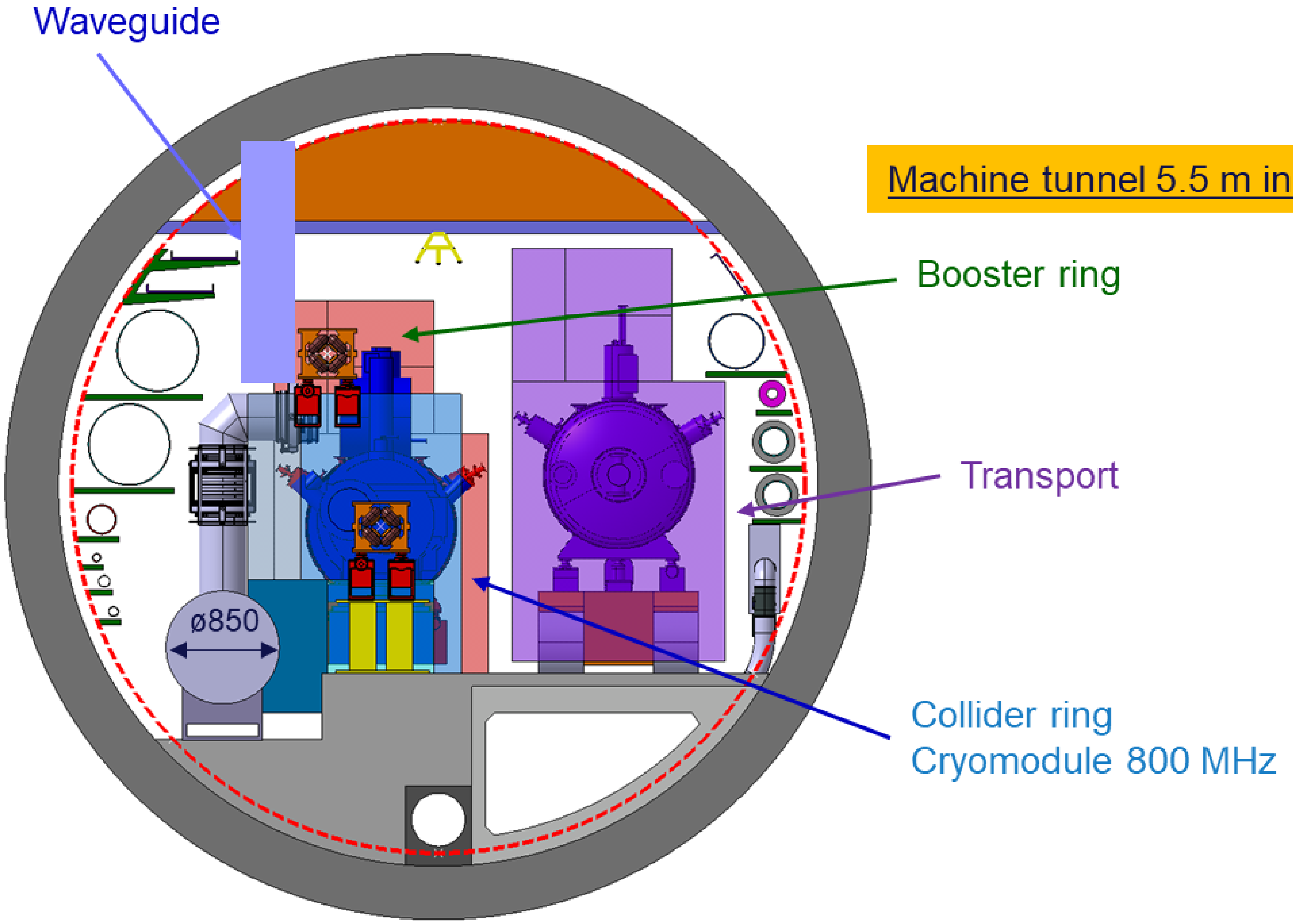
8-site baseline “PA31-3.0”

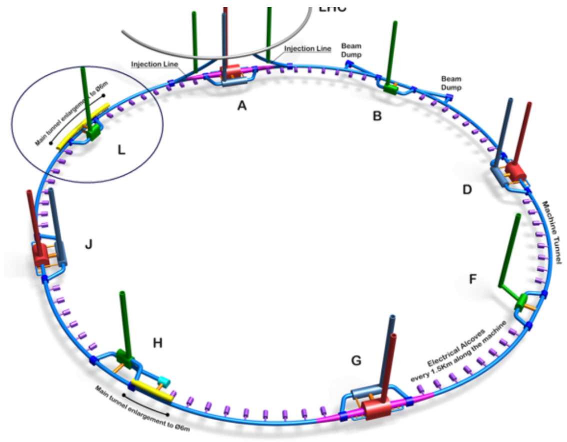
Number of surface sites	8
LSS@IP (PA, PD, PG, PJ)	1400 m
LSS@TECH (PB, PF, PH, PL)	2032 m
Arc length	9.6 km
Sum of arc lengths	76.9 m
Total length	**90.6 km**

- 8 sites – less use of land, <40 ha instead 62 ha
- Possibility for 4 experiment sites in FCC-ee
- All sites close to road infrastructures (< 5 km of new road constructions for all sites)
- Vicinity of several sites to 400 kV grid lines
- Good road connection of PD, PF, PG, PH suggest operation pole around Annecy/LAPP
- **Exchanges with ~40 local communes in preparation**



Integration FCC-ee RF section (ttbar), point L



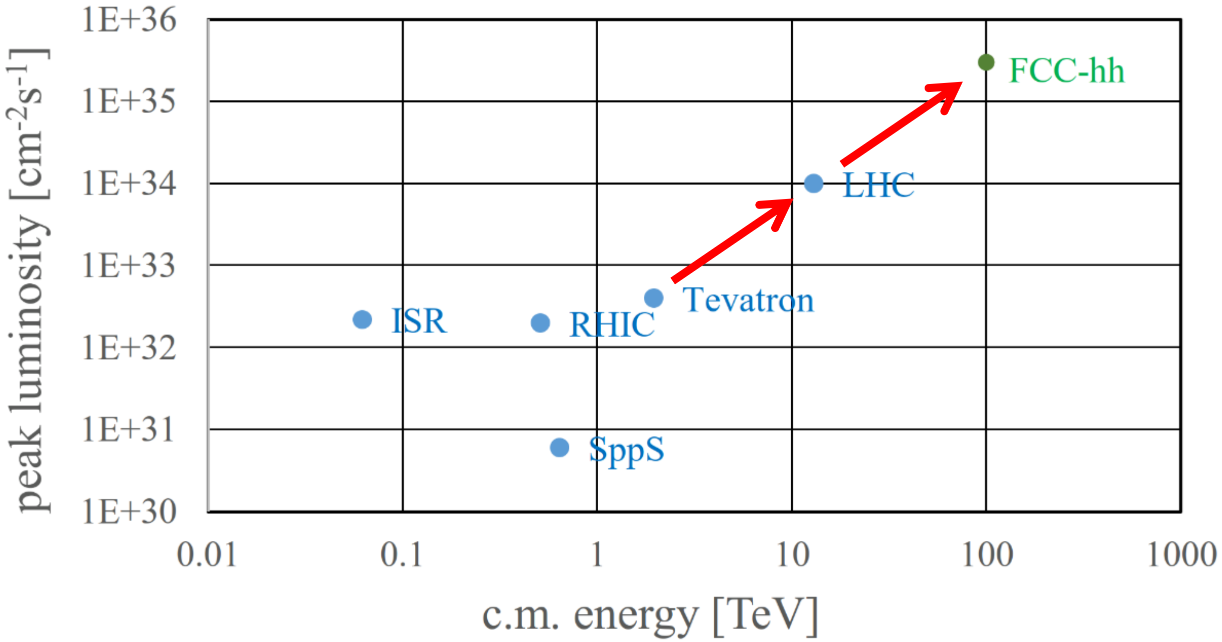


- Entire collider RF in section L
- Entire booster RF in section H
- Lattice adaptatîon to optimize space for cryomodules
- Considerations on grouping cryo-modules and number of cold-warm transitions for overall optimum configuration.
- QRL Ø along 800 MHz section 0.85 m.

Stage 2: FCC-hh (pp) Collider Parameters

parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	~17 (~16 comb.function)		8.33	8.33
circumference [km]	91.2		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2700		7.3	3.6
SR power / length [W/m/ap.]	32.1		0.33	0.17
long. emit. damping time [h]	0.45		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [μm]	2.2		2.5	3.75
peak luminosity [10^{34} $cm^{-2}s^{-1}$]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	7.8		0.7	0.36

FCC-hh: Highest Collision Energies



Order of magnitude performance increase in both energy & luminosity

100 TeV cm collision energy (vs 14 TeV for LHC)

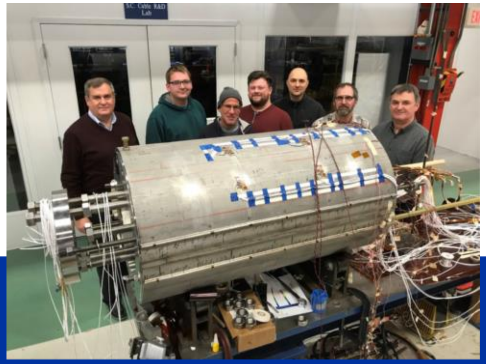
20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

Similar performance increase as from Tevatron to LHC

Key technology: high-field magnets

from
LHC technology
8.3 T NbTi dipole

via
HL-LHC technology
12 T Nb_3Sn quadrupole



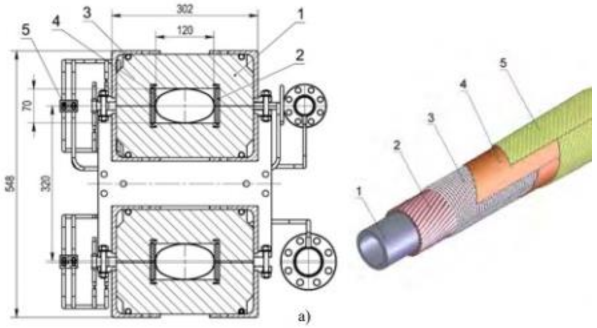
FNAL dipole
demonstrator
14.5 T Nb_3Sn

The future

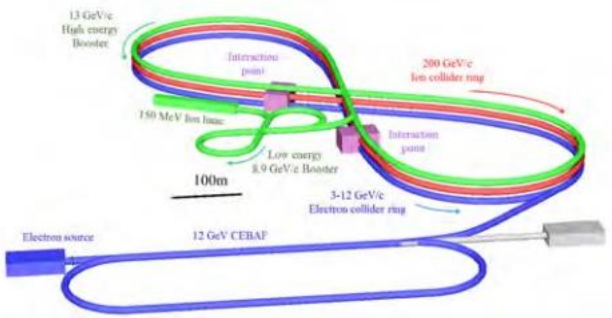
Others

Panorama

Ion, e-A and e-p colliders



NICA



High-energy electron-ion collider (EIC)

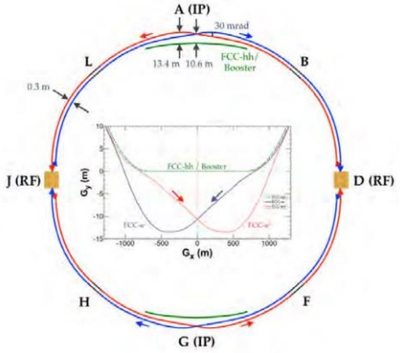
But also LHeC, HE-LHeC and FCC-eh

Lepton colliders studying Higgs boson and electroweak sector

Higgs Factories

ILC CLIC

FCC-ee CEPC

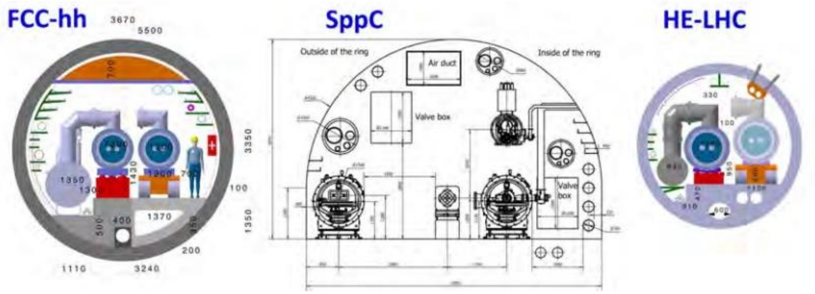


Tau-Charm Factories

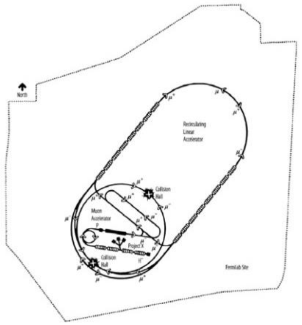
SCT HIEPA

Energy frontier colliders

HE-LHC, FCC-hh, SppC,



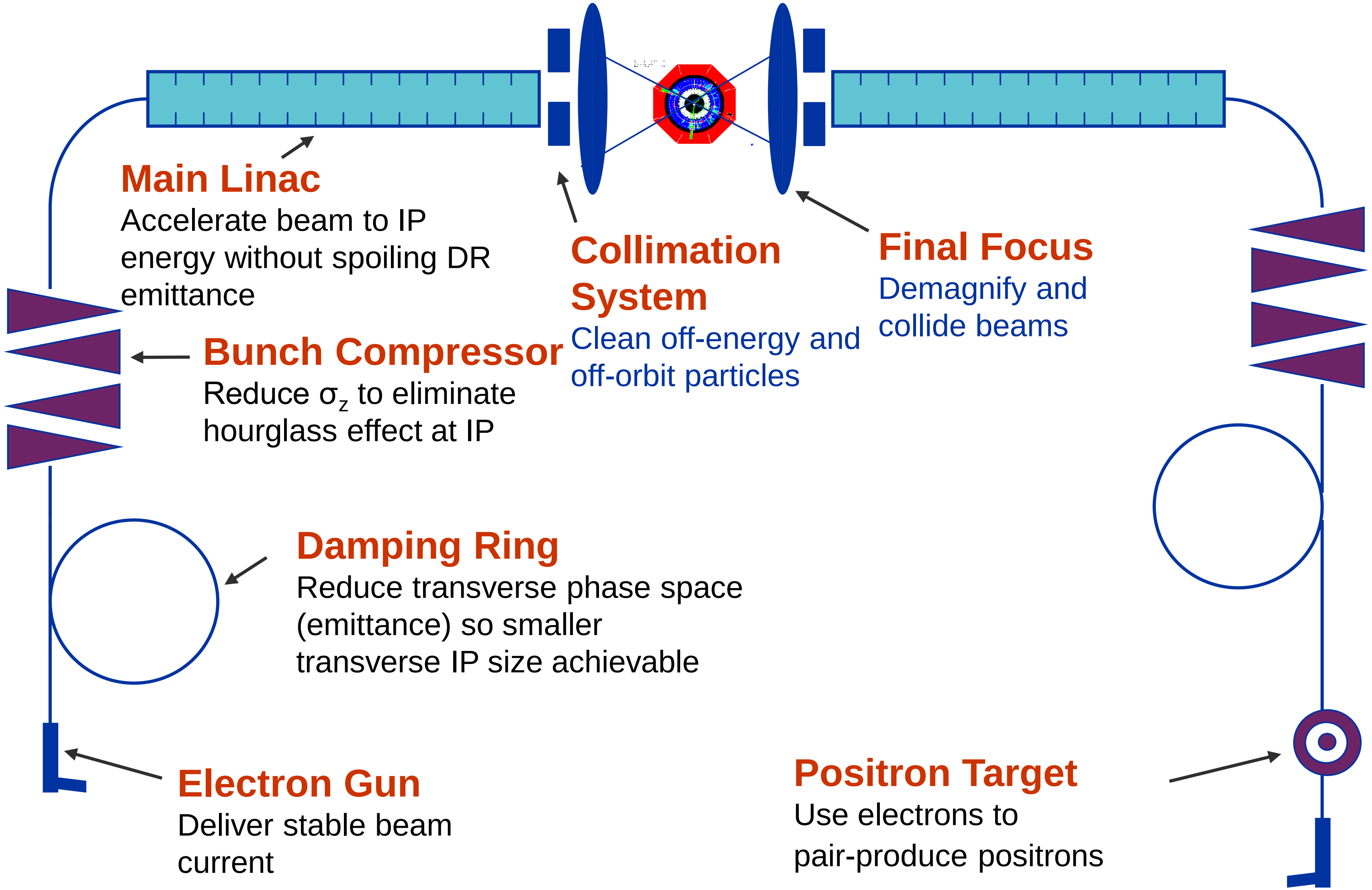
Muon Colliders



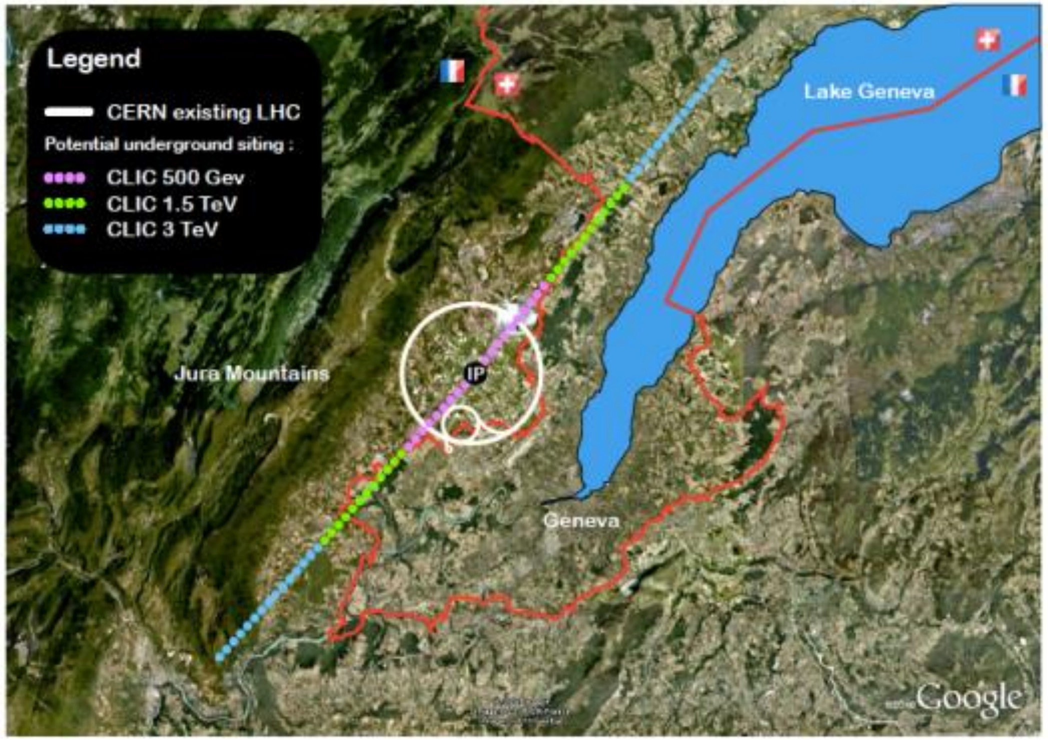
Concepts

plasma and plasma-based collider

Generic Linear Collider



CLIC Implementation



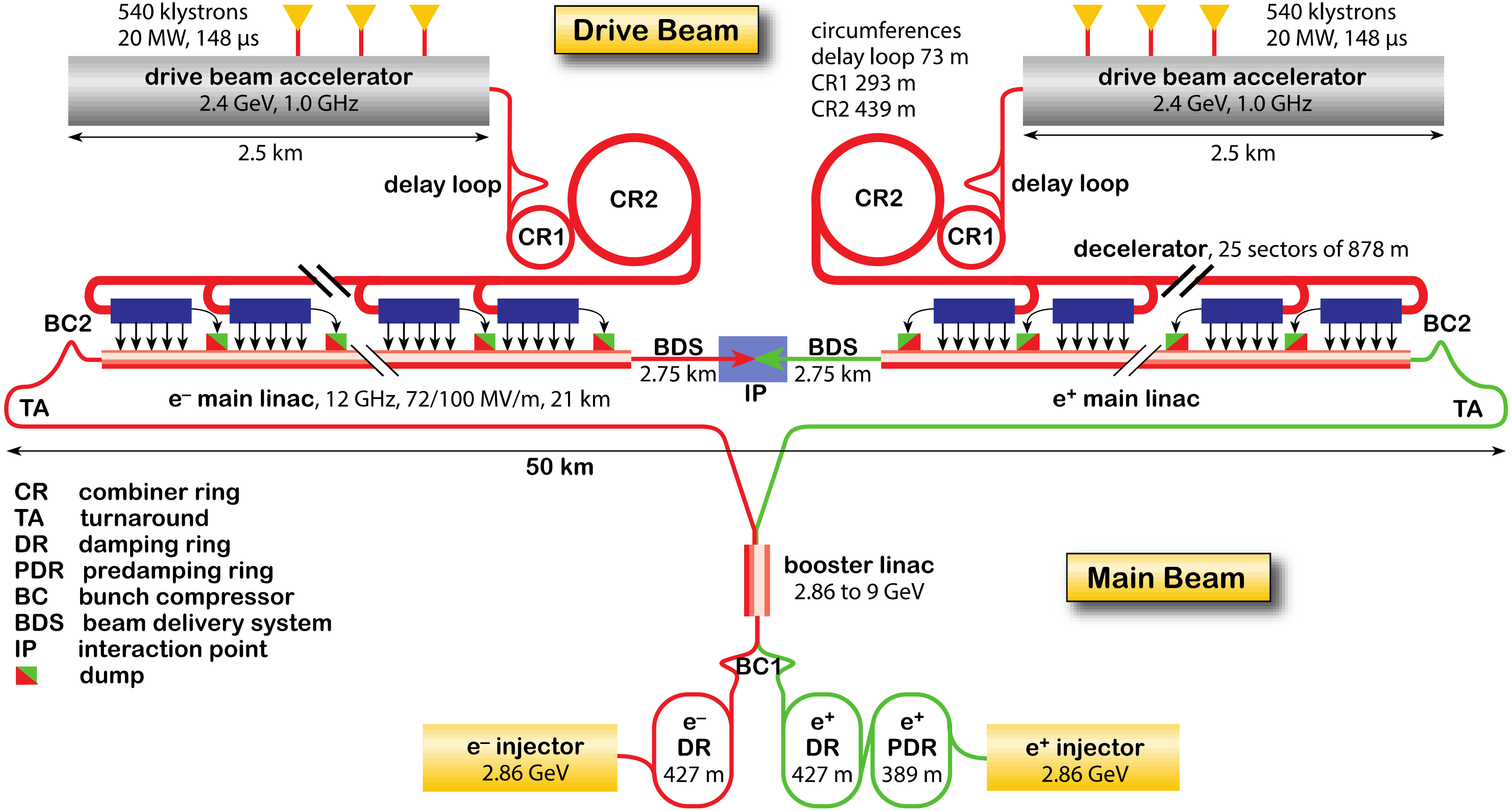
🡐 Possible lay-out near CERN

Note: the design is currently being re-optmised, e.g. to include 350 GeV as the first stage

🡓 CLIC parameters

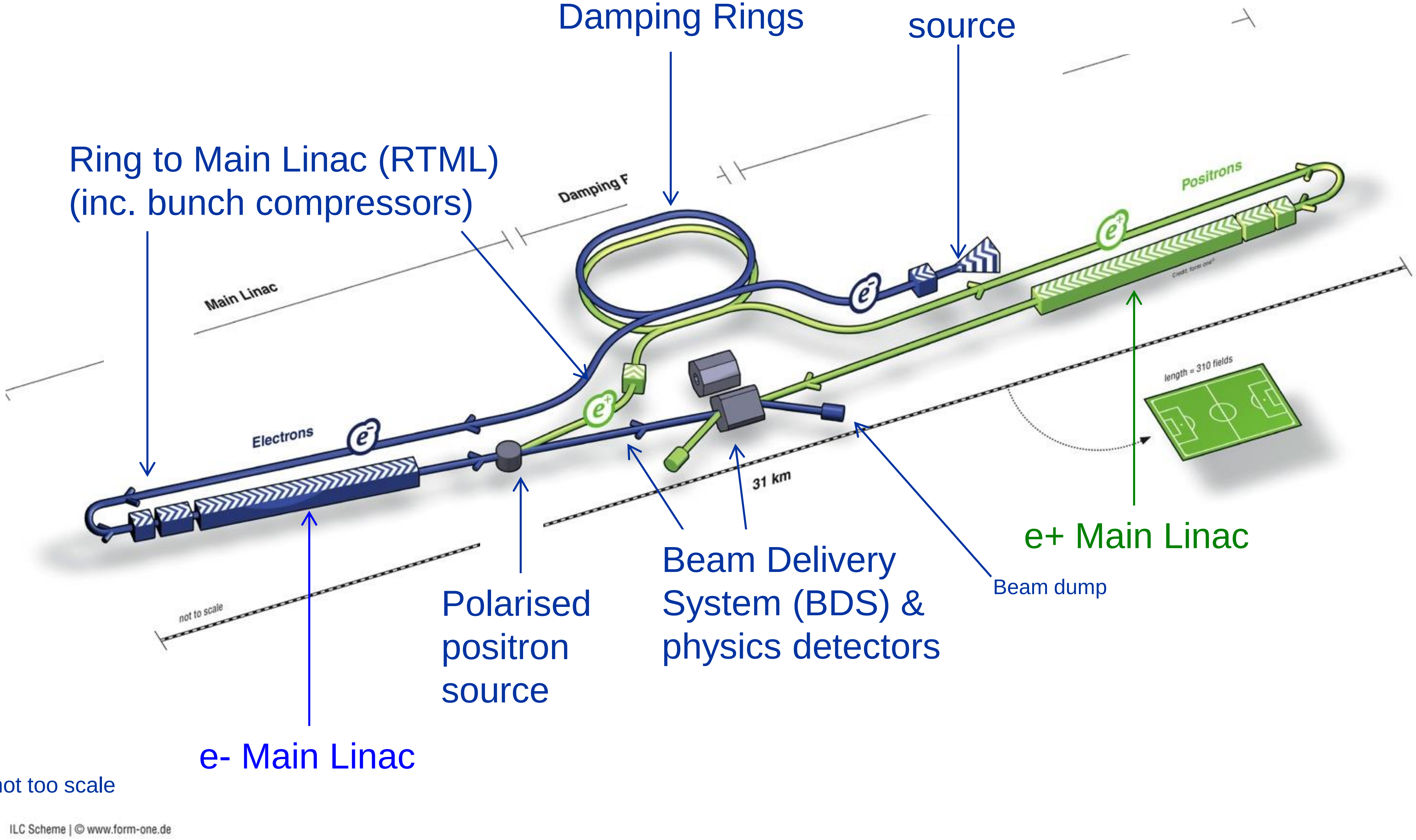
Parameter	Symbol	Unit			
Centre-of-mass energy	$\sqrt{s}$	GeV	500	1500	3000
Repetition frequency	f_{rep}	Hz	50	50	50
Number of bunches per train	n_b		312	312	312
Bunch separation	Δ_t	ns	0.5	0.5	0.5
Accelerating gradient	G	MV/m	100	100	100
Total luminosity	$\mathscr{L}$	10^{34} cm^{-2}s^{-1}	1.3	3.7	5.9
Luminosity above 99% of $\sqrt{s}$	$\mathscr{L}_{0.01}$	10^{34} cm^{-2}s^{-1}	0.7	1.4	2
Main tunnel length		km	11.4	27.2	48.3
Charge per bunch	N	10^9	3.7	3.7	3.7
Bunch length	σ_z	µm	44	44	44
IP beam size	σ_x/σ_y	nm	100/2.6	≈ 60/1.5	≈ 40/1
Normalised emittance (end of linac)	$\varepsilon_x/\varepsilon_y$	nm	—	660/20	660/20
Normalised emittance	$\varepsilon_x/\varepsilon_y$	nm	660/25	—	—
Estimated power consumption	P_{wall}	MW	235	364	589

CLIC – overall layout – 3 TeV

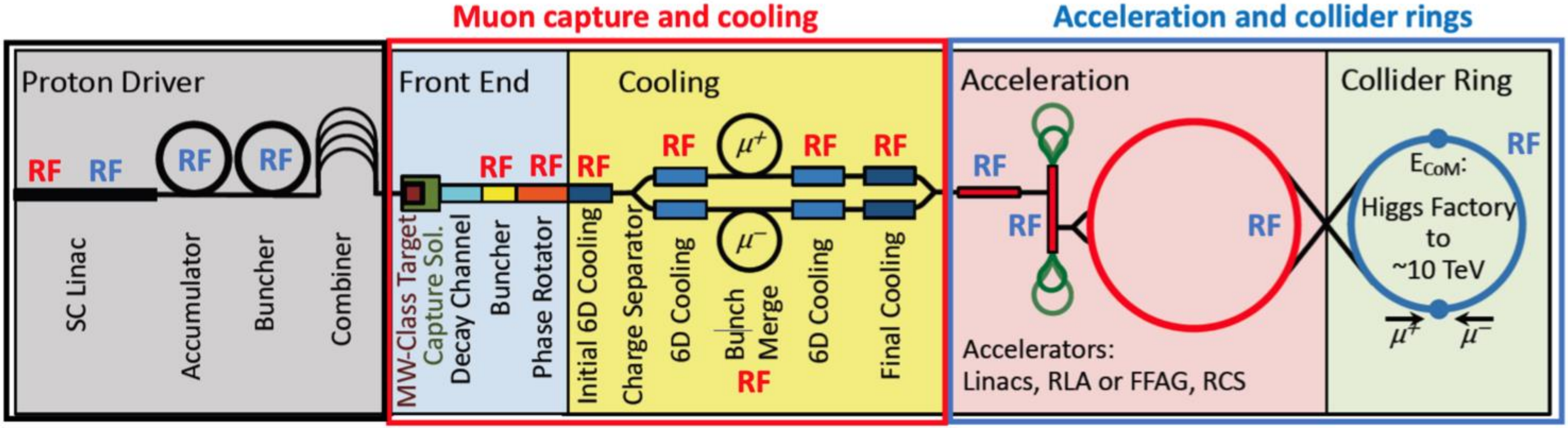


CLIC (Compact Linear Collider): only multi-TeV design 3 TeV, 100 MV/m, warm technology, 12 GHz, two beam scheme

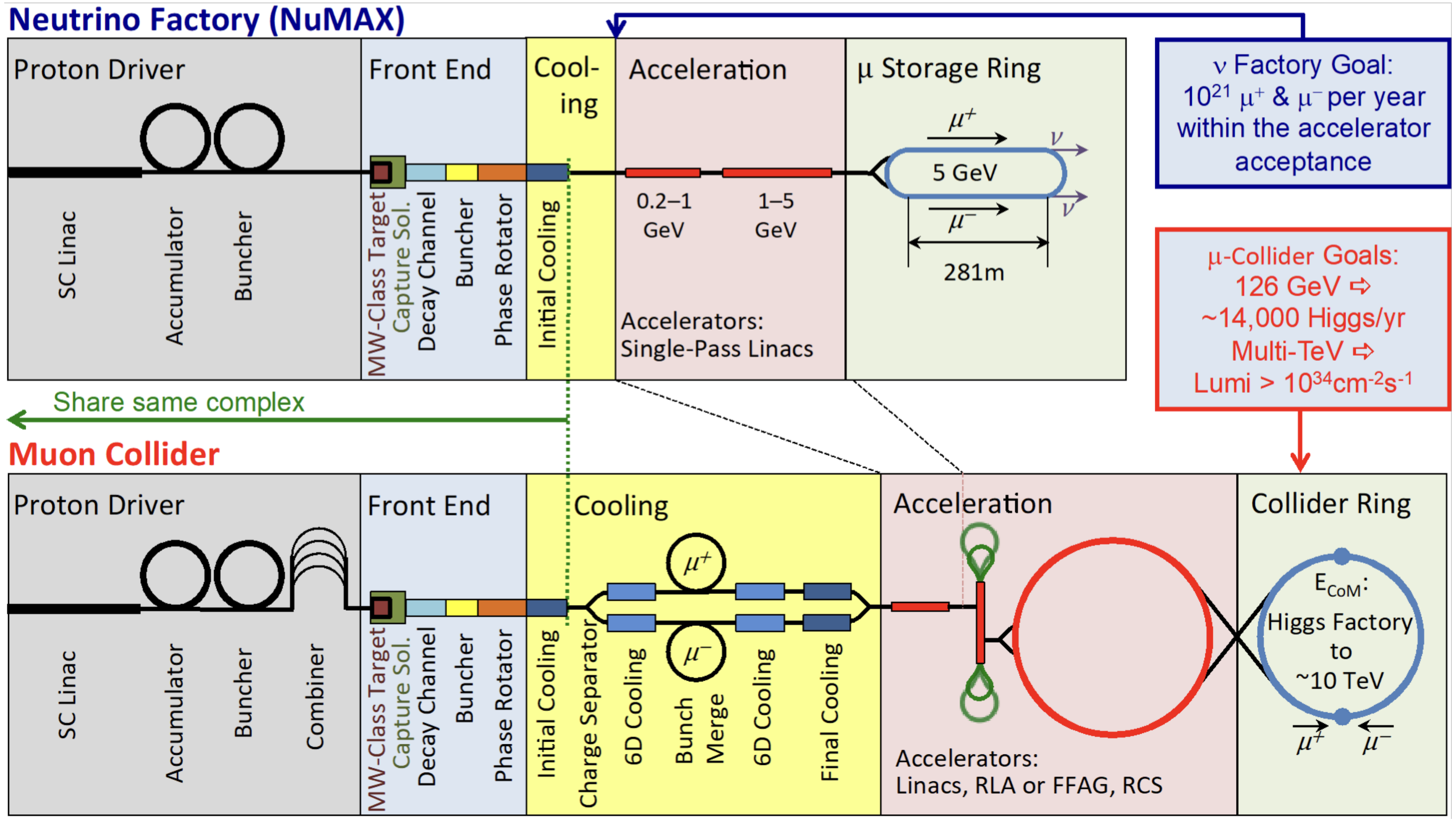
ILC


Damping Rings
Polarised electron source
Ring to Main Linac (RTML)
(inc. bunch compressors)
Damping R
Main Linac
Positrons
Electrons
31 km
length = 310 fields
not to scale
e+ Main Linac
Beam dump
Beam Delivery System (BDS) & physics detectors
Polarised positron source
e- Main Linac
not too scale
ILC Scheme | © www.form-one.de

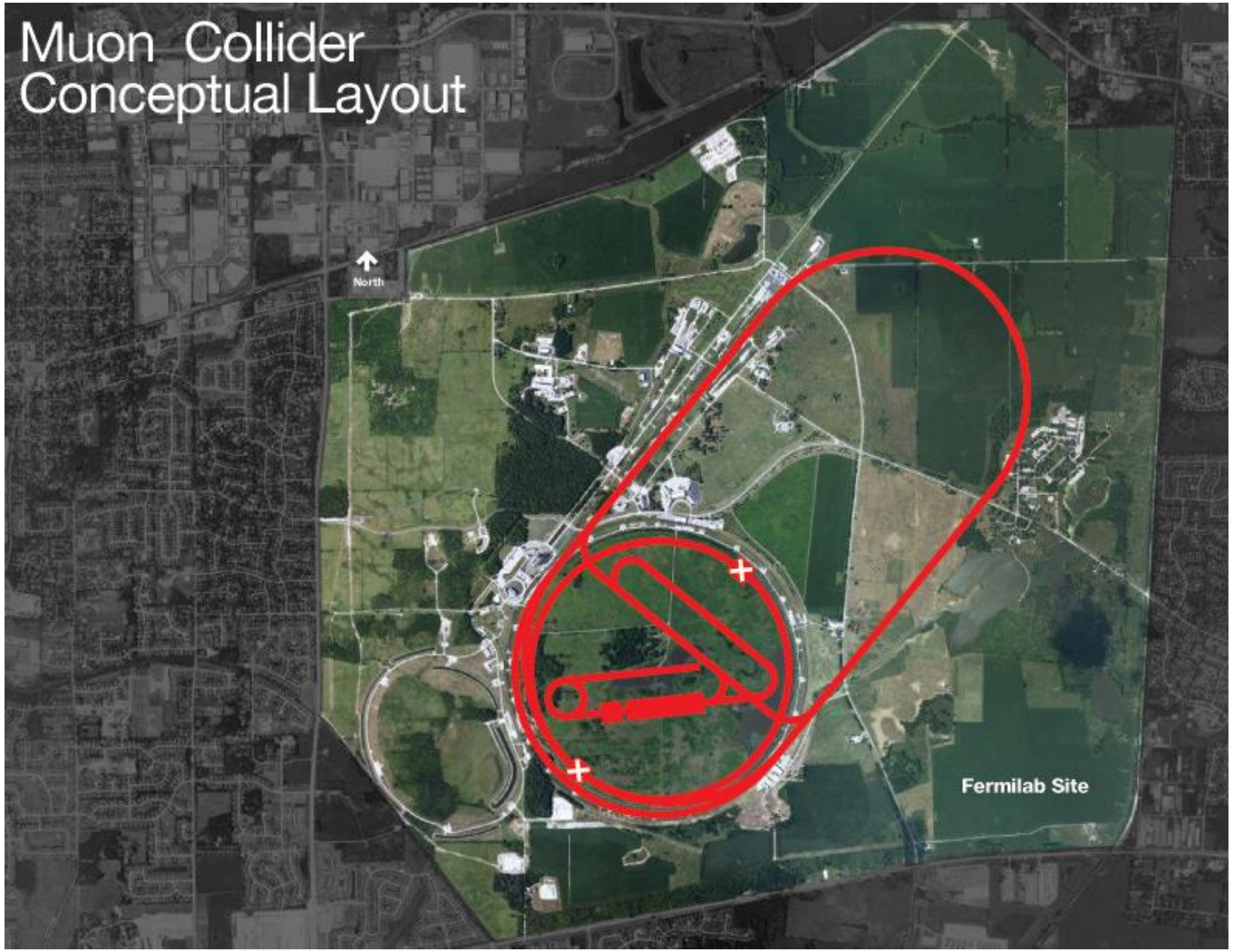
An alternative: the muon collider



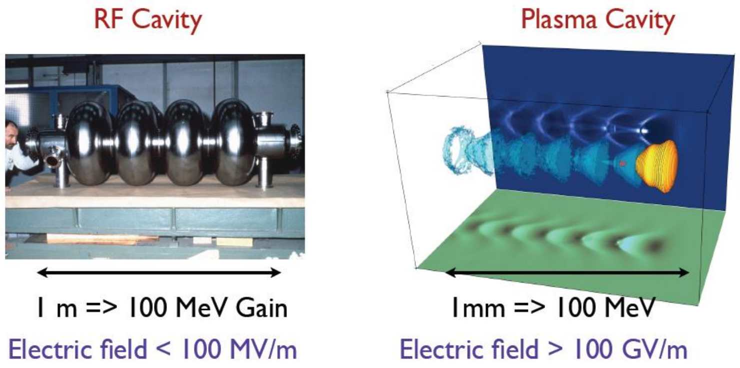
Muon Accelerator Synergies



Muon collider proposal at Fermilab (US)



Plasma Accelerators



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

e.g. AWAKE at CERN

Demonstration experiment to verify novel technique of p-driven plasma wakefield acceleration

Plasma Accelerators

Transform transverse fields into longitudinal fields.

Significantly higher accelerating gradients than conventional RF.

- **Laser driven**
- **e- driven**
- **p driven**
- **Dielectric wakefields**

More reading

If you want to learn more

- **The Evolution of Particle Accelerators & Colliders by WOLFGANG K. H. PANOFSKY** https://www.slac.stanford.edu/pubs/beamline/27/1/27-1-panofsky.pdf

- **Obsessed by a Dream The Physicist Rolf Widerøe – a Giant in the History of Accelerators** https://link.springer.com/book/10.1007/978-3-030-26338-6

- **Accelerators for America's Future** http://www.acceleratorsamerica.org/ **https://science.osti.gov/-/media/hep/pdf/files/pdfs/Accel_for_Americas_Future_final_report.pdf**

- **Reviews of accelerator science and technology A.W. Chao**

- **Engines of Discovery Revised & Expanded Edition, Andrew Sessler & Edmund Wilson, World Scientific, 2014**

If you want to learn more

- Accelerator Physics Graduate Course John Adams Institute for Accelerator Science
  https://indico.cern.ch/category/5869/
- FCC Conceptual Design Report
  http://fcc-cdr.web.cern.ch/
- CLIC Conceptual Design Report– Vol.2
  http://arxiv.org/abs/1202.5940
- ILC Technical Design Report – Vol.2 – Physics at the ILC
  www.linearcollider.org/ILC/Publications/Technical-Design-Report
- CERN Outreach:
  https://home.cern/resources
- Modern and Future colliders, V.Shiltsev, F.Zimmerman

If you want to learn more

- Modern and Future Colliders https://cds.cern.ch/record/2713605/files/23bace0fb97ee7ebeb6f4c8c15607c55.pdf
- LHC page https://www.lhc-closer.es
- Tevatron Overview: https://iopscience.iop.org/article/10.1088/1748-0221/6/08/T08001
- CERN Accelerator Schools: https://cas.web.cern.ch
- SuperKEKB https://www-superkekb.kek.jp
- RHIC https://www.bnl.gov/rhic/
- Duoplasmatron: https://accelconf.web.cern.ch/ipac2011/papers/thps025.pdf
- HL TDR https://e-publishing.cern.ch/index.php/CYRM/issue/view/127/111
- CEPC http://cepc.ihep.ac.cn/ http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf
- This presentation https://edms.cern.ch/document/2825582

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