Few words on Accelerators
The CERN Accelerator Complex

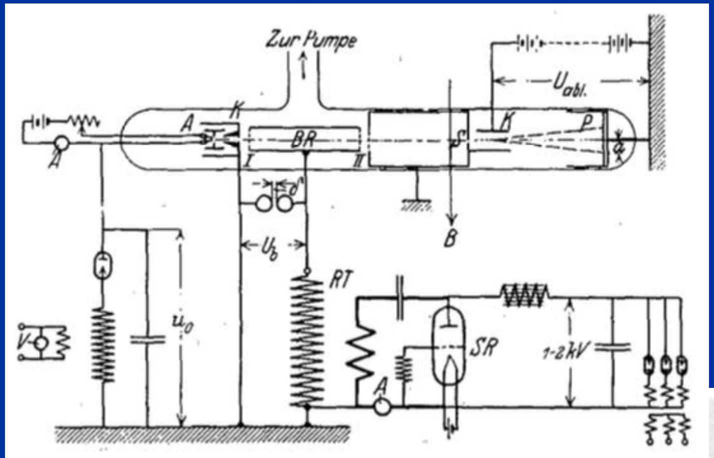


Bild 5. Die verwendete Schaltung.


Rolf Wideroe – Thesis (1926)
First resonant accelerator

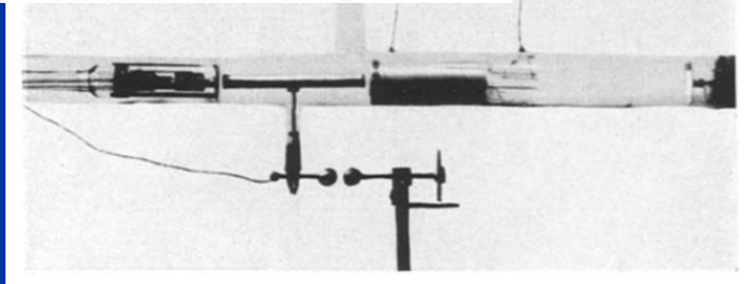
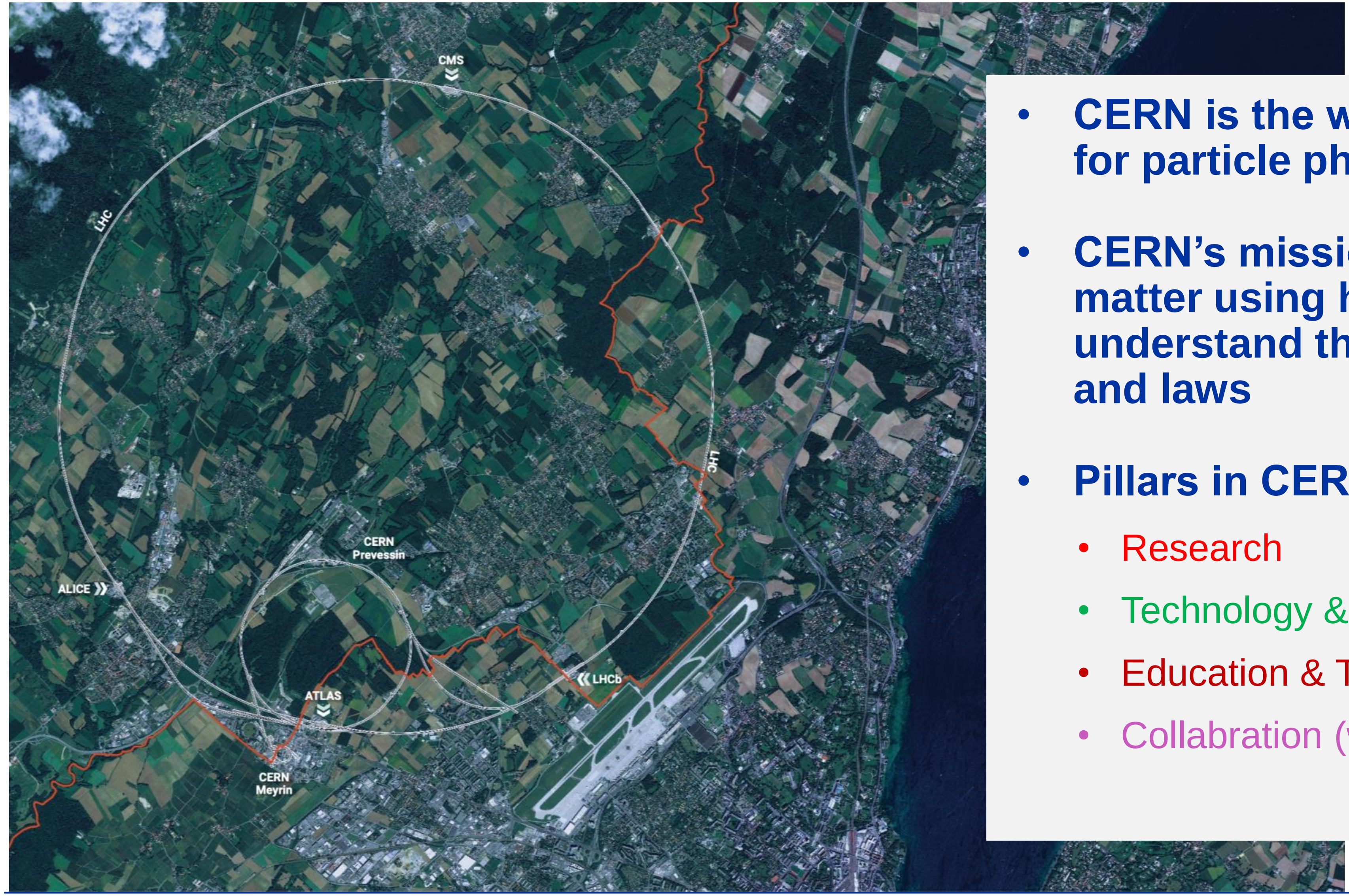


Bild 6. Die Versuchsröhre.

Ilias Efthymiopoulos Ph.D. – Accelerators Physics Group (ABP)

ATSOA – 03.06.2024, CERN

The CERN



- **CERN is the world’s biggest laboratory for particle physics.**
- **CERN’s mission: explore the origins of matter using high-energy particles, understand the fundamental particles and laws**
- **Pillars in CERN’s mission**
  - Research
  - Technology & Innovation
  - Education & Training
  - Collabration (world – wide)

What are the accelerators?

The accelerators or strictly speaking

the charged particle accelerators

Are electromechanical systems “machines” capable of producing

high-energy particle beams

Why do we need high-energy?

- **To create new particles**

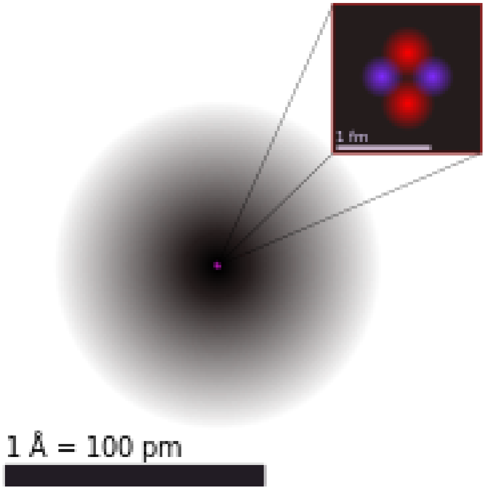
$$E = m\,c^2$$

- **To probe and study the structure of matter**

$$E = h\,\nu = h\,\frac{c}{\lambda}$$

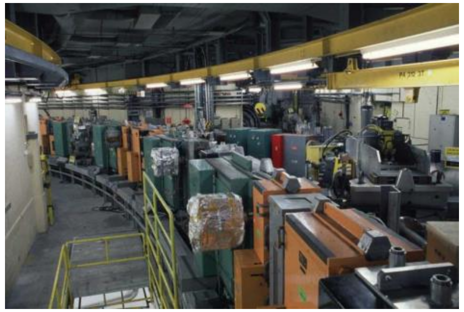
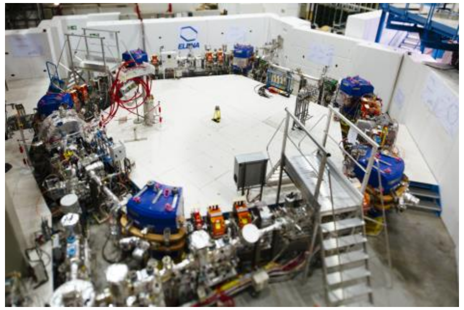
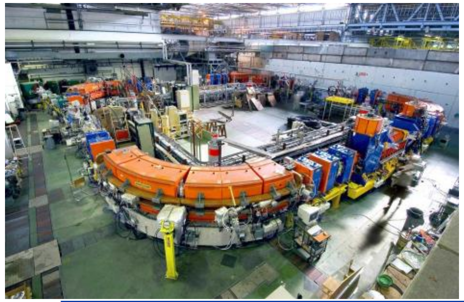
Planck's constant

$\hbar c = 197.3269\ MeV\ fm$

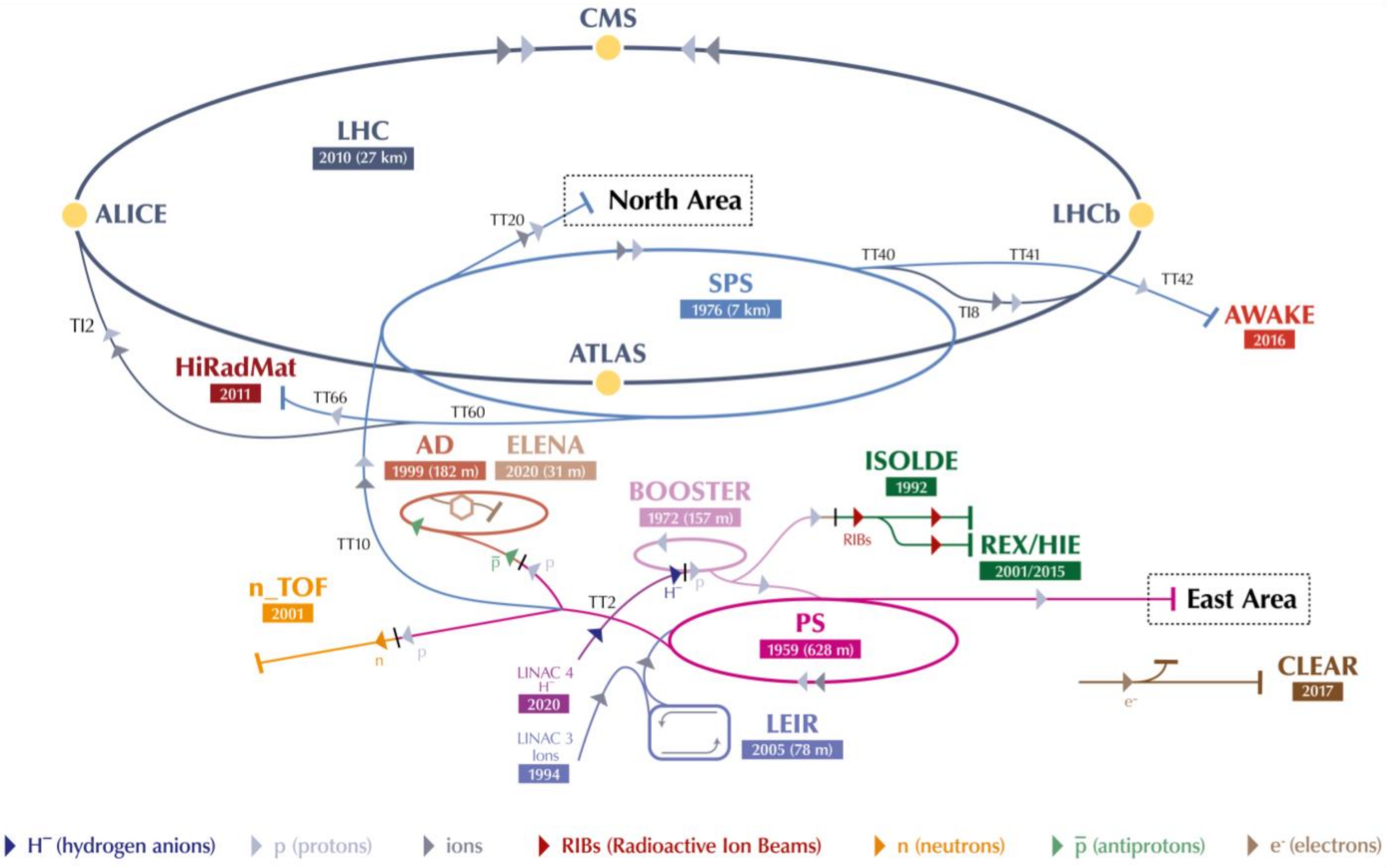


Structure	size [m]	energy [GeV]
atom	$10 - 100$ Å ⇒ 10^{-10}	~10^{-5}
nucleus	10 ferm ⇒ 10^{-14}	~0.1
nucleons	1 fm ⇒ 10^{-15}	~1
quark	10^{-3} fm ⇒ 10^{-18}	**~10^{3}**
< quark	**10^{-4} fm ⇒ 10^{-19}**	**~10^{4}**

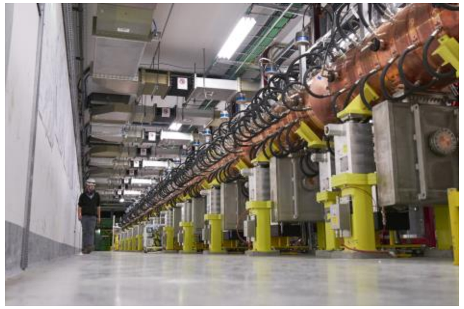
Energy of LHC!

The CERN Accelerator Complex

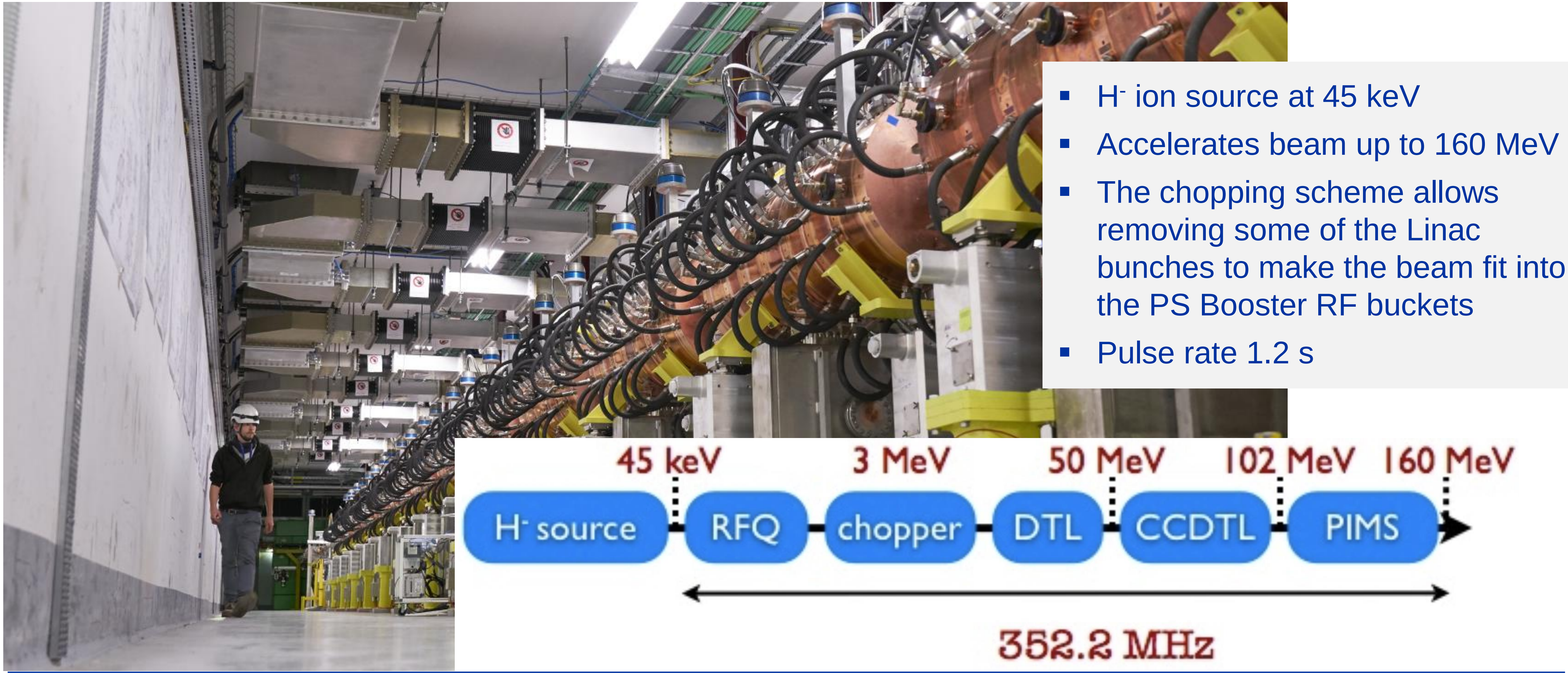







The LINAC 4

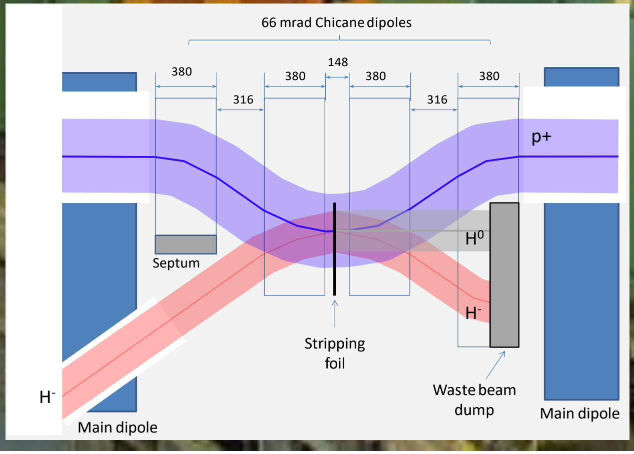
Proton source and linear acceleration

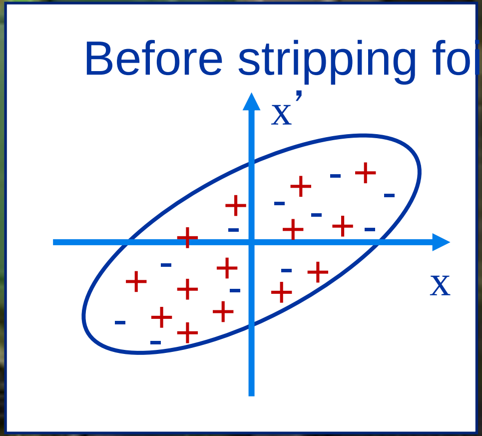


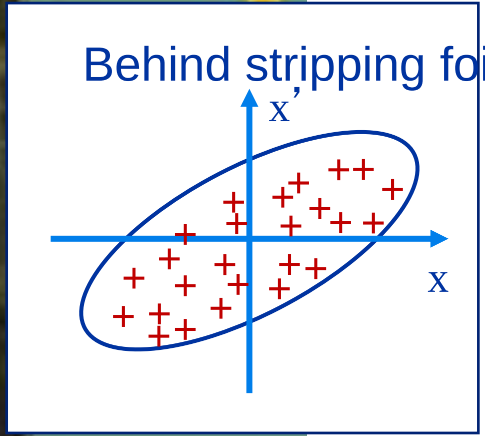
- H^- ion source at 45 keV
- Accelerates beam up to 160 MeV
- The chopping scheme allows removing some of the Linac bunches to make the beam fit into the PS Booster RF buckets
- Pulse rate 1.2 s

The LINAC 4
Proton acceleration

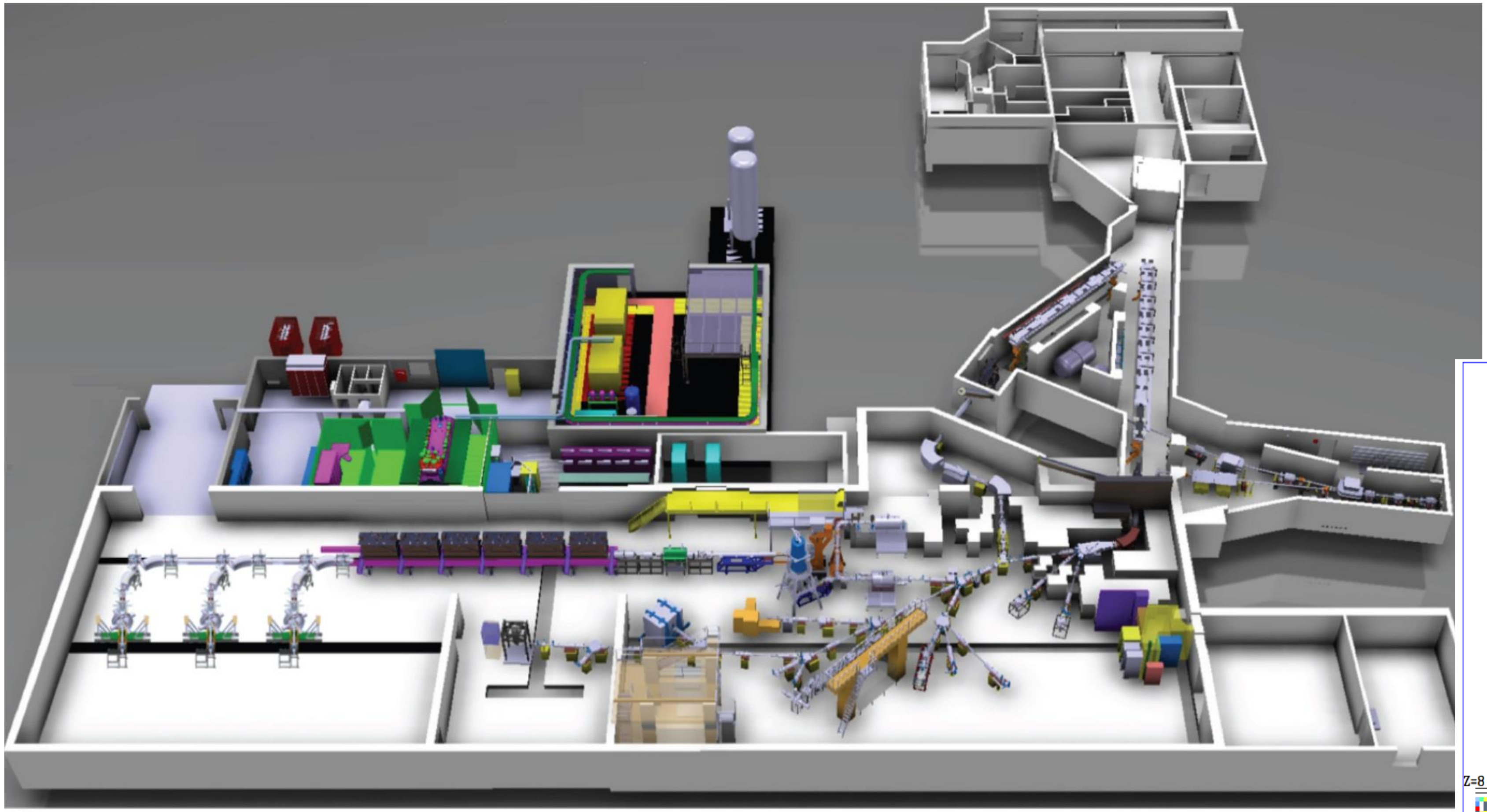
- 1st Synchrotron with 4 superposed rings
- Circumference of 157 m
- Proton energy from 160 MeV to 2 GeV
- Can cycle every 1.2 s
- Each ring will inject over multi-turns, using charge exchange injection

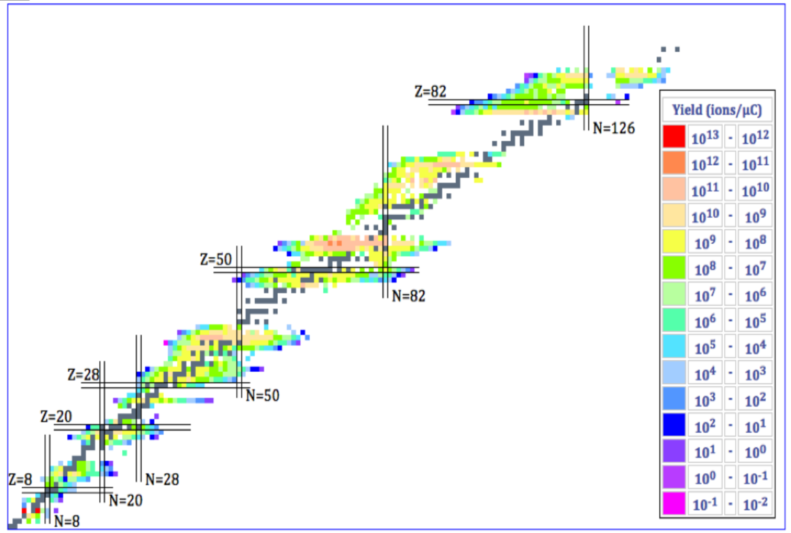






The ISOLDE Facility
Radioactive Ion Beam production and Acceleration

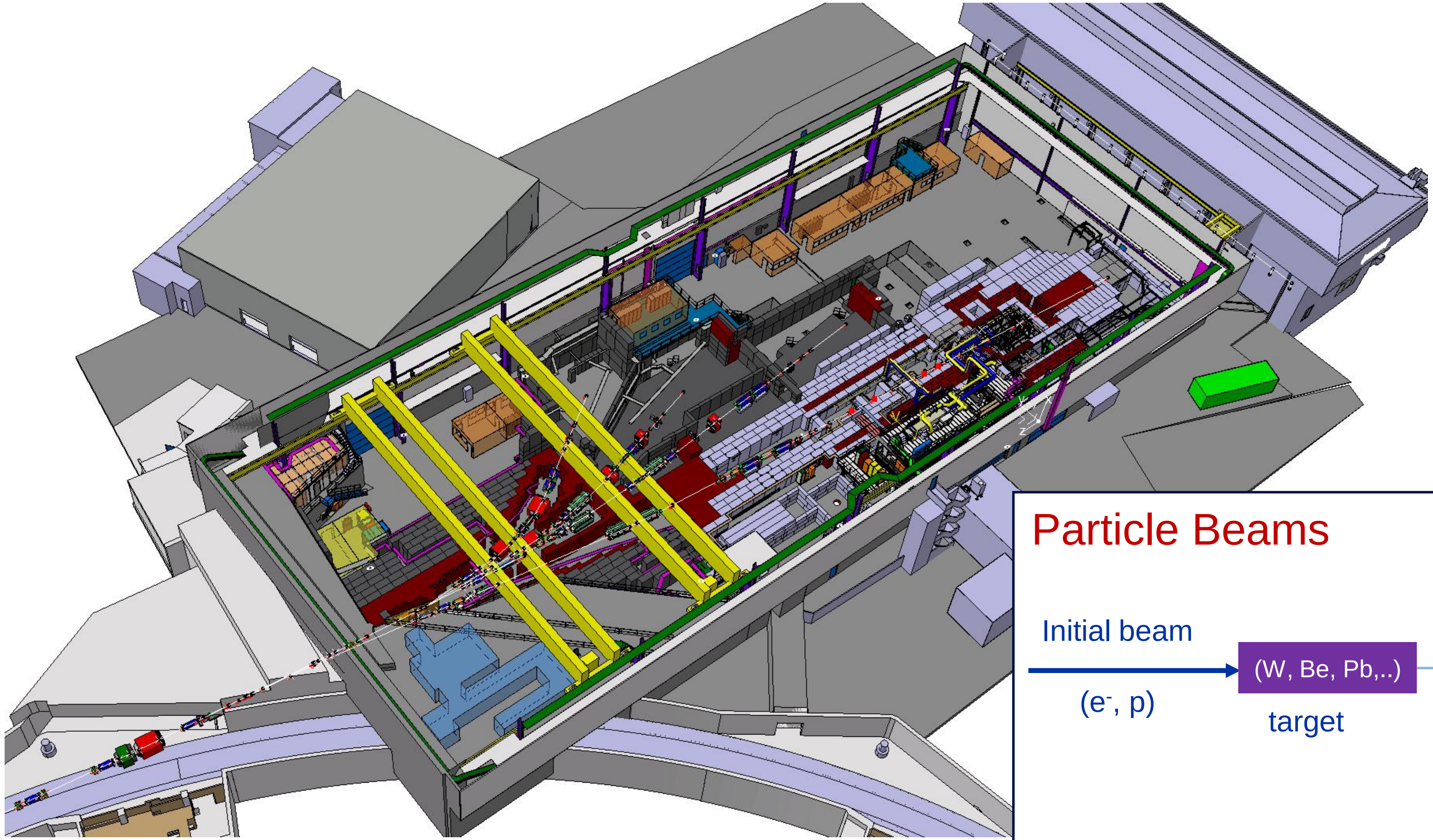


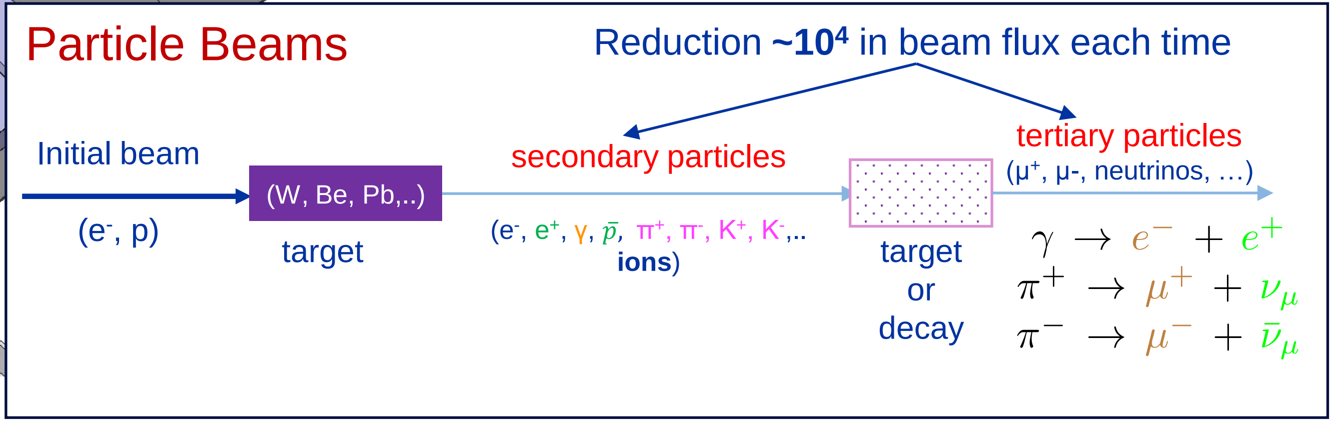


The PS
Proton & ion acceleration

- The oldest operating synchrotron at CERN
- Circumference of 628m
  4 x PSB circumference
- Increases proton energy from 2 GeV to max. 26 GeV
- Cycle length ranges from 1.2s to 3.6s
- Many RF systems allow for complex RF gymnastics
- Various types of extractions:
  Fast extraction
  Multi-turn extraction (MTE)
  Slow extraction

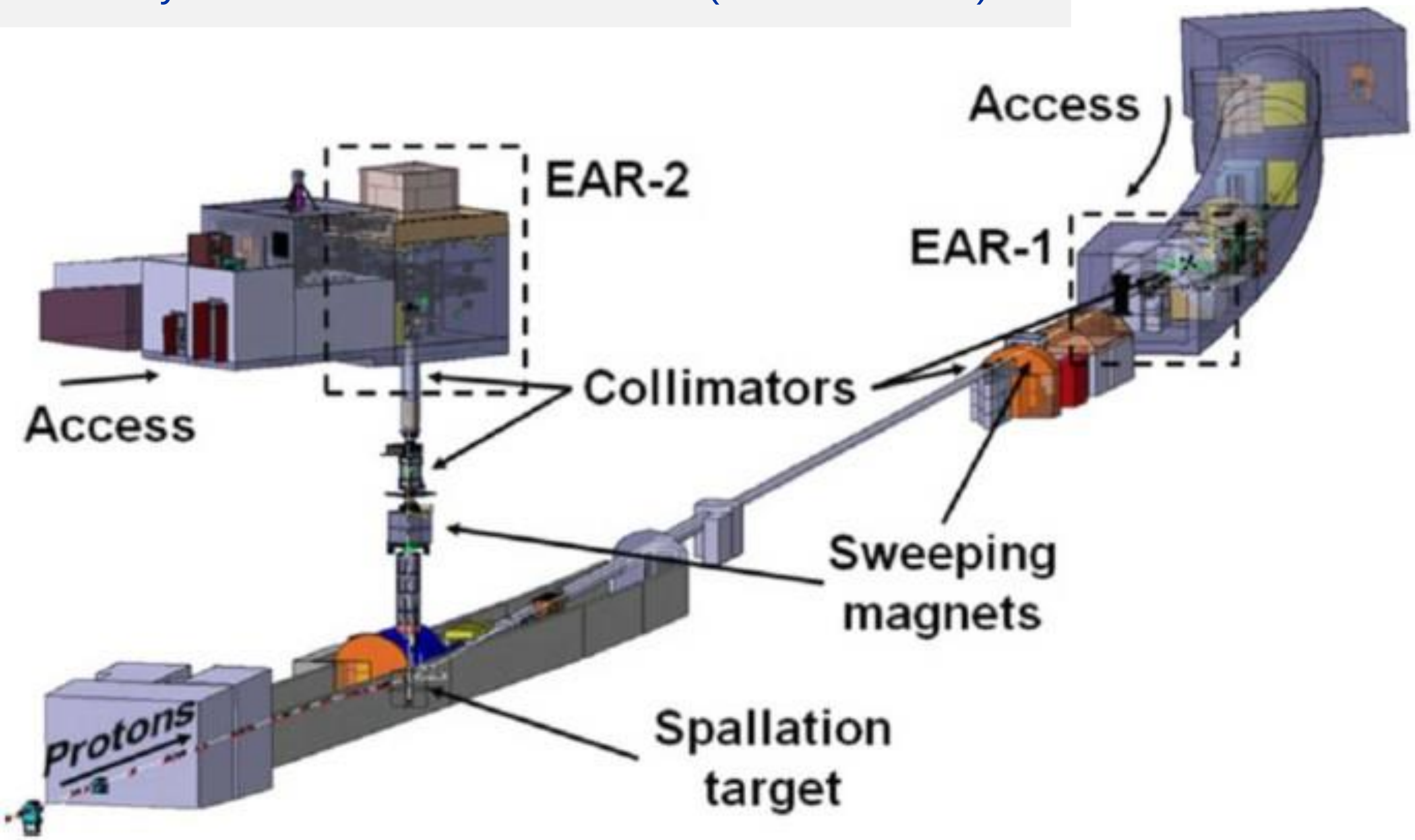
The PS East Area
Proton extraction – secondary beams, experiments

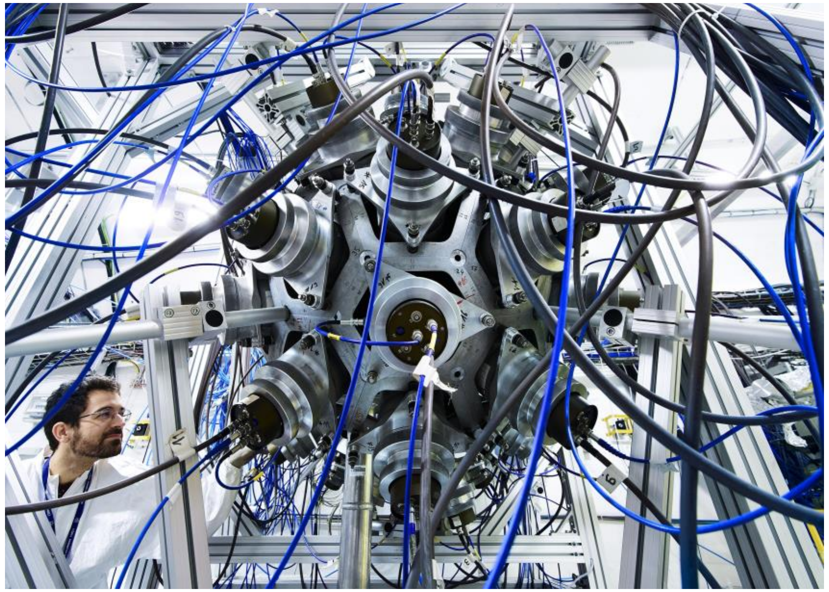




The nTOF
Proton extraction – neutron beam

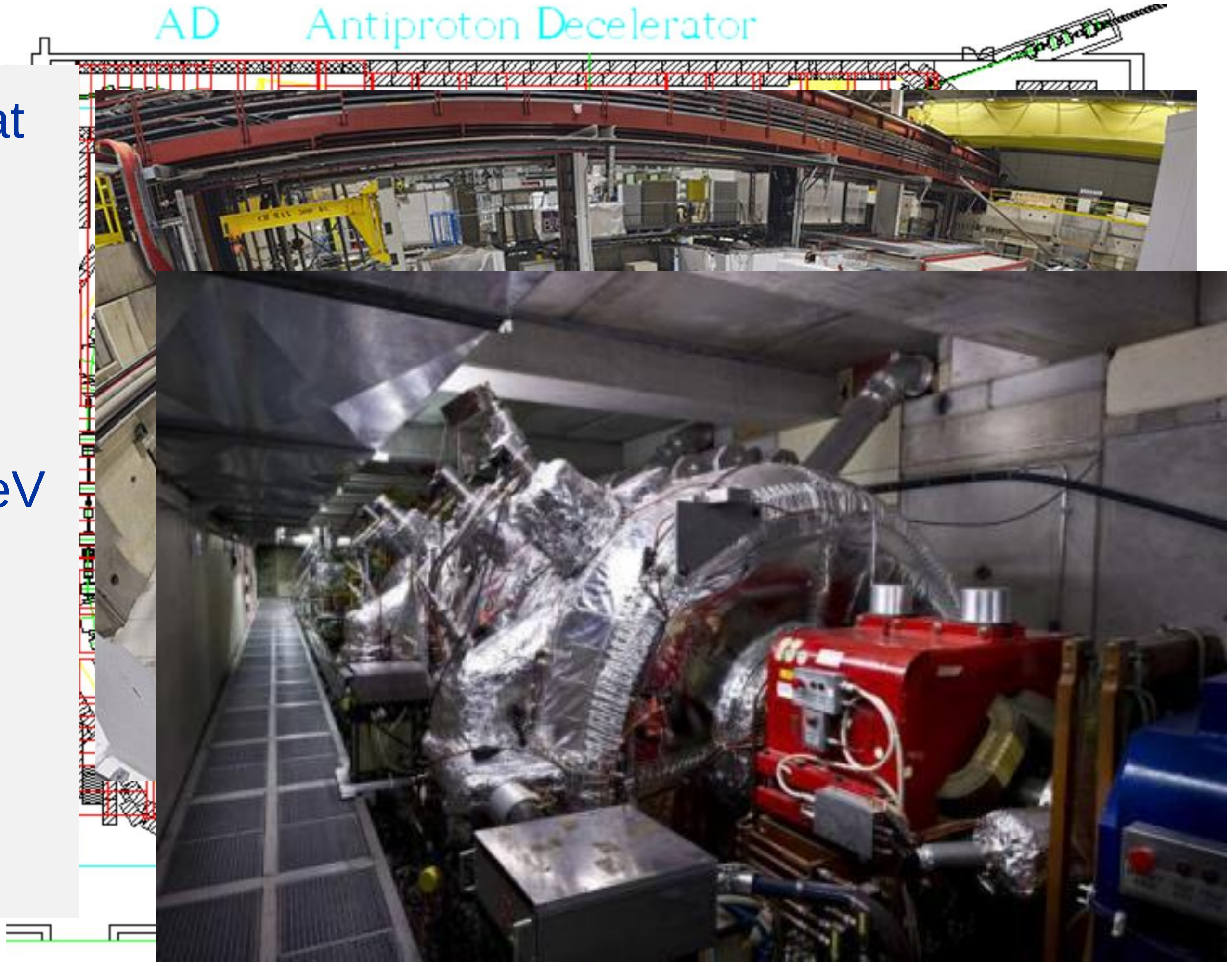
- Study neutron-nucleus interactions (cross-sections)





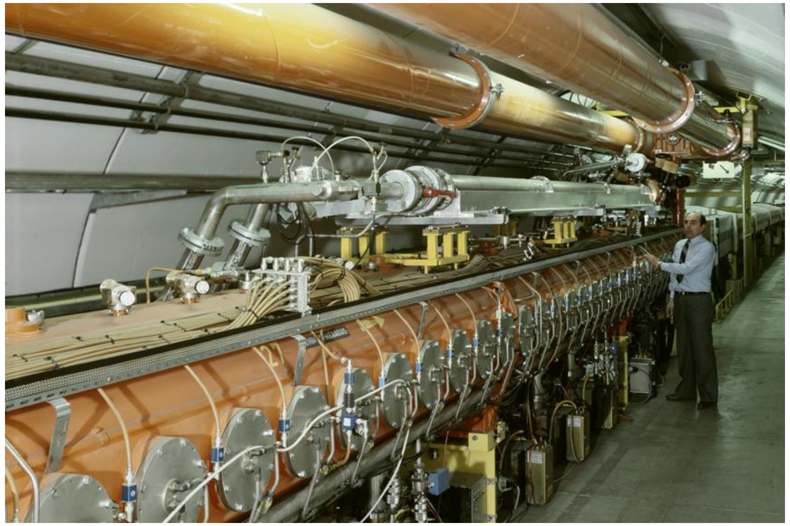
The Antimatter Factory (AD – ELENA)
Anti-proton beams - deceleration

- Receives fast extracted proton beam from PS at 26 GeV/c on a target
- Every million protons yields about one usable antiproton at 3.5 GeV/c.
- AD decelerates beam in stages down to 5.3 MeV
- ELENA will further decelerate down to 100 keV
- Experiments:
  ASACUSA, ALPHA, AEGIS, BASE, GBAR,
  PUMA



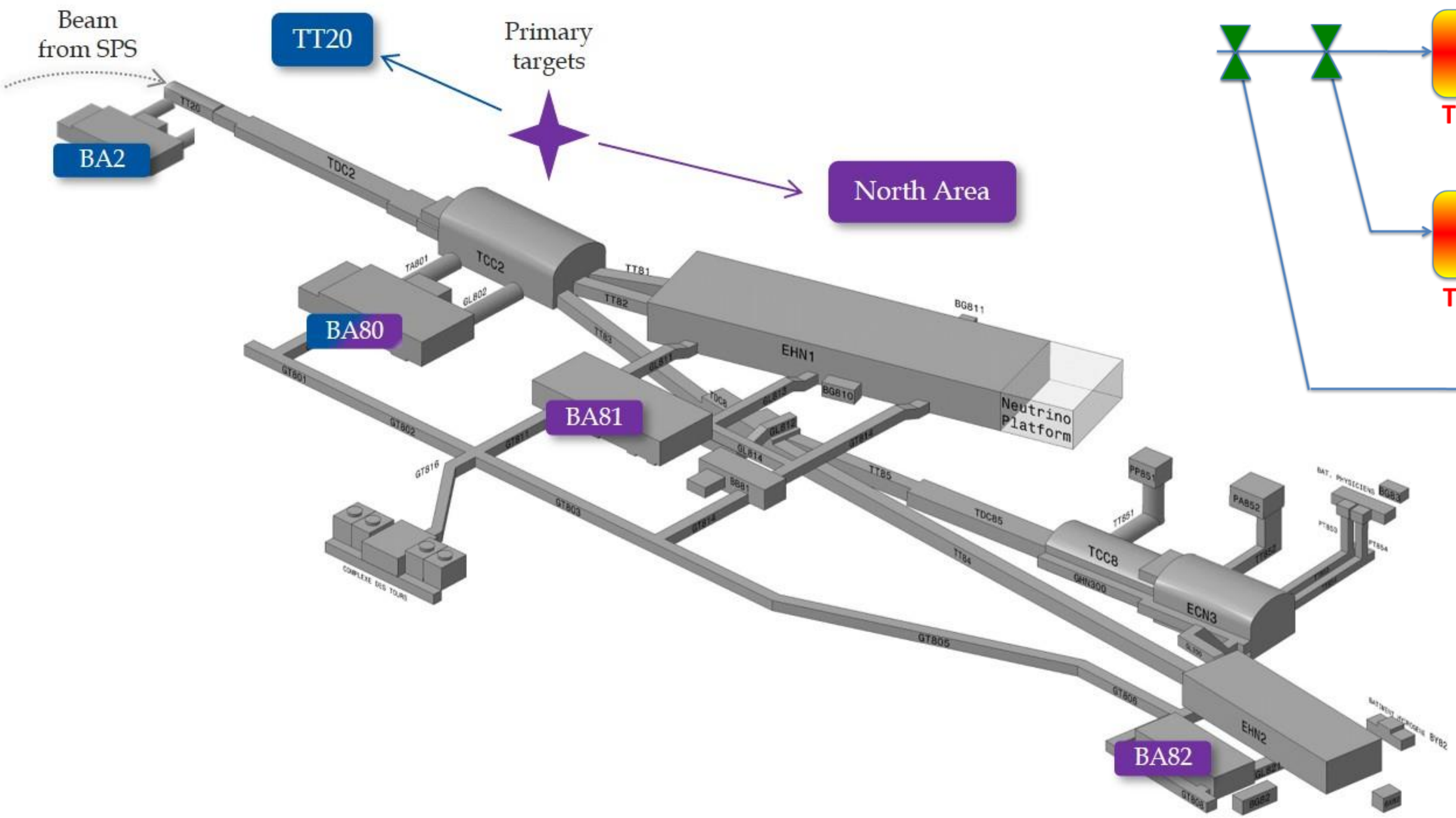
The SPS
Proton & Ion acceleration

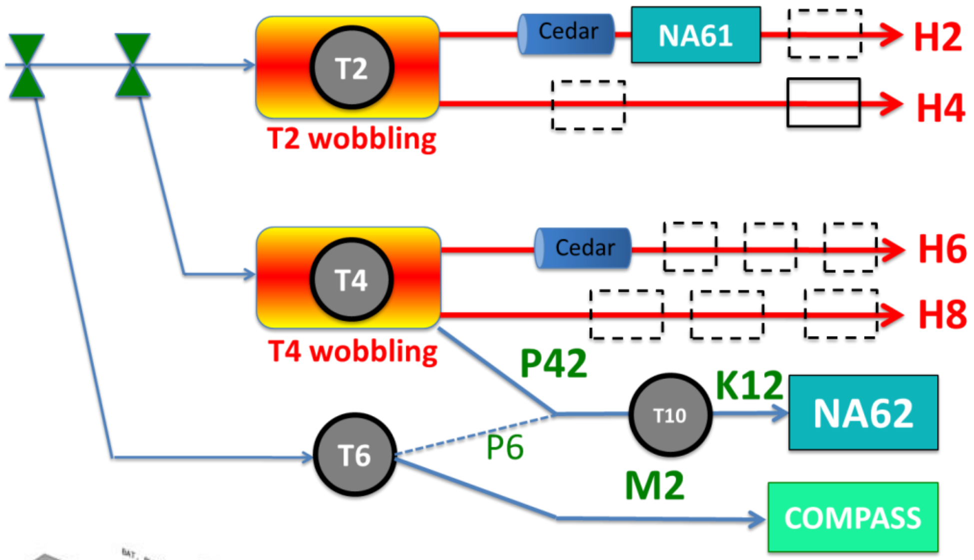
- The first synchrotron in the chain at ~30m under ground
- Circumference of 6.9 km
  - 11 x PS circumference
- Increases proton beam energy up to 450 GeV with up to ~$5x10^{13}$ protons per cycle
- Provides slow extracted beam to the North Area and fast extracted beam to LHC, AWAKE and HiRadMat



The SPS North Area

Particle beams – Fixed target experiments

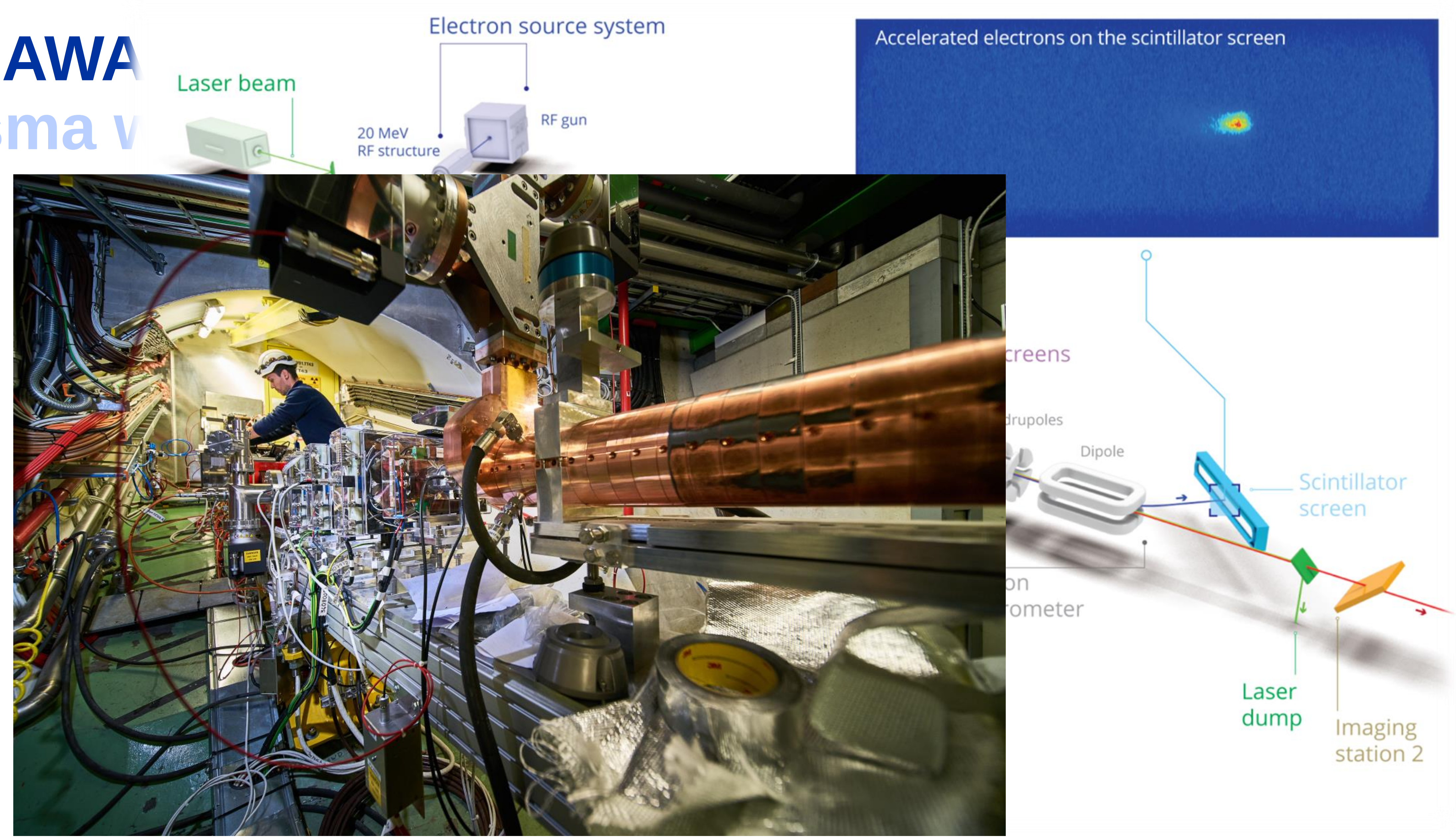




Fixed target physics:

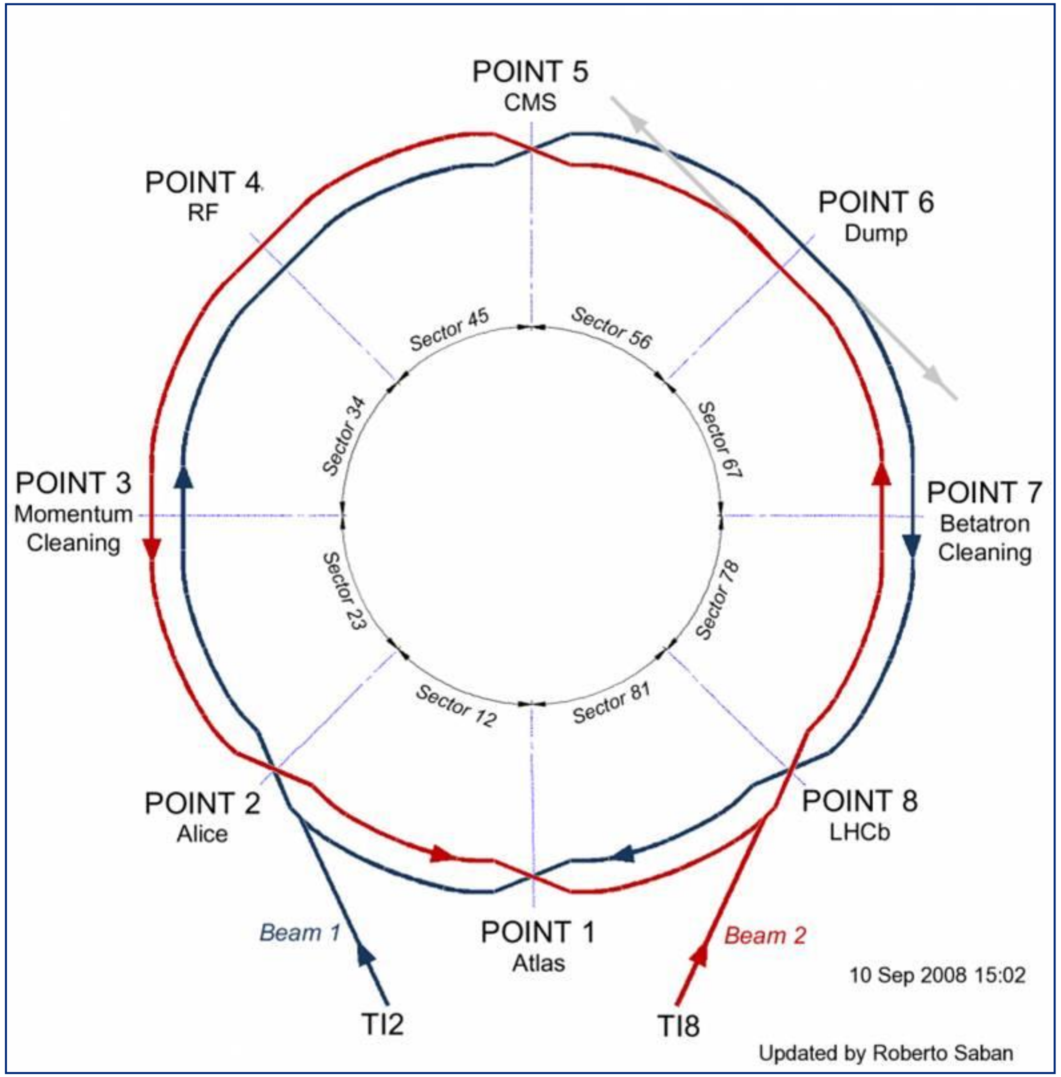
$$E_{CM} = \sqrt{2E_b m_T c^2}$$

The AWA
Plasma w

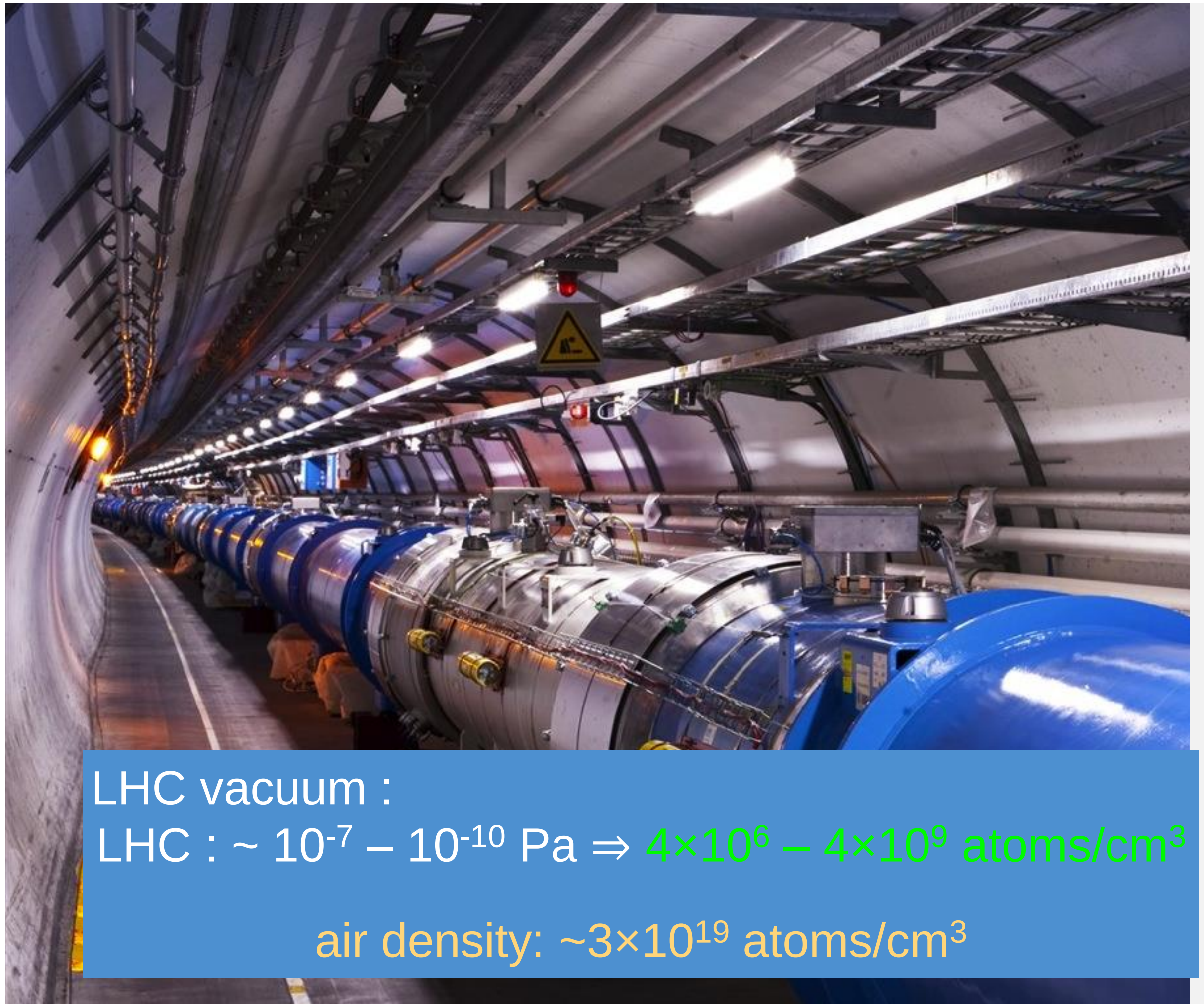


The LHC
Proton & ion beam collider

- Situated on average ~100 m under ground
- Four major experiments
- Circumference 26.7 km
- Two separate beam pipes going through the same cold mass 19.4 cm apart
- 150 tons of liquid helium to keep the magnets cold and superconducting



The LHC
Proton & ion beam collider



LHC vacuum :
LHC : ~ 10^{-7} – 10^{-10} Pa ⇒ 4×10^{6} – 4×10^{9} atoms/cm^{3}

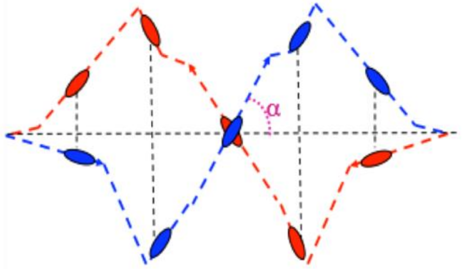
air density: ~3×10^{19} atoms/cm^{3}

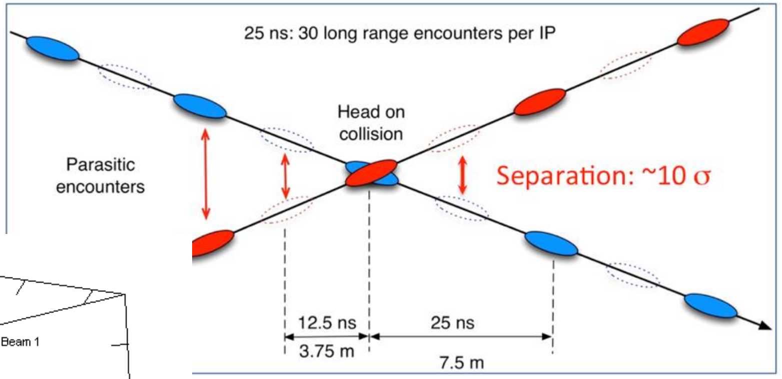
- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality
- Main magnets use superconducting cables (Cu-clad Nb-Ti)
- 12’000 A provides a nominal field of 8.33 Tesla
-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

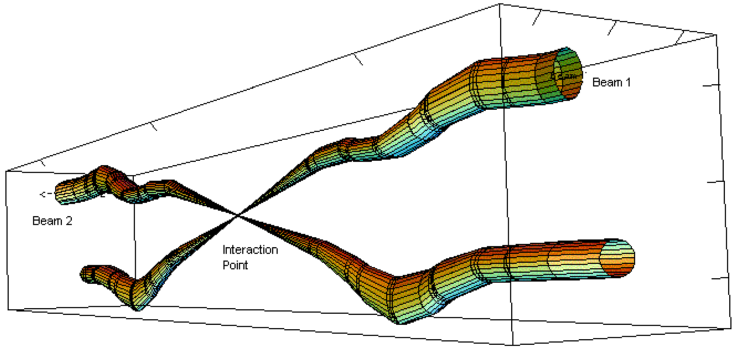
The LHC

Proton & ion beam collider

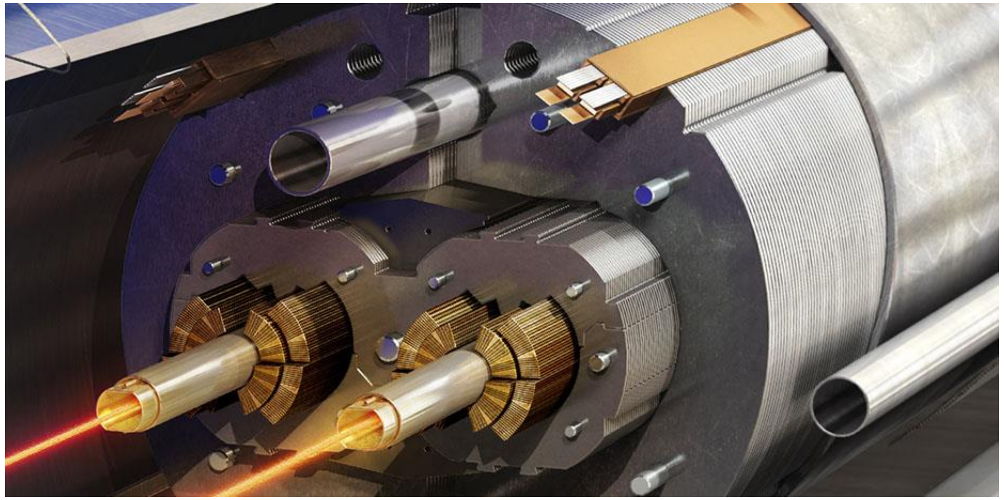
Beam collisions

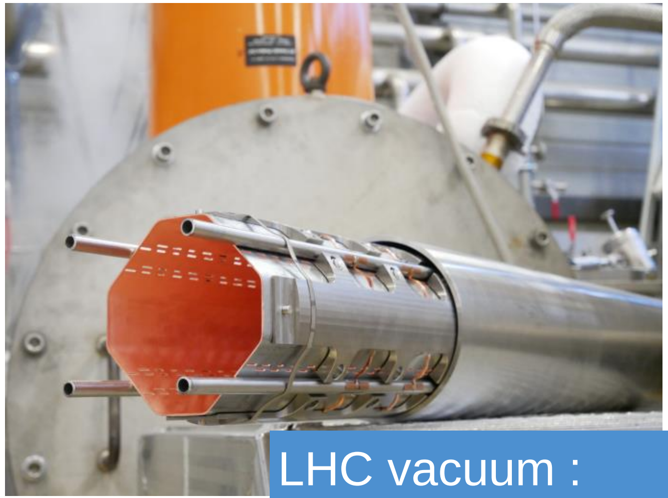






Relative beam sizes around IP1 (Atlas) in collision





LHC vacuum :

$\sim 10^{-7} - 10^{-10}$ Pa or

$4\times10^{6} - 4\times10^{9}$ atoms/cm^3

air density: $\sim3\times10^{19}$ atoms/cm^3

The LHC

LHC Beam Collisions and Luminosity

- **In a collider the figure of merit for the performance is the Luminosity**

$$N_{exp} = \sigma_{exp} \times \int \mathcal{L}(t)dt$$

Events in experiment

cross-section for the process under stydy **the physics**!

beam luminosity **accelerator**

Protons/bunch

bunches

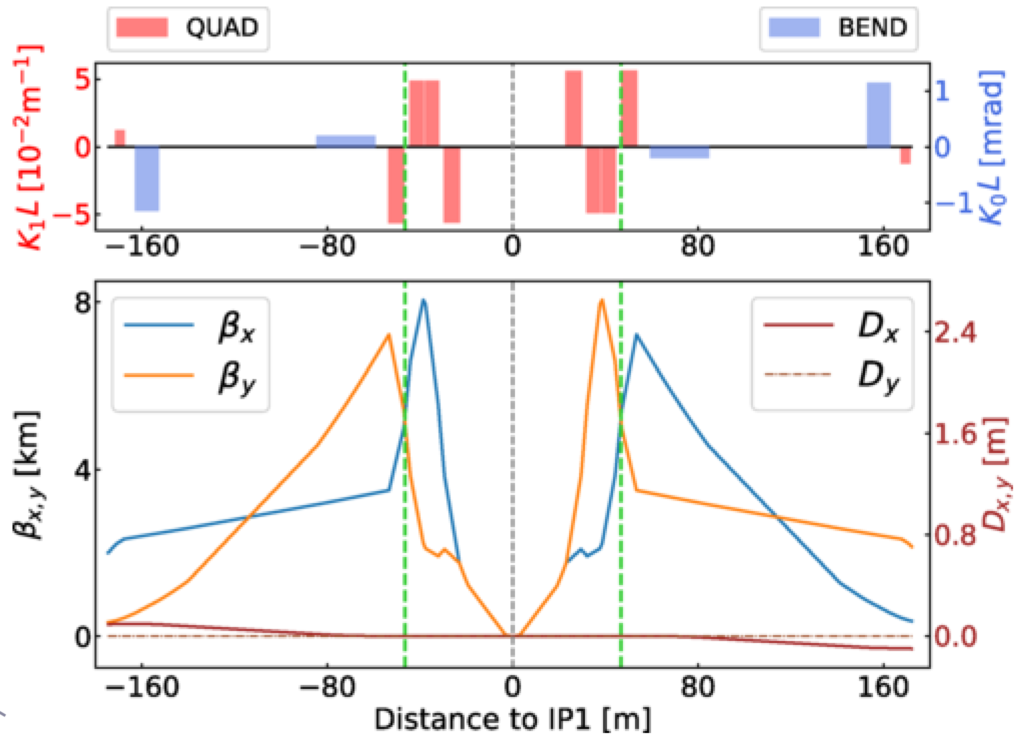
$$\mathcal{L} = f_{rev}\, M_{KLF}\, \frac{k_b\, N_1\, N_2}{4\pi\, \sigma_x\, \sigma_y}\, S\, F$$

Kinematic of the collision

transverse beam size

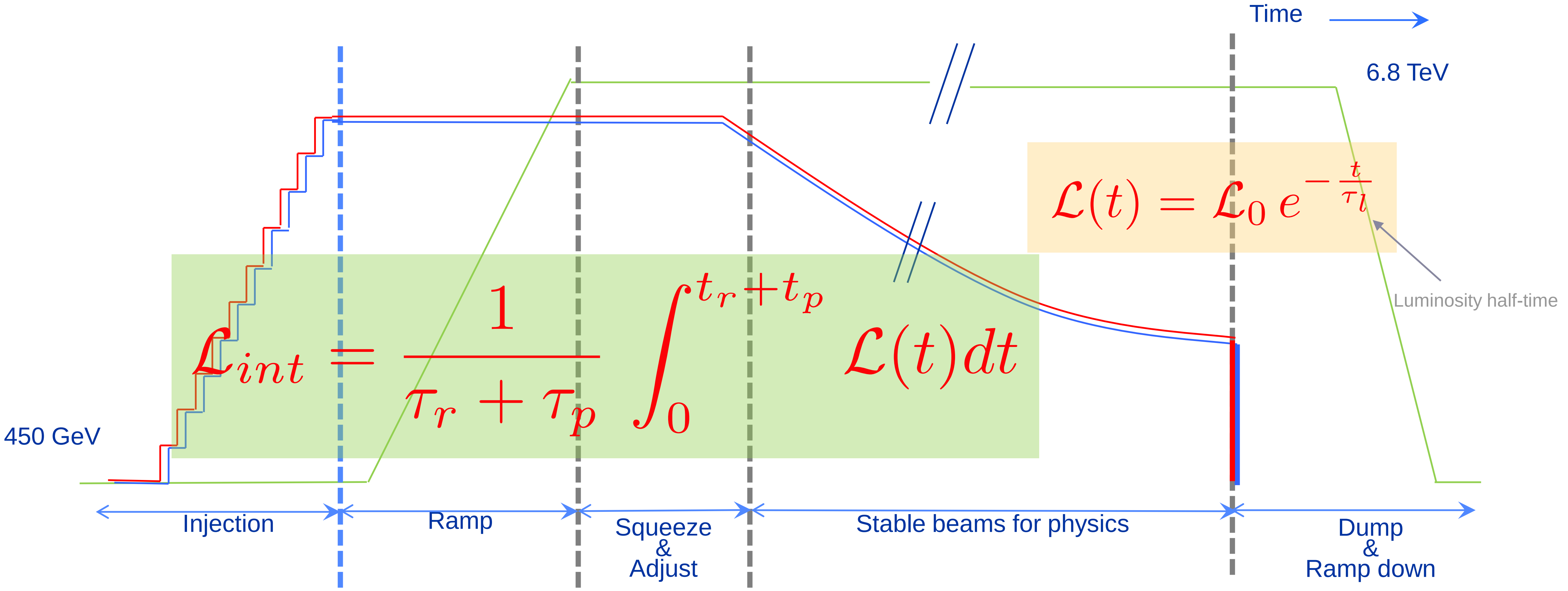
geometry of the collision

geometry of collision (impact parameter)

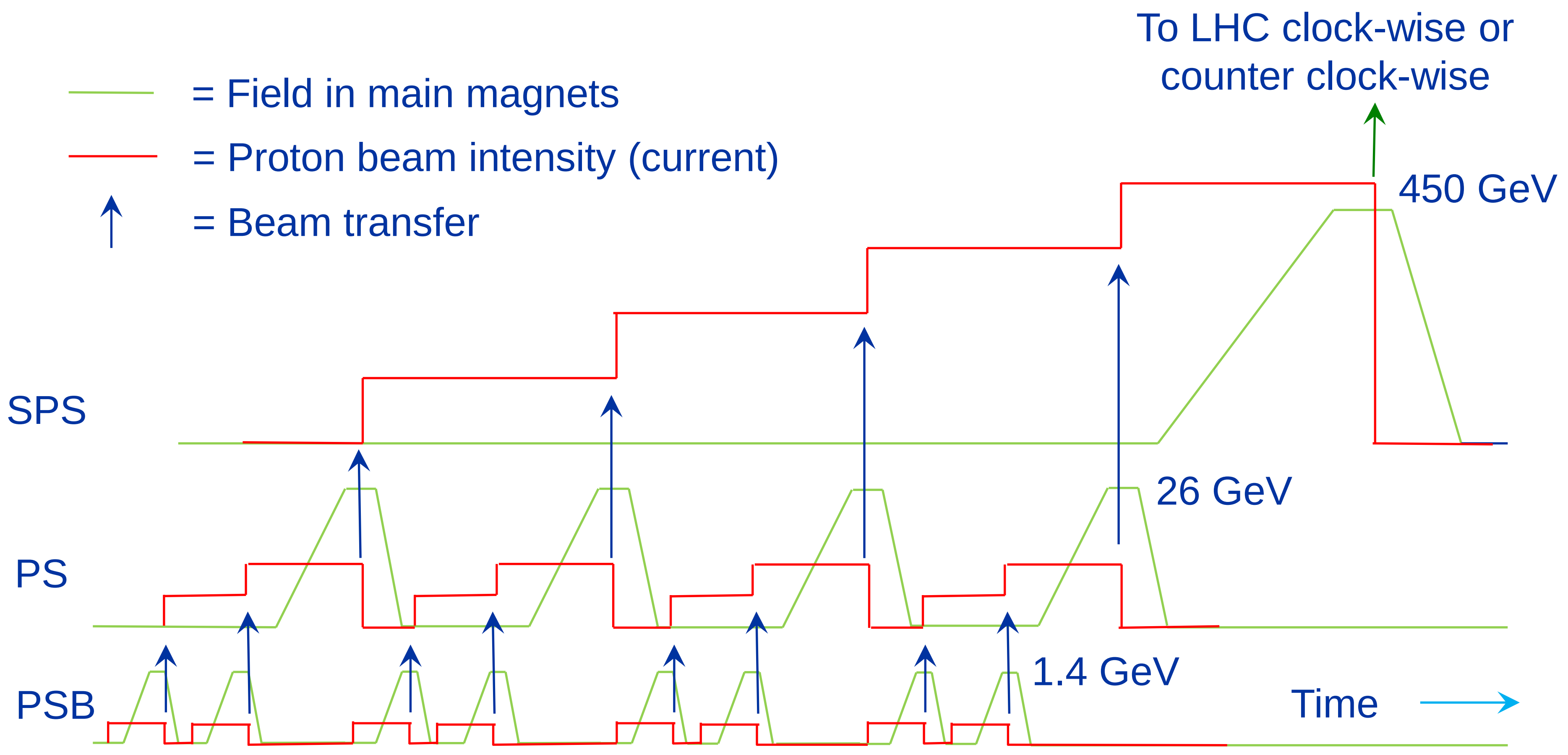


The LHC
Operation beam cycle

= Field in main magnets
= Beam 1 intensity (current)
= Beam 2 intensity (current)



The LHC
Operation – beam filling in injectors



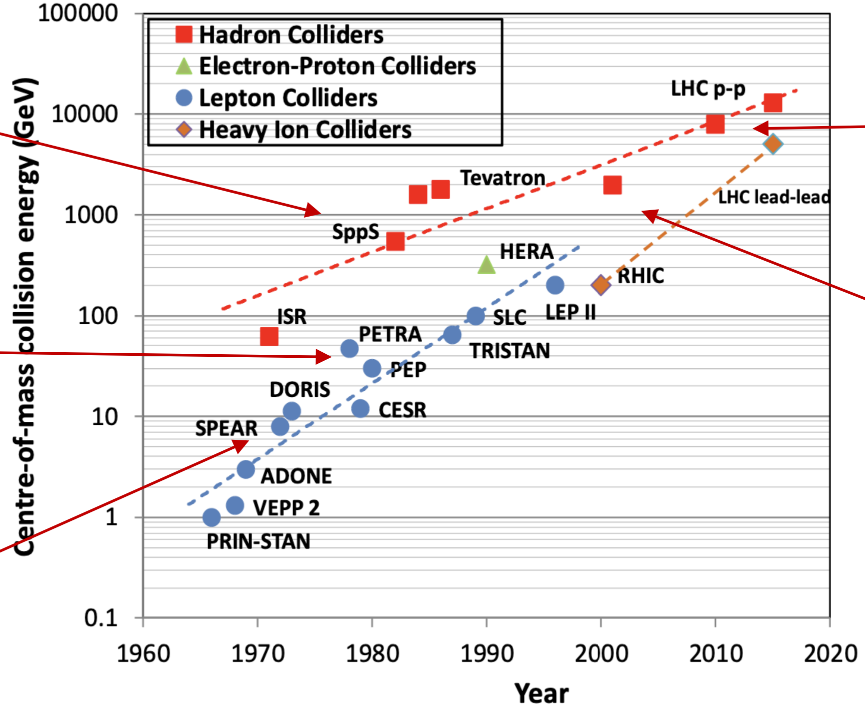
The evolution of accelerators
…the past

- **The accelerators played a pivotal role in the foundation of the Standard Model**

SppS
- W,Z bosons

PETRA
- gluon

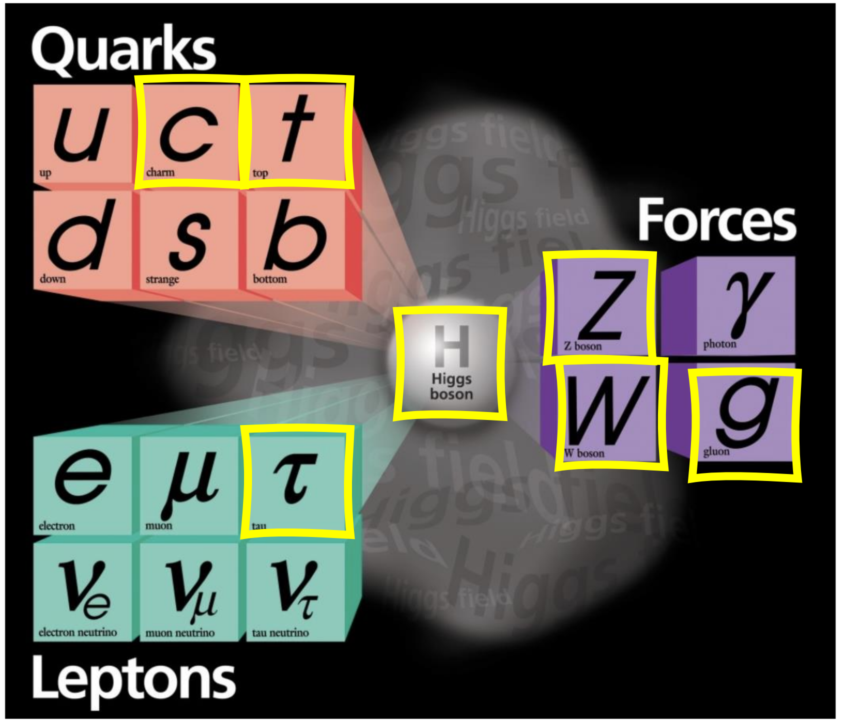
SPEAR
- c-quark
- τ-lepton



LHC
- Higgs

Tevatron
- t-quark

Standard Model
Particles and forces

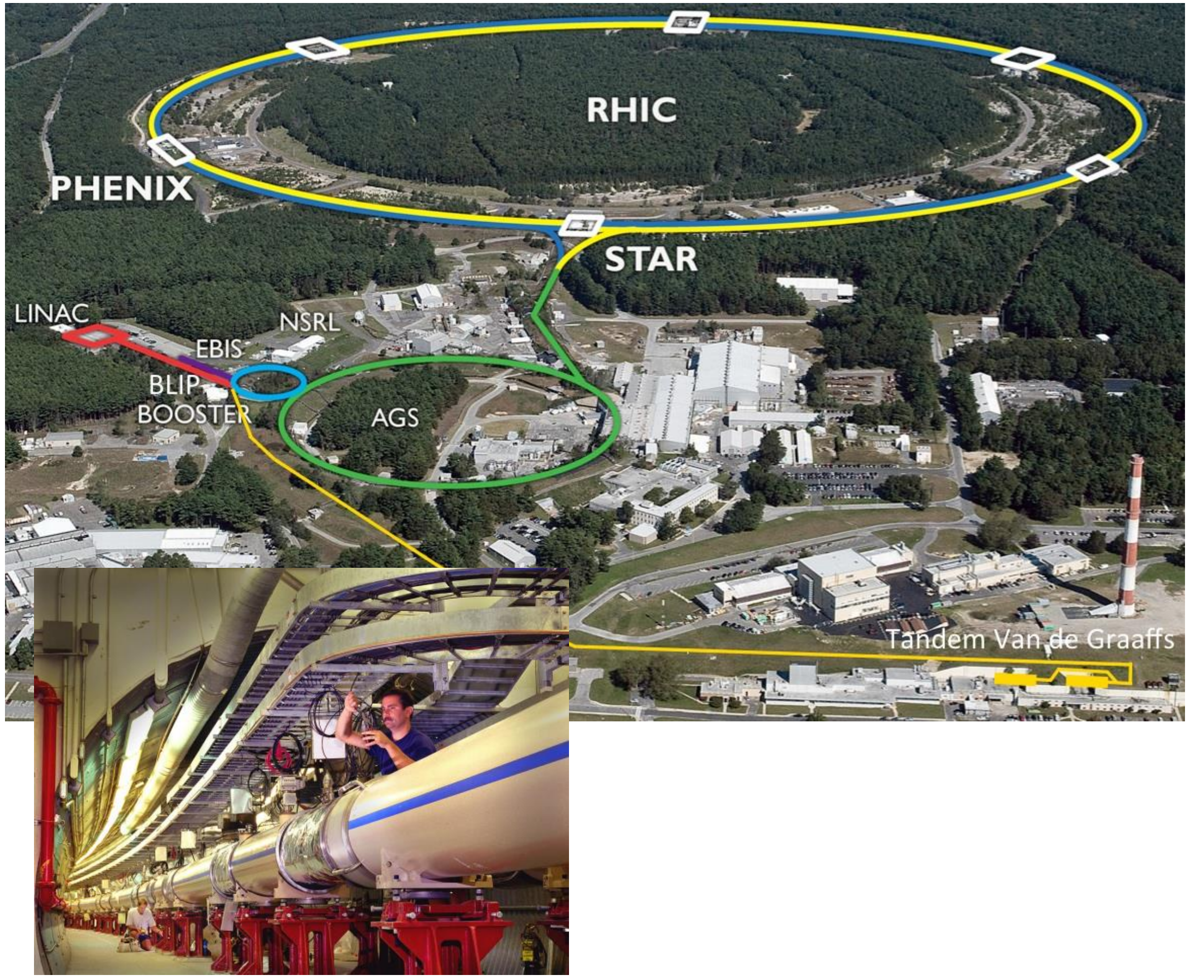


The evolution of accelerators
… the present

Brookhaven National Lab (BNL) - USA

First use of super-conducting cables in the design of magnets, access to high-magnetic fields

- **Ion collider** (Au, Cu, … ions) energies up to 100 GeV/u
- Length ~4 km, 1740 magnets
- 4 experiments (BRAHMS, PHENIX, PHOBOS, STAR)
- Basic research for quark-gluon plasma as part of the creation of the Universe
- Plans for the construction and operation of EIC – Electron-Ion collider

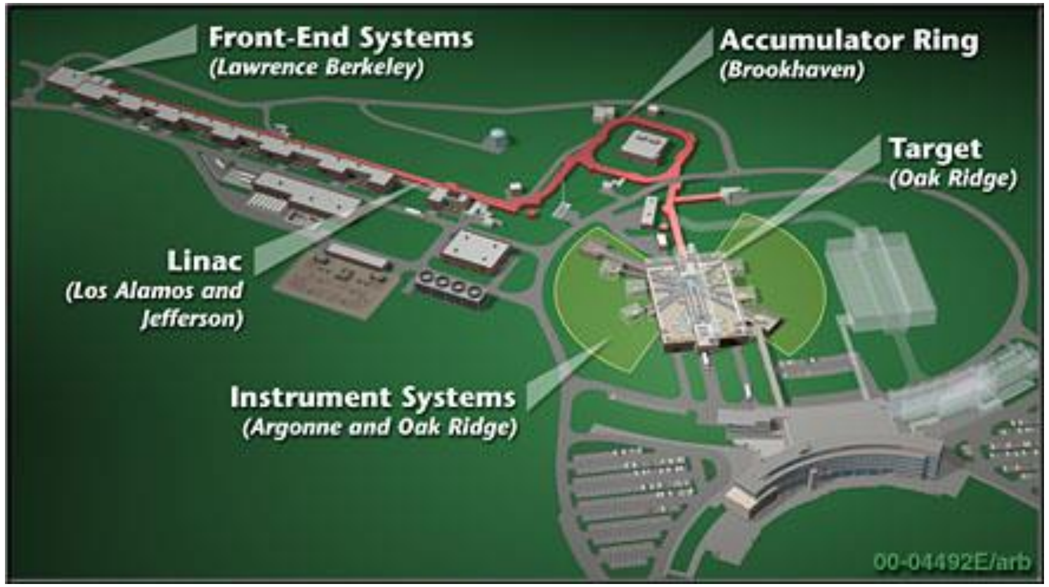


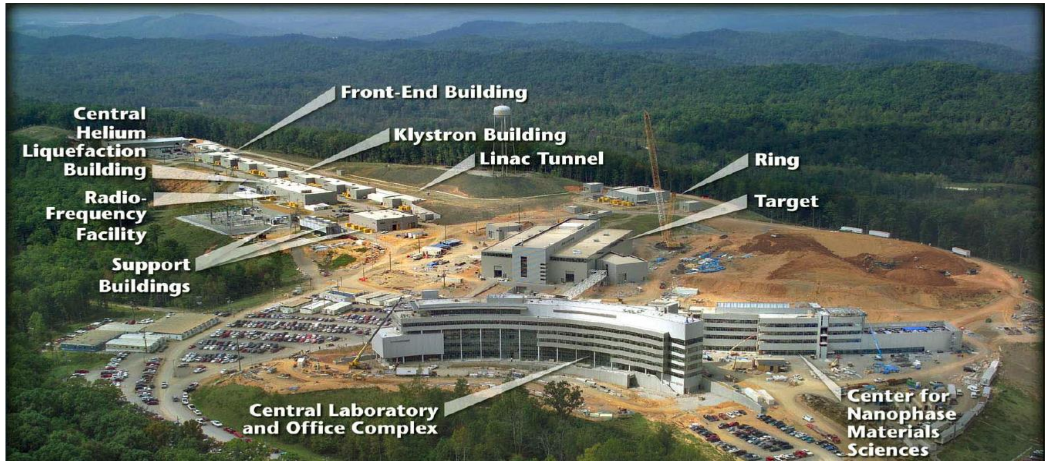
The evolution of accelerators
… the present

Spallation Neutron Source (SNS), Oak Ridge - USA

- H- source (p+2e)
- 300m linear accelerator with superconducting RF
- accumulator ring (1 MW)
- Liquid mercury (Hg) target

- Scattering experiments with neutron beams, material studies, nano-materials, …

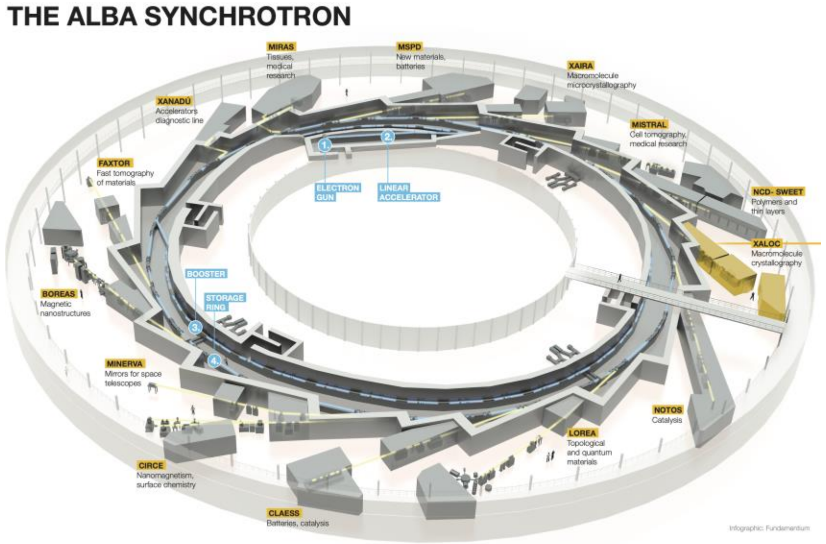




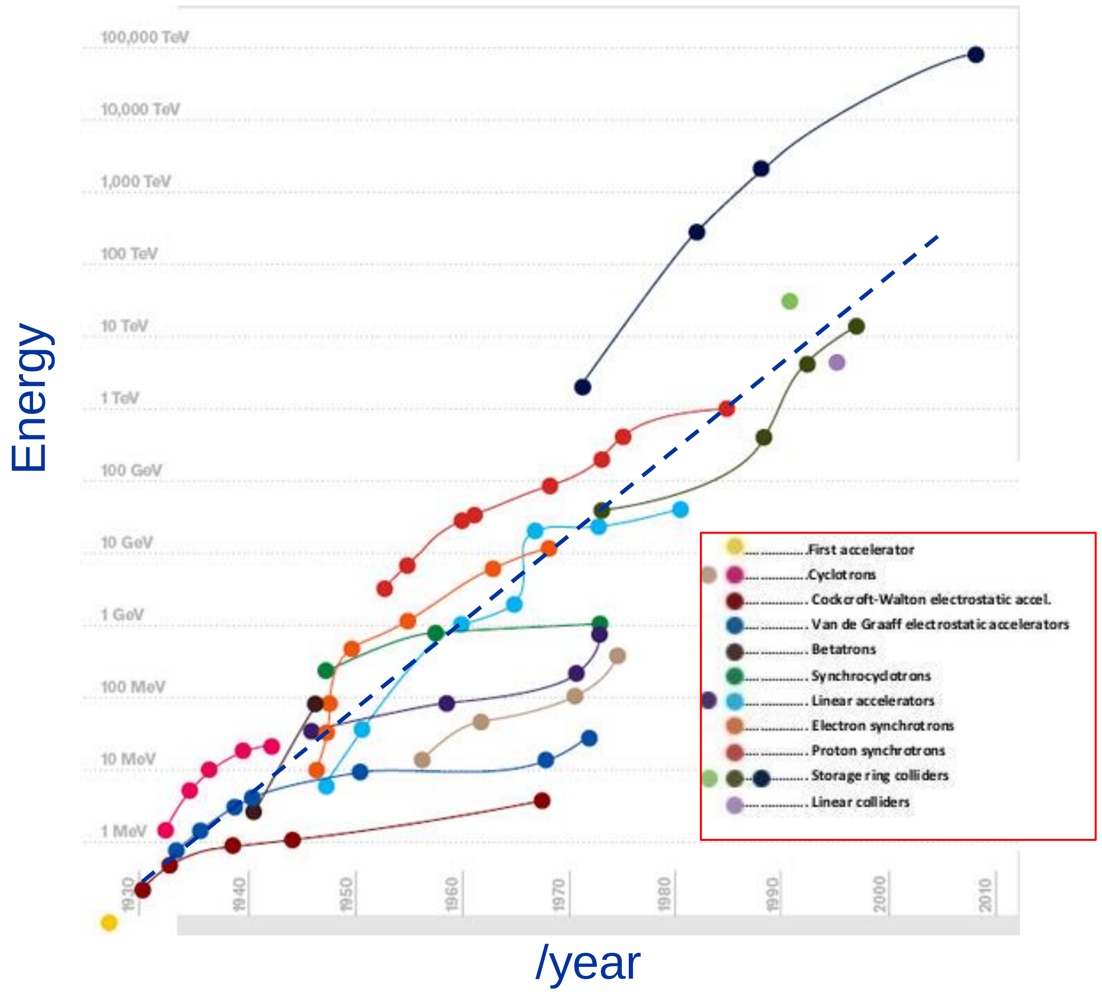
The evolution of accelerators
… the present

ALBA Synchrotron Light Facilities – Barcelona Spain

- 3rd generation synchrotron light, the newest center in the Mediterranean
- 3 GeV electron beams, 270m long ring
- Experiments with soft και hard X-rays
- Studies for bio-technology, material science, nano-technology
- 6’000 beam hours/year for the experiments, 2’000 users/year from Universities, Research Centers, and Industry.
  - 65% users from Spain, 35% from other countries



The evolution of accelerators
The Livingston diagram



- The Livingston graph shows the evolution of accelerators in the past century
- Until the end of 20th century, the achieved energy increased by an order of magnitude every 6-10 years
- New technologies emerge to replace or complement older ones

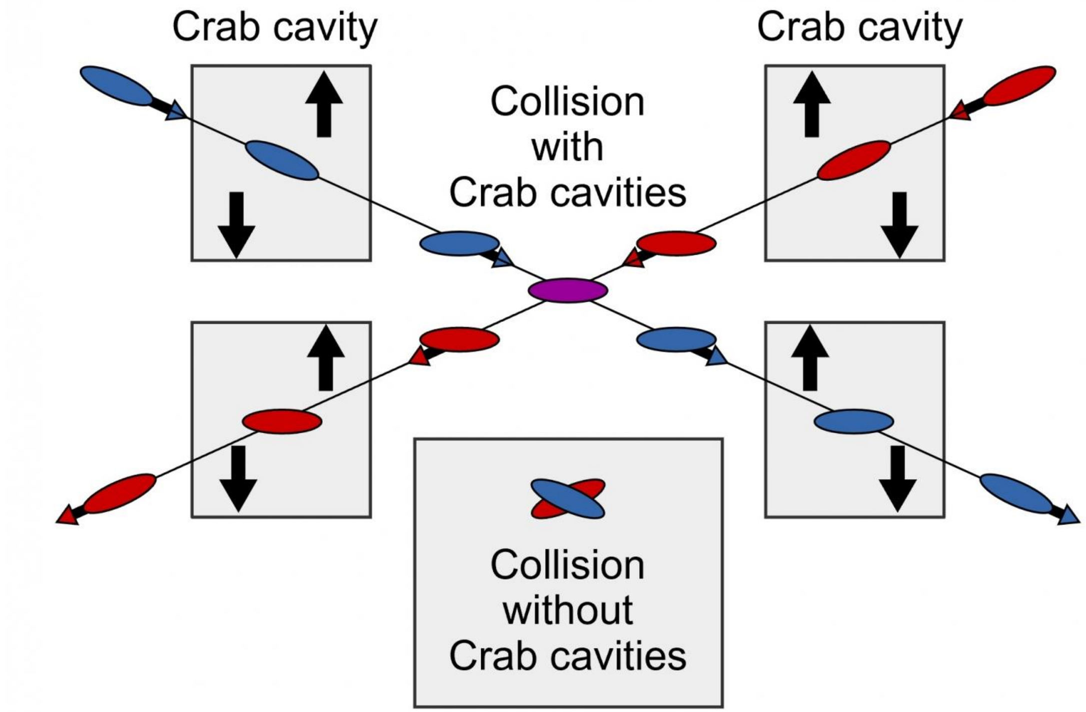
But:

- The beam energy is not the only performance figure for the accelerator evolution
- The beam intensity, beam size or brightness are also importan parameters, depending on the application

The evolution of accelerators
CERN – the HL-LHC upgrade

$$\mathcal{L} = f_{rev}\, M_{KLF}\, \frac{k_b\, N_1\, N_2}{4\pi\, \sigma_x\, \sigma_y}\, S\, F$$

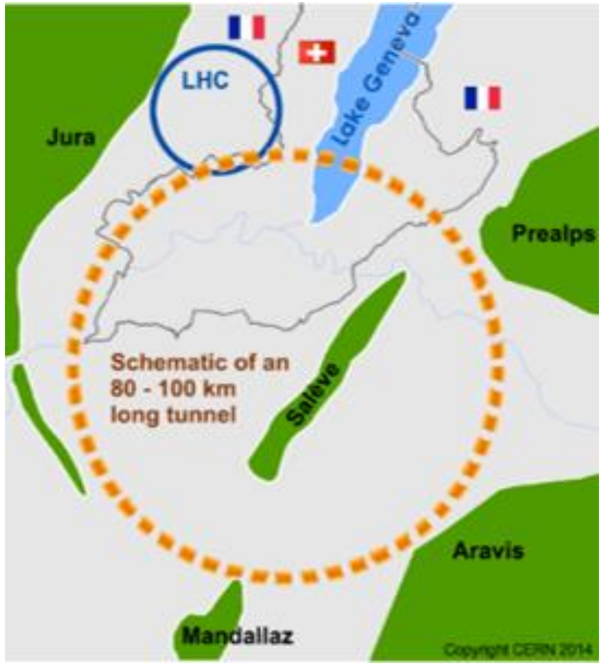
- The HL-LHC will use new technologies to provide 10 times more collisions than the LHC.
- Two fronts:
  - higher bunch intensity up to 2.1e11 ppb
  - crab crossing scheme
- Higher luminosity would give access to rare phenomena, greater precision and discovery potential.
- HL-LHC will start operating in 2028 and run until 2041.

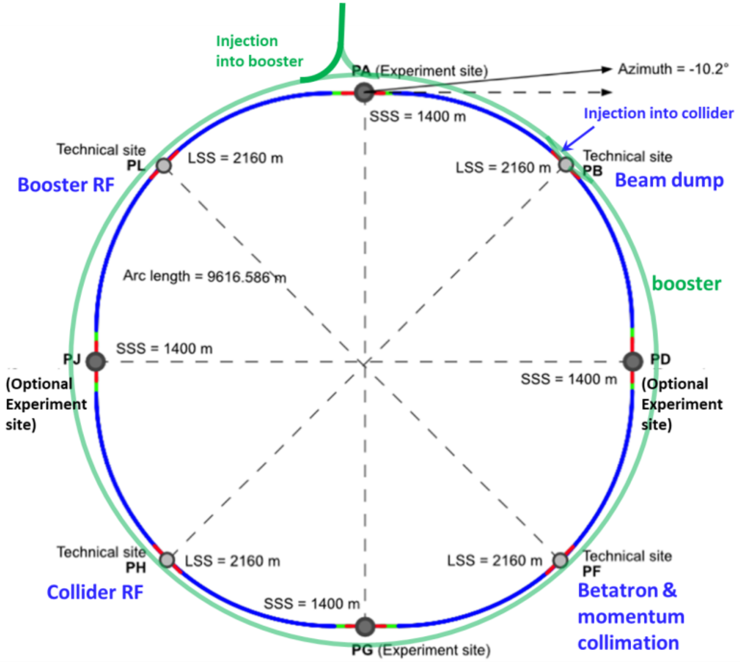


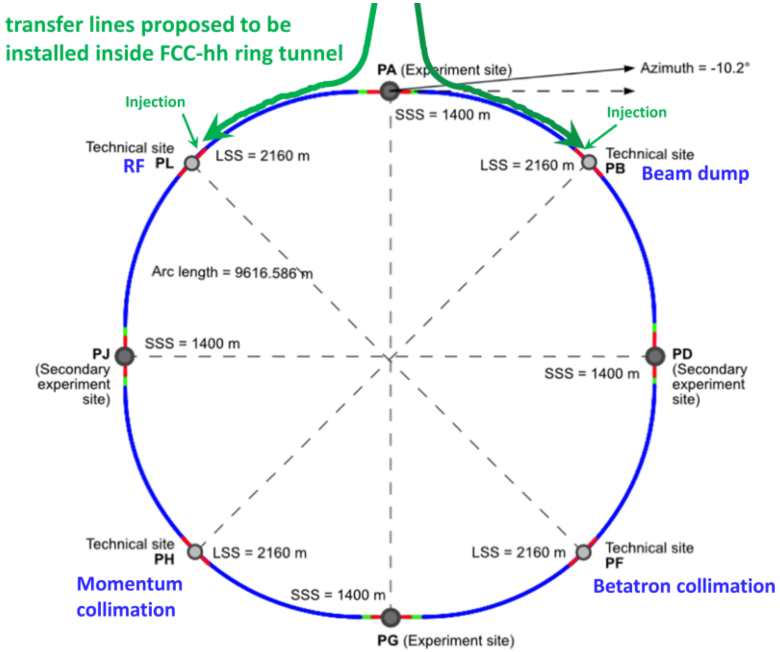
The evolution of accelerators
CERN – the high-energy frontier

FUTURE CIRCULAR COLLIDER

- **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, pp & AA collisions; e-h option**
- highly synergetic and complementary physics programme, common civil engineering and technical infrastructures
- FCC integrated project allows the start of a new, major facility at CERN within a few years of the end of HL-LHC

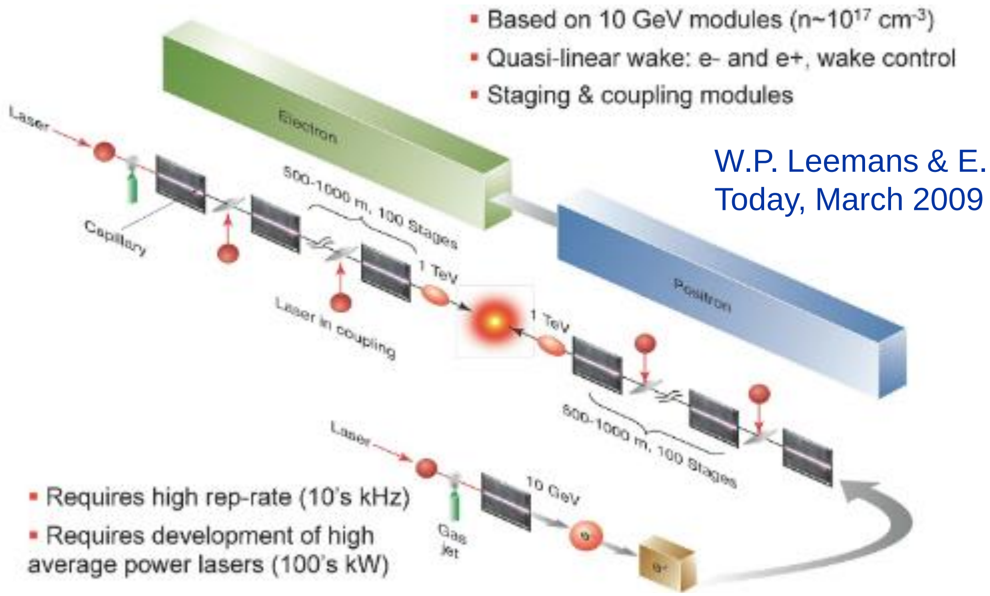




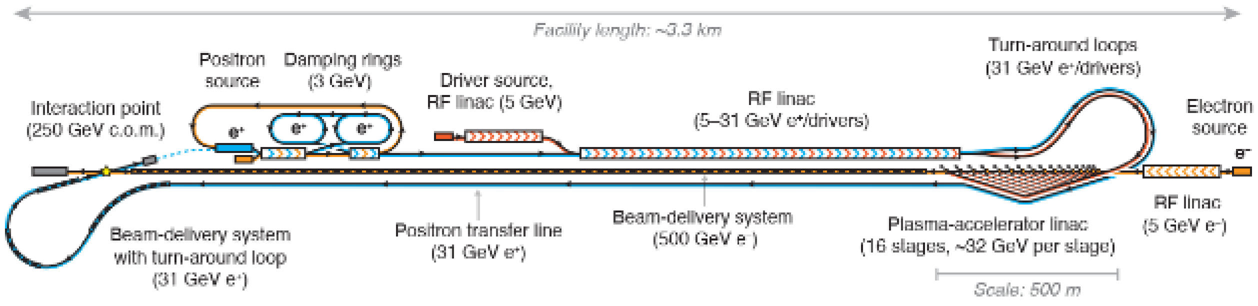


- 2040	2045 - 2060	2070 - 2095

The evolution of accelerators
… the future



W.P. Leemans & E. Esarey, Physics Today, March 2009



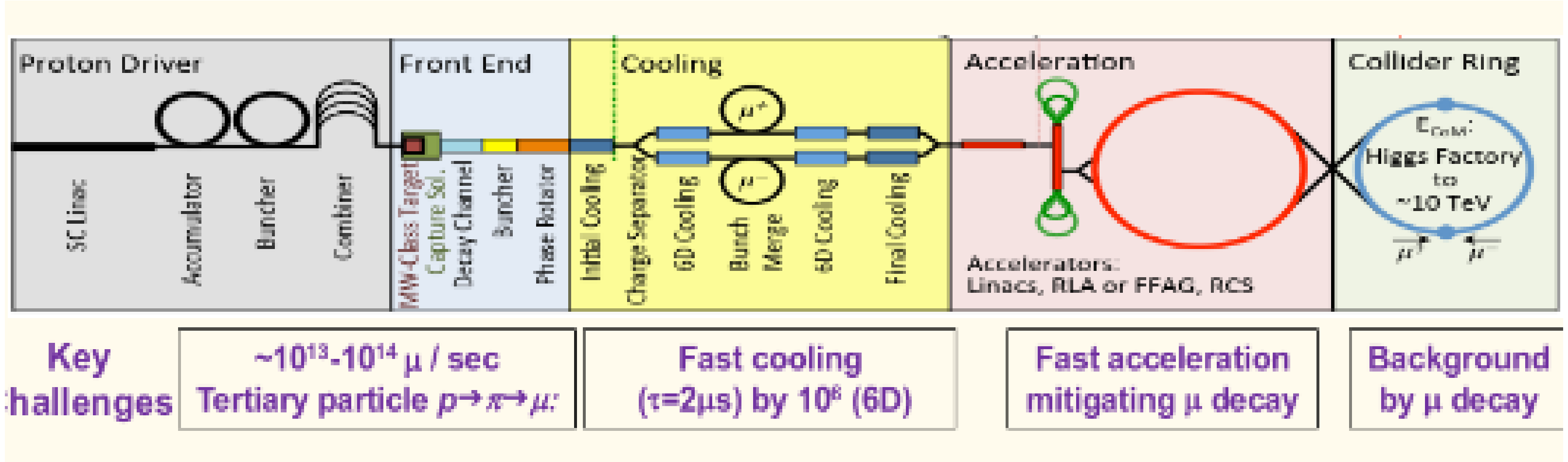
Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

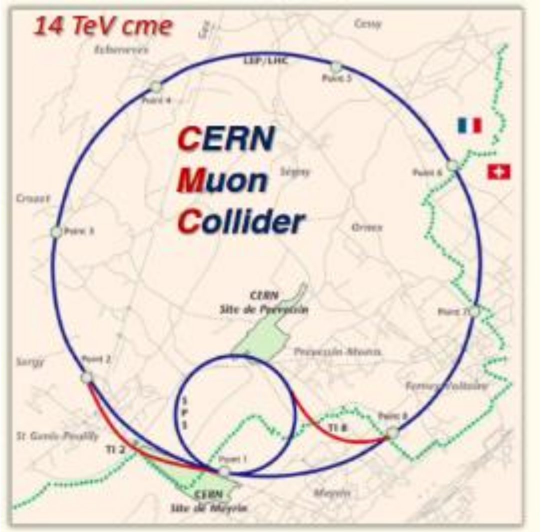
- **Linear electron accelerator with plasma wake-field technology as Higgs factory:** $e^+e^- \rightarrow H\,Z$ **(CM ~216 GeV)**
- **<u>Advantages:</u> acceleration with small energy spread in energy, small emittances**
- **<u>Challenges:</u> acceleration of positron, multiple plasma cells, integrated luminosity**

A hybrid, asymmetric, linear Higgs factory
based on plasma-wakefield and radio-frequency acceleration

B. Foster,[1,2,*] R. D'Arcy,[1,2] and C. A. Lindstrøm[3]
[1] John Adams Institute for Accelerator Science at University of Oxford, Oxford, UK
[2] Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
[3] Department of Physics, University of Oslo, Oslo, Norway
(Dated: August 24, 2023)

The evolution of accelerators
… the future





MOPMF072, IPAC18, V. Shiltzev, D. Neuffer

Muon Collider

- Variable center of mass from Z, H (~200 GeV) up to 10 TeV – clear path for higher energies !
- Advantages : no synchrotron radiation losses for muons, optimized energy consumption
- Challenges : required development of several new technologies for the production of the muon beams, the emittance reduction and fast acceleration

For the slides I used images and text from past presentations from collegues, past CAS or JUAS schools, publications and information from web and Wikipedia. Many thanks to all.

In case of questions contact met in my e-mial: **Ilias.Efthymiopoulos@cern.ch**