The CERN LHC Injector Complex

for the UK Accelerator Institutes Seminar Series

Rende Steerenberg - CERN

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Content

The CERN Accelerator Complex

Cycling the Accelerators & Satisfying Users

Concluding Remarks

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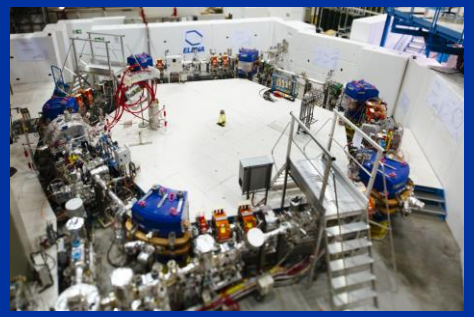
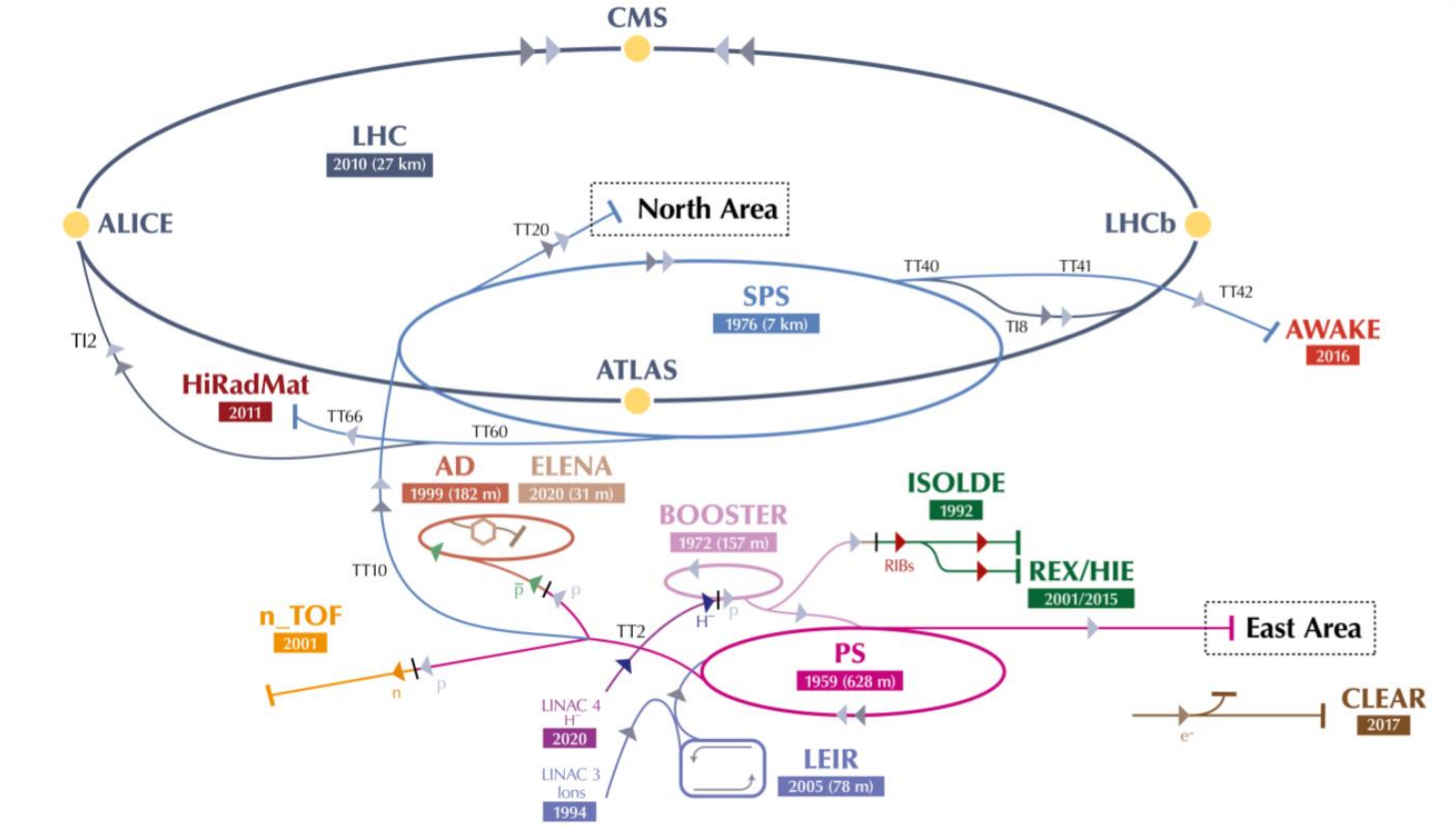
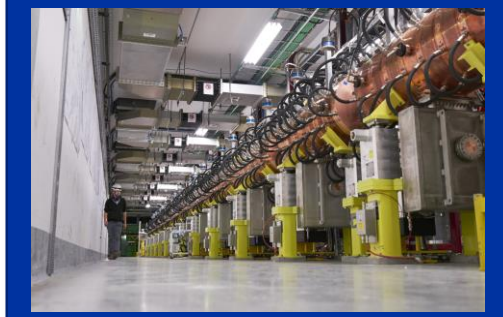
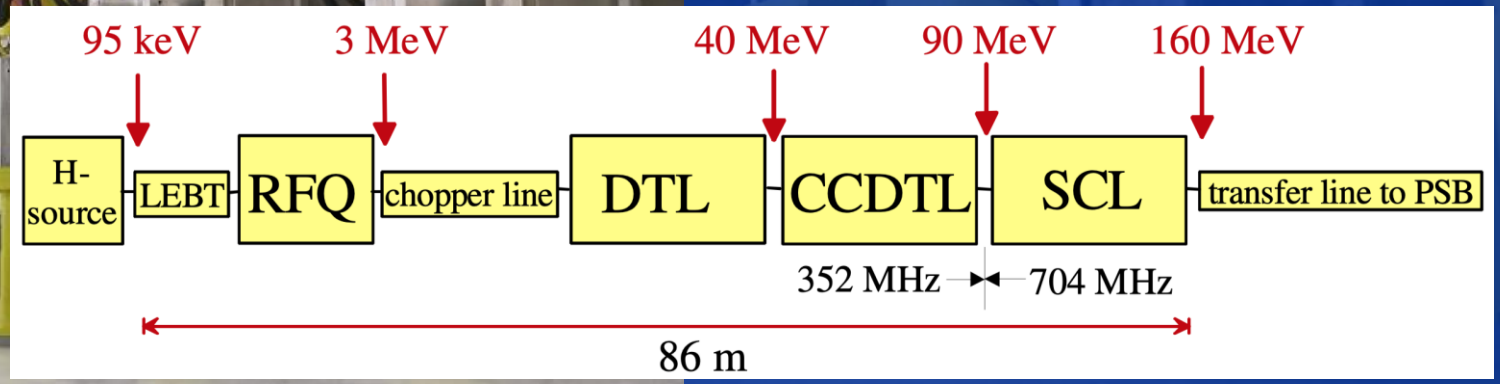






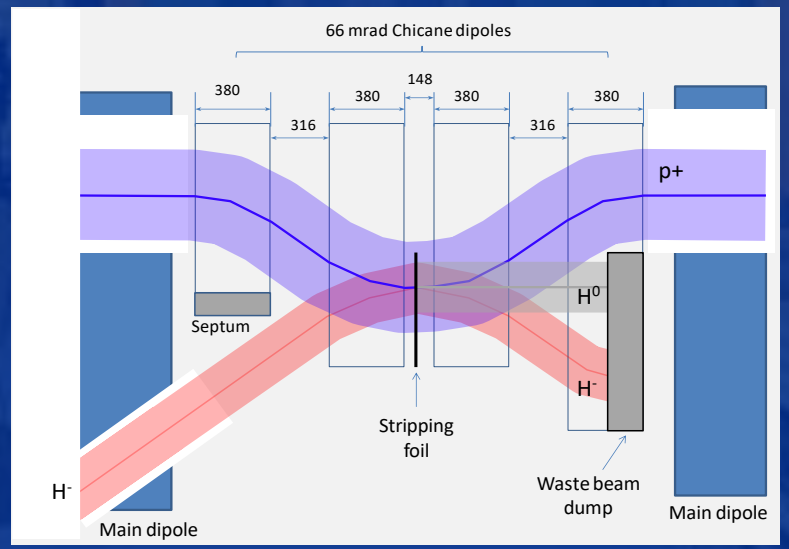
Linac 4

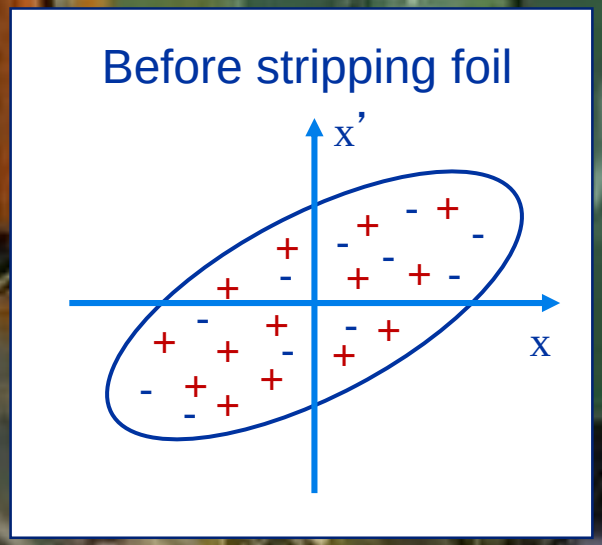
- H^- ion source at 95 keV
- Accelerates beam up to 160 MeV
- The chopping scheme allows removing some of the Linac bunches to make the beam fit into the PS Booster RF buckets
- Pulse rate 1.2 s

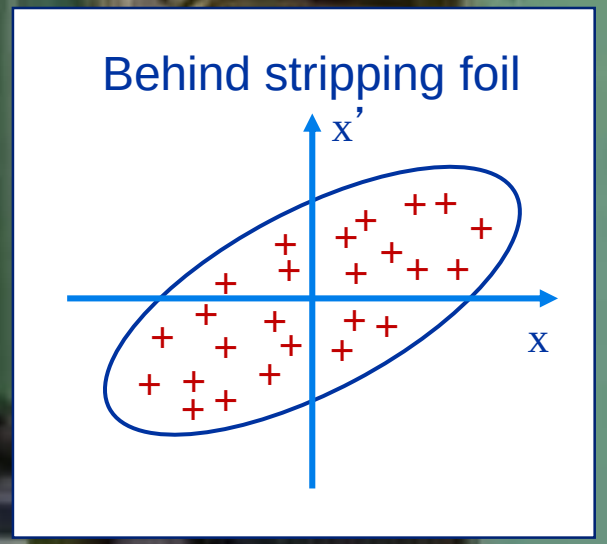


PS Booster

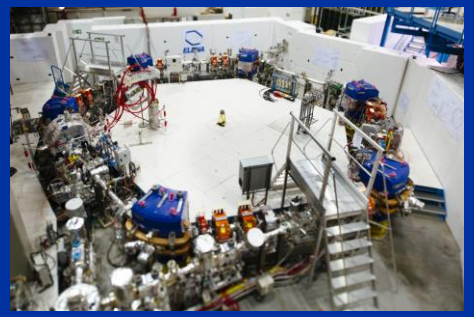
- 1st Synchrotron with 4 superposed rings
- Circumference of 157 m
- Proton energy from 160 MeV to 2 GeV
- Can cycle every 1.2 s
- Each ring will inject over multi-turns, using charge exchange injection

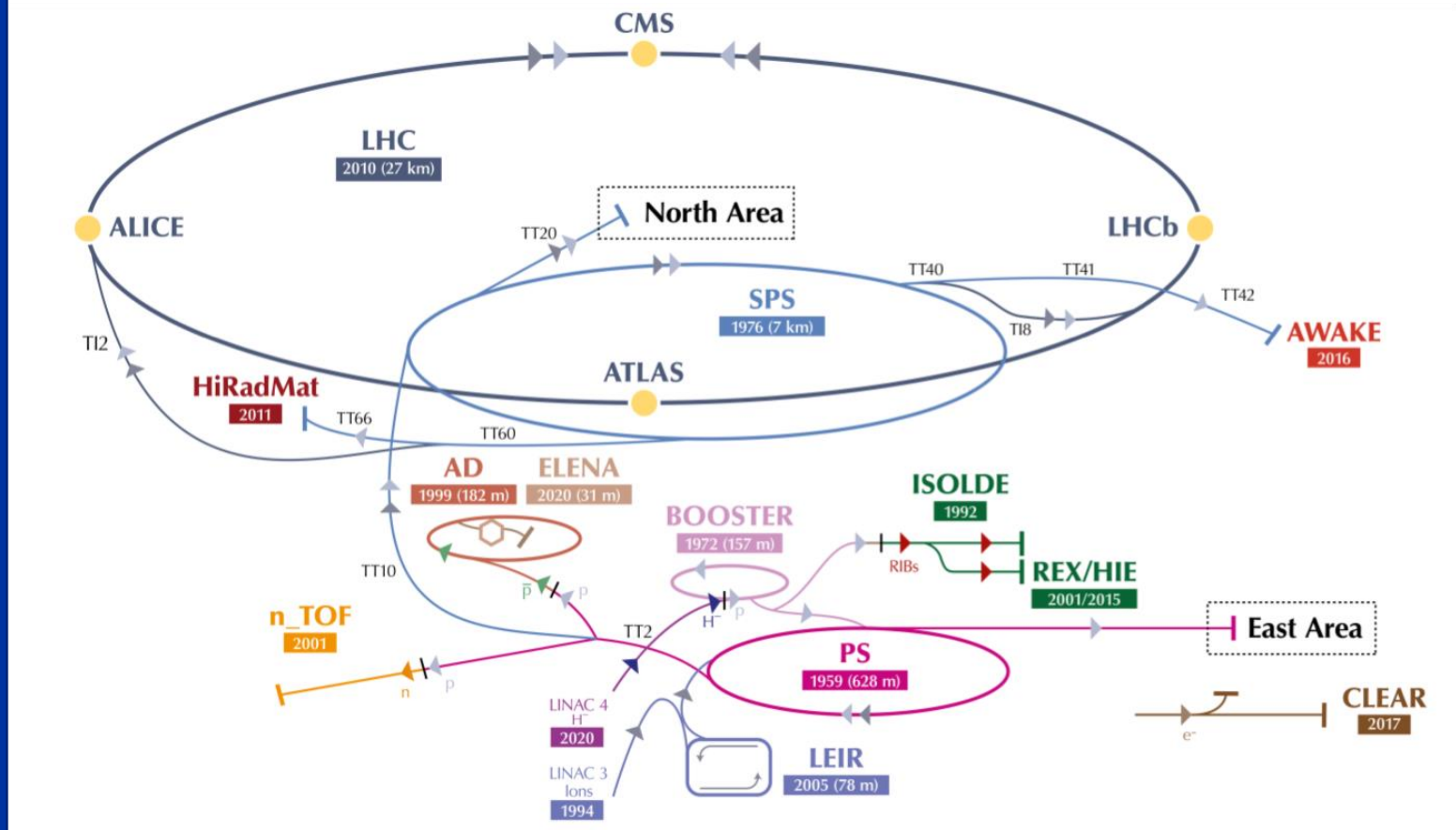


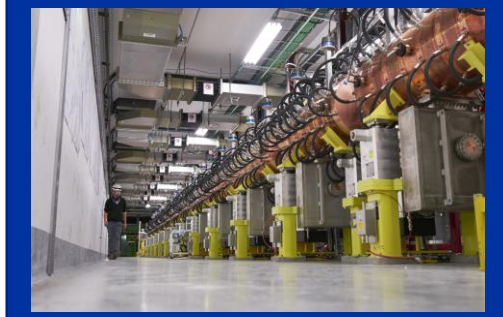




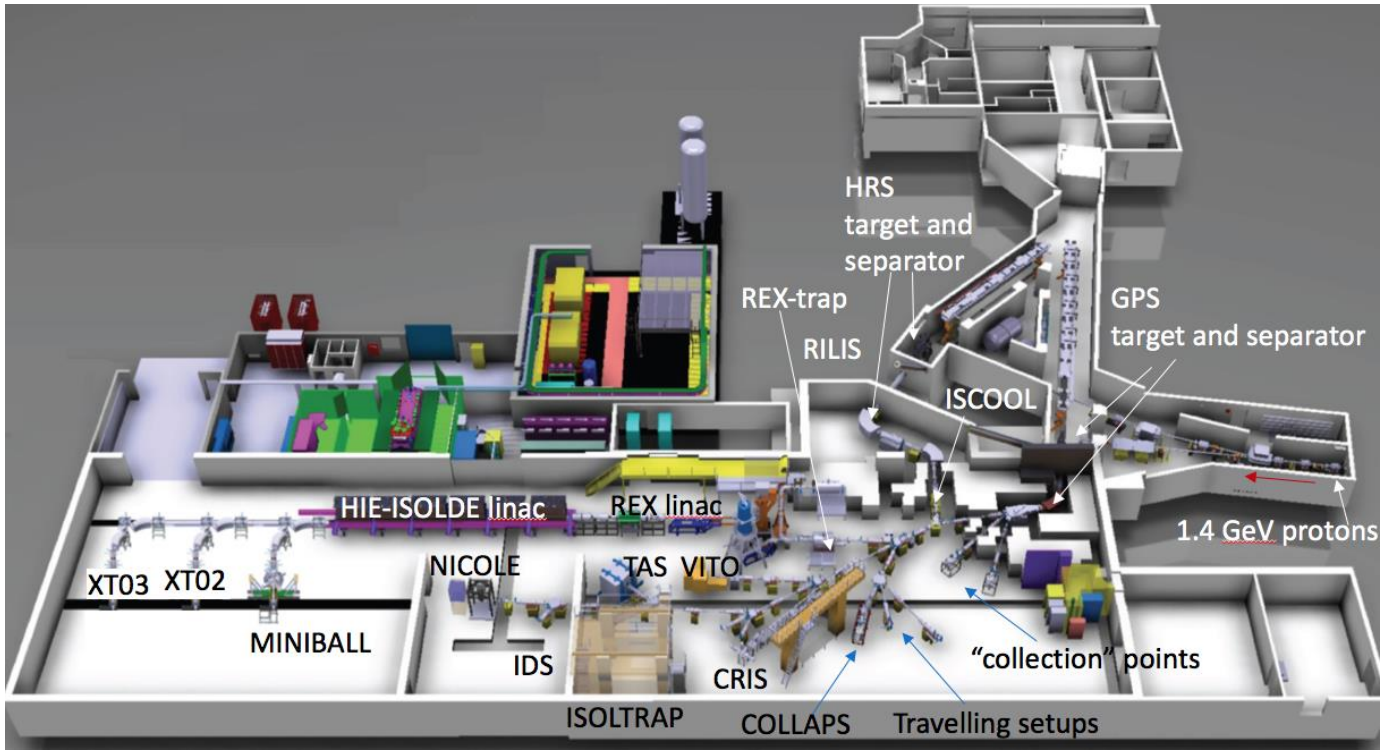
The CERN Accelerator Complex







ISOLDE / HIE-ISOLDE



- **The fast extracted PSB proton beam impinges on a target producing a range of isotopes**
- **Two mass separators (GPS & HRS) allow selection of isotopes**
  - These can be used in the low energy lines for various experiments
- **The post acceleration of isotopes is being extended**
  - REX, normal conducting accelerating structures
  - HIE-ISOLDE, super conducting LINAC for post acceleration up to 10 MeV/nucleon

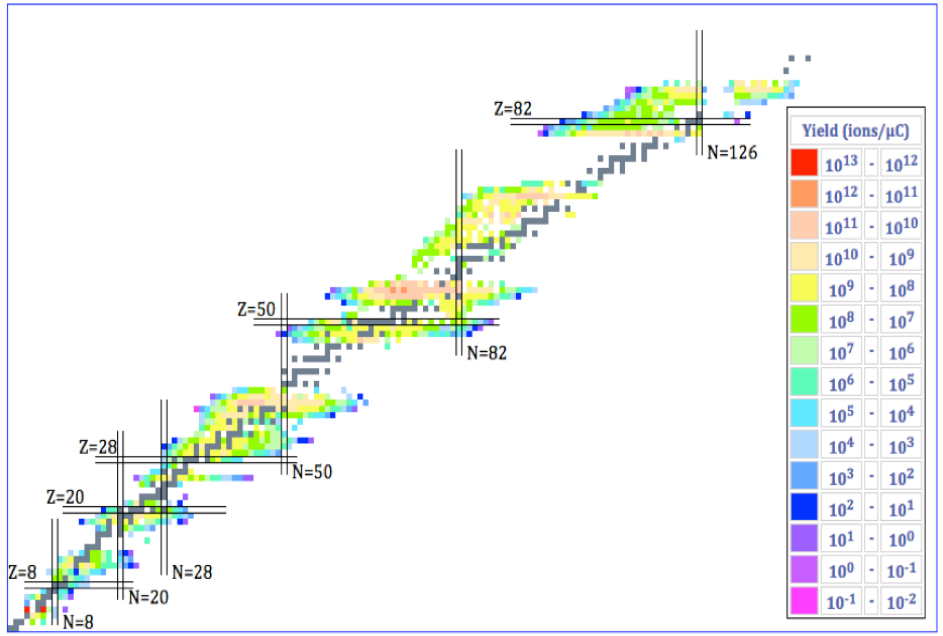
Nuclear physics at ISOLDE

ISOLDE: Radioactive Ion Beams (RIB) production

- 1000 nuclides of over 75 elements produced for ~50 experiments every year
- Nuclear physics
- Fundamental interactions
- Nuclear Astrophysics
- Applications (Medicine, Material Science)

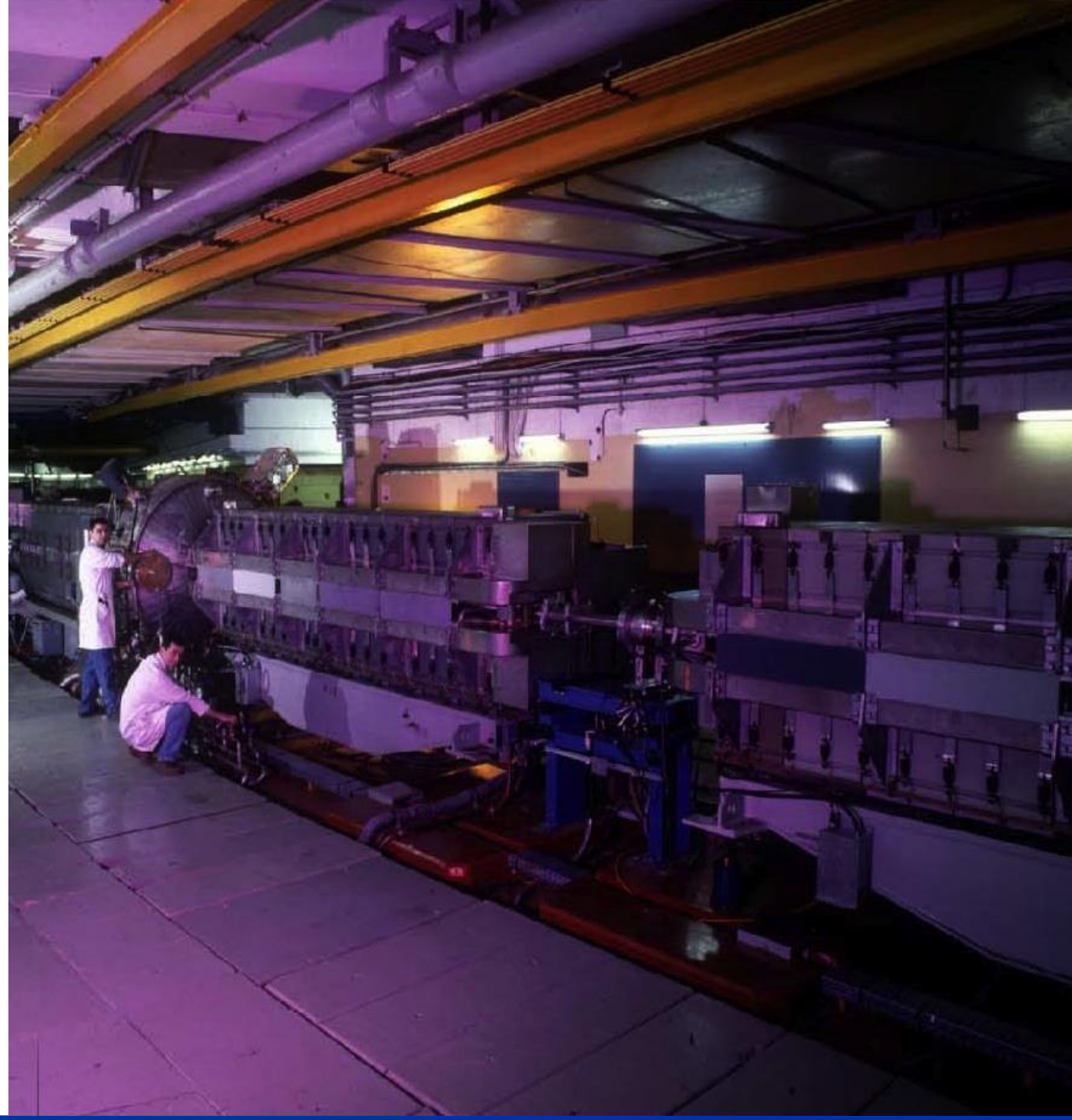
Over 20 different target materials are used:

- Carbides, oxides, solid metals, molten metals and molten salts (U, Ta, Zr, Y, Ti, Si, …)
- 3 types of ion sources: surface, plasma, laser

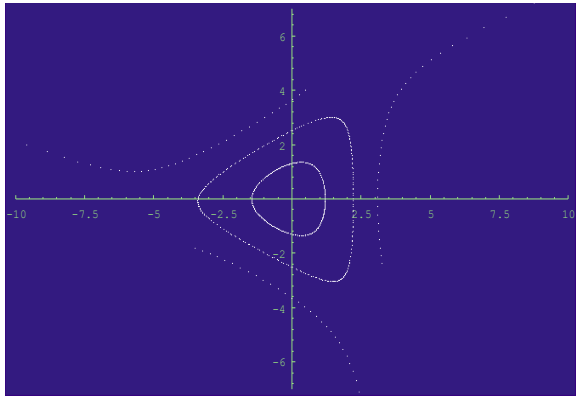


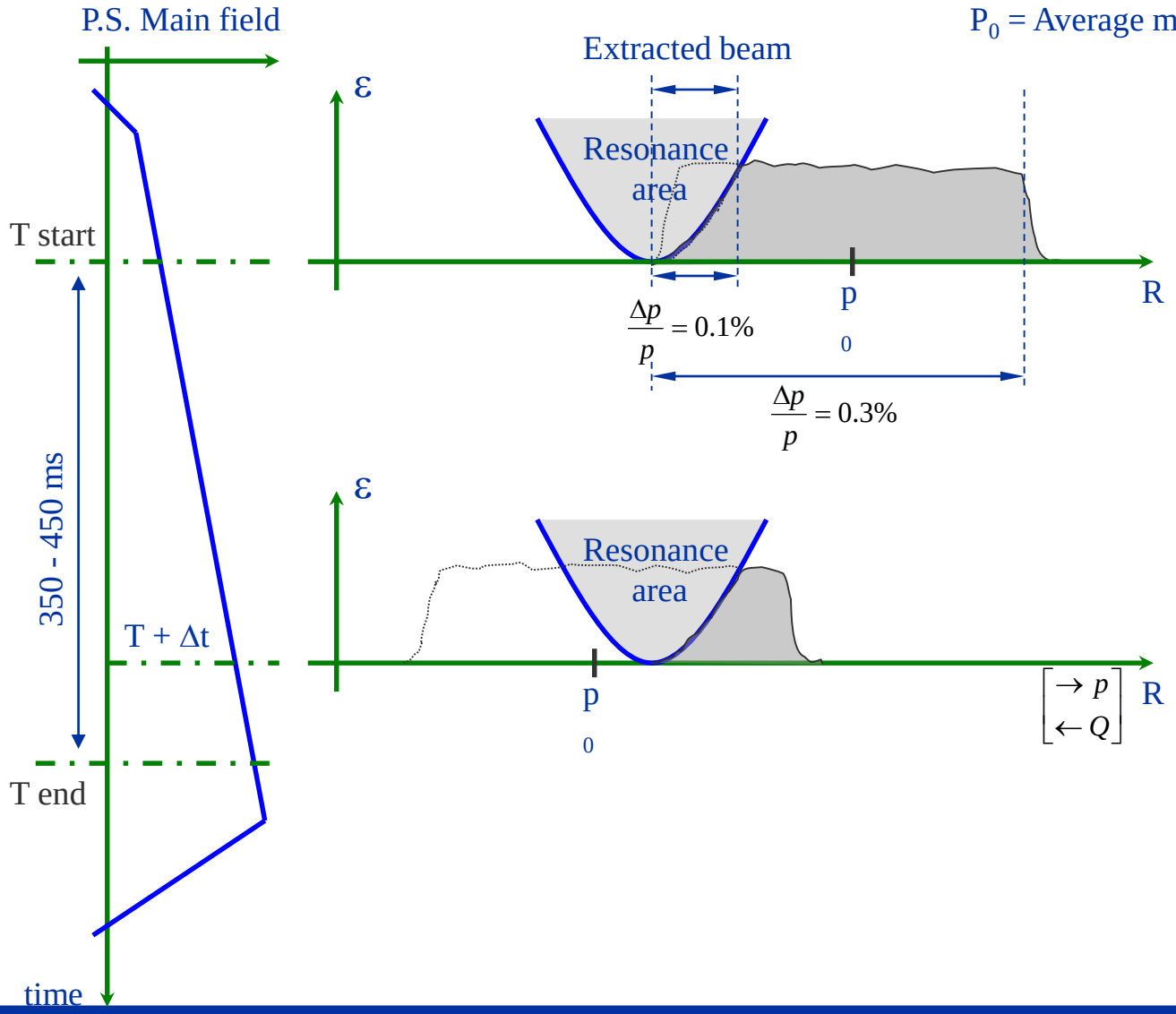
PS

- **The oldest operating synchrotron at CERN (1959)**
- **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)
  - Resonant slow extraction



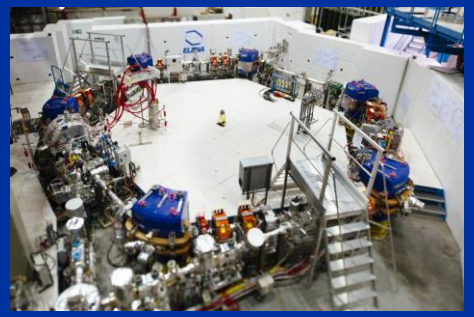
PS Resonant Slow Extraction

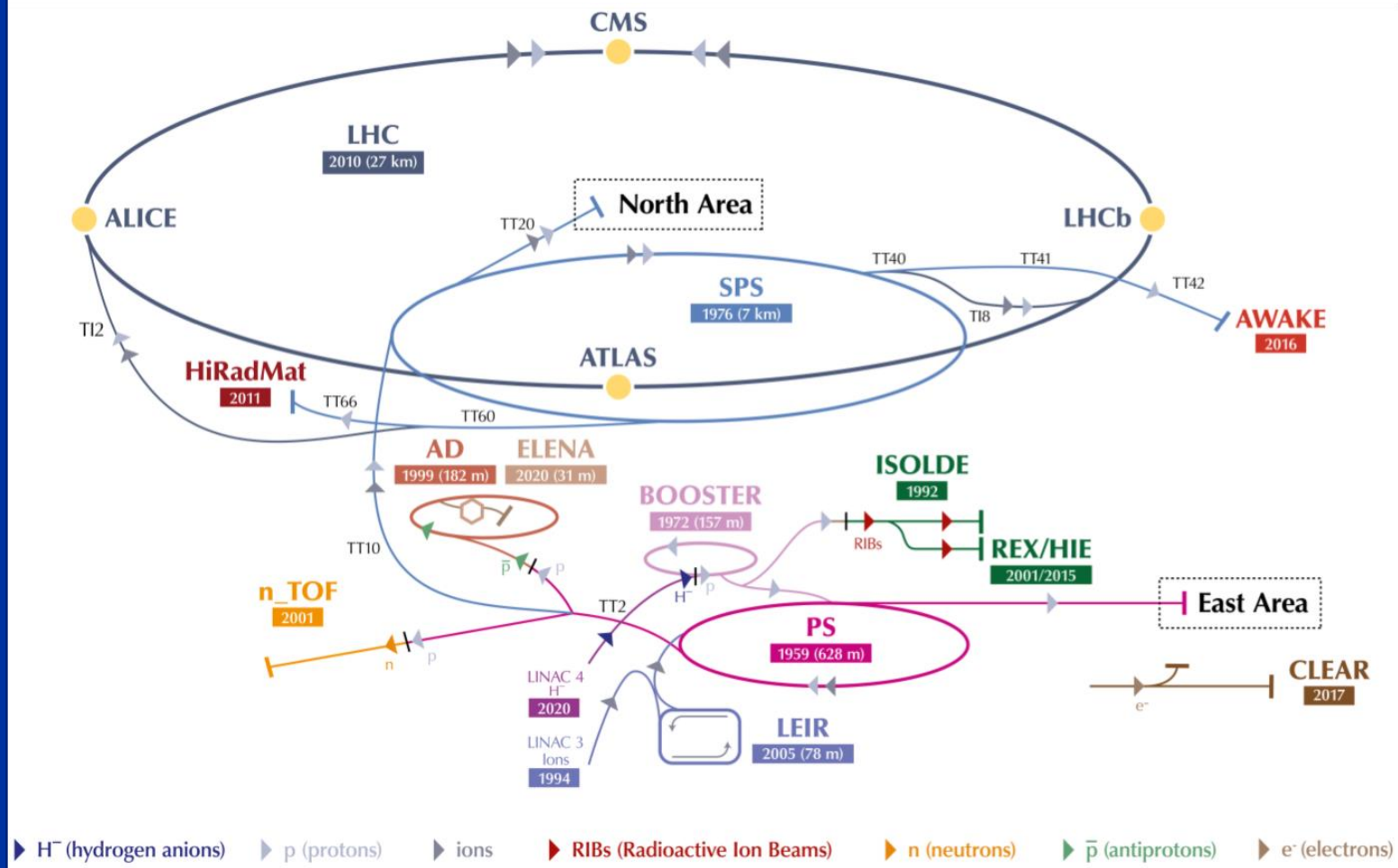


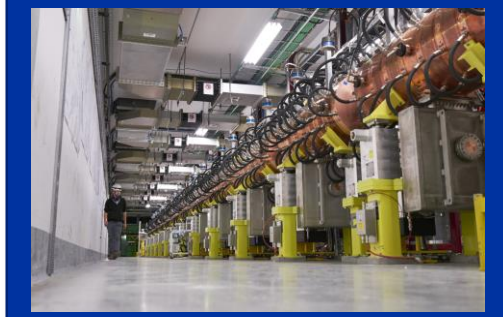


- **Procedure:**
  - De-bunch the beam with the desired momentum spread
  - Change optics setting of the machine for resonant conditions:
    - Non-linear elements (e.g. Sextupoles)
    - Adjust the tune to enable the resonance
  - Slightly ramp the magnetic field such that the beam spiralises into the resonance
  - Extraction elements such as electro-static and magnetic septum magnets will guide the extracted part of the beam into the transfer line.

The CERN Accelerator Complex







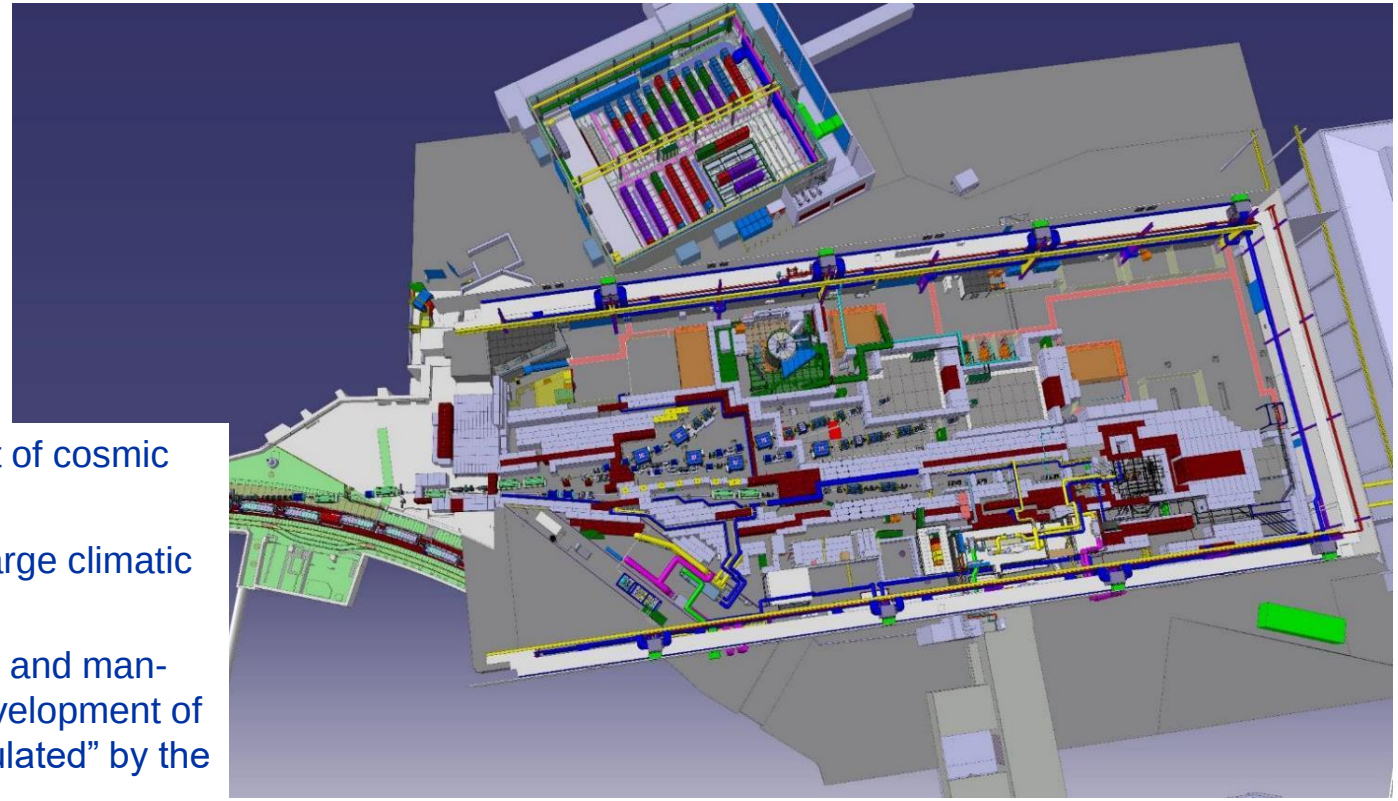
PS East Area Exp. zones

- **Receives a 24 GeV/c resonant slow extracted beam from the PS during ~ 400 ms**
- **4 Beam lines:**
  - T8: Irradiation facility with protons & ions
  - T9: Multi-purpose secondary beam lines
  - T10: Multi-purpose secondary beam lines
  - T11: CLOUD experiment

CLOUD studies the effect of cosmic rays on cloud formation

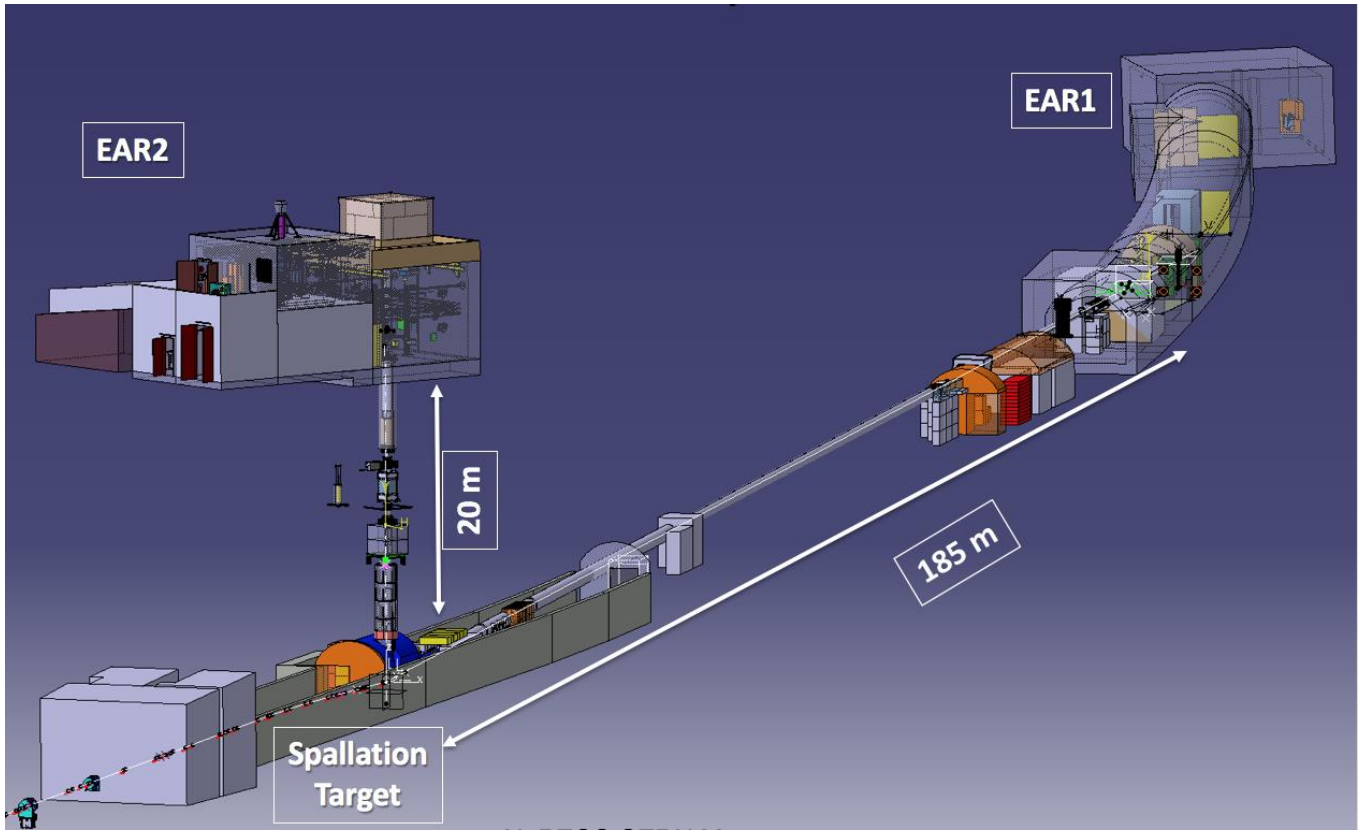
Clouds are created in a large climatic chamber

Study influence of natural and man-made aerosols on the development of clouds, cosmic rays “simulated” by the secondary beam.

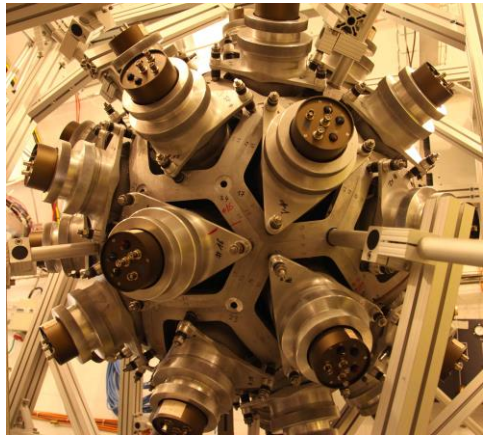


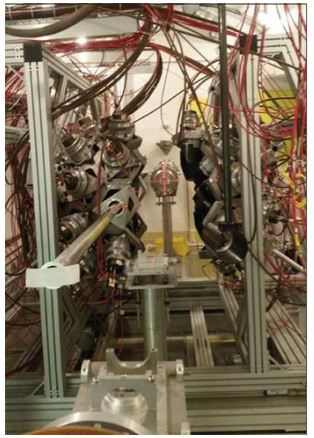
nToF: Neutron Time of Flight Facility

- **Receives a fast extracted single short bunch from the PS at 20 GeV/*c***



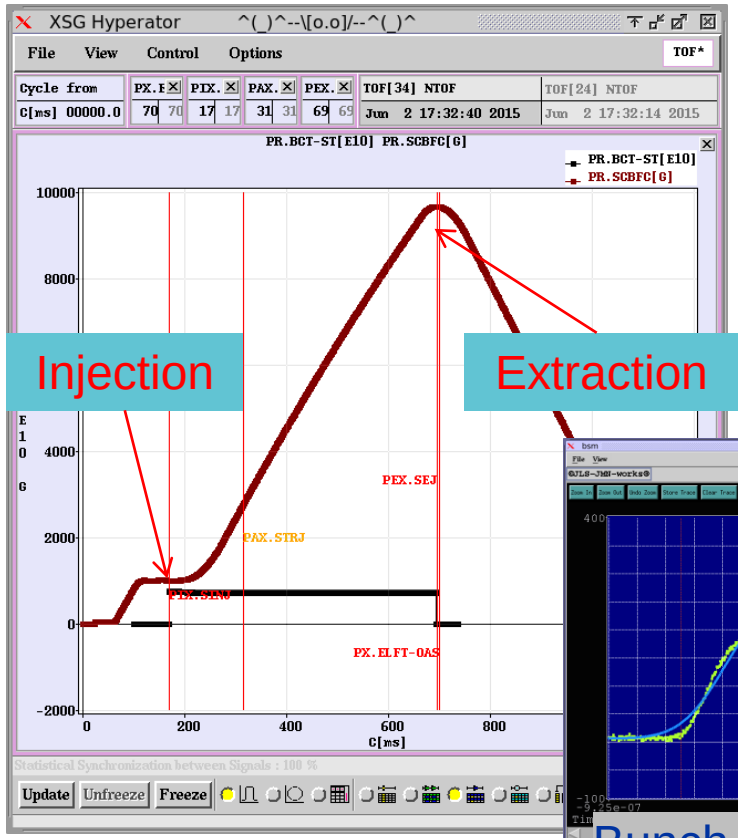
- **Neutron cross-section measurements**
  - *Astrophysics*
  - *Nuclear Physics*
  - *Medical Applications*
  - *Nuclear Waste Transmutation*





nToF Beam Production

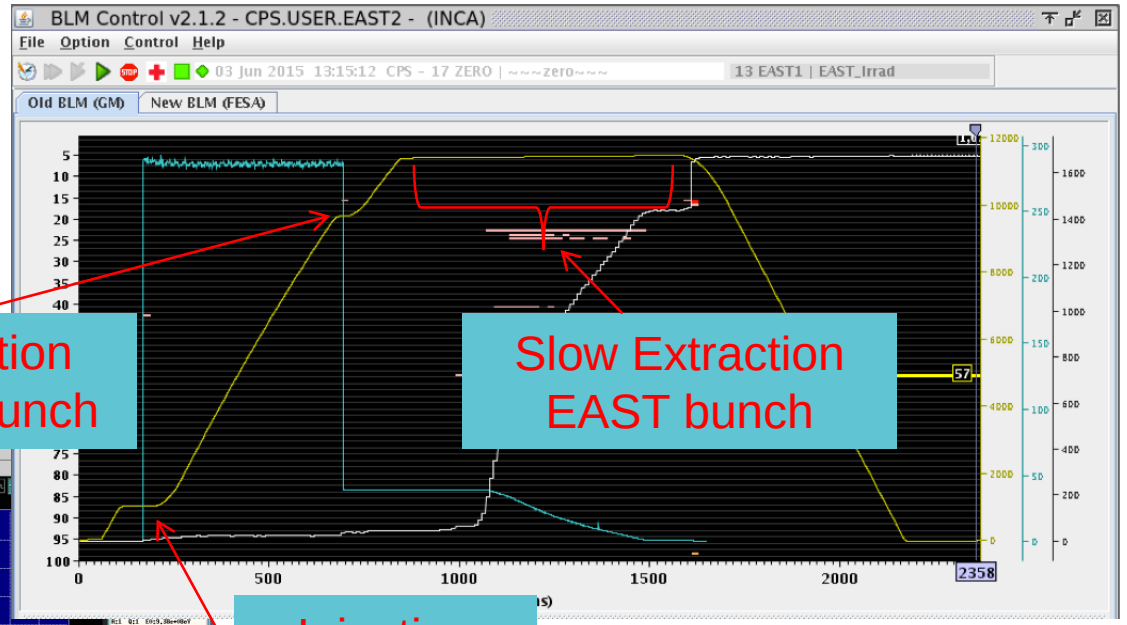
nTof dedicated cycle



Injection

Extraction

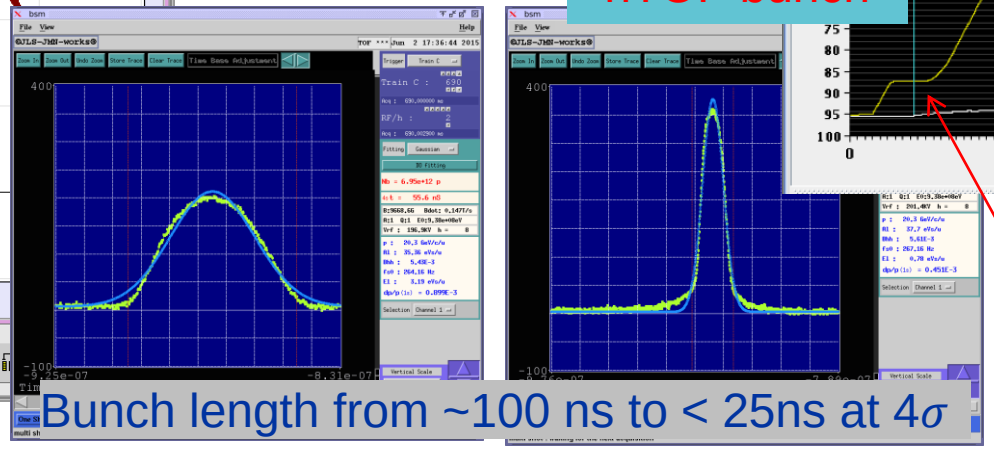
nToF parasitic cycle



Extraction nTOF bunch

Slow Extraction EAST bunch

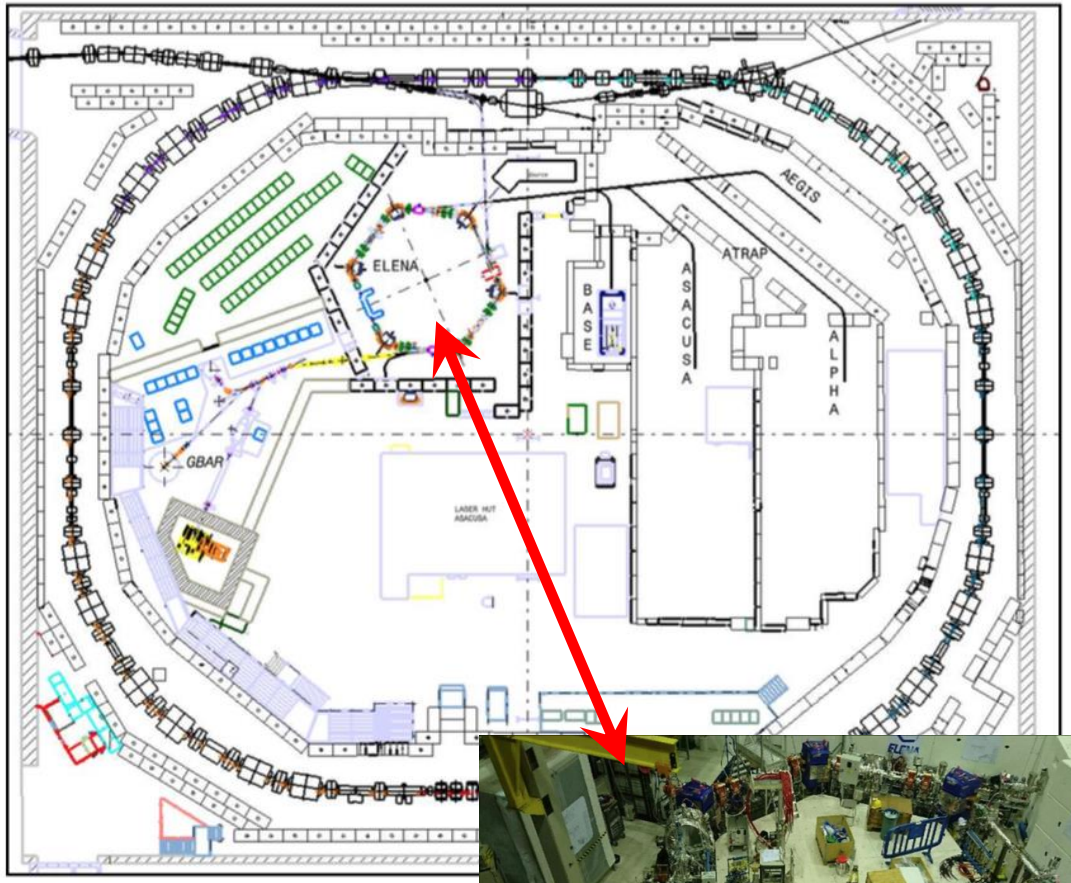
Injection 2 bunches



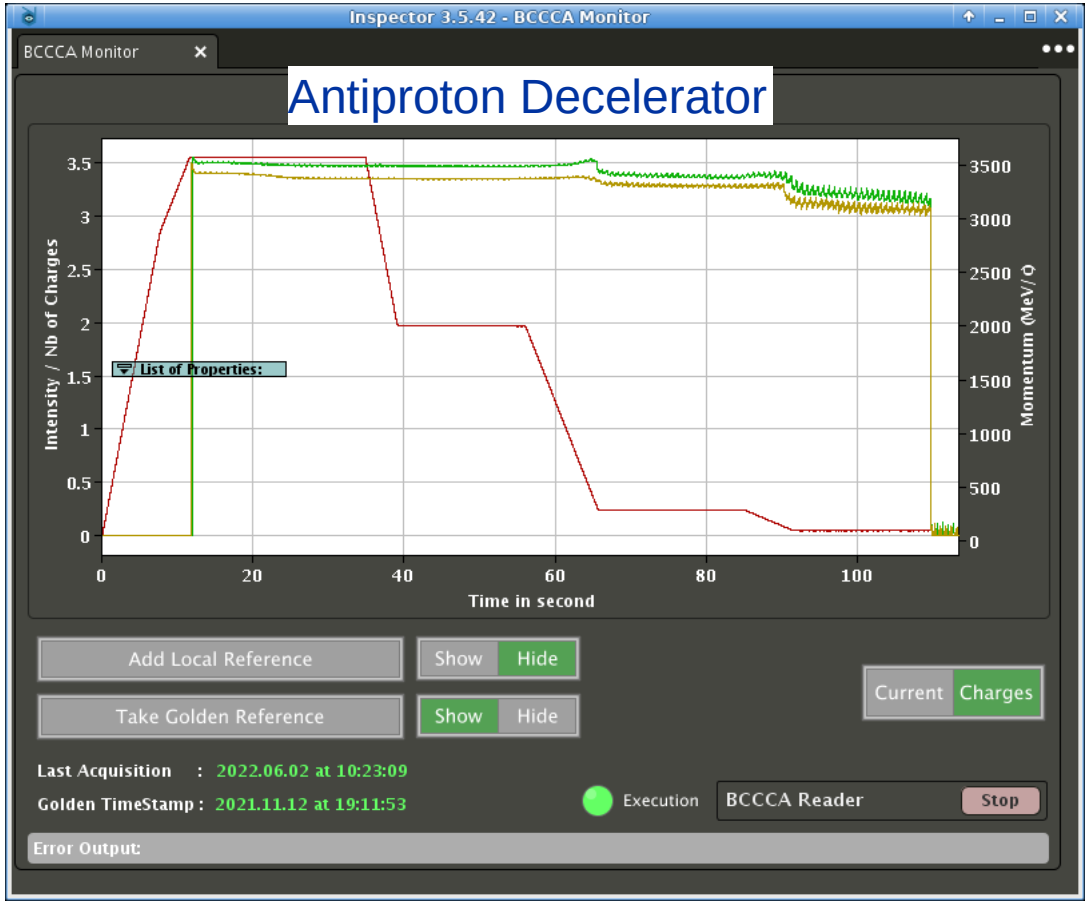
Bunch length from ~100 ns to < 25ns at 4σ

AD – ELENA

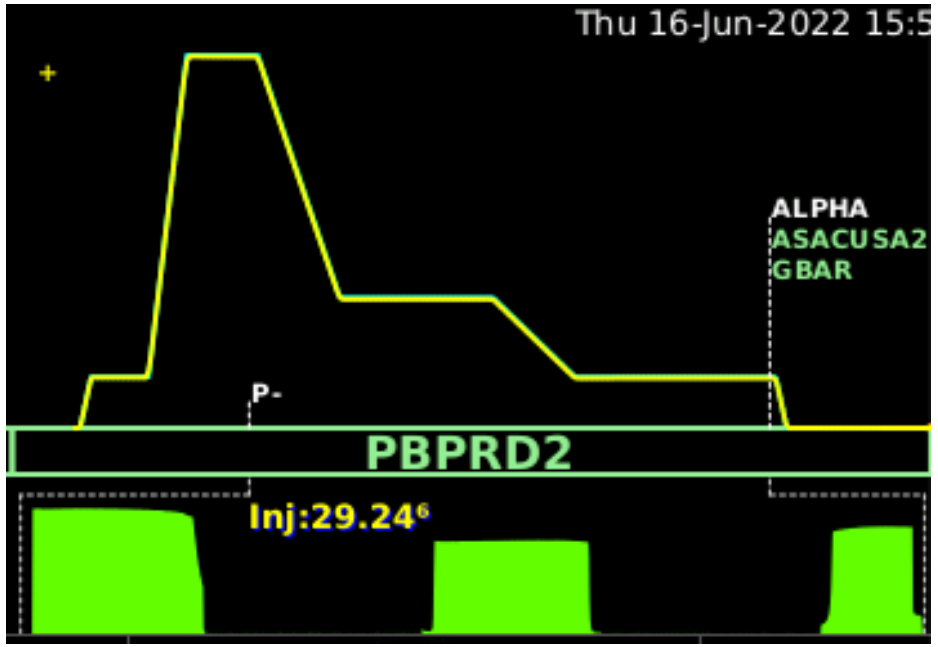
- **Receives fast extracted proton beam from PS at 26 GeV/c on a target (5 bunches)**
  - Total intensity on the target: 1.5 x 10^{11} ppp
- **About every million protons yields about one usable antiproton at 3.5 GeV/c.**
- **AD decelerates beam in stages down to 5.3 MeV**
- **ELENA will further decelerate down to 100 keV**
  - Available p- intensity: ~7 x 10^{6} p^{-}pp
- **Individual bunches can be extracted to different experiments, one each per extraction**



Antiproton Deceleration



Extra Low ENergy Antiproton ring (ELENA)



- **Out of the Linac 4 source we get 95 keV H-**
- **We accelerate the resulting p^+ to 26 GeV/c in PS**
- **We decelerate p^- from 3.5 GeV/c to 100 keV**

Electron Cooling and Stochastic Cooling are key for efficient deceleration hence long plateaus in the cycles

Antiproton & Antihydrogen Physics

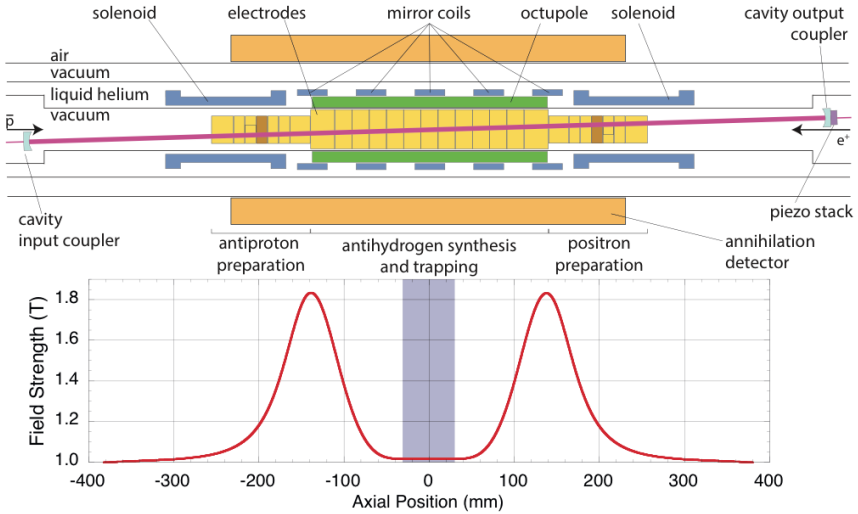
Matter-Antimatter comparison

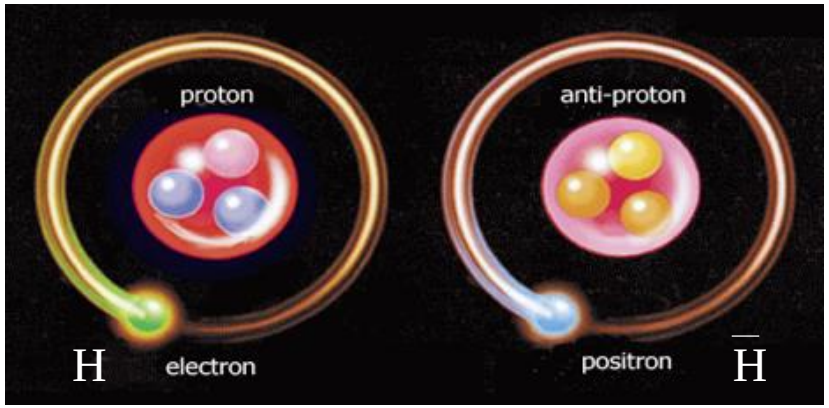
- **Fundamental in the current theory of physics:**

$$m = \overline{m}, \qquad g = \overline{g}$$

6 experiments:

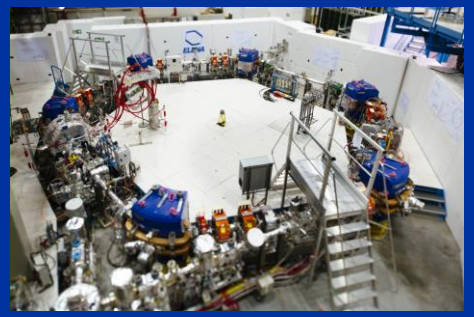
- **ASACUSA** spectroscopy of exotic atoms (antiprotonic Helium), and nuclear collision cross section
- **BASE** magnetic moment of the antiproton
- **ALPHA/ALPHA-g** spectroscopy and gravity
- **AEgIS** spectroscopy, antimatter gravity experiment
- **GBAR** antimatter gravity experiment
- **PUMA** transporting antiprotons from the AD to **ISOLDE**

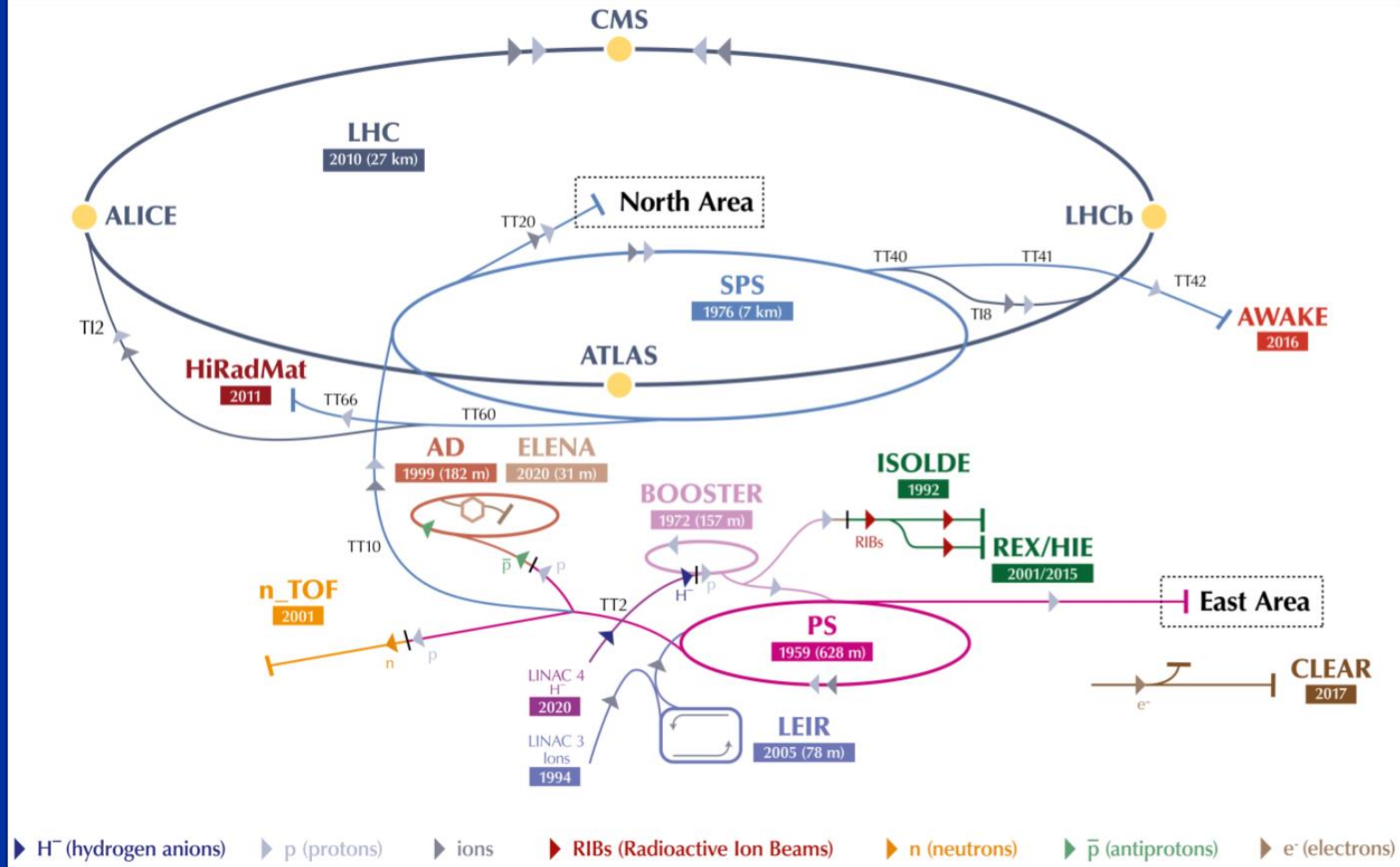




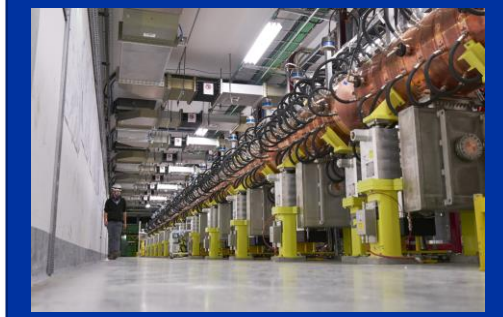
The CERN Accelerator Complex





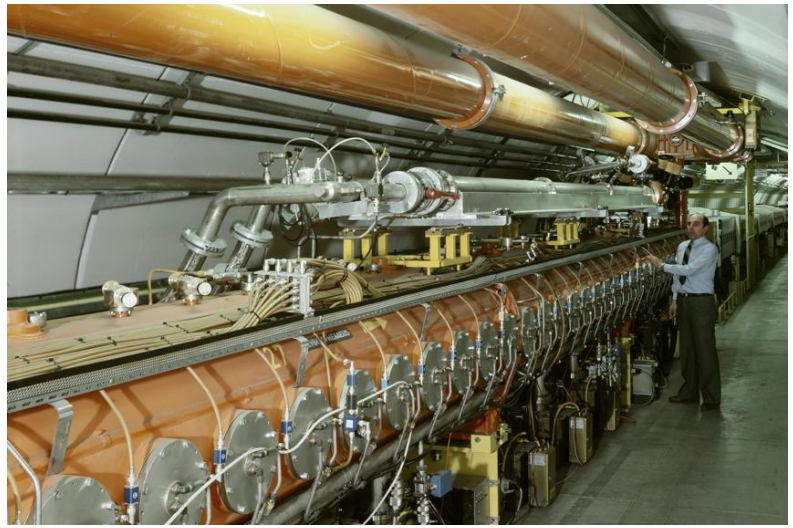





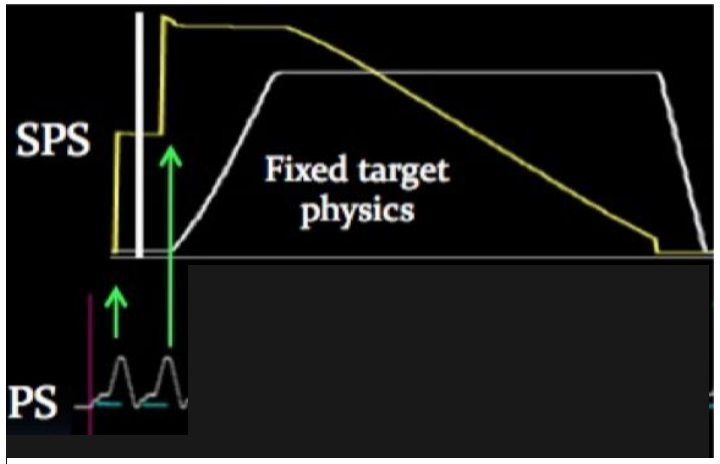



SPS

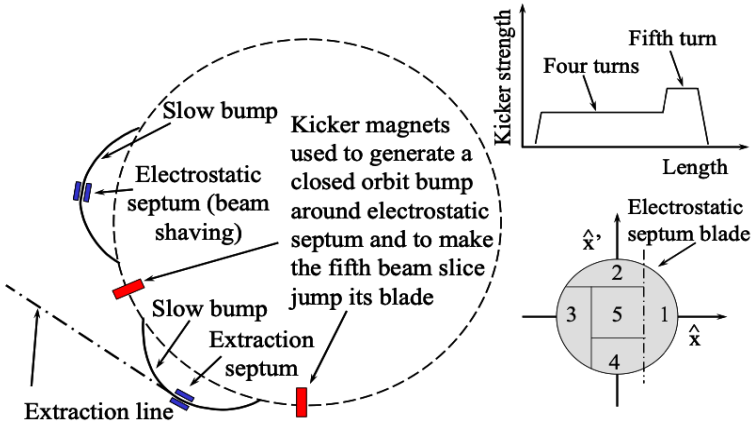
- **The first synchrotron in the chain at ~30m under ground**
- **Circumference of 6.9 km**
  - 11 x PS circumference
- **Increases proton beam energy up to 450 GeV with up to ~5x10^{13} protons per cycle**
- **Provides slow extracted beam to the North Area**
- **Provides fast extracted beam to LHC,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



Filling the SPS with the PS for the fixed target beam



$$C_{SPS} = 11 \cdot C_{ps}$$

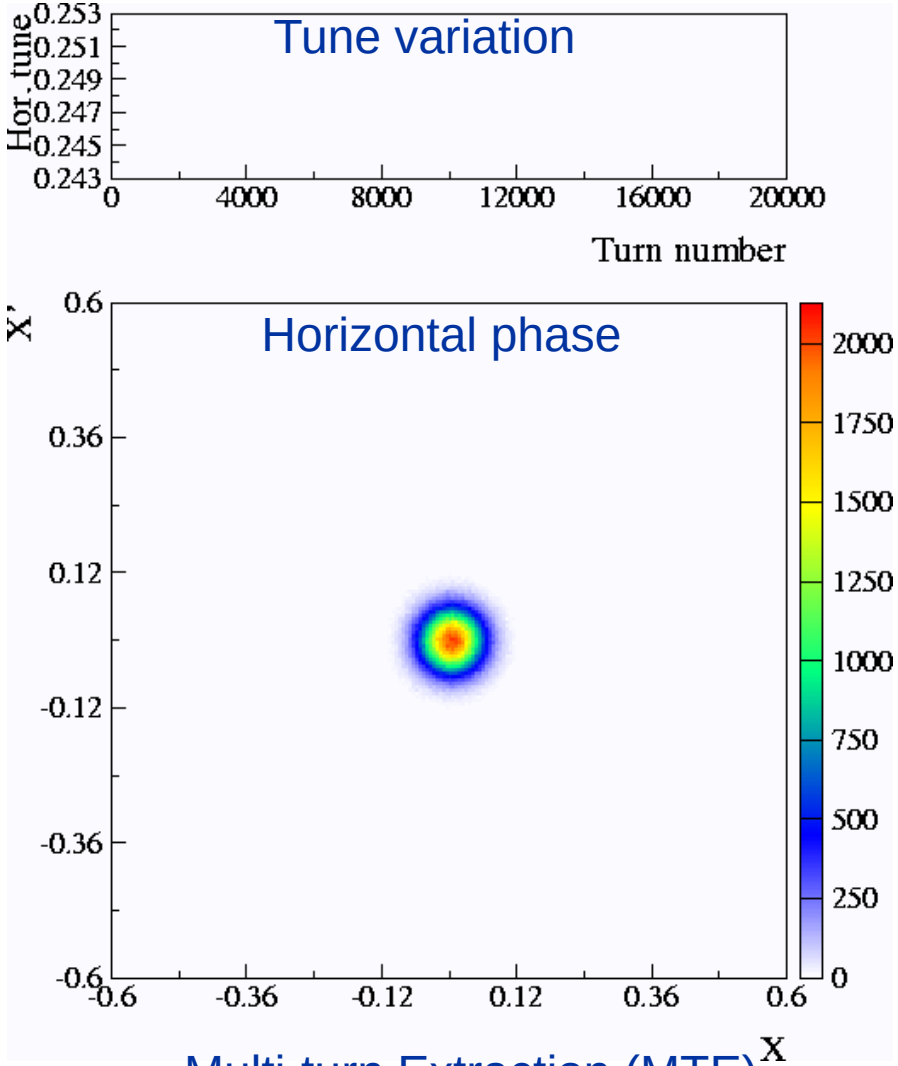


5-turn Continuous Transfer (CT)

- Injecting 11 times is time consuming
- Injection twice 5 slices is efficient, leaving a gap for the kicker
- CT extraction scheme with substantial beam losses

- The more modern Multi-Turn Extraction (MTE) uses non-linear resonances to create sable islands in phase space
- Space between islands and core unpopulated – low losses

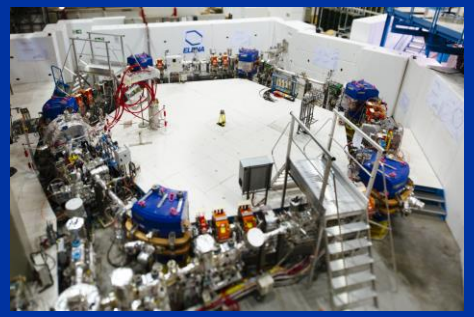
- MTE uses strong non-linear resonances to create stable islands in phase space

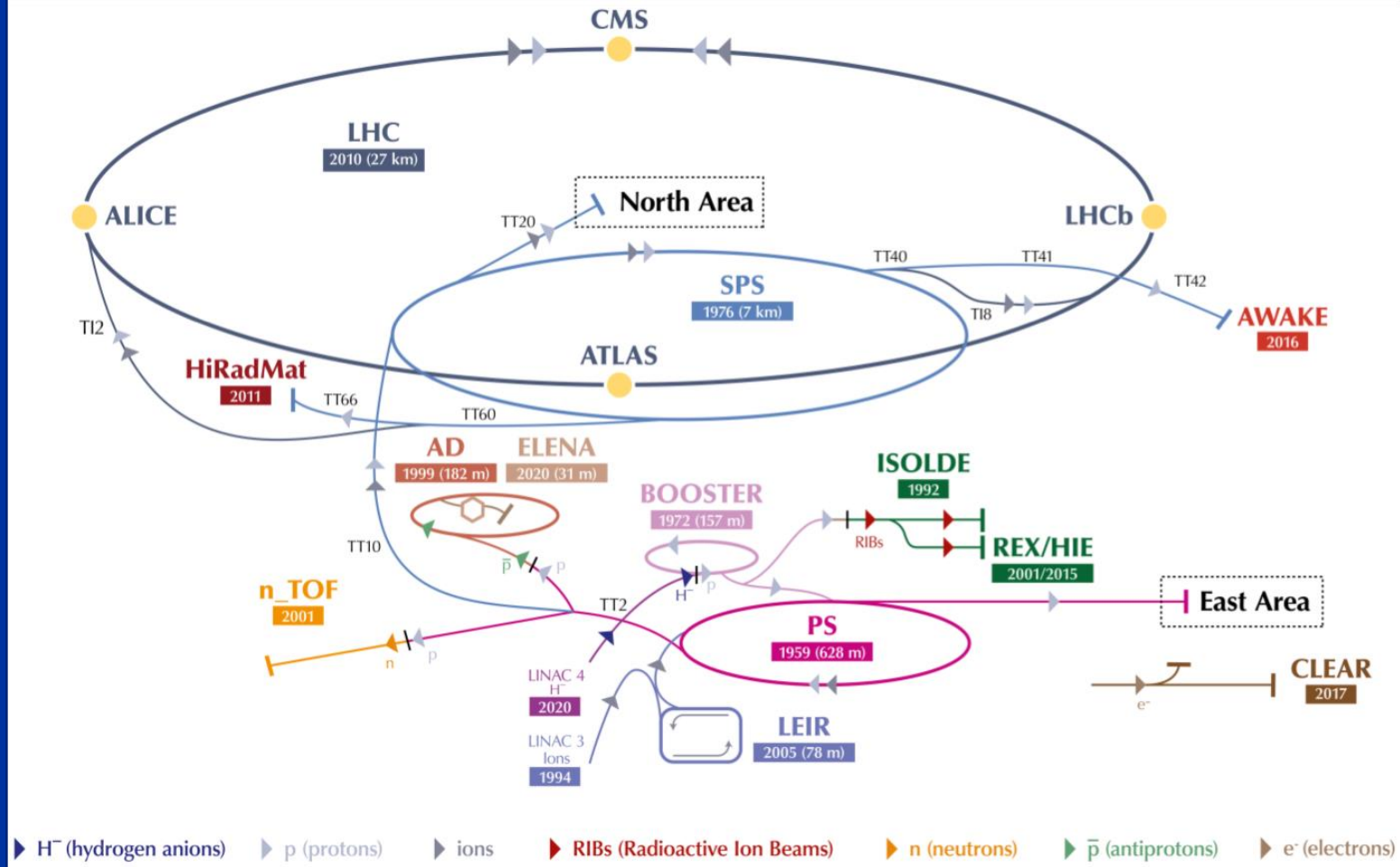


Multi-turn Extraction (MTE)

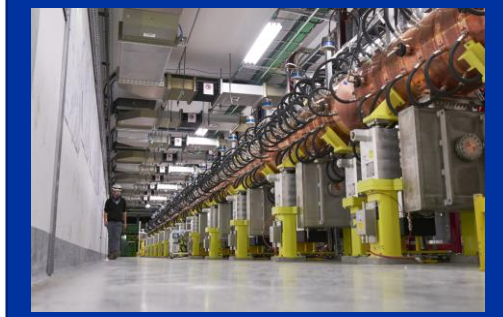
The CERN Accelerator Complex





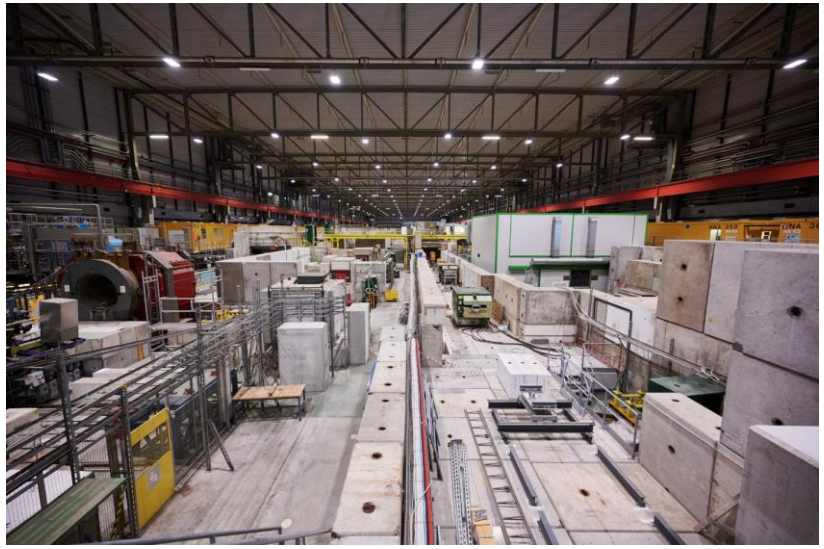



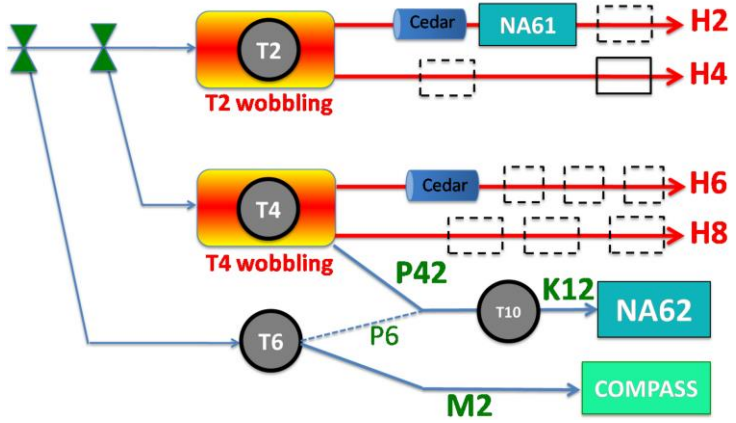





SPS North Area Exp. Zones

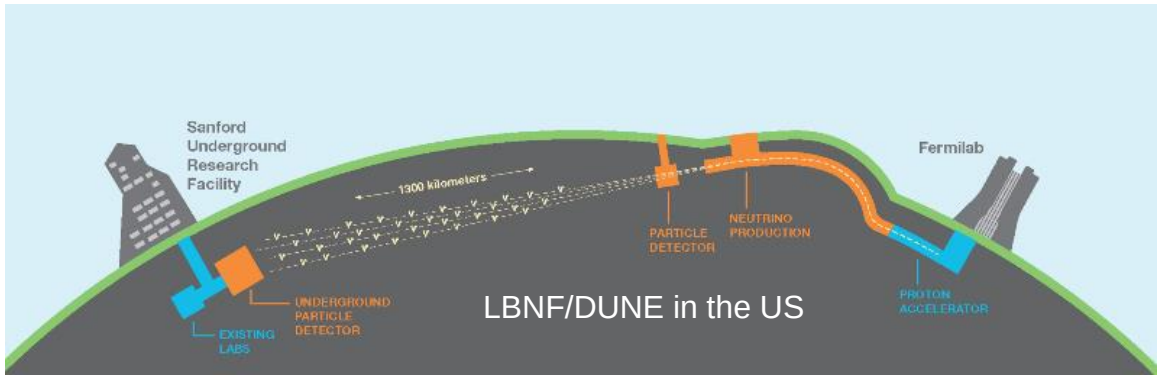
- **Receives a 400 GeV/c resonant slow extracted beam from the SPS during ~ 5 seconds**
- **After splitting, the primary proton beam impinges on 3 targets:**
  - Several km of beam lines then distribute the secondary beam to the various experimental zones
- **High energy fixed target experiments allow precision measurements and comparison with theory**
  - Spot deviations that can be a sign of new physics at higher energies
- **Approved experiments:**
  - NA58 (COMPASS): muon spin physics, hadron spectroscopy
  - NA61 (SHINE): strong interaction, quark gluon plasma, neutrino and cosmic ray program (uses p^+ and ^{208}Pb)
  - NA62: rare K decays BR($K^+ \rightarrow \pi^+\nu\nu$)
  - NA63: electromagnetic processes in strong crystalline fields
  - NA64: search for dark sectors in missing energy events
  - NA65 (DsTau): study of ν_τ production



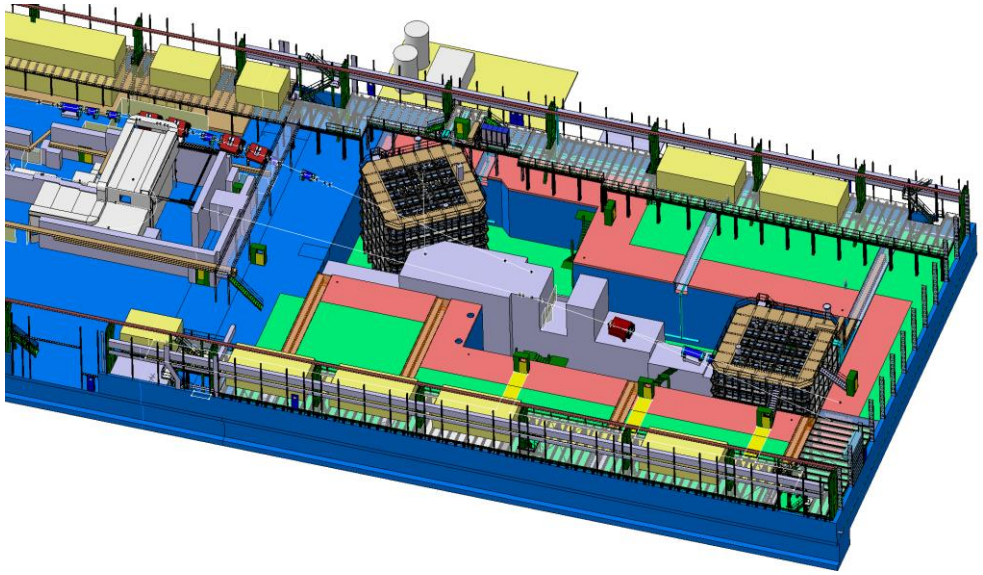


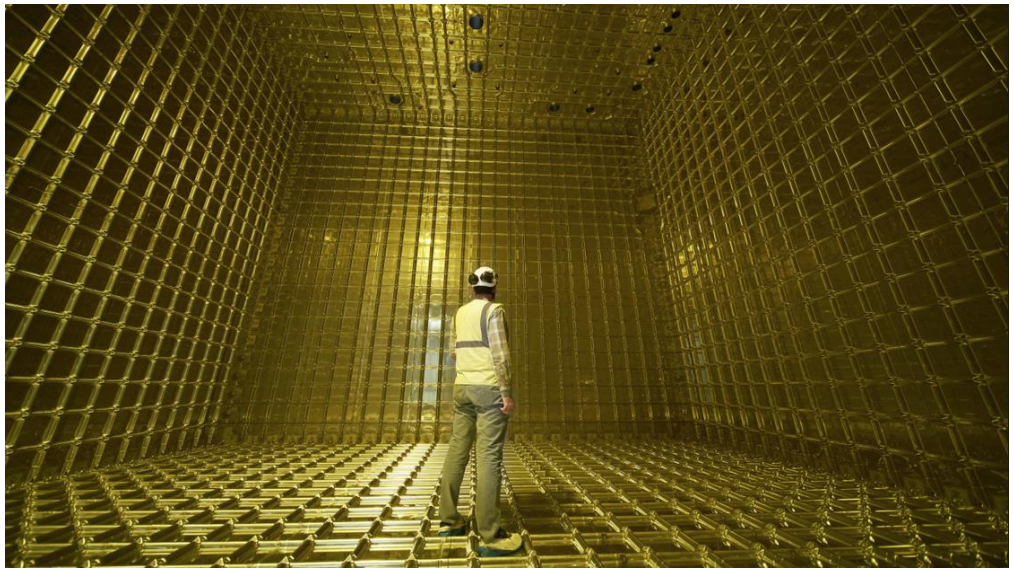
SPS North Area Neutrino Platform

- R&D and test facility for neutrino detectors
  - Test with tertiary low energy beam produced from 400 GeV/c slow extracted SPS proton beam
  - Contributes to neutrino experiments in the US and Japan



- Paving the way to very large scale liquid Argon detectors

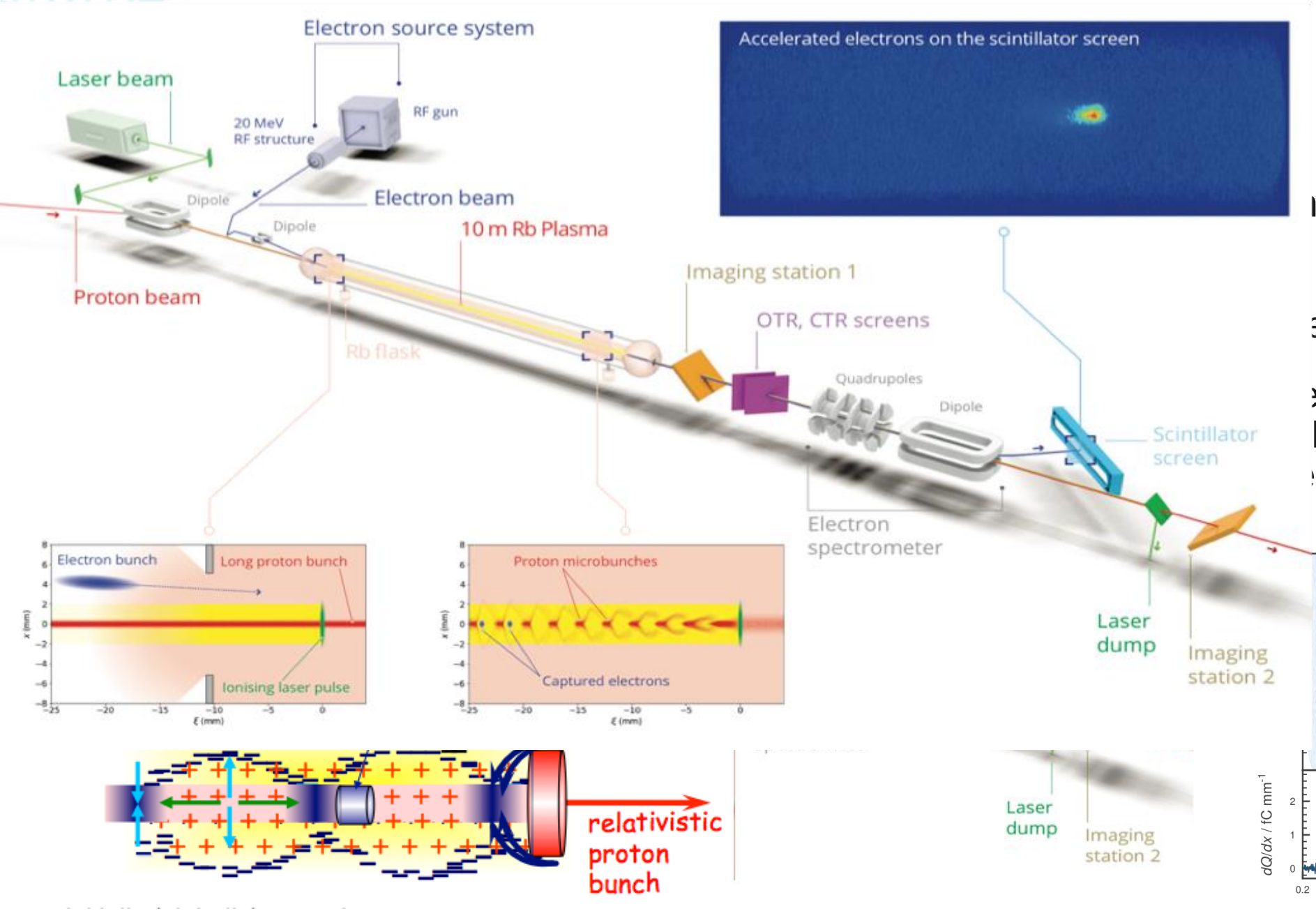


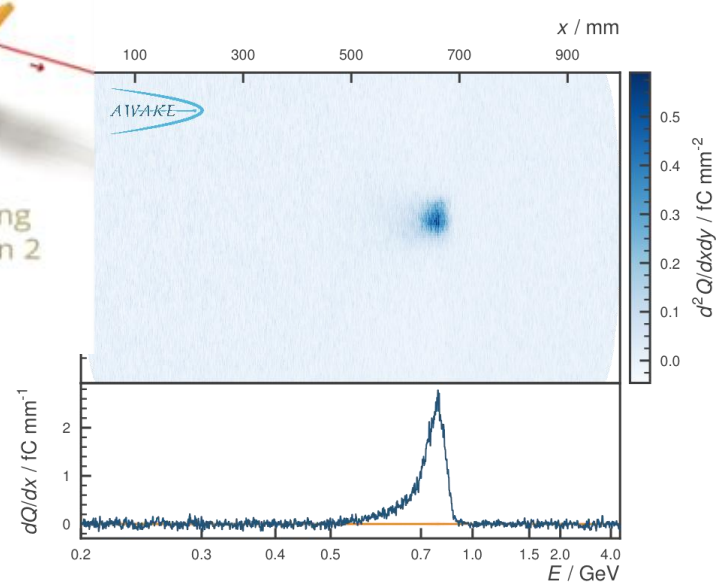


the SPS

bunch drives wakefields
er long plasma length

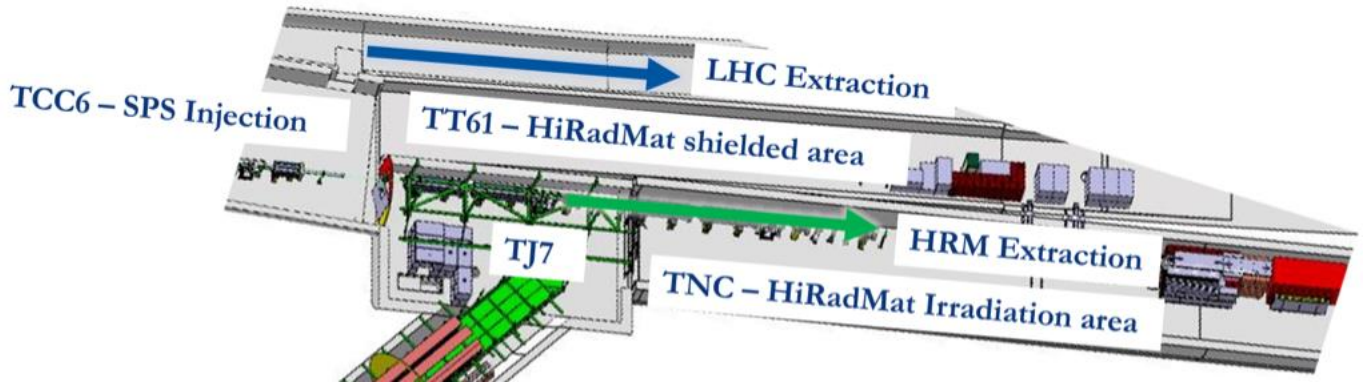
ectrons get accelerated
h the aim to reach the
V/m range

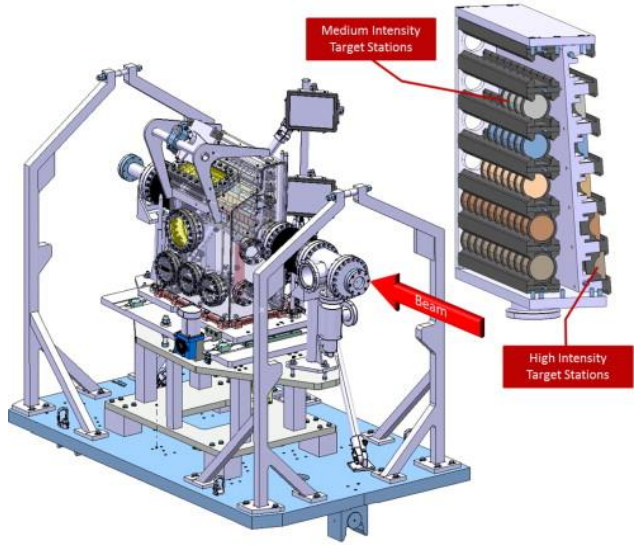




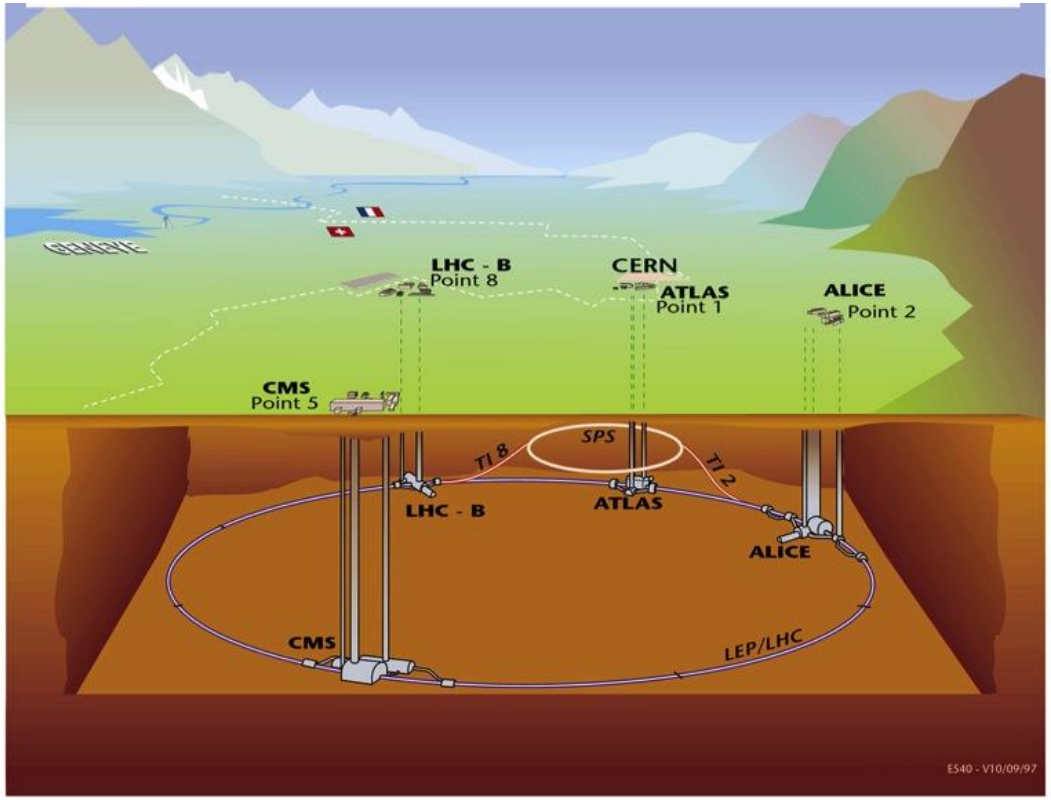
HiRadMat - High-radiation to Materials

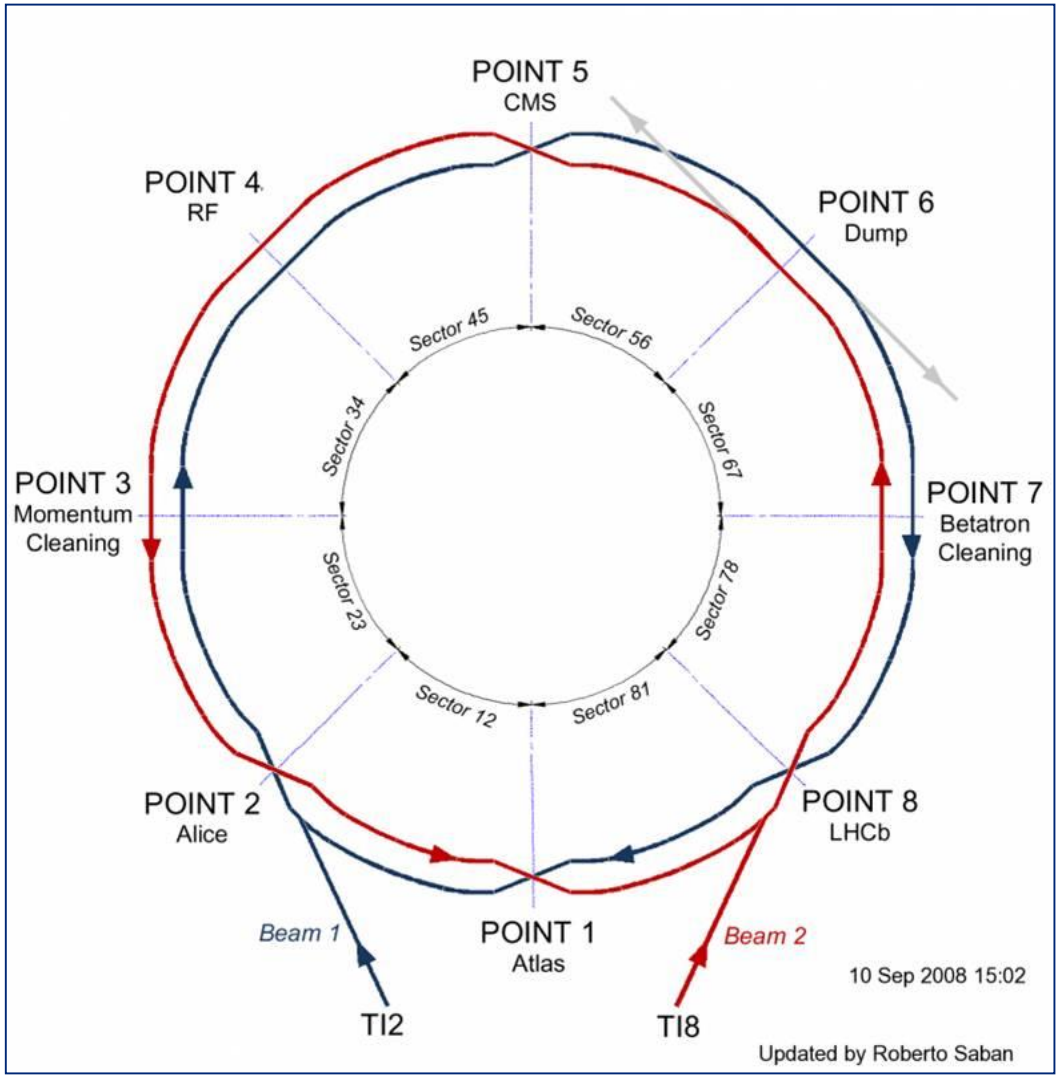
- HiRadMat is a users facility, designed to provide high-intensity short-pulse 440 GeV proton or 173.5 GeV/n ^{208}Pb beams to a dedicated target area
  - Make it possible to test the dynamic effects of short beam pulses on material samples, in conditions that are comparable to the LHC.
  - LHC beam with various intensities is provided by the SPS
  - HiRadMat is not a facility where large doses can be accumulated during an experiment.



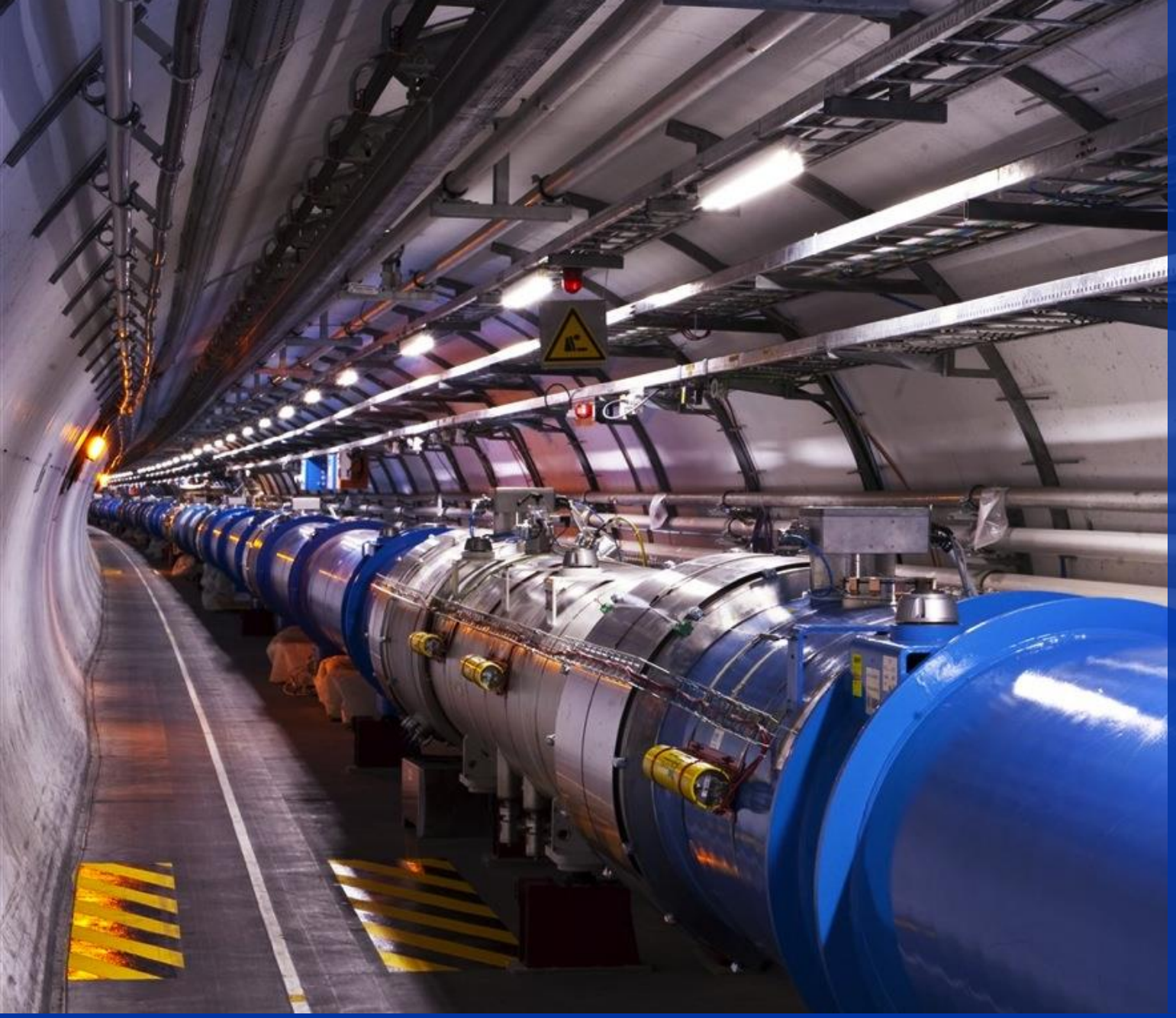


LHC





- **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**



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

Content

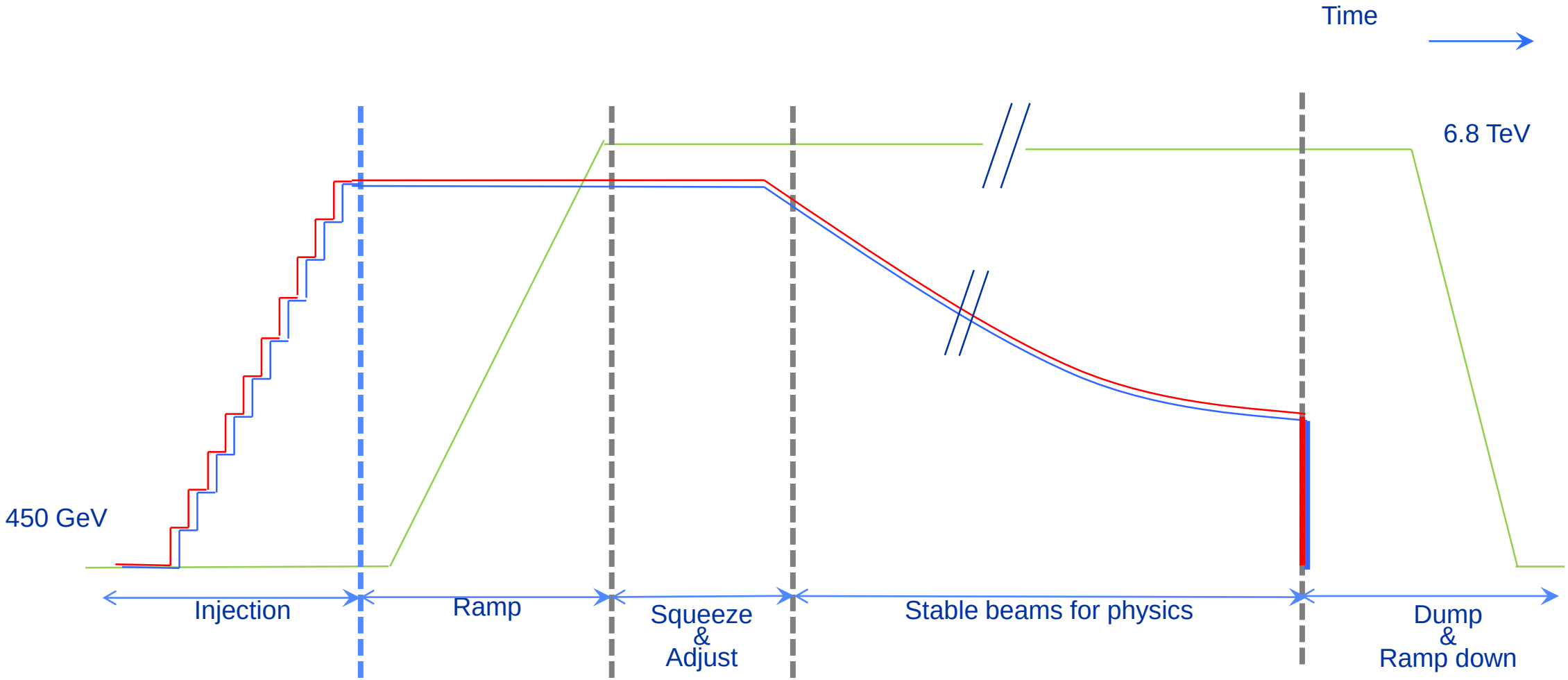
The CERN Accelerator Complex

Cycling the Accelerators & Satisfying Users

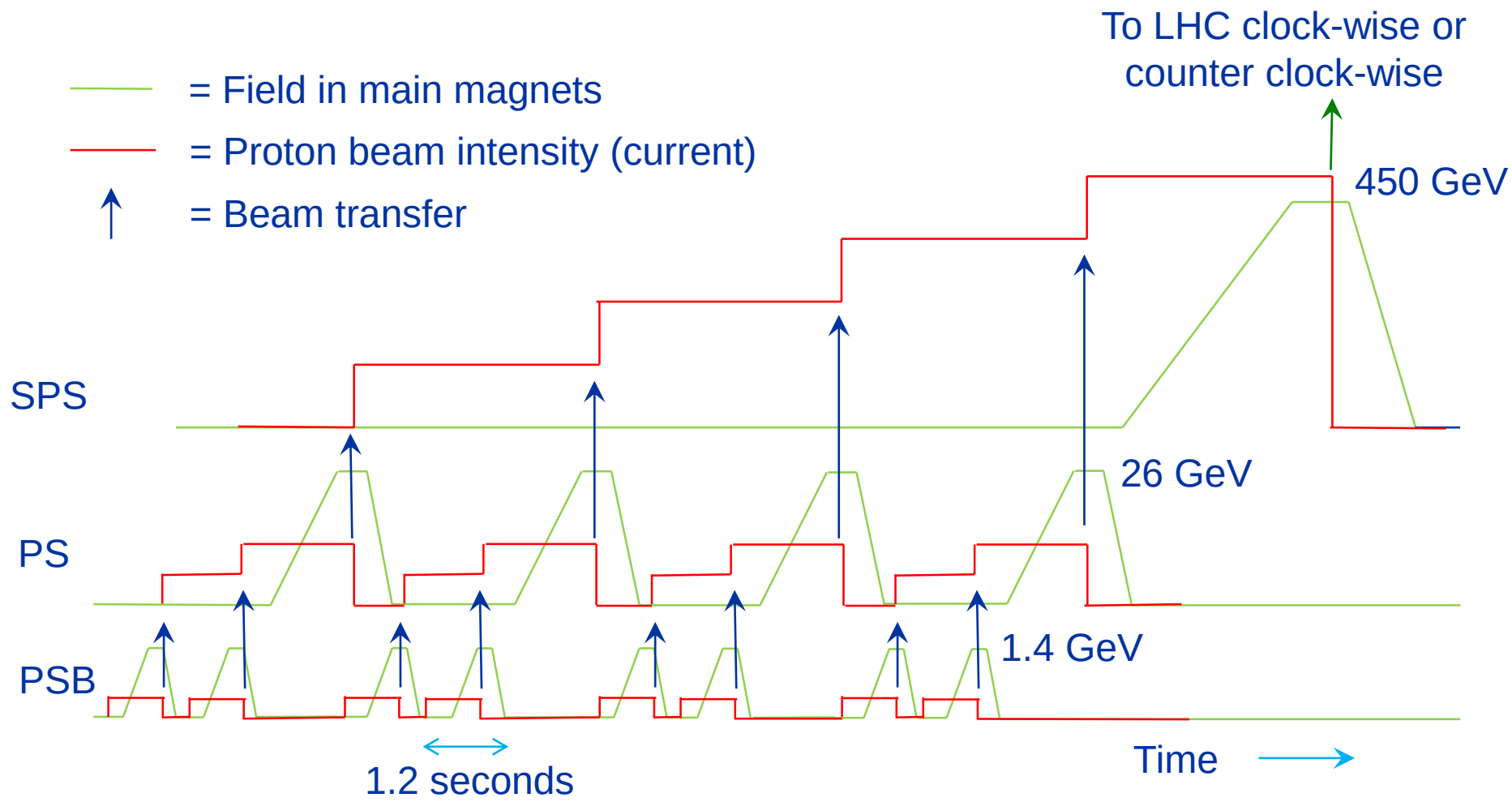
Concluding Remarks

The LHC Cycle

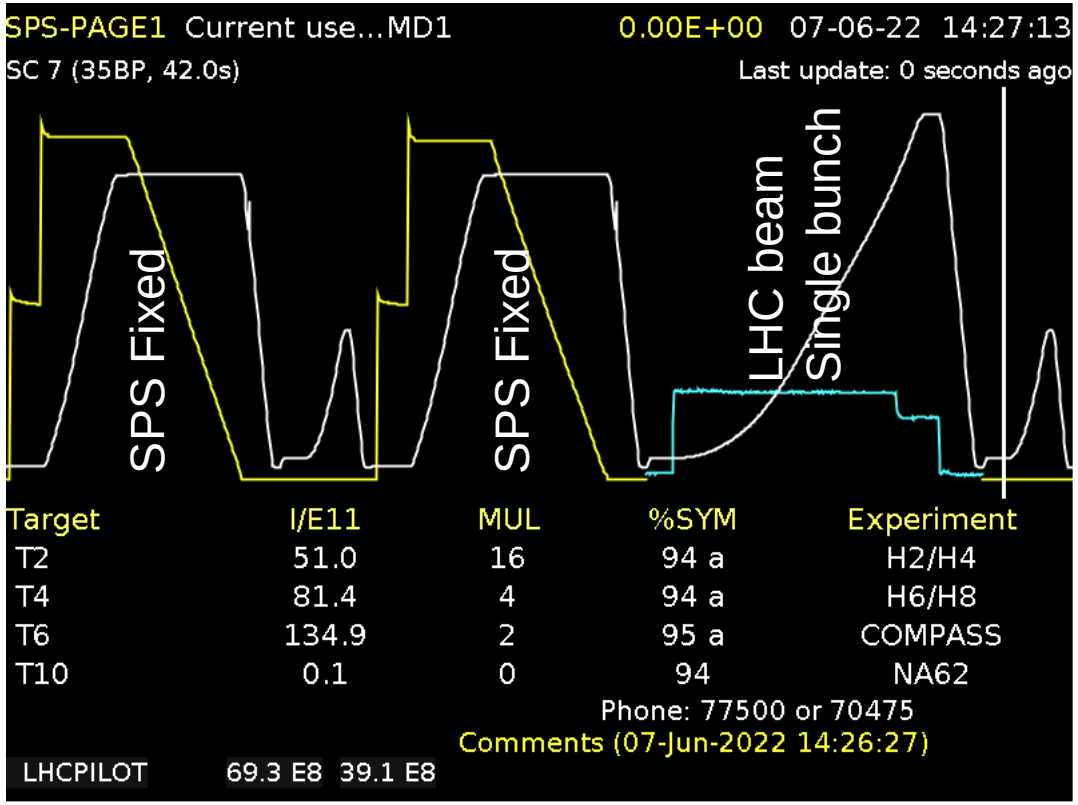
= Field in main magnets
= Beam 1 intensity (current)
= Beam 2 intensity (current)

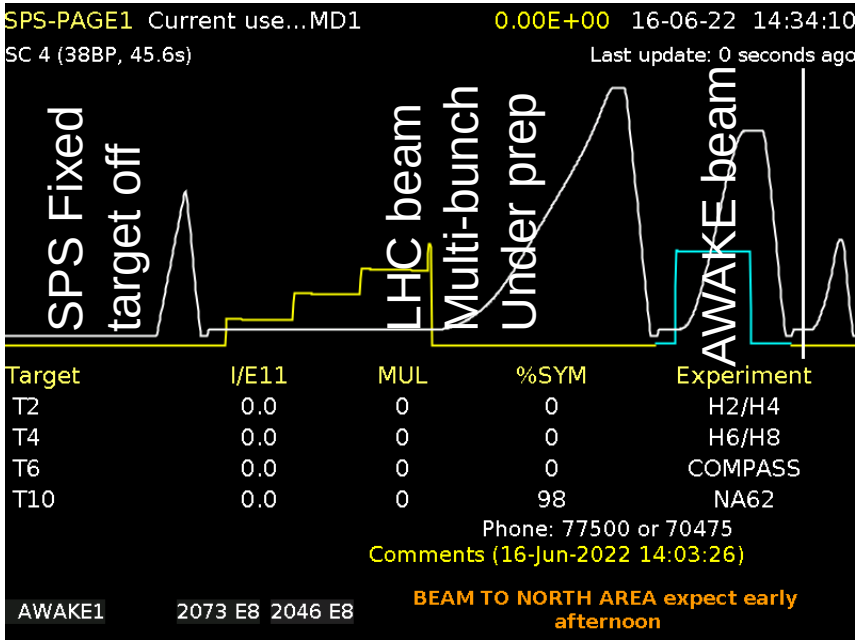


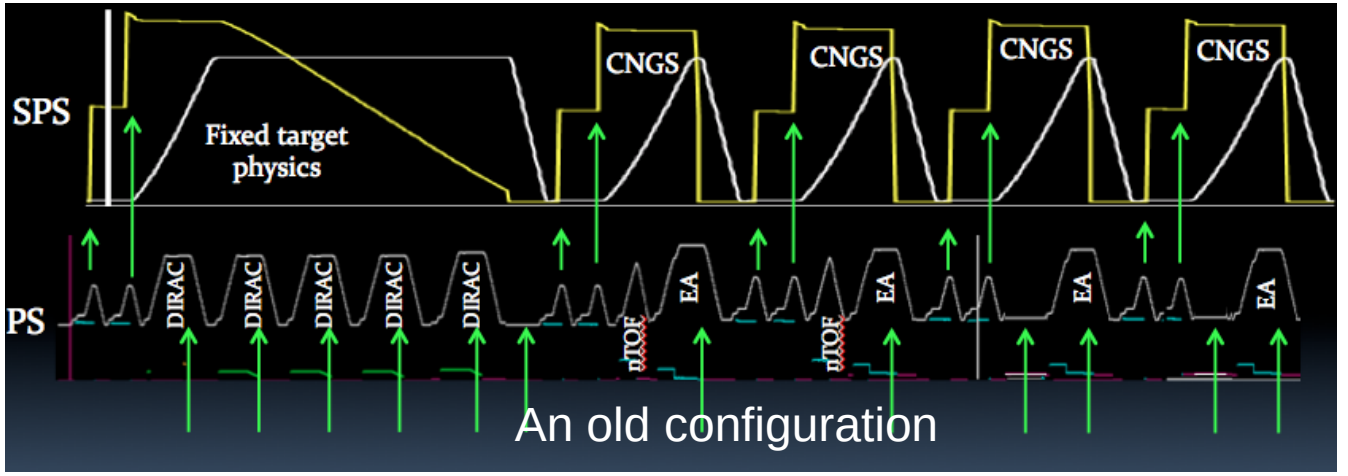
Filling the LHC & Satisfying Fixed Target users



Some Examples of Super Cycles







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Concluding Remarks

Besides the Beam production for the LHC, the injectors provide a wide variety of beam types to a very rich and varied fixed-target physics programme

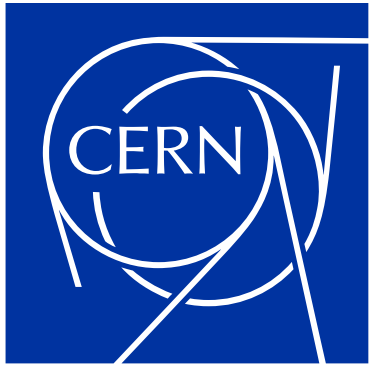
- Various energies and large range of particle types
- Different types of extractions – Fast, Mutli-turn and slow extraction from msec. to sec. range

The LHC injector upgrades done during Long shut-down 2 (2019 & 2020) will provide brighter LHC beams for the HL-LHC era, actually already now…

- It provides also potential for higher performance for fixed target beams, which is being addressed/explored in the scope of the Physics Beyond Colliders (PBC) study

Pulse-to-Pulse modulation of all machine settings make it possible to produce one type of beam immediately followed by another type of beam, even different particle species, in a matter of seconds

- Cycles within a repeating super cycles with each cycle having its particular settings
- Timesharing: Whenever the downstream machine is accelerating, the upstream machine produces beam for its own Users.



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