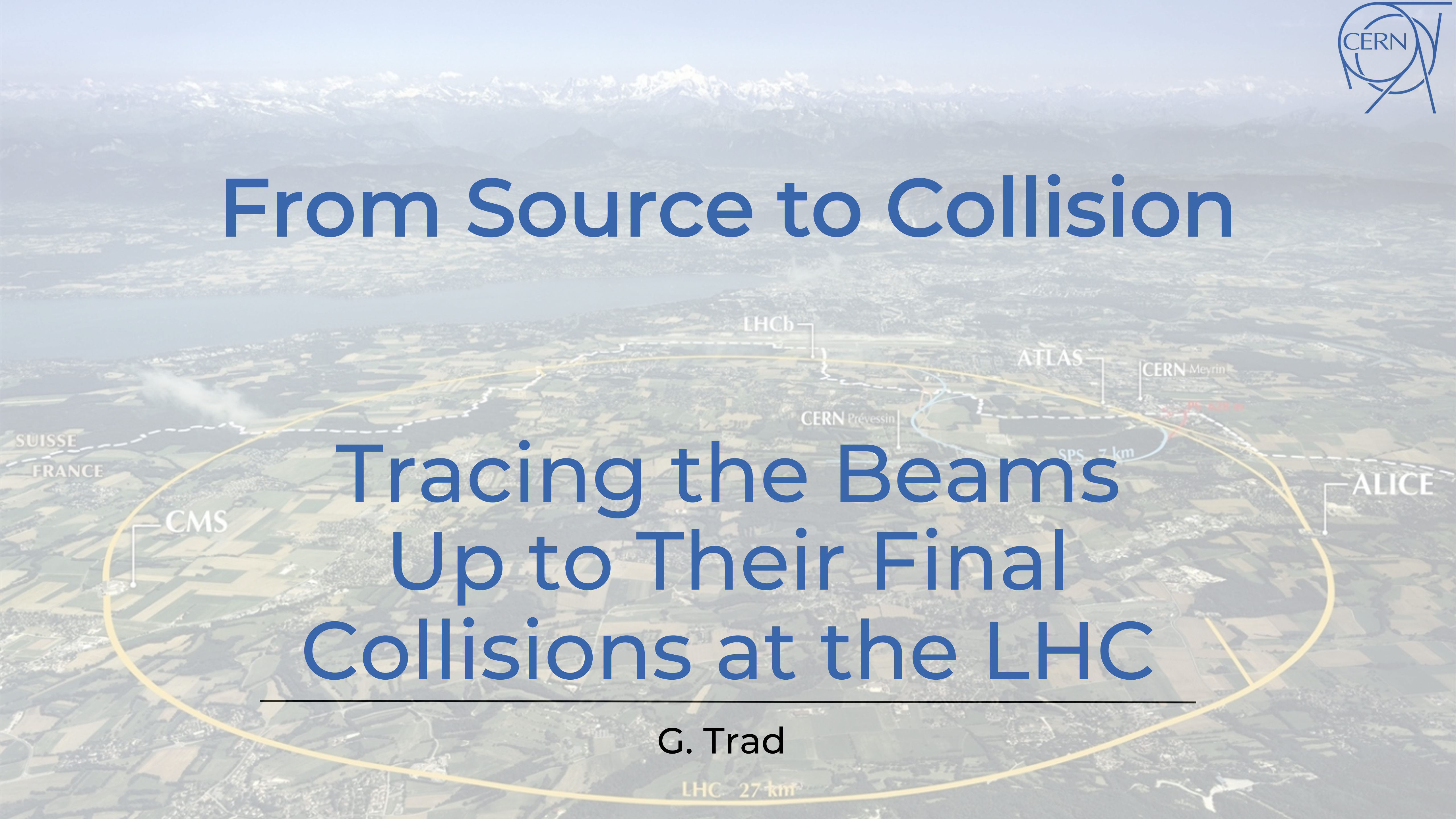

LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SUISSE
FRANCE
SPS 7 km
ALICE
CMS
LHC 27 km

From Source to Collision

Tracing the Beams Up to Their Final Collisions at the LHC

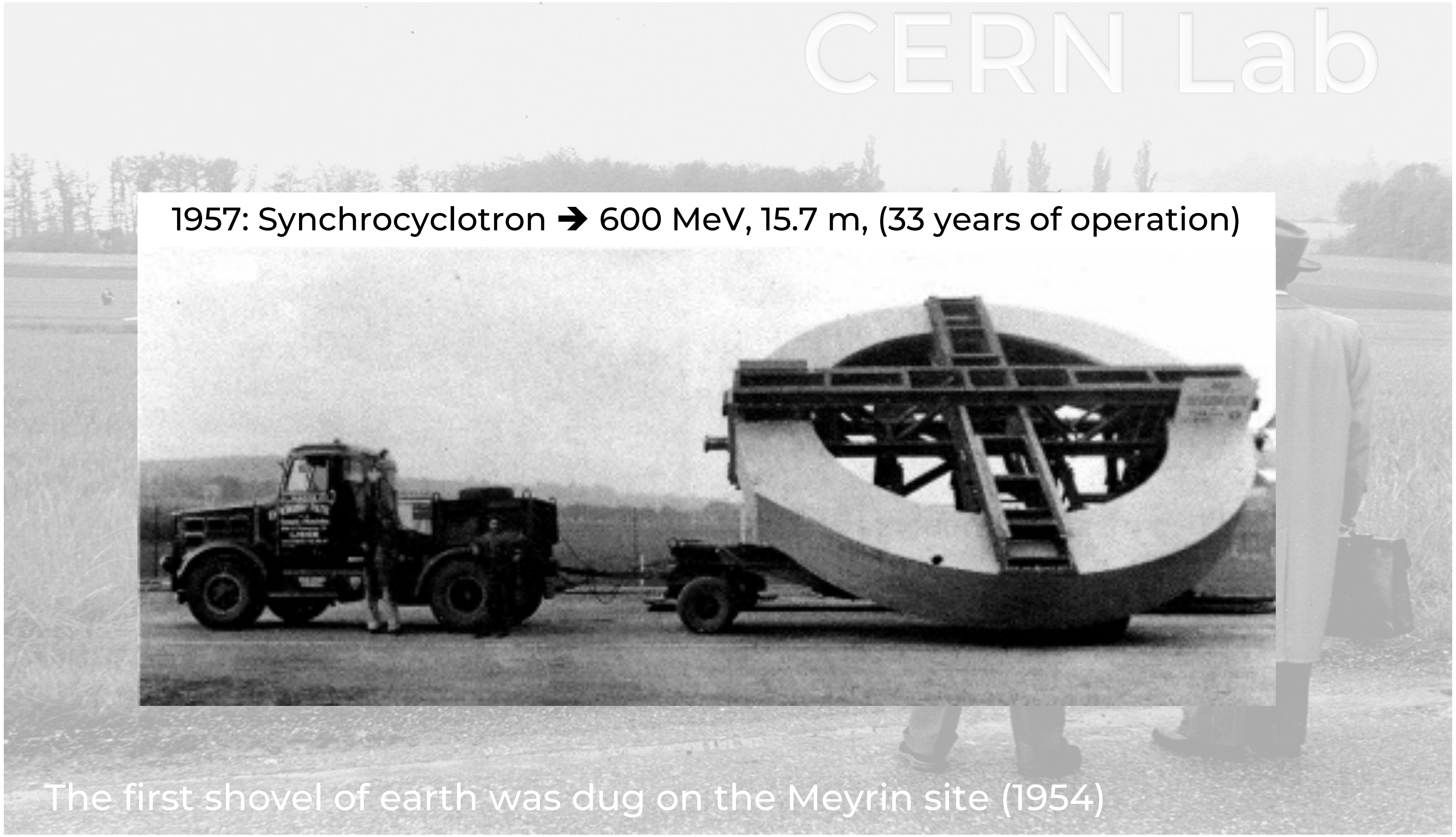
G. Trad




CERN Lab
The first shovel of earth was dug on the Meyrin site (1954)

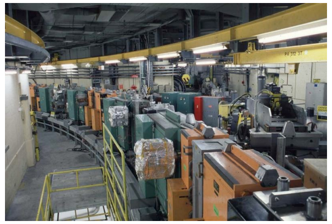
CERN Lab

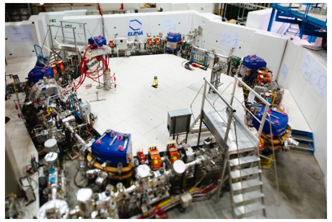
1957: Synchrocyclotron ➔ 600 MeV, 15.7 m, (33 years of operation)

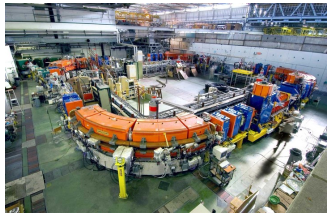


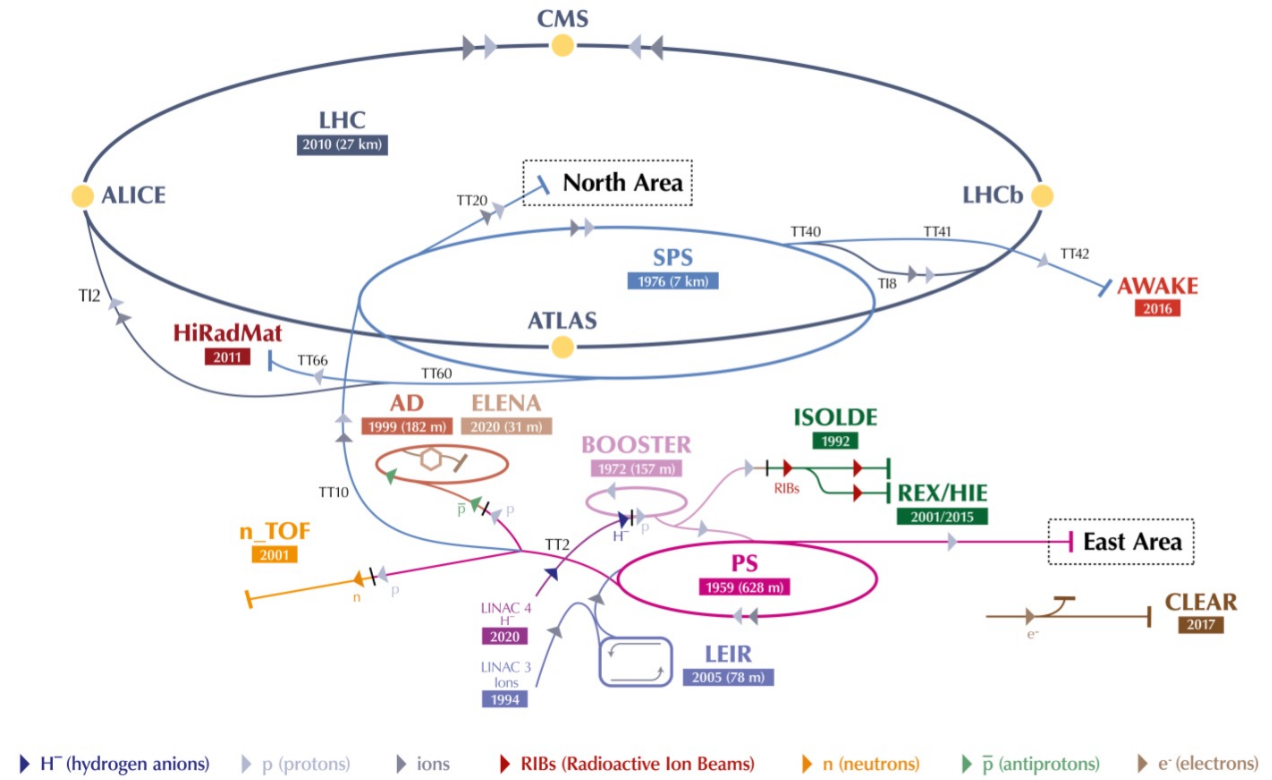
The first shovel of earth was dug on the Meyrin site (1954)

OUTLINE







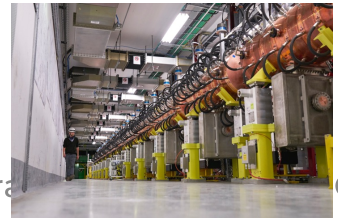


Overview of the injector complex

Experiments along the chain

Introducing the LHC for proton Physics:
- LHC Cycle
- LHC beams
- LHC Collisions

Glance at Ions Operation



Why Accelerators and colliders?

Creating Matter from Energy

In our accelerators we provide energy to the particles we accelerate.

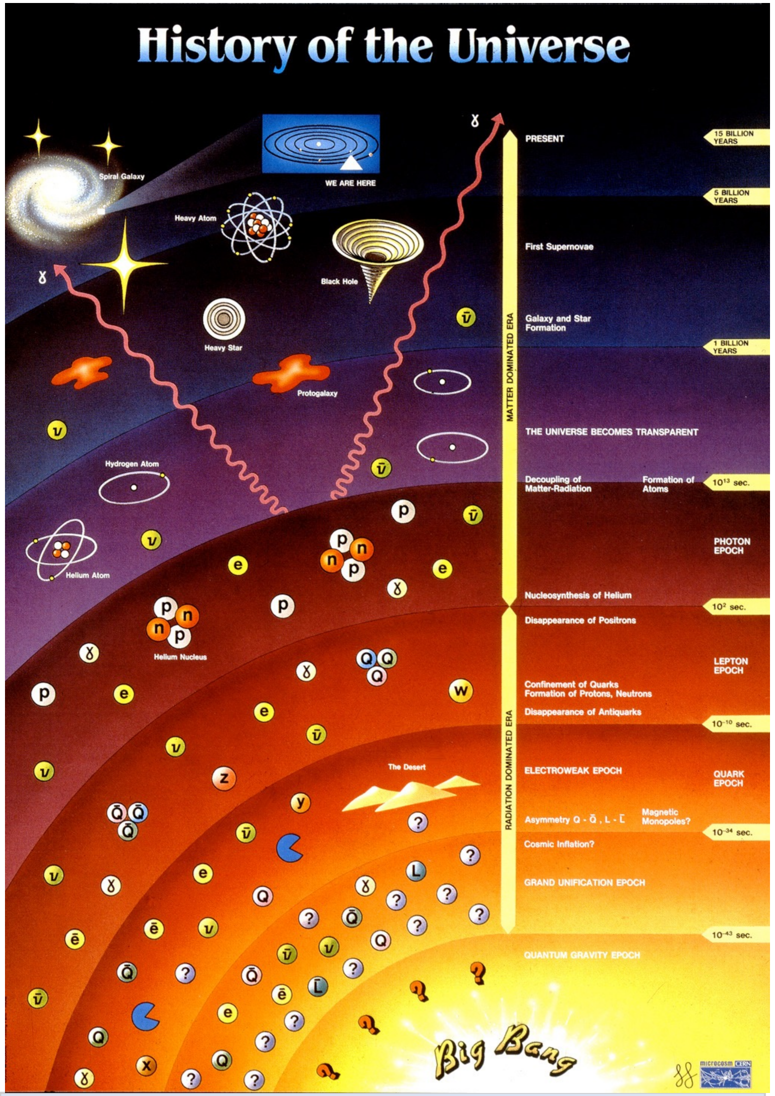
In the detectors we observe the matter created

Fixed target

$$E \propto \sqrt{E_{beam}}$$

Collider

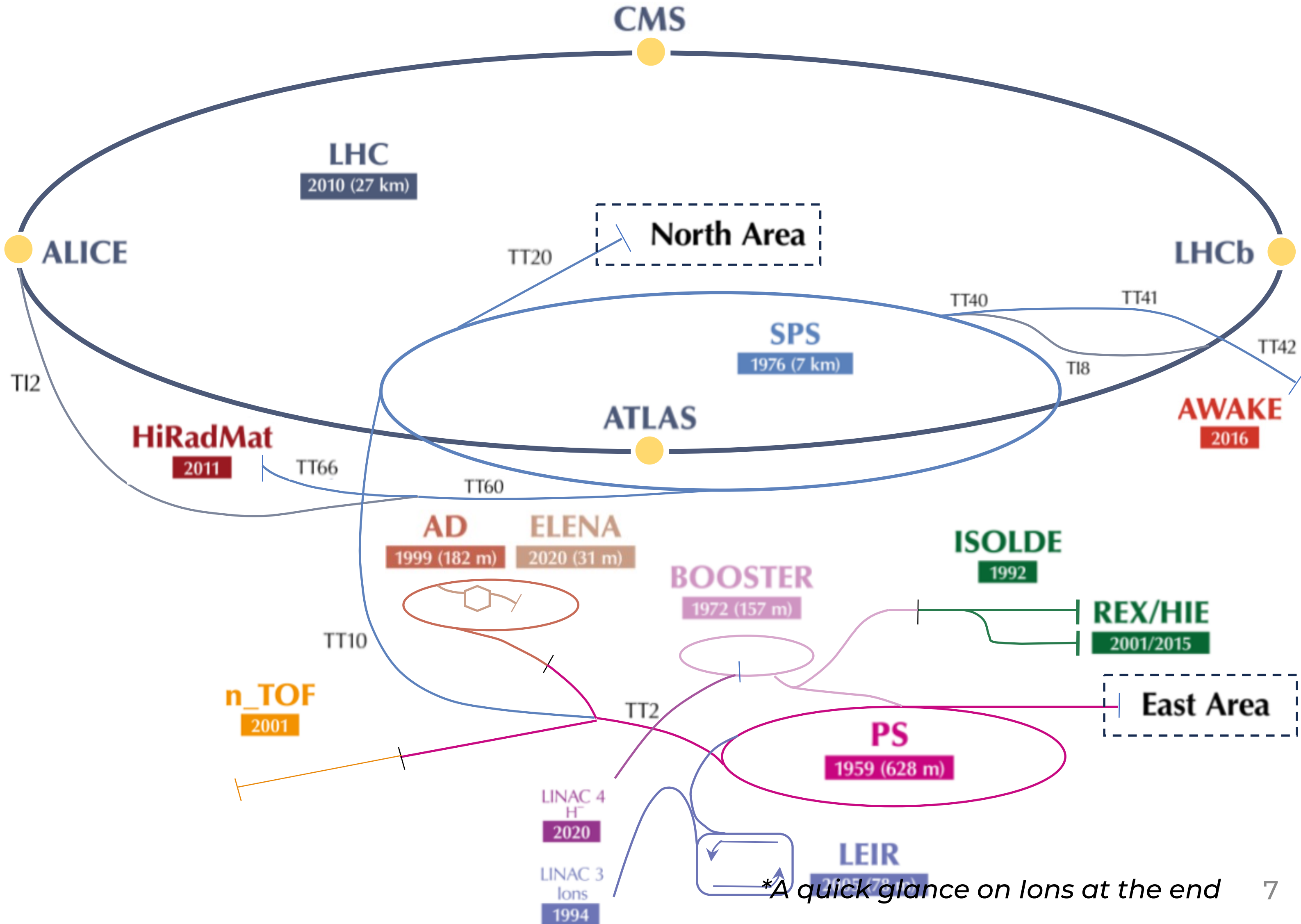
$$E = E_{beam1} + E_{beam2}$$



During the Big Bang Energy was transformed in matter

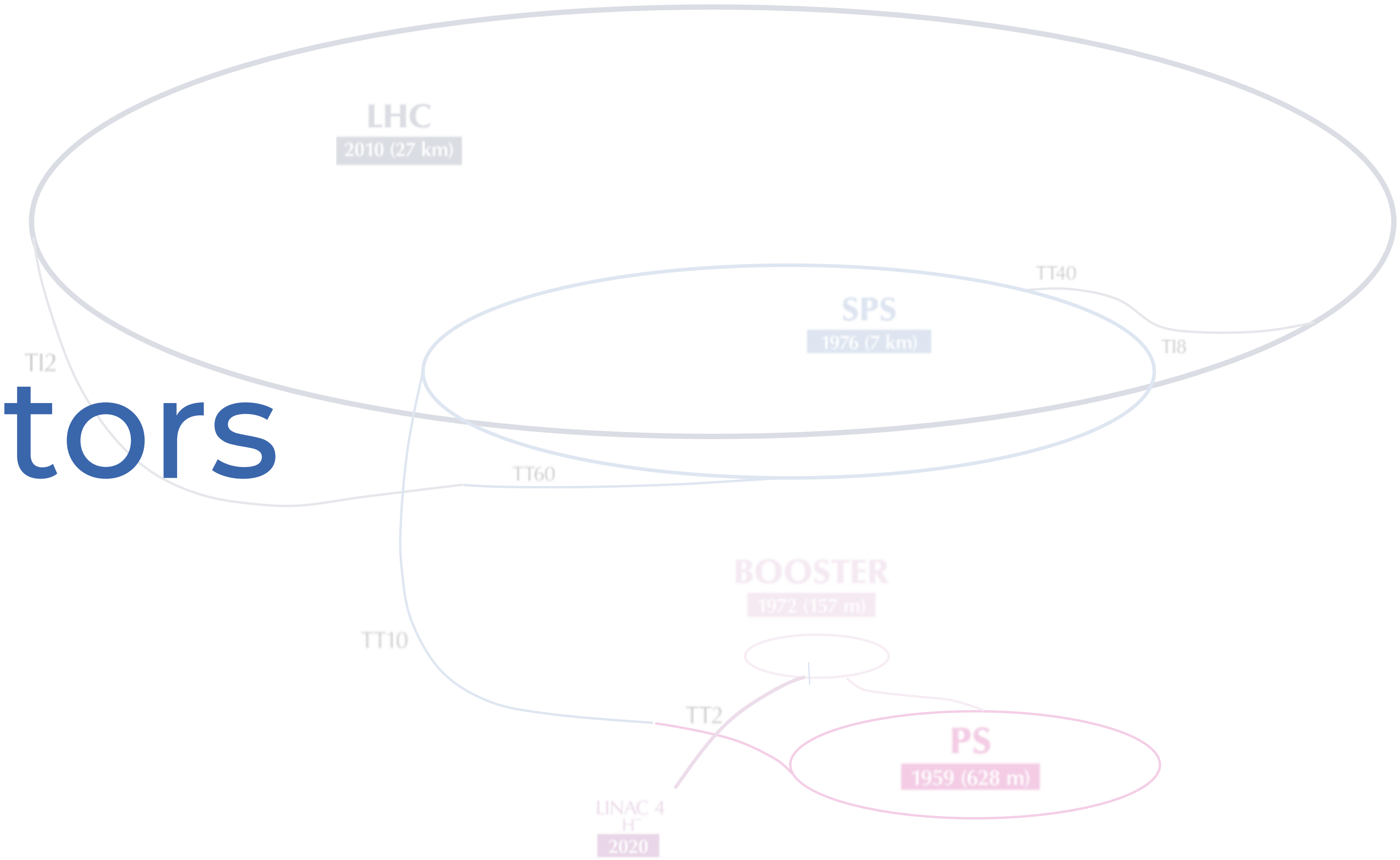
Accelerator complex

- Chain of accelerators providing beams up to 7 TeV (LHC design, protons)
- A total acceleration exceeding x10^8
- Featuring experiments at various energy levels, very broad physics reach
- (De)Accelerated Species: hydrogen anions, protons, ions, Radioactive Ion Beams, neutrons, antiprotons and electrons.

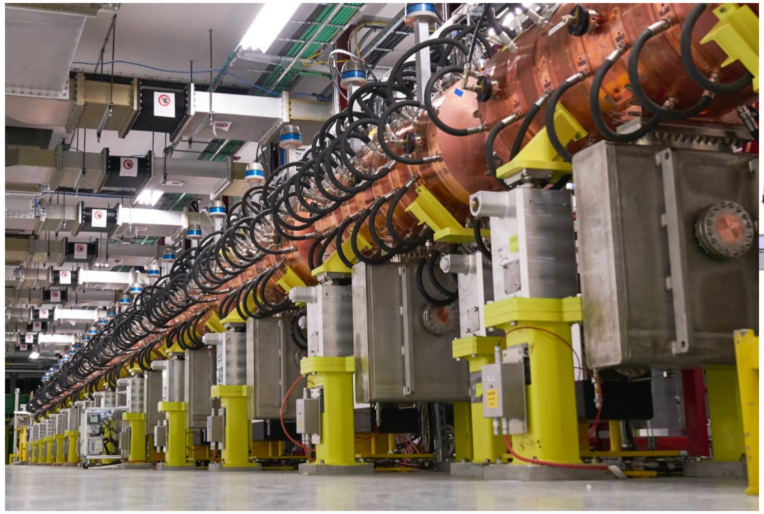


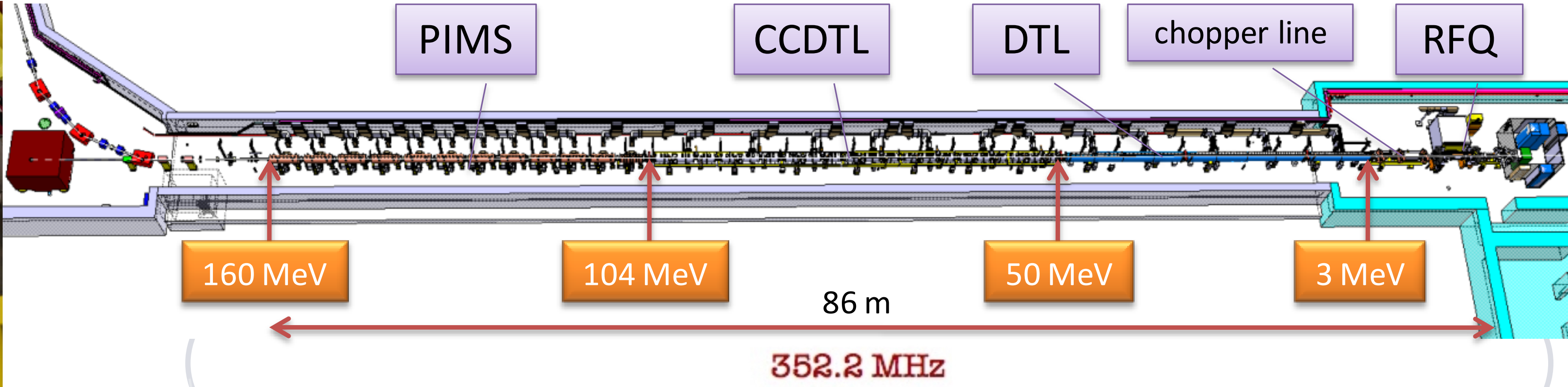
*A quick glance on Ions at the end

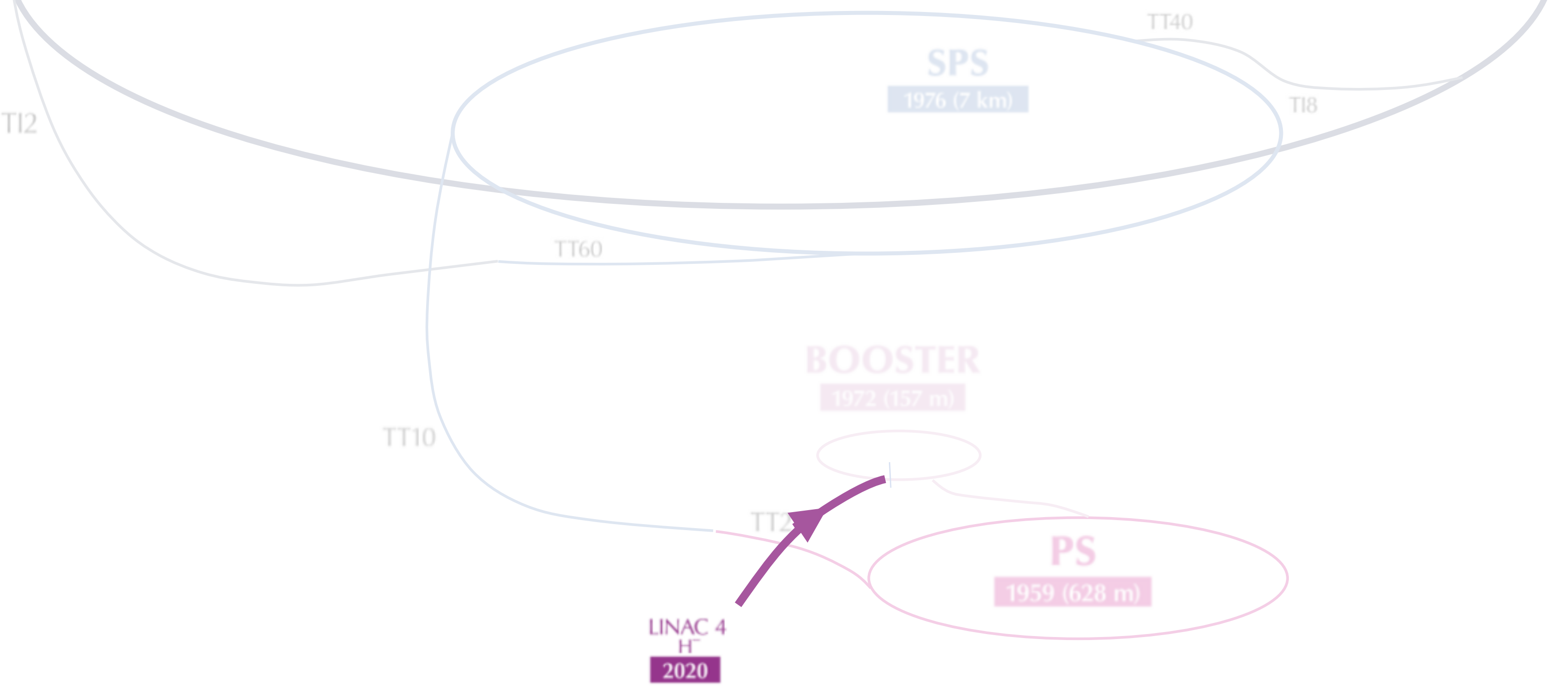
LHC injectors



LHC injectors – LINAC 4

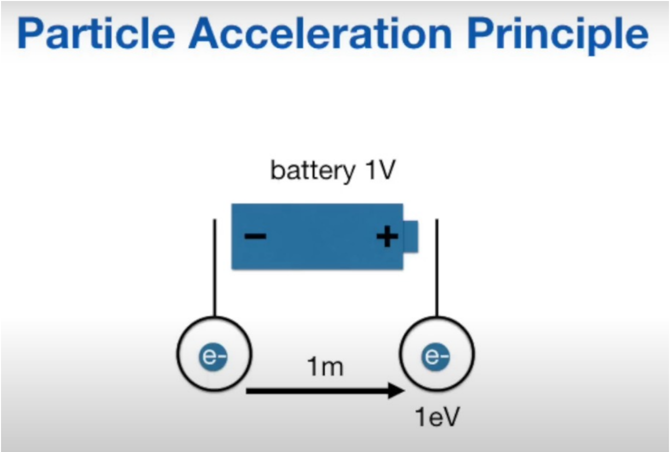


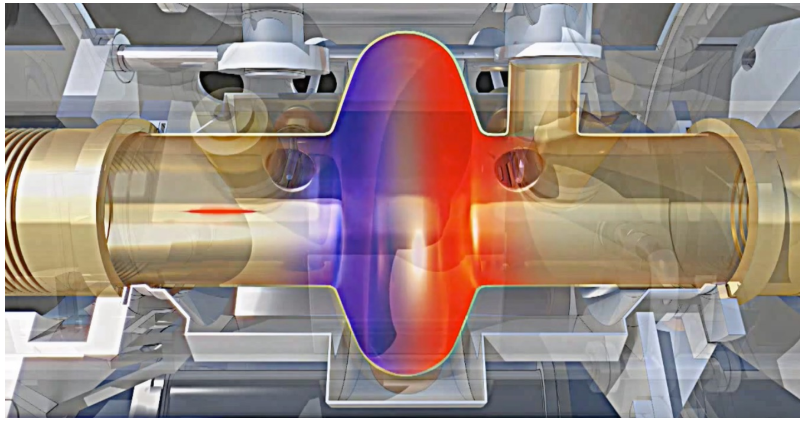




- H⁻ ion source at 45 keV

Acceleration and Bunching





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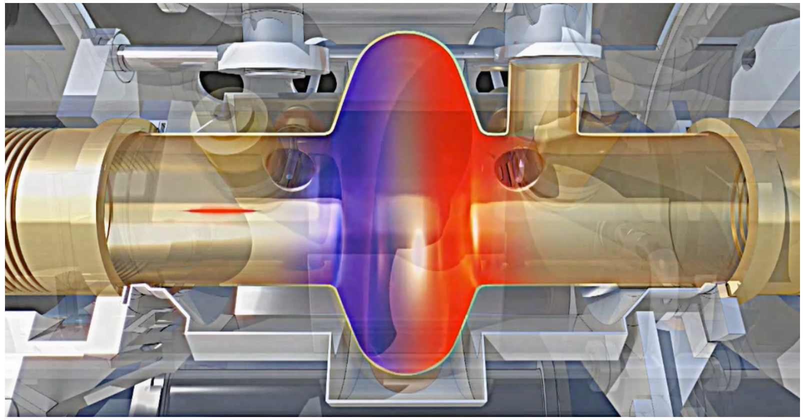
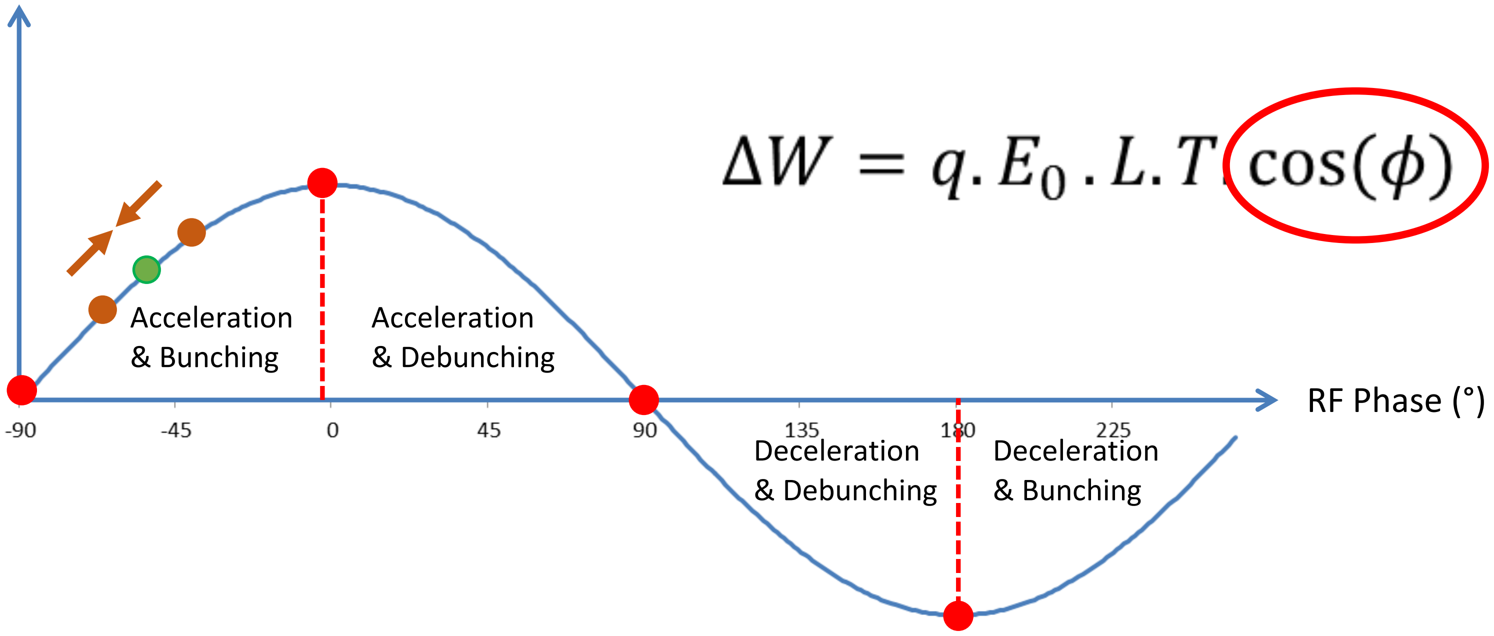




Energy gain for the synchronous particle

$$\Delta W_s = qE_0 LT\cos(\phi_s)$$

Energy gain for a particle with phase φ

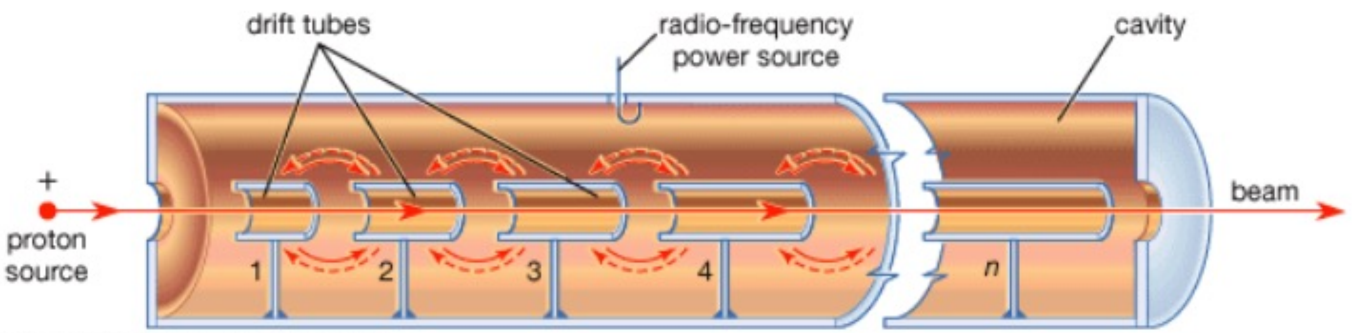
$$\Delta W = qE_0 LT\cos(\phi)$$

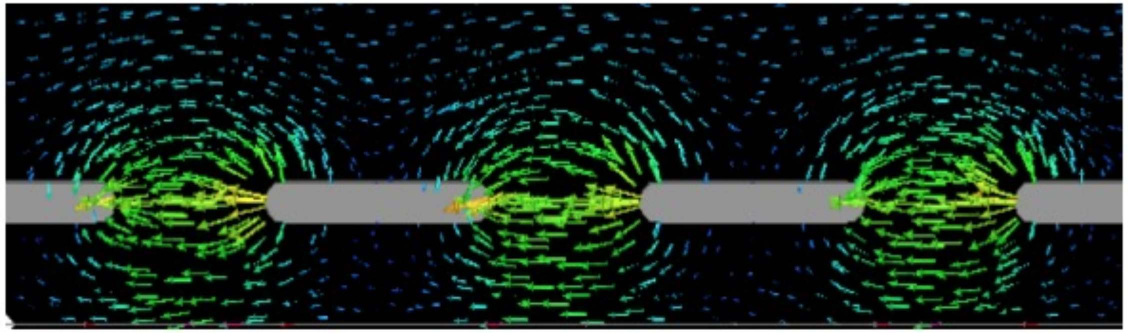
By accelerating on the rising slope of the positive RF wave, a longitudinal force keeps the beam **bunched**.

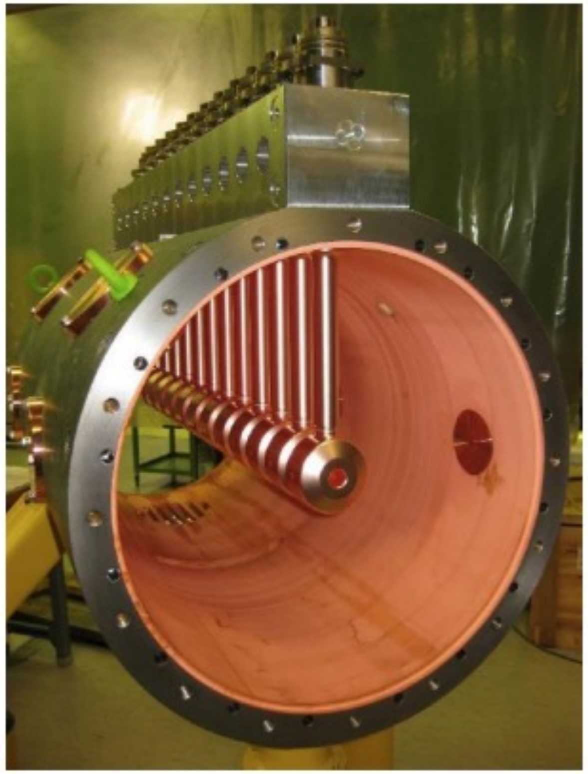
RF gymnastics are just a very fine control over the frequency and phase of the voltage seen by the beams.
Additional RF systems provide the machine with the “flexibility”

LHC injectors – LINAC 4

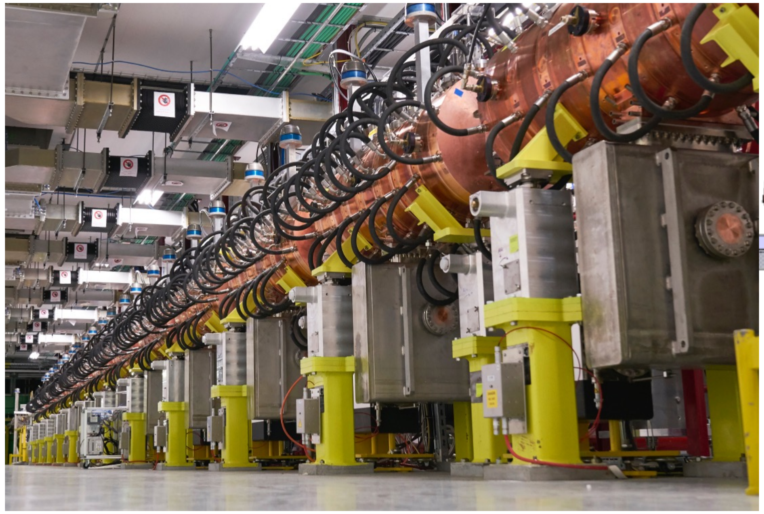
- **Drift Tube LINAC**
  - Particles accelerated by a sequence of gaps
  - Distance between gaps increases proportionally to the particle velocity, to keep synchronicity
  - Used in the range where velocity increases rapidly

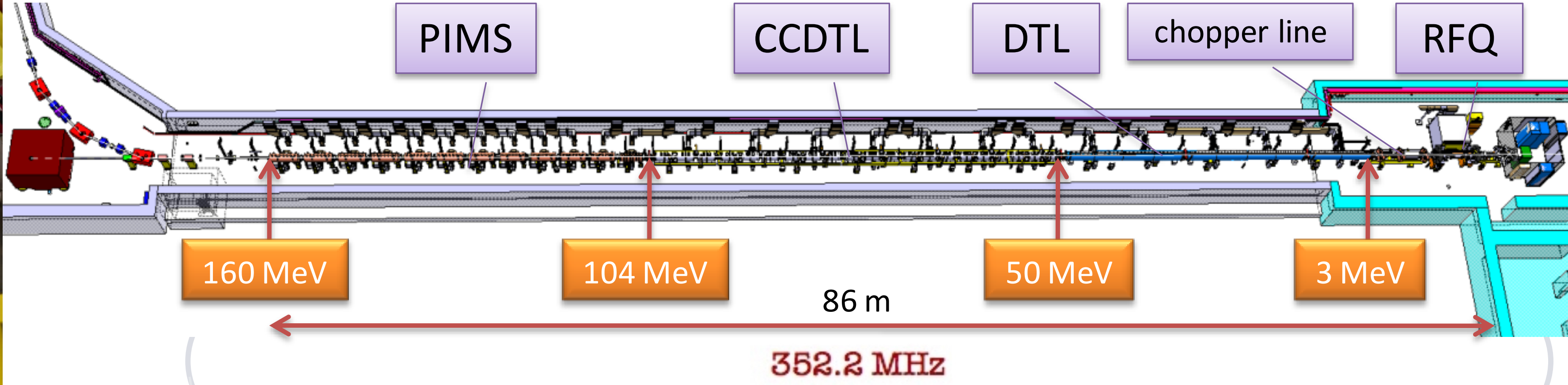


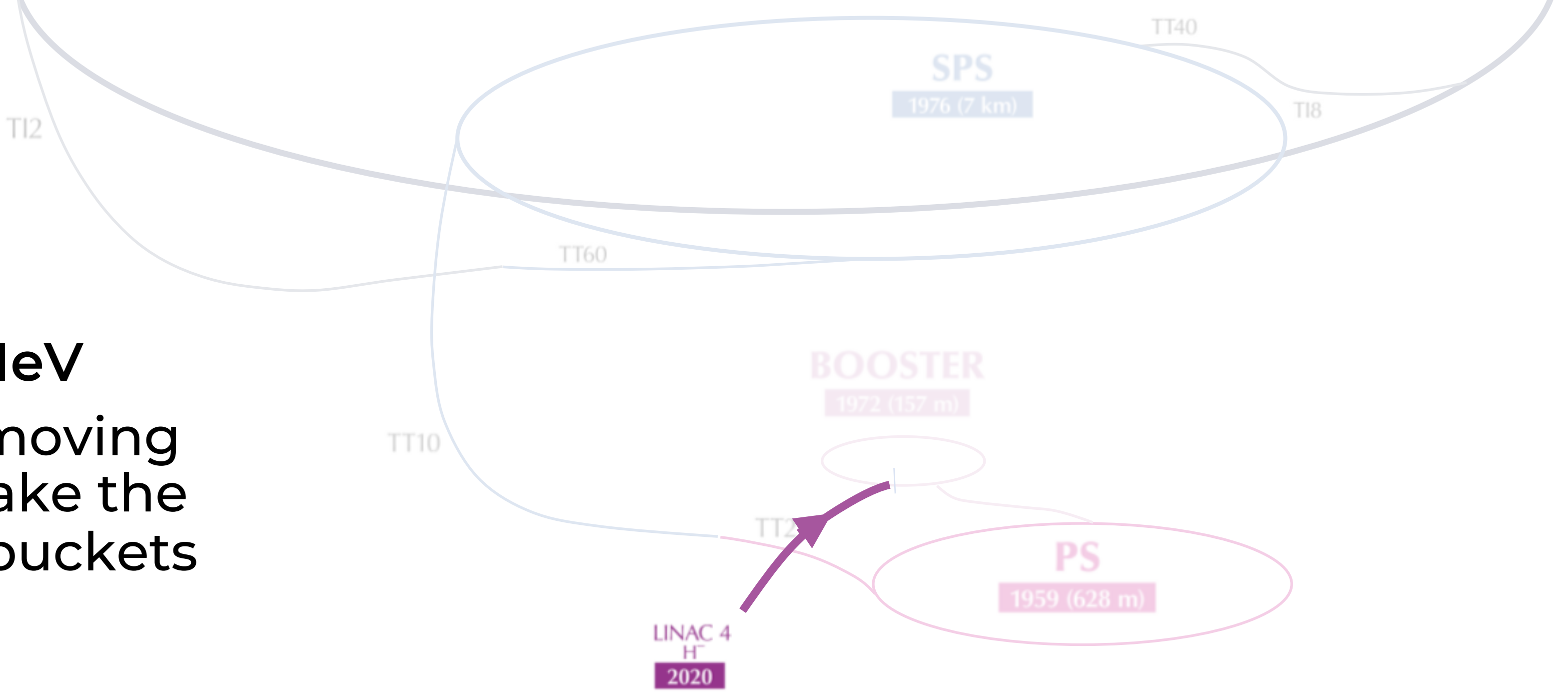




LHC injectors – LINAC 4





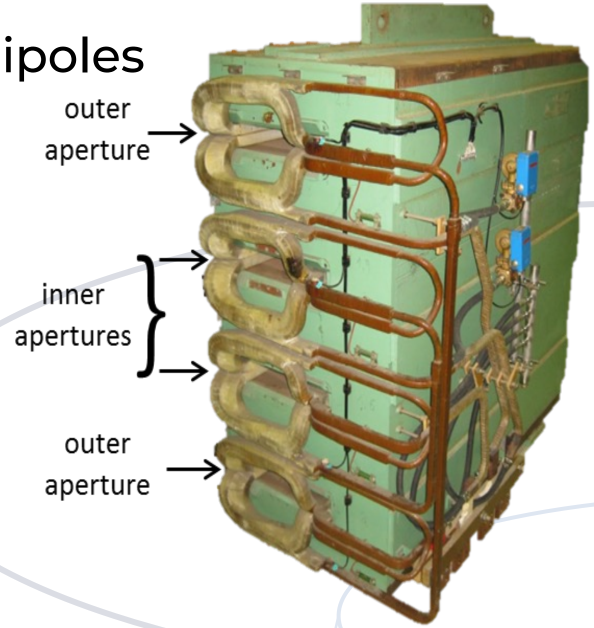


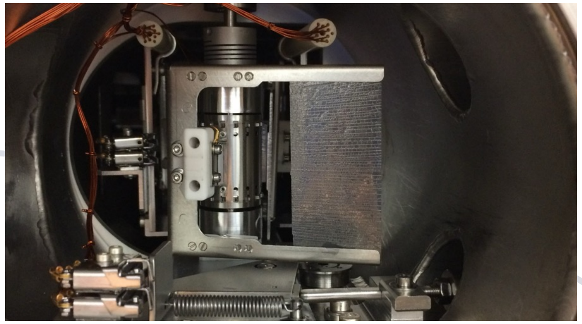
- **H^- ion source** at 45 keV
- L4 Accelerates beam up to **160 MeV**
- The chopping scheme allows removing some of the Linac bunches to make the beam fit into the PS Booster RF buckets
- Pulse rate 1.2 s

Proton Synchrotron Booster

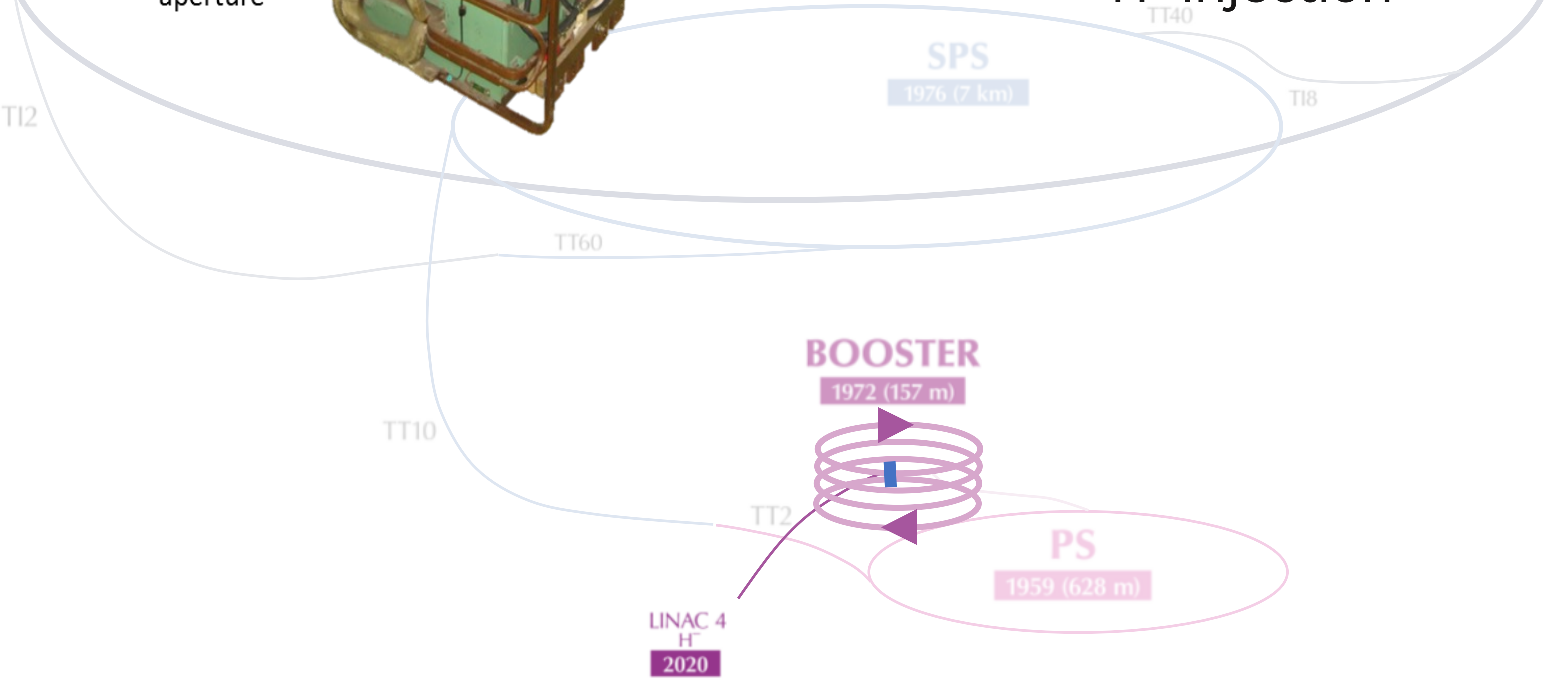
LHC injectors – PS Booster

Main dipoles



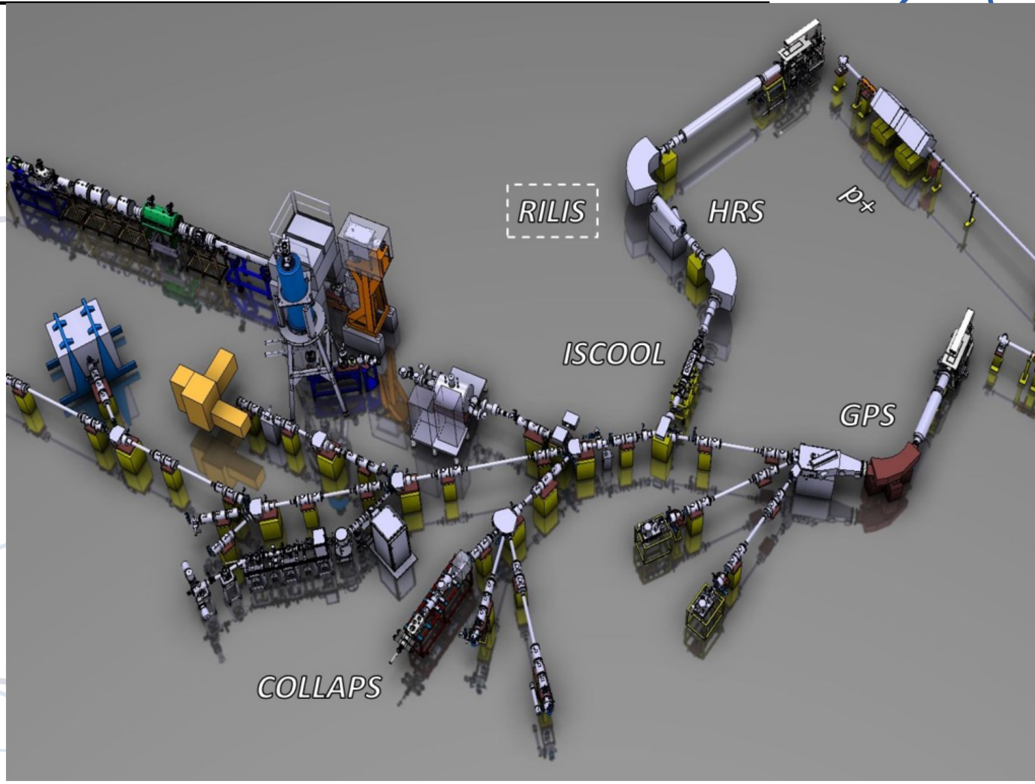


Stripper foil for H- injection



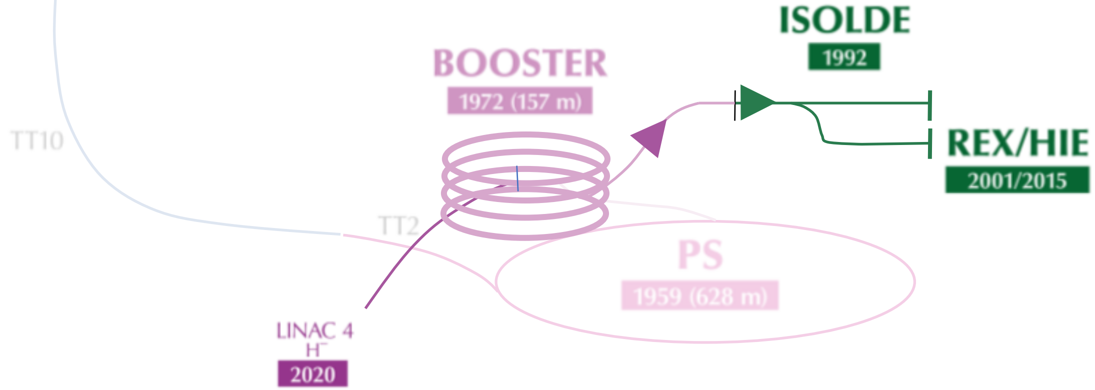
- 1st Synchrotron with 4 superposed rings
- Circumference of 157 m
- Proton energy from 160 MeV to 2 GeV
- Can cycle every 1.2 s
- Each ring will inject over multi-turns, using charge exchange injection

PSB – Experiments - ISOLDE



- The PSB proton beam impinges on a target producing a range of isotopes
- Two mass separators (GPS & HRS) allow selection of isotopes
- The post acceleration of isotopes is being extended
  - REX, normal conducting accelerating structures
  - HIE-ISOLDE, super conducting LINAC

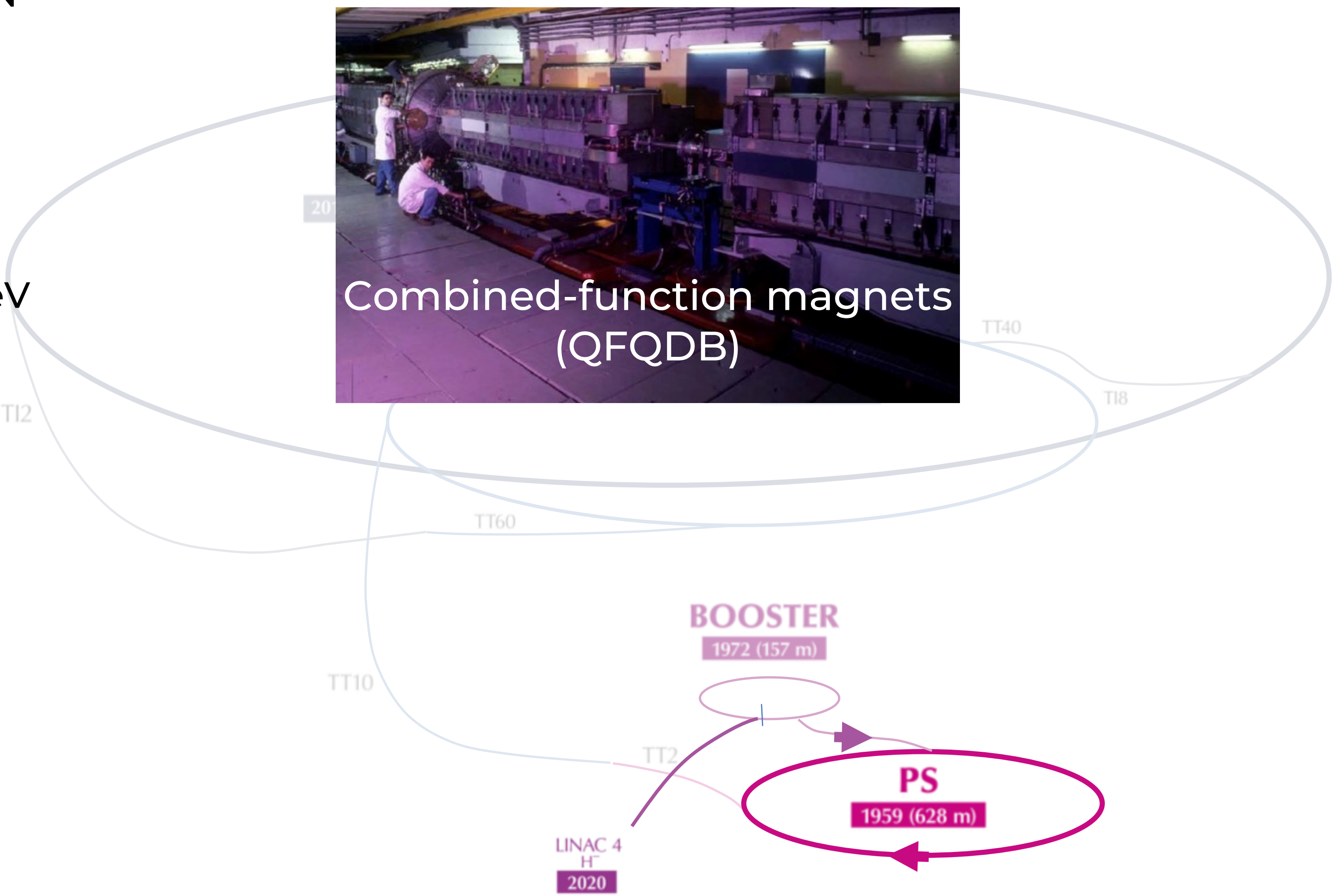
(3x of Energy/nucleon up to 10 MeV/u)



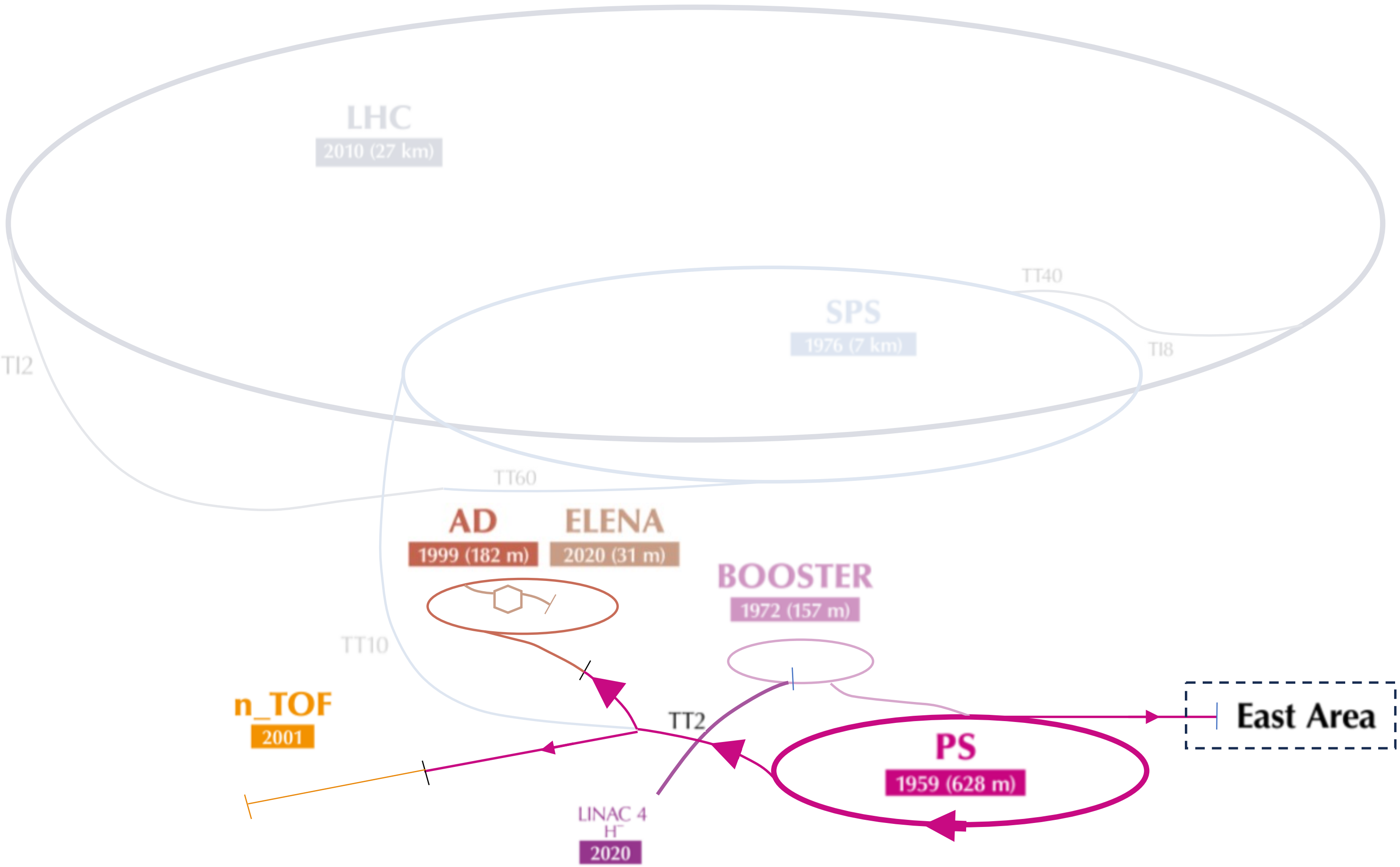
Proton Synchrotron

LHC injectors – Proton Synchrotron (PS)

- The oldest operating synchrotron at CERN
- Circumference of 628m
    - 4 x PSB circumference (200p m)
- Increases proton energy up 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



PS – Experiments - AD-ELENA



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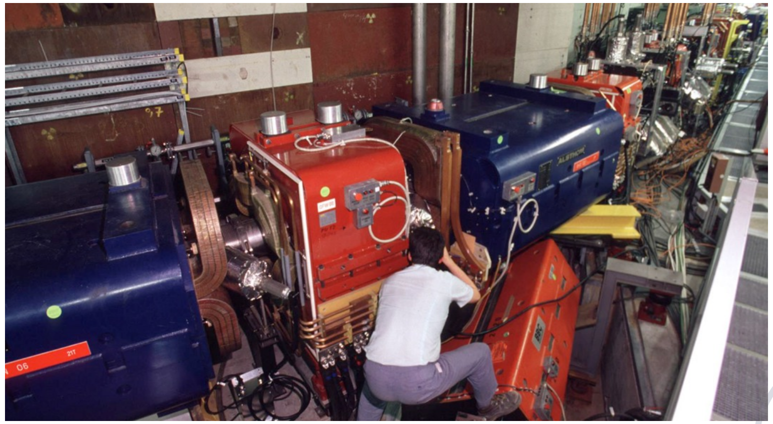
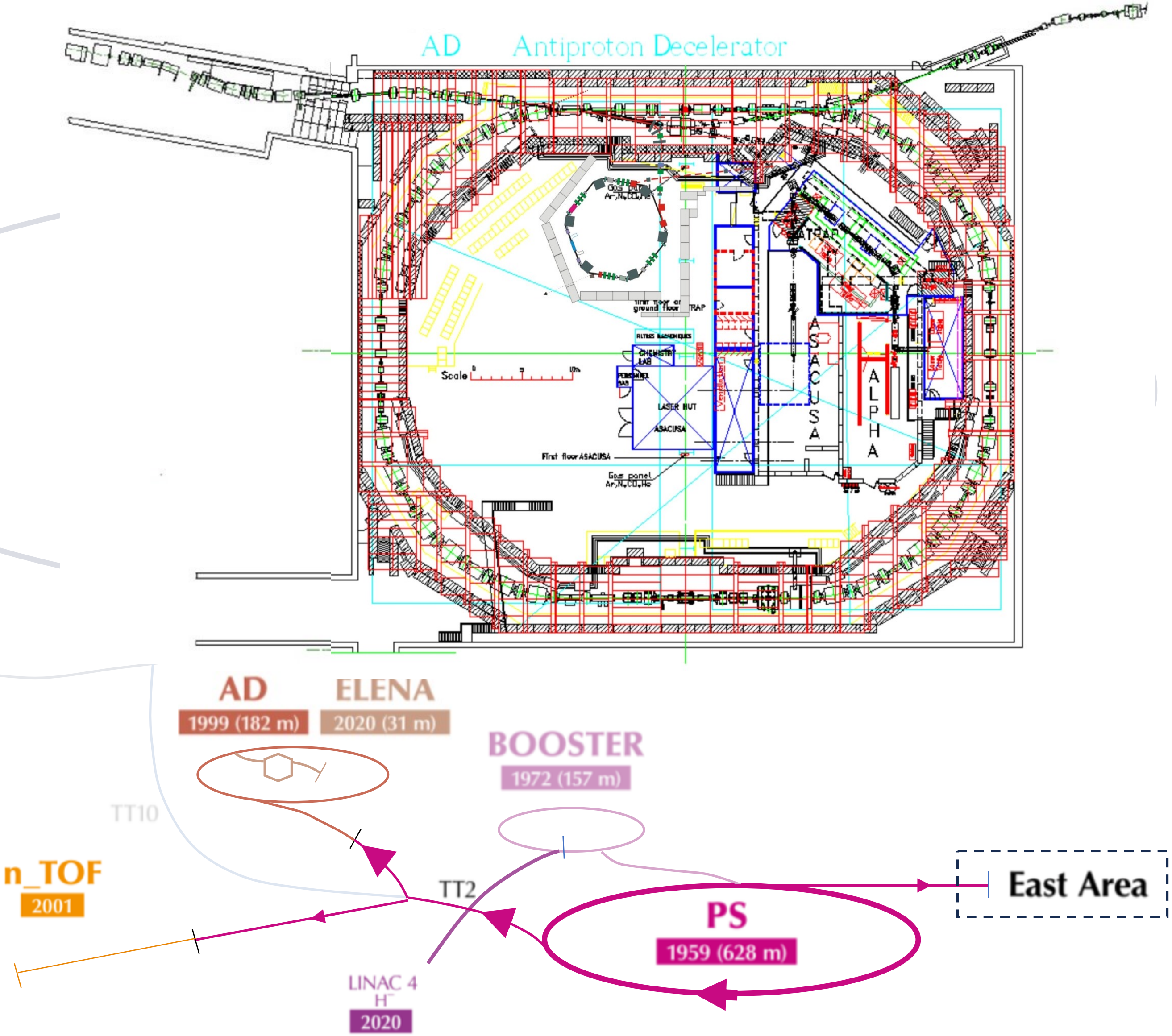
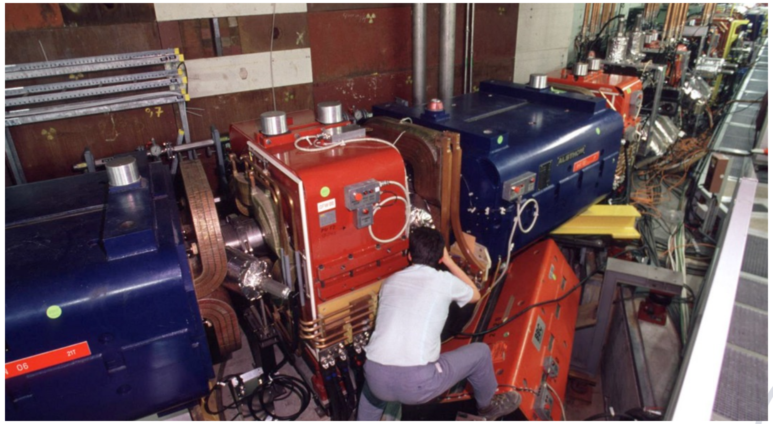


- Receives fast extracted proton beam from PS at 26 GeV/c on a target
- Every million protons yields about one usable antiproton at 3.5 GeV/c.
- AD decelerates beam in stages down to 5.3 MeV
- ELENA will further decelerate down to 100 keV
- Experiments:
  - ASACUSA, ALPHA, AEGIS, BASE, GBAR



PS – Experiments - AD-ELENA



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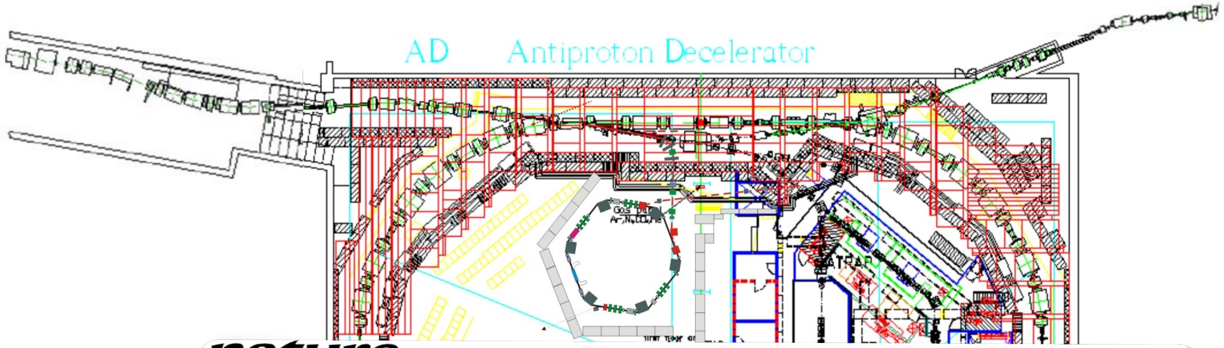

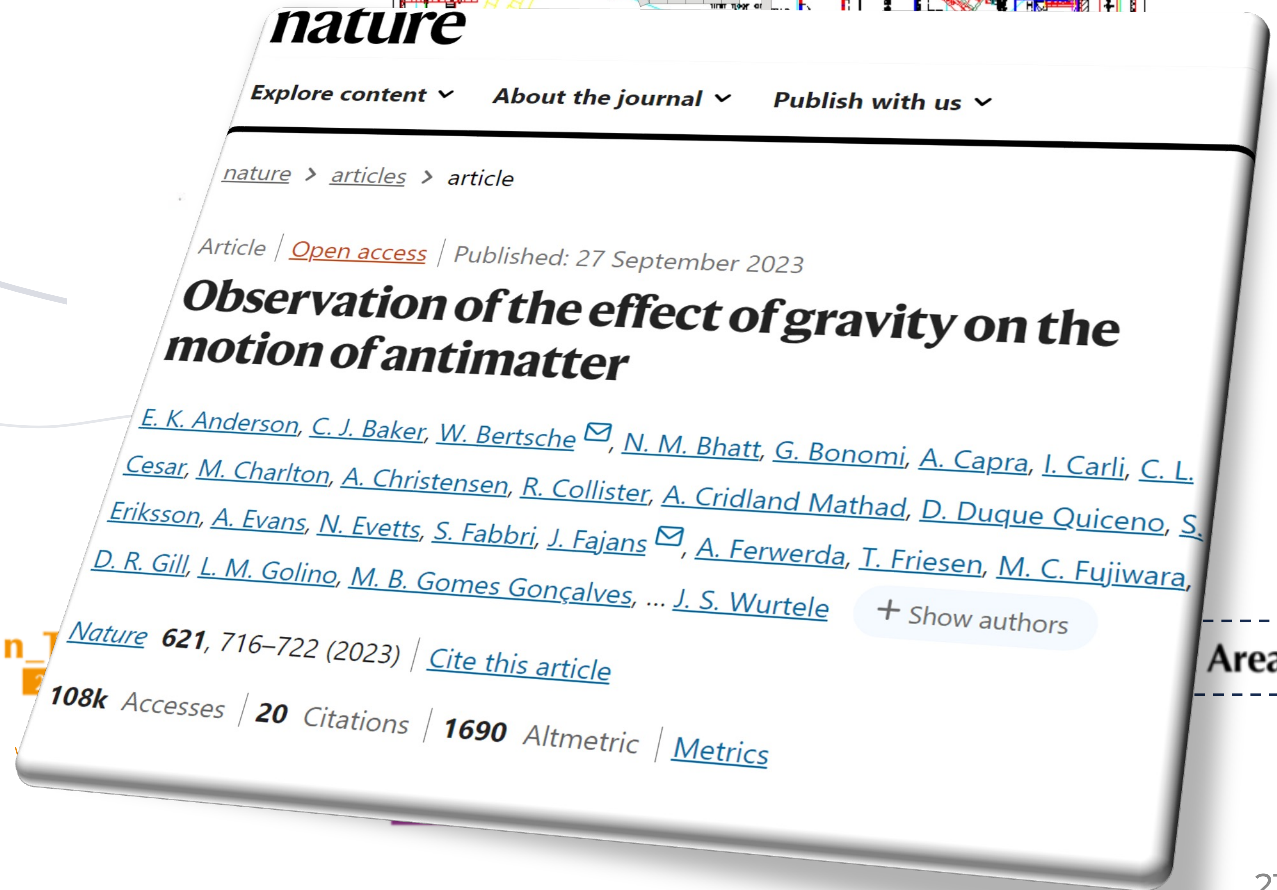

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Observation of the effect of gravity on the motion of antimatter

E. K. Anderson, C. J. Baker, W. Bertsche, N. M. Bhatt, G. Bonomi, A. Capra, I. Carli, C. L. Cesar, M. Charlton, A. Christensen, R. Collister, A. Cridland Mathad, D. Duque Quiceno, S. Eriksson, A. Evans, N. Evetts, S. Fabbri, J. Fajans, A. Ferwerda, T. Friesen, M. C. Fujiwara, D. R. Gill, L. M. Golino, M. B. Gomes Gonçalves, ... J. S. Wurtele + Show authors

Nature 621, 716–722 (2023) | Cite this article

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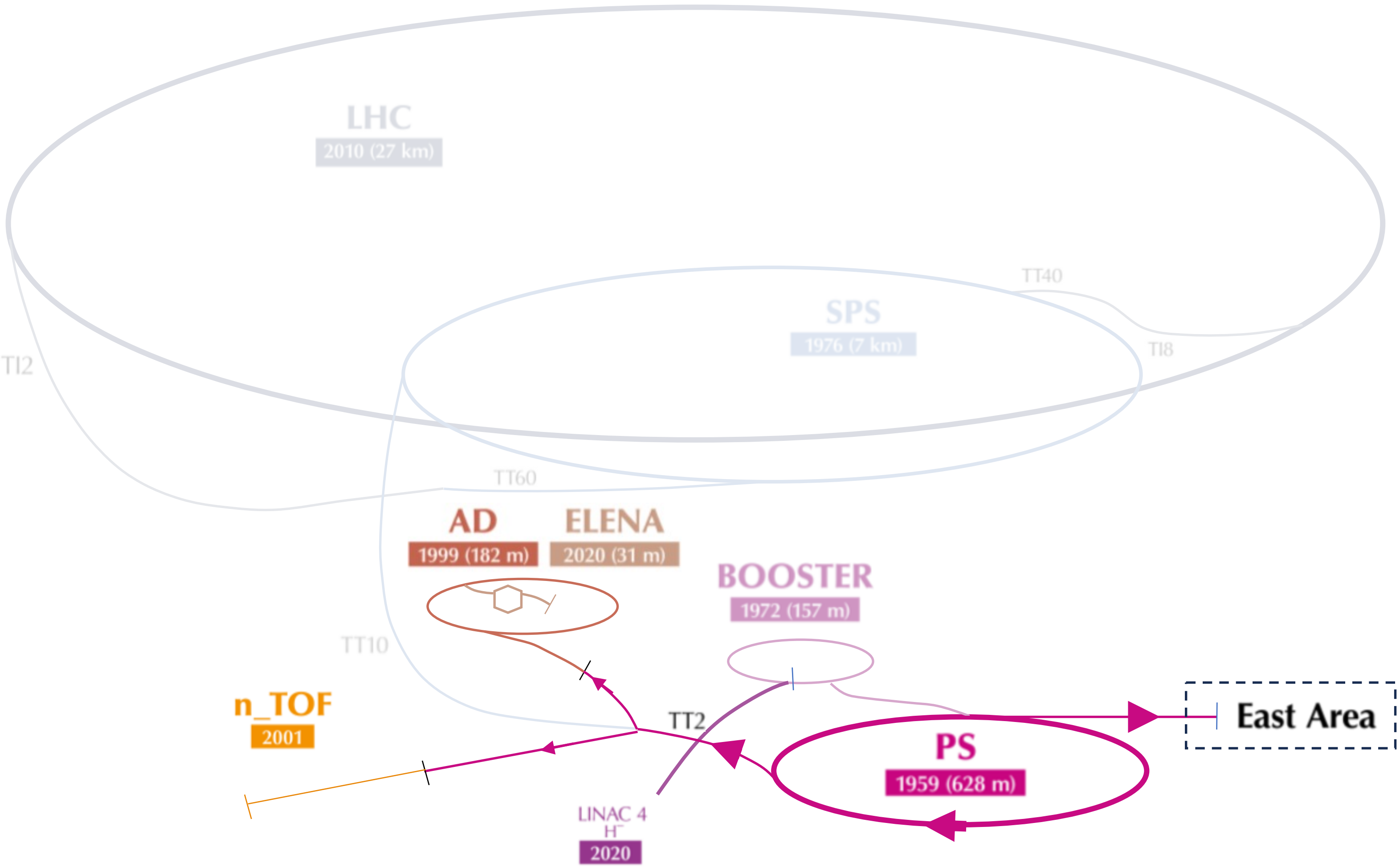
PS – Experiments – EAST HALL

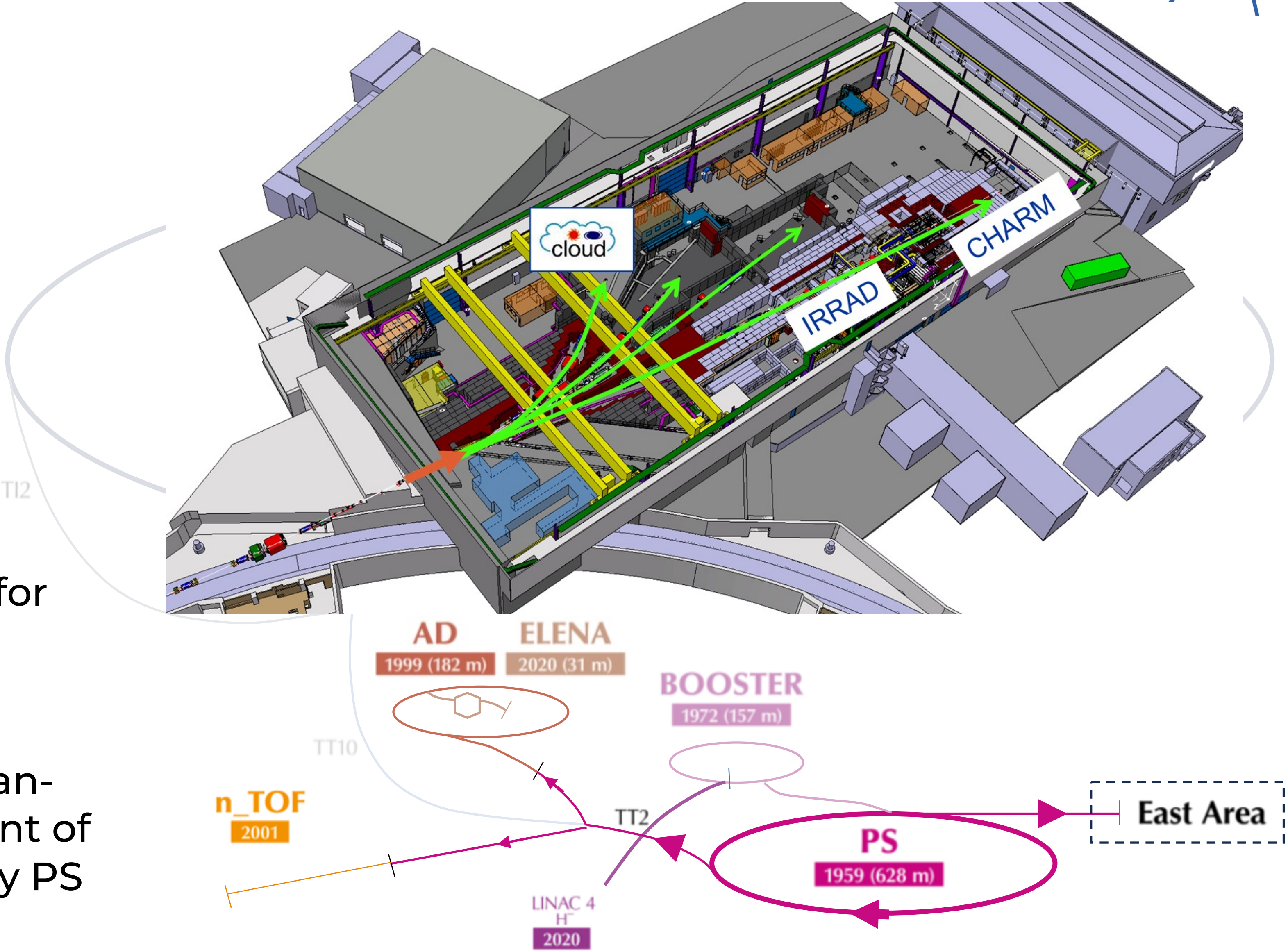


PS – Experiments – EAST HALL

p+ (26 GeV) on target -> Secondary Beams

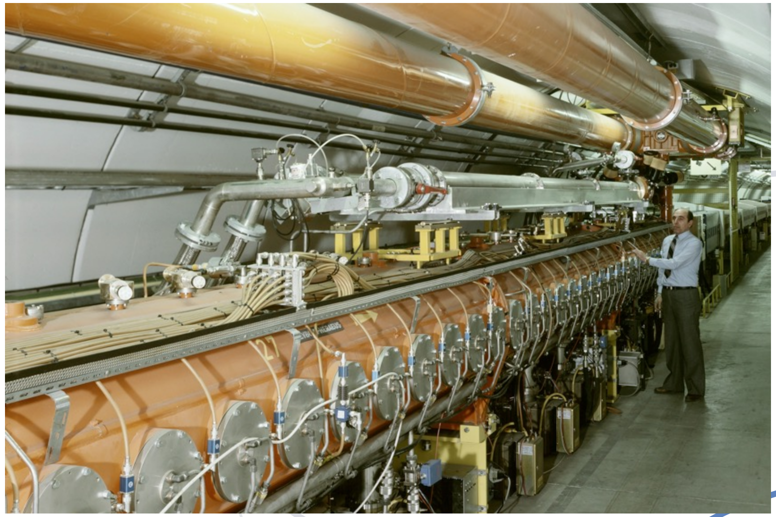
Secondary Beams:
Momentum range 1-15 GeV/c
Electrons, Hadrons & Muons
(Max 1-2 10^6 particles per spill)

- **Detector calibration**
- Proton& neutron **irradiation facilities** for particle detectors and satellites
- **environmental physics (CLOUD):**
  - Study influence of natural and man-made aerosols on the development of clouds, cosmic rays “simulated” by PS beam



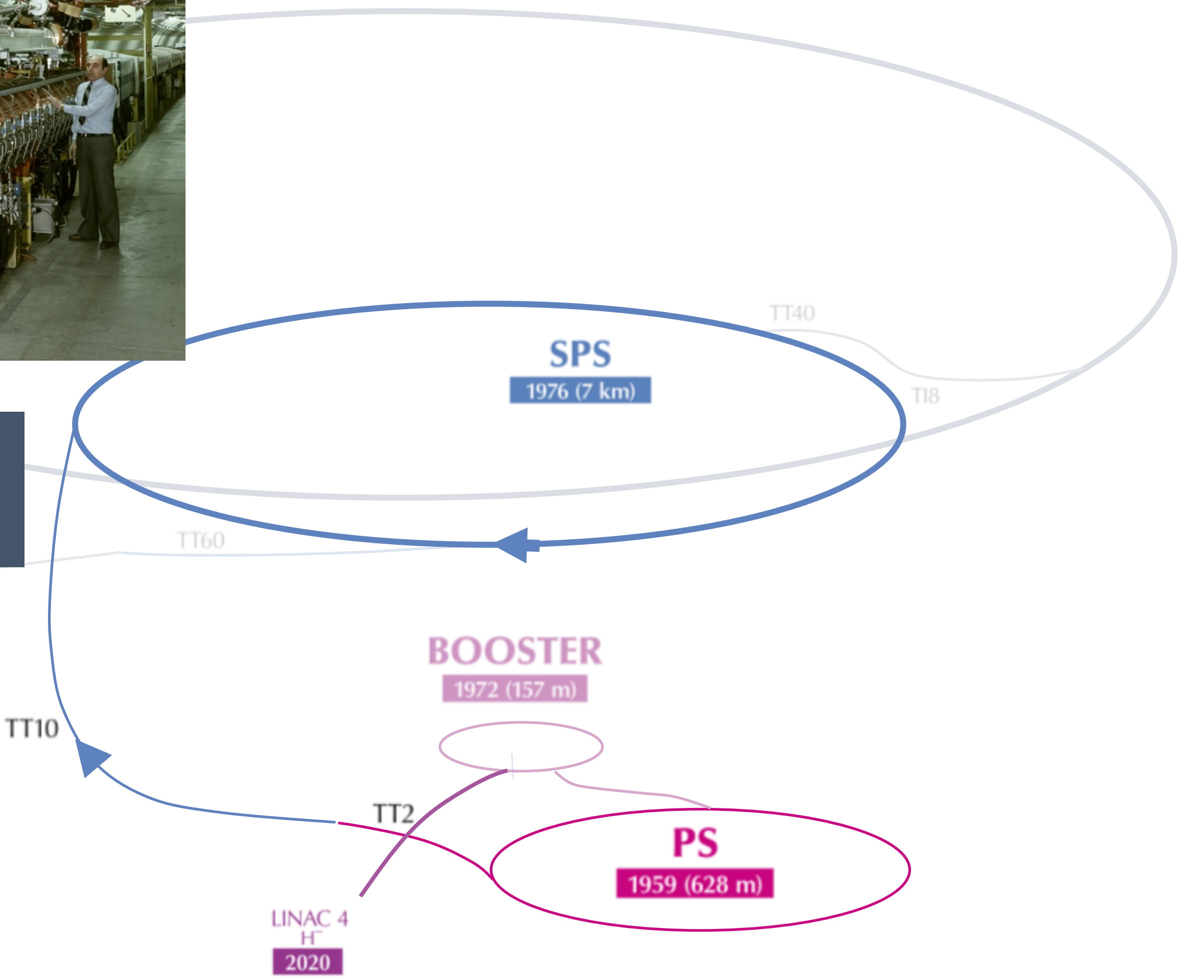
Super Proton Synchroton

LHC injectors – SPS



$Sp\bar{p}S$

- has probed the inner structure of protons
- investigated matter antimatter asymmetry
- searched for exotic forms of matter

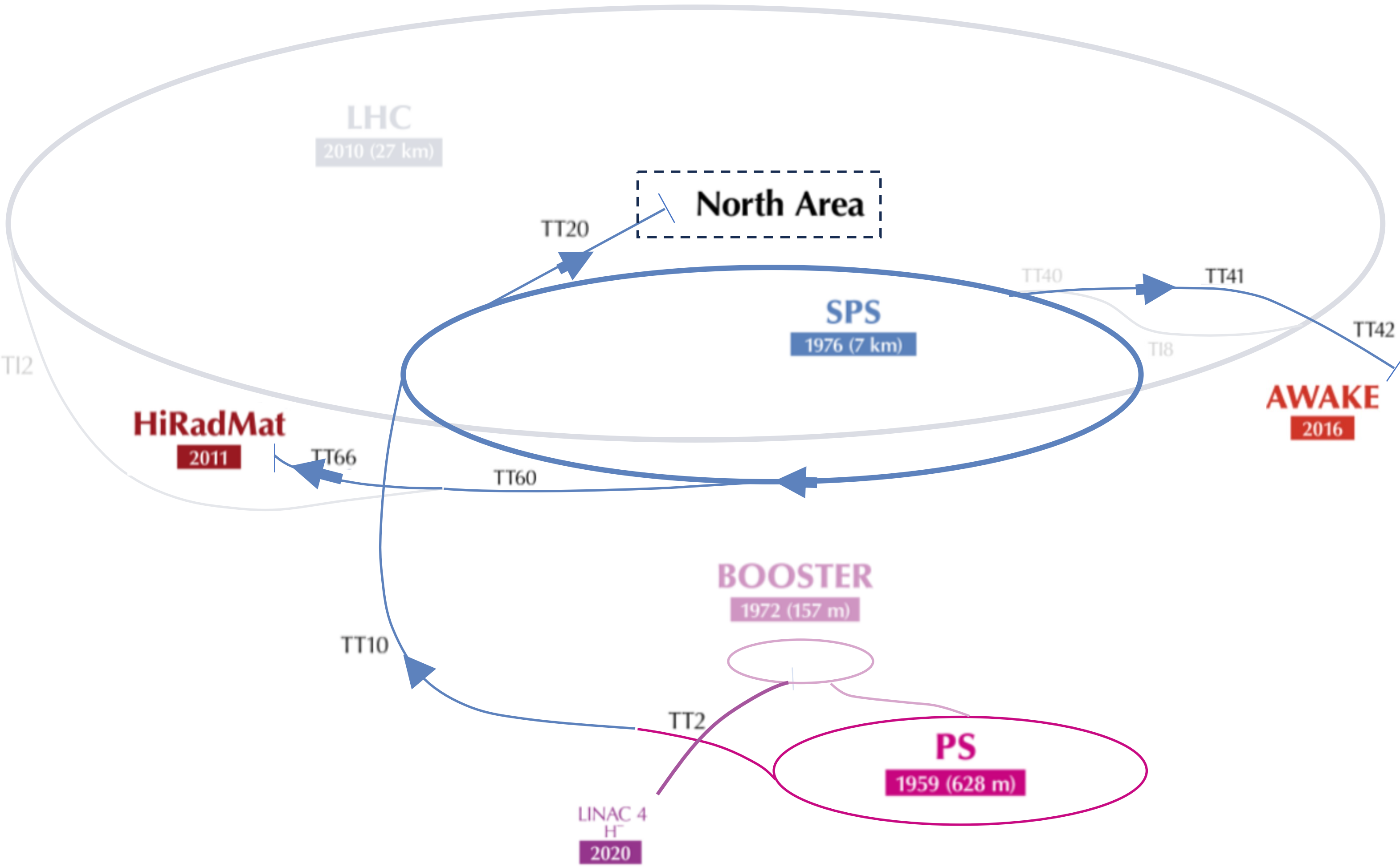


- The first synchrotron in the chain at ~30m under ground
- Circumference of 6.9 km
    - 11 x PS circumference
- Increases proton beam energy up to 450 GeV with up to ~5x10^{13} protons per cycle

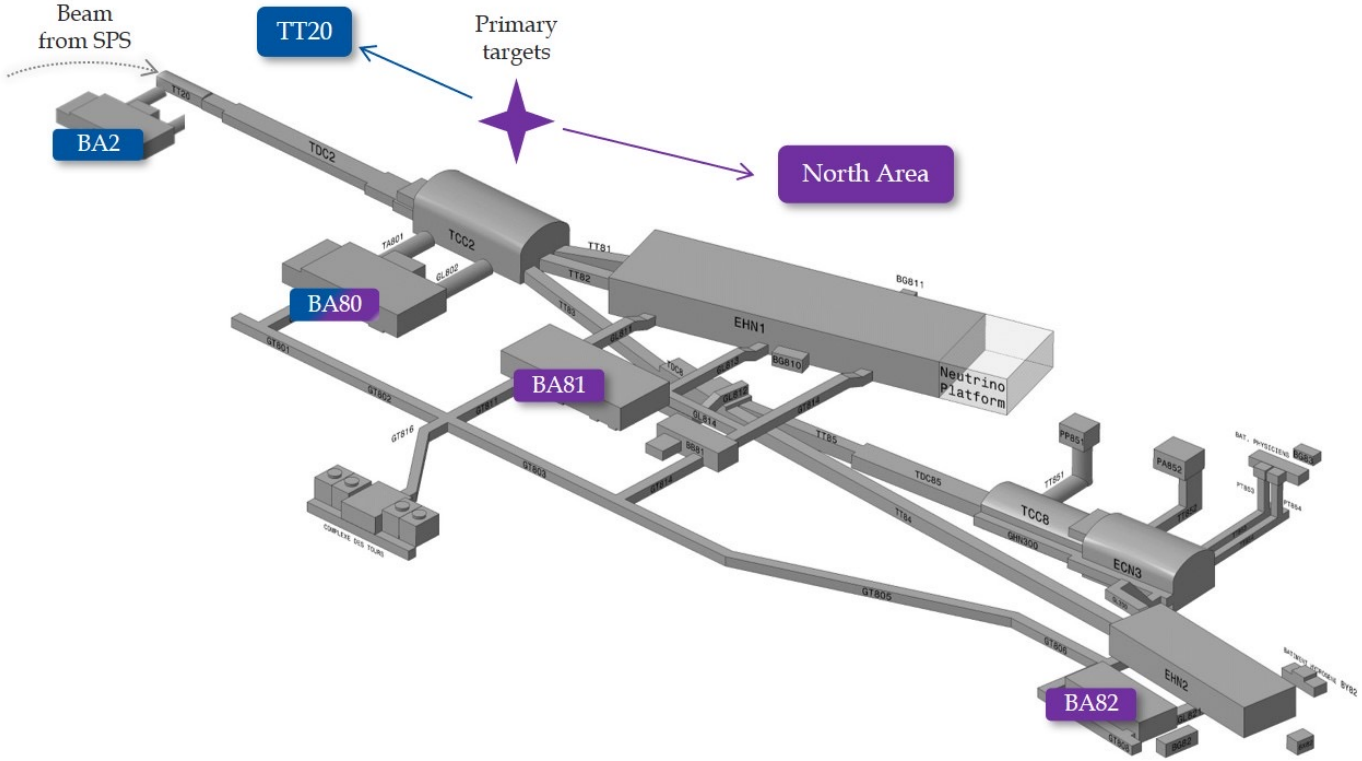
SPS - Experiments

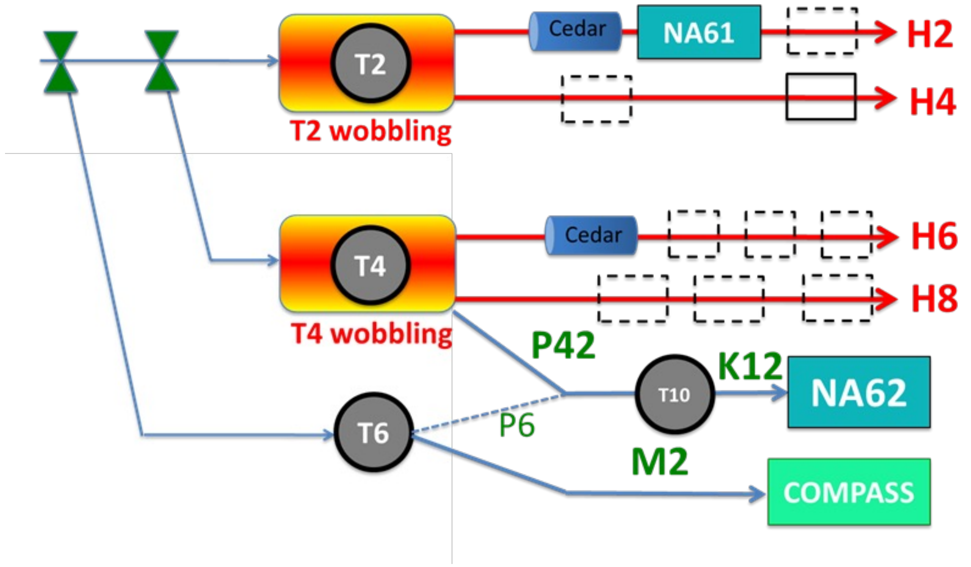
- Provides slow extracted beam to the North Area

- Provides fast extracted beam to LHC, AWAKE and HiRadMat



SPS – Experiments – NORTH AREA

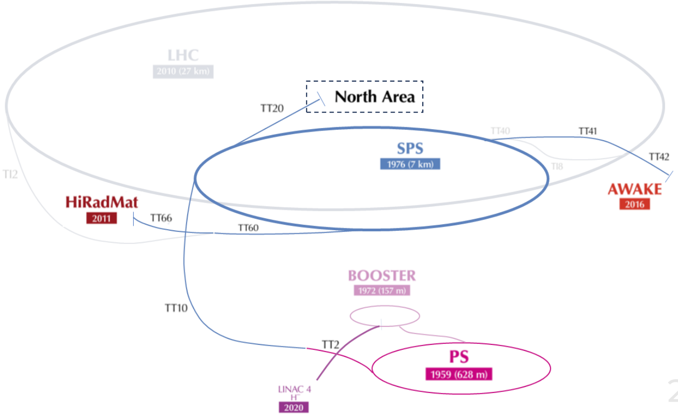




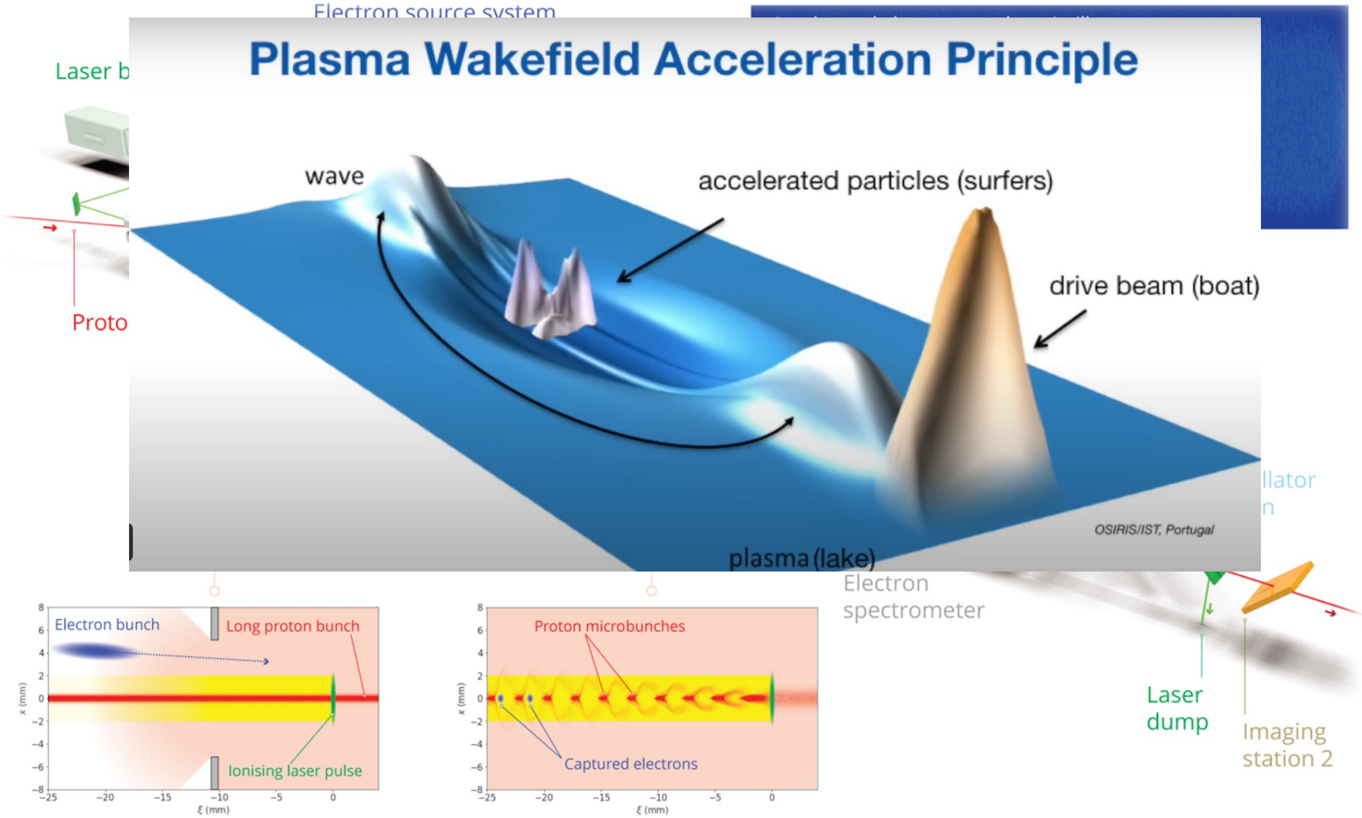
Lower energy experiments at PS or SPS (in 1 - 400 GeV range) allow precision measurements and comparison with theory. Deviations can be sign of new physics at higher energies.

6 approved experiments:

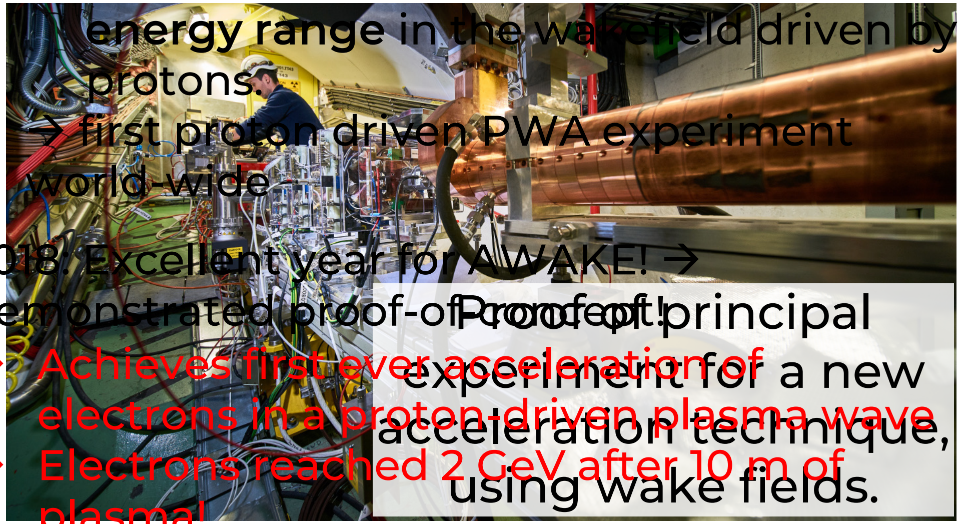
- NA58 (COMPASS): muon spin physics, hadron spectroscopy
- NA61 (SHINE): strong interaction, quark gluon plasma, neutrino and cosmic ray program
- NA62: rare K decays $BR(K^+ \rightarrow \pi^+ nn)$
- NA63: electromagnetic processes in strong crystalline fields
- NA64: search for dark sectors in missing energy events
- NA65 (DsTau): study of nt production



SPS – Experiments - AWAKE



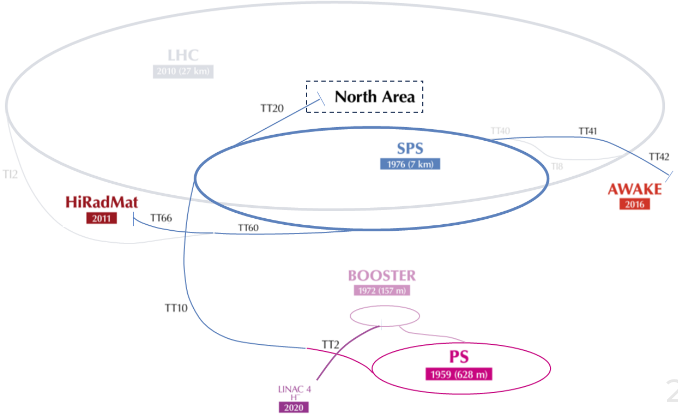
→ Inject 10-20 MeV electron beam
→ acceleration of electrons to **multi-GeV** energy range in the wakefield driven by protons
→ first proton driven PWA experiment world-wide



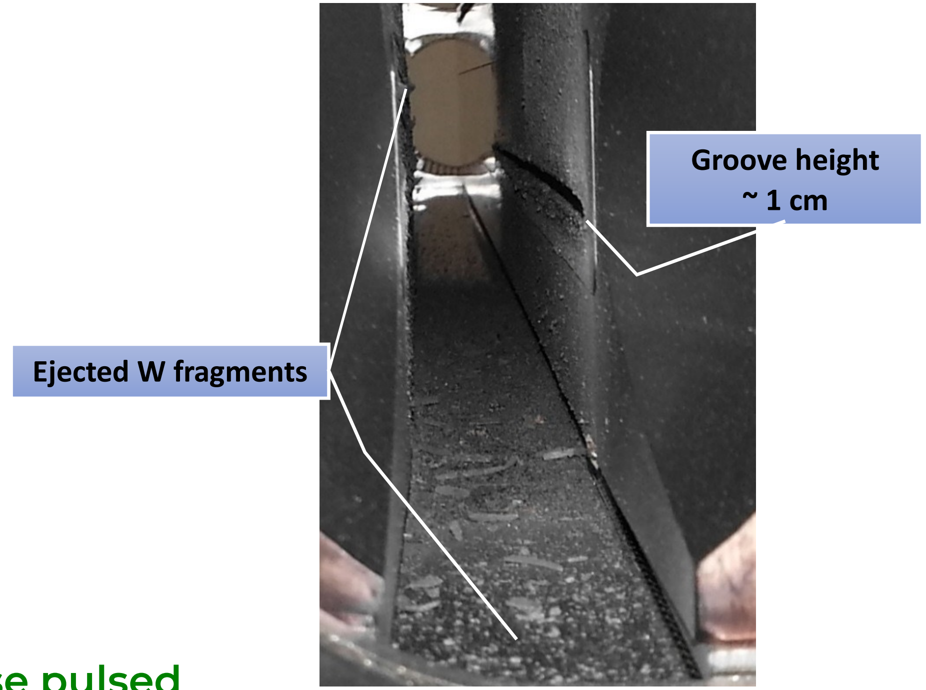
2018: Excellent year for AWAKE! → demonstrated proof-of-concept!

→ Achieves first ever acceleration of electrons in a proton-driven plasma wave
→ Electrons reached 2 GeV after 10 m of plasma!

Proof of principal experiment for a new acceleration technique, using wake fields.

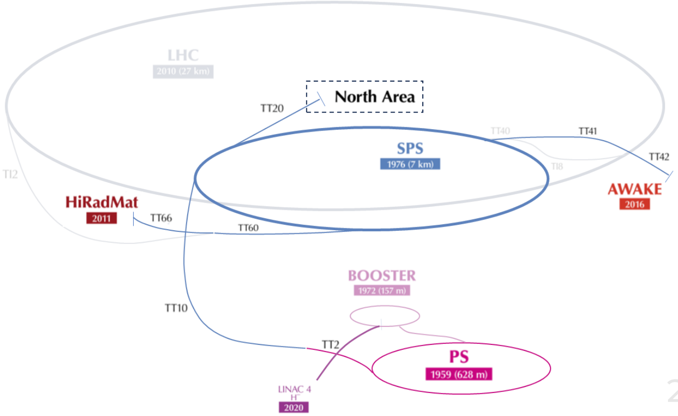


SPS – Experiments - HIRADMAT



HiRadMat is a facility designed, to study the impact of intense pulsed beam on materials, fundamental for testing and simulations benchmarking of beam matter interaction (ex: LHC beams up to 350 MJ)

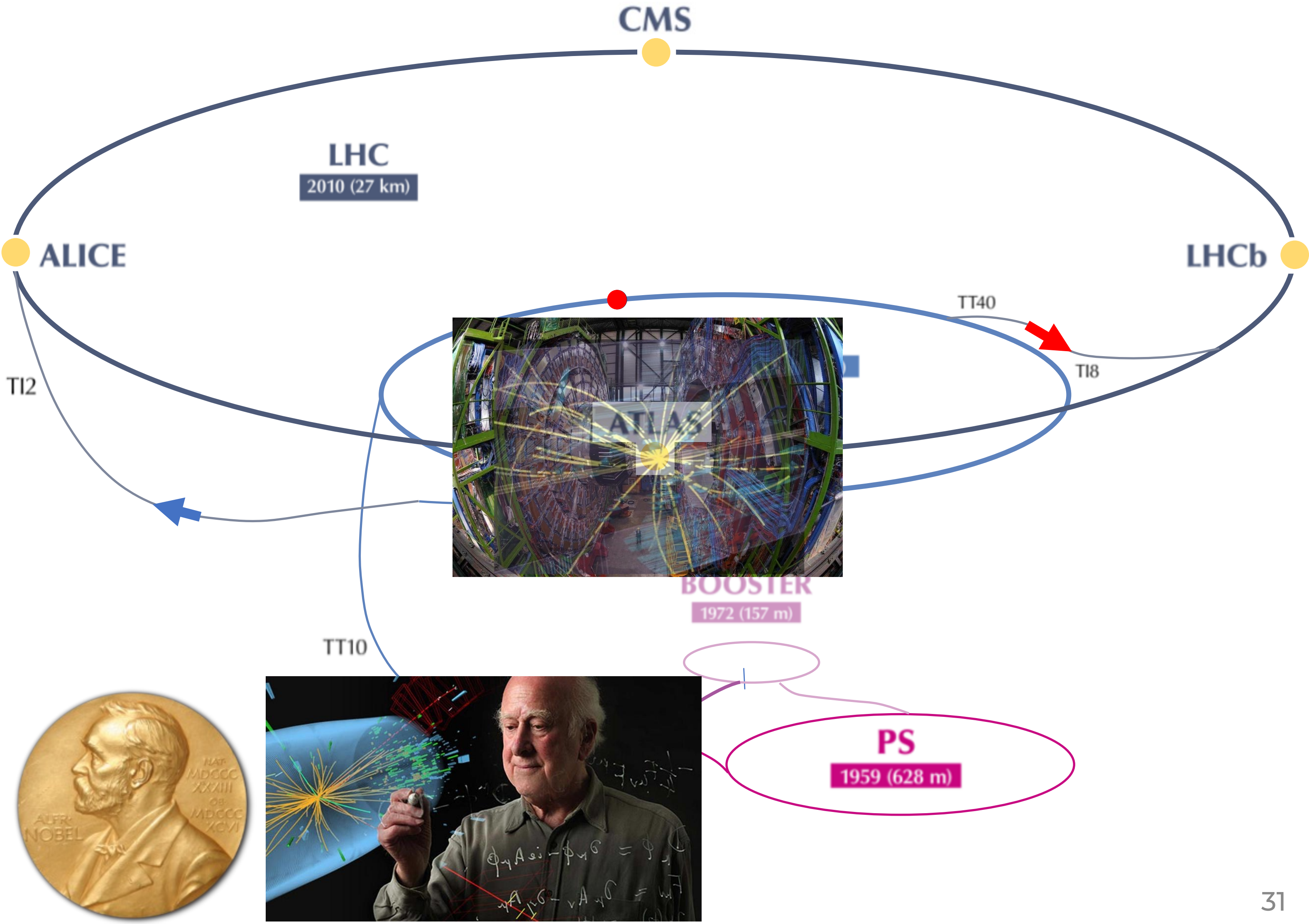
- Thermal management
- Radiation Damage to materials
- Thermal shock – beam induced pressure waves



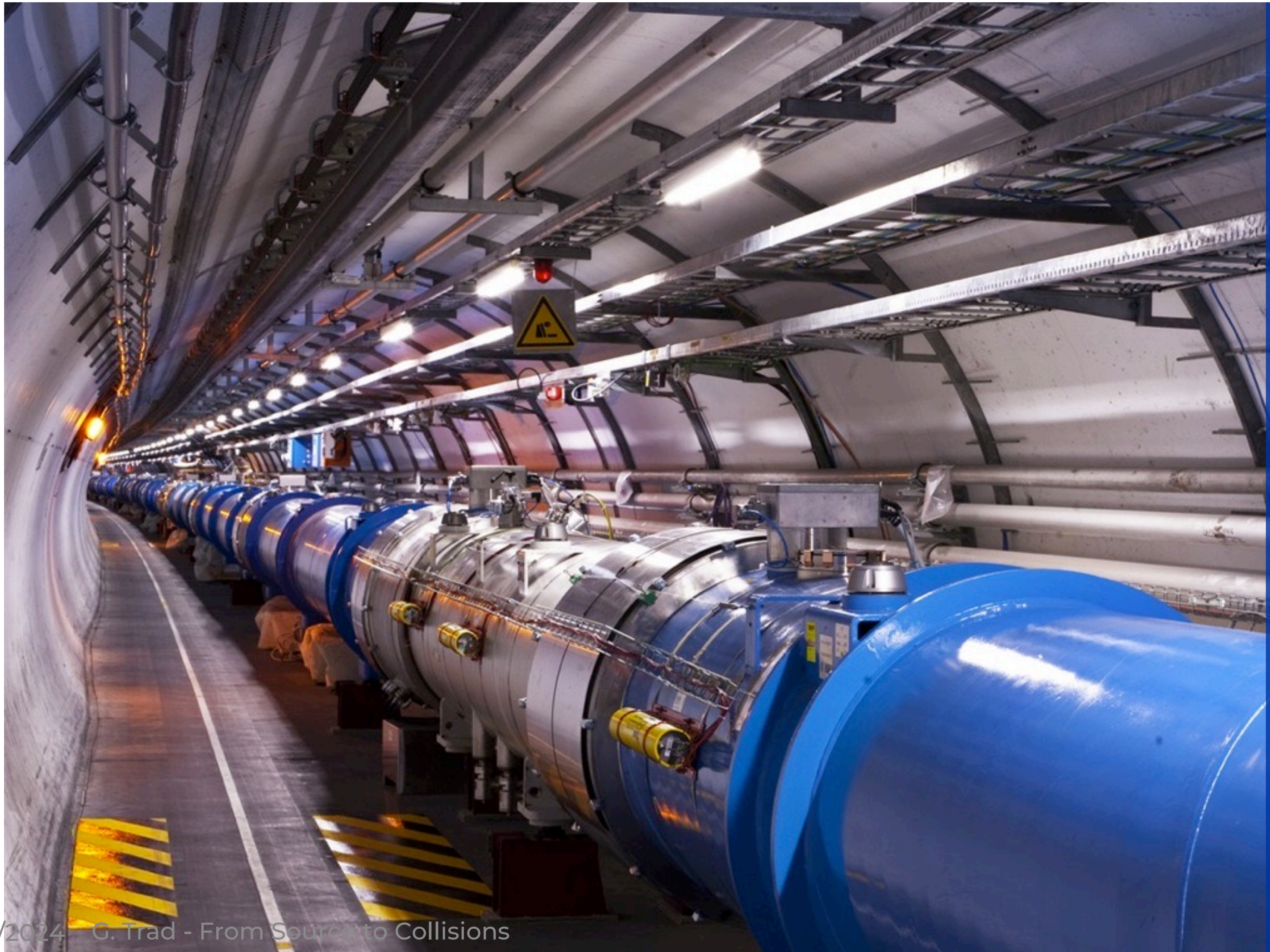
Large Hadron Collider

LHC

- Situated on average ~100 m under ground
- Circumference 26.7 km
- Accelerate protons up to 7 TeV (design)
- Four major experiments
- 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
- Colliding up to ~2800 bunches at 11245 Hz



LHC



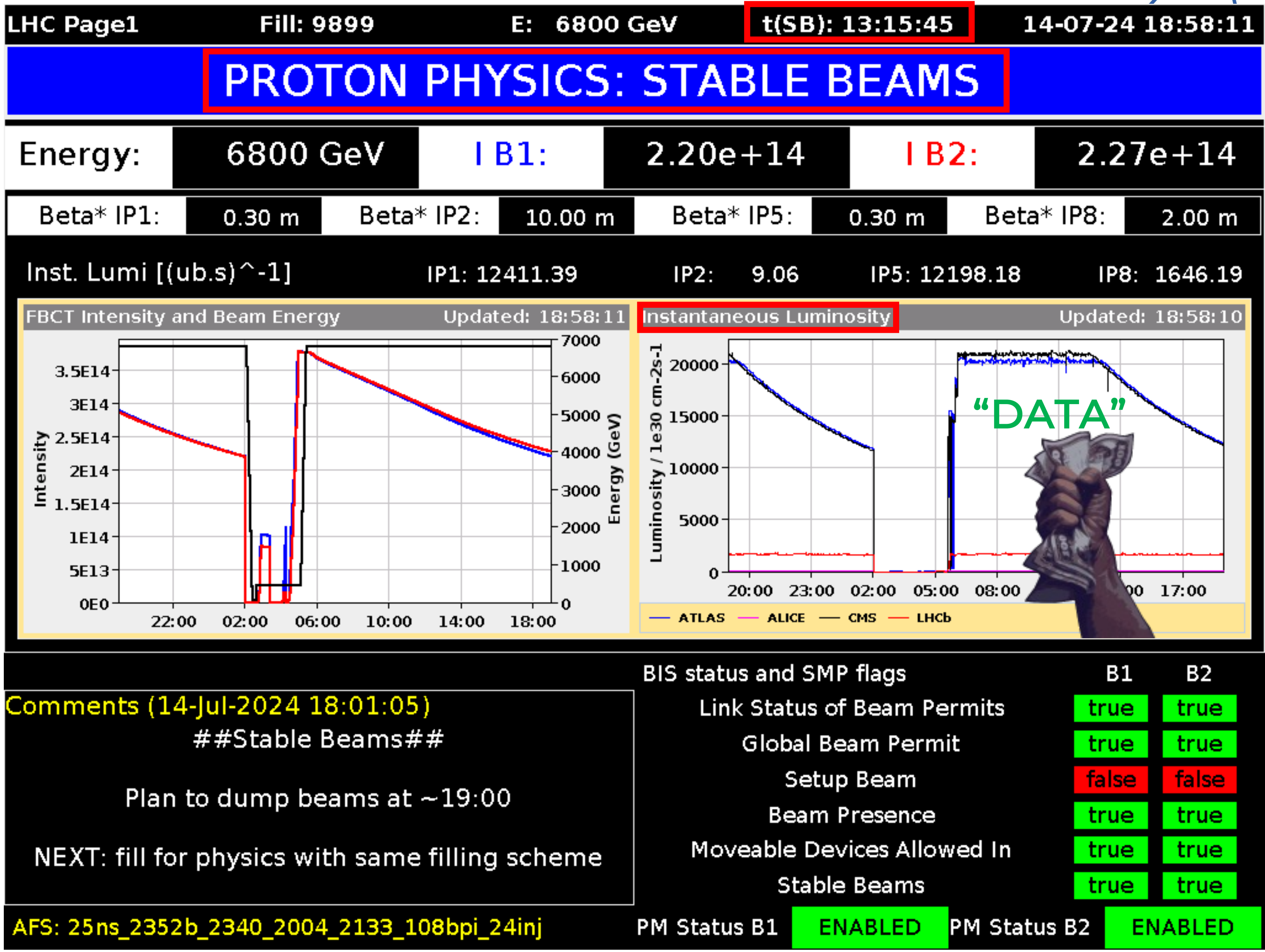
- 1232 main dipoles of 15 m each that deviate the beams around the 27 km circumference
- 858 main quadrupoles that keep the beam focused
- 6000 corrector magnets to preserve the beam quality
- Main magnets use superconducting cables (Cu-clad Nb-Ti)
- 12’000 A provides a nominal field of 8.33 Tesla
-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

LHC PHYSICS PRODUCTION

LHC serves its experiments with up to 2800 bunches colliding at 11245 Hz (ideally over fills >10h of Stable Beams)

The Luminosity is the proportionality factor between:
events per second (dR/dt) and the Physics cross-section (cm^2) at the collision energy σ

$$\frac{dR}{dt} = L\sigma$$



LHC - Luminosity

Overlap of the beam densities; (Gaussian distributions approx.)

$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F$$

Accelerator features

g:Energy of the machine 6.8 TeV

l: Length of the machine 27 km

Beam geometry features

ε_n: Size of the beam ~2 mm mrad

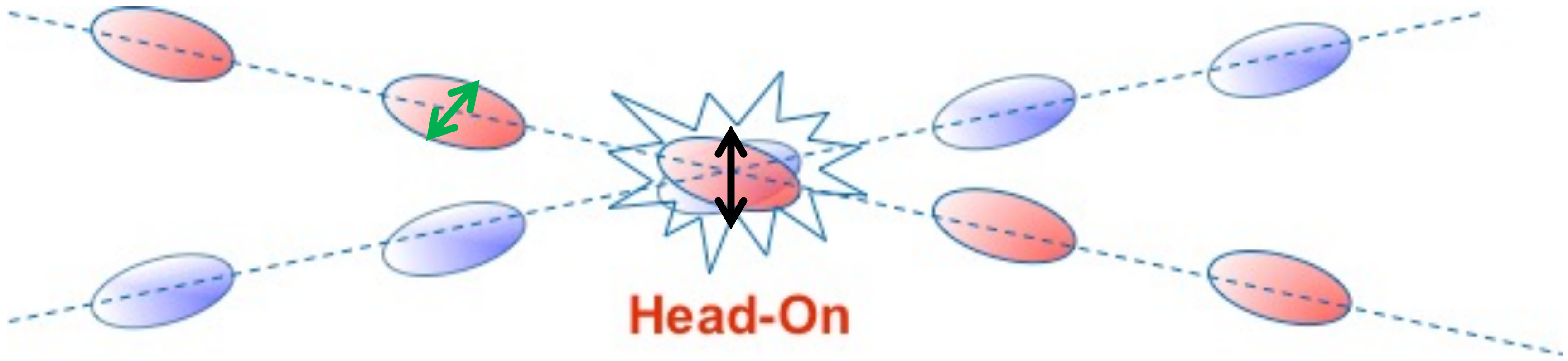
β^* : Squeeze of the beam in IP 30 cm

F: geometry reduction factor: 0.55

Beam intensity features

N_b Number of particles per bunch 1.6×10^{11}

n_b Number of bunches ~2500

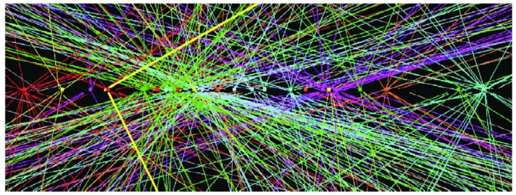


N_b	**Number of particles per bunch**
n_b	**Number of bunches**
f_{rev}	Revolution frequency
σ^*	**Beam size at interaction point**
F	Reduction factor due to crossing angle
ε_n	**Normalized emittance**
β^*	**Beta function at IP**

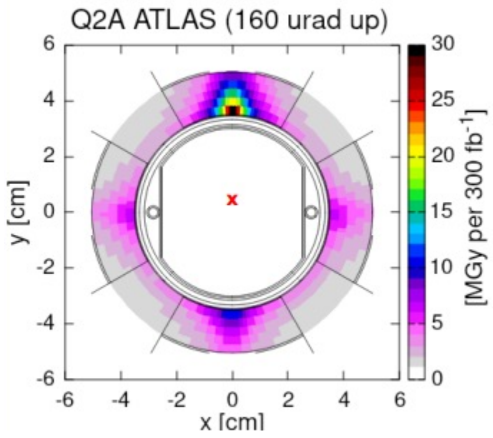
LHC - Luminosity

Experiments wants the highest luminosity, however:

- *Instantaneous luminosity* is limited by:
  - The **Experiment accepted rate of events**/bunch crossing for efficient data reconstruction (pileup ~ 60-65 /bunch crossing)
  - **Cryogenic system ability of cooling** the magnets surrounding the IP to compensate for the heat deposited from the debris of the collisions (Lmax: <2.4 E34 $cm^{-2}s^{-1}$ for Stable safe operation)

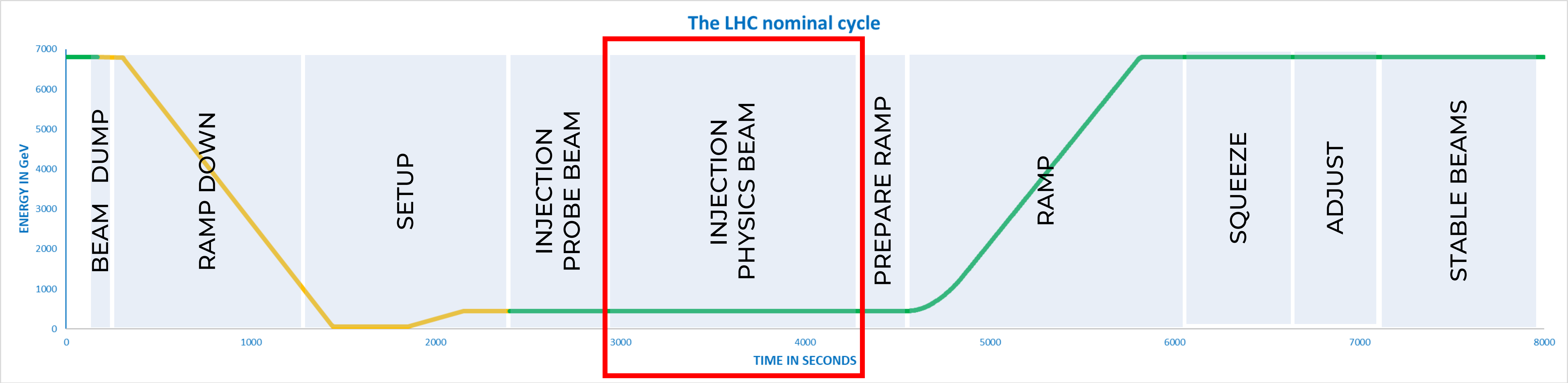


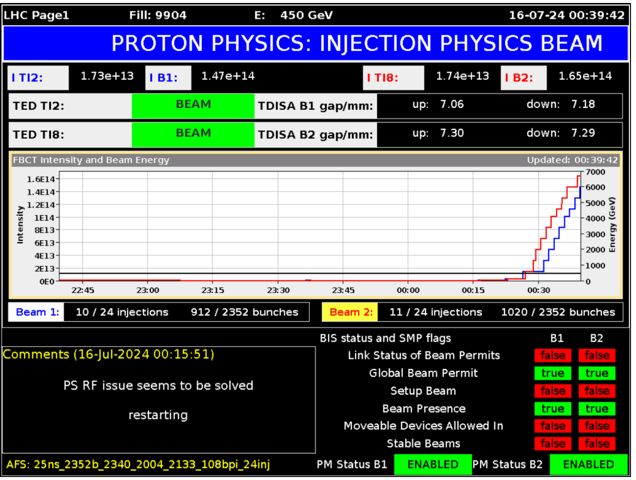
- *Integrated luminosity* could be limited by the **radiation damage** to the magnets surrounding the IP caused by proton–proton collision products (mostly pions) impacting the final focus magnet string in specific hotspots
  - Machine is continuously optimized (change of optics) to ensure that the magnets lifetime will exceed the planned integrated luminosity in LHC lifetime



LHC CYCLE

LHC CYCLE





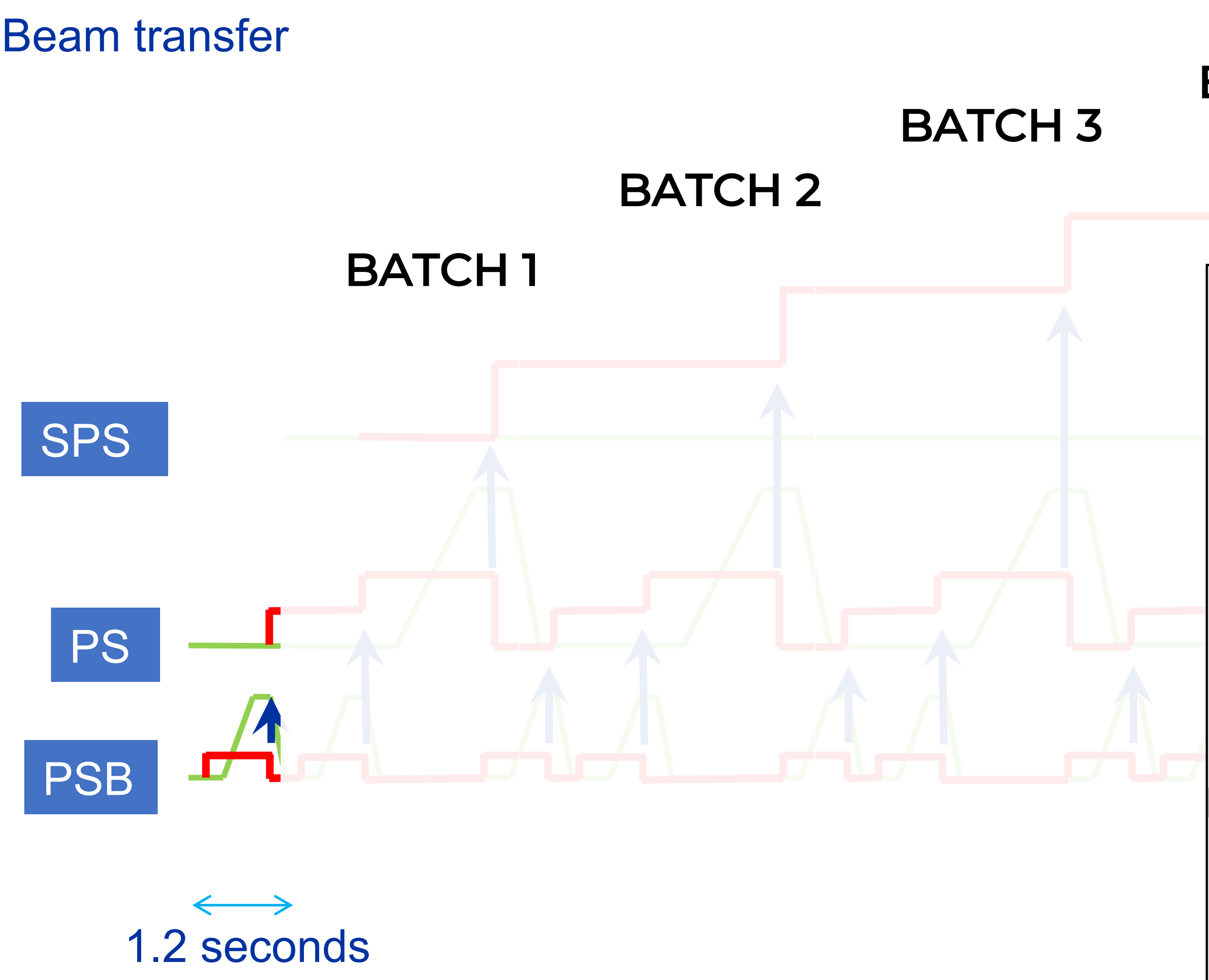
LHC is filled via a sequence of injections, each consisting of a “Train” of bunches grouped in “Batches”

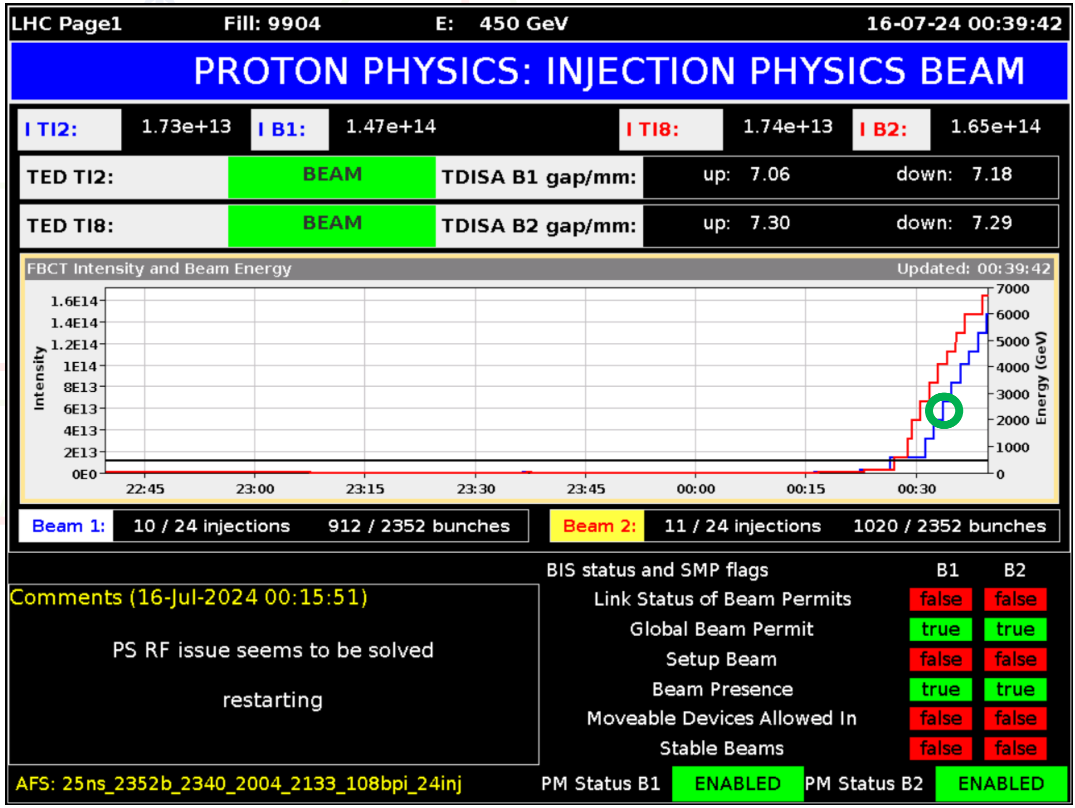
LHC TRAINS

— = Field in main magnets

— = Proton beam intensity (current)

↑ = Beam transfer





LHC TRAINS

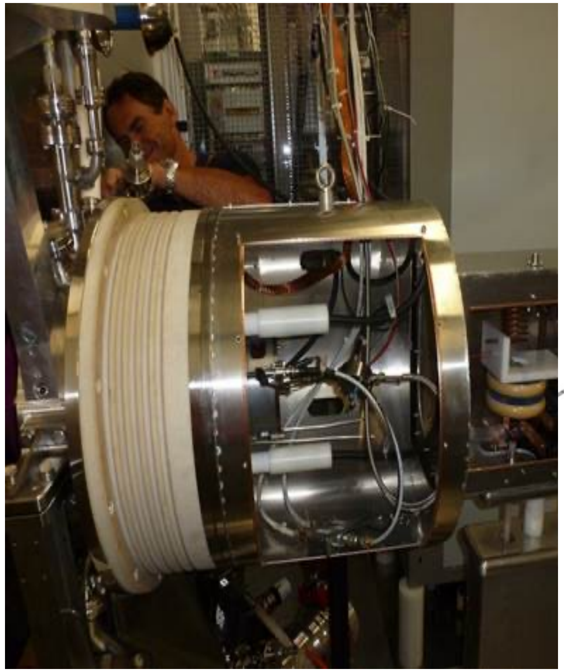
- LINAC 4 is accelerating H-
- Charge exchange H- Injection in PSB
- RF gymnastics in the PS
  (Triple splitting)
- SPS acceleration to LHC injection energy

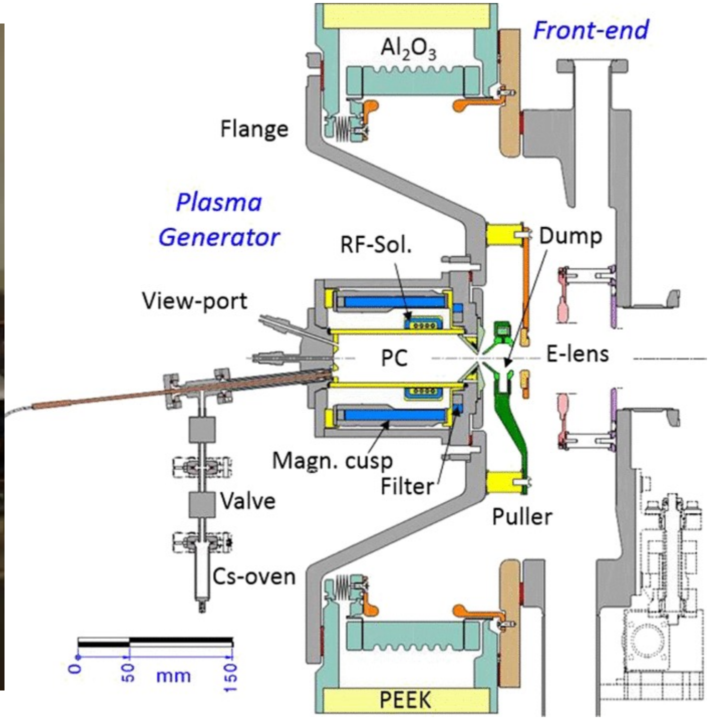
Hydrogen bottle – atoms (proton+electron) are injected in the plasma chamber

An externally applied electric field **heats the atoms and separates protons and electrons – creation of a plasma**, confined by magnetic fields

The **RF field applied excites a resonance of the atoms,** that can attract an electron and **create an H- ion**

The H- is then extracted via the high voltage electrodes of the source.





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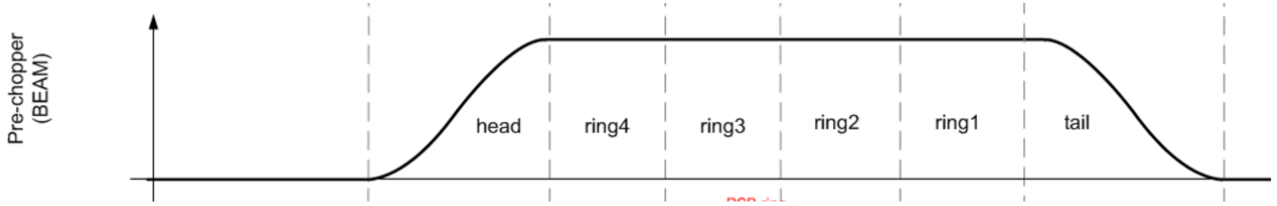

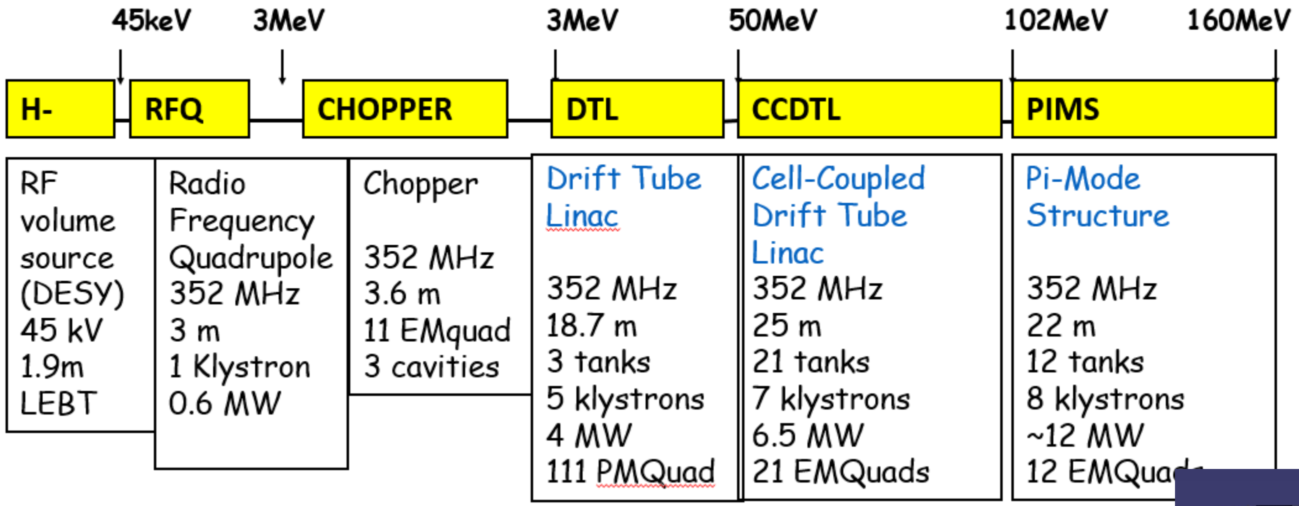

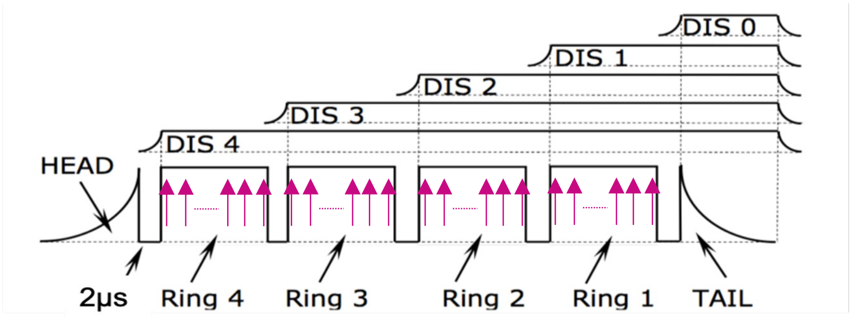

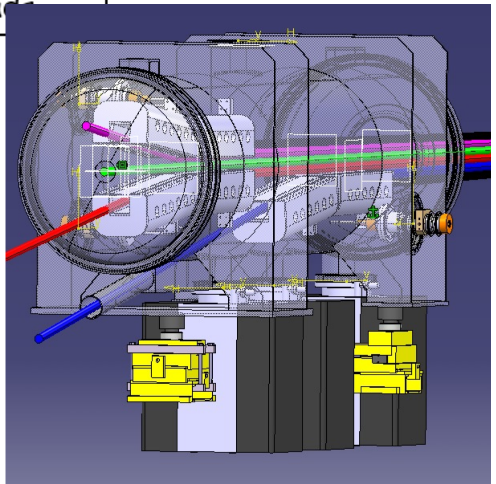

LHC TRAINS

- LINAC 4 is accelerating H-
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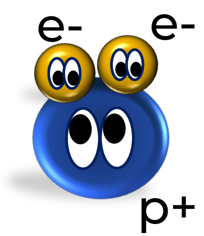
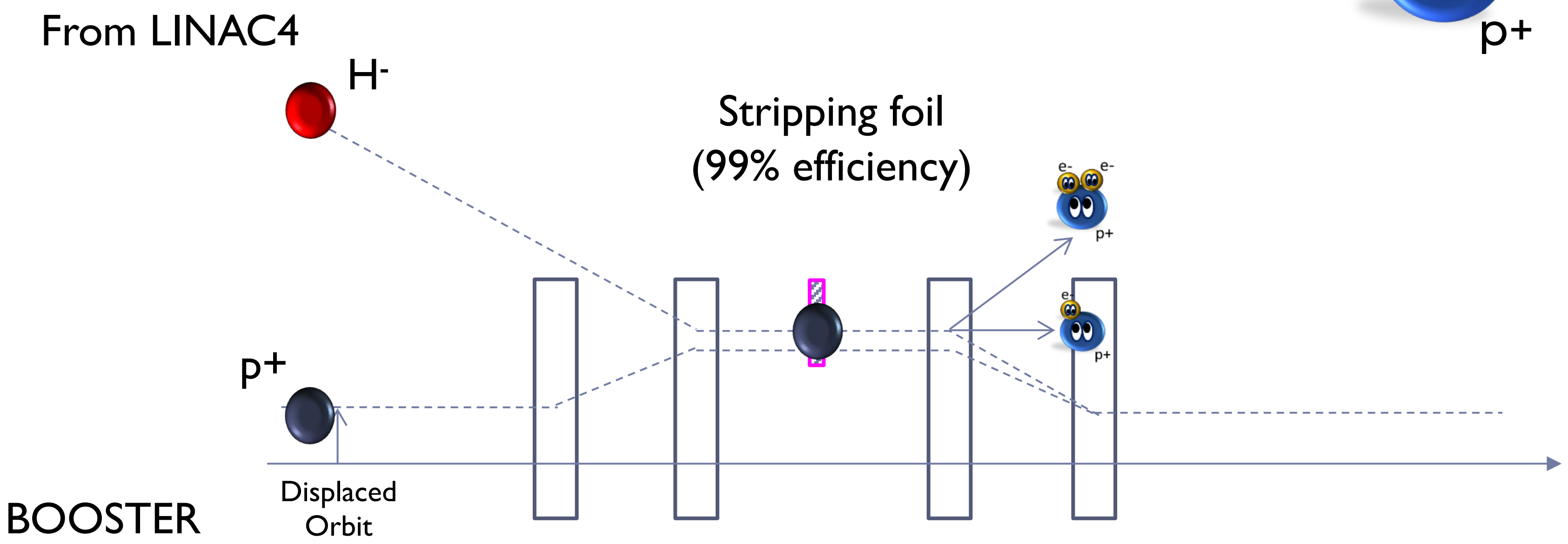


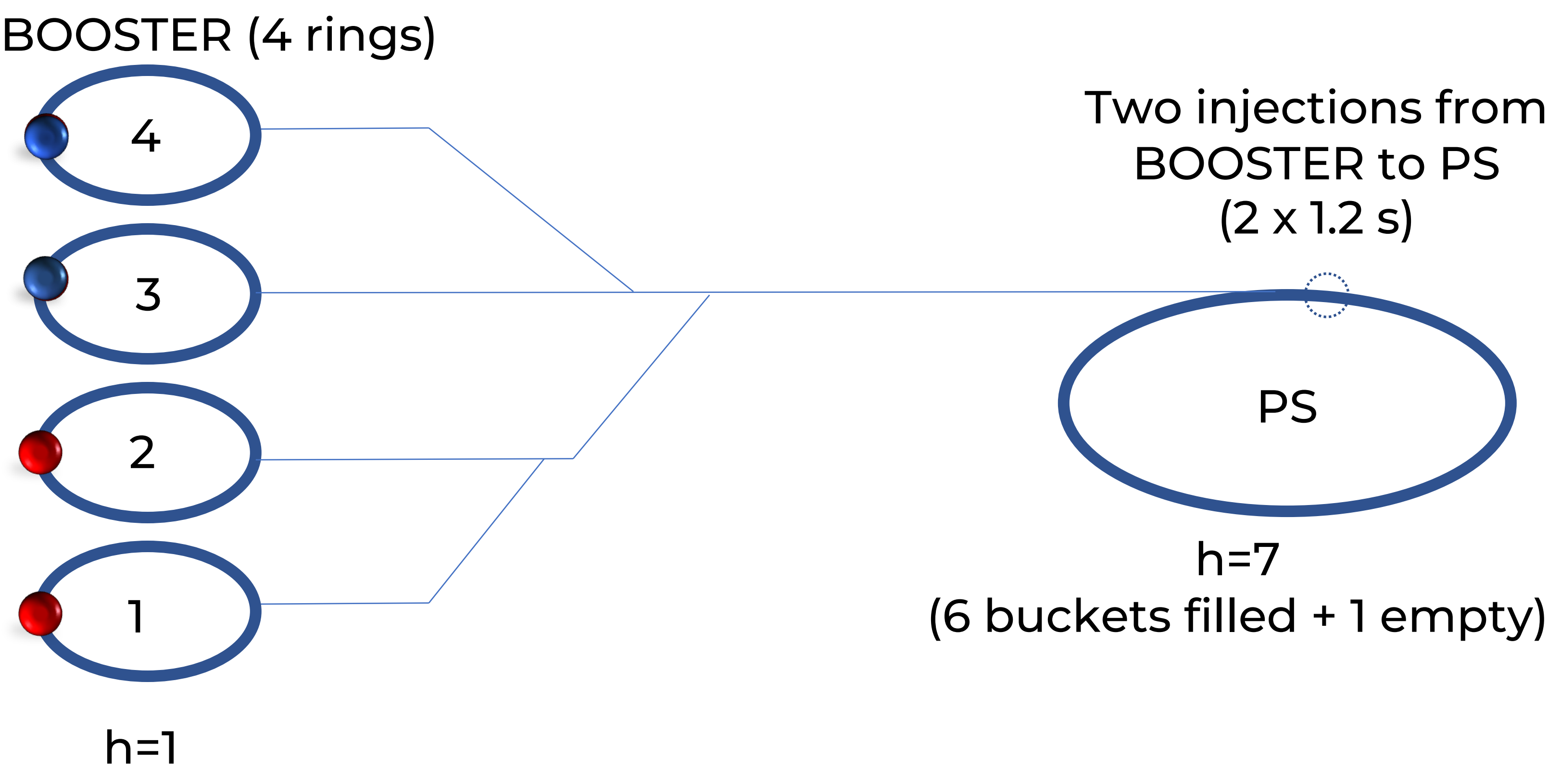


<u>The beam brightness is defined in the PSB</u>

For LHC high brightness beams, we over inject for several turns in the same phase space of the circulating protons

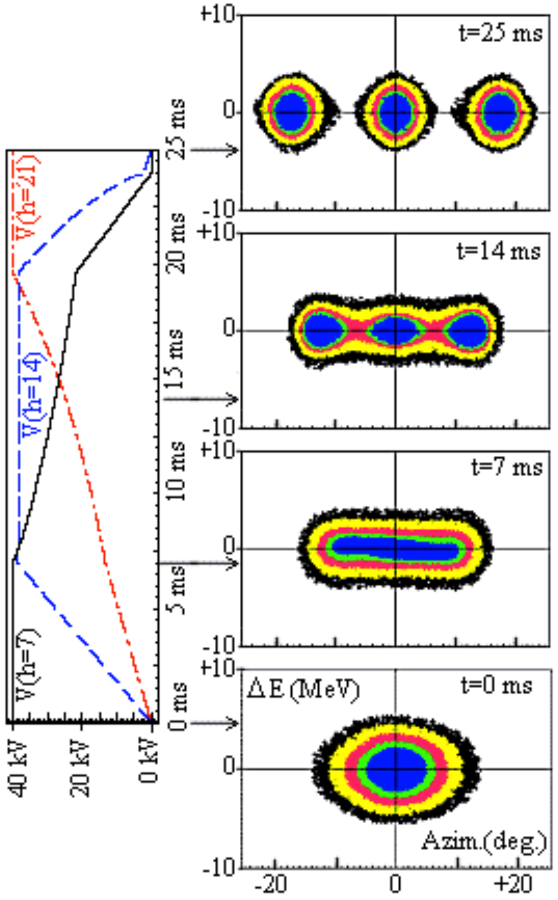
LHC TRAINS

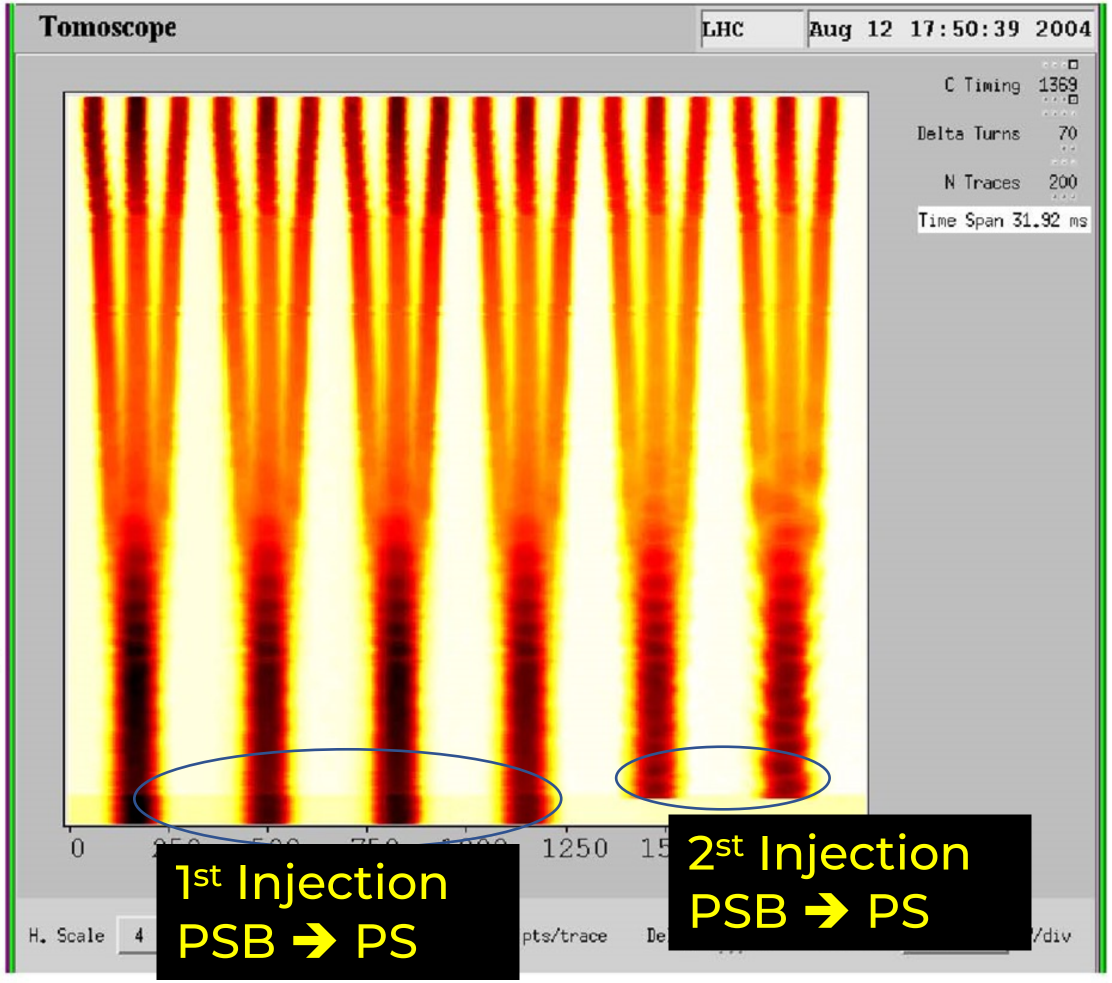
- LINAC 4 is accelerating H-
- Charge exchange H- Injection in PSB
- RF gymnastics in the PS
(Triple splitting)
- SPS acceleration to LHC injection energy



LHC TRAINS

- LINAC 4 is accelerating H-
- Charge exchange H- Injection in PSB
- **RF gymnastics in the PS (Triple splitting)**
- SPS acceleration to LHC injection energy





LHC TRAINS

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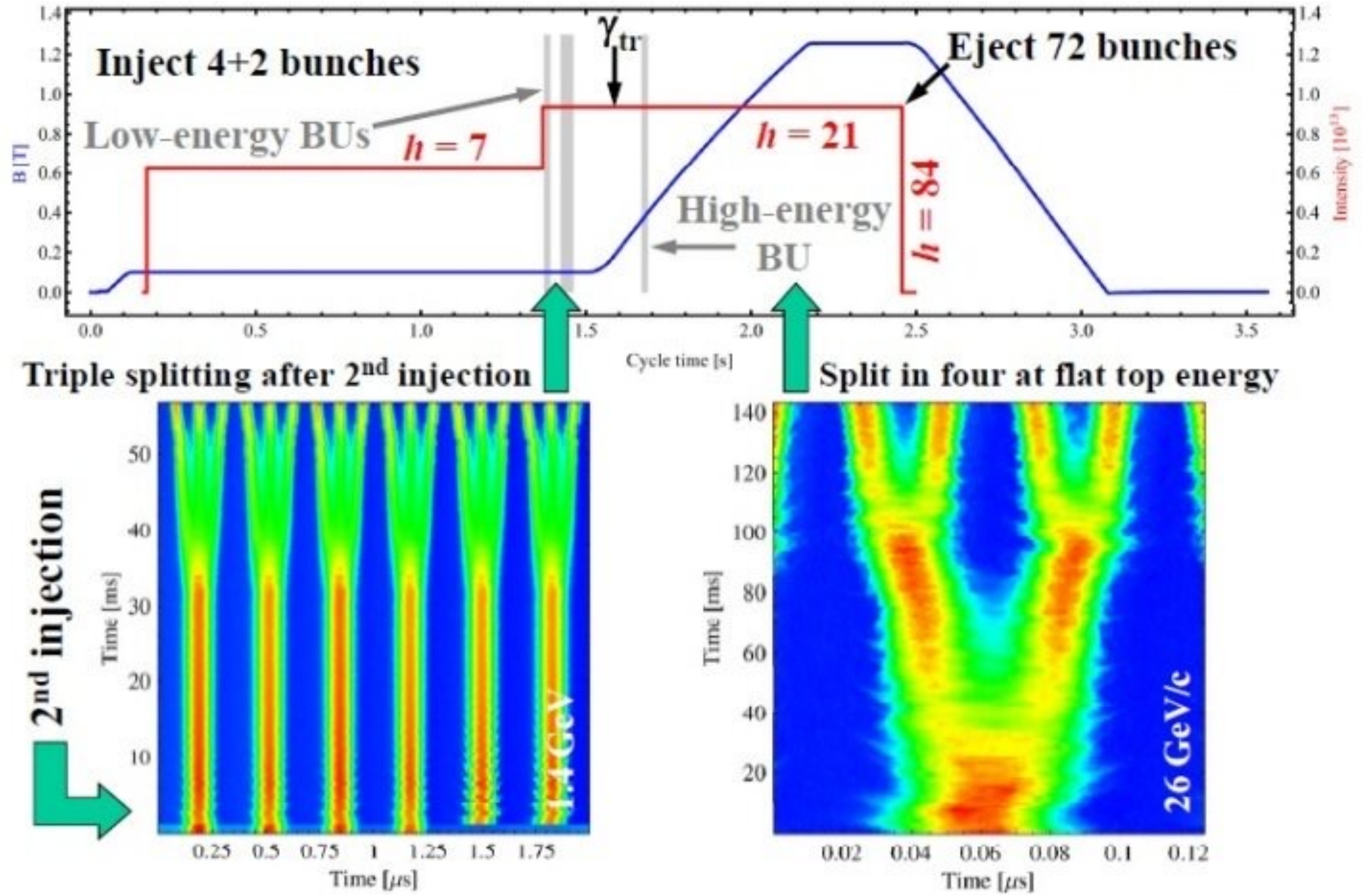
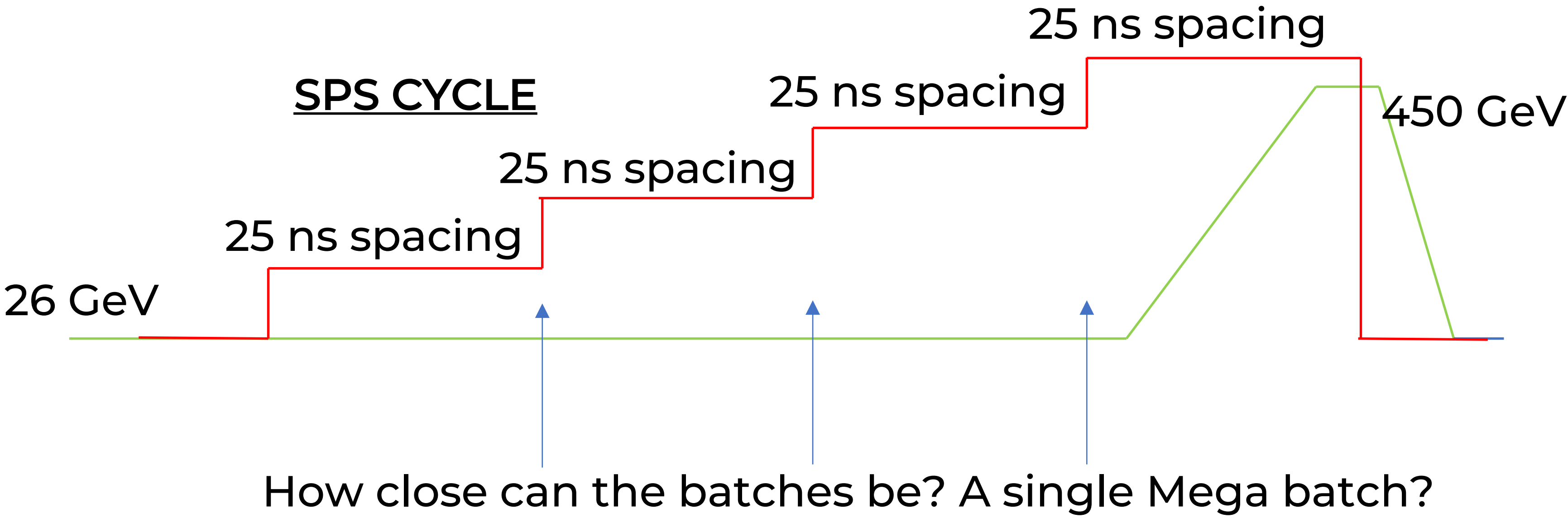


The PS is the machine in the LHC Injector Chain where the Longitudinal characteristics of the LHC beam are determined

LHC TRAINS

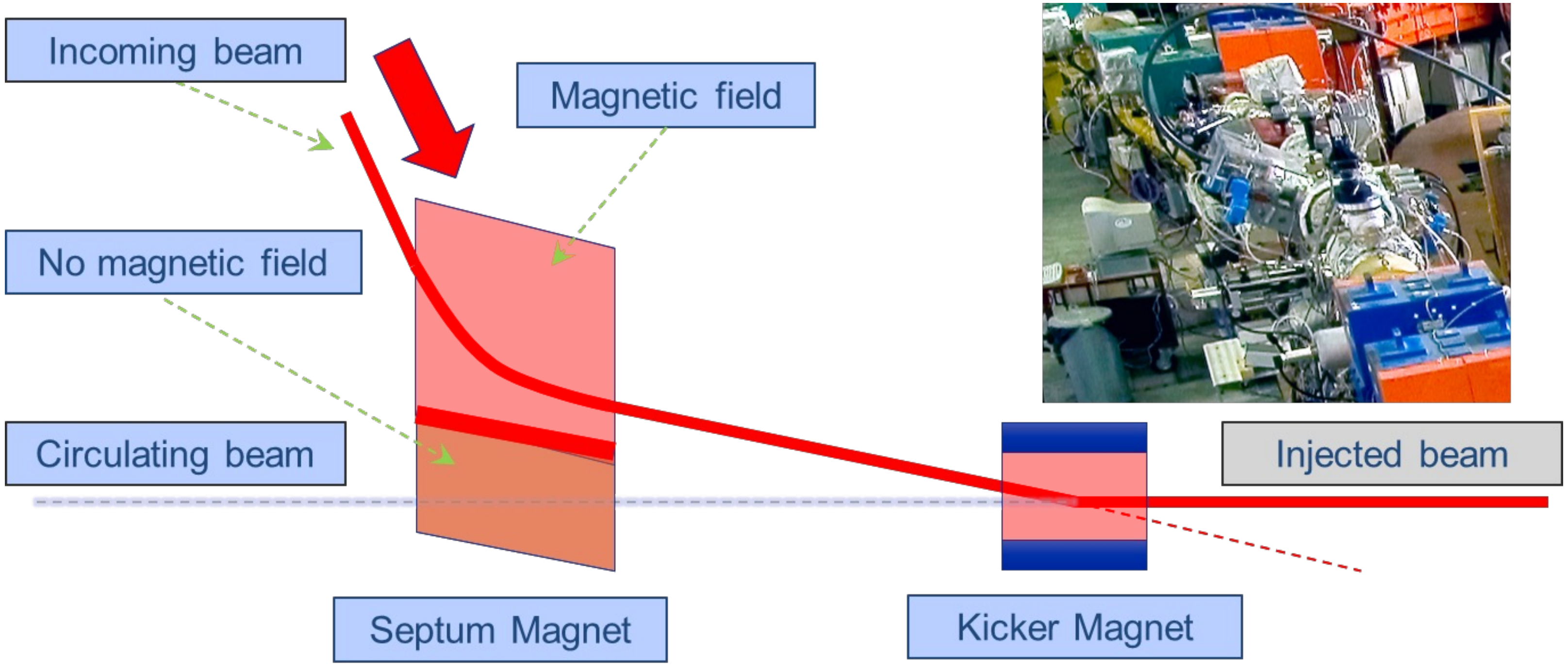
- LINAC 4 is accelerating H-
- Charge exchange H- Injection in PSB
- RF gymnastics in the PS
  (Triple splitting)
- SPS acceleration to LHC injection energy



LHC TRAINS

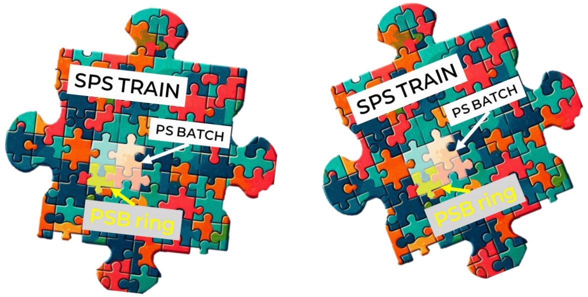
- LINAC 4 is accelerating H-
- Charge exchange H- Injection in PSB
- RF gymnastics in the PS (Triple splitting)
- SPS acceleration to LHC injection energy

How does beam transfer(injection/ extraction) work



SPS kicker needs about 200 ns to reach full kick (minimum spacing to not perturb circulating beams)

LHC collisions scheme



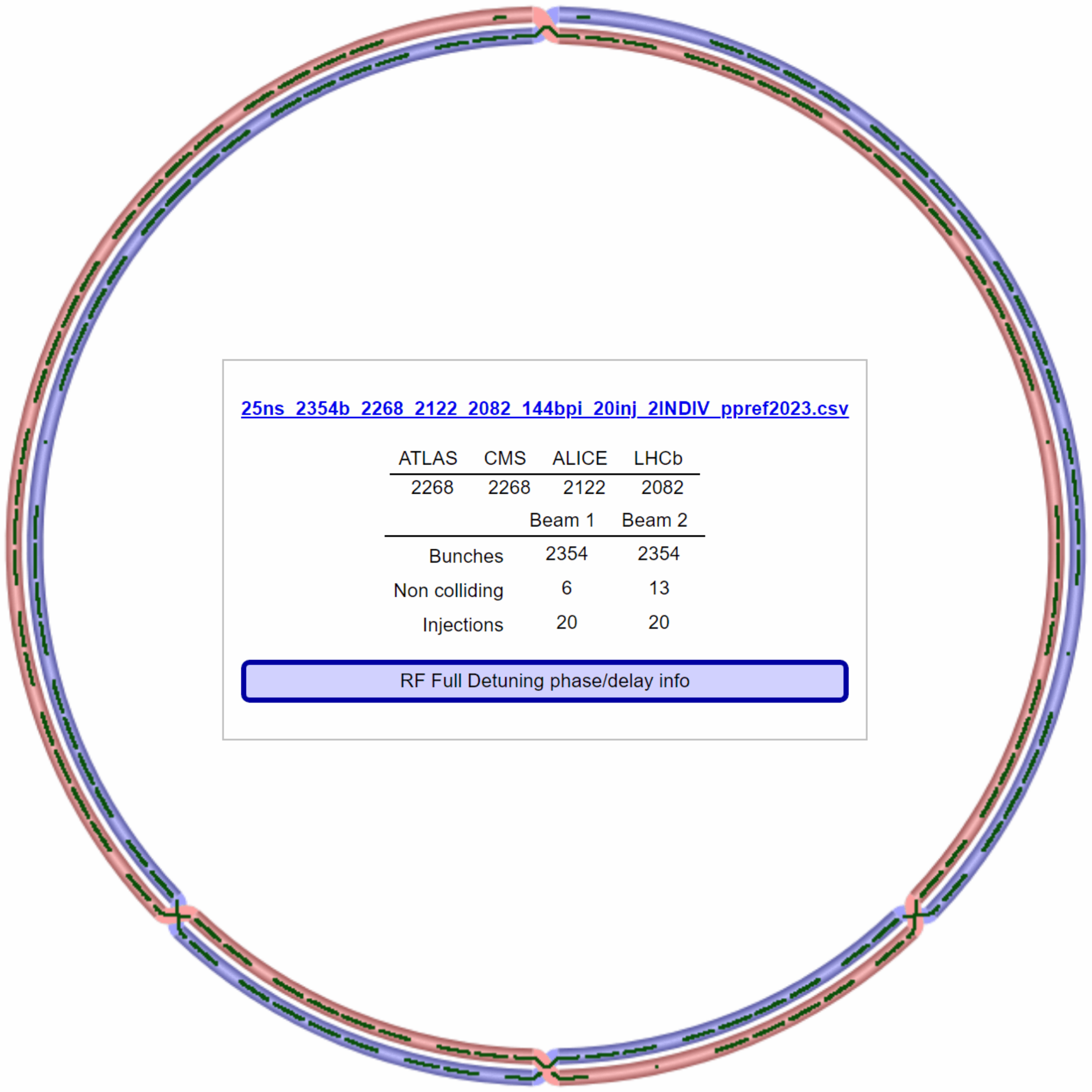
LHC RF operating at 400 MHz => RF buckets 2.5ns

35640 buckets

Minimum bunch spacing production (injectors) 25ns

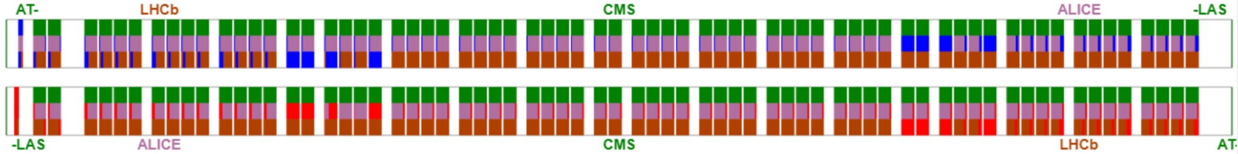
“Fillable” buckets 3564

Collisions scheme is obtained from the injected buckets
And used for triggers computation

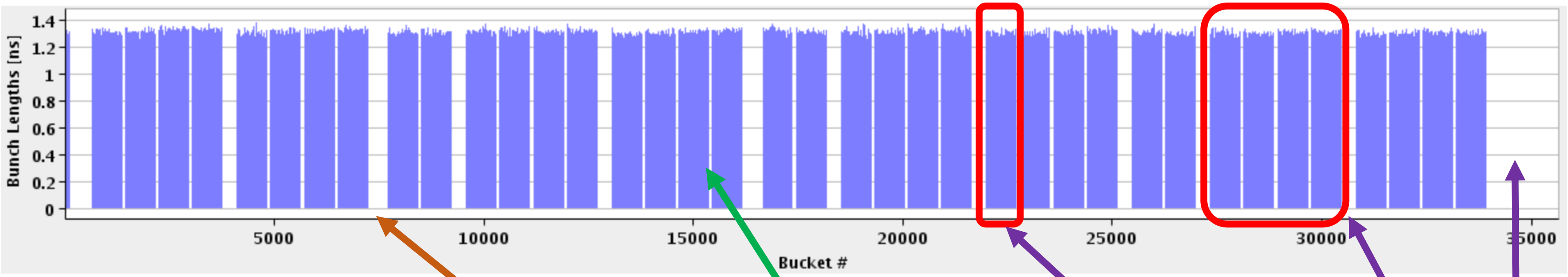


ATLAS	CMS	ALICE	LHCb
2268	2268	2122	2082

	Beam 1	Beam 2
Bunches	2354	2354
Non colliding	6	13
Injections	20	20



LHC collisions scheme



LHC injection kicker rise time

SPS injection kicker rise time

PS batch

SPS TRAIN

LHC dump kickers rise time

LHC RF operating at 400 MHz => RF buckets 2.5ns

35640 buckets

Minimum bunch spacing production (injectors) 25ns

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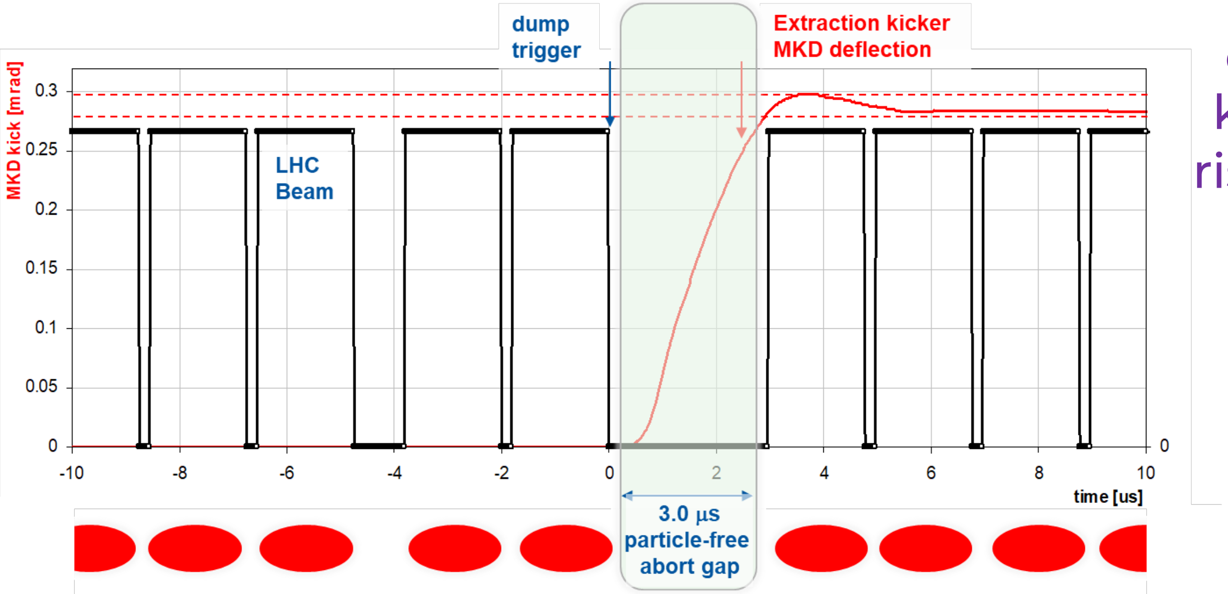
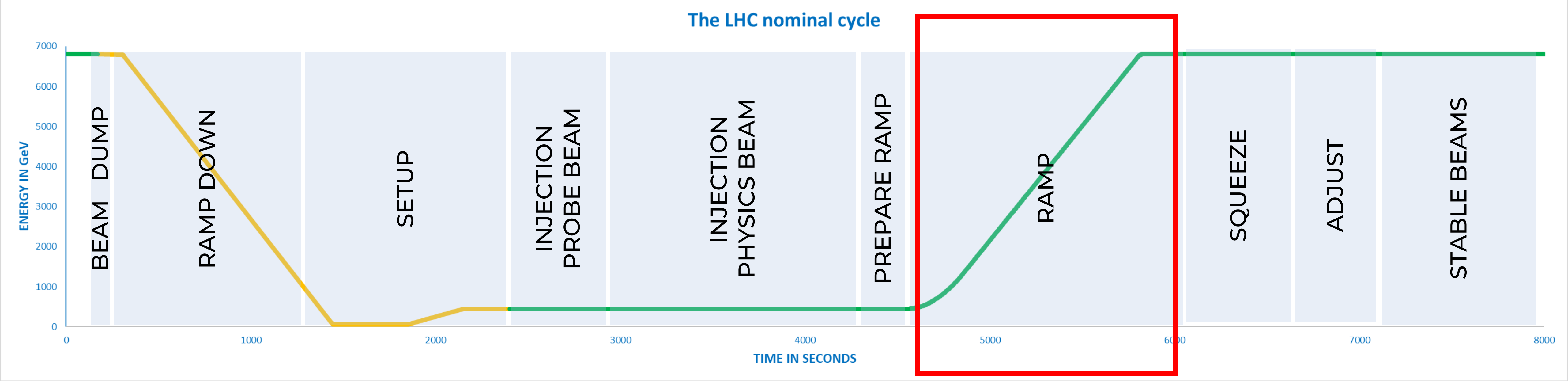
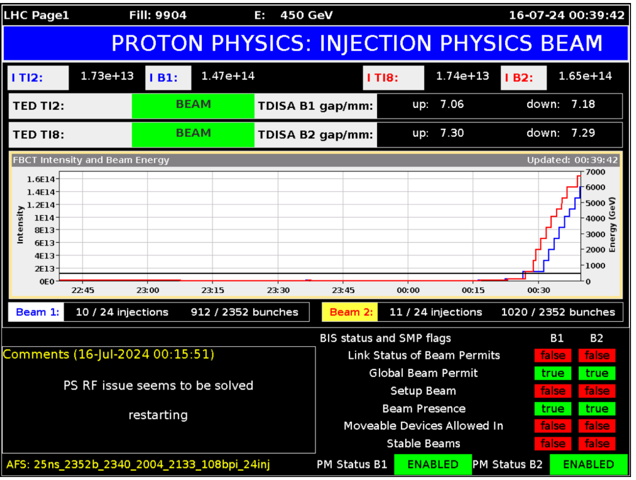
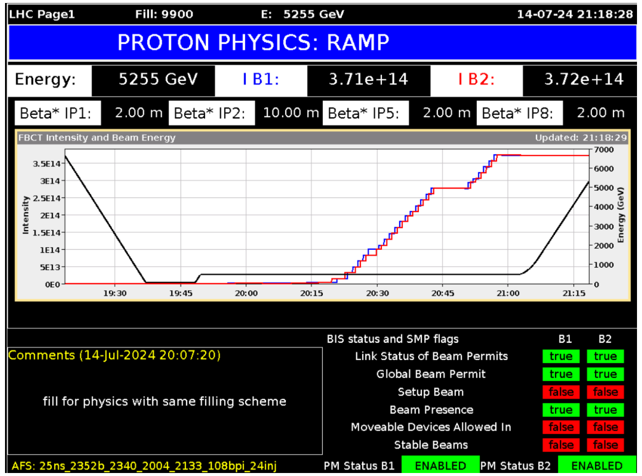
Collisions scheme is obtained from the injected buckets
And used for triggers computation



LHC CYCLE



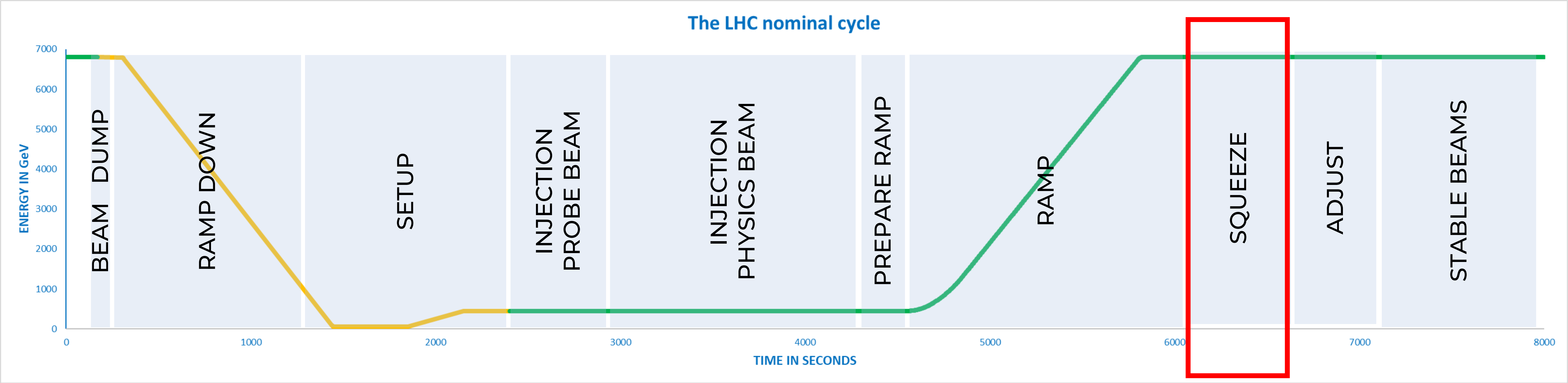


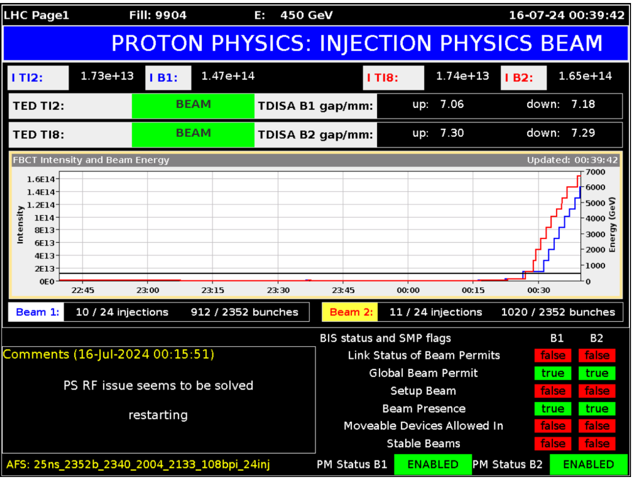


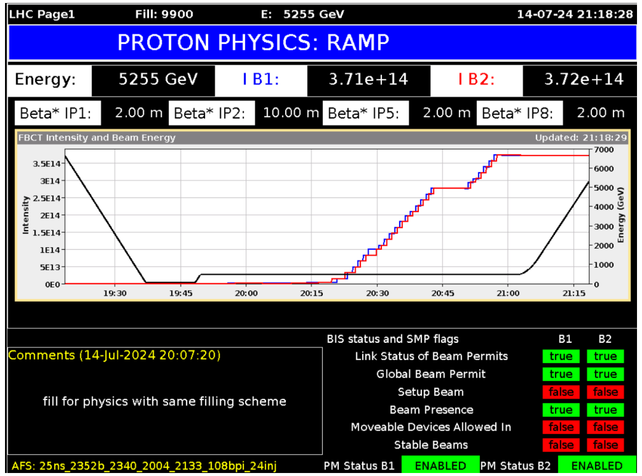
LHC systems are "ramped" synchronously:

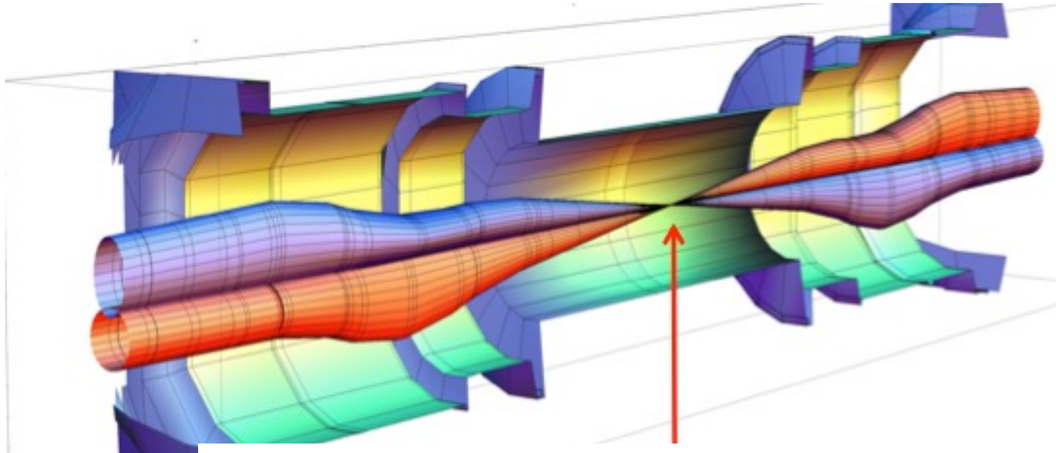
- Magnets power converters
- Cavities RF
- Collimation system
- Feedback system (Dampers…)

LHC CYCLE



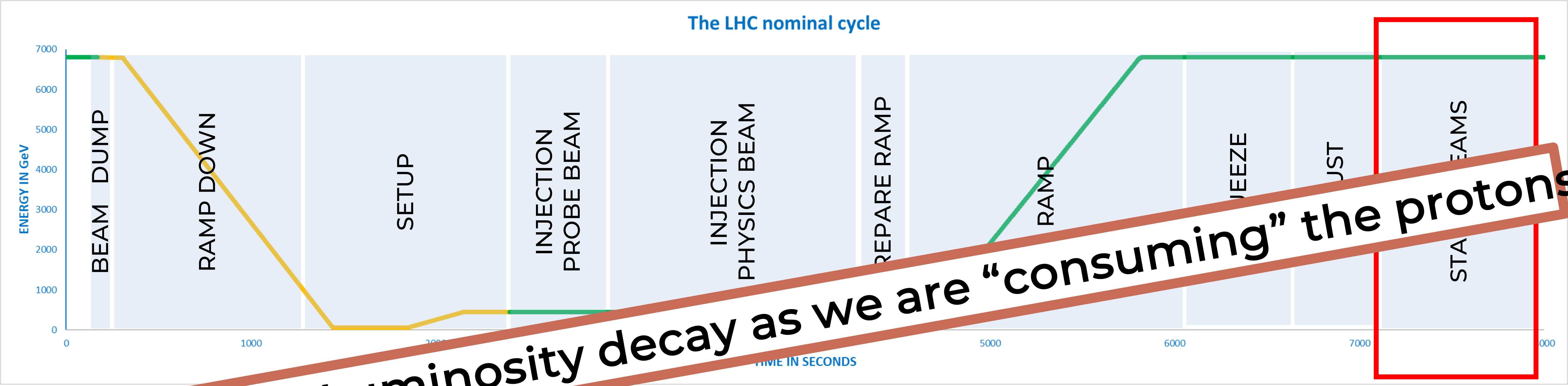




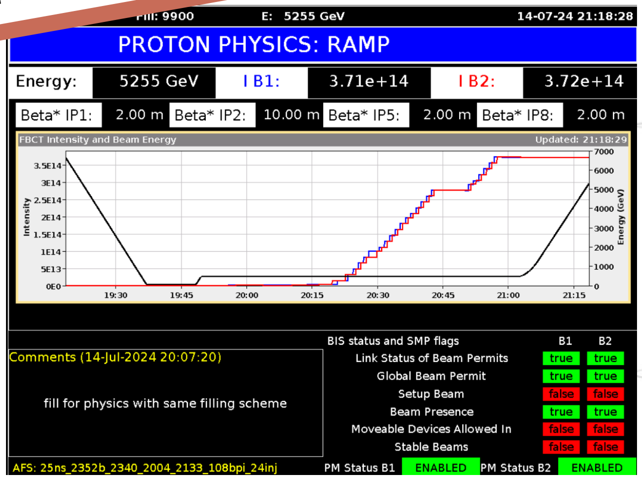


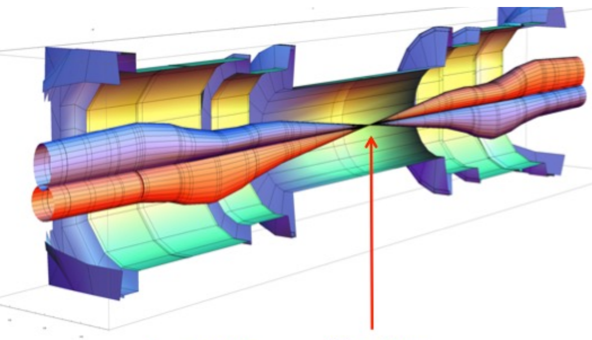
At collision as small as 10 um
In the squeezing magnets x100 bigger

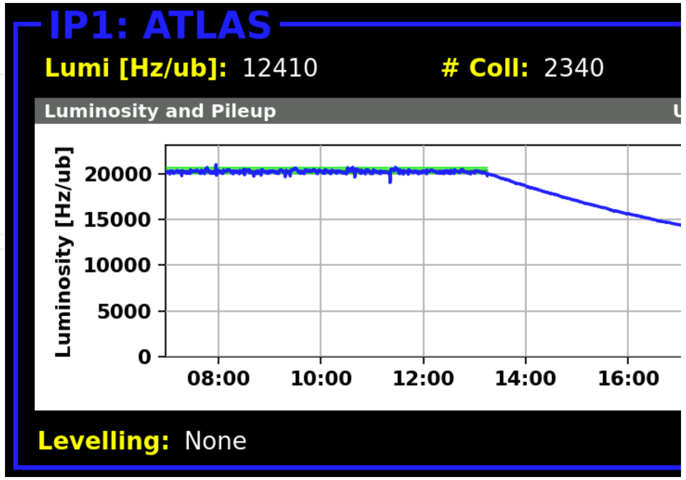
LHC CYCLE



Shouldn't Luminosity decay as we are "consuming" the protons







LHC - Luminosity

How to maximize L?

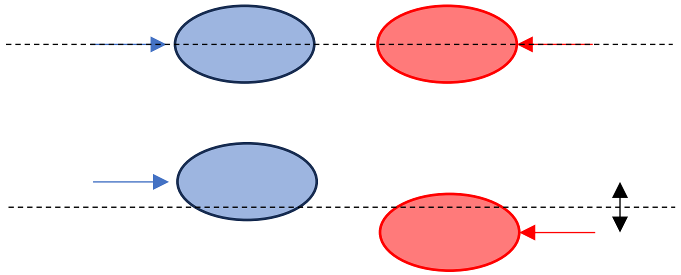
$$L = \frac{N_b^2 n_b f_{rev} \gamma}{4\pi \varepsilon_n \beta^*} F = \frac{c}{4\pi} \frac{\gamma}{l} N_b^2 n_b \frac{1}{\varepsilon_n \beta^*} F$$

n_b: linked to bunch spacing, train length, number of injections, filling scheme
F: maximized reducing crossing angle, limited by parasitic “Long Range” encounters
b*: Minimum limited by physical aperture in the triplets (small beam at IP, big beam in surrounding magnets)
N_b: capped by the most stringent of several factors (beam coupling impedance, e- cloud heatload, instabilities…)
e_n: At best preserve the injected emittance from injectors

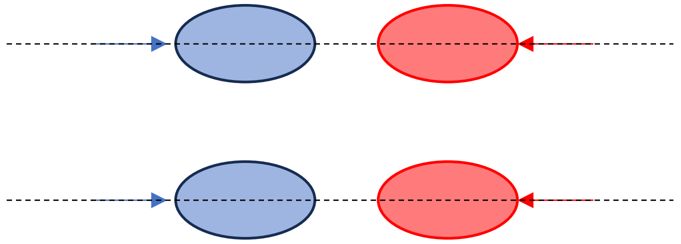
“Virtual Luminosity” would be more than what the machine and Experiments can cope with!

<u>**Luminosity control techniques (Levelling):**</u>

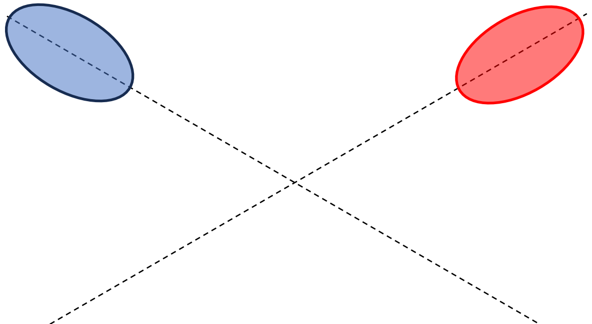
By Separation



By b*



By crossing angle



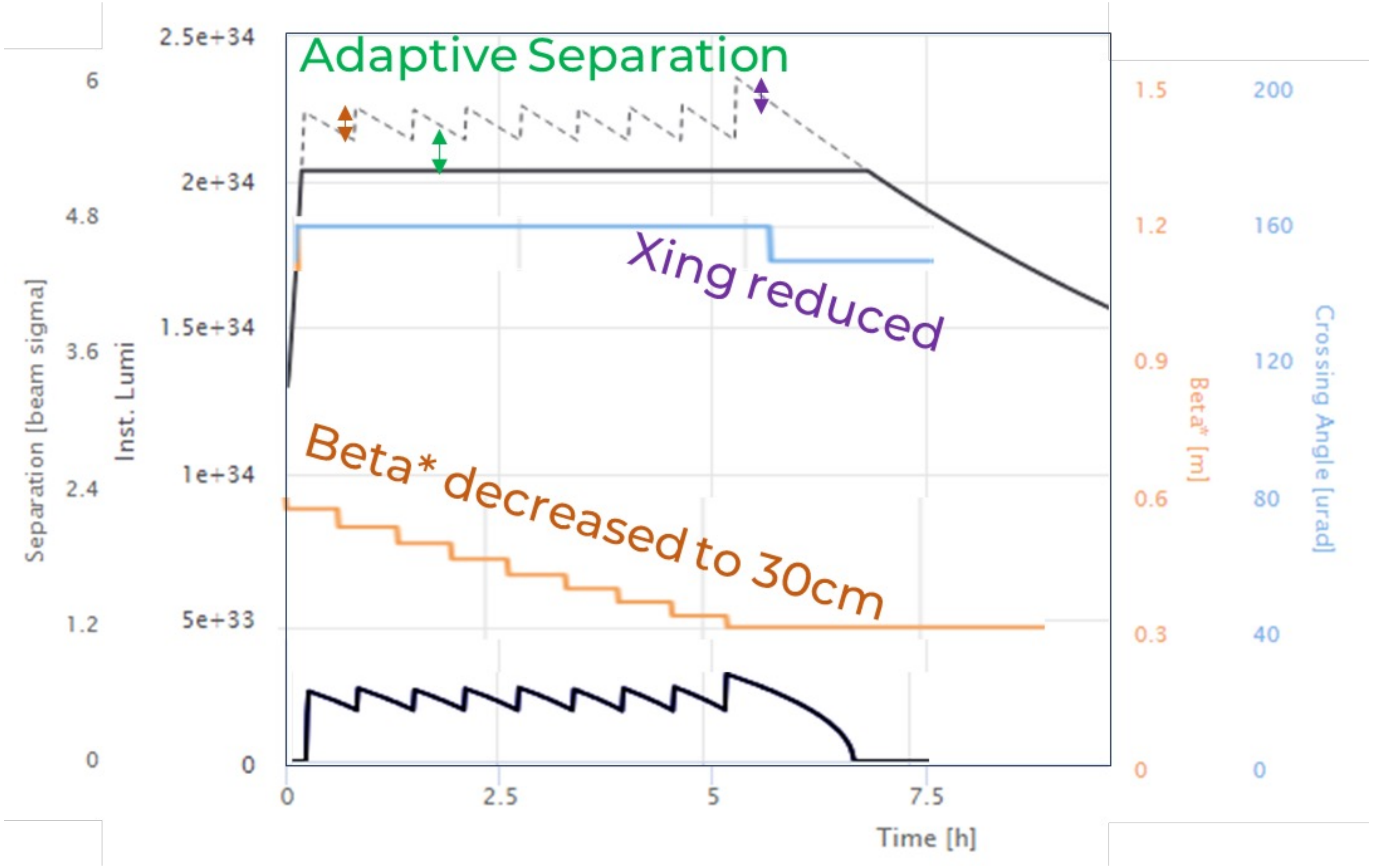
Luminosity Evolution

All levelling techniques are applied in the LHC during Stable Beams to maximize integrated luminosity

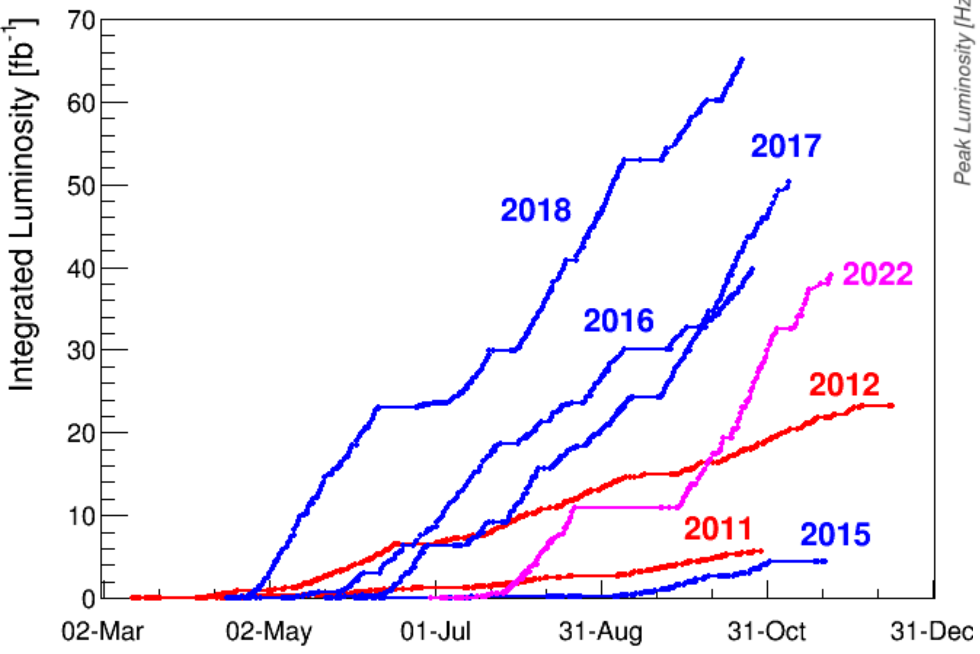
$$\mathcal{L}_{\mathrm{int}} = \int_0^T \mathcal{L}(t')dt'$$

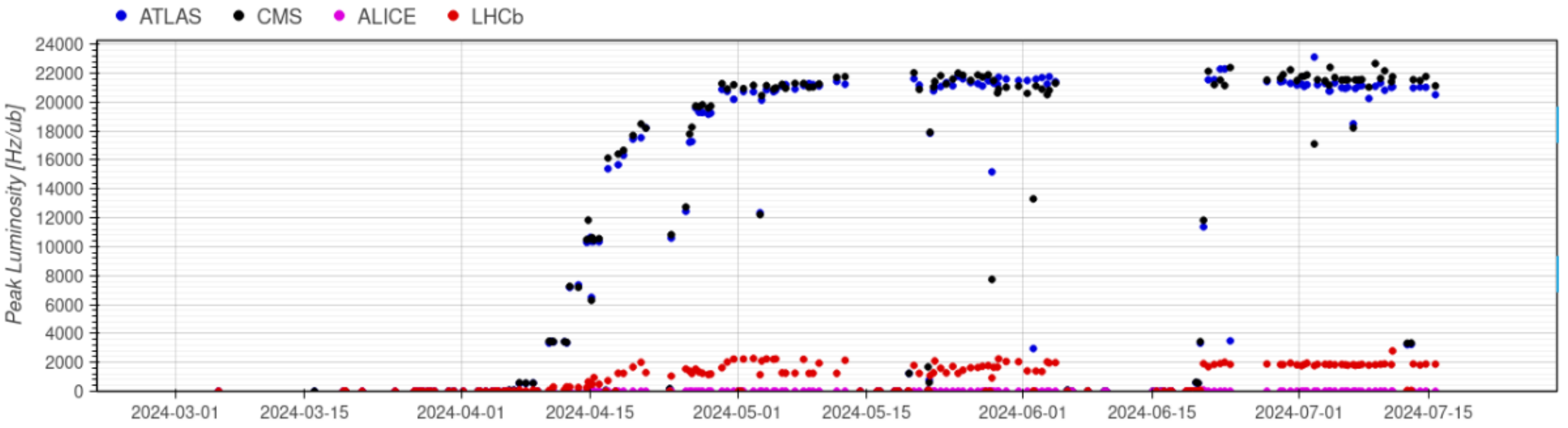
$$\mathcal{L}_{\mathrm{int}} \cdot \sigma_p = \text{number of events of interest} .$$

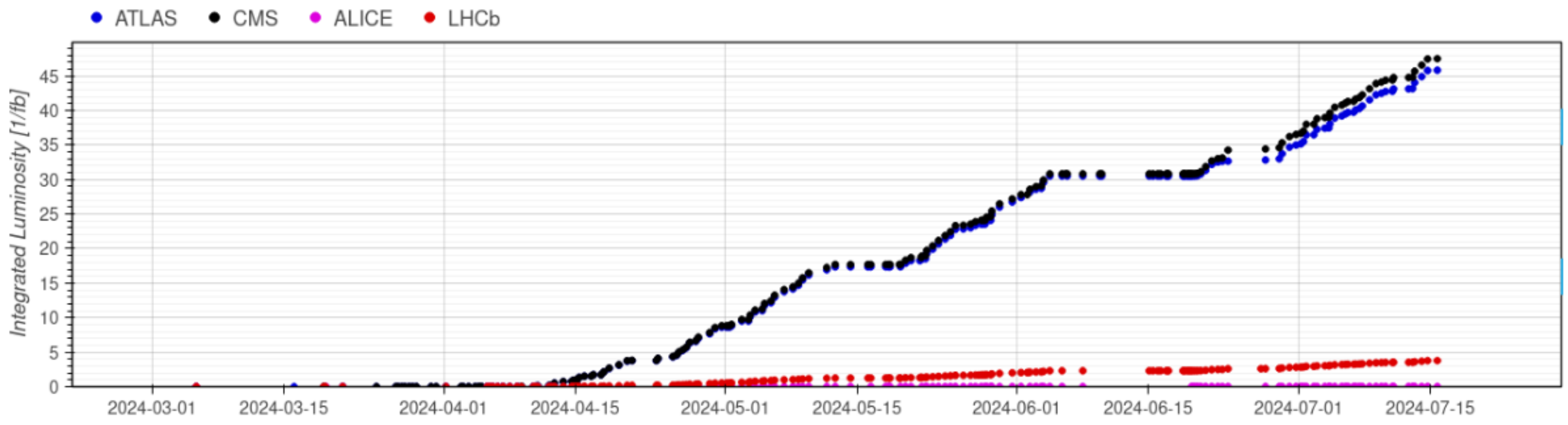
Aiming for average production of 0.8 fb^{-1}/day
Reaching peaks of 1.4 fb^{-1}/day



Ongoing Lumi Production





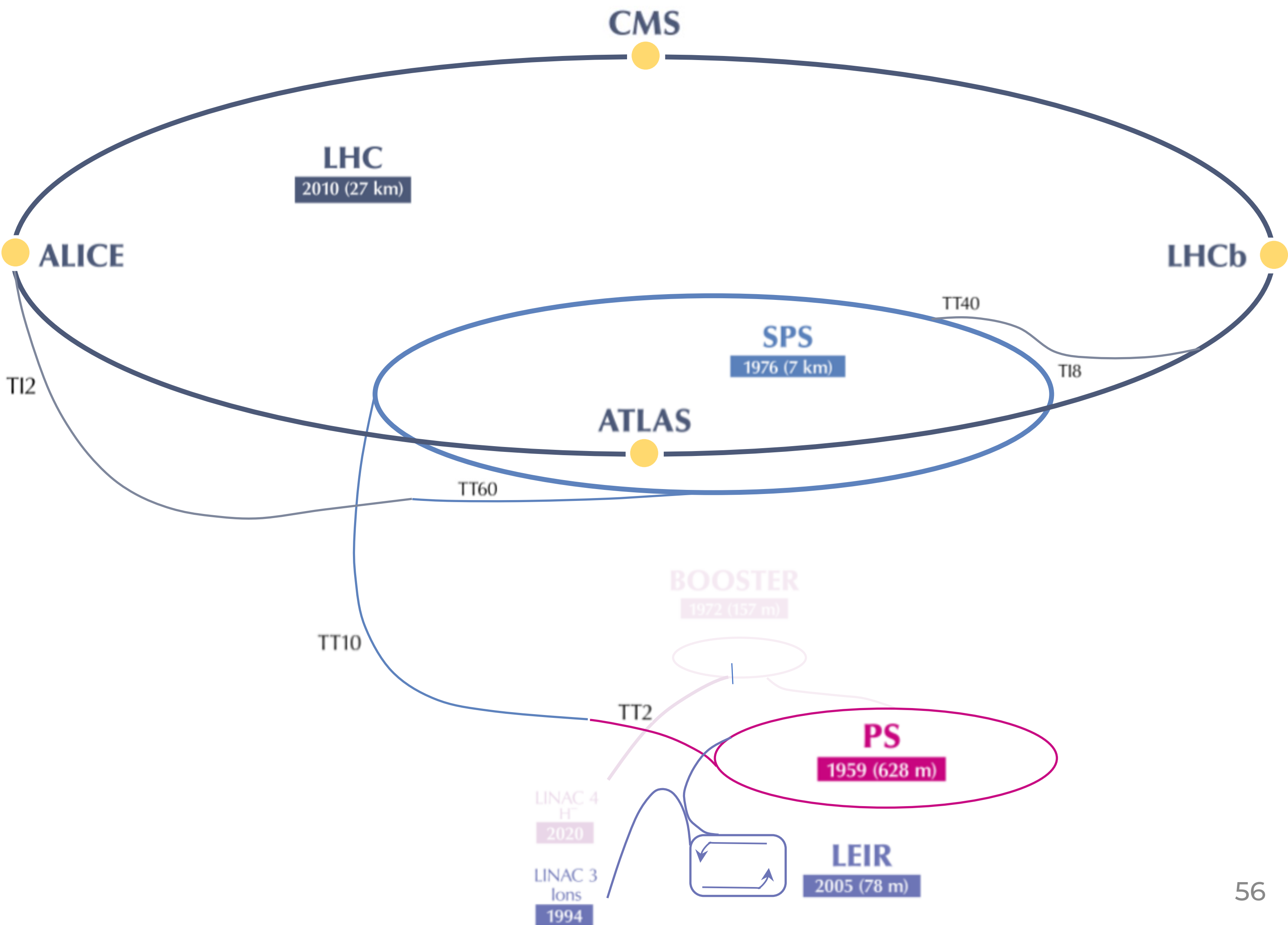


What about Ions Operation?

IONs Chain – LINAC 3

- Small sliver of solid isotopically pure 208Pb heated to around 800°C and ionized to become plasma.

- Ions Pb29+ are then extracted from the plasma and accelerated up to 2.5 keV/nucleon.

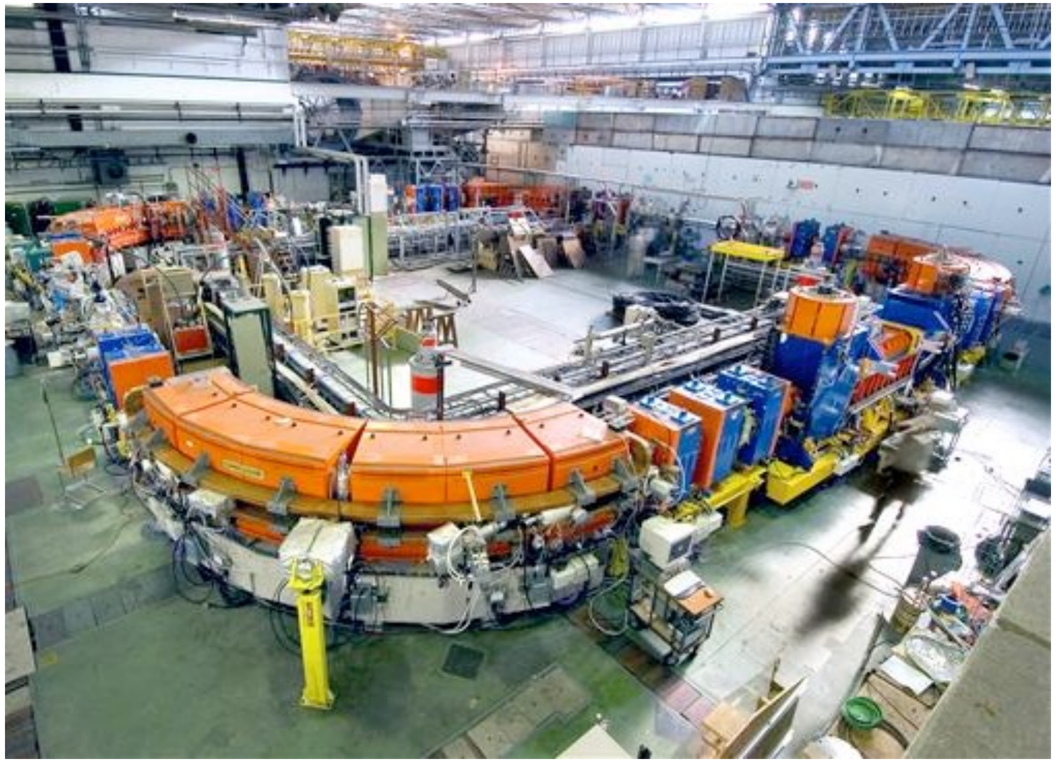


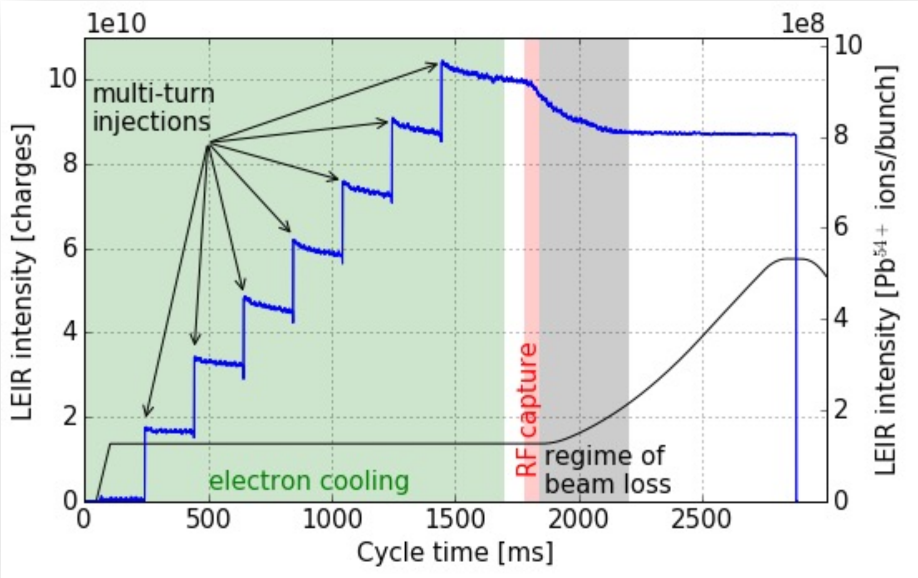
<u>**In Linac3**</u>

  - Lead ions are further stripped to Pb54+
  - Beam accelerated up to 4.2 MeV/n

- **N.B:** The source can also be set up to deliver other species: O, Ar, Xe …

IONs Chain - Low Energy Ion Ring (LEIR)



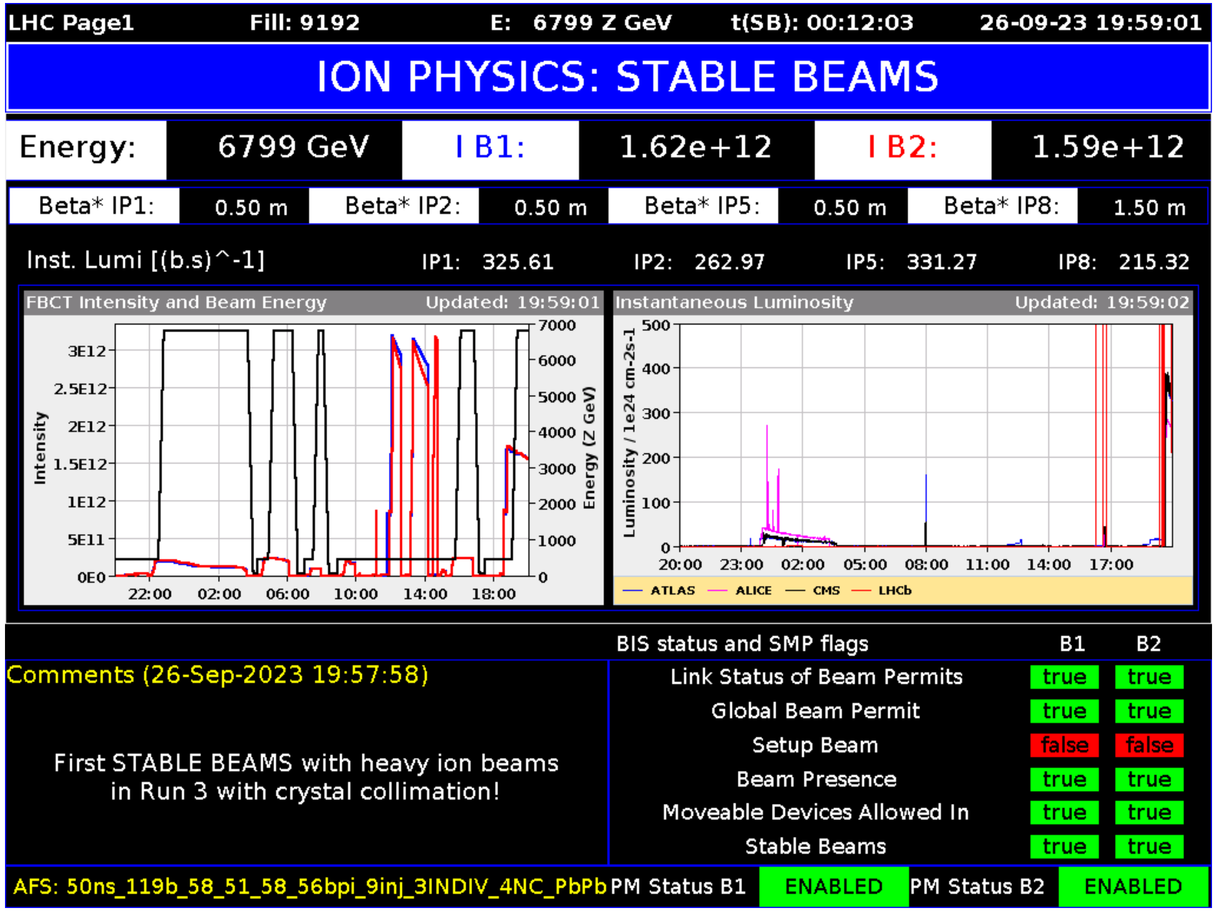


- LEIR Accumulates the 200 ms pulses from Linac3; then splits into 2 bunches (3.6 s)
- Electron Cooling is used to achieve the required brightness
- Acceleration to 72 MeV/nucleon before transfer to the PS
- The Pb54+ is finally fully stripped to Pb82+ in the transfer line from PS to SPS

IONs PHYSICS

Acceleration continues:

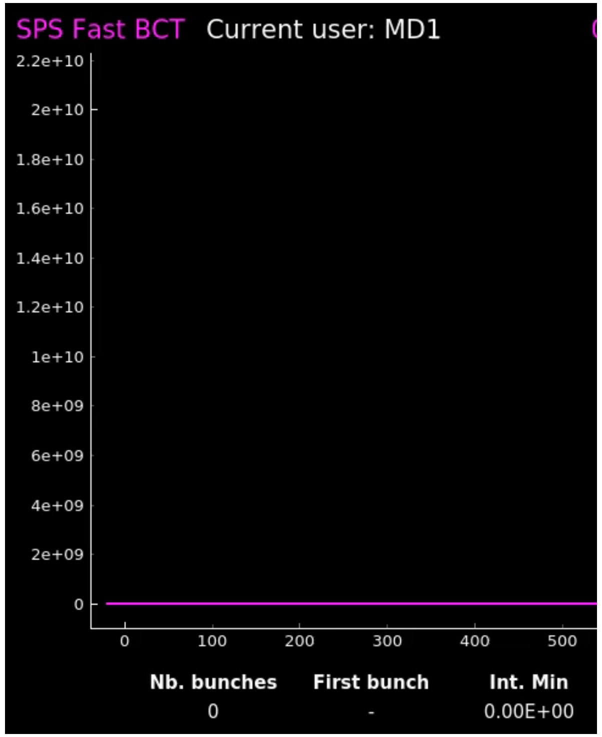
- in the PS where a double splitting also takes place (2b -> 4b, bunch separation 100 ns)
- In the SPS ions are accelerated to 17 GeV/u

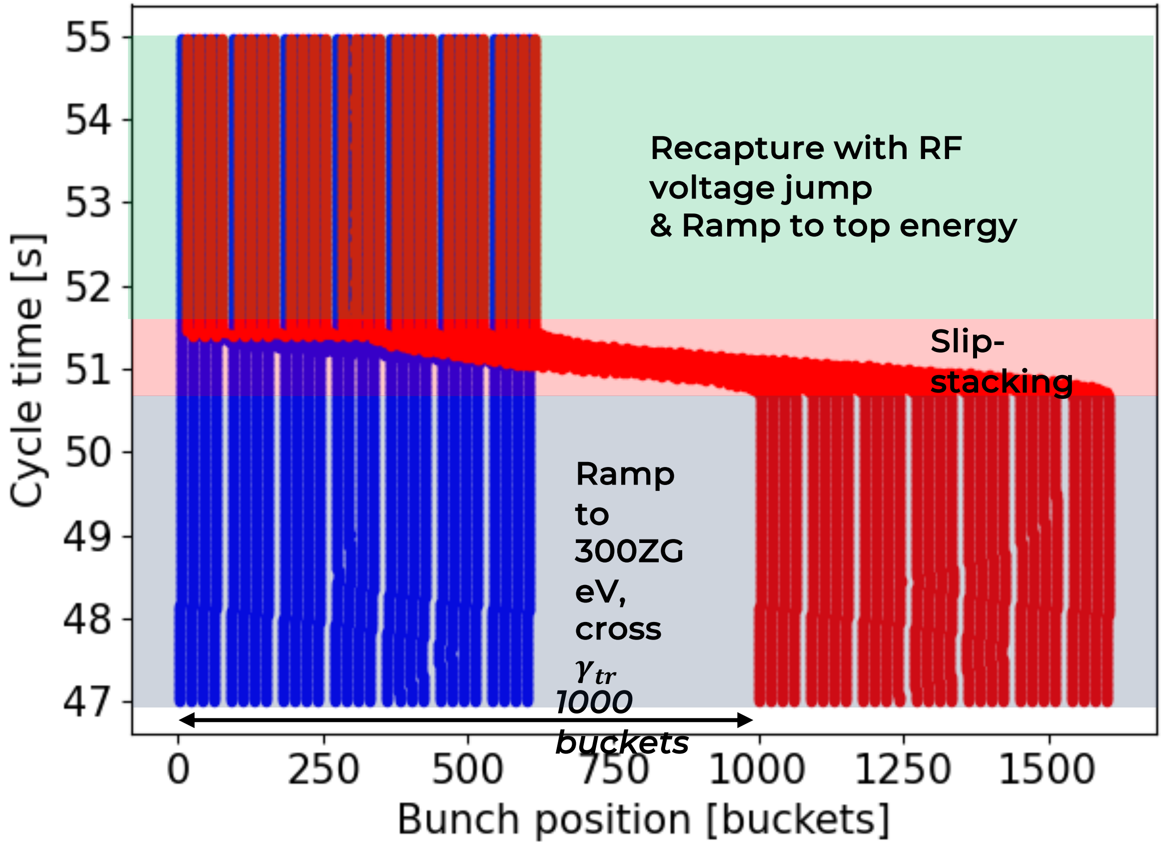


- Run 3 Ion physics started in 2023 and is scheduled also for 2024/25
- N.B: In Run 2 LHC also operated as Proton-Lead collider
- In 2023, 1240 bunch per beam were used for Physics (max. 740 b in 2018)
    - Key: 50ns beams from SPS (momentum split stacking)

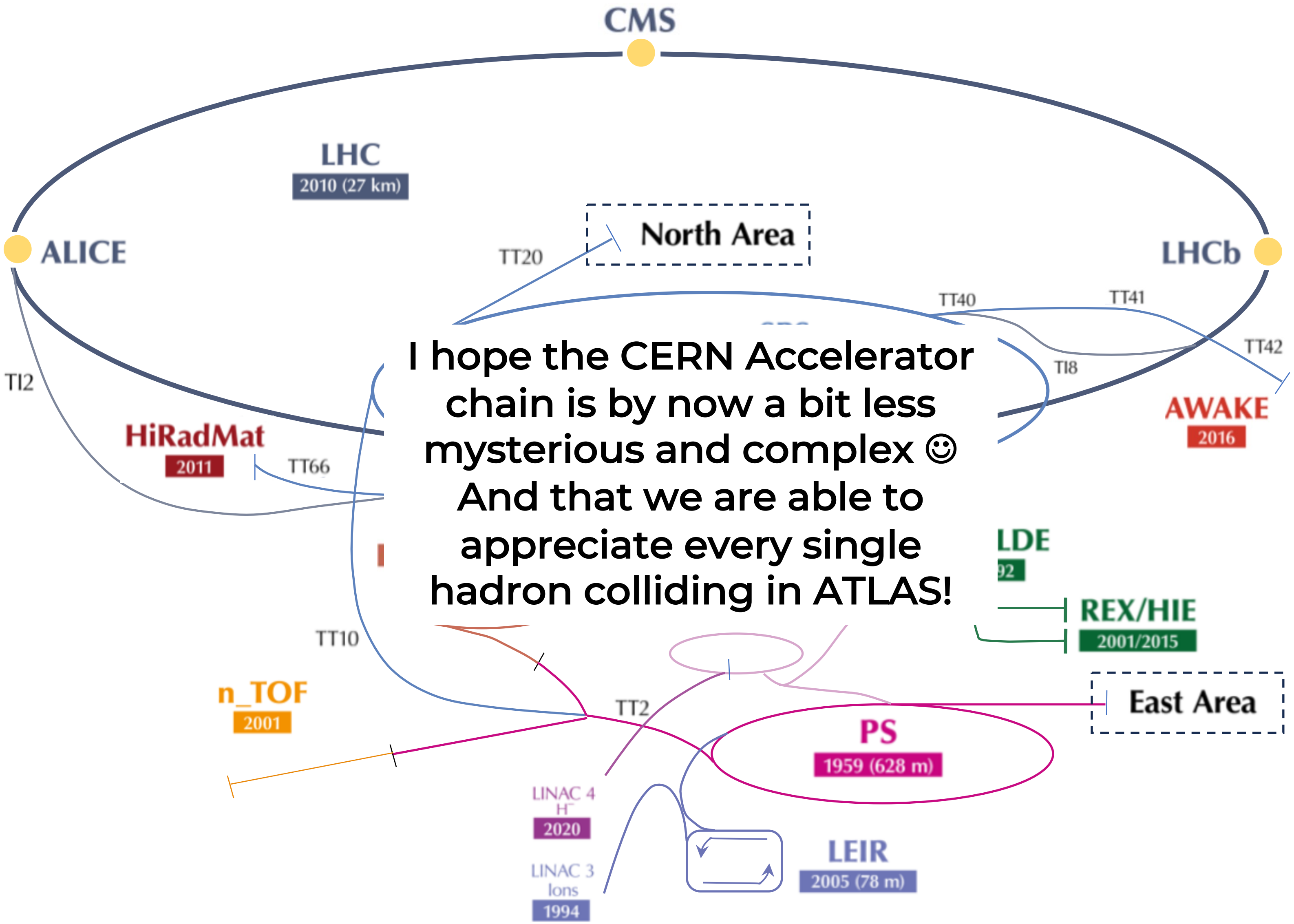
SPS – SLIP STACKING (MSS)

- **Injection** of **14 PS-batches** (4 bunches, spaced by 100ns):
  Beam1: first 7 batches, **Beam2:** last 7 batches
- **Ramp** to **slip-stacking energy plateau** (300 ZGeV) → **cross transition energy**
- **Each beam** follows **different frequency programs:** two groups of 200 MHz RF cavities (3 per beam) → slip longitudinally close to each other
- **Interleave** the beams: reduce bunch distance to 50 ns
- **Recapture** with a **non-adiabatic voltage jump** at the **average frequency** and **accelerate**





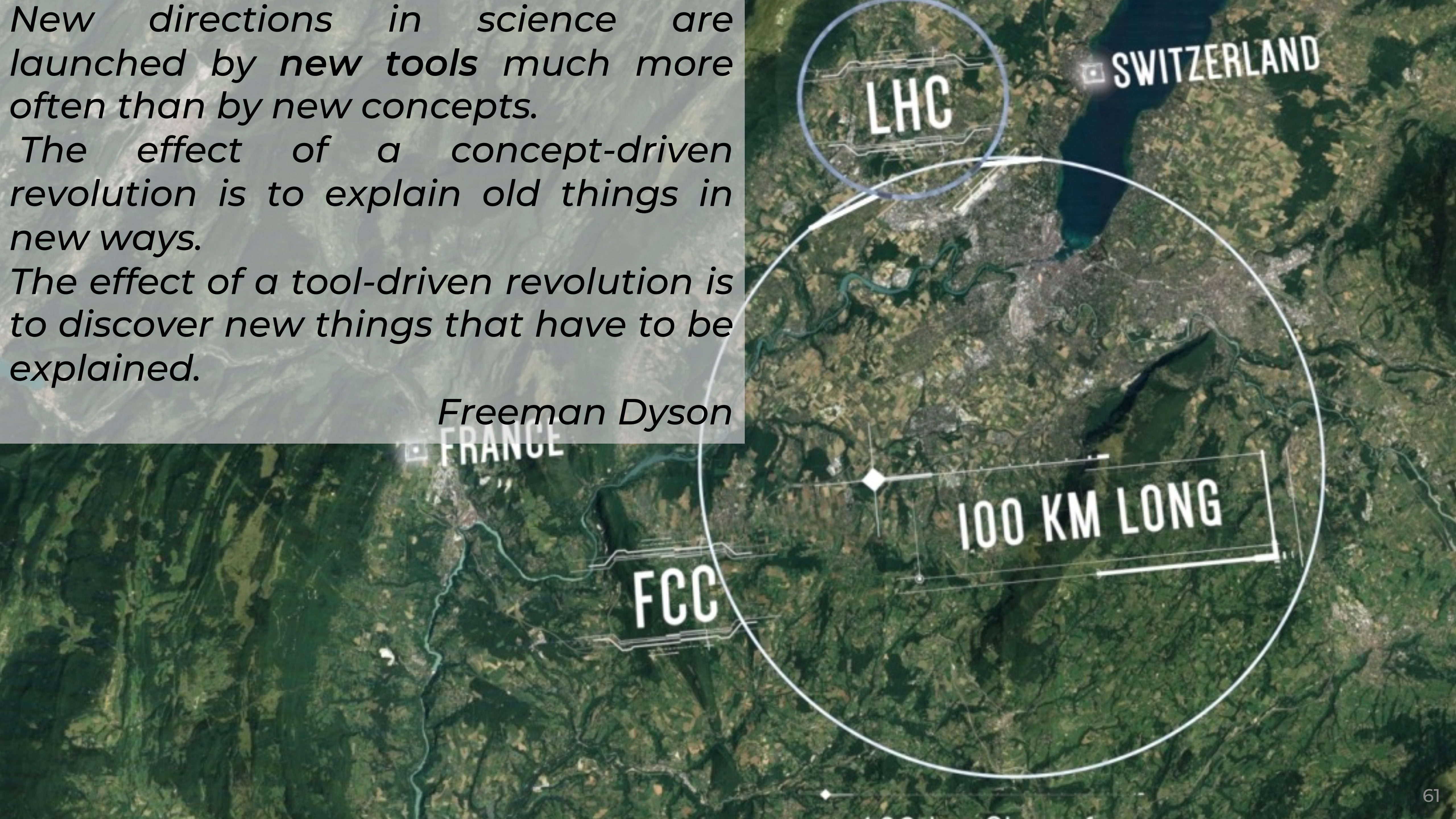
Conclusions



I hope the CERN Accelerator chain is by now a bit less mysterious and complex ☺ And that we are able to appreciate every single hadron colliding in ATLAS!

New directions in science are launched by ***new tools*** *much more often than by new concepts.*
The effect of a concept-driven revolution is to explain old things in new ways.
The effect of a tool-driven revolution is to discover new things that have to be explained.

Freeman Dyson



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The effect of a concept-driven revolution is to explain old things in new ways.
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Freeman Dyson

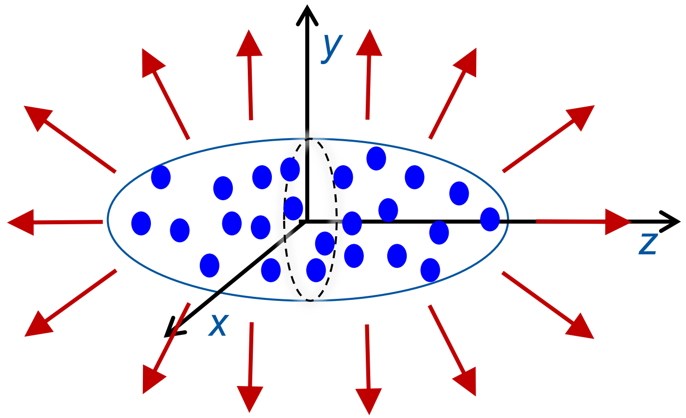
CERN staff in front of one of the first High Luminosity LHC quadrupoles 2023

Acknowledgments

- JUAS 2023 (Course 1): The Science of Particle Accelerators (R. Alemany) Introduction to CERN & its Accelerator Complex
- JUAS 2024 (Course 1): The Science of Particle Accelerators (R. Steerenberg) Introduction to CERN & its Accelerator Complex
- The Large Hadron Collider a challenging machine (M. Solfaroli)
- The new PSB H- injection system (C. Bracco)
- LINAC4 Introduction (G. Bellodi)
- Linac4 at the Heart of CERN Proton Operation after LS2 (B. Mikulec)
- CERN accelerator school – Accelerators for beginners and the CERN complex (R. Steerenberg)
- cern.ch

Why need to upgrade the PSB?

- **Brightness Limitations: Space-Charge**
- **Particles within a bunch moving at speed lower than speed of light generate a repulsive force**



- This is an additional defocusing force on single particles
  → transverse tune shift (negative)
- Particles feel different space charge defocusing forces according to their positions in the bunch
  → **tune spread**

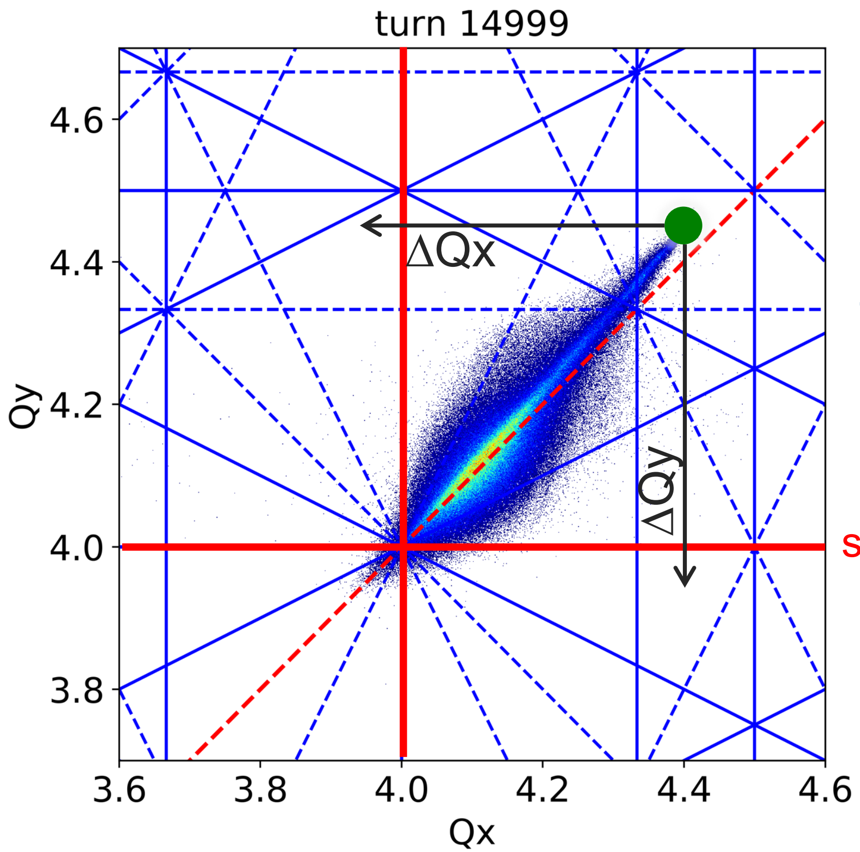
Slide from H. Bartosik's shutdown lecture: *"Overview of the beam commissioning strategy to reach LIU parameters across the complex and required MDs"*

Brightness Limitations: Space-Charge

- **Due to their shifted tunes, some of the particles can hit resonances so that the trajectories of those particles can**
  - Grow to large amplitudes and get stabilised → **emittance growth**
  - Become unstable and hit the machine aperture → **beam loss**

$$\Delta Q_{x,y}^{\max} = -\frac{r_0 R N_b C}{2\pi e \beta \gamma^2 \epsilon_{x,y} \sigma_z}$$

Brightness limitation!



PSB simulation for 50 MeV inj.

strong resonances

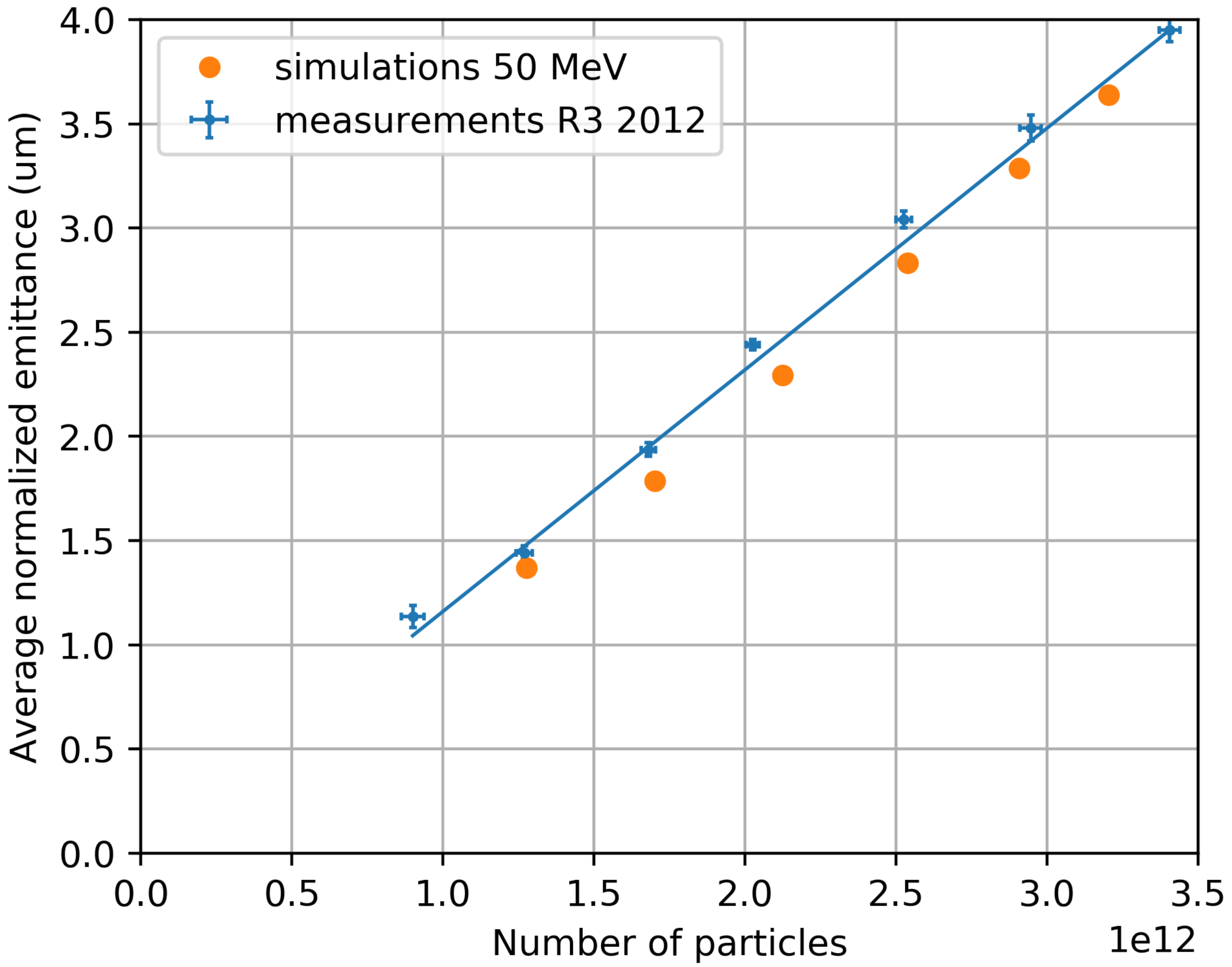
Slide from H. Bartosik's shutdown lecture: *"Overview of the beam commissioning strategy to reach LIU parameters across the complex and required MDs"*

Brightness Limitations: Space-Charge

Example of the PSB:

Due to the brightness limitation imposed by space charge effects, the transverse emittance increases linearly with intensity!

$$\Delta Q_{x,y}^{\max} = -\frac{r_0 R N_b C}{2\pi e \beta \gamma^2 \epsilon_{x,y} \sigma_z}$$



Slide from H. Bartosik's shutdown lecture: *"Overview of the beam commissioning strategy to reach LIU parameters across the complex and required MDs"*

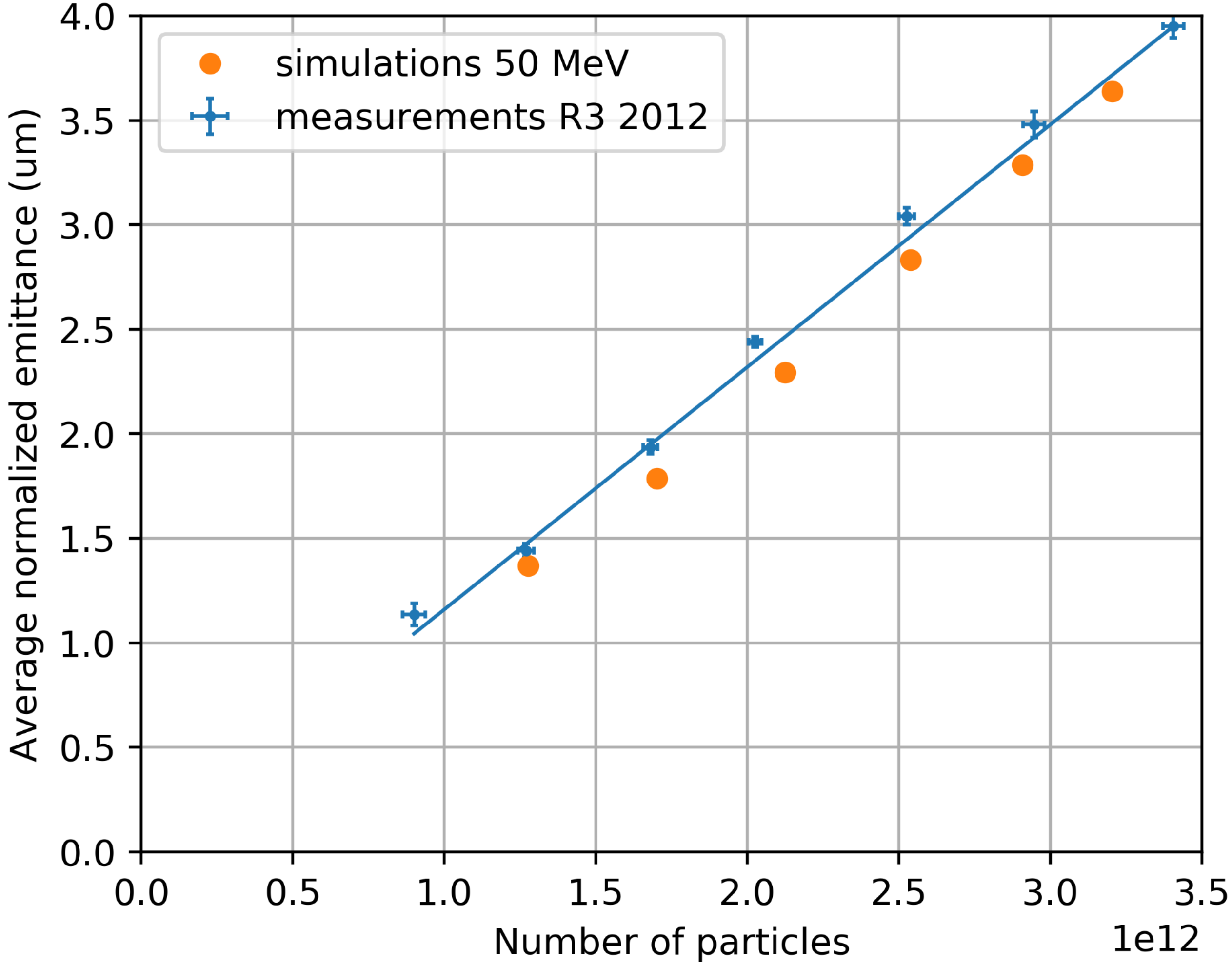
Brightness Limitations: Space-Charge

Example of the PSB:

Due to the brightness limitation imposed by space charge effects, the transverse emittance increases linearly with intensity!

$$\Delta Q_{x,y}^{\max} = -\frac{r_0 R N_b C}{2\pi e \beta\gamma^2 \epsilon_{x,y}\sigma_z}$$

Need to increase beam energy to overcome brightness limitation!
Injection energy from 50 MeV to 160 MeV

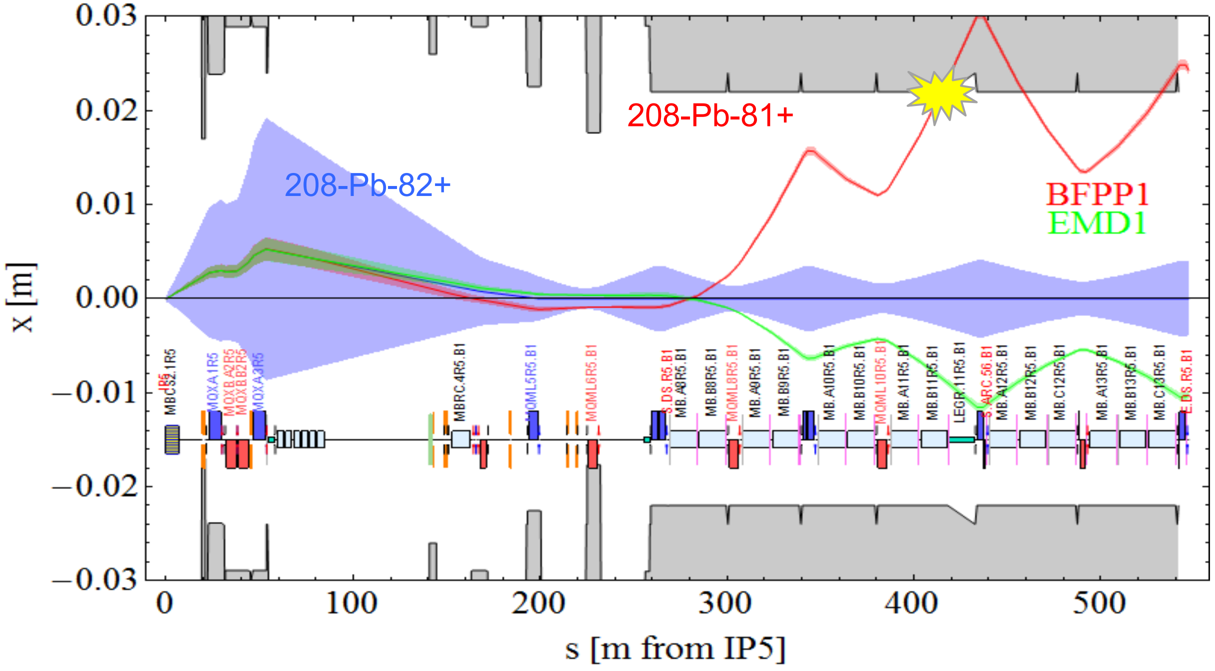


Slide from H. Bartosik's shutdown lecture: *"Overview of the beam commissioning strategy to reach LIU parameters across the complex and required MDs"*

IONs PHYSICS – LHC

BFPP bumps

orbit bumps method was implemented to move the secondary beam into the connection cryostat to reduce risk of quenches and **successfully removed ATLAS and CMS limitation.**

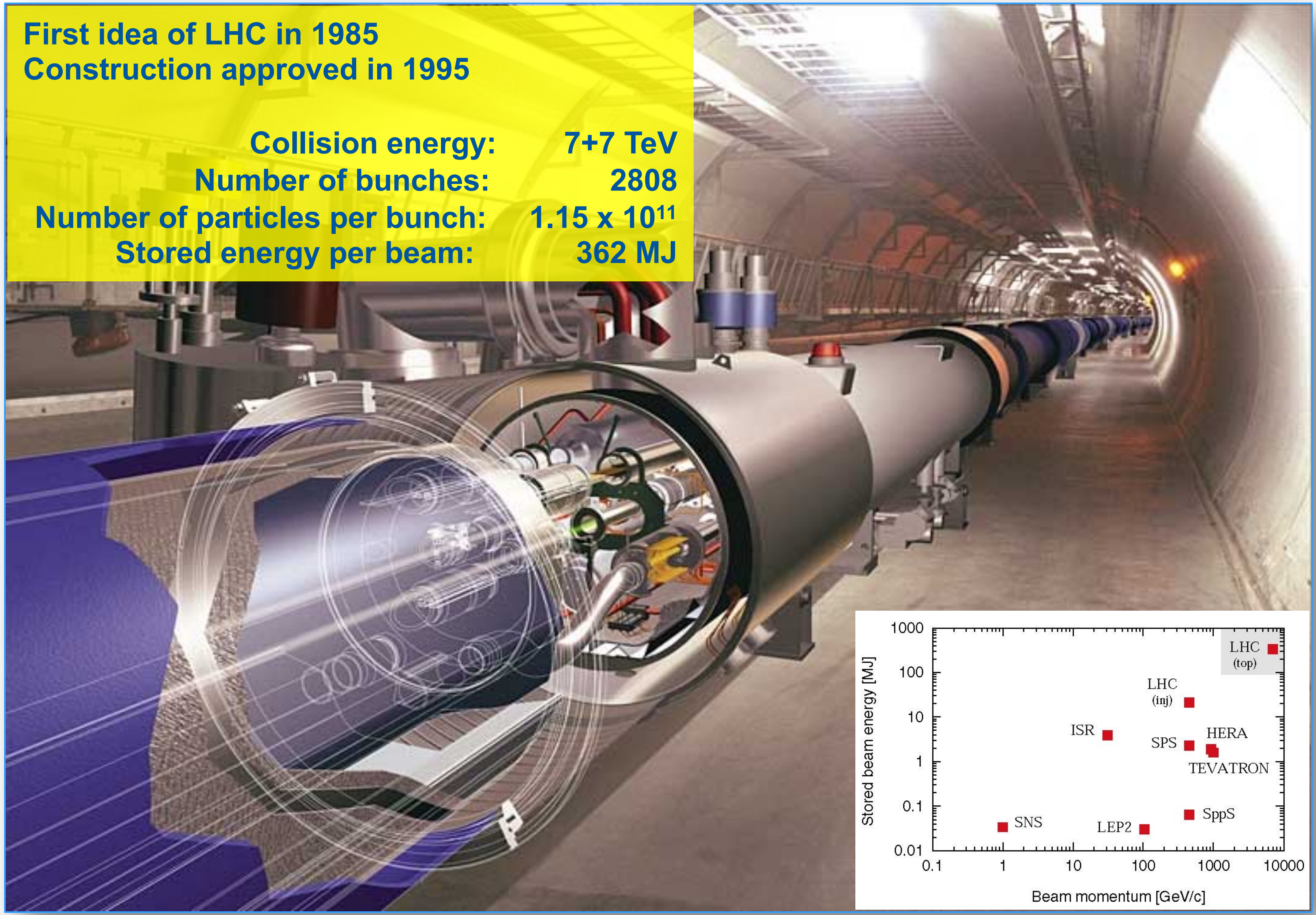


Thanks to J. Jowett and M. Schaumann

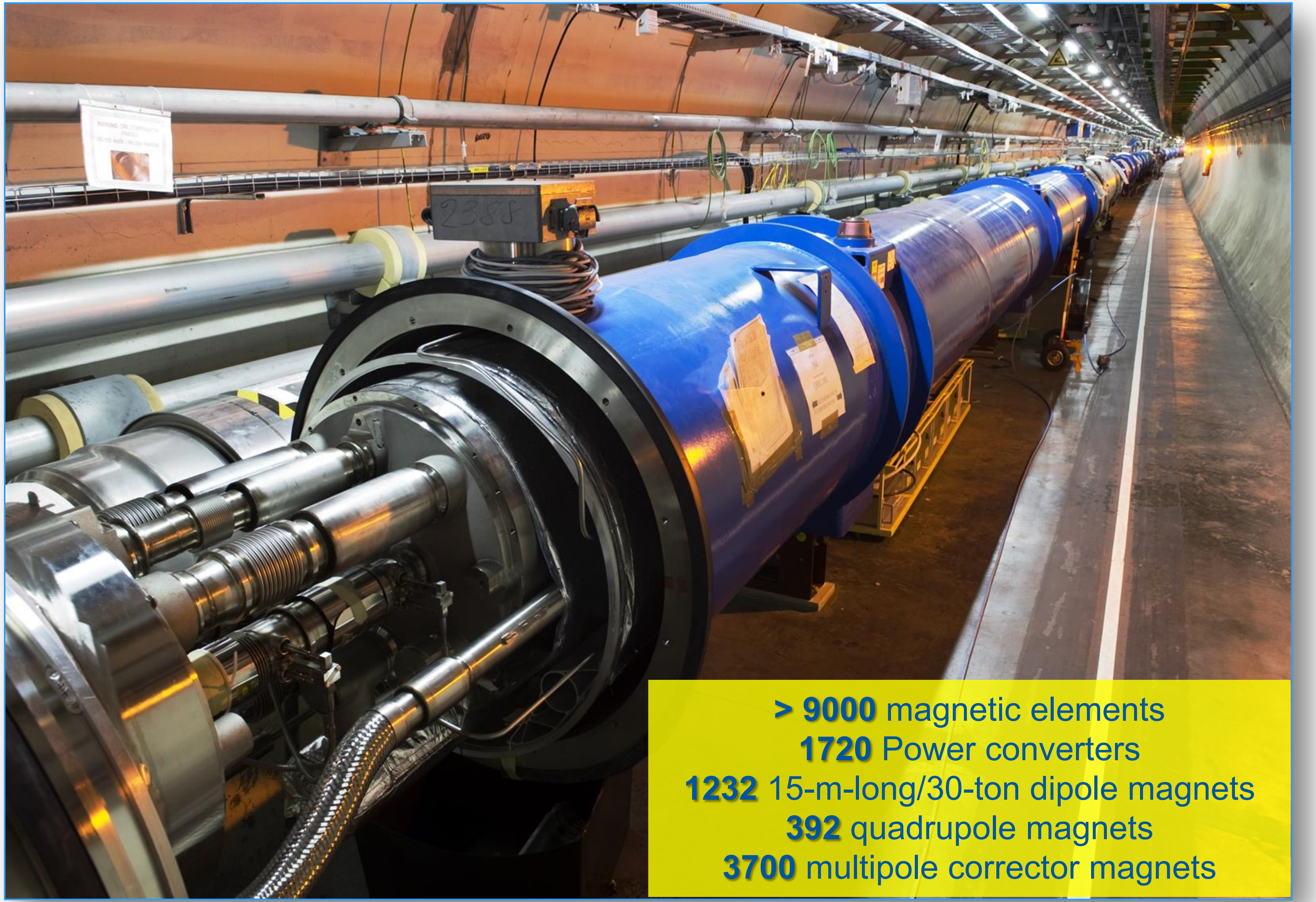
LHC from design…

First idea of LHC in 1985
Construction approved in 1995

Collision energy:	7+7 TeV
Number of bunches:	2808
Number of particles per bunch:	1.15×10^{11}
Stored energy per beam:	362 MJ



...to reality

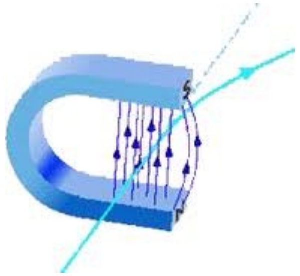


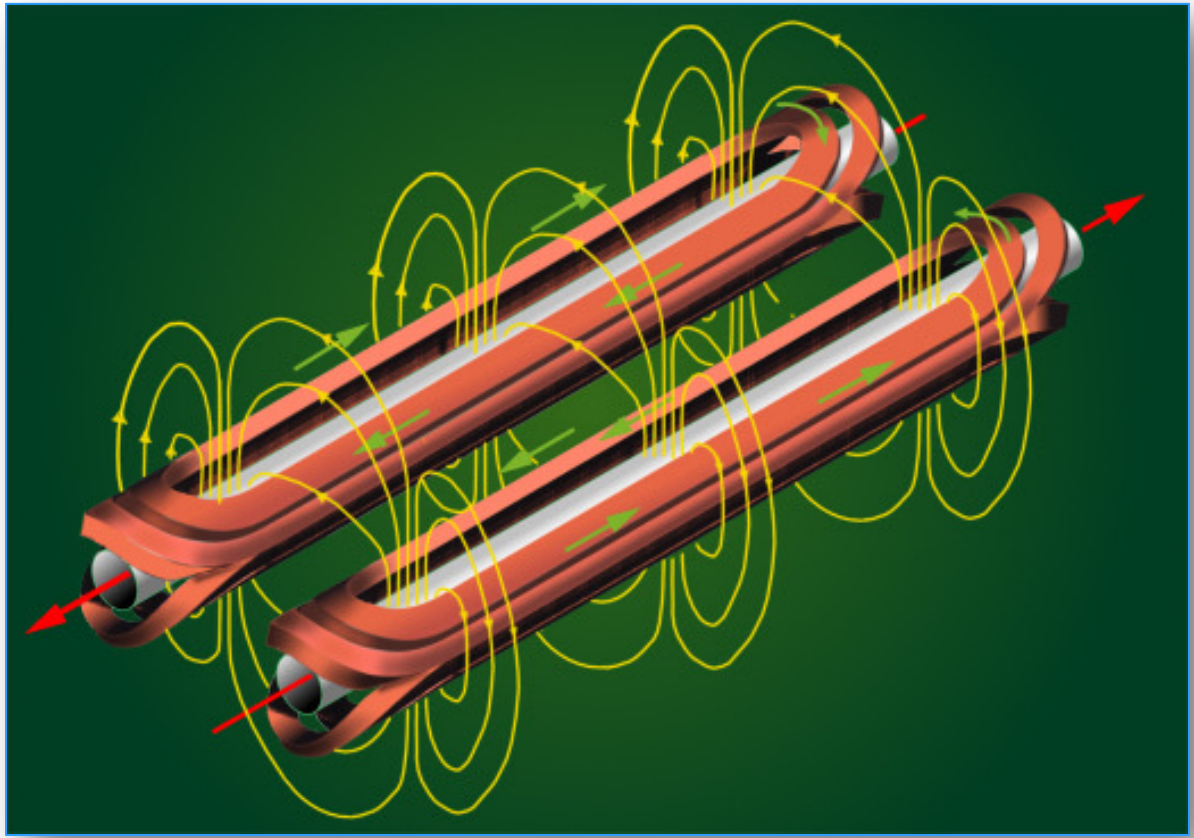
> 9000 magnetic elements
1720 Power converters
1232 15-m-long/30-ton dipole magnets
392 quadrupole magnets
3700 multipole corrector magnets

The main dipoles

The Lorentz's force

$$F = q[vXB]$$





REQUIREMENTS

Bending radius
2803.95 m

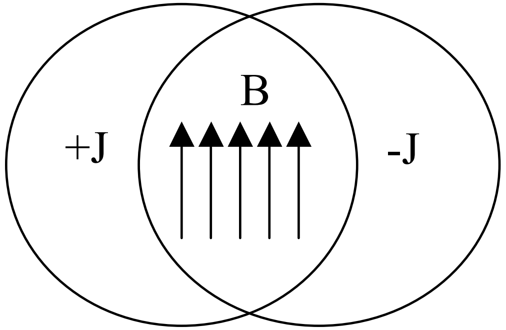
Dipole field at 450 GeV
0.535 T

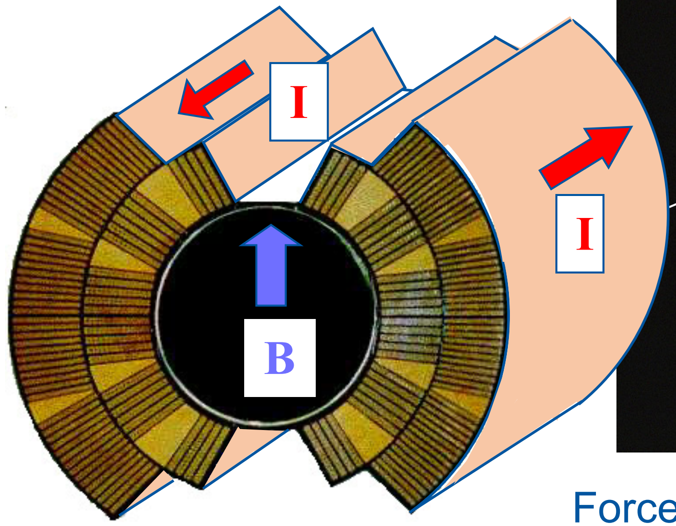
Dipole field at 7 TeV
8.33 T

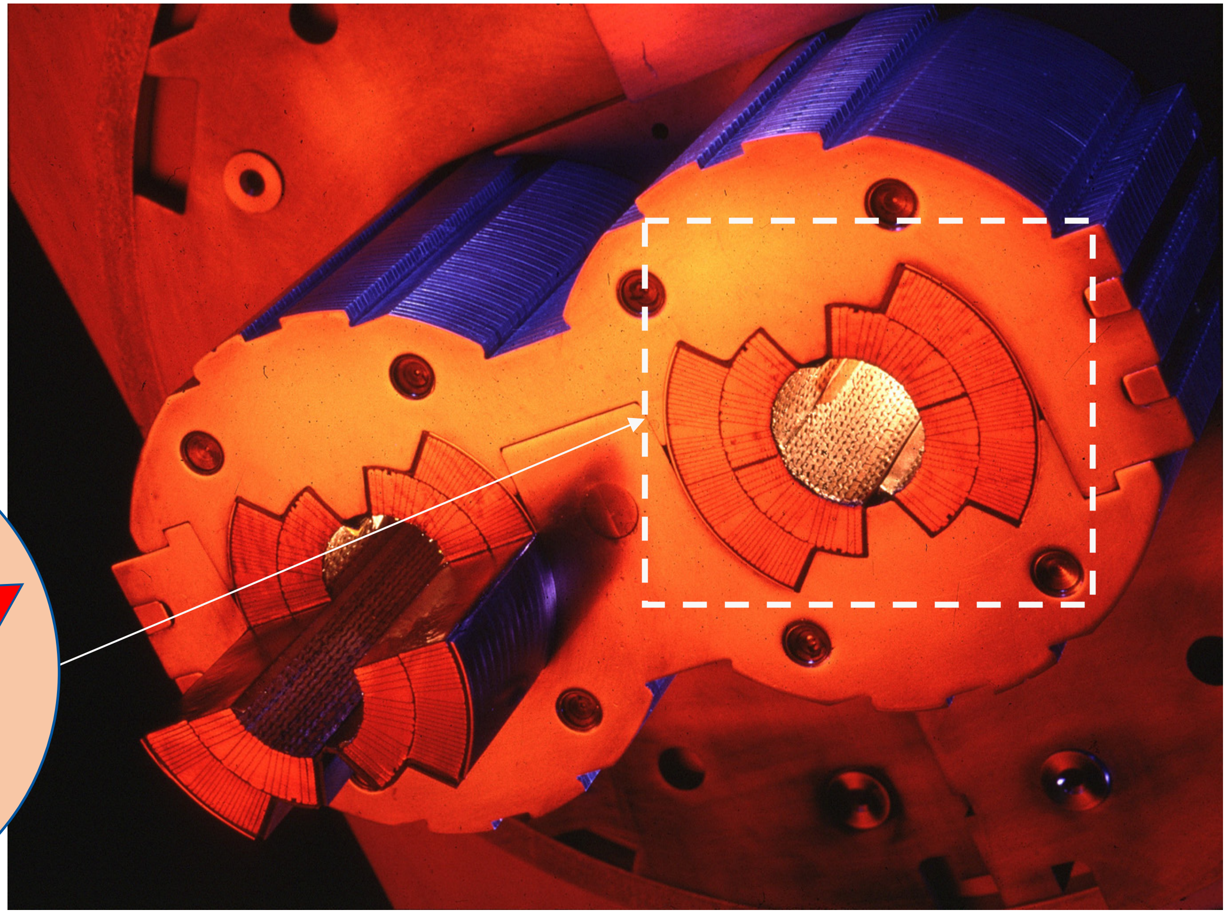
The main dipoles

1500 tonnes of top quality SC cables

15000 MJ of magnetic energy

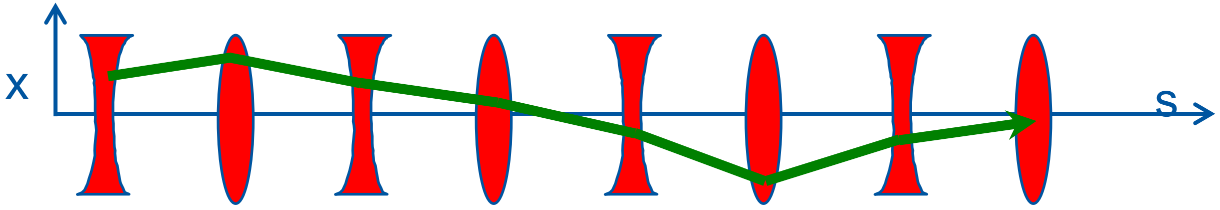


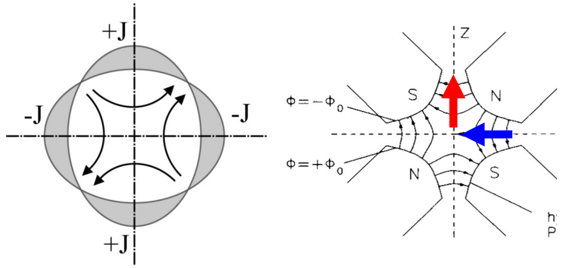




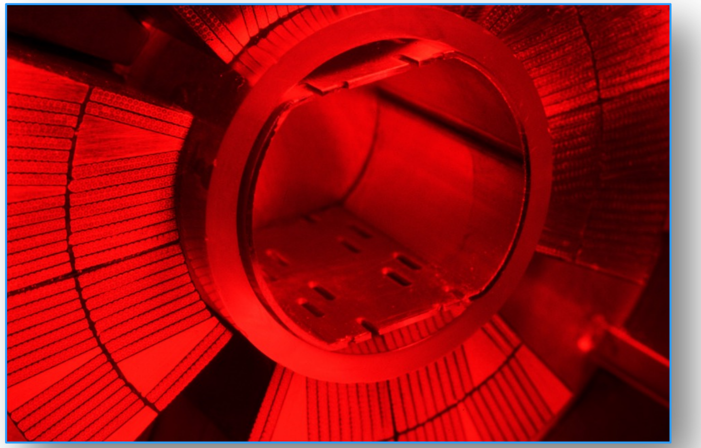
Force tends to “open” the magnet, hence the Austenitic steel collars

The main quadrupoles





The linear magnet lattice can be parameterized by a ‘varying spring constant’, K=K(s).



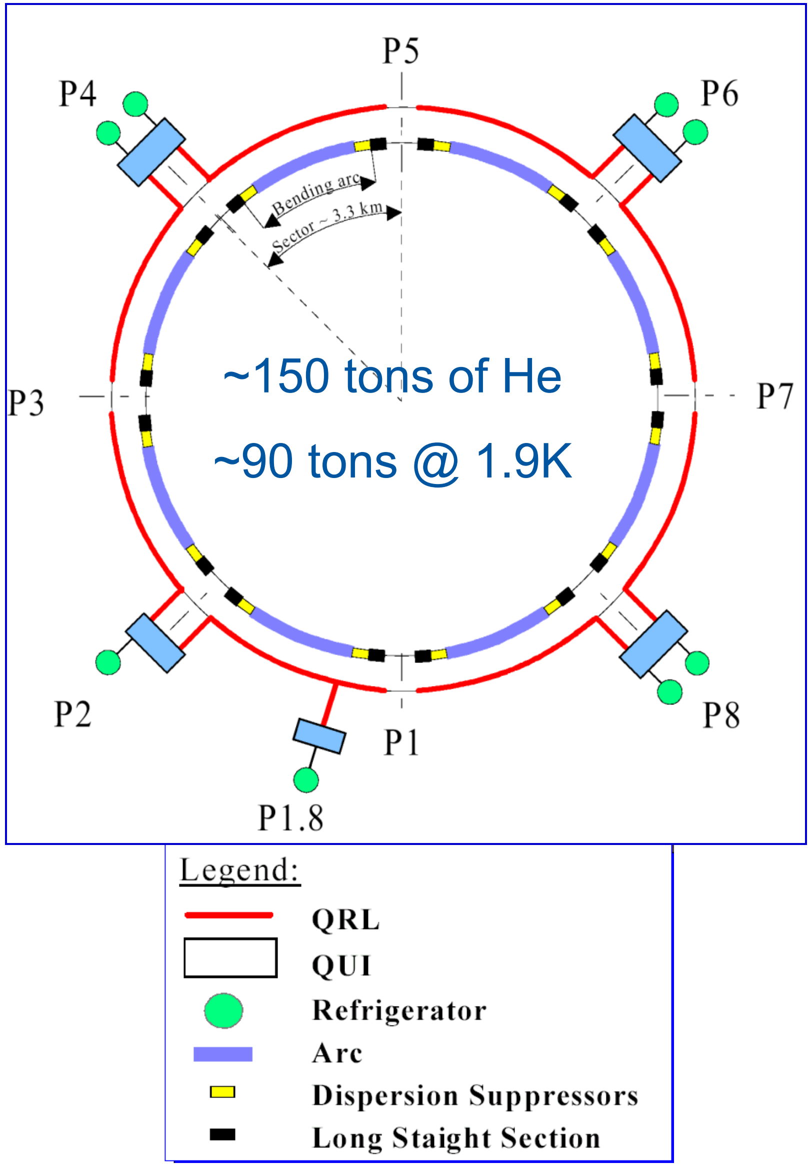
K(s) describes the distribution of focusing strength along the lattice and is periodic.

$$\frac{d^2x}{ds^2} + K(s)x = 0$$

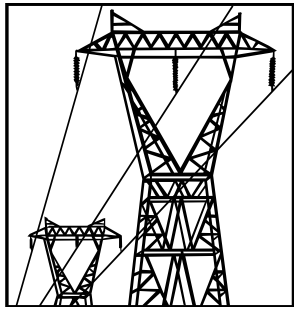
The Hill’s equation

(and similarly for the vertical plane y)

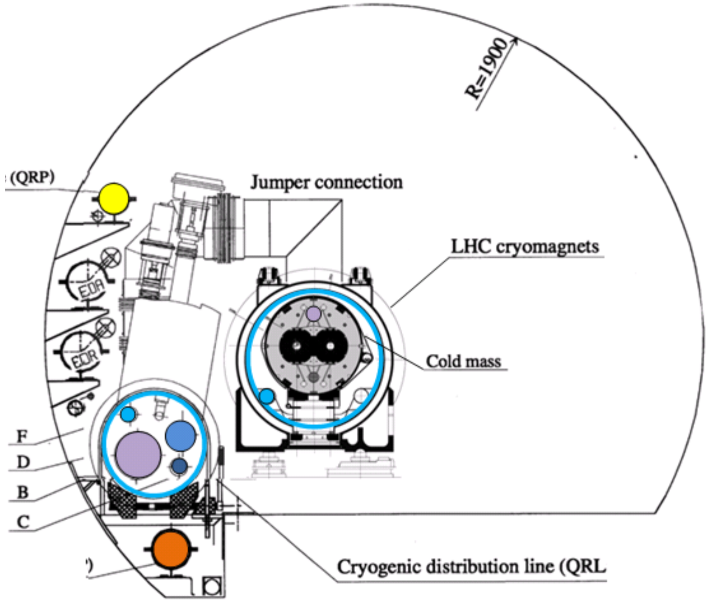
The cryogenic system



Electric power consumption
24 GW/month
Cost **1.2 MCHF/month**



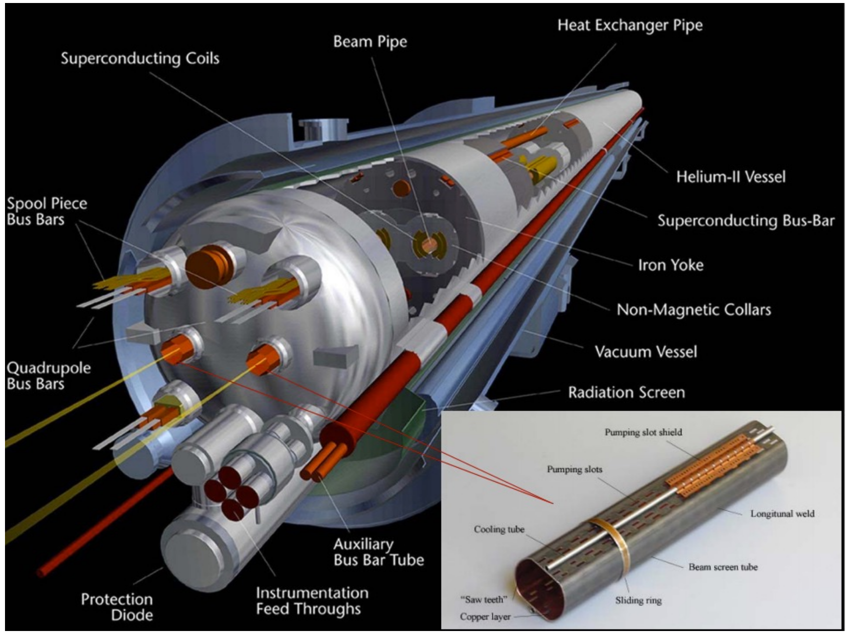
Helium and nitrogen
150 tons of He – **4 MCHF**
10’000 tons of LN2 – **1.6 MCHF**



The vacuum system

The insulation vacuum

- Between the cryomagnet and its cryostat – both wrapped with superinsulation
- Before the cooldown this vacuum is pumped out to **10^{-1} Pa**
- The cooldown will bring a huge additional pumping of the water up to **10^{-4} Pa**

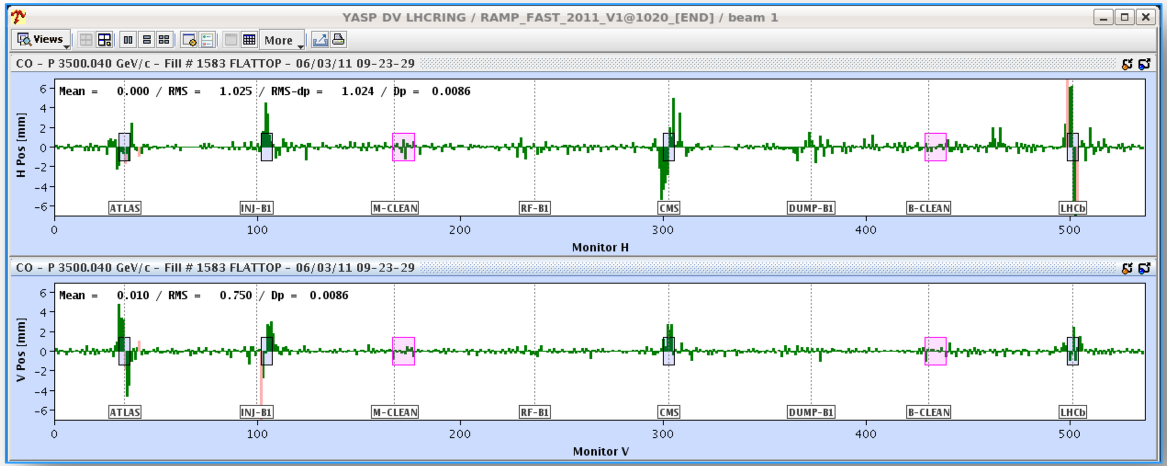


The beam vacuum

- It aims at reducing beam-gas interactions, responsible for:
  - Machine performance limitations
  - Background to the experiments
- Innovative conceptual design with "beam screen" to absorb the heat load
- Pressure < **10^{-10} Pa** (10 times lower than on the Moon) – **ULTRAHIGH VACUUM**

The beam instrumentation (our eyes)

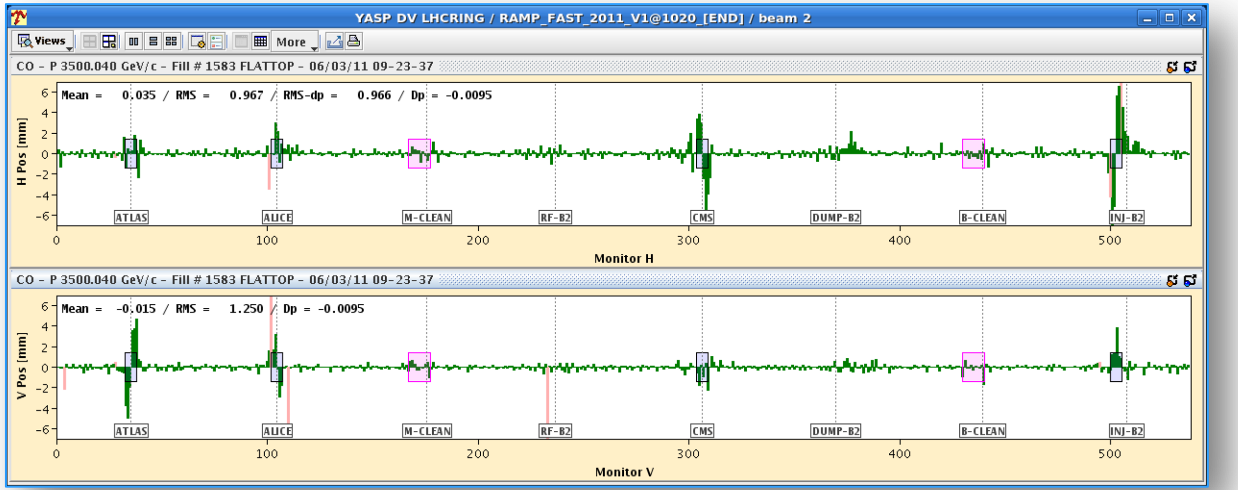
Beam 1



Beam Position Monitors

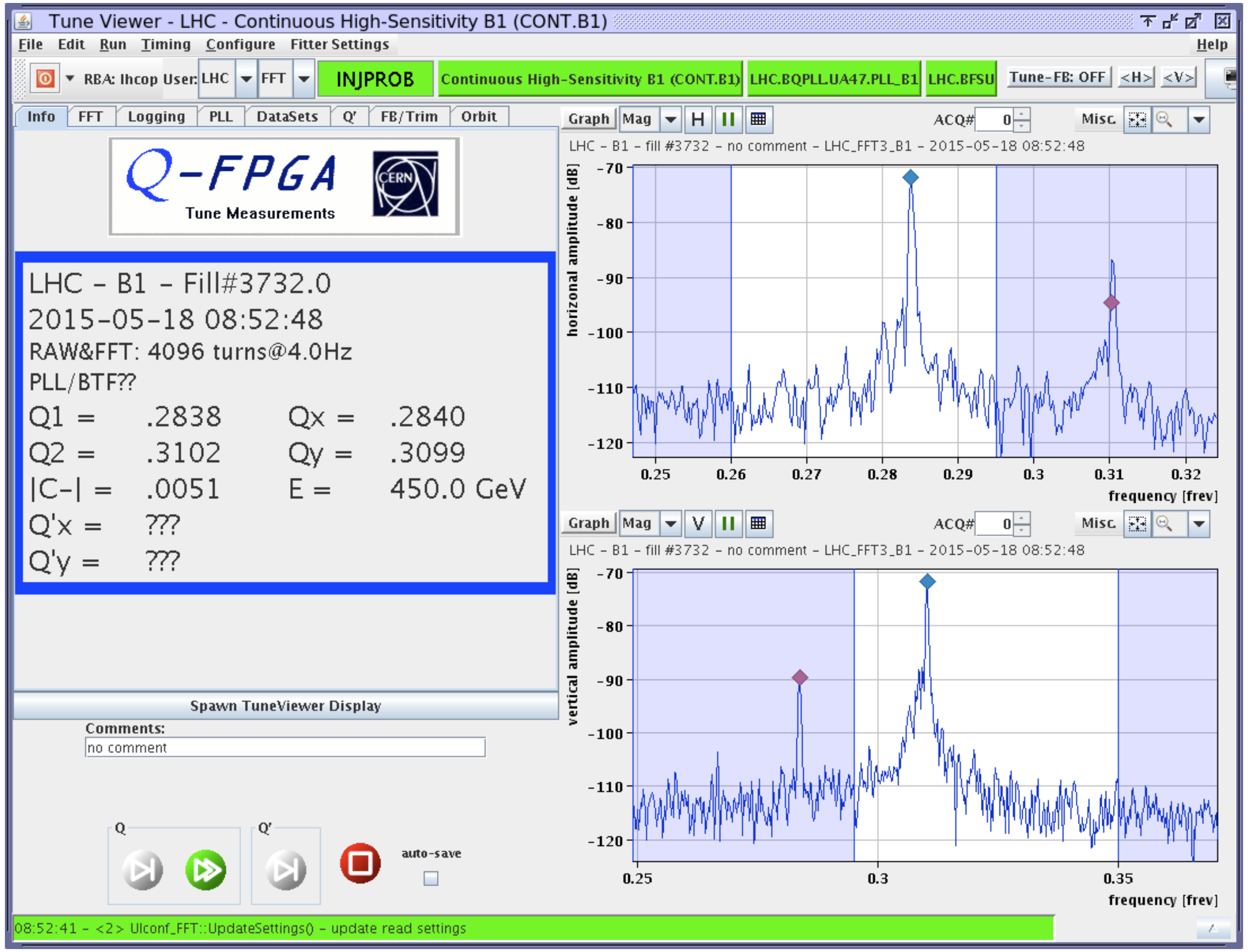
Beam 2

Typical orbits

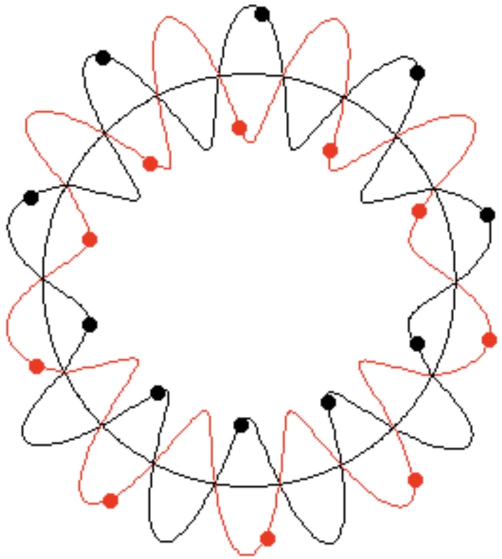


- ***2176 position readings***
- ***Excellent availability***

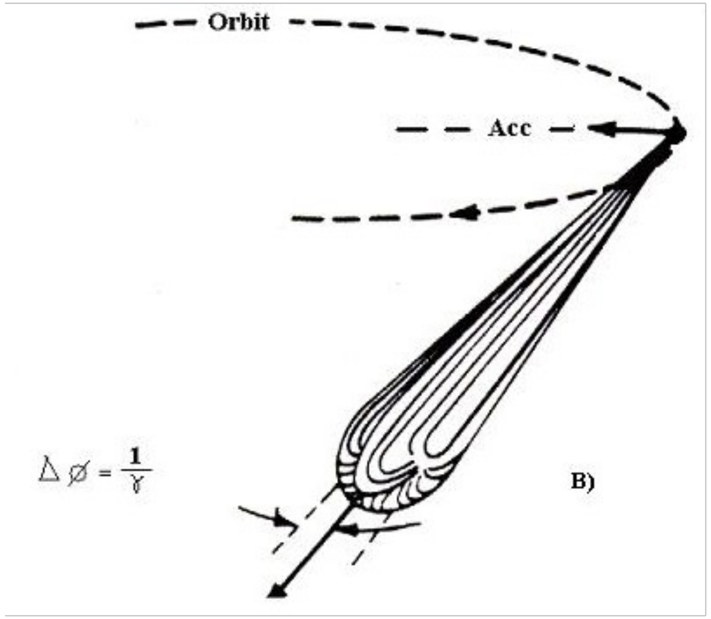
The beam instrumentation (our eyes)



Base Band Tune



The beam instrumentation (our eyes)



Beam Synchronous Radiation Telescope

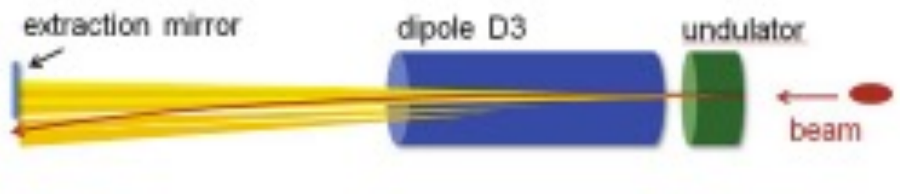
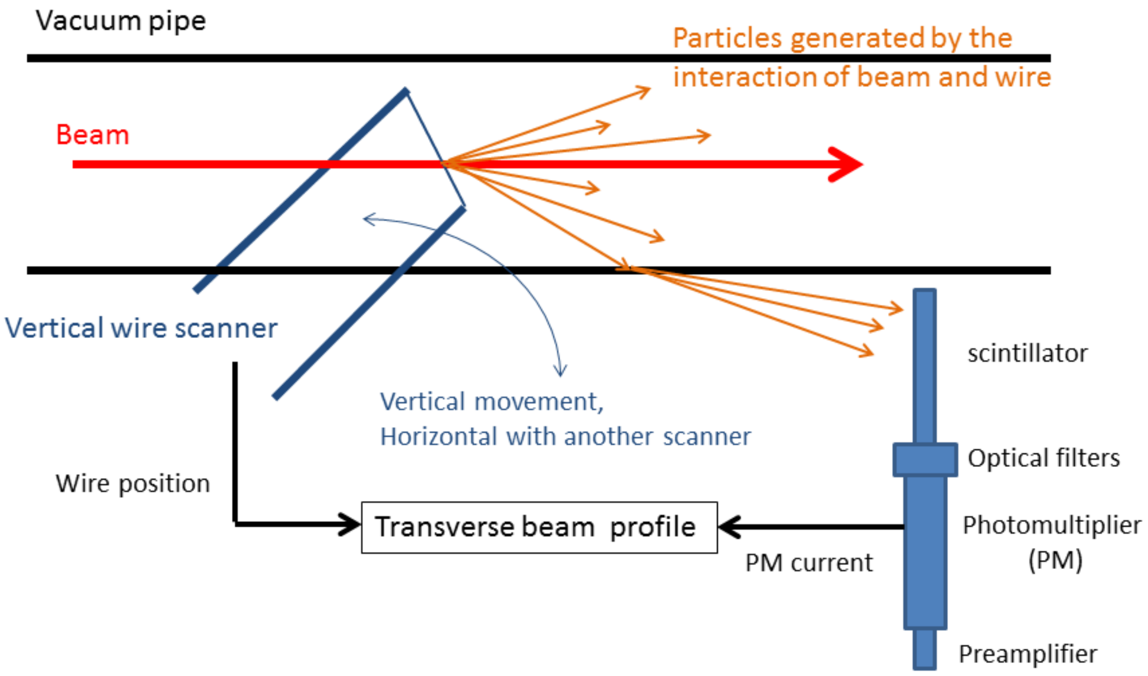
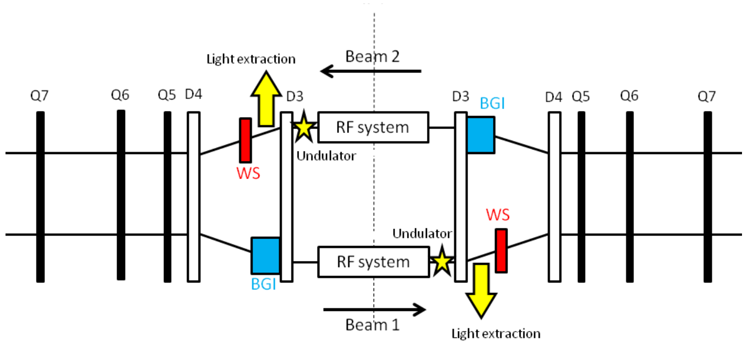


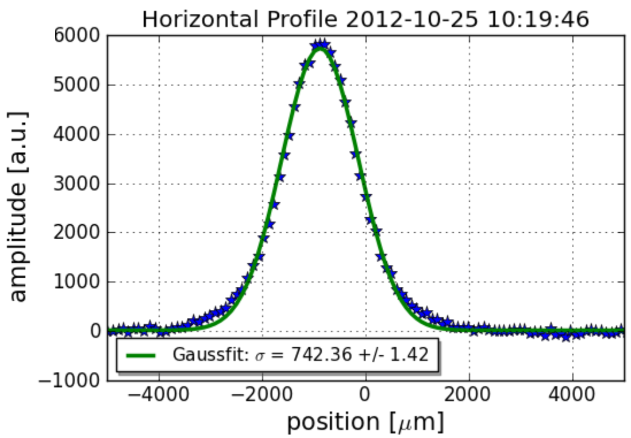
Figure 1: Sketch of the BSRT light sources.

The beam instrumentation (our eyes)



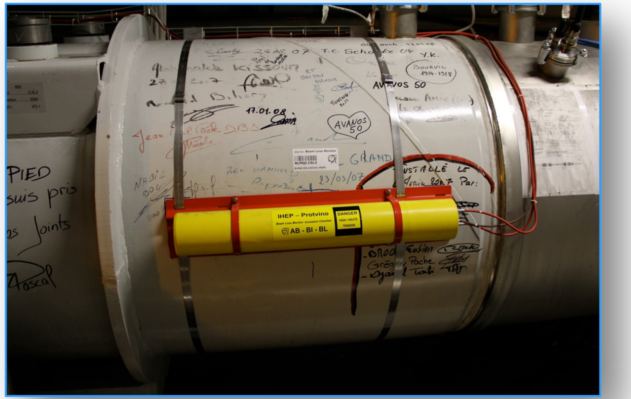
Wire Scanner





The beam instrumentation (our eyes)

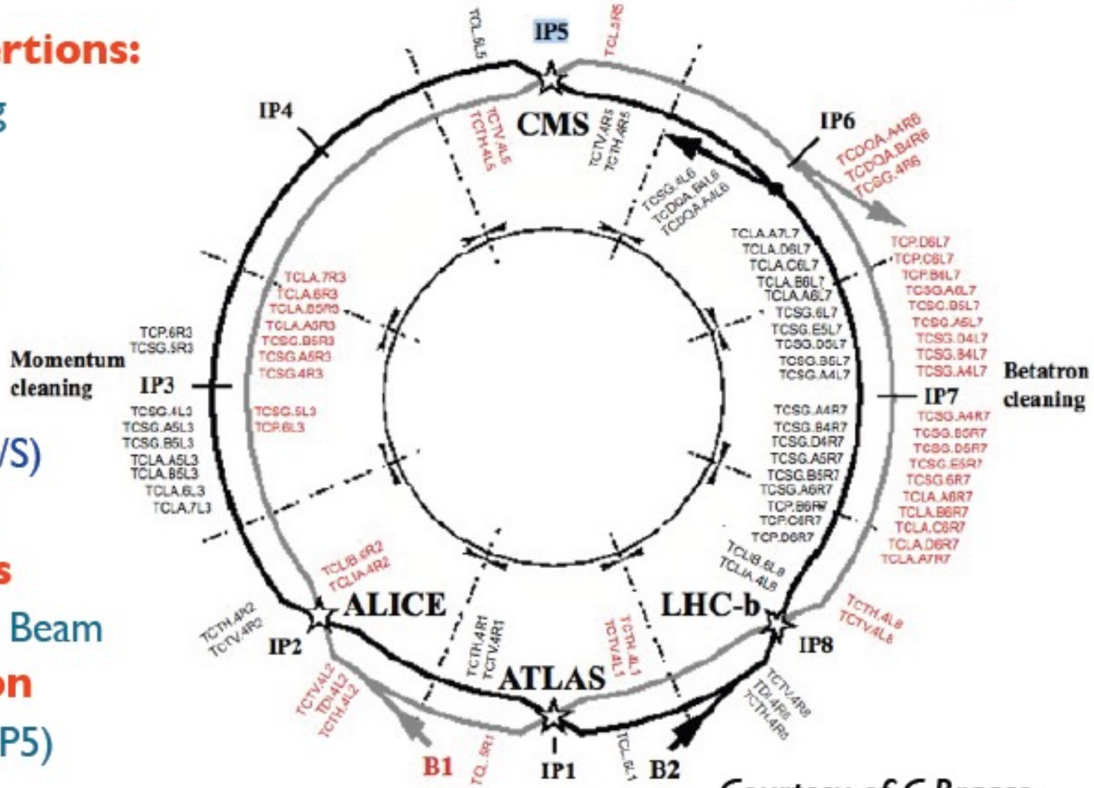
Beam Loss Monitors



- **Around 4000 ionization chambers protect the LHC superconducting magnets against quenches and damage from beam loss.**
- **The system has been designed with high safety standard (SIL3) and is an essential component of the LHC Machine Protection System.**
  - Smallest loss integration interval is 40 microseconds => ~½ LHC turn.
  - The BLM system will dump if a SINGLE monitor goes above threshold.

LHC Collimation Layout

- **Two warm cleaning insertions:**
  - IR3: momentum cleaning
    - 1 Primary (H)
    - 4 Secondaries (H/S)
    - 4 Shower Abs. (H/V)
  - IR7: betatron cleaning
    - 3 Primaries (H/V/S)
    - 11 Secondaries (H/V/S)
    - 5 Shower Abs. (H/V)
- **Local cleaning at triplets**
  - 8 tertiaries: 2 per IP per Beam
- **Physics debris absorption**
  - 2 TCL (1 per beam IP1/IP5)



Courtesy of C.Bracco

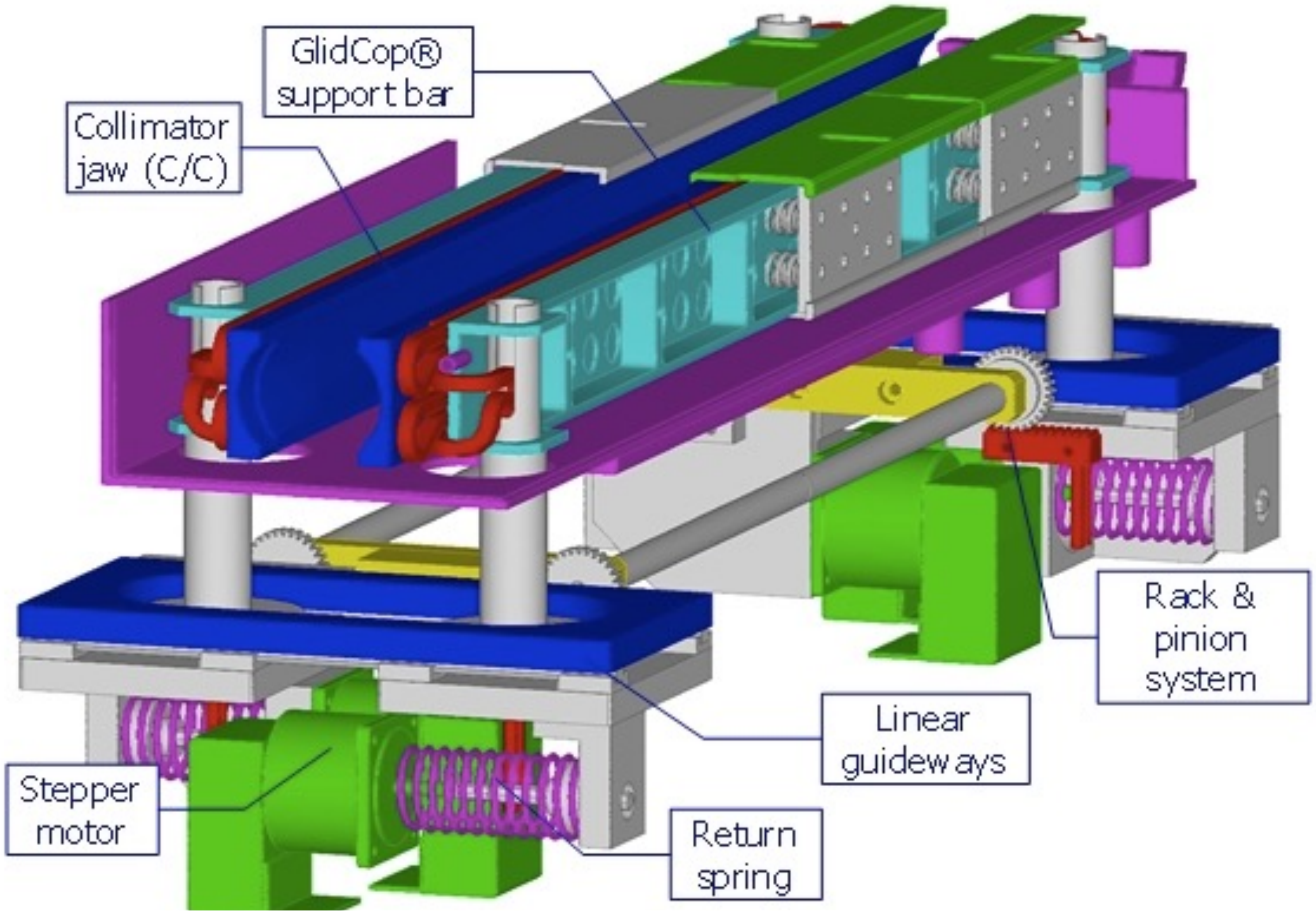
8 passive absorbers for warm magnets in IP3/IP7

Transfer lines (13 collimators)

Injection and dump protection (10 collimators)

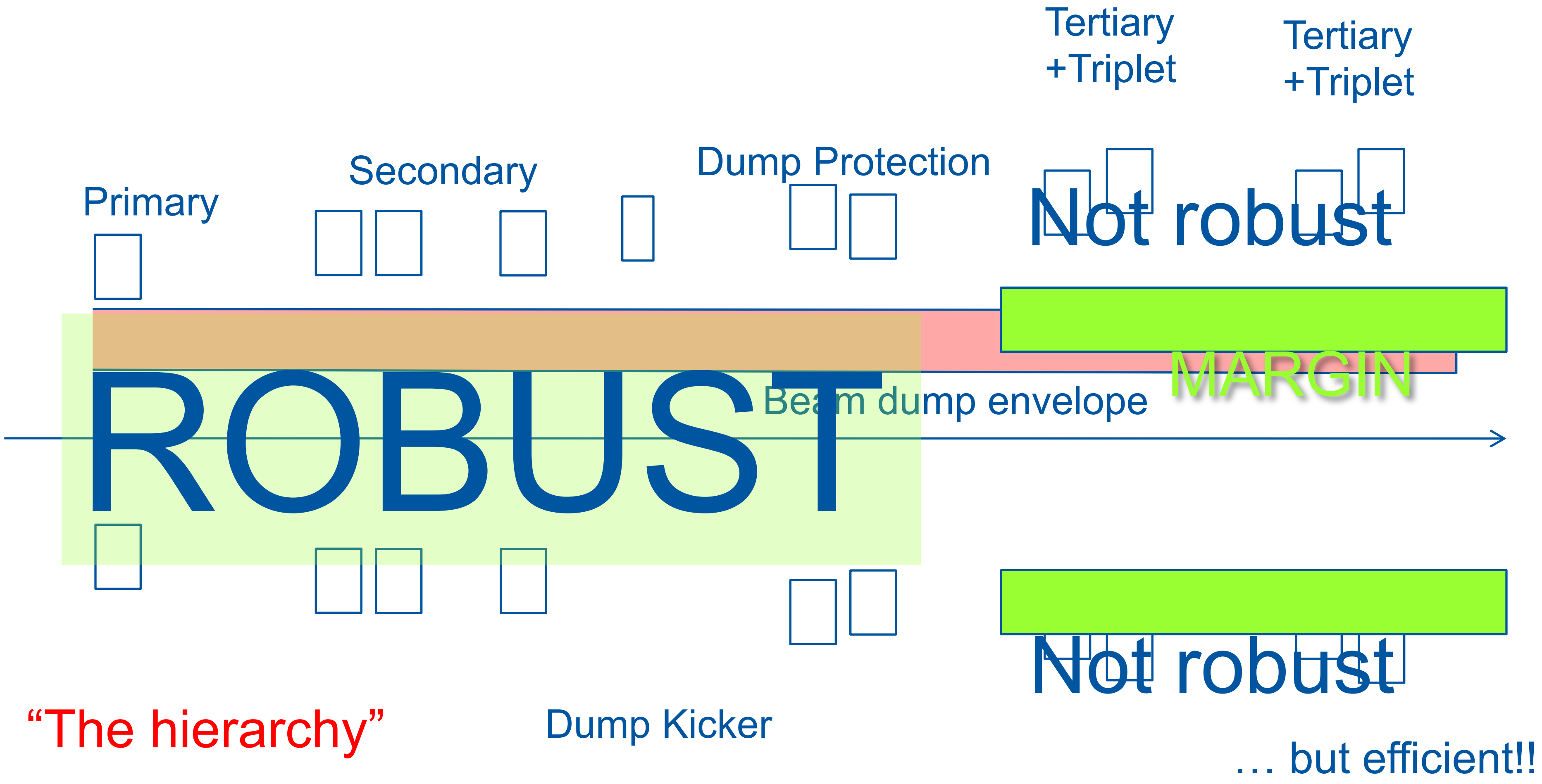
Total of 108 collimators (100 movable)

The Collimation System



The Collimation System

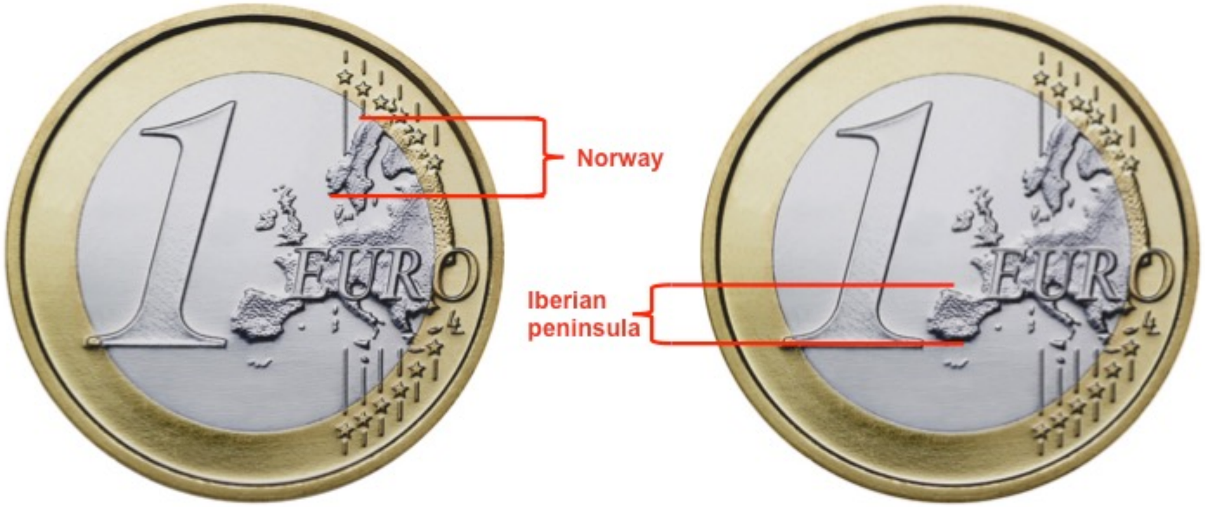
- **Collimation is set up with multi-stage logic for cleaning and protection**
- **Let's look in normalized phase space, talking in nominal sigmas:**



The Collimation System

- **The hierarchy must be respected at all times.**
- **The collimators and protection devices are positioned with respect to the closed orbit. Therefore the closed orbit must be in tolerance at all times all along the cycle…REPRODUCIBILITY IS ESSENTIAL!**

- Orbit feedback mandatory
- Interlock on orbit position mandatory



Intermediate settings:
~3.1 mm gap at primary collimators

Tight settings:
~2.2 mm gap at primary collimators

The beam energy

2808 bunches, 1.15 10^{11} protons per bunch

Energy per beam ~ 360 MJ


TGV @ 150 km per hour

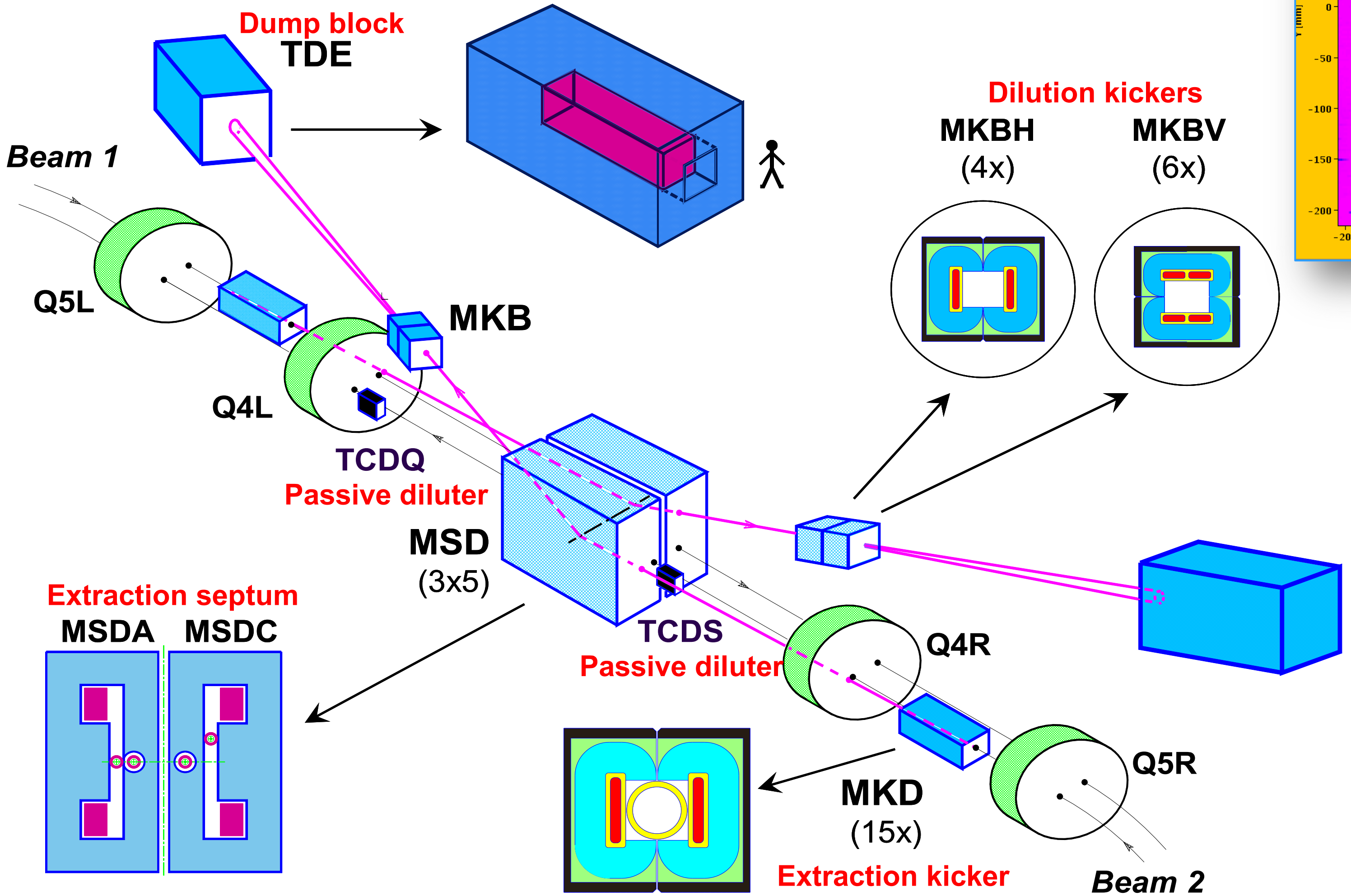

British aircraft carrier at 12 knots

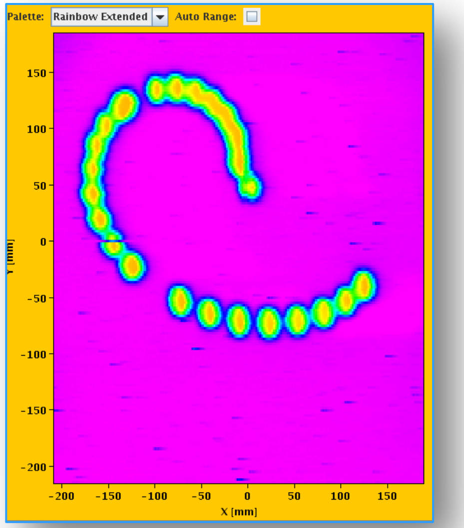

Boeing 747 at take-off

…concentrated in the dimension of a hair!!

…sent through a very cold, dark and small hole!

The beam dump system

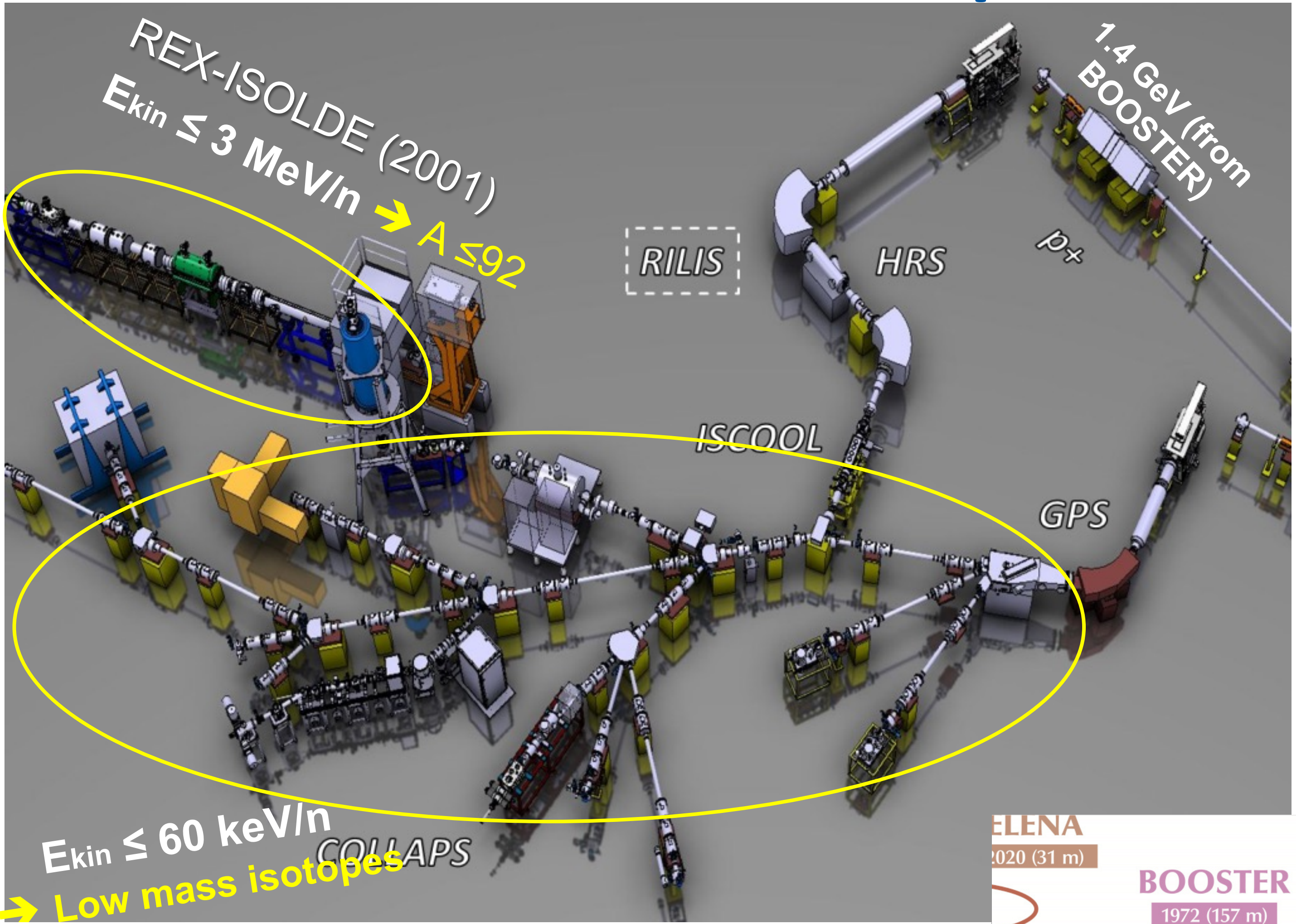




It must be absolutely reliable…

ISOLDE Synchrocyclotron: 1967-1990
ISOLDE PSB: 1992

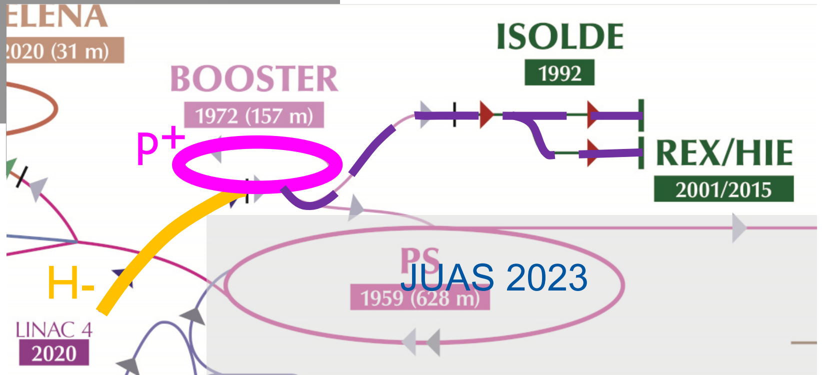
PSB Experimental Areas: ISOLDE



Solid and liquid target materials ➔ wide spectrum of radioactive isotopes up to *A* =< 92.
Radioactive isotopes are produced via proton-induced target fragmentation, spallation and fission reactions

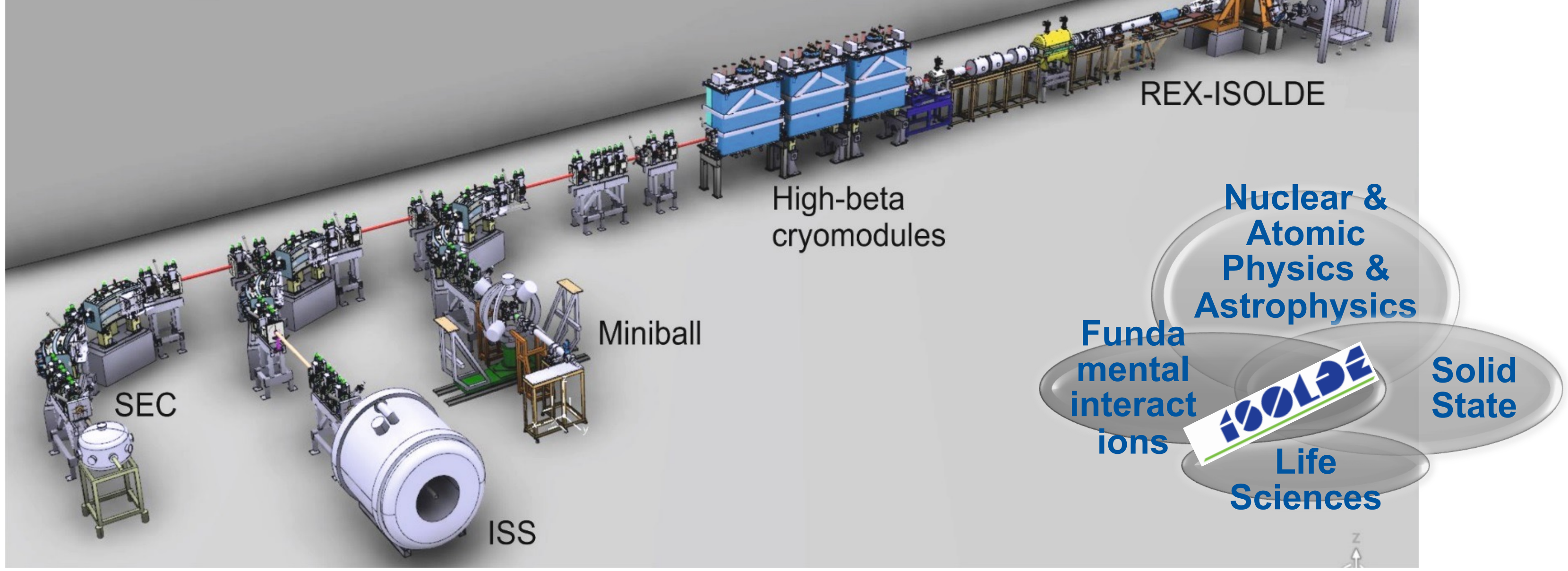
GPS: Global Purpose Separator
HRS: High Resolution Separator
HIE-ISOLDE: High Intensity and Energy ISOLDE

In 2017 we celebrated 50 years of physics at ISOLDE
(Isotope mass Separator On-Line Device)
➔ on October 16, 1967 the first radioactive beam



Next generation of nuclear physics:

HIE-ISOLDE (+SC RF): Ekin ≤ 10 MeV/n ➔ A ≤200



MEDICIS (Medical Isotopes Collected from ISOLDE)

➔ wide range of radioisotopes, some of which can be produced only at CERN thanks to the unique ISOLDE facility, for hospitals and research centres in Switzerland and across Europe.

➔ devise and test unconventional radioisotopes with a view to developing new approaches to fight cancer

Plasma wake acceleration

SPS Experimental Areas: AWAKE

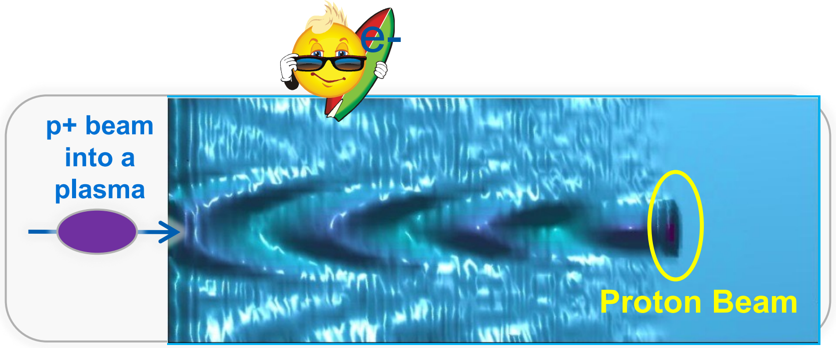
A “wake” is created when something is quickly pushed through a f
or gaseous substance, like a boat cutting through water. In this ca
the substance is “plasma”.

“Acceleration” simply refers to the effect: when a bunch of particles is placed behind a plasma wake, it accelerates, like a wake surfer.

There are a variety of ways to create plasma wake-field acceleration (PWFA): by sending a laser beam or a beam of particles

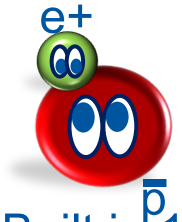
The concept was developed in an audacious 1979 paper by scientists Toshiki Tajima and John Dawson, both then at the University of California, Los Angeles.

Proof-of-principle:



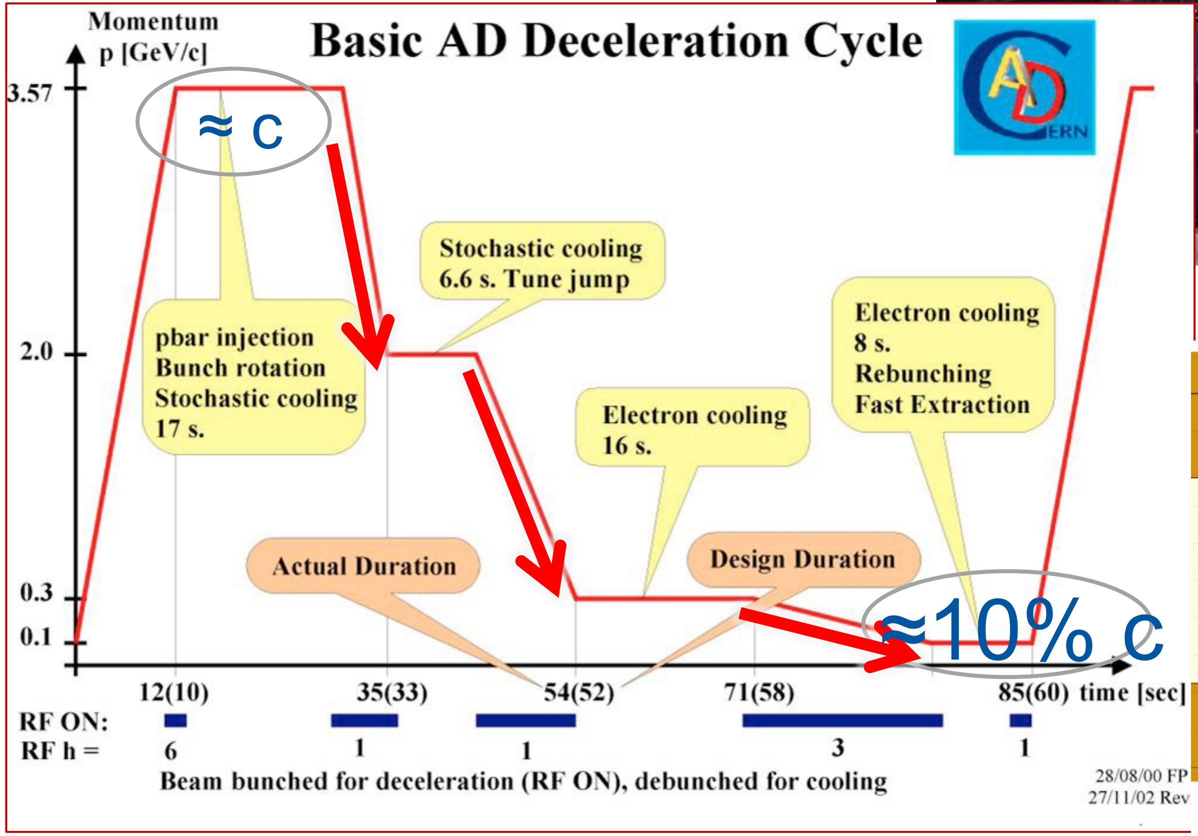
→ Inject 10-20 MeV electron beam
→ acceleration of electrons to **multi-GeV energy range** in the wakefield driven by protons.

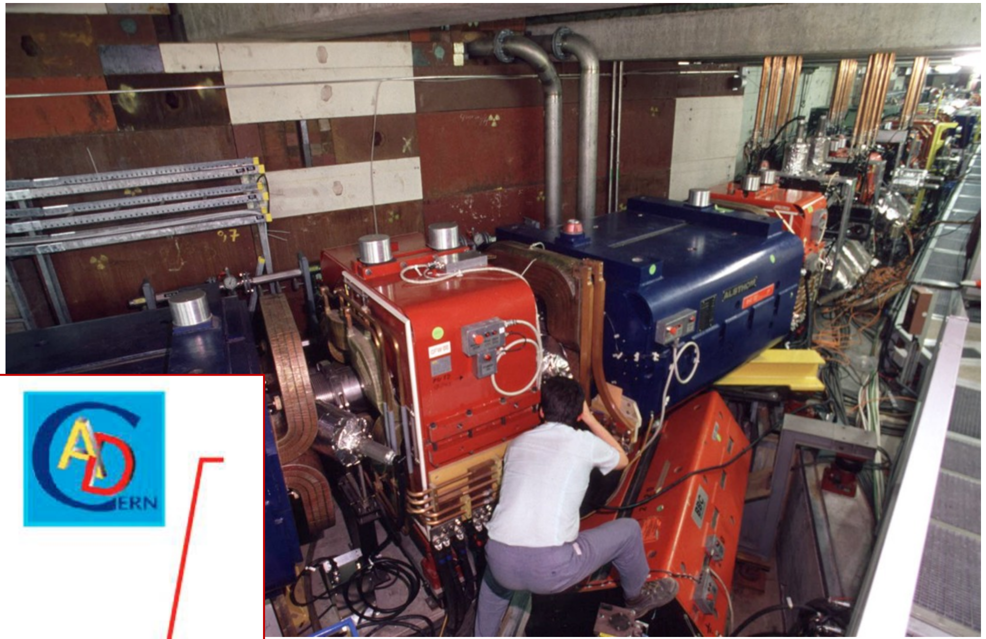
→ first proton driven PWA experiment world-wide

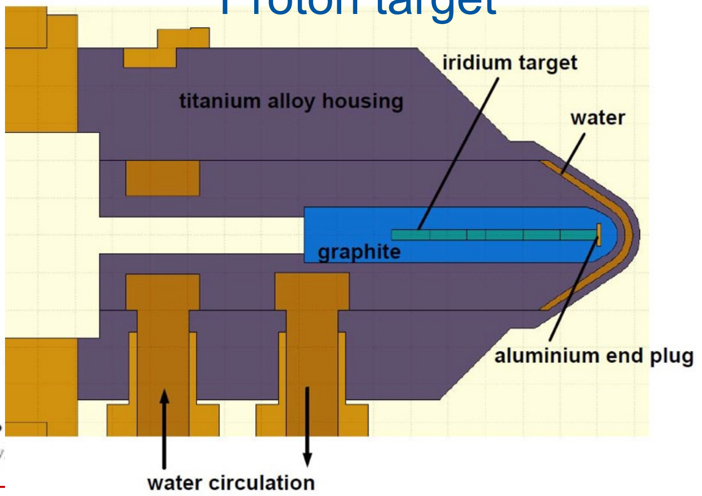


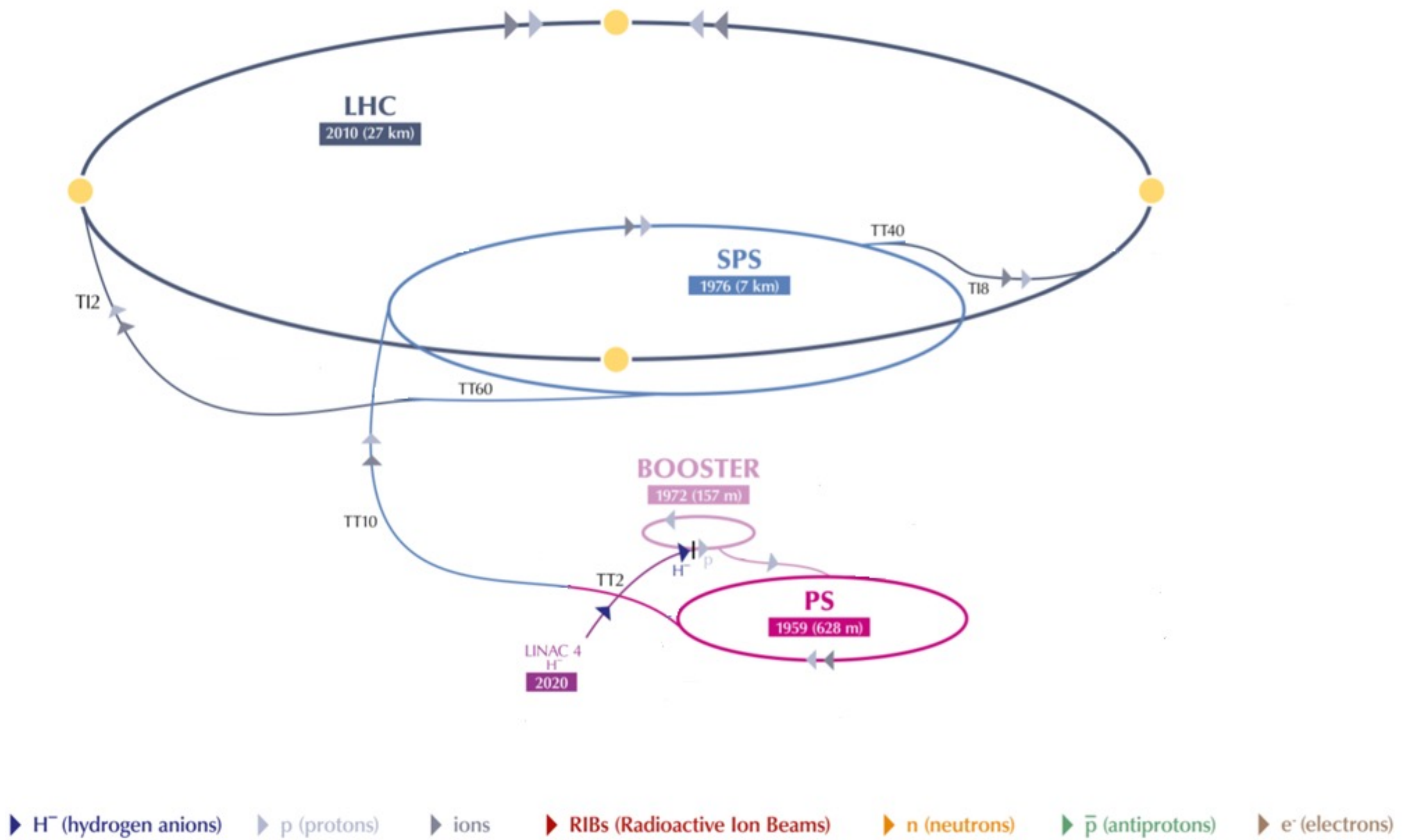
Antiproton Decelerator : AD

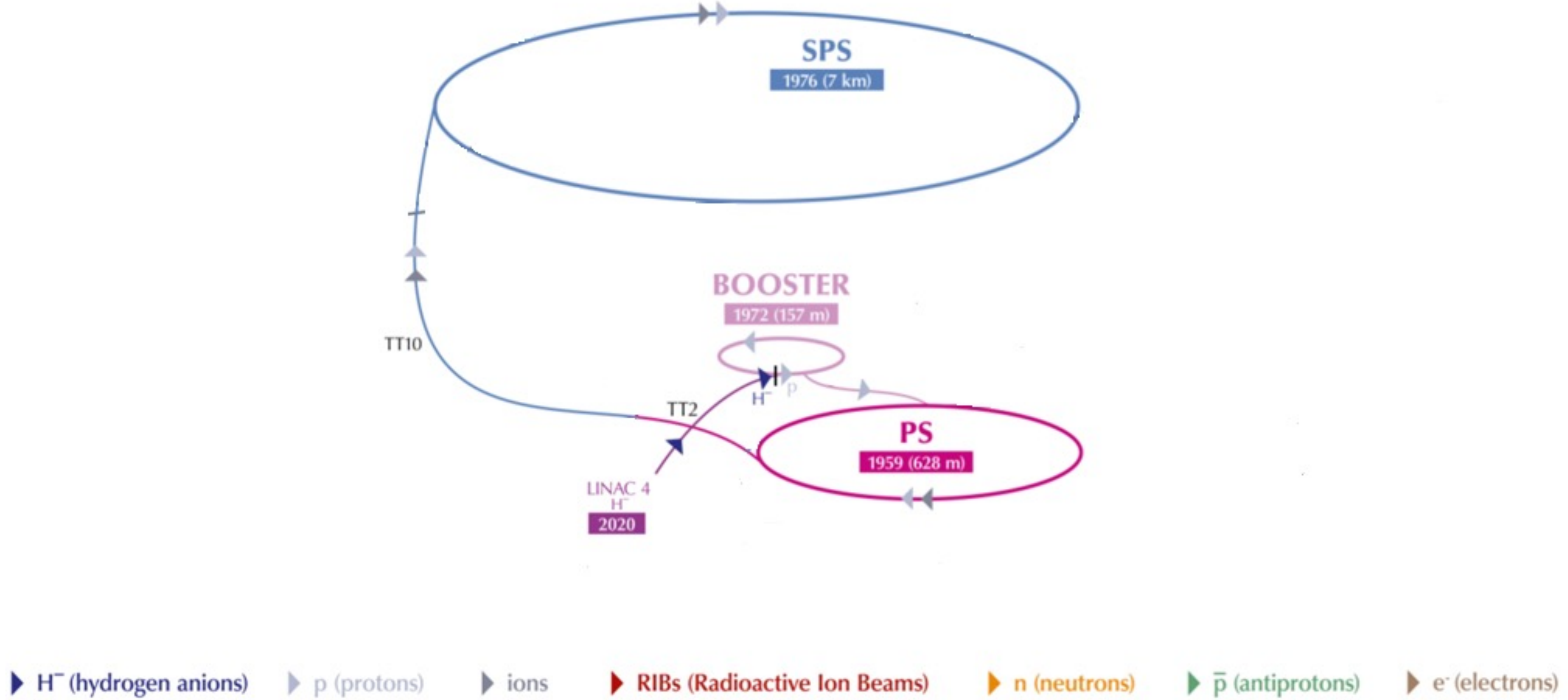
Built in 1999 (from the old AC)
26 GeV/c PS Proton beam produces $\bar{p}$ (1 in 10^7) which are focused and captured in the AD and decelerated to 100 MeV/c (5.3 MeV)








LHC
2010 (27 km)
SPS
1976 (7 km)
TT40
TI8
TI2
TT60
TT10
BOOSTER
1972 (157 m)
H⁻
p
TT2
PS
1959 (628 m)
LINAC 4
H⁻
2020
H⁻ (hydrogen anions)
p (protons)
ions
RIBs (Radioactive Ion Beams)
n (neutrons)
p̄ (antiprotons)
e⁻ (electrons)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1976 (7 km)
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TT10
TT2
H⁻
p
PS
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2020
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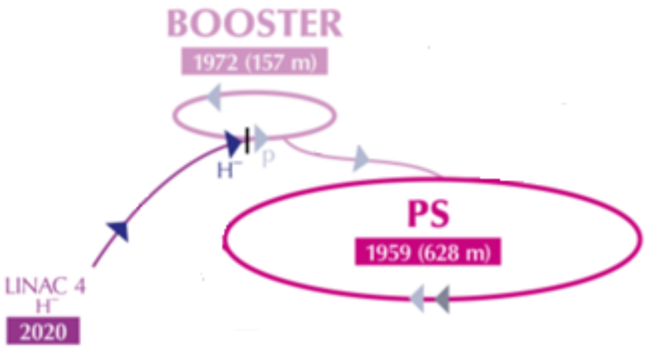
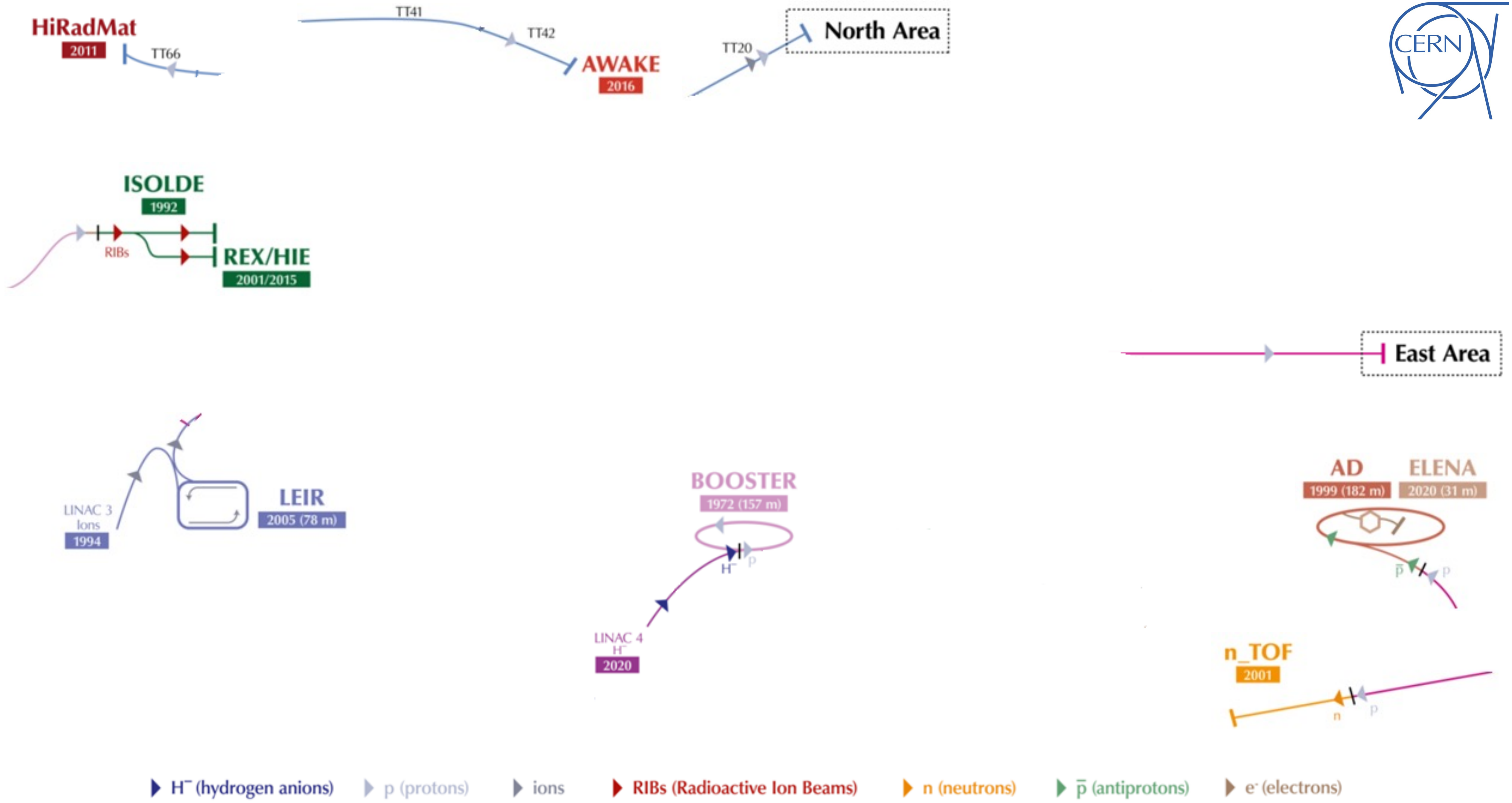
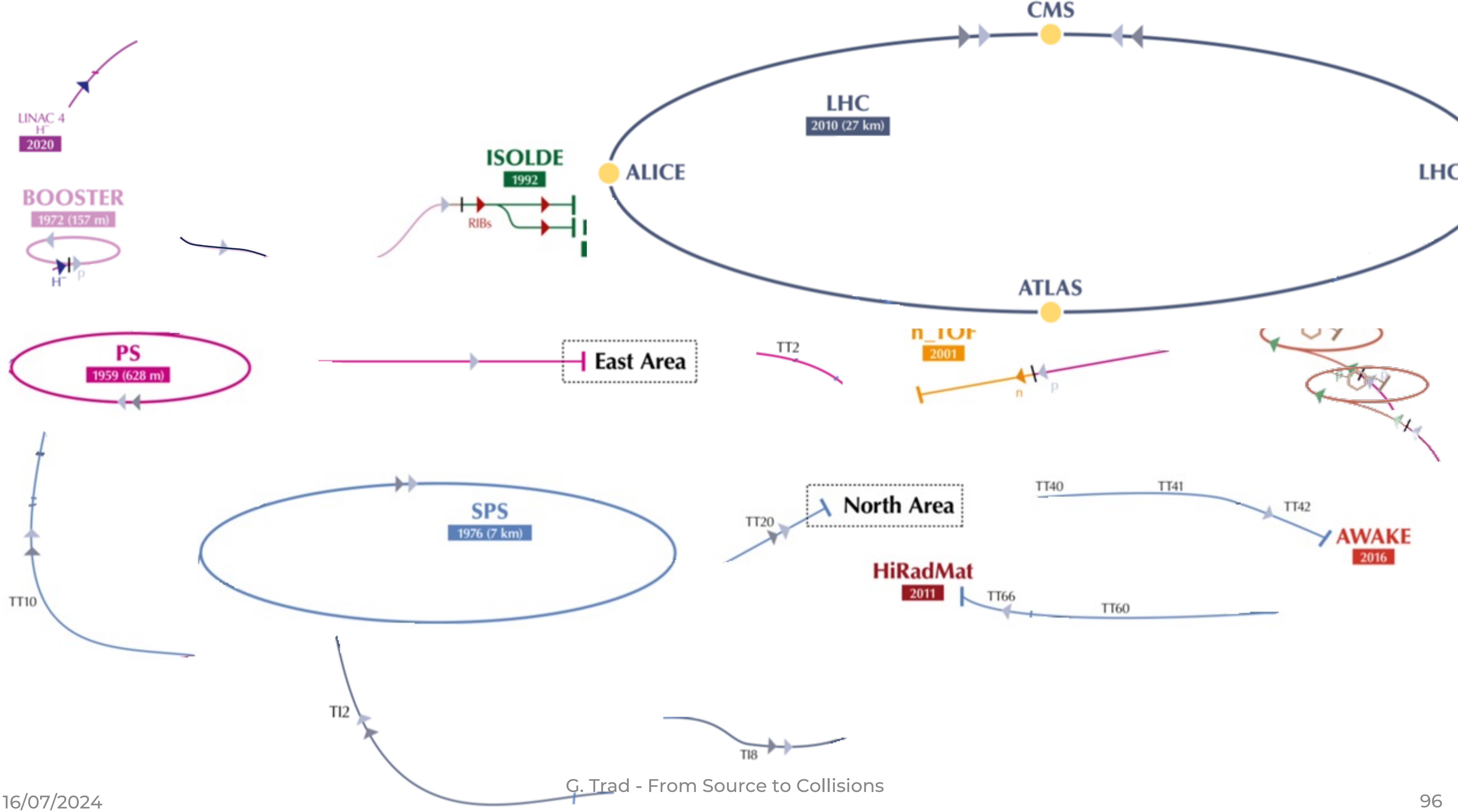


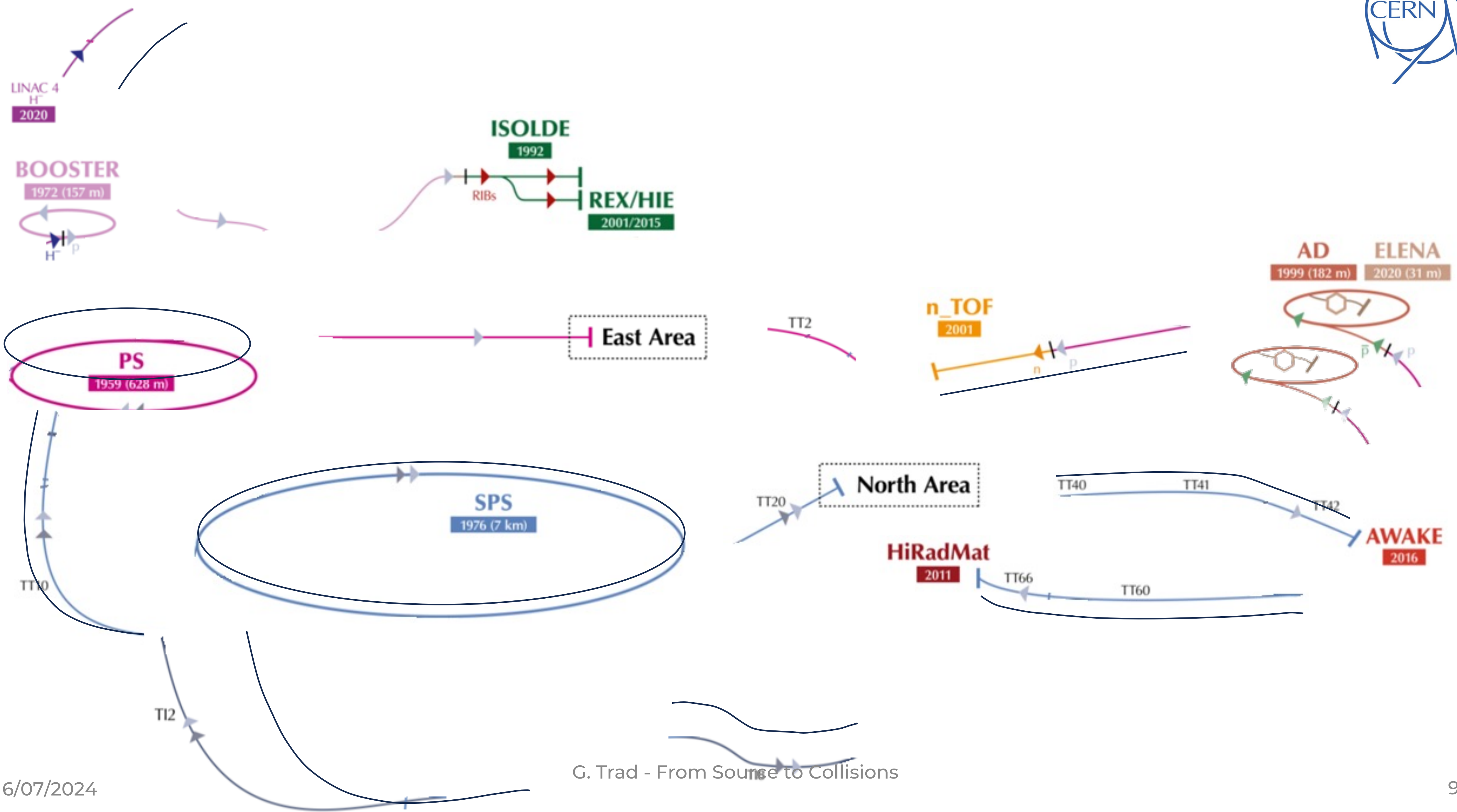
H⁻ (hydrogen anions) p (protons) ions RIBs (Radioactive Ion Beams) n (neutrons) p̄ (antiprotons) e⁻ (electrons)



HiRadMat
2011
TT66
TT41
TT42
AWAKE
2016
TT20
North Area
ISOLDE
1992
RIBs
REX/HIE
2001/2015
East Area
LINAC 3
Ions
1994
LEIR
2005 (78 m)
BOOSTER
1972 (157 m)
H^-
p
LINAC 4
H^-
2020
AD
1999 (182 m)
ELENA
2020 (31 m)
$\bar{p}$
p
n_TOF
2001
n
p
H^- (hydrogen anions)
p (protons)
ions
RIBs (Radioactive Ion Beams)
n (neutrons)
$\bar{p}$ (antiprotons)
e^- (electrons)

▶ H^- (hydrogen anions) ▶ p (protons) ▶ ions ▶ RIBs (Radioactive Ion Beams) ▶ n (neutrons) ▶ $\bar{p}$ (antiprotons) ▶ e^- (electrons)


CMS
LHC
2010 (27 km)
ALICE
ATLAS
LINAC 4
H^-
2020
BOOSTER
1972 (157 m)
H^-
p
ISOLDE
1992
RIBs
PS
1959 (628 m)
East Area
TT2
2001
n
p
SPS
1976 (7 km)
TT10
TT20
North Area
TT40
TT41
TT42
AWAKE
2016
HiRadMat
2011
TT66
TT60
TI2
TI8



LINAC 4
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2001/2015
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n_TOF
2001
AD
1999 (182 m)
ELENA
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2016
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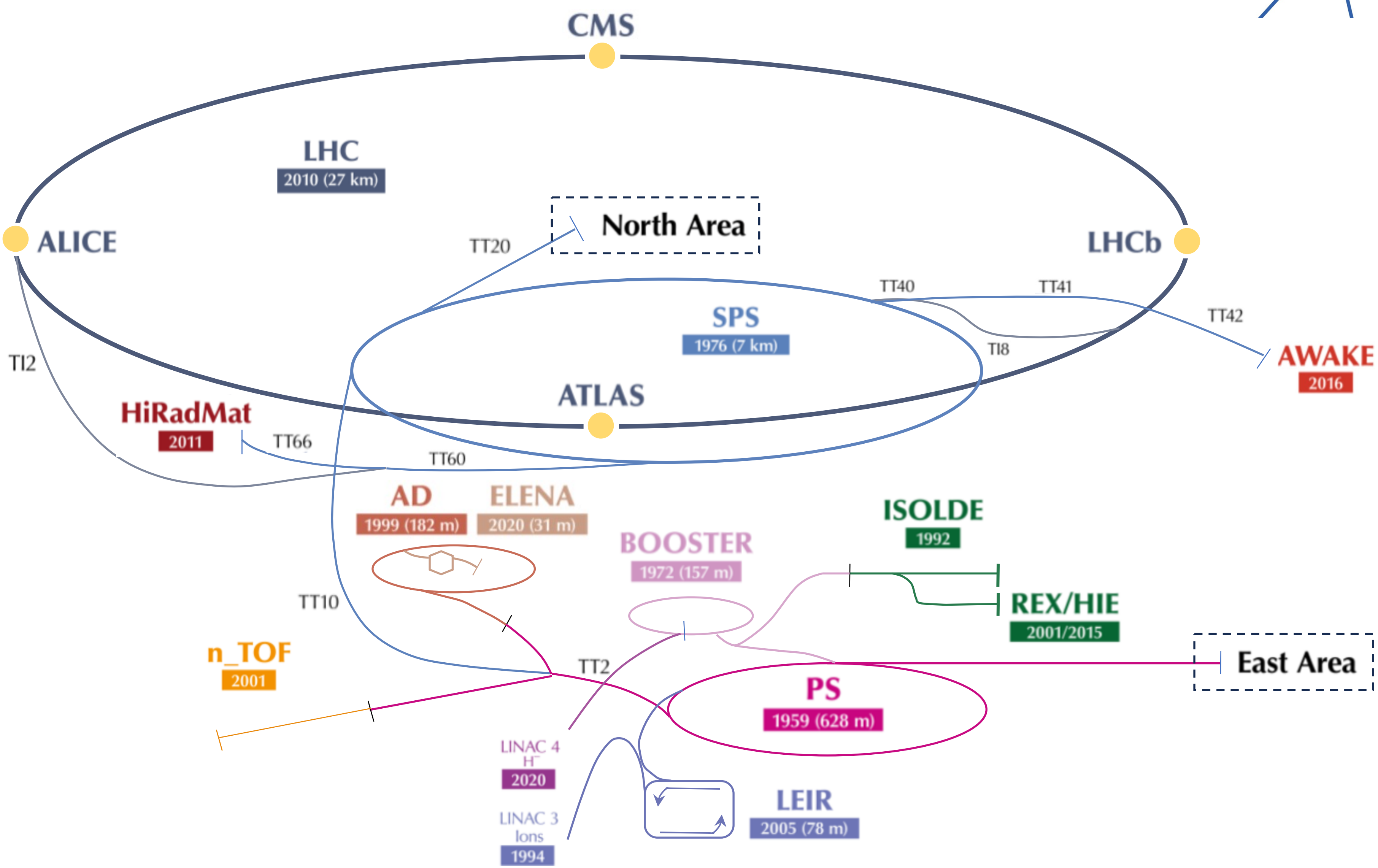
TT66
TT60
TT10
TI2


CMS
LHC
2010 (27 km)
North Area
ALICE
TT20
LHCb
TT40
TT41
SPS
1976 (7 km)
TT42
TI8
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
TT10
REX/HIE
2001/2015
n_TOF
2001
TT2
East Area
PS
1959 (628 m)
LINAC 4
H⁻
2020
LEIR
2005 (78 m)
LINAC 3
Ions
1994

LHC Cryogenics

- → System capacity to remove "heatload" is limited
- → Heatload from beam coupling to accelerator equipment (impedance)
  - Cryo systems by design are dimensioned to deal with it;
- → Heatload from Collisions debris around the Interaction regions
  - Limits maximum instantaneous luminosity at the experiments;
- → Heatload from "e-cloud" (multipacting)
  - Depends on Surface SEY, Bunch intensity, bunch spacing, batch spacing
  - Limits the trains length, total number of bunches, bunch intensity
  - Opens the door to get "creative" with beams; i.e. 8b4e beams

Radiation Around IR

- In high luminosity Interaction points (IP1/IP5) debris from collisions irradiate the machine components (triplets and separation dipoles)

- Total integrated luminosity accumulated may create hot spots that exceed equipment tolerances leading to failure

- Clever solutions tackling the problems to spread the radiation spatially by changing the optics configuration around the IP or change the crossing angle (RP optics!)