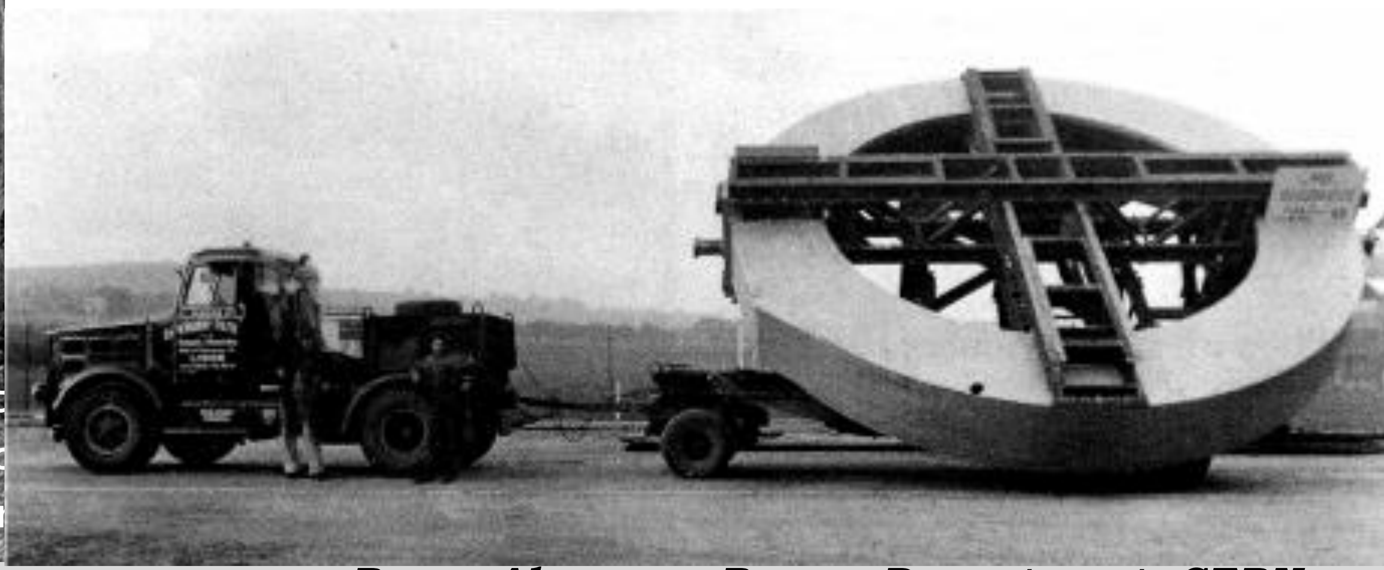
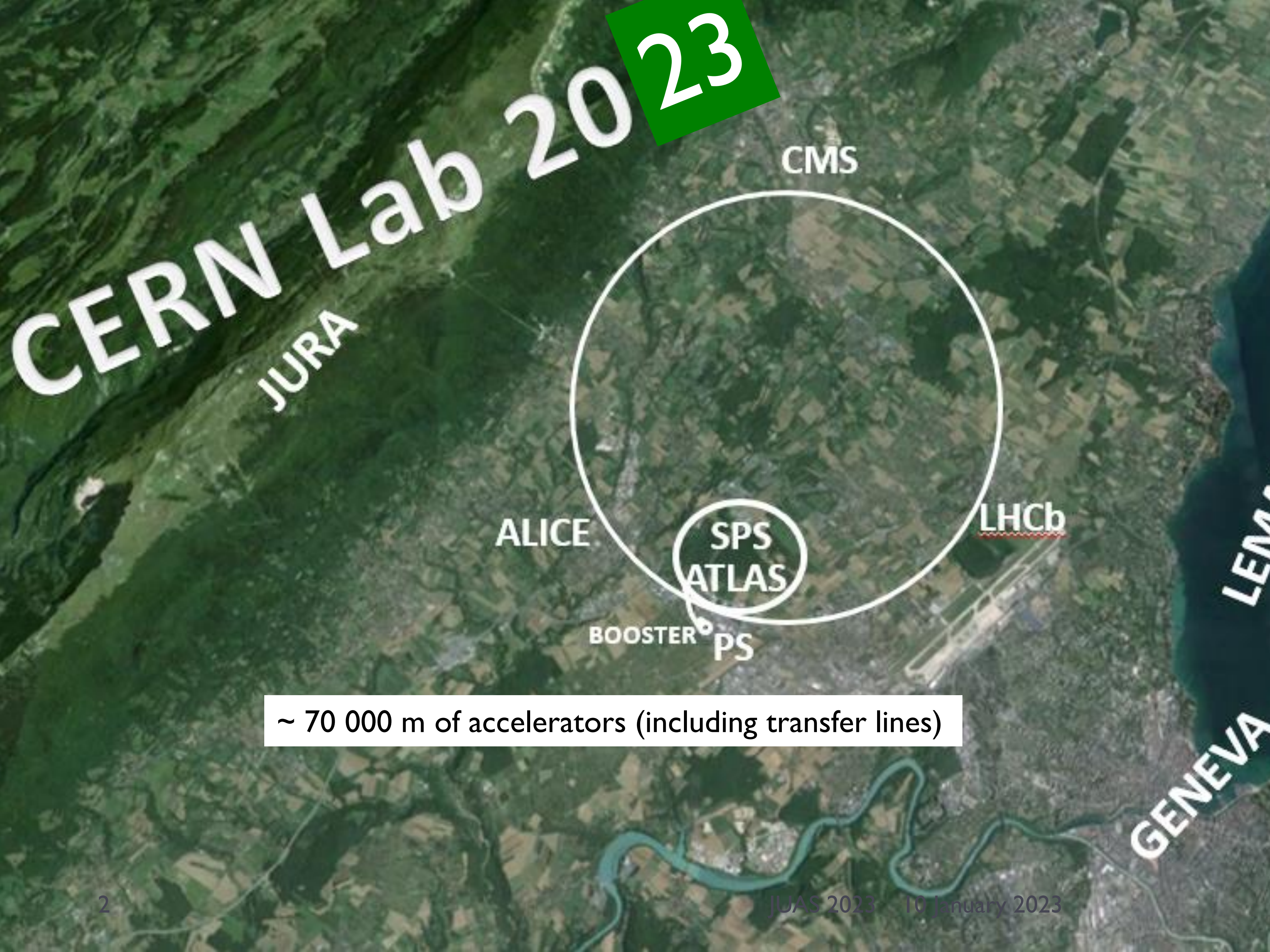
Overview of the CERN Accelerator Complex

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



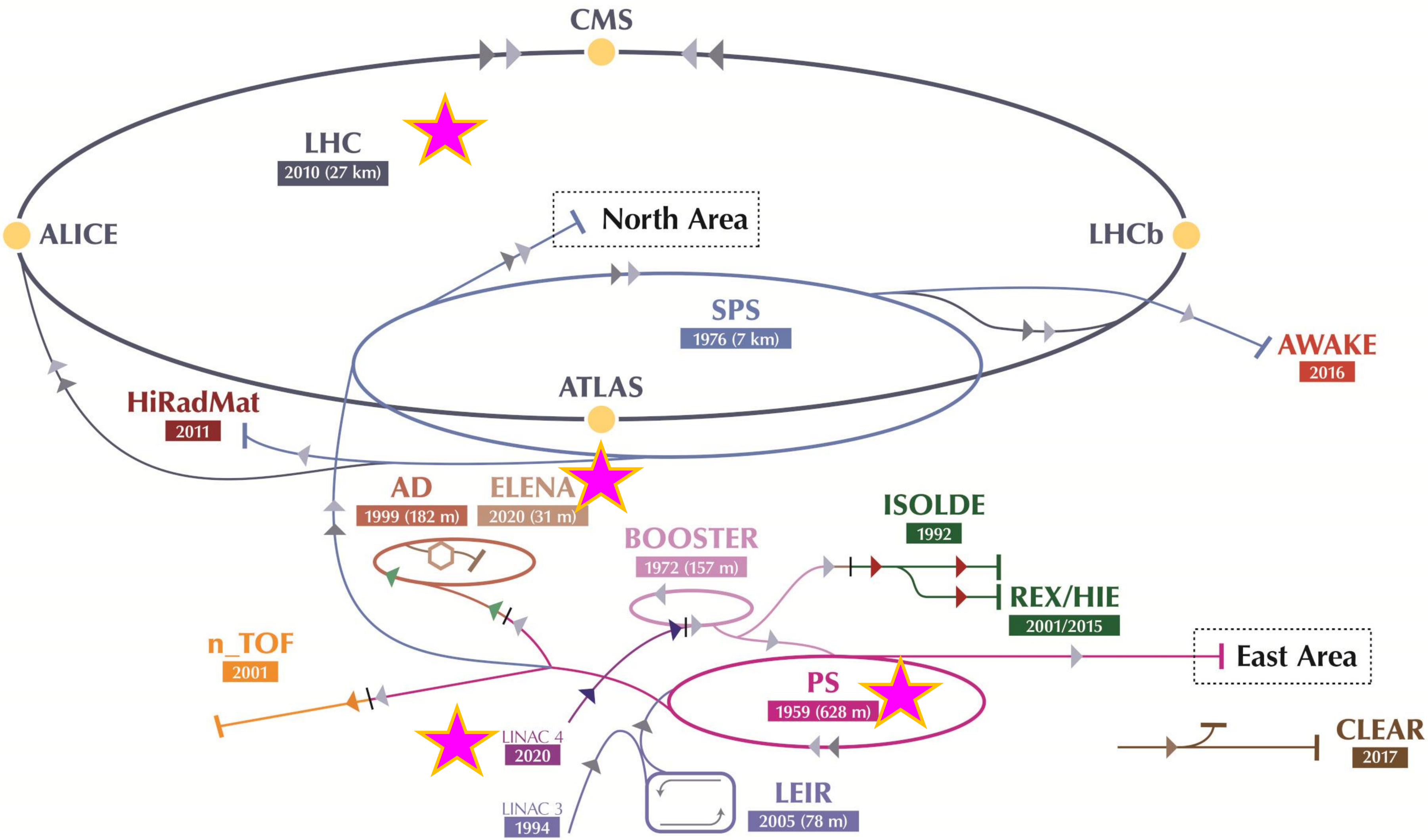
Reyes Alemany, Beams Department, CERN

CERN Lab 2023

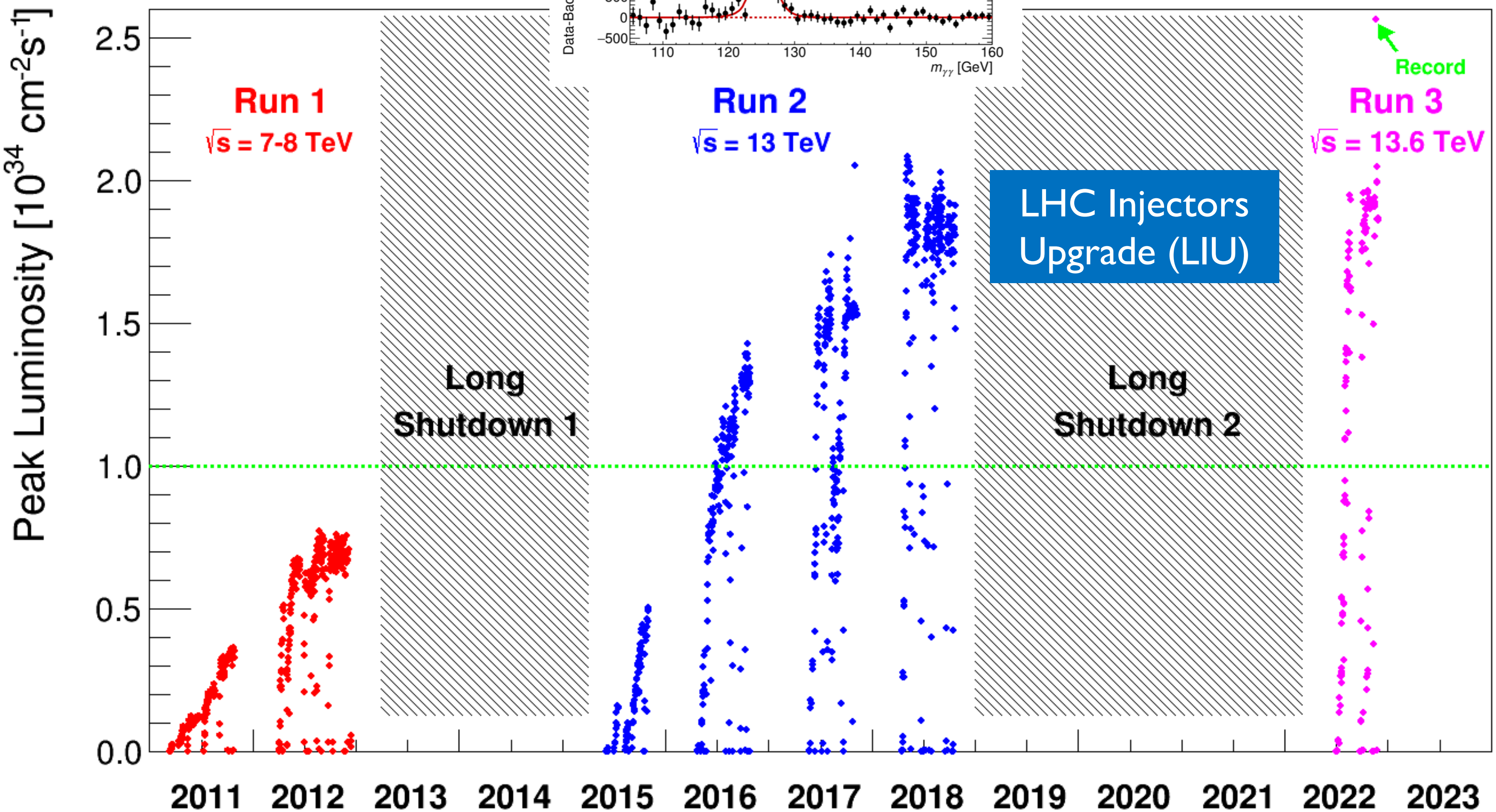


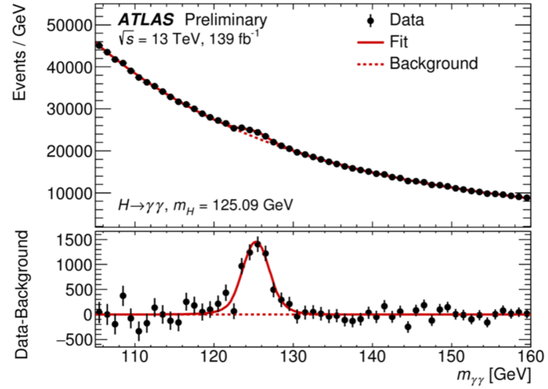
~ 70 000 m of accelerators (including transfer lines)

CERN Accelerator Complex Layout



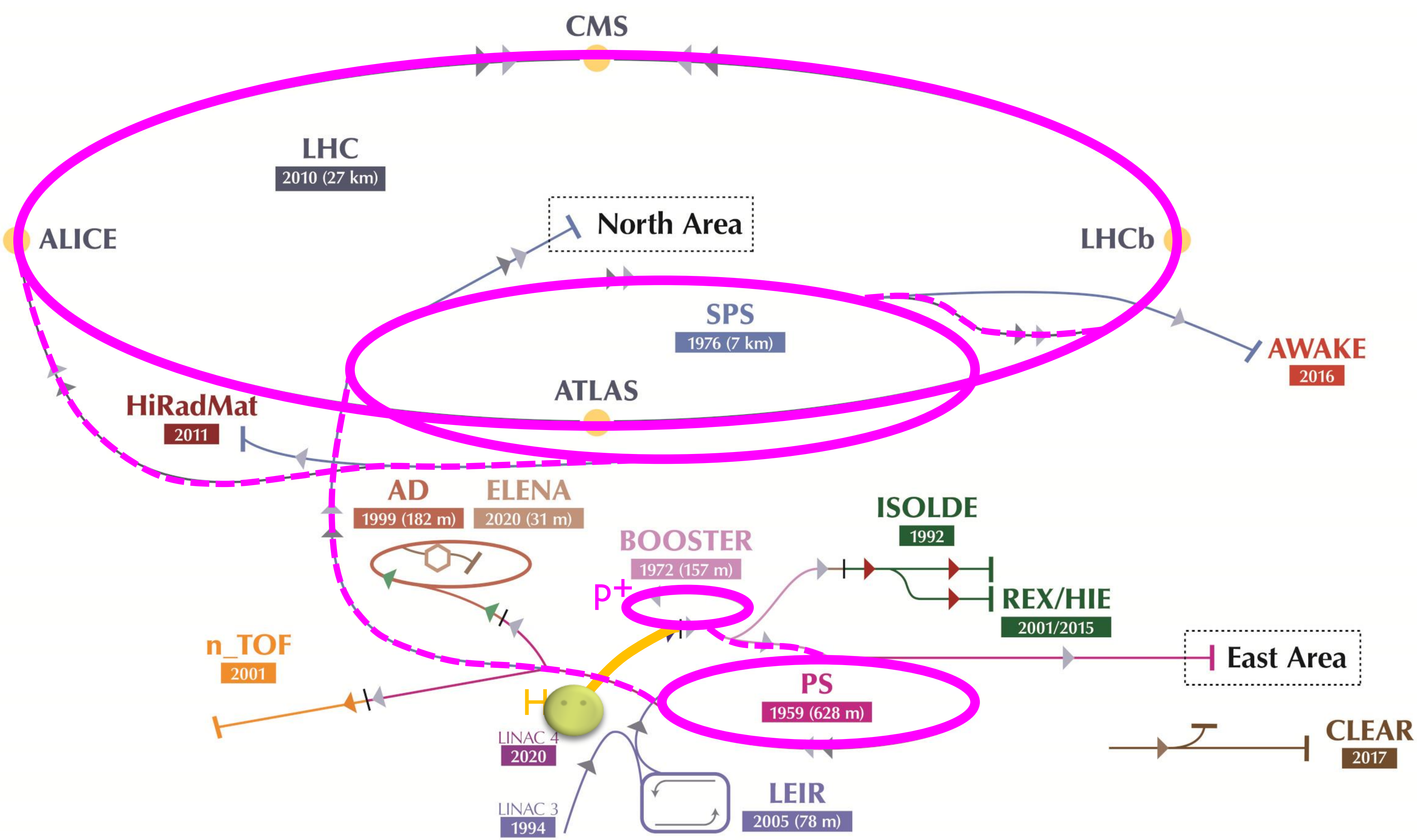
CERN Accele[…] Layout



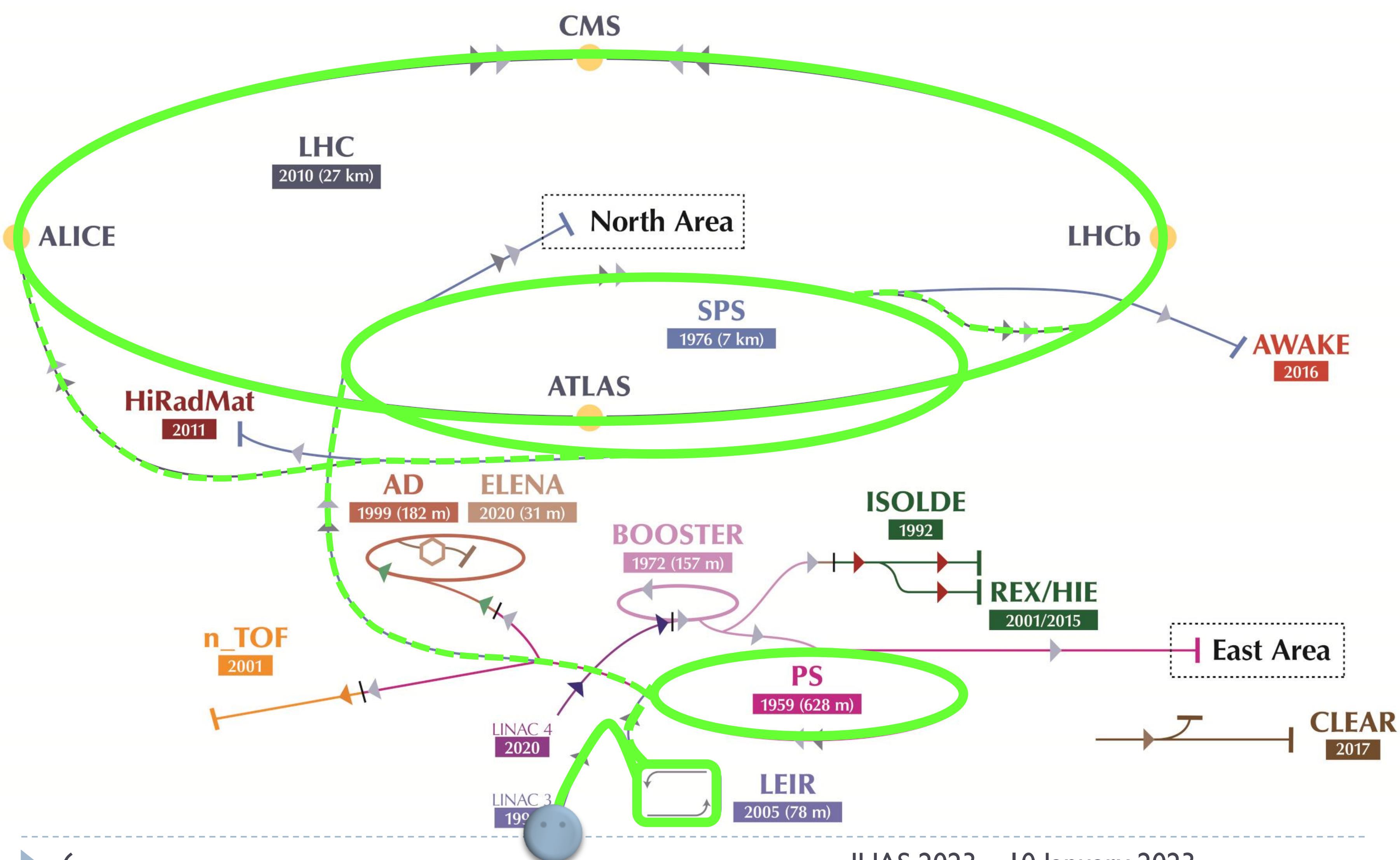


LHC Injectors Upgrade (LIU)

CERN Proton Accelerator Complex



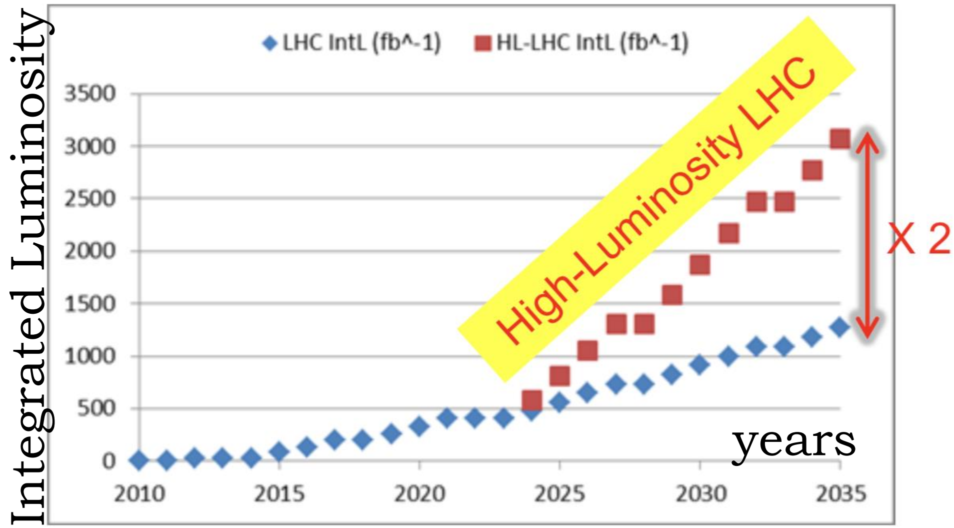
CERN Ion Accelerator Complex



Injectors Post-LS2 era ➔ meet HL-LHC performance

What HL-LHC requires? ➔ increase by a factor of 2 the integrated luminosity

What is luminosity? ➔ one of the most important figures of merit of a collider



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

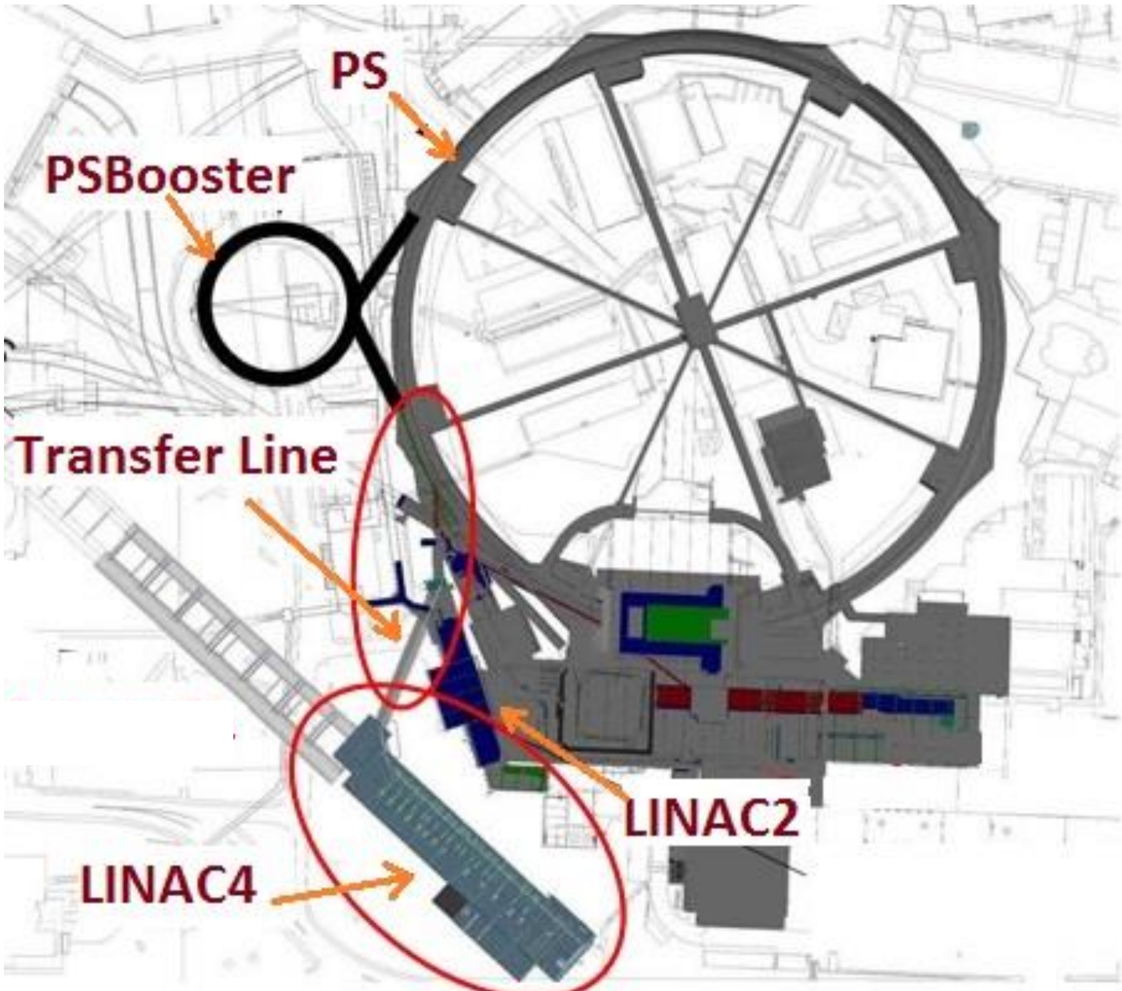
Physics cross-section (cm^2) at the collision energy (e.g. H➔$\gamma\gamma$)

cm^{-2} . s^{-1}

(Instantaneous) Luminosity ∝ number of interactions per unit of time & area

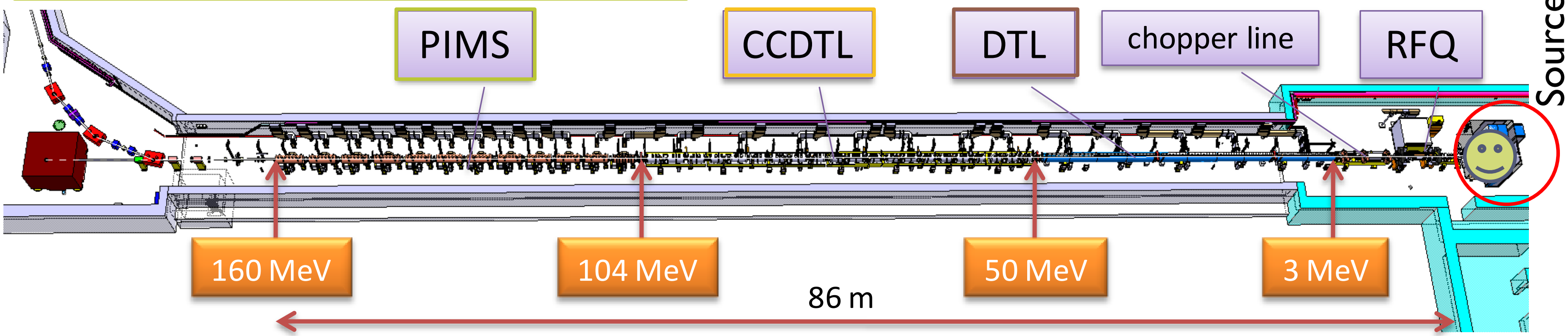
(Integrated) Luminosity ∝ instantaneous luminosity **x Δt**

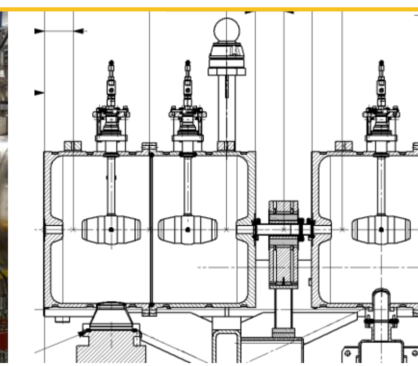
Linac 4

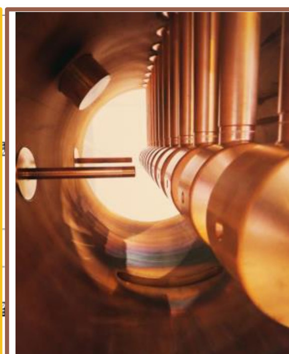


Source and Linac 4

DTL: drift tube linac
CCDTL: cell-coupled drift-tube linac
PIMS: pi-mode structure

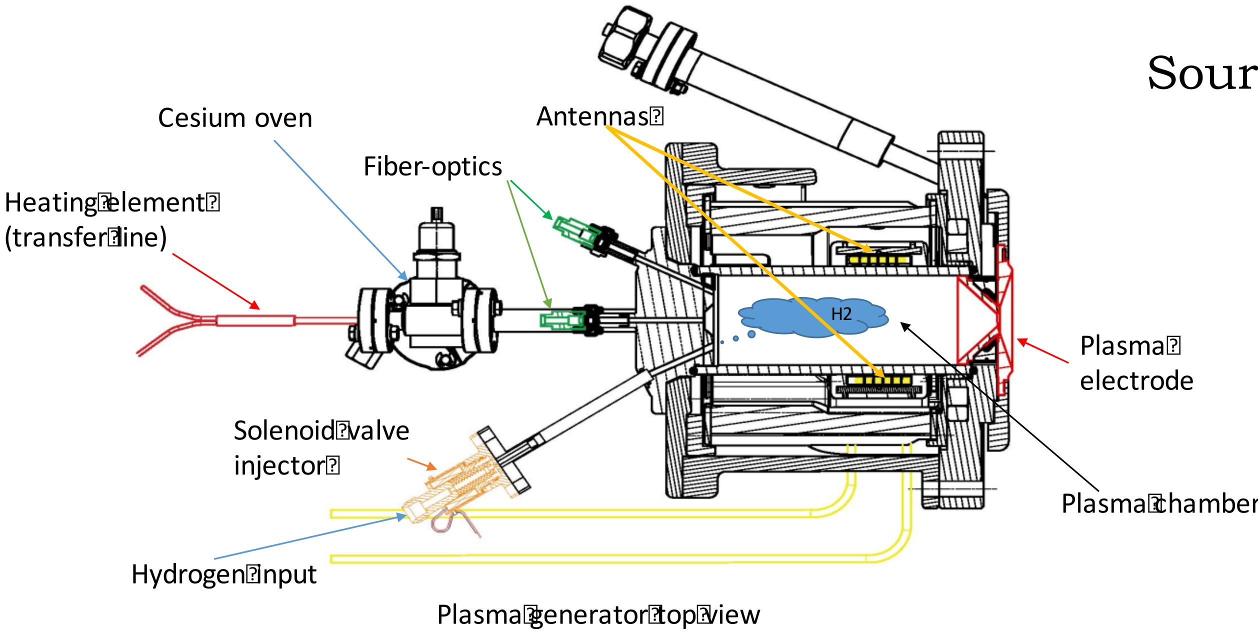






Source and Linac 4

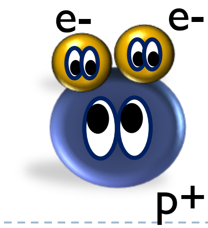
Source H-

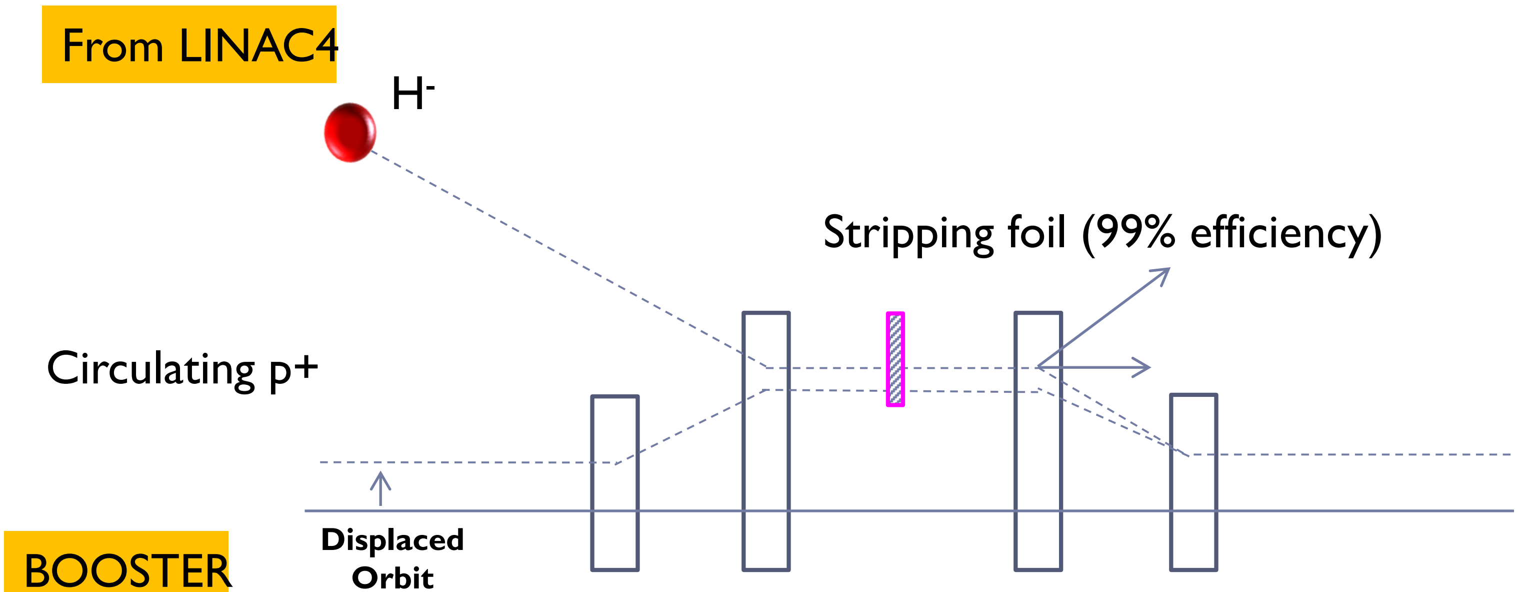


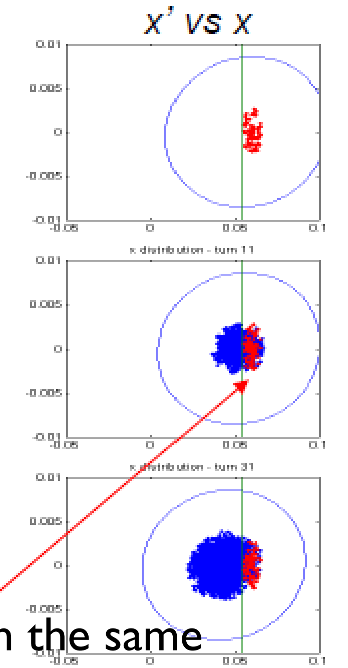
Two H- production mechanism:

1. H- from the plasma cell: $e + H_2 \rightarrow H^- + H$
2. H- from the surface: electron transfer from the surface to an atom leaving the surface. This process is enhanced by lowering the surface work function via the deposition of alkali: e.g. Cesium

H^- Injection







Injection chicane dipoles:
Bump off after injection to preserve the foil from unnecessary heating

Injection in the same phase space region!!!

Emittance better preserved

Not possible with LINAC2

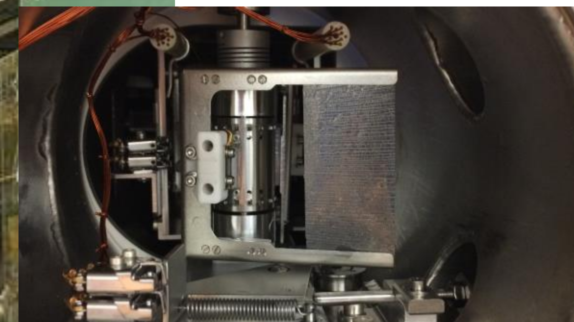
$Brightness^{LINAC4} \approx 2\ Brightness^{LINAC2}$

Brightness=Intensity/emittance

PS Booster

Newly installed
H- injection

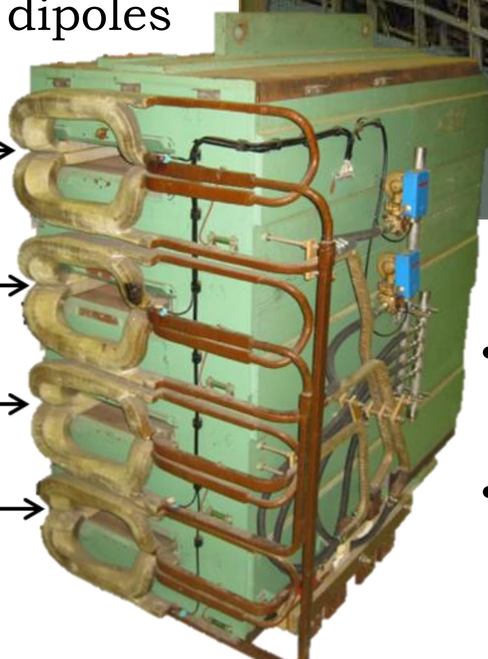
C = 154 m
Commissioned in 1972



Stripper foil for
H- injection

Pre-LS2 (p+):
E_{inj}=50 MeV
E_{ext}=1.4 GeV
LIU era (H-):
E_{inj}=160 MeV
E_{ext}=2 GeV

Main dipoles



outer aperture →

inner apertures }

outer aperture →

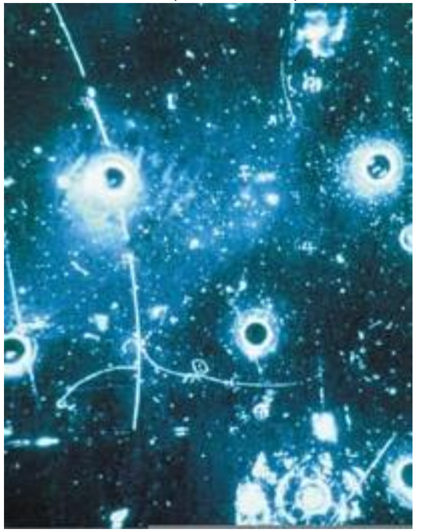
- Synchrotron with 4 vertically stacked rings, each ¼ of PS Circumference
- Duty cycle 1.2 s ➔ two cycles needed to fill the PS with protons for LHC

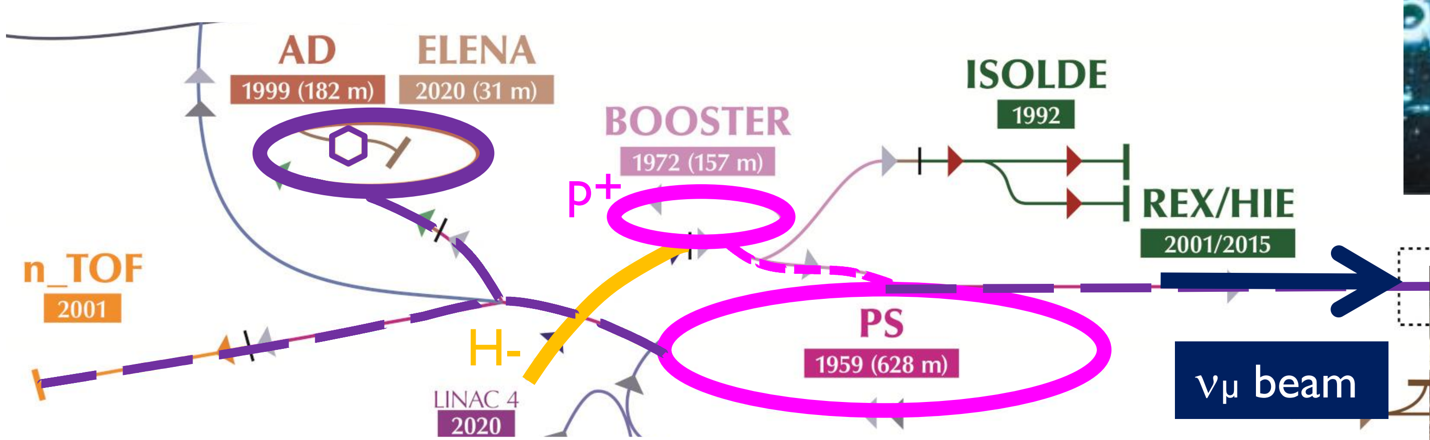
Proton Synchrotron (PS)

The oldest functioning machine at CERN

The first Alternating Gradient Machine!

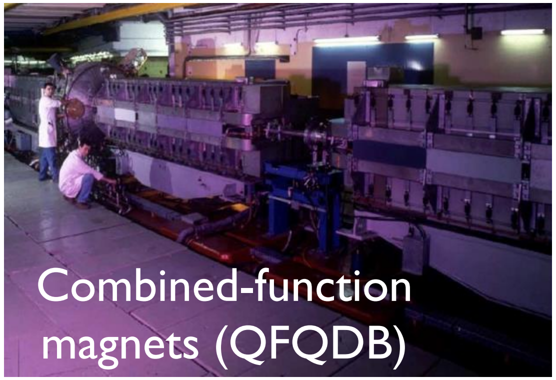
1959





GARGAMELLE

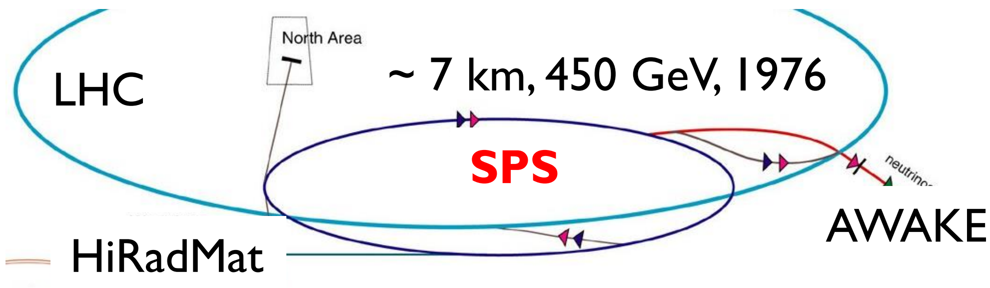
First evidence of weak neutral currents



Combined-function magnets (QFQDB)

Super Proton Synchrotron (SPS)

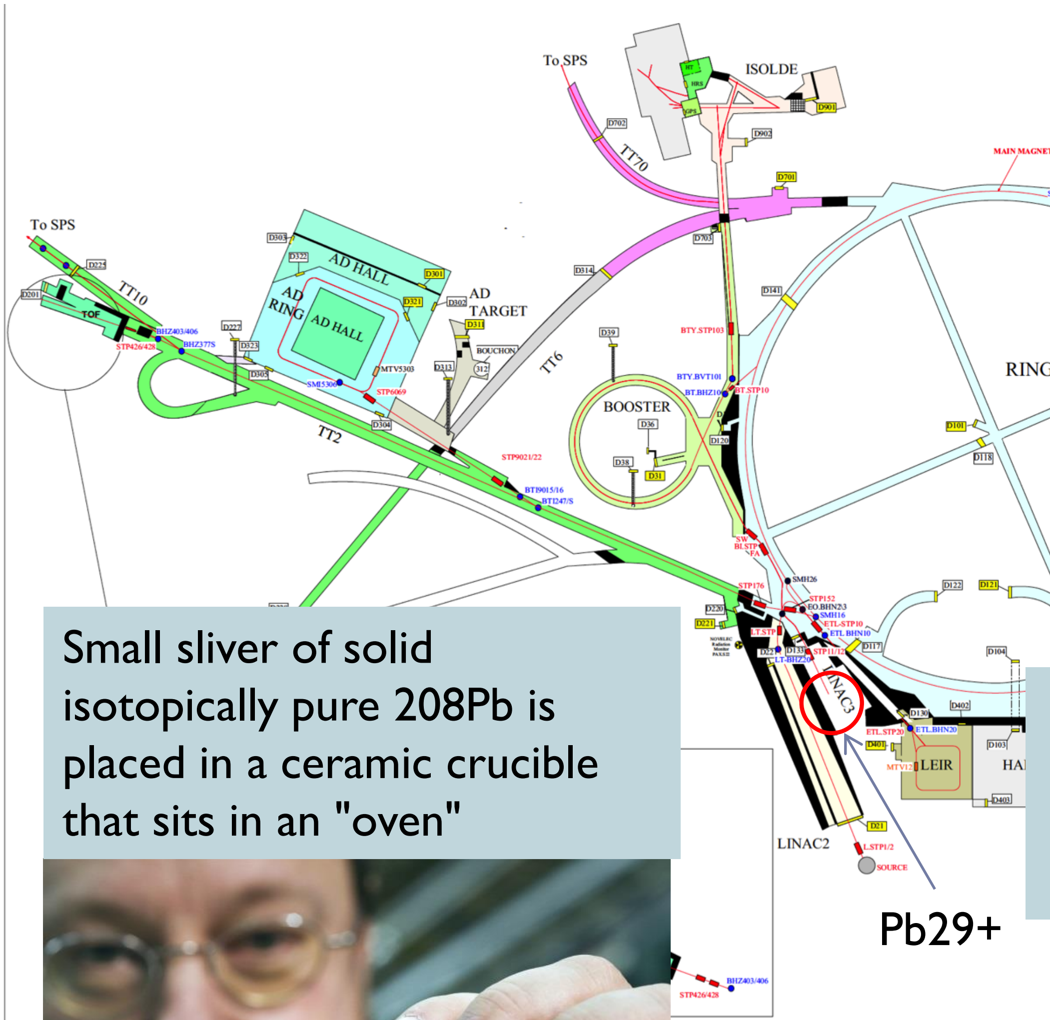
North area

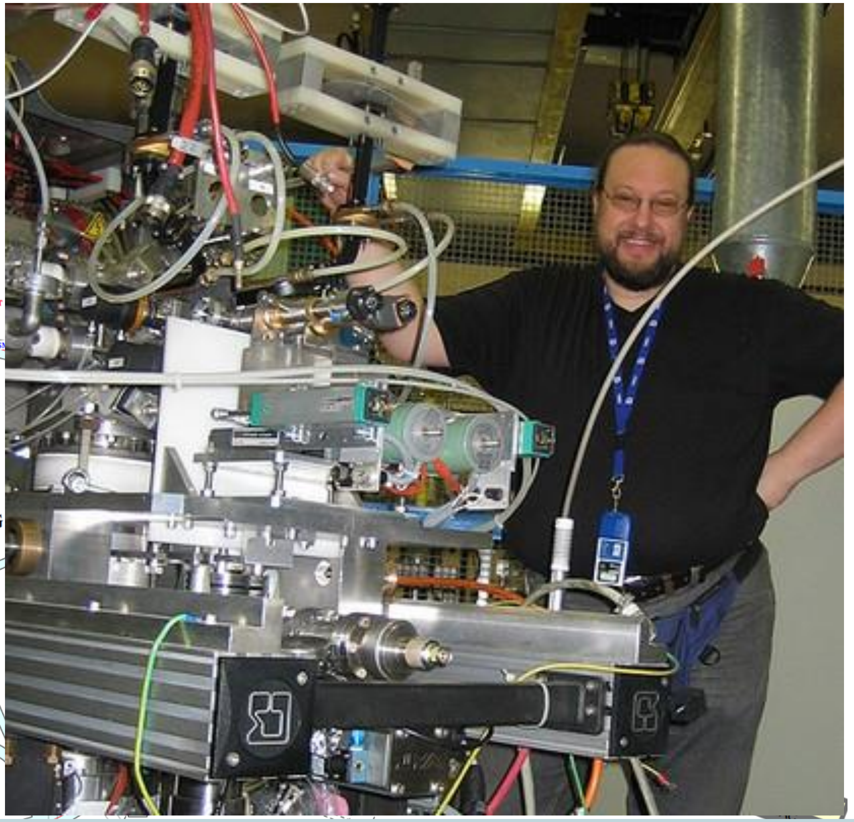


Spp̄S

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

Ion Chain



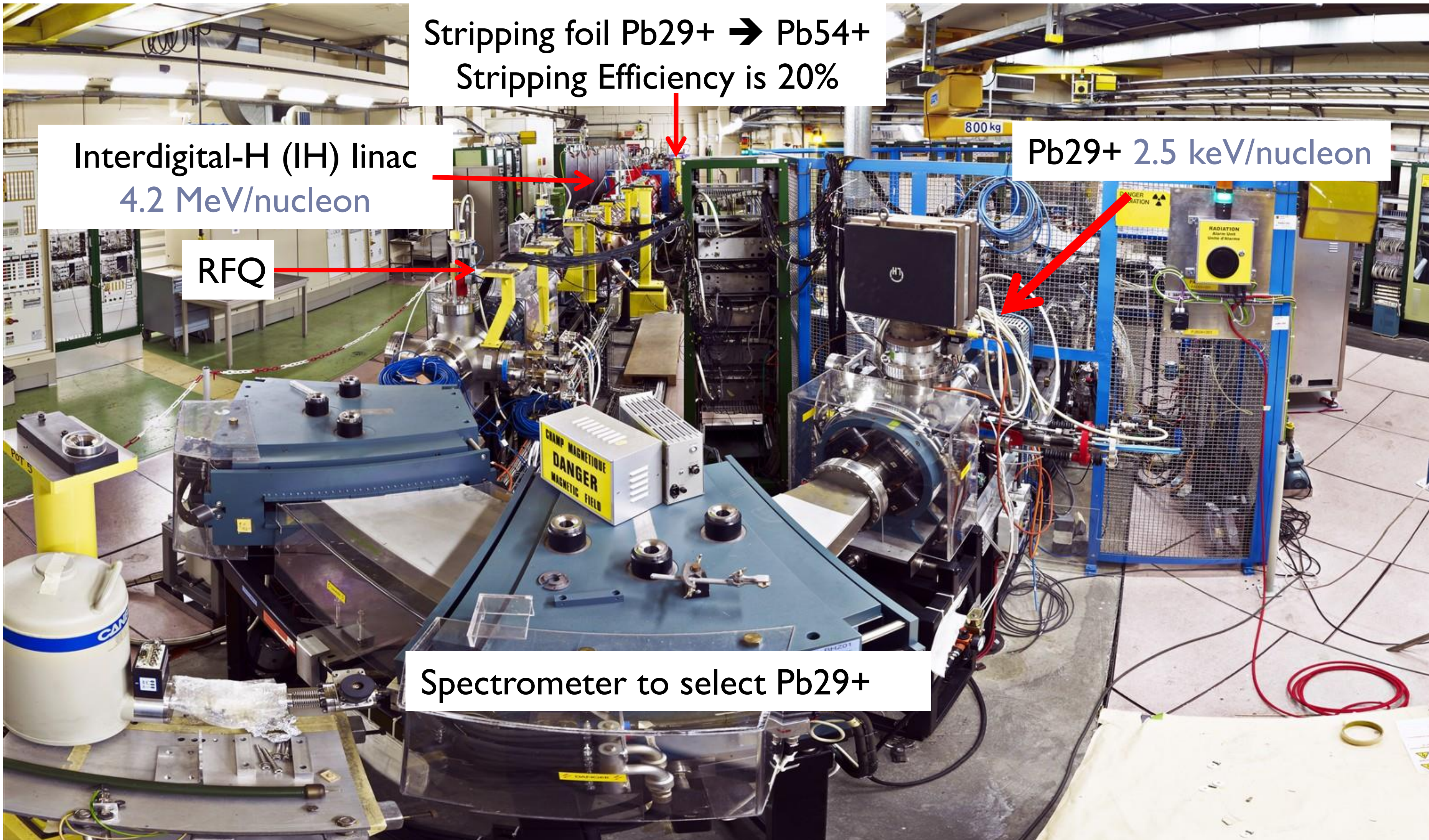


Small sliver of solid isotopically pure 208Pb is placed in a ceramic crucible that sits in an "oven"

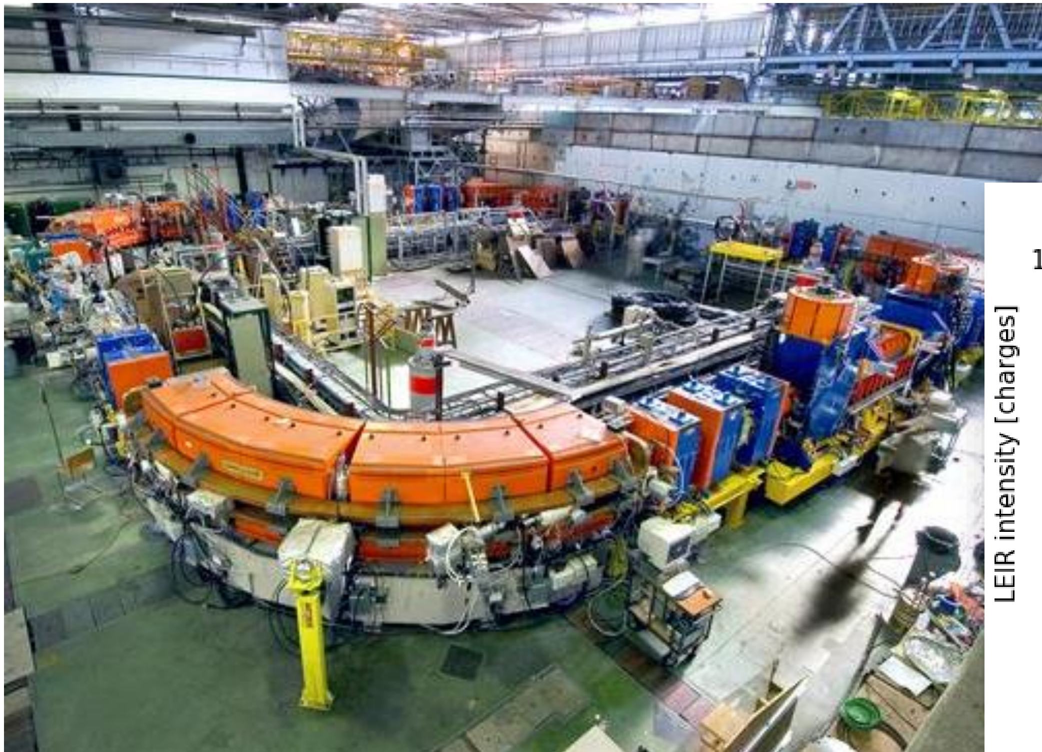
The metal is heated to around 800°C and ionized to become plasma. Ions are then extracted from the plasma and accelerated up to 2.5 keV/nucleon.

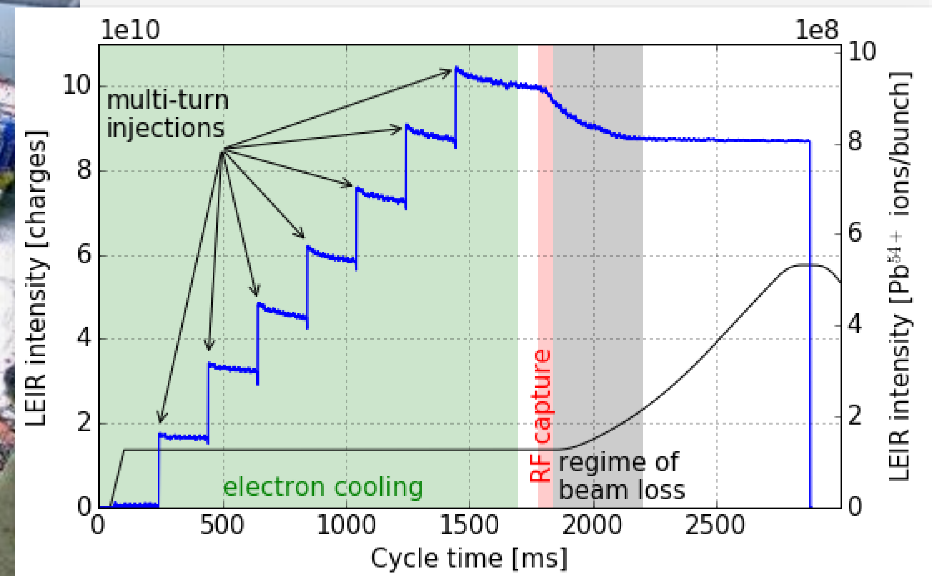
The source can also be set up to deliver other species… O, Ar, Xe …

Linac 3


Stripping foil Pb29+ → Pb54+
Stripping Efficiency is 20%
Interdigital-H (IH) linac
4.2 MeV/nucleon
RFQ
Pb29+ 2.5 keV/nucleon
Spectrometer to select Pb29+
800 kg
DANGER

Ion Chain : Low Energy Ion Ring (LEIR)





LEIR Accumulates the 200 ms pulses from Linac3; then splits into 2 bunches

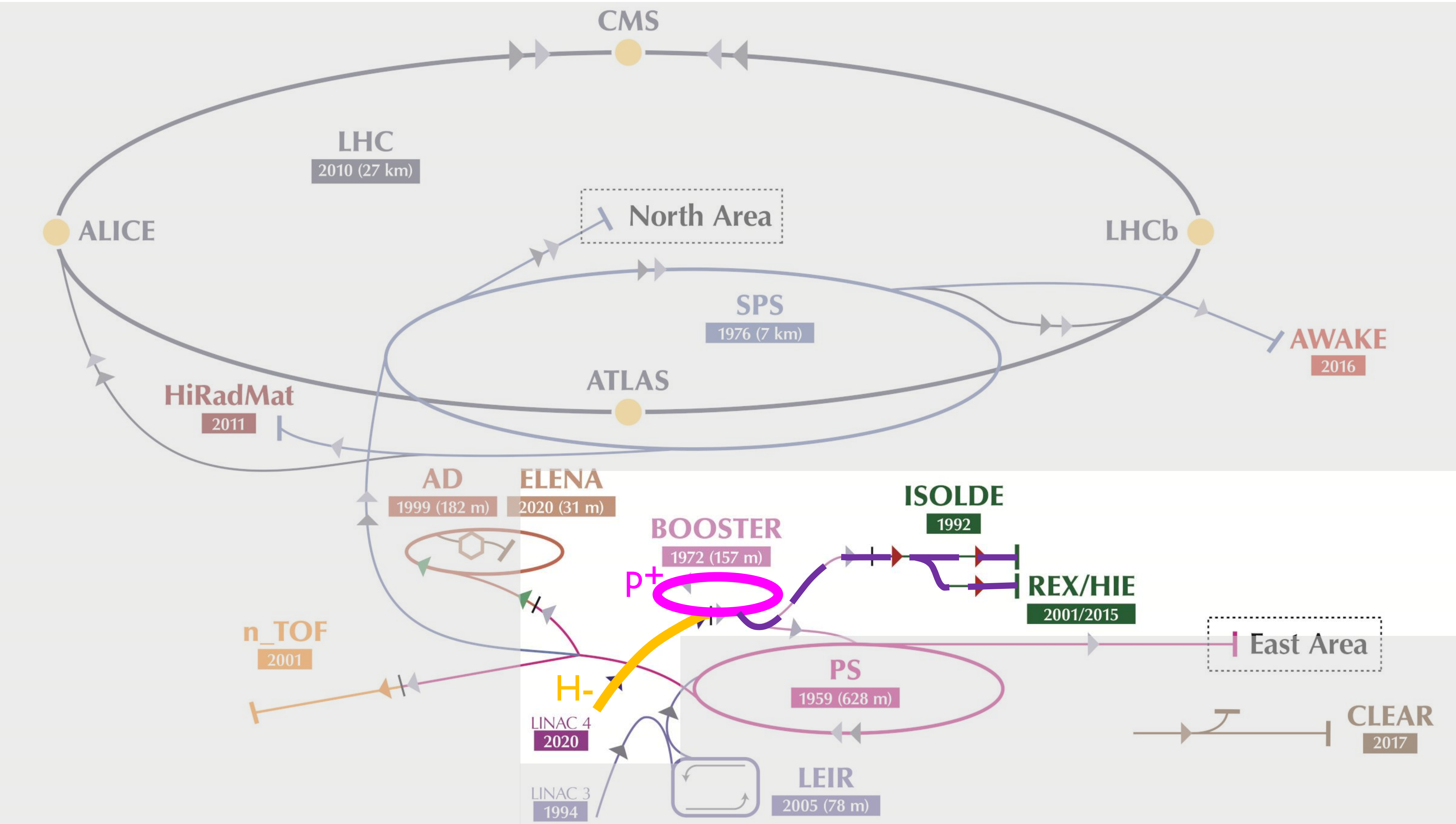
Electron Cooling is used to achieve the required brightness

Acceleration to 72 MeV/nucleon before transfer to the PS

LEIR Cycle is 3.6 s

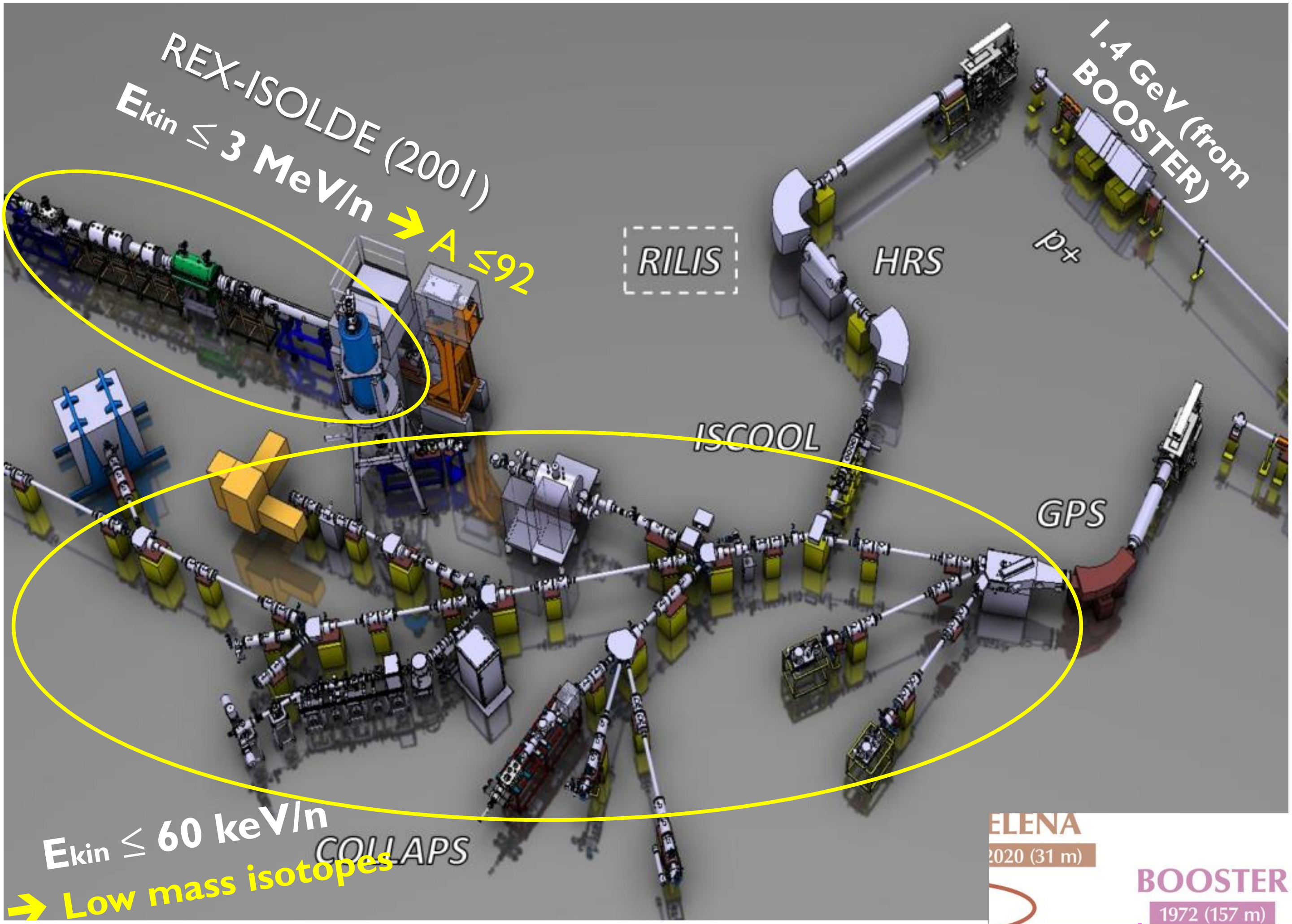
The Pb54+ is finally fully stripped to Pb82+ in the transfer line from PS to SPS

Booster Experimental Areas



ISOLDE Synchrocyclotron: 1967-1990
ISOLDE PSB: 1992

PSB Experimental Areas: ISOLDE



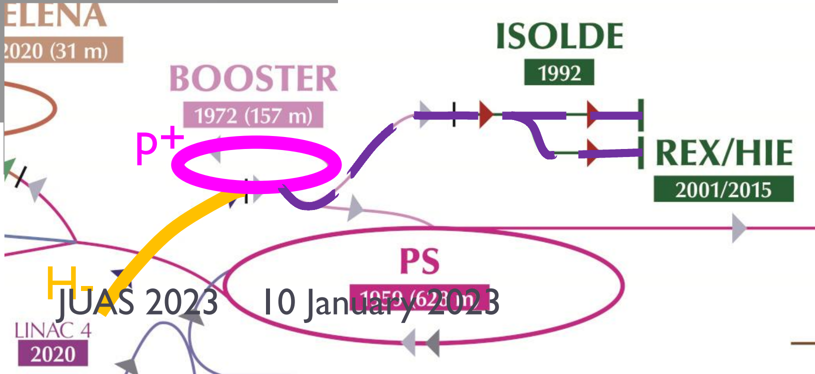
Solid and liquid target materials ➔ wide spectrum of radioactive isotopes up to A =< 92. Radioactive isotopes are produced via proton-induced target fragmentation, spallation and fission reactions

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)

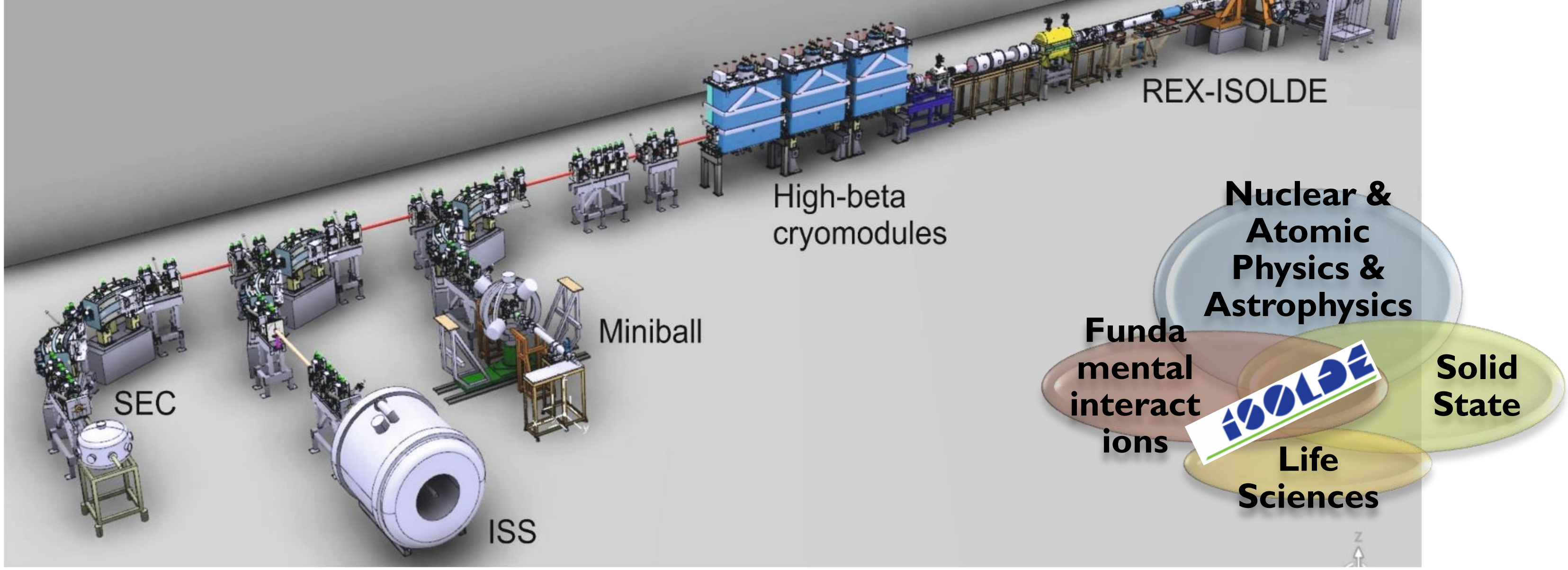
➔ on October 16, 1967 the first radioactive beam

➔ CERN's longest-running experiment site



Next generation of nuclear physics:

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

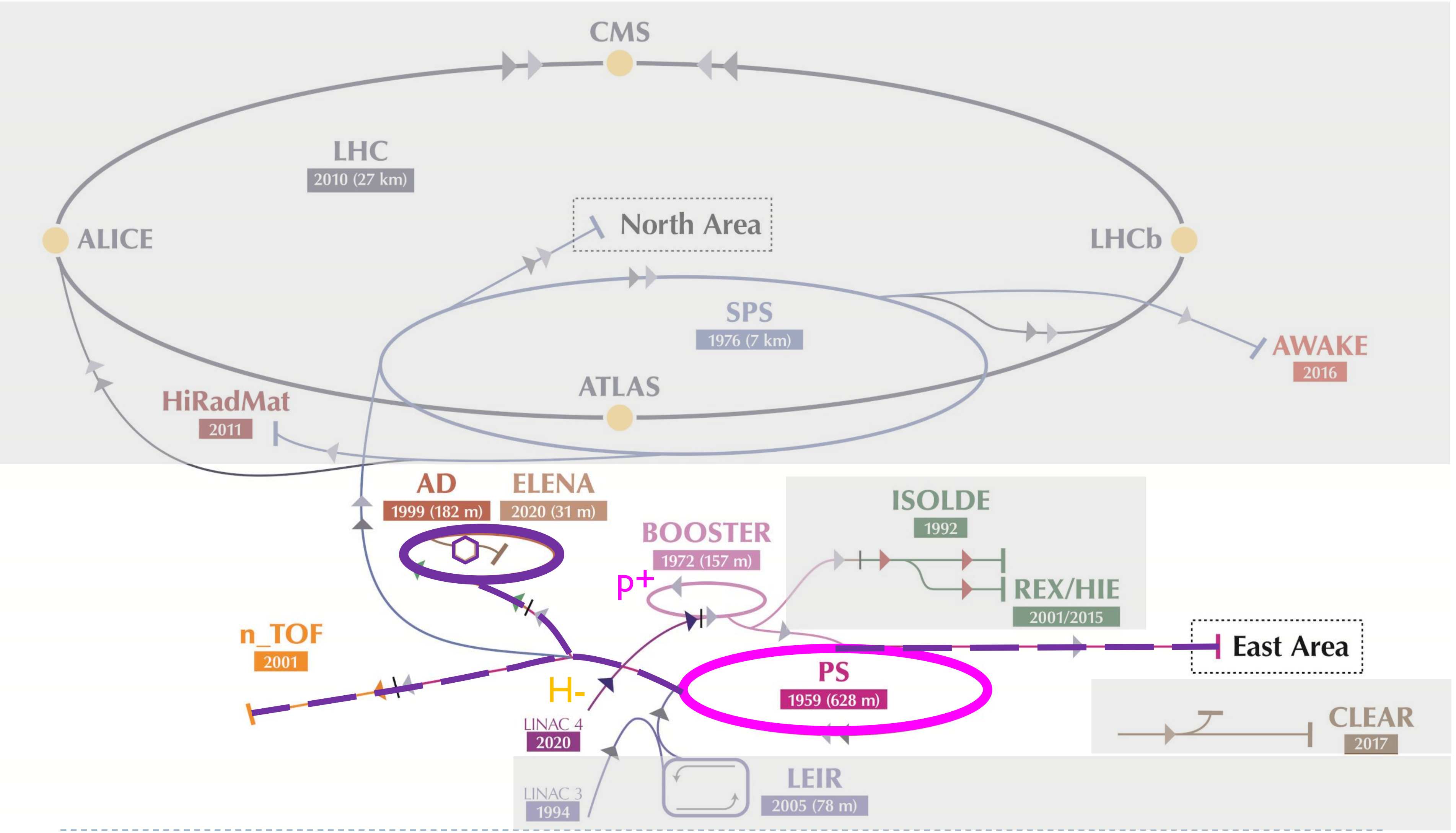


MEDICIS (Medical Isotopes Collected from ISOLDE)

➔ 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.

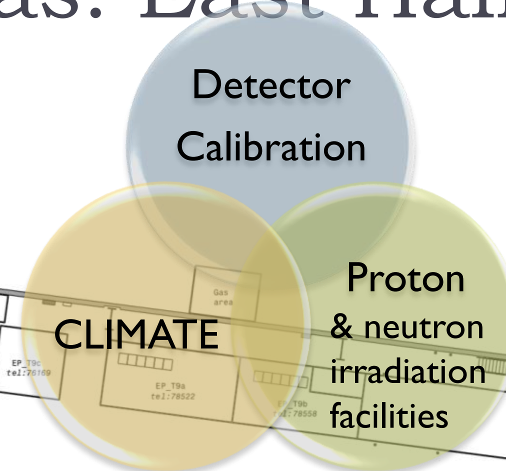
➔ devise and test unconventional radioisotopes with a view to developing new approaches to fight cancer

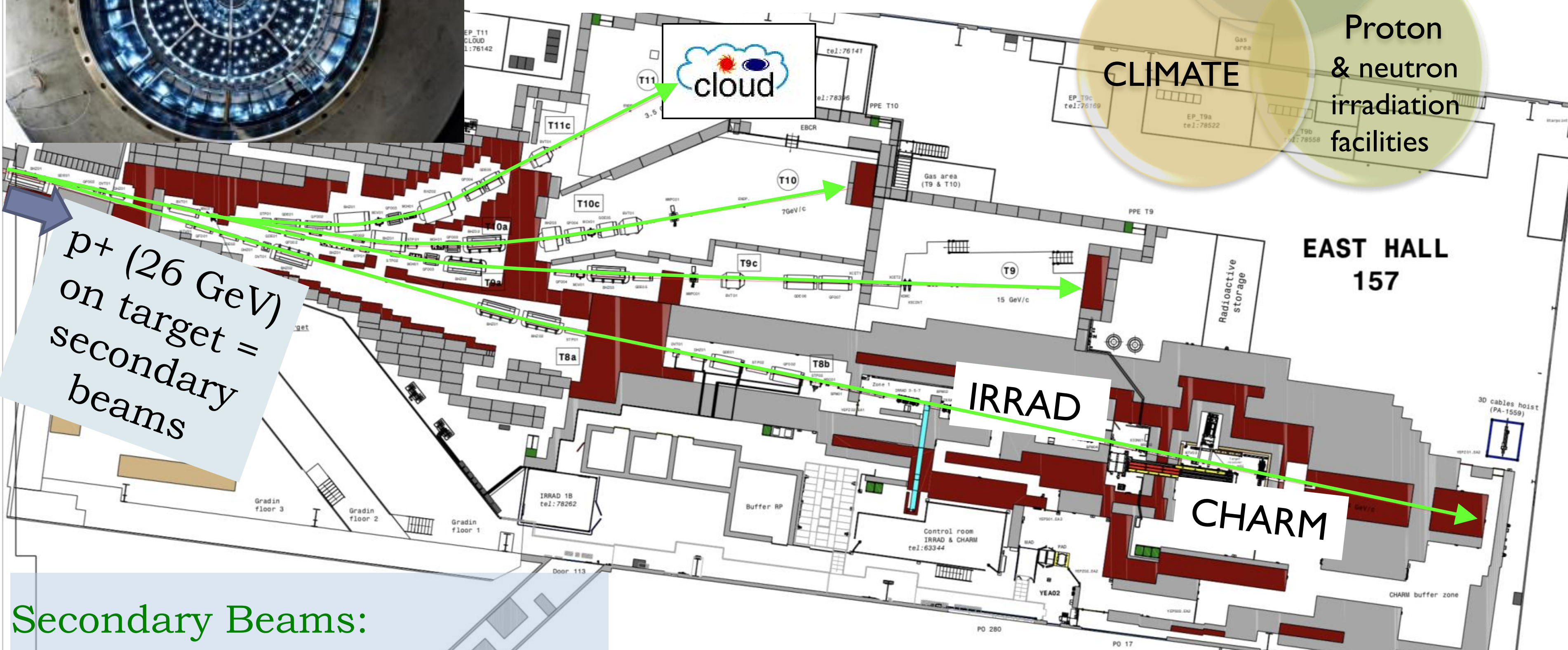
PS Experimental Areas



PS Experimental Areas: East Hall

Study the influence of galactic cosmic rays on the **Earth's climate** through the media of aerosols and clouds



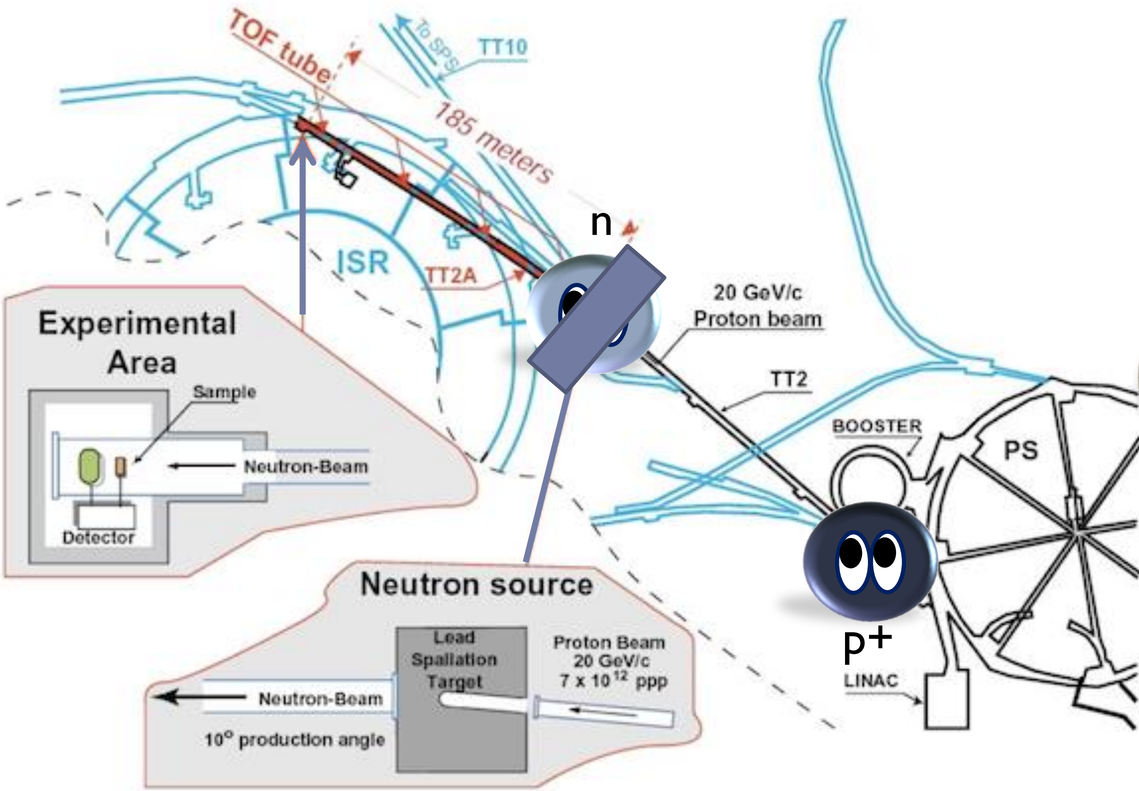


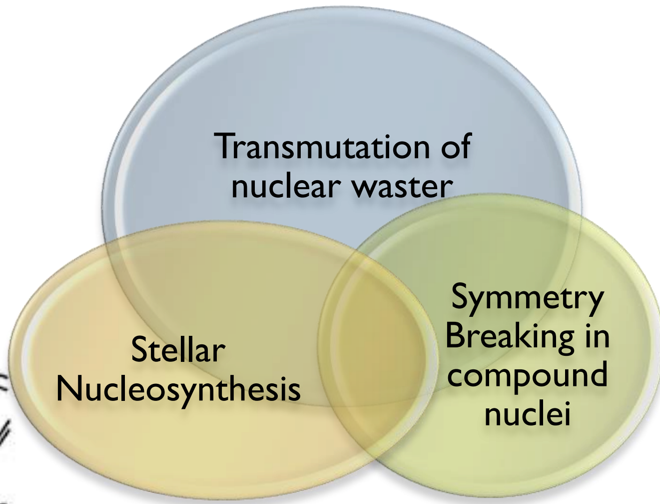
Secondary Beams:
Momentum range 1-15 GeV/c
Electrons, Hadrons & Muons
Max 1-2 10^6 particles per spill

For particle detectors and satellites

PS Experimental Areas: n-TOF

Study of neutron-induced reactions

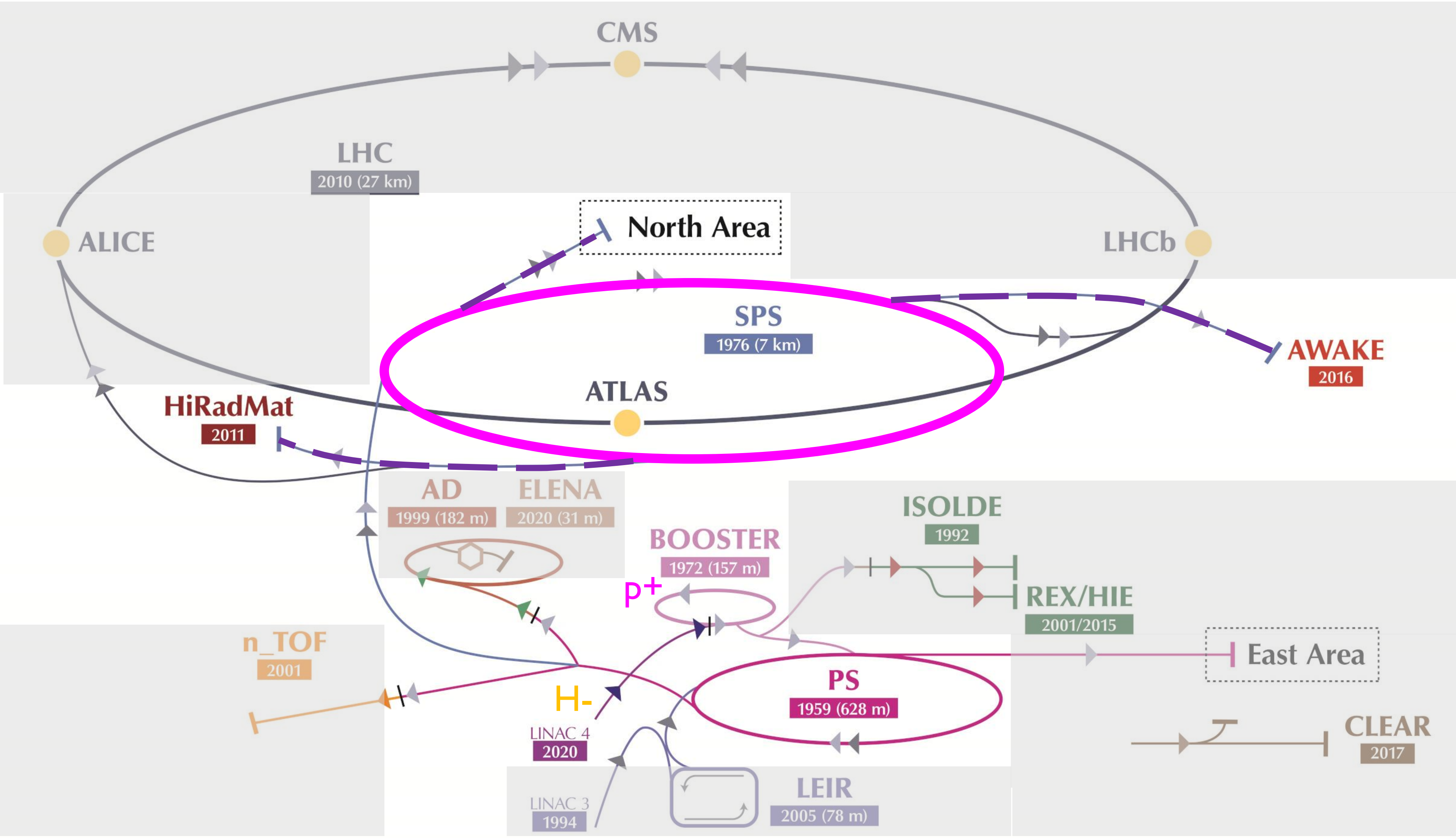




Each primary proton produces ~300 neutrons
$E_{neutron}$ → meV - GeV

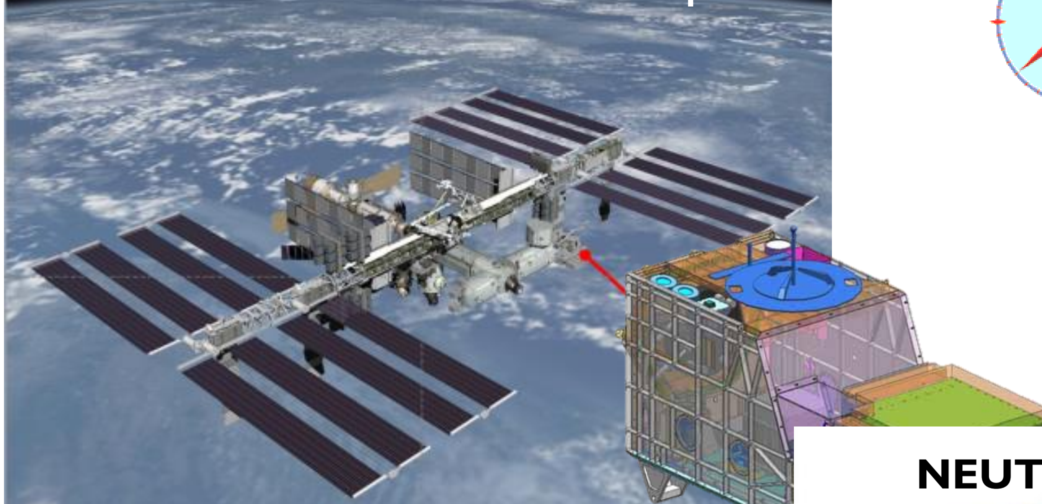
The neutron kinetic energy is determined by **time-of-flight**

SPS Experimental Areas

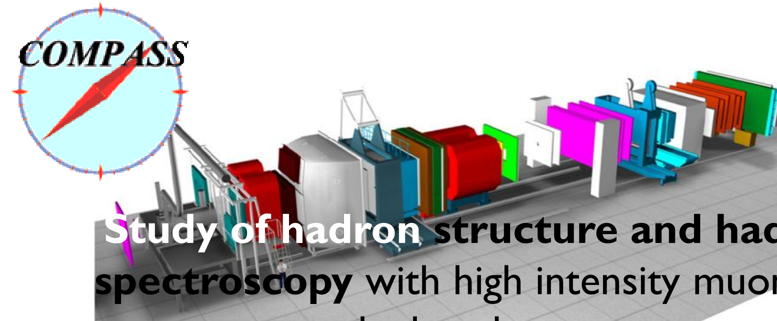


SPS Experimental Areas: North Area

CALET: Calorimetric Electron Telescope



High energy astroparticle physics on the International Space Station



Study of hadron structure and hadron spectroscopy with high intensity muon and hadron beams

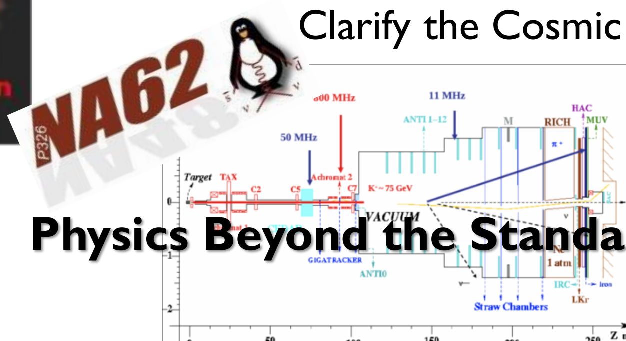
- 7 beam lines (tot:5.8 km)
- 3 experimental halls
- ~ 2000 scientist/year
- Slow extraction
- 3 primary targets
- Ion physics program: (Be, Ar, Xe)
- ~ 50 different clients/year

NEUTRON

Russian regular satellite

Clarify the Cosmic Rays origin

NA61/SHINE (QCD experiment)



Physics Beyond the Standard Model

COMPASS: Common Muon and Proton Apparatus for Structure and Spectroscopy

Plasma wake acceleration

SPS Experimental Areas: AWAKE

A "wake" is created when something is quickly pushed through a fluid or gaseous substance, like a boat cutting through water. In this case, 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

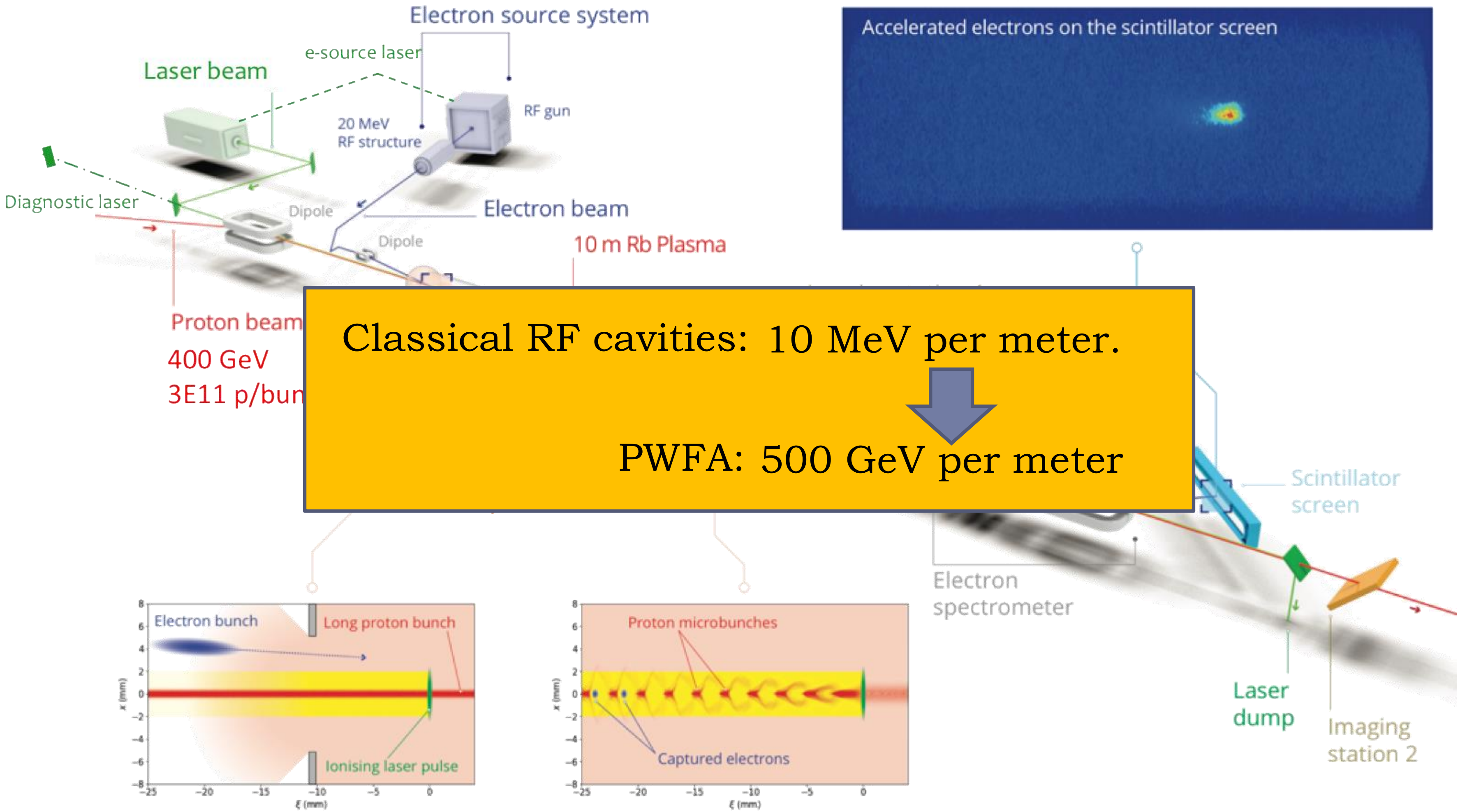
The concept was developed in an audacious 1979 paper by scientists Toshiki Tajima and John Dawson, both then at the University of California, Los Angeles.

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

SPS Experimental Areas: AWAKE



Classical RF cavities: 10 MeV per meter.

PWFA: 500 GeV per meter

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!

SPS Experimental Areas: HiRadMat

High-Radiation to Materials

Current and Future Accelerators operate with higher energy, higher intensity, smaller size beams.

LHC nominal beam (2808 bunches with 1.5 1011 p+/b at 7 TeV) energy = **362 MJ/beam** ➔ energy

HiRadMat is a facility designed, to study the impact of intense pulsed beam on materials

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

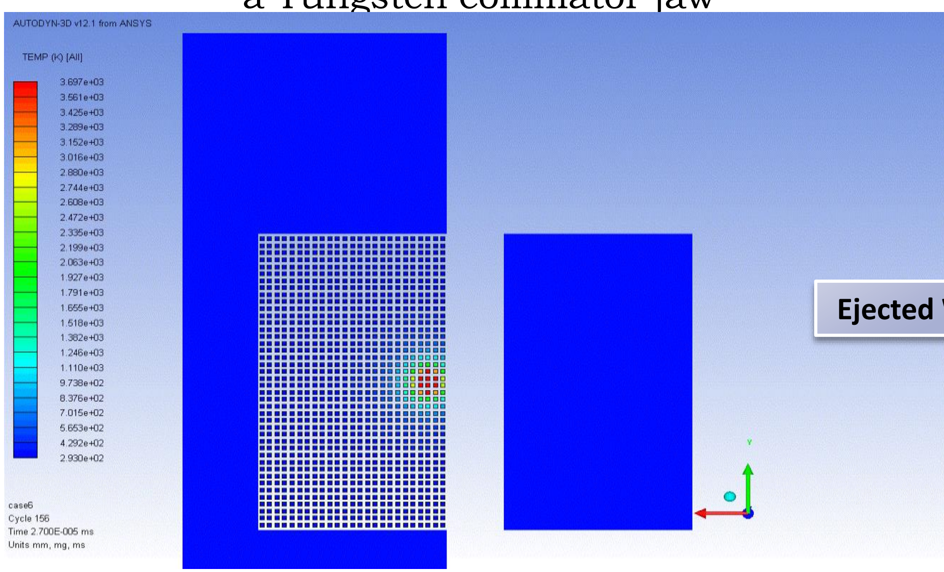
SPS Experimental Areas: HiRadMat

High-Radiation to Materials

Current and Future Accelerators operate with higher energy, higher intensity, smaller size beams.

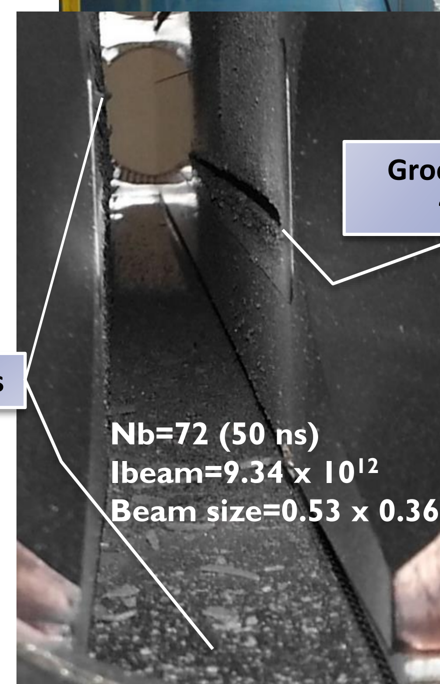
LHC nominal beam (2808 bunches with 1.5 1011 p+/b at 7 TeV) energy = **362 MJ/beam** ➔ energy

Simulation: 8 LHC bunches @5 TeV impacting a Tungsten collimator jaw

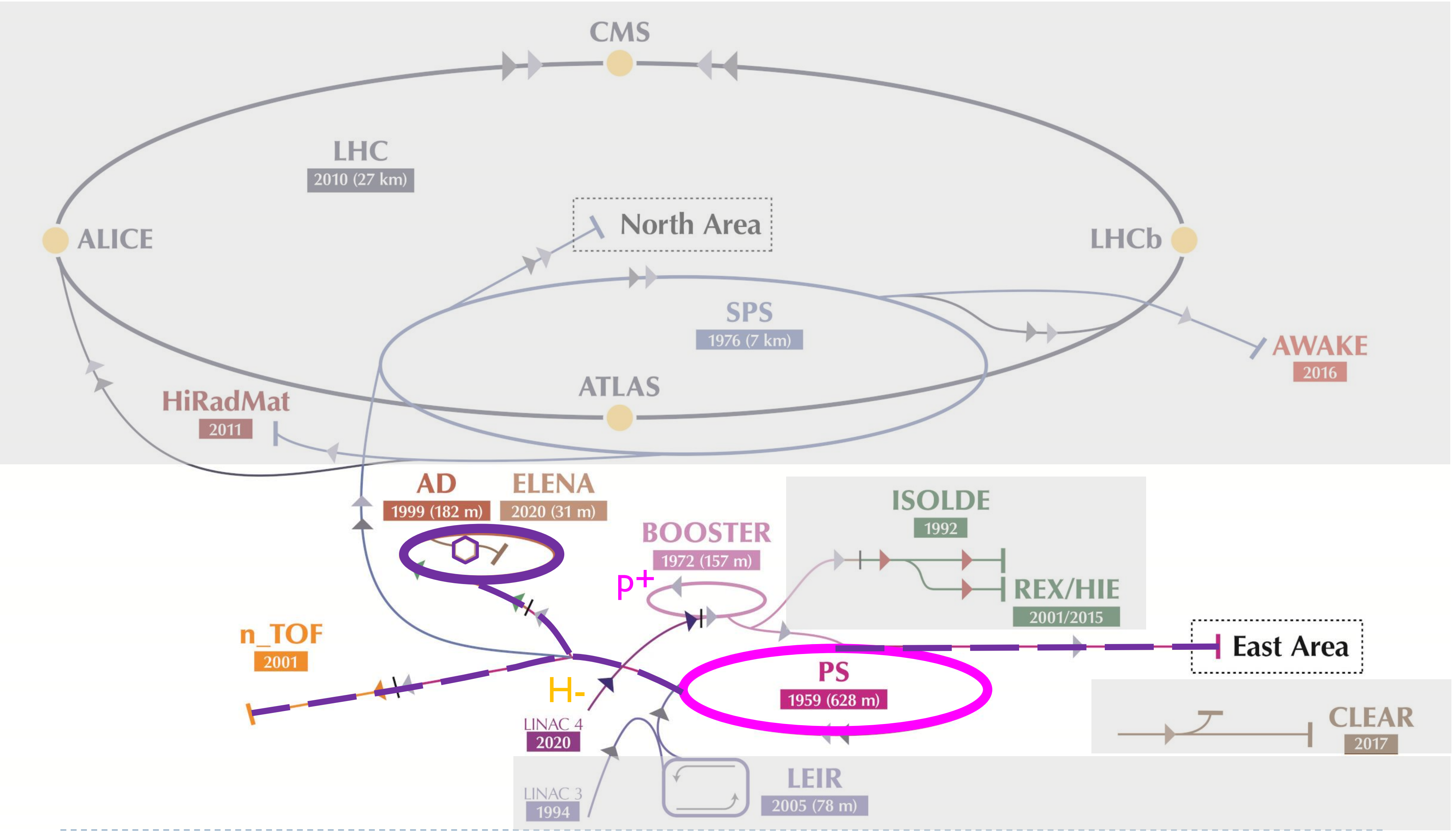


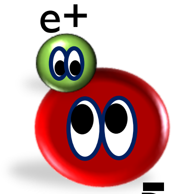
HiRadMat is a facility designed, to study the impact of intense pulsed beam on materials

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



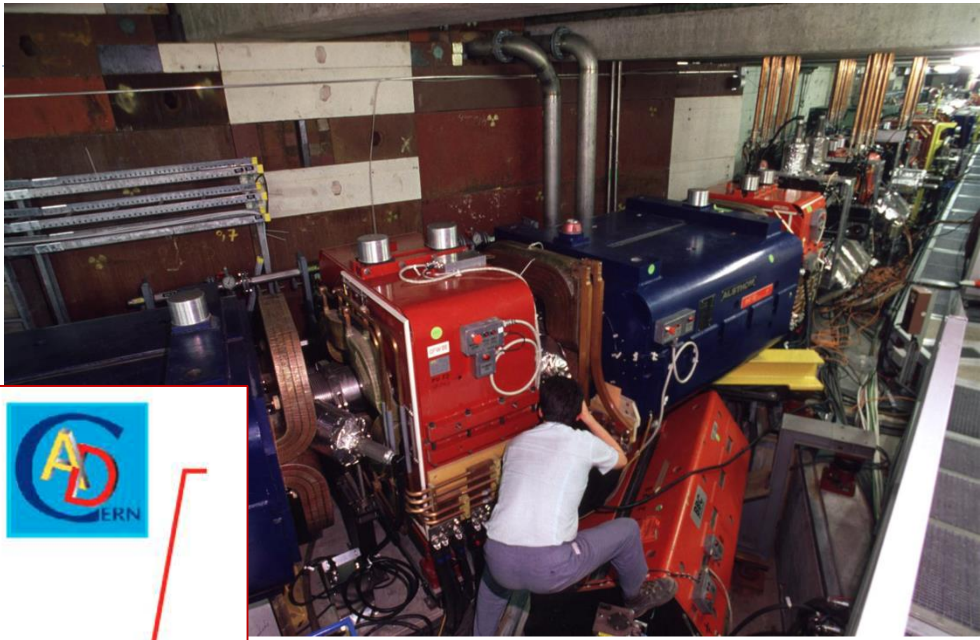
AD and ELENA

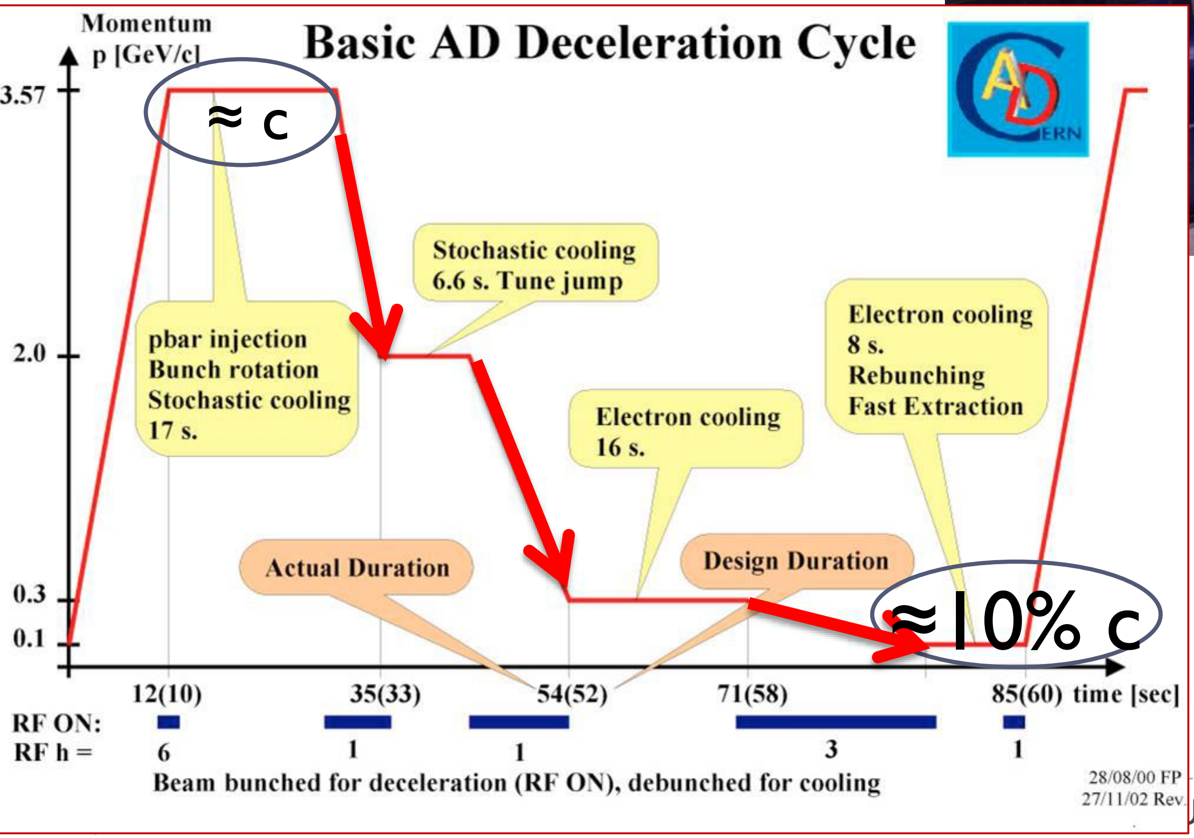

CMS
LHC
2010 (27 km)
North Area
ALICE
LHCb
SPS
1976 (7 km)
AWAKE
2016
ATLAS
HiRadMat
2011
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
p+
REX/HIE
2001/2015
n_TOF
2001
East Area
H-
PS
1959 (628 m)
LINAC 4
2020
CLEAR
2017
LINAC 3
1994
LEIR
2005 (78 m)



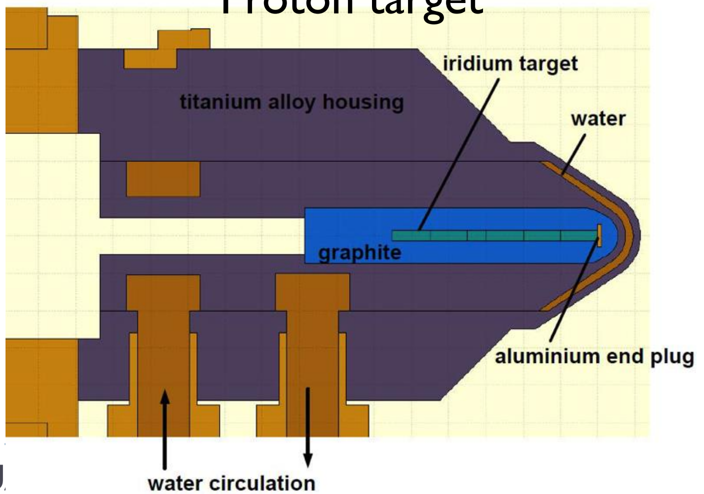
Antiproton Decelerator : AD

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

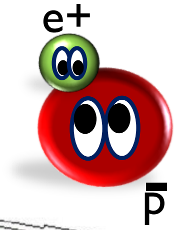


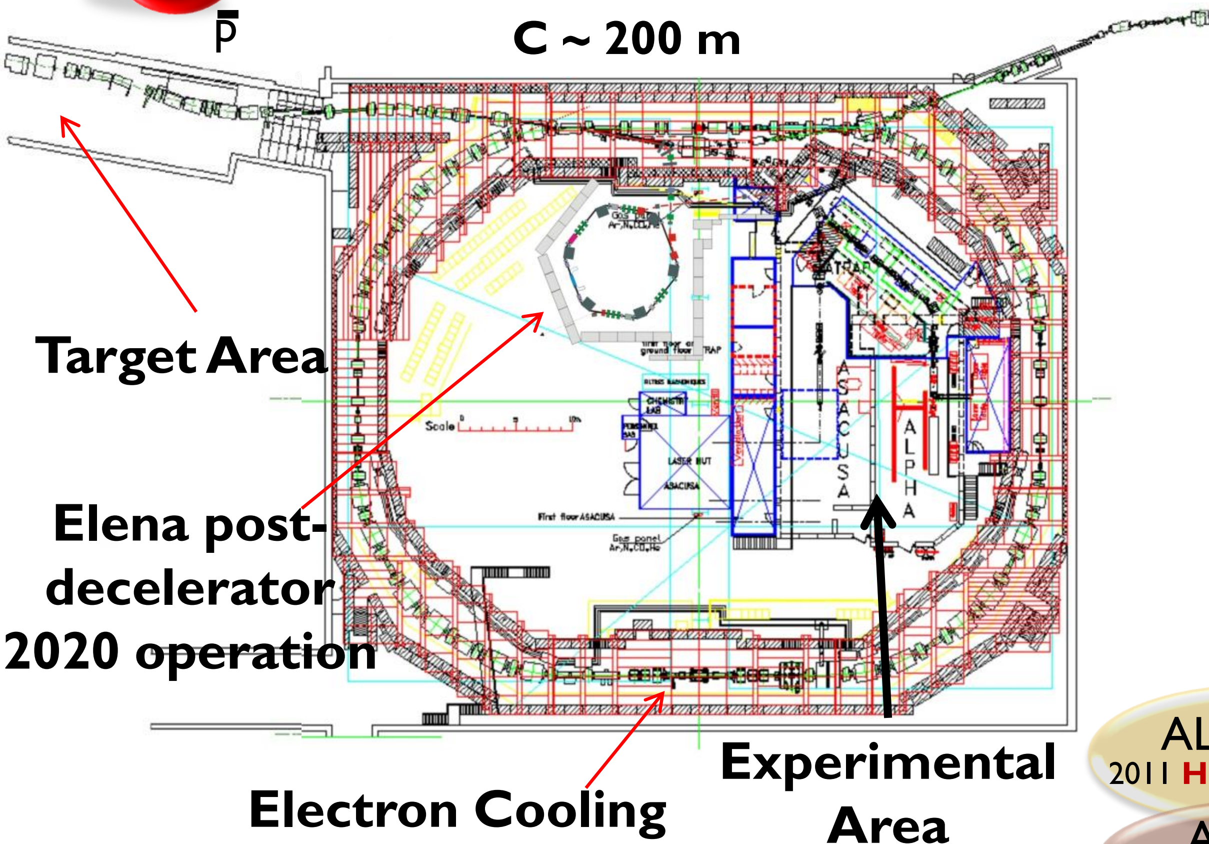


Proton target



AD Layout





ASACUSA
Antiprotonic helium → m $\bar{p}$

ALPHA
2011 $\bar{H}$ trapped for 16'

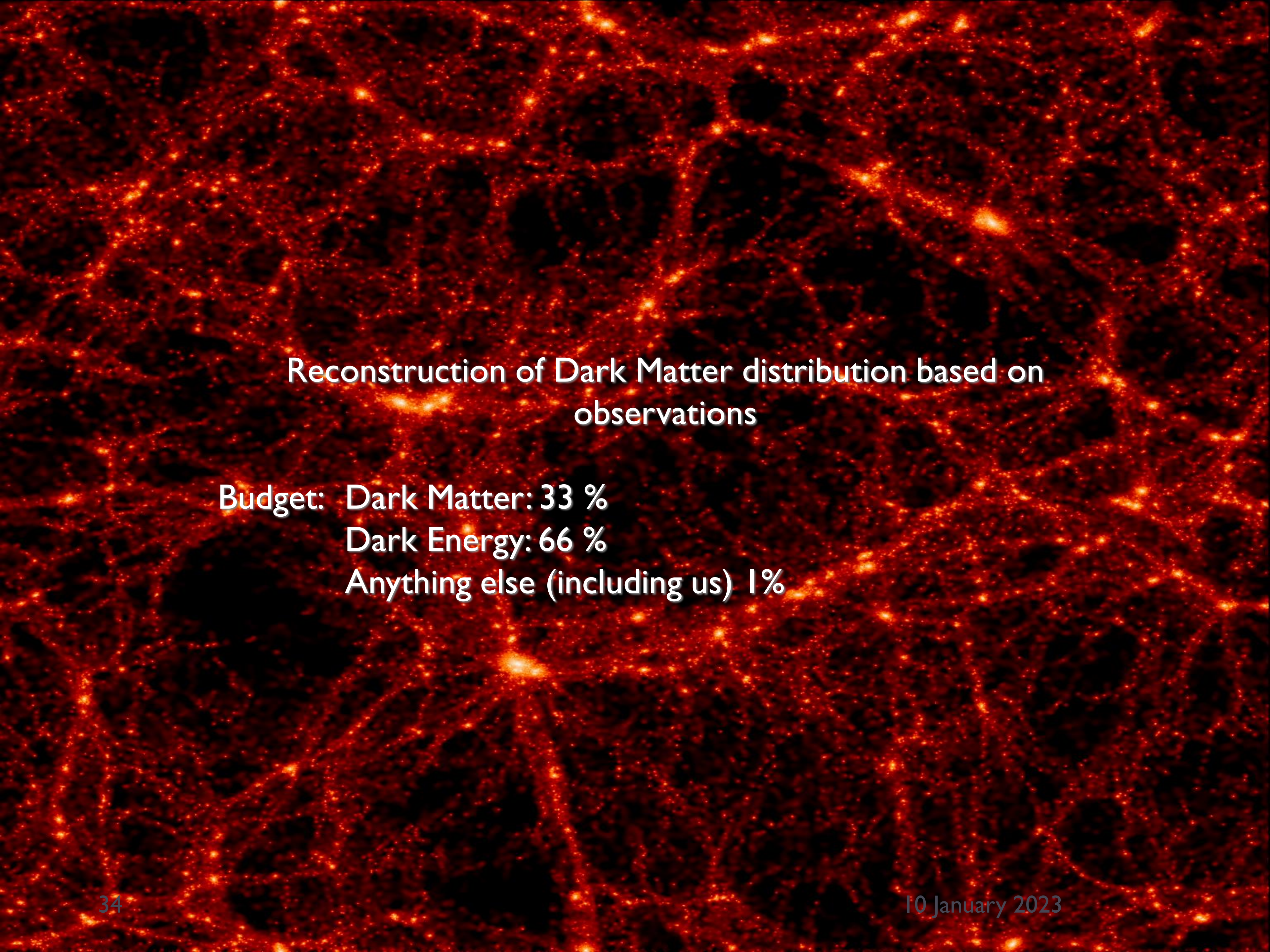
ATRAP
2002 first glimpse inside $\bar{H}$

AEGIS
1st meas. of gravitational effect on $\bar{H}$

BASE
$\bar{p}$ magnetic moment

GBAR[1]
Gravitational effect on $\bar{H}$

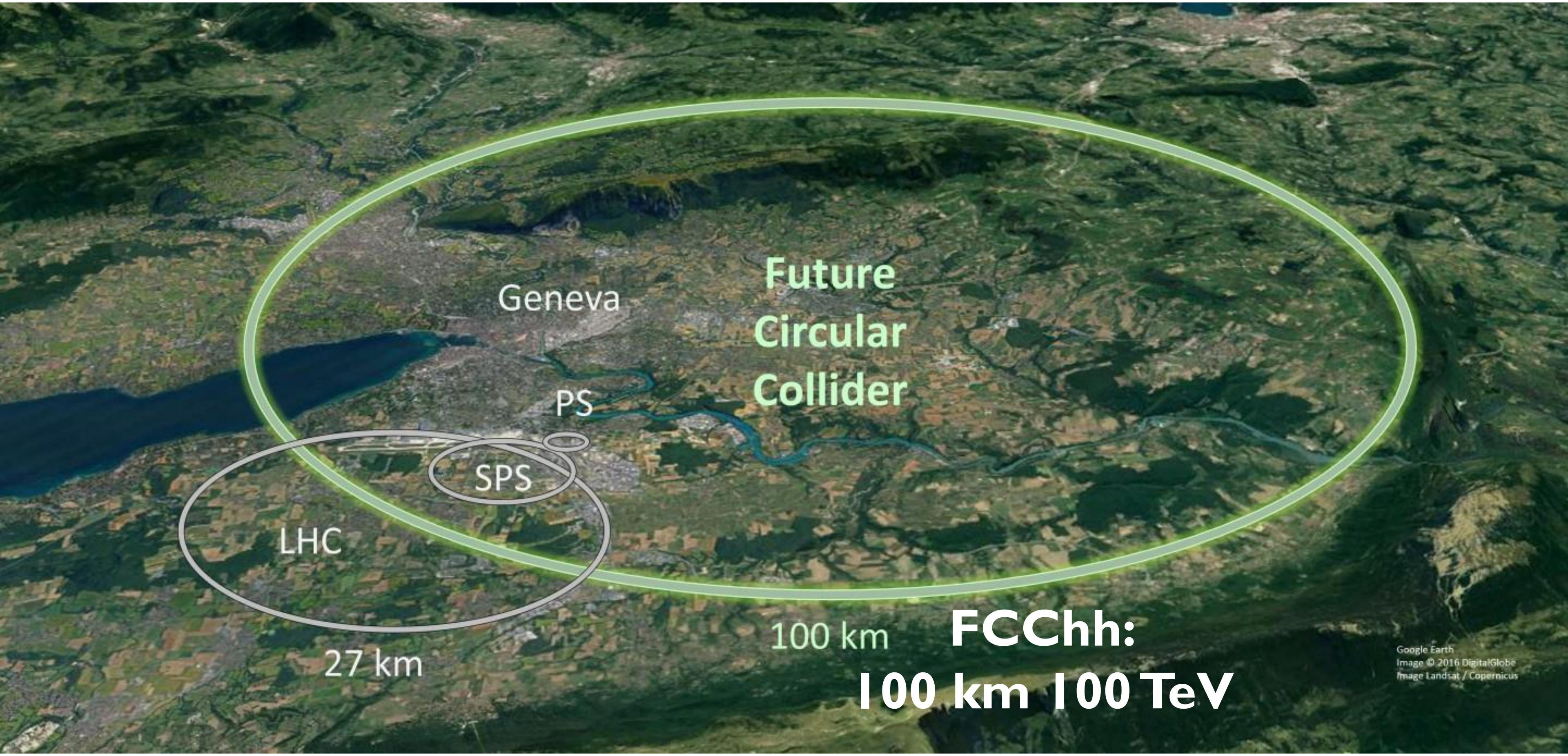

Hubble Deep Field
HST · WFPC2
u
d
c
s
t
e
b
μ
τ
ν_e
ν_μ
ν_τ
H
STARKE WW
ELEKTROMAGNETISCHE WW
SCHWACHE WW
QUARKS
GELADENE LEPTONEN
NEUTRALE LEPTONEN
1
2
3
FAMILIE



Reconstruction of Dark Matter distribution based on observations

Budget: Dark Matter: 33 %
Dark Energy: 66 %
Anything else (including us) 1%

CERN Lab 20??



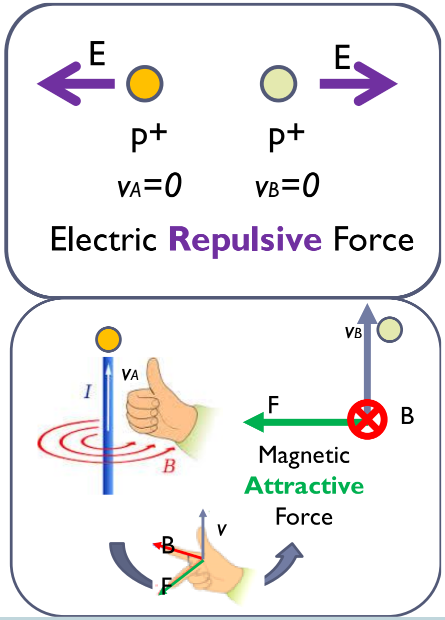
Geneva
Future
Circular
Collider
PS
SPS
LHC
27 km
100 km
FCChh:
100 km 100 TeV
Google Earth
Image © 2016 DigitalGlobe
Image Landsat / Copernicus

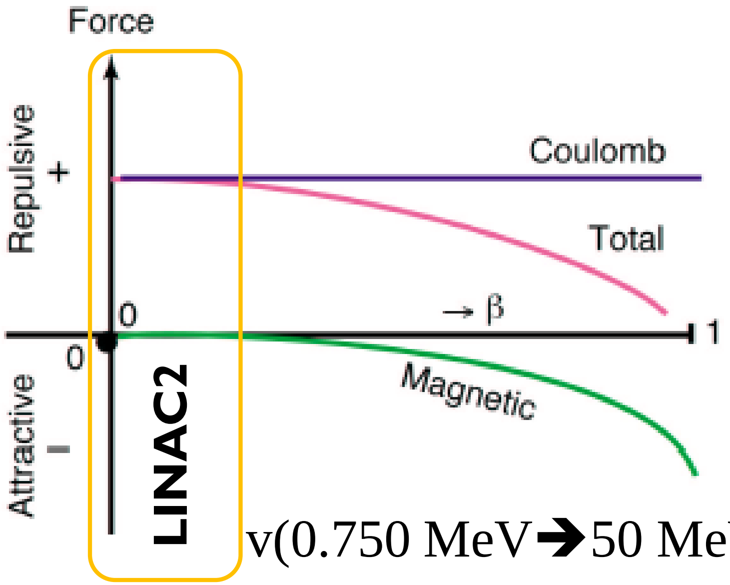
Backup slides

How Linac 4 contributes to reach the HL-LHC requirements?

Linac 2 (50 MeV) ➔ Linac 4 (160 MeV)

- At the beginning of the injector chain the particle energy is not yet relativistic
- Space charge = Coulomb repulsive force is a problem





$$\beta = \frac{v}{c}$$

v(0.750 MeV➔50 MeV)=4% ➔31% of c

- What can we do to suppress as much as possible the space charge?

We have to increase the velocity/energy of the particles as high as possible

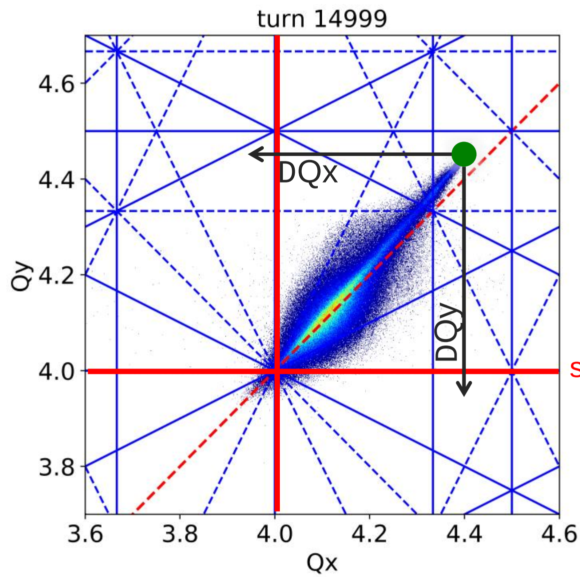
Linac 2 (50 MeV) ➔ Linac 4 (160 MeV)

- Space charge = Coulomb **repulsive force** is a problem

Defocusing force ➔ **changes the tune** of the particles

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

Increasing the energy decreases the tune change ☺



PSB simulation for 50 MeV inj.

strong resonances

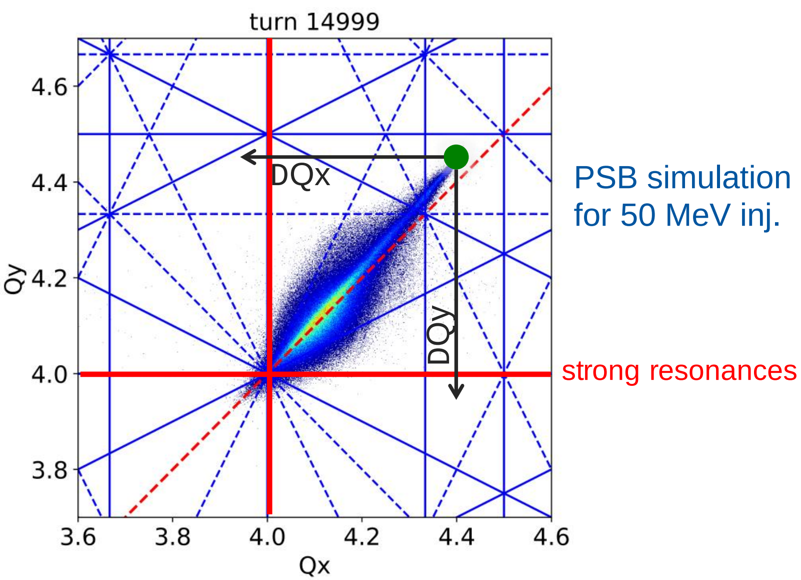
"Straight lines are forbidden areas for the beam"

Linac 2 (50 MeV) ➔ Linac 4 (160 MeV)

Defocusing force ➔ **changes the tune** of the particles

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

If one does the calculation it arrives to the conclusion that increasing the **Linac energy to 160 MeV** with respect to 50 MeV, **reduces the tune change by a factor of 2**.



But, we can operate the Booster with this tune spread!

How can we make **best** use of the factor 2 that we just gained?

We can increase by a factor of two the brightness ☺!!

	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (µm)
HL-LHC	2.3	2.1
Achieved	1.3	2.7

Injectors Post-LS2 era ➔ meet HL-LHC performance

How can we increase luminosity?

➔ Increasing the number of particles per colliding package (bunches) at the interaction point : N_1 and N_2

➔ Decreasing the size of the beams at the interaction point: σ's

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi \sqrt{\sigma_{1x}^2 + \sigma_{2x}^2} \sqrt{\sigma_{2y}^2 + \sigma_{2y}^2}} F$$

$$Brightness = N/\sigma$$

F: geometrical factors; can also be optimized to increase the luminosity

Injectors Post-LS2 era ➔ meet HL-LHC performance

How can we increase luminosity?

➔ Increasing the number of particles per colliding package (bunches) at the interaction point : N_1 and N_2

➔ Decreasing the size of the beams at the interaction point: σ's

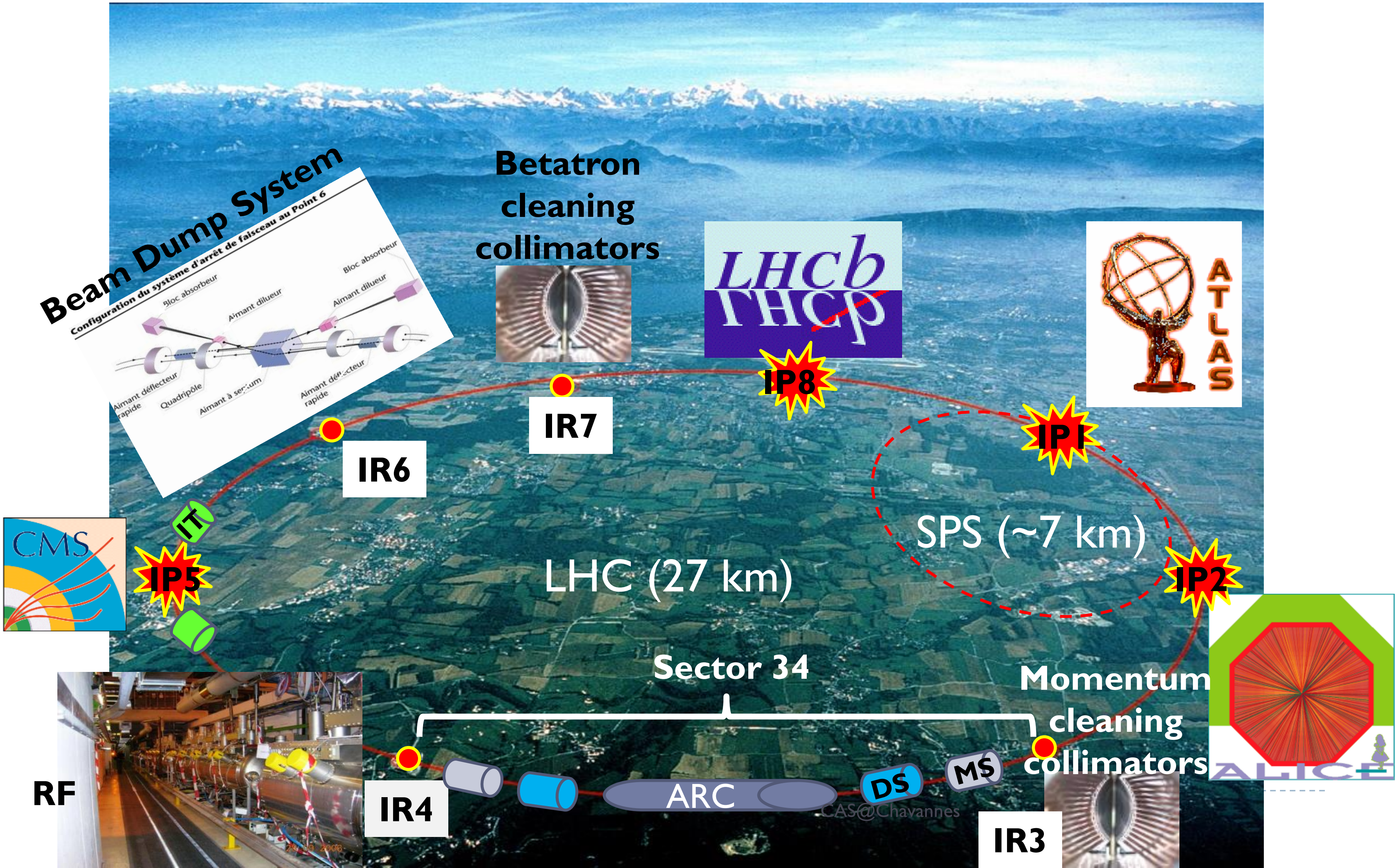
$$\mathcal{L} = \frac{N_1 N_2 f N_b}{2\pi\sqrt{\sigma_{1x}^2 + \sigma_{2x}^2}\sqrt{\sigma_{2y}^2 + \sigma_{2y}^2}} F$$

$$\sigma = \sqrt{\beta \frac{\epsilon_n}{(\beta\gamma)_{rel}}}$$

	N_b (x 10^{11} p/b)	$\varepsilon_{x,y}$ (μm)	Bunch/batch spacing	Bunches
HL-LHC	2.3	2.1	25 ns / 200 ns	4x72 per injection
Achieved	1.3	2.7	25 ns / 200 ns	4x72 per injection

How can we get there? ➔ LIU upgrades

Large Hadron Collider (LHC)

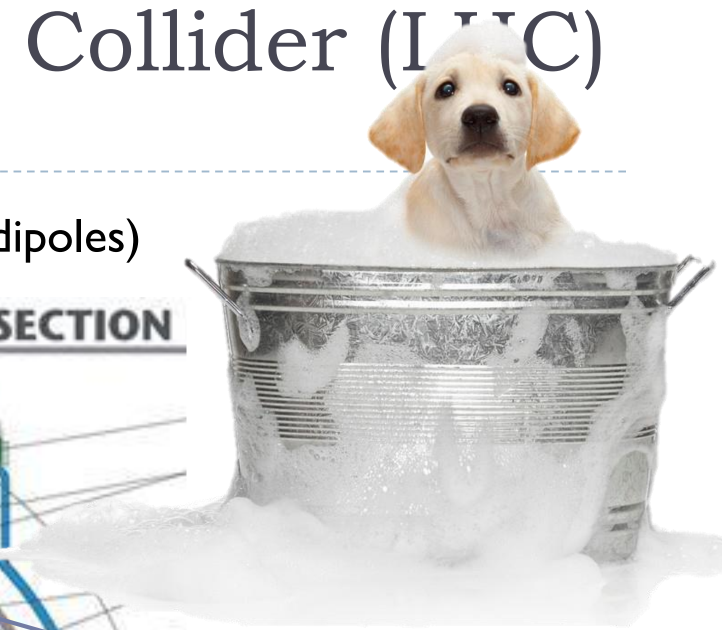


CAS@Chavannes

Large Hadron Collider (LHC)

Geometry of the main dipoles

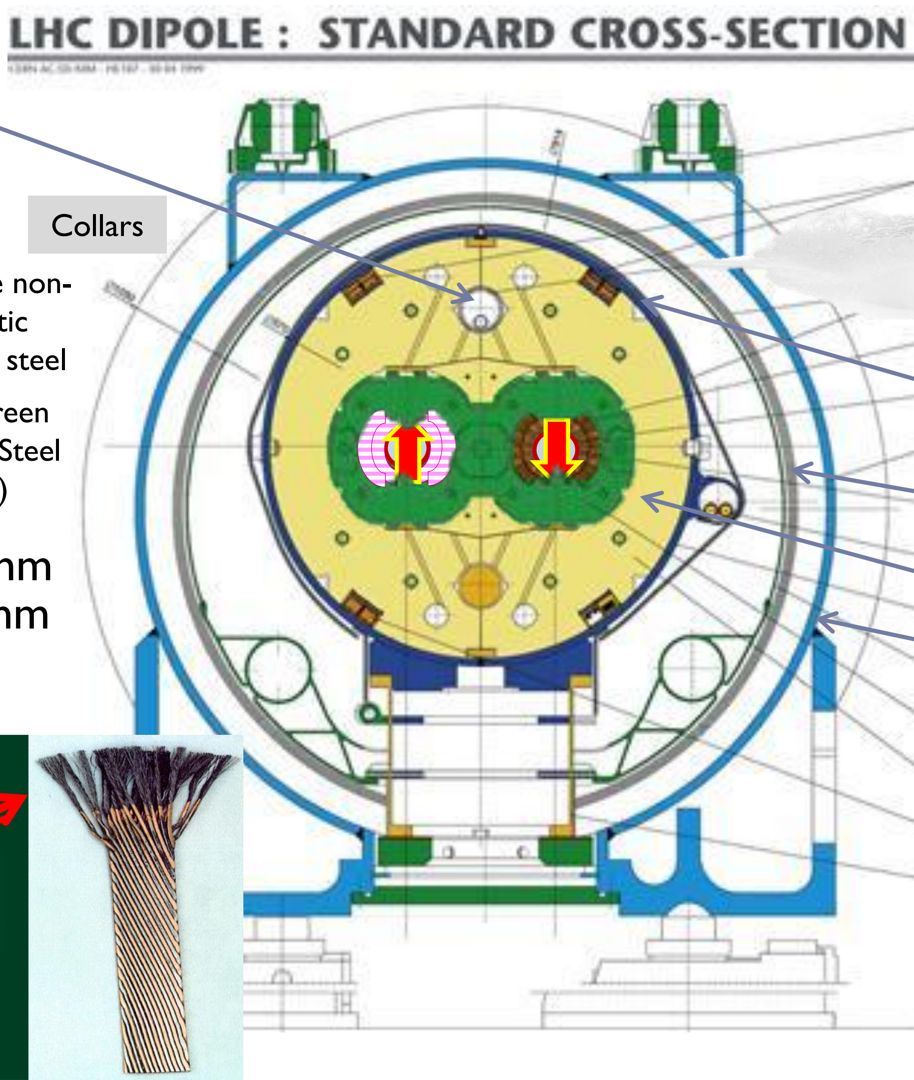
(Total of 1232 cryodipoles)

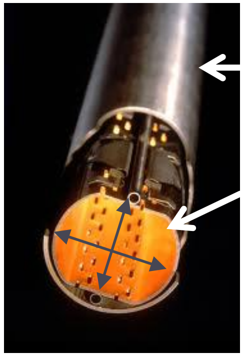


Heat exchanger

Beam pipe (Ultrahigh **beam** vacuum 10^{-10} Torr like at 1000 km over sea)

Collars





Cold bore non-magnetic austenitic steel

Beam Screen (Stainless Steel + Cu)

36.9 mm
46.5 mm

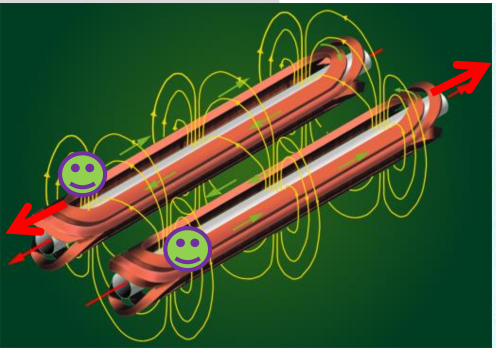
He Vessel

Thermal shield

Iron yoke

Vacuum vessel (10^{-6} mbar)

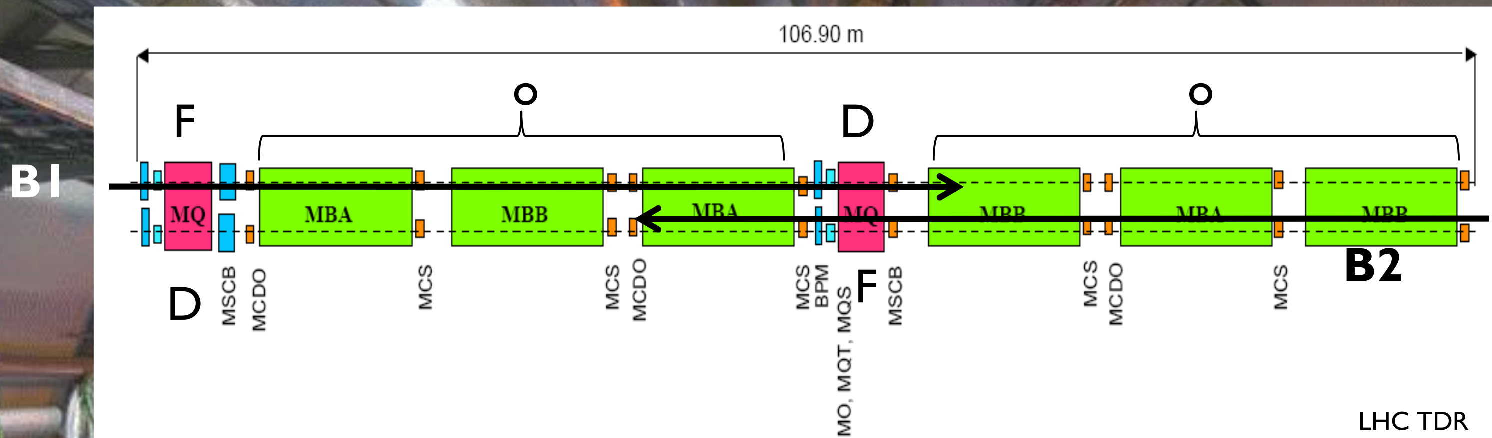
Superconducting coils



L ~ 15 m
8.3 T, 11.87 kA
T = 1.9 K, ~27.5 ton

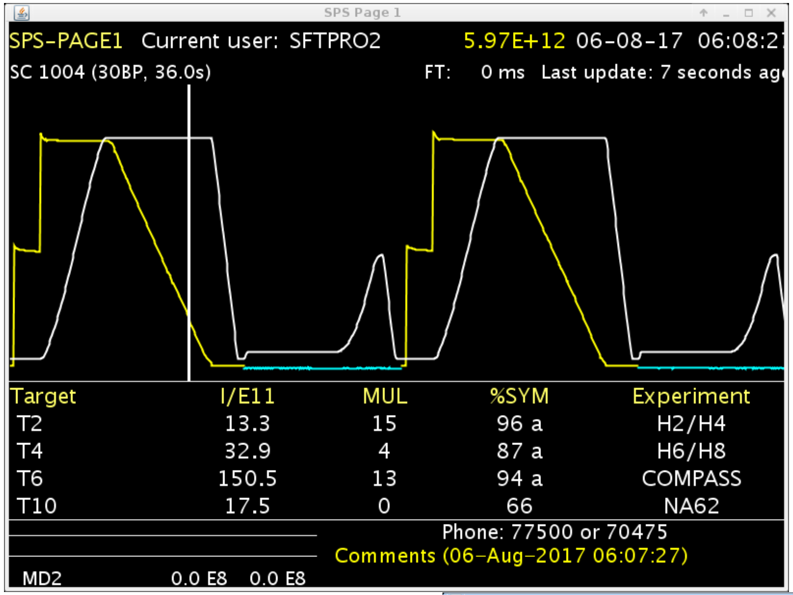
Large Hadron Collider (LHC)

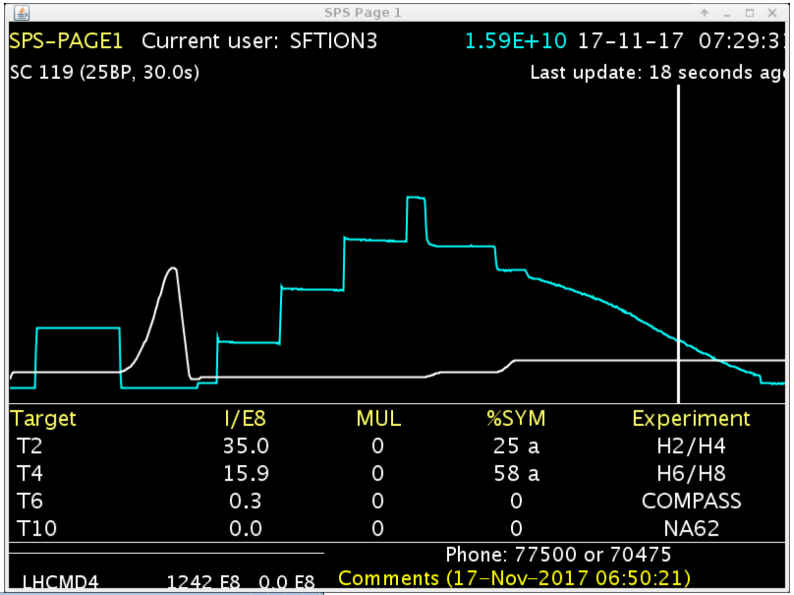
LHC arc cells = FoDo lattice* with
~ 90° phase advance per cell in the V & H plane

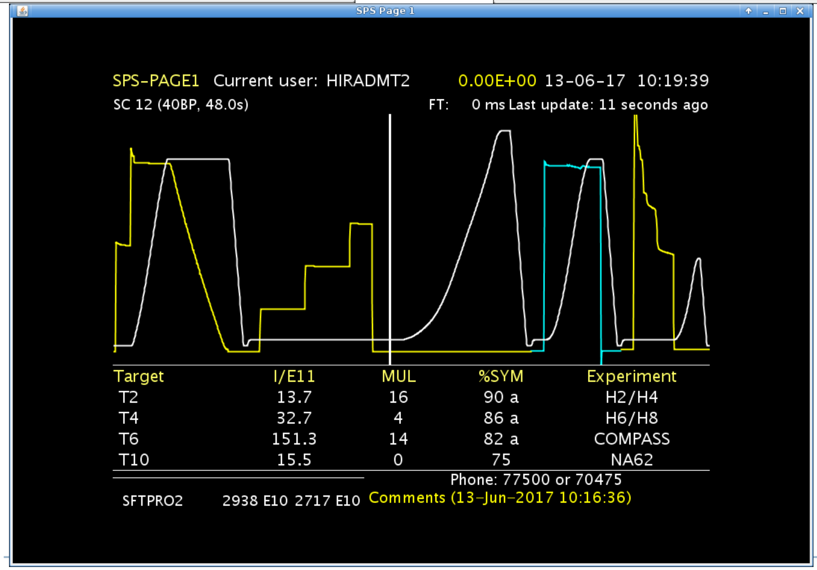


MB: main dipole
MQ: main quadrupole
MQT: Trim quadrupole
MQS: Skew trim quadrupole
MO: Lattice octupole (Landau damping)
MSCB: Skew sextupole + Orbit corrector (lattice chroma+orbit)
MCS: Spool piece sextupole
MCDO: Spool piece octupole + Decapole
BPM: Beam position monitor

Fast cycle machines E.g. SPS

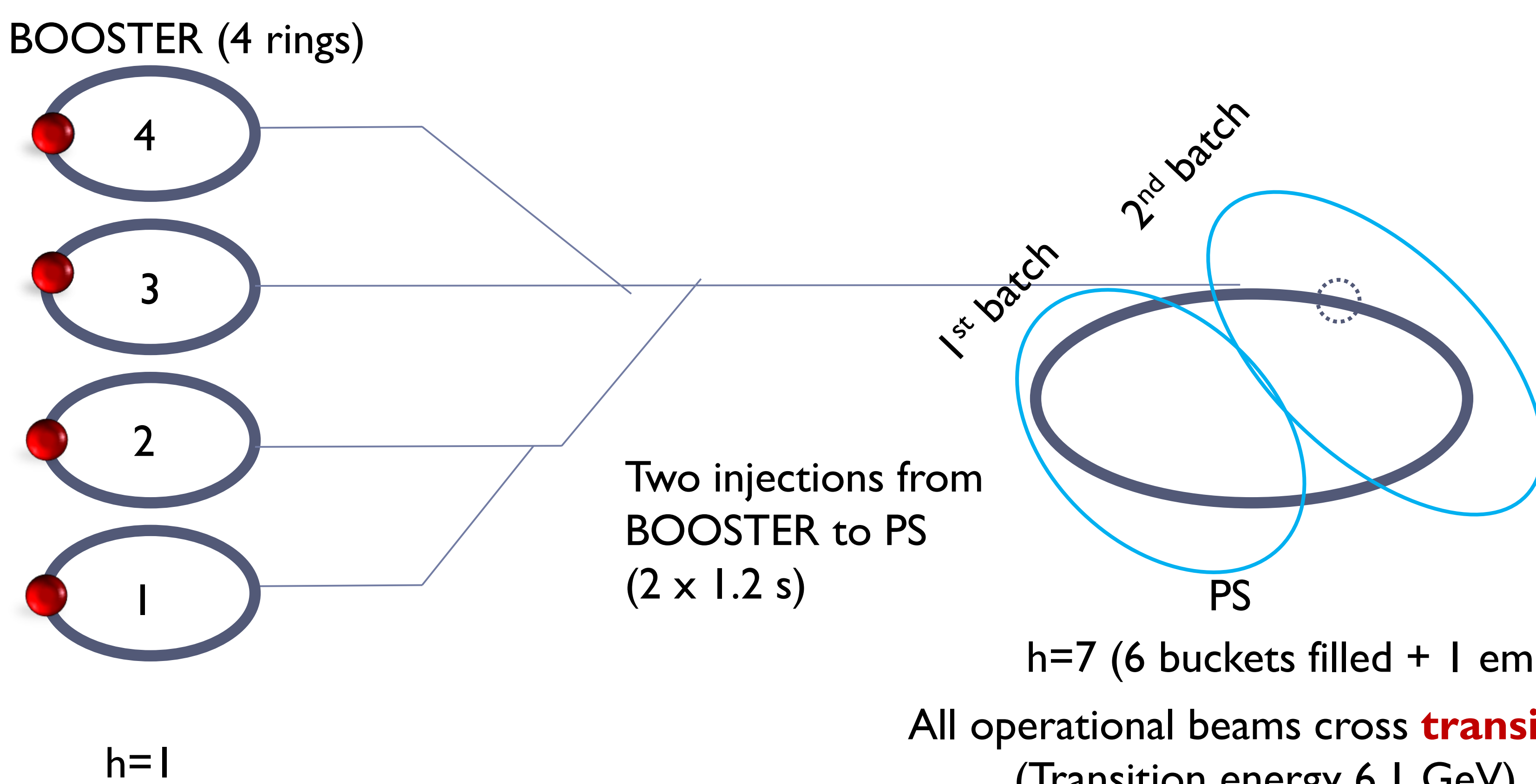






Proton Synchrotron (PS)

BOOSTER (2 GeV) ➔ PS (26 GeV) ➔ SPS (450 GeV) ➔ LHC

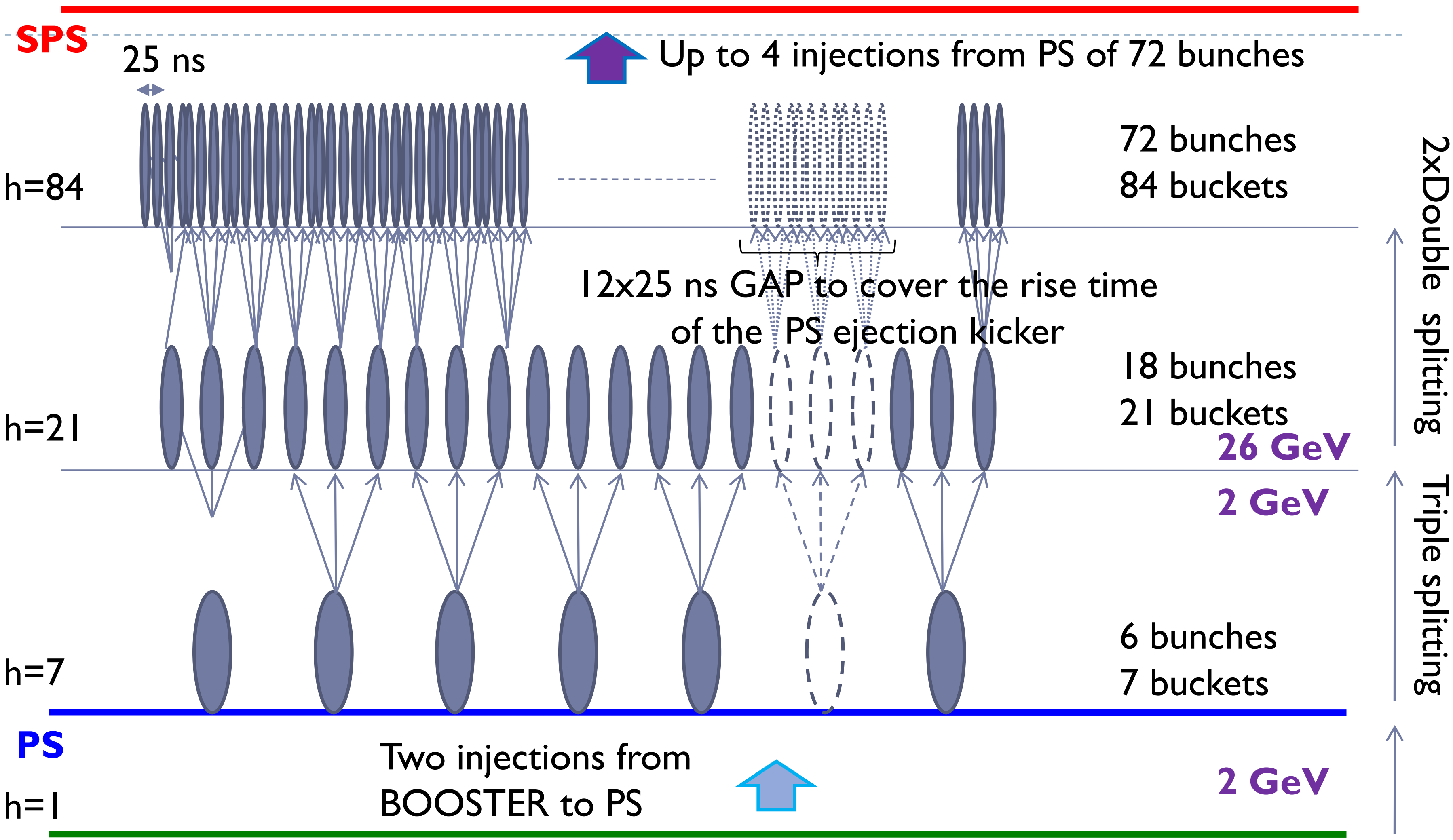


Two injections from BOOSTER to PS (2 x 1.2 s)

h=7 (6 buckets filled + 1 empty)

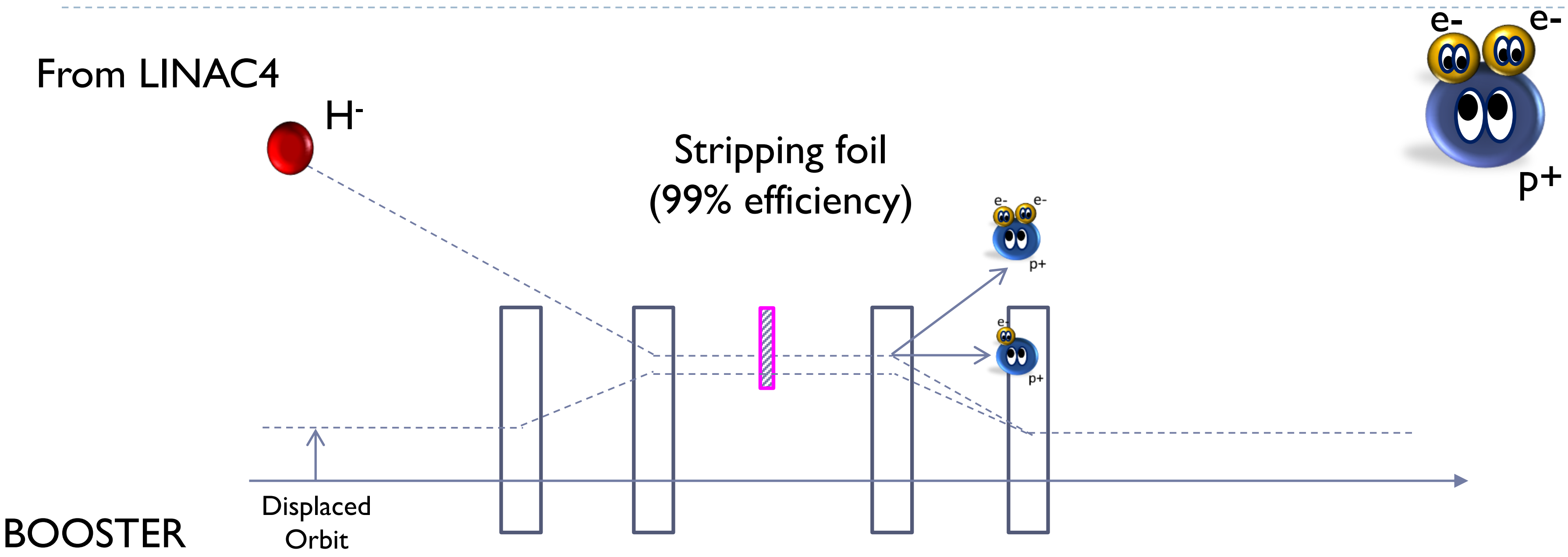
All operational beams cross **transition**
(Transition energy 6.1 GeV)

Proton Synchrotron (PS)

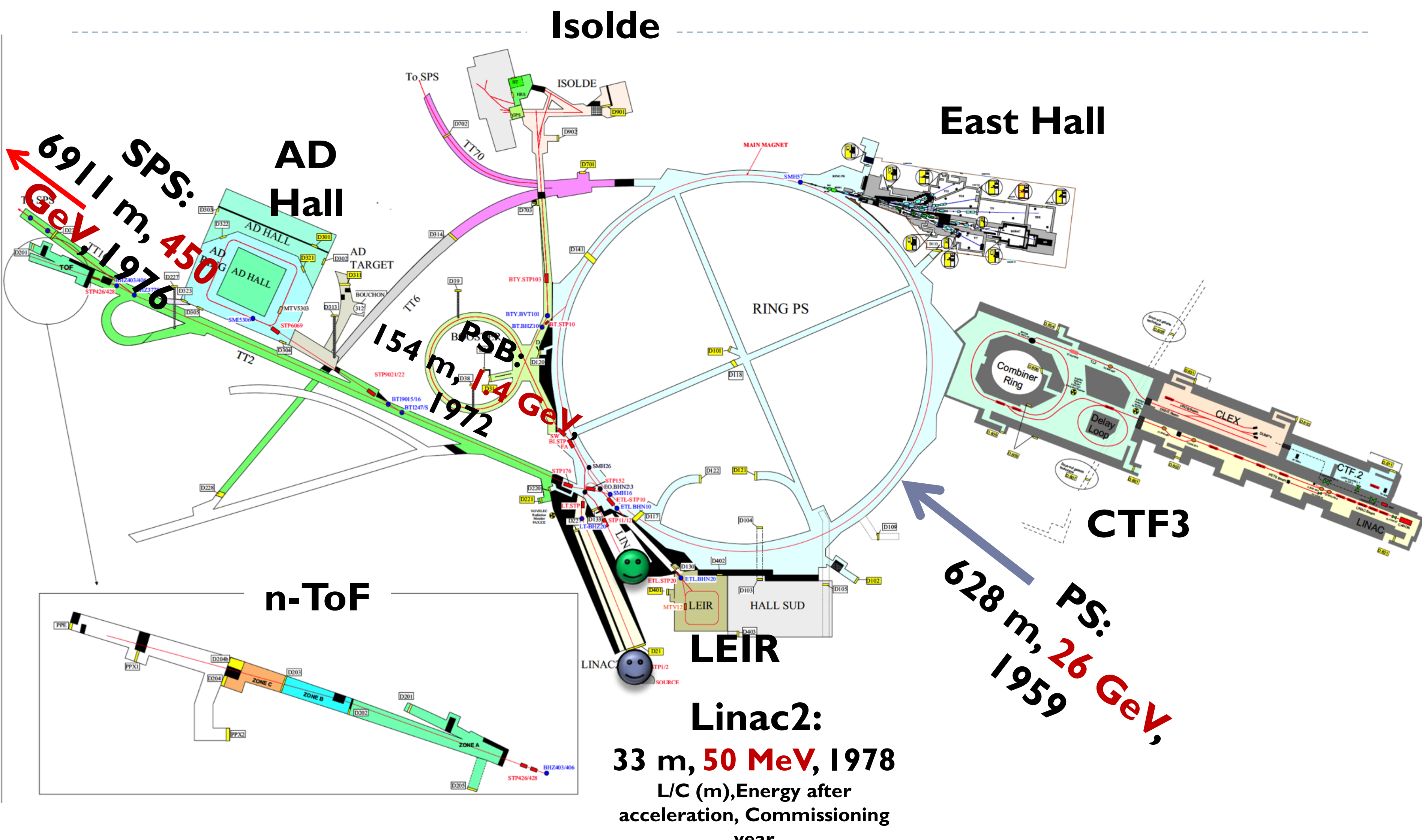


Nominal 25 ns beam production

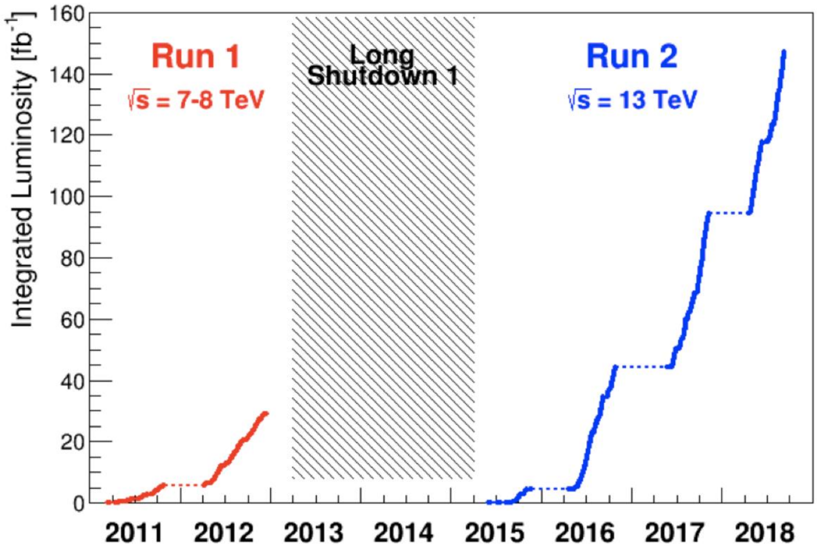
H⁻ Injection into the Booster



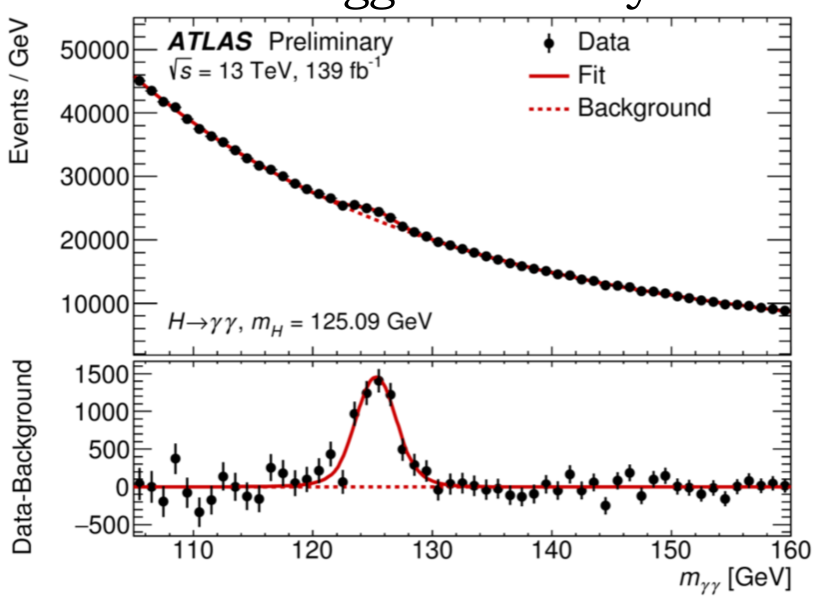
CERN injector accelerator complex



LHC Integrated performance



Higgs discovery



Further Reading

The LHC Design Report Volume 1: The LHC Main Ring, CERN-2004-003-V-1,
http://cds.cern.ch/record/782076/files/CERN-2004-003-V1.pdf

The LHC Design Report Volume 1: The LHC Infrastructure and Services, CERN-2004-003-V-2,
http://cds.cern.ch/record/782076/files/CERN-2004-003-V2.pdf

The LHC Design Report Volume 3: The LHC Injector Chain : CERN-2004-003-V-3:
http://cds.cern.ch/record/823808/files/CERN-2004-003-V3.pdf

Fifty years of the CERN Proton Synchrotron: Volume 1 :CERN-2011-004,
http://cds.cern.ch/record/1359959/files/cern-2011-004.pdf

Fifty years of the CERN Proton Synchrotron: Volume 2 :CERN-2013-005,
http://cds.cern.ch/record/1597087/files/CERN-2013-005.pdf

Linac4 Technical Design Report::
http://cds.cern.ch/record/1004186/files/ab-2006-084.pdf

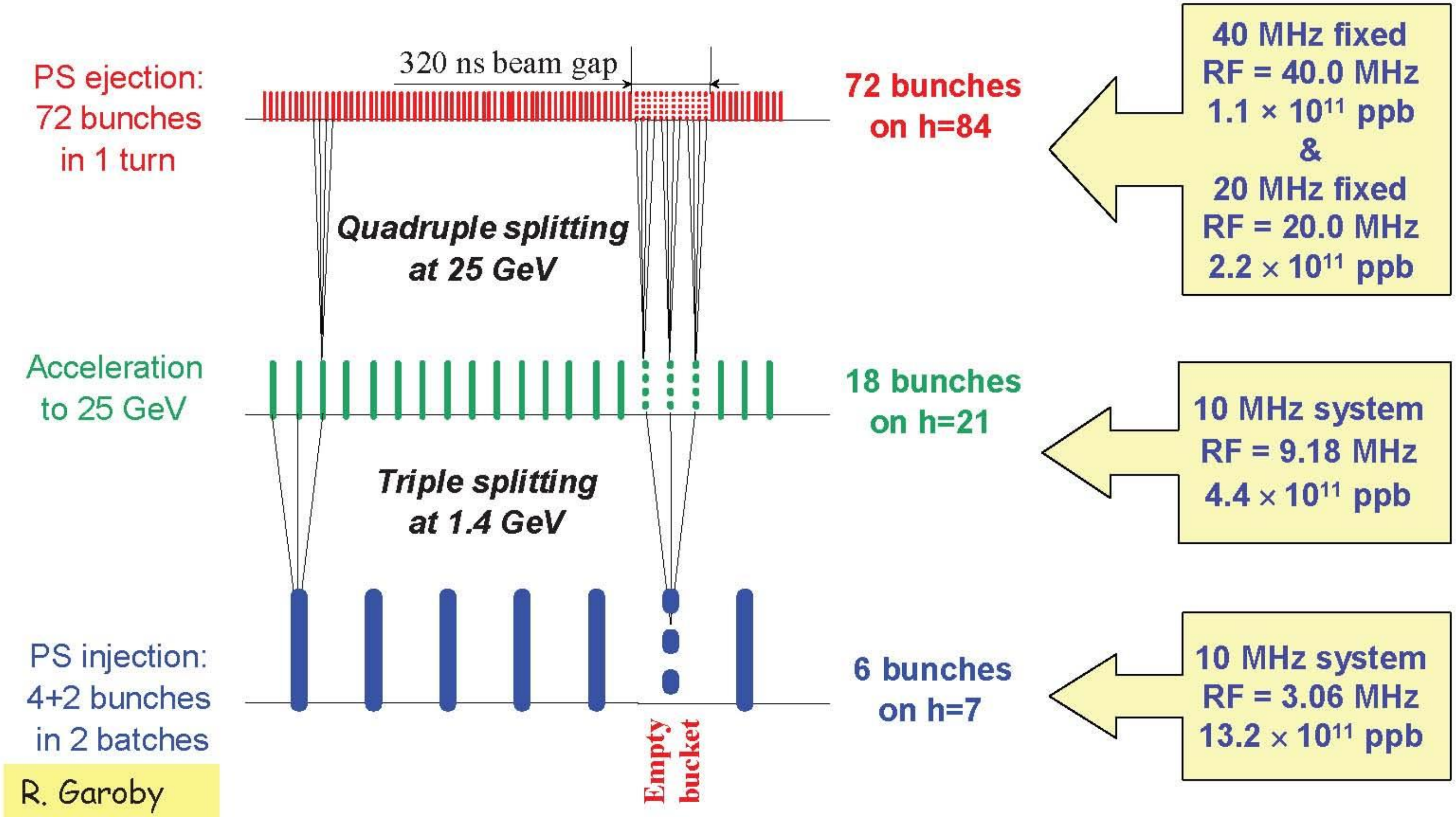
Elena Conceptual Design Report:
http://cds.cern.ch/record/1309538/files/CERN-BE-2010-029.pdf

AWAKE Technical Design Report:
http://cds.cern.ch/record/1537318/files/SPSC-TDR-003.pdf

HiRadMat:
http://cds.cern.ch/record/1403043/files/CERN-ATS-2011-232.pdf

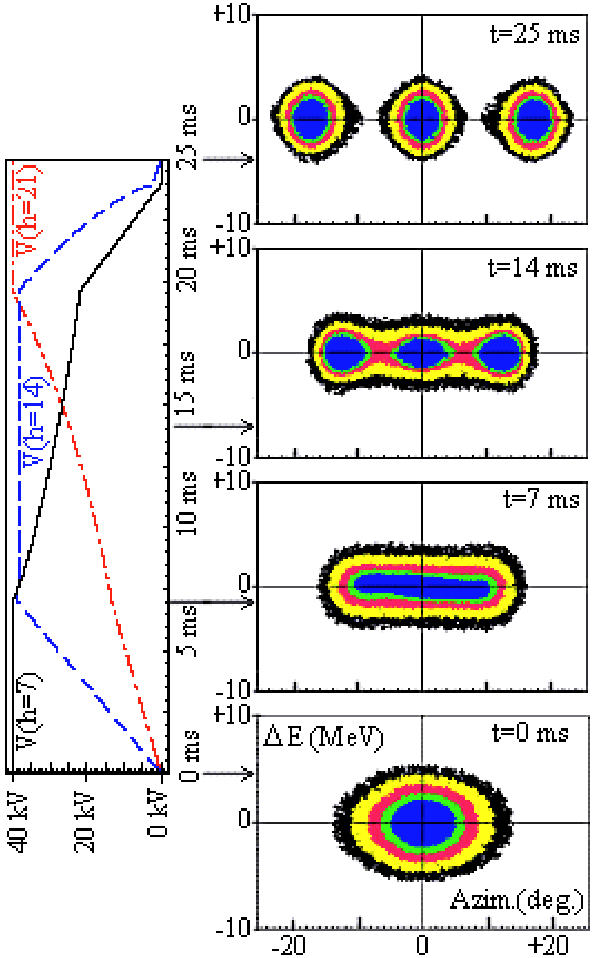
Generating a 25ns Bunch Train in the PS

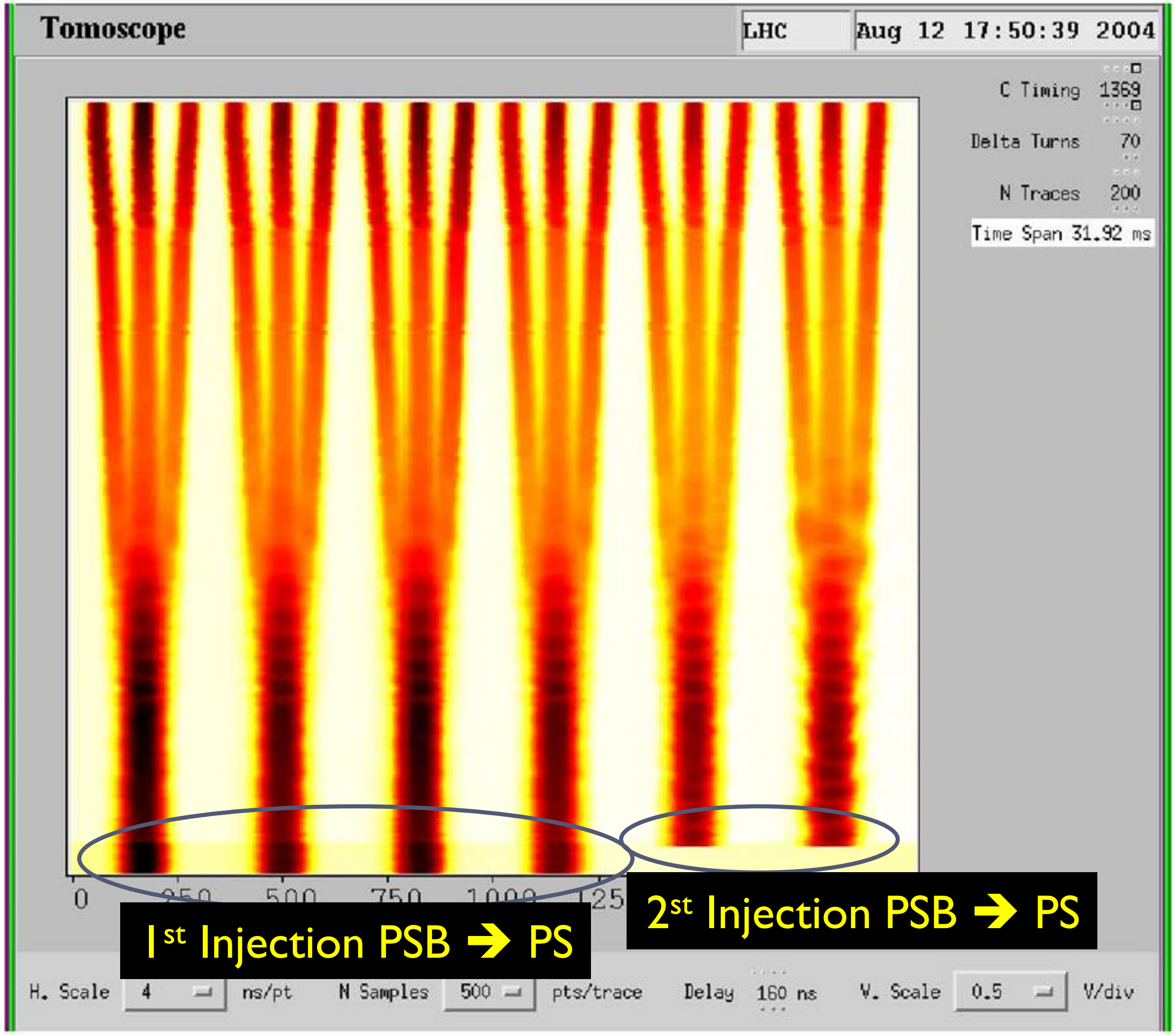
- **Longitudinal bunch splitting (basic principle)**
  - Reduce voltage on principal RF harmonic and simultaneously rise voltage on multiple harmonics (adiabatically with correct phase, etc.)



Use double splitting at 25 GeV to generate 50ns bunch trains instead

Proton Synchrotron (PS)





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

Large Hadron Collider (LHC)

Golden formula (you should know by heart)

$$B\rho = \frac{p}{Ze}$$

Circumference ➔ FIXED!!! by LEP

FIXED, no choice

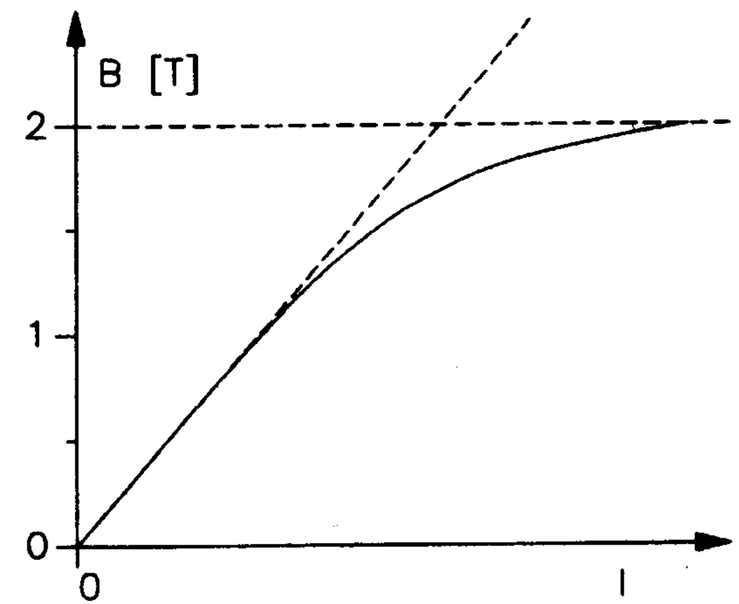
$$\rho \approx \frac{26658.9\ m}{2\pi} \cdot 66\% \approx 2780\ m$$

~ 66% of the lattice elements are dipoles

p = nucleon momentum ➔ defined by the physics case ➔ TeV range ➔ **7 TeV**

$$B = \frac{p}{\rho Ze} \approx 3.33 \frac{p\left(\frac{GeV}{c}\right)}{\rho(m)} = 8.39\ T$$

We need SUPERCONDUCTING technology

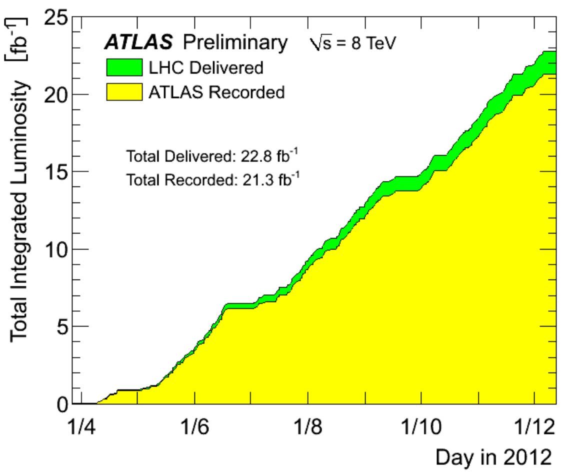


Field limit for normal conducting magnets due to saturation

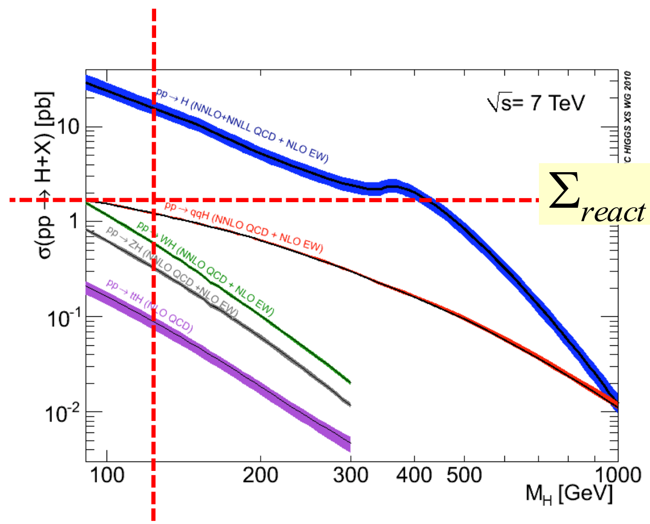
Large Hadron Collider (LHC)

Production rate of events is determined by the cross section Σ_{react} and a parameter L that is given by the design of the accelerator:
… the luminosity

$$R = L * \Sigma_{react} \approx 25 \frac{1}{10^{-15} b} 10^{-12} b = some\, 1000 H$$



remember:
1b=10^{-24} cm^2



$$\Sigma_{react} \approx 1\, pb$$

Integrated luminosity during RUN I

$$\int L dt \approx 25\, fb^{-1}$$

Official number: 1400 clearly identified Higgs particles "on-tape"

Overall Protons Delivered in 2012

Facility	Protons Deliverd	% of Total
Isolde	$1.15x10^{+20}$	63.8%
CNGS	$3.9x10^{+19}$	21.6%
n-TOF	$1.9x10^{+19}$	10.2%
The rest	$8.13x10^{+18}$	4.5%
LHC	$3.25x10^{+16}$	0.018%
Total	$1.81x10^{+20}$	

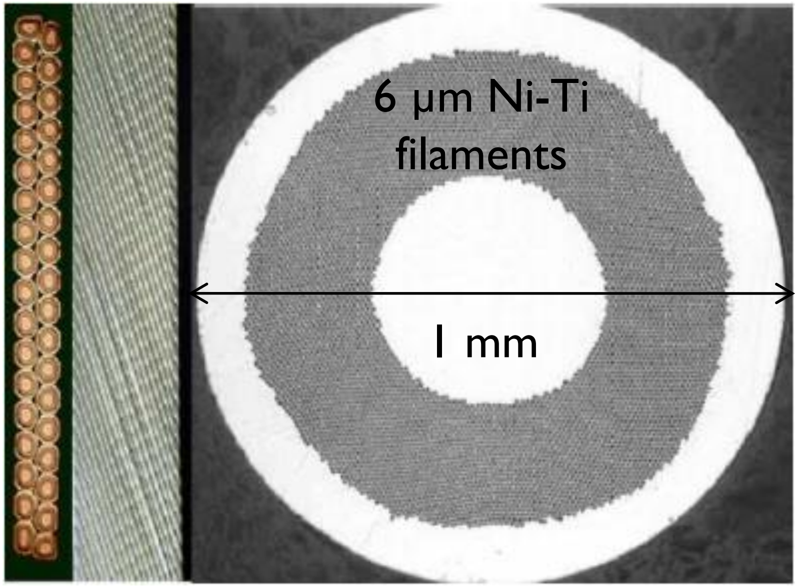
Colliders are very Efficient!

The LHC Physics Program Used 0.018% of the protons produced in CERN accelerators during 2012!

- **Intensities as delivered to the facility, upstream losses ignored,**
- **Beams for Machine Setup and Studies Excluded**
- **The total delivered protons represents roughly 0.27mg (rest mass!)**

Large Hadron Collider (LHC)

Superconducting cables of Nb-Ti

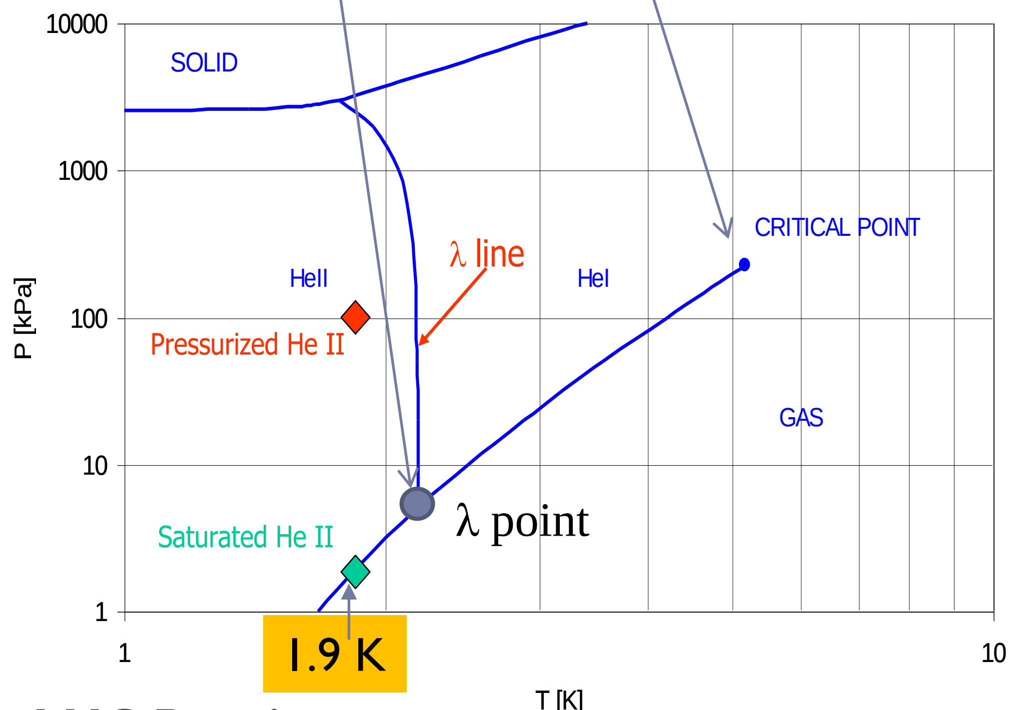


LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power station

Liquid Nitrogen

Cold compressors

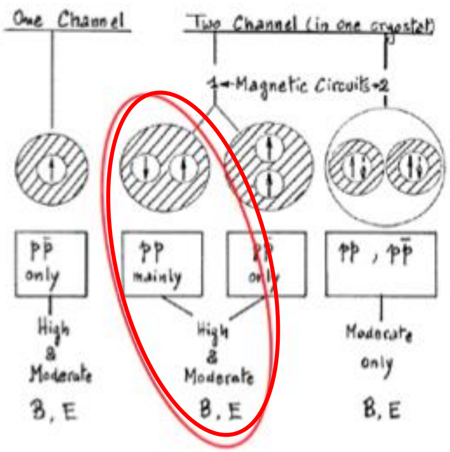
He gas ➔ liquid @ 4.2 K ➔ superfluid @ 2.17 K



LHC Requires

- **90,000 T of liquid Nitrogen**
- **130 T of Liquid Helium to keep it cold**

ECFA-CERN workshop



June 1994
first full scale prototype dipole

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

June 2007 First sector cold

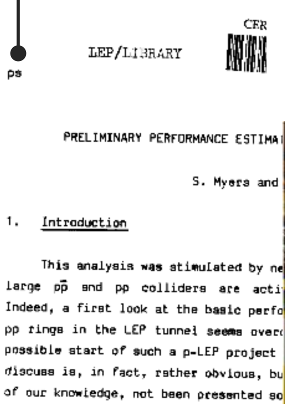
April 2008
Last dipole down

25 y

SSC cancelled

Main contracts signed

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



ps

LEP/LIBRARY

CER

PRELIMINARY PERFORMANCE ESTIMA

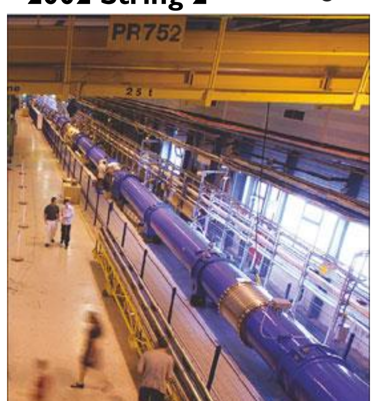
S. Myers and

1. Introduction

This analysis was stimulated by ne
large pp̄ and pp colliders are acti
Indeed, a first look at the basic perfo
pp rings in the LEP tunnel seems overc
possible start of such a p-LEP project
discuss is, in fact, rather obvious, bu
of our knowledge, not been presented so

First set of twin 1 m prototypes Over 9 T

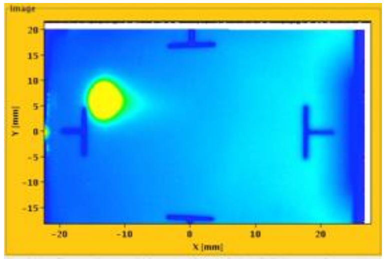
2002 String 2

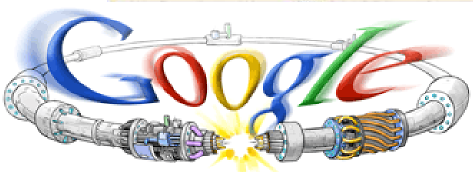


November 2006
1232 delivered

September 10, 2008
First beams around

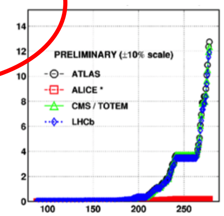
August 2008
First injection test





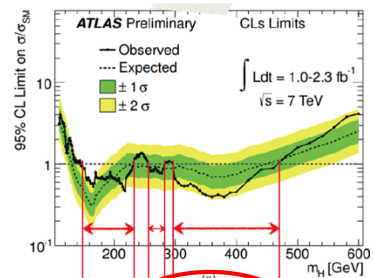
Sept. 10, 2008
First beams around

November 29, 2009
Beam back



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

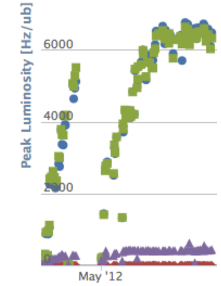
Repair and Consolidation



October, 2011
3.5x10^{+33}, 5.7 fb^{-1}
First Hints!!

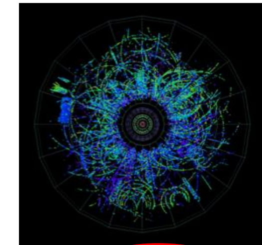
June 28 2011
1380 bunches

1380

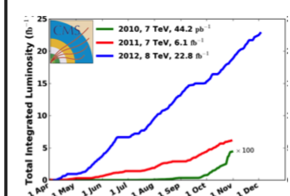


May 2012
Ramping
Performance

March 14th 2012
Restart
with Beam



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

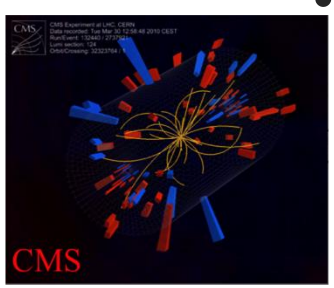


Nov. 2012
End of p^{+} Run I

2008 | 2009 | 2010 | 2011 | 2012 | 2013

Sept. 19, 2008
Disaster

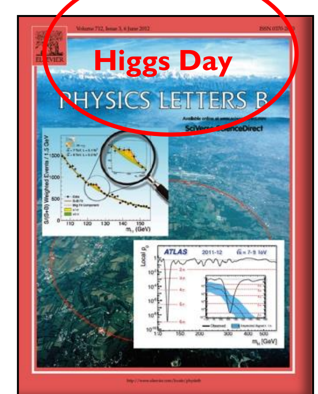
March 30, 2010
First collisions at 3.5 TeV



November 2010
Pb^{82+} Ions

November 2011
Second Ion Run

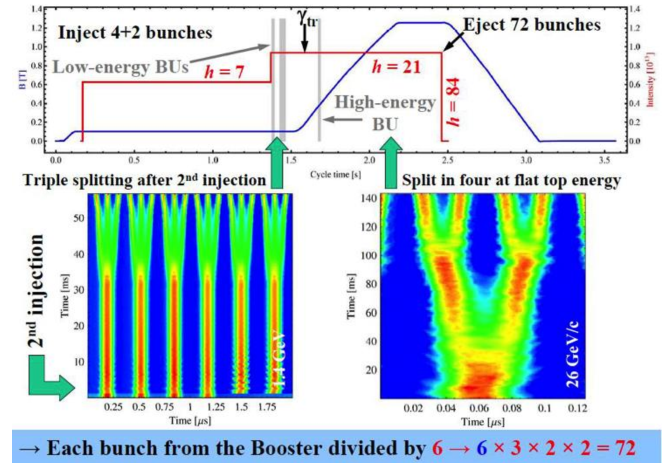
Higgs Day



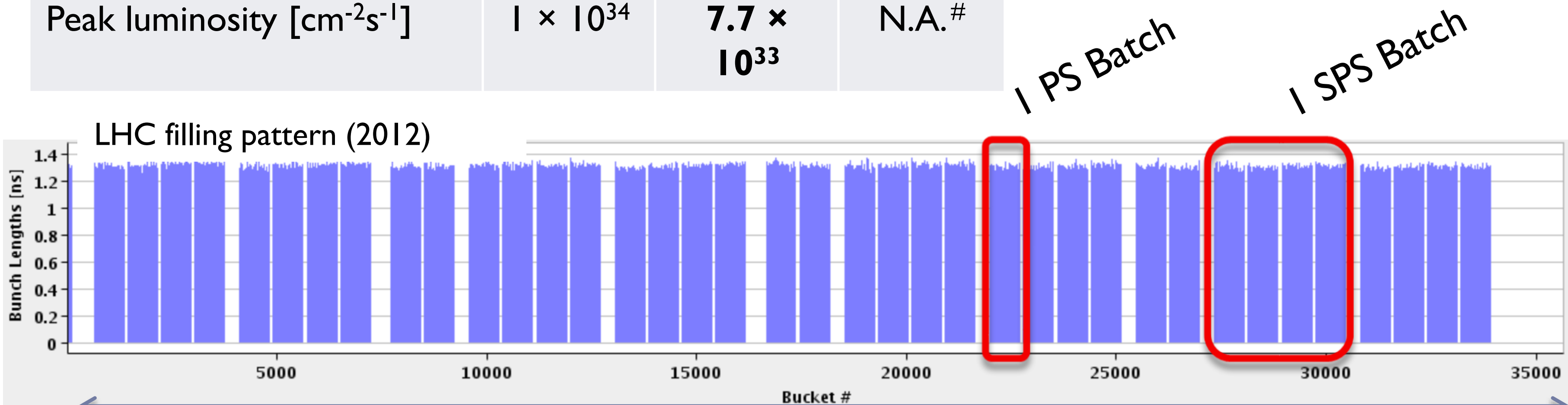
LS1

Filling the LHC (2012)

	25 ns (design)	50 ns (2012)	25 ns (2012)#
Energy per beam [TeV]	7	**4**	4
Intensity per bunch [$\times 10^{11}$]	1.15	**1.7**	1.2
Norm. Emittance H&V [μm]	3.75	**1.8**	2.7
Number of bunches	2808	**1380**	N.A.#
β* [m]	0.55	**0.6**	N.A.#
Peak luminosity [$cm^{-2}s^{-1}$]	1×10^{34}	**7.7×10^{33}**	N.A.#



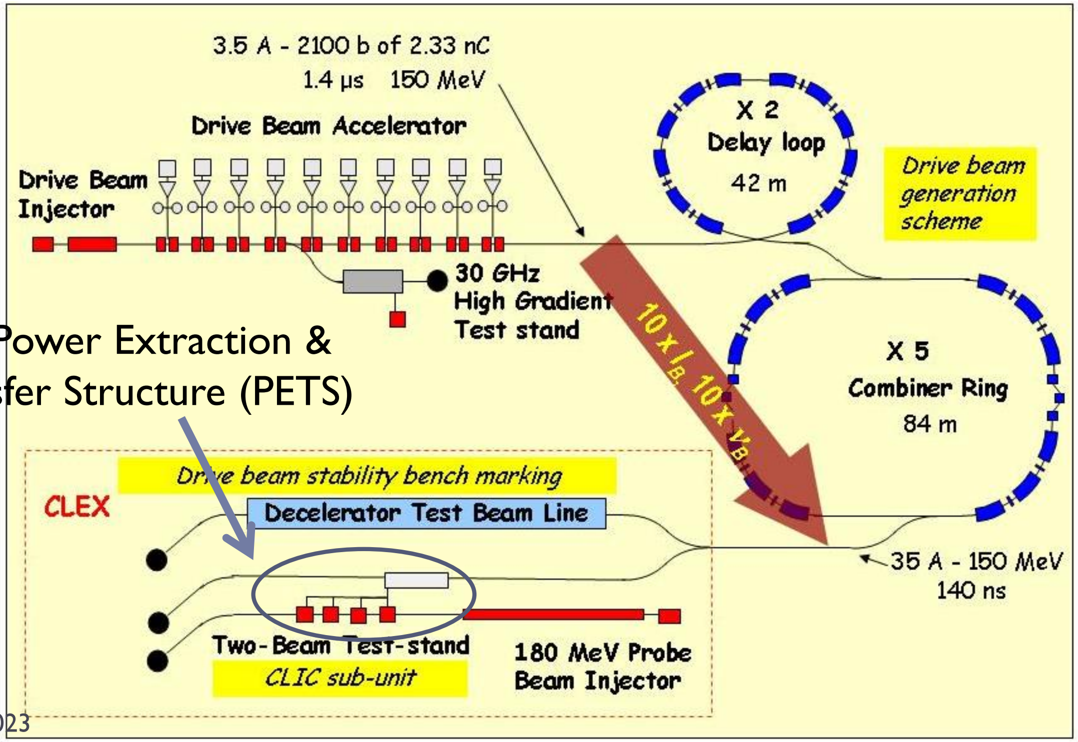
The 25 ns PS production scheme (2012)



The 25 ns was only used for scrubbing and tests in 2012

CTF 3 – CLIC Test Facility

RF Power Extraction & Transfer Structure (PETS)



CLIC goal:

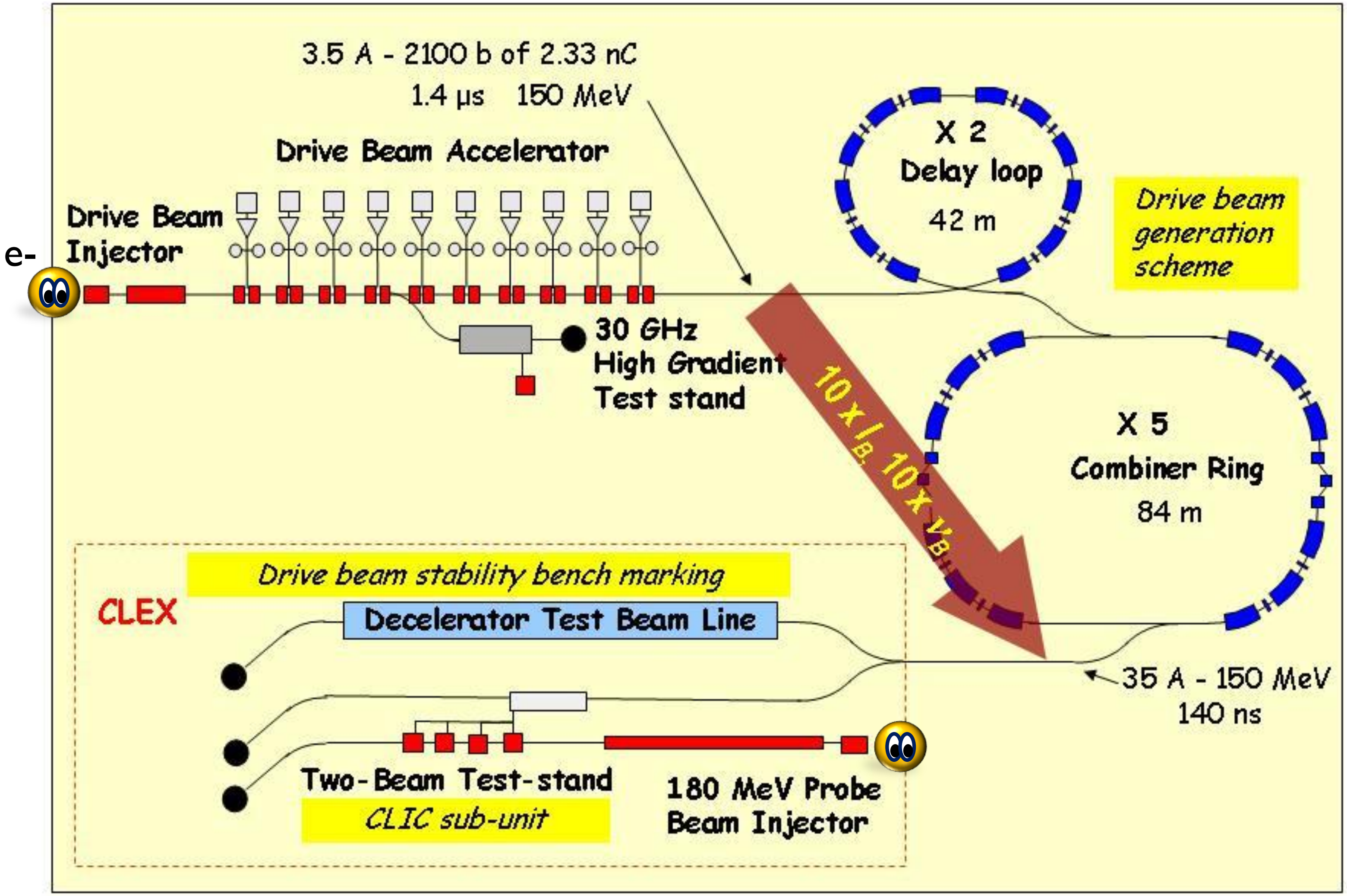
Drive Beam 100 A, 239 ns

2.38 GeV → 240 MeV

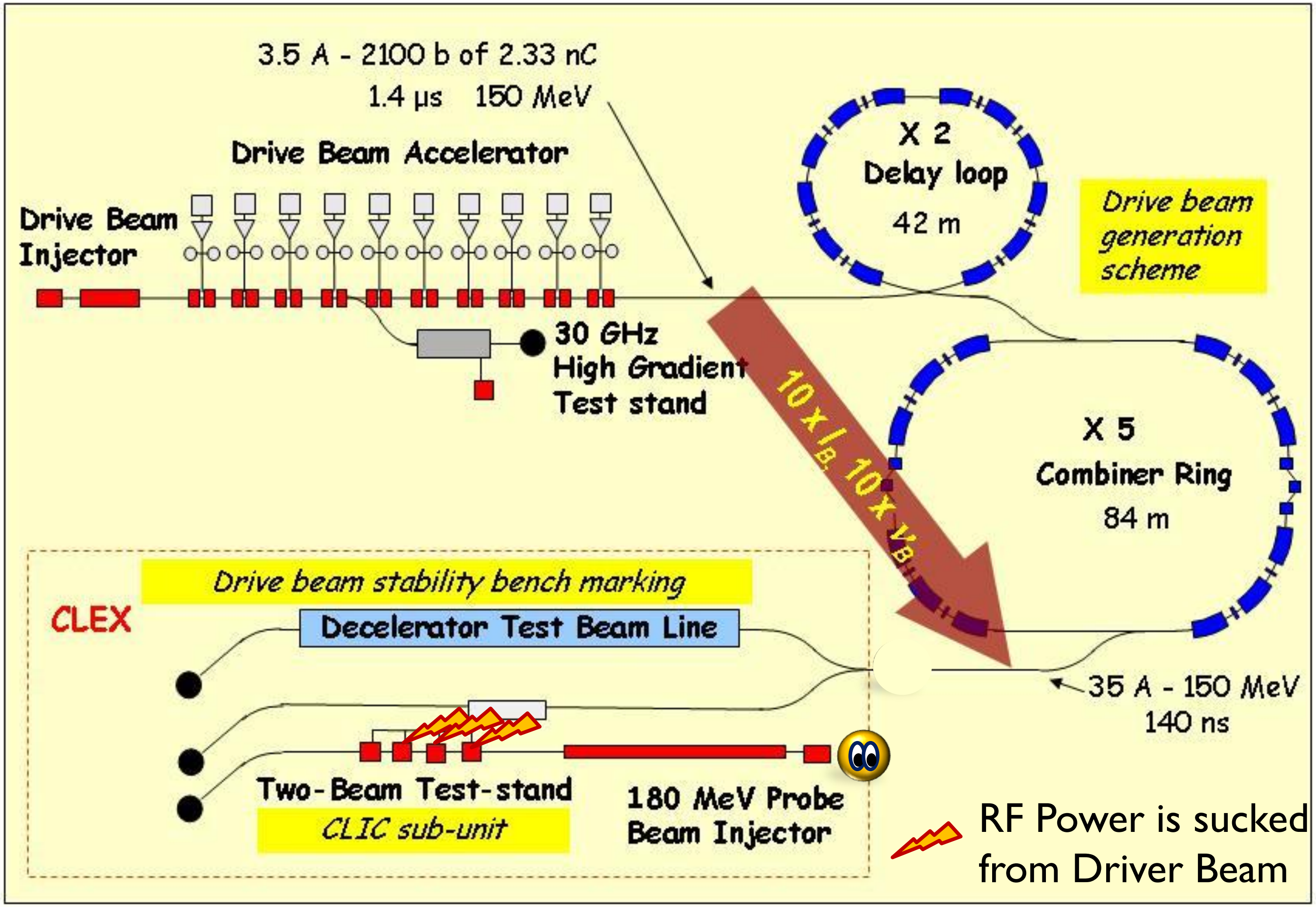
Main Beam 1.2 A, 156 ns

9 GeV → 1.5 TeV

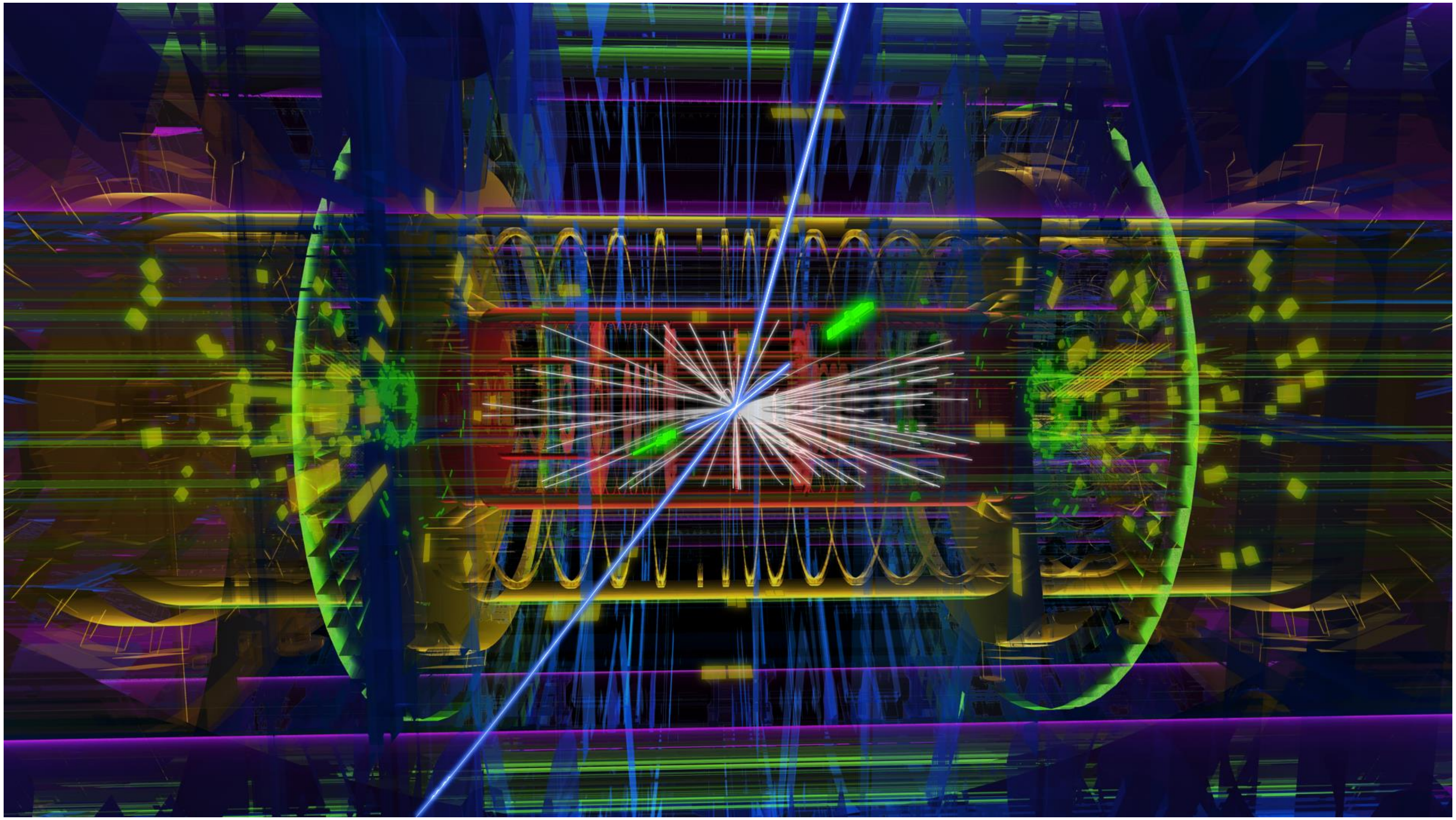
CTF 3 – CLIC Test Facility



CTF 3 – CLIC Test Facility



High Light Of HEP -Year

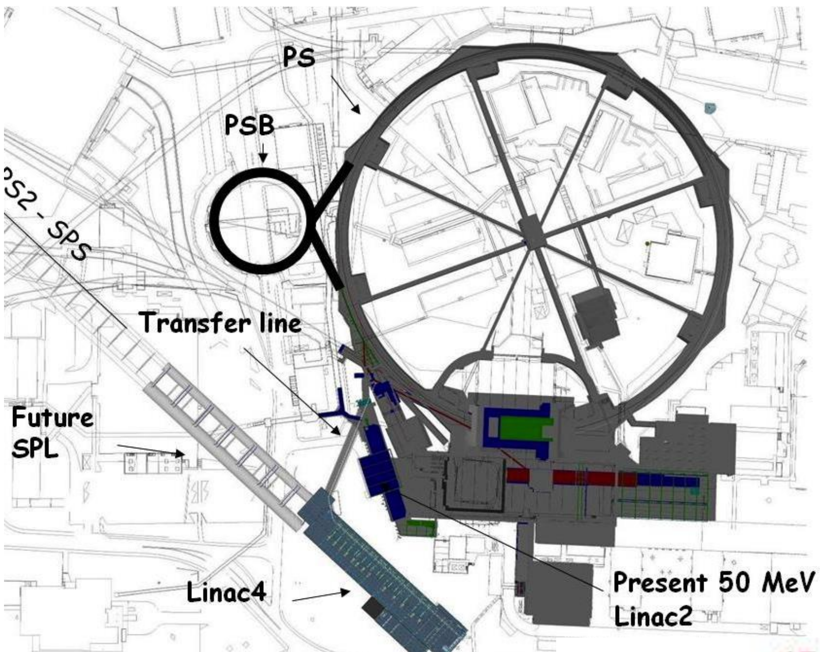


ATLAS event display: Higgs => two electrons & two muons

Linac4 : Replacing Linac2

Linac4 : Approved in 2007 as a replacement to Linac2

- Energy 160 MeV (cf 50 MeV in Linac2) Doubles the space charge tune shift limit at injection into the PS Booster
- H- Injection : CERN is one of the few labs still using p^+
- Connection to PSB LS2 (~ 2019)



50 Mev → 160 MeV

0.31*1.12=0.35 →0.52*1.37=0.70

$\Delta Q_{LINAC4} \approx$ **0.5**ΔQ_{LINAC2}

$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

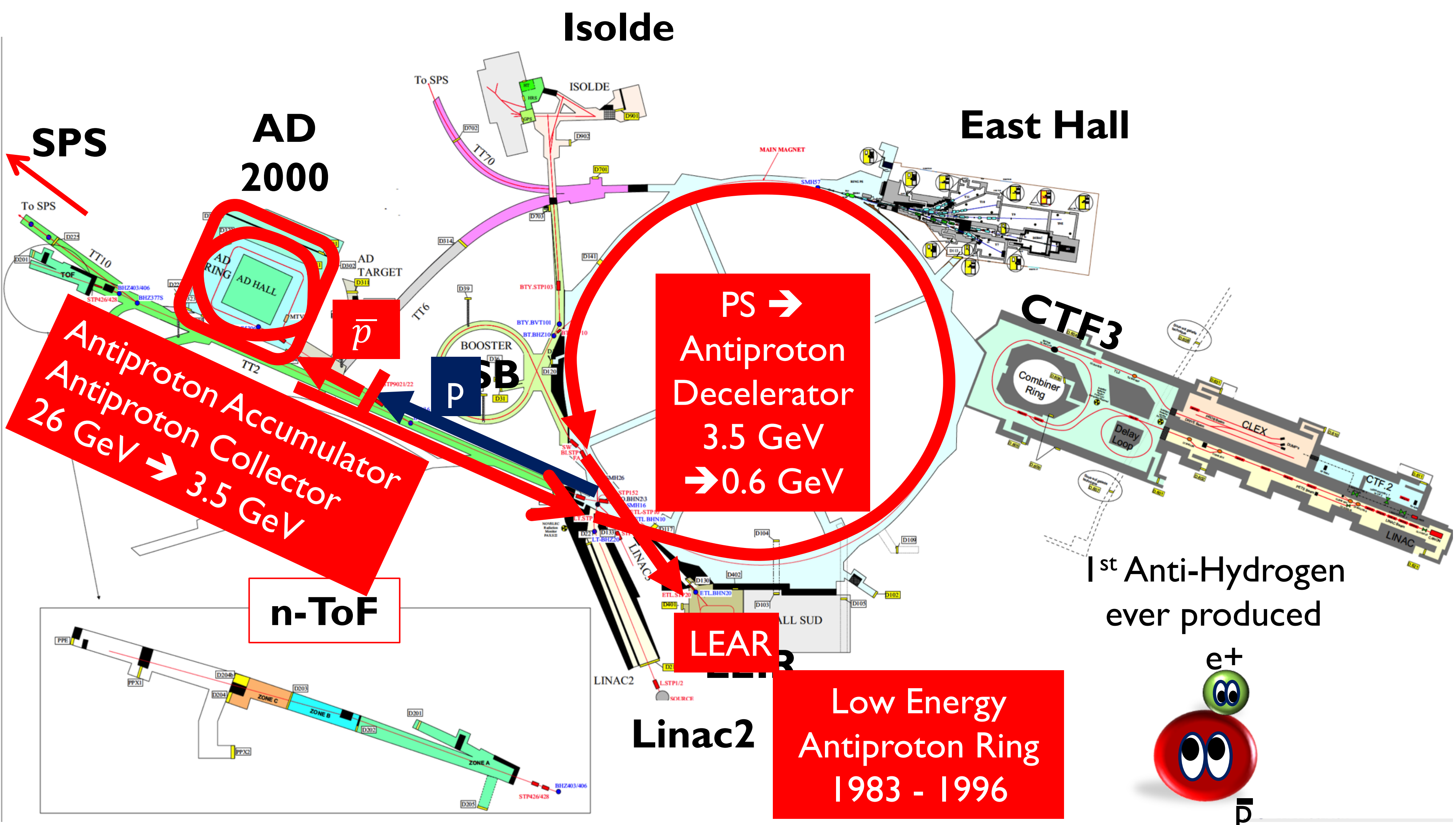
with N_b : number of protons/bunch

$\varepsilon_{X,Y}$: norm. transverse emittances

R : mean radius of the accelerator

Delivers 40 mA, 400 μs pulses at 2 Hz

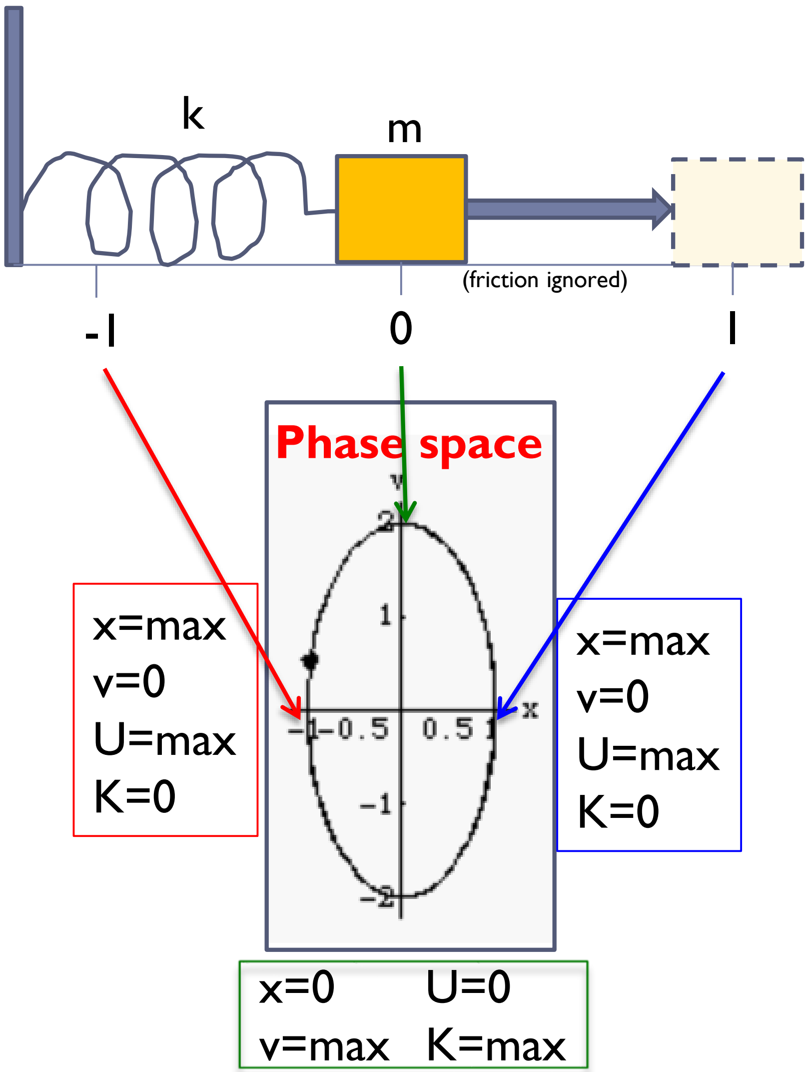
History of the Antiproton Decelerator Chain



Let me open a parenthesis here to talk about

EMITTANCE and PHASE SPACE

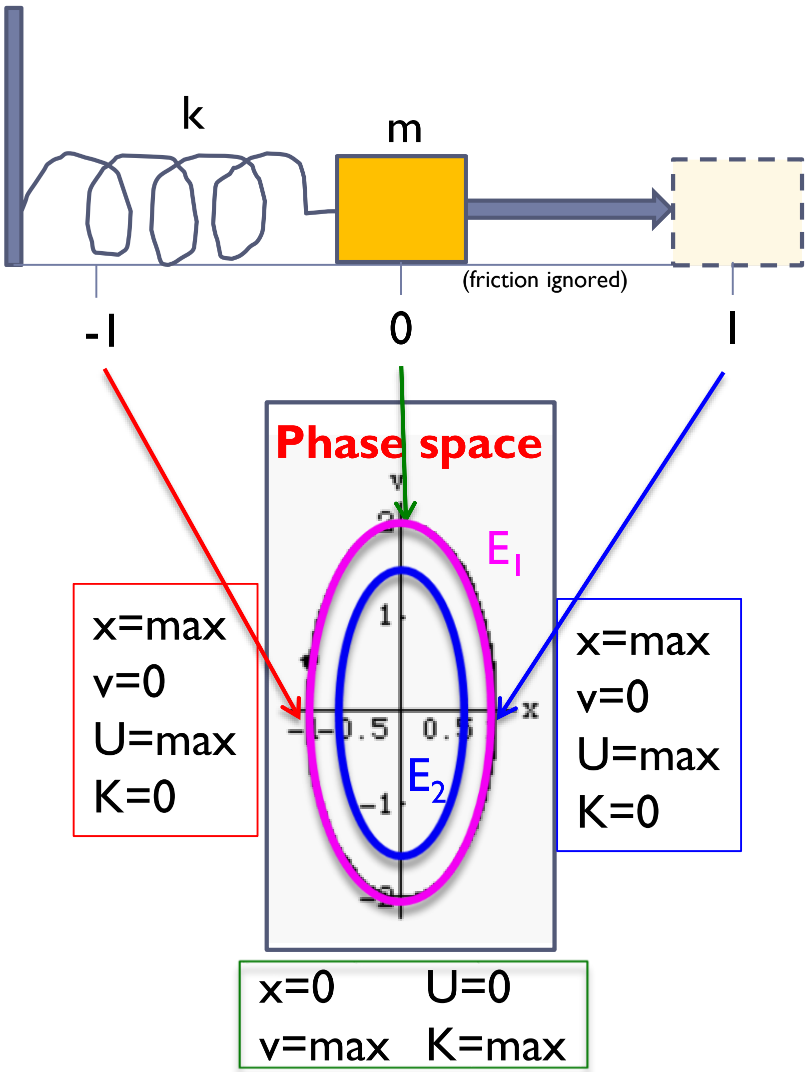
(Phase space and emittance)



U=potential energy
K=kinetic energy

Analysis of **x=f(t)** ➔ provides information about the **path** taken by the system **BUT NOT** about the **energy**.
Analysis of **v=f(t)** ➔ provides information about the **energy** of the system **BUT NOT** about the **trajectory** taken.
… Let's be inventive and try to analyse the evolution of the velocity as a function of position v=f(x)

(Phase space and emittance)



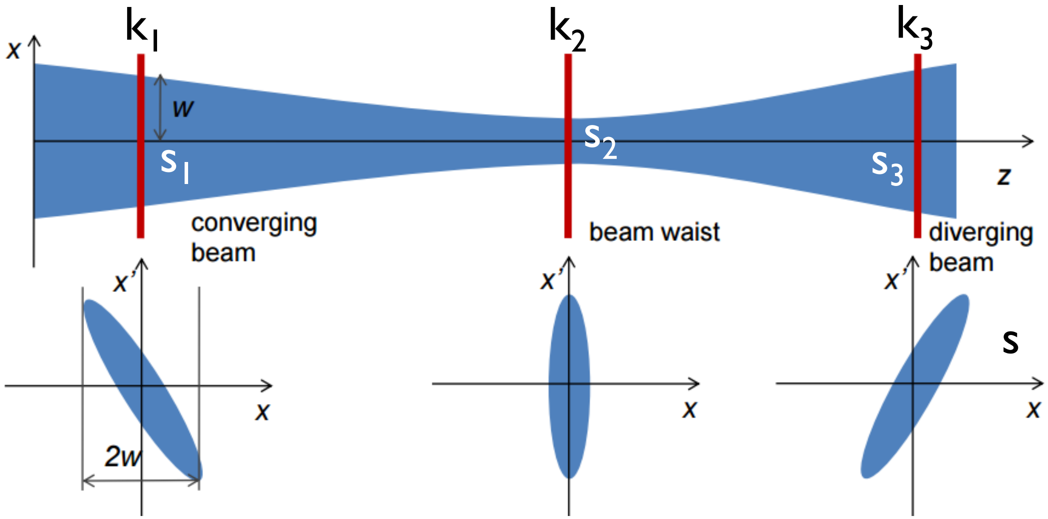
U=potential energy
K=kinetic energy

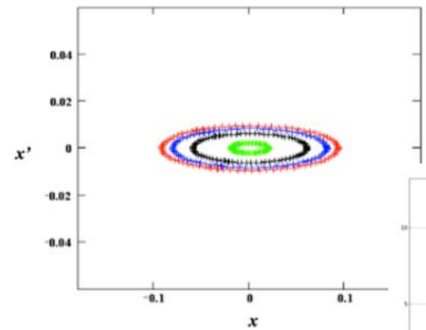
- Each point (x,v) in the ellipse represents an STATE of the physical system with well define position and velocity.
- All the points (x,v) in the ellipse have the SAME ENERGY (E_1)
- If the initial elongation is smaller, then we get a smaller ellipse with energy E_2 ($E_2<E_1$).
- If we change K the ellipse shape will change.

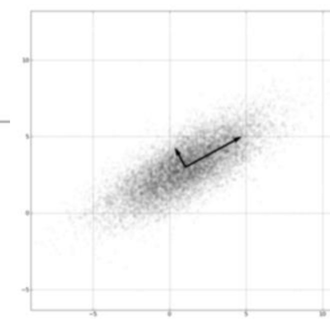
A **beam of charged particles** in an accelerator subjected to **focusing and defocusing forces** have the same dynamics as the system above. The beam dynamics also **reproduces an ellipse in phase space** …

(Phase space and emittance)

All particles with the **<u>same initial betatron amplitude</u>** (equivalent to x) at a given position in the accelerator (or time) but different phases or momentum due to momentum spread (equivalent to v), describe the **same ellipse** turn after turn







Along a beam line, the orientation and aspect ratio of the ellipse varies, **BUT THE AREA** remains **CONSTANT** in the absence of non-linear forces or acceleration

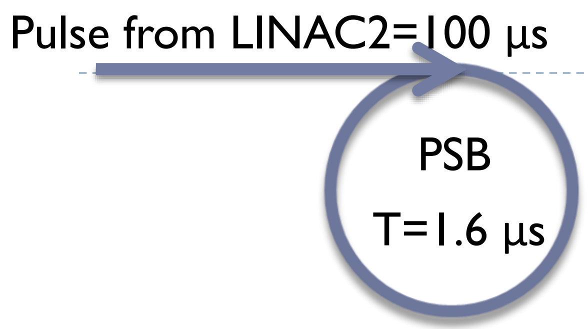
AREA ≈ EMITTANCE (Ɛ)

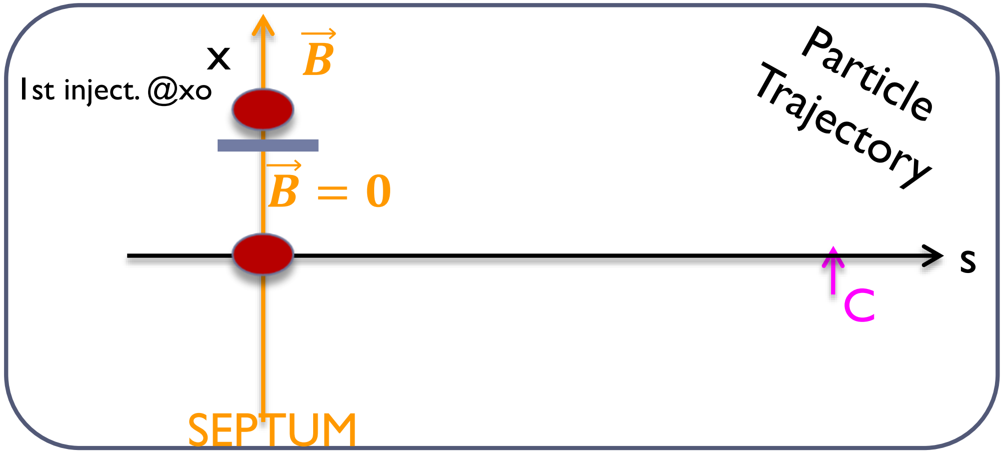
Beam size ➔ $\sigma = \sqrt{\varepsilon\beta}$ (in places without dispersion)

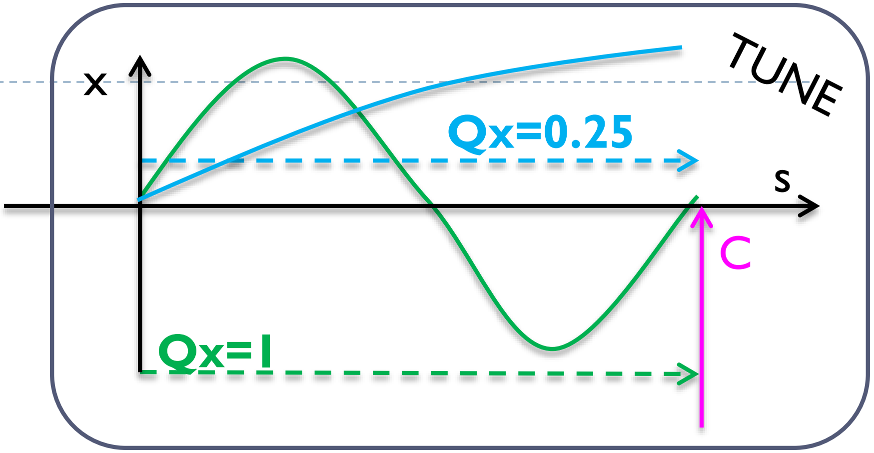
Let me use the BOOSTER injection to talk about

TUNE, PHASE SPACE PAINTING, SPACE CHARGE, BRIGHTNESS

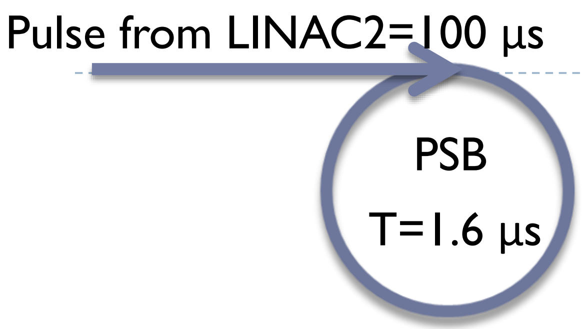
PS Booster: E_{inj}=50MeV, C=154 m

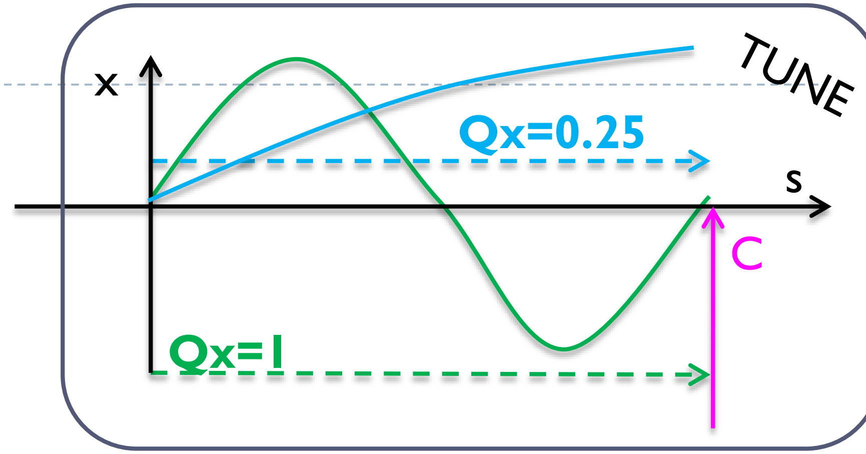


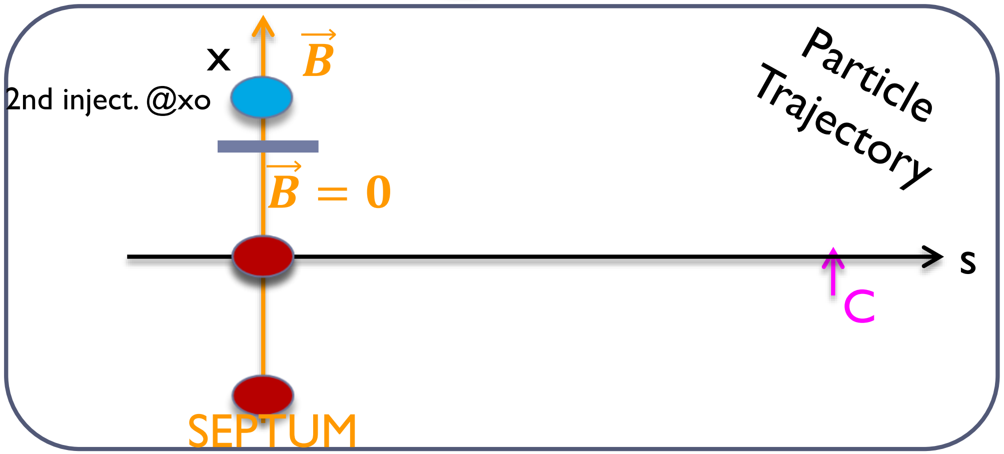




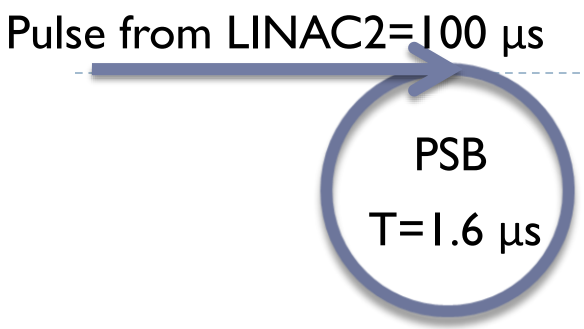
PS Booster: E_{inj}=50MeV, C=154 m

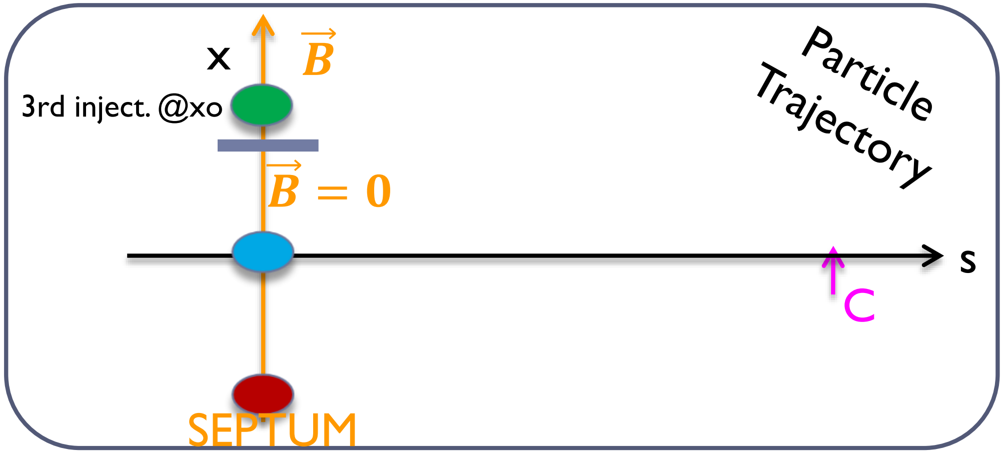


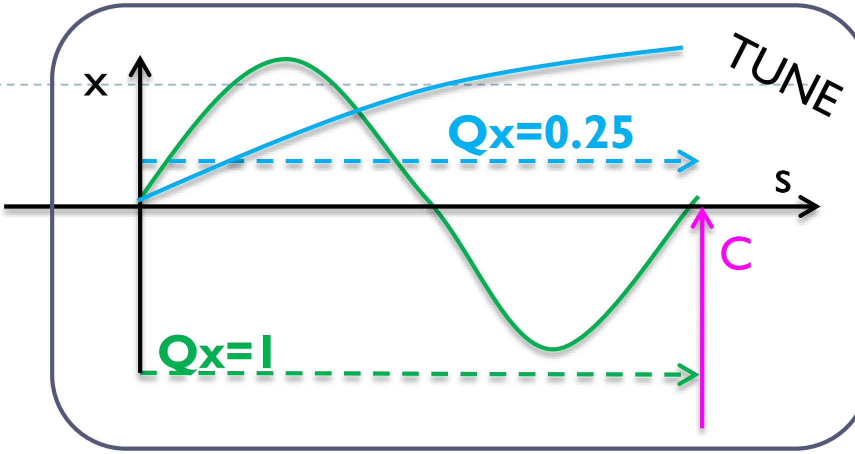




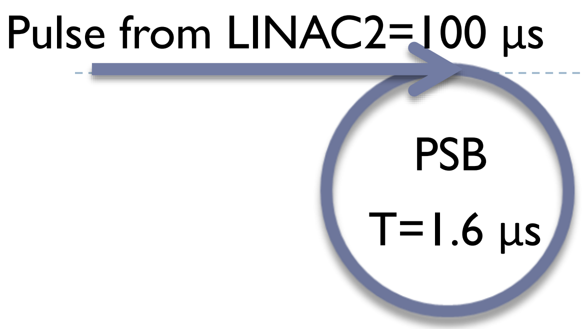
PS Booster: E_{inj}=50MeV, C=154 m

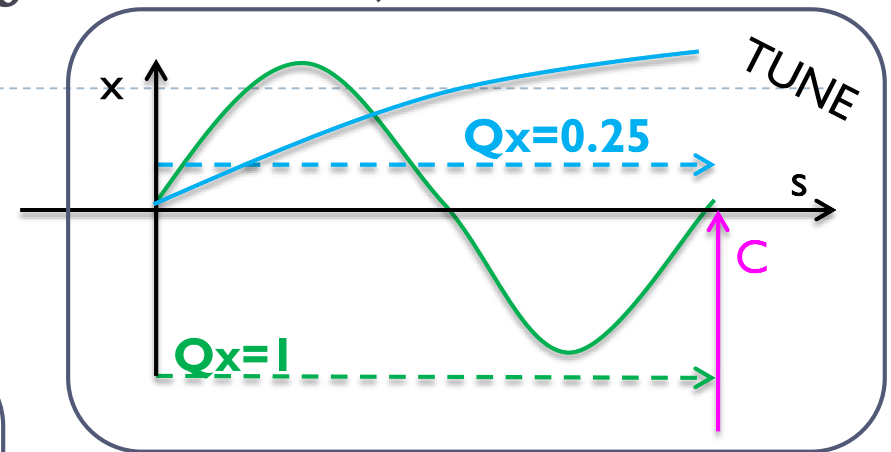


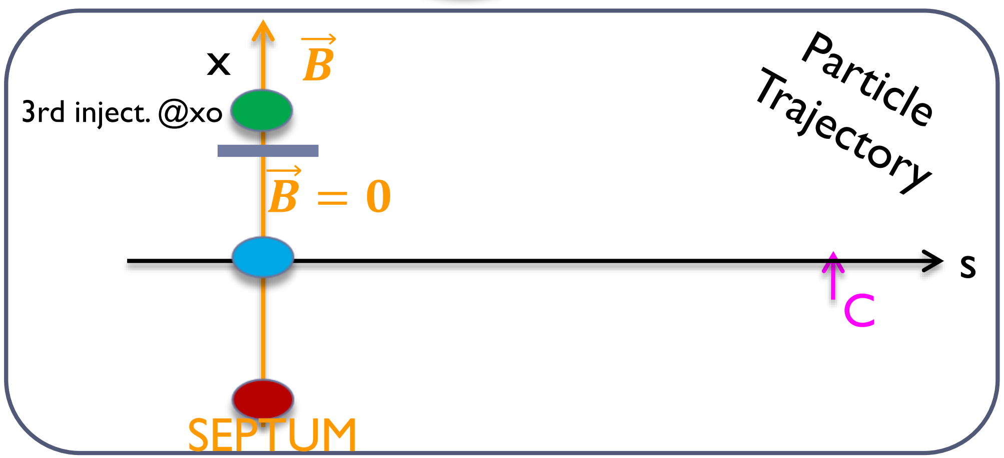


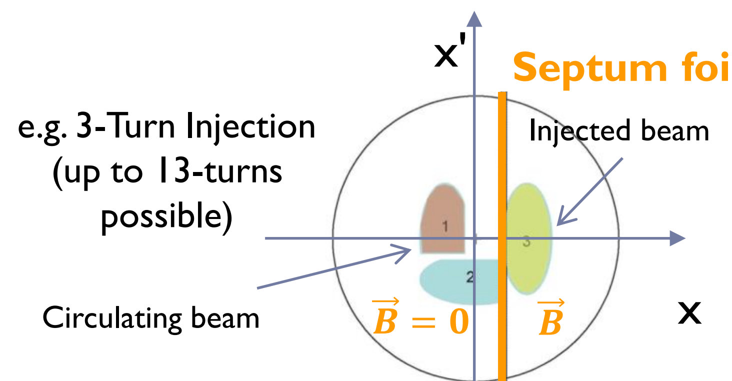


PS Booster: Einj=50MeV, C=154 m







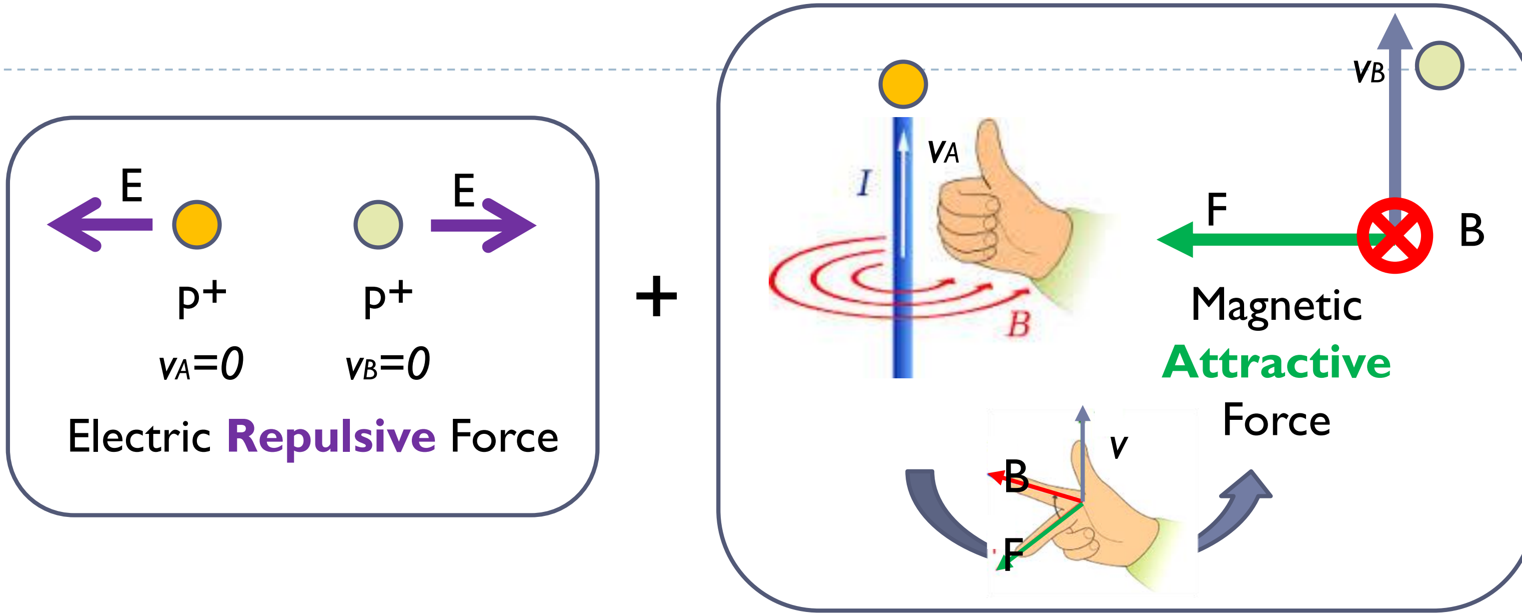


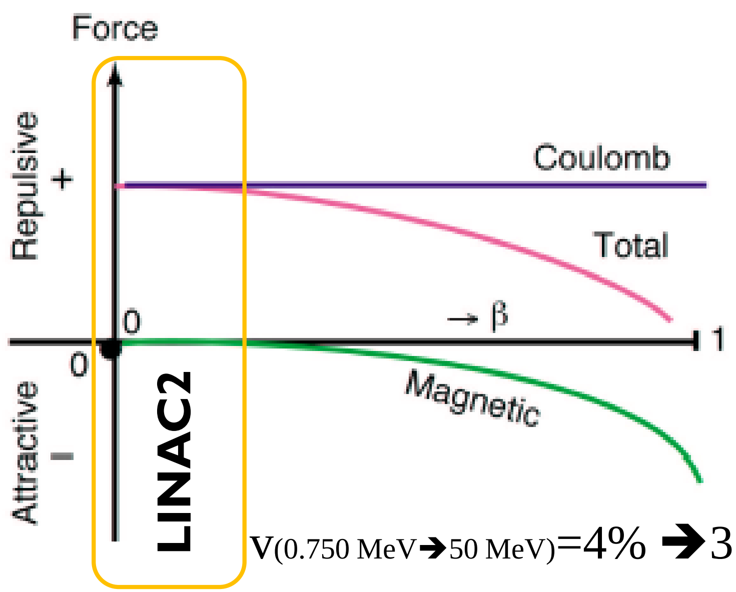
Transverse Phase Space (x,x')

- The bigger the number of turns the more intensity we can accumulate
- The problem is that the longer the injection takes, the more time the particles have to fill the whole available phase space + SPACE CHARGE ➔ emittance increases ➔ beam size increases
- **The Booster is the machine in the LHC Injector Chain where the <u>transverse brightness</u> of the LHC beam is determined**

Brightness = Intensity/Emittance

(Space Charge in One Slide)



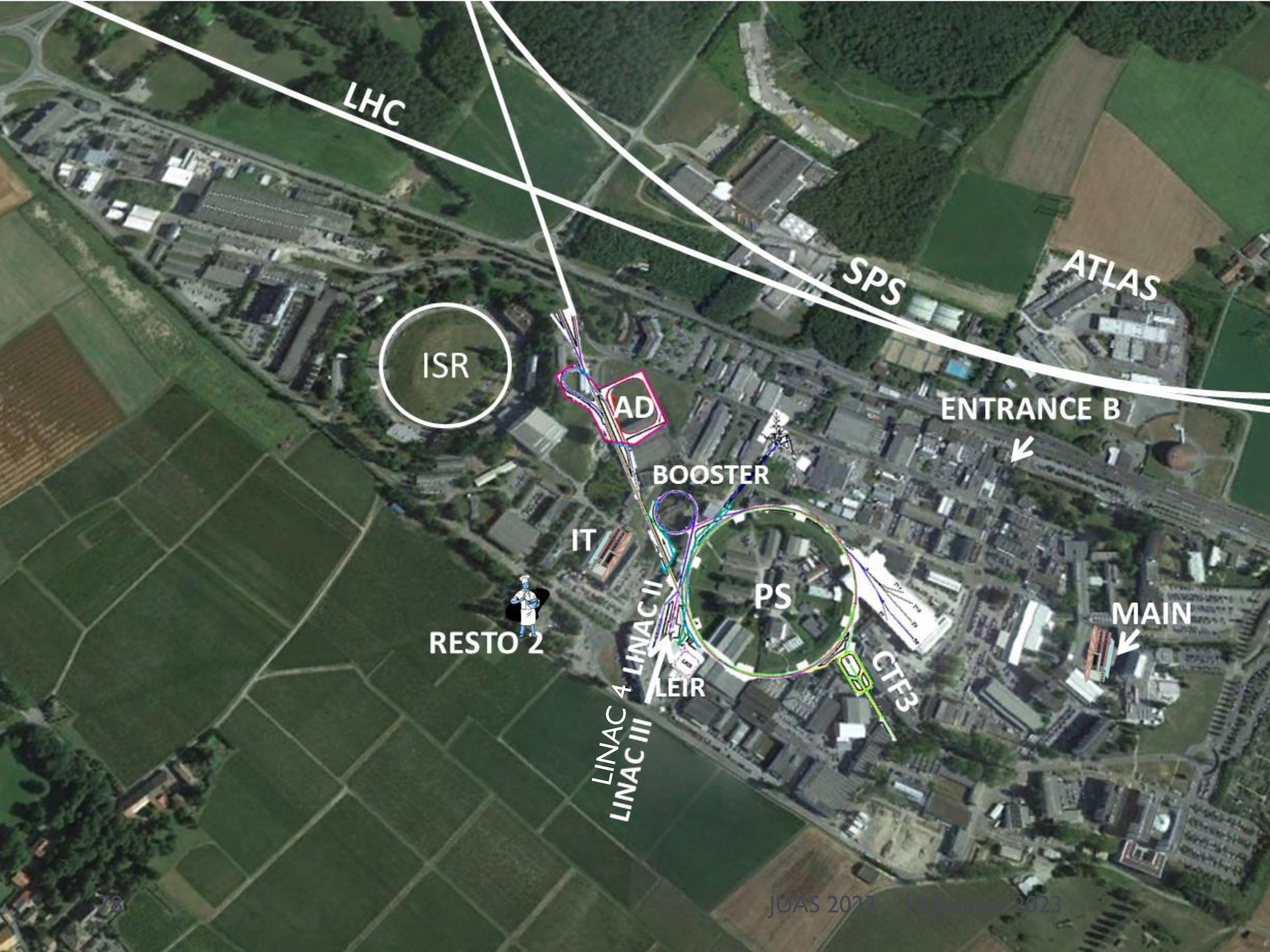


$$\beta = \frac{v}{c}$$

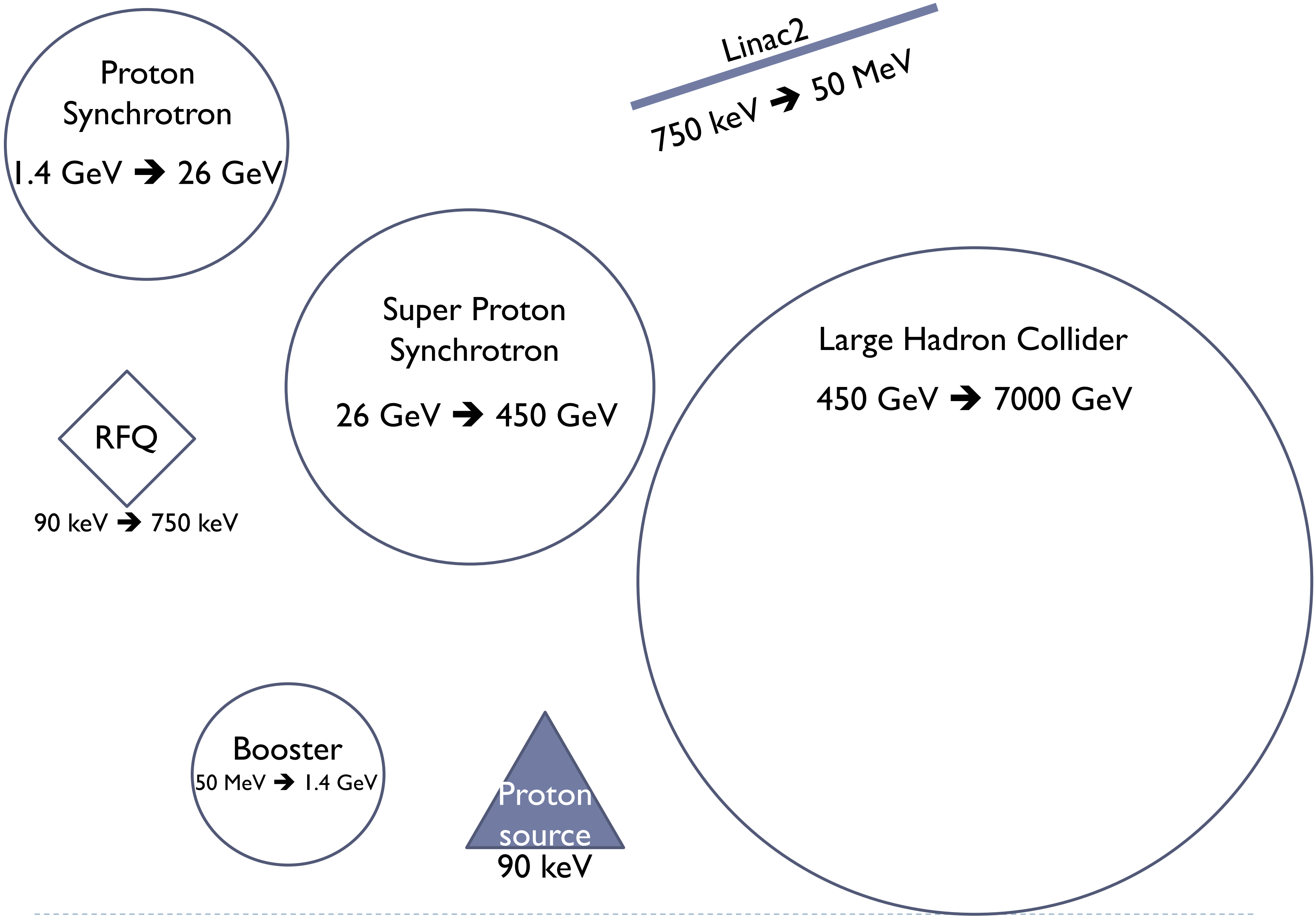
Particles in the beam feel a strong repulsive force = defocusing quadrupole ➔

change in tune

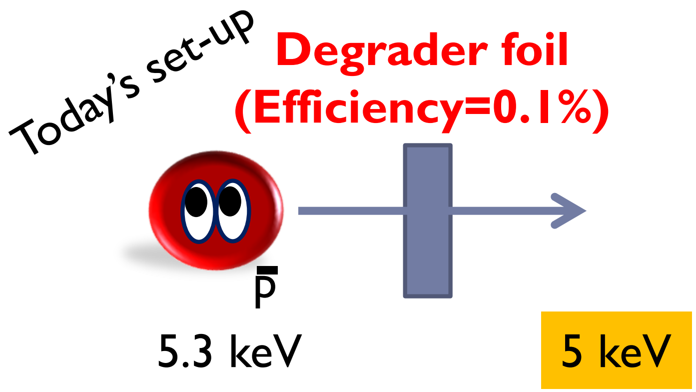
V(0.750 MeV➔50 MeV)=4% ➔31% of c

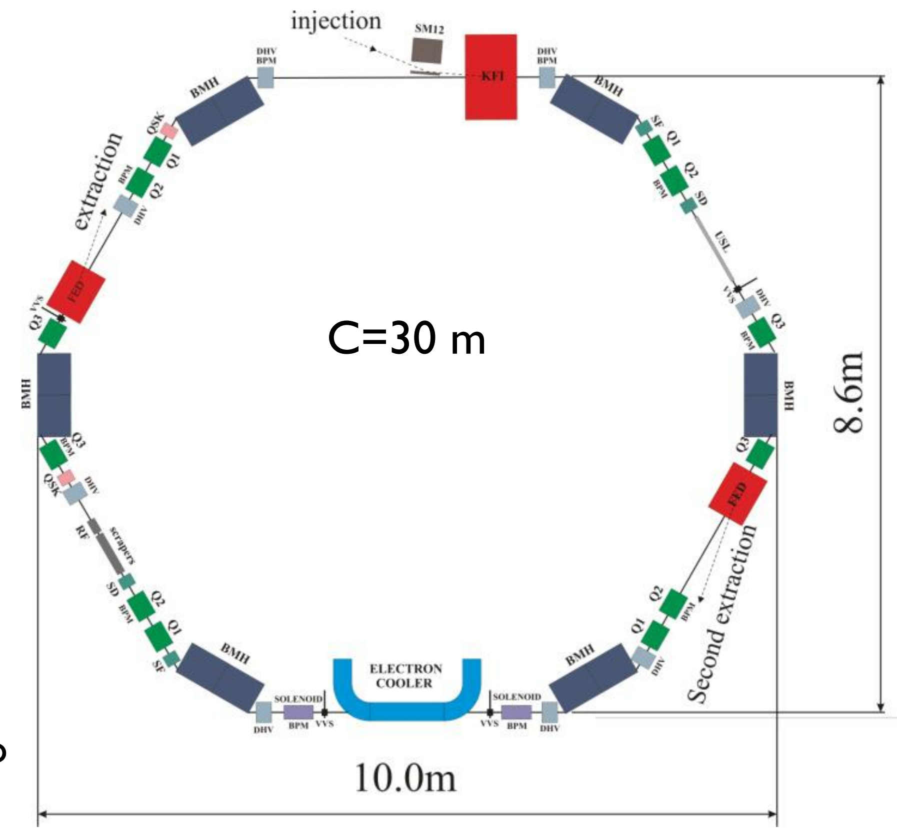


LHC
SPS
ATLAS
ISR
AD
ENTRANCE B
BOOSTER
IT
PS
MAIN
RESTO 2
LINAC II
LINAC 4
LEIR
CTF3
LINAC III


Proton
Synchrotron
1.4 GeV ➔ 26 GeV
Linac2
750 keV ➔ 50 MeV
Super Proton
Synchrotron
26 GeV ➔ 450 GeV
Large Hadron Collider
450 GeV ➔ 7000 GeV
RFQ
90 keV ➔ 750 keV
Booster
50 MeV ➔ 1.4 GeV
Proton
source
90 keV

Elena … More Deceleration

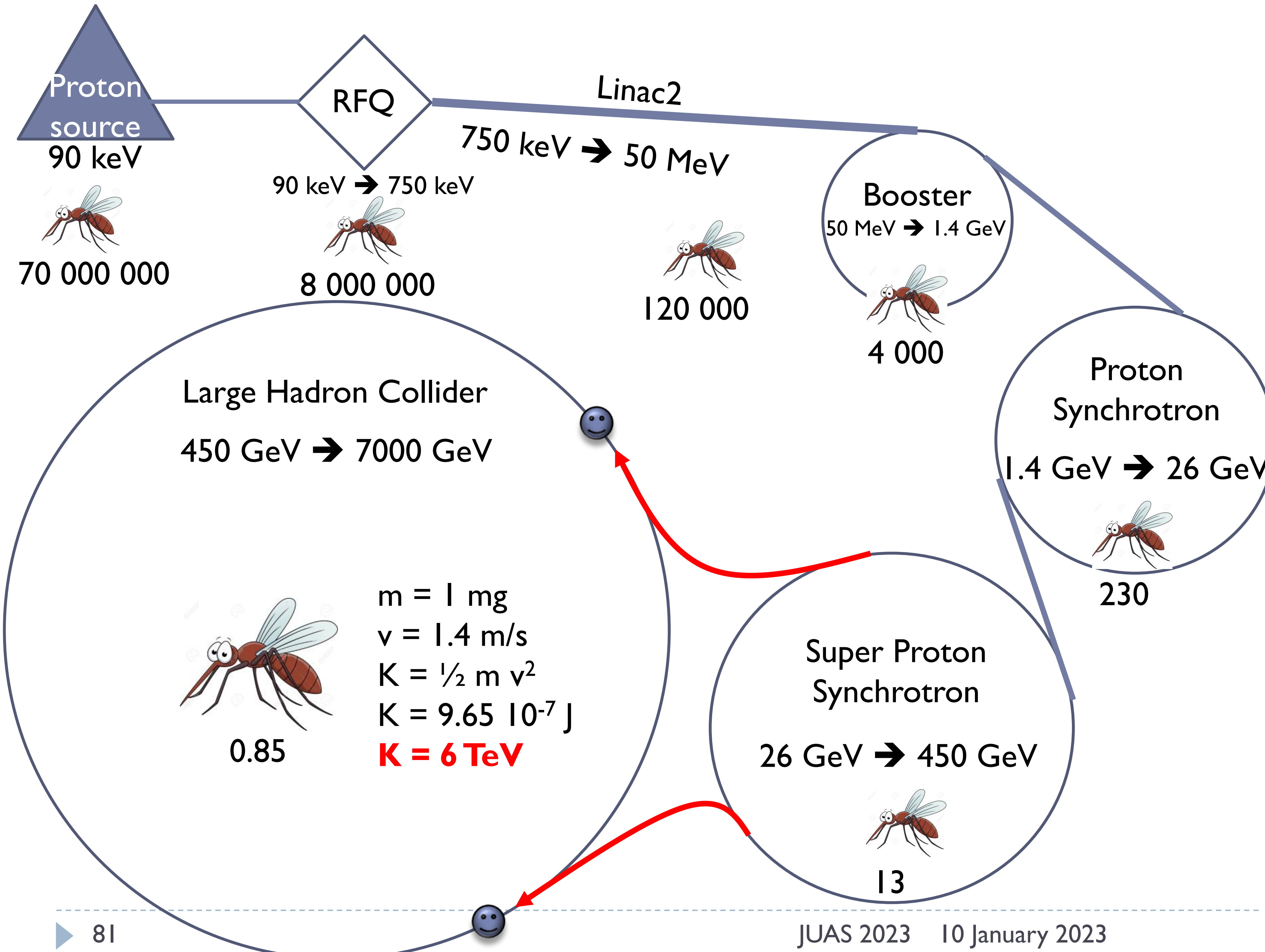




ELENA will overcome this problem + will be able to deliver beams almost simultaneously to all four experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone.

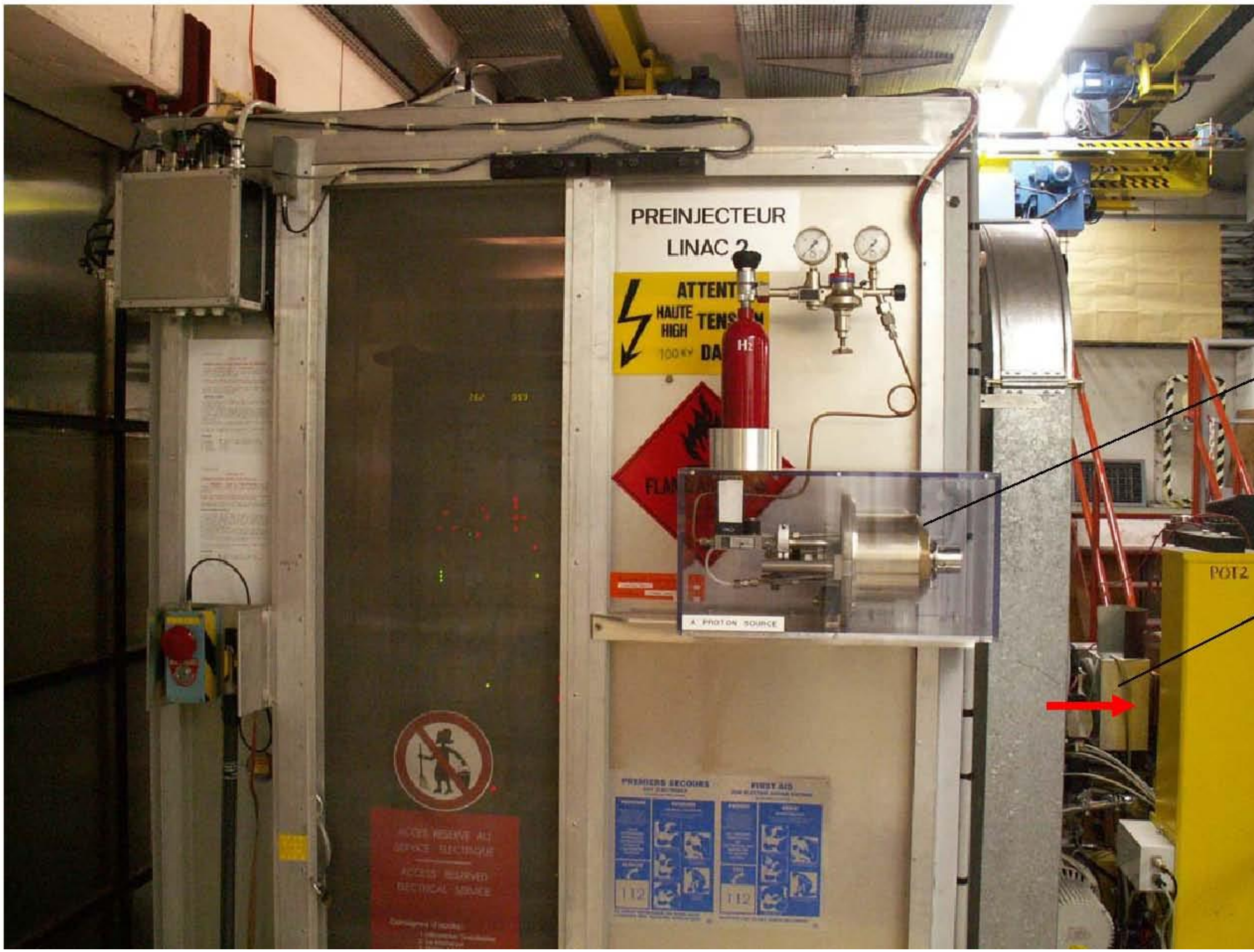
Commissioning in 2016
Operation since 2017

A second stage of deceleration after AD Momentum: 100 – 13.7MeV/c
Kinetic : 5.3 – 0.1 MeV


Proton source
90 keV
70 000 000
RFQ
90 keV ➔ 750 keV
8 000 000
Linac2
750 keV ➔ 50 MeV
120 000
Booster
50 MeV ➔ 1.4 GeV
4 000
Proton Synchrotron
1.4 GeV ➔ 26 GeV
230
Super Proton Synchrotron
26 GeV ➔ 450 GeV
13
Large Hadron Collider
450 GeV ➔ 7000 GeV
0.85
m = 1 mg
v = 1.4 m/s
K = ½ m v²
K = 9.65 10⁻⁷ J
K = 6 TeV

The Proton Beam Starts Here …

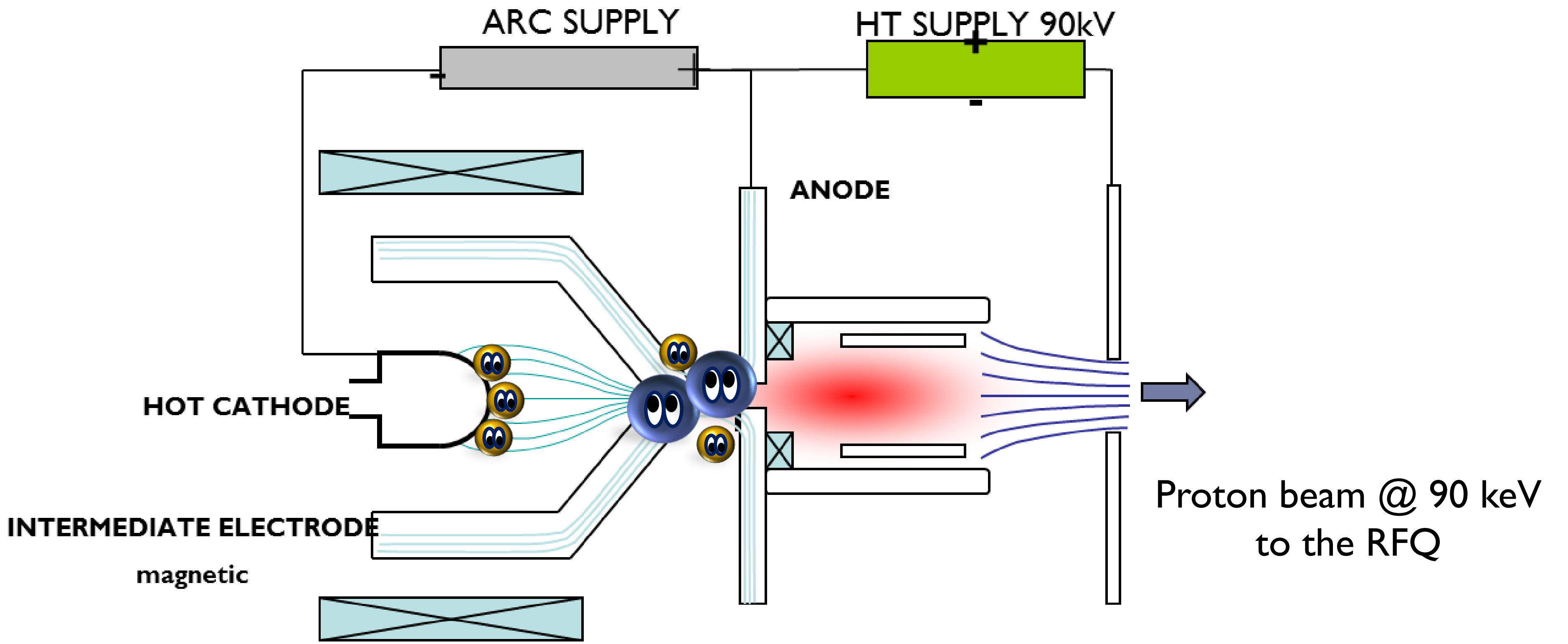
- **The source cage houses the HV platform at 90 kV.**

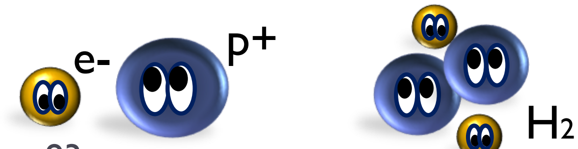


Source model (1 to 1)

Beam path to RFQ

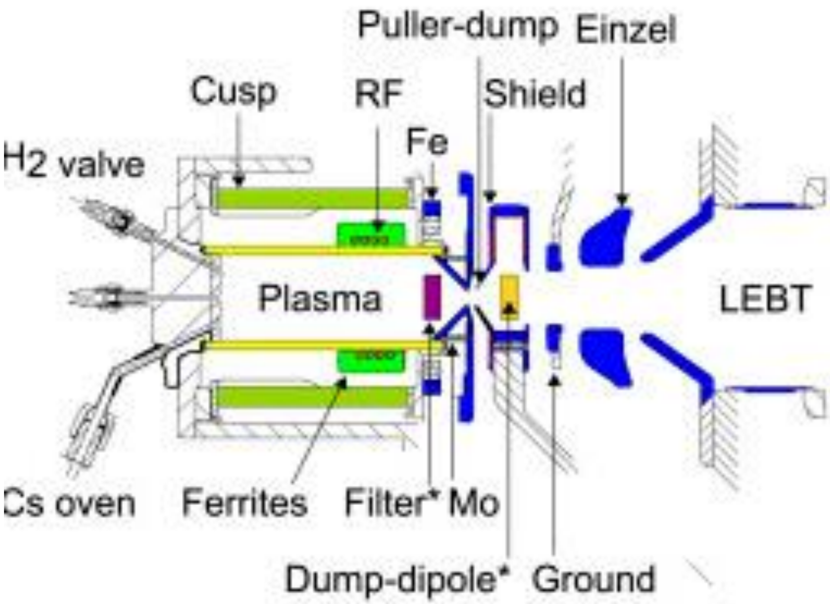
Duoplasmatron Proton Source



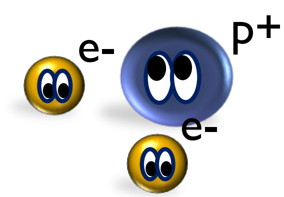


Protons (at 90 keV) are produced by creating a plasma using H_2 which is charged due to interaction with free electrons from the cathode. The plasma is then accelerated and becomes an ion beam.

H- source for Linac 4



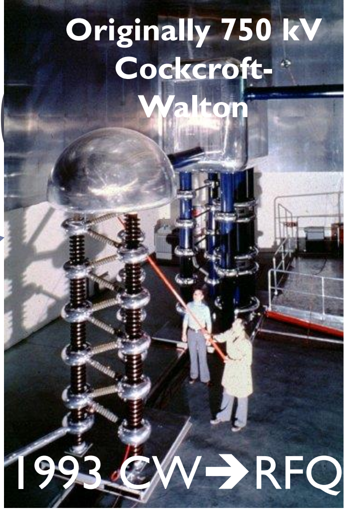
Instead creating protons from H, an electron is added, making a negatively charged hydrogen-ion. The ion source is fed with hydrogen gas. A discharge plasma is formed and a strong electric field strips away an electron from each hydogen atom.



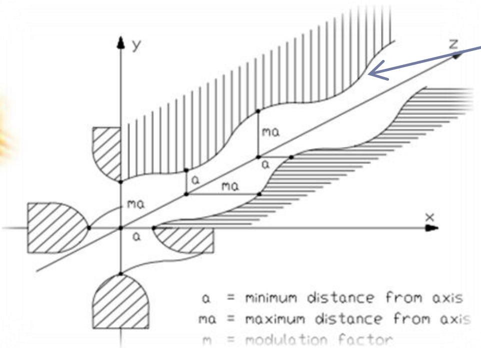
The positively charged (protons) from the plasma are attracted towards a cathode surface (metal surface with caesium) ➔ donor of electrons to the positively charged hydrogen ions, thus enhancing H- ion production

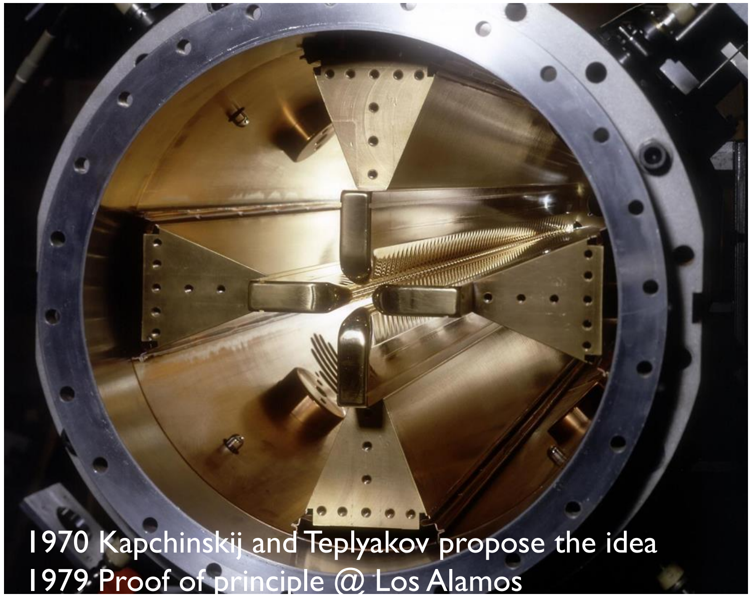
The H- ions leave the ion source with an energy of 45 keV

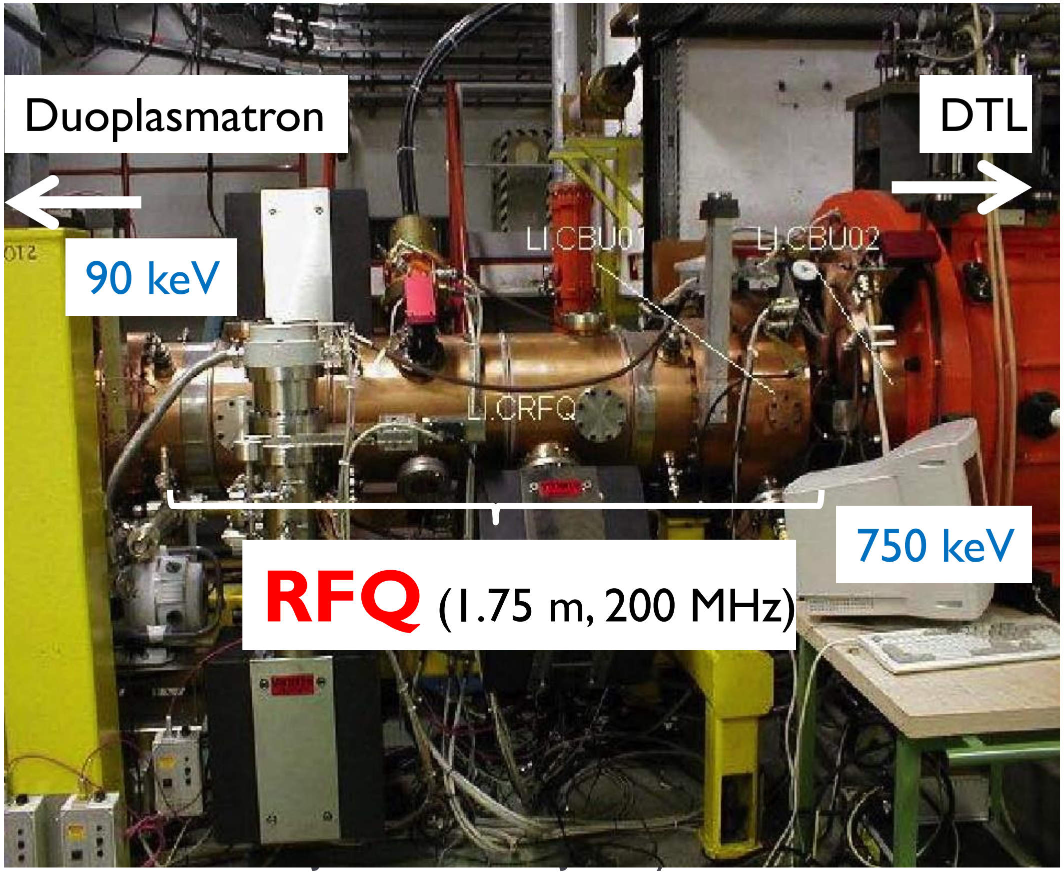
Radio Frequency Quadrupole



- RFQ is a linear accelerator that **FOCUSES, BUNCHES & ACCELERATES** with **HIGH EFFICIENCY** (90% w.r.t. 50% of conventional accelerators) and **PRESERVES THE EMITTANCE**
- The whole beam dynamics depends upon the shape of the vane tips

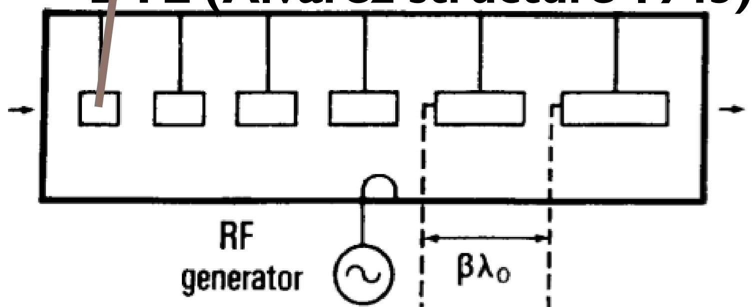


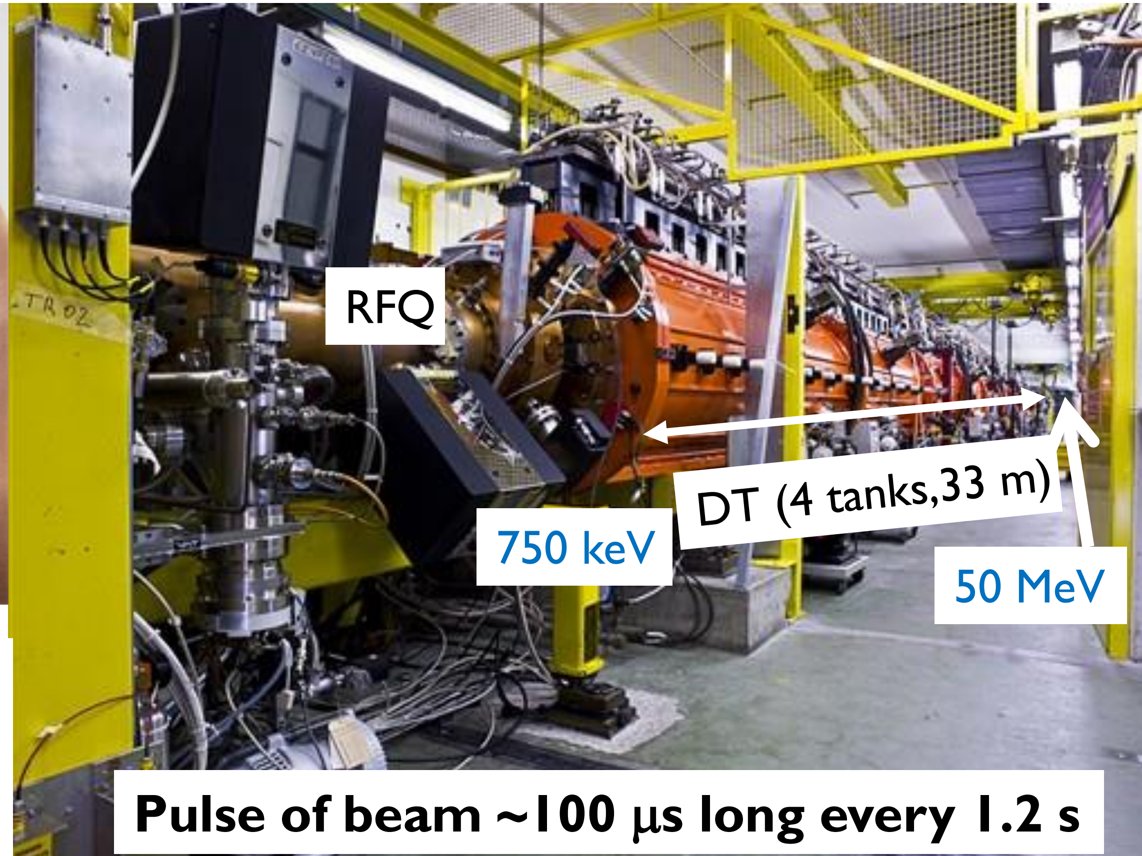




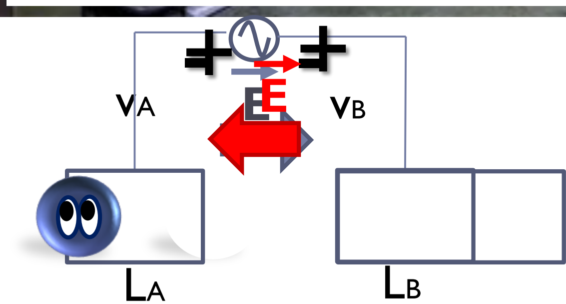
Linac 2

DTL (Alvarez structure 1945)





Drift tubes and spacing become larger as the energy increases
Focusing quads inside drift tubes



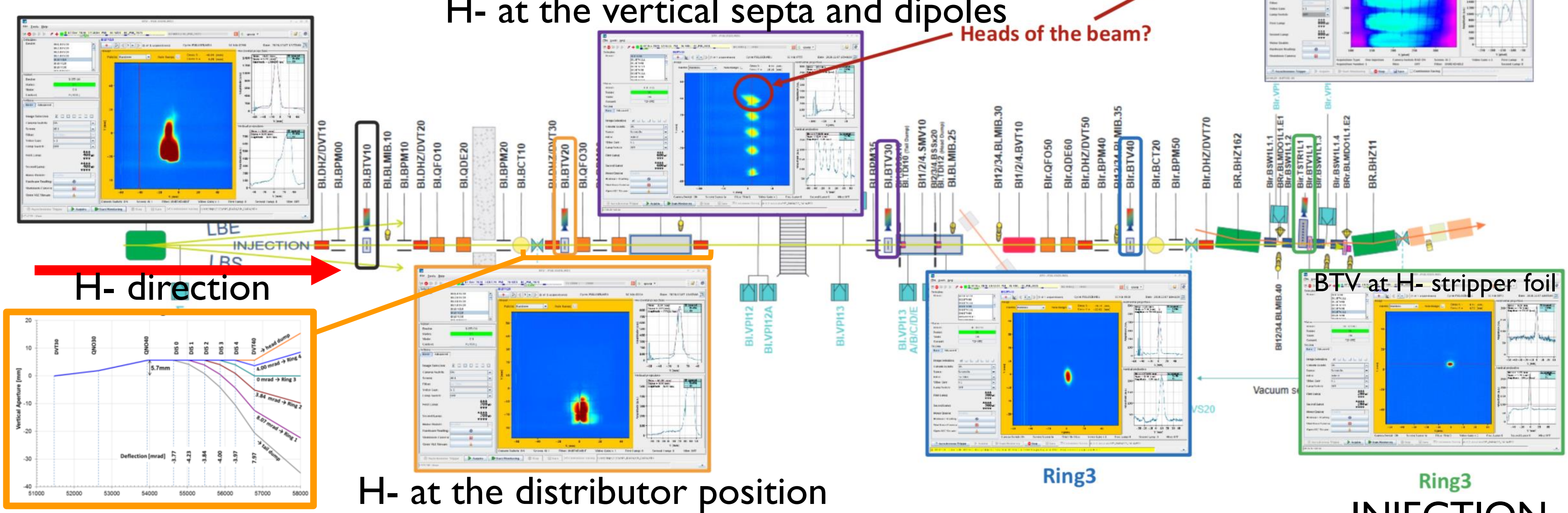
$v_A < v_B \rightarrow L_B > L_A$

$\rightarrow L = vT_{rf} = \beta_{rel}\lambda_o$

First H- beam in Booster Ring 3 (07.12.2020)

PSB Beam Commissioning: BI Line Commissioning Started on 7/12

- Rocky start with an access in the PSB to investigate a few issues with the Section 5 of the RF system.
- Most of the morning invested in checking the setting and cleaning-up the interlocks.
- **At 13h00 first beam crossing LTB.BHZ40 and threading to the first BTV, BI.BTV10**

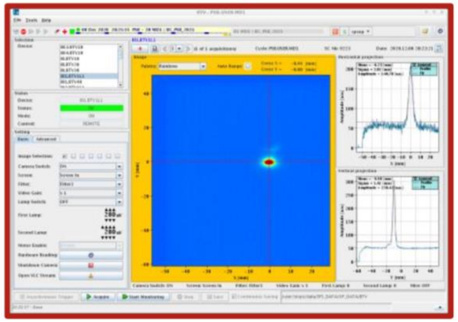


- **By the evening we reached the BTV at the stripping foil location in the PSB Ring3, BI3.BTV1L1**
  - **Next steps are to calibrate all instrumentations, repeat the process for the remaining 3 rings, inject protons in the PSB**

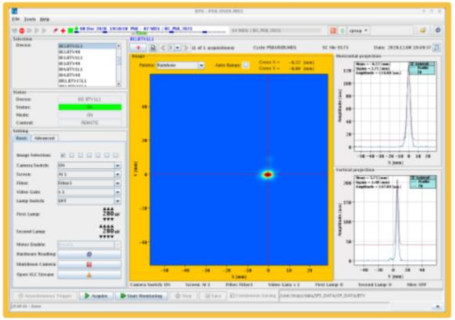
08.12.2020 G.P. Di Giovanni / B. Mikulec – FOM #24 4

First H- beam in all Booster Rings entrance point (07.12.2020)

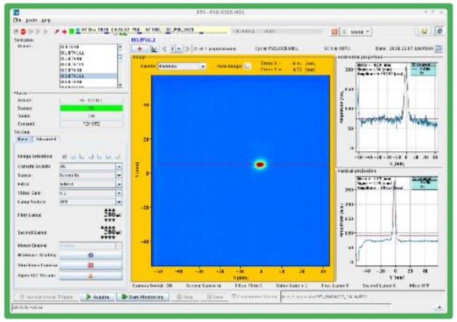
Ring1



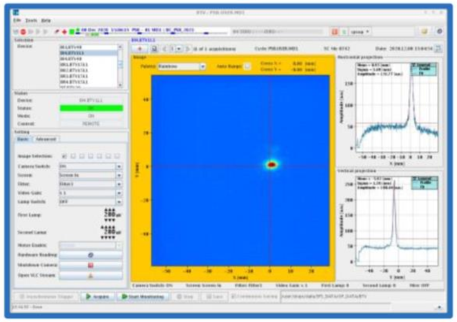
Ring2



Ring3



Ring4



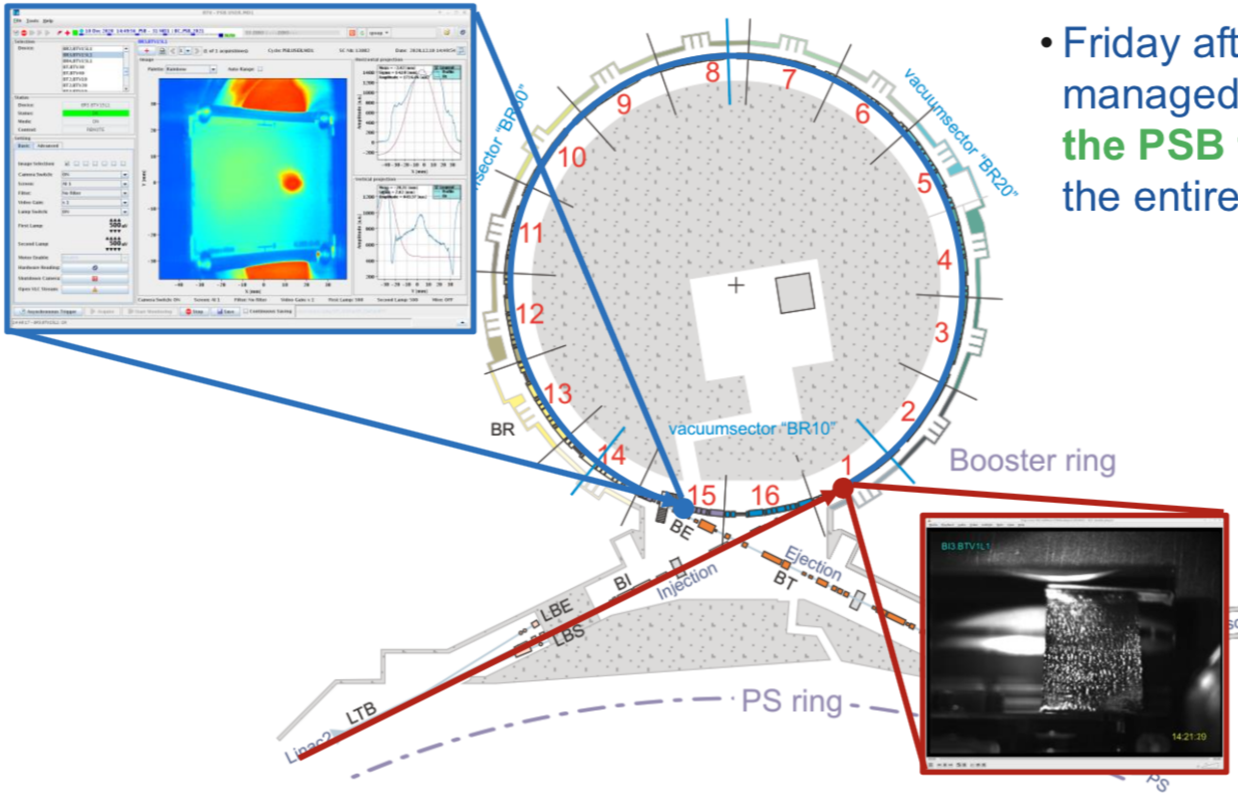
BTVs at the stripper foil position of each ring

First protons circulating in Booster

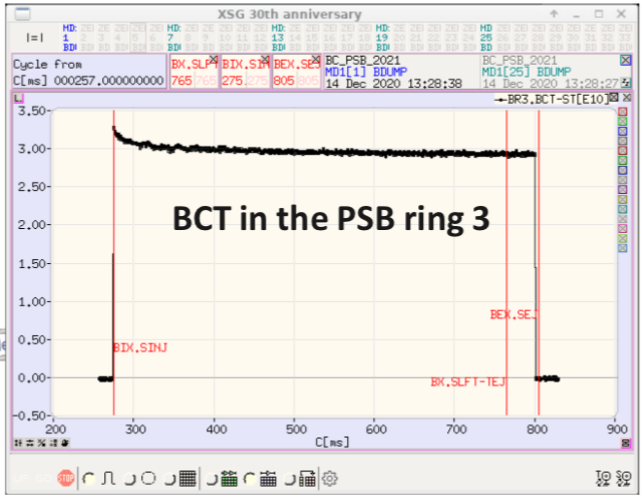
Report w50 (3)

Thursday/Friday:

- Thursday inject H- beam, strip electrons with foil → proton beam circulating for 1 turn, until the BTV in sector 15L1!



- Friday after optimizing injection parameters, managed to **circulate a few E10 protons in the PSB for several 100s of ms**, i.e. almost the entire length of the magnetic cycle.



- Had to stop in the evening due to an interlock setting issue solved Saturday.