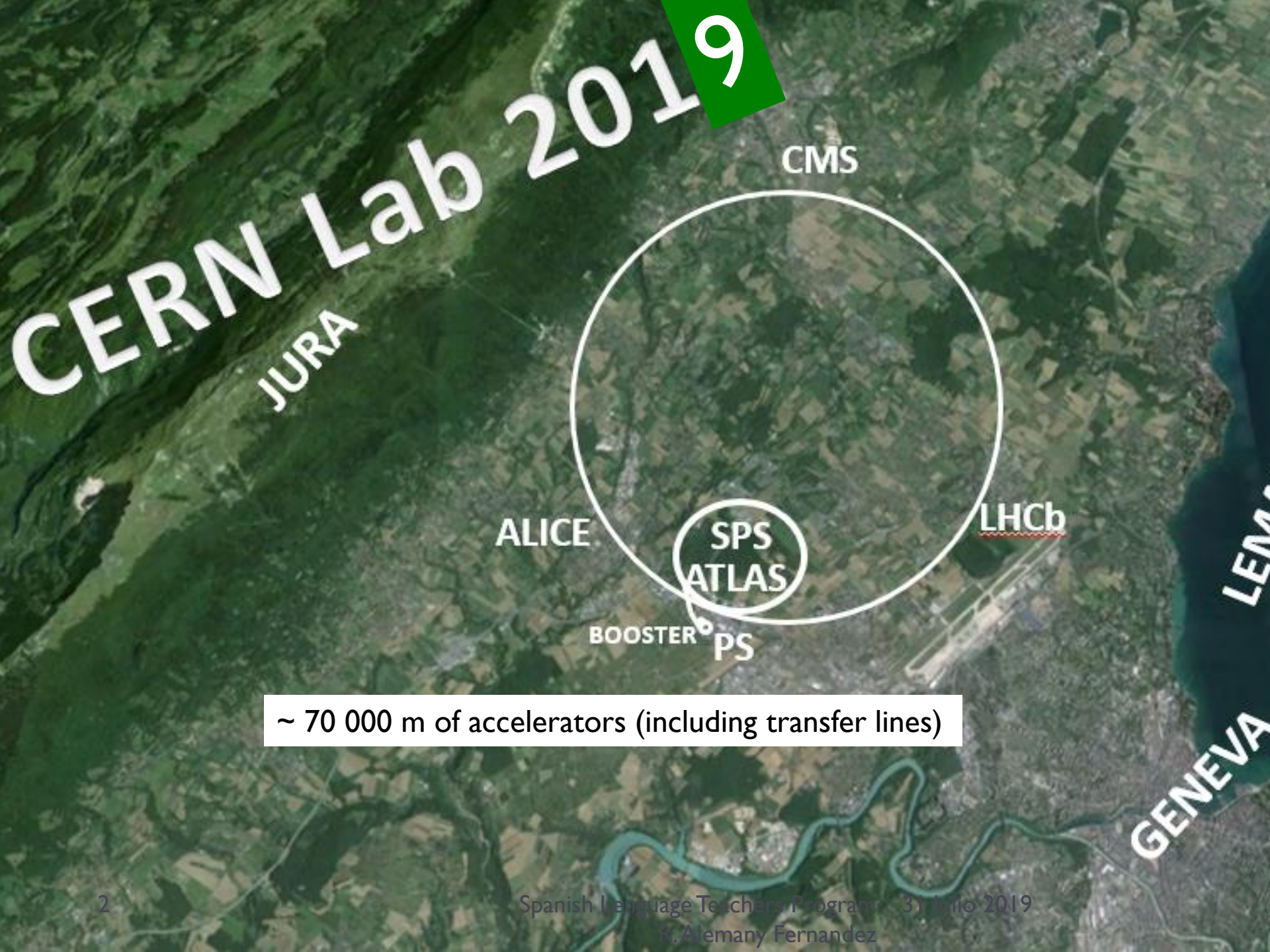
Overview of the CERN Accelerator Complex

CERN Lab 1954

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

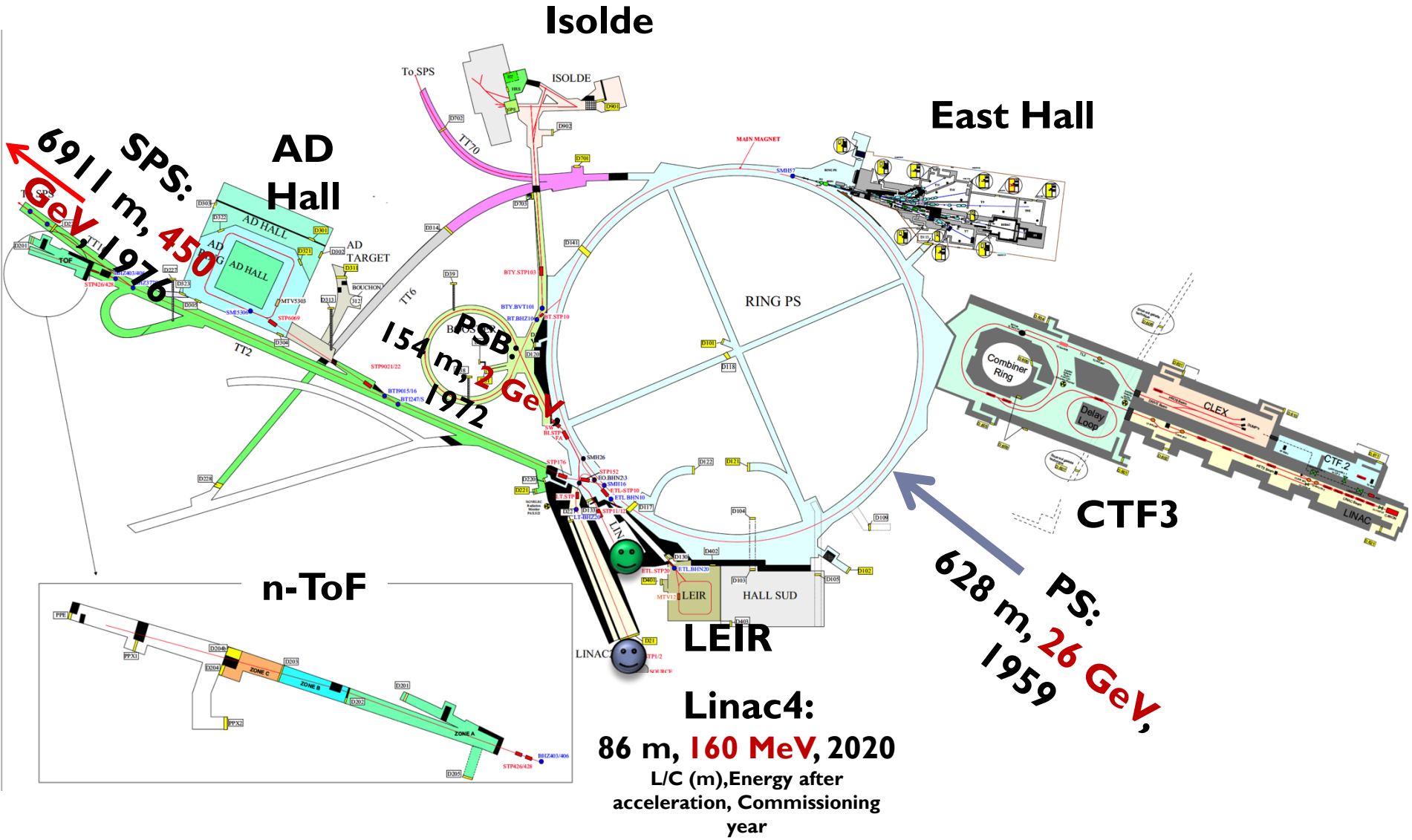
1952: Geneva selected by the provisional Council as site for CERN
1953: approved by referendum in Canton Genève
1954: the first shovel of earth was dug on the Meyrin site

R. Alemany Fernandez
Reyes Alemany, Beams Department, CERN



~ 70 000 m of accelerators (including transfer lines)

PS accelerator complex



$\beta_{particle}^{source} = 0.98\%$

H- source

45 keV

$R = \frac{K_{mosquito}}{K_{particle}} \approx 136\,000\,000$

Linac4

45 keV ➔ 160 MeV

$\beta_{particle}^{Linac4} \sim 52\%$

R ≈ 40 000

Booster

160 MeV ➔2 GeV

$\beta_{particle}^{Booster} \sim 95\%$

$C_{Booster}$ = 154 m

Normal conducting ~ 2 T

R ≈ 3 000

$\beta_{particle}^{PS} = 99.94\%$

Proton Synchrotron

2 GeV ➔ 26 GeV

C_{PS} = 628 m

Normal conducting ~ 2 T

R ≈ 240

C_{SPS} = 7000 m

Normal conducting ~ 2 T

Large Hadron Collider

450 GeV ➔ 7000 GeV

Super Proton Synchrotron

26 GeV ➔ 450 GeV

R ≈ 14

R ≈ 1

m = 1 mg

v = 1.4 m/s

K = ½ m v^2

K = 9.65 10^{-7} J

$K_{mosquito}$ ≈ 6 TeV

$\beta_{particle}^{LHC} = 99.9999999\%$

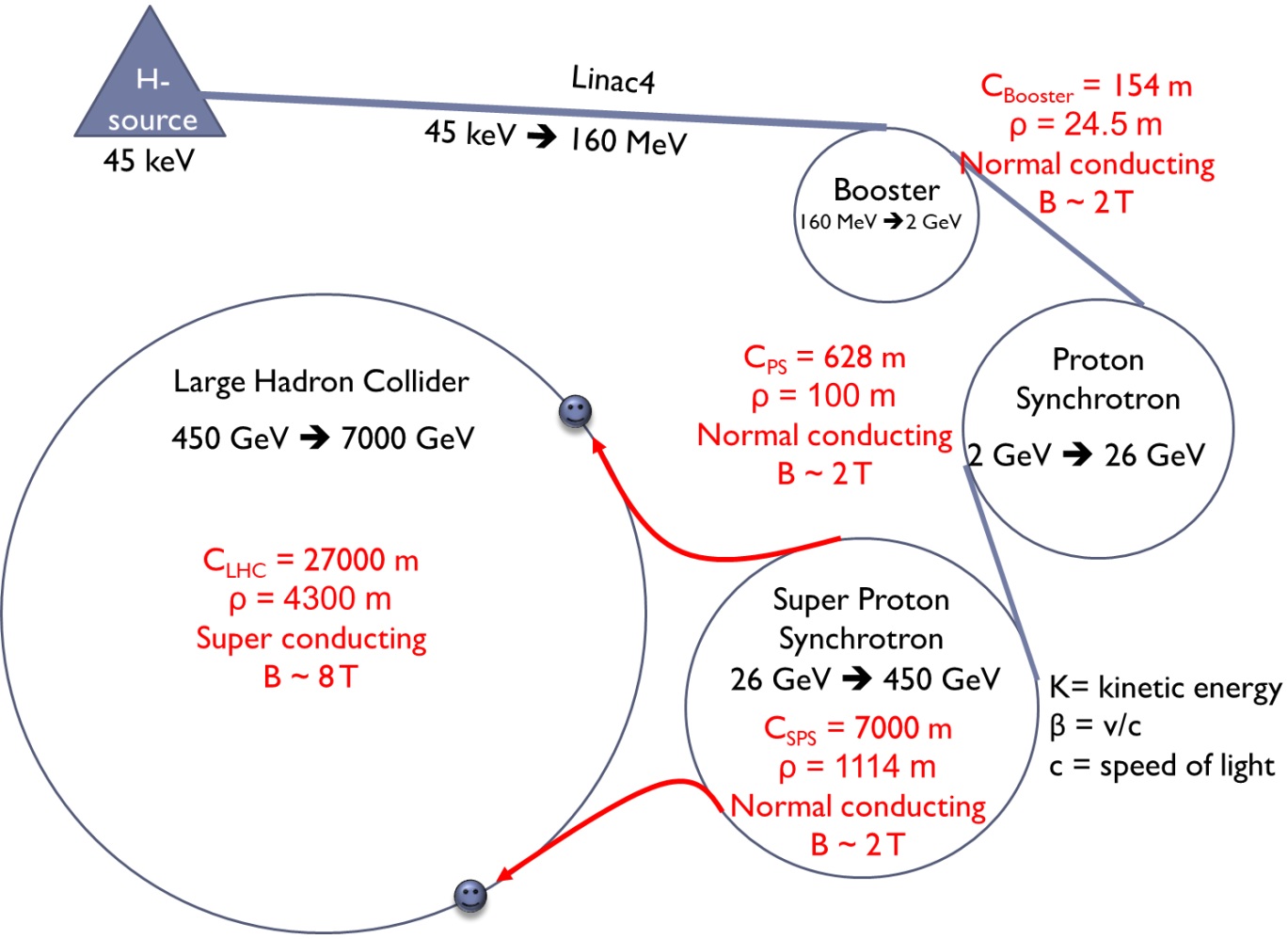
$\beta_{particle}^{SPS} = 99.999998\%$

K= kinetic energy

β = v/c

c = speed of light

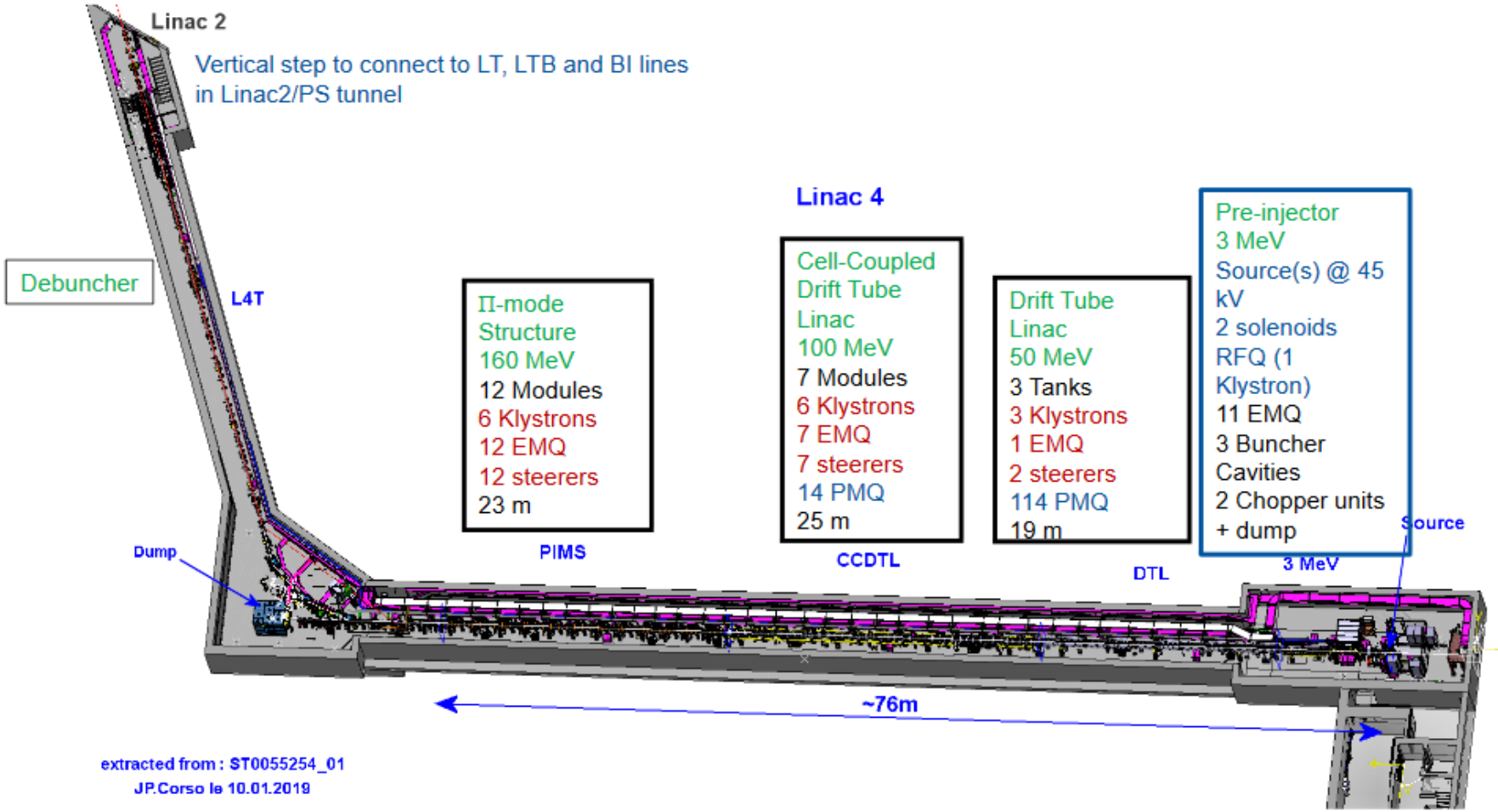
¿Por qué los sincrotrones del la cadena de aceleración del CERN son cada vez más grandes?



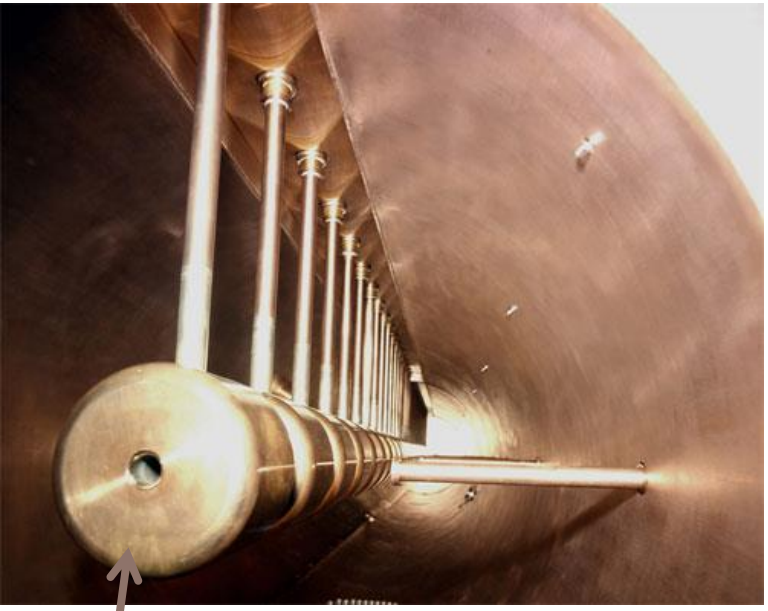
$$B\rho = \frac{p}{q}$$

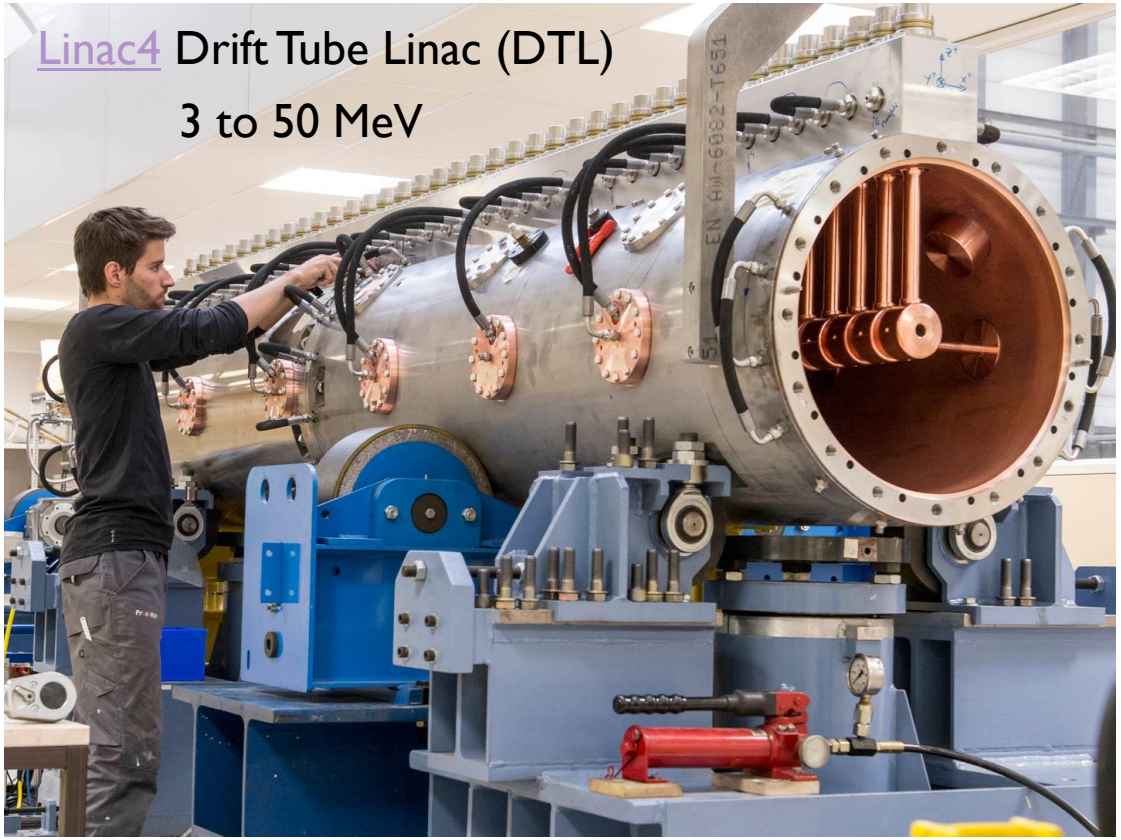
Fórmula de la rigidez del haz

H- (1 p, 2 e-) source & Linac4

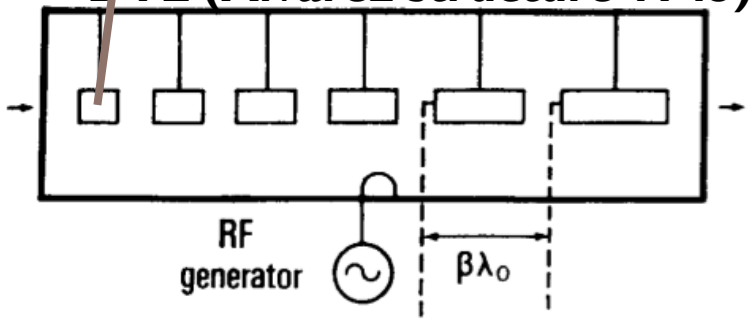


Linac 4

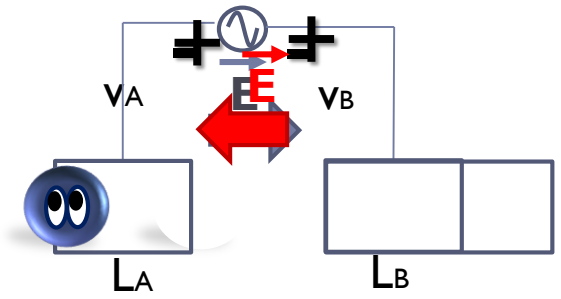




DTL (Alvarez structure 1945)



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



$v_A < v_B \rightarrow L_B > L_A$

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

PS Booster

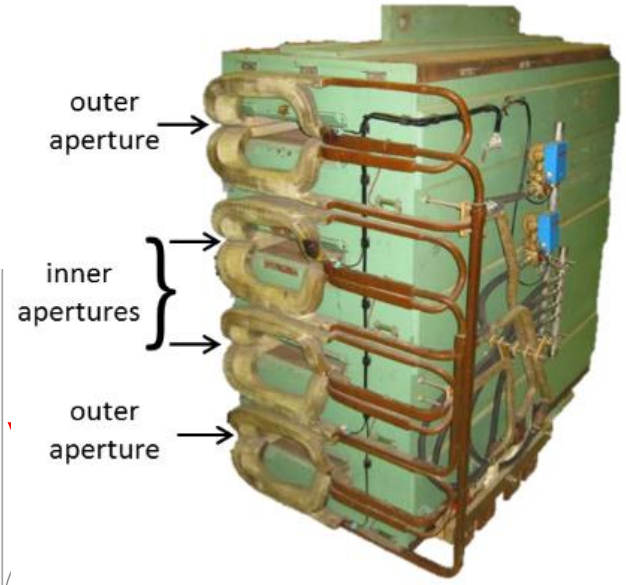
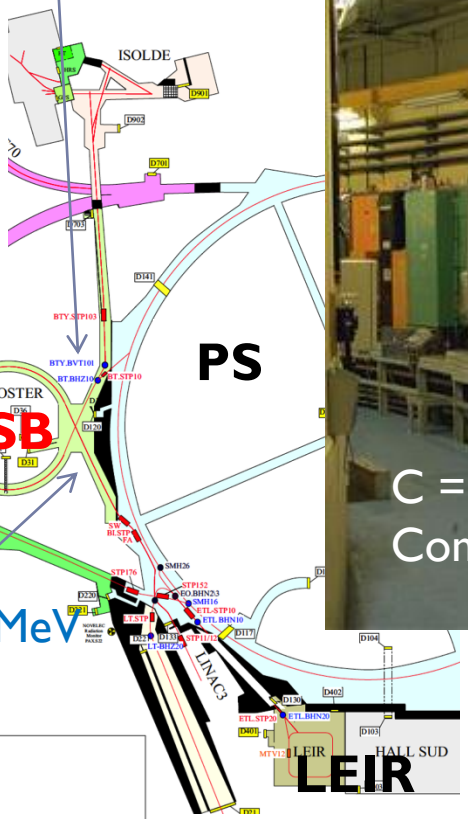
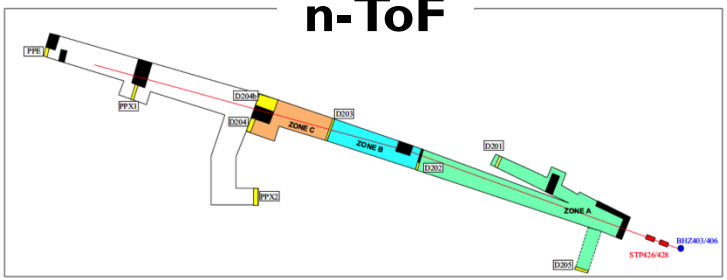


Fig.1. The PSB four aperture main dipole magnet

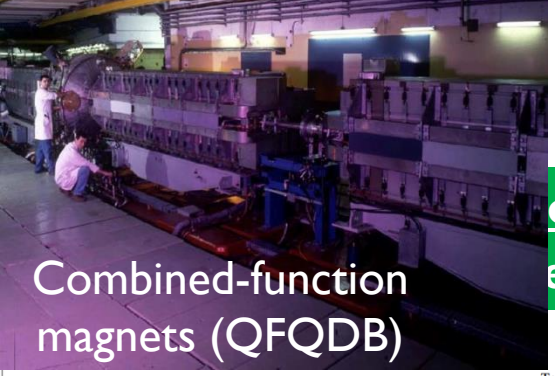
E_{ext}=2000 MeV





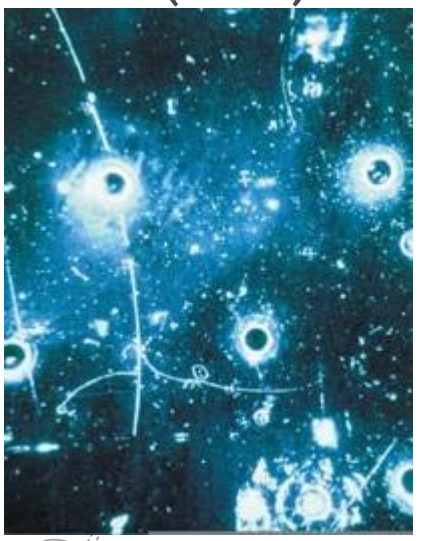
- **Synchrotron with 4 vertically stacked rings, each ¼ of PS Circumference**
- **Duty cycle 1.2 s ➔ two cycles needed to fill the PS with protons for LHC**

Proton Synchrotron (PS)

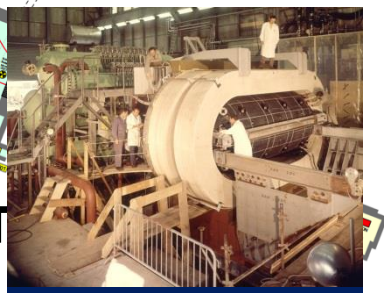


oldest functioning machine at CERN

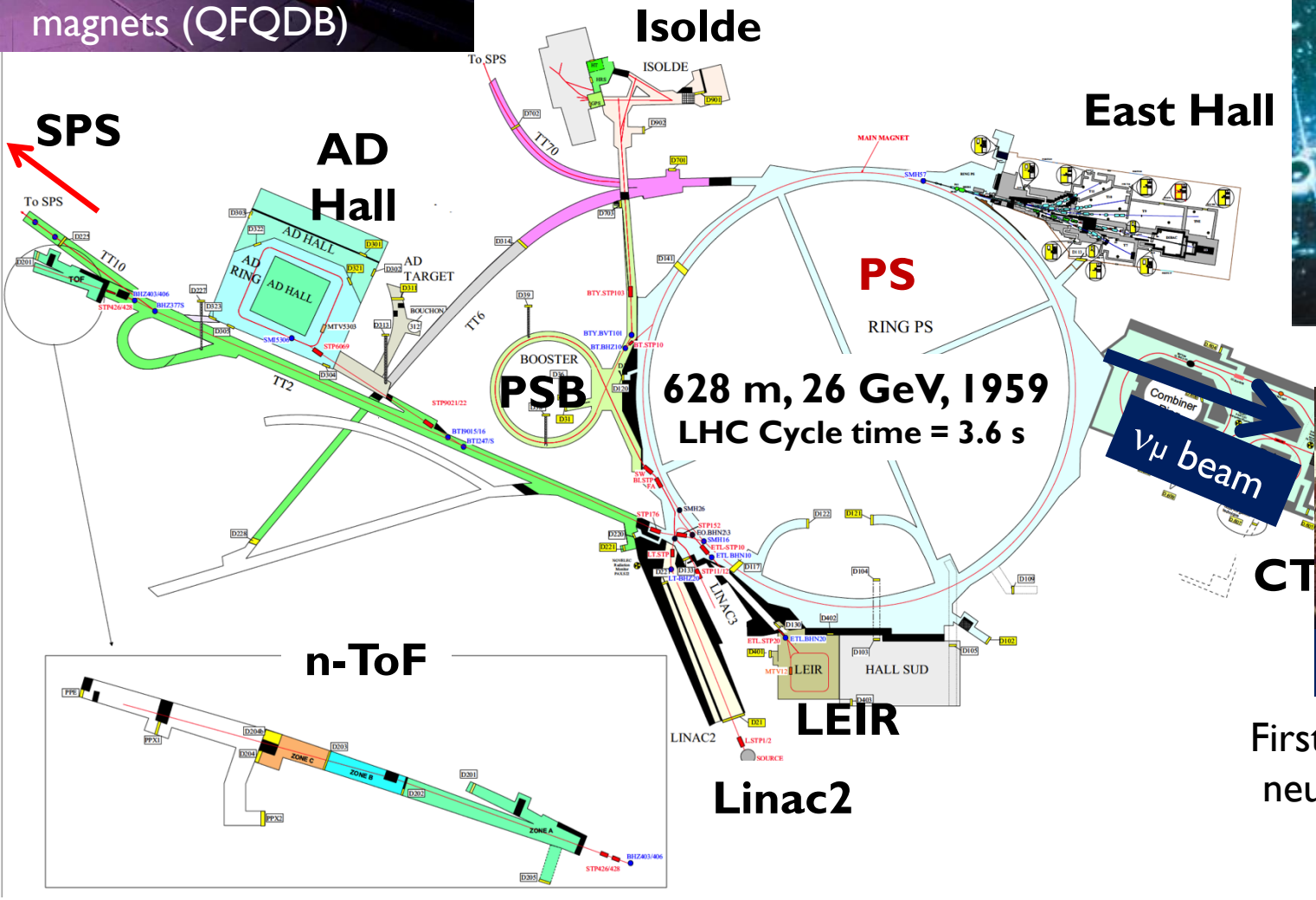
e first Alternating Gradient Machine!

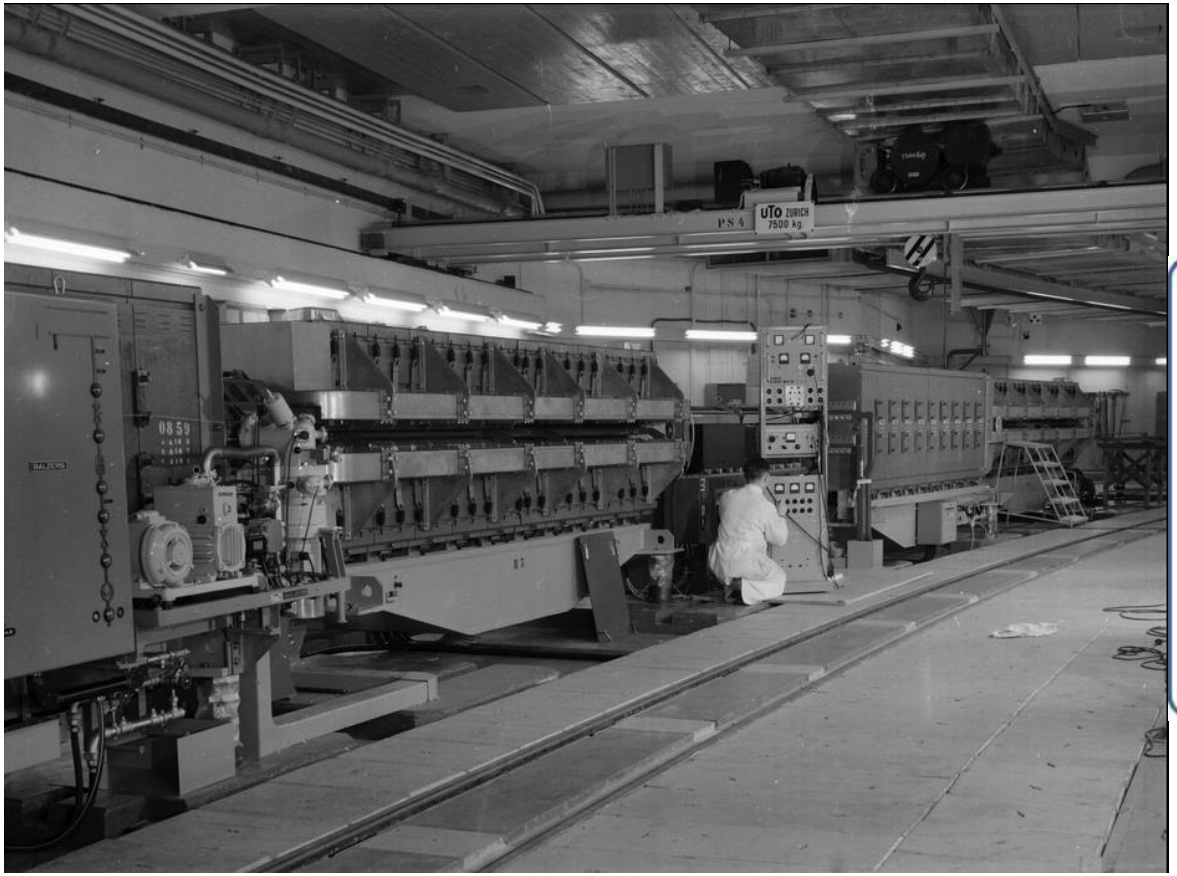


1970-1976

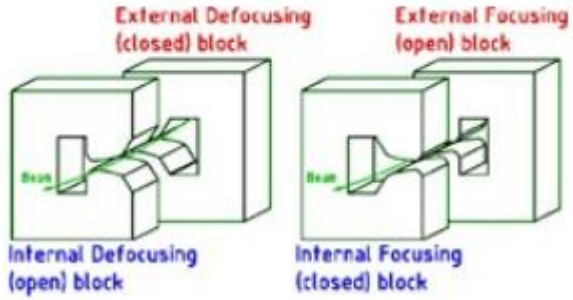


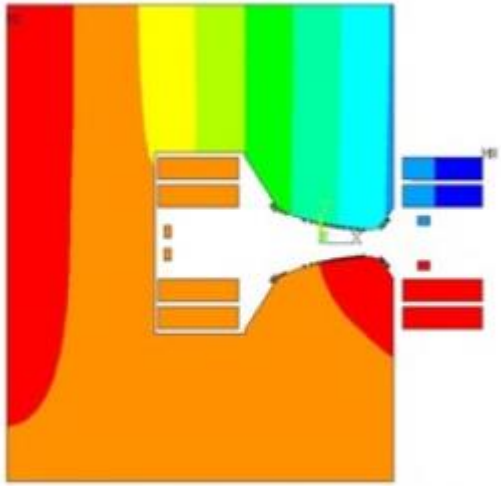
First evidence of weak neutral currents (Z^o)



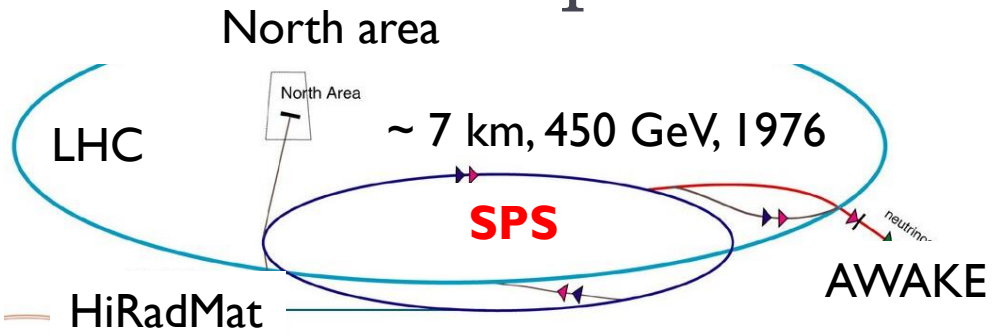


- Combined-function magnet with hyperbolic pole shape (4 types)



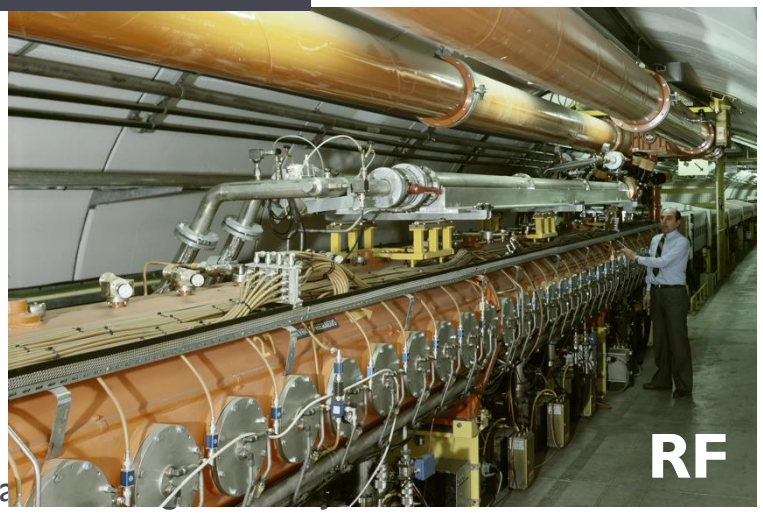


Super Proton Synchrotron (SPS)

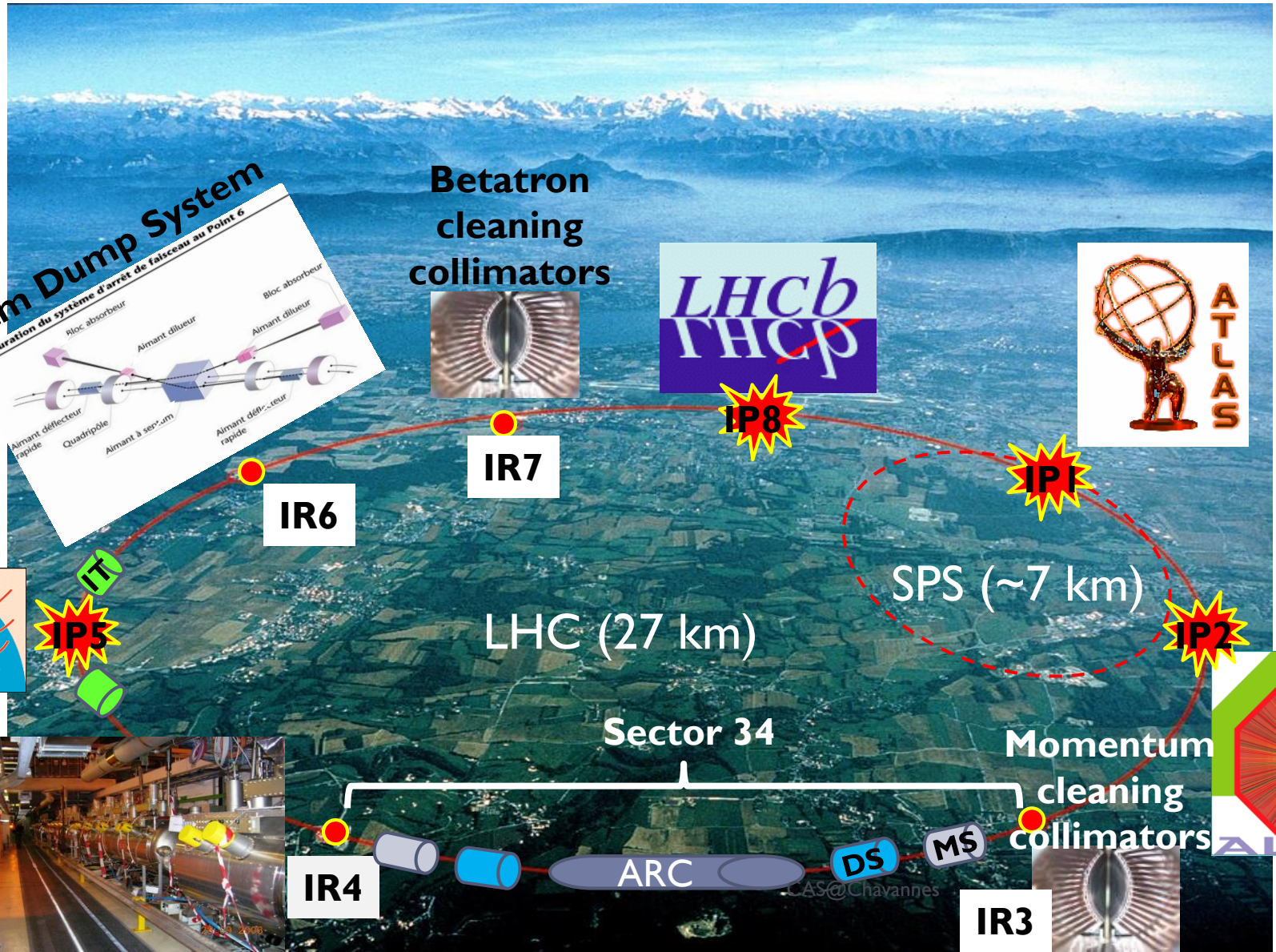


SppS

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



Large Hadron Collider (LHC)



Large Hadron Collider (LHC)

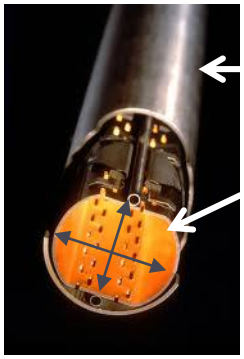
Geometry of the main dipoles

(Total of 1232 cryodipoles)

Heat exchanger

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

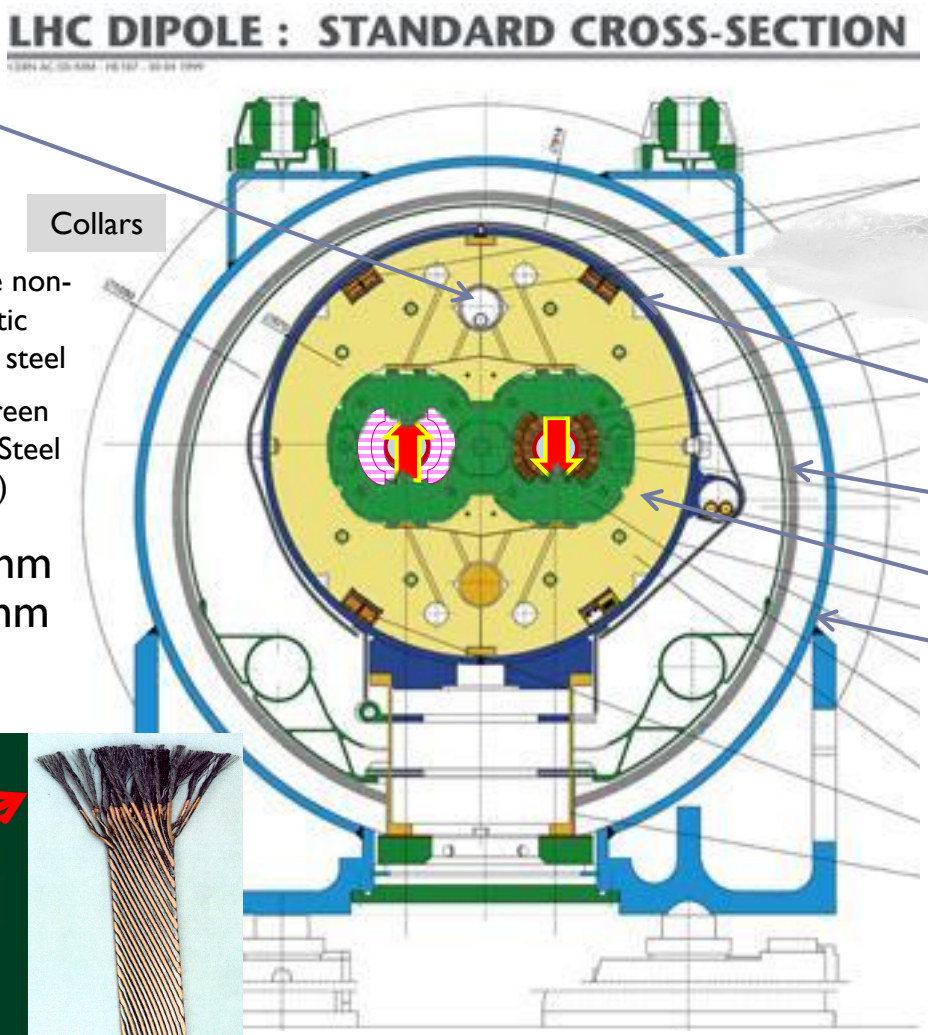
Collars



Cold bore non-magnetic austenitic steel

Beam Screen (Stainless Steel + Cu)

36.9 mm
46.5 mm



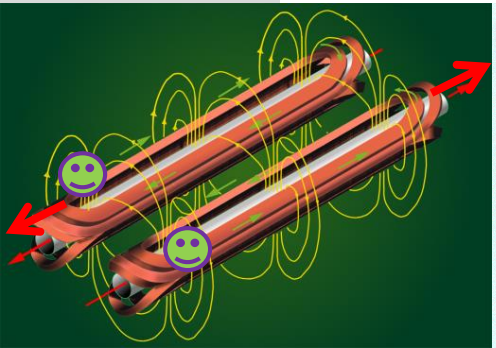
He Vessel

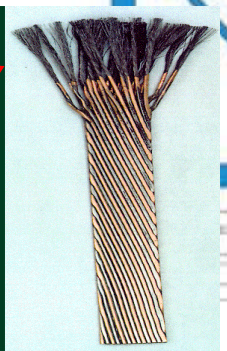
Thermal shield

Iron yoke

Vacuum vessel (10^{-6} mbar)

Superconducting coils



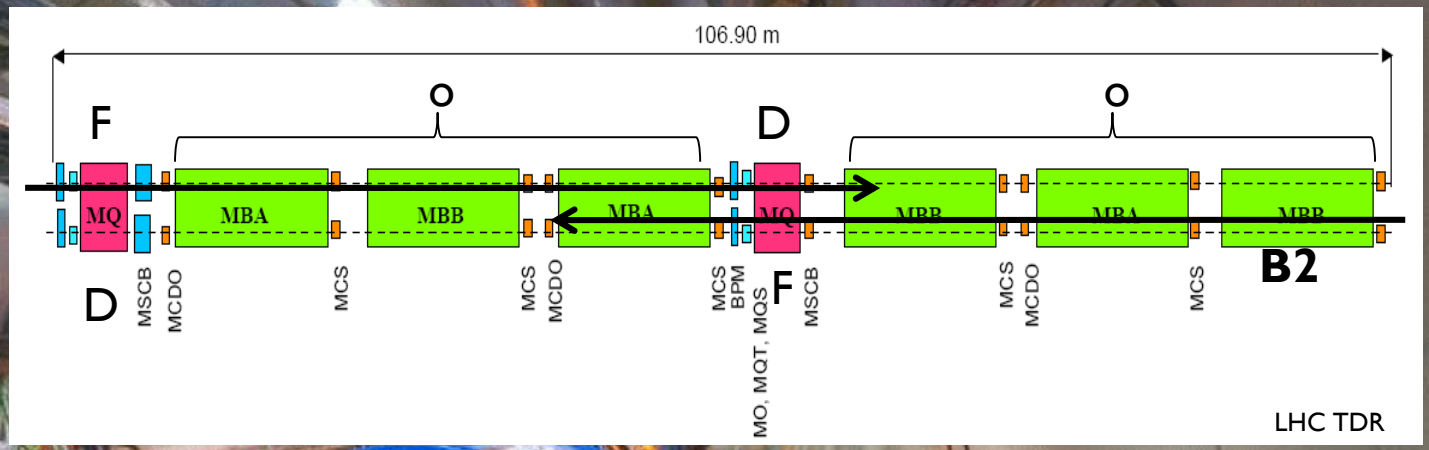


R. Alemany Fernandez

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

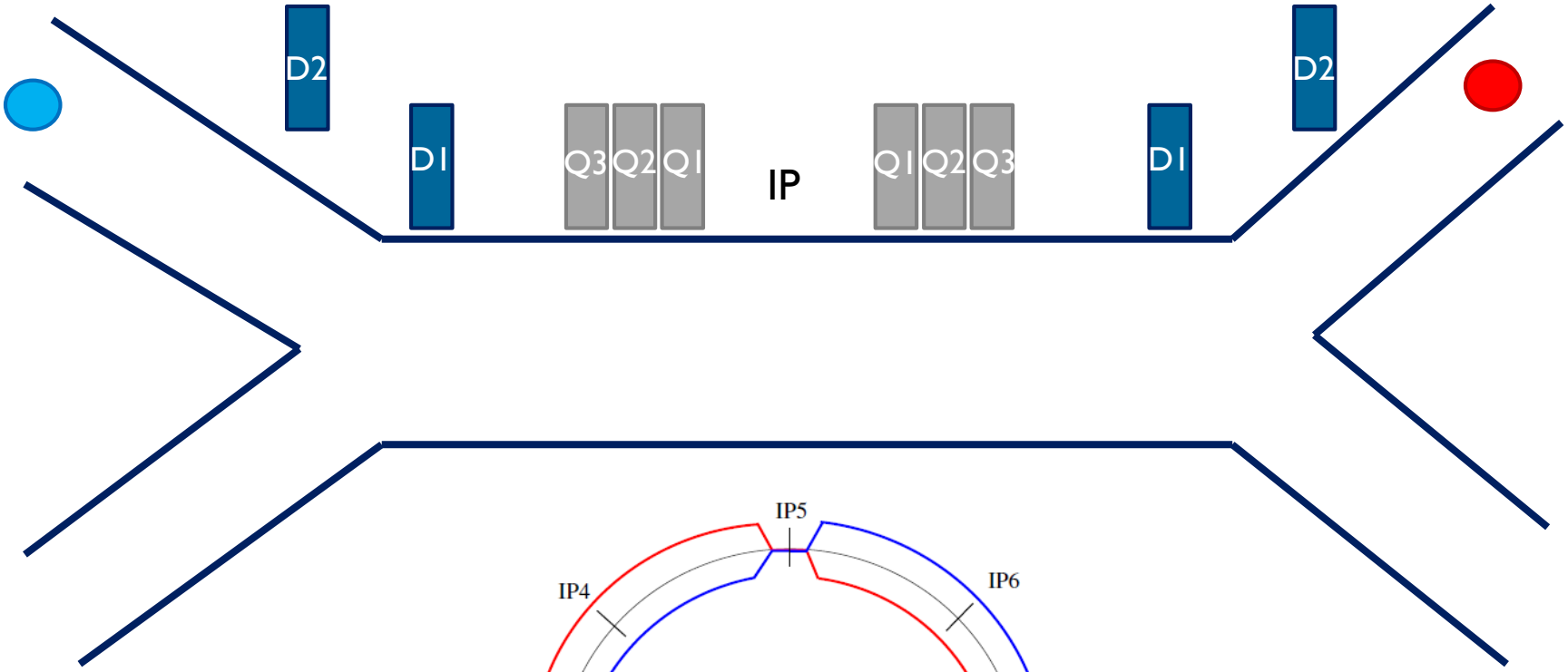
Large Hadron Collider (LHC)

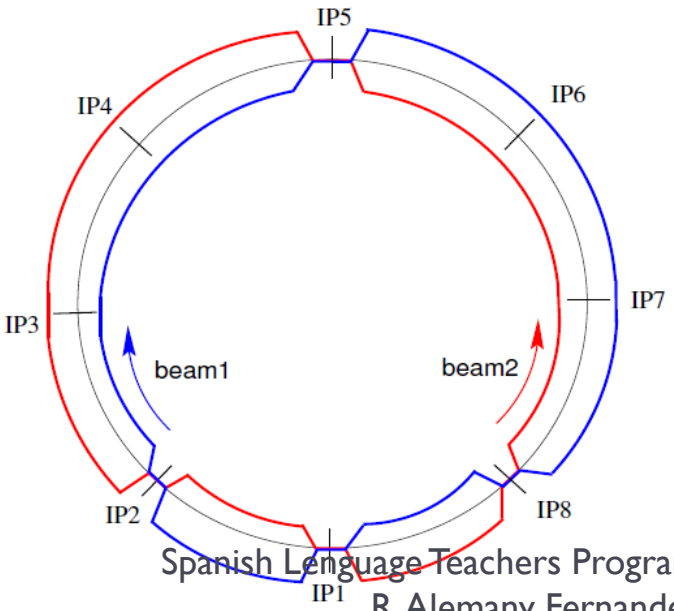
LHC arc cells = FoDo lattice* with
~ 90° phase advance per cell in the V & H plane



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

I. Basic layout of the machine: Luminosity insertions





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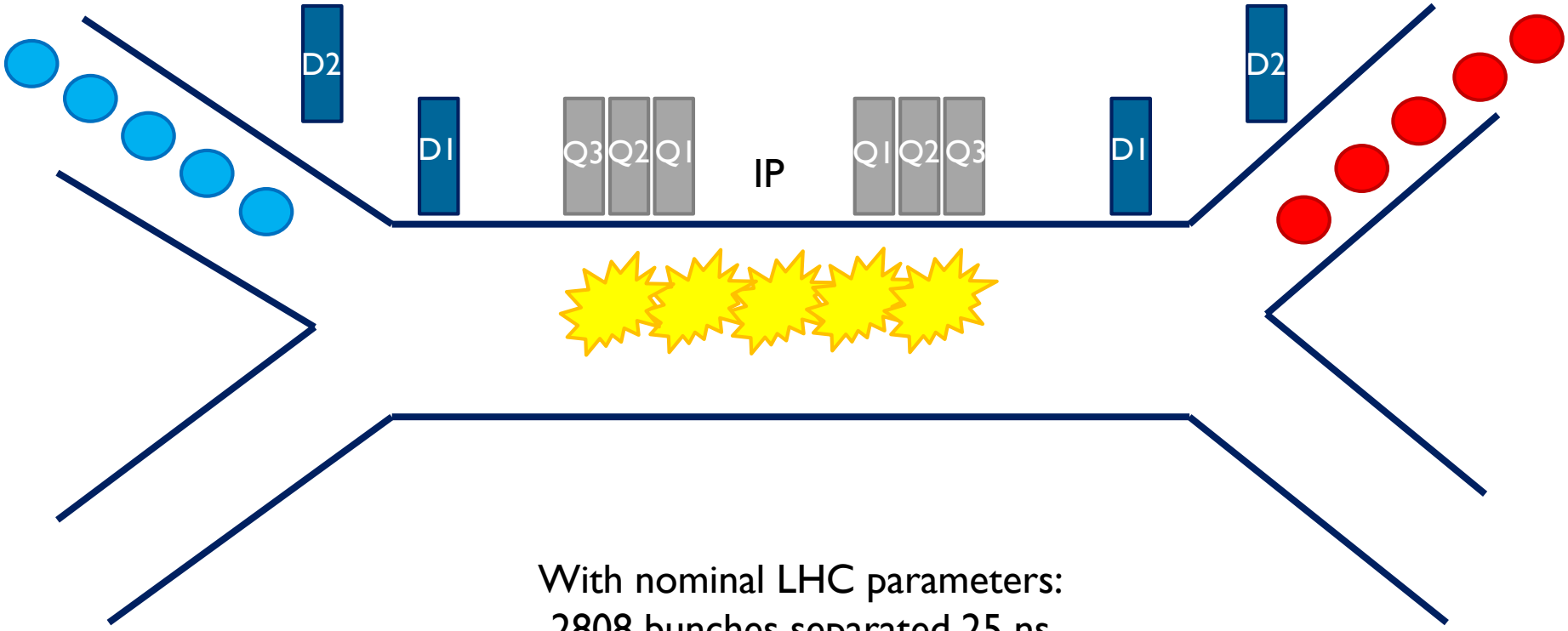
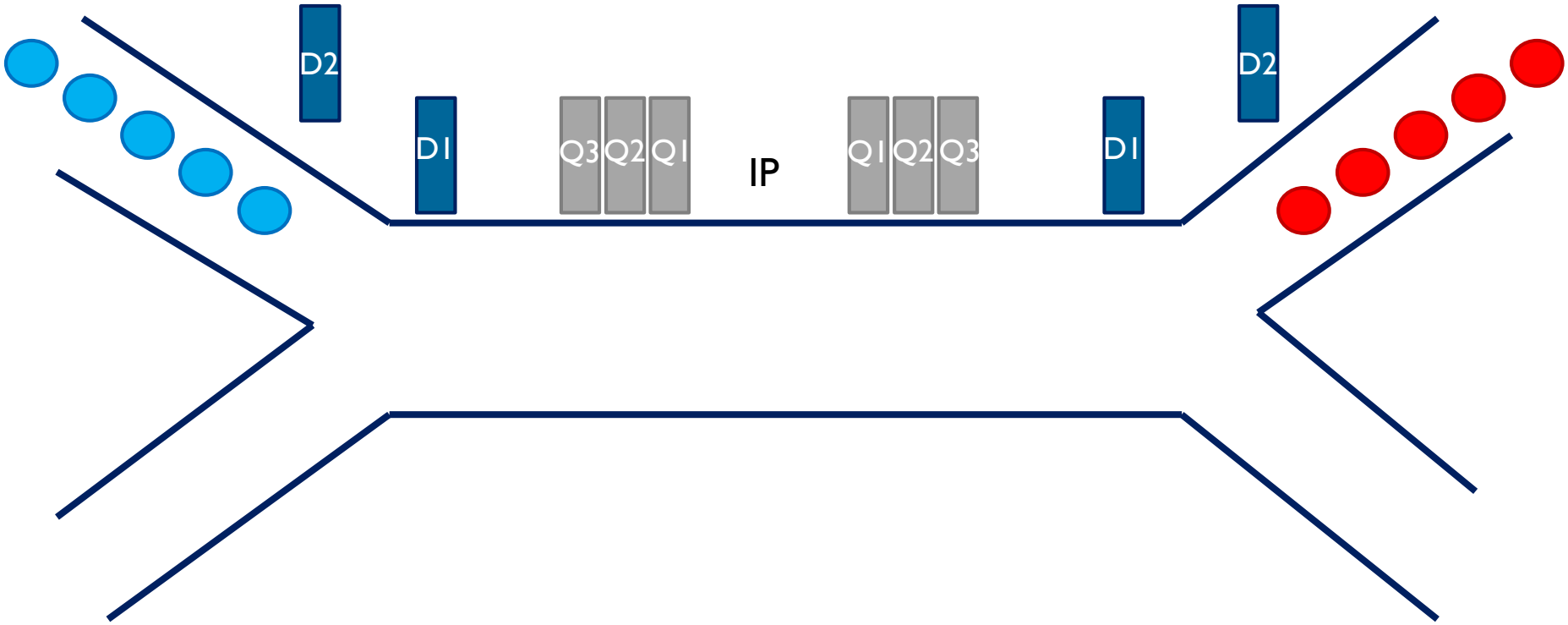


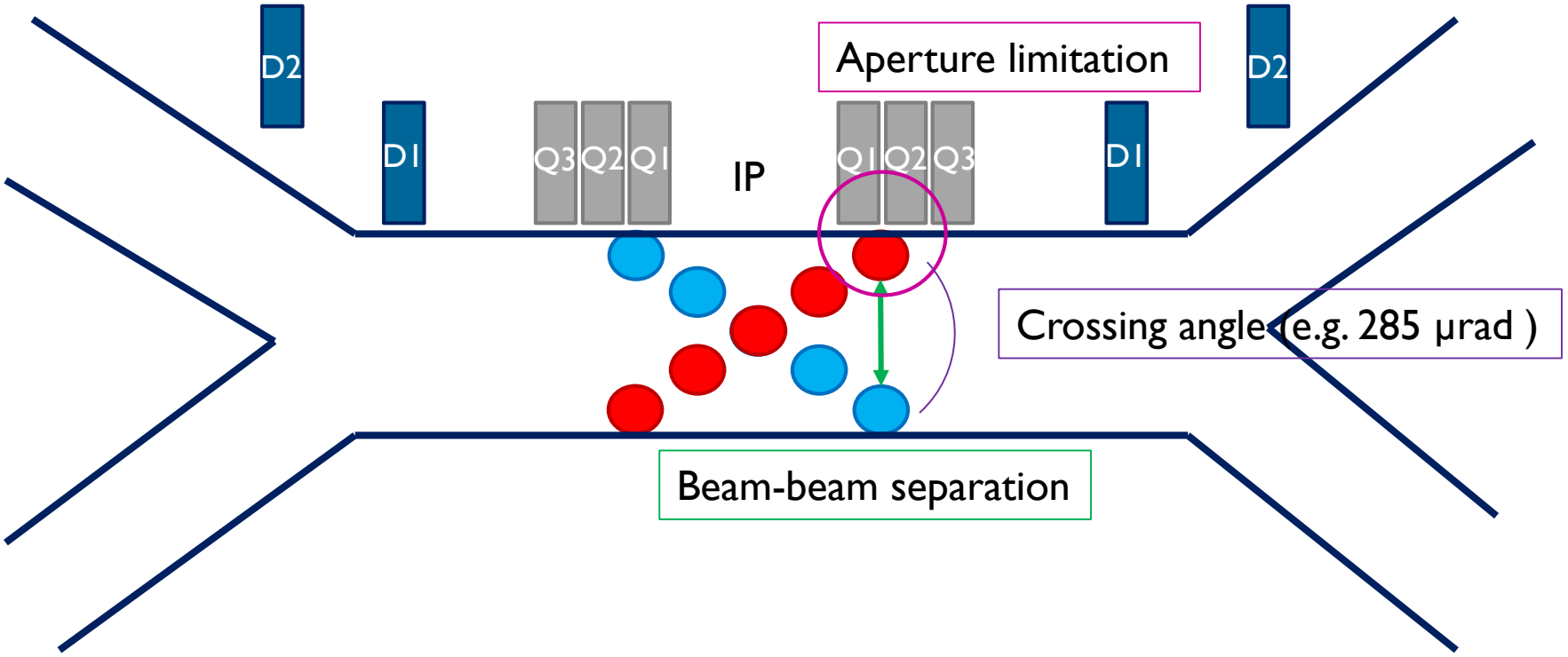
With nominal LHC parameters:
2808 bunches separated 25 ns

We can have up to **30 parasitic interactions** around the IP

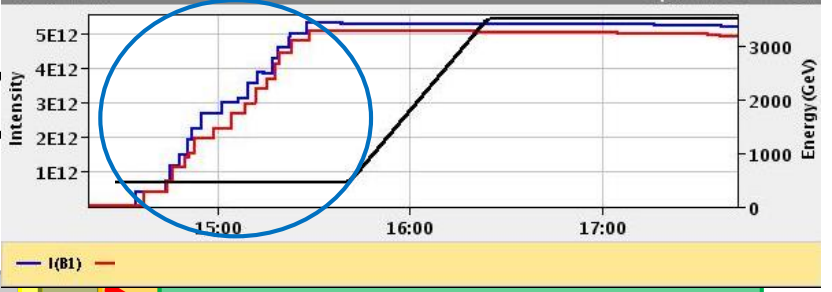
I. Basic layout of the machine: Luminosity insertions

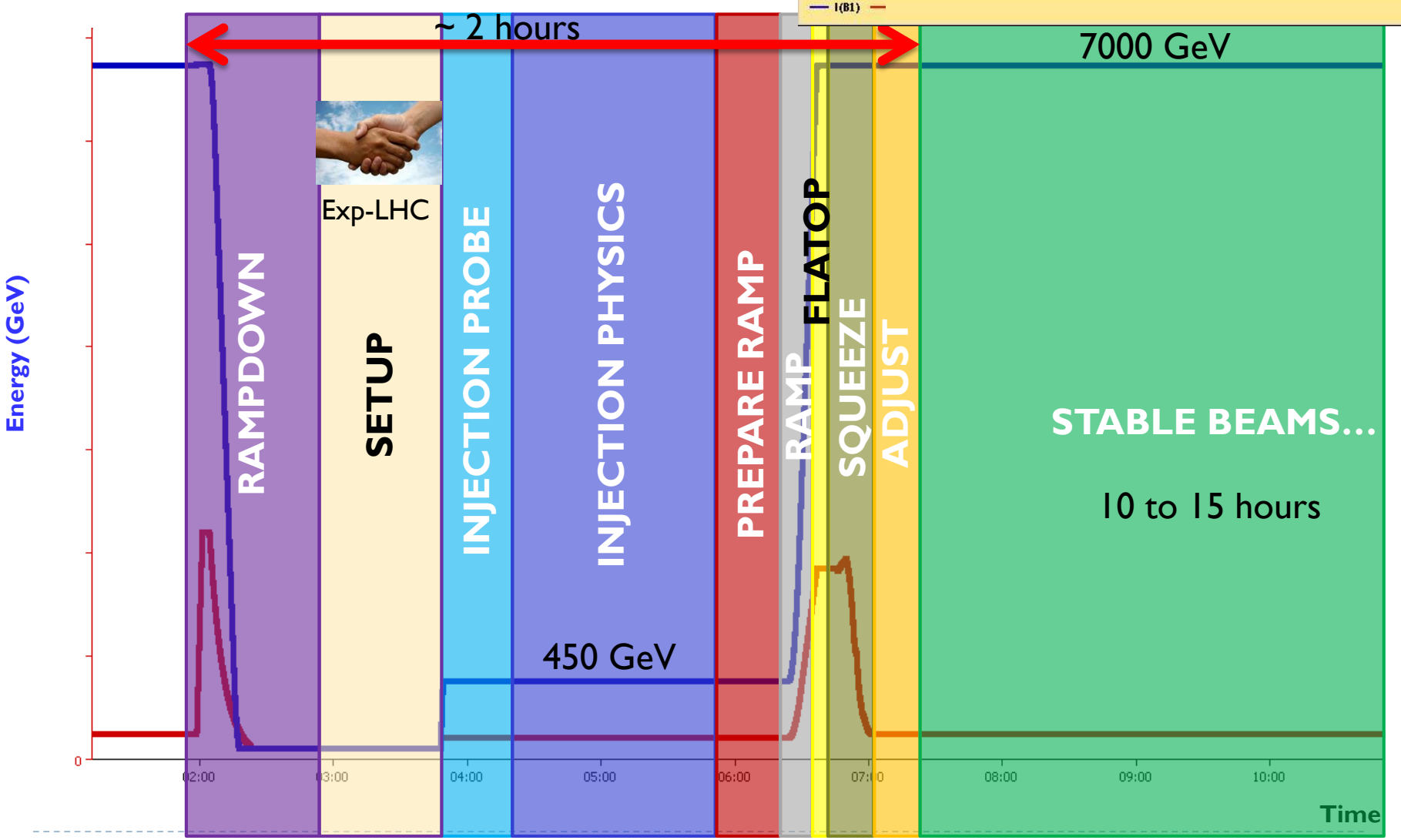


I. Basic layout of the machine: Luminosity insertions

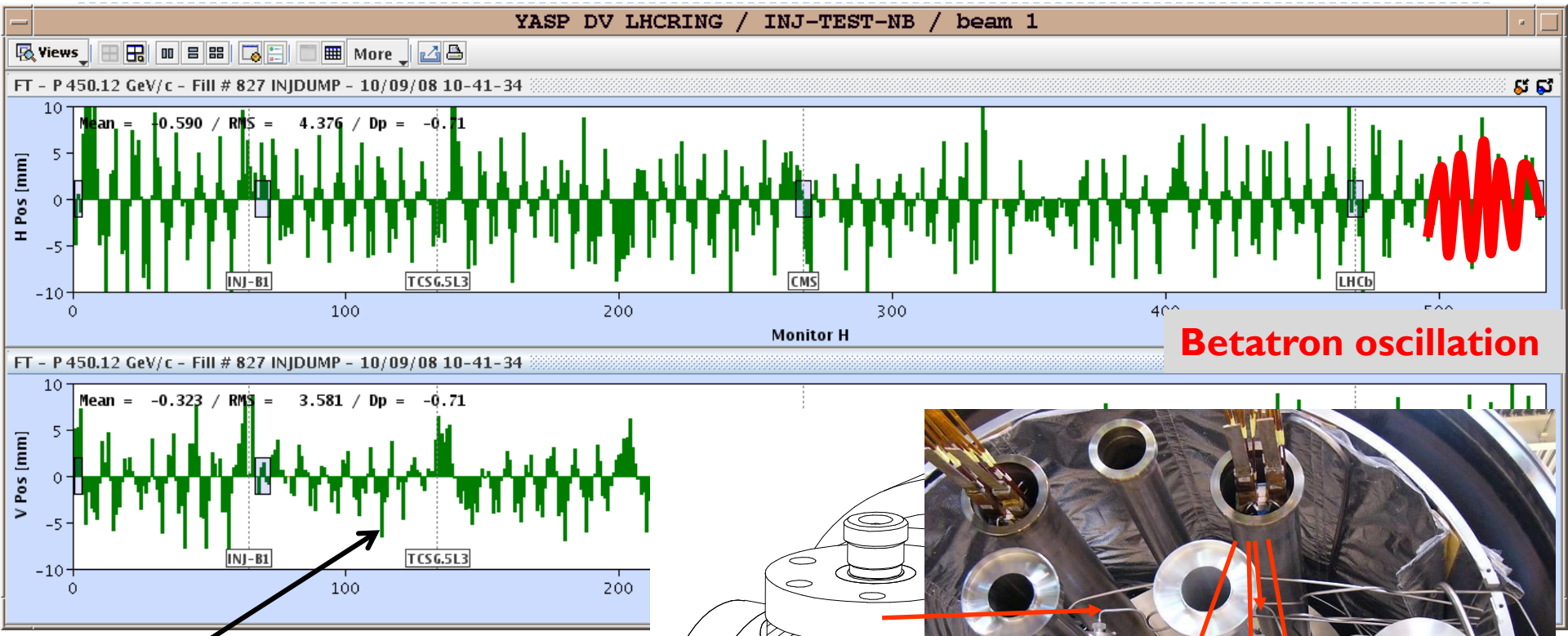


II. LHC Operational cy



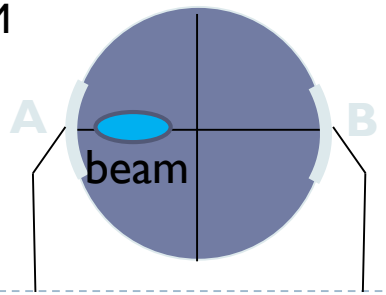


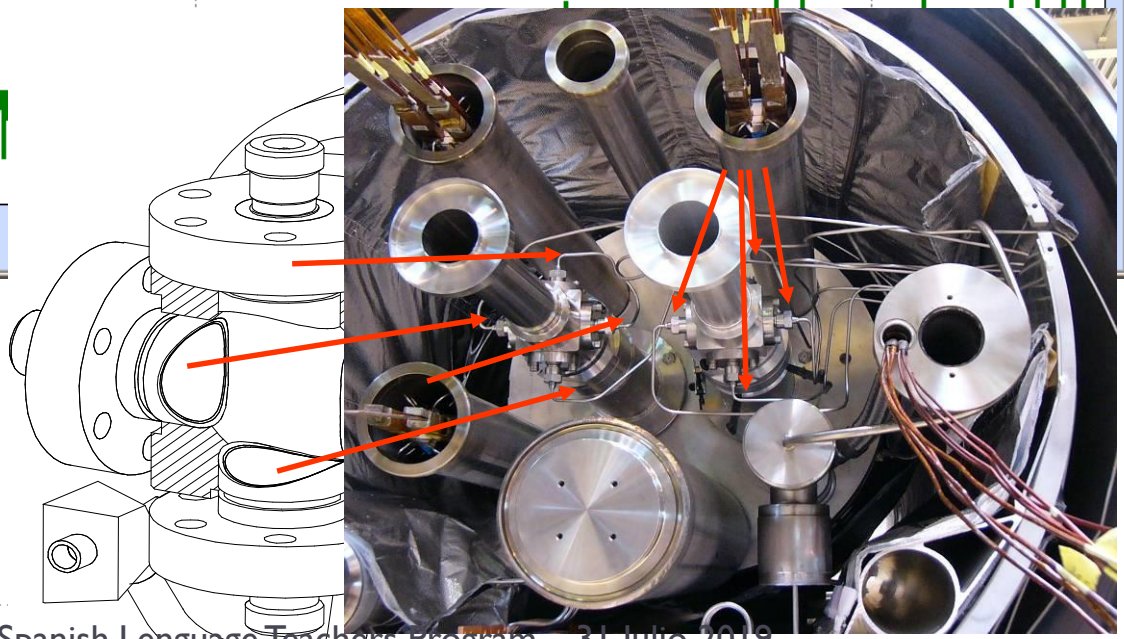
II. Beam measurements: Beam trajectory



Betatron oscillation

Each point is a BPM (Beam Position Measurement)

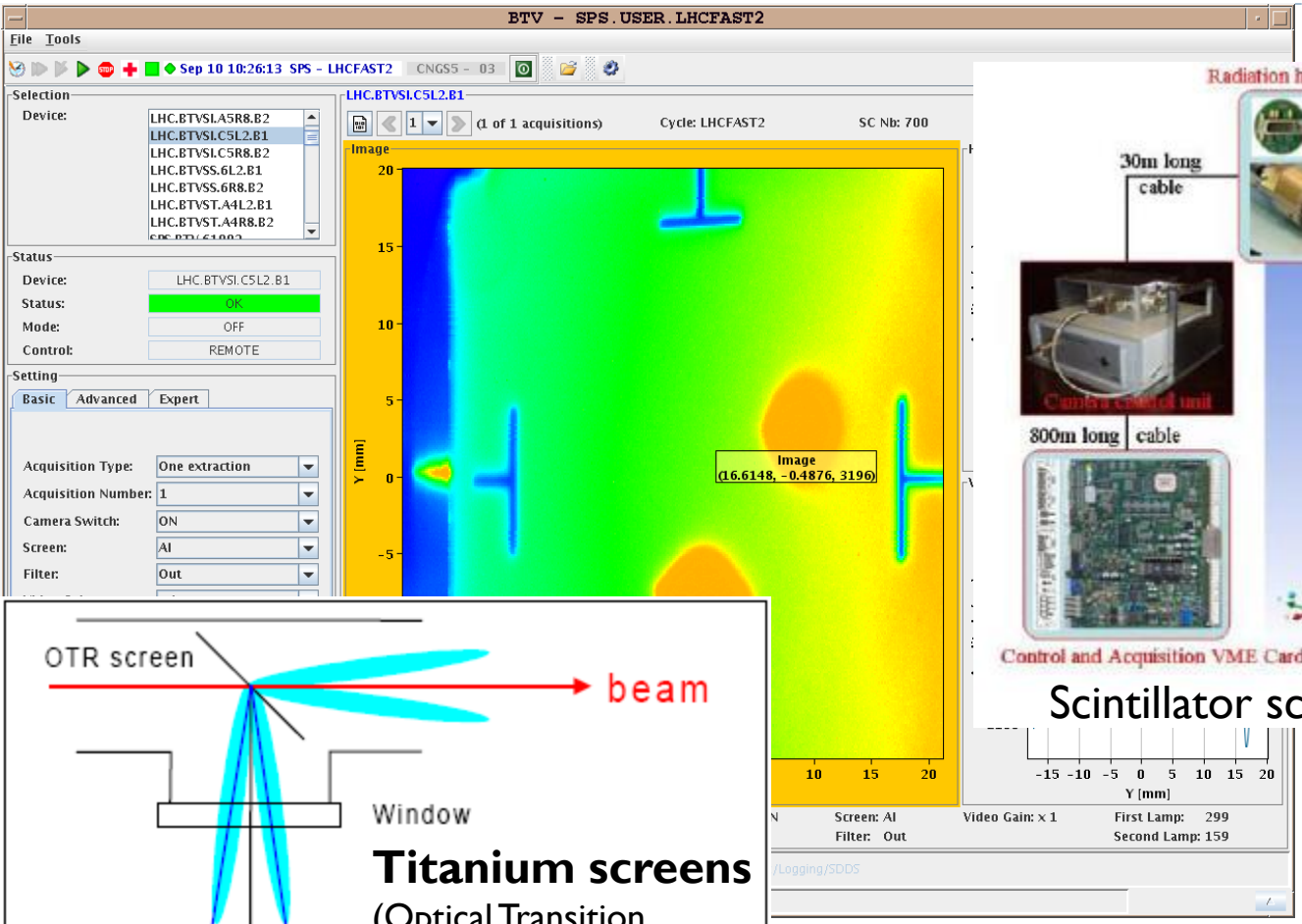


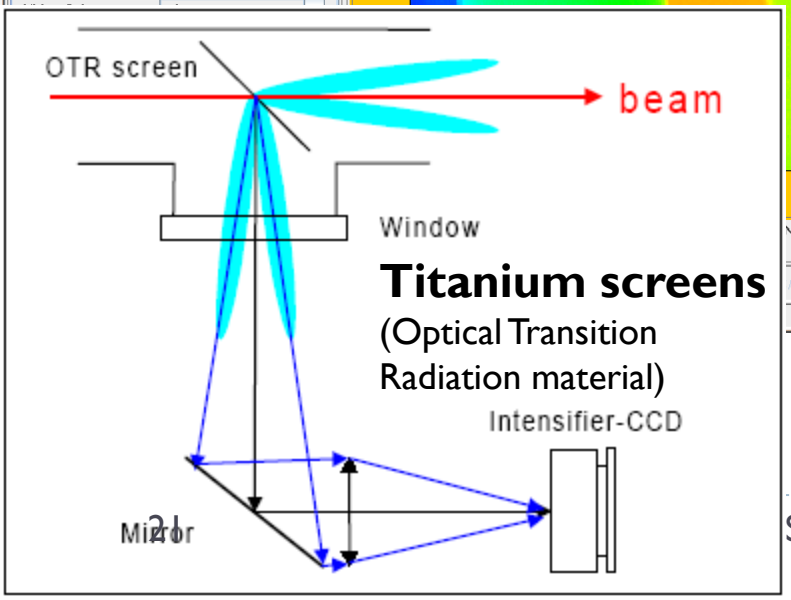


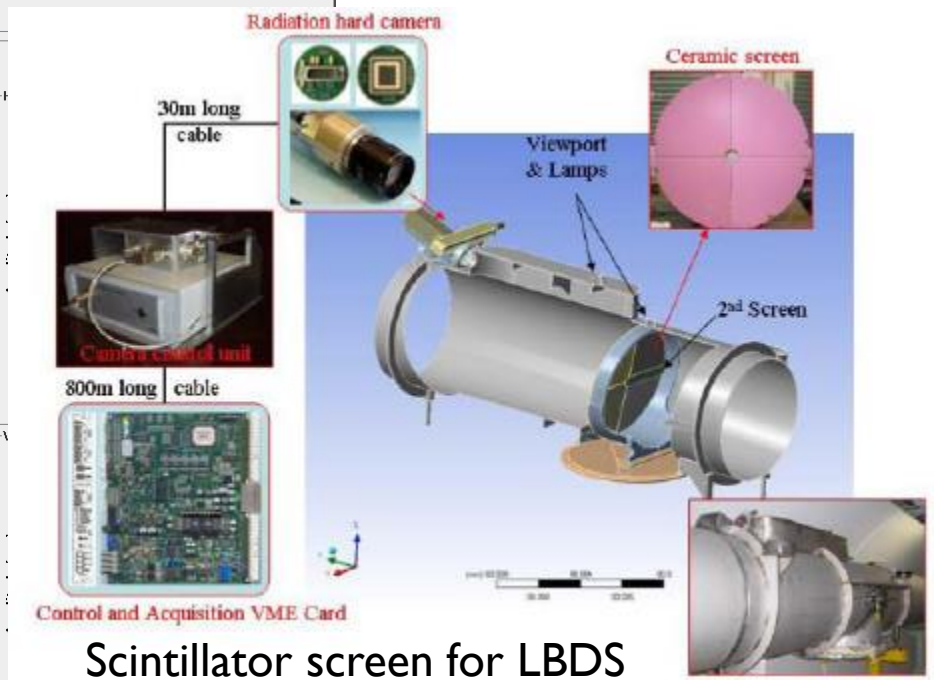
49 mm aperture

T_A T_B

II. Beam profile measurements: Beam 1 on TDI screen – 1st and 2nd turns

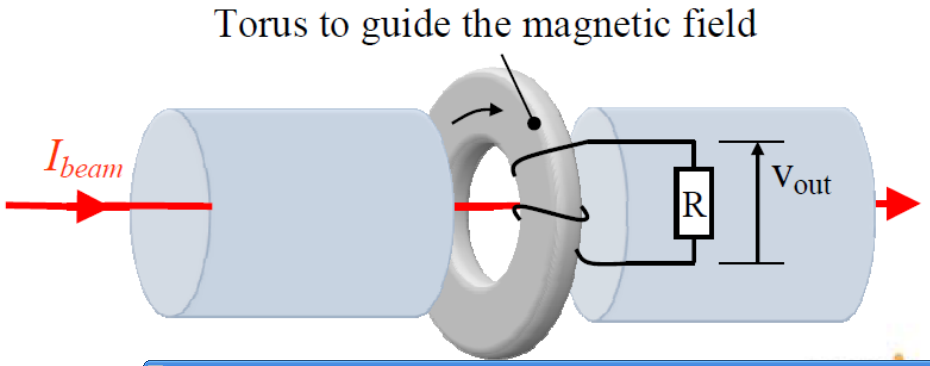


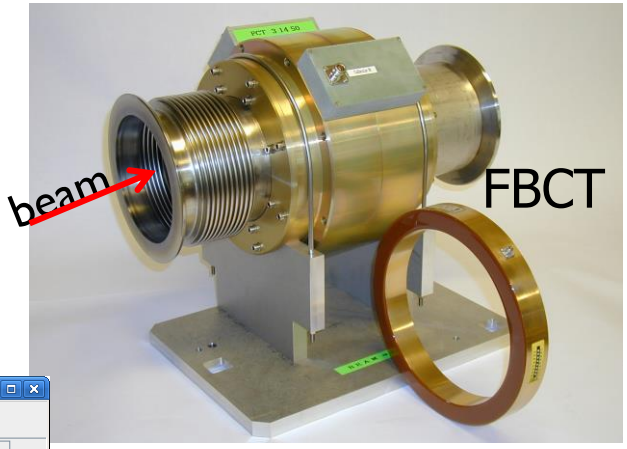


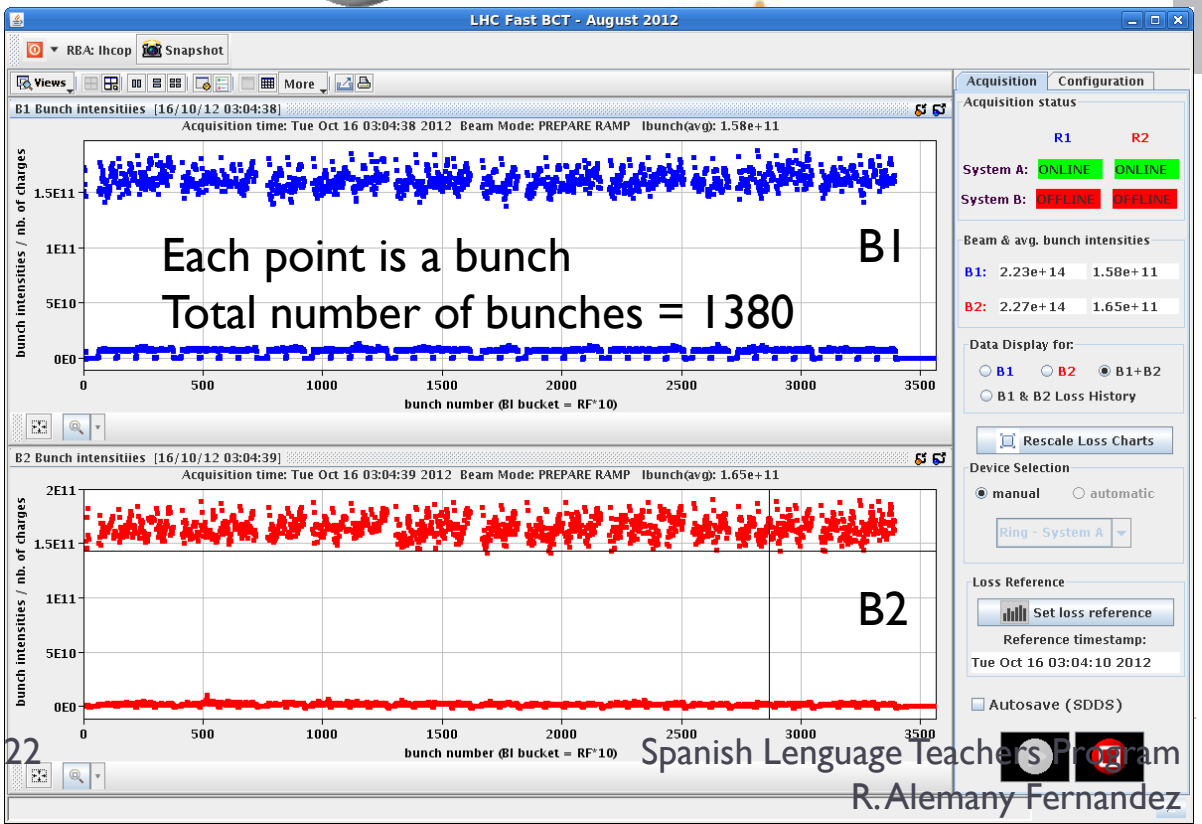


Scintillator screen for LBDS

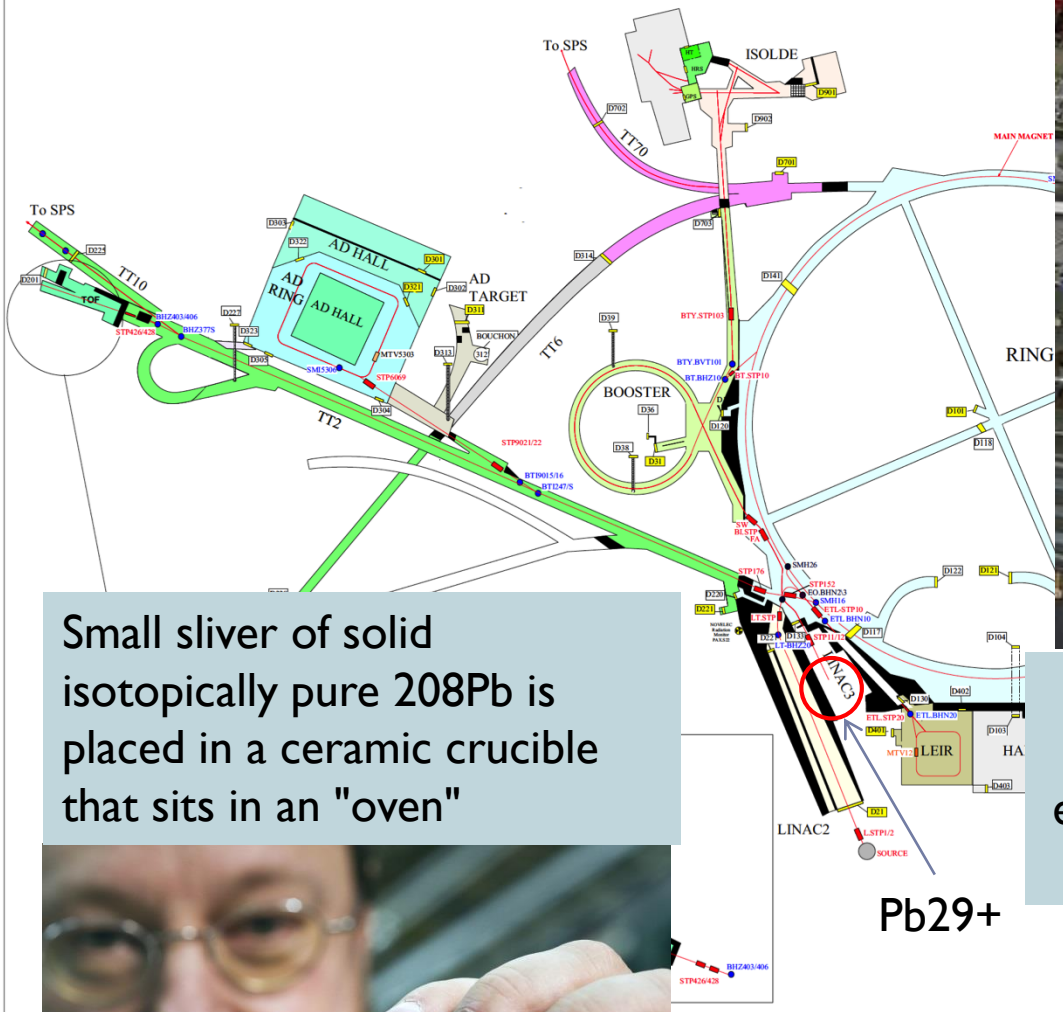
II. Beam measurements:
Fast BCT (Beam Current Transformer)

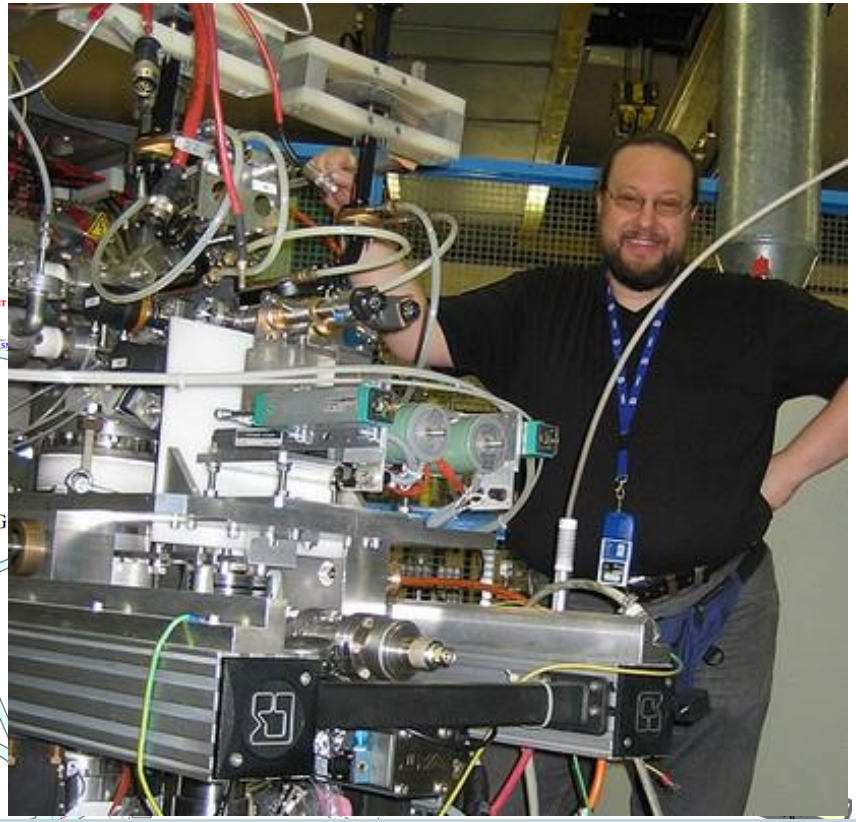






Ion Chain



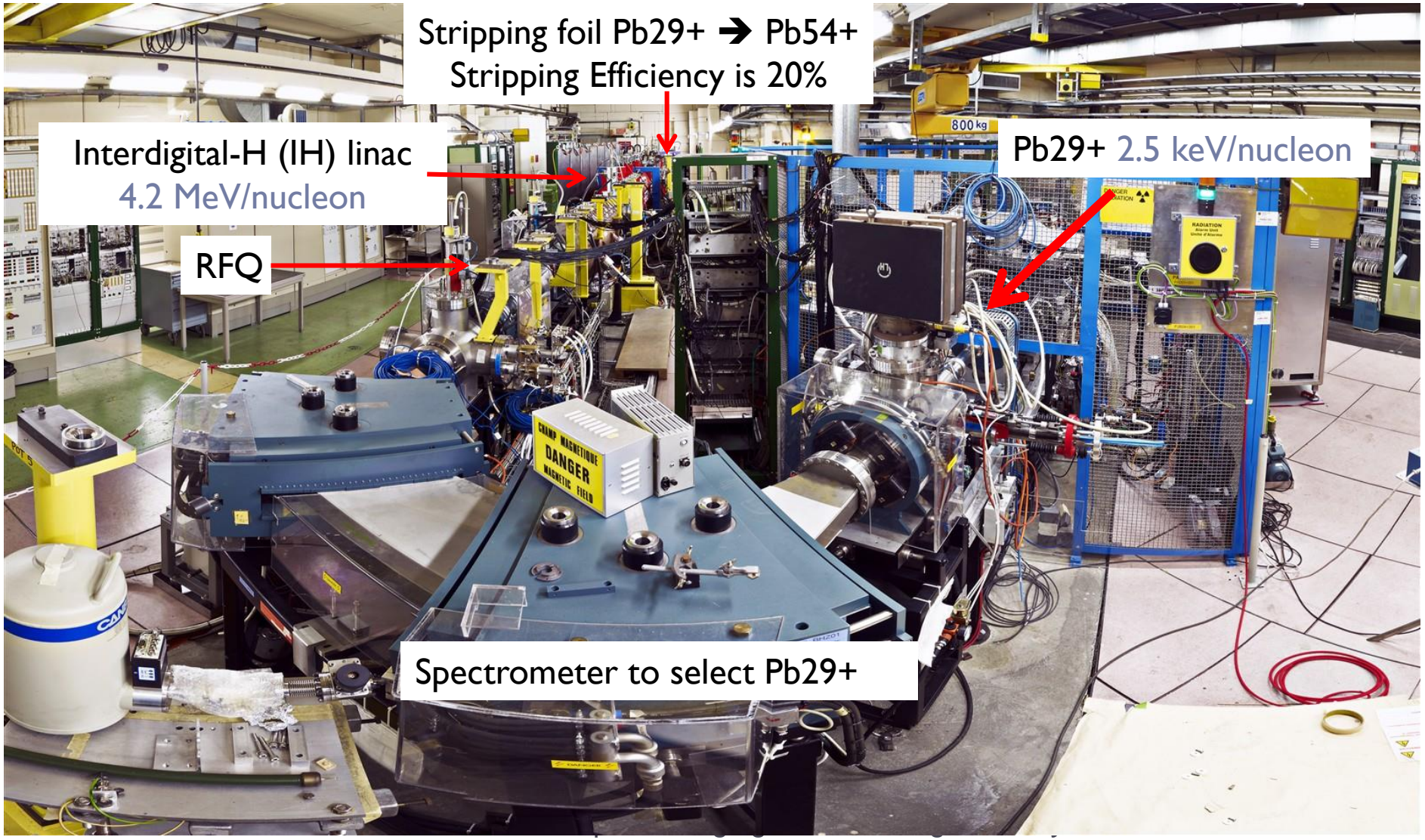


Small sliver of solid isotopically pure 208Pb is placed in a ceramic crucible that sits in an "oven"

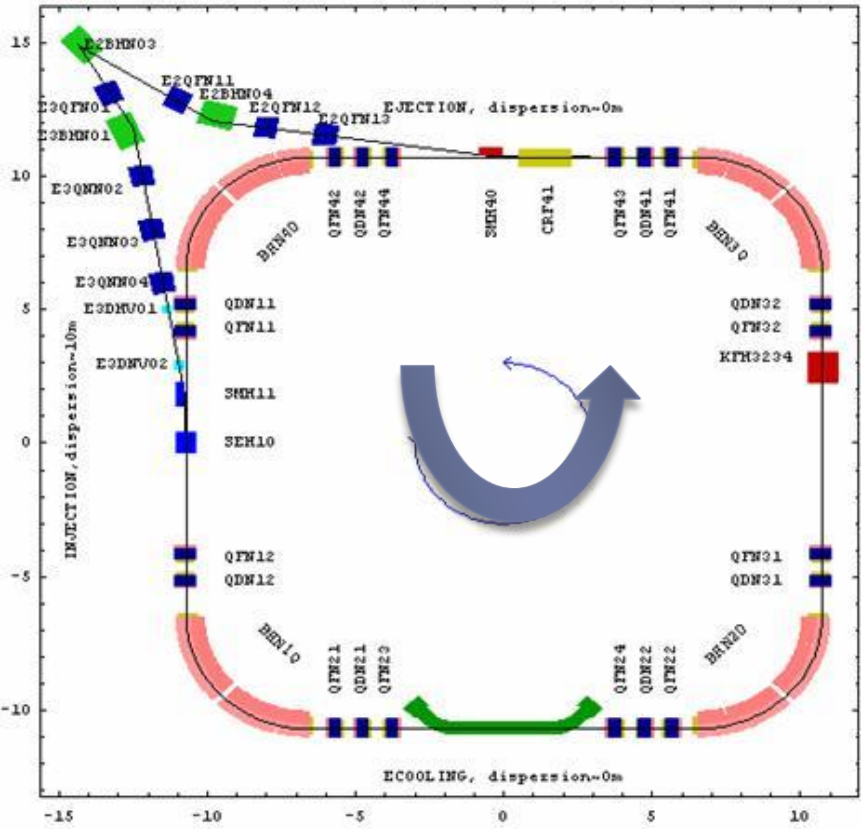
The metal is heated to around 800°C and ionized to become plasma. Ions are then extracted from the plasma and accelerated up to 2.5 keV/nucleon.

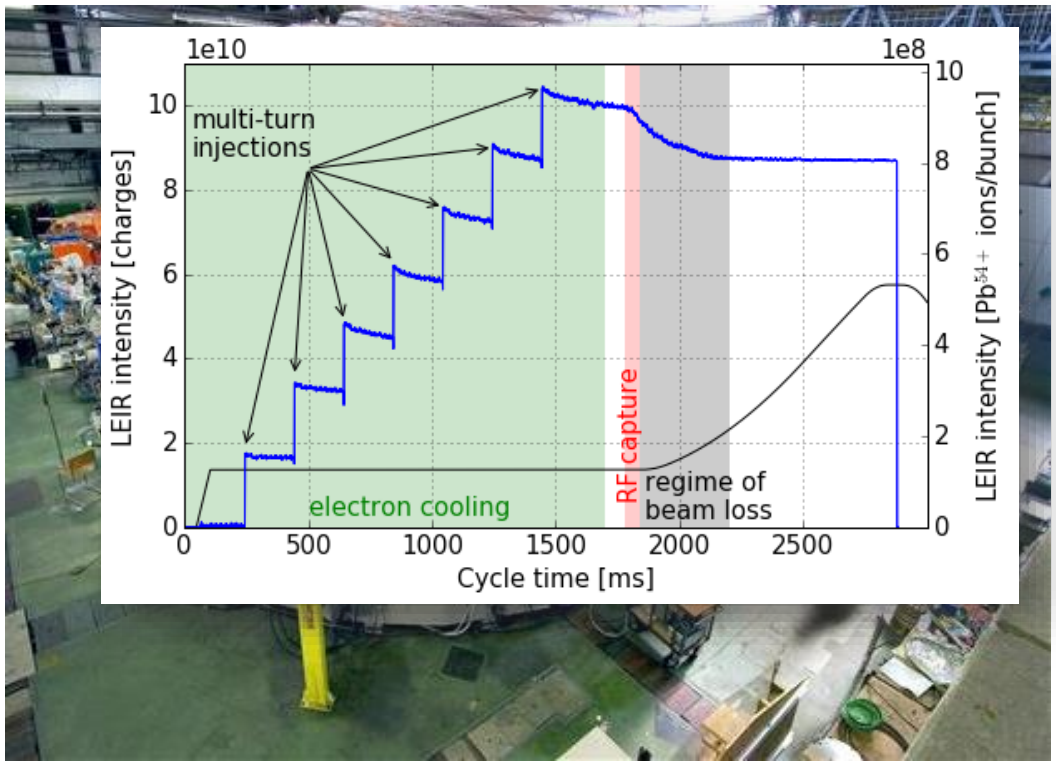
The source can also be set up to deliver other species… Ar and Xe

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
MAGNETIC FIELD

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

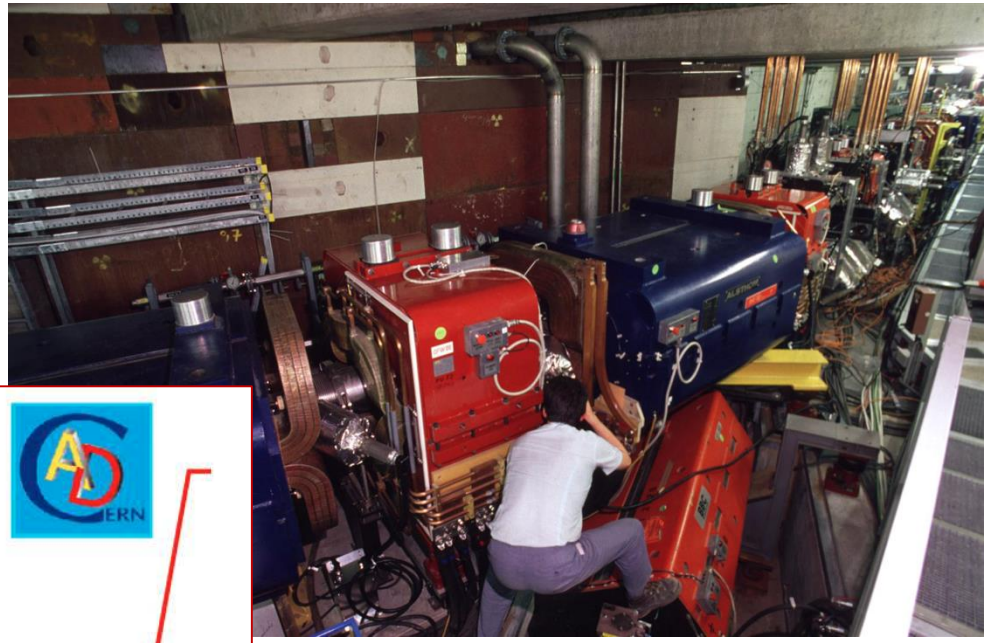
The Pb54+ is finally fully stripped to Pb82+ in the transfer line from PS to SPS

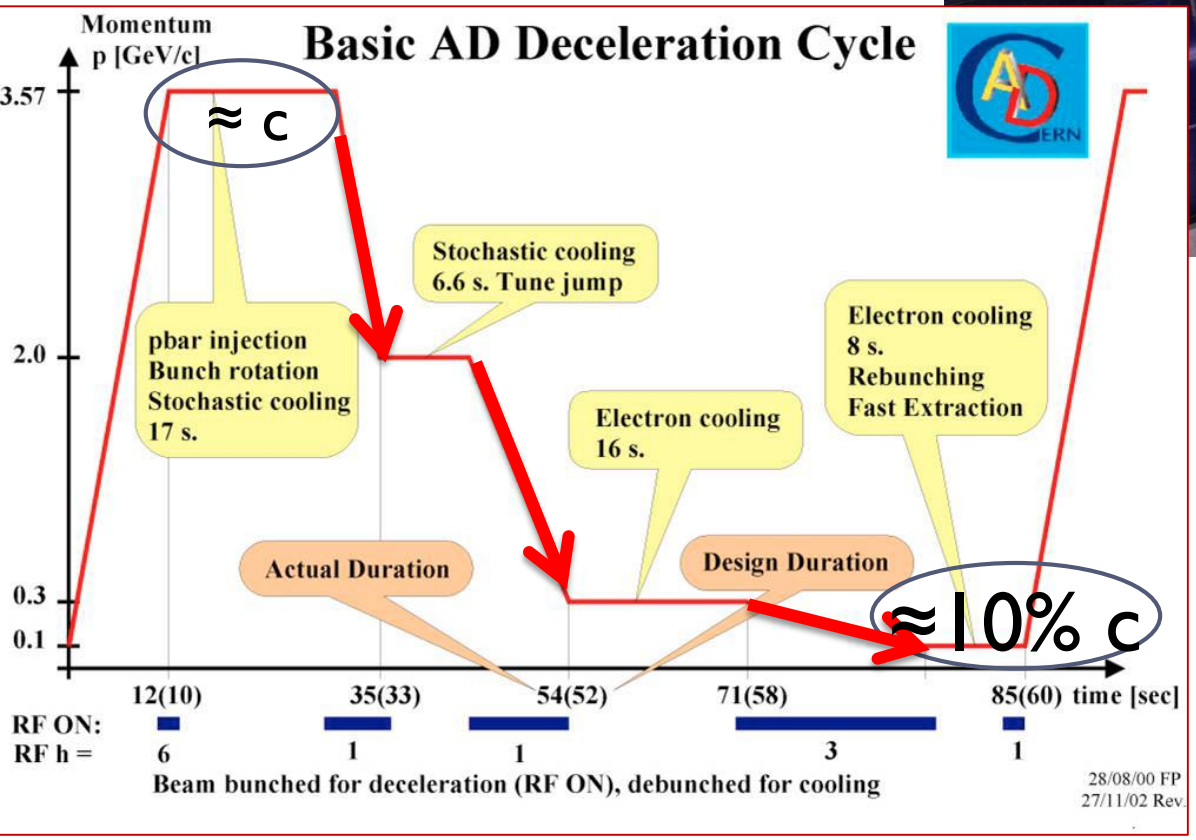
What else besides injection into LHC our CERN Accelerator Complex does?

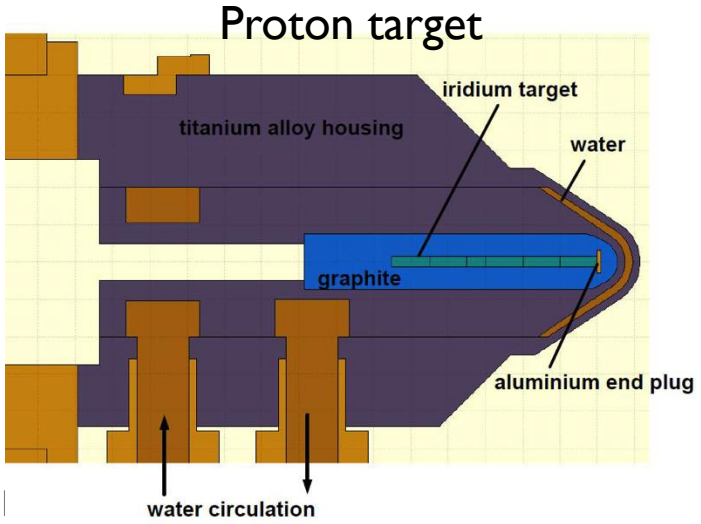
There is quite some amazing physics going on beyond the LHC

Antiproton Decelerator : AD

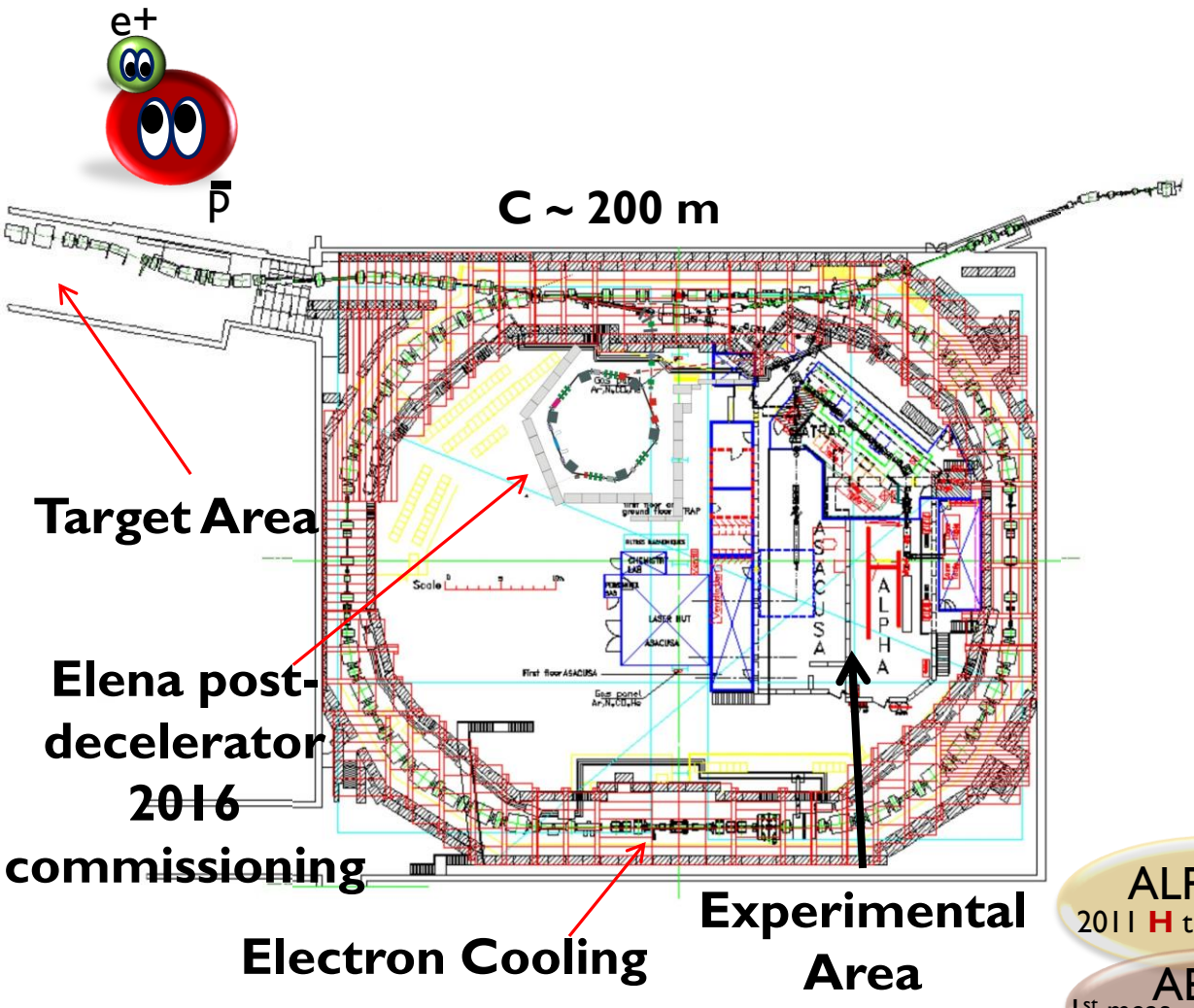
Built in 1999 (from the old AC)
26 GeV/c PS Proton beam produces $\bar{p}$ (1 in 10^7) which are focused and captured in the AD and decelerated to 100 MeV/c (5.3 MeV)







AD Layout



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

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

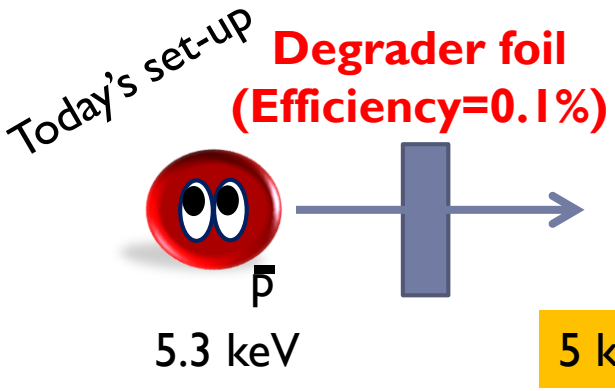
ATRAP
2002 first glimpse inside $\bar{H}$

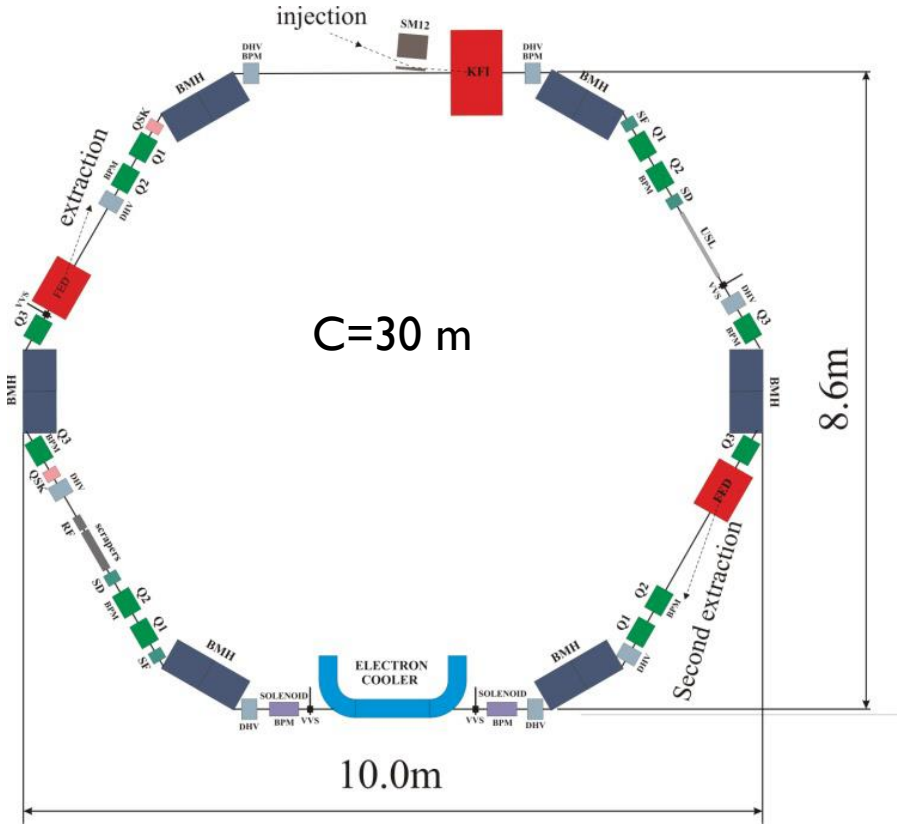
AEGIS
1st meas. of gravitational effect on $\bar{H}$

BASE
$\bar{p}$ magnetic moment

GBAR(1)
Gravitational effect on $\bar{H}$

Elena … More Deceleration





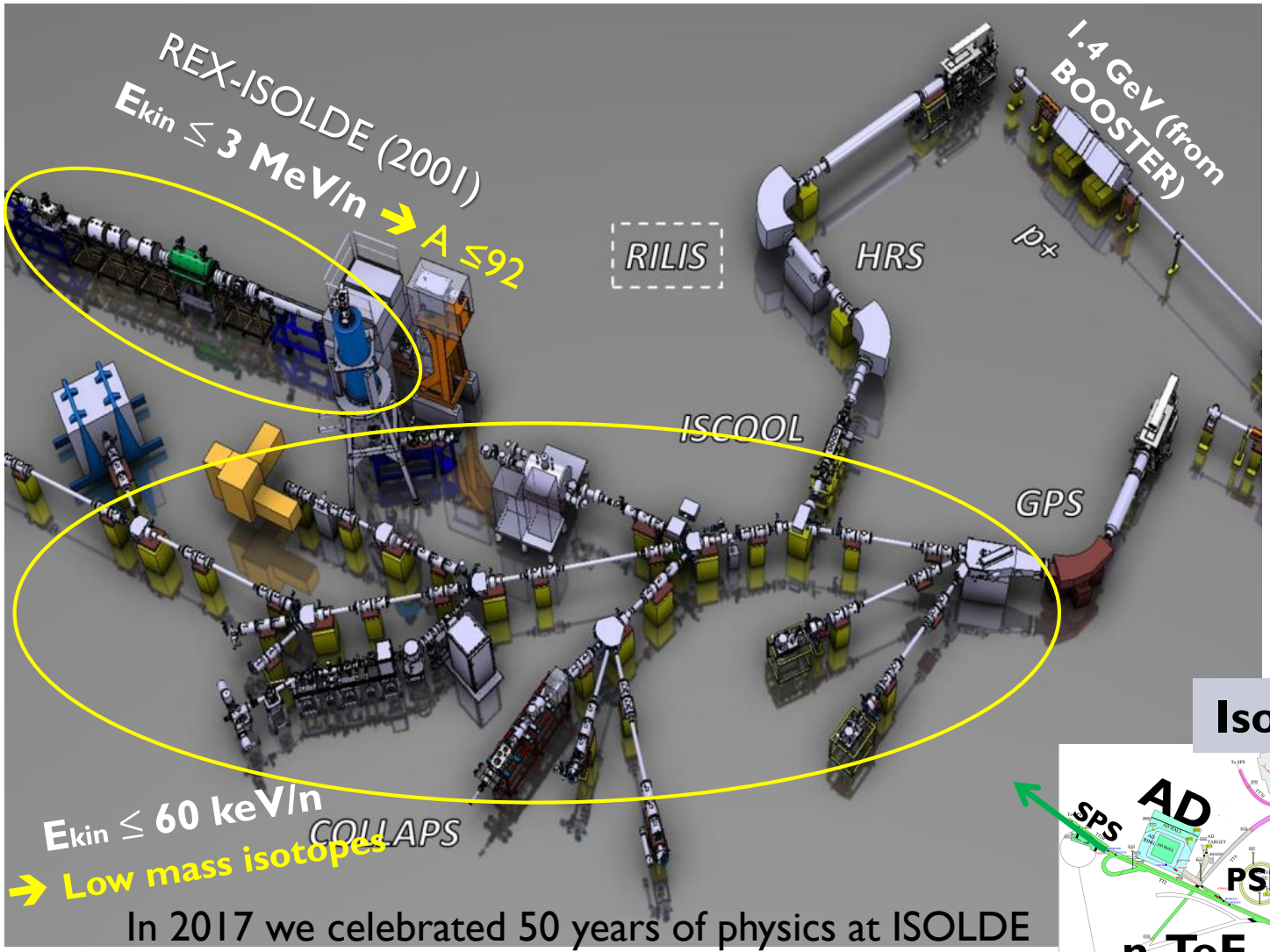
ELENA will overcome this problem + will be able to deliver beams almost simultaneously to all four experiments resulting in an essential gain in total beam time for each experiment. This also opens up the possibility to accommodate an extra experimental zone.

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

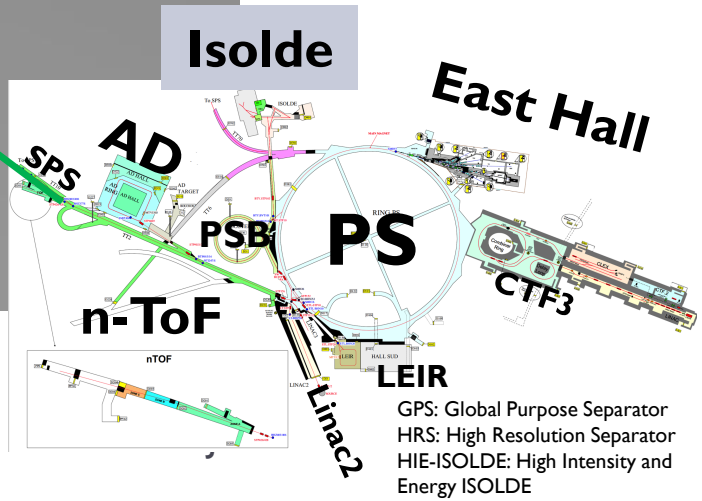
Commissioning in 2016
Operation 2017

ISOLDE Synchrocyclotron: 1967-1990
ISOLDE PSB: 1992

PSB Experimental Areas: ISOLDE

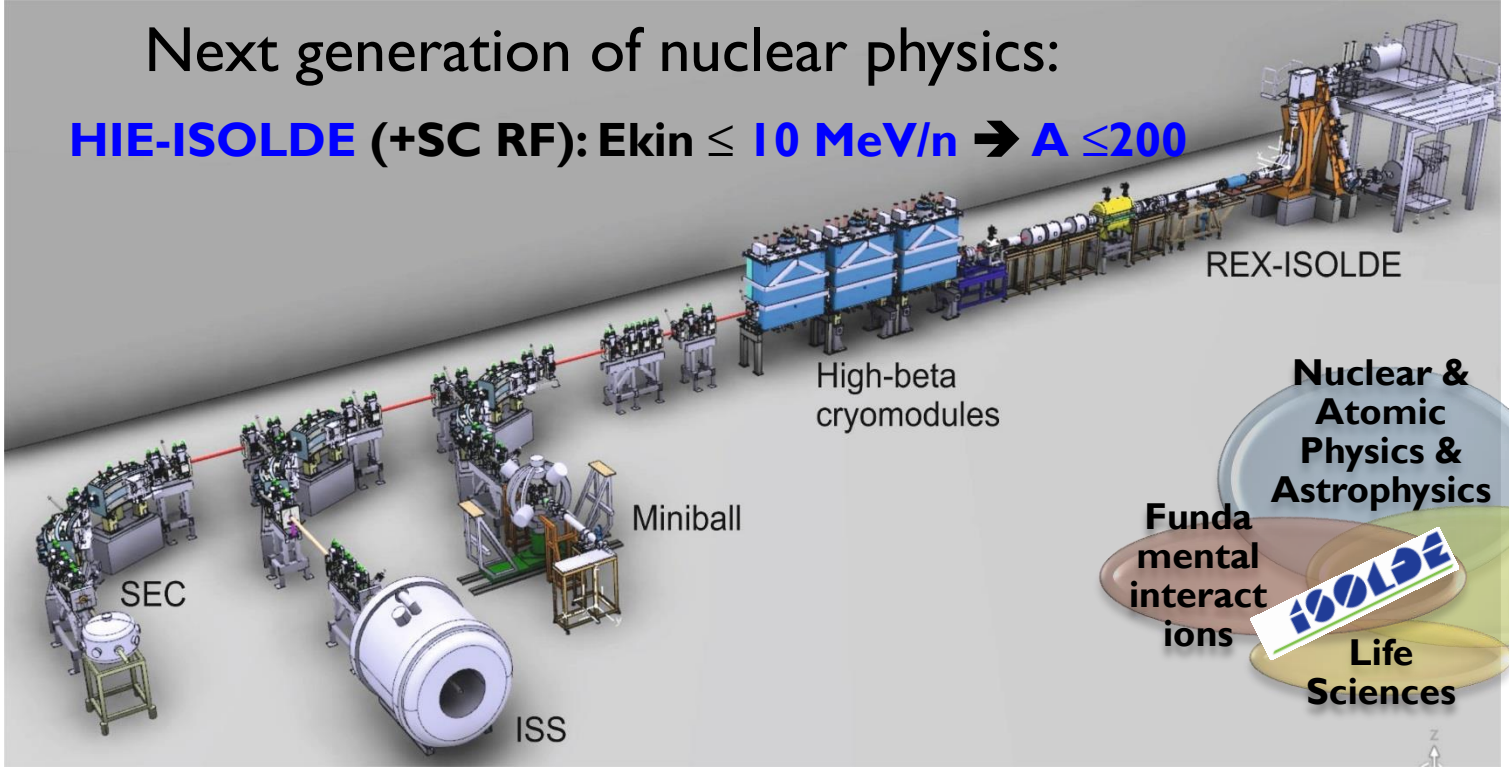


Solid and liquid target materials → wide spectrum of radioactive isotopes up to $Z =< 92$. Radioactive isotopes are produced via proton-induced target fragmentation, spallation and fission reactions



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



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: East Hall

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

CLOUD

ATLAS, CMS, SATELLITE EXP

CHARM

IRRAD

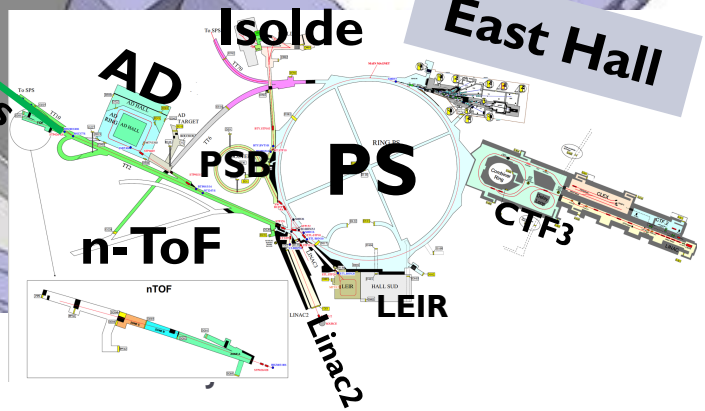
Detector Calibration

CLIMATE

Proton & neutron irradiation facilities

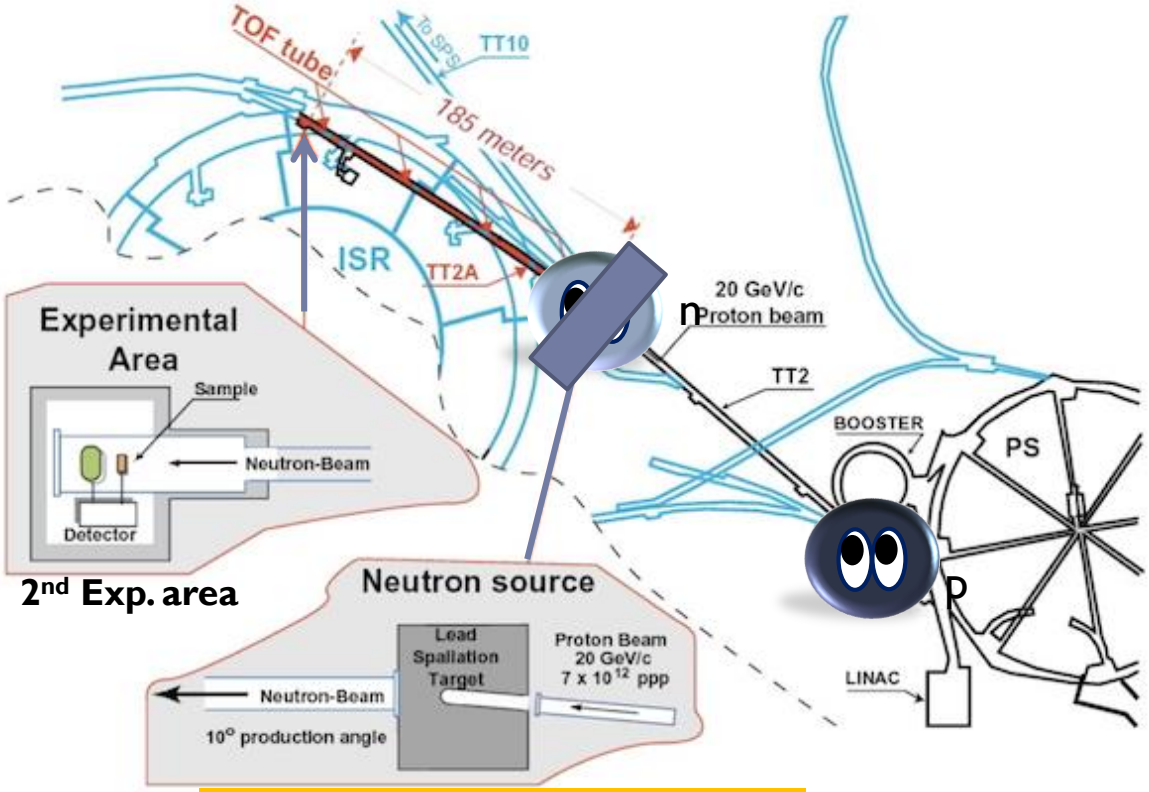
p+ (26 GeV)

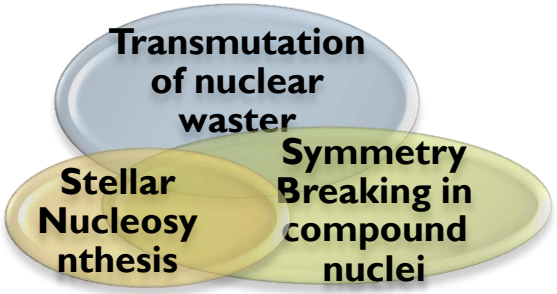
Secondary Beams:
Momentum range 1-15 GeV/c
Electrons, Hadrons & Muons
Max 1-2E^{+6} particles per spill



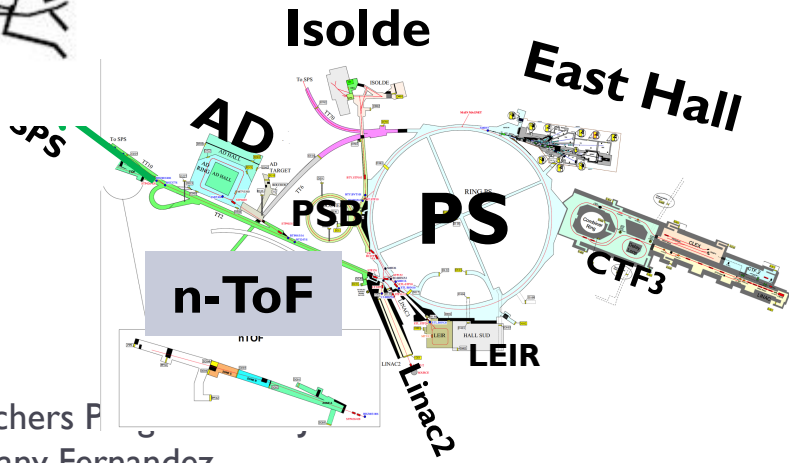
PS Experimental Areas: n-TOF

Study of neutron-induced reactions



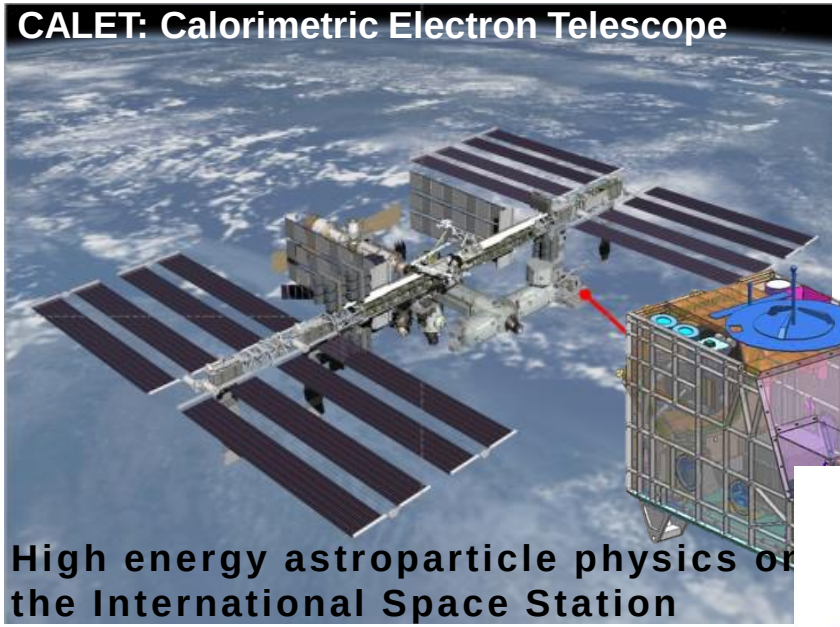


Each primary proton produces ~300 neutrons
Eneutron → meV - GeV



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

SPS Experimental Areas: North Area



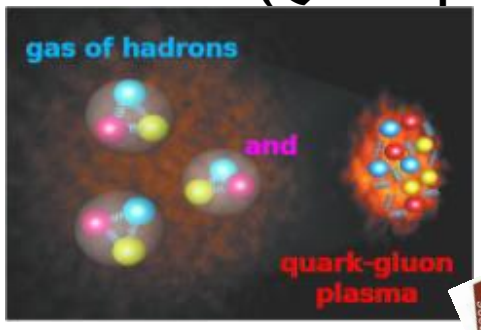
High energy astroparticle physics on the International Space Station

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

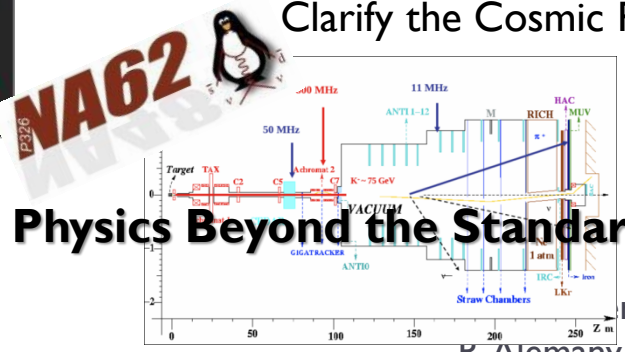
North Experimental Area

NA61/SHINE (QCD experiment)



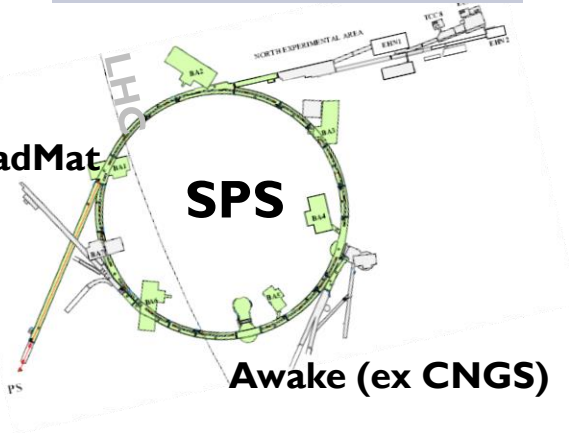
NEUTRON

Russian regular satellite
Clarify the Cosmic Rays origin



Physics Beyond the Standard Model

HiRadMat



Awake (ex CNGS)

COMPASS: Common Muon and Proton Apparatus for Structure and Spectroscopy

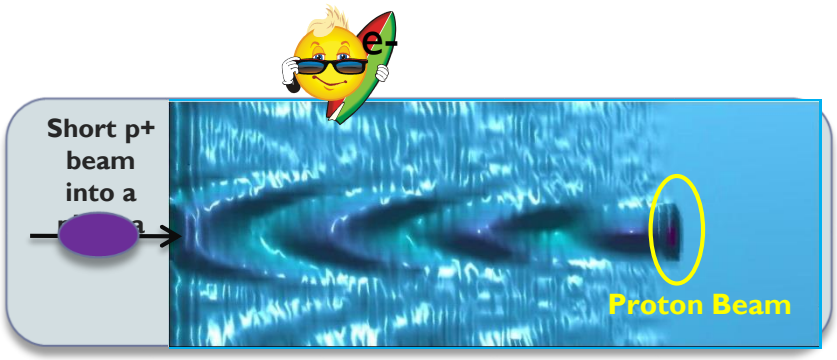
rs Program
R. Alemany Fernandez

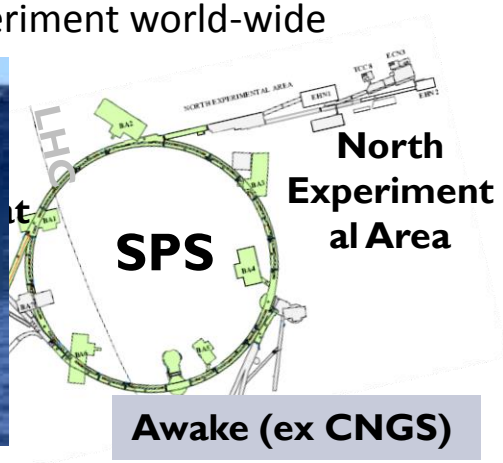
SPS Experimental Areas:

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:

HiRadMat
High-Radiation to Materials

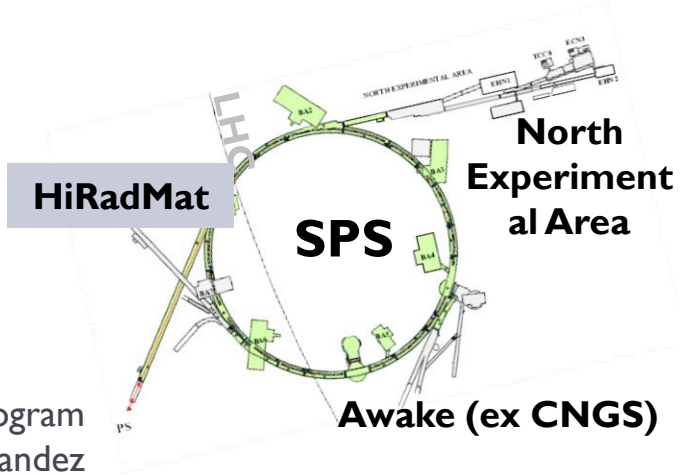
Current and Future Accelerators operate with higher energy, higher intensity, smaller size beams.

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

➔ energy equivalent to

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**



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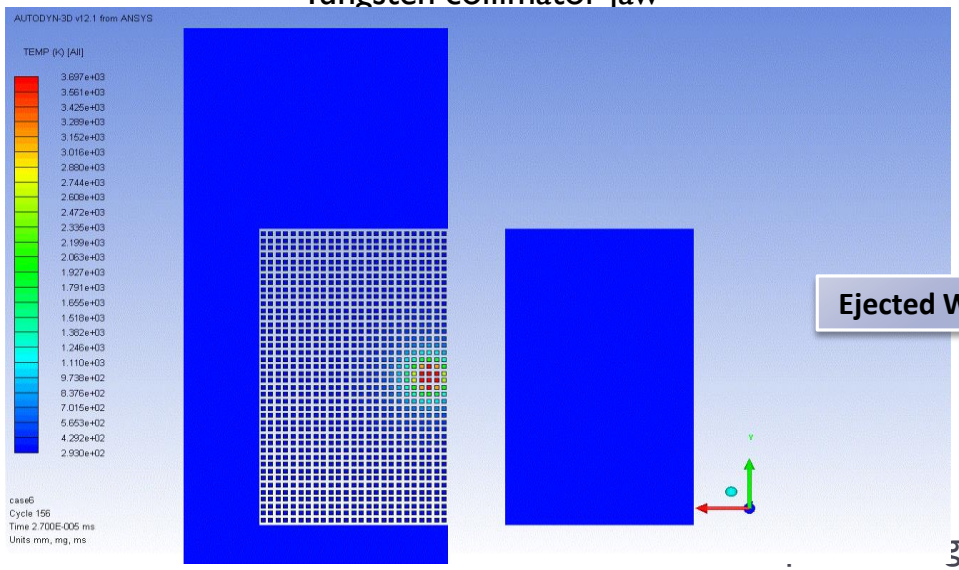
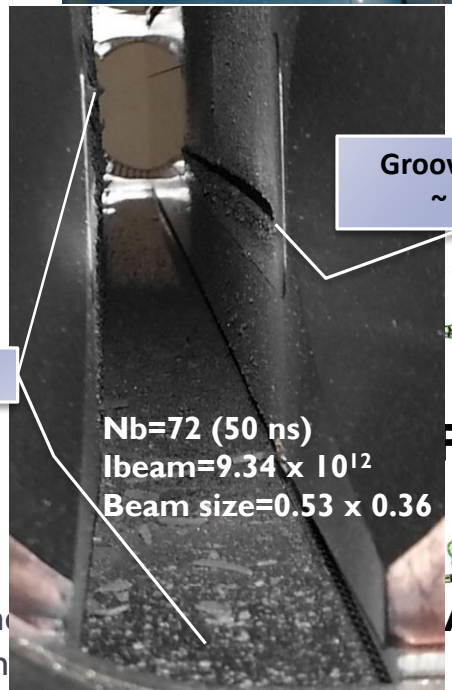
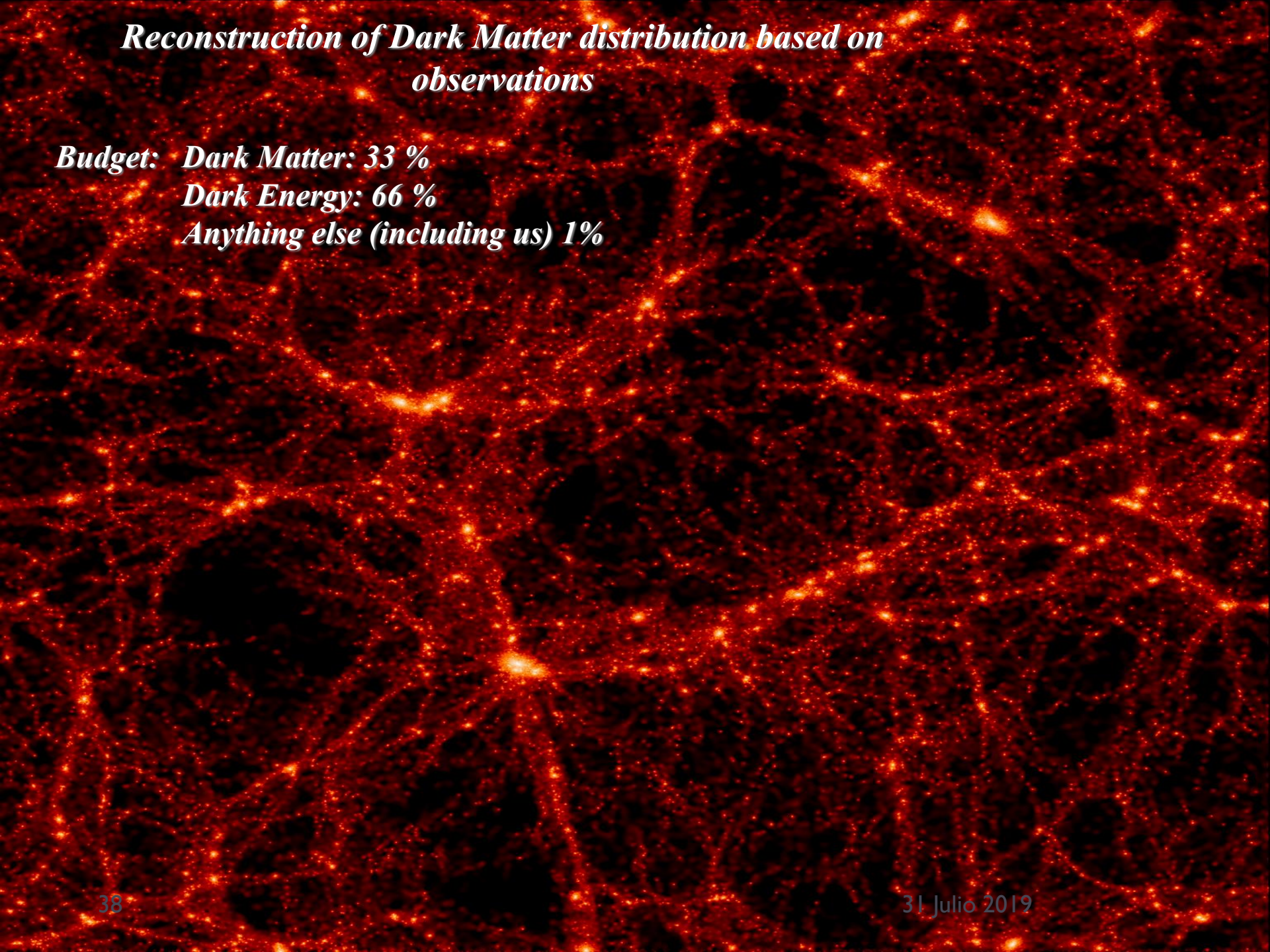
- Thermal management
- Radiation Damage to materials
- Thermal shock – beam induced pressure waves

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



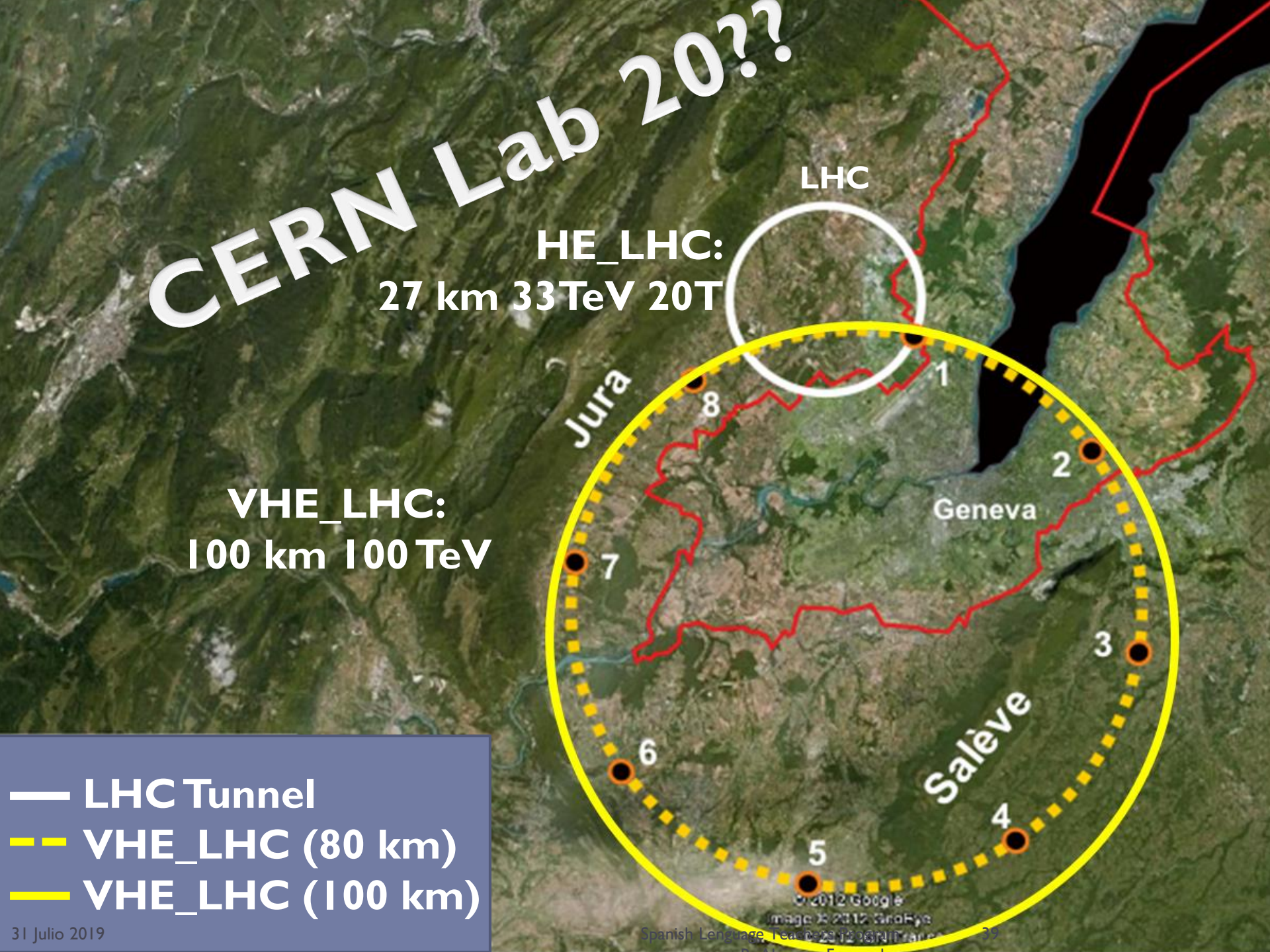


guage Teach
R. Aleman

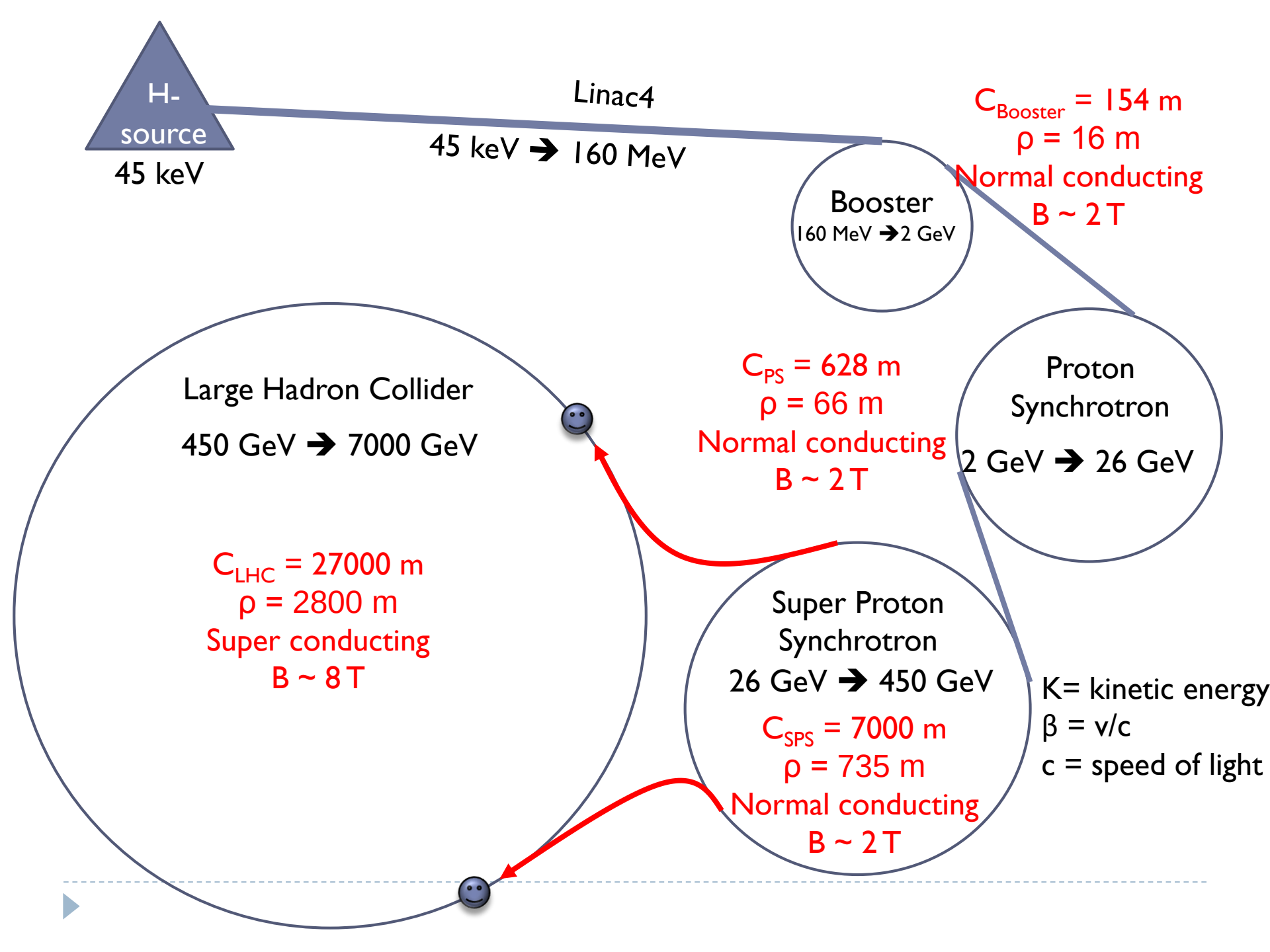


Reconstruction of Dark Matter distribution based on observations

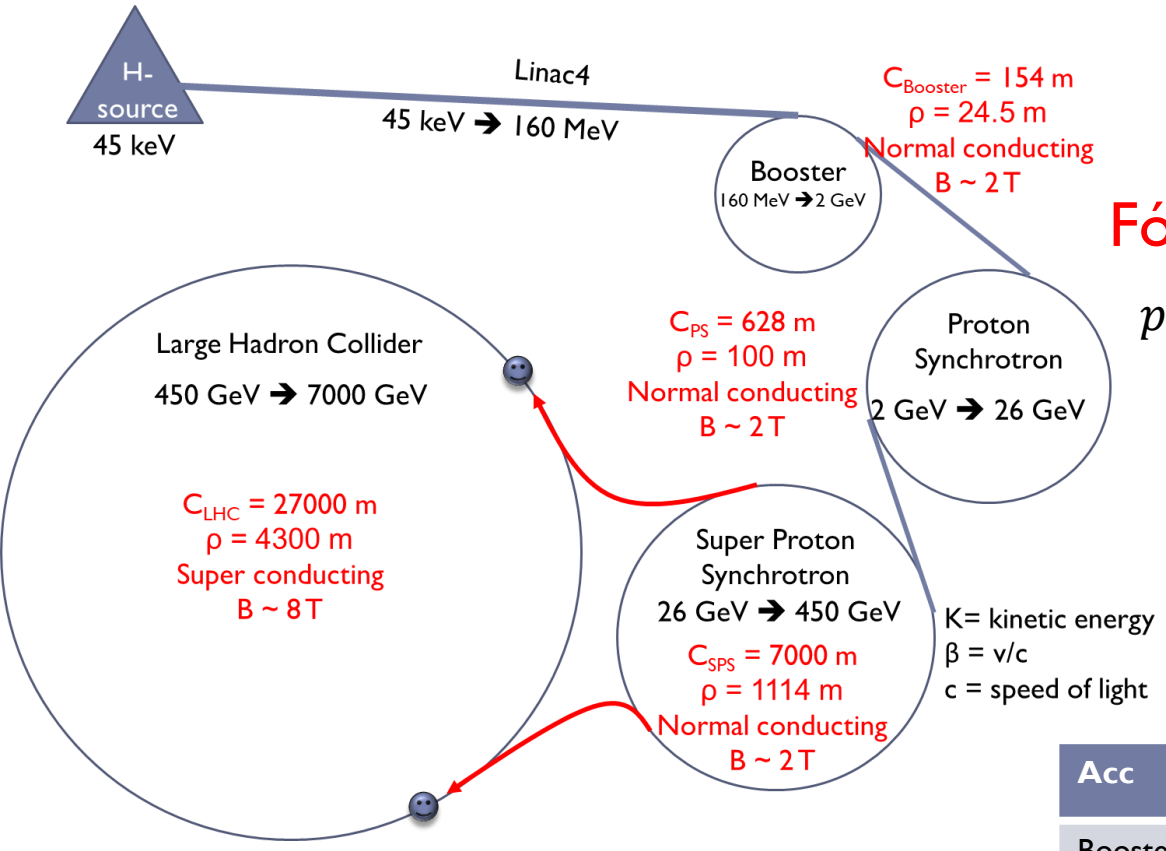
Budget: *Dark Matter: 33 %*
Dark Energy: 66 %
Anything else (including us) 1%


CERN Lab 20??
LHC
HE_LHC:
27 km 33TeV 20T
VHE_LHC:
100 km 100 TeV
Jura
Geneva
Salève
1
2
3
4
5
6
7
8
LHC Tunnel
VHE_LHC (80 km)
VHE_LHC (100 km)

Backup slides


H-
source
45 keV
Linac4
45 keV ➔ 160 MeV
Booster
160 MeV ➔2 GeV
$C_{Booster}$ = 154 m
ρ = 16 m
Normal conducting
B ~ 2 T
Proton
Synchrotron
2 GeV ➔ 26 GeV
C_{PS} = 628 m
ρ = 66 m
Normal conducting
B ~ 2 T
Large Hadron Collider
450 GeV ➔ 7000 GeV
C_{LHC} = 27000 m
ρ = 2800 m
Super conducting
B ~ 8 T
Super Proton
Synchrotron
26 GeV ➔ 450 GeV
C_{SPS} = 7000 m
ρ = 735 m
Normal conducting
B ~ 2 T
K= kinetic energy
β = v/c
c = speed of light

¿Por qué los sincrotrones del la cadena de aceleración del CERN son cada vez más grandes?



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

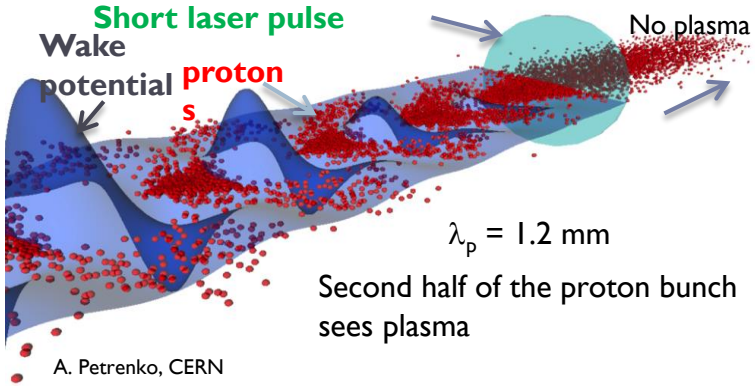
Fórmula de la rigidez del haz

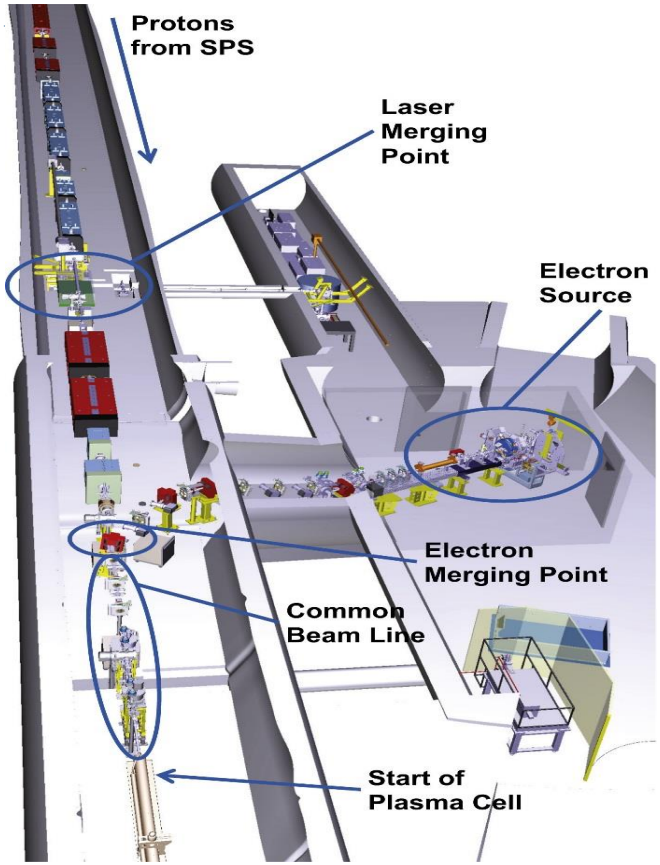
$$p(GeV/c) = 0.33 \cdot q \cdot B(T) \cdot \rho(m)$$

Acc	Q	B (T)	ρ(m)	p (GeV/c)
Booster	1	0.86	16	4.5
		1.7	4	
PS	1	1.5	66	33
		1.3	11	
SPS	1	2	735	485
LHC	1	8.3	2800	7000

AWAKE

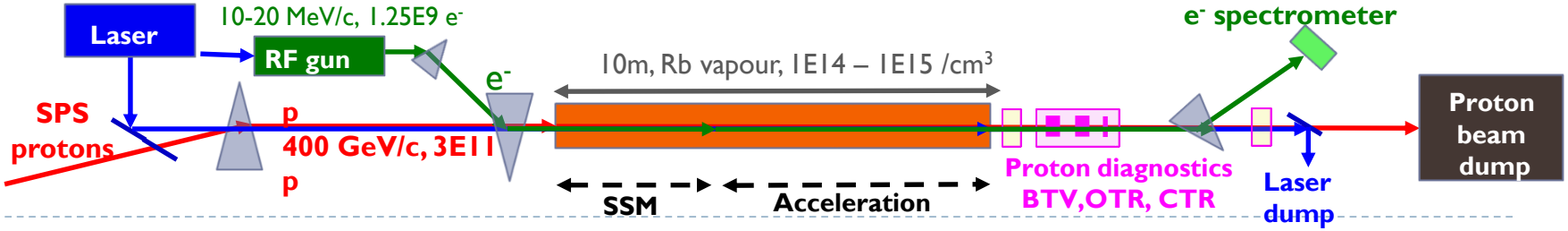
- **Probe beam given**
- **e^- line commissioning -**
- **Bunch rotation**





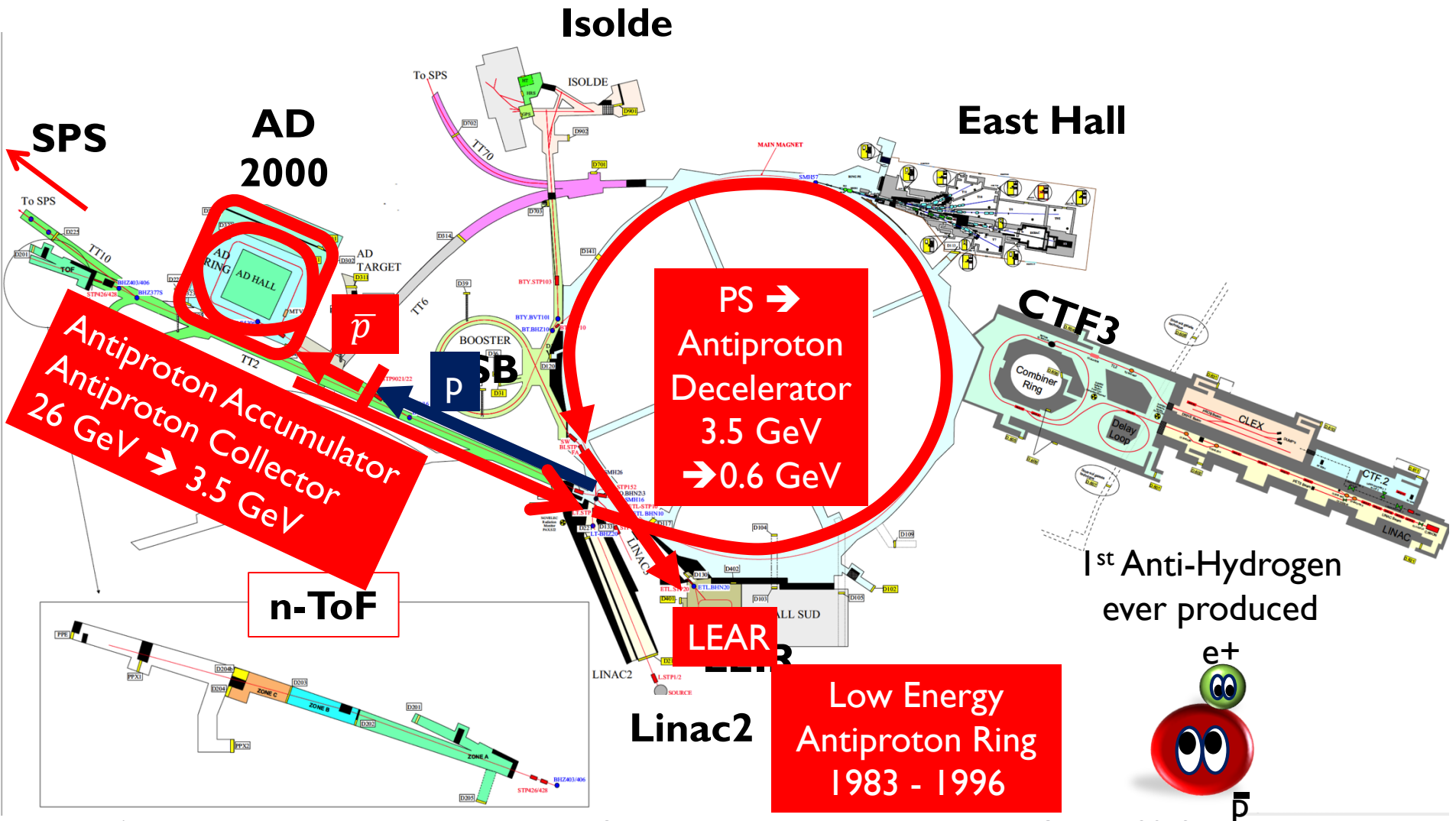
2017: 1st milestone reached!

First demonstration of seeded self-modulation of a high energy proton bunch in plasma

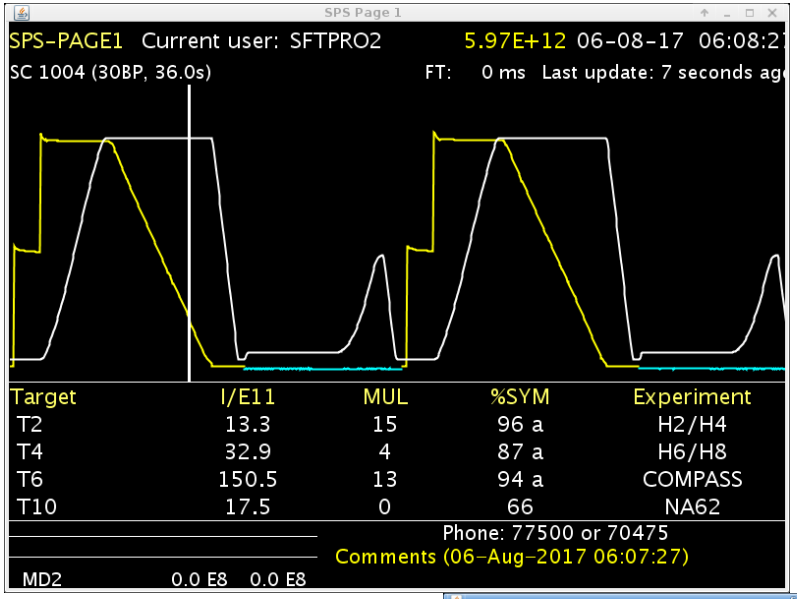


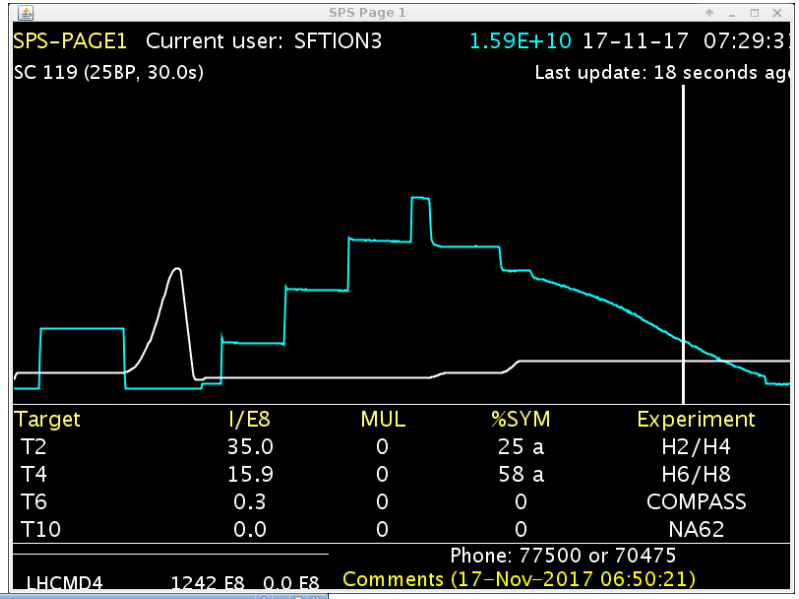
ANTIMATTER'S GONE MISSING …
WHEN DID THIS HAPPEN, SIR?
ABOUT 15 BILLION YEARS AGO …
LOST-PROPERTY OFFICE
CERN

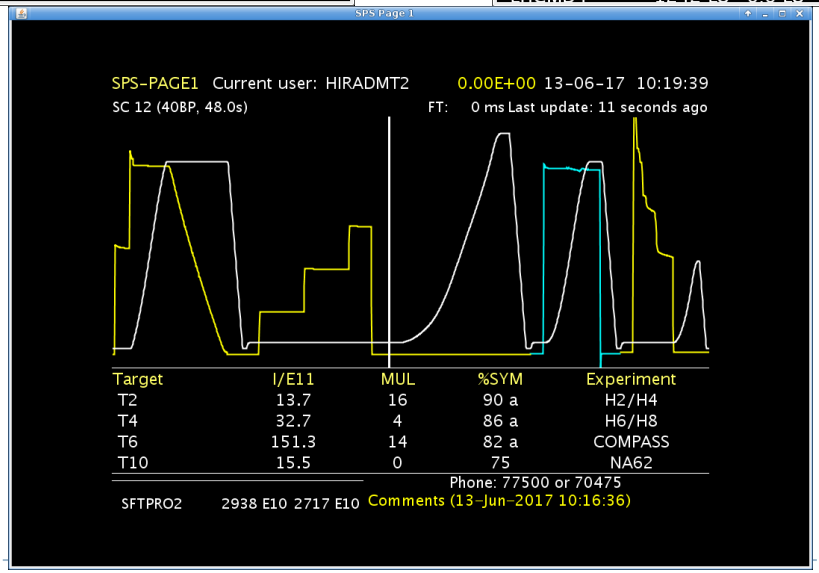
History of the Antiproton Decelerator Chain



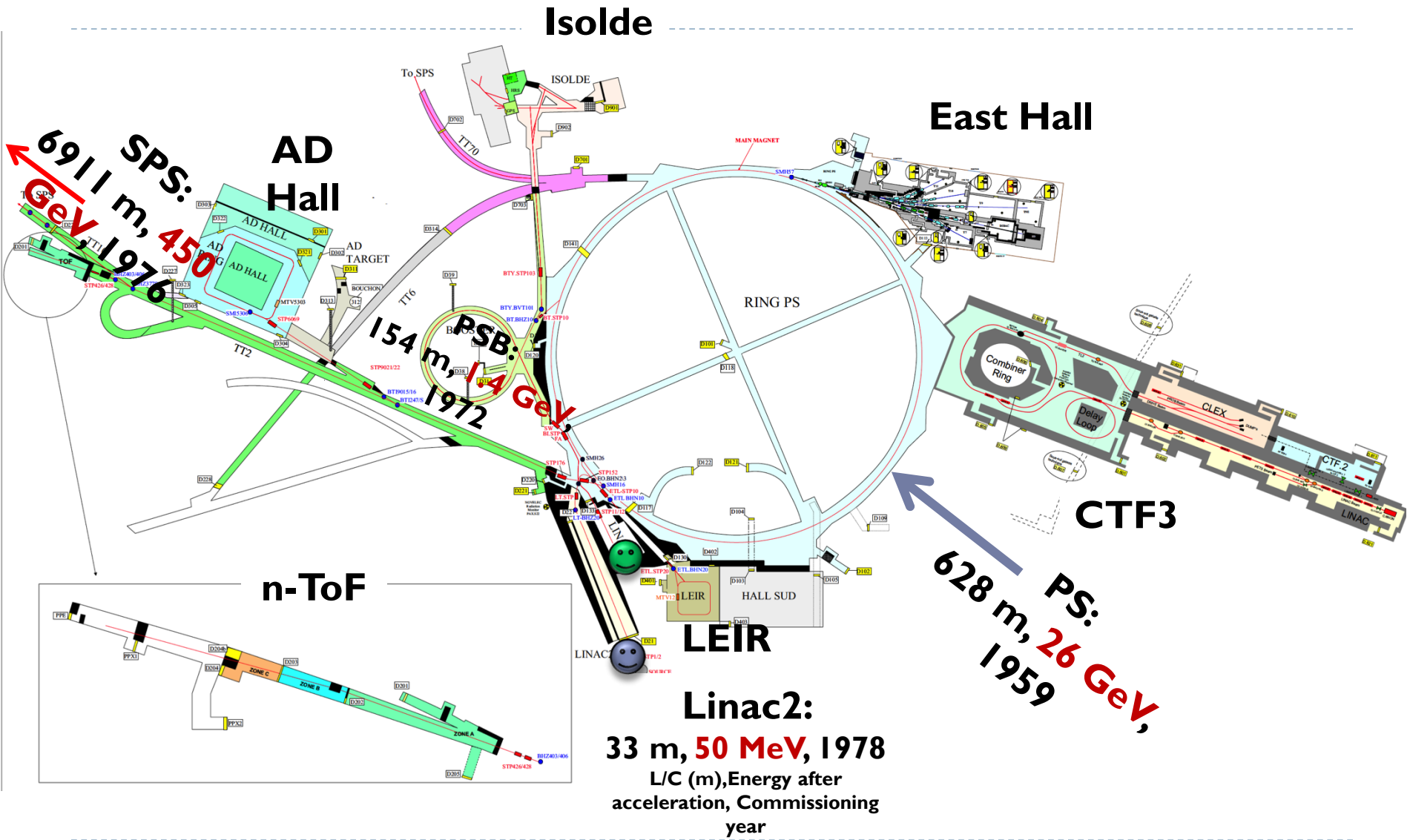
Fast cycle machines E.g. SPS







CERN injector accelerator complex



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

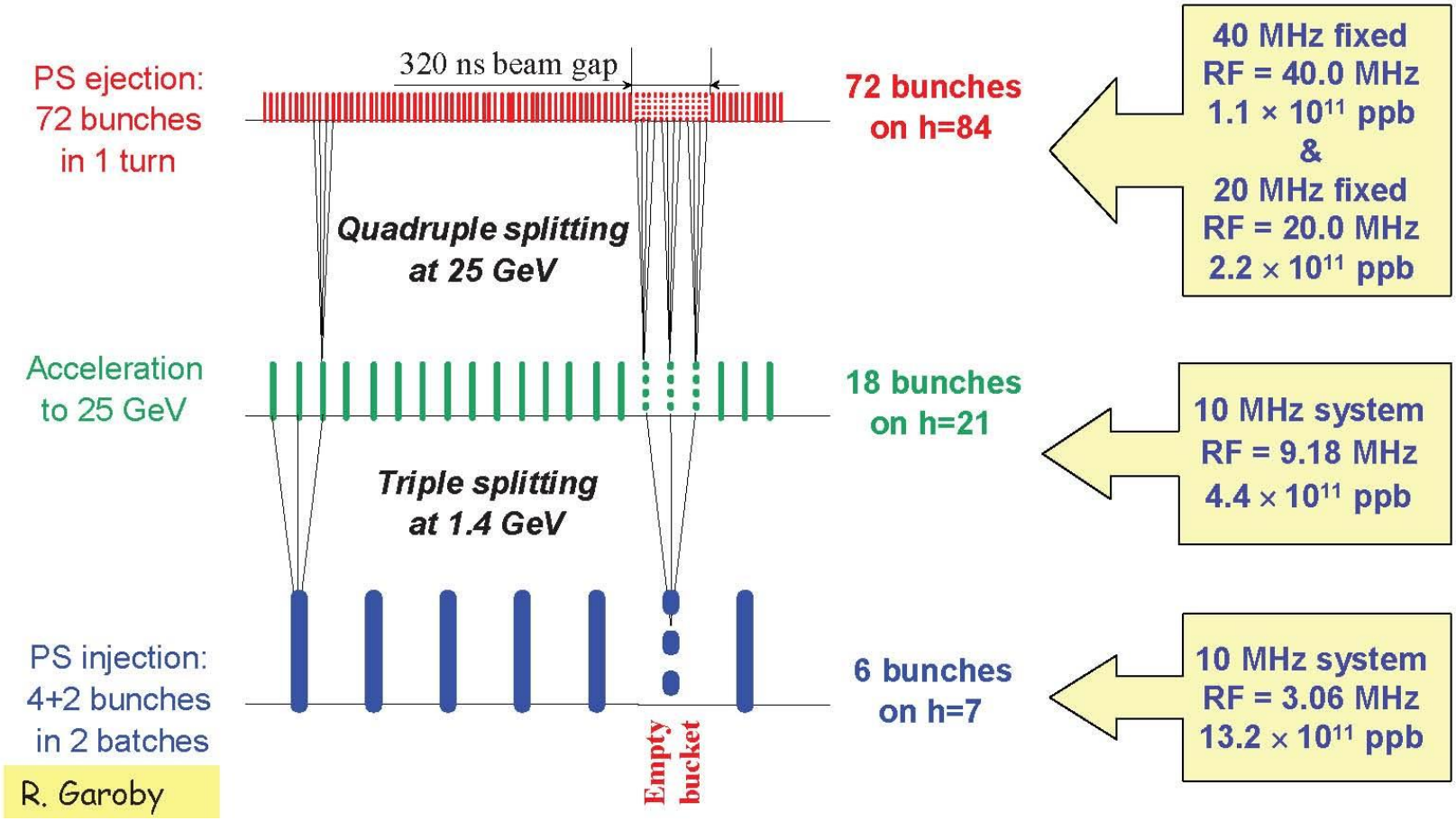
Elena Conceptual Design Report:
http://cds.cern.ch/record/1309538/files/CERN-BE-2010-029.pdf

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

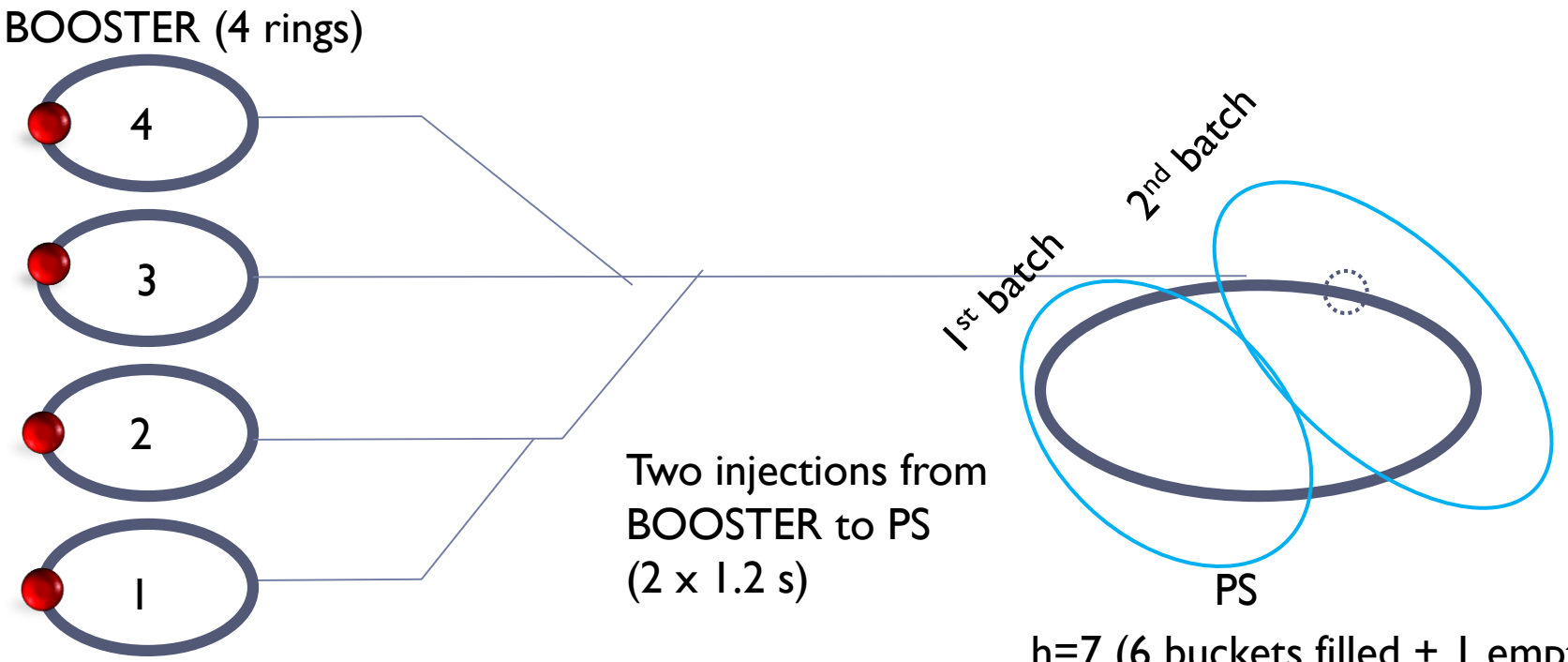
- **Longitudinal bunch splitting (basic principle)**
  - Reduce voltage on principal RF harmonic and simultaneously rise voltage on multiple harmonics (adiabatically with correct phase, etc.)



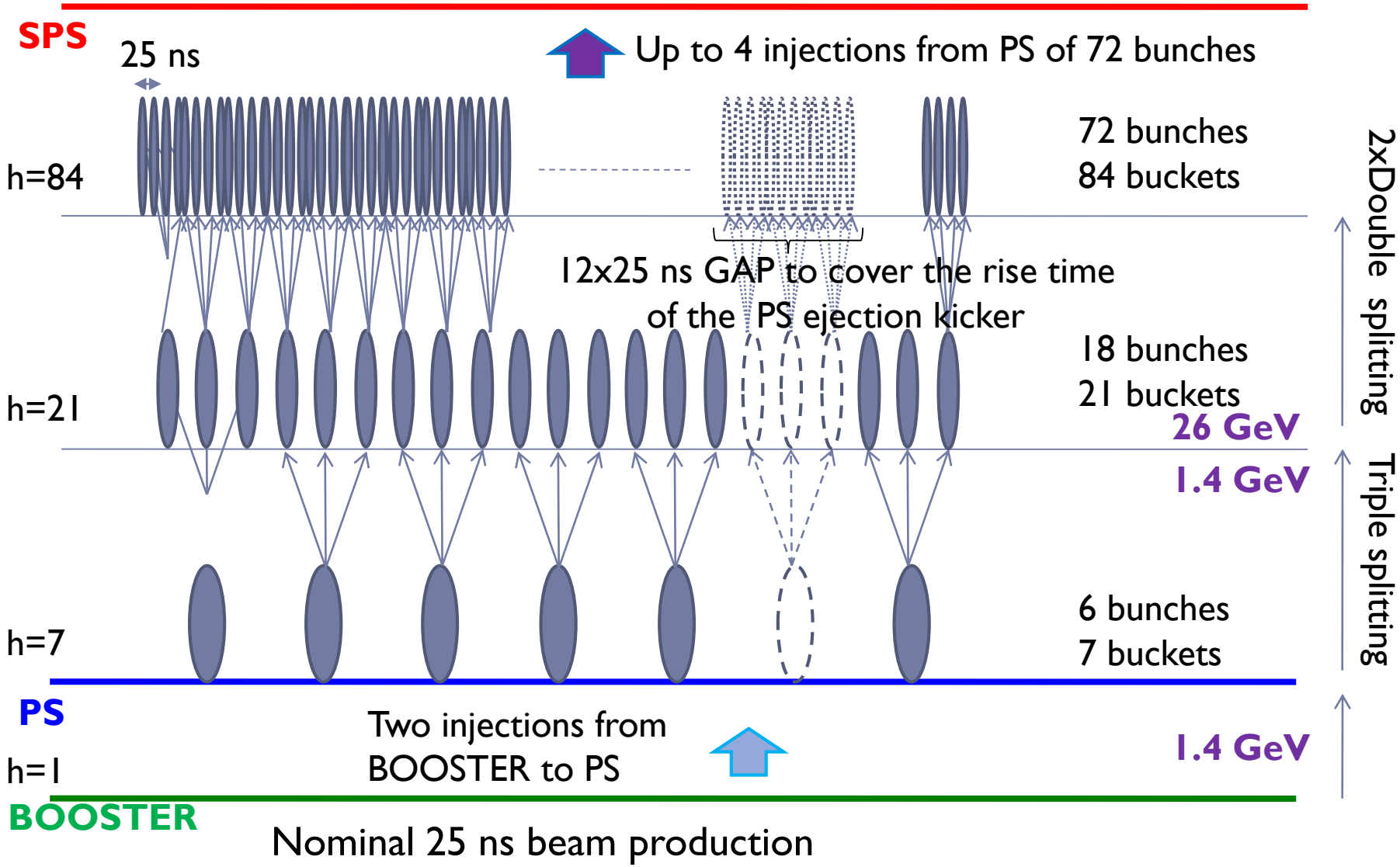
Use double splitting at 25 GeV to generate 50ns bunch trains instead

Proton Synchrotron (PS)

BOOSTER (1.4 GeV) ➔ PS (26 GeV) ➔ SPS (450 GeV) ➔ LHC

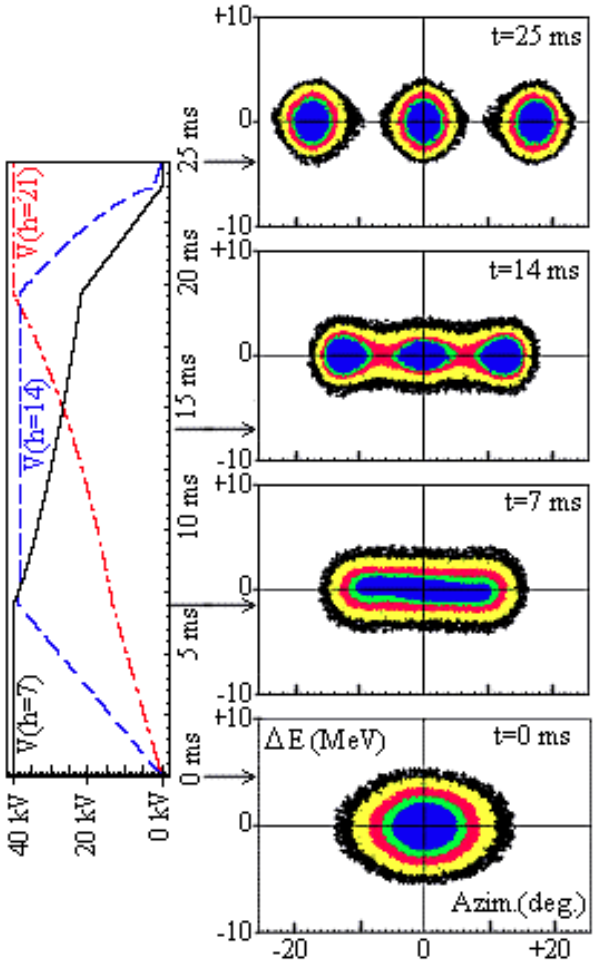


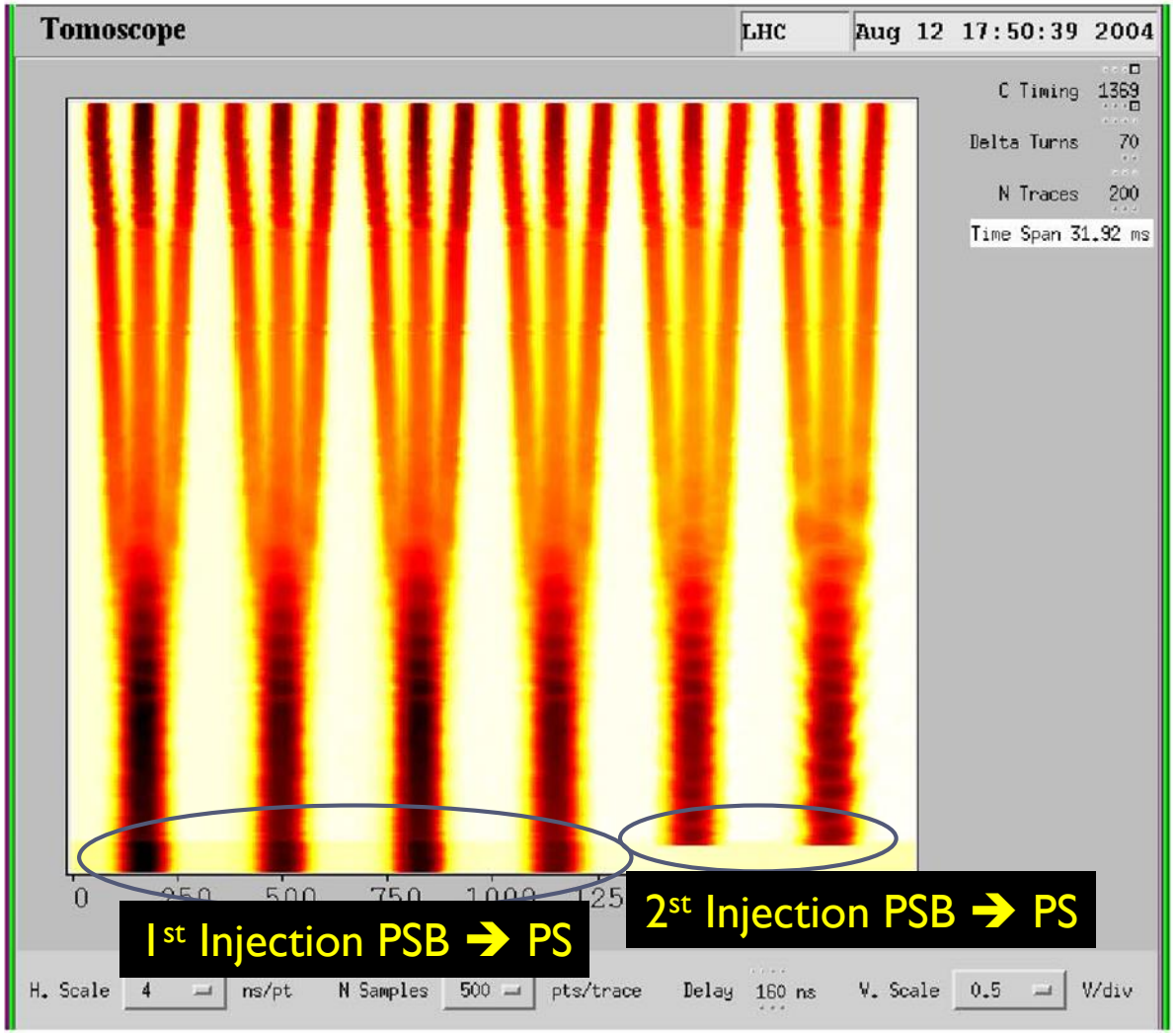
Proton Synchrotron (PS)



Nominal 25 ns beam production

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

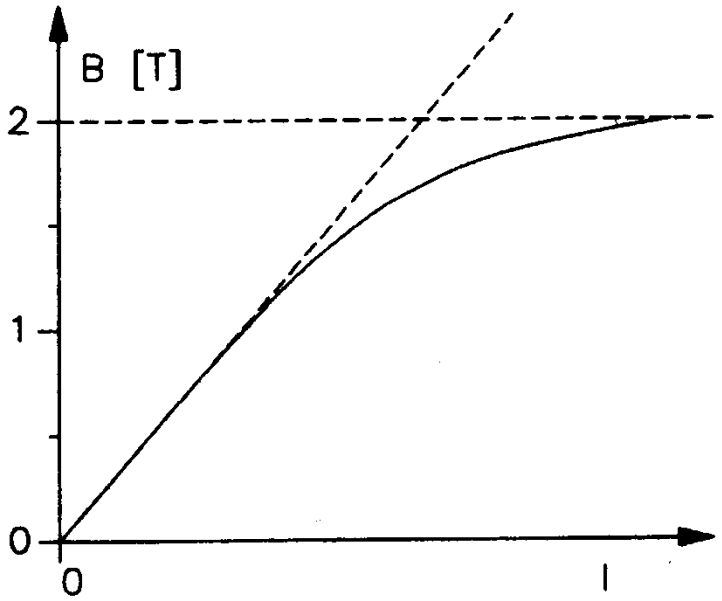
$$\rho \approx \frac{26658.9\ m}{2\pi} \cdot 66\% \approx 2780\ m$$

~ 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

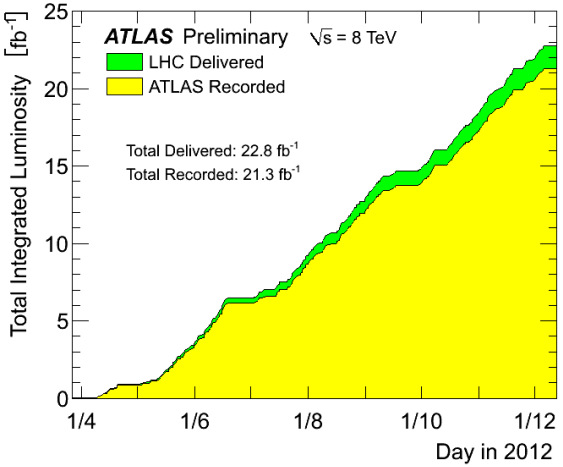


Field limit for normal conducting magnets due to saturation

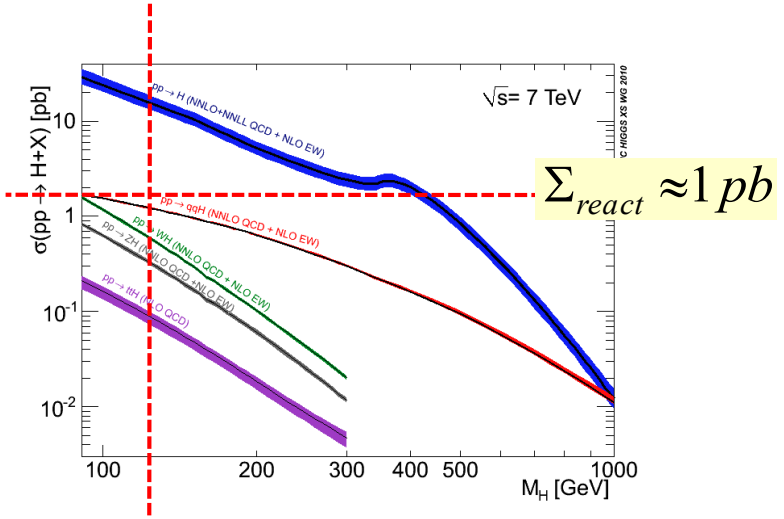
Large Hadron Collider (LHC)

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

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

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

Overall Protons Delivered in 2012

Facility	Protons Deliverd	% of Total
Isolde	$1.15 \times 10^{+20}$	63.8%
CNGS	$3.9 \times 10^{+19}$	21.6%
n-TOF	$1.9 \times 10^{+19}$	10.2%
The rest	$8.13 \times 10^{+18}$	4.5%
LHC	$3.25 \times 10^{+16}$	0.018%
Total	$1.81 \times 10^{+20}$	

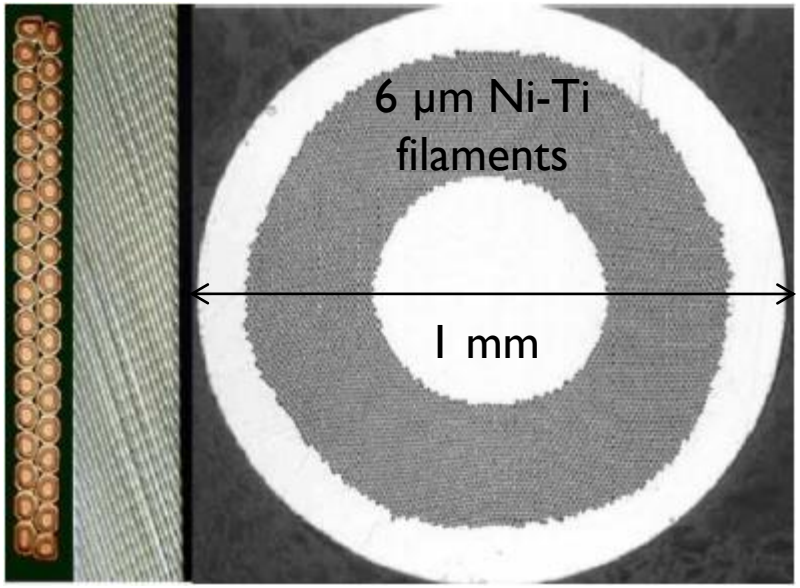
Colliders are very Efficient!

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

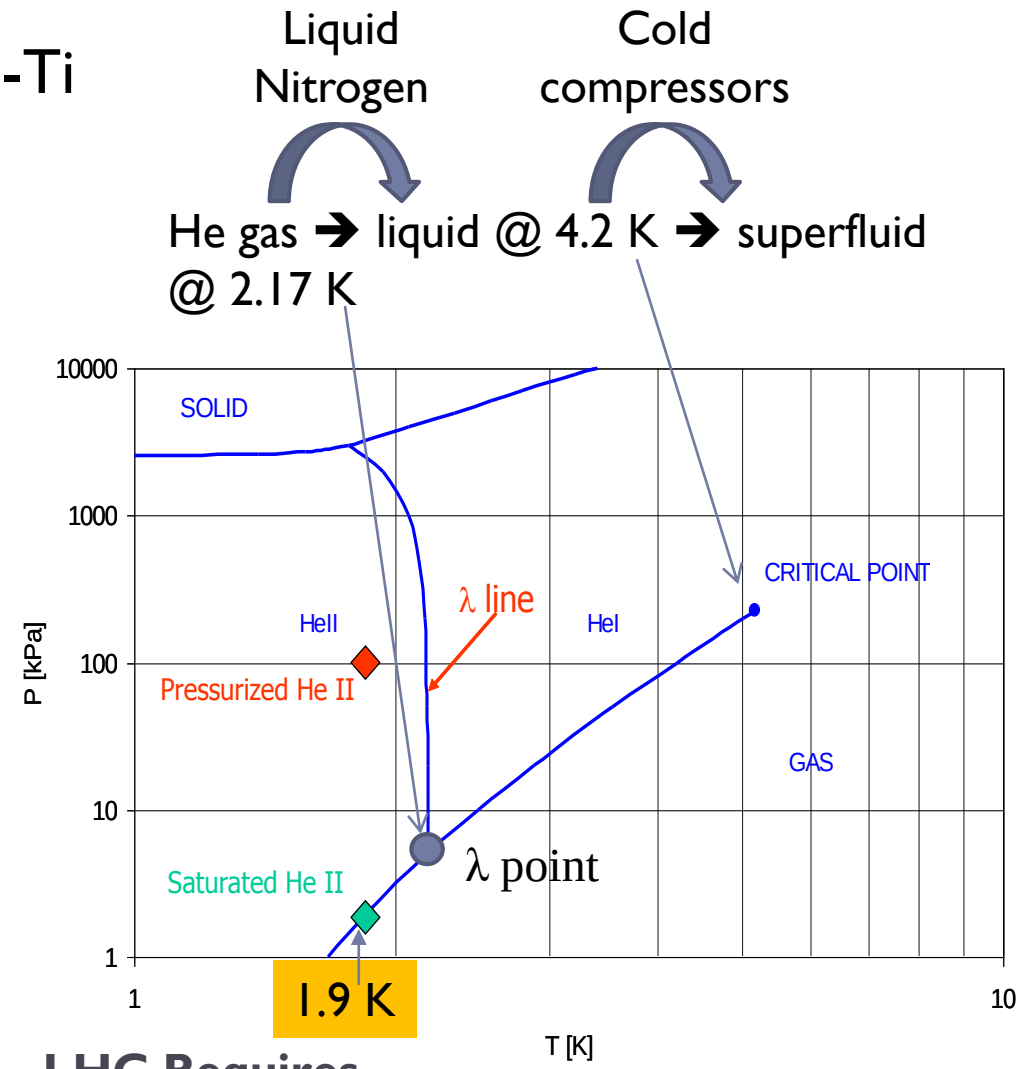
- Intensities as delivered to the facility, upstream losses ignored,
- Beams for Machine Setup and Studies Excluded
- The total delivered protons represents roughly 0.27mg (rest mass!)

Large Hadron Collider (LHC)

Superconducting cables of Nb-Ti



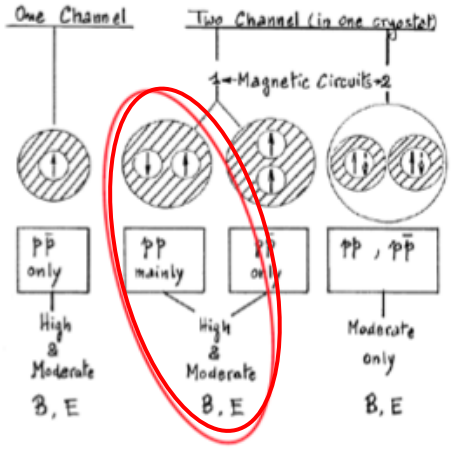
LHC ~ 27 km circumf. with 20 km of superconducting magnets operating @8.3 T. An equivalent machine with normal conducting magnets would have a circumference of 100 km and would consume 1000 MW of power ➔ we would need a dedicated nuclear power station for such a machine. LHC consumes ~ 10% nuclear power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



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

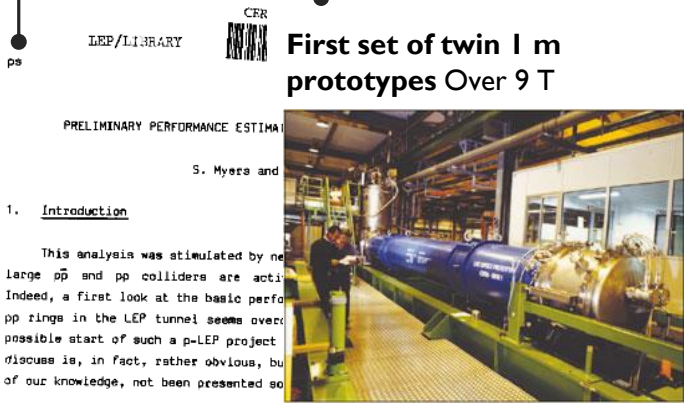
25 y

SSC cancelled

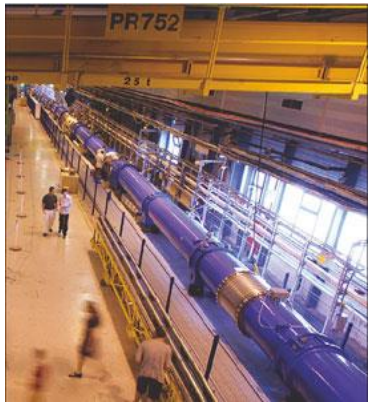
Main contracts signed

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

First set of twin 1 m prototypes Over 9 T



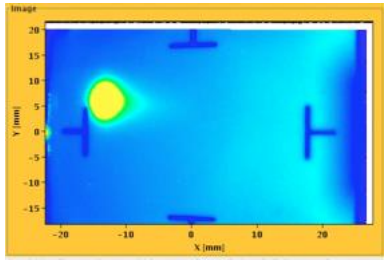
2002 String 2

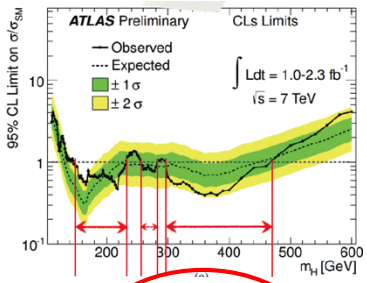


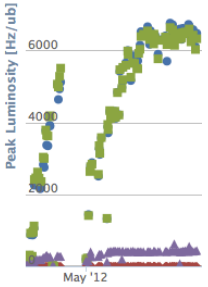
November 2006
1232 delivered

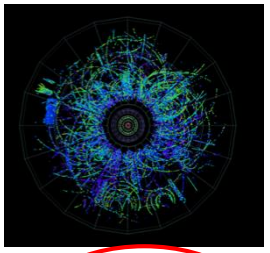
September 10, 2008
First beams around

August 2008
First injection test







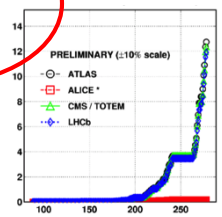


Feb. 2013
p-Pb^{82+}
New Operation Mode

May 2012
Ramping Performance

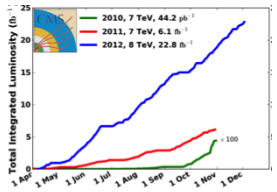
October, 2011
3.5x10^{+33}, 5.7 fb^{-1}
First Hints!!

November 29, 2009
Beam back



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

June 28 2011
1380 bunches
1380



March 14th 2012
Restart with Beam

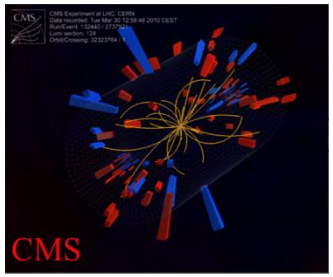
Nov. 2012
End of p^{+} Run 1

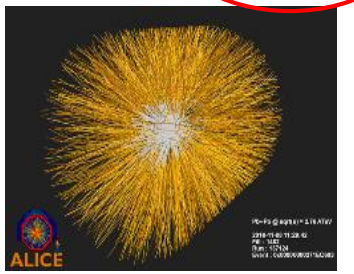
Repair and Consolidation

2008 | 2009 | 2010 | 2011 | 2012 | 2013

Sept. 19, 2008
Disaster

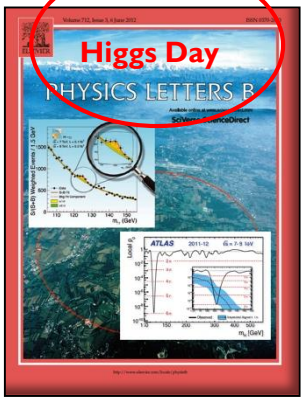
March 30, 2010
First collisions at 3.5 TeV





November 2010
Pb^{82+} Ions

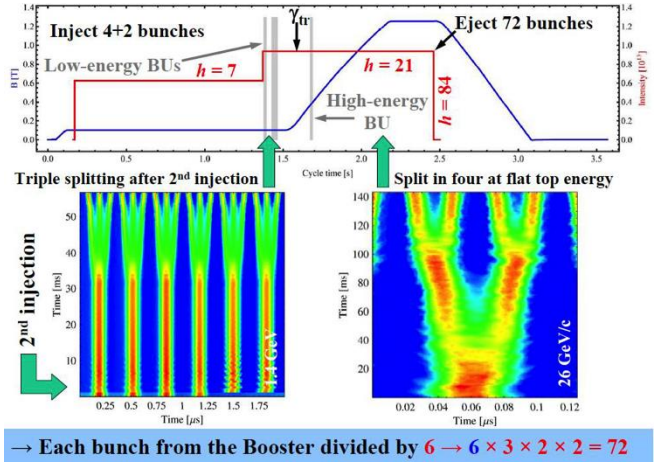
November 2011
Second Ion Run



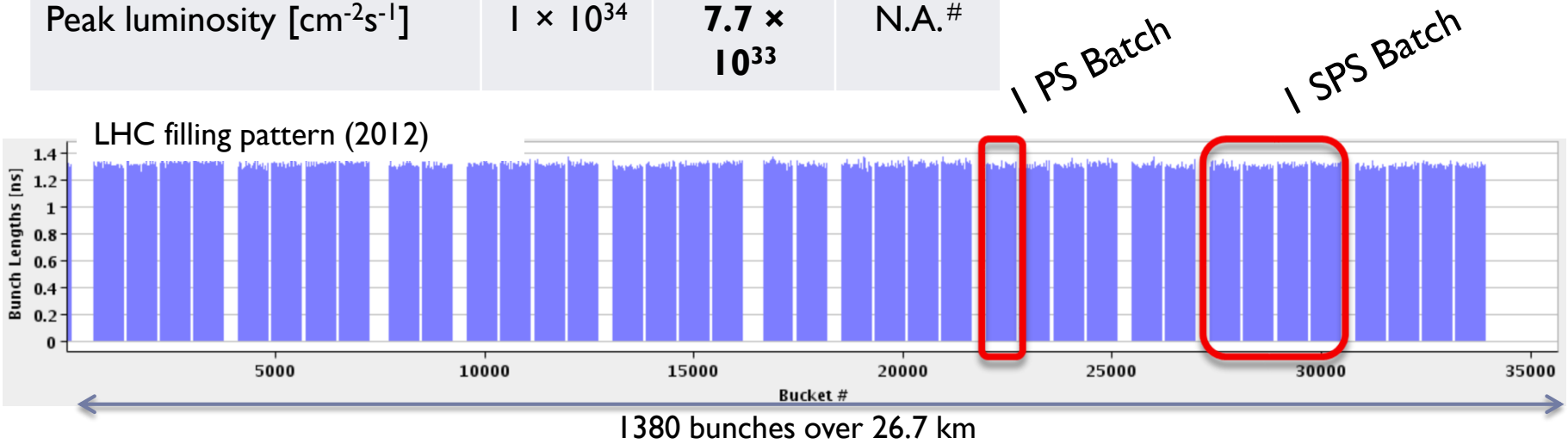
LS1

Filling the LHC (2012)

	25 ns (design)	50 ns (2012)	25 ns (2012)#
Energy per beam [TeV]	7	**4**	4
Intensity per bunch [x10^{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.#

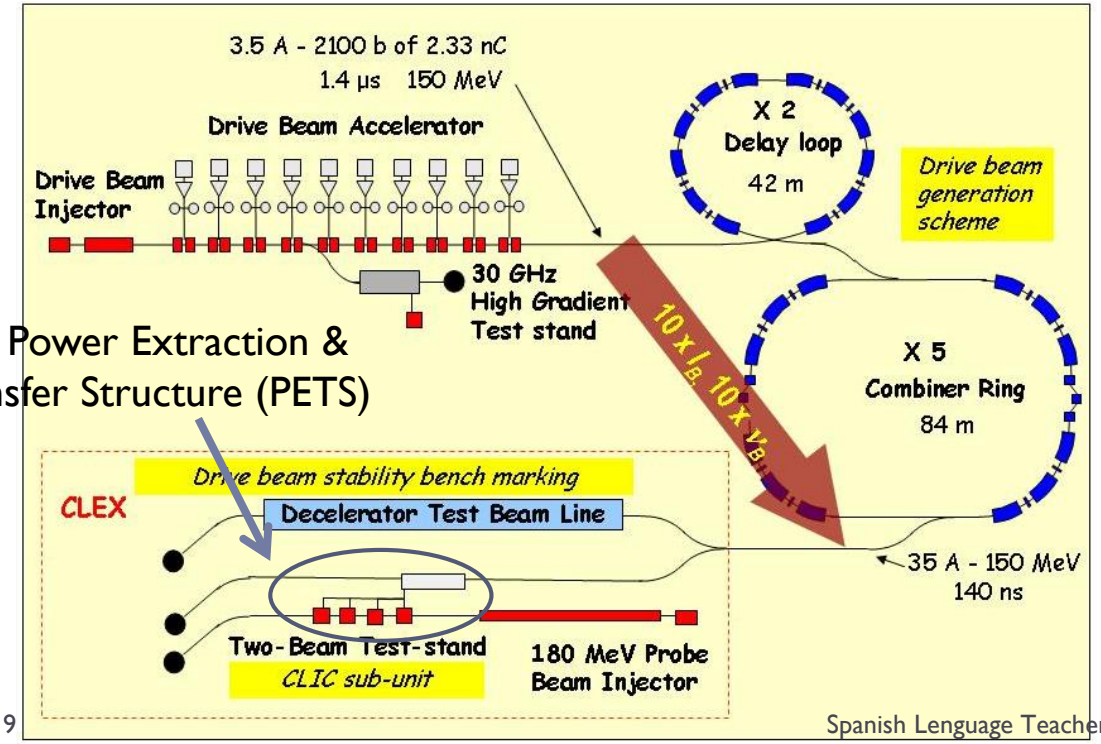


The 25 ns PS production scheme (2012)



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:

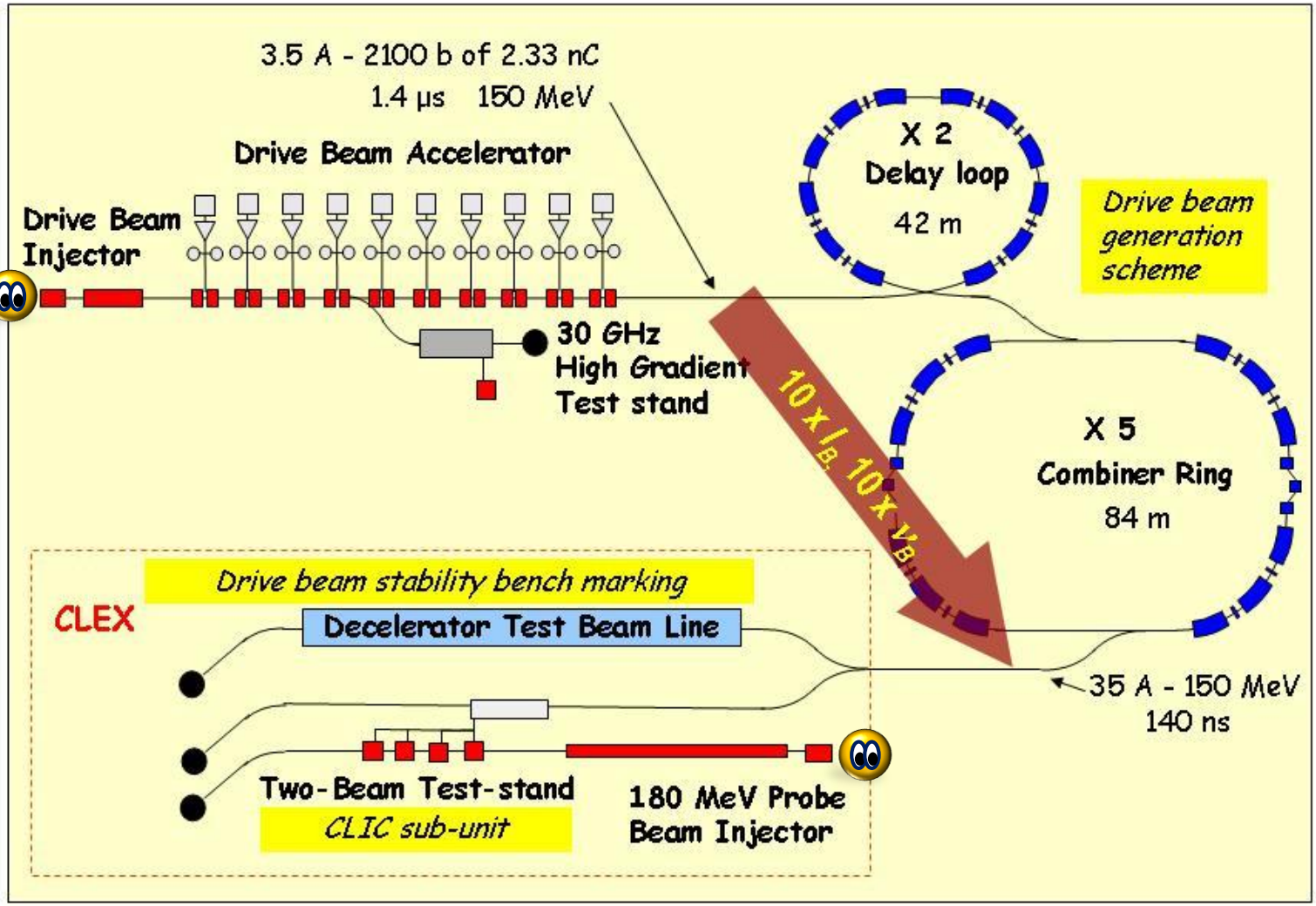
Drive Beam 100 A, 239 ns

2.38 GeV ➔240 MeV

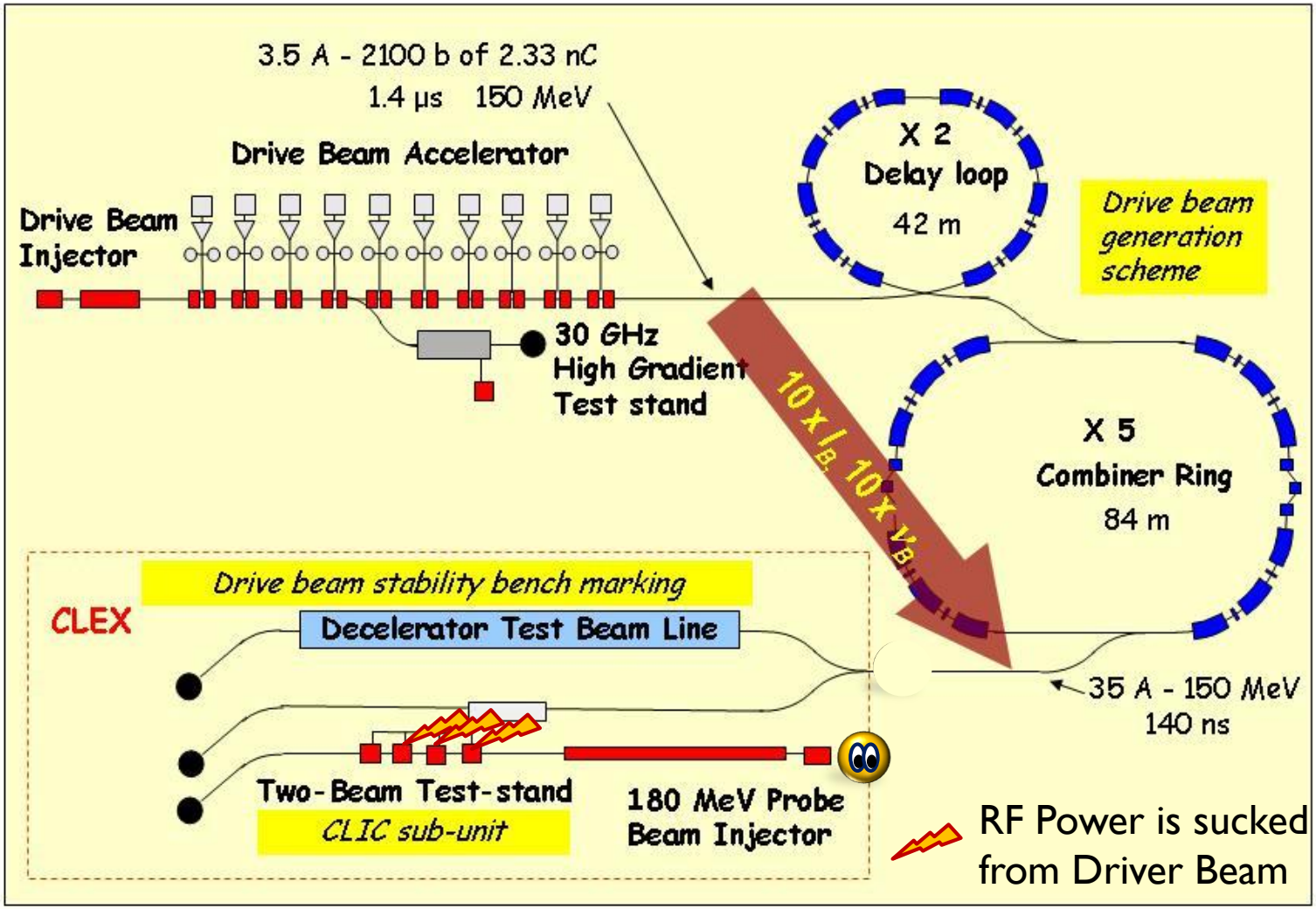
Main Beam 1.2 A, 156 ns

9 GeV ➔ 1.5 TeV

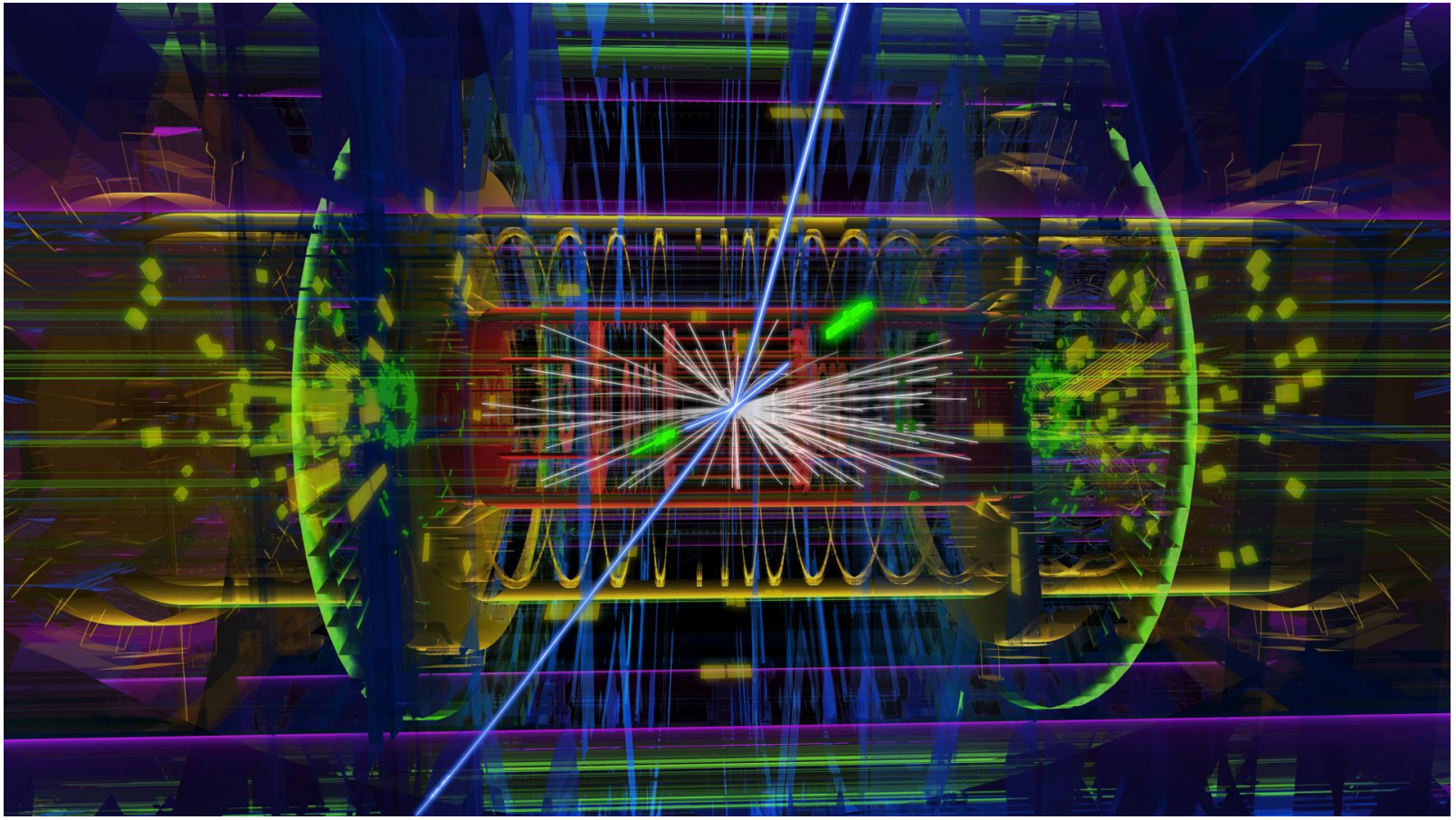
CTF 3 – CLIC Test Facility



CTF 3 – CLIC Test Facility



High Light Of HEP -Year

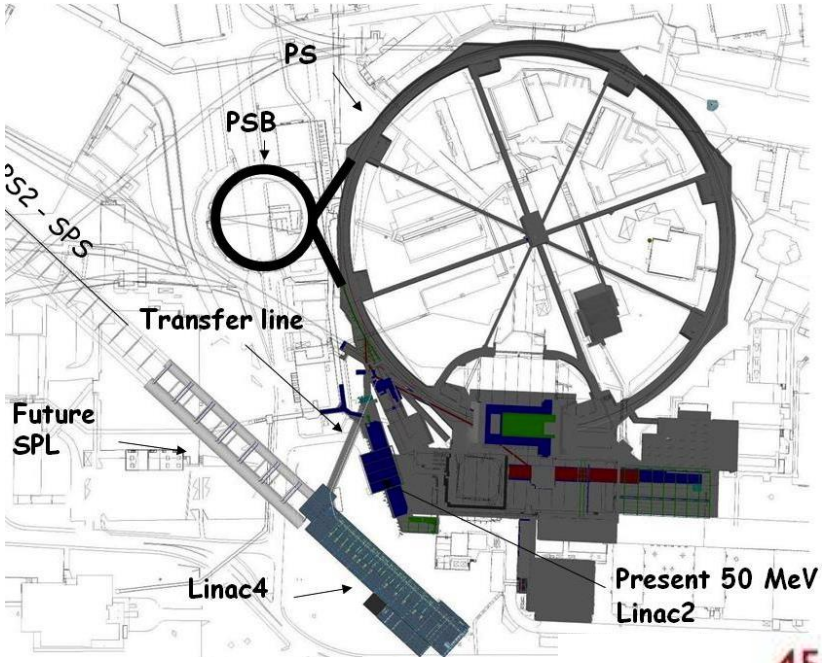


ATLAS event display: Higgs => two electrons & two muons

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

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

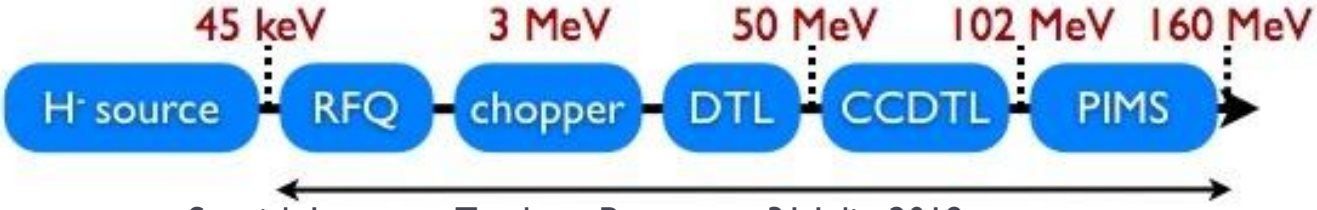
$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

with N_b : number of protons/bunch

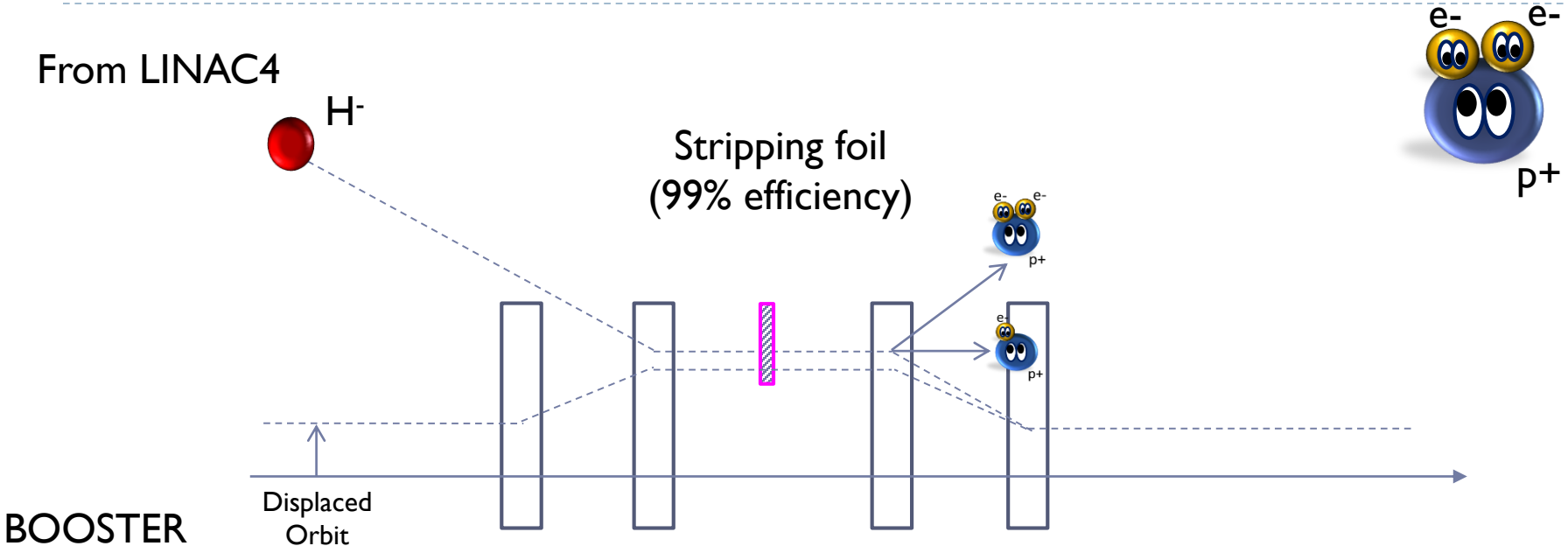
$\varepsilon_{X,Y}$: norm. transverse emittances

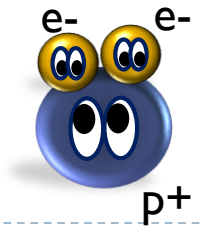
R : mean radius of the accelerator

Delivers 40 mA, 400 μs pulses at 2 Hz



H^- Injection


From LINAC4
H-
Stripping foil
(99% efficiency)
e-
e-
p+
e-
e-
p+
e-
p+
BOOSTER
Displaced
Orbit



H- Injection

From LINAC4

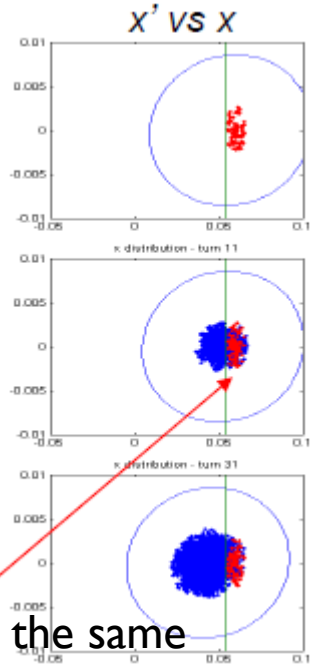
H-

Stripping foil (99% efficiency)

Circulating p+

BOOSTER

Displaced Orbit



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

The most important plus! ➔ since we can afford a SPACE CHARGE ΔQ_{50MeV} ➔

But $\Delta Q_{LINAC4(160MeV)} \approx 0.5 \Delta Q_{LINAC2(50MeV)}$

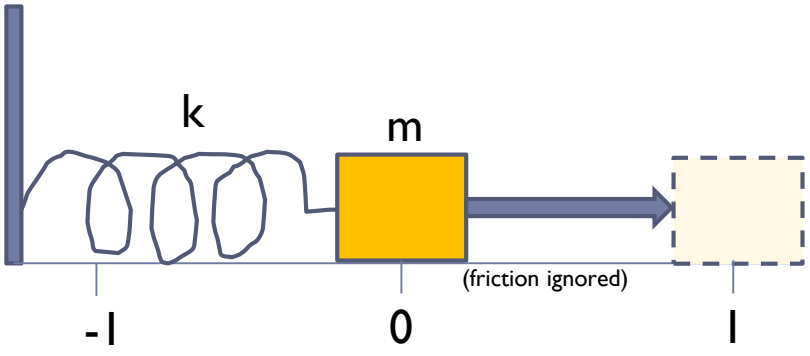
$$\Delta Q_{SC} \propto \frac{N_b}{\varepsilon_{X,Y}} \cdot \frac{R}{\beta\gamma^2}$$

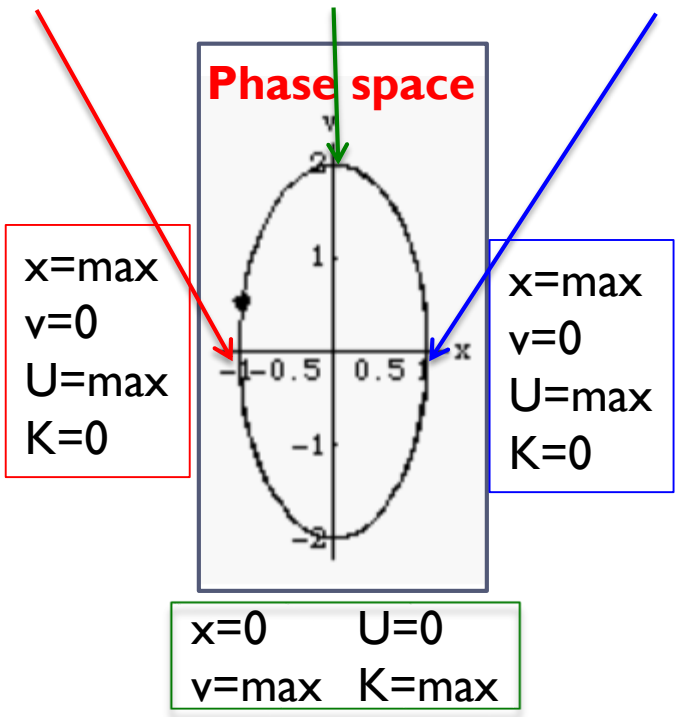
$N_b^{LINAC4} \approx 2\ N_b^{LINAC2}$!!!!

Let me open a parenthesis here to talk about

EMITTANCE and PHASE SPACE

(Phase space and emittance)





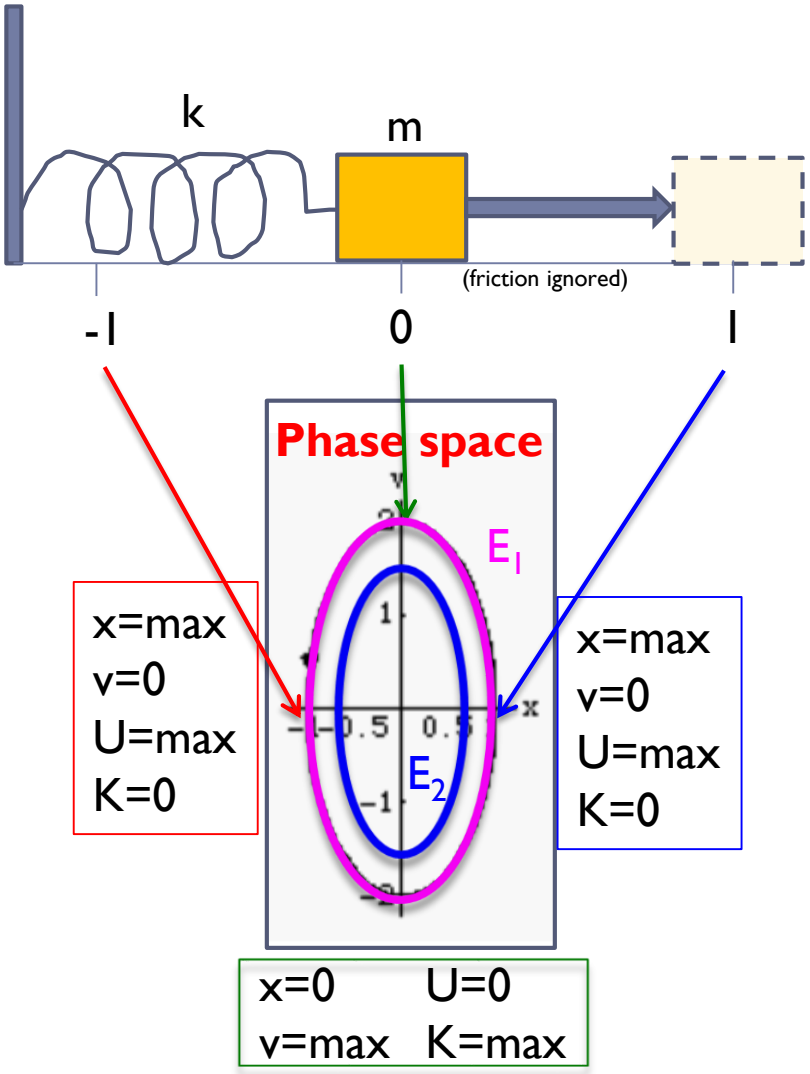
Analysis of **x=f(t)** ➔ provides information about the **path** taken by the system **BUT NOT** about the **energy**.

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)

U=potential energy
K=kinetic energy

(Phase space and emittance)



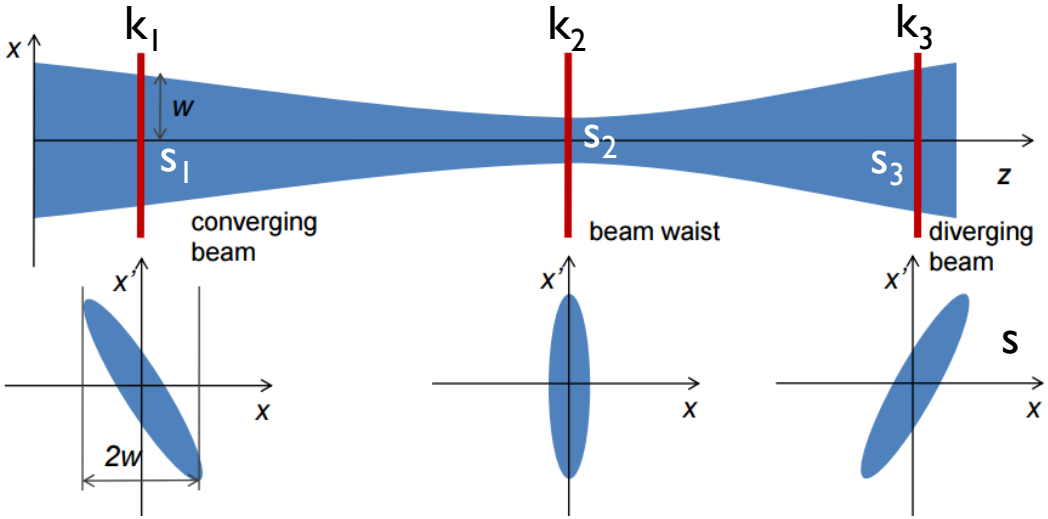
- Each point (x,v) in the ellipse represents an STATE of the physical system with well define position and velocity.
- All the points (x,v) in the ellipse have the SAME ENERGY (E_1)
- If the initial elongation is smaller, then we get a smaller ellipse with energy E_2 ($E_2<E_1$).
- If we change K the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

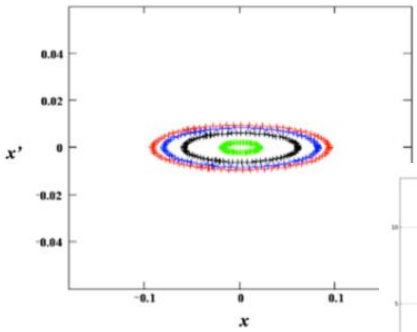
A **beam of charged particles** in an accelerator subjected to **focusing and defocusing forces** have the same dynamics as the system above. The beam dynamics also **reproduces an ellipse in phase space** …

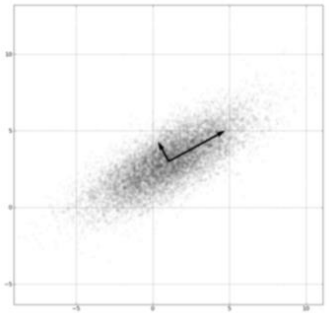
U=potential energy
K=kinetic energy

(Phase space and emittance)

All particles with the **same initial betatron amplitude** (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)

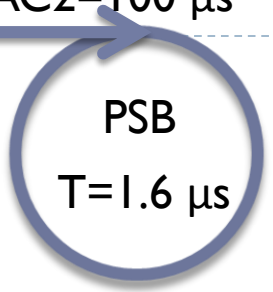
Beam size ➔ σ = √Ɛβ (in places without dispersion)

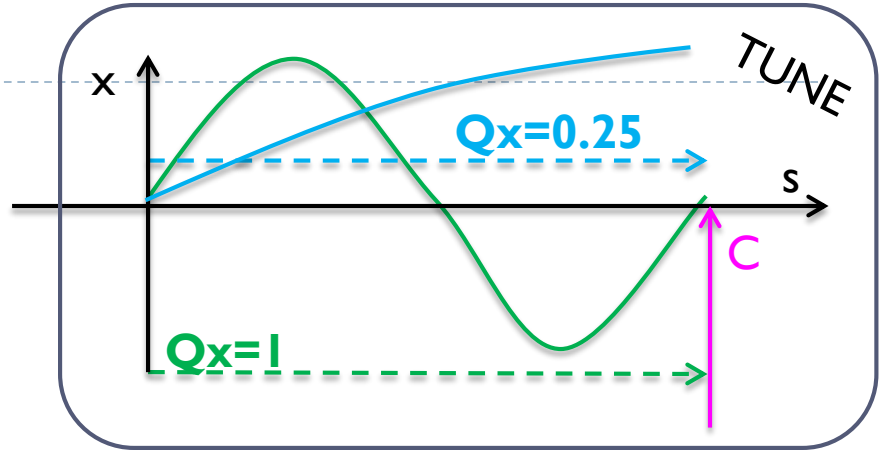
Let me use the BOOSTER injection to talk about

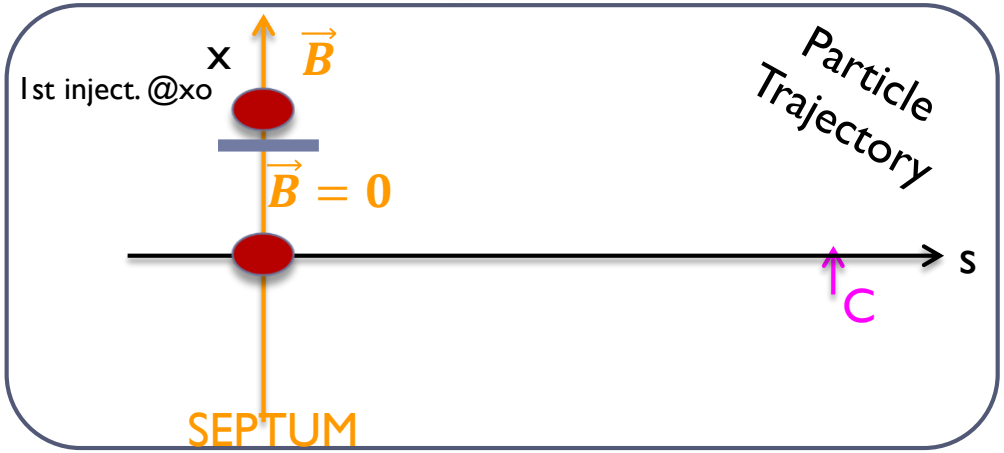
TUNE, PHASE SPACE PAINTING, SPACE CHARGE, BRIGHTNESS

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

Pulse from LINAC2=100 μs

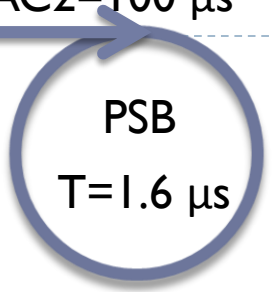


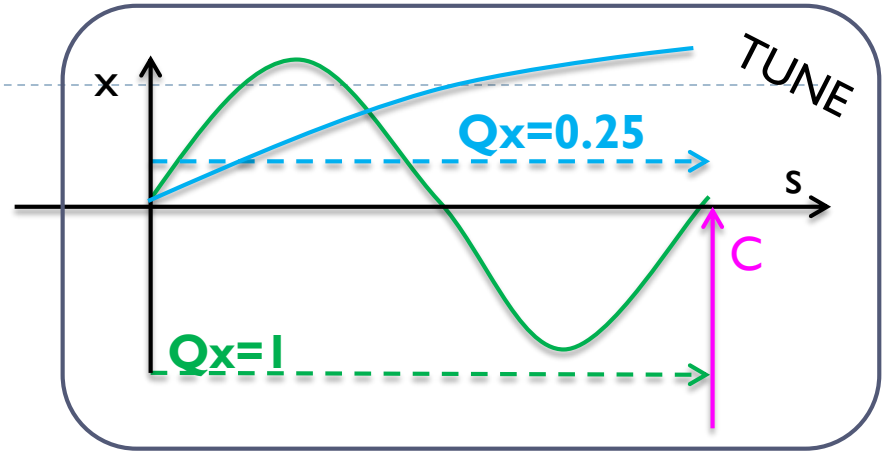


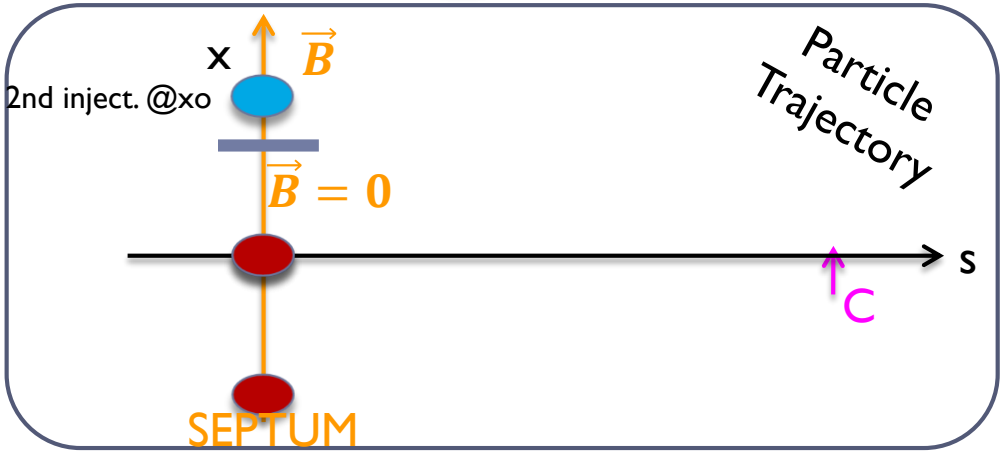


PS Booster: E_{inj}=50MeV, C=154 m

Pulse from LINAC2=100 μs

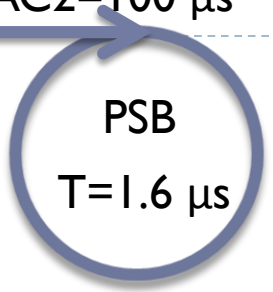


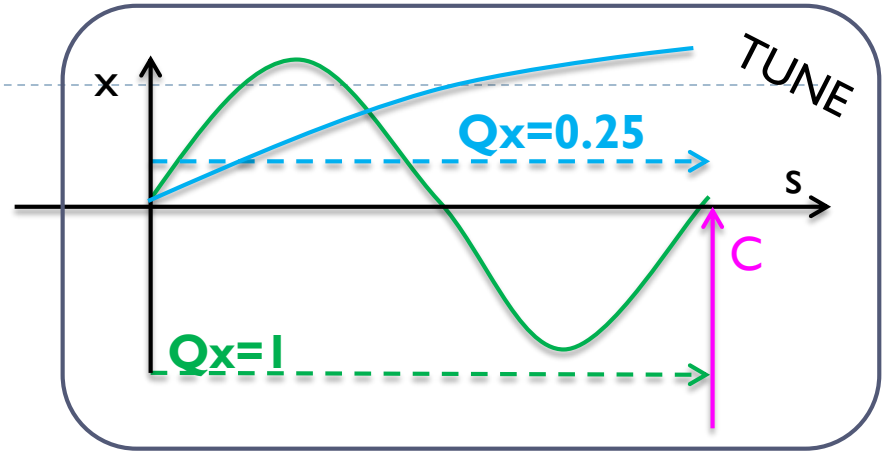


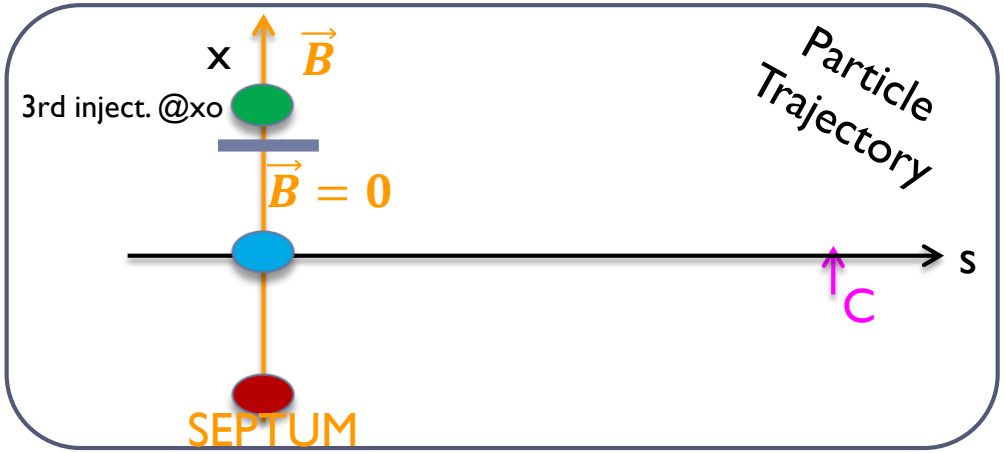


PS Booster: E_{inj}=50MeV, C=154 m

Pulse from LINAC2=100 μs

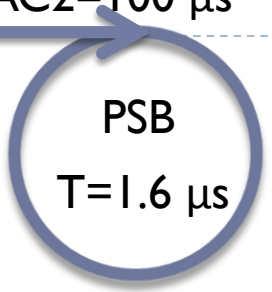


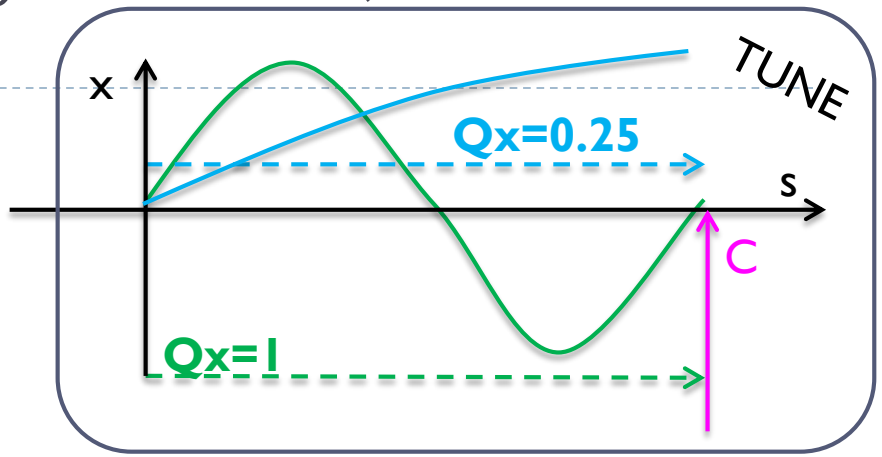


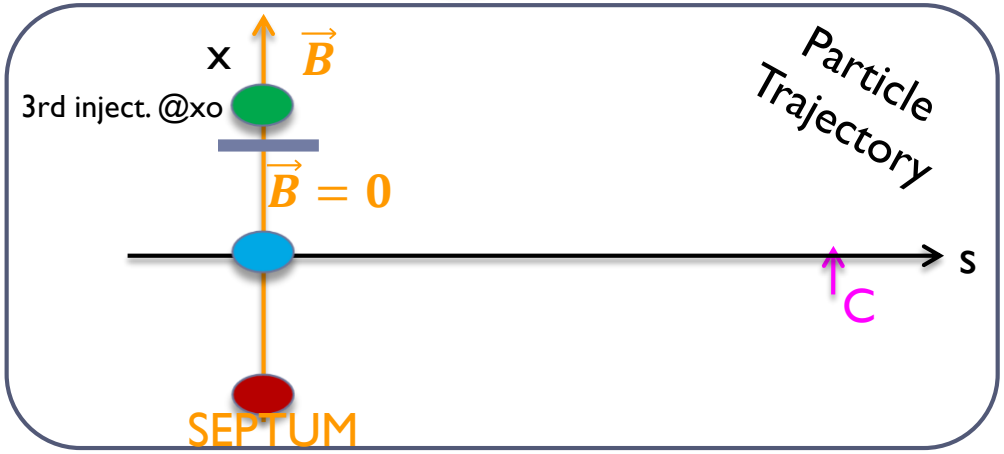


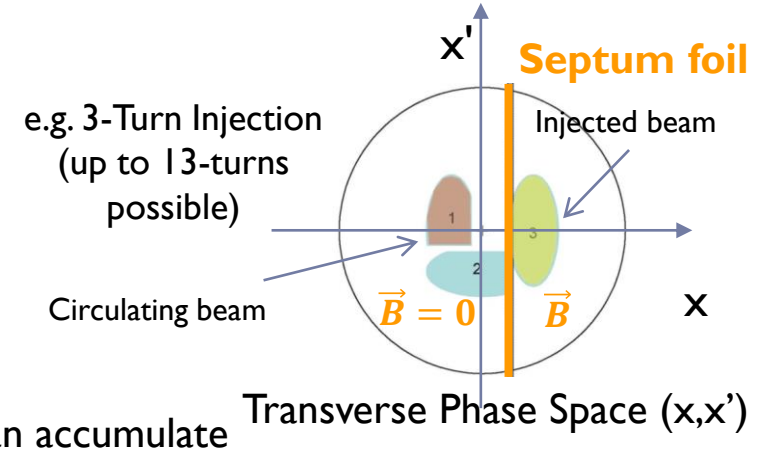
PS Booster: Einj=50MeV, C=154 m

Pulse from LINAC2=100 μs





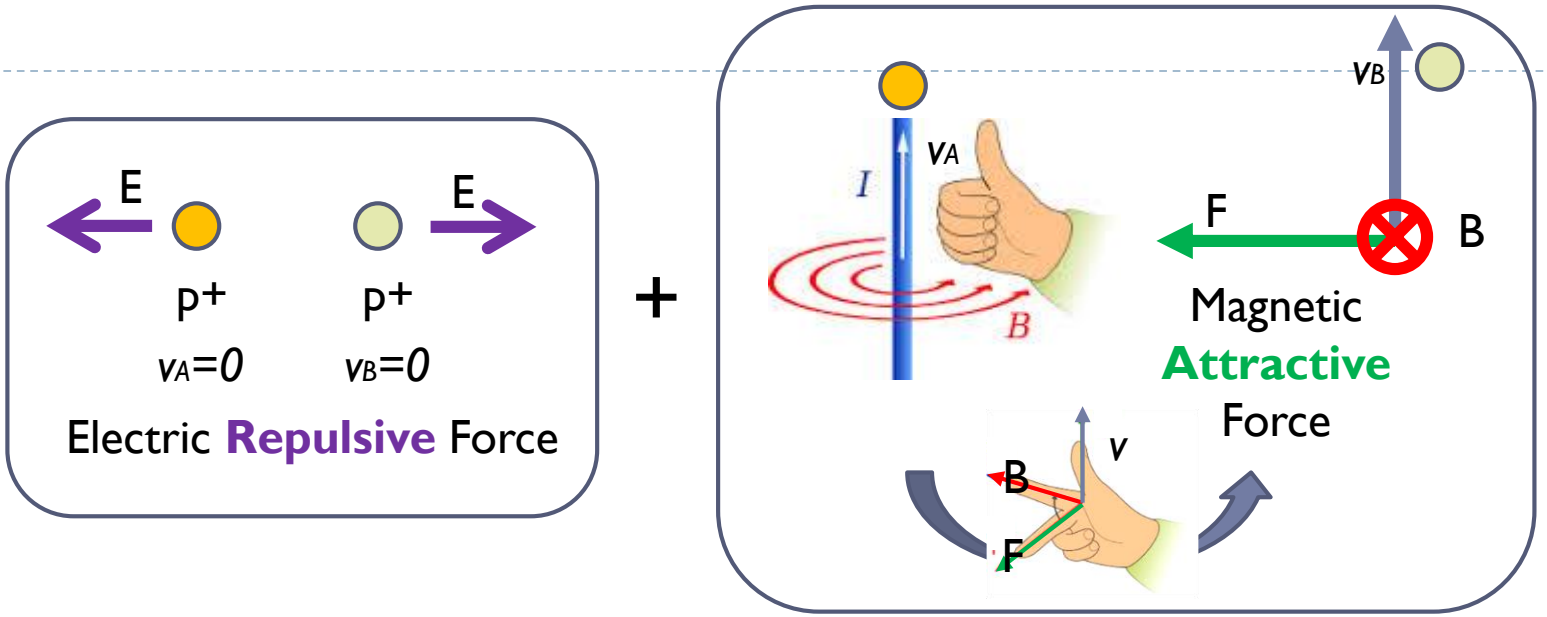


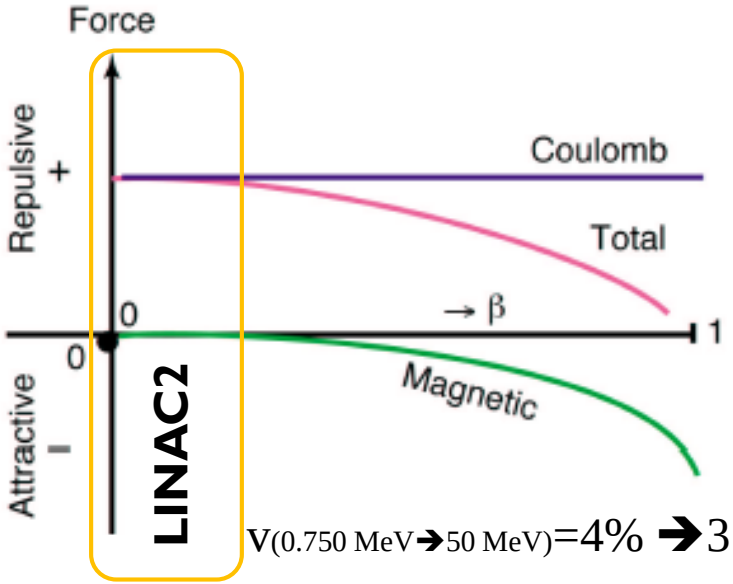


- The bigger the number of turns the more intensity we can accumulate
- The problem is that the longer the injection takes, the more time the particles have to fill the whole available phase space + SPACE CHARGE ➔ emittance increases ➔ beam size increases
- **The Booster is the machine in the LHC Injector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

Brightness = Intensity/Emittance

(Space Charge in One Slide)



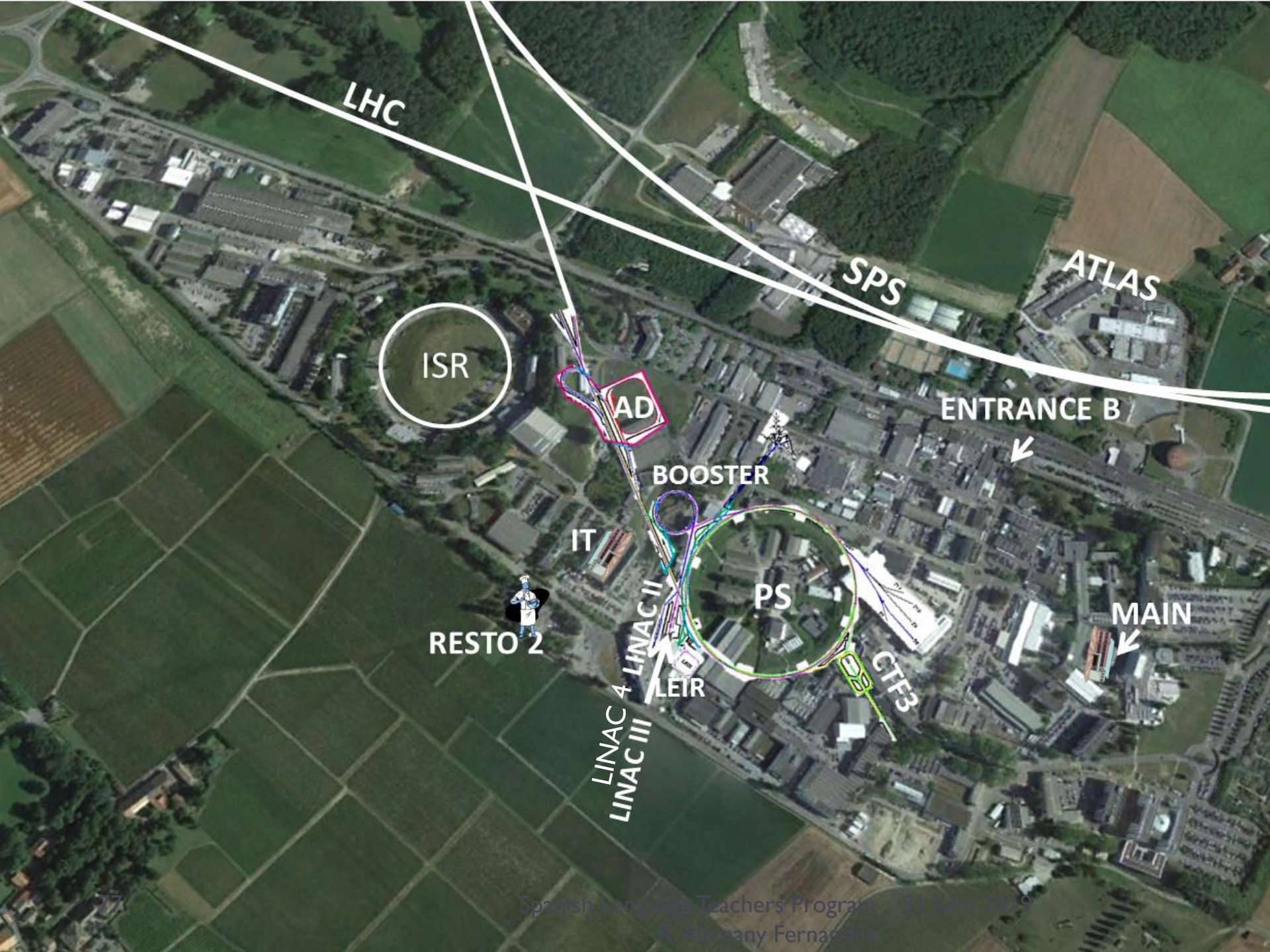


$$\beta = \frac{v}{c}$$

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

change in tune

$V(0.750\ \text{MeV} \rightarrow 50\ \text{MeV}) = 4\% \rightarrow 31\%$


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