Overview of the CERN Complex

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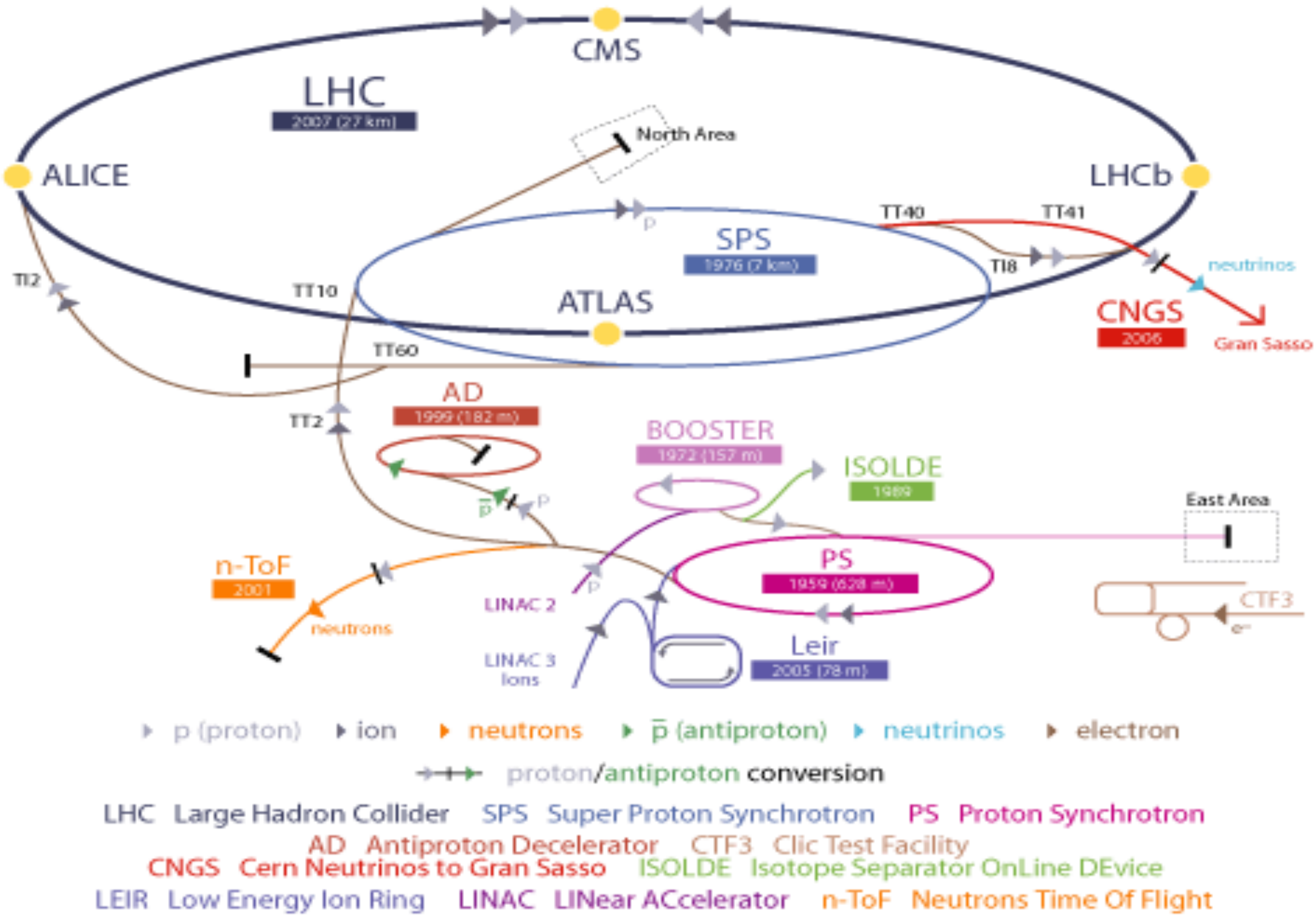
The CERN Accelerator Complex today

- **The LHC and Injector Chain**
  - The Proton Chain: Linac2, (Linac4), PSB, PS, SPS, LHC
  - The Ion Chain: Linac3, LEIR, PS, SPS, LHC
  - The Antiproton Chain: Linac2, PSB, PS, AD, (ELENA)

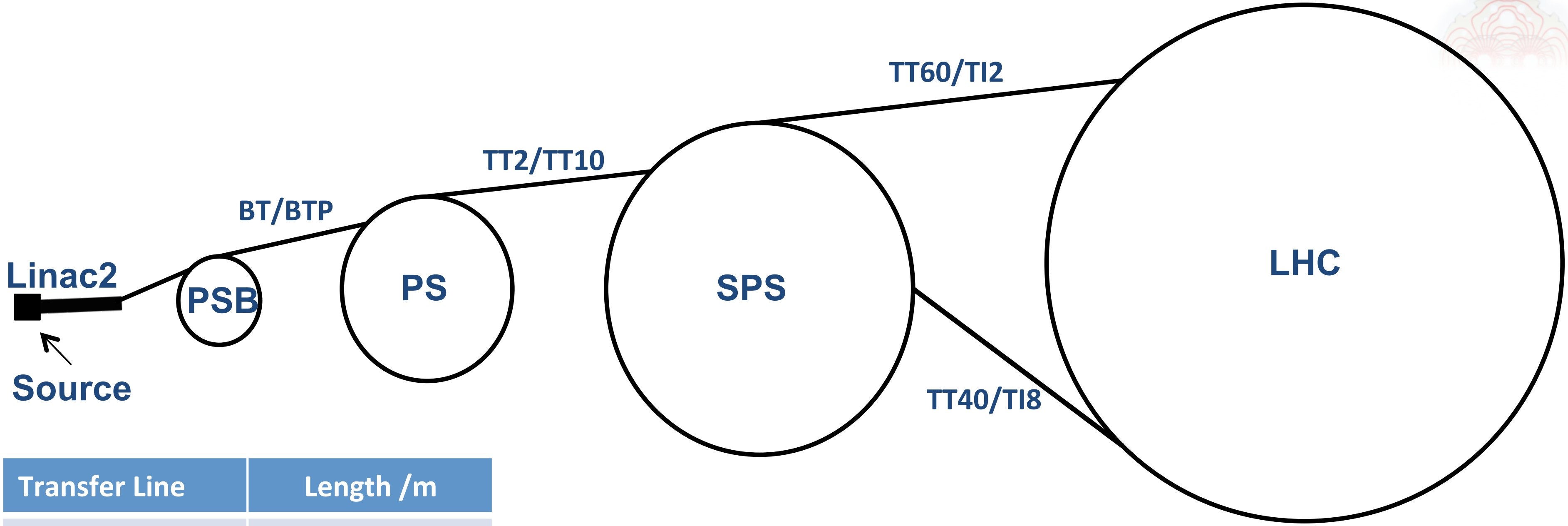
- **The Experimental Areas and Facilities**
  - Isolde, Rex-Isolde, (HIE-Isolde)
  - AD Experiments
  - n-ToF
  - Fixed Target Experiments and Test Beams, ~~(CNGS)~~

- **Test Facilities**
  - CTF3
  - HiRadMat
  - (AWAKE)

Particle Accelerators at CERN



LHC Proton Injector Chain



Transfer Line	Length /m
Linac2-PSB	80
BT	35.1
BTP	30.5
TT2 + TT10	250 860
TT60 + TI2	241 2947
TT40 + TI8	110 2587

	Circumference /m	Energy /GeV
Source+RFQ	-	0.00075
Linac2	(33m Long)	0.05
PS Booster	157	1.4
PS	628	25
SPS	6911	450
LHC	26659	7000

Proton Source

90 keV, pulsed every 1.2 s.

Radio Frequency Quadrupole

750 keV, pulsed every 1.2 s.

Linac2 (linear accelerator)

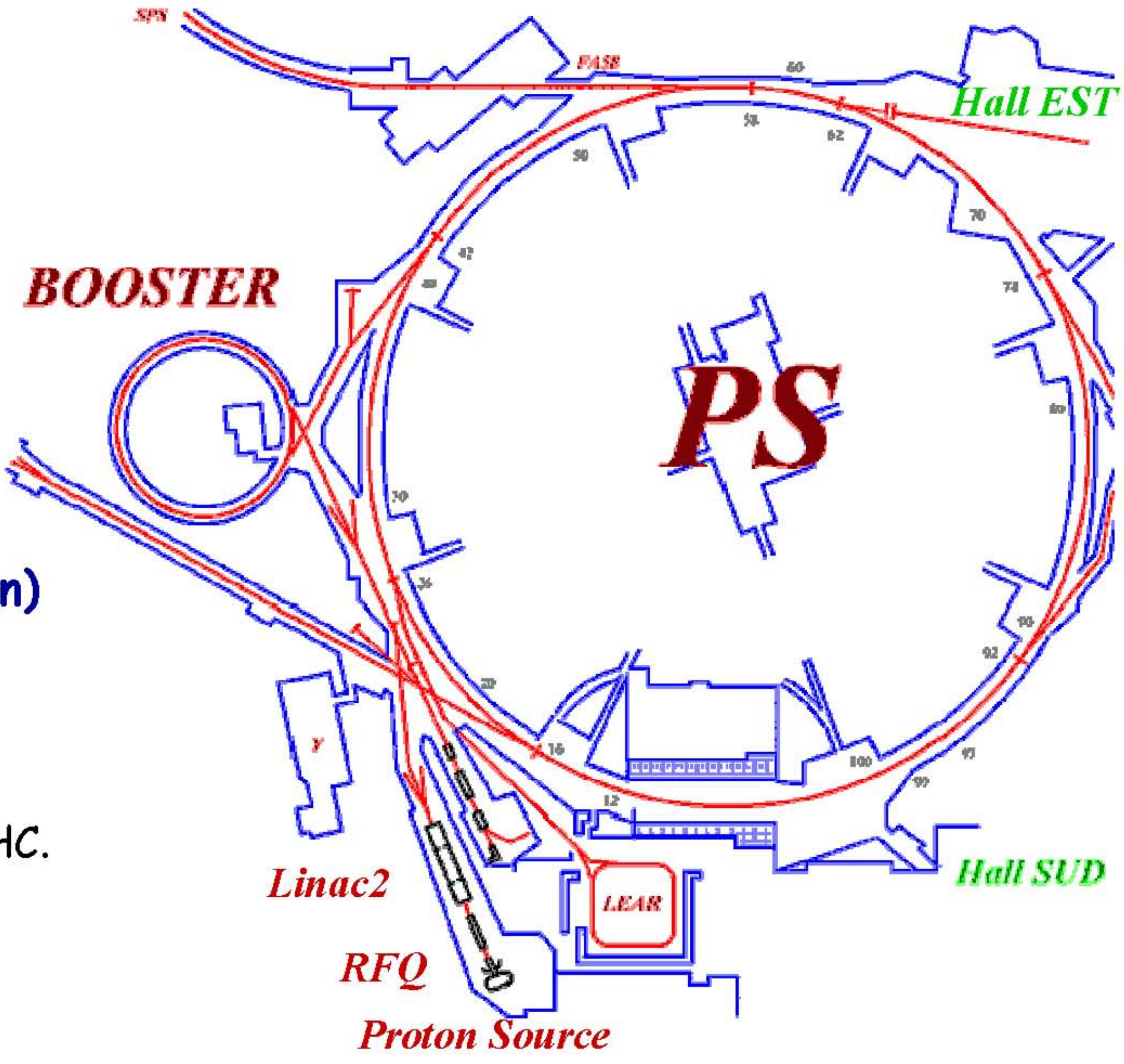
50 MeV, pulsed every 1.2 s.

PS Booster (4-ring synchrotron)

1.4 GeV, 1.2 s cycle time.

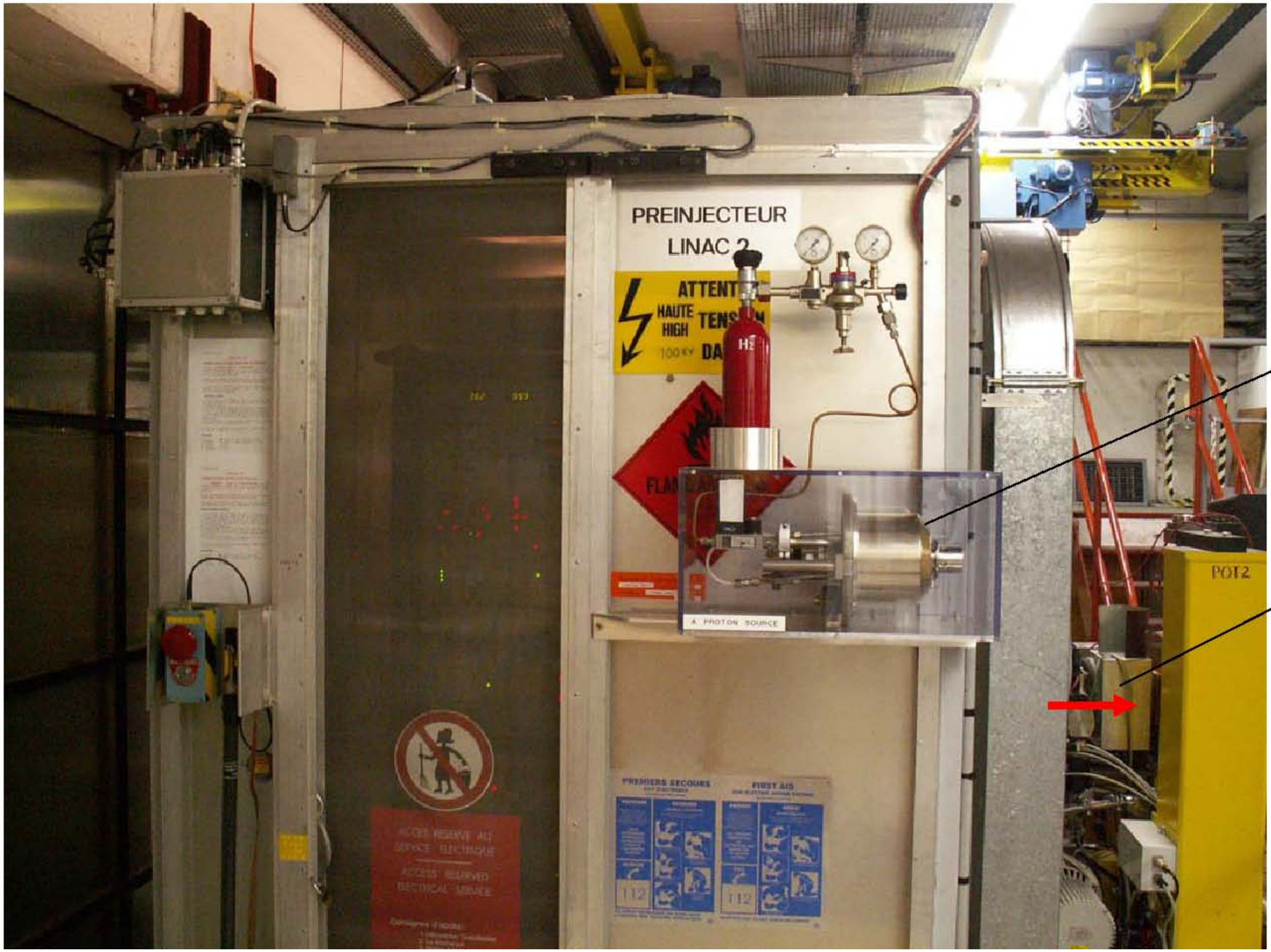
PS (Synchrotron)

25 GeV, 3.6 s cycle time for LHC.



Beam Starts Here ...

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



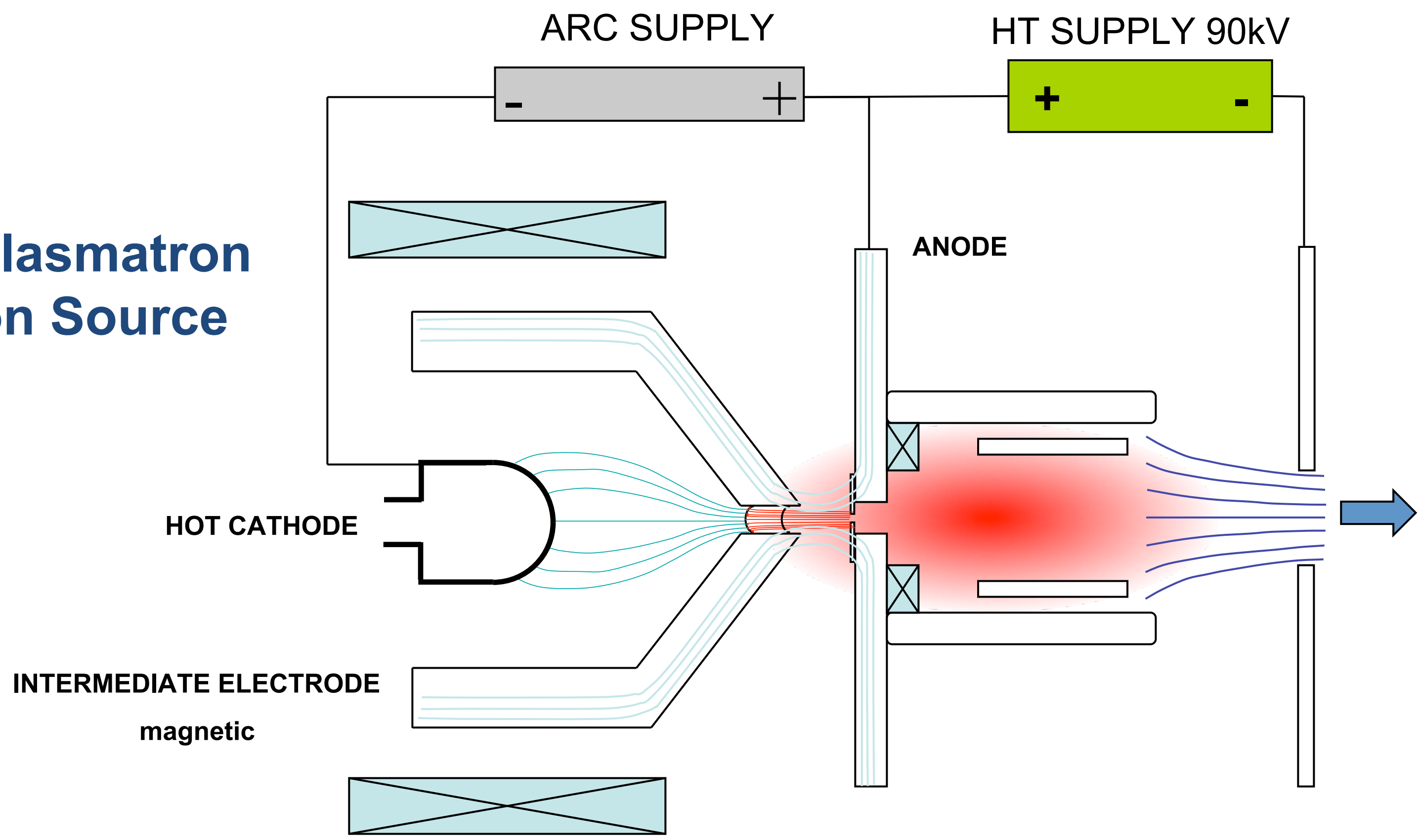
Source model (1 to 1)

Beam path to RFQ

Duoplasmatron Proton Source

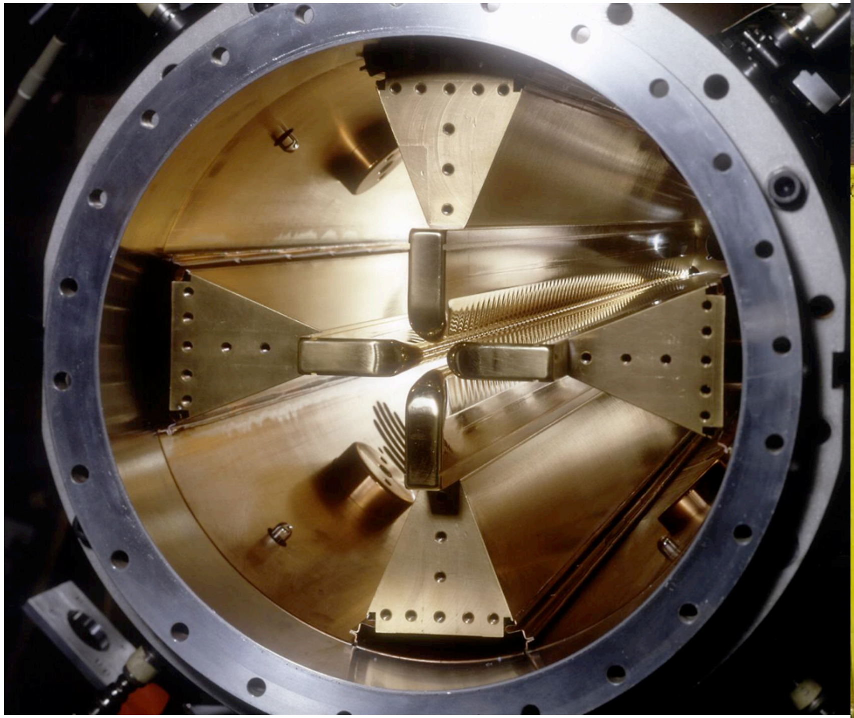
Protons (at 90 keV) are produced by creating a plasma using H_2 which is charged due to interaction with free electrons from the cathode. The plasma is then accelerated and becomes an ion beam

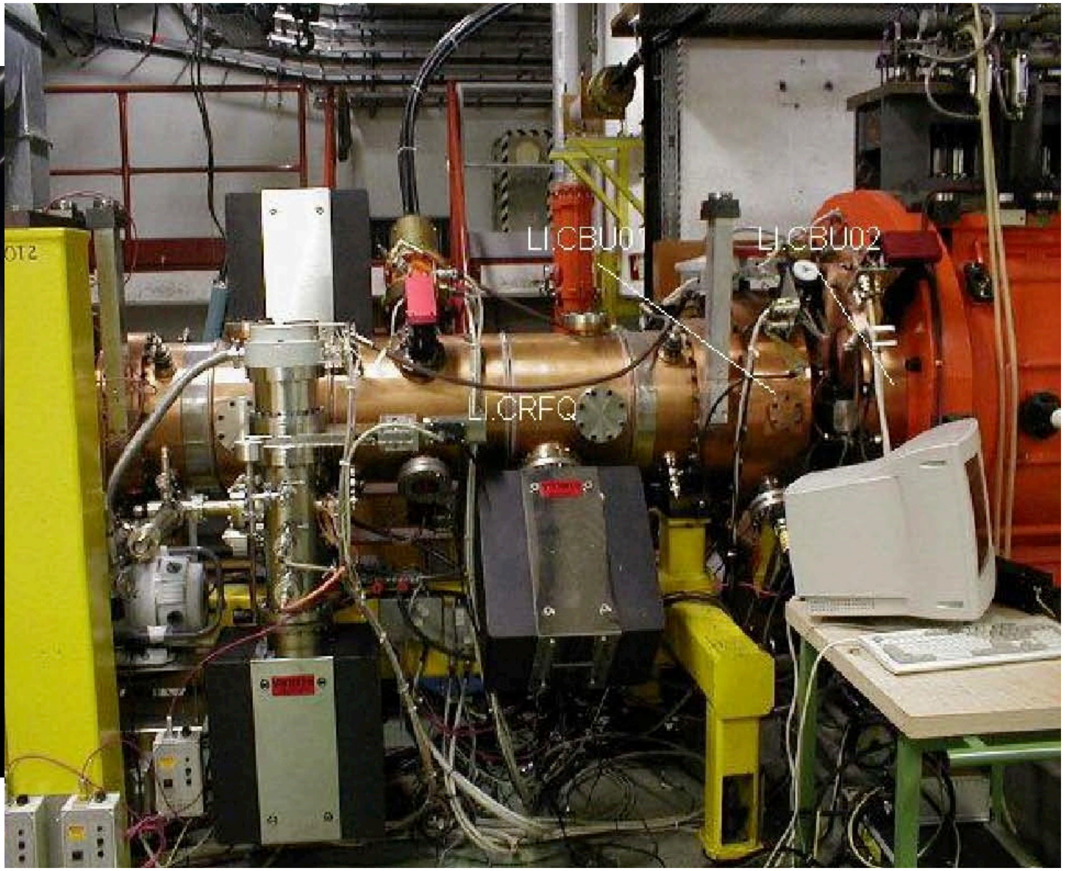
Duoplasmatron Proton Source



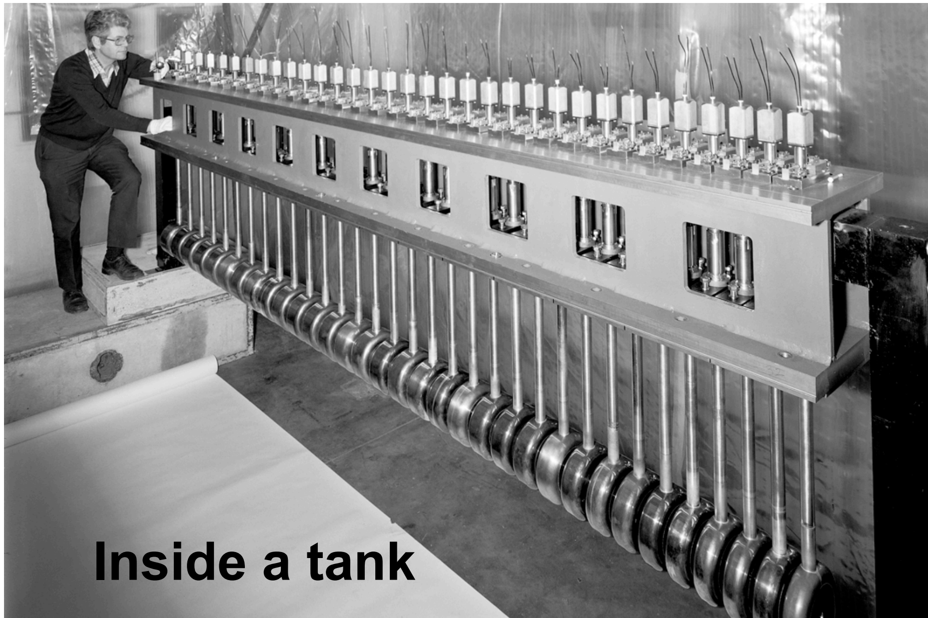
Radio Frequency Quadrupole (RFQ)

- Directly after the source, accelerates beam to 750 keV
- Acceleration and focusing achieved with electrical fields created with the help of specially shaped electrodes
- Length = 1.75m, frequency 200MHz

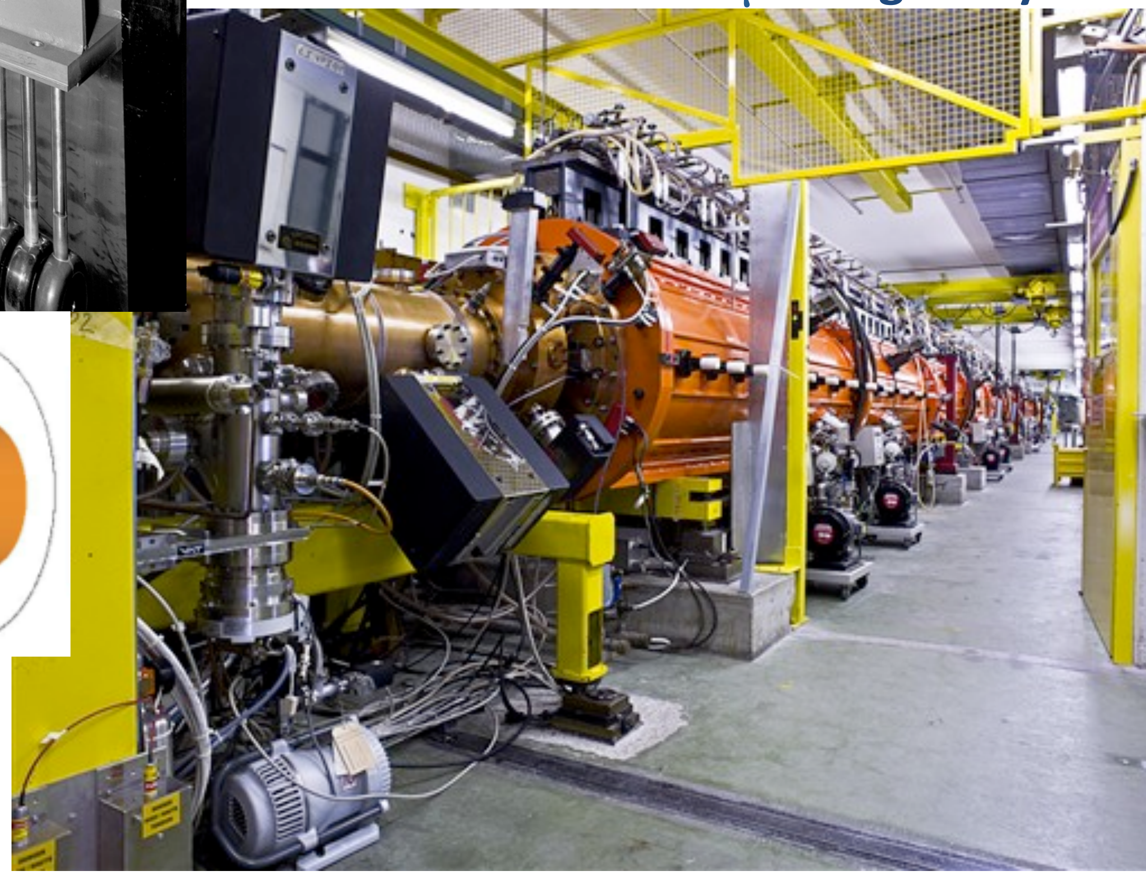


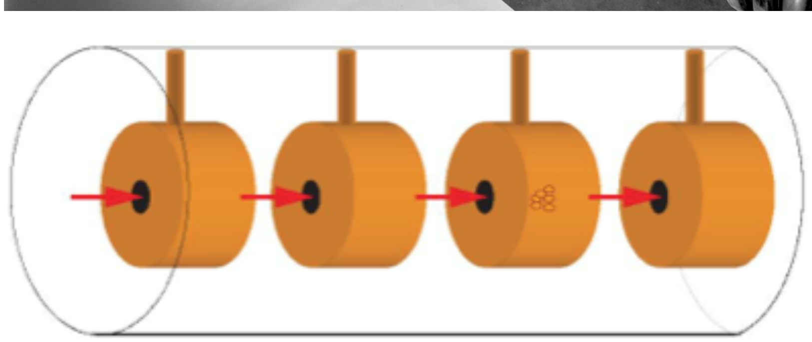


Linac 2



- Follows RFQ
- Accelerates beam to 50 MeV
- DTL (Alvarez structure)
- 4 Tanks, Total 33m Long
- Pulse of beam ~100μS long every 1.2s





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

PS Booster

Synchrotron with 4 vertically stacked rings, each ¼ of PS Circumference

Accelerates beam from 50MeV to 1.4 GeV in a cycle of 1.2s

Operates on Harmonic 1 for LHC : 1 bunch per ring.

2 cycles needed to fill the PS for

Also serves Isolde and all downstream faciliti

The Linac2 bea the 4 rings by fast kicke eral turns

The Booster is the machine in the LHC Injector Chain where the transverse brightness of the LHC beam is determined

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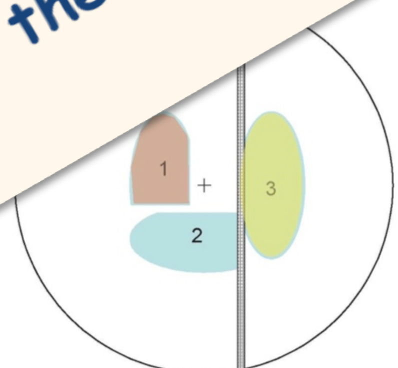
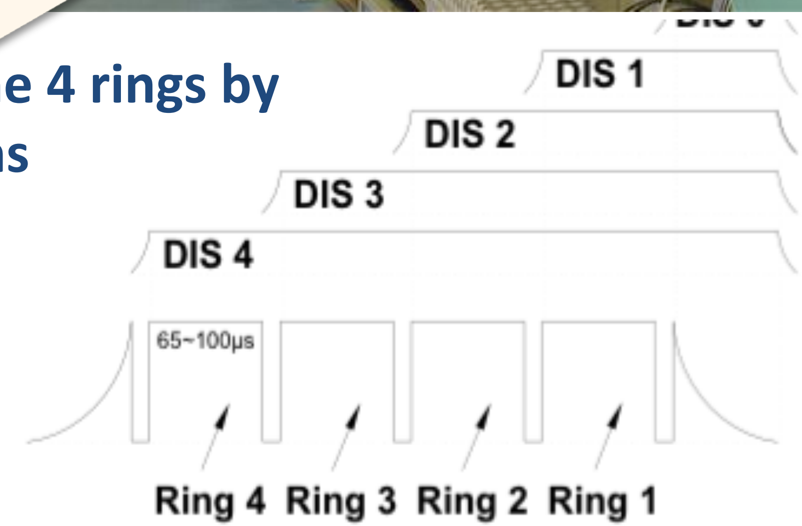
In

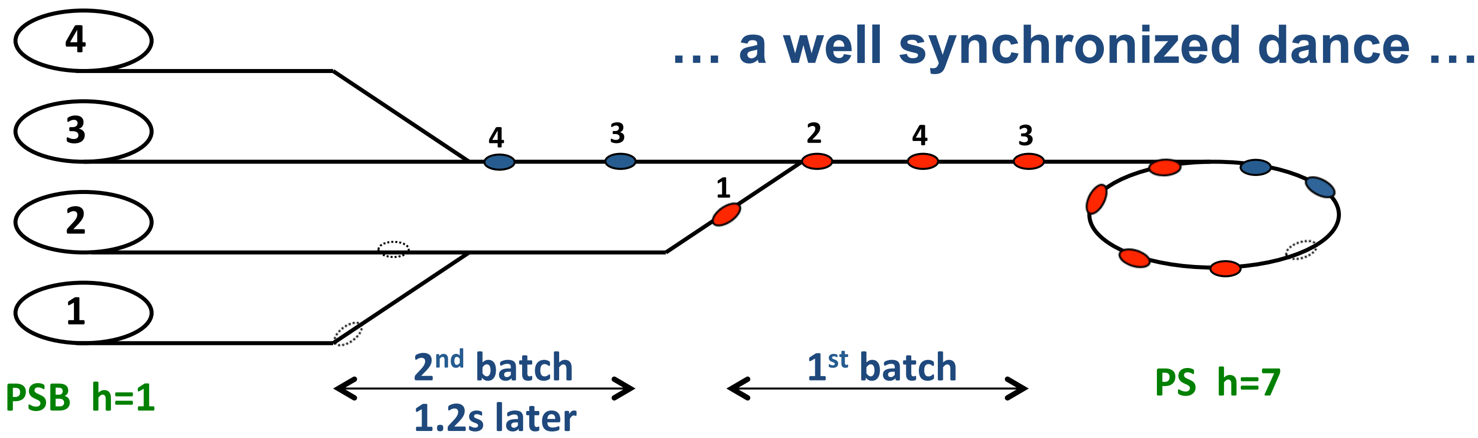
(up to

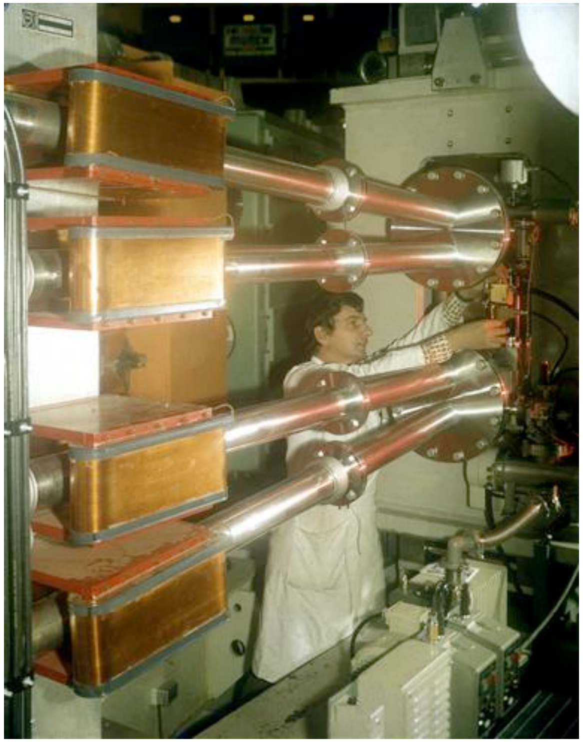
pos





PS Booster – PS Transfer



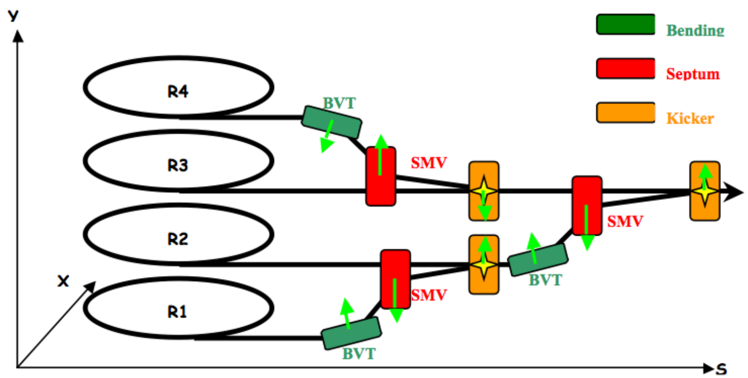


Inject 6 bunches on h=7 in the PS (1 empty bucket) …

- **Either 3+3 bunches, or 4+2 (operational)**

The Bunches spaced by 327ns as they leave the Booster:

- **Corresponds to 1/7 of a PS turn, or 1.75 PSB turns**



The PS

The oldest machine at CERN

(commissioned in 1959)

Synchrotron with combined function magnets

Acceleration from 1.4 to 25 GeV

Cycling time (LHC beams) 3.6

RF Gymnastics used t
bunch structure r
(25 or 50 ns s
systems

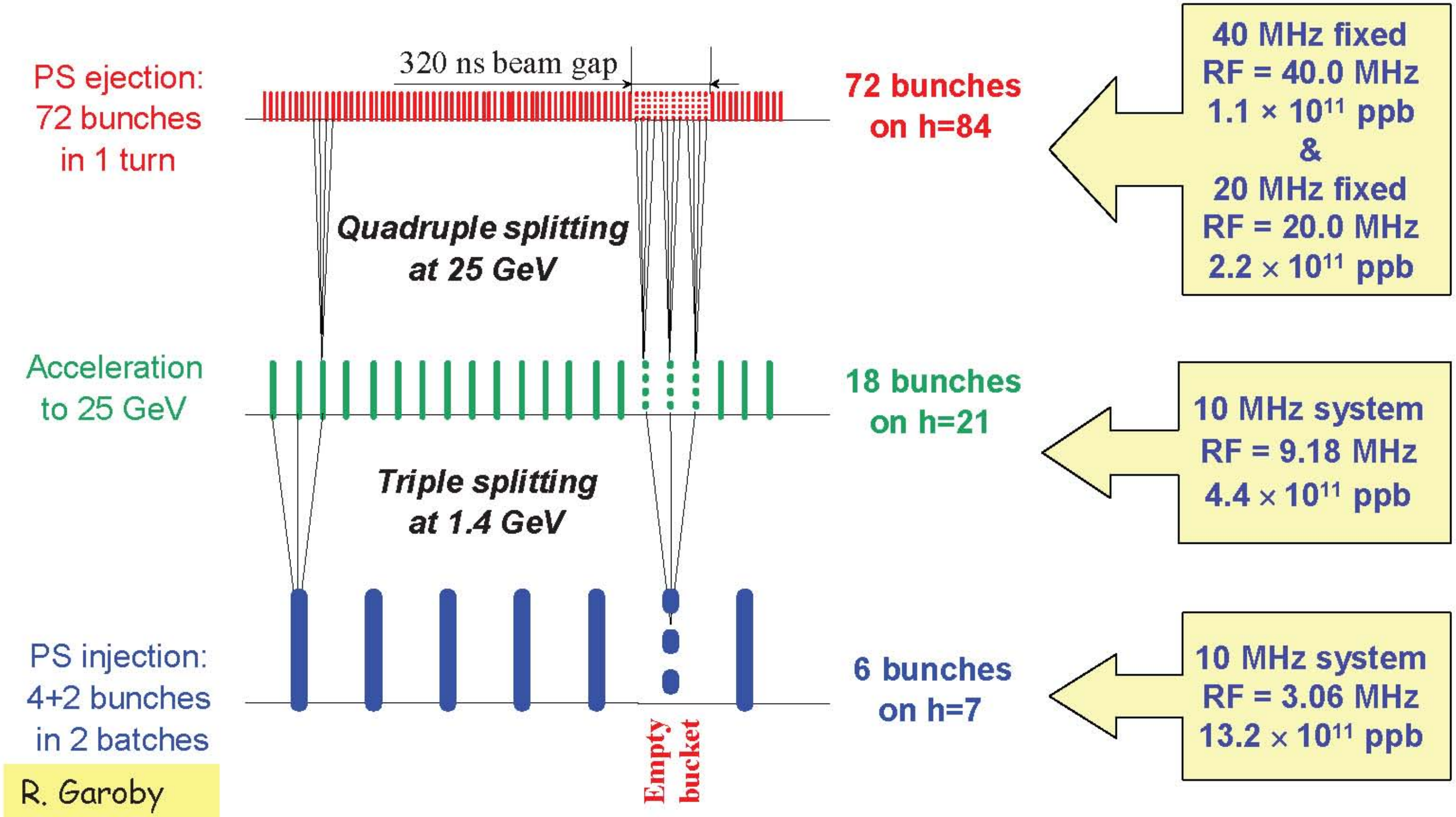
Slo to East Hall

Also s and n-ToF as well as all beams in SPS (& LHC)

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

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.)



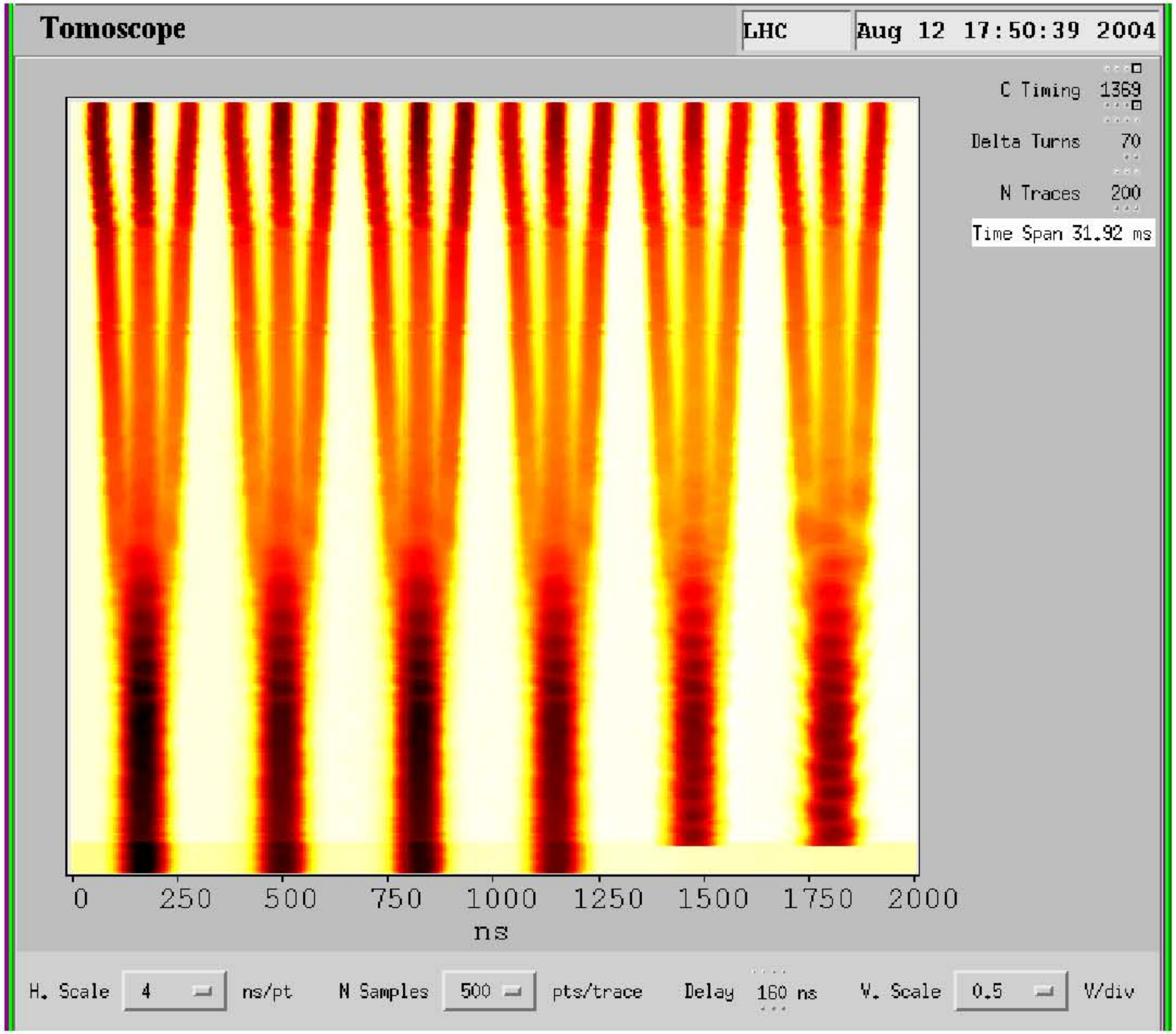
Use double splitting at 25 GeV to generate 50ns bunch trains instead

Triple Splitting at PS Injection (1.4GeV)

- Waterfall view of longitudinal gymnastics
- Injection of 2nd PSB batch (bunches 5 & 6)
- Triple splitting with different cavities of 10 MHz system.

  h=7 to h=21

  - Horizontal scale 2μs (~1 turn)
  - Vertical scale 32 ms
  - Z-direction intensity



Super Proton Synchrotron (SPS)

11 x PS circumference

Uses Conventional magnets

(2 T vs. 4.4 T for Tevatron)

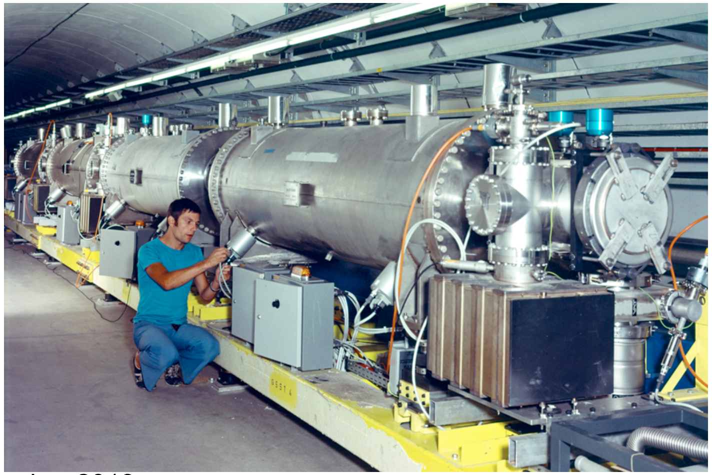
Accelerates beam up to 450 GeV energy

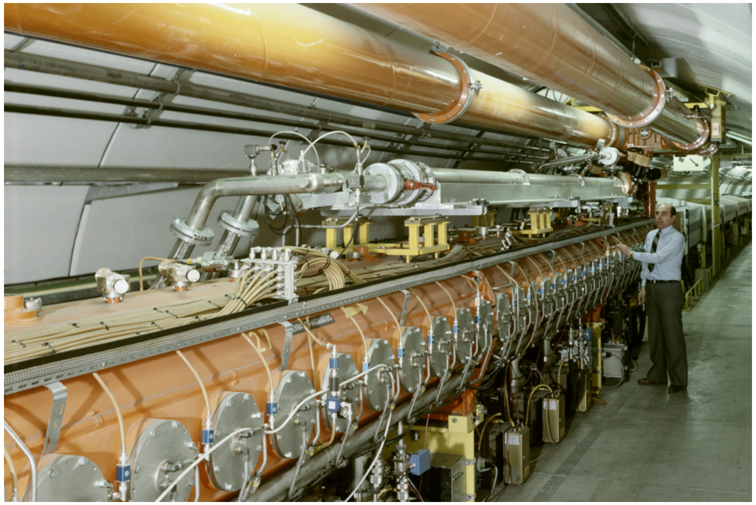
Up to ~5×10^{13} protons/cycle

For LHC the ring is only partly filled (~1/3) with up to 288 bunches

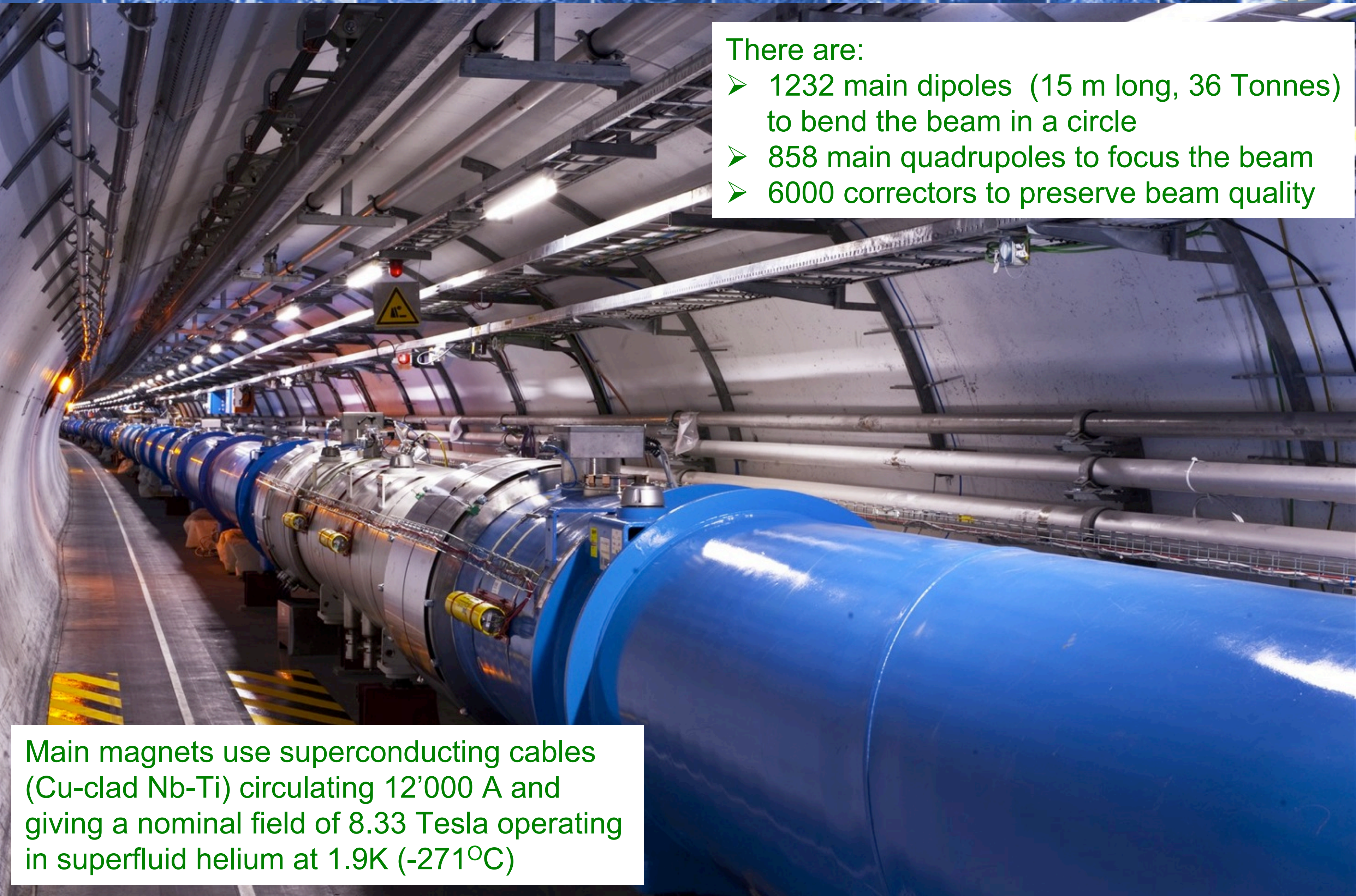
Serves the North area with a slow extracted beam. Also served CNGS up to last year

New Facilities: HiRadMat and AWAKE (under construction)





LHC

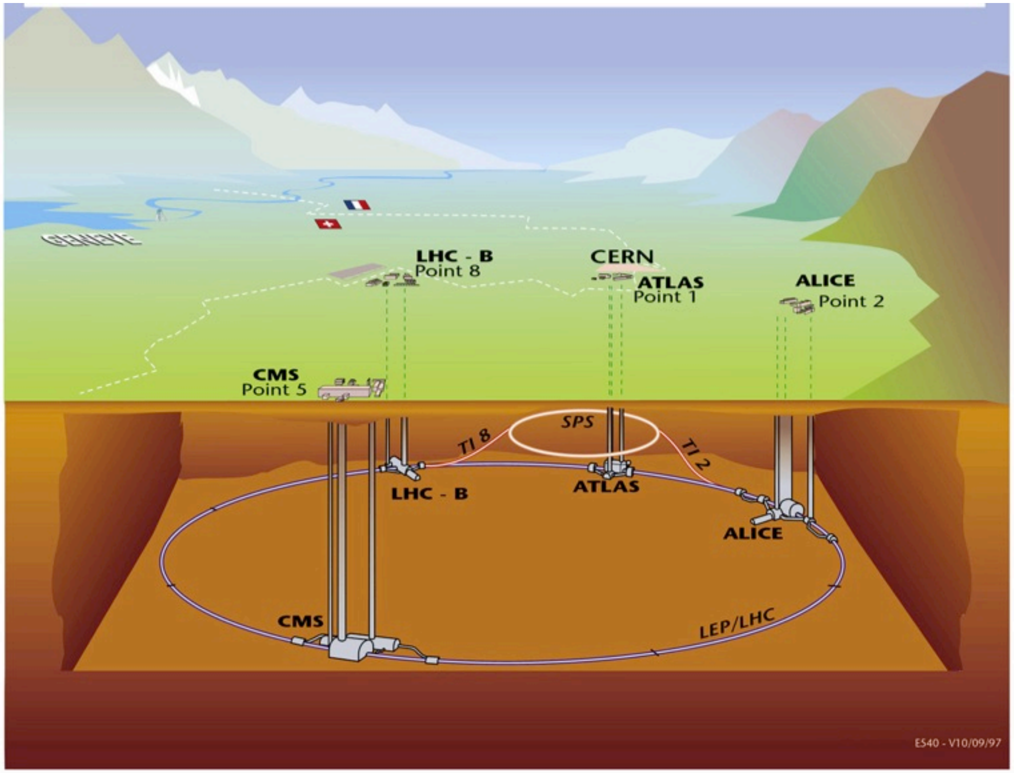


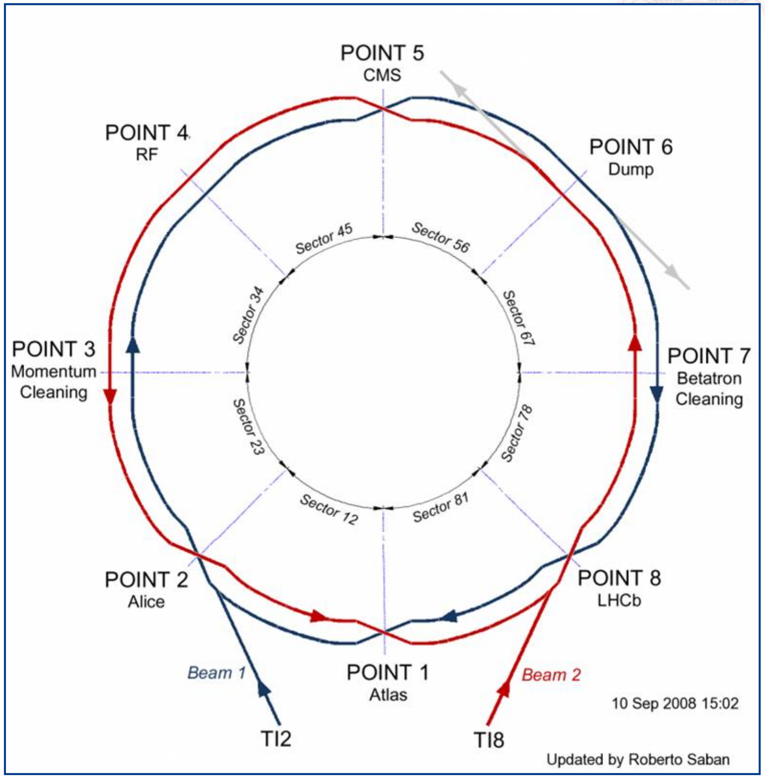
There are:

- 1232 main dipoles (15 m long, 36 Tonnes) to bend the beam in a circle
- 858 main quadrupoles to focus the beam
- 6000 correctors to preserve beam quality

Main magnets use superconducting cables (Cu-clad Nb-Ti) circulating 12’000 A and giving a nominal field of 8.33 Tesla operating in superfluid helium at 1.9K (-271^{O}C)

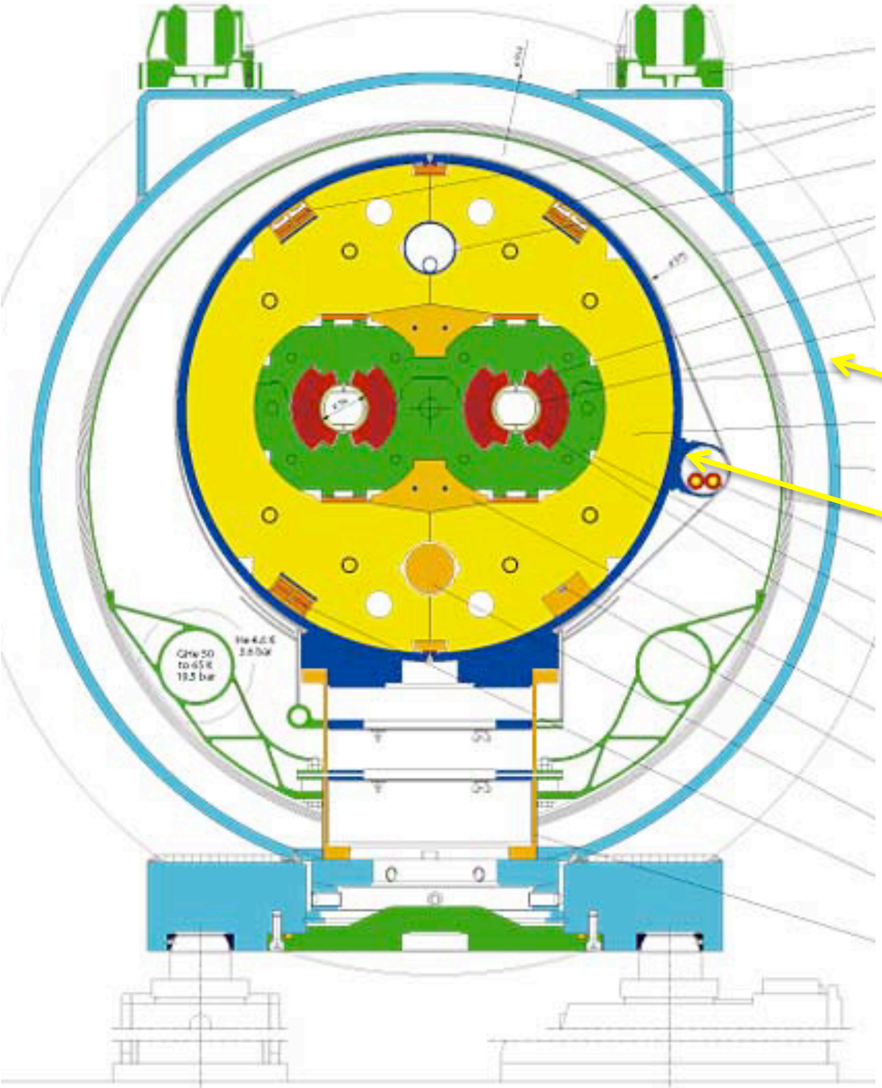
LHC Layout





4 Major Experiments + 3 smaller ones

Designed for 7 TeV on 7 Tev collisions (protons and ions)
Nominally ~2800 bunches of $1.15 \times 10^{+11}$ protons per bunch
Nominal Luminosity $1 \times 10^{+34}$ cm^{-2} s^{-1}



In total 42,000 tonnes of material to cool to -271^0C

Room temperature, 20^0C

Cold! , -271^0C

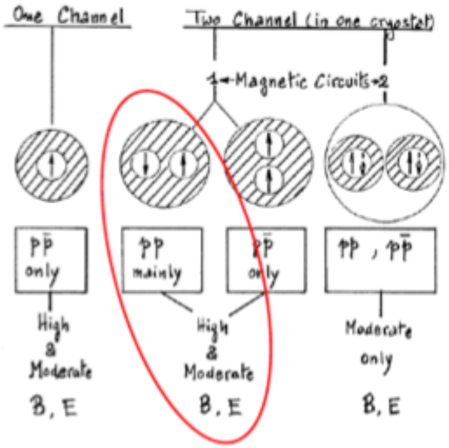
LHC Requires

- 90,000 tonnes of liquid Nitrogen to cool it down, and
- 130 tonnes of Liquid Helium to keep it cold

LHC Some of the Technical Challenges

Circumference (km)	26.7	100-150m underground
Number of Dipoles	1232	Cable Nb-Ti, cold mass 37million kg
Length of Dipole (m)	14.3	
Dipole Field Strength (Tesla)	8.4	Results from the high beam energy needed
Operating Temperature (K)	1.9	Superconducting magnets needed for the high magnetic field Super-fluid helium
Current in dipole sc coils (A)	13000	Results from the high magnetic field 1ppm resolution
Beam Intensity (A)	0.5	$2.2.10^{-6}$ loss causes quench
Beam Stored Energy (MJoules)	362	Results from high beam energy and high beam current. 1MJ melts 2kg Cu
Magnet Stored Energy (MJoules)	10000	Results from the high magnetic field
Sector Powering Circuit	8	1612 different electrical circuits

ECFA-CERN workshop



June 1994
first full scale prototype dipole

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

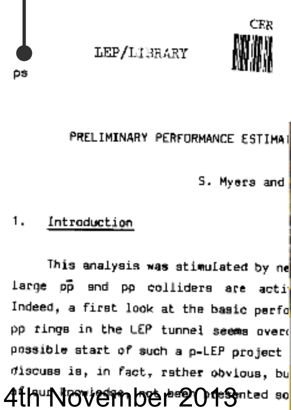
June 2007 First sector cold

April 2008
Last dipole down

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

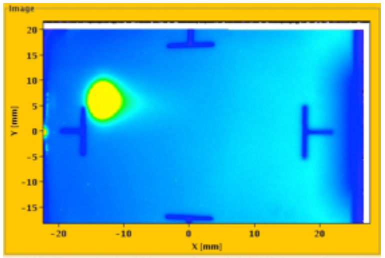
First set of twin 1 m prototypes Over 9 T

2002 String 2

November 2006
1232 delivered

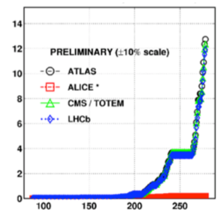
September 10, 2008
First beams around

August 2008
First injection test



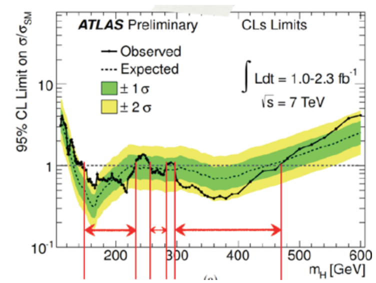
Sept. 10, 2008
First beams around

November 29, 2009
Beam back



October 14, 2010
L= $1\times10^{+32}$
248 bunches

Repair and Consolidation

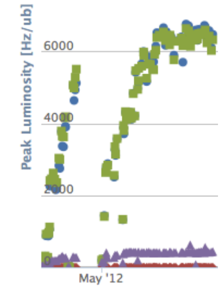


October, 2011
$3.5\times10^{+33}$, 5.7 fb^{-1}

First Hints!!

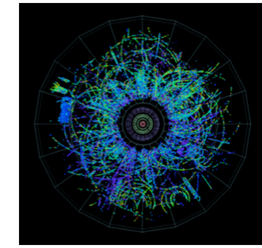
June 28 2011
1380 bunches

1380

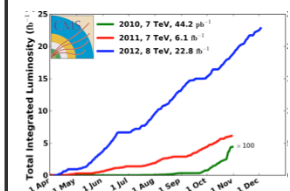


May 2012
Ramping
Performance

March 14th 2012
Restart
with Beam



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

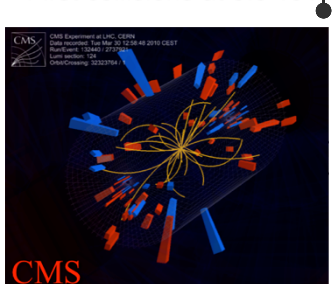


Nov. 2012
End of p^{+} Run 1

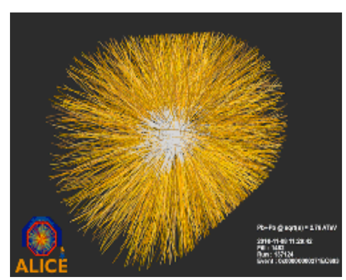
2008 | 2009 | 2010 | 2011 | 2012 | 2013

Sept. 19, 2008
Disaster

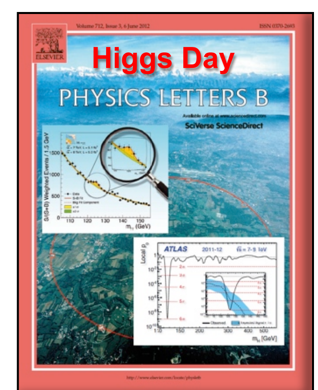
March 30, 2010
First collisions at 3.5 TeV



November 2010
Pb^{82+} Ions



November 2011
Second Ion Run

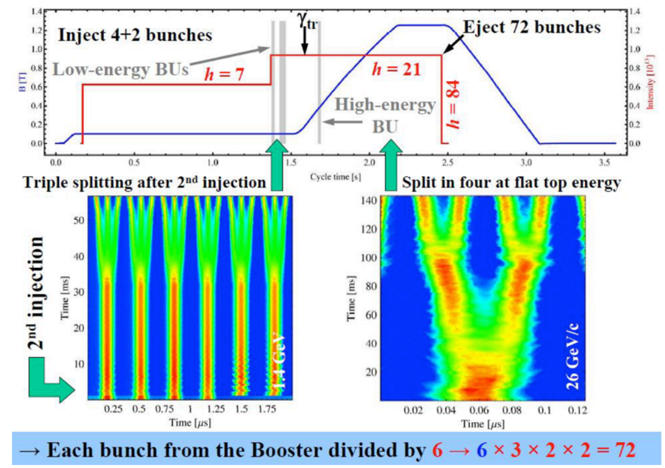


LS1

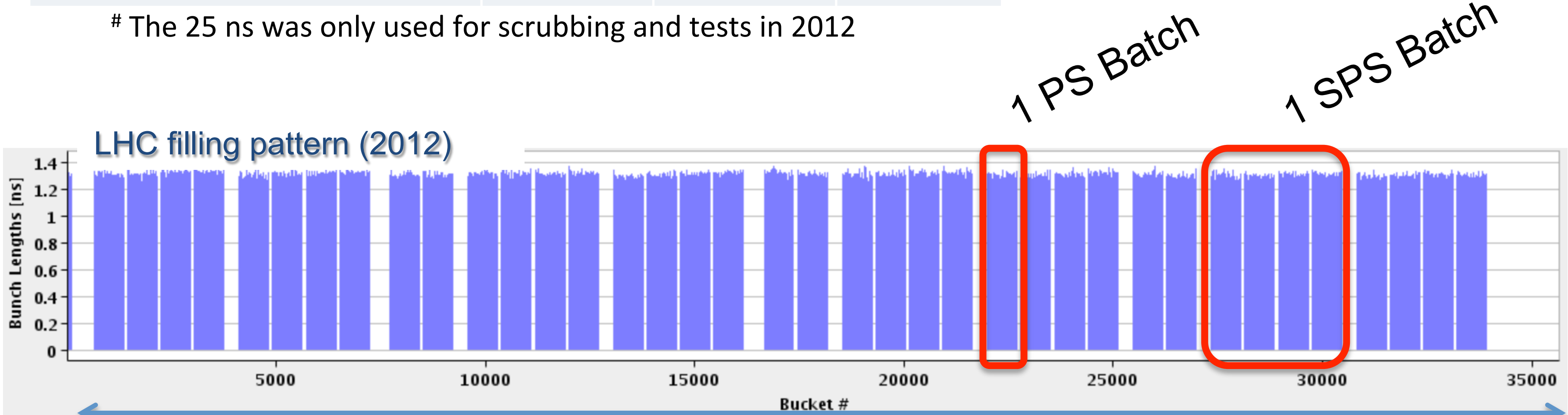
Filling the LHC (2012)

	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}	$\mathbf{7.7 \times 10^{33}}$	N.A. #

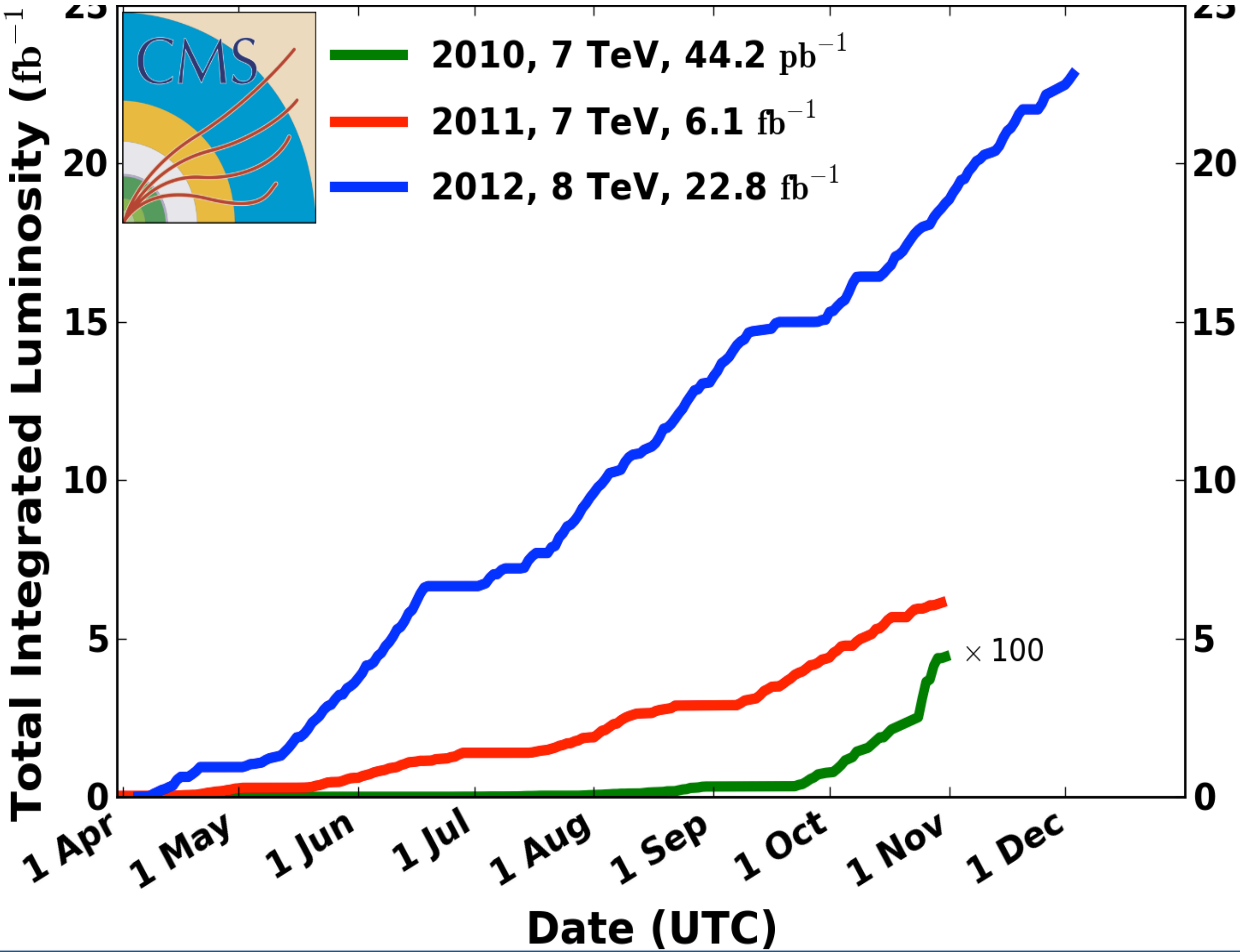
The 25 ns was only used for scrubbing and tests in 2012



The 25 ns PS production scheme (2102)



LHC Proton Run #1 (3-Years)

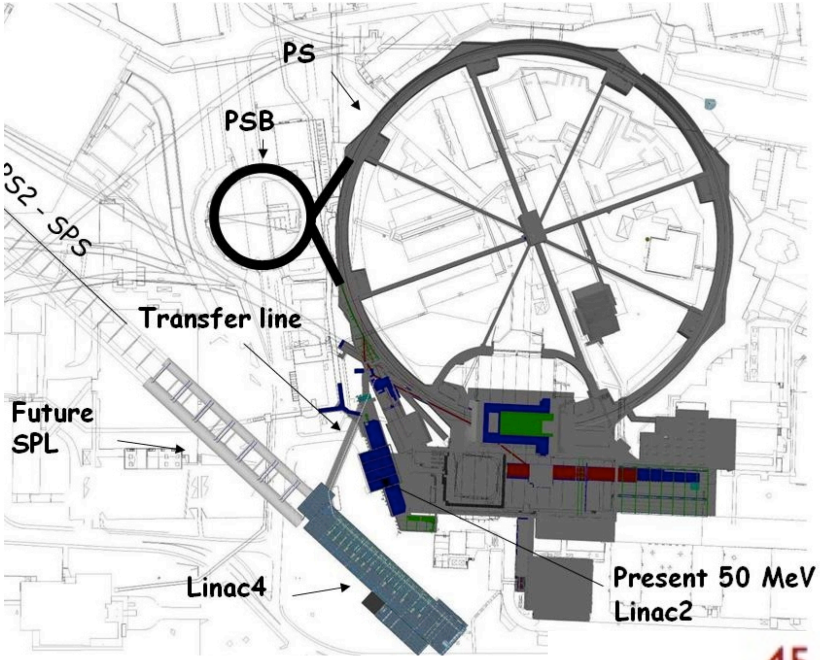


1 fb^{-1} represents ~100 Trillion (10^{14}) proton-proton collisions

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 booster
- H- Injection : CERN is one of the few labs still using p$^+$
- Connection to PSB depends on finding a ~8 month shutdown of LHC after 2015.



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

with N_b : number of protons/bunch

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

R : mean radius of the accelerator

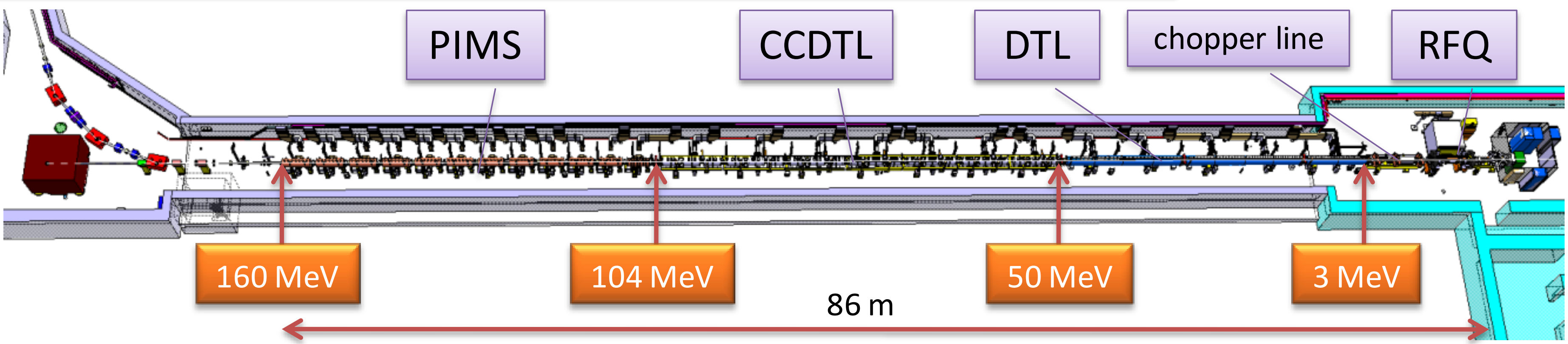
Delivers 40mA, 400μs pulses at 2Hz

Ion species	H^-	
Output Energy	160	MeV
Bunch Frequency	352.2	MHz
Max. Rep. Frequency 2	Hz	
Max. Beam Pulse Length	0.4	ms
Max. Beam Duty Cycle	0.08	%
Chopper Beam-on Factor	65	%
Chopping scheme:	222 transmitted /133 empty buckets	
Source current	80	mA
RFQ output current	70	mA
Linac pulse current	40	mA
Tr. emittance (source)	0.25	π mm mrad
Tr. emittance (linac exit)	0.4	π mm mrad

Max. repetition frequency for accelerating structures 50 Hz

Construction well underway

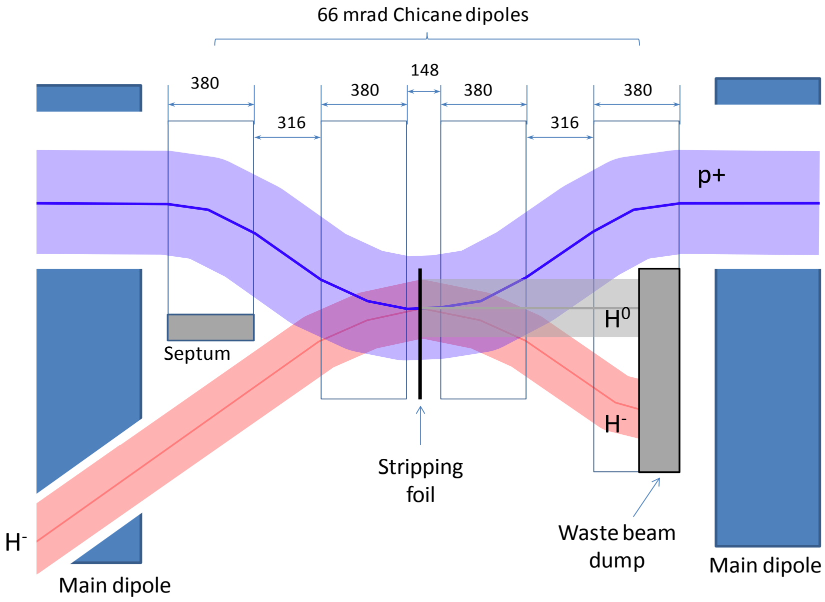
Progressive commissioning 2014-2015



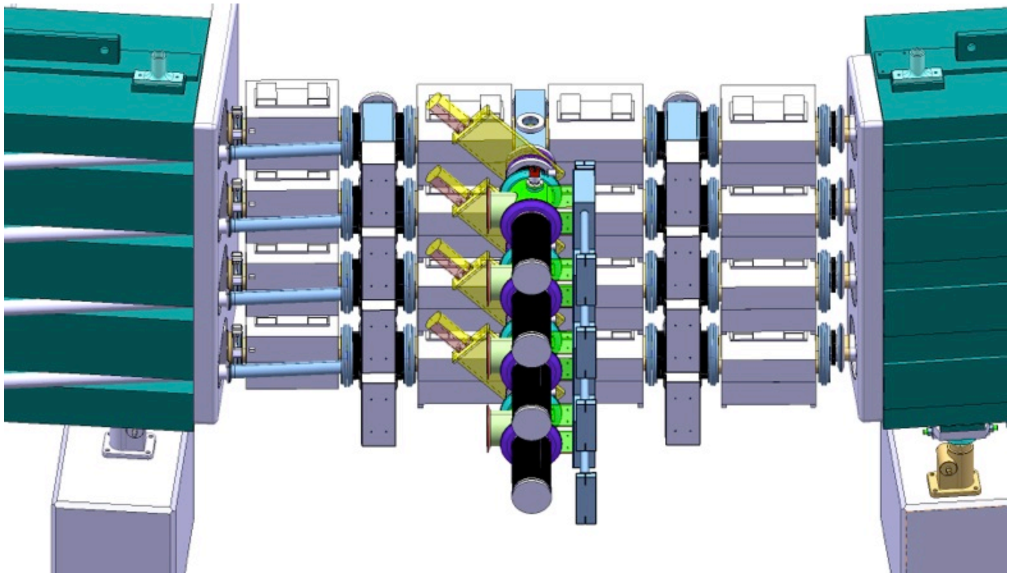
Why H- ?

Charge exchange injection of H- into a ring allows accumulation over many turns with no emittance blow-up

Principle of H- injection in the PSB

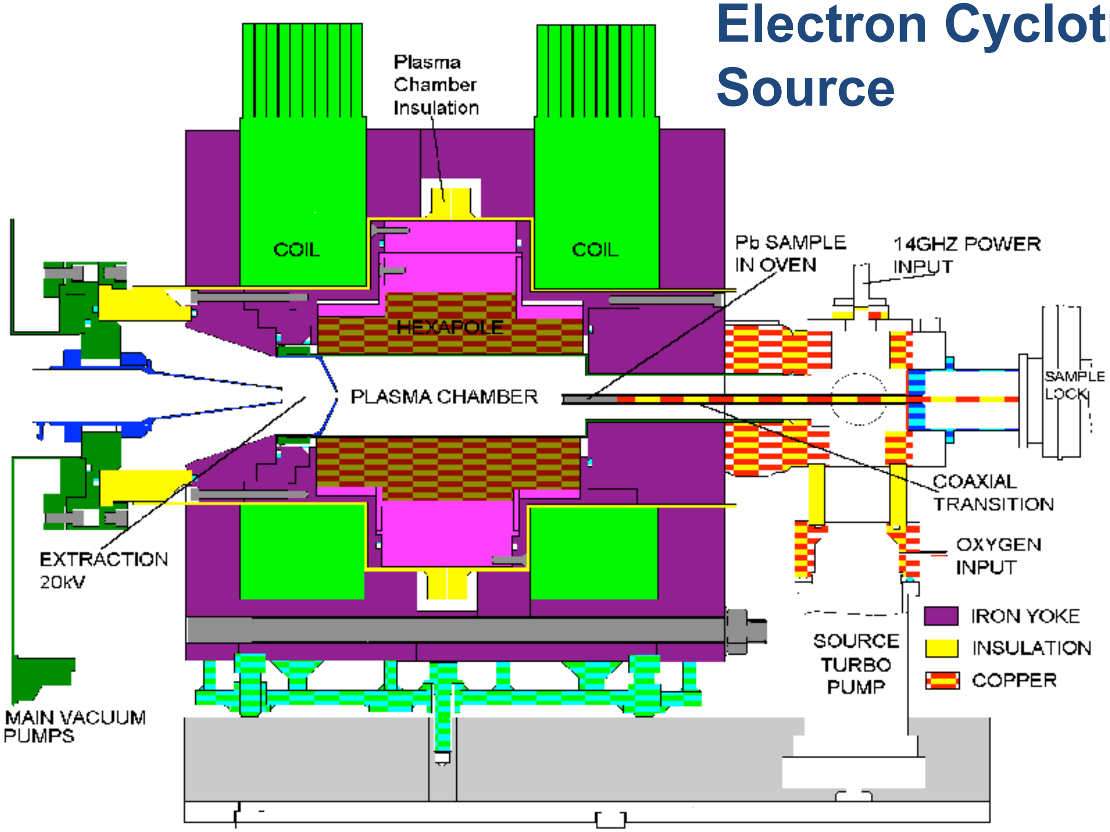


3D layout of injection region



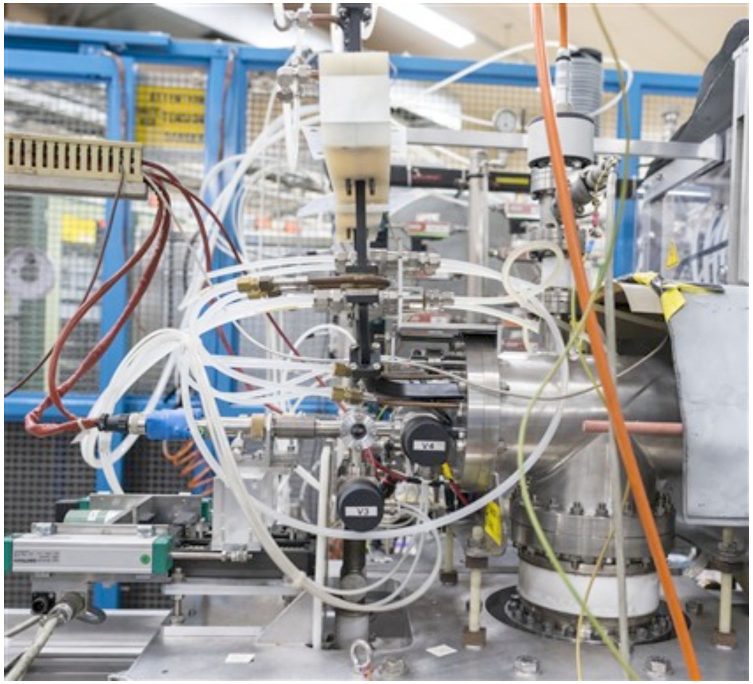
But it does require a major modification to the PSB Injection region

The Ion Chain: Linac3 Source



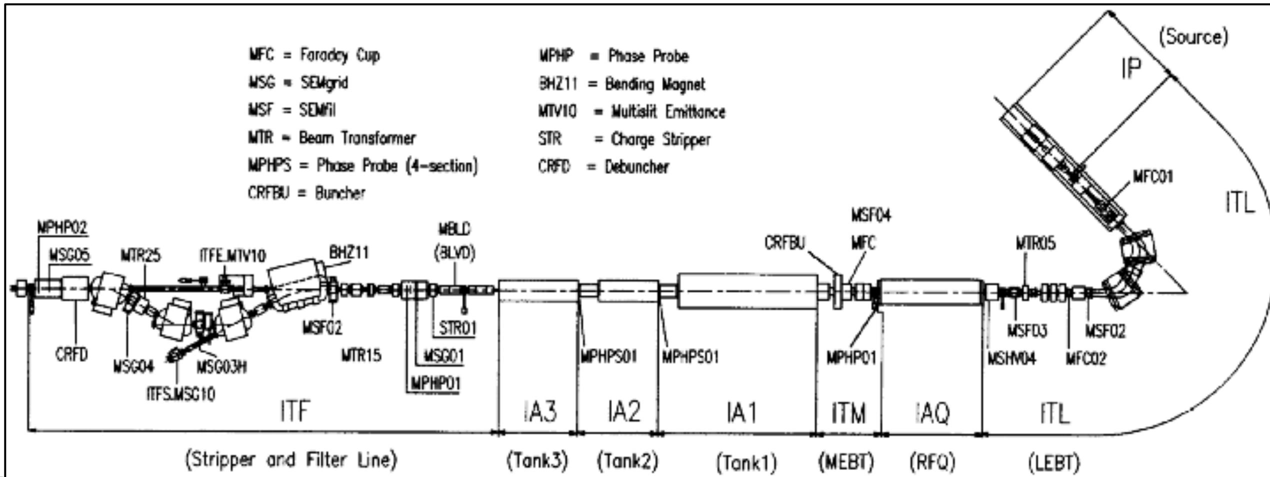
Electron Cyclotron Resonance (ECR), 14GHz Source

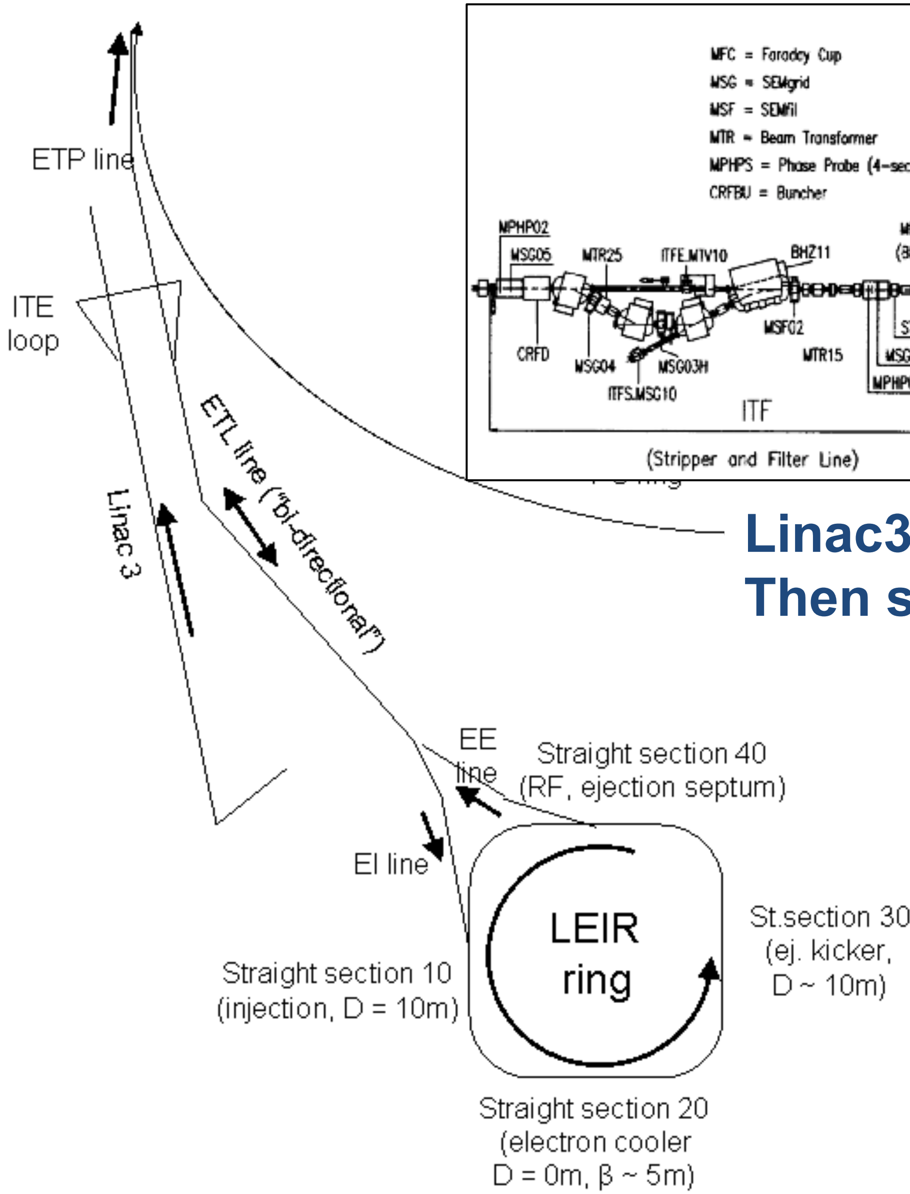
Produces around 0.8mA of Lead ions with a range of charge states centered around Pb^{+29} @2.5KeV/n
The LEBT selects one : presently Pb^{+29}



The source can also be set up to deliver other species…
Argon and Xenon are being prepared for the SPS Physics programme

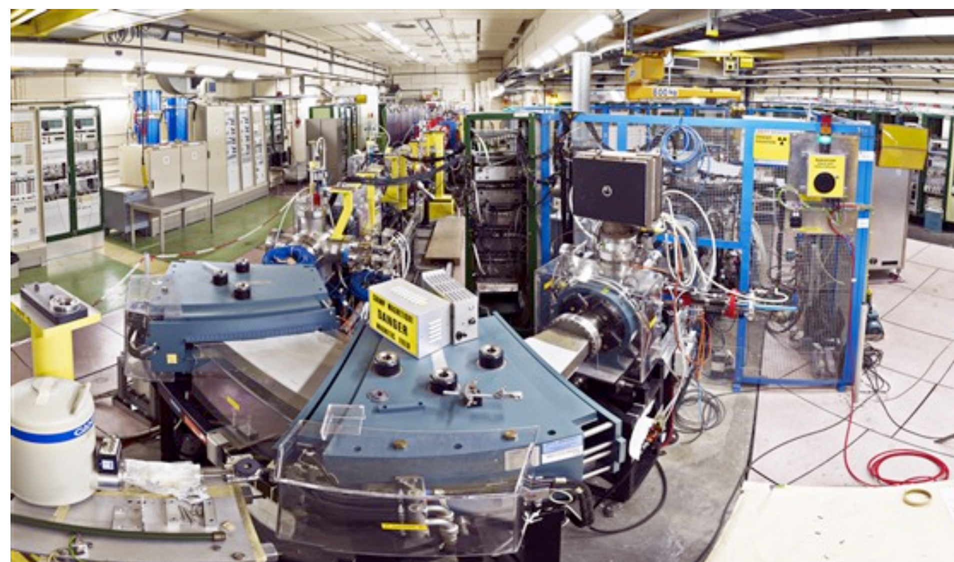
The Ion Chain: Linac3



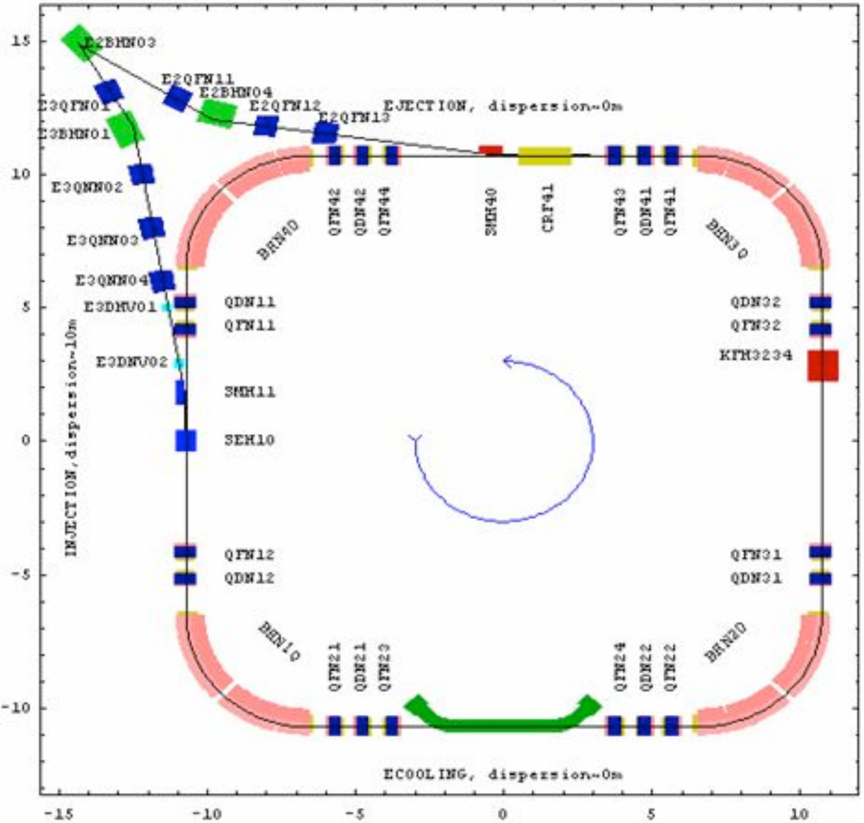


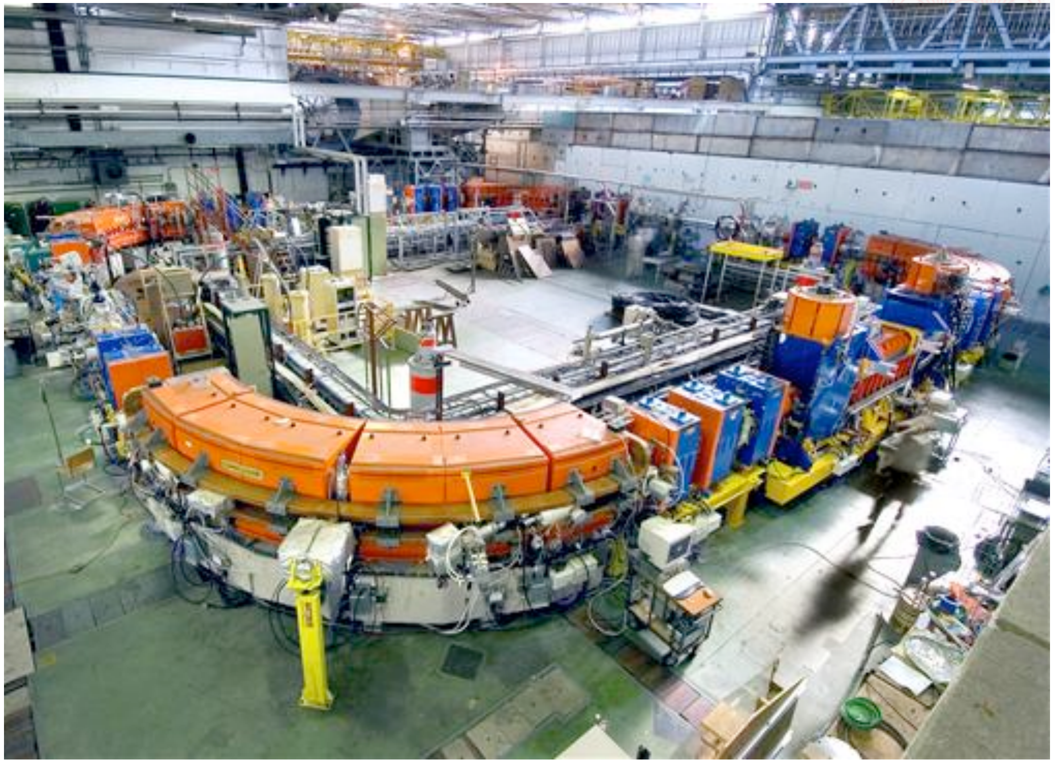
Linac3 accelerates Pb^{29+} to 4.2 MeV/n at 5Hz

Then stripped to Pb^{54+} for injection into LEIR



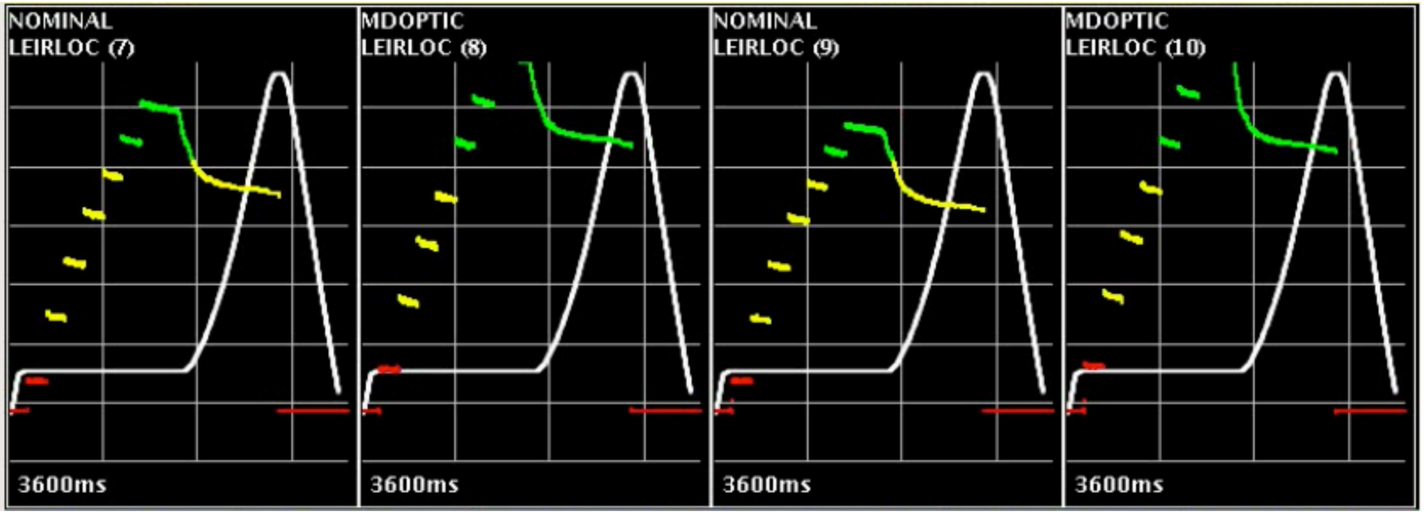
The Ion Cain : LEIR





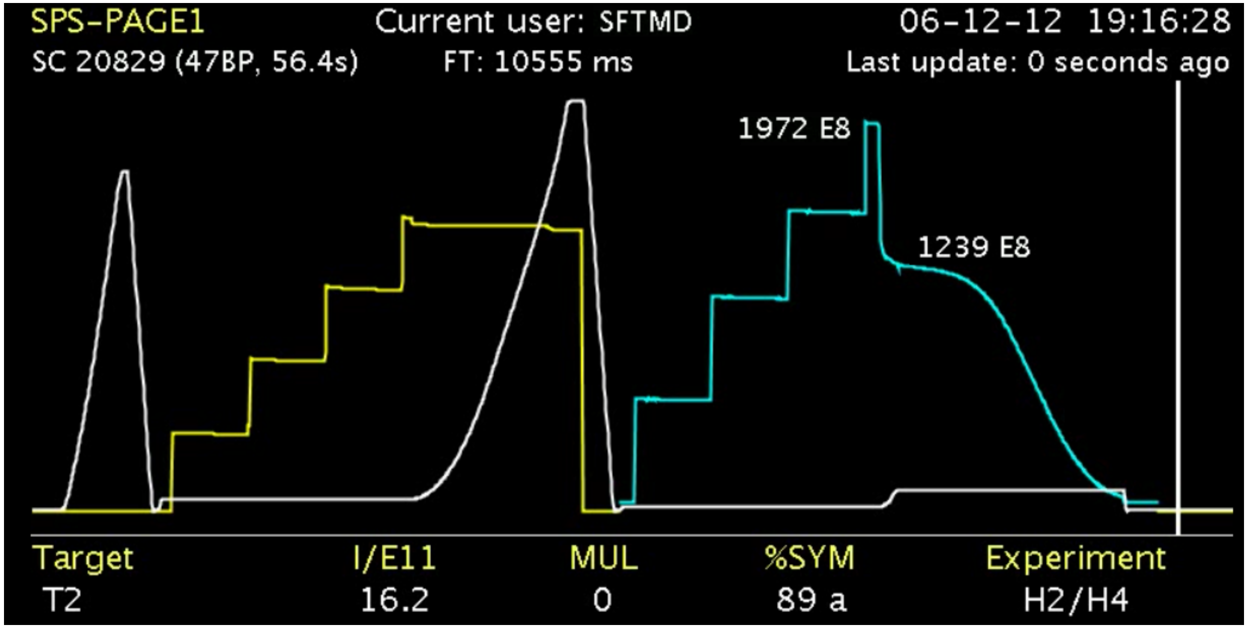
LEIR Accumulates the 200ms pulses from Linac3 into 2 bunches
Electron Cooling is used to achieve the required brightness
Finally, acceleration to 72 MeV/n before transfer to the PS
LEIR Cycle is 3.6s

The Ion Chain



LEIR Cycles

$5x10^{10}$ charges of Pb^{54+} routinely extracted to PS then accelerated to 5.9 GeV/n



Final Stage

Several injections into SPS from PS, then acceleration to 177GeV/n for the LHC

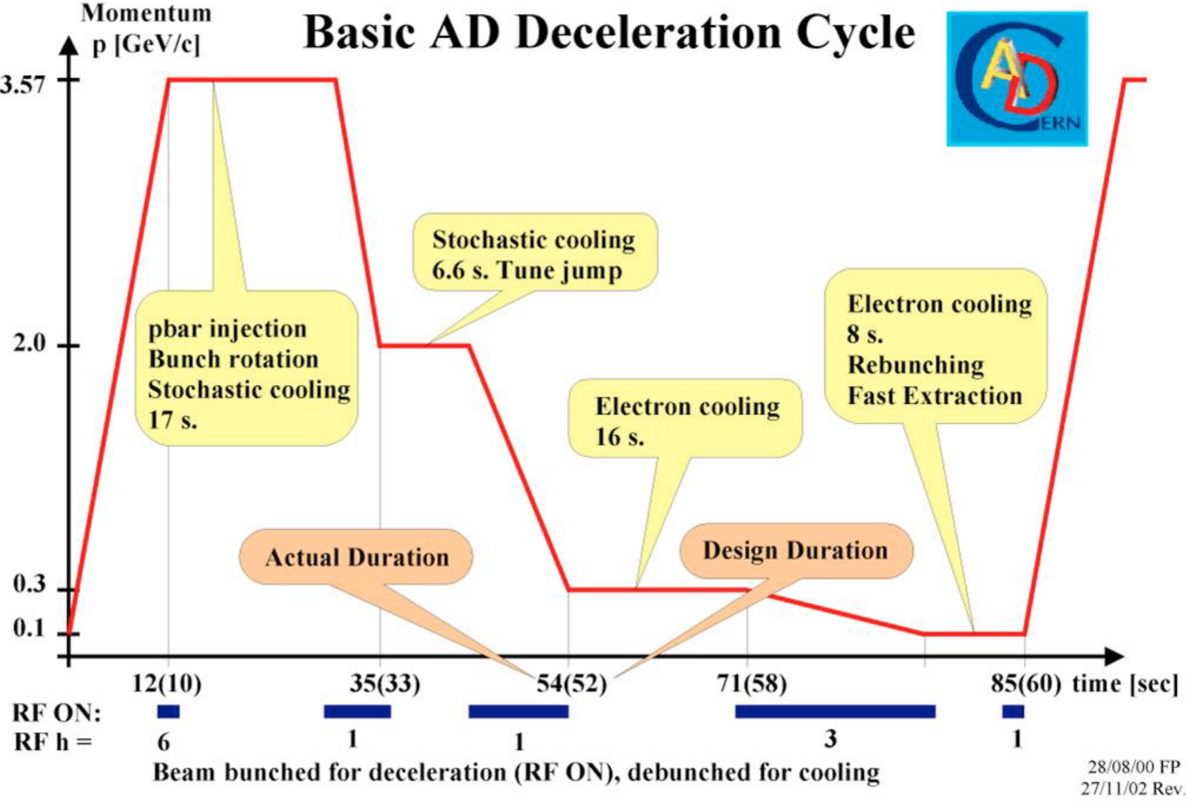
… or SPS Physics

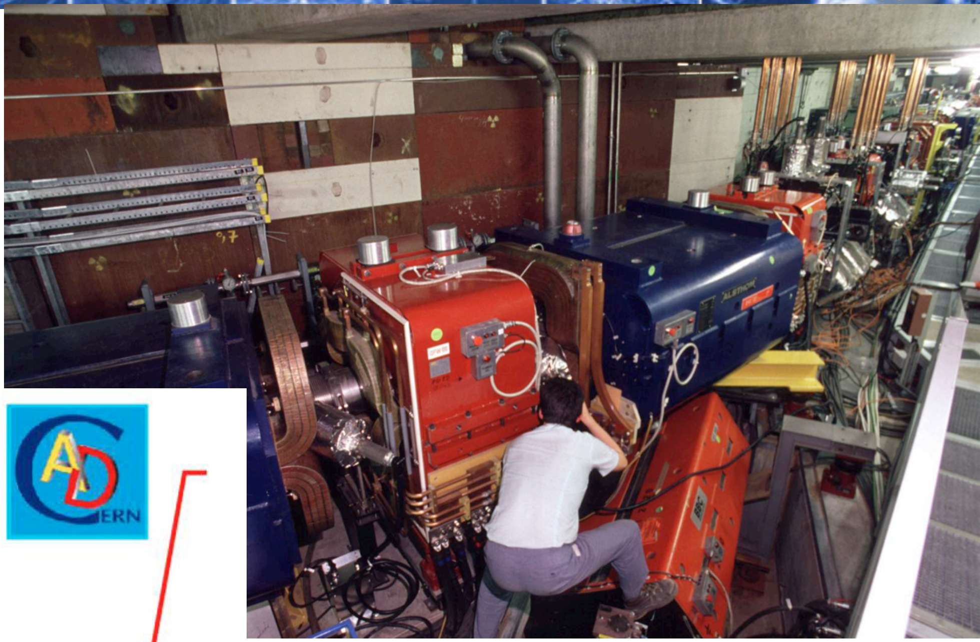
The Antiproton Chain

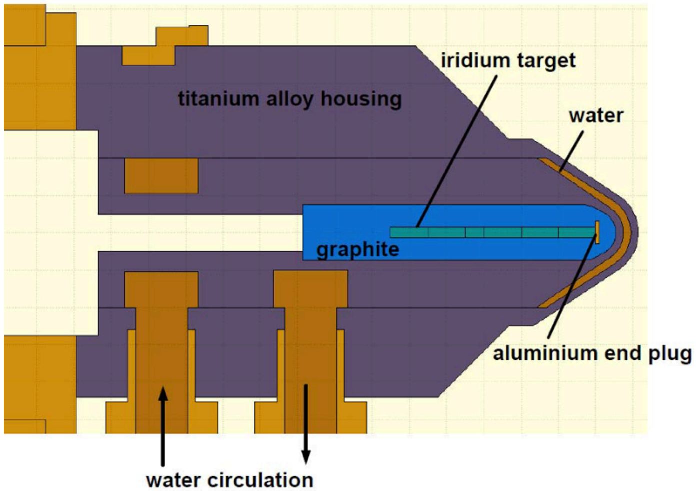
The Antiproton Chain : AD

Built in 1999 (from the old AC)

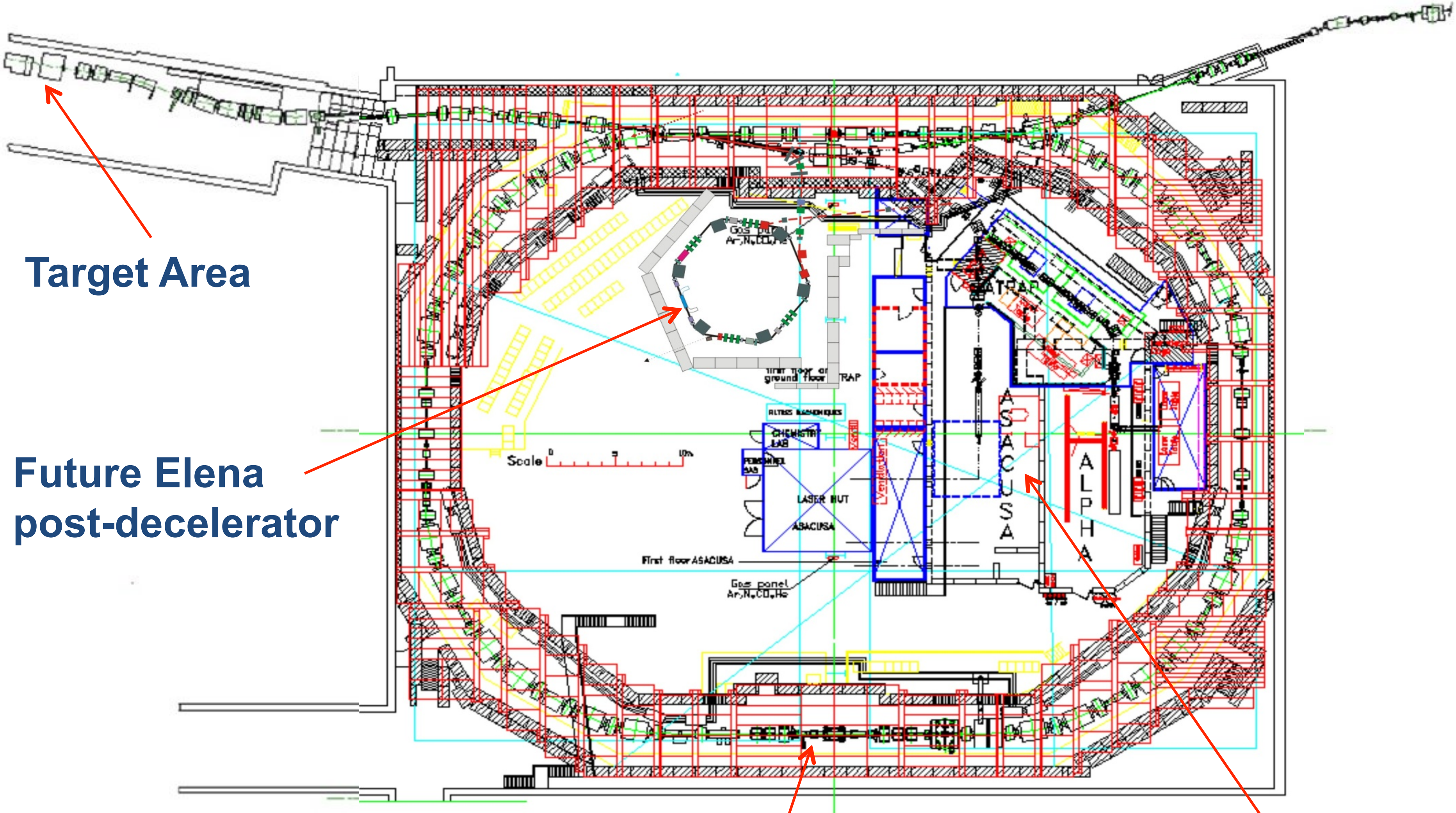
26GeV/c PS Proton beam produces p-bar (1 in 10^{-7}) which are focused and captured in the AD







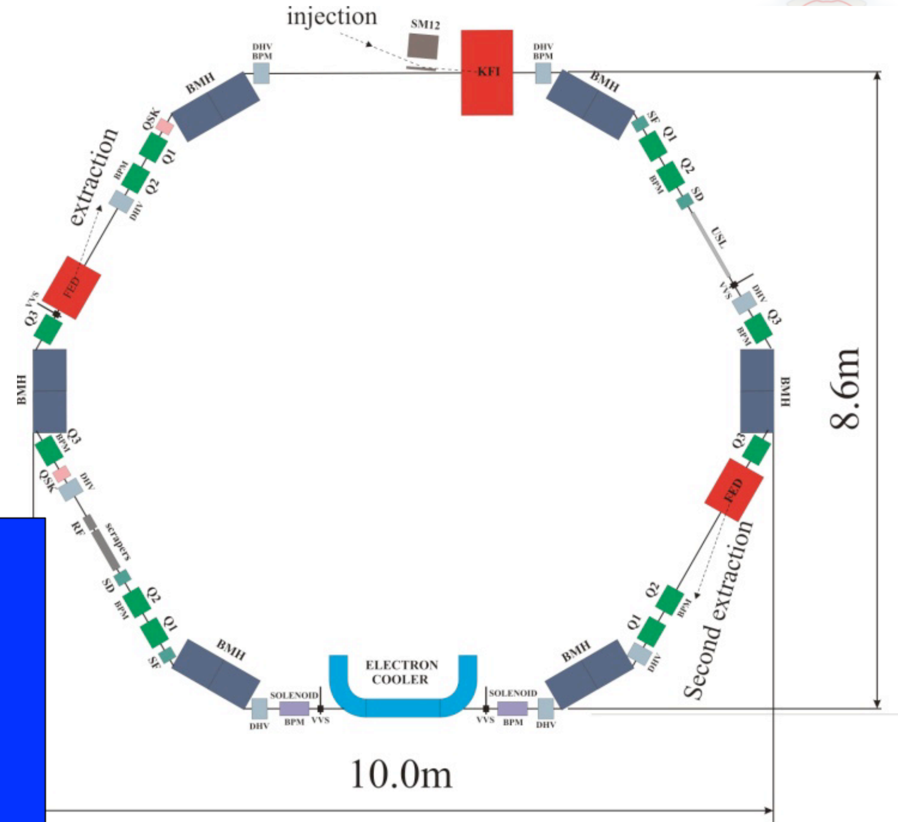
AD Layout


Target Area
Future Elena
post-decelerator
Electron Cooling
Experimental
Area
ATRAP
ASACUSA
ALPHA
Scale
LASER HUT
ASACUSA
First floor ASACUSA
Gas panel
Ar,N₂CO₂He
CHEMISTRY LAB

Elena … More Deceleration

Under Construction

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

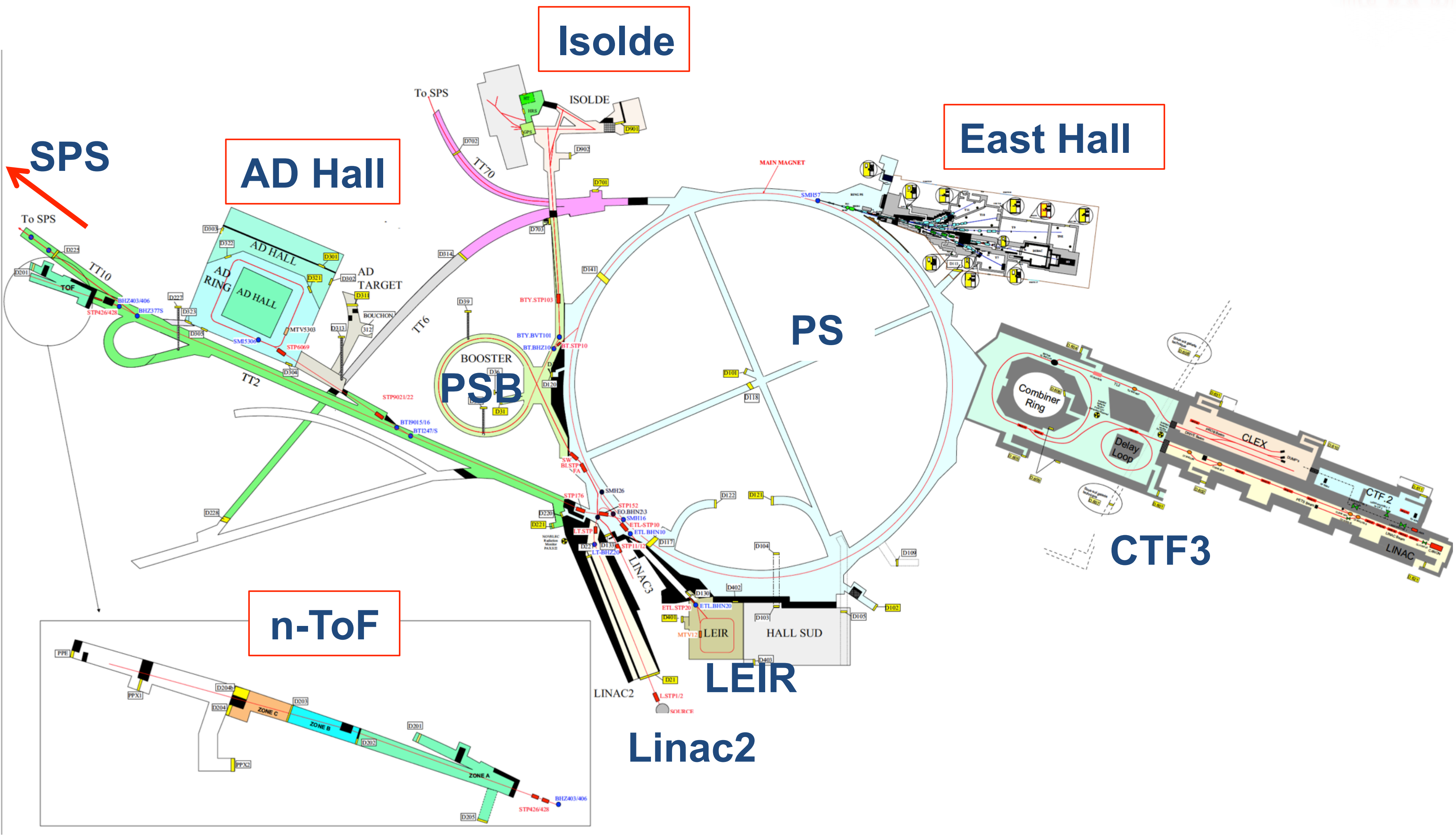


ELENA main parameters

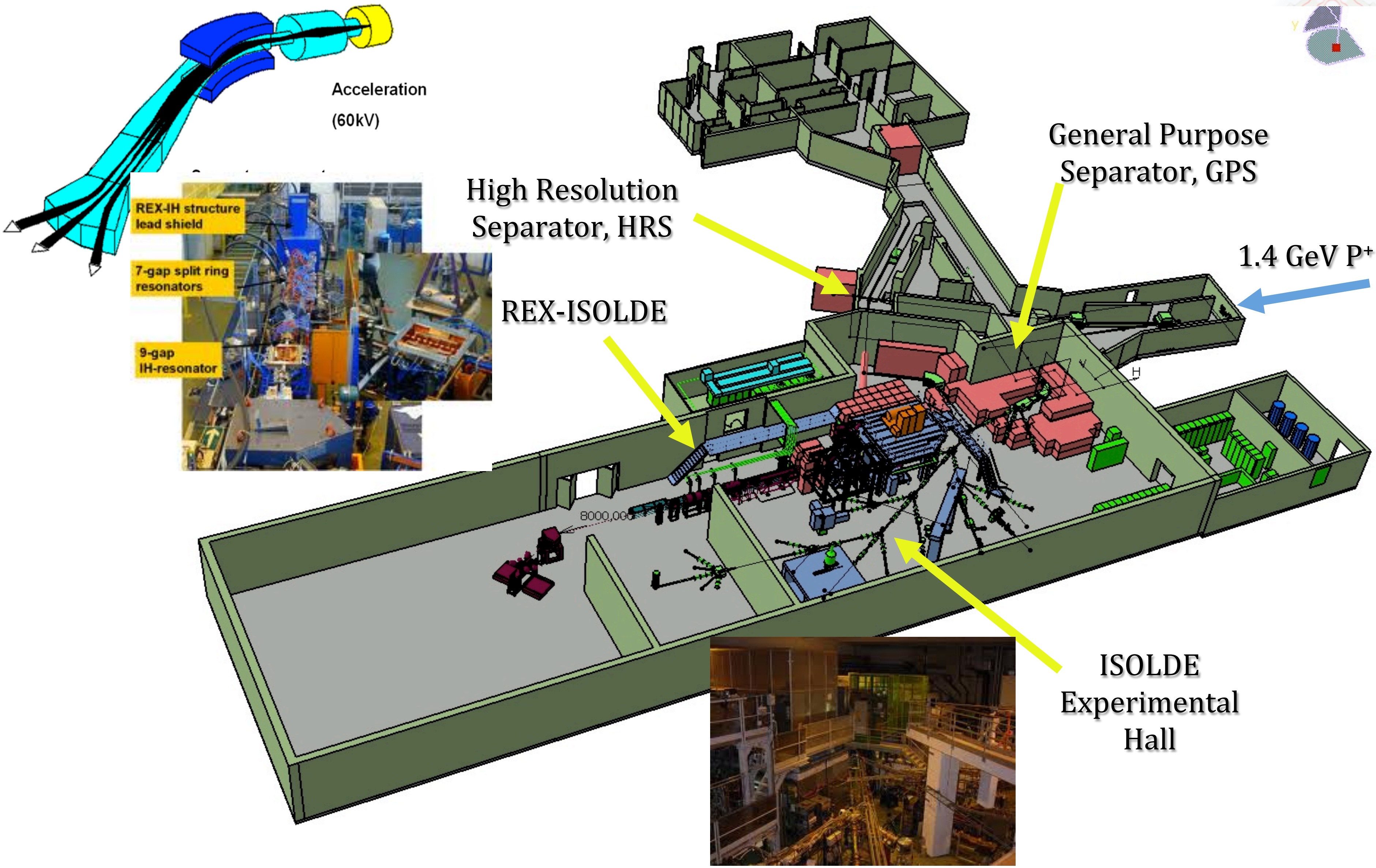
Momentum range, MeV/c	100 - 13.7
Energy range, MeV	5.3 - 0.1
Circumference, m	30.4
Intensity of injected beam	3×10^7
Intensity of ejected beam	2.5×10^7
Number of extracted bunches	4
Emittances (h/v) at 100 KeV, π·mm·mrad, [95%]	4 / 4
$\Delta p/p$ after cooling, [95%]	10^{-4}
Bunch length at 100 keV, m / ns	1.3 / 300
Required (dynamic) vacuum, Torr	3×10^{-12}

In operation 2017

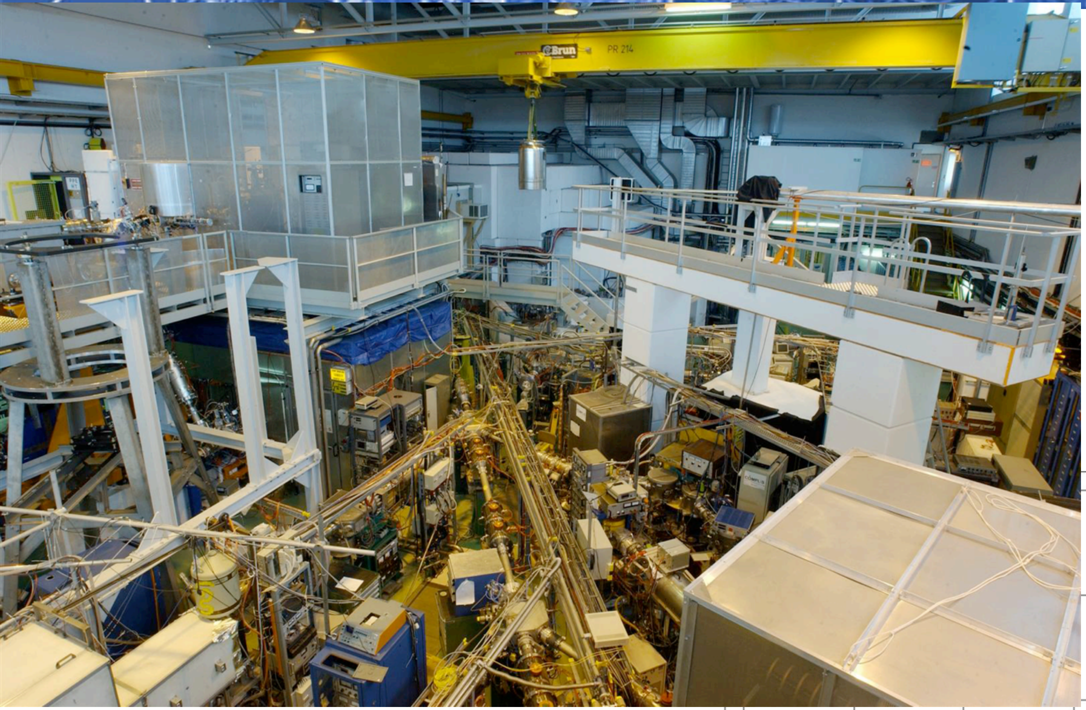
Experimental Areas Around the PS

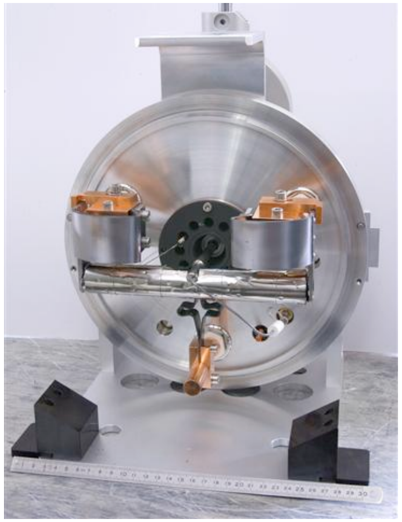


Isolde

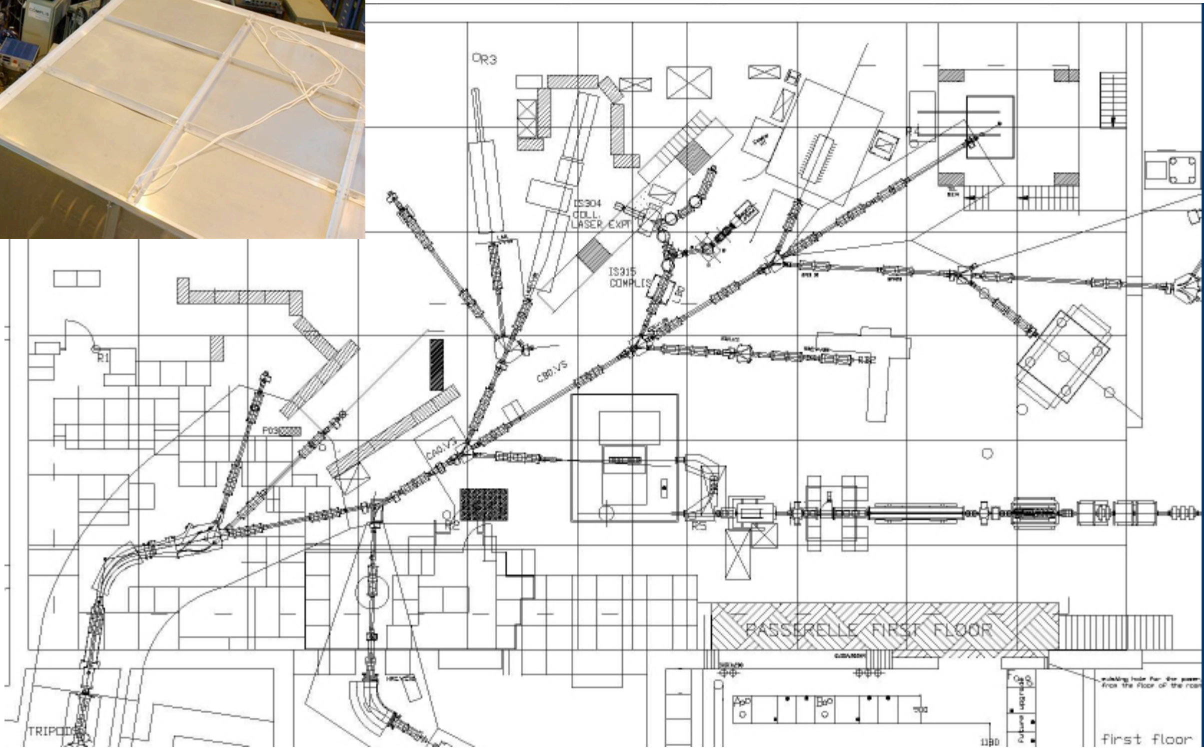

Acceleration
(60kV)
REX-IH structure lead shield
7-gap split ring resonators
9-gap IH-resonator
High Resolution Separator, HRS
General Purpose Separator, GPS
1.4 GeV P+
REX-ISOLDE
ISOLDE Experimental Hall

Isolde

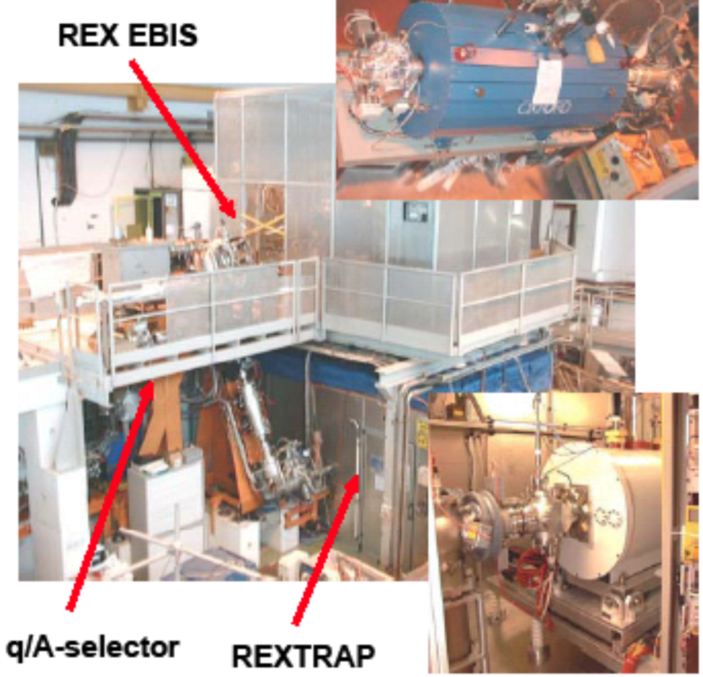




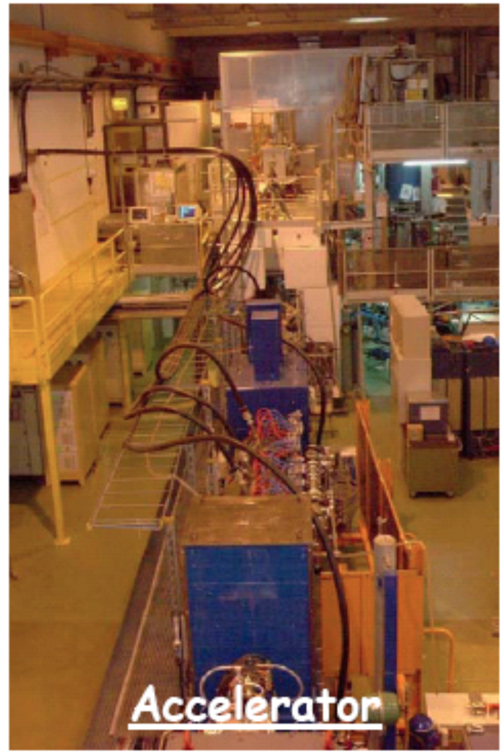
An Isolde Target



Rex-Isolde

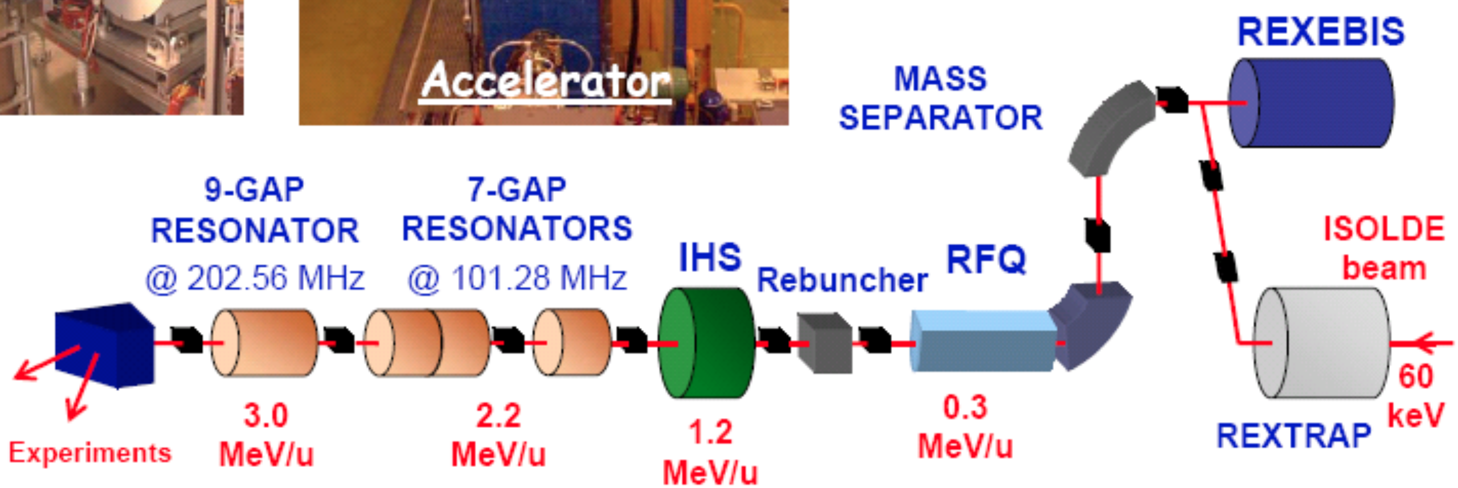


Charge Breeder



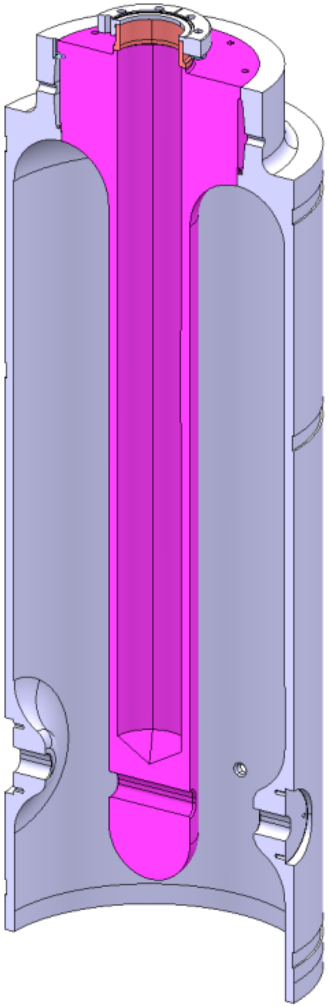
Efficiencies (design values):

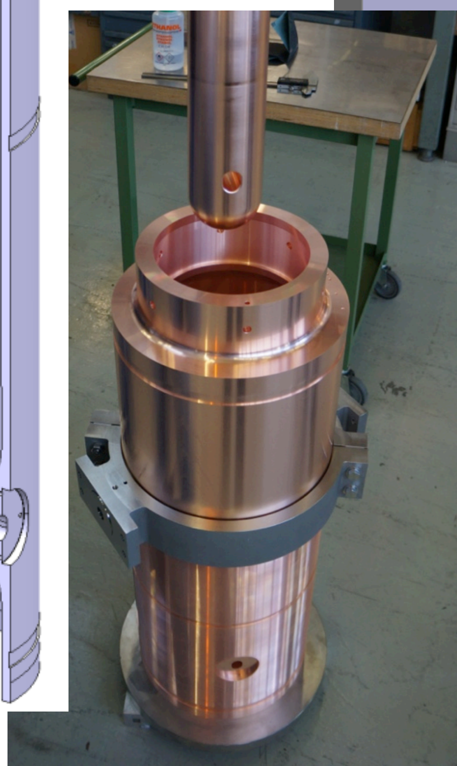
Trap Bunching:	90%
Beam Transport:	>85%
EBIS Injection:	>50%
EBIS Qi/ΣQi:	30%
Linac:	90%

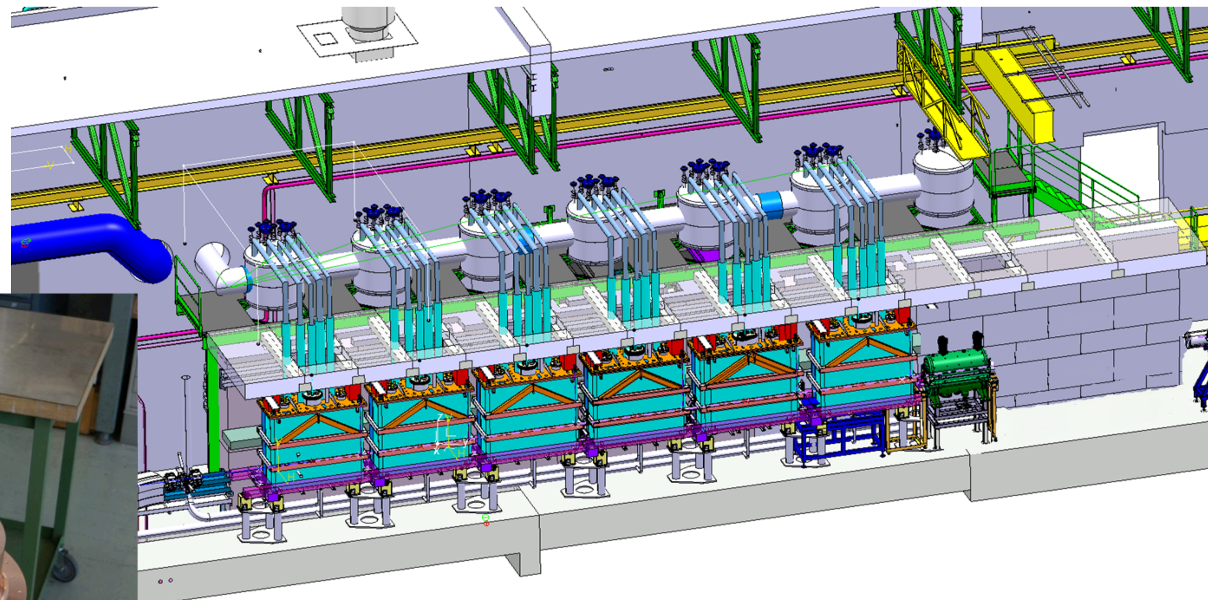


HIE-Isolde

New Post-Accelerator for the Isolde Facility
SC linac based on sputter-coated ¼-wave resonators

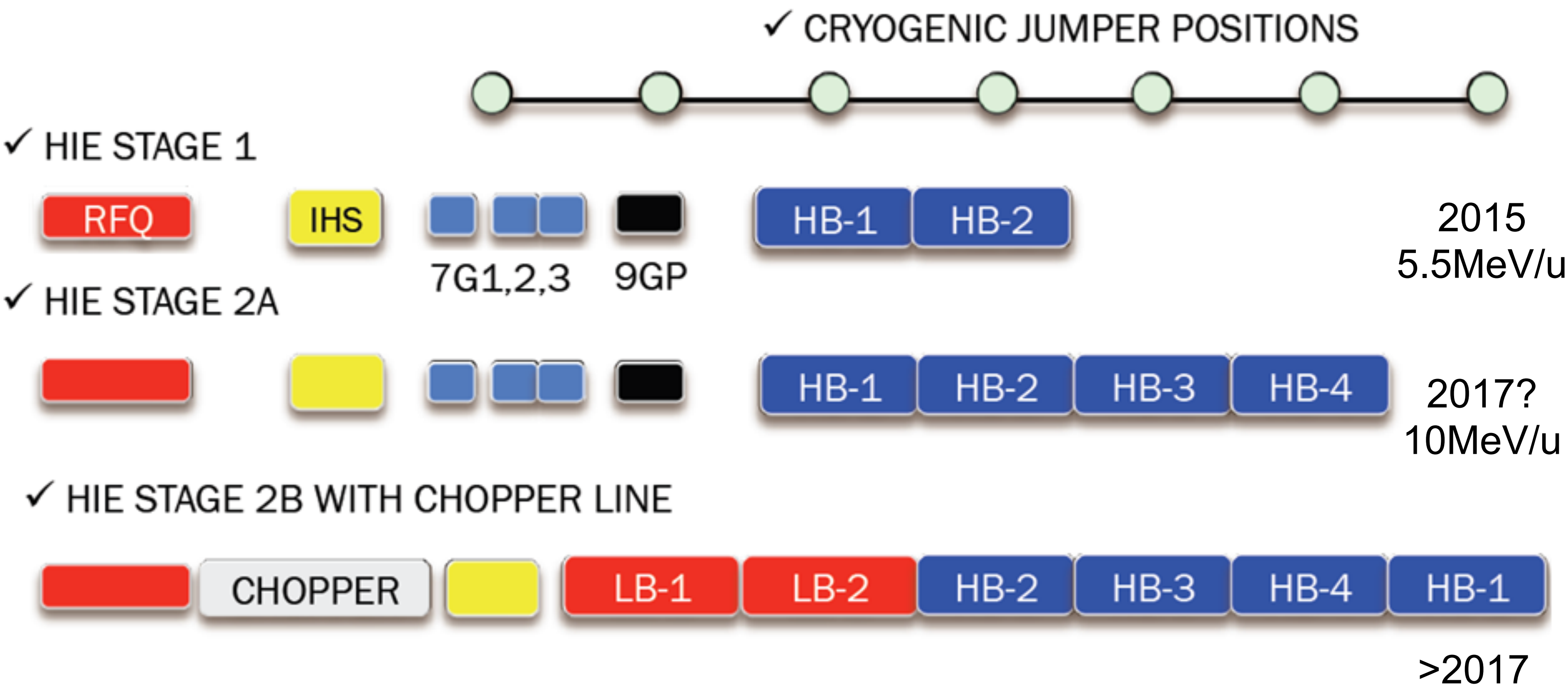






Frequency	101.28 MHz
Gradient	6 MV/m
Active length/cavity	30 cm
Number of Cavities	20 (10MeV/u)

HIE-Isolde Staging

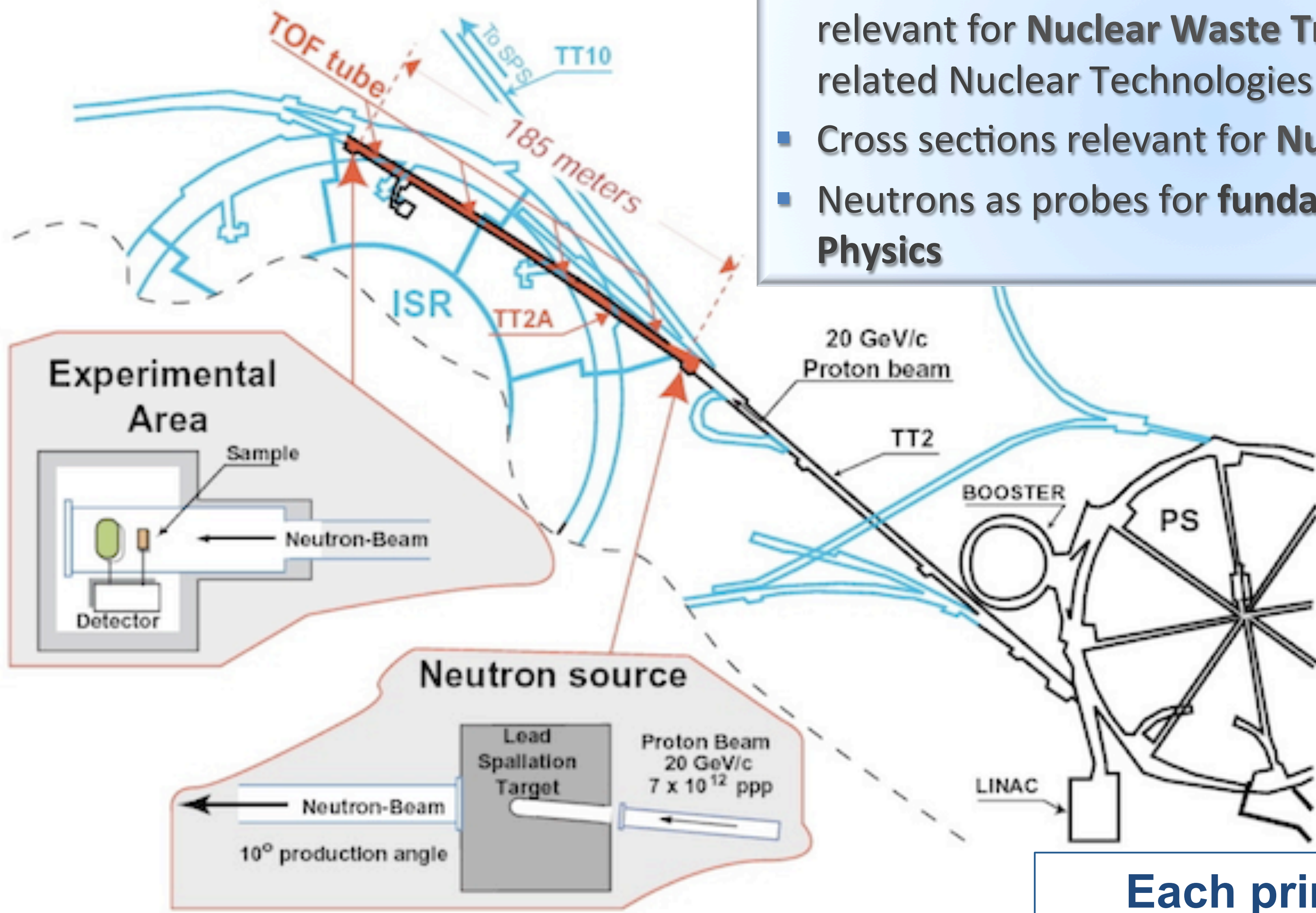


Construction & installation for Phase1 in full swing

Funding for following stages not fully secured (yet)

n-ToF

- Measurements of **neutron cross sections** relevant for **Nuclear Waste Transmutation** and related Nuclear Technologies
- Cross sections relevant for **Nuclear Astrophysics**
- Neutrons as probes for **fundamental Nuclear Physics**

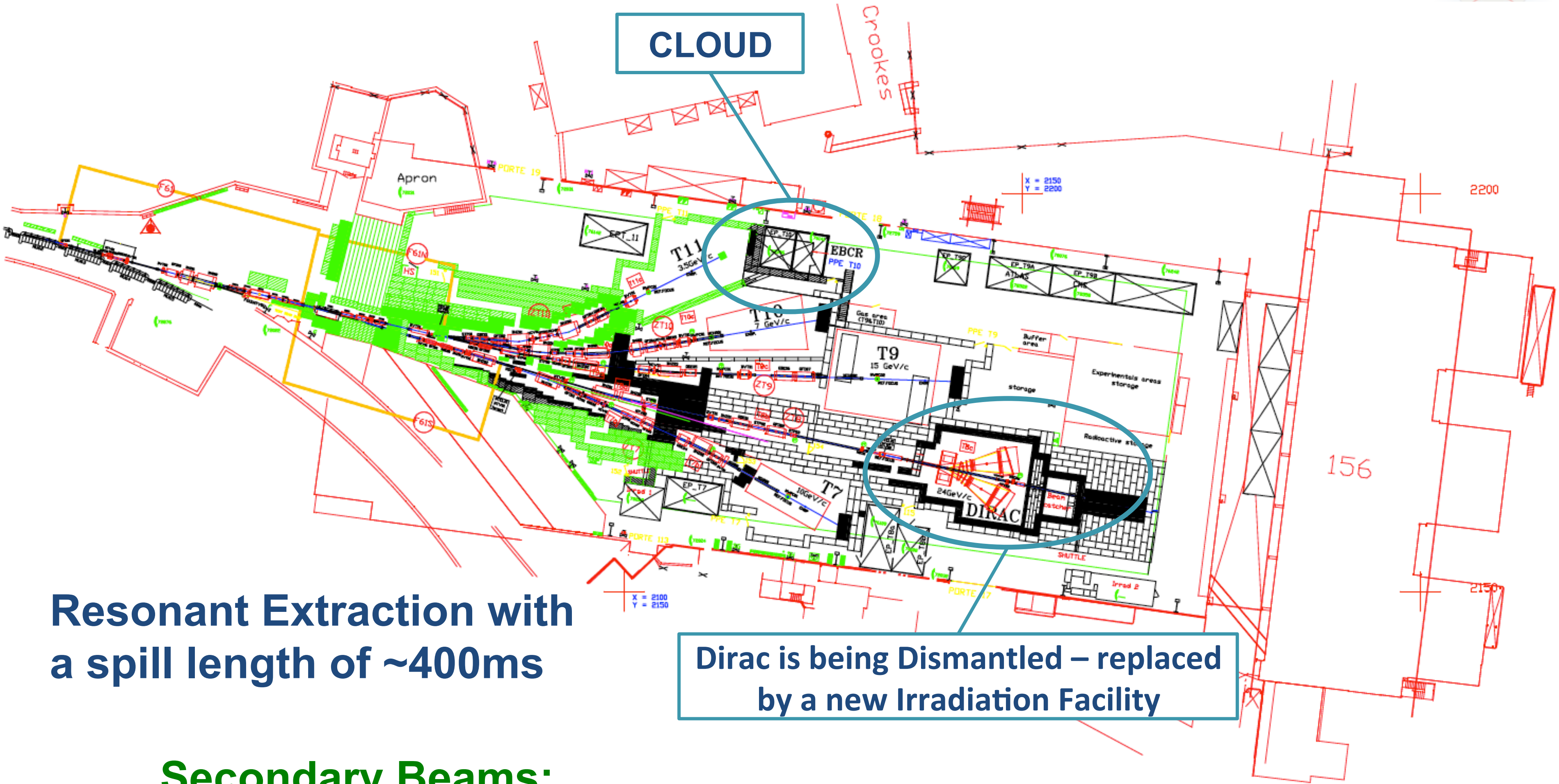


A second Experimental area vertically above the target is presently under construction

Neutron Spectrum in the meV - GeV range

Each primary proton produces ~300 neutrons

The East Hall



Resonant Extraction with a spill length of ~400ms

Secondary Beams:

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

AD Hall

Experiments:

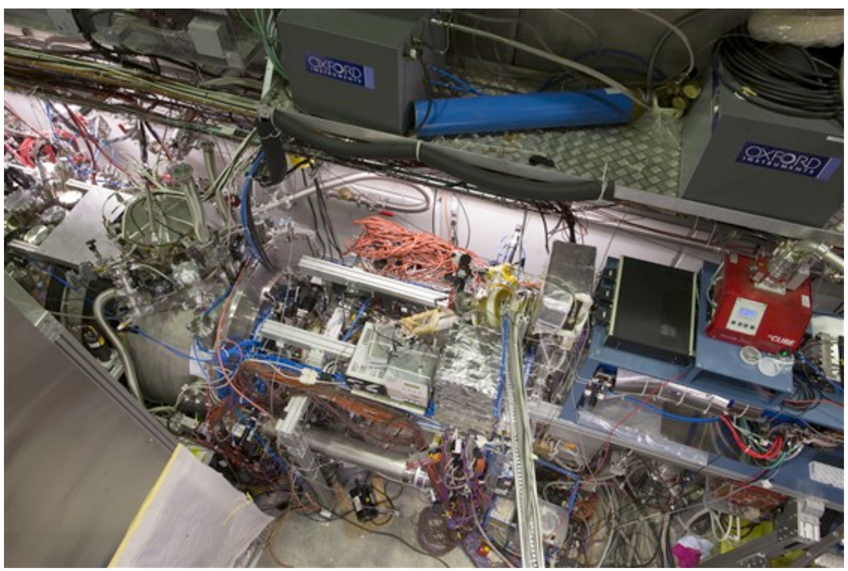
(ACE)	: completed
AEGIS	
ALPHA	
ASACUSA	
ATRAP	
Base	: Under Construction
Gbar	: Under construction

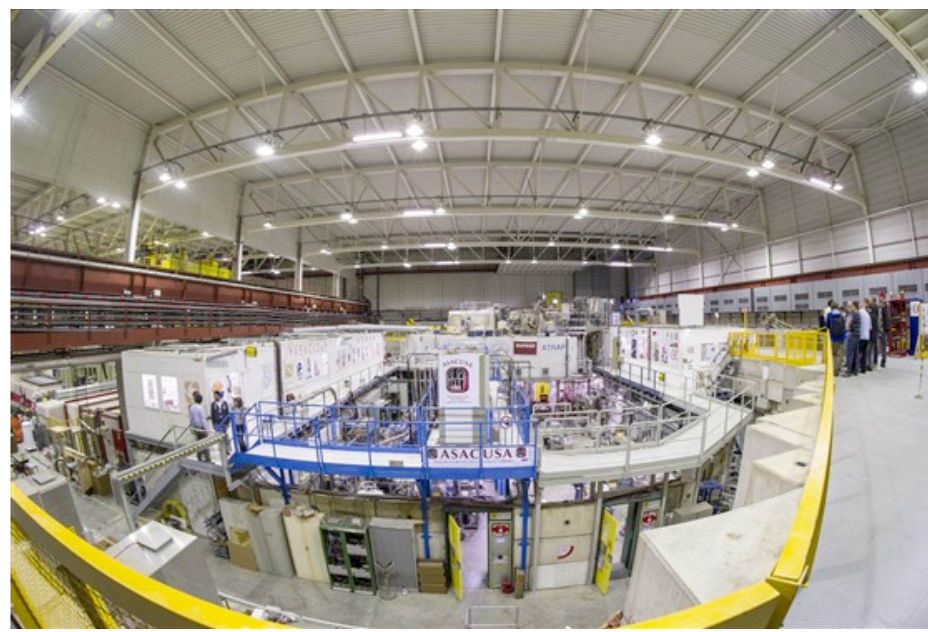
Anti-Hydrogen Capture:

- Spectroscopy
- Magnetic moment etc.

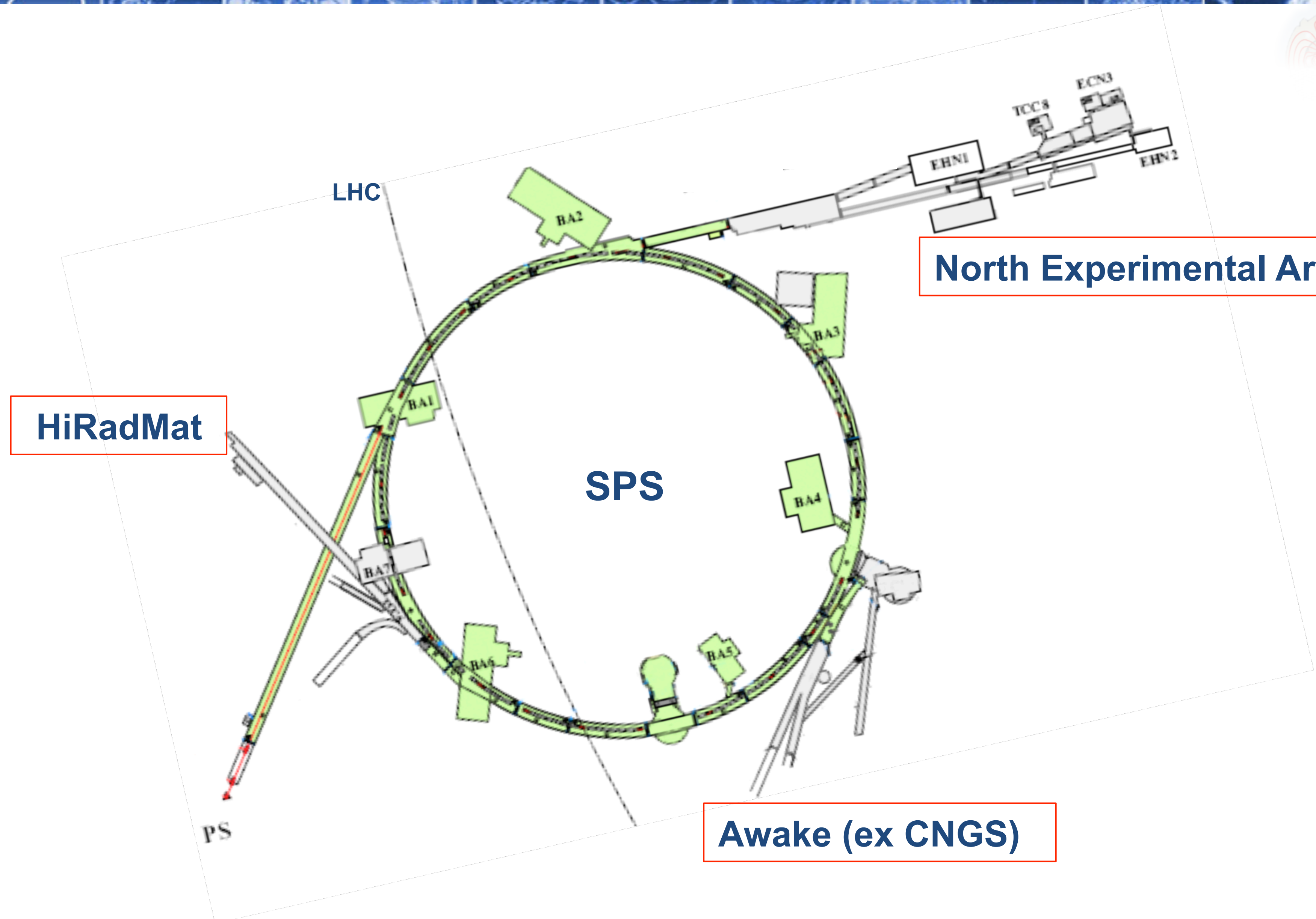
Gravity and anti-matter

Medical Applications





Facilities Around the SPS



Prevessin & The North Area

7 beam lines

Total length (secondary beam lines) 5.8 km

3 Experimental halls

~2000 scientists/year

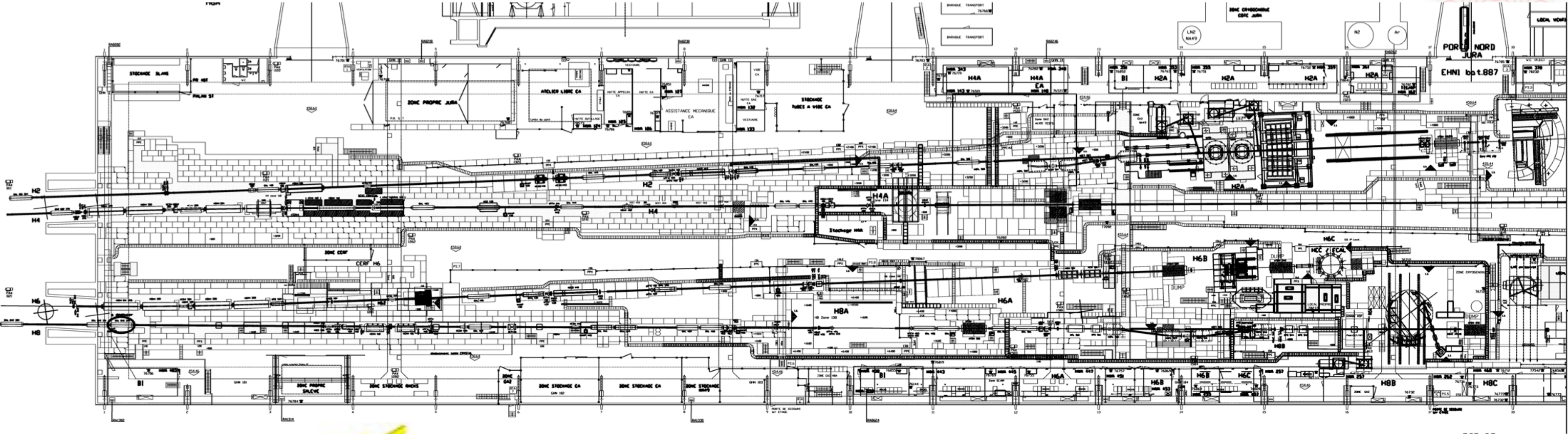
Slow Extracted beam over several seconds

3 Primary Targets

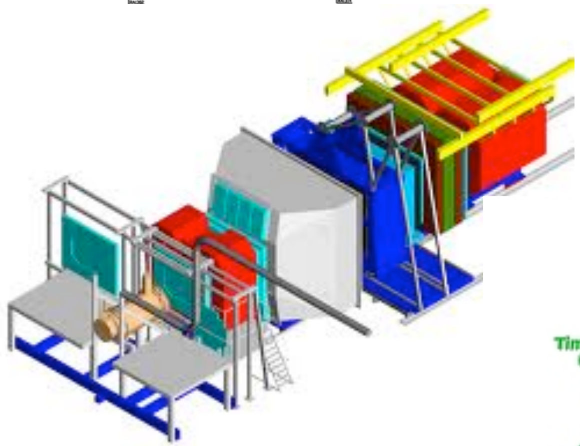
Also Ion Physics Program

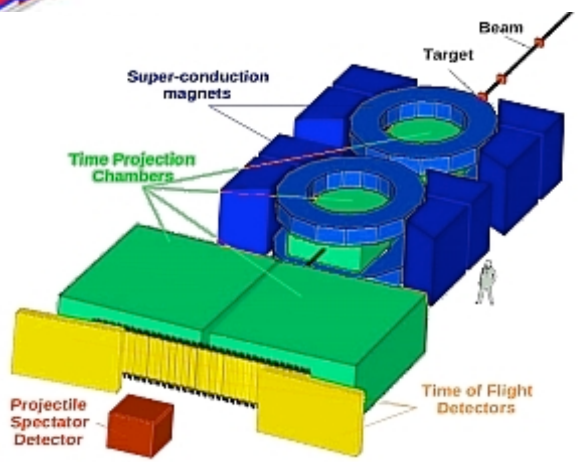
- Be (Fragmented)
- Argon
- Xenon

North Experimental Area



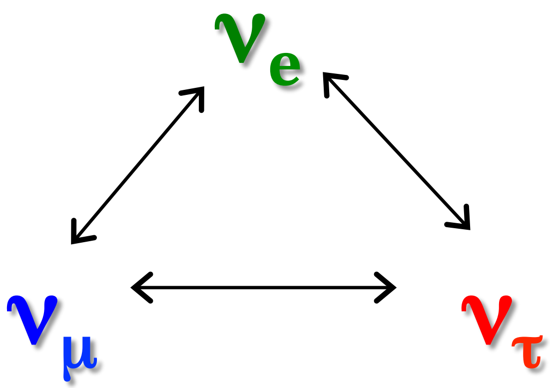
Compass





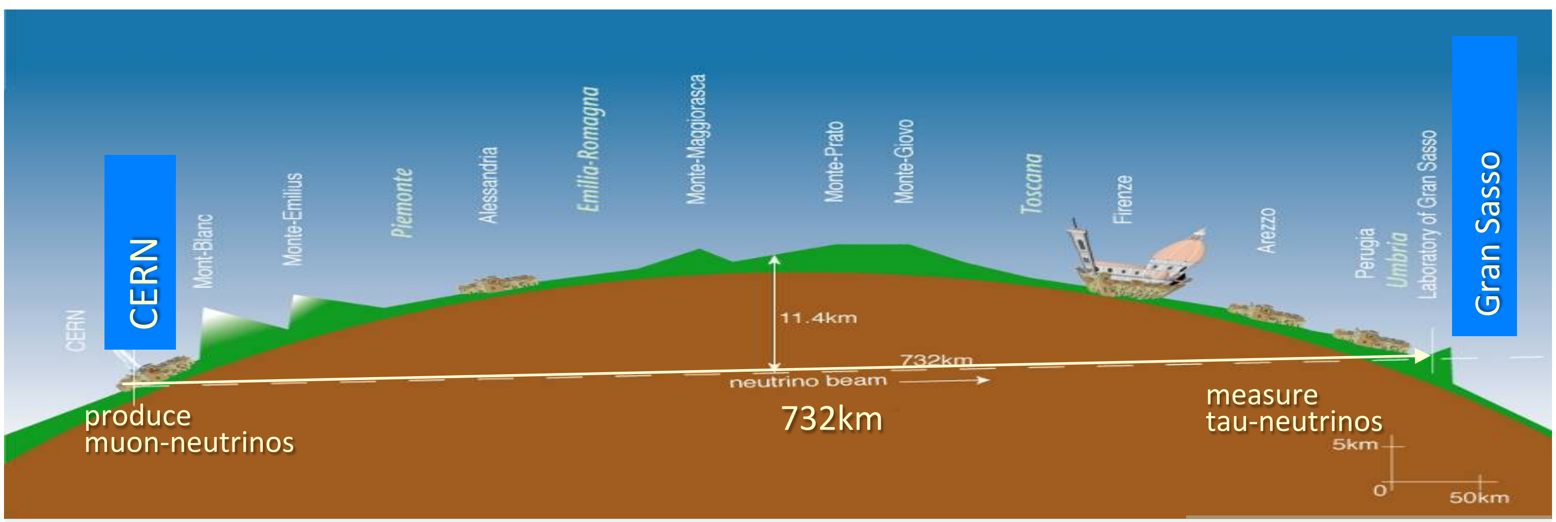
NA61 Shine

CNGS (2008-2012)



Neutrino Oscillation of ν_μ to ν_τ:

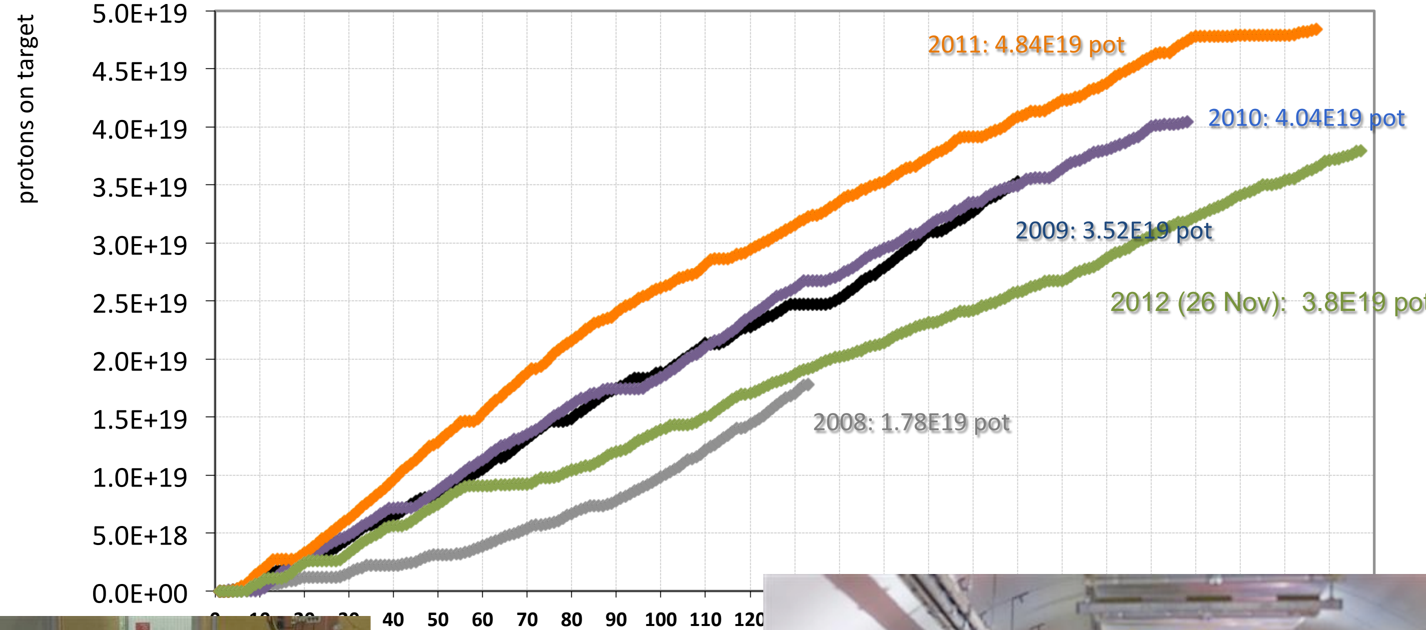
- Up to now: only measured by **disappearance** of muon neutrinos
- CNGS: **appearance experiment**

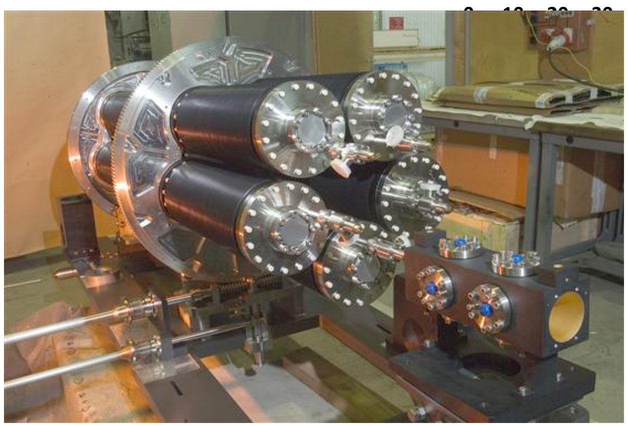


$\sim 4 \cdot 10^{19}$ p/year | $\sim 2 \cdot 10^{19}$ ν_μ/year | ~ 2 ν_τ/year

CNGS Infrastructure

CNGS approved for 22.5E19 protons on target
Ended in 2012 after 5 years of physics run: 81% of approved protons on target





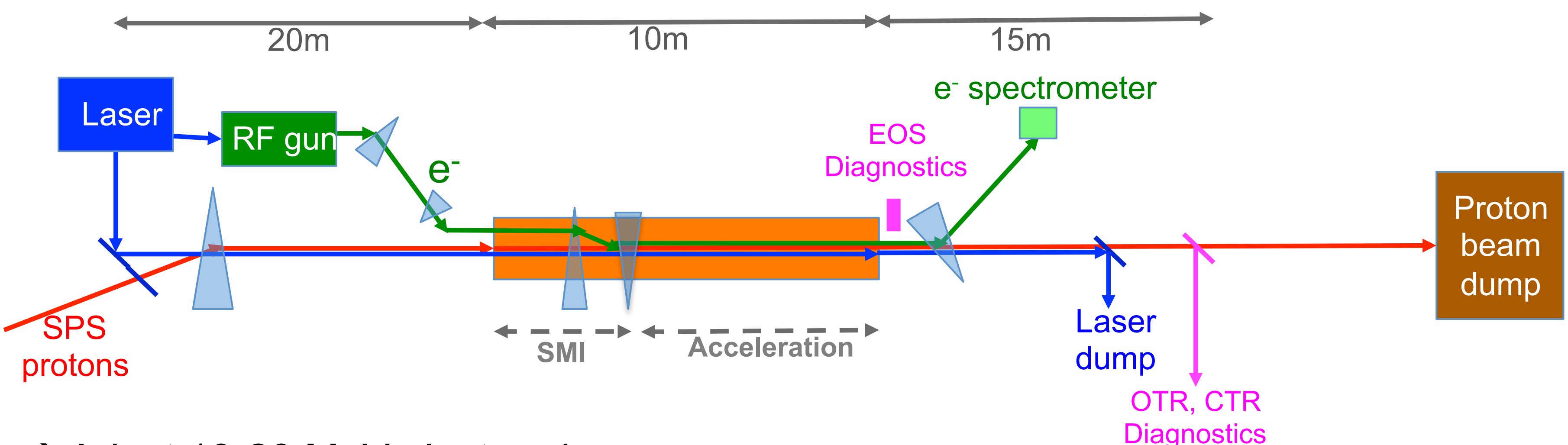
CNGS Underground Structures

Re-use for AWAKE

AWAKE – A Proton Driven Plasma Wakefield Acceleration Experiment at CERN

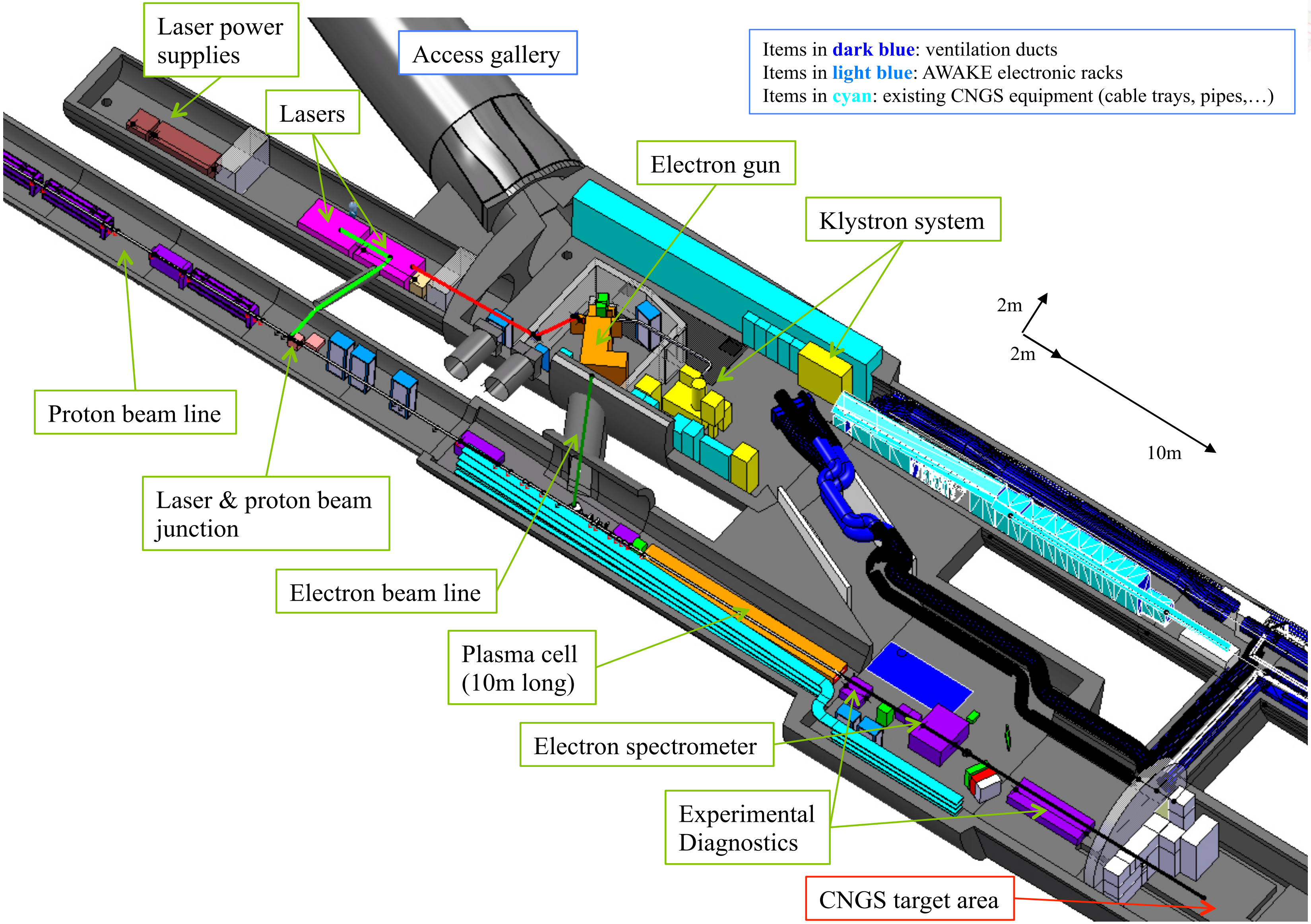
- Proof-of-principle demonstration experiment proposed at CERN
  → first proton driven PWA experiment world-wide.

- Advantages of using protons as driver: single stage acceleration
  - Higher stored energy available in the driver (~kJ)
  - Electron/laser driven requires many stages to reach the TeV scale.



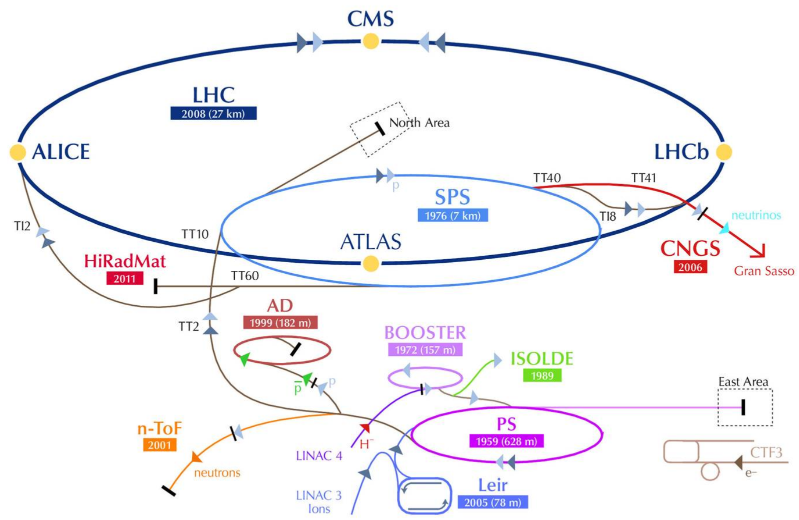
→ Inject 10-20 MeV electron beam
→ acceleration of electrons to **multi-GeV energy range** in the wakefield driven by protons.

AWAKE at CNGS



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.

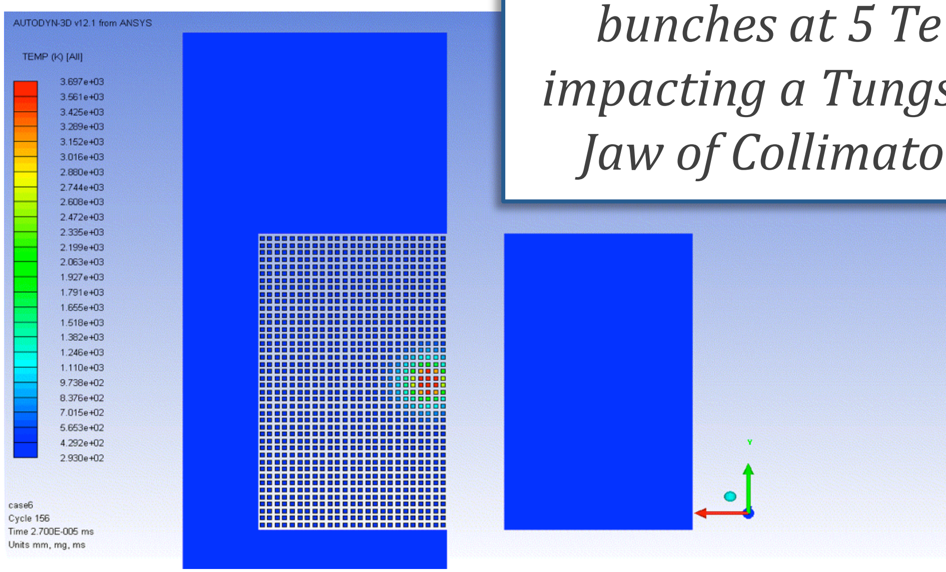


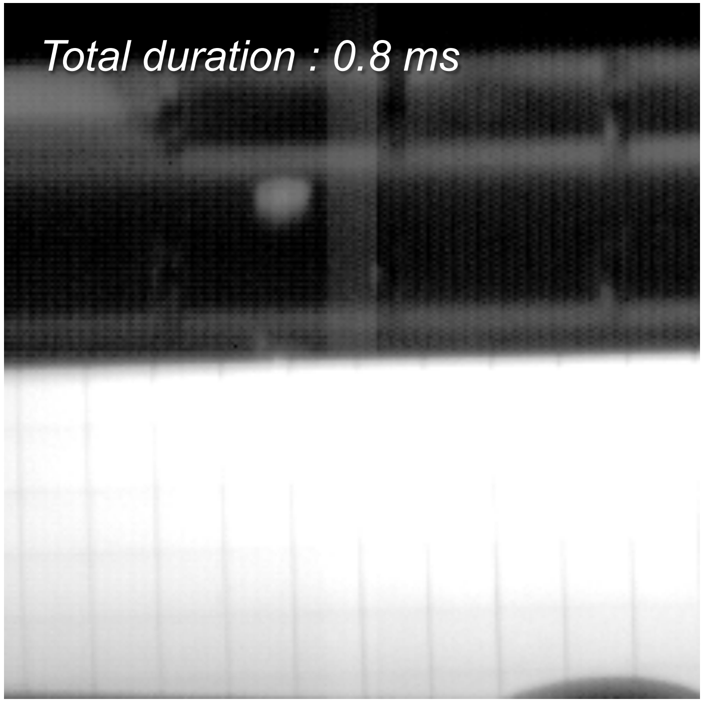
Built for the LHC Upgrades (especially collimation system)
Makes use of the Infrastructure of a previous Neutrino facility

HiRadMat

- To test materials for under the extreme conditions they may encounter in case of accidental beam impacts.
- To characterize novel materials currently under development for Phase II Collimators.
- To benchmark advanced numerical simulations.

Simulation of 8 LHC bunches at 5 TeV impacting a Tungsten Jaw of Collimators



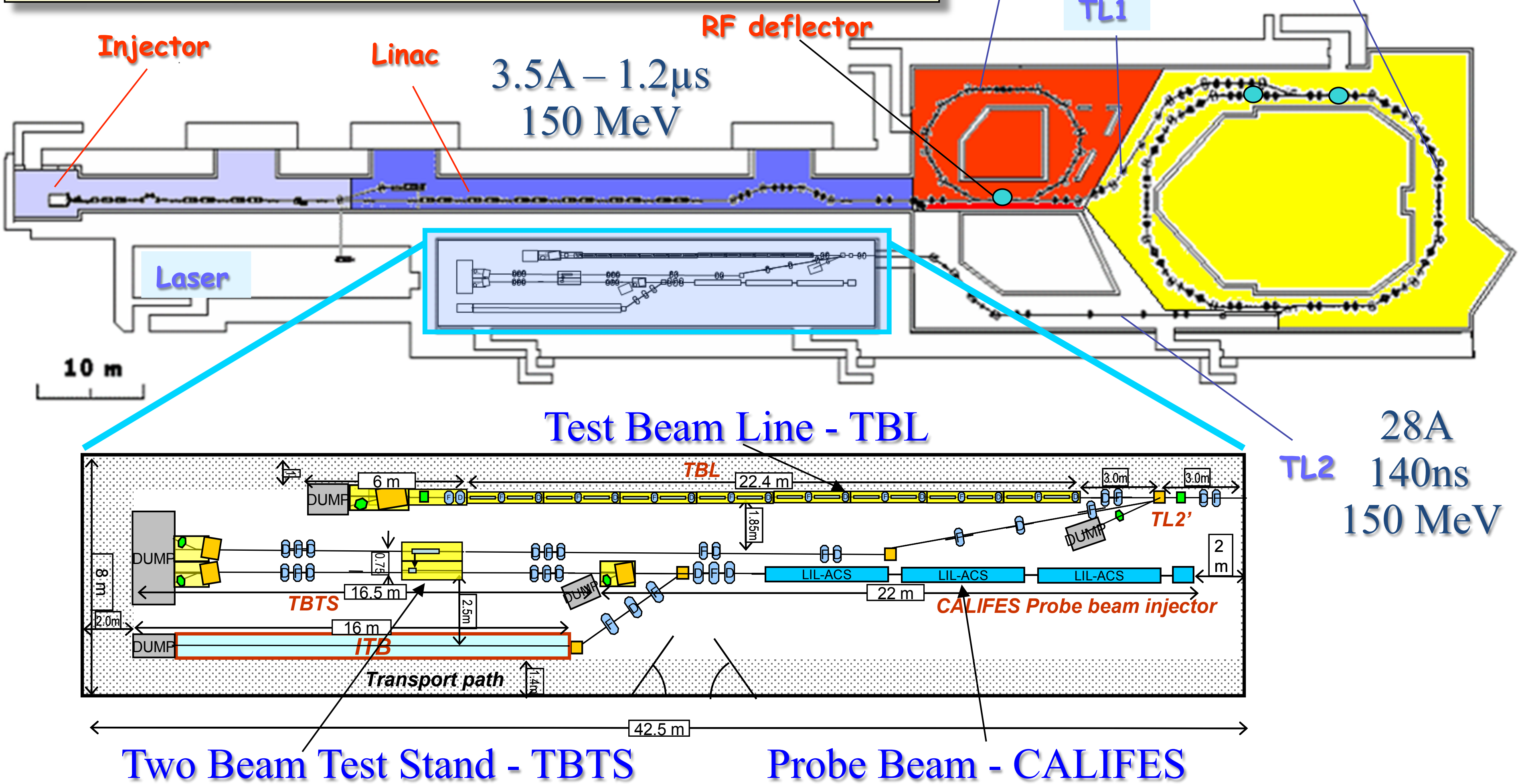


CTF 3 – CLIC Test Facility

- demonstrate CLIC RF power source Drive Beam generation (fully loaded acceleration, bunch frequency multiplication 8x)
- Test CLIC accelerating structures
- Test power production structures (PETS)

Delay Loop 42m

Combiner Ring – 84m



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!

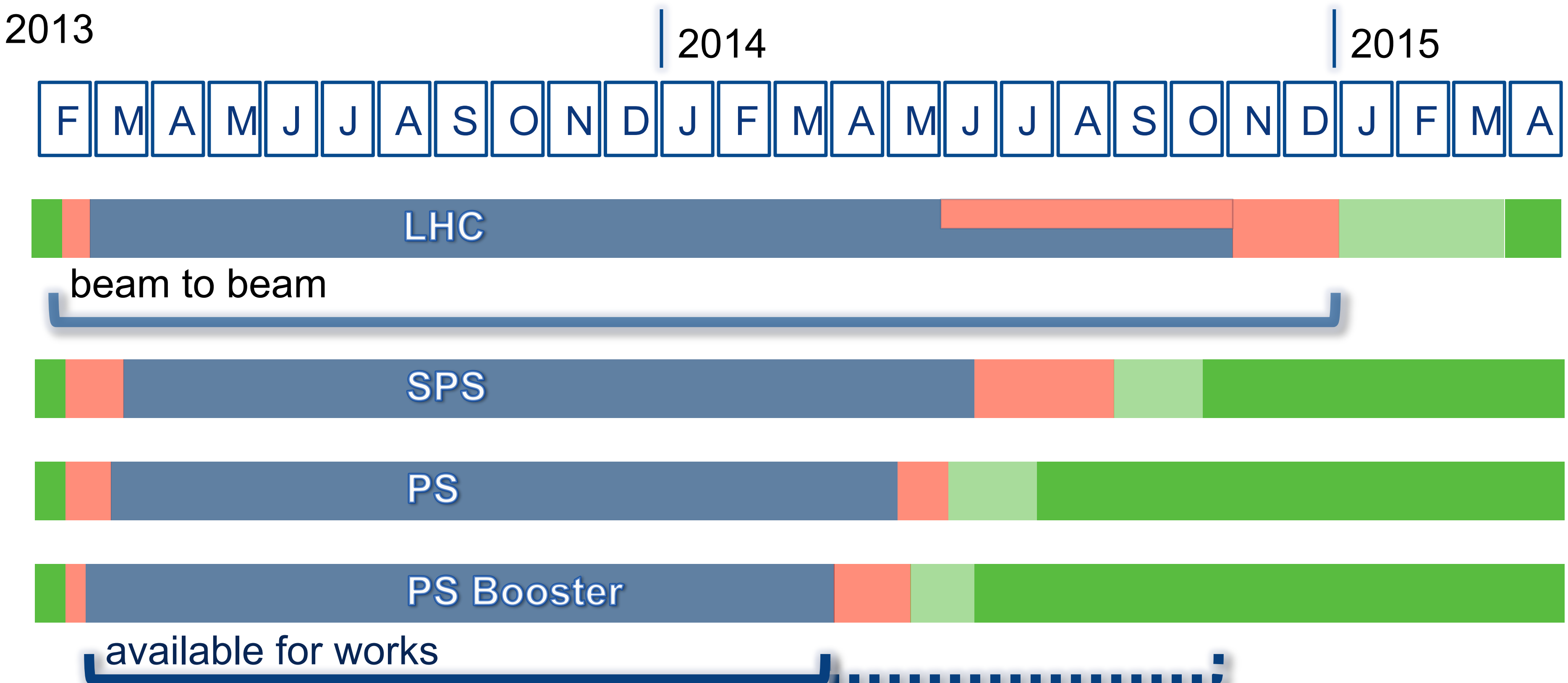
- **Intensities as delivered to the facility, upstream losses ignored,**
- **Beams for Machine Setup and Studies Excluded**
- **The total delivered protons represents roughly 0.27mg (rest mass!)**

Long Shutdown 1

- Physics
- Beam commissioning
- Shutdown
- Tests

LS1

from mid February 2013 to end December 2014



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