Proton Facilities at CERN With some brainstorming

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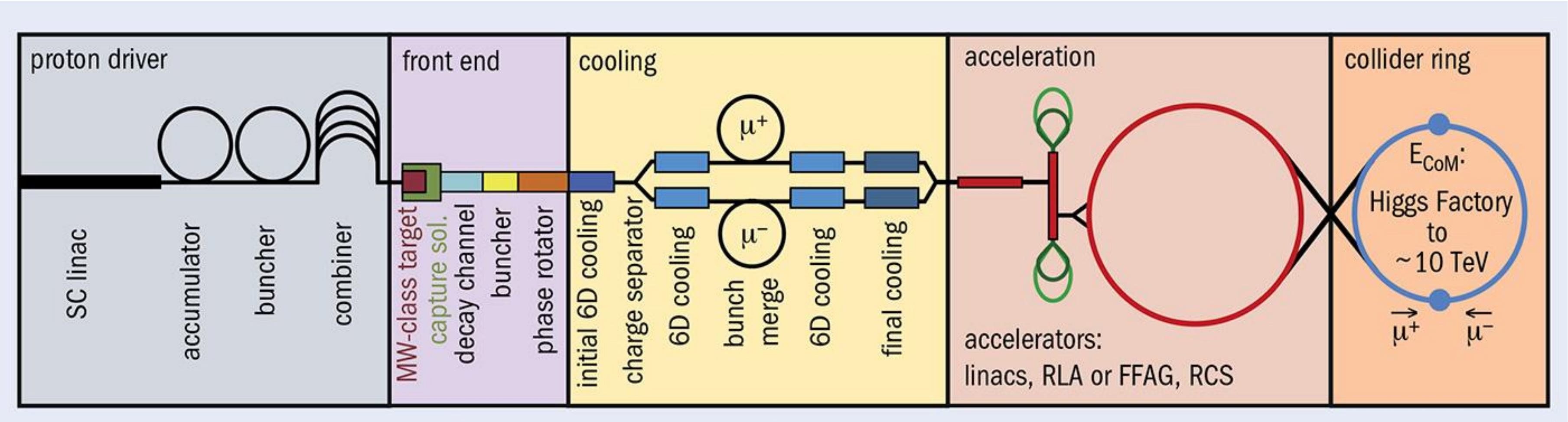
March 2021

What could be tested? Why? Where?

Proton driver
- Single beam impact
- Material damage
- Obs: Linac4 is running

Cooling
- Material testing
- *6D cooling*



Target station – including dump
- Material choices for p production
- Pion production
- Single beam impact
- Material damage

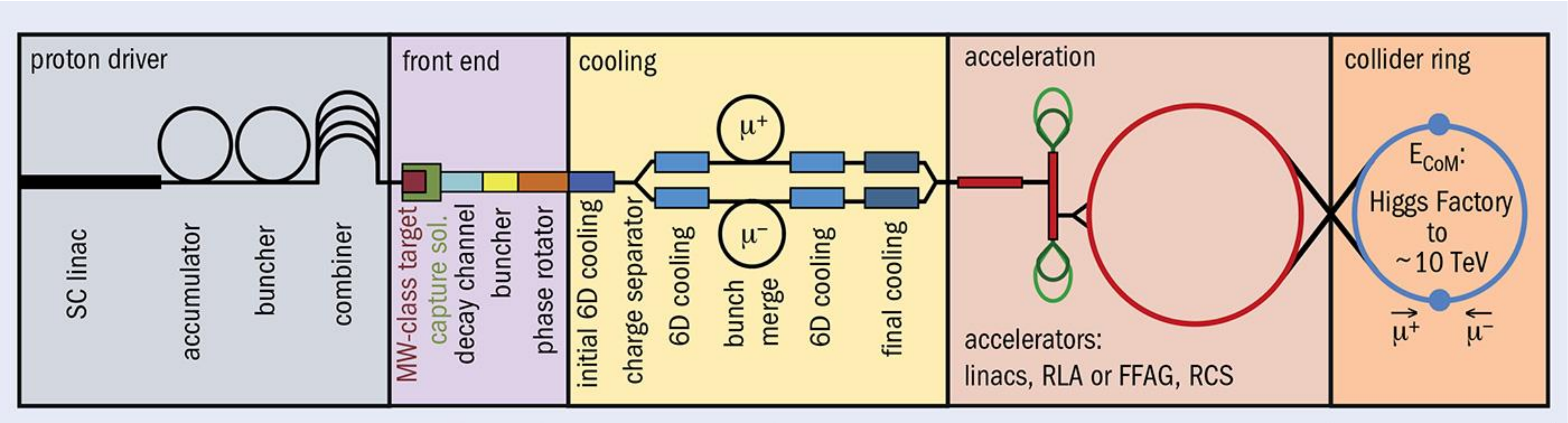
Acceleration
- Material testing (damage)
- Acceleration techniques
- Recombination

Lemma discussed yesterday

What could be tested? Why? Where?

Proton driver
- Protons
- Few GeV

Cooling
- Muons
- *Few hundreds MeV/GeV*

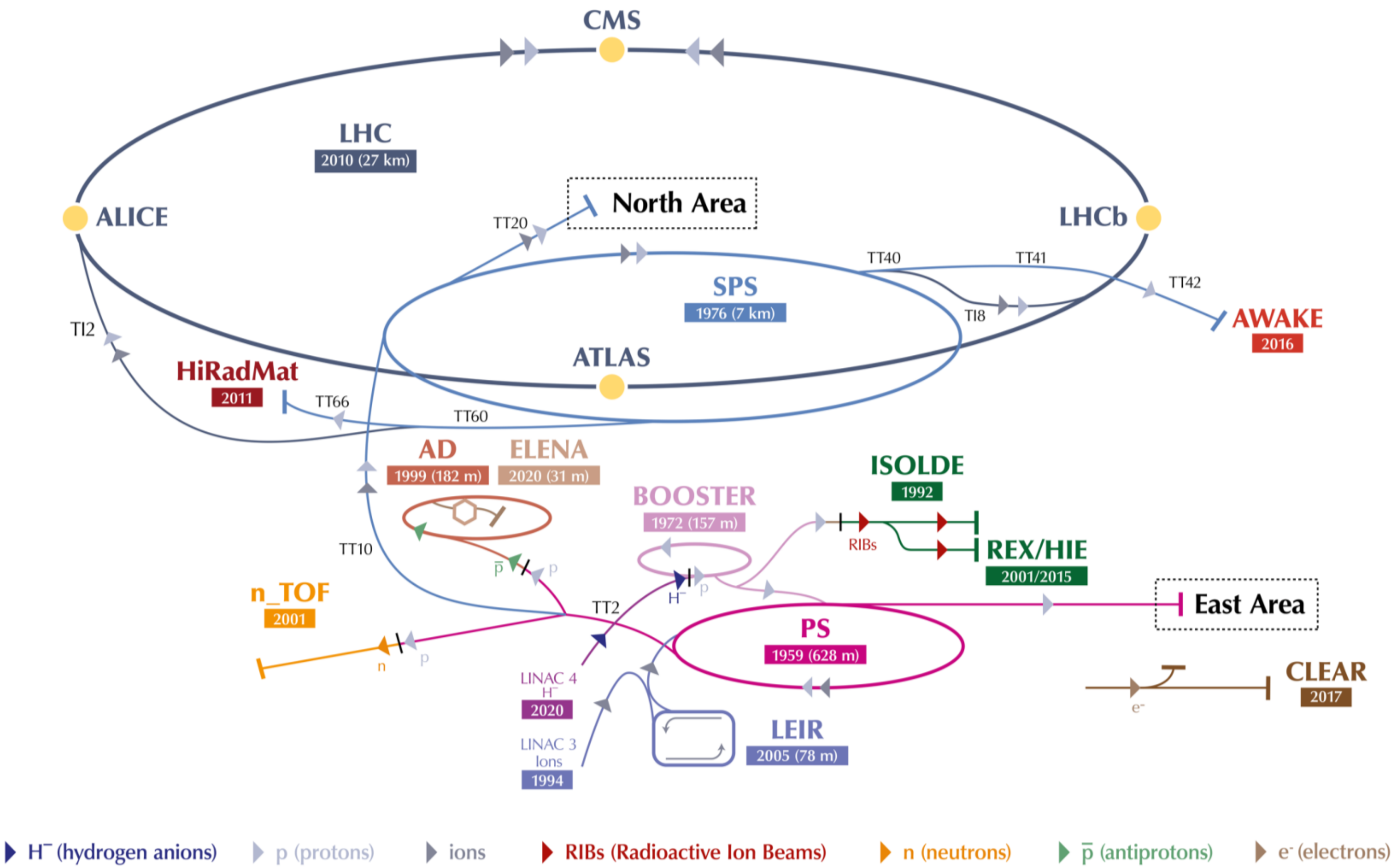


Target station – including dump
- Protons and mixed field
- Few GeV protons
- Few hundreds MeV mixed field

Acceleration and SR
- Muons at some GeV
- Muons at some TeV

Lemma discussed yesterday

CERN accelerator complex as now



Different test zones

Existing test/experimental areas – already available for beam tests
- PS-EAST area
- SPS-North Area
- Hiradmat
- Charm

Possible test areas – will be available soon or requires modifications
- ISOLDE - ISIS
- n_TOF - Near
- Beam dump locations (Linac4, PSB, ISOLDE, PS, LHC(?))

Green field solution
- New test areas
- New machines to test

Synergies with other projects
- FCC
- PBC
- ISOLDE renovation

Questions: single particles, bunched beam, single impact, irradiations?

LINAC4 - layout

- Intermediate energies are not accessible however something learned from installed equipment
- **Chopper dump designed for SPL-like operation**

- Some investigation to use 3 MeV test stand for material testing

Linac 4

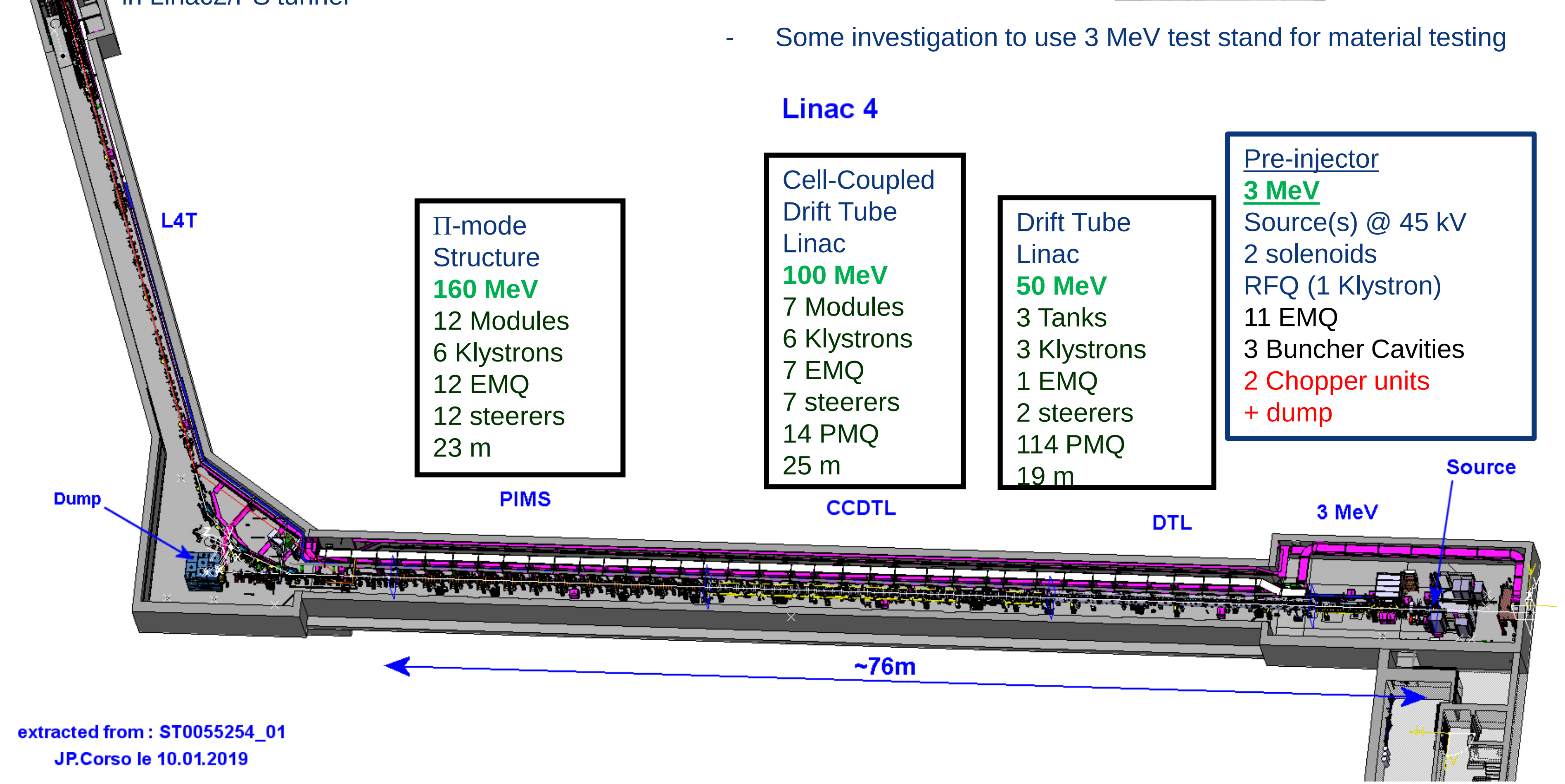
Vertical step to connect to LT, LTB and BI lines in Linac2/PS tunnel

Π-mode Structure
160 MeV
12 Modules
6 Klystrons
12 EMQ
12 steerers
23 m

Cell-Coupled Drift Tube Linac
100 MeV
7 Modules
6 Klystrons
7 EMQ
7 steerers
14 PMQ
25 m

Drift Tube Linac
50 MeV
3 Tanks
3 Klystrons
1 EMQ
2 steerers
114 PMQ
19 m

Pre-injector
3 MeV
Source(s) @ 45 kV
2 solenoids
RFQ (1 Klystron)
11 EMQ
3 Buncher Cavities
2 Chopper units
+ dump



extracted from : ST0055254_01
JP.Corso le 10.01.2019

Linac4 Parameters – For reference

	CDR Design Parameters	Goal Post-LS2 Parameters
Ion Species	H^-	H^-
Output Energy	160 MeV	160 MeV
Bunch Frequency	352.2 MHz (LEP!)	
Max. Repetition Rate	2 Hz	
Max. Beam Pulse Length	400 μs @ 0.833 Hz	600 μs @ 0.833 Hz
Max. Beam Duty Cycle	0.08%	0.12%
Chopper Beam-on Factor	~65%	Max. ~65%
Source Peak Current	80 mA	~60 mA
Linac Peak Current	65 mA	40 mA
Linac Chopped Current	40 mA	26 mA
Transv. Emittance (Source)	0.25 π mm mrad	
Transv. Emittance (Exit)	0.4 π mm mrad	0.4 π mm mrad

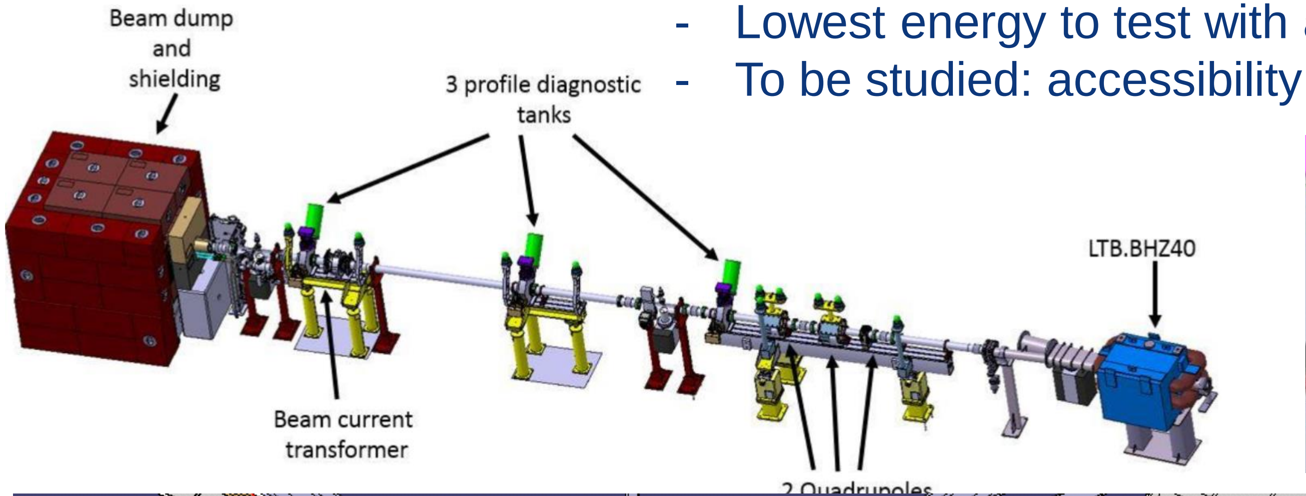
Require only 0.833 Hz (1.2 s basic cycle)

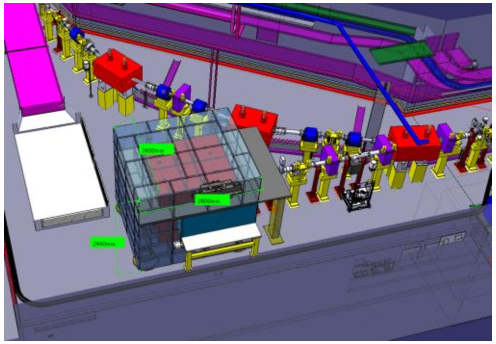
Chopping at 3 MeV for ~loss-free injection into the PSB RF bucket (~630 ns beam ON)

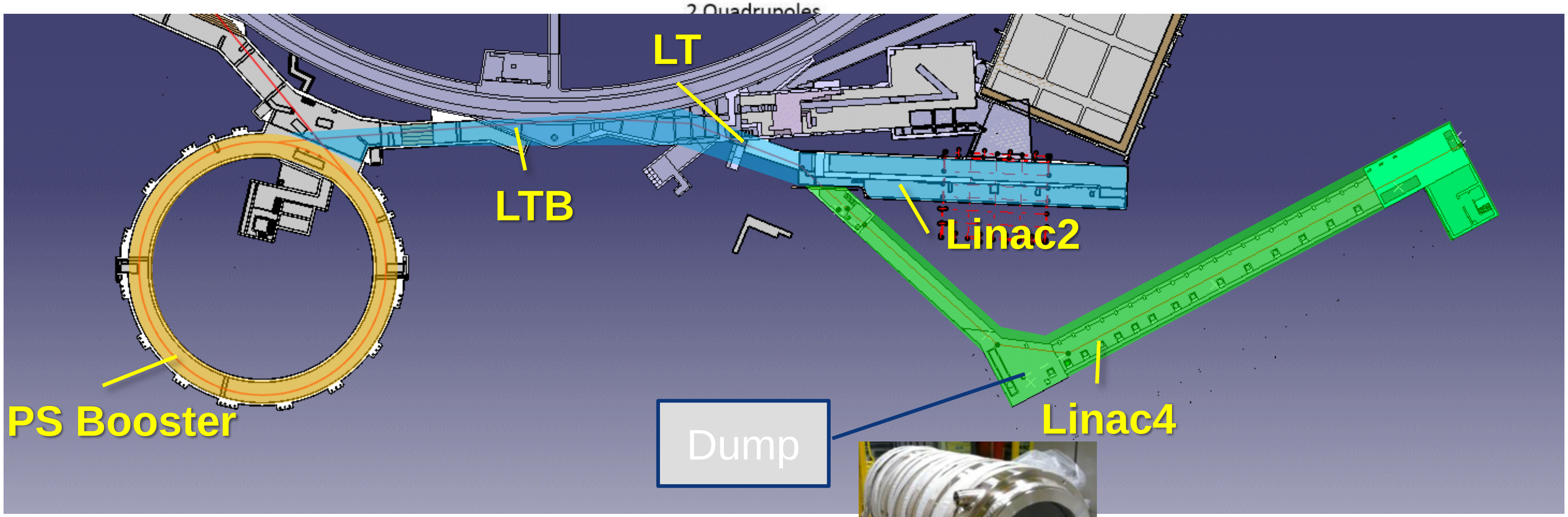
RF structures dimensioned for 50 Hz, power supplies, electronics, electricity, cooling for 2 Hz

Linac4 - LBE Line

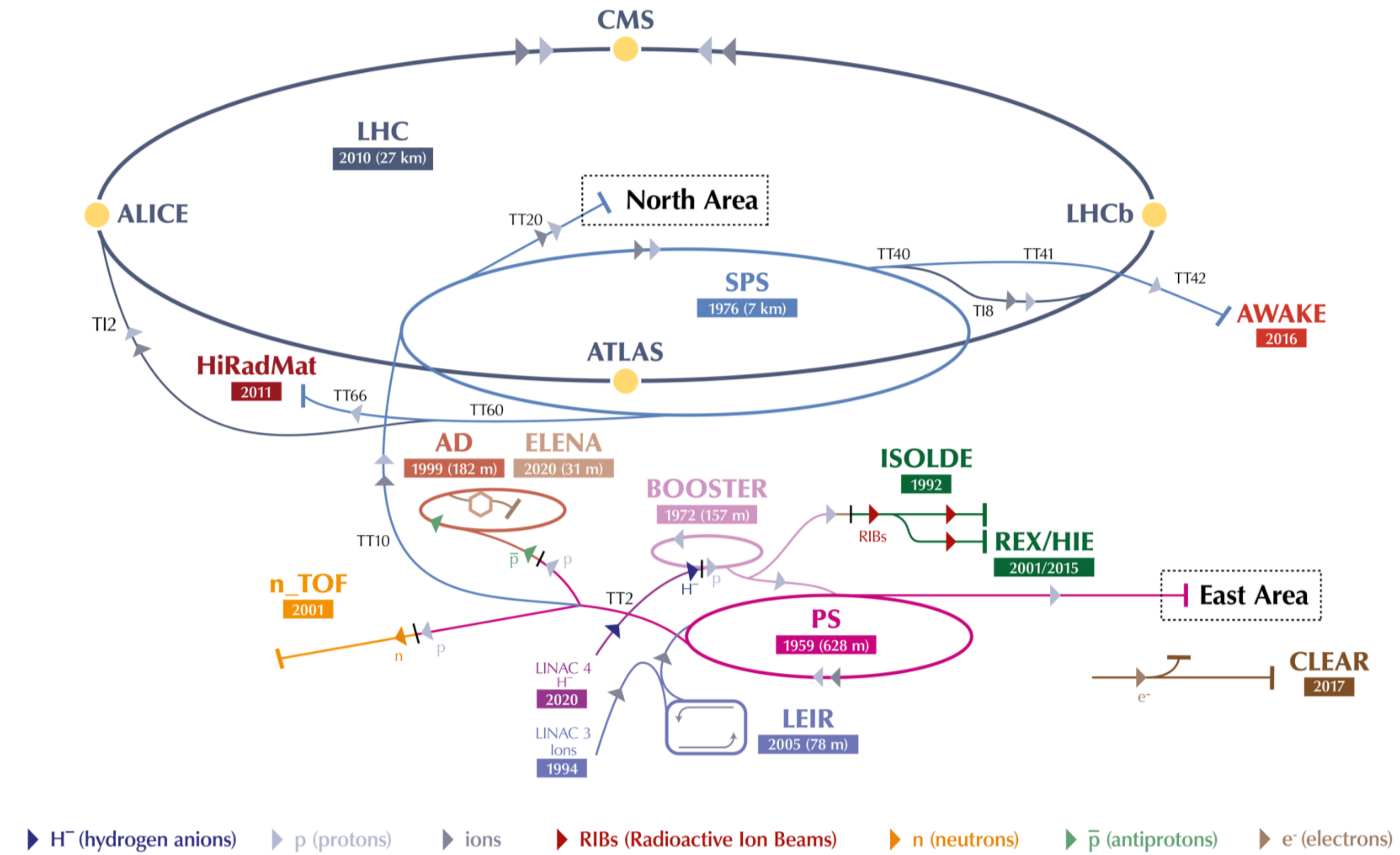
- H^- 160 MeV Linac beam dump in measurement line
- Lowest energy to test with an accelerator-type beam
- To be studied: accessibility to an operational machine







CERN accelerator complex



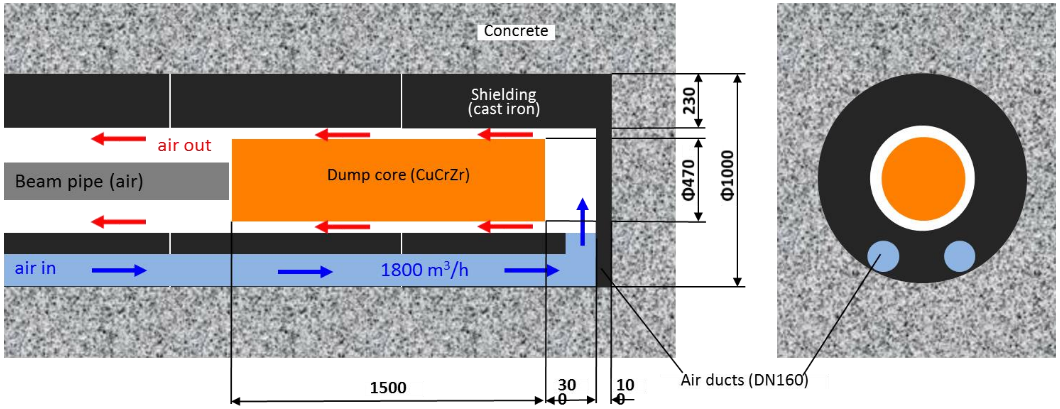
PSB main features

- Injection
  - 160 MeV H^-
  - Multiturn charge exchange injection with transverse and longitudinal painting up to thousand turns
- 4 superimposed ring magnetically coupled
- Lattice: Triplet, FDF
  - Operating below transition
- Acceleration cycle
  - ~ 700 ms
  - 1.2 cycling period
- RF: Finemet
  - Operation with h=1 and h=2
- Extraction:
  - 2 GeV (1.4 GeV)
  - Single turn fast extraction with vertical recombination
- Particles types:
  - Protons, (~~Ions - O, S, In, Xe~~)
- Max total intensity: ~ 4e13 ppp
- External Exp. Area: ISOLDE

PSB Dump

To be studied: accessibility to an operational machine

- **Design parameters:**
  - Max beam intensity: 1E14 p+/pulse
  - Beam energy: 2 GeV
  - Pulse period: 1.2 s
  - **Max. Average power to dump : 9.44 kW**

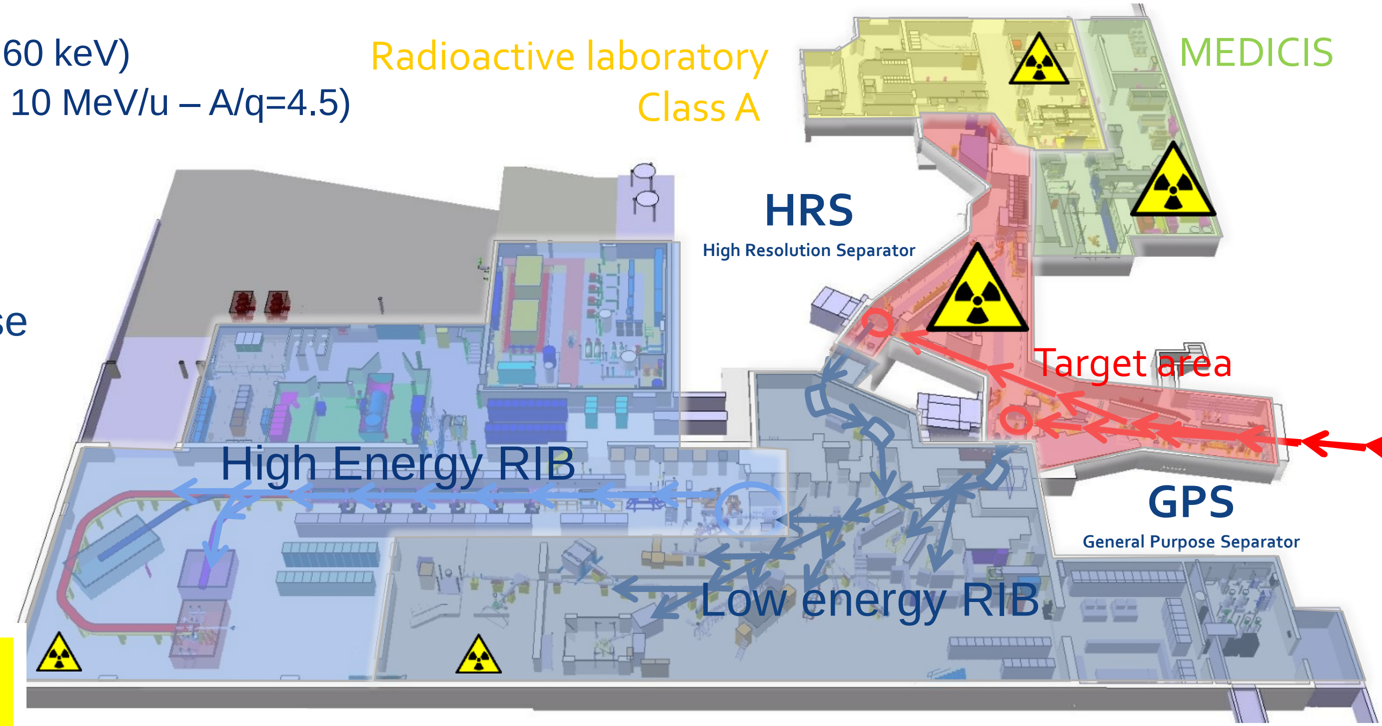


A. Perillo-Marcone - RaDIATE 2018

ISOLDE : Radioactive Ion Beam facility

- Protons (1.4 GeV)
- Low energy RIBs (up to 60 keV)
- High energy RIBs (up to 10 MeV/u – A/q=4.5)

Pulsed protons (1.2 s)
1.4 GeV
3.3×10^{13} protons per pulse



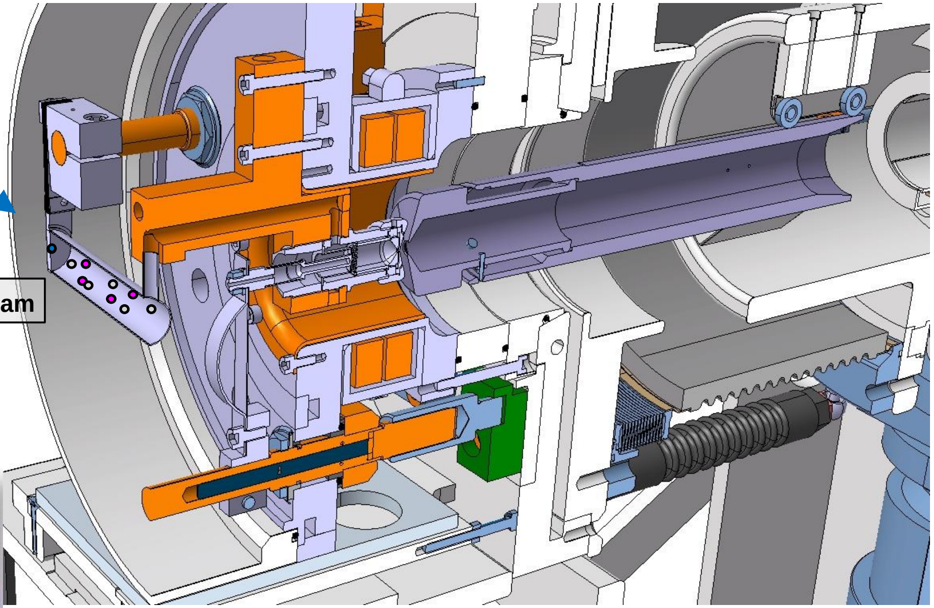
*picture courtesy of M. Delonca

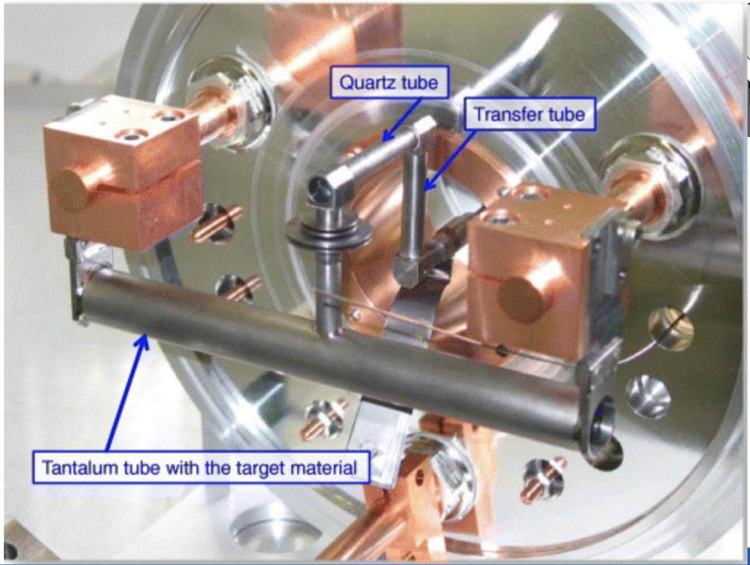
More than 50% of the protons at CERN are delivered to ISOLDE

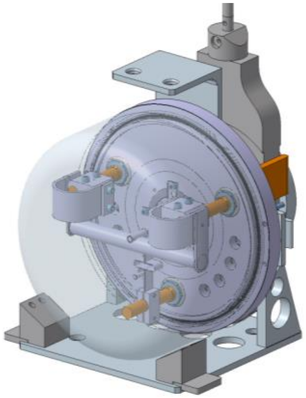
Rare isotope production

- Isotope production from **proton interacting in a target**
- **Atoms** migrates from the target to the front-end
- Once **ionized** they are transported to the users

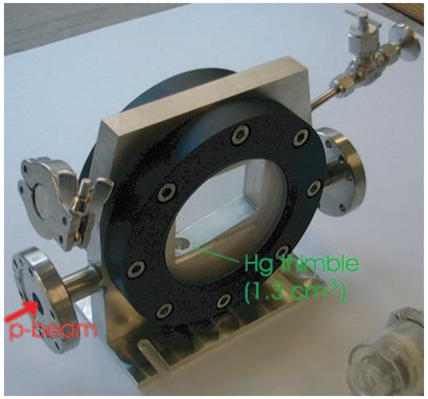
- **Different target materials produce different isotopes**
- **Isotopes can be post accelerated**

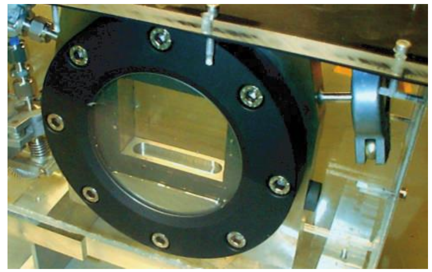


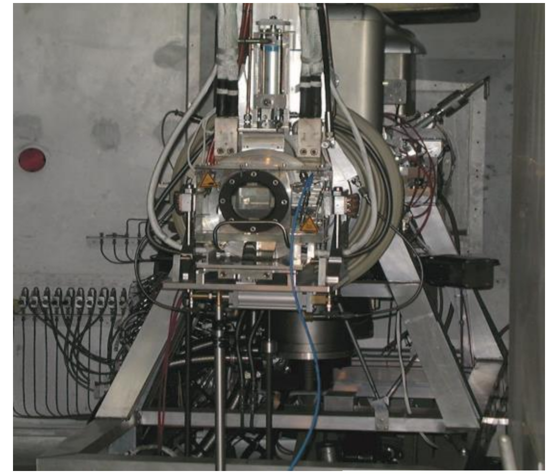


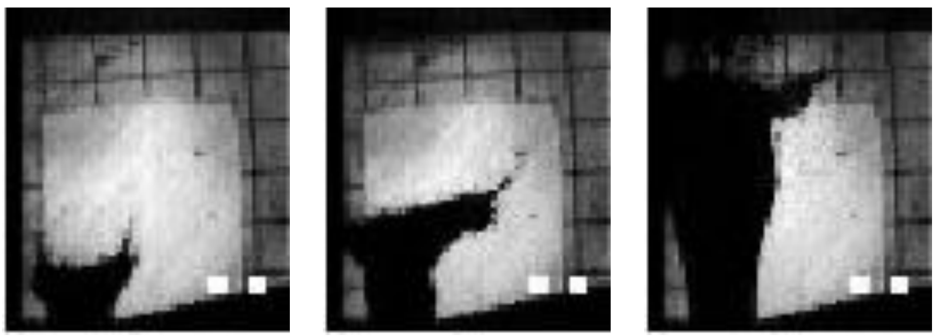


First mercury target experiments@ISOLDE



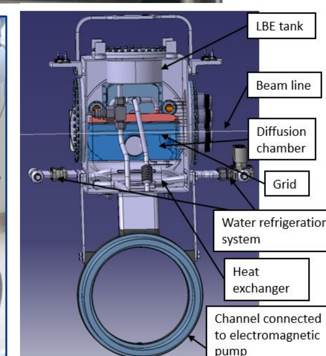






- Successor could be a LIEBE like test with Pb-Bi if not in Hiradmat.
- Mercury cannot be used anymore

See M. Calviani presentation



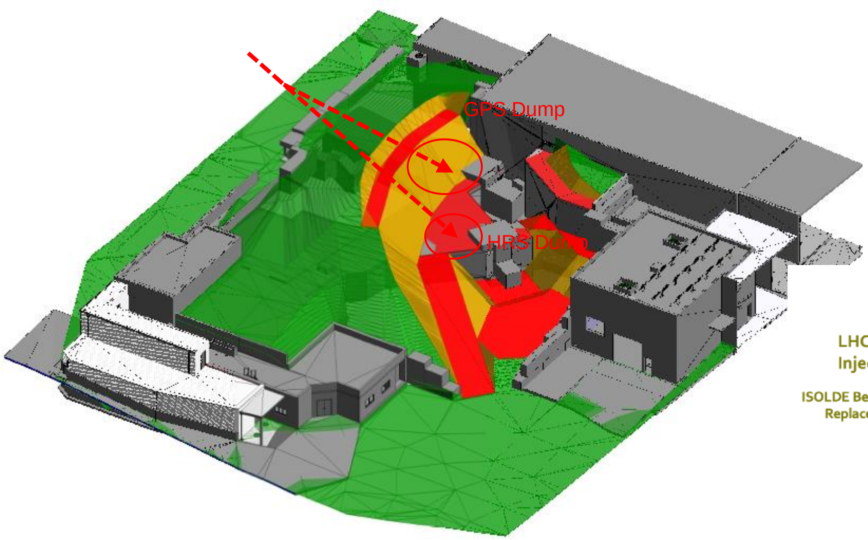
Liquid Lead Bismuth Eutectic Shower

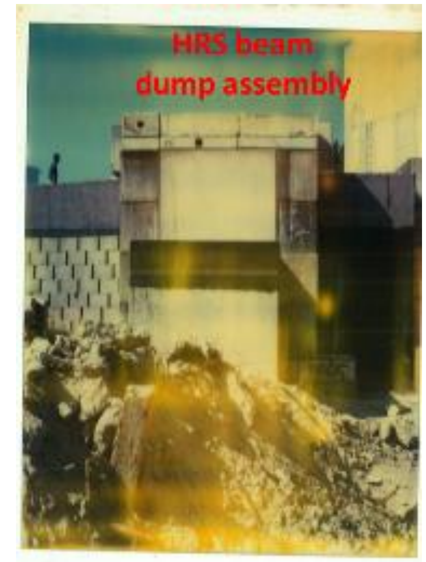
ISOLDE beam dump renovation

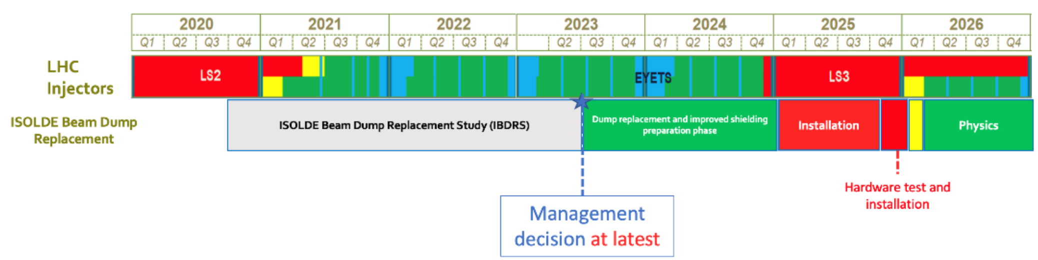
ISOLDE Beam Dump Replacement Study launched in view of

- Brainstorming on requirements and opportunities when reconstructing the area (accessibility, safety, overcome beam intensity/energy limitations….)

New irradiation station?

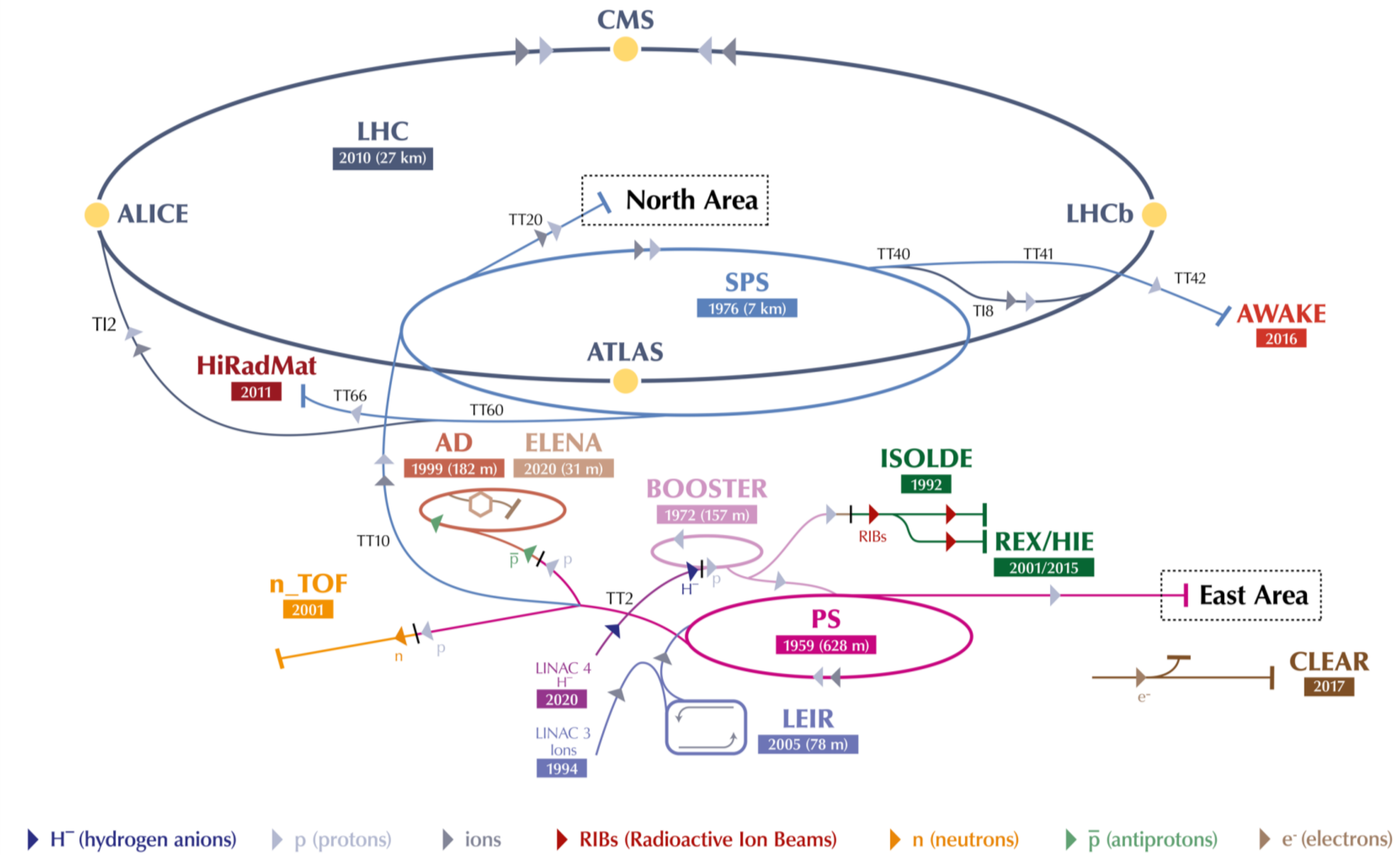




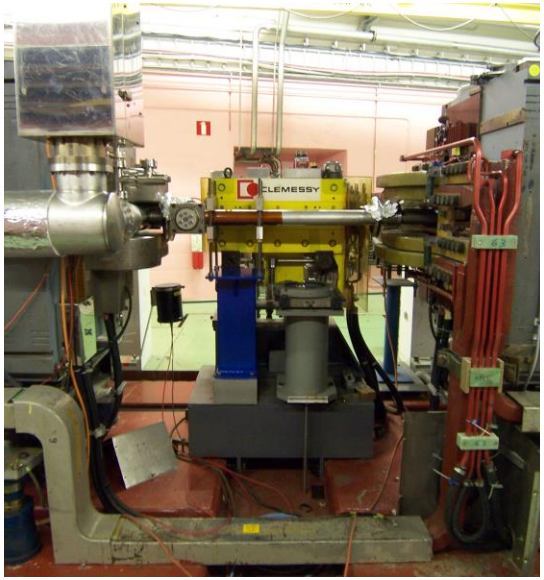


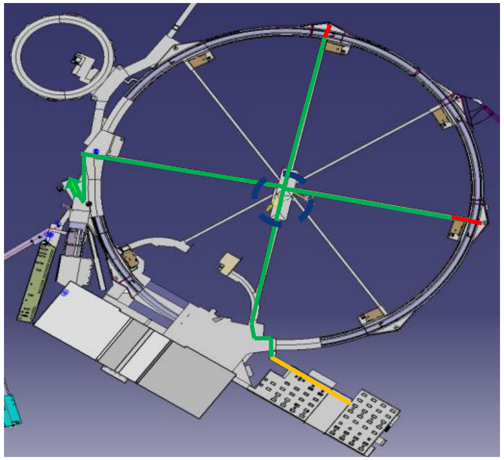
A.- P. Bernardes presentation @ EPIC workshop

CERN accelerator complex



PS main features





- Injection
  - 2 GeV protons
  - 70 MeV/n lead ions
  - Single turn injections
- Lattice: FODO with combined-function magnets
  - Transition crossing with gamma-jump at 6.1 GeV
- Acceleration cycle
  - Up to 3.6 s depending on final user
  - 1.2 cycling period
- RF:
  - 10 MHz ferrite loaded main RF system
  - 20, 40, 80 MHz for LHC beams production
  - 200 MHz for beam recapture after de-bunching
  - h=7, 8,16, 21, 42, 84,168
  - Finemet as longitudinal feedback system
- Extraction:
  - Fast extraction at 20 GeV and 26 GeV
  - Multiturn (5 turns) extraction at 14 GeV
  - Slow extraction 24 GeV
- Particles types:
  - Protons, Ions (Pb, O, S, In, Xe)
  - In the past: anti-protons, e+, e-
- Max total intensity: ~ 4e13
- External Exp. Area: East hall, AD

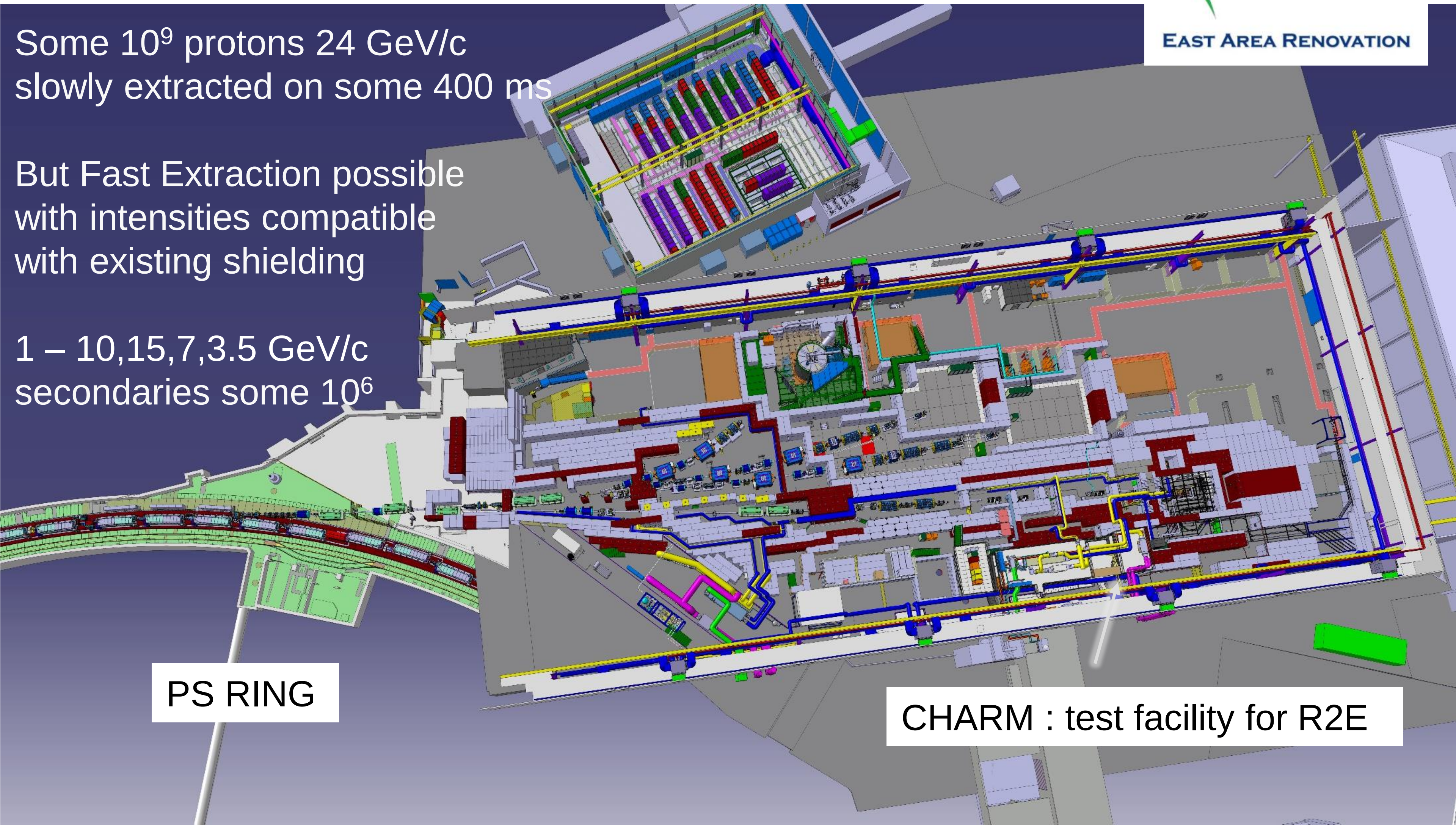
Experimental area : EAST HALL

EAST AREA RENOVATION

Some 10^9 protons 24 GeV/c slowly extracted on some 400 ms

But Fast Extraction possible with intensities compatible with existing shielding

1 – 10,15,7,3.5 GeV/c secondaries some 10^6

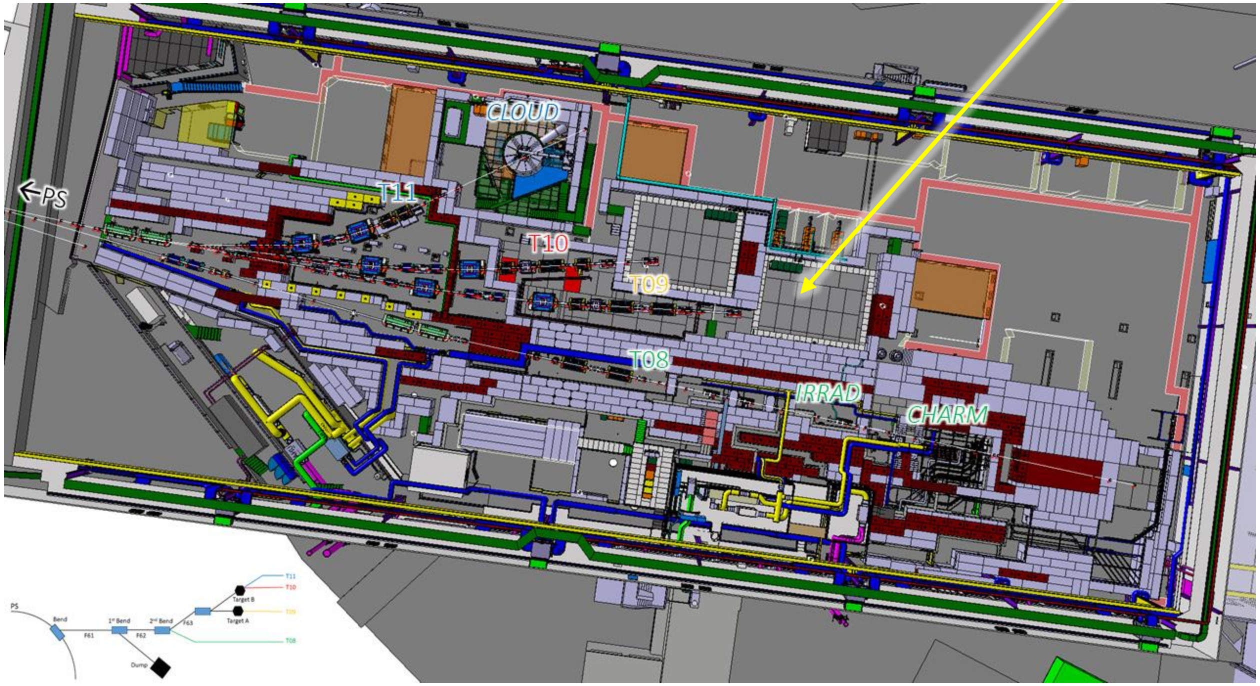


Experimental area : EAST HALL

Possible options:

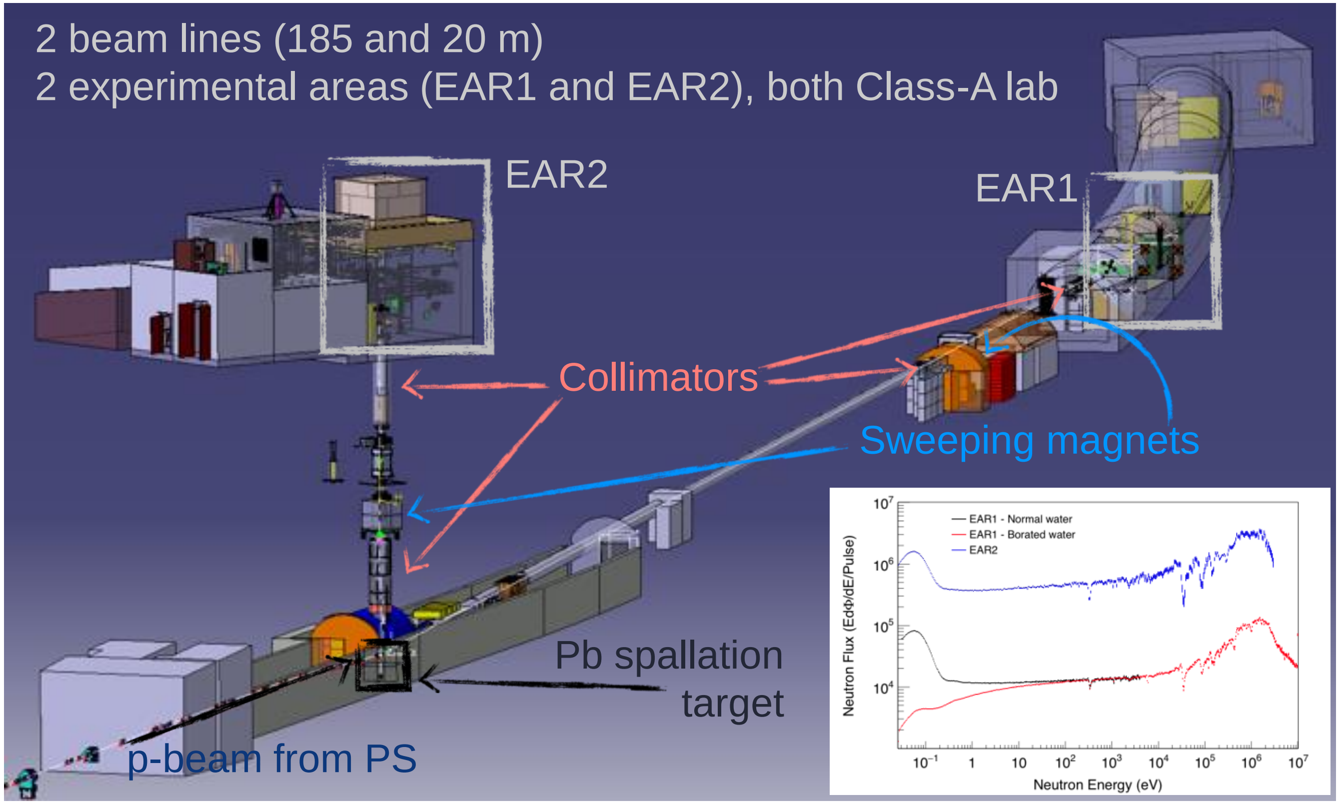
- CHARM : material irradiation (but mainly electronics)
- A new single particle cooling experiment with muons (cells)
- Think of primary proton beam fast-extracted at some GeV up to 24 GeV, think of secondary beam with a time structure

Harp used to be here



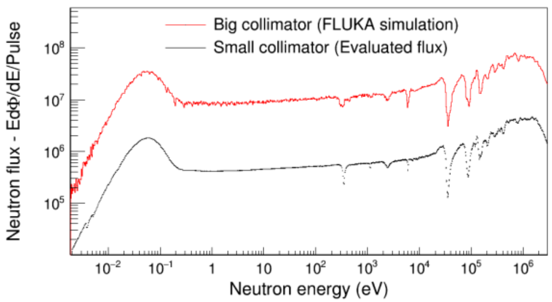
- **Secondary beams:**
  - Momentum < 15 GeV/c
  - Irradiation facilities CHARM and IRRAD
  - Test beamlines T9 and T10
  - T11 beamline for CLOUD experiment
  - Horizontal momentum selection
- **Particle types and intensity**
  - Pure electrons, hadrons, muons
  - Max. ~$5 \cdot 10^6$ particles per spill
- **Spill structure from PS**
  - 400ms spill length
  - Typically 1 spill every 18s (15bp), more on request
- Quick access from control room to experimental area (< 1 minute)
- Short cables

The n_TOF beam: neutron beam lines



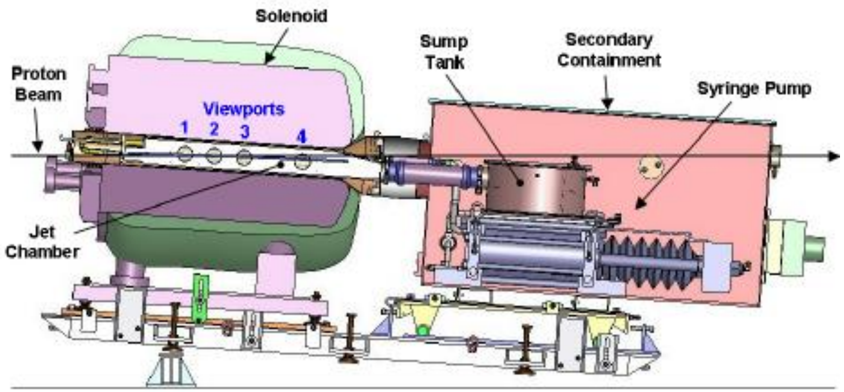
Some figures

	EAR1	EAR2
Wide energy range	thermal to 1 GeV	thermal to 300 MeV
High instantaneous neutron flux	2 x 10^5 n/cm^2/pulse	3 x 10^6 n/cm^2/pulse
Low repetition rate	< 0.8 Hz (1 pulse/2.4 s max)	
High energy resolution	$\Delta E/E=10^{-4}$ (@10 keV)	$\Delta E/E=10^{-3}$ (@10 keV)

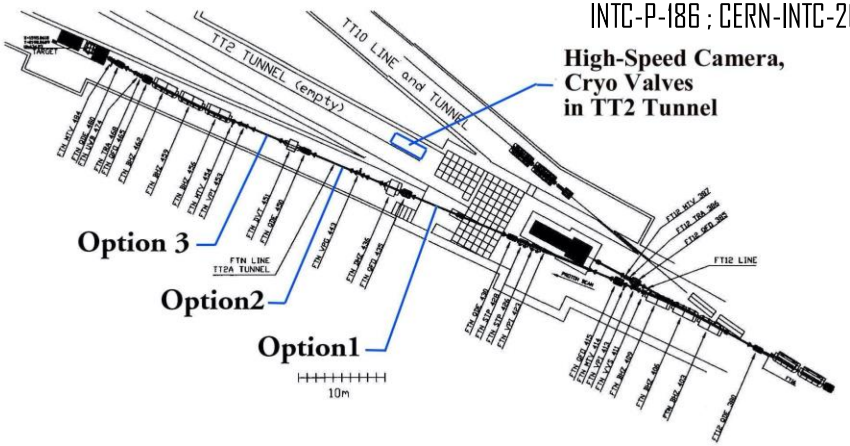


- Main feature of n_TOF is the synthesis of extremely high instantaneous neutron flux and excellent energy resolution
- Unique facility for measurements of radioactive isotopes (maximize S/N)
  - Branch point isotopes (astrophysics)
  - Actinides (nuclear technology)

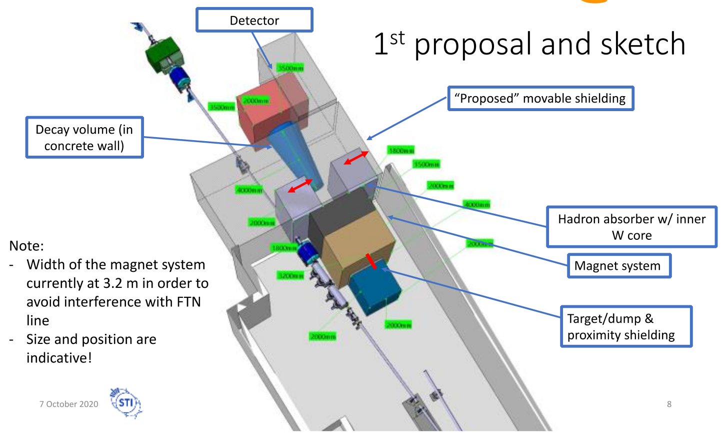
Merit Experiment Location



INTC-P-186 ; CERN-INTC-2004-016

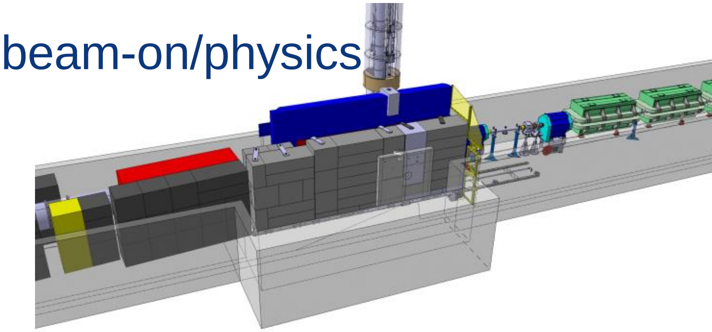


SHiP@PS

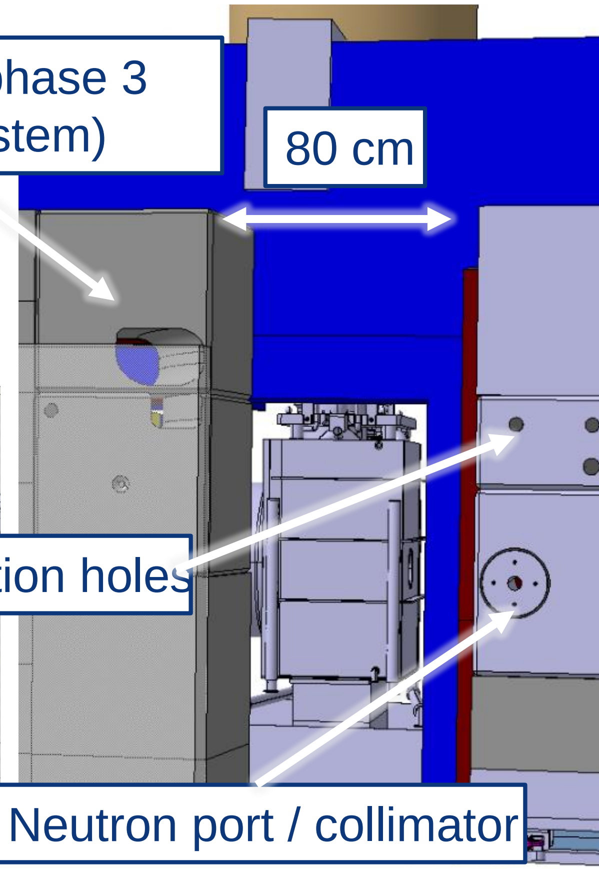


FTN – line : Location explored in the past for a colling experiment at CERN
Same flexibility as in MERIT not possible because of n_TOF operation.
Proposal by M. Calviani et al. in the framework of the PS external dump renovation with horizon LS3

n_TOF NEAR



Open configuration (“beam-off/access”)

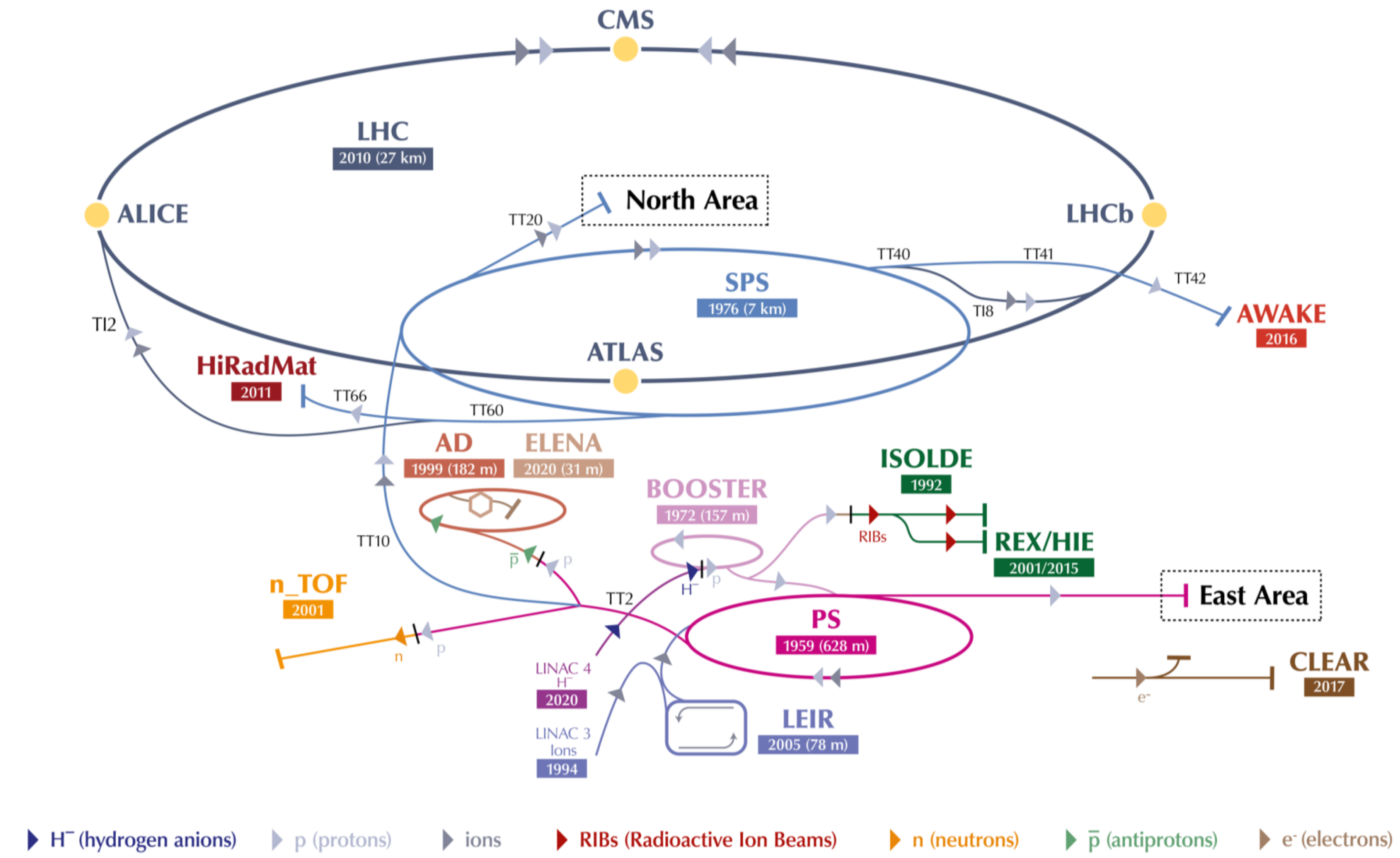


Irradiation facility summary

FACILITY	status	Radiation field	Fluence/dose	Goal - limits
CHARM	existing	Mixed, high E p, n, p...	≈10^{11} weekly HEH* 100 Gy/week	R2E – particle damage to electronics low fluence for materials
IRRAD	existing	Protons, 24 GeV/c	10^{16} p cm^{-2} /5 days	Detectors, electronics, accelerator component; Small irradiation spot
ISIS @ ISOLDE	In progress	Mixed field n, p, g...	>2.5 MGy/y @50 cm /target	✓ Materials studies at low dose rate in mixed field
NEAR @ n-TOF	In progress	Mixed field mostly n	≈ 1 MGy/y	✓ Materials studies at low dose rate in mixed field

Matteo Ferrari – ISOLDE EPIC 2020

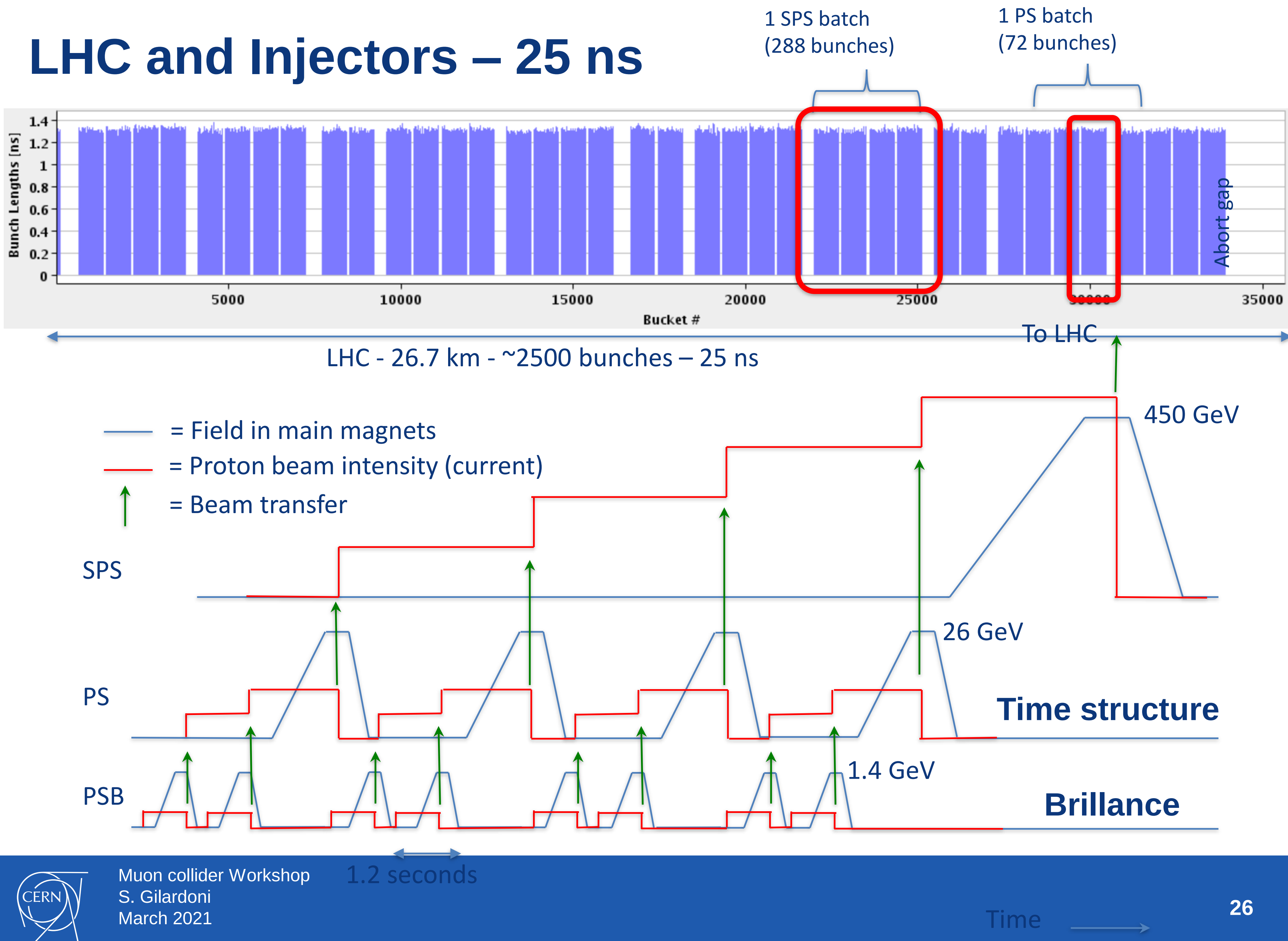
CERN accelerator complex



SPS main parameters

- Injection
  - 14 GeV or 26 GeV protons
  - 26 GeV proton equivalent Pb ions
  - Multi-batch injection from PS
- Lattice: FODO with dispersion free SS
  - Transition crossing for injection below 20 GeV. No gamma-jump
- Acceleration cycle
  - Up to 21.6 s (depending on user)
  - 1.2 cycling period
- RF:
  - Main system: 200 MHz travelling wave
  - 800 MHz to control longitudinal emit.
- Extraction:
  - Slow extraction at 400 GeV
  - Fast extraction at 450 GeV
- Operation in p-pbar collider mode
  - Machine on indefinite coast @ 270 GeV
- Particles types:
  - Protons, Pb, pbar, e+,e-, O, In, S, Xe
- Max total intensity: ~$5.3e10^{13}$
- External Exp. Area: North Area, HIRADMAT, AWAKE, Neutrino Platform

LHC and Injectors – 25 ns



North-Area and Neutrino Platform

North Area: 400 GeV/c slow extracted protons
4.8 s spill length

Secondaries depending on the line:
10 - 400 GeV/c, up to 10^8 particles/spill

North Area beamlines characteristics

Primary mode Secondary mode

Parameters	T2		T4	
Beam Line	H2	H4	H6	H8
Maximum Momentum [GeV/c]	400 / 360	400 / 330	- / 205	400 / 360
Maximum Acceptance [µSr]	1.5	1.5	2	2.5
Maximum Δp/p [%]	± 2.0%	± 1.4 %	±1.5%	±1.5%
Maximum Intensity / spill * (Hadrons / Electrons)	10^7/10^5	10^7/10^6	10^7 **/10^5	10^7 **/10^5
Available Particle Types	Primary protons*** OR pure electrons OR mixed hadrons (pions, protons,kaons)			
Other / Special requests	sba-physicists@cern.ch & sps.coordinator@cern.ch			

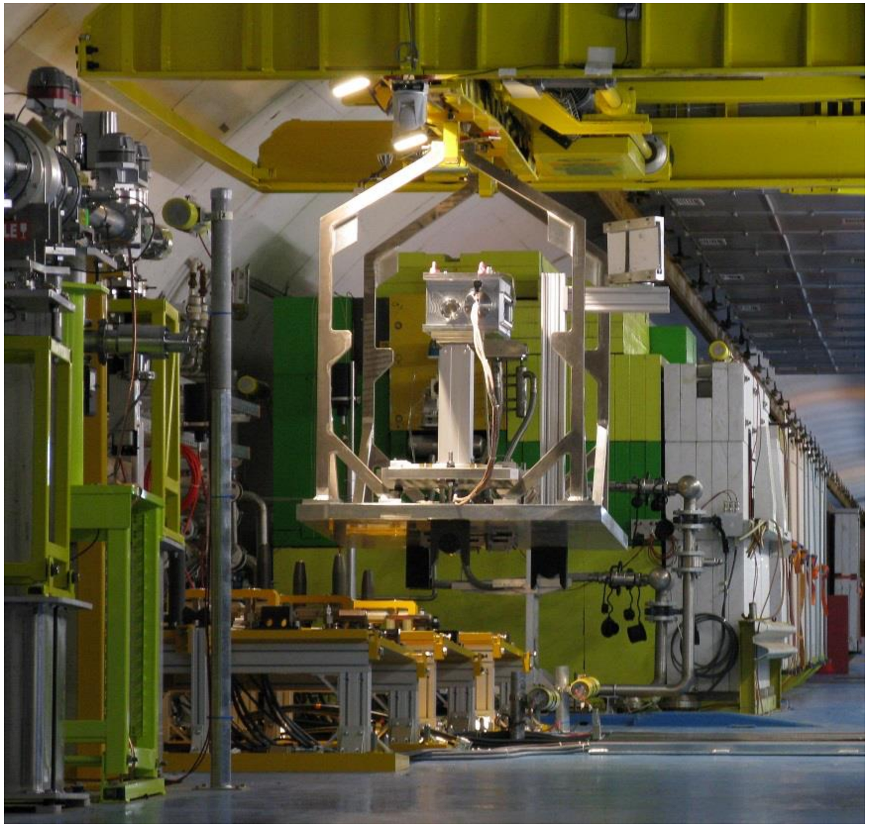
* Imposed by Radio Protection, and not available to every zone
** In some zones can be elevated up to 10^8 subject to certain restrictions
*** Not available in H6

A. Gerbershagen - CERN Test Beamlines

HIRADMAT at SPS

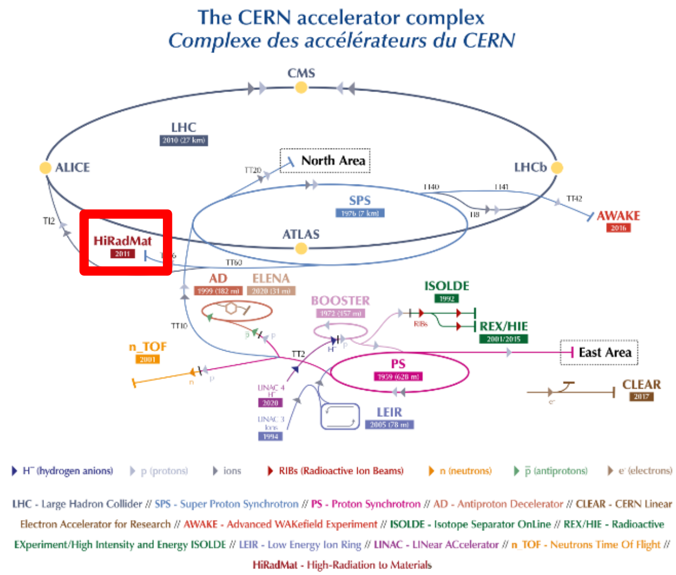
HiRadMat (High-Radiation to Materials) : users facility designed to provide high-intensity pulsed beams to irradiate material samples and accelerator component with single or multiple beam impact at 440 GeV.

Can receive LHC type beams pulses

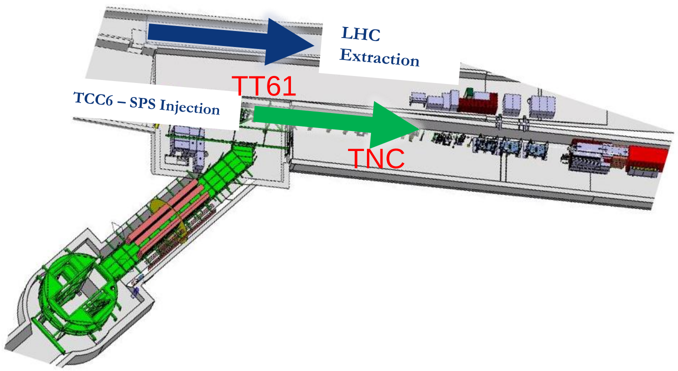


HiRadMat in a flash

- A unique, high-energy, high-intensity pulsed beam facility dedicated to targetry & accelerator components material R&D
- LHC-like proton or ions beams, with a maximum pulse intensity of 3.4×10^{13} protons / pulse can be delivered in controlled conditions and to be monitored with special instrumentation.



HiRadMat Proton Beam		Additional information
Beam Energy	440 GeV	
Energy per pulse	2.436 MJ	
Bunch Intensity	5E9 to 1.2E11 protons	
Number of Bunches	1 to 288	
Minimum Pulse Intensity	5E9 protons	(1b at 5E9 ppb)
Maximum Pulse Intensity	3.46E13 protons	(288b at 1.2E11 ppb)
Current during pulse	696.4 mA	
Power during pulse	3.1E5 MW	
Pulse Length (max)	7.95 μs	
1 σ r.m.s. beam radius	0.5 to 2.0 mm (standard)	0.25 to 4.0 mm currently upon request
Total allocated protons/year into facility	2E16 protons	Maximum allowance per experiment is 1E16 protons



Contact: hiradmat-operation@cern.ch

HIRAMAT tests interesting crystal-based schemes

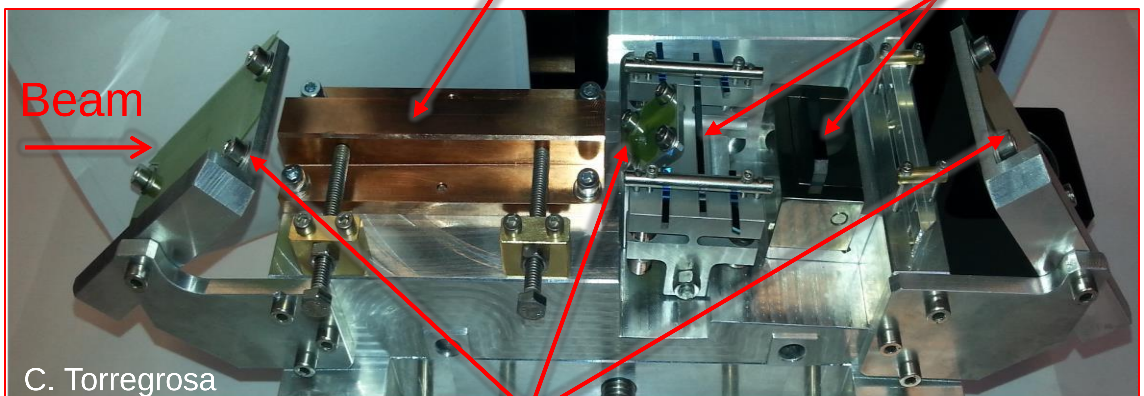
E = 440 GeV 0.3x0.3 mm size (1σ)
3 pulses with 216 bunches (~2.5e13 ppp)
1 pulse with 288 bunches (~3.2e13 ppp)

2 LHC crystals irradiated in HiRadMat and tested before and after in H8

The Setup

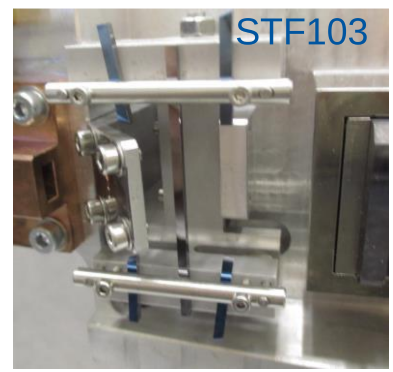
CuCrZr Mask for beam based alignment

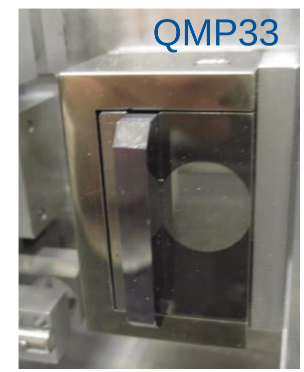
2 different types of crystals



Gafchromic foils for beam impact crosscheck

No macroscopic damages after irradiation





From M. Garattini

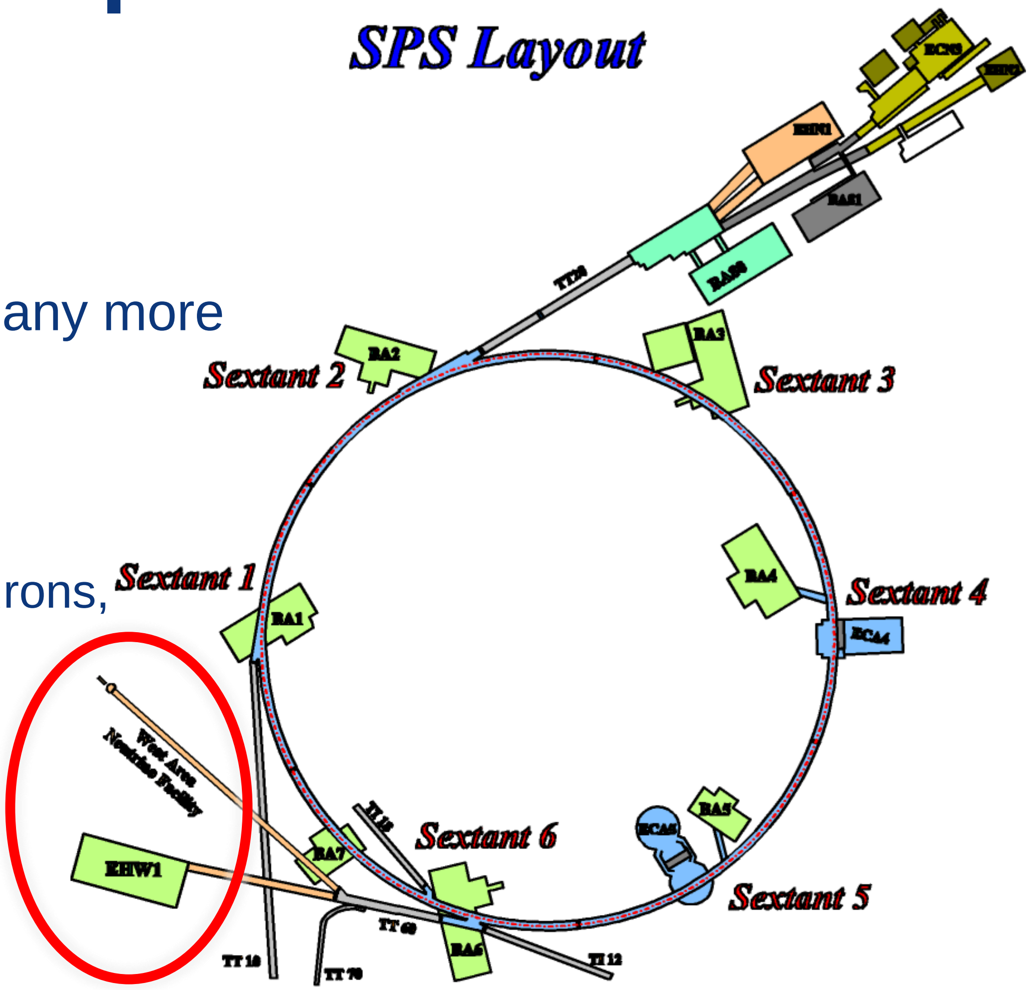
The European Physical Journal C **volume 79**, Article number: 933 (2019)

A green solution option?

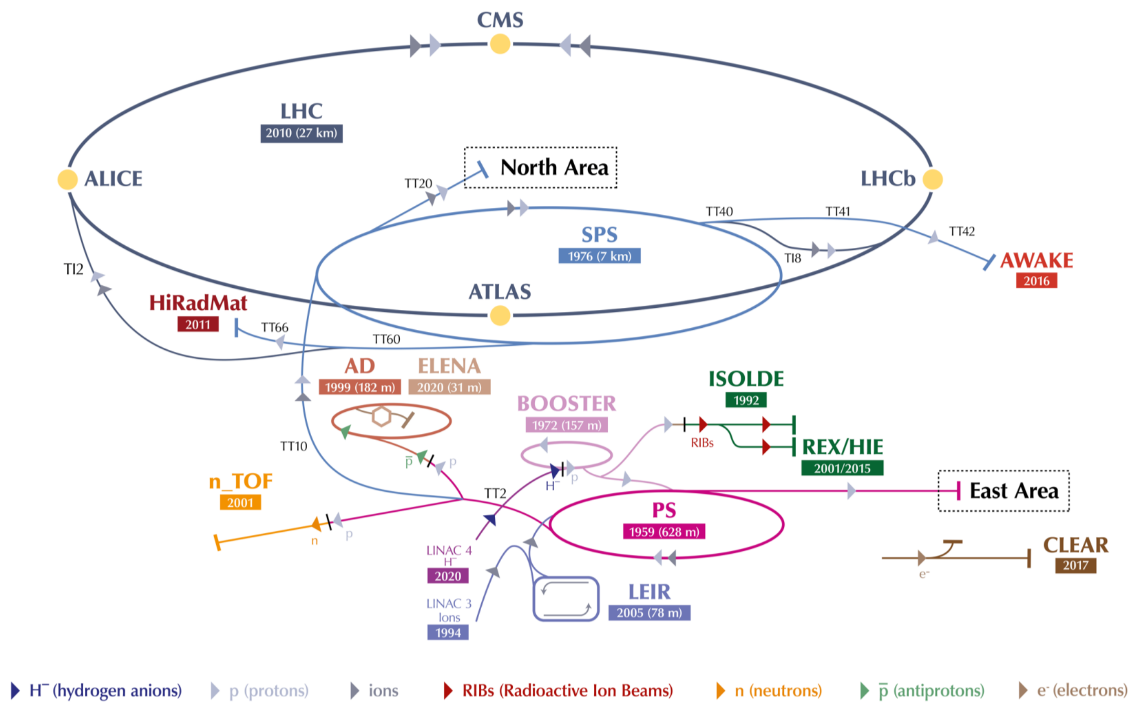
- West Are in Meyrin site
- Closed in 2004, no extraction any more
- Used to have

5 – 250 GeV/c, electrons/muons/hadrons,
< 10^6 particles/spill

What about a muon campus…
together with looking into
the WANF revamping?
(West Area Neutrino Facility)



CERN accelerator complex



Machine development time could be accessible for beam dynamics studies, like space-charge limits in the accumulator/compressor, muon (with protons) bunch merging for the collider, etc…

Machine development time in the LHC is precious, but accessible (beam-beam, etc..)

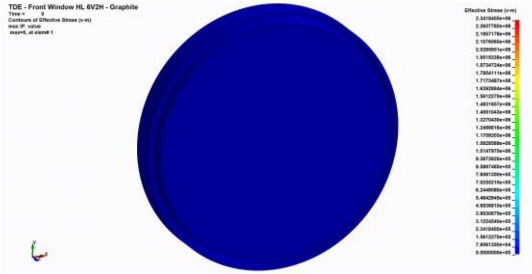
LHC main parameters

- Injection
  - 450 GeV protons
  - Multi-batch injection from SPS
- Lattice: FODO with insertions
- Collision energy:
  - 6.5 TeV (7 TeV) per beam
- RF:
  - Main system: 400 MHz SC
- Operation in collider mode
  - Machine on indefinite coast
- Particles types:
  - Protons, Ions
- Max total intensity:
- 4 Insertions for collisions
- 4 insertions for services

LHC Beam parameters achieved

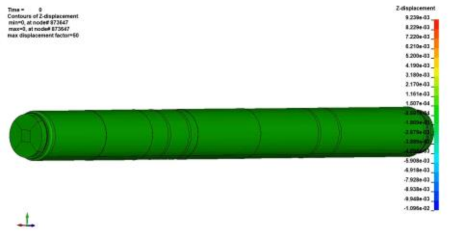
Parameter	2018	Design
Energy [TeV]	**6.5**	7.0
No. of bunches	**2556**	2808
Max. stored energy per beam (MJ)	**312**	362
β* [cm]	**30→25**	55
p/bunch (typical value) [10^{11}]	**1.1**	1.15
Typical normalized **emittance** [μm]	**~1.8**	3.75
Peak **luminosity** [10^{34} $cm^{-2}s^{-1}$]	**2.1**	1.0

LHC Dump - cavern



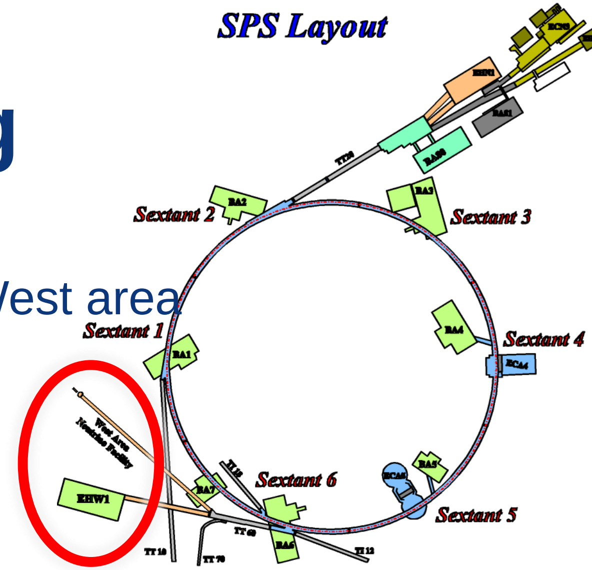
- 350+ MJ dumped every 8ish hours:
- High energy density somehow at low power
- Few tons of graphite jumping by few mm at every dump
- Dump instrumented with termocouples and LDVTs

Area not accessible during runs but space in the cavern to think about tests with 7 TeV protons



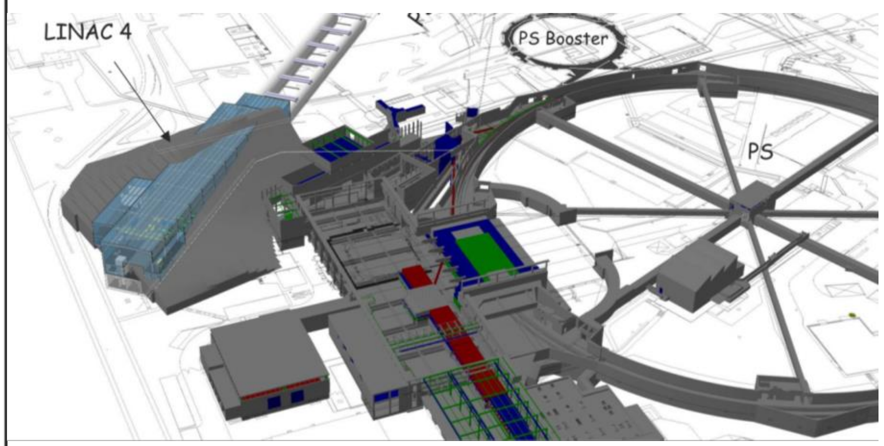
Green field – just brainstorming

One could think of building a ~few kw - 100 kW proton source based on different technology, like an FFAG, that could serve also other purposes (R2E, FCC…)



West area

South hall

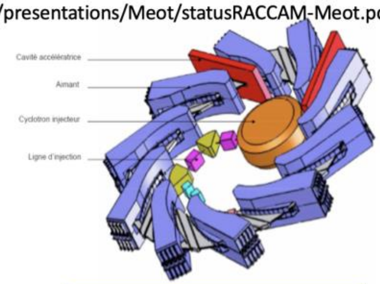


New PS Injector: FFAG
Extrapolation for scaling FFAG from RACCAM proposal

Scaling FFAG for medical applications (1.7 T peak field, 6 kV RF, acceleration in ~10 ms)

Final parameters of the RACCAM 10 cell ring and magnet :

Slide from FFAG08: http://www.cockcroft.ac.uk/events/FFAG08/presentations/Meot/statusRACCAM-Meot.pdf



Extracion energy, variable	70 – 180 MeV
Injection energy	5.5 – 17 MeV
Nomentum ratio	3.62
Number of cells	10
Packing factor	0.34
Field index, k	5
Spiral angle	53.7 deg.
Qh / Qv	2.76 / 1.55~1.60
Radius on extraction/injection orbit : dR	3.46 m / 2.78 m / 0.67 m
Drift length, extraction/injection orbit	1.42 m / 1.15 m
Frev, 15->180 MeV	3.03 -> 7.54 MHz
Frev, 5.5->70 MeV	1.86 -> 5.07 MHz

Scaling size by 5.6 yields:
- energy range:
  440 MeV -> 2.5 GeV
- injection/ejection radius:
  15.57m/19.38m
- RF: 2.2 MHz to 2.4 MHz

More sectors and larger spiral angle would improve a bit

Chamonix 2010 – Session 7 Other Scenarios for a partial Upgrade of the Injector Complex C. Carli 13 /16

Thanks for your attention