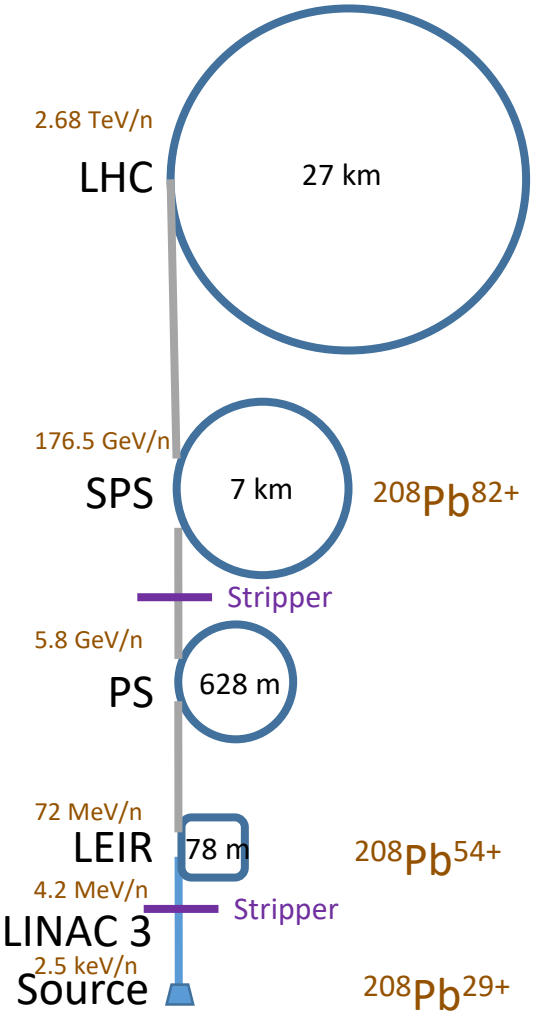
Milestones of the CERN Ion Complex and LHC

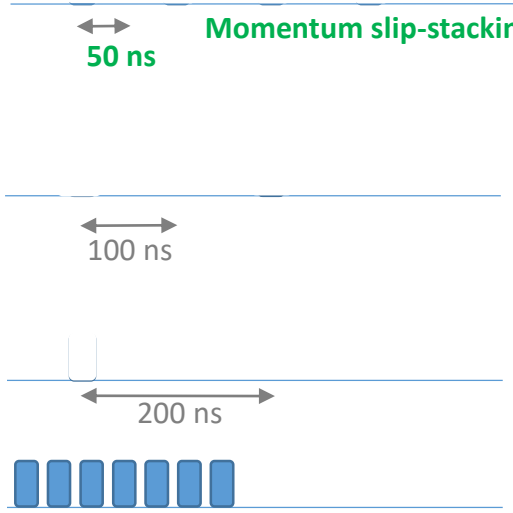
Reyes Alemany Fernandez (BE/ABP)

Overview of the CERN Ion Complex

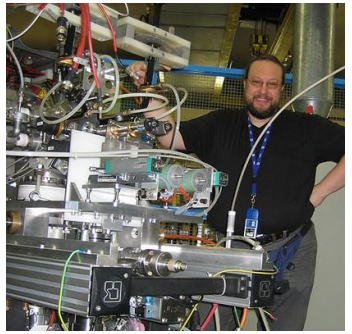
CERN Ion Complex Overview



2 X 22 injections SPS to LHC of **56-b 50 ns** ➔ **1240-b 50 ns per beam HL-LHC**



Solid isotopically pure ^{208}Pb is placed in a ceramic crucible that sits in an "oven"



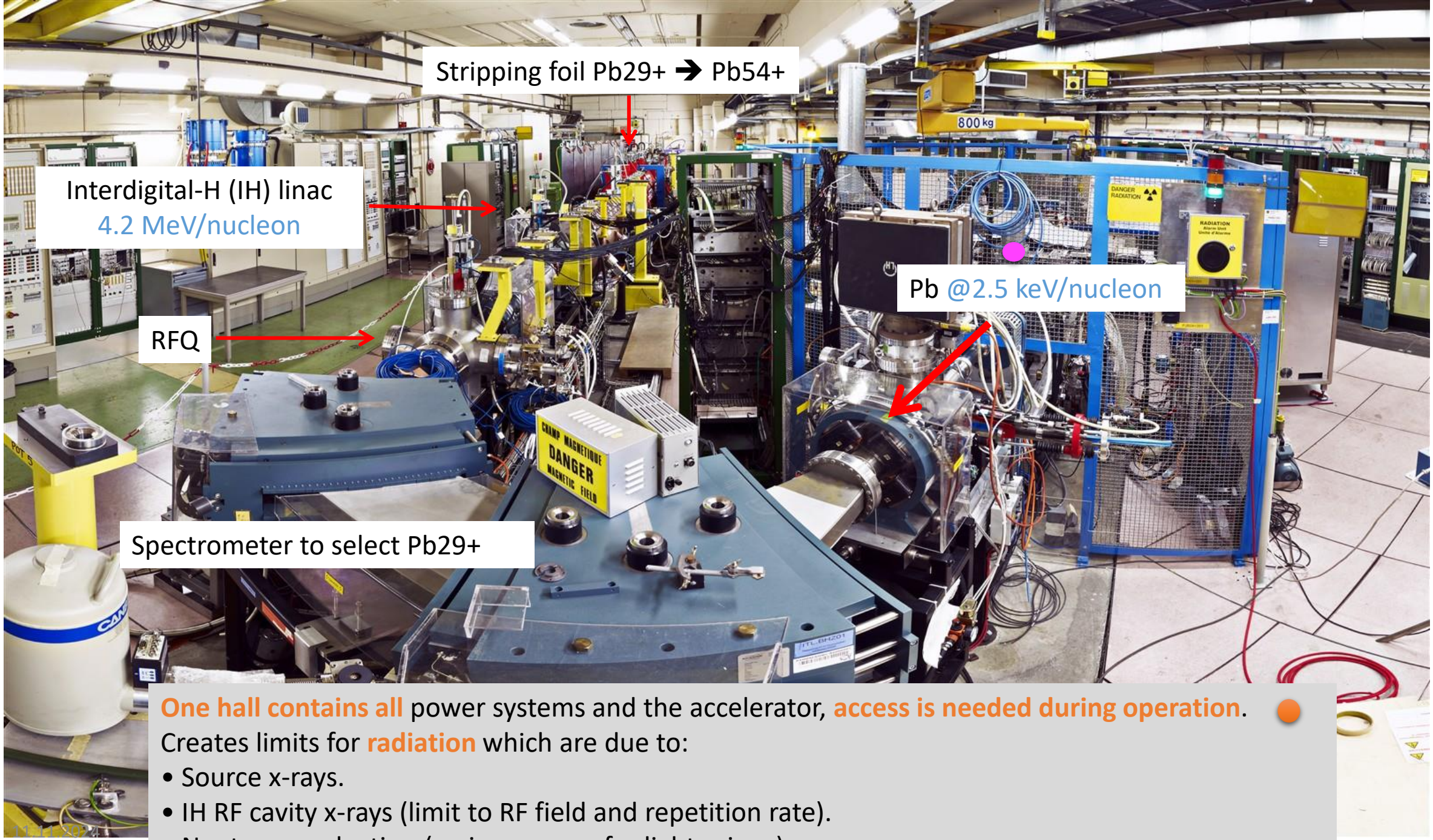
1 Electron Cyclotron Resonance Ion Source (ECRIS), installed in 2005

The **metal** is heated to ~800°C and ionized to become plasma

Equipped with gas injection and 2 microwave ovens

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

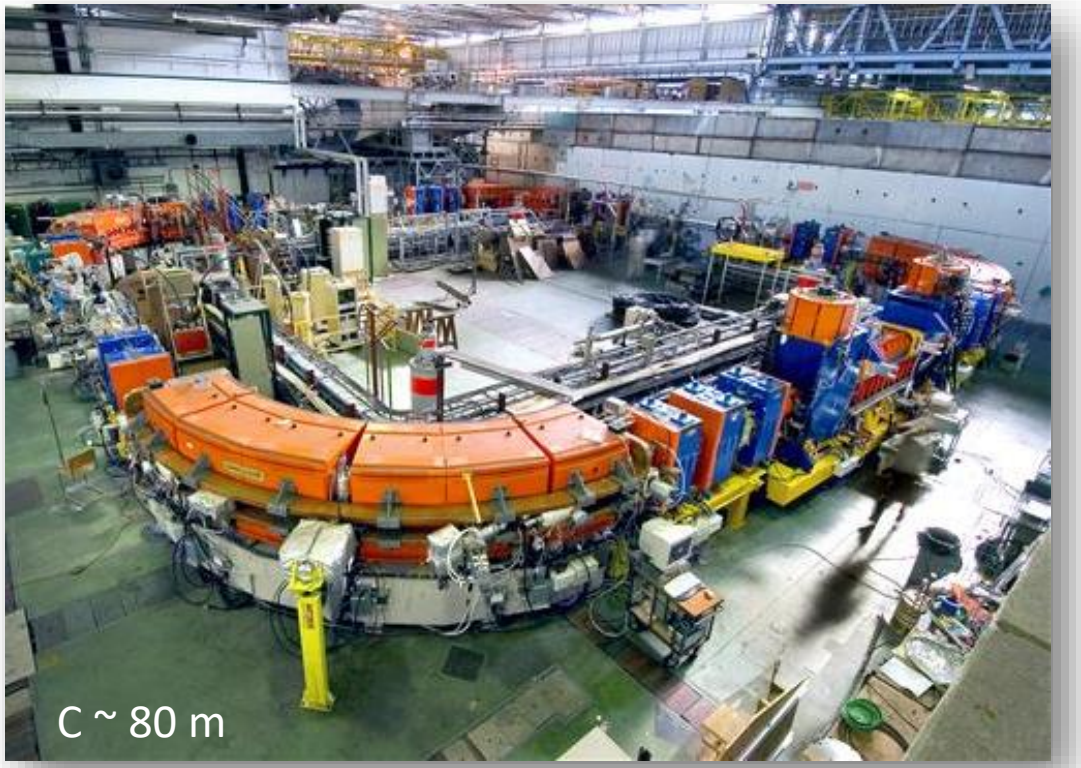
Linac 3 (1994)



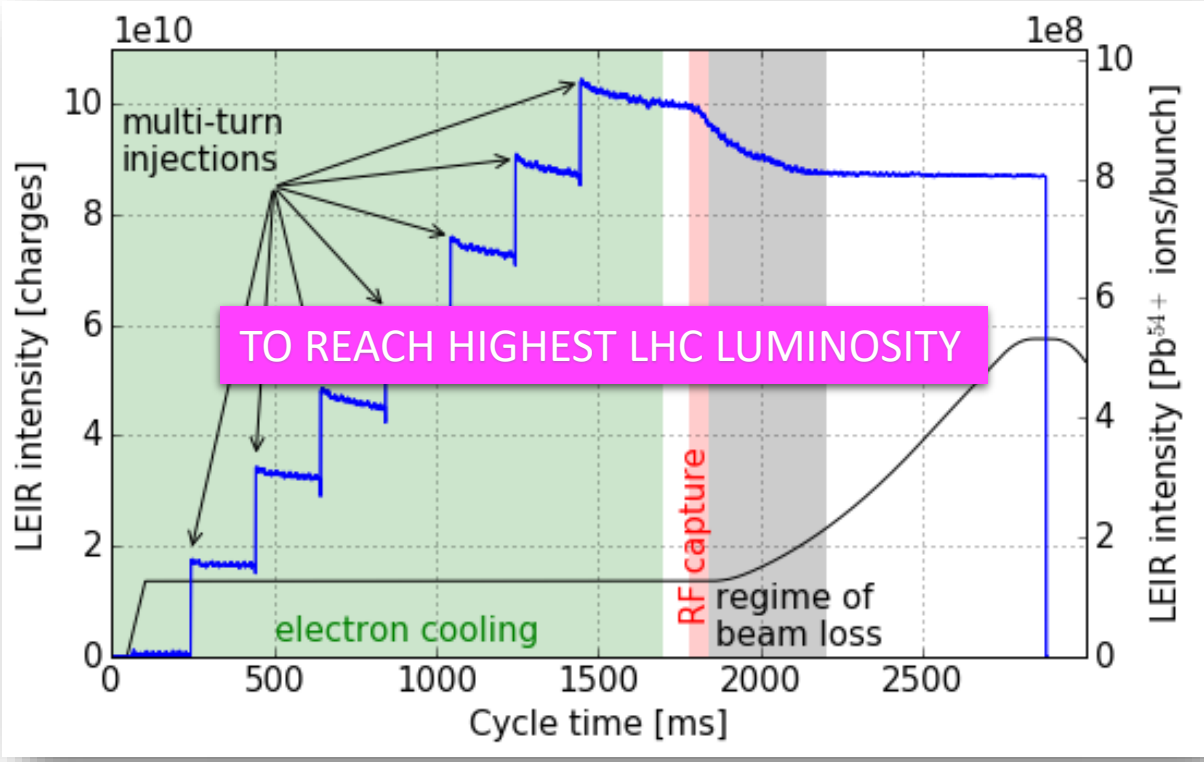
One hall contains all power systems and the accelerator, **access is needed during operation**.
Creates limits for **radiation** which are due to:

- Source x-rays.
- IH RF cavity x-rays (limit to RF field and repetition rate).
- Neutron production (an issue more for lighter ions)

Low Energy Ion Ring (LEIR)



1. Accumulation of ~200 µs pulses from Linac3: multi-turn injection and **electron cooling (A↓ Cooling efficiency ↓)**
2. Capture in 1, 2 or 3 bunches
3. Acceleration to 72 MeV/nucleon ($^{208}Pb^{54+}$)
4. Transfer to the PS

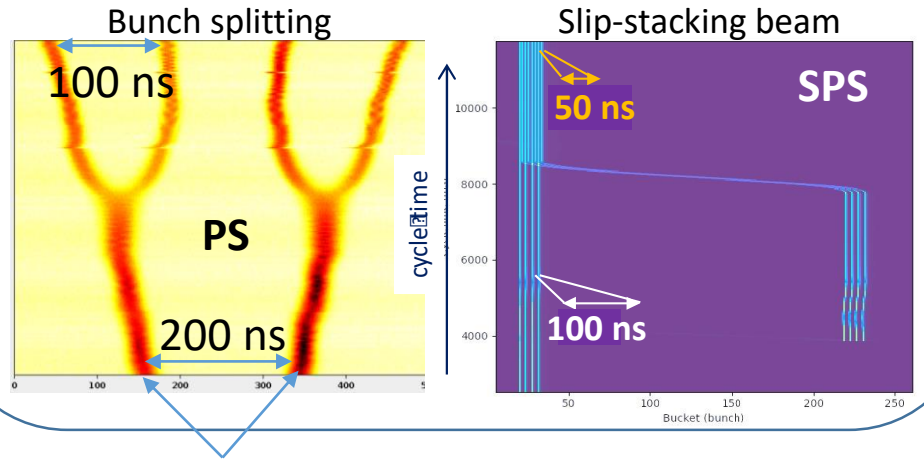


Proton Synchrotron (PS) & Super PS (SPS)

PRESENT → FUTURE

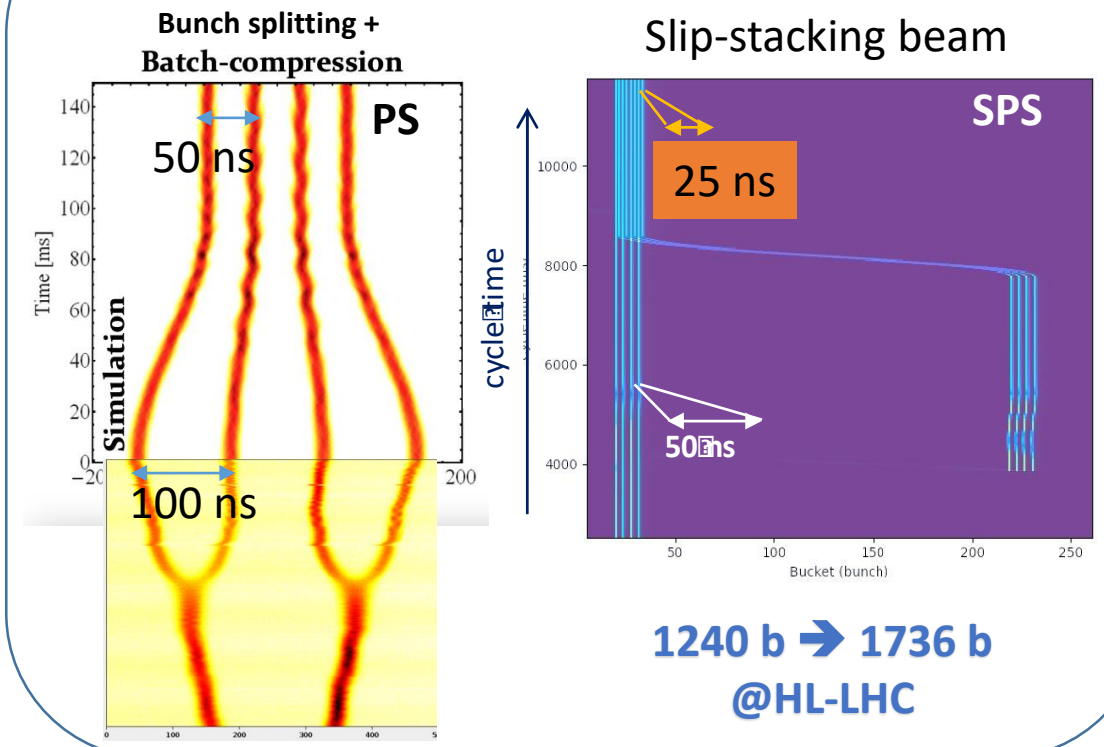
2019-2021 Upgrade of SPS RF system: momentum slip-stacking

550 b ➔ 1240 b per LHC ring for High-Luminosity LHC (HL-LHC)



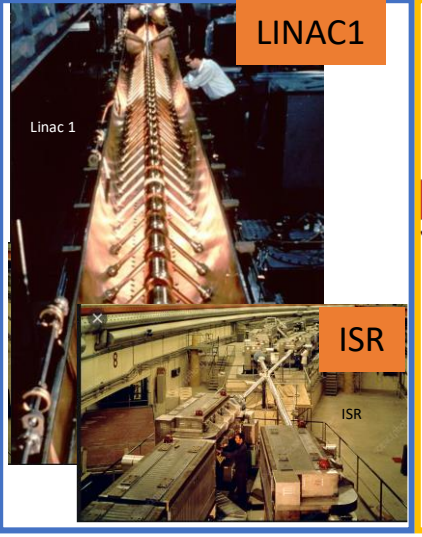
2 bunches from LEIR are injected into PS

2034-2035 Upgrade of PS RF system: 50 ns batch compression



1240 b ➔ 1736 b @HL-LHC

A bit of history …



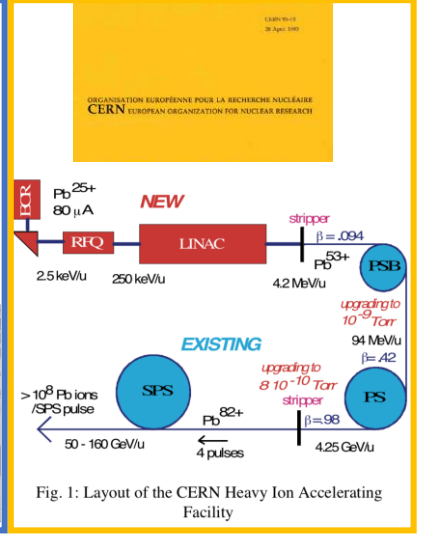
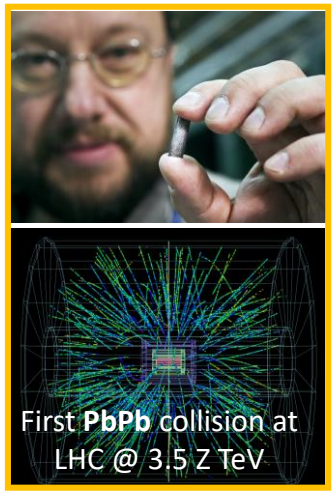
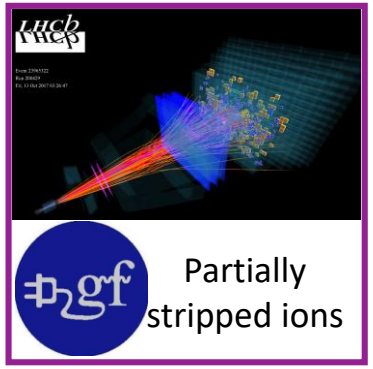


Fig. 1: Layout of the CERN Heavy Ion Accelerating Facility



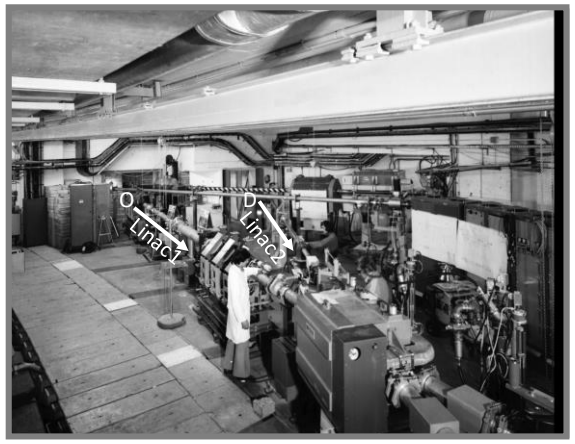


1964 1990's 2003 2010 2012-2016 2017

RUN 1 RUN 2

D_α D_O D_S Pb Pb In O PbPb pPb PbPb pPb Ar Xe^{39+} XeXe Pb^{81+} Pb^{80+} Pb

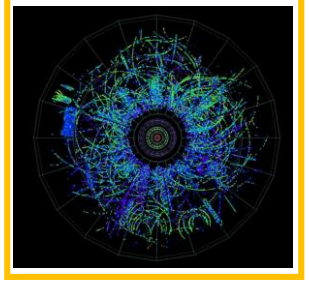
1980's 1993 2005 2012 2015 2018



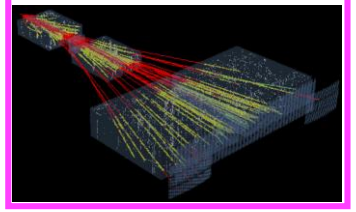
LEIR FIRST COMMISSIONING with O4+

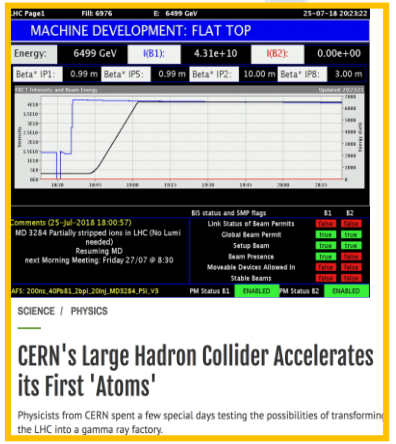
LHC Project Report 923

pPb pilot run



Ar NA61/SHINE





54 Xe Xenon 131.29

Ions for NA61 & LHC

$^{139}Xe^{54+}$

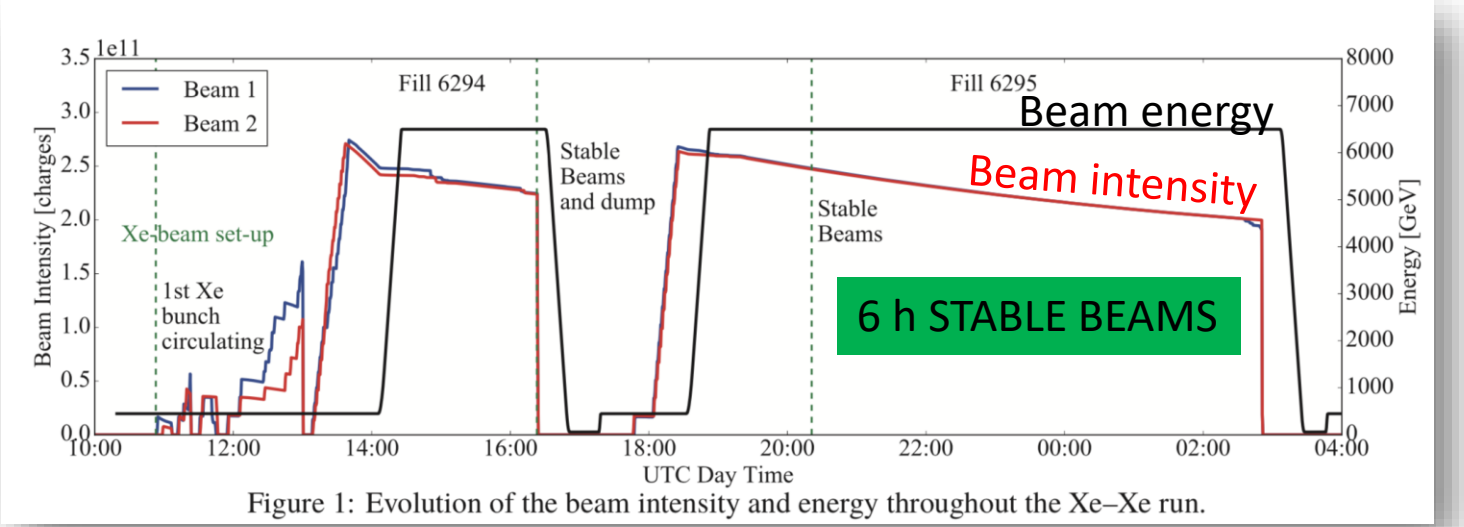
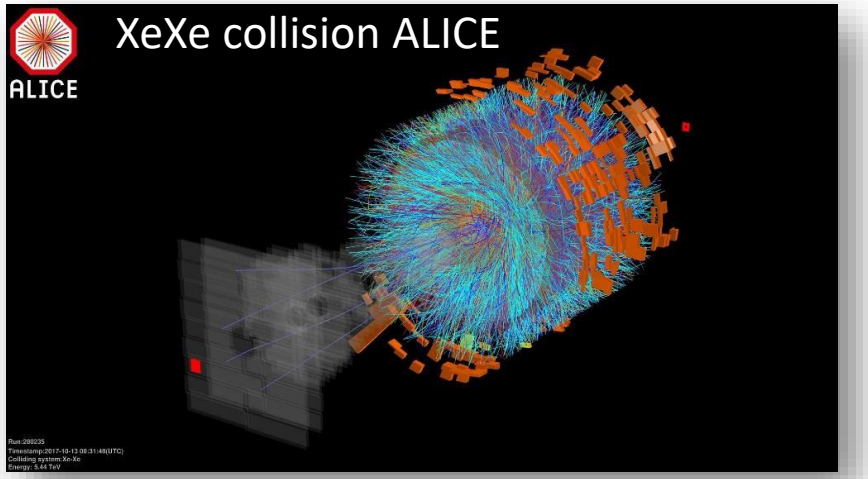
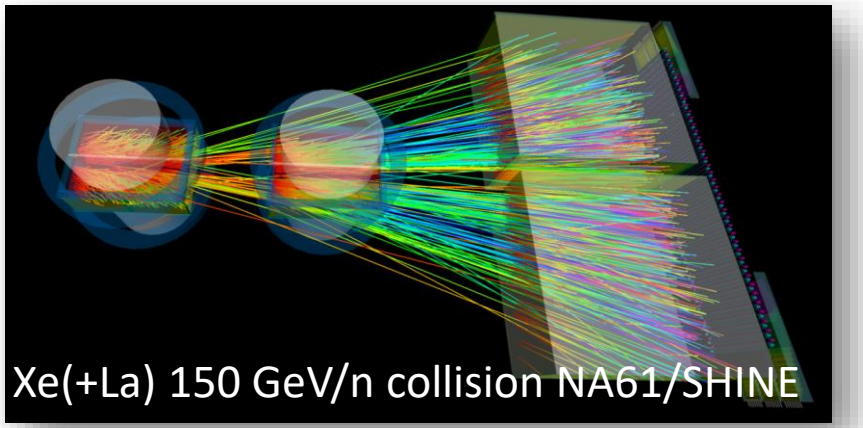


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.



FIRST XENON-XENON COLLISIONS IN THE LHC

CERN-ACC-2018-126, https://doi.org/10.18429/JACoW-IPAC2018-MOPMF039

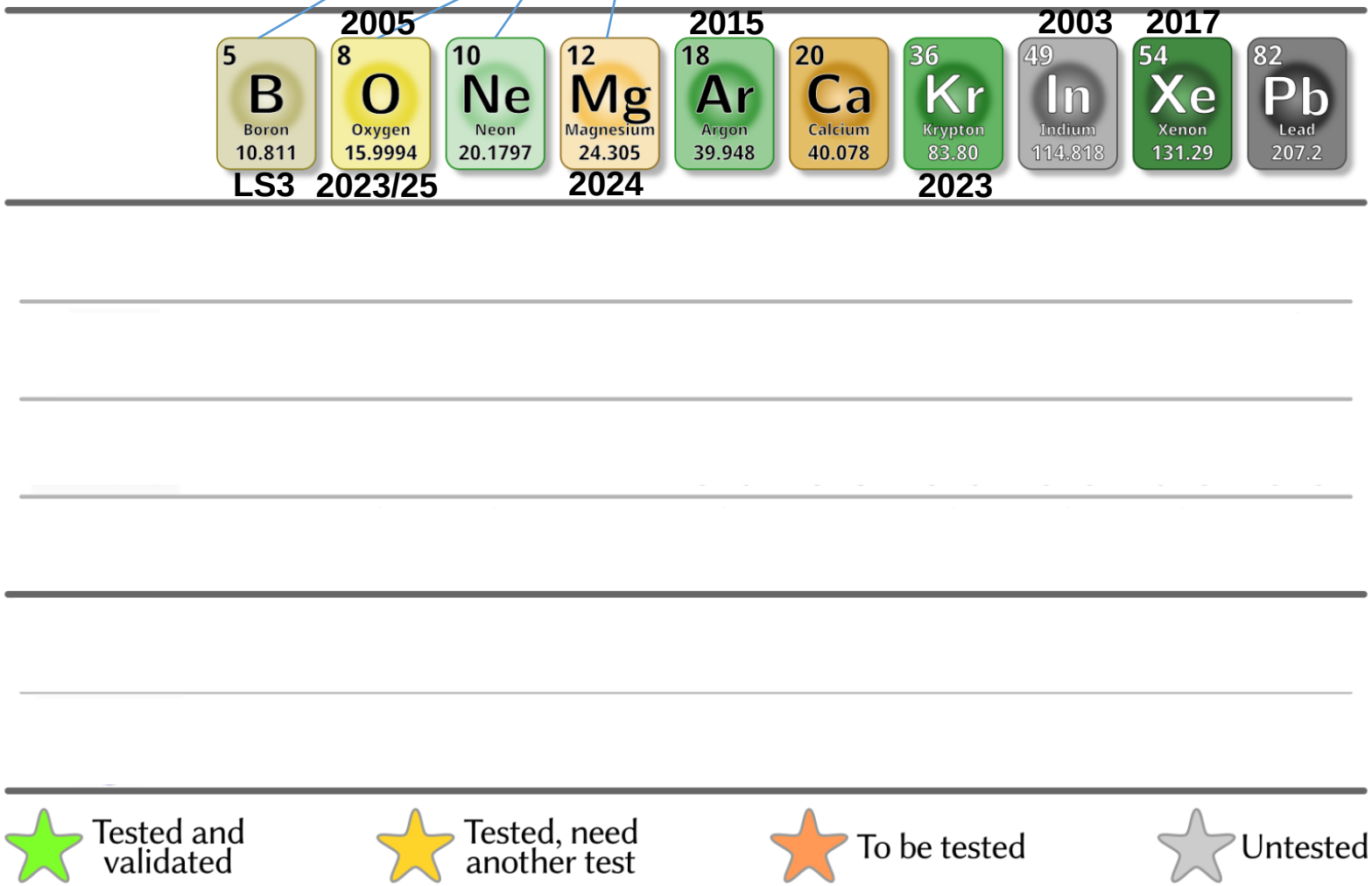


- Xenon already sent to NA61 and LHC in 2017
- During **6 h of stable collisions** about **3 μb^{-1}** were delivered to ATLAS and CMS. Because of the larger β∗ values, fractions of 1 µb−1 were delivered to ALICE and LHCb.

The present …

Future Ion physics users

14.11.2024 Thursday
Maciej Slupecki “Prospects with light nuclear species (10B, 24Mg, 20Ne)”
Natalia Triantafyllou “LHC Oxygen run: preparation status and plans”



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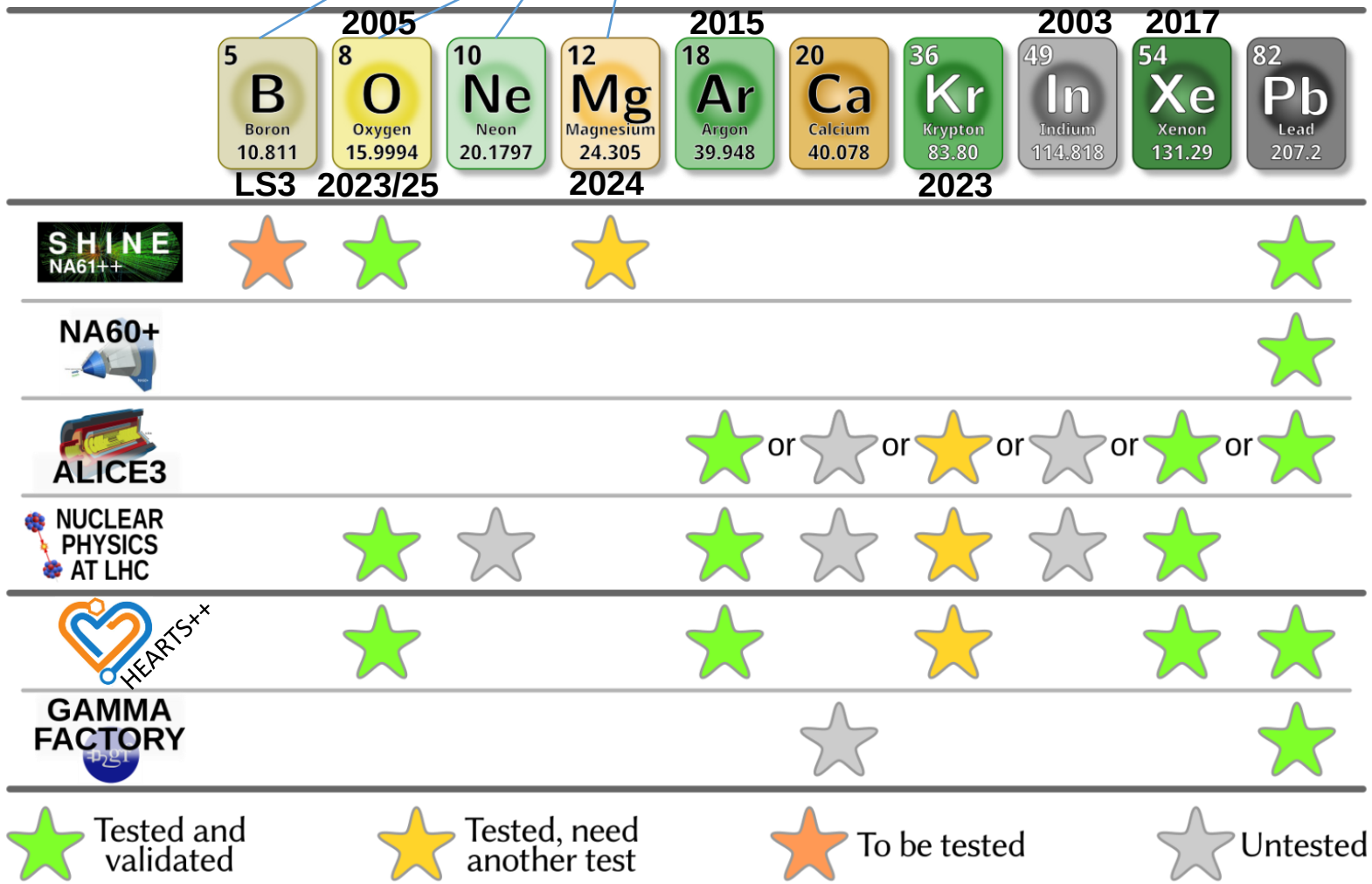


Run 4 (2029-2033)

A↑ Lnn↑
Run 5&6 (2036-2041)

PS fixed target
15’ switch 4 species

SPS Proof of Principle

Future Ions Working Group 2022 [1]

Based on experiments and facilities request

- Define future ion operation needs and their implications for the Ion Injector Accelerator Complex
- Quantify performance reach
- Propose realistic implementation plans with:
  - Costing and resource estimates
  - Personnel needed to operate the complex with more ions (as well as testing)
  - Impact on accelerator schedule
  - Exploit synergies with other studies

OXY4LHC Project 2021 [2]

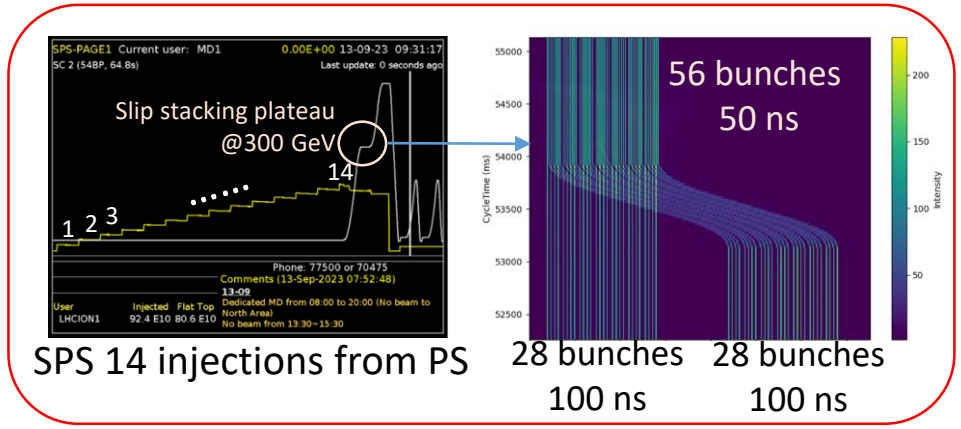
[1] EDMS doc 3157188 v.1
[2] CERN-ACC-NOTE-2024-0001

Performance reach studies

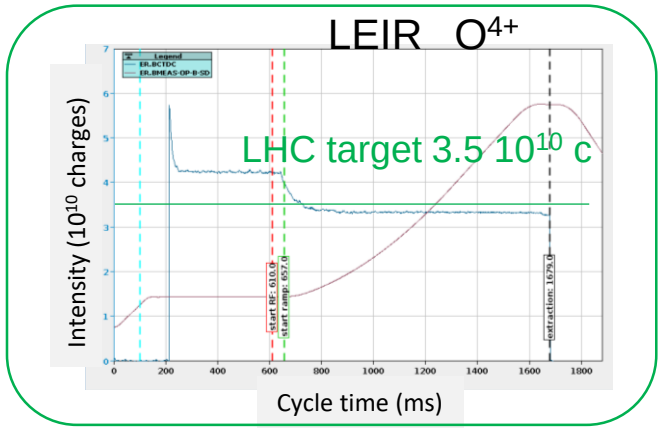
Performance assessment for LHC beams

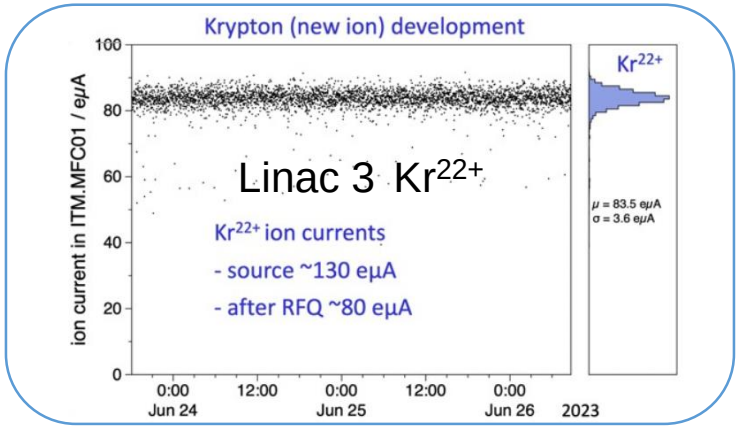
Experimental tests

- Lead physics run
  - Excellent, stable Pb^{54+} beam from Linac3 with ≥ 30 eμA
  - SPS slip-stacking with LIU parameters demonstrated
- Oxygen tests up to PS in Nov 2023
  - Ready for 2025 O-O & p-O collisions at LHC
  - Beam intensity from Linac3: 88 eμA (target: 70 eμA)
- Krypton tests in 2023
  - New Kr^{22+} beam, good stability
  - Intensity after source 130 eμA and 80 eμA after RFQ



After 2 days of commissioning!!

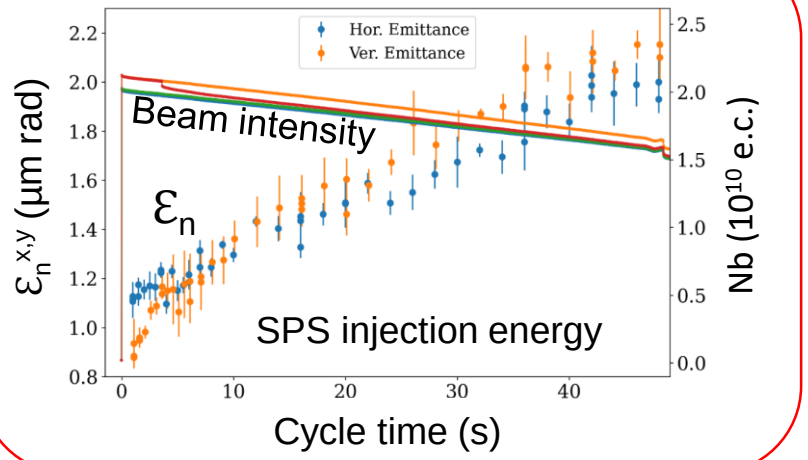


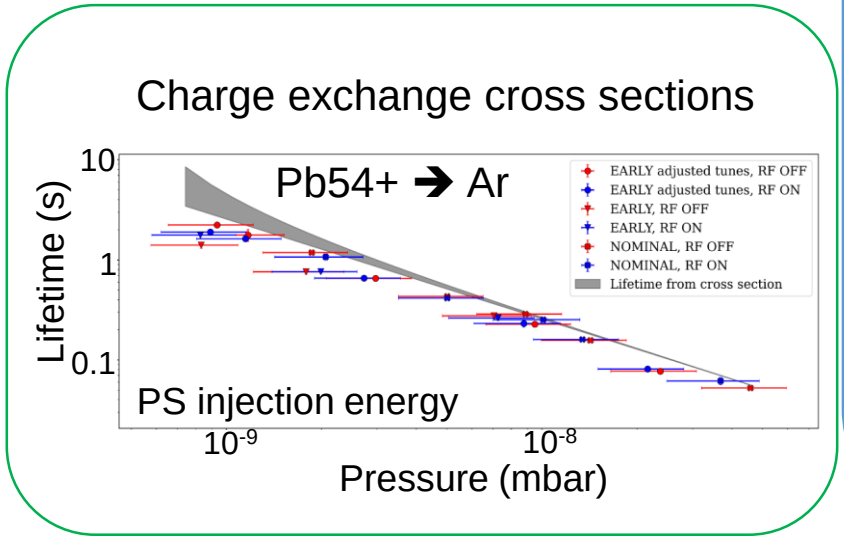


Performance assessment for LHC beams

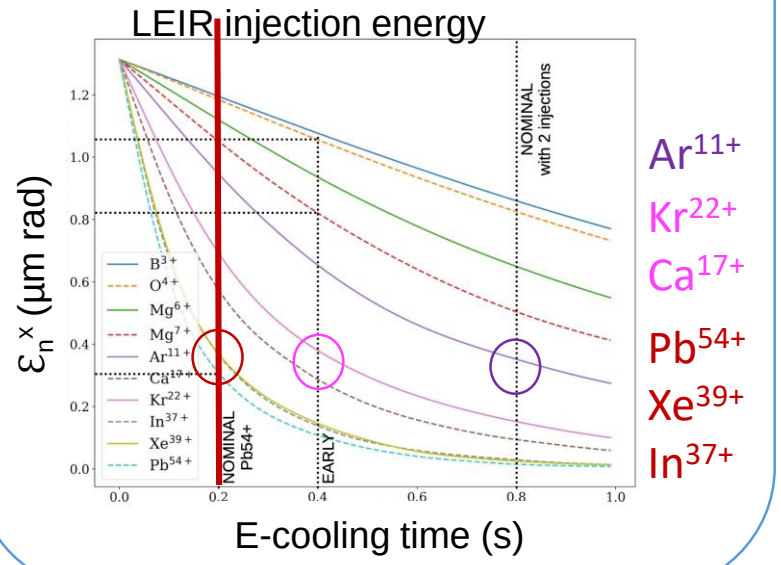
Benchmark simulations

- Detailed measurements with Pb in 2023 [9]
  - Beam intensity and emittance
  - Intra Beam Sscattering growth rates
  - Tune shifts from Space Charge
  - Beam gas interactions studies with Pb & Mg [10]
  - LEIR Electron cooler [11]





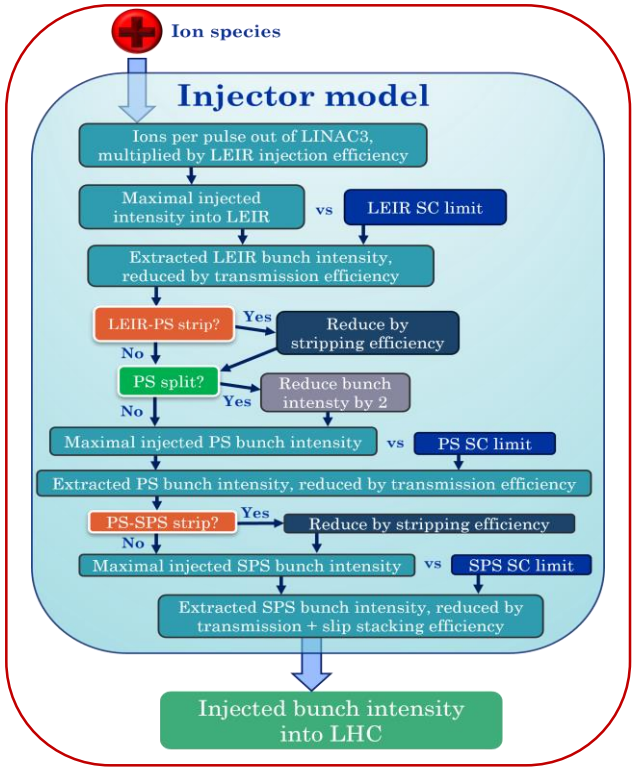
NOMINAL beam for LHC high performance = 200 ms/injection



Performance assessment for LHC beams

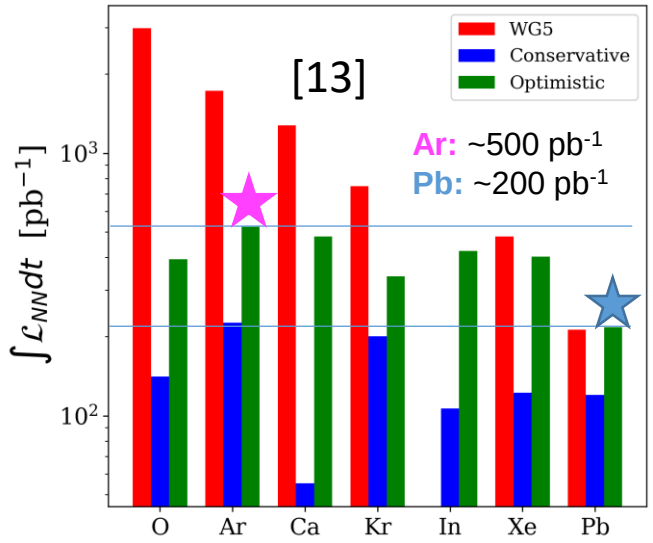
Benchmark simulations

- First time an **LHC Injector Model** being developed for ions including:
  - Tune shifts from Space Charge
  - Intra Beam Scattering growth rates
  - Beam gas interactions studies with Pb & Mg
  - LEIR Electron cooler



Very Preliminary Results

Nucleon-Nucleon integrated luminosity for 1 month run



WG5 [12]: too optimistic no Beam Dynamics Limits (BDL) in the injectors

Conservative:
today's Ion Complex

Optimistic:
LEIR-PS stripping
PS no-splitting
Isotope optimization

Both Conservative and Optimistic includes BDL

The future …

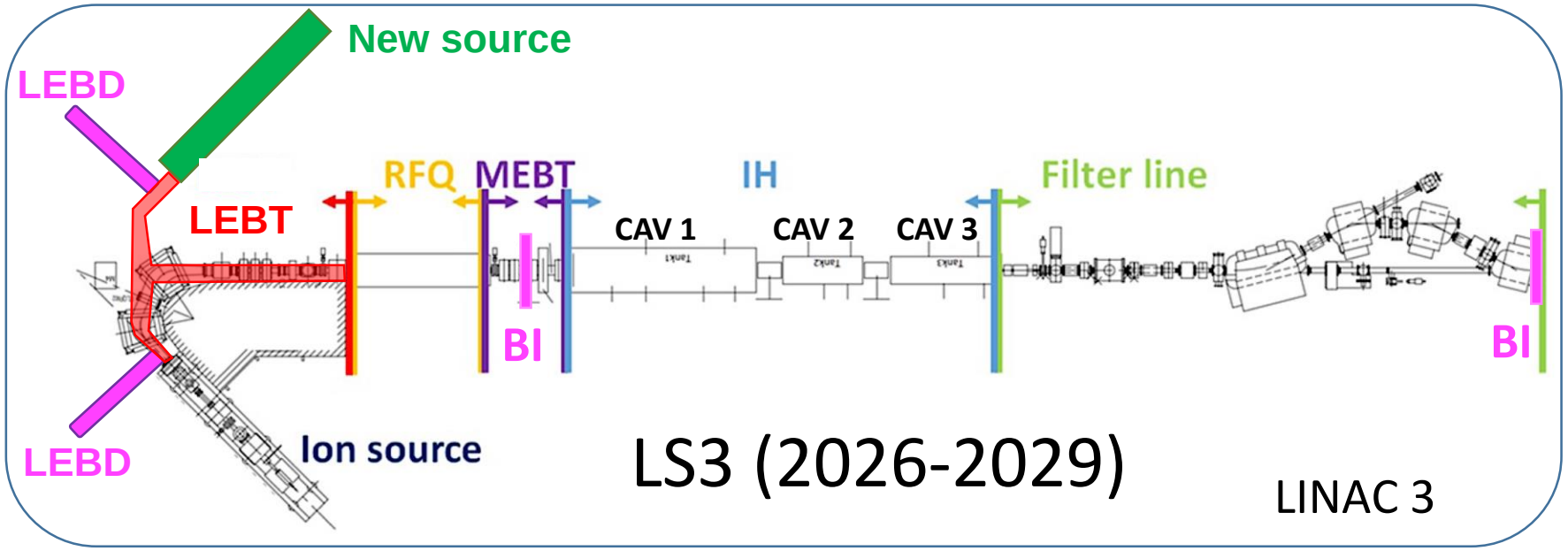
Ion Complex Upgrade (ICU) proposal

ICU DELIVERABLE 1

- New Linac3 source and LEBD out of both sources:
  - Operate up to 4 ions per year
  - Parallel commissioning of new ion beams for LHC, NA61++ and HEARTS++

ICU DELIVERABLE 2

- Connection of ion sources and BI downstream
  - Fast (15') switching between ions for HEARTS++
  - Automation of operation
  - Beam parametrization along Linac 3

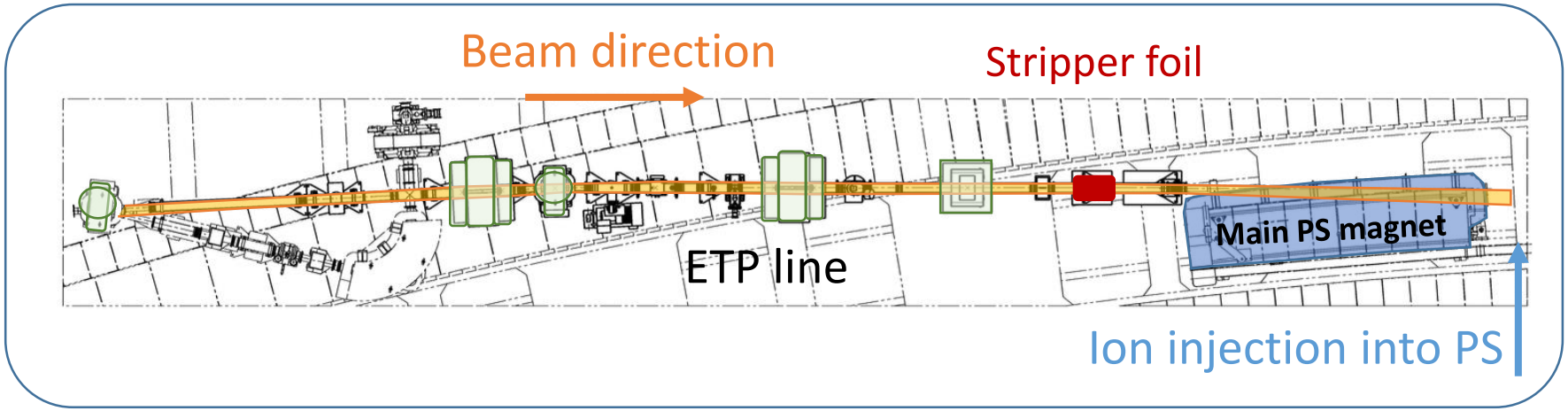


Ion Complex Upgrade (ICU) proposal

ICU DELIVERABLE 3

RUN 4 (2029-2033)

- Alternative stripping scenario?
  - Increase LHC brightness by reducing space-charge and IBS effects in SPS



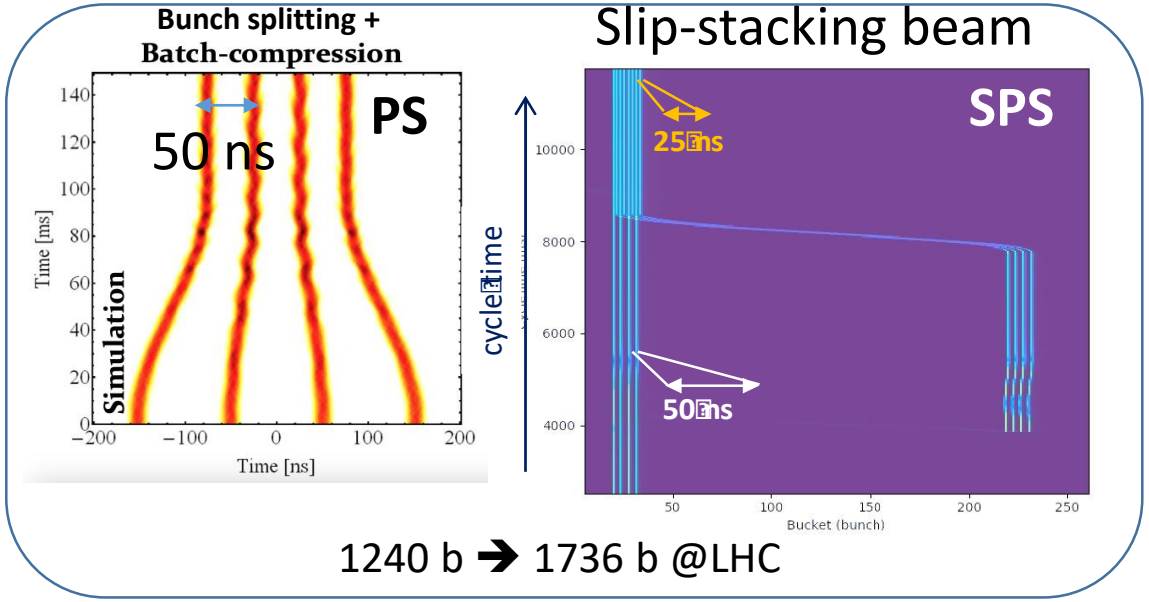
Alternative stripping system does not replace TT2 stripper system for heavy ions

Stripping scenario	p^{SPS}_{inj} (proton-equiv.) [GeV/c]
$Pb^{54+} \rightarrow Pb^{80+}$	17.1 → 25.4
$Kr^{22+} \rightarrow Kr^{36+}$	16 → 26

Ion Complex Upgrade (ICU) proposal

ICU DELIVERABLE 4

- 25 ns bunch spacing at LHC?
  - Increase LHC luminosity by increasing number of bunches



1240 b ➔ 1736 b @LHC

2 new PS RF cavities

ICU DELIVERABLE 5

- Ion Complex Consolidation

LS4 (2034-2035)

Conclusions

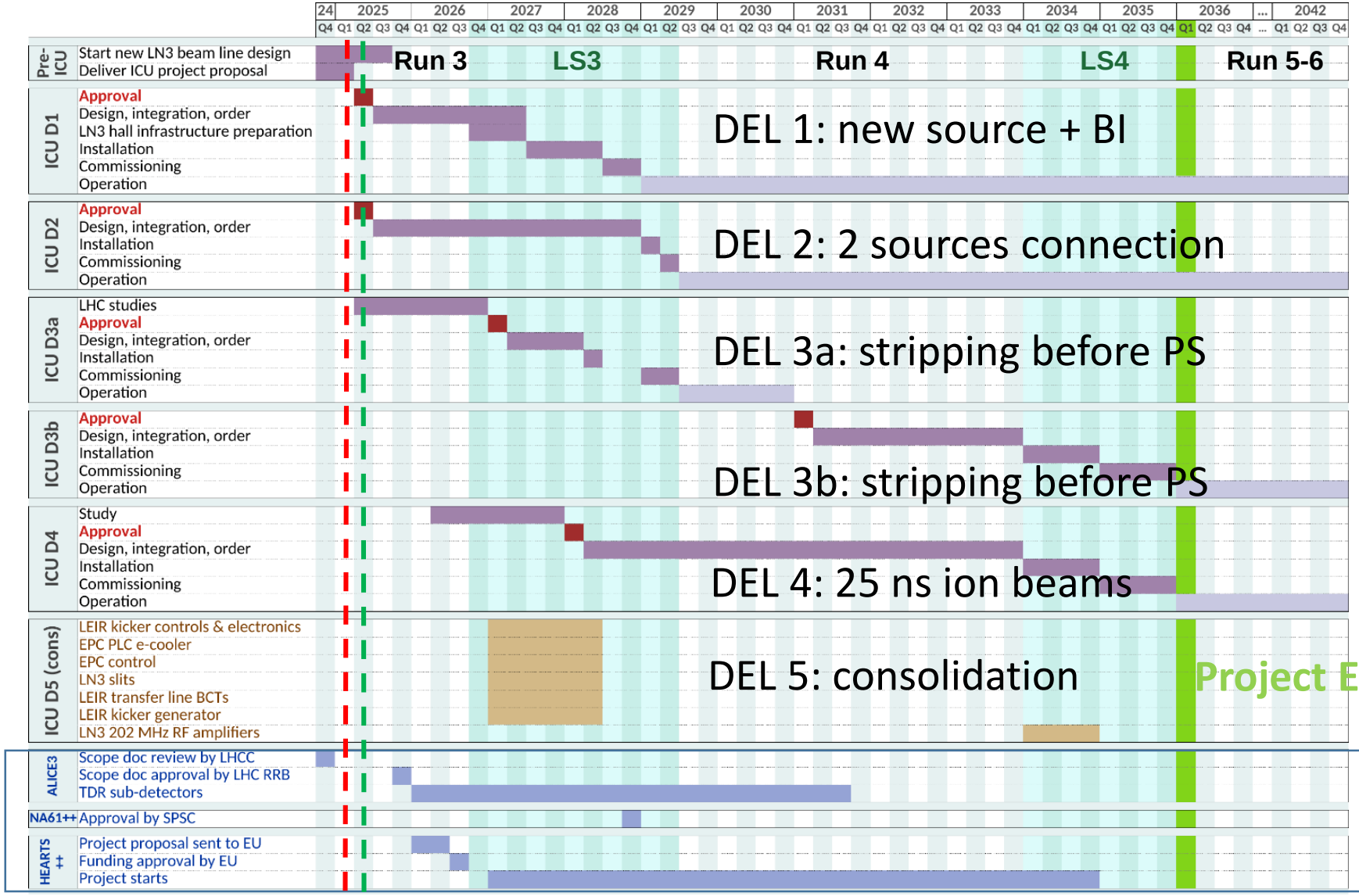
- Increased interest of physics with lighter ions from different physics communities and facilities
- All show important synergies ➔ explore different physics landscapes with the same effort

- The current CERN Ion Accelerator Complex offers opportunities to test new ions at the same time it fulfils its physics production commitments
- But we are hitting the limits
- To go beyond this limits an upgrade of part of the Ion Complex is needed

- ATS sector framework exists now, Future Ions WG, OXY4LHC project & PBC, where light ions operation feasibility is addressed taking into account beam dynamics limitations, alternative beam production schemas, beam intensities and LHC luminosity predictions …

- We can rather easily provide ion-gasses for pilot runs, e.g. O-O, p-O, Xe-Xe, Ne-Ne …
- High Luminosity is more involved and more time is needed for preparation

Project timeline proposal



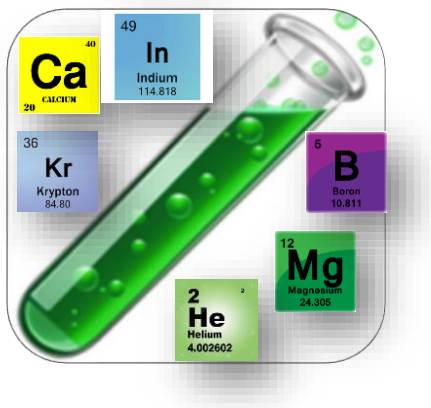
Assuming the involved groups can meet the milestones

Project proposal ready

Project approval @MTP

The baseline plan is still that LS3 will include new ion testing in Linac3 (but might be modified if a project is approved).

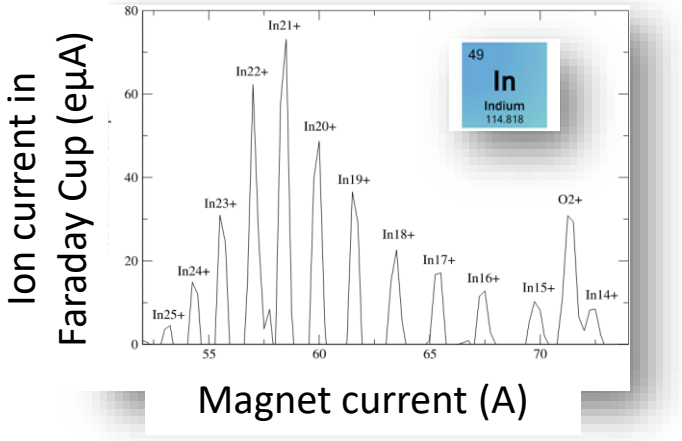
Accelerator Complex current constraints



Ion species development needs weeks to months:

- Need to address **stability**
- Need to address **long-term operation issues**
- Need to address **safety** procedures

Charges out of the source

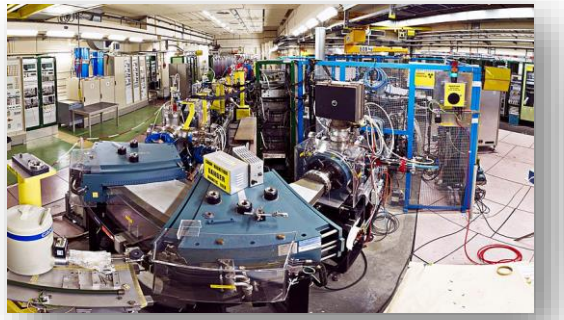


Experimental tests:

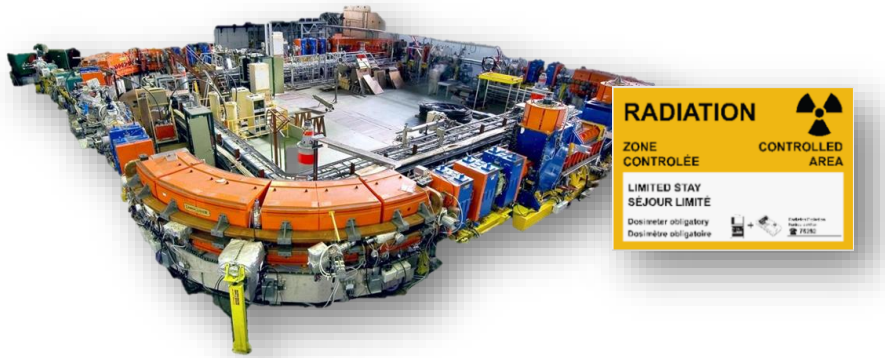
- Without tests there is **no valid prediction** of:
  - intensities or
  - dominant charge states

Accelerator Complex current constraints

Linac 3



LEIR



Some ion species require special personnel protection measures
➔ neutron generation – material activation

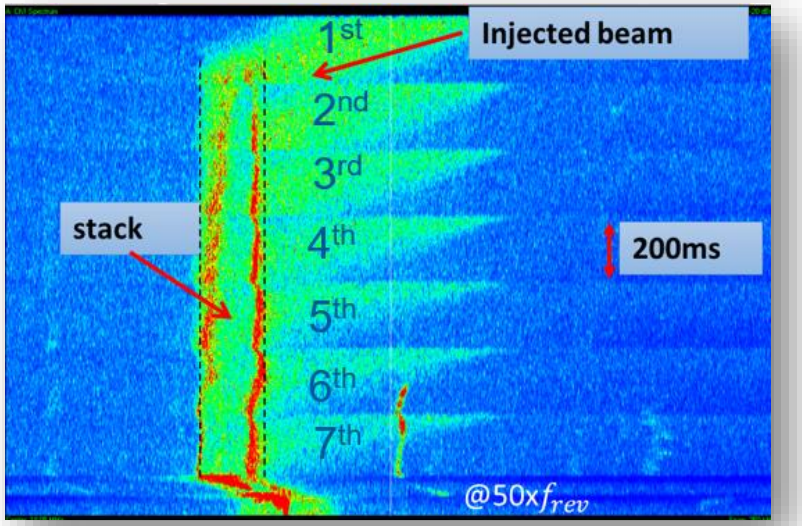
- **Linac 3** is a **simple controlled** area ➔ access possible during beam operation
  - Some ion species and/or beam intensities are **prohibitive unless personnel protection upgraded**

- **LEIR** is a controlled-limited stay area
  - But LEIR **open roof ➔ stray radiation?** in building 150, on-site and off-site areas
  - Some ion species and/or beam intensities are **prohibitive unless personnel protection upgraded**

Some ion species might have an impact on Radiation to electronics
➔ neutron generation – single even upsets

Accelerator Complex current constraints

LEIR Pb54+ ion beam cooling process(*)



LEIR electron cooling is fundamental to accumulate enough intensity:

- Is the **LEIR electron cooler** capable of cooling down the new ions in the available time (200 ms)?

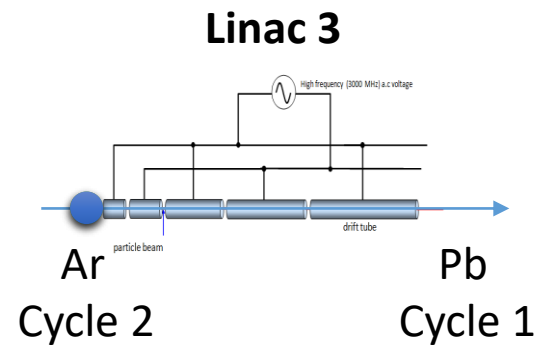
Beam dynamics with new ions across complex:

- Lifetime of the different species
- Space charge and Intra Beam Scattering effects

(*) Pb NOMINAL beam with 7 injections (LHC beam)

Accelerator Complex current constraints

Schedule constraints



Simplified sketch of PPM(*) operation

Even if we could have two sources we cannot do PPM operation with different elements:

- **Linac 3** is not PPM
- LEIR **transfer line** and **injection** elements are not PPM

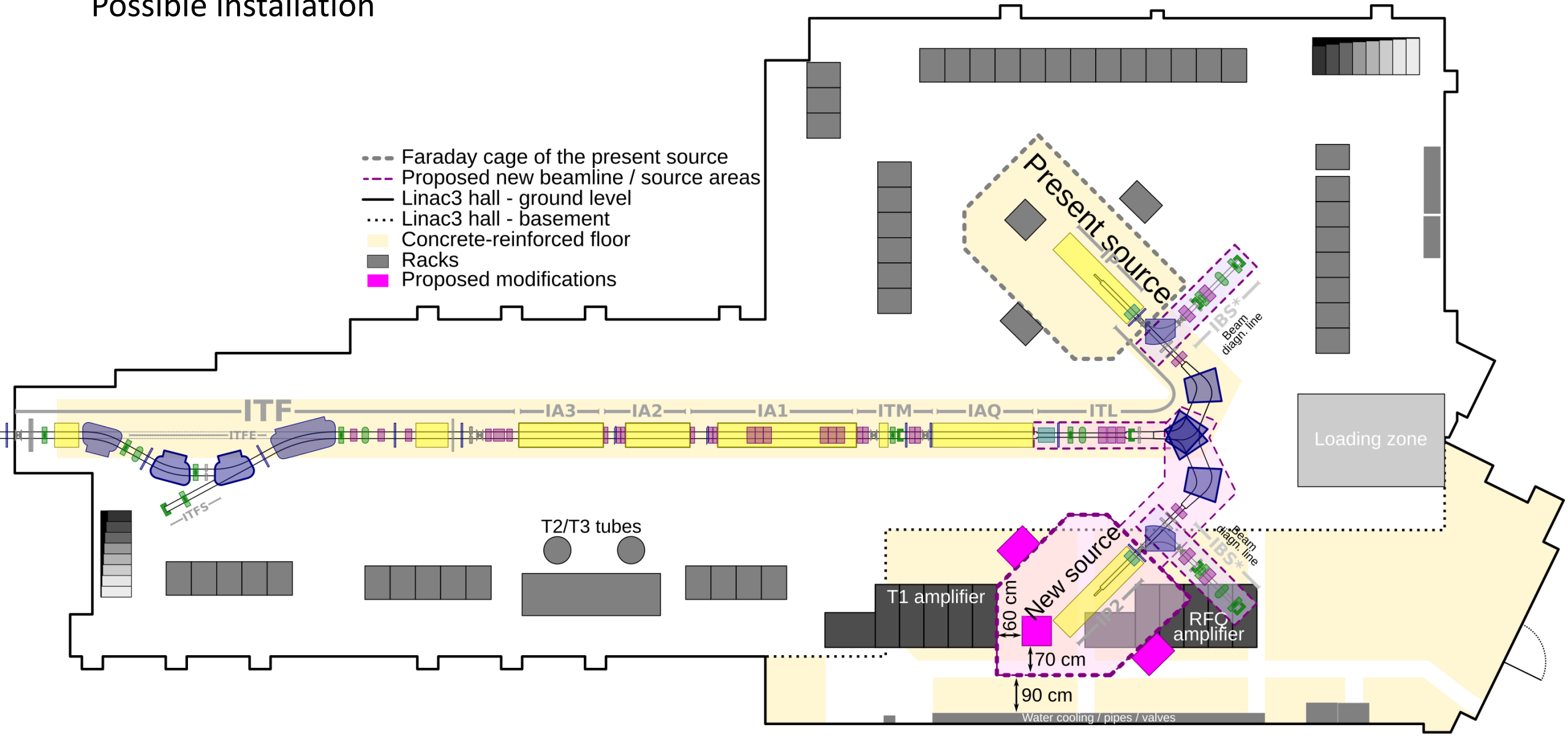
(*) PPM: Pulse to Pulse Modulation: Many elements are DC, not pulsing ➔ we cannot provide different particle types within the same super-cycle

Accelerator Complex current constraints

LHC

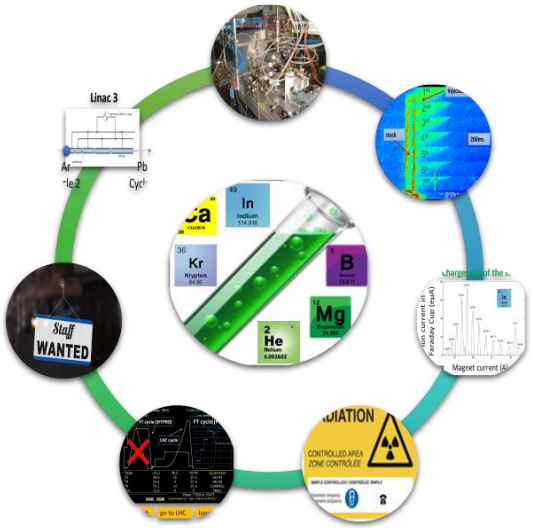
- Specific challenges related to higher stored beam energy and luminosity
- Collimation, machine protection and beam loss mechanisms
  - Is cleaning gain from crystal collimation sufficient for higher stored beam energy? Limits for absorber?
- Energy deposition from collisional losses

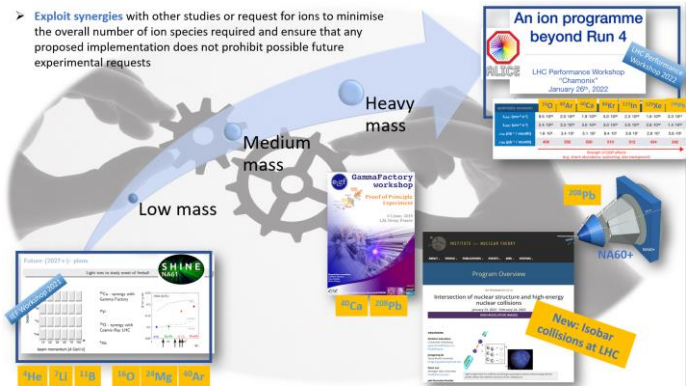
Possible installation



Summary

- **Several possible ion species requested after LS3**
- **Is our actual Ion Injector Complex able to operate all those species?**
  ➔ Large number of accelerator “unknowns/constraints”
- **ATS sector mandates BE to lead a Working Group to define future ion operation needs** based on the requests from **LHC** and **NA experiments** and their implications for the Ion Injector Accelerator Complex





Spares

Summary

- The New Ions working group has to include synergies with other potential programs, therefore, **INT requests will be studied by this working group**

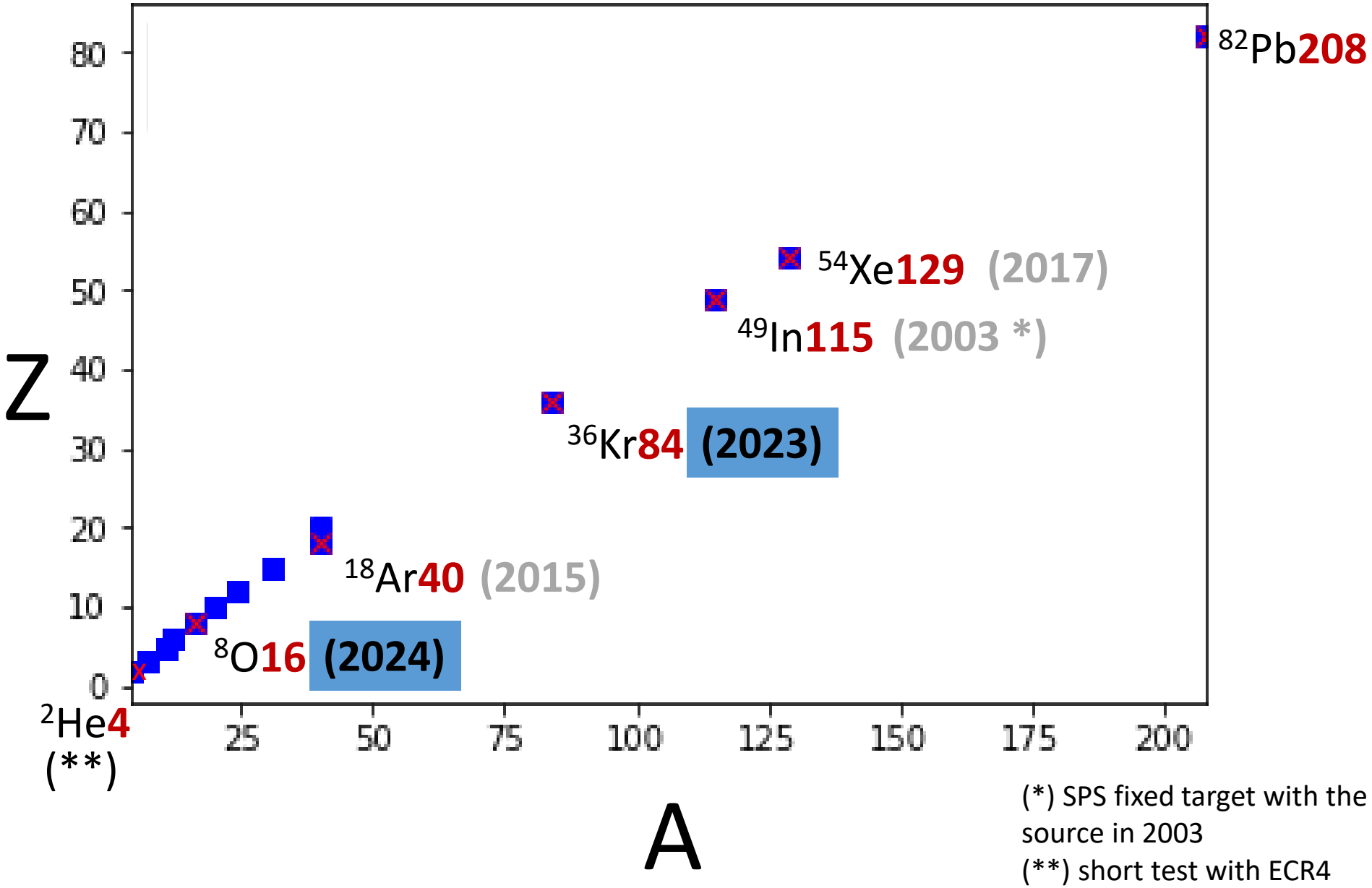
- NeNe collisions in Run 3? ➔ request needs to be approved by the LHCC and RB first, and no later than before the end of 2023

A	isobars	A	isobars	A	isobars	A	isobars	A	isobars	A	isobars
36	Ar, S	80	Se, Kr	106	Pd, Cd	124	Sn, Te, Xe	148	Nd, Sm	174	Yb, Hf
40	Ca, Ar	84	Kr, Sr, Mo	108	Pd, Cd	126	Te, Xe	150	Nd, Sm	176	Yb, Lu, Hf
46	Ca, Ti	86	Kr, Sr	110	Pd, Cd	128	Te, Xe	152	Sm, Gd	180	Hf, W
48	Ca, Ti	87	Rb, Sr	112	Cd, Sn	130	Te, Xe, Ba	154	Sm, Gd	184	W, Os
50	Ti, V, Cr	92	Zr, Nb, Mo	113	Cd, In	132	Xe, Ba	156	Gd,Dy	186	W, Os
54	Cr, Fe	94	Zr, Mo	114	Cd, Sn	134	Xe, Ba	158	Gd,Dy	187	Re, Os
64	Ni, Zn	96	Zr, Mo, Ru	115	In, Sn	136	Xe, Ba, Ce	160	Gd,Dy	190	Os, Pt
70	Zn, Ge	98	Mo, Ru	116	Cd, Sn	138	Ba, La, Ce	162	Dy,Er	192	Os, Pt
74	Ge, Se	100	Mo, Ru	120	Sn, Te	142	Ce, Nd	164	Dy,Er	196	Pt, Hg
76	Ge, Se	102	Ru, Pd	122	Sn, Te	144	Nd, Sm	168	Er,Yb	198	Pt, Hg
78	Se, Kr	104	Ru, Pd	123	Sb, Te	146	Nd, Sm	170	Er,Yb	204	Hg, Pb

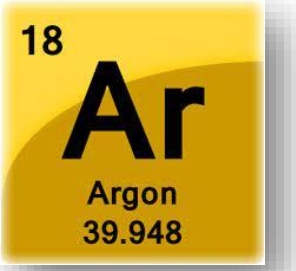
TABLE I. Pairs and triplets of stable isobars (half-life $> 10^8$ y). 141 nuclides are listed. The region marked in red contains large strongly-deformed nuclei ($\beta_2 > 0.2$). The region marked in blue corresponds to nuclides which may present an octupole deformation in their ground state [48].

arXiv:2209.11042v1 [nucl-ex] 22 Sep 2022

spares



(*) SPS fixed target with the ECR4 ion source in 2003
(**) short test with ECR4



Ions for NA61 & LHC

Current status of the studies

- Argon already sent to NA61 in 2015
- No issues expected from the Ion Complex if we keep the same LEIR flat top energy as 2015 for NA61, otherwise ➔ RP issues