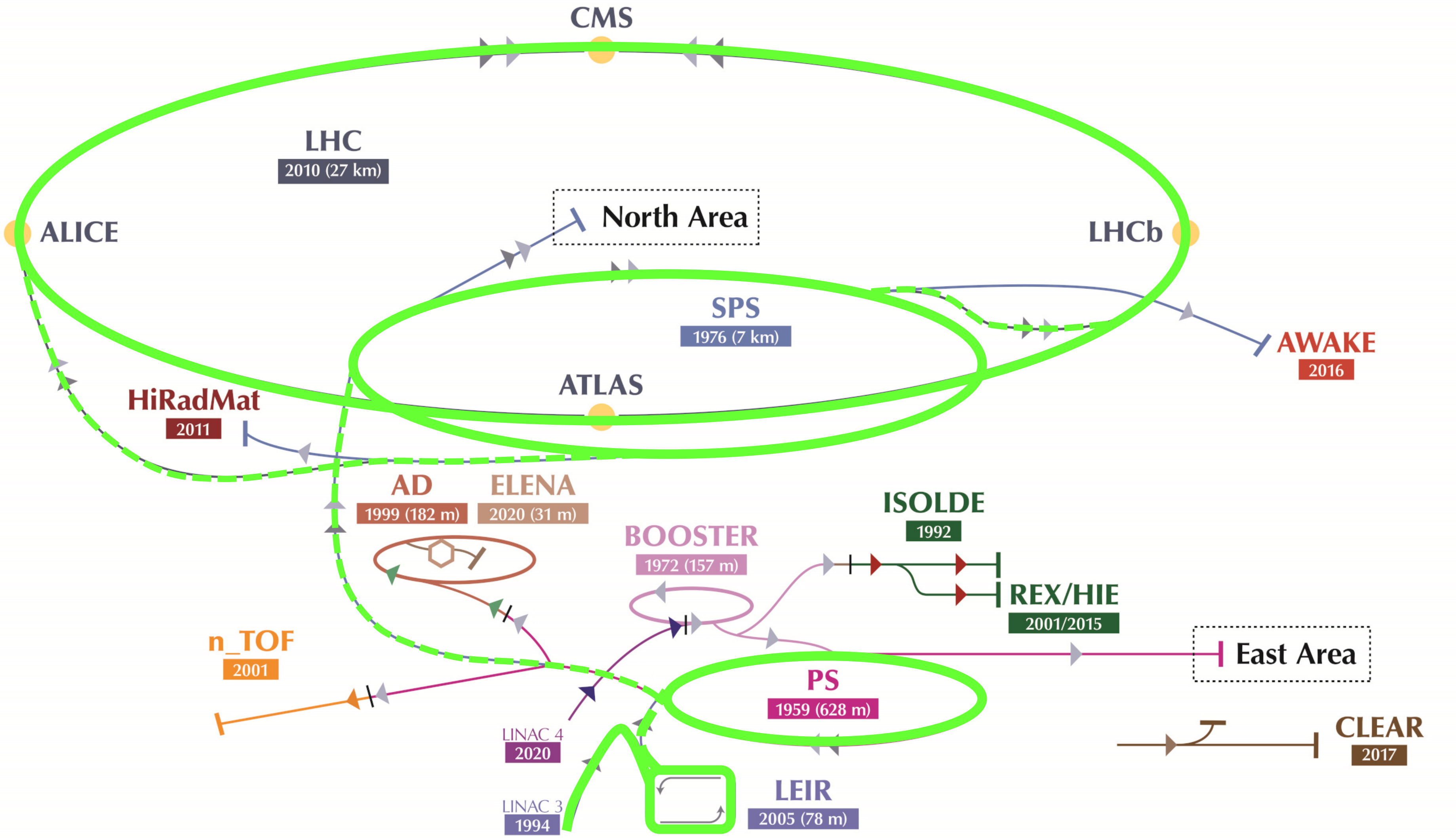
New ions operation in the CERN Accelerator Complex

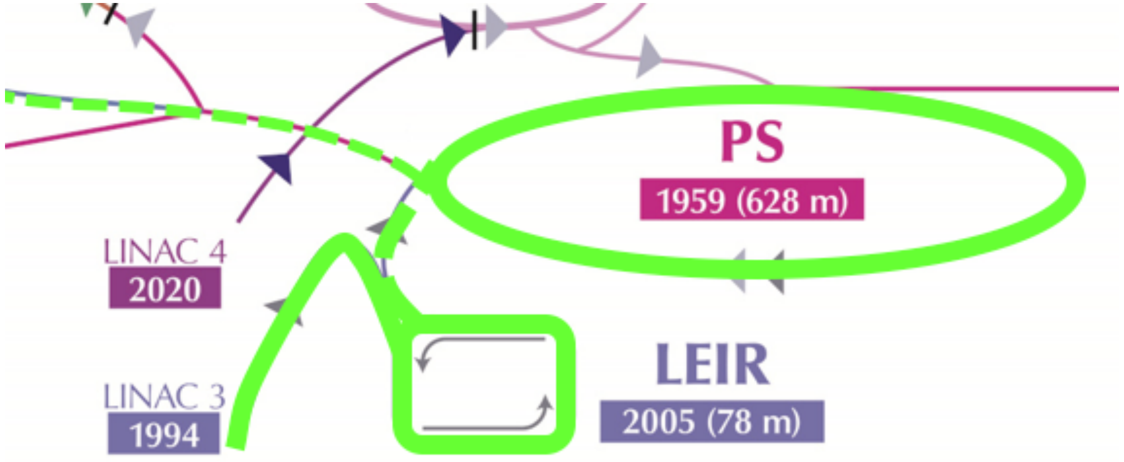
Acknowledgments: J. Jowett, R. Bruce, D. Kuchler, M. Widorski

CERN Ion Accelerator Complex



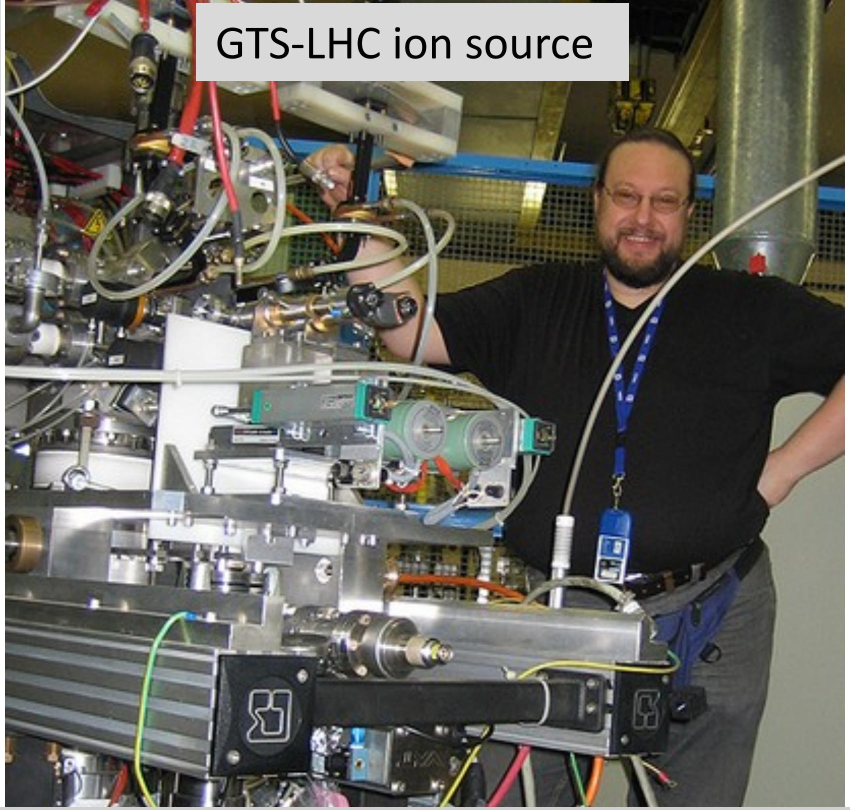
Ion Chain

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



Pb operation

GTS-LHC ion source



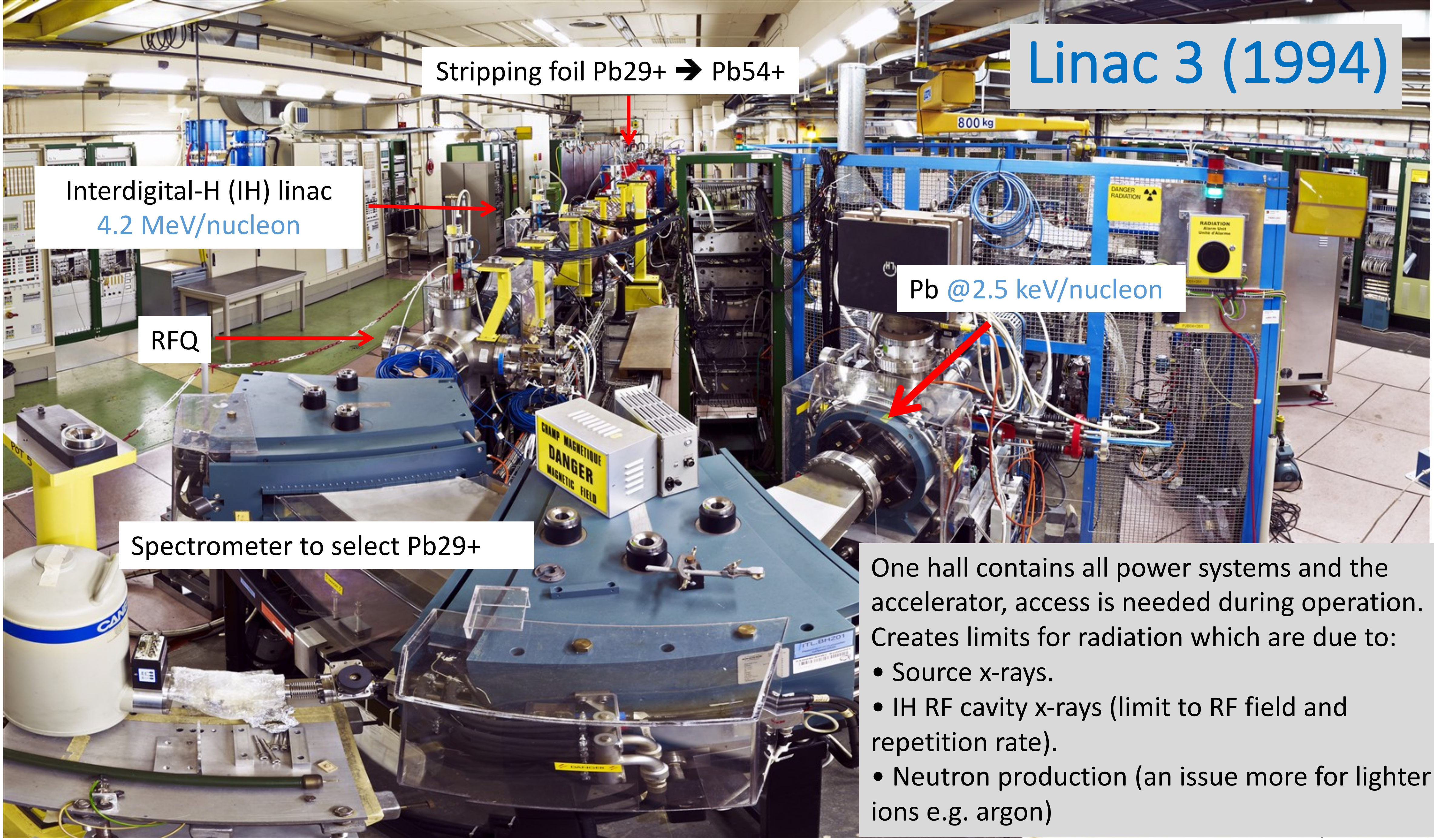
The metal is heated to around 800°C and ionized to become plasma. Ions are then extracted from the plasma and accelerated up to 2.5 keV/nucleon.

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

- Pulsed operation in afterglow mode, produces ~ms long pulses at 10Hz, only ~200 us pulses are accelerated, not all pulses.
- Equipped with gas injection and 2 micro ovens

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

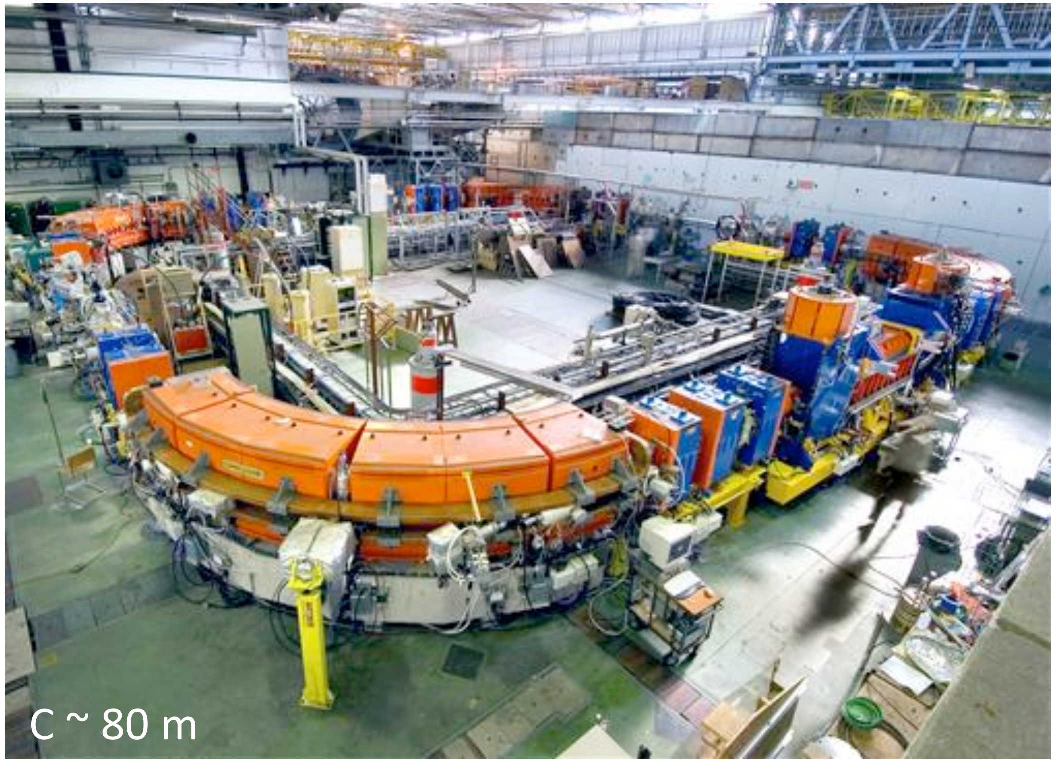
Linac 3 (1994)

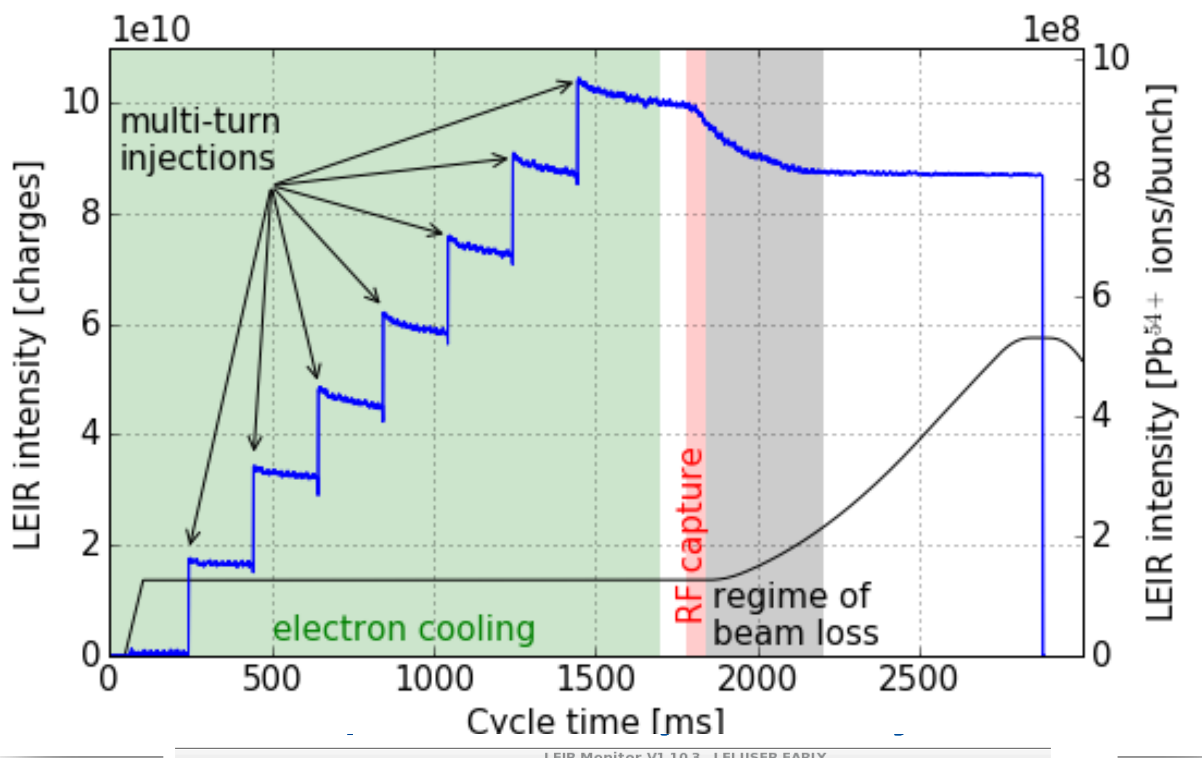


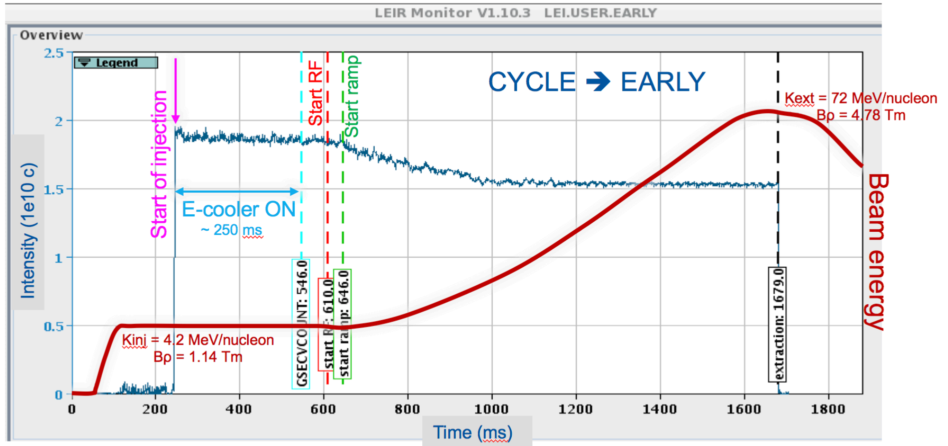
One hall contains all power systems and the accelerator, access is needed during operation. Creates limits for radiation which are due to:

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

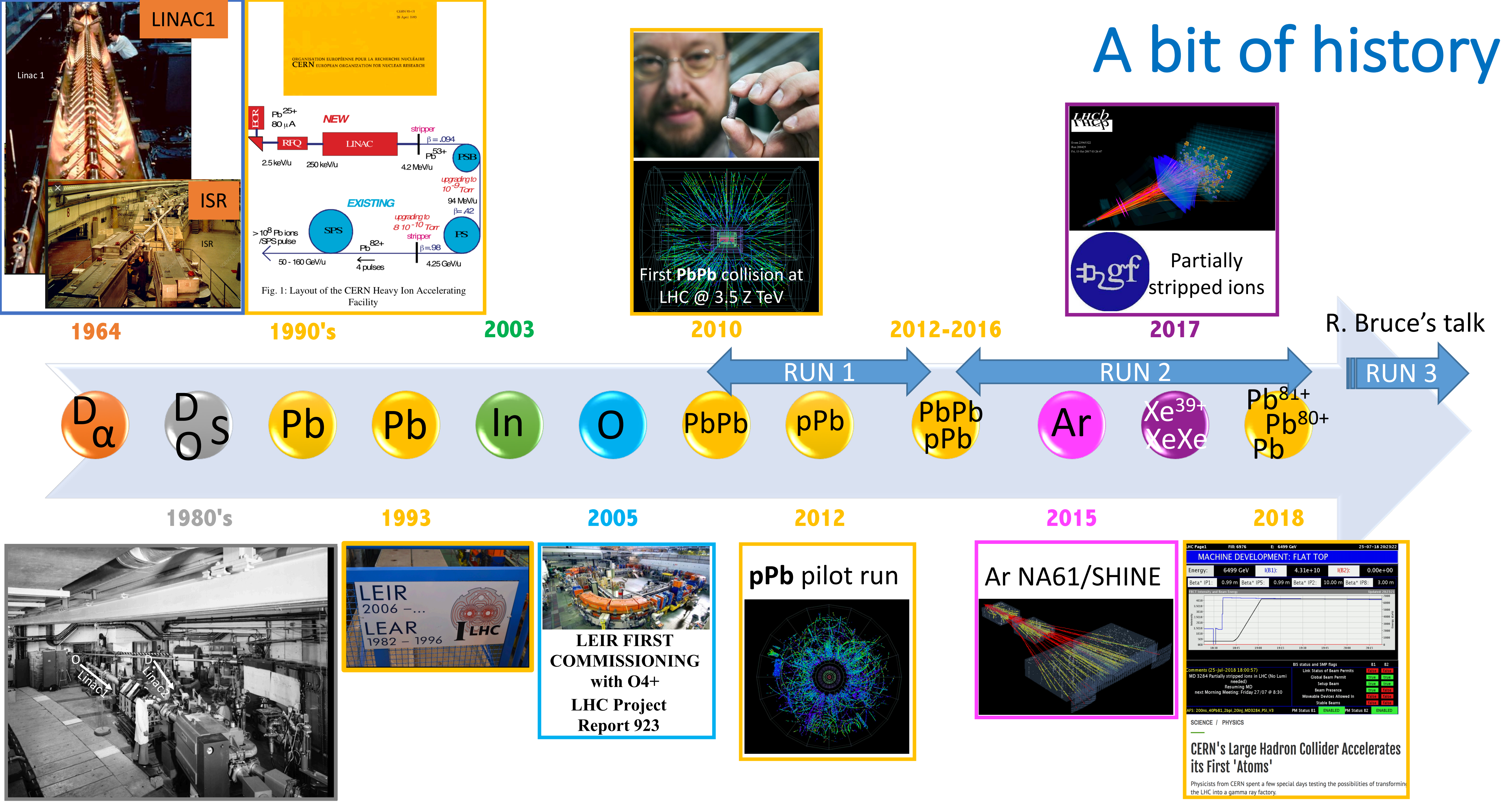
Ion Chain : Low Energy Ion Ring (LEIR)







LEIR accumulates the 200 μs pulses from Linac3;
then it bunches the beam (1 or 2 or 3 bunches)
Electron Cooling is used to achieve the required brightness
Acceleration to 72 MeV/nucleon (Pb) before transfer to the PS
LEIR Cycle is 2.4 s or 3.6 s
Pb54+ is fully stripped to Pb82+ in the transfer line from PS to SPS


A bit of history
LINAC1
Linac 1
ISR
ISR
NEW
ECR
Pb25+
80 μA
RFQ
LINAC
stripper
β=.094
Pb53+
PSB
2.5 keV/u
250 keV/u
4.2 MeV/u
upgrading to 10-9 Torr
EXISTING
94 MeV/u
β=.42
SPS
upgrading to 8 10-10 Torr
stripper
PS
> 10^8 Pb ions /SPS pulse
Pb82+
β=.98
50 - 160 GeV/u
4 pulses
4.25 GeV/u
Fig. 1: Layout of the CERN Heavy Ion Accelerating Facility
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
First PbPb collision at LHC @ 3.5 Z TeV
LHCb
Partially stripped ions
1964
1990's
2003
2010
2012-2016
2017
R. Bruce's talk
RUN 1
RUN 2
RUN 3
D α
D O S
Pb
Pb
In
O
PbPb
pPb
PbPb pPb
Ar
Xe39+ XeXe
Pb81+ Pb80+ Pb
1980's
1993
2005
2012
2015
2018
O Linac1
D Linac2
LEIR 2006 –...
LEAR 1982 – 1996
LHC
LEIR FIRST COMMISSIONING with O4+
LHC Project Report 923
pPb pilot run
Ar NA61/SHINE
MACHINE DEVELOPMENT: FLAT TOP
Energy: 6499 GeV
MD 3284 Partially stripped ions in LHC (No Lumi needed)
SCIENCE / PHYSICS
CERN's Large Hadron Collider Accelerates its First 'Atoms'
Physicists from CERN spent a few special days testing the possibilities of transforming the LHC into a gamma ray factory.

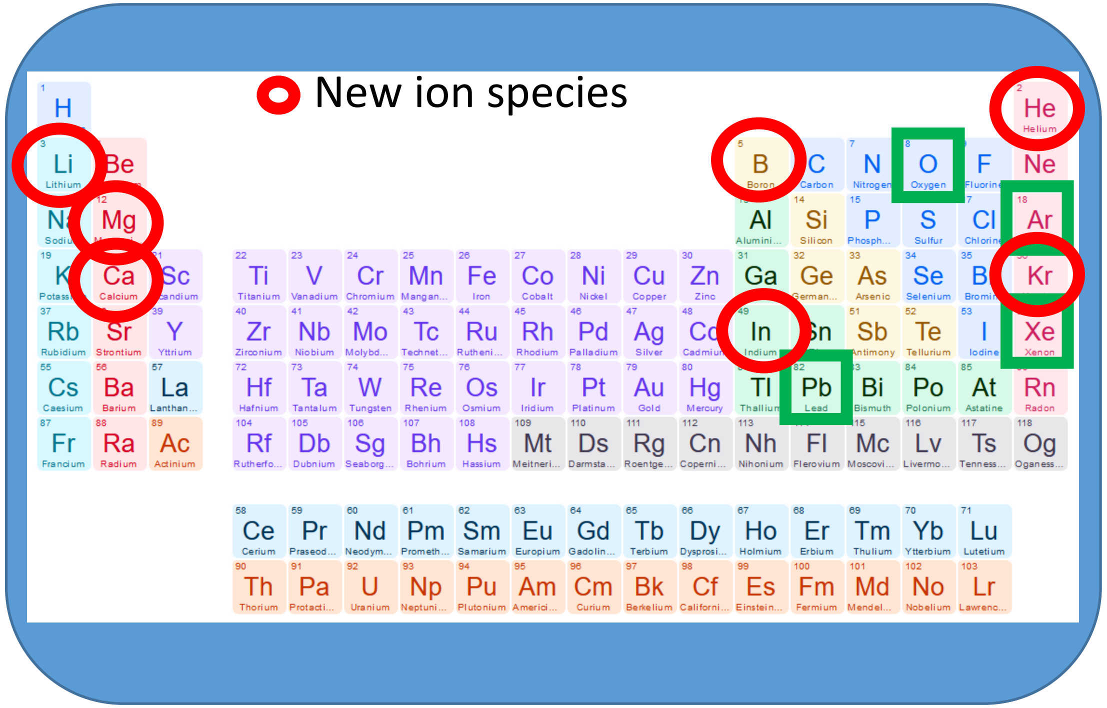
Summary of the requests for RUN 4 and beyond

Run 4 request

- **NA61++ (QGP)** ➔ [**Lithium**, **Helium**, **Boron**], **Magnesium**, **Oxygen (*)** and **Argon**
- **NA60++ (QCD)** ➔ **Lead**
- North Area experiments ➔ proton
- **LHC** ➔ **Lead**

Run 5 and Run 6 request

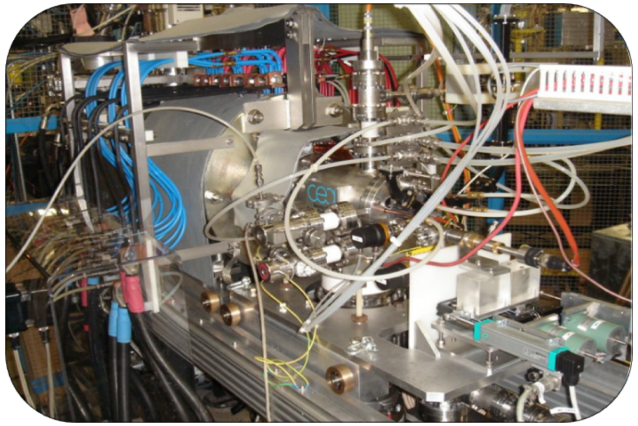
- Besides NA61++ requesting new ions species, **ALICE3** experiment requests highest possible LHC $\mathcal{L}_{NN}$, which, in principle, cannot be reached with Pb, but other lighter ions
- The list of possible LHC ions is: **Oxygen(*)**, **Argon**, **Calcium**, **Krypton**, **Indium(**)** and **Xenon**
- **Only the one with highest ℒ_NN (and mass)** will be selected for Run 5 and Run 6 operation



$\mathcal{L}_{NN}$ nucleon-nucleon luminosity
(*) commissioning expected in 2024
(**) tested with old ECR4 source
NA61++ and ALICE3 not yet approved

- **Red elements** ➔ needs development in the Accelerator Complex

Accelerator Complex current constraints



Only ONE source:

- New **developments** and **operational** beams **share** the **same source**
- Therefore, studies have to be done outside the operational run and with minimal impact on source performance

No beam diagnostics right after source:

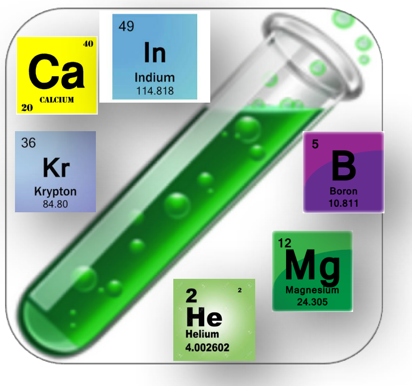
- Not possible to **characterize** the beam
- Not possible to **develop** realistic Linac 3 **models** (relying on scaling laws)
- Not possible to identify **new bottle necks**

Insufficient beam diagnostics:

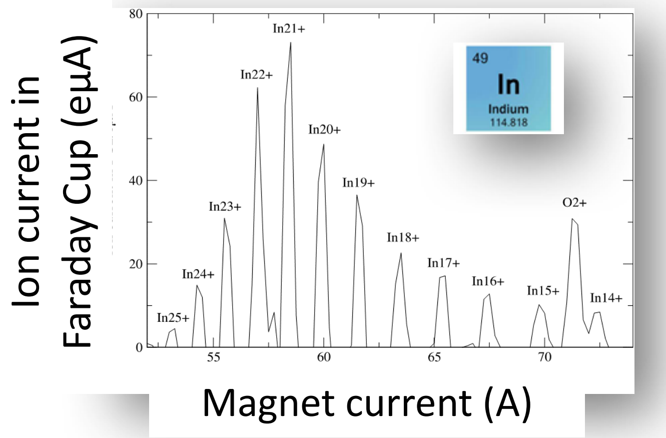
- Very limited beam diagnostics in LEBT

LEBT: Low Energy Beam Transport in Linac 3

Accelerator Complex current constraints



Charges out of the source



Ion species development needs weeks to months:

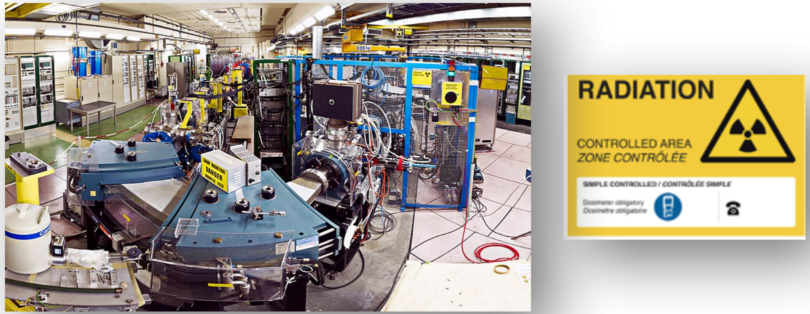
- Need to address **stability**
- Need to address **long-term operation issues**
- Need to address **safety** procedures

Experimental tests:

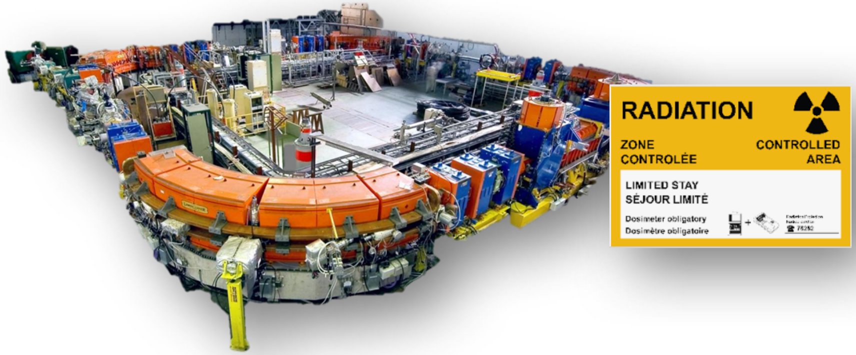
- Without tests there is **no valid prediction** of:
  - intensities or
  - dominant charge states

Accelerator Complex current constraints

Linac 3



LEIR



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

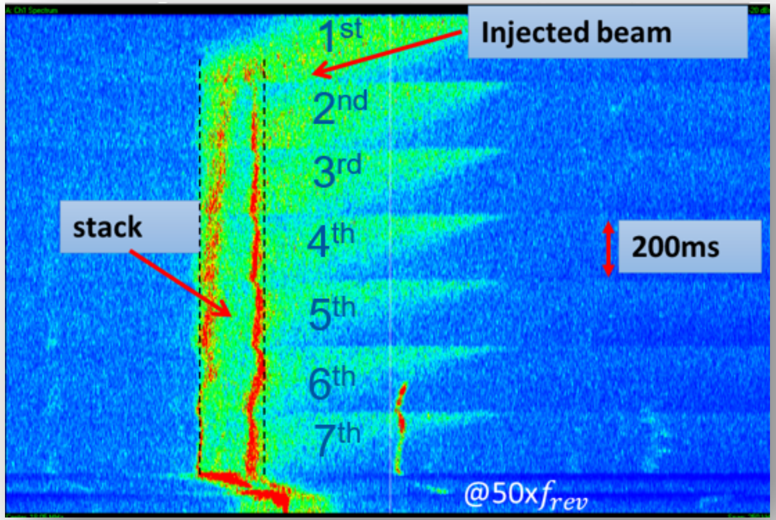
- **Linac 3** is a **simple controlled** area ➔ access possible during beam operation
  - Some ion species and/or beam intensities are **prohibitived unless personnel protection upgraded**

- **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 **prohibitived 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:

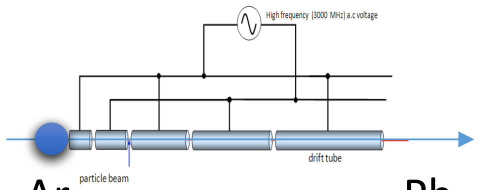
- Lifetime of the different species
- Space charge and Intra Beam Scattering effects

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

Accelerator Complex current constraints

Schedule constraints

Linac 3



Ar Pb

Cycle 2 Cycle 1

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

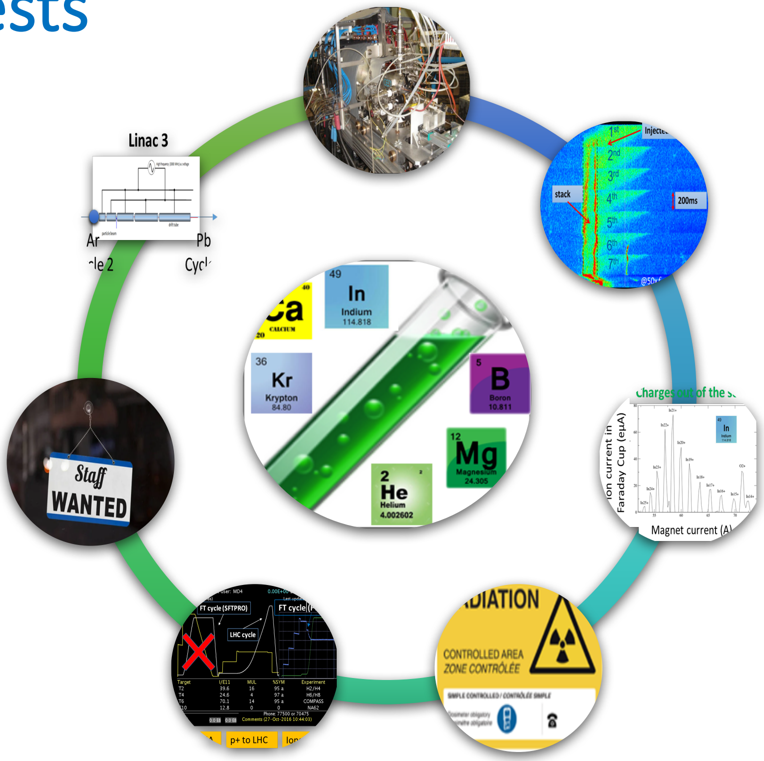
Accelerator Complex current constraints

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

Given the large number of requests after LS3

Given the large number of Accelerator Complex current constraints



The Accelerator and Technology Sector saw the need of creating a study group to evaluate

- the implications of the recent LHC requests for highest-luminosity-highest-density ion collisions as from Run 5
- the implications of the NA61 request for light ion runs as from Run 4

Working Group on Future Ions in the CERN Accelerator Complex

Working Group Mandate

- Determine the **current limitations** in the complex:
  - From beam dynamics
  - From radio protection
  - From source operation (chemical hazards)
  - From radiation to electronics
  - From radio frequency systems
  - From beam instrumentation
  - ….
- Deliver a list of **possible improvements**
- Quantify the **expected performance** reach
- Propose **realistic implementation plans** with **costing** and **resource estimates**

- **Exploit synergies** with other studies or request for ions to minimise the overall number of ion species required and ensure that any proposed implementation does not prohibit possible future experimental requests

Low mass

Medium mass

Heavy mass

An ion programme beyond Run 4

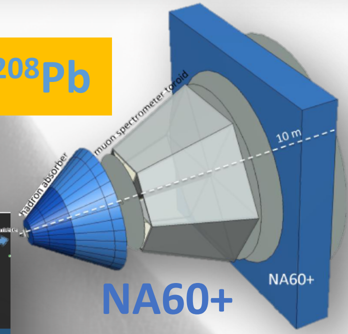
ALICE

LHC Performance Workshop
"Chamonix"
January 26th, 2022

LHC Performance Workshop 2022

optimistic scenario	^{16}O	^{40}Ar	^{40}Ca	^{84}Kr	^{115}In	^{129}Xe	^{208}Pb
$\langle L_{AA} \rangle$ ($cm^{-2} s^{-1}$)	$9.5 \cdot 10^{29}$	$2.0 \cdot 10^{29}$	$1.9 \cdot 10^{29}$	$5.0 \cdot 10^{28}$	$2.3 \cdot 10^{28}$	$1.6 \cdot 10^{28}$	$3.3 \cdot 10^{27}$
$\langle L_{NN} \rangle$ ($cm^{-2} s^{-1}$)	$2.4 \cdot 10^{32}$	$3.3 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$3.0 \cdot 10^{32}$	$2.6 \cdot 10^{32}$	$1.4 \cdot 10^{32}$
$\mathcal{L}_{AA}$ (nb^{-1} / month)	$1.6 \cdot 10^{3}$	$3.4 \cdot 10^{2}$	$3.1 \cdot 10^{2}$	$8.4 \cdot 10^{1}$	$3.9 \cdot 10^{1}$	$2.6 \cdot 10^{1}$	$5.6 \cdot 10^{0}$
$\mathcal{L}_{NN}$ (pb^{-1} / month)	409	550	500	510	512	434	242

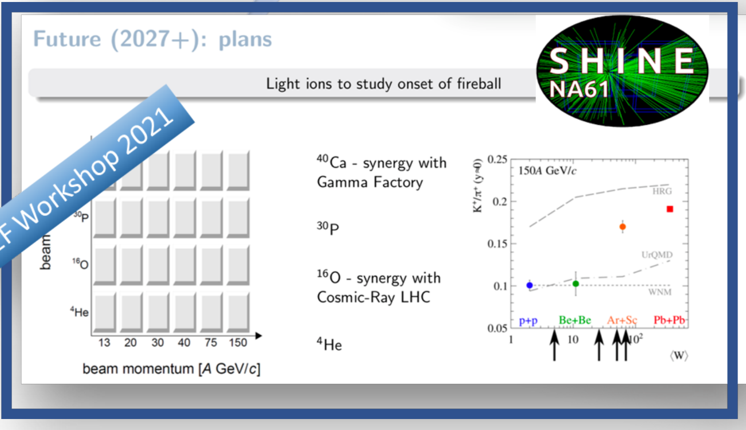
Strength of QGP effects
(e.g. charm abundance, quenching, also background)



^{208}Pb

^{40}Ca ^{208}Pb

New: Isobar collisions at LHC



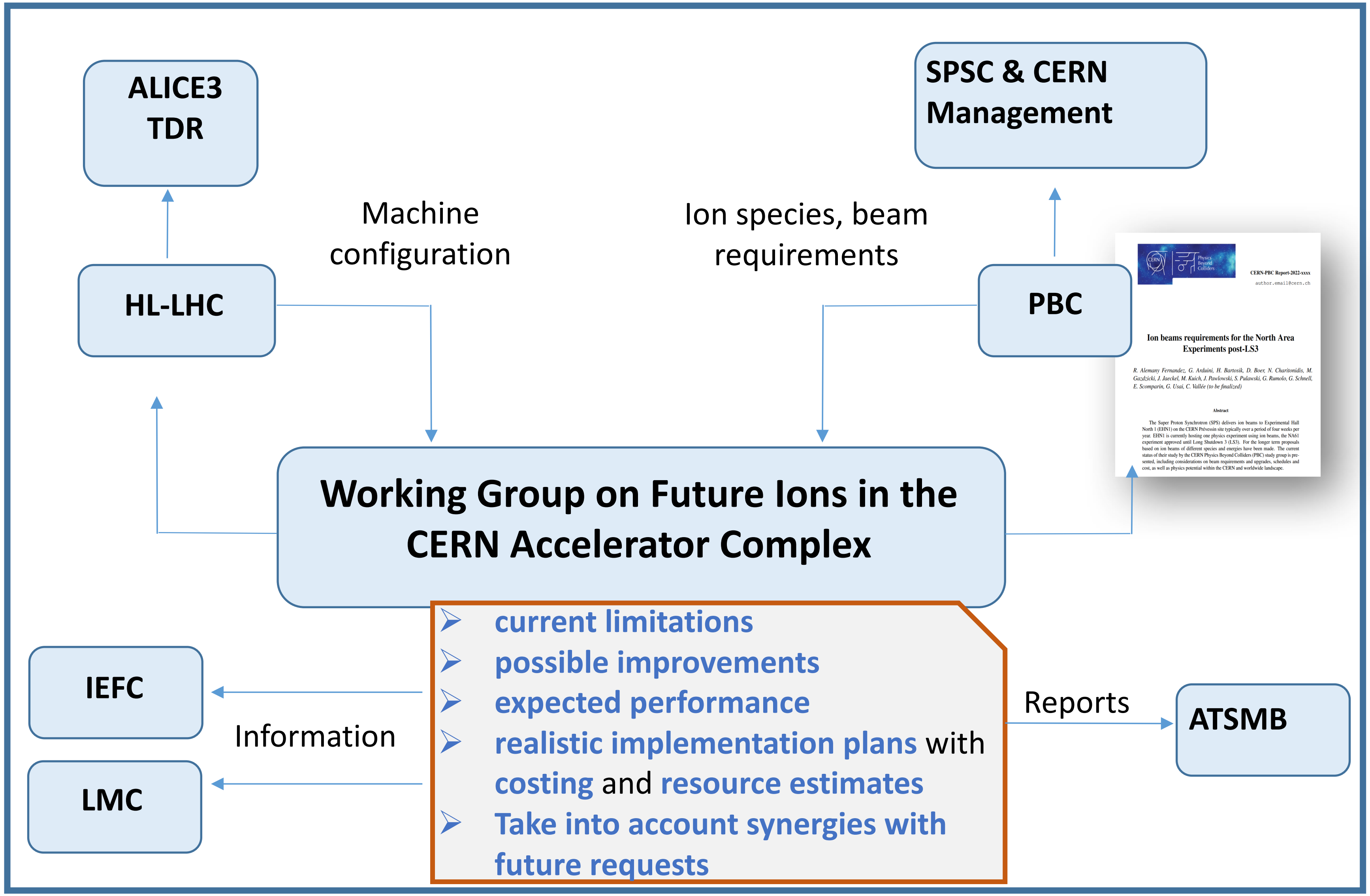
^{4}He ^{7}Li ^{11}B ^{16}O ^{24}Mg ^{40}Ar

Reporting & WG members & dead lines

The working group reports to the **ATSMB** and informs the **IEFC**, **LMC**, **PBC** Accelerator Capabilities Working Group about progress (PBC ACWG members are part of the Future Ions Working Group)

Timeline:

- Some deliverables will be finished along Run3, in particular everything affecting NA61, since “in principle” A10-30 physics is due in Run4
- WG should complete **all feasibility studies by end 2025**

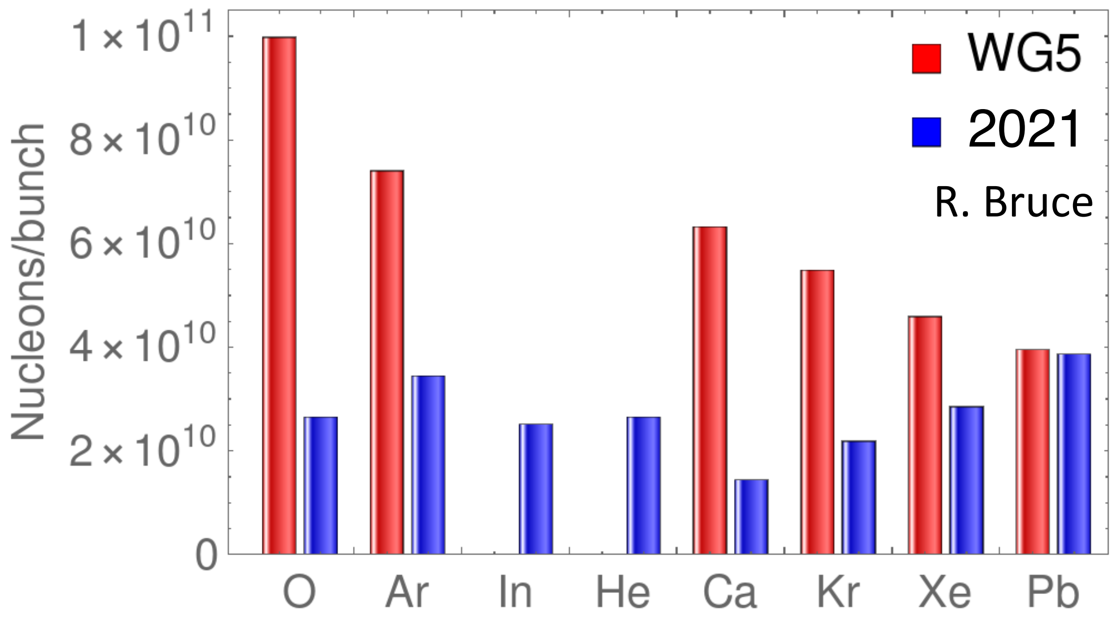

ALICE3 TDR
HL-LHC
Machine configuration
Ion species, beam requirements
SPSC & CERN Management
PBC
CERN-PBC Report-2022-xxxx
Ion beams requirements for the North Area Experiments post-LS3
Working Group on Future Ions in the CERN Accelerator Complex
current limitations
possible improvements
expected performance
realistic implementation plans with costing and resource estimates
Take into account synergies with future requests
IEFC
LMC
Information
Reports
ATSMB

Ions for LHC

Current status of the studies

- Initial study of potential LHC performance with new ions done in the WG5 yellow report
  - Based only on empirical charge scaling from earlier FT experience, detailed limits in injectors not accounted for
  - indicated a large gain in bunch intensity, and LHC integrated luminosity, for the lightest ion species
- **Refined studies in 2021**, including most important present limitations in injectors
  - space charge in LEIR and SPS, assessed through scaling from Pb observations
  - Today, can't disentangle the limits on Pb from IBS and space charge at SPS injection. Assuming conservatively the that space charge dominates
  - Accounting for current from Linac3, bunch splitting, stripping, γ at entrance and exit of each machine depending on the charge state
- Results: significantly lower bunch intensity delivered to LHC than in WG5

Estimated intensity injected to LHC



JAPW Dec'22
https://indico.cern.ch/event/1194548/contributions/5093964/attachments/2563454/4419007/2021.12.08--JAPW_future_ion_operation.pdf

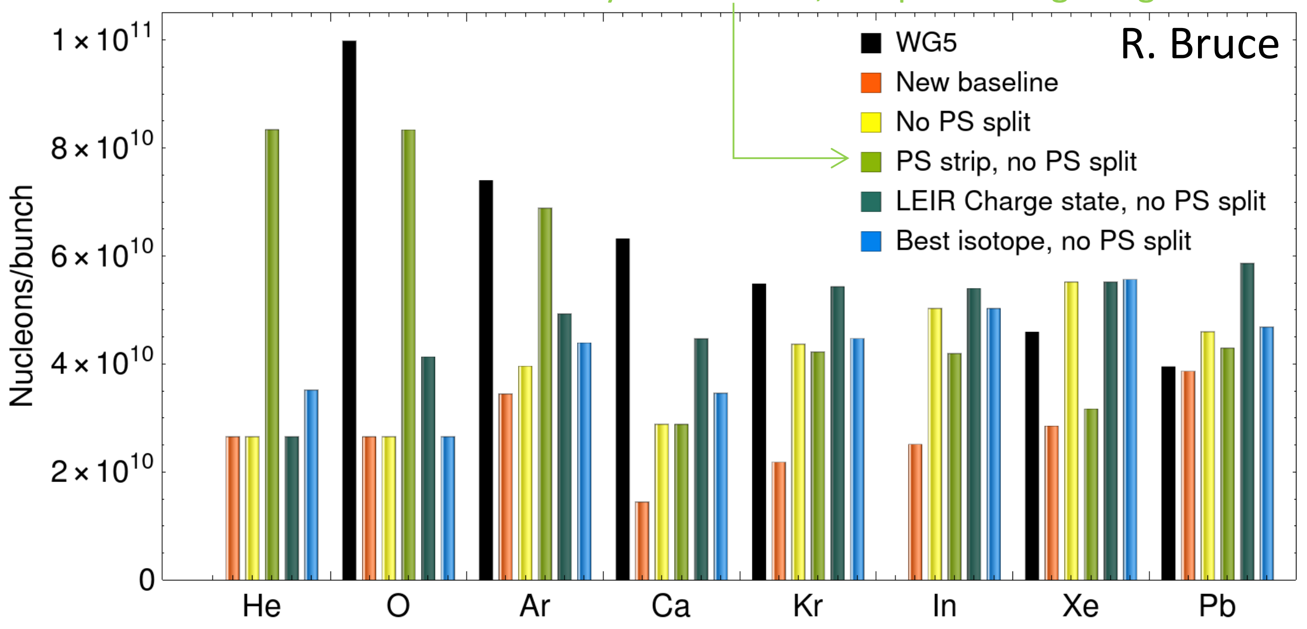
Ions for LHC

Current status of the studies

- In addition, studied in calculations various ways of improving the bunch intensity from the injectors
  - **Omit splitting in PS** (gives higher intensity to SPS if LEIR is limiting)
  - Introduce **new stripping stage** between LEIR and PS
    - Could introduce space-charge limits in PS
    - See talk N. Biancacci
  - **Optimize charge-to-mass** ratio
    - Vary charge states after stripping in LINAC3
    - Explore the use of different isotopes (to optimize charge-to-mass ratio)
  - Operational feasibility still to be proven for these ideas – relying on new and untested concepts

- Defined two scenarios for LHC studies, pending more detailed investigations
  - conservative – what we hope we could realistically achieve based on today's best knowledge
  - Optimistic - assume a variation in LEIR charge state and no PS splitting
    - Not tested – can't promise to deliver this

Likely not realistic, PS space charge neglected



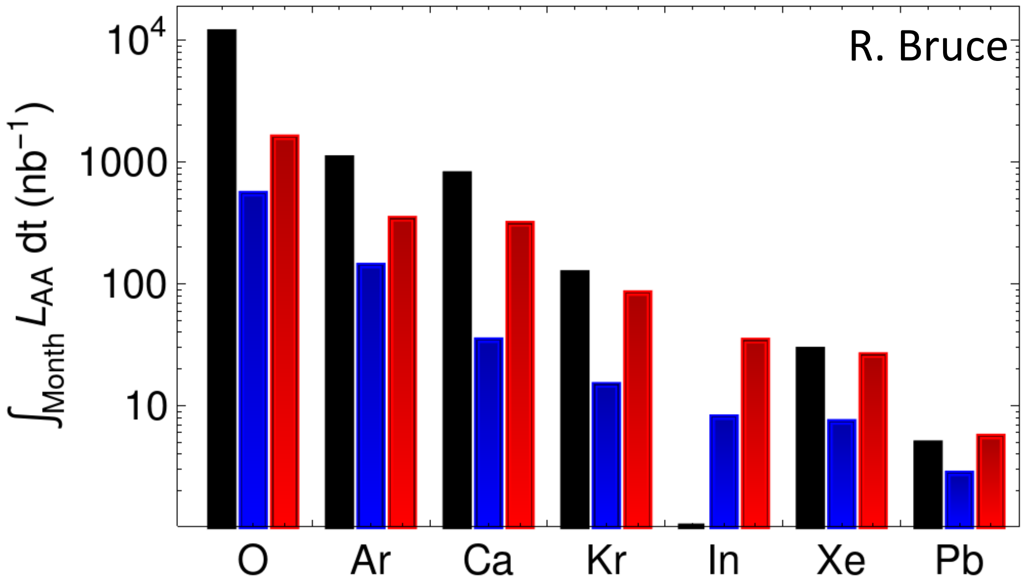
JAPW Dec'22
https://indico.cern.ch/event/1194548/contributions/5093964/attachments/2563454/4419007/2021.12.08--JAPW_future_ion_operation.pdf

1-month LHC integrated luminosity

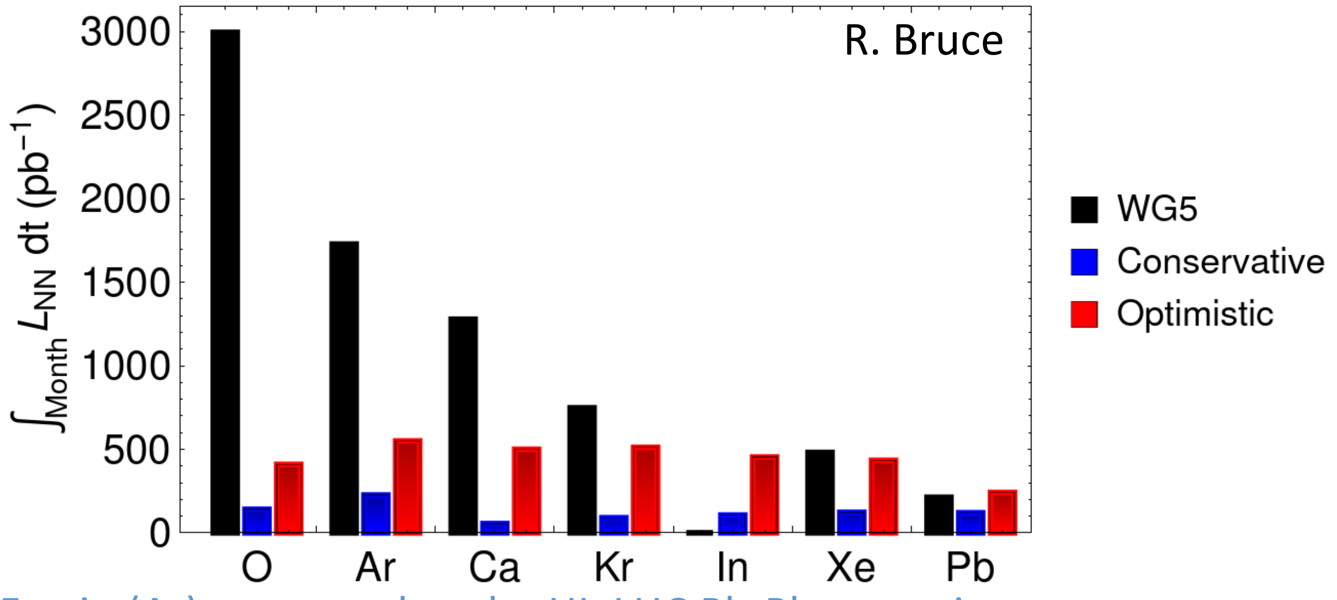
- LHC beam and luminosity evolution simulated, extrapolated to one-month run as for standard Pb-Pb
  - Rough assumptions on LHC filling scheme, to be refined

$$\mathcal{L}_{NN} = A_1 A_2 \mathcal{L}$$

Integrated AA luminosity



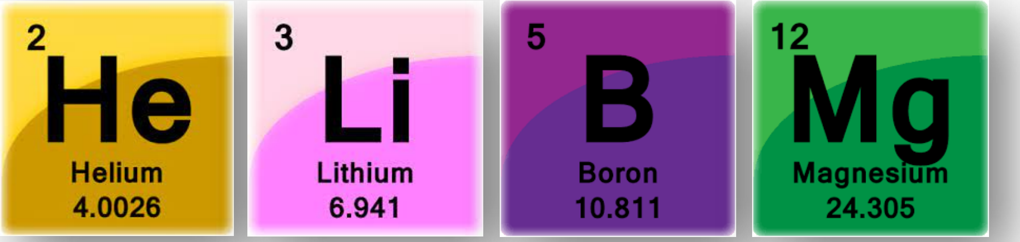
Integrated NN luminosity



- For optimistic scenario, we get up to a factor 4.5 gain (Ar) compared to the HL-LHC Pb-Pb scenario
  - several intermediate ion species give integrated NN luminosities of 400-550 pb^{-1} in optimistic scenario
  - In conservative scenario, highest luminosity (Ar) is factor 2.5 less

- These estimates provided to ALICE3, pending more detailed studies

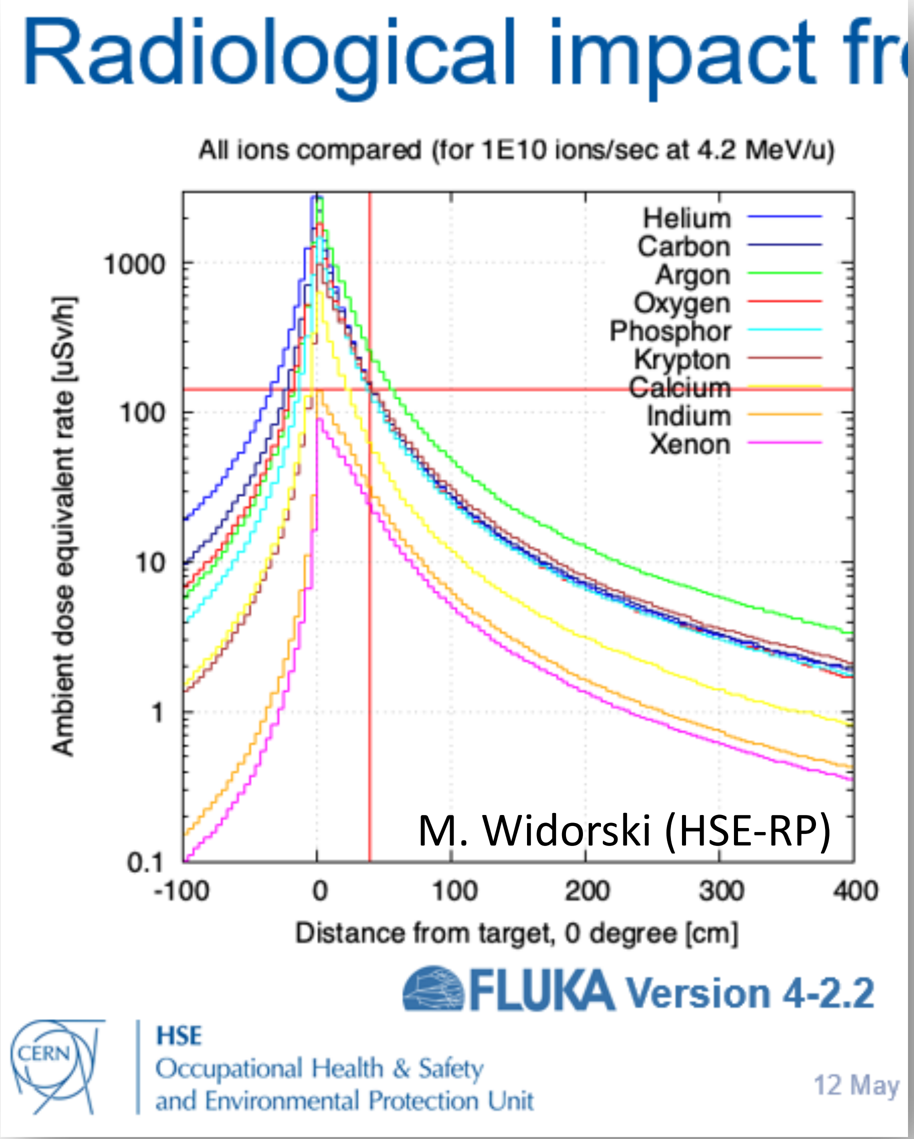
JAPW Dec'22
https://indico.cern.ch/event/1194548/contributions/5093964/attachments/2563454/4419007/2021.12.08--JAPW_future_ion_operation.pdf



Ions for NA61

Current status of the studies

- Currently Radio Protection group is addressing the radiological impact of the ion species relevant for the NA61++ program proposed for Run 4
- In parallel, our source expert, is addressing the operational feasibility of those species, i.e. "do they bring chemical hazards? If so, what is the protocol to be followed up for manipulation? Do we need any upgrade at the source to hold hazardous species?



8
O
Oxygen
15.9994

Ions for NA61 & LHC

Current status of the studies

- Operational feasibility in the Accelerator Complex, including modifications to the complex, already studied and put in place in the context of the **OXY4LHC project**
- This beam will be operated in the Ion Complex during the **first half of 2024**
- In the context of the **OXY4LHC project** we have defined two ion modes for beams out of Linac 3 according to the radiological impact (EDMS DOC 2737738) ➔ will be useful for other species

Radiation protection aspects for ion operation at 4.2 MeV/u in Linac3, PS SWY, Booster and LEIR

M. Widorski (HSE/RP), R.Scrivens (BE/ABP), R. Alemany Fernandez (BE/OP), B. Morand (EN/AA)

Ion beams at 4.2 MeV/u and radiological impact

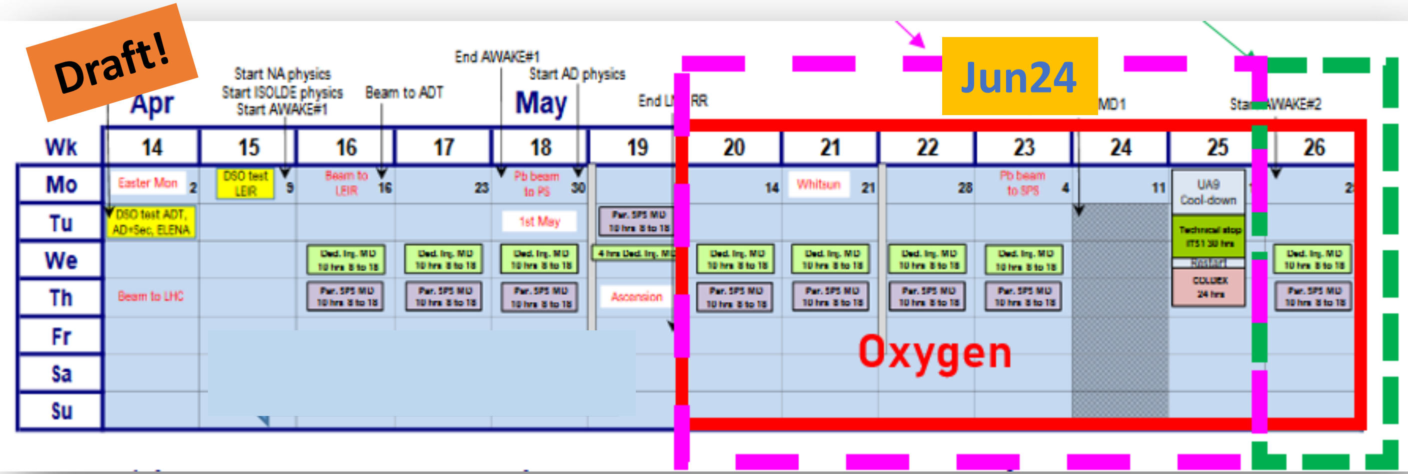
Radiological impact is determined by **beam intensity** and **ion type.** We distinguish new two operation modes:

HEAVY ION MODE

No relevant radiological impact: unrestricted access to beam line with heavy ion operation, such as **Lead**. Past and current operation.

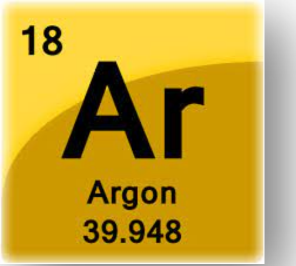
LIGHT ION MODE New

Potential relevant radiological impact: no access to beam line with light ion operation, such as **Oxygen**, **Argon**, Indium, Calcium, Helium, Carbon, Phosphor, …



O8+ commissioning in the injectors

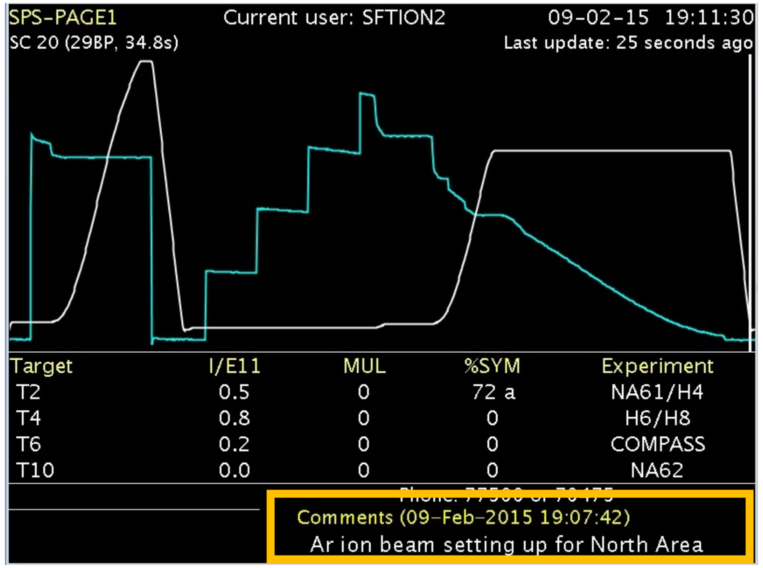
O8+ to LHC

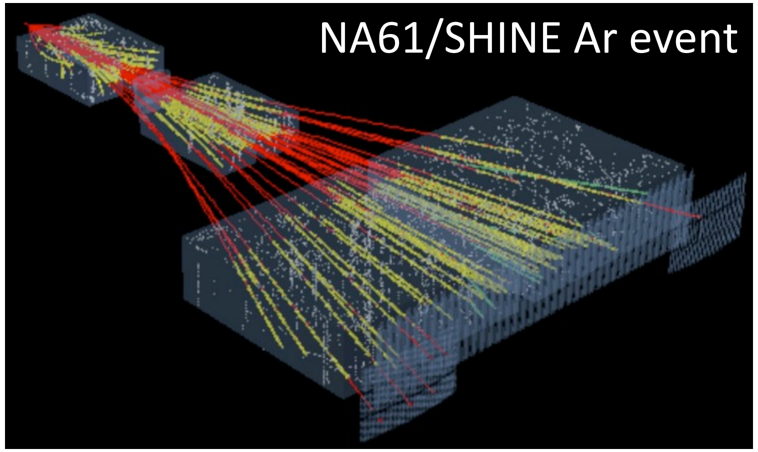


Ions for NA61 & LHC

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





54
Xe
Xenon
131.293

Ions for NA61 & LHC

Current status of the studies

M. Schaumann et al. FIRST XENON-XENON COLLISIONS IN THE LHC

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

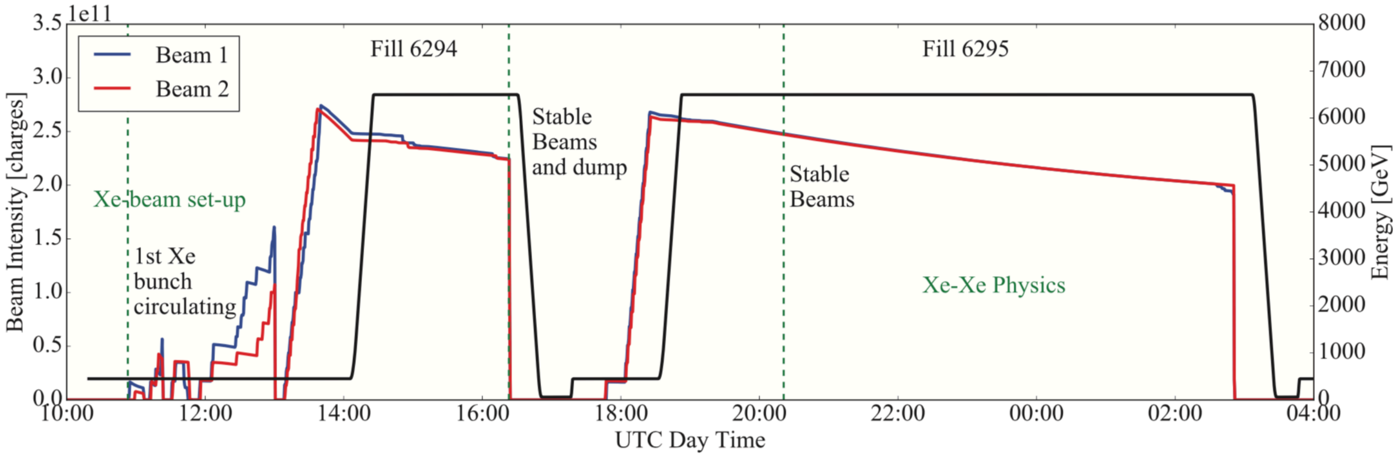
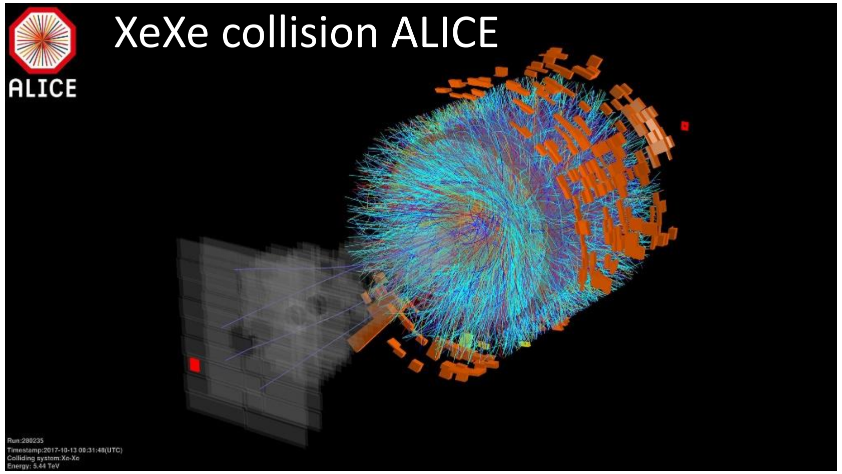
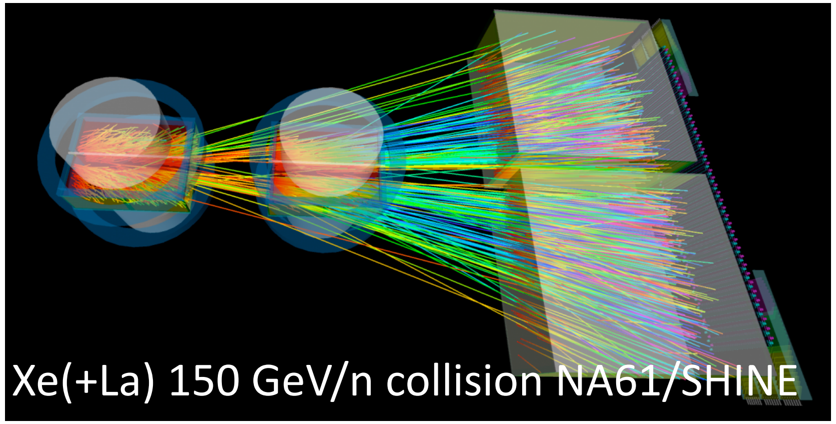


Figure 1: Evolution of the beam intensity and energy throughout the Xe–Xe run.

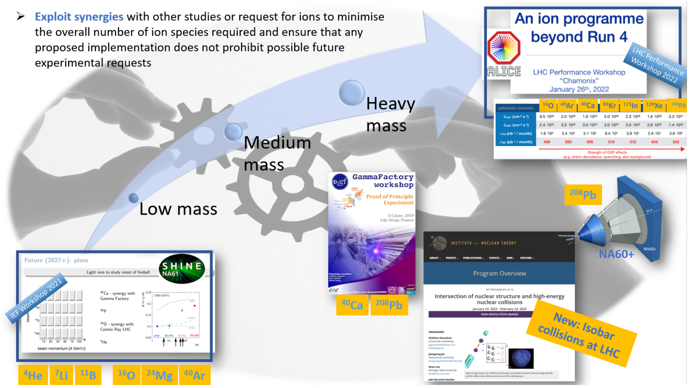




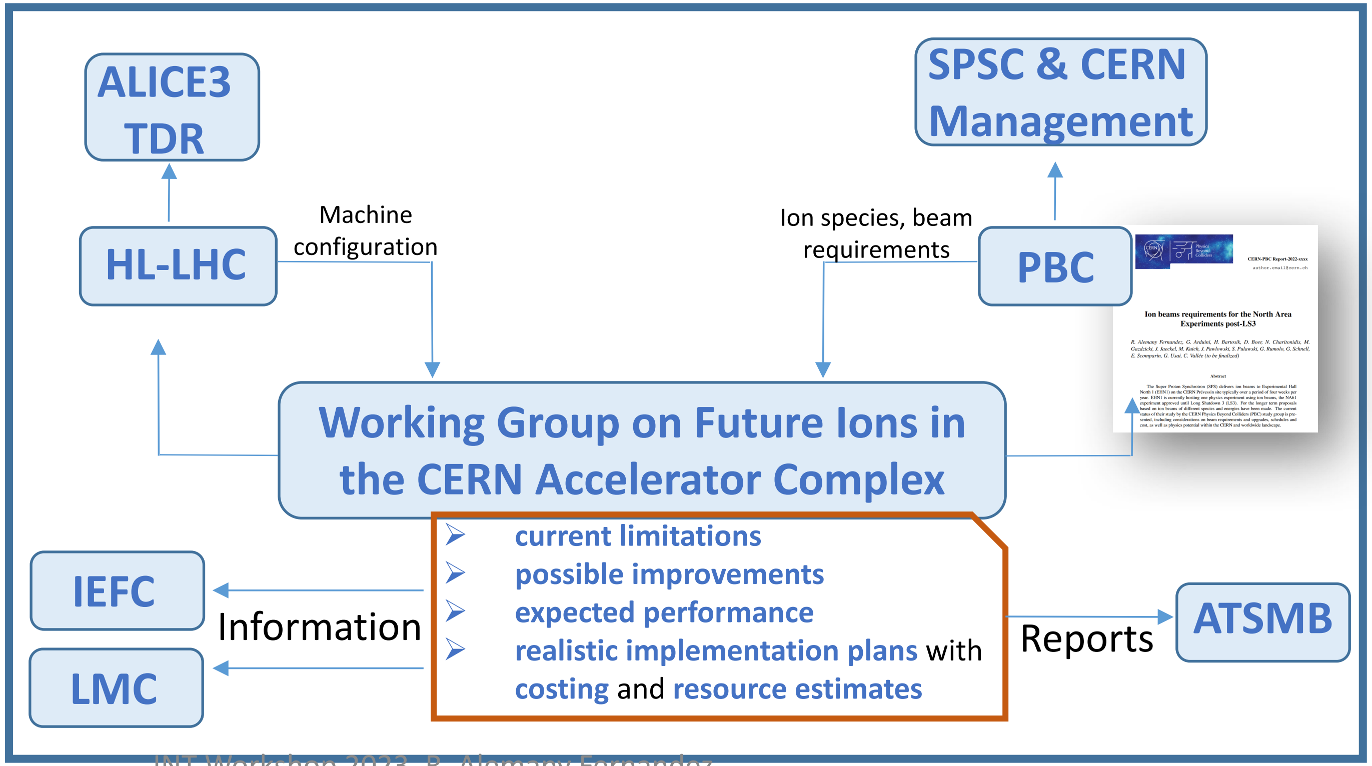
- Xenon already sent to NA61 and LHC in 2017
- During 6 h of stable collisions about 3 μb−1 were delivered to ATLAS and CMS. Because of the larger β∗ values, fractions of 1 μb−1 were delivered to ALICE and LHCb.

- No issues expected from the Ion Complex

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



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].

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