New ions operation in the CERN accelerator complex and future LHC

Maciej Slupecki

Acknowledgements: Reyes Alemany Fernandez, Theodoros Argyropoulos, Hannes Bartosik, Giulia Bellodi, Roderik Bruce, Heiko Damerau, Davide Gamba, Peter Kruyt, Edgar Mahner, Richard Scrivens, Natalia Triantafyllou, Elias Waagaard

Exploring nuclear physics across energy scales 2024: intersection between nuclear structure and high energy nuclear collisions , 22 April 2024

Contents

Introduction

- Motivation for using different ions, proposed projects and associated challenges

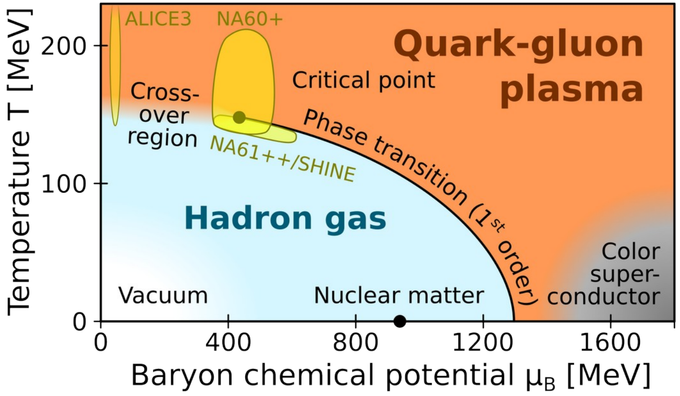
CERN ion injector complex

- Source limitations
- EARLY: fixed-target beam vs. NOMINAL: beam for HL-LHC
- Limitations (LEIR e-cooler, space-charge)
- Possible hardware upgrades

Operation with ions at CERN

- Past and present experience
- Future plans, summary and outlook

Motivation for using different ions
General

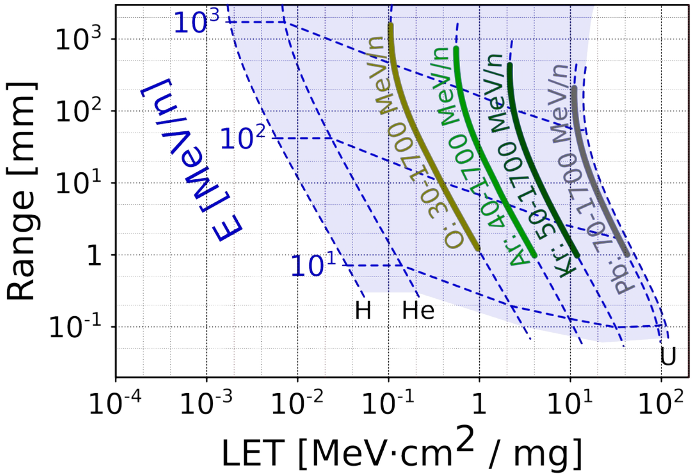


Physics

- Explore different regions of the phase diagram of quark-gluon plasma
  - ALICE, NA61/SHINE, NA60+
- Nuclear physics at LHC → this conference

Facilities

- Irradiation using wide range of linear energy transfer (LET) beams
  - CHIMERA / HEARTS
- Gamma factory
  - Using principle of resonant absorption and emission of photons
  - Better intensity and higher energy than traditionally used methods (inverse compton scattering)
  - Spin-off:
    - Enable high-brilliance Ca beams and high-rate collisions



Motivation for using different ions

Experimental landscape at CERN

		5 B Boron 10.811	8 O Oxygen 15.9994	10 Ne Neon 20.1797	12 Mg Magnesium 24.305	18 Ar Argon 39.948	20 Ca Calcium 40.078	36 Kr Krypton 83.80	49 In Indium 114.818	54 Xe Xenon 131.29	82 Pb Lead 207.2
Beam tests ongoing	SHINE NA61++	★	★		★						★
	NA60+ 										★
	 ALICE3					★ or	★ or	★ or	★ or	★ or	★
This conference	NUCLEAR PHYSICS AT LHC		★	★		★		★	★	★	
Most demanding	CHIMERA HEARTS		★			★		★		★	★
Proof of principle in preparation	GAMMA FACTORY						★				★

Projects’ status and challenges

Experimental physics projects

Tests to assess feasibility in Run3

- NA61++ / SHINE
  - Ongoing beam tests with Mg up to PS
- NA60+
  - Ongoing beam tests with Pb
- ALICE3
  - Beam tests with Kr up to Linac3 done in 2023
  - One ion species to be selected to maximize luminosity
  - Need inputs from source operational tests with new ions and development of simulations

Facilities

- **HEARTS** – most demanding request
  - Provide: O, Ar, Kr, Pb
  - Every operational day, with switching times between species of max 15’
  - The experiment decides the order in which the species are delivered
  - Switch between ions at will
  - **Impossible with present injectors**: switching between ions takes weeks
- Gamma Factory
  - Proof of principle in the SPS is being prepared

Projects’ status and challenges

Experimental physics projects
Tests to assess feasibility in Run3

- NA61++ / SHINE
  - Ongoing beam tests with Mg up to PS
- NA60+
  - Ongoing beam tests with Pb
- ALICE3
  - Beam tests with Kr up to Linac3 done in 2023
  - One ion species to be selected to maximize luminosity
  - Need inputs from source operational tests with new ions and development of simulations
- **Nuclear physics at LHC**
  - Discussion to follow

Facilities

- **HEARTS** – most demanding request
  - Provide: O, Ar, Kr, Pb
  - Every operational day, with switching times between species of max 15’
  - The experiment decides the order in which the species are delivered
  - Switch between ions at will
  - Impossible with present injectors: switching between ions takes weeks
- Gamma Factory
  - Proof of principle in the SPS is being prepared

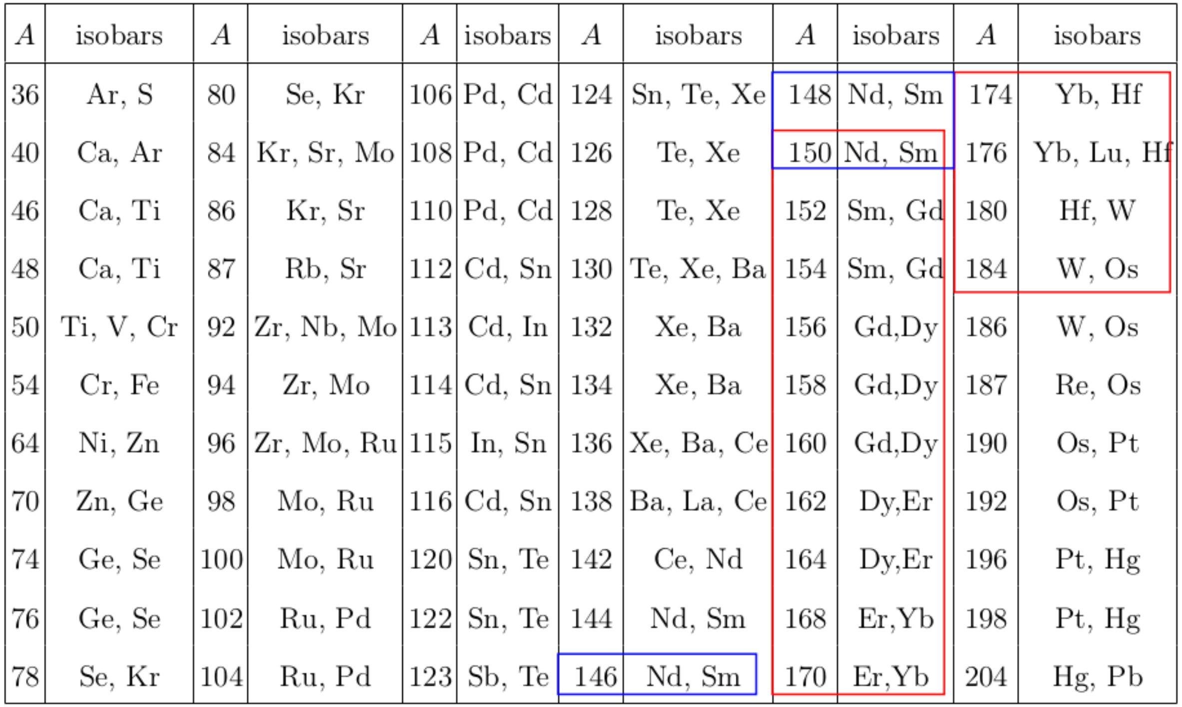
Nuclear physics at LHC

Ion requests

Bally et al. https://arxiv.org/abs/2209.11042

Challenges

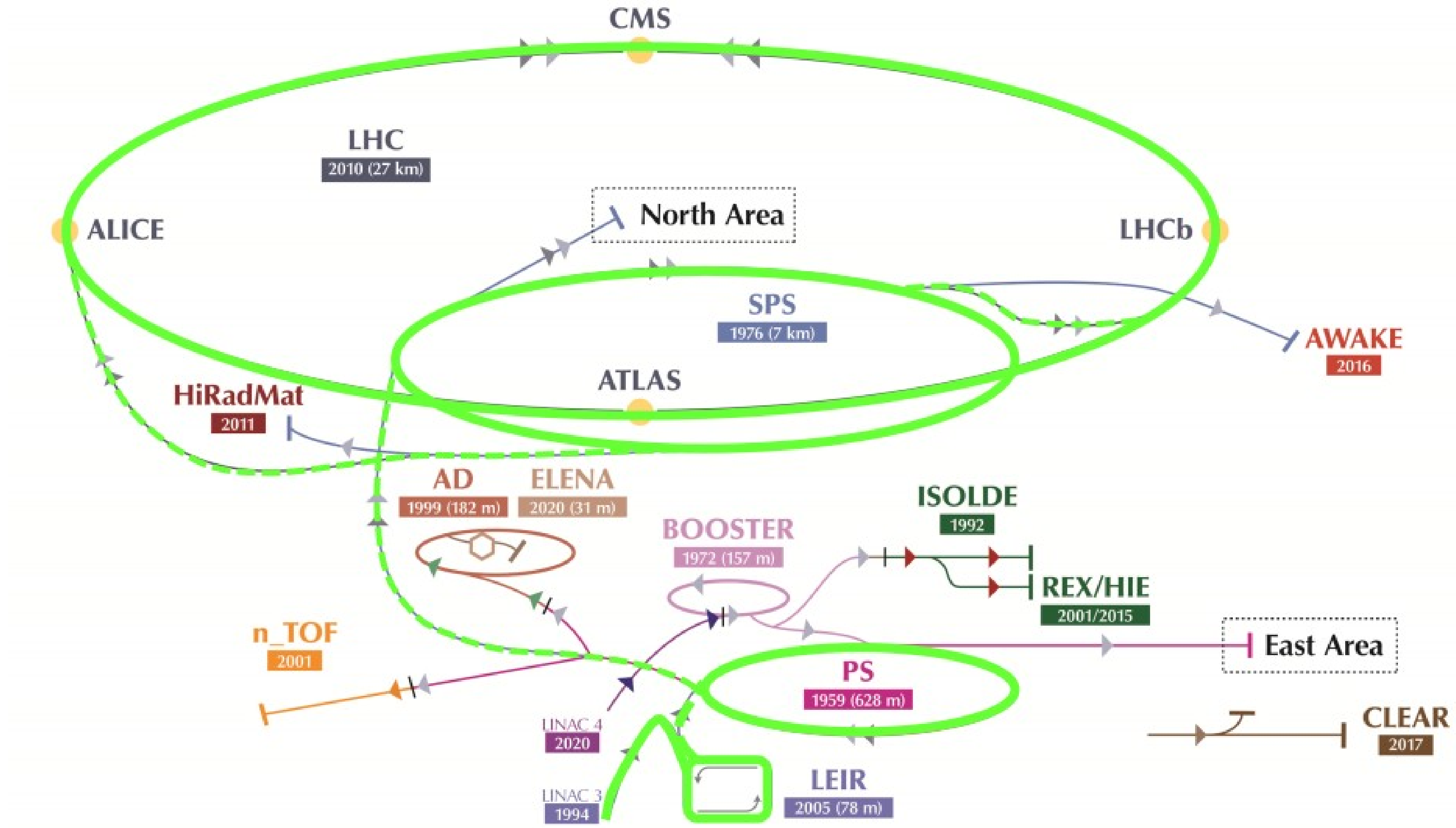
- At present the list is long
- Need to narrow it down:
    - Satisfying physics goals
    - In synergy with other ion requests at CERN
    - Prioritize pairs, where one ion has been used before
    - Prioritize pairs of two gases or one solid and one gas

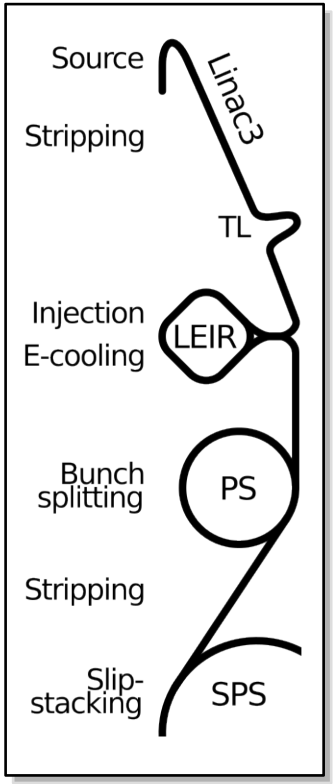


A	isobars	A	isobars	A	isobars	A	isobars	A	isobars	A	isobars
36	Ar, S	80	Se, Kr	106	Pd, Cd	124	Sn, Te, Xe	148	Nd, Sm	174	Yb, Hf
40	Ca, Ar	84	Kr, Sr, Mo	108	Pd, Cd	126	Te, Xe	150	Nd, Sm	176	Yb, Lu, Hf
46	Ca, Ti	86	Kr, Sr	110	Pd, Cd	128	Te, Xe	152	Sm, Gd	180	Hf, W
48	Ca, Ti	87	Rb, Sr	112	Cd, Sn	130	Te, 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].

CERN ion injector complex





CERN ion injector complex
GTS-ECR Source limitations

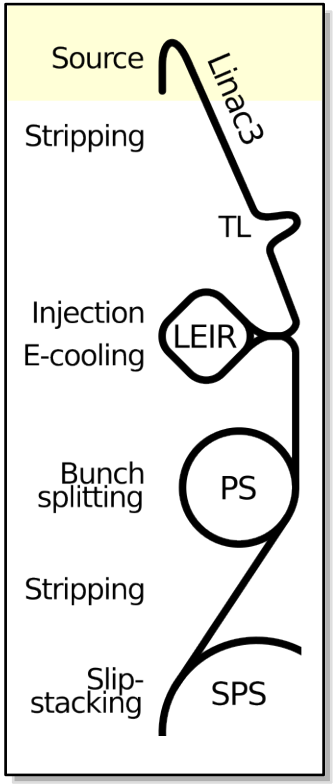
Availability for tests

- Only one operational source available
  - Very limited time to test new ions, advanced planning needed

Material input

- Support gas usage
- Gasses vs. solids
  - Gasses are quick & thermally reactive
  - Oven-fill lifetime limit for solids; some solids are excluded due to high melting point
- Pure material (chemically or isotopically) vs. compounds
  - Better physical, chemical or handling-related properties vs. reduced beam stability and intensity due to plasma contamination with undesired elements or isotopes
  - Significant cost of enrichment to obtain rare isotopes
- Safety considerations: reactivity, toxicity, flammability

Quick test vs. stable, many-week operation



CERN ion injector complex

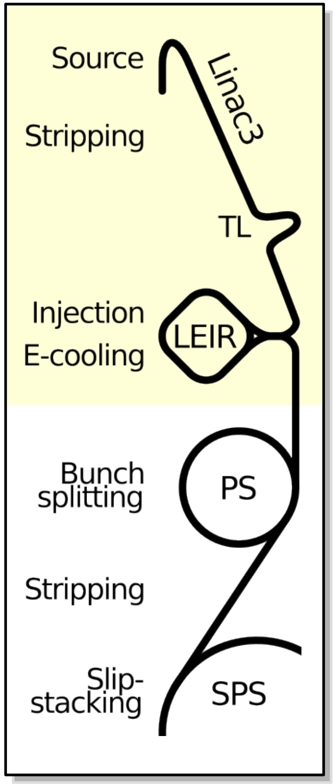
Constraints in Linac3 and LEIR

Limits on charge states

- Source: A/Q > 3.5
- Linac3 RF power: A/Q < 8.3
- Transfer line to LEIR (after possible stripping): A/Q < 4

Radioprotection assessment

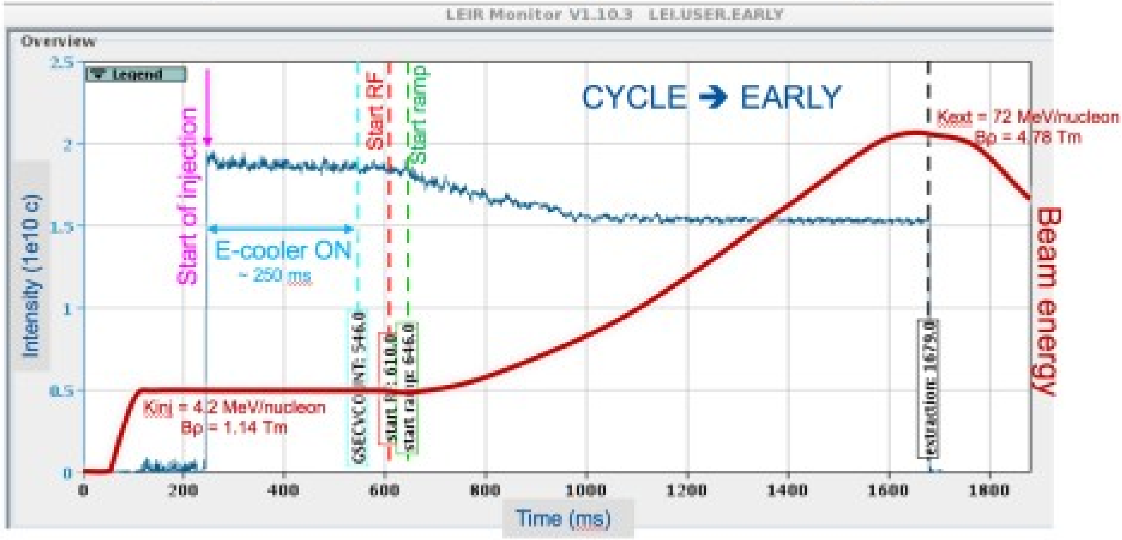
- Radiation levels for:
  - He and Li: too high
  - O and Mg: generally acceptable (with constraints in place)
  - Xe and Pb: OK

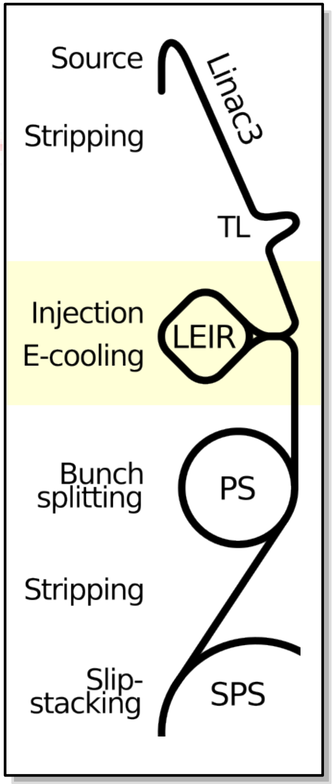


CERN ion injector complex

EARLY: fixed-target beam and LHC pilot runs

- Single Linac3 injection
- Intensities below space-charge limit or onset of significant IBS effects
- E-cooling important,
  but not critical



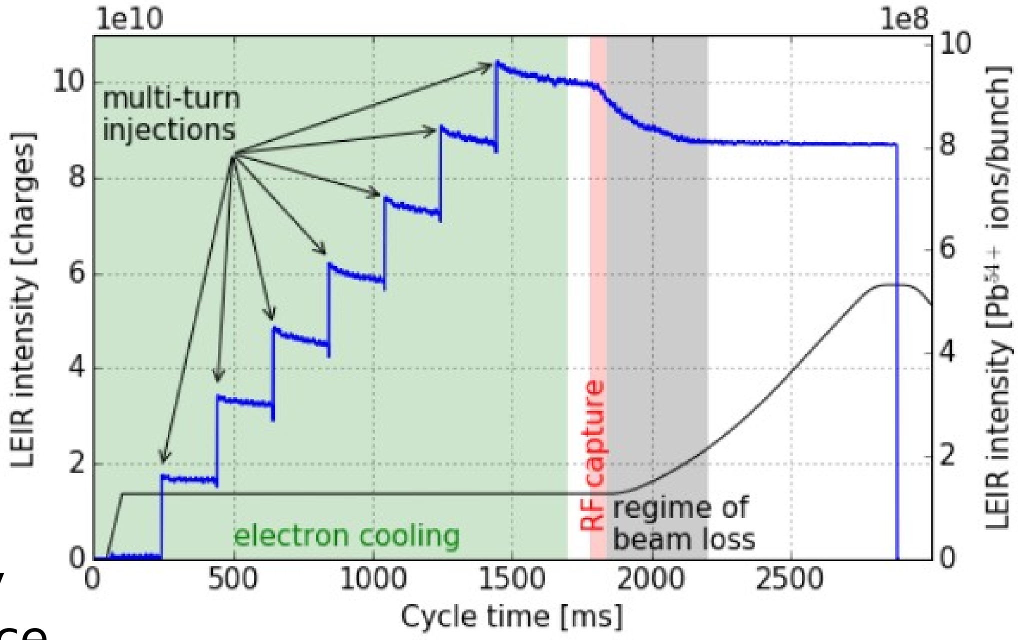


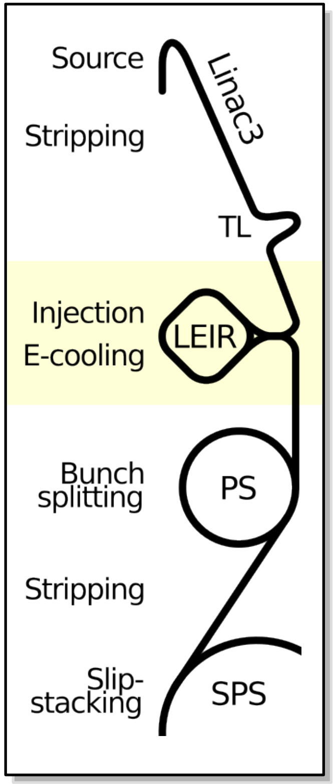
- Relatively ‘easy & quick’ beam commissioning
- Low-maintenance beam type

CERN ion injector complex

NOMINAL: beam for high-luminosity LHC

- Up to seven Linac3 injections
- High intensities with significant collective effects
- Injection and e-cooling critical
- Long source conditioning for stability and high-maintenance
  - Performance is sensitive to drifts and interferences

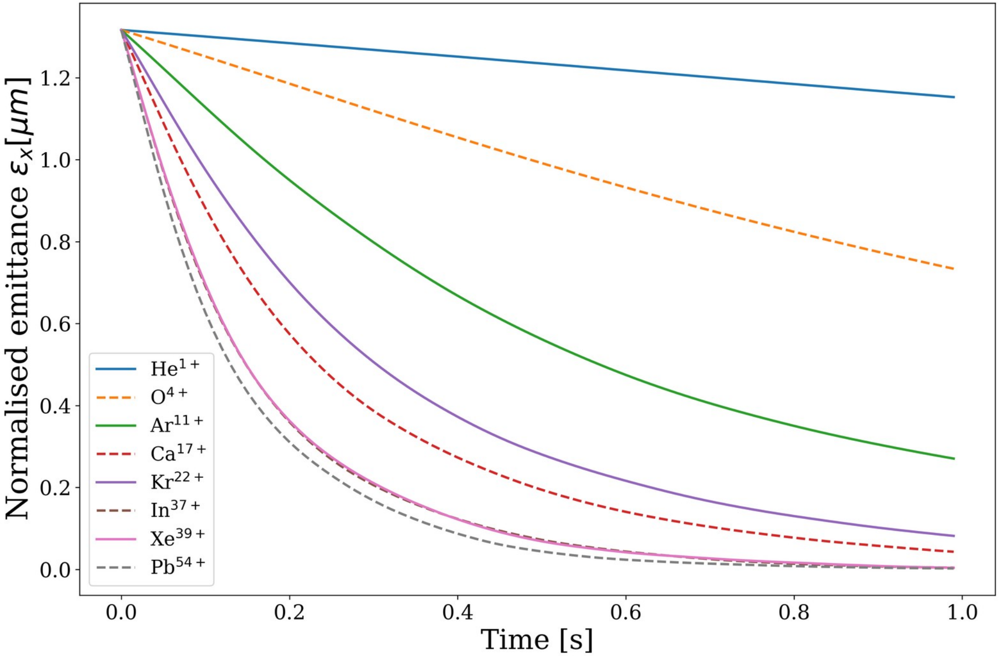


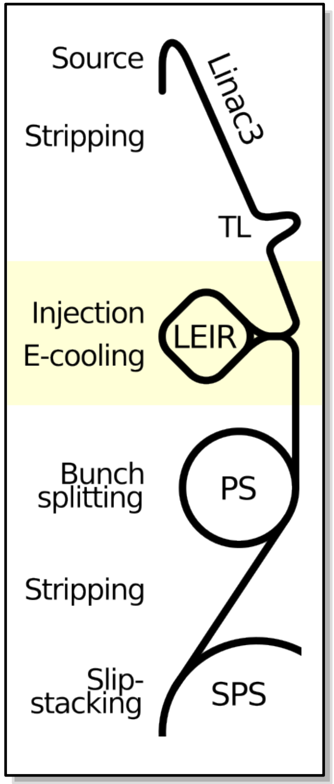


CERN ion injector complex
NOMINAL: e-cooler

Electron cooling

- Reduce beam emittance
    - Fit the beampipe aperture
    - Crucial for charge accumulation
- Less efficient for lighter ions
    - Needs more time, but …
    - More time at low energy translates to quality and intensity losses further down the injector chain

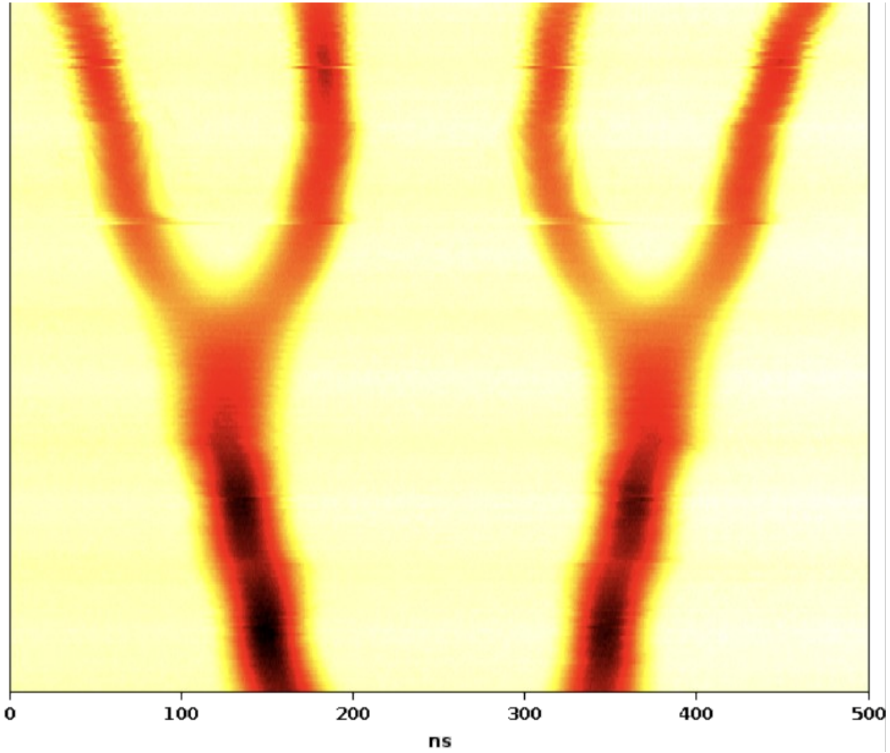


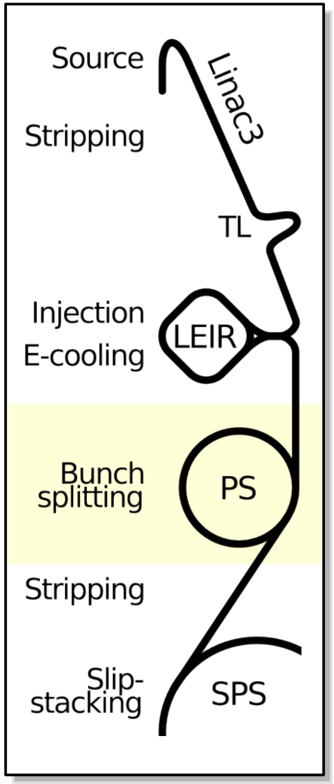


CERN ion injector complex
NOMINAL: bunch splitting

RF manipulation

- Split the total charge into more bunches
- Alleviates collective effects in SPS, further downstream
- Bunch separation at extraction: 100 ns

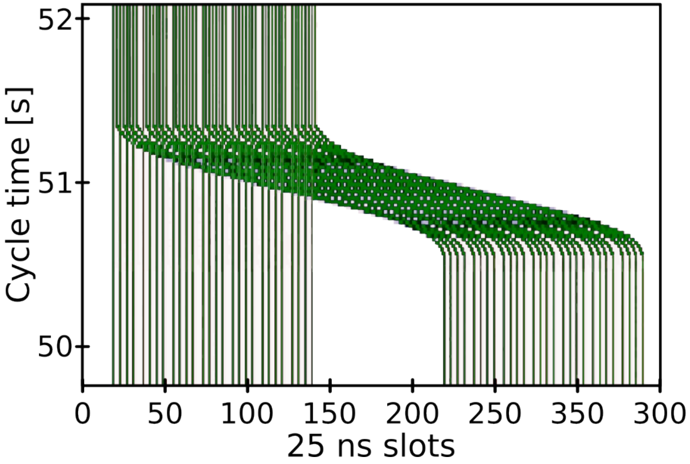


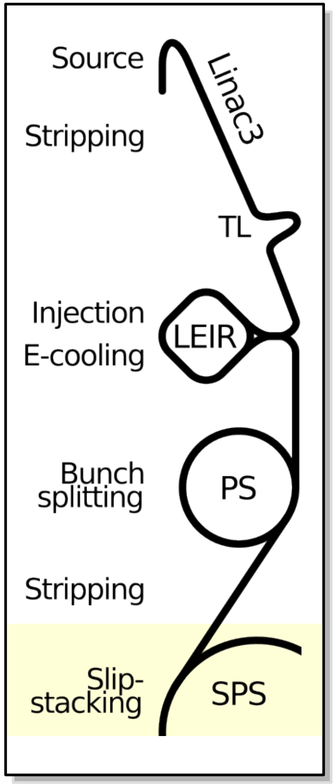


CERN ion injector complex
NOMINAL: slip-stacking

Slip-stacking

- Two particle beams of different momenta and different RF frequencies slip longitudinally relative to each other in the same beam pipe
- When the two beams are in the correct longitudinal position, the full beam is recaptured with a non-adiabatic voltage jump at the average RF frequency
- Reduction of bunch spacing
  - from 100 ns
  - to 50 ns

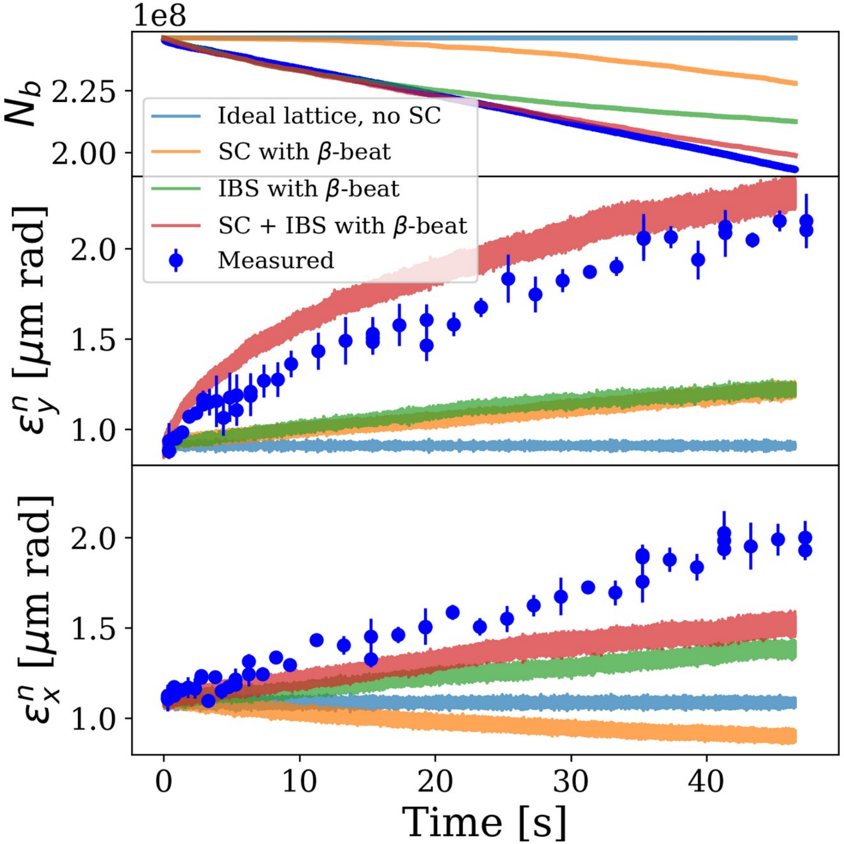


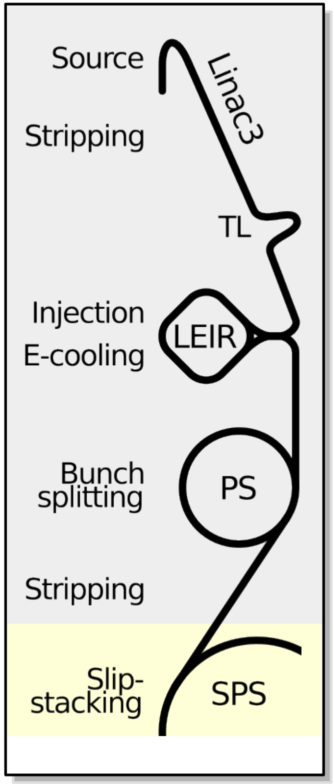


CERN ion injector complex
NOMINAL: space-charge

Beam evolution across the complex

- Simulation framework in development
  - Includes collective effects
  - Need experimental data from more ion species
- Example of Pb beam intensity and emittance evolution in SPS along 50 s-long injection plateau
  - Increase of emittance
  - Intensity losses
-





CERN ion injector complex

Possible hardware upgrades

Second Linac3 source

- Evaluate expected intensities vs. experimental requirements

New low-energy diagnostic line in Linac3

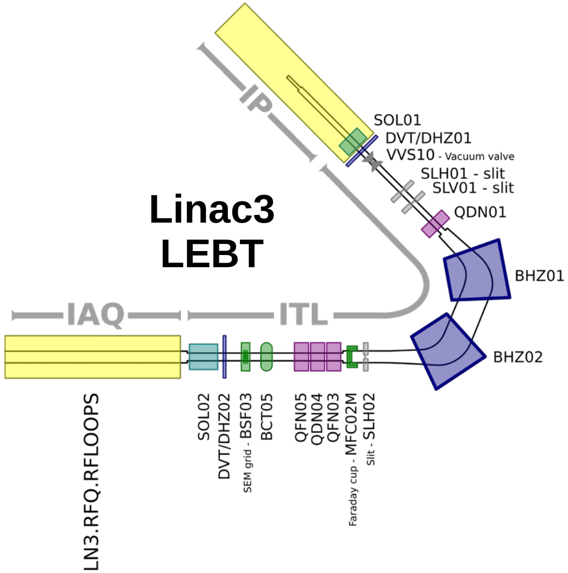
- Improve models, better-tune settings to maintain performance of the source(s)

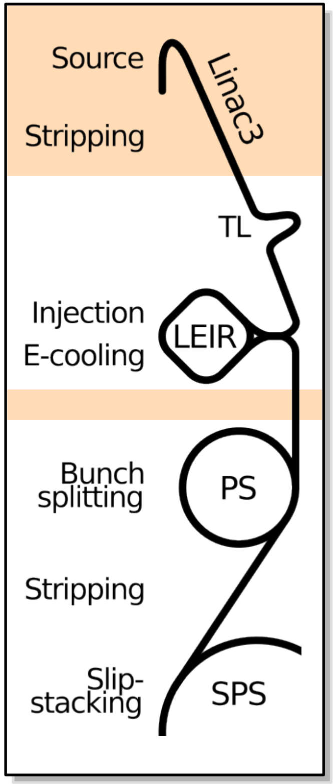
Replacement of Linac3 elements to pulsed-versions

- Fast ion switching (for HEARTS & NUCLEAR PHYSICS)

Stripper foil between LEIR and PS

- Maximize luminosity (for ALICE3)





Operation with ions at CERN

Past and present experience

* Before 2005 ions were sent to PSB instead of LEIR
† Approved and scheduled

Year	Ion in LEIR	Beam type	Intensity in LEIR	Space-charge limit in LEIR
			[10^{10} charges / pulse]	
2003*	$^{115}\mathrm{In}^{37+}$	EARLY	1.5	8.1
2015	$^{40}\mathrm{Ar}^{11+}$	EARLY	2.5	9.5
2017	$^{129}\mathrm{Xe}^{39+}$	NOMINAL, fixed-target and LHC pilot	8	8.5
2023 (2025)†	$^{16}\mathrm{O}^{4+}$	EARLY (LHC pilot)†	3.5	10.5
2024	$^{24}\mathrm{Mg}^{7+}$	EARLY for fixed-target NOMINAL for tests	May 2024	8.9
Many	$^{208}\mathrm{Pb}^{54+}$	EARLY and NOMINAL	8.5-10	10

Operation with ions at CERN
Future plans

Future Ions Working Group

- Coordination of efforts to determine limitations, possible improvements, performance reach and implementation plan including resources needed

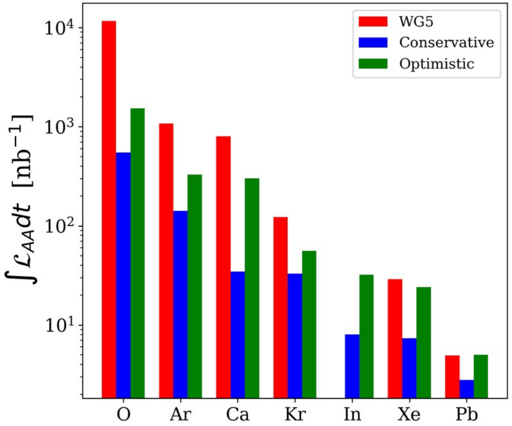
Possible ions for LHC Run5 and 6

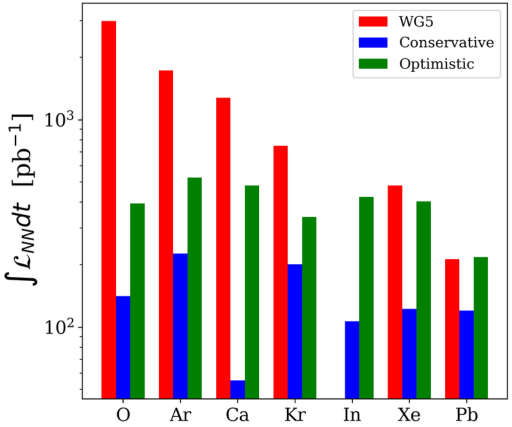
Ion	Z	A	charge in LEIR-PS	mass [GeV]	LINAC3 current [μA]
He	2	4	1	3.727	160
O	8	16	4	14.895	70
Ar	18	40	11	37.216	60
Ca	20	40	17	37.215	25
Kr	36	86	22	80.0252	40
In	49	115	37	107.007	25
Xe	54	129	39	120.047	30
Pb	82	208	54	193.687	30

All currents out of Linac3 are experimental values except for Ca, which has never been tested

Study to find which ion maximizes nucleon-nucleon luminosity

- Needed by HL-LHC by the end of 2025
- Two scenarios:
  - Conservative: similar production scheme to Pb
  - Optimistic: includes alternative stripping between LEIR and PS, no bunch splitting in PS and other optional optimizations


One month integrated ion-ion luminosity


One month integrated nucleon-nucleon luminosity

Summary and conclusions

- The **main ion** operated at the **LHC** until the end of Run4 (2032) **will be Pb**
    - Ongoing studies to select the ion yielding highest nucleon-nucleon luminosity to be possibly used in Run5 and 6
    - Preparation of beam evolution simulation across the ion complex
- **Preparations** to accommodate **NA61++** requests are ongoing
    - Feasibility of operation was assessed
        - No showstoppers from the source or radioprotection were identified
    - Magnesium test in May 2024
    - Oxygen test done in 2023, LHC pilot scheduled for 2025
    - Boron test scheduled for LS3
- Ongoing **assessment** of possible upgrades of the complex needed for **HEARTS**

Outlook

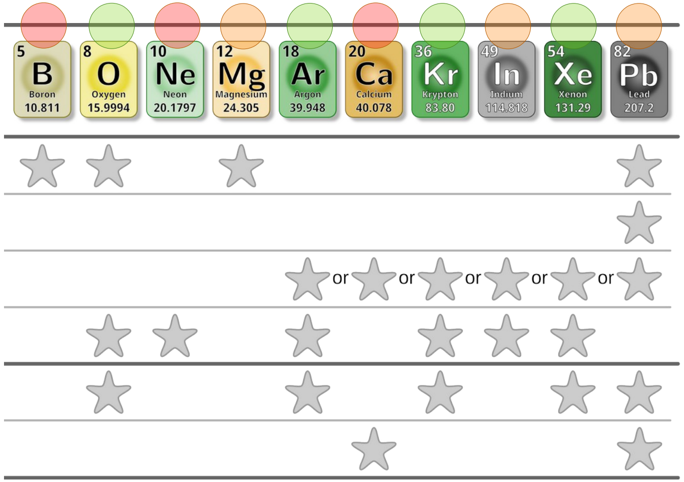
- Detailed preparations and **advanced scheduling** are required for operating any **new ion**, no rapid ion switching is currently possible
- Reaching **operational stability** is much more demanding than running a short test
- Ion injector upgrades will be needed if some of the proposed projects would be approved and funded
- **Requests for new ions** should take into account **synergies** with the ongoing or proposed projects
    - Which ions are preferred by the nuclear physics community?

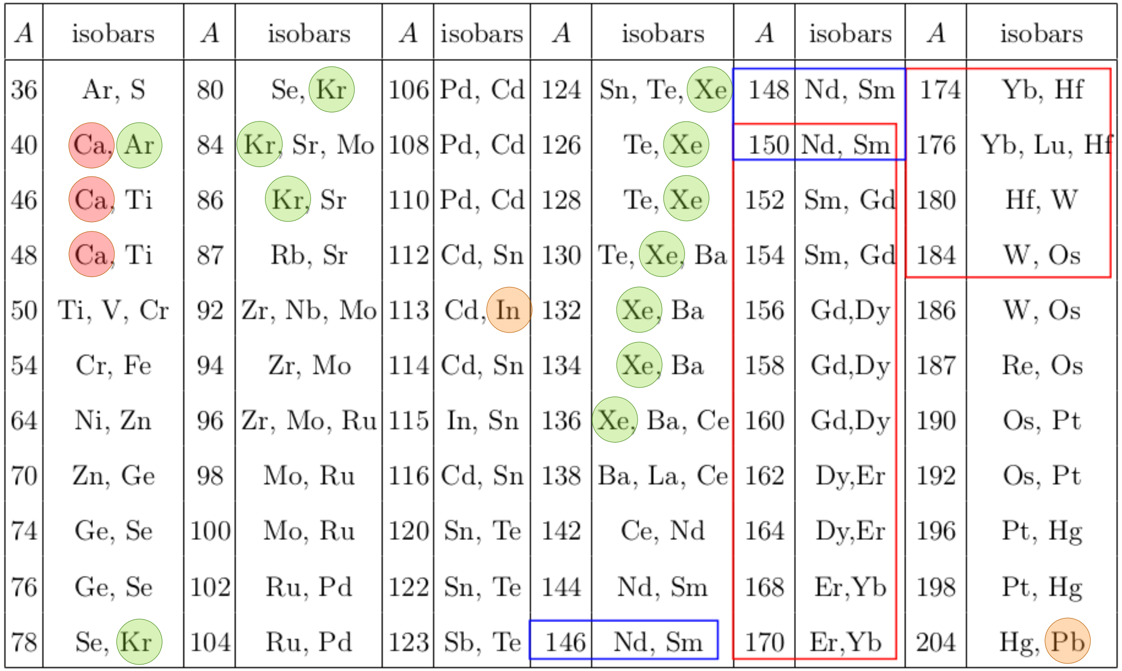
Discussion

Any other synergies? Preferences?

- 🟢 Gas tested at CERN
- 🟠 Solid tested at CERN
- 🔴 Untested with synergy

Are any other ions of interest for the nuclear structure studies?





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].

home.cern

Backup

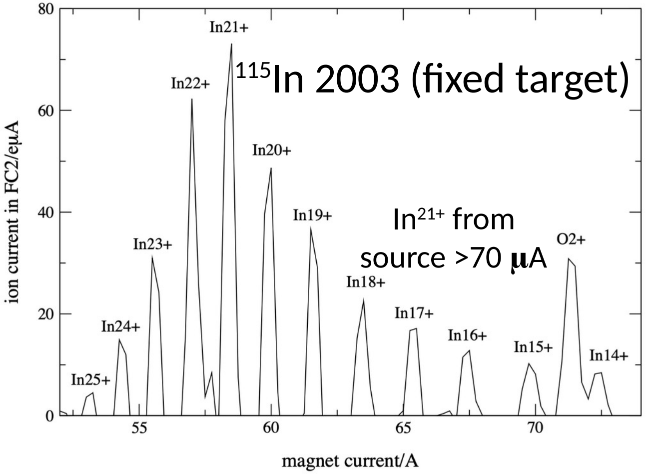
Gamma factory

Gamma factory

- Using principle of resonant absorption and emission of photons
    - Requires very specific partially stripped ions such that electrons, after laser-induced excitation, relax emitting photons
    - Pb^{79+} and Pb^{81+}
- Better performance than traditionally used unverse compton scattering in terms of gamma intensity (~γ_{rel}^4) and energy (~400 GeV)
- Spin-off: Ca collisions at LHC
    - Use the same principle to cool the beam by emitting gammas, reducing emittance and increasing brilliance, leding to overall increase in luminosity

Operation with ions at CERN

Past experience



^{115}In 2003 (fixed target)

In^{21+} from source >70 µA

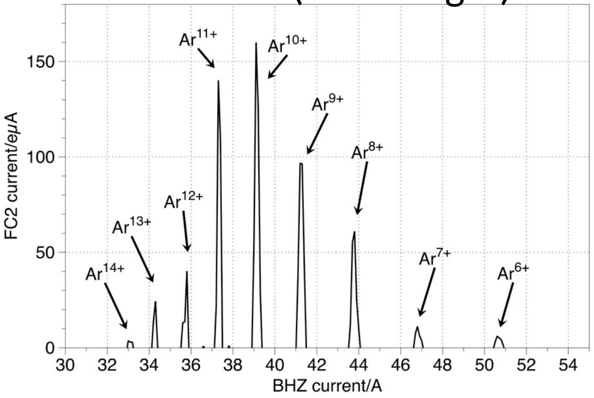
Stripped at the end of Linac3 to In^{37+}, ~ 25 µA
Stripped to In^{49+} before SPS
No attempt at LEIR NOMINAL beam
Ref: CERN-PS-2002-058-PP

PSB injected ~ 1.5 10^{10} charges/pulse

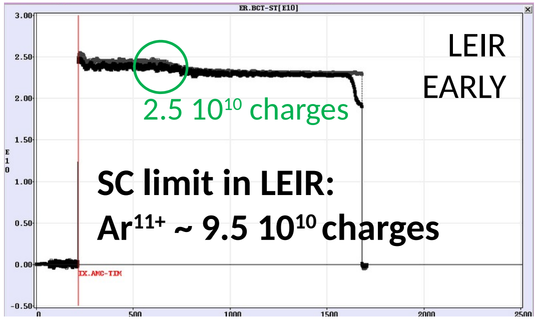
SC limit in LEIR: In^{37+} ~ 8.1 10^{10} charges

For reference **SC limit in LEIR for ^{208}Pb^{54+} ~10 10^{10} charges**

^{40}Ar 2015 (fixed target)



Not stripped; at the end of Linac3: ~60 µA
Stripped to Ar^{18+} before SPS
No attempt at LEIR NOMINAL beam

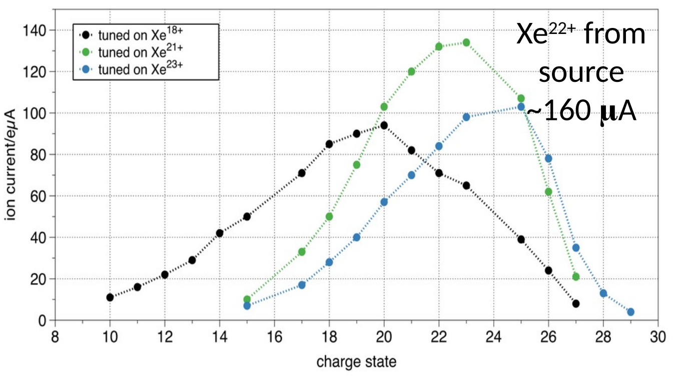


LEIR EARLY

2.5 10^{10} charges

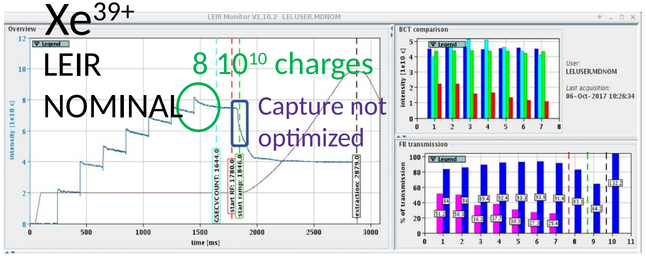
SC limit in LEIR:
Ar^{11+} ~ 9.5 10^{10} charges

^{129}Xe 2017 (fixed target & LHC pilot run)



Xe^{22+} from source ~160 µA

Stripped to Xe^{39+} at the end of Linac3, ~ 30 A
Stripped to Xe^{54+} before SPS
Attempted LEIR NOMINAL beam



Xe^{39+}

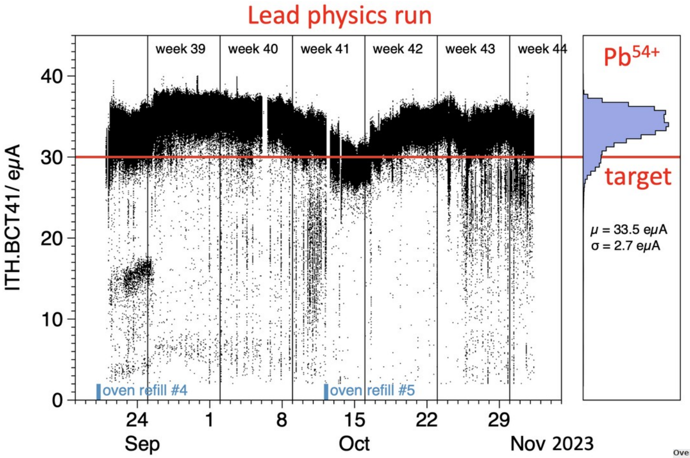
LEIR NOMINAL

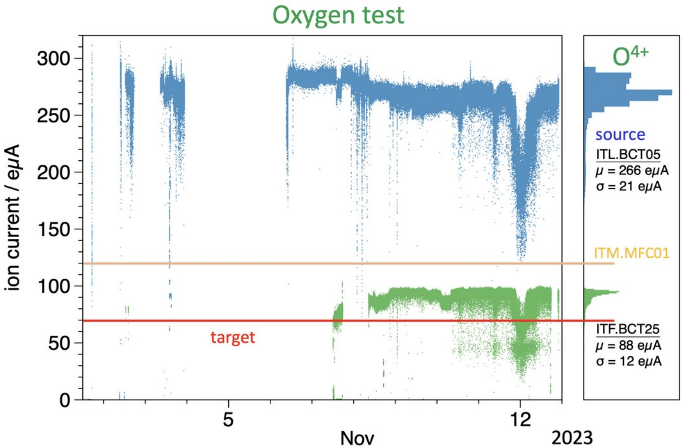
8 10^{10} charges

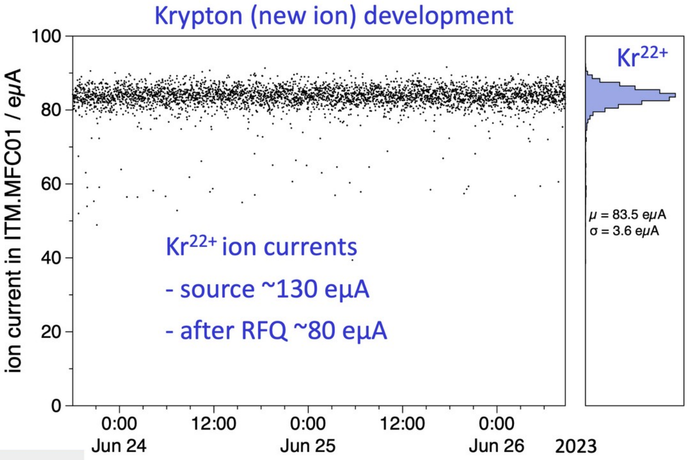
Capture not optimized

SC limit in LEIR: Xe^{39+} ~ 8.5 10^{10} charges

Operation with ions at CERN
2023: Pb, O, Kr

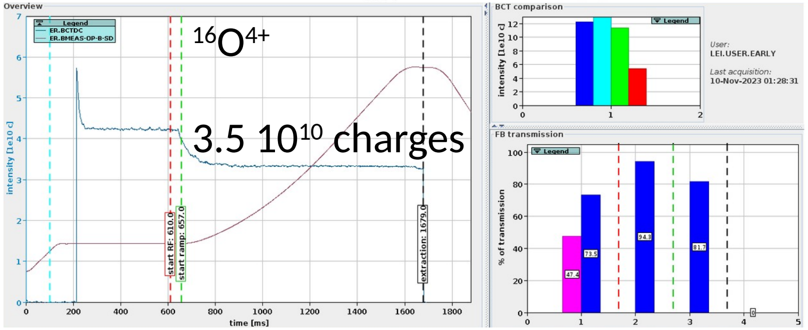






Kr^{22+} ion currents

- source ~130 eμA
- after RFQ ~80 eμA



User:
LEI.USER.EARLY

Last acquisition:
10-Nov-2023 01:28:31

$^{16}O^{4+}$

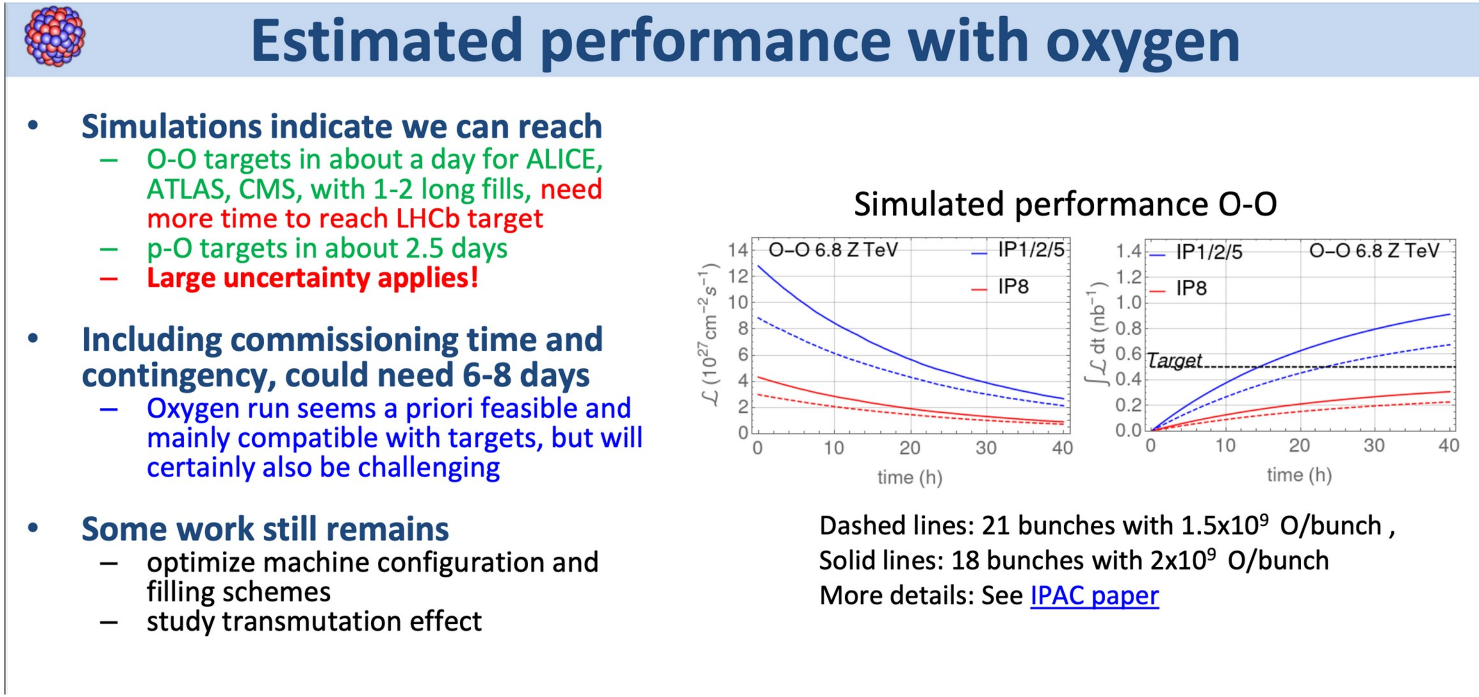
3.5 10^{10} charges

SC limits in LEIR:
$^{16}O^{4+}$: 10.5 10^{10} charges
$^{208}Pb^{54+}$: 10 10^{10} charges

Operation with ions at CERN
Ongoing projects

2024: Mg & Pb

2025: O & Pb



Estimated performance with oxygen

- **Simulations indicate we can reach**
  - O-O targets in about a day for ALICE, ATLAS, CMS, with 1-2 long fills, need more time to reach LHCb target
  - p-O targets in about 2.5 days
  - **Large uncertainty applies!**
- **Including commissioning time and contingency, could need 6-8 days**
  - Oxygen run seems a priori feasible and mainly compatible with targets, but will certainly also be challenging
- **Some work still remains**
  - optimize machine configuration and filling schemes
  - study transmutation effect

Simulated performance O-O

Dashed lines: 21 bunches with 1.5×10^9 O/bunch ,
Solid lines: 18 bunches with 2×10^9 O/bunch
More details: See IPAC paper