Overview of the planned R&D of future ions post-LS3 in the CERN injector chain

M. Slupecki, R. Alemany Fernandez, H. Bartosik, B. Bhaskar, G. Bellodi, E.C. Cortes Garcia,
H. Damerau, R. Garcia Alia, A. Huschauer, D. Kuchler, J.B. Lallement, A. Lasheen, E. Mahner,
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3 Dec 2025, Light Ion Collisions at the LHC

Contents

Ion injector complex at CERN

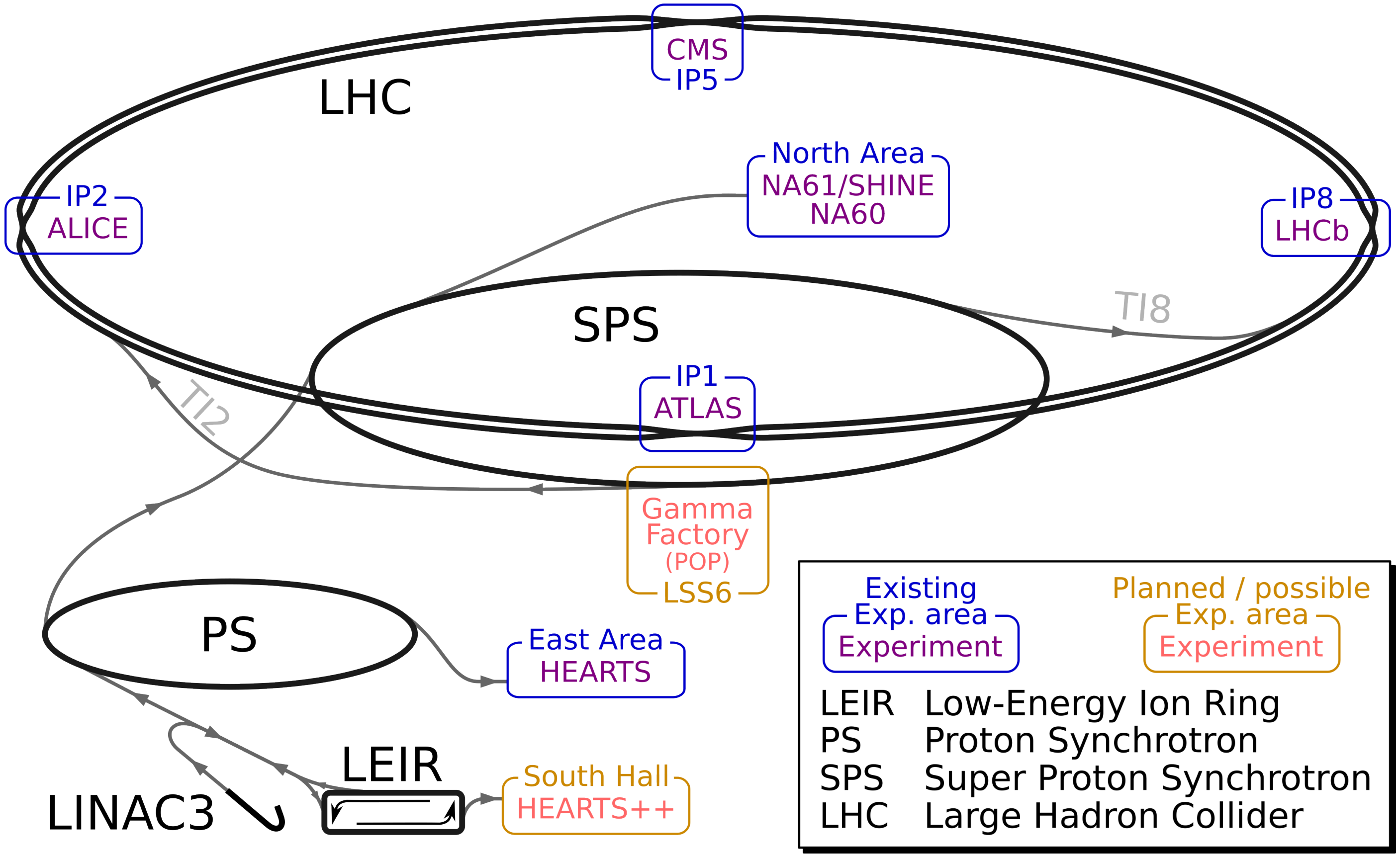
- Present and future experiments & facilities

New ions

- Projects’ status and challenges
    - Fixed-target & LHC
- Past and present ion operation at CERN
- Ion Complex Upgrade study
- Long-term schedule

Summary and outlook

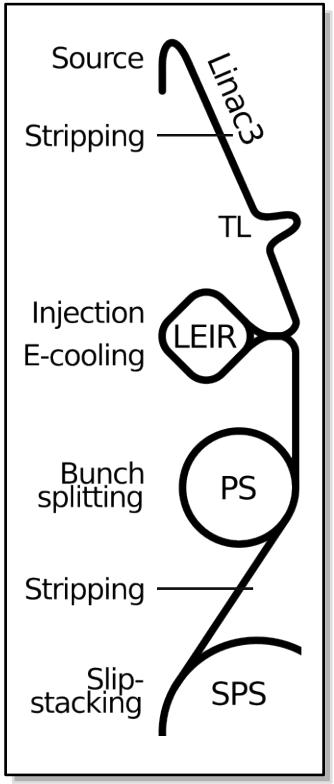
Ion injector complex at CERN



Existing
Exp. area
Experiment

Planned / possible
Exp. area
Experiment

LEIR	Low-Energy Ion Ring
PS	Proton Synchrotron
SPS	Super Proton Synchrotron
LHC	Large Hadron Collider



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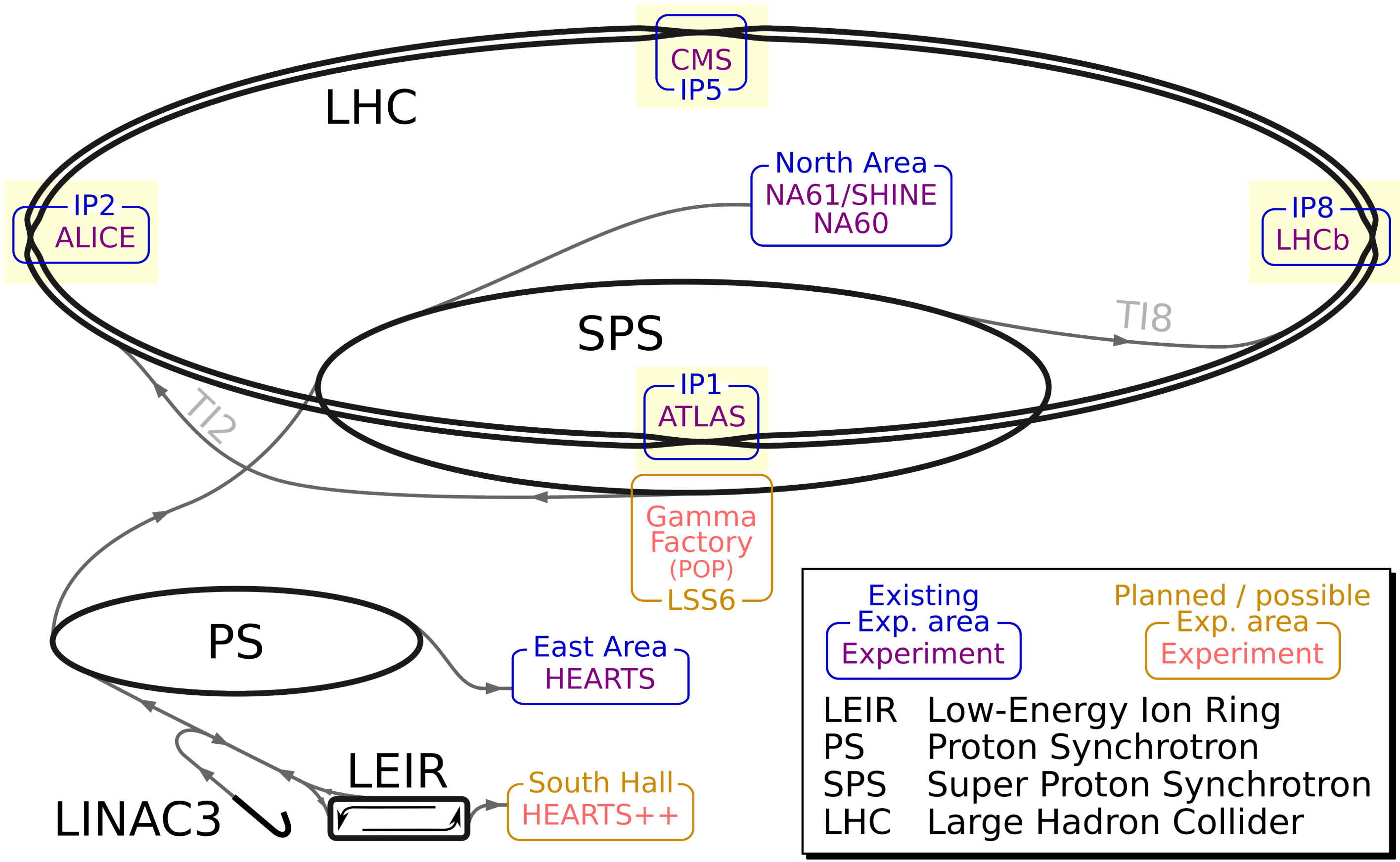

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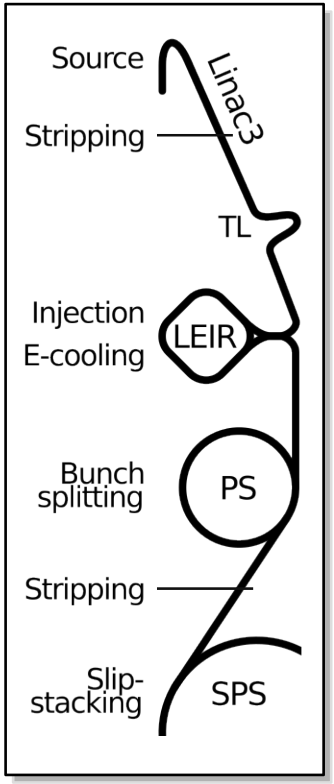

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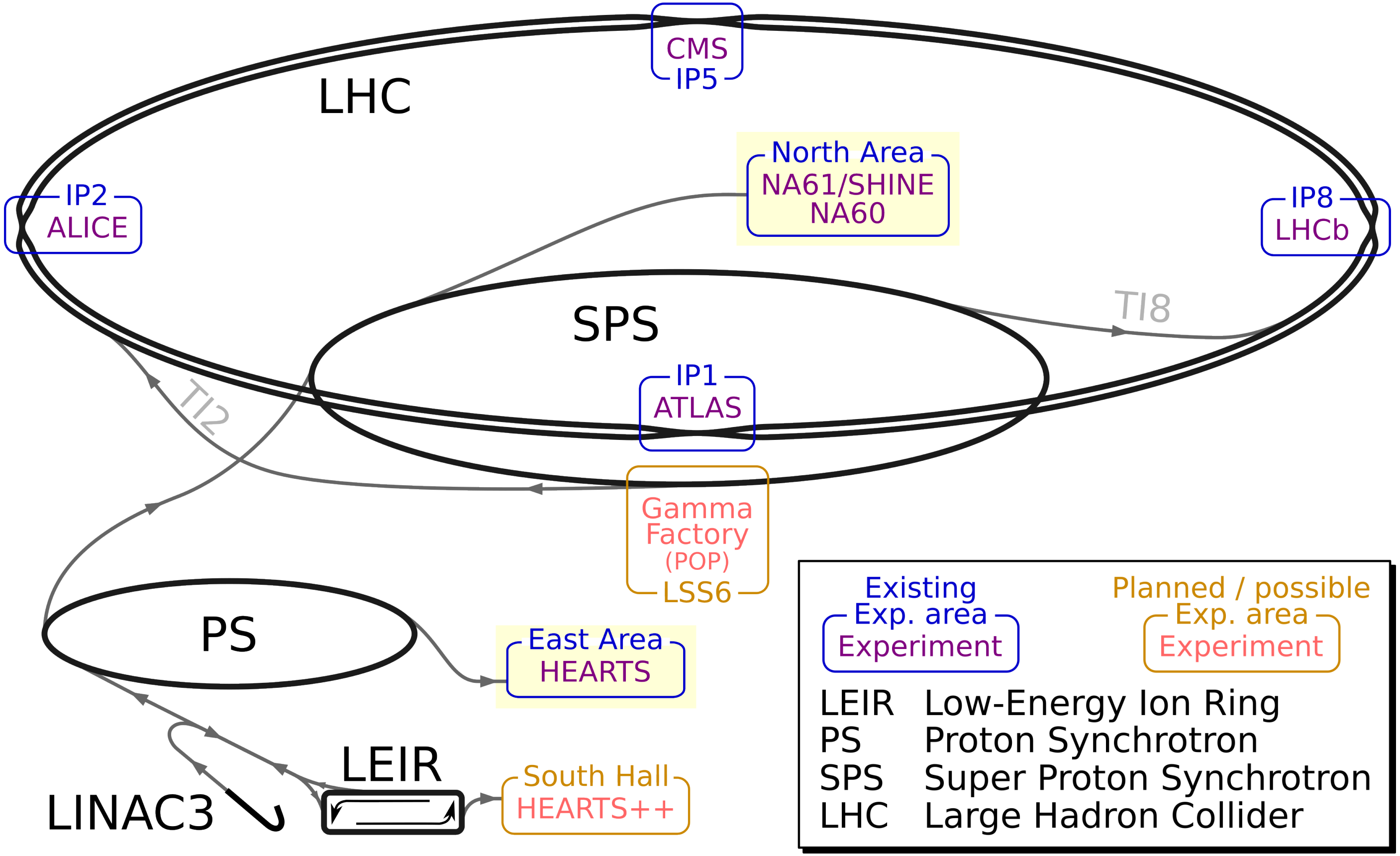

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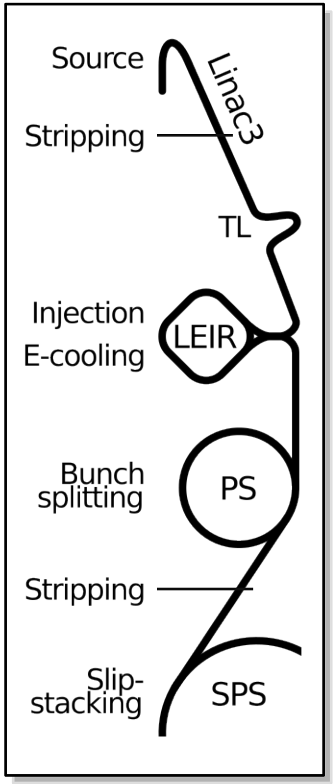

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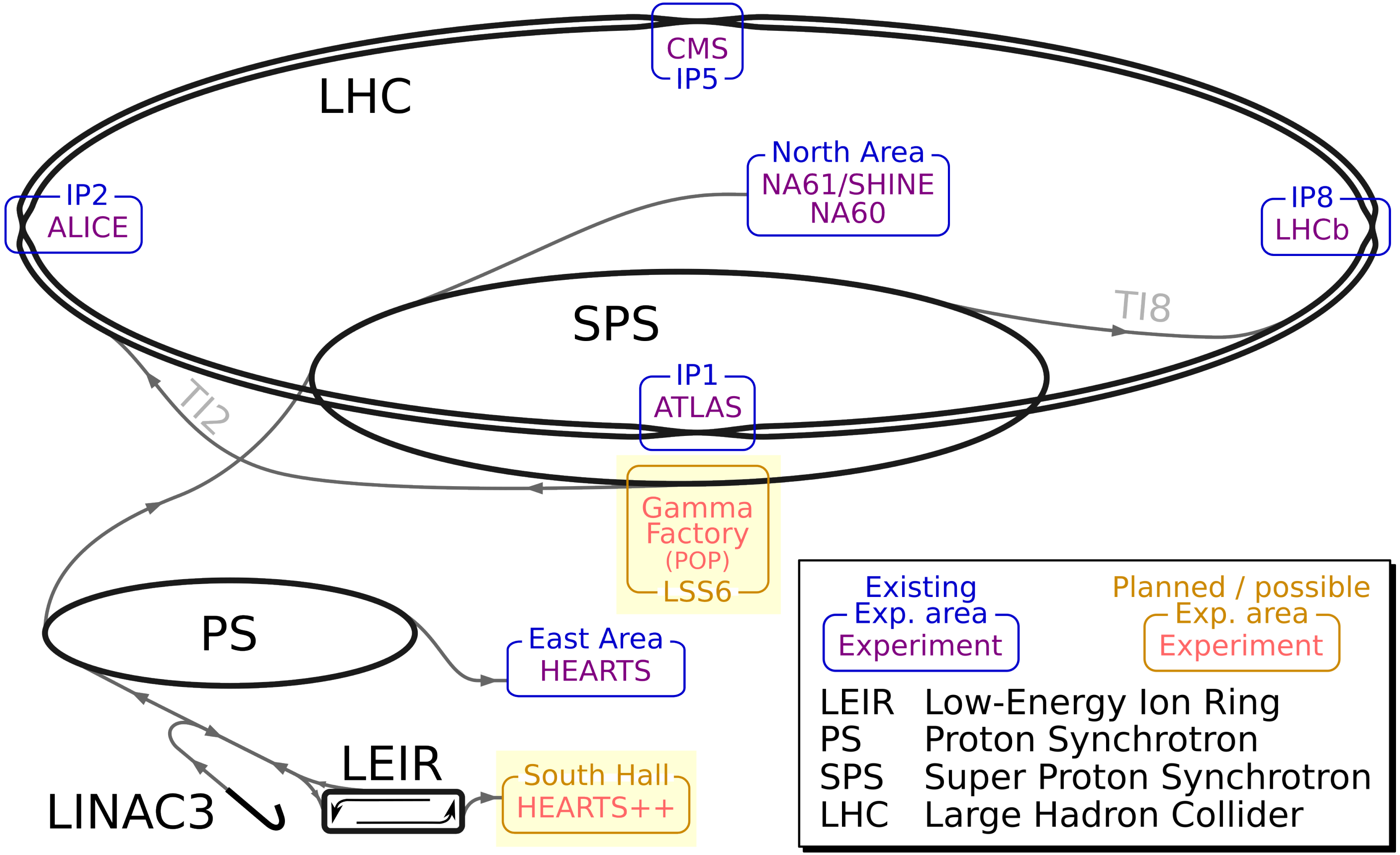

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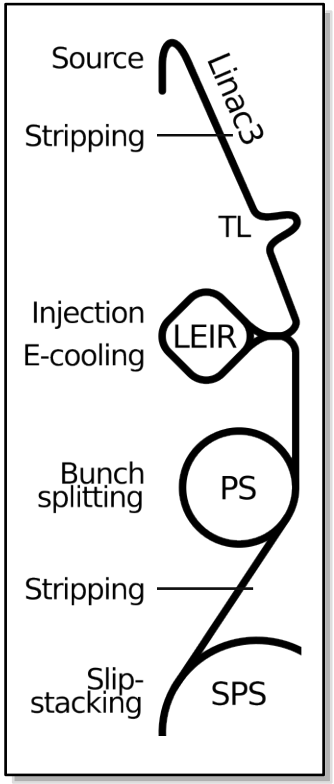
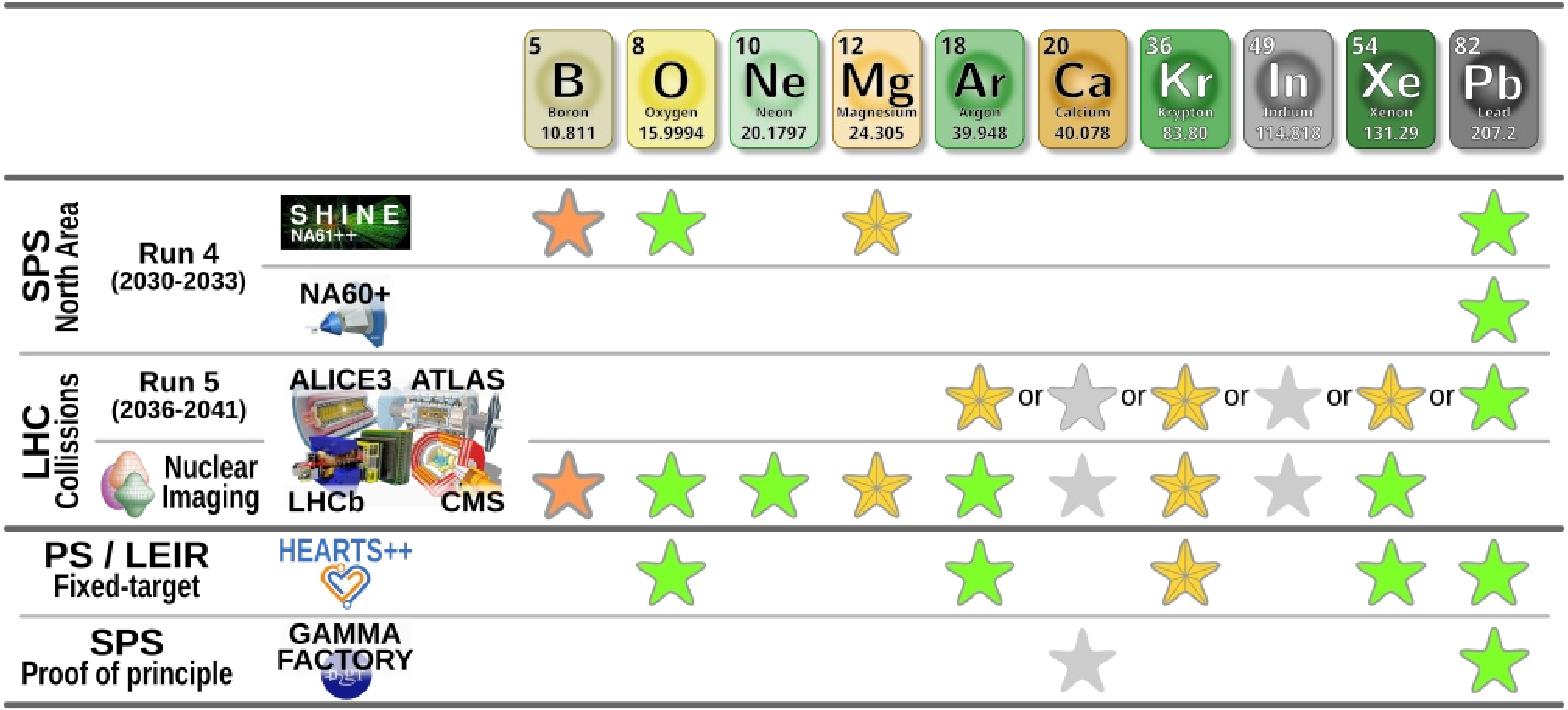


After-LS3 ion users



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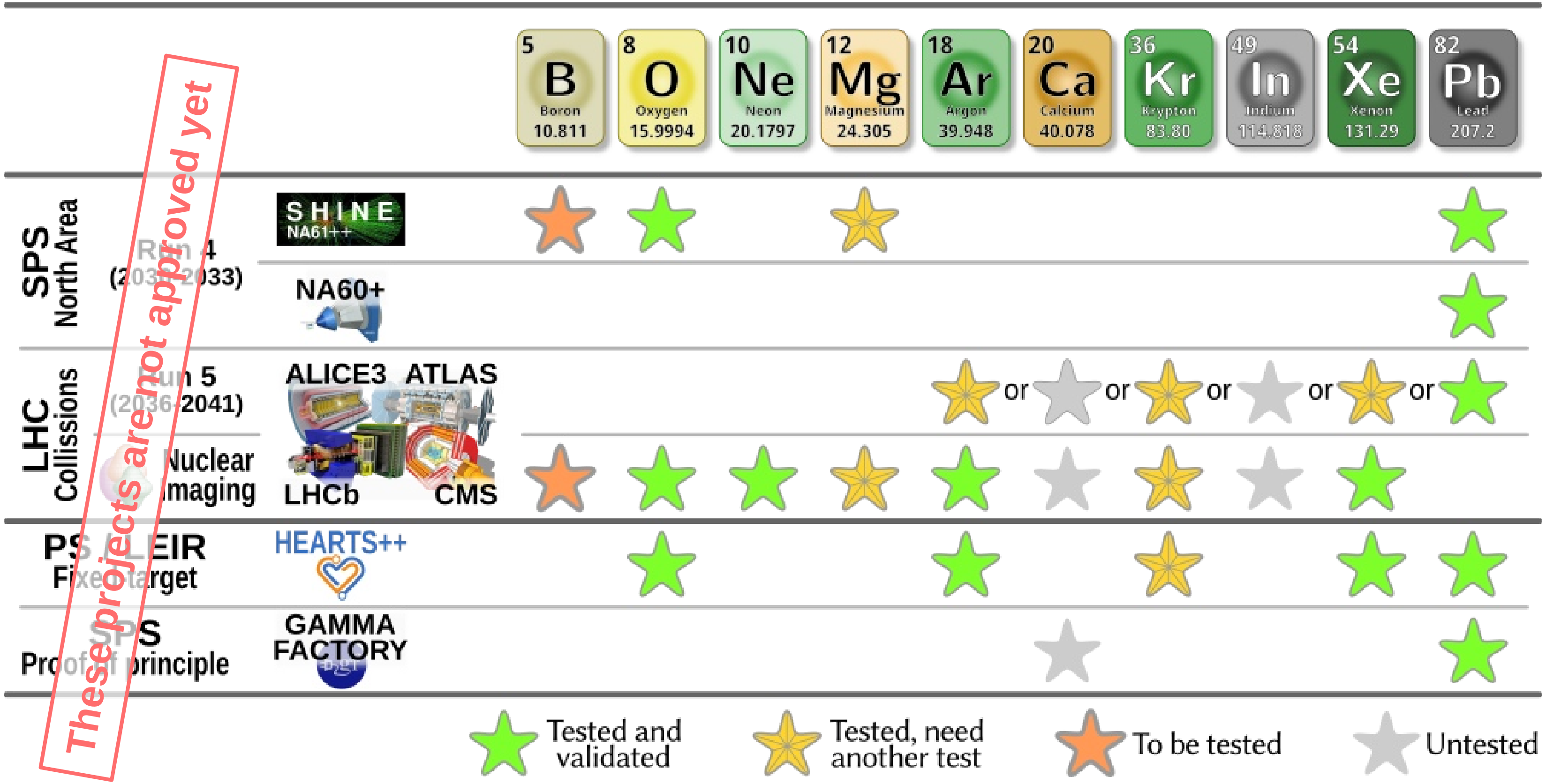
SPS North Area	**Run 4** (2030-2033)	SHINE NA61++	🟠	🟢		🟡						🟢
		NA60+										🟢
LHC Collisions	**Run 5** (2036-2041)	**ALICE3** **ATLAS** **LHCb** **CMS**					🟡 or	⚪ or	🟡 or	⚪ or	🟡 or	🟢
	Nuclear Imaging		🟠	🟢	🟢	🟡	🟢	⚪	🟡	⚪	🟢	
PS / LEIR Fixed-target		HEARTS++		🟢			🟢		🟡		🟢	🟢
SPS Proof of principle		**GAMMA FACTORY**						⚪				🟢

🟢 Tested and validated 🟡 Tested, need another test 🟠 To be tested ⚪ Untested

After-LS3 ion users



These projects are not approved yet

			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
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Projects’ status and challenges

Experimental physics projects
Tests done in Run 3 to assess future feasibility

- NA61++ / SHINE

  → Beam test with **magnesium** done in 2024
    → Bottleneck found, to be retested
  → **Boron** beam has to be developed for Run 4 (2030+)

- NA60+

  → Ongoing beam tests with **lead**

- LHC experiments in Run 5

  → Beam tests with **krypton** 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 the LHC

  → Many ideas, short LHC **neon** run
    → complementing oxygen run

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Facilities

- **HEARTS++**
  – most demanding request for 2031+

  → Provide: **O**, **Ar**, **Kr**, **Xe**, **Pb**
  → Every operational day, with switching times between species of maximum 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

Operation with ions at CERN
Past and present experience

Stable part of the source pulse > 200 µs
(required for efficient LEIR injection)

Single Linac3 pulse should contain ≳ $4 \cdot 10^{10}$ e
and be repeatable every 200 ms

Past short ion runs or tests

- **Argon run** in 2015 up to SPS
  → for **NA61**
- **Xenon run** in 2017
  → for **NA61** & **LHC**
- **Krypton test** in 2023
  → input for injector model & **LHC** Run 5
- **Oxygen test** in 2023
  → validation of **LHC** oxygen run in 2025
- **Magnesium test** in 2024
  → validation for **NA61++** (Run 4, 2030+)
- **Oxygen run** in 2025
  → for **LHC** & **NA61**
- **Neon run** on 8 July 2025
  → for **LHC** (Nuclear imaging)

Ion	I_b [μA]			Beam intensity [10^{10} e]	
	Src	RFQ	Ln3	LEIR	PS
^{40}Ar	140	–	60	2.2	2.0
^{129}Xe	175	–	34	4.0	1.4
^{86}Kr	130	83	–	–	–
^{24}Mg	50	$25^{\#}$	19	1.8	1.0
^{16}O	239	121	93	5.7	3.6
^{20}Ne	181	–	59	2.3	1.4
^{208}Pb*	182	$118^{\#}$	31	10.3	9.0

$^{\#}$Calculated with transmission efficiency measured at different time

*Lead performance from the 2024 LHC ion run shown for reference

Operation with ions at CERN

LHC plans

Study to find an ion maximizing nucleon-nucleon luminosity

- Needed by the end of 2025 for Run 5 of HL-LHC
- Two relevant scenarios (WG5 is too optimistic)

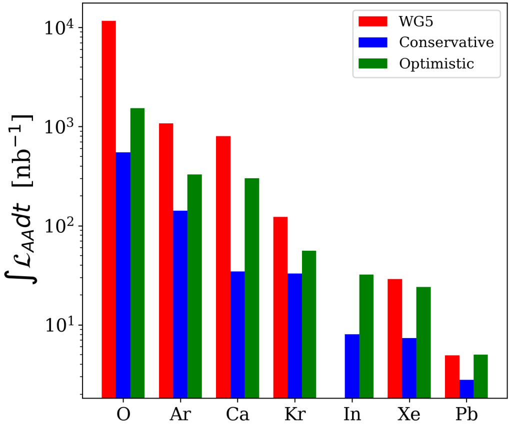
→ Conservative: similar production scheme to Pb
→ Optimistic: reduced β*, crossing, 8 injections into LEIR
no bunch splitting in PS and other optional optimizations

Possible ions for LHC Run 5 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 Linc3 currents are experimental values as known in 2024, except for Ca, which has never been tested

One month integrated
ion-ion luminosity



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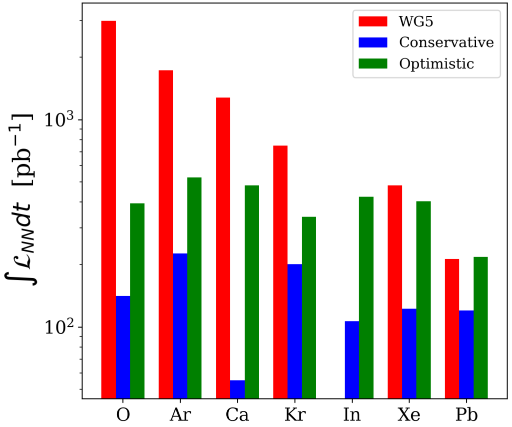

Operation with ions at CERN
LHC plans

Future test for LHC Run 5

- **2^{nd} krypton test** possibly in Run 4

  → At least up to PS or SPS

  → input for the injector model

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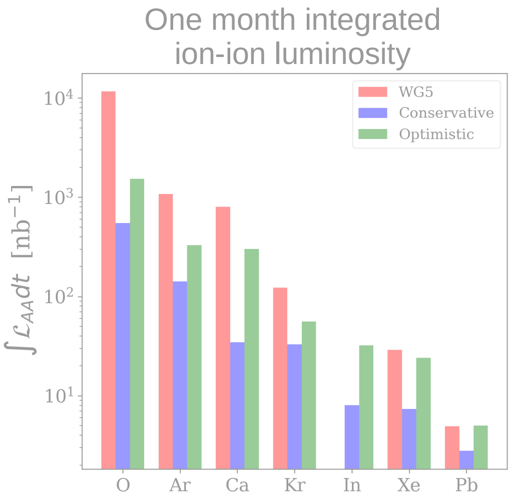
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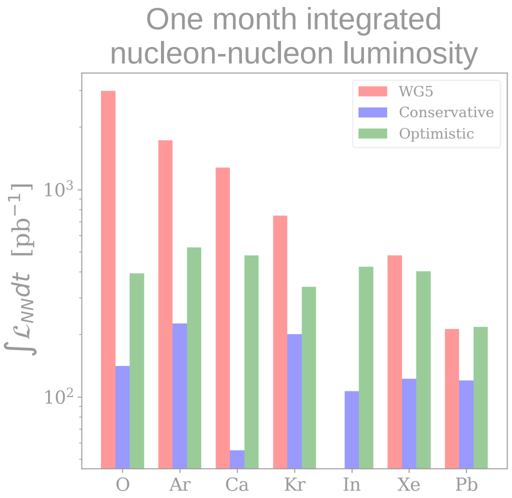
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Operation with ions at CERN
Fixed-target plans

Future tests for NA61++ (Run 4, 2030+)

- **2nd magnesium test** possibly in 2026

  → Validation of mitigation against short
  oven lifetime bottleneck
  → Reduce magnesium consumption by
  adding a tantalum hotscreen in
  the plasma chamber

- **Boron test** possibly in 2027

  → At the source and Linac3

  → Validation of decaborane ($B_{10}H_{14}$)
  or m-carborane ($C_2B_{10}H_{12}$)
  delivered with MIVOC setup

  → Stability & intensity reach

Operation with ions at CERN

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  - → Stability & intensity reach

Future tests for HEARTS++ (Run 4, 2031+)

- **Cocktail beams test** – unplanned yet
  - → At the source (& RFQ)
  - → HEARTS++ doesn't require specific ions, but rather a menu consisting of ions covering wide mass range
  - → Use noble gases (Ar, Kr, Xe) & oxygen mixture
    - → Prior operational experience with Ar, Xe & O when used individually
    - → Highest intensity predictions
  - → Test to validate setup difficulty (duration), intensity reach and stability

Ion Complex Upgrade study

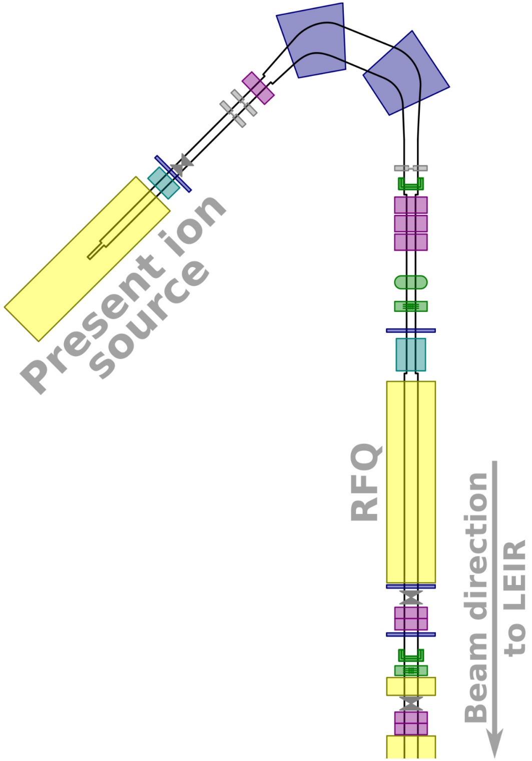
Low-energy region of Linac3 – present limitations

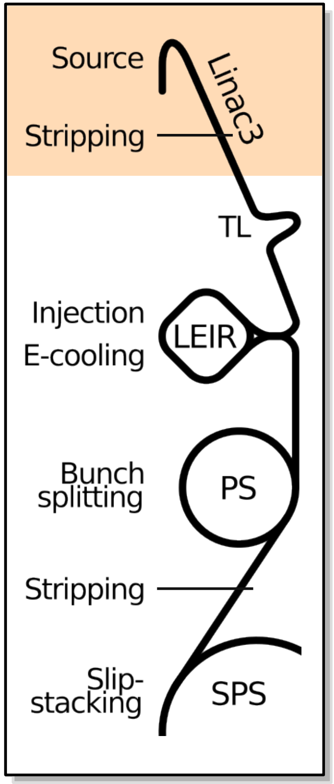
Present limitations

- One ion source, fully commited to operation from Run 4

  → Limited time for any tests (new ions, automation)

  → Only two ion species (mixtures) can be operated per year





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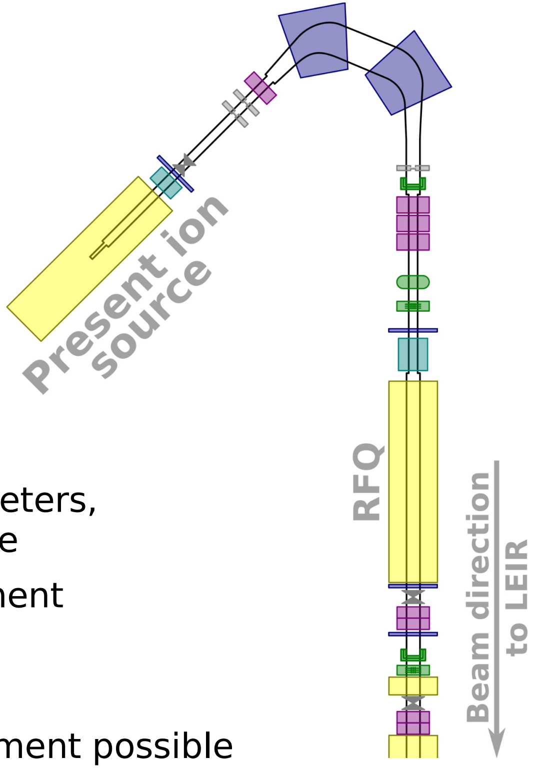
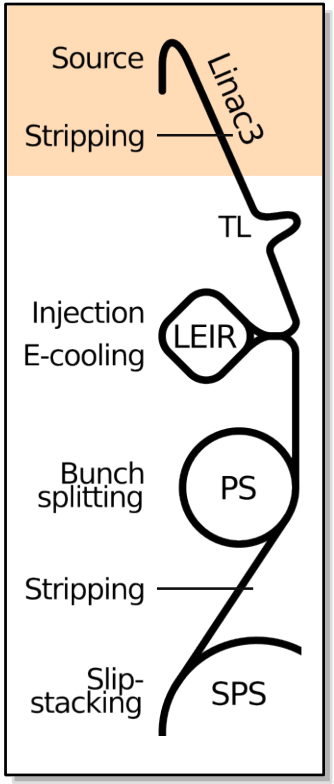
- One ion source, fully commited to operation from Run 4
  - → Limited time for any tests (new ions, automation)
  - → Only two ion species (mixtures) can be operated per year
- Beam-destructive instrumentation located far away from the source extraction & lengthy CSD scan
  - → Minimal feedback while tuning parameters, especially when the source is unstable
  - → Time-consuming new beam development with trial-and-error approach
  - → Limited feedback for automation
  - → Little beam dynamics model improvement possible



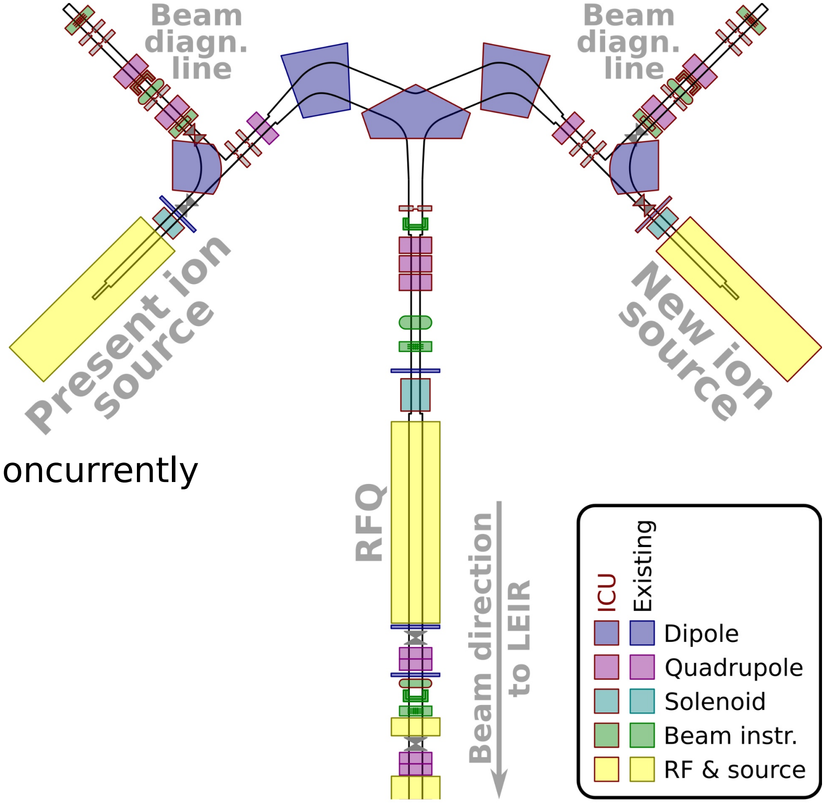


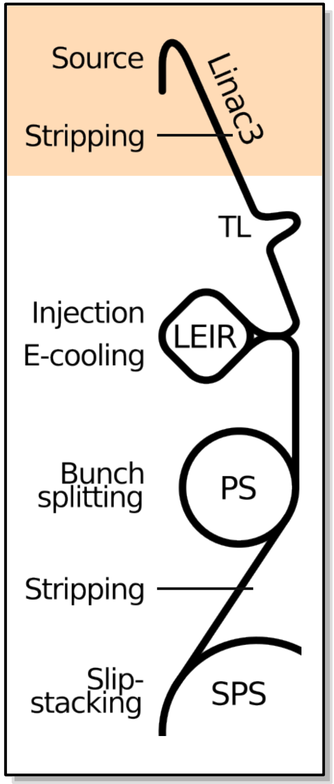
Ion Complex Upgrade study

2nd source & new low-energy beam diagnostics

Specifications and caveats

- Position and connection of the new source is indicative
  - → Need thorough market and beam dynamics study to select an optimal source type and LEBT
  - → Most LEBT components need to be pulsed to monitor and optimize the performance of both sources when coupled with the RFQ concurrently





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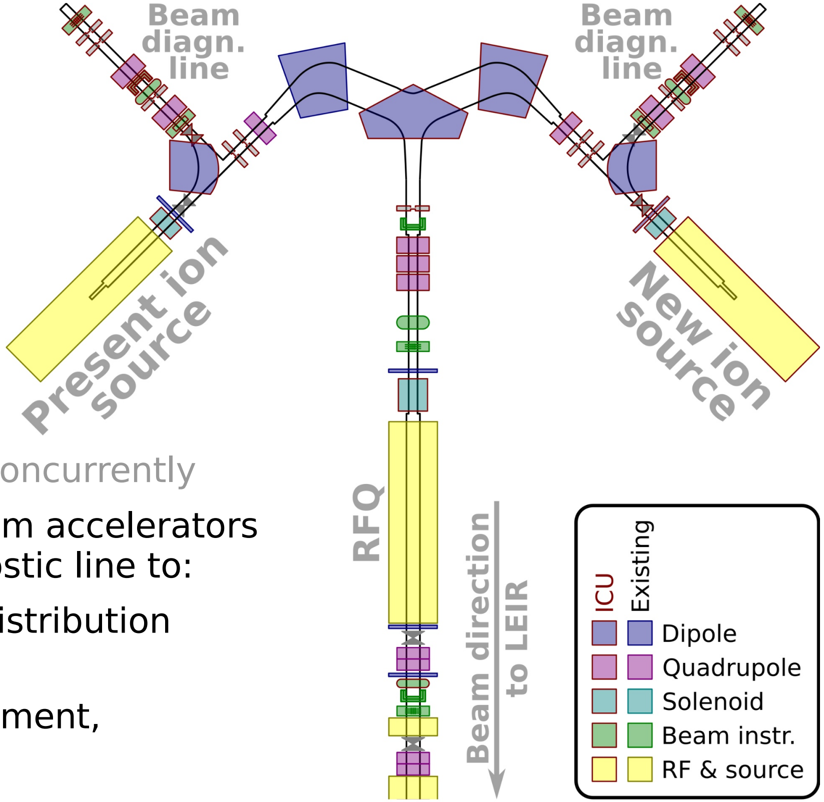
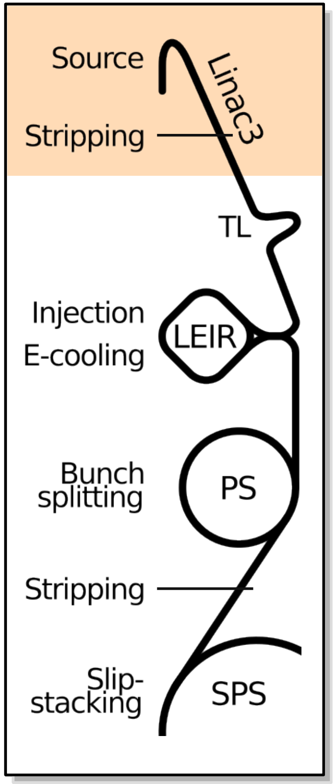
  - → Most LEBT components need to be pulsed to monitor and optimize the performance of both sources when coupled with the RFQ concurrently
- Every beam pulse unused by downstream accelerators would be redirected to the beam diagnostic line to:
  - → Continuously measure charge-state distribution (2 min per full scan)
  - → On demand 2D beam profile measurement, emittance and energy distibution





Ion Complex Upgrade study

Alternative stripping between LEIR and PS

New hardware

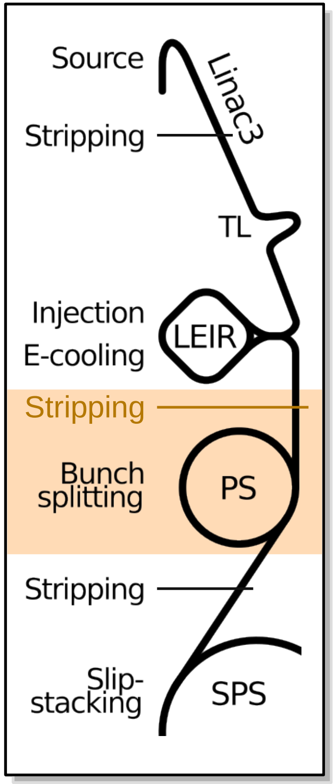
- Quick stripper assembly (with per-cycle position) downstream of LEIR
- Instrumentation downstream of the stripper and before PS injection
- Pulsed injection kicker into PS

New beam transfer scheme from LEIR to PS

- Due to energy loss at stripping, the PS revolution frequency (f_{rev}) is no longer a multiple of the LEIR f_{rev}

  → Transfer is not possible at every PS turn

  → New synchronization scheme is needed
    → PS has to wait for a suitable turn to trigger transfer



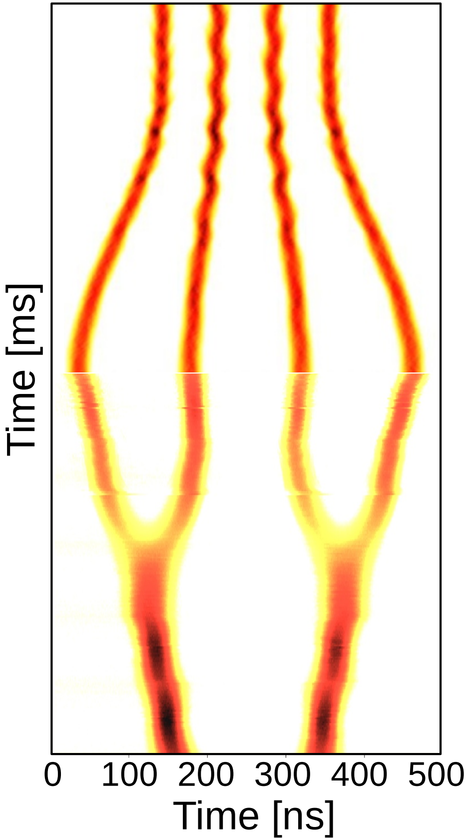
Ion Complex Upgrade study

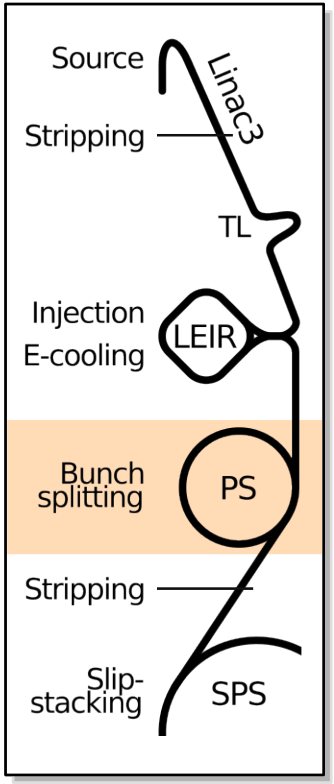
25-ns ion bunch spacing for the LHC

New hardware

- New RF cavities for the PS to enable batch compression and reduce bunch spacing from 100 to 50 ns

  → Downstream, the SPS can use slip-stacking to reduce bunch spacing to 25 ns
  (without additional upgrades)





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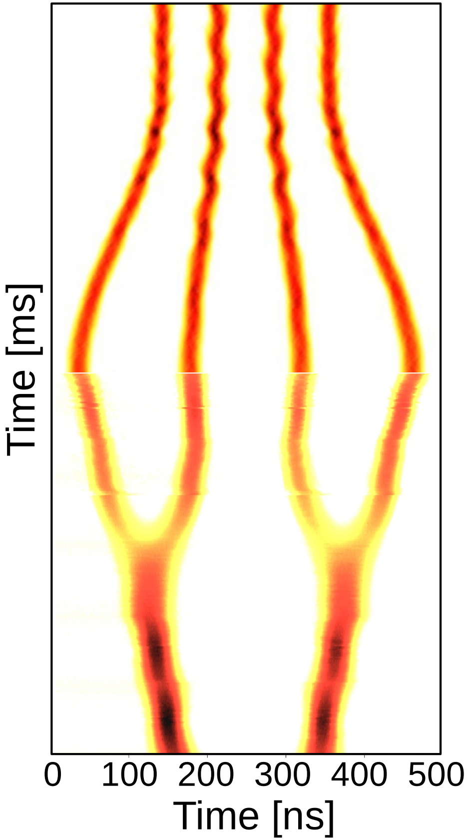
  → Downstream, the SPS can use slip-stacking to reduce bunch spacing to 25 ns (without additional upgrades)

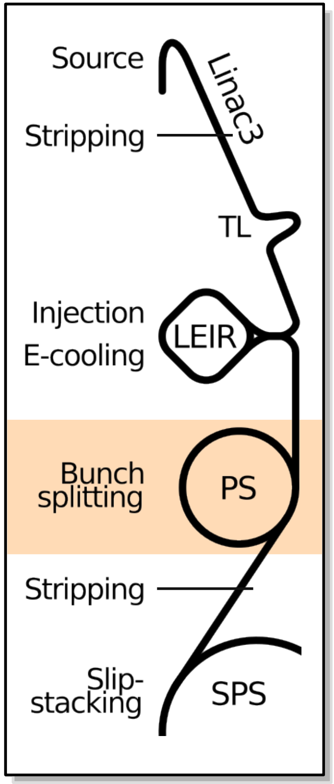
- The design of new cavitites is challenging

  → Wide-band Finemet type under consideration
  → Designs exist up to 10 MHz

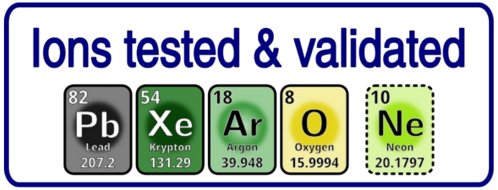
  → Needs to be developed to reach 20 MHz, including amplifiers

  → Operation at the limit of the Finemet material properties

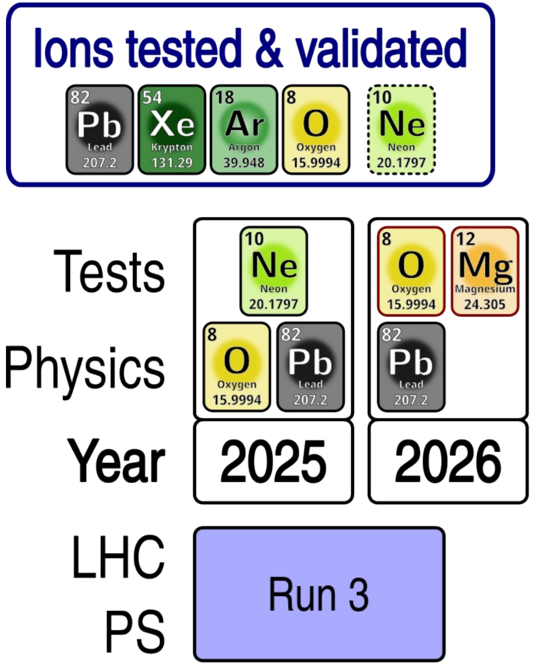




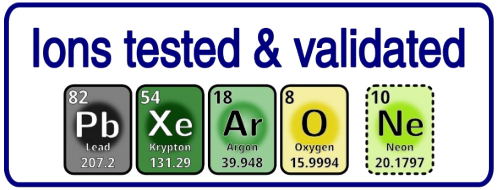
Future ion long-term schedule → The past



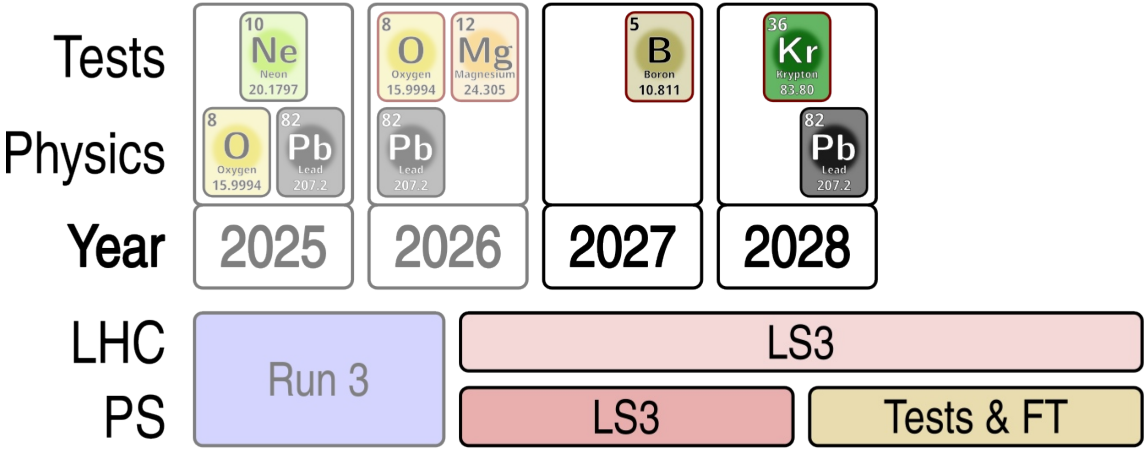
Future ion long-term schedule → Run 3



Future ion long-term schedule
→ Long Shutdown 3



Ions tested & validated

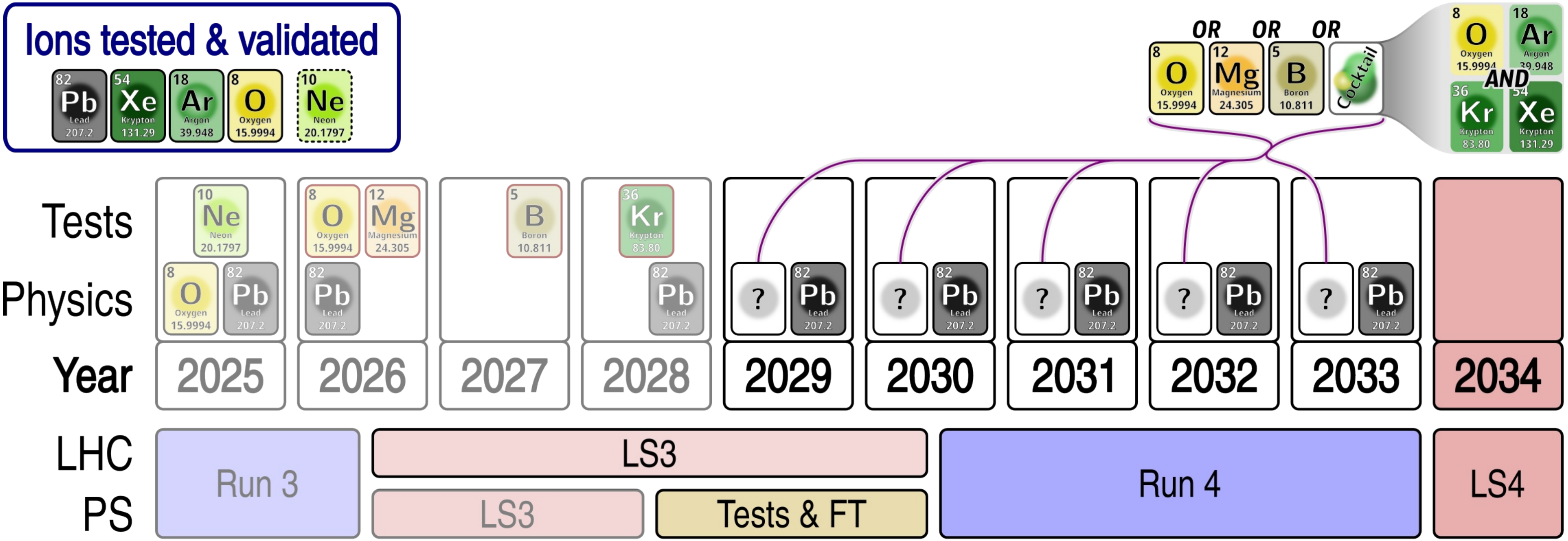


	2025	2026	2027	2028
Tests	10 Ne Neon 20.1797	8 O Oxygen 15.9994 12 Mg Magnesium 24.305	5 B Boron 10.811	36 Kr Krypton 83.80
Physics	8 O Oxygen 15.9994 82 Pb Lead 207.2	82 Pb Lead 207.2		82 Pb Lead 207.2

LHC: Run 3 | LS3

PS: Run 3 | LS3 | Tests & FT

Future ion long-term schedule → Run 4



Ions tested & validated

82 Pb Lead 207.2 · 54 Xe Krypton 131.29 · 18 Ar Argon 39.948 · 8 O Oxygen 15.9994 · 10 Ne Neon 20.1797

8 O Oxygen 15.9994 OR 12 Mg Magnesium 24.305 OR 5 B Boron 10.811 OR Cocktail

Cocktail: 8 O Oxygen 15.9994 · 18 Ar Argon 39.948 AND 36 Kr Krypton 83.80 · 54 Xe Krypton 131.29

Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
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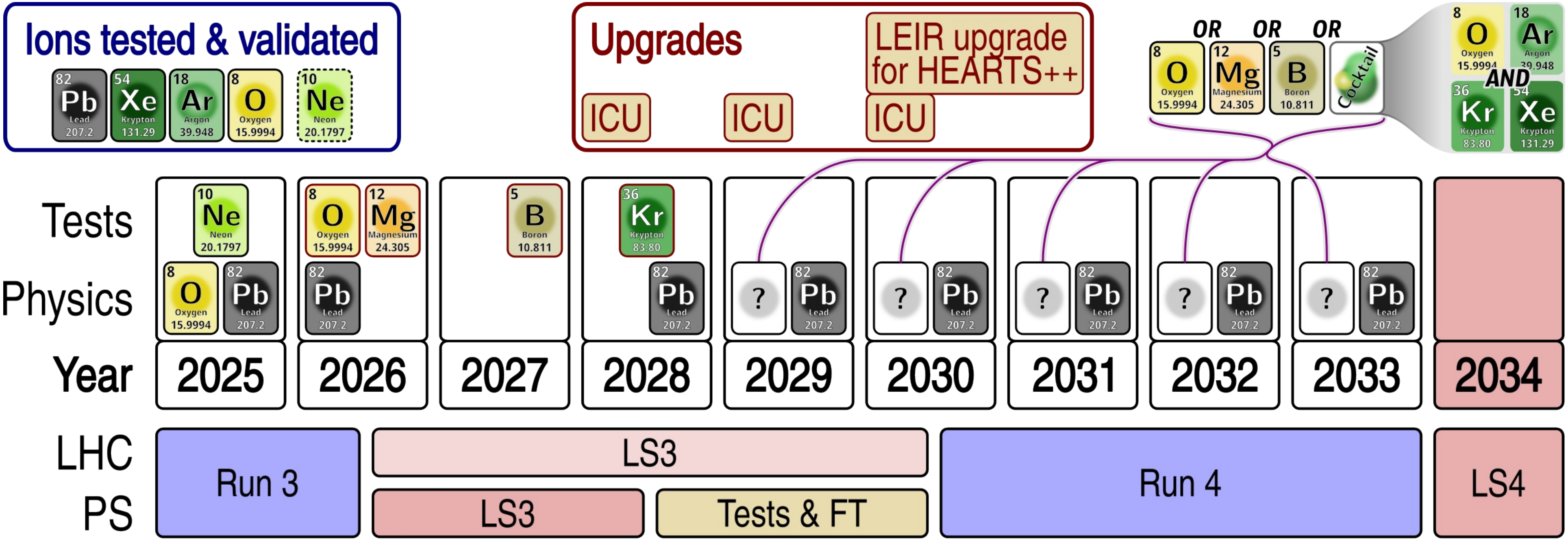
LHC: Run 3 · LS3 · Run 4 · LS4

PS: Run 3 · LS3 · Tests & FT · Run 4 · LS4

No ions besides Pb@LHC are approved beyond 2026

Future ion long-term schedule
→ Possible upgrades



Ions tested & validated

Upgrades

ICU

ICU

LEIR upgrade for HEARTS++

ICU

Year	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
Tests	Ne	O Mg	B	Kr						
Physics	O Pb	Pb		Pb	? Pb	? Pb	? Pb	? Pb	? Pb	

	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034
LHC	Run 3	Run 3 / LS3	LS3	LS3	LS3	Run 4	Run 4	Run 4	Run 4	LS4
PS	Run 3	Run 3 / LS3	LS3	LS3	Tests & FT	Run 4	Run 4	Run 4	Run 4	LS4

No ions besides Pb@LHC are approved beyond 2026

LS	→ Long Shutdown
ICU	→ Ion Complex Upgrade
FT	→ Fixed-target physics experiments
HEARTS++	→ Heavy ion irradiation facility for space and industrial applications (co-funded by the European Commission)

Summary and outlook

- The **main ion** operated at the **LHC** until the end of Run4 (2033) **will be Pb**
  - Ongoing studies to identify the optimal ion species for maximizing nucleon-nucleon luminosity in Run 5

    → Krypton was tested at the source
  - Preparation of beam evolution simulation across the ion complex
  - There is growing interest in short LHC runs with lighter ions
- Several **new ion species** (O, Mg, Ne) have recently been tested in view of expected LHC, NA61++, HEARTS and Gamma Factory requests
  - More tests should be performed

    → 2^{nd} magnesium & krypton tests, boron, cocktail for HEARTS++
- **Ion injector upgrades** will be needed if some of the proposed projects would be approved and funded

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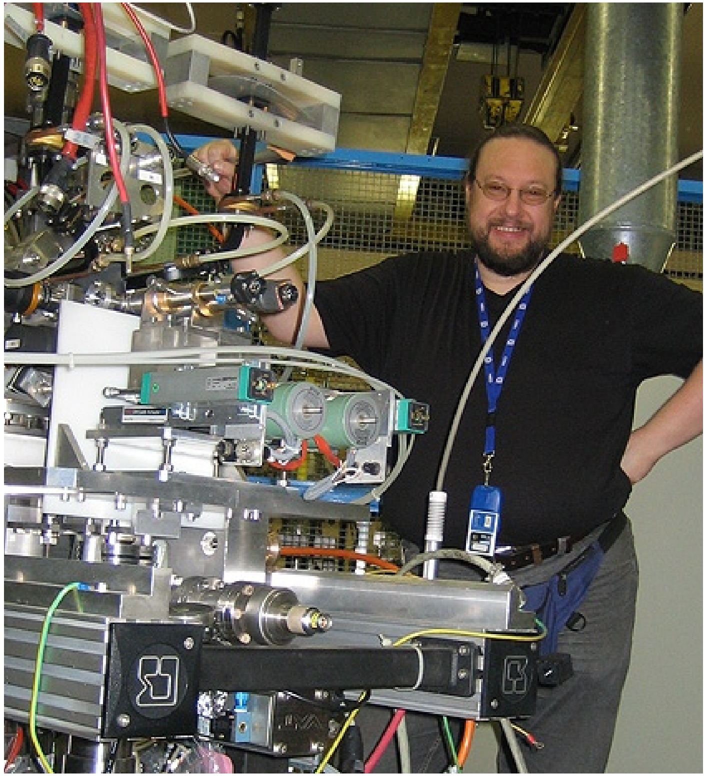
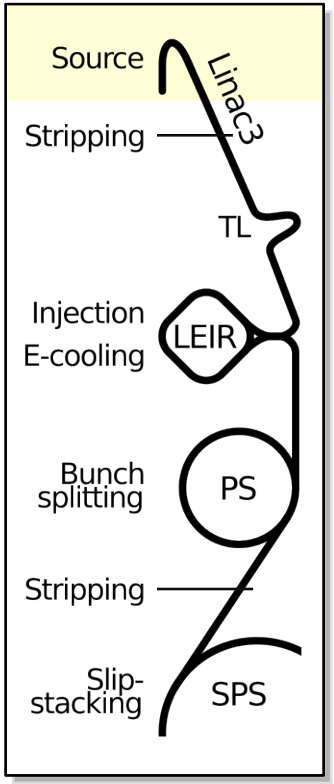
Ion injector complex at CERN

GTS-ECR source operation

Material input

- Gases and solids
  - Gases are quick to setup
  - Oven-fill lifetime limit for solids; some solids are excluded (too high melting point)



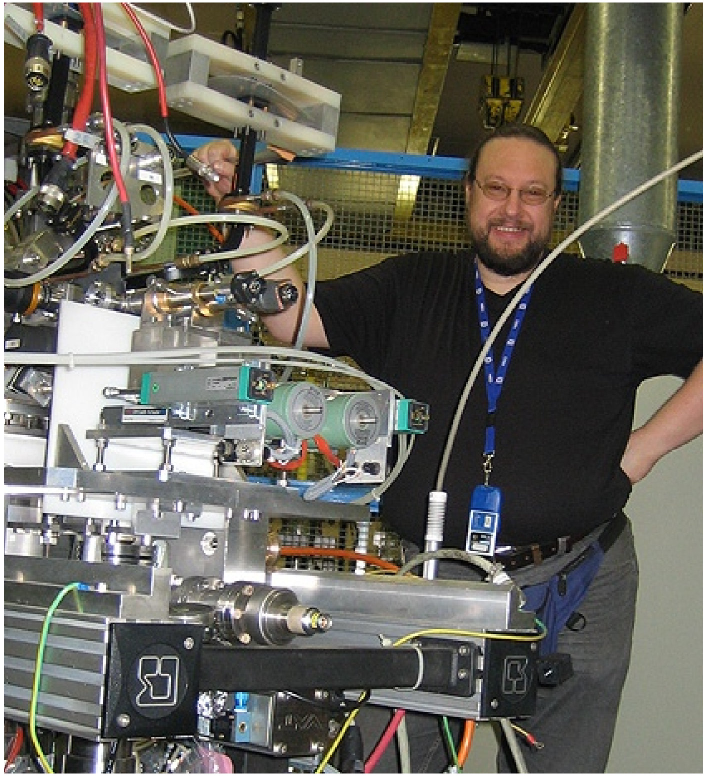


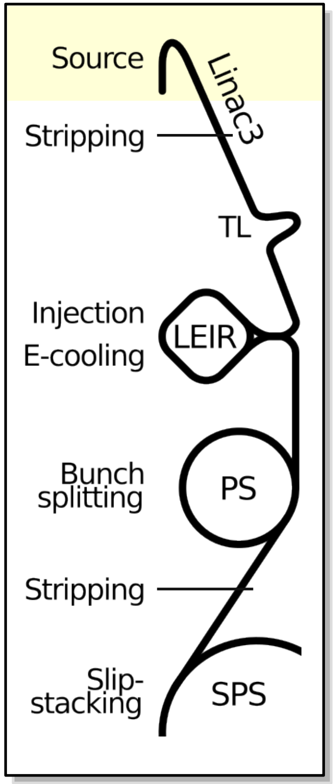
Ion injector complex at CERN

GTS-ECR source operation

Material input

- Gases and solids
  - Gases are quick to setup
  - Oven-fill lifetime limit for solids; some solids are excluded (too high melting point)
- Pure material (chemically or isotopically) vs. compounds
  - Better physical, chemical or handling properties vs. reduced beam stability and intensity due to presence of undesired elements or isotopes in the plasm
  - Significant cost of enrichment
- Safety considerations: reactivity, toxicity, flammability
- Support gas usage





Quick test vs. stable, many-week operation

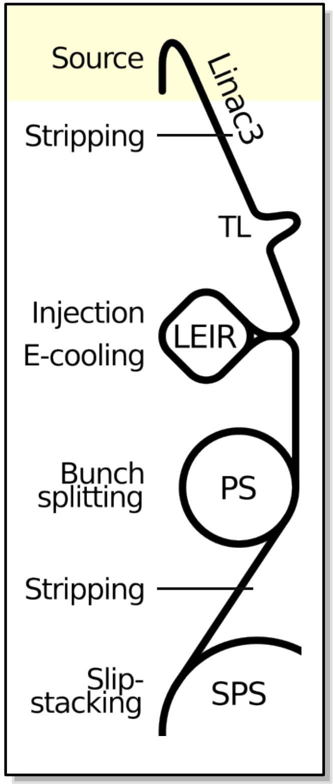
Ion injector complex at CERN
GTS-ECR source limitations

Availability for development of new ion beams

- Only **one source** available
  - Very **limited time** to develop new beams
  - **Switching** between solids, gases, or gas mixtures **takes weeks** to reach the required stability (with only few exceptions)

    → Considering scheduling, equipment experts availability, and lack of prior operational experience with cocktail beams

    → Only **two ions** (mixtures) **per year** can be operated
- Planning in advance is needed



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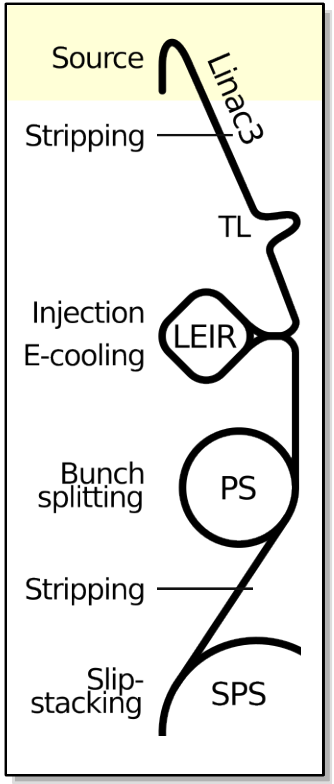
Beam instrumentation

- The beam measurement closest to the source is a Faraday cup (FC) 5m away, downstream of spectrometer dipoles and slit
  - Due to space-charge and aperture limitation **losses upstream of FC**

    → Limited success in **backtracking** of **beam parameters** to the source
    → Limited insight into the source state
- Charge-state distr. (CSD) scan takes 80 min

  → Only feasible when the source is stable
  → Minimal beam feedback on the source state at startup
- CSD scan is beam-destructive

  → **Can't measure concurrently** with operation
  → Minimal beam feedback on the long-term source state evolution (growing instabilities, or performance loss)
- **Limited** source tuning **automation**



Ion injector complex at CERN

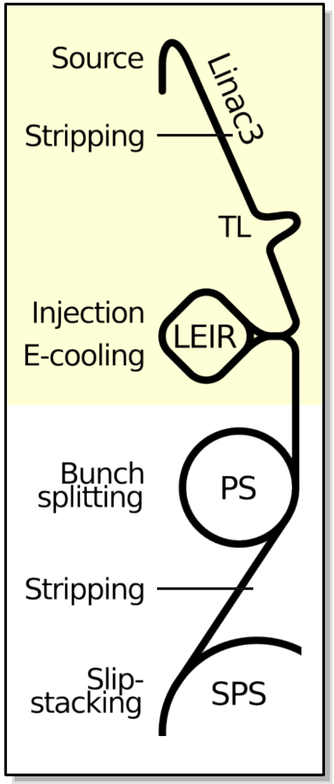
Particle and charge-state constraints in Linac3 and LEIR

Limits on charge states

- Source: A/Q > 3.4
- Linac3 RF power: A/Q < 8.3
- Transfer line to LEIR (after possible stripping): A/Q < 4

Radioprotection assessment

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



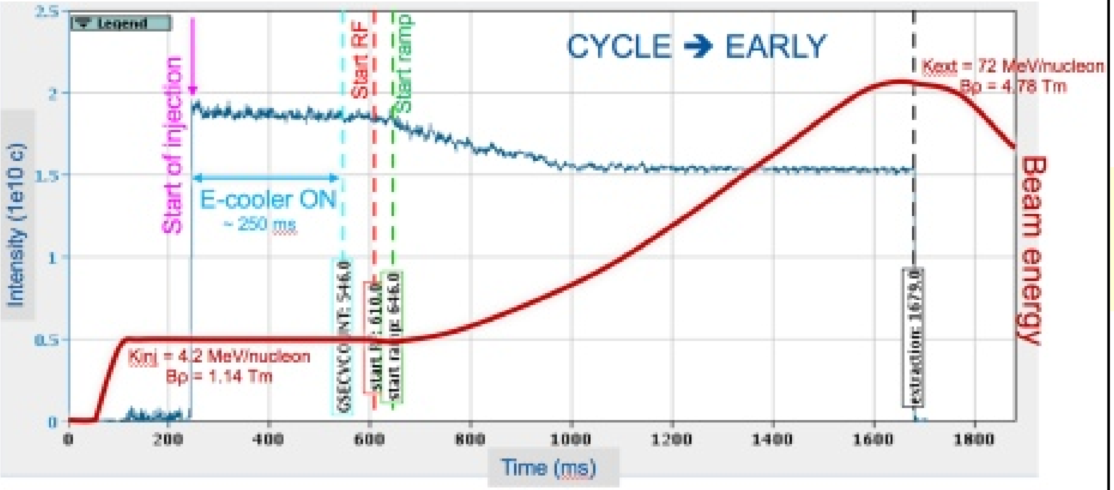
Ion injector complex at CERN

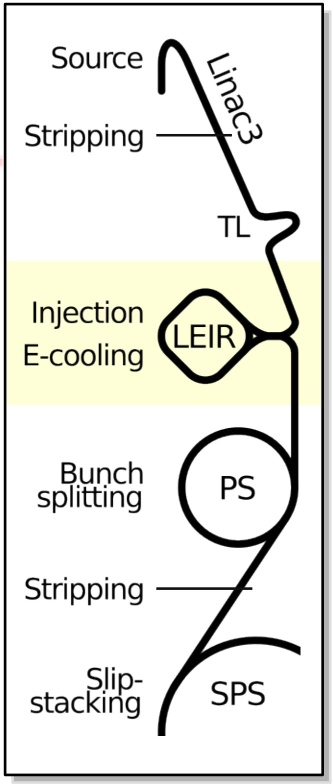
EARLY: Fixed-target beam and LHC commissioning

Basic, initial cycle

- Single Linac3 injection
- Intensities below space-charge limit or onset of significant intra-beam scattering (IBS) effects
- Electron-cooling

  → Pb, Xe: not critical
  → Light ion: important
- Relatively ‘quick & easy’ beam commissioning
- Low-maintenance beam type

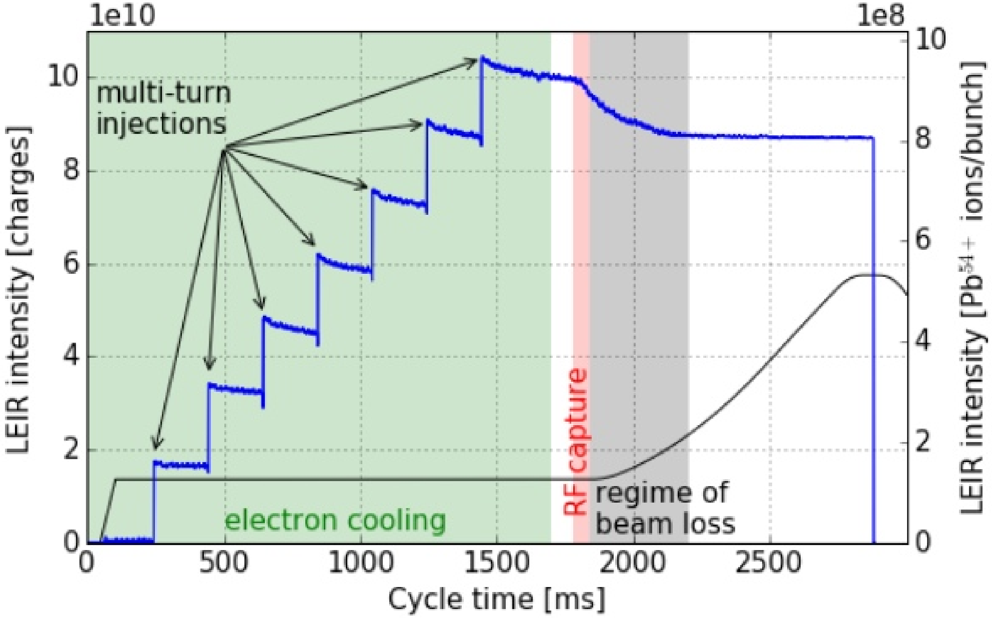


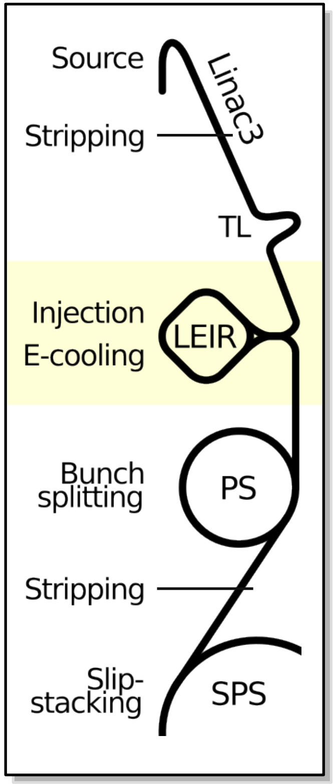


Ion injector complex at CERN
NOMINAL: High-intensity beam for LHC

Performant cycle

- Up to 8 Linac3 injections
- High intensities with **significant collective effects**
  - Essential transverse feedback
  - RF shaping harmonic → to lengthen bunch(es)
- Electron cooling is critical
- Long source conditioning for stability





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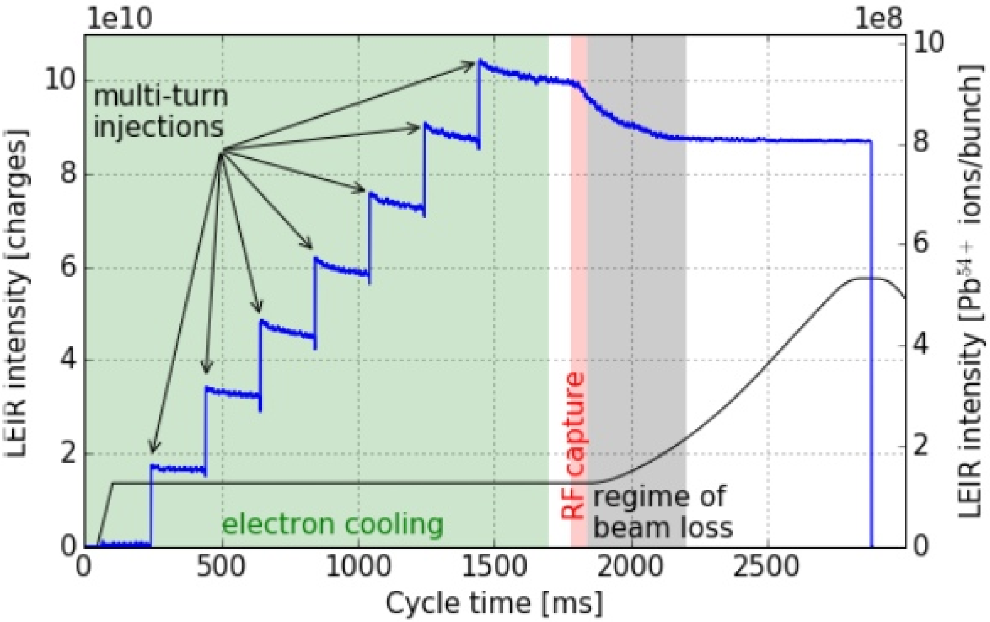
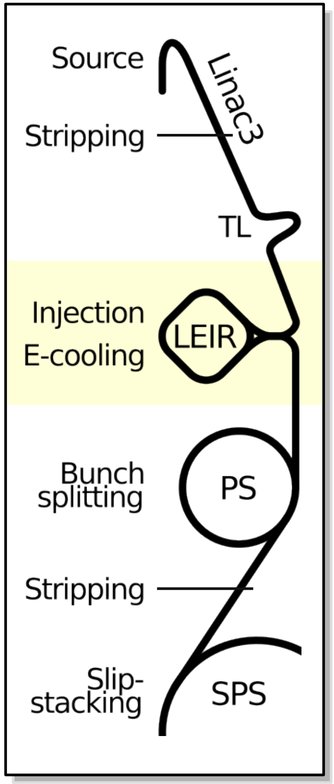
- Long source conditioning for stability
- **High-maintenance**

→ Peak performance is sensitive to drifts and interferences
→ deteriorates with time if unattended
→ Labour-intensive recovery after power cuts





Ion injector complex at CERN

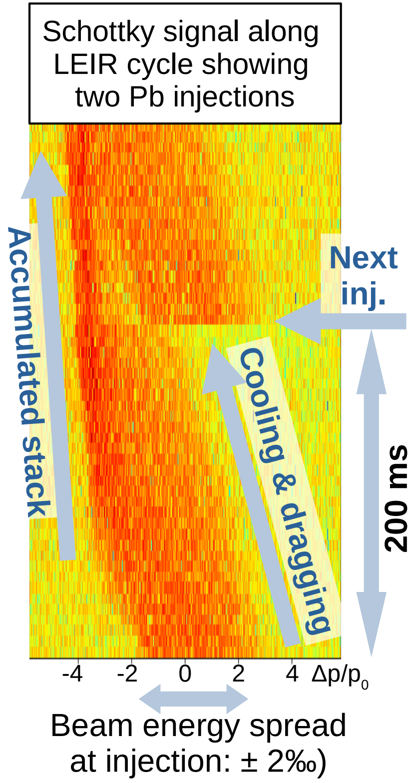
NOMINAL: Electron cooling

Reduce beam emittance

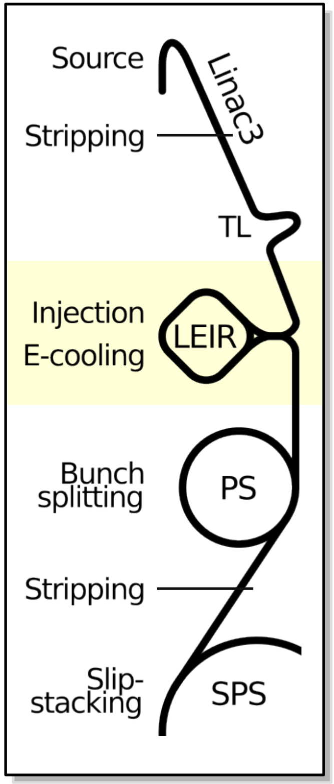
- Naturally large after multiturn injection

Stack multiple injections

- Drag the energy of the injected beam to the stack at lower energy, making phase-space available for the next injection


Schottky signal along LEIR cycle showing two Pb injections

Beam energy spread at injection: ± 2‰)



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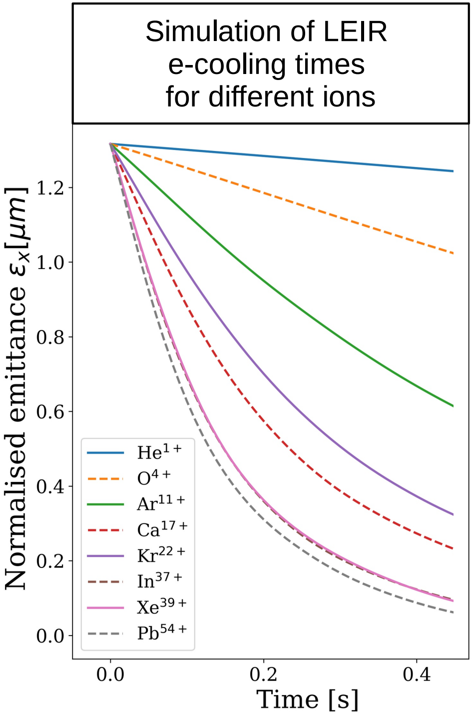
Stack multiple injections

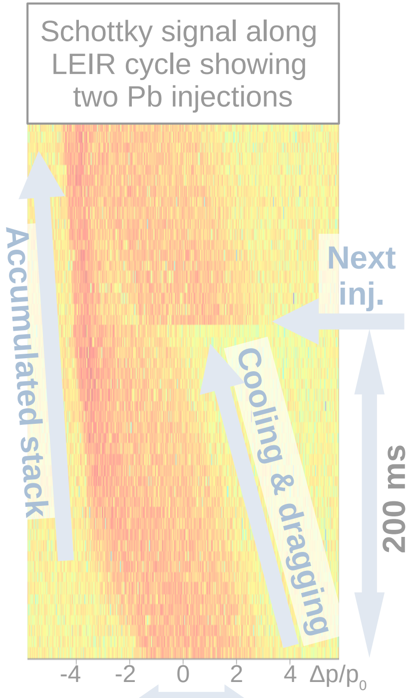
- Drag the energy of the injected beam to the stack at lower energy, making phase-space available for the next injection

Less efficient for lighter ions

- Needs more cooling time, but …
- More intensity losses in LEIR due to beam-gas, e-capture / e-loss
- Longer injection in SPS and LHC
  → Intra-beam scattering (IBS),
  beam-gas, space-charge



Simulation of LEIR e-cooling times for different ions



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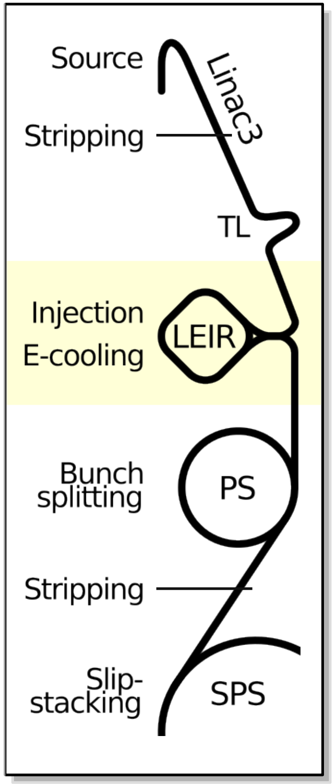


Ion injector complex at CERN

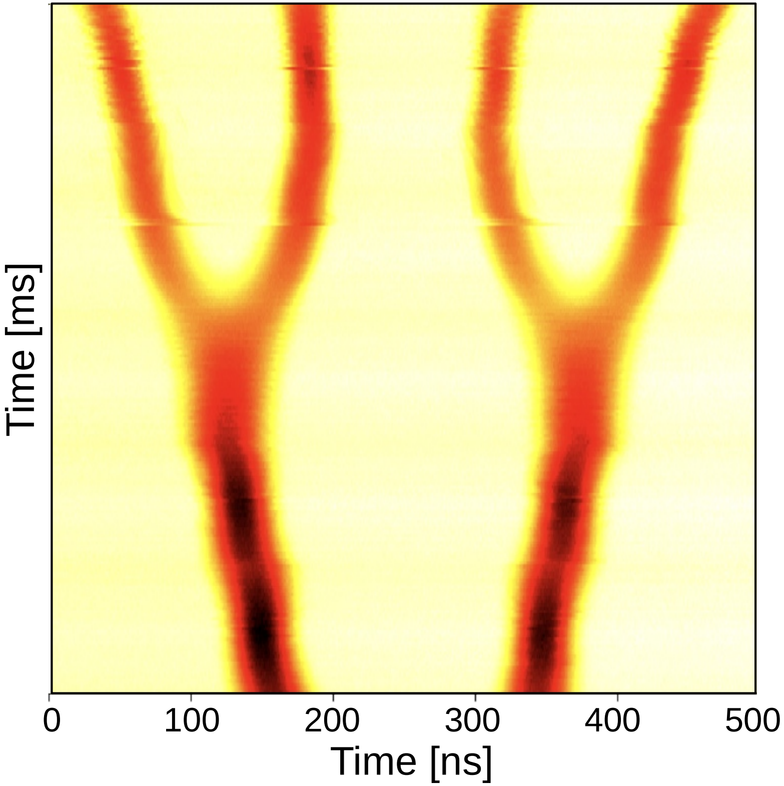
NOMINAL: RF manipulations in PS

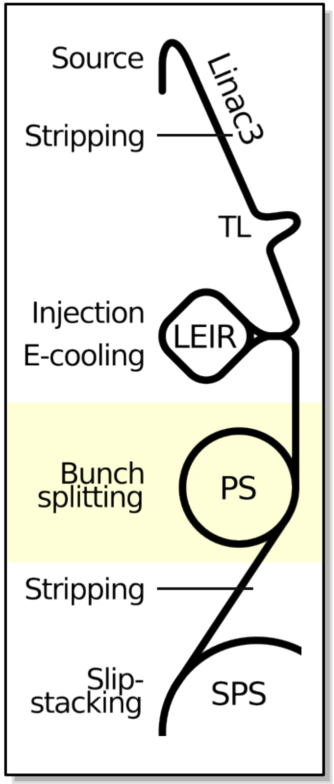
Bunch splitting

- Less charge per bunch
- Facilitates recapture after transition crossing
- Alleviates collective effects downstream, in SPS

Rebucketing

- From 10 MHz to 80 MHz system for SPS transfer
- Bunch spacing: 100 ns





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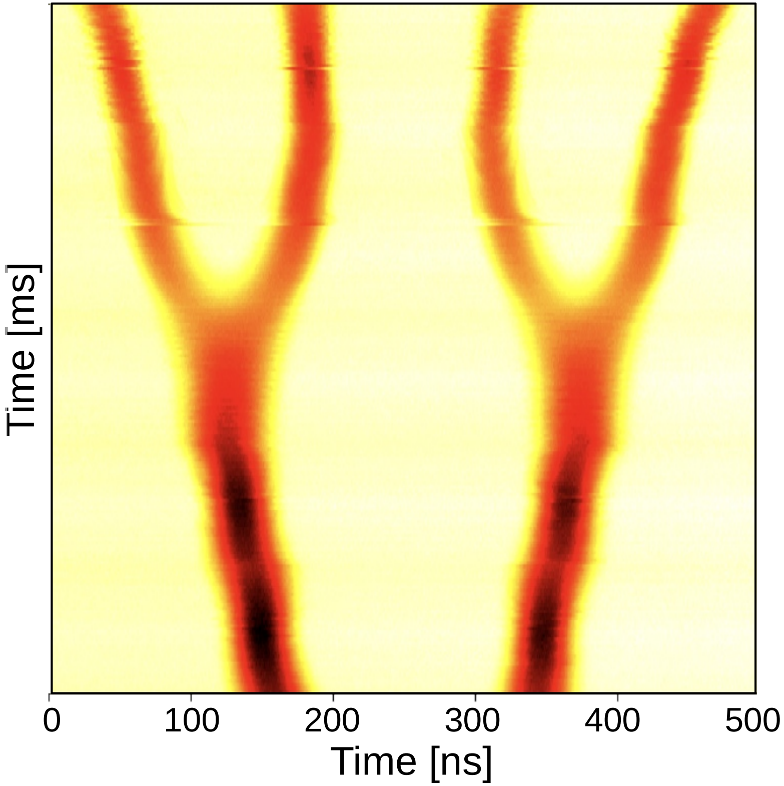
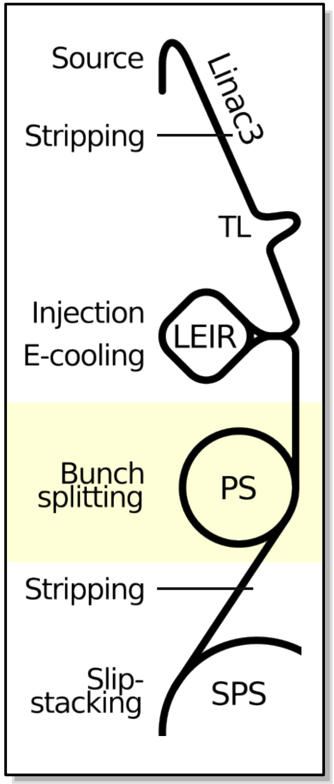
Limitation

- Impossible to reduce bunch spacing to 50 ns with 4 or 6 bunches
  → Missing RF frequency range for batch compression





Ion injector complex at CERN

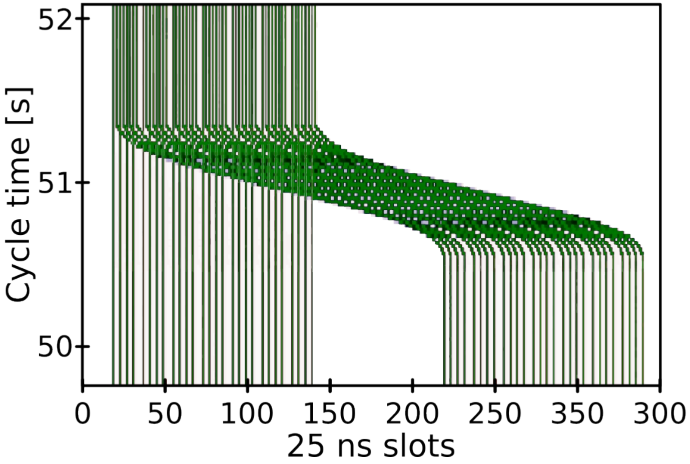
NOMINAL: Slip-stacking in SPS

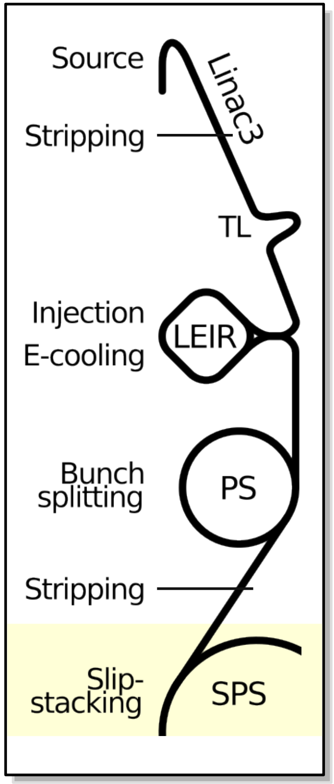
Mechanism

- 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

Use case

- Reduction of bunch spacing from 100 ns to 50 ns





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Use case

- Reduction of bunch spacing from 100 ns to 50 ns

Caveats and limitations

- Only half of the ring can be populated with bunches at injection
- Moderate bunch length increase