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The CERN Ion Injector Complex: Current Status, Recent Achievements and Future Plans

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21 September 2026, EMMI Workshop: Light-Ion Collisions

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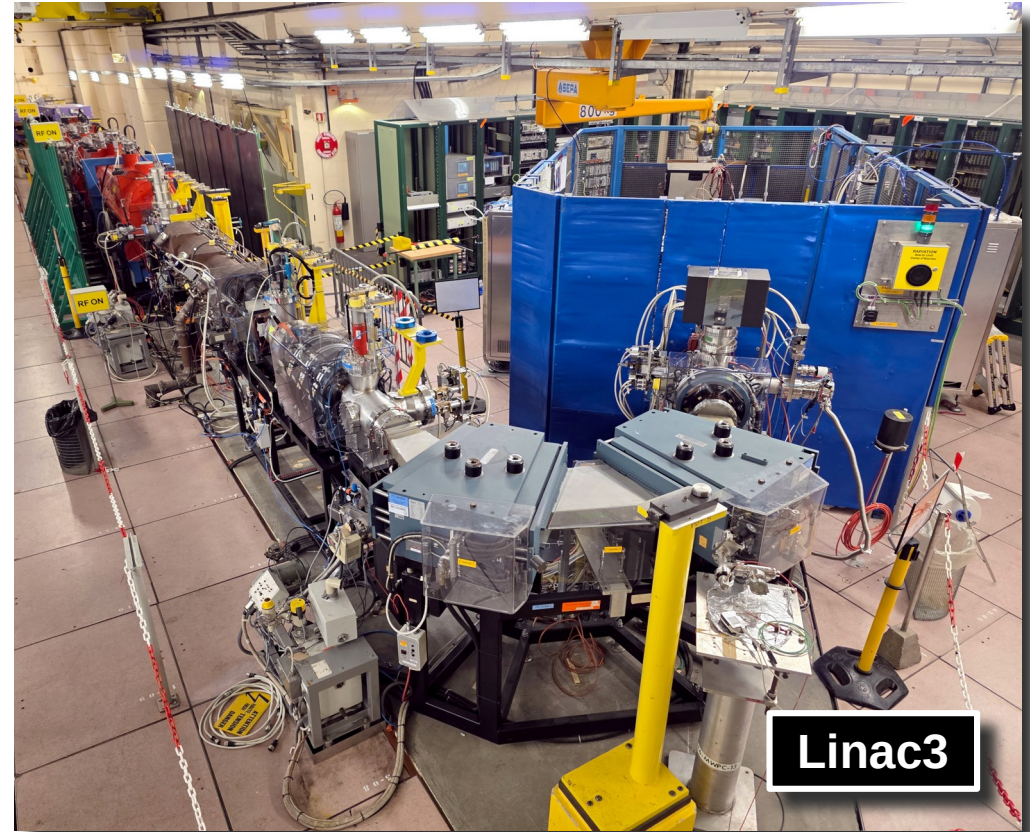
Ion injector complex at CERN

- Present and future experiments & facilities

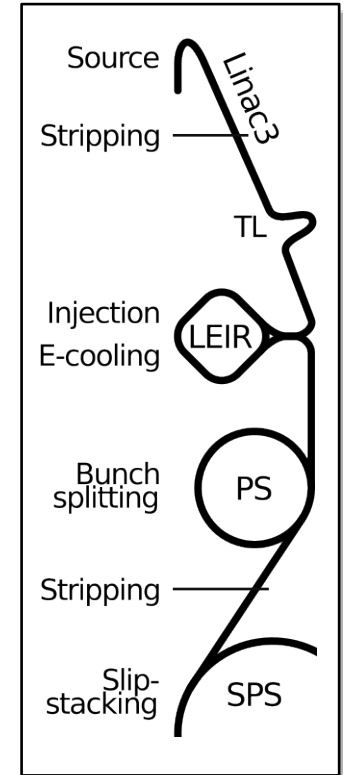
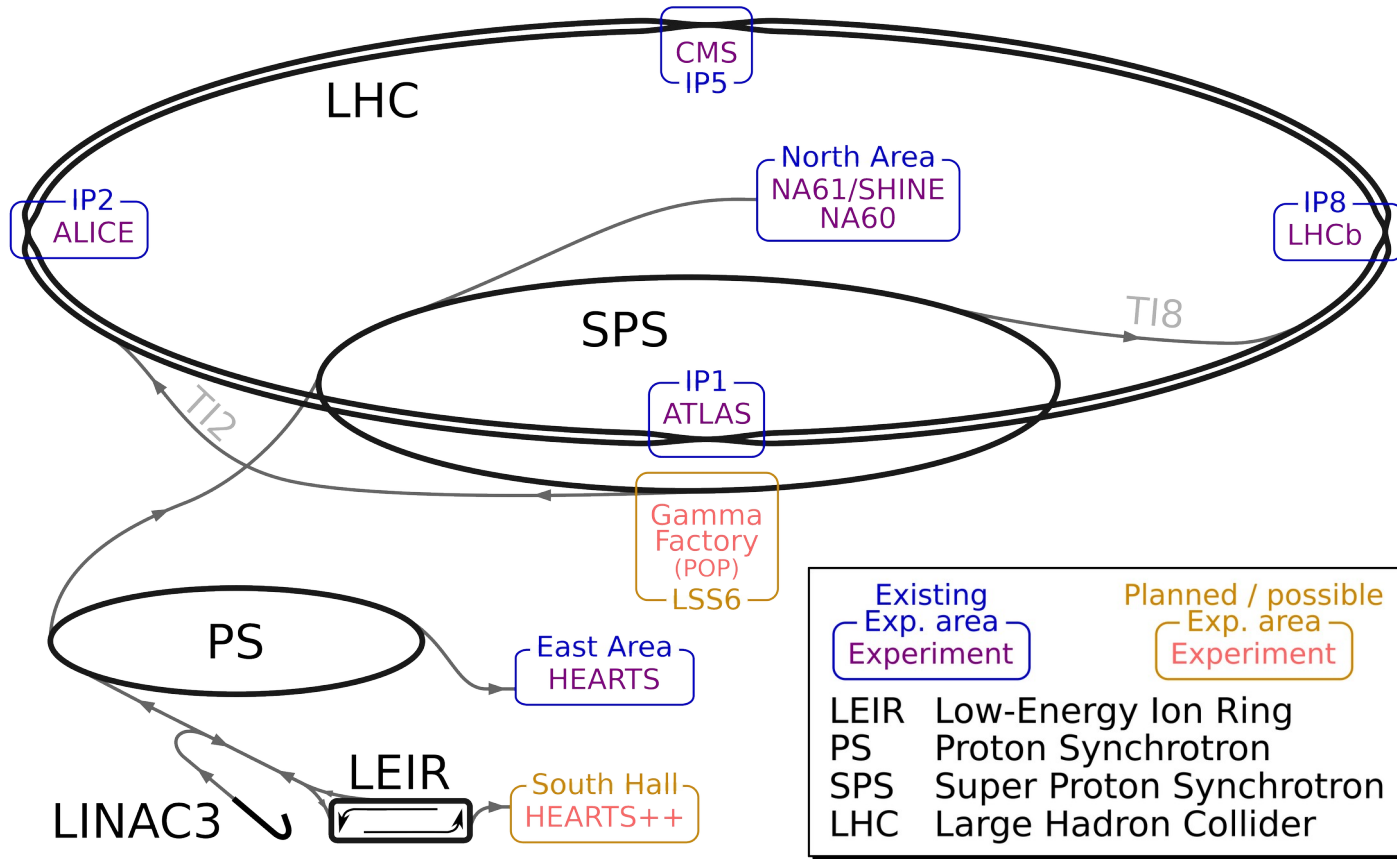
New ions

- Projects' status and challenges
- Past and present ion operation at CERN
- New beam production pre-feasibility checks
- Ion Complex Upgrade study

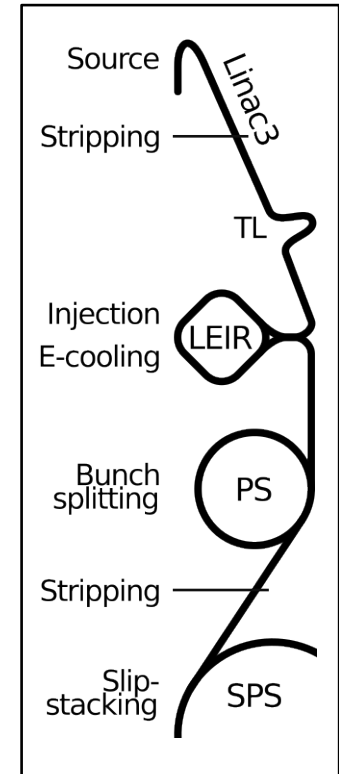
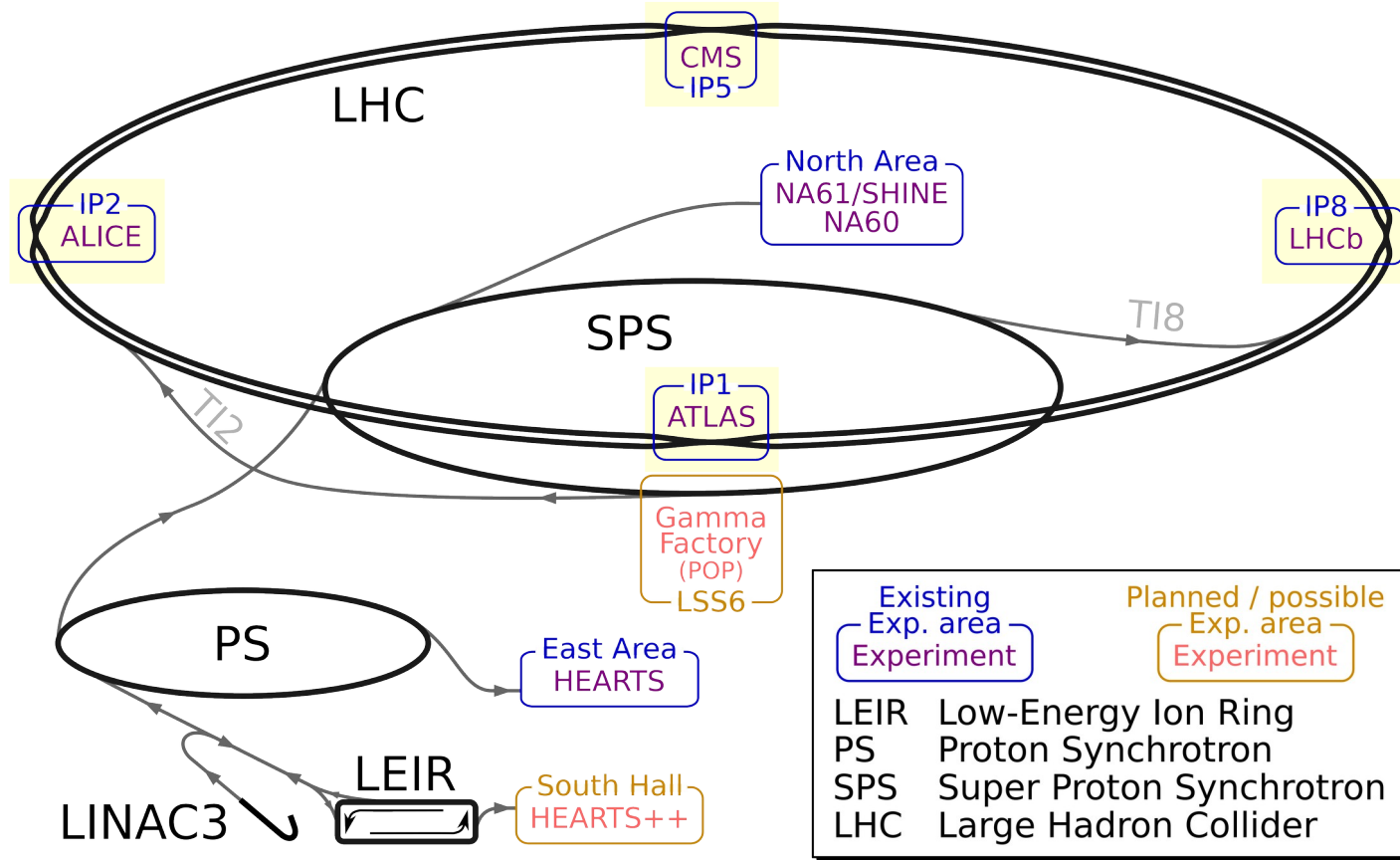
Summary and outlook



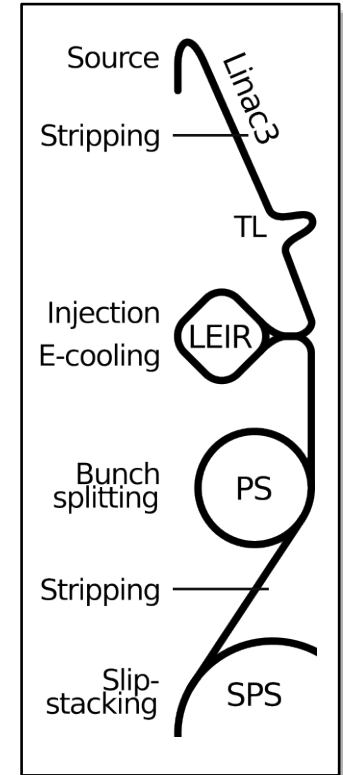
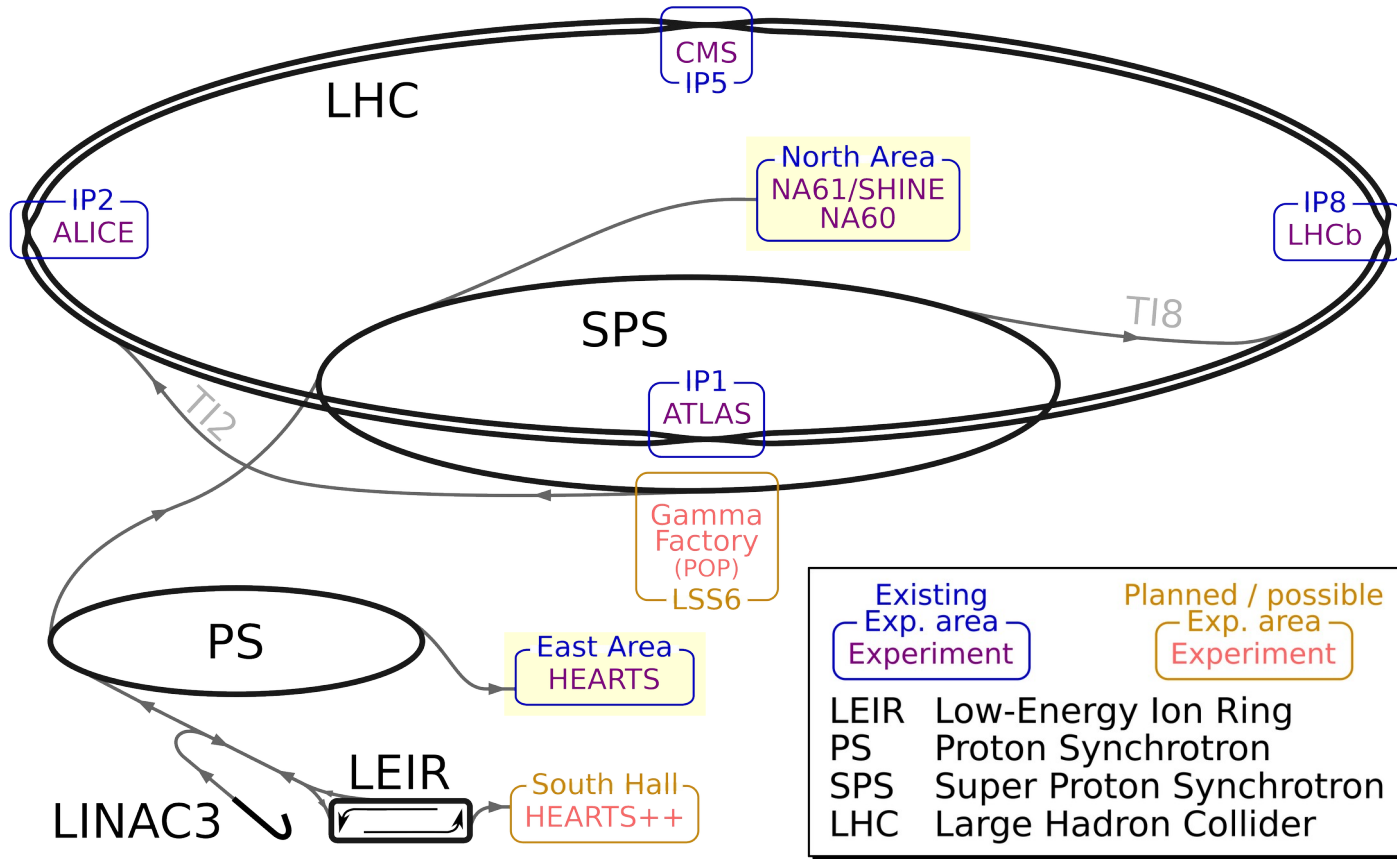
Ion injector complex at CERN



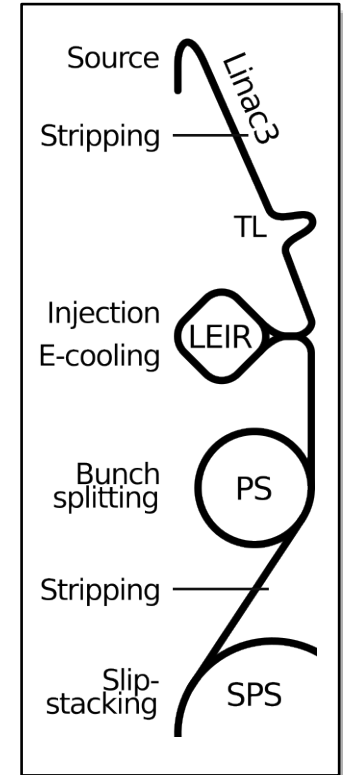
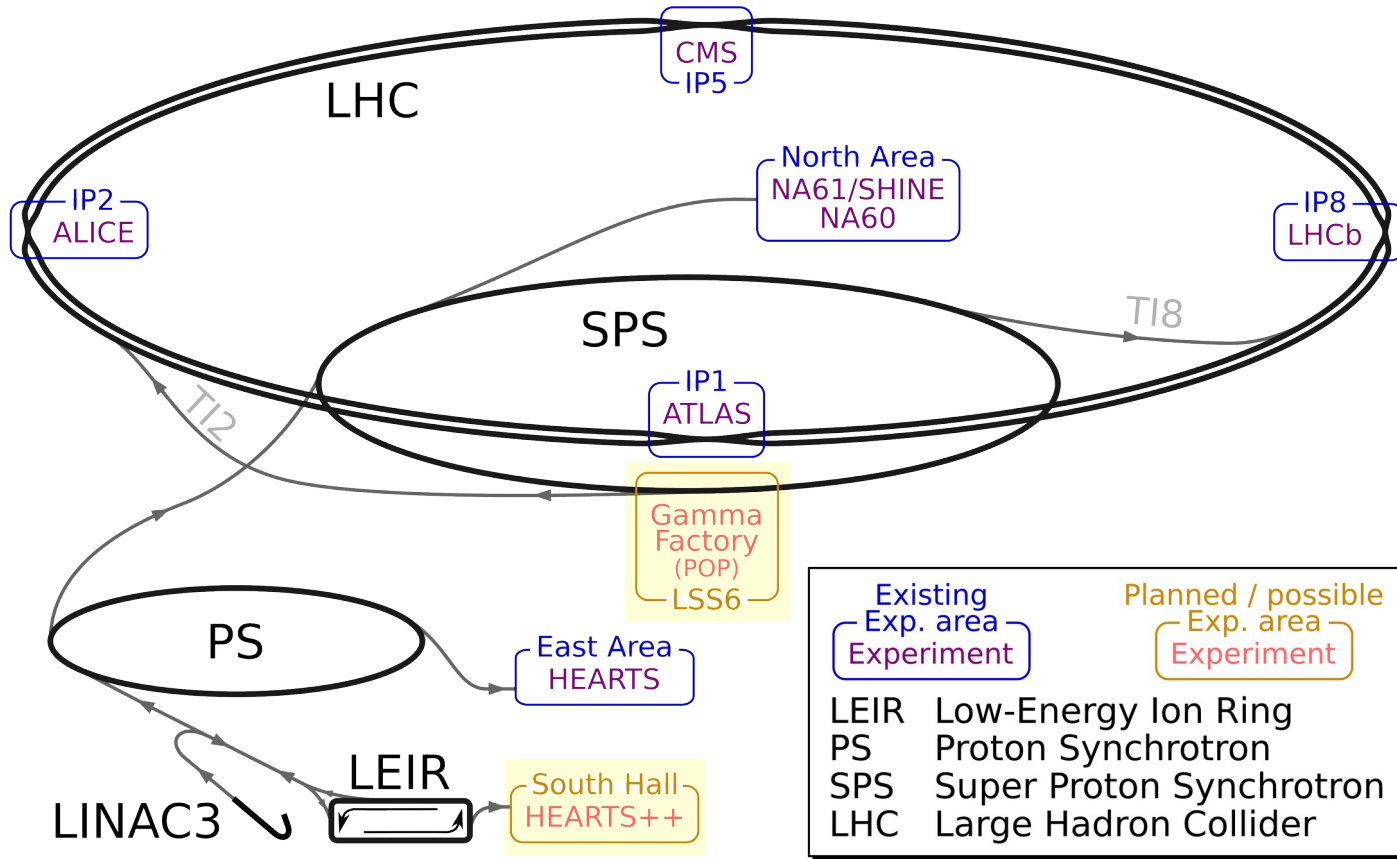
Ion injector complex at CERN



Ion injector complex at CERN



Ion injector complex at CERN



After-LS3 ion users

		Delivered as solid Delivered as gas														
		2 He Helium 4.003	3 Li Lithium 6.94	6 C Carbon 12	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	32 Ge Germanium 72.63	34 Se Selenium 78.971	36 Kr Krypton 83.80	49 In Indium 114.818	54 Xe Xenon 131.29	56 Ba Barium 137.33	82 Pb Lead 207.2
SPS North Area	Run 4 (2030-2033)	SHINE NA61++														
		NA60+														
LHC Collisions	Run 5 (2036-2041)	ALICE3 ATLAS														
	Nuclear Imaging	LHCb CMS														
PS / LEIR Fixed-target	HEARTS++															
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SPS Proof of principle		GAMMA FACTORY															

These projects are not approved yet

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~~ **Carbon** beam – to be developed for Run 4 (2032+)
- NA60+
 - Continuous testing and use of **lead** beams
- 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
 - Done a short LHC **neon** run adjacent to **oxygen** run in 2025
 - Physics-driven *white paper* proposal in preparation (due in 2029)

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Facilities

- **HEARTS++**
 - **Cocktail** beams to be tested before 2030
 - TDR to be prepared in 2030-2031
 - Provide: **O, Ar, Kr, Xe, Pb**
 - Every operational day, with switching times between species $\leq 15'$
 - 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 $> 200 \mu\text{s}$
(required for efficient LEIR injection)

Single Linac3 pulse should contain $\geq 4 \cdot 10^{10} e$
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 – **bottleneck**
→ validation for **NA61++** (Run 4, 2030+)
- **Oxygen & neon runs** in 2025
→ for **LHC** & **NA61** (neon for Nuclear Imaging)
- **Oxygen(8+)** test in 2026 – **failed at LEIR injection**
→ input for **HEARTS++**, injector model & **LHC** Run 5

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
$^{208}\text{Pb}^*$	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

Future plans – LS3

Tests in LS3 (2026-2027) and start of Run 4 (2028-2030)

- **Mg** and **C** (as CO₂) for NA61++
- **Cocktail beams** for HEARTS++
- Ge / Kr / Xe / O with SPS slip-stacking and O⁸⁺ in LEIR

- **2nd magnesium test:** scheduled 'now'
 - Mitigation against short oven lifetime
 - Reduce Mg consumption with hotscreen

Status: Hotscreen production **delays**

Outcome: **Postpone** the Mg test until 2027 and **switch** to carbon test
- ~~Boron~~ **Carbon test**
 - At the source and Linac3
 - Use of CO₂ or CH₄
 - Stability & intensity reach

Operation with ions at CERN

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- **Cocktail beams**
 - HEARTS++ doesn't require specific ions, but a menu with wide ion mass range
 - Use noble gasses (O, Ar, Kr, Xe) mixture
 - Operational experience with Ar, Xe & O (when used individually)
 - Test setup difficulty (duration), intensity reach and stability

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- Refine ion injector model and find the most promising LHC Run 5 ion scheme
- Unlock light-ion species
- **Need prioritizing**

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- **Last chance to test new ions if NA61++ is approved**
 - Unless a **second ion source** is installed

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 - Reduce Mg consumption with hotscreen
 - Status:** Hotscreen production **delays**
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Operation with ions at CERN

Possible LS3 & Run 4 scenario

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LHC Run 4 (2030-2033)

- **Pb** will dominate ion run periods
- Other-ion operation expected between 2031-2033
 - Short runs with ≤ 3 collision systems*
 - ⇒ Only if NA61++ is not approved

*One collision system per year possible
if officially approved (with limited exceptions)

Operation with ions at CERN

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Schedule beyond 2027 is speculative

Year	Spring	Summer		Autumn
	[User]			
2026	Run 3	Run 3		Mg or C [NA61++]
2027	LS	LS		C or Mg [NA61++]
2028	LS	Cocktail / Ge / Kr / Xe		Pb [HEARTS]
2029	?	O SPS slip-stacking & O ⁸⁺ in LEIR		Pb [HEARTS]
2030	O [NA61++]	?		Pb [HEARTS & NA]
2031	Mg [NA61++]	OR / AND	Mg → C [LHC]	Pb [HEARTS & NA & LHC]
2032	C [NA61++]	OR	O → He [LHC]	
2033	?	OR	Ge → Kr or (Ba → Xe) or (⁴⁸ Ca) [LHC]	

X – test, no physics users **Y – physics run** LS – Long Shutdown

Operation with ions at CERN

Distant future – Run 5

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LHC Run 5 (2036-2041)

- ALICE3 requests higher integrated nucleon-nucleon luminosity – by an order of magnitude
→ using heavy ion beam ($A > 100$)
- **Unclear** how the present injector complex could deliver it
 - ⇒ Evolutionary improvements are projected to result in a factor 2-3 higher luminosity
 - ⇒ **Opportunity** to think of **hardware upgrades**, exploiting synergy between high-lumi and light-ion pilot programmes

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New ions ranking – beam development difficulty

Based on experience from other laboratories

Ion	Baseline form / compound	Delivery method	Main challenges	Estimated oven sample lifetime* [days]	Price per fill [kEUR] (enrichment %)
⁷⁶ Ge	GeO ₂	Micro-oven	High T Deposition on the plasma chamber walls	10	7 (96%)
⁷⁶ Se	metallic	Low-T reservoir & heated transfer pipe	Too volatile → parasitic plasma heating Condensation in transfer pipes	12	12 (98%)
⁶ Li	metallic	Micro-oven	Very high reactivity Contamination with C Molten Li wetting and migration Condensation on cold surfaces	1	0.05
¹³⁶ Ba	Ba(NO ₃) ₂ + Al	Sputtering	Extreme reactivity No mature micro-oven design No beam production experience worldwide	8**	5 (95%)
⁴⁸ Ca	CaO + Al or metallic	Micro-oven	Very high reactivity Deposition on the plasma chamber walls Parasitic plasma heating	4	40 (57%)

CO₂, He, Kr, Xe – gaseous and relatively straightforward

*assuming consumption of 3 mg/h

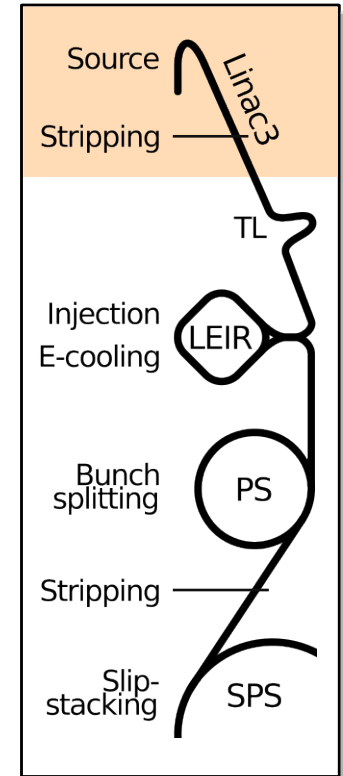
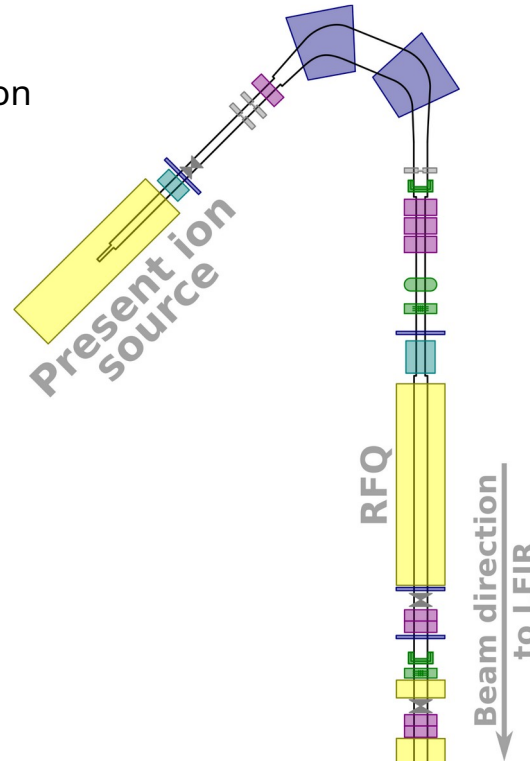
**not comparable with oven operation

Ion Complex Upgrade study

Low-energy region of Linac3 – present limitations

Present limitations

- One ion source, fully committed to operation
 - Limited time for any tests (new ions, automation)
 - Only two ion species (mixtures) can be operated per year

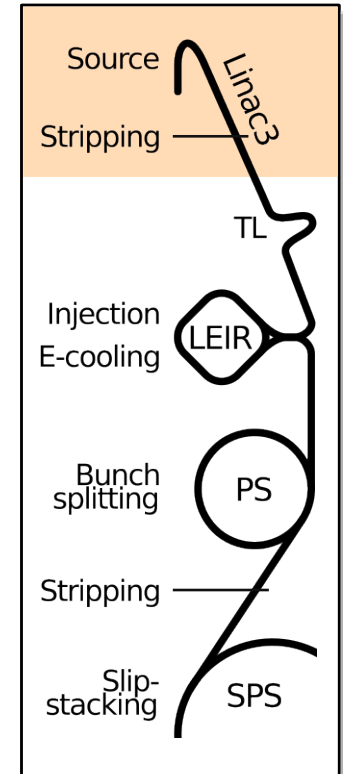
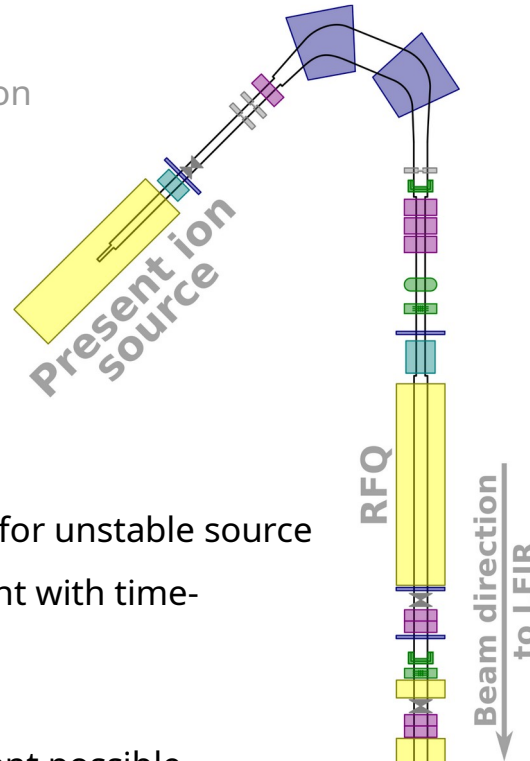


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 - Limited time for any tests (new ions, automation)
 - Only two ion species (mixtures) can be operated per year
- Beam-destructive instrumentation located far away from the source
 - Minimal feedback for tuning, especially for unstable source
 - Time-consuming new beam development with time-consuming trial-and-error approach
 - Limited feedback for automation
 - Little beam dynamics model improvement possible

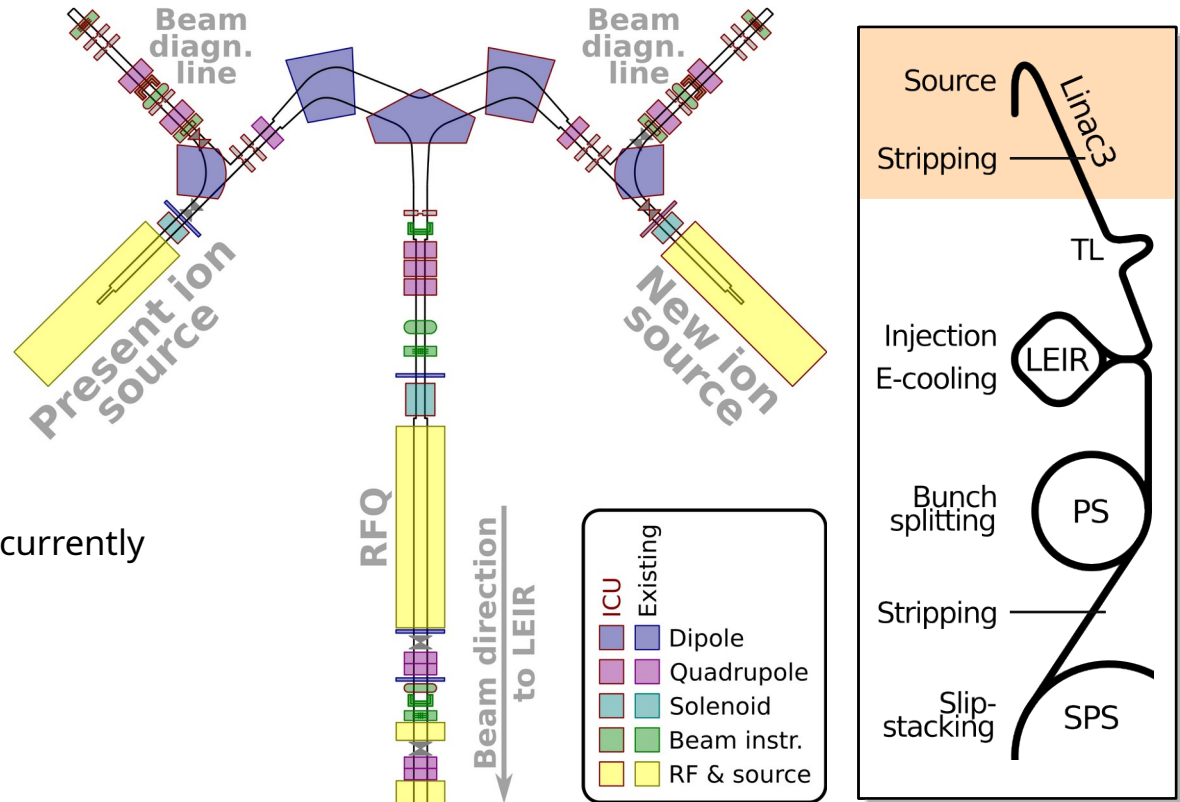


Ion Complex Upgrade study

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

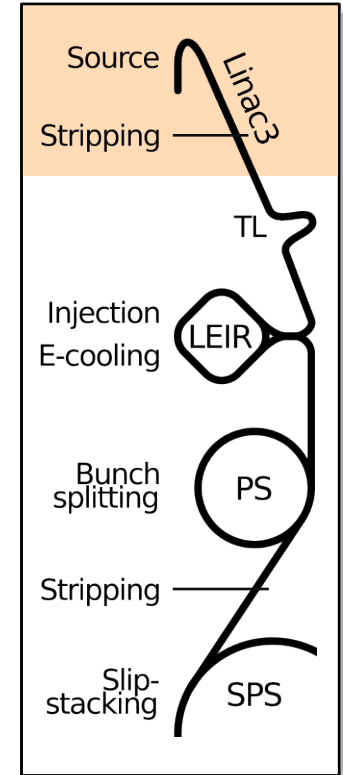
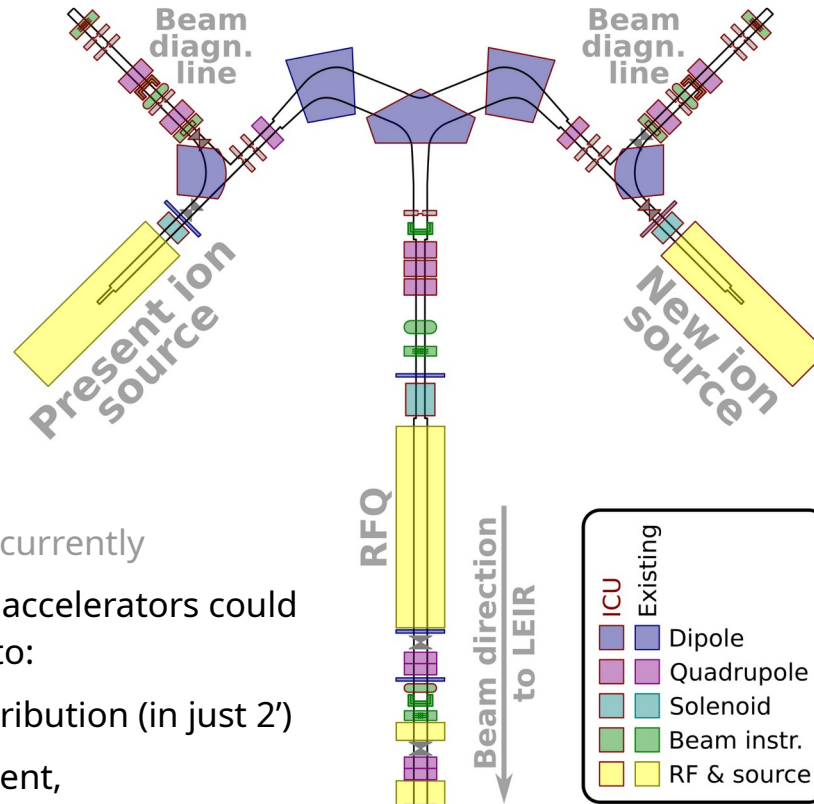


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2nd source & new low-energy beam diagnostics

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- 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
- Every beam pulse unused by downstream accelerators could be redirected to the beam diagnostic line to:
 - Continuously measure charge-state distribution (in just 2')
 - On demand 2D beam profile measurement, emittance and energy distribution



Ion Complex Upgrade study

Alternative stripping between LEIR and PS

New hardware

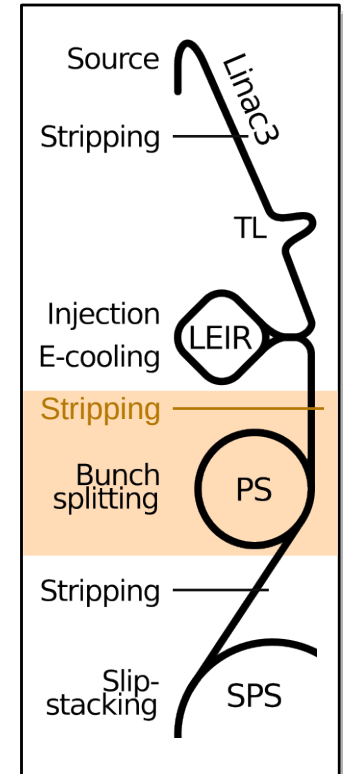
- Quick stripper assembly (with per-cycle position) downstream of LEIR
- Instrumentation downstream of the stripper and before PS injection
- Pulsed injection kicker into PS

New beam transfer scheme from LEIR to PS

- Energy loss at stripping $\rightarrow$ the PS f_{rev} is no longer a multiple of the LEIR f_{rev}
 - $\rightarrow$ Transfer is not possible at every PS turn
 - $\rightarrow$ New synchronization scheme is needed
 - $\rightarrow$ PS has to wait for a suitable turn to trigger transfer

Recent test with O^{8+} beam as a feasibility check of this proposal

- Aimed to verify the beam lifetime in PS for a fully-stripped ion
- Result: Failed to inject beam in LEIR $\rightarrow$ more beamline / magnets studies needed

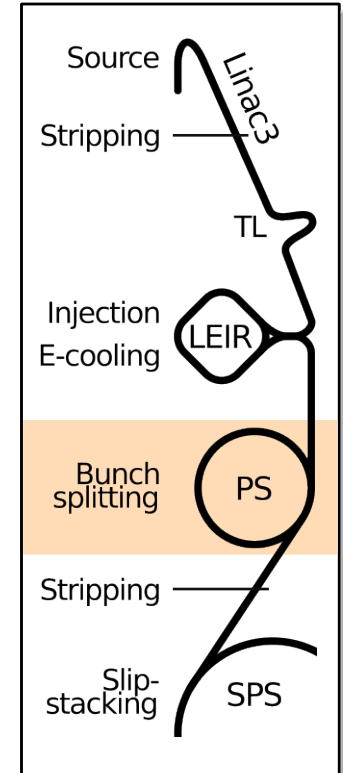
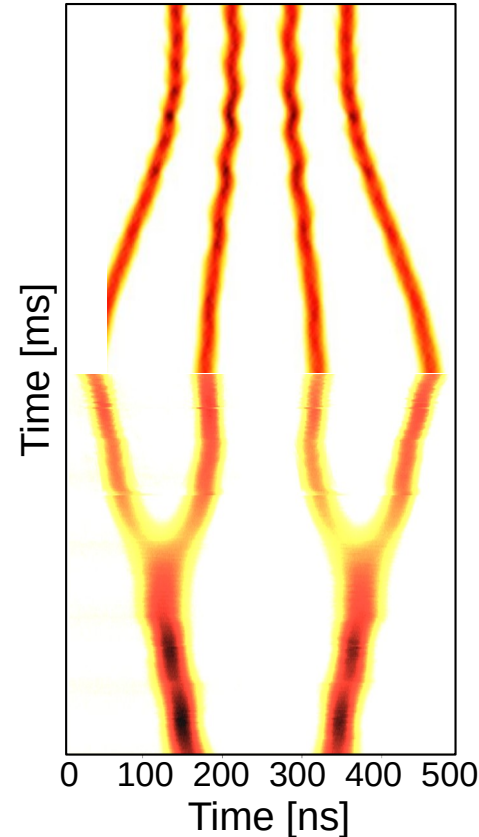


Ion Complex Upgrade study

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)

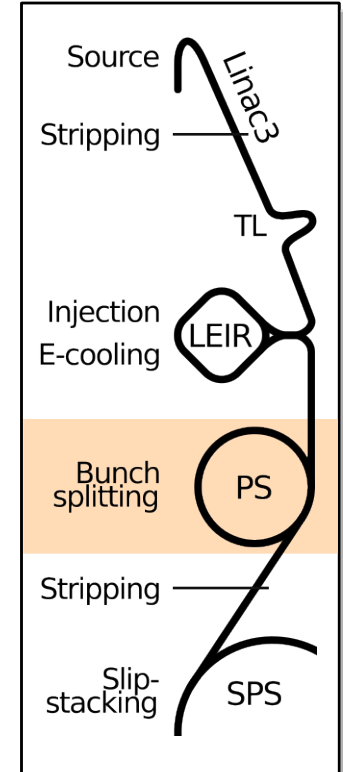
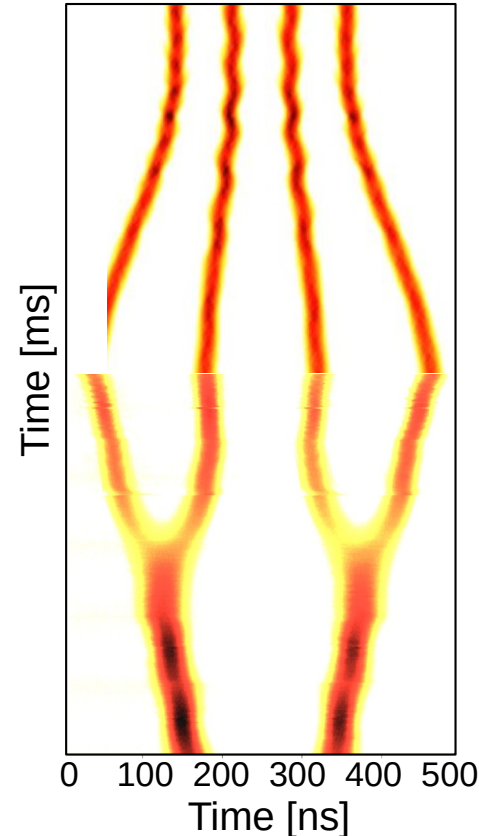


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 - Downstream, the SPS can use slip-stacking to reduce bunch spacing to 25 ns (without additional upgrades)
- The design of new cavities is challenging
 - Wide-band Finemet type under consideration
 - Designs exist up to 10 MHz
 - Needs to be developed to reach 20 MHz, including amplifiers
 - Operation at the limit of the Finemet material properties



Summary and outlook

- The **main ion** operated at the **LHC** until the end of Run 4 (2033) **will be Pb**
 - Ongoing studies to identify the optimal ion species to match ALICE3 Run 5 request
→ No clear solution → Potential for upgrade proposal
 - Growing interest in short LHC runs with lighter ions
- Several **new ion species** (O, Mg, Ne, Kr) have recently been tested in view of the expected LHC, NA61++ and HEARTS++ requests
 - **Excellent overall performance** of the ion complex → many records broken **in Run 3**
 - More tests should be performed with
 - Magnesium & krypton tests, carbon, cocktail for HEARTS++
 - New elements, as an outcome of **this meeting** (Ge, Se, Li, Ba, Ca, ...)
 - Ongoing pre-feasibility check of Ge beam production with GeO_2
- **Ion injector upgrades** will be needed if some of the proposed projects would be approved and funded

Discussion

Pb-O collisions

- Unrealistic switching time with single ion source → ~1 day
 - Feasible with two ion sources → potential for achieving switching time of ~15 min
 - Fill one LHC ring with O beam*
 - Switch to Pb in 15 min and fill second LHC ring with Pb beam
- *O-beam quality deterioration should be acceptable in ~1h waiting time according to latest checks of beam lifetime

Runs possible with single ion source,

- but no time for preparation of operational beams unless a second source is available
- ^{76}Ge run followed by Kr run → which Kr isotope is of interest?
 - Potentially straightforward to have a follow-up beam of a noble gas
- ^{76}Ge run followed by ^{76}Se run
 - Aimilar as with O → Ne: same Q/A possible
 - Quick switch possible even with single source, but similar contamination possibility as with O/Ne runs
 - Entirely new material delivery hardware setup needed for Se beam production



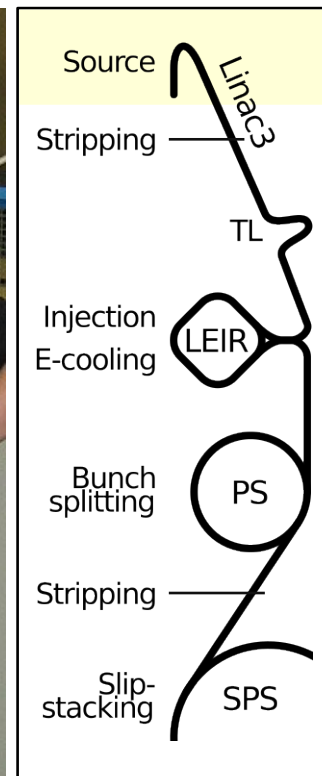
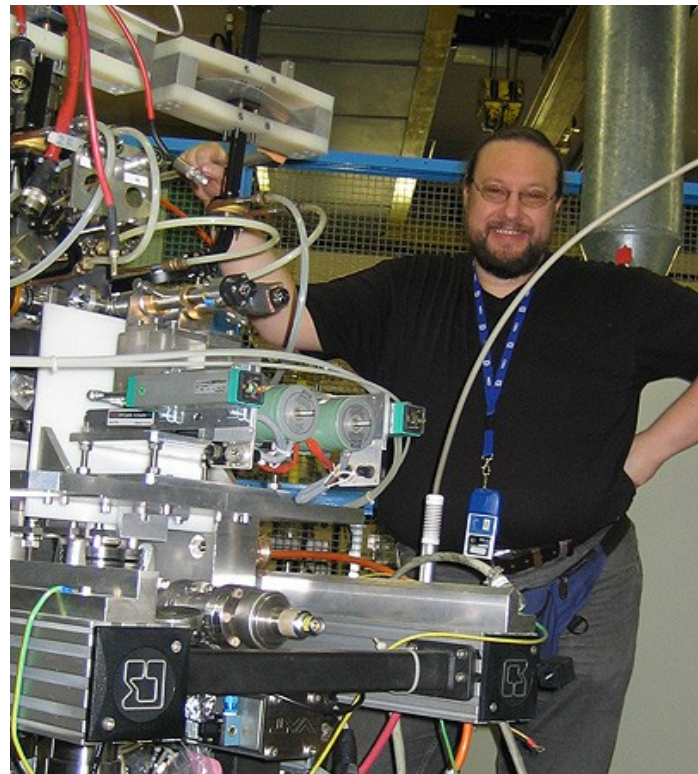
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Ion injector complex at CERN

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)

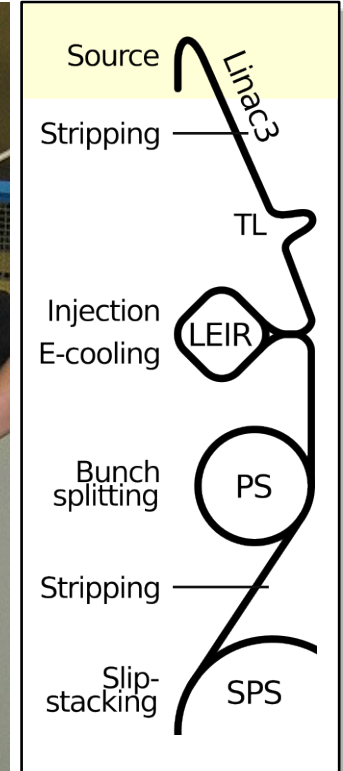
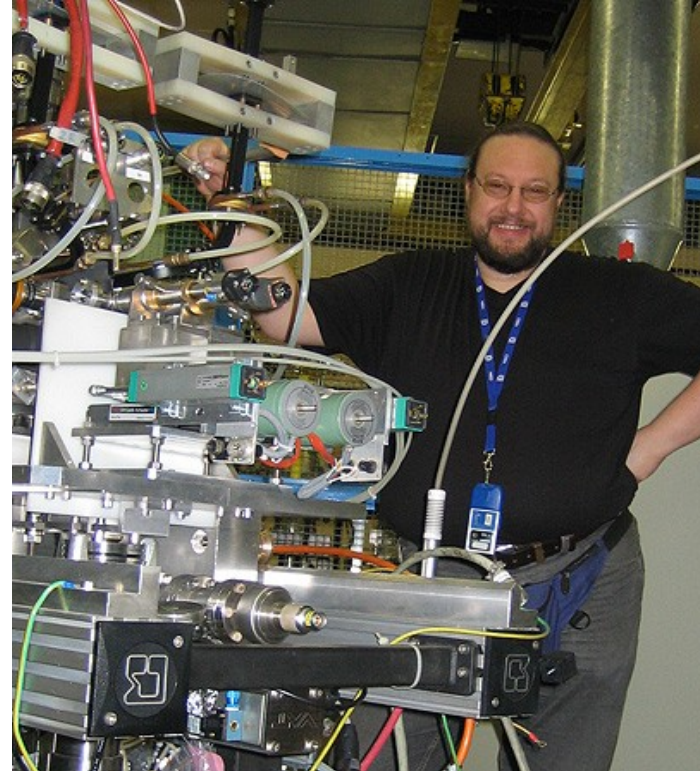


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- Pure material (chemically or isotopically) vs. compounds
 - Better physical, chemical or handling properties vs. reduced beam stability and intensity due to presence of undesired elements or isotopes in the plasm
 - Significant cost of enrichment
- Safety considerations: reactivity, toxicity, flammability
- Support gas usage

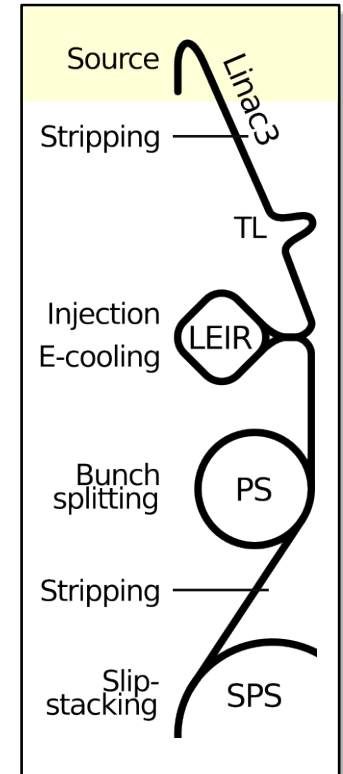


Ion injector complex at CERN

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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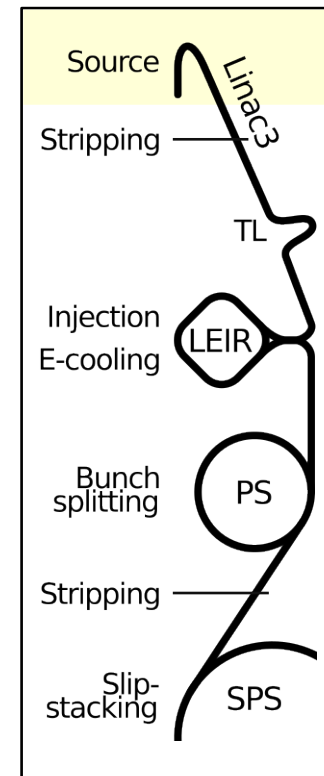
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Beam instrumentation

- 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

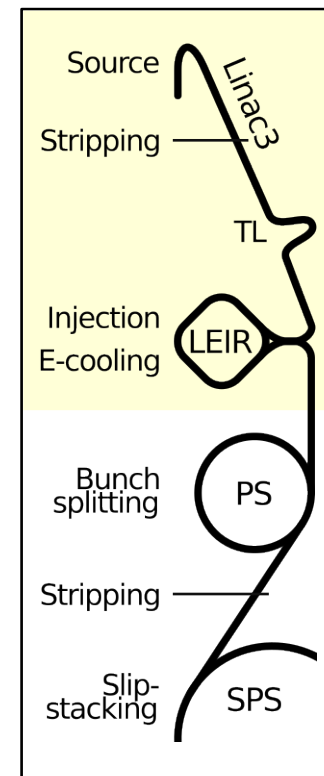
Particle and charge-state constraints in Linac3 and LEIR

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

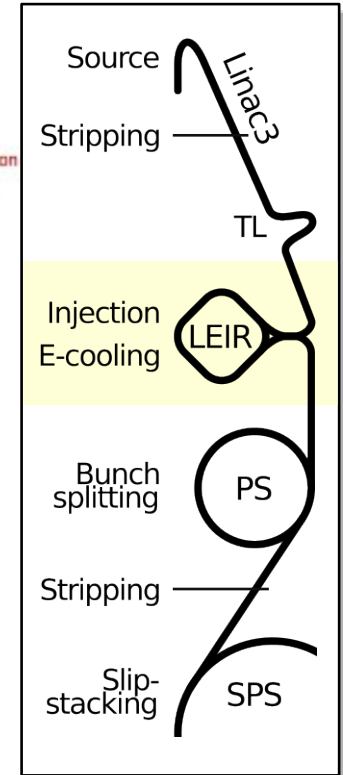
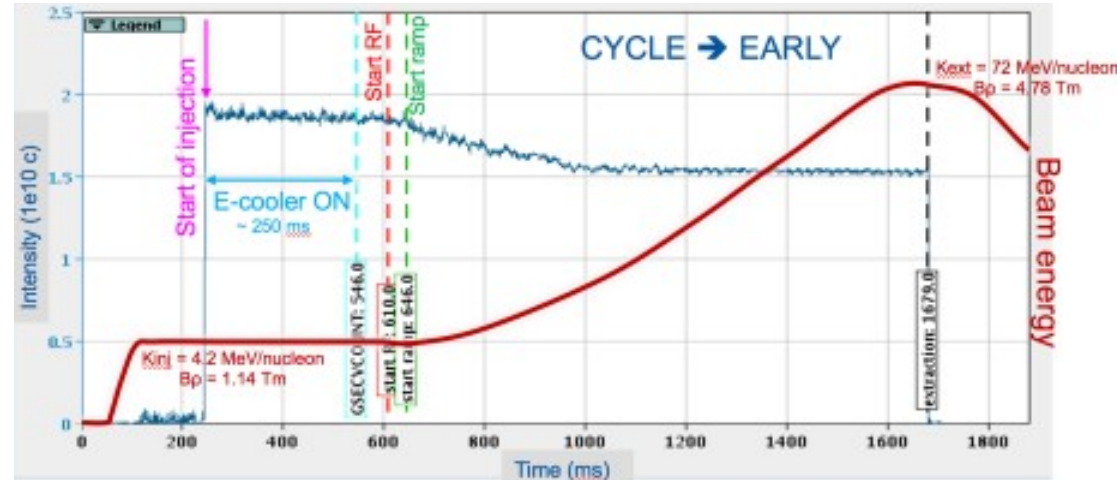


Ion injector complex at CERN

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

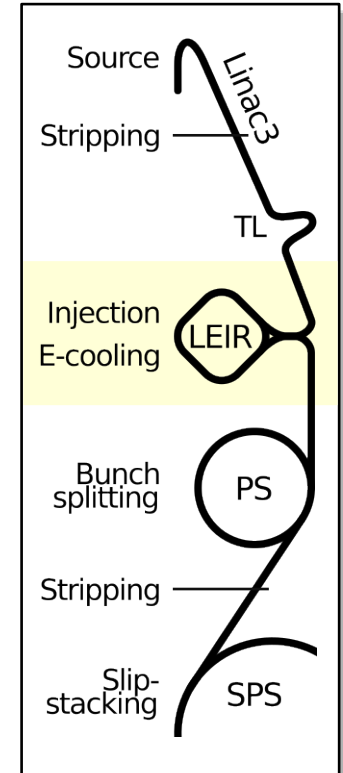
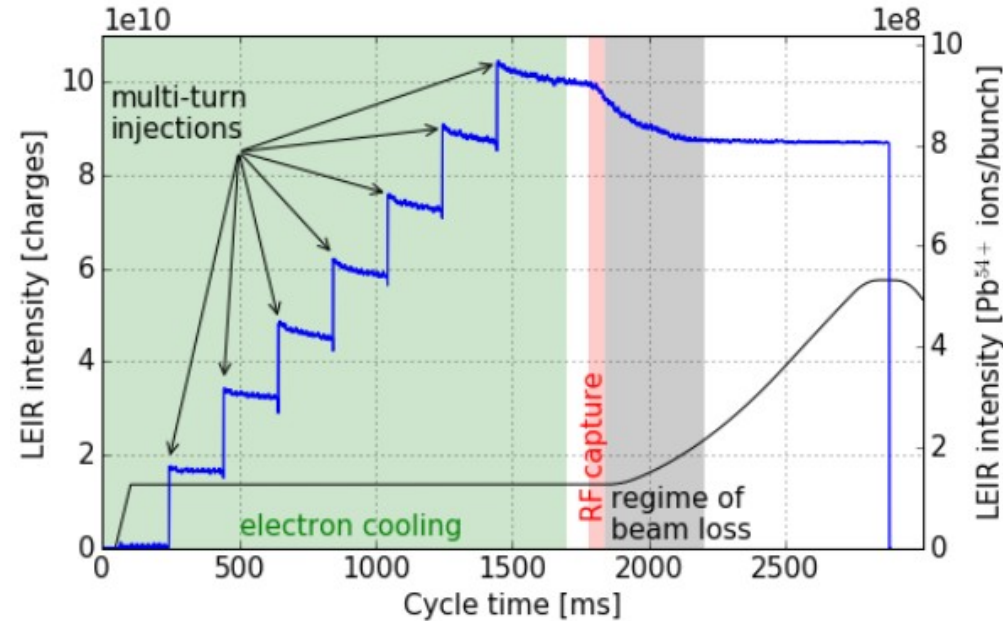


Ion injector complex at CERN

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

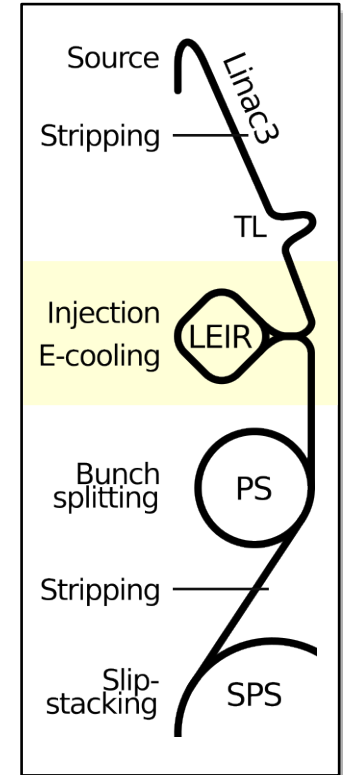
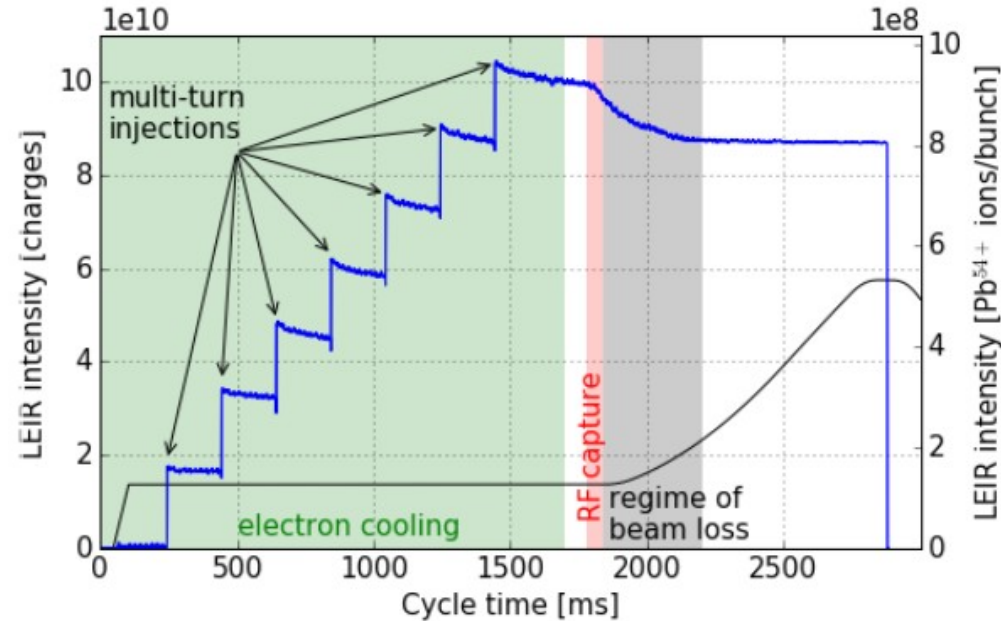


Ion injector complex at CERN

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
- **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

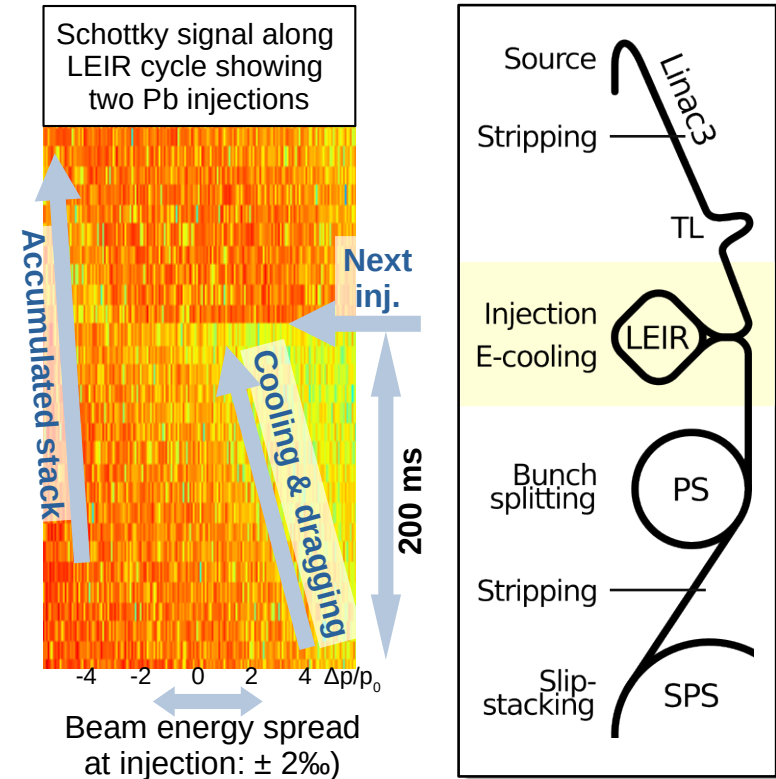
NOMINAL: Electron cooling

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



Ion injector complex at CERN

NOMINAL: Electron cooling

Reduce beam emittance

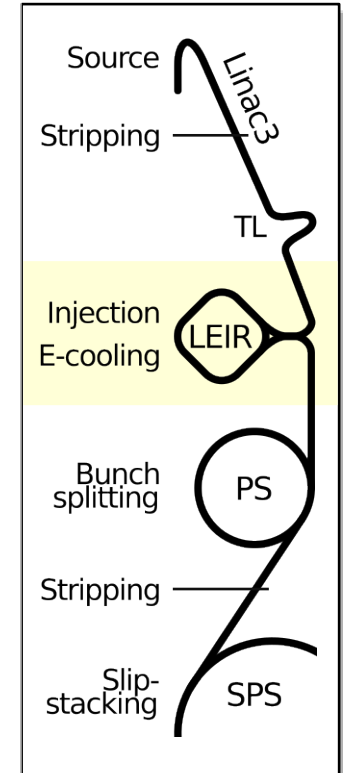
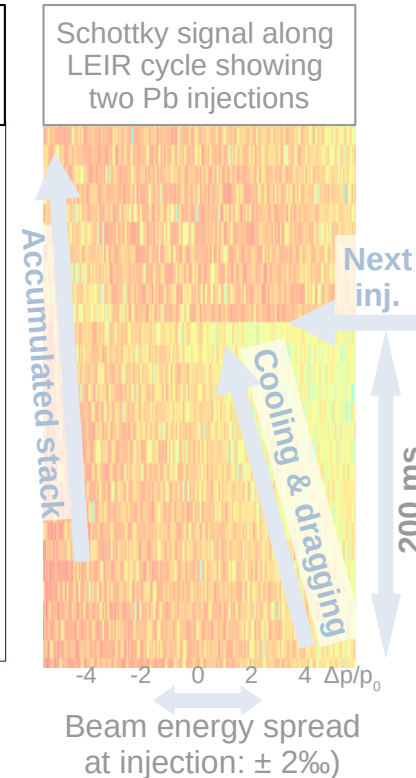
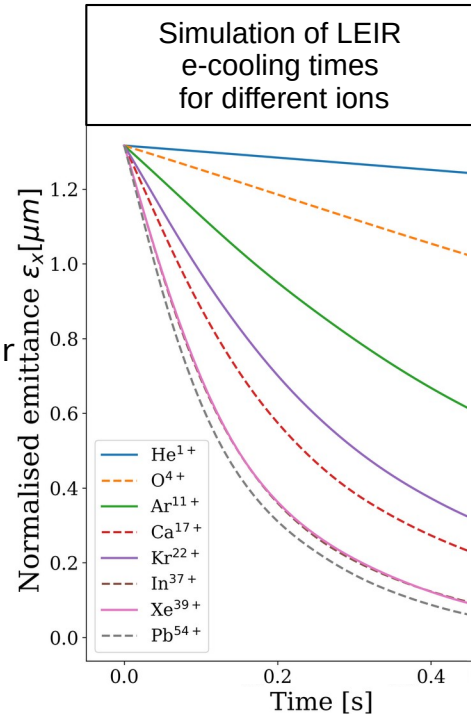
- Naturally large after multiturn injection

Stack multiple injections

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

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



Ion injector complex at CERN

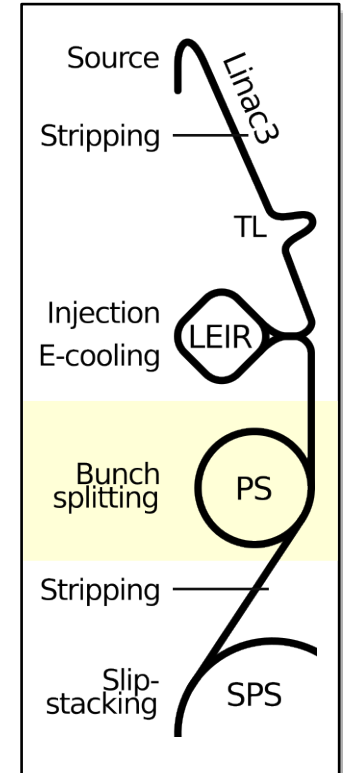
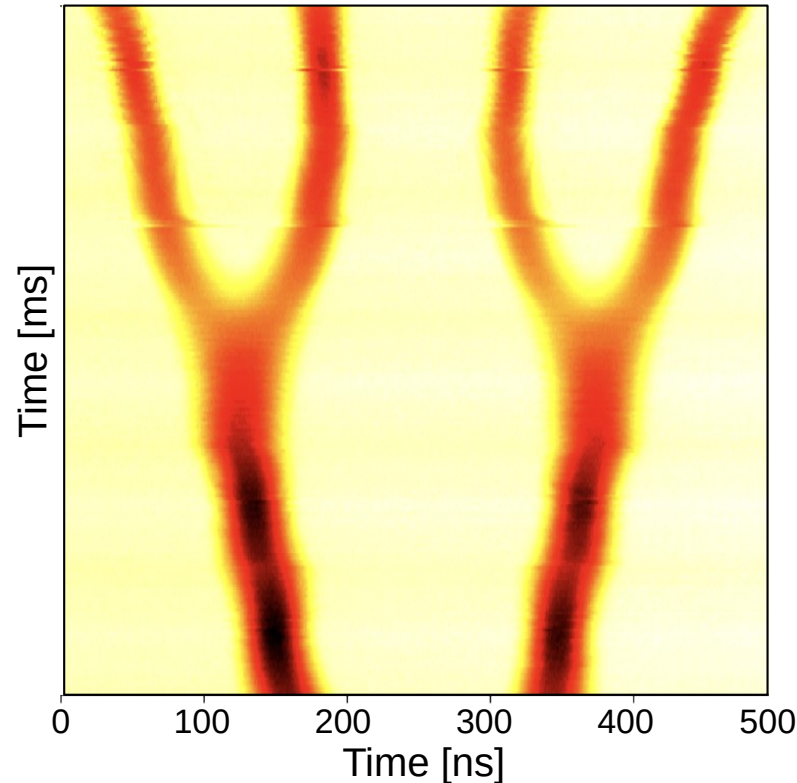
NOMINAL: RF manipulations in PS

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
-



Ion injector complex at CERN

NOMINAL: RF manipulations in PS

Bunch splitting

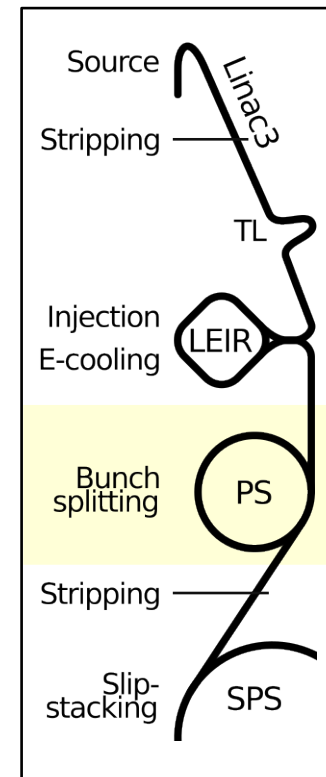
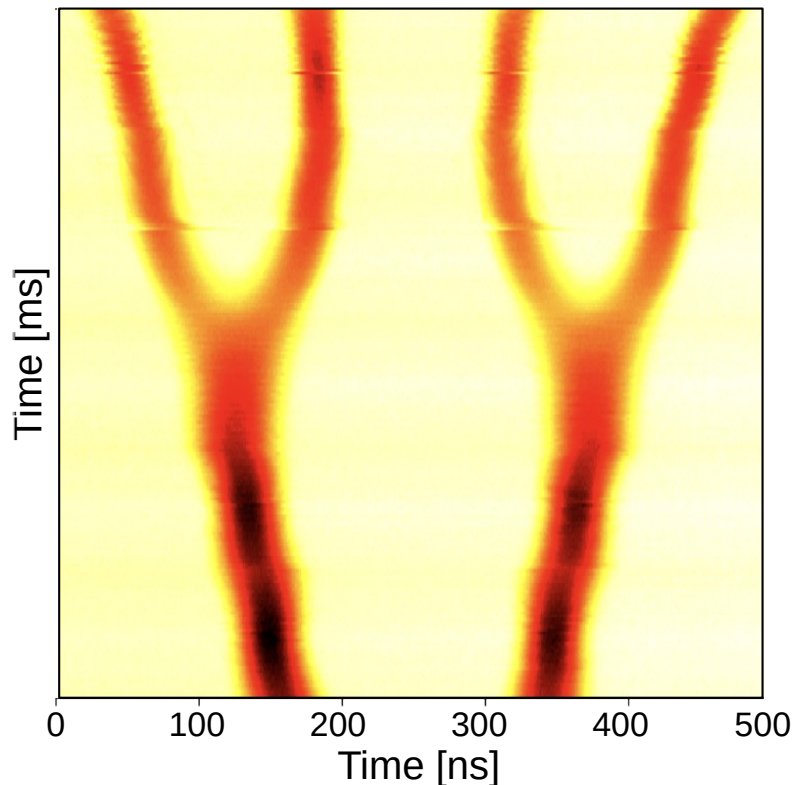
- Less charge per bunch
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Rebucketing

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

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

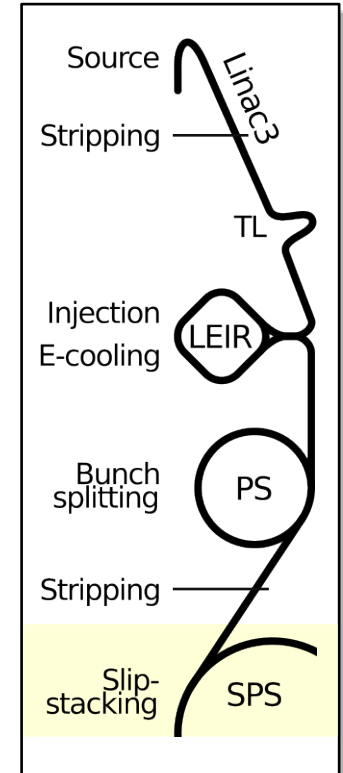
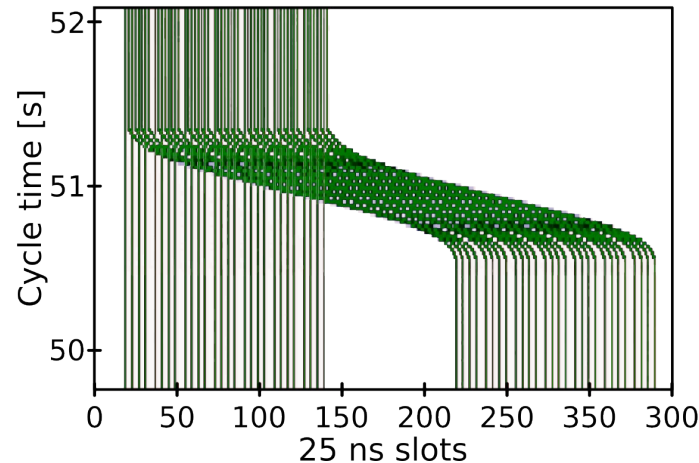
NOMINAL: Slip-stacking in SPS

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



Ion injector complex at CERN

NOMINAL: Slip-stacking in SPS

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- 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

Caveats and limitations

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

