Ions: Overview and Outlook Across the Complex

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Acknowledgements: S. Albright, D. Almeida, M.E. Angoletta, F. Asvesta, P. Arrutia, P. Baudrenghien, D. Bodart, B. Bradu, S. Burger, F. Carlier, J. Cenede, D. Cotte, R. Denz, M. Dolenc, S. Fartoukh, A. Ferrero, A. Frassier, J.F Gruber, G. Hagmann, P. Hermes, M. Hostettler, S. Jensen, V. Kain, I. Karpov, G. Khatri, A. Lechner, E. Matheson, O. Marqversen, B. Mikulec, M. Monikowska, S. Morales Vigo, C. Mutin, S. Paiva, K. Paraschou, T. Persson, G. Piccinini, A. Rey, S. Redaelli, G. Rumolo, B. Salvachua, M. Schenk, M. Solfaroli, F. Soubelet, A. Spierer, G. Sterbini, V. Toivanen, A. Topaloudis, N. Triantafyllou, G. Tranquille, D. Quartullo, D. Valuch, R. Wegner, J. Wenninger, C. Wetton, M. Widorski, PS, SPS and LHC OP teams

Joint Accelerator Performance Workshop, 11 December 2024

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Overview 2024

- Injectors performance (ion source, Linac3, LEIR, PS, SPS)
- LHC performance & crystals stability
- Fixed-target performance in East Area and North Area

The future

- LHC oxygen run in 2025
- Future ions after LS3

Overview 2024

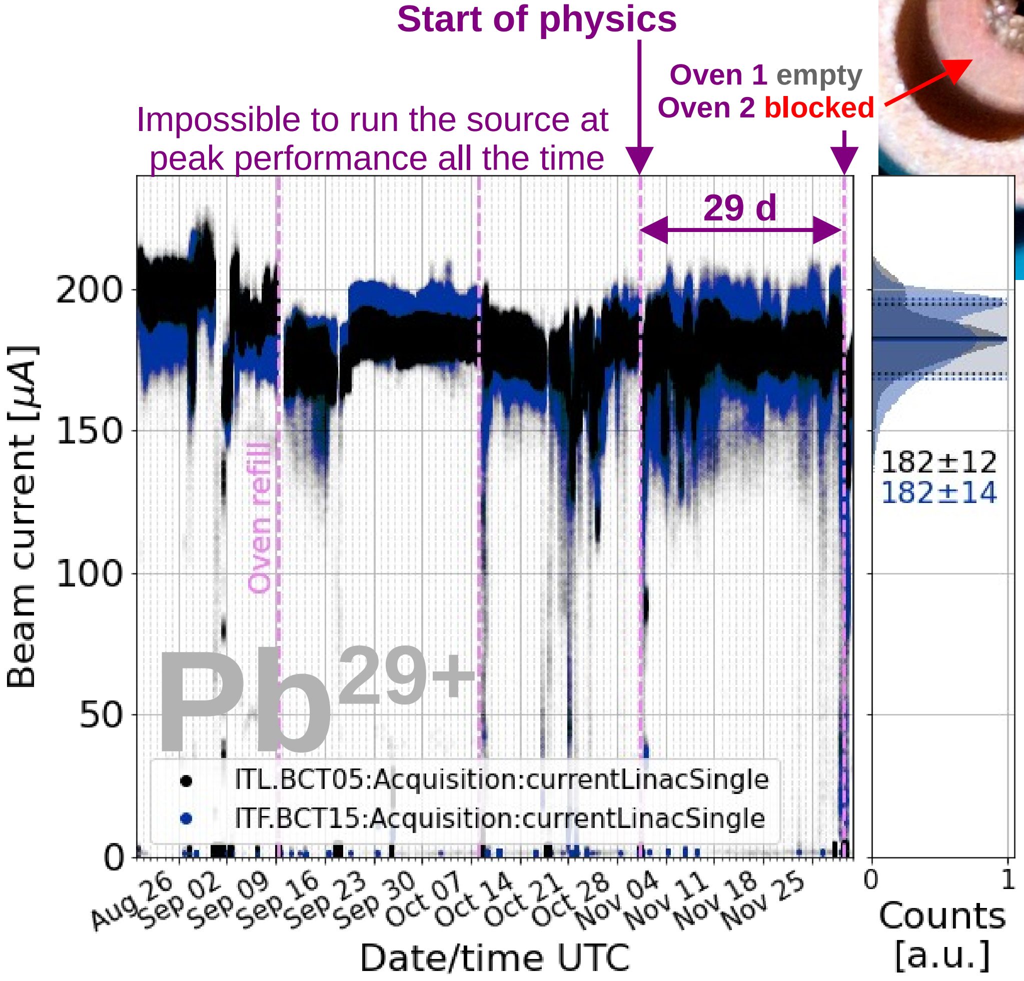
Linac3 Ion Source

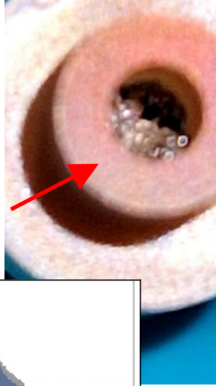
Various issues with both microwave generators (operational and spare)

- Loss of 2 weeks of BC → recovered at LEIR thanks to contingency beam conditioning time
- Actions undertaken
  - New consolidation request
  - Work order with the manufacturer is active → faster response to issues
  - Many component spares ordered

Source 'dips' in 2024

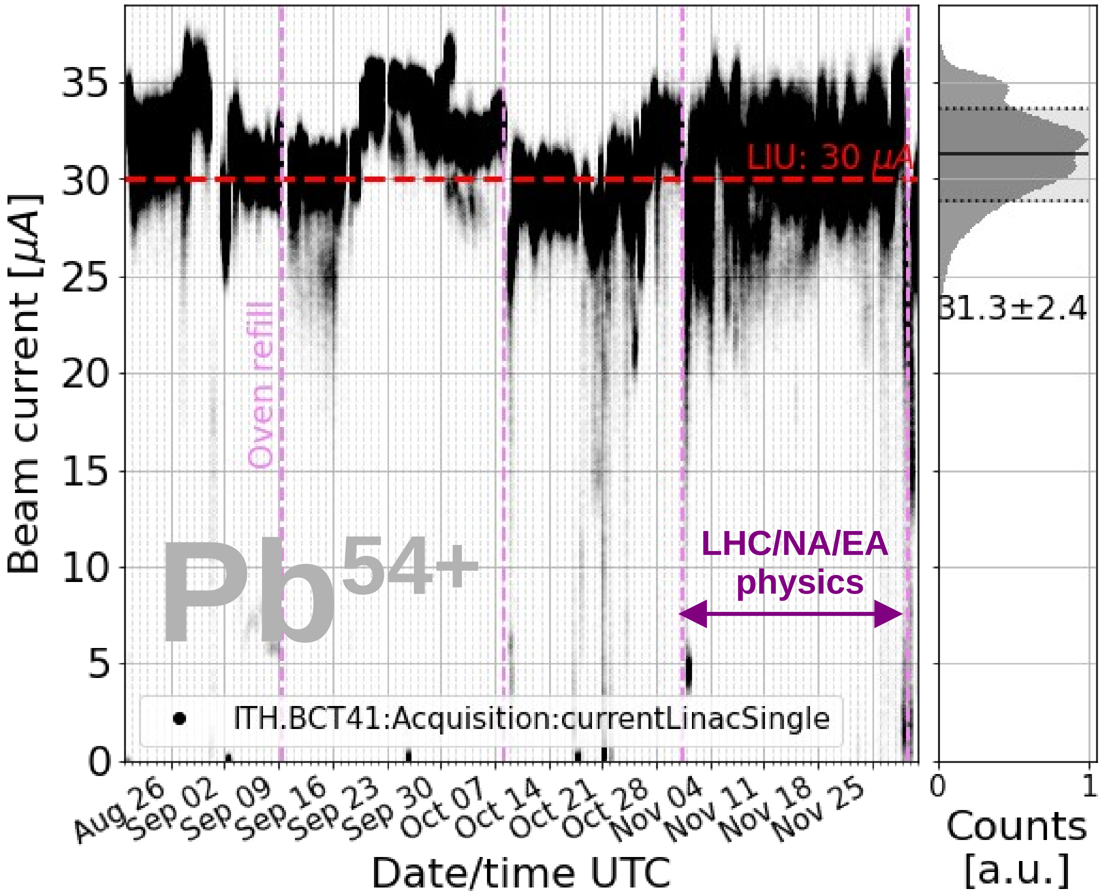
- More variation of the beam intensity
  → dips were harder to spot
  → also less frequent
- Proposed mitigation
  → power down an empty oven
  → not always practical (not clear when an oven is empty, esp. during operations)





Linac3

Above-LIU mean beam current out of Linac3



Configuration in 2024

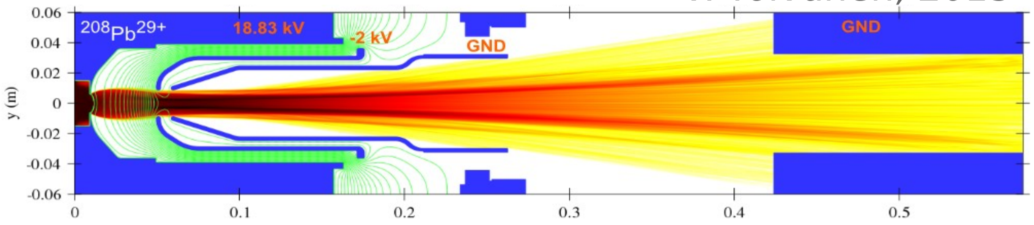
- 50% longer pulse length
    - 200 μs → 300 μs
    - Shorter stripper foil lifetime

Development of ML optimizer

- Intended as operational aid for source tuning
- Good progress, promising results → not yet ready for operations

Linac3
Status of the Accelerator Model

V. Toivanen, 2015



Source beam extraction

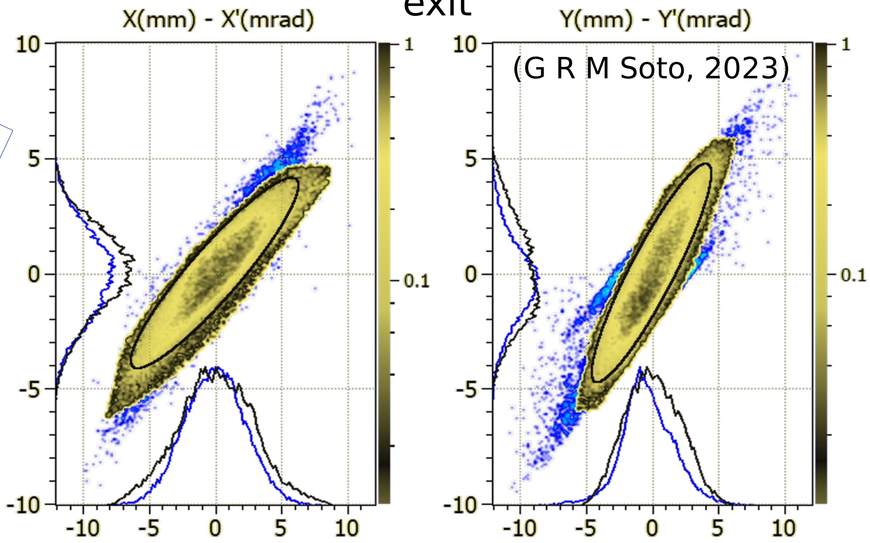
- Simulated with IBSIMu
  - 3D geometry
  - 3D magnetic field from Opera (solenoids & hexapole)
  - Measured charge-state distribution (CSD) spectrum
- Large error bars in the extracted beam specs
  - Uncetainty in the source modelling assumptions
    → due to **lack of instrumentation** at source extraction

See Ion Complex Upgrade proposal

ITL-to-ITF Linac3 beam dynamics

- Modelled in PATH/Travel
  - Using as input the beam distribution reconstructed from profile measurements after the ITL spectrometer
  - Good agreement between simulation results and beam measurements (transmission, beam transverse profiles)

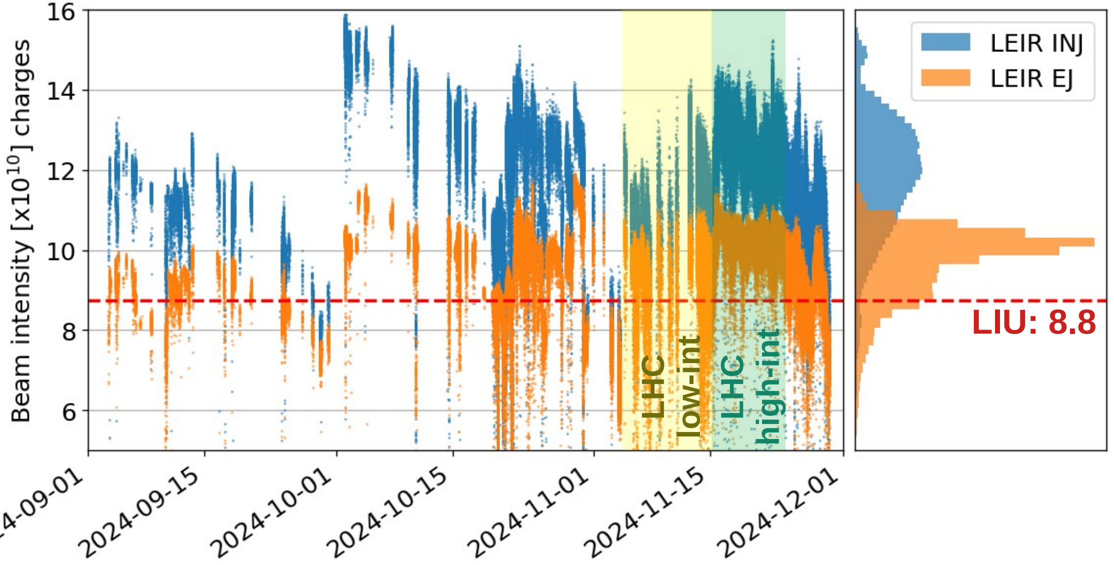
Simulated vs **measured** beam @ T3 exit

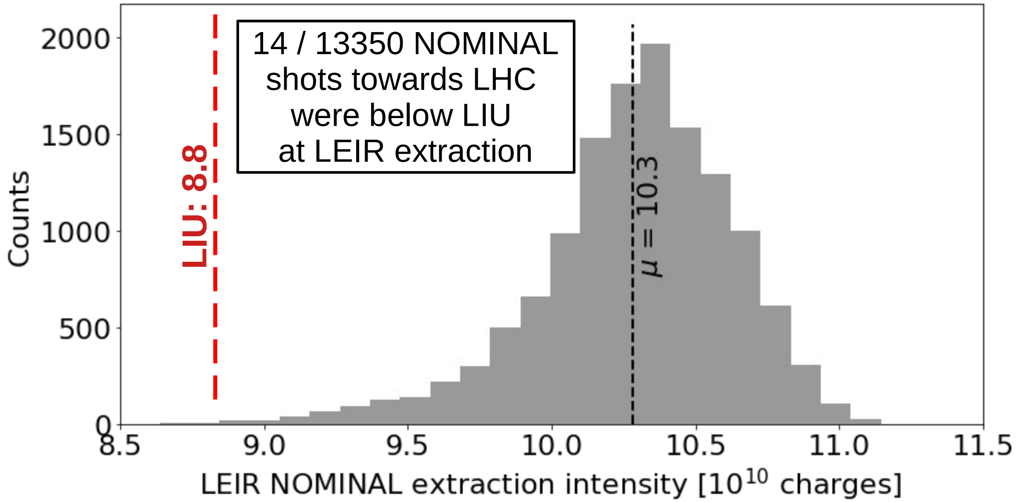


LEIR: Intensity

Intensity gain

- Adjusted injection system to benefit from longer pulses out of Linac3
- Cleaned orbit bumps
- Improved ejection and transfer efficiency to PS
    - Overestimated EE, ETP → max transmission at 104%
- Corrected ETL.BHN10 function, preventing degradation of the next cycle
- Extensive use of optimizers
  → Injection
  → RF-capture

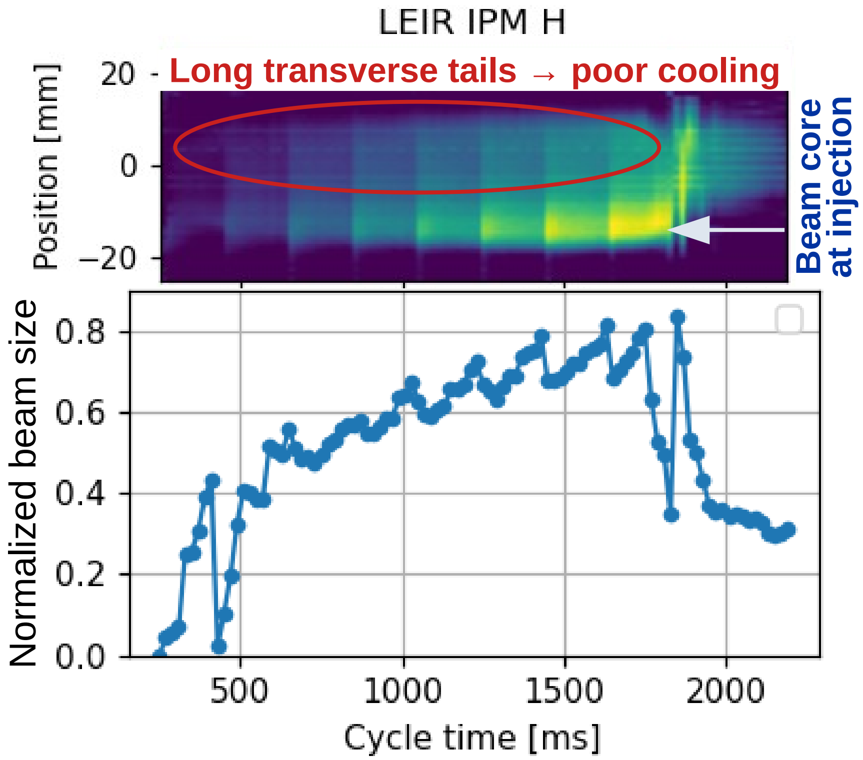


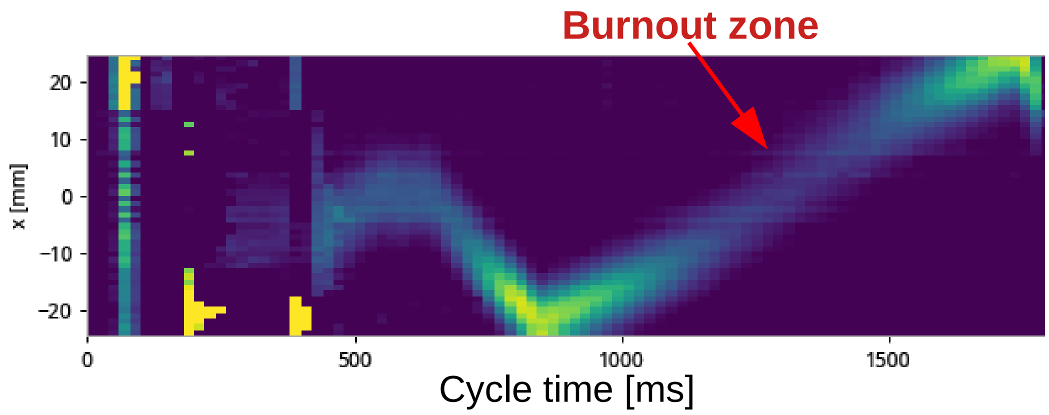


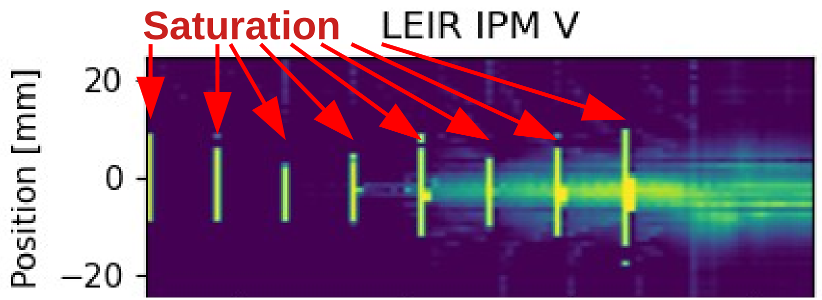
LEIR: Emittance & Cooling

Mainly longitudinal cooling in 2024

- Minimal transverse cooling visible in IPM data
- Issues with IPM emittance measurement
  - Burnout of central sensor parts
  - Saturation of the whole sensor at injection time
    → Suspected of affecting the data later in the cyycle





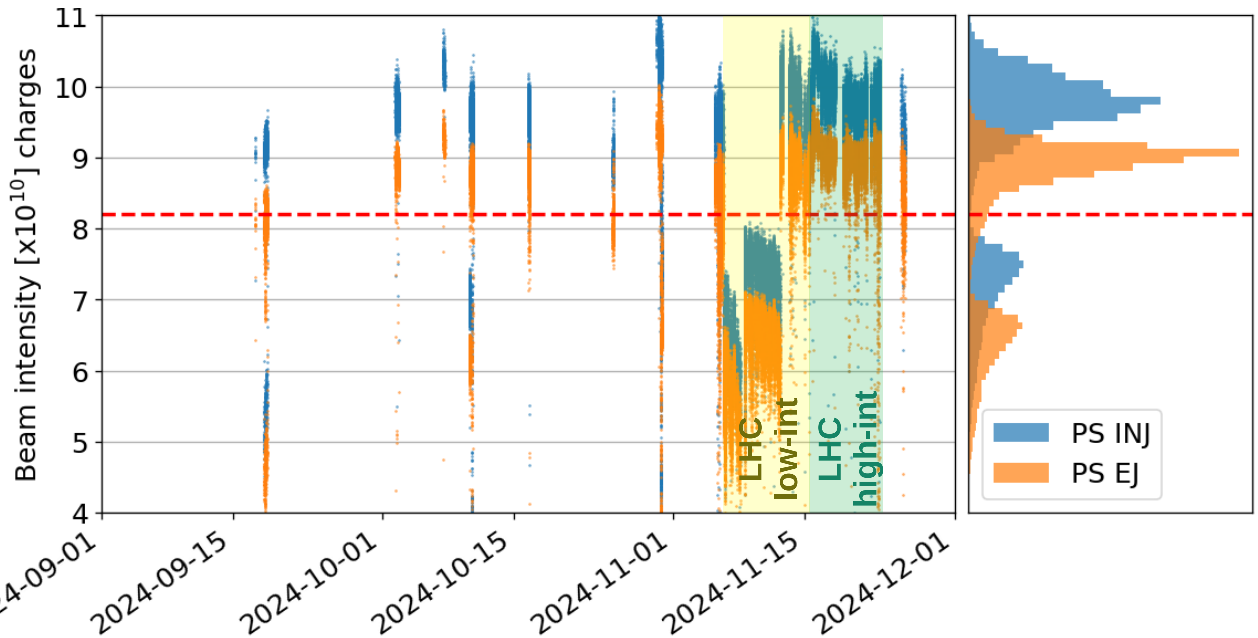


T. Argyropoulos

PS

Above-LIU performance

- Issue with ring BCT
  - Systematic baseline offset due to low beam intensity (compared to protons)
- Possible emittance blow-up along the cycle → To be verified
  - BGI not operational
  - Wire scanners → issues measuring vertical emittance at injection

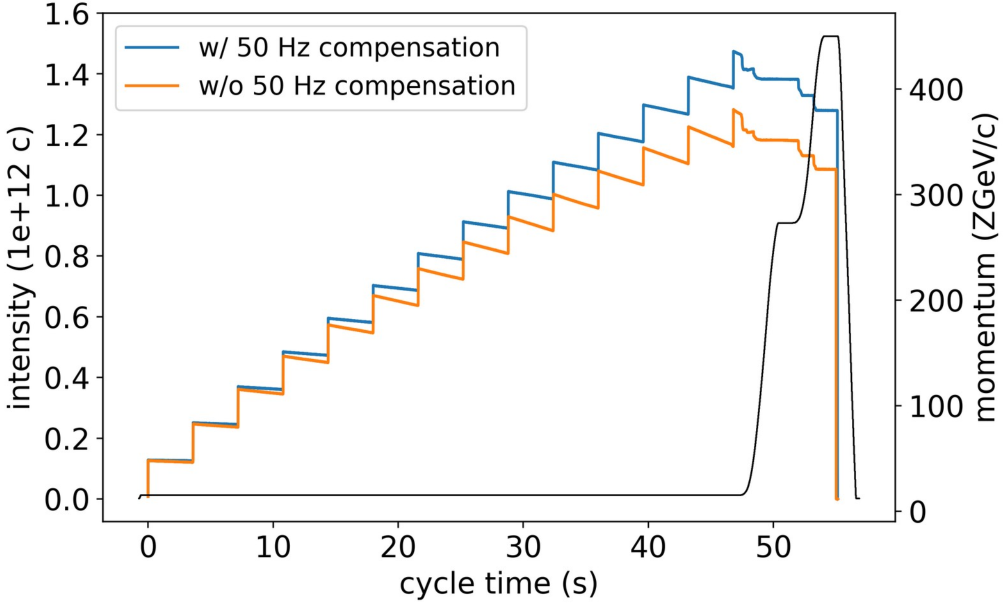


H, Bartosik, T. Argyropoulos

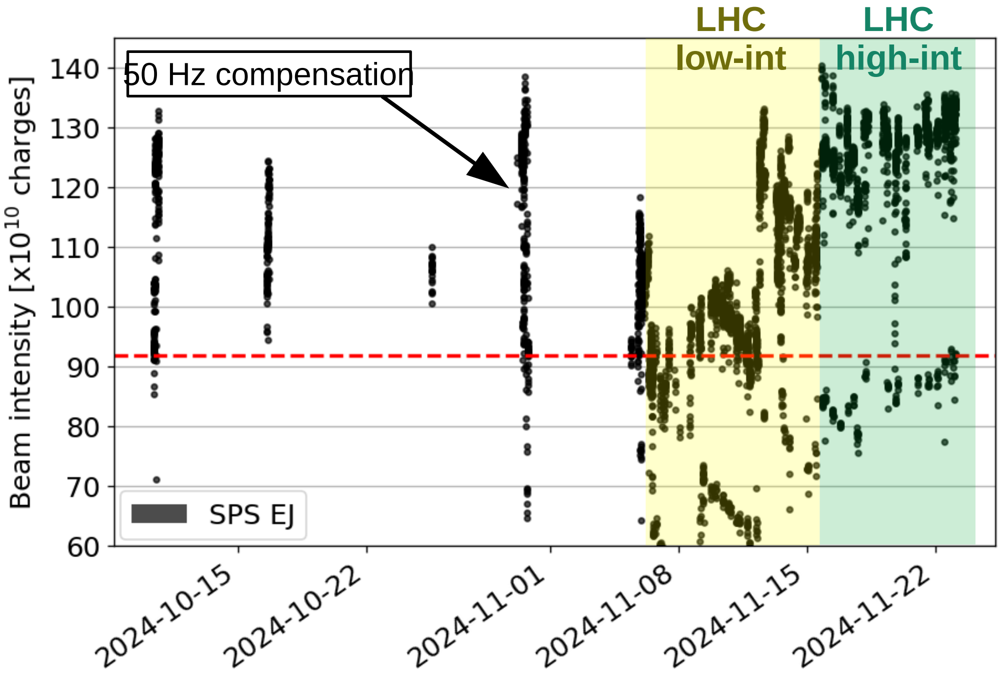
SPS – Flat-bottom Transmission Improvement and Ejection Intensity

~20% gain with 50-Hz compensation

- Optimizer available to OP from CCM



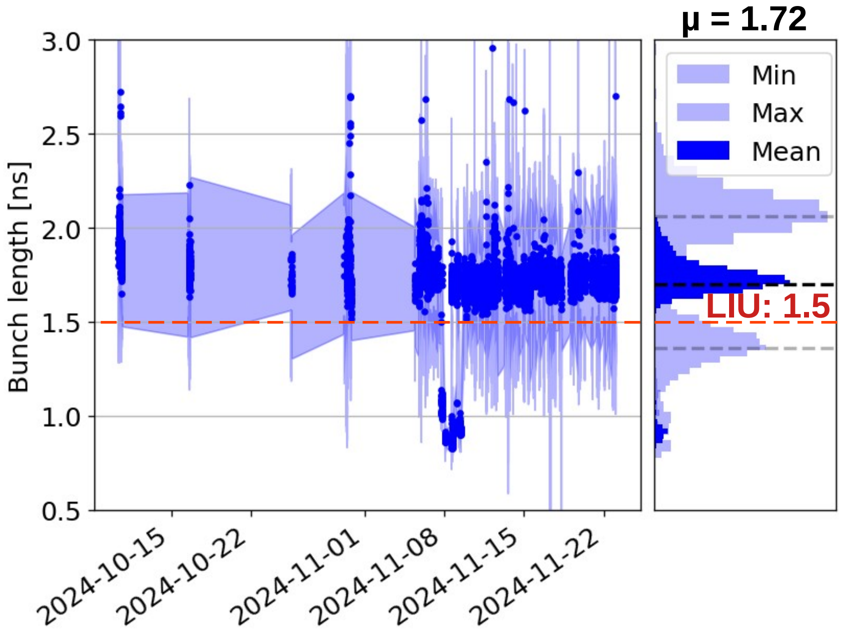
Above-LIU extracted intensity out of SPS



SPS – Bunch Length, Tune and Emittance

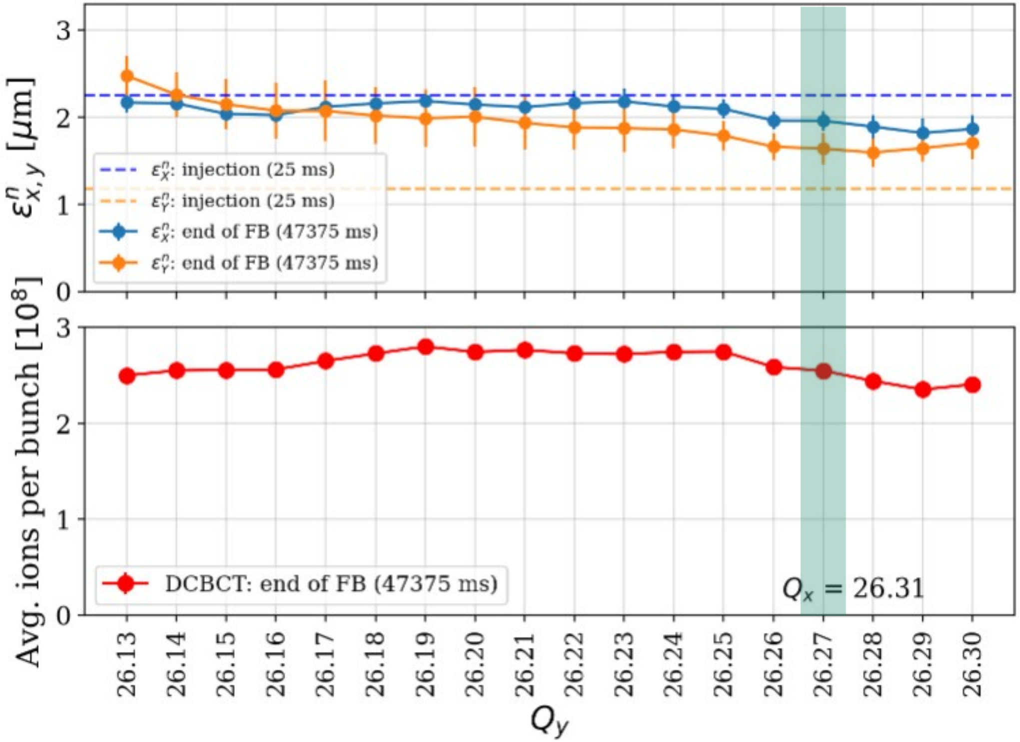
Bunch length at SPS extraction

- Not reaching LIU → missing 15%
  - LHC can still inject without bunch rotation



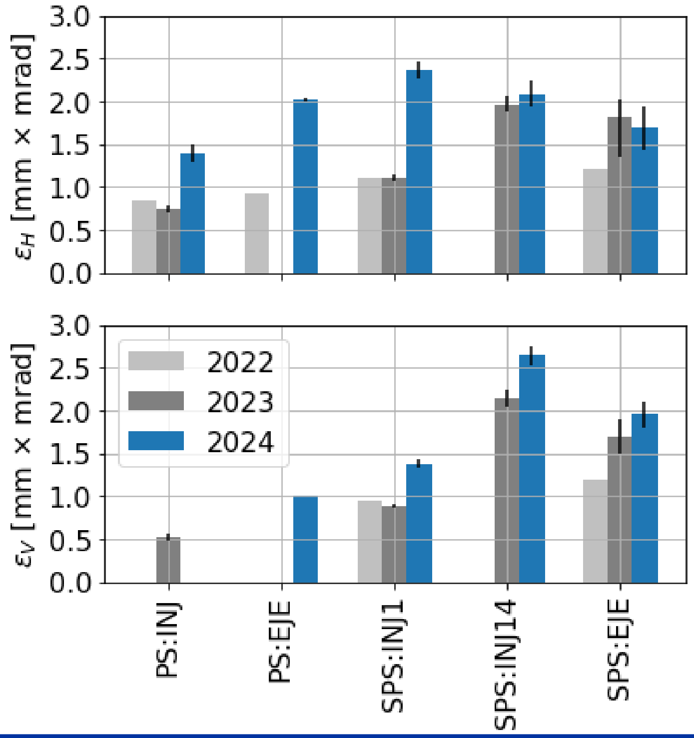
SPS working point

- Balance between transverse emittance and intensity

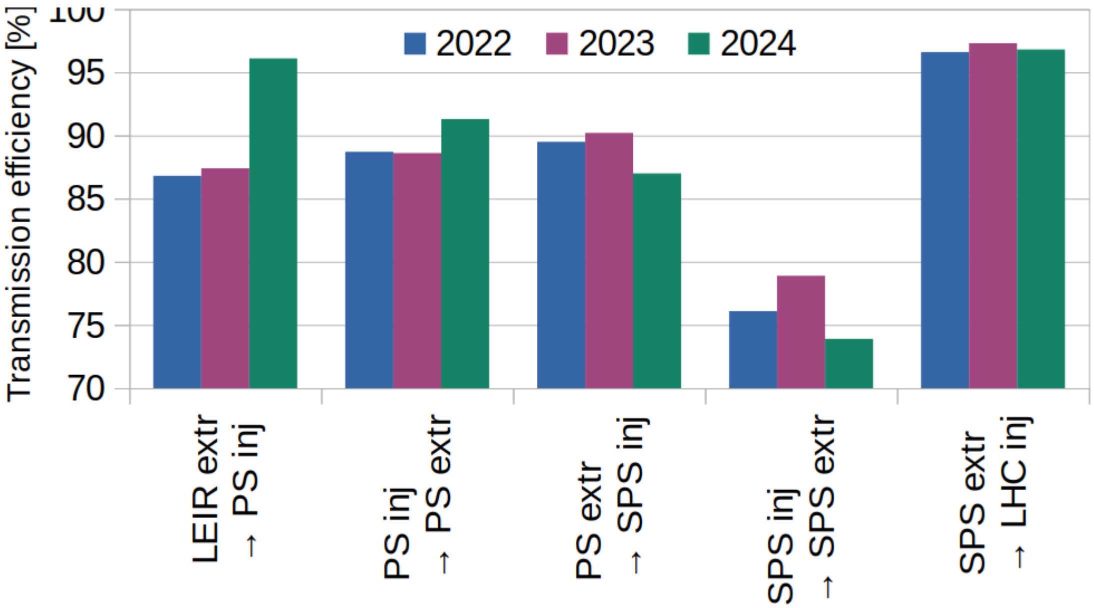


Transmission and Emittance

- Bigger transverse emittances across the injector complex
  → new LEIR configuration
  → much higher intensities

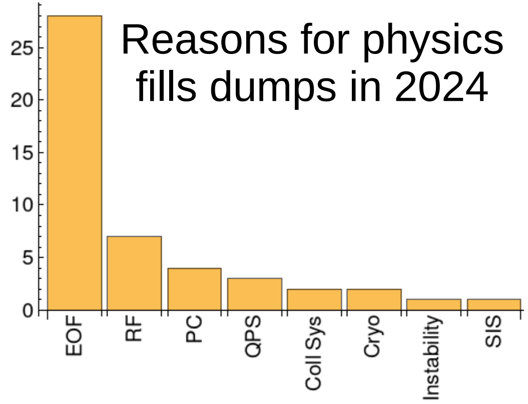


- Better LEIR-to-PS transfer than in previous years
- Slightly worse transmission from PS to SPS than in 2023
- More intensity losses along the SPS cycle
  → Degraded slip stacking → shorter bunch length
  → Tail scraping → smaller emittance
  → Price to pay for >30% higher per-bunch intensity



R. Bruce

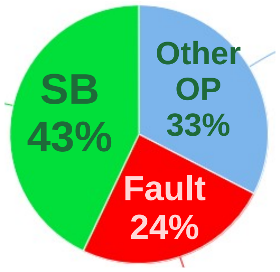
Summary of Issues at the LHC



The following issues were fully mitigated (none observed in 2024)

- 10 Hz losses
- High losses towards end of ramp
- Losses at start of ramp
  - Increased BLM thersholds
- 2023-type QDS issues
- RF issues

In 2024



In 2023

SB: 33%

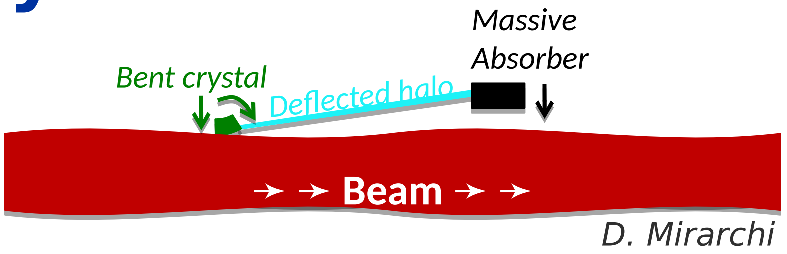
Fault: 33%

Remaining issues

- New QDS issues in 2024
  - Three **new-type issues** observed in 2024
    → multiple quench heaters firing following
    → fast power aborts in dipoles and quadrupoles
  - Planned mitigation → LMC #499
    https://indico.cern.ch/event/1484357/#3-quench-events-during-the-ion
    - Remove 140 DQQBSv2 boards,
    - Remove Y-capacitors from the boards
    - Reinstall the boards after testing
- Power converter trips

R. Bruce
D. Mirarchi

Crystal Channeling Stability



Importance of crystals alignment w.r.t. beam

- O(μrad) at top energy

Observation of drifts of crystals orientation in 2023

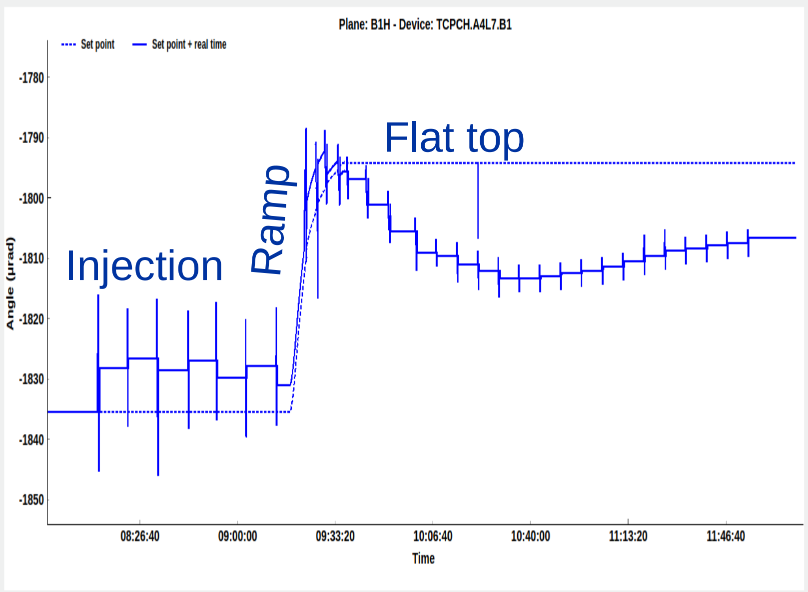
- Degraded cleaning performance when channeling less efficient

Mitigations in 2024

- Automatic optimizations at tunable intervals
- Coverage for the whole cycle
  - Real-time trims during the ramp

Observations in 2024

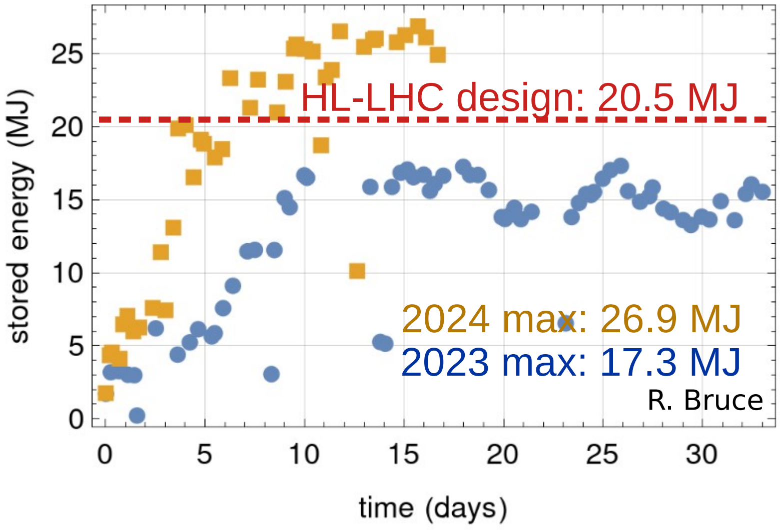
- Drifts of tens of μrad observed within fills
- Unknown root cause → **studies ongoing**
  - Why vertical device is more stable than horizontal?
- Thanks to the optimizer
  maintained orientation efficiency (most of the time)



LHC Performance

Parameter	2023	HL-LHC	2024
Avg injected intensity [10^8 Pb/b]	-	2.0	**2.6**
Transm.: inj. → stable beams	84%	-	**88%**
Avg intensity at start of collissions [10^8 Pb/bunch]	1.6	1.8	**2.3**
Maximum stored beam energy at start of collisions	17.3	20.5	**26.9**
Luminosity production rate* [nb^{-1} / day]	-	-	IP1/2/5: 0.144 IP8: 0.036
Emittance at injection [mm × mrad]	-	~1.5	**2.1-2.4**

*Only full-intensity part (excluding VdM and intensity ramp-up)



- Achieved levelling time of ~2h in ALICE
- Luminosity production in 2024 surpassed HL-LHC projections (and 2023 by far)

- On average: 2.6 × 10^8 Pb/bunch injected in LHC from SPS
  → 30% above LIU
- Larger-than-LIU emittance
  → still net gain due to high intensity

Integrated Luminosity

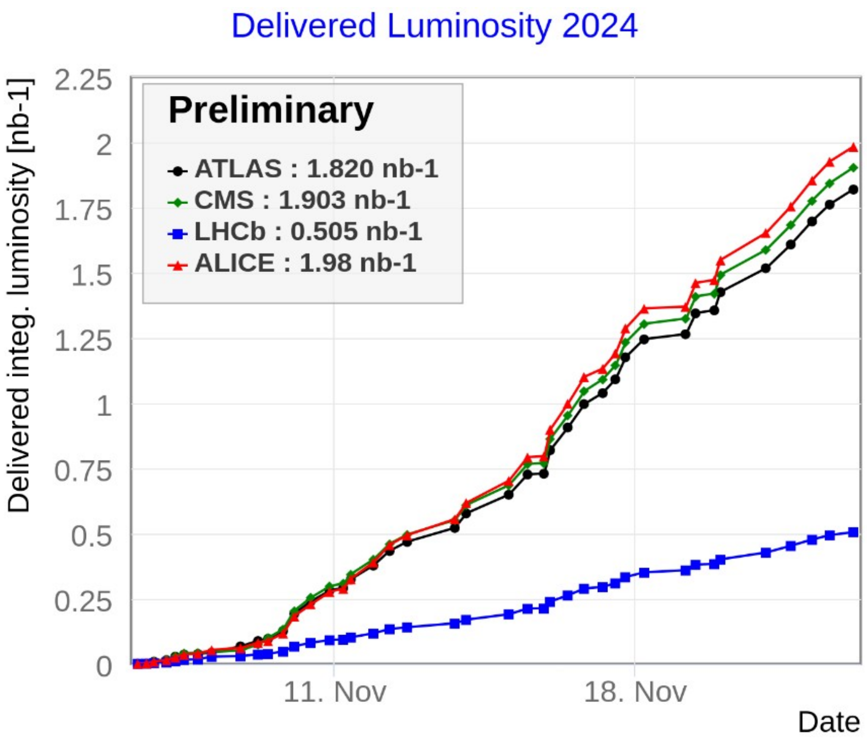
More info: D. Jacquet → JAP24 Tuesday

Luminosity collected in Run3 up to 2024 vs. targets:

- 1 → 2 nb^{-1} in LHCb
- 6.5 nb^{-1} elsewhere

ATLAS: 3.73 nb^{-1} (57%)
CMS: 3.93 nb^{-1} (60%)
LHCb: 0.75 nb^{-1} (75% → 37%)°
ALICE: 4.14 nb^{-1} (64%)

- At Chamonix 2024: experiments' targets were calculated ambitiously assuming sustaining the peak daily production in 2023 over the full run
- Targets reached in spite of 1 day less, due to longer pp reference run, thanks to:
  - Mitigations of the 2023 limitations in the LHC
  - Substantially higher intensity delivered by the injectors



North Area Performance

N. Charitonidis, M. Van Dijk, F. Velotti
More info: D. Banerjee → JAP24 Tuesday

High Energy Beam (150 AGeV/c)

- Primary beam Intensity and spot size
→ **very good**
- Challenging steering in T2 & T4
  - **ML** optimizer **in preparation** for T2
- Instrumentation in the secondary lines had to be commissioned during physics
  - **Request more beam commissioning** time next year
  - Issues at target and downstream

Low Energy Beam (13.5 AGeV/c)

- **Better intensity** and **reduced beam size**
  - Thanks to the new low-energy TT20 optics
  - Transmission improved by a factor 4-5
  - **Beam size** reduced from ~cm to 1-2 mm at T2 & T4
→ still **too large**
→ inefficiency of secondary production
- Main challenges at low energy
→ large beams and sensitivity to noise
→ **inaccurate measurement** of beam size

H2/H4

- Autopilot for controlling H2/H4 symmetry unusable due to low BSP signal
→ beam drift
  - Beam **position** and **intensity fluctuations**
→ need investigation

H8

- Identified **intensity limit** (with collimators fully open)
  - Observed 1.1×10^7 ions
→ Expected 25 times more

→ **Optics development needed**

East Area – HEARTS

HEARTS
High-Energy Accelerators for Radiation Testing and Shielding

Location

- IRRAD @ EA T8

Aim

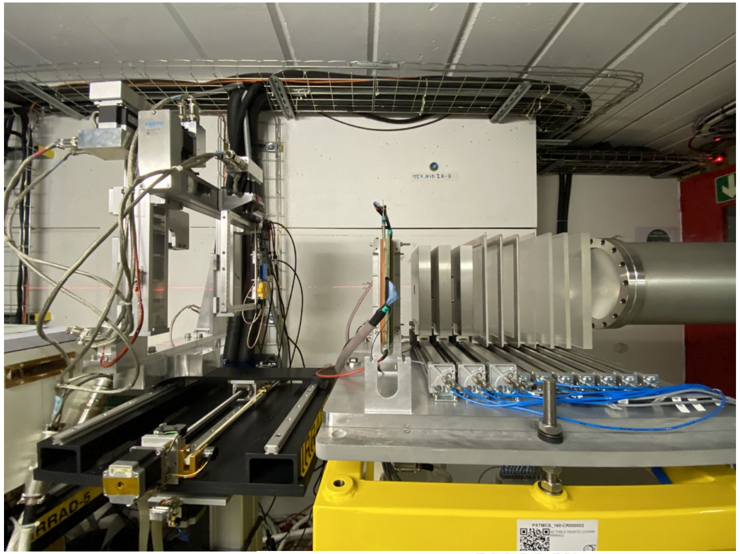
- Radiation testing of electronics for space applications

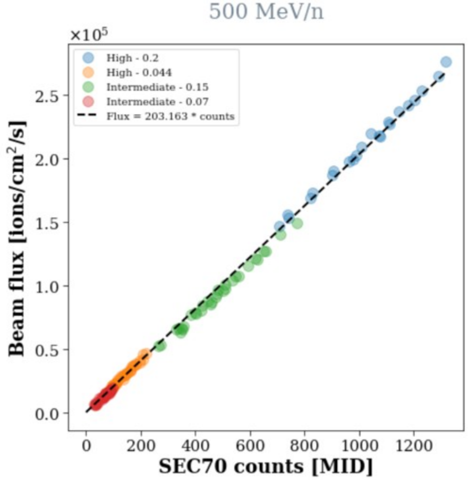
Beams out of PS

- Requirements:
  → large beam size
  (7.5×7.5 cm^2)
  → good homogeneity (±10%)
- Energies
  → 1 GeV/u
  → 0.5 GeV/u
  - Local use of PMMA degraders to tune the beam energy further

Performance

- Beam availability: 90%
  - Main downtime (12h) due to unscheduled Linac3 source oven refill
    - The affected users managed to complete their hours afterwards
- Duration:
  - 12 days, ~150 h of beam time
    → 100% of the original plan
- Users
  - 10 user teams
    → 4 scientific
    → 6 industrial





The Future

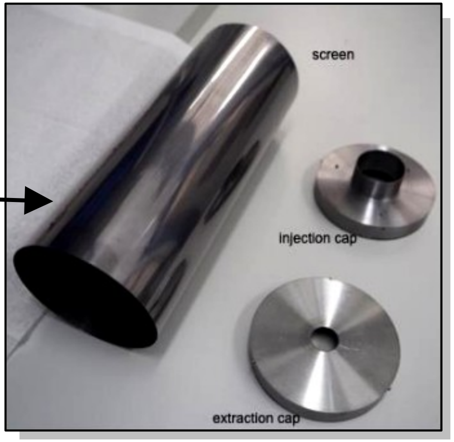
Magnesium Beam Test up to PS

For NA61++/SHINE – Issues and mitigations

Short oven lifetime

Reduce downtime

- Addition of *tantalum hotscreen* in the plasma chamber to recirculate Mg
  → Significant reduction of Mg consumption
  → Need a **follow-up test** (earliest in LS3)
- Oven with a bigger crucible
  → Existing design is hard to manufacture
- Use magnesocene
  → delivered as gas, not preferred due to handling difficulties

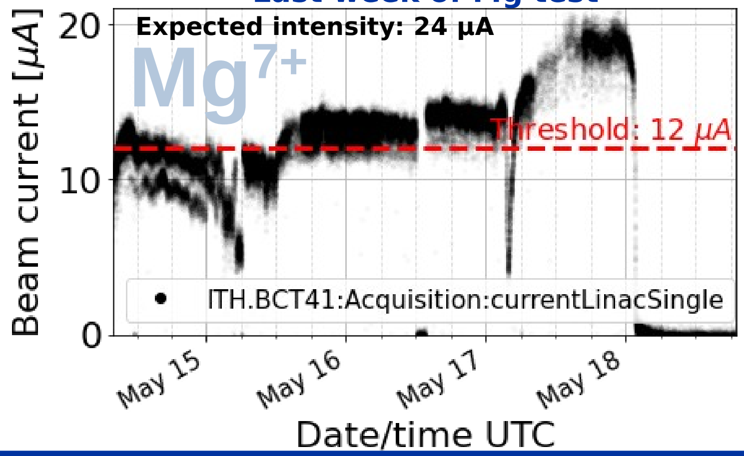


Low intensity

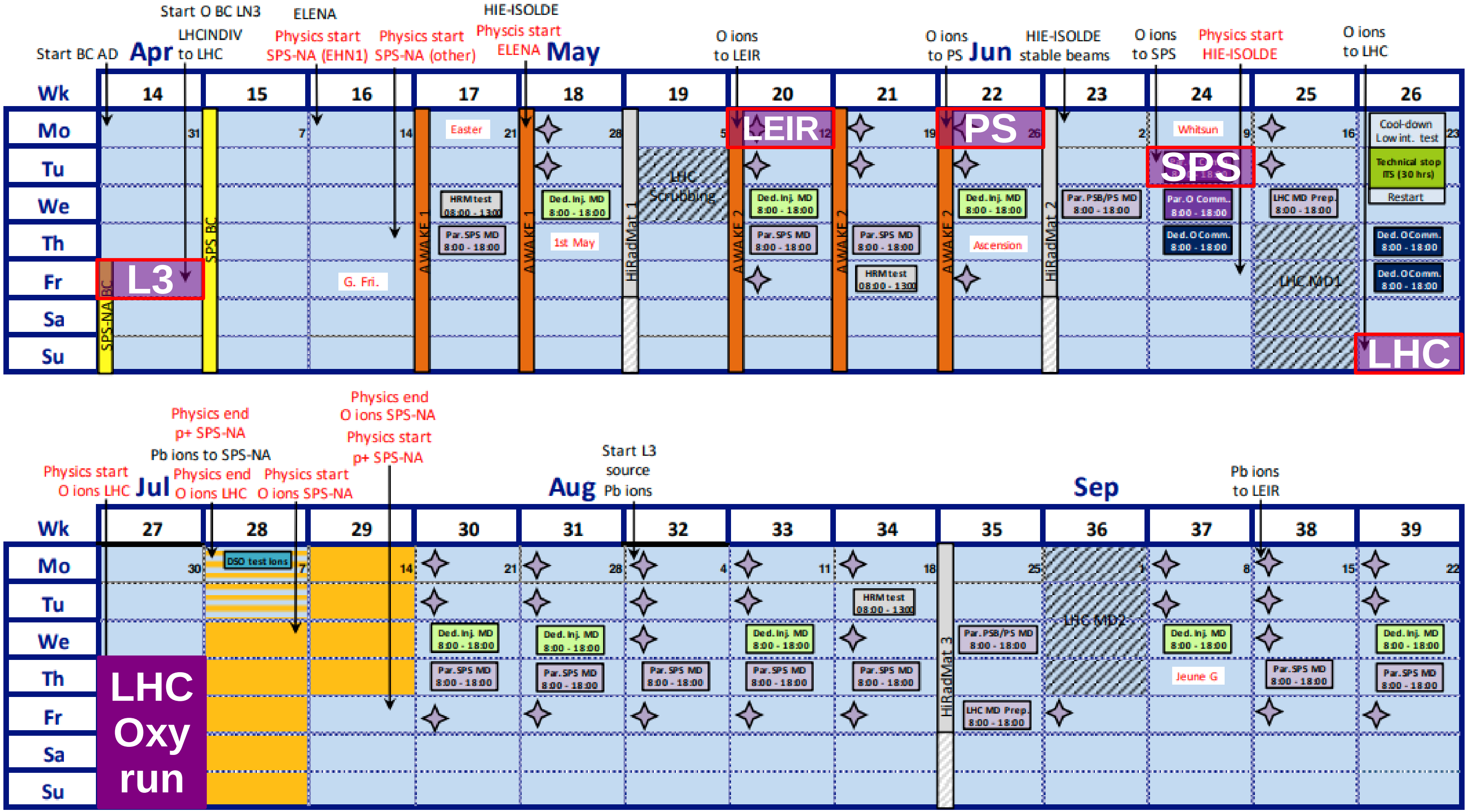
Increase intensity

- The source could be pushed to deliver more intensity at the cost of increased rate of Mg consumption
  → 40% gain, as shown in the last day of the test
- Better-optimize LEIR and PS
  → 20-30% improvement possible → need **more commissioning time**
- Improve transmission through Linac3
  → 10-20% improvement possible
  → **need more tests**

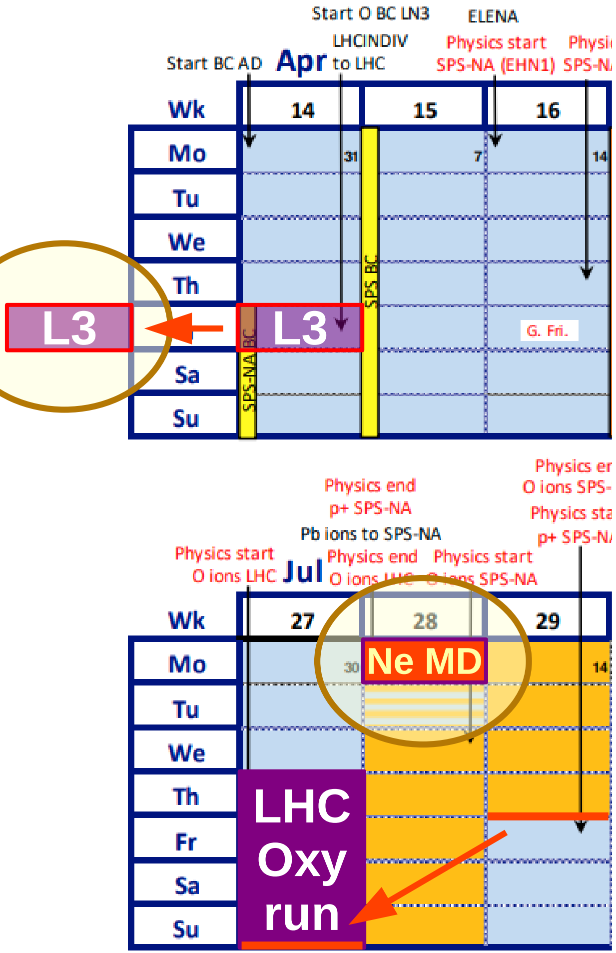
Last week of Mg test



Oxygen Run in 2025



Future Ions WG proposal → Neon test in 2025



Motivation:

If Ion Complex Upgrade delayed & no 2nd source available after LS3

- Mitigation: deliver two different ions with the same A/Q (beam rigidity) across the complex in a short time
  - Species: $^{16}O^{8+}$ → $^{20}Ne^{10+}$ → Same A/Q and motivated **physics case**

https://arxiv.org/pdf/2402.05995
https://arxiv.org/pdf/2405.20210

Goals of the test:

1. Assess switching time of ~hours: **O** → **Ne**
2. Assess oxygen source contamination & purging speed
3. Confirm same settings across the complex are transparent for both ions
4. Beam dynamics limitation studies across the complex with a new ion → Ion Injector Model benchmark
5. Eventually, send the beam to LHC for **Ne**-**Ne** collisions

Timeline:

- To check 1 & 2 → start the source 1 week in advance
  (as proposed by the LN3 team)
- After the LHC oxygen run, perform a 24 hours test to bring the beams up to SPS
  - Best-effort beam to LHC directly after oxygen run, with collisions if the experiments are interested

Future Ions – Identified Limitations

Concurrent feasibility studies within a LHC and NA physics year is challenging

- One ion source for development and operation
  - Limited time for studies → small number of issues can be addressed experimentally
  - New ions at the source can potentially contaminate the source → Pb may be compromised
  - Limited beam instrumentation → trial and error è time consuming

If NA61++ Run 4 program approved

→ Ion complex fully committed to operation
→ No development for post-LS4 LHC ions possible
→ No light ions for LHC in Run 4

LHC luminosity could be improved by further increasing intensity

→ Push boundaries for space charge and IBS in injectors, explore shorter bunch spacing than 50 ns

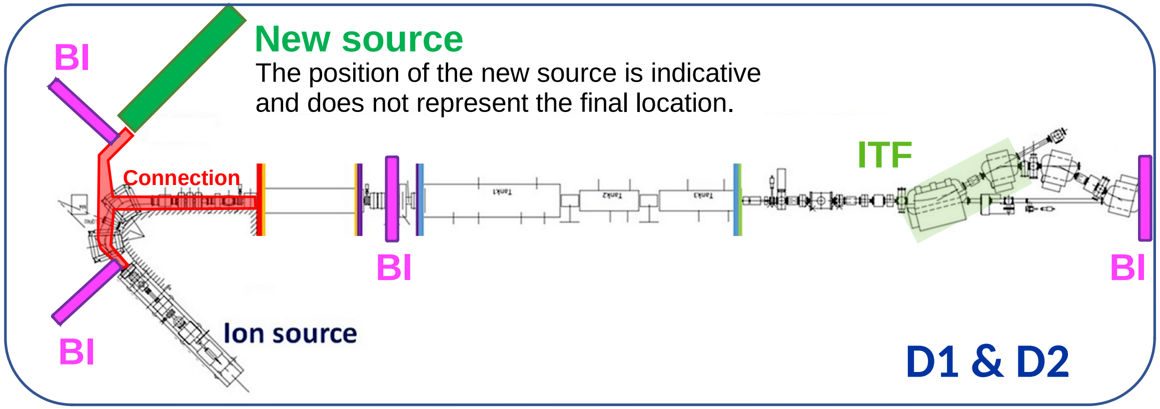
Current ion complex cannot fulfil HEARTS++ request

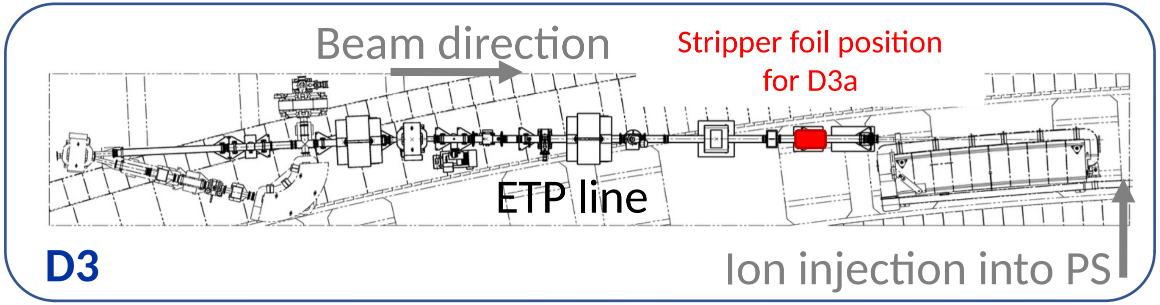
→ 15’ switching time between 4 different species

Ion Complex Upgrade (ICU) Proposal

ICU DELIVERABLES

1. New Linac3 source and BI out of both sources
2. Connection of ion sources and BI downstream
3. Alternative stripping scenario
4. 25 ns bunch spacing at LHC
5. Consolidation





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

Ambitious timeline

- Aiming at D1,D2 & D5 MTP25 approval
- CDR in preparation → 2026
- Implementation in phases → flexibility depending on available resources within the groups
  → First installation at the end of LS3
  → Project completion in LS4

Summary and Outlook

Issues from 2023

- Poor intensity and stability at the injectors
  → mitigated
  → improved steering, 50-Hz @ SPS
- LHC
  - QDS
    → Mostly mitigated (new-type issue)
  - Beam losses
    → All mitigated (10 Hz, start/end of ramp)
  - Crystals stability
    → Mitigated, but not understood
  - ALICE background
    → Acceptably mitigated

2024 new-filling scheme MD

- Cancelled due to QPS issues

Observations in 2024
→ to be followed up

- High emittance out of injectors
- New-type QDS events at the LHC
- NA: BI accuracy, optics
  (further beam size reduction)
- Long LHC filling time
  → intensity losses → how to improve?

Future

2025: Oxygen run & neon MD proposal

LS3: ^{10}B and ^{24}Mg test at Linac3

Ion Complex Upgrade (ICU)

- Proposal in preparation to mitigate ion complex limitations for future ion requests

Altogether 2024 was a very good year for ions

Injectors performed well above LIU (except emittance)
LHC is already reaching above-HL performance
Luminosity production exceeded by far projections from Chamonix 24
Fixed-target experiments and users were happy

Thanks to dedication and hard work of all the involved teams

Let’s break even more (positive) records next year!

home.cern

R. Bruce
More info: F. Alessio → JAP24, Tuesday

ALICE Background

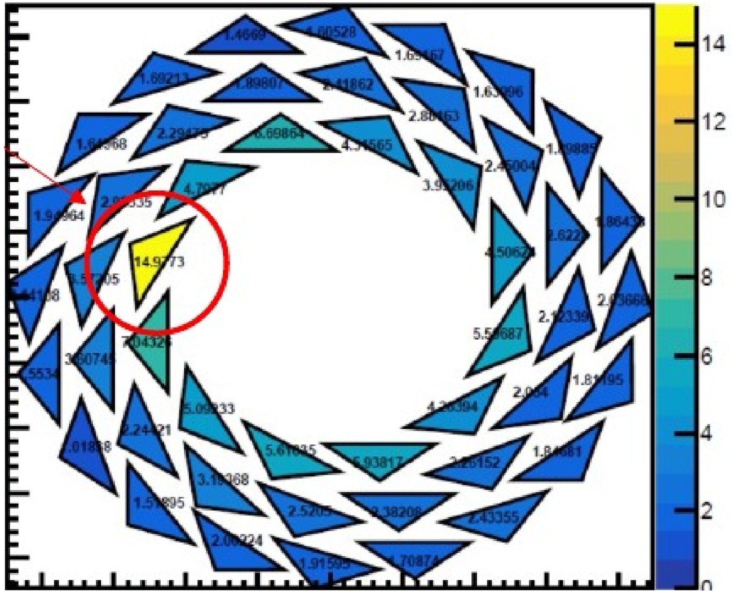
In 2023 observed strong background at IR2
→ severe impact on ALICE data taking

- Main source: $^{207}Pb^{82+}$ from IR7 hitting IR2 tertiary collimator
- Applied mitigation: **`on_disp`** knob
  → Some residual background remained

Background in 2024

- Continued using **`on_disp`** knob
- Physics background as in 2023 after mitigation
  → **Residual background still present** → not a showstopper
  → Unknown source
- Performed end-of-fill tests to identify the source of the residual background
  - Background still present after dumping one beam only, regardless of beam direction
- Studies ongoing
  - Need to understand the source before devising mitigation measures

Busy violations in 15 out of 1M readout frames at interaction rate of 47 kHz.



Linac3 source oven 2 blockage

Inspection after oven refill on 29th Nov

- Identified oven 2 nozzle blocked by the silvery surface of Pb
- Later measurements show that only 437 mg were used out of 1388 mg installed in oven 2

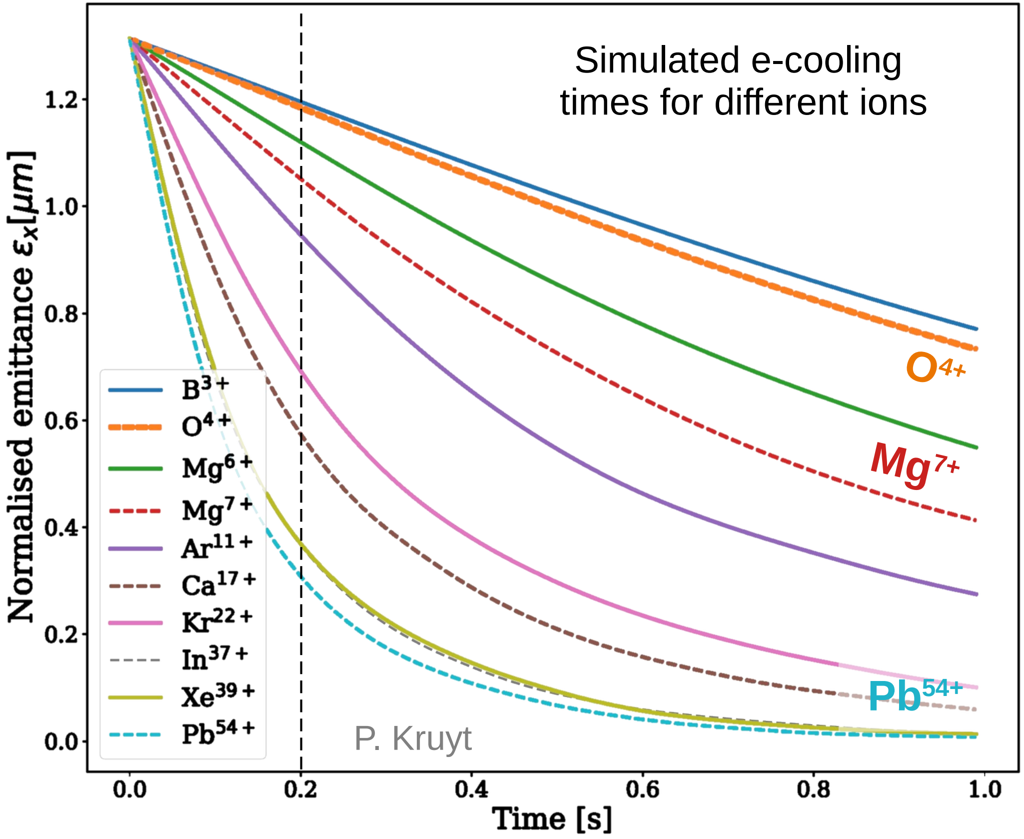
Linac3 source oven2 after removal on 29 Nov 2024
Photos by Mike O'Neil

Linac3 source oven refill scheduling

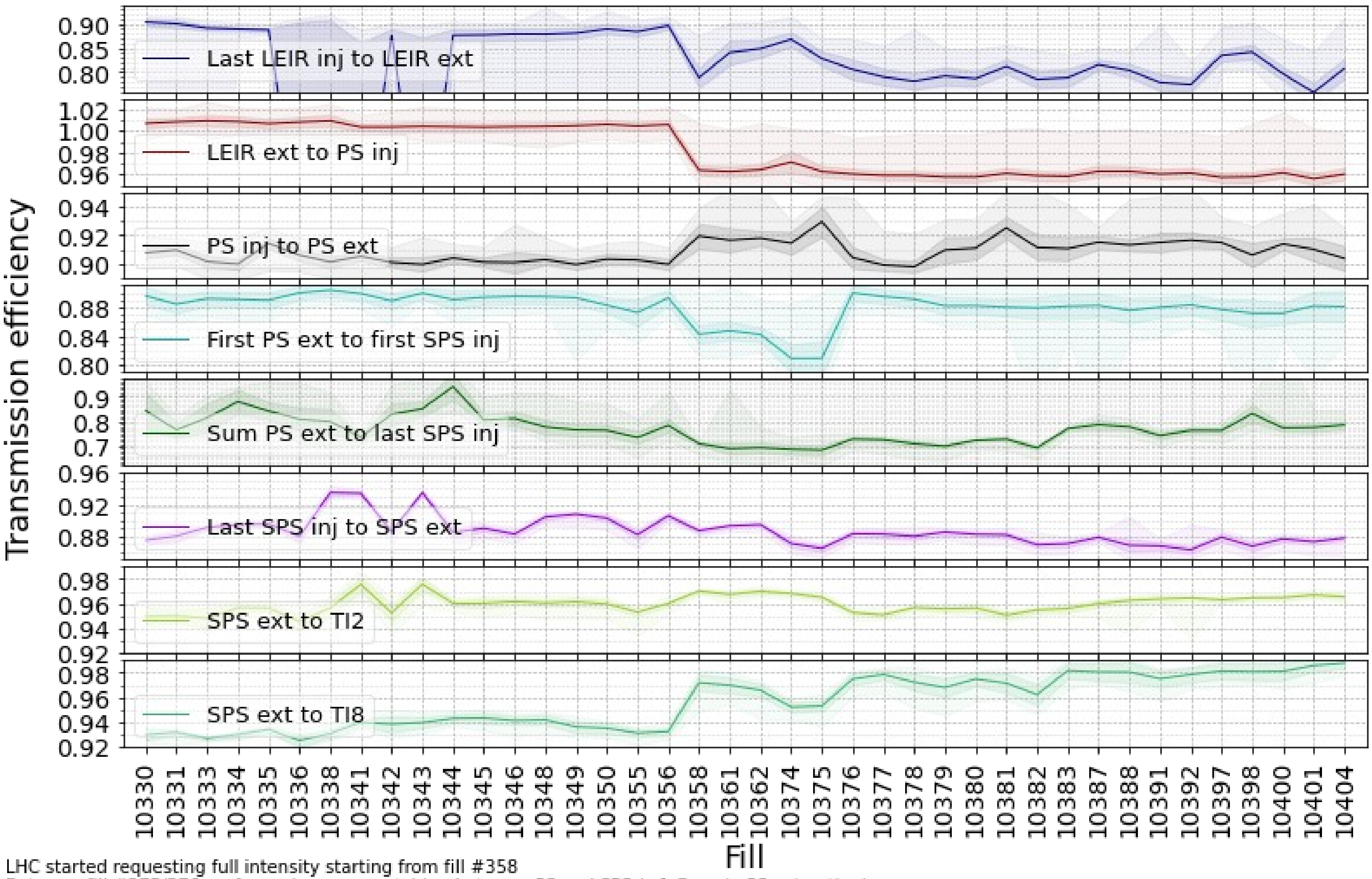
Do we need to revise the refill planning strategy?

- Scheduling oven refills assuming the second oven would fail seems excessive
- Around 30 days of operation per two-oven-fill is the expected minimum
  → But never tested explicitly (we always anticipate the refill)
  - For runs longer than 30 days we either have to:
    - Schedule the refill
      → Downtime at the chosen time (working hours, no short-term users affected)
    - Run until the intensity fades away (ovens empty/malfunctioning)
      → Chance to avoid unnecessary refill and downtime altogether
      → Risk of downtime in the most inconvenient moment

LEIR cooling efficiency for light ions

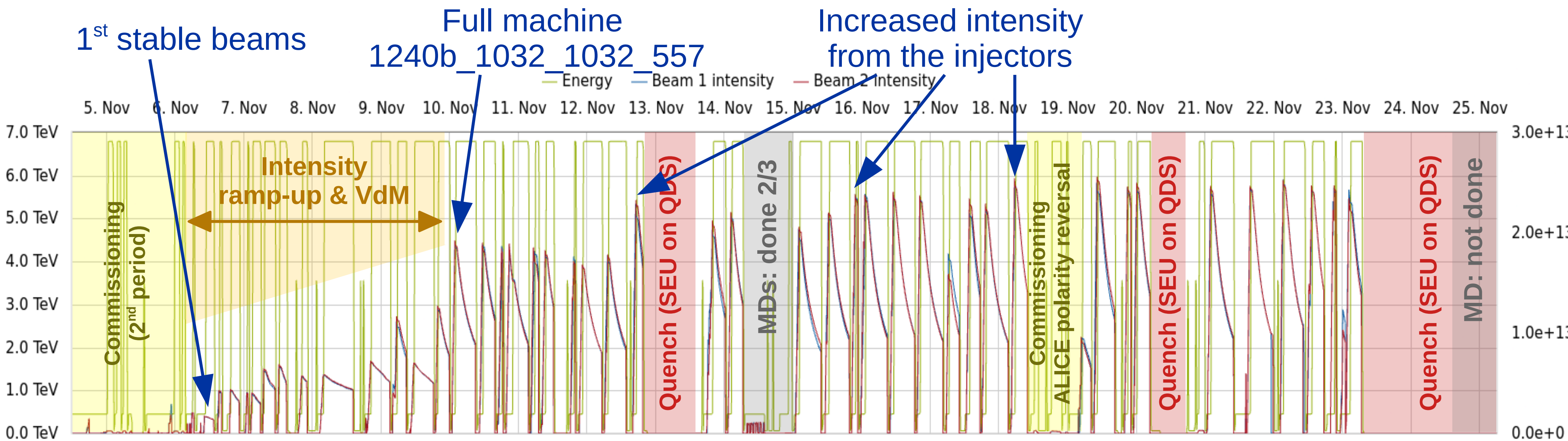


Transmission in the injectors per LHC fill



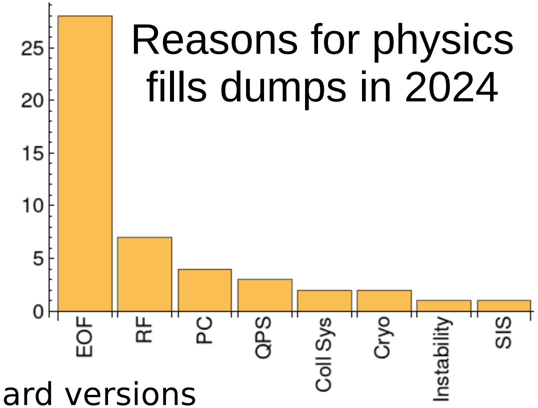
LHC started requesting full intensity starting from fill #358
Between fill #375/376 performed energy matching between PS and SPS (+1 Gaus in PS extraction)

Overview of 2024 Ion Run at the LHC



Excellent physics production over extended periods! Some downtime and premature dumps.

Summary of Issues at the LHC



The following beam losses were fully mitigated (none observed in 2024)

- 10 Hz losses
  → Delayed opening cryo valve
  → More open collimators
- High losses towards end of ramp
  → More open colimators
  → Better orbit correction
  → Lifting out part of squeeze
- Losses at start of ramp
  → Increased BLM thersholds

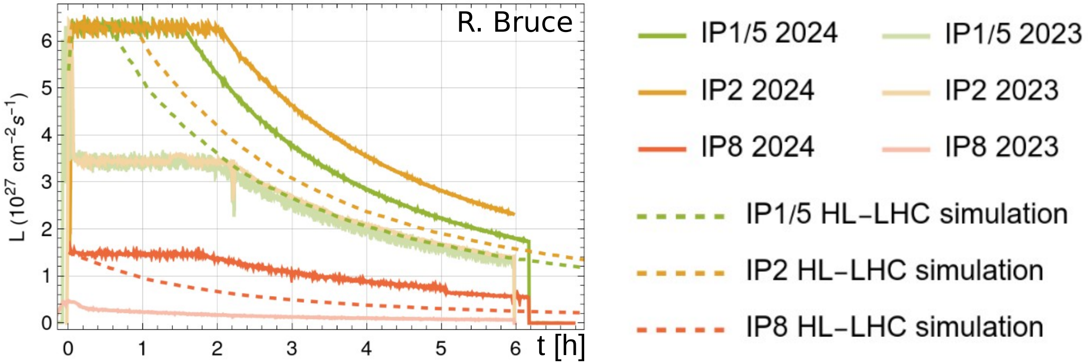
Faults and downtime

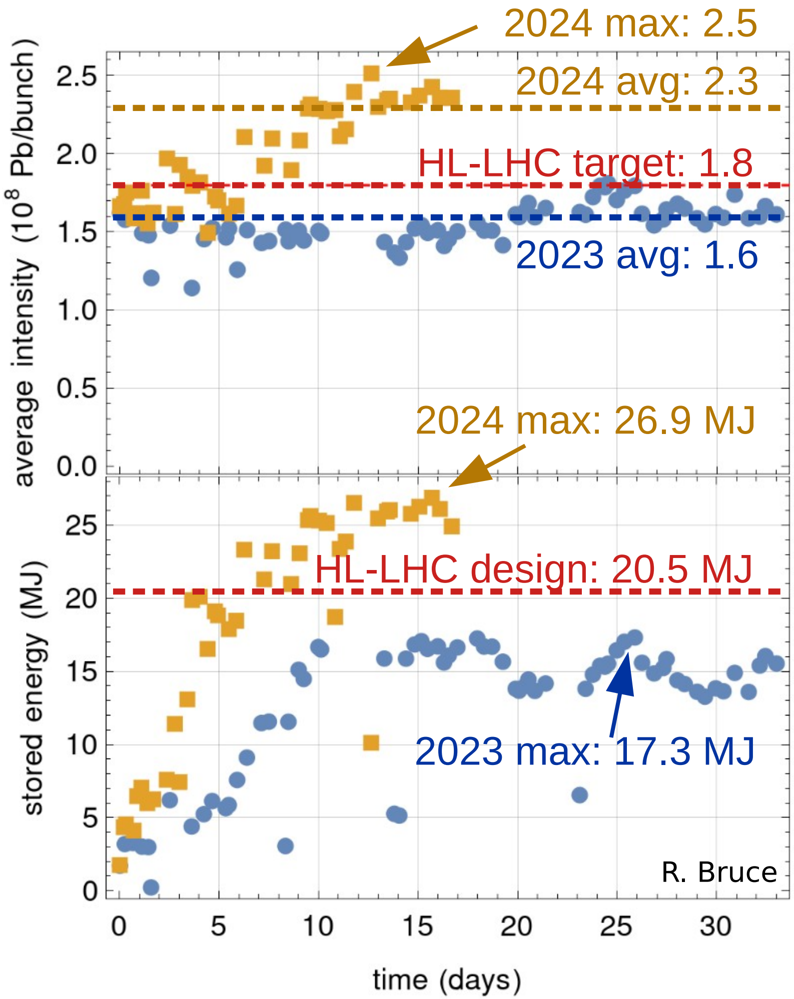
- Old QDS issues from 2023
  - **Mitigated** by replacing ~200 boards with radiation-hard versions
- New QDS issues in 2024
  - Three **new-type issues** observed in 2024
    → multiple quench heaters firing following
    → fast power aborts in dipoles and quadrupoles
  - Planned mitigation → LMC #499
    https://indico.cern.ch/event/1484357/#3-quench-events-during-the-ion
    - Remove 140 DQQBSv2 boards, remove Y-capacitors, reinstall the boards
- RF issues
  - **Mitigated** by gradually decreasing voltage from 16 MV down to 12 MV
    → increase of availability
- Power converter trips

LHC Performance

Parameter	2023	HL-LHC	2024
Avg injected intensity [10^8 Pb/b]	-	2.0	**2.6**
Transm.: inj. → stable beams	84%	-	**88%**
Avg intensity at start of collissions [10^8 Pb/bunch]	1.6	1.8	**2.3**
Maximum stored beam energy at start of collisions	17.3	20.5	**26.9**
Luminosity production rate* [nb^{-1} / day]	-	-	IP1/2/5: 0.144 IP8: 0.036

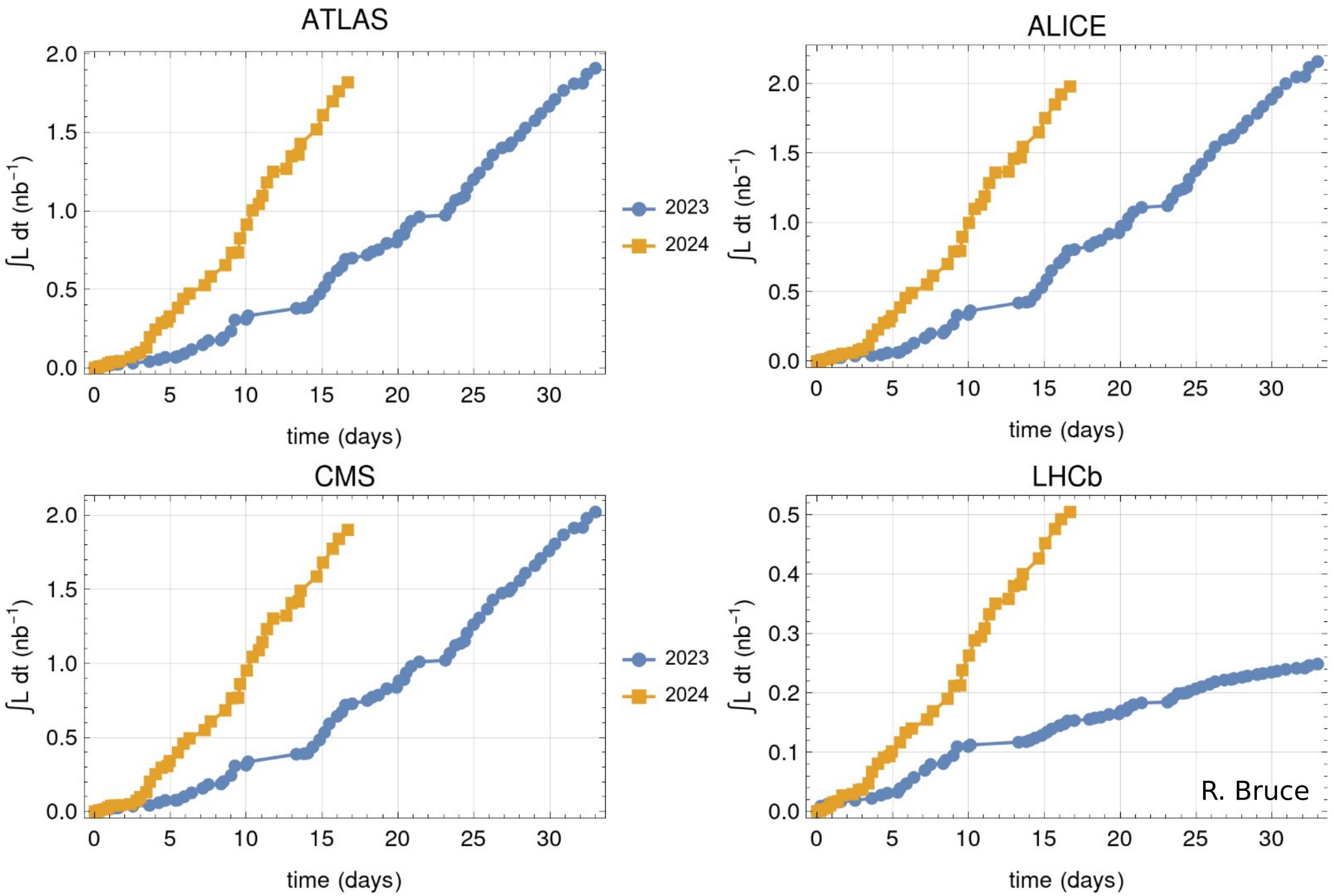
*Only full-intensity part (excluding VdM and intensity ramp-up)





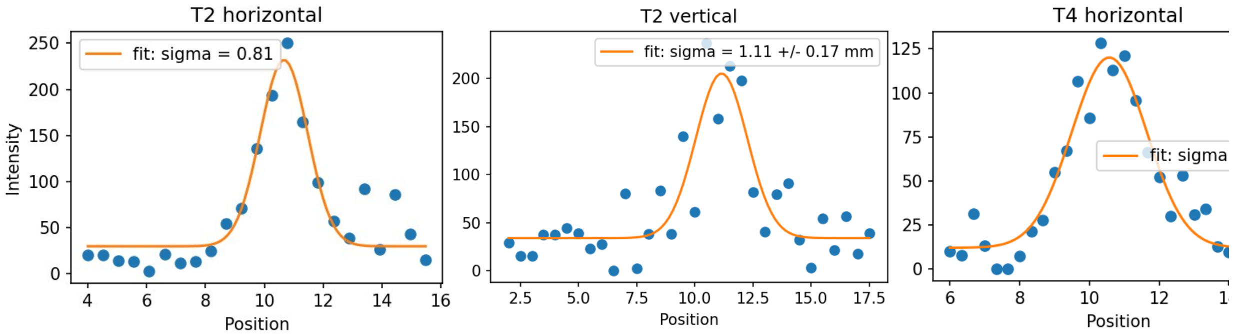
LHC integrated luminosity

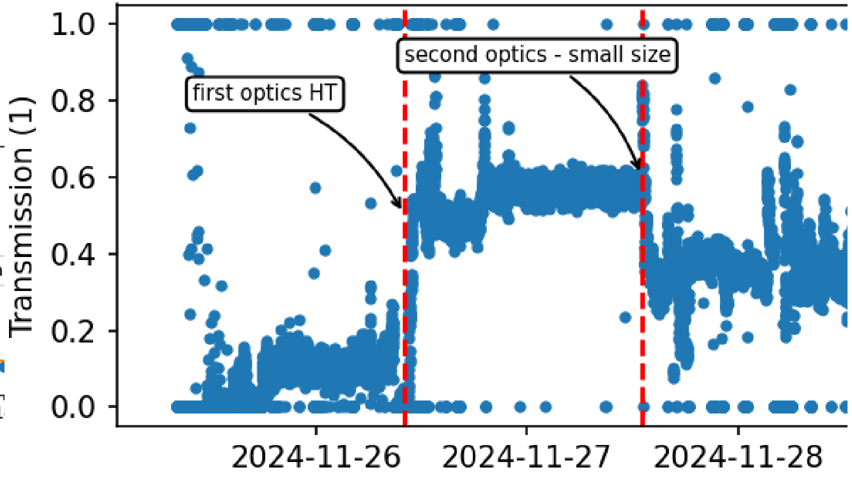
Same luminosity as in 2023, but in half the time!

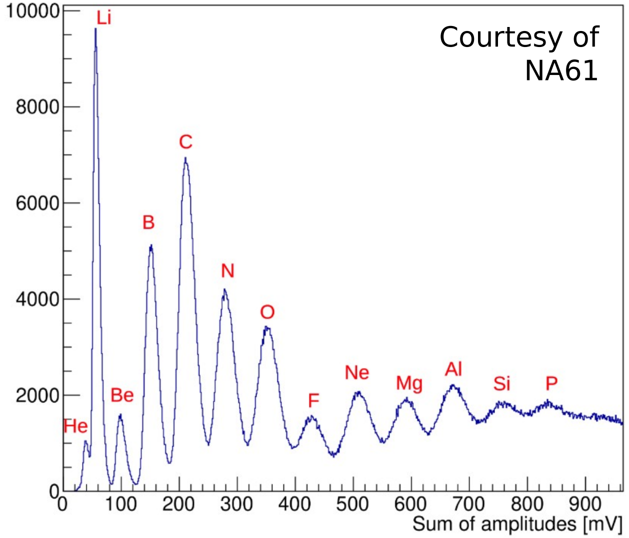


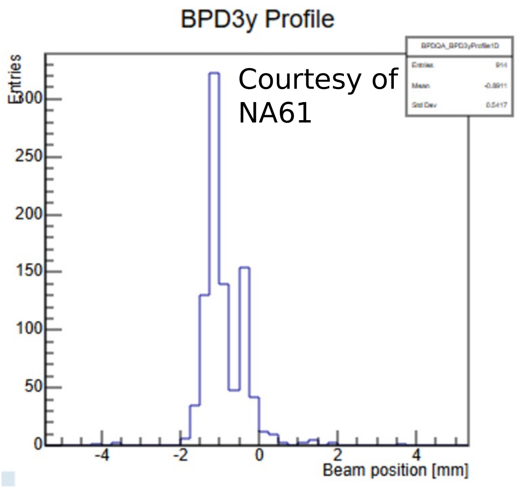
F. Velotti

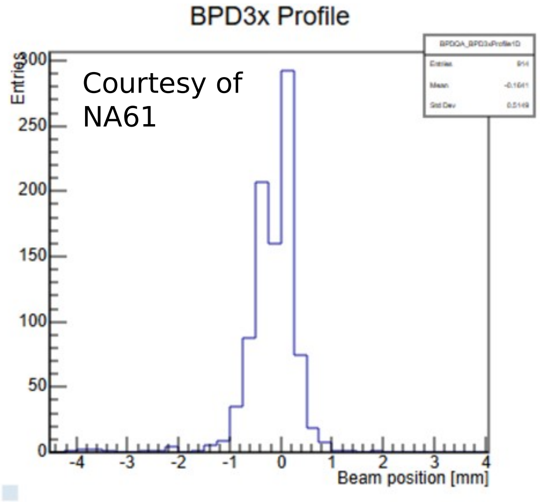
North Area performance











LIU beam parameters

(https://edms.cern.ch/document/1420286/2)

	N_{ions}/bunch (10^8)	$\varepsilon_{x,y}$ (μm)	Bunches /injection	Bunch spacing (ns)	N_{ions}/bunch (10^8)	$\varepsilon_{x,y}$ (μm)	Bunches	Bunch spacing (ns)
LEIR	**Before RF capture (54^+, E_{kin}=0.0042 GeV/u)**				**Extraction (54^+, E_{kin}=0.0722 GeV/u)**			
Achieved (2015)	15.5	0.4, 0.4	coasting beam		6.0		2	354
LIU-ions (TDR)	18.6	0.4, 0.4			7.4		2	354
Achieved (2016)	19.1	0.4, 0.4			8.1		2	354
LIU-ions (2016)/HL-LHC	19.1	0.4, 0.4			8.1		2	354
PS	**Injection (54^+, E_{kin}=0.0722 GeV/u)**				**Extraction (54^+, E_{kin}=5.9 GeV/u)**			
Achieved (2015)	5.5		2	354	5.1	0.9, 0.8	2	100
LIU-ions (TDR)	6.8		2	354	3.1	1.0	4	3x100
Achieved (2016)	8.1		2	354	3.8	1.0	4	3x100
LIU-ions (2016)/HL-LHC	8.1		2	354	3.8	1.0	4	3x100
SPS	**Injection (82^+, E_{kin}=5.9 GeV/u)**				**Extraction (82^+, E_{kin}=176.4 GeV/u)**			
Achieved (2015)	4.3	1.0, 0.9	2	100	2.2	1.5	24	11x(100+150)+100
LIU-ions (TDR)	2.6	1.0	4	3x100	1.7	1.3	48	5x(7x50+100)+7x50
Achieved (2016)	3.5	1.0	4	3x100	2.2	1.5	28	6x(100+150)+100
LIU-ions (2016)/HL-LHC	3.5	1.0	4	3x100	2.0	1.5	56	6x(7x50+100)+7x50
LHC	**Injection (82^+, E_{kin}=176.4 GeV/u)**			MKI gap (ns)	Abort gap (ns)		Total number of bunches	
Achieved (2015)	2.2	1.5	24	900	3300		518	
LIU-ions (TDR)	1.7	1.3	48	900	3300		1152	
Achieved (2016)	2.2*	1.5	28	900	3300		548	
LIU-ions (2016)/HL-LHC	1.9*	1.5	56	800	2900		1256	

* these bunch intensity values refer to the start of the LHC ramp.