Overview of performance of the 2025 Oxygen and Neon run

Light ion collisions at the LHC, 01 December 2025

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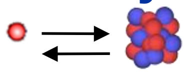
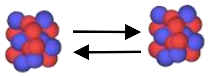
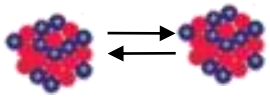
Outline

- ❑ Introduction
- ❑ Timeline of the Runs
- ❑ Beam performance and issues of the injectors
- ❑ LHC physics performance of Oxygen runs
- ❑ Neon run tests in the injectors and LHC physics performance

Introduction

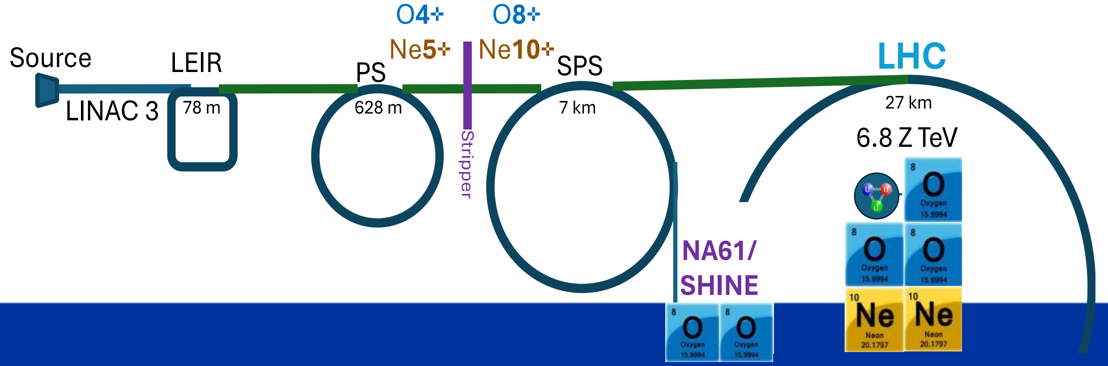
- **Special LHC ion run of a few days in the middle of 2025 run:**
  - Proton-oxygen (pO) 
  - Oxygen-oxygen (OO) 

  8 days (commissioning + physics)

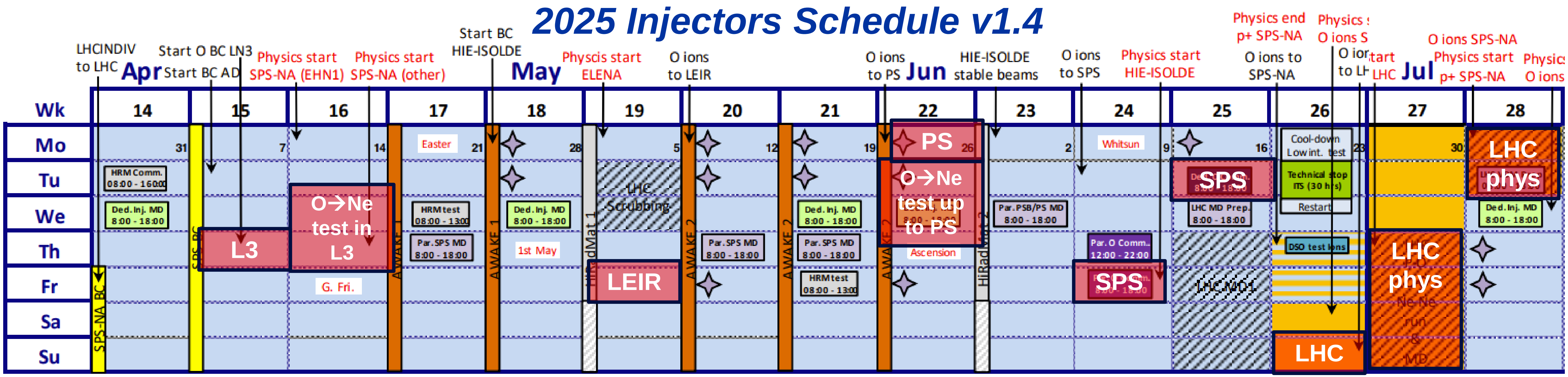
  - Neon-Neon (NeNe) 

  1 day (source switch, commissioning, physics)

- **Challenging and complex run**
  - Commission the full ion injector chain with a new particle type
  - Three non-standard configurations in the LHC
  - Very short period and little time to debug and optimize
  - Dynamic shifts in the schedule requiring quick response to emerging problems.



Timeline



10th April: LINAC 3 beam commissioning started

16th-17th April: First **oxygen/neon swap test** at the **LINAC3 source**

8th May: LEIR beam commissioning started (2 days ahead of schedule)

26th May: PS beam commissioning started

27th-28th May: Second **oxygen/neon swap test** up to **PS** extraction

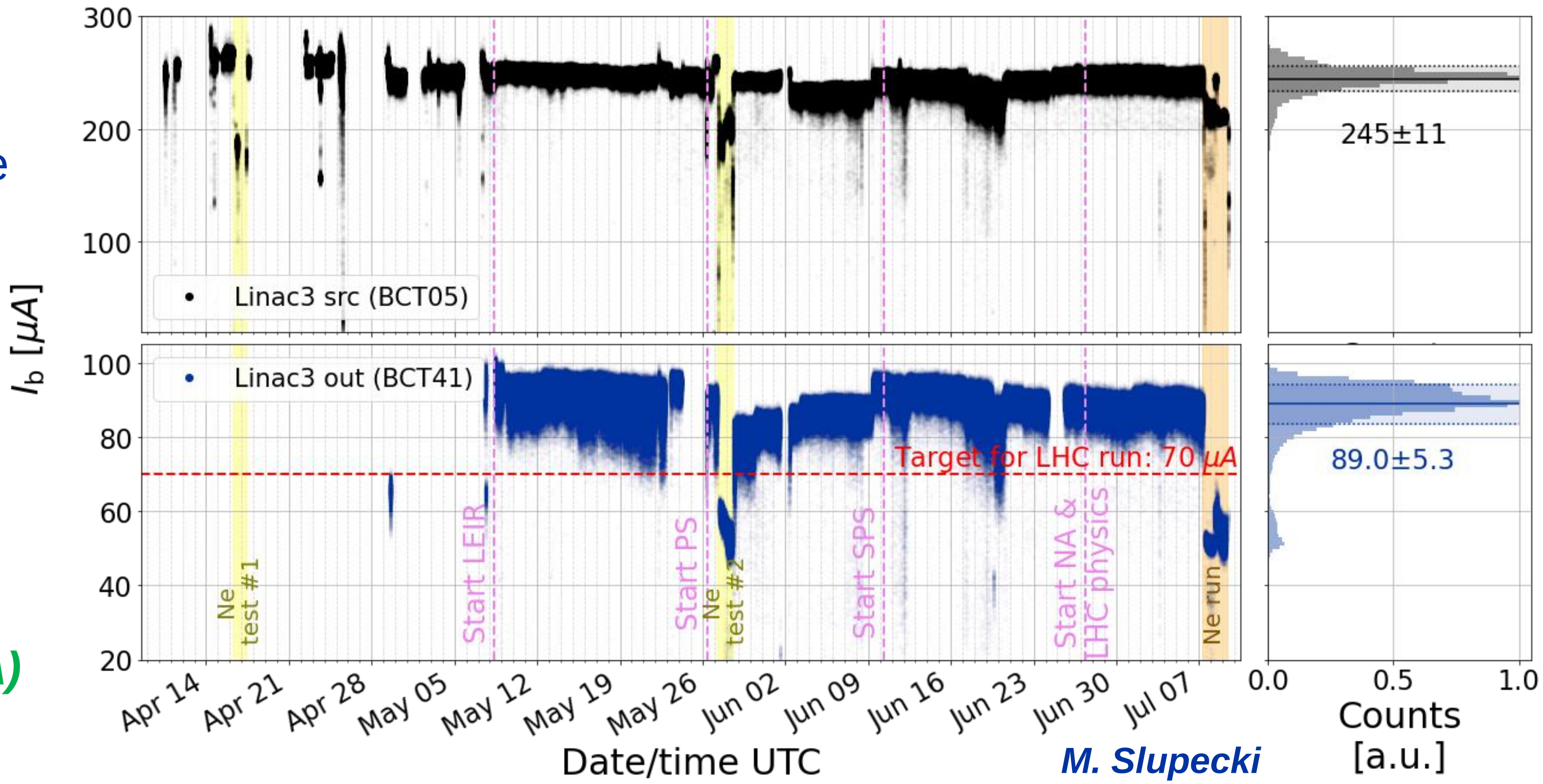
13th, 17th June: SPS beam commissioning started rescheduled due to hardware issues (MKP, magnet replacement, LEIR RF)

29th June: LHC beam commissioning with O started (first commissioning steps done with protons on 28th of June)

1st – 8th July: LHC physics and beam commissioning

Source & Linac3

- **LINAC3 RF phases optimized for better transmission**
  - Slightly larger energy spread of the beam pulse → **no problem in operation**
- **Excellent and very stable intensity from the source and at the end of Linac3**
  - Source: 245 μA
  - Linac3: 89 μA → ***~27% above the target set for the LHC run (70 µA)***



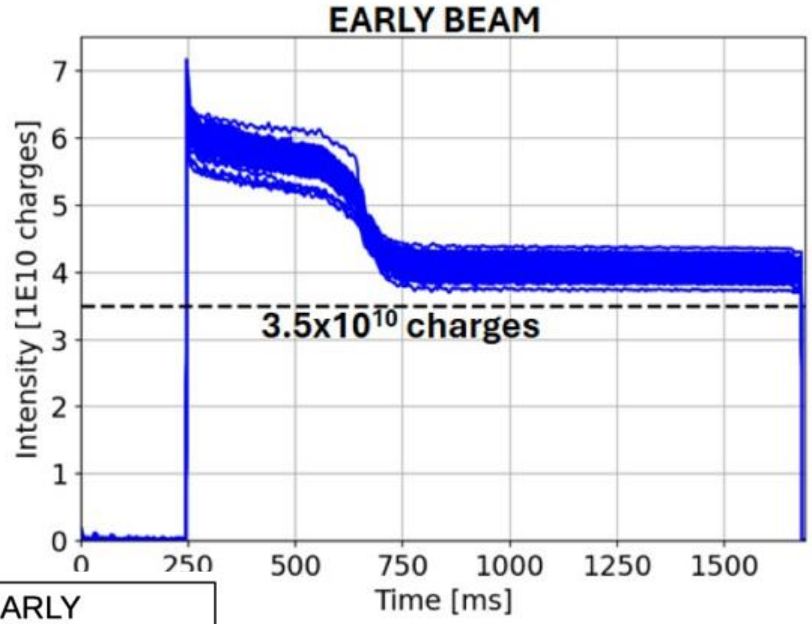
LEIR (1)

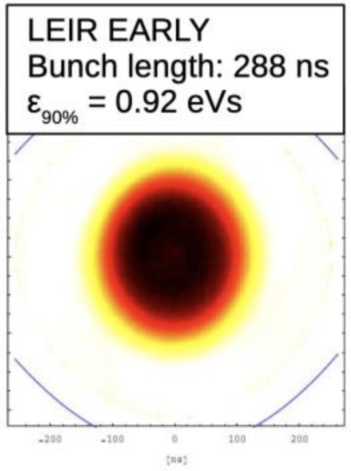
- **LEIR commissioning initially carried out with the EARLY cycle (1 bunch from LEIR)**

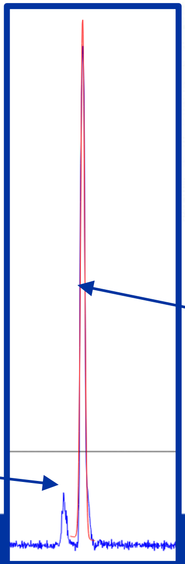
  - **2BP cycle (2.4s)** used for **single bunches in LHC** (in Pb physics)

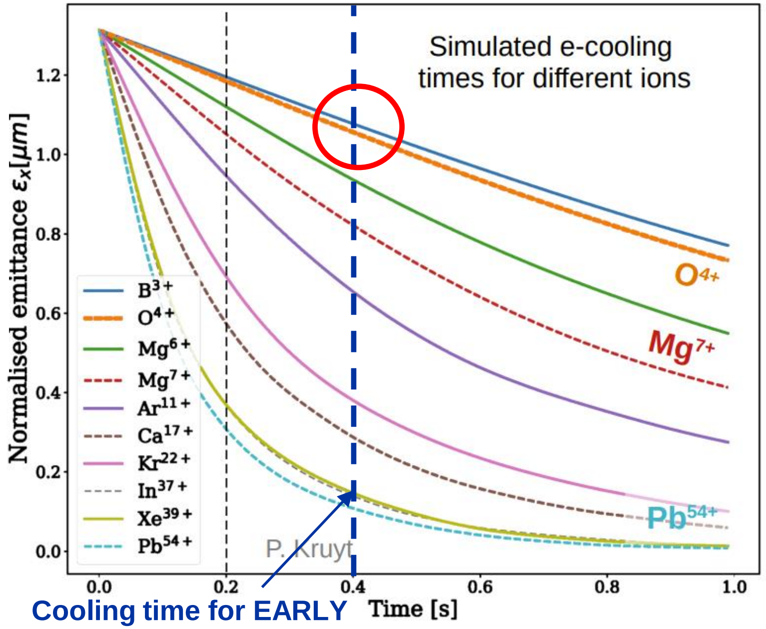
  - Reached **intensities of ~4x10^{10} c** at extraction (target 3.5x10^{10} c)

  - However, **lighter ions** require **longer electron cooling times** (400 ms available in EARLY)
    → **Large emittances & bunch length → more losses in LEIR & PS and creation of satellite bunches**









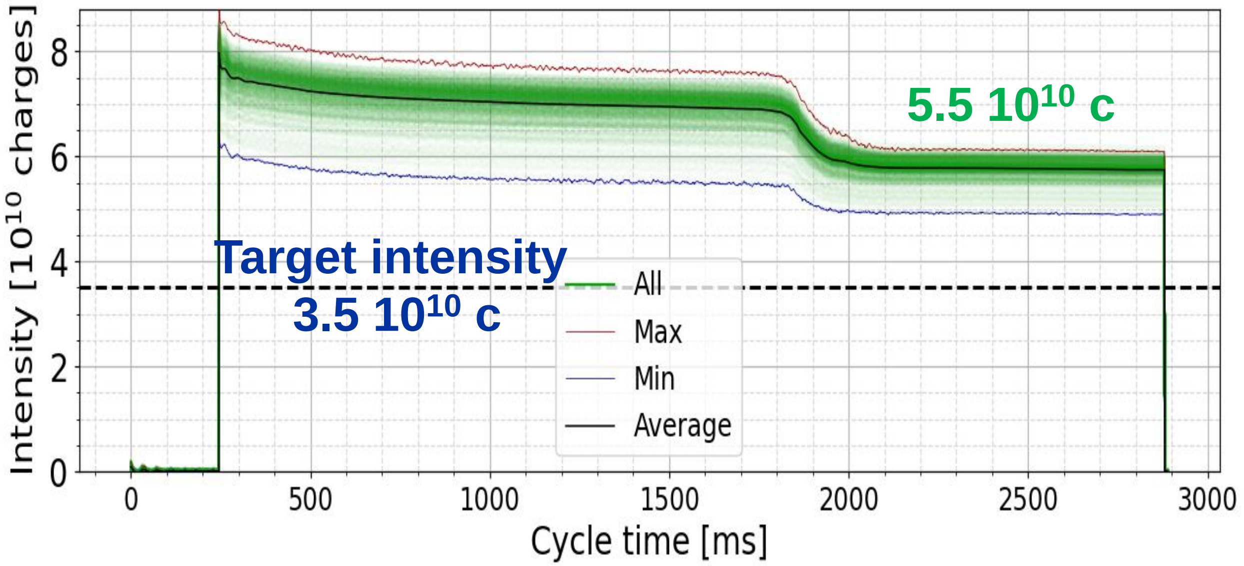
P. Kruyt

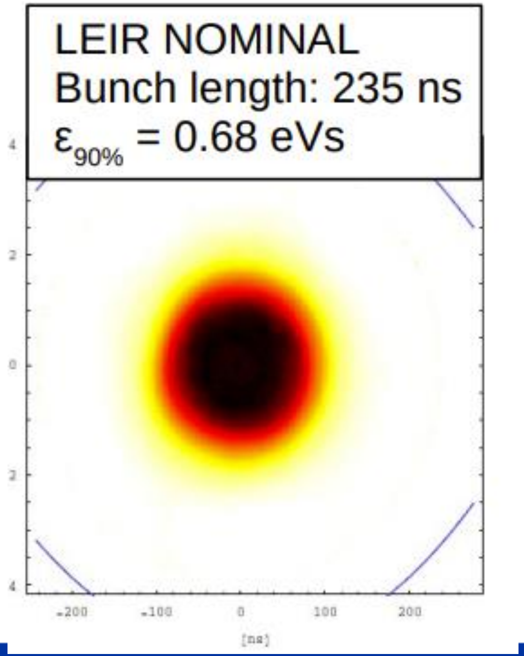
LEIR (2)

- **Mitigation by commissioning the NOMINAL beam (3BP, 3.6s, 1 bunch in LEIR)**

  - Available **cooling time ~1.5s**
    - Better beam parameters at LEIR extraction
      - **intensities of ~5.5x10^{10} c**
      - **Bunch length ~240 ns**
    - Better transmission to PS, **95%** (as in Pb beams)

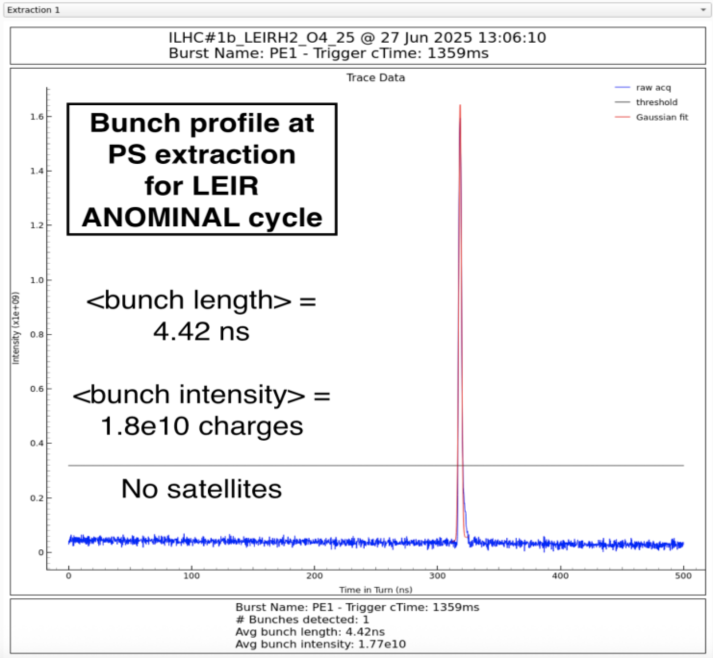
  - However, this **higher intensity beam led to other issues in the downstream machines** (PS, SPS, LHC)
    - **PS** longitudinal instabilities after transition crossing → creation of satellite bunches
    - **SPS** beam life-time due to space-charge
    - **LHC** intensity on the limit between high and low BPM gain and ADT gain



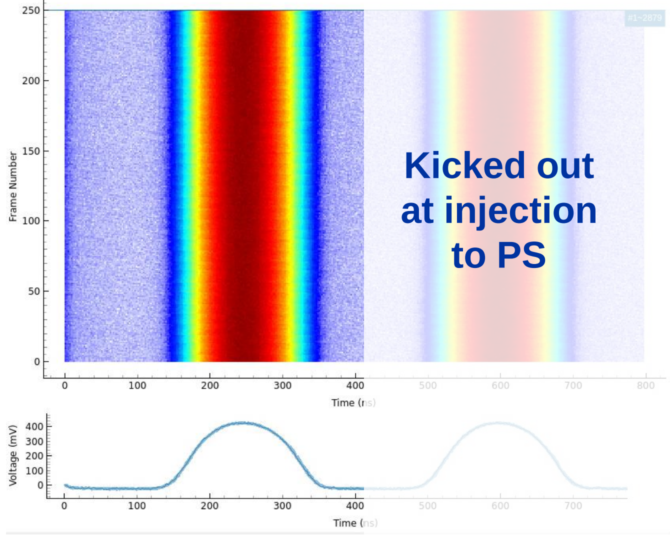


LEIR (3)

- **Mitigation by commissioning the ANOMINAL beam (3BP, 3.6s, 2 bunches in LEIR)**
  - Same **cooling time ~1.5s**
  - Similar **intensity at LEIR extraction** (~5.0x10^{10} c)
  - Smaller longitudinal emittance of the two bunches → **No satellites at PS extraction**
  - **Wrong beam pattern for the LHC** (single bunch needed)
    - kick one bunch out before PS injection**.**
    - Reduced the bunch intensity by half (~2.5x10^{10} c)



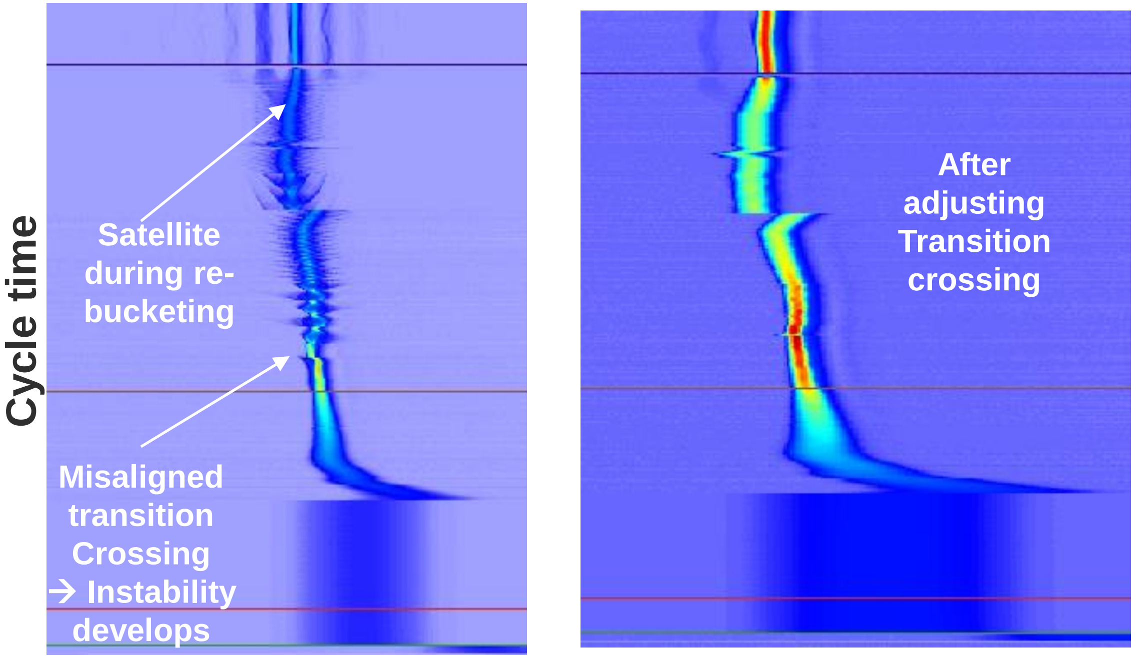
Bunches in ANOMINAL at LEIR extraction



PS

- **Straight forward single-bunch cycle**
  - Initial **issue** with the **large LEIR EARLY** beam
    - **Solved** by going to **NOMINAL/ANOMINAL**
  - **Transition crossing** needed **careful adjustment**
    - **Double single-bunch intensity** (wrt to the 2 Pb-bunches) → **instability** after trans. crossing
    - **Controlled long. emittance blow-up** to mitigate the instability → **satellites created** during re-bucketing (10→80MHz RF)
    - **No-problem with the ANOMINAL beam**
  - **Losses** along the cycle due **to beam-gas interactions**
    - **Increased frequency of sublimation** to improve vacuum levels (every 3h during physics) → **transmission in the PS from 50% to 70%**

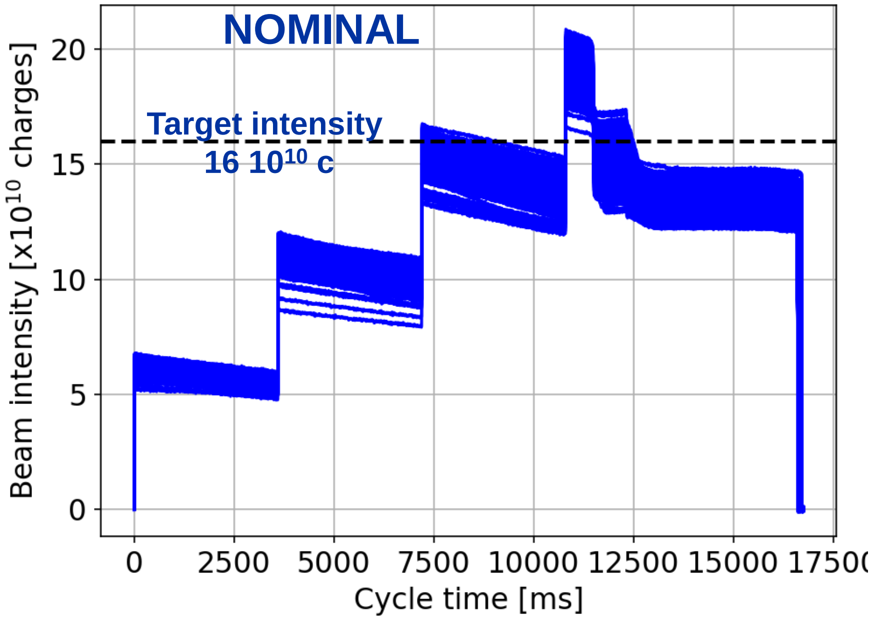
Longitudinal bunch evolution along the PS cycle

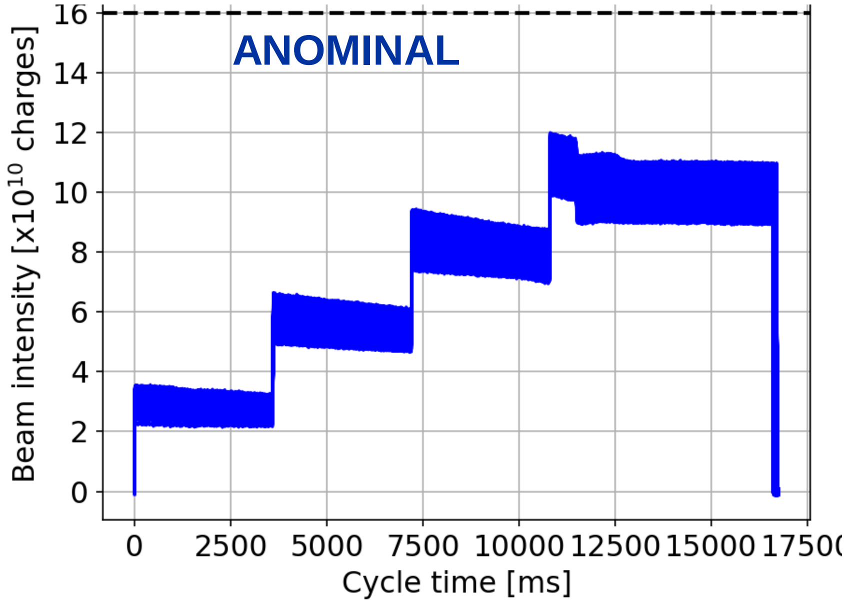


Titanium sublimation pump in the PS

SPS

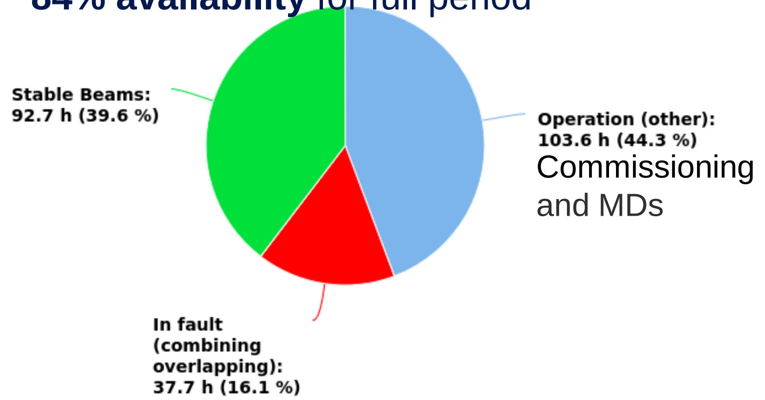
- **SPS beam of 4 single bunches from PS spaced by 1µs**
  - Started with EARLY type of beam (2BP) but **quickly adapted to the NOMINAL (3BP)**
    - **Increased cycle time by 3.6s**
  - Enhanced space charge
    - Better lifetime with the ANOMINAL beam (lower intensity)
    - Small effect of the 50Hz compensation
  - Ejection intensity below initial target, but confirmed to be fine for the LHC
    - Projected luminosity targets reachable within scheduled time





LHC

Time distribution for pO, OO, NeNe combined
84% availability for full period

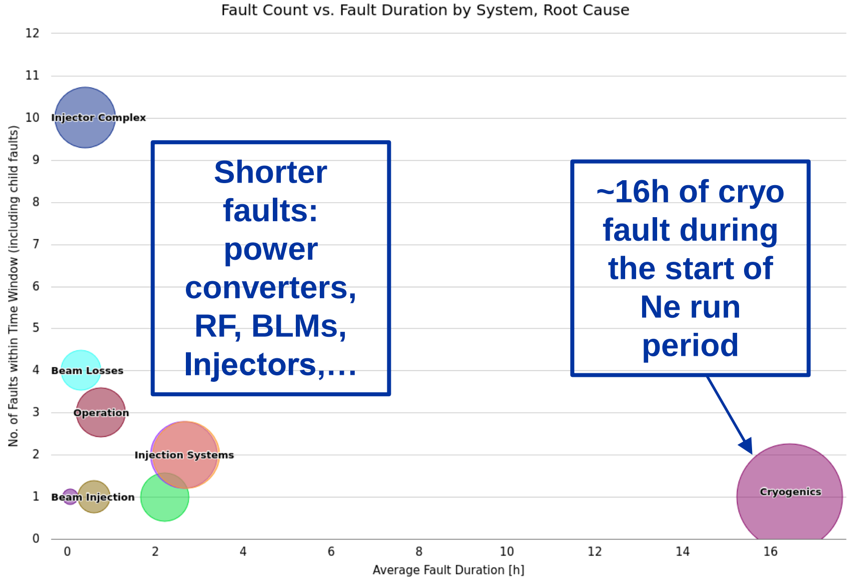


- **Single bunches spaced by 1 μs**
  - Settled on **scenario** with up to **62 bunches and 40 collisions/experiment**
  - (1.0 – 1.5)x10[12] charges/ring - **above setup beam flag → Dedicated validation added → Important to reach the Lumi targets set**

- **Overall smooth commissioning**
  - ~1.5 days for p-O and 1.5 days for O-O
  - Re-use Pb-ion cycle as much as possible
  - Special RF modification/testing needed for p-O run (“cogging”)

- **Excellent availability during the p-O and O-O runs (>90%)**
  - **Very critical for a successful run**

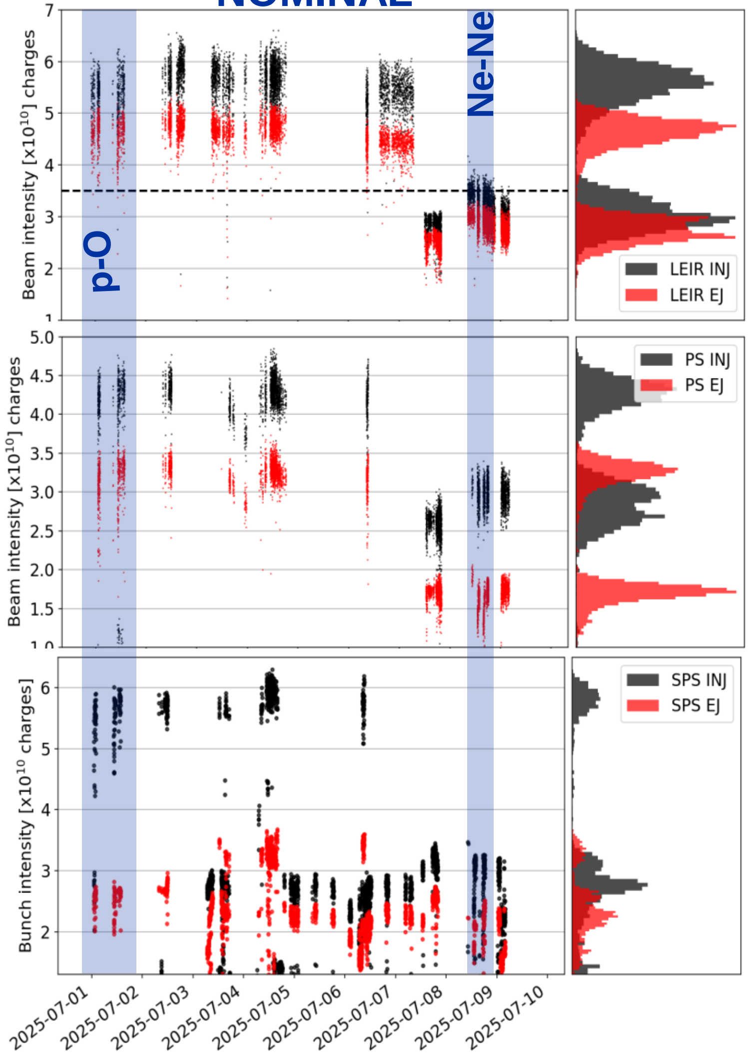
Faults for pO, OO, NeNe combined



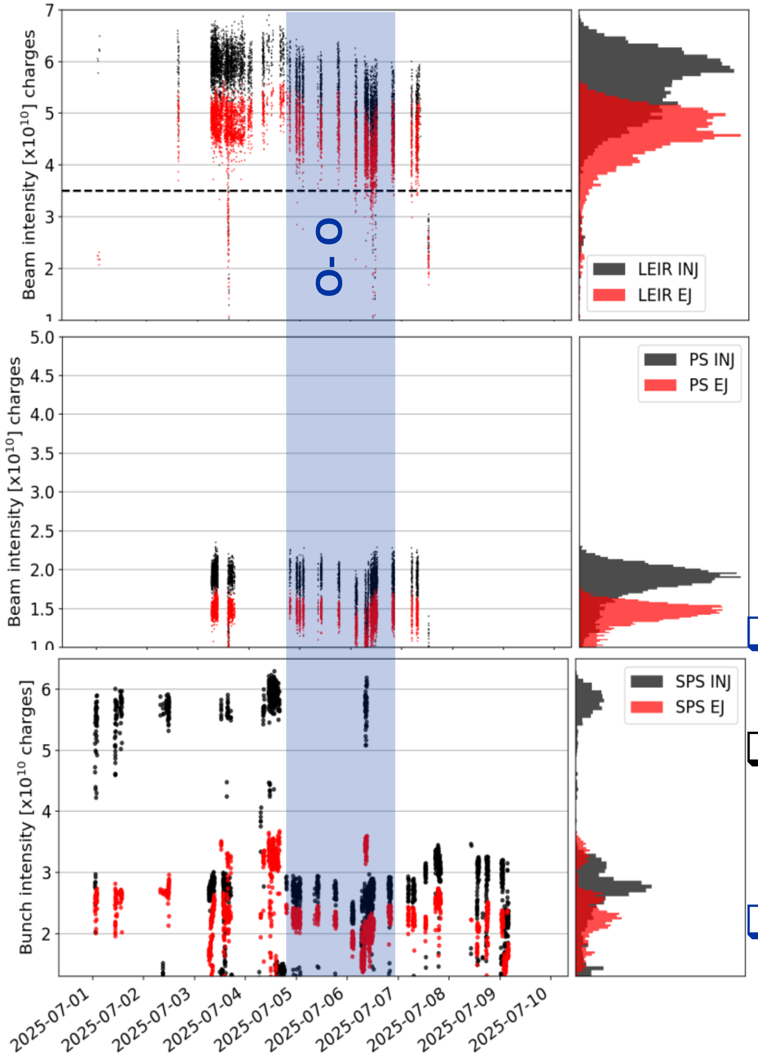
For a complete summary of the LHC O/Ne run see talk of R. Bruce in LMC, 16/07/2025

Beam performance - intensities

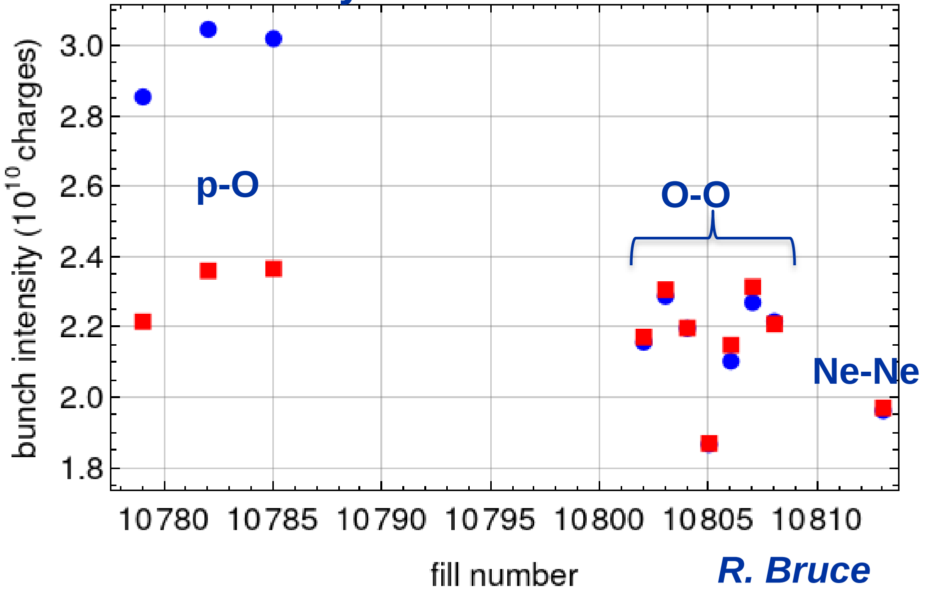
NOMINAL



ANOMINAL



Bunch intensity at the start of STABLE BEAMS



R. Bruce

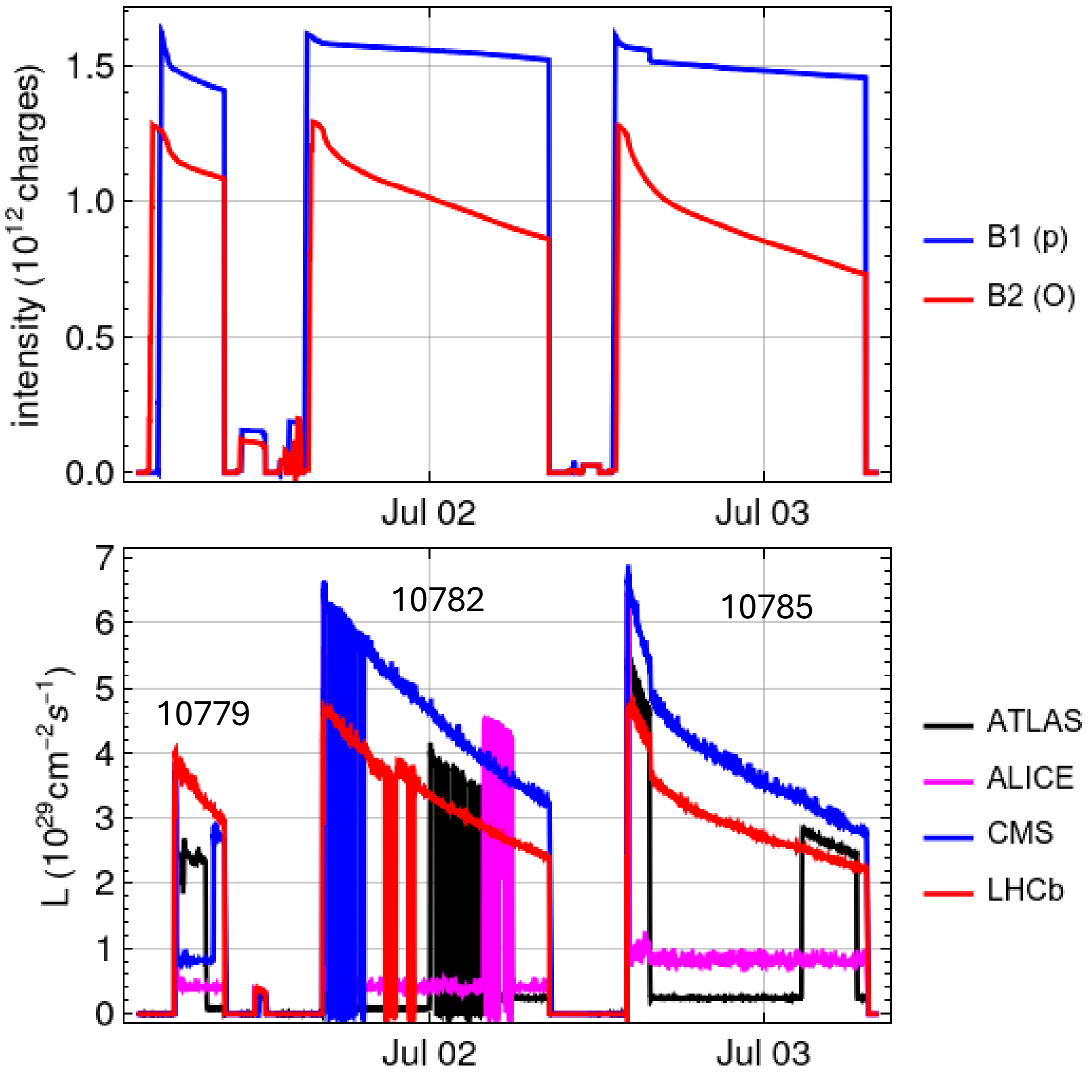
- **Higher intensities** with the **NOMINAL** beam
- Slightly less intensity with **ANOMINAL** but **no satellites**
- **No issue** with the **NOMINAL Neon** beam due to **lower intensity** and **better adjustment** in injectors (LEIR, PS)

R. Bruce

p-O physics

- **NOMINAL beam from injectors** → satellites detected
- **2 long fills; 16-17h stable beams each; 2 days**
  - First short fill interrupted to include LHCb IP offset
  - Instabilities observed – increased chroma and octupoles
- **All luminosity targets reached and exceeded**
  - Bottleneck: LHCf/ATLAS due to levelling at low pileup
  - **Unlevelled experiments exceeded targets by factor 16!**

	Target (nb^{-1})	Delivered (nb^{-1})	Ratio
LHCf/ATLAS	1.5	1.8	**1.2**
ATLAS	--	6.9	**--**
ALICE	5	7.85	**1.6**
CMS	3	48.4	**16**
LHCb	2	33.1	**16.6**

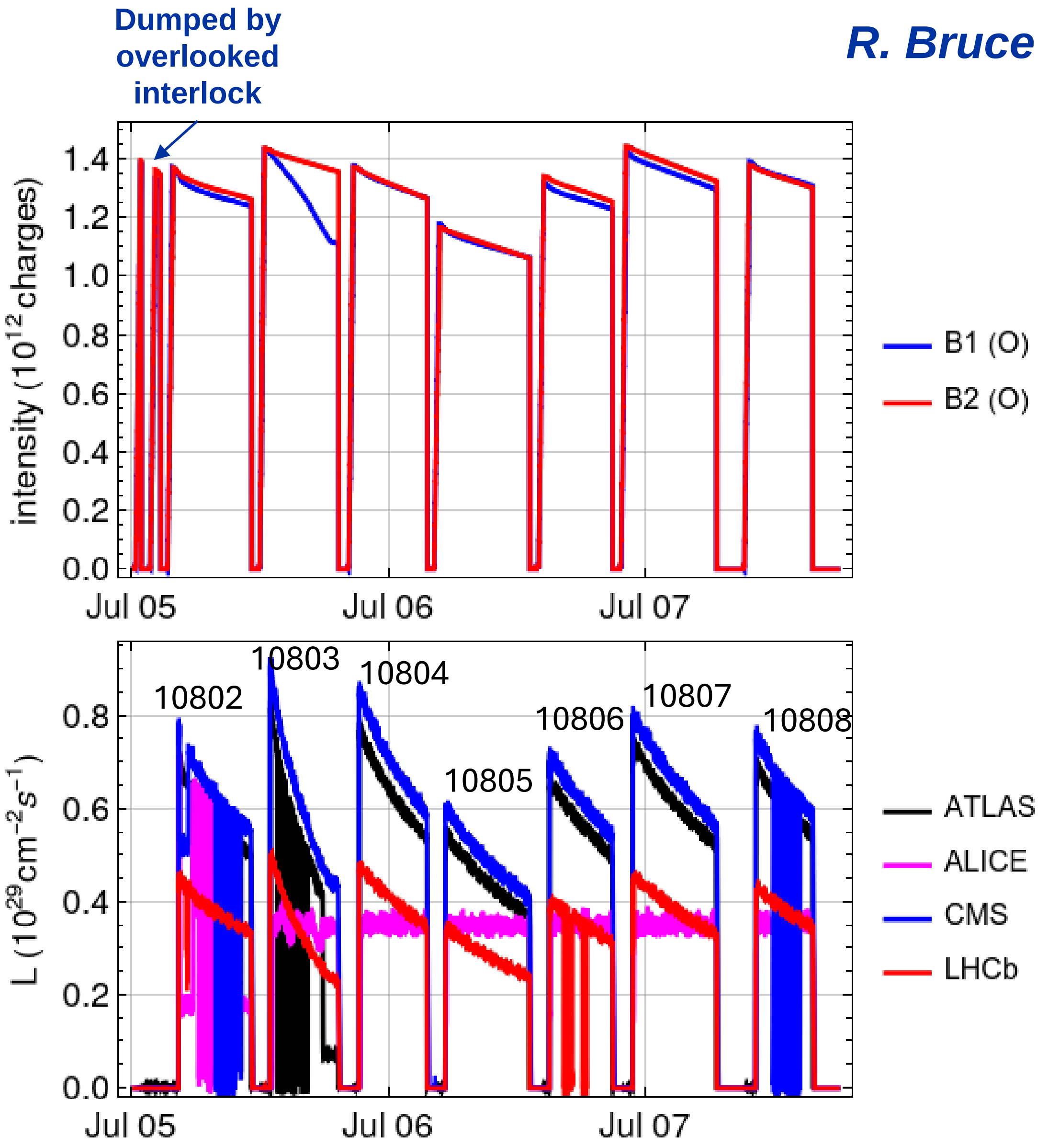


O-O physics

R. Bruce

- **ANOMINAL beam from injectors**
- **Single 6h-fill sufficient to reach targets**
  - could do 7 fills back-to-back, ~2.6 days in total
  - Perfect availability – contingency not needed
  - Fills kept ~6h to minimize transmutation
- **All targets surpassed by factor ~10-12!**

	Target (nb^{-1})	Delivered (nb^{-1})	Ratio
ATLAS	0.8	8.2	**10.3**
ALICE	0.5	5.15	**10.3**
CMS	0.8	9.4	**11.8**
LHCb	0.5	5.75	**11.5**



Neon run

- **2 Neon beam test took place before to validate the (very) short Neon run** (*see talk of M. Slupecki, IPP 20/06/2025*)

- **Test1 (16-17 April):** Lican3 ion source, **Test2 (27-28 May):** up to the PS extraction
  - **Time required** to switch O → Ne
  - **Contamination of Ne beam with O** as a function of time
  - Estimate **Ne beam intensity** and **source stability**
  - Confirm **transparency** of the switch **across the accelerator complex**
    - Use the same settings as in O since the two species have very similar charge-to-mass ratio ($\Delta(Q/M)=6\cdot10^{-5}$)

- **Successful result of the tests led to proceed for the Neon run in the LHC**

- **Smooth and quick switch of species from O → Ne during the run**
  - Good **stability** and **performance of the source** (~220 μA, ~65 μA out of Linac3)
  - **Low contamination of Ne^{5+}** beam with **O^{4+}** (< 0.5%) **after 4h**

R. Bruce

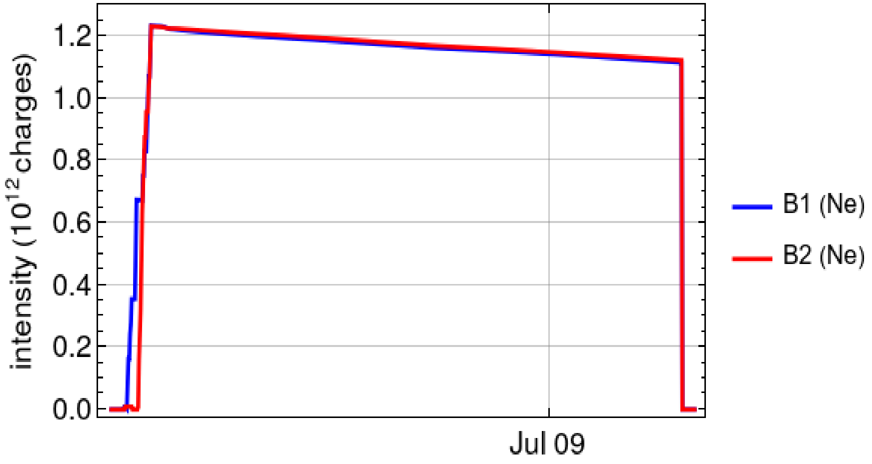
Ne-Ne physics

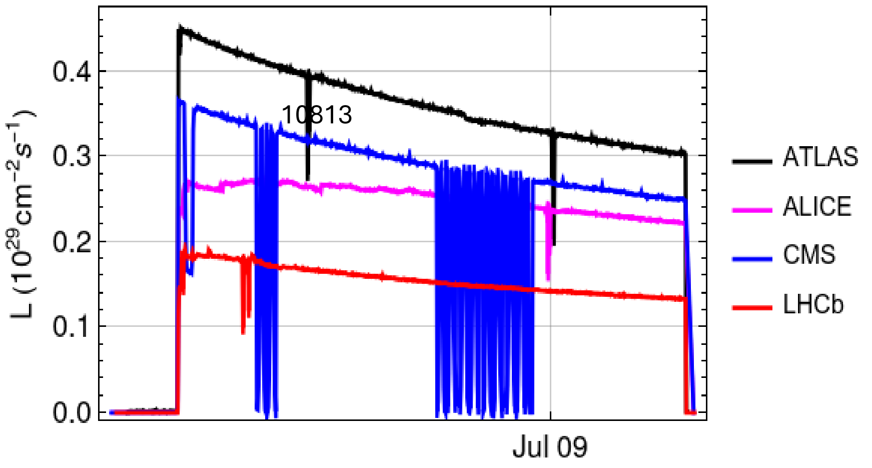
- **NOMINAL beam from injectors**
  - Smaller intensity and no satellites
  - About **double the intensity out of SPS than initially projected**

- **Time for only one physics fill**
  - 10h stable beams – 2h taken from following crystal MD and following access delayed by 2h
  - Request by CMS to extend by 24h not supported by all the other experiments

- **Exceeded targets by large factors thanks to higher intensity**

	Target (nb^{-1})	Delivered (nb^{-1})	Ratio
ATLAS	0.1	1.0	**10**
ALICE	0.1	0.91	**9.1**
CMS	0.1	0.91	**9.1**
LHCb	0.1	0.61	**6.1**





Summary

- **Very challenging run:**
  - Very fast commissioning of the injector chain for 2 different species! (in 3months)
  - 3 special configurations in less than 10 days
  - Never switched particle species so quickly before!

    Main limitation the single ion source

- **Very successful outcome**
  - **All luminosity targets met** and **most were exceeded** by large factors
  - for **p-O** up **to factor ~16**, for **O-O factor 10-11**, for **Ne-Ne factor 6-10**

- **Keys to success**
  - **Good injector performance:** and beam quality **of the injectors including fast adaptability to incoming problems**
  - Accepting **maximum number of single bunches** (beyond setup beam flag), while **keeping commissioning** and **validation short**
  - **Optimization of commissioning activities** in the LHC (early commissioning steps with protons before the actual run)
  - **Exceptional availability** – contingency finally not needed for OO
  - **Dedication, availability and flexibility** of many **experts at injectors and LHC**

Big thanks to everyone for the efforts and a fantastic run!

home.cern

R. Bruce

Key machine parameters

p-O

	Injection	Flat top	Physics
Energy (Z TeV)	0.45	6.8	6.8
β* (m) IP1,2,5,8	11, 10, 11, 10	1.0,1.0,1.0, 1.5	1.0,1.0,1.0, 1.5
Half external crossing (μrad) IP1,2,5,8	170, 170, 170, -170	60, 72, 60, -139	60, 112, 60, -179
Net half crossing (μrad) IP1,2,5,8		60, 0, 60, 0	60, 40, 60, -40

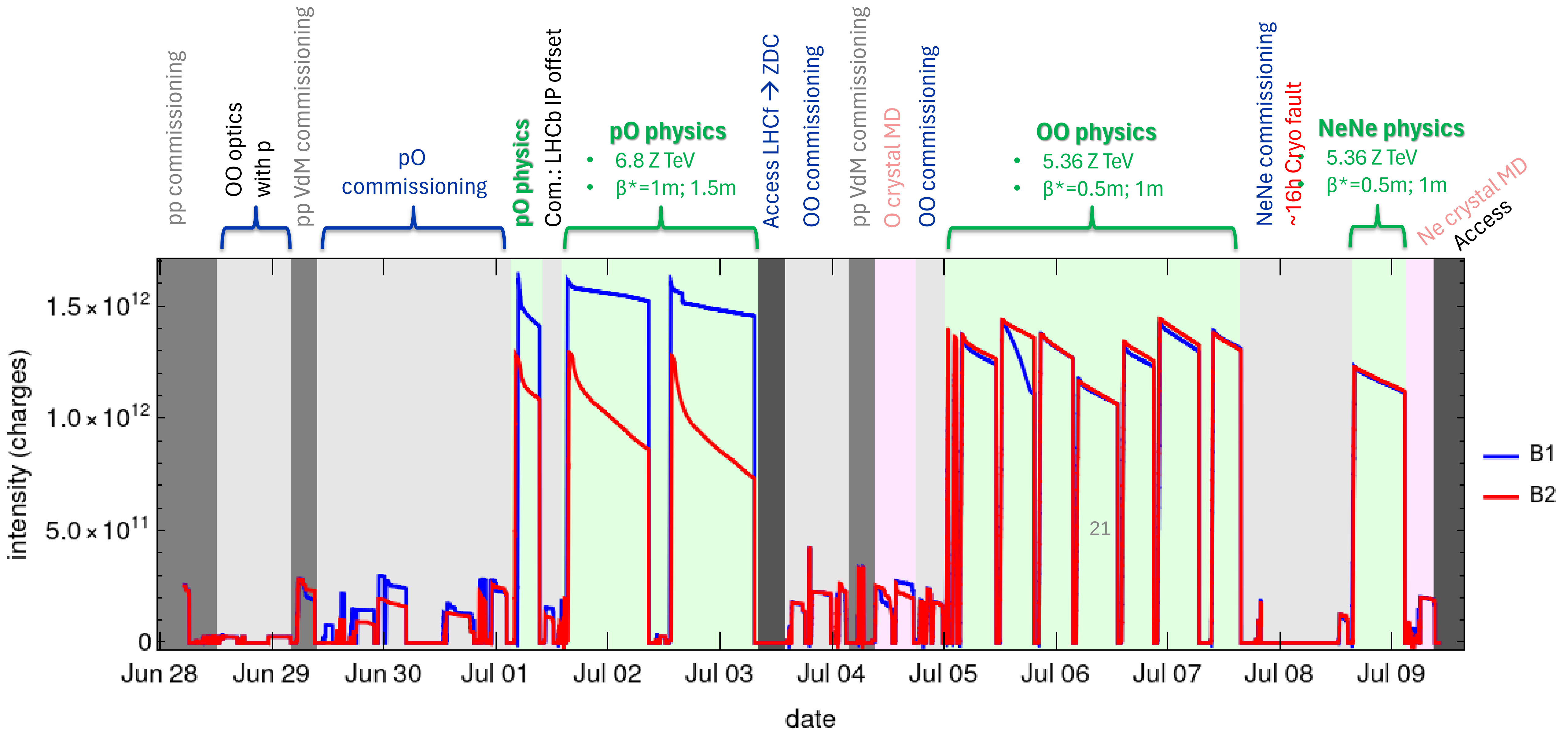
O-O and Ne-Ne

	Injection	Flat top	End of squeeze	Physics
Energy (Z TeV)	0.45	5.36	5.36	5.36
β* (m) IP1,2,5,8	11, 10, 11, 10	1.0,1.0,1.0, 1.5	0.5, 0.5, 0.5, 1.0	0.5, 0.5, 0.5, 1.0
Half external crossing (μrad) IP1,2,5,8	170, 170, 170, -170	100, 91, 100, -176	100, 91, 100, -176	100, 151, 100, -226
Net half crossing (μrad) IP1,2,5,8		100, 0, 100, 0	100, 0, 100, 0	100, 60, 100, -50

Used same collimator settings as in proton run, addition of crystals in OO – see appendix

R. Bruce

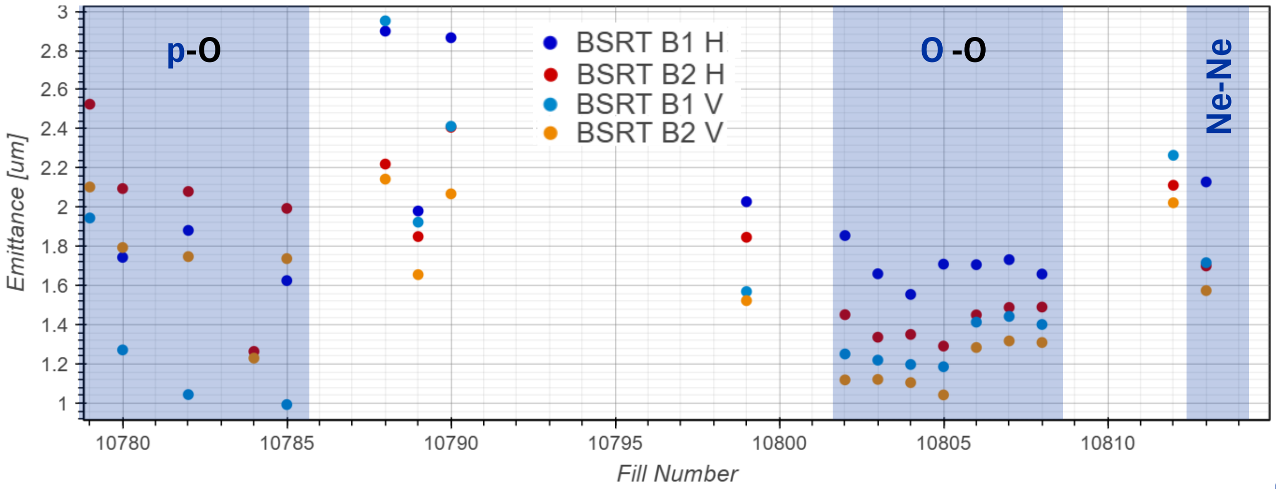
Overview of the run



Beam performance - emittances

- At **SPS ejection:**
  - Working point: (Q_X = 26.31; Q_Y = 26.25)
    $\langle \varepsilon_H \rangle$ = 1.88 +/- 0.08 μm (for Pb: 1.67)
    $\langle \varepsilon_V \rangle$ = 2.24 +/- 0.27 μm (for Pb: 1.95)
  - Emittance blow-up during injection energy due to space-charge
- At **LHC start of SB** emittances measured from the BSRTs

Average bunch emittance at the start of STABLE BEAMS



M. Slupecki

Oxygen contamination in Neon beam