OVERVIEW OF THE LHC PERFORMANCE IN RUN 3*

Reyes Alemany-Fernández

CERN, Geneva, Switzerland

Received 31 March 2025, accepted 31 March 2025, published online 26 June 2025

This contribution provides an overview of the Large Hadron Collider operation during Run 3, highlighting key achievements and challenges encountered. A detailed account of major LHC events and results in 2023 and 2024 is presented, including notable milestones in machine operation, luminosity evolution, and beam performance for protons and ions. Additionally, prospects for LHC operations in 2025 and 2026 are discussed, outlining planned improvements and expected operational scenarios. Finally, the status of the High-Luminosity LHC preparation is reviewed, focusing on key upgrades, infrastructure developments, and current schedule.

DOI:10.5506/APhysPolBSupp.18.5-A5

1. LHC operation in 2023, an eventful year

The LHC operation in 2023 was very eventful. The proton beam commissioning started in April, and the first stable beams were declared on April 21. First collisions with 2374 bunches took place 21 days later. Machine operation continued smoothly for two weeks until May 25, when, during the ramp of 2358 bunches per beam with 1.63×10^{11} protons per bunch, anomalous beam losses led to a beam dump, accompanied by a pressure spike in sector A4L1 that was four orders of magnitude higher than the operational value. X-ray imaging investigations and beam-loss studies led to the conclusion that an annealed or plasticized spring on the vacuum module, figure 1, due to localized temperature increase to more than 500°C, was degrading the pressure in that area and caused slow local beam losses [1]. Four days were needed to repair the affected unit. Since the LHC has 71 identical components to the one that failed, and later inspections revealed eight degraded modules while full replacement was not feasible, the bunch intensity was limited to 1.6×10^{11} protons with bunch length above 1.2 ns to mitigate beam-induced RF heating. The proposed strategy involves a staged replacement of the modules during the two consecutive YETS[1] (2023–2024

---

* Presented at the 31st Cracow Epiphany Conference on the *Recent LHC Results*, Kraków, Poland, 13–17 January, 2025.

[1] Year End Technical Stop.

and 2024–2025), with the bunch intensity limited to 1.6×10^{11} protons per bunch in 2023 and 2024. However, this limitation will be lifted in 2025.

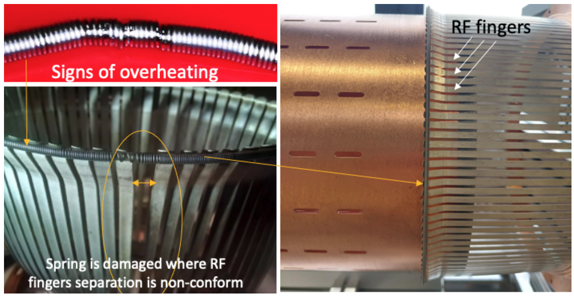

Fig. 1. Annealed or plasticized spring on the 212 mm vacuum module due to localized temperature increase to more than 500°C.

Operations continued smoothly until July 17, when a fallen tree in Canton de Vaud caused a power glitch in the electrical network, leading to a magnet quench in the Inner Triplet to the left of Point 8 (IT-L8). Although the quench generated normal high pressures in the helium lines, it resulted in a small (1 mm^2) hole in an edge-welded, non-conformed bellow, figure 2. This led to significant consequences, including degraded vacuum vessel pressure and necessary bellow repairs.

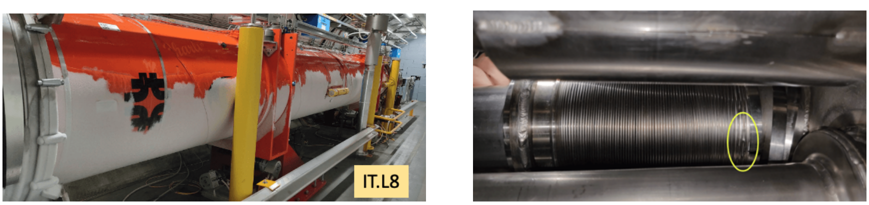

Fig. 2. Left: IT-L8. Right: edge-welded, non-conformed bellow.

Fortunately, an *in-situ* repair with partial cryogenic warm-up was possible, but it caused approximately 50 days of downtime. Similar events remain a risk for the remaining triplets, particularly in Q1–Q2 interconnections. However, inspection without warm-up is not feasible and must be postponed until LS3[2]. Avoiding warm-up during an operational run is crucial, as it poses a significant risk due to the thermal cycling of irradiated triplets. The consolidation of the ITs at Points 2 (IP2) and 8 (IP8) is planned for LS3, while the ITs at Points 1 (IP1) and 5 (IP5) will be replaced as part of the HL-LHC upgrade.

[2] Long Shutdown 3.

The following issue arose on August 31 and September 8, when two vacuum leaks developed in the injection protection devices called TDIS[3] [2], figure 3.

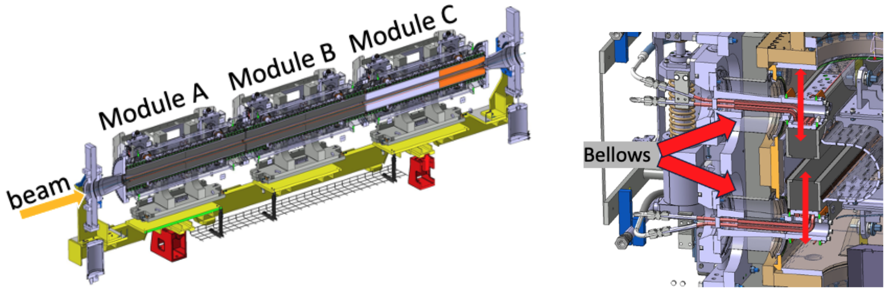

Fig. 3. Left: TDIS. Right: TDIS non-conformed bellows.

TDIS devices are critical machine protection components used during the injection phase. They move into position only for injection and retract for the rest of the cycle (ramp, collisions, *etc.*). These devices are located in front of IP2 for beam 1 and IP8 for beam 2, each consisting of three modules with 12 edge-welded bellows per TDIS. Within one week, two separate leaks appeared on different bellows of the same IP8 TDIS, which were temporarily sealed with varnish, and the corresponding TDIS module was locked in the retracted position.

The root cause was traced to a bellow specification issue, leading to wear-out after 2–3 years of operation. As a consequence, beam intensity per injection had to be severely limited, prompting the early termination of high-intensity proton physics. This led to an extension of the ion run, while the proton–proton reference run was rescheduled to 2024.

The mitigation strategy involved replacing both TDIS during YETS 2023–2024 with non-conforming spares, as their expected lifecycle should cover the operational year. These will then be replaced during YETS 2024–2025 with conforming spare modules based on refurbished TDIS equipped with new bellows.

2. Other limitations in Run 3

2.1. Electron cloud and cryogenics heat load

Another important limitation of the beam intensity that has been present since the start-up of LHC comes from the electron cloud phenomenon and the corresponding cryogenics load. This effect occurs when residual gas ionization or synchrotron radiation produces secondary electron emission from

[3] Target Dump Injection Segment.

beam-induced interactions and causes a build-up of low-energy electrons inside the vacuum chamber, potentially leading to beam instabilities, emittance growth, and heat load on the cryogenic system if the SEY[4] of the beam pipe surface is above 1 [3]. As a consequence, the heat load of the eight LHC sectors is continuously monitored as can be seen in figure 4, where the evolution of the heat load in watts per half cell ($\simeq 53$ m) during 2024 is plotted. The heat load has to be kept below a threshold value which guarantees there is enough cryogenics cooling capacity during routine operation. Around 10% of heat load reduction happened between April and September 2024, and afterwards stayed constant. The additional 10% scrubbing leaves room to increase the number of bunches and bunch intensity in 2025 to, for example, 2400 bunches per beam with 1.8×10^{11} protons per bunch with trains of four or five times 36 bunches per injection.

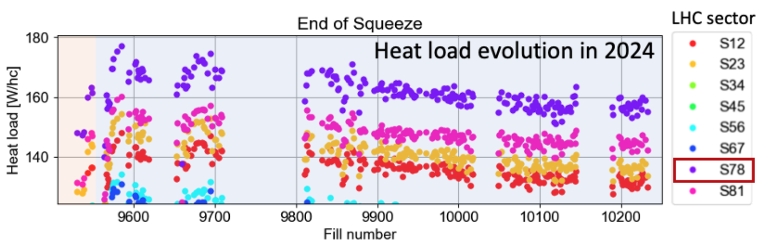

Fig. 4. Heat load evolution in watts per half cell ($\simeq 53$ m) during 2024.

2.2. Ensuring the longevity of the IT until LS3

The Inner Triplets (ITs) are the first magnets downstream of the interaction points, capturing most of the collision debris, primarily pions. The resulting high-radiation levels reduce the magnets' lifetime, requiring their replacement before LS3 if no countermeasure is applied. To address this, a mitigation strategy was implemented by reversing the IT polarity from the nominal Focusing–Defocusing–Focusing (F–D–F) configuration to a Reverse Polarity (RP) Defocusing–Focusing–Defocusing (D–F–D) scheme [4]. This strategy was applied to the IP1 IT in 2024. As shown in figure 5, which plots the peak dose distribution as a function of the distance from the IP, the nominal polarity concentrates the peak dose in the Q2A magnet with losses occurring in the vertical plane. In contrast, with RP, losses at this location are significantly reduced and redirected to the horizontal plane.

In 2025, a similar strategy will be applied to the IP5 IT, while the IP1 IT will be powered back to the nominal polarity. In this case, the losses in Q2B of IP5 IT will be reduced and changed from the horizontal plane to the bottom-vertical plane.

[4] Secondary Electron Yield.

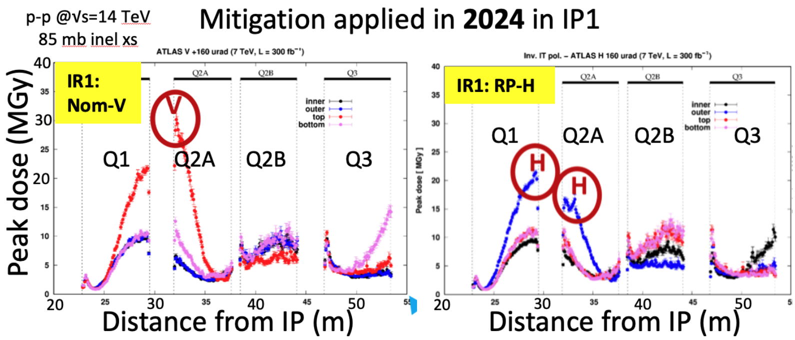

Fig. 5. Peak dose distribution in Mega Grays as a function of the distance from the IP. Left: normal IT polarity (F–D–F), where the maximum dose occurs in Q2A in the vertical plane. Right: reverse polarity (D–F–D), where the dose is significantly reduced and redistributed in the horizontal plane.

3. LHC performance review in 2023 and 2024

Though 2023 was a very rocky year for proton [5] and ion [6] operation, during the proton period, the best-recorded availability was 76%, and 52% of the time the beams were delivering collisions. Unfortunately, many long-term faults, as explained in the previous section, prevented the delivery of the target integrated luminosity of 75 fb^{-1} per experiment. However, 2024 led to the highest production rate ever, reaching up to 1.5 fb^{-1} in 24 h, with a peak luminosity of approximately $\simeq 2.1\times10^{34}$ $\text{cm}^{-2}\text{s}^{-1}$, constrained by the IT cryogenic cooling capacity. Figure 6 shows the integrated proton–proton luminosity from Run 1 to Run 3.

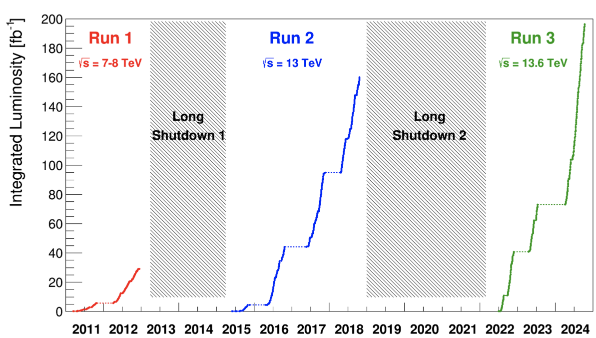

Fig. 6. Integrated proton–proton luminosity from Run 1 to Run 3.

In 2023, the ion run [6] relied on several new concepts all successfully used in operation which are listed as follows:

— Slip-stacked 50 ns bunch separation beams from injectors to provide a higher number of bunches to LHC;

— Crystal collimation to handle higher intensity without quenches;

— TCLD[5] betatron collimators (HL-LHC equipment) and BFPP[6] bump in IP2 to allow for full luminosity for ALICE;

— BFPP bump in IP8 to allow for higher LHCb luminosity.

Additionally, several problems were encountered in 2023, all mitigated or fixed before the 2024 run started. The most important ones were the background issues in the ALICE experiment, the high beam losses in the ramp and the beam losses from 10 Hz orbit oscillations, and the single-event upsets on the quench protection system.

Thanks to the mitigation measures put in place for the 2024 ion run, the luminosity production met the targets. ALICE, ATLAS, and CMS got an average of 1.9 nb^{-1} per experiment. LHCb doubled the 2023 production in half of the time. The excellent injectors' performance allowed for higher bunch intensities and higher transmission efficiencies than the target defined by LHC Injectors Upgrade project. Figure 7 shows the integrated luminosity in 2023 and 2024. The experiments' expectations for the full Run 3 are 5.35 nb^{-1} in ATLAS/CMS/ALICE and 1 nb^{-1} in LHCb, though a request for a higher target exists.

Though the HL-LHC era for protons will start in Run 4, the HL-LHC era for ions started already in Run 3.

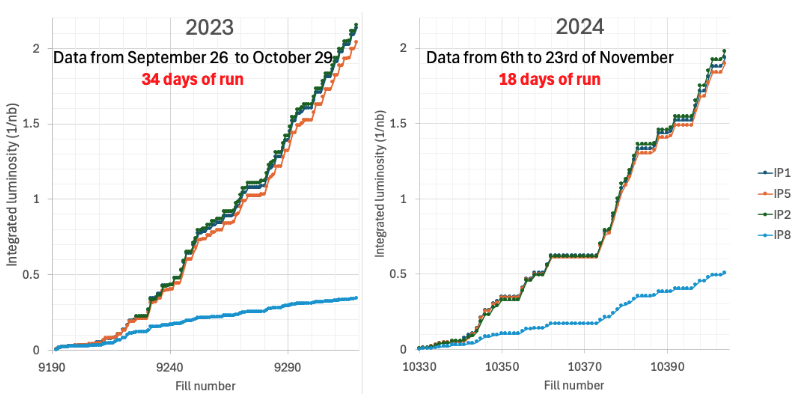

Fig. 7. Integrated ion–ion luminosity in 2023 and 2024. The amount of integrated luminosity is more or less the same for both years, however, in 2024, it was delivered in half of the time, and it doubled in LHCb.

[5] Target Collimator Long Dispersion suppressor.
[6] Bound-Free Pair Production.

4. 2025 and 2026 schedules

On September 18, 2024, the Research Board approved an update to the Run 3/LS3/Run 4 schedule. The YETS 2025–2026 will last 11 weeks and the LHC will operate until June 2026, concluding with a heavy-ion run. The official end of the LHC Run 3 is set for June 29, 2026, while SPS North Area physics will continue for an additional month.

Additionally, the 2025 schedule is officially approved with 138 days of proton physics, 2 days of luminosity calibration (Vdm), and 25 days of lead run at the end of 2025. There will not be a proton–proton reference run, since all the statistics was successfully accumulated in 2024. The 2025 run will benefit, for the very first time, from an LHC pilot run with oxygen–oxygen and proton–oxygen collisions the first week of July.

The 2026 schedule is not yet approved, but tentatively, it will have 66 days of proton physics, 2 days of Vdm, 25 days of Pb run in June (PbPb or pPb), and no proton–proton reference run.

5. HL-LHC preparation

The High-Luminosity era [7, 8] for protons will start in Run 4, aiming at delivering 2.3×10^{11} protons per bunch, 2.1 μm rad normalized transverse emittance, 25 ns bunch spacing, and a β^* of 0.15 m in ATLAS and CMS ($\beta^* = 0.3$ m at the current LHC). With the crab cavities, the virtual peak luminosity will be 1.7×10^{35} cm^{-2}s^{-1}, however, the luminosity will be levelled to 5×10^{34} cm^{-2}s^{-1} with a pile-up of 131.

5.1. New superconducting magnets with Nb_3Sn

To achieve a β^* of 0.15 m, high-gradient magnets are required, providing both stronger focusing and a larger aperture [7, 9–11]. The latter is essential because the beam size at the IT locations will increase significantly, as the expected β will exceed 10 km. The well-established NbTi technology used in the LHC cannot meet the required performance, and requires the development of a new superconducting technology based on Nb_3Sn.

Significant progress has been made across all key technologies, with magnet production well underway at both CERN and in the US. The Inner Triplet String test bed is taking shape, with infrastructure for testing — known as the Inner Triplet String facility — being placed and magnet installation in progress. The first magnets, Q2A and D1, were in place and aligned in November 2024. The IT String will provide the first complete experience of operating the HL-LHC Inner Triplets with an operational current of 16.5 kA, and an ultimate current of 17.5 kA.

5.2. MgB_2 superconducting link

The MgB_2 superconducting link for HL-LHC [7, 12, 13] is designed to transmit high currents with minimal resistive losses over long distances, enabling the relocation of the power converters away from radiation-sensitive areas. This enhances machine availability, reduces radiation-induced failures, and simplifies maintenance, while ensuring efficient power transmission to the superconducting magnets in the upgraded interaction regions. The superconducting link consists of a flexible, double-wall, corrugated cryostat containing 19 MgB_2 superconducting cables, twisted together into a compact bundle, as shown in figure 8. It can carry a total DC current of approximately 120 kA at 20 K. The first cold powering system for the HL-LHC triplets has been successfully validated, meeting all cryogenic, electrical, and mechanical design parameters. Today, the system is in an advanced phase of series production.

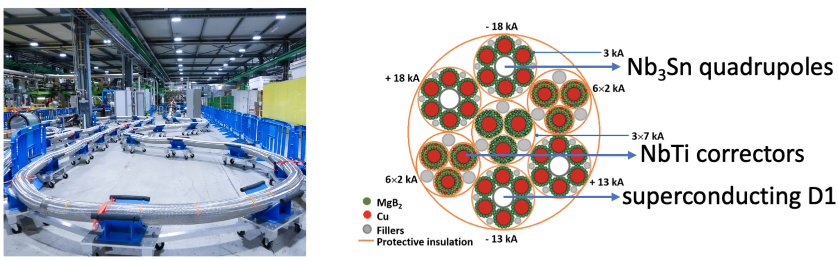

Fig. 8. Left: MgB_2 superconducting link. Right: schematic view of the 19 MgB_2 superconducting cables, twisted together into a compact bundle.

5.3. Crab cavities

The bigger the beam size at the IT, the larger the beam–beam separation of the parasitic encounters has to be to avoid the harmful effects of the beam–beam interaction. This requires a larger crossing angle, $\phi = 590$ μrad in figure 9 (left), than the one currently used at the LHC $\phi = 285$ μrad. However, the bigger the crossing angle the smaller is the luminosity, due to the so-called geometrical reduction factor. For example, at the LHC, this factor reduces the luminosity by 15%, at the HL-LHC, the luminosity will be reduced by 70%. If this effect is not counteracted, the HL-LHC will not reach the luminosity target. This is the reason why a new RF cavity technology called crab cavities is under development [7, 14]. The crab cavities will rotate the bunches before they arrive at the interaction point to put them horizontally and ensure they collide fully head-on, as illustrated in figure 9 (centre).

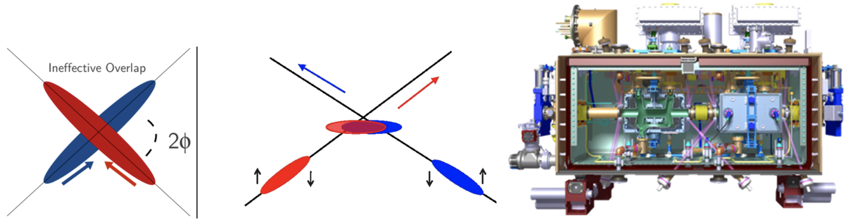

Fig. 9. Left: bunch crossing at the LHC. Centre: bunch crossing in HL-LHC called crab crossing. Right: DQW cryomodule.

Two crab cavity technologies are in development: the Double Quarter Wave (DQW) in Europe and the Radio Frequency Dipole (RFD) in the US and Canada. Figure 9 (right) shows the DQW system, set for installation around IP5 for vertical crabbing. Despite delays in RFD cryomodules, used for IP1 horizontal crabbing, a mitigation strategy aims to keep LS3 installation on schedule.

5.4. HL-LHC schedule

Figure 10 shows the current HL-LHC schedule starting from the design study back in Run 1. Installation of the remaining HL-LHC equipment will take place during LS3. As indicated in the schedule, all the HL-LHC underground and surface buildings in IP1 and IP5 have been finished. Beam commissioning will start in 2030 and the operation of the upgraded machine and detectors will continue until 2041. At the end of HL-LHC, the integrated luminosity should be 3000 fb^{-1} with the nominal parameters, and 4000 fb^{-1} with the ultimate parameters.

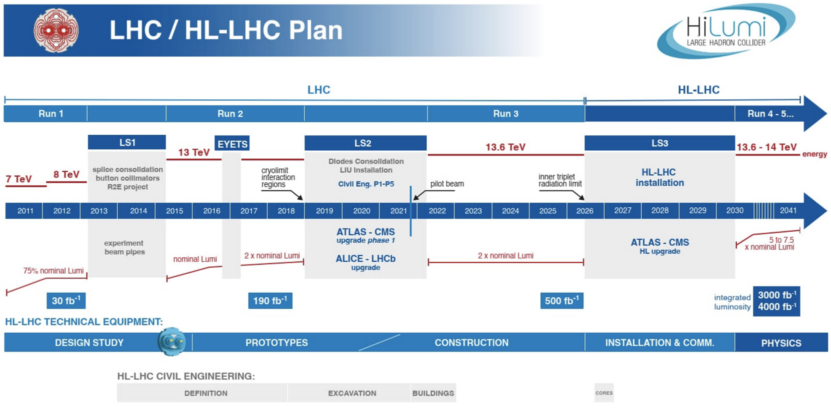

Fig. 10. HL-LHC schedule.

REFERENCES

[1] P. Krkotic *et al.*, in: «Proceedings of the 15th International Particle Accelerator Conference (IPAC 2024), Nashville, USA», *JACoW Publishing*, Geneva, Switzerland, 2024, pp. 947–950.

[2] D. Carbajo Pérez, in: «Proceedings of the 12th International Particle Accelerator Conference (IPAC 2021), Campinas, Brazil», *JACoW Publishing*, Geneva, Switzerland, 2021, pp. 3548–3551.

[3] L. Mether *et al.*, in: «Proceedings of the 14th International Particle Accelerator Conference (IPAC 2023), Venice, Italy», *JACoW Publishing*, Geneva, Switzerland, 2023, pp. 2850–2853.

[4] G. Arduini *et al.*, «LHC Triplet Task Force Report», CERN-ATS Report-2023-0004.

[5] A. Calia *et al.*, in: «Proceedings of the 15th International Particle Accelerator Conference (IPAC 2024), Nashville, USA», *JACoW Publishing*, Geneva, Switzerland, 2024, pp. 87–90.

[6] N. Triantafyllou, R. Bruce, S. Redaelli, in: «Proceedings of the 15th International Particle Accelerator Conference (IPAC 2024), Nashville, USA», *JACoW Publishing*, Geneva, Switzerland, 2024, pp. 955–958.

[7] I. Béjar Alonso *et al.*, «High-Luminosity Large Hadron Collider (HL-LHC): Technical Design Report», CERN Yellow Reports: Monographs, Vol. 10, *CERN*, Geneva, Switzerland 2020.

[8] O. Brüning, in: «Proceedings of the 14th International Particle Accelerator Conference (IPAC 2023), Venice, Italy», *JACoW Publishing*, Geneva, Switzerland, 2023, pp. 132-1327.

[9] E. Todesco *et al.*, *IEEE Trans. Appl. Supercond.* **28**, 4008809 (2018).

[10] S.I. Bermudez *et al.*, *IEEE Trans. Appl. Supercond.* **31**, 4002007 (2021).

[11] M. Baldini *et al.*, in: «Proceedings of the 15th International Particle Accelerator Conference (IPAC 2024), Nashville, USA», *JACoW Publishing*, Geneva, Switzerland, 2024, pp. 2943–2947.

[12] M.B. Bajko *et al.*, in: «Proceedings of the 12th International Particle Accelerator Conference (IPAC 2021), Campinas, Brazil», *JACoW Publishing*, Geneva, Switzerland, 2021. pp. 3592–3595.

[13] M. Bajko *et al.*, *IEEE Trans. Appl. Supercond.* **35**, 9500205 (2025).

[14] R. Calaga *et al.*, *Phys. Rev. Accel. Beams* **24**, 062001 (2021).