

# FIRST PARTIALLY STRIPPED IONS IN THE LHC ( $^{208}\text{Pb}^{81+}$ )

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## Abstract

The Gamma Factory initiative proposes to use partially stripped ion (PSI) beams as drivers of a new type of high intensity photon source. As part of the ongoing Physics Beyond Collider studies, initial beam tests with PSI beams have been executed at CERN. On 25 July 2018 lead ions with one remaining electron ( $^{208}\text{Pb}^{81+}$ ) were injected and accelerated in the LHC for the first time. After establishing the injection and circulation of a few  $^{208}\text{Pb}^{81+}$  bunches, beam lifetimes of about 50 hours could be established at 6.5 TeV proton equivalent energy. This paper describes the setup of the beam tests and observations made.

## THE GAMMA FACTORY PROPOSAL

The principal objective of the Gamma Factory proposal [1, 2] is to create and store relativistic atomic beams and to exploit their atomic degrees of freedom. Atomic beams are composed of Partially Stripped Ions (PSI) from which all but a few electrons have been stripped on the way between an ion source and the final storage ring, which at CERN is the Super Proton Synchrotron (SPS) or the Large Hadron Collider (LHC). These synchrotrons store beams at very high energies over a large range of the Lorentz factor:  $30 < \gamma_L < 3000$ , at high intensities:  $10^8 < N_b < 10^9$  ions/bunch, and at high bunch repetition rates of up to 20 MHz.

When a laser, tuned to the atomic transition frequencies of the PSI beam, interacts with the circulating particles, resonant absorption of laser photons is induced. The subsequent spontaneous atomic-transition emits secondary photons boosted by a factor of up to  $4\gamma_L^2$  with respect to the initial laser-photon frequency. The resonant absorption cross section is in the giga-barn range, and the high  $\gamma_L$  factors available in the SPS and the LHC open the possibility of exciting atomic transitions even of high-Z ions with fairly conventional laser systems.

PSI beams stored at LHC energies could produce photons in the energy range of  $1 \leq E_\gamma \leq 400$  MeV, which is above the muon-pair production threshold. CERN is the only place in the world where such a light source could be realised.

## GOALS OF LHC TEST BEAM

Studies with PSI beams in the SPS started in 2017 with partially stripped xenon ( $^{129}\text{Xe}^{39+}$ ) beams [3] and continued in 2018 with the well-known lead-208 isotope with one ( $^{208}\text{Pb}^{81+}$ ) or two ( $^{208}\text{Pb}^{80+}$ ) remaining electrons [4]. Based on the observation of a better beam lifetime for  $^{208}\text{Pb}^{81+}$  this charge state was selected for injection into the LHC. In the

scope of a machine development experiment, 10 hours of beam time were granted for the first operation of PSI beams in the LHC on 25 July 2018. The goals of this initial test were:

- Injection of the new particle type.
- Establish stable circulation of a few bunches.
- Acceleration and storage at 6.5  $Q$  TeV<sup>1</sup>.
- Study of beam lifetime and evolution at injection and top energy.
- Beam loss characterisation.

All goals were successfully achieved and an analysis of the measurements is presented in the following chapters. Storing partially stripped ions in the LHC at 6.5  $Q$  TeV fulfilled the first of five milestones of the Gamma Factory proposal [5].

## CONFIGURATION

It had already been proven with the p-Pb pilot run in 2012 [6, 7] and the Xe-Xe run in 2017 [8] that short LHC runs with new species (lasting only a few hours) can have significant physics output. Given the limited time, it is crucial to keep the setup time short and the accelerator configuration simple. Therefore, similarly to the Xe-Xe and p-Pb pilot runs, the nominal LHC cycle was used just until top energy (no squeeze, no collisions) for the PSI operation. As a consequence of the change in particle type, the transfer lines had to be steered, the injection kicker timings adjusted, the RF systems of the SPS and the LHC were re-synchronised and the RF frequency in the LHC tuned to the value for  $^{208}\text{Pb}^{81+}$  ions<sup>2</sup>. These are the standard tasks when moving from proton to heavy-ion operation.

The beam provided by the injectors for this experiment consisted of two bunches spaced by 200 ns per SPS injection in the LHC. Each bunch featured an intensity of up to  $1.1 \times 10^{10}$  charges, equivalent to  $1.3 \times 10^8$  ions. Because of machine protection requirements the total circulating beam intensity had to stay below  $3 \times 10^{11}$  charges throughout the experiment, which allowed a maximum of 24 circulating bunches.

## EXPERIMENT EVOLUTION

Only about 2 h after the official start of the experiment the LHC circulated its first partially stripped ions. While

<sup>1</sup>  $Q = Z - 1$  in this case is the charge number of the ion.

<sup>2</sup> The RF frequency required for  $^{208}\text{Pb}^{81+}$  is lower than for fully stripped  $^{208}\text{Pb}^{82+}$  and was therefore the lowest used in the LHC so far.

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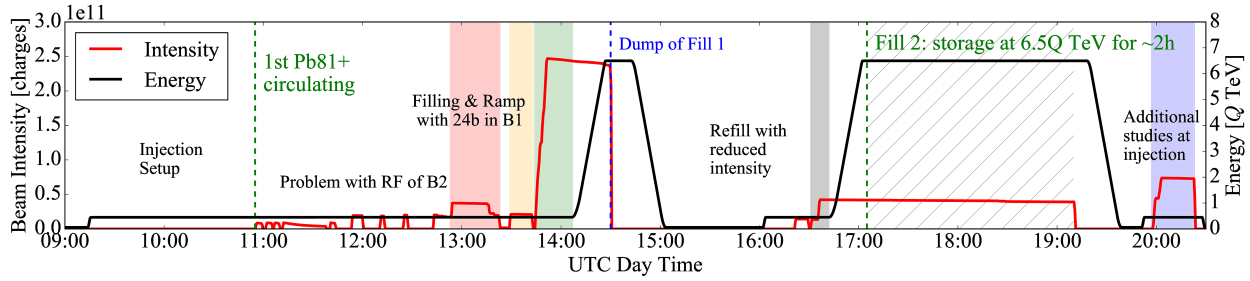


Figure 1: Evolution of the beam intensity and energy throughout the experiment.

the setup of Beam 1 went smoothly, the RF phase loop of Beam 2 could not be closed due to a drift of the generated reference frequency for ions. This problem caused Beam 2 to debunch. It would have taken too long to optimise the oscillators concerned during the experiment, and, more importantly, this modification would potentially not have been transparent for resuming proton operation. The success of the experiment did not rely on circulating both beams (since no collisions were foreseen) so it was decided to continue with Beam 1 only.

After performing loss maps<sup>3</sup> at injection energy of 450 Q GeV, the LHC was filled with 24 bunches that were then accelerated up to 6.5 Q TeV. Shortly after arriving at top energy, a small instability caused an increased loss rate and, in conjunction with the high collimation inefficiency of PSI (see Ref. [9] and below) a beam dump was triggered. The instability developed because the stabilisations from both the octupoles and transverse dampers were inactive.

For the next fill the octupole current was increased. Due to time constraints and the uncertainty on the intensity limit imposed by the high collimation inefficiency, the total beam intensity was reduced by both limiting the number of circulating bunches to six and reducing the single bunch intensity to about  $0.75 \times 10^{10}$  charges. This second fill was stored for about 2 h at 6.5 Q TeV.

After collecting sufficient data for beam lifetime studies, transverse loss maps were also taken at this energy. Because of doubts about machine safety based on the quench risk induced by the unexpectedly high collimation inefficiency, the foreseen off-momentum loss maps and asynchronous dump test were cancelled. Following the ramp-down the remaining time was used for lifetime studies at injection energy.

The evolution of the beam intensity and energy throughout the experiment is shown in Fig. 1.

### OBSERVATIONS AT 450 Q GeV

Thanks to the reduced bunch intensity for the second high-energy fill, data on two bunch intensity regimes around  $0.74 \times 10^{10}$  and  $1.0 \times 10^{10}$  charges was obtained at injection energy. The coloured areas in Fig. 1 indicate the five time periods when bunches were circulating undisturbed for

<sup>3</sup> A loss map is an excitation of a safe low-intensity beam to study the distribution of beam losses around the ring and ensure that no sensitive elements are exposed.

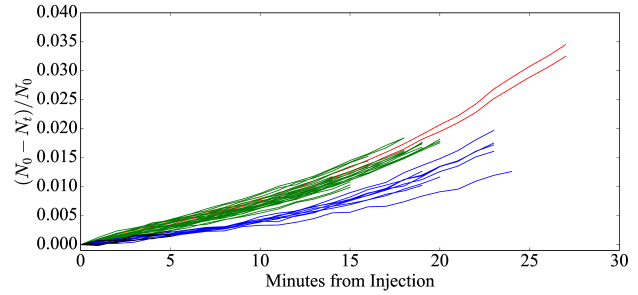


Figure 2: Evolution of losses per bunch at injection plateau. Colours indicate different time periods throughout the experiment, corresponding to Fig. 1.

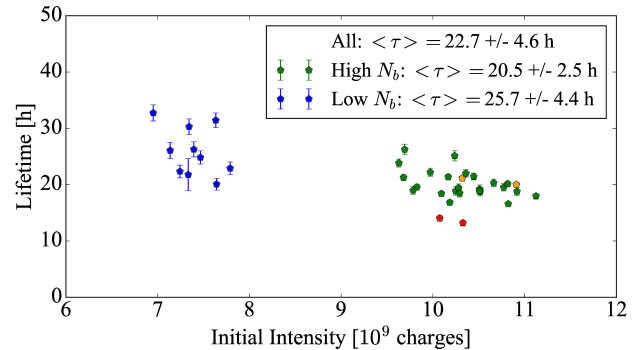


Figure 3: Fitted intensity lifetimes for all bunches shown in Fig. 2 (same colour code).

20 – 30 min. The relative intensity losses  $((N_0 - N_i)/N_0)$  over storage time of the bunches stored in the respective five time periods, starting from the moment of their injection, are shown in Fig. 2.

A clear separation between the high and low intensity bunches is visible, which is even more evident from the fitted single bunch lifetimes displayed in Fig. 3. On a bunch-by-bunch basis, exponential fits of the form

$$f(t; A, \tau) = Ae^{-t/\tau} \quad (1)$$

were performed on the intensity evolution, obtaining the lifetime from the fit parameter  $\tau$ .

As expected from intra-beam scattering (IBS), the higher the bunch intensity the lower the lifetime. On average the high intensity cluster (green, red, yellow) showed a lifetime of  $\tau = 20.5 \pm 2.5 \text{ h}$ , for the lower intensity bunches (blue)  $\tau = 25.7 \pm 4.4 \text{ h}$  was observed. The observed increasing loss

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rate with time is expected from IBS simulations using the Collider Time Evolution (CTE) tracking code [10, 11] (details are shown in Ref. [12]) with a small initial bunch length, since the bucket first has to fill up before the debunching effect from IBS leads to particle losses. A similar observation, which has been shown to be in good agreement with CTE simulations, was made for fully stripped  $^{208}\text{Pb}^{82+}$  ions with similar initial bunch parameters in previous LHC heavy-ion runs [11]. Therefore, at the level of accuracy of the present measurement, no indication of sizeable beam losses due to the intra-beam stripping process<sup>4</sup> was observed.

## OBSERVATIONS AT 6.5 Q TeV

The striped area in Fig. 1 indicates the data analysed at top energy. In this period, six bunches (in pairs of two) were circulating undisturbed for about 80 minutes. All bunches showed an equivalent loss evolution as plotted in Fig. 4. The start of the loss map campaign is clearly visible from the sudden loss of the two bunch pairs being excited. The third bunch pair stayed in for an extra 40 min. Figure 5 shows the fitted lifetimes as a function of bunch intensity over the first 80 min (blue) and for the two not excited bunches additionally over the full 120 min of storage (red). The reduction of the lifetime between the two fits of the third bunch pair indicates that the loss rate increases with storage time. This is predicted by CTE simulations for the given bunch parameters. The average observed lifetime at 6.5 Q TeV for the low intensity bunches is  $\tau = 54.5 \pm 1.7$  h.

The loss maps allowed to study the performance of the LHC collimation system with PSI beams. The details of this analysis are presented in a separate contribution to this conference [9], where it is shown that the observed cleaning inefficiency is orders of magnitude higher than for fully stripped  $^{208}\text{Pb}^{82+}$  ions. The explanation is that when the halo particles of the  $^{208}\text{Pb}^{81+}$  beam hit the primary collimator (TCP), the electron is immediately stripped off, resulting in a change of the particle's rigidity that leads to its loss in cell 11R7 in the downstream dispersion suppressor. These secondary losses were higher than the primary losses on the TCP, which is unacceptable for standard operation due to the risk of magnet quenches. For a circulating beam intensity close to  $3 \times 10^{11}$  charges (first fill) the losses in cell 11R7 were already high at injection and increased further through the energy ramp. This limited the total beam intensity for the second fill. Since the underlying effect was not fully clear at the time of the experiment, after the dump of the first fill the number of bunches and bunch intensity were reduced to increase the probability of surviving to top energy. Possible mitigation strategies to improve the collimation performance are discussed in Ref. [9].

## CONCLUSION

Once again, the LHC has proven its great flexibility by adding a new operating mode with partially stripped

<sup>4</sup> Intra-beam stripping is the process of intra-beam scattering leading to the ionisation of at least one of the colliding ions.

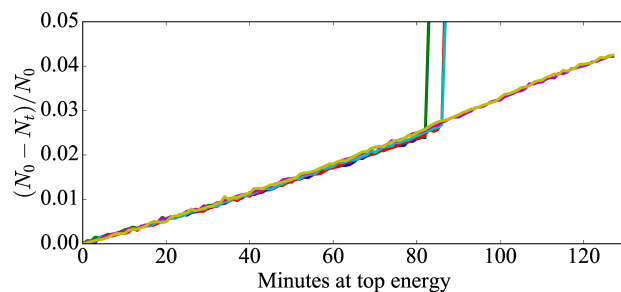


Figure 4: Evolution of losses per bunch at 6.5 Q TeV.

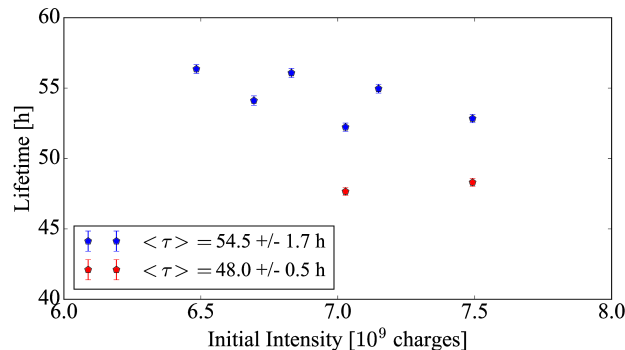


Figure 5: Fitted intensity lifetimes for all bunches shown in Fig. 2. The two red points show a second fit of the two bunches not affected by loss maps over their total storage time.

ions to its repertoire. The first operation with this particle type achieved lifetimes of  $^{208}\text{Pb}^{81+}$  beams of about 20 h at 450 Q GeV and about 50 h at 6.5 Q TeV. The observed lifetimes and beam evolution are in good agreement with expectations from intra-beam scattering. Preliminary estimates suggest that other sources of beam losses, like intra-beam stripping and Lorentz stripping (related to the Stark effect), are minor. The dominant limit on the beam intensity was found to be the collimation efficiency. As shown in Ref. [9], additional dispersion suppressor collimators, foreseen to be installed around the collimation insertion in the current shutdown of the LHC (LS2) [13], are expected to improve the collimation performance and reduce significantly the quench risk for the future high-intensity operation with PSI beams.

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