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# LIFETIME AND BEAM LOSSES STUDIES OF PARTIALLY STRIP IONS IN THE SPS ($^{129}$Xe$^{39+}$)

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## *Abstract*

The CERN multipurpose Gamma Factory proposal relies on using Partially Stripped Ion (PSI) beams, instead of electron beams, as the drivers of its light source. If such beams could be successfully stored in the LHC ring, fluxes of up to $10^{17}$ photons/s, in the $\gamma$-ray energy domain of $1 \leq E_\gamma \leq 400$ MeV could be achieved. This energy domain is out of reach for the FEL-based light sources as long as the multi TeV electron beams are not available. The CERN Gamma Factory proposal has the potential of increasing by seven orders of magnitude the intensity limits of the present Inverse Compton Scattering sources. In 2017 the CERN accelerator complex demonstrated its flexibility by producing a new, xenon ion beam. The Gamma Factory study group, based on this achievement, requested special studies. It aimed to inject and to accelerate, in the SPS, partially stripped xenon ions ($^{129}$Xe$^{39+}$) measure their lifetime, and determine the relative strength of the processes responsible for the PSI beam losses. The study presented in this contribution was a preparatory step in view of the future studies programmed for 2018 with lead PSI beams.

## INTRODUCTION

On the 14th of September 2017, a beam of partially stripped $^{129}$Xe$^{39+}$ions was successfully transferred and injected from the CERN ion injector chain to the SPS for the first time. It circulated at the SPS injection momentum of 23.6Q GeV/c for several seconds. In later runs the beam was accelerated to 107Q GeV/c, 189Q GeV/c, and 270Q GeV/c, with Q denoting the charge of the ion ($Q = 39$ for the $^{129}$Xe$^{39+}$beam).

These test runs represented the first step towards studying the stability aspects of partially stripped ion beams in the CERN accelerator rings and to validate the Gamma Factory concept.

The dominant process leading to losses of partially stripped ions in storage rings is the ionization process, where one or more electrons of the beam particles are stripped off. For the overview of ionization processes see [1] and references quoted therein.

We consider in the following two classes of ionization processes. The first one includes processes that depend on beam parameters such as bunch population and emittance. An example of this kind is intra-beam scattering leading to a loss of one or more electrons referred to as intra-beam stripping. The second class of processes is independent of the beam characteristics. An example of this case would be collisions of the beam particles with the rest gas in the storage ring. The induced losses by the various processes can be considered as sources of reducible and irreducible beam losses, respectively. The relative contribution of losses generated by the two classes has to be determined experimentally. This result can then be used to extrapolate the SPS lifetime measurements with partially stripped xenon ions ($^{129}$Xe$^{39+}$) to other ion species of interest for the Gamma Factory project in the SPS and LHC. The results of such measurements with partially stripped xenon ions in the SPS are presented in this paper.

## LIFETIME MEASUREMENTS

The CERN ion injector chain is extensively discussed in [2]. Beam tests with partially stripped ion beams in the SPS were performed over several days using special magnetic cycles in parallel with the SPS standard operation for North Area fixed target physics and as LHC injector. In this paper, the results of the analysis of the data collected on the $22^{nd}$ of November 2017 are presented where the most stable beam conditions could be achieved.

The lifetime measurements were performed at four different beam energies, two different beam intensities as well as with coasting and bunched beam. Finally, a dedicated chromaticity scan was performed at injection energy to study the lifetime stability exposed to changes in the machine settings.

An overview of the measurement campaign is presented in Fig. 1. This plot shows the evolution of the beam intensity during the cycle as measured by the SPS beam current transformer (BCT) for all the SPS beam injections used in the analysis for the different test configurations (high and low intensity as well as RF on/off). The magnetic cycle converted to beam energy is shown as well.

## RESULTS AND THEIR INTERPRETATION

The data in Fig. 1 was averaged per test configuration and fitted with $f(x) = Ae^{x/\tau} + c$, with $A, \tau$ and $c$ as fit parameters. $\tau$ corresponds to the lifetime. The obtained results were cross-checked with fitting each intensity evolution and aver-

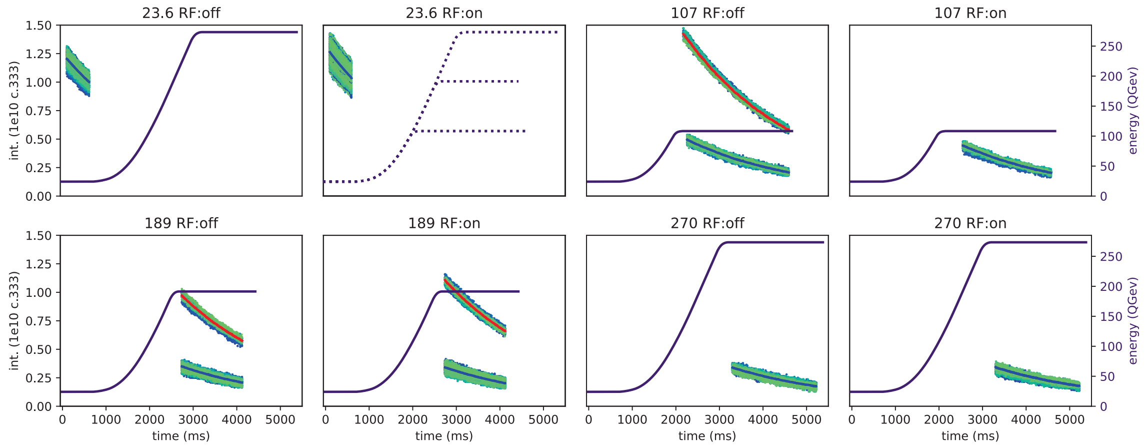

Figure 1: The overview of all measurement campaigns performed on the 22$^{\mathrm{nd}}$ of November. The colors, within the beam intensity evolution bands, correspond to the individual beam injections. The time dependence of the beam energy is represented by the full and dotted lines. The "NOMINAL" cycles have a higher intensity (mean -red) than the "EARLY" cycles (mean-blue). For the 23.6Q GeV measurement with RF on, all low intensity injections (no matter to which final energy the beam was accelerated), were used to improve the statistics. The magnetic cycles for this combined dataset are represented by the dotted lines.

aging the fit results. No significant difference was observed between the methods.

A summary of the results of the beam lifetime fits is shown in Fig. 2 for the different test configurations. No evidence of dependence on energy, intensity and the RF settings of the $^{129}\mathrm{Xe}^{39+}$beam lifetime is observed[1]. The impact of the bunch length on the beam lifetime was also studied. Again no influence on the beam lifetime was measured. The average measured lifetime of the $^{129}\mathrm{Xe}^{39+}$beam in the SPS ring from the measurements above is thus 2.550±0.085 s.

The fact that the $^{129}\mathrm{Xe}^{39+}$beam lifetime was independent of beam parameters during the 2017 measurement series suggests that the ion losses in the SPS are driven predominantly by the irreducible processes of collisions of the beam particles with the rest gas in the SPS ring.

The actual running conditions are subject to considerable uncertainty. The vacuum pressure depends strongly on the operational mode of the SPS preceding and parallel to the beam lifetime measurement tests, and it is also not uniform along the circumference of the SPS ring.

Assuming the average pressure along the SPS ring as measured during the lifetime measurement runs of $10^{-8}$ mbar and the SPS vacuum composition as measured on the $10^{th}$ of May 2011 [3], then the predicted $^{129}\mathrm{Xe}^{39+}$beam lifetime is 4.0± 0.1 s. If, on the other hand, the vacuum composition is the one measured during the last SPS shut-down period in 2018 (following the vacuum closure) [3], the predicted $^{129}\mathrm{Xe}^{39+}$beam lifetime is rather 1.38±0.04 s. Hence the measured lifetime from the $^{129}\mathrm{Xe}^{39+}$intensity evolution fits is well within the uncertainty of the knowledge of the molecular composition. All lifetime calculations were performed with the simulation code RICODE-M, for more details see [4].

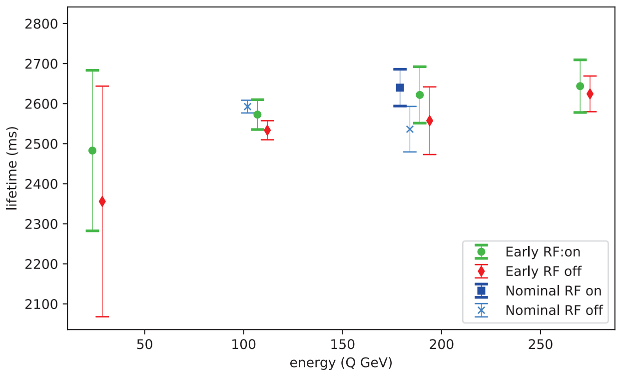

Figure 2: The lifetime dependence of the beam energy, intensity and the RF settings.

## EXTRAPOLATIONS

The goal of the SPS tests with the $^{129}\mathrm{Xe}^{39+}$ions was to prepare the 2018 test runs with the Hydrogen- ($^{208}\mathrm{Pb}^{81+}$) and Helium-like ($^{208}\mathrm{Pb}^{80+}$) lead beams - the candidate beams for the LHC-based Gamma Factory. By extrapolating from the $^{129}\mathrm{Xe}^{39+}$lifetime measurements to the case of the $^{208}\mathrm{Pb}^{81+}$and $^{208}\mathrm{Pb}^{80+}$, rather than relying on the absolute predictions for their lifetimes, several sources of uncertainty, related both to the theoretical calculations and to the vacuum quality control, can be avoided.

The extrapolation was performed, again employing RICODE-M, in two steps. In the first step the measured lifetime of the $^{129}\mathrm{Xe}^{39+}$ions was used to "calibrate" the rest gas density, by assuming its molecular compositions

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[1] Note that the lifetime measurements at the injection energy have large error bars. This is because no dedicated data set with a special magnetic cycle with a long flat bottom at the injection energy was prepared in the 2017 runs.

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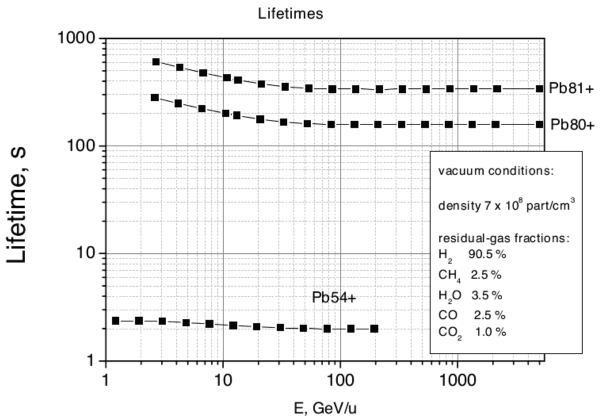

Figure 3: The energy dependence of the extrapolated $^{208}Pb^{81+}$, $^{208}Pb^{80+}$, $^{208}Pb^{54+}$beam lifetimes for the molecular composition of the rest gas given in the plot insert and the rest gas molecular density as determined using the $^{129}Xe^{39+}$runs. The energy values are specified in the units of the beam energy per nucleon.

as measured in the SPS when the SPS was used as a proton-antiproton collider [5]. The assumed gas composition, with the dominant contribution of the $H_2$ molecules ( ≈ 90 %), approximates the vacuum composition of the LHC ring. The corresponding rest gas density was determined to be 7.05 × $10^8$ molecules/$cm^3$. In the second step, the lifetimes for $^{208}Pb^{81+}$, $^{208}Pb^{80+}$and also the Nickel-like ($^{208}Pb^{54+}$) beams were calculated assuming the calibrated rest gas density and molecular composition as discussed before.

The extrapolation results are shown in Fig. 3 as a function of the beam energy. Note, that in this plot the beam energy is expressed in units of energy carried by each nucleon such that, e.g., $^{208}Pb^{81+}$the SPS energies range from 9.2 to 175 GeV/u, while for the LHC from 175 to 2529 GeV/u for the same ion. As can be seen in Fig. 3, the predicted lifetimes become beam-energy independent already within the SPS energy range, and the asymptotic values for the $^{208}Pb^{81+}$and $^{208}Pb^{80+}$beams are larger than 100 s. Taking into account that the SPS cycle duration is of 40 s, we conclude that such beams can be successfully injected into the SPS, accelerated to 450Q GeV/c and subsequently injected into the LHC.

It is worth stressing that the ratios of the partially stripped ion beam lifetimes, for varying number of left-over electrons, are only weakly sensitive to the gas molecular composition. Therefore, the strategy for the 2018 runs with the Pb ions will be to first re-calibrate the 2018 SPS vacuum quality with the parasitic cycle $^{208}Pb^{54+}$runs and then to use this calibration while preparing the runs with the $^{208}Pb^{81+}$and $^{208}Pb^{80+}$ions, both in the SPS and the LHC.

Since the vacuum quality in LHC is expected to be significantly better than in the SPS, lifetimes of at least one hour are expected for $^{208}Pb^{81+}$and $^{208}Pb^{80+}$. This is of course only true if the irreducible beam losses will remain the dominating loss source at LHC energies.

## CONCLUSION

The lifetime of the $^{129}Xe^{39+}$beam was measured to be 2.550± 0.085 s in the SPS and found to be independent of the parameters of the ion bunches. The dominant process leading to the $^{129}Xe^{39+}$beam losses is the process of electron stripping in collisions of the beam particles with rest gas remaining in the SPS ring. Based on this result the lifetime for $^{208}Pb^{81+}$and $^{208}Pb^{80+}$beams was estimated and found to be sufficiently large to perform the Gamma Factory beam test in 2018 in the SPS and the LHC.

## ACKNOWLEDGEMENTS

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