Summary of Gamma Factory LoI submitted as SPSC-I-253

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1 Scientific objectives for SPS

The Gamma Factory proposes ultimately to use the large relativistic boost of partially stripped ions stored in the LHC to produce gamma-ray beams with unprecedented intensity. This would open new opportunities in a wide range of research programs, including production of secondary beams [1] and the ability to cool down and collide iso-scalar ion beams in LHC, as emphasized in the Physics briefing book input document for the ESPP Update [2].

The proposed experiment in the SPS is intended to prove the main Gamma Factory principles. The SPS is chosen for cost purposes, ease of implementation and operation, while offering a representative accelerator environment and set of parameters.

The main objectives of the SPS experiment are therefore the experimental validation of technological choices and operations of the necessary apparatus. The physics reach of this proof of principle (PoP) experiment itself is limited to two aspects: (1) beam cooling and (2) atomic spectroscopy of high-Z atoms in strong fields.

1.1 Beam cooling

The first goal of the proposed SPS experiment is to demonstrate longitudinal cooling of ^{208}Pb^{79+} beams. Simulations show that that the relative energy spread of such a beam could be reduced by a factor of 10 reaching the value of 10^{-5}. The cooled beam can then be used for demonstrating high precision spectroscopy in the SPS of atomic levels of the highly charged ions.

A related goal is to demonstrate transverse cooling, aiming at an emittance reduction of a factor of 10. This would open the path towards high luminosity operation of LHC with isoscalar beams [3].

1.2 Spectroscopy of relativistic highly ionized high-Z atoms

Partially stripped ions in high–charge states provide a unique tool for investigating many fundamental, yet poorly understood, problems in various areas of science. In the realm of atomic physics, these ions serve as natural laboratories to probe few–electron systems exposed to strong electromagnetic fields produced by nuclei. An electron in the 1s ground state of hydrogen-like lead experiences an electric field strength of about $10^{16}\ \mathrm{V/m}$, only two orders of magnitude below the Schwinger field and larger than the highest field strengths attainable in multi PW laser installations. Spectroscopy of Partially Stripped Ions (PSI) in the high–Z region has thus attracted much theoretical and experimental attention during the last decades.

The Gamma Factory offers a very promising alternative to current techniques [4, 5] for the X–ray spectroscopy of heavy PSI. Atomic transitions can be directly induced by the (Doppler–boosted) primary infrared photon beam.

The SPS PoP experiment will allow a measurement of the transition energy down to a relative accuracy of about 10^{-4}, that will challenge the theoretical prediction [8]. It will be the first measurement of the $1s^22s \to 1s^22p_{1/2}$ transition in ^{208}Pb^{79+}. These measurements will push forward the developments of relativistic QED theory in the strong–field regime. In the future this technique could be extended in the SPS to other isotopes of lead and/or others atomic species.

2 Milestones and deliverables

The project advancement is defined by the achievement of several milestones, discussed in more details in [6].

2.1 Resonance finding

This first phase aims at inducing excitation of the $2s \rightarrow 2p_{1/2}$ transition. It requires the careful overlapping in all three dimensions of the ion bunch and laser pulse. The detection system (see [7]) will measure the X-ray flux produced by the ion de-excitation. The detected X-ray photons on the detector screen marks the achievement of this first phase.

This stage requires $32\,\mathrm{h}$ of beam time, spread over 4 weeks. This can mostly be done in parallel with North Area (NA) lead operation, using only a small part of the SPS supercyle. However, $8\,\mathrm{h}$ of dedicated beam time are requested to allow commissioning of the system with PSI beam before the start of the yearly ion run.

2.2 Optimisation and characterisation

Following the production of X-ray photons, this step aims at controlling the photon flux and resonant condition for a duration of at least $5\,\mathrm{s}$. The success is established by the measurement of an excitation rate stable within $\pm 25\,\%$ for at least $5\,\mathrm{s}$. It also requires the reproducibility of this result in consecutive SPS cycles and for different excitation rates.

A total of $16\,\mathrm{h}$ of beam time, spread over at least 2 weeks, are required for this phase. Of this beam time, $8\,\mathrm{h}$ can make use of a small part of the SPS supercycle while the other $8\,\mathrm{h}$ will require the SPS supercycle be dedicated to the experiment.

2.3 Cooling demonstration

Careful control of the resonant condition over seconds timescale opens the way towards beam cooling. This is demonstrated by the measurement of the ion bunch peak current normalised to the bunch charge and its increase by at least a factor 2 within up to $20\,\mathrm{s}$.

The request for completion of this step totals $24\,\mathrm{h}$ of beam time spread over at least 3 weeks. Of that time, at least $16\,\mathrm{h}$ need the SPS supercylce entirely dedicated to the experiment.

2.4 Atomic physics precision measurement

This phase will push the boundaries of beam stability and rely on the yet to be determined best absolute measurement of the ion beam energy. The goal of that last phase it to use the measurement of de-excitation X-ray photons in specific machine conditions to determine the $2s \rightarrow 2p_{1/2}$ transition energy with a relative accuracy of at least 10^{-4}. Its completion will be ascertained by the publication and associated review process of the results in a relevant peer-reviewed journal since the challenge lies in the understanding and control of both systematic and statistical uncertainty sources.

That phase requires a total beam time of $16\,\mathrm{h}$, spread over at least 2 weeks and of which $8\,\mathrm{h}$ make use of the entire SPS supercycle.

2.5 Requested beam time

In both 2023 and 2024, it is planned to have a series of PoP runs for about $48\,\mathrm{h}$ per year. Beam time requested that may make use of only a small part of the SPS supercyle is referred to as *parallel* while

Table 1: Summary of the total beam time requested for the experimental program.

Project milestone	Beam time [h]		Time in calendar weeks
	parallel	dedicated	
Resonance finding	24	8	4
Optimisation and characterisation	8	8	2
Cooling demonstration	8	16	3
Atomic physics precision measurement	8	16	3
Total	48	48	12

beam time that requires the SPS to be entirely dedicated to the experiment is called *dedicated.* Summary of the beam time requested to achieve each stage is showed Table 1.

3 Interventions in the SPS

3.1 SPS Tunnel Installations

The proposed SPS tunnel installations comprises:

- The $50\,\mathrm{W}$ laser system (amplifier, oscillator, electronics) in a climate-controlled optical room located on the unused TI18 side-tunnel;
- A $4\,\mathrm{m}$ long interaction vacuum chamber installed in SPS LSS6, incorporating the Fabry-Perot cavity for laser pulse enhancement and beam position monitors of existing design for accurate PSI-laser alignment;
- A high-vacuum laser beam transport chamber between laser room and Fabry-Perot cavity;
- The X-ray detection monitor, similar to the existing SPS BTV design;
- The upgraded TT2 stripper to allow PSI cycles in a regular SPS supercycle.

3.2 Ion species and source

All PoP experiments in Run 3 will be performed with a single species, $^{208}\mathrm{Pb}^{79+}$. The acceleration and storage of $^{208}\mathrm{Pb}^{80+}$ and $^{208}\mathrm{Pb}^{81+}$ has already been demonstrated through the injector chain, SPS and even LHC. It is fully compatible with Pb operation for the NA and LHC, and no changes to the source are required. From the CERN side the only additional installation is the upgrade to the TT2 stripper.

3.3 Installation methodology and planning

The laser room and oscillator will be installed during the first YETS of Run 3 (2021/22) by the relevant CERN groups and external contributors. Access will be through the nearby BA6 building.

The laser beam transport, laser system, interaction vacuum chamber and Fabry-Perot cavity will be installed in the second YETS of RunIII (2022/23), by the Gamma Factory collaboration and CERN groups. The Fabry-Perot cavity will be pre-aligned on the surface and its alignment will be checked after SPS installation. Fine on-line alignment will be possible by integrated actuators and relevant diagnostics.

RunIII data-taking with PSI beams and the laser will be in 2023 and 2024. Overall project resources requirements are discussed in [12].

3.4 Impact on SPS operation

During operation the PoP experiment will be fully remotely controlled and any required access will be during scheduled SPS technical stops or year-end shutdowns. It has been conceived so as to be compatible with normal SPS operation when not taking dedicated data:

– The laser room is located in the side tunnel to shield the sensitive electronics from SPS radiation [13];
– The preliminary optical cavity and X-ray detector designs respect SPS impedance and aperture constraints, as already verified by CERN experts [9–11]. A formal verification of the final systems will be made, including impedance measurements and metrology. It is worth noting that the Gamma Factory members responsible for the development of the Fabry-Perot cavity have long-standing experience in integrating such systems, in stringent environments such as the KEK ATF low emittance ring [14];
– Much of the PoP operation will use a PSI cycle between NA physics cycles, with a flat-top of a few seconds [15];
– One week is needed for commissioning and synchronisation of the laser system. This can be performed without impact on the proton beams, and will therefore be transparent for operation.

4 Physics motivation of the GF project

The SPS PoP experiment is one of the six necessary R&D steps to establish the Gamma Factory project at CERN. The GF project provide an attractive option allowing to significantly enrich the LHC-based research programme beyond the year 2030.

Physics motivations for the Gamma Factory project are numerous. They are discussed in [16]. Examples of *particle physics* applications are presented in [3,17,18]. An overview of the GF applications to *nuclear physics* will be presented in [19]. For an overview of the GF applications to *atomic physics* see [20]. For selected GF applications to *accelerator physics* see [21–27]. Two *applied physics* use cases, are presently studied [28,29].

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