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GAMMA FACTORY AT CERN: DESIGN OF A PROOF-OF-PRINCIPLE EXPERIMENT

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Abstract

The Gamma Factory (GF) initiative proposes to create novel research tools at CERN by producing, accelerating and storing highly relativistic partially stripped ion beams in the LHC rings and by exciting their atomic degrees of freedom by lasers, to produce high-energy photon beams. Their intensity would be several orders of magnitude higher than those of the presently operating light sources in the particularly interesting gamma-ray energy domain reaching up to 400 MeV. In this energy domain, the high-intensity photon beams can be used to produce secondary beams of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions. Over the years 2017-2018 we have demonstrated that these partially stripped ion beams can be successfully produced, accelerated and stored in the CERN accelerator complex, including the Large Hadron Collider (LHC). The next step of the project is to build a proof of principle experiment in the SPS to validate the principal GF concepts. This contribution will present the initial conceptual design of this experiment along with its main challenge — the demonstration of the fast cooling method of partially stripped ion beams.

INTRODUCTION

High flux and high energy photon sources can have many applications, not only in high energy physics but also in atomic and nuclear physics. Such sources usually involve the use of electrons within a facility that can produce highly relativistic electron beams. However, it is also possible to produce such photon beam by exploiting the atomic degrees of freedom of a highly relativistic partially stripped ion (PSI) [1].

Figure 1 schematically shows the principle of high energy photon production using PSI. An optical photon of angular frequency ω travelling against the PSI is boosted in the ion frame to:

$$\omega' = (1+\beta)\gamma\omega \simeq 2\gamma\omega, \quad (1)$$

where β is the ratio of the ion speed to that of light and γ the Lorentz factor. It is clear from the 2γ term that the Lorentz boost gives access to the excitation of electronic transitions of much higher energies than what is commonly reachable.

The spontaneous de-excitation of the ion then produces a photon, whose angular distribution is isotropic in the ion frame. Boosting back that photon to the rest frame has two important consequences:

- the emitted photons are concentrated in a small angle $\simeq 1/\gamma$ in the forward direction of the ion beam.
- the angular frequency ω'' of the photon propagating back along its incoming direction is boosted by another factor 2γ such that :

$$\omega'' \simeq 2\gamma\omega' \simeq 4\gamma^2\omega. \quad (2)$$

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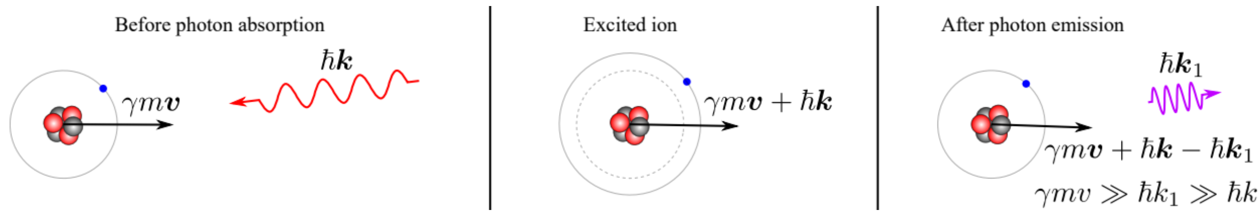

Figure 1: Schematic representation of the absorption and spontaneous emission of photon by a partially stripped ion as seen in the laboratory frame [2].

We have shown how high energy photon can be generated but one might question the possibility of reaching high flux. Since the photon absorption is a resonant process its cross section is much higher than that for photon scattering from bare nuclei or electrons. More quantitative discussions can be found on the subject in [1, 3, 4].

SPS PROOF-OF-PRINCIPLE

Many scenarios are investigated to deploy this scheme at the Large Hadron Collider (LHC). However, a shorter-term project at the Super Proton Synchrotron (SPS) to demonstrate the principle and build up associated expertise is discussed here.

The SPS Proof-of-Principle (PoP) is being designed around a few core objectives, namely:

- Demonstrate integration and operation of a laser and Fabry-Perot cavity in a hadron storage ring;
- Verify simulations of the rate of atomic excitation;
- Demonstrate matching of characteristics of ion bunches to those of the laser bunches, match laser spectrum to the width of the atomic excitation and achieve resonance for adequate fraction of ion population;
- Measure emitted X-rays produced at the Interaction Point (IP), characterise the flux and spectrum, and demonstrate photon extraction from the collision zone;
- Demonstrate laser cooling of relativistic beams and investigate different approaches;
- Demonstrate feasibility of relativistic atomic physics measurements.

Experiment Parameters

The choice of the PoP parameters accounts for the accessible range of magnetic rigidity by the SPS, possible incoming photon energy based on laser technologies and ion species with which CERN already has experience. It was decided to use a Li-like lead ion (Pb^{79+}, a lead nucleus with 3 electrons) and its $2s_{1/2} \rightarrow 2p_{1/2}$ transition. Table 1 summarises the experimental parameters establishing the baseline of the experiment.

Table 1: Experimental Parameters

Parameter	Value
crossing angle	2.6°
Ion magnetic rigidity	787 T m
Ion γ factor	96.3
Ion beam horizontal RMS size at IP	1.3 mm
Ion beam vertical RMS size at IP	0.8 mm
Ion revolution frequency	43.4 kHz
Laser photon energy	1.2 eV
Laser frequency	40 MHz
Laser pulse energy	5 mJ
Ion $2s_{1/2} \rightarrow 2p_{1/2}$ transition energy	230.8 eV
Maximum energy of back scattered photon	44.5 keV

Laser Cavity

In the baseline version, optical photons would be stored in an optical resonator, a Fabry-Perot cavity, installed in the path of the circulating ion beam. The cavity crosses the ion beam trajectory with a vertical angle and with a length of around 3.75 m.

The laser electronics need to be located close to the cavity. This poses specific issues in the SPS environment as high levels of radiation are common during operation. Significant uncertainties on the reliability of laser electronics in such environment would have made a usual implementation, with all equipment directly bellow the cavity, risky.

A location at the end of the Long Straight Section 6 (LSS6) was identified where an old transfer tunnel behind the wall of the SPS tunnel could be used to house the laser electronic, shielding it from radiation coming from the SPS ring.

LSS621 Location

Figure 2 shows the layout around the proposed location for the laser cavity. it is located at the start of the arc, in the missing dipoles of the dispersion-suppression cell. This straight section is mostly free of equipment, with only a bumper magnet and an octupole immediately upstream of the QF.62210 quadrupole.

This layout provides around 10 m of free space downstream of the IP to place specialised instrumentation systems.

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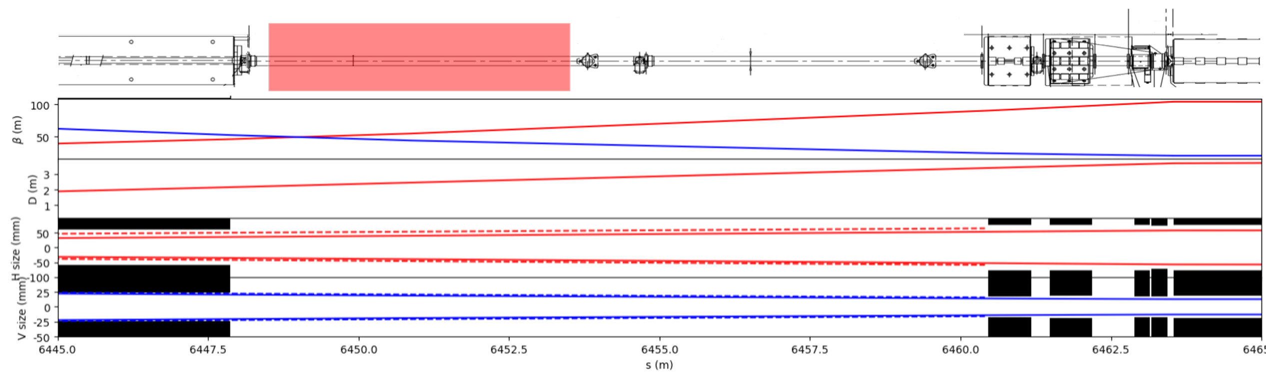

Figure 2: Layout of the SPS section 621 on top with the foreseen position of the laser cavity in red. Bellow, optical functions and beam sizes are shown in red for the horizontal plane and in blue for the vertical one. Dotted lines presents the minimum physical aperture required for compatibility with the other beams accelerated in the SPS.

Photon Detection Instrumentation

The observable to detect and quantify the excitation of the PSI is the photons emitted in their relaxation. Two main detection schemes have been identified. Photons emitted at large angles from the IP fall into the visible range due to the angular effect of the Lorentz boost and could be guided towards a camera. Closer to the beam axis and somewhere between 5 m and 10 m downstream of the IP, a system could be used to detect the high-energy photons at high rapidity and possibly extract them out of the beampipe. Those two methods are being studied and both could be used in the experiment.

Experimental Protocol

For the realisation of the PoP experiment a three-phase experimental protocol is being discussed.

Phase 1, search for the resonance, which would aim at scanning the ion beam position and energy until photons produced by the PSI radiative decay are detected. This would heavily rely on automated algorithms interacting with the PoP and SPS control systems to efficiently and reliably scan the parameter space.

Phase 2, photon-flux optimisation, would focus on careful tuning of the beam parameters to be able to excite a specific part of the beam. In particular, this includes selective excitation of PSI above the synchronous momentum.

Phase 3, beam cooling, would aim at detecting the longitudinal cooling effect caused by the loss of energy of the PSI during its relaxation and energy recovery by the RF cavity. This effect is critical for the GF project and is the most challenging goal of the PoP experiment.

Additional phase, atomic physics, is considered to measure the energy of the transition with high accuracy. Manipulation of the beam and laser parameters, together with an absolute energy calibration of the beam, give direct access to the transition energy. Measurement at the present SPS momentum uncertainty would already be unique while an improved relative uncertainty of 10^{-5} would compare with the best calculations to date [5].

Schedule

The current schedule aims at an installation of the experiment inside the SPS tunnel during the annual shutdown of the CERN complex between 2021 and 2022. This would allow to run the experiment during the following ion run at the end of 2022.

CONCLUSION

Over the last few month all the aspects of the PoP experiment have been discussed. Simulations, benchmarked using different approaches and codes, confirmed that both excitation and cooling will be strong enough to be observed.

The laser system and detailed specifications are being discussed but the parameters envisioned seems to be achievable with the current technology. Exchanges between radiation and laser experts led to the consideration of the location presented here, to allow the laser electronics to be shielded behind the SPS tunnel wall.

Detector requirements and implementation are currently discussed as it is currently the axis of design where most of the work remains to be completed. In particular, detector technologies and their implementation in or around the SPS vacuum chamber need to be compatible with the other usage of the SPS such as North Area fixed target experiments as LHC injector.

As the project now involves many scientist from around the world, covering all the required area of expertise, a founding document detailing both the PoP experiment and the wider scope of Gamma Factory will be released later this year.

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