

## THE GAMMA FACTORY PROJECT AT CERN: A NEW GENERATION OF RESEARCH TOOLS MADE OF LIGHT\*

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The Gamma Factory project offers the possibility of creating novel research tools by producing relativistic beams of highly ionised atoms in CERN's accelerator complex and exciting their atomic degrees of freedom by lasers to produce strongly collimated high-energy photon beams. Intensity of such beams would exceed by several orders of magnitude the ones offered by the presently operating light sources, in the particularly interesting energy domain from about 100 keV to above 400 MeV. In this energy regime, the high-intensity photon beams can be used to produce secondary beams of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions. New research opportunities in many domains of physics, from particle physics through nuclear physics to atomic physics, can be opened by the Gamma Factory scientific programme based on the above primary and secondary beams. Except for basic research, it offers also a possibility for various application studies, *e.g.* in medical physics and nuclear power.

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## 1. Introduction

The idea of a Gamma Factory (GF) project for CERN has been initiated in Ref. [1]. Its main goal is to produce at CERN's accelerator complex high-energy beams of partially-stripped ions (PSI) and to excite their atomic degrees of freedom using lasers in order to create highly energetic photon beams [2–5]. Owing to ultra-relativistic velocities of the PSI achievable in the SPS or LHC accelerators which provide a Doppler-effect boost of laser-photon energy in the PSI-rest frame by a factor  $\sim 2\gamma_L$ , where  $\gamma_L$  is the relativistic Lorentz factor, resonant excitations of atomic levels are possible even for heavy atoms, such as Pb. In the laboratory frame, the energy of spontaneously emitted photons moving in the direction of the PSI beam is boosted by another factor of  $2\gamma_L$ , resulting in an energy amplification of the incident laser photon by a factor of up to  $4\gamma_L^2$ . In the SPS and the LHC, it is possible to accelerate and store the PSI beams over a wide range of the Lorentz factor:  $30 < \gamma_L < 3000$ . For the LHC, this means that the photon beams with energies up to about 400 MeV, *i.e.* in a domain of  $\gamma$ -rays, can be produced.

Due to a very high resonant-absorption cross section, the intensity of  $\gamma$ -rays to be achieved in the GF is by many orders of magnitude higher than in the existing facilities relying on the Compton scattering process and comparable to the best *X*-ray sources, *e.g.* the European XFEL at DESY-Hamburg, Germany. Photon absorption and spontaneous emission by partially stripped ions opens new possibilities of beam cooling based on the atomic Doppler effect [6–8].

High-energy and high-intensity  $\gamma$ -ray beams can be scattered on stationary targets to produce efficiently secondary beams of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons and radioactive ions. Such beams can offer new research opportunities in a broad area of fundamental and applied physics.

This article is organised as follows: in Section 2, basic concepts of the GF are introduced, in Section 3, physics opportunities offered by the GF research tools are briefly presented, in Section 4, the progress of the project development is reported, in Section 5, a brief discussion the GF Proof-of-Principle (PoP) experiment at the SPS is given and, finally, Section 6 contains a short summary.

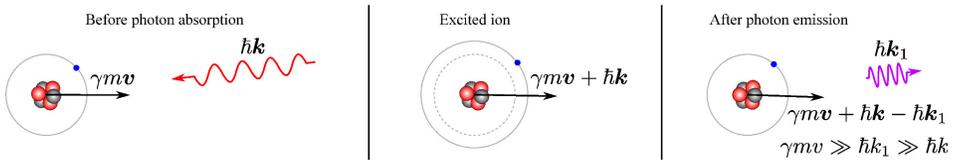
### 2. Basic concepts

In Fig. 1, the photon–PSI collision process is presented. Due to the relativistic Doppler shift, the photon energy in the PSI-rest frame,  $E'$ , is much higher than in the laboratory (LAB) frame,  $E$ ,

$$E' = \gamma_L(1 - \beta \cos \psi)E \xrightarrow{\beta \rightarrow 1, \psi \rightarrow \pi} 2\gamma_L E, \tag{1}$$

with  $\psi$  being the collision angle between the PSI and the photon directions in the LAB frame (typically  $\psi \approx \pi$ ),  $\gamma_L$  — the Lorentz relativistic factor of the PSI (at the LHC, it can reach up to  $\sim 3000$ ) and  $\beta$  — the ratio of the PSI velocity in the laboratory frame to the speed of light  $c$  (for the LHC  $\beta \approx 1$ ). From Eq. (1) one can see that the photon energy in the PSI-rest frame is 2 $\gamma$ -times of that in the laboratory frame for back-to-back collisions,  $\psi = \pi$ .

In the laboratory reference frame:



In the initial ion reference frame:

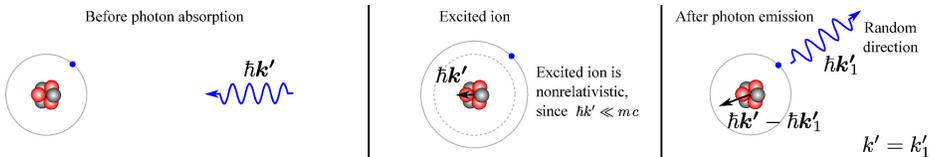


Fig. 1. The process of photon absorption and spontaneous emission in the laboratory and PSI-rest reference frames.

Due to this photon-energy amplification, using laser light one can excite high- $Z$  atoms accelerated in the LHC, such as Pb, for which the transition energy between the atomic levels is up to several tens of keV.

When an excited atom de-excites by spontaneous emission, it produces a photon whose energy  $E_1$  in the LAB frame is given by

$$E_1 = \frac{E'_1}{\gamma_L(1 - \beta \cos \theta)} \xrightarrow{\beta \rightarrow 1, \theta \rightarrow 0} \frac{2\gamma_L E'_1}{1 + (\gamma_L \theta)^2} \underset{E'_1 \approx E'}{\approx} \frac{4\gamma_L^2 E}{1 + (\gamma_L \theta)^2} \leq 4\gamma_L^2 E, \quad (2)$$

where  $E'_1$  is the emitted photon energy in the PSI-rest frame and  $\theta$  is the photon emission angle in the LAB frame. The photons are emitted in a random direction in the PSI-rest frame, but in the LAB frame due to the high- $\gamma_L$  Lorentz boost they are strongly collimated (for the uniform emission in the PSI-rest frame half of the photons are emitted with  $\theta \leq 1/\gamma_L$ ). As one can see from Eq. (2), the maximum amplification factor for the incoming-photon energy achievable at the GF is  $4\gamma_L^2$ , which for the LHC can reach the value  $\sim 10^7$ . This means that using the laser photons with the energy up to  $\sim 10$  eV, one can produce  $\gamma$ -rays with the energy up to  $\sim 400$  MeV. Moreover, as the energy of the outgoing photon increases with decreasing emission angle, it can be selected by using simple angular collimators.

The cross section for the resonant absorption and spontaneous emission of the PSI can reach a gigabarn range, to be compared with a barn-range cross section for the Compton scattering, which corresponds to a factor of  $\sim 10^9$  leap in the  $\gamma$ -ray beam intensity of the GF w.r.t. the Compton-based sources of similar photon energies and is comparable with that of the best FEL facilities, however producing photons with energies up to  $\sim 20$  keV.

Since the energy of the PSI at the LHC can be by a factor  $\sim 10^7$  higher than the emitted photon energy, the PSI-beam is very stable even in the regime of multi-photon emission per turn and, as a result, the GF photon-source intensity is driven only by the power of the storage-ring RF cavities.

### 3. Physics opportunities

The GF project offers a variety of novel research tools at CERN that could open new research opportunities in many areas of fundamental and applied physics. Examples of physics domains and relevant research opportunities of the GF are shown in Fig. 2. The above research can be conducted by exploiting the primary beams of highly ionised atoms and emitted  $\gamma$ -rays as well as secondary beams of electrons, positrons, muons, neutrinos, neutrons and radioactive nuclei which can be produced by scattering primary  $\gamma$ -ray beams on stationary targets. In the secondary-beam production, the GF offers an important change of paradigm from a “mining” to a “production-

on-demand” via electromagnetic interaction in which only a tiny fraction of the primary-beam energy is wasted. Intensities of these secondary beam can surpass that of the currently available sources by 3–4 orders of magnitude.

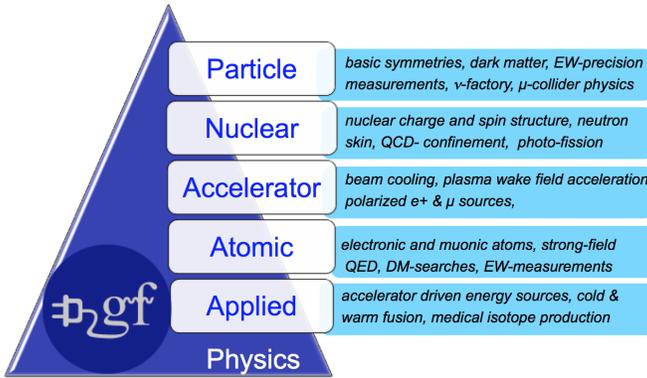


Fig. 2. Physics domains and examples of specific research opportunities of the Gamma Factory.

By using the polarised laser light, one can produce polarised secondary beams of electrons, positrons and muons. The latter can be exploited for production of well-separated high-intensity beams of  $\nu_e$ ,  $\bar{\nu}_e$ ,  $\nu_\mu$  and  $\bar{\nu}_\mu$ , to be used for important neutrino-physics measurements, such as the CP violation in the neutrino sector. Other possible applications of high-intensity electron/positron and muon beams include electron–ion and muon colliders, respectively.

The PSI beams, contrary to proton beams, can be efficiently cooled by exploiting the Doppler effect associated with absorption and spontaneous emission of photons — the technique well-known in atomic physics but not used so far in high-energy particle accelerators. By applying the laser Doppler-cooling method [6–8] to the PSI beams, one can reduce their bunch sizes and the energy spread. Such a beam-cooling can be useful for increasing the intensity of the produced  $\gamma$ -ray beam, for plasma wakefield acceleration or for a high-luminosity LHC option with iso-scalar ion beams, *e.g.* Ca or O, to be used for high-precision tests of the Standard Model [9–12].

More details on the possible GF research programme can be found in Refs. [1–5, 13].

#### 4. Progress

Over the years 2017 and 2018, first important tests of the PSI beams were performed in the SPS and the LHC. First, in 2017, the  $Xe^{39+}$  beam was accelerated, stored in the SPS and studied at different flat-top energies [14].

The analysis of the measured lifetime was used to estimate the expected lifetimes of the  $\text{Pb}^{81+}$  and  $\text{Pb}^{80+}$  beams in the SPS ring. They turned out to be sufficient to fill the SPS and to accelerate the bunches up to the LHC injection energy. This opened the possibility of injecting such beams to the LHC ring. In June 2018, the  $\text{Pb}^{81+}$  and  $\text{Pb}^{80+}$  beams were successfully injected to the SPS and accelerated to the proton-equivalent energy of 270 GeV [15]. The achieved bunch intensity for the  $\text{Pb}^{81+}$  beam of  $8 \times 10^9$  unit electric charges exceeded requirements for monitoring such bunches both in the SPS and in the LHC.

On 25th July 2018, the  $\text{Pb}^{81+}$  beam was injected for the first time to the LHC and accelerated to the proton-equivalent energy of 6.5 TeV. The observed beam lifetime was  $\sim 40$  hours. This date will be remembered for accelerating the first beams of “atoms” in the LHC [15].

The main outcome of the 2017 and 2018 GF test runs was the proof that the PSI beams can be created, accelerated and stored in the existing CERN accelerator complex. These tests also validated our initial software tools for simulations of electron-stripping in metallic foils and beam–gas collisions of highly charged ions [16].

As in the case of any high-energy physics experiment, for the GF software tools are needed to simulate various aspects of its performance, both technical and scientific. Some of them can be developed by customising the existing software, like *Geant4* or *Fluka*, but many of them need to be created from scratch. Over the last two years, two parallel projects have been pursued to develop the software tools for simulations of internal PSI-beam dynamics: (1) based on a semi-analytical approach and (2) based on Monte Carlo methods to study dynamics of individual ions [3, 13, 17].

## 5. Proof-of-Principle experiment

The next important milestone of the GF project is validation of its photon-beam production scheme in a special Proof-of-Principle (PoP) experiment in the SPS [5, 13] in which a dedicated laser system will be used to excite resonantly the atomic degrees of freedom the PSI beam, resulting in the spontaneous emission of high-energy photons. In this experiment, many practical aspects of the GF concept will be tested. Its important goals include also tests of the Doppler beam-cooling techniques and some atomic physics measurements.

Due to limitations of the SPS, such as low vacuum quality in the beam-pipe and not very high beam energy, the PSI beam of the lithium-like lead,  $\text{Pb}^{79+}$ , has been chosen for the PoP experiment. The expected lifetime of such a beam in the SPS is estimated at  $\sim 100$  seconds, which is comfortably longer than the expected beam-cooling time of  $\sim 20$  seconds. To produce

the photon beam, the atomic transition  $1s^2 2s^2 S_{1/2} \rightarrow 1s^2 2p^2 P_{1/2}$  with the energy difference of 230.76 eV has been selected. It can be excited with a 1030 nm pulsed laser for the PSI-beam  $\gamma_L$ -factor tuned to the value  $\approx 96$ , resulting with the spontaneously emitted photons with the energy be up to  $\approx 44$  keV.

In September 2019, a Letter-of-Intent (LoI) for the PoP experiment at the SPS [18] was submitted to the SPC Committee and is now under a reviewing process. This experiment is planned to be performed in the years 2023/2024. Its outcome will be crucial for the ultimate goal of the GF which is its implementation in the LHC.

## 6. Summary

In this contribution, we have presented briefly the Gamma Factory (GF) project for CERN. Its main idea is to produce, accelerate and store in the CERN accelerator complex partially-stripped ion (PSI) beams and excite their atomic degrees of freedom with laser light to generate a high-energy photon beams. These beams can then be collided on stationary targets to produce secondary beams of polarised electrons/positrons, polarised muons, neutrinos, neutrons and radioactive ions. The above primary and secondary beams can provide a variety of novel research tools and open new research opportunities in many domains of fundamental and applied physics.

The R&D programme of the GF started in 2017 with creation of the GF Working Group (currently consisting of 65 scientists from 23 institutes in 10 countries) within the Physics Beyond Colliders Study Group at CERN. It has already demonstrated the first important milestone, *i.e.* the ability to produce, accelerate and store the PSI beams within the CERN scientific infrastructure, particularly the SPS and the LHC. Now, it has entered the second phase: preparation of the Proof-of-Principle (PoP) experiment in the SPS and continuation of developing dedicated software tools. Results of the PoP experiment will be essential for the possible implementation of the GF in the LHC which is its ultimate goal.

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