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Chapter 21

Gamma Factory

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At the core of the Gamma Factory (GF) proposal[1] was the identification of an enormous, but thus far hidden, potential of the CERN accelerator infrastructure in conducting a new research programme at the crossroads of fundamental, particle, nuclear, atomic, and applied physics. All these disciplines could jointly profit from the novel research tools which can be created by the Gamma Factory facility. The key GF idea is to produce, accelerate, and store highly relativistic atomic beams in the LHC rings — acting as effective atomic traps — and to resonantly excite the atomic degrees of freedom of the beam particles by laser photons to: (1) cool atomic beams, and (2) produce high-energy, polarised photon beams. Their intensity can be, in the particularly interesting gamma-ray energy domain, higher than those of the presently operating light sources by at least seven orders of magnitude. Photons in this energy range are proposed to be used to produce unprecedented-intensity tertiary beams of polarised electrons, polarised positrons, polarised muons, neutrinos, neutrons, and radioactive ions. The LHC atomic traps, the laser-cooled nuclear beams, the high-intensity, polarised photon beams, and the tertiary beams constitute the principal research tools of the proposed GF facility.

1. Scientific context

It is highly unlikely that the next CERN high-energy frontier project will be approved, built, and become operational before the 2050's. The present LHC research programme will certainly reach its discovery saturation earlier, perhaps in the late 2030's. By then, there will be a strong need for a novel multidisciplinary research programme which could re-use (co-use) the existing CERN accelerator infrastructure (including LHC) in ways and at levels that were not conceived of when the machines were first designed.

The Gamma Factory (GF) facility and its research programme[1] can fulfill such a role. It can exploit the existing opportunities offered by the CERN accelerator complex (not available elsewhere) to conduct unique research in particle, nuclear, atomic, fundamental and applied physics.

The GF project's primary goal is to create *novel research tools and novel research methods*, rather than to execute predefined measurements. At the present moment, creating new research tools, or increasing the precision of the existing ones by several orders of magnitude is of particular importance for the accelerator-based research, since we neither have any hints for a new, high-energy frontier physics that is attainable with current existing technologies at a reasonable cost, nor a certainty that our discipline remains scientifically attractive — if it remains solely on the inertial and incremental-progress path.

Historically, new directions in science are launched by new tools much more often than by new theory concepts. The effect of a concept-driven revolution is to explain known phenomena in new ways. The effect of a tool-driven revolution is to discover new phenomena that will have to be explained.

2. Key principles

The primary goal of the GF project is to create and store new types of beams — the ultra-relativistic atomic beams of partially stripped ions (PSI) — and to exploit the atomic degrees of freedom of the beam particles. In the LHC rings, atomic beams can be stored at very high energies, over a large range of the Lorentz factor: $200 < \gamma_L < 3000$, at high bunch intensities: $10^8 < N_{\mathrm{bunch}} < 5 \times 10^9$, and a bunch repetition rate of up to 20 MHz.

Lasers tuned to the atomic transition frequencies can be used to manipulate such beams. The resonant excitation of atomic levels is possible due to the high energies of the ions. For the first time, utilising the large relativistic Lorentz factor γ_L of the LHC PSI beams, all the atomic degrees of freedom — including those of high-Z atoms — can be resonantly excited by the infrared, visible, UV or EUV laser photons, thanks to the Doppler upshift of the laser-photon energies by a factor of $2\gamma_L$. Besides, spontaneously emitted photons produced in the direction of the ion beam, when seen in the LAB frame, have their energies boosted by a further factor of $2\gamma_L$, so that the process of absorption and emission results in a frequency boost of the initial laser photon of up to $4\gamma_L^2$ (by a factor of $\sim 10^8$ for the LHC beams).

The atomic beams play, in the proposed scheme, the role of highly-efficient photon frequency converters. With the present circumferential voltage of the LHC cavities and the available state-of-the-art lasers, megawatt-class photon beams, in the energy range of 10 keV–400 MeV, can be efficiently produced by the Gamma Factory. The selective photon absorption and random emission naturally opens a unique path to a very efficient manipulation and collimation of high-energy hadronic beams. In particular, it provides new methods of longitudinal and transverse beam cooling, allowing significant boost to the luminosities of the present and future hadronic colliders.

3. Principal Gamma Factory research tools made out of light

3.1. *Traps for highly-charged, small size atoms*

Highly charged high-Z atoms, such as hydrogen-like or helium-like lead, are proposed to be used to probe the QCD vacuum and EW processes in compact atomic systems. They are of particular interest for the Atomic, Molecular and Optical (AMO) physics community because of their simplicity.[2] GF traps of highly-charged atoms allow the observation of the sample of $\sim 10^{10}$ atoms with 200 kHz observation/laser-manipulation frequency. Manipulation of these atoms with optical lasers becomes possible in GF owing to the large γ_L-factor of the trapped atoms. The first LHC operation with trapped hydrogen-like lead (208Pb81+) atoms demonstrated the trapping lifetime to be 20 hours at the LHC injection energy and 50 hours at top LHC energy.[3]

3.2. *High intensity polarised photon beams*

The concept of the GF photon source is illustrated in Fig. 1, and its characteristics can be summarised as follows:

- *point-like* — for high-Z, hydrogen- and helium-like atoms the distance between the laser photon absorption and fluorescence photon emission, $c\tau\gamma_L \ll 1$ cm;
- *very high intensity* — a leap in the intensity by at least seven orders of magnitude w.r.t. the electron-beam-based Inverse Compton Sources (ICS) (at the fixed γ_L and laser pulse power);

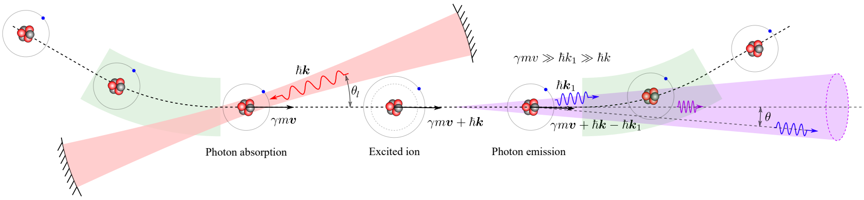

Fig. 1. The Gamma Factory concept. Laser photons with momentum $\hbar k$ (the primary photon beam) impinge onto ultra-relativistic ions (relativistic factor γ, mass m, velocity v) circulating in a storage ring. Resonantly scattered photons, as seen in the laboratory frame, are emitted in a narrow cone with an opening angle $\approx 1/\gamma$ in the direction of the motion of the ions. The energy of these secondary photons is boosted by a factor of up to $4\gamma^2$ with respect to the energy of the initial photons.

- *tuneable energy and polarisation* — the choice of: (1) the PSI beam energy (at the SPS or the LHC), (2) the ion Z and A, (3) the number of unstripped electrons, (4) the laser type, and (5) the laser light polarisation, allows to tune the secondary photon beam energy at CERN in the energy range of 10 keV–400 MeV (extending by a factor of $\sim$ 1000 the energy range of the present and future FEL X-ray sources and providing for the first time fully polarised gamma-beams);
- *high plug-power efficiency* — PSIs lose a tiny fraction of their energy in the process of the photon emission. There is thus no need to refill the stored PSI beam. The available LHC RF power can be fully converted to the power of the GF photon beam.

3.3. *Laser-cooled isoscalar ion beams for precision electroweak physics at LHC*

High-luminosity collisions of isoscalar nuclei at the LHC are optimal for the LHC electroweak (EW) precision measurement programme.[4] The use of the Ca nucleus — the isoscalar nucleus with the highest atomic mass A and the charge number, Z — opens, in addition, the possibility of observing direct production of the Higgs boson and its decays in photon-photon collisions. The GF proposal for HL-LHC with nuclear beams[5] is to: (1) cool transversely beams of lithium-like Ca ions at the flat-top SPS energy, (2) strip the electrons in the SPS-to–LHC transfer line, and (3) collide the small transverse emittance Ca beams in the LHC.

3.4. *High intensity GF sources of tertiary beams*

The high-intensity photon beams with tuneable energy and polarisation open new and highly-efficient ways of creating tertiary beams of polarised electrons and positrons, polarised muons, pions, neutrinos, neutrons, and radioactive ions of unprecedented intensity — exceeding, by up to 4 orders of magnitude, the intensity of the present sources.[6,7] Polarised leptons can be produced by conversions of the GF photons in the EM field of stationary atoms.[8] Pions, produced abundantly by the photo-excitation of Δ-resonances, are proposed to drive the high-intensity, low-emittance, GF muon source.[8] Muons, following their quick PWFA acceleration,[a] can be used to produce high-purity neutrino and antineutrino beams. Thanks to the muon polarisation, muon-neutrino (muon-antineutrino) beams could be separated from the electron-antineutrino (electron-neutrino) ones on the bases of their respective angular distributions.[10] Neutrons and radioactive ions can be produced by photo-excitation of the giant dipole resonances[11] and by exciting nuclear fission resonances.[12] The GF leap in the neutron source intensity, and in the rate of the fission processes, can open new avenues: (1) for the development of the photon-beam-driven advanced energy source based on subcritical reactor, and (2) for the highly efficient transmutation of nuclear waste products.

3.5. *Electron beam for ep collisions in the LHC interaction points*

The hydrogen-like or helium-like lead beams can be considered as the carriers of the effective electron beams circulating in the LHC rings. Collisions of such a beam with the counter propagating beam of protons provides a unique, costless option to study the electron-proton collisions in the existing LHC detectors.[13]

3.6. *Drive beams for plasma wakefield acceleration*

The GF high-intensity, laser-cooled atomic beams can play the role of efficient driver beams for hadron-beam-driven plasma wakefield acceleration.[14] Electrons exploited initially in the cooling and micro-bunching process of the driver beam can be subsequently used — following their stripping — to form a precisely synchronised electron witness bunches.[15]

[a]They can reach energy of 10 GeV over the distance of ≈ 3 m.[9]

4. GF project milestones and status

The path towards full feasibility proof of the GF concepts is landmarked by the following six milestones: (1) demonstration of efficient production, acceleration, and storage of atomic beams in the CERN accelerator complex; (2) development of the requisite GF simulation tools; (3) building up the physics cases for the GF research program and attracting wide scientific communities to evaluate the merits of the GF tools in their respective research; (4) successful execution of the GF Proof-of-Principle (PoP) experiment at SPS; (5) verification of the GF performance parameters on the basis of the PoP experiment results and simulations; (6) elaboration of the GF Technical Design Report (TDR).

The first three of the six milestones have been already achieved.[3,16–21] The present status of the software development was summarised at the recent GF software workshop at CERN.[22] So far, about one hundred physicists contributed to the GF project's development. The recent studies of the physics highlights of the GF research programme has been published in a special issue of the "Annalen der Physik" journal.[23] The GF PoP experiment has already been designed[24] and its proposal, presented to the SPSC. The GF R&D on the low phase-noise laser system has achieved its goals.[25] Dedicated SPS beam tests with hydrogen-like and helium-like lead ions were performed — demonstrating sufficient stability of the atomic lead beams in the SPS and LHC rings. The GF-PoP experiment is waiting for the "go-ahead' decision by CERN.

5. Outlook

If realised, the proposed GF facility, shown in Fig. 2, can inject a new scientific life to the LHC storage rings, following the completion of its HL-LHC programme, by addressing new research domains in atomic, nuclear, particle, fundamental and applied physics with novel research tools of unprecedented quality. The GF research tools can significantly increase the LHC discovery potential. Such an unexpected bonus should not be missed.

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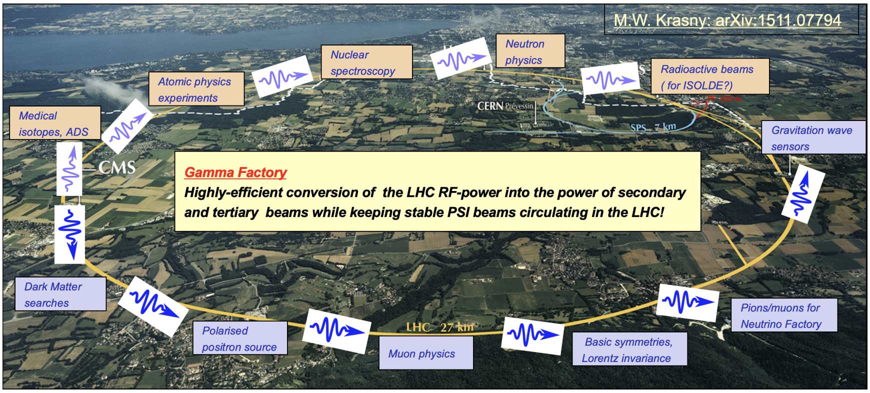

Fig. 2. The schematic view of the proposed LHC-based Gamma Factory facility. Two counter propagating, but non-interacting PSI beams, collide with the laser photons in eleven, application-specific, collision points. The clock-wise moving beam drives the low energy GF applications (highlighted with the yellow colour), while the anti-clock-wise beam drives the high energy GF applications (highlighted with the blue colour).

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