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Gamma Factory:
A novel research programme for CERN

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"New directions in science are launched by new tools more often than by new concepts."
At the current stage of accelerator-technology-based research, where conventional methods have reached the saturation limits of particle beam energy and intensity, the Gamma Factory (GF) project proposes breakthroughs in beam intensity (up to seven orders of magnitude), quality (low emittance, polarization with CP tagging, and flavor tagging), and precision control for several types of particle beams. The Gamma Factory can produce primary (ions), secondary (photons), and tertiary (polarized positrons, muons, neutrinos, neutrons, and radioactive ions) beams with unprecedented wall-plug-to-beam power efficiency—outperforming existing schemes by several orders of magnitude. GF aims to extend CERN's scientific program across multiple domains of research (particle, nuclear, atomic, astrophysics, accelerator, and applied physics) with reasonable investment costs by reusing CERN's existing accelerator infrastructure. Its environmental impact is expected to be minimal, as the plug power required for its research program could be generated by a novel GF-beam-driven, waste-transmuting, subcritical nuclear reactor. New GF beam-cooling techniques and innovative methods for producing polarized muon beams could improve the precision of Standard Model parameter measurements and enable the first observation of exclusive production of Higgs bosons in photon–photon collisions. If implemented at CERN, the GF experimental program could follow the HL-LHC phase and be carried out during the preparation period for the next large-scale, energy-frontier accelerator. This contribution presents the ongoing GF R&D studies, including the recent world record in laser–photon beam power, the status of the GF proof-of-principle SPS experiment, and selected highlights from the latest quantitative analyses of GF research applications.

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1. Rationale behind the Gamma Factory initiative

The maximal intensities of CERN's PS, PS-Booster, and SPS-extracted beams have already been achieved. The maximal luminosities of LHC proton–proton and ion–ion collisions will be reached at the beginning of the 2030s. At that point, new paradigms for reusing the existing CERN accelerator infrastructure will be urgently needed to bridge the gap between the end of the HL-LHC phase and the launch of a next-generation, high-energy frontier research program. The Gamma Factory (GF) multidisciplinary research program [1–4] offers a cost-effective solution by providing unprecedented intensity particle beams produced with high wall-plug-to-beam efficiency, along with novel research tools which include:

- Atomic traps of highly charged atoms [5–7].
- Polarized [8, 9] and twisted [10] gamma-ray beams with intensities at least seven orders of magnitude higher than current and future gamma-ray sources.
- Novel high-intensity sources of polarized electrons, polarized positrons [11], polarized muons [11], CP- and flavor-tagged neutrinos, neutrons [12], and radioactive ions [13], exceeding the present source intensities/brightness by more than three orders of magnitude.
- Laser cooling methods for high-energy beams [14, 15], enabling unprecedented precision in beam control and high partonic luminosities in hadron colliders [16, 17].
- A novel GF photon-beam-driven energy source capable of covering the plug power consumption of CERN's accelerator infrastructure [12].
- An electron beam that can be delivered to the LHC interaction points for ep collisions [18].

2. Basic principles

The Gamma Factory project proposes storing atomic beams of partially stripped ions (PSIs) in the SPS or LHC and colliding them with laser pulses to produce photon beams with tunable energy, polarization, and intensity for: (1) photon-beam-driven research and (2) the production of polarized electrons, positrons, muons, neutrons, and radioactive ions through collisions with dedicated targets. This is illustrated in Fig. 1.

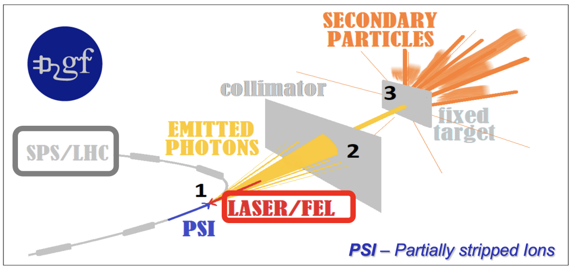


Figure 1: GF in a nutshell: Partially Stripped Ions (PSIs) circulating in the SPS/LHC rings collide with laser photons and produce secondary photon and tertiary beams.

In the GF scheme, high-energy PSI beams act as passive frequency converters, boosting the laser-photon energies from the eV range to the keV or MeV range, depending on the choice of beam energy, atomic number A, charge Z, and the laser wavelength. The laser photon energy is boosted by a factor of up to $4\gamma_L^2$, where γ_L is the Lorentz factor of the PSI beam. The intensity gain of this scheme—compared to canonical electron-beam–driven gamma-ray sources, shown in Fig. 2—results from the dramatic increase in the photon-beam particle cross section when the laser wavelength is tuned to a selected atomic resonance.

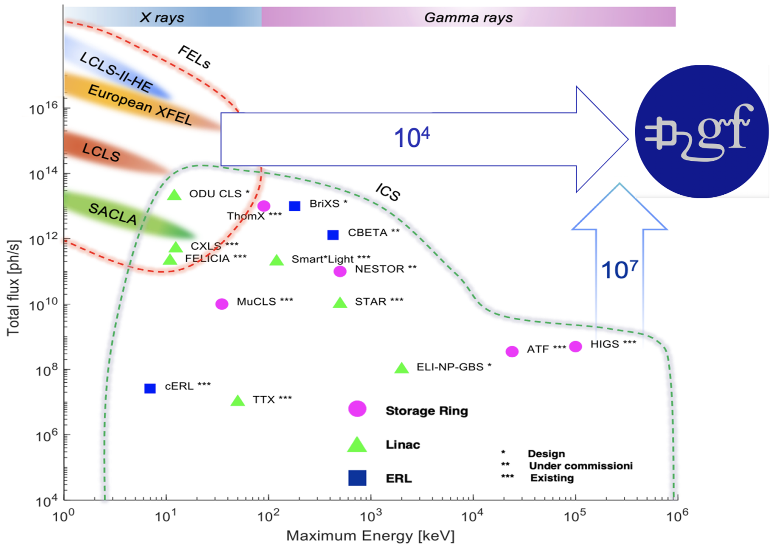


Figure 2: Expected Gamma Factory photon fluxes — comparison with the existing electron-beam-driven and FEL-driven photon sources.

Gamma Factory exploits resonant photon scattering over a wide energy range. GF laser photons excite atomic resonances. GF energy-boosted photons can excite nuclear Giant Dipole Resonances (GDR) or nucleon Δ resonances. The GF beam-cooling methods enhance the luminosity of ion-beam–driven photon–photon colliders, enabling the observation of exclusive, resonant Higgs boson production. The energy scales involved in the above processes, together with the corresponding resonant cross sections, are shown in Fig. 3.

3. Gamma Factory beams

Beams of unpolarized or polarized hydrogen-like and helium-like ions. These beams can open new research opportunities in atomic and nuclear physics [5, 6, 19]. They can be controlled with a precision unattainable by conventional beams. For example, the current absolute LHC beam energy calibration precision could be improved by two to three orders of magnitude [9], as illustrated in Fig. 4. The internal (atomic) degrees of freedom of hydrogen-like and helium-like ion beams allow their stability to be controlled on the microsecond timescale with lasers—opening the possibility of detecting gravitational waves with high-energy storage rings [20].

Beams of small-emittance, fully stripped ions. These beams can be used for high-precision studies of electroweak phenomena. The GF beam-cooling methods [14, 15] allow the longitudinal

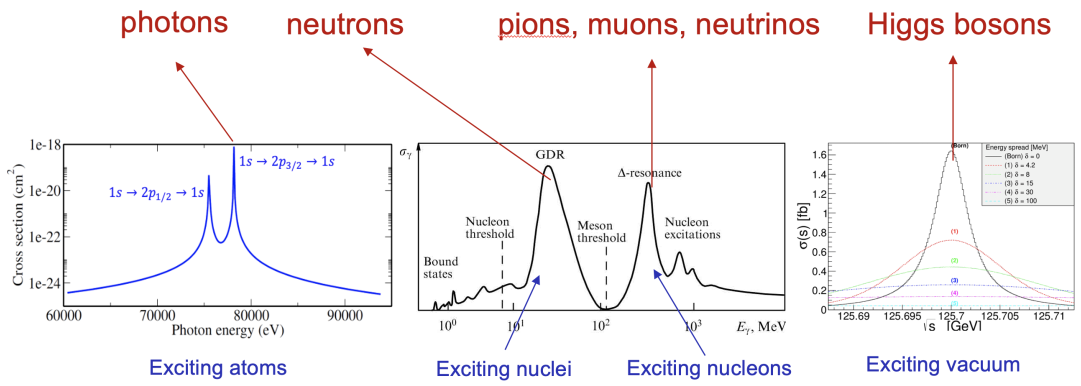


Figure 3: Photon collision resonances in the eV to GeV energy range. The particles produced in the resonant photon collisions are shown in red.

and transverse beam emittances of ion beams to be reduced within seconds. Cold isoscalar ion beams, ensuring the symmetry of down and up quarks, are optimal for improving the present measurement precision of SM electroweak parameters [14, 16]. In addition, cold ion beams could boost photon–photon collision luminosity in peripheral ion collisions, enabling the observation of exclusive Higgs boson production at the LHC. A comparison of Higgs boson production rates in the GF scheme with those of FCC-ee and LHeC is presented in Fig. 5.

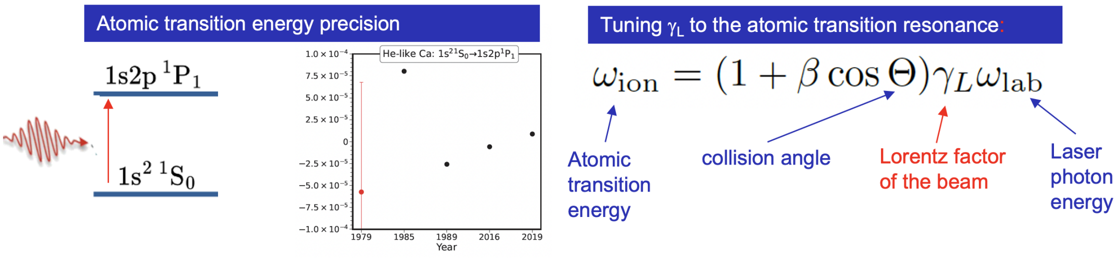


Figure 4: Progress in the calculation precision of the transition energies in helium-like calcium atoms. The beam energy calibration precision is driven by the precision of the calculation of the atomic transition energies according to the formula on the RHS of the figure. For more information, see [9].

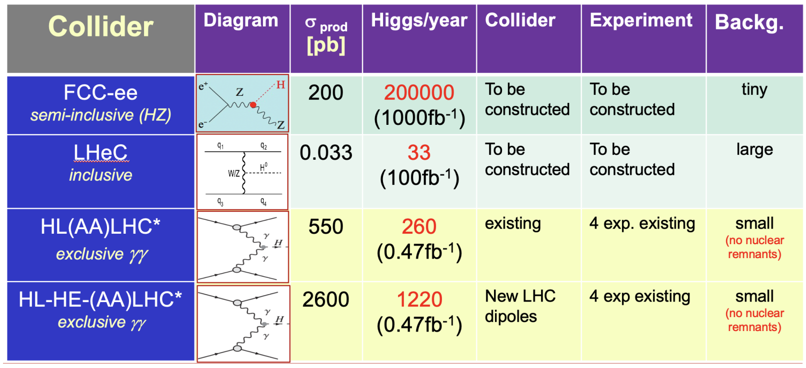
Beams of nuclear isomers. A notable example is a beam of $^{229\mathrm{m}}$Th ions [21], a candidate for a nuclear clock [21, 22].

Electron beam. GF can deliver electron bunches with a 20 MHz repetition frequency to the current ATLAS, CMS, LHCb, and ALICE interaction points on the LHC ring [18].

Photon beams. The GF photon beams have unique properties:

- they originate from a point-like source and are characterized by a sub-milliradian divergence,
- they allow for an intensity increase of more than 7 orders of magnitude, reaching fluxes of 10^{18} photons/second,
- their energies can be tuned within the range 10 keV–400 MeV, extending the energy range of FEL photon sources by a factor of more than 1000 at comparable, or higher, beam intensities,

- photon polarization can be precisely tuned by using the Pauli blocking principle,
- they can be produced with unprecedented efficiency—the wall-plug power efficiency of the GF photon source is expected to be a factor of 300 better than that of DESY-XFEL.



Collider	Diagram	σ prod [pb]	Higgs/year	Collider	Experiment	Backg.
FCC-ee *semi-inclusive (HZ)*		200	200000 (1000fb^{-1})	To be constructed	To be constructed	tiny
LHeC *inclusive*		0.033	33 (100fb^{-1})	To be constructed	To be constructed	large
HL(AA)LHC* *exclusive $\gamma\gamma$*		550	260 (0.47fb^{-1})	existing	4 exp. existing	small (no nuclear remnants)
HL-HE-(AA)LHC* *exclusive $\gamma\gamma$*		2600	1220 (0.47fb^{-1})	New LHC dipoles	4 exp existing	small (no nuclear remnants)

Figure 5: The Higgs production diagrams, cross-sections, and production rates for the FCC-ee, LHeC, HL(AA)LHC, and HL-HE(AA)LHC. The HL(AA)LHC and HL-HE(AA)LHC options assume using the existing or energy-upgraded (HE) [23] CERN accelerator infrastructure complemented by the Gamma Factory PSI-beam cooling at the SPS [24], stochastic cooling [25] at the LHC injection energy, and BNL-like performance of the ion injection and storage system [26]. For more info, see [24].

High-intensity GF photon beams can open new research opportunities, including high-precision tests of fundamental symmetries of the universe [27], dark matter searches [28, 29], vacuum property studies [30], or precision studies of pionic atoms [31].

Polarized muon beam. It can be produced by the high-intensity GF photon beam colliding with an external target [11]. Its energy is tuned to excite Δ resonances in the target nuclei. Such collisions produce, exclusively, quasi-monochromatic pions. The spectral density of pions is shown in Fig. 6. For the monochromatic pion source, muon polarization is determined uniquely by the muon emission angle. The GF muon source could outperform current proton-beam-driven muon sources by two to three orders of magnitude, achieving intensities of up to 7×10^{13} $\mu^+(\mu^-)$ per second.

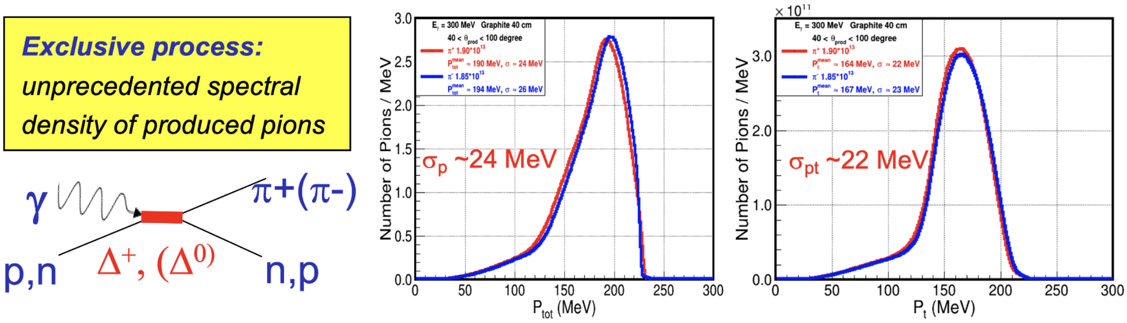


Figure 6: Spectral density and rates of pions produced by an optimal Gamma Factory photon beam [11] exciting Δ resonances in the target isoscalar nuclei, ensuring charge symmetry of the produced pions. For more info, see [11].

Polarized positron beam. Such a beam can be produced by converting circularly polarized photons into electron–positron pairs using the high-intensity GF photon beam, colliding with a stationary target. Polarized positron fluxes of 10^{16} e^{+}/sec can be achieved in such a scheme [11].

Quasi-monochromatic neutron beam. Such a beam can be produced by colliding the GF photon beam with a high-Z target. The energy band of the photon beam can be optimized to cover the region of the Giant Dipole Resonance (GDR). Neutrons, generated in such a scheme, could drive the Advanced Nuclear Energy System (ANES) [12]. The GF-beam-driven ANES is capable to produce the requisite plug power to execute the GF research program and transmute its loaded and produced nuclear waste, as shown in Fig. 7.

4. Feasibility studies

Extensive feasibility studies have been performed to validate the underlying Gamma Factory concepts. Efficient production, storage, and operation of the atomic beams in the SPS and LHC have been demonstrated [32–37]. The optical system for the GF Proof-of-Principle experiment, at the CERN's Super Proton Synchrotron, has been designed [38]. Stable and high-power (world record of 700 kW stored average power) operation of the Fabry–Perot cavity has been demonstrated [39–41]. The required precision of beam steering at the collision point of laser pulses with atomic beam bunches has been achieved in dedicated beam tests [37]. The software required to simulate the production of atomic beams, GF photon beams, and secondary beams produced in collisions of photon beams with stationary targets has been created and benchmarked [17, 42, 43]. The successful implementation of the GF requires the validation of the following additional requirements:

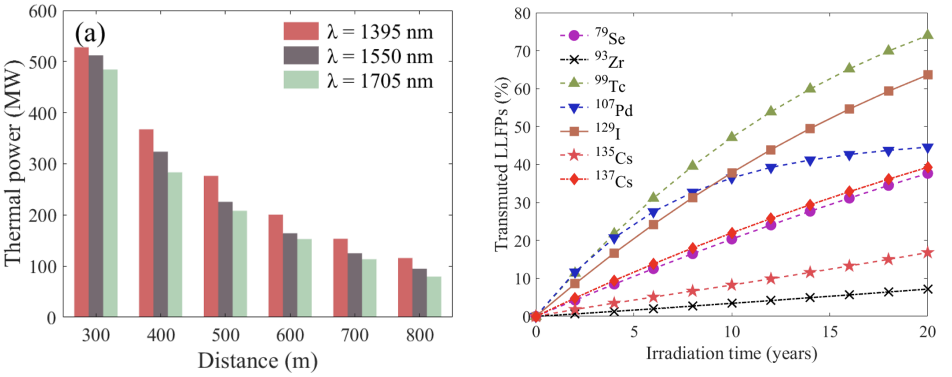


Figure 7: LHS: thermal power of the Gamma-Factory-beam-driven nuclear reactor for three laser-photon wavelengths; RHS: the long-lived fission product transmutation capacity of the GF-beam-driven ANES system. For more info, see [12].

- stable laser transport and injection of the laser beam into the long Fabry–Perot cavity with fully remote controls and diagnostics. The beam stability is comparable to that of the interferometric systems of the Laser Interferometer Gravitational-Wave Observatory (LIGO);
- fully remote and continuous operation of the laser source system in a high-intensity hadron accelerator tunnel,

- operational tools to guarantee the requisite control of the PSI beam momentum and its spread, and the spatial and temporal overlap of the ion and laser beams in a reproducible fashion;
- agreement between simulations and measurements of atomic excitation and ion beam cooling rates;
- atomic and photon beam diagnostic methods to measure and characterize the photon flux.

The Gamma Factory Proof-of-Principle (PoP) experiment [44] was proposed to validate the Gamma Factory operational aspects in the most challenging SPS environment.

5. Proof-of-Principle experiment at the SPS

The Gamma Factory Proof-of-Principle experiment location is presented in Fig. 8. The modeling of the radiation environment at the GF SPS PoP experiment site has been performed [45] and measurements are ongoing to validate them. Procurement of an ultra-low phase-noise laser and amplification chain is being finalized. The final design of the controls and diagnostics of the laser beam transport system and optical cavity is in progress, with dedicated studies on stabilization reported in [46].

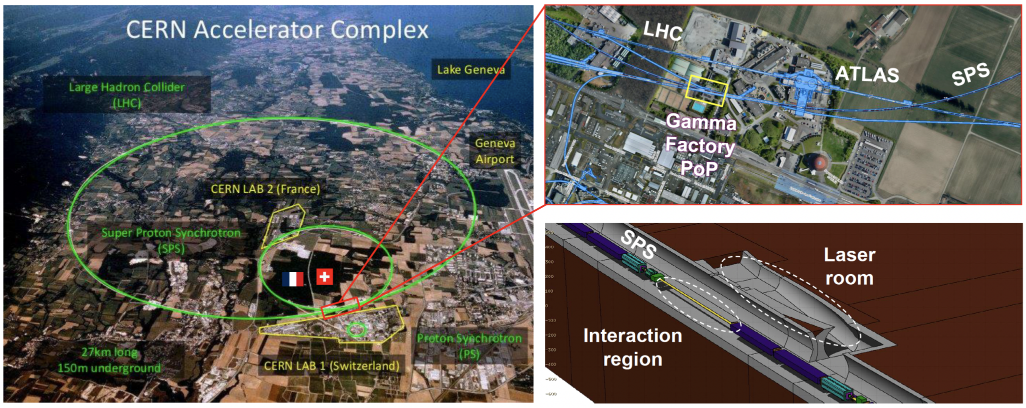


Figure 8: GF PoP experiment location and its laser room layout.

6. Conclusions

The Gamma Factory can create, at CERN, a wide range of novel beams and experimental tools, opening research opportunities across both fundamental and applied sciences, well beyond the high-energy physics domain. Its program reuses CERN's existing accelerator infrastructure in innovative ways and requires only modest new investments. The project's emphasis on research diversity is especially relevant today, as there is neither clear theoretical guidance suggesting imminent new physics within reach of future colliders such as FCC, ILC, or CLIC, nor an affordable technology for a major leap into unexplored very-high-energy domains. The final step of the feasibility proof is the execution of the SPS Gamma Factory PoP experiment. A key remaining open question is whether CERN's community and management will embrace new research paradigms and the broader scientific collaborations that would share its accelerator infrastructure.

References

[1] M. W. Krasny, “The Gamma Factory proposal for CERN: Executive Summary,” hep-ex 1511.07794 November, 2015.

[2] M. W. Krasny, “Gamma Factory,” in *The Future of the Large Hadron Collider: A Super-Accelerator with Multiple Possible Lives* (O. Brüning, M. Klein, L. Rossi, and P. Spagnolo, eds.), pp. 297–303, Singapore: World Scientific, November 2023.

[3] A. Wu Chao, M. Tigner, H. Weise, and F. Zimmermann, eds., *Handbook of Accelerator Physics and Engineering, Gamma Factory chapter*. World Scientific, 2 2023.

[4] D. Budker, M. Gorchtein, M. W. Krasny, A. Pálffy, and A. Surzhykov, “Physics Opportunities with the Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2200004, 2022.

[5] D. Budker *et al.*, “Atomic Physics Studies at the Gamma Factory at CERN,” *Annalen Phys.*, vol. 532, no. 8, p. 2000204, 2020.

[6] D. Budker *et al.*, “Expanding Nuclear Physics Horizons with the Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2100284, 2021.

[7] M. S. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, and C. W. Clark, “Search for New Physics with Atoms and Molecules,” *Rev. Mod. Phys.*, vol. 90, no. 2, p. 025008, 2018.

[8] A. Volotka, D. Samoilenko, S. Fritzsche, V. G. Serbo, and A. Surzhykov, “Polarization of Photons Scattered by Ultra-Relativistic Ion Beams,” *Annalen Phys.*, vol. 534, no. 3, p. 2100252, 2022.

[9] J. Richter, M. W. Krasny, J. Gilles, and A. Surzhykov, “Resonant photon scattering in the presence of external fields and its applications for the CERN Gamma Factory project,” *Phys. Rev. A*, vol. 111, no. 6, p. 062820, 2025.

[10] V. G. Serbo, A. Surzhykov, and A. Volotka, “Resonant Scattering of Plane-Wave and Twisted Photons at the Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2100199, 2022.

[11] A. Apyan, M. W. Krasny, and W. Płaczek, “Gamma Factory high-intensity muon and positron source: Exploratory studies,” *Phys. Rev. Accel. Beams*, vol. 26, no. 8, p. 083401, 2023.

[12] H. Baolong, M. W. Krasny, W. Placzek, Y. Yuan, X. Shi, K. Luo, and W. Luo, “Efficient transmutation of long-lived fission products in a Gamma Factory beam driven advanced nuclear energy system,” *Sci. Rep.*, vol. 15, no. 1, p. 12562, 2025.

[13] D. Nichita, D. L. Balabanski, P. Constantin, M. W. Krasny, and W. Placzek, “Radioactive Ion Beam Production at the Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2100207, 2022.

[14] M. W. Krasny, A. Petrenko, and W. Płaczek, “High-luminosity Large Hadron Collider with laser-cooled isoscalar ion beams,” *Prog. Part. Nucl. Phys.*, vol. 114, p. 103792, 2020.

PoS(EPS-HEP2025)579

[15] P. Kruyt, D. Gamba, and G. Franchetti, “Simulation studies of laser cooling for the Gamma Factory proof-of-principle experiment at the CERN SPS,” *JACoW*, vol. IPAC2024, p. MOPS50, 2024.

[16] W. Płaczek and M. W. Krasny, “Gamma Factory and Precision Physics at the LHC,” *Acta Phys. Polon. Supp.*, vol. 17, no. 5, p. A28, 2024.

[17] W. Placzek *et al.*, “Gamma Factory at CERN - Novel Research Tools Made of Light,” *Acta Phys. Polon. B*, vol. 50, no. 6, pp. 1191–1203, 2019.

[18] M. W. Krasny, “Electron beam for LHC,” *Nucl. Instrum. Meth. A*, vol. 540, pp. 222–234, 2005.

[19] J. Bieroń, M. W. Krasny, W. Placzek, and S. Pustelny, “Optical Excitation of Ultra-Relativistic Partially Stripped Ions,” *Annalen Phys.*, vol. 534, no. 3, p. 2100250, 2022.

[20] T. Schmirander, V. Miltchev, S. Rao, M. Brüggen, F. Grüner, W. Hillert, and J. Liske, “Concept study of a storage ring-based gravitational wave observatory: Gravitational wave strain and synchrotron radiation noise,” *Phys. Rev. D*, vol. 110, no. 8, p. 082002, 2024.

[21] J. Jin, H. Bekker, T. Kirschbaum, Y. A. Litvinov, A. Pálffy, J. Sommerfeldt, A. Surzhykov, P. G. Thirolf, and D. Budker, “Excitation and probing of low-energy nuclear states at high-energy storage rings,” *Phys. Rev. Res.*, vol. 5, no. 2, p. 023134, 2023.

[22] P. G. Thirolf, B. Seiferle, and L. von der Wense, “The 229-thorium isomer: doorway to the road from the atomic clock to the nuclear clock,” *J. Phys. B*, vol. 52, no. 20, p. 203001, 2019.

[23] O. Bruning, O. Dominguez, S. Myers, L. Rossi, E. Todesco, and F. Zimmermann, “HE-LHC beam-parameters, optics and beam-dynamics issues,” in *EuCARD HE-LHC10 AccNet mini-workshop on a High-Energy LHC*, 8 2011.

[24] M. W. Krasny, A. Petrenko, and W. Płaczek, “The Gamma Factory path to high-luminosity LHC with isoscalar beams,” *PoS*, vol. ICHEP2020, p. 690, 2021.

[25] J. Jarvis *et al.*, “Experimental demonstration of optical stochastic cooling,” *Nature*, vol. 608, no. 7922, pp. 287–292, 2022.

[26] W. Fischer *et al.*, “RHIC Performance with Stochastic Cooling for Ions and Head-on Beam-beam Compensation for Protons,” in *7th International Particle Accelerator Conference*, p. WEZA01, 2016.

[27] B. Wojtsekhowski and D. Budker, “Local Lorentz Invariance Tests for Photons and Hadrons at the Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2100141, 2022.

[28] R. Balkin, M. W. Krasny, T. Ma, B. R. Safdi, and Y. Soreq, “Probing Axion-Like-Particles at the CERN Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2100222, 2022.

[29] S. Chakraborti, J. L. Feng, J. K. Koga, and M. Valli, “Gamma factory searches for extremely weakly interacting particles,” *Phys. Rev. D*, vol. 104, no. 5, p. 055023, 2021.

[30] F. Karbstein, “Vacuum Birefringence at the Gamma Factory,” *Annalen Phys.*, vol. 534, no. 3, p. 2100137, 2022.

[31] V. V. Flambaum, J. Jin, and D. Budker, “Resonance photoproduction of pionic atoms at the proposed Gamma Factory,” *Phys. Rev. C*, vol. 103, no. 5, p. 054603, 2021.

[32] S. Hirlaender *et al.*, “Lifetime and Beam Losses Studies of Partially Strip Ions in the SPS (^{129}Xe^{39+}),” in *9th International Particle Accelerator Conference*, 6 2018.

[33] F. M. Kröger *et al.*, “Charge state tailoring of relativistic heavy ion beams for the Gamma Factory project at CERN,” *X Ray Spectrom.*, vol. 49, no. 1, pp. 25–28, 2019.

[34] Y. Dutheil *et al.*, “Gamma Factory for CERN initiative - progress report,” *PoS*, vol. EPS-HEP2019, p. 020, 2020.

[35] A. Gorzawski *et al.*, “Collimation of partially stripped ions in the CERN Large Hadron Collider,” *Phys. Rev. Accel. Beams*, vol. 23, no. 10, p. 101002, 2020.

[36] M. Schaumann *et al.*, “MD3284: Partially Stripped Ions in the LHC,” Tech. Rep. CERN-ACC-NOTE-2019-0012, CERN-PBC-Note-2021-019, CERN, 2019.

[37] R. L. Ramjiawan *et al.*, “SPS MD5044: machine stability characterisation of Gamma Factory SPS Proof-of-Principle Experiment,” Tech. Rep. CERN-ACC-NOTE-2022-0014, CERN-PBC-Notes-2022-006, CERN, 2022.

[38] A. Martens *et al.*, “Design of the optical system for the gamma factory proof of principle experiment at the CERN Super Proton Synchrotron,” *Phys. Rev. Accel. Beams*, vol. 25, no. 10, p. 101601, 2022.

[39] X. Y. Lu *et al.*, “Stable 500 kW average power of infrared light in a finesse 35 000 enhancement cavity,” *Appl. Phys. Lett.*, vol. 124, no. 25, p. 251105, 2024.

[40] E. Granados *et al.*, “Prospects for extreme light sources at the CERN accelerator complex,” in *High-Brightness Sources and Light-Driven Interactions Congress*, p. ETu3A.3, Optica Publishing Group, 9 2024.

[41] X. Y. Lu *et al.*, “710 kW stable average power in a 45,000 finesse two-mirror optical cavity,” *Opt. Lett.*, vol. 49, no. 23, pp. 6884–6887, 2024.

[42] C. Curatolo, M. Krasny, W. Placzek, and L. Serafini, “New Simulation Programs for Partially Stripped Ions - Laser Light Collisions,” in *9th International Particle Accelerator Conference*, 6 2018.

[43] M. W. Krasny, A. Petrenko, and W. Placzek, “BE-ABP Gamma Factory Software Workshop,” 2021.

[44] M. W. Krasny *et al.*, “Gamma Factory Proof-of-Principle experiment - Letter of Intent,” Tech. Rep. CERN-SPSC-2019-031, SPSC-I-253, CERN, 2019.

[45] G. Mazzola *et al.*, "Radiation to electronics studies for CERN gamma factory-proof of principle experiment in SPS," *JACoW*, vol. IPAC2024, p. TUPC80, 2024.

[46] E. Granados, Y. Dutheil, B. Marsh, and G. Arduini, "Laser beam transport and stabilization considerations for the Gamma Factory proof-of-principle experiment," Tech. Rep. CERN-PBC-Notes-2023-007, CERN, 2023.