ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEYGBD3

THE CERN GAMMA FACTORY INITIATIVE: AN ULTRA-HIGH INTENSITY GAMMA SOURCE

M. W. Krasny
LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France and CERN, Geneva, Switzerland
P. S. Antsiferov, Institute of Spectroscopy, Russian Academy of Science, Moscow, Russia
A. Apyan, A. I. Alikhanyan National Science Laboratory, Yerevan, Armenia
E. G. Bessonov, V. P. Shevelko, P. N. Lebedev Physical Institute, Moscow, Russia
D. Budker, Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany;
K. Cassou, I. Chaikovska, R. Chehab, K. Dupraz, A. Martens, F. Zomer, LAL Orsay, France
F. Castelli, C. Curatolo, V. Petrillo, L. Serafini
Department of Physics, INFN-Milan and University of Milan, Milan, Italy
H. Bartosik, N. Biancacci, P. Czodrowski, B. Goddard, J.M. Jowett, R. Alemany Fernandez,
S. Hirlander, R. Kersevan, M. Kowalska, M. Lamont, D. Manglunki, A. Petrenko, M. Schaumann,
C. Yin-Vallgren, F. Zimmermann,
CERN, Geneva, Switzerland
J. Bieron, K. Dzierzega, W. Placzek, S. Pustelny, Jagiellonian University, Krakow, Poland
F. Kroeger, T. Stoehlker, G. Weber, HI Jena, IOQ FSU Jena and GSI Darmstadt, Germany
Y. K. Wu, FEL Laboratory, Duke University, Durham, USA
M. S. Zolotorev, Center for Beam Physics, LBNL, Berkeley, USA.

Abstract

This contribution discusses the possibility of broadening the present CERN research programme by a new component making use of a novel concept of the light source. The proposed, Partially Stripped Ion beam driven, light source is the backbone of the Gamma Factory initiative. It could be realized at CERN by using the infrastructure of the already existing accelerators. It could push the intensity limits of the presently operating light-sources by 7 orders of magnitude, reaching the flux of up to 10^{17} photons/s. It could operate in the particularly interesting γ-ray energy domain of $1 \leq E_\gamma \leq 400$ MeV. This domain is out of reach for the FEL-based light sources based on sub-TeV energy-range electron beams. The unprecedented-intensity, energy-tuned, gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrinos, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. A broad spectrum of new opportunities, in a vast domain of uncharted fundamental and applied physics territories, could be opened by the Gamma Factory research programme.

MEV-RANGE LIGHT SOURCES

The light sources in the discussed MeV energy range have already been constructed and are operating in several countries: HIγS-USA, LEPS-Japan, LADON-Italy, ROKK-1-Russia, GRAAL-France and LEGS-USA. The leading future project entering the construction phase is the European Union project ELI-NP. The ELI-NP facility is expected to produce the flux of 10^{13} photons/s with the maximal energy of 20 MeV. The highest photon flux which has been achieved so far is 10^{10} photons/s.

All the above facilities generate, or are expected to generate, the photon beams by the process of the inverse Compton scattering of the laser photons on the highly relativistic electron beams. Since the cross section of the inverse Compton process is small, in the $O(1$ barn$)$ range, in order to achieve the quoted above fluxes, the laser system and the energy recovery linac technologies had to be pushed to their technological limits.

THE GAMMA FACTORY PROPOSAL

The idea underlying the Gamma Factory proposal [1] is to use Partially Stripped Ion (PSI) beams, instead of electron beams, as the drivers of its light source[1]. The PSI beams are the beams of ions carrying one or more electrons which have not been stripped along the way from the ion source to the final PSI beam storage ring. In the process of the resonant absorption of the laser photons by the PSI beam, followed by a spontaneous atomic-transition emissions of secondary photons, the initial laser-photon frequency is boosted by a factor of up to $4 \times \gamma_L^2$, where γ_L is the Lorenz factor of the partially stripped ion beam. Therefore, the light source in the energy range of $1 \leq E_\gamma \leq 400$ MeV must be driven by the high-γ_L, LHC-stored, PSI beams. CERN is a unique place in the world where such a light source could be realized.

The cross-section for the resonant absorption of laser photons by atomic systems is in the **giga-barn range**, while the cross section for the point-like electrons is in the **barn range**. As a consequence, the PSI-beam-driven light source intensity could be higher than those of the electron-beam-driven ones by a large factor. For the light source working

[1] For the discussion of the light sources based on PSI beams see e.g. [2] and the references quoted therein.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEYGBD3

in the regime of multiple photon absorption and emission cycles by each of the beam ions, the photon beam intensity is expected to be limited no longer by the laser light intensity but by the available RF power of the ring in which partially stripped ions are stored. For example, the flux of up to 10^{17} photons/s could be achieved for photon energies in the 10 MeV region already with the present, U = 16 MV, circumferential voltage of the LHC cavities. This photon flux is by a factor of 10^7 higher than that of the highest-intensity electron-beam-driven light source, HIγS@Durham, operating in the same energy regime.

If photon beams carrying more than O(100 kW) of beam-power can be safely handled, and if the present circumferential voltage could be increased (at LEP2 the corresponding value was 3560 MV), even higher fluxes could be generated.

PSI BEAMS AT CERN

The first steps to understand the storage stability of the PSI beams were already made at BNL. The $^{77+}$Au beam with two unstripped electrons was successfully circulating in the AGS ring at BNL and, more recently, in its RHIC ring [3]. These tests may be considered as a departure point for further beam tests which have been and will be carried out over the year 2018 – firstly at the CERN SPS and, if successful, at the LHC.

If stable PSI beams could be produced and stored in the CERN rings, they would not only drive the photon source, but could also be used for the following four unconventional applications.

Firstly, they would allow the LHC to operate as an **electron–proton(ion) collider** [4]. The LHC experiments could simply record collisions of electrons, brought to LHC experiment's interaction points "on the shoulders" of the ion-carriers, with the counter-propagating proton(ion) beam.

Secondly, they may turn out to be efficient driver beams for the hadron beam driven plasma-wakefield acceleration [5] of a witness beam. This is because the PSI bunches, contrary to the proton bunches, could be very efficiently cooled by the Doppler laser cooling techniques, allowing to compress their bunch sizes. A profit could thus be made from the fact that the maximal achievable plasma electric field acceleration gradient increases quadratically with the decreasing bunch length of the driver beam.

Thirdly, the PSI beams of isoscalar ions, Doppler-cooled at the SPS, could be stripped of the remaining electrons in the transfer line between SPS and LHC, before injection to the LHC rings. By using the low emittance beams the nucleon–nucleon luminosity can be significantly increased at the LHC. By using the low emittance, **isoscalar beams** systematic uncertainty of measuring the Standard Model parameters at the LHC could be significantly reduced with respect to the measurements using proton beams.

Fourthly, they could provide new possibilities for precision electroweak measurements in hydrogen-like high-Z atoms for indirect searches of new, Beyond the Standard Model (BSM), effects.

It remains to be stressed that a large fraction of the beam cooling and beam manipulation techniques exploiting the internal degrees of freedom of the beam particles, which have been mastered over three decades by the atomic physics community, could be directly applied to the high energy PSI beams.

PHOTON COLLISION SCHEMES

High intensity and high brilliance gamma beams could be used to realize, for the first time, a **photon-photon collider at CERN**: (1) in the range of CM energies of 1–100 KeV, for collisions of the gamma beam with the laser photons, and (2) in the energy range of 1–800 MeV, for the gamma beam collisions with the counter propagating twin gamma beam.

Gamma beams could also collide with the LHC proton and fully stripped ion beams. The CM energy range of the corresponding **photon-proton** and **photon–nucleus colliders** would be 4–60 GeV.

SECONDARY BEAMS

Gamma beams could be extracted from the LHC and used to produce high intensity secondary beams of:

- **Polarized electrons and positrons with the expected intensity which could reach 10^{17} positrons/s**. Such an intensity would be three orders of magnitude higher than that of the KEK positron source and largely satisfy the source requirements for both the ILC and CLIC colliders, and even that of a future high luminosity ep (eA) collider project based on the energy recovery linac.

- **Polarized muon and the tertiary neutrino beams**. The intensity of the Gamma Factory polarized muon beams could be sizably higher than that of the Paul Scherrer Institute's "πE5" muon beam. If accelerated, they could be used to produce high intensity neutrino beams. Thanks to the initial muon polarization the muon-neutrino (muon-antineutrino) beams could be uncontaminated by the electron-neutrino (electron-antineutrino) contributions. The neutrino and antineutrino bunches could be separated with 100% efficiency on the bases of their timing. In addition, their fluxes could be predicted to a very high accuracy, providing an optimal neutrino-beam configuration for the high systematic precision measurements e.g. of the CP-violating phase in the neutrino mixing (PMNS) matrix. To reach high muon (neutrino) intensities two paths could be envisaged. In the first one, based on the conversion of the high energy gamma beam into muon pairs, the present circumferential voltage of the LHC would have to be upgraded and a specialized design of the gamma conversion targets would have to be made. An alternative scheme would be to tune the gamma beam energy to a significantly lower energy – just above the electron–positron pair production threshold, reducing thus both the circumferential voltage and the beam

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEYGBD3

power strains. The positron bunches, produced by such a low energy gamma beam, would need to be accelerated in the dedicated positron ring to the energy exceeding the muon pair production threshold in collisions with the stationary target electrons, $E_e \sim (2m_\mu^2)/(m_e)$. The intensity of the muon beam produced in such a scheme could be increased by replacing the single-pass collisions of the positron beam by the multipass collisions [6]. For both the above two types of muon beams the product of the beam longitudinal and transverse emittances could be at least four orders of magnitude smaller than that for the pion-decay-originated muon source.

- **Neutrons with the expected intensity reaching 10^{15} neutrons/s (first generation neutrons) and radioactive, neutron-rich ions with the intensity reaching 10^{14} ions/s**. Preliminary estimates show that the intensity of the Gamma Factory beams of neutrons and radioactive ions could approach those of the European projects under construction, like ESS (and FAIR) and the planned EURISOL facility. The Gamma Factory beams may turn out to be more effective in terms of their power consumption efficiency since almost 10% of the LHC RF power could be converted into the power of the neutron and radioactive ion beams if the energy of the photon beam is tuned to the Giant Dipole Resonance (GDR) region of the target nuclei.

RESEARCH HIGHLIGHTS

The physics research domains which could be explored by this proposal include: fundamental QED measurements (for example, for the first time ever, the elastic light-light scattering could be observed with the rate of ≈1000 events/s, providing the high-precision QED test); dark matter searches (mainly via the dark photon, axion-like particles and neutron portals); investigation of basic symmetries of the Universe (neutron dipole moment, neutron–antineutron oscillations, forbidden muon decays); studies of color confinement; nuclear photonics; physics of neutron-rich radioactive beams, physics with energy-tagged neutron beam and the vast domain of the atomic physics of muonic and electronic atoms.

The Gamma Factory's high brilliance beams of polarized positron and muons may help in addressing at CERN the research programme of: (1) **a TeV-energy-scale muon collider**[2]; (2) **a neutrino factory**, (3) **a lepton–hadron collider**, and (4) **fixed-target Deep Inelastic Scattering (DIS)**.

The CERN Gamma Factory project could open a wide spectrum of industrial and medical applications in the following domains: muon catalyzed cold fusion; gamma-beam catalyzed hot fusion; Accelerator Driven System (ADS) and Energy Amplifier (EA) research; nondestructive assay and segregation of nuclear waste; transmutation of nuclear waste; material studies of thick objects and production of ions for Positron Emission Tomography (PET) and for the selective cancer-cell therapy with alpha emitters.

[2] For more info see Frank Zimmermann's contribution to IPAC2018 [7]

THE WAY FORWARD

The presented above research option for CERN may turn out not only to be scientifically attractive but also cost-effective because it proposes to re-use, in a novel manner, the existing CERN accelerator infrastructure. It may be considered as complementary to the present hadron-collision programme and could be performed at any stage of the LHC lifetime.

In order to prove that such a future option is not only conceptually attractive but also viable, two initial investigation paths have recently been initiated.

The goal of the first one is to perform a detailed validation of the achievable performance figures of the Gamma Factory initiative for each branch of its application domains, to build up the physics case for its research programme and, most importantly, to attract a wide community to this initiative.

The goal of the second one is to prove experimentally the concepts underlying the Gamma Factory proposal. Most of the feasibility tests are being and will be performed at the SPS and organized such that the ongoing CERN research programme is hardly affected. The experimental beam tests started already over the year 2017 with special SPS runs with partially stripped Xe+39 beams. Thanks to the installation of new strippers over the recent YETS, these tests will be followed over the year 2018 by the dedicated SPS runs with Pb+54, Pb+80 and Pb+81 beams. If successful, they will be followed by the test runs in the LHC. The goal of these tests is to address the stability aspects of the PSI beams in the CERN accelerator complex.

To complete the feasibility proof, these tests will need to be followed by a "proof-of-principle" SPS experiment. Such an experiment could be done in the North Hall using the extracted PSI beam or – if CERN is interested in developing new Doppler beam cooling techniques – in the specially designed (e.g. in the UA2 cavern) laser-PSI-beam collision point in the SPS tunnel.

ACKNOWLEDGEMENTS

We are indebted to Fabiola Gianotti, the CERN Director General, for launching the Physics Beyond Collider (PBC) studies which provided an efficient framework for the initiative discussed in this contribution, and to Mike Lamont, the PBC Accelerator Physics Convener, for his precious support in all the aspects of the Gamma Factory initiative. Last but not the least we thank Gianluigi Arduini for his critical reading of the manuscript and for his useful comments and suggestions.

REFERENCES

[1] M.W. Krasny, The Gamma Factory proposal for CERN, arxiv:1511.07794 (2015).

[2] E.G. Bessonov, Nucl. Instrum. Meth. **B309** (2013) 92–94 and the references quoted therein.

ISBN: 978-3-95450-184-7 doi:10.18429/JACoW-IPAC2018-WEYGBD3

[3] D. Trbojevic, Private communication.

[4] M.W. Krasny, Nucl. Instrum. Meth. **A540** (2005) 222.

[5] A. Caldwell et al., Nature Phys. **5** (2009) 363–367.

[6] M. Antonelli et al., Nucl. Inst. Meth. **A807** (2016) 101–107.

[7] F. Zimmermann, "LHC/FCC-based Muon Colliders", presented at IPAC2018, Vancouver, Canada, April-May 2018, paper MOPMF065.