Gamma Factory

Physics Beyond Colliders Working Group Meeting
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Mieczyslaw Witold Krasny
LPNHE, CNRS-IN2P3 and University Paris Sorbonne
The Gamma Factory proposal for CERN†

Abstract

This year, 2015, marks the centenary of the publication of Einstein's Theory of General Relativity and it has been named the International Year of Light and light-based technologies by the UN General Assembly. It is thus timely to discuss the possibility of broadening the present CERN research program by including a new component based on a novel concept of the light source which could pave a way towards a multipurpose Gamma Factory. The proposed light source could be realized at CERN by using the infrastructure of the existing accelerators. It could push the intensity limits of the presently operating light-sources by at least 7 orders of magnitude, reaching the flux of the order of $10^{17}$ photons/s, in the particularly interesting γ-ray energy domain of $1 \lesssim E_{\text{photon}} \lesssim 400$ MeV. This domain is out of reach for the FEL-based light sources. The energy-tuned, quasi-monochromatic gamma beams, together with the gamma-beams-driven secondary beams of polarized positrons, polarized muons, neutrons and radioactive ions would constitute the basic research tools of the proposed Gamma Factory. The Gamma Factory could open new research opportunities at CERN in a vast domain of uncharted fundamental physics and industrial application territories. It could strengthen the leading role of CERN in the high energy frontier research territory by providing the unprecedented-brilliance secondary beams of polarized muons for the TeV-energy-scale muon collider and for the polarized-muon-beam based neutrino factory.

Mieczyslaw Witold Krasny*

LPNHE, Universités Paris VI et VII and CNRS–IN2P3, Paris, France

† An Executive Summary of the proposal addressed to the CERN management.

*e-mail: krasny@lpnhe.in2p3.fr

2017:
Creation of the Gamma Factory PBC study group
Gamma Factory PBC study group

A. Abramov¹, S.E. Alden¹, R. Alemany Fernandez², P.S. Antsiferov³, A. Apyan⁴, H. Bartosik², E.G. Bessonov⁵, N. Biancacci², J. Bieron⁶, A. Bogacz⁷, A. Bosco¹, R. Bruce², D. Budker⁸, K. Cassou⁹, F. Castelli¹⁰, I. Chaikovska⁹, C. Curatolo¹¹, P. Czodrowski², A. Derevianko¹², K. Dupraz⁹, Y. Dutheil², K. Dzierzega⁶, V. Fedosseev², N. Fuster Martinez², S. M. Gibson¹, B. Goddard², A. Gorzawski¹³, S. Hirlander², J.M. Jowett², R. Kersevan², M. Kowalska², M.W. Krasny¹⁴, F. Kroeger¹⁵, D. Kuchler², M. Lamont², T. Lefevre², D. Manglunki², B. Marsh², A. Martens⁰, J. Molson², D. Nutarelli⁹, L. J. Nevay¹, A. Petrenko², V. Petrillo¹⁰, W. Placzk⁶, S. Redaelli², S. Pustelny⁶, S. Rochester⁸, M. Sapinski¹⁶, M. Schaumann², M. Scrivens², L. Serafini¹⁰, V.P. Shevelko⁵, T. Stoehlker¹⁵, A. Surzhikov¹⁷, I. Tolstikhina⁵, F. Velotti², G. Weber¹⁵, Y.K. Wu¹⁸, C. Yin-Vallgren², M. Zanetti¹⁹,¹¹, F. Zimmermann², M.S. Zolotorev²⁰ and F. Zomer⁰

¹ Royal Holloway University of London Egham, Surrey, TW20 0EX, United Kingdom
² CERN, Geneva, Switzerland
³ Institute of Spectroscopy, Russian Academy of Sciences, Troitsk, Moscow Region, Russia
⁴ A.I. Alikhanyan National Science Laboratory, Yerevan, Armenia
⁵ P.N. Lebedev Physical Institute, Russian Academy of Sciences, Moscow, Russia
⁶ Marija Smoluchowska Institute of Physics, Jagiellonian University, Krakow, Poland
⁷ Center for Advanced Studies of Accelerators, Jefferson Lab, USA
⁸ Helmholtz Institute, Johannes Gutenberg University, Mainz, Germany
⁹ IAL, Univ. Paris-Sud, CNRS-IN2P3, Université Paris-Saclay, Orsay, France
¹⁰ Department of Physics, INFN–Milan and University of Milan, Milan, Italy
¹¹ INFN–Padua, Padua, Italy
¹² University of Nevada, Reno, Nevada 89557, USA
¹³ University of Malta, Malta
¹⁴ LPNHE, University Paris Sorbonne, CNRS–IN2P3, Paris, France
¹⁵ HJ Jena, IQQ FSU Jena and GSI Darmstadt, Germany
¹⁶ GSI, Helmholtzzentrum für Schwerionenforschung, 64291 Darmstadt, Germany
¹⁷ Braunschweig University of Technology and Physikalisch-Technische Bundesanstalt, Germany
¹⁸ FEL Laboratory, Duke University, Durham, USA
¹⁹ University of Padua, Padua, Italy
²⁰ Center for Beam Physics, LBNL, Berkeley, USA

GF group is open to everyone willing to contribute to this initiative!

Today:
66 scientists
20 institutes
9 countries
Gamma Factory research tools: primary and secondary beams

**Primary beams:**
- partially stripped ions
- electron beam (for LHC)
- gamma rays

**Secondary beam sources:**
- polarised electrons,
- polarised positrons
- polarised muons
- neutrinos
- neutrons
- vector mesons
- radioactive nuclei

**Collider schemes:**

- $\gamma$-$\gamma$ collisions,
  $E_{CM} = 0.1 - 800$ MeV

- $\gamma$-$\gamma_L$ collisions,
  $E_{CM} = 1 - 100$ keV

- $\gamma$-p(A), ep(A) collisions,
  $E_{CM} = 4 - 200$ GeV

A leap in production efficiency, intensity and purity
Opening new research domains and a leap in the measurement precision in existing research domains – a paradise for creative physicists…

Gamma Factory research potential

- **Particle**
  - basic symmetries, dark mater, EW precision measurements with PSI, n, μ and ν beams…

- **Nuclear**
  - nuclear charge and spin structure, neutron skin, confinement studies, photo-fission…

- **Accelerator**
  - beam cooling, plasma wake field acc., high-int. polarized e+ & μ sources, ν-sources…

- **Atomic**
  - physics of highly charged electronic and muonic atoms: strong EM fields, EW effects…

- **Applied**
  - accelerator driven energy sources, cold & warm fusion, medical isotope production…
### Gamma Factory milestones – where we are?

1. **Demonstration of efficient production, acceleration and storage of “atomic beams” in the CERN accelerator complex.**

2. **Development “ab nihilo” the requisite Gamma Factory software tools.**
   - LoI submitted to the SPSC on the 25\textsuperscript{th} of September 2019.

3. **Successful execution of the GF Proof-of-Principle (PoP) experiment in the SPS tunnel.**

4. **Building up the physics cases for the LHC-based GF research programme and attracting wide scientific communities to use the GF tools in their respective research.**

5. **Extrapolation of the PoP experiment results to the LHC case and realistic assessment of the performance figures of the GF programme.**

6. **Elaboration of the TDR for the LHC-based GF research programme.**

   - Documents summarising highlights of the GF research potential in the domains of Atomic and Nuclear physics in preparation.
Gamma Factory
Proof-of-Principle Experiment

LETTER OF INTENT

Gamma Factory Study Group

Contact persons:
M. W. Krasny, krasny@lnhe.in2p3.fr, krasny@mail.cern.ch – Gamma Factory team leader
A. Martens, martens@lal.in2p3.fr – Gamma Factory PoP experiment spokesperson
Y. Dutheil, yann.datheil@cern.ch – Gamma Factory PoP study – CERN coordinator
The experimental studies of elementary particle collisions at the high energy frontier of the accelerator technologies have established, over the last century, the basic laws that govern our Universe at small distances. Each new generation of particle accelerators and particle colliders have delivered important discoveries. It is thus natural to continue the high-energy frontier path as the leading one in the High Energy Physics (HEP) research at CERN. The basic question which triggered the GF initiative is not whether this research path needs to be pursued – it certainly does – but if it is the most optimal one in the present phase of the HEP research in which:

- a large number of theoretical model scenarios for Beyond the Standard Model (BSM) phenomena exist without pointing to the optimal energy and beam particles for the future particle collider to observe these phenomena,
- the quantum field theory framework providing the link between the results of precise measurements of the quantum loop virtual phenomena and their (future) direct observation no longer provides any solid landmarks for predicted discoveries that are accessible for the present accelerator technologies or their incremental upgrades,
- we do not have a mature, affordable technology to make a significant leap into high energy “terra incognita”.

The Gamma Factory (GF) initiative and its associated Proof-of-Principle (PoP) experiment, presented in this Letter of Intent (LoI), target a new and complementary research path which can be pursued concurrently with the ongoing CERN research programme and in parallel to preparing a novel technology for a cost-efficient return to the high-energy frontier research. Its primary goal is to extend the research scope of the existing world-unique CERN accelerator infrastructure. It is proposed at a crucial moment for CERN. The approval, financing and construction of CERN’s next high-energy frontier project will very likely be a lengthy process. It is also possible that the on-going LHC-based research program will reach earlier its discovery potential saturation. This generates an opportunity for novel research programmes in basic and applied science which could re-use CERN’s existing facilities in ways and at levels that were not conceived when the machines were designed.
PoP experiment in the SPS tunnel

Placement of the FP cavity in the SPS tunnel

Table 3: SPS PoP experiment parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( m ) – ion mass</td>
<td>193.687 GeV/c²</td>
</tr>
<tr>
<td>( E ) – mean energy</td>
<td>18.652 TeV</td>
</tr>
<tr>
<td>( \gamma = E/mc^2 ) – mean Lorentz relativistic factor</td>
<td>96.3</td>
</tr>
<tr>
<td>( N ) – number ions per bunch</td>
<td>( 0.9 \times 10^8 )</td>
</tr>
<tr>
<td>( \sigma_E/E ) – RMS relative energy spread</td>
<td>( 2 \times 10^{-1} )</td>
</tr>
<tr>
<td>( \epsilon_n ) – normalised transverse emittance</td>
<td>1.5 mm mrad</td>
</tr>
<tr>
<td>( \sigma_x ) – RMS transverse size</td>
<td>1.047 mm</td>
</tr>
<tr>
<td>( \sigma_y ) – RMS transverse size</td>
<td>0.83 mm</td>
</tr>
<tr>
<td>( \sigma_z ) – RMS bunch length</td>
<td>6.3 cm</td>
</tr>
<tr>
<td>Laser</td>
<td>Infrared</td>
</tr>
<tr>
<td>( \lambda ) – wavelength (( \hbar \omega ) – photon energy)</td>
<td>1034 nm (1.2 eV)</td>
</tr>
<tr>
<td>( \sigma_{\lambda}/\lambda ) – RMS relative band spread</td>
<td>( 2 \times 10^{-1} )</td>
</tr>
<tr>
<td>( U ) – single pulse energy at IP</td>
<td>5 mJ</td>
</tr>
<tr>
<td>( \sigma_L ) – RMS transverse intensity distribution at IP (( \sigma_L = \omega_L/2 ))</td>
<td>0.65 mm</td>
</tr>
<tr>
<td>( \sigma_I ) – RMS pulse duration</td>
<td>2.8 ps</td>
</tr>
<tr>
<td>( \theta_L ) – collision angle</td>
<td>2.6 deg</td>
</tr>
<tr>
<td>Atomic transition of ( ^{208}\text{Pb}^{79+} )</td>
<td>( 2s \rightarrow 2p_{1/2} )</td>
</tr>
<tr>
<td>( \hbar \omega_0 ) – resonance energy</td>
<td>230.81 eV</td>
</tr>
<tr>
<td>( \tau ) – mean lifetime of spontaneous emission</td>
<td>76.6 ps</td>
</tr>
<tr>
<td>( \hbar \omega_{\text{max}} ) – maximum emitted photon energy</td>
<td>44.473 keV</td>
</tr>
</tbody>
</table>
What we want to learn/demonstrate with the GF Proof-of-Principle (PoP) experiment at the SPS?

1. Demonstrate integration and operation of laser and a Fabry-Perot cavity in a high energy hadron storage ring.
2. Benchmark simulations of atomic excitation rates.
3. Develop a collision scheme and implement the operational tools, match the laser photon spectrum to the atomic excitation width to maximise excitation rate.
4. Demonstrate laser and atomic bunches synchronisation.
5. Measure and characterise the photon flux.
6. Develop atomic and photon beams diagnostic methods.

7. Evaluate the performance of laser cooling techniques of the atomic beams

8. Perform atomic physics measurements in the ultra-relativistic regime.
Two complementary paths to HL-LHC

\[ L = f_{\text{coll}} \frac{n_1 n_2}{4\pi \sigma_x^* \sigma_y^*} \]

The beam width \( \sigma \) can be expressed in terms of the \( \beta^* \) parameter describing beam focusing strength in the interaction point and a beam emittance \( \varepsilon \).

\[ \varepsilon_x \equiv \frac{\sigma_x^2}{\beta_x} \]

\[ L = f \frac{n_1 n_2}{4\pi \sqrt{\varepsilon_x \beta_x^* \varepsilon_y \beta_y^*}} \]

Two ways to increase the machine luminosity:
1. Increase beam focusing at the IPs of the experiments.
2. Decrease transverse beam emittance of colliding beams.

... and, perhaps the best option, a mixing of the previous two
On-going HL(pp) - LHC project

The largest HEP accelerator in construction

Levelled Luminosity: $2.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$

estimated cost ~ 1 billion euro
Beam cooling of atomic beams at the SPS:

MERIT OF ATOMIC BEAMS: highly efficient, selective, manipulation of the beam particles confined in the particle bunches by the laser photons – opening a path to a very fast beam cooling.

TRANVERSE BEAM COOLING AT THE SPS – Li-LIKE CALCIUM IONS:
- (2s→3p)_{1/2} transition
- Laser light wavelength: 768 nm (t.c.), 768.3 nm (l.c.)
- Laser pulse energy: 2 mJ (t.c.), 0.25 mJ (l.c.)
- Laser pulse length: 2 ps
- Laser transverse pulse size: 1.1 mm
- Crossing angle: 1.3 deg
- Expected cooling time ~ 7 s

... to be experimentally confirmed by the GF PoP experiment...
Gamma Factory proposal for HL(NN)-LHC: An implementation scheme with Ca beams

- Laser cooling $(2s \rightarrow 3p)^{1/2}$
- Fully stripped Calcium –Ca(+20)
- Lithium-like Calcium - Ca(+17)
- Source+Linac: Charge state after stripping: Ca$^{17+}$, 80 K cooler than Pb!

Initial estimates

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Cooling only</th>
<th>Cooling/focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s^{1/2}$ [TeV]</td>
<td>7.0</td>
<td>7.0</td>
</tr>
<tr>
<td>$\sigma_{\text{BFPP}}(\text{Ca})/\sigma_{\text{BFPP}}(\text{Pb})$</td>
<td>$5 \times 10^{-5}$</td>
<td>$5 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\sigma_{\text{had}}(\text{Ca})/\sigma_{\text{tot}}(\text{Ca})$</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>$\text{Nb}$</td>
<td>$6 \times 10^9$</td>
<td>$3 \times 10^9$</td>
</tr>
<tr>
<td>$\epsilon_{(x,y)_{\text{n}}} [\mu m]$ (1)</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>IBS horizontal [h]</td>
<td>1.2</td>
<td>2.3</td>
</tr>
<tr>
<td>$\beta^*$</td>
<td>0.5</td>
<td>0.15</td>
</tr>
<tr>
<td>$L_{\text{NN}}$ [cm-2s-1]</td>
<td>$5.1 \times 10^{34}$</td>
<td>$4.3 \times 10^{34}$</td>
</tr>
<tr>
<td>$\text{Nb of bunches}$</td>
<td>1404</td>
<td>1404</td>
</tr>
<tr>
<td>Collisions/beam crossing</td>
<td>3.9</td>
<td>3.3</td>
</tr>
</tbody>
</table>

(1) Beam emittance must be preserved through the LHC acceleration cycle
Gamma Factory PoP experiment at the SPS (2.4 MCHF) may open a complementary path to HL-LHC (with equivalent, …or higher partonic luminosities), by storing quark and gluons in “cold”-nucleus rather than in “hot”-proton bunches…

…the most likely achievable luminosity limit of this scheme is IBS – a stochastic optical cooling at the beam collision energies, and blow up of the longitudinal emittance over the LHC acceleration cycle, may be required to preserve the beam emittance of the SPS-cooled beam…
Three merits of HL(NN)-LHC w.r.t. HL(pp)-LHC (at equivalent partonic luminosities)

1. Better signal to noise for point-like partonic processes:
   - lower number of collisions/b.c.
   - lower average multiplicity of soft hadrons

\[ n_{\text{soft}}(AA) \sim N_{\text{part}} < N_{\text{coll}} \]

2. Maximizing the luminosity of photon-photon collisions:
   - avoid excessive beam burning at high \( Z \)
   - profit from the \( Z^4 \) (coherence) enhancement
The canonical LHC \textit{pp collision mode} (including HL-LHC) is not optimal for the precision EW programme\textsuperscript{(1)}, why?

\textbf{u} and \textbf{d} quarks have different
charges, weak isospin and vector and axial couplings:

\[ g_V^i = t_{3L}(i) - 2Q_i \sin^2 \theta_W, \]
\[ g_A^i = t_{3L}(i), \]

\textit{Need to know -- to a very high precision -- the composition of partonic beam: in particular the relative momentum distributions of \textbf{u} and \textbf{d} quarks in the proton!}

\textsuperscript{(1)} \textit{For the quantification of these statements see e.g.}:

Three merits of HL(\text{NN})-LHC w.r.t. HL(\text{pp})-LHC (at equivalent partonic luminosities)

3. Why choosing the Ca ions? \rightarrow \text{Isoscalar (Z=A/2) ion beam}

Profit from the flavour symmetry of strong interactions to control the partonic beam composition and their longitudinal and transverse emittances:

\[ u_{\text{neutron}}(x,pt,Q2) = d_{\text{proton}}(x,pt,Q2) \quad \text{and} \quad d_{\text{neutron}}(x,pt,Q2) = u_{\text{proton}}(x,pt,Q2) \]

\[ d_{\text{Ca}}(x,pt,Q2) = u_{\text{Ca}}(x,pt,Q2) \]

\[ \text{allowing to equalize}^{(1)} \text{ the distributions of the } u \text{ and quarks:} \]

\[ (1) \quad \text{Up to a tiny EM corrections} \]
An illustration of the gain in the measurement precision by using isoscalar ion instead of proton beams

Measurement of the ratio of the pseudo-rapidity distributions of the charged lepton for W and Z production at the LHC. *Gain in precision a factor of ~8.*


*Isoscalar LHC beams provide the unique way to improve our present knowledge of the SM basic parameters such as $M_W$, $\sin^2 \theta_W$, …*
Conclusions

- Over the last **2 years** the **Gamma Factory** initial ideas developed into a **well-defined project** involving a group of **~70 scientists** from 19 institutes in 9 countries.

- Progress has been impressive. The next steps are clear.

- **GF** had already passed its first and **most important milestone**: the **proof** that one can **produce**, **accelerate** and **store atomic beams** in the **CERN accelerator complex**.

- It is now entering its **second and decisive phase** with a proposition of a **GF Proof-of-Principle experiment** at the **CERN SPS**.
Conclusions

- The ultimate target of the GF initiative is to develop a variety of novel research tools and research concepts which could open new exciting opportunities in a broad domain of basic and applied science.

- A specific example of the HL(NN)-LHC concept and its physics potential was presented in this talk as an illustration of a possible impact of the Gamma Factory ideas and tools on the ongoing and the future CERN research programme.

- We hope that the SPS PoP experiment will be approved and the requisite resources (2.4 MCHF) allocated by CERN and by the national Funding Agencies (ERC funds) allowing to pass the next and decisive Gamma Factory R&D phase.
Postscriptum

- PBC has provided an ideal cradle for the development of the GF project in its initial stage (we are grateful for this “early childhood” care).

- For the success of the subsequent GF R&D stages a recognition of the enormous GF research potential is crucial (ESPP process).

“Strong minds discuss ideas, average minds discuss events, weak minds discuss people.”

— Socrates
The GF timeline (2020-2024)

<table>
<thead>
<tr>
<th>GF Phase 2: SPS PoP</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC operation</td>
<td>LS2</td>
<td></td>
<td></td>
<td>LS3</td>
<td></td>
</tr>
<tr>
<td>SPS operation</td>
<td>LS2</td>
<td></td>
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</tr>
</tbody>
</table>

**Activities**
- Design studies
- SPS Pb$^{79+}$ tests
- Install laser room
- SPS Pb$^{79+}$ tests
- Install laser & FP system tests
- SPS PoP Pb$^{79+}$ experiments
- SPS PoP Pb$^{79+}$ experiments
- Prepare GF MoU
- F-P system construction
- Laser procurement
- Prepare LHC GF Demo TDR

**Milestones**
- Sign GF MoU
- Validate Laser radiation tolerance
- X-ray detector and TT2 stripper ready for installation
- All equipment ready for SPS installation
- System HW & beam commissioned in SPS
- Proof of GF concept and LHC TDR launch
An additional merit of HL(AA)-LHC w.r.t. HL(pp)-LHC

Tagged beams of transversely and longitudinally polarized W and Z bosons

Quantum uncertainty of the Longitudinal position of W-production

\[ L_{Ioffe}(x_A) = \frac{1}{2M_W x_A} \]

Quantum formation lengths of W-boson

\[ \delta z = \gamma_W / M_W \]

M.W. Krasny, S. Jadach, W. Placzek.