Contribution aux exercices de prospective nationale 2020-2030

Accélérateurs et instrumentation associée

GAMMA FACTORY

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1. Informations générales

Titre : Gamma Factory

Acronyme : *GF*

Résumé *(max. 600 caractères espaces compris)*
A new concept of radiation source based on the interaction of highly relativistic atomic beams and laser beams is proposed. The Proof of Principle of this context is targeted in the coming years. It may open a very large numbers of new perspectives in various fields of physics, including applied physics, fundamental particle physics, precision measurements with atoms. It may also allow to produce unprecedented flux of muons with excellent quality.

Préciser le domaine de recherche *(plusieurs choix possibles)*

- ✓ *Physique des accélérateurs (nouveaux concepts machines, optique et dynamique des faisceaux…)*
- ✓ *Sources de particules (électrons, positrons, muons, protons, ions lourds stables, ions radioactifs…) et cibles associées*
- o *Développement durable de la discipline (infrastructures technologiques, efficacité énergétique, fiabilité…)*
- o *Autre R&D spécifique : (préciser)*

Préciser la motivation principale visée par la contribution :

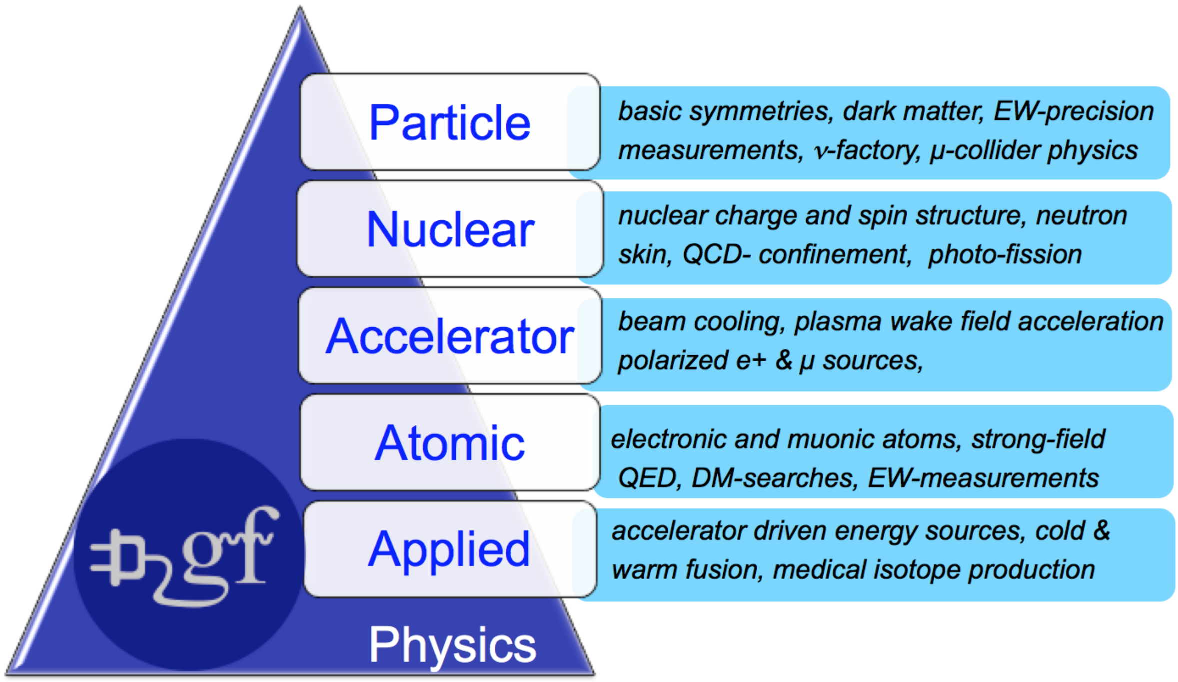
- o *Accélérateurs pour la physique nucléaire*
- ✓ *Accélérateurs pour la physique des particules*
- o *Accélérateurs pour les sources de lumière ou de neutrons*
- o *Accélérateurs pour les applications sociétales (santé, énergie, industrie…)*
- o *Autre : (préciser)*

2. Description des objectifs scientifiques et techniques *(2 pages max incl. figures)*

We propose the Gamma Factory Proof-of-Principle (GF-PoP) experiment to study collisions of a laser beam with ultra-relativistic atomic beam of Partially Stripped Ions (PSI), circulating in the SPS ring. It would be the first *collider experiment* of photons from a laser beam with ultra-relativistic, $\gamma \gg 1$, atomic beams ever made. The GF scheme is based on resonant excitation of the atoms with the laser beam tuned to the atomic transitions frequencies, followed by the process of spontaneous emission of photons. The resonant excitation of atomic levels of highly ionised atoms (ions) is possible due to the large energies of the ions generating a Doppler frequency boost of the counter-propagating laser beam photons. The process of absorption and emission results in a frequency boost of the incoming photon of up to, and about, $4\gamma^2$. In the GF scheme, the SPS (LHC) atomic beams play the role of passive photon frequency converters of eV-photons into keV (MeV) X-rays (γ-rays).

Over the years 2017 and 2018 the Gamma Factory (GF) study group, in the framework of the Physics Beyond Colliders (PBC) studies, demonstrated the capacity of the CERN accelerator complex to produce and store highly-charged atomic beams in its high-energy accelerator rings [1]. As a next step towards opening a wide set of applications, it is proposed to implement first an experimental demonstration of the concept within the next 5 years [2]. This will allow to quantitively assert the potential of several applications within the next 5 to 10 years with potentially an implementation in the LHC and the start of physics operations with this new concept. For the concrete implementation of the GF scheme at the SPS we propose to collide a lithium-like lead, $^{208}Pb^{79+}$, beam with a 1034 nm photon beam generated by a pulsed laser, based on Yb-doped optical materials. The beam energy will be tuned to resonantly excite the 2s → $2p_{1/2}$ atomic transition of the $^{208}Pb^{79+}$ atoms. Such a specific choice of beam particles and a laser is purely technical. It minimizes both the necessary work and the cost of the experiment while remaining, as far as the tuning of the laser wavelength to the resonant atomic transition is concerned, more challenging than the ultimate implementation of the GF γ-ray production scheme at the LHC. Laser systems together with Fabry–Perot (FP) optical cavities, allowing to enhance the power of laser pulses, have already been implemented at DESY and KEK electron beam storage rings [3] by LAL team involved in GF, with a high level of synergy for many of the technical issues, like the bunch synchronization scheme. A specificity of hadron storage rings is the much higher beam rigidity in conjunction with the longer bunch lengths. Once this scheme will be effectively demonstrated in the SPS, quantitative measurements of the flux of photons will be made along with the demonstration of the cooling (longitudinal and transverse) of the atomic beams. Methods of cooling of stationary atoms – exploiting internal degrees of freedom and the Doppler effect – have been mastered over the last three decades by the atomic physics community, and the elements of these cooling techniques could be implemented to the atomic beams stored in the SPS storage ring. A successful demonstration of the Doppler beam cooling of atomic beams at the SPS could open the possibility of injecting low-emittance beams of fully stripped iso-scalar ions into the LHC. Such beams will be very important in the “precision measurement phase" of the LHC experimental program. Secondly, the production of high-intensity photon beams may open, among others, a path to a muon collider based on electromagnetic production of low-emittance muon beams. Also cooled, high-energy, atomic beams could be useful for improving the performance of AWAKE [2].

By being able to deliver an unprecedented yield of photons at energies ranging from several tens of keV to hundreds of MeV, the GF naturally opens a wide range of otherwise unreachable applications both in applied and fundamental physics. Indeed for some specific cases preliminary estimates indicate that 10^24 photons per year could be produced [2]. The figure below schematically represented some of the potential applications. Of course, the actual performance of the scheme has to be carefully evaluated. The first step towards this being to execute a Proof of Principle experiment. Most applications listed in the figure also require some specific studies and if judged realistic an additional R&D to clearly establish the potential of GF. This will be done once the performance of the PoP is well established.



3. Développements associés, calendrier et budget indicatifs
(1 page max. incl. figures)

It is estimated that three years will be needed for the preparation of the Proof of principle experiment at CERN with a strong involvement from LAL on the critical aspect of the laser system and the Fabry Perot cavity. The installations are foreseen to take a place during the 2021/22 and 2022/23 winter Year End Technical Stops. In 2023 and 2024, data taking will take place. Analysis of the obtained data will be made, and will allow to extrapolate some performance for LHC operations and some specific physics applications. The cost of the hardware for the experiment is slightly below 2M€ and is expected to be covered by CERN. It is necessary that LAL starts R&D well in advance, re-using existing facilities at LAL (clean rooms) and hardware (laser oscillator, amplifier, optical cavity and pumping system, part of the electronics). The R&D work will be focused on the aspects of a design of a 2-mirror optical cavity with large mode, matched to that of the atomic beam, that may induce modal instabilities that are more difficult to avoid than in 4-mirror cavities [4]. It will also concentrate on a specificity that is requested for optimization of the beam cooling, namely the tuning of the spectrum and the pulse duration. These aspects are new in the context of optical cavities for accelerator to the best of our knowledge.

A limited hardware contribution of about 75k€ in the first year will be needed to start R&D well in advance on the specific topic of pulse duration and spectrum adaptation, one of the key aspects of the design proposed by LAL. 6k€ per year need to be considered for the yearly operation of the clean room. For the next two years optical cavity maintenance, and setup optimization would require about 10k€ per year. The project is expected to require 0.75 researcher FTE and 0.75 engineer (optics/accelerator and mechanics) FTE. The experimental developments related to the R&D and the design and commissioning at LAL of the optical cavity with its laser system would be an attractive PhD thesis subject. This requested manpower will be completed by the request of a post-doctoral fellowship for the operation, data taking analysis of the experiment in the SPS and also the design of some high potential applications of the GF scheme for its future use, thus starting in 2022 for two to three years. Travels to and presence at CERN will require a large budget (65k€) on the first year (2020) of the project since many interfaces issues will need to be solved. A 25k€/year budget is estimated for the next years to support conferences contributions, presence of members of the collaboration to collaboration wide meetings. In the operation period of the experiment the travel budget may be kept at this level by profiting from a long duration presence at CERN of a post-doctoral fellowship. After the data taking period, the travel budget will be extremely dependent on what is the outcome of the PoP experiment.

Beyond 2024, there will be an option for the laser system and photon detector upgrade over the long shutdown (LS3) period for the use of the SPS PoP for an atomic physics research program over years 2026 to 2029. Alternatively, the experiment could be turned into a physics experiment at the LHC to exploit the wide physics potential of GF scheme, including production of secondary beams, dark matter or axion like particle searches, etc.

Impact
(0.5 page max.).

If the expected performances are actually demonstrated a very wide range of applications will be opened. It will essentially allow to use the existing CERN infrastructure to increase significantly its high energy physics reach (EW physics for instance); nuclear physics (fundamental) including the touchy question of photo-fission with its critical societal application for nuclear waste transmutation for instance; accelerator physics by providing unprecedented low emittance low energy spread ion beams for colliders (electron-ion), new acceleration techniques (plasma wakefield in the AWAKE configuration), high quality high flux polarized positron and muon sources; fundamental physics by measuring properties of high-Z atoms (EW physics, strong-field QED); societal applications (medical isotope production for instance) [2].

Références

[1] : https://home.cern/news/news/accelerators/lhc-accelerates-its-first-atoms

[2] : *Gamma Factory Proof of Principle experiment, Letter of Intent*, CERN-SPSC-2019-031, SPSC-I-253.

[3] : Chaikovska et al, *High flux circularly polarized gamma beam factory: coupling a Fabry-Perot optical cavity with an electron storage ring*, Scientific Reports 6 (2016) 36569 EP.

[4] : A. L. Bullington, B. T. Lantz, M. M. Fejer, and R. L. Byer, *Modal frequency degeneracy in thermally loaded optical resonators*, Appl. Opt. 47 (May, 2008) 2840–2851.