PROCEEDINGS OF SCIENCE

Novel high intensity gamma-source at CERN: the Gamma Factory Initiative

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Collisions of Partially Stripped Ions (PSI) with laser light to produce high intensity gamma-ray beams are the backbone of the Gamma Factory (GF) initiative. The source, if realised at LHC, could significantly push up the intensity limits of the presently operating ones, reaching the flux of the order of 10^{17} photons/s, in the particularly interesting gamma-ray energy domain of 1 to 400 MeV. 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. We discuss the GF concept and the preliminary estimates of the emitted gamma beams phase spaces given by two newly developed Monte Carlo codes which simulate the PSI-laser interactions.

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1. The Gamma Factory proposal

The Gamma Factory proposal [1, 2] is based on the idea to use Partially Stripped Ion (PSI) beams as the drivers of a high intensity gamma-ray source [3]. The PSI beam (beam 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) collides head-on with a laser. The laser energy is tuned to enable the resonant absorption of the laser photons by the PSI beam which is followed by spontaneous atomic-transition emissions of secondary photons. The initial laser-photon frequency is boosted by a factor of up to $4 \times \gamma_i^2$, where γ_i is the Lorenz factor of the partially stripped ion beam. From the kinematic point of view the process is similar to inverse Compton scattering (light sources in the MeV energy range operating via ICS have already been constructed and are operating in several countries: HIγS-USA, LEPS-Japan, LADON-Italy, ROKK-1-Russia, GRAAL-France and LEGS-USA), moreover the PSI-beam-driven light source intensity could be much higher thanks to the giga-barn resonant absorption cross section (ICS cross section $\sim$ barn).

2. PSI-laser collision simulations

A preliminary attempt to simulate the PSI-laser collisions has been performed by modifying the existing Monte Carlo codes Cain and CMCC [4]. Cain, written by K. Yokoya et al. [5], is a stand-alone Monte Carlo program for simulations of beam-beam interactions involving high-energy electrons, positrons and photons. CMCC [6] is a Monte Carlo event generator useful to simulate asymmetric electron-photon or proton-photon collisions [7, 8]. These two codes have been adapted to the new interaction scheme and they have been named respectively GF-CAIN and GF-CMCC. At the moment we have assumed a very short lifetime of the PSI in the excited state, a negligible probability of double photon absorption, a flat differential cross section for the spontaneous emission, a monochromatic laser colliding head-on with the PSI beam. By means of the newly developed GF-CAIN and GF-CMCC, we have simulated the interaction between Xe^{39+}, Pb^{81+} and laser light. The parameters of the two specific examples we have considered are reported in Table 1. For the Xenon partially stripped ions, SPS-like parameters have been adopted, while for the Lead PSI typical LHC parameters have been used. In the first case the collision is performed with a green laser, in the latter case with a free electron laser. All the parameters are purely indicative and we adopted in the Pb^{81+} example an arbitrarily increased value for the beam emittance (9 mm mad instead of the expected value, to be confirmed in the 2018 Pb runs, of about 1.3 mm mrad) in order to better illustrate its effect on the energy-angle correlation and on the efficiency of angular beam collimation. The emitted photon beam features simulated by the two codes are presented in Figs. 1 (only GF-CMCC), 2 (GF-CAIN and GF-CMCC). The first column of Fig. 1 shows the angular distribution of the full photon beam: in both cases half of the photons are emitted within a cone of $1/\gamma_i$ aperture around the incoming PSI direction. The lower emittance of the Xenon beam with respect to the Lead one is mapped onto the photons as we can see in the second and third columns of Fig. 1: the energy-angle correlation is shown for different collimation angles $\theta_\gamma = 15, 35, 75$ mrad in the Xenon case and $\theta_\gamma = 0.25, 0.5, 1$ mrad for the Lead. The data reported in Fig. 2 have been simulated by with the two independent codes and the comparison of the results is shown for the Pb^{81+}-FEL collision case.

PSI Beam	Xe^{39+}	Pb^{81+}
M_i ion mass	120 GeV/c^2	193 GeV/c^2
E_i ion energy	4.19 TeV	579 TeV
$\gamma_i = E_i/M_i$	34.66	3000
N_i ions per bunch	$2 \cdot 10^9$	$9.4 \cdot 10^7$
$\Delta\gamma_i/\gamma_i$ rel. en. spread	$3 \cdot 10^{-4}$	0
ε^n norm. trans. emitt.	2 mm mrad	9 mm mrad
$\beta_x = \beta_y$ beta function	50 m	0.5 m
σ_x rms trans. size	1.7 mm	38.7 μm
σ_z rms bunch length	12 cm	15 cm
Laser	Green	FEL
λ_L wavelength (E_L photon energy)	532 nm (2.33 eV)	108.28 nm (11.45 eV)
N_L photons per pulse	$8.73 \cdot 10^{14}$	$3 \cdot 10^{13}$
U_L pulse energy	0.33 mJ	56 μJ
P_L mean power (rep. rate 40 MHz)	13.2 kW	2.24 kW
w_0 waist at IP (2 σ_L)	3.4 mm	50.84 μm
R_L Rayleigh length	68.23 m	7.5 cm
σ_t rms pulse length	1 m	15 cm
γ photons		
$E_{res} = E'_L$ resonance energy	161.5 eV	68.7 keV
E_γ^{max} maximum photon energy	11.2 keV	412 MeV

Table 1: Simulation parameters for Xe^{39+} and Pb^{81+}-laser collisions.

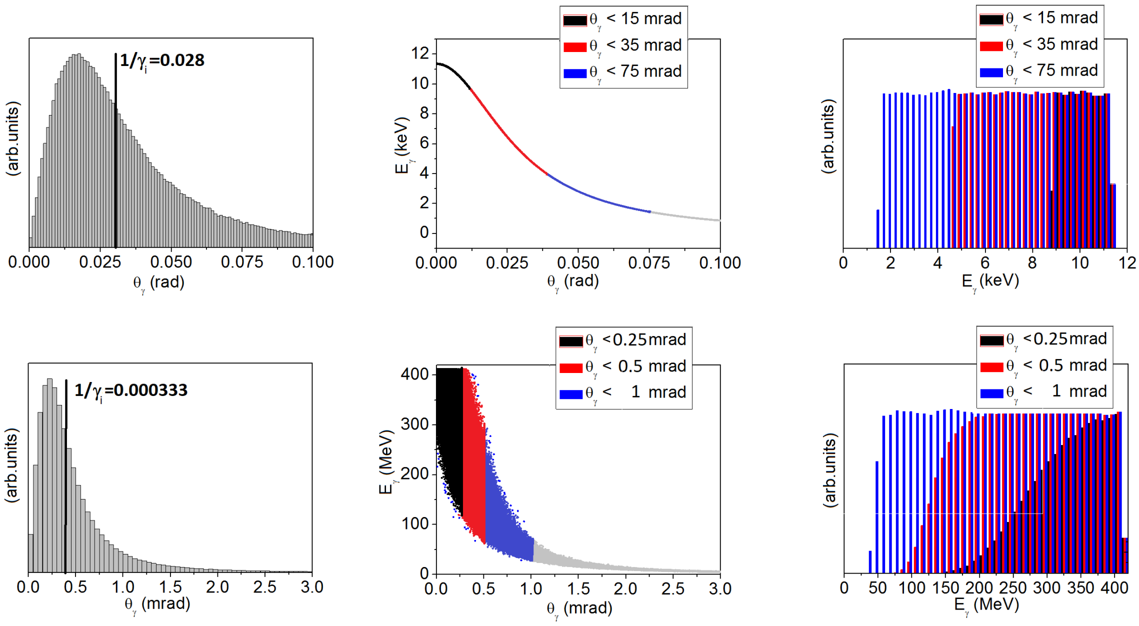


Figure 1: Features of secondary photons emitted by Xe^{39+}-laser collision first row and Pb^{81+}-FEL second row, simulation with GF-CMCC. First column: angular distribution of the full emitted photon beam and $1/\gamma_i$ value reported on the graph. Second column: energy as a function of the emission angle, colours represent different collimation angles. Third column: energy distribution for three possible collimated beams.

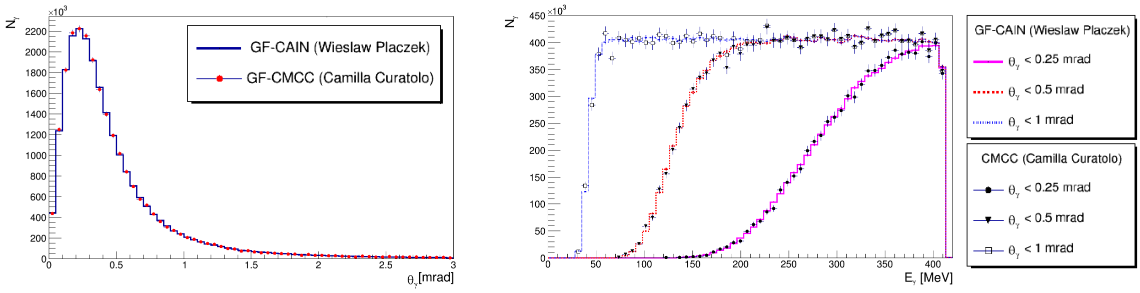
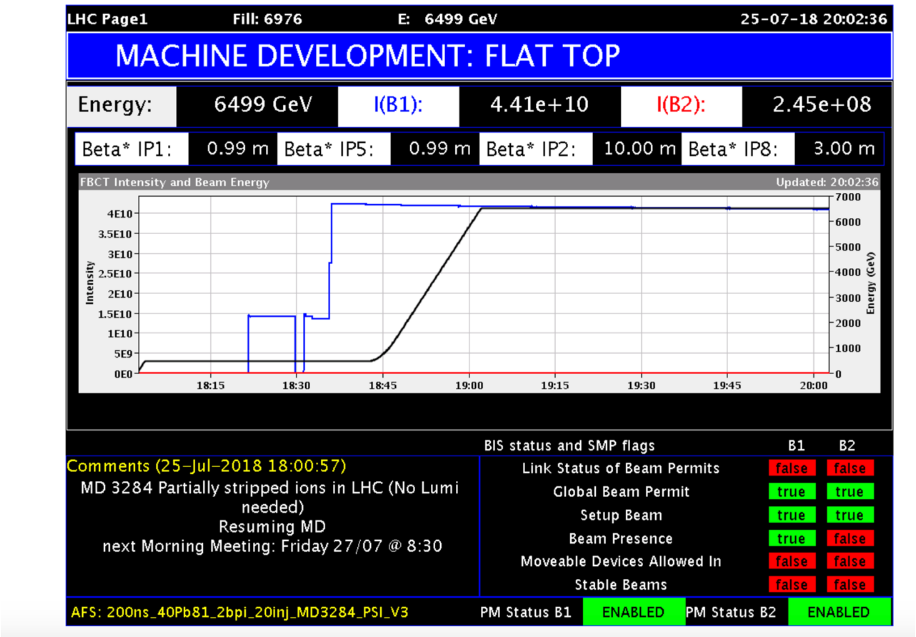


Figure 2: GF-CAIN and GF-CMCC results comparison in case Pb^{81+}-FEL collision. Left: angular distribution of the full emitted photon beam. Right: spectrum of the emitted photon beam collimated at $\theta_\gamma = 0.25, 0.5, 1$ mrad.

3. PSI beams at CERN

The first important step towards the GF is to analyze the storage stability of the PSI beams. 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. After a first attempt carried out at SPS with Xe^{39+}, on the 25th of July this year Pb^{81+} beam has been injected in the LHC. The Pb^{81+} beam lifetime was measured to be $\sim$ 38 hours, a very impressive result (see Fig. 3).


LHC Page1 Fill: 6976 E: 6499 GeV 25-07-18 20:02:36

MACHINE DEVELOPMENT: FLAT TOP

Energy:	6499 GeV	I(B1):	4.41e+10	I(B2):	2.45e+08

Beta* IP1:	0.99 m	Beta* IP5:	0.99 m	Beta* IP2:	10.00 m	Beta* IP8:	3.00 m

Comments (25-Jul-2018 18:00:57)
MD 3284 Partially stripped ions in LHC (No Lumi needed)
Resuming MD
next Morning Meeting: Friday 27/07 @ 8:30

BIS status and SMP flags	B1	B2
Link Status of Beam Permits	false	false
Global Beam Permit	true	true
Setup Beam	true	true
Beam Presence	true	false
Moveable Devices Allowed In	false	false
Stable Beams	false	false

AFS: 200ns_40Pb81_2bpi_20inj_MD3284_PSI_V3 PM Status B1 ENABLED PM Status B2 ENABLED

Figure 3: Screenshot of the LHC monitor: Pb^{81+} bunch trains (4.4×10^{10} total charges) ramped to the maximal LHC energy of 6.5 TeV proton equivalent observed for about two hours.

4. Future plans

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.

We have discussed here our first attempt to simulate PSI-laser collisions. The simulations for Xe^{39+}, Pb^{81+} and laser light have been performed with the two independent codes GF-CAIN and GF-CMCC and the results are in very good agreement. Nevertheless, these results are still very preliminary since many important approximations have been done: the details of the interaction have to be considered more carefully, we have to insert the correct density, spectrum and temporal shape of the incoming photon beam in order to have a reliable estimation of the total number of emitted photons. Moreover, the incoming beams parameters have to be optimized and the interaction region geometry remains to be designed.

Tests to understand the storage stability of the PSI beams have been carried out at the LHC showing a very long lifetime. To complete the feasibility proof, a “proof-of-principle” SPS experiment should be performed.

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. It is necessary to perform a detailed validation of the achievable performances 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.

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