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# NEW SIMULATION PROGRAMS FOR PARTIALLY STRIPPED IONS – LASER LIGHT COLLISIONS

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*Abstract*

We present for the first time two new independent Monte Carlo codes for simulating the collisions of Partially Stripped Ions with Laser light. Such collisions if realised at LHC could drive a high intensity gamma source and are the backbone of the recent Gamma Factory proposal.
The implementation aspects will be discussed and the simulation results will be compared.

## GAMMA FACTORY

The Gamma Factory proposal [1, 2] is based on the production of high intensity gamma beams via the resonant absorption of laser light by Partially Stripped Ions (PSI). The idea is to use existing CERN facilities, SPS and LHC, to accelerate and store the PSI beam and a counter propagating laser or free electron laser beam tuned to hit the resonance. Such a novel light source could significantly push up the intensity limits of the presently operating ones, reaching the flux of the order of $10^{17}$ photons/s, thanks to the resonance giga-barn cross section (7-9 orders of magnitude higher than inverse Compton scattering cross section of 0.67 barn). The emitted $\gamma$-ray beam could reach 400 MeV, energy value which is out of reach for the FEL-based light sources based on sub-TeV energy-range electron beams. A sketch of the Gamma Factory light source is reported in Fig. 1.

## PSI-LASER COLLISIONS

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. The process of the resonant absorption of the laser photons by the PSI beam is followed by a spontaneous atomic-transition emissions of secondary photons. The resonance energy $E_{res}$ depends on the PSI and the energy of the laser in the PSI rest frame has to be $E'_L = E_{res}$. Therefore, the laser photons energy $E_L$ has to be tuned considering that $E'_L = (1 - \underline{\beta_i} \cdot \underline{e_k})\, \gamma_i\, E_L$ where $\gamma_i$, $\underline{\beta_i}$ are the ion Lorentz factor, velocity and $E_L$, $\underline{e_k}$ are the photon energy, direction. Since we are considering ions with energy $E_i$ in the TeV range and eV-class laser photons colliding head-on, $E'_L \simeq 2\, \gamma_i\, E_L$. The secondary photons are emitted by spontaneous (isotropic) emission in the PSI rest frame and in the laboratory they are emitted within a small cone around the PSI direction of propagation and they reach hundreds of MeV energy because of the high Lorentz boost imparted by the ions. The maximum energy of the emitted photons (the ones emitted along the PSI direction in the laboratory frame) is $E_\gamma^{max} = 4\gamma_i^2 E_L = 2\gamma_i E'_L$. The spectrum of the emitted photons is flat and it spans from the laser light energy to $E_\gamma^{max}$: in case LHC is involved, the photons can reach up to 400 MeV. The beam can be used for further collisions, it can be collimated and/or sent against a fixed target to produce secondary beams of polarized positrons, polarized muons, neutrinos, neutrons and radioactive ions.
The first attempt to simulate the PSI-laser collisions has been performed by modifying the existing Monte Carlo codes Cain and CMCC. Cain, written by K. Yokoya et al. [3], is a stand-alone Monte Carlo program for simulations of beam–beam interactions involving high-energy electrons, positrons and photons. CMCC [4] is a Monte Carlo event generator useful to simulate asymmetric electron-photon or proton-photon collisions [5, 6]. 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.

## TWO EXAMPLES: $Xe^{39+}$ AND $Pb^{81+}$

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 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.
The emitted photon beam features simulated by the two codes are presented in Figs. 2 (only GF-CMCC), 3 (GF-CAIN and GF-CMCC). The first column of Fig. 2 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 beam one is mapped onto the photons as we can see in the second and third columns of Fig. 2: the energy-angle correlation is shown for different collimation angles $\theta_\gamma = 15, 35, 75$ mrad

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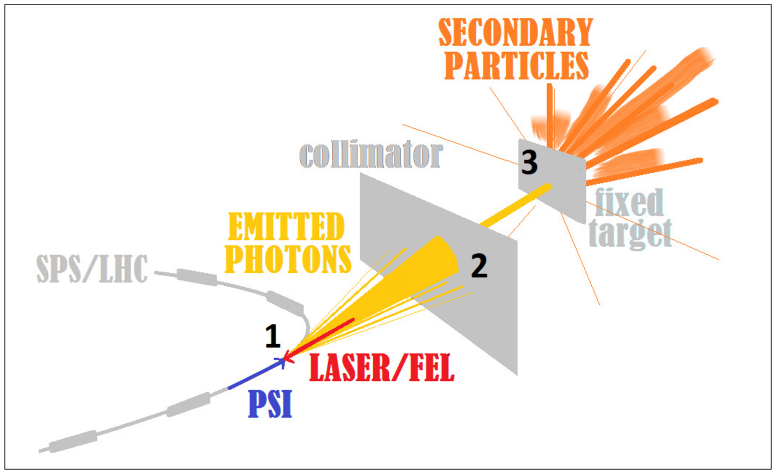


Figure 1: Gamma Factory sketch. 1- Partially stripped ions from SPS or LHC collide head-on with laser/Free electron laser light. Resonant absorption of the laser photons by the PSI beam followed by spontaneous emission of secondary photons. 2- Emitted photon beam used entirely or collimated to reach lower bandwidth. 3- Possible use: impinging photons on fixed target to produce secondary particles (polarized positrons, polarized muons, neutrinos, neutrons, radioactive ions).

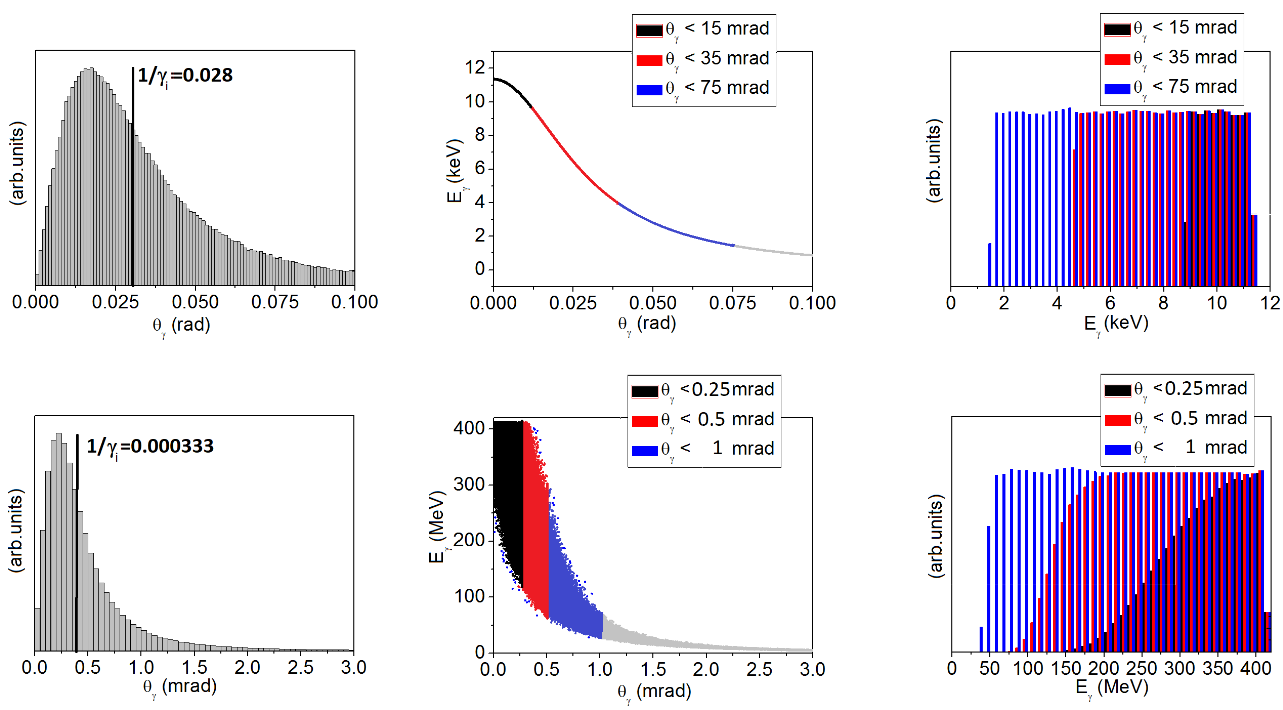


Figure 2: Features of secondary photons emitted by $Xe^{39+}$-laser collision first row and $Pb^{81+}$-FEL second row, simulation with GF-CMCC. First column: angular distribution of the full emitted photon beam and $1/\gamma_i$ value reported on the graph. Second column: energy as a function of the emission angle, colours represent different collimation angles. Third column: energy distribution for three possible collimated beams.

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in the Xenon case and $\theta_\gamma = 0.25, 0.5, 1$ mrad for the Lead. The data reported in Fig. 3 have been simulated by with the two independent codes and the comparison of the results is shown for the $Pb^{81+}$-FEL collision case.

Table 1: Simulation Parameters for $Xe^{39+}$ and $Pb^{81+}$-laser Collisions

| 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 |
| $\epsilon^n$ norm. trans. emitt. | 2 mm mrad | 9 mm mrad |
| $\beta_x = \beta_y$ beta function | 50 m | 0.5 m |
| $\sigma_x$ rms trans. size | 1.7 mm | 38.7 $\mu$m |
| $\sigma_z$ rms bunch length | 12 cm | 15 cm |
| Laser | Green | FEL |
| $\lambda_L$ wavelength | 532 nm | 108.28 nm |
| $E_L$ energy | 2.33 eV | 11.45 eV |
| $N_L$ photons per pulse | $8.73 \cdot 10^{14}$ | $3 \cdot 10^{13}$ |
| $U_L$ laser energy | 0.33 mJ | 56 $\mu$J |
| $w_0$ waist at IP (2 $\sigma_L$) | 3.4 mm | 50.84 $\mu$m |
| $R_L$ Rayleigh length | 68.23 m | 7.5 cm |
| $\sigma_t$ rms pulse length | 1 m | 15 cm |
| $\gamma$ photons | | |
| $E_{res} = E'_L$ | 161.5 eV | 68.7 keV |
| $E_\gamma^{max}$ | 11.2 keV | 412 MeV |

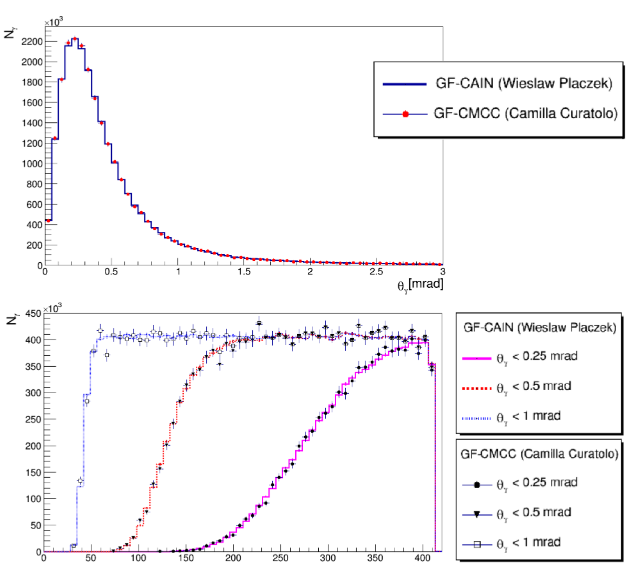


Figure 3: GF-CAIN and GF-CMCC results comparison in case $Pb^{81+}$-FEL collision. Top: angular distribution of the full emitted photon beam. Bottom: spectrum of the emitted photon beam collimated at $\theta_\gamma = 0.25, 0.5, 1$ mrad.

## CONCLUSION

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.

Tests to understand the storage stability of the PSI beams have been and will be carried out over the year 2018 – firstly at the CERN SPS and, if successful, at the LHC.

We have discussed here our first attempt to simulate PSI-laser collisions. The existing CAIN Monte Carlo code and CMCC event generator have been modified for PSI-laser collision and named respectively GF-CAIN and GF-CMCC. The simulations for $Xe^{39+}$, $Pb^{81+}$ and laser light have been performed with the two independent codes 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.

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