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High intensity X/γ photon beams for nuclear physics and photonics

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Abstract

In this manuscript we review the challenges of Compton back-scattering sources in advancing photon beam performances in the $1-20\ MeV$ energy range, underlining the design criteria bringing to maximum spectral luminosity and briefly describing the main achievements in conceiving and developing new devices (multi-bunch RF cavities and Laser recirculators) for the case of ELI-NP Gamma Beam System (ELI-NP-GBS).

A new generation of high brilliance gamma ray photon beams is under development at several laboratories world-wide, based on Compton back-scattering Sources run as mini-colliders of high brightness electron beams and high power laser beams, with the aim to generate photon beams in the 1-20 MeV energy range characterized by unprecedented performances in terms of mono-chromaticity, brilliance, spectral density, tunability and polarization.

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Such a new generation of gamma photon beams are aimed at opening the era of Nuclear Photonics stepping up by orders of magnitude w.r.t. present generation machines, therefore enabling to use the Nuclear Resonance Fluorescence technique: nuclear waste remote sensing and diagnosis, special nuclear material recognition for national security and non-proliferation related issues, isotope sensitive imaging for medical and cultural heritage investigations are among the most appealing and high social impact applications that will be made feasible by such advanced gamma photon beams [1]. Not to mention several research fields in nuclear physics dealing with fundamental nuclear structure studies about giant resonances and astro-physical open problems in star nucleo-synthesis that will greatly benefit from the availability of these new probes.

One of the main projects in progress in this field is the ELI-NP Gamma Beam System [2], designed and being constructed by the European EuroGammaS collaboration under a contract with IFIN-HH, the Romanian Institution in charge of developing the ELI-NuclearPhysics Romanian Pillar of E.L.I. (Extreme Light Infrastructure) in Bucharest.

The availability in the near future of gamma ray photon beams of high mono-chromaticity (less than 0.5%), high peak brilliance (larger than $10^{21} N_{ph}/(s.0.1\%.mm^2 mrad^2)$), large tunability, fully controlled polarization, spectral density larger than $10^4 N_{ph}/(s.eV)$ and focused down to micron-scale spot sizes, open several further horizons in the photon-photon and photon-particle collider scenarios.

Quite often in the literature radiation sources based on back-scattering of optical photons carried by laser pulses by relativistic (MeV to GeV energy) electron beams are referred as either Thomson or Compton back-scattering Sources (hereafter referred as TCS). The reason for such an ambiguity is the particular regime of photon back-scattering that is applied, either with (Compton) or without (Thomson) electron recoil. As a matter of fact, the frequency ν of the back-scattered photon, for the simplest case of head-on collision between the laser optical photon (frequency ν_L) and the electron (relativistic factor γ) is given by:

$$\nu \simeq \nu_L \frac{2}{\frac{1}{2\gamma^2} + \frac{2h\nu_L}{\gamma mc^2}} \tag{1}$$

where the first term in the denominator is responsible for the typical $4\gamma^2$ scaling of Thomson Sources (and recalls the $2\gamma^2$ scaling for FEL's based on a classical view of relativistic Doppler effect combined to Lorenz boost of the incoming e.m. wave which induces dipole radiation emission onto the electron), while the second term in the denominator accounts for quantum

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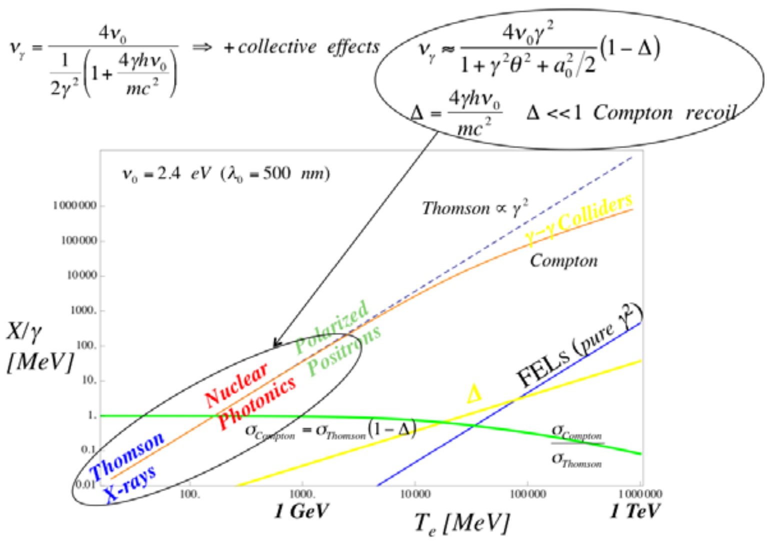

Figure 1: Operating Diagram for Thomson/Compton Sources, showing the elastic (no-recoil) Thomson regime for X-rays and the small recoil regime typical of Compton Sources for Nuclear Photonics. The deep Compton regime, dominated by recoil effects and typical of $\gamma - \gamma$ collider is also shown, together with the behavior of the recoil parameter Δ and the Compton cross section decrease together with increasing Δ. The enhancement of the formula for the frequency of the back-scattered photon is also shown, taking into account the red-shift effects due to scattering angle θ and non-linear multi-photon effects generated by laser field intensity (represented by the laser parameter α_0).

effects, namely the electron recoil, and it is responsible for the correct energy and momentum conservation in the scattering reaction. This second term is negligible for FEL's and X-ray Thomson Sources, while it is small but not negligible for Compton Sources of Nuclear Physics and Photonics, and becomes the dominant term for deep Compton Sources as those planned for $\gamma - \gamma$ colliders in TeV range. The scaling of eq.1 for the typical case of a green light laser ($\lambda_L = 500$ nm) back-scattered by an electron beam of variable energy (from 10 MeV up to 1 TeV) is illustrated in Fig.1.

There are at least two nice properties of the Thomson and quasi-Thomson regions, where the electron recoil is either negligible or quite small (the region enclosed inside an oval in Fig. 1), which are of great interest for the design of an optimized TCS: the total cross section is very close to the maximum value achievable of $0.64 barn$ at zero recoil, and the X/γ beam is almost fully polarized even using unpolarized electrons [3] as shown in Fig. 2 where distribution of the Stokes parameters as the color-map of intensity distribution is plotted.

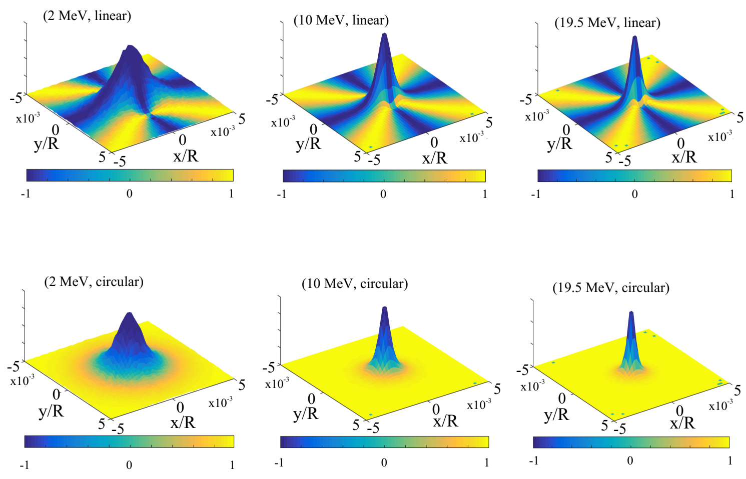

Figure 2: Intensity-polarization graphs for photons at 2, 10 and 19.5 MeV, with linear and circular laser polarization.

The Klein-Nishina cross section for Compton scattering σ_C is in fact almost equal to the Thomson cross section $\sigma_T = 8\pi r_e^2/3 = 0.64$ barn (where r_e is the classical electron radius) whenever the recoil parameter $\Delta \ll 1$, and its value is given approximately by $\sigma_C = \sigma_T(1 - \Delta)$ under this approximation, as plotted in fig. 1 [4]. Furthermore, since the back-scattering in Thomson or quasi-Thomson region is basically elastic, the incident laser photon is bouncing on the electron as if the electron were an ideal mirror moving at relativistic speed in the laboratory frame: this guarantees the preservation of the photon polarization as far as the scattering angle θ is small. As a consequence the back-scattered photon beam collimated within a small angle of scattering $\theta < 1/\gamma$, i.e. corresponding to a small bandwidth bdw $bdw \approx \theta^2\gamma^2 \ll 1$, will keep the same polarization of the laser pulse colliding with the electron beam: as discussed extensively in [3]. This leads to very high polarized X/γ beams which are strategic and of great interest for Nuclear Physics and Photonics applications.

New generation TCS machines are characterized by narrow bandwidths, below 0.5%, combined to large spectral flux, i.e. number of photons/sec per unit bandwidth. In order to achieve these performances the luminosity L_{TSC} of the TCS must be larger than $10^{35}\ s^{-1}cm^{-2}$, as specified by

$$L_{TSC} = \frac{N_L N_e}{4\pi\sigma_x^2} f \qquad (2)$$

where N_L are the photons carried by the laser pulse at collision, N_e the electrons carried in the bunch, σ_x the spot size at collision IP (Interaction Point) and f the repetition rate of the collisions (assuming ideal overlap in space and time of the two colliding pulses, as well as negligible diffraction of the two beams over the interaction distance). Using ELI-NP-GBS nominal values for the 2 colliding beams (0.4 J for the laser pulse energy, 250 pC the electron bunch charge, focused down to about 20 μm with an effective rep. rate of 3.2 kHz) we find $L_{TSC} = 1.2\ 10^{35}\ s^{-1}cm^{-2}$, a quite impressive value, similar to the high-luminosity upgrade of LHC.

The total number of back-scattered photons per second, all over the spectrum and solid angle, would be $N_{all} = L_{TSC}\sigma_T$, i.e. $N_{all} = 7\ 10^{10}\ photons/s$. As discussed in details in ref. [2]- [4], any TCS is a polychromatic source of back-scattered photons: most of energetic photons are confined in a narrow solid angle (semi-aperture $1/\gamma$) with a large frequency spread (at $\theta = 1/\gamma$ the photons have half the energy than that given by eq. 1, which determines the maximum energy of photons back-scattered on axis at $\theta = 0$). In order to produce a mono-chromatic photon beam one needs to select a narrow angle around the electron beam propagation axis quite smaller than $1/\gamma$ - this is achieved by means of special collimators, which become quite challenging at photon energies above 1 MeV [2], [5].

So what really matters for experiments and applications, of the collimated photon beams, is the number of photons N_γ^{bw} carried by the back-scattered radiation pulse within such a small angle, and the rms bandwidth associated with it - that is the concept of spectral luminosity and spectral density, which are the real figure of merit for Nuclear Physics and Photonics. These are approximately given by

$$N_\gamma^{bw} = 7\ 10^8 \frac{U_L[J]Q[pC]}{h\nu_L[eV]\sigma_x^2[\mu m^2]}\gamma^2\theta^2 \tag{3}$$

in terms of the laser pulse energy U_L, the electron bunch charge Q, σ_x the spot size at collision IP, and the laser photon energy $h\nu_L$ [2], [4]. The rms bandwidth $\Delta\nu/\nu$ of the photon beam collimated within the acceptance angle $\Psi = \gamma\theta_{max}$ is approximately given by:

$$\frac{\Delta\nu}{\nu} \cong \sqrt{\left(\frac{\Psi^2}{\sqrt{12}} + 2\frac{\epsilon_n^2}{\sigma_x^2}\right)^2 + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta\nu_L}{\nu_L}\right)^2 + \left(\frac{M^2\lambda_L}{2\pi W_0}\right)^2 + \left(\frac{a_0^2/3}{1+a_0^2/2}\right)^2} \tag{4}$$

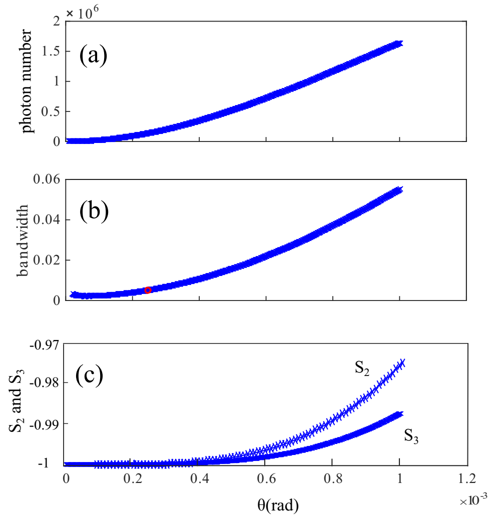

Figure 3: Number of scattering photons (a), bandwidth (b) and Stokes parameters (c) for the case of linear (S_3) and circular (S_2) polarizations as function of the acceptance angle. The red dot marks the bandwidth 0.5%.

in terms of the collimation angle θ, the electron beam phase space density parameters (rms energy spread $\Delta\gamma/\gamma$ and transverse total normalized emittance ε_n and the laser quality parameters, rms spectral bandwidth $\Delta\nu_L/\nu_L$ and mode purity M^2. The last term represents the non-linear effects due to the laser intensity: when the laser parameter a_0 is not much smaller than 1, multi-photon absorption start being effective and the radiation spectrum is significantly modified in shape and frequency distribution [6]. Narrow bandwidth TCS, as those for Nuclear Physics and Photonics, must minimize these non-linear effects by using laser pulses characterized by small value of $a_0 = 4.3\frac{\lambda_L}{W_0}\sqrt{\frac{U_L[J]}{\sigma_t[ps]}}$ (dimensionless amplitude of the vector potential associated to the laser e.m. wave), where W_O is the laser waist size at the IP and σ_t its rms pulse length. In case of ELI-NP-GBS we have, at maximum, $a_0 = 0.04$. In fig. 3 we present the dependence of the number of scattered photons, bandwidth and Stokes parameters as functions of the acceptance angle.

An important figure of merit is the Spectral Density, defined as $SPD = N_\gamma^{bw}/\sqrt{2\pi}h\Delta\nu$, typically expressed in units of $photons/s.eV$. Various generations of γ-ray sources have improved this figure of merit, from values of the order of 1 for bremsstrahlung sources, to about 100 for the present $Hi\gamma S$ facility [7], [8], toward the 10^4 range which is the goal of ELI-NP-GBS.

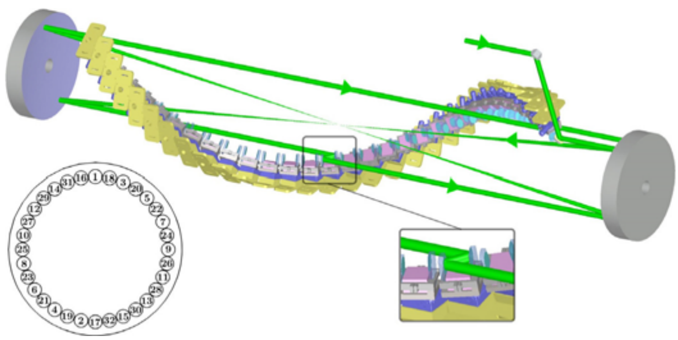

Figure 4: Lay-out of the laser recirculator under construction for ELI-NP-GBS, made of two confocal parabolic mirrors and 32 plane mirror pairs to focus, deflect, collimate and re-circulate the J-class green light $Yb : Yag$ laser pulse for collision at IP (at the center of the device) with each of the 32 electron bunches accelerated to the IP by the multi-bunch RF Linac.

In order to achieve such an impressive upgrade in the performances, the strategy of our TCS is to adopt a multi-bunch operation mode for the electron Linac and to re-circulate the laser pulse as many times as possible at the Interaction Point. In this way we will combine the capability of a RF Linac driven by high brightness photo-injector to provide outstanding peak electron beam quality in the single bunch (as per FEL Linac drivers) with a higher repetition rate than the one typical of such Linacs (100 Hz). As a matter of fact eq. 3 and eq.4 foresee about $N^b w_\gamma = 7\ 10^7\ s^{-1}$ with $\frac{\Delta\nu}{\nu} = 0.4\%$, which means about $SPD \approx 700$ for a single bunch operation at 100 Hz repetition rate, for a TCS radiating 10 MeV γ-rays (530 MeV electrons). Since the laser pulse carries about 10^{18} photons at the IP, but only 10^7 photons maximum are back-scattered at each collision (in other words the electron beam is almost transparent to the laser pulse), then we can conceive to re-use the laser pulse and bring it back to a new collision at the same IP with a new fresh incoming electron bunch. This requires a Linac able to operate in multi-bunch mode and an optical device able to re-circulate the laser pulse. The laser recirculator for 32 pulses was conceived as shown in fig.4. For a full description of this new optical device see ref. [2], [9].

Such an advanced and innovative laser re-circulator is under test by the EuroGammaS collaboration and will be integrated in the ELI-NP-GBS installation phase starting in 2016. Due to several constraints to fulfil in its design, concerning mirror quality, damage threshold, alignment and synchronization of the 2 parabolic mirrors and the 32 plane mirror pairs (a challenging 20 μm and 20 μrad alignment tolerance is required), the fo-

Table 1: ELI-NP-GBS expected performances: ranges for electron beam, laser pulse and γ-ray photon beam parameters are listed.

Electron beam Parameters, 32 bunches per RF pulse, 16 ns separation bunch-to-bunch, 100 Hz rep rate	
Electrons $[MeV]$	$75 - 750$
Bunch charge $[pC]$	$25 - 250$
Bunch rms length $[\mu m]$	$200 - 300$
Total projected rms transverse emittance $\varepsilon_n [mm\ mrad]$	$0.3 - 0.5$
Total projected rms energy spread [%]	$0.05 - 0.1$
Focal spot size σ_x, σ_x $[\mu m]$	$15 - 18$
Laser Parameters, 100 Hz rep rate	
Laser pulse energy $[J]$	$0.2 - 0.4$
Laser pulse length $[psec]$	1.5
Laser focal spot size W_0 $[\mu m]$	28
Laser rms bandwidth [%]	< 0.1
Laser M^2	< 1.2
Laser parameter a_0	$0.02 - 0.04$
Collision angel α_0 $[deg]$	8
Synchronization to RF $[ps]$	< 1
Pulse energy stability [%]	< 1
γ-ray Photon beam Parameters	
Photon Energy $[MeV]$	$0.2 - 19.5$
Spectral Density $[ph/s.eV]$	$0.5 - 2\ 10^4$
Bandwidth rms [%]	$0.2 - 0.5$
Collimation angle $[\mu rad]$	$60 - 400$
# photons per shot within collimation angle	$1.1 - 3.5\ 10^5$
# photons/sec within collimation angle	$0.3 - 1.1\ 10^9$
Source rms size $[\mu m]$	$10 - 15$
Peak Brilliance $[N_ph/s.mm^2.mrad^2.0.1\%]$	$2\ 10^{19} - 4\ 10^{21}$
Radiation pulse length $[ps]$	$0.7 - 1.0$

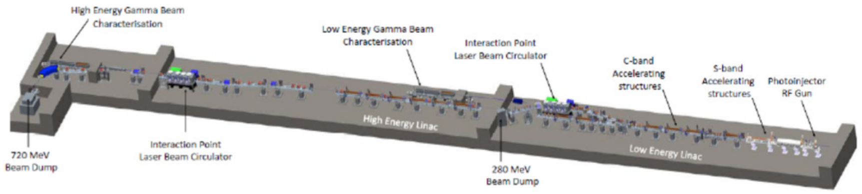

Figure 5: Lay-out of ELI-NP-Gamma Beam System as designed by EuroGammaS (CAD provided by STFC members of EuroGammaS).

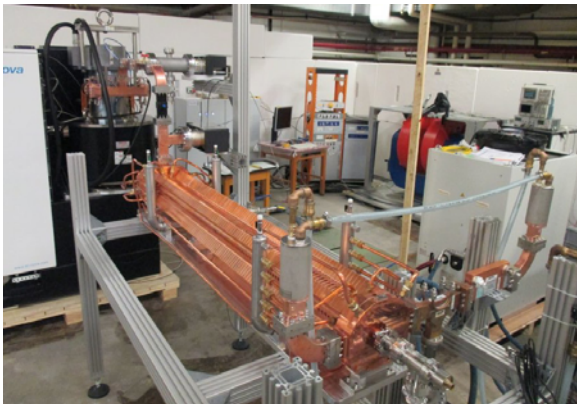

Figure 6: High-Order Mode damped C-band accelerating RF cavities, designed and built by INFN-LNF for EuroGammaS, under full power test.

cal length of the parabolic mirrors was set at 1.2 m, implying a round-trip time for the laser pulse of about 16 ns. A total of 32 round-trips have been designed and carefully simulated with a physical laser transport simulation code in order to asses the quality of the laser pulse at the IP at any round-trip. The expected performance is quite close to 100% in the total accumulated spectral density over the 32 pulses as far as the 32 electron bunches will collide at the IP with same constant beam quality over the multi-bunch train. The time structure of the generated γ-ray pulses will be therefore made of 32 long trains repeating at 100 Hz (10 $msec$ far apart), consisting of 32 micro-pulses separated by 16 ns (each micro-pulse with rms pulse length a bit shorter than 1 ps).

In order to generate the high brightness electron beam requested, ELI-NP-GBS adopts an advanced photo-injector coupled to a C-band high gradient RF Linac capable to bring the electron beam up to a maximum energy of 750 MeV [10], [11] with outstanding beam quality. The lay-out of the machine is shown in Fig.5.

An innovative C-band High Order Mode damped RF cavity has to be conceived and designed in order to avoid emittance and energy spread degradation due to the Beam Break-Up instability along the Linac over the 32 multi-bunch train. The low level RF tests successfully conducted at INFN-LNF were followed by successful high power tests with achievement of the nominal 33 MeV/m accelerating gradient in the accelerating structures with the requested rejection level of high order RF modes which are potentially dangerous for BBU [12] as shown in Fig. 6.

Thanks to these advanced components and to many other devices developed specifically for the ELI-NP-GBS (like the collimator-characterization stage for the γ photon beam), the expected performances are at least 2 orders of magnitude higher than the present state of the art, in terms of bandwidth, brilliance and spectral density. These are listed Table 1.

Conclusions

The future availability of advanced X/γ ray photon beams in the energy range $1-20$ MeV range will open many opportunities of addressing strategic applications in Nuclear Photonics.The EuroGammaS collaboration is building the most advanced source in this field that will start operation in 2018.

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