The 10th International Conference "Charged & Neutral Particles Channeling Phenomena"

Geant4 implementation of inverse Compton scattering

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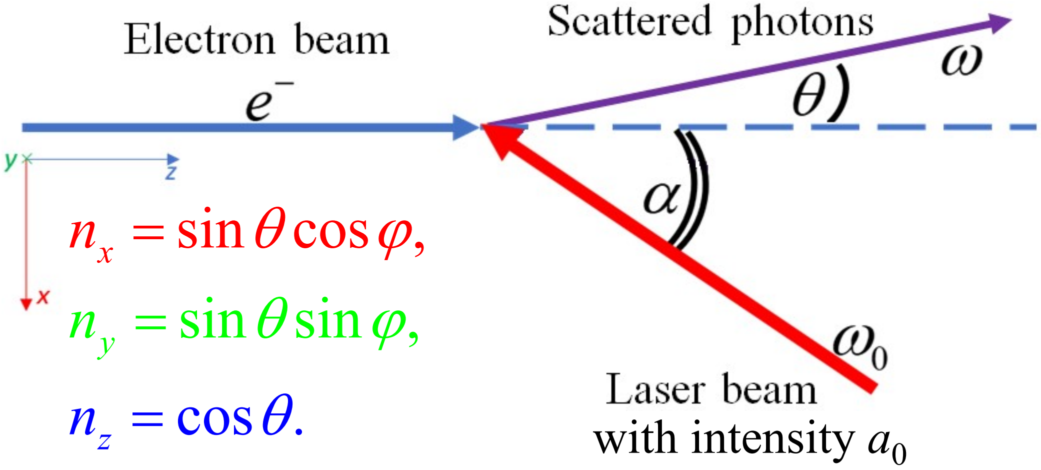
8-13 September 2024
Riccione, Italy

INVERSE COMPTON SCATTERING X-RAY SOURCE

We need compact and bright source



$$n_x = \sin\theta\cos\varphi,$$
$$n_y = \sin\theta\sin\varphi,$$
$$n_z = \cos\theta.$$

$$\omega \approx \frac{4\gamma^2\omega_0}{1+\gamma^2\theta^2}$$

$$\omega_{\max} = 4\gamma^2\omega_0$$

Predicted average flux ~$\underline{10^{14}\ \text{ph/s}}$

*W.S. Graves et al., NIM A **608**, 103 (2009)*

Medical applications – 10^{12} - 10^{16} ph/s

POSSIBILITIES TO INCREASE THE NUMBER OF PHOTONS

- Increasing e-bunch population

space-charge effect

- Using more intense laser

nonlinear effects make source more unpredictable

- One can decrease beam area size

emittance is growing

$$N_{ph} \propto \frac{\sigma_{Thomson}}{\sigma_{laser}^2 + \sigma_e^2} T_{int} a_0^2 N_e$$

- Generation of coherent radiation

special e-beam is needed

- Synchronization of fronts of laser and e-beams

crab crossing, superluminal Cherenkov radiation

D.V. Gavrilenko - CH2023, 05.06.2023 D.V. Gavrilenko - Tuesday, 10.09.2024

We need simulation tool capable of comprehensive calculations!

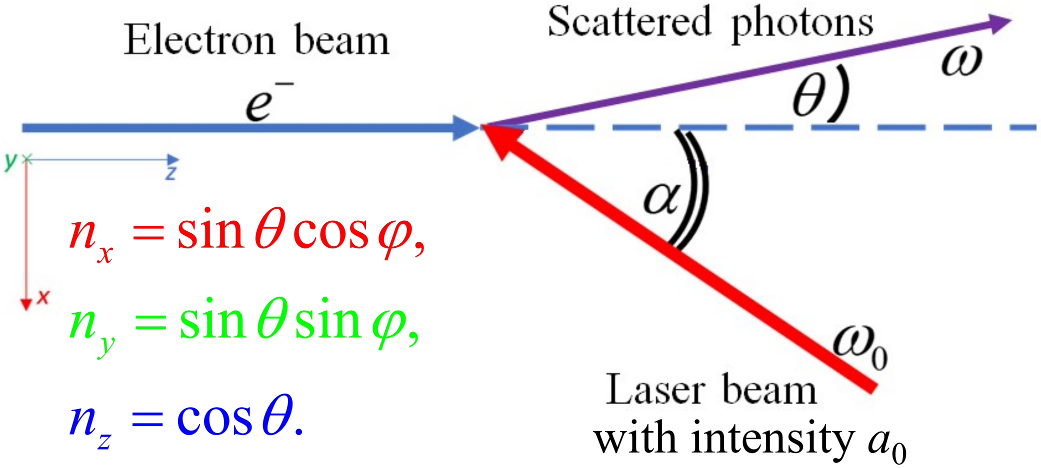
A.D. Debus et al., Appl. Phys. B **100**, 61 (2010).
A.P. Potylitsyn, D.V. Gavrilenko, M.N. Strikhanov, A.A. Tishchenko,, Phys. Rev. AB **26**, 040701 (2023).

SOME SIMULATION TOOLS

- CAIN (Monte-Carlo, beam-to-beam interaction)
- ICCS (Semi-analytical, individual electron to laser interaction, can cover low-probability regions of distributions)
- GEANT4 LCS code (Monte-Carlo, restriction method, generation of primary particles, very fast)
- Our Geant4 code (Analytical models, Monte-Carlo, fixed target/primary particles)

P. Chen, G. Horton-Smith, T. Ohgaki, A. Weidemann, and K. Yokoya, Nucl. Instrum. Methods A **355**, 107 (1995).
N. Ranjan, B. Terzić, G. A. Krafft, V. Petrillo, I. Drebot, and L. Serafini, Phys. Rev. Accel. Beams **21**, 030701 (2018).
G. Paterno, P. Cardarelli, M. Bianchini, A. Taibi, I. Drebot, V. Petrillo and H. Hajima, Phys. Rev. AB **25**, 084601 (2022).
R. Hajima, Nucl. Instr. Meth. A **985**, 164655 (2021).
A.A. Savchenko, A.A. Tishchenko, D.Yu. Sergeeva, Proc. of RUPAC, TUPSB29, 286, 2021

GENERAL PROPERTIES OF RADIATION



$$n_x = \sin\theta\cos\varphi,$$
$$n_y = \sin\theta\sin\varphi,$$
$$n_z = \cos\theta.$$

$$\omega = m\omega_0 \frac{1-\beta_{0z}}{1-\mathbf{n}\boldsymbol{\beta}_0}$$

arbitrary $\alpha : \omega_1 = \omega_0 \dfrac{1-\beta_0\cos\alpha}{1-\beta_0\cos\theta'}$

$\theta = \pi - \theta'$

head – on collision : $\omega_1 = \omega_0 \dfrac{1+\beta_0}{1+\beta_0\cos\theta}$

$$\frac{d^2N(\mathbf{n},\omega)}{d\theta d\hbar\omega} = \frac{\omega}{137}\frac{\sin\varphi d\varphi}{4\hbar\pi^2c^2}\left|\sum_{s=-\infty}^{\infty} e^{i(A+s\eta)\frac{T}{2}} F\left[\mathbf{H}J_s(B) + \frac{\mathbf{K}}{2}J_{s-1}(B) + \frac{\mathbf{K}}{2}J_{s+1}(B)\right]\right|^2$$

$$F = \frac{\sin\left(T(A+s\eta)/2\right)}{(A+s\eta)/2}, \mathbf{H} = [\mathbf{n}\mathbf{v}_0], B = \frac{\omega}{\omega_0}\frac{a_0}{\gamma_0}\frac{n_x(1-\beta_{0z}) + n_z\beta_{x0} - \beta_{x0}(\mathbf{n}\boldsymbol{\beta}_0)}{(1-\beta_{0z})^2}$$

$$\eta = \omega_0(1-\beta_{0z}), A = \omega(1-\mathbf{n}\boldsymbol{\beta}_0), \mathbf{K} = \frac{a_0}{\gamma_0}\frac{\beta_{x0}}{1-\beta_{0z}}[\mathbf{n}\mathbf{v}_0] - \frac{ca_0}{\gamma_0}\frac{\beta_{x0}}{1-\beta_{0z}}[\mathbf{n}\mathbf{e}_z] - \frac{ca_0}{\gamma_0}[\mathbf{n}\mathbf{e}_x]$$

$$s = -m, \quad m > 0$$

GENERAL PROPERTIES OF RADIATION

Spectral distribution

$$\frac{dW(\omega)}{d\hbar\omega} = \frac{1}{137}\frac{\omega T}{2\pi c^2}\sum_{i=1}^{I}\int d\varphi\, f(\cos\theta_i,\varphi,\omega)$$

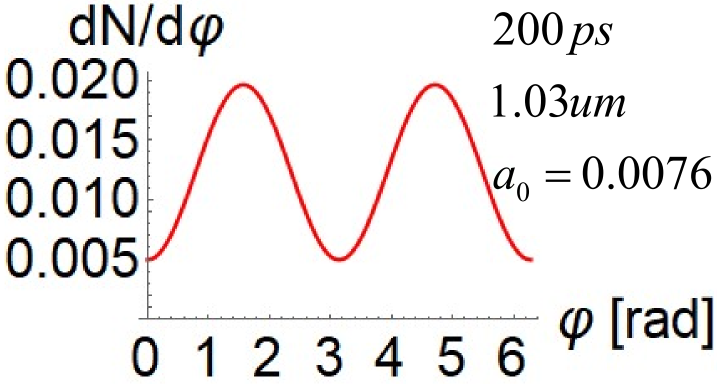
Numerical integration over azimuthal angle is still needed

$$f(\cos\theta,\varphi,\omega) = \left[\mathbf{H} - m\frac{\mathbf{K}}{B}\right]^2 J_m^2(B) \bigg/ \left|\beta_{0x}\frac{\cos\theta\cos\varphi}{\sin\theta} - \beta_{0z}\right|$$

I=1 for head-on collision or I=2 for other cases

$$\cos\theta_{1,2} = \frac{w\beta_{0z} \pm \beta_{0x}\cos\varphi\sqrt{\beta_{0z}^2 + \beta_{0x}^2\cos^2\varphi - w^2}}{\beta_{0z}^2 + \beta_{0x}^2\cos^2\varphi}$$

$$1 - m\frac{\omega_0}{\omega}(1-\beta_{0z}) = w < 1$$



$\gamma = 44$

$200\,ps$

$1.03um$

$a_0 = 0.0076$

Angular distribution

$$\frac{dW(\mathbf{n})}{d\Omega} = \frac{\hbar}{137}\frac{m^2\omega_0^2}{2\pi c^2}\frac{T(1-\beta_{0z})^2}{|1-\mathbf{n}\boldsymbol{\beta}_0|^3}\left[\mathbf{H} - m\frac{\mathbf{K}}{B_m}\right]^2 J_m^2(B_m)$$

$$B_m = \frac{m}{1-\mathbf{n}\boldsymbol{\beta}_0}\frac{a_0}{\gamma_0}\frac{n_x(1-\beta_{0z}) + n_z\beta_{x0} - \beta_{x0}(\mathbf{n}\boldsymbol{\beta}_0)}{1-\beta_{0z}}$$

GENERAL PROPERTIES OF RADIATION
COHERENT GENERATION

$$\frac{dN^{bunch}(\mathbf{n},\omega)}{d\hbar\omega d\Omega} = \frac{dN^{el}(\mathbf{n},\omega)}{d\hbar\omega d\Omega} F^{bunch} \longrightarrow F^{bunch} = N + N(N-1)G_{coh}$$

For one electron

Bunch form-factor

Coherent form-factor $G_{coh} = G^{l} G^{tr}$

Longitudinal

$$G^{l} = \exp\left[-\frac{\sigma_z^2 (k_z \cos\alpha - k_x \sin\alpha)^2}{2}\right] \frac{1}{N_b^2} \frac{\sin^2\left(N_b l_0 (k_z \cos\alpha - k_x \sin\alpha)/2\right)}{\sin^2\left(l_0 (k_z \cos\alpha - k_x \sin\alpha)/2\right)}$$

Transverse

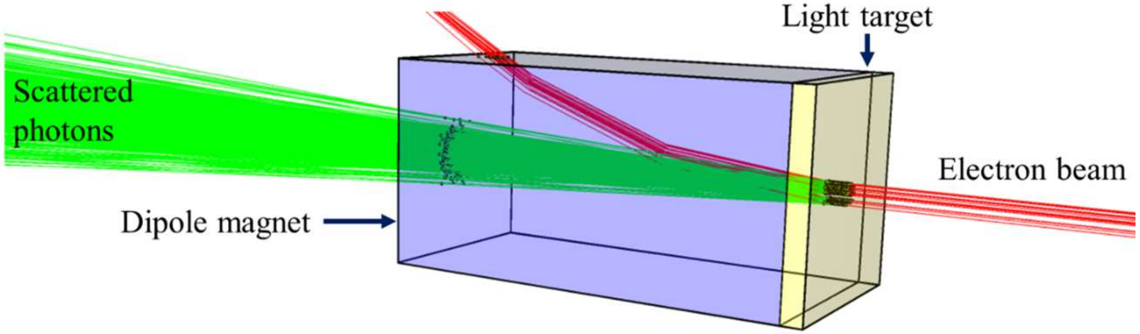
$$G^{tr} = \exp\left[-\frac{\sigma_y^2 k_y^2}{2} - \frac{\sigma_x^2}{2}(k_x \cos\alpha + k_z \sin\alpha)^2\right]$$

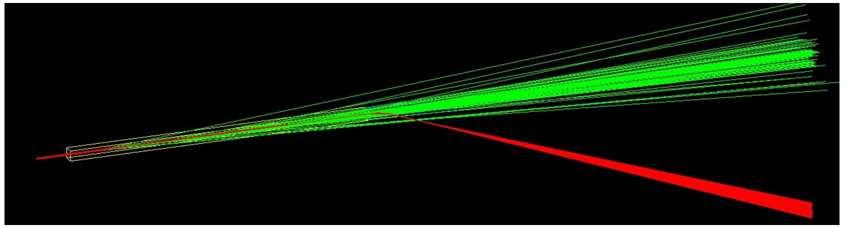
l_0 – *period of microbunched beam*

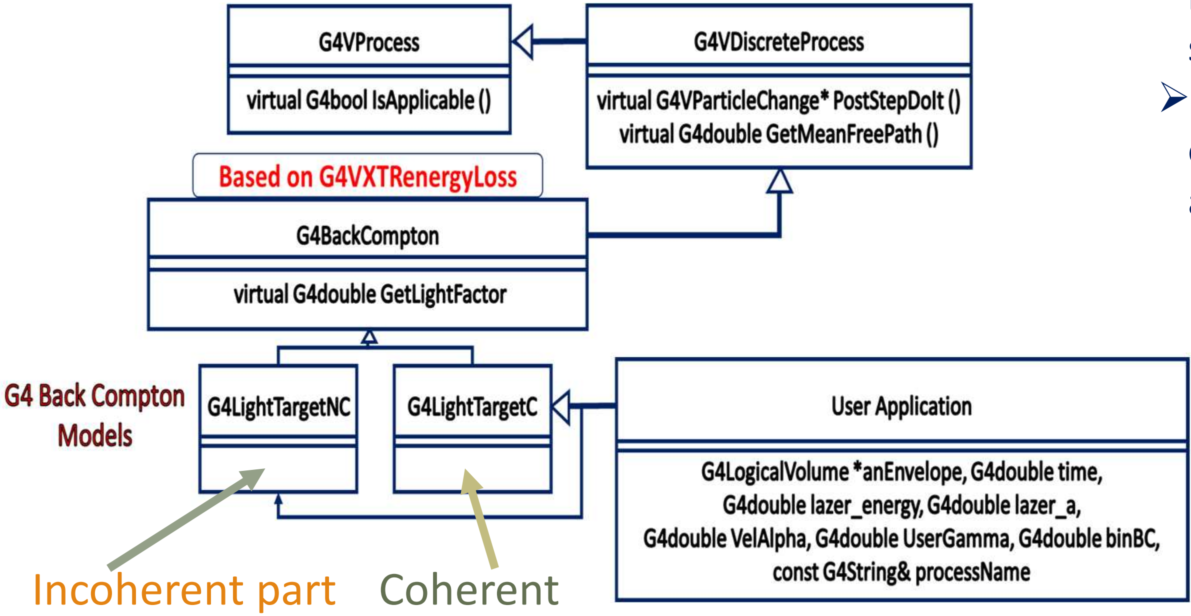
N_b – *number of microbunches*

A.A. Tishchenko, A.M. Feshchenko, Coherent Thomson Backscattering: Prospects of Compact X-ray Laser, Proc. of OSA High-brightness Sources and Light-driven Interactions Congress, (2020).
D.Yu. Sergeeva, A.A. Tishchenko, X-ray Thomson inverse scattering from periodically modulated laser pulses, CERN-Proceedings, vol. 2021-September, 283 (2021).

GEANT4 IMPLEMENTATION OF ICS



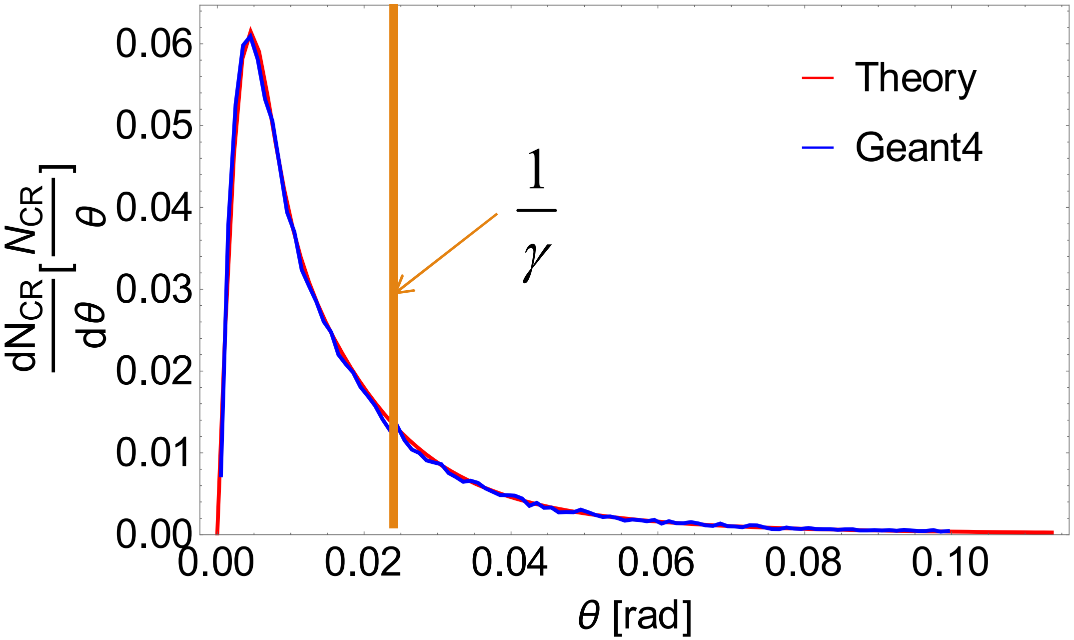


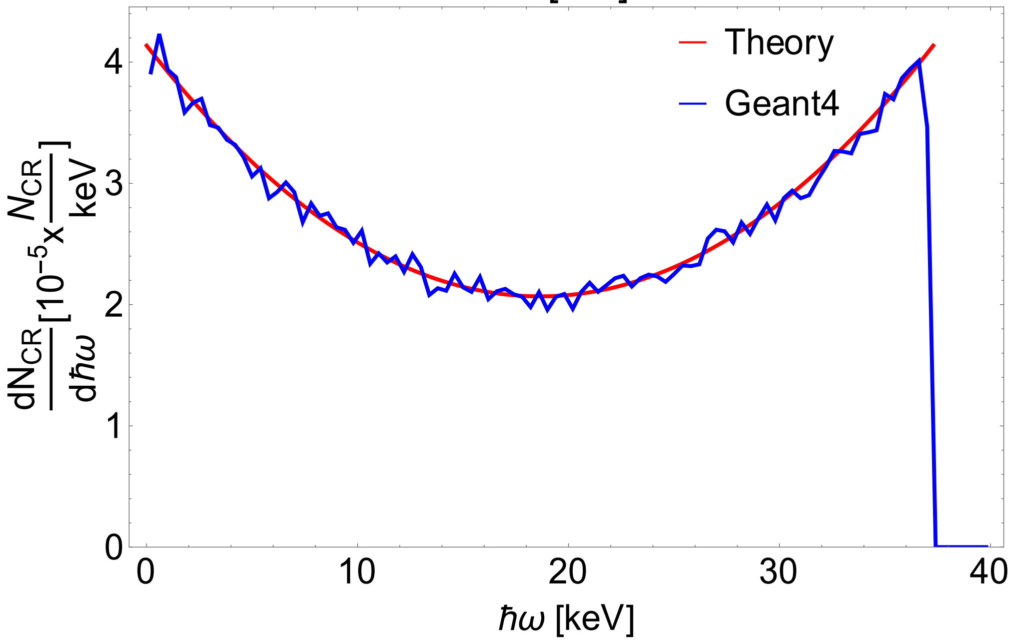


- Laser beam is substitute by the "Light target";
- G4BackCompton is discrete physical process;
- G4BackComptonModel includes expressions, which can be activated by G4LightTarget model;
- G4LightTarget is a class for incoherent simulations;
- G4LightTargetC is a class for coherent radiation from micro-bunched beams simulations;
- User Application include geometry and other physics descriptions, as well as analysis part for information retrieving.

GEANT4 A SIMULATION TOOLKIT

A. Savchenko and W. Wagner, Journal of Instrumentation **16**, P12042 (2021).
A.A. Savchenko, A.D. Khudyakova, W. Wagner, Nucl. Instr. and Meth. A **1060**, 169057 (2024).





GEANT4 SIMULATION

$\gamma = 44$

$2\,ps$

$1.03um$

$a_0 = 0.0076$

Collimation is needed to make spectral distribution narrower

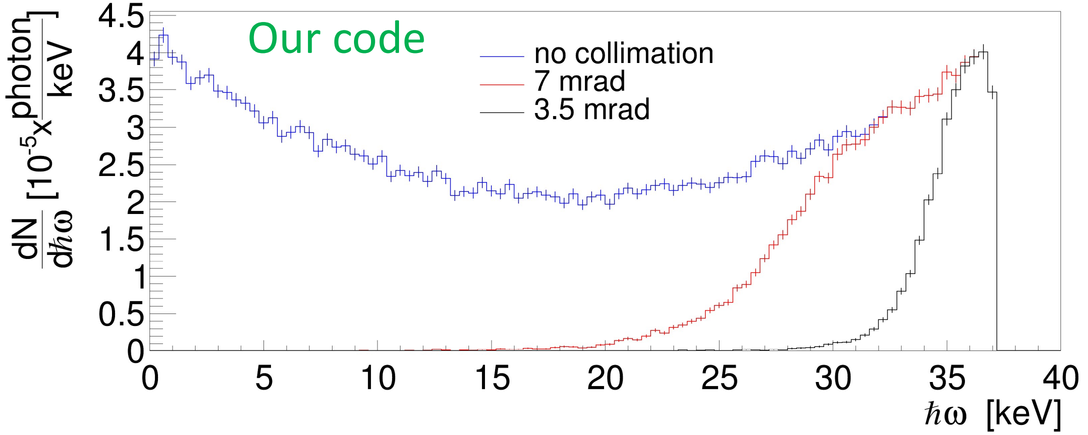
According to

$$\omega_1 = \omega_0 \frac{1+\beta_0}{1+\beta_0 \cos\theta}$$

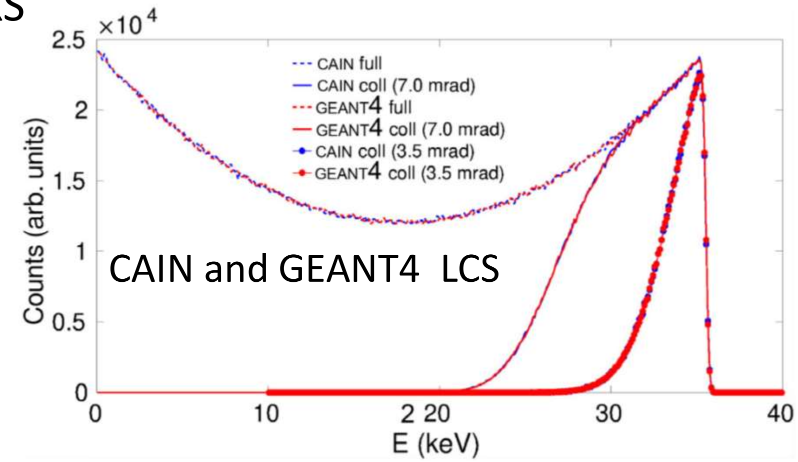
the lower radiation angle
the higher the energy of photons

GEANT4 SIMULATION

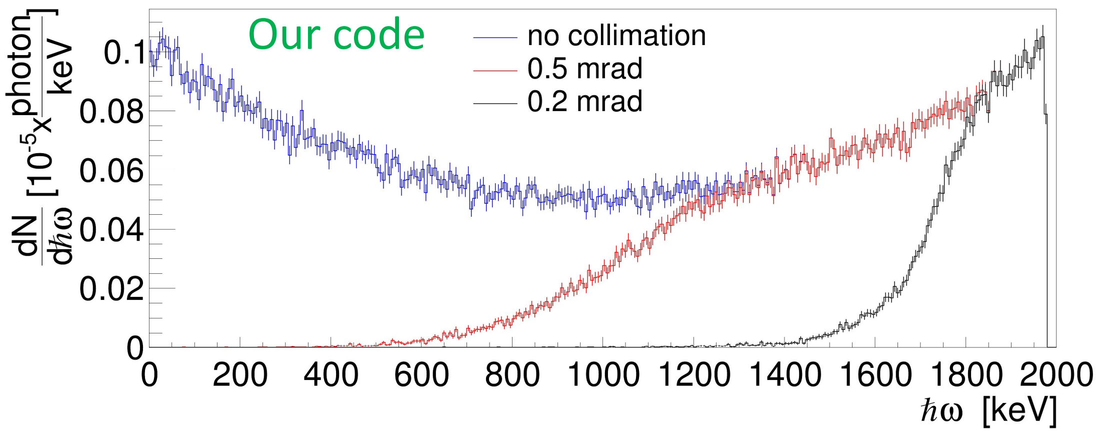
$$\gamma = 44, 2\,ps, 1.03um, a_0 = 0.0076, \alpha = 7^\circ$$



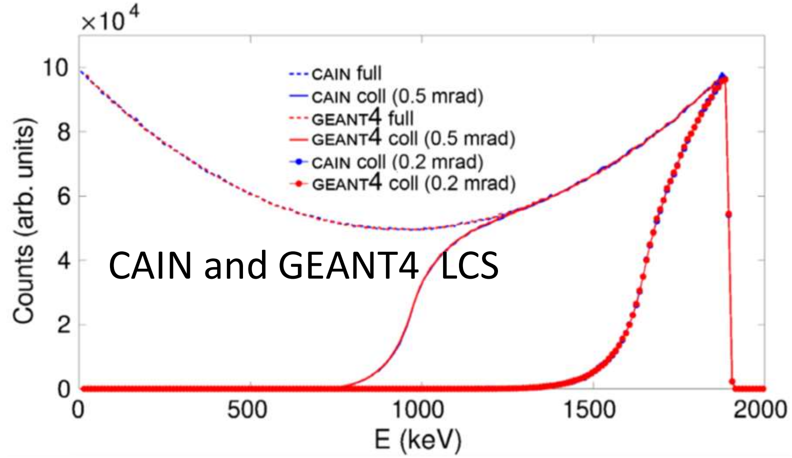
BriXS



$$\gamma = 2000, 1\,ps, 10um, a_0 = 0.0381$$

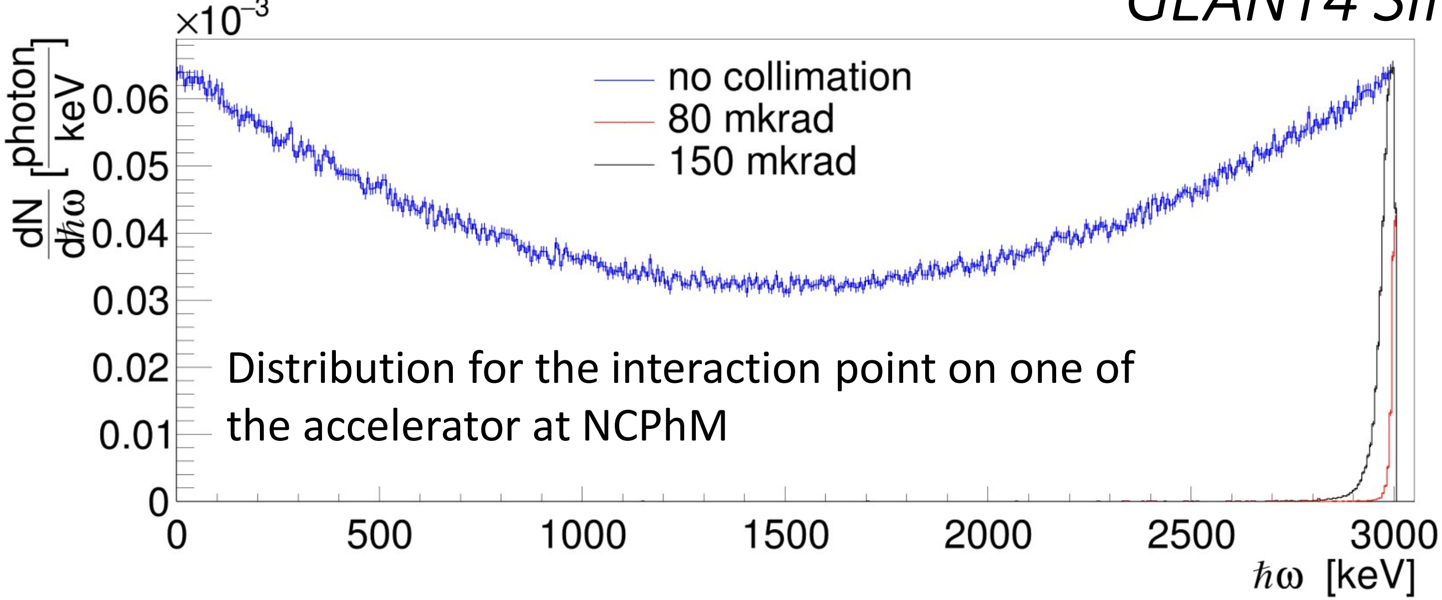


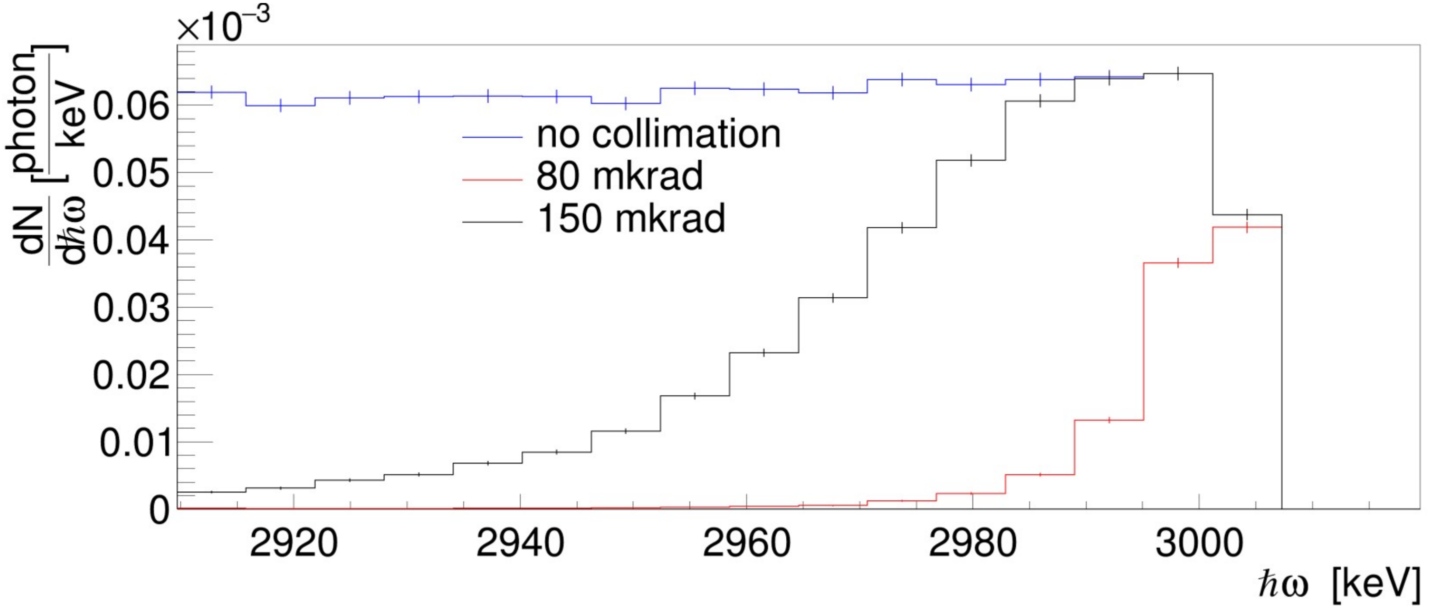
NewSUBARU



G. Paterno, P. Cardarelli, M. Bianchini, A. Taibi, I. Drebot, V. Petrillo and H. Hajima, Phys. Rev. AB **25**, 084601 (2022).

GEANT4 SIMULATION





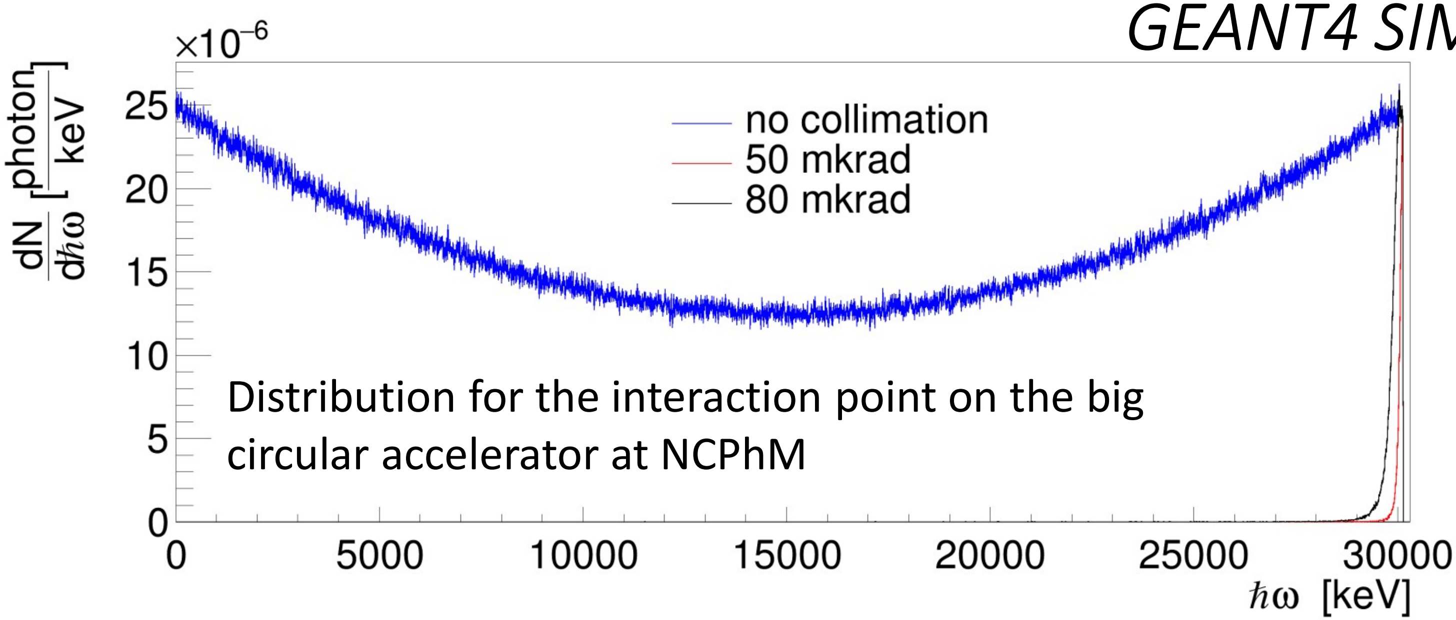
$\gamma = 808$

$10\,ps$

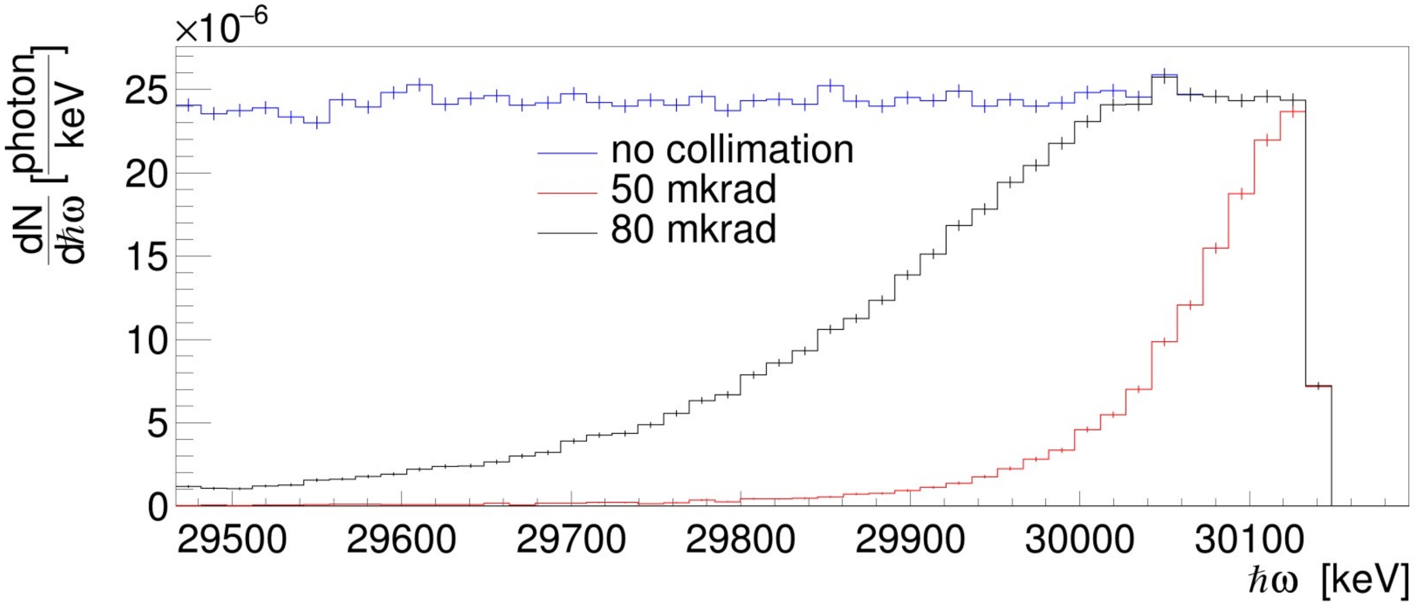
$1.03um$

$a_0 = 0.0381$

GEANT4 SIMULATION



Distribution for the interaction point on the big circular accelerator at NCPhM



$\gamma = 1298$

$10\,ps$

$0.265um$

$a_0 = 0.0381$

GEANT4 SIMULATION

One can also calculate spectral brightness ***R*** of the source

$$R = \frac{\dot{N}_{ph}}{4\pi^2 dS d\Omega \frac{d\omega}{\omega}}, \quad \dot{N}_{ph} = \left(\frac{dW}{\hbar\omega}\right) \nu_{\text{int}} N_e$$

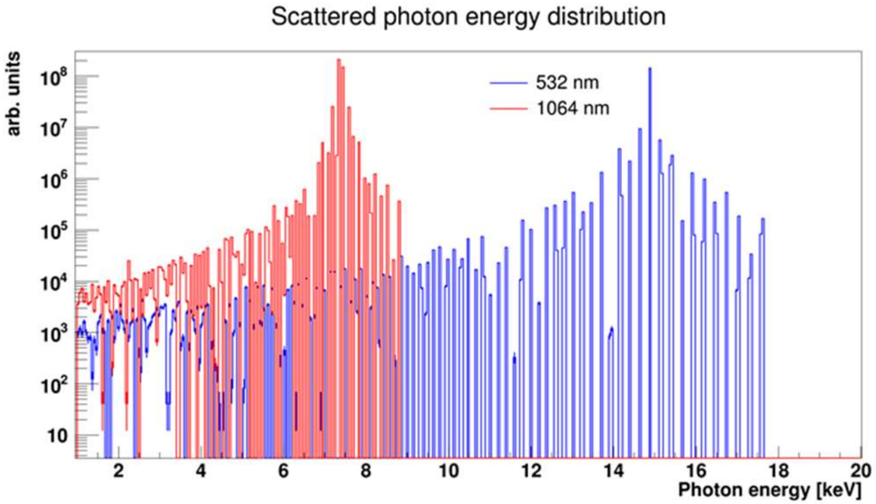
$N_e - e^-$ *bunch population*

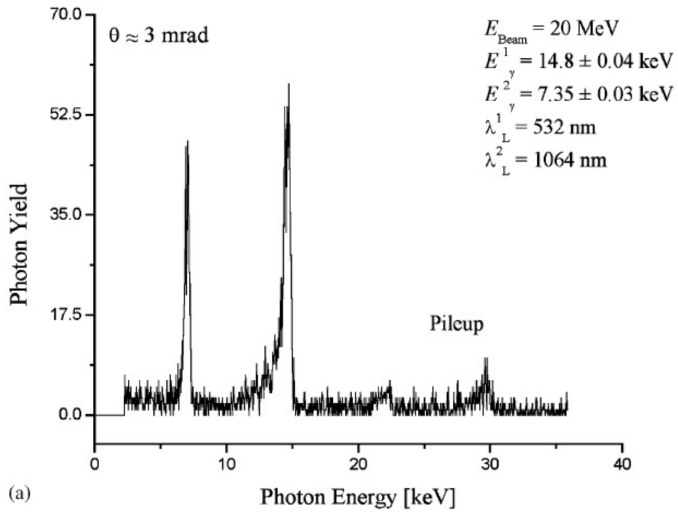
$\nu_{\text{int}} -$ *repetition rate* $(e.g. 1MHz)$

```
flazer_wavelen   0.000265
flazer_energy   4.67865e-06
fomega0   7.10812e+06
ftime   0.01
fNosc   71081.2
flazer_a   0.0381
falpha   0
fUsGamma   1270.06
NofParticle   10000000
MaxEenrgy = 30187.7
brightness = 2.32312e+10 Nph/(s*mm2*mrad2*0.1%)
```

Electron beam 20 MeV

Laser beam a_0 = 0.03, 7 ns, 532 nm and 1064 nm





K. Chouffani et al., *Nucl. Inst. and Meth. A* **495**, 95 (2002).

DISCUSSION

- We developed a Geant4-based **C++ application** for simulation and design of **inverse Compton** x-ray sources using **G4FastSimulation** principles;
- Comparison with other **simulation** programs and **available experimental data** shows that created physical module provides **predictable** and **reliable** results;
- The module operates with a **fixed light target** - virtual volume transparent for any particle and having properties of laser beam;
- The module allows simulation of laser and electron beams interaction under **arbitrary angles**, which can be of primary importance for reaching maximum luminosity of the radiation source. Using expressions for arbitrary angles allows implementation of so called crab crossing geometry – this work is in progress as well as investigations of possibility to add model for evaluation of laser-electron interaction effect on the electron beam emittance for designing big circular Compton sources.

Thank you for your attention!