

Recoil dominated e-photon beam collisions – a way towards novel radiation sources, advanced secondary beams and new phenomena in astrophysics

255.5 keV photons can stop ANY relativistic electron
 $0.5m_p c^2$ photons can stop ANY relativistic m_p particle

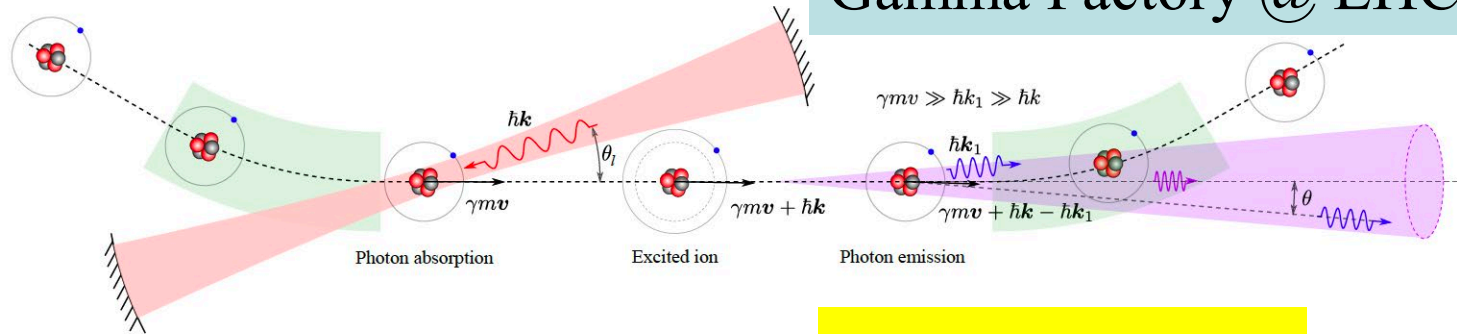
Luca Serafini, Vittoria Petrillo and Sanae Samsam
INFN-Milano and Università degli Studi di Milano

- *Deep Recoil Inverse Compton Scattering revisited, how to stop (MeV's, GeV's, TeV's ...) electrons in a single-collision event: a portal towards quantum gravity?*
- *From Thomson back-scattering to Full Inverse Compton Scattering (FICS, total transfer of energy/momentum from an electron to a photon)*
- *New findings with impacts in several fields like Plasma Physics (e^- trapping in plasma mirrors), Astro-Physics (cosmic gamma-ray sources) and QED&QuantumGravity (Unruh radiation)*

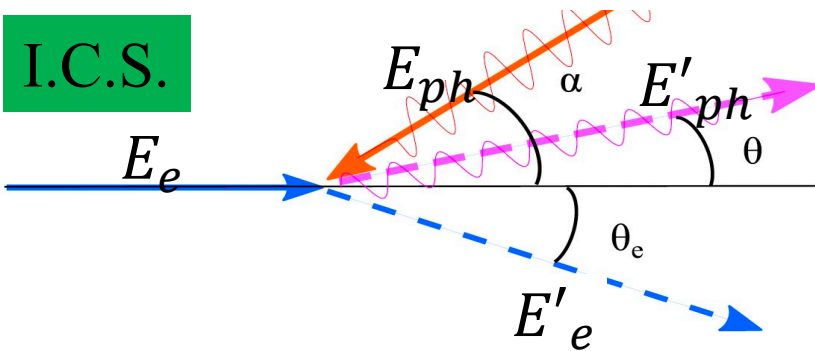
Collisional radiation

(quantum nature of light essential: Inverse Compton Scattering, Deep Recoil ICS for e^+ or μ^+ , μ^- secondary beam generation, Relativistic Rayleigh Scattering)

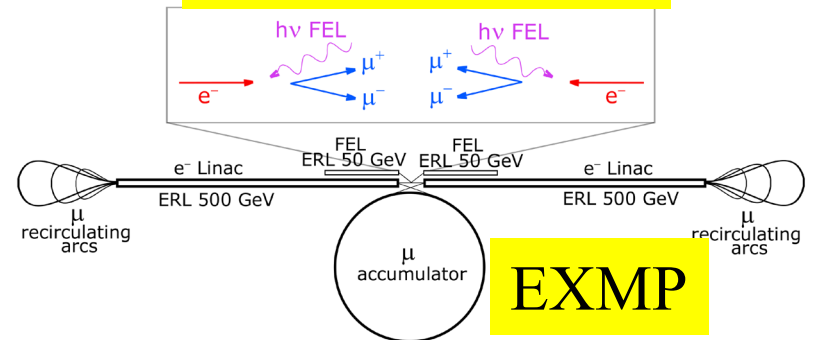
Gamma Factory @ LHC



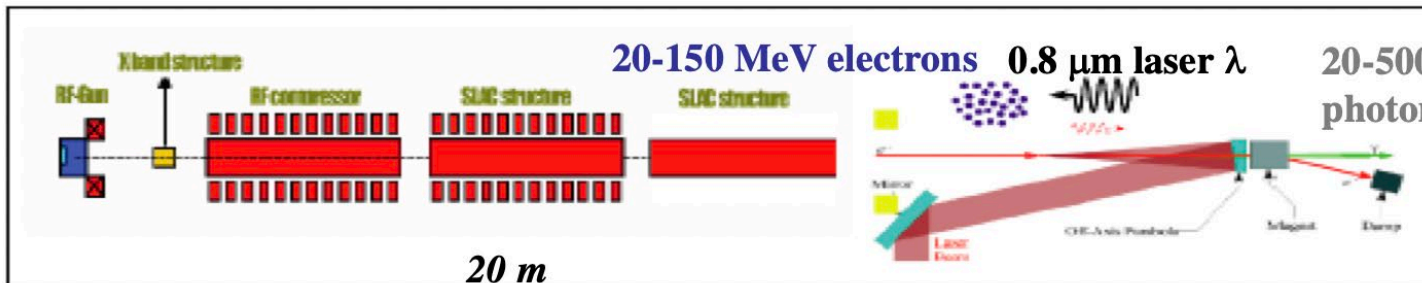
I.C.S.



deep recoil I.C.S.



EXMP



low recoil I.C.S. - STAR

Commissioning the STAR Inverse Thomson Scattering X-ray source: progress report

Marcel Ruijter¹, Adolfo Esposito², Alberto Bacci¹, Luigi Faillace², Alessandro Gallo², Alessandro Vannozzi², Andrea Ghigo², Angelo Stella², Dario Giannotti¹, Alesini David², Ezio Puppini³, Fabio Cardelli², Francesco Prelz¹, Gaetano Catuscelli², Gianluca Luminati², Giorgio Scarselletta², Ilyya Drebot¹, Luca Piersanti², Luca Serafini¹, Luigi Pellegrino², Marcello Rossetti Conti¹, Marco Bellaveglia², Sanae Samsam¹, Sandro Vescovi², Simone Bini², Simone Tocci², Vittoria Petrillo⁴

Abstract

The Southern European Thomson back-scattering source for Applied Research (STAR) is a high energy photon facility located on the campus of the University of Calabria (UniCal). The facility was designed for its first phase to operate with an electron and photon energy up to 85MeV and 140keV respectively. For the second phase of the project the energy of the electrons, and thereby the photons, would be increased up to 150MeV and 300keV respectively. The Italian Institute for Nuclear Physics (INFN) was awarded the project for installing, testing and commissioning the energy upgrade of the electron beamline. Here we will outline the progress made regarding the RF system and the Control System Software (CSS). The former consists out of two C-band linacs connected to their individual RF power stations for which the site acceptance test has recently been performed. For the latter the network of the STAR site has been extended to allow the EPICS based CSS to be further developed, including top level GUIs and IT security infrastructure.



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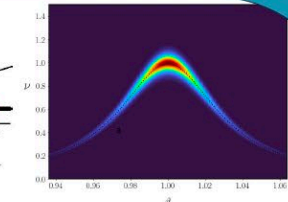
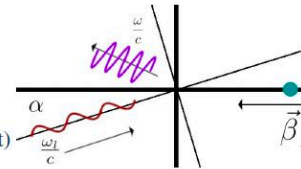
Upgrade to High Energy Line

Upgrade to High Energy line (HE-line) consist out of:

- > Installation of solenoid (8 cm) in front of S-band cavity for emittance control
- > Installation of two C-band RF cavities incl. powerstations, for higher beam energy
- > Cooling system upgrade
- > Electric system upgrade, incl. backup power, power supplies and cabling
- > IT infrastructure & control system software

STAR Facility

- Generating high energy radiation for
- > Biological & Medical Imaging
 - > Cultural Heritage
 - > Composite Materials
 - > Metallurgy (Hydrogen embrittlement)
 - > Mineralogy



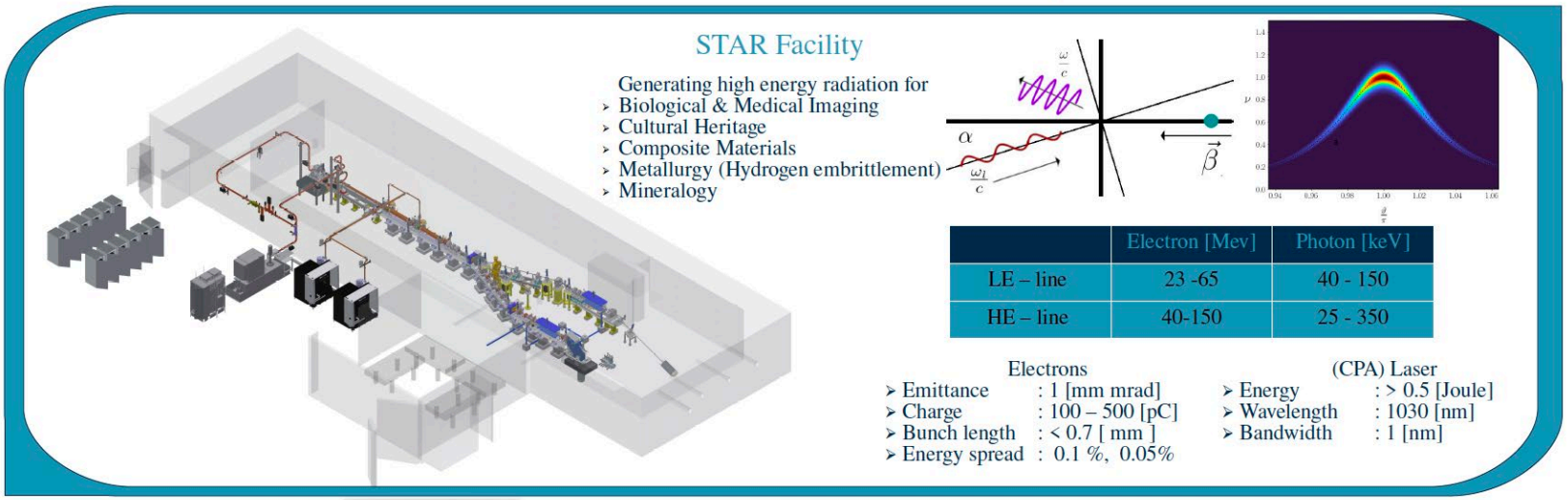
	Electron [Mev]	Photon [keV]
LE – line	23 -65	40 - 150
HE – line	40-150	25 - 350

Electrons

- > Emittance : 1 [mm mrad]
- > Charge : 100 – 500 [pC]
- > Bunch length : < 0.7 [mm]
- > Energy spread : 0.1 %, 0.05%

(CPA) Laser

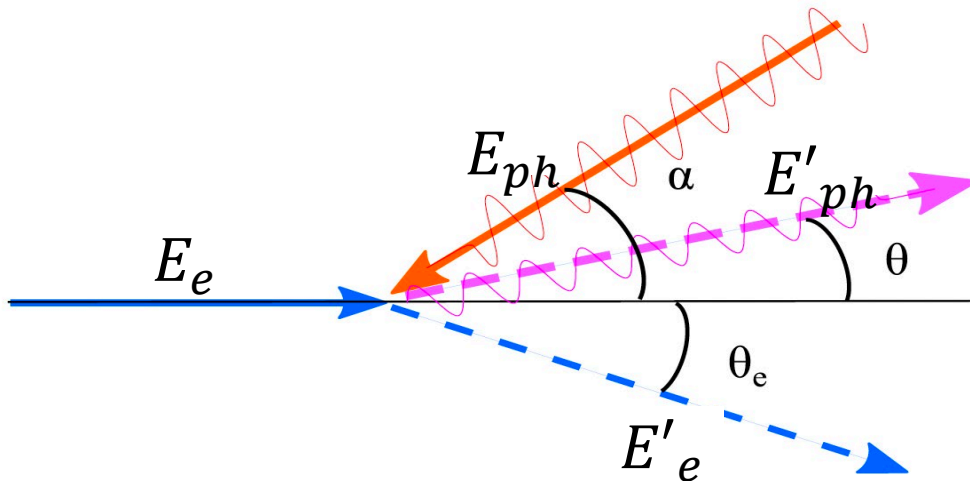
- > Energy : > 0.5 [Joule]
- > Wavelength : 1030 [nm]
- > Bandwidth : 1 [nm]





The $\gamma^2\theta^2$ issue/disease

All radiation originated by a Lorentz Boost associated to relativistic emitting particles (electrons, heavy ions) is intrinsically poli-chromatic because of $\gamma\theta$ correlation (energy boost of scattered photons depends on scattering angle, at $\theta=1/\gamma$ photon energy is 50% of max photon energy at $\theta=0$) of single electron spectrum (on top of inhomogeneous effects)



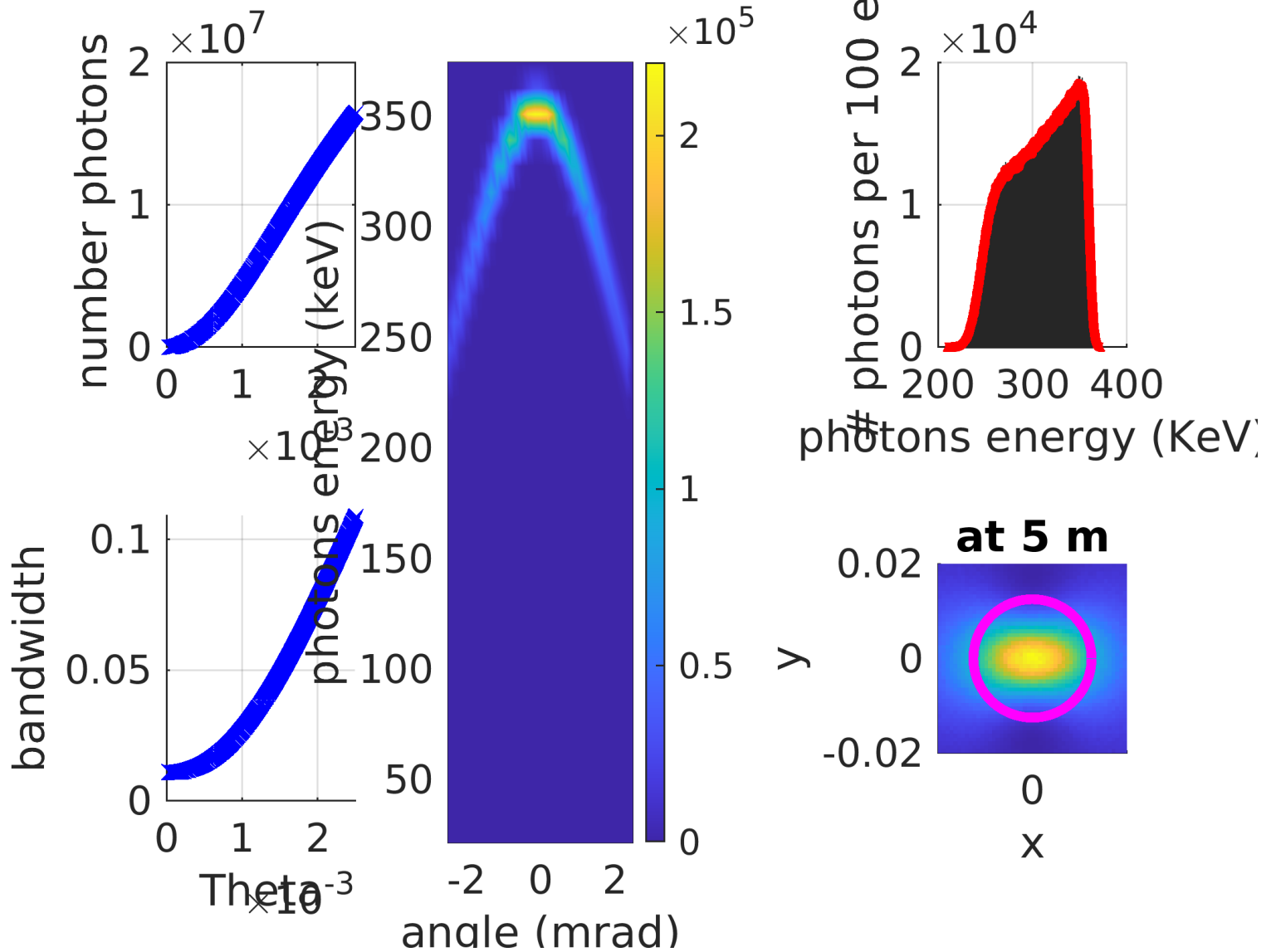
$$E_e = \gamma mc^2$$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + X + \gamma^2 \vartheta^2}$$

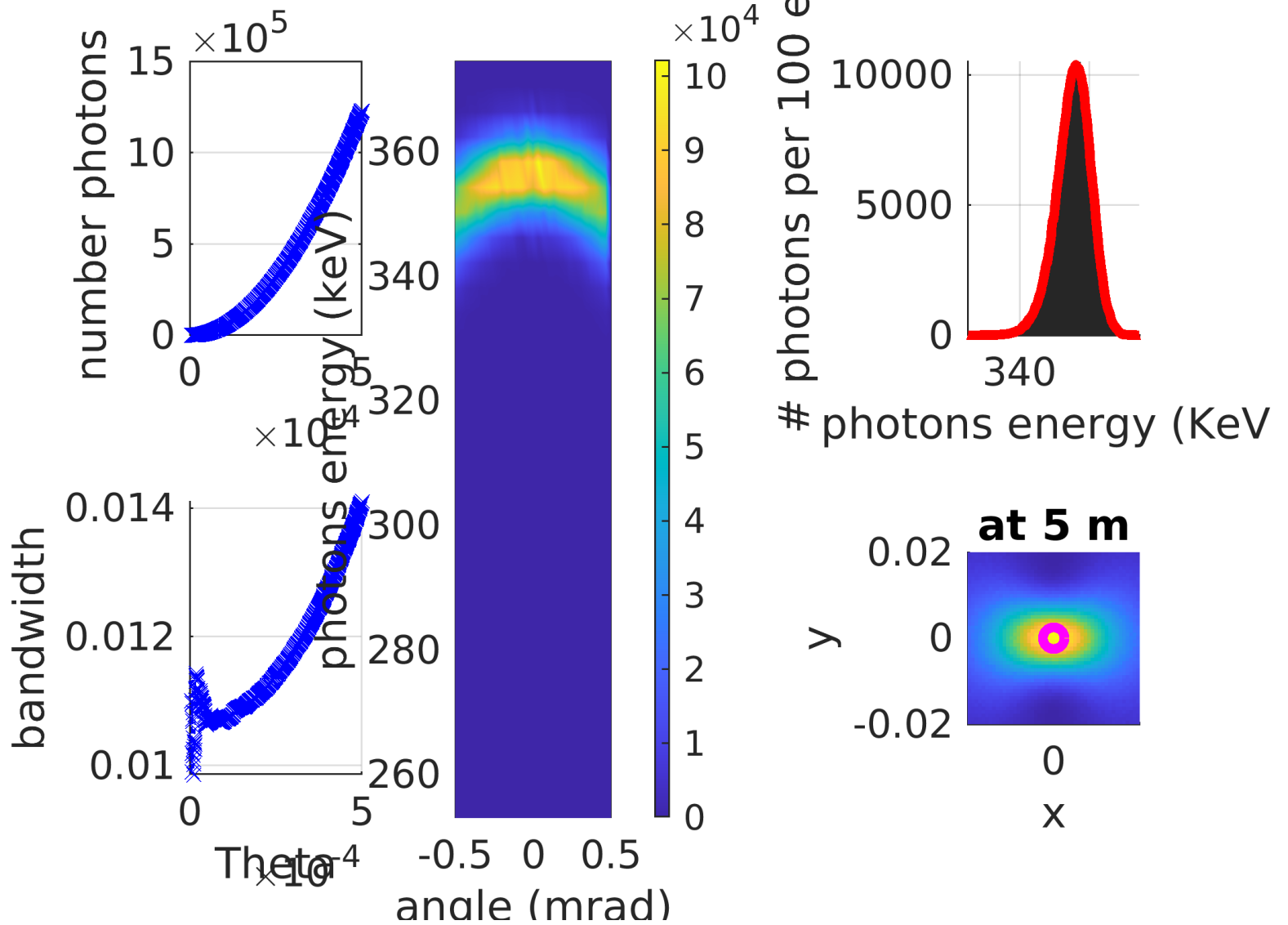
$$X \equiv \frac{4\gamma E_{ph}}{mc^2} = \frac{2E_{ph}^{ERF}}{mc^2}$$

True for all kinds of Undulatory and Collisional radiation (bremsstrahlung, wiggler/betatron, synchrotron, RRS, ICS), while resonant or amplified radiation (undulators, FELs), that are diffraction limited thanks to their beam quality, are not (or only partially) affected

WP 140 MeV

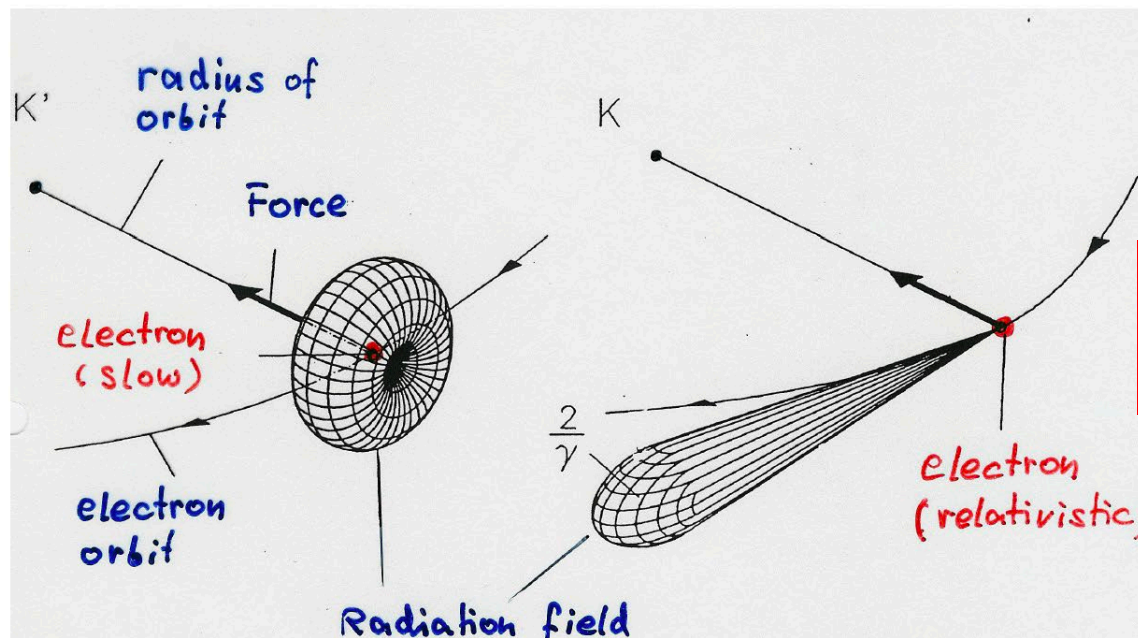
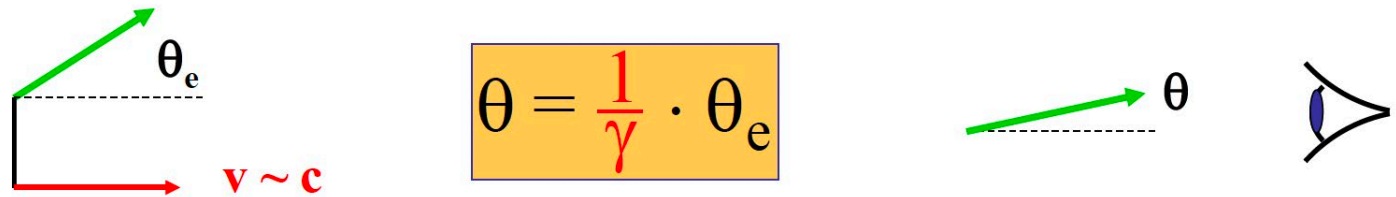


WP 140 MeV



Also synchrotron radiation is affected by the $\gamma^2\theta^2$ red shift

Radiation is emitted into a narrow cone



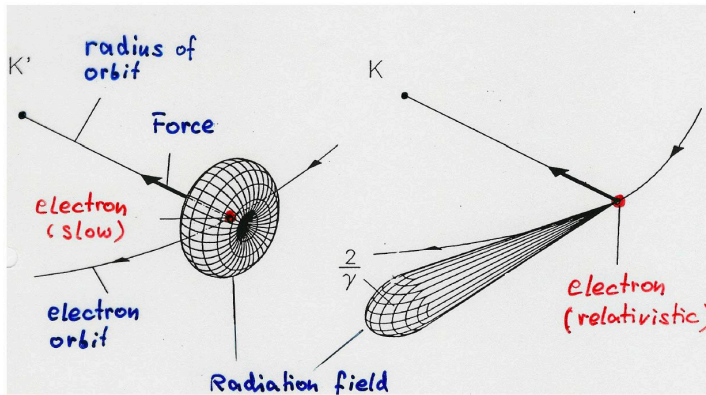
Lorentz boost

$v \ll c$

$v \approx c$

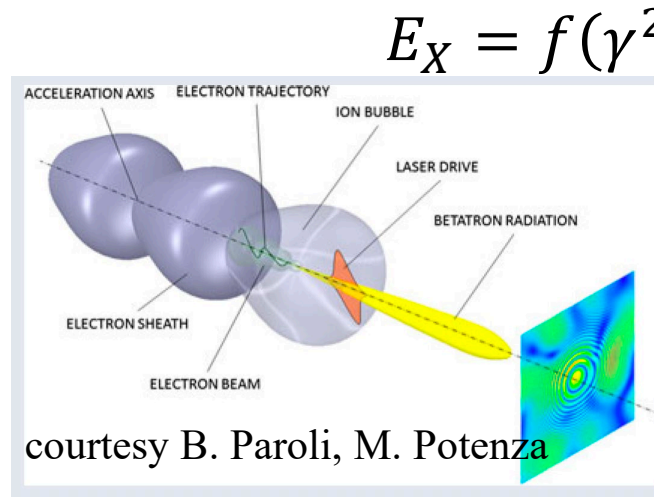
All spontaneous undulatory X/γ Radiation Sources (keV, MeV, GeV...) are affected by the angular correlation

Spontaneous undulatory radiation (synchrotron, wiggler, betatron, channeling, bremsstrahlung)

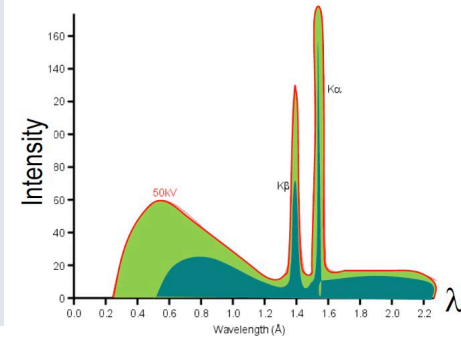
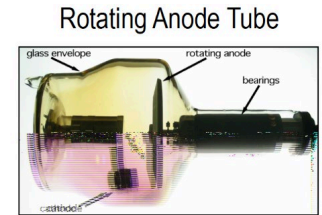


$v \ll c$

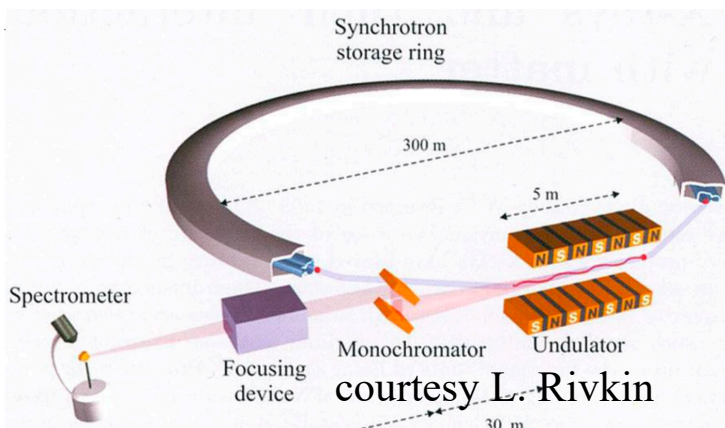
$v \approx c$



$E_X = f(\gamma^2 \vartheta^2)$



Resonant/amplified undulatory radiation (undulator, FEL)



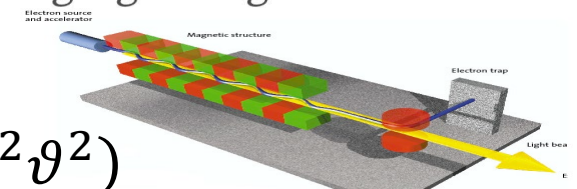
Optics Communications
Volume 50, Issue 6, 15 July 1984, Pages 373-378



Collective instabilities and high-gain regime in a free electron laser

R. Bonifacio *, C. Pellegrini, L.M. Narducci

$E_X \neq f(\gamma^2 \vartheta^2)$



A simple yet fundamental question:

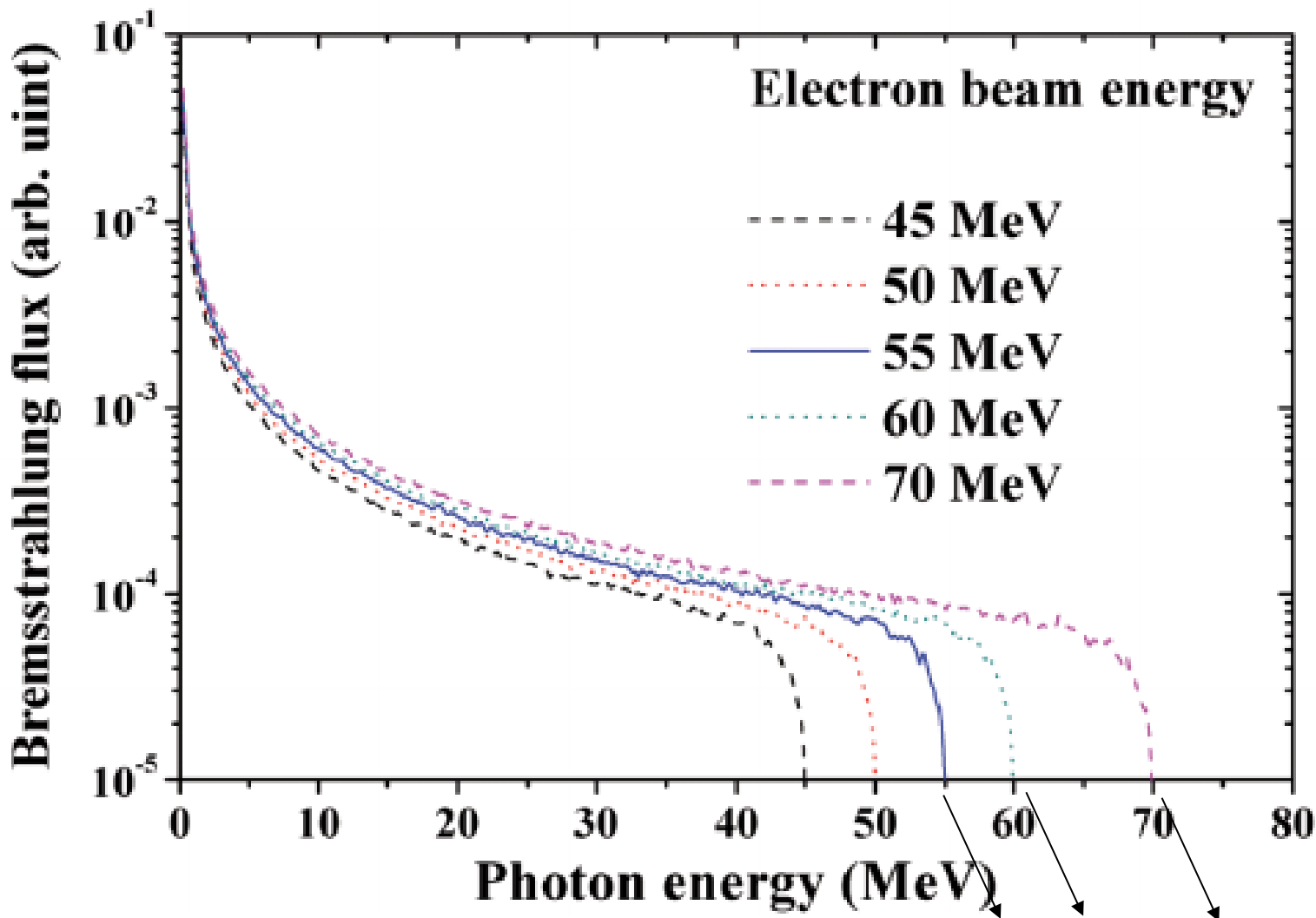
“Why do I need **150 Mega-electronVolt electrons** to generate **350 kilo-electronVolt photons**” ??
(STAR biased...)

(not to mention a storage ring based light source where a GeV electron beam radiates tens keV photons)

*How to transfer maximum energy
from an electron to a photon...*

Bremsstrahlung is clearly not an option:

- a) total electron energy loss not actually achievable
- b) brilliance of bremsstrahlung sources is orders of magnitude smaller



100% e^- energy loss

beginning of the story – the photon, quantum of energy

THE

PHYSICAL REVIEW

A QUANTUM THEORY OF THE SCATTERING OF X-RAYS BY LIGHT ELEMENTS

BY ARTHUR H. COMPTON

ABSTRACT

The change in wave-length due to scattering.—Imagine, as in Fig. 1A,

rays by light elements. quantum is scattered it ticular electron. This

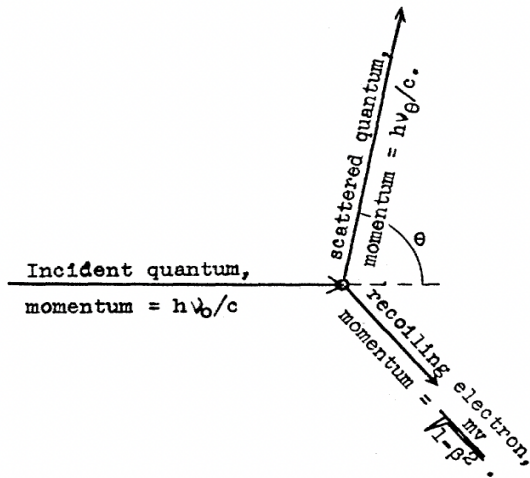


Fig. 1 A

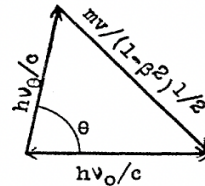
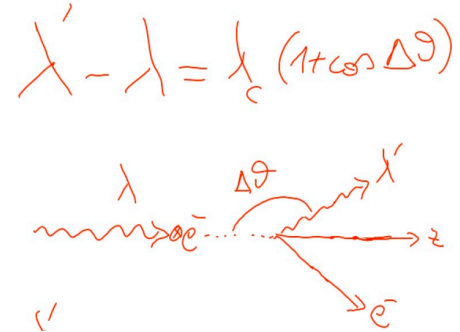


Fig. 1 B

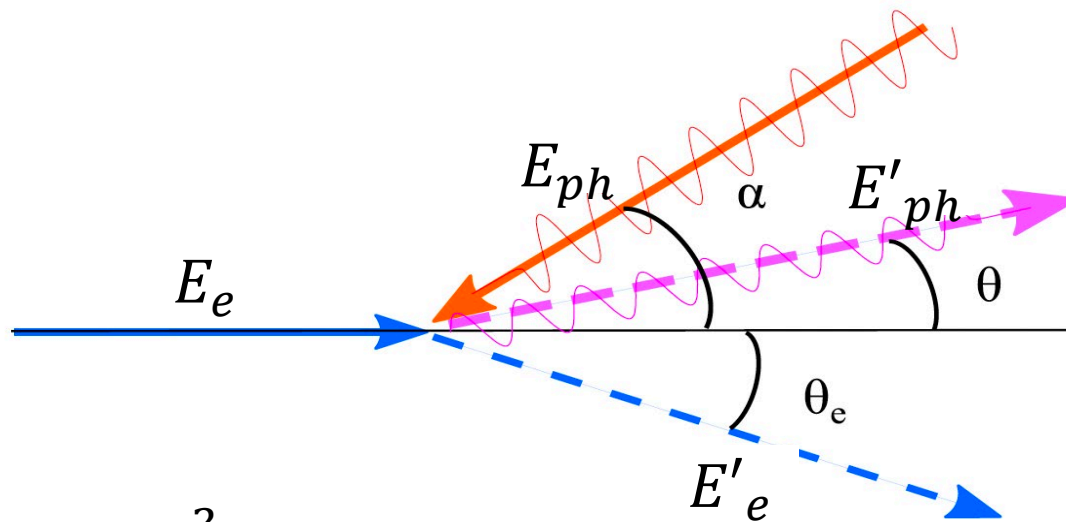


$$E'_{ph} = \frac{E_{ph}}{1 + \frac{E_{ph}}{mc^2} (1 + \cos \vartheta)}$$

that an X-ray quantum of frequency ν_0 is scattered by an electron of mass m . The momentum of the incident ray will be $h\nu_0/c$, where c is

angular correlation!

General Compton Scattering geometry
 between an incident electron E_e and a photon E_{ph}
 at a collision angle α , photon E'_{ph} scattering angle θ
 and electron E'_e scattering angle θ_e



$$E_e = \gamma mc^2$$

- a) $\gamma = 1$ *Direct Compton effect* Energy/momentum transferred from photon to e-
 b) $\gamma \gg 1$ *Inverse Compton* Energy/momentum transferred from e- to photon

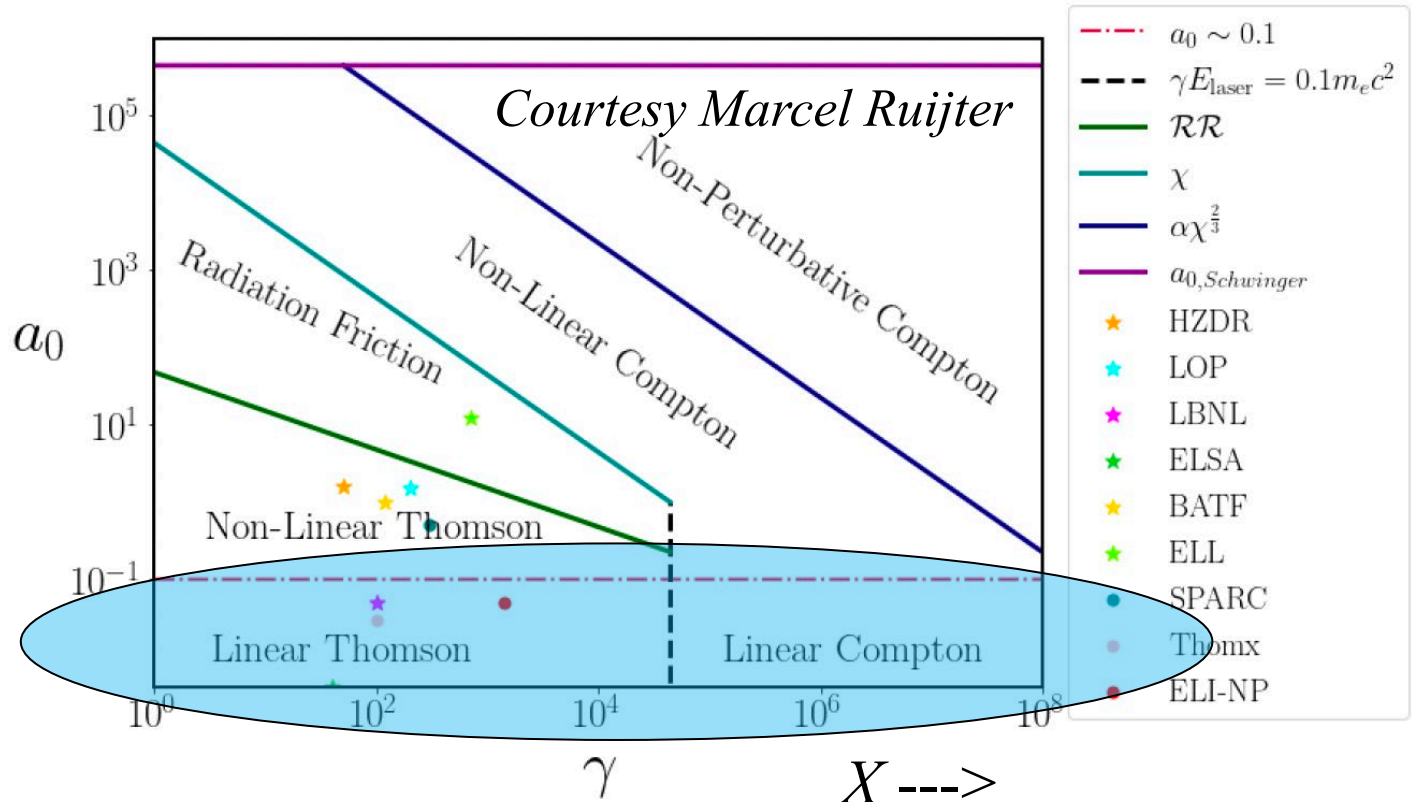
We are not considering in this study non-linear effects due to photon (laser) pulse intensity

$$a_{0,\text{linear}} = \frac{q}{mc^2} \sqrt{\frac{c}{4\pi}} \frac{\lambda}{2\pi} \sqrt{2I_{\text{peak}}}$$

$$= 0.85 \lambda [\mu\text{m}] \sqrt{\frac{I_{\text{peak}} [\frac{\text{W}}{\text{cm}^2}]}{10^{18}}}$$

$$a_{0,\text{circular}} = \frac{q}{mc^2} \sqrt{\frac{c}{4\pi}} \frac{\lambda}{2\pi} \sqrt{I_{\text{peak}}}$$

*no collective multi-photon effects
only single electron-photon interaction
(à la Klein-Nishina, linear QED)*



Deep Recoil ICS
FICS

First physicists forced to think at Inverse Compton Scattering,
i.e. a mechanism by which electrons loose energy in favor to photons,
(opposite than direct Compton effect) were...

The developers of the Nuclear Bomb!

and, soon later,

first observers of cosmic rays in the upper atmosphere,
trying to figure out why there are many protons and very few electrons

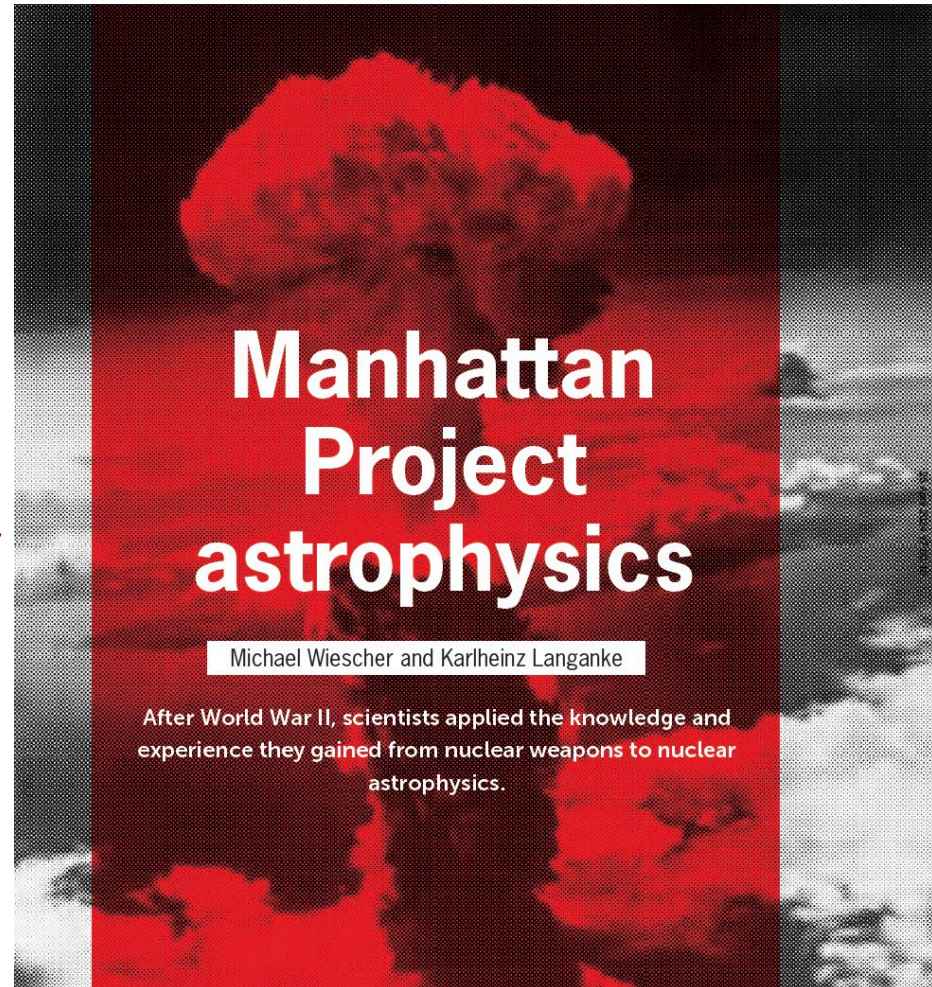
A. Compton 1923 - Direct Compton effect

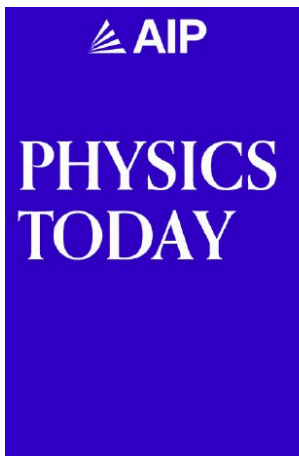
First consideration and study of Inverse Compton Scattering....

During the development of the nuclear bomb!

The Manhattan Project

*Will the back-scattered photons,
by hot electrons of the plasma
created in the initial stage of the
nuclear bomb explosion, release
energy from the fire-ball decreasing
its temperature???*





Manhattan Project astrophysics

After World War II, scientists applied the knowledge and experience they gained from nuclear weapons to nuclear astrophysics.

Michael Wiescher; Karlheinz Langanke



Physics Today 77 (3), 34–41 (2024);
<https://doi.org/10.1063/pt.jksg.hage>

*of initiating nuclear fusion
of the whole atmosphere!!!*

MANHATTAN PROJECT ASTROPHYSICS

an ignition could not be deemed impossible. The Trinity test took place in July 1945, and the atomic bombs were dropped on Hiroshima and Nagasaki shortly thereafter. Despite the bombs' tremendous damage, they did not set the atmosphere on fire.

Theory mitigates fear

The year after the test, Teller, his graduate student Emil Konopinski, and local technician Cloyd Marvin Jr wrote a classified Los Alamos National Laboratory report in which they summarized theoretical considerations on the possible ignition of the atmosphere by an atomic explosion.¹ The paper, declassified in 1979, argues that propagation of nuclear burning in the atmosphere is possible only if the energy gained from nuclear reactions is greater than the energy loss through the emitted gamma and beta radiation.

Konopinski, Teller, and Marvin considered the fusion of two ¹⁴N nuclei as the most important energy-producing reaction, because ¹⁴N is the dominant component in Earth's atmosphere.

On the other hand, when compared to the stable oxygen-16 isotope, ¹⁴N nuclei can easily be broken up. Therefore, the fusion of two ¹⁴N atoms should lead mainly to a rearrangement of the nucleons by the nuclear force and produce a light fragment and a heavy fragment. Energetically, the most favorable result would be their breakup into alpha particles and a magnesium-24 nucleus.

Up to 17.7 MeV of kinetic energy from the reaction can be



FIGURE 2. J. ROBERT OPPENHEIMER in typical postures—at the blackboard and with a cigarette. His goal as scientific director of the Manhattan Project was to develop a nuclear device that exploded from the fission of uranium-235 and plutonium-239. (Illustration by David McMacken.)

The electron gas cools by inelastic scattering and by emitting bremsstrahlung in the form of a continuous x-ray spectrum. Because the atmosphere is transparent to that radiation, it loses energy. Konopinski, Teller, and Marvin found that the rate of

gen content. Of even more concern were the tests of 20-megaton thermonuclear weapons (so-called hydrogen bombs), and scientists even considered the possibility of the fusion of ^{16}O atoms in ocean water.² Their explosions would increase the sudden energy release by up to three orders of magnitude. The uncertainties in the initial crude energy release and cooling calculations required experimental verification.

Experiment confirms theory

To experimentally clarify the troubling situation, a dedicated accelerator was built at Oak Ridge National Laboratory in the early 1950s, which made it possible to measure fusion cross sections for $^{14}\text{N} + ^{14}\text{N}$, $^{16}\text{O} + ^{16}\text{O}$, and other reactions of medium-heavy nuclei.³ Alexander Zucker, one of the young scientists who was to measure the effective cross sections and who would later be director of Oak Ridge, noted that for security reasons he and other experimentalists were not

fire-ball becomes transparent to photons, that can take energy off the fire-ball, limiting the maximum temperature down to a "safe" level

the data. megaton ly—a became ns re-) igni- mains asure- mon- maller ed by atmo- a few fusing s—are well below the Coulomb barrier, and the likelihood of fusion is low.

The Oak Ridge fusion tests were not confined to nitrogen and oxygen nuclei; they also included tests on light isotopes such as deuterium and tritium and were meant to inform Teller's plans and ideas for developing the "Super," his label for a thermonuclear weapon based on fusion. The idea for the fusion bomb based on the fusion of deuterium and tritium

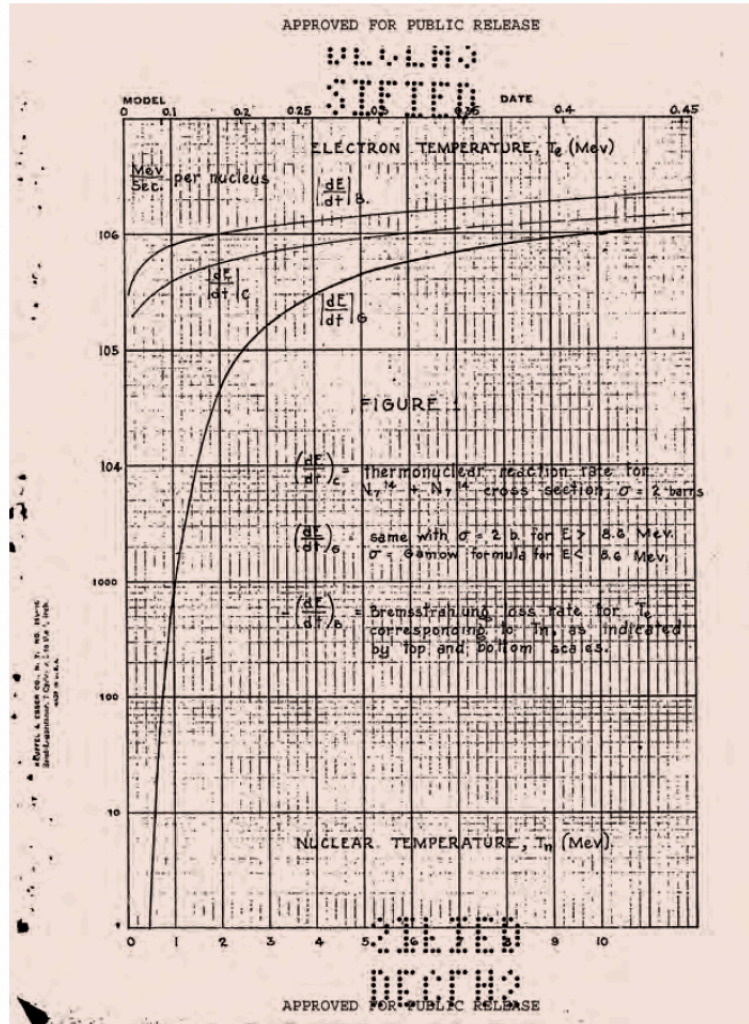


FIGURE 3. A CRITICAL PLOT of the rate of energy production as a function of temperature (in megaelectron volts), from the originally classified 1946 Los Alamos report *Ignition of the Atmosphere with Nuclear Bombs*.¹ Three curves characterize the energy-transport conditions for different temperatures in the nuclear fireball. The $(dE/dt)_c$ curve shows the reaction rate for the fusion of two nitrogen-14 nuclei when a constant cross section is assumed. The $(dE/dt)_G$ curve shows the $^{14}\text{N} + ^{14}\text{N}$ fusion reaction rate when the cross section is assumed to rapidly decrease at low energies, as predicted by George Gamow. And the $(dE/dt)_b$ curve shows the radiative energy loss through x-ray emission, as predicted by Arthur Compton. (From ref. 1.)

Gen. Leslie Groves asking Robert Oppenheimer about chances of atmosphere ignition - *”Robert, don’t blow-up the world”*



A. Compton 1923 - Direct Compton effect

● J. Follin 1947 - Inverse Compton Scattering
*first published (non classified) study on ICS**

PROPAGATION OF COSMIC RAYS THROUGH
INTERSTELLAR SPACE

Thesis by

James Wightman Follin, Jr.

● Second motivation to study ICS in the late '40s was understanding why electrons are almost missing in cosmic rays bombarding the upper atmosphere

In Partial Fulfilment of the Requirements for the

Degree of Doctor of Philosophy

Both directions (nuclear bomb and astrophysics) were looking for a mechanism capable to transfer maximum energy from the electrons to the photons

California Institute of Technology

Pasadena, California

1947

* *but unknown and not credited in the whole literature on ICS*

Interaction of Cosmic-Ray Primaries with Sunlight and Starlight*

E. FEENBERG AND H. PRIMAKOFF

Washington University, St. Louis, Missouri

(Received November 20, 1947)

This paper discusses collision processes between cosmic-ray primaries (protons and electrons) and the thermal photons of sunlight and starlight. In particular, electron-positron pair production and Compton scattering in interplanetary, intragalactic, and intergalactic space are treated in detail. It is found that the number of collisions between primary particles and thermal photons in single traversals

energetic scattered photons. The same statement holds for the primary protons even on an intergalactic scale. On the other hand, energetic primary electrons may experience a sufficient number of Compton collisions in intergalactic space (travel time of the order 2×10^9 years) to eliminate them effectively from the cosmic radiation reaching the neighborhood of the earth.

* The research described in this paper was supported in part by contract N60RI-117, U.S. Navy Department.

¹ T. H. Johnson, *Rev. Mod. Phys.* 11, 208 (1939); M. Schein, W. P. Jesse, and E. O. Wollan, *Phys. Rev.* 59, 615 (1941); 59, 930 (1941).

² Collisions between high energy photons, considered as cosmic-ray primaries, and thermal photons, with resultant electron-positron pair creation have been considered by G. Breit and J. A. Wheeler, *Phys. Rev.* 46, 1087 (1934);

45, 134 (A) (1934). Extensive calculations similar to the present have been carried out by J. W. Follin, *Bull. Am. Phys. Soc.* July 11, 1947, Abstract D5. Through the courtesy of Dr. J. R. Oppenheimer, we have seen a manuscript copy of Dr. Follin's paper.

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PHYSICAL REVIEW LETTERS

VOLUME 10

1 FEBRUARY 1963

NUMBER 3

ELECTRON SCATTERING BY AN INTENSE POLARIZED PHOTON FIELD*

Richard H. Milburn

Department of Physics, Tufts University, Medford, Massachusetts

(Received 26 December 1962)

Compton scattering by starlight quanta has been postulated by Feenberg and Primakoff to be a mechanism for the energy degradation of high-energy electrons in interstellar space.¹ We shall discuss here the possibility of observing this phenomenon directly in the laboratory by scattering a multi-GeV electron beam against the intense flux of visible photons produced by a typical laser. It will be shown that using existing laser systems and electron accelerators, one may expect to obtain of the order of several thousand collimated high-energy scattered photons during each accelerator pulse, and that these quanta retain to a high degree the polarization of the original beam of optical photons.

The kinematic formulas for Compton scattering on moving electrons are given by Feenberg and Primakoff.² We shall consider the special case of an extreme-relativistic electron of energy $E = \gamma mc^2$, $\gamma = 1/(1 - \beta^2)^{1/2} \gg 1$, incident head-on upon a beam of photons of energy $k_i = (1-3)$ eV propagating in the opposite direction. An observer moving with the incident electron will see a photon of energy $k_0 = 2\gamma k_i$. In Table I are listed for various laboratory electron energies, E , the corresponding values of k_0 tabulated in terms

The approximation fails only near $x = 1$, for which $k_f = k_i$ is required. However, for large $\gamma = E/mc^2$ the bulk of the scattered photons is folded back and emerges in the laboratory in the direction of motion of the incident electron, making angles with that direction given by $\theta = 2 \tan(\frac{1}{2}\theta) = (1/\gamma) \times \cot(\frac{1}{2}\theta_0)$. Thus for 1-GeV electrons, all photons having $23^\circ < \theta_0 < 180^\circ$ will end up within 0.0025 radian of the electron direction. We shall confine our discussion to these high-energy quanta. The


Table I. Energy, λ , polarization, and cross section for highest energy photons produced by ruby-laser photons scattered on electrons of energy E . The quantity $\sigma_{1/2}$ is the cross section for higher half of k_f spectrum.

E (GeV)	λ	$(k_f)_{\max}$ (MeV)	P_{\max}	$\sigma_{1/2}$ (mb)
1.02	0.014	28	1.00	320
2.92	0.040	216	1.00	310
4.16	0.057	426	0.99	300
4.60	0.063	515	0.99	290
5.11	0.070	628	0.99	290
5.48	0.075	715	0.99	290
5.84	0.080	806	0.99	280

Good recap of the whole ICS history

PHYSICAL REVIEW ACCELERATORS AND BEAMS 27, 080701 (2024)

From Compton scattering of photons on targets to inverse Compton scattering of electron and photon beams

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(Received 2 May 2024; accepted 1 August 2024; published 28 August 2024)

We revisit the kinematics of Compton scattering (electron-photon interactions producing electrons and photons in the exit channel) covering the full range of energy/momenta distribution between the two colliding particles, with a dedicated view to statistical properties of secondary beams that are generated in beam-beam collisions. Starting from the Thomson inverse scattering, where electrons do not recoil and photons are backscattered to higher energies by a Lorentz boost effect (factor $4\gamma^2$), we analyze three transition points, separating four regions. These are in sequence, given by increasing the electron recoil (numbers are for transition points and letters for regions): (a) Thomson backscattering, (1) equal sharing of total energy in the exit channel between electron and photon, (b) deep recoil regime where the bandwidth/energy spread of the two interacting beams are exchanged in the exit channel, (2) electron is stopped, i.e., taken down at rest in the laboratory system by colliding with an incident photon of $mc^2/2$ energy, (c) electron backscattering region, where incident electron is backscattered by the incident photon, and (3) symmetric scattering, when the incident particles carry equal and opposite momenta, so that in the exit channel they are backscattered with same energy/momenta, and (d) Compton scattering [*à la* Arthur Compton, see A. J. Compton, A quantum theory of the scattering of X-rays by light elements, *Phys. Rev.* **21**, 83 (1923)], where photons carry an energy much larger than the colliding electron energy. For each region and/or transition point, we discuss the potential effects of interest in diverse areas, like generating monochromatic gamma-ray beams in deep recoil regions with spectral purification, or possible mechanisms of generation and propagation of very high energy photons in the cosmological domain.

DOI: [10.1103/PhysRevAccelBeams.27.080701](https://doi.org/10.1103/PhysRevAccelBeams.27.080701)

Narrow-band GeV photons generated from an x-ray free-electron laser oscillator

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¹Quantum Beam Science Center, Japan Atomic Energy Agency, Tokai, Naka, Ibaraki 3191195, Japan

²Research Center for Nuclear Physics, Osaka University, Mihogaoka 10-1, Ibaraki 5670047, Japan

(Received 17 July 2015; published 16 February 2016)

We propose a scheme to generate narrow-band GeV photons, γ -rays, via Compton scattering of hard x-ray photons in an x-ray free-electron laser oscillator. Generated γ -rays show a narrow-band spectrum with a sharp peak, $\sim 0.1\%$ (FWHM), due to large momentum transfer from electrons to photons. The γ -ray beam has a spectral density of $\sim 10^2$ ph/(MeV s) with a typical set of parameters based on a 7-GeV electron beam operated at 3-MHz repetition. Such γ -rays will be a unique probe for studying hadron physics. Features of the γ -ray source, flux, spectrum, polarization, tunability and energy resolution are discussed.

DOI: 10.1103/PhysRevAccelBeams.19.020702

Deep Recoil
and its 2 benefits:
spectral purification
and
suppression of $\gamma^2\theta^2$ disease

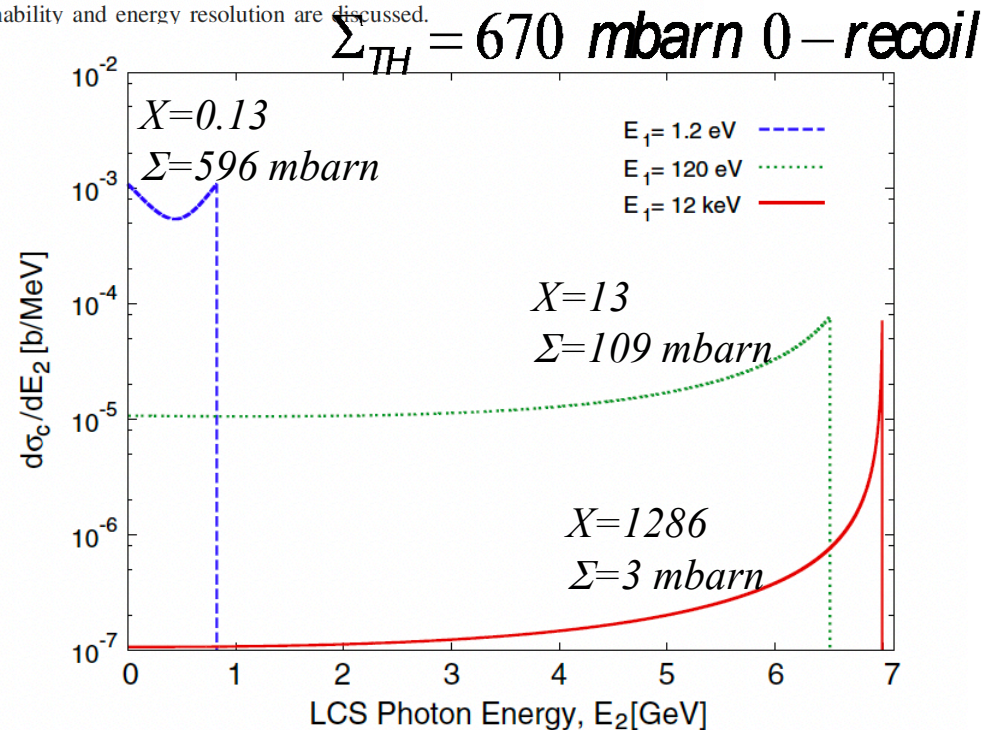


FIG. 3. Energy-differential cross section of Compton scattering for 7 GeV electrons and laser photons at three different energies of 1.2 eV, 120 eV and 12 keV.

Inverse Compton Scattering of photons on relativistic electrons, $\theta < 1/\gamma$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + \gamma^2 \vartheta^2 + X}$$

$$X = \frac{4E_{ph}E_e}{(mc^2)^2}$$

Thomson limit: $X \ll 1$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + \gamma^2 \vartheta^2}$$

$$E'_{ph} \left(\vartheta = \frac{1}{\gamma} \right) = 2\gamma^2 E_{ph} = \frac{E'_{ph}(\vartheta=0)}{2}$$

Deep recoil Compton: $X \gg 1$

$$E'_{ph} \sim \left(1 - \frac{1}{X} - \frac{\gamma^2 \vartheta^2}{X} \right) E_e$$

$$E'_{ph} \left(\vartheta = \frac{1}{\gamma} \right) \sim \left(1 - \frac{2}{X} \right) E_e$$

note that $E_{cm} = mc^2 \sqrt{1 + X}$, if $X \gg 1 \Rightarrow X \sim \left(\frac{E_{cm}}{mc^2} \right)^2$

Previous Seminars: 1) Cooling of Photons in Symmetric Compton Scattering (S.C.S.)

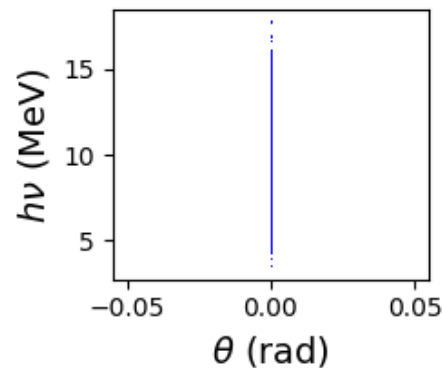
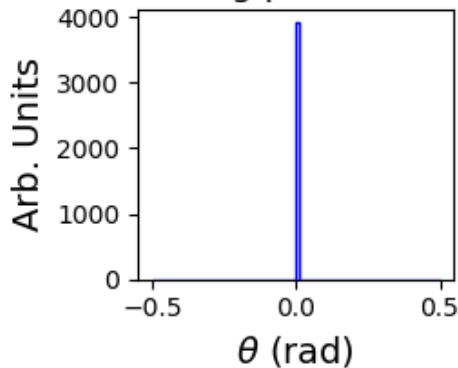
Istituto Nazionale di Fisica Nucleare

20% rms spread

Electron
Cooling of
photons!!

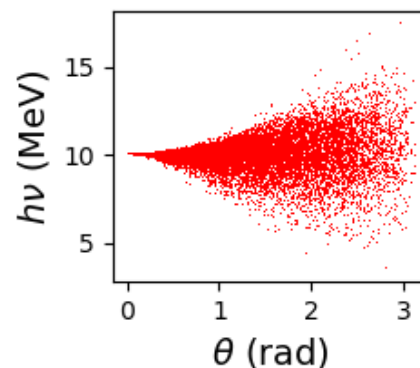
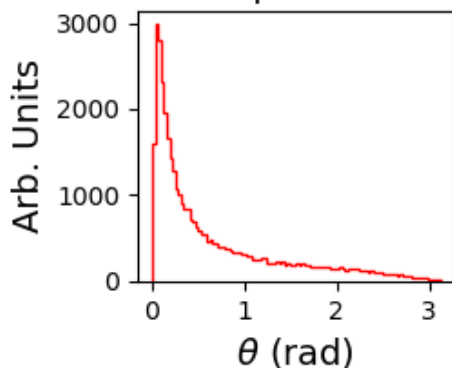
e- beam
is heated

Incoming photon beam



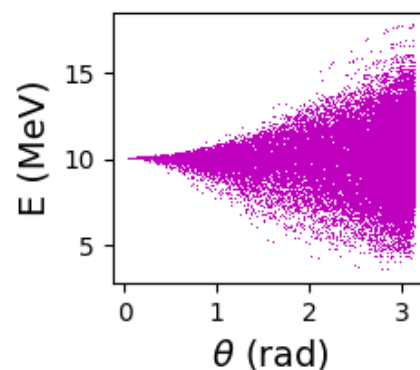
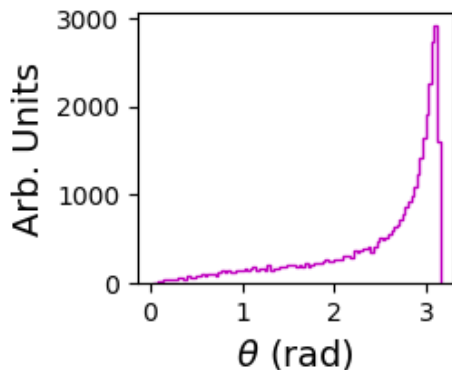
input e⁻ beam
10 MeV, 10⁻⁴
rms en. spread

Emitted photon beam



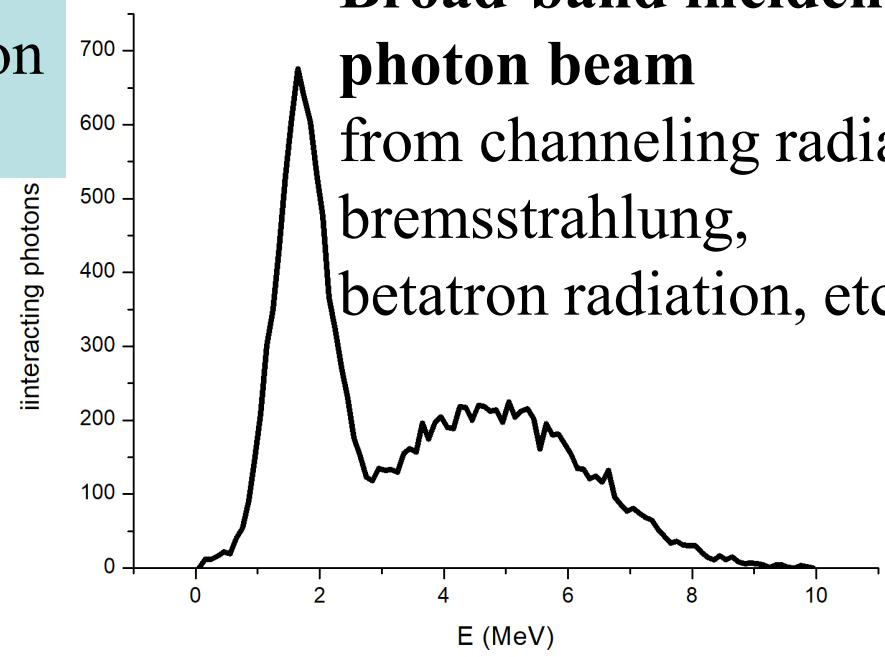
no energy-
angular
correlation

Emitted electron beam

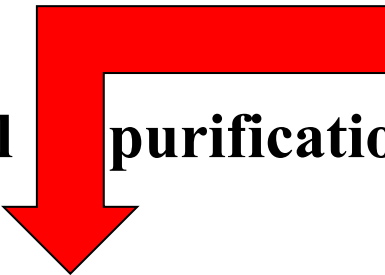
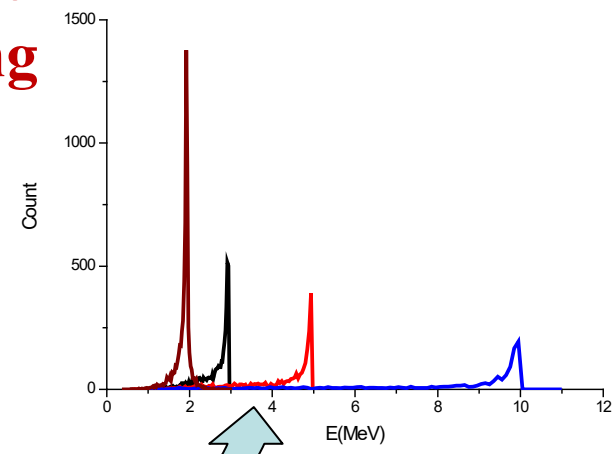
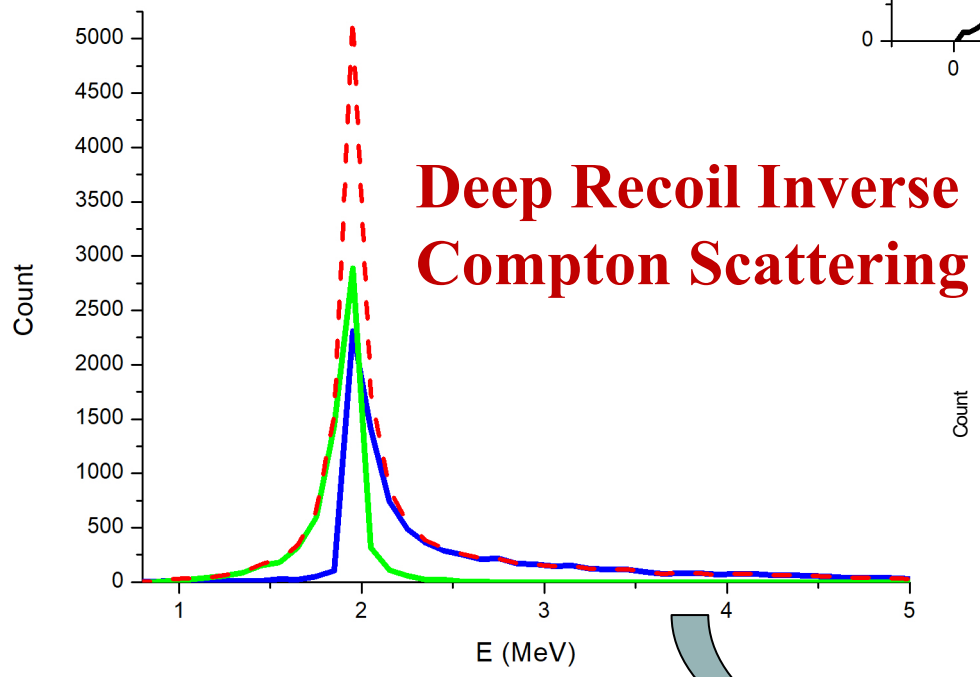


Previous Seminars:
2) Spectral Purification
in deep recoil I.C.S.

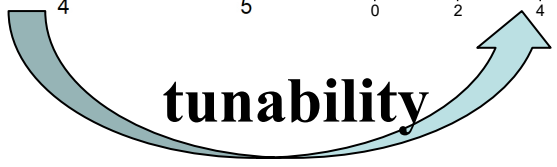
**Broad-band incident
photon beam**
from channeling radiation,
bremsstrahlung,
betatron radiation, etc



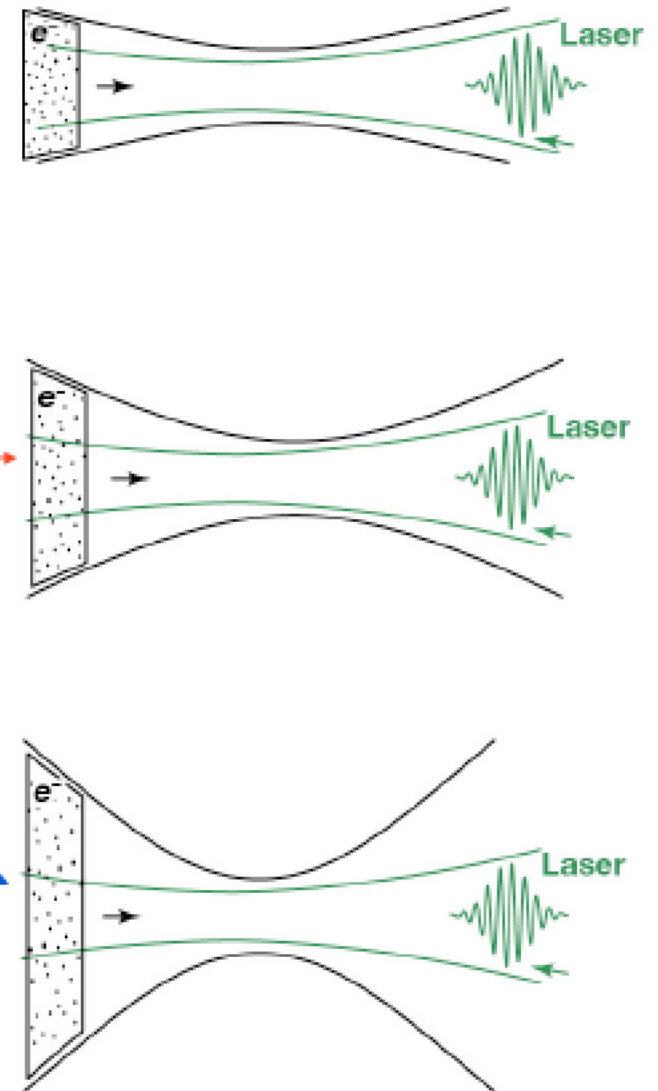
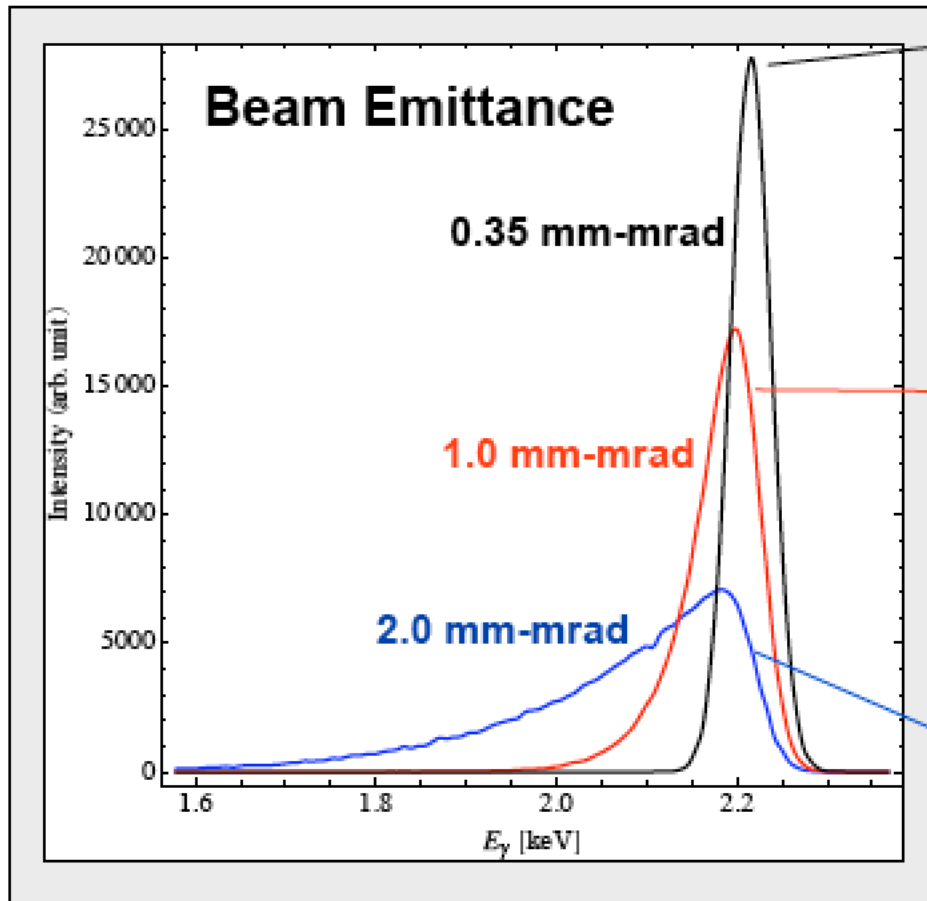
spectral purification

tunability



Lorentz boosted radiation (synchrotron, ICS, FEL, etc) is strongly affected by the emittance of the electron beam



Deep Recoil suppresses the $\gamma^2\theta^2$ disease and the bandwidth broadening effect due to electron beam emittance according to *Petrillo-Serafini criterion*

$$\left\{ \begin{array}{l} bw \geq \frac{2\varepsilon_n^2}{\sigma_x^2} \\ S_d \propto \frac{\langle I_e \rangle U_{las}}{\varepsilon_n^2 E_x} \end{array} \right.$$

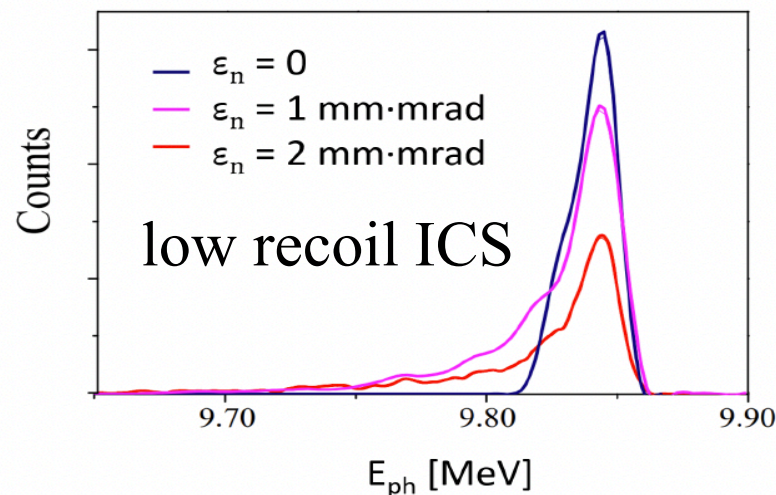
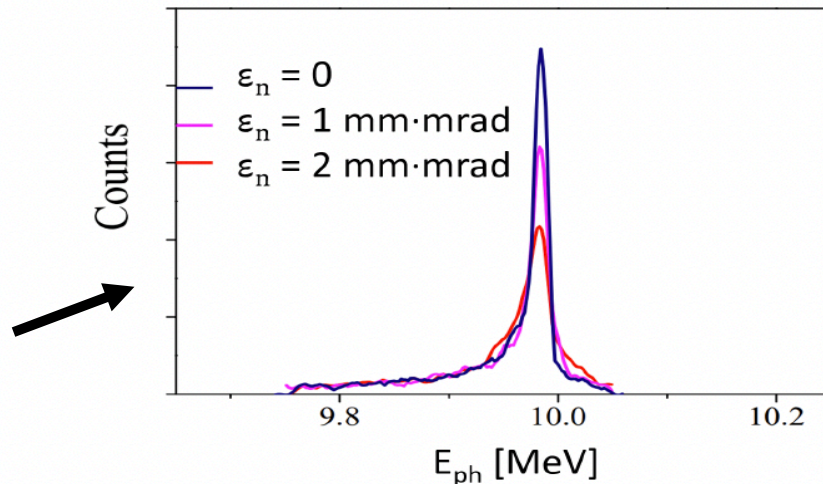


Figure 4: Bandwidth dependence on electron beam emittance. Comparison between SCS and ICS. Upper window: electron energy 10 MeV, incident photon energy 10 MeV with 20% relative bandwidth, emitted photon energy 10 MeV, interaction rms spot size 10 μm , normalized emittance 0 mm·mrad, 1 mm·mrad, 2 mm·mrad. Lower window: electron energy 659 MeV, incident photon energy 1.5 eV ($5 \cdot 10^{-4}$ relative bandwidth), collimation angle = 50 μrad , emitted photon energy about 10 MeV, interaction rms spot size 10 μm , normalized emittance 0 mm·mrad, 0.17 mm·mrad, 0.25 mm·mrad

Large Recoil in MPP damps the normalized emittance of the secondary generated muon beam

Article

Electrons and X-rays to Muon Pairs (EXMP)

Camilla Curatolo *  and Luca Serafini 

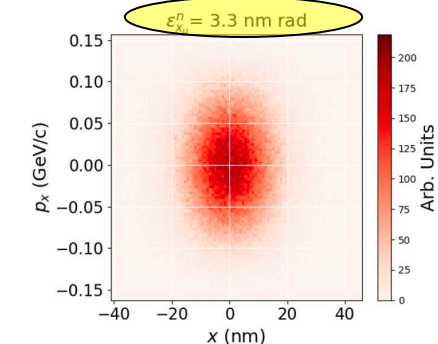
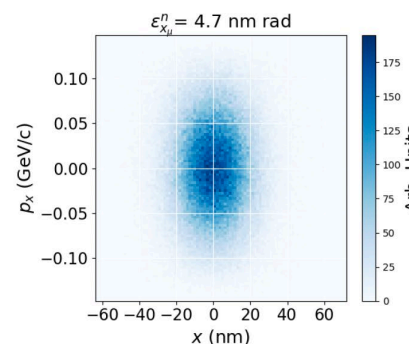
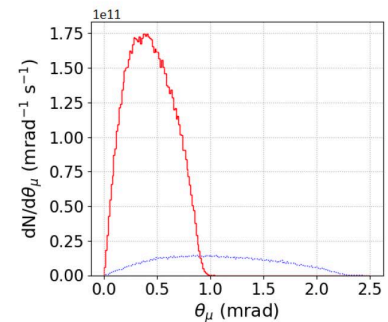
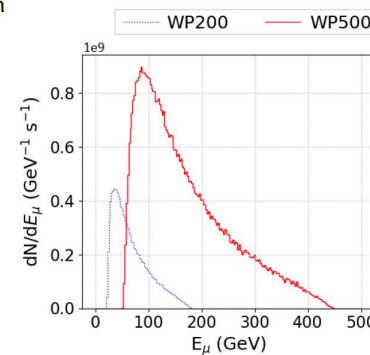
INFN Sezione di Milano, via Celoria 16, 20133 Milan, Italy; luca.serafini@mi.infn.it

* Correspondence: camilla.curatolo@mi.infn

muon beam norm. emittance

$$\epsilon_{\mu}^n \simeq \frac{2}{3} \sigma_0 \left(\frac{M_e}{2M_{\mu}} \sqrt{X} - 1 \right) + \frac{\epsilon_e^n}{\sqrt{X}}$$

*cmp. MAP norm. emitt. $2.5 \cdot 10^4$ nm·rad
after ionization cooling*



Ultra-low emittance positron beams from deep recoil electron-photon collider: 5 GeV ERL vs. 5 keV FEL, $X=391$

up to 10^{13-14} e^+ /s at 50 MeV within 5% en. spread

Son of EXMP

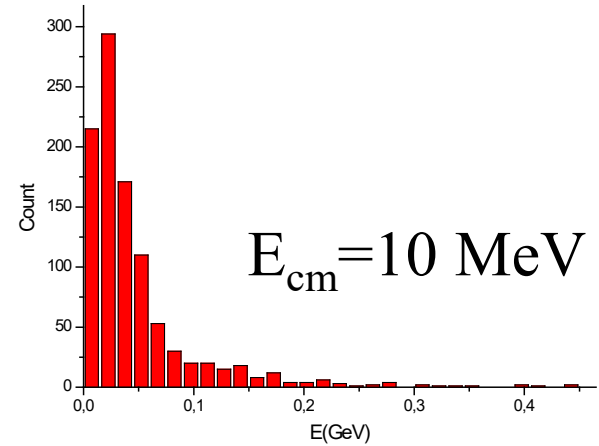
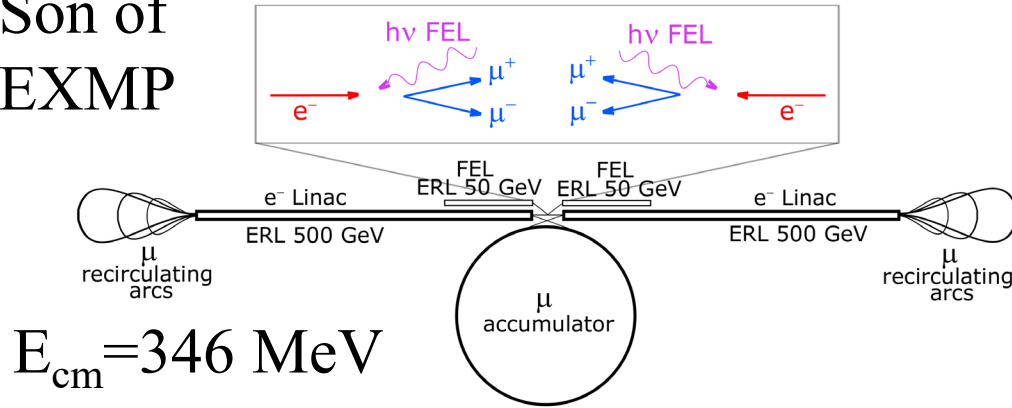


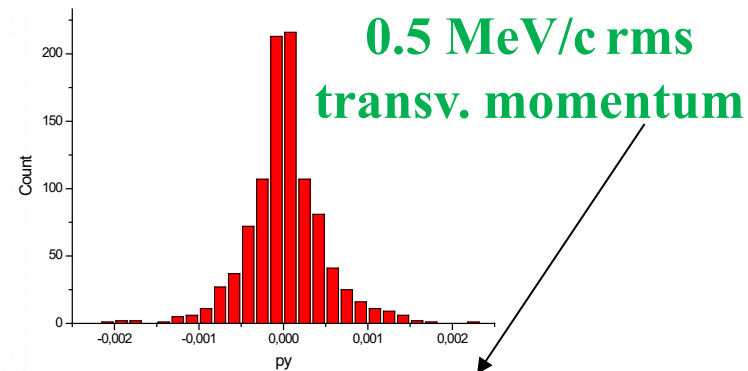
Table 4: Future Positron Collider Projects [53, 59, 61–66].

Project	CLIC	ILC	LHeC (pulsed)	LEMMA	CEPC	FCC-ee
Final e^+ energy [GeV]	190	125	140	45	45	45.6
Primary e^- energy [GeV]	5	128** (3*)	10	–	4	6
Number of bunches per pulse	352	1312 (66*)	10^5	1000	1	2
Required charge [10^{10} e^+ /bunch]	0.4	3	0.18	50	0.6	2.1
Horizontal emittance $\gamma\epsilon_x$ [μm]	0.9	5	100	–	16	24
Vertical emittance $\gamma\epsilon_y$ [μm]	0.03	0.035	100	–	0.14	0.09
Repetition rate [Hz]	50	5 (300*)	10	20	50	200
e^+ flux [10^{14} e^+ /second]	1	2	18	10–100	0.003	0.06
Polarization	No/Yes***	Yes/(No*)	Yes	No	No	No

* The parameters are given for the electron-driven positron source being under consideration.

** Electron beam energy at the end of the main electron linac taking into account the losses in the undulator.

*** Polarization is considered as an upgrade option.



$0.5-1 \cdot 10^{-7}$ m-rad rms norm. transv.

V. Petrillo, A. Puppini – Whizard emittance with round beam (no-cooling)

FICS - Full Inverse Compton Scattering - how to achieve 10^{30} m/s² acceleration to sense Unruh radiation

Full Inverse Compton Scattering: Total Transfer of Energy and Momentum from Electrons to Photons

L. Serafini^a, V. Petrillo^{a,b}, S. Samsam^{a,*}

^aINFN-Milano and LASA, Via G. Celoria 16, Milan, 20133, , Italy

^bUniversity of Milan, Via G. Celoria 16, Milan, 20133, , Italy

arXiv:2408.00012v1 [physics.gen-ph] 26 Jul 2024

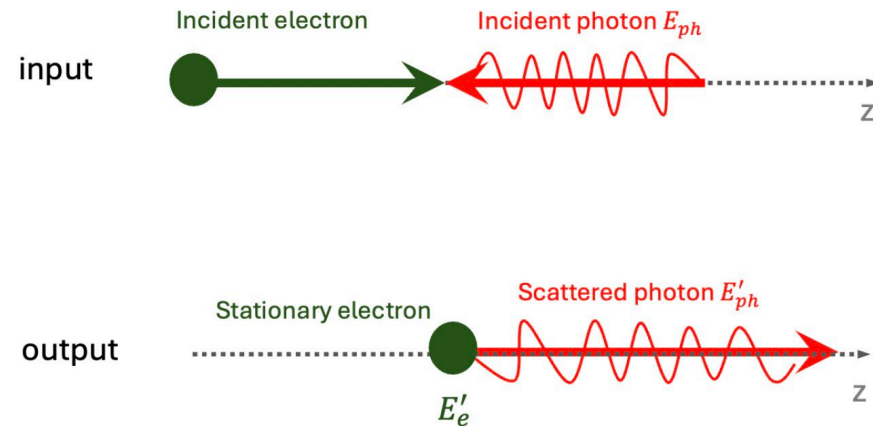
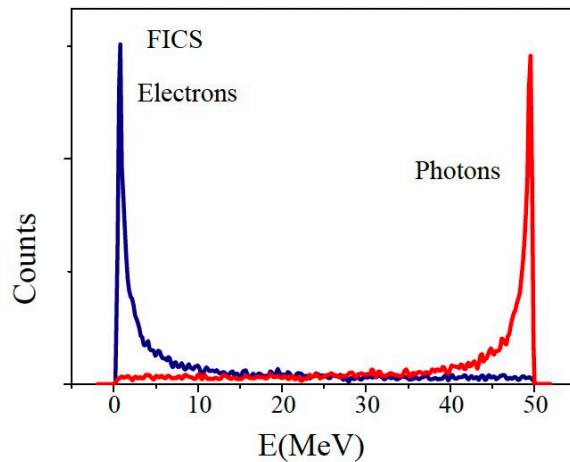


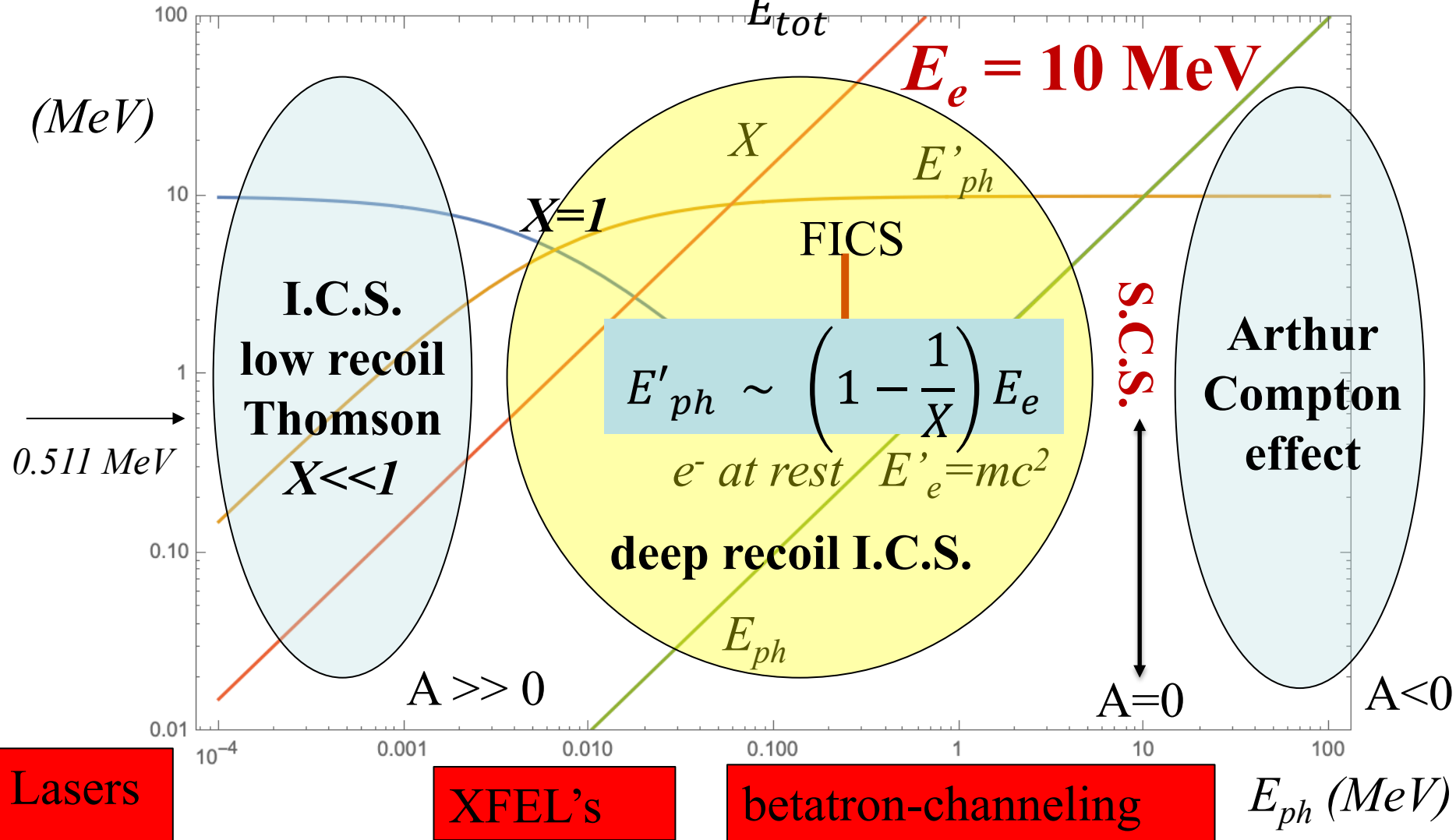
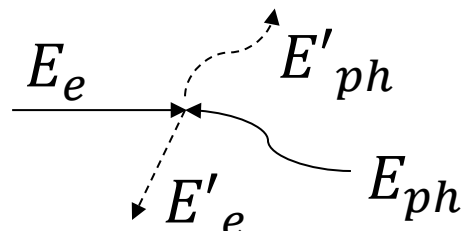
FIG. 5: Full Inverse Compton Scattering (FICS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue: scattered electrons. $E_{ph} = 255.5 keV$, $E_e = 50 MeV$, $bw_{ph} = 5\%$

V. Petrillo, ad-hoc developed Montecarlo code for linear QED

$$X = 4 E_e E_{ph} / (mc^2)^2 \quad A = \beta\gamma^2 - X/4$$

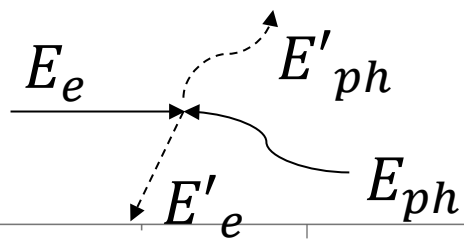
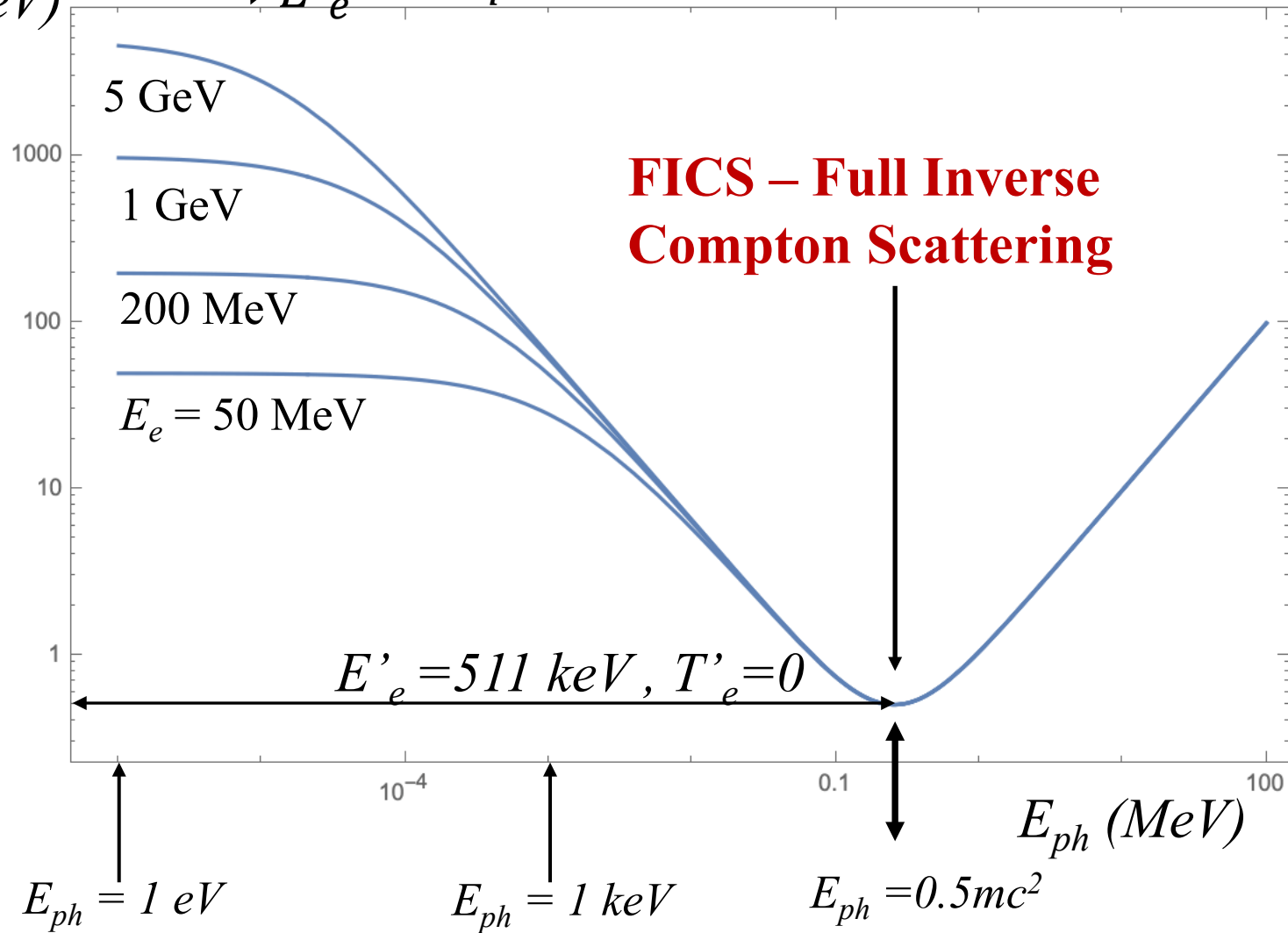
$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + X}$$

$$E'_e = \underbrace{E_e + E_{ph}}_{E_{tot}} - \frac{4\gamma^2 E_{ph}}{1 + X}$$

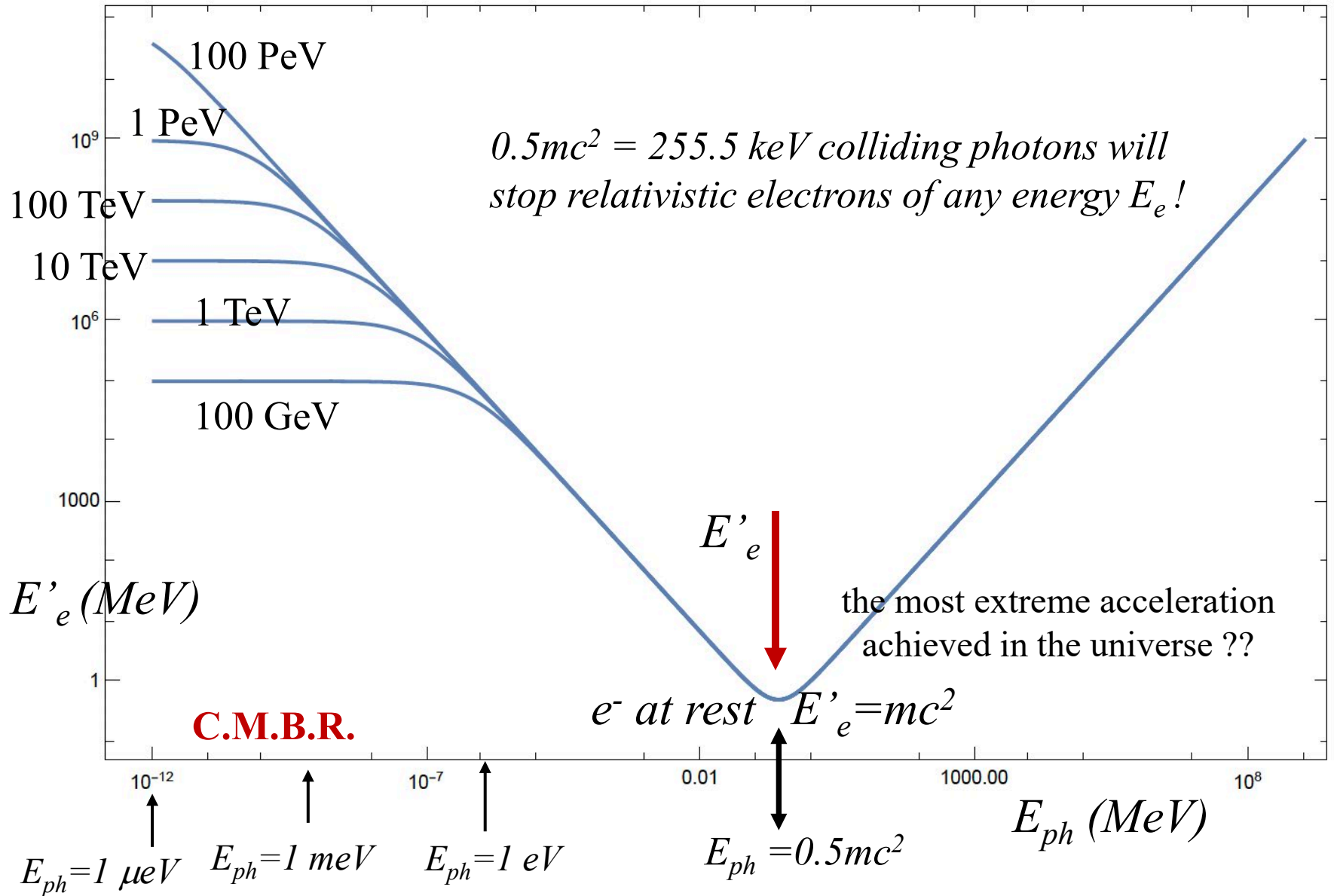


in vacuum electron-photon collision

E'_e (MeV)



Full Inverse Compton Scattering: amazing power of 255.5 keV photons to stop ANY colliding electron



*hadronic threshold ($E_{cm} < 600 \text{ MeV}$) with 255.5 keV photons $\approx 360 \text{ GeV}$

From Feenberg-Primakoff

collisions, N_s^c , and the average energy loss, ΔE_s^c , experienced by a primary falling radially from infinity through the sun's radiation field to the orbit of the earth ($\theta \cong 0$). It is convenient to distinguish two extreme cases: "rest-frame non-relativistic" and "rest-frame extreme relativistic," depending on whether $\epsilon^* = \gamma\epsilon(1 + \beta \cos\theta)$ is $\ll Mc^2$ or $\gg Mc^2$ for $\epsilon \cong 2.7 kT$. An equivalent statement is

$$u_c = \frac{(Mc^2)^2}{EkT} \left. \begin{array}{l} \gg 1 \text{ ("rest-frame non-relativistic"} \\ E \ll 2 \times 10^{18} \text{ ev-protons;} \\ E \ll 5 \times 10^{11} \text{ ev-electrons)} \\ \ll 1 \text{ ("rest-frame extreme relativistic").} \end{array} \right\} \quad (54)$$

In the "rest-frame non-relativistic" case one

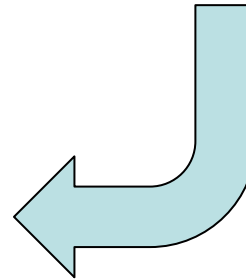
4. COMPTON SCATTERING IN PROTON-PHOTON AND ELECTRON-PHOTON COLLISIONS

We shall now discuss those collisions of the primary cosmic-ray protons and electrons with thermal photons which result in Compton scattering. In the primary rest frame the photon energies ϵ^* and ϵ'^* before and after scattering, and the scattering angle χ^* are connected by the relation,³²

$$\epsilon'^* = \frac{\epsilon^*}{1 + \frac{(\epsilon^*)^2}{Mc^2}(1 - \cos\chi^*)}. \quad (45)$$

Correspondingly, in the earth's frame,³³

$$\epsilon' = \gamma\epsilon'^*(1 - \beta \cos\theta'^*)$$



From Follin

3.2. Theory of the Interaction of Electrons and Photons

The interaction of electrons with radiation is just Compton scattering in the coordinate system moving with the electrons but the treatment is more complicated since large energy transfers can take place so that fluctuations are important. Hence, we must compute the probability for various fractional energy losses for all values of the energy. Similar considerations hold for the interactions of photons. The situation is further complicated by the fact that high energy electrons generate photons and high energy photons generate electrons so that a sort of "cosmic cascade" ensues.

If we now consider a photon γ in the moving coordinate system incident along the negative z - axis and assume a Compton scattering, then the energy of the scattered photon is given by

$$(3.18) \quad \gamma' = \frac{\gamma}{1 + \gamma(1 - \cos \theta)} ,$$

$$\begin{aligned}
 d\phi &= \frac{1}{2} \left(\frac{e^2}{mc^2} \right)^2 (1 - \delta)^2 \left\{ \frac{1}{1 - \delta} + \left[1 - \frac{\delta}{\gamma(1 - \delta)} \right]^2 + 1 - \delta \right\} \frac{dz}{d\delta} d\delta \\
 (3.25) \quad &= \frac{1}{2} \left(\frac{e^2}{mc^2} \right)^2 \left\{ \frac{1}{1 - \delta} + 1 - \delta - \frac{2\delta}{\gamma(1 - \delta)} + \frac{\delta^2}{\gamma^2(1 - \delta)^2} \right\} d\delta, \quad 0 \leq \delta \leq \frac{2\gamma}{1 + 2\gamma}
 \end{aligned}$$

It may be seen that there is a large probability of large fractional energy loss since $(1 - \delta)$ occurs in the denominator. An idea of the order of magnitude of the cross section may be obtained from the following table.

TABLE 5

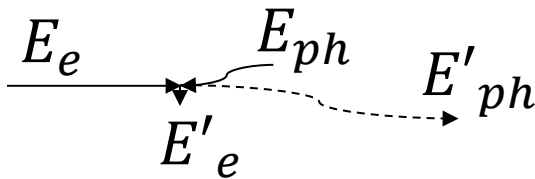
The Values of δ and $d\phi$ from (3.23) and (3.25)

γ		0	$\pi/4$	$\pi/2$	$3\pi/4$	π
δ	0.1	0	.028	.091	.146	.167
	1.0	0	.227	.50	.63	.80
	10.	0	.745	.91	.945	.952
$d\phi \times 10^{26} \text{cm}^2$	0.1	80.0	60.4	40.4	61.2	84.8
	1.0	8.00	6.28	6.00	10.32	13.32
	10.	0.80	1.28	4.04	7.04	8.44

$$\beta \gamma mc^2 - E_{ph} = 0 + E'_{ph}$$

FICS equations

$$\gamma mc^2 + E_{ph} = mc^2 + E'_{ph}$$



$$E'_e = mc^2$$

$$T'_e = 0$$

Let's focus on the
"turning point"
where electron starts
to be back-scattered:
FICS - Full Inverse
Compton Scattering

$$E_{ph} = \frac{mc^2}{2} (1 - (1-\beta)\gamma)$$


$$E'_{ph} = mc^2 \left(\gamma \frac{1+\beta}{2} - \frac{1}{2} \right)$$

$$E_e = \gamma mc^2$$

$$E'_e = mc^2$$

FICS solutions
for any value of γ !

From Compton scattering of photons on targets to inverse Compton scattering of electron and photon beams

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 (Received 2 May 2024; accepted 1 August 2024; published 28 August 2024)

ativistic case, where $\gamma \gg 1$ and therefore, β is approximately $1 - \frac{1}{2\gamma^2}$, Eqs. [9](#) and [10](#) can be rewritten as follow:

$$E_{ph} = \frac{m_e c^2}{2} \left(1 - \frac{1}{2\gamma}\right) \quad (12)$$

$$E'_{ph} = m_e c^2 \left(\gamma - \frac{1}{2} - \frac{1}{4\gamma}\right) \quad (13)$$

$$E'_e = m_e c^2$$

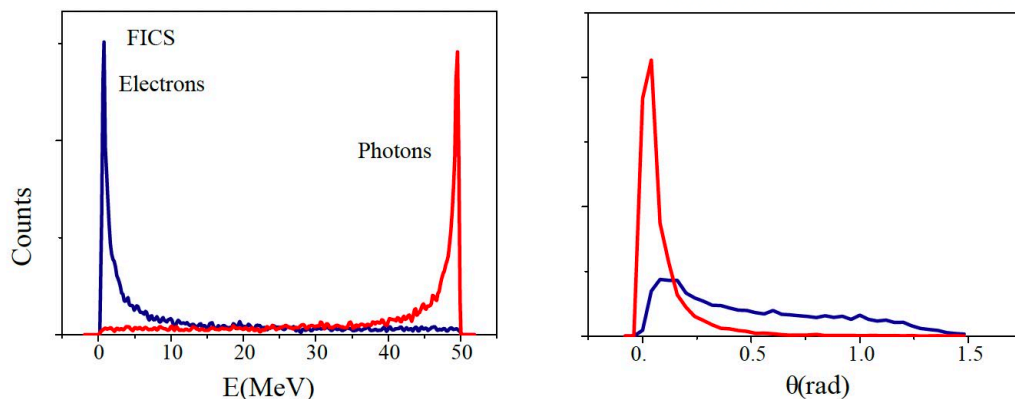
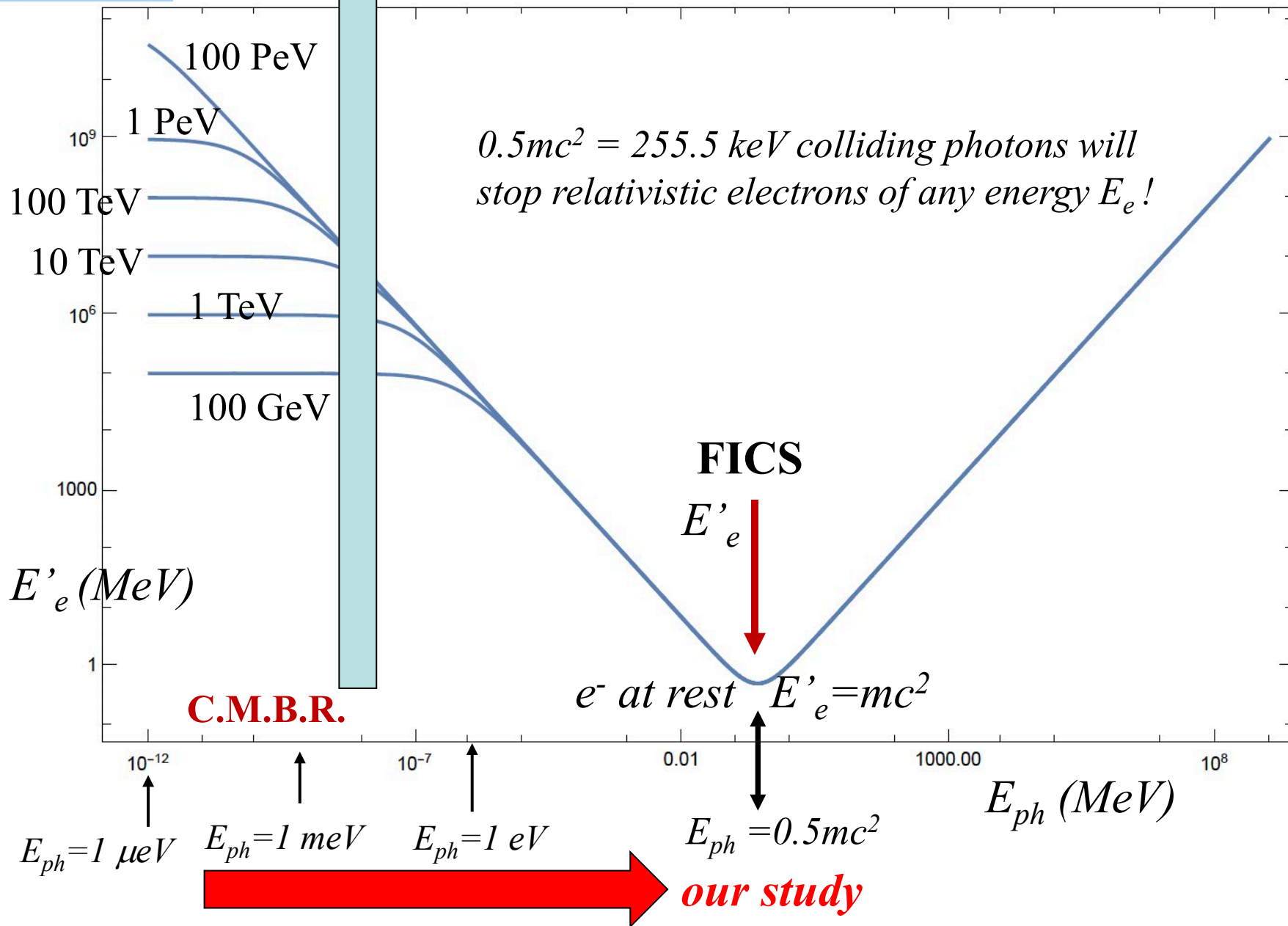


FIG. 5: Full Inverse Compton Scattering (FICS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue: scattered electrons. $E_{ph} = 255.5 keV$, $E_e = 50 MeV$, $bw_{ph} = 5\%$

Follin, Primakoff, etc



The **Unruh** effect gives rise to a Planckian photon spectral distribution at a temperature

$$T = \frac{\hbar a}{2\pi k_B c}, \quad (91)$$

where a is the acceleration and k_B the Boltzmann con-

The **Unruh temperature**, sometimes called the Davies–Unruh temperature,^[5] was derived separately by Paul Davies^[3] and William Unruh^[4] and is the effective temperature experienced by a uniformly accelerating detector in a **vacuum field**. It is given by^[6]

$$T = \frac{\hbar a}{2\pi c k_B} \approx 4.06 \times 10^{-21} \text{ K} \cdot \text{s}^2 \cdot \text{m}^{-1} \times a,$$

where \hbar is the **reduced Planck constant**, a is the proper uniform acceleration, c is the **speed of light**, and k_B is the **Boltzmann constant**. Thus, for example, a **proper acceleration** of $2.47 \times 10^{20} \text{ m} \cdot \text{s}^{-2}$ corresponds approximately to a temperature of 1 K. Conversely, an acceleration of $1 \text{ m} \cdot \text{s}^{-2}$ corresponds to a temperature of $4.06 \times 10^{-21} \text{ K}$.

Black-hole $a=10^{10}$ $T=4.1 \cdot 10^{-11} \text{ K}$

Plasma acceleration (100 GV/m) $a=1.8 \cdot 10^{22}$ $T=74 \text{ K}$

?? how about FICS ??

Signatures of the Unruh Effect from Electrons Accelerated by Ultrastrong Laser Fields

Ralf Schützhold,^{1,*} Gernot Schaller,¹ and Dietrich Habs²

¹*Institut für Theoretische Physik, Technische Universität Dresden, 01062 Dresden, Germany*

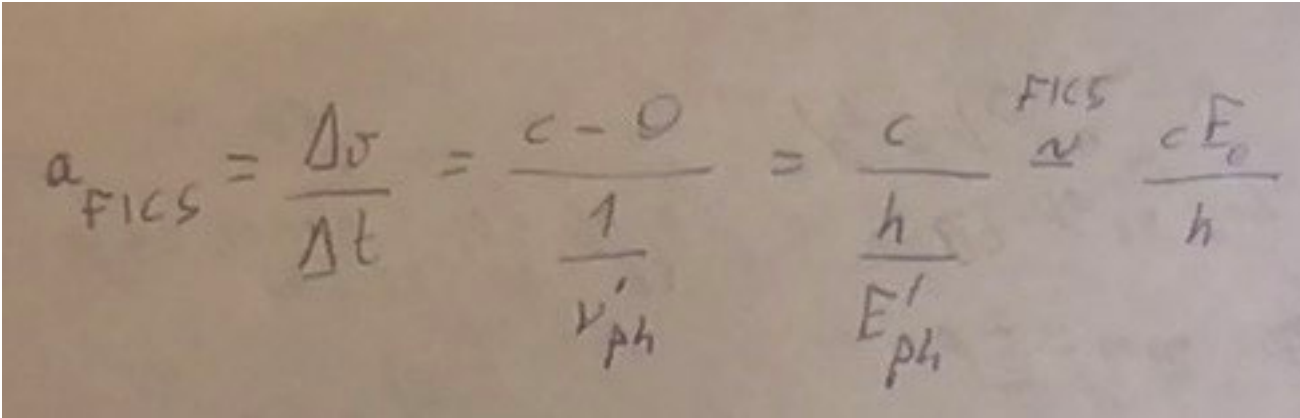
²*Department für Physik der Ludwig-Maximilians-Universität München und Maier-Leibnitz-Laboratorium, Am Coulombwall 1, 85748 Garching, Germany*

(Received 18 April 2006; revised manuscript received 23 June 2006; published 22 September 2006; publisher error corrected 22 September 2006)

We calculate the radiation resulting from the Unruh effect for strongly accelerated electrons and show that the photons are created in pairs whose polarizations are perfectly correlated. Apart from the photon statistics, this quantum radiation can further be discriminated from the classical (Larmor) radiation via the different spectral and angular distributions. The signatures of the Unruh effect become significant if the external electromagnetic field accelerating the electrons is not too far below the Schwinger limit and might be observable with future facilities. Finally, the corrections due to the birefringent nature of the QED vacuum at such ultrahigh fields are discussed.

Probably $a_{laser} = 10^{23-25}$

Unruh radiation during FICS and SCS



$$a_{FICS} = \frac{\Delta v}{\Delta t} = \frac{c - 0}{\frac{1}{\gamma'_{ph}}} = \frac{c}{\frac{h}{E'_{ph}}} \stackrel{FICS}{\approx} \frac{c E_0}{h}$$

$$a_{FICS} \text{ (m/s}^2\text{)} = 7.3 \cdot 10^{28} * E_e \text{ (MeV)}$$

$$T_{Unruh-FICS} \text{ (K)} = 3.1 \cdot 10^8 * E_e \text{ (MeV)}$$

$$T_{Unruh-FICS} \text{ (MeV)} = 0.026 * E_e \text{ (MeV)}$$

going from 100 MeV up to 2 GeV electrons the Unruh photons at FICS would cover the 2.6 – 52 MeV range (easy detection in vacuum with low background)

$$a_{SCS} = 2 \cdot a_{FICS}$$

but E_{ph} must be = E_e in SCS, while in FICS $E_{ph} = 255.5 \text{ keV}$

Conclusions

Old Physics revisited shows new regimes of extreme electron-photon beam collisions with potentials towards:

New generation Radiation Sources based on Spectral Purification (ICS in deep recoil)

Amazing tests of stopping ultra-relativistic electrons in vacuum, attaining extreme accelerations (many orders of magnitude higher than any other mechanism) to detect Unruh radiation

Trapping/charging plasma mirror devices with electrons via S.C.S.

Universe opacity to high energy (TeV, PeV) photons: a Compton relay based on FICS&Breit-Wheeler cosmic cascade. Cosmic gamma ray sources and the role of FICS.

Direct Compton $\gamma=1, \beta=0, X = 4E_{ph}/mc^2$

$$E'_{ph-min} = \frac{E_{ph}}{1 + 2E_{ph}/mc^2} \quad \text{if } E_{ph} \gg mc^2 \quad E'_{ph-min} = \frac{mc^2}{2}$$

Very energetic photons are scattered back at 255 keV
and electrons pushed to $E_{ph} + 0.5mc^2$

$$E'_{e-max} = mc^2 + E_{ph} - E'_{ph-min}, \text{ if } E_{ph} \gg mc^2 \quad E'_{e-max} = E_{ph} + \frac{mc^2}{2}$$

*So FICS is the time reversal of Compton scattering
at infinitely large recoil*

*kinematics is similar for any particle interacting with photons
(protons, μ , neutrinos? $h\nu_{inc}=0.5*m_p c^2$ - next step in progress...)*

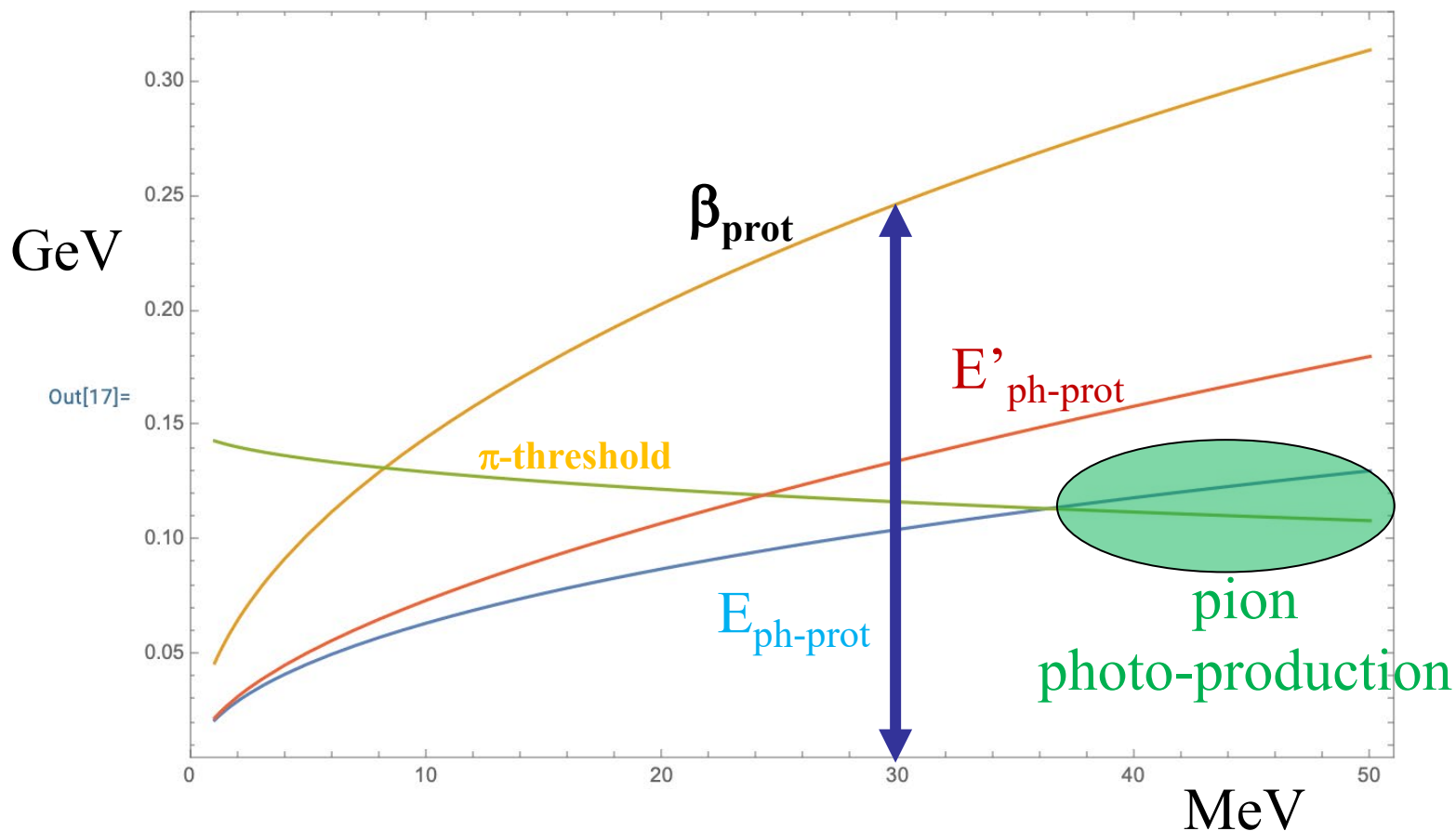
you won't believe how much you don't know about
the sport you've practiced all your life"

Mikey Mantle (big baseball player of the past, after Danilo Babusci INFN-LNF)

Stopping Protons with photons

Relativistic protons require 938/2 MeV photons

```
In[17]:= Plot[{ficsprot/1000., bet, Tpioneff/1000., ficspprot/1000.}, {T, 1., 50.}, Frame -> True]
```



electrons do not have internal degree of freedom (apart from spin) while protons do have - protons can act as detectors of Unruh thermal photon bath (they can “click”) - but protons cannot be driven to strong accelerations by intense lasers... FICS is the only way??

Eur. Phys. J. C (2024) 84:475
<https://doi.org/10.1140/epjc/s10052-024-12849-9>

THE EUROPEAN
PHYSICAL JOURNAL C



Regular Article - Experimental Physics

Measuring Unruh radiation from accelerated electrons

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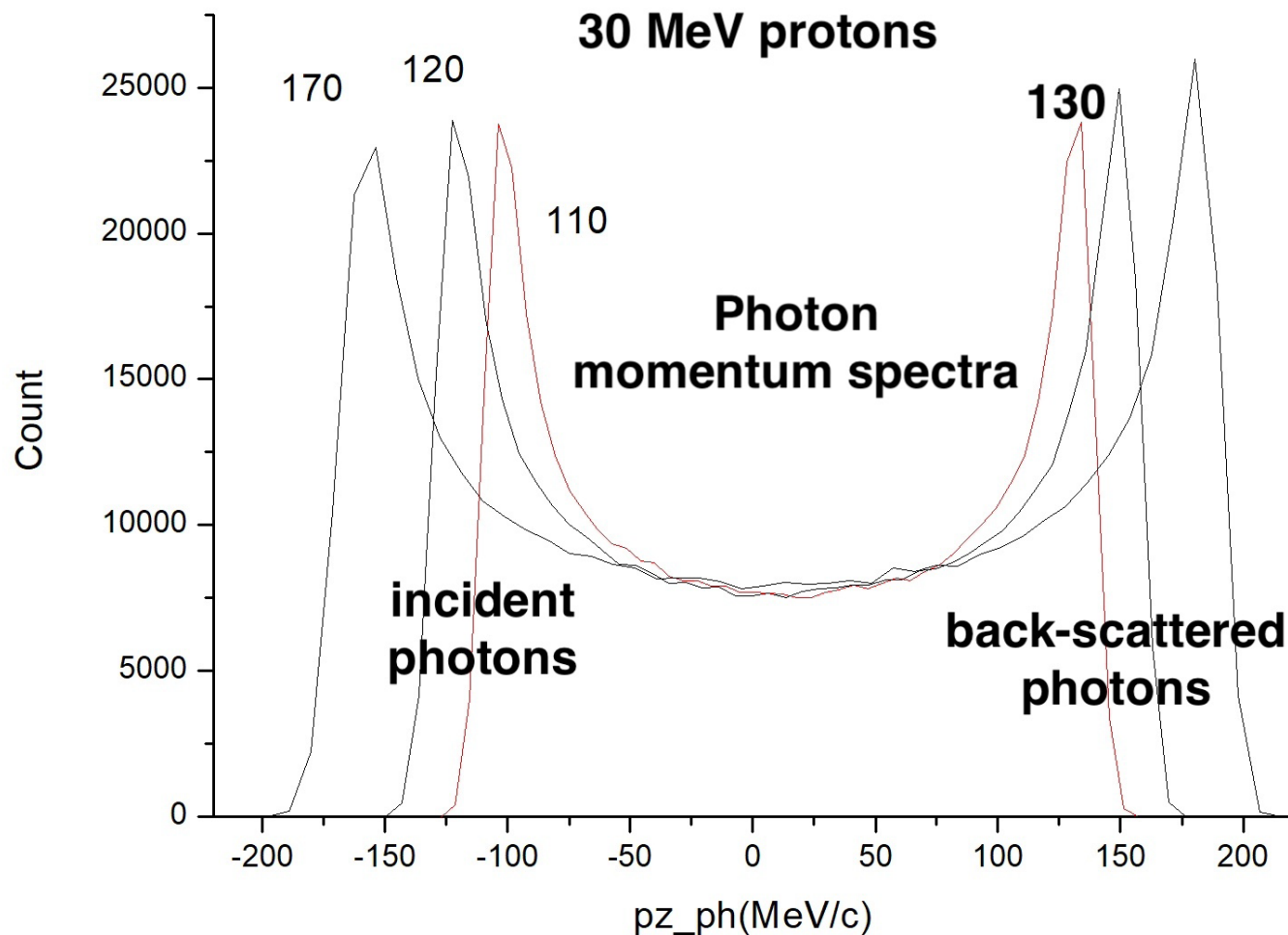
⁴ Department of Physics, University of Strathclyde SUPA, Glasgow G4 0NG, UK

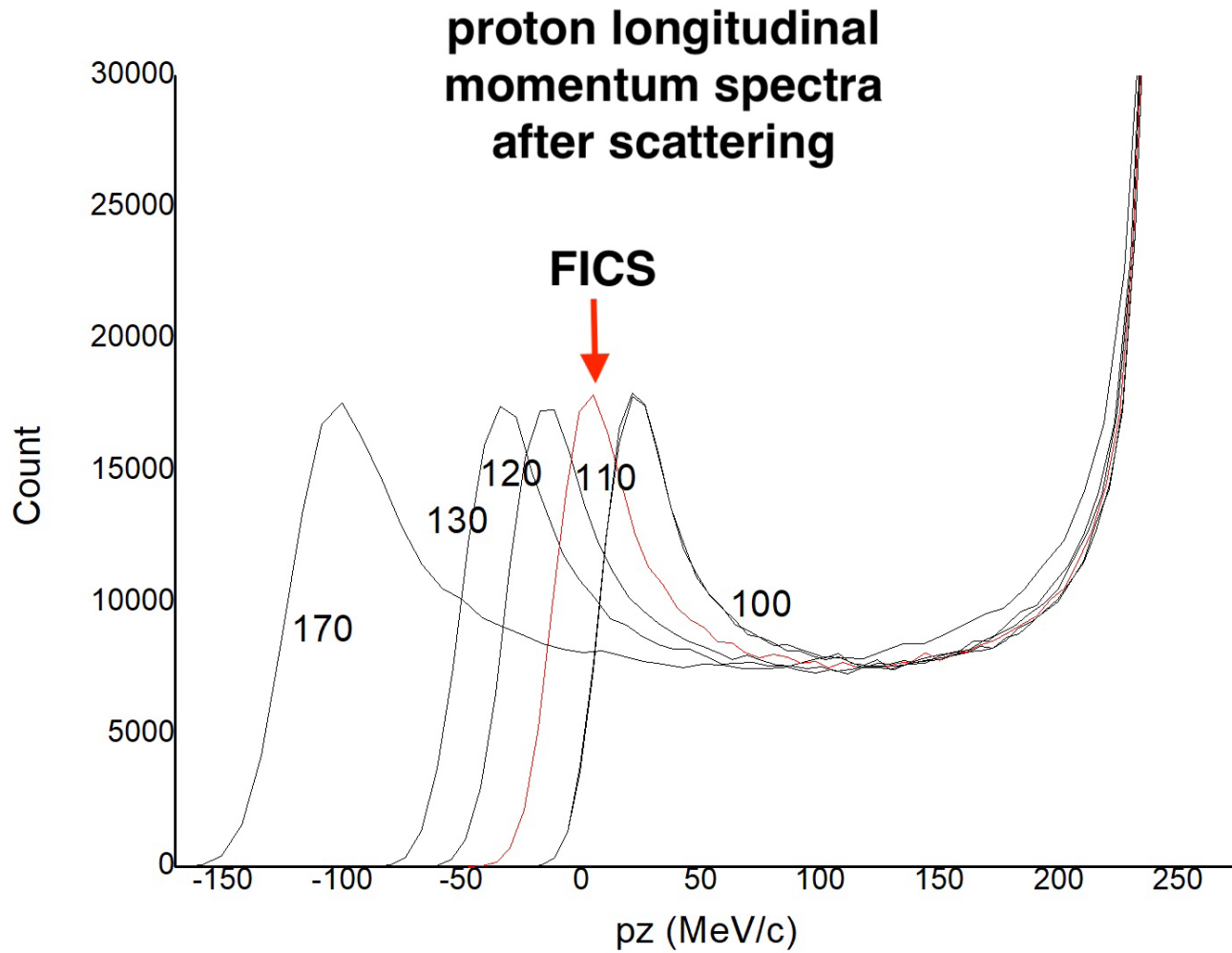
⁵ Department of Physics, University of Aberdeen, Aberdeen AB24 3UE, UK

Received: 13 March 2024 / Accepted: 23 April 2024

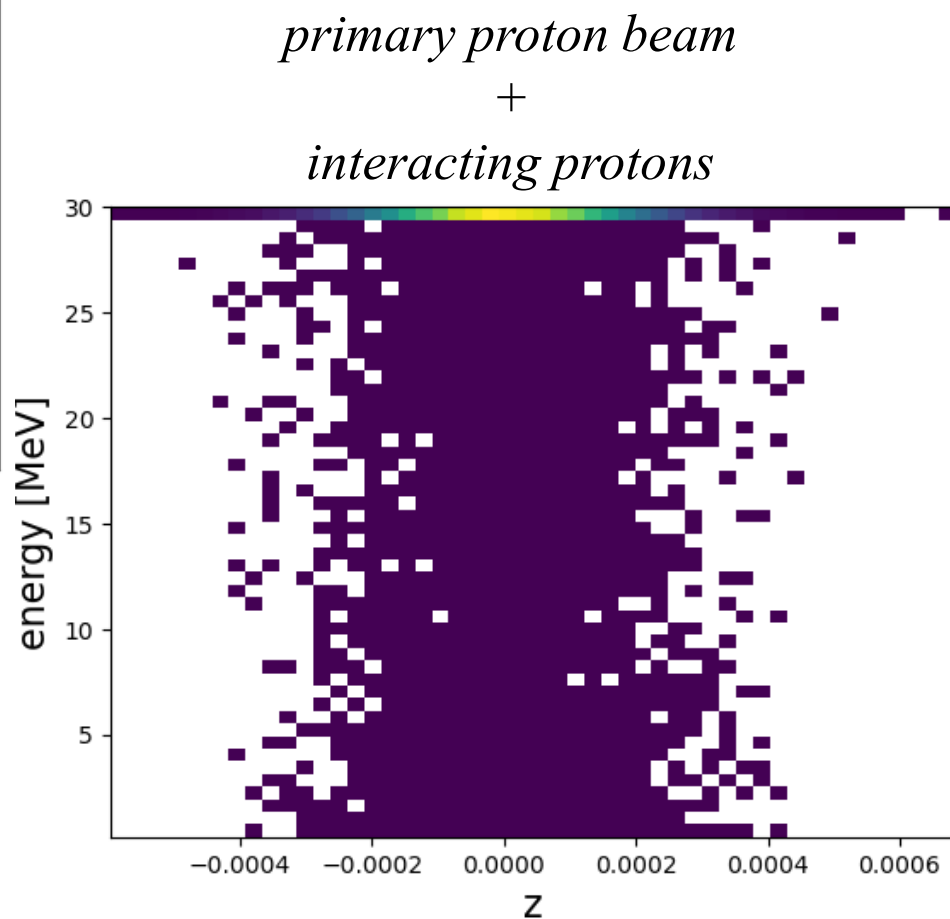
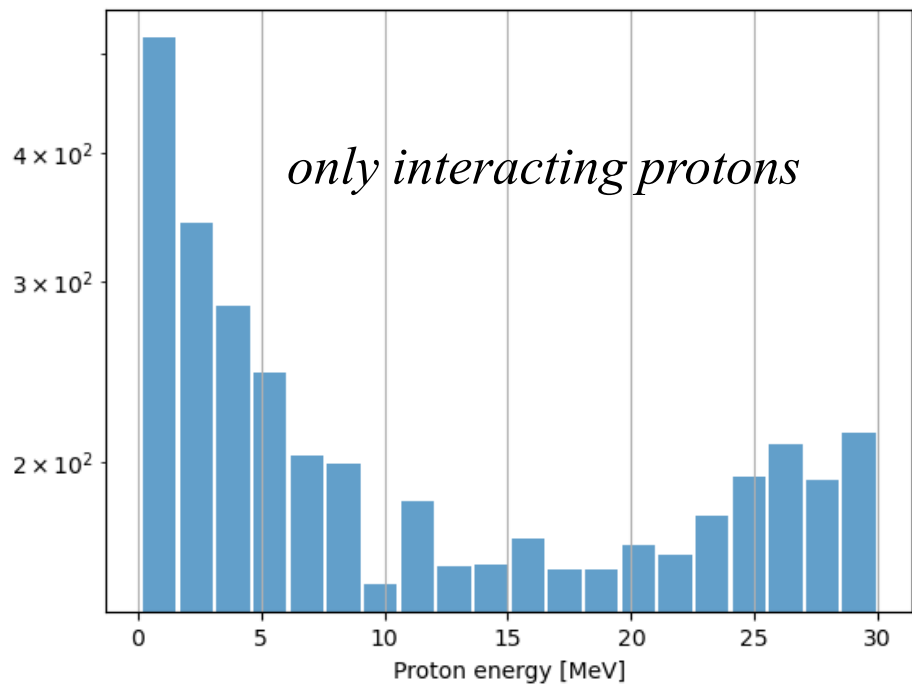
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30 MeV protons vs. photon beams of different energies (110, 120, 170 MeV)





Checked with CAIN modified for protons (I. Drebot, A. Bacci)

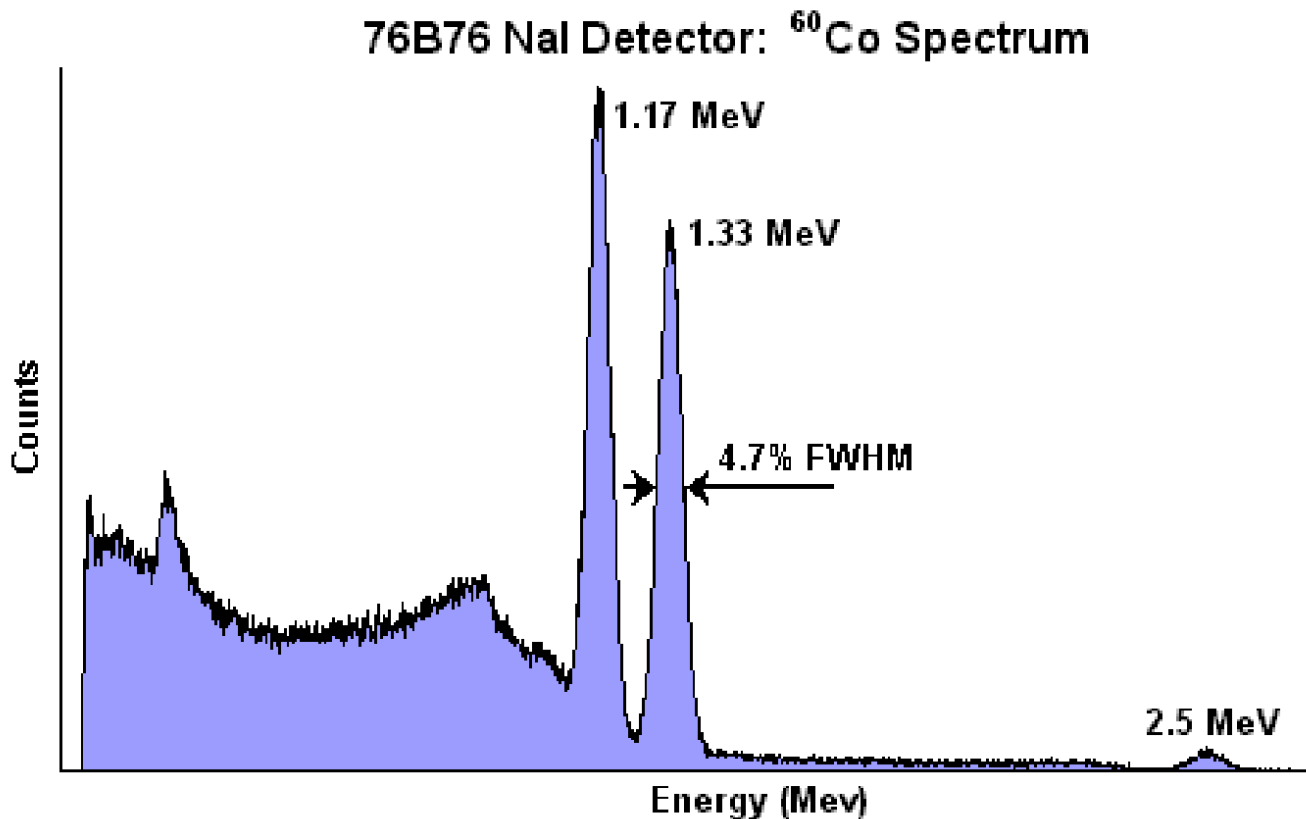


Grazie per l'attenzione

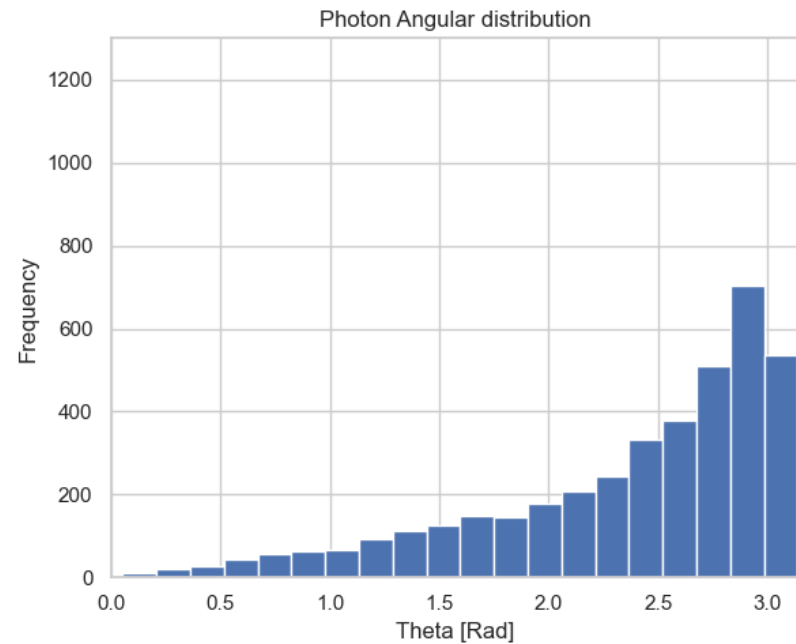
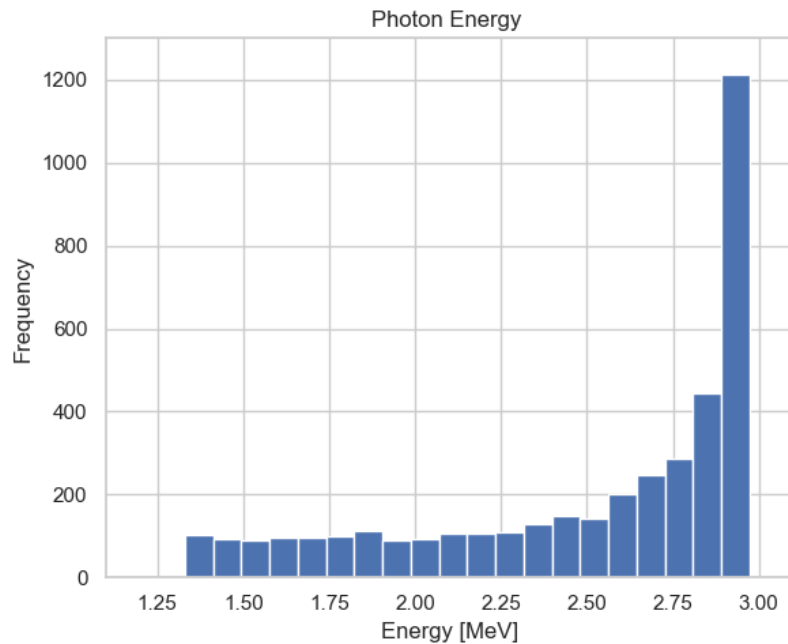
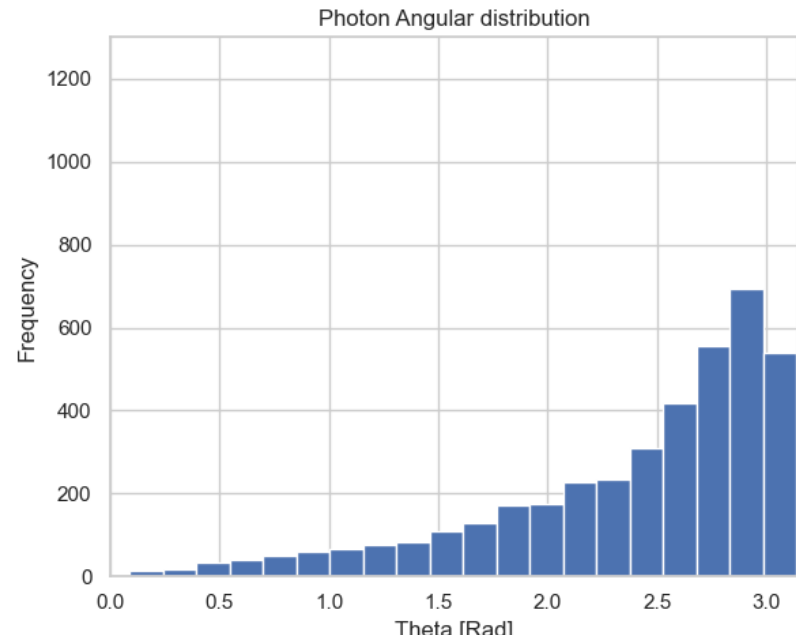
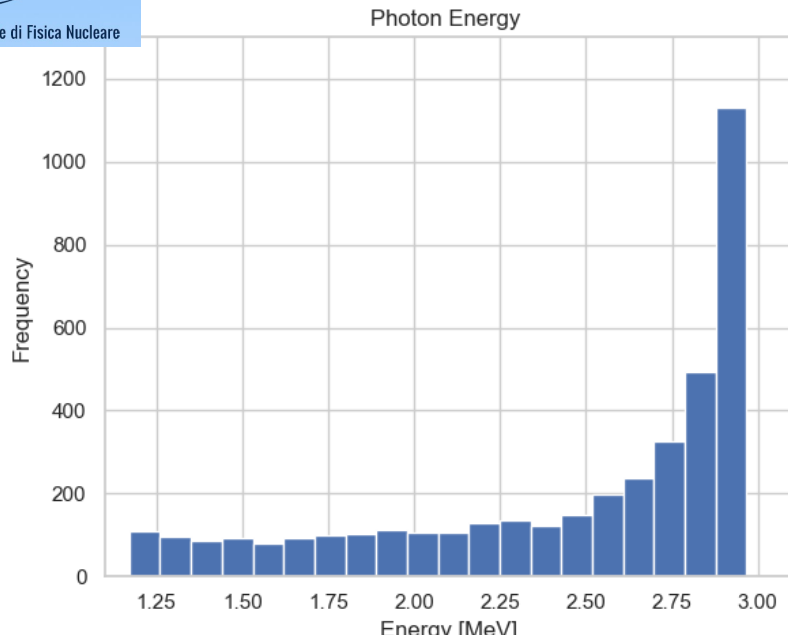
Turning a radio-active Cobalt-60 fixed energy gamma-ray source into a tunable source of gamma-rays

Previous Seminars:

3) Tunable mono-chromatic γ -rays using radio-active sources



2 spectral lines merged into a single tunable line



If you ask Chat-gpt :

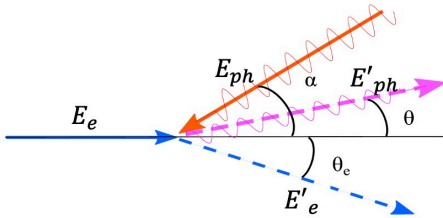
“can an electron transfer its total kinetic energy to a photon?”

It will answer “no” - a wrong answer

The mechanism of total energy transfer from an electron to a photon, where the electron essentially stops and transfers all its kinetic energy to a photon, is not typically described within the framework of conventional Compton scattering. However, such an extreme scenario can be considered in specific contexts:

1. **Inverse Compton Scattering:** Inverse Compton scattering is a process where a high-energy electron transfers part of its energy to a low-energy photon, resulting in a higher-energy photon. However, the electron does not typically come to a complete stop; it just loses some of its energy.
2. **Photon Emission in Strong Fields:** In extremely strong electromagnetic fields, such as those generated by intense laser pulses, the dynamics can be different. The interaction of an electron with a strong electromagnetic field can lead to significant energy transfer through a process known as non-linear Compton scattering or non-linear Thomson scattering. Here, the electron can emit high-energy photons and lose a substantial amount of its kinetic energy.
3. **Bremsstrahlung in Extreme Fields:** When electrons decelerate rapidly in the presence of strong electromagnetic fields, they can emit radiation (bremsstrahlung). If the deceleration is extreme, the electron can lose a large fraction of its kinetic energy to the emitted photon(s).
4. **Quantum Effects and Pair Production:** In extremely high-energy environments, quantum electrodynamics (QED) effects become significant. An electron interacting with a high-intensity photon field could potentially transfer a large fraction of its energy to photons, but this process might also involve phenomena like pair production (e.g., electron-positron pairs).

Considering the Compton interaction between photon pulses and counter-propagating electrons, we can derive the well-known equation for the photon energy ($E'_{\text{ph}} = \hbar\omega'$, with ω' being the photon angular frequency and \hbar the reduced Planck constant) scattered at an angle θ . Following the notation of Eq. 3 in Ref. [18], we can write:



$$E'_{\text{ph}}(\theta) = \frac{(1 + \beta)\gamma^2}{\gamma^2(1 - \beta \cos \theta) + \frac{X}{4}(1 + \cos \theta)} E_{\text{ph}}, \quad (1)$$

where the incident photon energy is $E_{\text{ph}} = \hbar\omega$, $\beta = v_e/c$ is the dimensionless electron velocity v_e (c being the speed of light), $\gamma = 1/\sqrt{1 - \beta^2}$ is electron Lorentz factor and X is the electron recoil factor that introduces an important contribution at high energy of both incident photons and electrons. X has been defined in [17] (eq. 4) as:

$$X = \frac{4E_e E_{\text{ph}}}{(m_0 c^2)^2} = \frac{4\gamma E_{\text{ph}}}{m_0 c^2} = 4\gamma^2 \frac{E_{\text{ph}}}{E_e}, \quad (2)$$

with m_0 the electron rest mass and $E_e = \gamma m_0 c^2$. Eq. (1) can be cast in a more schematic form as a function of the incident particle energies.

$$E'_{\text{ph}} = \frac{(1 + \beta) E_{\text{ph}} E_e}{(1 - \beta \cos \theta) E_e + (1 + \cos \theta) E_{\text{ph}}}$$

$$T_e = E_e - m c^2$$

If $E'_{\text{ph}} = T_e$ then $T'_e = 0$!

*Electron Recoil effect in γ -ray I.C.S. for Nuclear Photonics:
C.E.M. fails to evaluate the correct red-shift in the spectrum*

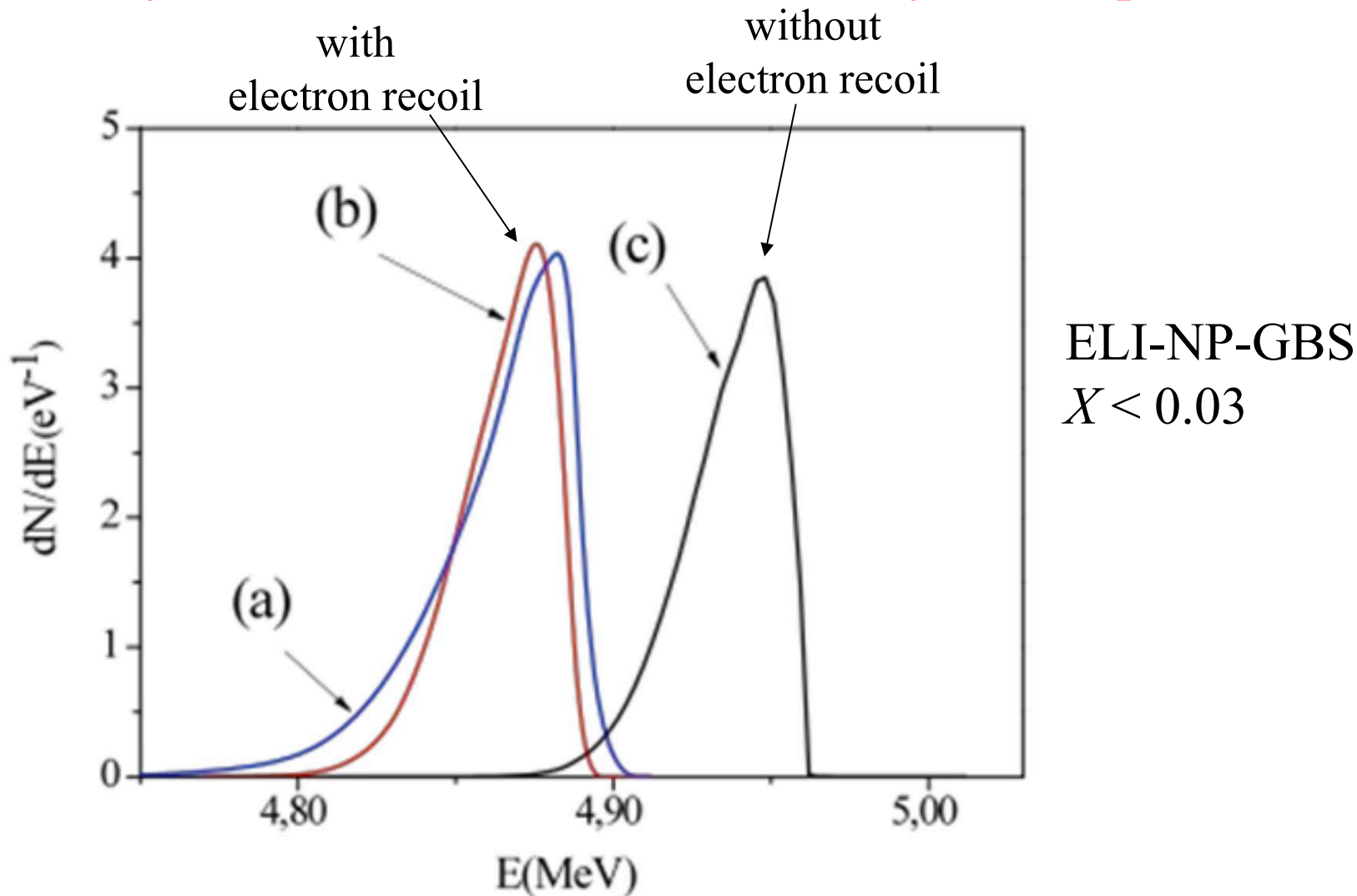


Fig. 5. Spectra of the rays. (a) CAIN (b) Quantum model (c) Classical treatment in the case of beam (A) and for the laser parameter of Table 1 and interaction angle $\alpha=\pi$; rms acceptance angle $\theta_{rms} = 25\mu rad$

So surprising that FICS was not mentioned nor described
in the previous literature on Compton direct/inverse Scattering
that

we really wanted to re-examine the first historical phases
of the studies on electron-photon QED interaction

How comes that nobody yet identified FICS as the only regime
of complete/full transfer in-vacuum of
energy and momentum between an electron and a photon?

- 1) R. Rabinowitz et al., Proc. Inst. Radio Engrs. (correspondence) 50 (1962) 2365.
- 2) A. Javan, E. A. Ballik and W. L. Bond, J. Opt. Soc. Am. 52 (1962) 96.
- 3) S. Jacobs and P. Rabinowitz, Proc. of the 3rd Quantum Electronics Conf., Paris, 1963 (to be published).
- 4) K. D. Froome and R. H. Bradsell, J. Sci. Instr. 38 (1961) 458.
- 5) J. Terrien, J. phys. radium 19 (1958) 390.
- 6) G. R. Hanes, Can. J. Phys. 37 (1959) 1283.
- 7) C. F. Bruce and R. M. Hill, Australian J. Phys. 14 (1961) 64; 15 (1962) 152.
- 8) R. M. Hill and C. F. Bruce, Australian J. Phys. 15 (1962) 194.

* * * * *

Almost at the same time as Arutyunian and co-workers

THE COMPTON EFFECT ON RELATIVISTIC ELECTRONS AND THE POSSIBILITY OF OBTAINING HIGH ENERGY BEAMS

F. R. ARUTYUNIAN and V. A. TUMANIAN

Physical Institute of the State Committee of the Council of Ministers
of the USSR for the Use of Atomic Energy

Received 20 February 1963

A characteristic feature of the Compton effect on relativistic electrons is the appearance of photons with energies exceeding those of the primary photons. As a result, even when light photons are scattered on extremely relativistic electrons, the energies of the scattered photons will be of the same order of magnitude as those of the electrons. This feature may possibly be exploited for obtaining high energy γ -ray beams in electron accelerators. An important point to be mentioned is that the characteristics of such γ -beams will significantly differ from those obtained by bremsstrahlung.

In the Compton effect involving moving electrons

Of course in order to obtain γ -beams by the method considered here high photon fluxes will be required. A high intensity photon source that should be feasible is the laser. At present ruby lasers seem to be the most reliable.

For ruby laser photons ($\lambda = 6943 \text{ \AA}$) scattered on 6 GeV electrons one gets $\omega_{2 \text{ max.}} = 848 \text{ MeV}$. This effect rapidly grows with increase of the electron energy. Thus for the same ruby lasers and $\epsilon_1 = 40$ and 500 GeV the maximal energy is correspondingly $\omega_{2 \text{ max.}} \sim 21$ and 497 GeV.

Of course if lasers emitting shorter wavelengths or other sources of high energy photons be employed,

First measured ICS – 500 MeV

COMPTON EFFECT ON MOVING ELECTRONS

O. F. KULIKOV, Y. Y. TELNOV, E. I. FILIPPOV and M. N. YAKIMENKO

Lebedev Physical Institute, Moscow University, Moscow, USSR

Received 3 November 1964

Until recent times only the Compton effect on electrons at rest has been investigated. The electron acceleration technique having been improved, there arises the possibility of investigating the scattering of photons by electrons moving with speeds near to the speed of light. New powerful sources of photon-lasers make possible the scattering of visible photons on electrons, moving in an orbit of a cyclic accelerator.

telescope tube (T) which was used while positioning the laser beam. A photomultiplier is installed beyond the telescope's ocular. The signals from the photomultiplier are proportional to the energy of the light. Gamma-quanta of scattered radiation, passing through the glass plate (G), the lens (L), the turning mirror (TM) and the collimator (C) (diameter 15 mm) cause scintillation in the crystal of NaI. This is registered by the photo-

The theory of Compton's effect on relativistic electrons [1] has been considered in detail for interactions of laser photons with relativistic electrons [2 - 4]. According to these authors a head-on collision of laser radiation ($\gamma = 6943 \text{ \AA}$) with relativistic electrons of energy of the order of 500 MeV, will cause the appearance of γ -quanta of energy near 6.75 MeV, moving in the direction of motion of electrons.

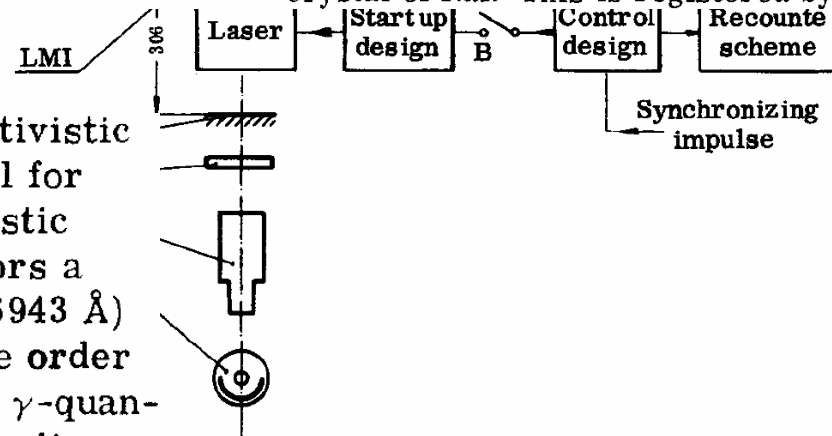


Fig. 1

Second measured ICS – 6 GeV

PHYSICAL REVIEW

VOLUME 138, NUMBER 6B

21 JUNE 1965

High-Energy Photons from Compton Scattering of Light on 6.0-GeV Electrons*

CARLO BEMPORAD†, RICHARD H. MILBURN, AND NOBUYUKI TANAKA
Department of Physics, Tufts University, Medford, Massachusetts

AND

MIRCEA FOTINO
Cambridge Electron Accelerator, Harvard University, Cambridge, Massachusetts
(Received 28 January 1965; revised manuscript received 1 March 1965)

Compton scattering of optical photons on 6.0-GeV electrons has been observed at the Cambridge Electron Accelerator. A giant-pulsed ruby-laser burst of 0.2 J, impinging upon a 2-mA circulating electron current, was observed to yield about 8 scattered photons per pulse. These photons acquire, through a twofold Doppler shift, energies of hundred of MeV, and are expected to retain to a high degree the polarization of the laser beam. The observed yield is compatible with predictions based upon the theory of Compton scattering.

THE scattering of optical photons from a laser on extreme-relativistic electrons has been predicted¹⁻³ to yield a high-energy output photon beam which preserves to a high degree the polarization of the incident light beam. Photons of energy up to 0.85 GeV are expected from the interaction of 6943-Å quanta from commercial laser cavity, a cylindrical reflector, together with and parallel to a single flash lamp.⁵ The optical pumping energy was normally between 750 and 850 J. Total measured output energies were typically about 0.2 J appearing in two or three giant pulses, each about 30 nsec wide and 200-300 nsec apart. Electrical pulses de-

Theoretical and simulation studies of characteristics of a Compton light source

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and DFELL, Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308, USA*

(Received 25 January 2011; published 21 April 2011)

Design of narrow-band Compton scattering sources for nuclear resonance fluorescence

F. Albert,^{*} S. G. Anderson, D. J. Gibson, R. A. Marsh, S. S. Wu, C. W. Siders, C. P. J. Barty, and F. V. Hartemann

Lawrence Livermore National Laboratory, NIF and Photon Science, 7000 East Avenue, Livermore, California 94550, USA

(Received 20 December 2010; published 13 May 2011)

Reviews of Accelerator Science and Technology

Vol. 3 (2010) 147–163

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**Many studies in the literature on electron-photon beam collisions
collective/statistical properties (phase spaces, etc)**

Compton Sources of Electromagnetic Radiation*

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Gerd Priebe

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Relevance of recoil in electron-photon beam-beam collisions

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20**, 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

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(Received 9 March 2017; published 3 August 2017)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21**, 030701 (2018)

Simulation of inverse Compton scattering and its implications on the scattered linewidth

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(Received 17 November 2017; published 6 March 2018)

Article

Electrons and X-rays to Muon Pairs (EXMP)

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Fundamental Plasma Physics 7 (2023) 100026

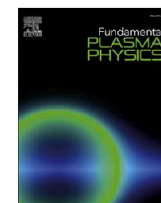


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Fundamental Plasma Physics

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Original research article

Symmetric Compton Scattering: A way towards plasma heating and tunable mono-chromatic gamma-rays

L. Serafini ^{a,b}, A. Bacci ^{a,b}, C. Curatolo ^{a,b}, I. Drebot ^{a,b}, V. Petrillo ^{a,c}, A. Puppini ^{a,c},
M. Rossetti Conti ^{a,b,*}, S. Samsam ^{a,b}

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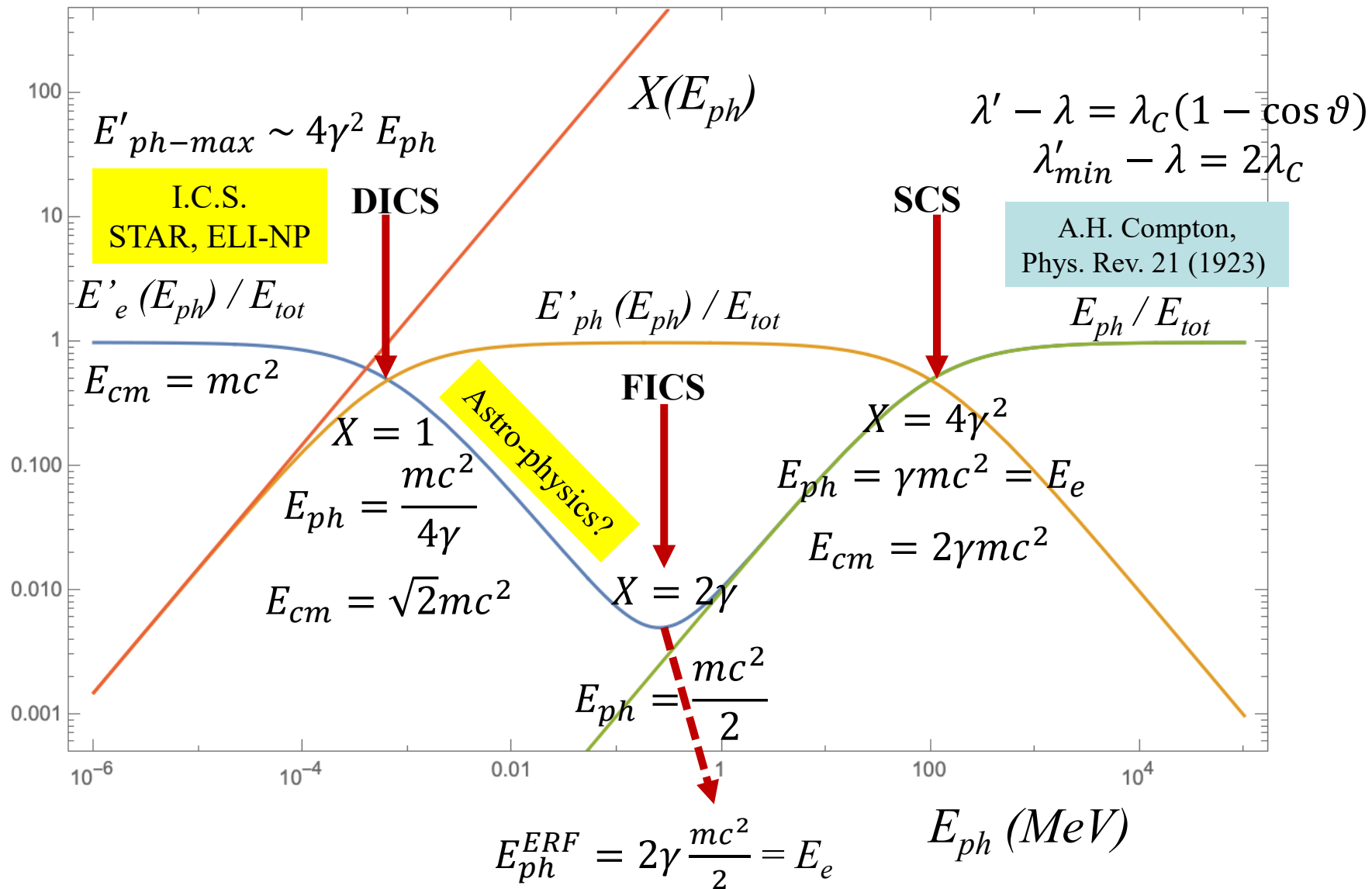


$$\frac{E'_{ph}}{E_{tot}} = \frac{X}{(1 + X)\left(1 + \frac{X}{4\gamma^2}\right)}$$

$$\frac{E'_e}{E_{tot}} = 1 - \frac{X}{(1 + X)\left(1 + \frac{X}{4\gamma^2}\right)}$$

All quantities normalized to
the total energy $E_{tot} = E_e + E_{ph}$

$E_e = 100 \text{ MeV}$



Largest value of recoil factor X achieved in experiments so far is $X=1.8$ at SLAC in 1999

PHYSICAL REVIEW D, VOLUME 60, 092004

Studies of nonlinear QED in collisions of 46.6 GeV electrons with intense laser pulses

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Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

C. Bula,[¶] K. T. McDonald, and E. J. Prebys

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

D. L. Burke, R. C. Field, G. Horton-Smith,** J. E. Spencer, and D. Walz

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309

S. C. Berridge, W. M. Bugg, K. Shmakov,^{††} and A. W. Weidemann

Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996

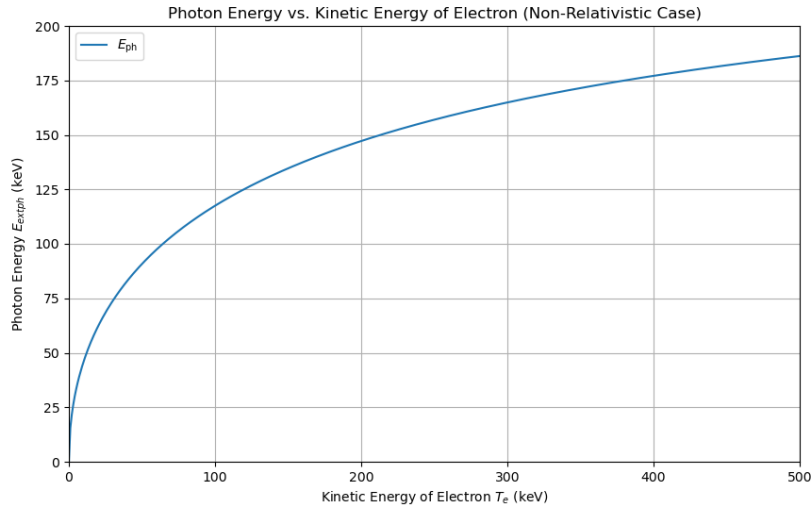
(Received 1 February 1999; published 8 October 1999)

We report on measurements of quantum electrodynamic processes in an intense electromagnetic wave, where nonlinear effects (both multiphoton and vacuum polarization) are prominent. Nonlinear Compton scattering and electron-positron pair production have been observed in collisions of 46.6 GeV and 49.1 GeV electrons of the Final Focus Test Beam at SLAC with terawatt pulses of 1053 nm and 527 nm wavelengths from a Nd:glass laser. Peak laser intensities of $\approx 0.5 \times 10^{18}$ W/cm² have been achieved, corresponding to a value of ≈ 0.4 for the parameter $\eta = eE_{\text{rms}}/m\omega_0 c$ and to a value of ≈ 0.25 for the parameter $Y_e = E_{\text{rms}}^*/E_{\text{crit}} = eE_{\text{rms}}^* \hbar/m^2 c^3$, where E_{rms}^* is the rms electric field strength of the laser in the electron rest frame. We present data on the scattered electron spectra arising from nonlinear Compton scattering with up to four photons absorbed from the field. A convolved spectrum of the forward high energy photons is also given. The observed positron production rate depends on the fifth power of the laser intensity, as expected for a process where five photons are absorbed from the field. The positrons are interpreted as arising from the collision of a high-energy Compton scattered photon with the laser beam. The results are found to be in agreement with theoretical predictions. [S0556-2821(99)02519-9]

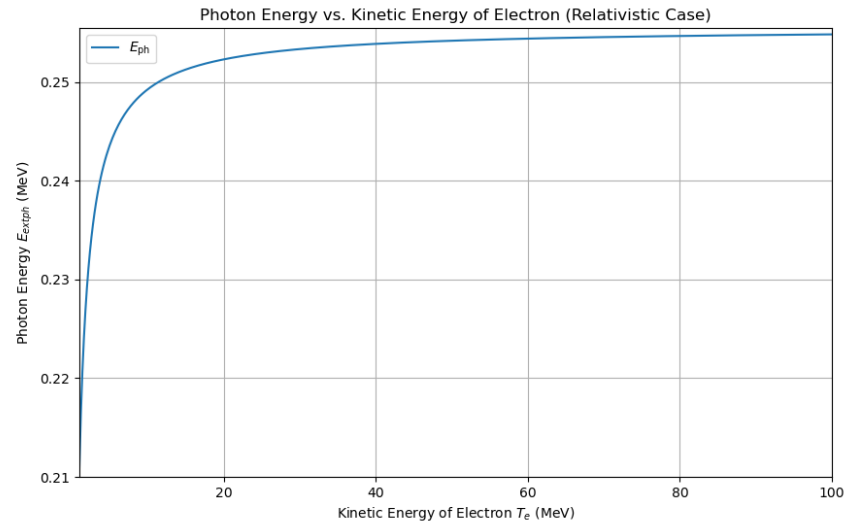
PACS number(s): 13.40.-f, 12.20.Fv, 13.10.+q, 42.65.-k

Colliding the XFEL photon beam (12 keV) with the 19.5 GeV electron beam would achieve $X=3585$!!!

$$E_{ph}^{FICS} (T_e \leq 500 \text{ keV})$$

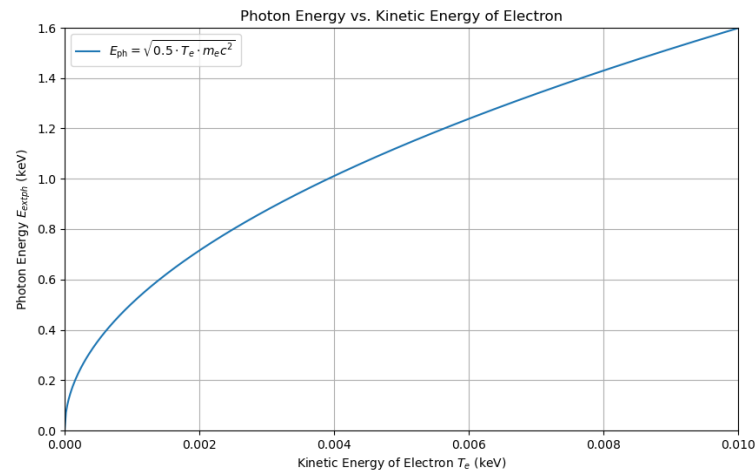


$$E_{ph}^{FICS} (T_e \leq 100 \text{ MeV})$$

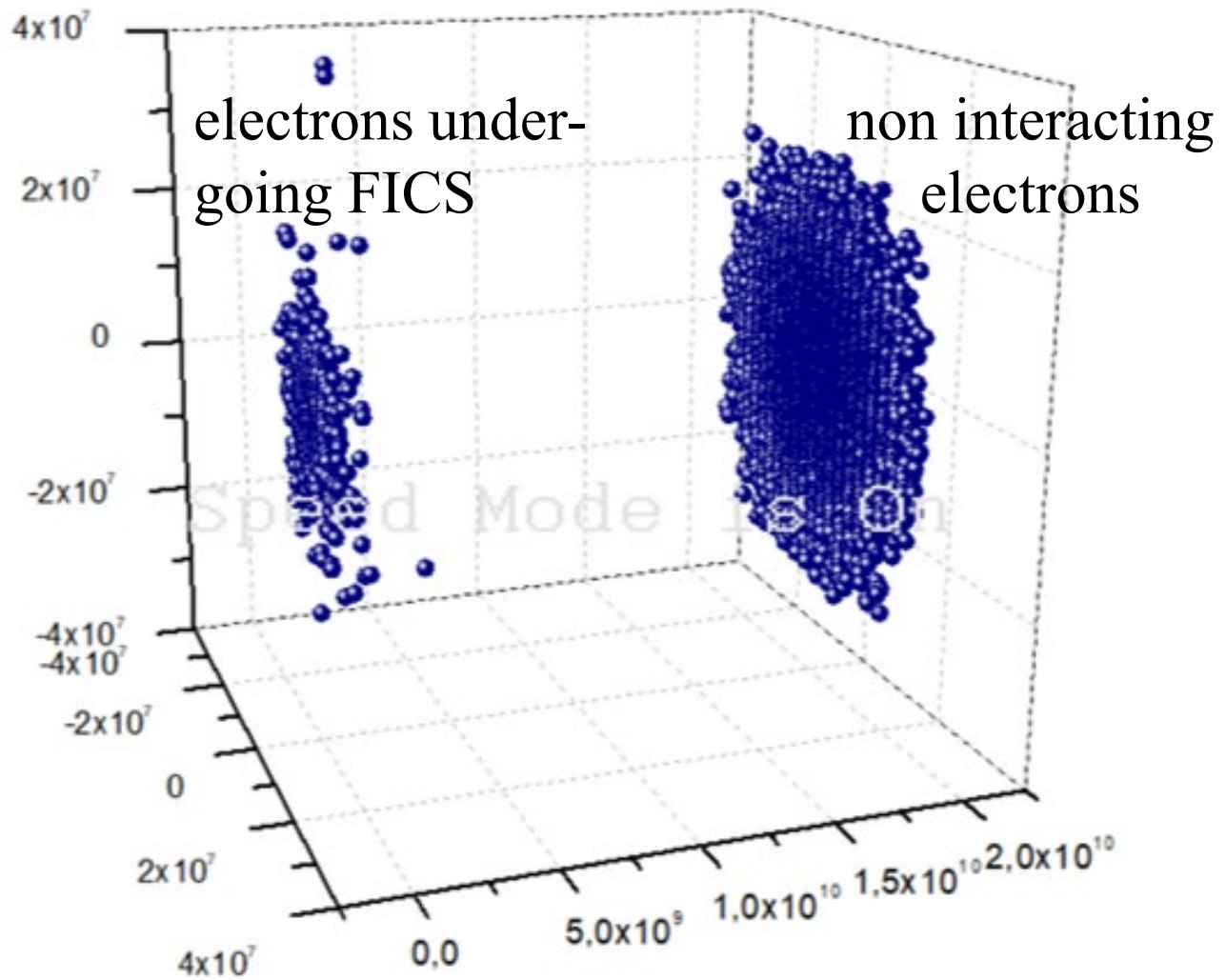


$$\frac{mc^2}{2}$$

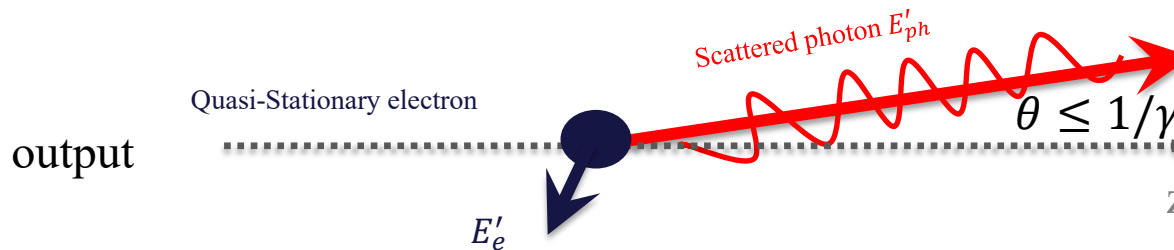
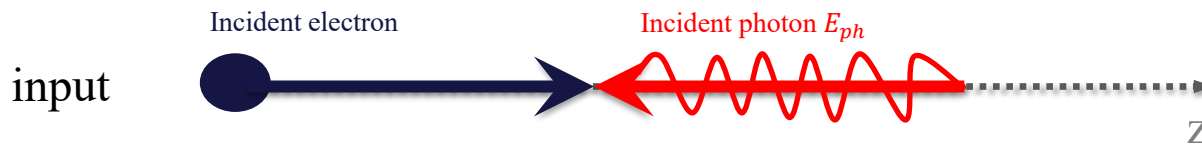
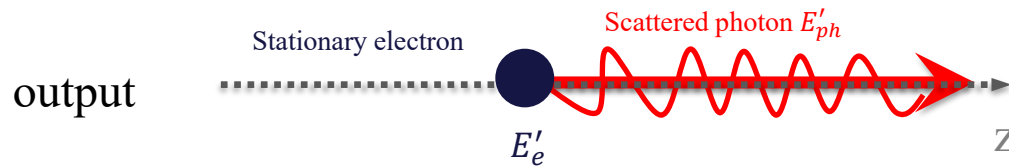
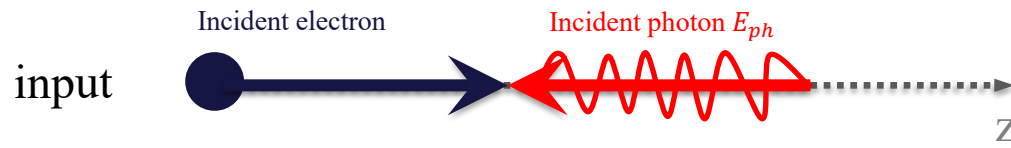
$$E_{ph}^{FICS} (T_e \leq 10 \text{ eV})$$



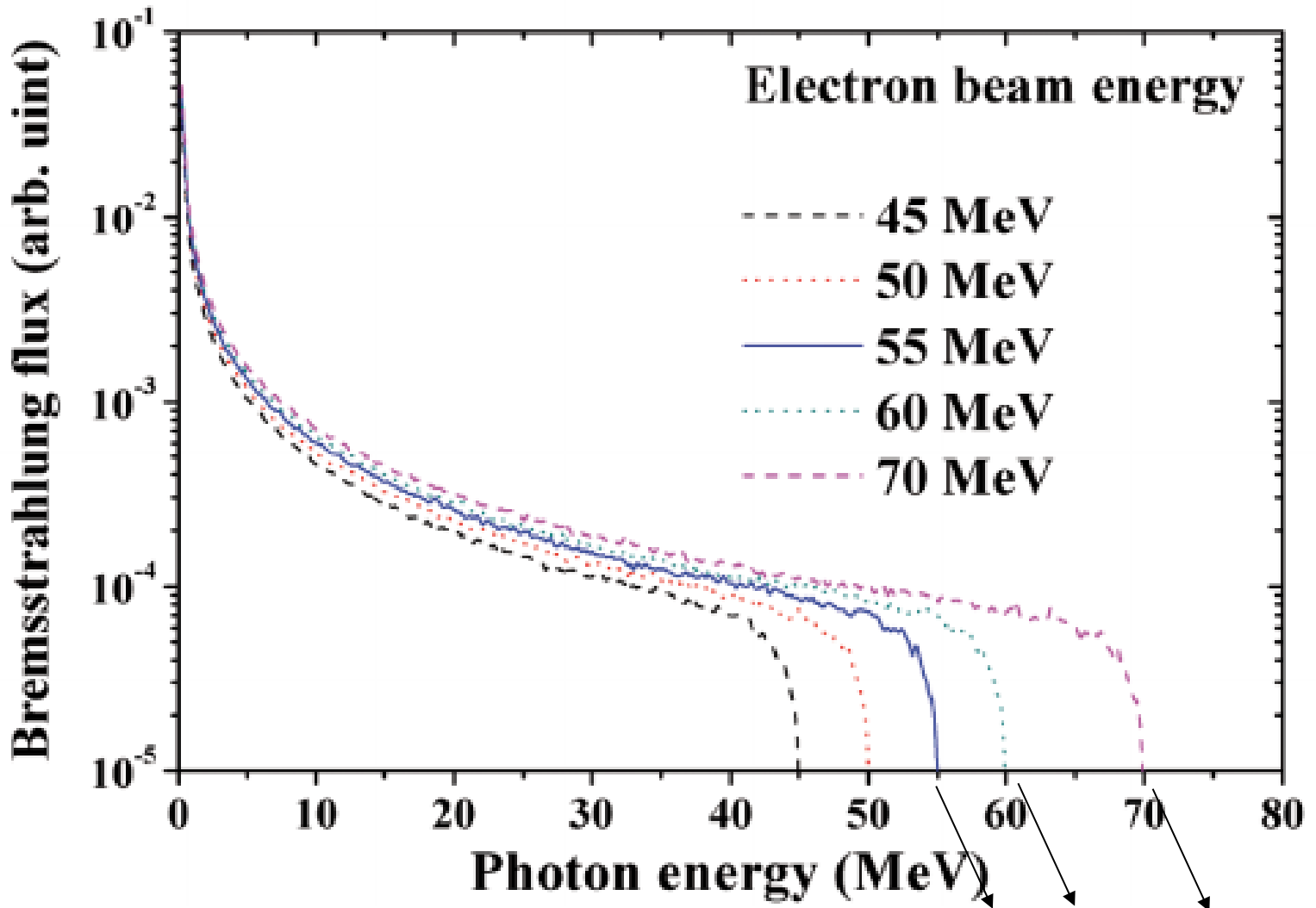
$E_e = 200 \text{ MeV}$; $E_{ph} = 255.5 \text{ keV}$
electron momenta distribution after FICS



FICS lay-out



cmp. Bremsstrahlung
maximum electron energy loss very unlikely



100% e^- energy loss

$$T'_e = (\gamma - 1)m_e c^2 + E_{ph}^{FICS} - \frac{\gamma(1 + \beta)E_{ph}^{FICS} m_e c^2}{(1 - \beta \cos \theta)\gamma m_e c^2 + (1 + \cos \theta)E_{ph}^{FICS}} \quad (21)$$

After scattering, the kinetic energy T'_e of the electron (valide for $\gamma \gg 1$ and $\theta \approx \frac{1}{\gamma}$) is given by:

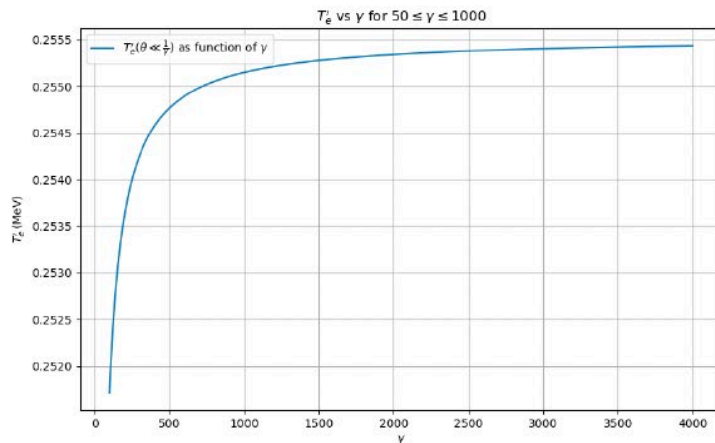
$$T'_e = \frac{m_e c^2}{2} \gamma^2 \theta^2 \quad (22)$$

For a small angle θ , where $\cos \theta \approx 1 - \frac{\theta^2}{2}$, T'_e simplifies to the following form:

$$T'_e = m_e c^2 \frac{4\gamma^2 - 4\gamma - 1}{8\gamma^2 - 4\gamma} \quad (23)$$

As γ approaches infinity, T'_e converges to:

$$T'_e \xrightarrow{\gamma \rightarrow \infty} \frac{m_e c^2}{2} \quad (24)$$



$$\beta (T_e = 255 \text{ keV}) = 0.75$$

Figure 6: Kinetic energy of the scattered electron T'_e as function of the Lorentz factor

electrons undergoing FICS with photons back-scattered
between $\theta=0$ and $\theta=1/\gamma$ have $\beta < 0.75$

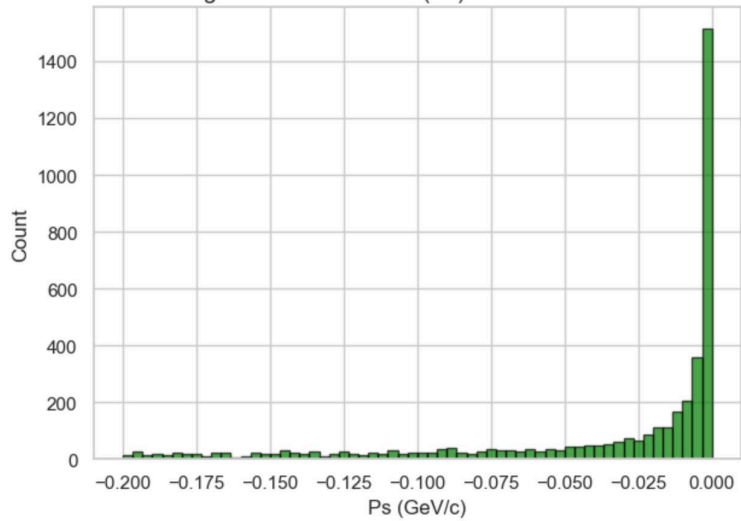
back-scattered photons in FICS have energy E'_{ph} in the range

$$E'_{ph}(\theta=0) = E_e(1-1/2\gamma) \quad ; \quad E'_{ph}(\theta=1/\gamma) = E_e(1-1/\gamma)$$

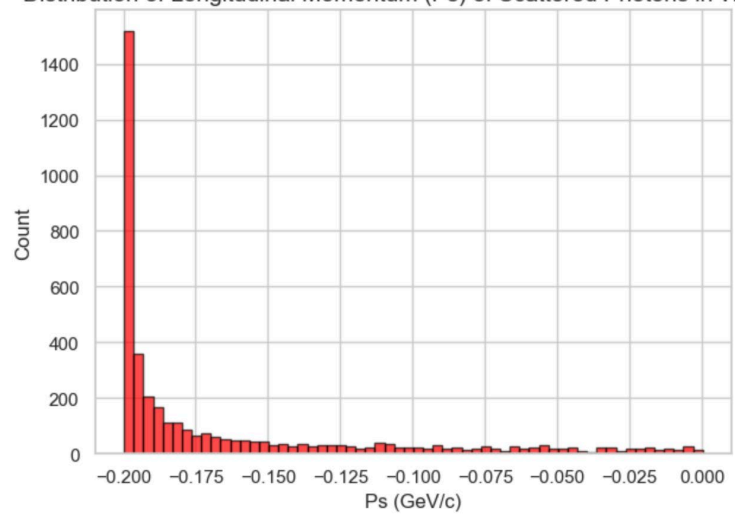
to be compared with low recoil ICS, where

$$E'_{ph}(\theta=0) = 4\gamma^2 E_{ph} \quad ; \quad E'_{ph}(\theta=1/\gamma) = 2\gamma^2 E_{ph}$$

Distribution of Longitudinal Momentum (P_s) of Scattered Electrons in Whizard

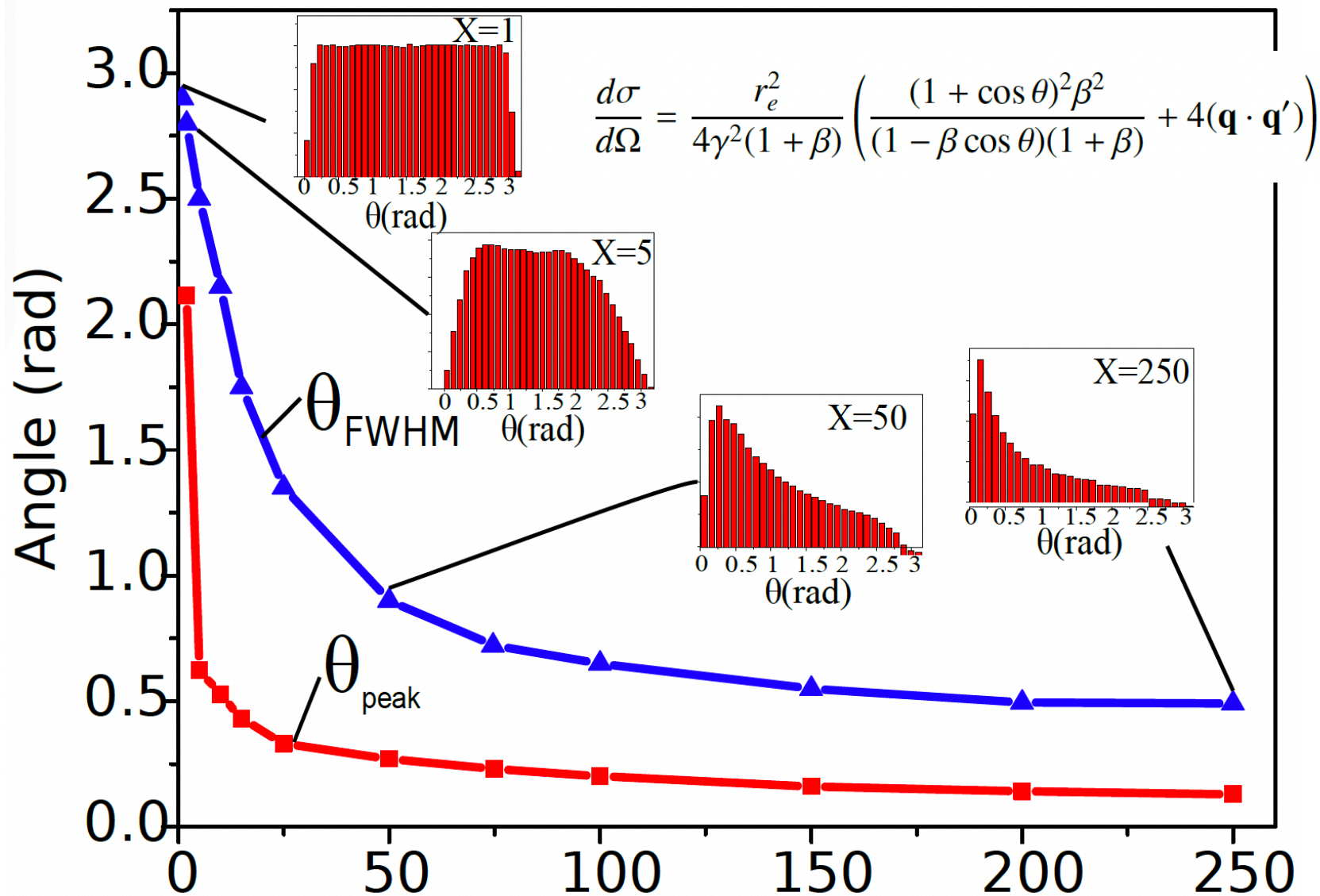


Distribution of Longitudinal Momentum (P_s) of Scattered Photons in Whizard



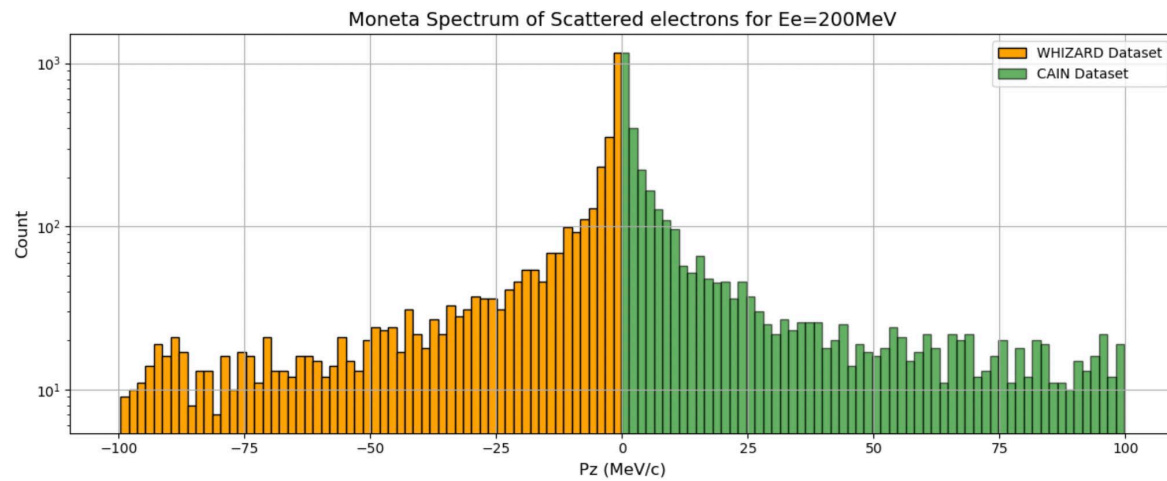
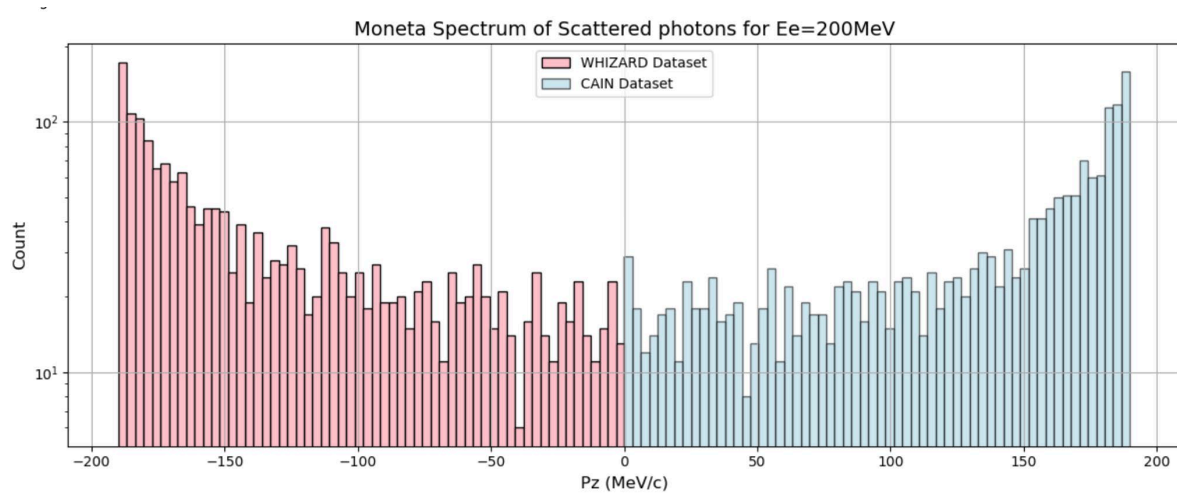
S.C.S. Spectra at different recoil factors X

back-scattering of the photon is most likely in deep recoil



if an electron/photon interaction occurs in deep recoil it must be back-scattering

Longitudinal momentum Pz



$$f^{FICS} = \frac{6.25}{4.2} \frac{(1 + \sqrt[3]{X} \frac{\Psi^2}{3}) \Psi^2}{(1 + (1 + \frac{X}{2}) \Psi^2)(1 + \Psi^2)} \cdot \frac{\sigma_T}{\sigma} \quad (28)$$

where $\Psi \approx \frac{\gamma\theta}{\sqrt{1+X}}$ is the acceptance angle, σ is the unpolarized Compton cross section and σ_T is the Thomson cross section [9].

Taking the fact that $\frac{\sigma_T}{\sigma} = \frac{4X}{\ln X + \frac{1}{2}}$, $X \gg 1$, $\gamma \gg 1$ and $\theta \leq \frac{1}{\gamma}$, Eq.28 simplifies to the following form:

$$f^{FICS}(\theta = \frac{1}{\gamma}) \approx \frac{4}{\ln X + \frac{1}{2}} \quad (29)$$

Taking into consideration that the recoil X for FICS is equal to 2γ (see Tab. 1 in Ref. [3]). Eq. 29 can be written as:

$$f^{FICS}(X = 2\gamma) = \frac{4}{\ln \gamma + 1.19} \quad (30)$$

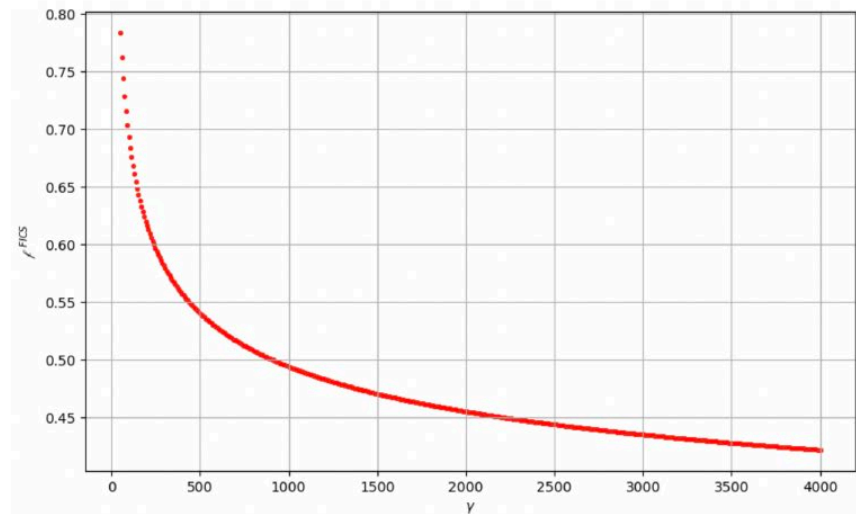


Figure 7: FICS fraction factor $f^{FICS} = \frac{\mathcal{N}^\Psi}{\mathcal{N}}$ as function of the Lorentz factor γ .

Grazie per l'attenzione

V. Petrillo, ad-hoc developed Montecarlo code for linear QED

1) low recoil 2) DICS (X=1) 3) deep recoil (X=8)

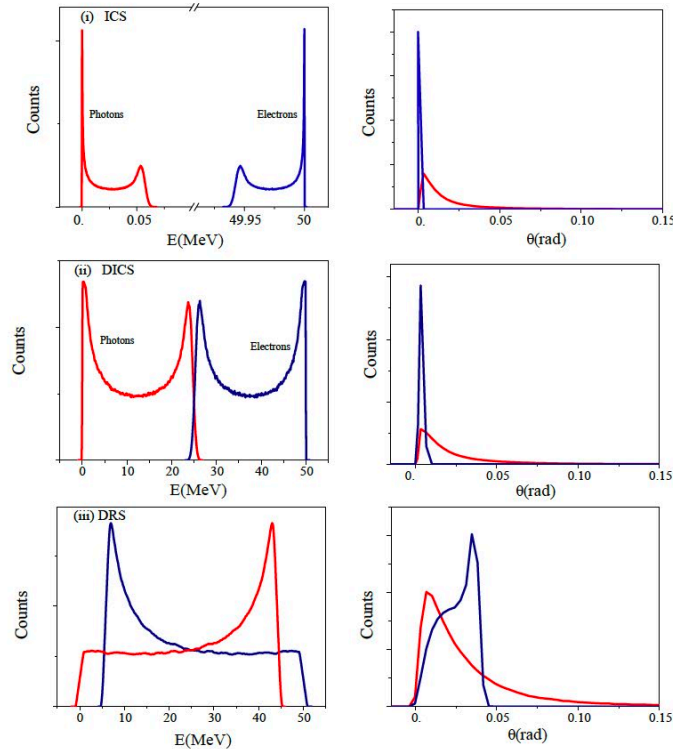


FIG. 4: (i) Inverse Thomson Scattering (ITS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue: scattered electrons. $E_{ph}=1.5$ eV, $E_e=50$ MeV, $bw_{ph} = 5\%$. (ii) Democratic Inverse Compton Scattering (DICS). $E_{ph}=1.3$ keV, $E_e = 50$ MeV, $bw_{ph} = 5\%$. (iii) Deep Recoil Scattering (DRS). $E_{ph}=10$ keV, $E_e=50$ MeV, $bw_{ph} = 5\%$.

- 1) electron back-scattering ($X=12.000$)
- 2) SCS ($X=40.000$)
- 3) Direct Compton ($X=1.2 \cdot 10^5$)

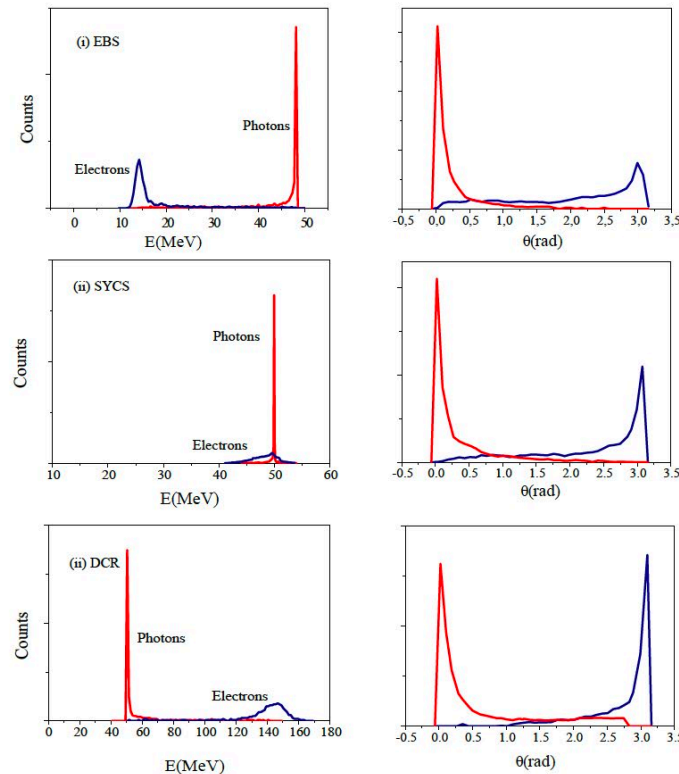


FIG. 6: (i) Electron Back-Scattering (EBS). Left: energy distribution, right: angular distribution. Red: scattered photons, blue: scattered electrons. $E_{ph} = 15 \text{ MeV}$, $E_e = 50 \text{ MeV}$, $bw_{ph} = 5\%$. (ii) Symmetric Compton Scattering (SYCS): $E_{ph} = 50 \text{ MeV}$, $E_e = 50 \text{ MeV}$, $bw_{ph} = 5\%$. (iii) Relativistic Direct Compton Scattering: $E_{ph} = 150 \text{ MeV}$, $E_e = 50 \text{ MeV}$, $bw_{ph} = 5\%$

$$\left\{ \begin{aligned} E_{ph} &= \frac{mc^2}{2} (1 - (1-\beta)\gamma) \\ E'_{ph} &= mc^2 \left(\gamma \frac{1+\beta}{2} - \frac{1}{2} \right) \\ E_e &= \gamma mc^2 \\ E'_e &= mc^2 \end{aligned} \right.$$

Spectral Purification of incident Channeling Radiation

Compact, sustainable, mono-chromatic gamma-ray source

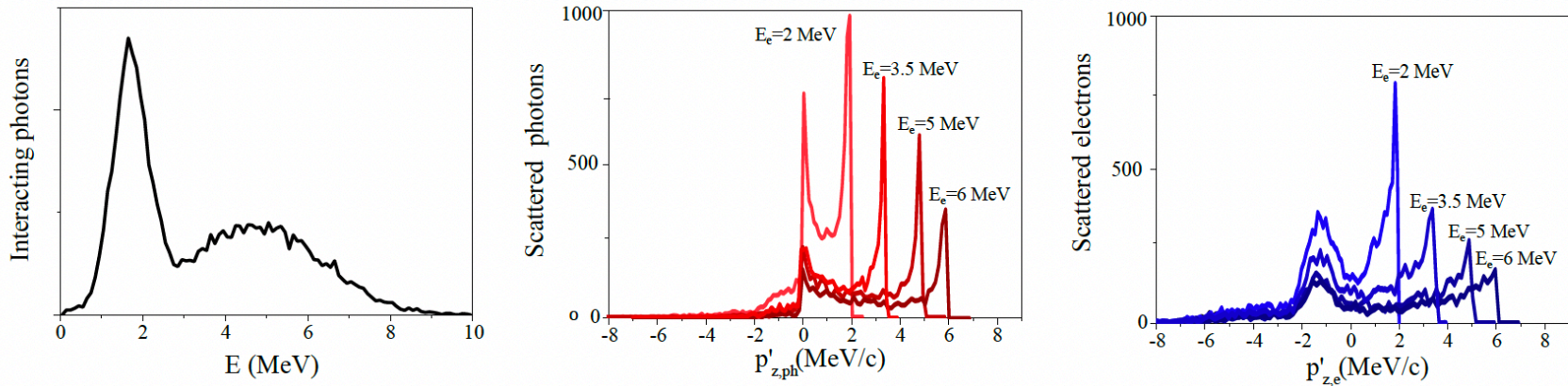


FIG. 8: Left window: Spectrum of the incident photon similar to channelling radiation in crystals, with colliding electron beams of energy $E_e = 2\text{MeV}, 3.5\text{MeV}, 5\text{MeV},$ and 6MeV . Central window: Momentum spectrum of scattered photons. Right window: Momentum spectrum of scattered electrons

Deep recoil cancels the $\gamma^2\theta^2$ disease/correlation, therefore strongly decreases the dependence of the back-scattered photon beam bandwidth on the electron beam transverse emittance

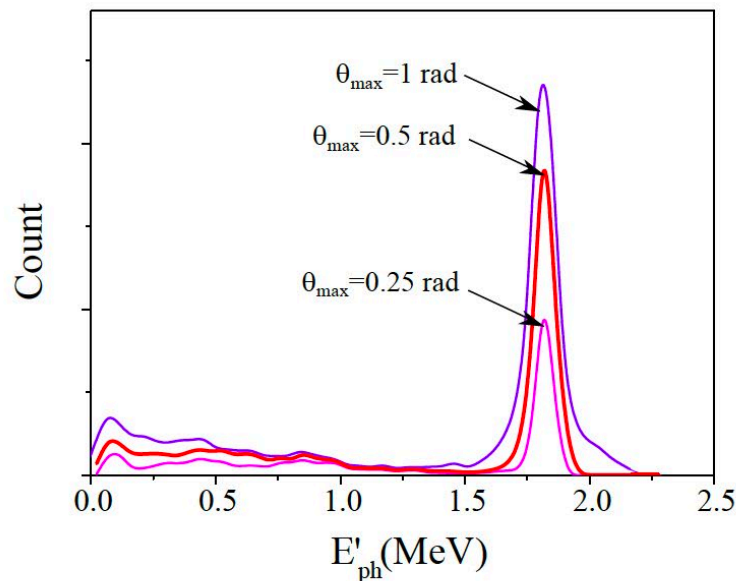
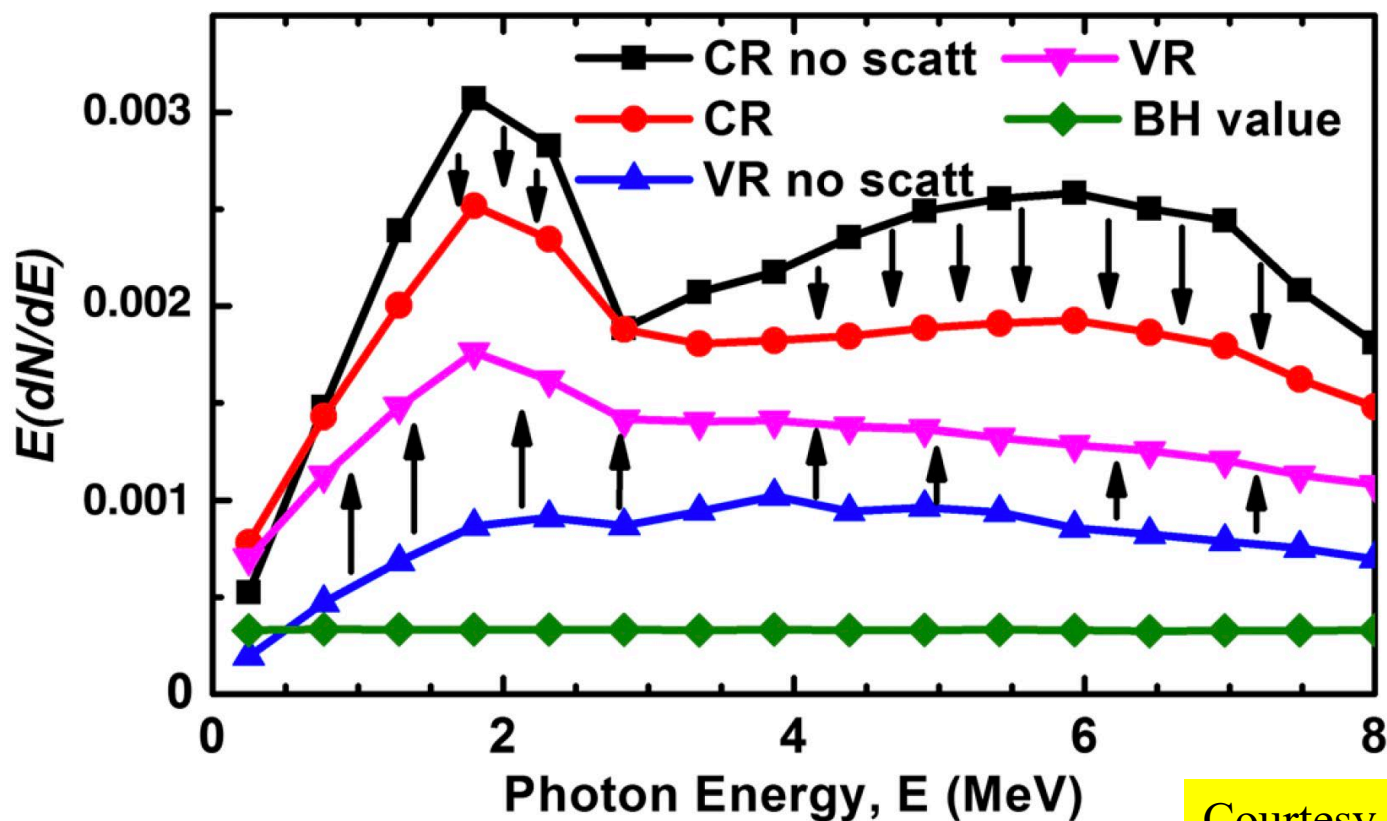


FIG. 9: Collimated energy spectrum. $E_e = 1.9\text{MeV}$, curve magenta: $\theta_{max} = 0.25\text{rad}$, red: $\theta_{max} = 0.5\text{rad}$, blue: $\theta_{max} = 1\text{rad}$

Investigation of the Electromagnetic Radiation Emitted by Sub-GeV Electrons in a Bent Crystal

L. Bandiera, E. Bagli, G. Germogli, V. Guidi,* and A. Mazzolari
*INFN Sezione di Ferrara and Dipartimento di Fisica e Scienze della Terra,
 Università degli Studi di Ferrara Via Saragat 1, 44122 Ferrara, Italy*



Courtesy L. Bandiera

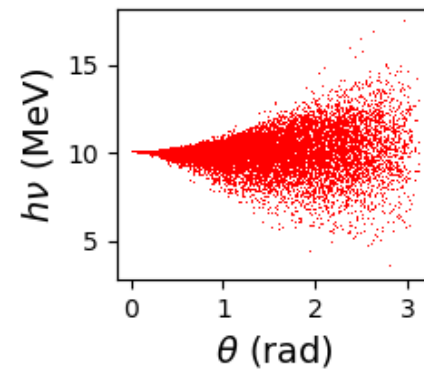
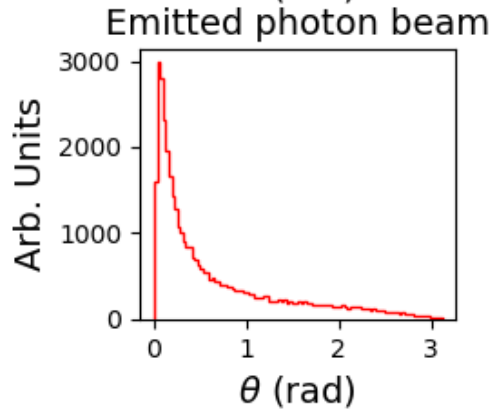
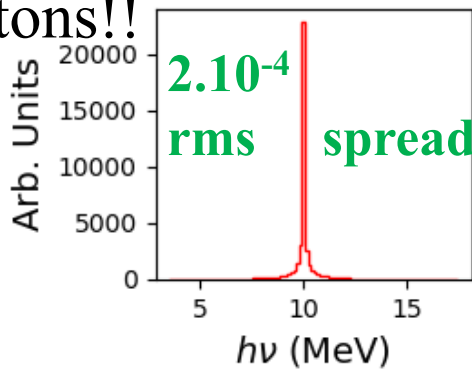
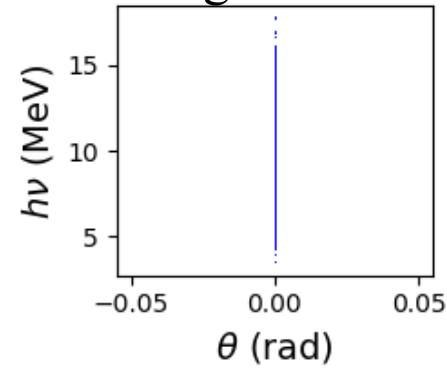
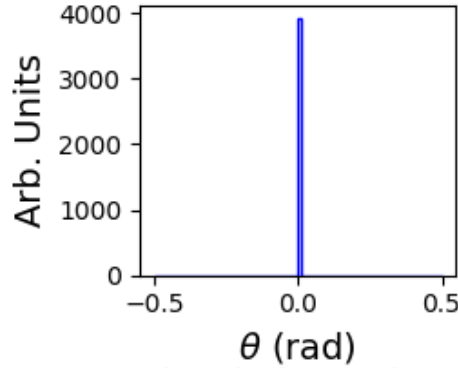
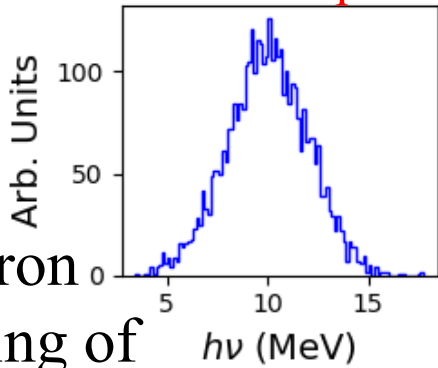
γ -ray in-vacuum mono-chromatization, SCS at large Recoil

20% rms spread

Incoming photon beam

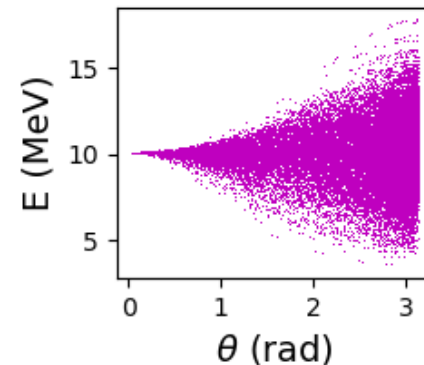
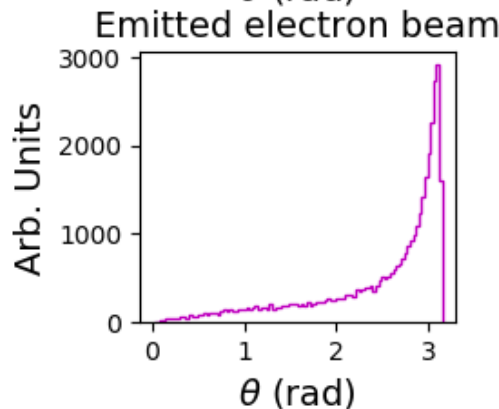
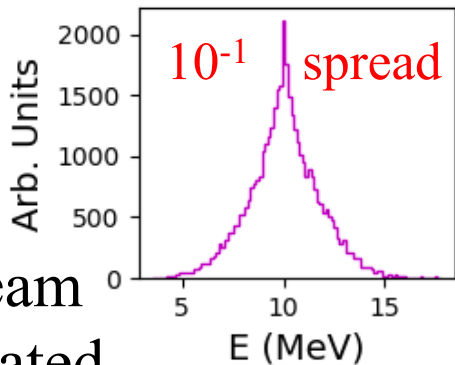
Incoming e- beam 10^{-4} rms spread

Electron
Cooling of
photons!!

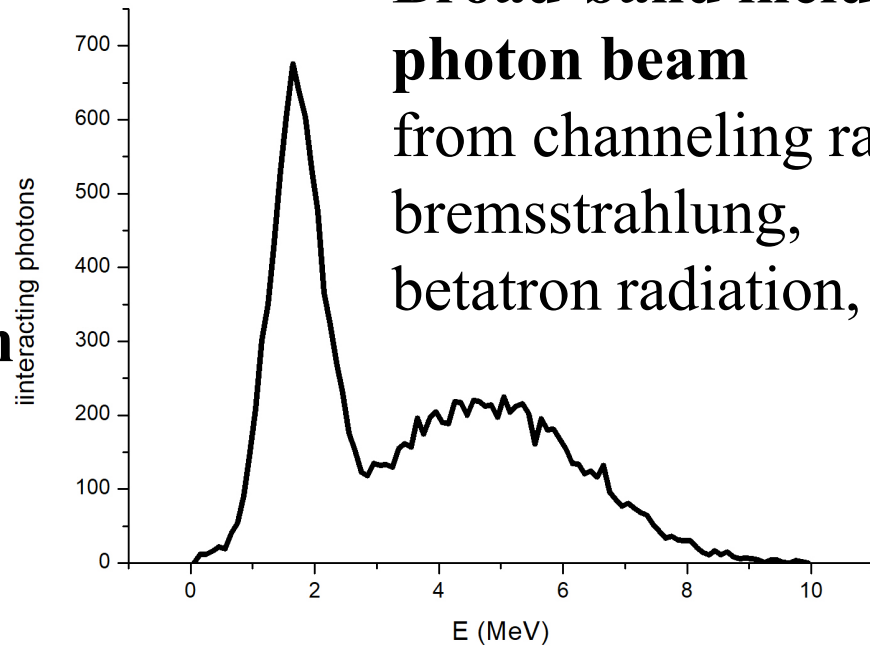


no energy-
angular
correlation

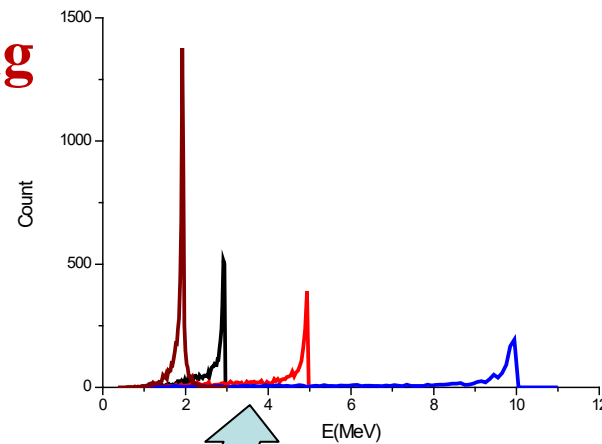
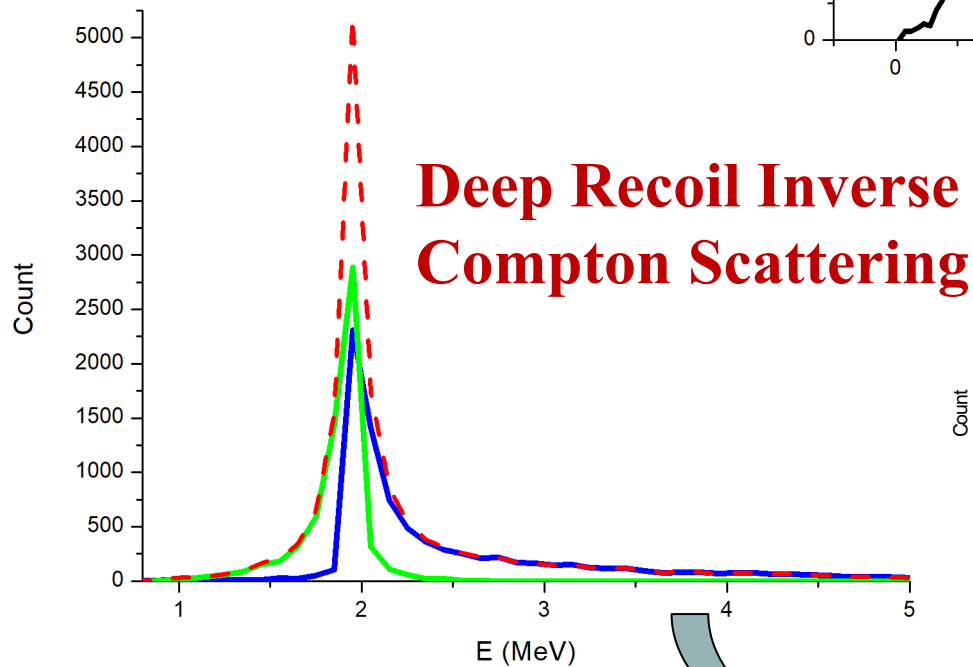
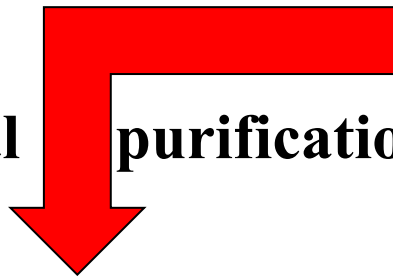
e- beam
is heated



Broad-band incident photon beam
from channeling radiation,
bremsstrahlung,
betatron radiation, etc

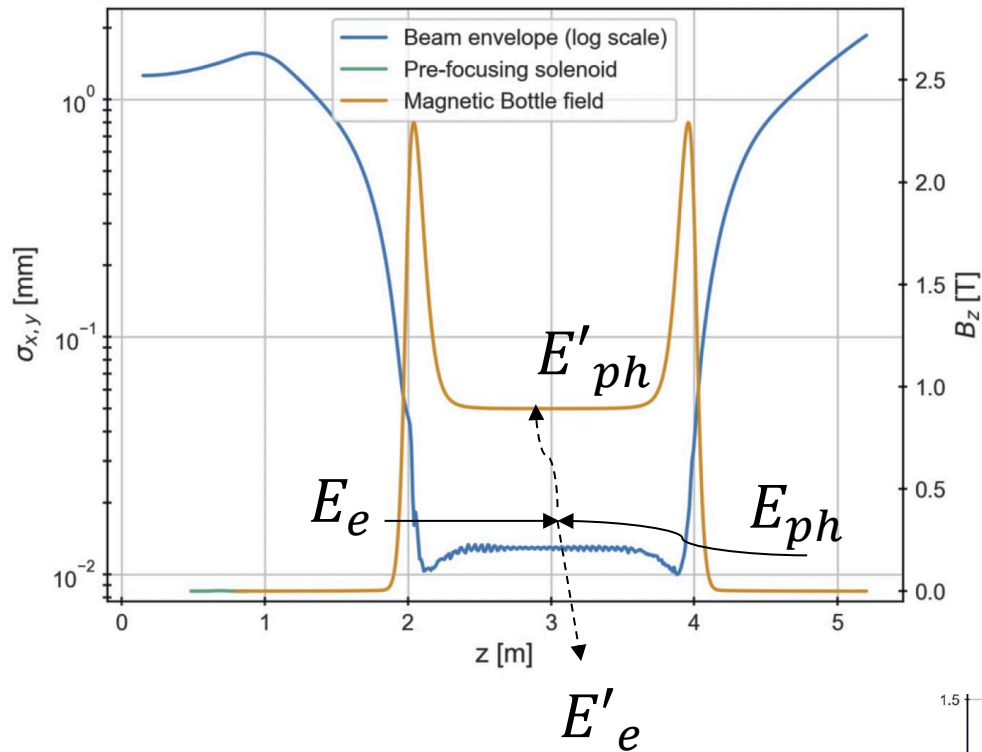


spectral purification

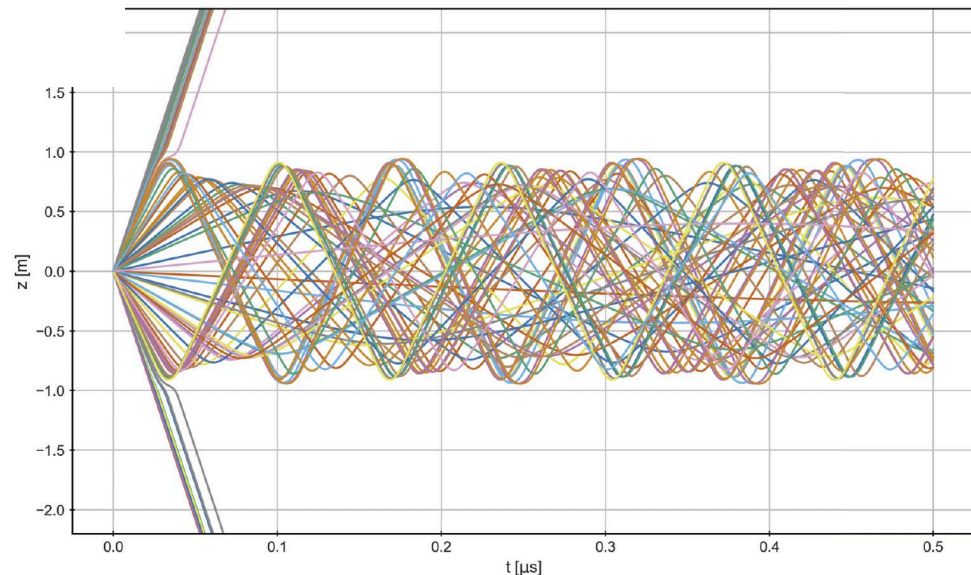


tunability

Trapping electrons (positrons) into a magnetic bottle by SCS at low recoil (72 keV photon beam heats up 5 keV e⁻ beam)

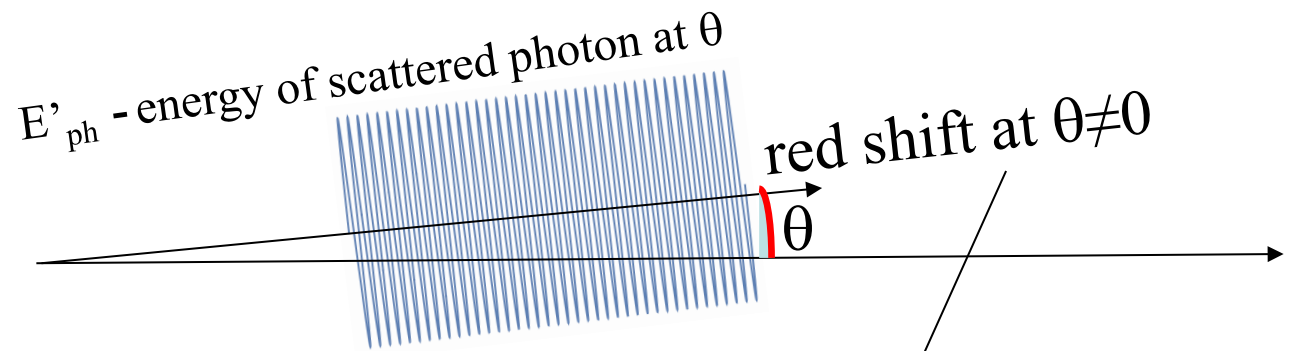


SCS - Symmetric Compton Scattering



scattered electron

$$E'_e = \gamma mc^2 + E_{ph} - E'_{ph}$$



$$E'_{ph}(\theta) = \frac{4E_{ph}\gamma^2}{1 + X + \gamma^2\theta^2}$$

$$X = \frac{4E_e E_{ph}}{m^2 c^4} = \frac{4\gamma E_{ph}}{m c^2} = 4\gamma^2 \frac{E_{ph}}{m c^2}$$

All I.C.S. X/gamma Sources work at $X < 1$ and $A \gg 1$

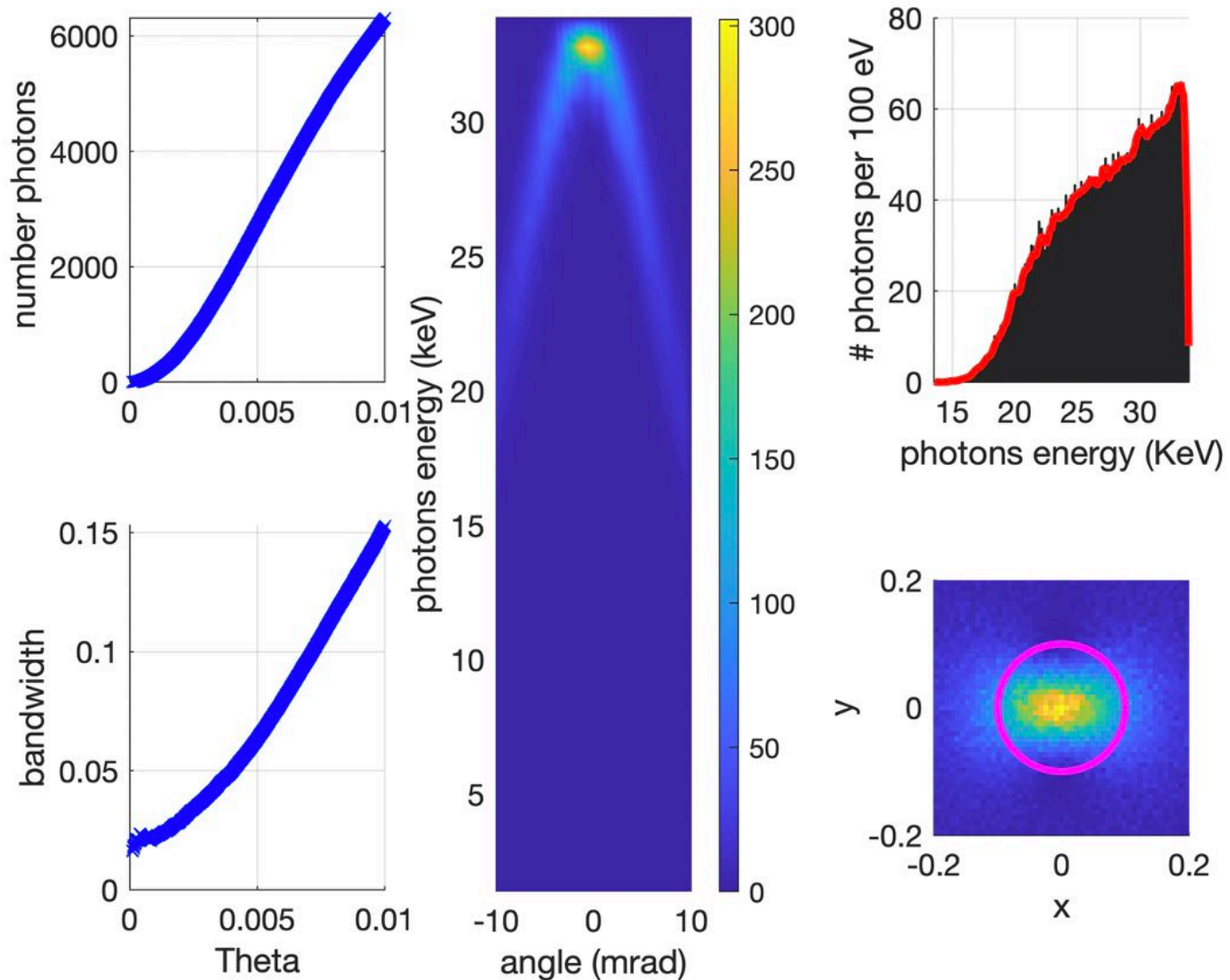
$$STAR (350 \text{ keV}) \quad X_{STAR} < 2.6 \cdot 10^{-3} \quad A_{STAR} > 10^4$$

$X =$ recoil
by the ele

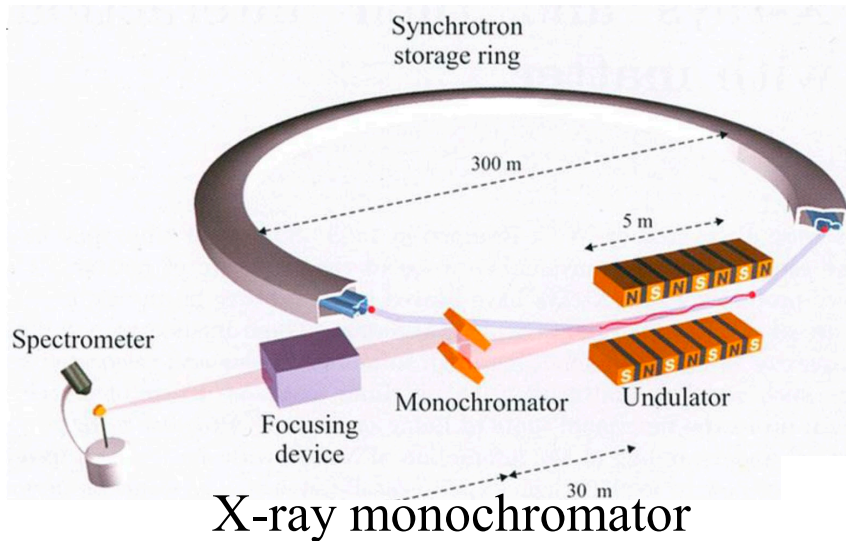
$$ELI-NP (20 \text{ MeV}) \quad X_{ELI-NP} < 0.026 \quad A_{ELI-NP} > 2.4 \cdot 10^5$$

n seen
d to mc^2

BriXSinO's ICS source – Illya Drebot with CAIN – ICS Moustache



Poli-chromaticity implies using mono-chromators of different kinds (bragg-reflectors, collimators) to select a narrow bandwidth line from a broad-band spectrum



ELI-NP-GBS γ -beam collimator (2-19 MeV)

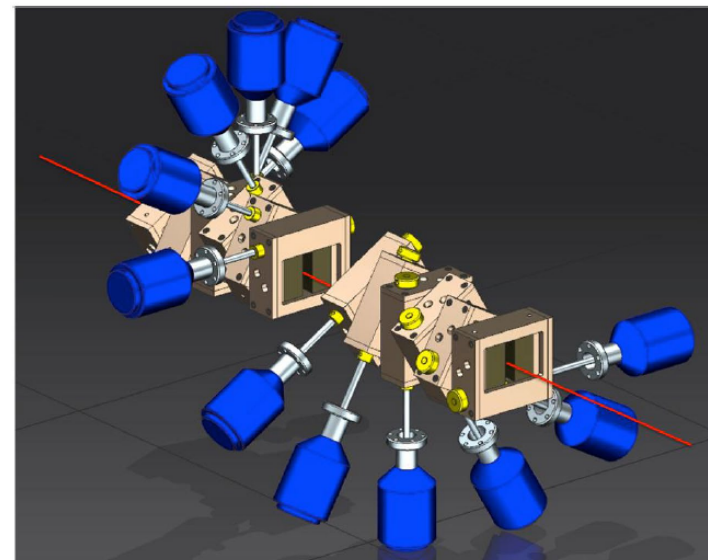
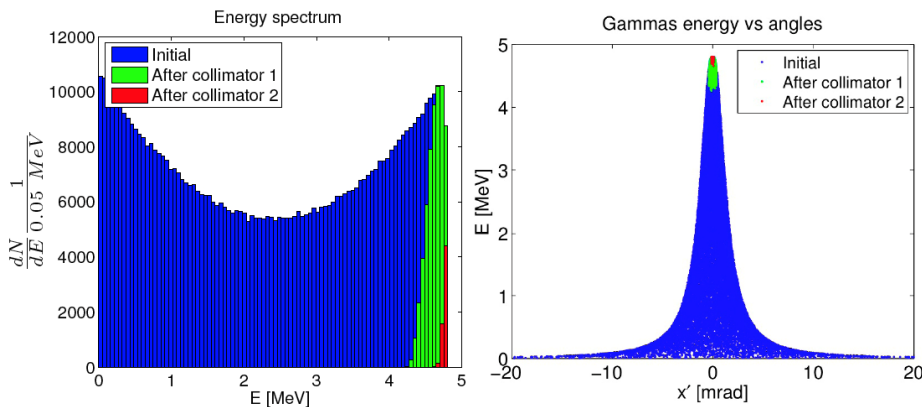
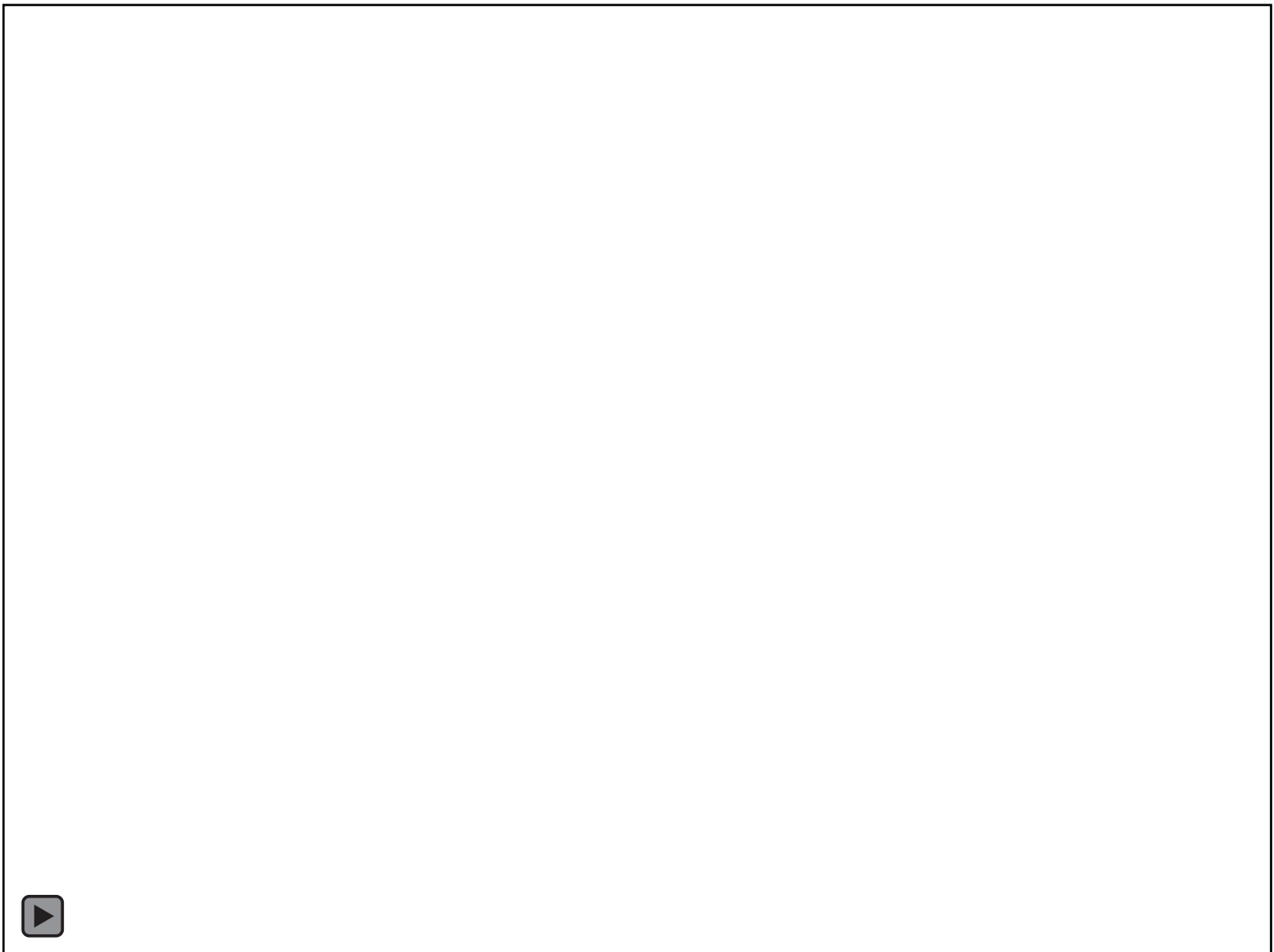


Fig. 184. Drawing of the configuration of low energy collimator made up of 12 tungsten adjustable slits with a relative 30° rotation each



*Mission of African Light Source initiative and
Compact Light Source based on STAR model*

Converting X-ray beams to tunable monochromatic γ -rays using Symmetric Compton Scattering and FICS with spectral purification

- Electron-photon interaction in linear QED (in vacuum) is characterized by 2 dimensionless parameters:

$$\text{Recoil } X = 4\gamma^2 h\nu/E_e \quad \text{and} \quad \text{Asymmetry } A = \beta\gamma^2 - X/4 = \gamma^2 (\beta - h\nu/E_e)$$

- When Recoil is large ($X \gg 1$) we have “cooling of photons”, *i.e.* monochromaticity of incident electron beam is mapped into the scattered photon beam
- When the scattering is symmetric ($A=0$, the divide between Inverse and Direct Compton Scattering) the energy-angular correlation (so-called $\gamma^2\theta^2$ disease) vanishes and, at low recoil, the electron beam is heated by the photon beam
- SCS or Quasi-Symmetric Compton Scattering (QSCS) will allow to extend the photon energy range (10-40 MeV)

All I.C.S. X/ γ ray Sources work at $X < 1$ and $A \gg 1$

STAR (350 keV) $X_{STAR} < 2.6 \cdot 10^{-3}$ $A_{STAR} > 10^4$

ELI-NP (20 MeV) $X_{ELI-NP} < 0.026$ $A_{ELI-NP} > 2.4 \cdot 10^5$

will allow to
g low energy e⁻

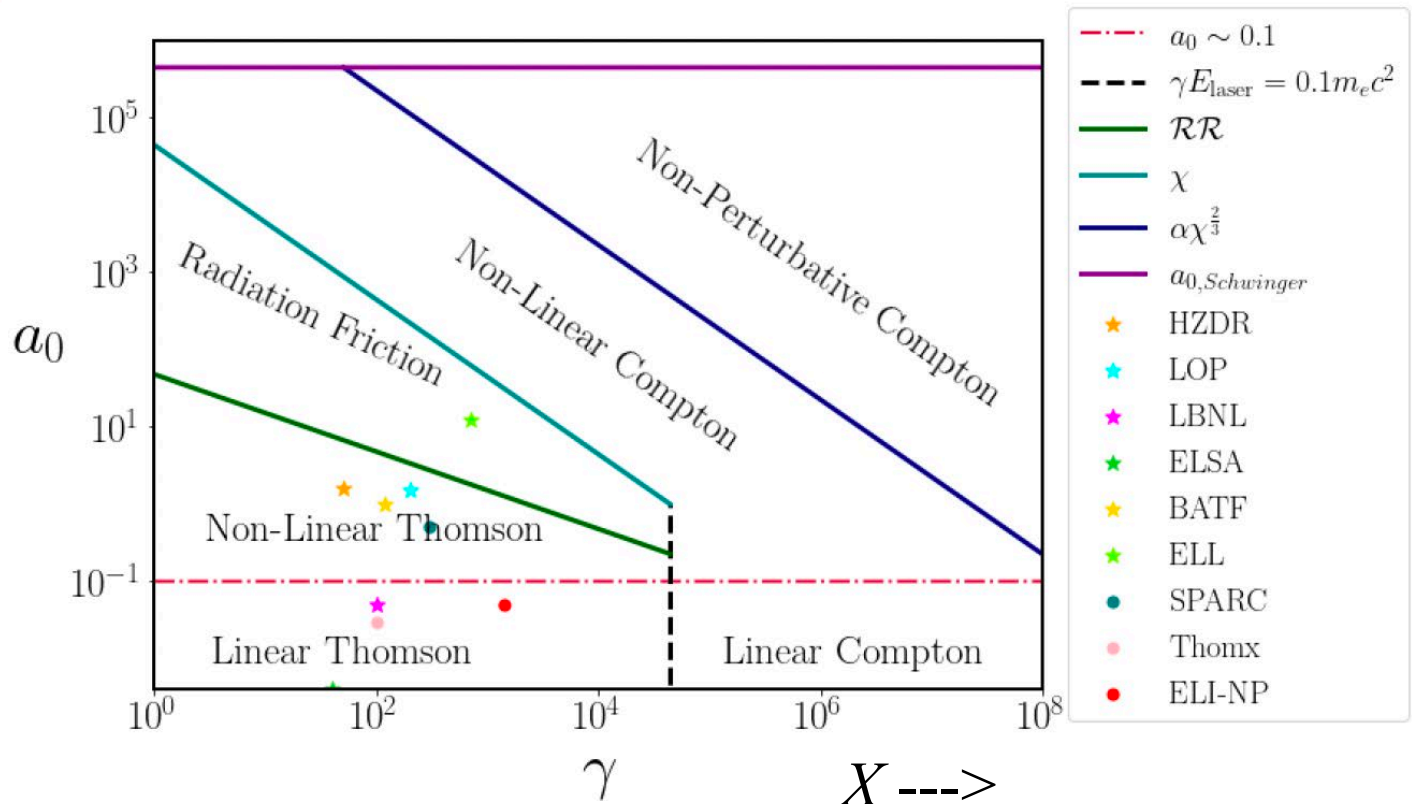
We are not considering in this seminar non-linear effects due to photon (laser) pulse intensity

$$a_{0,\text{linear}} = \frac{q}{mc^2} \sqrt{\frac{c}{4\pi}} \frac{\lambda}{2\pi} \sqrt{2I_{\text{peak}}}$$

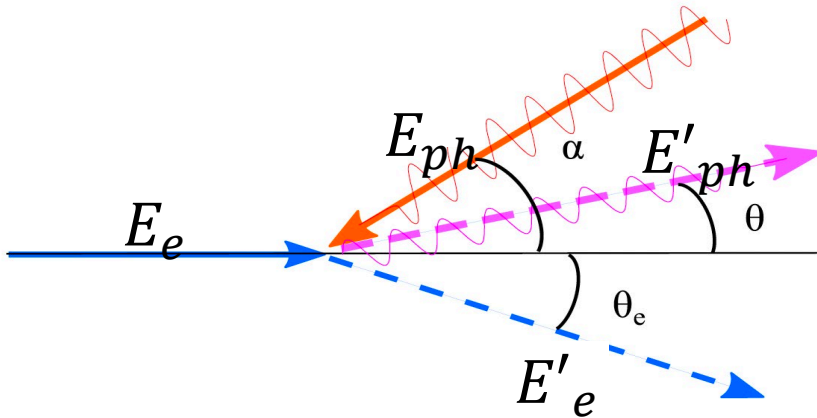
$$= 0.85 \lambda [\mu\text{m}] \sqrt{\frac{I_{\text{peak}} [\frac{\text{W}}{\text{cm}^2}]}{10^{18}}}$$

$$a_{0,\text{circular}} = \frac{q}{mc^2} \sqrt{\frac{c}{4\pi}} \frac{\lambda}{2\pi} \sqrt{I_{\text{peak}}}$$

Courtesy Marcel Ruijter

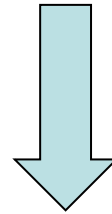


$$E'_{ph} = \frac{\gamma^2(1 + \beta)}{\gamma^2(1 - \beta \cos \theta) + \frac{X}{4}(1 + \cos \theta)} E_{ph}$$



$$X \equiv 4\gamma^2 E_{ph}/E_e$$

$$A \equiv \beta\gamma^2 - X/4 = \gamma^2(\beta - E_{ph}/E_e)$$



$$E'_{ph} = \frac{4(\gamma^2 + A) + X}{4(\gamma^2 - A \cos \theta) + X} E_{ph}$$

$A=0$, *i.e.* Symmetric Compton Scattering cancels the $\gamma^2\theta^2$ correlation

An invariant view at Compton effect - 1

(any inertial ref. frame)

Simulation of inverse Compton scattering and its implications on the scattered linewidth **Phys. Rev. AB (2018) 21, 030701**

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²Department of Physics, Center for Accelerator Science, Old Dominion University, Norfolk, Virginia 23529, USA

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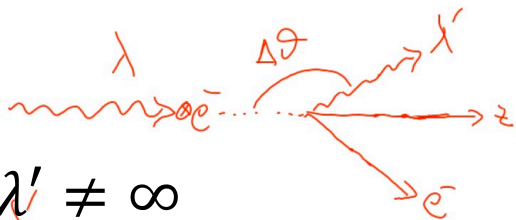
⁵Universita degli Studi di Milano, via Celoria 16, 20133 Milano, Italy

$$X = \frac{4\gamma\hbar\omega}{mc^2}$$

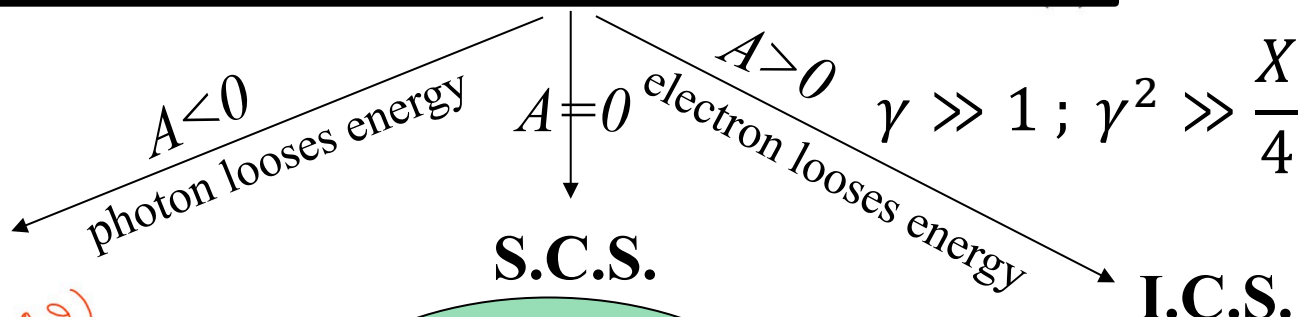
$$\omega'(\theta) = \frac{\omega(1+\beta)^2\gamma^2}{\gamma^2(1-\beta\cos\theta)(1+\beta) + \frac{X}{4}(1+\cos\theta)(1+\beta)} \quad (3)$$

Arthur Compton,
Nobel Prize 1927
 $\beta = 0$

$$\lambda' - \lambda = \lambda_c (1 + \cos\Delta\vartheta)$$



isolated e^- cannot absorb a photon



$$\beta\gamma^2 = \frac{X}{4}$$

$$E'_{ph} = \beta E_e = \beta\gamma mc^2$$

$$E'_{ph} \neq f(\gamma^2\vartheta^2)$$

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + X + \gamma^2\vartheta^2}$$

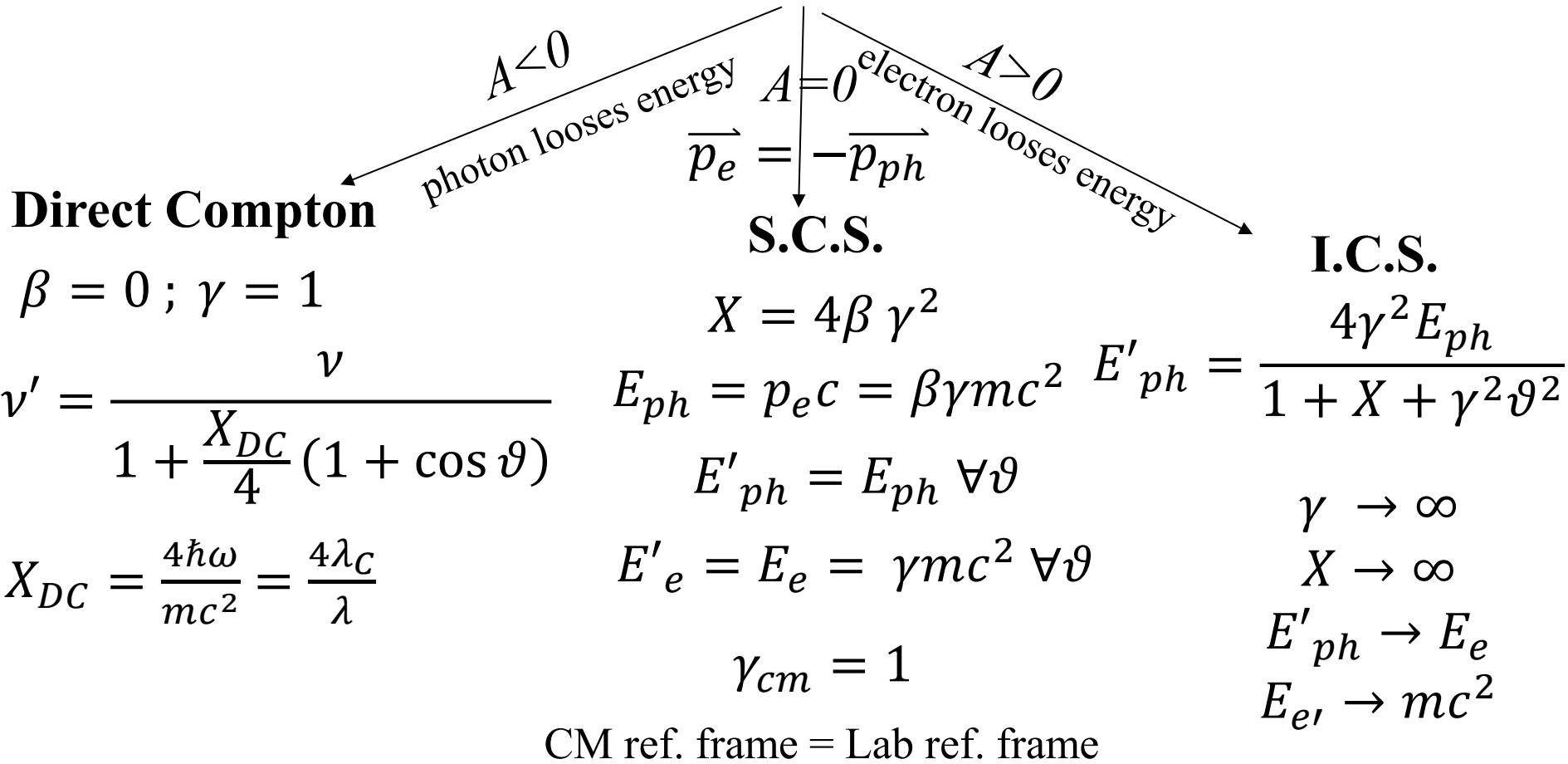
$$\lim_{X \rightarrow \infty} E'_{ph} = E_e$$

An invariant view at Compton effect - 2

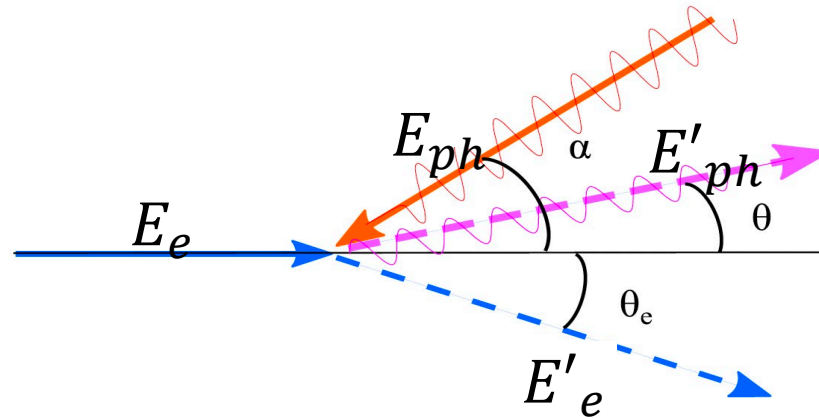
(any inertial ref. frame)

$$X = \frac{4\gamma\hbar\omega}{mc^2}$$

$$\omega'(\theta) = \frac{\omega(1 + \beta)^2\gamma^2}{\gamma^2(1 - \beta \cos \theta)(1 + \beta) + \frac{X}{4}(1 + \cos \theta)(1 + \beta)} \quad (3)$$

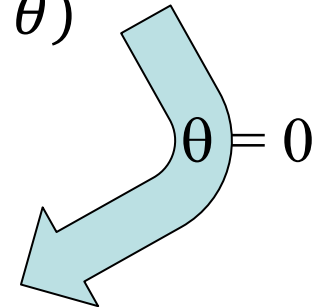


Let's consider the condition of maximum energy/momentum transfer between electron and photon, *i.e.* $\theta = 0$



$$E'_{ph} = \frac{\gamma^2(1 + \beta)}{\gamma^2(1 - \beta \cos \theta) + \frac{X}{4}(1 + \cos \theta)} E_{ph}$$

$$E'_{ph} = \frac{2\gamma^2}{\gamma^2(1 - \beta) + \frac{X}{2}} E_{ph}$$



$\theta = 0$ corresponds to:
 maximum energy of back-scattered photon E'_{ph-max}
 and
 minimum energy of electron after scattering E'_{e-min}

$$E'_{ph-max} = \frac{4\gamma^2 E_{ph}}{1 + X}$$

Thomson limit: $X \ll 1$

Deep recoil Compton: $X \gg 1$

$$E'_{ph-max} = 4\gamma^2 E_{ph}$$

$$E'_{ph-max} \sim \left(1 - \frac{1}{X}\right) E_e$$

$$E_{TOT} = E_e + E_{ph} = E'_{e-min} + E'_{ph-max}$$

$$E'_{e-min} = E_e + E_{ph} - E'_{ph-max} = E_e + E_{ph} - \frac{4\gamma^2 E_{ph}}{1 + X}$$

All quantities normalized to
the total energy $E_{tot} = E_e + E_{ph}$

$$E_e = 100 \text{ MeV}$$

$$\frac{E'_{ph}}{E_{tot}} = \frac{X}{(1 + X)\left(1 + \frac{X}{4\gamma^2}\right)}$$

$$\frac{E'_e}{E_{tot}} = 1 - \frac{X}{(1 + X)\left(1 + \frac{X}{4\gamma^2}\right)}$$

Energy Budget towards γ -rays with high spectral density

- **25 GeV** electrons would be needed to generate 2 MeV photons via ***synchrotron radiation*** (highest spectral density $S \ 10^{12} \text{ s}^{-1}\text{eV}^{-1}$, very small bdw 10^{-4})
- **850 MeV** electrons were used to ***Channeling Radiate*** 2 MeV γ -rays (high $S \ 10^5\text{-}10^6 \text{ s}^{-1}\text{eV}^{-1}$, broad bdw 10 %)
- **350 MeV** e⁻s are needed to ***Inverse Compton Scatter*** 2 MeV γ -rays (good $S \ 10^4\text{-}10^5 \text{ s}^{-1}\text{eV}^{-1}$, small bdw 10^{-3})
- **3.5 MeV** electrons to ***bremsstrahlung*** 2 MeV γ -rays (poor $S \ 1 \text{ s}^{-1}\text{eV}^{-1}$, very broad bandwidth)
- **2 MeV** e⁻s to ***Symmetric Compton Scatter*** a photon target 2 MeV γ -ray photons ($S \ 10^4 \text{ s}^{-1}\text{eV}^{-1}$) **spectral purification!**

when recoil X is large electron swaps with photon,
maximum energy loss by the electron in favour to the photon

$$E'_{ph-max} = \frac{4E_{ph}E_e^2 / (mc^2)^2}{1 + 4E_{ph}E_e / (mc^2)^2}$$

if $\gamma \gg 1$ $E'_{e-min} \approx E_e \frac{1 + (1 + X) E_{ph}/E_e}{1 + X}$

$X \ll 1$ $E'_{e-min} \approx E_e$

$X \gg 1$ $E'_{e-min} \approx E_{ph}$

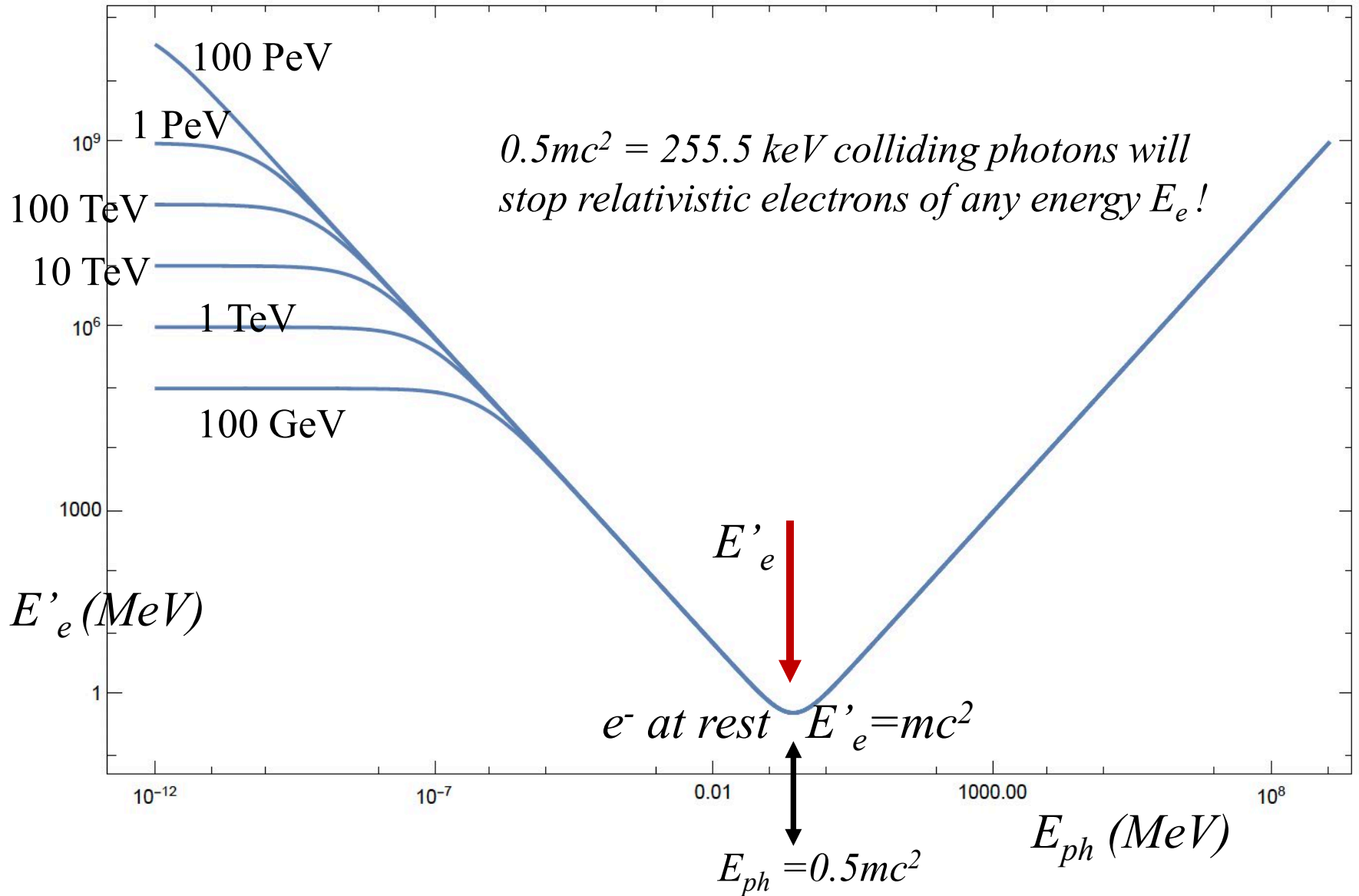
$$E_{ph} = \frac{mc^2}{2} \left(1 - \frac{1}{2\gamma} \right)$$

$$E'_{ph} = mc^2 \left(\gamma - \frac{1}{2} - \frac{1}{4\gamma} \right)$$

$$E_e = \gamma mc^2$$

$$E'_e = mc^2$$

$mc^2/2$ photons can stop any relativistic electron !
The fractional energy loss of FICS is 100%



*hadronic threshold ($E_{cm} < 600 \text{ MeV}$) with 255.5 keV photons $\approx 360 \text{ GeV}$

The interaction of relativistic particles with strong crystalline fields

Ulrik I. Uggerhøj

Department of Physics and Astronomy, University of Aarhus, Denmark

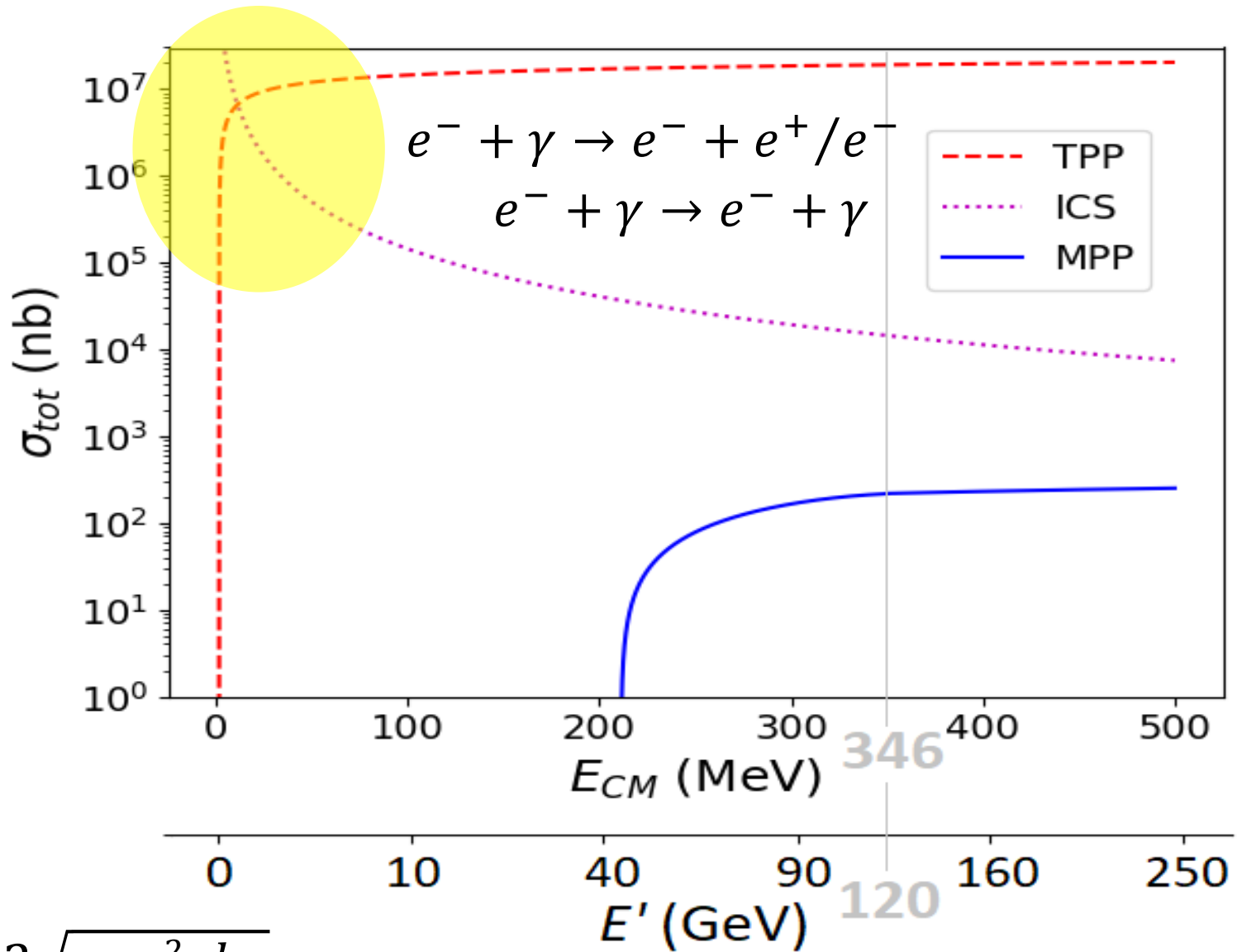
(Published 20 October 2005)

E. Unruh effect and Hawking radiation

The equivalence between the temperature of the Hawking radiation from a black hole and the temperature of the vacuum in a constantly accelerated frame (Davies, 1975; Unruh, 1976) has been widely discussed—the so-called Unruh effect. As channeled particles are subject to enormous fields and accelerations, outlines for possible detection schemes using strong crystalline fields have been proposed (Darbinian *et al.*, 1989; MacDonald, 1998). Darbinian *et al.* (1989) estimated that a planar-channeled positron with $\gamma \gtrsim 10^8$ will emit Unruh radiation as intense as the incoherent bremsstrahlung. These estimates, however, do not take into account the subtleties connected to the inherently nonconstant acceleration for a channeled particle.

50 TeV electrons !!!!

Total cross-section for QED (e, γ) reactions

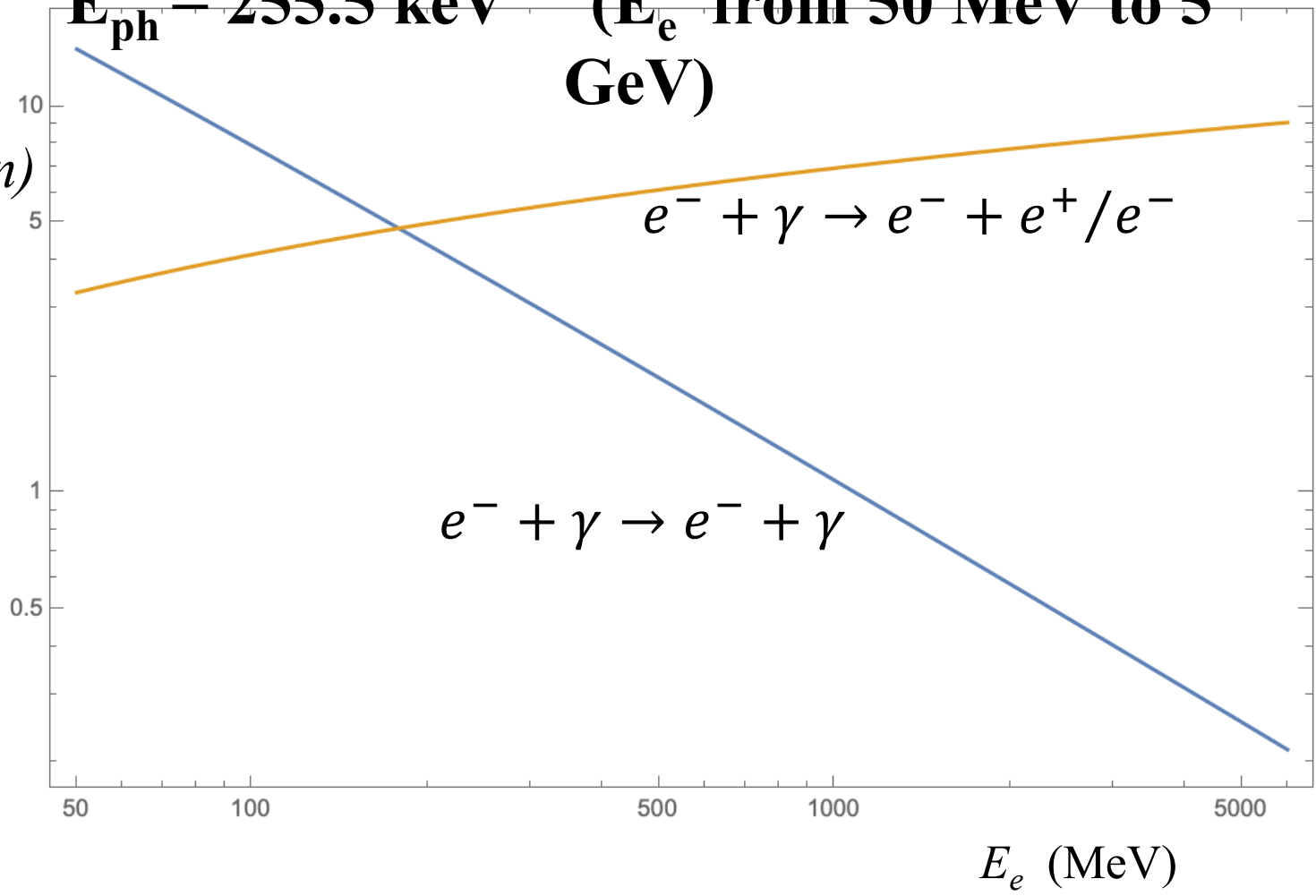


$$E_{CM} = 2\sqrt{m_e c^2 \gamma h\nu}$$

Total cross-sections for Compton and Bethe-Heitler

$E_{\text{ph}} = 255.5 \text{ keV}$ (E_e from 50 MeV to 5 GeV)

Σ_{tot} (mbarn)



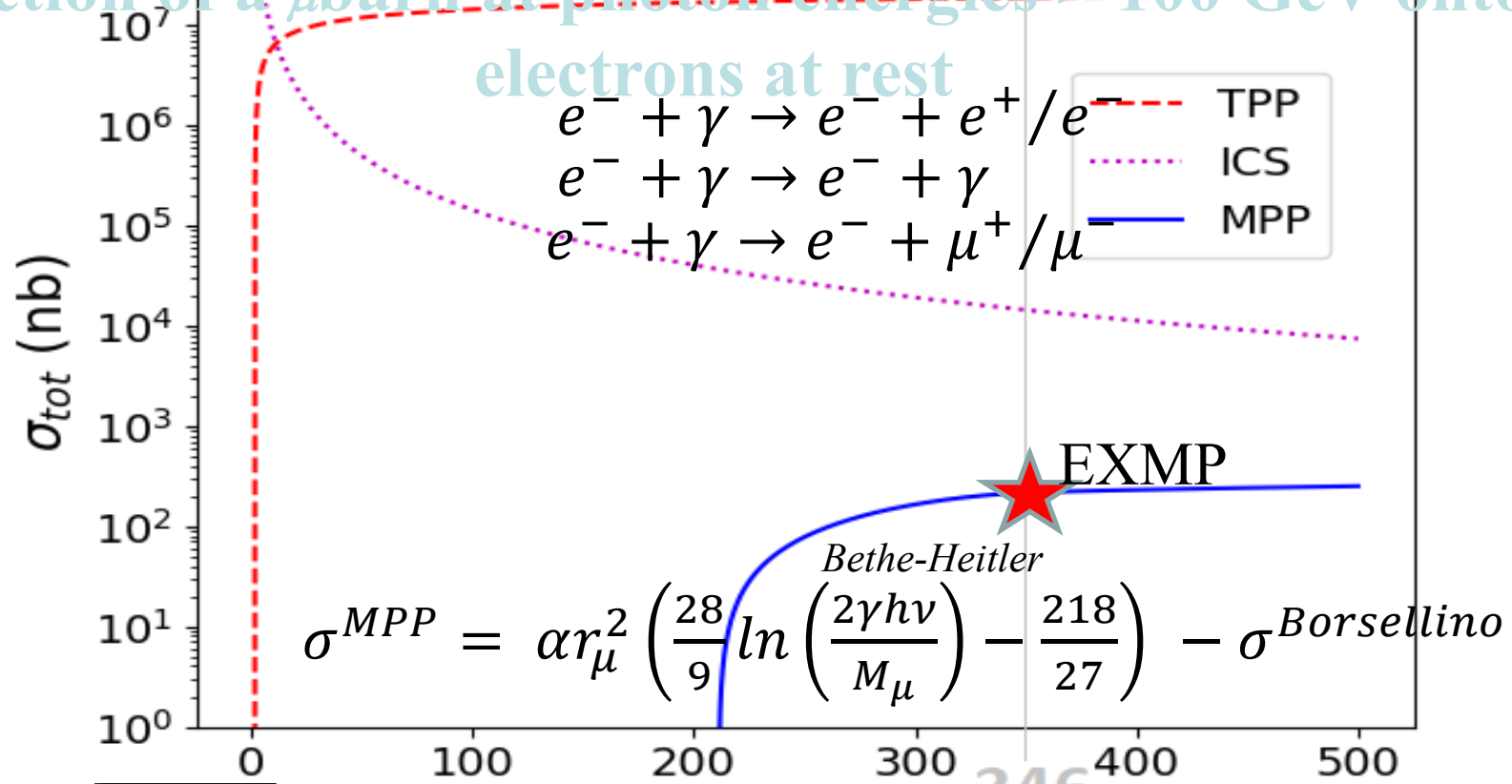
$e^- + \gamma \rightarrow e^- + e^+ / e^-$

$e^- + \gamma \rightarrow e^- + \gamma$

E_e (MeV)

INFN Total cross-section for MPP (muon pair production),
Bethe-Heitler:

fraction of a μ barn at photon energies > 100 GeV onto electrons at rest



$$\sigma^{MPP} = \alpha r_{\mu}^2 \left(\frac{28}{9} \ln \left(\frac{2\gamma h\nu}{M_{\mu}} \right) - \frac{218}{27} \right) - \sigma^{Borsellino}$$

$$E_{CM} = 2\sqrt{M_e \gamma h\nu}$$

$$E' = 2\gamma h\nu = \frac{E_{CM}^2}{2M_e}$$

EXMP

Bethe-Heitler

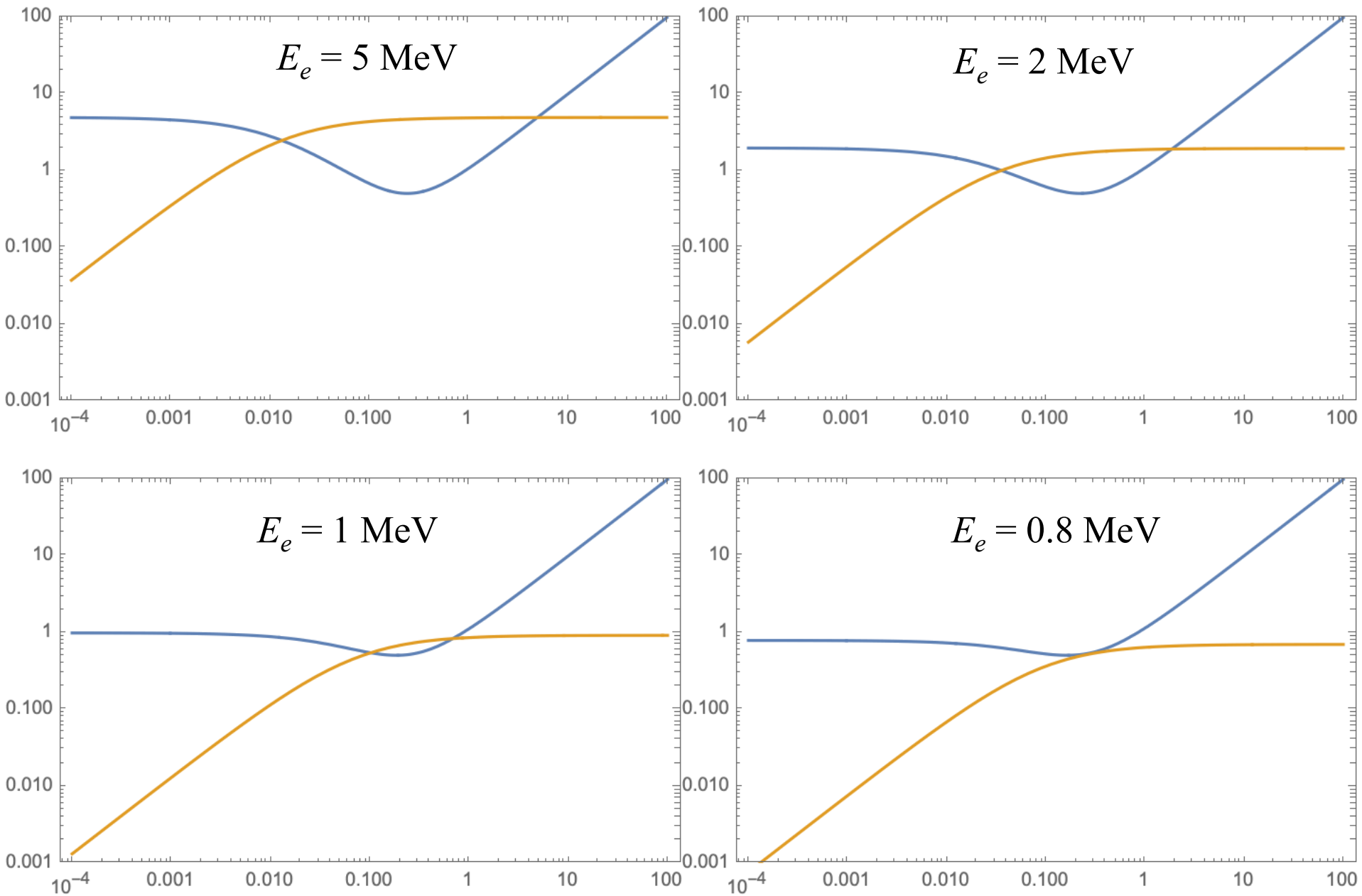
346

120

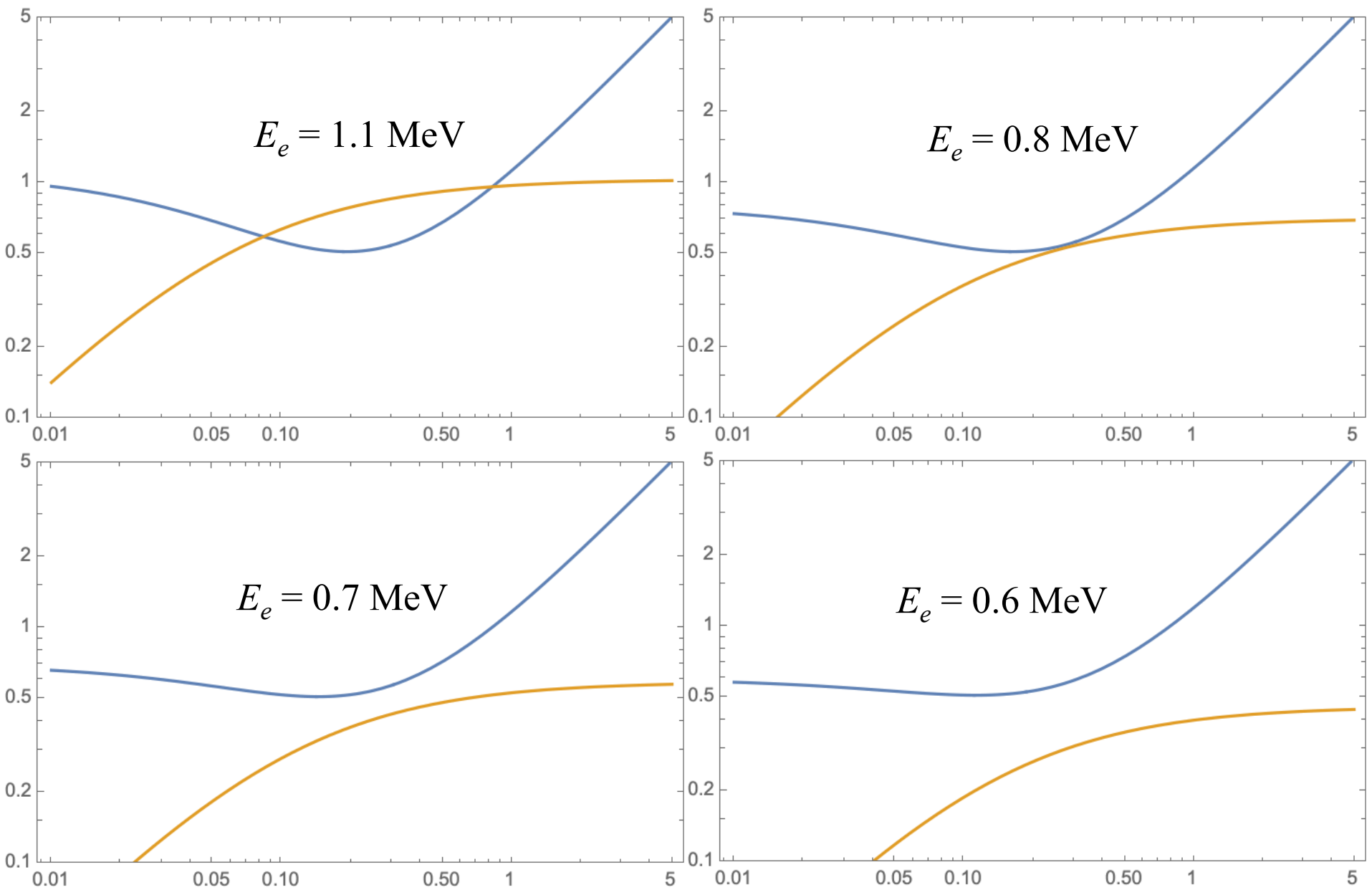
E_{CM} (MeV)

E' (GeV)

FICS low relativistic



FICS very low relativistic



Inverse Compton Sources rivaling/overcoming

Synchrotron Light Sources at photon energies above 80-100 keV

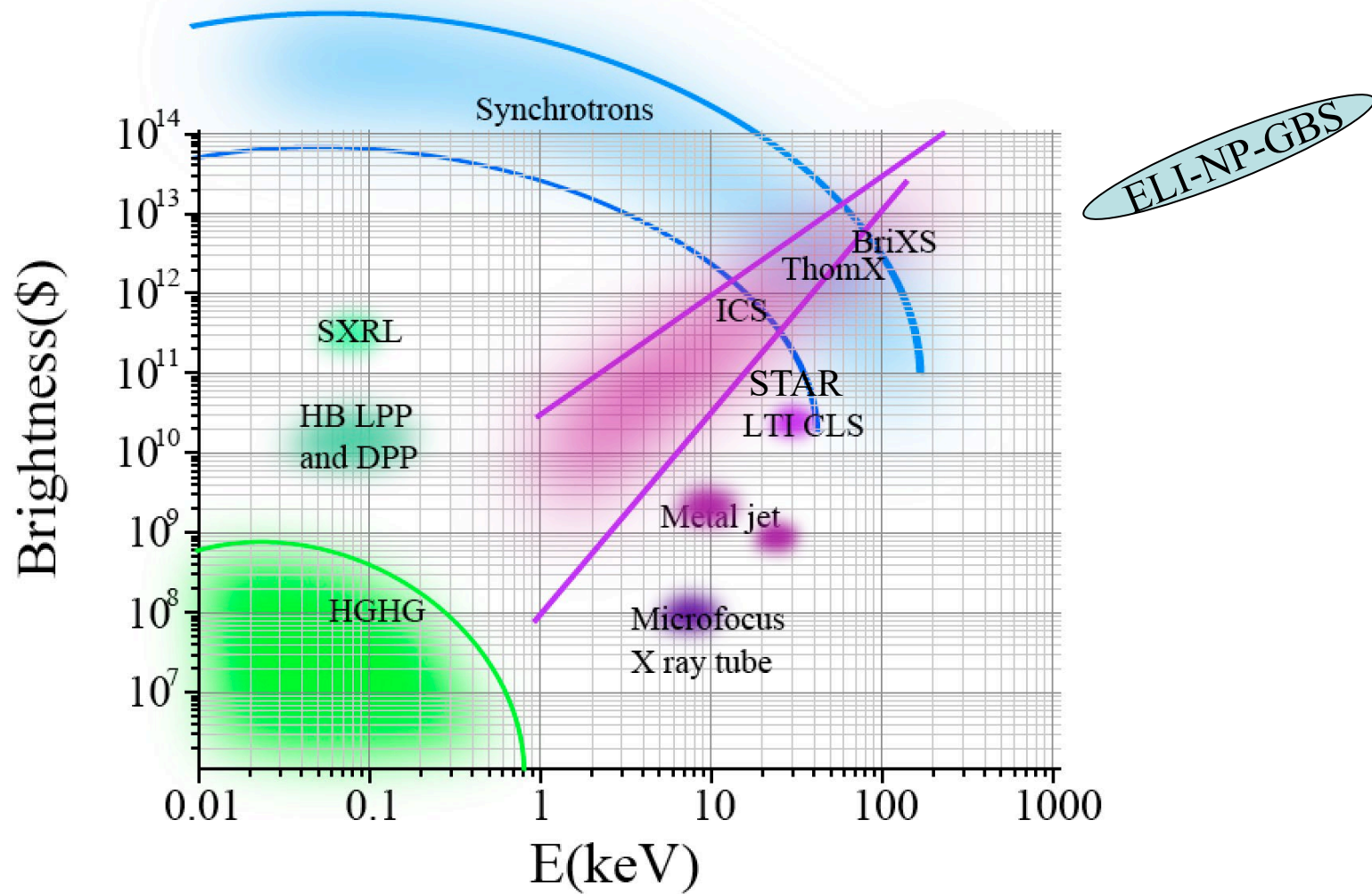


Figure 1: Brightness of several radiation sources as a function of the photon energy. \$: Photon $number/s/mm^2/mrad^2/(0.1\%$. I.C.S. Sources (LTI-CLS, ThomX, STAR, UH-FLUX and BriXS) are compared to Synchrotron Light Sources and the most performing X-ray tube so far (Metal Jet).

3rd-4th Generation Light Sources

- Synchrotron light sources: < 50 keV, > 50 ps (100 m, 300 M\$)
- X-ray FEL (LCLS): energy ≤ 25 (50?) keV, 1-100 fs (1 km, 1 G\$)



- **New approach: inverse Compton scattering (ICS) 20-200 keV , sub-ps, (10 m , 10 M\$) – sometimes called Laser Synchrotron since a laser pulse substitutes the magnetic undulators**

Brilliance of Lasers and X-ray sources

$$N_{ph} = 10^{19} - 10^{20}$$

ELI

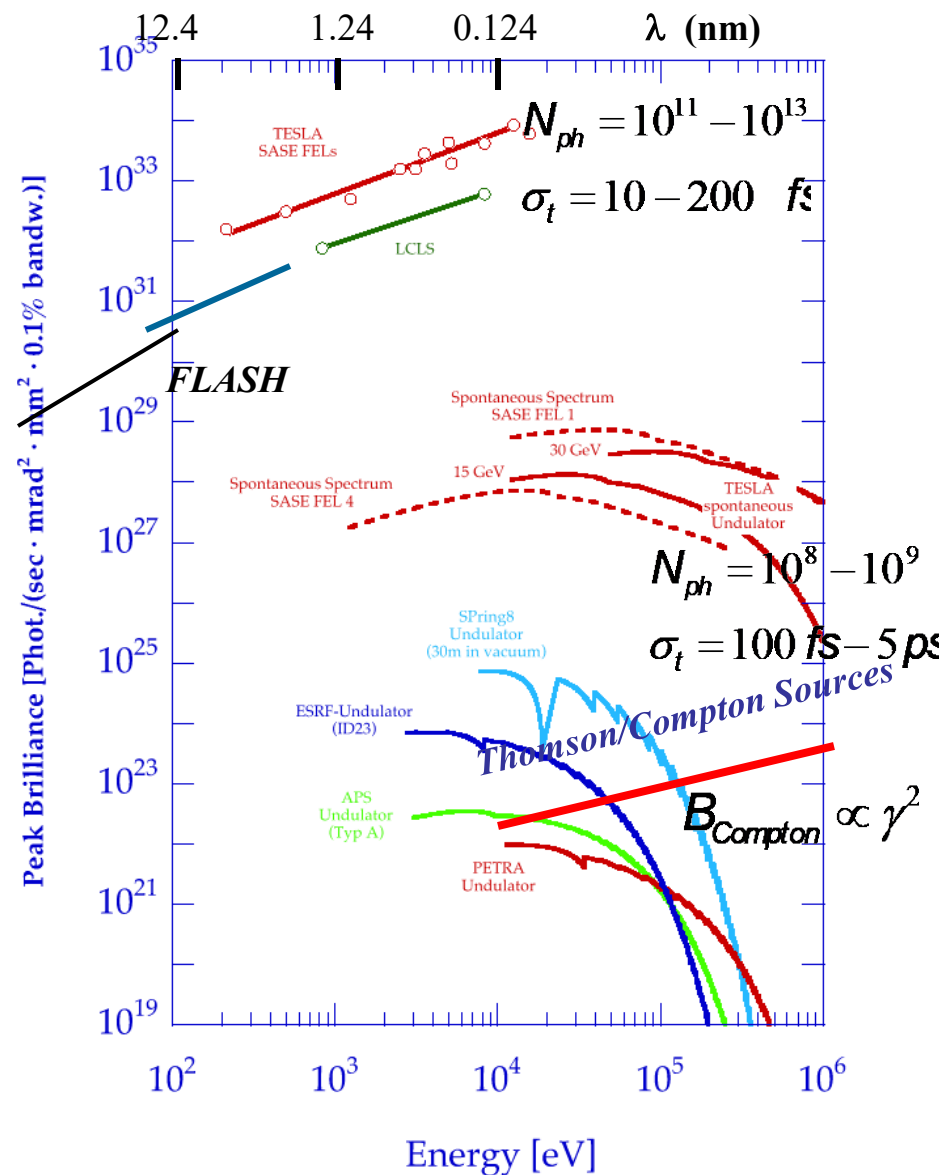
$$\sigma_t = 10 - 20 \text{ fs}$$

BELLA

$$B = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t (M^2\lambda)^2 \frac{\Delta\lambda}{\lambda}}$$

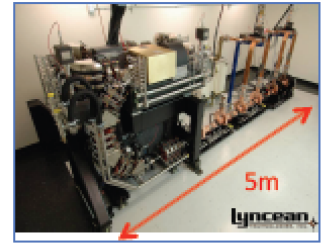
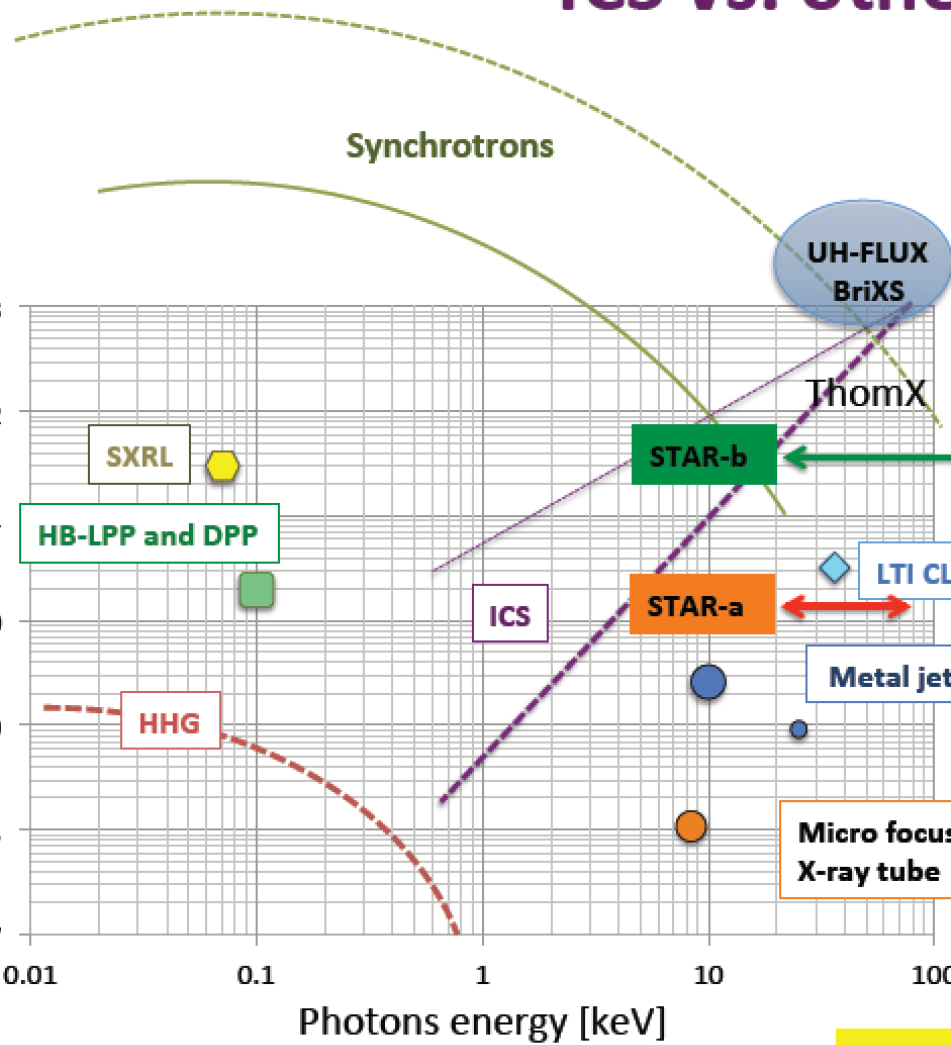
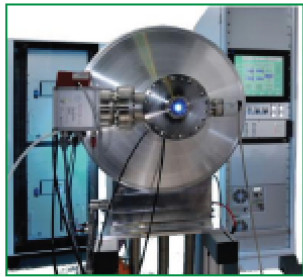
$$B_{peak} = \frac{N_{ph}}{\sqrt{2\pi}\sigma_t \varepsilon_x^2 \frac{\Delta E_X}{E_X}}$$

$$B_{av} = \frac{N_{ph} f}{\varepsilon_x^2 \frac{\Delta E_X}{E_X}}$$



Rivaling with Synchr. Light Sources for energies above 50 keV

ICS vs. other sources



Brightness [ph/s-mm²-mrad²-0.1% BW]

Photons energy [keV]

$$B_{av} = \frac{N_{ph} f}{\epsilon_x^2 \frac{\Delta E_X}{E_X}}$$

High Brightness Beams, Havana, Cuba

Courtesy of A. Murokh
RadiaBeamTechnology

Large Recoil in ICS damps the effect of large bandwidth incident photon beams onto the bandwidth of scattered photons

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20**, 080701 (2017)

Analytical description of photon beam phase spaces in inverse Compton scattering sources

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(Received 9 March 2017; published 3 August 2017)

equivalent to FELs Kim-Pellegrini crit. on 3D inhomogeneous effects on photon bandwidth

$$\frac{\Delta E_{\text{ph}}}{E_{\text{ph}}} \simeq \sqrt{\left[\frac{\Psi^2/\sqrt{12}}{1+\Psi^2} + \frac{\bar{P}^2}{1+\sqrt{12}\bar{P}^2} \right]^2 + \left[\left(\frac{2+X}{1+X} \right) \frac{\Delta\gamma}{\gamma} \right]^2 + \left(\frac{1}{1+X} \frac{\Delta E_L}{E_L} \right)^2 + \left(\frac{M^2\lambda_0}{2\pi w_0} \right)^4 + \left(\frac{a_0^2/3}{1+a_0^2/2} \right)^2}$$

collimation
angle

beam
emittance

beam
en. spread

incident
photons
en. spread

diffraction

non
linearity

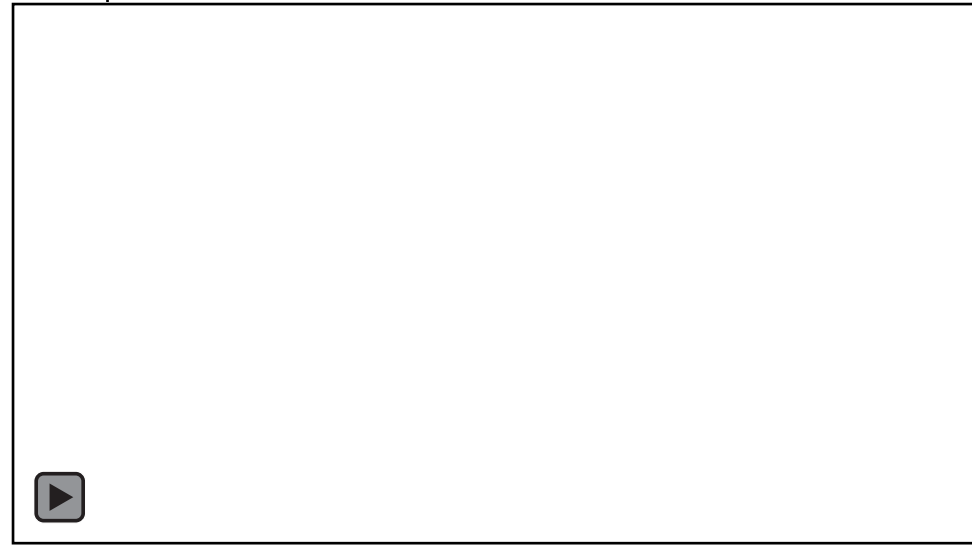
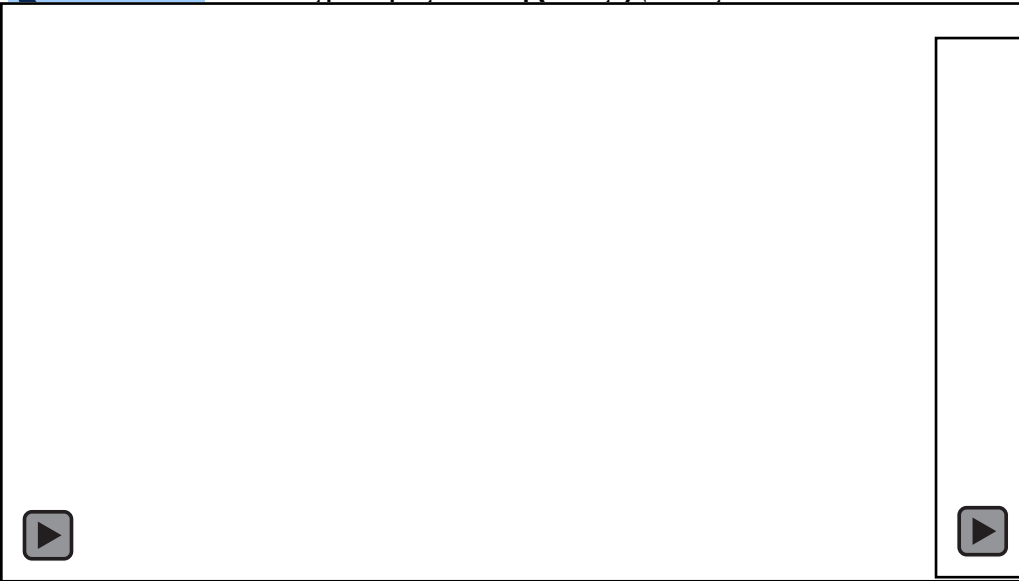
**where is the Continental Divide
between
Compton Scattering
and
Inverse Compton Scattering?**

**when the electron becomes
a projectile (as in ICS)
instead of
a target (as in Compton)?**

*Does it depend only on electron energy?
No, it depends only on asymmetry in colliding momenta*

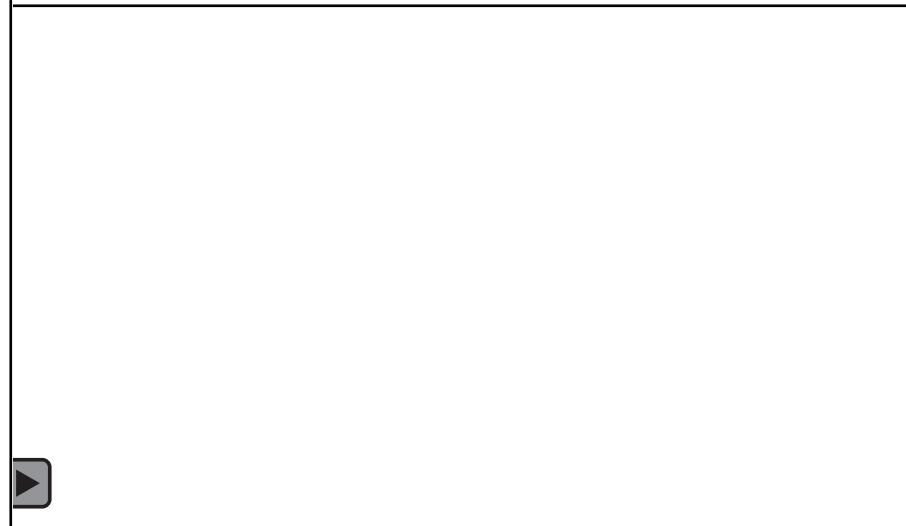
CM rest frame moves with

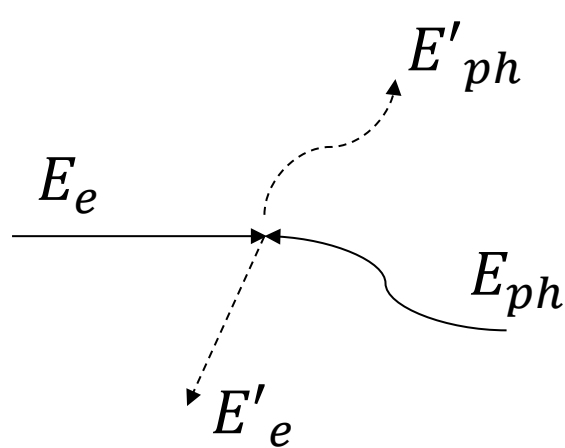
CM rest frame moves with the electron in
Inverse Compton, FEL, Synchrotron light



CM rest fr. slows down in Inv. Compton with deep recoil

CM rest frame is steady in Symmetric Compton





$$X \equiv 4\gamma^2 E_{ph}/E_e$$

$$A \equiv \beta\gamma^2 - X/4 = \gamma^2(\beta - E_{ph}/E_e)$$

$$E'_{ph} = \frac{4(\gamma^2 + A) + X}{4(\gamma^2 - A \cos \theta) + X} E_{ph}$$

I.C.S. low recoil $X \ll 1$

$$A \sim \beta\gamma^2 \sim \gamma^2 - 1/2$$

$$E'_{ph-max} \sim 4\gamma^2 E_{ph}$$

I.C.S. deep recoil $X \gg 1$

$$A \sim \beta\gamma^2 - X/4 \sim \gamma^2 - 1/2 - X/4$$

$$E'_{ph-max} \sim \frac{4\gamma^2}{1 + X} E_{ph} \sim \left(1 - \frac{1}{X}\right) E_e$$

**S.C.S. ($A = 0$) or
quasi-SCS ($|A| \ll 1$)**

$$\left[\begin{array}{l} E'_{ph-max} \sim E_{ph} \left(1 + \frac{2A}{(1 + \beta)\gamma^2}\right) \\ E'_{e-min} \sim E_e - E_{ph} \frac{2A}{(1 + \beta)\gamma^2} \end{array} \right.$$

D.C. $\gamma = 1, \beta = 0, A = -X/4$

$$E'_{ph-min} = \frac{1}{1 + X/2} E_{ph} = \frac{1}{1 - 2A} E_{ph}$$

Direct Compton $\gamma=1, \beta=0, X = 4E_{ph}/mc^2$

$$E'_{ph-min} = \frac{E_{ph}}{1 + 2E_{ph}/mc^2} \quad \text{if } E_{ph} \gg mc^2 \quad E'_{ph-min} = \frac{mc^2}{2}$$

Very energetic photons are scattered back at 255 keV
and electrons pushed to $E_{ph} + 0.5mc^2$

$$E'_{e-max} = mc^2 + E_{ph} - E'_{ph-min}, \text{ if } E_{ph} \gg mc^2 \quad E'_{e-max} = E_{ph} + \frac{mc^2}{2}$$

General Formula expressed in terms of energies of primary colliding particles, valid for any γ, A, X, θ

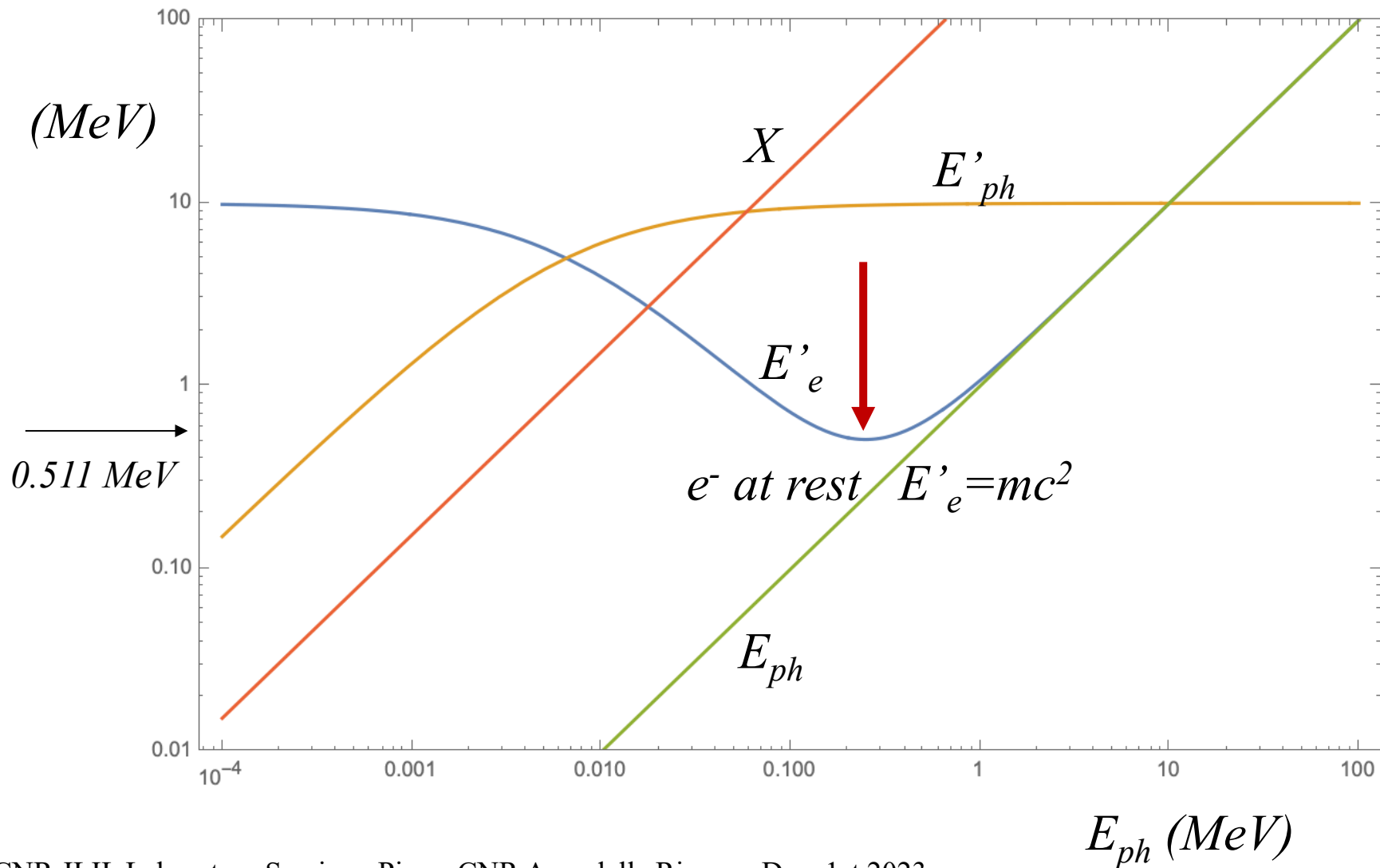
$$E'_{ph} = \frac{(1 + \beta) E_{ph} E_e}{(1 - \beta \cos \theta) E_e + (1 + \cos \theta) E_{ph}}$$

$$E'_{ph-max} = \frac{(1 + \beta) E_{ph} E_e}{(1 - \beta) E_e + 2E_{ph}}$$

$$X = 4 E_e E_{ph} / (mc^2)^2$$

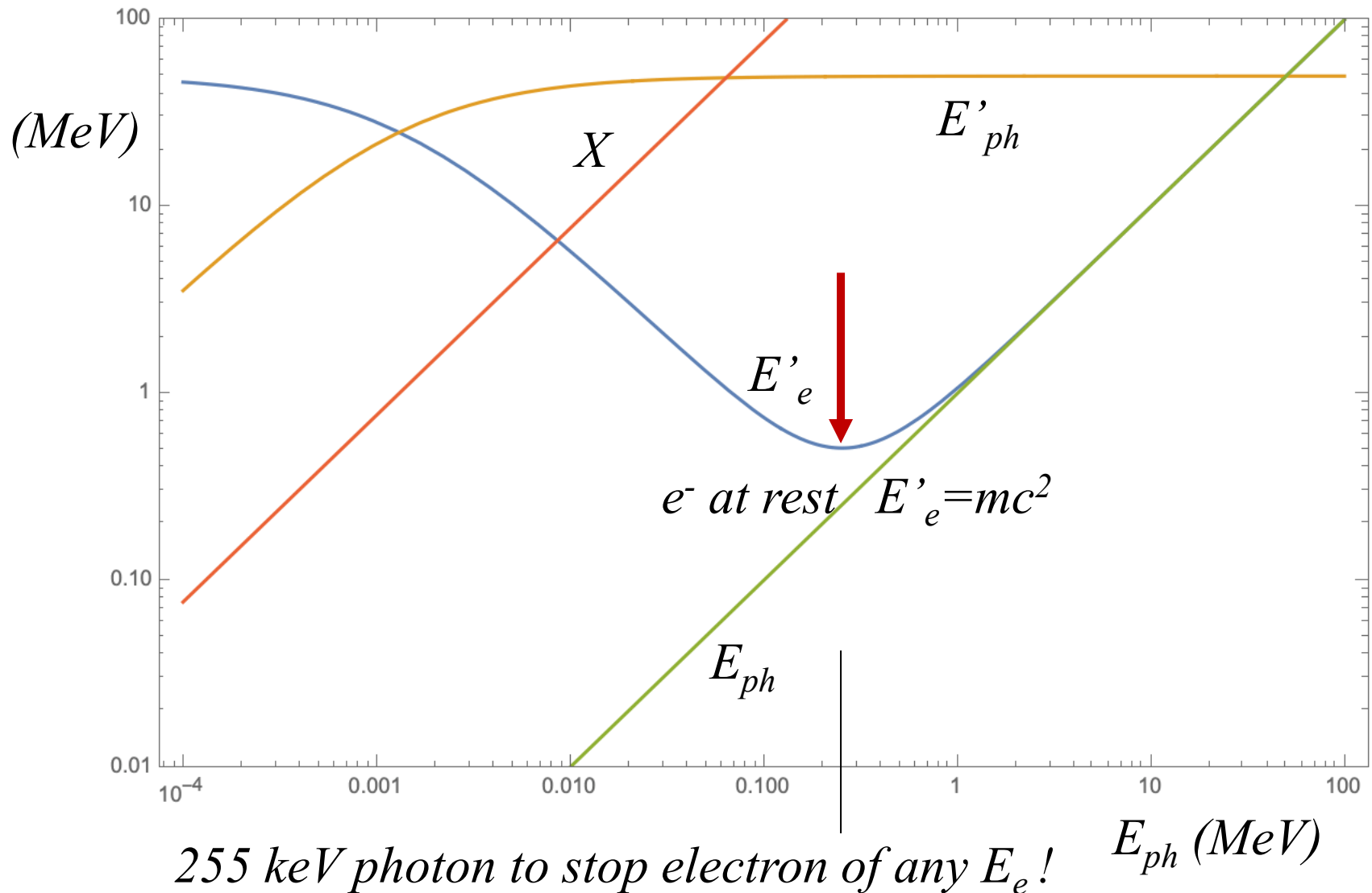
$$E'_{ph-max} = \frac{(1 + \beta) E_{ph} E_e}{(1 - \beta) E_e + 2 E_{ph}}$$

$E_e = 10 \text{ MeV}$



$$E'_{ph-max} = \frac{(1 + \beta)E_{ph}E_e}{(1 - \beta)E_e + 2E_{ph}}$$

$$E_e = 50 \text{ MeV}$$



$$E'_{ph-max} = \frac{(1 + \beta)E_{ph}E_e}{(1 - \beta)E_e + 2E_{ph}}$$

$$E'_{e-min} = E_e + E_{ph} - E'_{ph-max} = E_e + E_{ph} - \frac{(1 + \beta)E_{ph}E_e}{(1 - \beta)E_e + 2E_{ph}}$$

$$E'_{ph-max} = \frac{4E_{ph}E_e^2 / (mc^2)^2}{1 + 4E_{ph}E_e / (mc^2)^2}$$

if $\gamma \gg 1$ $E'_{e-min} \approx E_e \frac{1 + (1 + X) E_{ph}/E_e}{1 + X}$

$X \ll 1$ $E'_{e-min} \approx E_e$

$X \gg 1$ $E'_{e-min} \approx E_{ph}$

$$\text{if } E_{ph} = \frac{mc^2}{2} - (1 - \beta)E_e \implies E'_{e-min} = mc^2$$

255 keV photon to stop electron of any E_e !

$$\text{if } E_{ph} = \frac{mc^2}{2} - (1 - \beta)E_e \implies E'_{e-min} = mc^2$$

$$\text{if } \gamma \gg 1 \text{ and } E_{ph} = \frac{mc^2}{2} \left[1 - \frac{1}{\gamma} \right] \implies E'_{e-min} = mc^2$$

If the incident photon energy is given by $E_{ph} = \frac{mc^2}{2} \left[1 - \frac{1}{\gamma} \right]$

any relativistic electron (i.e. $\gamma \gg 1$) will be stopped
in a head-on collision with such a photon

255 keV photons will stop electrons of any E_e as far as $\gamma \gg 1$

$$E_{ph} = \frac{mc^2}{2} \left[1 - \frac{1}{2\gamma} \right] \quad \text{to stop any (relativistic) electron}$$

Incidentally, the condition is almost the same needed to make the total energy in the lab ref. frame (LAB) equal to the total energy in the electron rest frame (ERF)

$$\begin{aligned} \text{LAB total energy } E_{\text{LAB}} &= \gamma mc^2 + E_{ph} \\ \text{ERF total energy } E_{\text{ERF}} &= mc^2 + 2\gamma E_{ph} \end{aligned}$$

$$E_{\text{LAB}} = E_{\text{ERF}}$$

if

$$E_{ph} = \frac{mc^2}{2} \frac{2\gamma - 2}{2\gamma - 1} \quad \xrightarrow{\gamma \rightarrow \infty} \quad \frac{mc^2}{2}$$

Dual color x rays from Thomson or Compton sources

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Each electron, characterized by normalized velocity $\underline{\beta}_i$ forming an angle θ_i with the z axis, scatters photons with frequency ν_p given by

$$\nu_p = \nu_0 \frac{1 - \underline{e}_k \cdot \underline{\beta}_i}{1 - \underline{n} \cdot \underline{\beta}_i + \frac{h\nu_0}{mc^2\gamma_i} (1 - \underline{e}_k \cdot \underline{n})}, \quad (1)$$

where ν_0 is the frequency of the incident laser photon, \underline{e}_k the unit vector of its direction, \underline{n} is the direction of the scattered photon, h the Planck constant and γ_i the electron Lorentz factor before the scattering. The last term in the

$$E'_{ph} = \frac{4\gamma^2(1 - \beta \cos \alpha)}{4\gamma^2(1 - \beta \cos \theta) + X(1 - \cos \alpha \cos \theta + \sin \alpha \sin \theta)} E_{ph}$$

$$\alpha = \pi, \text{ head-on } \textcircled{R} \quad E'_{ph} = \frac{\gamma^2(1 + \beta)}{\gamma^2(1 - \beta \cos \theta) + \frac{X}{4}(1 + \cos \theta)} E_{ph}$$

in agreement with Eq.3 in *N. Ranjan et al., PRAB 21, 030701 (2018)*

$$E'_{ph} = \frac{4\gamma^2(1 - \beta \cos \alpha)}{4\gamma^2(1 - \beta \cos \theta) + X(1 - \cos \alpha \cos \theta + \sin \alpha \sin \theta)} E_{ph}$$

$$\text{if } \gamma \gg 1 \text{ and } \beta \approx 1 - \frac{1}{2\gamma^2} \text{ and } \theta \ll 1$$

$$E'_{ph} = \frac{4\gamma^2 \left(\frac{1 - \cos \alpha}{2} \right)}{1 + \gamma^2 \theta^2 + X \left(\frac{1 - \cos \alpha}{2} \right)} E_{ph}$$

$$\text{if } \theta = 0 \quad E'_{ph} = E'_{ph-max} \quad E'_{ph-max} = \frac{4\gamma^2 \left(\frac{1 - \cos \alpha}{2} \right)}{1 + X \left(\frac{1 - \cos \alpha}{2} \right)} E_{ph}$$

in agreement with Eq.1 in *I. Drebot et al., EPL 120, 14002 (2017)*

$$E'_{ph-max} = \frac{4\gamma^2 \left(\frac{1 - \cos \alpha}{2} \right)}{1 + X \left(\frac{1 - \cos \alpha}{2} \right)} E_{ph}$$

$$X \ll 1 \quad \textcircled{R} \quad E'_{ph-max} = 4\gamma^2 \left(\frac{1 - \cos \alpha}{2} \right) E_{ph}$$

$$\alpha = \pi, \text{ head-on} \quad \textcircled{R} \quad E'_{ph-max} = \frac{4\gamma^2}{1 + X} E_{ph}$$

$$\alpha = \pi/2, \quad X \ll 1 \quad \textcircled{R} \quad E'_{ph-max} = 2\gamma^2 E_{ph}$$

$$X \gg 1 \quad \textcircled{R} \quad E'_{ph-max} = \frac{4\gamma^2}{X} E_{ph} = E_e \quad \forall \alpha \quad !!$$

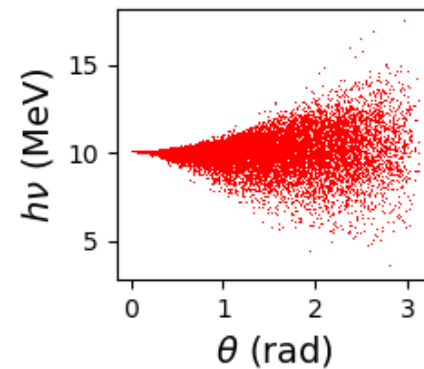
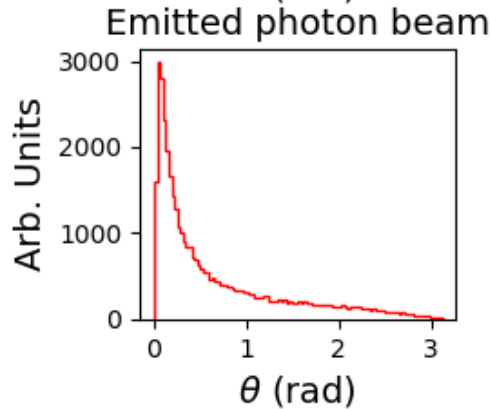
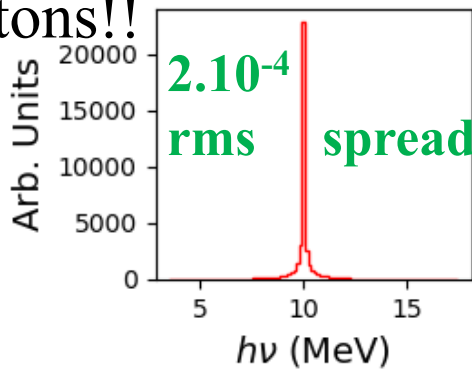
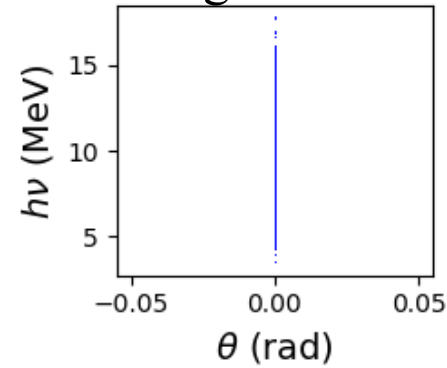
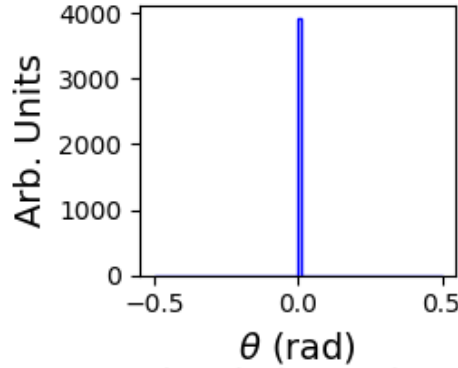
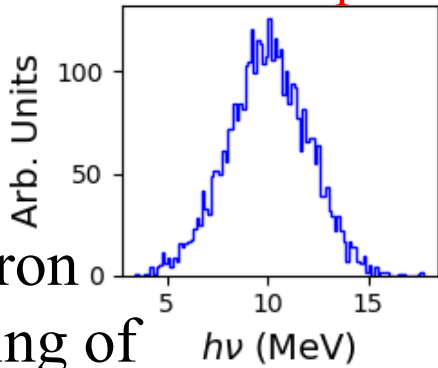
γ -ray in-vacuum mono-chromatization, SCS at large Recoil

20% rms spread

Incoming photon beam

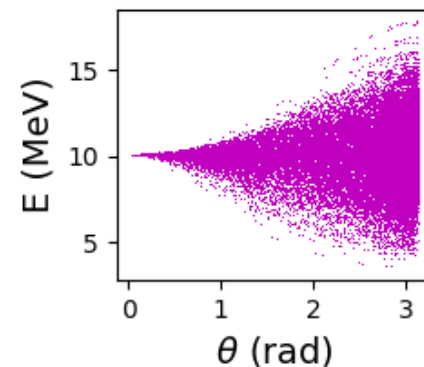
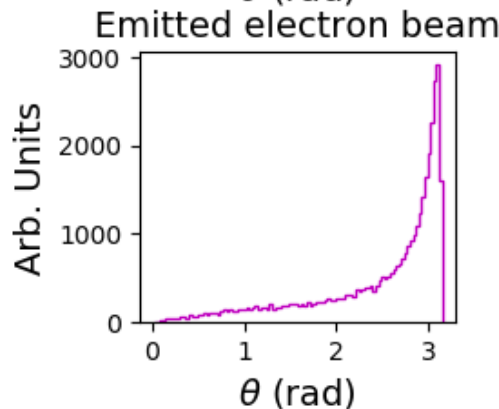
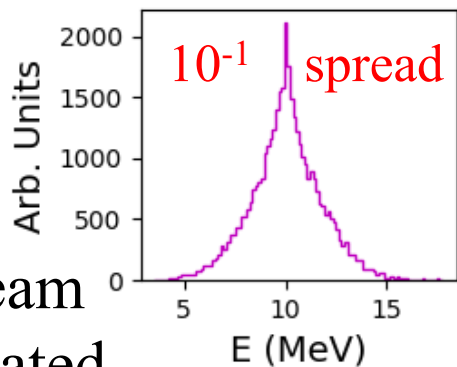
Incoming e- beam 10^{-4} rms spread

Electron
Cooling of
photons!!



no energy-
angular
correlation

e- beam
is heated



*Symmetric Compton Scattering suppresses
the $\gamma^2\theta^2$ correlation*

Photons are scattered at same energy at any angle

Lorentz Boost is damped

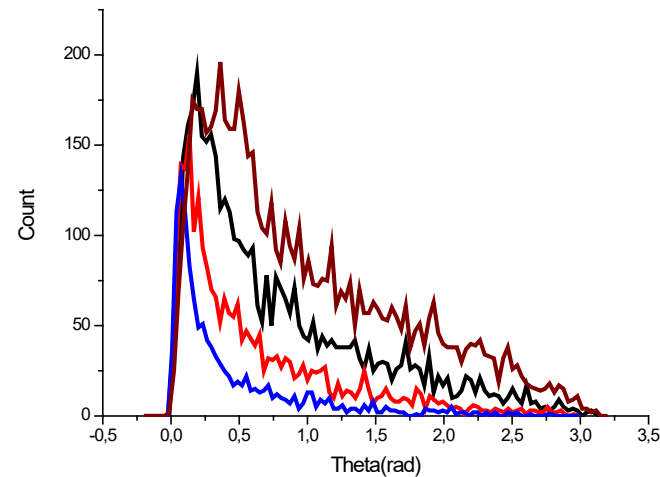
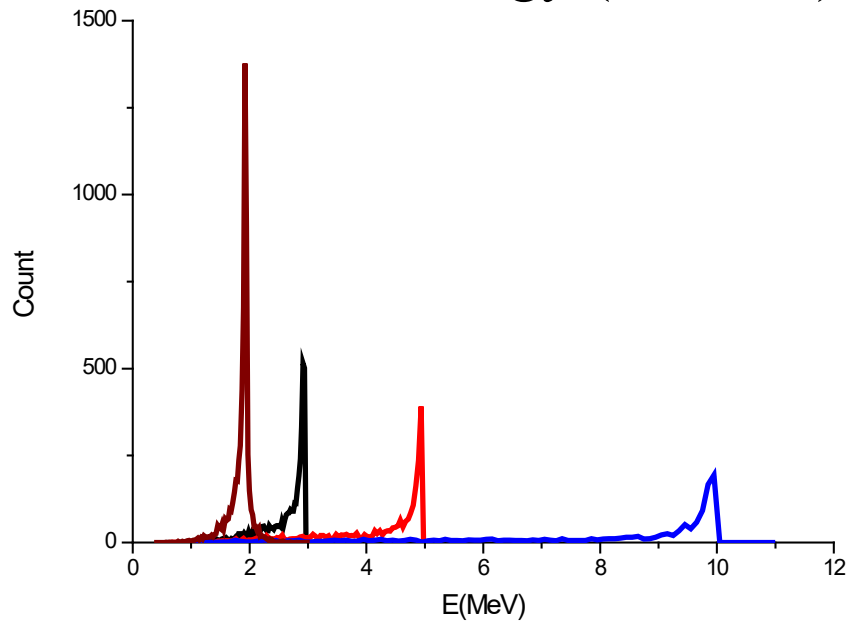
Radiation emission is intrinsically mono-chromatic

*Poli-chromaticity of incident photon beam is
transferred to the scattered electron beam and
viceversa (photon cooling, electron heating)*

SCS - What Matters?

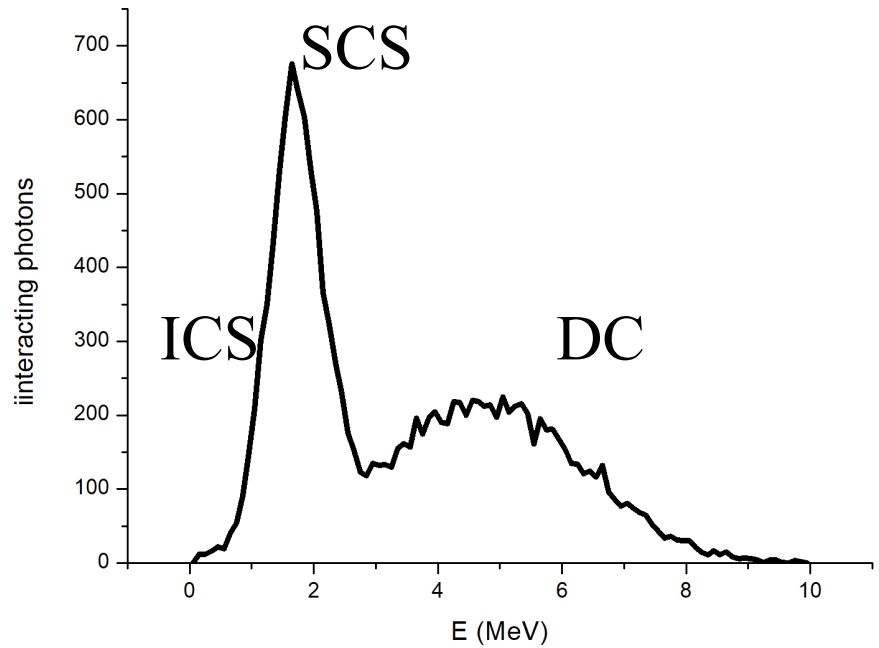
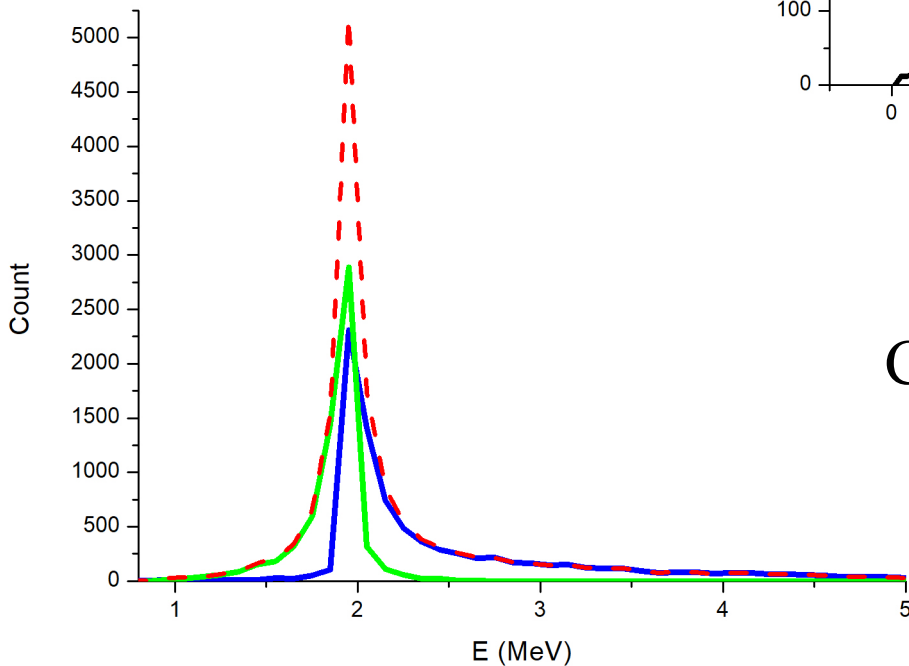
- **SCS may allow to design a laser-less γ -ray source for nuclear photonics, aka ELI-NP-GBS, using a compact low energy Linac (20-30 MeV versus 750 MeV)**
- **It can be used to extend the photon energy range of Light Sources and Free Electron Lasers up to MeV's photon beams (LCLS 12 keV, XFEL 19 keV, ESRF 100 keV \Rightarrow 1-10 MeV)**
- **Follow-ups in Astrophysics: Synchro-Compton catastrophe (see *Malcolm Longair, High Energy Astro-Physics*)**
- **Applications to Plasma Physics: additive trapping of electrons (positrons?) in magnetic bottles**

Colliding a gaussian distributed (20% rms spread) broad-band radiation beam, representing the first peak of channeling spectrum at 2 MeV, with a low energy (variable) electron beam (2,3,5,10 MeV)



Mono-chromatization, Tunability

Colliding the full spectrum



Spectral purification Compton Scattering across SCS



Optics Communications
Volume 50, Issue 6, 15 July 1984, Pages 373-378



Collective instabilities and high-gain regime
in a free electron laser

R. Bonifacio*, C. Pellegrini, L.M. Narducci



A muon source based on plasma accelerators

L. Serafini^a, I. Drebot^{a,*}, A. Bacci^a, F. Broggi^a, C. Curatolo^a,
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^c Università degli Studi di Milano, via Celoria 16, 20133 Milano, Italy

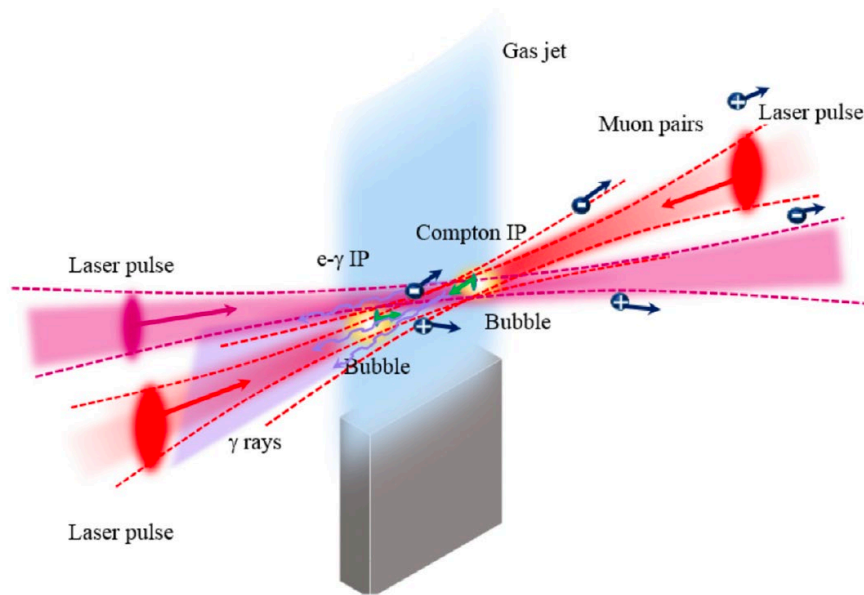
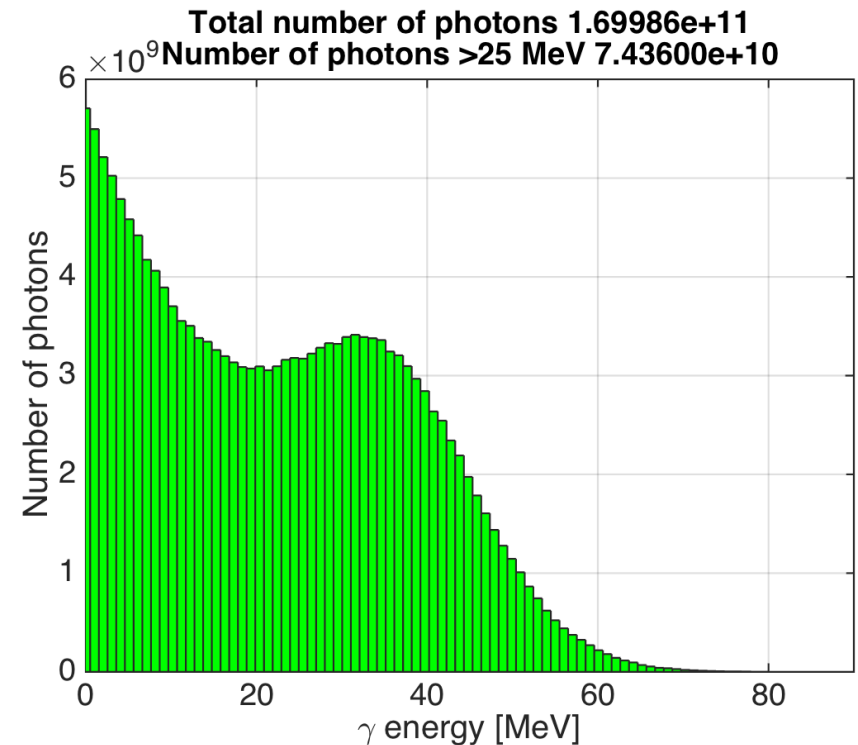
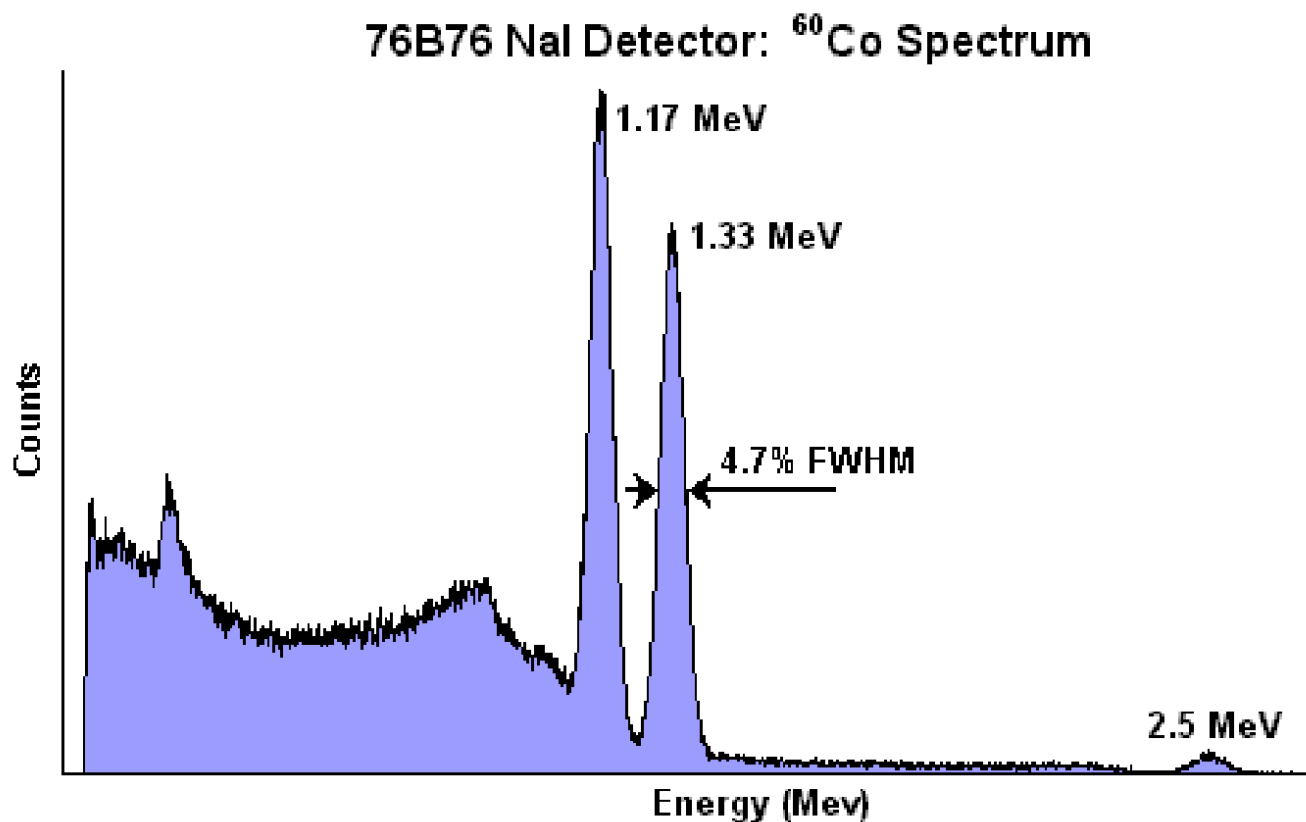


Fig. 2. Scheme of source.

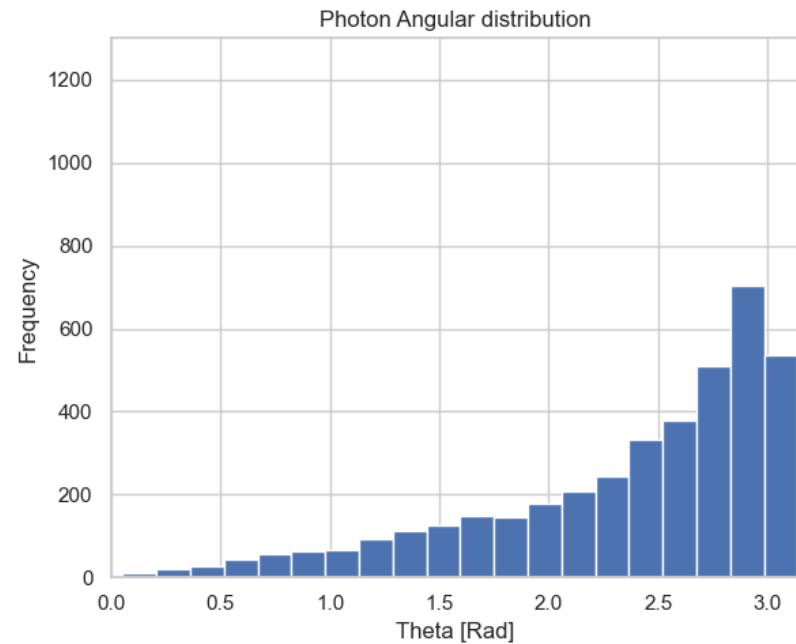
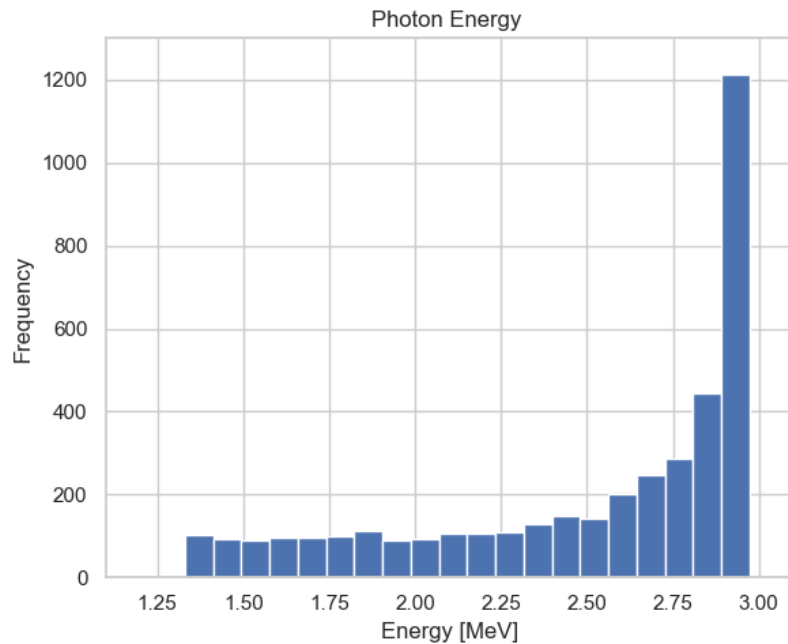
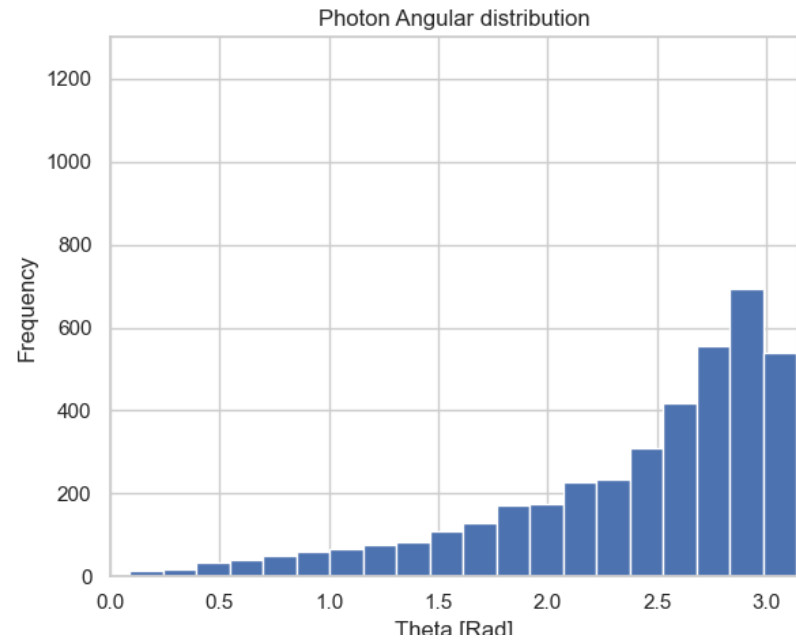
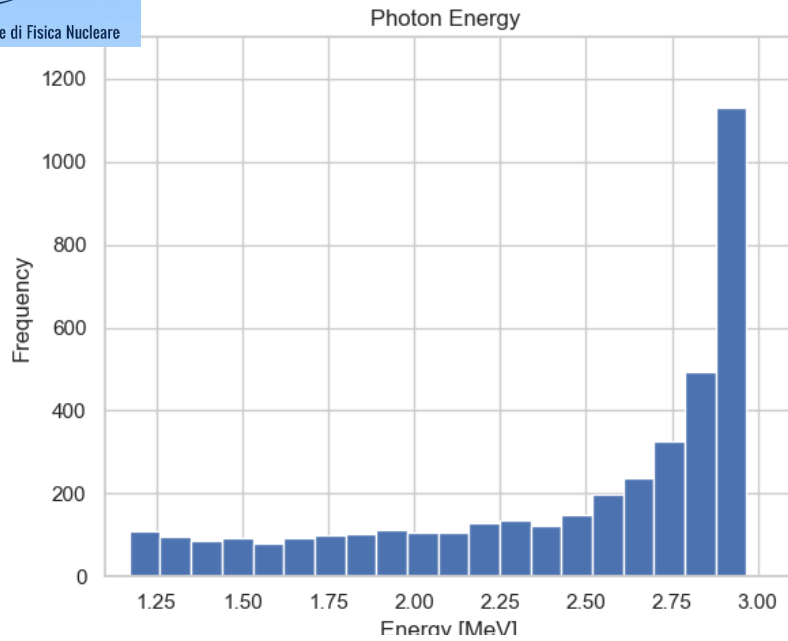
Spectral purification towards tunable mono-chromatic γ -rays with laser plasma deep recoil ICS-SCS?



Turning a radio-active Cobalt-60 fixed energy gamma-ray source into a tunable source of gamma-rays



2 spectral lines merged into a single tunable line



Trapping electrons (positrons) into a magnetic bottle by SCS at low recoil (72 keV photon beam heats up 5 keV e⁻ beam)

$$\frac{v_z}{v_r} < \sqrt{\frac{B_{\max}}{B_{\min}} - 1},$$

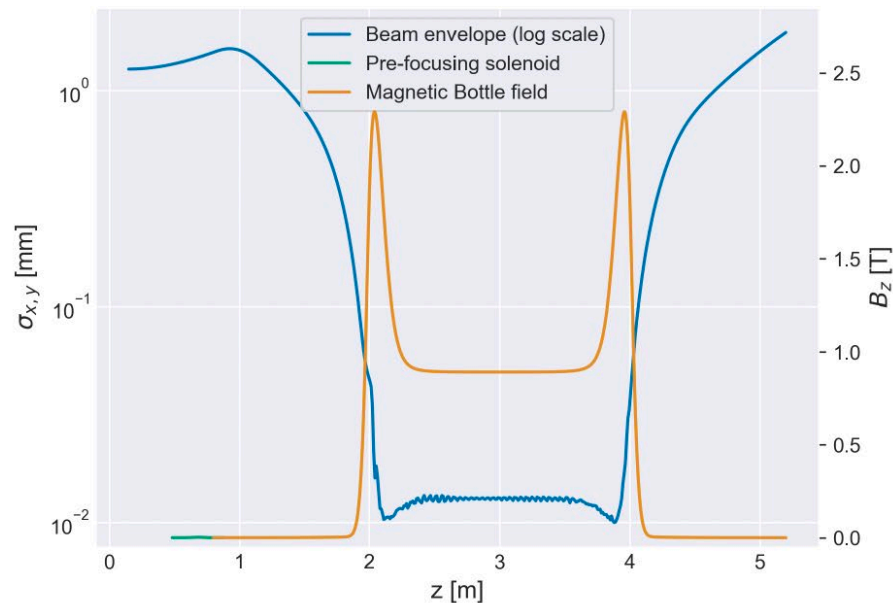
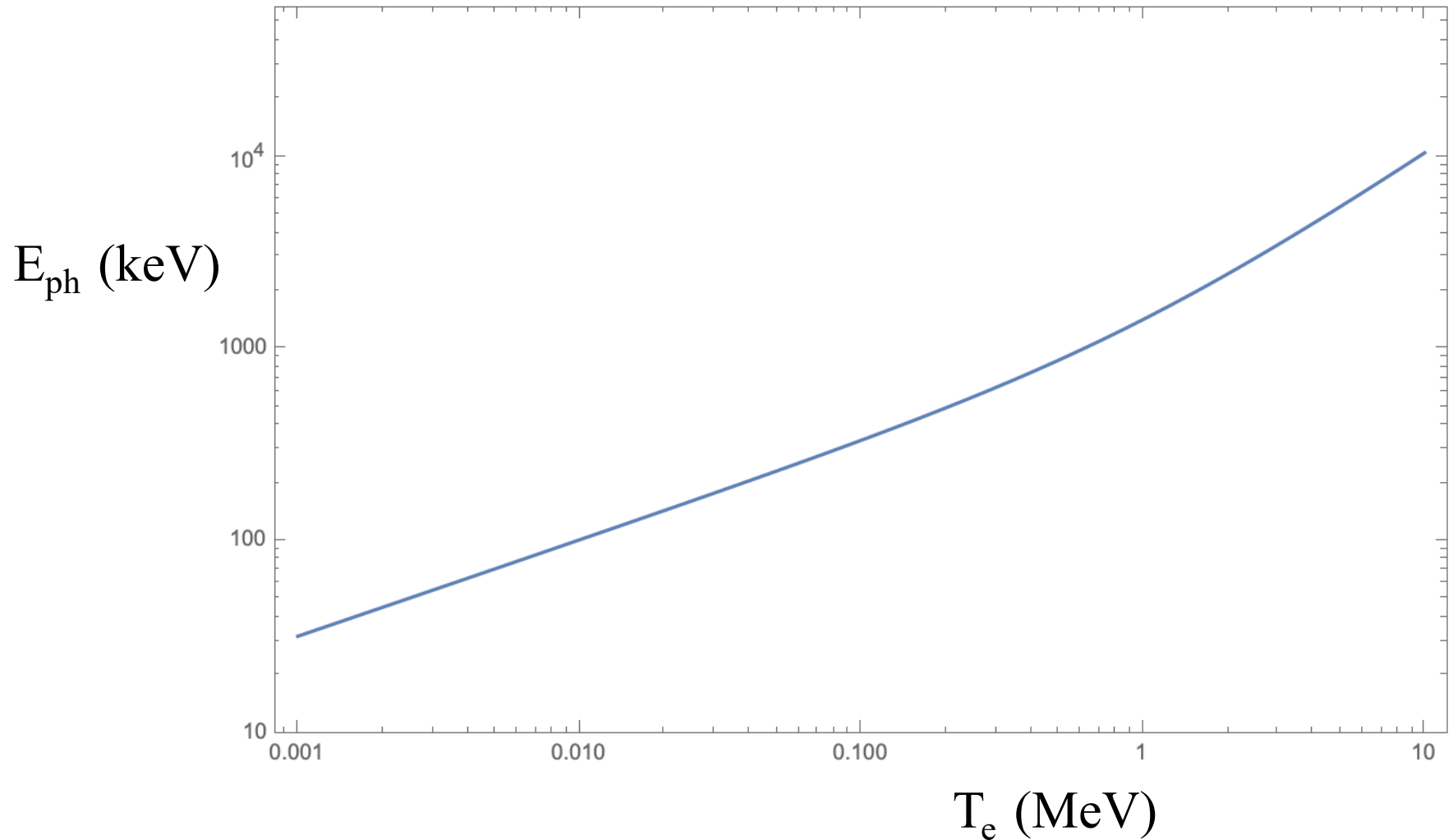


Figure 8: This image shows the transverse envelope of the primary electron beam (in blue) before, during, and after propagation in the MB field (in gold the B_z field distribution). Before the bottle, the weak field (in green) of a solenoid, peaking at 2.5 mT, is visible and is used for matching into the bottle.

S.C.S. – incident photon energy vs. incident electron kinetic energy



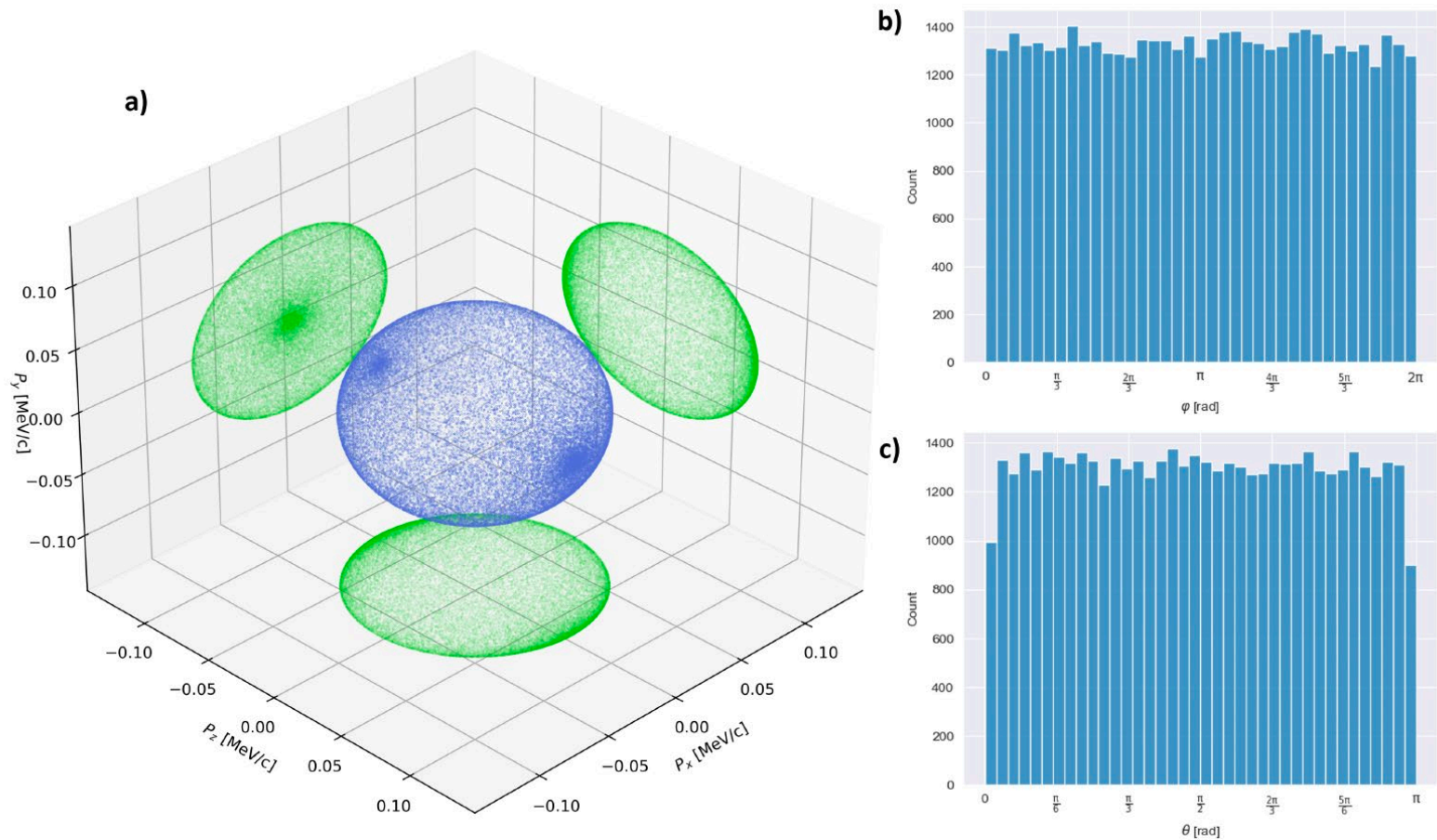


Figure 9: Representation of the momenta of the electrons that interacted with the photons in SCS regime. a) 3D representation of the momenta with their projections. b) Distribution of the momenta respect the φ angle around the z-axis. c) Distribution of the momenta respect the θ angle with the z-axis.

60% of scattered electrons are (additively) trapped into the magnetic bottle (w.o. any external field)

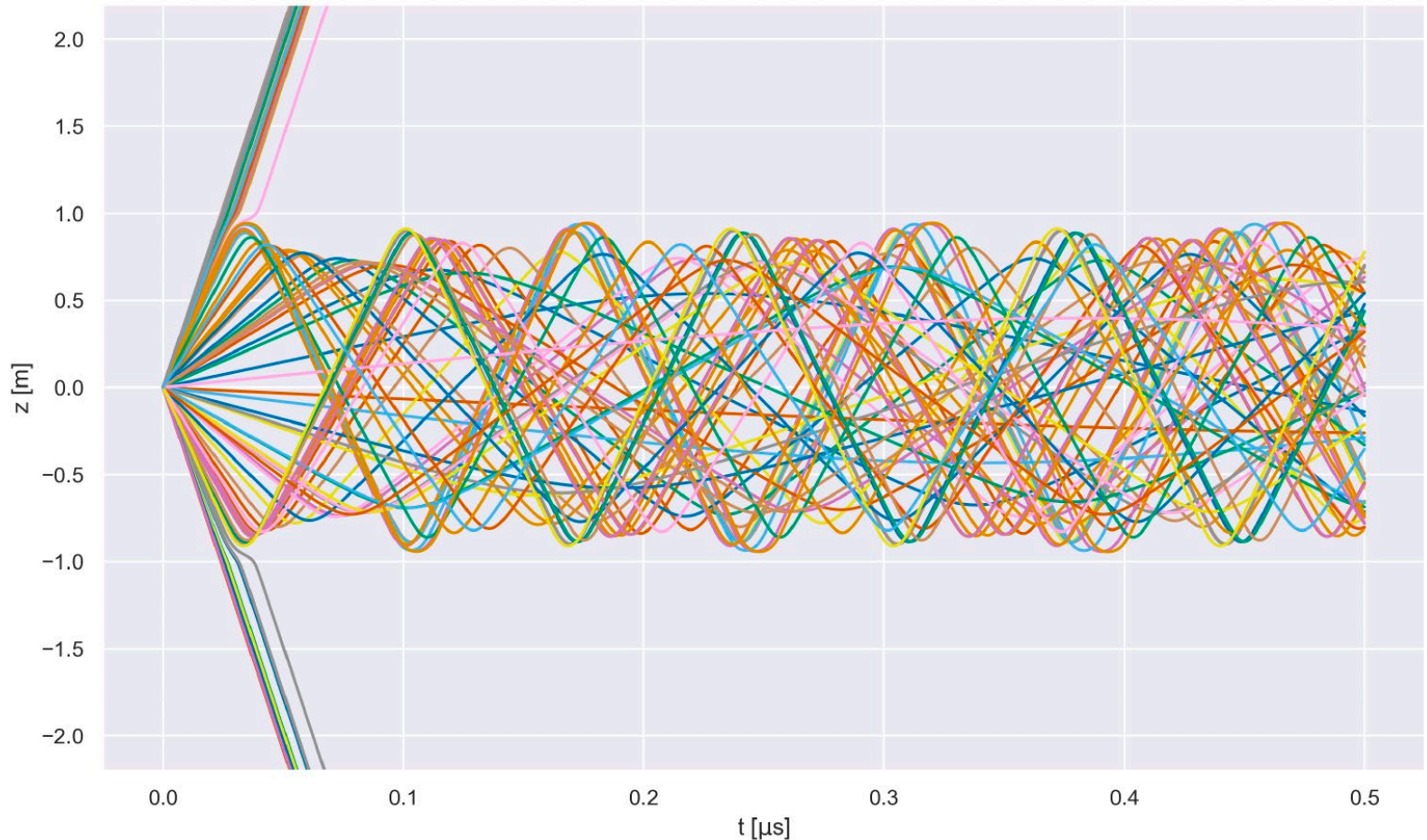


Figure 10: Evolution of the longitudinal position of 100 particles tracked in the MB, 60% where trapped.

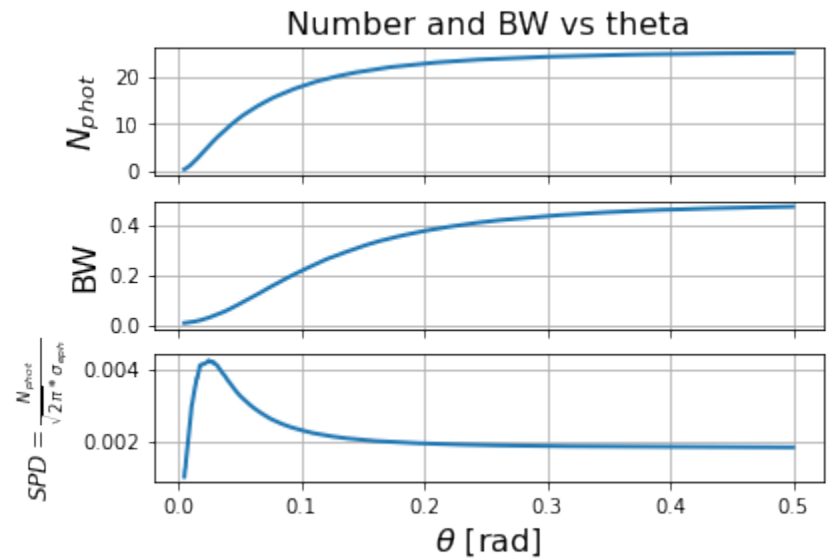
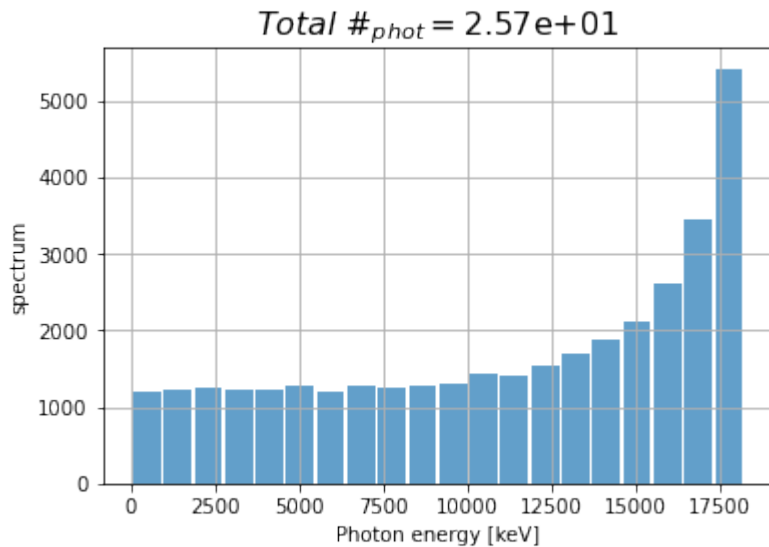
Conclusions

If S.C.S. will be the base of
Next Generation hard-X-Ray and gamma-rays,
we are not yet able to say,
but chances are quite promising.

If S.C.S. will play a role in plasma heating,
soon we'll be able to say.

Within Astro-physics context more studies
must be pursued to check about
Compton Catastrophe and related topics.

Undulator radiation (33 keV from Elettra) vs.
20 MeV e- beam from BriXSinO ERL
about 10^9 photons/s in 1% bdw (100 MHz rep rate)



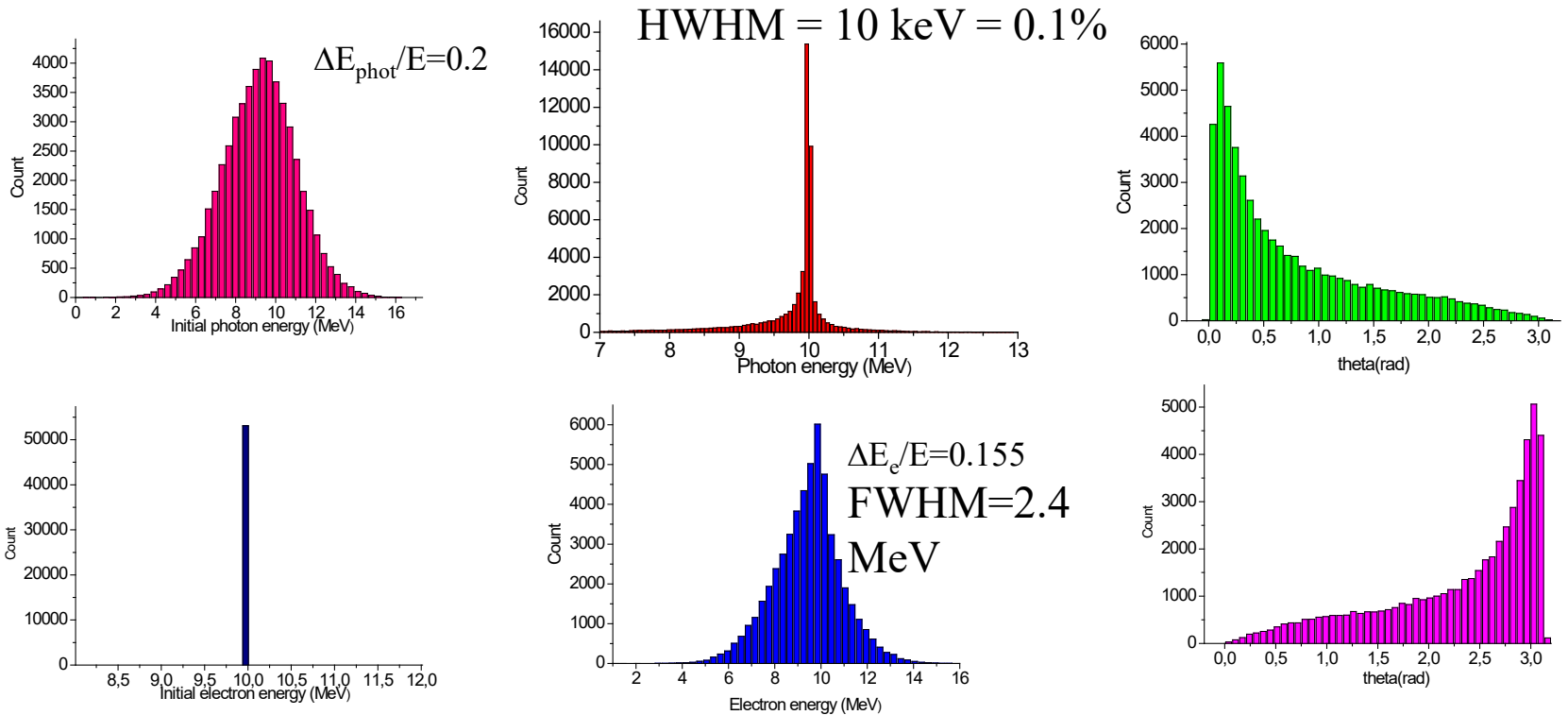
V. Petrillo, I. Drebot (INFN-Milan)
S. Dimitri (Elettra)

Symmetric Compton (CSC)

(10 MeV Linac vs. bremsstrahlung/betatron/
channeling/coherent bremsstrahlung beam)

Electron energy=10.013 MeV, Photon energy=10 MeV, $\Delta E_{\text{phot}}/E=20\%$ Deep Recoil X=1533

$Q=1.e-9$ C $N_X=2.*10^8$ $\sigma_0=1$ μm rep-rate=200 MHz

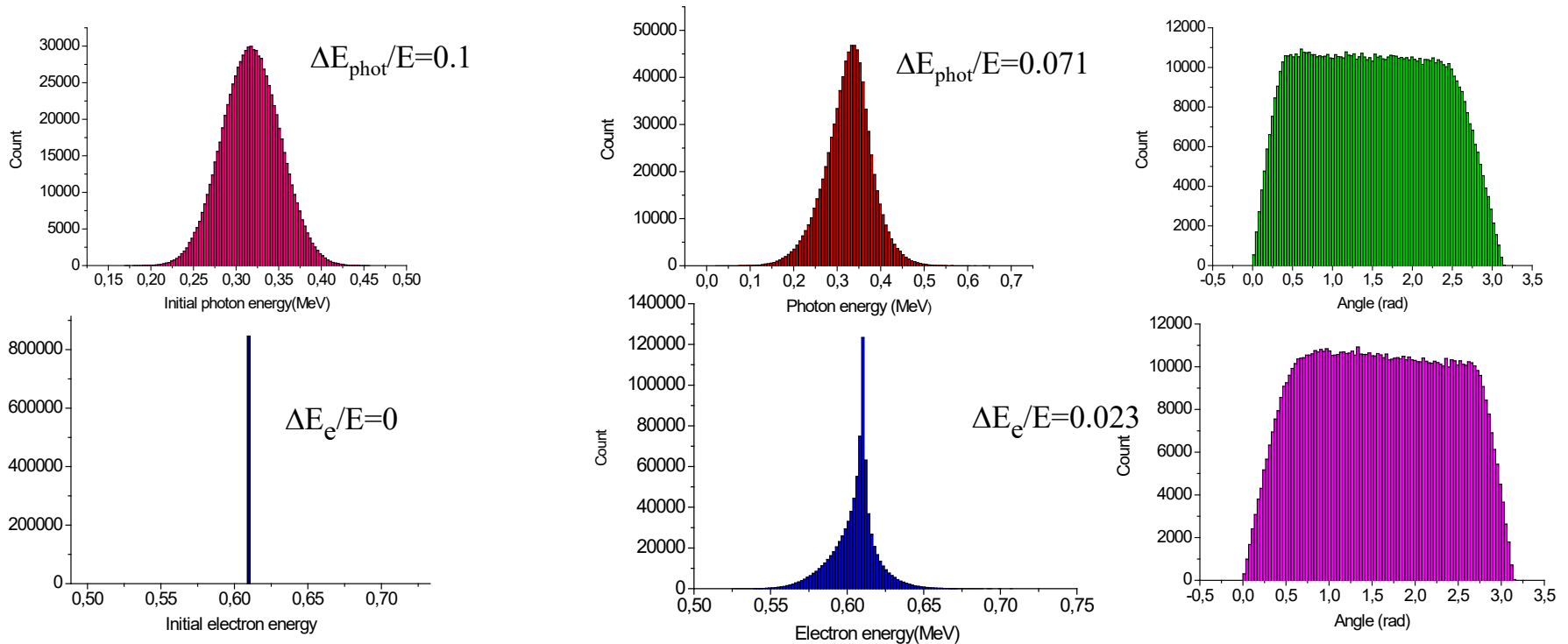


$N_{el}=6.*10^9$ $N_X=2.*10^8$ $\Sigma=2.6*10^{-27}=2.6$ mbarn N_X' (s^{-1})= $5*10^6$ $S=500$ $s^{-1}eV^{-1}$

$$\lim_{X \rightarrow 0} \sigma = \frac{8\pi r_e^2}{3} (1 - X) = \sigma_T (1 - X) \quad \lim_{X \rightarrow \infty} \sigma = \frac{2\pi r_e^2}{X} (\log X + \frac{1}{2})$$

Symmetric Compton at moderate recoil

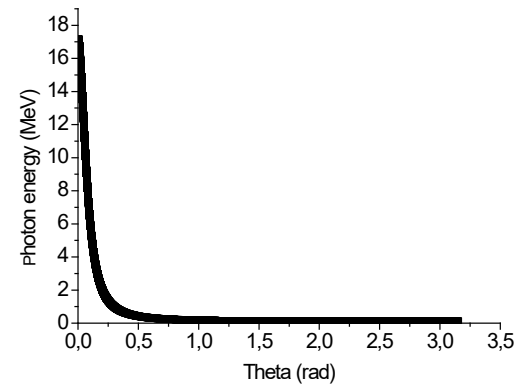
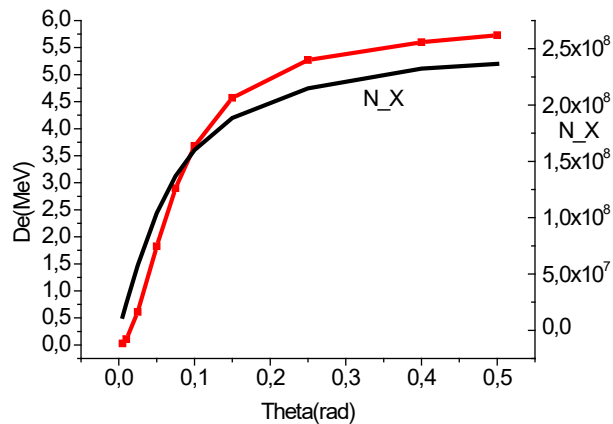
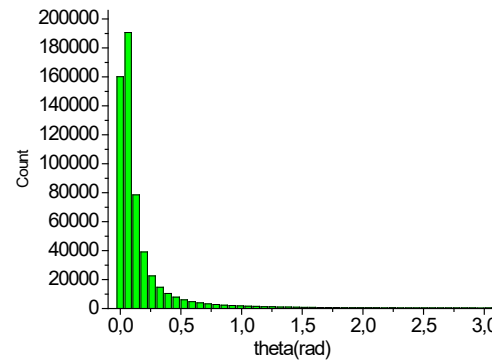
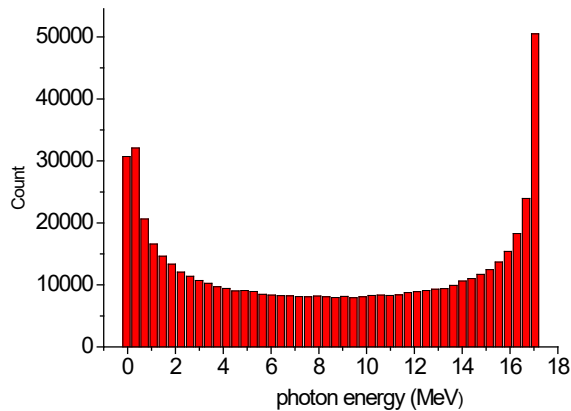
Initial Electron energy=611 keV, Initial Photon energy=335 keV, $\Delta E_{\text{phot}}/E=0.1$
 Symmetric Compton ($p_e = -p_{\text{phot}}$), **moderate recoil** $X=3.13$



SCS and large recoil factors are both needed to mono-chromatize broad band incident photon beams

FEL beam vs. compact Linac

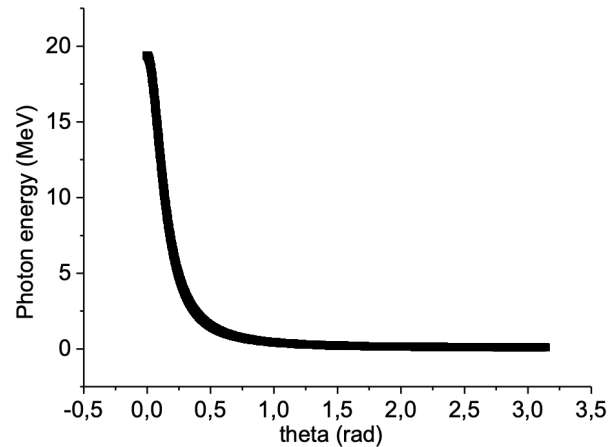
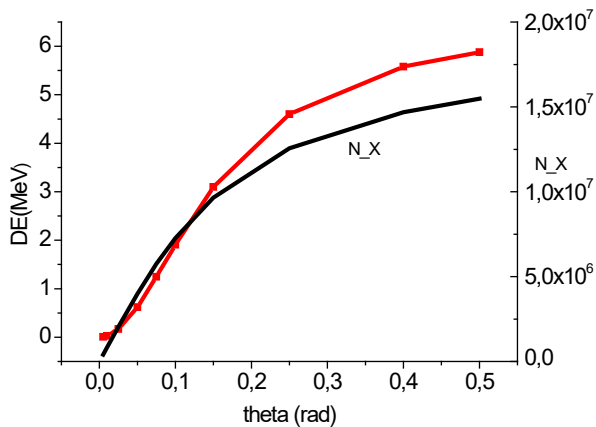
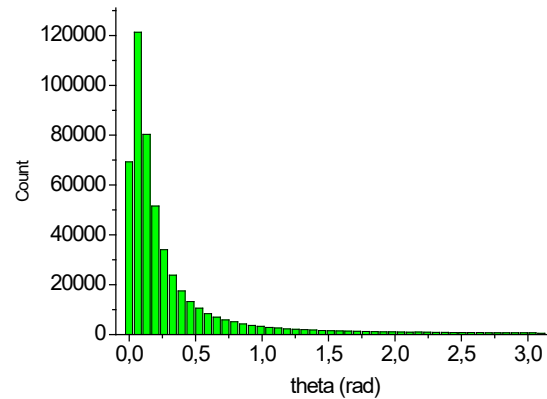
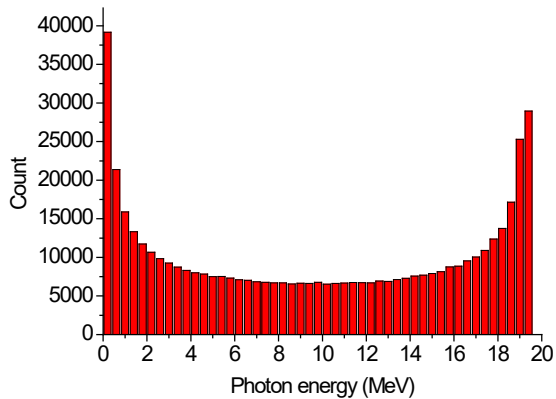
Initial Electron energy=20 MeV, Initial Photon energy=20 keV, $\Delta E_{\text{phot}}/E=0.0001$
 moderate recoil $X=6.12$



up to 10^8 photons/s at 17 MeV with 50 keV bdw: $S \approx 2000 \text{ s}^{-1} \text{ eV}^{-1}$

X-ray beam from Light Source vs. compact Linac

Electron energy=20 MeV, Photon energy=100 keV, $\Delta E_{\text{phot}}/E=0.001$ recoil X=30.63



up to 10^7 photons/s at 17 MeV with 50 keV bdw

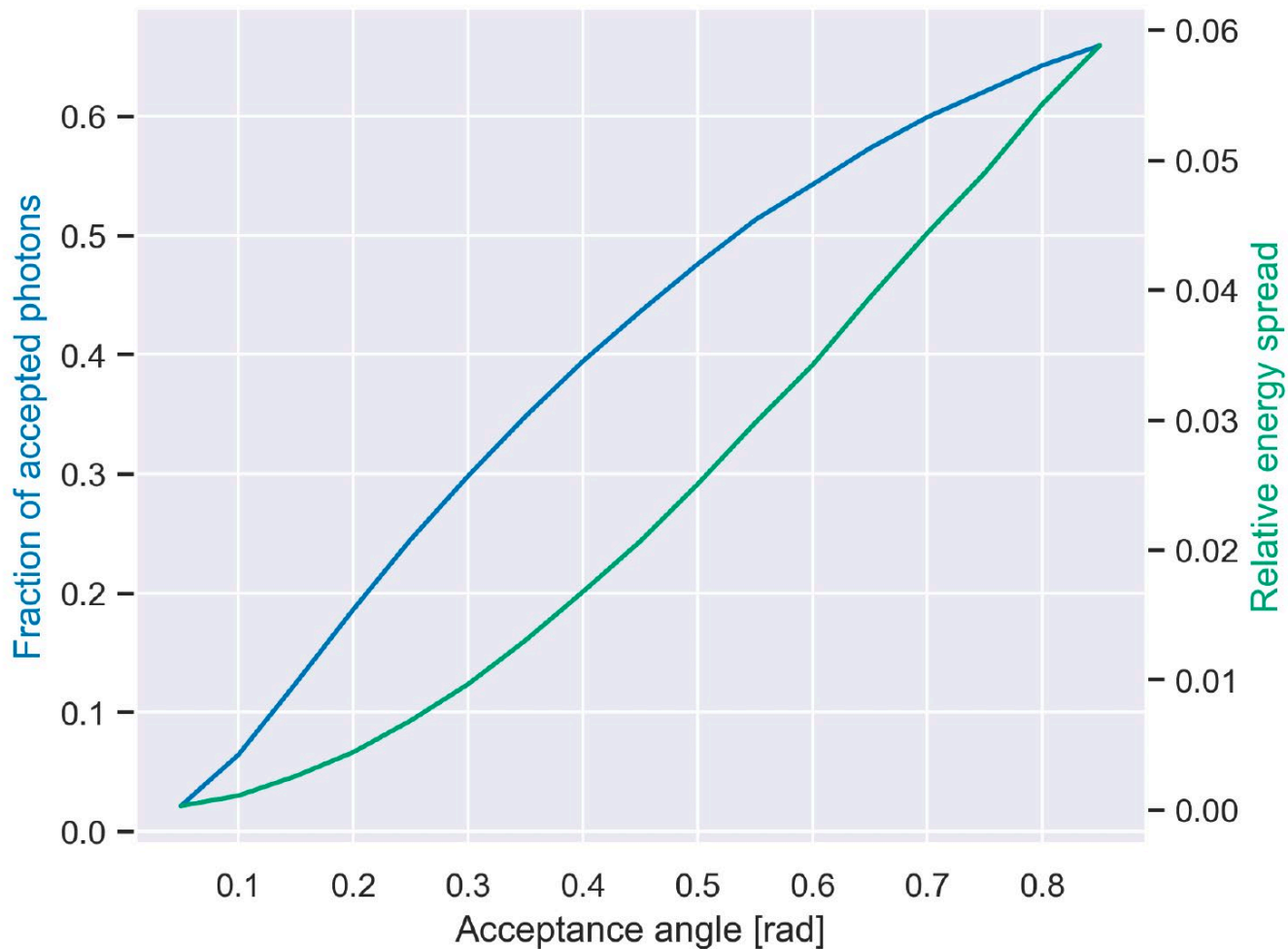


Figure 12: Relative fraction of scattered photons within the acceptance angle (blue curve) and relative bandwidth of the selected photon beam within the angular acceptance (green curve).

Inverse Compton Sources, Overview, Theory, Main Technological Challenges – Photonic Colliders

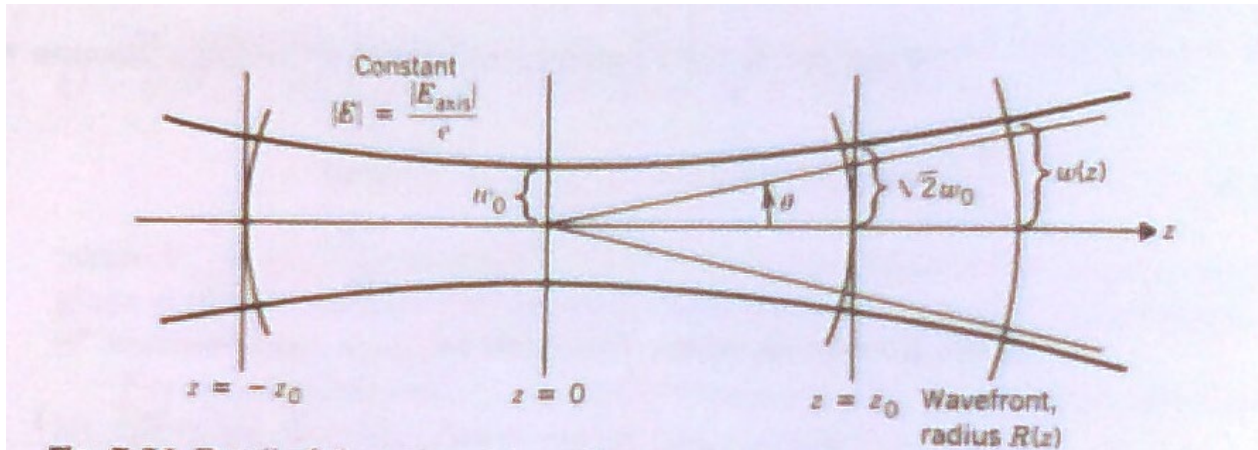
- **New Generation of X/γ ray beams via electron-photon beam collisions for advanced applications in medicine/biology-material science/cultural heritage/national security *and* fundamental research in nuclear physics and high energy physics ($e-\gamma$, $\gamma-\gamma$ colliders, pol. e^+ beams, hadron. physics, etc)**
- **Inverse Compton Sources (ICS) are e^- /photon colliders aimed at producing secondary beams of photons**
- **Several Test-Facilities world-wide: after a decade of machine test&development we are entering the era of User Facilities in X -ray imaging and γ -ray Nuclear Physics and Photonics**

Challenges of *electron-(optical)photon colliders as X/γ beam Sources using Compton back-scattering*

- Need of *high peak brightness/high average current* electron beams (cmp. FEL' s drivers) *fsec-class* synchronized and *μm-μrad-scale* aligned to *high peak/average power* laser beams
- **Main goal for Nuclear Physics and Nuclear Photonics:**
Spectral Densities $> 10^4 N_{ph}/(s \cdot eV)$
photon energy range 1-20 MeV, *bandwidths* 10^{-3} class
- **Main goal for Medical Applications with X-rays: tunability in the 20-120 keV range, good mono-chromaticity (1-10 %), high flux (10^{11} min., 10^{12} for radio-imaging, 10^{13} for radio-therapy)**

Photon / Particle Beams: diffraction, envelope, matching, co-propagation.

Example: TEM₀₀ Gaussian Laser mode (circ. pol. M²=1 diffr. limited)



$$E_0(x, y, z, t) = A_0 e^{i\omega t} e^{-ikz} \frac{Z_0}{Z_0 - iz} \exp \left[-\frac{k(x^2 + y^2)}{2} \frac{1}{Z_0 - iz} \right] \quad k = 2\pi / \lambda$$

$$|E_0(x, y, z, t)| = E_0 \frac{w_0}{w} e^{-\frac{x^2 + y^2}{w^2}}$$

$$w = w_0 \sqrt{1 + \frac{z^2}{Z_0^2}} \quad Z_0 = \frac{\pi w_0^2}{\lambda} \quad \vartheta = \frac{w_0}{Z_0} = \frac{\lambda}{\pi w_0}$$

$$I \propto |E_0(x, y, z, t)|^2$$

LASER

$$Z_0 = \frac{4\pi \left(\frac{w_0}{2}\right)^2}{\lambda}$$



PARTICLE BEAM

$$\beta^* = \frac{\sigma_0^2}{\varepsilon_n / \gamma}$$

$$\frac{w}{2} = \frac{w_0}{2} \sqrt{1 + \frac{z^2}{Z_0^2}}$$



$$\sigma(z) = \sigma_0 \sqrt{1 + \frac{z^2}{\beta^{*2}}}$$

$$\frac{\lambda}{4\pi} = \frac{\varepsilon_n}{\gamma}$$

and $w_0 = 2\sigma_0$

$$\varepsilon_n \leq \frac{\lambda_{FEL} \gamma}{4\pi}$$

$w(z) = 2\sigma(z)$ *and* $\vartheta(z) = 2\sigma'(z)$

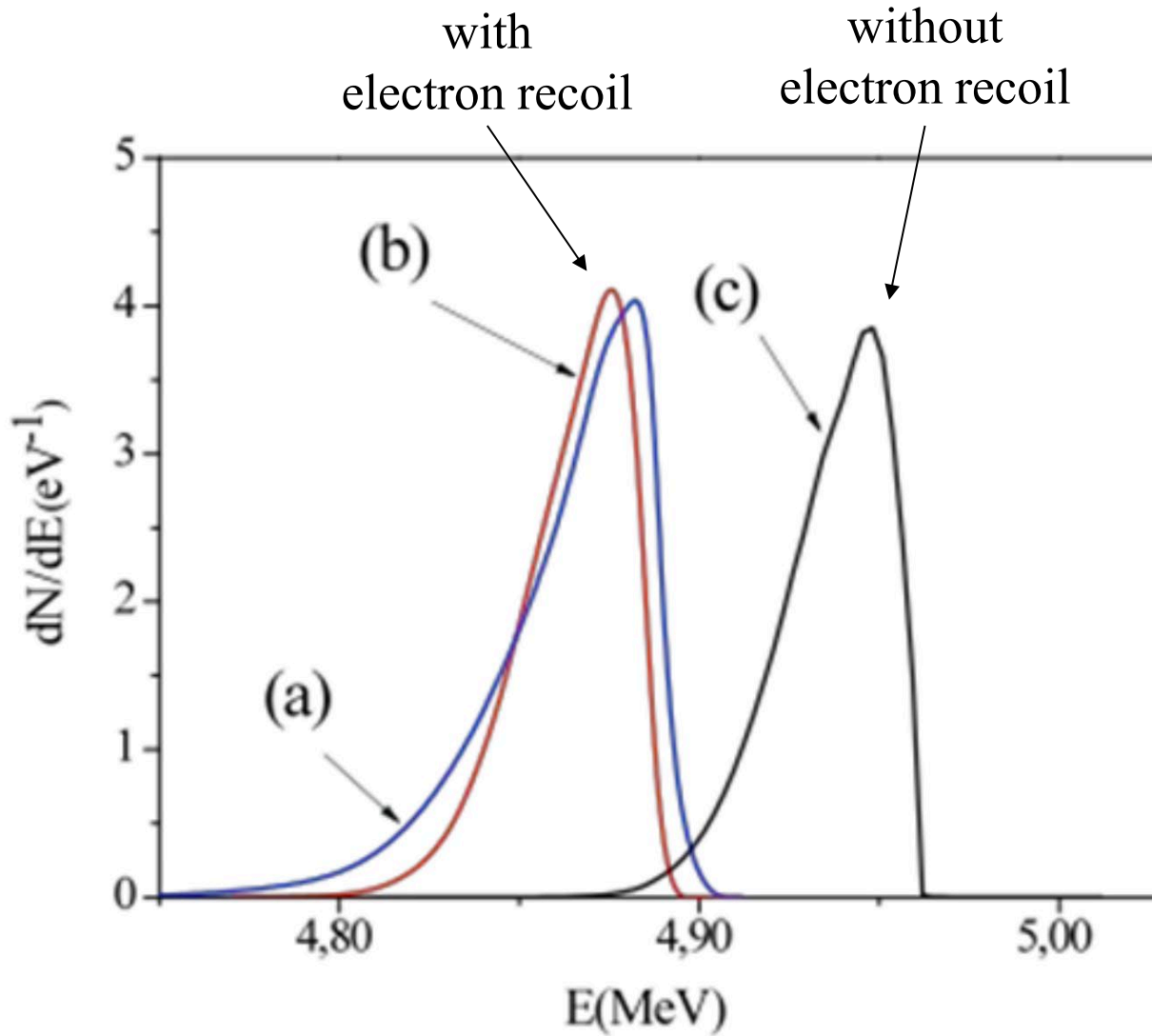
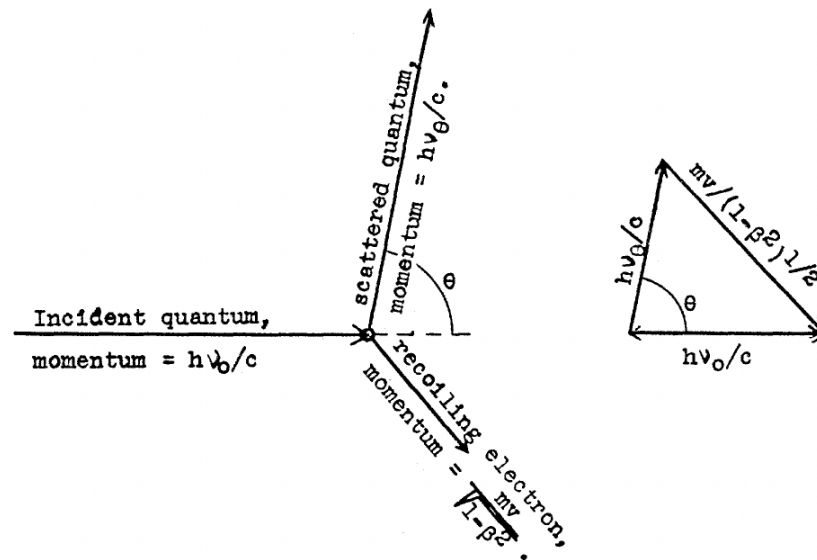


Fig. 5. Spectra of the rays. (a) CAIN (b) Quantum model (c) Classical treatment in the case of beam (A) and for the laser parameter of Table 1 and interaction angle $\alpha = \pi$; rms acceptance angle $\theta_{\text{rms}} = 25 \mu\text{rad}$

THE
PHYSICAL REVIEW

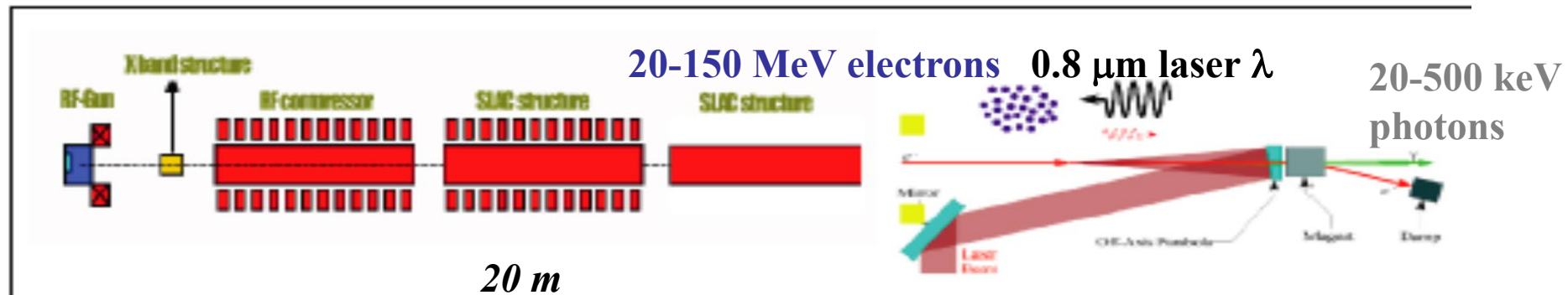
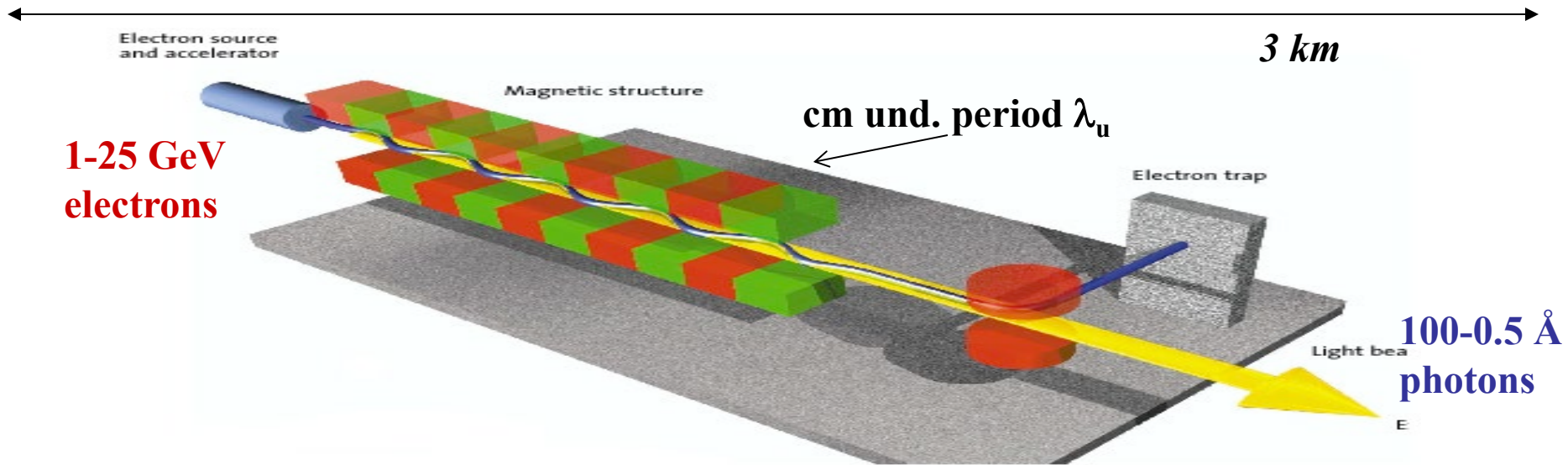
The change in wave-length due to scattering.—Imagine, as in Fig. 1A,

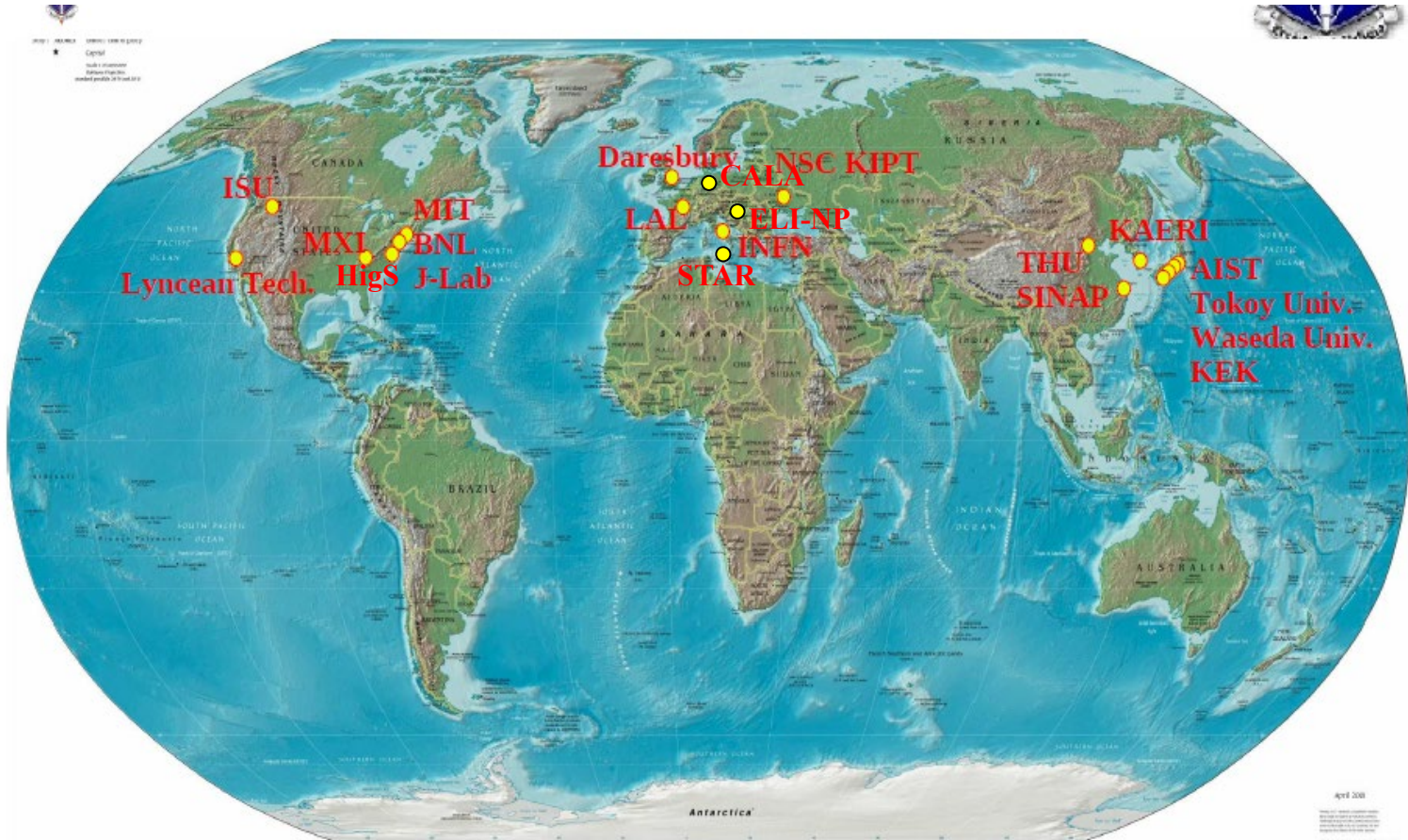


that an X-ray quantum of frequency ν_0 is scattered by an electron of mass m . The momentum of the incident ray will be $h\nu_0/c$, where c is

The Classical E.M. view (Maxwell eq.): Thomson Sources as synchrotron radiation sources with electro-magnetic undulator

FEL's and Thomson/Compton Sources common mechanism: collision between a relativistic electron and a (pseudo)electromagnetic wave





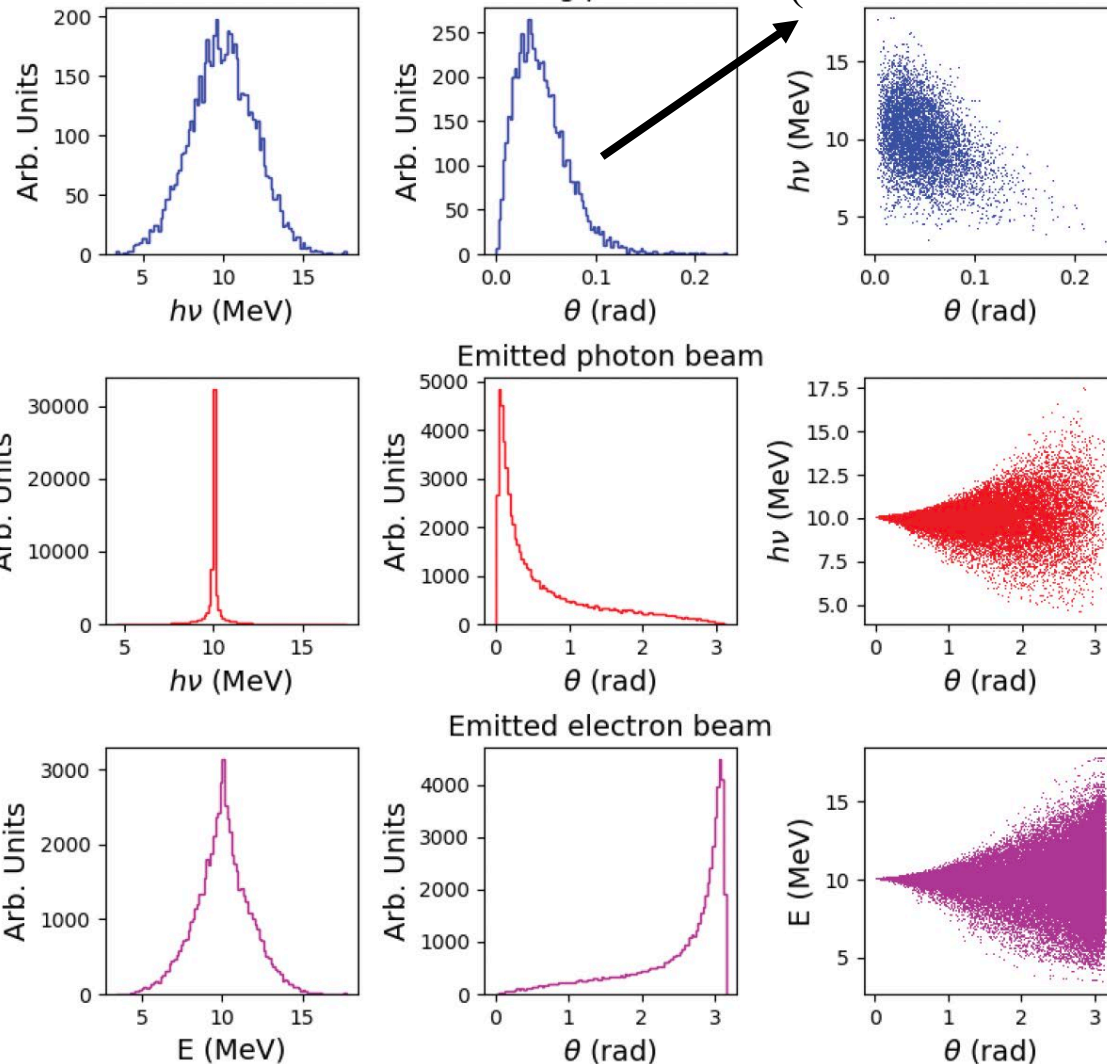
ICS are the most effective “photon accelerators” (boost twice than FELs)

“ $4\gamma^2$ boost effect” $E_{X/\gamma} = 4\gamma^2 E_{laser}$

with $T = 100\text{MeV}$ ($\gamma = 197$) $E_{laser} = 1.2\text{ eV} \Rightarrow E_{X/\gamma} = 186\text{ keV}$

Spread of incidence angle

Incoming photon beam (resembles emittance)



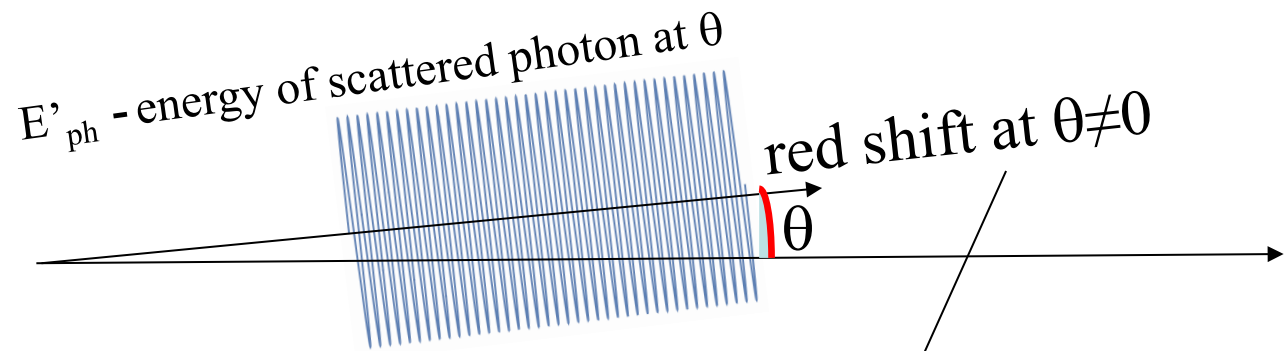
cooling of
photons still
effective

as well as
heating of
electrons

Figure 5: Simulations of SCS with an incoming photon beam displaying a correlation between angle of propagation and photon energy. The results are shown through 9 plots arranged in three rows as in fig. 4. The angular correlation of the incoming photon beam is removed in the interaction thanks to the high recoil factor ($X \sim 1500$).

scattered electron

$$E'_e = \gamma mc^2 + E_{ph} - E'_{ph}$$



$$E'_{ph}(\theta) = \frac{4E_{ph}\gamma^2}{1 + X + \gamma^2\theta^2}$$

$$X = \frac{4E_e E_{ph}}{m^2 c^4} = \frac{4\gamma E_{ph}}{m c^2} = 4\gamma^2 \frac{E_{ph}}{m c^2}$$

All I.C.S. X/gamma Sources work at $X < 1$ and $A \gg 1$

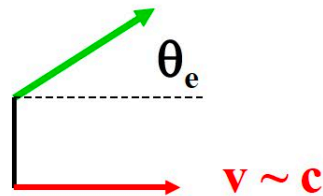
$$STAR (350 \text{ keV}) \quad X_{STAR} < 2.6 \cdot 10^{-3} \quad A_{STAR} > 10^4$$

$$ELI-NP (20 \text{ MeV}) \quad X_{ELI-NP} < 0.026 \quad A_{ELI-NP} > 2.4 \cdot 10^5$$

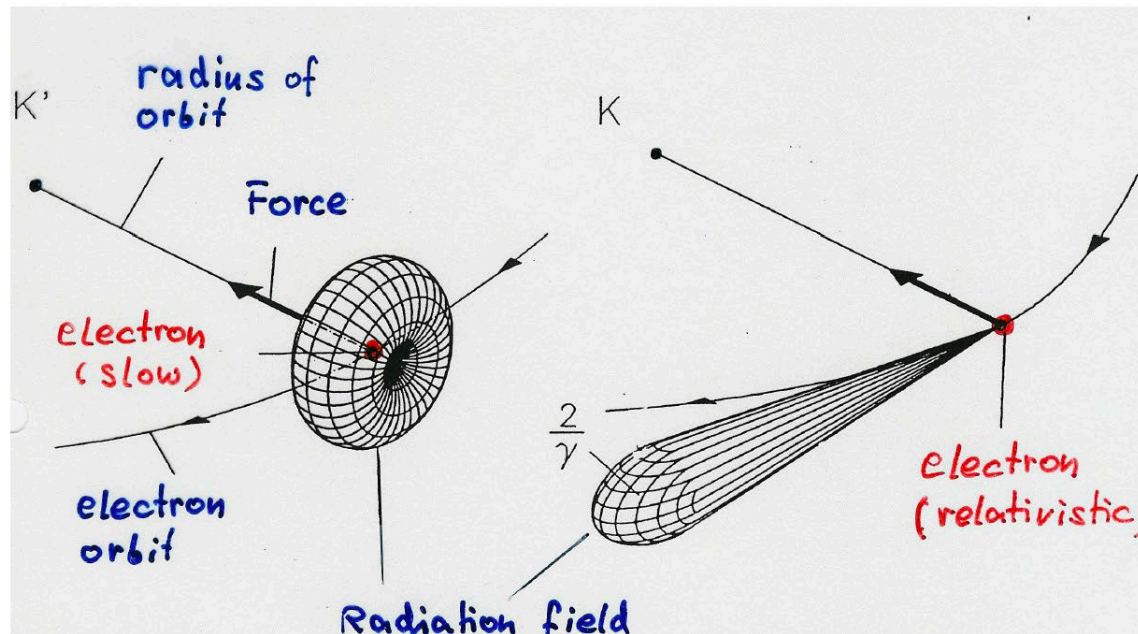
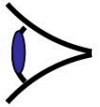
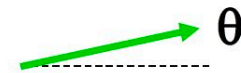
$X =$ recoil
by the ele

n seen
d to mc^2

Radiation is emitted into a narrow cone



$$\theta = \frac{1}{\gamma} \cdot \theta_e$$

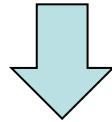


$$v \ll c$$

$$v \approx c$$

To transform to the Lab ref. system
we need to compute γ_{cm}

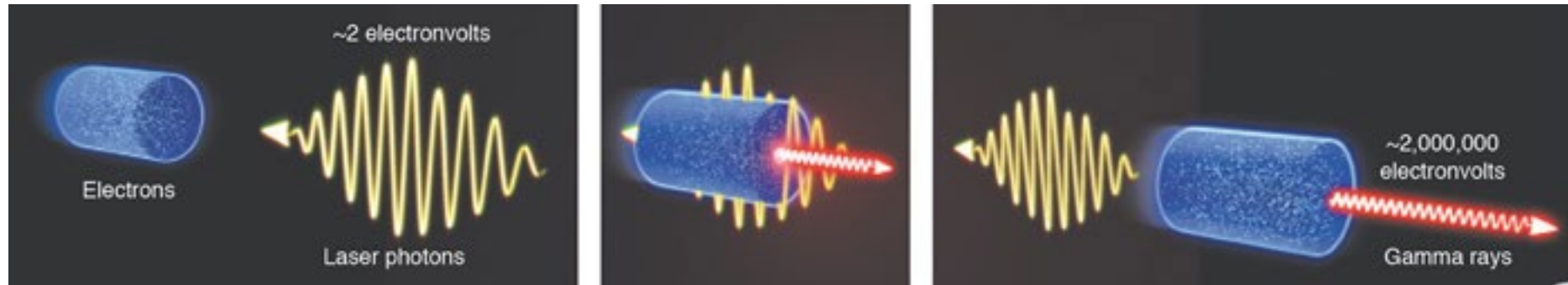
$$\gamma_{cm} = \frac{E_{lab}}{E_{cm}} = \frac{E_e + h\nu_L}{m_e c^2 \sqrt{1+\Delta}} \approx \frac{\gamma}{\sqrt{1+\Delta}}$$



Then apply a Lorentz transformation

$$\left\{ \begin{array}{l} E_{ph} = p_{ph}^* \gamma_{cm} \left(1 + \sqrt{1 - \frac{1}{\gamma_{cm}^2}} \cos \theta^* \right) \\ p_{phx} = p_{ph}^* \sin \theta^* \cos \phi^* \\ p_{phy} = p_{ph}^* \sin \theta^* \sin \phi^* \\ p_{phz} = p_{ph}^* \gamma_{cm} \left(\sqrt{1 - \frac{1}{\gamma_{cm}^2}} + \cos \theta^* \right) \end{array} \right.$$

I.C.S. : Inverse Compton Scattering



Inverse Compton Scattering: why Inverse?

(direct) Compton Scattering is performed by an energetic photon (X-rays) interacting with an atomic electron (eV)

Inverse Compton Scattering is performed by an energetic electron (MeV-GeV) onto a visible (eV) photon (“inverse” refers to the reaction kinematics, not the dynamics)

Deep Recoil ICS helps attenuating the $\alpha^2 Q^2$ problem

strong focusing to maximize
Peak Luminosity according
to Petrillo-Serafini criterion

$$S_d \propto \frac{\langle I_e \rangle U_{las}}{\epsilon_n^2 E_x}$$

30-150 MeV e^-
20-350 keV X

$\Psi =$

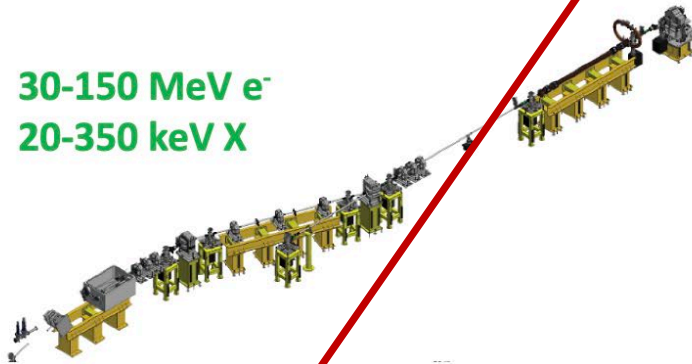
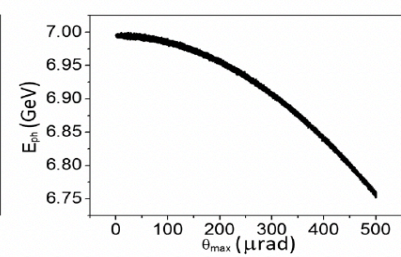
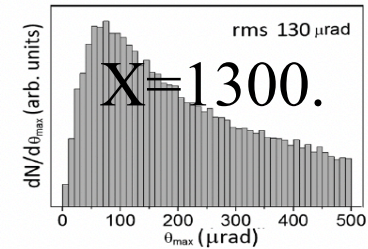
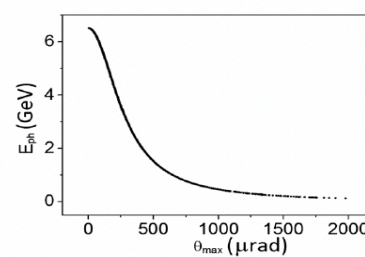
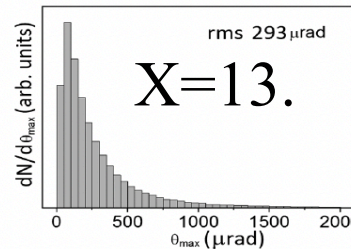
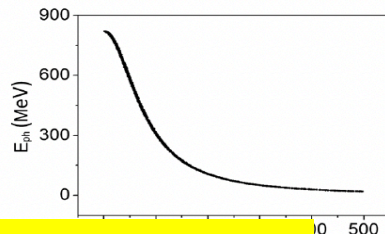
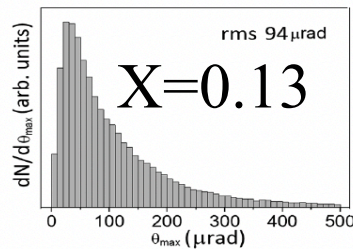


Fig.2 – STAR machine as an example of Paradigm A. Overall length about 12 m.

$$\bar{P} = \frac{\sqrt{2}\epsilon_n}{\sigma_x \sqrt{1+X}}$$

$$\gamma_{cm} = \frac{\gamma}{\sqrt{1+X}}$$



250-750 MeV e^-
1-19.5 MeV γ

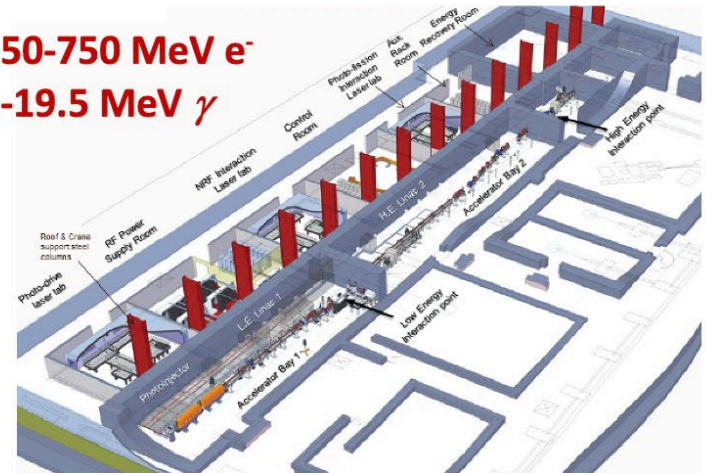
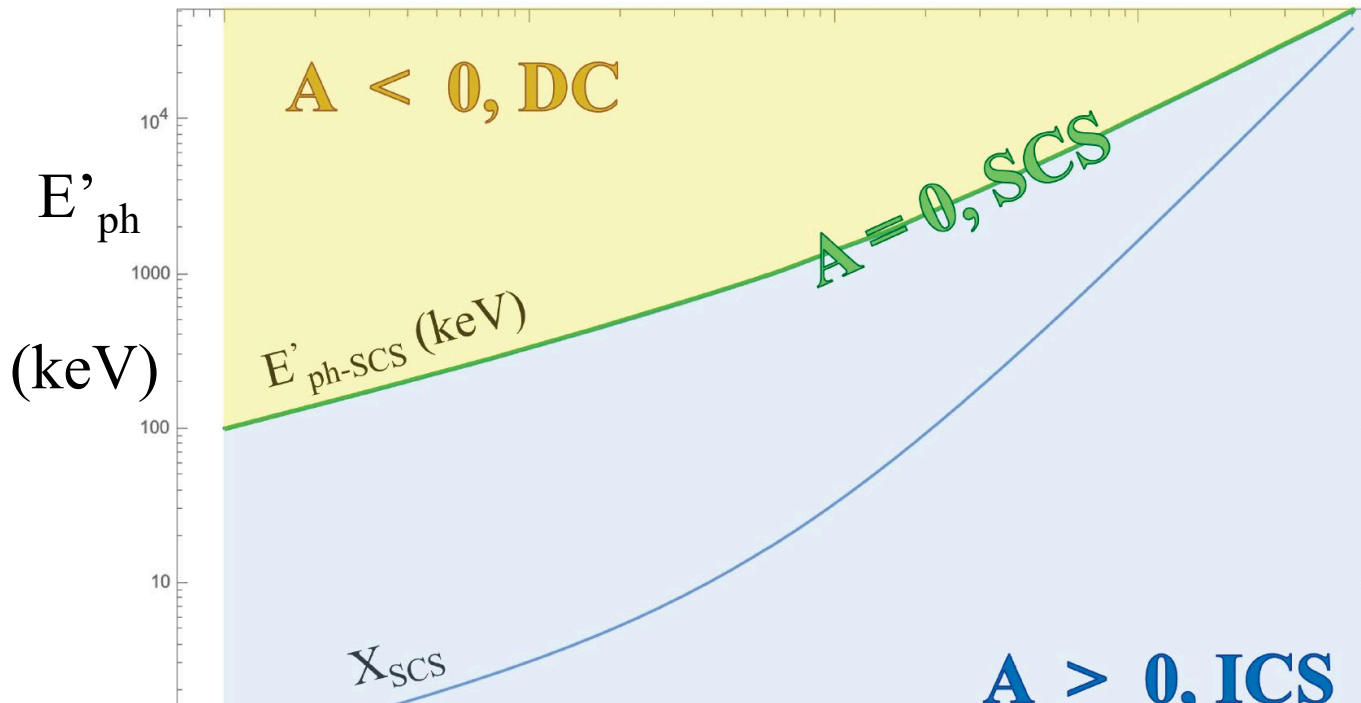


Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

R. Hajima and M. Fujiwara, Narrow-band GeV photons generated from an x-ray free-electron laser oscillator, Phys. Rev. Accel. Beams 19, 020702 (2016). XFELO Project

..., CAIN simulations. First line spectrum, second line angular distribution, third line energy as a function of angle. Left column, case A middle column, case E right column.



Article

State of the Art of High-Flux Compton/Thomson X-rays Sources

Vittoria Petrillo ^{1,2,*}, Illya Drebot ^{1,†}, Marcel Ruijter ^{1,†}, Sanae Samsam ^{1,†}, Alberto Bacci ¹, Camilla Curatolo ¹, Michele Opromolla ^{1,2}, Marcello Rossetti Conti ¹, Andrea Renato Rossi ¹ and Luca Serafini ^{1,†}

100 – 0(100) MeV

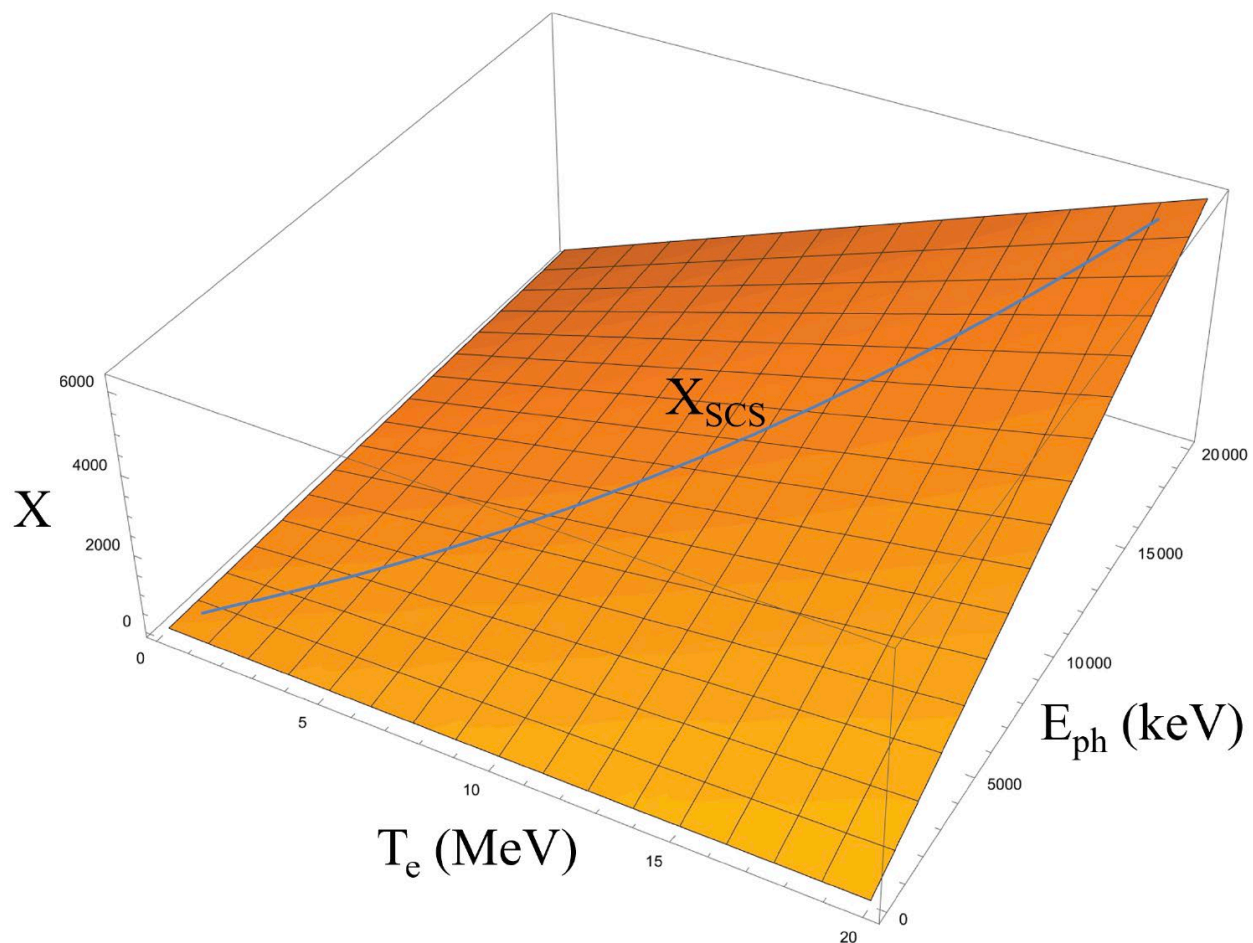
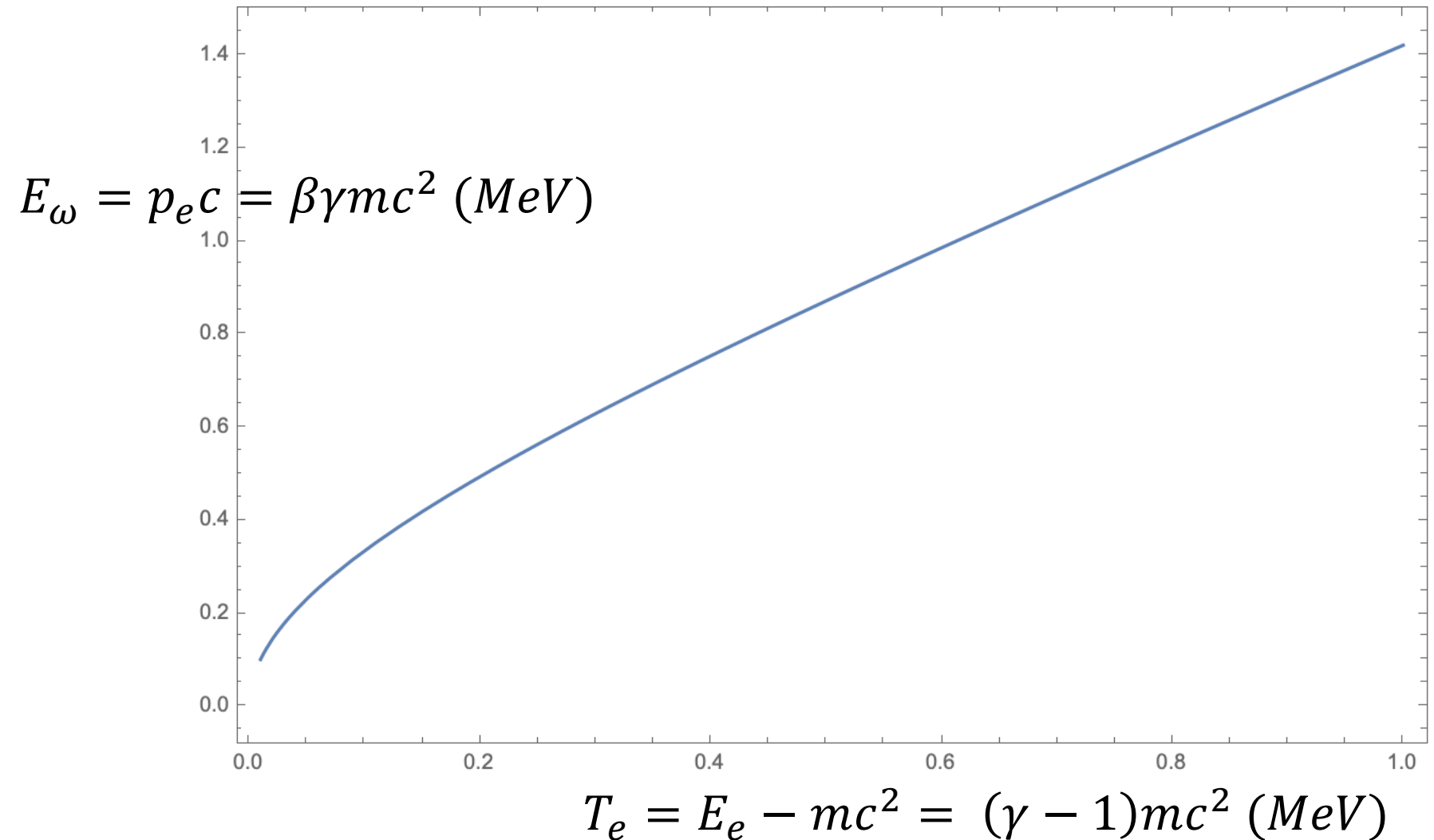


Figure 2: 3D representation of the value of the recoil factor X as a function of the interacting electron kinetic energy (T_e) and of the incident photon energy. The line shows the recoil value in SCS conditions

Symmetric Compton

Scaling of photon energy vs. electron kinetic energy



But Arthur Compton fundamental experiments, leading to Compton scattering interpretation and the proof of light quanta existence (the photon) wouldn't simply be possible without the discovery of X-rays by Roentgen (1895), who in turns couldn't obtain his result without the vacuum tubes invented by William Crookes, who in turns exploited the glass-to-metal welding technique invented by Heinrich Geissler.

The Paradigm of Particle Accelerators!

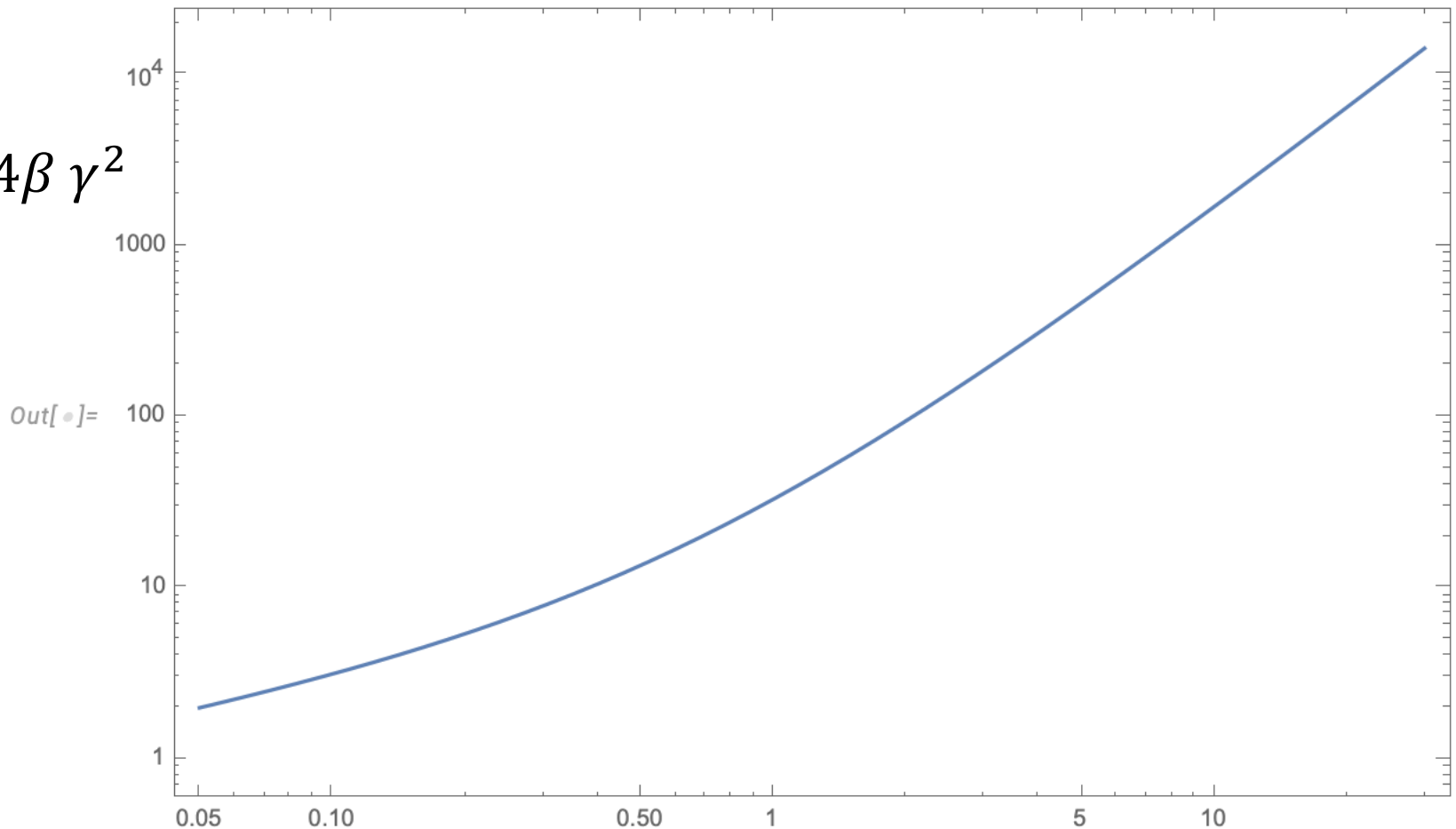


Symmetric Compton

Scaling of X , recoil factor, vs. electron kinetic energy

$$E_\omega = p_e c = \beta \gamma m c^2$$

$$X = 4\beta \gamma^2$$

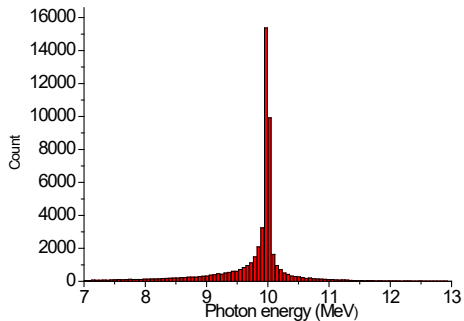


$$T_e = E_e - mc^2 = (\gamma - 1)mc^2 \text{ (MeV)}$$

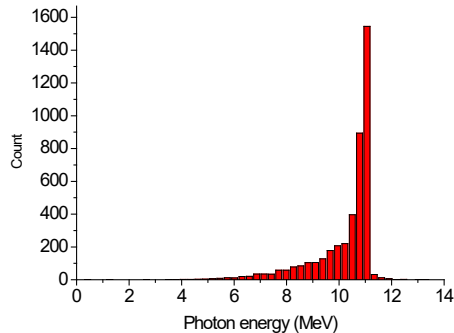
Fixed recoil $X=1531$

Moving away from Symmetric Compton

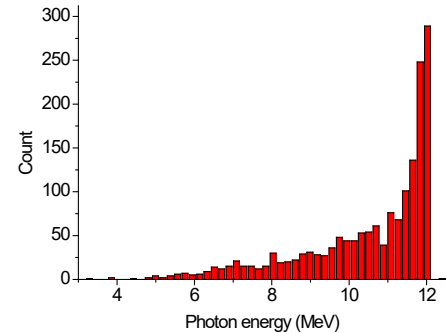
incident $\Delta E_{\text{phot}}/E=20\%$



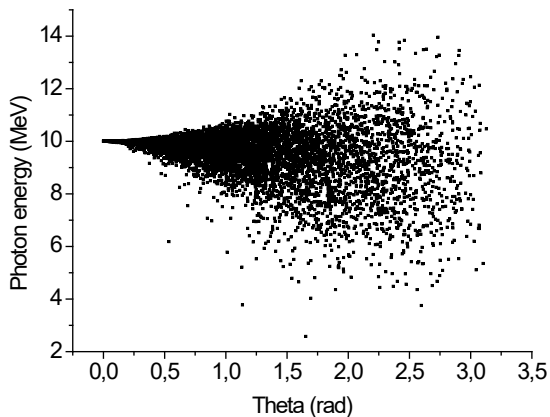
Initial Electron energy=10.013 MeV,
Initial Photon energy=10.0 MeV



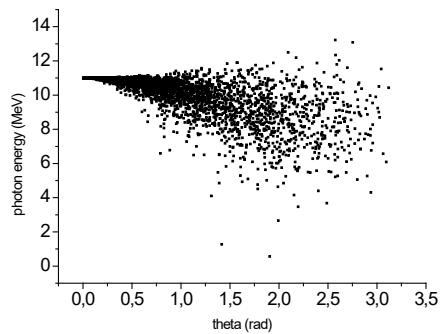
Initial Electron energy=11.0 MeV,
Initial Photon energy=9.08 MeV



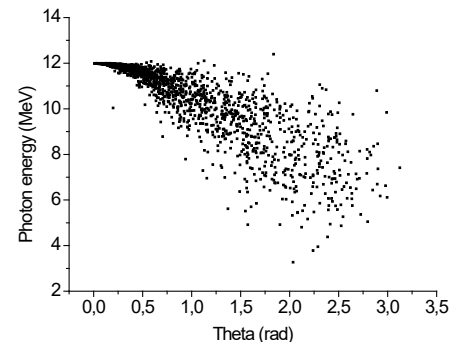
Initial Electron energy=12.0 MeV,
Initial Photon energy=8.33 MeV



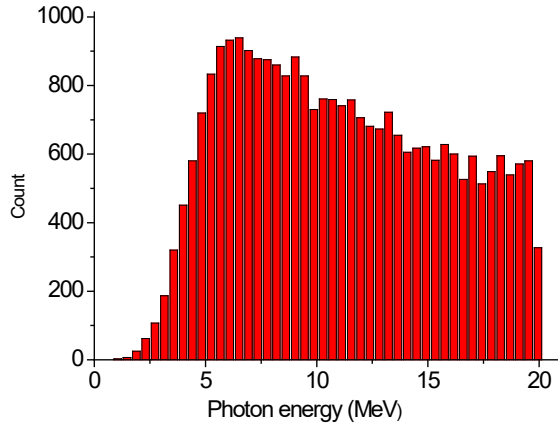
No $\gamma^2\theta^2$ disease



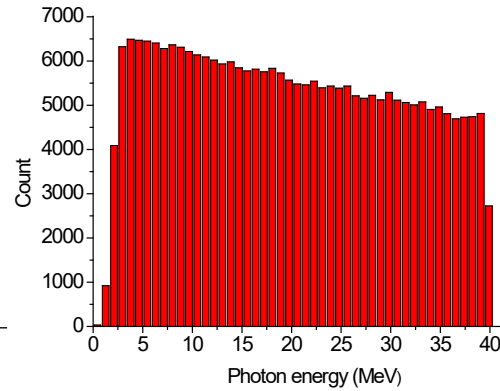
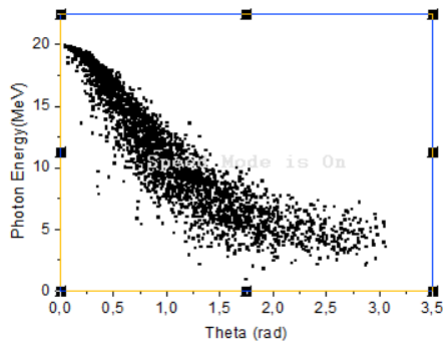
The onset of $\gamma^2\theta^2$ disease



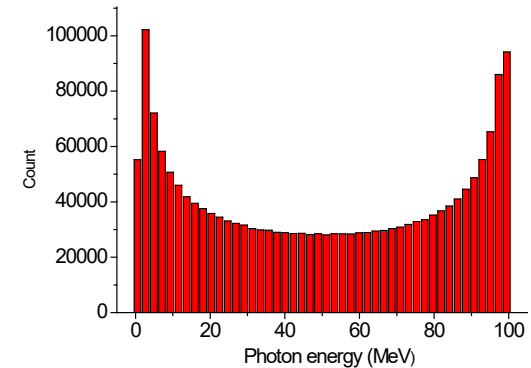
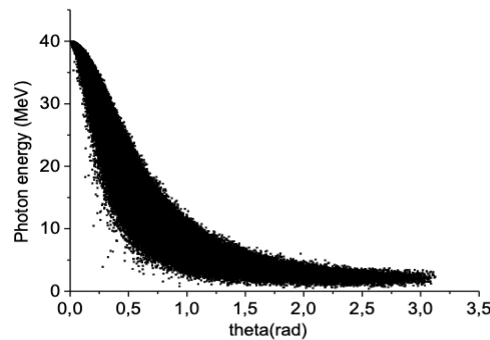
Fixed recoil $X=1531$ going from SCS to ICS



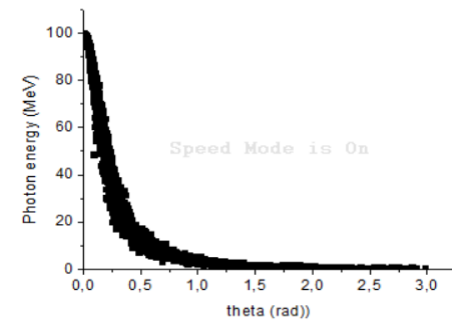
Initial Electron energy=20.0 MeV,
Initial Photon energy=5 MeV,
 $\Delta E_{\text{phot}}/E=0.2$



Initial Electron energy=40.0 MeV,
Initial Photon energy=2.5 MeV,
 $\Delta E_{\text{phot}}/E=0.2$



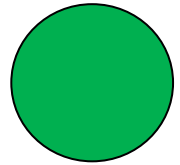
Initial Electron energy=100.0 MeV,
Initial Photon energy=1 MeV,
 $\Delta E_{\text{phot}}/E=0.2$



full $\gamma^2\theta^2$ disease – the moustache pattern

How do we derive fundamental I.C.S. formula?

$$E'_{ph} = \frac{\gamma^2(1 + \beta)}{\gamma^2(1 - \beta \cos \theta) + \frac{X}{4}(1 + \cos \theta)} E_{ph}$$

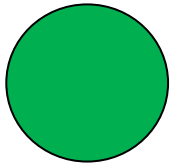


that is valid for head-on collision, where electron and photon counter-propagate along z-axis

$$\begin{cases} E_e + E_{ph} = E'_e + E'_{ph} \\ cp_e - E_{ph} = cp'_{ze} + E'_{ph} \cos \vartheta \\ 0 = cp'_{xe} + E'_{ph} \sin \vartheta \end{cases}$$

conservation of total momentum and total energy

$$\begin{cases} \gamma mc^2 + E_{ph} = \sqrt{c^2 p'^2_{xe} + c^2 p'^2_{ze} + m^2 c^4} + E'_{ph} \\ mc^2 \beta \gamma - E_{ph} = cp'_{ze} + E'_{ph} \cos \vartheta \\ 0 = cp'_{xe} + E'_{ph} \sin \vartheta \end{cases}$$



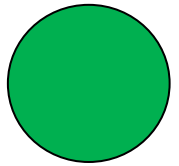
$$\left\{ \begin{array}{l} \gamma mc^2 + E_{ph} = \sqrt{c^2 p_{xe}'^2 + c^2 p_{ze}'^2 + m^2 c^4} + E_{ph}' \\ mc^2 \beta \gamma - E_{ph} = c p_{ze}' + E_{ph}' \cos \vartheta \\ 0 = c p_{xe}' + E_{ph}' \sin \vartheta \end{array} \right. :$$

$$c^2 p_{xe}'^2 = E_{ph}'^2 \sin^2 \vartheta$$

$$c^2 p_{ze}'^2 = (\beta \gamma mc^2 - E_{ph} - E_{ph}' \cos \vartheta)^2$$

$$\begin{aligned} & (\gamma mc^2 + E_{ph} - E_{ph}')^2 = \\ & E_{ph}'^2 \sin^2 \vartheta + (\beta \gamma mc^2 - E_{ph} - E_{ph}' \cos \vartheta)^2 + m^2 c^4 \end{aligned}$$

$$\begin{aligned} & \gamma mc^2 (E_{ph} - E_{ph}') - E_{ph} E_{ph}' = \\ & E_{ph} E_{ph}' \cos \vartheta - \beta \gamma mc^2 (E_{ph} + E_{ph}' \cos \vartheta) \end{aligned}$$



$$\gamma mc^2 (E_{ph} - E'_{ph}) - E_{ph} E'_{ph} = E_{ph} E'_{ph} \cos \vartheta - \beta \gamma mc^2 (E_{ph} + E'_{ph} \cos \vartheta)$$

$$E'_{ph} [\gamma mc^2 (\beta \cos \vartheta - 1) - E_{ph} (1 + \cos \vartheta)] = -E_{ph} \gamma mc^2 (1 + \beta)$$

$$E'_{ph} = \frac{\gamma(1 + \beta)}{\gamma(1 - \beta \cos \vartheta) + \frac{E_{ph}}{mc^2} (1 + \cos \vartheta)} E_{ph}$$

$$X \equiv \frac{4\gamma E_{ph}}{mc^2} = \frac{4E_{ph} E_e}{(mc^2)^2}$$

$$E'_{ph} = \frac{(1 + \beta)\gamma^2}{\gamma^2(1 - \beta \cos \vartheta) + \frac{X}{4} (1 + \cos \vartheta)} E_{ph}$$

$$E'_{ph} = \frac{(1 + \beta)\gamma^2}{\gamma^2(1 - \beta \cos \vartheta) + \frac{X}{4}(1 + \cos \vartheta)} E_{ph}$$

N.B. if $\theta = \pi$ $E'_{ph} = E_{ph}$ for any γ

$$E'_e = E_e + E_{ph} - E'_{ph}$$

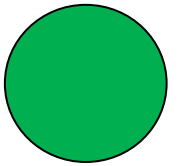
Compton Scattering of X-rays on atomic electrons

$$\beta = 0 ; \gamma = 1 \Rightarrow E'_{ph} = \frac{E_{ph}}{1 + \frac{X}{4}(1 + \cos \vartheta)}$$

Inverse Compton Scattering of photons on relativistic electrons

$$\gamma \gg 1 ; \beta \approx 1 - \frac{1}{2\gamma^2} \Rightarrow$$

$$E'_{ph} = \frac{2\gamma^2 E_{ph}}{\gamma^2 \left[1 - \cos \vartheta \left(1 - \frac{1}{2\gamma^2} \right) \right] + \frac{X}{4}(1 + \cos \vartheta)}$$



$$E'_{ph} = \frac{2\gamma^2 E_{ph}}{\gamma^2 \left[1 - \cos \vartheta \left(1 - \frac{1}{2\gamma^2} \right) \right] + \frac{X}{4} (1 + \cos \vartheta)}$$

$$\vartheta \ll 1 ; \quad \cos \vartheta \approx 1 - \frac{\vartheta^2}{2} \quad \Rightarrow$$

$$E'_{ph} = \frac{2\gamma^2 E_{ph}}{\gamma^2 \left[\frac{\vartheta^2}{2} + \frac{1}{2\gamma^2} \right] + \frac{X}{2}}$$

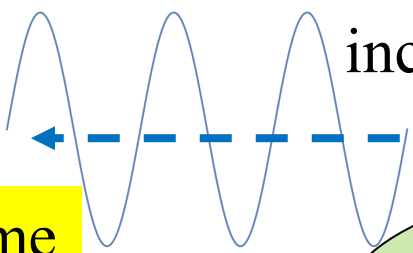
⇓

$$E'_{ph} = \frac{4\gamma^2 E_{ph}}{1 + \gamma^2 \vartheta^2 + X}$$

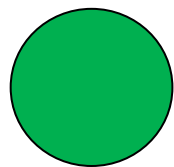
incident electron
 $E_e = \gamma mc^2$



Lab Reference Frame

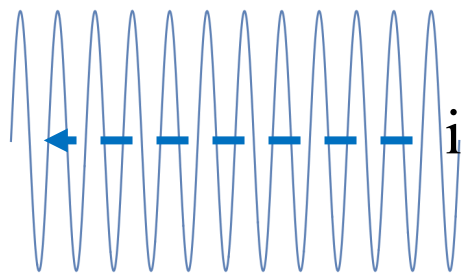


incident photon E_{ph}



Kinematics of Inverse Compton Scattering a Cartoon

Electron rest frame
 $E_e^* = mc^2$



incident photon $E_{ph}^* = 2\gamma E_{ph}$

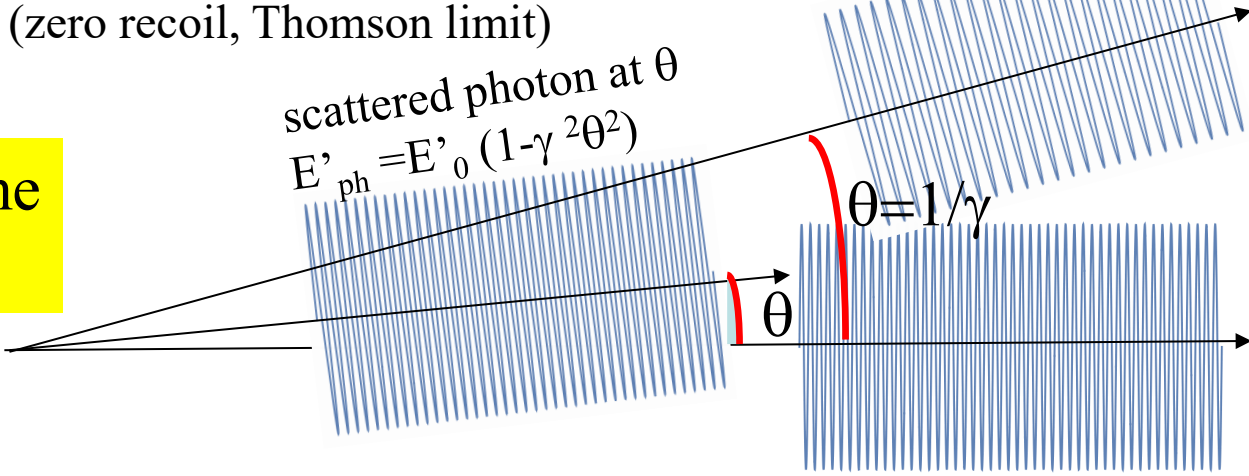
if $E_{ph}^* \ll mc^2$ the photon is scattered back elastically with same energy E_{ph}^* (zero recoil, Thomson limit)

scattered photon at $\theta = 1/\gamma$ $E'_{ph} = E'_0 / 2$

Lab Reference Frame after Scattering

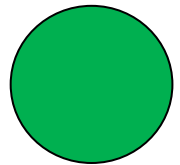


scattered electron
 $E'_e = \gamma mc^2 + E_{ph} - E'_{ph}$



scattered photon at θ
 $E'_{ph} = E'_0 (1 - \gamma^2 \theta^2)$

energy of scattered photon at $\theta=0$ $E'_0 = 2\gamma E_{ph}^* = 4\gamma^2 E_{ph}$



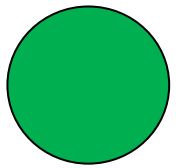
To obtain the momentum components of the emitted particles in the laboratory frame we have to apply the **Lorentz** transformations to the momenta values in CM:

$$\left\{ \begin{array}{l} \nu = \gamma_{CM}(k^* + k_x^*\beta_x + k_y^*\beta_y + k_z^*\beta_z) \\ k_x = k^*\beta_x\gamma_{CM} + k_x^*\frac{1 + \gamma_{CM}^2\beta_x^2}{1 + \gamma_{CM}} + k_y^*\frac{\gamma_{CM}^2\beta_x\beta_y}{1 + \gamma_{CM}} + k_z^*\frac{\gamma_{CM}^2\beta_x\beta_z}{1 + \gamma_{CM}} \\ k_y = k^*\beta_y\gamma_{CM} + k_x^*\frac{\gamma_{CM}^2\beta_x\beta_y}{1 + \gamma_{CM}} + k_y^*\frac{1 + \gamma_{CM}^2\beta_y^2}{1 + \gamma_{CM}} + k_z^*\frac{\gamma_{CM}^2\beta_y\beta_z}{1 + \gamma_{CM}} \\ k_z = k^*\beta_z\gamma_{CM} + k_x^*\frac{\gamma_{CM}^2\beta_x\beta_z}{1 + \gamma_{CM}} + k_y^*\frac{\gamma_{CM}^2\beta_y\beta_z}{1 + \gamma_{CM}} + k_z^*\frac{1 + \gamma_{CM}^2\beta_z^2}{1 + \gamma_{CM}} \end{array} \right. \quad (\text{C.0.6})$$

where $\underline{\beta}_{CM} = (\beta_x, \beta_y, \beta_z)$. If the scattering is head-on along the z axis, the above transformations simplify in

$$\left\{ \begin{array}{l} \nu = k^*\gamma_{CM}(1 + \beta_{CM}\cos\theta^*) \\ k_x = k^*\sin\theta^*\cos\phi^* \\ k_y = k^*\sin\theta^*\sin\phi^* \\ k_z = k^*\gamma_{CM}(\beta_{CM} + \cos\theta^*) \end{array} \right. \quad (\text{C.0.7})$$

A look at 4-vectors (head-on collision)



Inverse Compton

$$E_\omega \ll \gamma mc^2 ; \gamma \gg 1$$

$$\bar{P}_e = \{\gamma mc, 0, 0, \beta \gamma mc\}$$

$$\bar{P}_\omega = \{E_\omega/c, 0, 0, -E_\omega/c\}$$

$$\bar{P}_{tot} \cong \left\{ \gamma mc + \frac{E_\omega}{c}, 0, 0, \beta \gamma mc - \frac{E_\omega}{c} \right\}$$

$$E_{cm} \equiv c \sqrt{\bar{P}_{tot} \otimes \bar{P}_{tot}}$$

fixed target

$$E_{cm} = mc^2 \sqrt{1 + \frac{(1 + \beta)X}{2}} \approx mc^2 \sqrt{1 + 4\gamma E_\omega / mc^2}$$

$$\gamma_{cm} \cong \gamma / \sqrt{1 + X} ; \gamma_{cm} \xrightarrow{\gamma \rightarrow \infty} 1$$

Symmetric Compton

$$E_\omega = p_e c = \beta \gamma mc^2$$

$$\bar{P}_e = \{\gamma mc, 0, 0, \beta \gamma mc\}$$

$$\bar{P}_\omega = \{\beta \gamma mc, 0, 0, -\beta \gamma mc\}$$

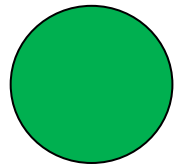
$$\bar{P}_{tot} = \{(1 + \beta)\gamma mc, 0, 0, 0\}$$

$$\gamma_{cm} \equiv \frac{E_{lab}}{E_{cm}}$$

collider

$$E_{cm} = (1 + \beta)\gamma mc^2$$

$$\gamma_{cm} = 1$$



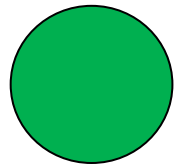
The four-momentum of a particle is defined as $\mathbf{p} = \left(\frac{E}{c}, p_x, p_y, p_z \right)$, where E is the total energy of the particle, c is the speed of light in vacuum, and p_x, p_y, p_z are the components of the particle's momentum along the x, y, z axes respectively.

Let us consider the case of a head-on collision between a photon and a counter-propagating electron along the z -axis. Before the collision, the electron and the photon have the following four-momenta:

$$\begin{aligned} \mathbf{p}_e &= (\gamma m_0 c, 0, 0, \beta \gamma m_0 c), \\ \mathbf{p}_{\text{ph}} &= \left(\frac{E_{\text{ph}}}{c}, 0, 0, -\frac{E_{\text{ph}}}{c} \right), \end{aligned} \quad (25)$$

and the total four-momentum is:

$$\mathbf{p}_{\text{tot}} = \left(\gamma m_0 c + \frac{E_{\text{ph}}}{c}, 0, 0, \beta \gamma m_0 c - \frac{E_{\text{ph}}}{c} \right). \quad (26)$$



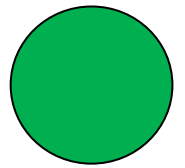
The energy available in the center of mass E_{cm} , in terms of the recoil factor introduced in Eq. (2), is:

$$\begin{aligned}
 E_{cm} &= c \sqrt{\mathbf{p}_{tot} \cdot \mathbf{p}_{tot}} = m_0 c^2 \sqrt{(1 + \beta) \frac{X}{2} + 1} = \\
 &= m_0 c^2 \sqrt{(1 + \beta) \frac{2E_e E_{ph}}{(m_0 c^2)^2} + 1}.
 \end{aligned}
 \tag{27}$$

The different regimes of Compton scattering can be analyzed in terms of their center of mass energy E_{cm} .

For the DC regime ($\beta = 0$, $\gamma = 1$):

$$E_{cm-DC} = m_0 c^2 \sqrt{\frac{2E_{ph}}{m_0 c^2} + 1}.
 \tag{28}$$



On the opposite side, in the ICS regime ($\beta \simeq 1$), we obtain:

$$E_{cm-ICS} = m_0 c^2 \sqrt{X + 1} = m_0 c^2 \sqrt{\frac{4\gamma E_{ph}}{m_0 c^2} + 1}. \quad (29)$$

Finally, for the SCS regime ($E_{ph} = \beta E_e = \beta \gamma m_0 c^2$):

$$E_{cm-SCS} = (1 + \beta)\gamma m_0 c^2. \quad (30)$$

In this peculiar situation, $E_{cm} \propto \gamma$ like in a collider. Being $\gamma_{cm} \equiv E_{lab}/E_{cm}$ the Lorentz boost factor associated to the center of mass reference frame. In SCS we have $\gamma_{cm} = 1$ (because $E_{lab-SCS} = E_{cm-SCS}$), meaning that the center of mass of the system is at rest in the laboratory system, and the radiation produced here has the same angular and spectral distribution seen by a detector at rest in the lab. On the other hand, DC and ICS exhibit a dependence of the available energy E_{cm} typical of a fixed target collision, where E_{cm} scales like $E_{cm} \propto \sqrt{T_p}$, where T_p is the projectile kinetic energy. ICS regime is characterized by $\gamma_{cm} \gg 1$ since the center of mass reference frame is almost traveling with the electron (as shown in Ref. [17] $\gamma_{cm} = \gamma/(1 + X)$).