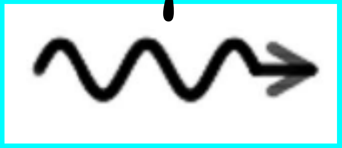
Applications and Approaches of Advanced Gamma ray Compton Sources

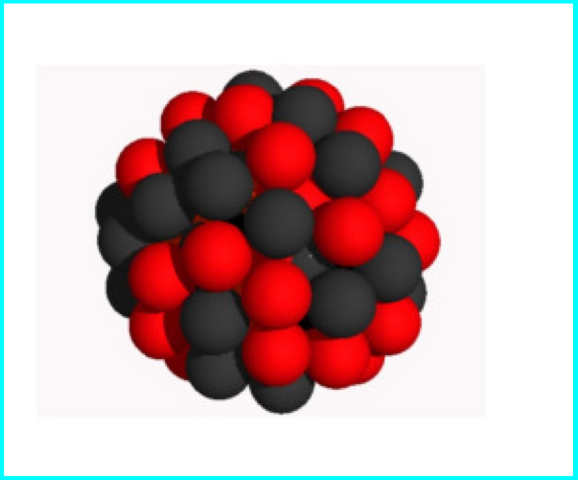
Luca Serafini – INFN-Milan

- **Mono-chromatic Gamma Ray beams (bdw < 0.5%) are needed for Nuclear Physics Research / Nuclear Photonics Applications**
- **Compton (back-scattering) Sources are (mini)Colliders aiming at achieving these demands**
- **Similarities with FELs - versus Peculiarities: from the physics of single electron-photon (back)scattering to electron-photon colliders with maximum (spectral)luminosity**
- **USA/Japan are leading (HIgS, MEGa-ray, KeK-ATF), Europe is following, with good perspectives to catch-up with ELI-NP**

Photonuclear Reactions

γ

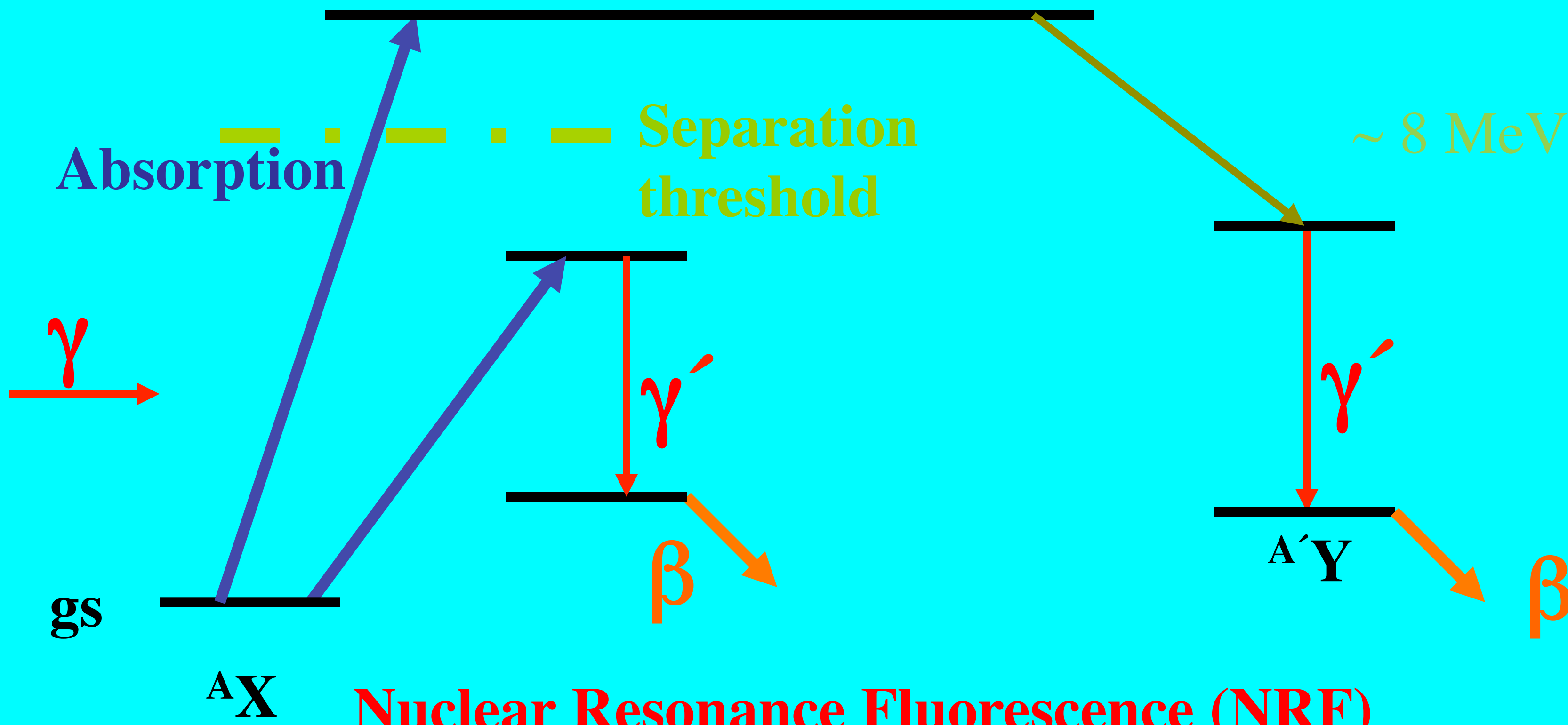




What happens?

courtesy of N. Pietralla (Darmstadt)

Photonuclear Reactions



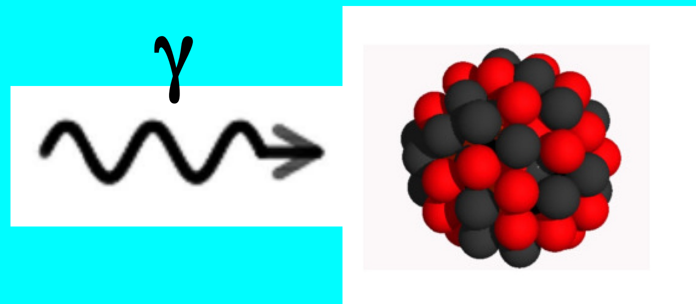
Nuclear Resonance Fluorescence (NRF)

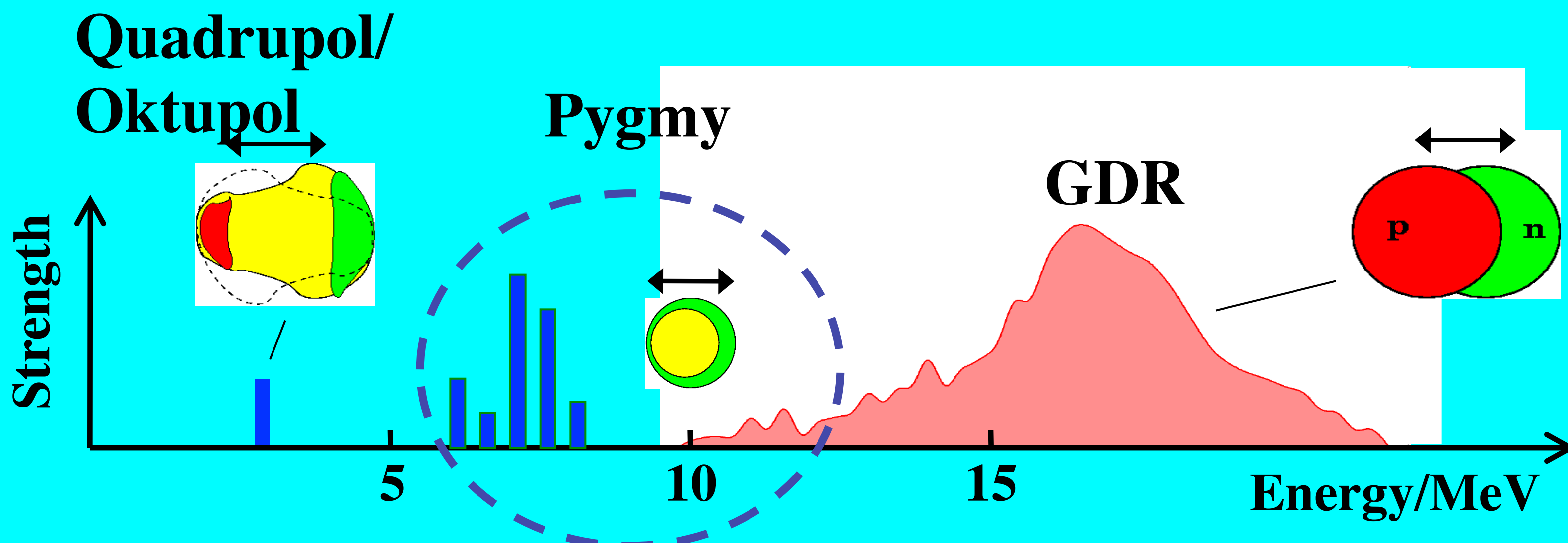
Photoactivation

Photodisintegration **(-activation)**

courtesy of N. Pietralla (Darmstadt)

E1 Strength Distribution





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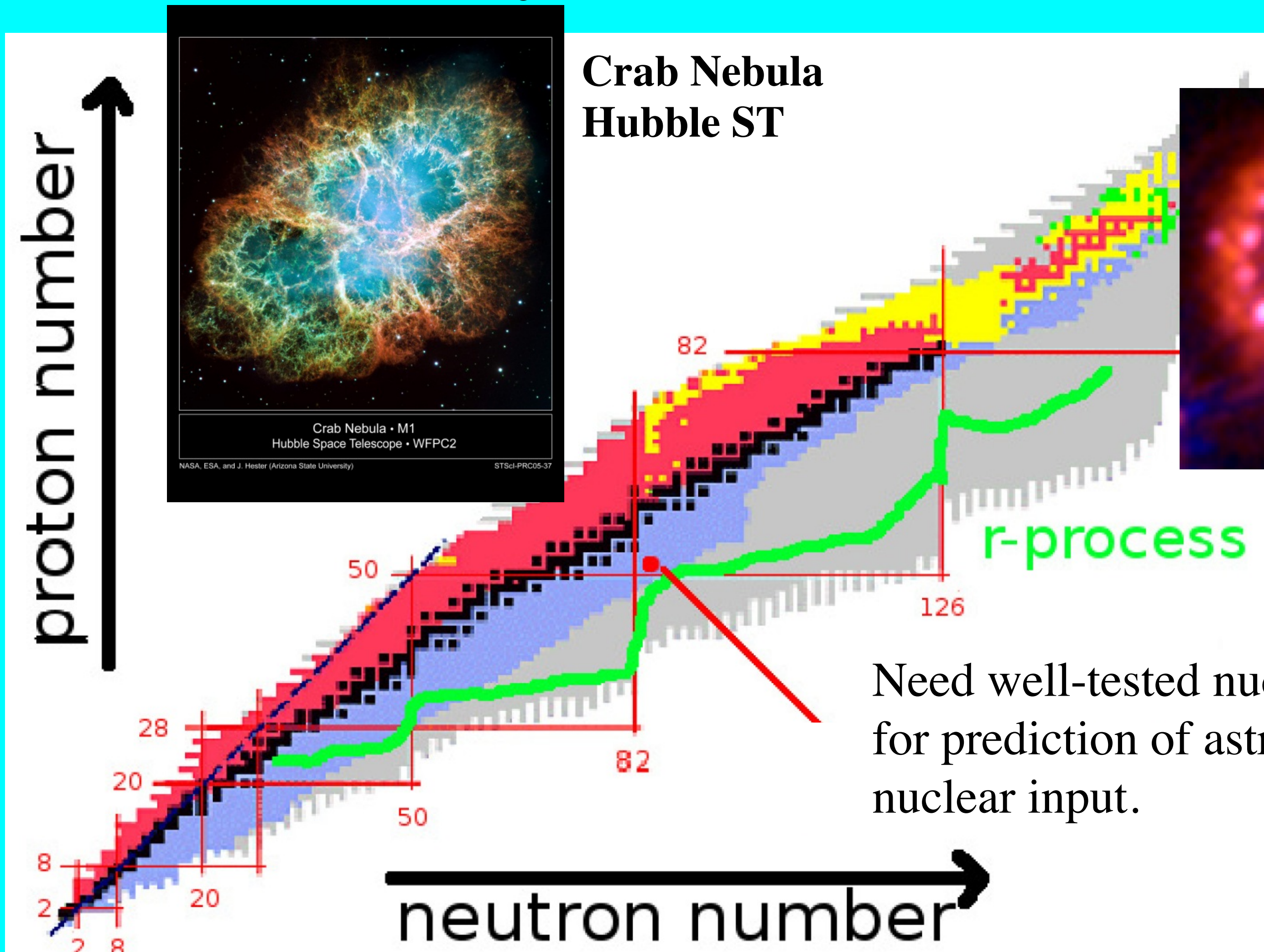
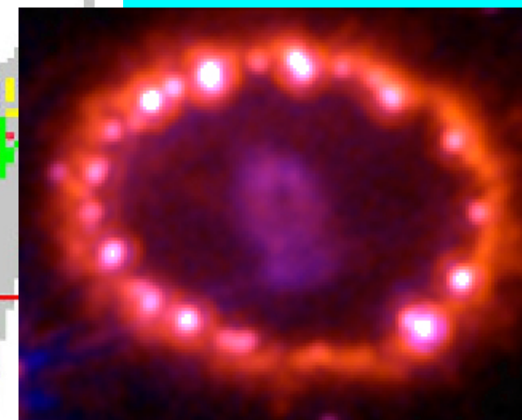
Journey to the „known Unknown“



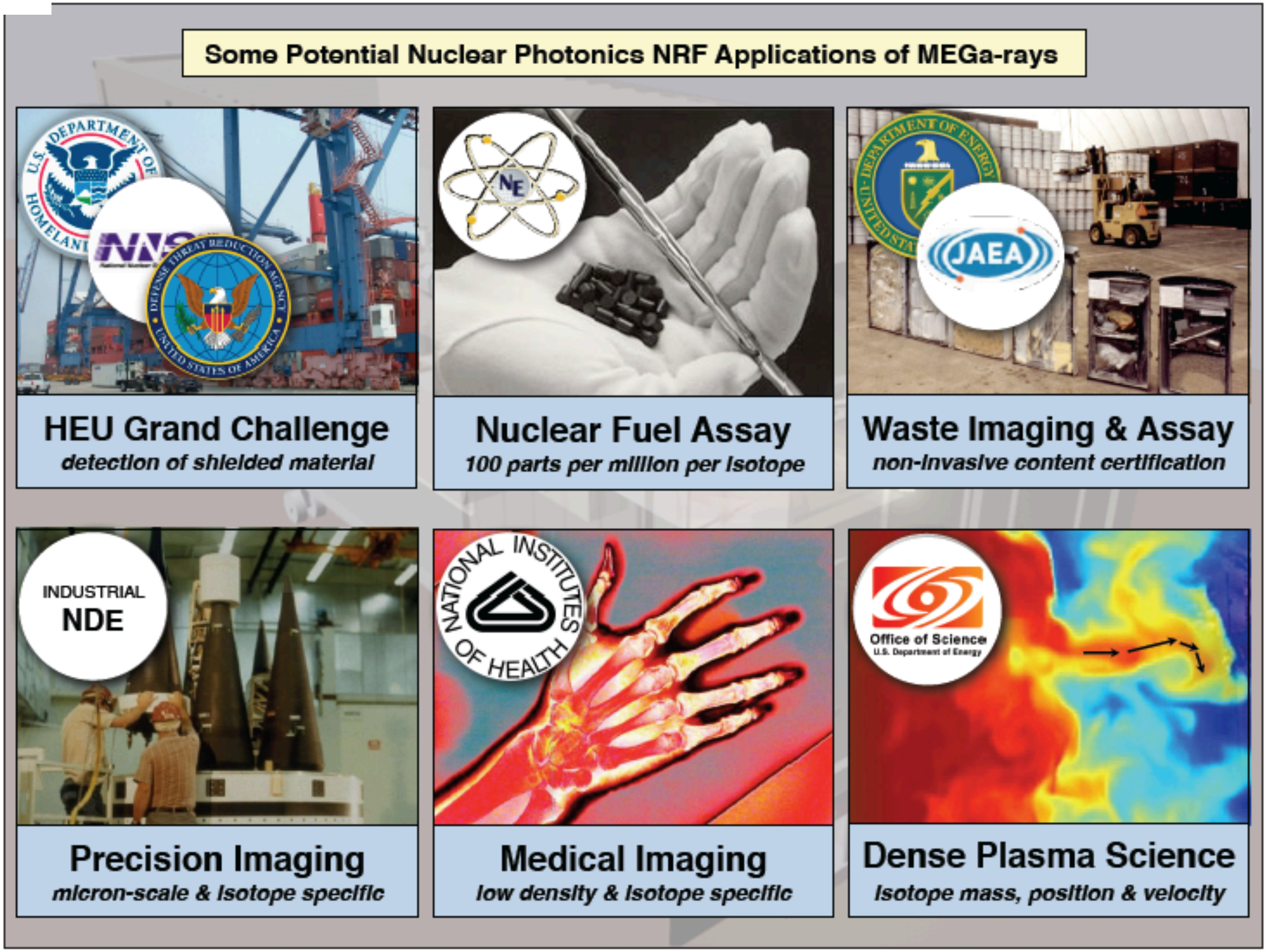
Crab Nebula
Hubble ST



SN 1987A
Hubble ST

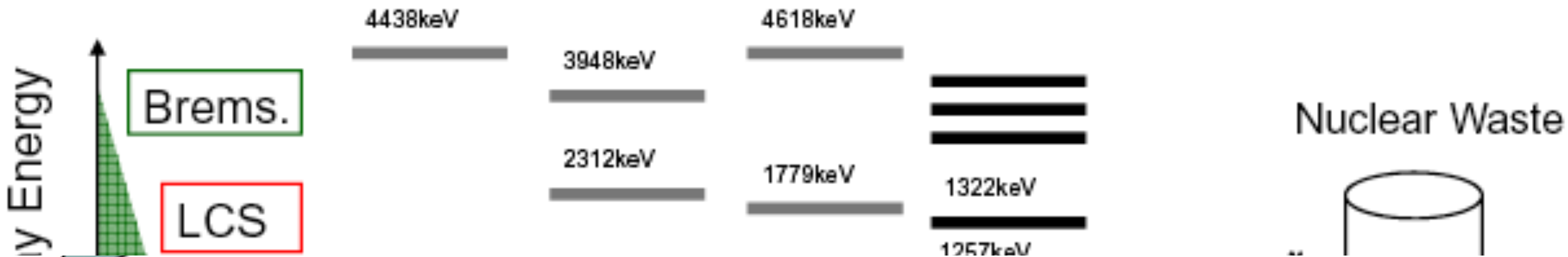
Need well-tested nuclear models for prediction of astro-relevant nuclear input.

courtesy of N. Pietralla (Darmstadt)

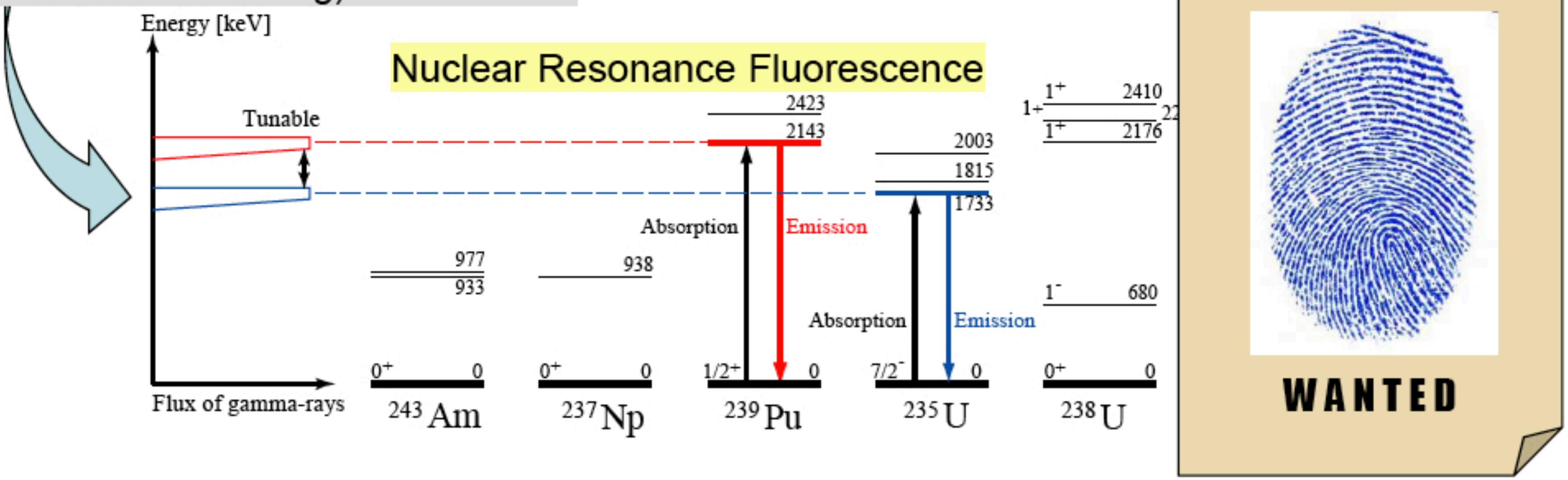


Courtesy C. Barty - LLNL

Nondestructive Assay by Nuclear Resonant Fluorescence

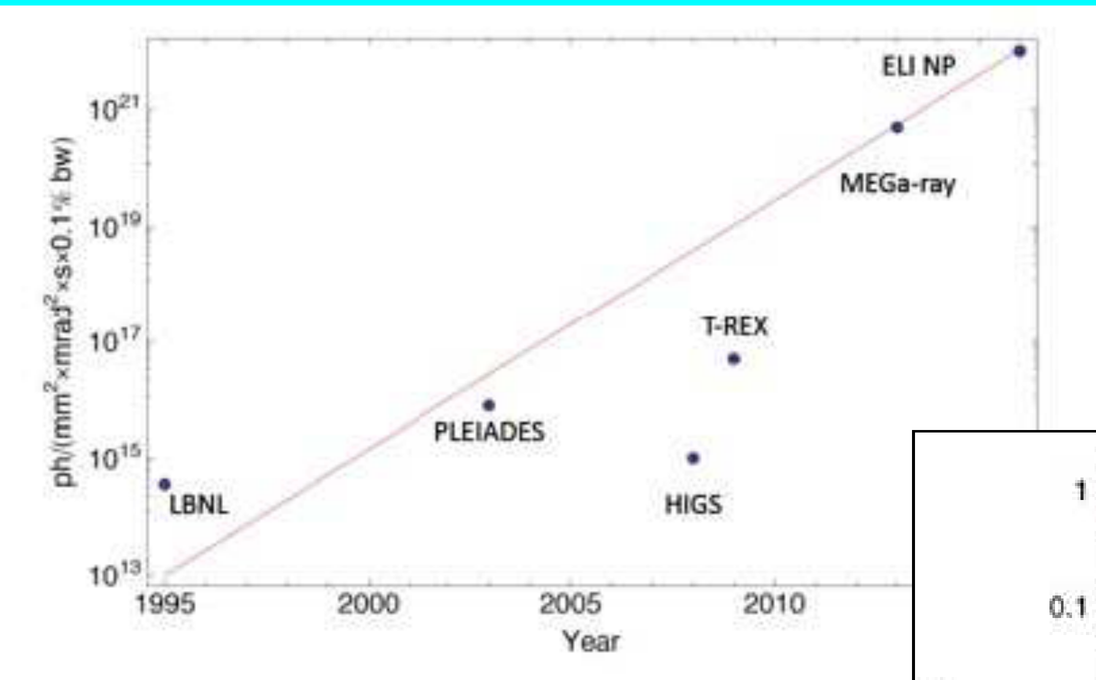


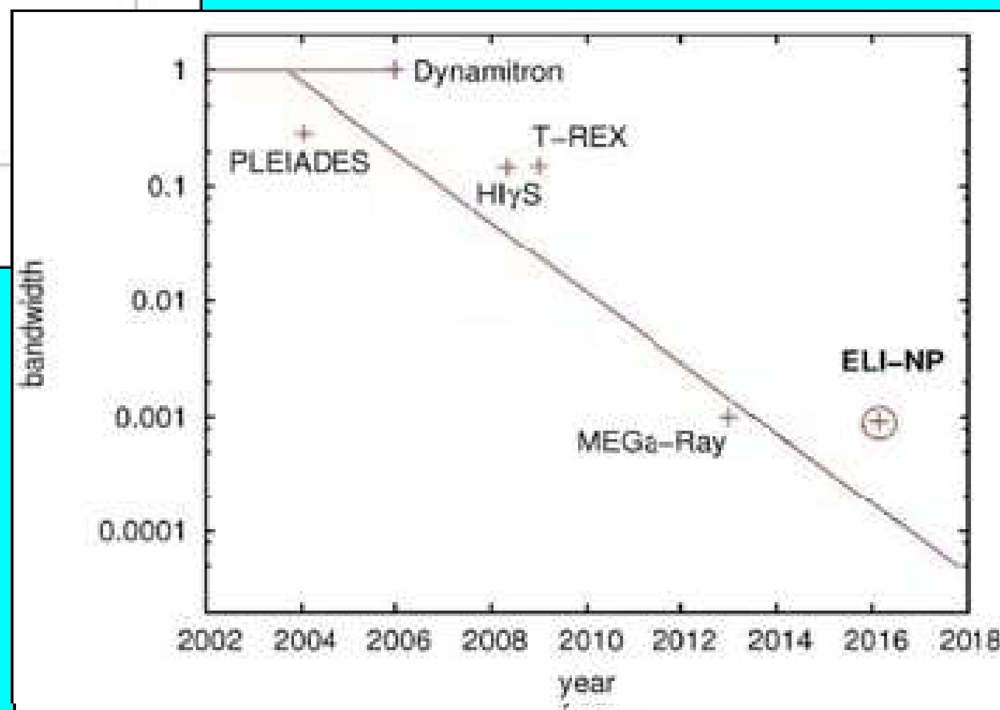
Mono-energetic & tunable γ-ray beam
(unlike bremsstrahlung)



R. Hajima et al., J. Nuclear Science and Technology, 45, 441-451 (2008).

ELI-NP γ beam: the quest for narrow bandwidths (from 10^{-2} down to 10^{-3})





Courtesy V. Zamfir – ELI-NP

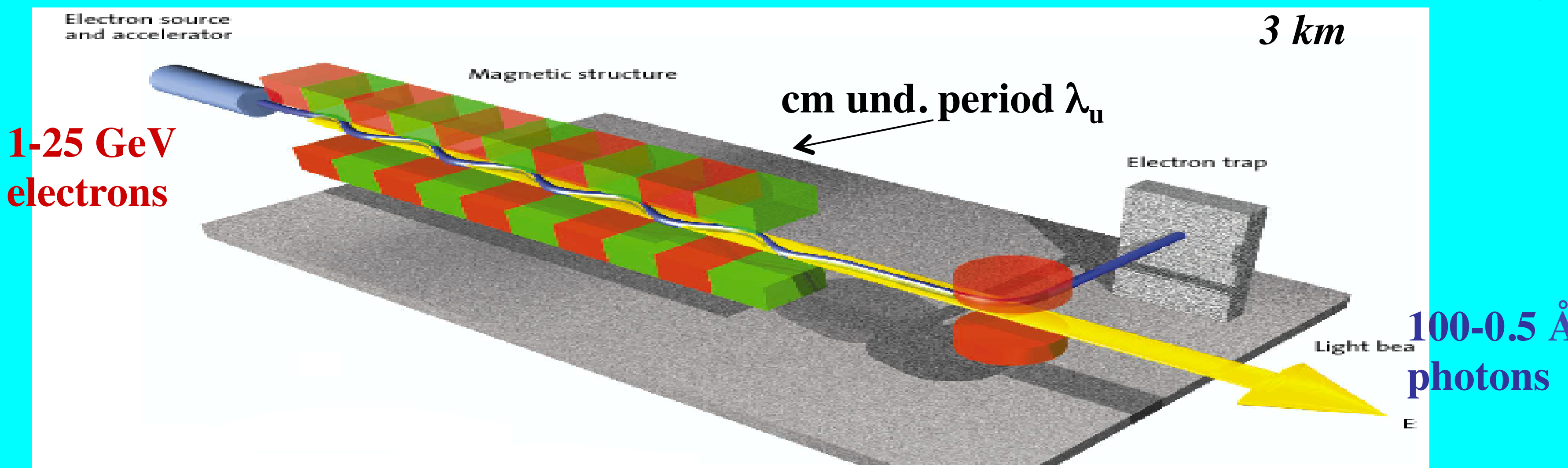
How do we produce a narrow bandwidth high spectral density (1-20 MeV) gamma ray beam?

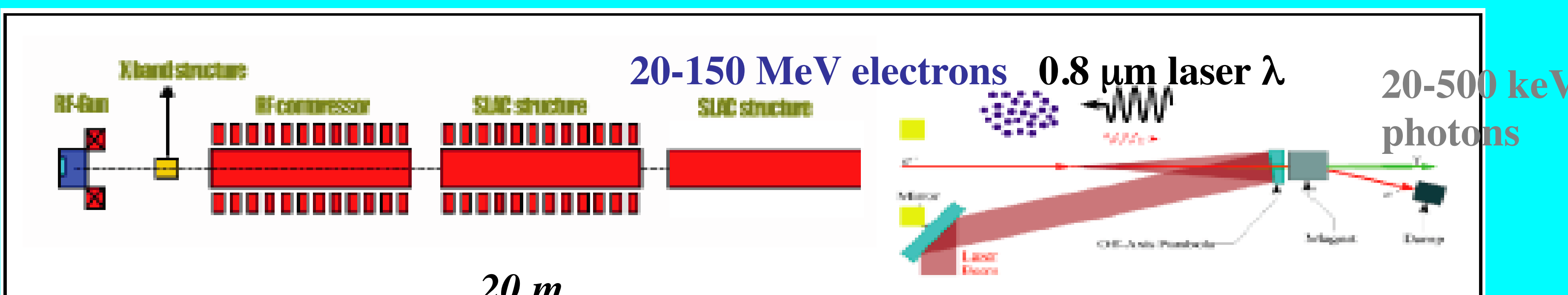
Compton back-scattering of high quality lasers by high phase space density electron beams (low energy spread, low transv. momentum – cold longitudinally, cold transversally) are good candidates

We need electron beams with 10 micron size focal spots at collision point (to achieve luminosity), with angular divergence smaller than 30 micro-radians (to achieve small bandwidth), energy spread lower than 0.1% (bandwidth…) and pointing stability better than 10 micro-radians (to produce a physical gamma ray beam via collimation)

We need high quality (M^2<1.2) psec laser pulses with 1 J at 100 Hz synchronized to 0.5 psec with the electron beam, pointing stable to better than 10 microradians at collision point

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





FEL resonance condition

$$\lambda_R = \lambda_w \frac{\left(1 + a_w^{\;2}\right)}{2\gamma^2}$$

(magnetostatic undulator)

Example : for λ_R=1A, λ_w=2cm, E=7 GeV

$$a_w = 0.93\lambda_w\left[cm\right]B_w[T]$$

$$\lambda_R = \lambda \frac{\left(1 + a_0^{\;2}/2\right)}{4\gamma^2}$$

(electromagnetic undulator)

Example : for λ_R=1A, λ=0.8μm, E=25MeV

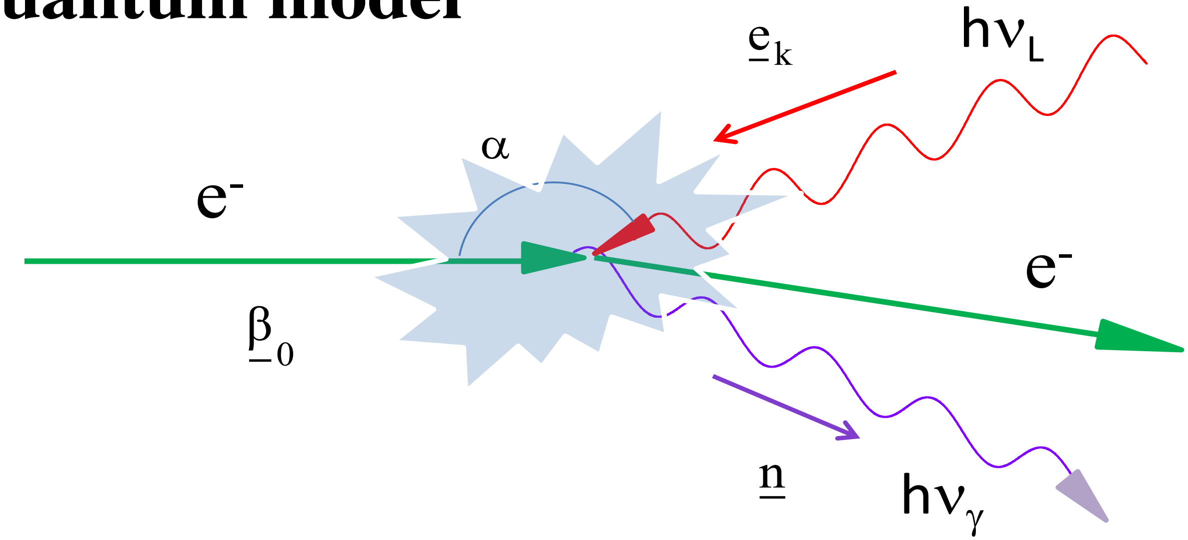
$$a_0 \propto \frac{\lambda\left[\mu m\right]\sqrt{P\left[TW\right]}}{R_0\left[\mu m\right]}$$

laser power

laser spot size

The Physics of Compton Inverse Scattering is quite straightforward

Quantum model



$$
\left\{
\begin{array}{l}
mc^2(\gamma-\gamma_0)=-h(\nu-\nu_L) \\
mc(\underline{\beta}\gamma-\underline{\beta}_0\gamma_0)=-h(\underline{k}-\underline{k}_L)/2\pi
\end{array}
\right.
$$

Energy and momentum conservation laws

γ_0:initial Lorentz factor

$$
\nu = \nu_L \frac{1-\underline{e}_k\cdot\underline{\beta}_0}{1-\underline{n}\cdot\underline{\beta}_0 \boxed{+\frac{h\nu_L}{mc^2\gamma_0}(1-\underline{e}_k\cdot\underline{n})}}
$$

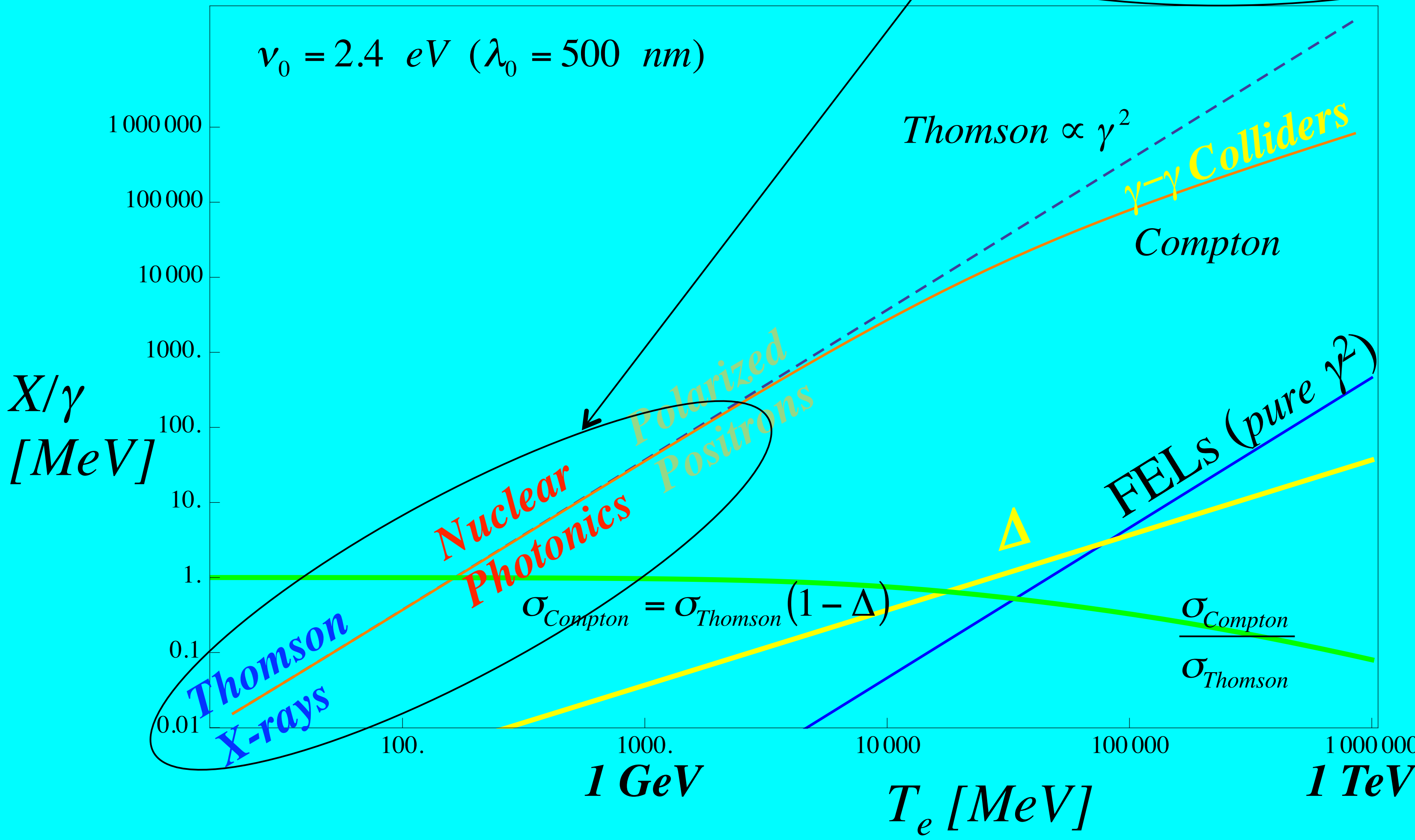
$$
\lambda = \boxed{\lambda_L \frac{1-\underline{n}\cdot\underline{\beta}_0}{1-\underline{e}_k\cdot\underline{\beta}_0}} + \boxed{\frac{h}{mc\gamma_0}\frac{1-\underline{e}_k\cdot\underline{n}}{1-\underline{e}_k\cdot\underline{\beta}_0}}
$$

3 regimes: a) Elastic, Thomson b) Quasi-Elastic, Compton with Thomson cross-section c) Inelastic, Compton, recoil dominated

$$\nu_\gamma = \nu_0 \frac{1 - \underline{n}\cdot\underline{\beta}_0}{1 - \underline{e}_k\cdot\underline{\beta}_0 - \dfrac{h\nu_0}{mc^2}(1+\cos\theta)} \Rightarrow + coll.\ eff.$$

$$\nu_\gamma = \nu_0 \frac{4\gamma^2}{1+\gamma^2\theta^2 + a_0^2/2}(1-\Delta)$$

$$\Delta = \frac{4\gamma h\nu_0}{mc^2} \quad \Delta << 1\ \ Compton\ \ recoil$$

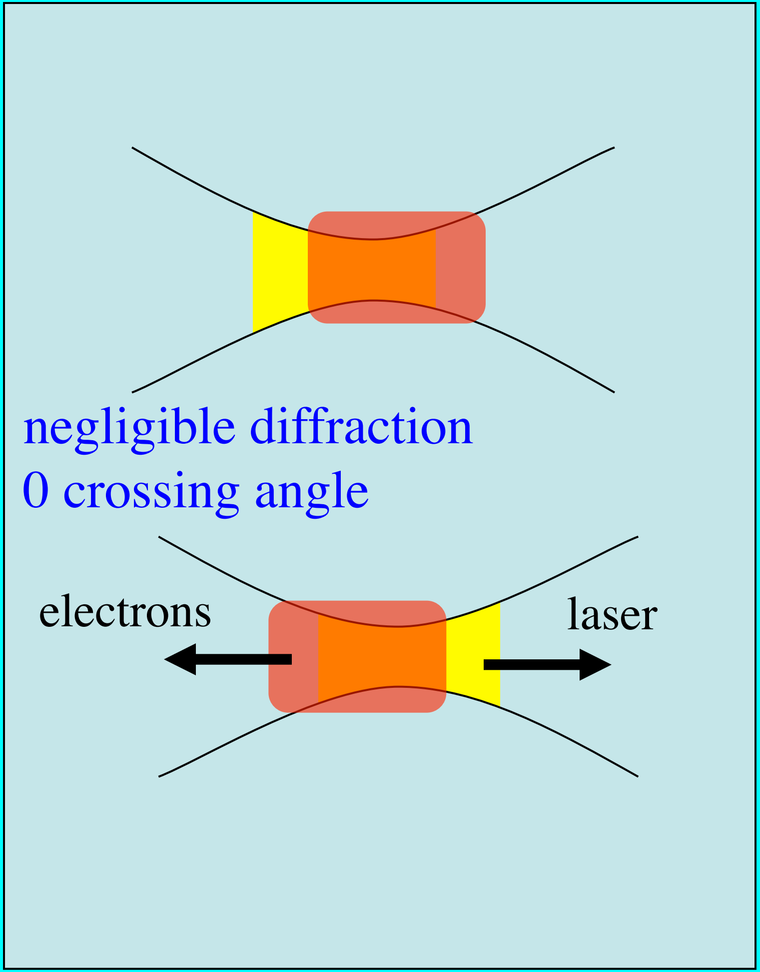


If the Physics of Compton/Thomson back-scattering is straightforward….

The Challenge of making a Compton Source out of an electron-photon beam Collider, and maximizing the spectral flux and quality of the generated X/gamma ray beam, is a completely different issue!

Build up a set of criteria for optimal design of the Gamma Beam System, based on the concept of *Spectral Luminosity*, *i.e.* Luminosity per unit bandwidth

$\sigma_T = 0.67 \cdot 10^{-24} cm^2 = 0.67 \ barn$

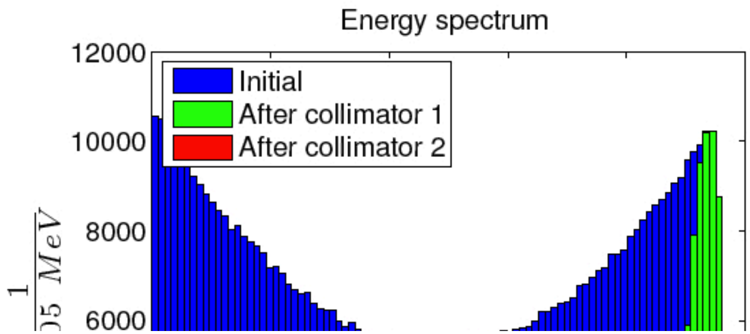


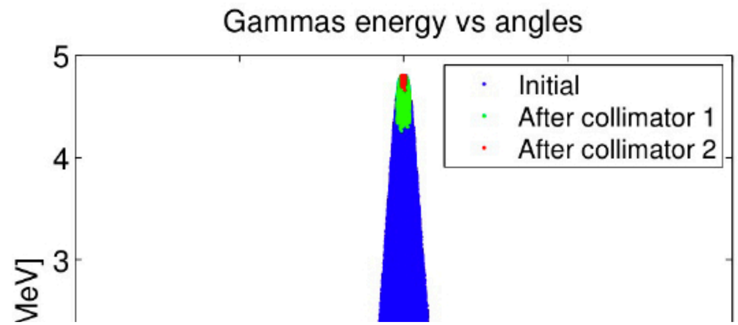
- Scattered flux $N_\gamma = \mathbf{L}\sigma_T$ $\sigma_T = \frac{8\pi}{3} r_e^2$
- Luminosity as in HEP collisions
  - Many photons, electrons
  - Focus tightly $\mathbf{L} = \frac{N_L N_{e-}}{4\pi\sigma_x^2} f$
  - ELI-NP

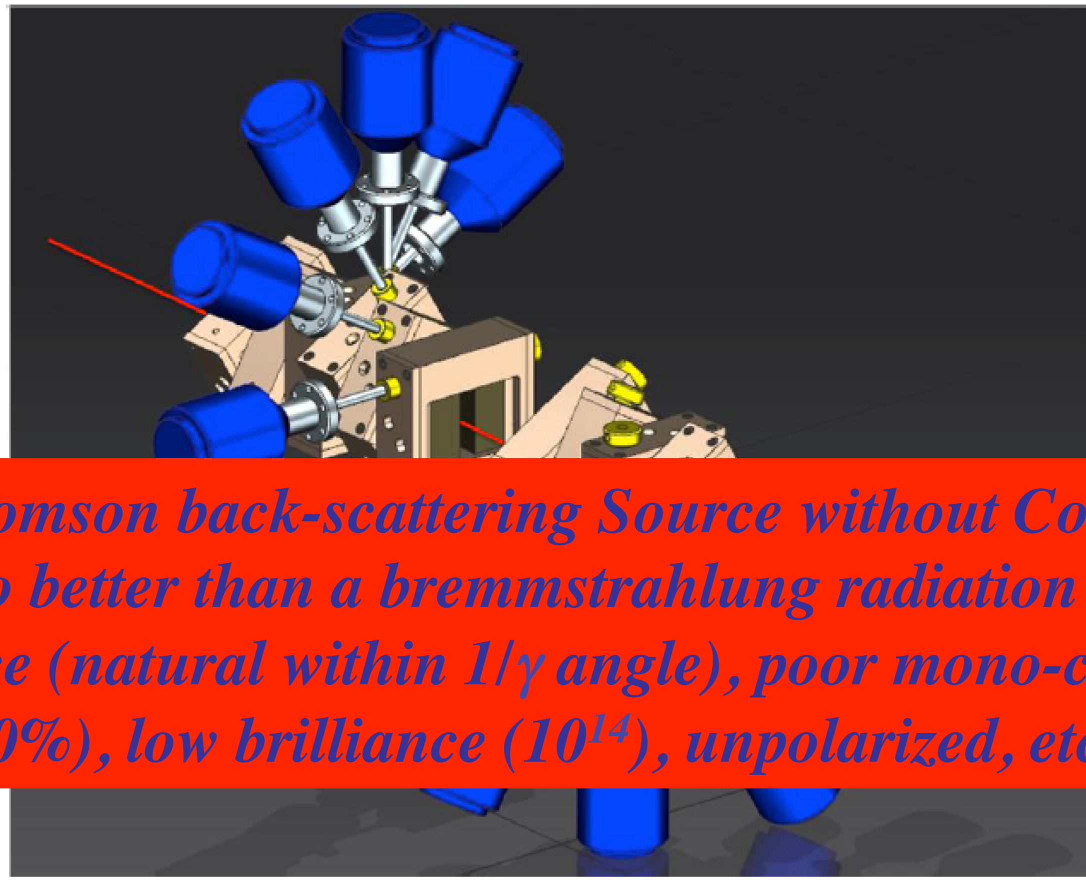
$L_S \equiv \frac{L}{\Delta\nu_\gamma}$

$$L = \frac{1.3 \cdot 10^{18} \cdot 1.6 \cdot 10^{9}}{4\pi(0.0015cm)^2} 3200(s^{-1}) = 2.5 \cdot 10^{35} cm^{-2} s^{-1}$$

cfr LHC 10^{34} SuperB-fac 10^{36}

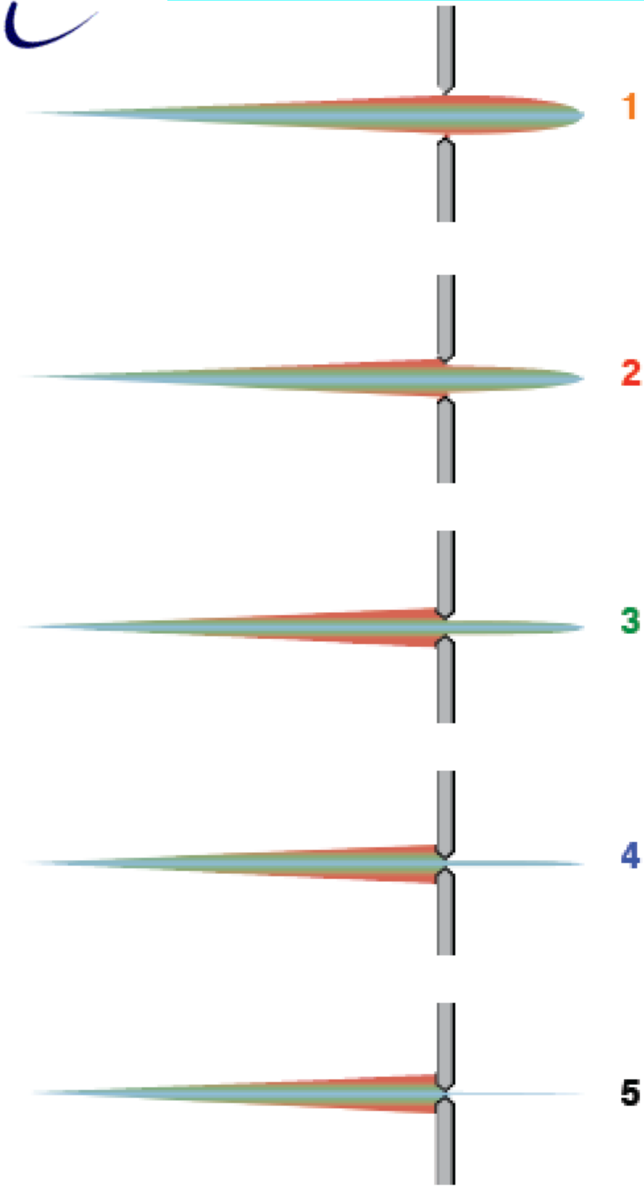




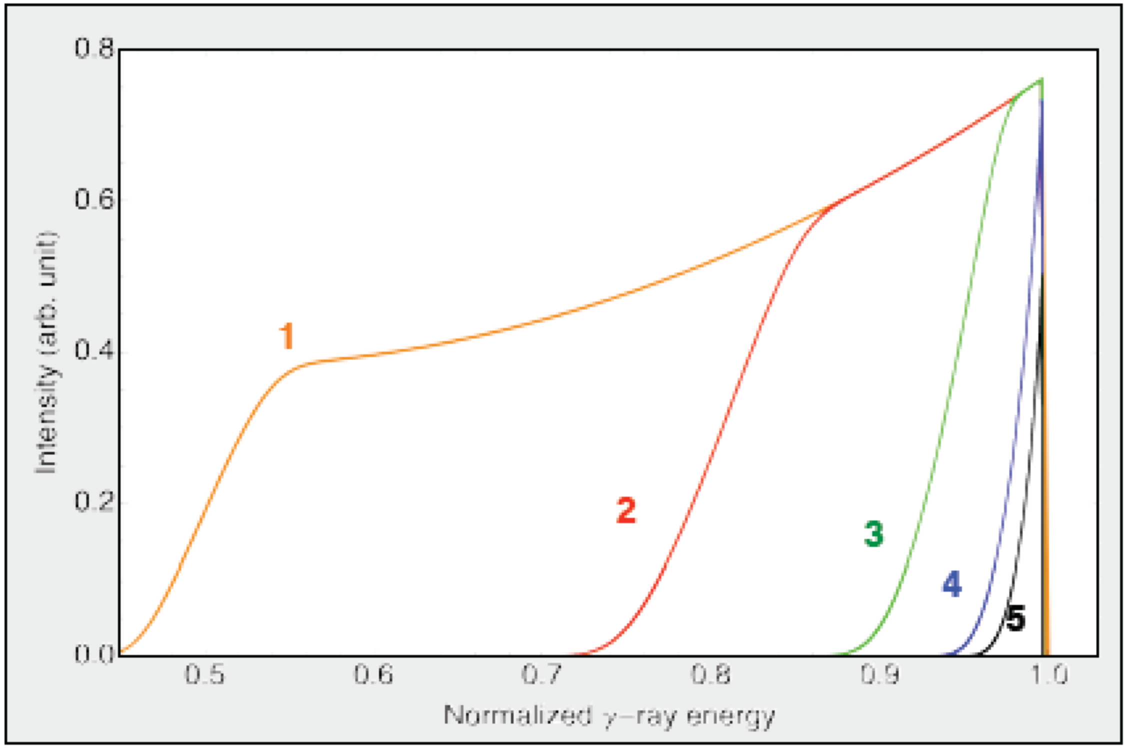


A Compton/Thomson back-scattering Source without Collimation is (probably) no better than a bremmstrahlung radiation source w.r.t. large divergence (natural within 1/γ angle), poor mono-chromaticity (rms bdw. 20-30%), low brilliance (10^{14}), unpolarized, etc

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

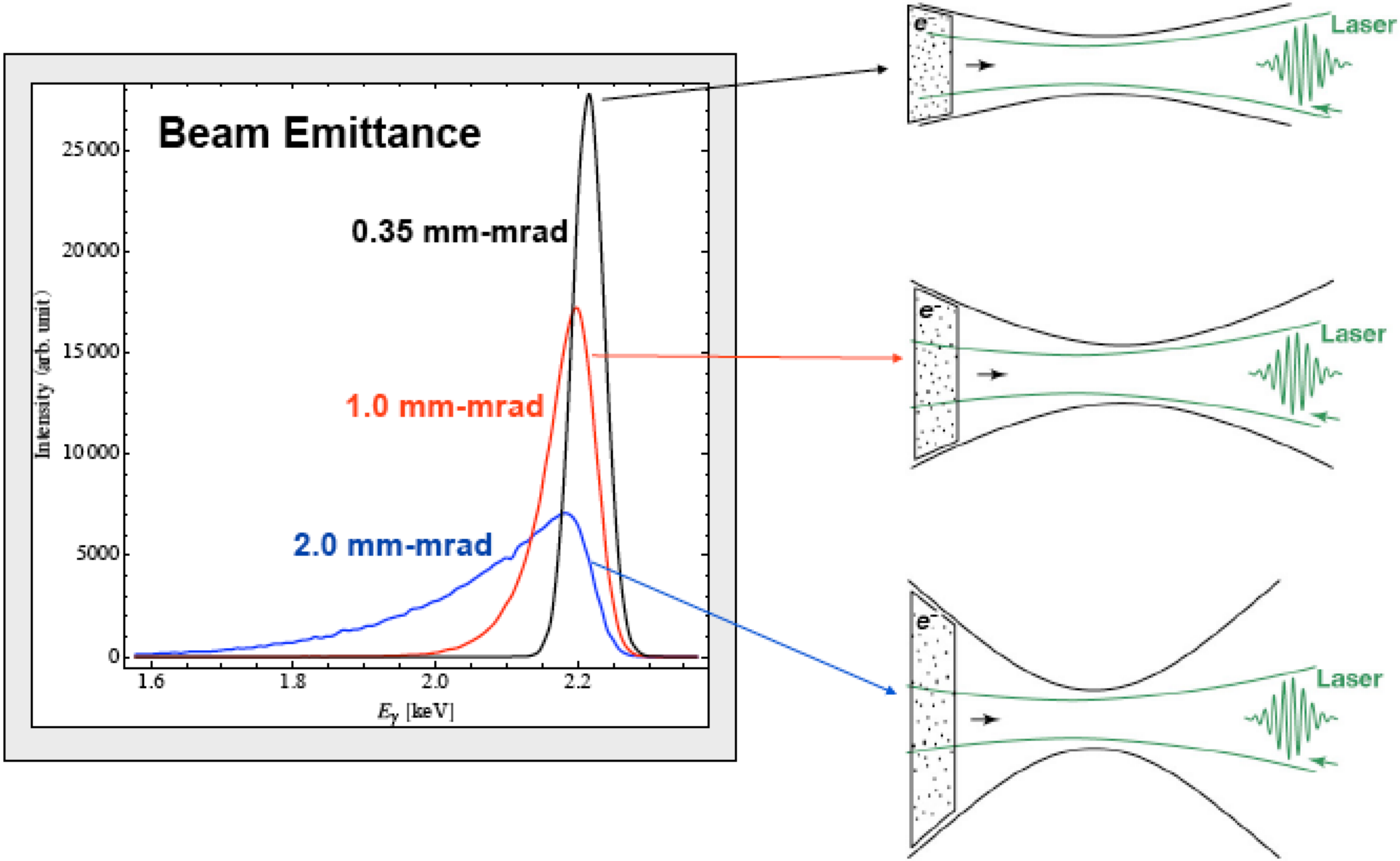


$$\Delta\theta \approx \frac{1}{\gamma} \; ; \; \Delta\nu_\gamma \approx 50\%$$



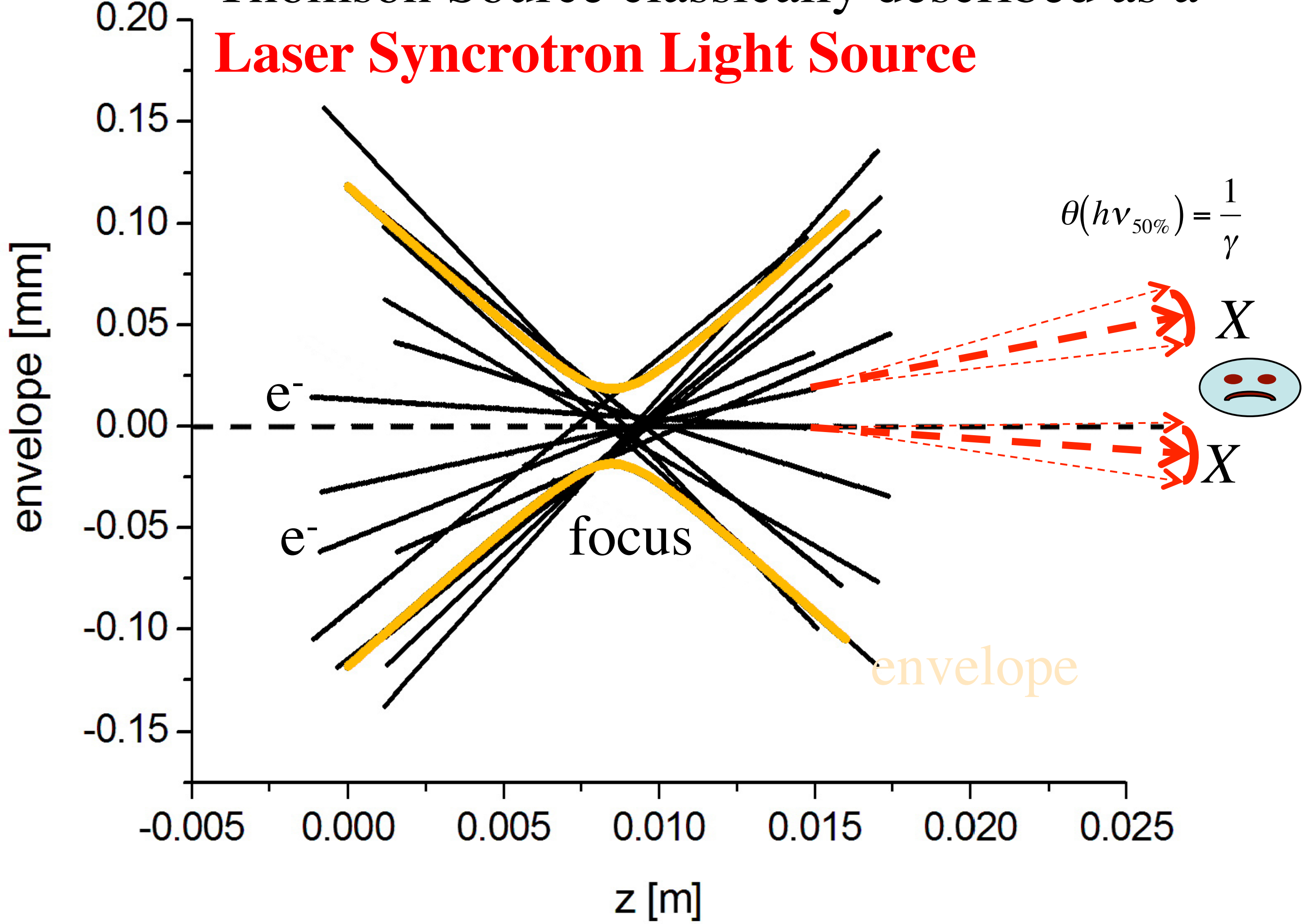
$$\Delta\theta \approx \sigma_{x'} = \frac{\varepsilon_n}{\gamma\sigma_x} \; ; \; \Delta\nu_\gamma \approx \left(\frac{\varepsilon_n^2}{\sigma_x^2}\right)$$

Courtesy C. Barty - LLNL



Courtesy C. Barty - LLNL

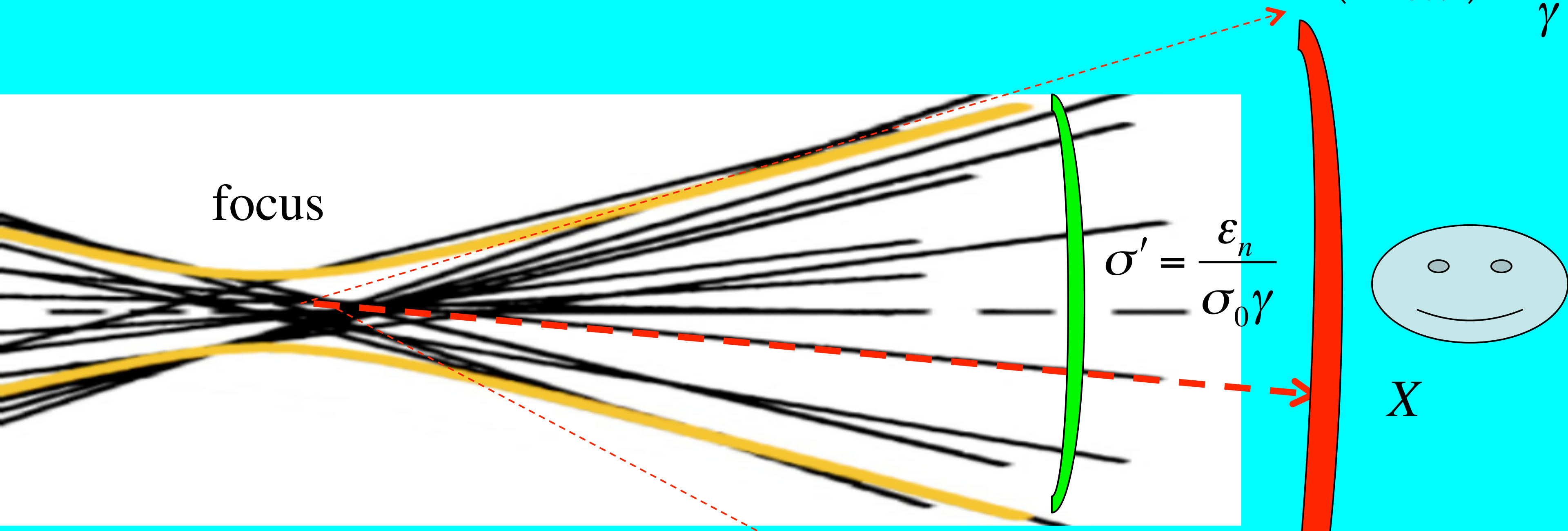
Spectral broadening due to ultra-focused beams:
Thomson Source classically described as a
Laser Syncrotron Light Source



Scattering angle in Thomson limit (no recoil) is small, i.e. < $1/\gamma$

Spectral broadening due to ultra-focused beams:
Thomson Source classically described as a
Laser Syncrotron Light Source

$$\theta\left(h\nu_{50\%}\right) = \frac{1}{\gamma}$$



$$\sigma' = \frac{\varepsilon_n}{\sigma_0 \gamma} << \frac{1}{\gamma} \quad \Rightarrow \quad \frac{\varepsilon_n}{\sigma_0} << 1 \quad \Rightarrow \quad \sigma_0 >> \varepsilon_n$$

Limit to focusability due to max acceptable bandwidth

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Photon flux and spectrum of γ-rays Compton sources

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ABSTRACT

We analyze the characteristics of the γ radiation produced by Compton back-scattering of a high brightness electron beam produced by a photoinjector and accelerated in a linac up to energies of 360–720 MeV and a laser operated at about 500 nm, by comparing classical and quantum models and codes. The interaction produces γ rays in the range 4.9–18.8 MeV. In view of the application to nuclear resonance fluorescence a relative bandwidth of few 10^{-3} is needed. The bandwidth is reduced by taking advantage of the frequency–angular correlation typical of the phenomenon and selecting the radiation in an angle of tens of μrads. The foreseen spectral density is 20–6 photons per eV in a single shot, a number that can be increased by developing multi-bunch techniques and laser recirculation. In this way a final value of 10^4 photon per eV per second can be achieved.

Bandwidth due to collection angle, laser and electron beam phase space distribution

$$\nu_\gamma = \nu \frac{4\gamma^2}{1+\gamma^2\theta^2 + a_0^2/2}(1-\Delta) \quad \Delta = \frac{4\gamma\, h\nu / mc^2}{1+2\gamma\, h\nu / mc^2} \quad \Delta << 1 \ \ Compton \ \ recoil$$

$$\left\langle \gamma^2\theta^2 \right\rangle \cong \left\langle \gamma^2\vartheta^2 \right\rangle + \left\langle \gamma^2\vartheta_e^2 \right\rangle \cong \gamma^2\vartheta_{rms}^2 + (\sigma_{p\perp}/mc)^2 \cong \gamma^2\vartheta_{rms}^2 + 2(\varepsilon_n/\sigma_x)^2$$

$$\frac{\Delta\nu_\gamma}{\nu_\gamma} \cong \sqrt{\boxed{(\gamma\vartheta)_{rms}^4} + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\sqrt{2}\varepsilon_n}{\sigma_x}\right)^4 + \left(\frac{\Delta\nu}{\nu}\right)^2 + \left(\frac{M^2\lambda_L}{2\pi w_0}\right)^4 + \left(\frac{a_{0p}^2/3}{1+a_{0p}^2/2}\right)^2}$$

$\gamma\vartheta = normalized$

$collection \ \ angle$

electron beam

laser

$$Optimized \ \ Bandwidth \cong 2(\varepsilon_n/\sigma_x)^2$$

$$Maximum \ \ Spectral \ \ Density \propto Luminosity/(\varepsilon_n/\sigma_x)^2 \propto Q/\varepsilon_n^2$$

$$Maximum \ \ Spectral \ \ Density \propto Phase \ \ Space \ \ density \ \ \eta_n$$

FEL CONDITIONS FOR EXPONENTIAL GROWTH

The instability can develop only if the undulator length is much larger than the power gain length, and some other conditions are satisfied:

$$\Delta\nu_{FEL}/\nu_{FEL} \le \rho \quad \rho_{LCLS} = 5\cdot 10^{-4}$$

a. Beam emittance of the order of or smaller than the wavelength:

$$\varepsilon \le \frac{\lambda}{4\pi} \tag{4.21}$$

b. Beam relative energy spread smaller than the FEL parameter:

$$\sigma_E / E < \rho \tag{4.22}$$

c. Power gain length shorter than the radiation Rayleigh range:

$$L_G < L_R \tag{4.23}$$

where the Rayleigh range is defined as $L_R = 2\pi\,\sigma_0^2/\lambda_r$, and σ_0 is the radiation rms beam radius.

Independent on electron energy !

$$\frac{\Delta\nu_\gamma}{\nu_\gamma} \le 0.3\%$$

$$\sigma_x = 15 \quad \mu m$$

$$\varepsilon_n \le 0.58 \quad mm\cdot mrad$$

$$\frac{\Delta\nu_\gamma}{\nu_\gamma} \ge 2\frac{\varepsilon_n^2}{\sigma_x^2}$$

$$2\frac{\varepsilon_n^2}{\sigma_x^2} = p_{\perp rms}^2 = \left(\gamma\sigma_{x'}\right)^2$$

$$\frac{\Delta\nu_\gamma}{\nu_\gamma} \le 1\%$$

$$\sigma_x = 1 \quad \mu m$$

$$\varepsilon_n \le 0.071 \quad mm\cdot mrad$$

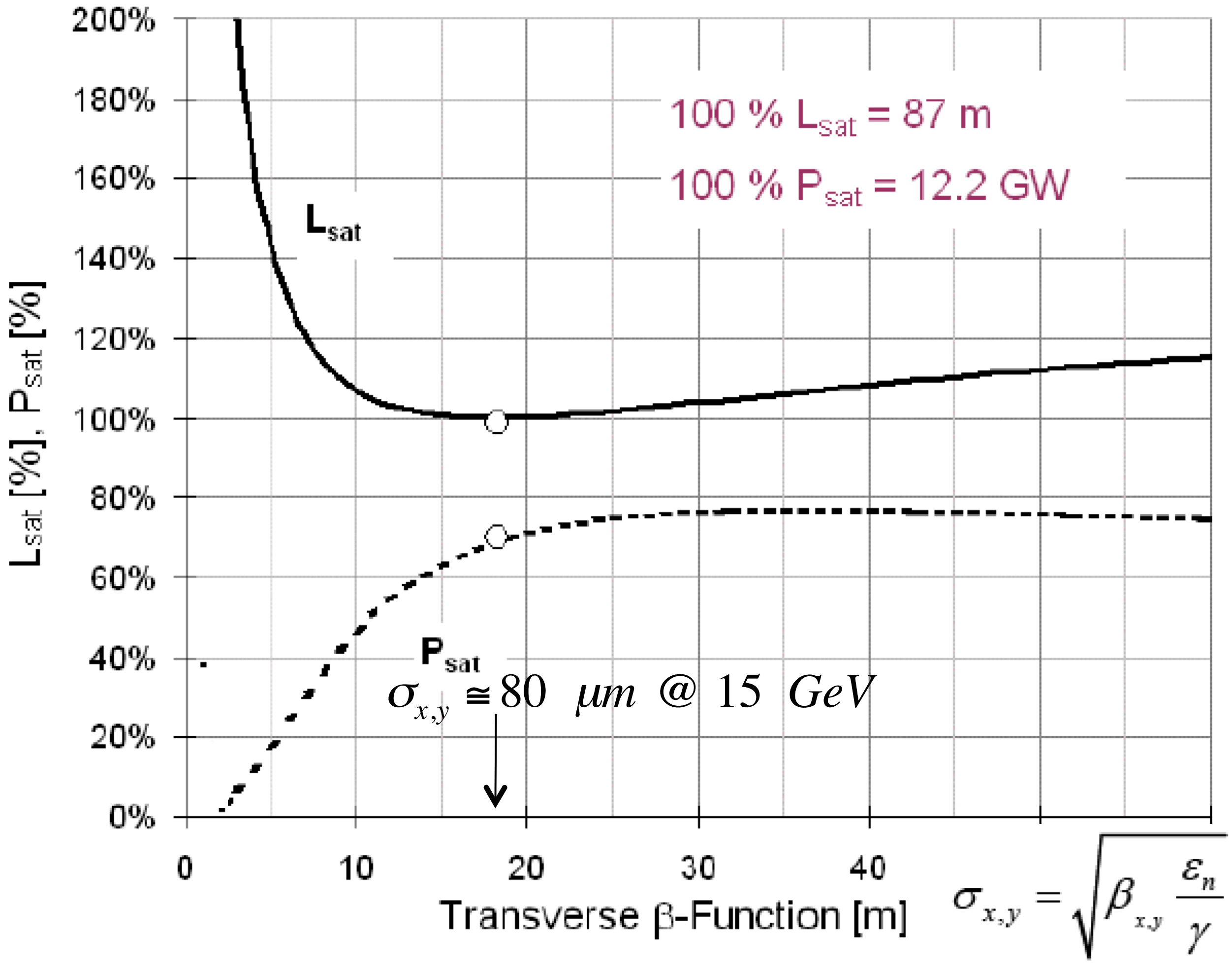
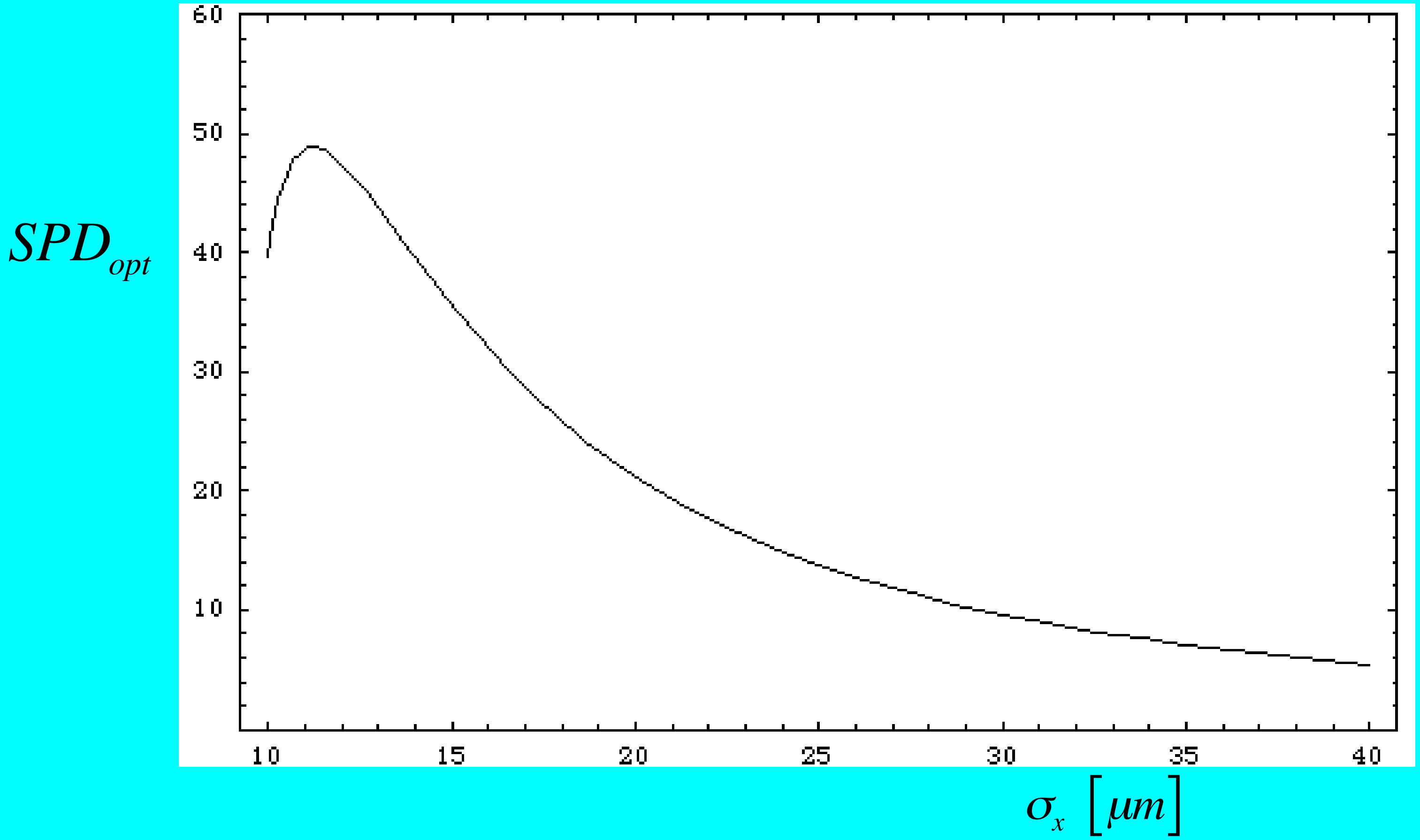


Figure 5.4 Power at saturation, P_{sat}, and saturation length, L_{sat}, as a percentage of 12.2 GW and 87 m, respectively, as a function of the average β-function at a radiation wavelength of 1.5 Å (14.35 GeV). The circles indicate the LCLS operating point.

ELI-NP Beam $\phi = 0$ $T = 360$ MeV

$\Delta\gamma/\gamma = 0.0007$ $\varepsilon_n = 0.46\ \mu m$ $\Delta\nu/\nu = 0.005$



N.B. with SPD(per shot)=25 we have 2500 photons/s·eV at f_{RF}=100 Hz, so we need only n_{RF}=4 to reach the ELI-NP specs at SPD=10^4 photons/s·eV

ELI-NP GBS (Extreme Light Infrastrucutre Gamma Beam System) as an example of Compton Source based on collisions of two cold beams of electrons and photons

$$Gamma-ray \quad Energy: \quad 1-20 \quad MeV$$

$$rms \quad Bandwidth: \quad 0.3\%$$

$$Spectral \quad Density: \quad 10^4 \quad photons/s \cdot eV$$

outstanding electron beam @ 720 MeV with high phase space density
(all values are projected, not slice!)

$$Q = 250\, pC \;;\; \varepsilon_n = 0.4 \quad mm \cdot mrad \;;\; \frac{\Delta\gamma}{\gamma} = 8 \cdot 10^{-4}$$

Scattering off a high quality J-class psec laser pulse

$$U_L = 400 \quad mJ \;;\; M^2 = 1.2 \;;\; \frac{\Delta\nu}{\nu} = 5 \cdot 10^{-4}$$

Technical Design Report

E-Gammas proposal for the ELI-NP Gamma beam System

With 79 tables and 252 figures

O. Adriani, S. Albergo, D. Alesini, M. Anania, D. Angal-Kalinin, P. Antici, A. Bacci, R. Bedogni, M. Bellaveglia, C. Biscari, N. Bliss, R. Boni, M. Boscolo, F. Broggi, P. Cardarelli, K. Cassou, M. Castellano, L. Catani, I. Chaikovska, E. Chiadroni, R. Chiche, A. Cianchi, J. Clarke, A. Clozza, M. Coppola, A. Courjaud, C. Curatolo, O. Dadoun, N. Delerue, C. De Martinis, G. Di Domenico, E. Di Pasquale, G. Di Pirro, A. Drago, F. Druon, K. Dupraz, F. Egal, A. Esposito, F. Falcoz, B. Fell, M. Ferrario, L. Ficcadenti, P. Fichot, A. Gallo, M. Gambaccini, G. Gatti, P. Georges, A. Ghigo, A. Goulden, G. Graziani, D. Guibout, O. Guilbaud, M. Hanna, J. Herbert, T. Hovsepian, E. Iarocci, P. Iorio, S. Jamison, S. Kazamias, F. Labaye, L. Lancia, F. Marcellini, A. Martens, C. Maroli, B. Martlew, M. Marziani, G. Mazzitelli, P. McIntosh, M. Migliorati, A. Mostacci, A. Mueller, V. Nardone, E. Pace, L. Palumbo, A. Pelorosso, F.X. Perin, G. Passaleva, L. Pellegrino, V. Petrillo, M. Pittman, G. Riboulet, R. Ricci, C. Ronsivalle, D. Ros, A. Rossi, L. Serafini, M. Serio, F. Sgamma, R. Smith, S. Smith, V. Soskov, B. Spataro, M. Statera, A. Stecchi, A. Stella, A. Stocchi, S. Tocci, P. Tomassini, S. Tomassini, A. Tricomi, C. Vaccarezza, A. Variola, M. Veltri, S. Vescovi, F. Villa, F. Wang, E. Yildiz, F. Zomer

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ELI-NP Gamma Beam System

STRATEGY for Optimization:

1) RF Linac as per Linear Collider and FEL's machines (max rep rate, multi-bunch, max ph. Sp. density per average beam power)

2) High average power, high quality J-class 100 Hz psec Collision Laser (strategic investment in new Yb:Yag laser technology)

3) Laser recirculation with μm and μrad and sub-psec alignment/ synchronization (metrology/interferometry optical cavities)

4) Multi-bunch and laser recirculation make the Compton Source run at 3.2 kHz rep rate

Accelerator and Equipments in ELI-NP Building

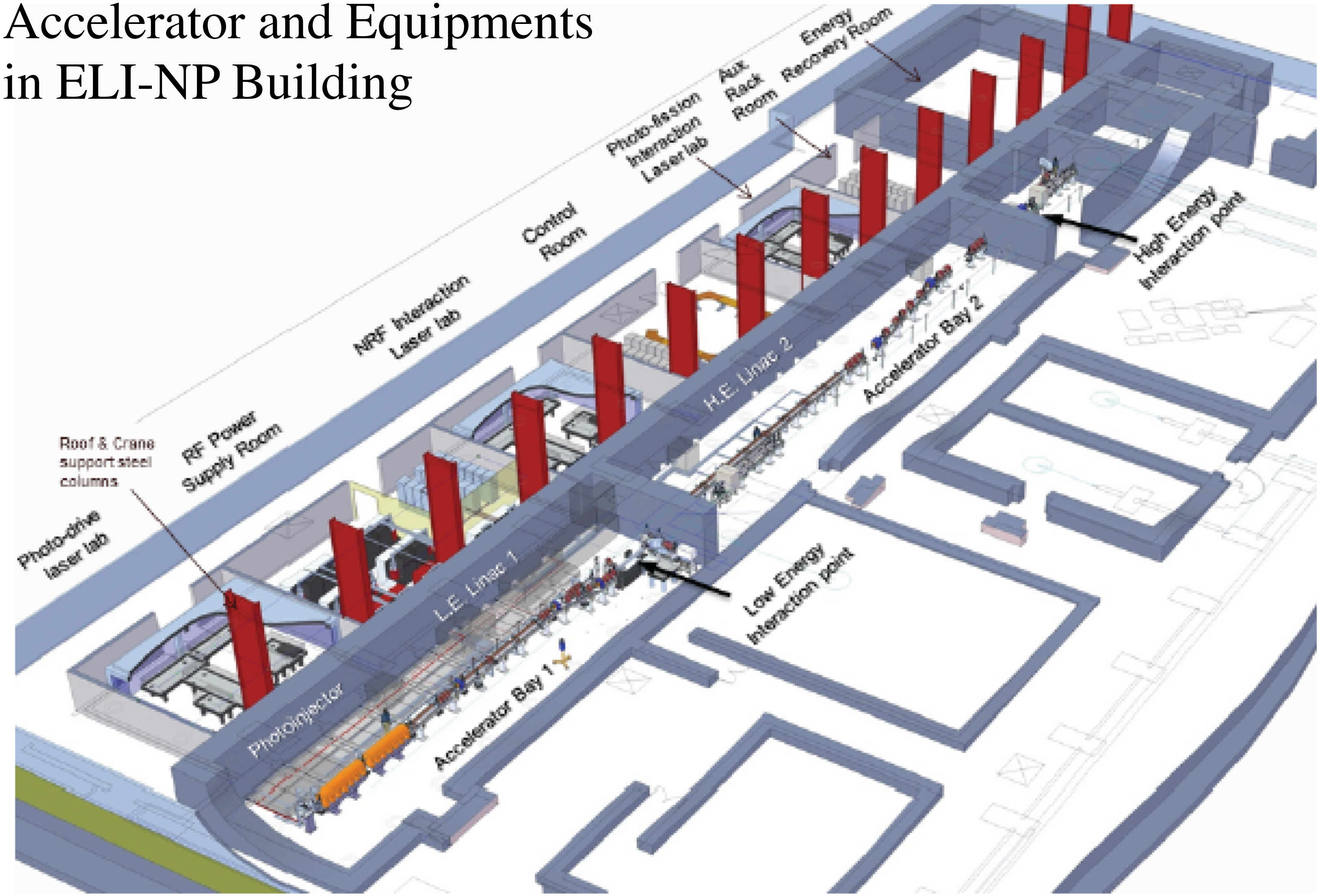
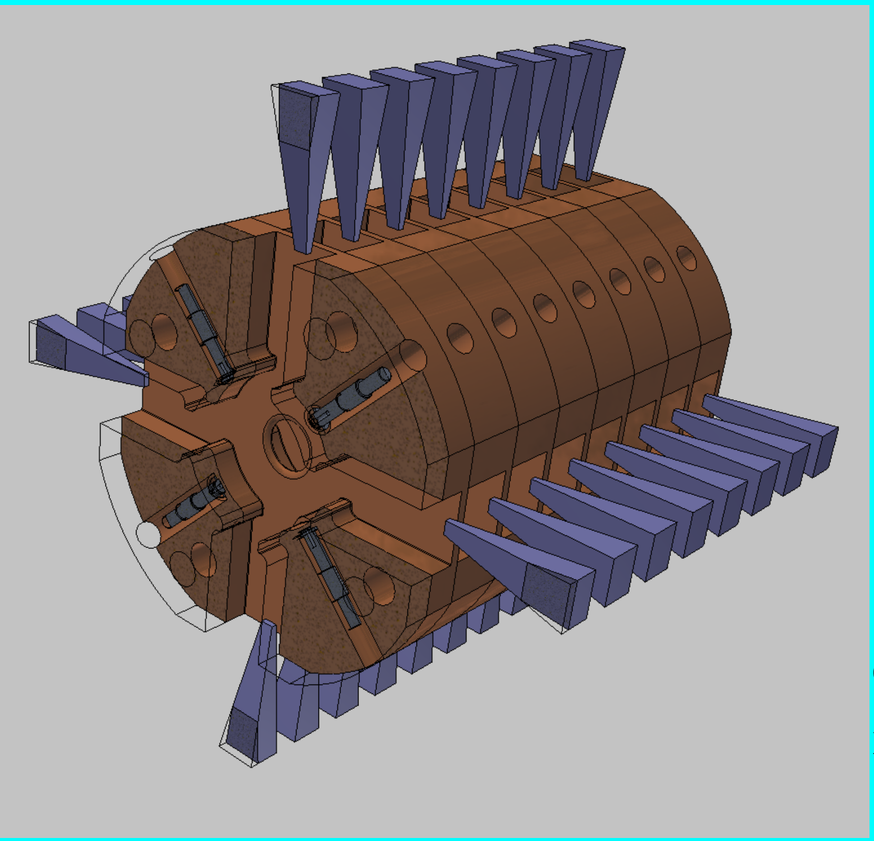
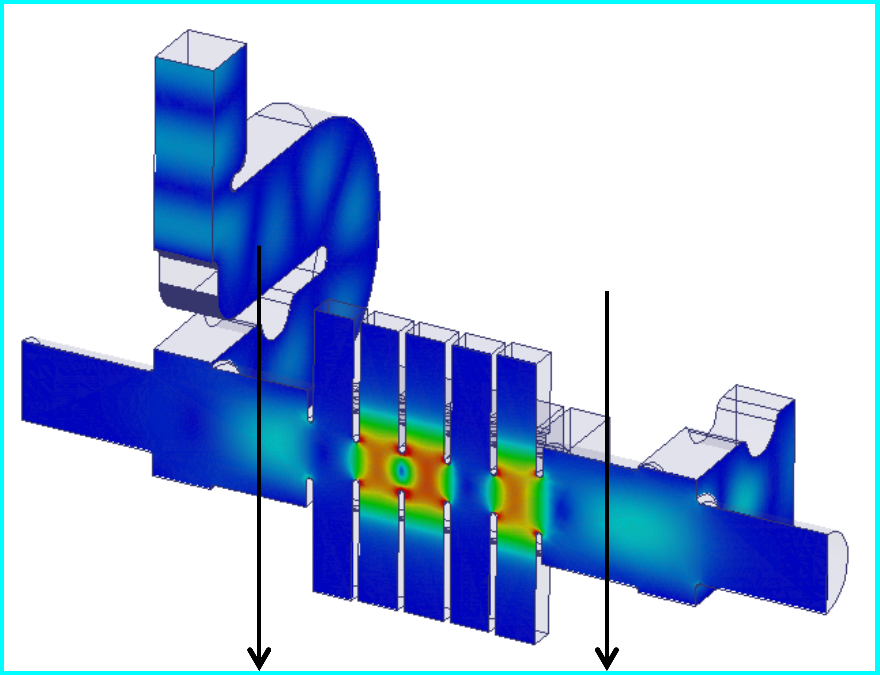


Fig. 197. Isometric 3D view of Building Layout of the Accelerator Hall & Experimental Areas

ELI Damped structure: Mechanical drawings, realization and prototype





General procedure we would like to follow: input/output couplers are fabricated separately and joined to the cells by a vacuum flange

The fabrication of a prototype with a reduced number of cells is necessary to:

A. Test the effectiveness of the dipole mode damping including the test the absorbing material performances
B. Test the vacuum properties of the structure with absorbing material
C. Perform the low power tests and the tuning of the structure
D. Test the high gradient performances of the structure

Laser Recirculator

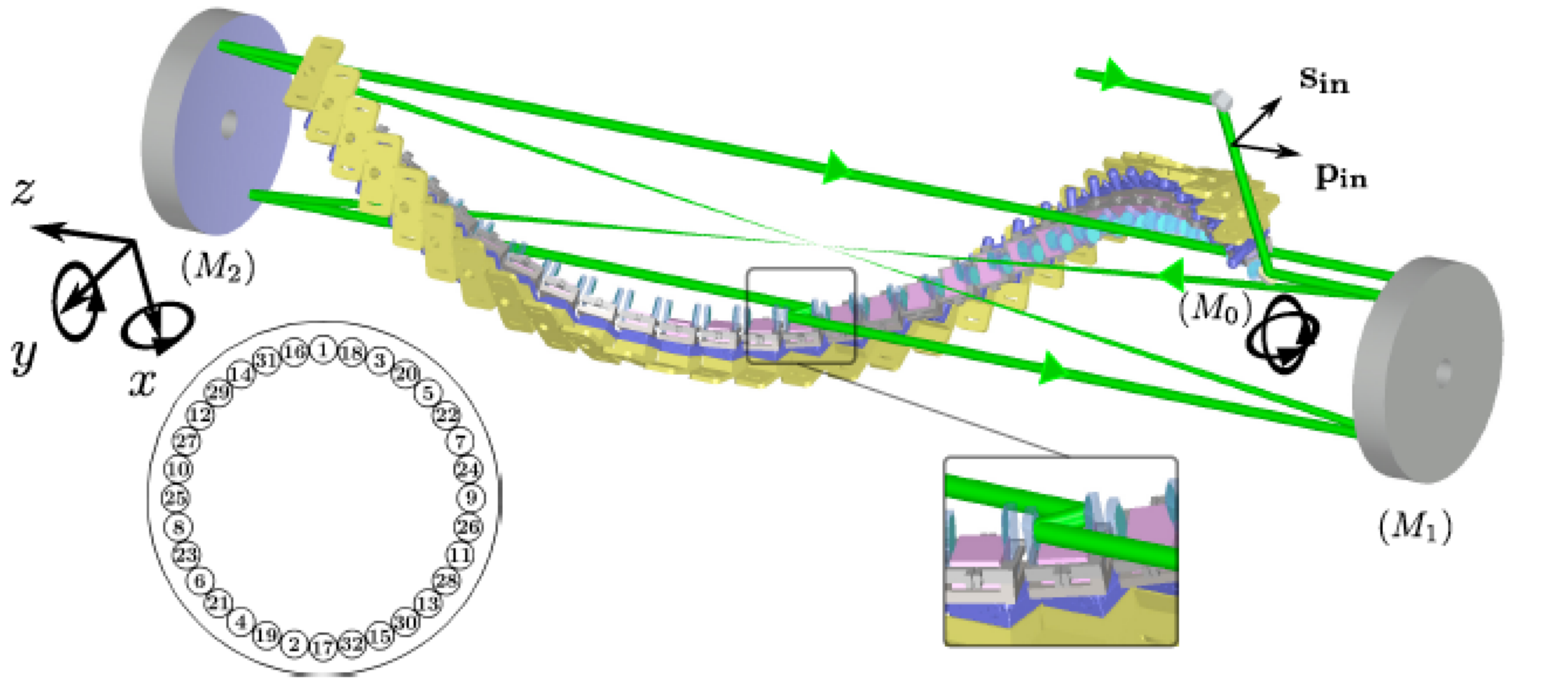


FIG. 2. (Color) Isometric view of ELI-NP-GBS recirculator. The mirror M_0 is used to inject the incident laser beam. The mirror-pair system (structures positioned on a circular helix) and the laser beam paths (green lines) are located between two parabolic mirrors M_1, M_2. Two of the 32 recirculation passes (green lines) are drawn. The polarization vectors $\mathbf{s}_{in}$ and $\mathbf{p}_{in}$ related to the incoming laser beam are also shown. The seven degrees of freedom for the mirror motions are sketched: 2 tilts for M_0; 2 tilts and 3 translations for M_2. The inset scheme shows the optical pass ordering.

Design and optimization of a highly efficient optical multipass system for γ-ray beam production from electron laser beam Compton scattering

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A new kind of nonresonant optical recirculator, dedicated to the production of γ rays by means of Compton backscattering, is described. This novel instrument, inspired by optical multipass systems, has its design focused on high flux and very small spectral bandwidth of the γ-ray beam. It has been developed to fulfill the project specifications of the European Extreme Light Infrastructure "Nuclear Pillar," i.e., the Gamma Beam System. Our system allows a single high power laser pulse to recirculate 32 times synchronized on the radio frequency driving accelerating cavities for the electron beam. Namely, the polarization of the laser beam and crossing angle between laser and electrons are preserved all along the 32 passes. Moreover, optical aberrations are kept at a negligible level. The general tools developed for designing, optimizing, and aligning the system are described. A detailed simulation demonstrates the high efficiency of the device.

Main Parameter Tables of ELI-NP-GBS

Table 1: Summary of Gamma-ray beam Specifications

Photon energy	0.2-19.5 *MeV*
Spectral Density	$0.8\text{-}4{\cdot}10^4$ *ph/sec.eV*
Bandwidth (rms)	≤ 0.5%
# photons per shot within FWHM bdw.	$\leq 2.6{\cdot}10^5$
# photons/sec within FWHM bdw.	$\leq 8.3{\cdot}10^8$
Source rms size	10 - 30 *μm*
Source rms divergence	25 - 200 *μrad*
Peak Brilliance ($N_{ph}/sec{\cdot}mm^2mrad^2{\cdot}0.1\%$)	10^{20} - 10^{23}
Radiation pulse length (rms, *psec*)	0.7 - 1.5
Linear Polarization	> 99 %
Macro rep. rate	100 *Hz*
# of pulses per macropulse	≤ 32
Pulse-to-pulse separation	16 *nsec*

- **Polarization: we conducted a study with CAIN on the nominal 13 MeV beam**
- **We know from previous studies that the laser polarization is conserved by the gamma ray beam if the backscattering is done in the weak recoil regime (Thomson/Compton), *i.e.* when the recoil parameter *Δ* is small**

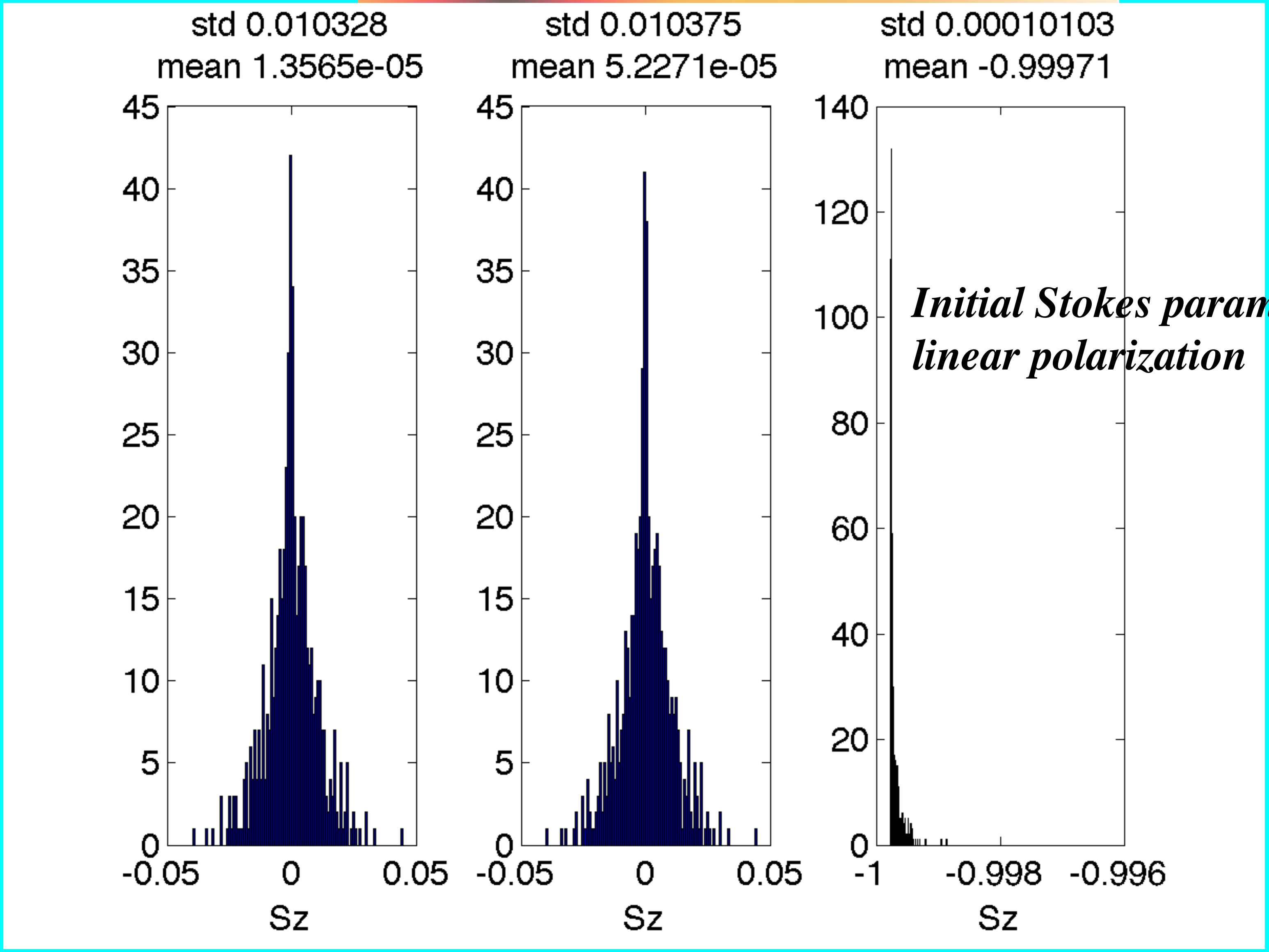
$$\nu_\gamma = \nu \frac{4\gamma^2}{1+\gamma^2\theta^2 + a_0^2/2}(1-\Delta) \qquad \Delta << 1$$

$$\Delta = \frac{4\gamma\, h\nu/mc^2}{1+2\gamma\, h\nu/mc^2} \qquad 0.005 < \Delta_{ELI-NP-GBS} < 0.025$$

$$P_\gamma \cong P_{las}\left(1-\frac{3}{2}\Delta^2\right)\left(1-\frac{\gamma^2\theta^2}{2}\right) \quad \Rightarrow \quad P_{\gamma-ELI-NP-GBS} > 0.995 P_{las-ELI-NP-GBS}$$

Laser polarization is mapped almost 1:1 into gamma ray beam

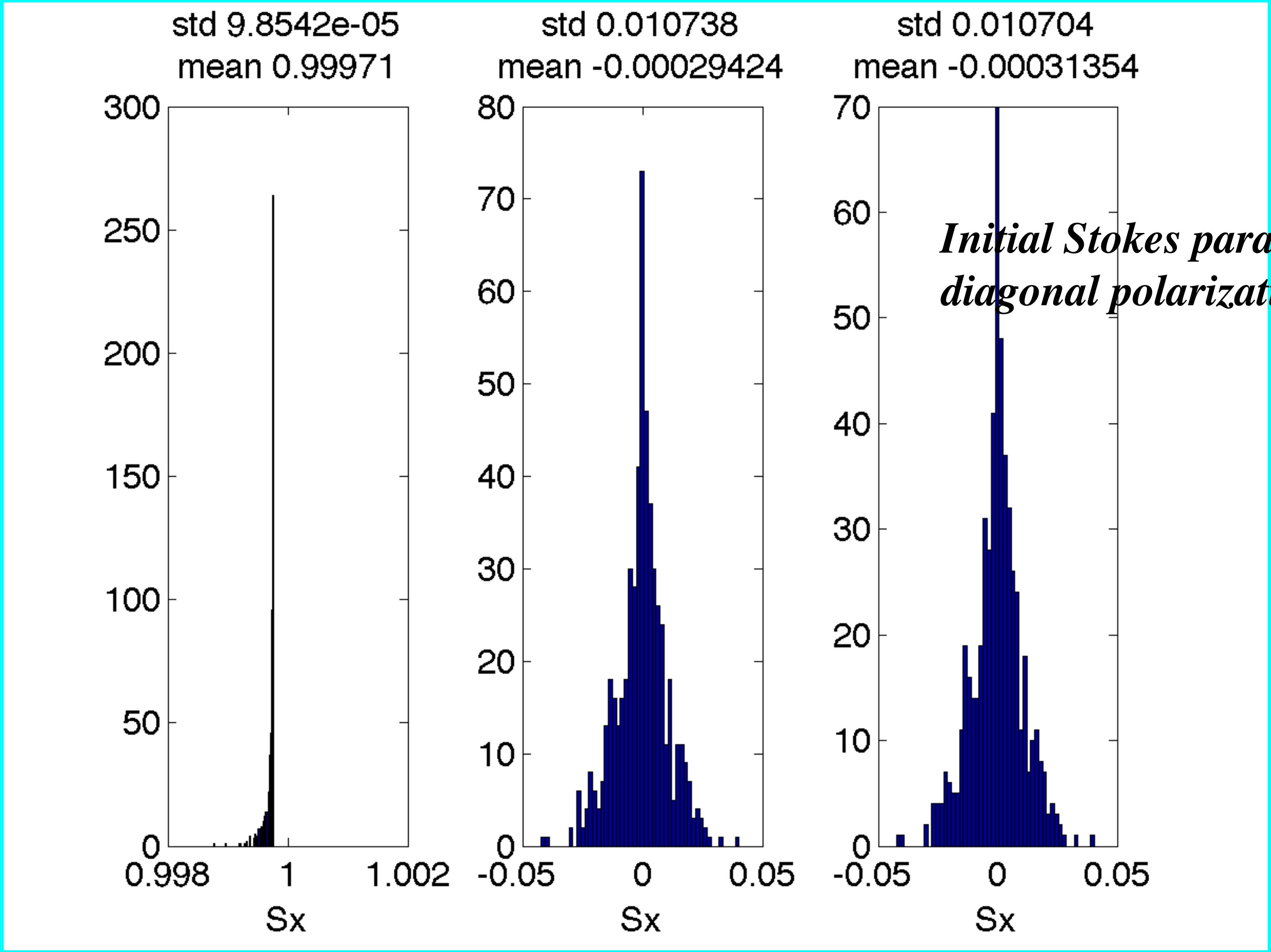
True for linear, diagonal, circular (checked with CAIN)



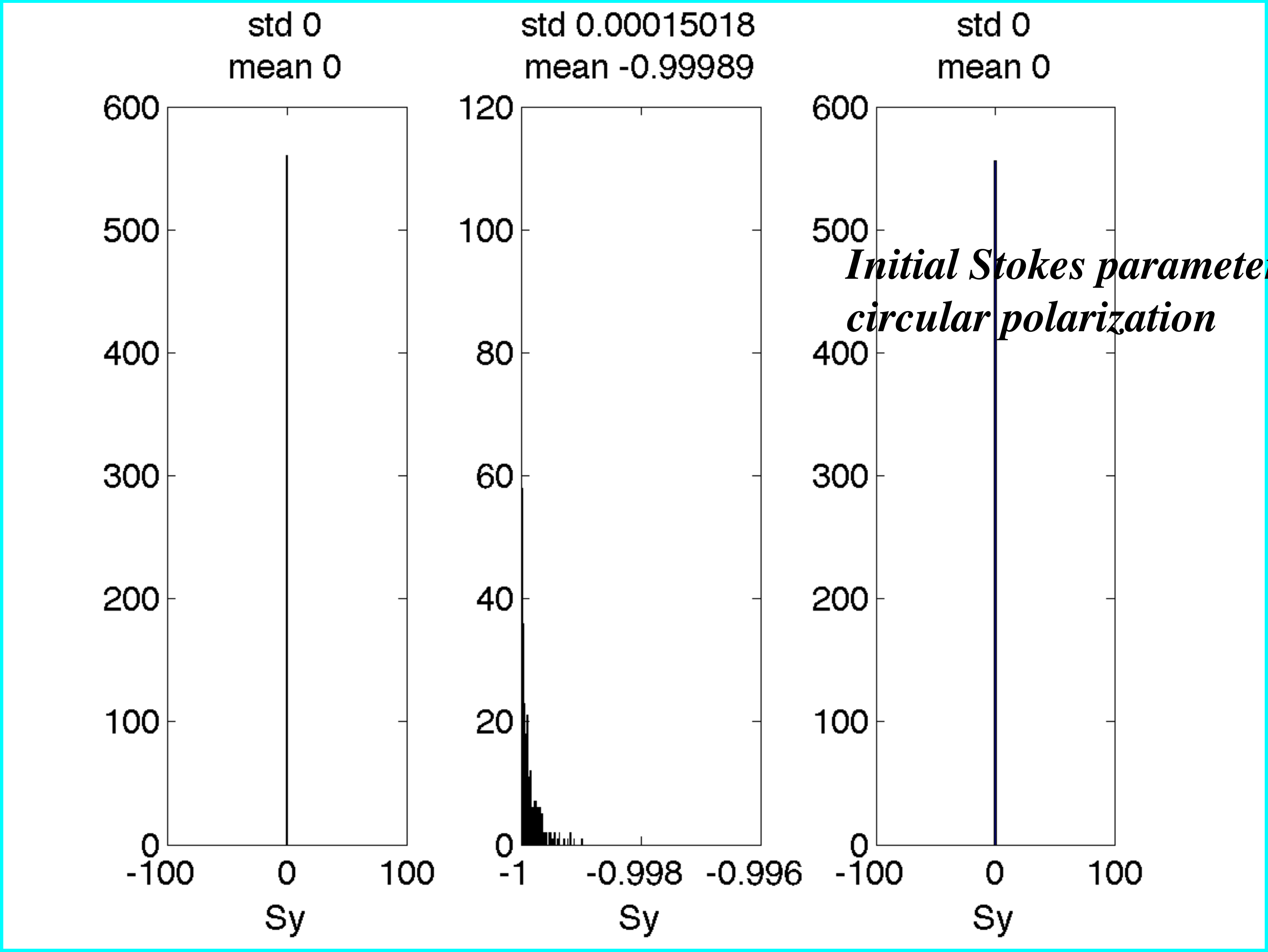
Initial Stokes parameters (0,0,1)
linear polarization

$$P_{\gamma-ELI-NP-GBS}(13\ \ MeV) \approx 0.995 P_{las-ELI-NP-GBS}$$

- **Polarization: we conducted a study with CAIN on the nominal 13 MeV beam**



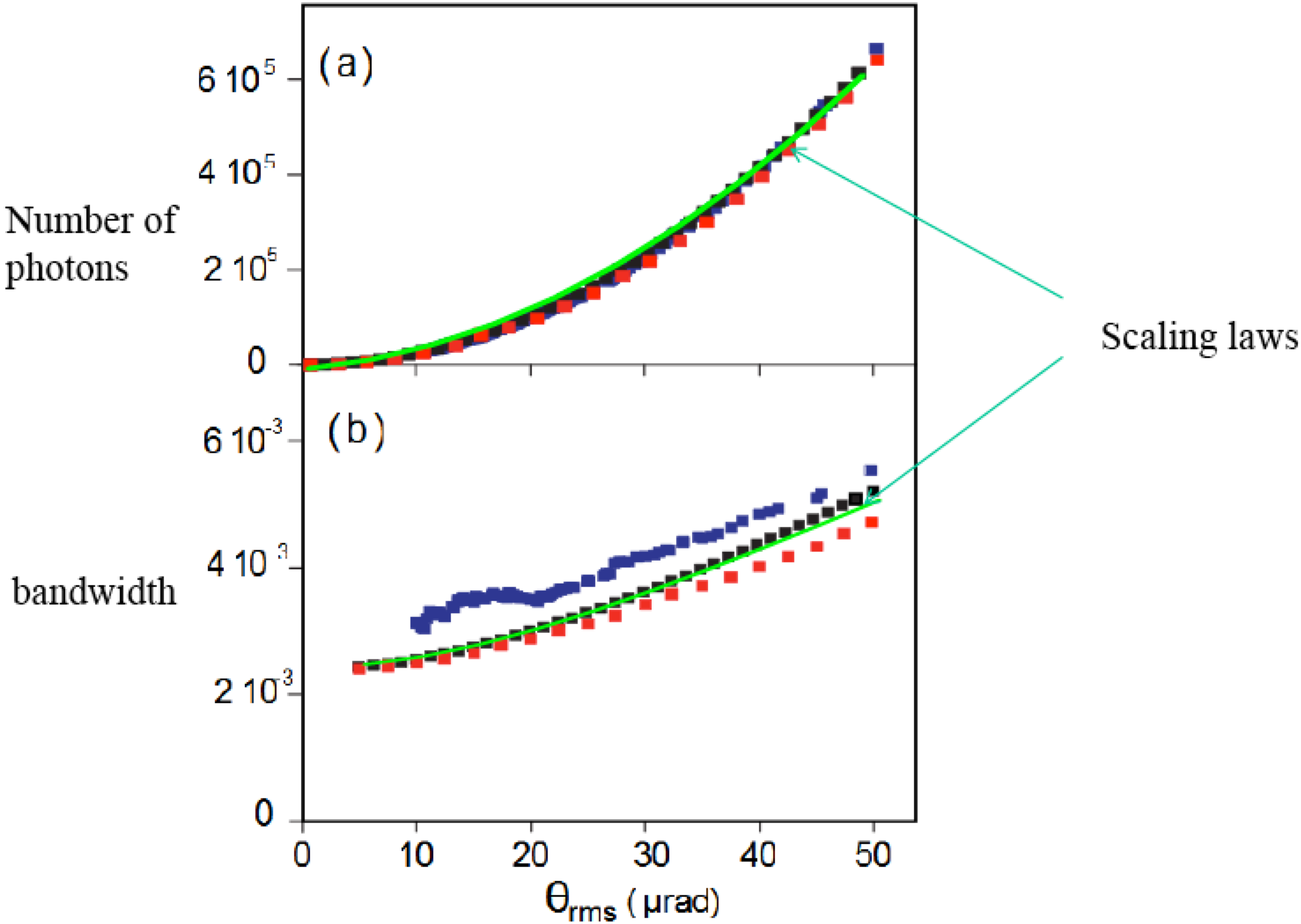
Initial Stokes parameters (1,0,0) diagonal polarization



Initial Stokes parameters (0,1,0) circular polarization

Summary on Challenges of Compton Sources for Nuclear Physics/Photonics

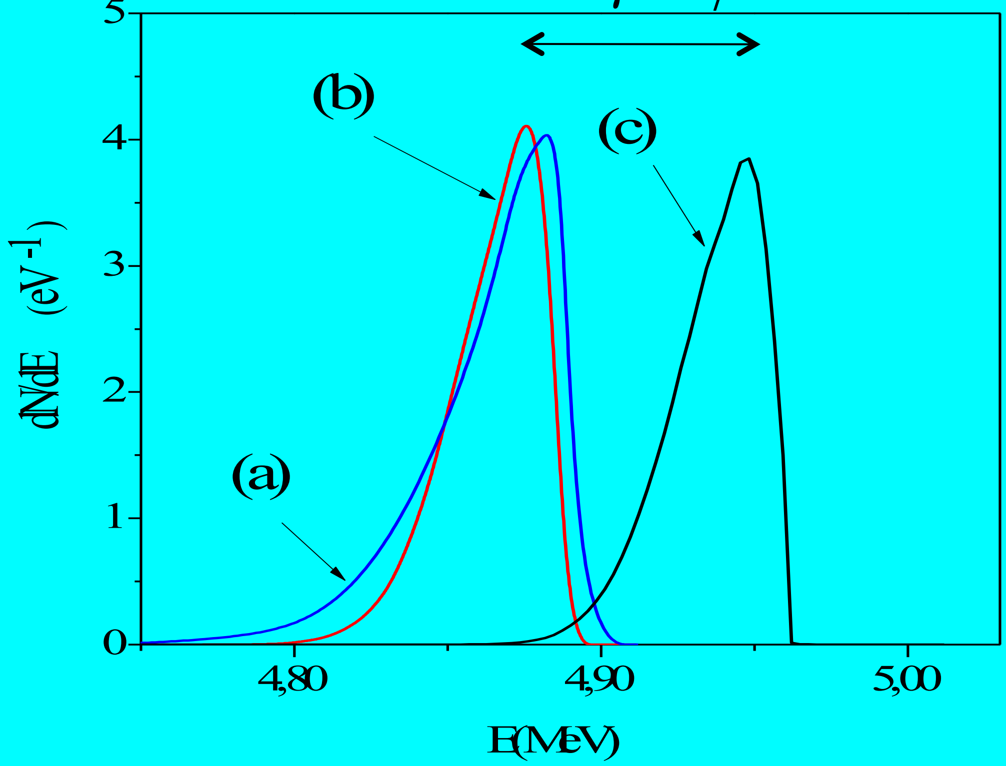
- Very small radiation bandwidths are requested: < 0.5%, going down to 10^{-3}
- Build and run a Linear Collider (electron/photon)
- Generate a secondary beam of photons with maximum brilliance, high mono-chromaticity, tunability, polarization control, micro-round source spot size
- Whatever is the acceleration technology under consideration (room temp. RF, SC ERL, storage ring, LPWA) and the laser technology (high quality high power psec recirculated lasers, Fabry-Perot storage cavities, etc) you need to generate low transverse momentum electron beams at IP (typically for 1 GeV beam intrinsic divergence < 20 μrad), with very small energy spread ($<10^{-3}$)
- Issue: contamination of gamma ray beam by background (collimated photons/ neutrons, other radiation from accelerator producing noise in the detectors -> use of dog-legs to disalign bremsstrahlung from gamma ray beam)



V. Petrillo et al., NIM-A693 (2012) 109

Quantum shift ΔE

$$\Delta = 4\gamma h\nu / mc^2$$



(a)CAIN
(b)Comp_Cross
(c)TSST

A part from the quantum shift, the spectra are very similar