Status report of nonlinear Inverse Compton Scattering study

Nonlinear ICS by $a_0 \sim 1$, CO_2 laser @ hν ~ 10 keV: ATF-AE70 & Before

↔ *Linear ICS by YAG laser @ hν ~ 100 keV: ATF-AE87*

AAC2022yr, WG7, November 7

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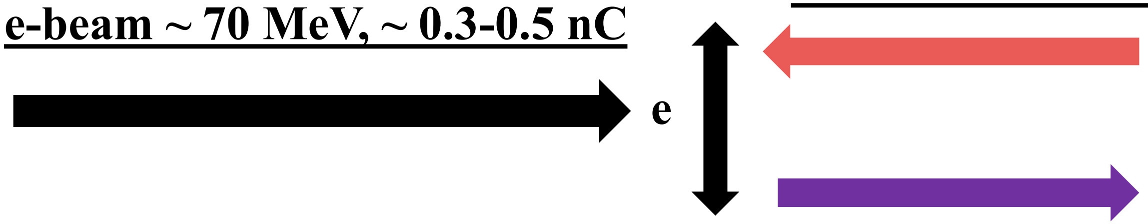
BNL ATF Experiment AE87: Experiment Goals
HARD X-ray ICS at *hv* ~ 100 keV range

- ✪ Applications: Photon activation as Medicine & Radiography of high *Z* materials
- ✪ Strong field physics: Bi-harmonic Compton interaction with ATF's CO_2 laser
- ✪ Hard X-ray optics developments: DDS measurement & Focusing or Collimation
- ✪ X-ray OAM investigation: Higher order harmonics by circular polarized CO_2 laser

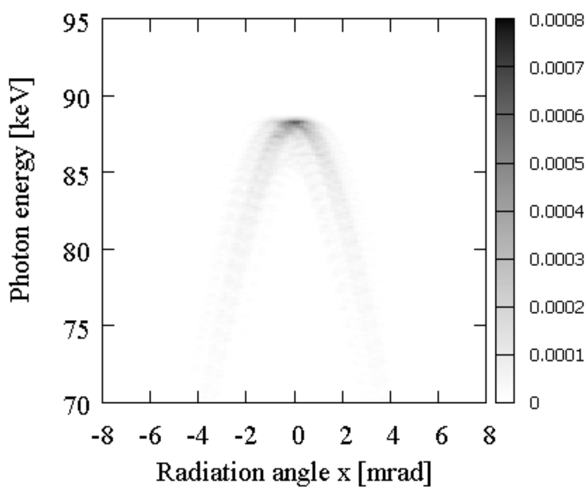
e-beam ~ 70 MeV, ~ 0.3-0.5 nC

YAG laser: 1064 nm, ~ 100-200 mJ

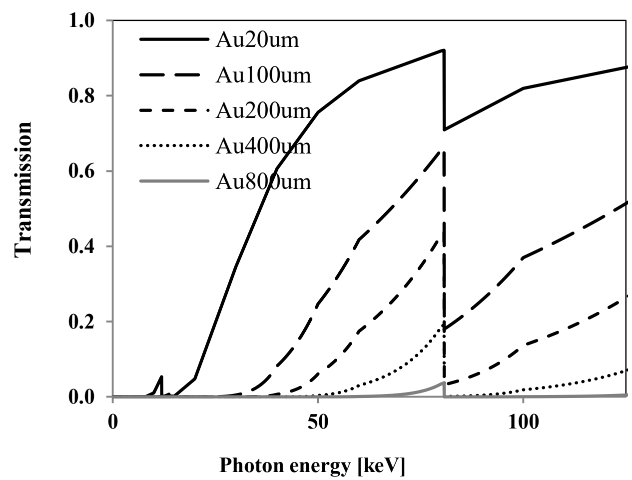


~ 1 μJ/pulse*
@ *hv* ~ 87.5 keV

**($10^{6\text{-}7}$ photons)×(100 keV) ×(1.6×10^{-19}) ~ 0.1 - 1 μJ / shot)*



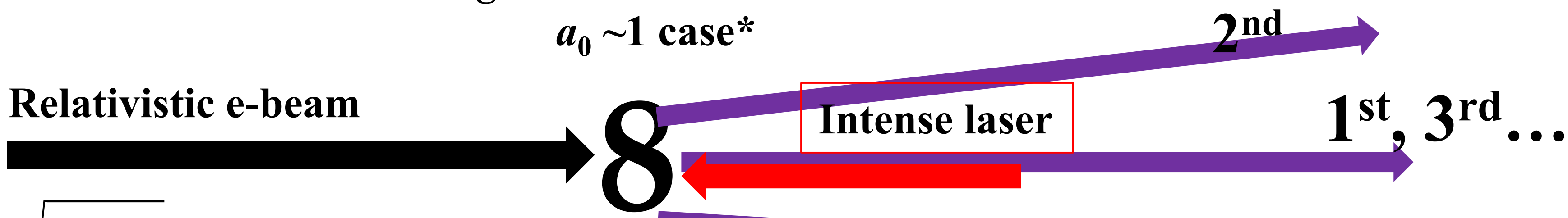
2021yr : Qualitative study by Au filters ↔



{Goals of AE87 as of now: Establish basic set up of ICS by YAG & upgraded a_0>1 CO_2 lasers}

TODAY: Overview of nonlinear Compton study by CO_2 laser in BNL ATF

Figure-8 electron motion
a_0 ~1 case*

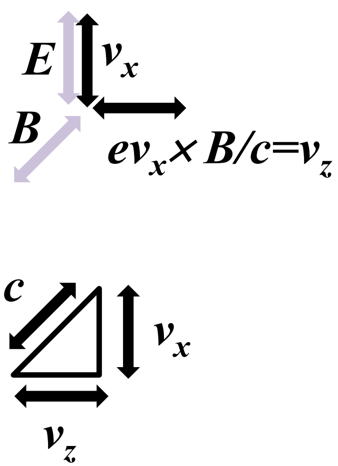


$$* \; a_{L,0} \equiv \frac{\sqrt{-e^2 A_\mu A^\mu}}{m_e c^2} = \frac{e E_{L,0}(\lambda_L/2\pi)}{m_e c^2}$$

Linear laser polarization

Nonlinear ICS: a_L~1, Transverse motion →Relativistic, nontrivial longitudinal oscillation**
Slow down electron's velocity, or Effective mass increase

**



★**Red-shifting *and* BW increase:**

Photon absorption by electron = Mass shift

$$h\nu_{X\text{-ray}} \Rightarrow h\nu_{X\text{-ray}} / (1 + a_L^2/2 + \gamma_0^2 \Theta^2)$$

★ **Harmonic generation/angular dependence:**

Multi-photon process in dense photon field

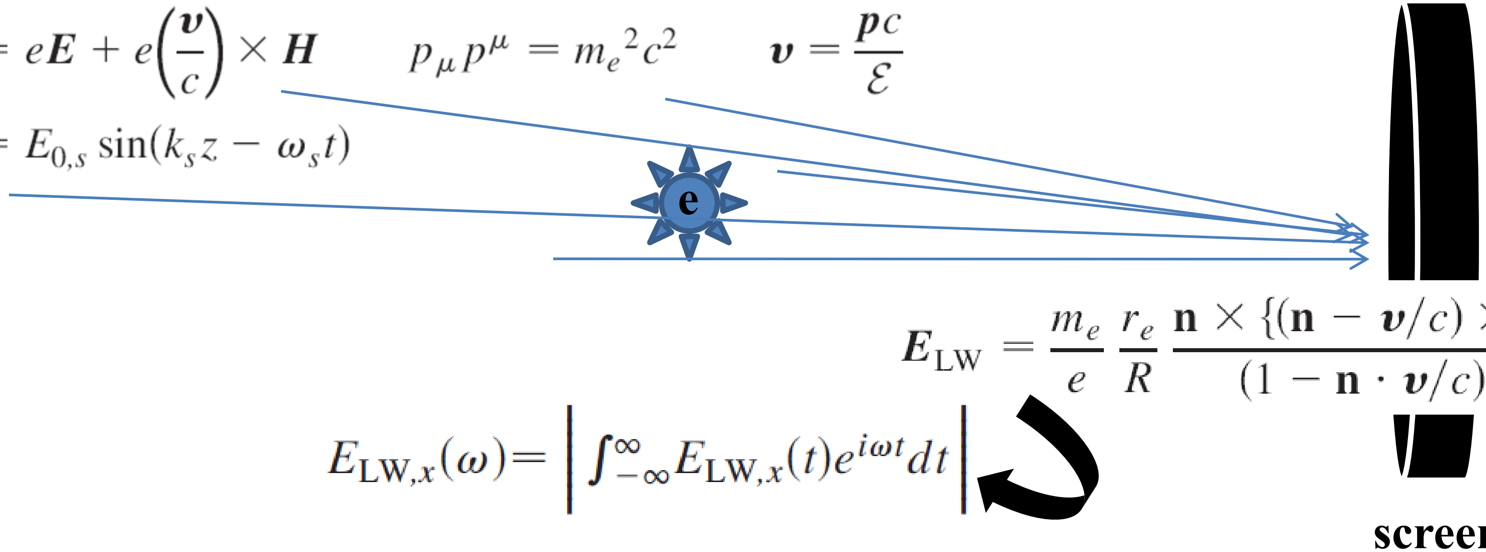
$$h\nu_{X\text{-ray}} = 4\gamma^2 h\nu_L n$$

Advantage of CO_2 laser: ♦*Longer wavelength*
♦ *Higher photon number per intensity*
♦*Narrow bandwidth emission*

Numerical spectrum estimate by Lenard-Wiechert calculation approach (Using extra RAM)

$$\frac{d\boldsymbol{p}}{dt} = e\boldsymbol{E} + e\left(\frac{\boldsymbol{v}}{c}\right) \times \boldsymbol{H} \qquad p_\mu p^\mu = m_e{}^2 c^2 \qquad \boldsymbol{v} = \frac{\boldsymbol{p}c}{\mathcal{E}}$$

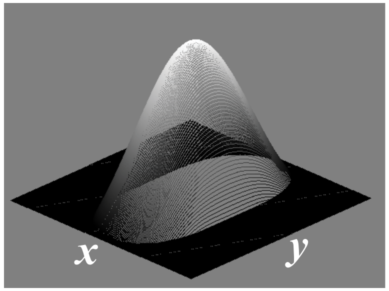
$$E_x = E_{0,s} \sin(k_s z - \omega_s t)$$



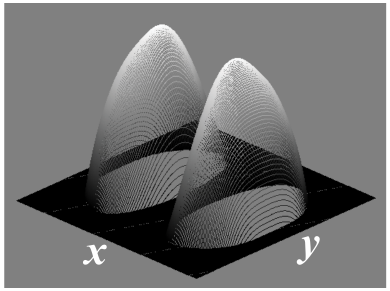
$$\boldsymbol{E}_{\mathrm{LW}} = \frac{m_e}{e} \frac{r_e}{R} \frac{\mathbf{n} \times \{(\mathbf{n} - \boldsymbol{v}/c) \times \boldsymbol{w}\}}{(1 - \mathbf{n} \cdot \boldsymbol{v}/c)^3}$$

$$E_{\mathrm{LW},x}(\omega) = \left| \int_{-\infty}^{\infty} E_{\mathrm{LW},x}(t) e^{i\omega t} dt \right|$$

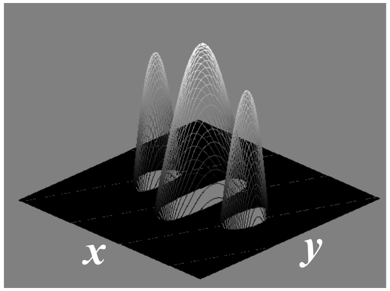
Example: Radiation distribution of single particle scattering, a_0~0.6, Linear polarization, ATF-AE70



1st ($h\nu$<7.6keV)
Cone angle $\Theta \sim 1/\gamma$



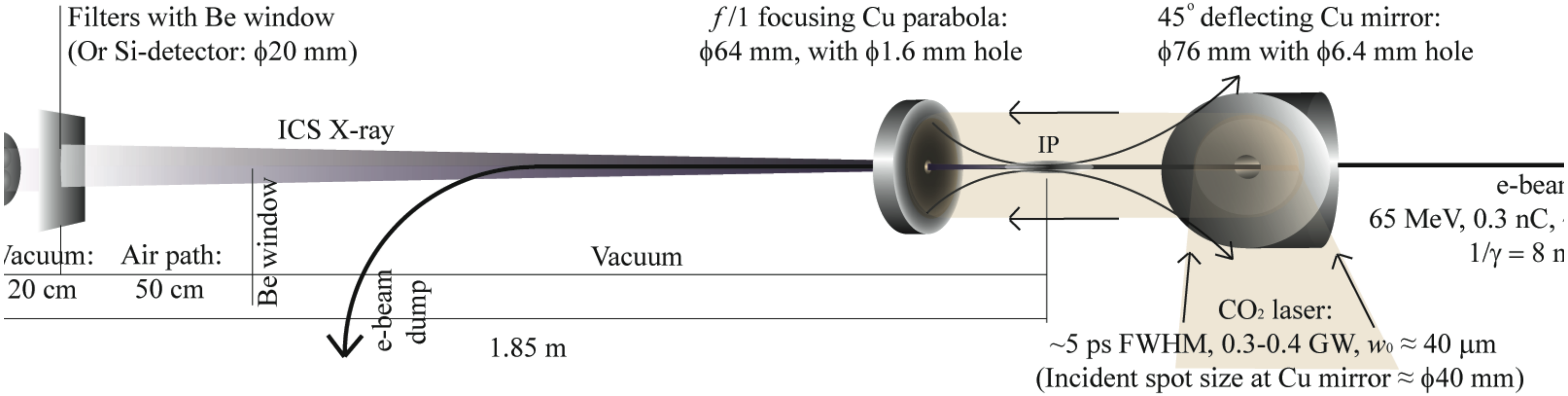
2nd (7.6<$h\nu$<15.2 keV)
$\Theta \sim 1/2\gamma$
$I_{peak,2nd} / I_{peak,1st} \sim a_L^2/4$



3rd (15.2<$h\nu$<22.8 keV)
$\Theta \sim 1/3\gamma$
$I_{peak,3rd} / I_{peak,2nd} \sim 3a_L^2/4$

REF: Phys. Rev. ST Accel. Beams 18, 060702 (2015)

AE70 experiment in BNL-ATF, 2014yr



BNL-ATF Beam parameters (as of 2014yr):

✦ **CO_2 laser: $a_L \approx$ 0.6 to 1.0**
(~0.4-0.8 TW, > 3 J), FWHM ≈ *3.5* – 5.0 ps,
10.6 μm, $w_0 \approx$ 40 μm, $Z_R \approx$ 500 μm

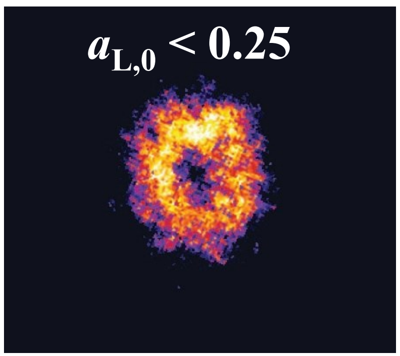
✦ **Electron beam: E = 65 - 70 MeV**
$Q \approx$ 0.3 nC, $\sigma_z \approx$ 300 μm, $\sigma_x \approx$ 30 μm, $\varepsilon_N \approx$ 1 mm mrad, $\beta \approx$ a few cm

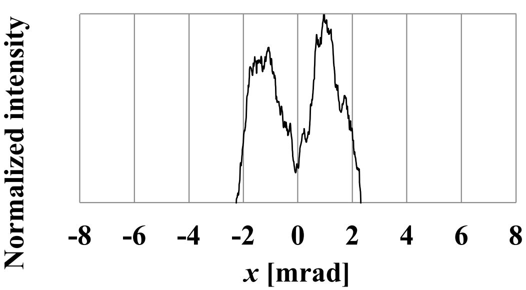
★Compton edge: $h\nu = 4\gamma^2 E_L \approx$ 7 - 10 keV

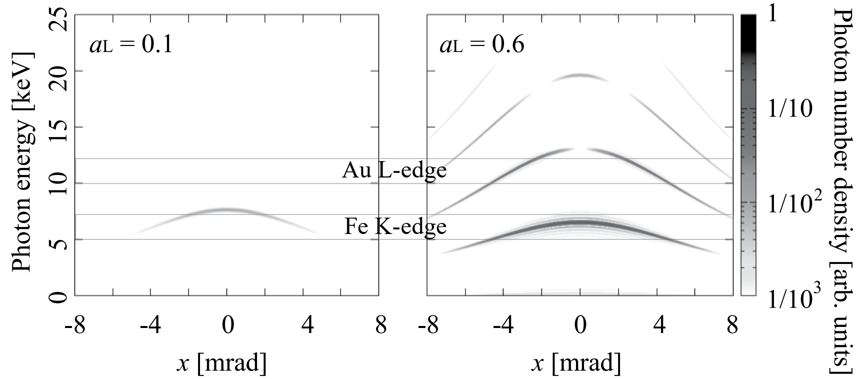
★Photons / pulse: $N_\gamma \approx 10^9$ (★ World record ★)

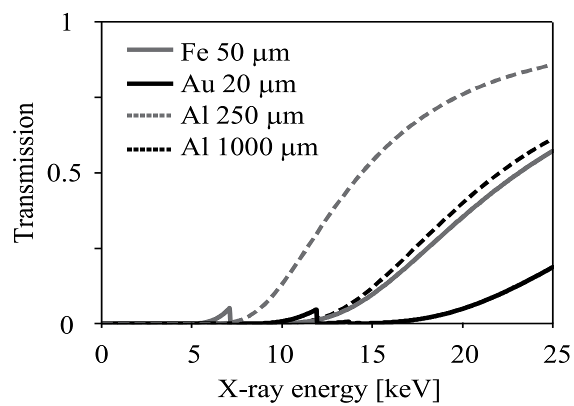
Observed red-shift (*Direct evidence of the figure-8 motion*)

7.6 keV < Fe k-edge
Off-axis component

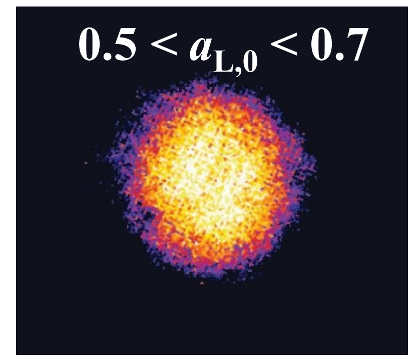


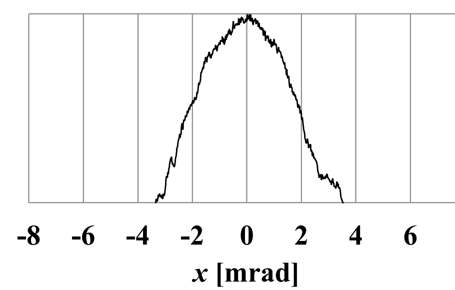






Red-shifting
to 5-6 keV



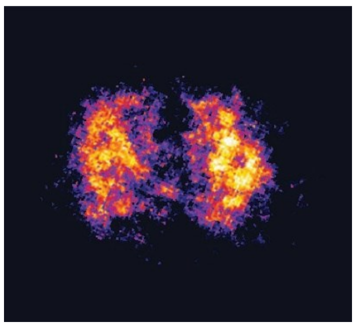


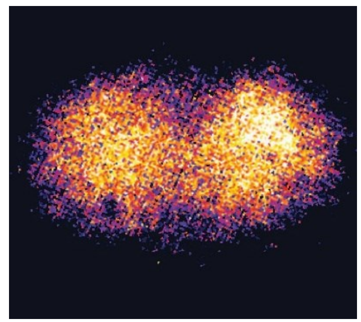
$$h\nu_{ICS,\,1^{st}} = 4\gamma^2 \nu_L/(1+a_{L,0}{}^2/2) \rightarrow \therefore 0.5 < a_{L,0} < 0.7$$

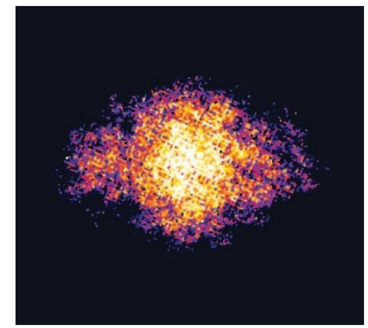
Y. Sakai, I. Pogorelsky, O. Williams et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

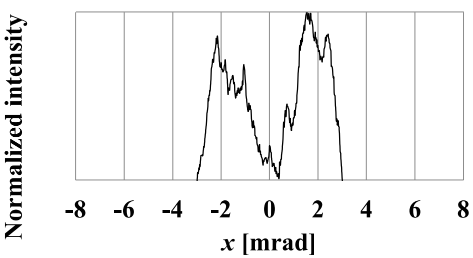
Angular distribution of harmonic radiation
(*Linear polarization case)*

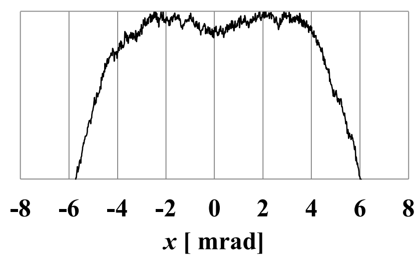
Au L-edge (12 keV) | **Al 250 μm > 10 keV** | **Al 1000 μm > 15 keV**

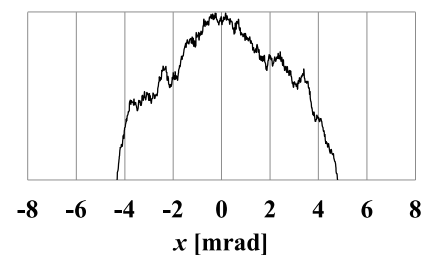








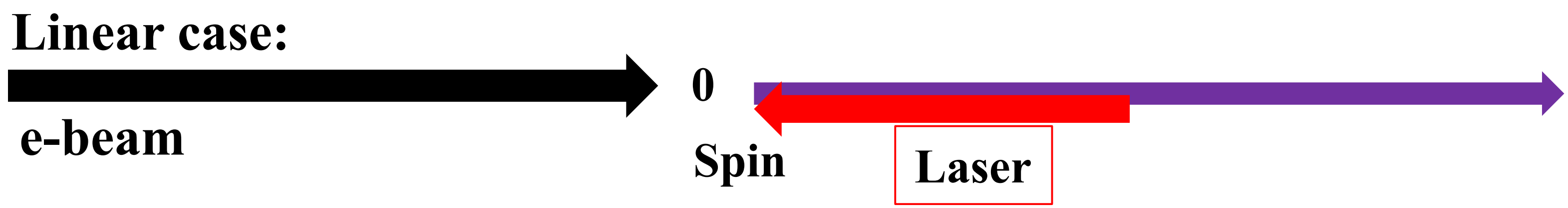


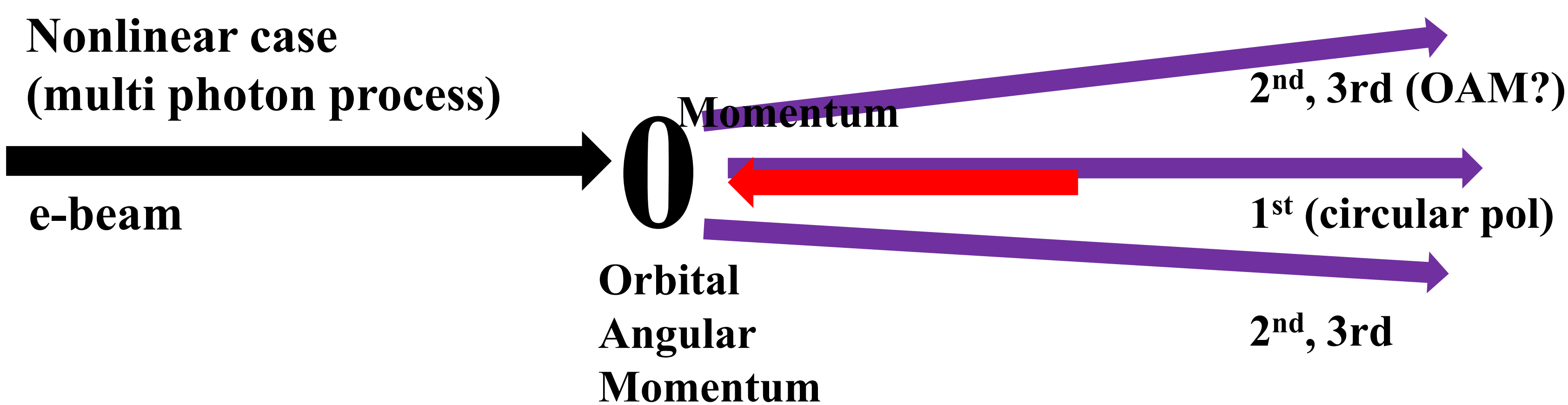


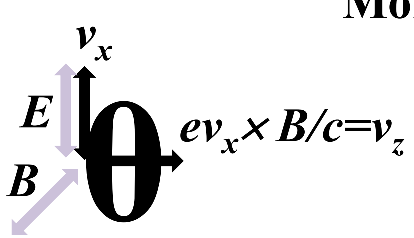
Narrow band 2nd | **2nd + 3rd** | **3rd (On-axis & lobes)**

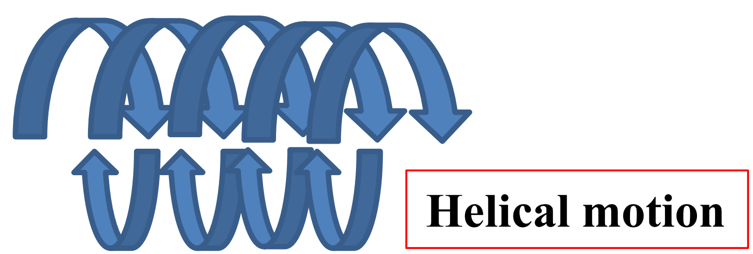
★On axis components of 3rd harmonics ↔ Direct evidence of the longitudinal motion

ICS of circular polarized laser – OAM X-Gamma ray ?







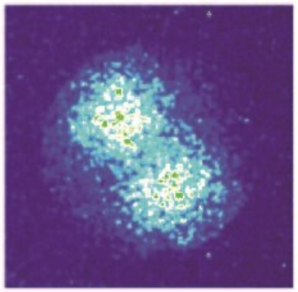
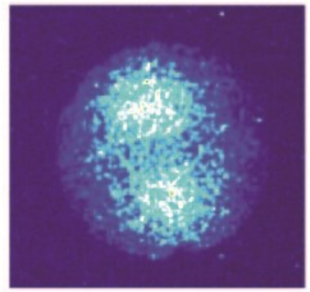
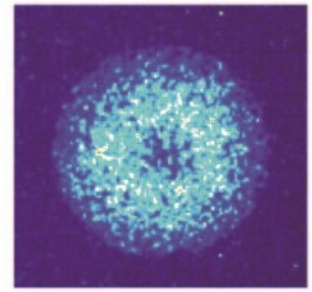


NOTE: OAM X-ray can be also generate by FEL & Linear ICS by OAM laser

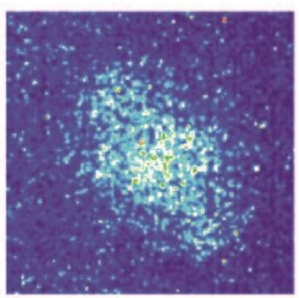
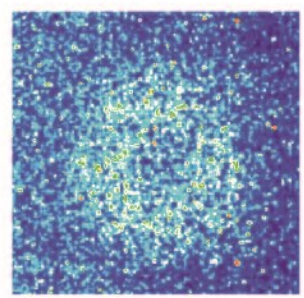
OAM X-ray generation by non linear ICS

¼ wave plate between regenerative and TW amplifier

Al 250 μm: **Linear, 2nd** **Elliptical, 2nd** **Circular, 2nd**

Al 1000 μm: **Linear, 3rd** **Circularlar, 3rd**

Gamma-ray vortices can be generated by only ICS

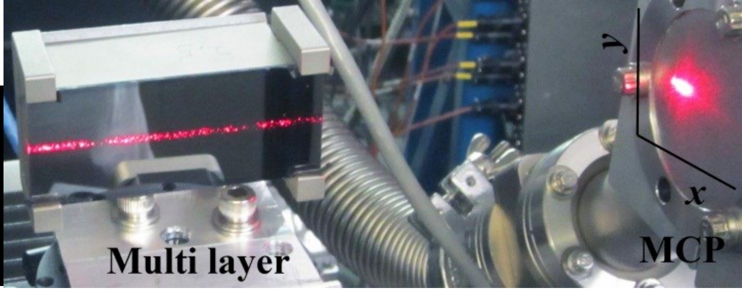
{Strong demands in Nuclear Photonics community:

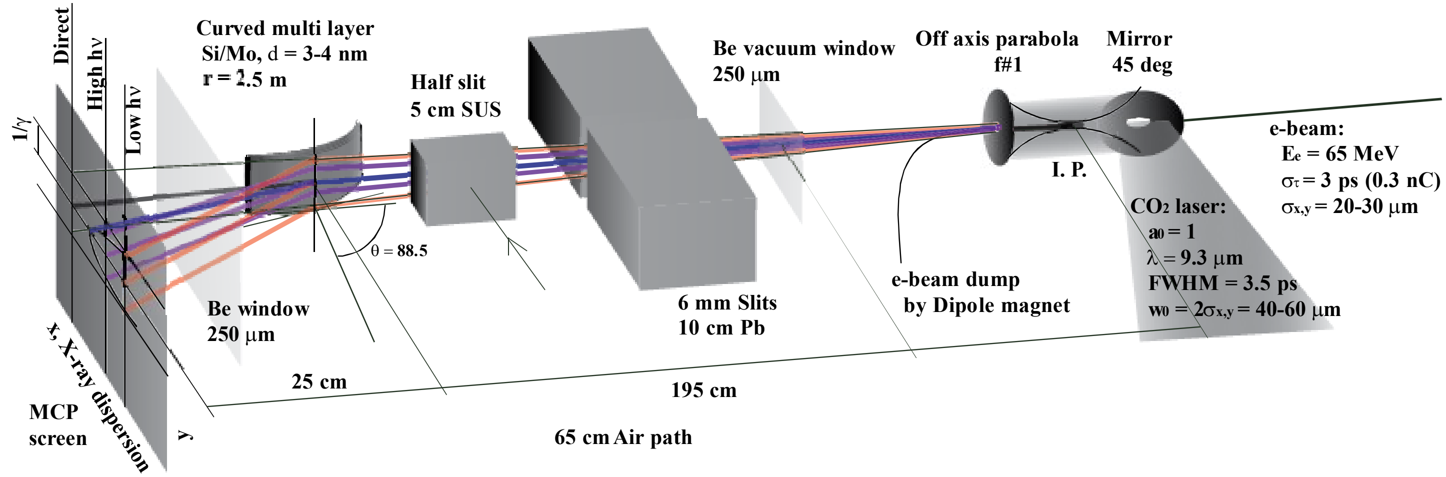
REF Y. Taira, T. Hayakawa, M. Katoh, Scientific Reports volume 7, 5018 (2017)}

→ Detailed spectrum distribution needs to be measured at 30 keV range.

Details of the ICS X-ray spectrum:

Mo/Si curved Multi-layer spectrometer





MCP image

✡ Mo-Si Multi (45) layer thickness: $d \approx 3.3$ nm

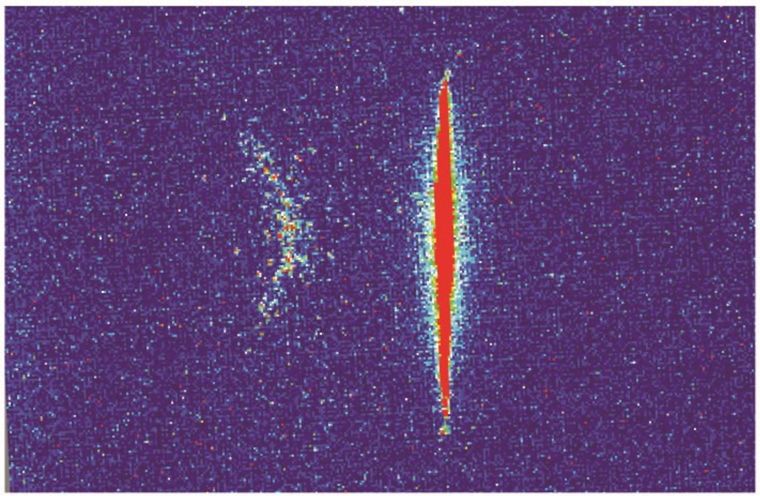
✡ Bragg angle: ~ 25 mrad

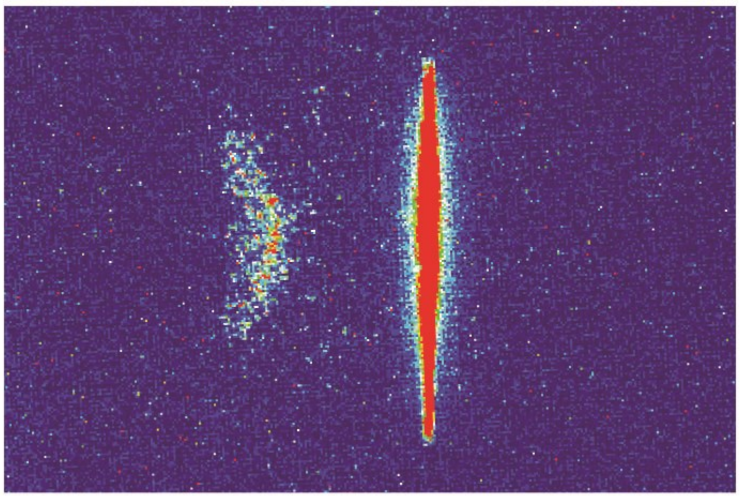
✡ Angle acceptance : ~ 50 mrad

✡ Reflectivity ~ 15% @ NSLS X15A (Z. Zhong)

Y. Kamiya, T. Kumita and P. Siddons et al., X-ray spectrometer for observation of nonlinear Compton scattering, Proc. Joint 28th Workshop on Quantum Aspects of Beam Physics (World Scientific), 103 (2003)

Projection of deflected ICS X-ray in a single shot



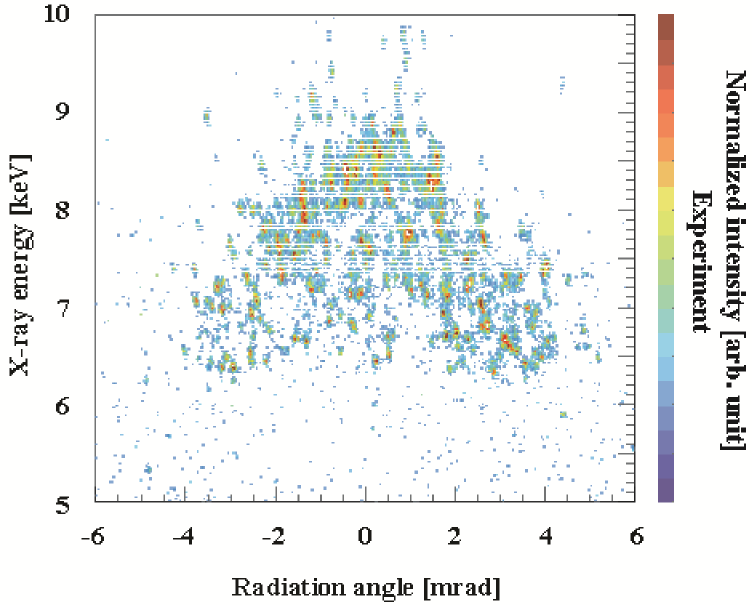


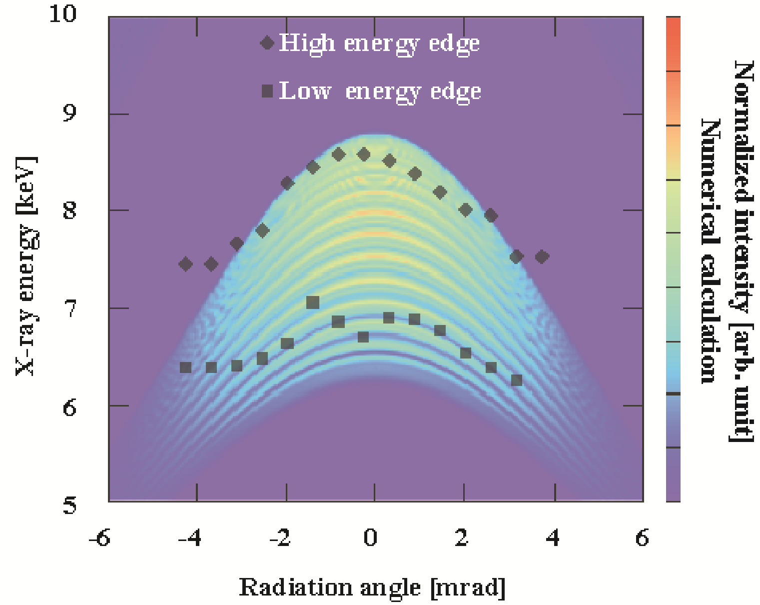
Laser energy 1.5 J,
$a_L = 0.7$

Laser energy 3.0 J
$a_L = 1$

Single shot, double differential spectral measurements of inverse Compton scattering in the nonlinear regime, Phys. Rev. ST Accel. Beams (2017), in press

Double Differential Spectrum at $a_0 = 1$

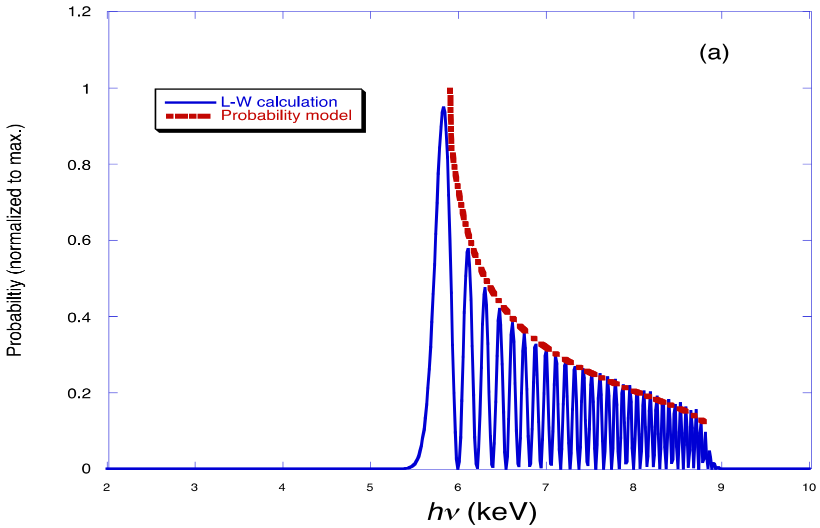




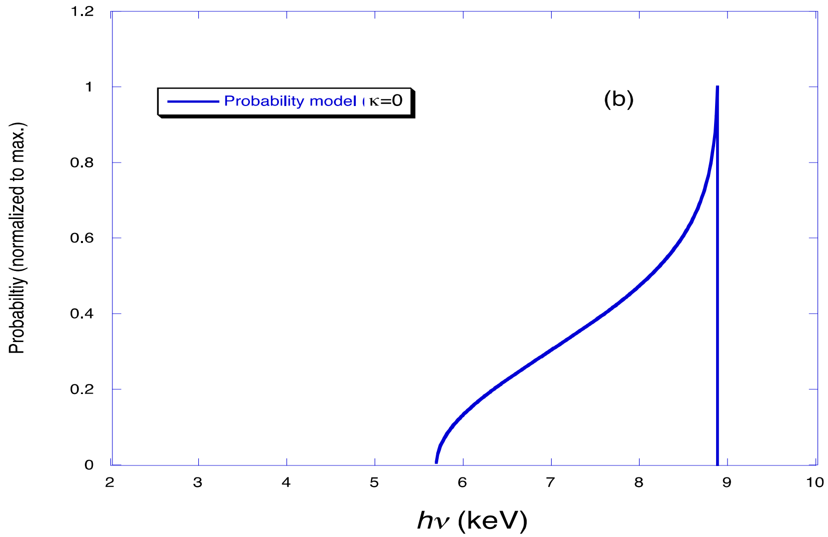
It figured out that Spectrum shape changes by e-beam & laser spot size:

Analysis: on-axis spectral structure

Temporal effect alone
($\sigma_{Laser} > \sigma_{electron}$)
Electron see only on-axis high intense laser field



Radial effect
($\sigma_{electron} > \sigma_{Laser}$)
Electron see radial variation



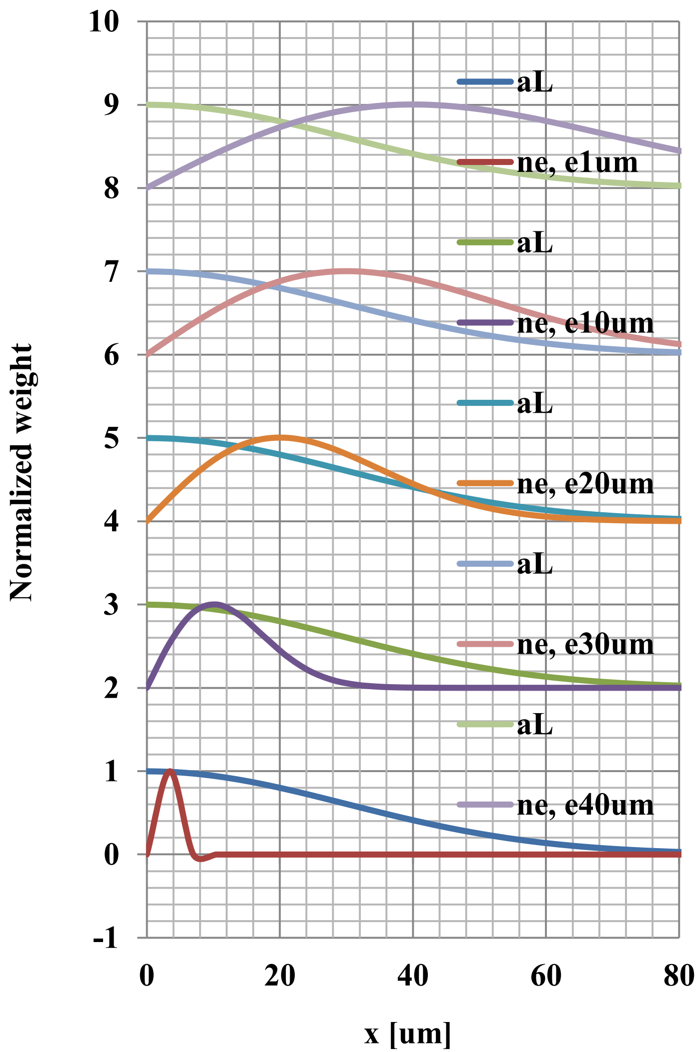
Scattering Probability Factor:

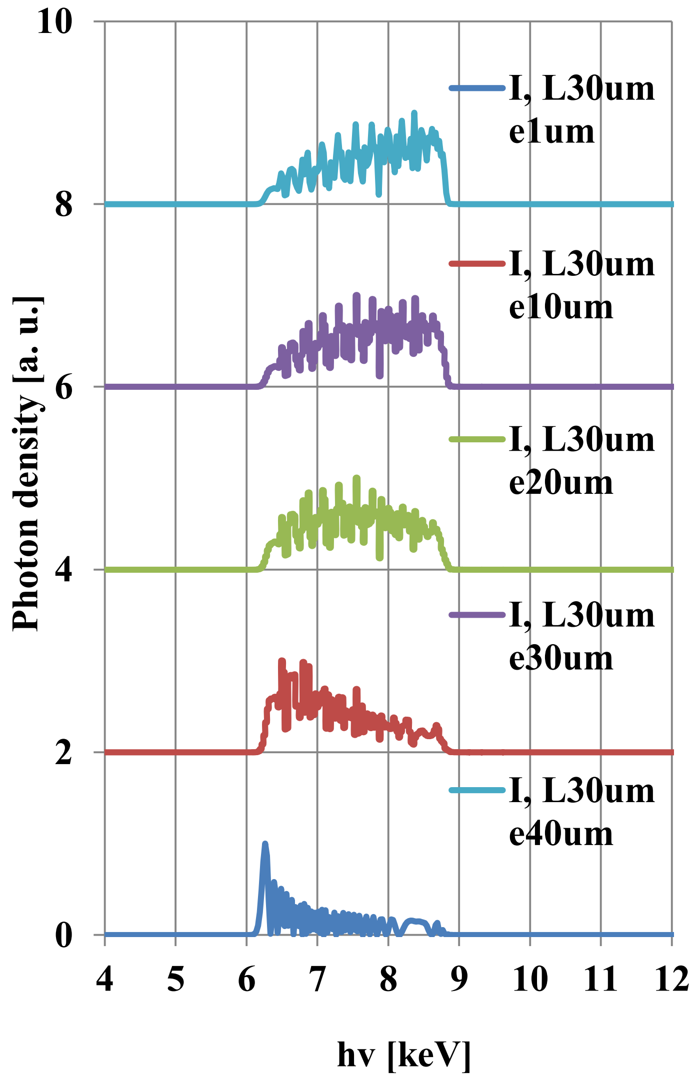
$$P_t(\Delta\lambda) \propto \frac{1}{\sqrt{\frac{\Delta\lambda_{max}}{\Delta\lambda}}}$$

$$P_r(\Delta\lambda) \propto \left(\frac{\Delta\lambda_{max}}{\Delta\lambda}\right)^{\kappa-1}$$

$$\kappa = \left(\frac{\sigma_L}{\sigma_e}\right)^2$$

Numerical example
Beam size effect:





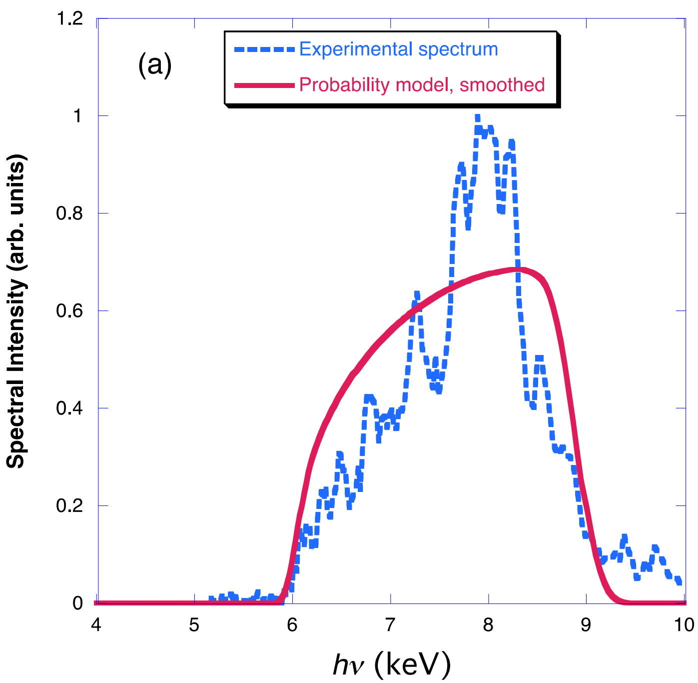
Approximation:

Radial weight
$I_{x\text{-}ray}(r) \propto a_L^2(r)\, N_e$
$N_e \propto n_e\, r\, dr$

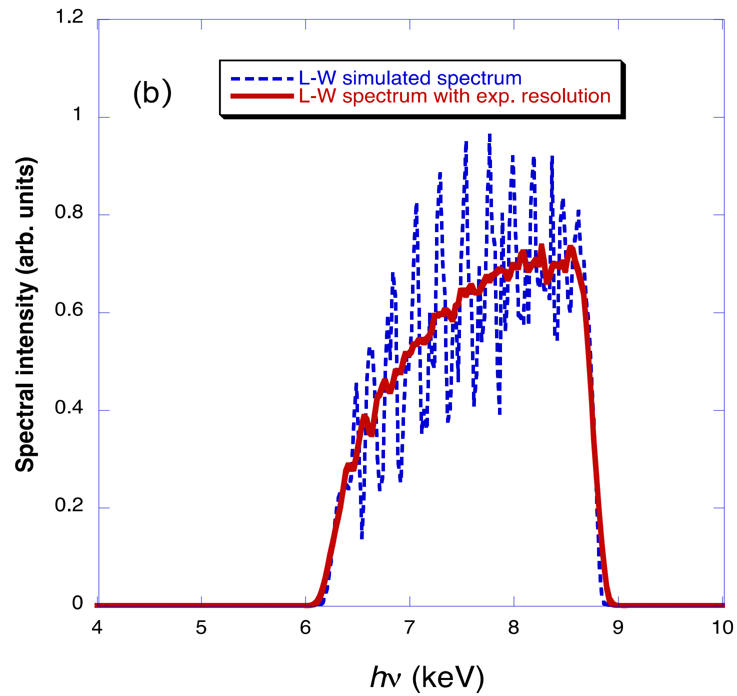
Longitudinal effect neglected
$\beta_e = 3$ *cm >>*
$Z_R = 0.5$ *mm*

Conclusion of on-axis spectrum analysis, BNL-AE70 experiment :

★ Spectral shape agrees with model, deduce $\sigma_e \approx \sigma_L \approx$ 20-30μm
★ On-axis emission; Total BW=33% with a_0 = 1.

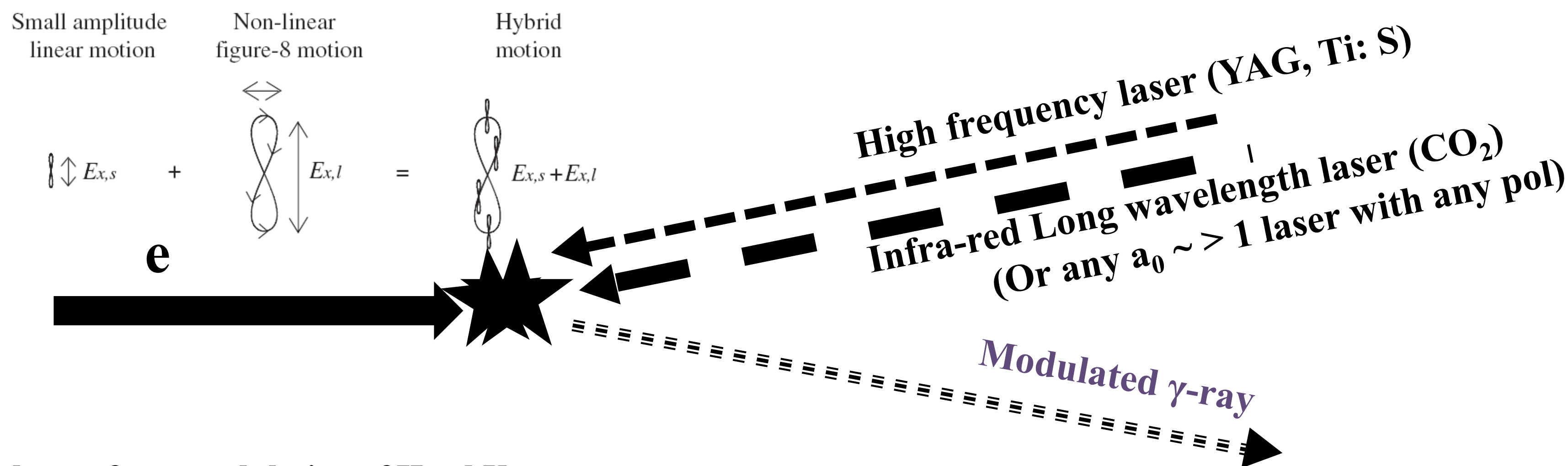


Data and analytical probability model



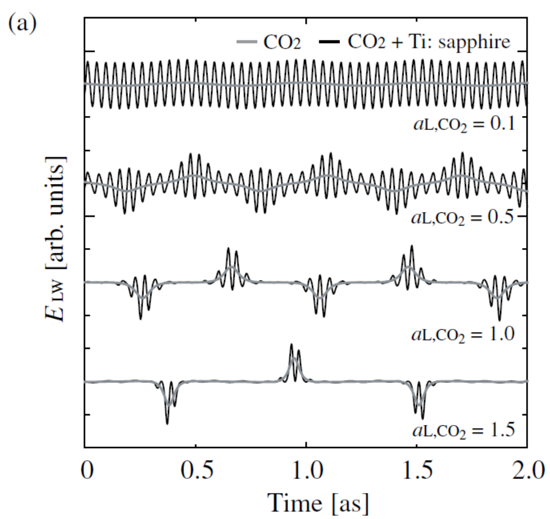
Lenard-Wiechert model (showing interference)

NEXT → Bi-harmonic nonlinear Compton experiment

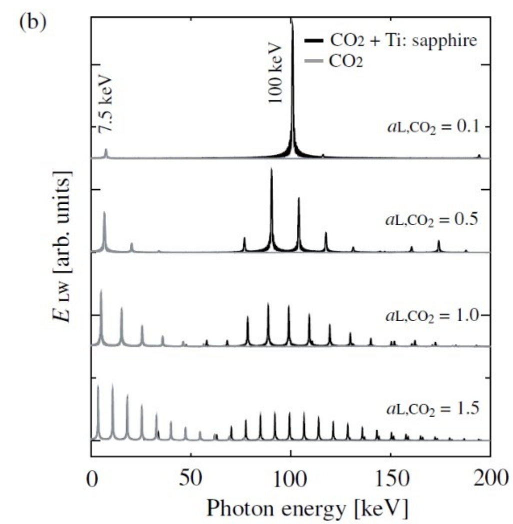


Pulsed waveform modulation of Hard X-ray component at less than < 10^{-18} s time scale {A few cycle X-Gamma RAY}

Observation of Red-Blue shifts & $h\nu_{L,YAG} \pm h\nu_{L,CO2}$



Fourier transform →

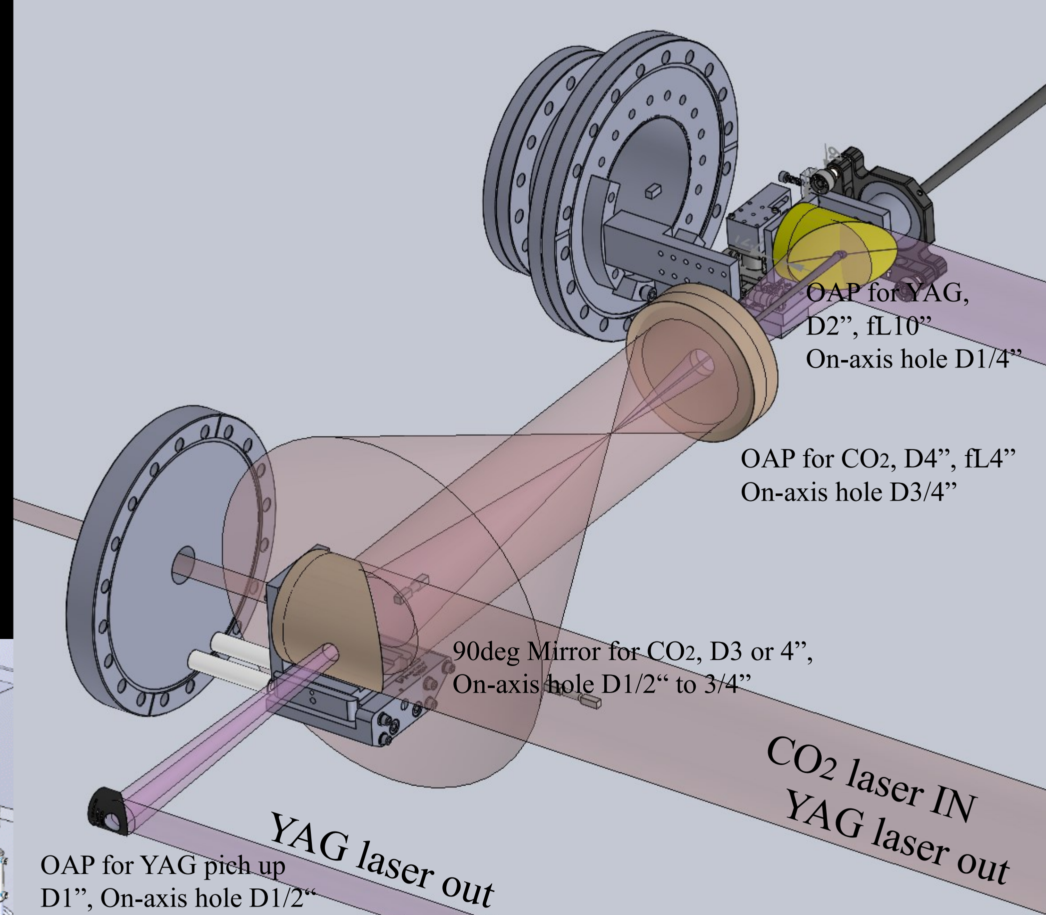


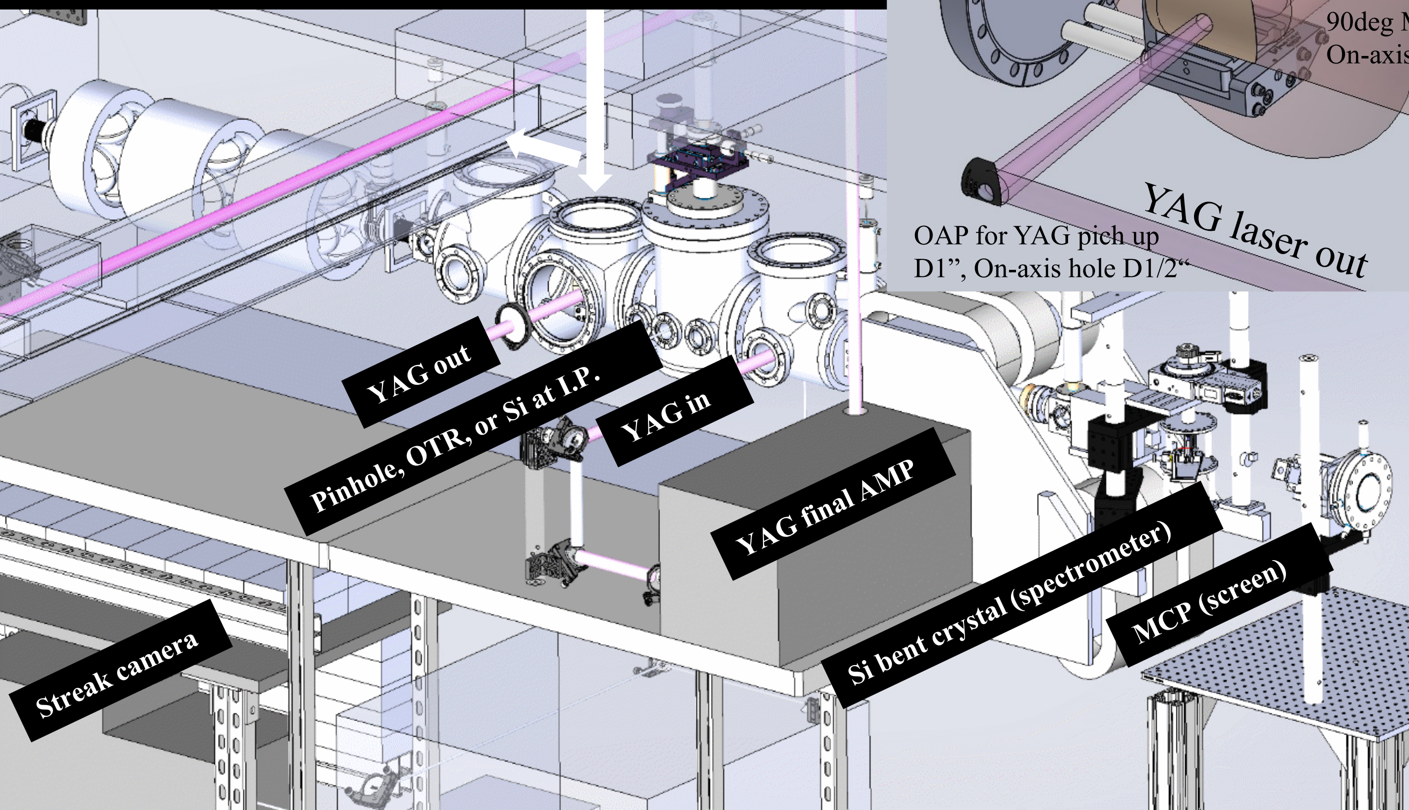
Numerically calculated Lienard-Wiechert potential $E_{LW,x}(t_{screen})$ on $(x, y, z) = (0, 0, 0)$

Experimental plans of AE87

Bi-harmonic Compton laser optics set up:

Input of CO_2 laser and YAG laser are opposite
CO_2 laser final optic has D ½ or ¾ inch hole

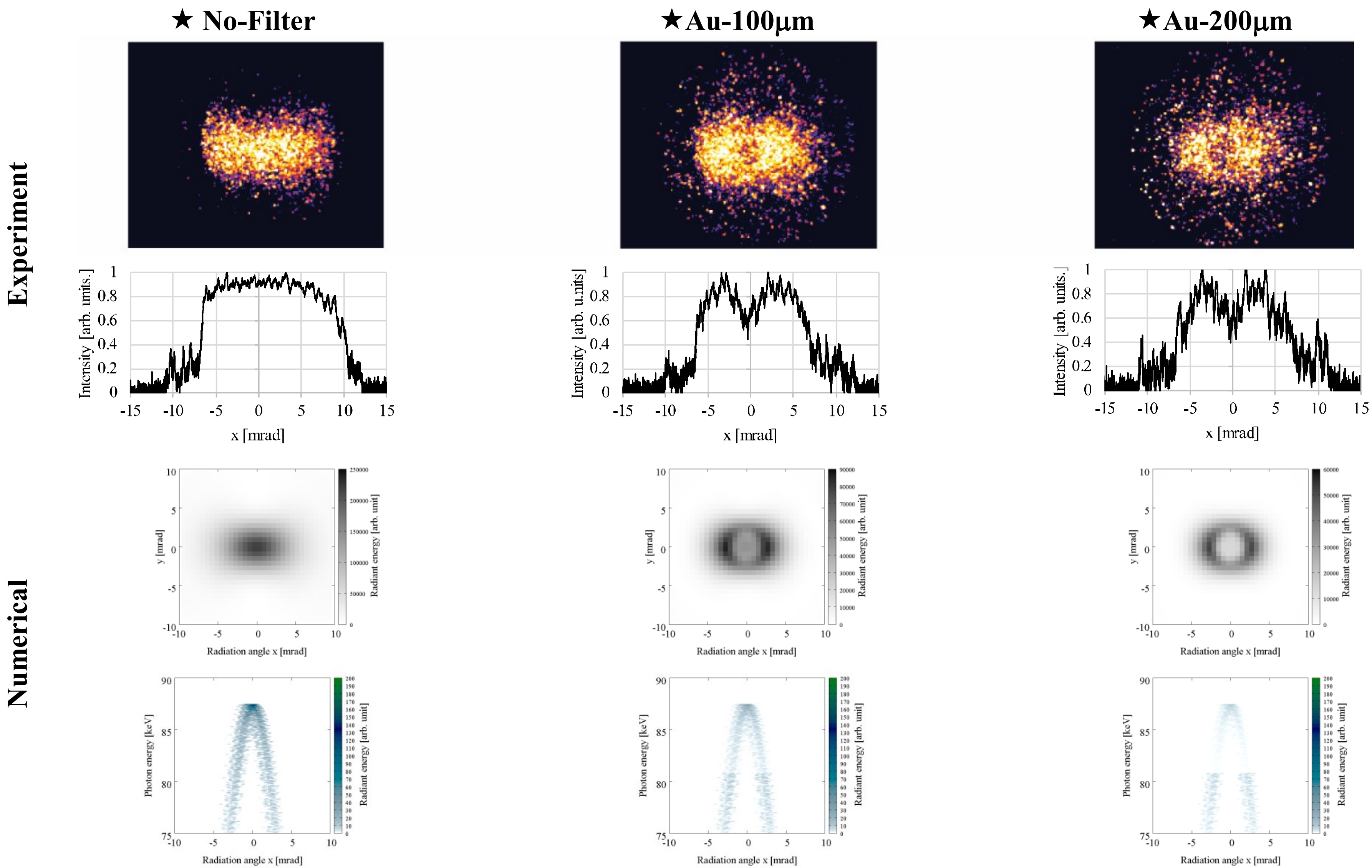




So far, YAG-ICS at hν 87.5 keV generated last year:

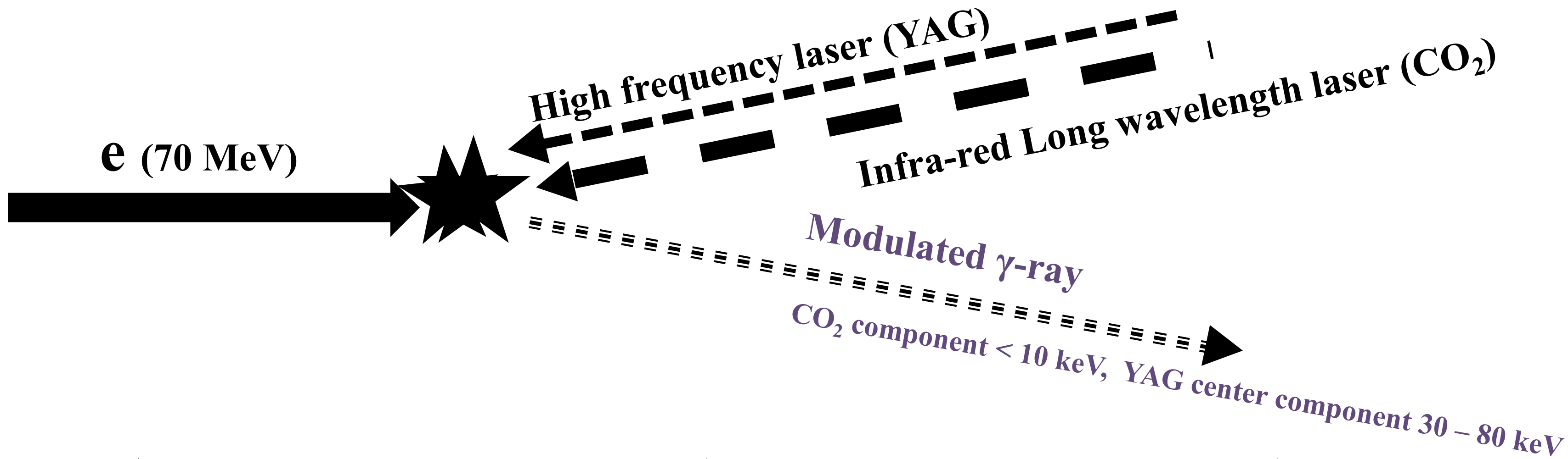
↓

Return to AE87 → Result: Observed attenuation of 87.5 keV Hard X-ray in a single shot (10^5-10^{6-7} photons / shot)

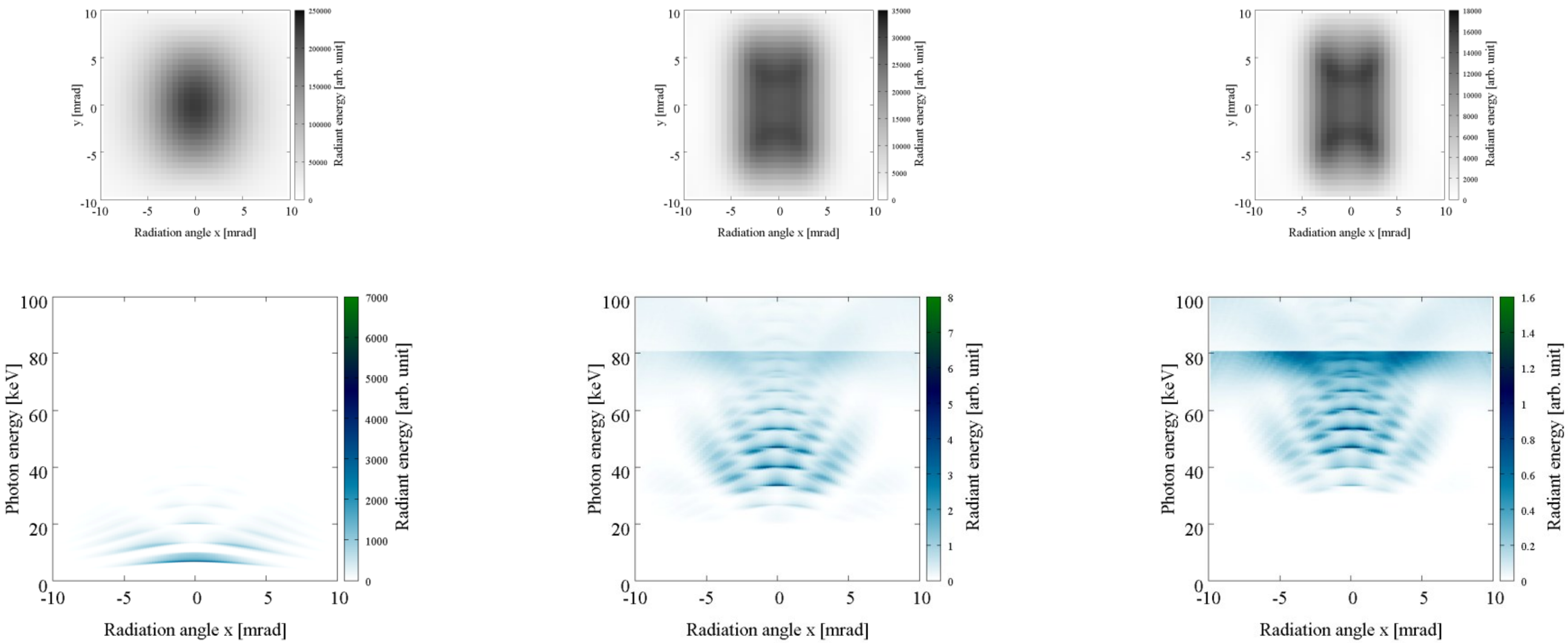


Sufficient contrast of radiation pattern of YAG laser ICS observed in a single shot

Numerical estimate of bi-harmonic spectrum by ATF parameter (Nonlinear Compton V2)



★ No-Filter ★Au-100μm ★Au-200μm



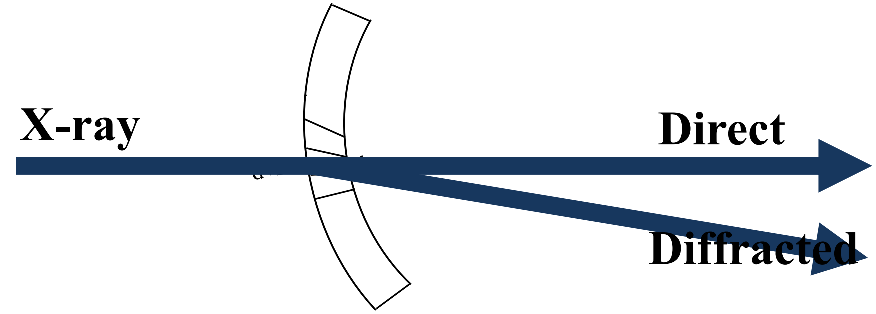
Only CO_2's component

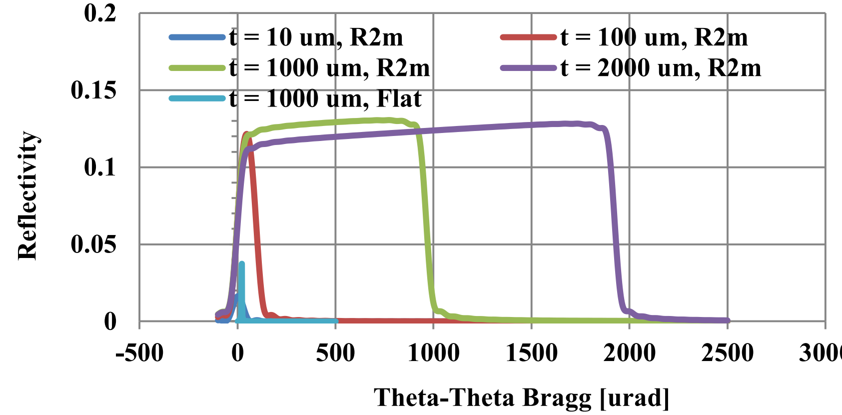
Bi-harmonic YAG's component

Single shot DDS measurement at X-ray energy of 87.5 keV <u>for quantitative study</u>

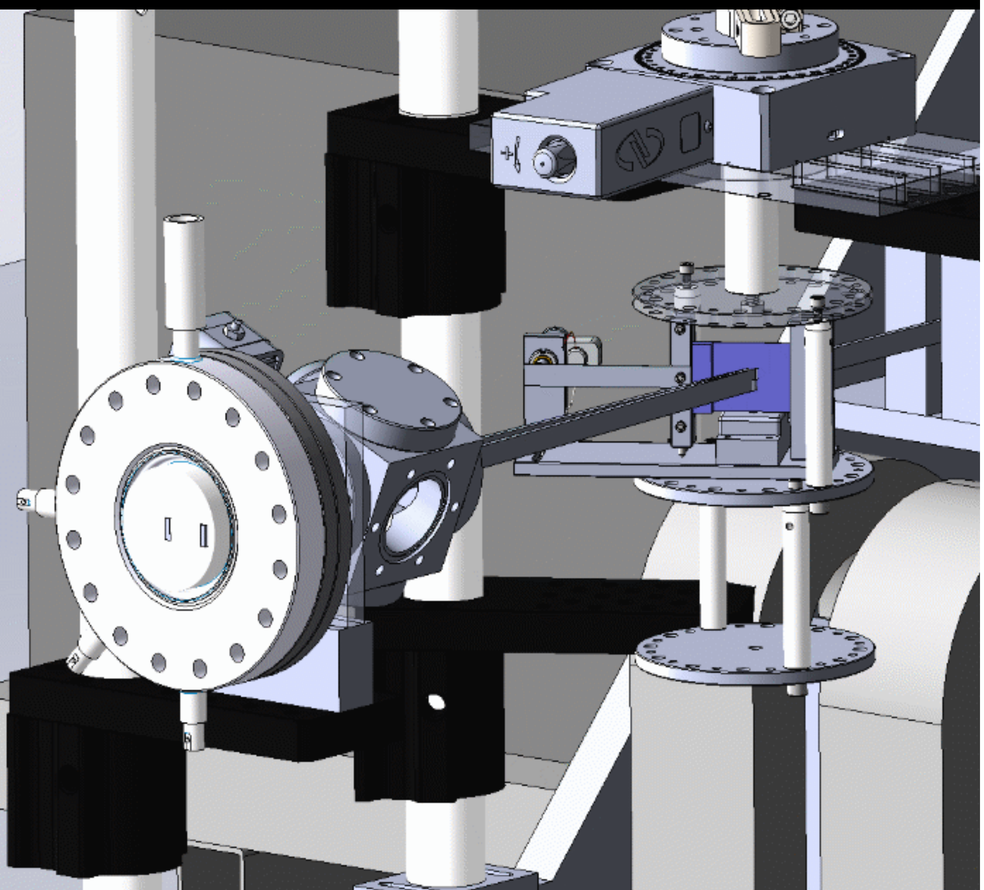
→ *Thick Laue Bent Crystal*
Efficiency > Bandwidth
(Collaboration with NSLS II 150 keV section, Z. Zhong)

Multi layer crystal: 5 – 20 keV (CO_2's ICS component)
Thick crystal: 20 keV – 200 keV (YAG's ICS component)





Rocking curve for Bent crystal,
R2m, Si[111], X-ray energy 80 keV. By XOP v2.3.



- Radius of curvature R: 2.5 m
- Thickness: 1 mm
- Bragg angle at 85keV: ~ 22 mrad
- Crystal to MCP screen 0.3 m
- Expected dispersion at screen: 10-20 mm:
- Band width: ~ 10 keV
- <u>Reflectivity (Efficiency): ~10%</u>

<u>Stats: Diffraction not observed yet, as this is a hard experiment as expected</u>

Application part math:
(In appreciation of observed 87.5 keV characteristic):
Examination of photon Activation with Gold Nano Particle (AuNP)

ICS X-ray energy hv > 80.7 keV (Au K-edge)

Enhanced does by monochromatic X-ray

Activation process:

X-ray absorption by Au K-shell

↓

Emission of Auger electron from outer shell (~90% of energy)

↓

Transfer energy to Radicals (OH etc) through water etc

Dose enhancement around surface of AuNP

↑↓

Required Gold particle size, for escape of electron from NP :

100 nm ↔ Auger, L-edge 11.9-14.3 keV

10 nm ↔ Auger, M-edge 2.2-2.4 keV

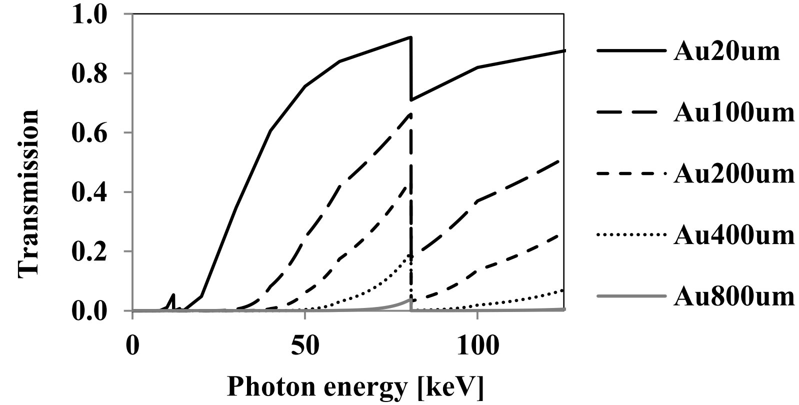
Penetration depth of keV electron in water (between AuNP)

→ ~ μm range

Spacing between particles

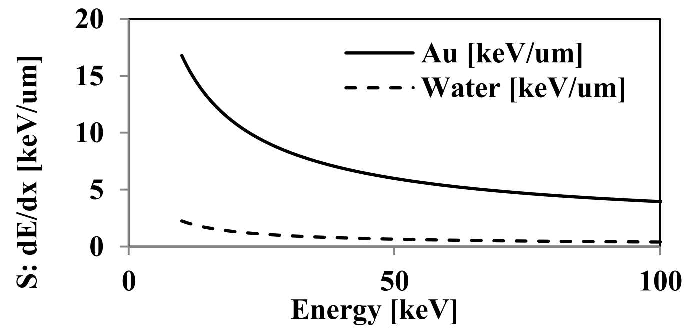
AuNP Dia 100 nm ↔ 10 μm, AuNP Dia 10 nm ↔ 1 μm,

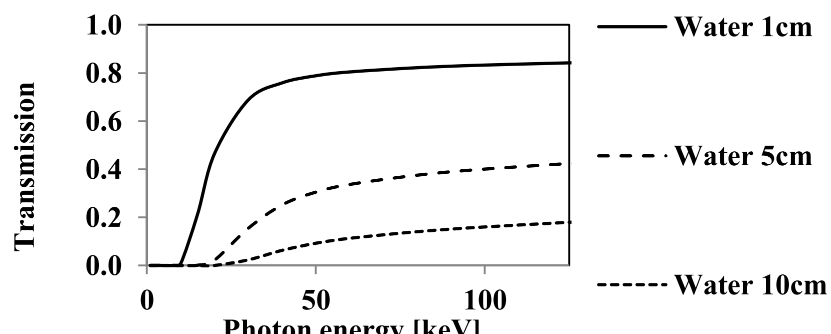
Because, 100 μm thick Au filter occupy 1% of volume in 1 cm thick volume of water.



Note: Density of 100 μm thick Au sheet in cubic cm of water of square volume corresponds to 194 mg / g uptake.

(Density of Au and H_2O are 19.3 g/cm^3 and 0.997 g/cm^3)





- - Hard X-ray flux requirement math- -

Assuming target dimension of $(L_{I.P.\ to\ target} \times 1/\gamma)^2 = 1\ \mathrm{cm}^3$,
(1 m away from I.P. at $1/\gamma = 10$ mrad, at ~60-70 MeV electron beam)

Radiation dose per kg of water per shot:
1 [Gy] = 1 J / $(10\ \mathrm{cm})^3$] ↔ 1 mJ / $(1\ \mathrm{cm})^3$.

While energy per X-ray pulse:
($10^{6\text{-}7}$ photons) × (87.5 keV) × (1.6×10^{-19}) ~ 0.1 - 1 μJ / shot)

↑↓

Total irradiation shot required: 1 mJ / 0.1 μJ = 10.000 shot

Flux can be increased by further tight focus down to a several σ_e~ μm →> X10 & YAG laser pulse > 1 J → ×10

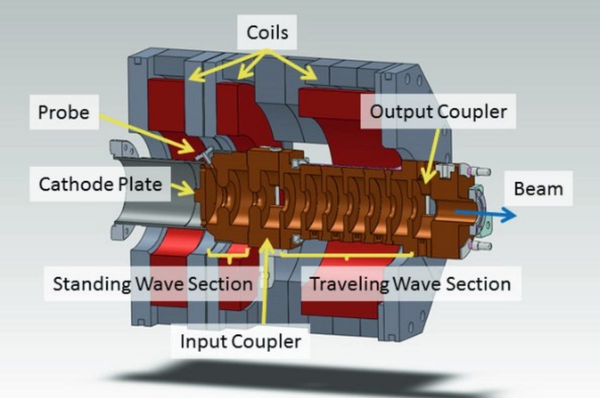
NOTE: But bandwidth will be 10s % range:

$$\omega_{ICS} \approx \frac{4\gamma_0{}^2\omega_L}{1+\gamma_0{}^2\Theta^2+\frac{a_0{}^2}{2}}, \qquad \gamma_0{}^2\Theta^2 \leftrightarrow \gamma_0{}^2\left(\frac{\Delta p_{x,y}}{p_z}\right)^2$$

$\sigma_{x,y}$ = 20 μm → beta function β= 3 cm ↔ σ'~0.6 mrad ↔ X-ray bandwidth: ~1 %
$\sigma_{x,y}$ ~5 μm → beta function β~1 mm ↔ σ'~5 mrad ↔ X-ray bandwidth: ~10 %
$1/\gamma_0$ ~ 7.3 mrad for 70 MeV e-beam, Normalized emittance 2 mm mrad case
{OR, can we lower e-beam emittance more??}

Direction depending on purposes:

- ✦ **Narrow band X-ray production based on single shot detection**
- ✦ **Less narrow band high flux X-ray production**
- ✦ **Strong field physics for Bi-harmonic & OAM production**

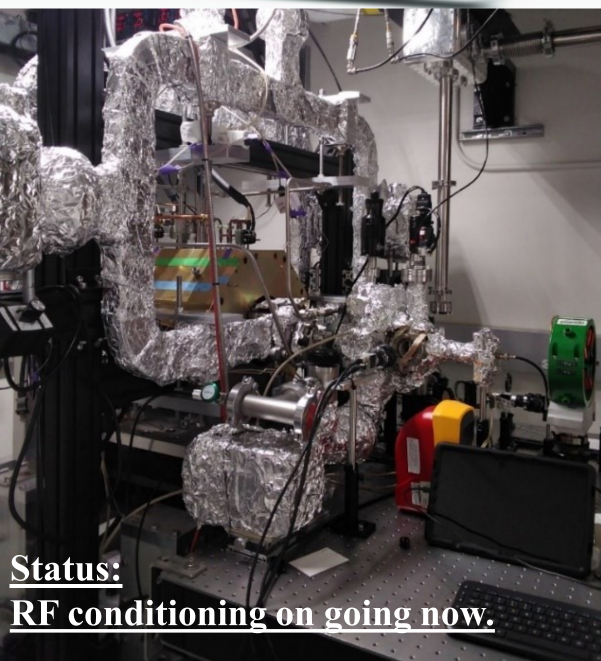


IN PARALLEL : **University scale test facility in Westwood L.A., UCLA campus:**

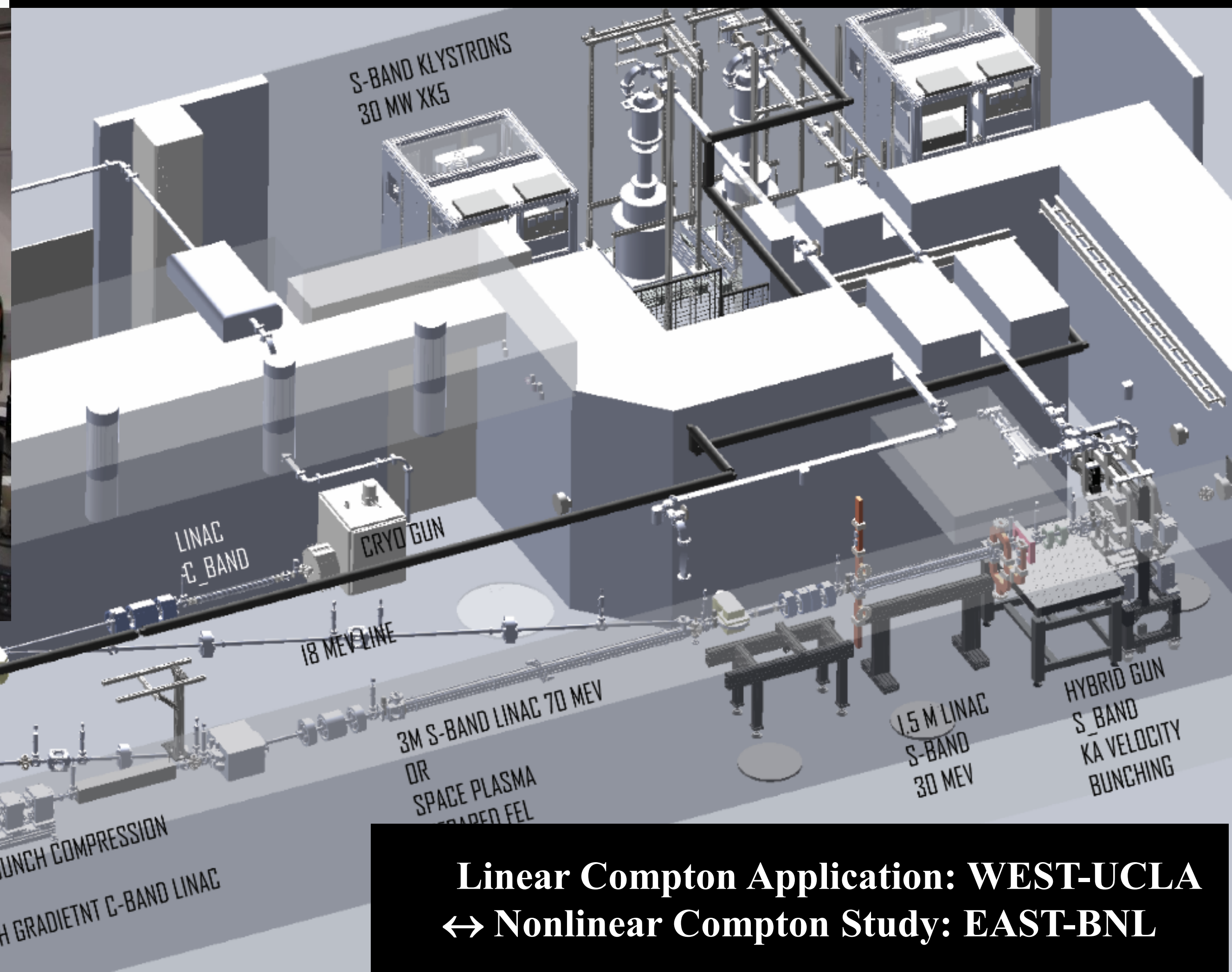
Based on S-band Hybrid gun:
RF gun and a short linac for velocity bunching, 100s fs, in one structure

REF: A. Fukasawa et al., "Progress on the hybrid gun project at UCLA", Physics Procedia, vol. 52, pp. 2–6, 2014.

& R & D of Cryo cooled high gradient ~200 MV/m, low emittance gun: Emittance ~ 1/ γ^2



Status:
RF conditioning on going now.



Linear Compton Application: WEST-UCLA
↔ Nonlinear Compton Study: EAST-BNL

FUTURE PLAN 2022-2024yr

IN BNL ATF:

- **Set up nonlinear CO_2 ICS with upgraded ATF's multi TW CO_2 laser at a_0~2**
- **Observe higher order harmonics & benchmark a_0 & X-ray production per pulse**
- **Measure 30 keV CO_2 ICS X-ray spectrum by thick bent crystal spectrometer**
- **Single shot DDS measurement by Bent crystal at ~100 keV range by YAG ICS**
- **Measure spectrum of Harmonics by circular polarized CO_2 laser (ATF's Polarization rotator)**
- **Production of Bi-Harmonic X-ray, A few cycle X-ray pulse**

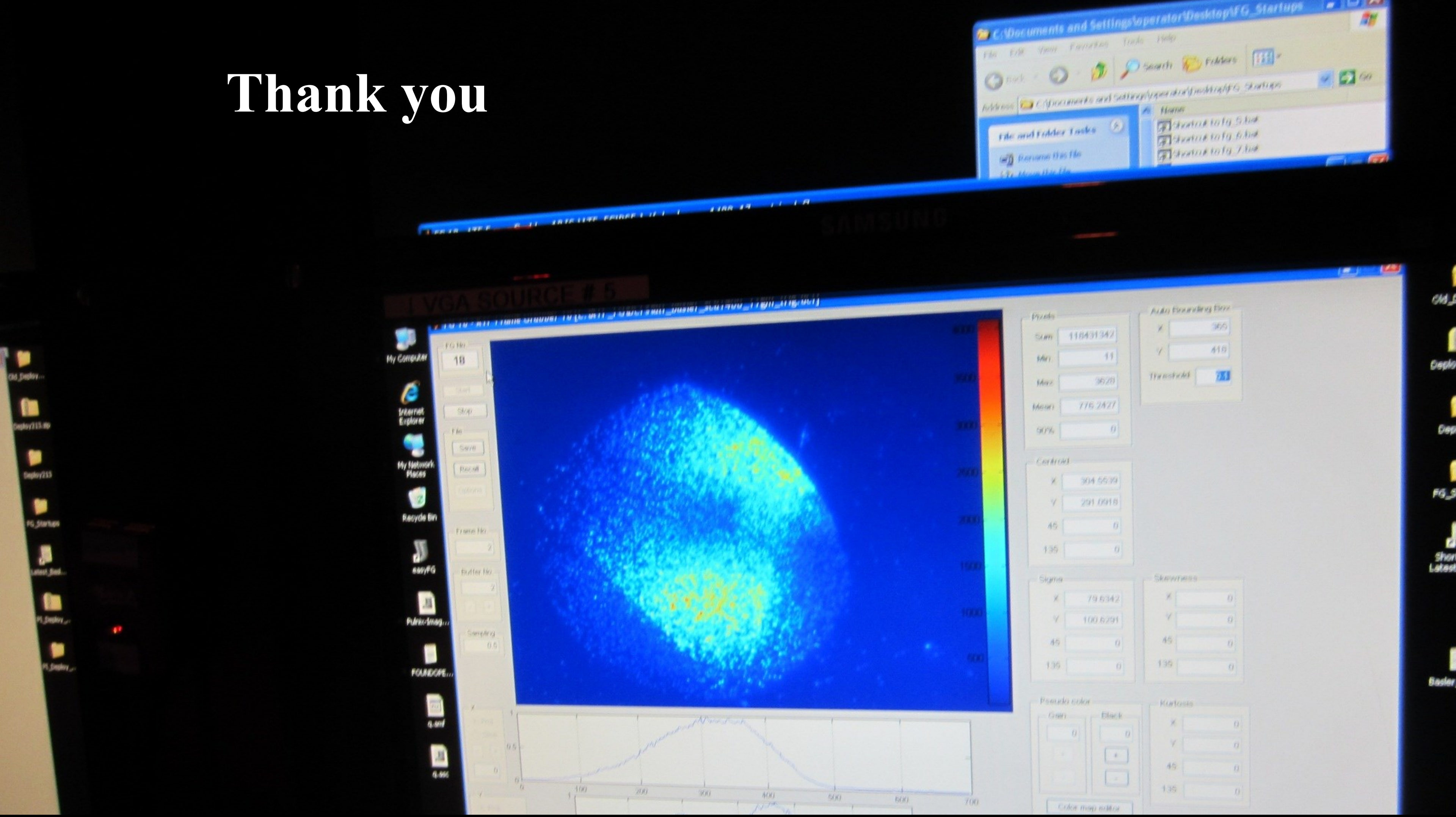
IN UCLA:

- **Keep constructing a PBPL-LINAC in Westwood**
- **Soft X-ray ICS by Ti: Sappire laser, 20 MeV e-beam (Let's cover all spectrum range)**

Conclusion:

Inverse Compton Scattering Study seems to be simple but endless

Thank you



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DOD DARPA GRIT Received (20204571)