P B P L University of California Los Angeles, Particle Beam Physics Laboratory

AE87: Hard X-ray ICS
Close out report

Nonlinear ICS by $a_0 \sim 1$, CO_2 laser @ hν ~ 10 keV

→→→ *Linear ICS by YAG laser @ hν ~ 100 keV*

BNL ATF user meeting
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BROOKHAVEN NATIONAL LABORATORY

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

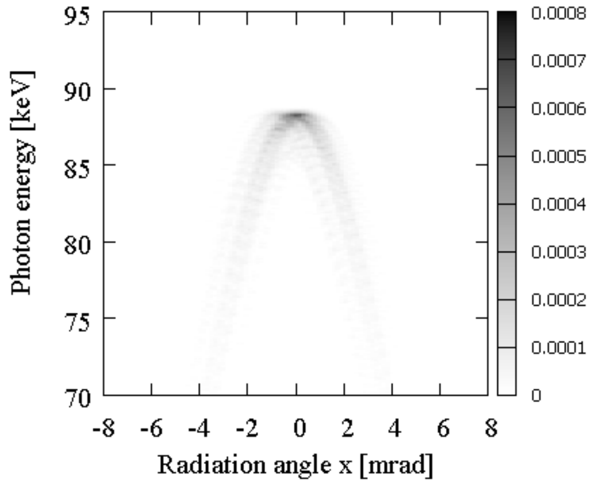
- ✪ <u>Applications: Photon activation as Medicine & Radiography of high *Z* materials</u>
- ✪ Strong field physics: Bi-harmonic Compton interaction with ATF's CO_2 laser
- ✪ <u>Hard X-ray optics developments: DDS measurement & Focusing or Collimation (NSLS II 150keV section)</u>
- ✪ X-ray OAM investigation: Higher order harmonics by circular polarized CO_2 laser

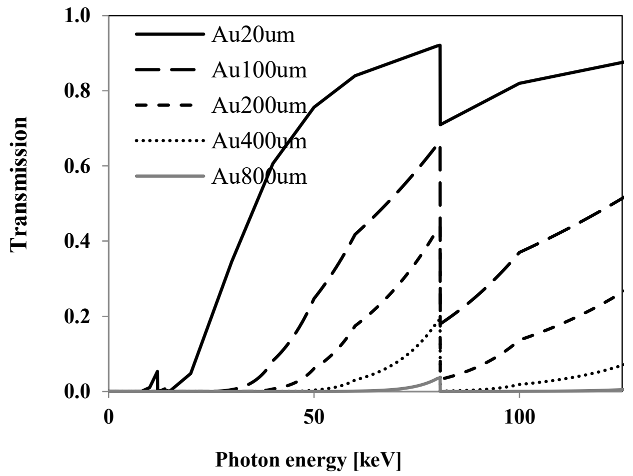
<u>YAG laser: 1064 nm, ~ 100-200 mJ</u>

<u>e-beam ~ 70 MeV, ~ 0.3-0.5 nC</u>

~ 1 µJ/pulse*
@ *hν* ~ 87.5 keV

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





✦ Qualitative spectrum study by Au filters has been done.

{Goal of AE87: Establish basic set up of ICS by Nd: YAG laser, wavelength 1064 nm}

Hard X-ray spectrum vs beam parameters (Numerical estimate based on Liénard–Wiechert potential)

Nonlinear Laser effect:

Experimental parameter AE87

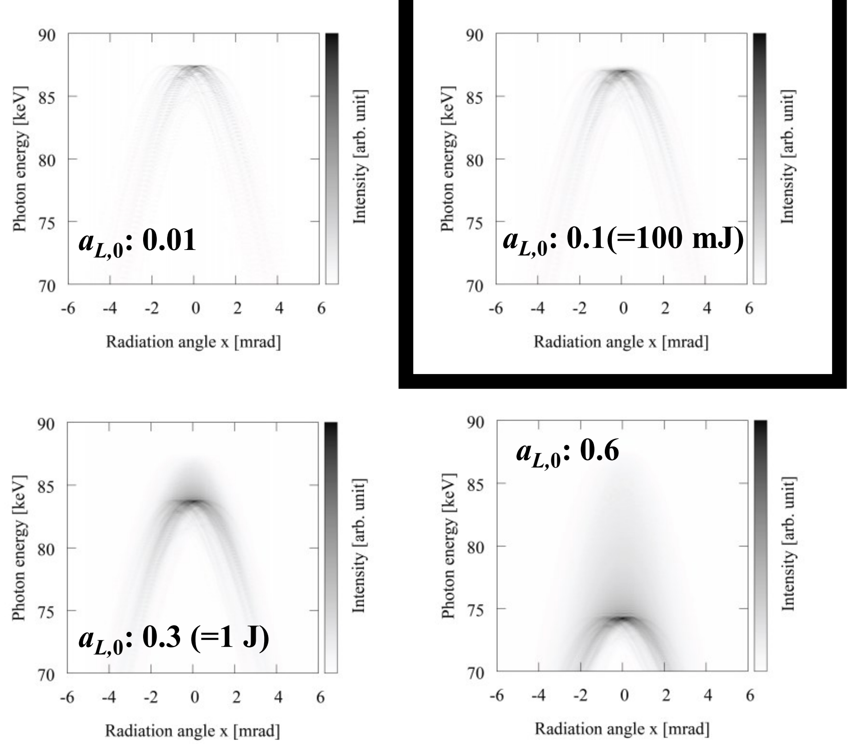


Figure 1. Double differential spectrum of inverse Compton scattering. Electron beam energy: 70 MeV, Laser wavelength: 1064 nm, Normalized emittance ε: 2 mm mrad, Beta function: 6 cm, e-beam transverse size: $\sigma_{x,y}$: 30 µm, Normalized vector potential of laser: a_0: 0.01, 0.1, 0.3 and 0.6.

Nd: YAG laser: 100 mJ, FWHM 15ps, FWHM at I.P. 10um $\rightarrow a_{L,0} < 0.1$

$$\gamma_0{}^2\Theta^2 \leftrightarrow \gamma_0{}^2\left(\Delta p_{x,y}/p_z\right)^2$$

$$\omega_{\mathrm{ICS}} \approx \frac{4\gamma_0{}^2\omega_L}{1+\gamma_0{}^2\Theta^2+a_{L,0}{}^2/2}$$

Emittance, e-beam effect:

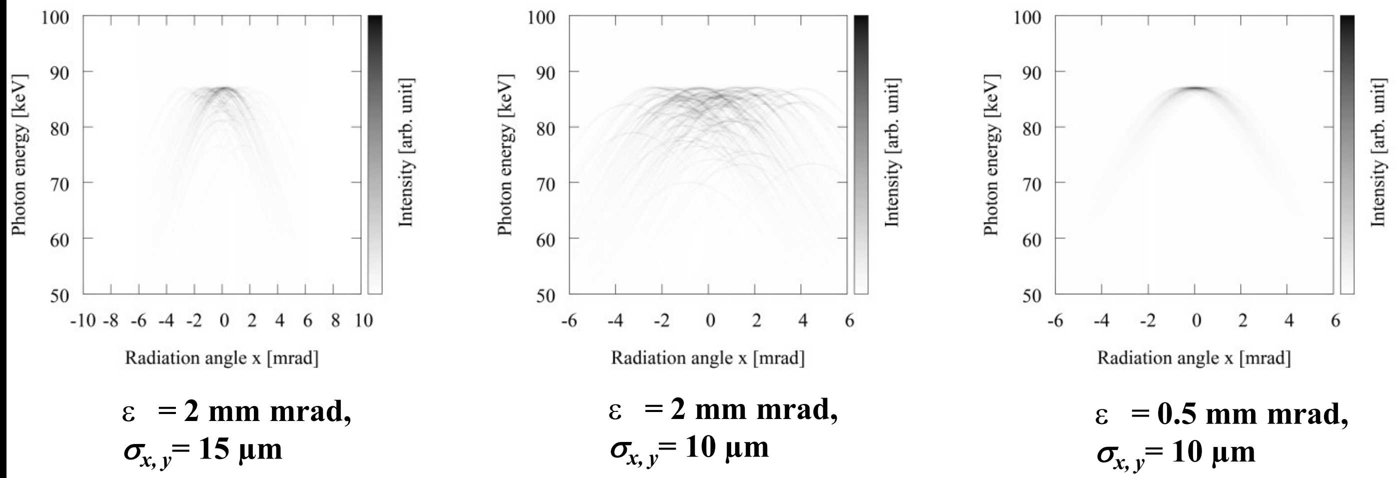
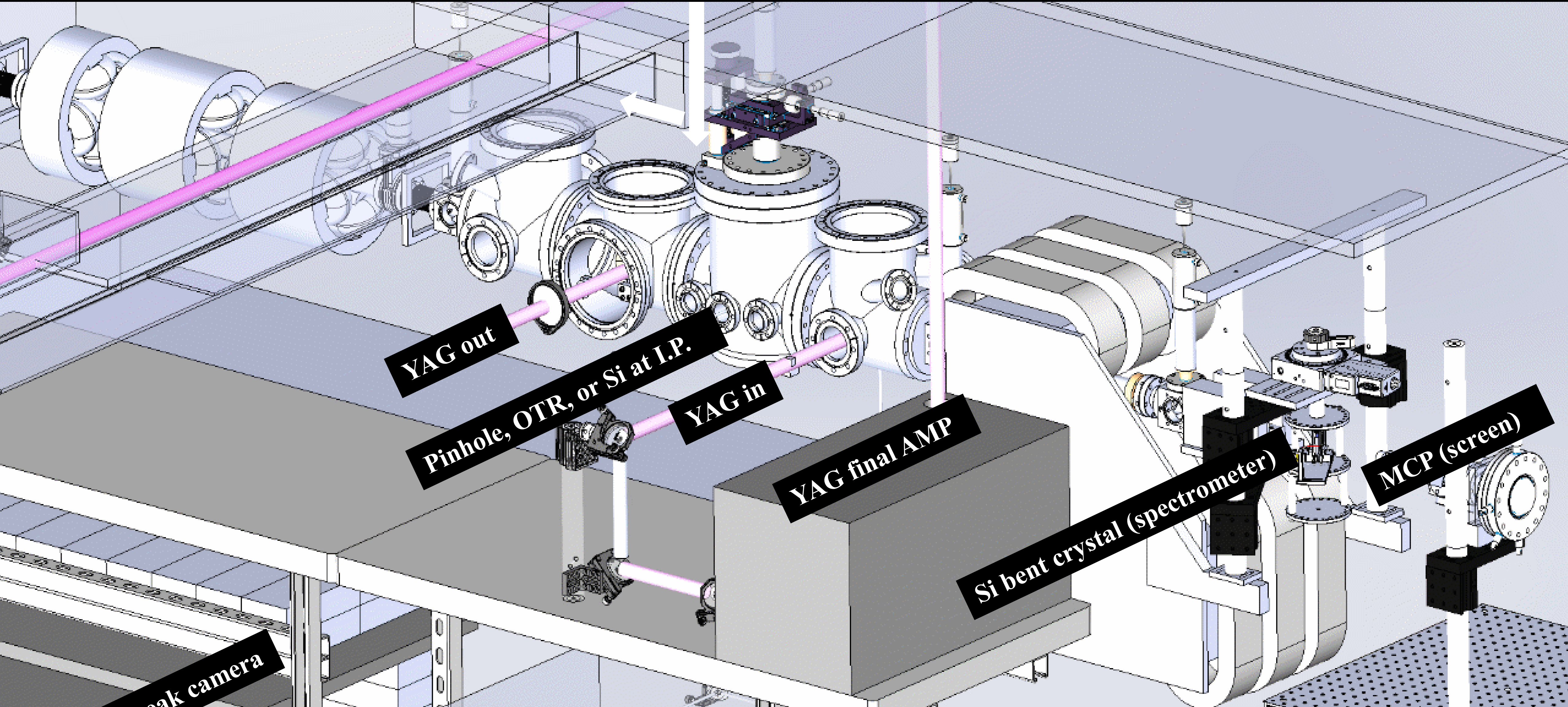


Figure 2. Numerically calculated double differential spectrum of hard X-ray Compton source with various e-beam emittance and focusing size at laser intensity of $\underline{a_{L,0} = 0.1}$. Left: ε = 2 mm mrad, $\sigma_{x,y}$= 15 µm, Middle: ε = 2 mm mrad, $\sigma_{x,y}$= 10 µm, Left: ε = 0.5 mm mrad, $\sigma_{x,y}$= 10 µm.

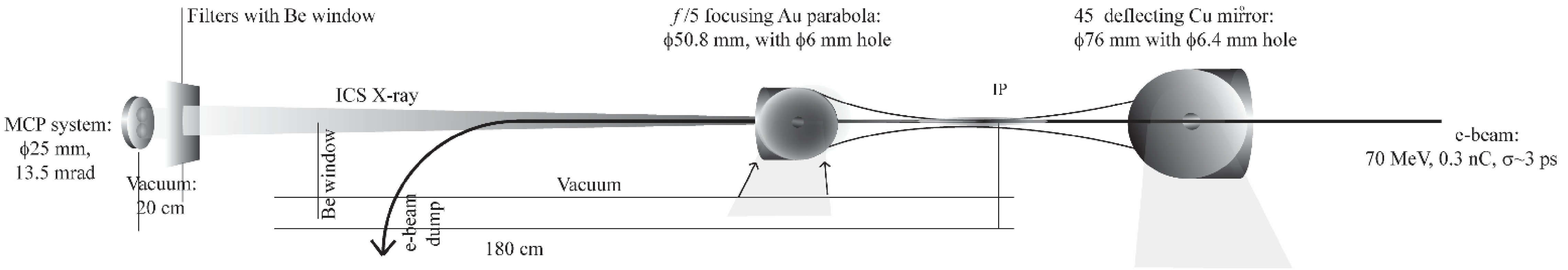
Focusing down to $\sigma_{e,x,y}$ = 10 um range should reduce bandwidth of X-ray at Emittance = 2mm mrad

Hard X-ray ICS Set-up in BL1

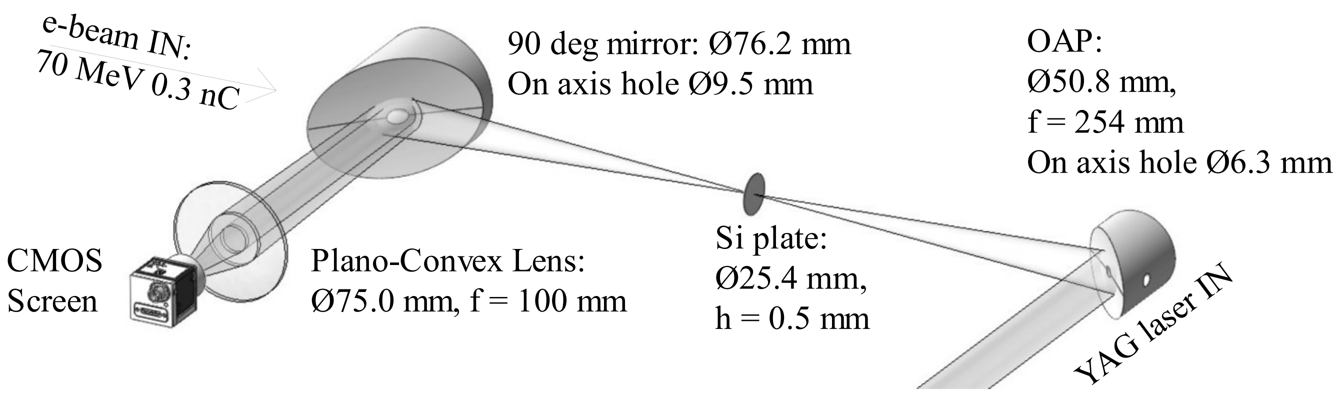
e-beam focus down to $\sigma \sim 30\ \mu m$ & Nd: YAG laser energy amplified to 100 < 200mJ / shot



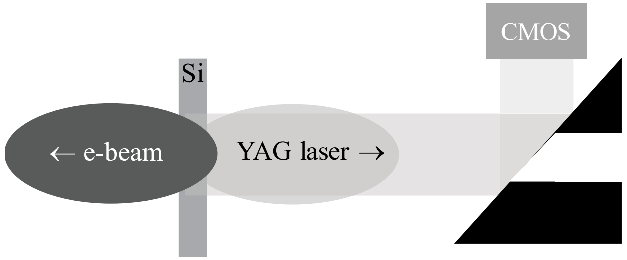
Nd: YAG laser optics, & Detector location



Optics for Timing & Synchronization established for Infra red laser:



Synchronization by Si semiconductor plasma switch established
Laser deflector, not attenuation



∗**Critical density of YAG laser, 1 μm: $n_{e,c}$ ~ 1×10^{21}[cm^{-3}]** ⇔ $\omega_p = \sqrt{n_e e^2/m\epsilon_0}$

∗**Electron-Hole Pairs number per incident particle:**

70 [MeV], $n_{e,\,ebeam}$ (q ~ 0.5 nC, σ_r ~ 20-30 μm) ~ 1×10$^{14\text{-}15}$ [cm^{-3}]

→ Electron number density created in Si plate (t500μm) $n_{e,Si,p}$ ~ 10^{20} [cm^{-3}]

$$\nabla n = \frac{d}{ds}\left(n\frac{dx}{ds}\right) \rightarrow \qquad \Theta_y = \int_{z_{In}}^{z_{Out}} \theta_y\, dz \sim \frac{1}{n}\frac{dn}{dy}\Delta z^2 \sim \text{A few mrad}$$

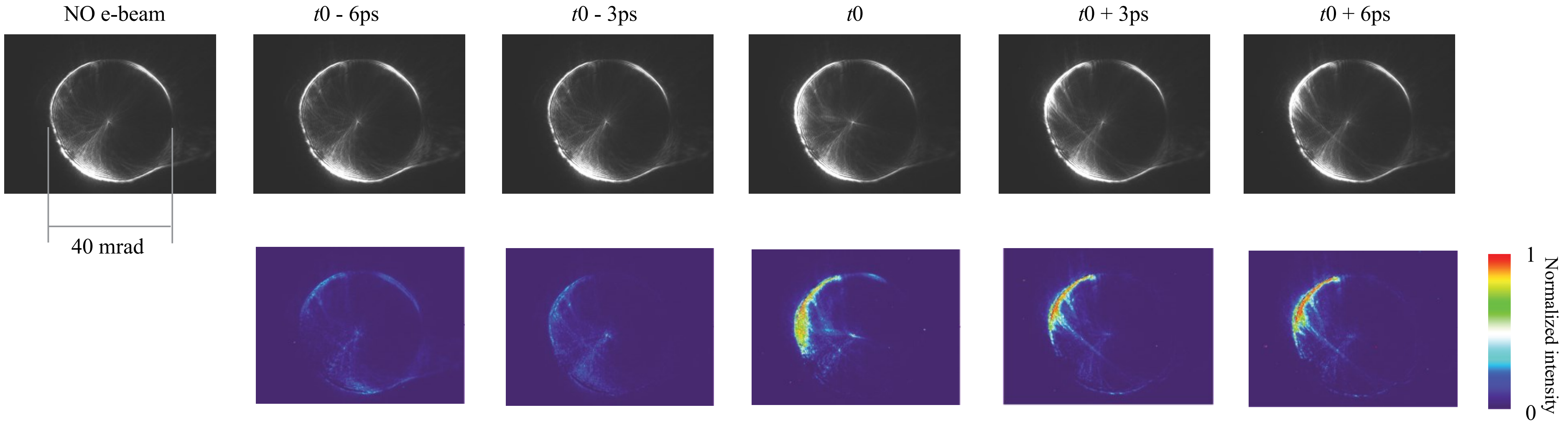


Figure 3. Deflection of YAG laser through Si semiconductor plasma. Specifically, the upper left corner of circular intensity distributions of the laser are the features of beams that overlap in this case. Upper: CMOS image. Lower (color): Intensity distribution with background(NO e-beam case) subtracted.

Example of spatial scan of e-beam

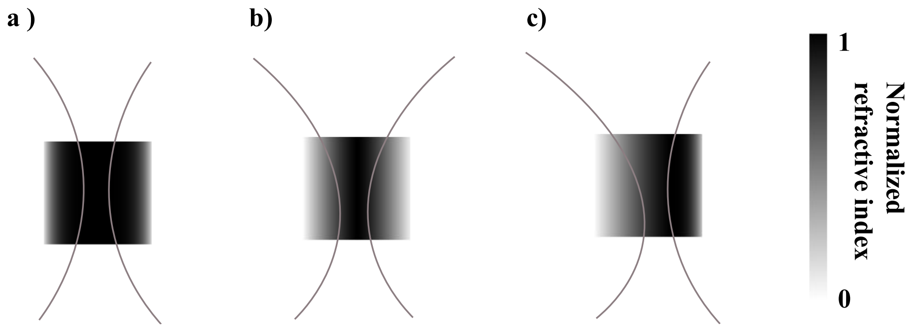
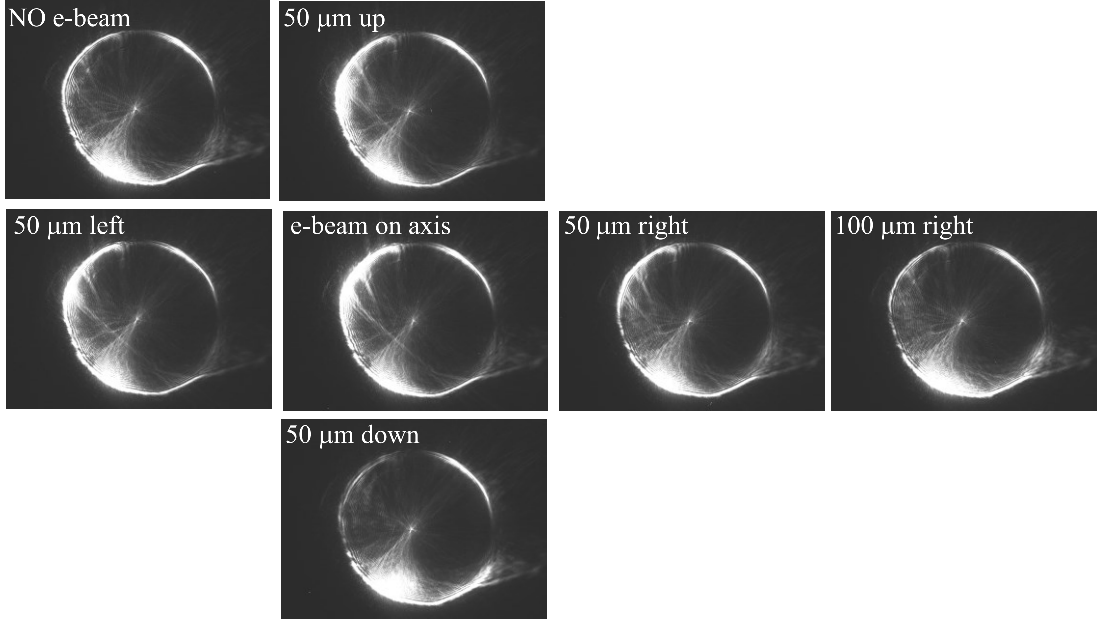
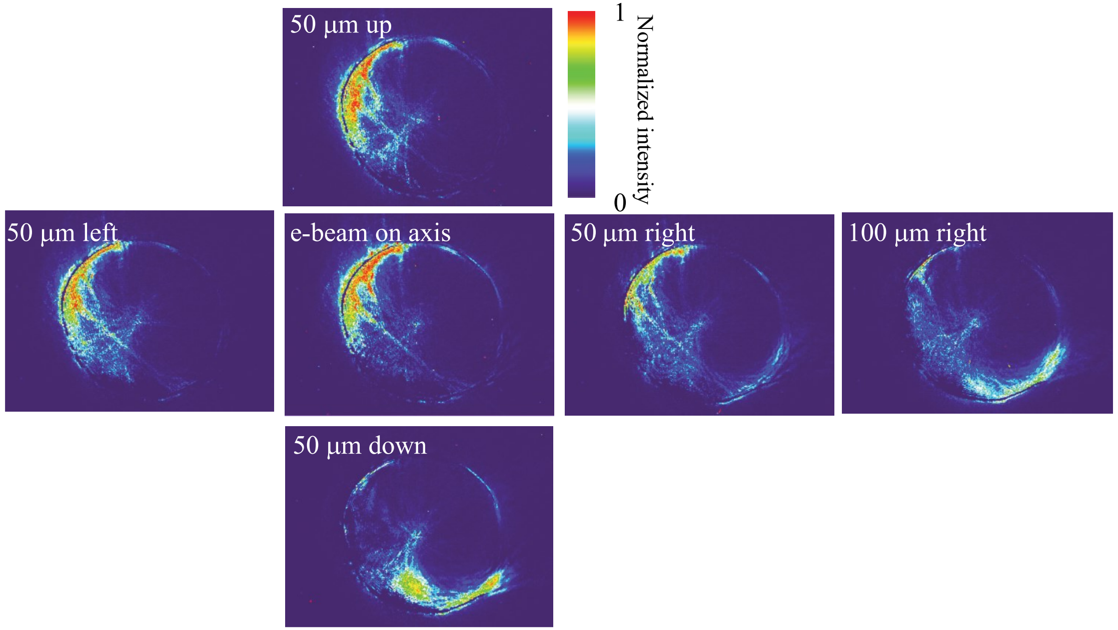


Figure. Schematic diagram of probe laser passage through semiconductor plasma with density gradient.

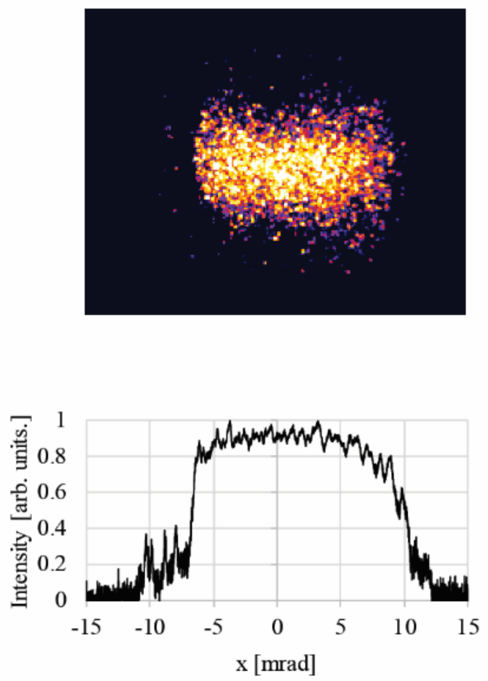
a) e-beam size is significantly larger than laser spot size.
b) e-beam size is equivalent or smaller than laser spot size.
c) Laser passage is on the off-axis of e-beam.



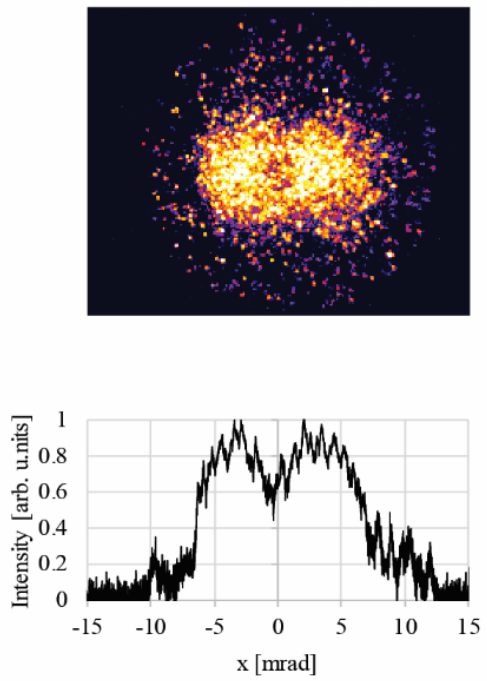


Result: Observed attenuation of 87.5 keV Hard X-ray in a single shot (in the order of ~ 10^6 photons / shot)

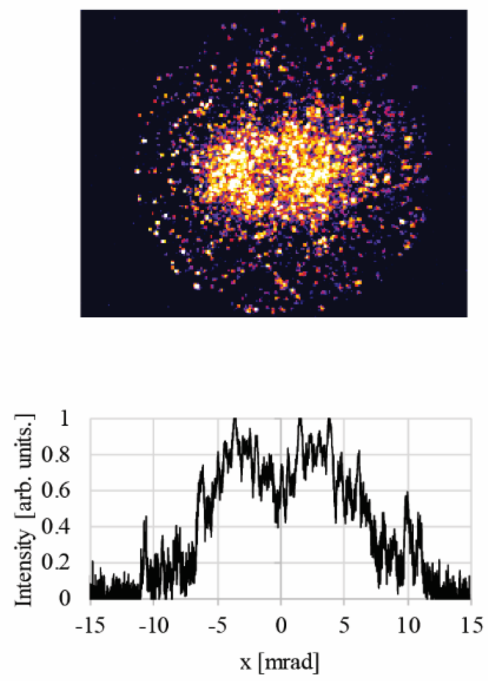
★ No-Filter

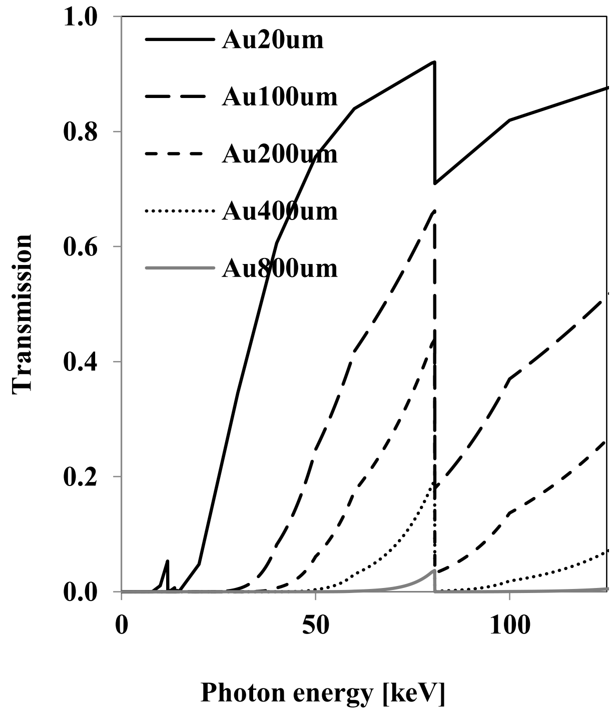


★Au-100μm

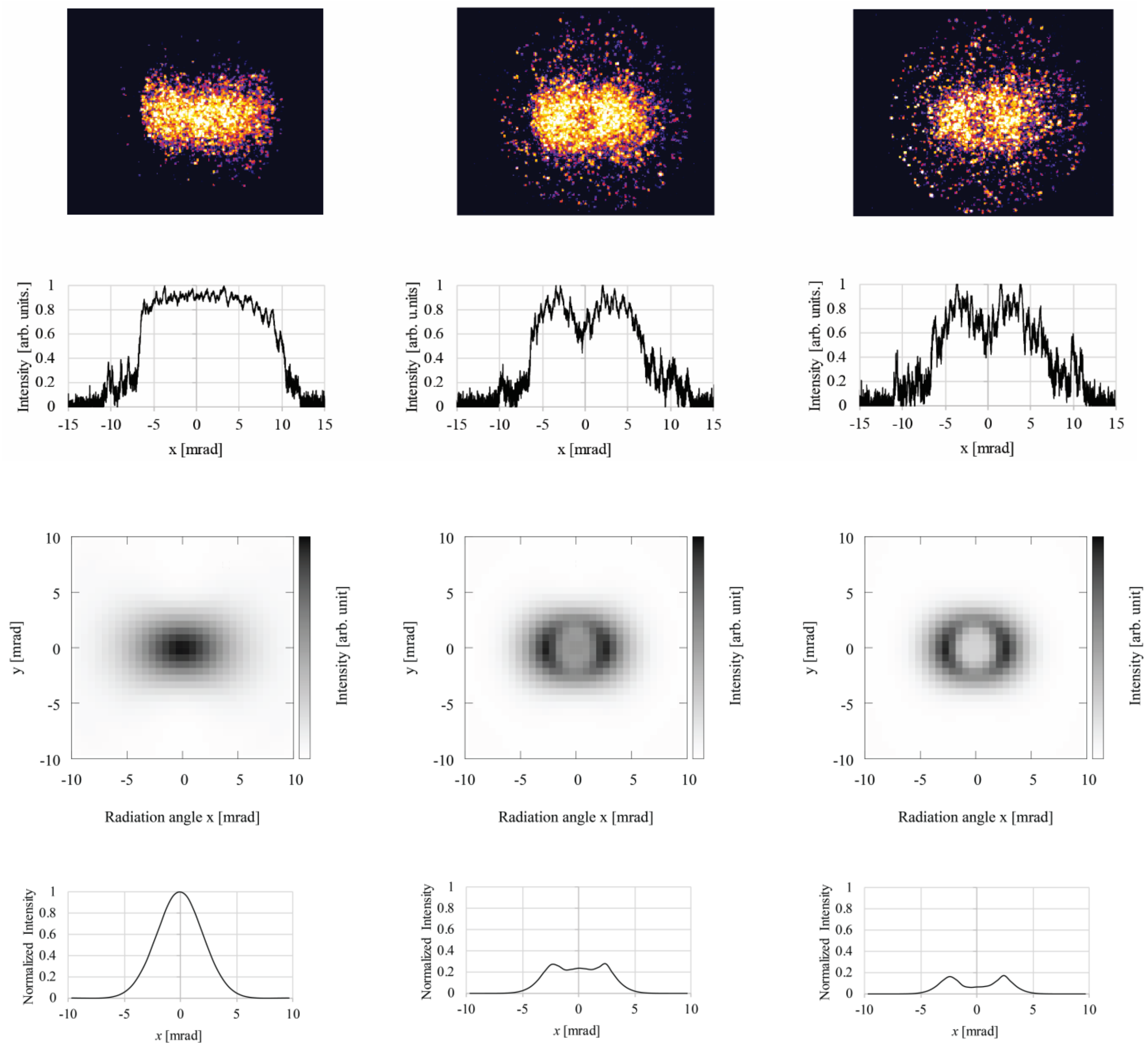


★Au-200μm





★ No-Filter ★Au-100μm ★Au-200μm



Numerical calculation:

Laser:

$a_{L,0} = 0.1$

E-beam:

$\sigma_{e,\,x,y}$ **= 30 um range should reduce**

Emittance = 2mm mrad

70 MeV

Attenuation by Au filter are consistent:

Local peaks: 2.5 mrad

Report to be submitted:

Hard X-ray inverse Compton scattering at photon energy of 87.5 keV

- DISCUSSION, Application part –

In appreciation of observed 87.5 keV characteristic, Photon Activation with Gold Nano Particle (AuNP) case:

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 :

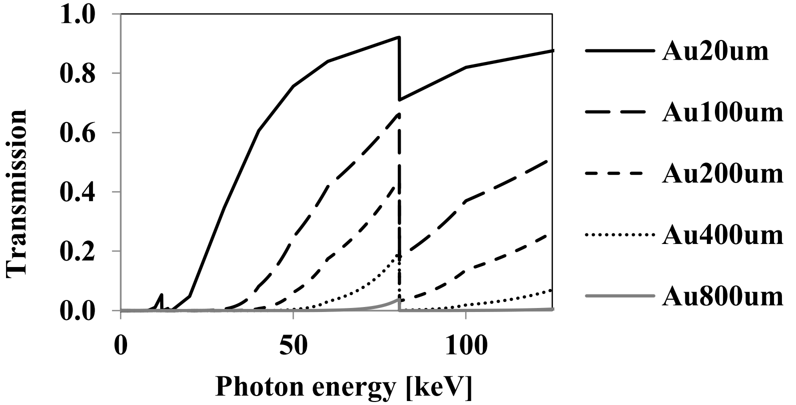
100 nm ↔ Auger, L-edge 11.9-14.3 keV , 10 nm ↔ Auger, M-edge 2.2-2.4 keV

Penetration depth of keV electron in water (between AuNP) → ~ µm range

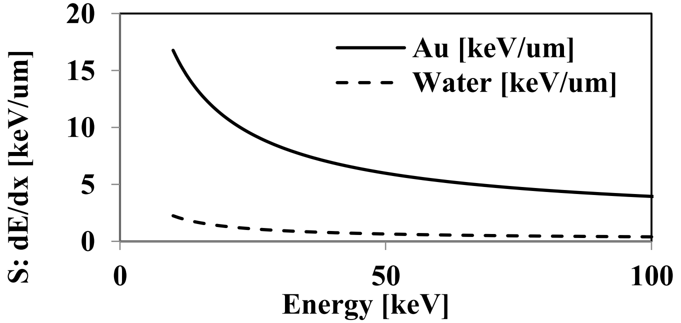
Spacing between particles

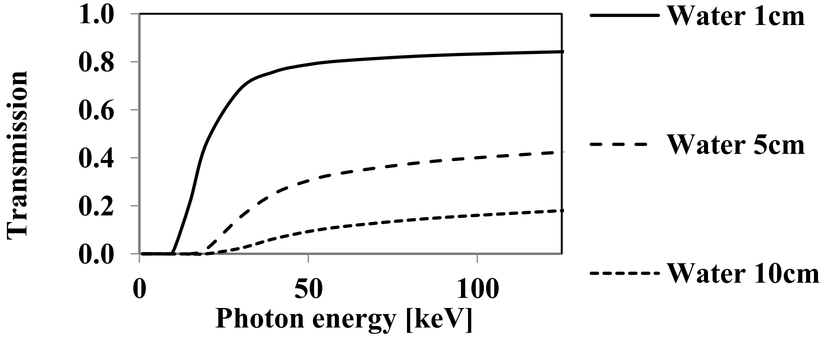
AuNP Dia 100 nm ↔ 10 µm, AuNP Dia 10 nm ↔ 1 µm,

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/cm³ and 0.997 g/cm³)





- - DISCUSSION: Sub 100 keV Hard X-ray flux requirement for applications - -

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

Radiation dose per kg of water per shot:
1 [Gy] = 1 J / (10 cm)^3] ↔ 1 mJ / (1 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:

- ✦YAG laser pulse can go 1 J → ×10
- ✦ Multi pulse interaction, Shift I.P. longitudinally. (Beta function >> Rayleigh range) → ×10
- ✦ Passive recirculation→ ×10
- ✦ Tight focus* of e-beamσ_e~ µm → ×10

***NOTE: But bandwidth will be 10 % range if emittance is mm mrad order:**

$\sigma_{x,y}$ = 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/γ_0 ~ 7.3 mrad for 70 MeV e-beam, Normalized emittance 2 mm mrad case

Then, can we lower e-beam emittance?

CONCLUSION

✸ Feasibility of producing 87.5 keV Hard X-ray for applications is confirmed qualitatively

✸ K-edge filter is verified to be sufficient to observe bi-harmonic Compton effect

DIRECTION OF LINEAR ICS FOR APPLICATIONS:

✧ Sub 100 keV hard X-ray optics R & D in BNL-ATF, NSLS II

In parallel:

✦ S-band Hybrid gun 80 MeV linac construction (Velocity bunching) in UCLA (4 MeV e-beam generated so far.)

✦ Cryo C-band Gun R& D in UCLA (Emittance in space charge dominant region ~ $1/\gamma^2$)

✧ Multi pulse laser interaction (Shift I.P. longitudinally, as Beta function >> Rayleigh range)

✧ Passive laser circulation (Can be reconsidered in future ATF experiment with bunch train operation)

NEXT PROPOSAL: RETURN OF NONLINEAR COMPTON IN BNL-ATF

Activities & Impacts Associated with this Experiment

- Status of nonlinear inverse Compton scattering studies at the BNL ATF: properties of 3rd-order harmonics by circularly polarized CO2 laser, AAC 2022yr, conference proceeding (Submitted)

- Electron beam controlled deflection of near infrared laser in semiconductor plasma, Journal of Applied Physics AIP (Submitted)

- Hard X-ray inverse Compton scattering at photon energy of 87.5 keV (To be submitted very soon)

COVID-19 Pandemic Impacts

None