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

AE131

# Harmonic Nonlinear Inverse Compton Scattering

*Nonlinear ICS by $a_0 > 1$, $CO_2$ (9.2 μm)laser with Nd:YAG laser(1 μm)*

**BNL ATF user meeting, March 23, 2024 yr**

**Y. Sakai, O. Williams, A. Fukasawa, J. Rosenzweig, *UCLA***
**Collaborator: Z. Zhong, *BNL NSLS***

***Funding source: DOE Accelerator Stewardship (DE-SC0009914)***

BROOKHAVEN NATIONAL LABORATORY

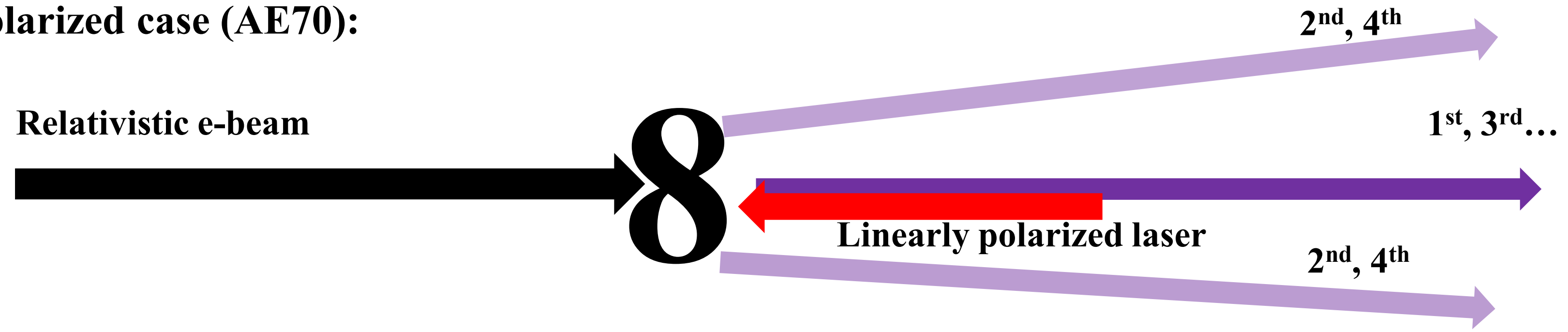
# Experiment Goala of AE131 Harmonic Nonlinear Inverse Compton Scattering

**AE70: Basic study on the nonlinear Compton & AE87: Hard X-ray ICS by Nd: YAG laser**

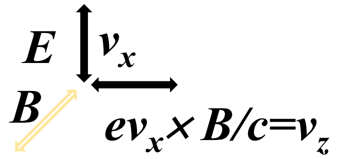
- ✪ **Strong field physics: Bi-harmonic Compton interaction**
- ✪ **X-ray OAM investigation: Higher order harmonics by circular polarized $CO_2$ laser**
- ✪ **Hard X-ray optics developments: DDS measurement & Focusing, Collimation**

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

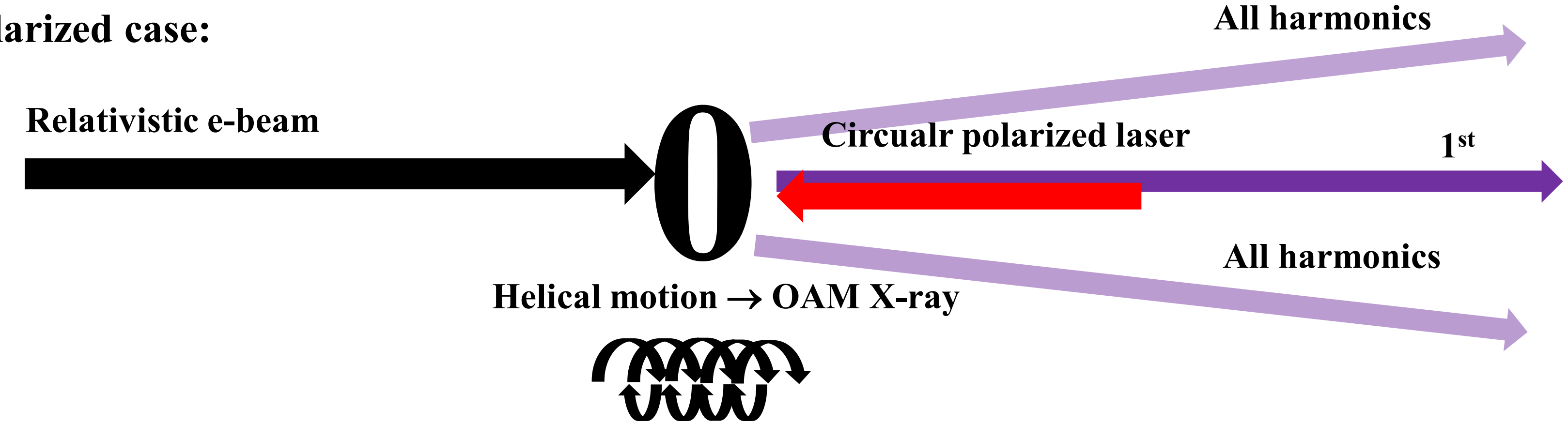
**Linearly polarized case (AE70):**

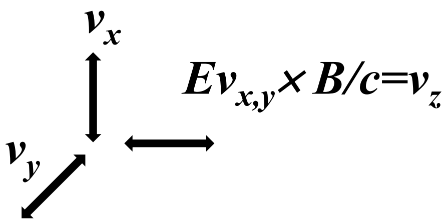



$$* a_{L,0} \equiv \frac{\sqrt{-e^2 A_\mu A^\mu}}{m_e c^2} = \frac{eE_{L,0}(\lambda_L/2\pi)}{m_e c^2}$$

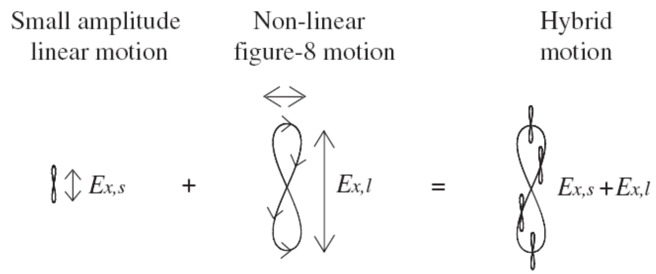


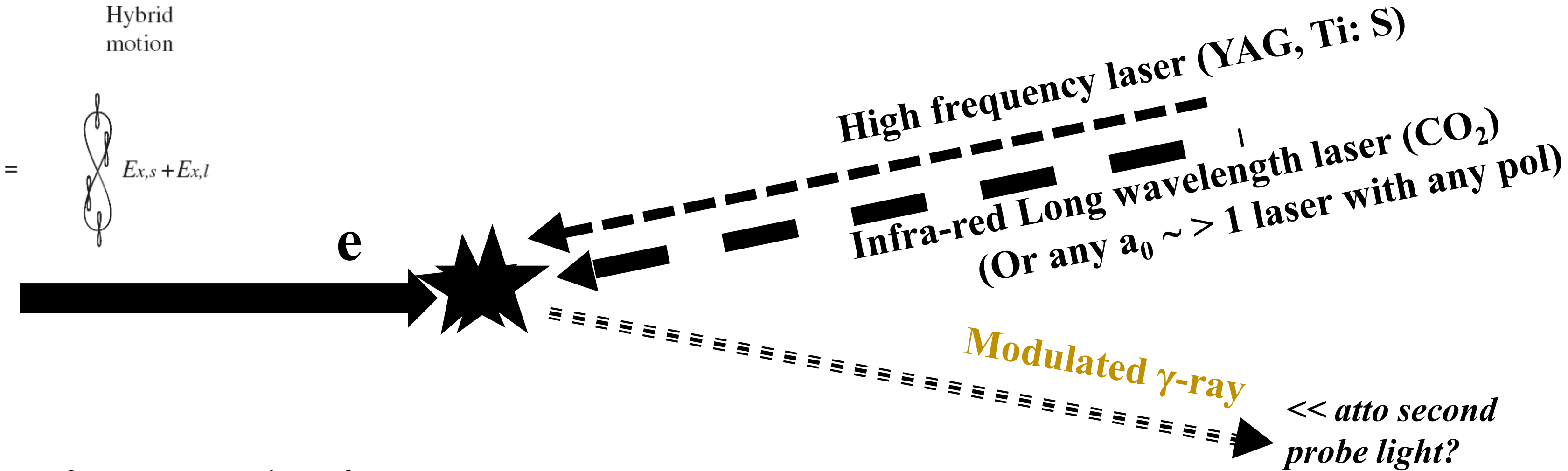

**Circular polarized case:**



# Bi-harmonic nonlinear Compton interaction

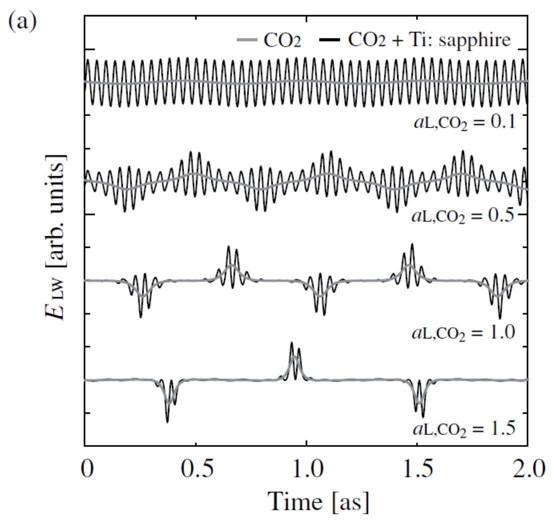



*<< atto second probe light?*

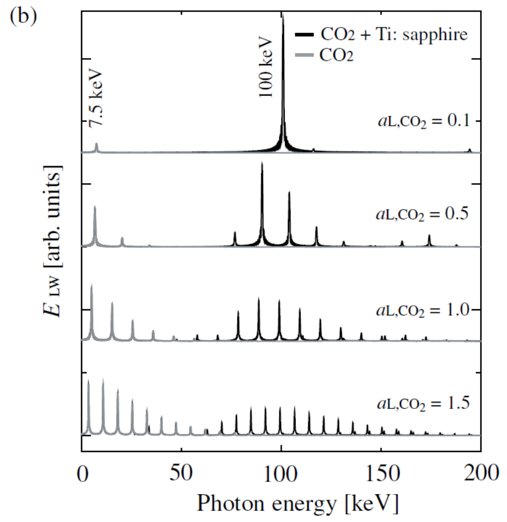
**Pulsed waveform modulation of Hard X-ray component at less than < $10^{-18}$ s time scale (Cycle of 10 keV X-ray)**

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

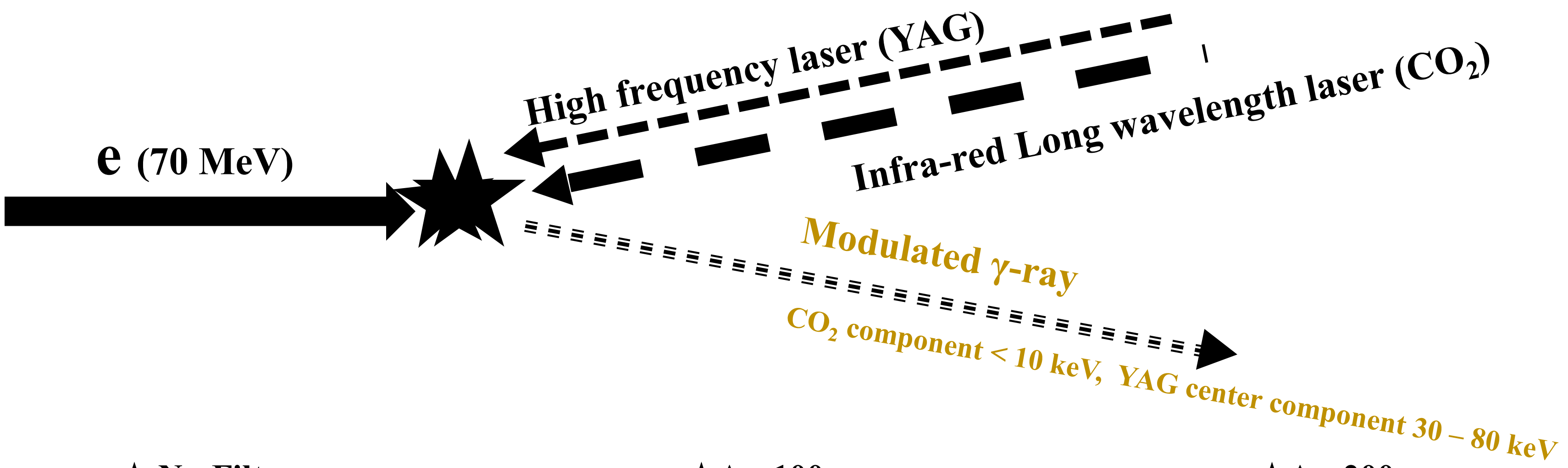


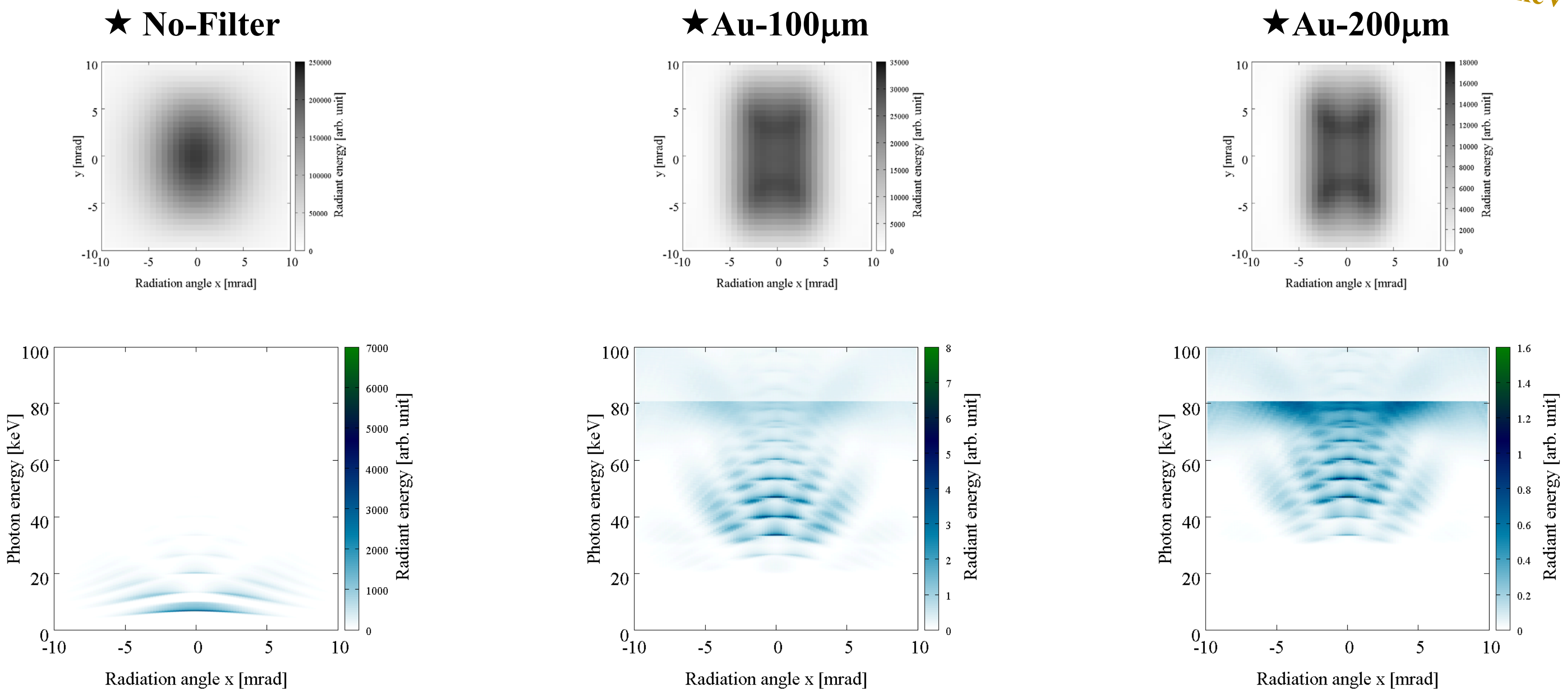

Numerically calculated Lienard-Wiechert potential $E_{LW,x}(t_{screen})$ on $(x, y, z) = (0, 0, 0)$

***Fourier Transform →***



# Numerical estimate of bi-harmonic spectrum by ATF parameter ($CO_2$: 9.2 μm, Nd: YAG 1064 nm)



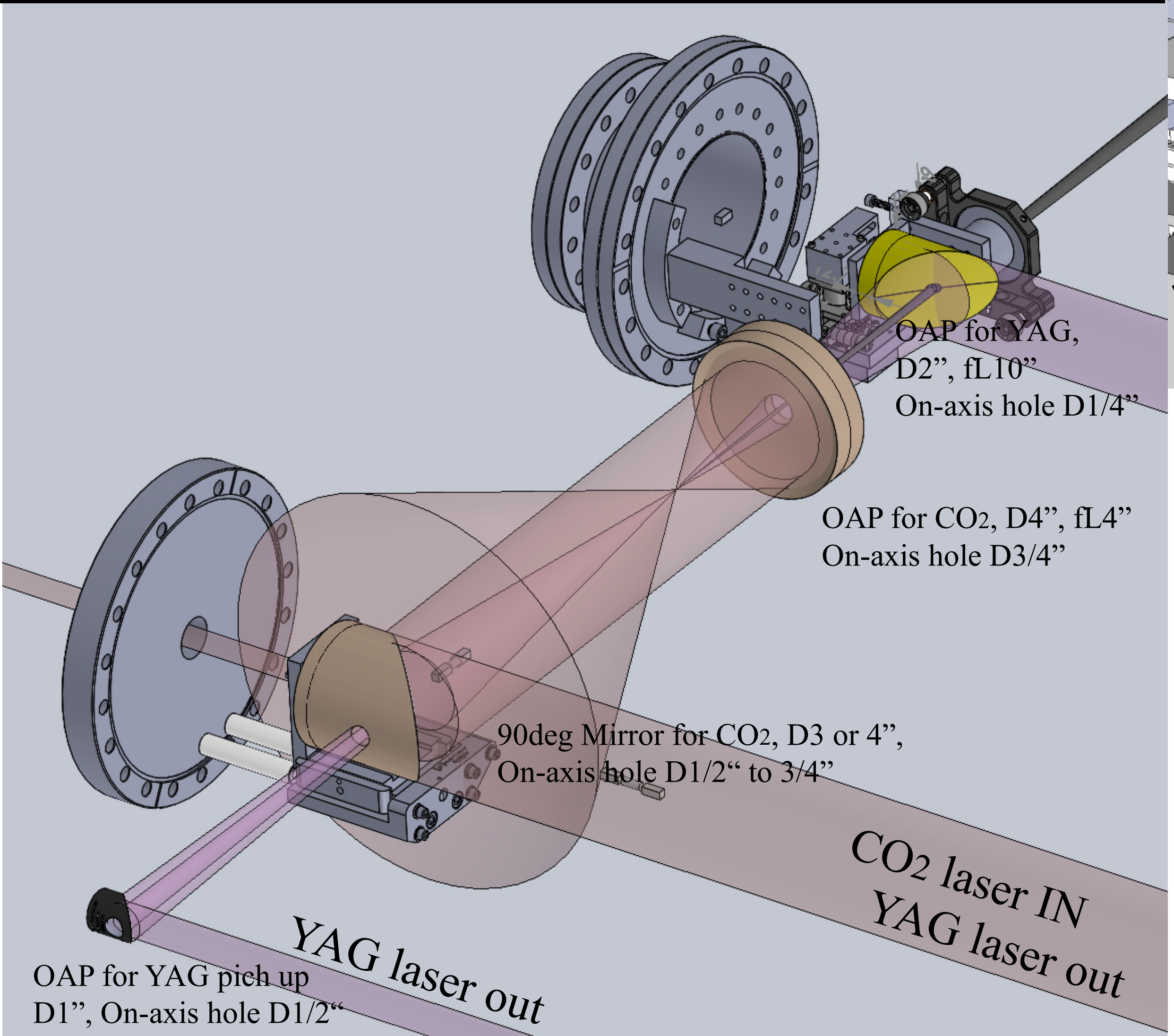



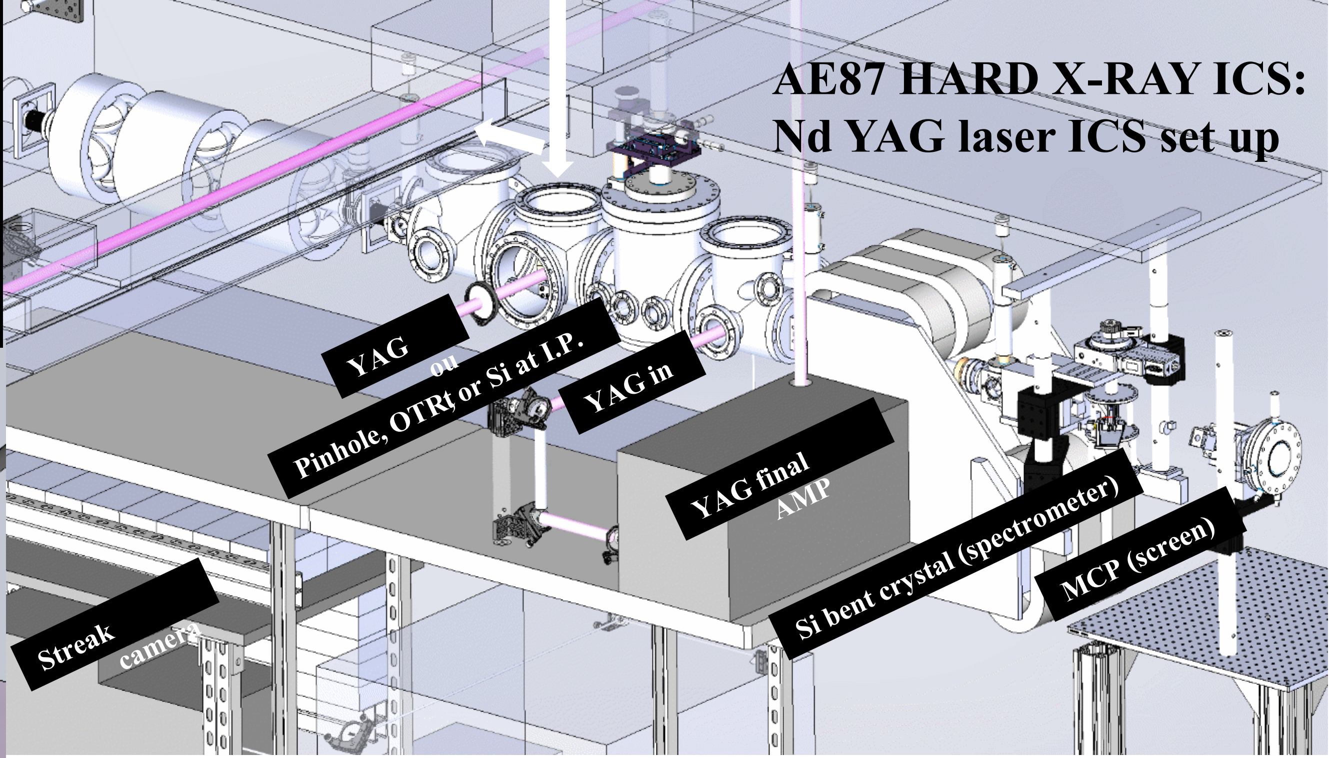

**Only $CO_2$'s component**

**Bi-harmonic YAG's component**

# Experimental set up
# for both YAG laser ICS in ATF

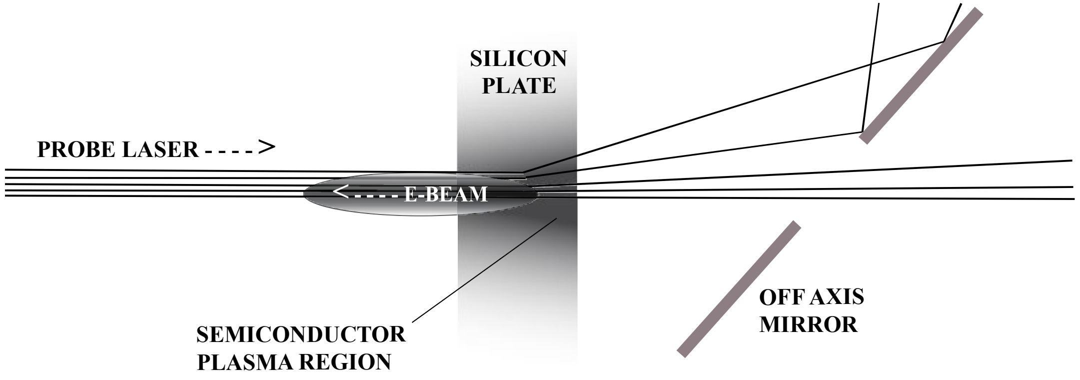
**Input of $CO_2$ laser and YAG laser are opposite**
**$CO_2$ laser final focusing optic has D3/8 inch hole for YAG laser path**



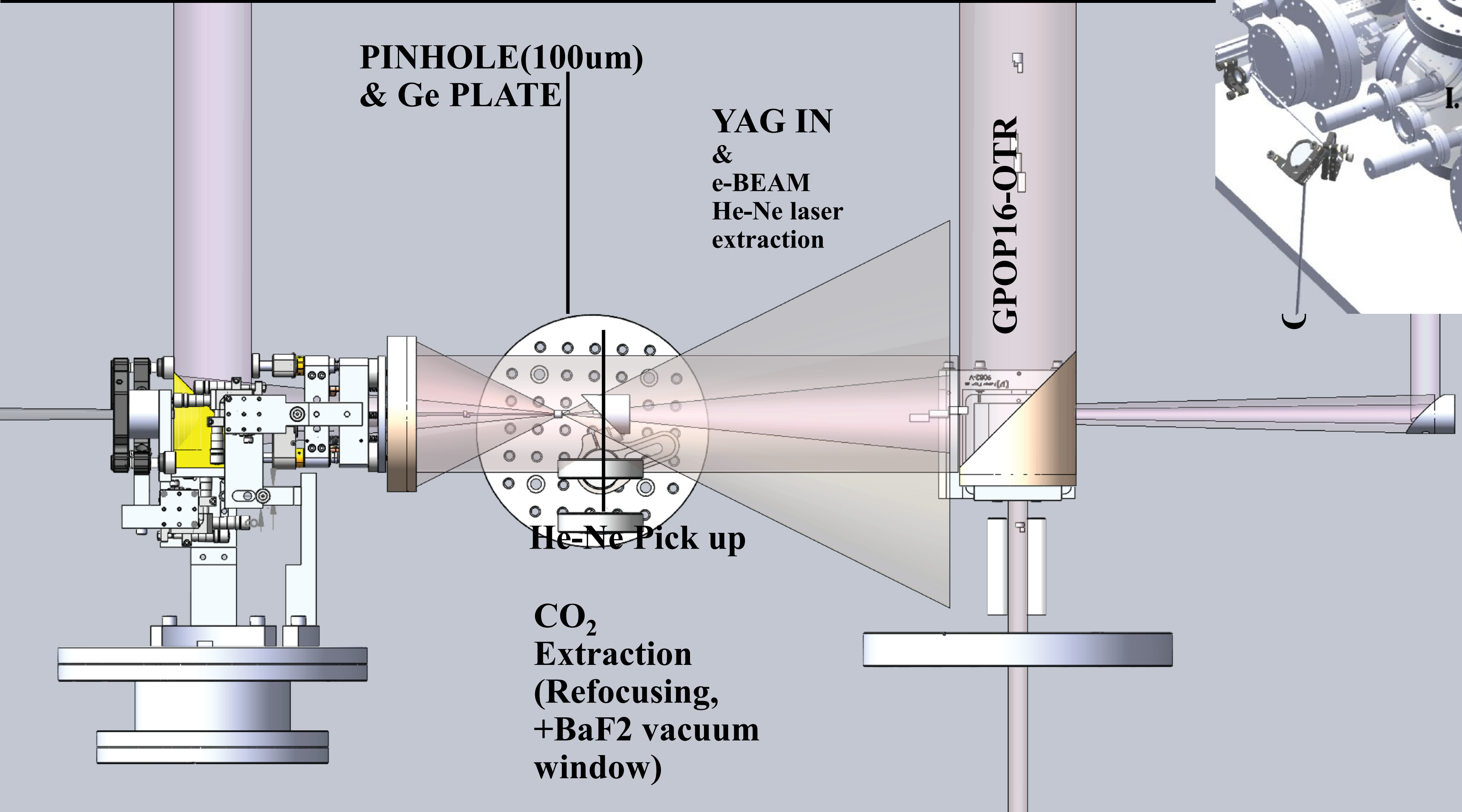

**YAG laser ICS optics, e-beam timing method established:**

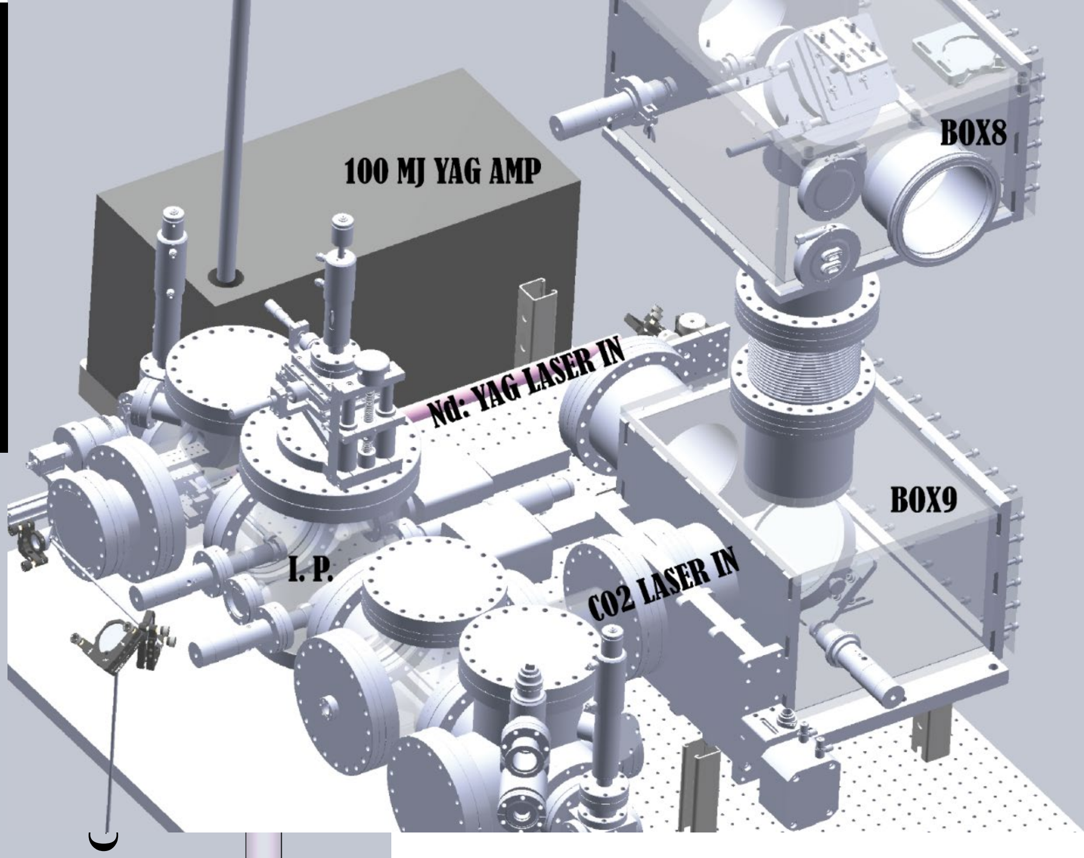
**Electron-beam–controlled deflection of near-infrared laser in semiconductor plasma, Y. Sakai, M. Polyanskiy, M. Babzien et. al. J. Appl. Phys. 133, 143102 (2023)**



# Experiment# AE131 Harmonic nonlinear Compton (2023yr-)

**Rebuilding nonlinear Compton set up**
**For alignment and timing of a both lasers:**




**Upgraded $CO_2$ ICS components worked well unexpectedly in 2023yr Oct-Nov run time**

↓↓

Summary of major results and/or critical experimental preparations to date

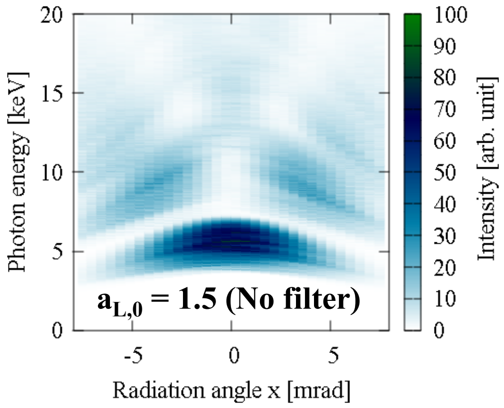
# Observed harmonics of linearly polarized ICS X-ray:

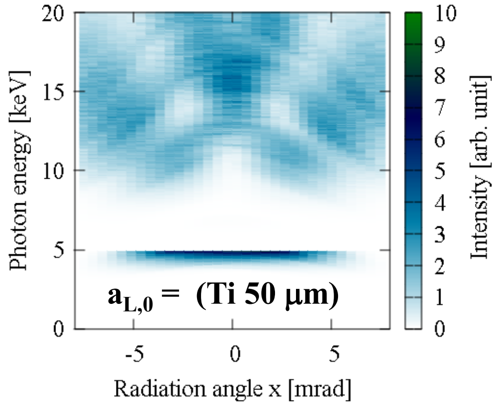
Ti 50 um filtering

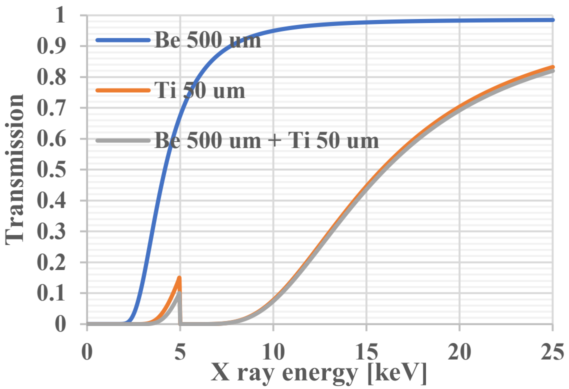
e-beam energy 60 MeV
$CO_2$ laser wavelength 9.2 µm

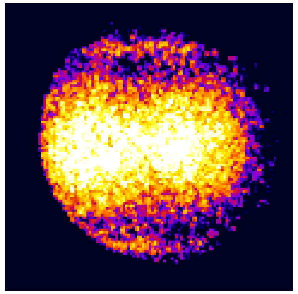
**Beam Gaussian parameters for numerical estimate**
→

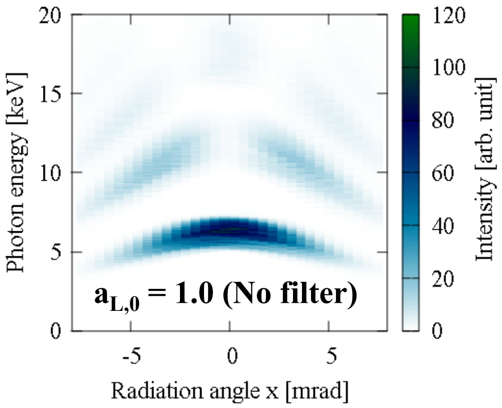
**Normalized emittance: 2 [mm mrad]**
**E-beam $\sigma_{e,r}$ at I.P.: 30 [um]**
**E-beam pulse length $\sigma$: 3 [ps]**
**$CO_2$ laser $\sigma_{L,r}$ at I.P. 30 [um]**
**$CO_2$ laser pulse length, FWHM: 2 [ps]**

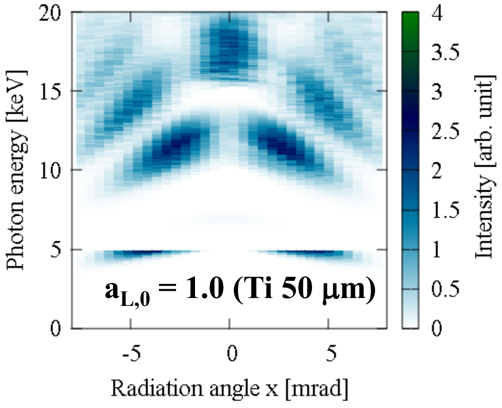


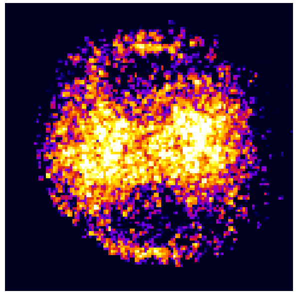



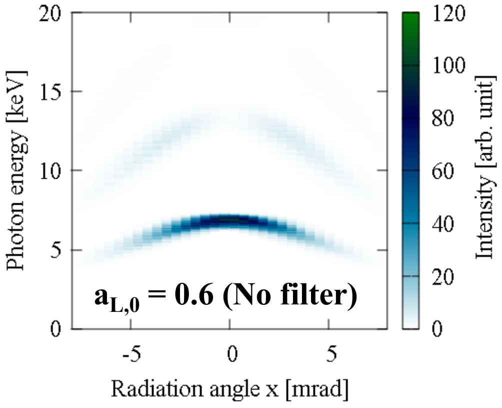


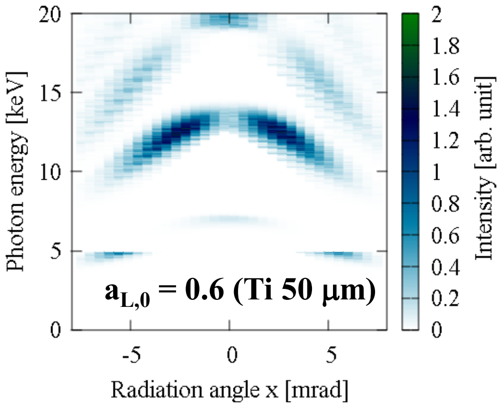




- ✧ **Outer ring at 5 [mrad]: Fundamental**
- ✧ **Off axis 2 peak: 2nd harmonic**
- ✧ **On-axis: 3rd harmonic**

**Estimated normalized vector potential: $a_{L,0} \sim 1$**

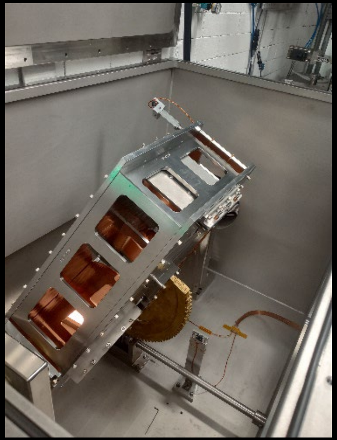


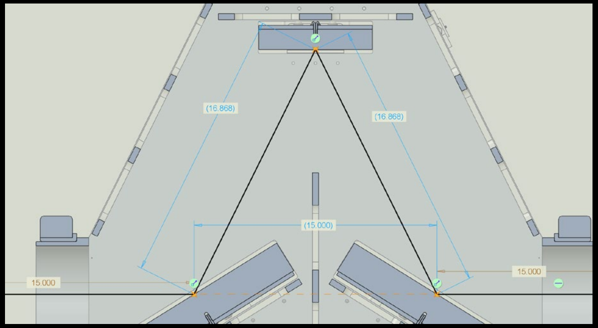


## Summary of major results

**Owing to newly installed ATF's polarization rotator of multi TW $CO_2$ laser** rotator
(2× 22.5 deg rotation + wave plate mirror)



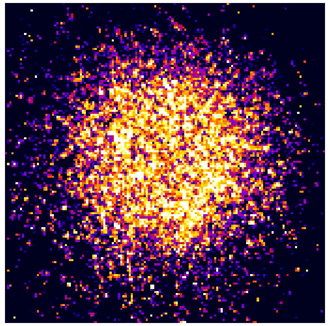


**Quick testing:**
**Circularly polarized ICS →**

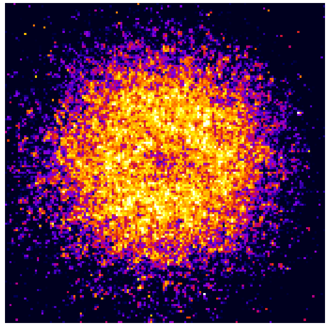
**2nd harmonic X-ray verified**

**2nd Harmonic:**

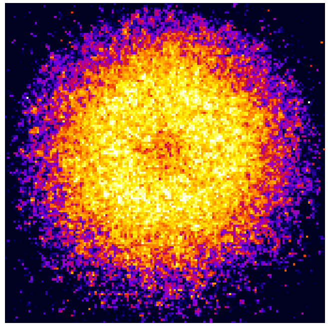
**Al 250um High energy X-ray Filtering**



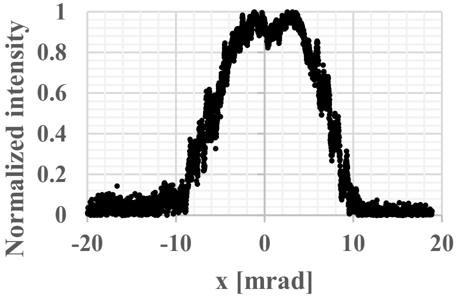
**Low energy shot**
**$a_{L,0} \sim 0.6$**

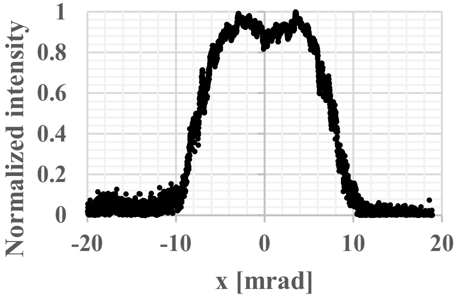


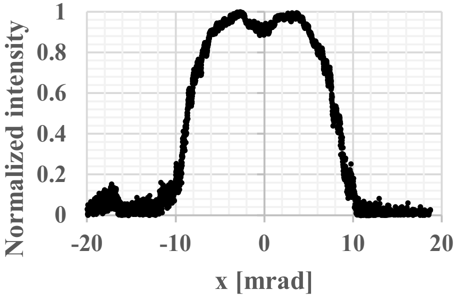
**3 J shot**
**$a_{L,0} \sim 1.0$**



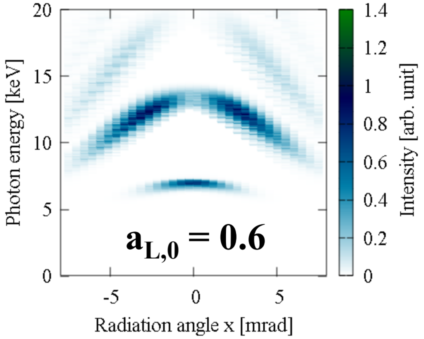
**6 J shot**
**$1 < a_{L,0} < 1.5$**

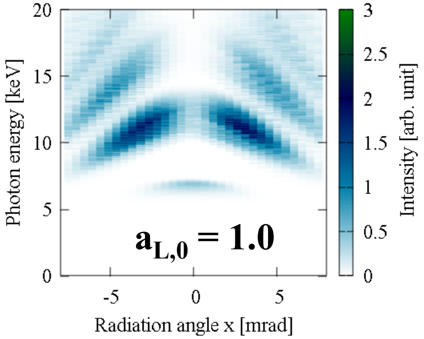


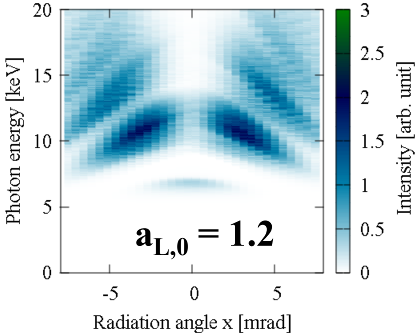




**Numerical Estimate With Al 250 μm Filter**




*****Although, 50% of laser flux goes through a on-axis hole**

# Experimental plans for the next year

- Recover Nd YAG ICS (with the $CO_2$ optics) set up (Includes some sub 100 keV detector testing) {Next run time in 2024yr}
- Bi-harmonic Compton interaction initial test {2025yr}
- OAM study (spectrum measurements) Circularly polarized $CO_2$ laser at $a_{L,0}$ 1.5-2.0 case {2025yr}
- Hard X-ray optics test at 30 keV and then 87.5 keV {2025yr – 2026yr}

# Summary of products delivered from the work to date

- **Electron-beam–controlled deflection of near-infrared laser in semiconductor plasma, Y. Sakai, M. Polyanskiy, M. Babzien et. al. J. Appl. Phys. 133, 143102 (2023)**

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

# Electron Beam Requirements

| Parameter | Units | Typical Values | Comments | Requested Values |
|---|---|---|---|---|
| Beam Energy | MeV | 50-65 | *Full range is ~15-75 MeV with highest beam quality at nominal values* | *70 MeV* |
| Bunch Charge | nC | 0.1-2.0 | *Bunch length & emittance vary with charge* | |
| Compression | fs | Down to 100 fs (up to 1 kA peak current) | *A magnetic bunch compressor available to compress bunch down to ~100 fs. Beam quality is variable depending on charge and amount of compression required.*<br><br>*NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level* | |
| Transverse size at IP ($\sigma$) | $\mu$m | 30 – 100 (dependent on IP position) | *It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.* | *30 $\mu m$* |
| Normalized Emittance | $\mu$m | 1 (at 0.3 nC) | *Variable with bunch charge* | *2 mm mrad* |
| Rep. Rate (Hz) | Hz | 1.5 | *3 Hz also available if needed* | *1* |
| Trains mode | --- | Single bunch | *Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.* | |

# $CO_2$ Laser Requirements

| Configuration | Parameter | Units | Typical Values | Comments | Requested Values |
|---|---|---|---|---|---|
| **$CO_2$ Regenerative Amplifier Beam** | Wavelength | µm | 9.2 | *Wavelength determined by mixed isotope gain media* | *9.2 µm* |
| | Peak Power | GW | ~3 | | |
| | Pulse Mode | --- | Single | | |
| | Pulse Length | ps | 2 | | |
| | Pulse Energy | mJ | 6 | | |
| | $M^2$ | --- | ~1.5 | | |
| | Repetition Rate | Hz | 1.5 | *3 Hz also available if needed* | |
| | Polarization | --- | Linear | *Circular polarization available at slightly reduced power* | |
| **$CO_2$ CPA Beam** | Wavelength | µm | 9.2 | *Wavelength determined by mixed isotope gain media* | *9.2 µm* |
| *Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.* | Peak Power | TW | 5 | *~5 TW operation will become available shortly into this year's experimental run period. A 3-year development effort to achieve >10 TW and deliver to users is in progress.* | *> = 2* |
| | Pulse Mode | --- | Single | | *Single* |
| | Pulse Length | ps | 2 | | *2* |
| | Pulse Energy | J | ~5 | *Maximum pulse energies of >10 J will become available within the next year* | *< 10* |
| | $M^2$ | --- | ~2 | | |
| | Repetition Rate | Hz | 0.05 | | *0.01* |
| | Polarization | | Linear | *Adjustable linear polarization along with circular polarization can be provided upon request* | *Linear & Circular* |

# Other Experimental Laser Requirements

| Ti:Sapphire Laser System | Units | Stage I Values | Stage II Values | Comments | Requested Values |
|---|---|---|---|---|---|
| Central Wavelength | nm | 800 | 800 | *Stage I parameters are presently available and setup to deliver Stage II parameters should be complete during FY22* | |
| FWHM Bandwidth | nm | 20 | 13 | | |
| Compressed FWHM Pulse Width | fs | <50 | <75 | *Transport of compressed pulses will initially include a very limited number of experimental interaction points. Please consult with the ATF Team if you need this capability.* | |
| Chirped FWHM Pulse Width | ps | ≥50 | ≥50 | | |
| Chirped Energy | mJ | 10 | 200 | | |
| Compressed Energy | mJ | 7 | ~20 | *20 mJ is presently operational with work underway this year to achieve our 100 mJ goal.* | |
| Energy to Experiments | mJ | >4.9 | >80 | | |
| Power to Experiments | GW | >98 | >1067 | | |

| Nd:YAG Laser System | Units | Typical Values | Comments | Requested Values |
|---|---|---|---|---|
| Wavelength | nm | 1064 | *Single pulse* | *1064* |
| Energy | mJ | 5 | | *5 (200 mJ at I.P.)* |
| Pulse Width | ps | 14 | | *FWHM 14* |
| Wavelength | nm | 532 | *Frequency doubled* | |
| Energy | mJ | 0.5 | | |
| Pulse Width | ps | 10 | | |

# Special Equipment Requirements and Hazards

- None: All item has been registered in ESR ver 2023yr

# Experimental Time Request

## CY2024 Time Request

| Capability | Setup Hours | Running Hours |
|---|---|---|
| Electron Beam | | 2 weeks |
| NIR Laser | 1 weeks | 2 weeks |
| LWIR Laser | | 2 weeks |

## Total Time Request for the 3-year Experiment  (including CY2024-26)

| Capability | Setup Hours | Running Hours |
|---|---|---|
| Electron Beam | | 2 weeks X 6 = 480 hours |
| NIR Laser | | (2 weeks X 1 = 480 hours) |
| LWIR Laser | | (2 weeks X 5 = 480 hours) |

*Appendix*

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

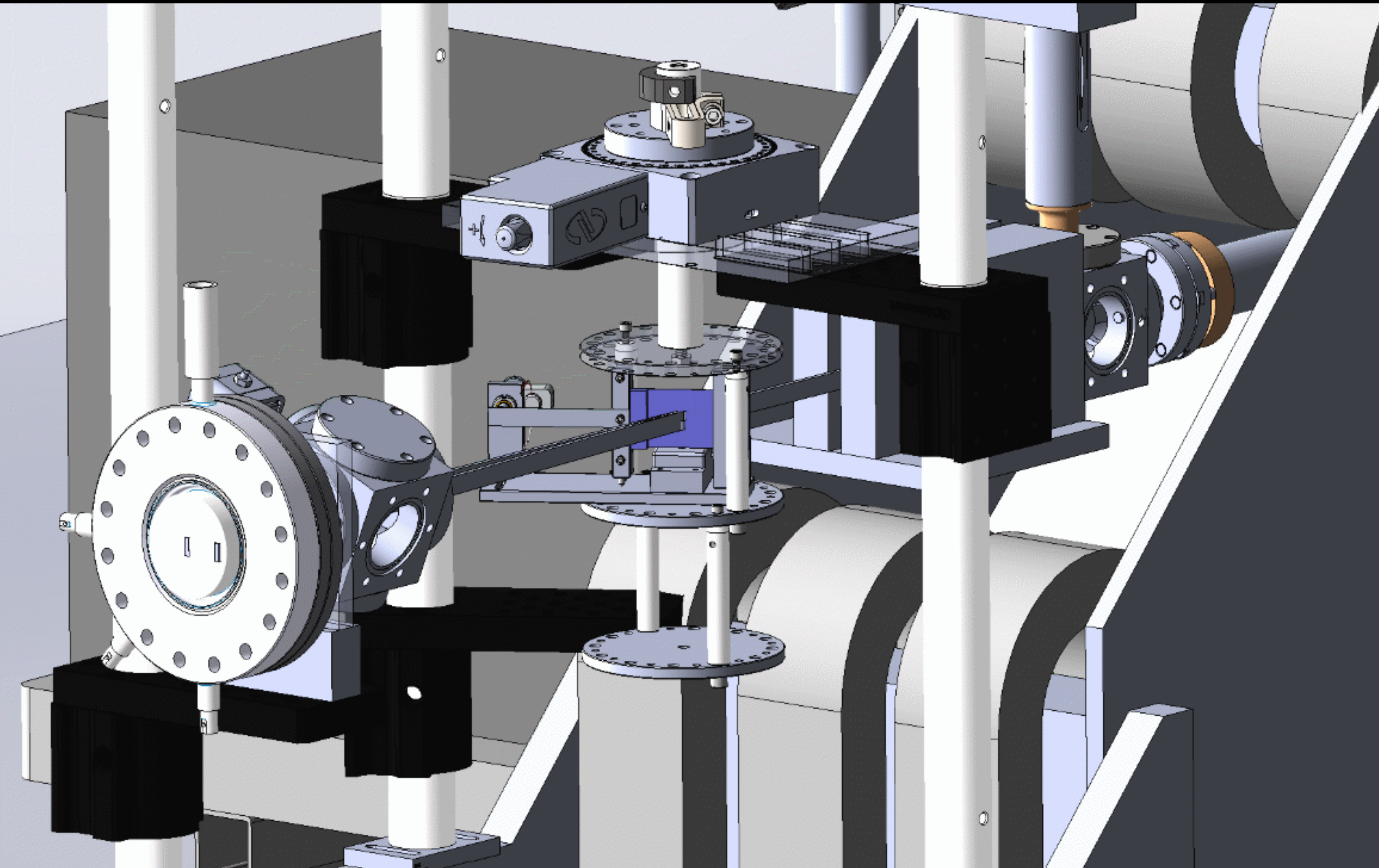
→ *Thick Laue Bent Crystal*

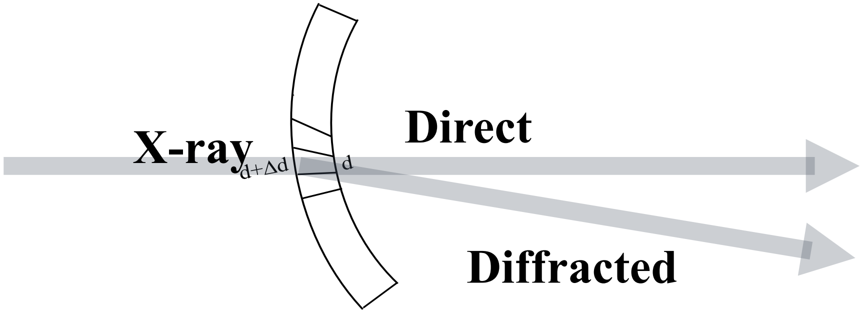
*Efficiency > Bandwidth*

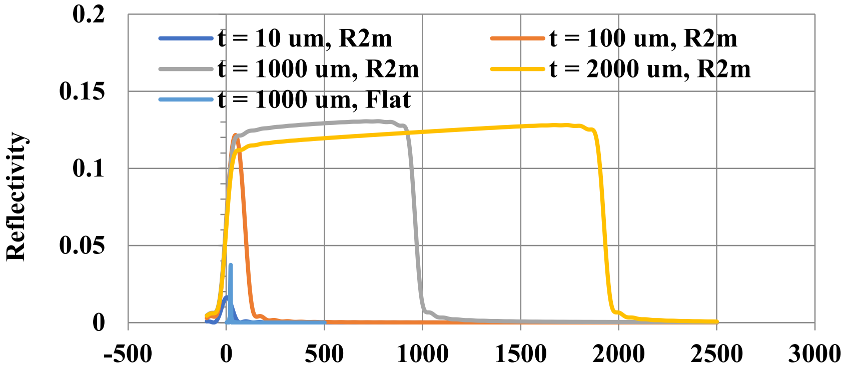
*(Collaboration with NSLS II 150 keV section, Z. Zhong)*

*Multi layer crystal: 5 – 20 keV ($CO_2$'s ICS component)*

*Thick crystal: 20 keV – 200 keV (YAG's ICS component)*






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

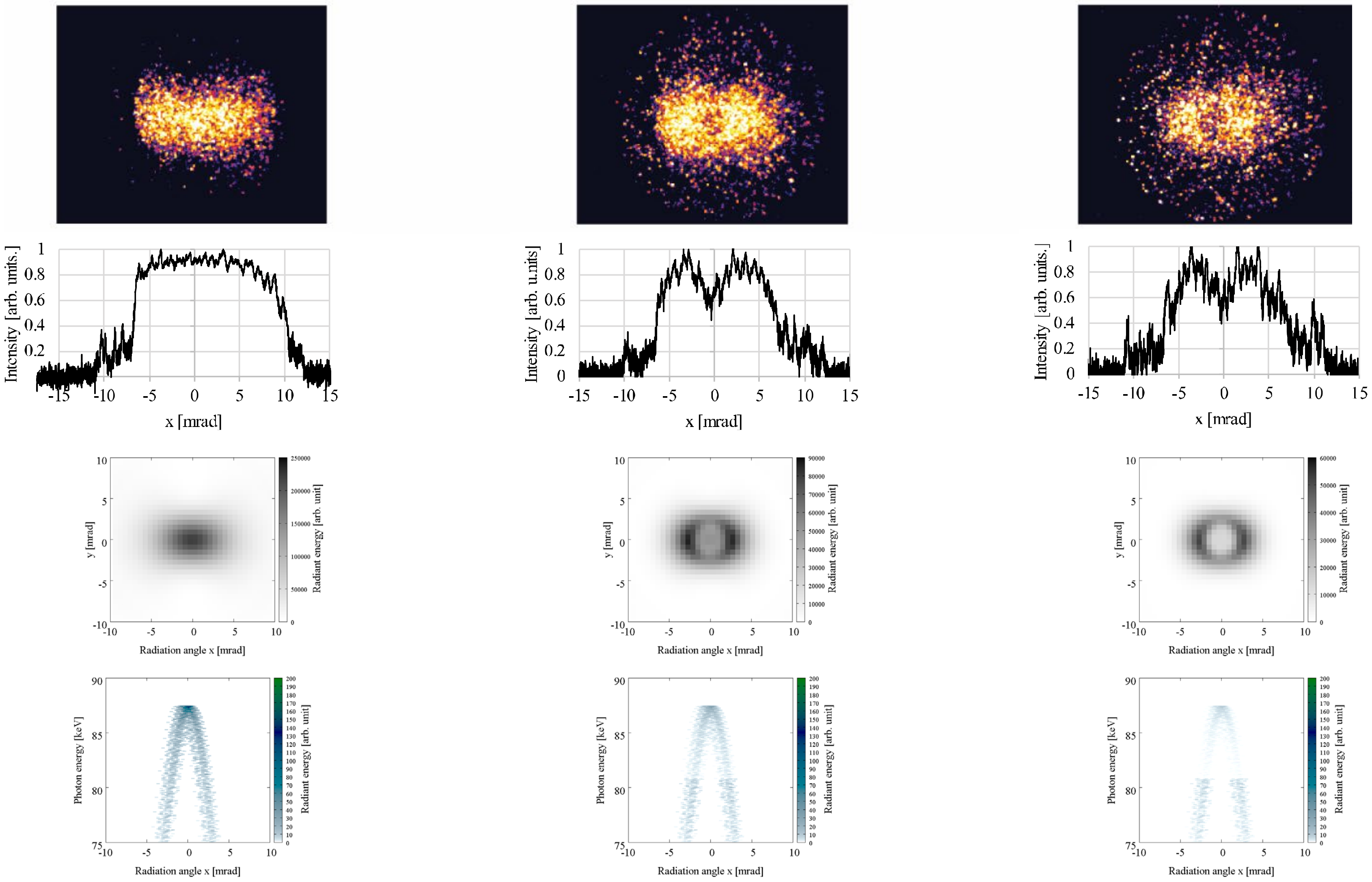
- ✶ Radius of curvature R: 2.5 m
- ✶ Thickness: 1 mm
- ✶ Bragg angle at 85keV: ~ 22 mrad
- ✶ Crystal to MCP screen 0.3 m
- ✶ Expected dispersion at screen: 10-20 mm:
- ✶ Band width: ~ 10 keV
- ✶ <u>Reflectivity (Efficiency): ~10%</u>

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

★ No-Filter | ★Au-100μm | ★Au-200μm

Experiment

Numerical




**Report to be submitted soon:**

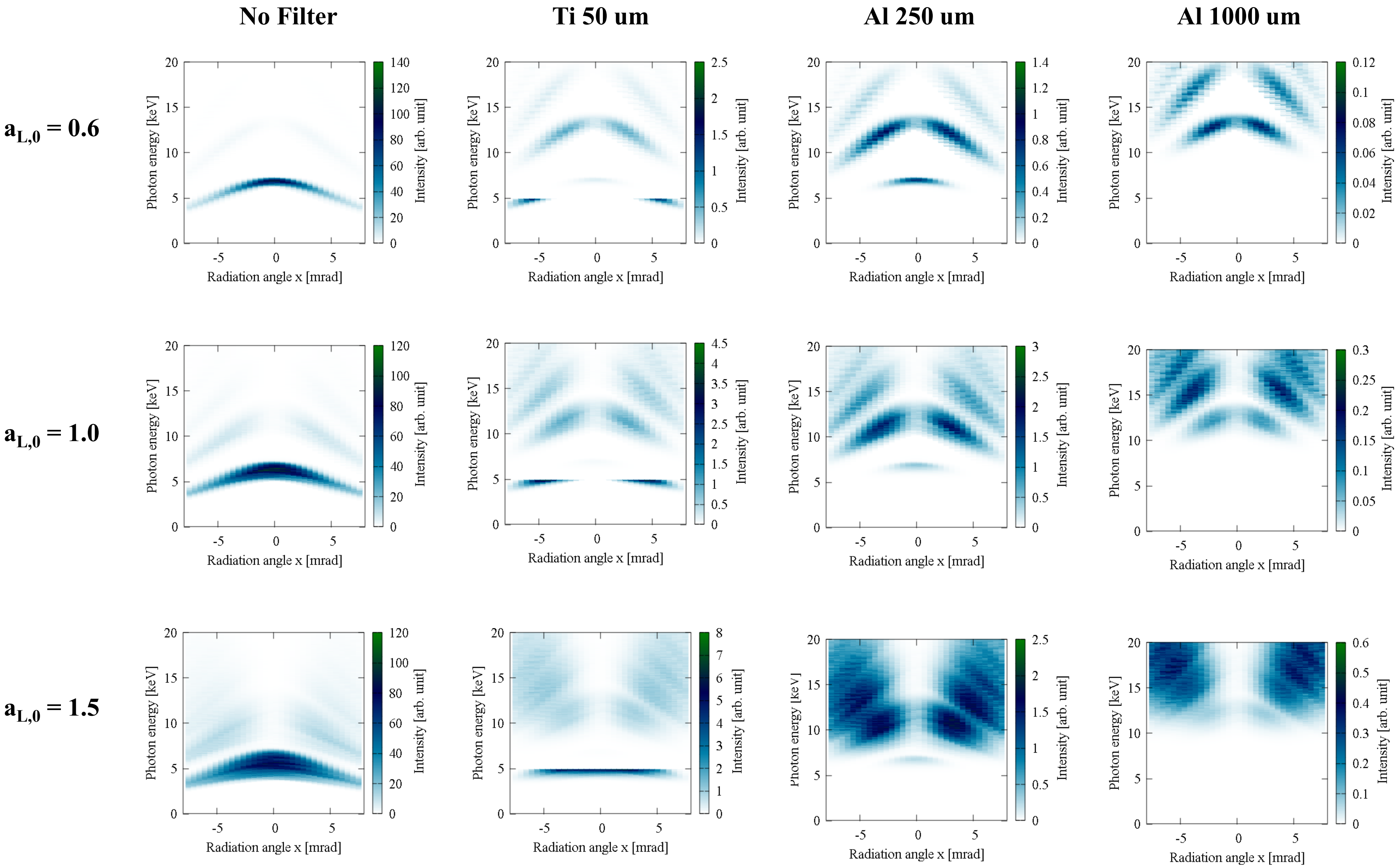
**Hard X-ray inverse Compton scattering at photon energy of 87.5 keV**

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

# *Appendix*

**Numerical Calculation Index →**

**No-Filter**
**Ti 50 um**
**Al 250 um**
**Al 1000 mm**



# *Appendix*

## 2023yr, Oct-Nov run

**3rd harmonic + higher order components**

**(***Although, 50% of laser flux goes through a on-axis hole )**

**>= 3rd Harmonic observed:**

**Al 1000 μm**
**High energy X-ray filtering**

**Estimated normalized vector potential at Compton I.P.: $a_{L,0} \sim 1$**