Proposal ID: 312815

Harmonic Nonlinear Inverse Compton Scattering

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

BNL ATF user meeting
March 2, 2023yr

Yusuke Sakai, Oliver Williams, Astushi Fukasawa, James Rosenzweig, ***UCLA***
Collaborator: Zhong Zhong, ***BNL NSLS***

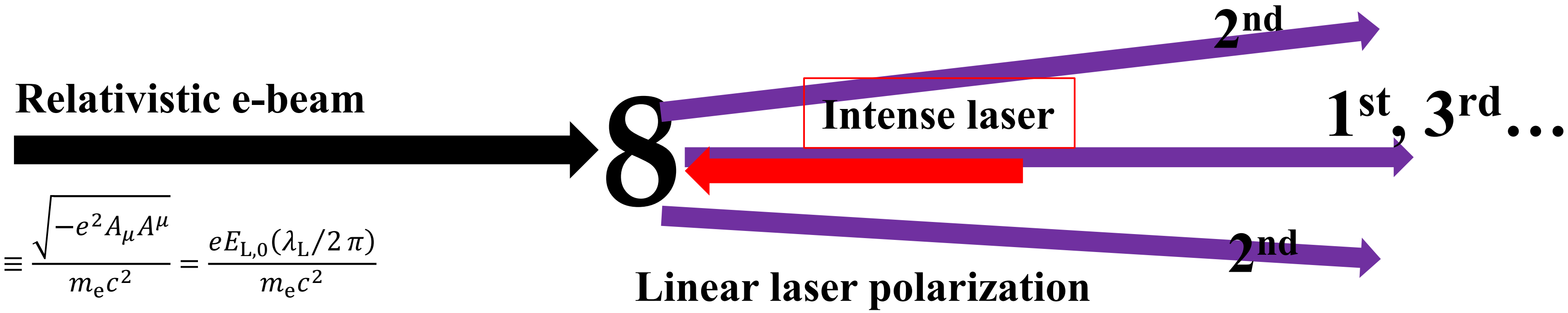
Funding source: DOE Accelerator Stewardship (DE-SC0009914)

BROOKHAVEN NATIONAL LABORATORY

BNL ATF Experiment Renewal: Experiment Goals {Return Of "Nonlinear"}

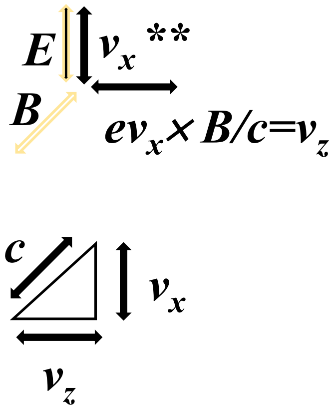
AE70: Nonlinear Compton, AE87: Hard X-ray ICS, AE##: Nonlinear Inverse Compton Scattering

✪ <u>Strong field physics: Bi-harmonic Compton interaction with ATF's CO_2 laser</u>
✪ <u>Hard X-ray optics developments: DDS measurement & Focusing or Collimation</u>
✪ <u>X-ray OAM investigation: Higher order harmonics by circular polarized CO_2 laser</u>



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

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

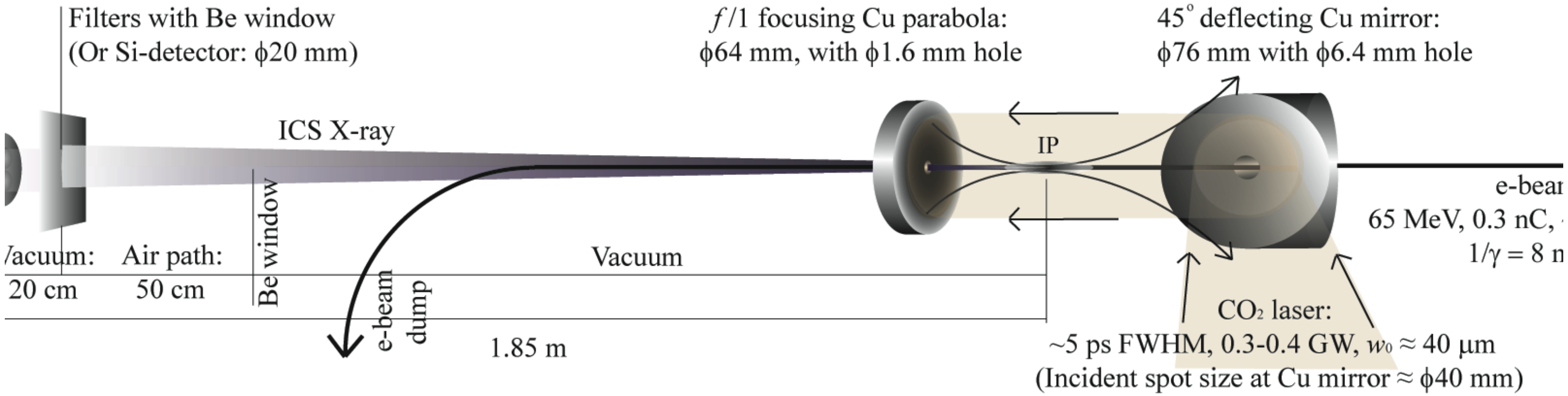
$$h\nu_{X\text{-ray}} \Rightarrow h\nu_{X\text{-ray}} / (1 + a_L^2/2 + \gamma_0^2 \Theta^2)$$

★ **Harmonic generation/angular dependence:**

Multi-photon process in dense photon field

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

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

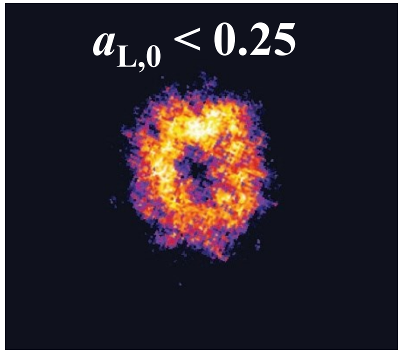
✦ **Electron beam: E = 65 - 70 MeV**
$Q \approx 0.3$ nC, $\sigma_z \approx 300$ μm, $\sigma_x \approx 30$ μm, $\varepsilon_N \approx 1$ mm mrad, $\beta \approx$ a few cm

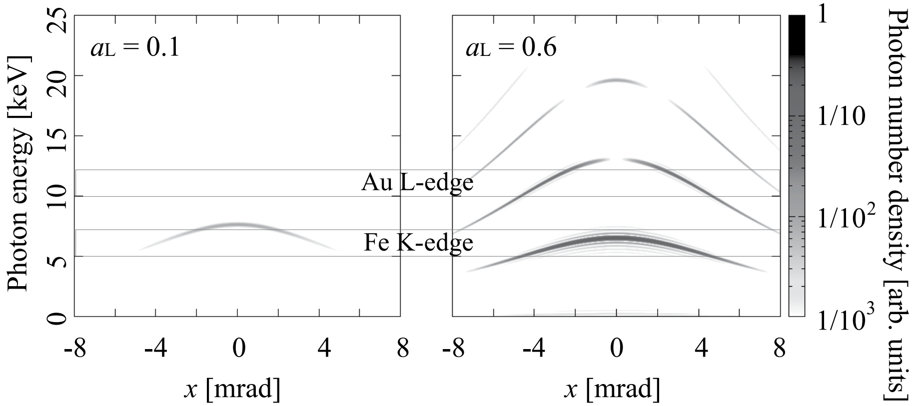
★**Compton edge: $h\nu = 4\gamma^2 E_L \approx 7$ - 10 keV**

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

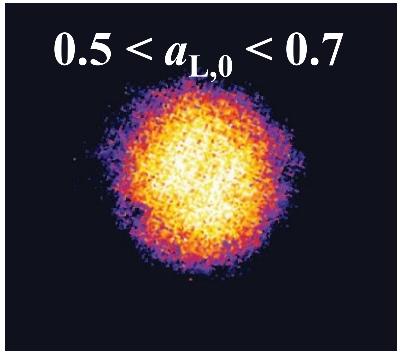
Observed red-shift (*Direct evidence of the figure-8 motion*)

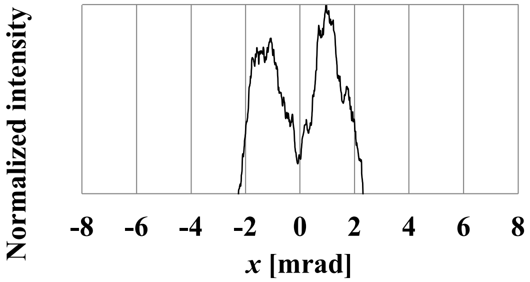
7.6 keV < Fe k-edge
Off-axis component

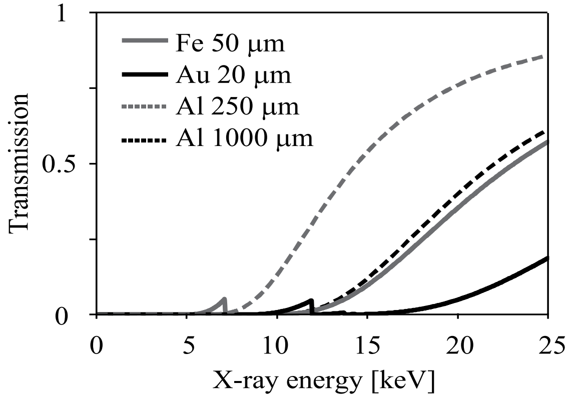


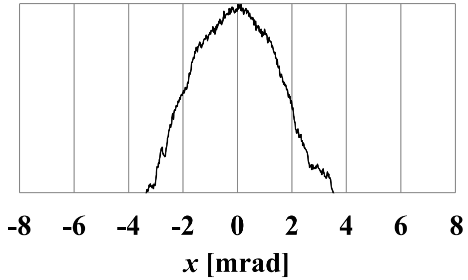


Red-shifting
to 5-6 keV







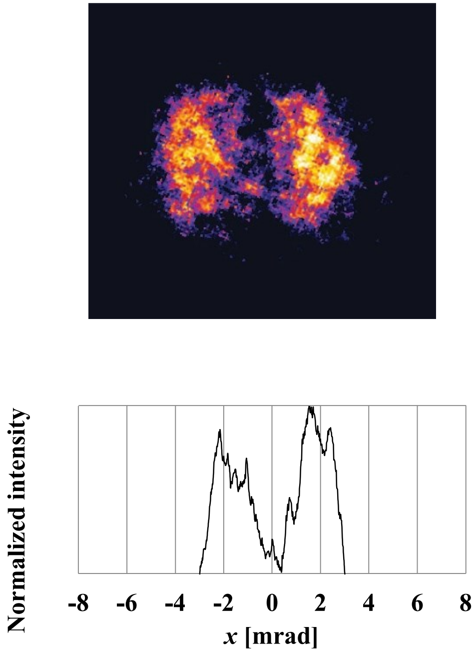


$$h\nu_{\mathrm{ICS},\,1^{\mathrm{st}}} = 4\gamma^2\nu_L/(1+a_{L,0}^2/2) \rightarrow \therefore\ 0.5 < a_{L,0} < 0.7$$

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

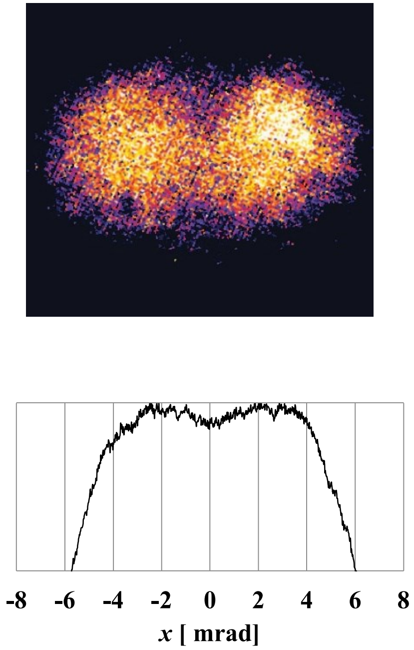
Angular distribution of harmonic radiation: *Linear polarization case*

Au L-edge (12 keV)



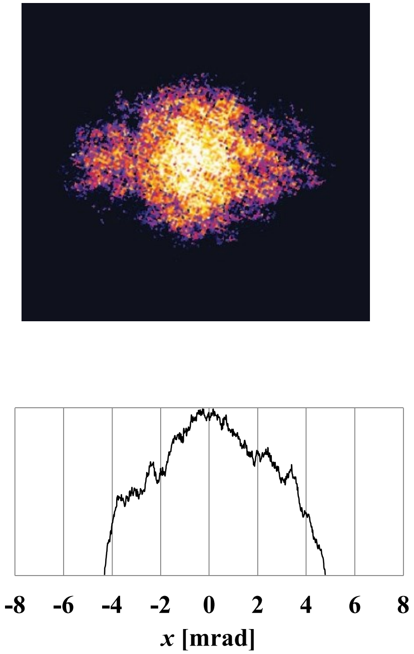
Narrow band 2nd

Al 250 μm > 10 keV



2nd + 3rd

Al 1000 μm > 15 keV

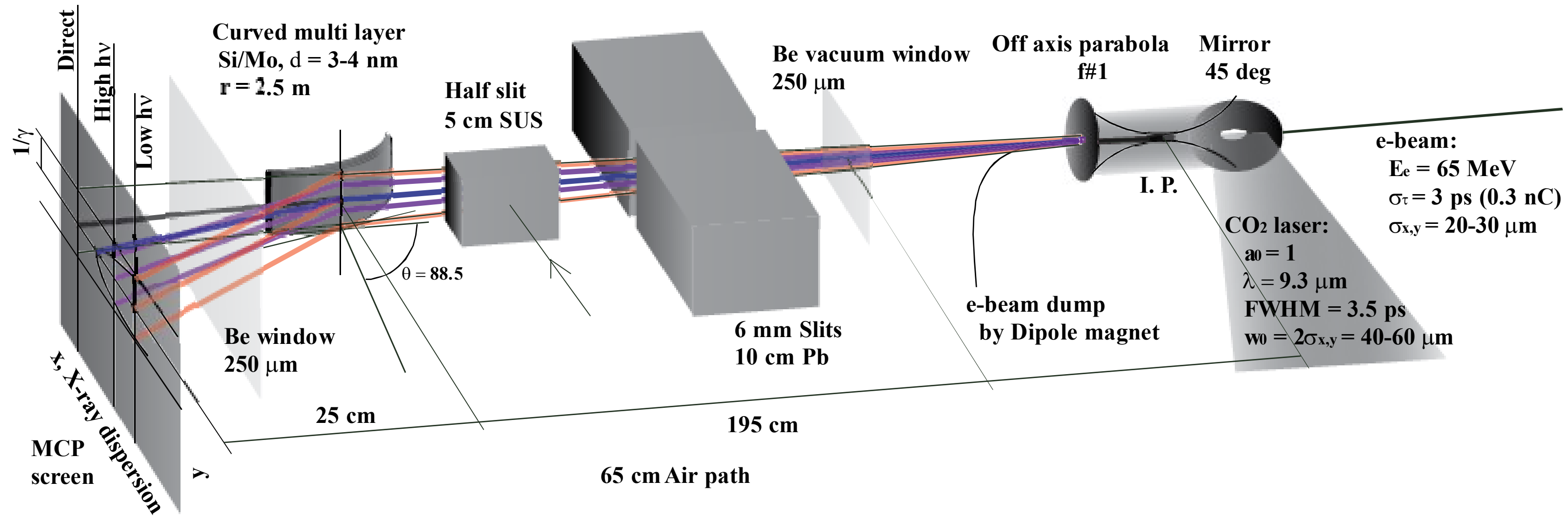


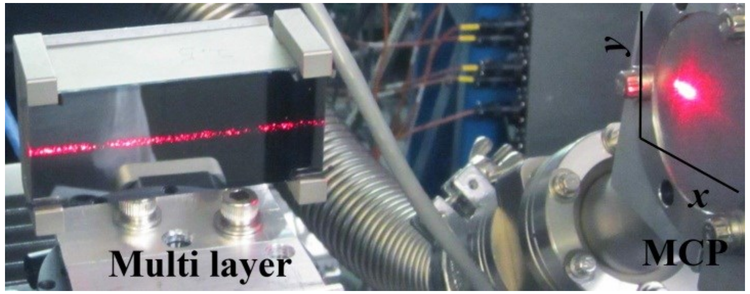
3rd

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

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

Details of the ICS X-ray spectrum: Mo/Si curved Multi-layer spectrometer - AE70





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

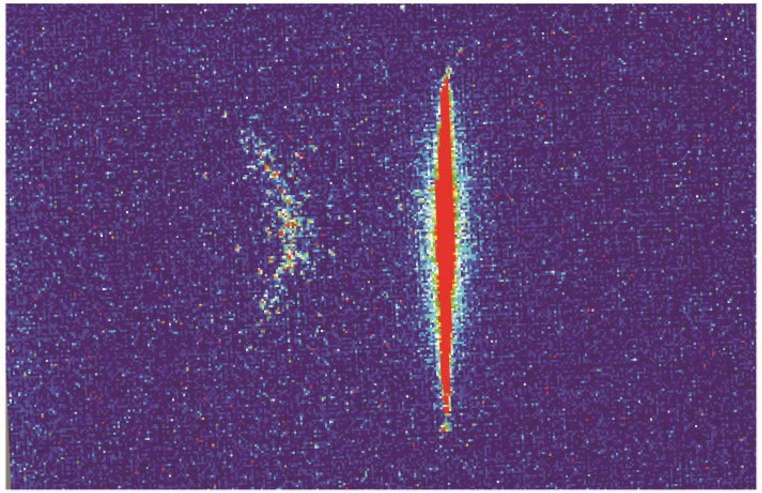
✡ Bragg angle:
~ 25 mrad

✡Angle acceptance :
~ 50 mrad

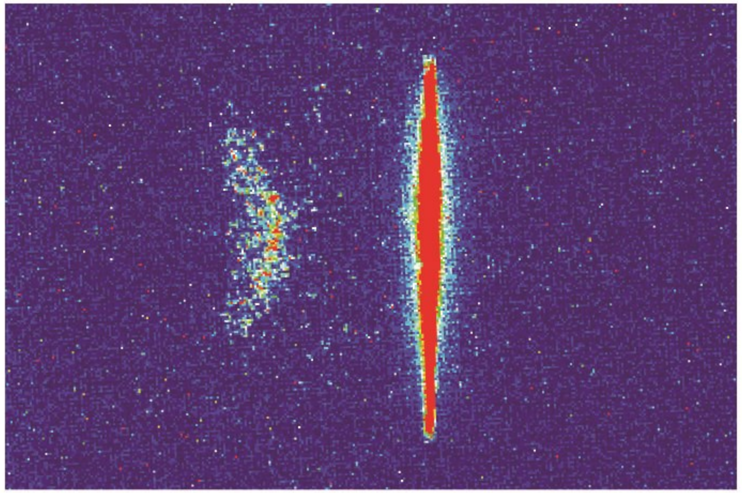
✡ Reflectivity ~ 15% @ NSLS X15A (Z. Zhong)

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 at *hv < 10 keV*   *(AE70)*



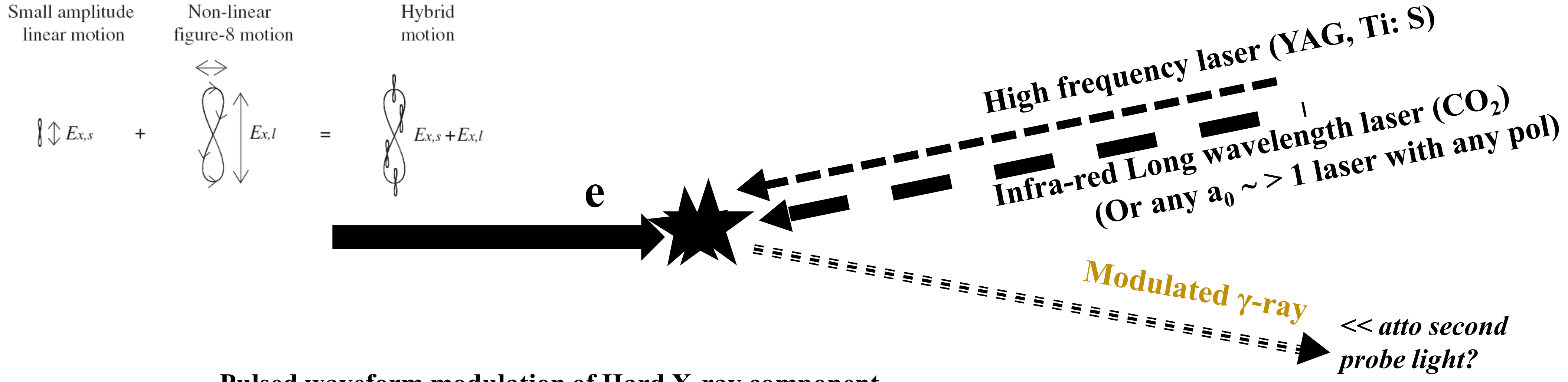
Laser energy 1.5 J,
$a_L = 0.7$



Laser energy 3.0 J
$a_L = 1$

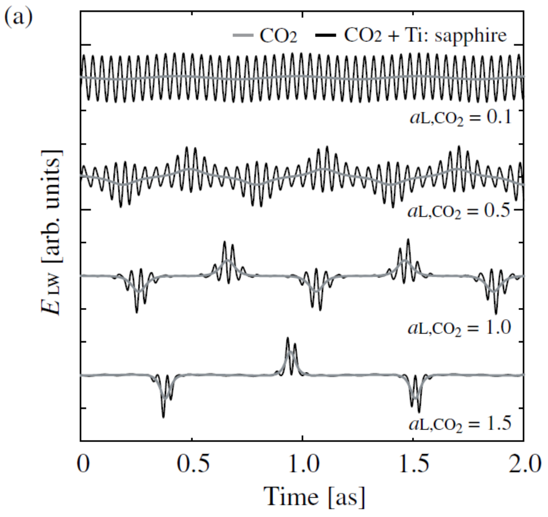
Single shot, double differential spectral measurements of inverse Compton scattering in the nonlinear regime,
Phys. Rev. ST Accel. Beams (2017)

Bi-harmonic nonlinear Compton interaction



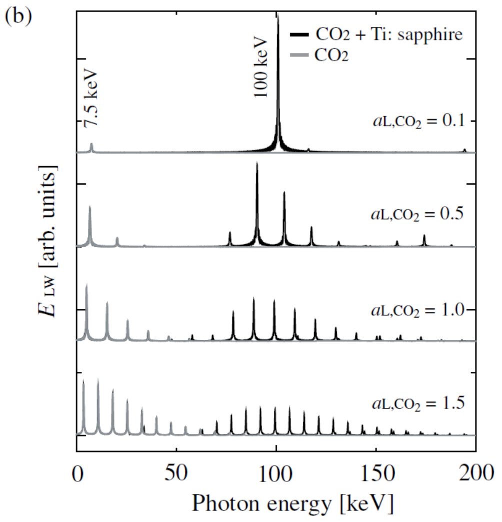
Pulsed waveform modulation of Hard X-ray component at less than < 10^{-18} s time scale (Cycle of 10 keV X-ray)

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

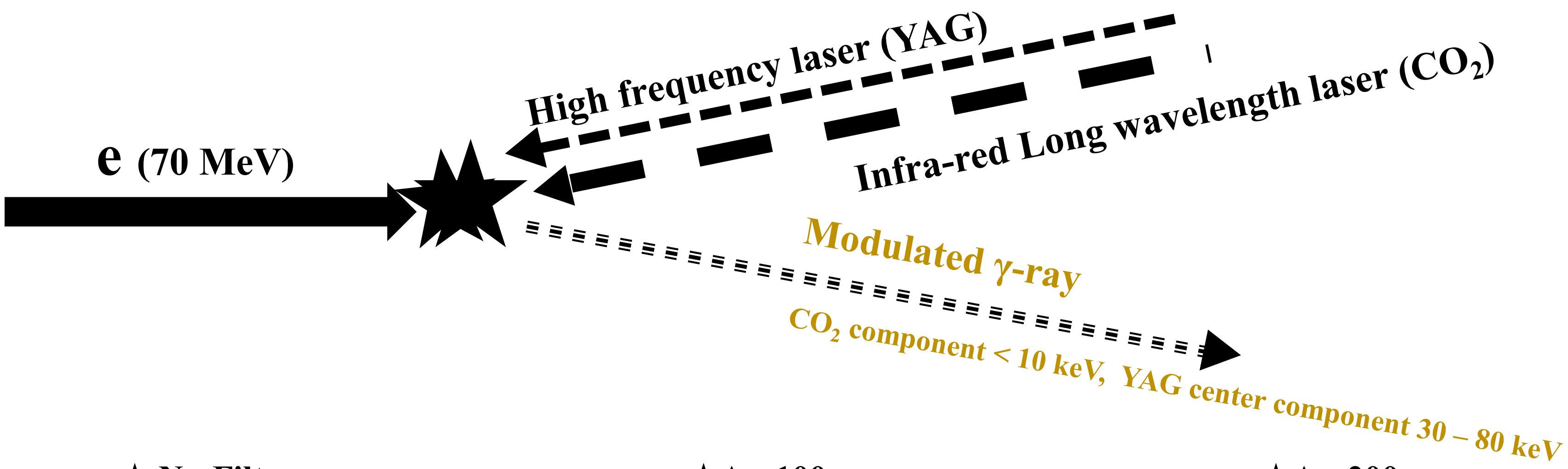


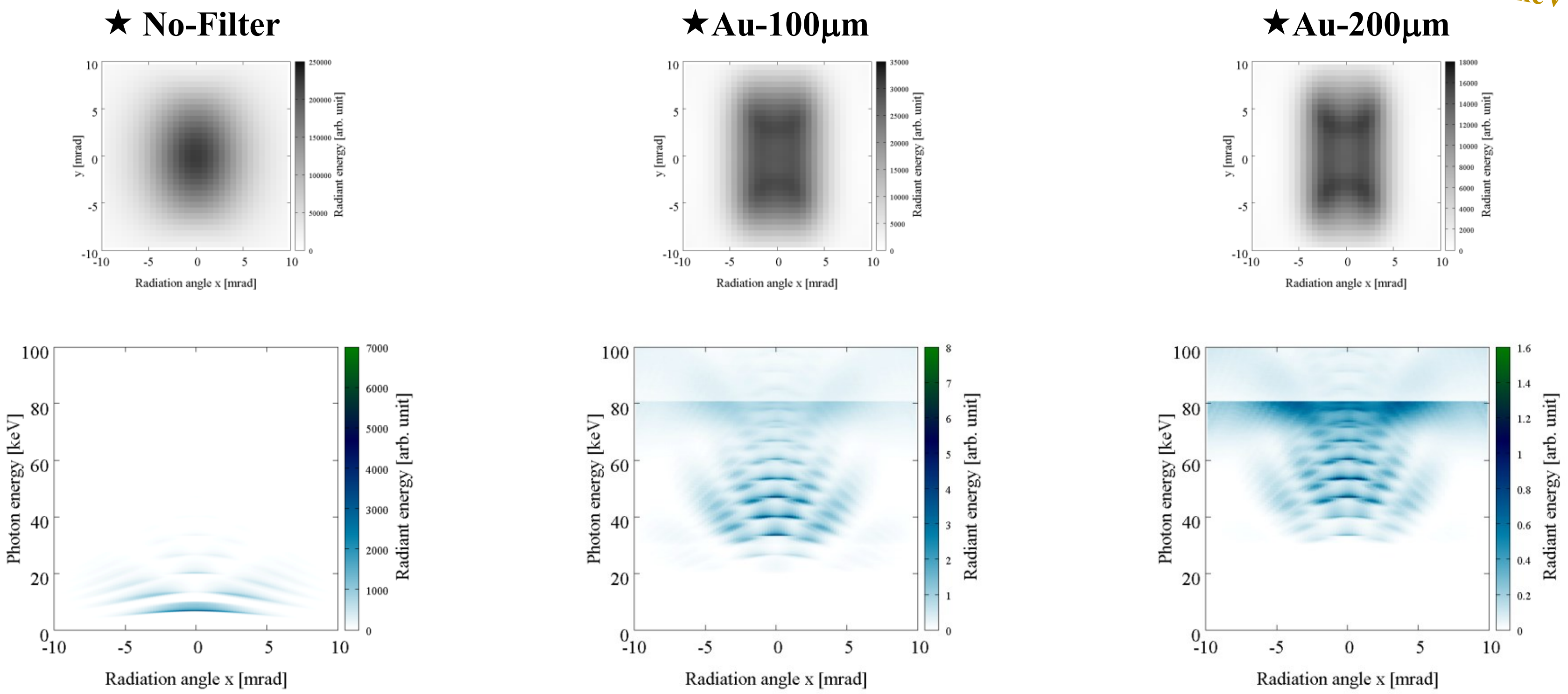
Numerically calculated Lienard-Wiechert potential $E_{LW,x}(t_{screen})$ on $(x, y, z) = (0, 0, 0)$

Fourier Transform →



Numerical estimate of bi-harmonic spectrum by ATF parameter (CO2: 9.2um, Nd: YAG 1064nm)





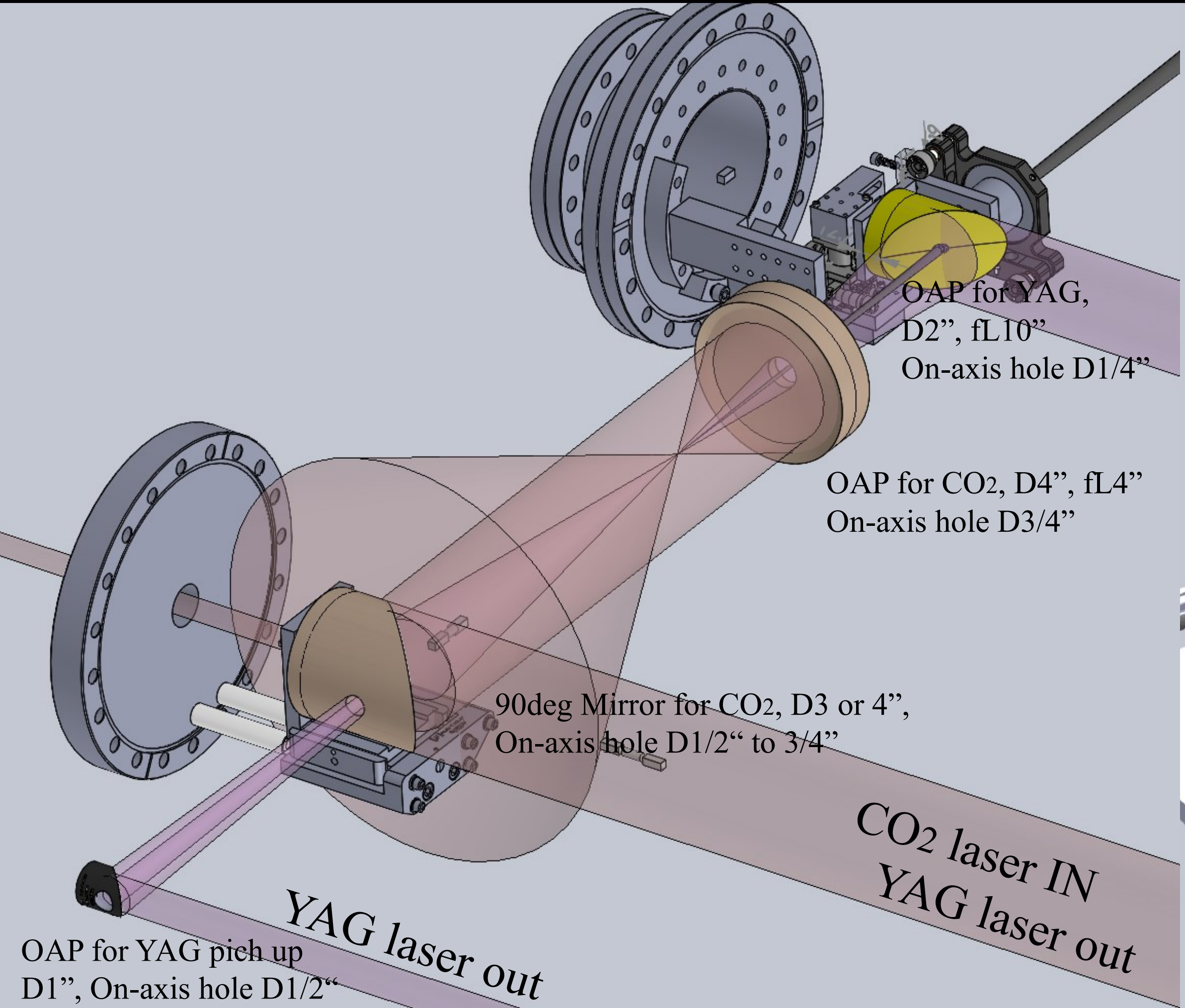
Only CO_2's component

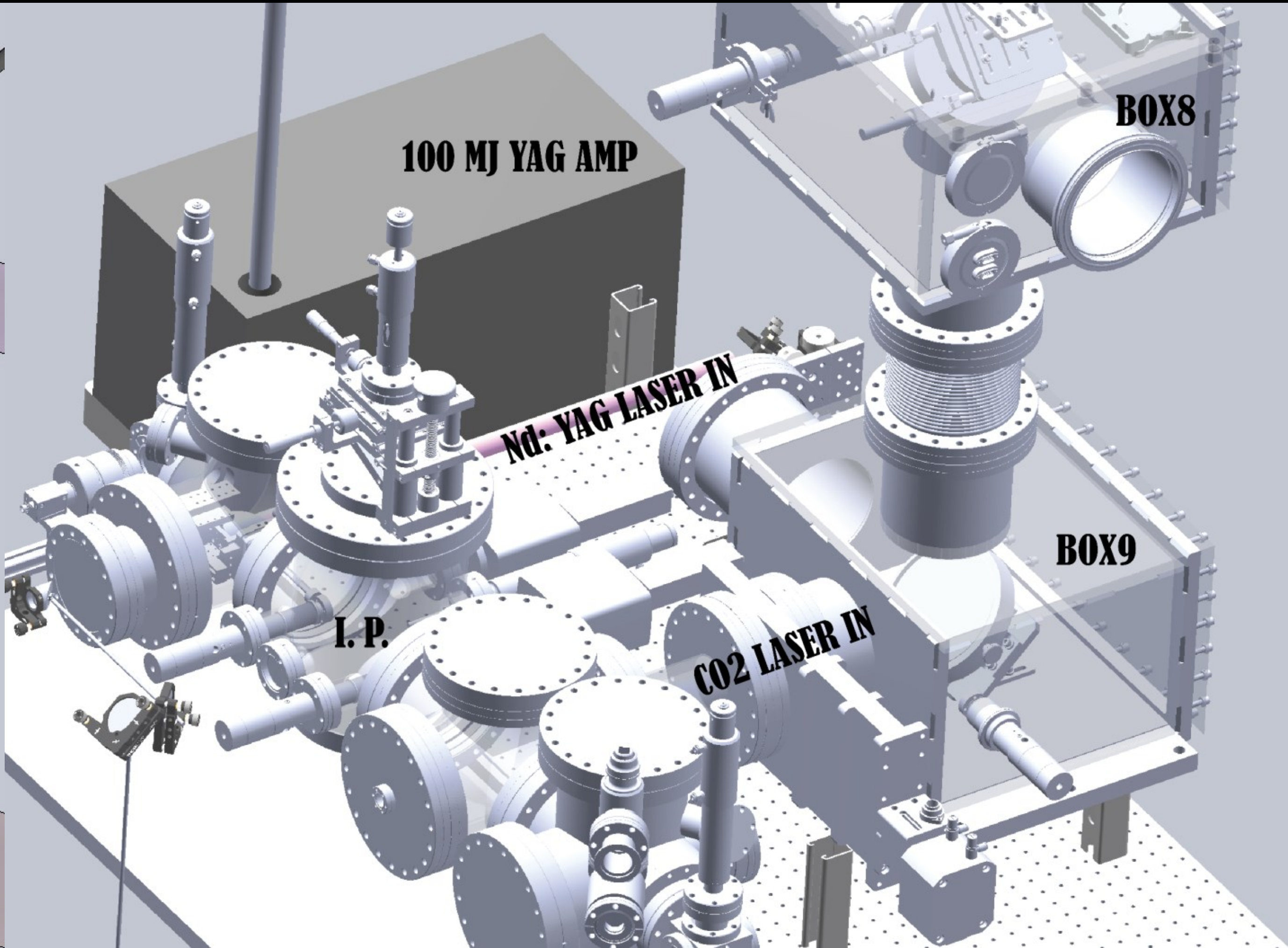
Bi-harmonic YAG's component

Experimental set up

Bi-harmonic Compton laser optics:

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





Experimental set up

Bi-harmonic Compton laser optics:

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

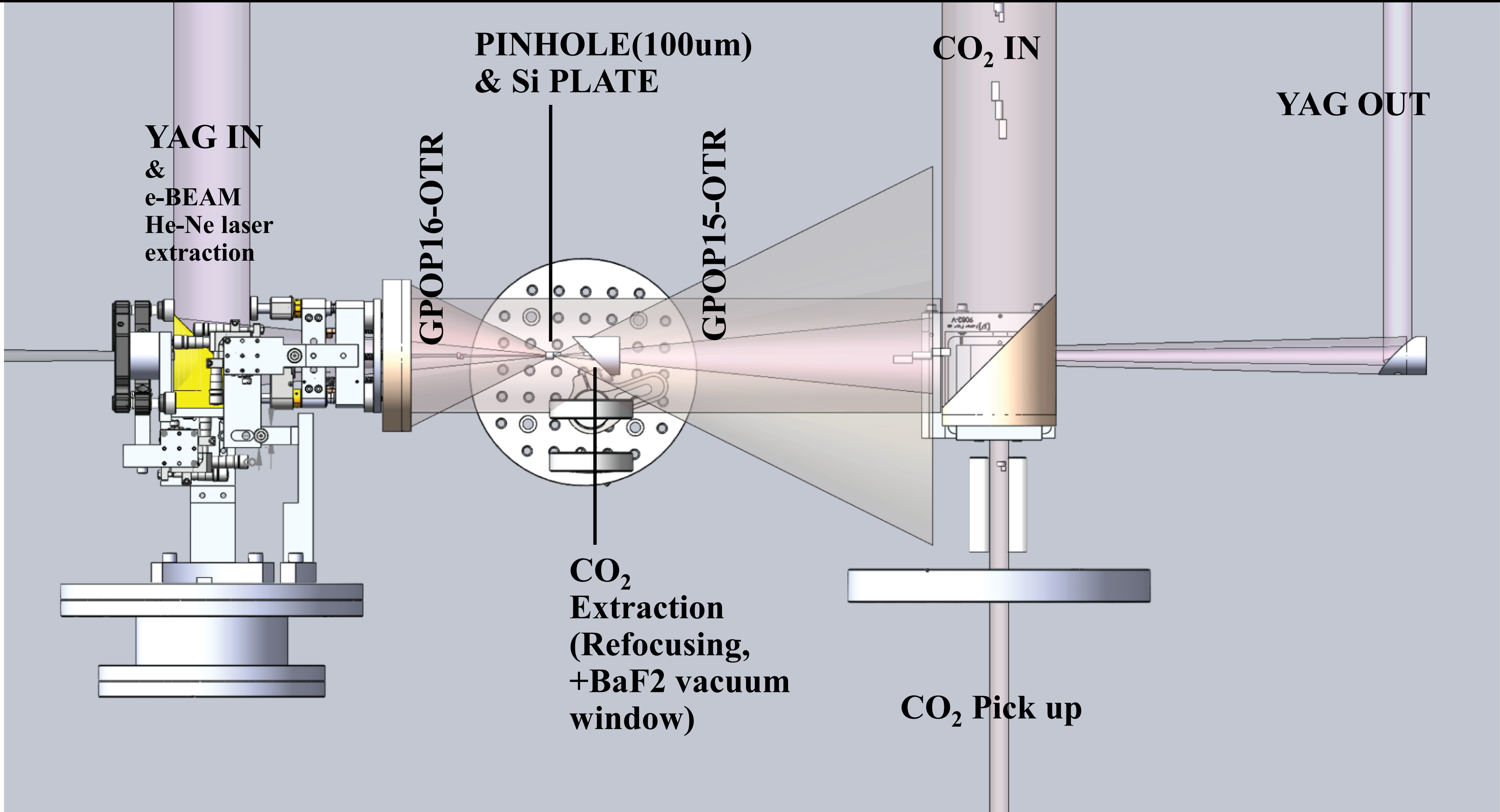
HOW TO DO

ALIGNMENT
& TIMING

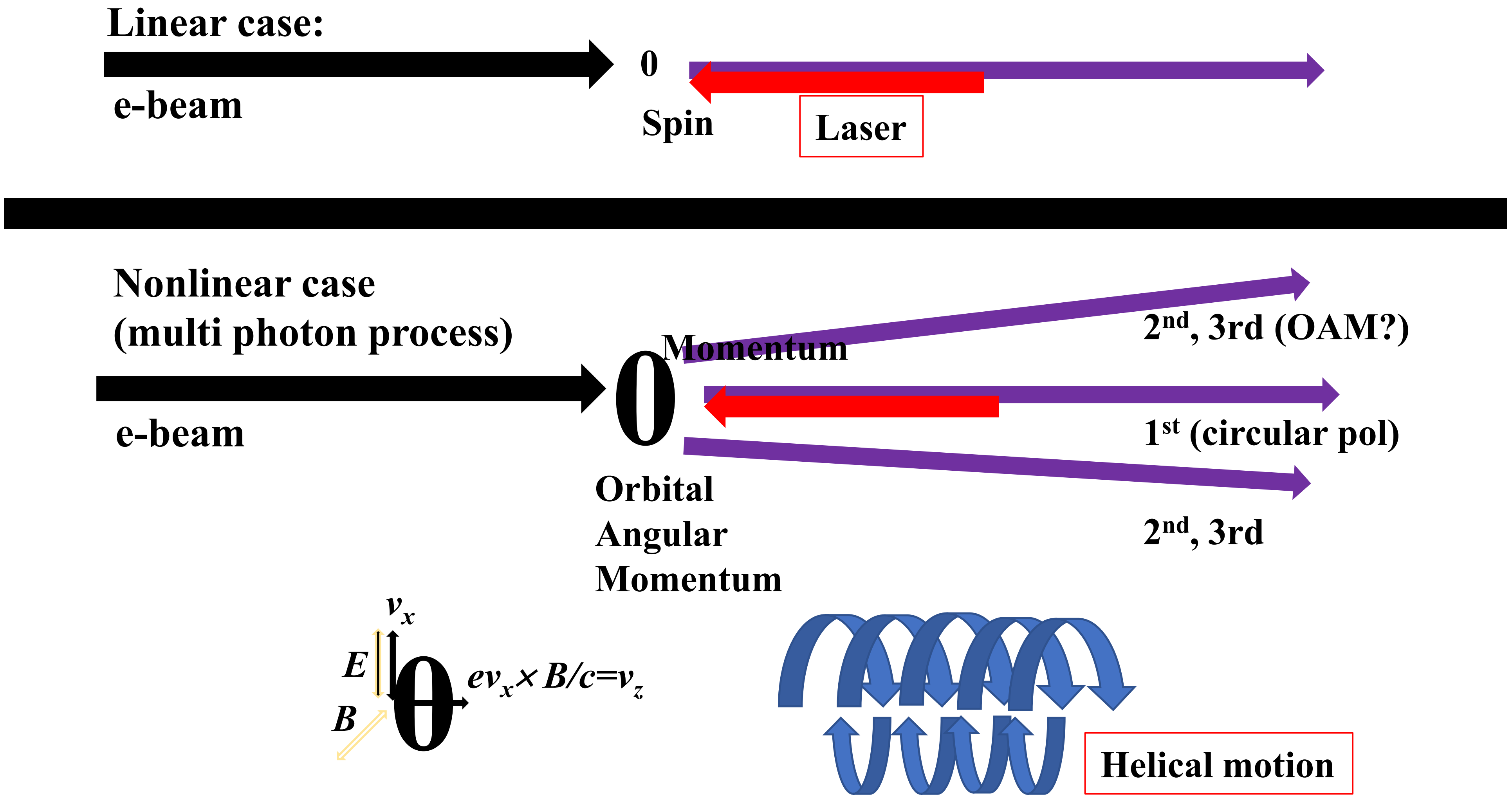
OF TWO LASER
& e-beam

***ICS**
≅ Experiment of Alignment in real life

Note:
Vacuum laser transport needs to be stable.



NEXT: ICS by circular polarized laser – OAM X-Gamma ray ?

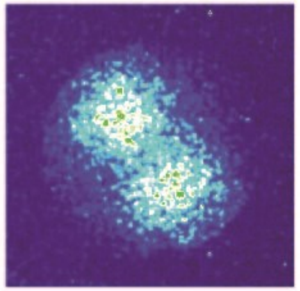


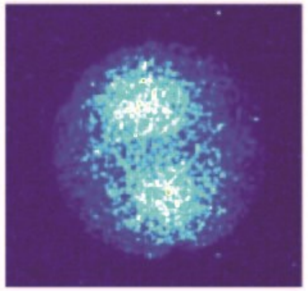
NOTE: OAM X-ray can be also generate by FEL & Linear ICS by OAM laser.

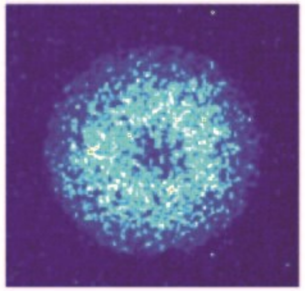
Harmonic generation by circulary polarized CO_2 laser, in AE70

¼ wave plate between regenerative and TW amplifier (Without compressor grating)

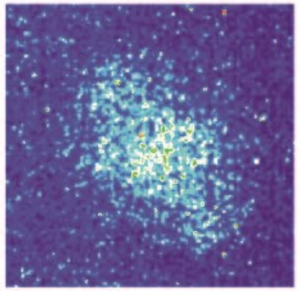
Al 250 μm: **Linear, 2nd** **Elliptical, 2nd** **Circular, 2nd**







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



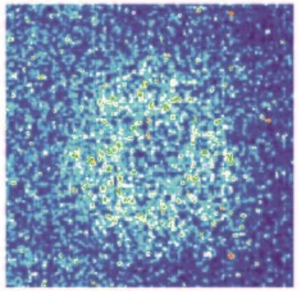


Figure Observation of 3rd order harmonics in ICS by circularly polarized CO_2 laser Upper and lower figure corresponds to radiation pattern through 250 μm thick Al filters and 1 mm thick Al filters respectively.
Left upper: Linearly polarized 2nd harmonics. Middle upper: Elliptically polarized 2nd harmonics. Right upper: 2nd harmonics generated from circularly polarized laser. Lower left: linearly polarized 3rd harmonics. Right lower: 3rd harmonic components generated by circularly polarized laser.

REF: AAC2022yr Proceeding

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)}

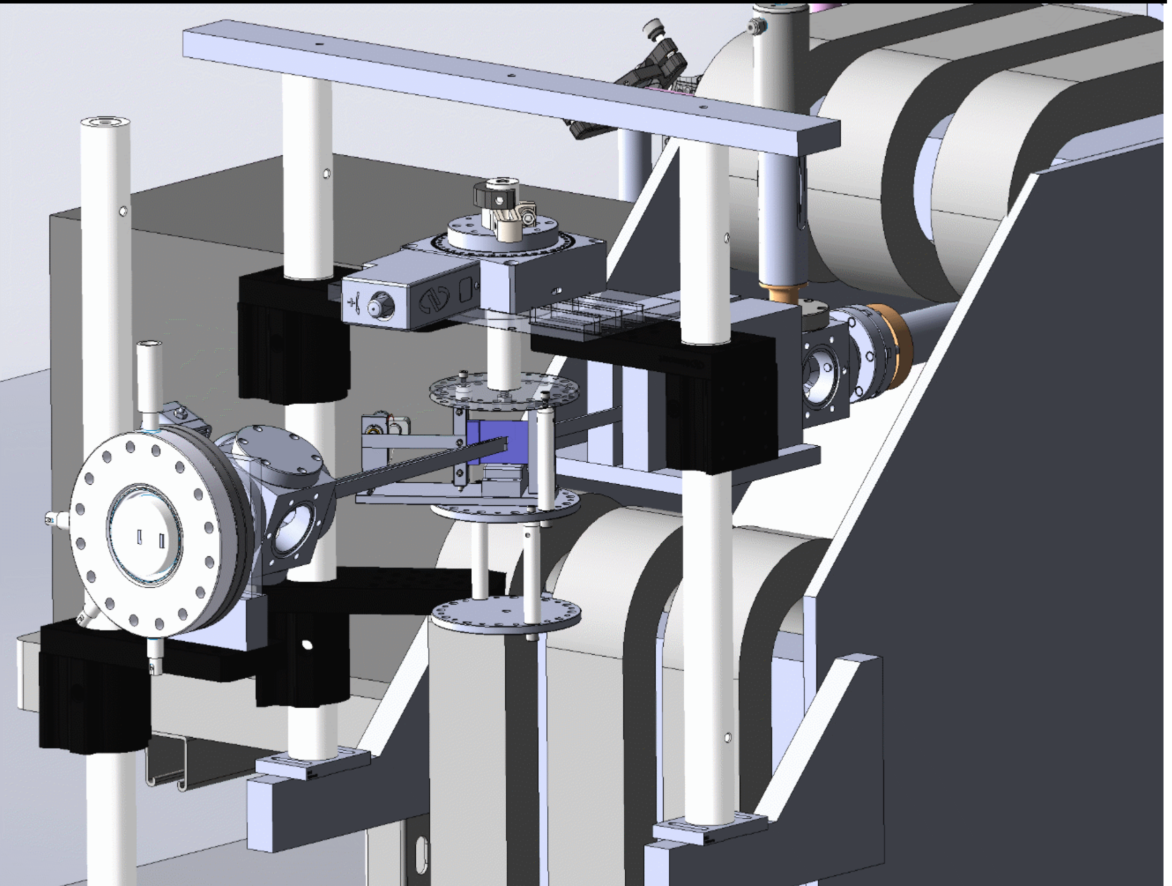
→ Detailed spectrum distribution needs to be measured at 10s keV range.

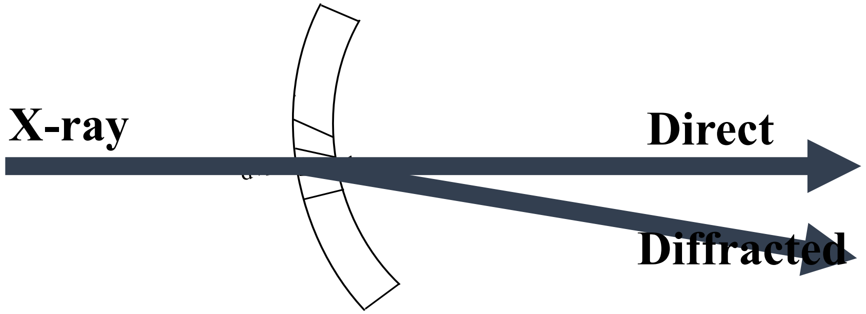
Single shot DDS measurement at X-ray energy of 87.5 keV > 10s keV

Quantitative study

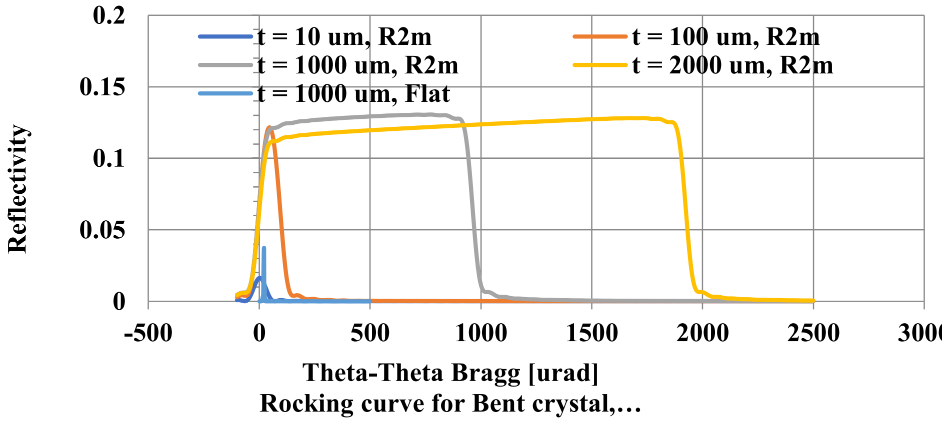
→ *Thick Laue Bent Crystal Efficiency > Bandwidth*

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





- ✶ 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>



Stats: Diffraction not observed yet in 87.keV Hard X-ray ICS run time.

→ First, 2nd – 3rd Harmonic radiation at 20-30 keV range should be examined. Much higher detector efficiency, with more photon flux.

P L A N

- Recover, or almost new installation of, nonlinear CO_2 ICS set up 1.5 year:
    1. Complete laser vacuum transport. <On going now>
    2. Installation of CO_2 laser optics with Regen signal at mJ; Establish alignment method <Summer 2023yr>
    3. CO_2 laser high power test (Protection of YAG system & source CO_2 laser) <2023-24 yr>
    4. Benchmarking $a_{L,0}$ measurement of upgraded 5 TW CO_2 laser through harmonic components of nonlinear ICS <2024yr>

- Single shot DDS measurement by Bent crystal 2^{nd}, 3^{rd} order harmonic (CO_2 laser) At ~30 keV range <2024yr>

- Recover Nd: YAG laser optics for Bi-harmonic Compton <2025yr->

- 87.5 keV hard X-ray DDS measurement by Bent crystal <2025yr->

- OAM study, Circularly polarized CO_2 laser. Depend on the polarization rotator <TBD>

T H A N K   Y O U

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*	*0.3 nC*
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.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*	*None*
Transverse size at IP (σ)	μm	30 – 100 (dependent on IP position)	*It is possible to achieve transverse sizes below 10 um with special permanent magnet optics.*	*< 30 um*
Normalized Emittance	μm	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 Hz*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*	*Single bunch*

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 um*
	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*	*Linear & Circular*
CO_2 CPA Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2 um*
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.*	*Max.* *aL>1*
	Pulse Mode	---	Single		*Single*
	Pulse Length	ps	2		*2 ps*
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*	*Max*
	M^2	---	~2		
	Repetition Rate	Hz	0.05		*<< 0.05*
	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*	*TBD*
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.*	*500 fs possible?*
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		*100-200 mJ*
Pulse Width	ps	14		*FWHM 14ps*
Wavelength	nm	532	*Frequency doubled*	
Energy	mJ	0.5		
Pulse Width	ps	10		

Special Equipment Requirements and Hazards

- All item has been registered in ESR of AE87.

Experimental Time Request

CY2023 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)		1 week (In EH. Only regen)
Laser* + Electron Beam TWCO2 only in EH	100 16 hours	1 week (CO2 – ebeam Timing). 1 hour (Damage test)

Total Time Request for the 3-year Experiment (including CY2023-25)

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)		
Laser* + Electron Beam		2 weeks X 6 = 480 hours

* Laser = Near-IR or LWIR (CO_2) Laser