27th Accelerator Test Facility (ATF) Users' Meeting

AE131 – Harmonic Nonlinear Inverse Compton Scattering

Yusuke Sakai & All ATF members (B N L)
James Rosenzweig (U C L A)

4 / 30 / 2025

Funding source: DOE Accelerator Stewardship (DE-SC0009914)
This year: T B D

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Accelerator Facilities Division

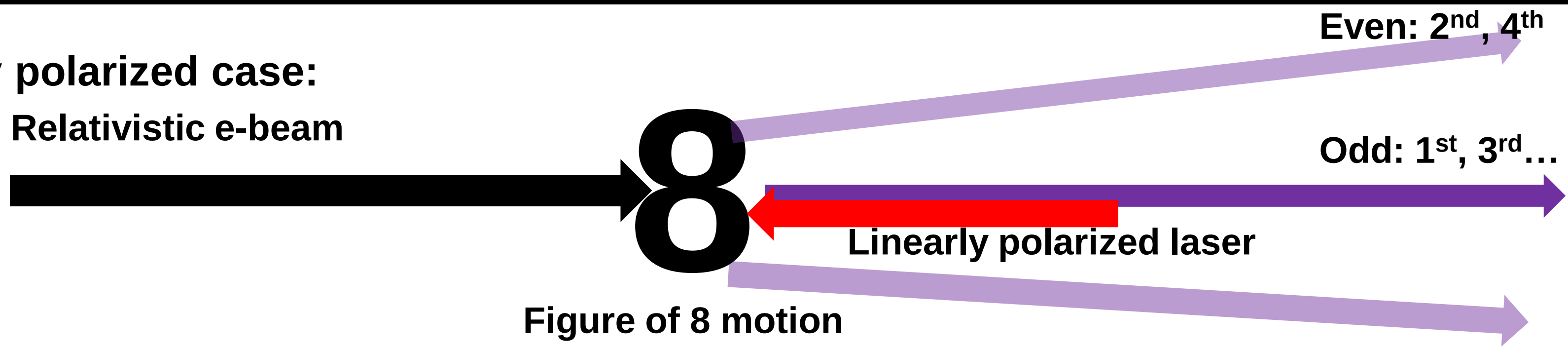
Goals of experiment AE131

Harmonic Nonlinear Inverse Compton Scattering {Basically, re-establish CO_2 ICS}

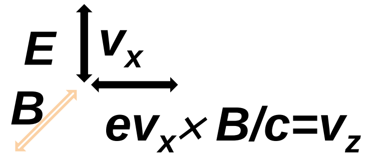
- ✪ <u>Bi-harmonic Compton interaction study: Sub attosecond X-ray pulse modulation</u>
- ✪ <u>X-ray OAM investigation: Higher order harmonics by circular polarized CO_2 laser</u>
- ✪ <u>Sub 100 keV hard X-ray optics R & D: Spectrum measurement, Collimation & Focusing</u>

Nonlinear ICS: a_L~1* laser induce Transverse motion → Relativistic, nontrivial Longitudinal oscillation → Slow down electron's velocity or Effective mass increase → Redshift & Harmonics

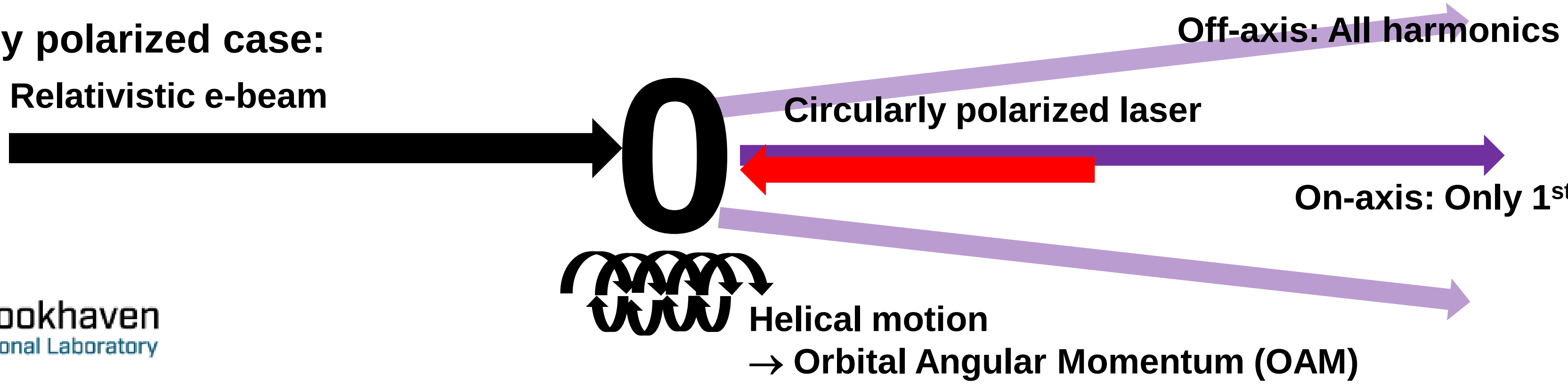
Linearly polarized case:

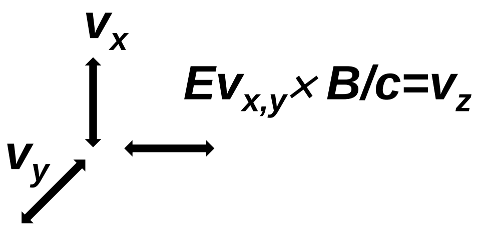


$$* \, a_{L,0} \equiv \frac{\sqrt{-e^2 A_\mu A^\mu}}{m_e c^2} = \frac{e E_{L,0}(\lambda_L/2\pi)}{m_e c^2}$$

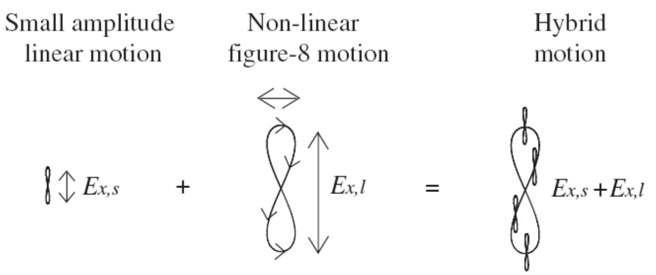


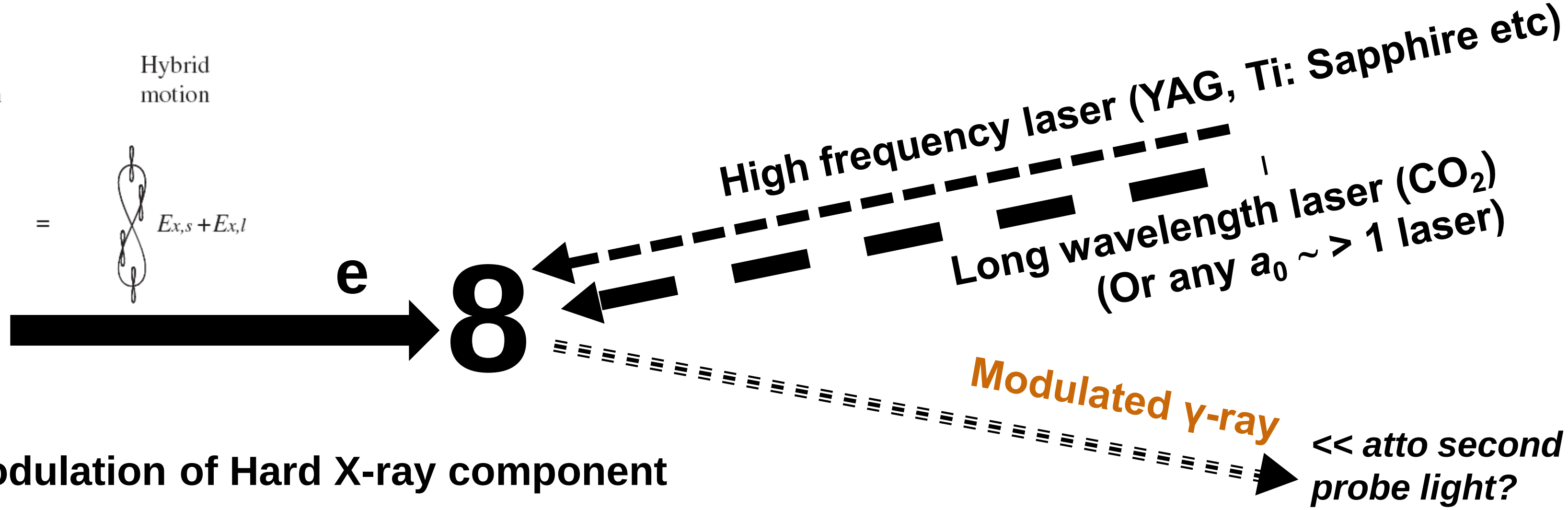
Circularly polarized case:





Bi-harmonic Compton interaction

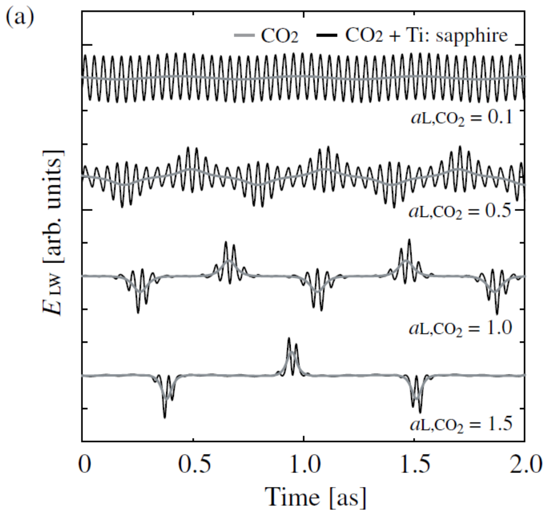




<< atto second probe light?

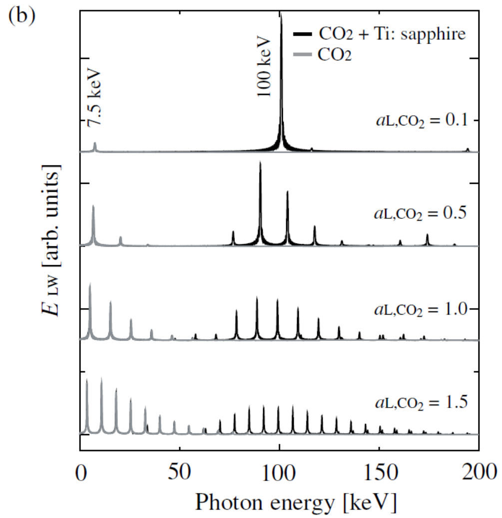
Pulsed waveform modulation of Hard X-ray component at less than < 10^{-18} s time scale (Cycle of 10 keV X-ray)

Observation of Blue & Red shifts & $h\nu_{Short} \pm n\, h\nu_{Long}$



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

Fourier Transform →



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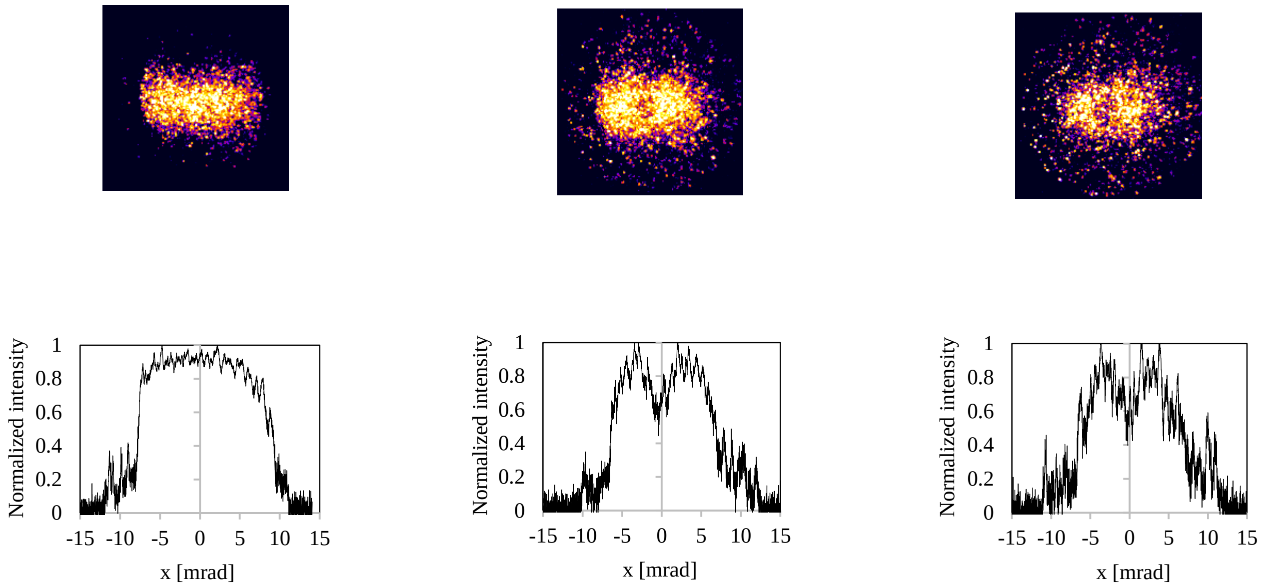
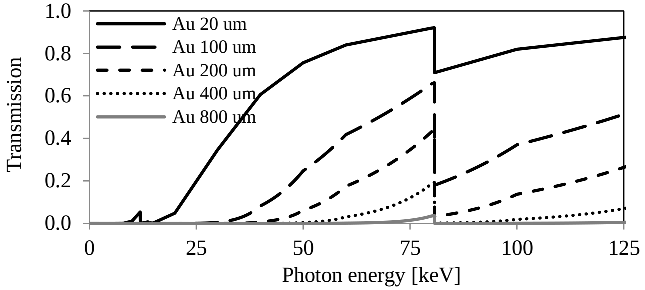
Phys. Rev. ST Accel. Beams Vo. 14, 120702 (2011)

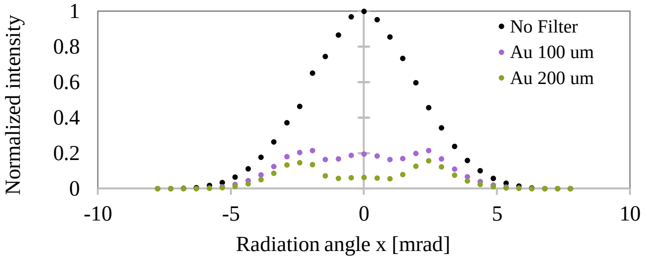
AE87: Established YAG-ICS setup

Nd: YAG laser 1064 nm & 70 MeV e-beam
→ Single shot measurement (~10^6 photon yield / pulse at 87.5 keV)
Observation of X-ray absorption by Au k-edge



a) No-Filter　　b) With 100 μm Au filter　　c) With 200 μm Au filter





Numerical calculation

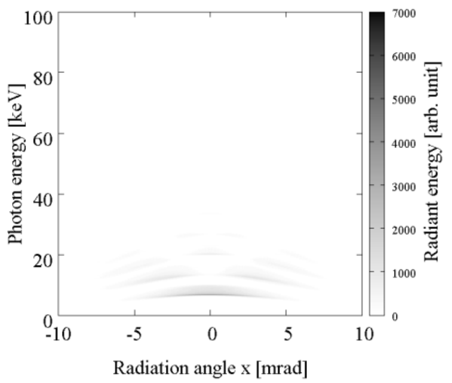
"Hard X-ray inverse Compton scattering at photon energy of 87.5 keV",
Scientific Reports volume 14, Article number: 18467, 2024
{Written for Photon activation therapy; Dose enhancement via Gold nano particle}

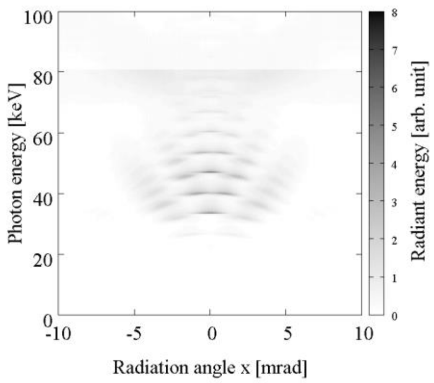
Computational prediction of Bi-Harmonic Spectrum

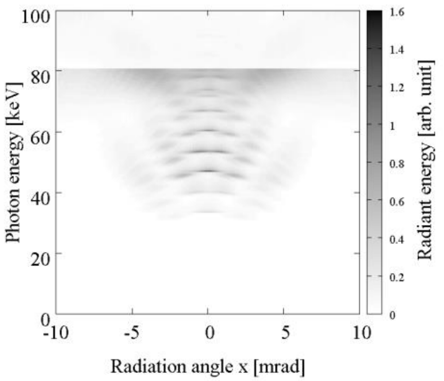
with Au K-edge filter / CO_2 laser 9.2 μm, Nd: YAG laser 1064 nm, & 70 MeV e-beam

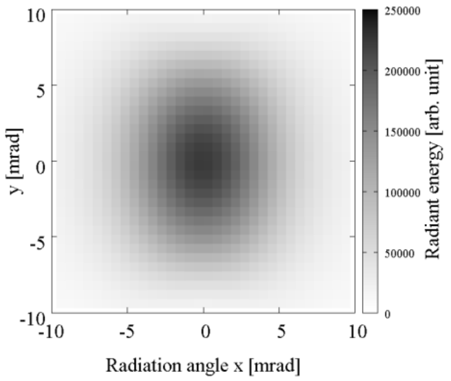
Only CO_2's component | **Bi-harmonic components**

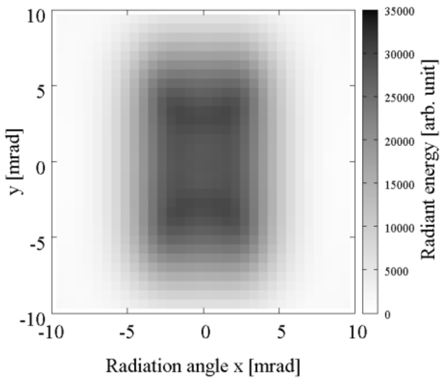
NO-Filter | **Au-100μm** | **Au-200μm**

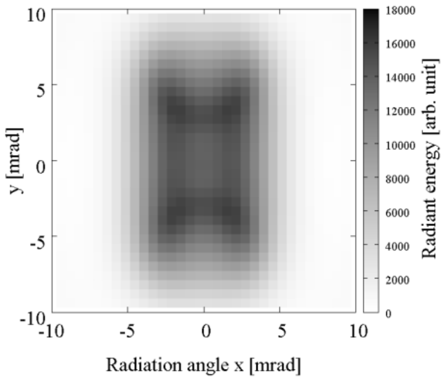






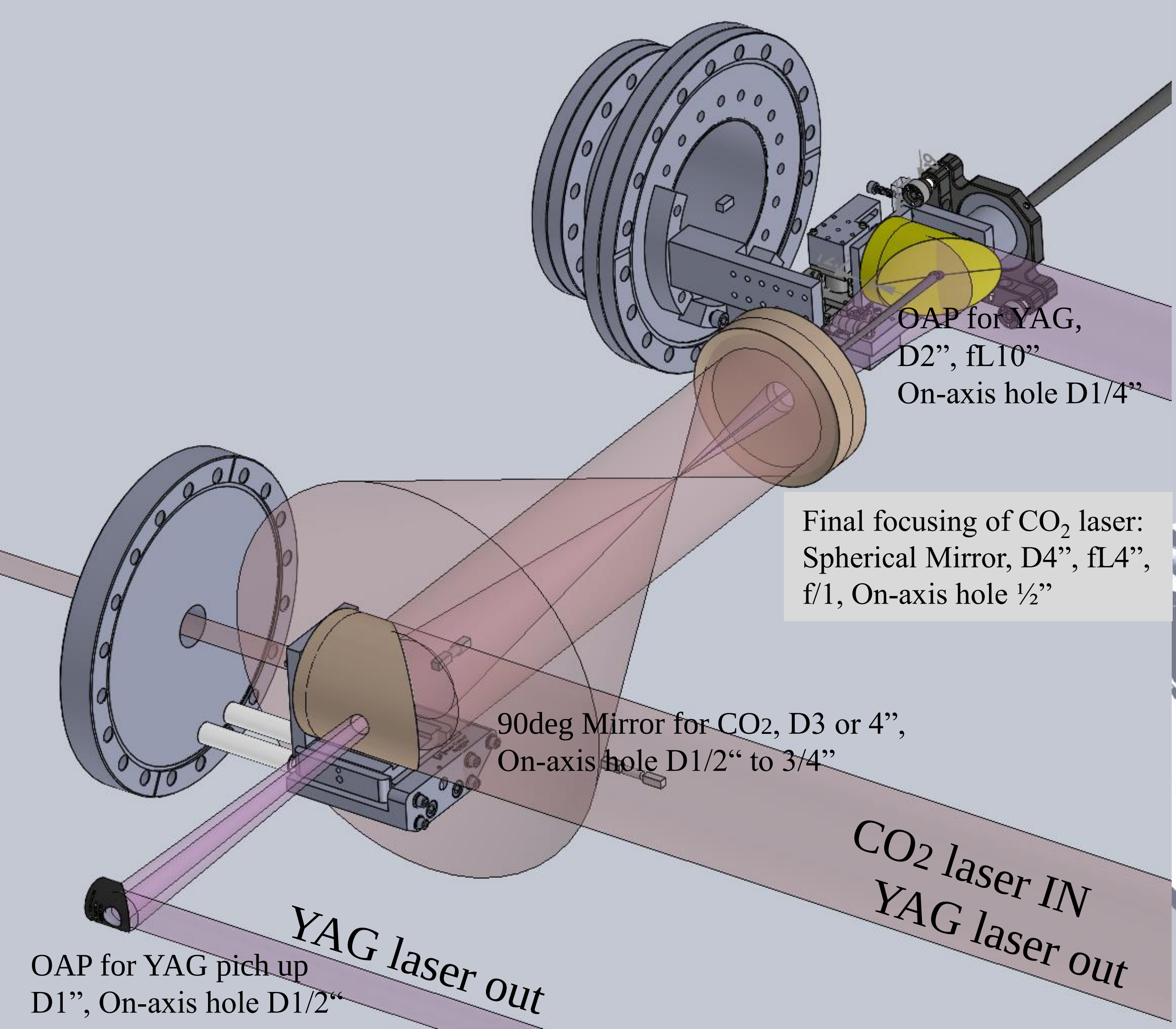


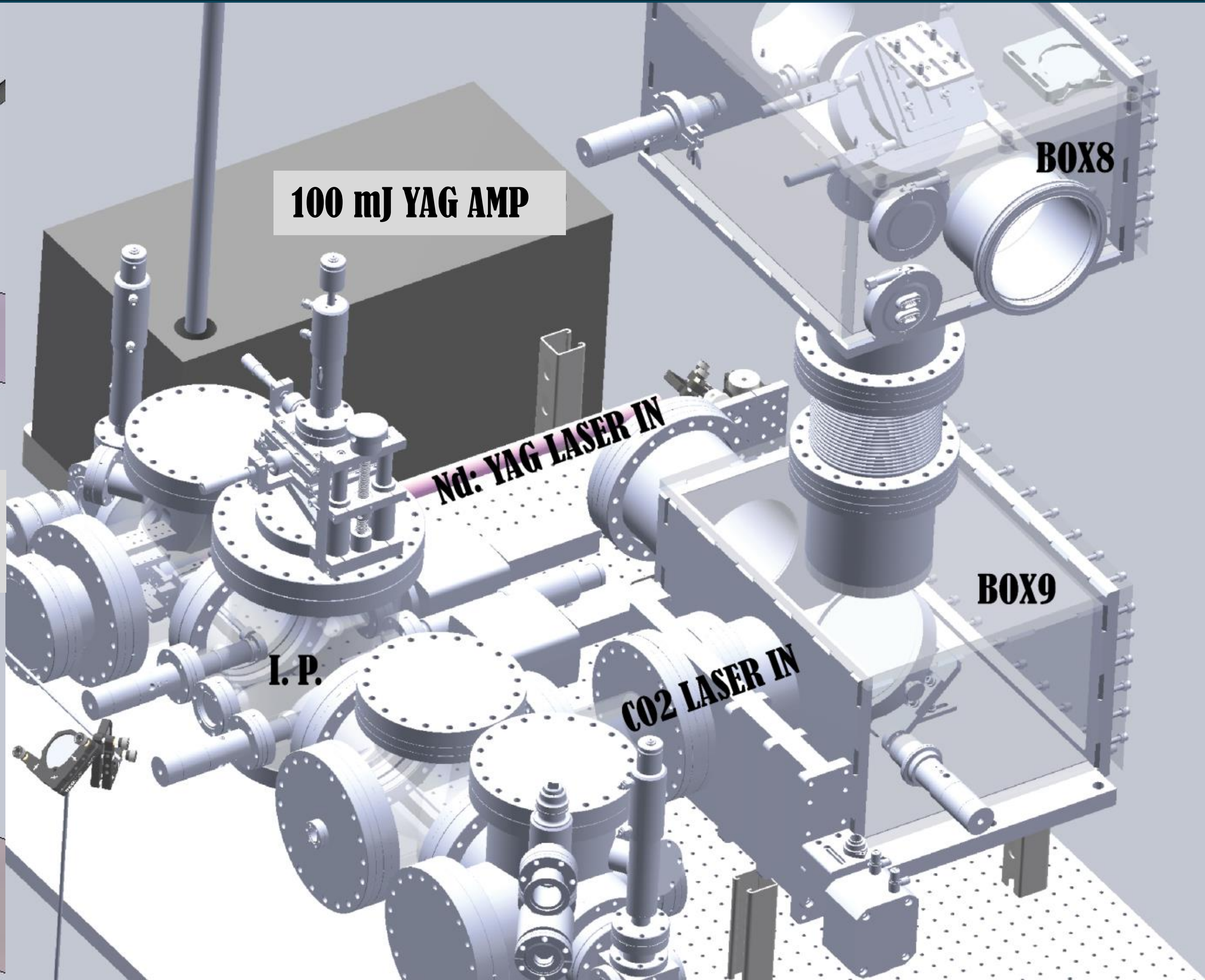




Experimental set up Bi-harmonic Compton I. P.

Input of CO_2 laser and YAG laser are opposite direction
& CO_2 laser's final focusing optic has D ½ inch hole on-axis





Setup for

Alignment

&

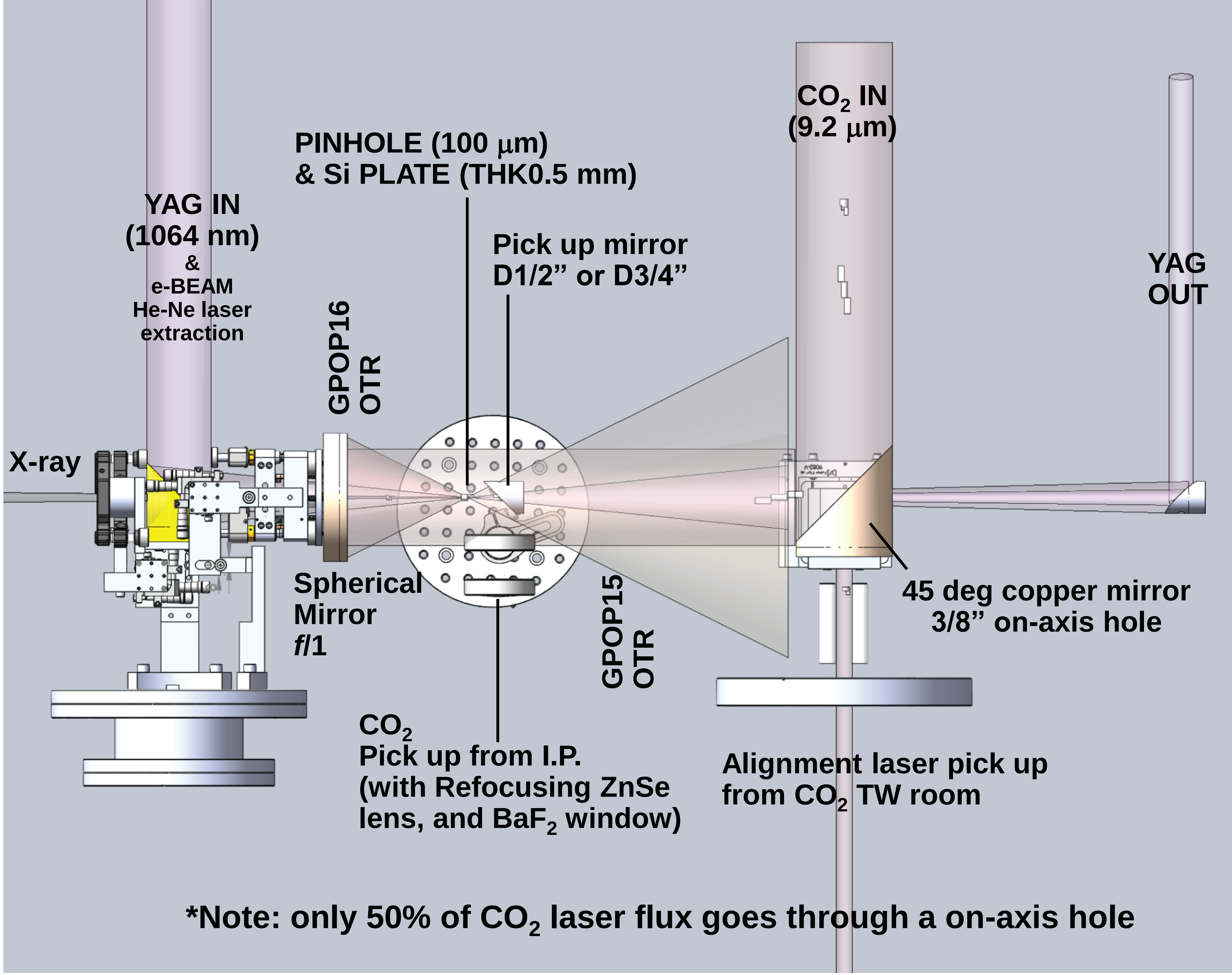
Timing

of CO_2 laser and e-beam

- GPOP15 & 16 → OTR
- CO_2 laser pick up from IP
- Timing with Si plate

Has been complete smoothly

↓

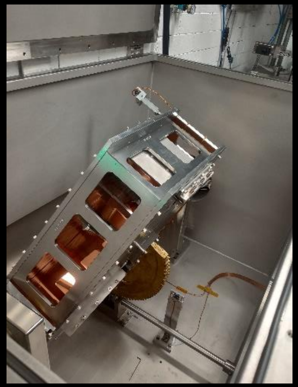


*Note: only 50% of CO_2 laser flux goes through a on-axis hole

Status so far

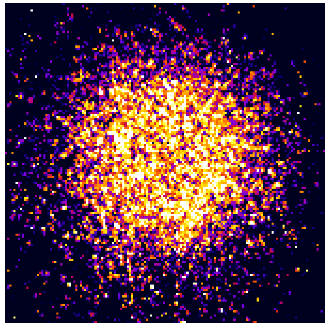
2^{nd} harmonic ICS X-ray by using Circularly polarized multi-TW laser → Verified

Owing to the polarization rotator
(2× 22.5 deg rotation + waveplate mirror)

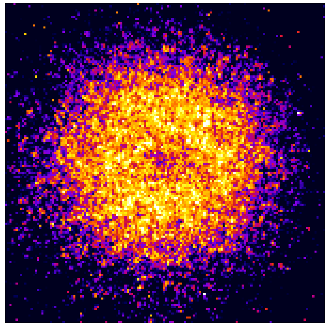


Effect on off axis radiation vs $a_{L,0}$ (Al 250μm high energy X-ray filtering)

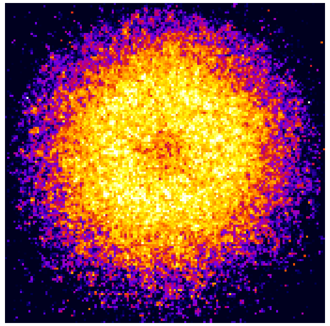
MCP Image



Low energy shot
$a_{L,0}$ ~ 0.6

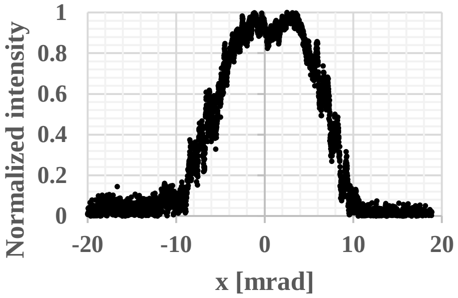


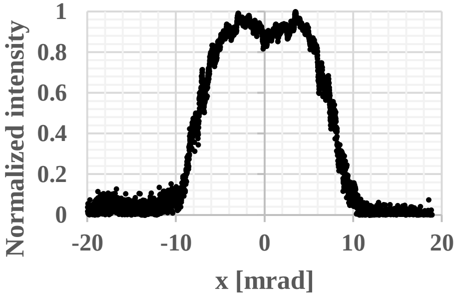
3 J shot
$a_{L,0}$ ~ 1.0

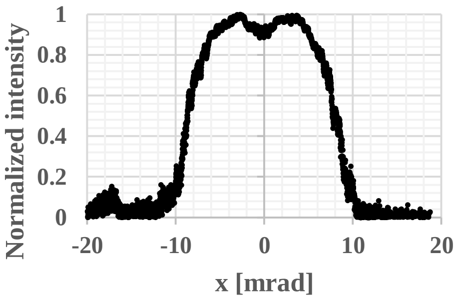


6 J shot
1 < $a_{L,0}$ < 1.5

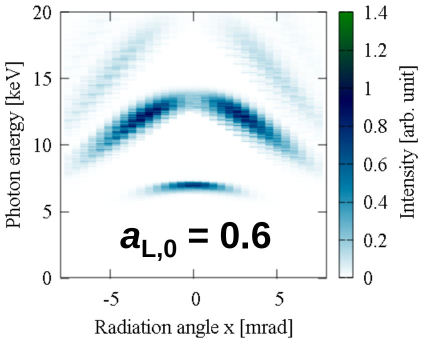
MCP On-axis profile

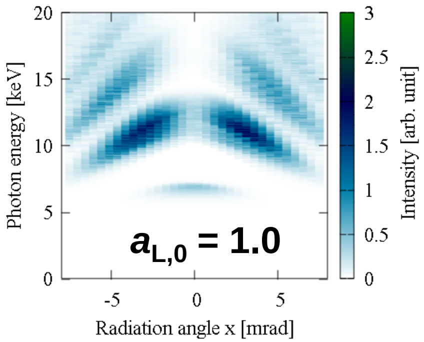


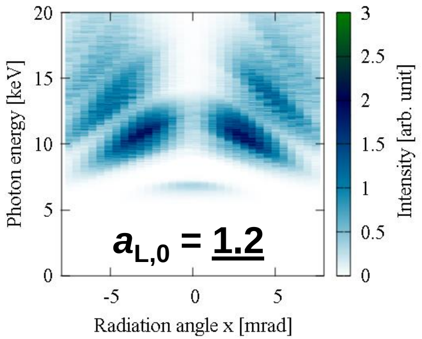




Numerical Estimate







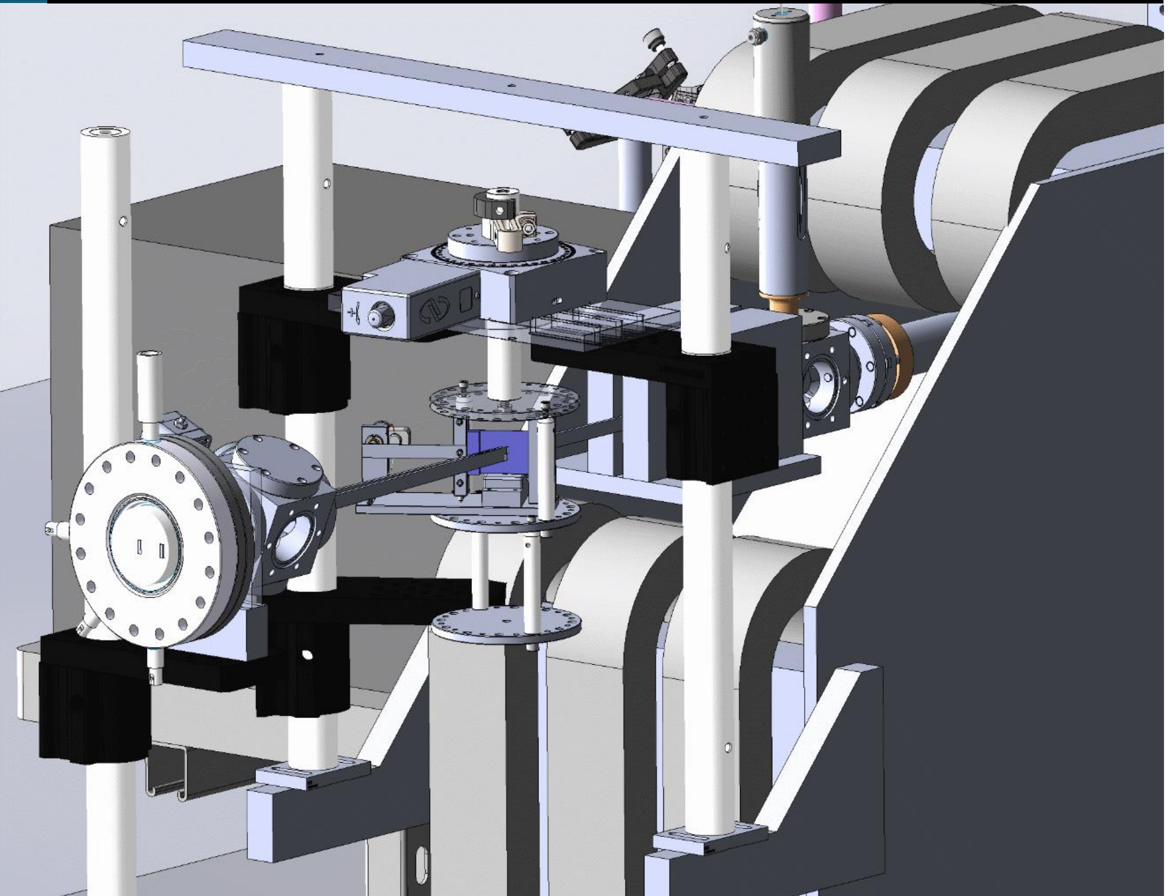
NEXT → Explore OAM case at $a_{L,0}$ ~ 2, & Measure DDS: TBD
→ Almost ready to observe Bi harmonic effect (Require stable 70 MeV e-beam) TBD

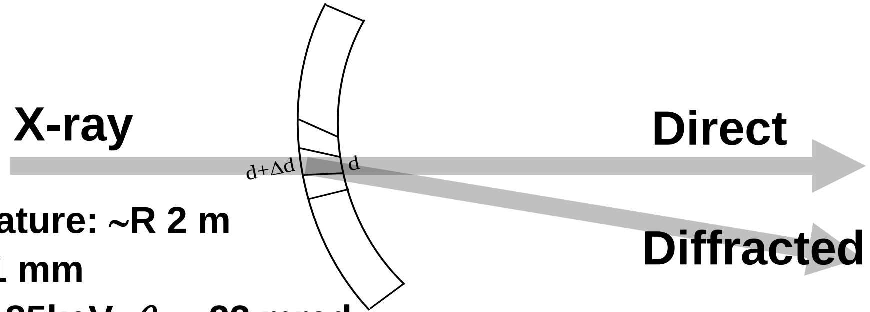
Pending Tasks:

Single shot Double Differential Spectrum (DDS) measurement of Sub-100 keV X-ray

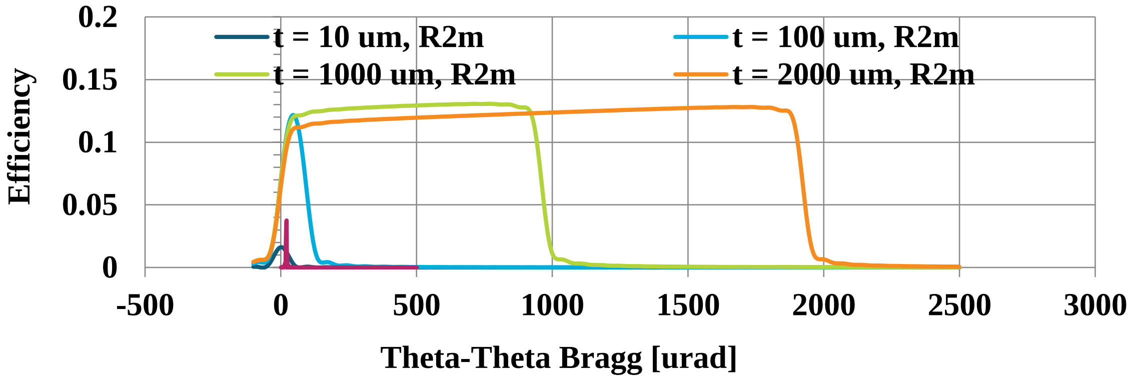
→ *Thick Laue Bent Crystal Efficiency > Bandwidth*

Mo/Si Multi layer crystal: 5 – 10 keV
Thick natural crystal: – 200 keV





- Radius of curvature: ~R 2 m
- Si Thickness: 1 mm
- Bragg angle at 85keV: $\theta_B \sim$ 22 mrad
- Crystal to MCP screen: 0.3 m
- Expected dispersion at screen: 10 - 20 mm:
- Band width: Δ *hv* ~ 10 keV
- <u>Reflectivity (Efficiency): ~10%</u>



Rocking curve for Bent crystal,…

<u>Status: Diffraction not observed yet for YAG-ICS.</u>

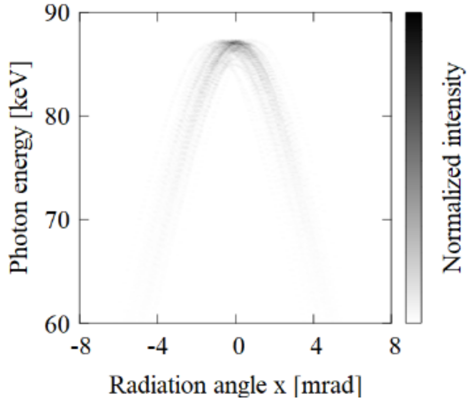
→ ***<u>2^{nd} - 3^{rd} Harmonic radiation at 20-30 keV range needs to be examined (CO$_2$ ICS with sufficient X-ray flux).</u>***

Ultimate future plan:

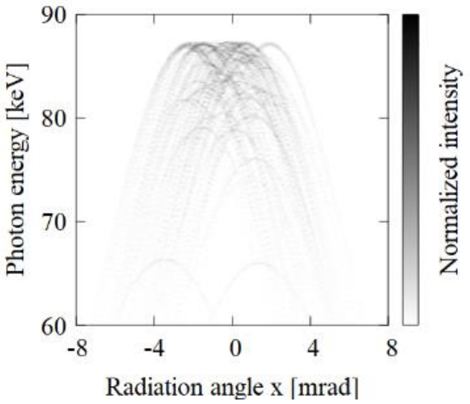
→ *ICS via 120 MeV e-beam & 10 J CO_2 laser for sub 100 keV X-ray*

Current Direction: Re-examine e-beam characteristics

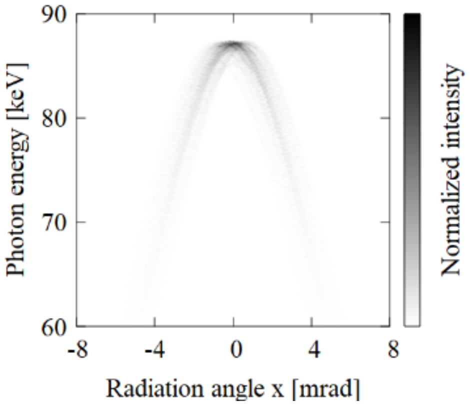
→ **E-beam’s Emittance effect on ICS spectrum (In addition: Higher energy & Stable e-beam)**



ε = 2 mm mrad, $\sigma_{x,\,y}$ = 30 μm,
Typical ATF parameter



ε = 2 mm mrad, $\sigma_{x,\,y}$ = 10 μm,
Tight focusing with PMQ



ε = 0.5 mm mrad, $\sigma_{x,\,y}$ = 10 μm
Example extreme case

Numerically calculated DDS of hard X-ray YAG ICS with various e-beam emittance and focusing size. Laser intensity a_0 = 0.1. e-beam energy 70 [MeV] (Linear Regime).

REF Scientific Reports v14, 18467, 2024

↔ Explore computational Feedback control {ML/AI} of emittance vs measured DDS for optimization, for the Compact RF Accelerators applications.

Initial variable: Gun solenoid magnet etc → T B D

Future plan summary, T B D

- Proceed with the main Bi-Harmonic ICS experiment

- Measurement of higher order harmonics in Circular polarized laser with $a_{L,0} = 2$

- R & D on the single shot hard X-ray spectrometer

- <u>+ Re-Examine e-beam characteristics: Emittance effect on the hard X-ray DDS for Computational feedback control { M.L. / A.I. }</u>

Questions?

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*
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	*0.3 – 0.5*
Bunch Length	ps	1-10	*Bunch charge & emittance vary with length*	*3 - 5*
Peak current	A	100	*Variable with bunch charge and length*	
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*	
Focused 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.*	*20 - 30*
Normalized Emittance	μm	1 (at 0.3 nC)	*Variable with bunch charge*	*1 - 2*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*	*1.5*
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 Regen. Amplifier	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	*9.2*
	Peak Power	GW	~3		
	Pulse Mode	---	Single		
	Pulse Length	ps	2		
	Pulse Energy	mJ	6		
	Repetition Rate	Hz	1.5	*3 Hz also available if needed*	
CO_2 CPA Beam	Wavelength	μm	9.2	*Wavelength determined by mixed isotope gain media*	
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	2-3	*Up to 5 TW operation will be available in a limited number of shots upon the user's request.*	*2 - 3*
	Pulse Mode	---	Single		
	Pulse Length	ps	2	*3-year development effort to achieve <500 fs at >10 TW and deliver to users is in progress.*	*2*
	Pulse Energy	J	~5	*10J will be available in a limited number of shots upon the user's request.*	*< 10*
	Strehl Ratio	---	~0.5	*Recommended conservative estimate subject to verification.*	
	Repetition Rate	Hz	0.01	*Burst operation at up to 0.05 Hz for a limited period is possible upon user's request. This regime should be avoided to extend the lifetime of the HV spark gaps in the amplifier's PFN*	*ANY*
	Polarization		Linear	*Adjustable linear polarization along with circular*	*Linear &*

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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 should be available summer 2025*	
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	>100	>1000		

Nd:YAG Laser System	Units	Typical Values	Comments	Requested Values
Wavelength	nm	1064	*Single pulse*	*1064*
Energy	mJ	100		*100 – 200*
Pulse Width	ps	14		*14*
Wavelength	nm	532	*Frequency doubled*	
Energy	mJ	0.5		
Pulse Width	ps	10		

Special Equipment Requirements and Hazards

No new adjustment.

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Experimental Time Request

CY2025 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)		
Laser* + Electron Beam		TBD (OR 2 WEEKS ?)

Total Time Request for the Experiment remaining duration

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Areas)		
Laser* + Electron Beam		

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