UCLA

Particle Beam Physics Lab

AE87: Hard X-ray ICS status report

Nonlinear ICS by a_0 ~ 1, CO_2 laser @ hv ~ 10 keV

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

2020 BNL ATF user meeting

Yusuke Sakai, Oliver Williams, *Zhong Zhong, James Rosenzweig
UCLA, *BNL NSLS

Funding source: DOE Accelerator Stewardship, Received

BROOKHAVEN NATIONAL LABORATORY

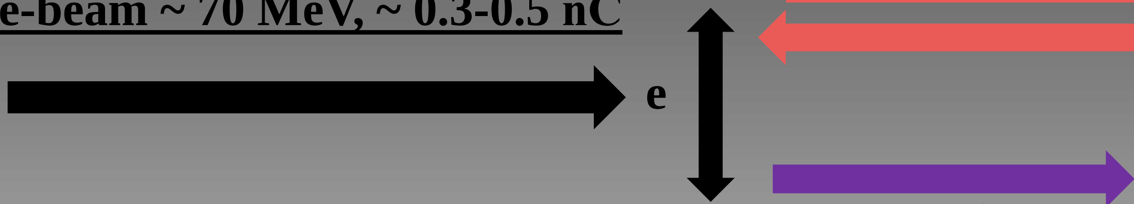
Monochromatic YAG ICS at *hv* ~ 100 keV range

- ✪ **Medical applications: Medicine as Photon activation**
- ✪ **Strong field physics: Bi-Harmonic Compton interaction with ATF's CO_2 laser**
- ✪ **Hard X-ray optics developments*: DDS measurement & Focusing or Collimation**

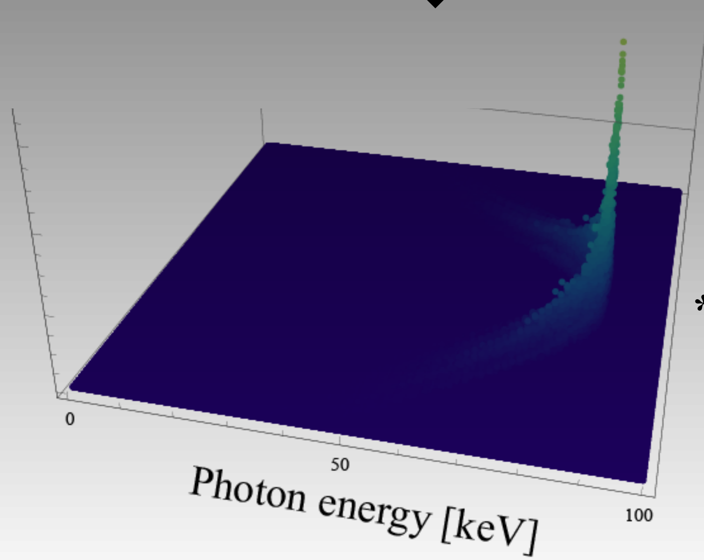
*** OAM investigation ↔ Measurement of Higher order harmonics (contain OAM) spectrum by circular polarized multi TW**

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

YAG laser: 1064 nm, ~ 30-200 mJ



~ 1 μJ/pulse*
@ *hv* ~ 87.5 keV



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

Initial examination of Photon Activation with Gold Nano Particle (AuNP) in ATF

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 :

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

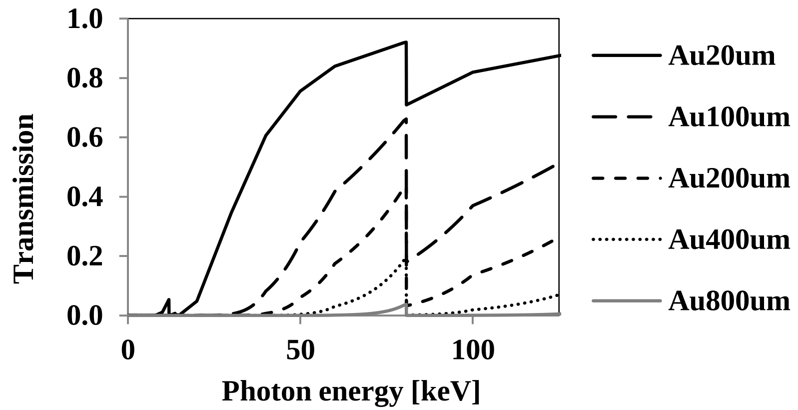
Spacing between particles:

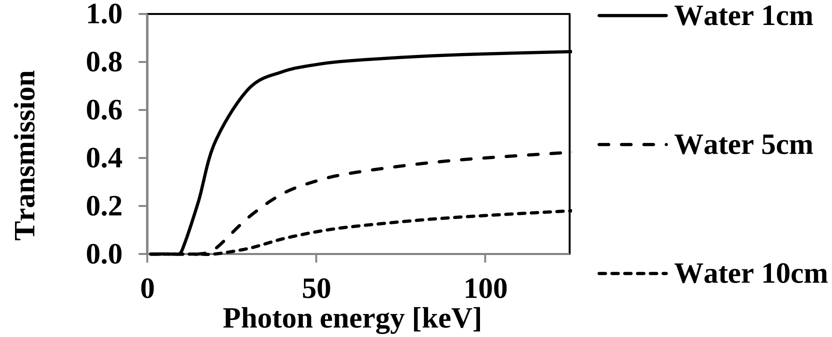
AuNP Dia 10 nm ↔ 1 μm, AuNP Dia 100 nm ↔ 10 μm

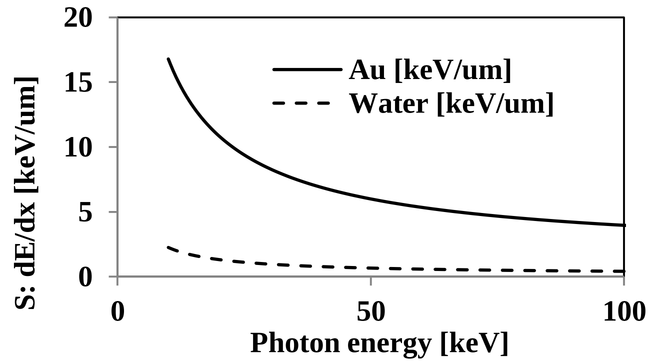
Details will be studied by monochromatic ICS.

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)







Initial examination of Photon Activation with Gold Nano Particle (AuNP) in ATF

AE87 requirement:
- - Flux to see response of target - -

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)

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

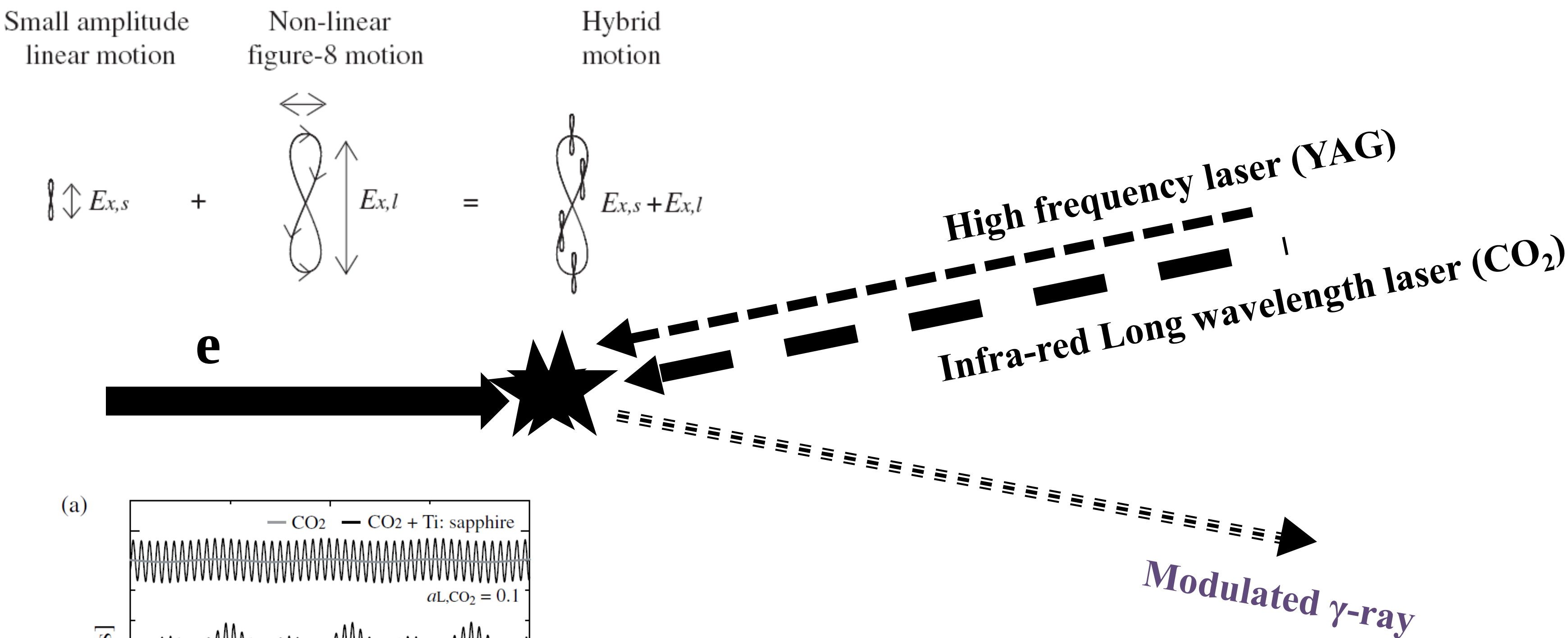
Total irradiation time required:
$1\ \mathrm{mJ} / 0.1\ \mu\mathrm{J} = 10.000$ shot

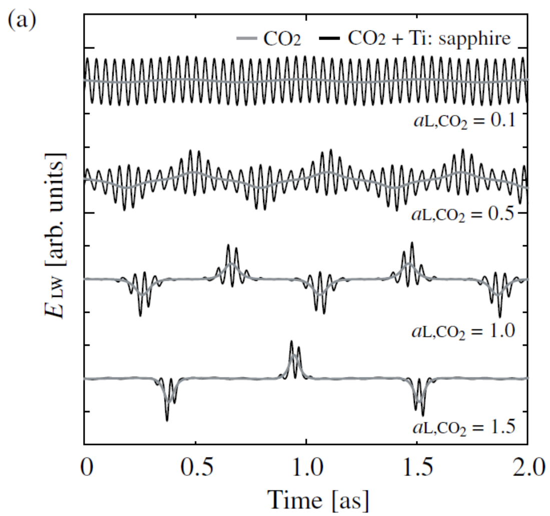
↔ <u>> 1.5 Hz × 60 min × 2 hour? run time</u>

↑↓

<u>(10^{6-7} photons) × (100 keV) × (1.6×10^{-19}) ~ 0.1 - 1 μJ / shot)</u>
↔ <u>10^{6-7} photons is also required for single shot Double Ddifferential Spectrum (DDS) measurment</u>

Bi-Harmonic nonlinear Compton



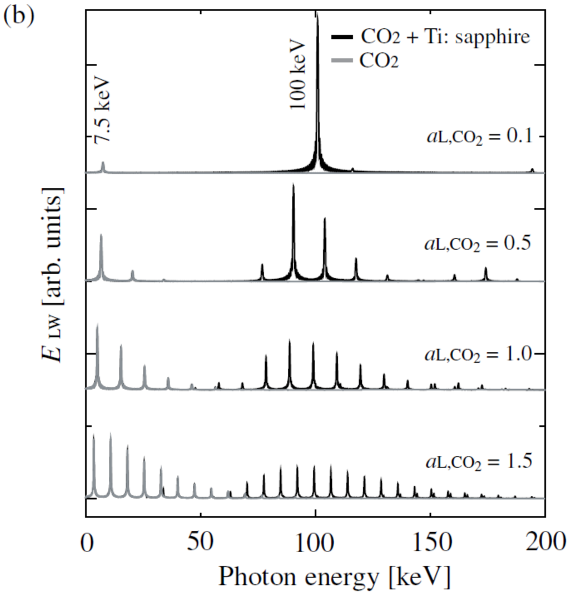


Numerically calculated Lienard-Wiechert potential $E_{LW,x}(t_{screen})$ on $(x, y, z) = (0, 0, 0)$

→ **Pulsed waveform modulation of Hard X-ray component at less than < 10^{-18} s time scale**

↓

Bi-Harmonic nonlinear Compton



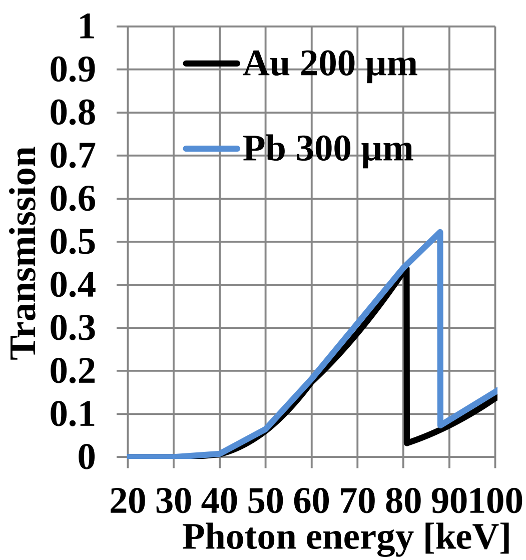
Bi-harmonic spectrum:

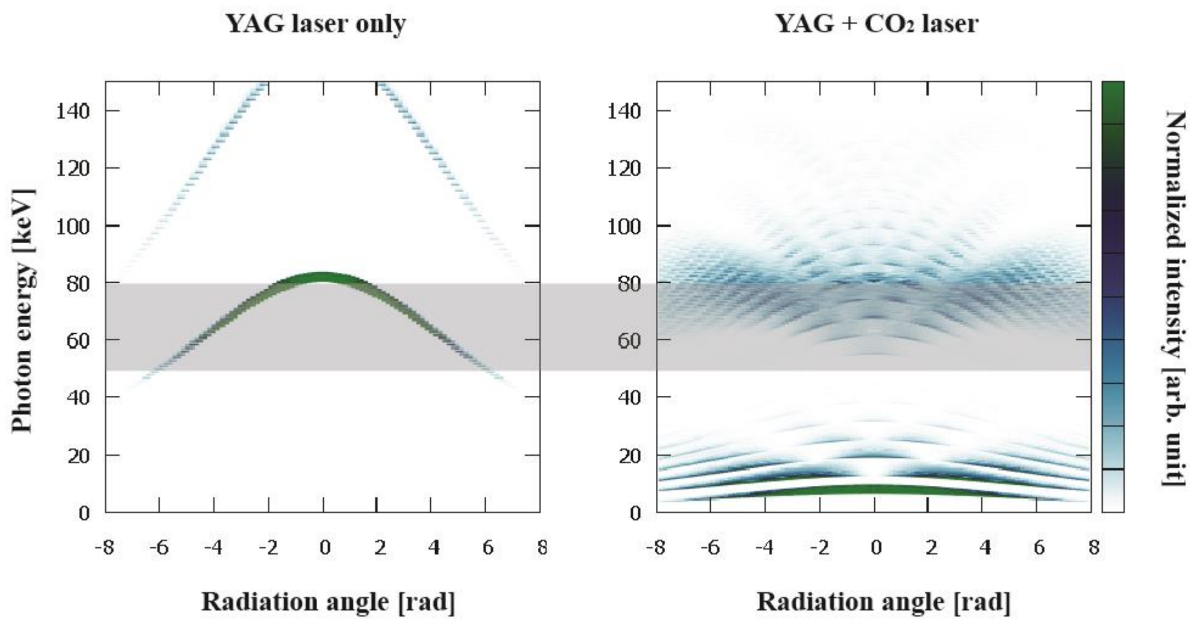
$$h\nu_{ICS} = 4\gamma^2 h(\nu_{L,YAG} \pm n\nu_{L,CO2})/(1 + a_0^2/2)$$

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

K-edge of Au (81 keV) and Pb (88 keV) k-edge,

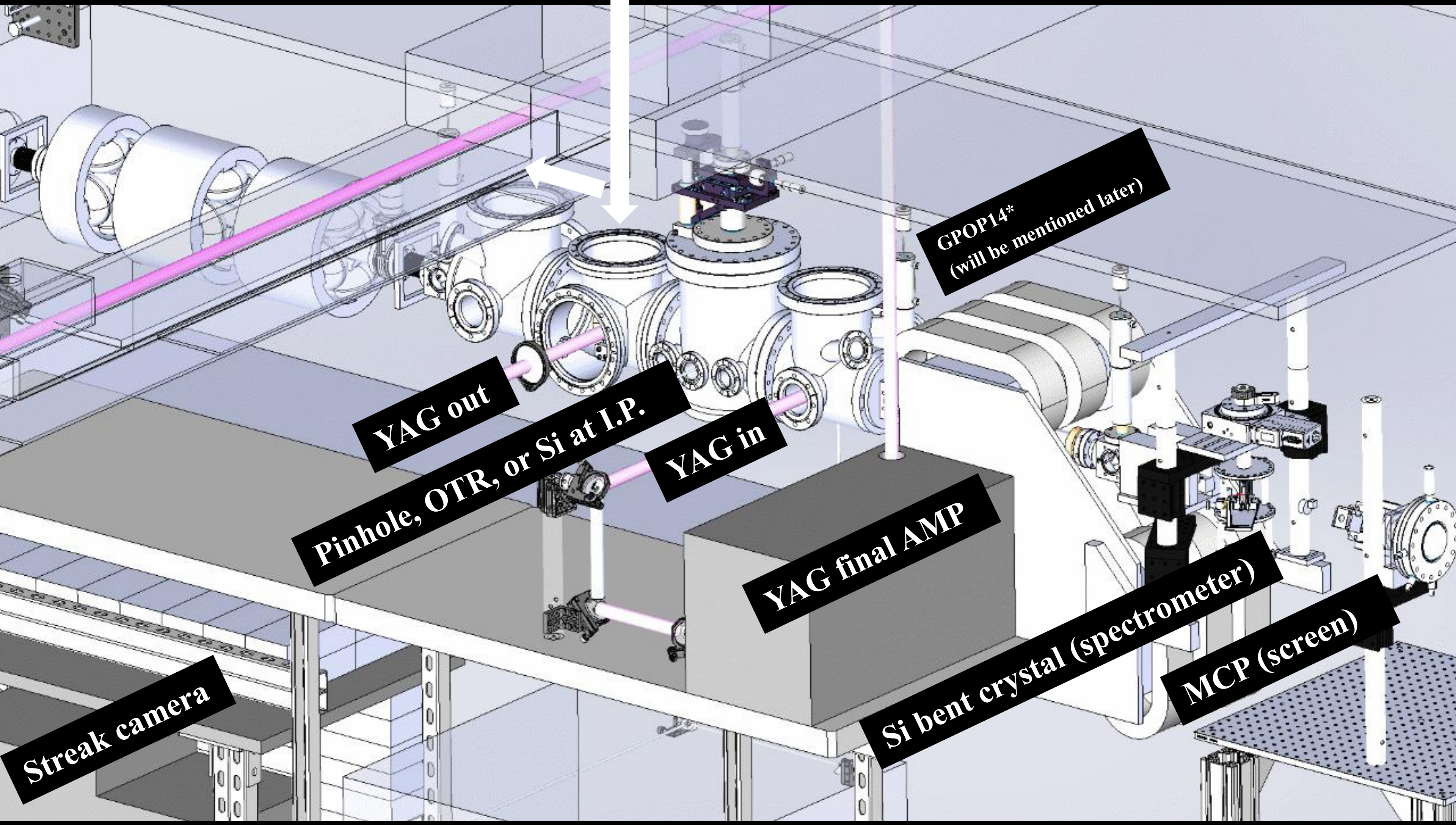
Natural bent crystal spectrometer ↓





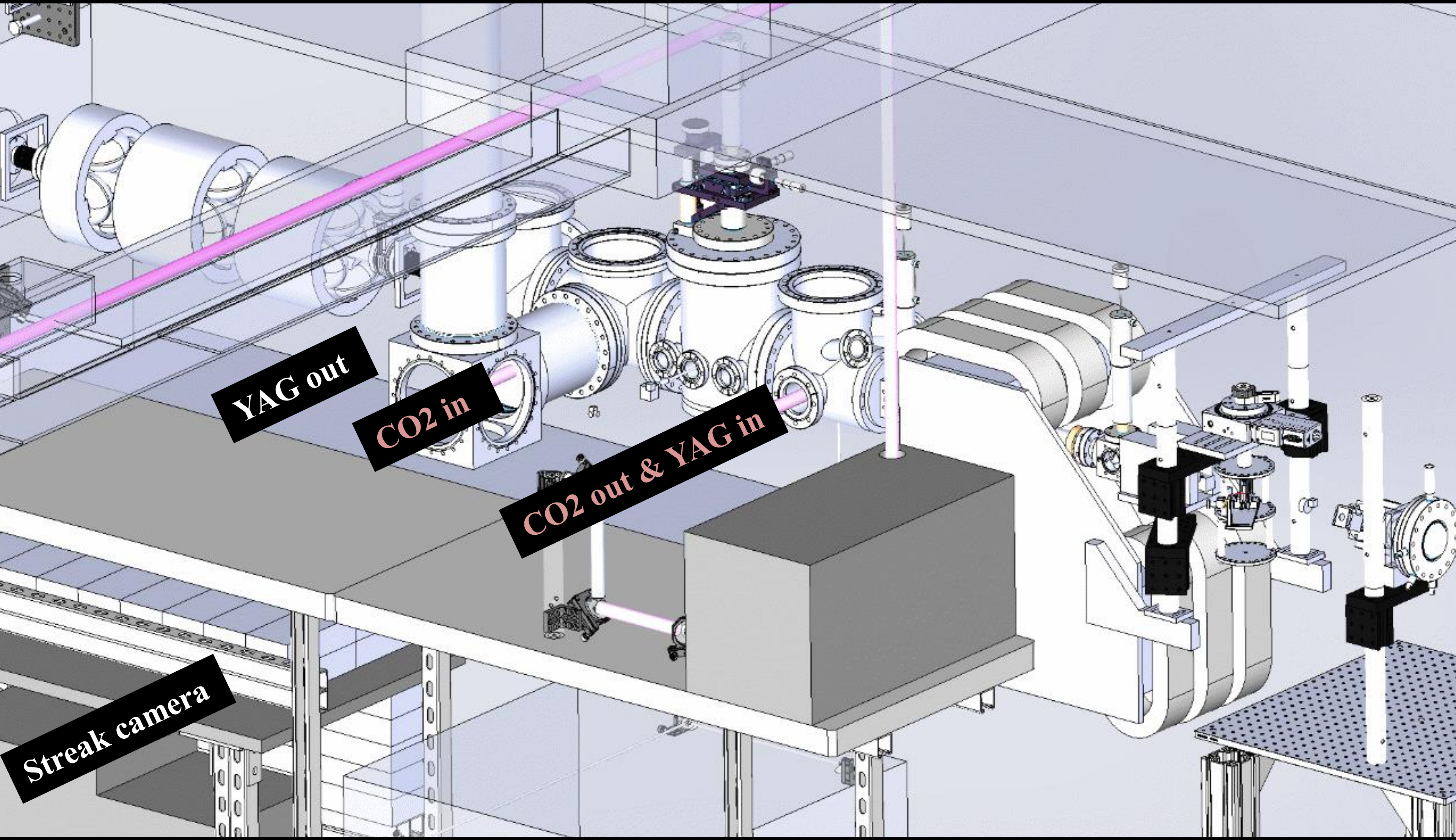
YAG ICS Set-up in BL1 (12/07/2020)

Modification: Fixed PMQ removed temporarily, Compton chamber extended



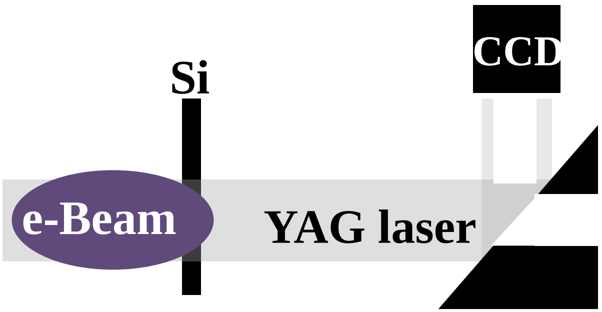
YAG ICS Set-up in BL1 (next year.)

Modification is planned: Vacuum transport of CO_2 laser for Bi-Harmonic Compton interaction.



For bi-harmonic Compton (2022yr -)

Synchronization by Si semiconductor plasma switch established (Plasma deflector, not by attenuation of laser)



Critical density of YAG laser, 1 μm:

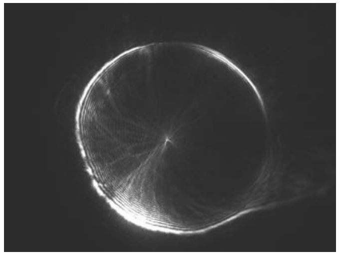
$$n_{e,c} \sim \underline{1\times10^{21}[\mathrm{cm}^{-3}]} \;\Leftrightarrow\; \omega_p = \sqrt{n_e e^2/m\epsilon_0}$$

Electron-Hole Pairs number per incident particle:

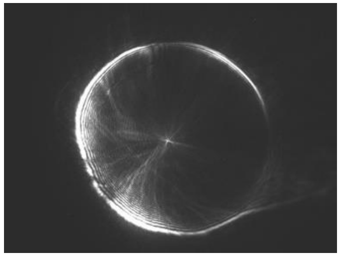
$$\sim 70\ [\mathrm{MeV}]\ /\ \varepsilon_{\mathrm{Si,ebeam}}{*}[\mathrm{eV}] \sim 1\times10^{7}$$

$n_{e,\,ebeam}$ (q ~ 0.5 nC, σ_r ~ 30 -100 μm) ~ $1\times10^{14\text{-}15}$ [cm^{-3}]

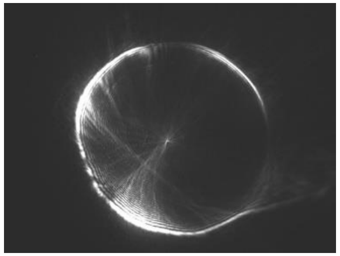
Electron number density created in Si plate $n_{e,Si,p}$ ~ $1\times10^{20\text{-}22}$ [cm^{-3}]



-3ps



0



+3ps

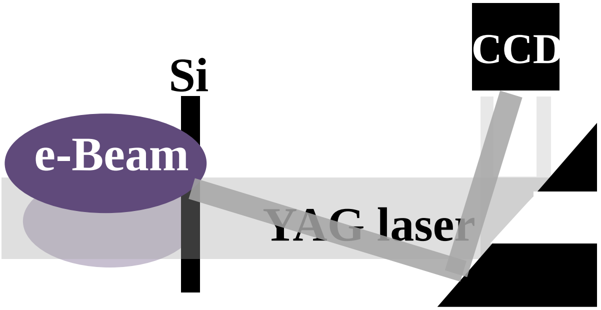
∗ Note: $\varepsilon_{Si,ebeam}$: ~ Pair-creation energies: $\varepsilon_{Si,ebeam} = (14/5)\,E_G + r(\hbar\omega_R)$] ~ 4 eV

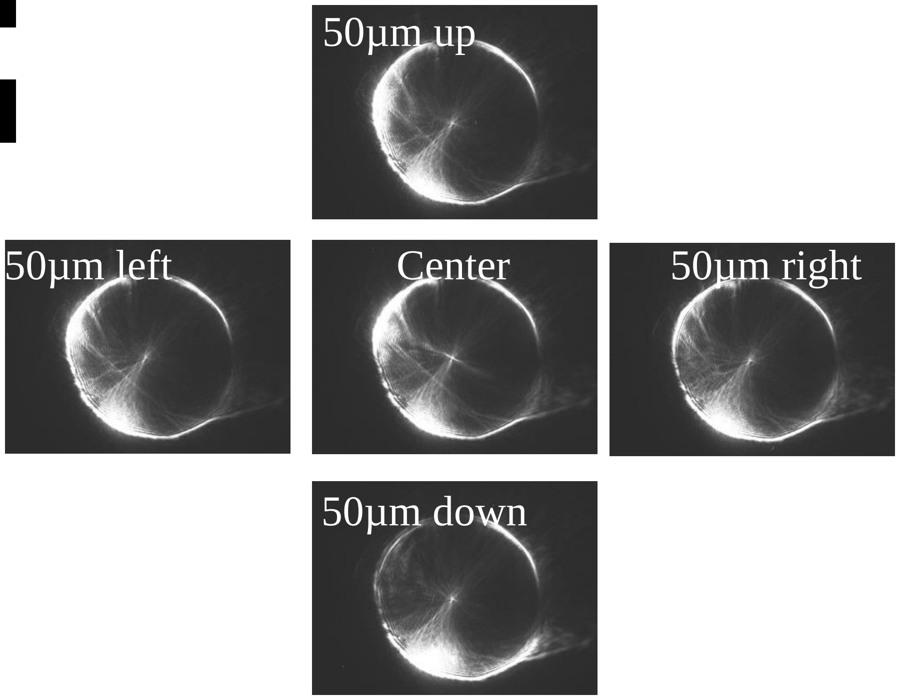
E_G: band gap Si = 1.14 eV, Ge= 0.67eV, $\hbar\omega_R$: phonon losses $0.5 \le r(\hbar\omega_R) \le 1.0$ eV

C. A. Klein, Journal of Applied Physics 39, 2029 (1968)

Synchronization by Si semiconductor plasma switch established (Plasma deflector, not by attenuation of laser)

Examination: Deflection of YAG laser by e-beam offset, density gradient



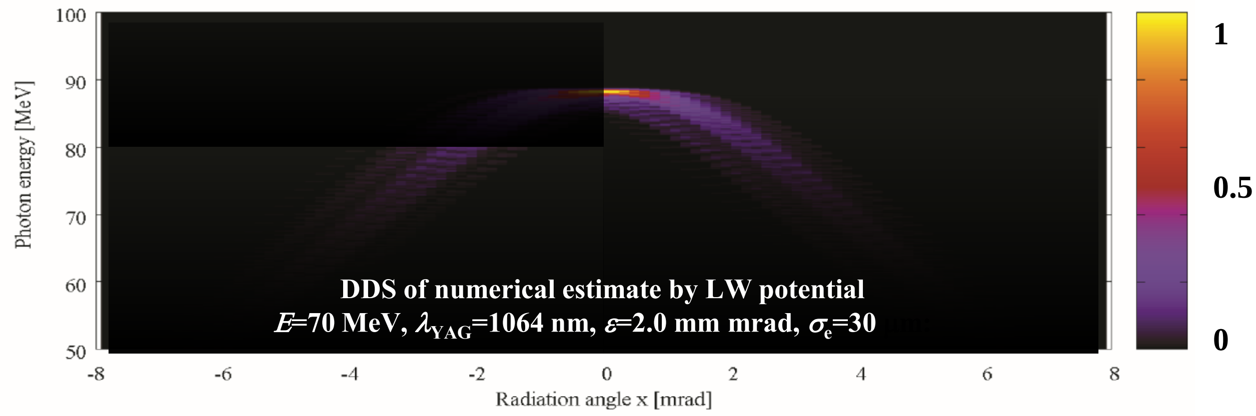


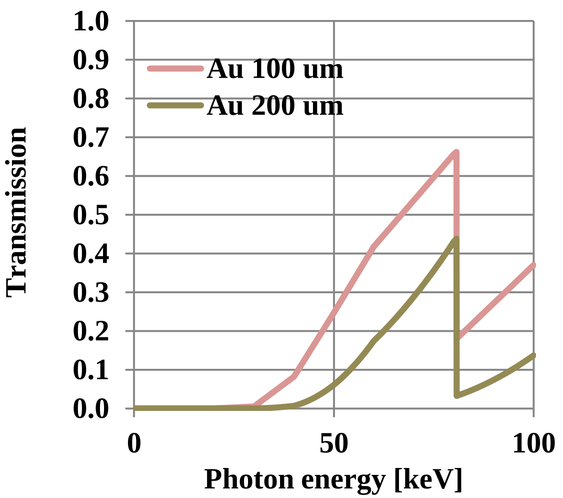
Preparation for publication (RSI ?)

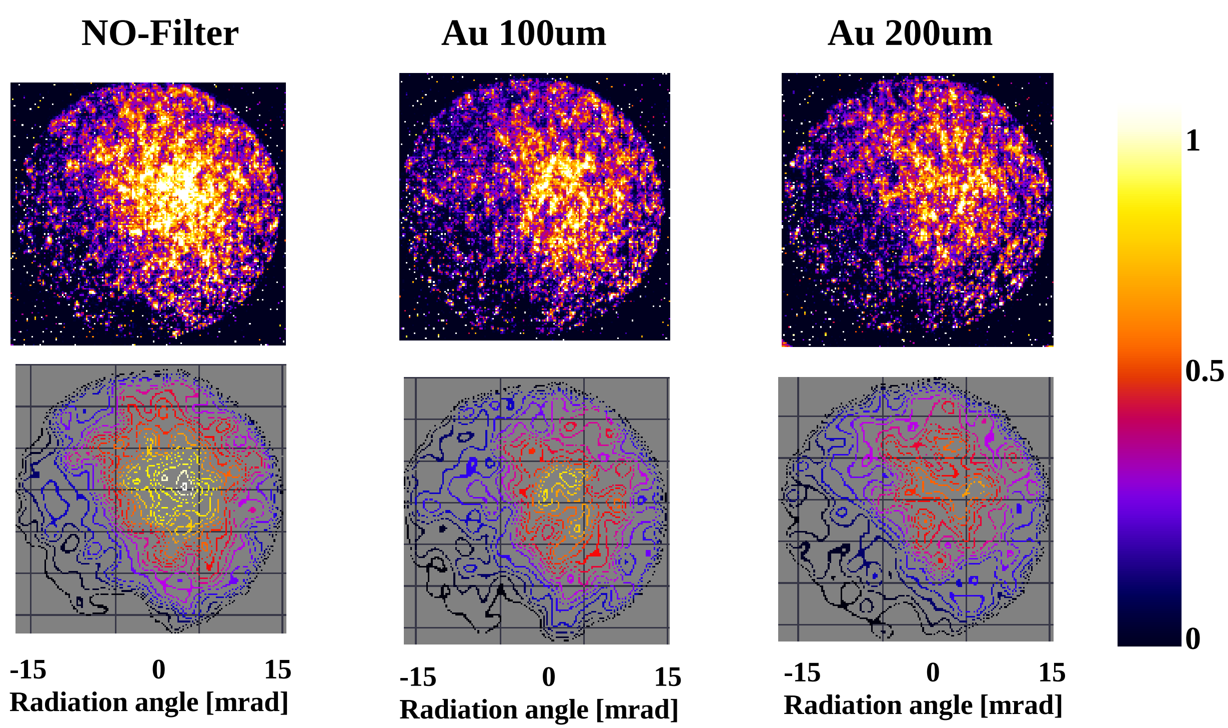
Observed Hard X-ray in a single shot (March-2020yr)

87.5 keV X-ray

by E_e = 70MeV
YAG laser energy ~ 30 mJ





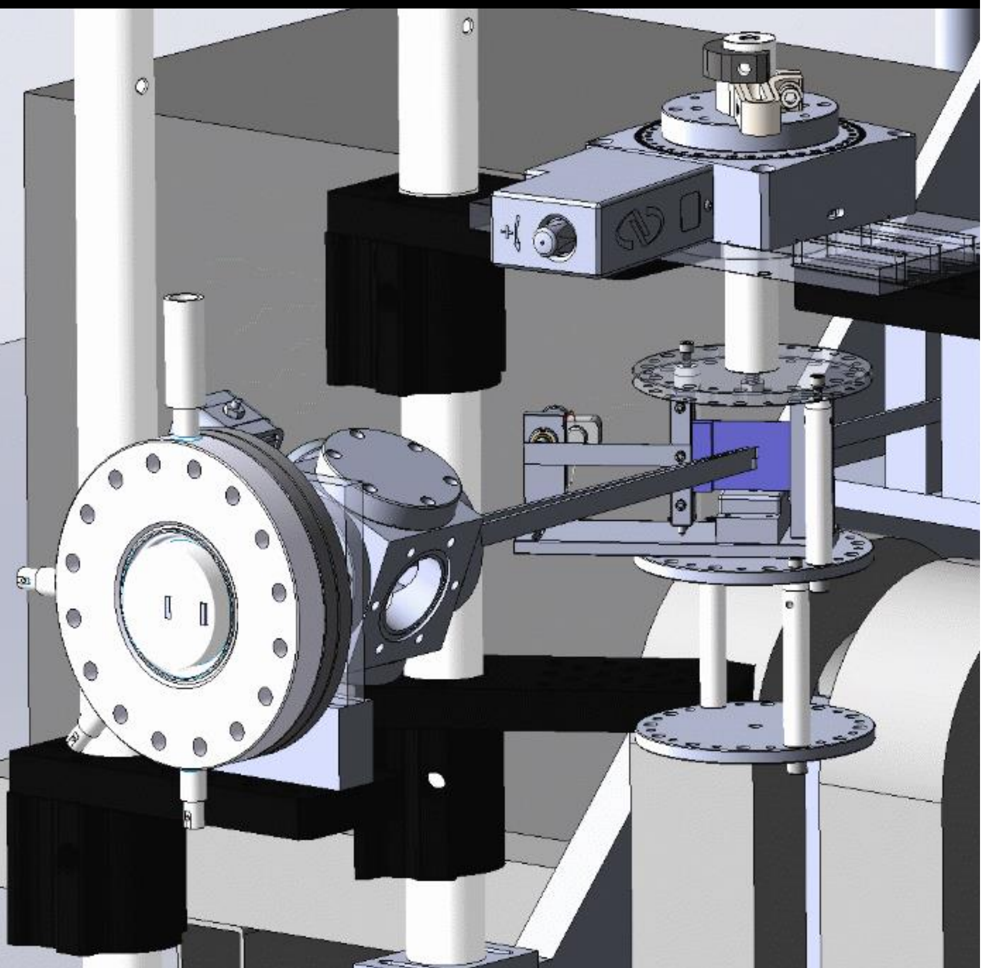


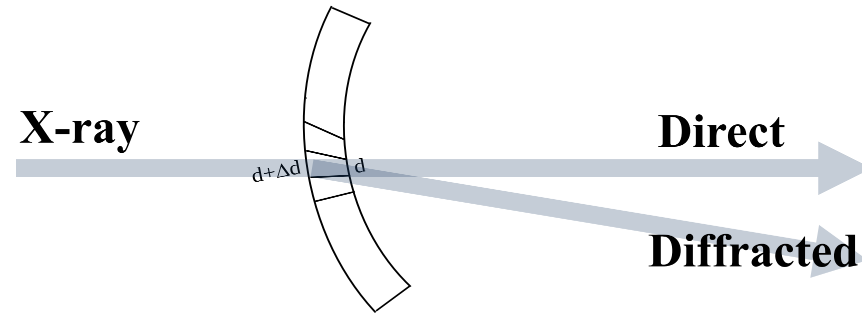
✷CdTe Diode estimate: 10^4-10^5 photons / shot (Need to be increased to 10^5-10^7)

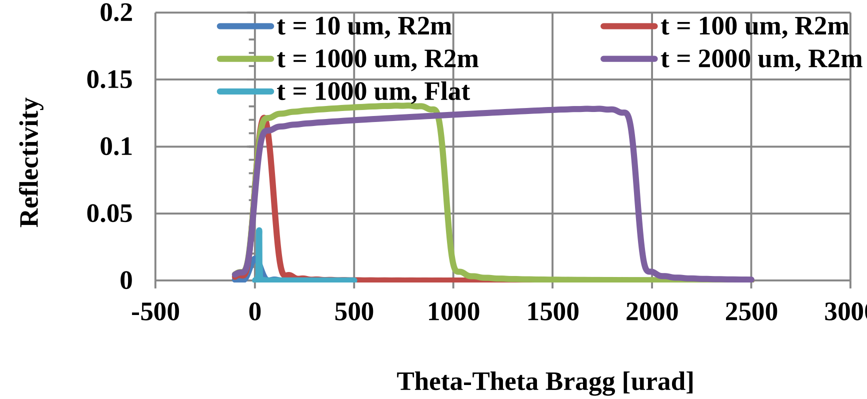
Next step:

Single shot DDS measurement at 87.5 keV

→ Thick Laue Bent Crystal Efficiency > Bandwidth







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

- **Radius of curvature R: A few m**
- **Thickness: 1mm**
- **Bragg angle at 85keV: A few 10s mrad (A few deg)**
- **Dispersion at screen: A several mm:**
- **Band width: ~50%**
- **Reflectivity: ~20%**

Stats: Photon flux needs to be increased (S/N ratio ~10% now) → Increase YAG output up to 150-200mJ by pre-amp in FEL room (Marcus is preparing now.) + Potential PMQ re-installation.

→ 10^6-10^7 X-ray photons / shot

2020-2021 plan

2021 A:

Single shot DDS measurement by Bent crystal At ~100 keV range

2021 B:

Initial examination of photon activation by target organic materials:

→ Distribution of absorption vs GDP density and size

→ Possibility of measuring emission spectrum

2022-202?:

Setup for advanced nonlinear Compton experiment by multi-TW laser

→ Bi-Harmonic Compton ($a_0 \sim 2$)

→ Spectrum measurement of 2^{nd} & 3^{rd} order harmonics (contains OAM) (Circular $a_0 \sim 1$)

→ Spectrum measurement of higher order harmonics, Wiggler mode (Linear $a_0 \sim 10$)

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*	**68 - 75 MeV**
Bunch Charge	nC	0.1-2.0	*Bunch length & emittance vary with charge*	**0.3-0.5 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 (s)	mm	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	mm	1 (at 0.3 nC)	*Variable with bunch charge*	***1***
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.*	***TBD***

CO_2 Laser Requirements *(For Bi-Harmonic ICS)*

Configuration	Parameter	Units	Typical Values	Comments	Requested Values
CO_2 Regenerative Amplifier Beam	Wavelength	mm	9.2	*Wavelength determined by mixed isotope gain media*	
	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	mm	9.2	*Wavelength determined by mixed isotope gain media*	***ANY***
Note that delivery of full power pulses to the Experimental Hall is presently limited to Beamline #1 only.	Peak Power	TW	2	*~5 TW operation is planned for FY21 (requires further in-vacuum transport upgrade). A 3-year development effort to achieve >10 TW and deliver to users is in progress.*	***NORMALIZED VECTOR POTENTIAL a0 >= 1***
	Pulse Mode	---	Single		***SINGLE***
	Pulse Length	ps	2		***ANY***
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available in FY20*	***5***
	M^2	---	~2		***ANY***
	Repetition Rate	Hz	0.05		***100 SHOTS/DAY***
	Polarization		Linear	*Adjustable linear polarization along with circular polarization will become available in FY20*	***LINEAR FIRST (THEN CIRCULAR ♦)***

♦ ***NOTE: Circular polarization is required for reconsideration of OAM study by nonlinear Compton process.***

Near IR Experimental Laser Requirements

Nd:YAG Laser System	Units	Typical Values	2021 Modifications	Comments	Requested Values
Wavelength	nm	1064	1064	*Single pulse*	***1064***
Energy	mJ	5	100		***30 mJ AT PRE-AMP ♦***
Pulse Width	ps	14	<20		***14***
Wavelength	nm	532		*Frequency doubled*	
Energy	mJ	0.5			
Pulse Width	ps	10			

♦ NOTE: ~30 mJ AT PRE-AMP is required,
for final AMP in order to generate < 200 mJ pulse located at ICS optical table

Special Equipment Requirements and Hazards

Any special equipment:

♦ CO_2 Laser: Circular polarization ($a_{L,0}$ ~ 2) for OAM study in year 2022-23 (No experimental plan this year.).
♦ Nd: YAG Laser: Pre-amp (> 10 mJ) in order to maximize designed out put power (< = 200 mJ) of final-amp.

Hazards & Special Installation Requirements:

♦ All items have been included in updated ESR a few months ago.

Large installation (chamber, insertion device, etc.):

♦ Now e-beam has been deflected by the magnet field around the BL1 final dipole at GPOP14 (p.7) location generating Bremsstrahlung radiation. A magnet shield is required which was installed years ago. Which necessitates shift of BL1 dipole location by 1 or 2 inch. However, the BL1 dipole magnet strength may be seeing saturation at 70 MeV.
♦ CO_2 laser's vacuum transport needs to be connected to the Compton chamber as shown in p.8 for 2022-23yr's study on the bi-harmonic Compton interaction.

Introducing new magnetic elements:

♦ Reinstallation of existing ATF's fixed medium strength PMQ with new adjustable mount in front of Compton I.P. (now it's removed temporarily with the chamber upgrade for e-beam alignment process & Bi-harmonic ICS.)

Experimental Time Request

CY2021 Time Request

Capability	Setup Hours	Running Hours
Electron Beam Only		
Laser* Only (in Laser Room & EH)		
Laser(s)* + Electron Beam		2WEEKS X 3 = 6 WEEKS (Total time requested including setups)

Time Estimate for Remaining Years of Experiment (including CY2021)

Capability	Setup Hours	Running Hours
Electron Beam Only	0	0
Laser* Only	1 WEEK (Setup needs running)	1 WEEK (Running includes setup) -- YAG amp test --
Laser(s)* + Electron Beam	TBD	TBD

- Laser = ONLY Near-IR this year is expected.
- Deign and Installation of CO_2 laser’s vacuum transport may be included flexibly.
- We also need pre-approval from our University for scheduling a N.Y. visit a month before.
- Thank you.