Development of Inverse Compton Scattering

→ For ~100 keV Hard X-ray ICS by TW CO_2 laser

BNL ATF Science Planning Workshop, 2024

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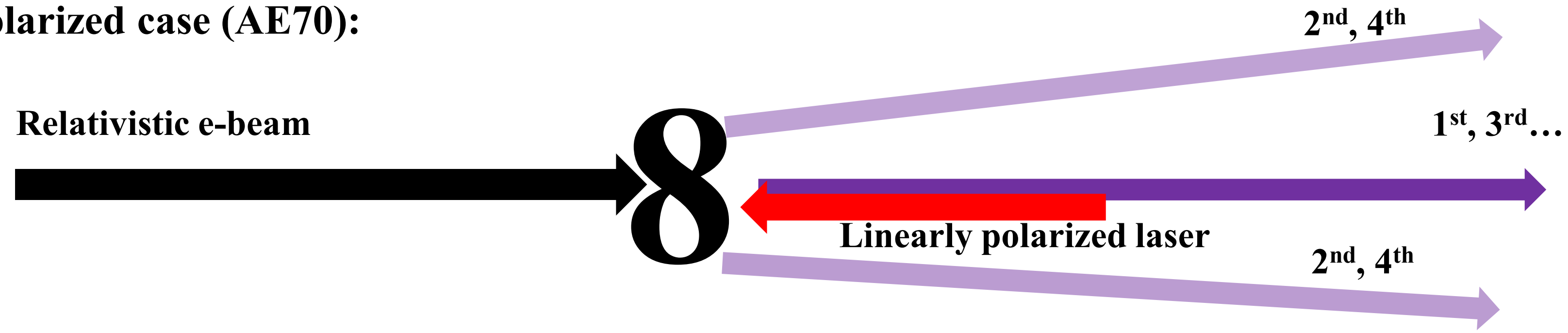
AE70: Basic study on the nonlinear Compton & AE87: Hard X-ray ICS by Nd: YAG laser
→ Goal of experiment AE131 Harmonic Nonlinear Inverse Compton Scattering

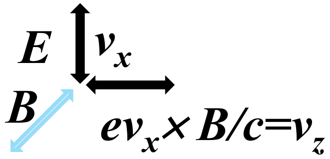
- ✪ Strong field physics: Bi-harmonic Compton interaction
- ✪ X-ray OAM investigation: Higher order harmonics by circular polarized CO_2 laser
- ✪ Hard X-ray optics developments: DDS measurement & Focusing, Collimation

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

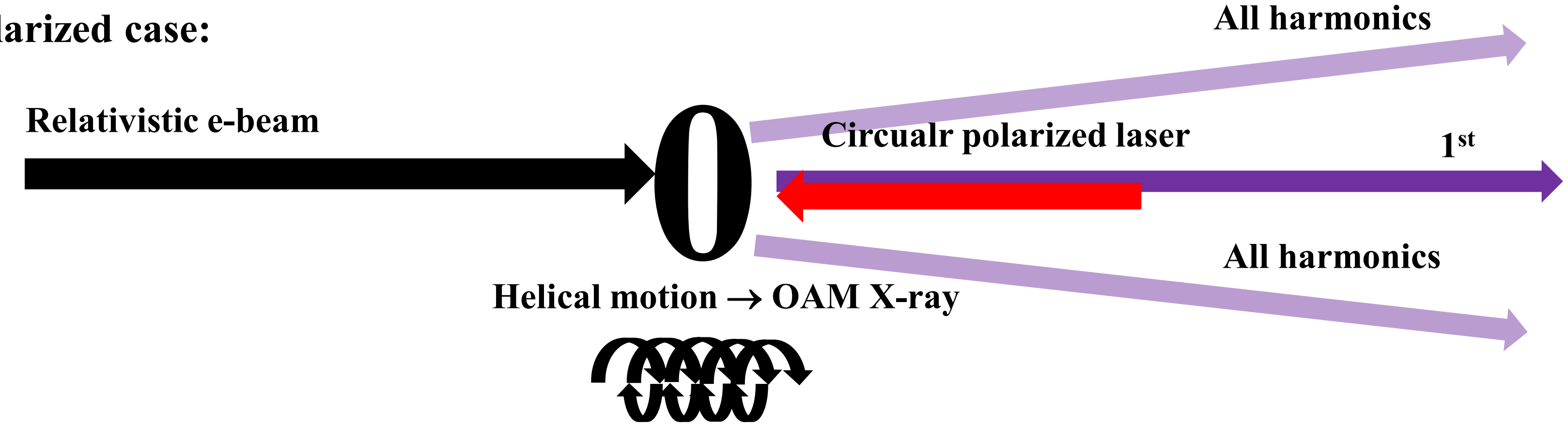
Linearly polarized case (AE70):

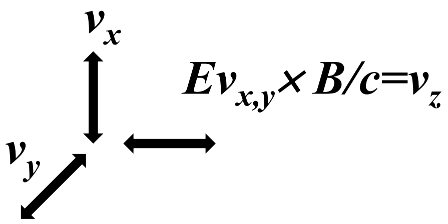


$$* \, a_{L,0} \equiv \frac{\sqrt{-e^2 A_\mu A^\mu}}{m_e c^2} = \frac{e E_{L,0}(\lambda_L/2\pi)}{m_e c^2}$$

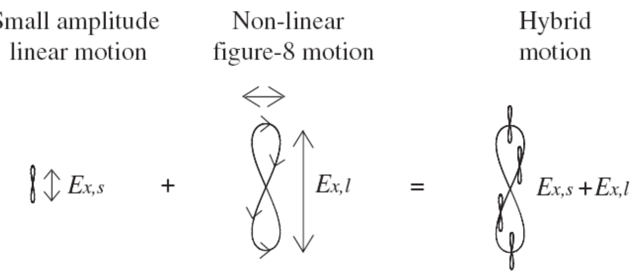


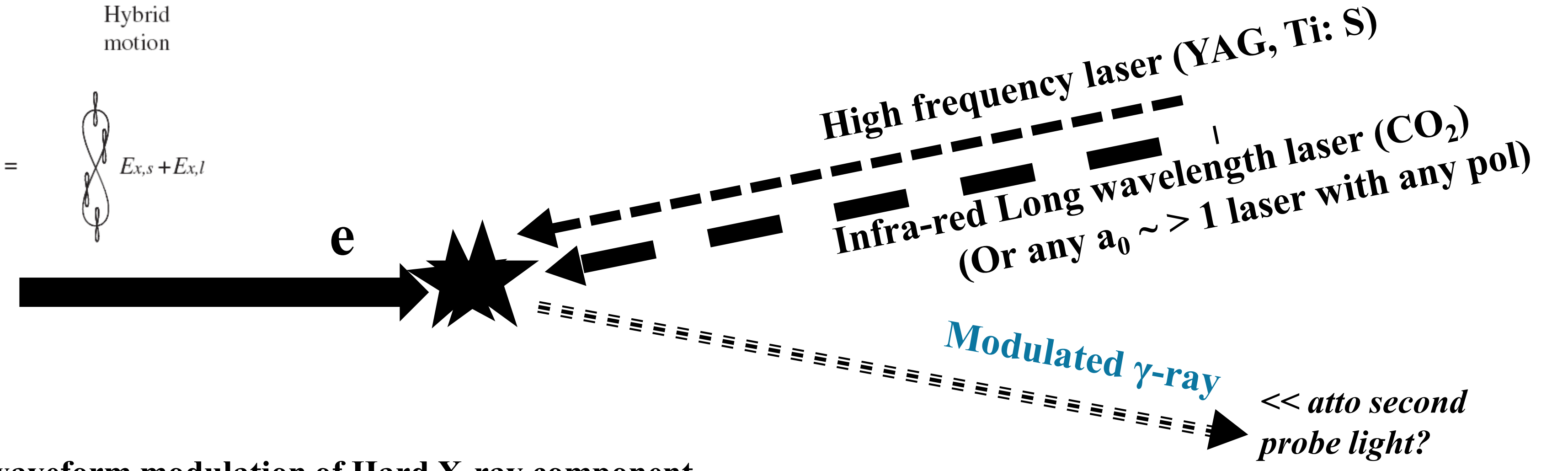
Circular polarized case:





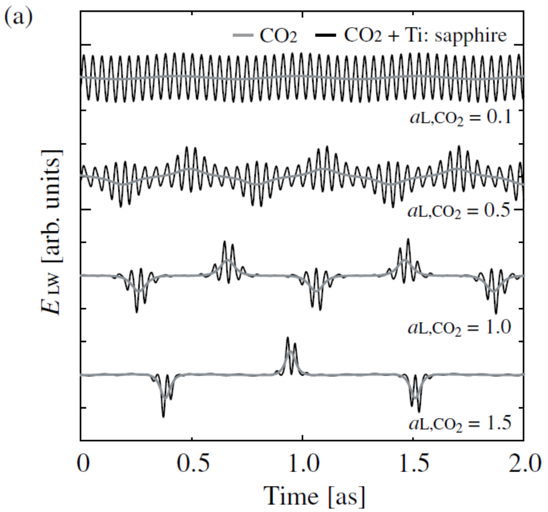
Bi-harmonic nonlinear Compton interaction (AE131)



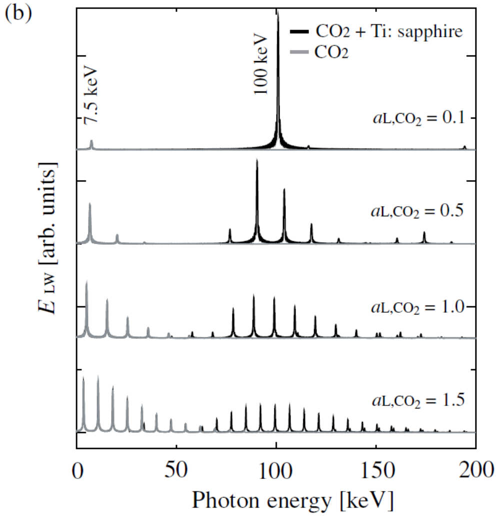


Pulsed waveform modulation of Hard X-ray component at less than < 10^{-18} s time scale (Cycle of 10 keV X-ray)

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

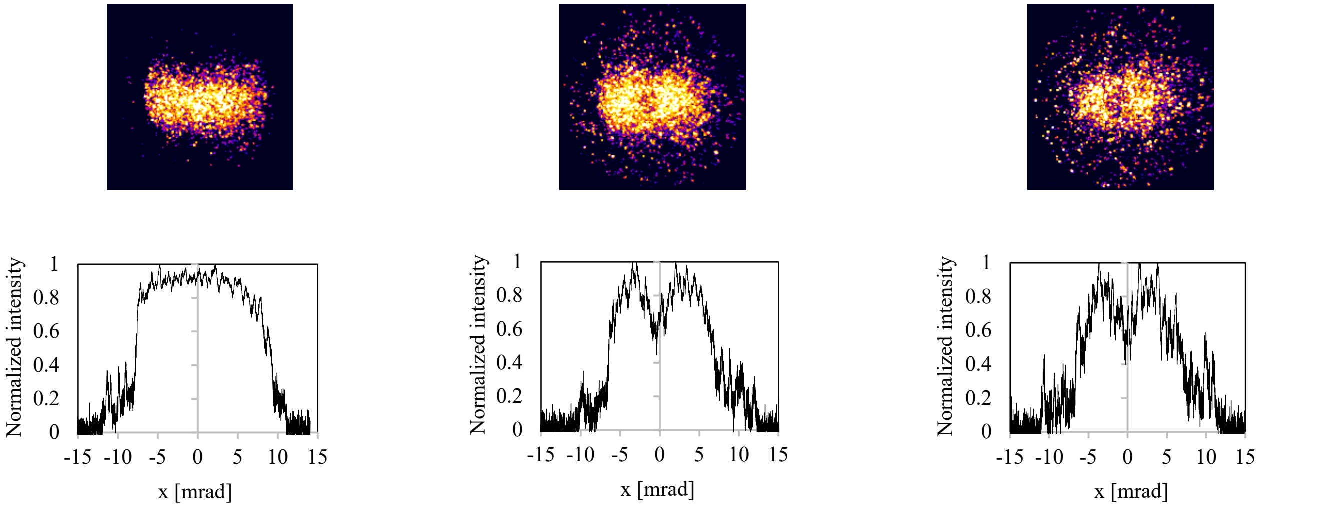


Fourier Transform →



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

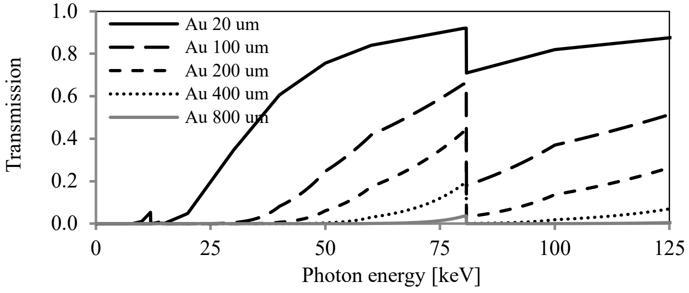
AE87:
Hard X-ray inverse Compton scattering at photon energy of 87.5 keV In a single shot (~10^6 photon yield / pulse) Nd: YAG laser 1064 nm & 70 MeV e-beam



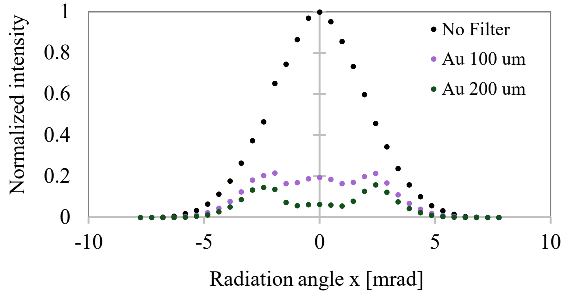
a) No-Filter filter

b) With 100 μm Au filter

c) With 200 μm Au

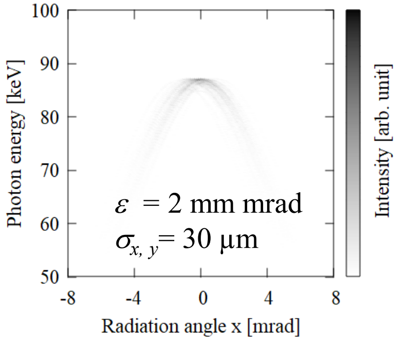


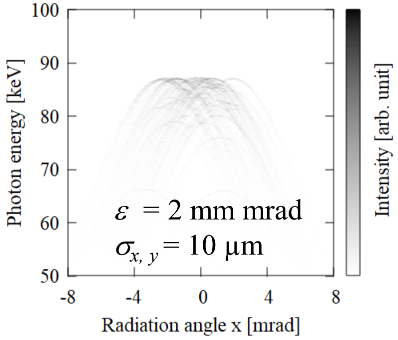
Au filter transmission

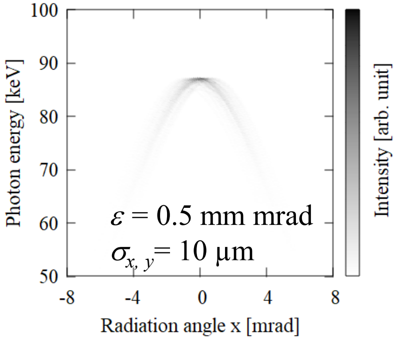


Numerical calculation

Numerically calculated DDS with various e-beam size ($a_{L,0}$ = 0.1)







NOTE:

Sub 100 keV ICS X-ray yield by Nd: YAG laser <u>~10^6 photons/shot</u>

↓

Near the limit due to beam ↔parameters

↓

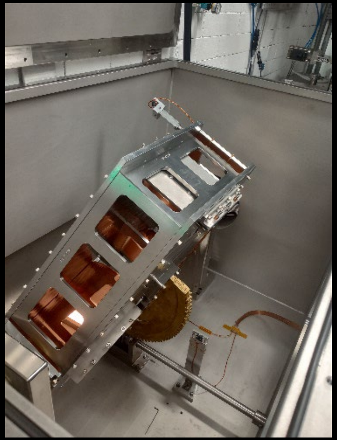
⌘ Increase YAG power to [J] class?

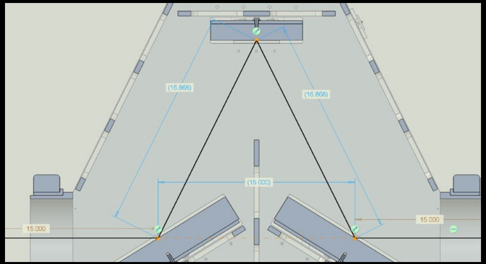
OR

⌘ 100 keV ICS by TW CO_2 laser with 100-200 MeV e-beam?

Status of AE131 experiment

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





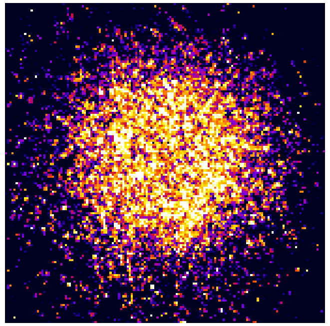
Quick testing:
Circularly polarized ICS →

2nd harmonic X-ray verified

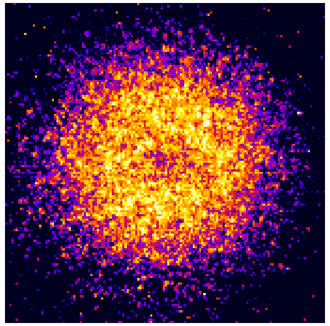
*Although,
50% of laser flux goes through a on-axis hole

2nd Harmonic:

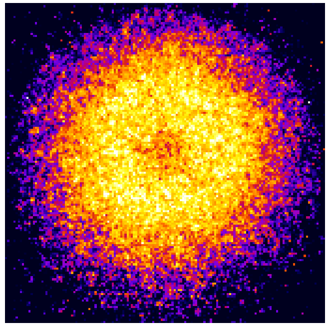
Al 250um High energy X-ray Filtering



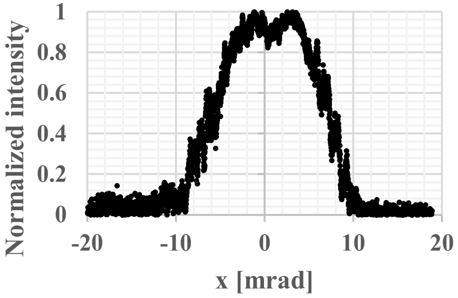
Low energy shot
$a_{L,0}$ ~ 0.6

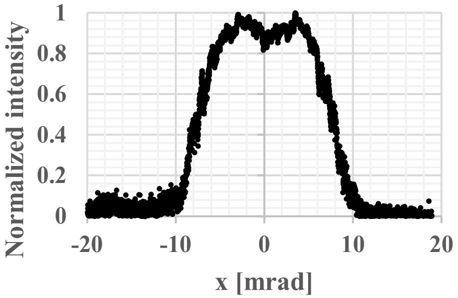


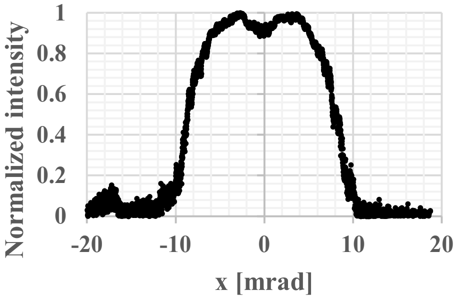
3 J shot
$a_{L,0}$ ~ 1.0



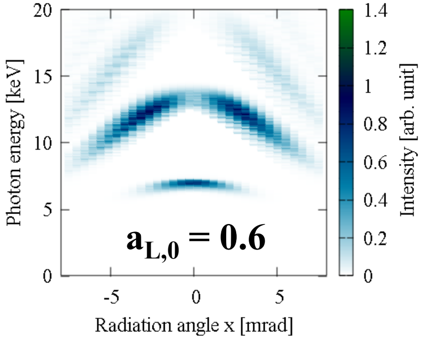
6 J shot
1 < $a_{L,0}$ < 1.5

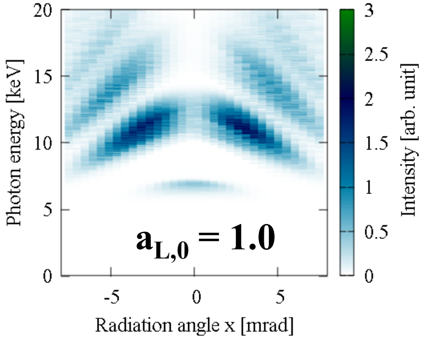


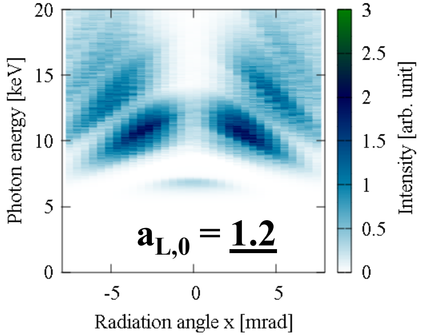




Numerical Estimate With Al 250 μm Filter



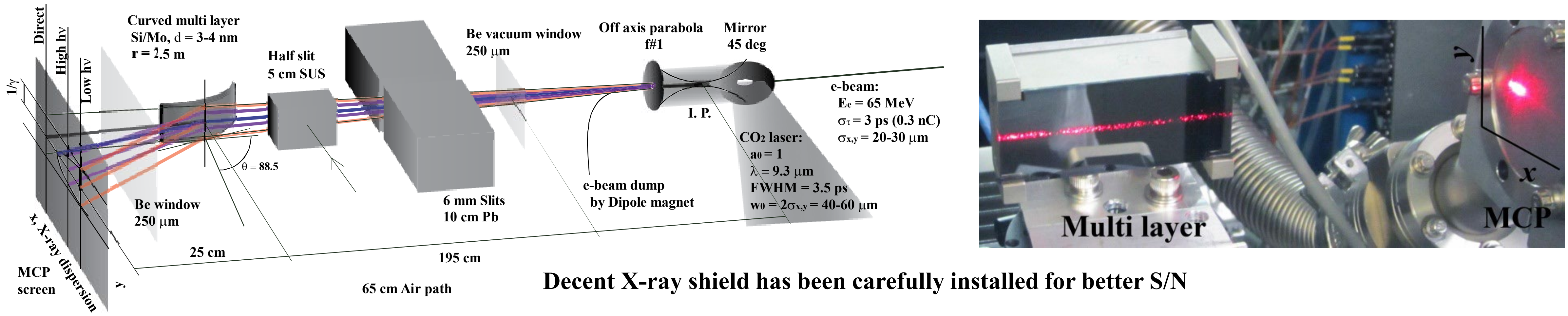




→ Ready to observe Bi harmonic effect in next 2 years
(via K-edge filtering to see the red shifting of 87 keV X-ray)

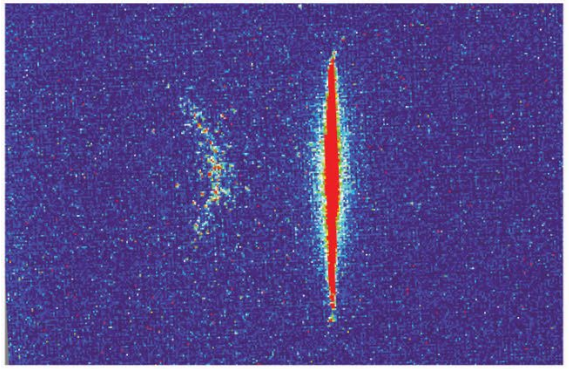
AE70: Double Differential Spectrum measurement of the ICS X-ray by
Mo/Si curved Multi-layer* spectrometer (2015-2017yr) 10^9 photons / shot at ~10 keV

*Developed by NSLS P. Siddons et. al. 2003yr

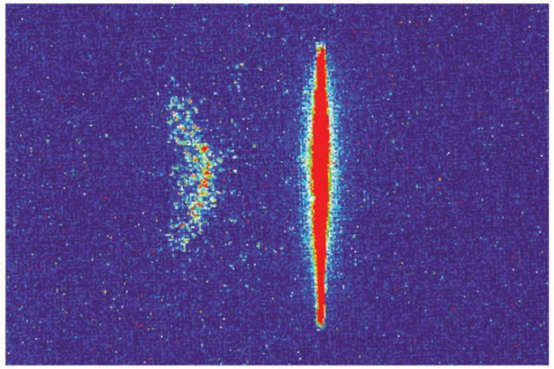


Decent X-ray shield has been carefully installed for better S/N

- ✡ 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)



Laser energy 1.5 J,
$a_L = 0.7$



Laser energy 3.0 J
$a_L = 1$

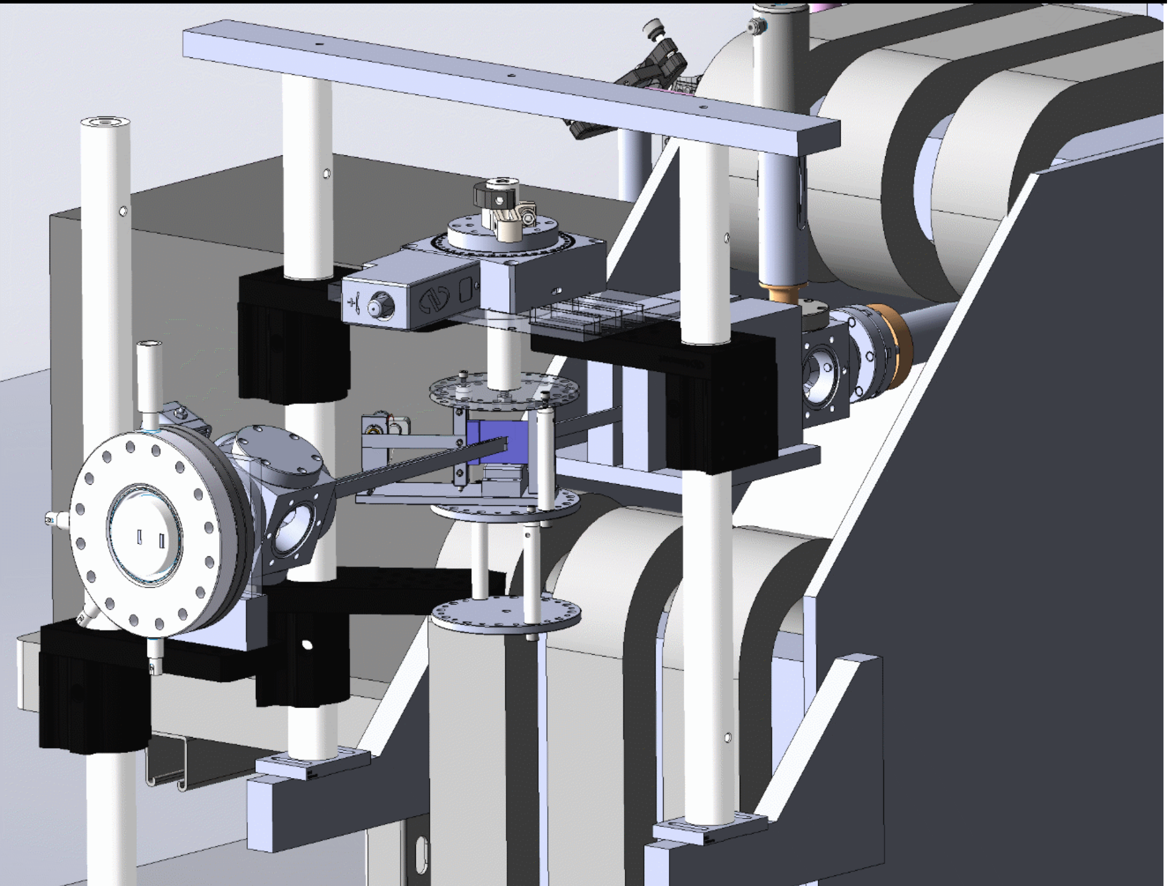
Single shot, double differential spectral measurements of inverse Compton scattering in the nonlinear regime,
Y. Sakai , J. Rosenzweig, T. Kumita, Y. Kamiya, P. Siddons, I. Pogorelsky, V. Yakimenko, et. al., Phys. Rev. ST Accel. Beams (2017)

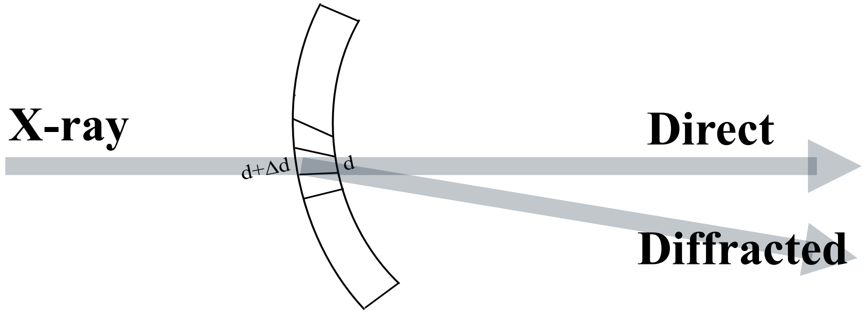
Single shot DDS measurement at 100 keV X-ray

→ ***100 keV X-ray optics developments***

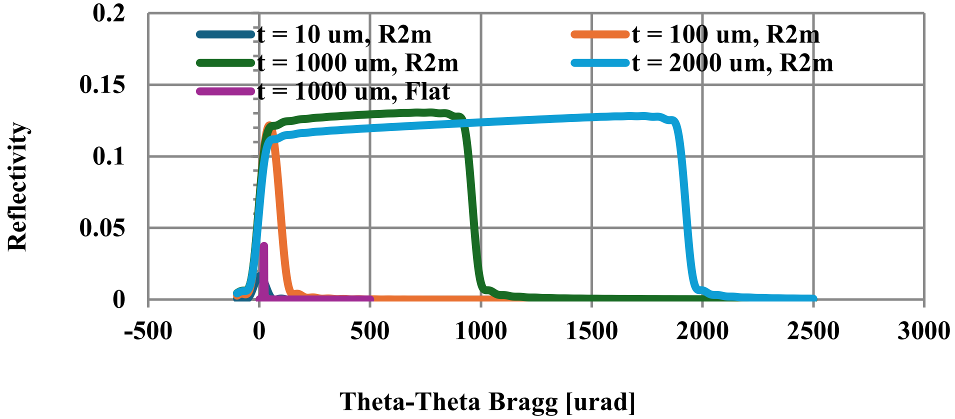
Collaboration with NSLS II 150 keV section Z. Zhong

→ *Thick Laue Bent Crystal Efficiency > Bandwidth*





- Radius of curvature R: 2.5 m
- Thickness: 1 mm
- Bragg angle at 85 keV: ~22 mrad ↔ *1/γ= ~10 mrad (60-70 MeV)*
- Crystal to MCP screen 0.3 m
- Expected dispersion at screen: ~ 20 mm ↔ *Screen size ~ 20 mm*
- Band width: ~ 10 keV
- Reflectivity (Efficiency): ~10%



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

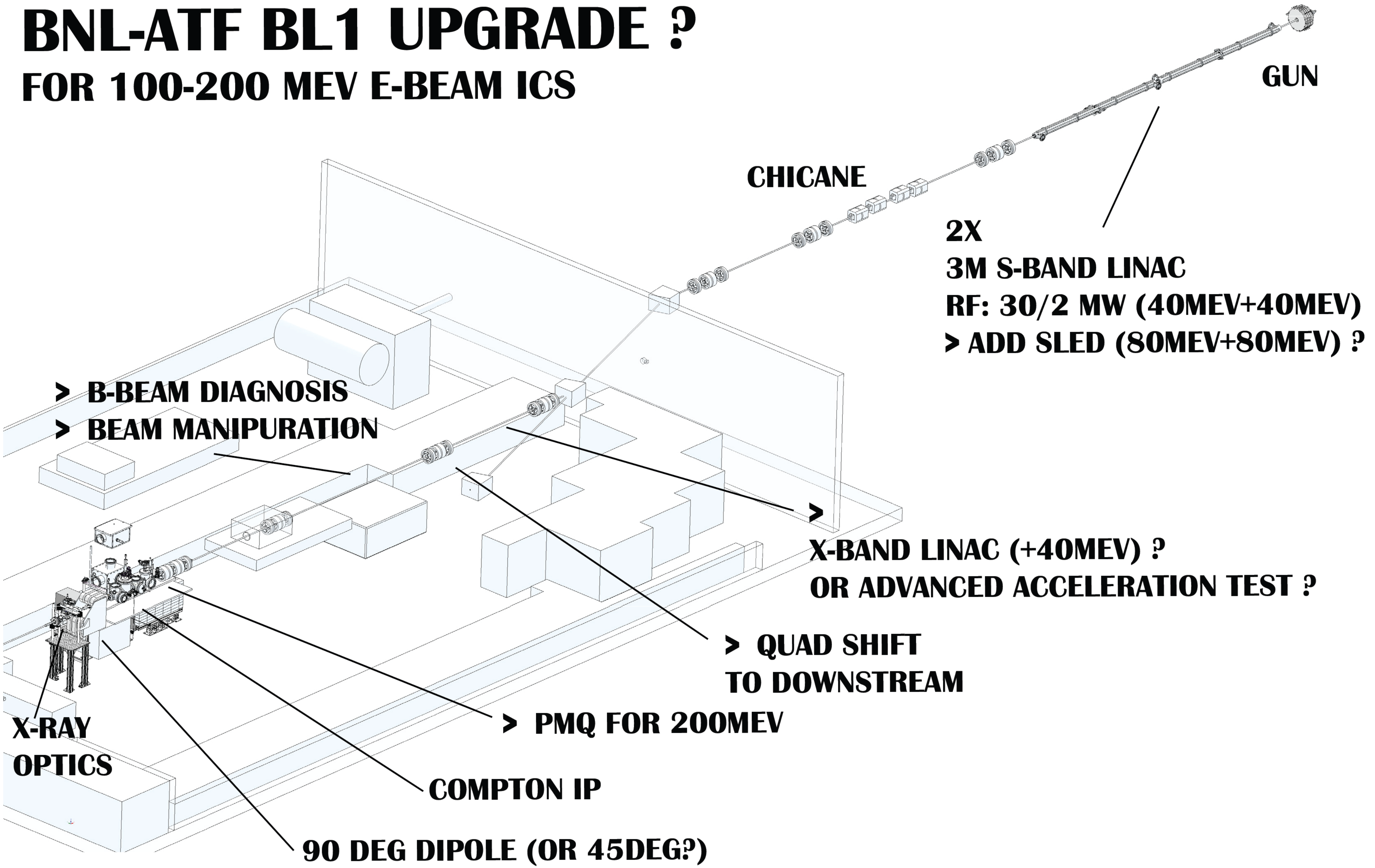
Stats: Diffraction not observed yet by YAG ICS (100 mJ / pulse), 70 MeV e-beam

→ ***~10^6 photon yield / shot is not enough***

→ ***TW CO_2 ? (10J / pulse), 200 MeV e-beam?***

BNL-ATF BL1 UPGRADE ?

FOR 100-200 MEV E-BEAM ICS



70 MeV ICS by
1064 nm, Nd: YAG
laser
(100 mJ / pulse)

$\sigma_{e,x,y}$ ~ 20 µm
→ 10^6 X-ray
photons / shot
1 / γ = 7.3 mrad

VS

200 MeV ICS by
9.2 um, CO_2 laser
(10 J / pulse)

$\sigma_{e,x,y}$ ~ 6 µm
→ 10^{9-11} X-ray
photons / shot
1 / γ = 2.6 mrad

Quad Chart

Scientific/Technical Outcomes

- Summary of approach
- **> AE131 (in 2 years) experiment mainly on proof of principle demonstration on the Bi harmonic Compton interaction**
- **>> NEXT, Development of ICS at ~100 keV X ray, ~$10^{9\text{-}11}$ photons / shot ?**

Lasers/e-beam Parameters Required

- What combination of capabilities enables you to make a breakthrough? **> Stable ~200 MeV electron beam in BL1**
- Required diagnostics **> Especially X-band T-Cav in BL2 first >> Repair of the 15MW X-band Klystron asap (Or Obtain a 5MW Klystron with SLED)**

ATF Facilities Upgrade Roadmap

- **> LLRF-RF entire system examination & rebuild for stable e-beam operation first (Detailed e-beam study from Gun & LLRF-Laser monitors)**
- **> NEXT, explore e-beam energy boost: SLED for linac RF & X-band (or C-band) linac in EH?**

Beyond the Current Roadmap

- **> Construction of sub GeV linac in Build 912 someday**
- **> Construction of the 100 J / pulse final CO_2 laser amplifier someday**
- **> Mode conversion of TW CO_2 laser for short range Vacuum Laser Acceleration**

Current Electron Beam

Parameter	Units	Typical Values	Comments
Beam Energy	MeV	50-65	*Full range is ~15-75 MeV with highest beam quality at nominal values*
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.* *NOTE: Further compression options are being developed to provide bunch lengths down to the ~10 fs level*
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.*
Normalized Emittance	mm	1 (at 0.3 nC)	*Variable with bunch charge*
Rep. Rate (Hz)	Hz	1.5	*3 Hz also available if needed*
Trains mode	---	Single bunch	*Multi-bunch mode available. Trains of 24 or 48 ns spaced bunches.*

Available CO_2 Laser Requirements

Configuration	Parameter	Units	Typical Values	Comments
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*
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.*
	Pulse Mode	---	Single	
	Pulse Length	ps	2	
	Pulse Energy	J	~5	*Maximum pulse energies of >10 J will become available within the next year*
	M^2	---	~2	
	Repetition Rate	Hz	0.05	
	Polarization		Linear	*Adjustable linear polarization along with circular polarization can be provided upon request*

Other Experimental Lasers

Ti:Sapphire Laser System	Units	Stage I Values	Stage II Values	Comments
Central Wavelength	nm	800	800	*Stage I parameters are presently available and setup to deliver Stage II parameters has been completed*
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
Wavelength	nm	1064	*Single pulse*
Energy	mJ	5	
Pulse Width	ps	14	
Wavelength	nm	532	*Frequency doubled*
Energy	mJ	0.5	
Pulse Width	ps	10	