Nonlinear Inverse Compton Scattering experiments enabled by Long-Wave Infrared Laser in BNL ATF

Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

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Advanced Accelerator Concepts 2026

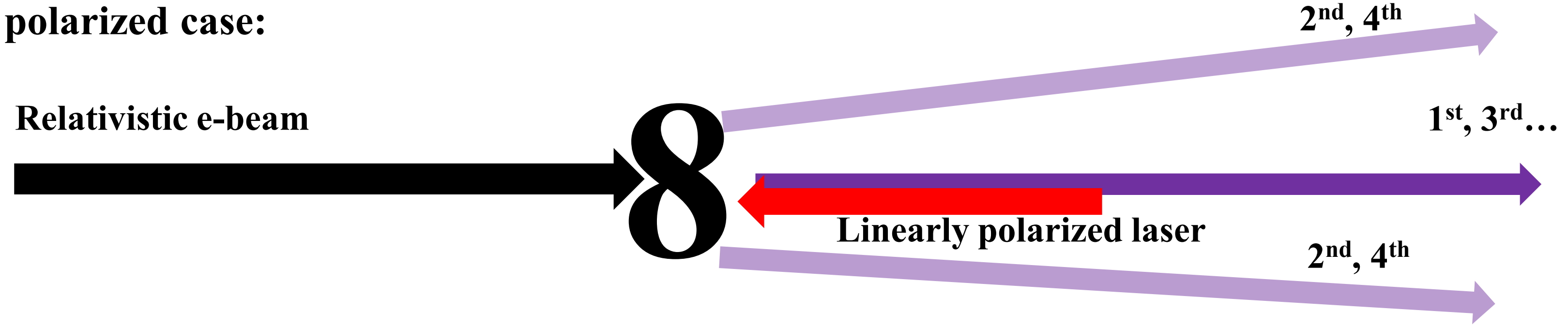
U.S. DOE Accelerator Stewardship grant DE-SC0009914
U.S. Department of Energy under contract DESC0012704

AE70: Basic study on the nonlinear Compton (CO_2 laser)
→ Current experiment# AE131 (Advanced) Harmonic Nonlinear Inverse Compton Scattering

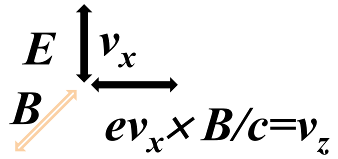
- ✪ 1. Strong field physics: Bi-harmonic Compton interaction
- ✪ 2. X-ray OAM investigation: Higher order harmonics by circular polarized CO_2 laser
- ✪ 3. Hard X-ray optics developments: DDS measurement & Focusing, Collimation for Applications

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

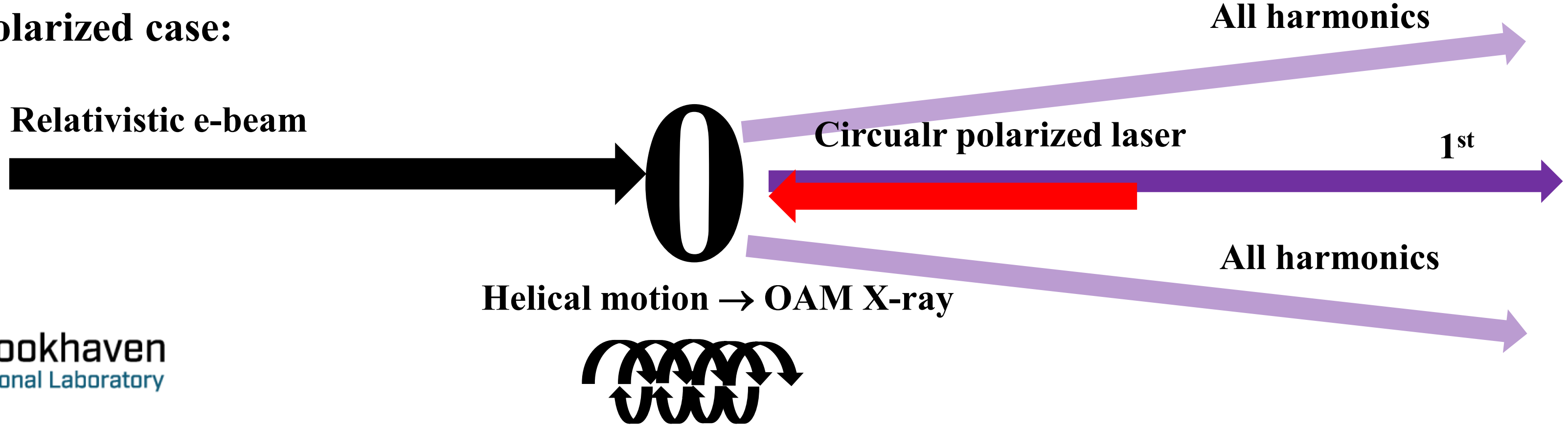
Linearly polarized case:

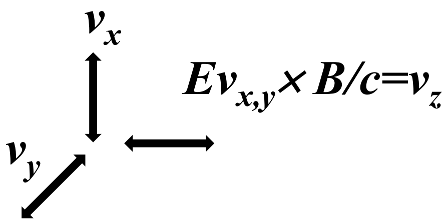


$$* \; a_{L,0} \equiv \frac{\sqrt{-e^2 A_\mu A^\mu}}{m_e c^2} = \frac{e E_{L,0}(\lambda_L/2\pi)}{m_e c^2}$$



Circular polarized case:





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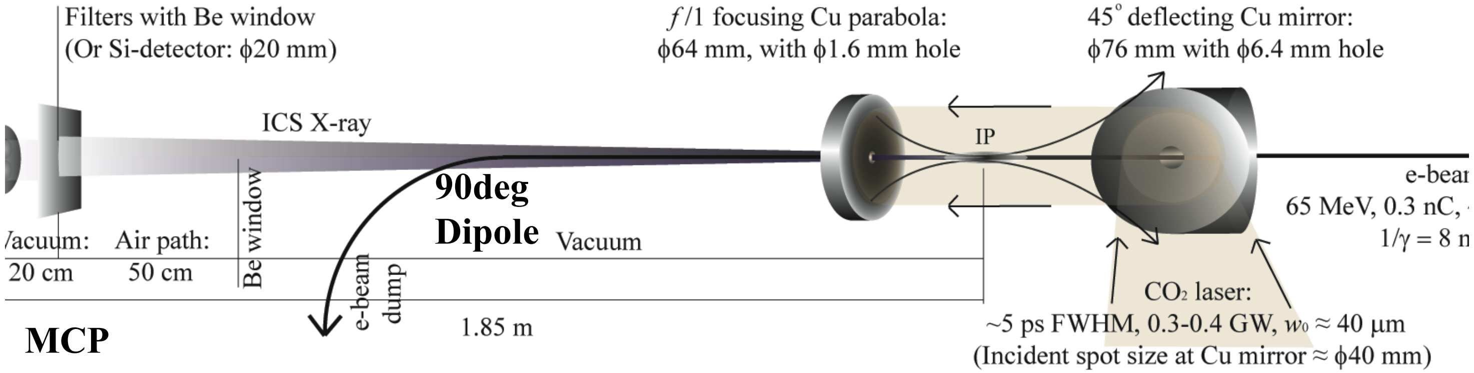
ATF beam parameters (AE70, 2014 yr)

BNL-ATF Beam parameters (as of 2014 yr):

✦ CO_2 laser: $a_L \approx 0.6 < 1$
(~0.4-0.8 TW, > 3 J), FWHM ≈ 3.5 – 5.0 ps, Wavelength: 10.6 μm
$w_0 \approx 40\ \mu$m, $Z_R \approx 500\ \mu$m

✦ Electron beam: E = 60 - 70 MeV
$Q \approx 0.3$ nC, Bunch length 3 ps, $\sigma_x \approx 30\ \mu$m,
$\varepsilon_N \approx 1$ mm mrad, β-function ≈ a few cm



ICS I. P. Optics

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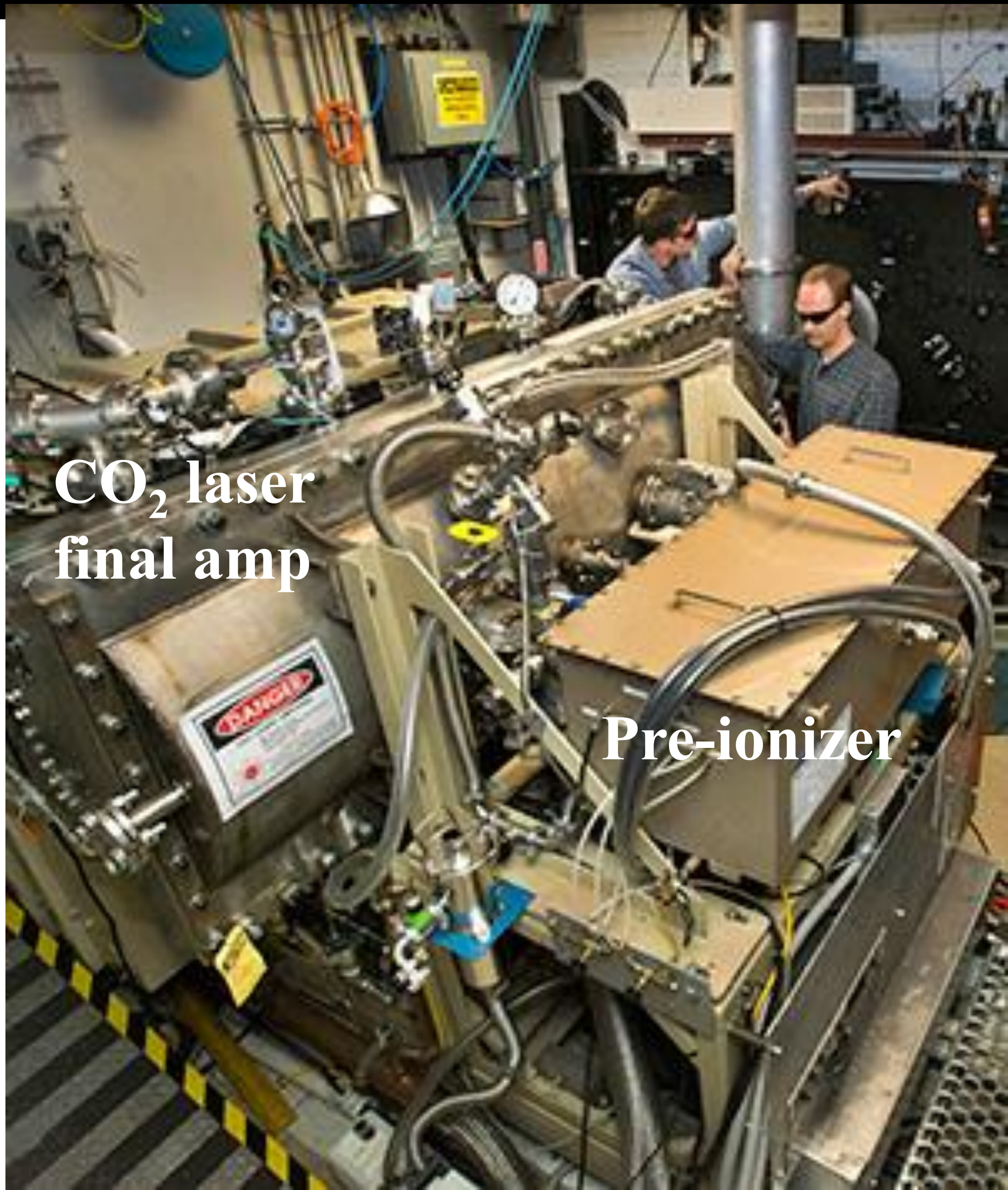
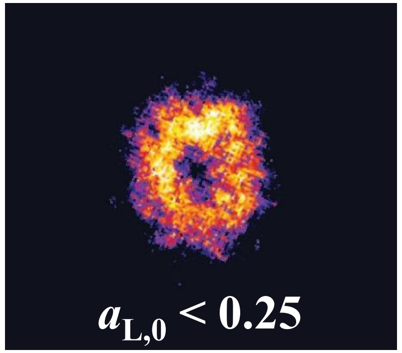
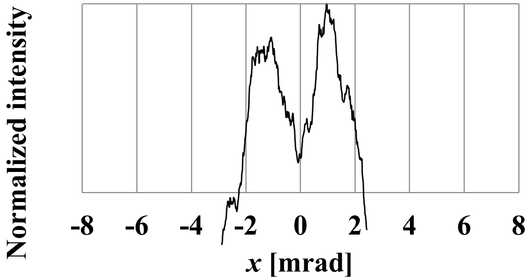


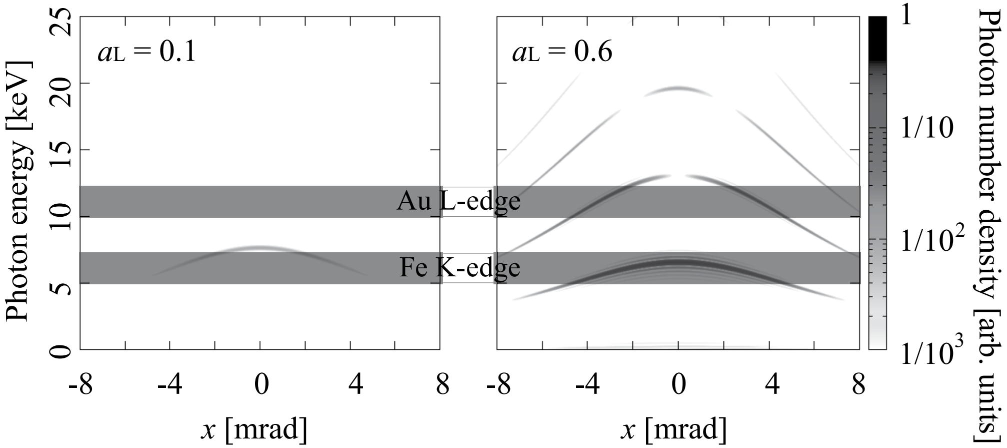
Observed red-shift (*Direct evidence of the figure-8 motion*)

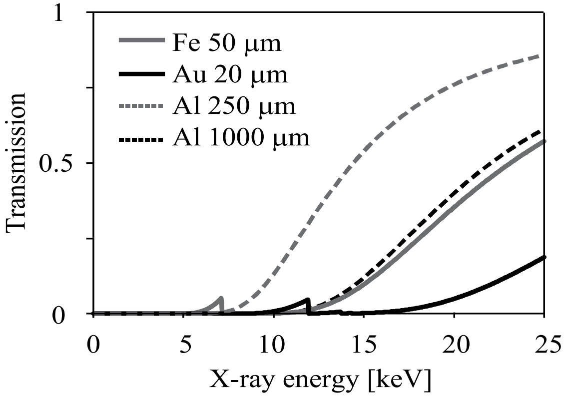
★Compton edge: $h\nu = 4\gamma^2 E_L \approx$ 7 - 10 keV, ★Photons / pulse: $N_\gamma \approx 10^9$ (★ World record ★)

7.6 keV < Fe k-edge
Off-axis component

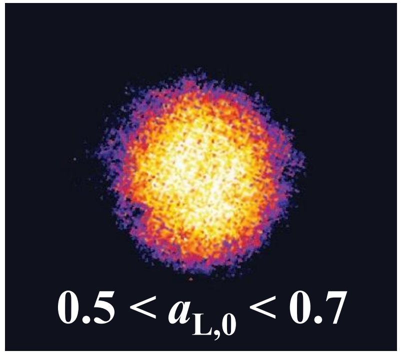


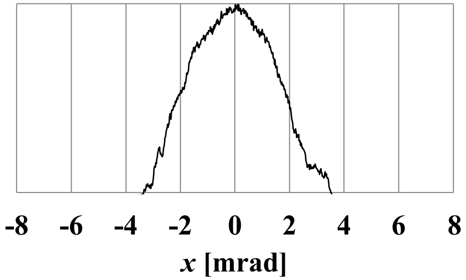






Red-shifting
to 5-6 keV



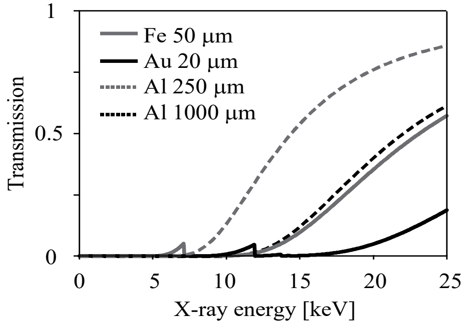


$$h\nu_{ICS,\,1^{st}} = 4\gamma^2 \nu_L / (1 + a_{L,0}^2 / 2) \rightarrow \therefore 0.5 < a_{L,0} < 0.7$$

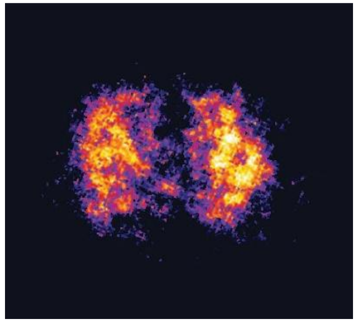
Y. Sakai, I. Pogorelsky, O. Williams et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

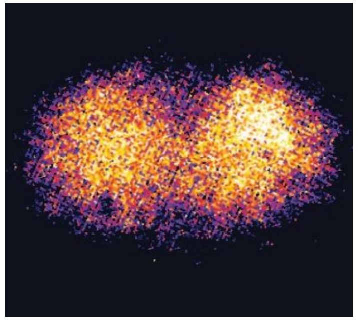
Angular distribution of harmonic radiation

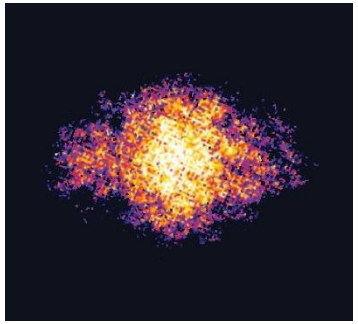
Linear polarization case $0.5 < a_{L,0} < 0.7$

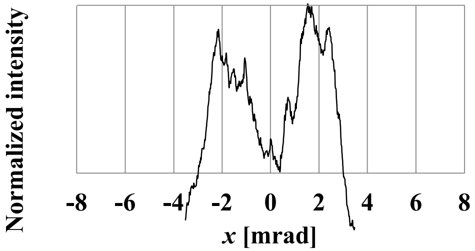


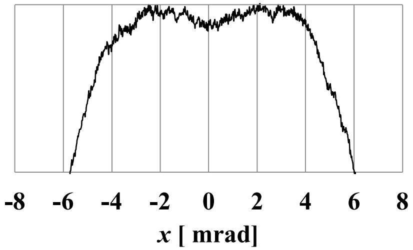
Au L-edge (12 keV)	Al 250 μm > 10 keV	Al 1000 μm > 15 keV
Narrow band 2nd	2nd + 3rd	3rd (On-axis & lobes)

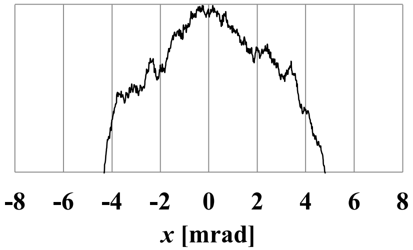












★On axis components of 3rd harmonics ↔ Direct evidence of the longitudinal motion

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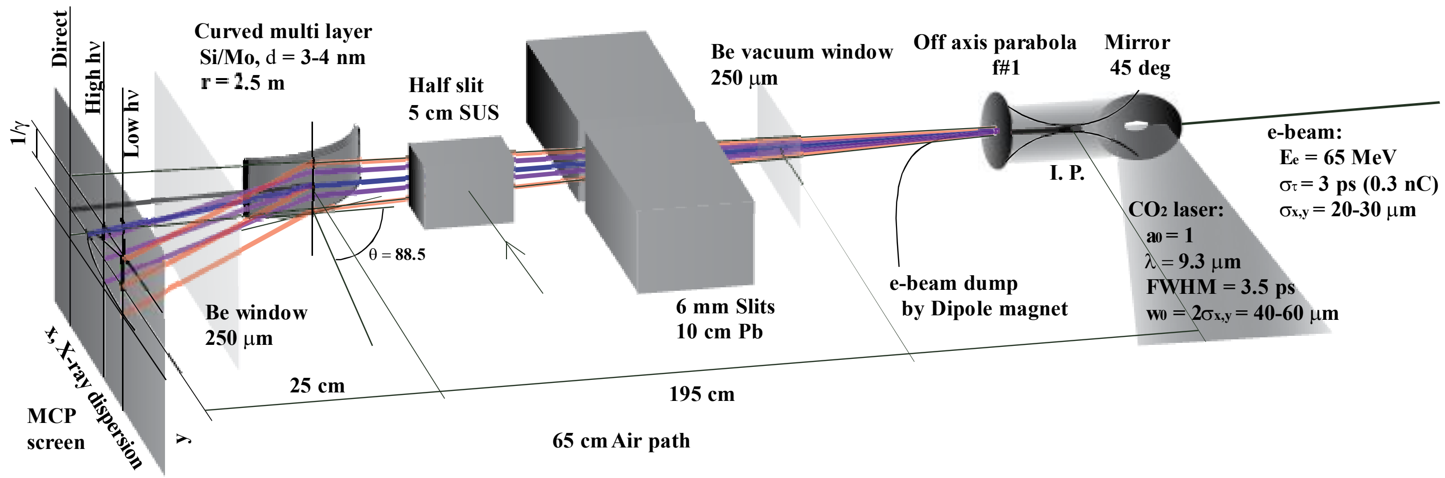
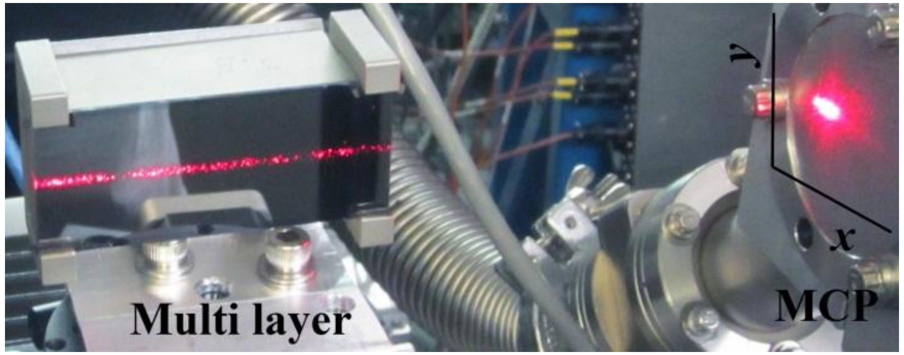
Y. Sakai, I. Pogorelsky, O. Williams et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

Red shifting measured by Mo / Si curved Multi-layer* spectrometer: *≈ $10^{7\text{-}8}$ photons deflected at ~ 10 keV*



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



Note: Decent X-ray shield has been carefully installed to minimize background radiation: It was very tricky.

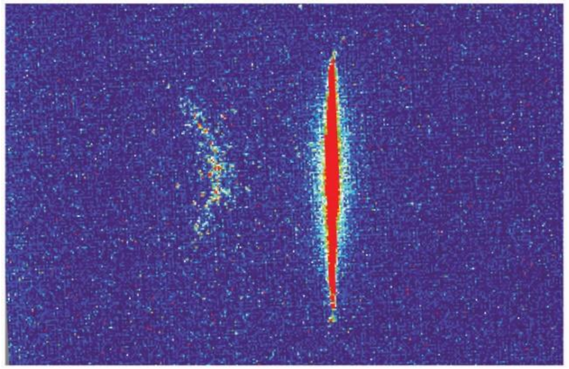
✡ Mo-Si Multi (45) layer thickness: $d \approx 3.3$ nm

✡ Bragg angle:
~ 25 mrad

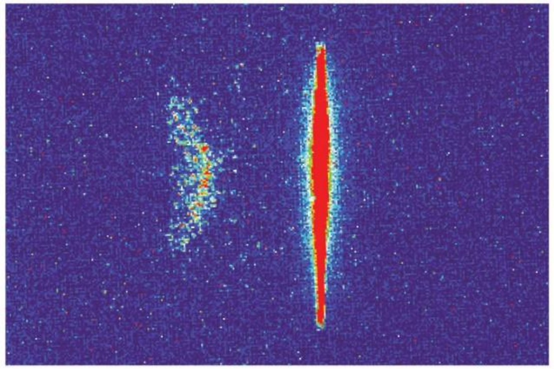
✡ Angle acceptance :
~ 50 mrad

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

Observed double differential spectrum on MCP screen



Laser energy 1.5 J,
$a_L = 0.7$



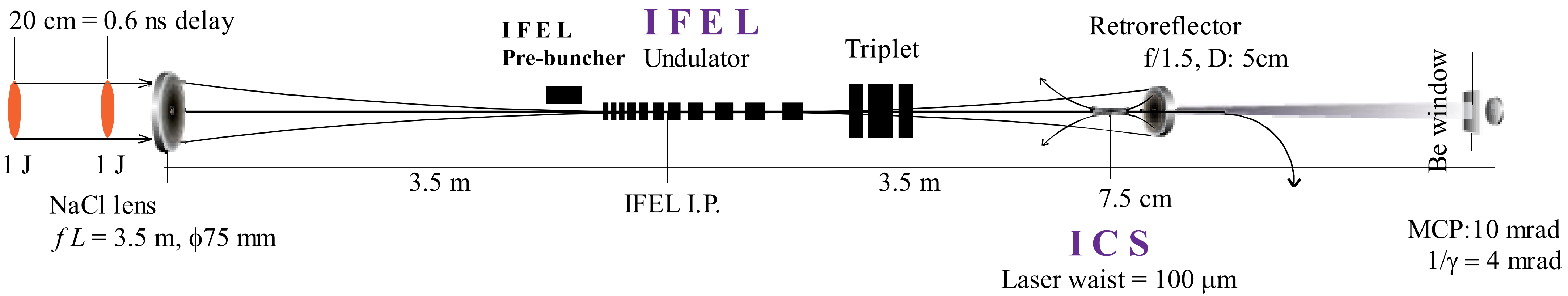
Laser energy 3.0 J
$a_L = 1$

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

+ Double pulse CO_2 laser ICS / IFEL (As Advanced Accelerator Concept)

I. Gadjev, N. Sudar, J. Duris, P. Musumeci et. al.,
An inverse free electron laser acceleration-driven Compton scattering X-ray source, Scientific Reports vol 9, 532 (2019)

Double pulse TW CO2 laser



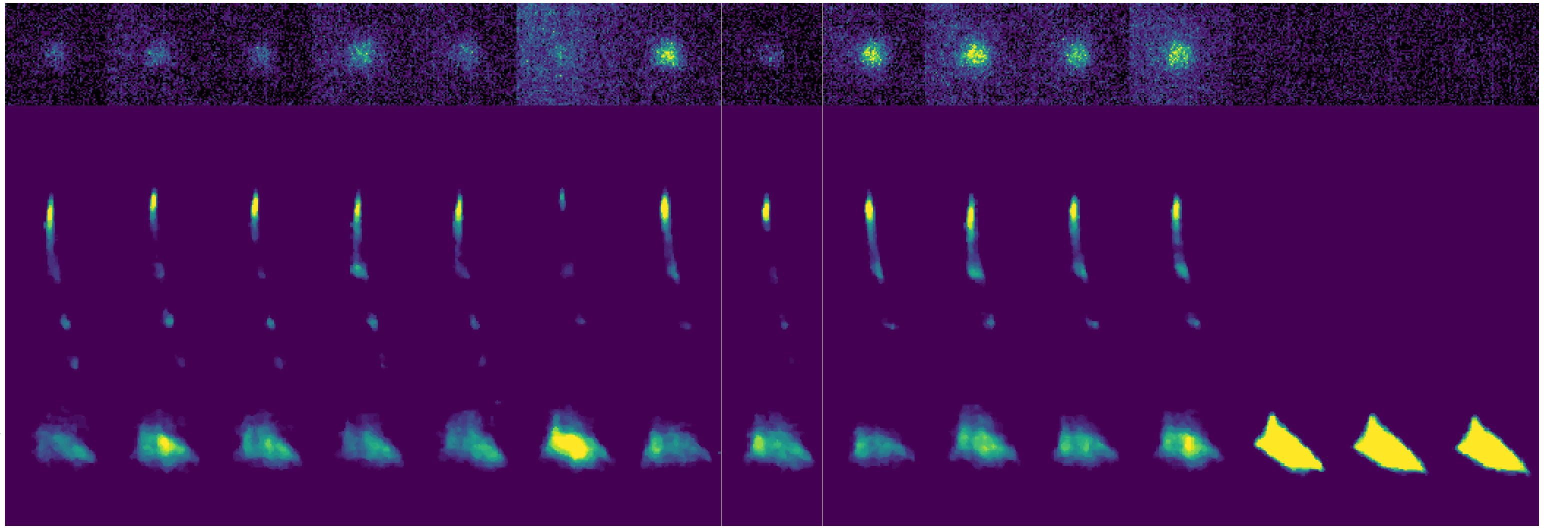
★ $5 \cdot 10^6$ - # of X-ray photons per shot at $11(\pm 2)$ keV (Al higher energy filter inserted)

MCP image:

80* MeV →

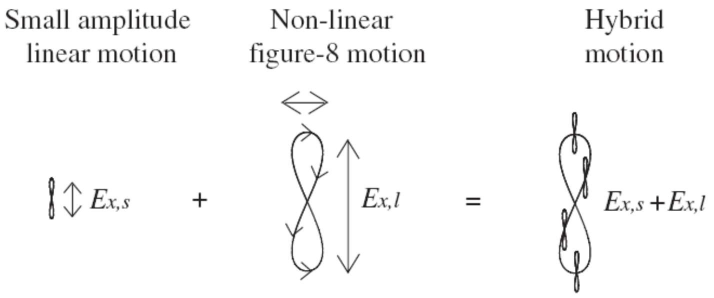
Energy

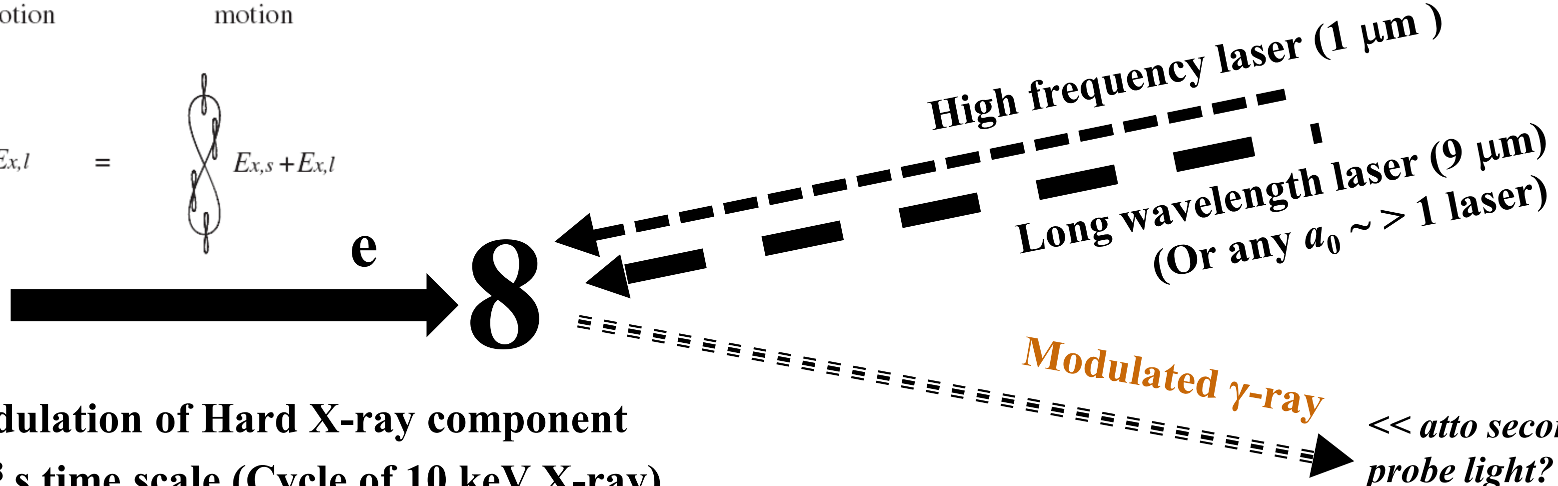
50 MeV →



* ≈ 30 % of each electron accelerated from 50 to 80 MeV ↔ Owing to the precise IFEL pre-buncher

Bi-harmonic Compton interaction

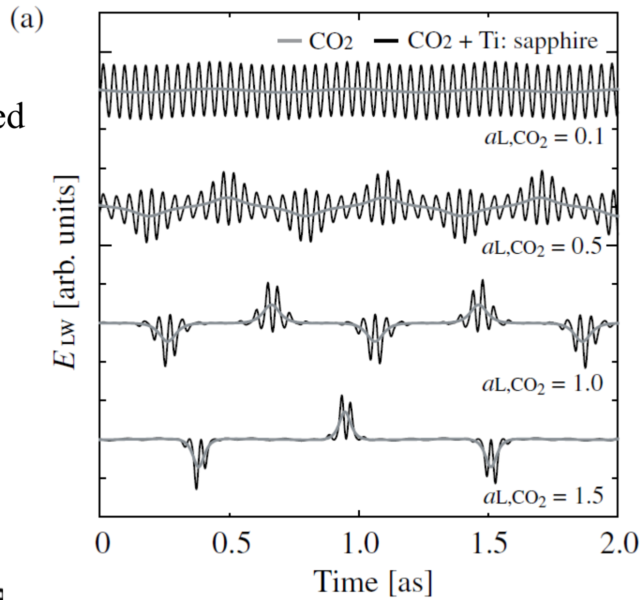




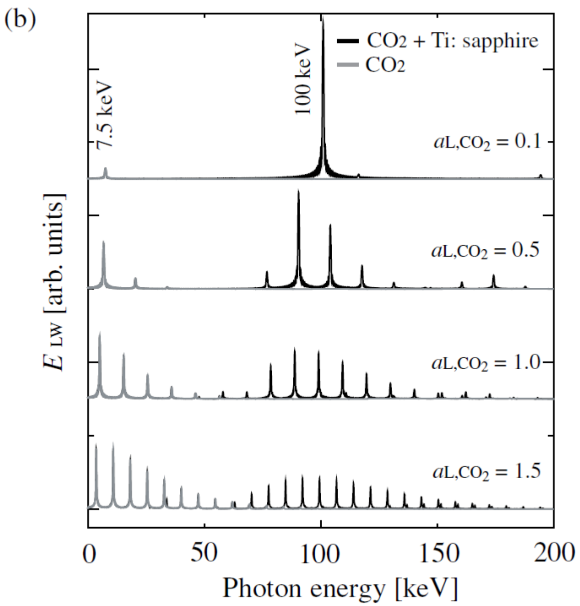
<< atto second probe light?

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

Numerically calculated Linenard-Wiechert potential of X-ray waveform →



Fourier Transform →



Pulsed modulated spectrum:

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

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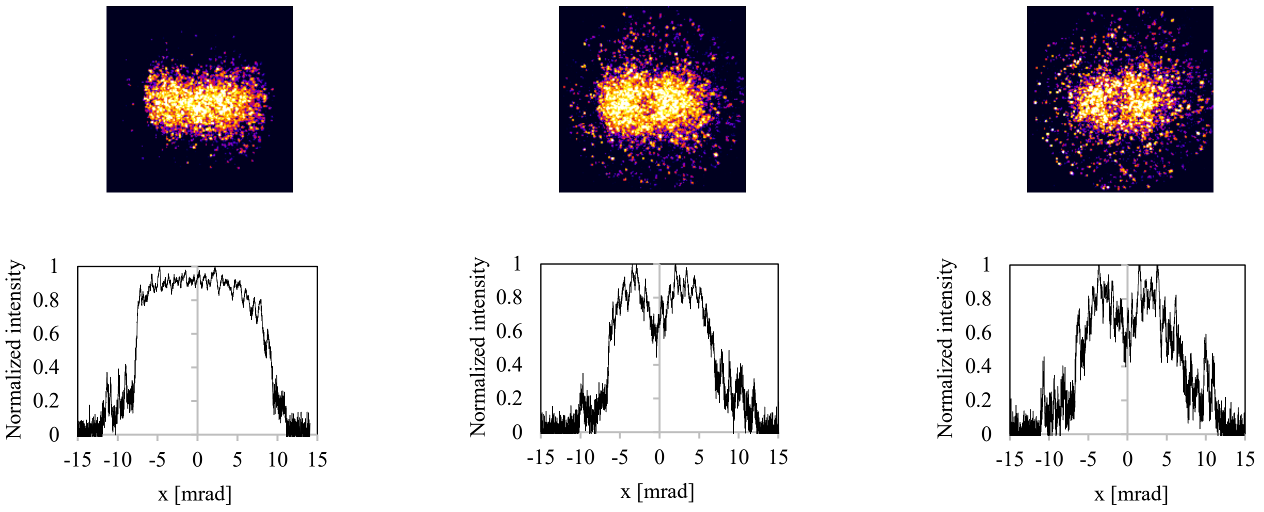
AE87: Established YAG-ICS setup
Nd: YAG laser 1064 nm (200 mJ / pulse)
& 70 MeV e-beam (~10^6 photon yield / pulse @*hv*: 87.5 keV)

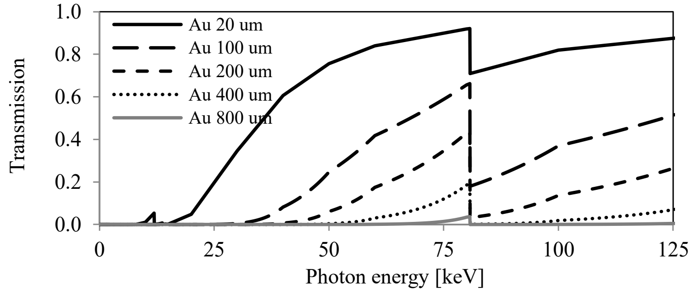
Y. Sakai, M. Babzien, A. Murkoh, J. Rosenzweig et. al., Hard X-ray inverse Compton scattering at photon energy of 87.5 keV, Scientific Reports volume 14, Article number: 18467 (2024)



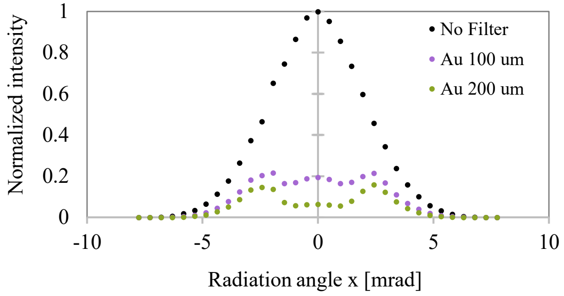
a) No-Filter filter

b) With 100 μm Au filter

c) With 200 μm Au

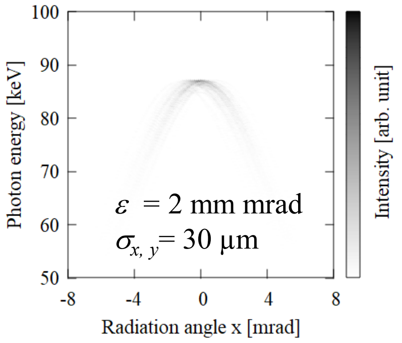


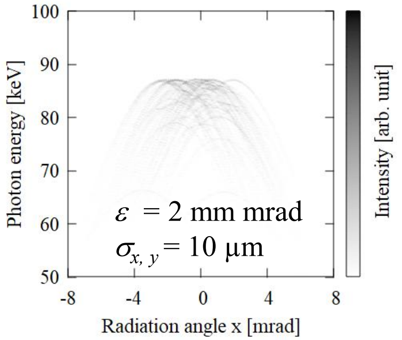
Au filter transmission

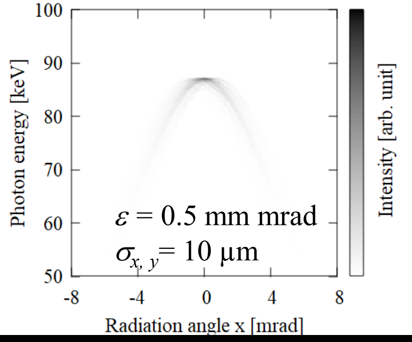


Numerical calculation

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







NOTE:

Focusing e-beam down to < 30 um increases bandwidth at emittance mm mrad range

In some Quasi monochromatic applications*,

Tight focusing & use of $a_{L0} \approx 1$ laser to yield higher flux

could be acceptable.

***Experiment intended for Photon activation therapy with AuNp (dose enhancement by k-edge)**

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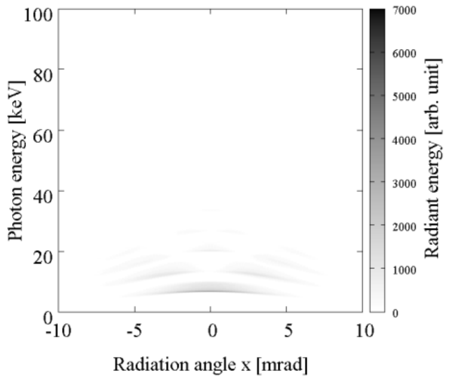
Computational prediction of Bi-Harmonic Spectrum

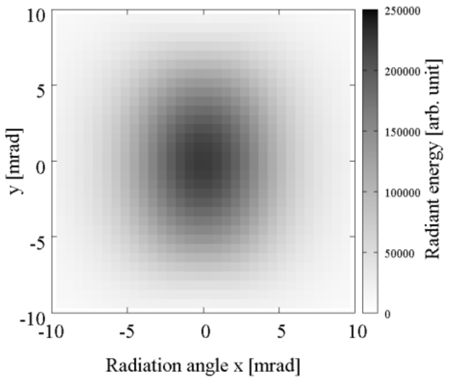
with Au K-edge filter / 9 μm and 1 μm lasers, & 70 MeV e-beam

Only CO_2's component

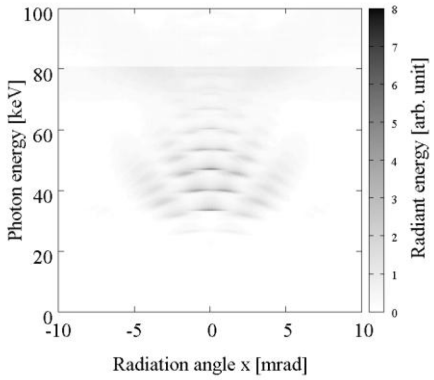
Bi-harmonic components

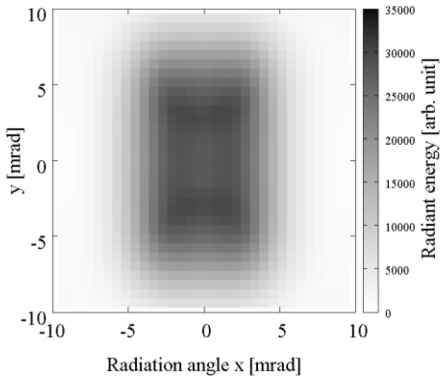
NO-Filter



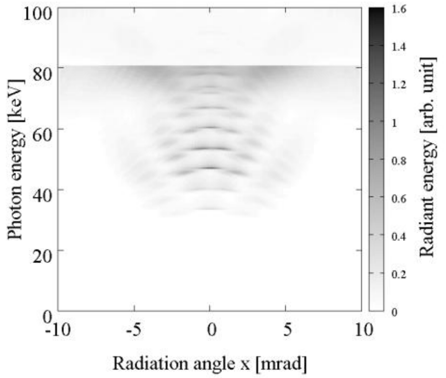


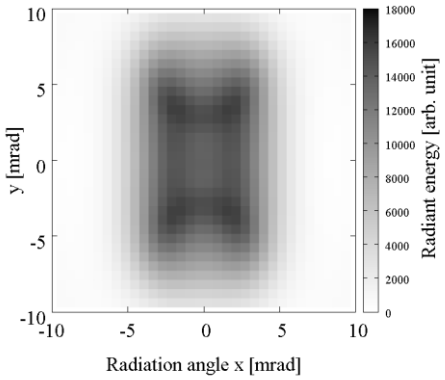
Au-100μm





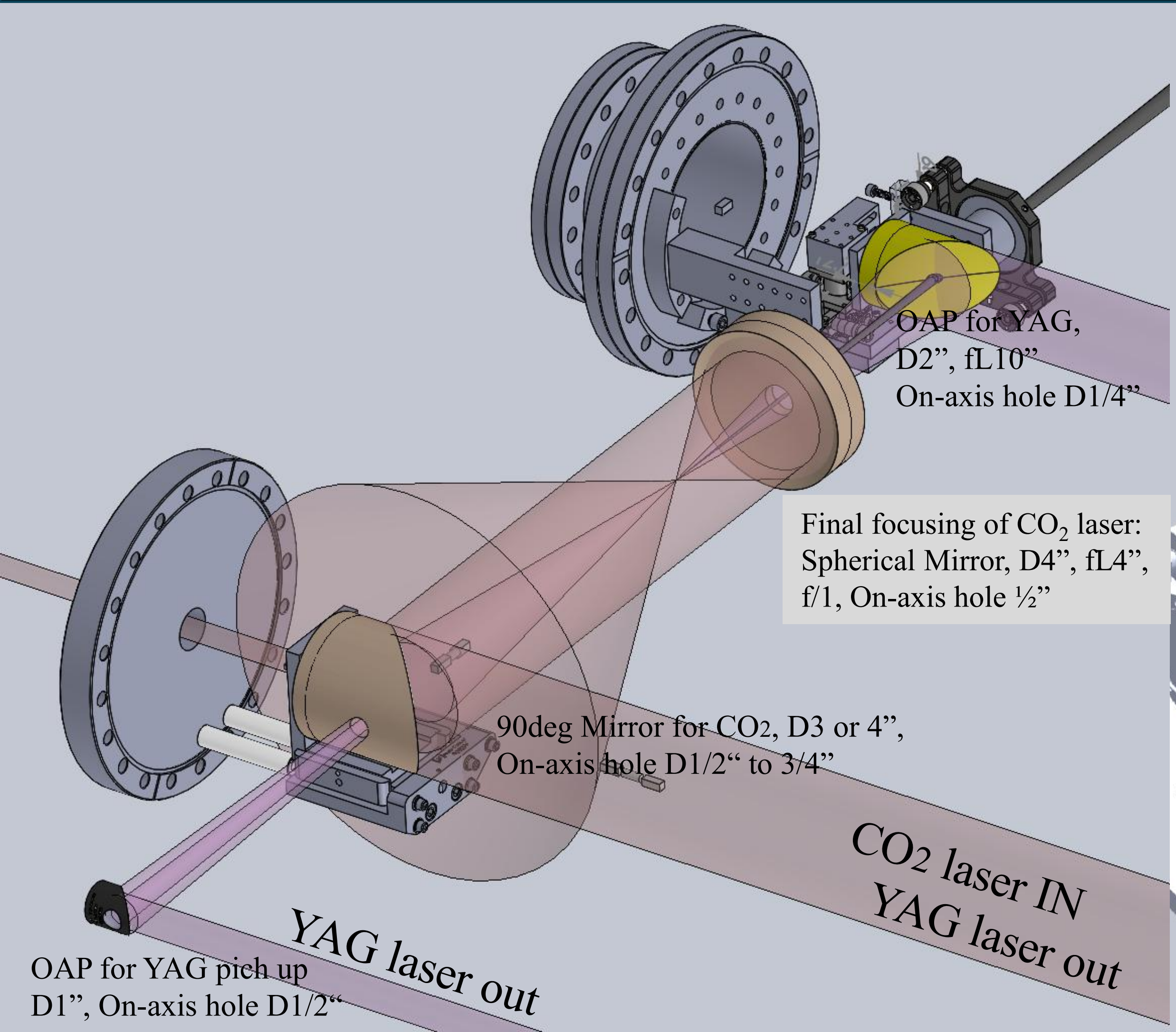
Au-200μm

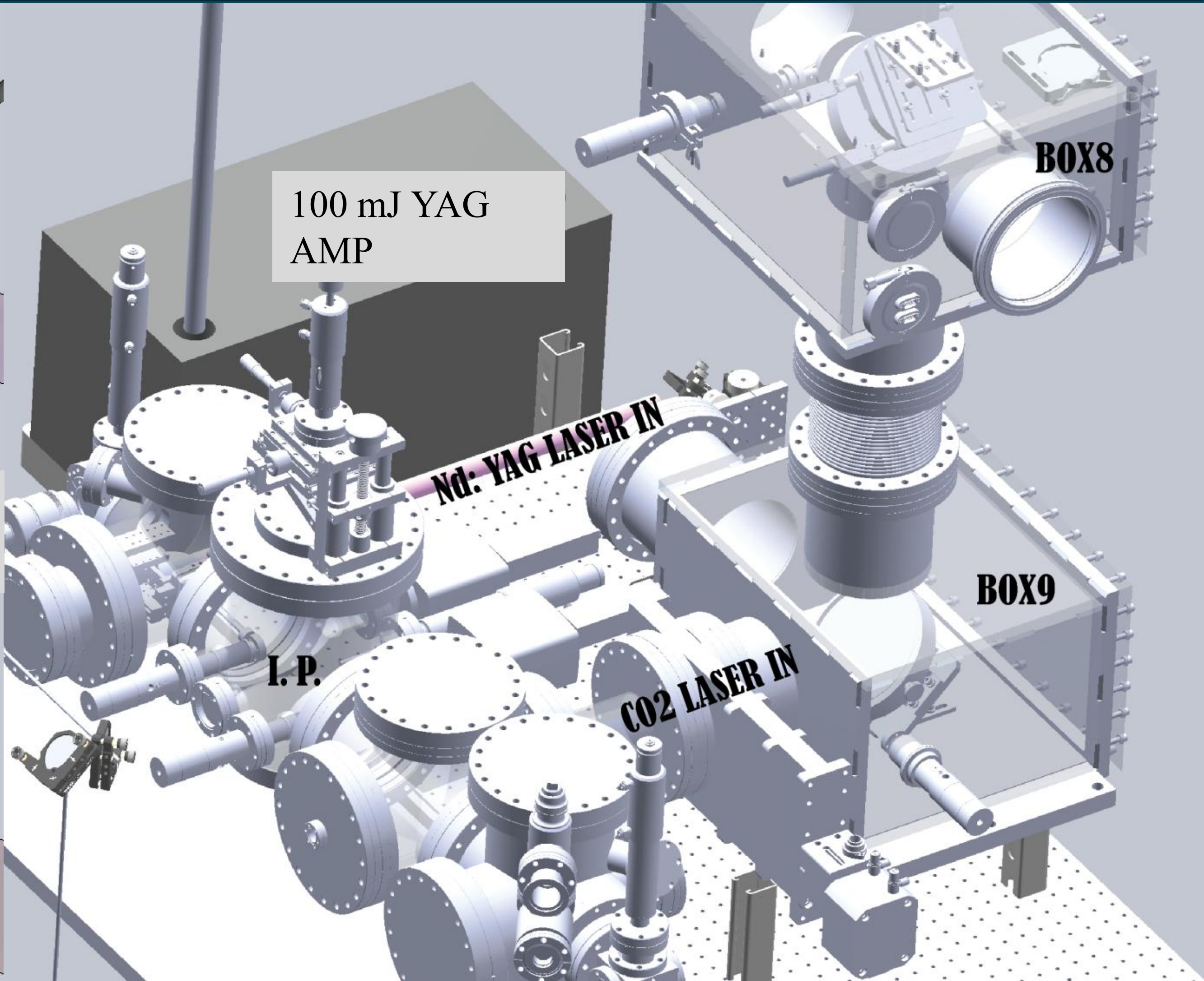




Experimental set up Bi-harmonic Compton I. P.

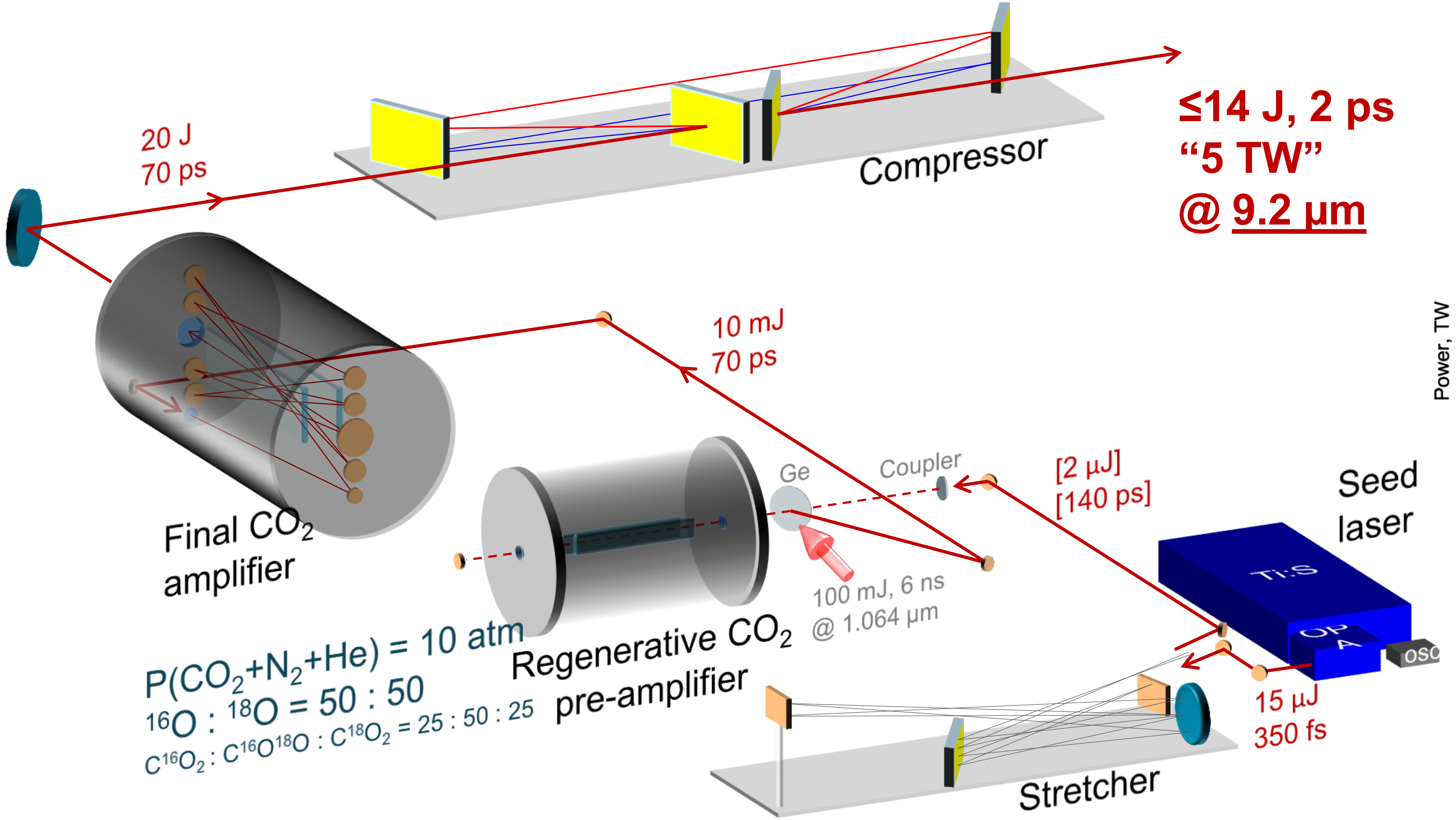
Input of CO_2 laser and YAG laser are opposite direction
& CO_2 laser's final focusing optic has D ½ inch hole on-axis

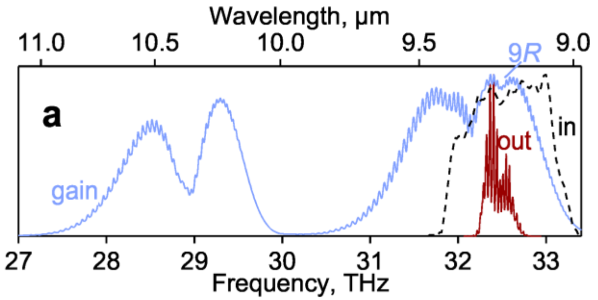


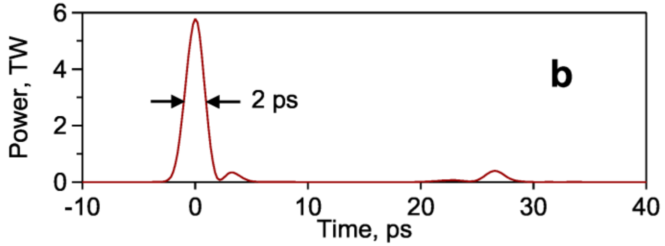


Updated (realistic / stable) number of the ATF's 9μm laser

(we might not call it CO2 laser anymore)







Beam parameters:

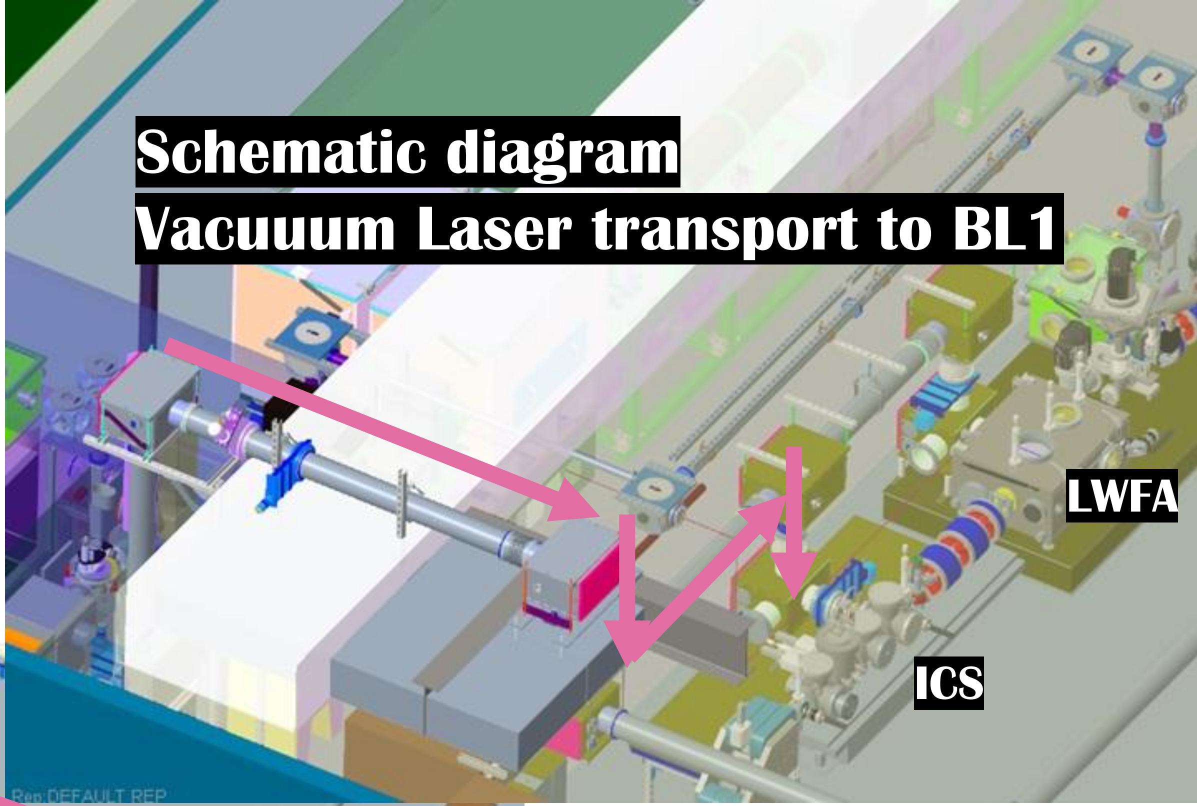
- ✦ CO_2 laser: $a_L > 2.0$?
- ✦ 2-3 TW, 4-6 [J] / 2 [ps]
- ✦ FWHM ≈ 2.0 ps
- ✦ Wavelength: 9.2 μm
- ✦ $w_{0,\,max} \approx 20\ \mu m$, $Z_R \approx 500\ \mu m$

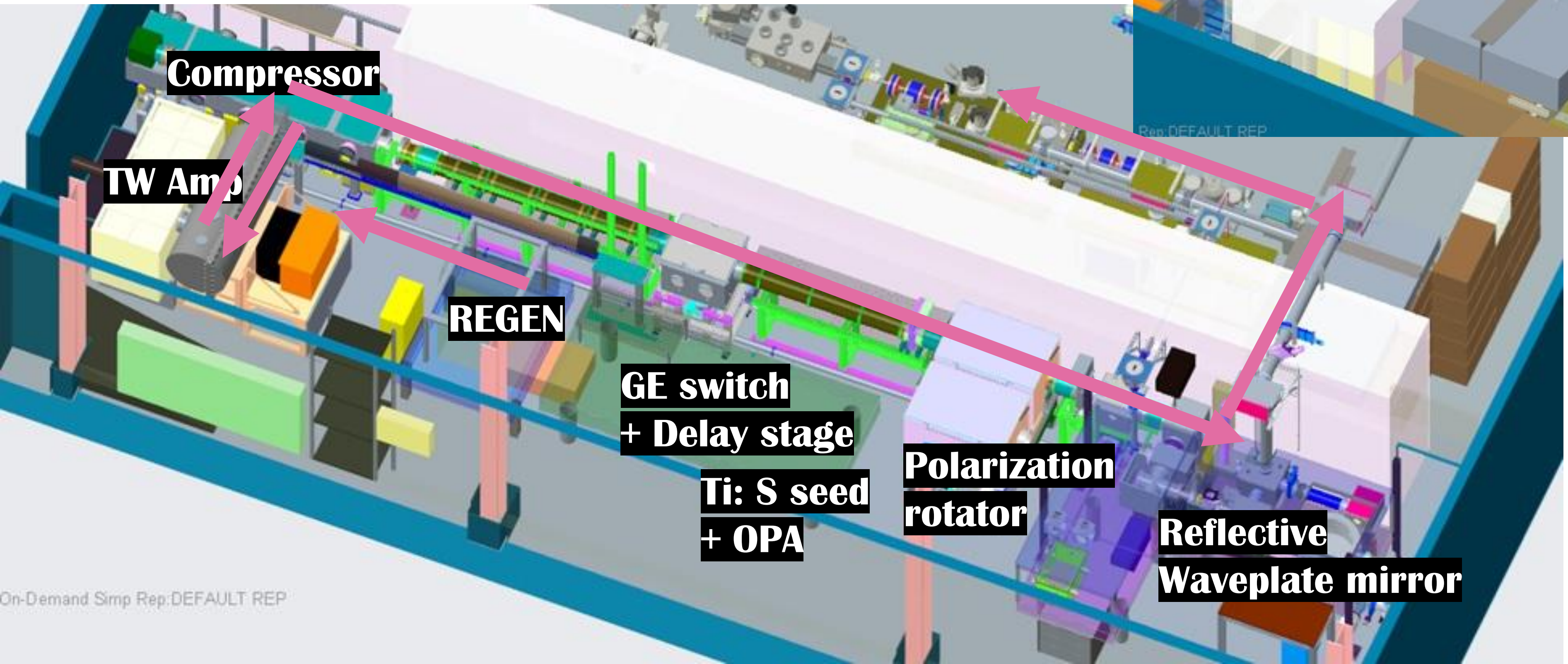
M. N. Polyanskiy et. al.,
Demonstration of a 2 ps, 5 TW peak power, long-wave infrared laser based on chirped-pulse amplification with mixed-isotope CO2 amplifiers,
OSA Continuum Vol. 3, Issue 3, pp. 459-472 (2020)

LWIR Laser Configuration / Transport to Experimental Hall (EH)

Vacuum laser transport to BL1: Nominal 2-3 TW
→ Short interaction:
LWFA-probe, Ion Generation, ICS etc

In air laser transport to BL2: Max 0.5 TW (BaF2 window)
→ Long interaction:
IFEL, Interaction with undulator, +e-LWFA, Coherent Compton etc





Note:
Beam energy limit:

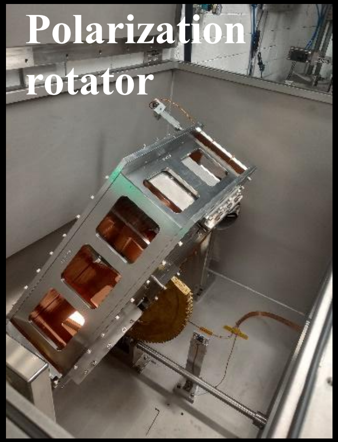
Linac Tunnel: 85 MeV
EH: 250 MeV

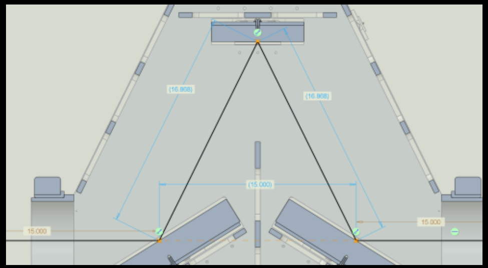
Energy boost by IFEL or X-band linac etc for 200 MeV ICS to be considered?

Bench Marked Update
in AE131 experiment

Owing to newly installed polarization rotator

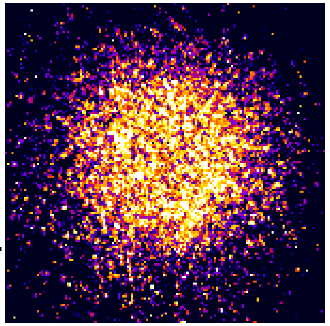
(2× 22.5 deg rotation + reflective wave plate mirror)

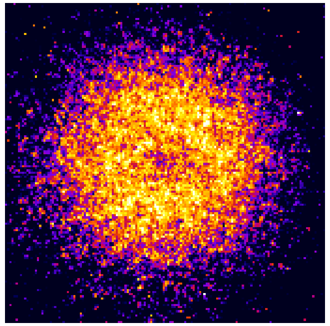


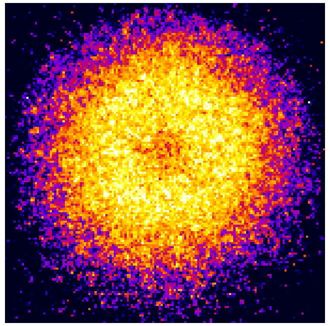


2^{nd} Harmonic:

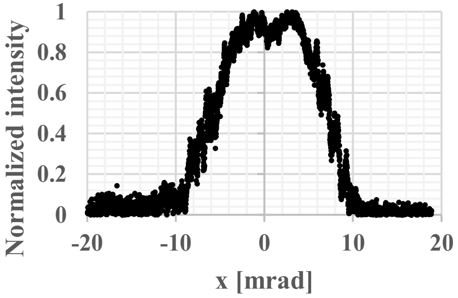
Al 250um High energy X-ray Filtering

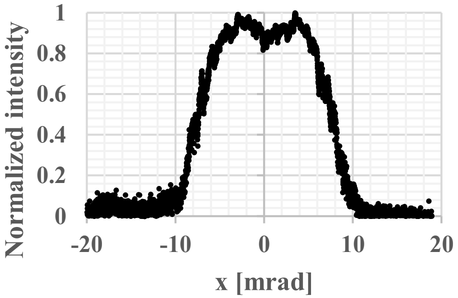


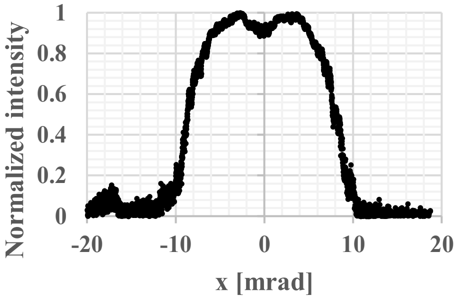




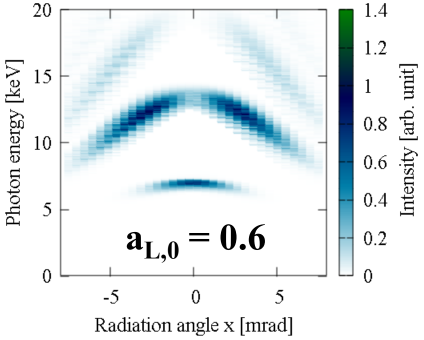
Low energy shot	3 J shot	6 J shot
$a_{L,0} \sim 0.6$	$a_{L,0} \sim 1.0$	$1 < a_{L,0} < 1.5$

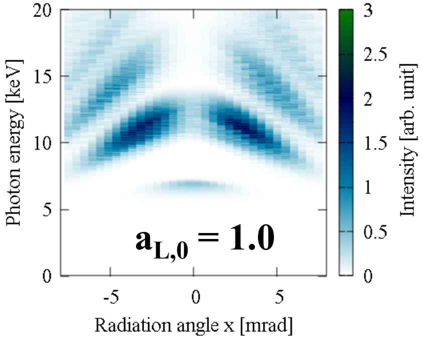


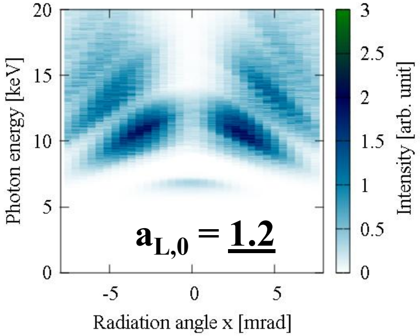




Numerical Estimate With Al 250 μm Filter







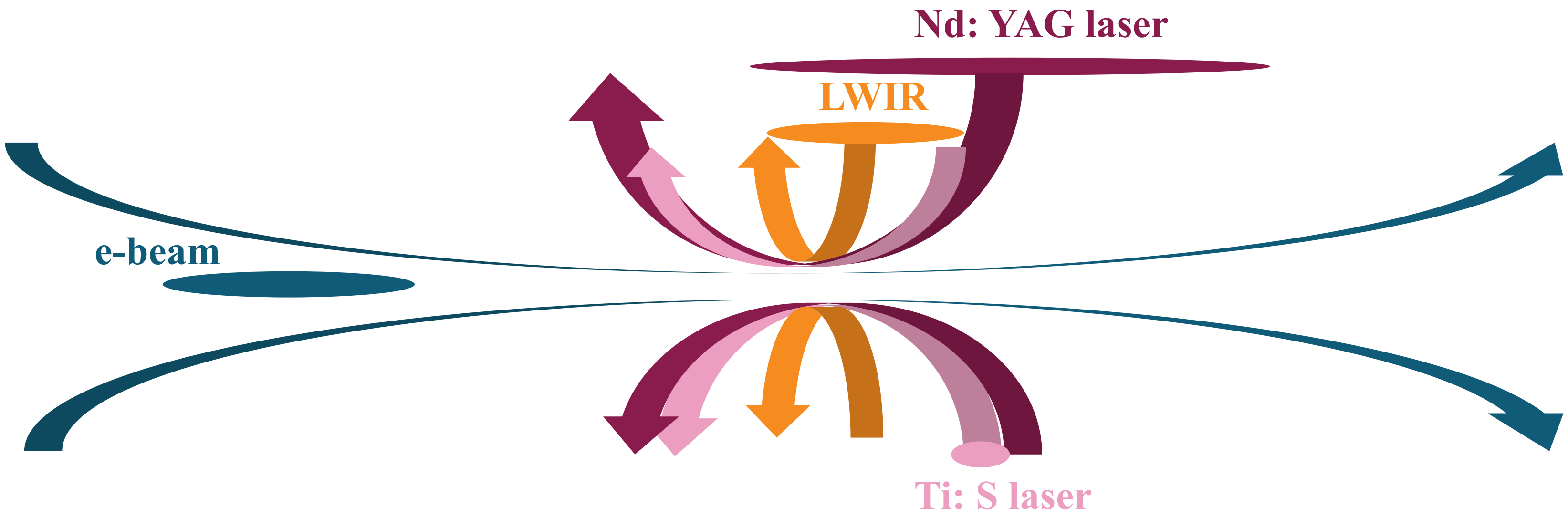
→ *Technically* ready to observe Bi harmonic effect.

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

Timing requirement for multi beam interaction
Example Bi-Harmonic ICS ↔ counter collision case:

	9 μm laser (LWIR)	1 μm laser (Nd: YAG)	0.8 μm laser (Ti: S)	e-beam
FWHM or Bunch length [ps]	2	15	0.15	3
Rayleigh range or Beta function [mm]	0.10	0.27	0.20	55
Rayleigh range or Beta function / c [ps]	0.33	0.90	0.66	183

- ♦ Nd: YAG laser / e-beam: Beta function & Laser pulse length are long → Jitter requirement low (< 900 fs)
- ♦ Ti: S laser / e-beam: Laser pulse length is short → Jitter requirement high (< 150 fs)
- ♦ LWIR / e-beam: Rayleigh range is short → Jitter requirement high (< 330 fs)
- ♦ LWIR / Ti: S laser: Laser pulse length is short → Jitter requirement high (< 150 fs)



Cause of relative timing jitter between e-beam & lasers:
RF timing jitter + Time of arrival for <u>e-beam</u> and lasers ↓

Relative timing jitter

Due to RF phase jitter in ≈ 100 MeV S band linac ATF case

⌘ GUN section:

Time of flight effect { 6 [MeV] , Drift ≈ 1 [m] }

♦ $\frac{dt_{Jitter}}{d\varepsilon} \sim \Delta t_{Jitter} / \Delta \mathcal{E}_e \approx$ 10 [ps / MeV] ↔ 10 [fs] per $\Delta \mathcal{E}_e$ =1[keV]

♦ $d\mathcal{E}_e / d\phi \approx$ 10 [keV / deg]*

∴ $\Delta t_{jitter} \approx$ *10 [fs] requires < 0.1 deg RF phase stability*

⌘ After the Two 3m LINAC section:

Time of flight effect { 70 [MeV] , Drift ≈ 30 [m] }

♦ $\frac{dt_{Jitter}}{d\varepsilon} \sim \Delta t_{Jitter} / \Delta\mathcal{E} \approx$ 0.1 [ps / MeV] ↔ 10 [fs] per $\Delta \mathcal{E}_e$ =100 [keV]

♦ $d\mathcal{E}_e / d\phi \approx$ 1 [MeV / deg]

∴ $\Delta t_{jitter} \approx$ *10 [fs] requires < 0.1 deg RF phase stability*

⌘ Timing jitter due to Laser transport, RF cable length etc: 10 [fs] ↔ 3 [μm]

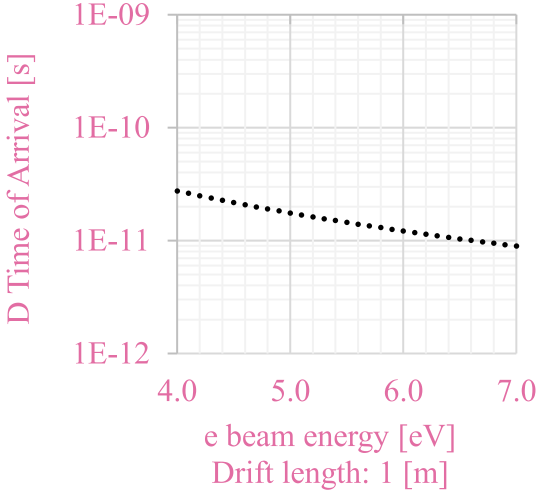
→ Starting from LLRF Phase shifter / Attenuator (< 0.1 deg ↔ > 12 bit resolution)

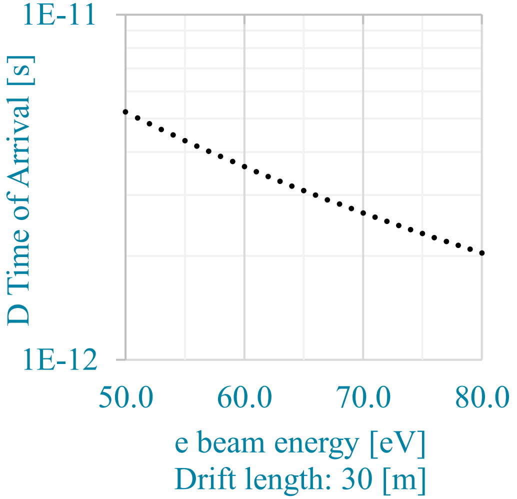
Setting up phase meter, RF power detectors, Frequency counter in multiple key locations.

↓

R & D s :

Optical LLRF long transport, Precise Klystron's modulator control . . . OR feedback LLRF control for Thermal effects.





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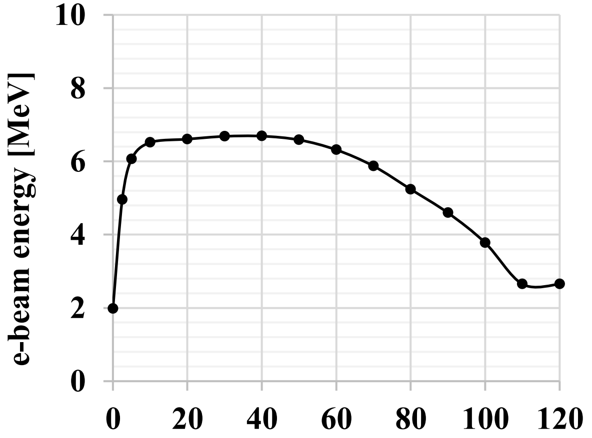

Gun injection phase [deg]
1.6 Cell Gun, Peak field: 130 MV/m
, 1 nC, 10 ps GPT sim.

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Summary

- **Status update on Nonlinear Inverse Compton Scattering experiments enabled by 9 μm laser in BNL ATF reported.**

- **Higher order harmonics induced by Circular polarized laser benchmarked. Maximum available 9 μm laser is estimated to be $1.2 < a_{L,0} < 2$.**

- **Activity to minimize RF timing jitter on going for multi beam interaction.**

→ Collaborative R & D of multiple key elements,
to realize stable Quasi monochromatic sub 100 keV Compton source,
at the highest flux per 10^{9-10} [photon/pulse] shot for *Applications will be intensively examined.

**** Applications: Photon activation, Nuclear photonics, γ - collider* etc.***

**γ E I C !?*

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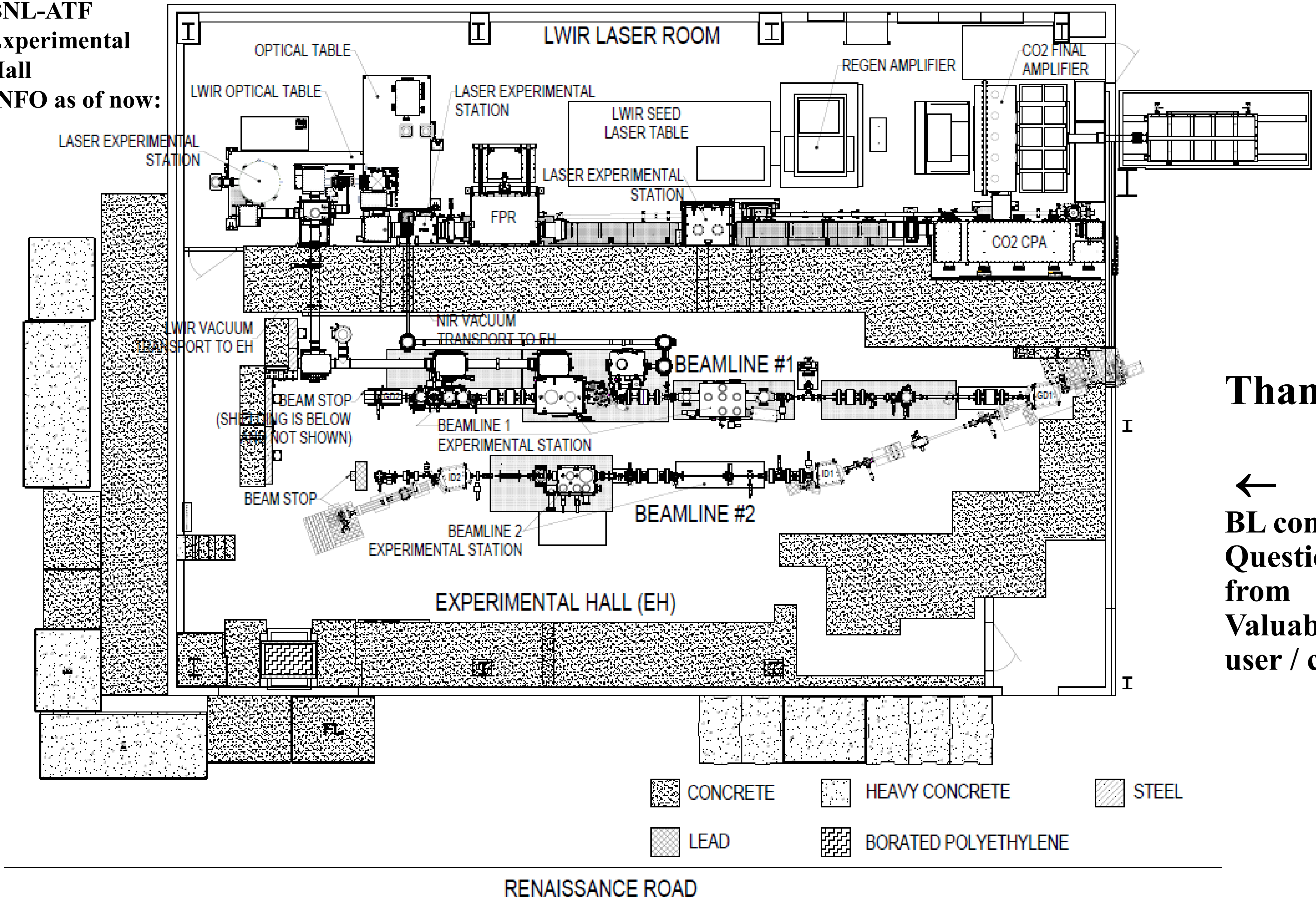
BNL-ATF Experimental Hall INFO as of now:



Thank you.

←

BL configuration for Questions from Valuable future user / collaborator