Nonlinear Inverse Compton Scattering

Transfer from feasibility study

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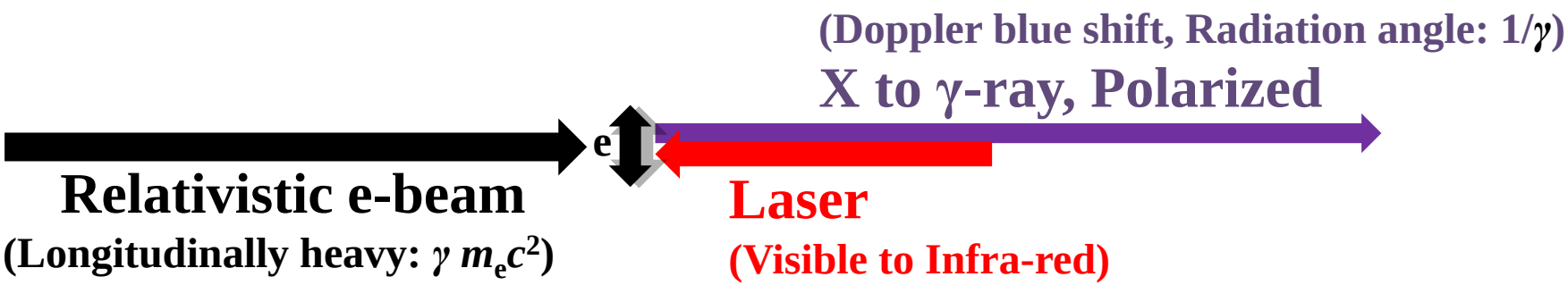
October 2014
BNL ATF User Meeting

Inverse Compton Scattering

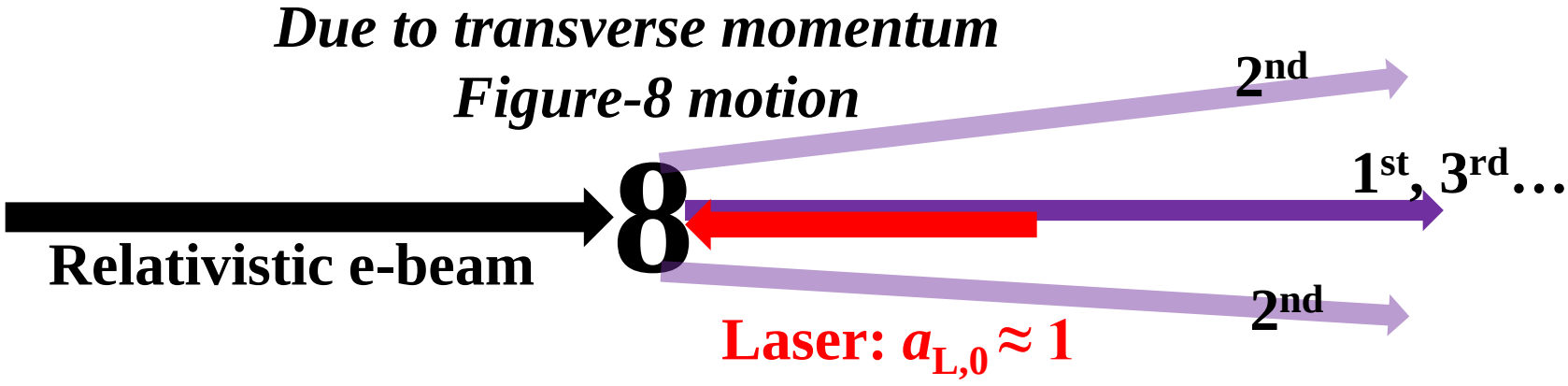


$$h\nu_{ICS} = 4\gamma^2 \nu_L > 10 \text{ keV}$$

- ✶ **Material science, Biology and Medicine [keV]**
  X-ray penetration, X-ray backlighter, Phase contrast imaging
- ✶ **Nuclear physics [MeV]**
  Photo fission, Nuclear resonance
- ✶ **High energy physics [MeV, GeV]**
  e+e- linear, γγ collider

Photon number is limited to $10^{6\text{-}8}$ /shot

Nonliner Inverse Compton Scattering



Use of $a_{L,0}$=1 laser is required. $\because a_{L,0} = eE_L\lambda_L/2\pi m_e c^2$

- **Harmonics generation:**

  (*Multi-photon process in dense photon field*)

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

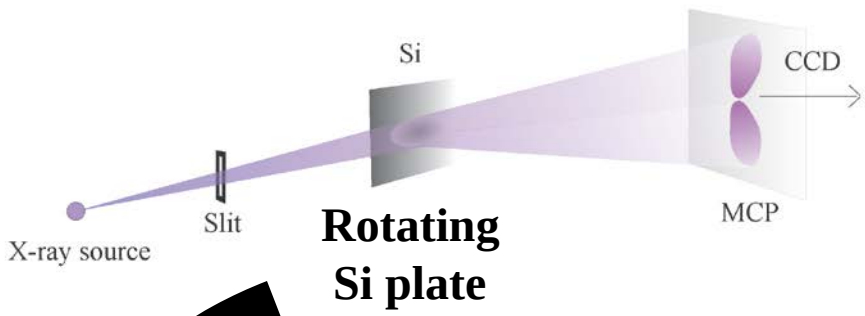
- **Red-shift, re-direction:**

  (*Mass shift effect*, $m_{Eff}^2 = m^2 + m_{L,x}^2$ [Kibbe, 1965yr])

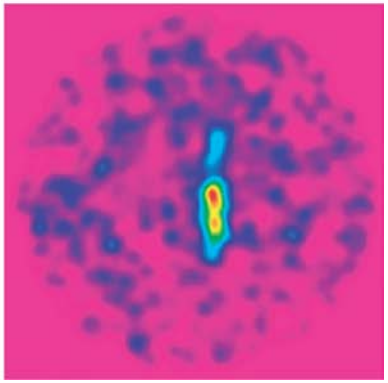
  $$h\nu_{X\text{-ray}}' = h\nu_{X\text{-ray}} / (1+a_{L,0}^2/2)$$

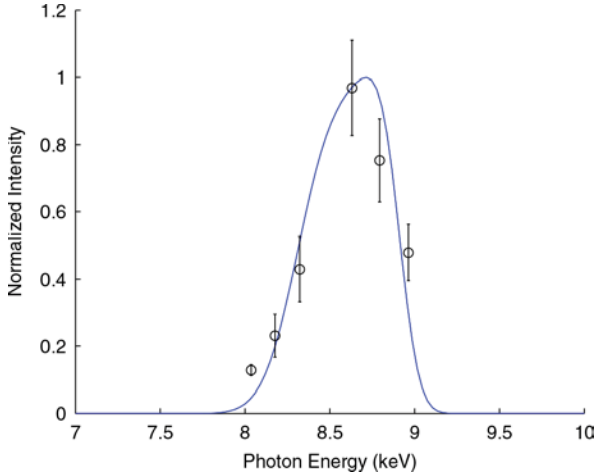
2011yr: Single shot diffraction of linear ICS ~10^8 photons/shot [1, 2]

10^4 photons diffracted from Si <111> crystal



Rotating Si plate

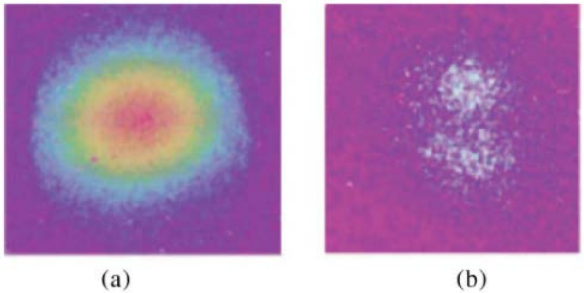




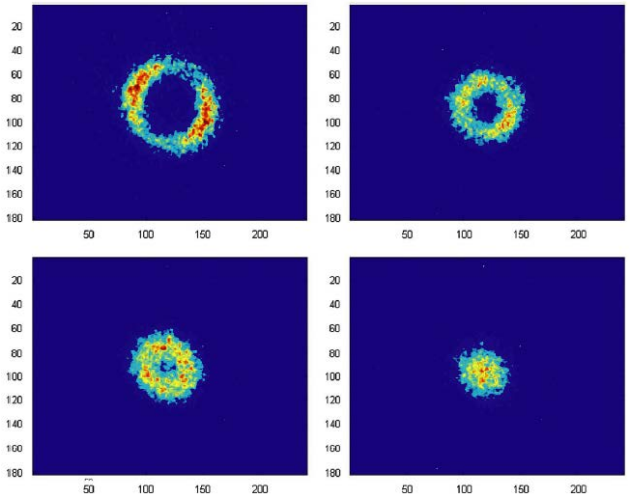
ICS Spectrum

[1, 2] F. H. O'Shea thesis and F. H. O'Shea, et al., Phys. Rev. ST Accel. Beams 15, 020702 (2012)

Previous ICS study in BNL ATF



Observation of 2nd harmonic
Ag attenuator used,
$a_{L,0} \approx 0.3$
2006yr, Kamiya, Kumita et.al.[3]



Narrow band linear ICS spectrum
Fe K-edge used,
$a_{L,0} \approx 0.2$
2009yr, Williams et. al.[4]

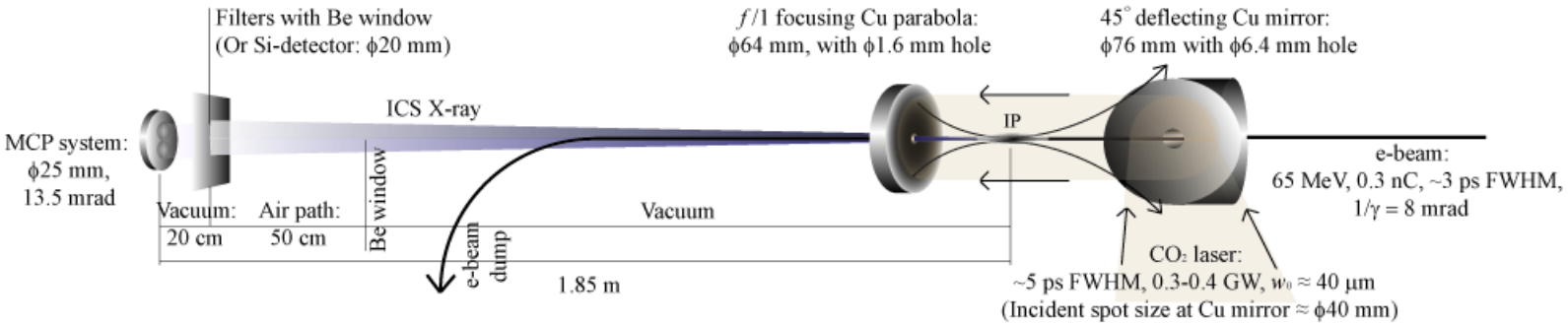
Concrete study of fully nonlinear ICS,
using $a_{L,0} \approx 1$ CO_2 laser and K-edge filter

[3] M. Babzien, Y. Kamiya and T. Kumita et. al., Phys. Rev. Lett. 96, 054802 (2006)
[4] O. Williams et al. Nucl. Instrum. Meth. A 608, S18 (2009)

Experimental condition

CO_2 laser: $a_{L,0} \approx 0.6$ (~0.3-0.4 TW, ~ 2-3 J), FWHM ≈ 5 ps, 10.6 μm, $w_0 \approx 40$ μm, $Z_R \approx 500$ μm

e-beam: $Q \approx 0.3$ nC, $\sigma_z \approx 300$ μm, $\sigma_x \approx 30$ μm, 65 MeV



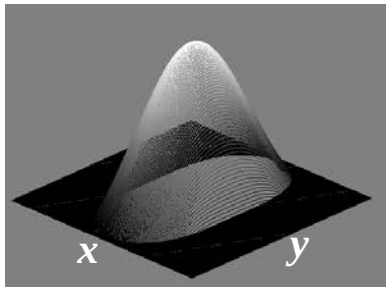
★**Compton edge: $h\nu = 4\gamma^2 E_L \approx 7.6$ keV**

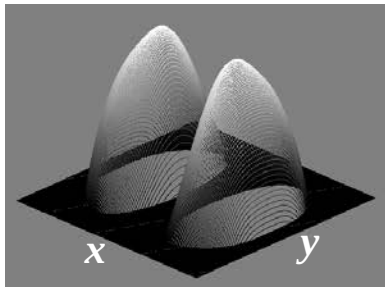
★**Photons/Pulse at I.P. : $N_\gamma = \sigma_T N_e N_L / \sigma_x^2 4\pi \approx 10^9$**

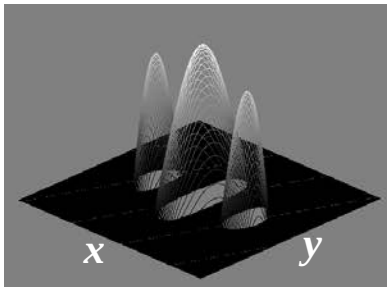
Numerical illustrations of radiation pattern

Lienard-Wiechert potential with $a_{L,0} = 0.6$

Photon number density distributions of harmonics,
in 16 mrad square ($1/\gamma \approx 8$ mrad @ 65 MeV, 10.6 μm)







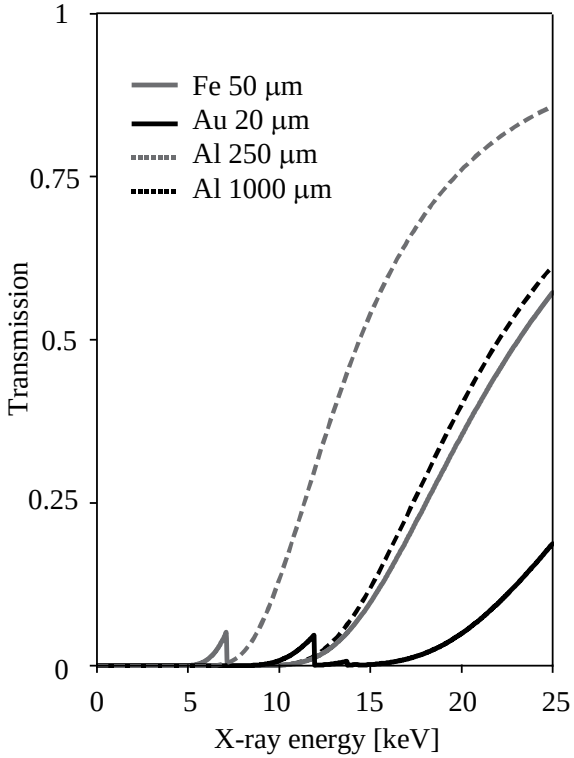
1st (0<$h\nu$<7keV), 2nd (7<$h\nu$<14keV), > 3rd (14<$h\nu$<25keV)

Geometric features:

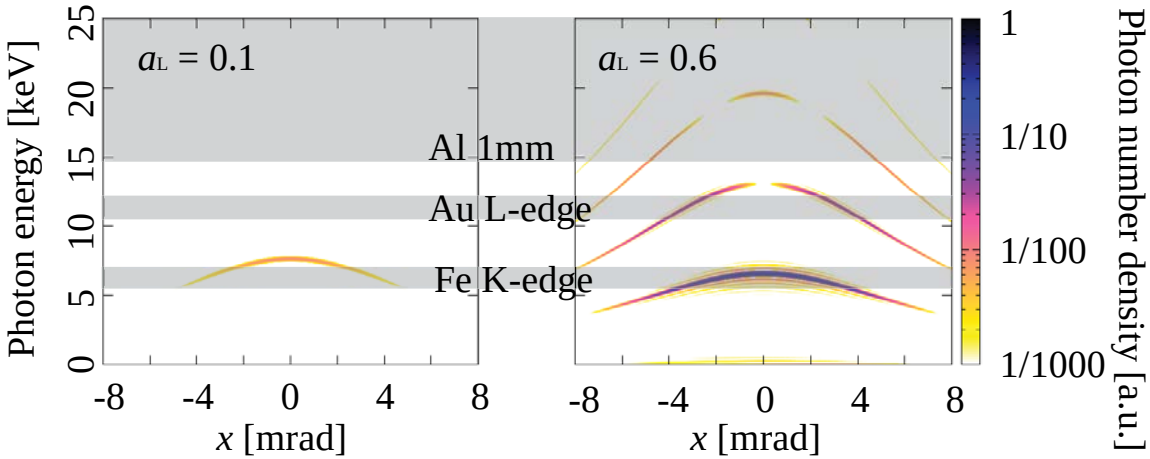
- **1st: Radiation angle < $1/\gamma \approx 8$ mrad (Slightly elliptical)**
- **2nd: Distance of crescent lobes center ≈ 10 mrad**
- **3rd: Radiation angle of on-axis component < $1/(\sqrt{3}\gamma) \approx 4$ mrad**

Specification of selected filters

Compton edge: 7.6 keV, @65 MeV, 10.6 μm

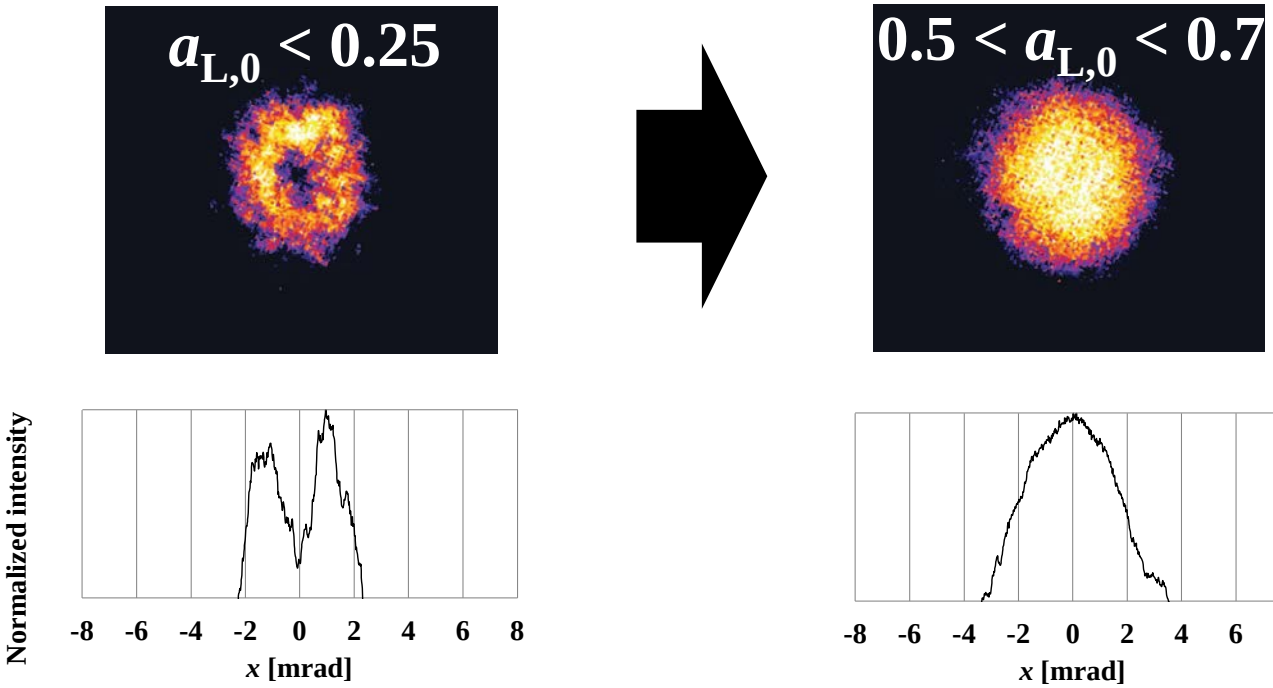


- ✶ **Fe (5 < $h\nu$ < 7 keV): Red-shift of 1st**
- ✶ **Au (10 < $h\nu$ < 12 keV): Narrow band 2nd**
- ✶ **Al 250 μm ($h\nu$ > 8 keV): > 2nd**
- ✶ **Al 1000 μm ($h\nu$ > 12 keV): = 3rd**



Lienard-Wiechert model

Observed red-shift (*mass shift effect*)



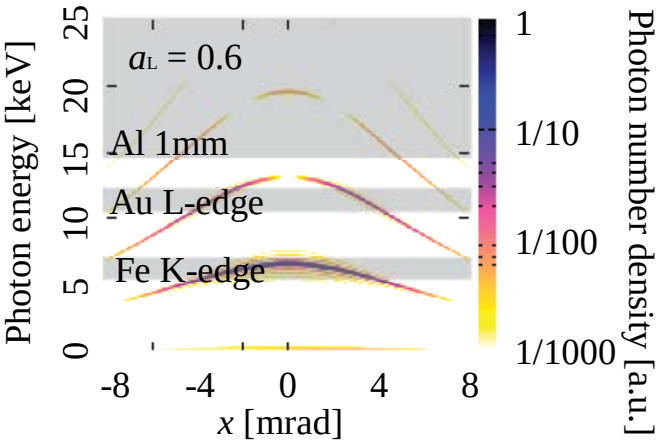
Compton edge is red-shifted from 7.6 keV to 5-7 keV

$$h\nu_{ICS,\,1^{st}} = 4\gamma^2 \nu_L/(1+a_{L,0}^2/2) \quad \rightarrow \quad \therefore a_{L,0} \approx 0.6$$

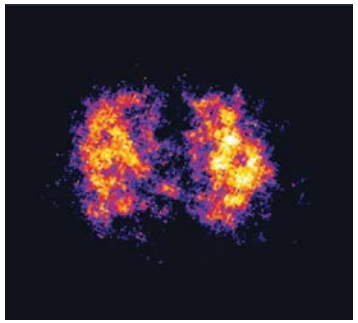
∵ Undulator equation

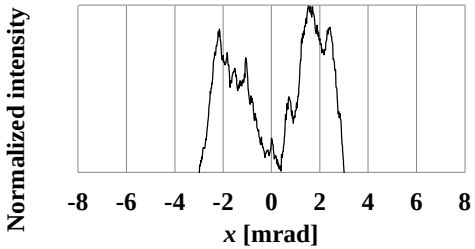
Harmonics

★Verification of 2nd harmonic energy



Au L-edge (12 keV)



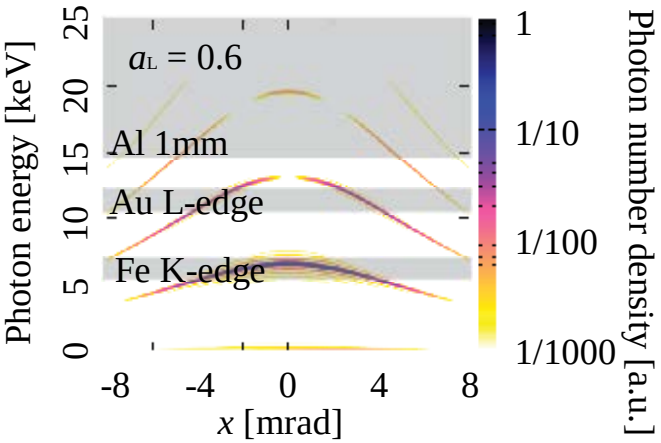


Narrow band

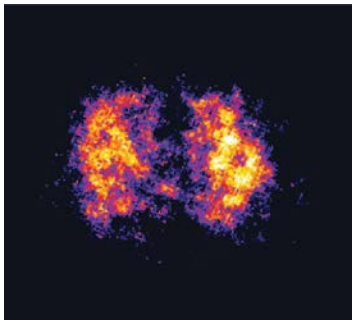
Harmonics

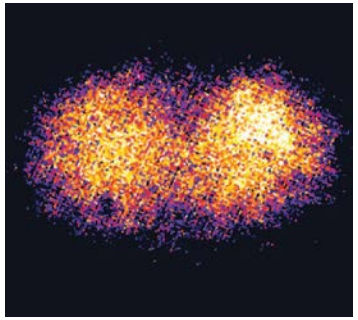
★Verification of 2nd harmonic energy

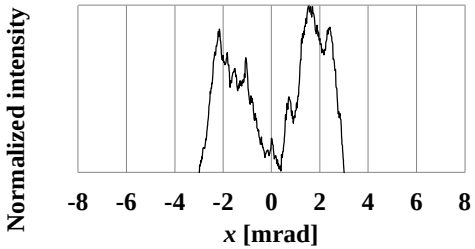
★ Relative intensity of 2nd & 3rd

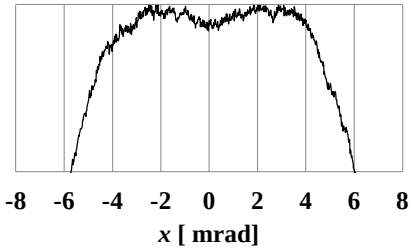


Au L-edge (12 keV) **Al 250 μm > 10 keV**









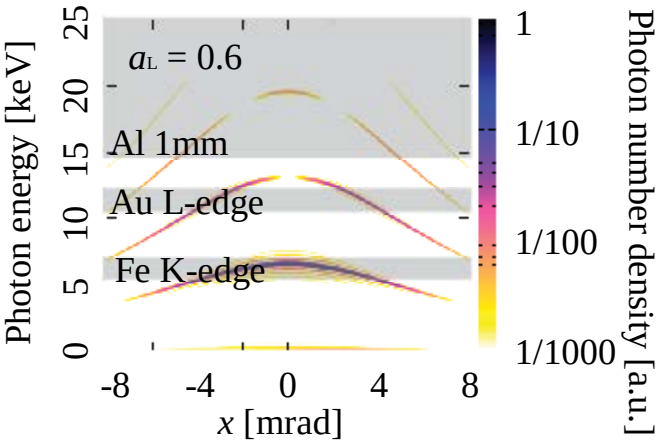
Narrow band 2nd **2nd + 3rd**

Harmonics

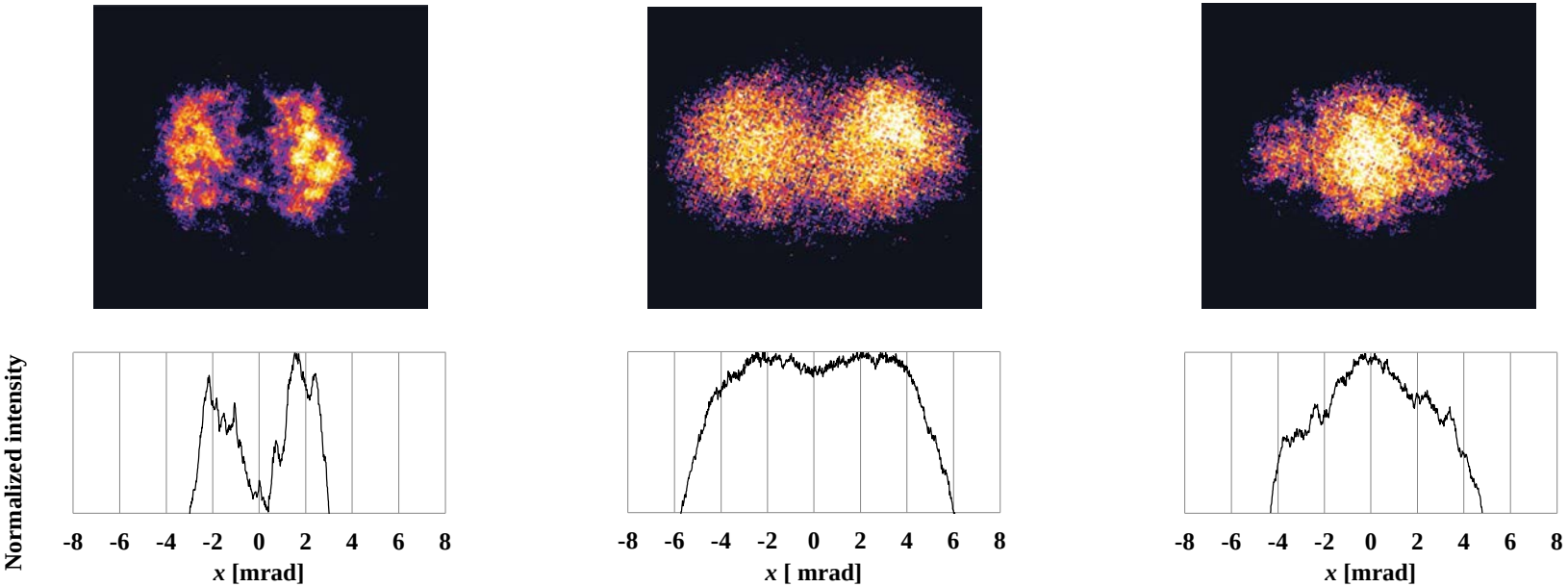
★Verification of 2nd harmonic energy

★ Relative intensity of 2nd & 3rd

★ 3rd components



Au L-edge (12 keV) | **Al 250 μm > 10 keV** | **Al 1000 μm > 15 keV**

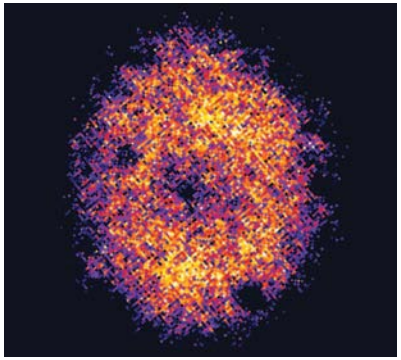


Narrow band 2nd | **2nd + 3rd** | **3rd (On-axis & lobes)**

Strong helical motion in Circular polarized laser field

¼ wave plate between regenerative and final amplifier

Off-axis Circular harmonic (> 2nd)

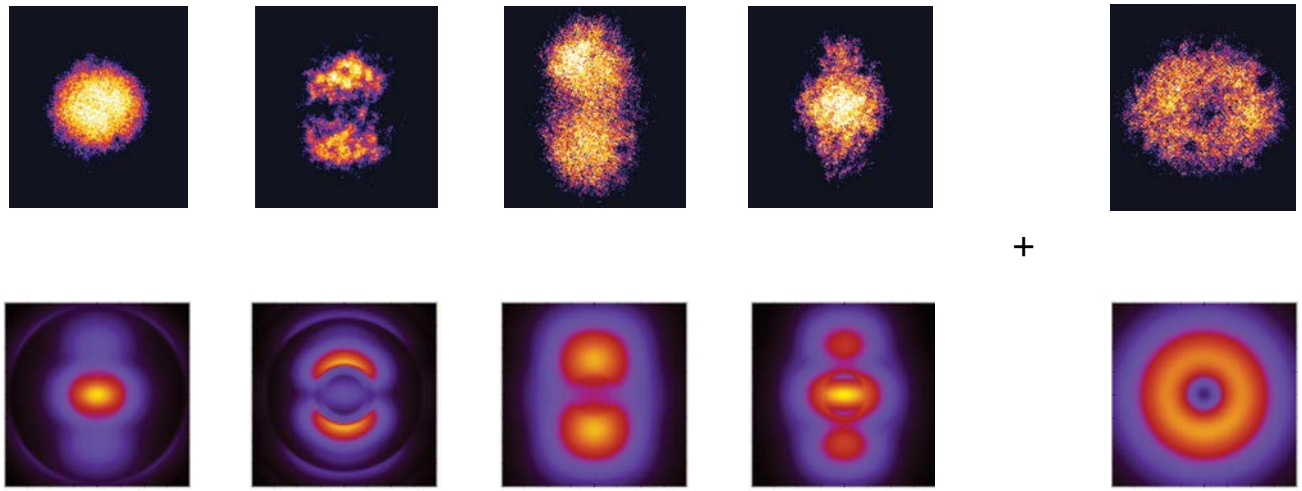


Al 250 μm > 10 keV

Verification of figure-8 motion

Linear
Transverse + Longitudinal motion (Figure-8)

Circular
Transverse motion

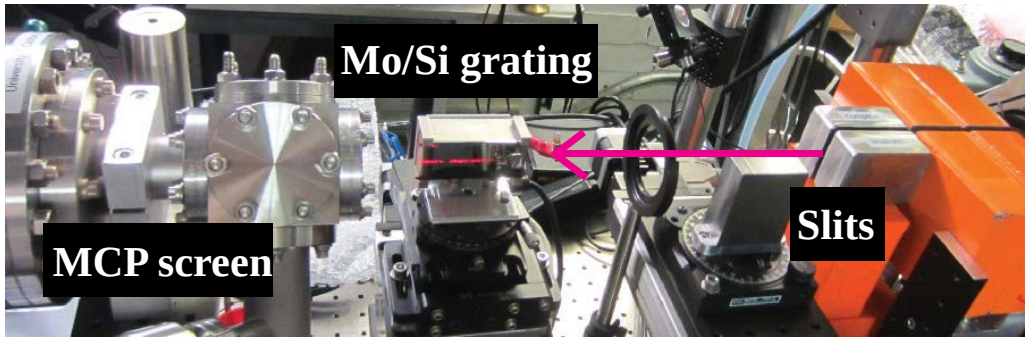


1st	2nd(narrow)	> 2nd+3rd	3rd	> 2nd+3rd
Fe 50 μm	Au 20 μm	Al 250 μm	Al 1 mm	Al 250 μm

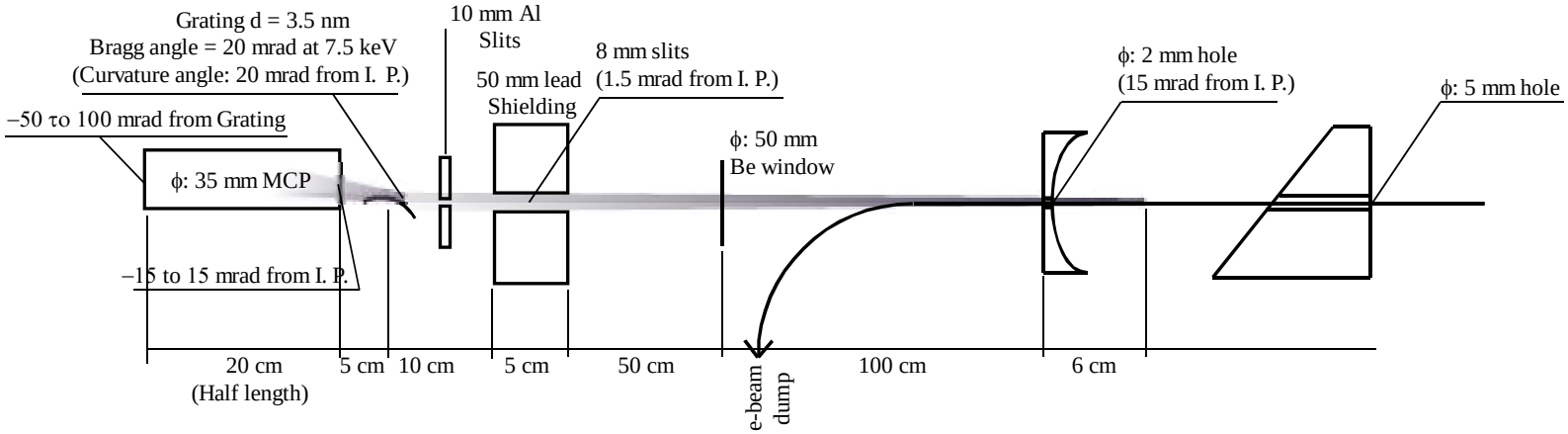
CO_2 laser: 10.6 μm, e-beam: 65 MeV, Compton edge: 7.6 keV

Observation vs Lienard-Wiechert model
with estimated $a_{L,0}$ = 0.6

Spectrum analysis using Curved Multi-layer [5]

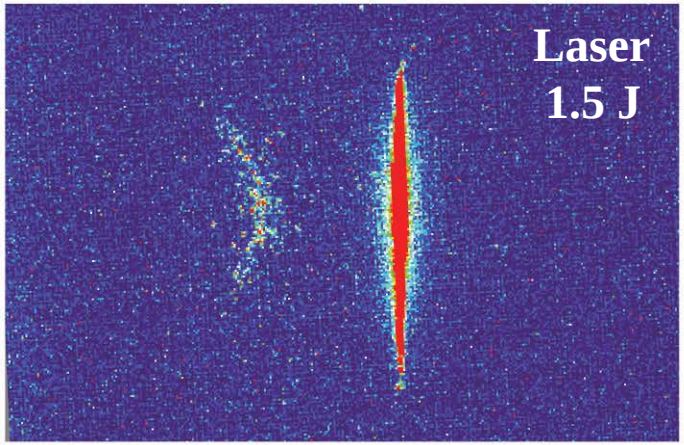


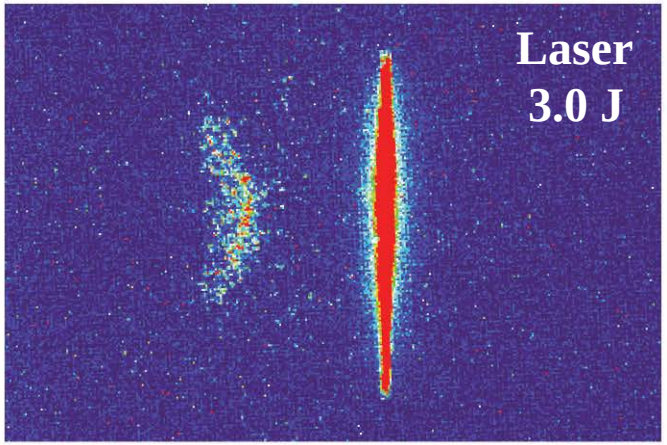
- ✡ Mo-Si Multi (45) layer thickness: $d \approx 3.3$ nm, Bragg angle ~ 25 mrad @ $h\nu$ = 7.6 keV
- ✡ Viewing angle of curved layer ~ 50 mrad (covers several keV)
- ✡ Reflectivity of Multi-layer ~ 15% @ NSLS X15A



[5] 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)

Result in July 2014 run



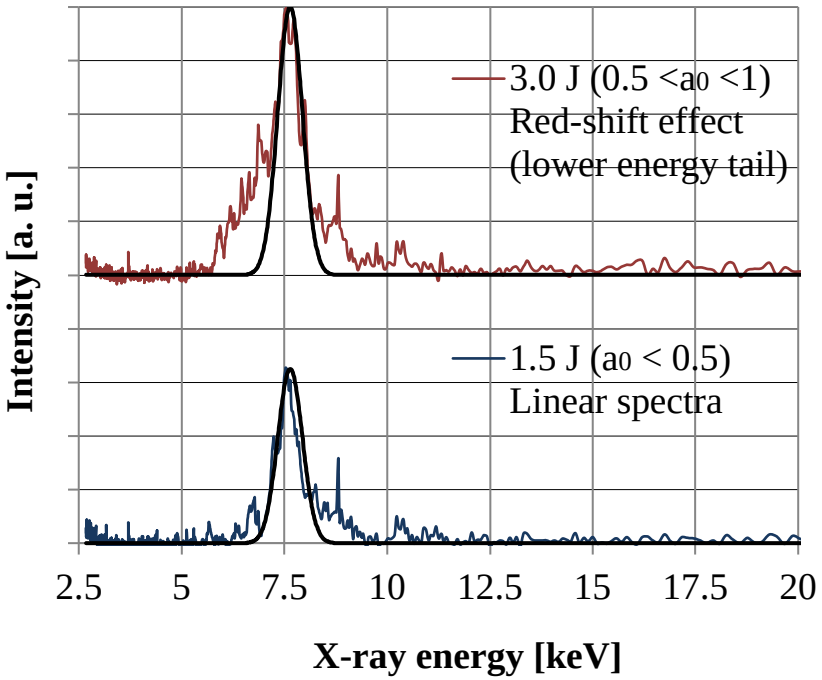


Single shot double differential spectrum is obtained.

CO_2: 9.25 μm, e-beam 61 MeV, Compton edge 7.6 keV

is under investigation
by both Quantum mechanical and Classical approach.

On-axis ICS spectrum



<u>Evidence of on-axis ref-shifting, mass shift, in strong laser field</u>

However: High energy component at 8-10 keV…? etc.

→ CO_2 laser's spectrum around 9.25 μm?

→ e-beam energy spectra in BL1?

Summary of feasibility study in 2012-2014yr

★ **3rd order harmonic radiation and red-shifting through angular spectrum distribution using foil filters is observed.**

★ **Single shot double differential spectrum and red-shifting using curved multi-layer grating is observed.**

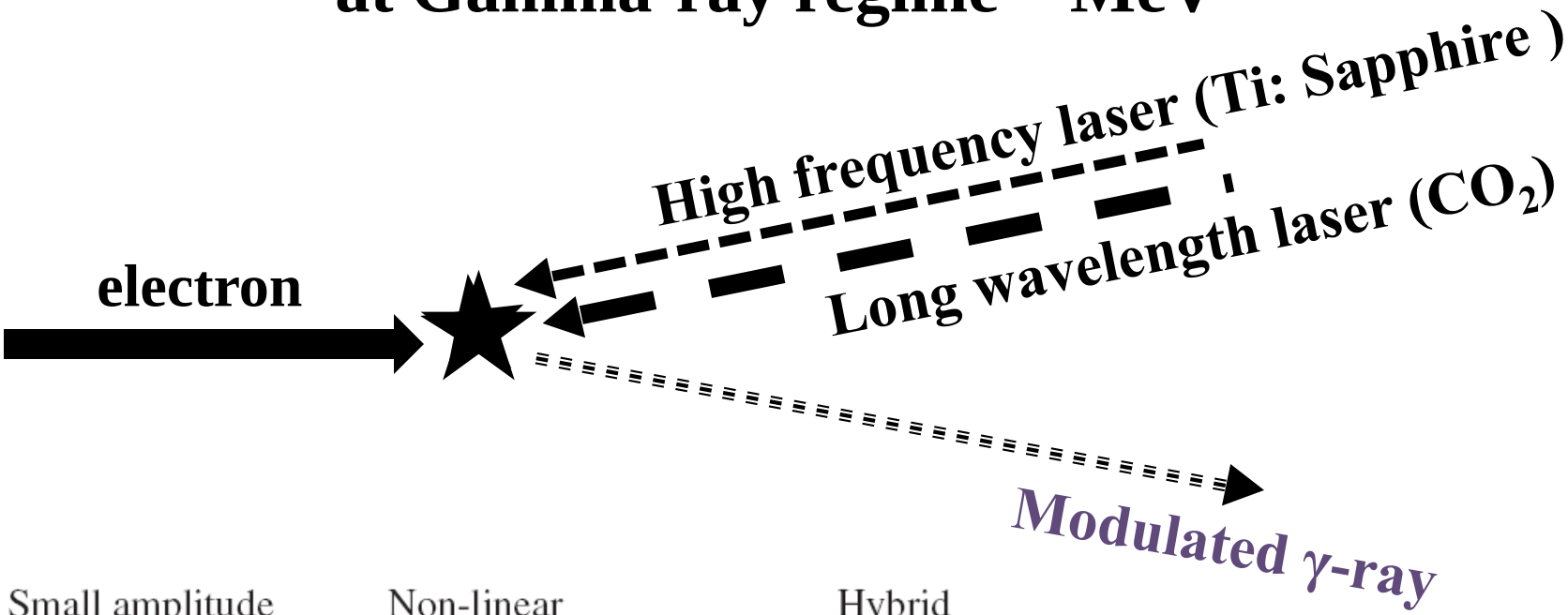
Future plan

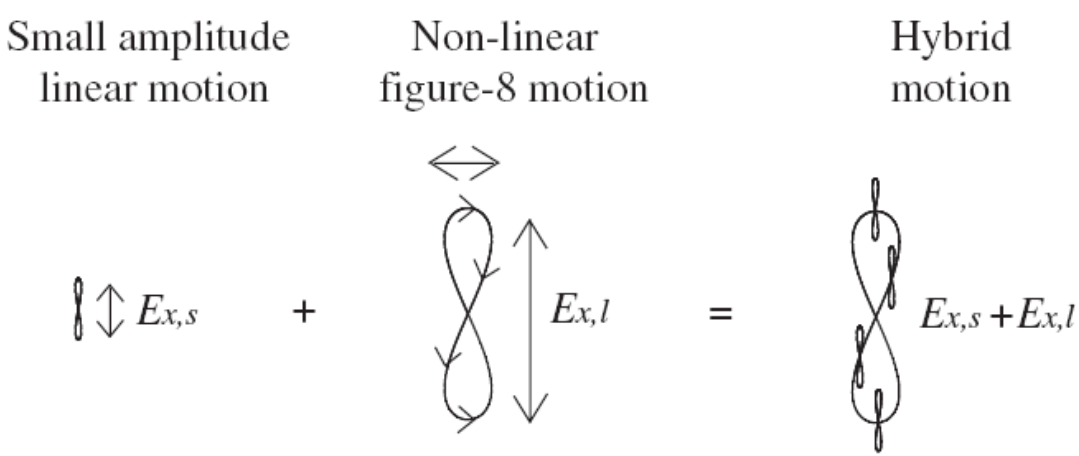
(a) Completion of the spectrum study BL1

(b) Design, and preparation for realization of the Two wavelengths nonlinear Gamma-ray ICS in ATF II

(c) Initial investigation of IFEL/ICS scheme using a laser reflector in BL2

Two wavelengths nonlinear ICS at Gamma-ray regime ~ MeV





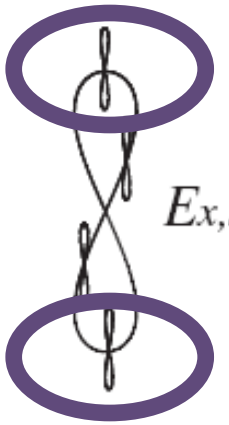
is under investigation.

[6] Y. Sakai et. al, Phys. Rev. ST Accel. Beams Vo. 14, 120702 (2011)

Small oscillation superimposed upon large figure-8

$$\boldsymbol{E}_{\mathrm{LW}} = \frac{m_e}{e}\frac{r_e}{R}\frac{\mathbf{n}\times\{(\mathbf{n}-\boldsymbol{v}/c)\times\boldsymbol{w}\}}{(1-\mathbf{n}\cdot\boldsymbol{v}/c)^3}$$

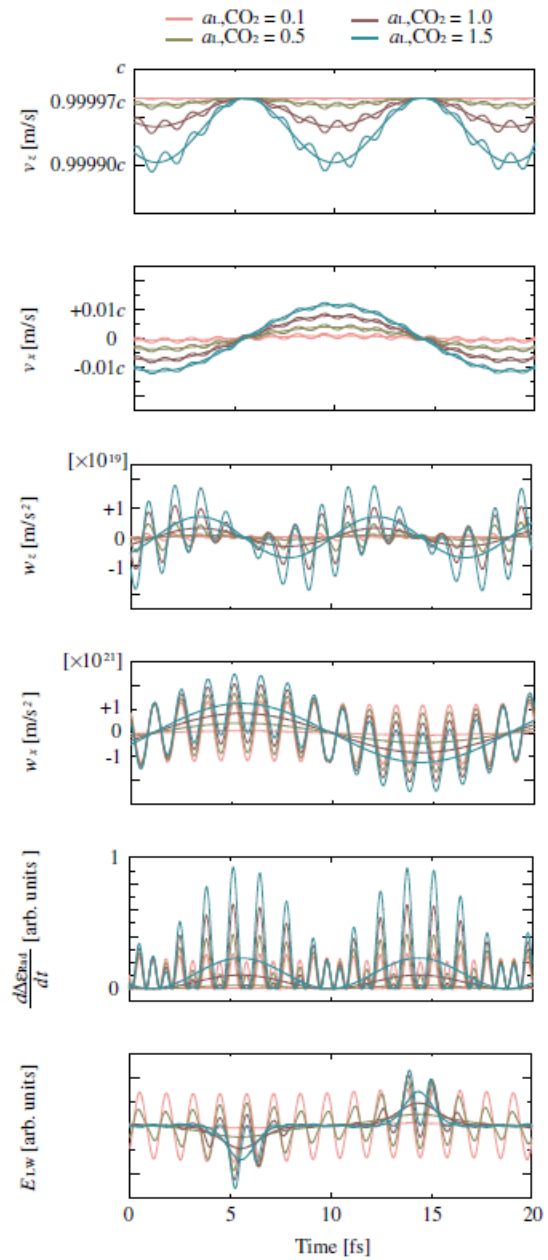
$$\frac{m_e}{e}\frac{r_e}{R_0}\frac{\overbrace{w_x(1-\frac{v_z}{c})+\frac{w_z v_x}{c}}^{\text{contains high frequency factor}}}{\underbrace{(1-\frac{v_z}{c})^3}_{\text{with cycle of figure-8 motion}}}$$



←Use of radiation phase

Directed toward observer

$E_{x,s} + E_{x,l}$



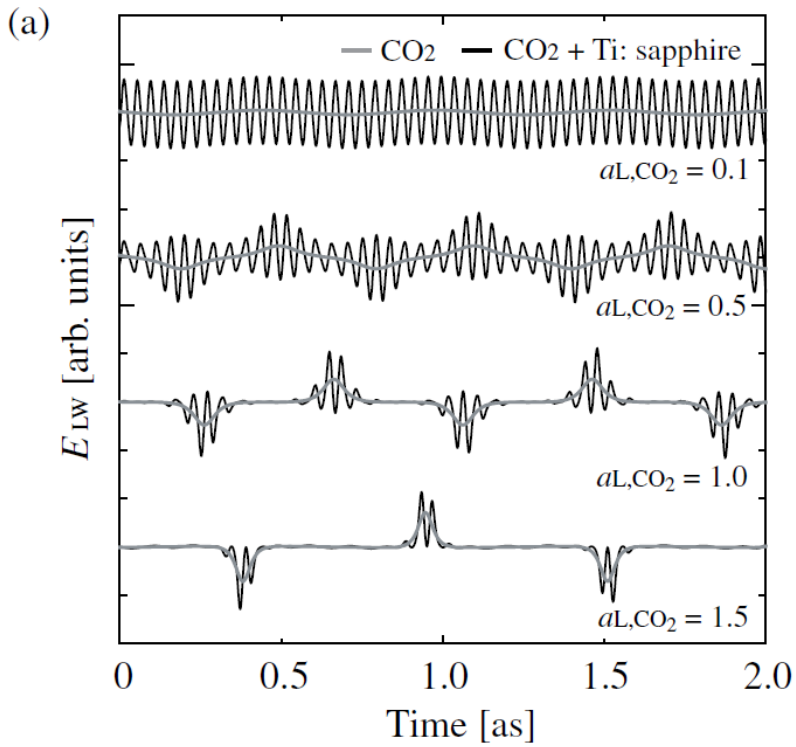
Particle motion & X-ray waveform

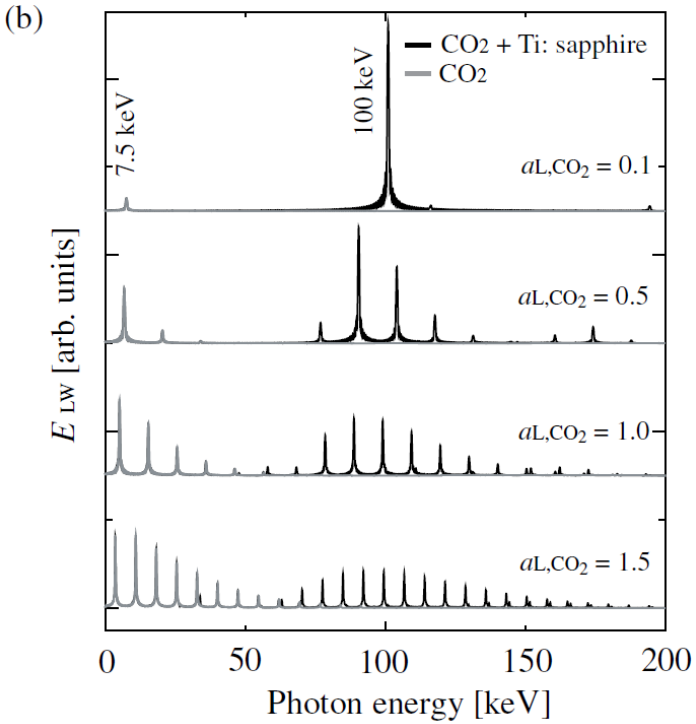
Controlling a ICS's radiation kinetics

Pulsed waveform modulation along figure-8 orbit

Harmonic radiation at

$$h\nu_{ICS} = 4\gamma^2 h(\nu_{L,Short} + n\nu_{L,Long})$$

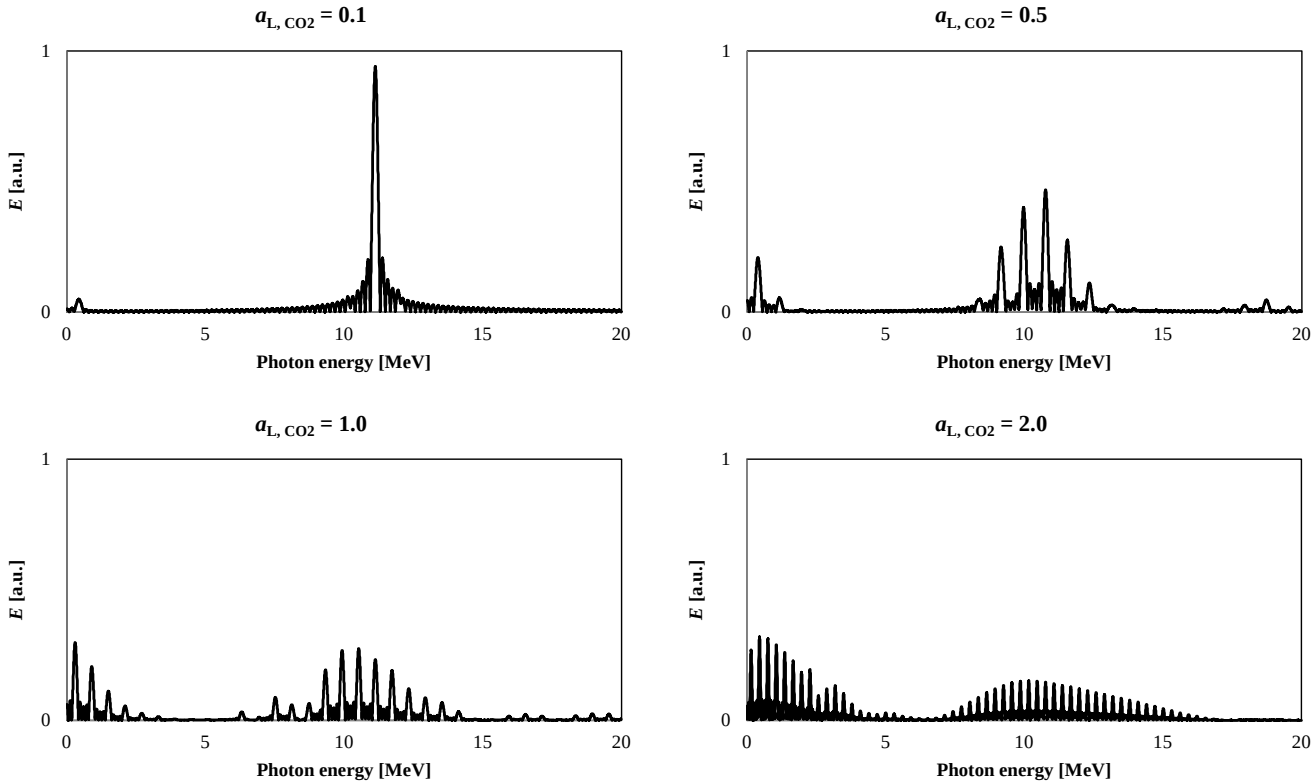




Numerically calculated Lienard-Wiechert potential $E_{LW,x}(t_{screen})$ on $(x, y, z) = (0, 0, 0)$

Anticipated γ-ray spectrum

e-beam: 1 GeV, CO_2 10.6 μm with $a_{L,0}$ = 2, and TW Ti: Sapphire 800 nm case



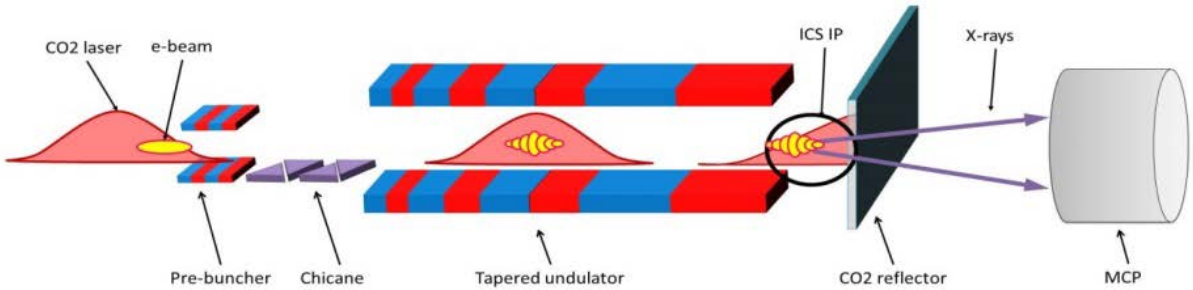
✶**Time encoding using laser's rising phase (tail)**

Initial demonstration can be done using observed red-shifting, (Δhν~20%), in BL1?

✶**Spectrum matching to photo fission cross section at ~ MeV**

Collaboration of IFEL/ICS for 10 MeV photon?

Initial IFEL/ICS combination test using a foil reflector



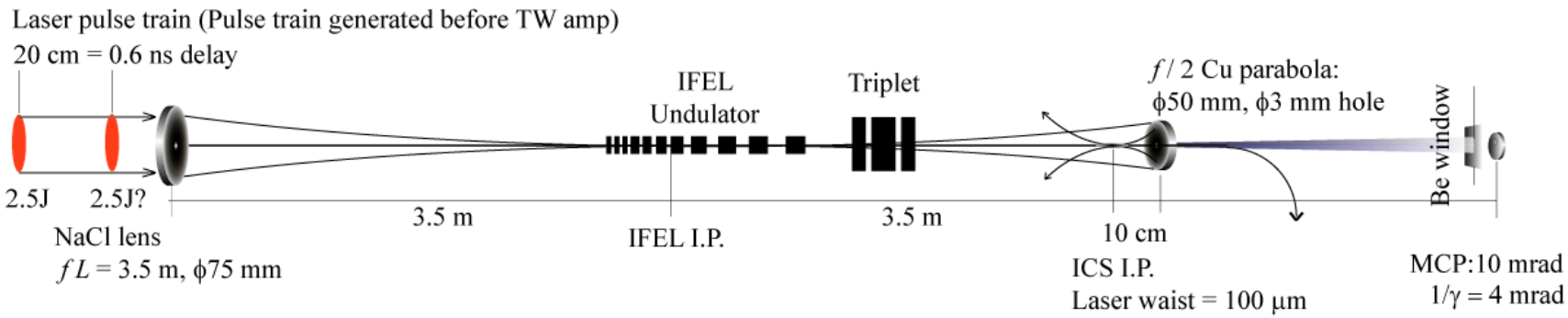
The IFEL/ICS concept lead by I. Gadjev

~ $10^{5\text{-}6}$ ICS photons/shot?

- ✡ **Al foil thickness = 10s μm,**
  (Transparent for 10-30 keV ICS X-rays, & Attenuate Bremsstrahlung)
- ✡ **Available e-beam charge at ~ 80-100 MeV is ~30 % (~0.1 nC),**
- ✡ **Rising component of CO_2 laser has 10 % of its total energy (~0.3 J)**
- ✡ **Laser waist at ICS I.P. ~ mm ?**

IFEL/ICS would be,

using a <u>laser pulsed train</u> and <u>beams focusing optics in BL2</u>?



~ $10^{7\text{-}8}$ ICS photons/shot??

Details will be shown in J. B. Rosenzweig's talk as ICS in ATF II!

Future plan >2015yr

(a) Completion of the observation of double differential spectrum in BL1

1. Discussions & Details of 9.25 μm laser and e-beam (*No beam time*)

(b) Design, and preparation for realization of

the Two wavelengths nonlinear Gamma-ray ICS in ATF II

1. Time encoding by using a nonlinear effect in BL1

2. Synchronization system for mJ level Ti:Sapphire (*No beam time*)

↓

(c) Initial investigation of IFEL/ICS scheme using a laser reflector in BL2

For use of focusing optics:

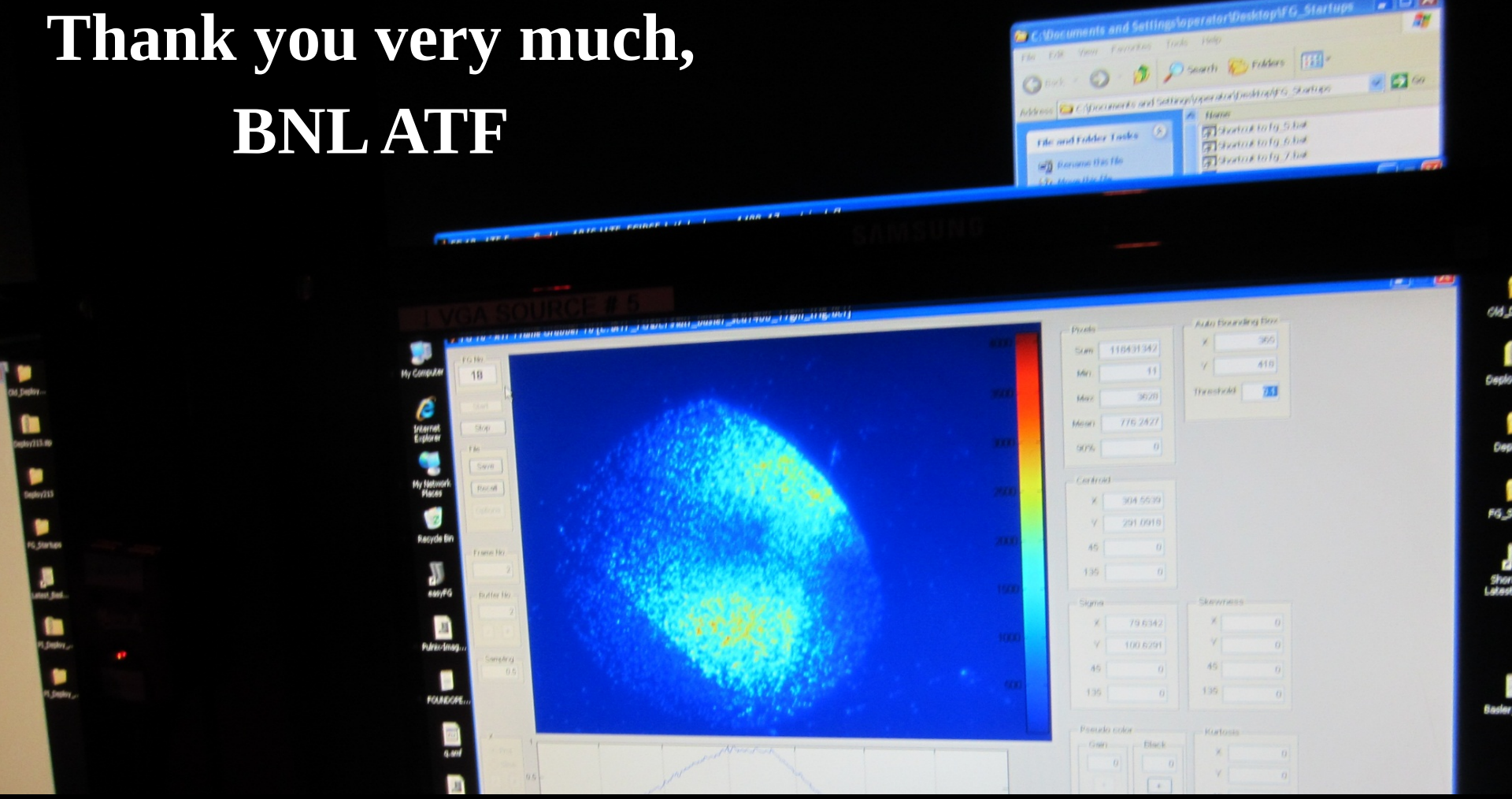
1. Single linear ICS X-ray verification in BL2, (with energy chirp?).

2. Generation of double 2-3J CO_2 pulse train in BL2

3. IFEL/ICS collaboration

Thank you very much,

BNL ATF



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