Progress in Nonlinear Inverse Compton Scattering at UCLA

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Advanced Medical Imaging with Synchrotron and Compton X-ray Sources

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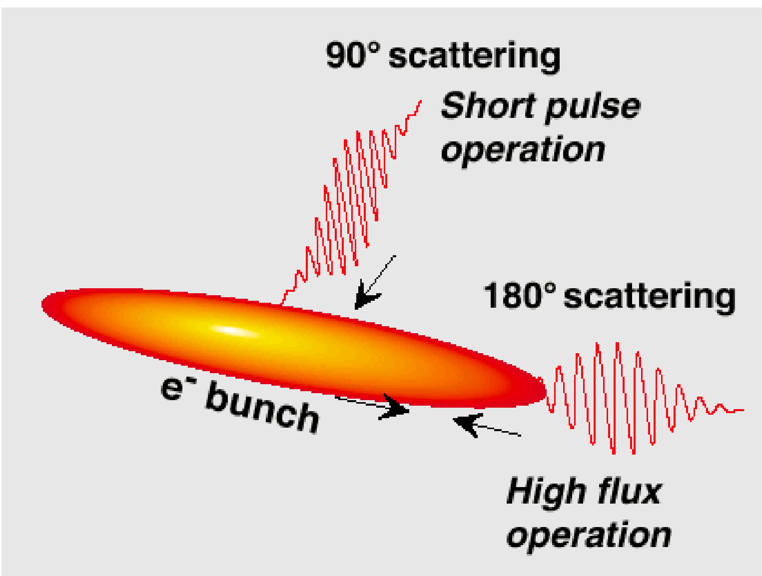
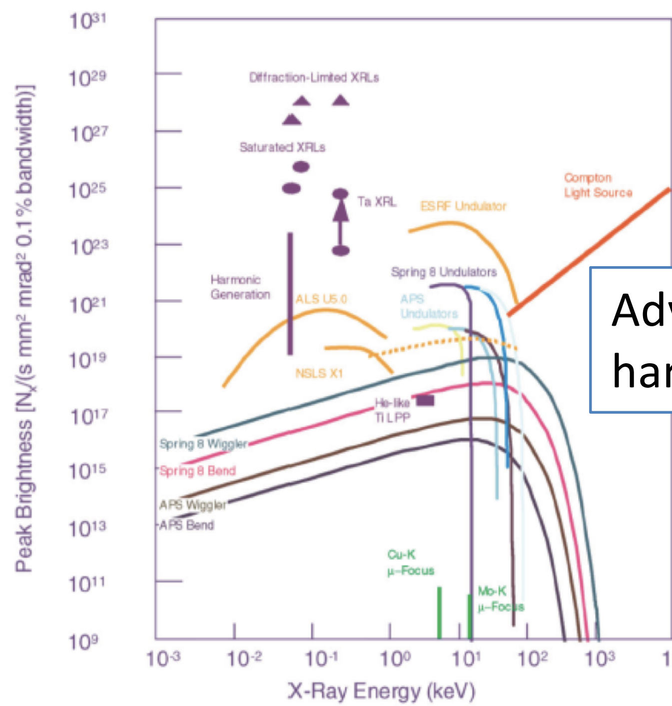
BROOKHAVEN NATIONAL LABORATORY

keV-to-MeV Photon Production: Inverse Compton Scattering (ICS)

- Collision of relativistic electron beam bunch with intense laser pulse
- Source is directional, – *to* sub-100 fs
- Scattered light is ultra-fast, quasi-**monochromatic**
- **Tunable wavelength** (relativistic Doppler, like FEL)
- Uniquely powerful source of monochromatic MeV γ's
  - UCLA theme - merge with novel accelerators: **5th generation light source**

$$\lambda_{sc} \approx \lambda_L / 4\gamma^2$$

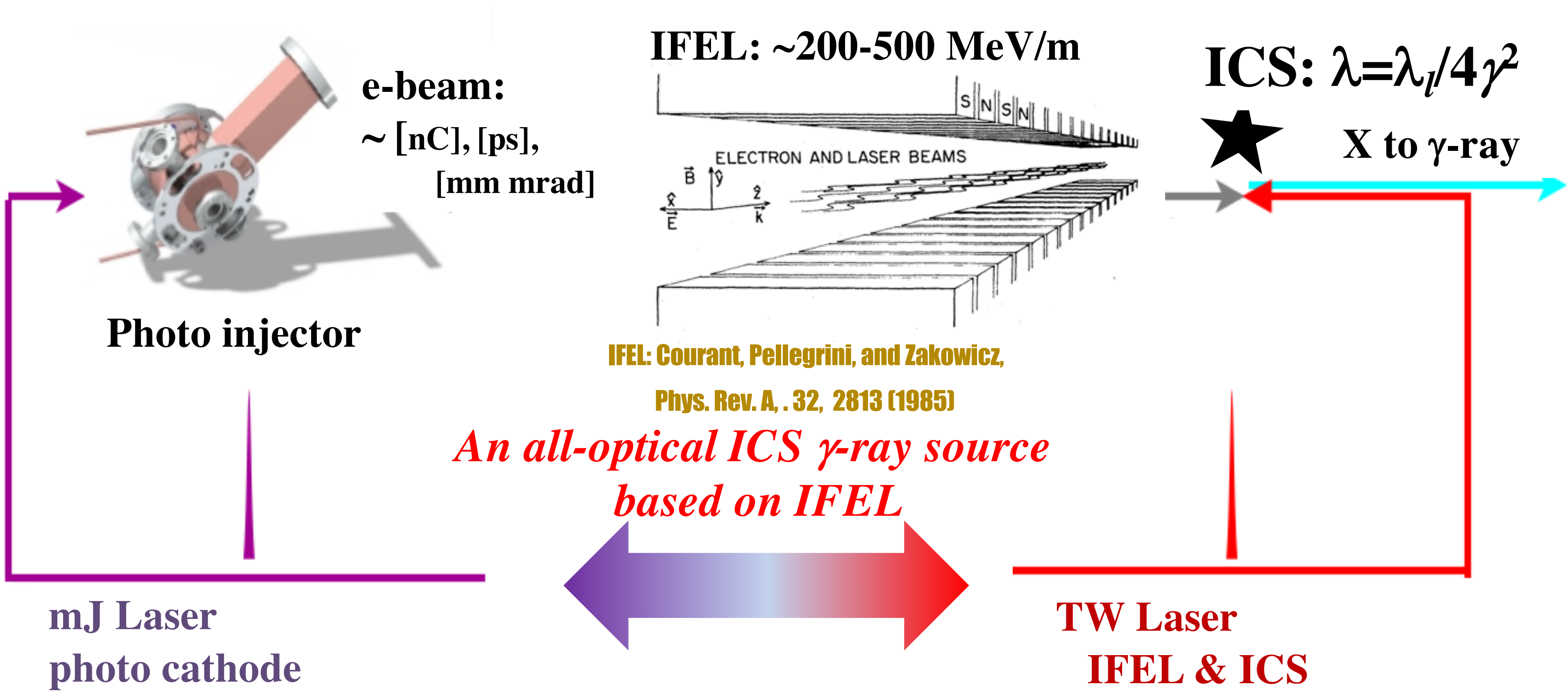




Advantages in hard γ's

F.V. Hartemann *et al.*, *PR ST AB* **8**, 100702, 2005

Recent emphasis: UCLA experiment *RUBICONICS*
Compact γ-ray source enabled by lasers and electron beams



ICS permits compact undulator, access to MeV photons

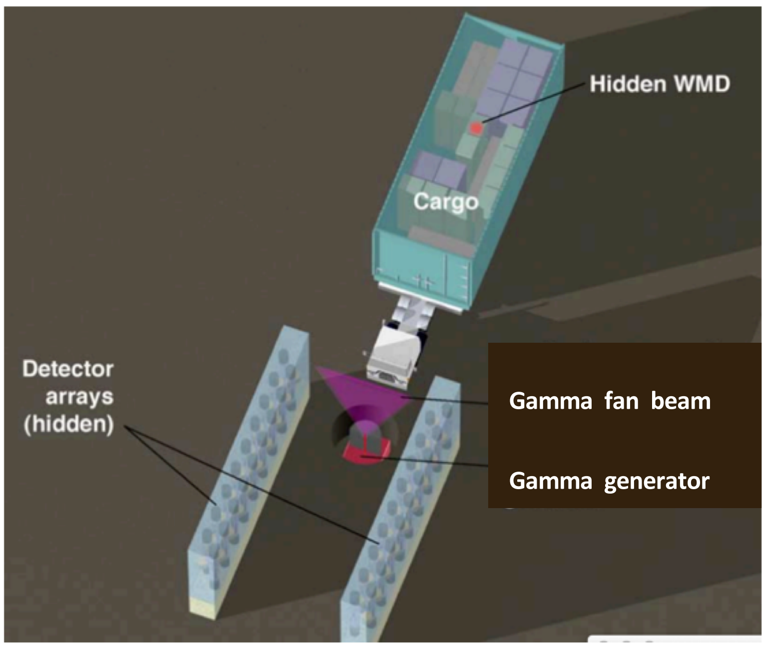
IFEL: high gradient laser-based, free-space acceleration scheme

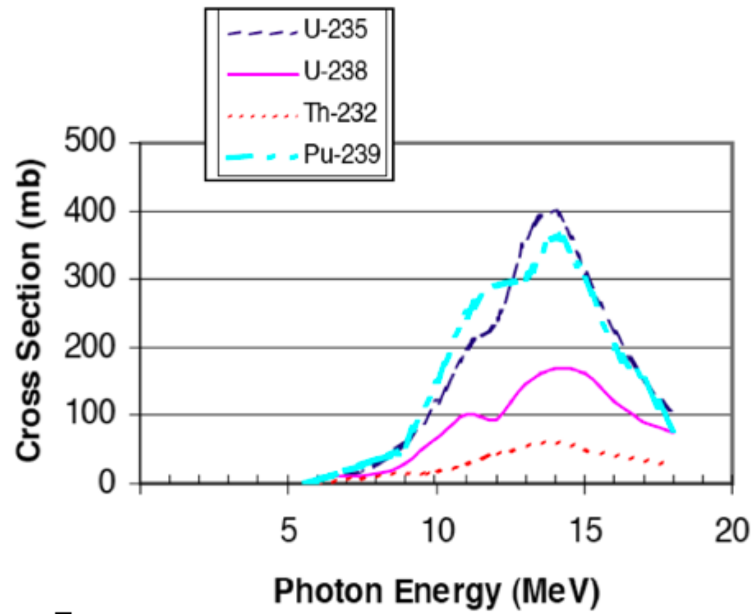
* Low collective e-beam effects
* Laser can be recirculated (unlike, *e.g,* in plasma)

Recent context: applications of narrow-spectrum MeV photons

★ Active detection of SNM for DHS; ideal mission for ICS

National security: Active detection of nuclear materials via photo-fission (also nuclear fluorescence). In basic research there is overlap with the ELI-NP mission.





★ Directed γ's, mrad divergence, *U*~10-15 MeV

★ Required photon number > 10^{12} /sec

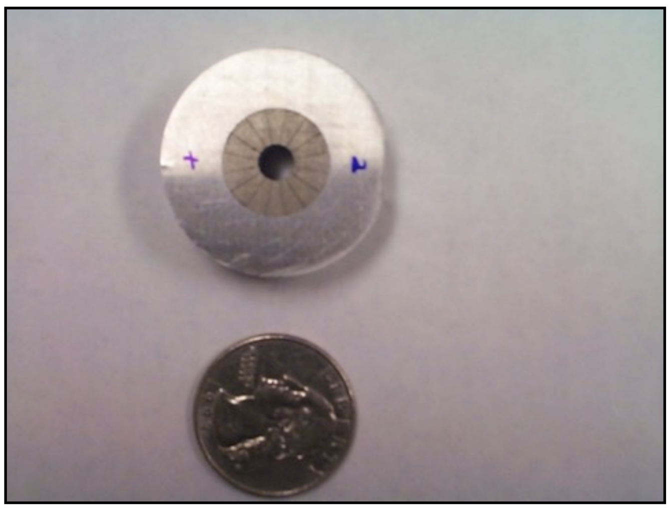
★ Similar flux requirements for keV γ's in *medicine*, etc. Spinoff!

High flux ICS Demands High Collision“Luminosity”

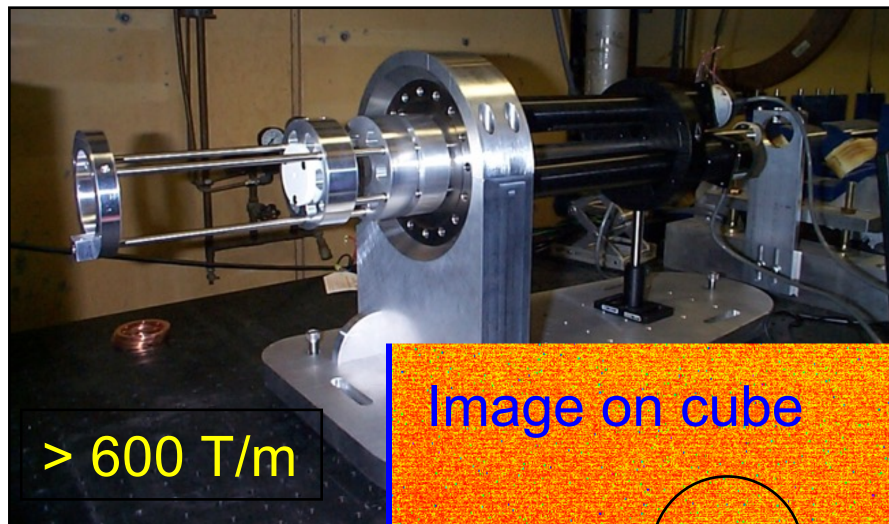
- **Like HEP collider: timing, pointing, *focusing***
- Low emittance electron beam
- Ultra-strong e- focusing (<10 μm e- spots)
- Innovation: ultra-strong PMQs, “camera” triplet

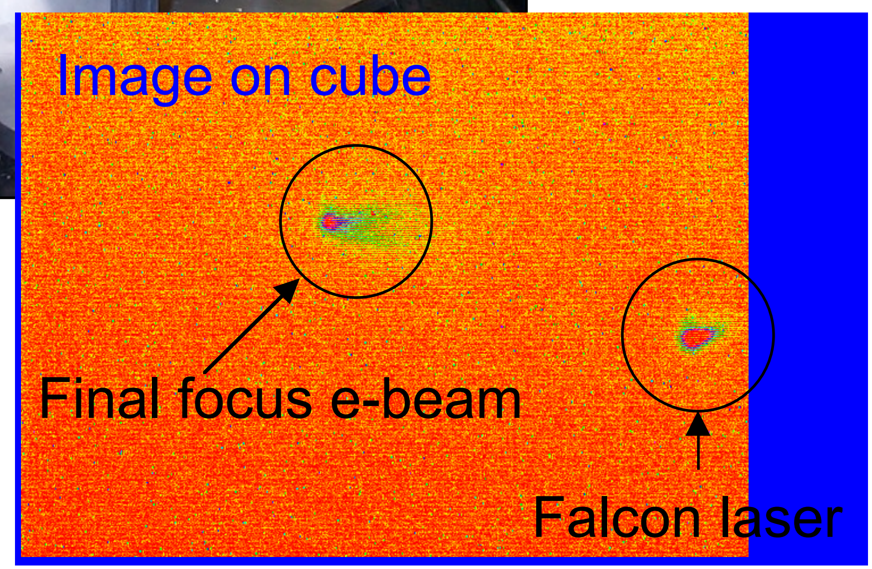
J. K. Lim, et al., *Phys. Rev. ST Accel. Beams* **8**, 072401 (2005)

Also used for PWFA@BNL!



Designed and built at UCLA





But there is a *limit* on focusing…

Intense, focused beams increase X-ray flux

High brilliance

Luminosity/pulse

$$N_\gamma = \sigma_T \mathcal{L} = \sigma_T N_e N_L / 4\pi\sigma_x^2 \approx 10^{10}$$

$$N_\gamma = 0.6\alpha\left(k_L\sigma_z\right)a_L^2 N_{e-} \propto a_L^2$$

$$a_L = \frac{eE_L\lambda_L}{2\pi m_e c^2}$$

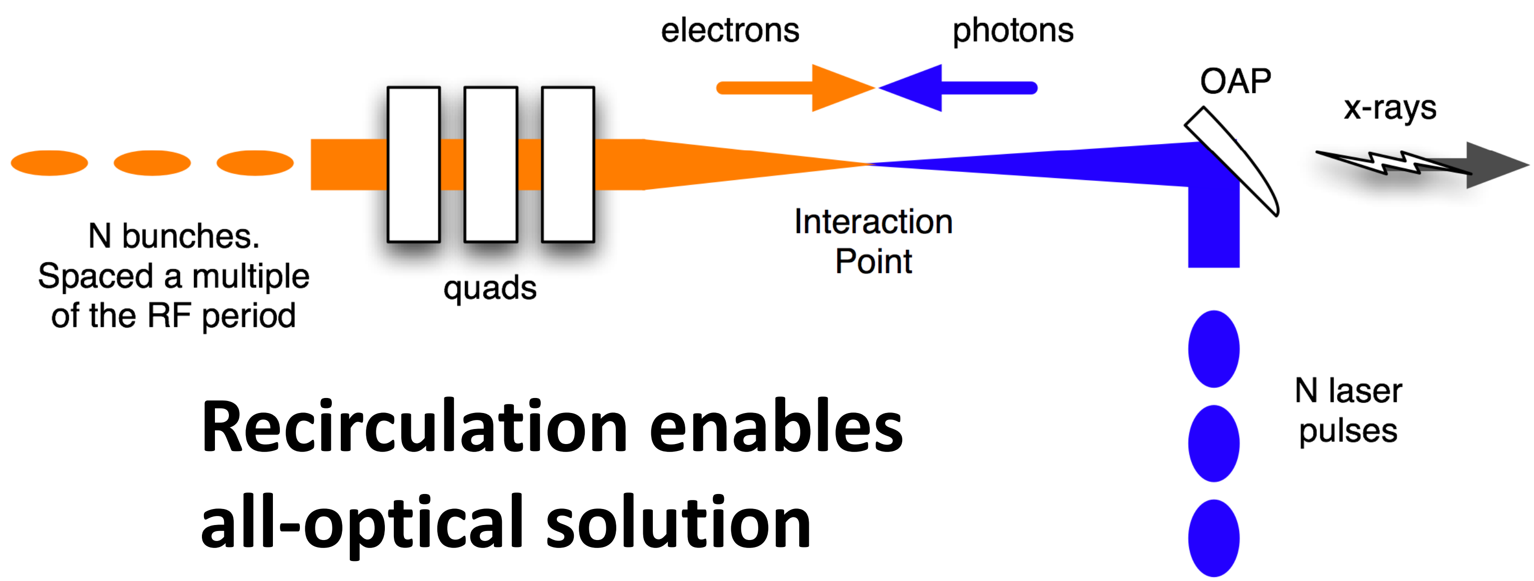
J. B. Rosenzweig, O. Williams, *Inter. J. Mod. Phys*. A 23, 4333 (2007)

Focused laser produces nonlinear electrodynamic effects – increased bandwidth~a^2, harmonic generation; lower γ brightness

We thus study fundamental *electrodynamics* in high intensity (E_L^2), long λ_L (high a_L) laser field

Alternative: multi-bunch ICS interaction

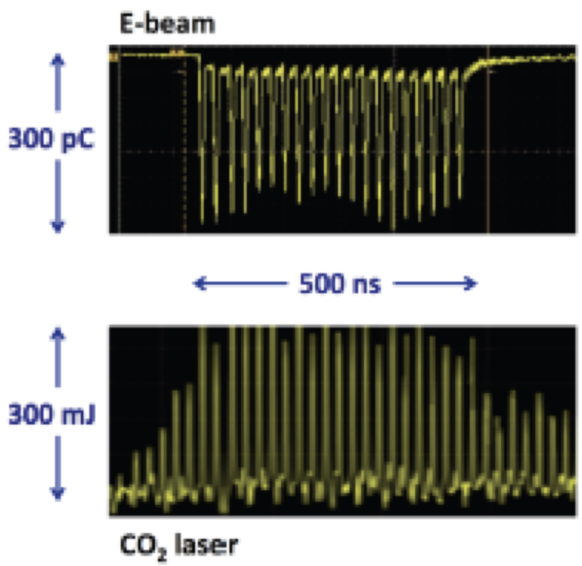
- Optimized ICS source produces ~10^8 photons *per pulse*
- Active interrogation/medicine needs >10^{12} photons/s
- State of the art accelerator and laser systems ~500 pps
- Few laser photons used up in ICS interaction
- **Solution: re-use photons, interact *N* time per RF pulse**
  - Produce *N* e- bunches per RF pulse, recirculate laser *N* times



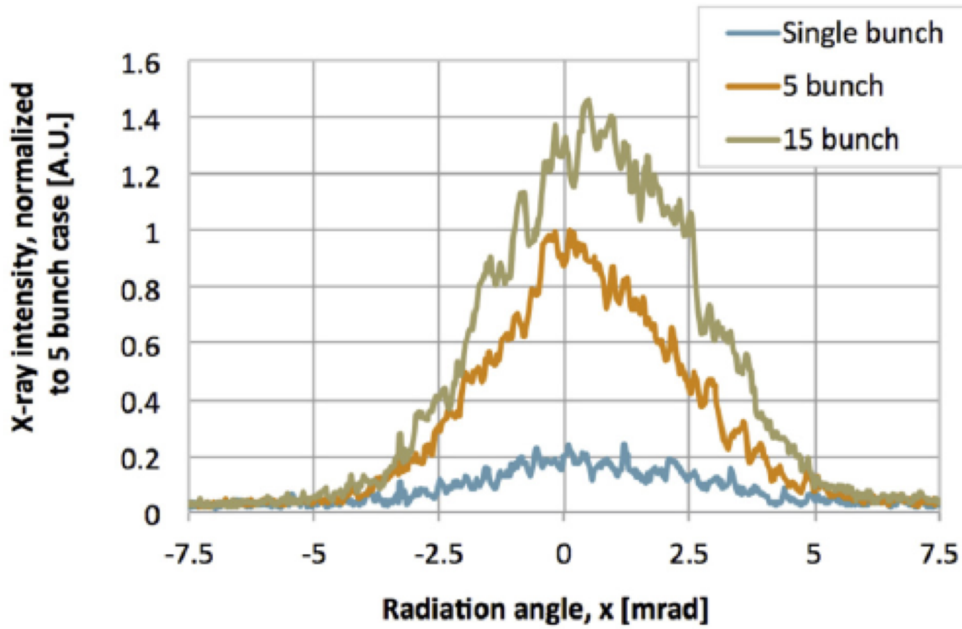
Recirculation enables all-optical solution

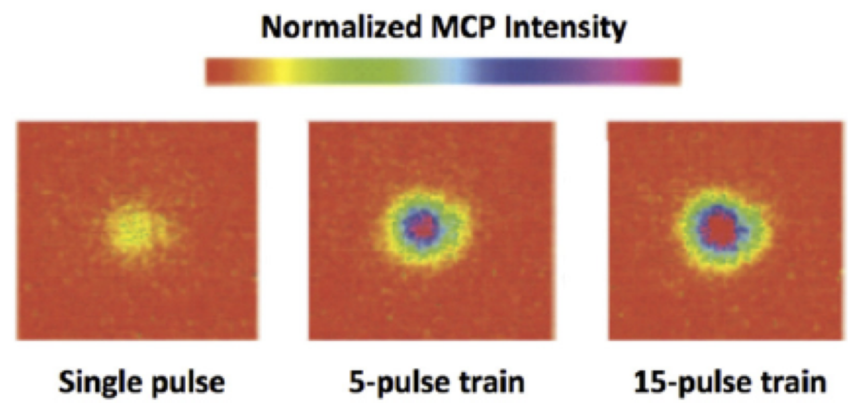
Recirculating ICS interaction demonstrated by RadiaBeam-UCLA

- 40 MHz pulse train, active cavity
- Demonstration of significant ICS output through pulse train



- Recirculation of IFEL...





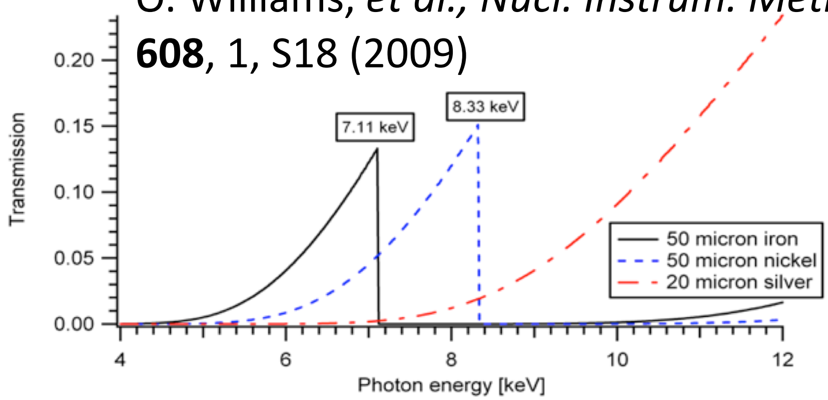
A. Ovodenko, *et al. Appl. Phys. Lett.*, 109, 253504 (2016)

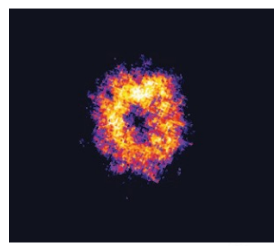
Inverse Compton Scattering: Experimental Context

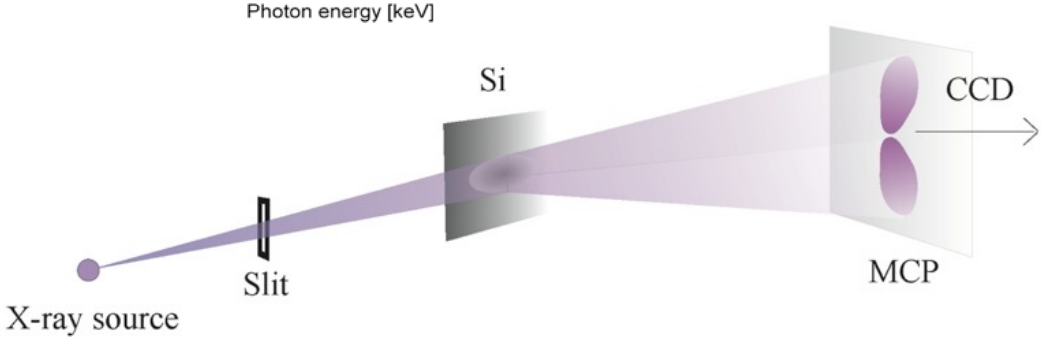
- *K*-edge filtering diagnostics
- Single-shot phase contrast imaging
- Single-shot diffraction

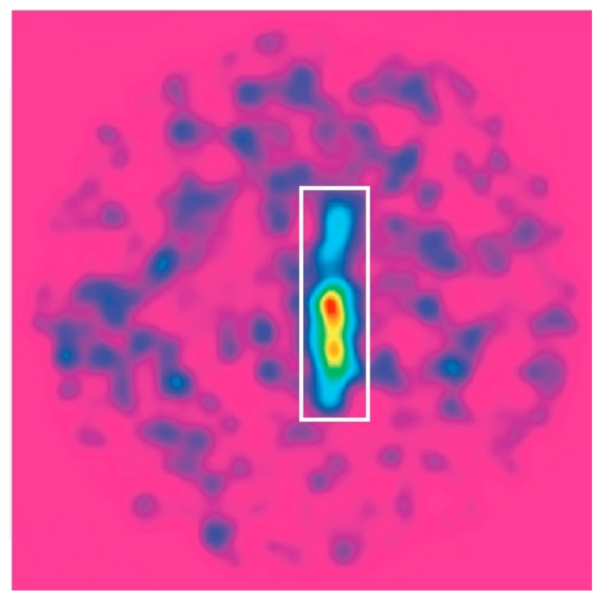
P. Oliva, et al., *Appl. Phys. Let.* 97, 134104 (2010)

O. Williams, *et al., Nucl. Instrum. Meth. A,* **608**, 1, S18 (2009)



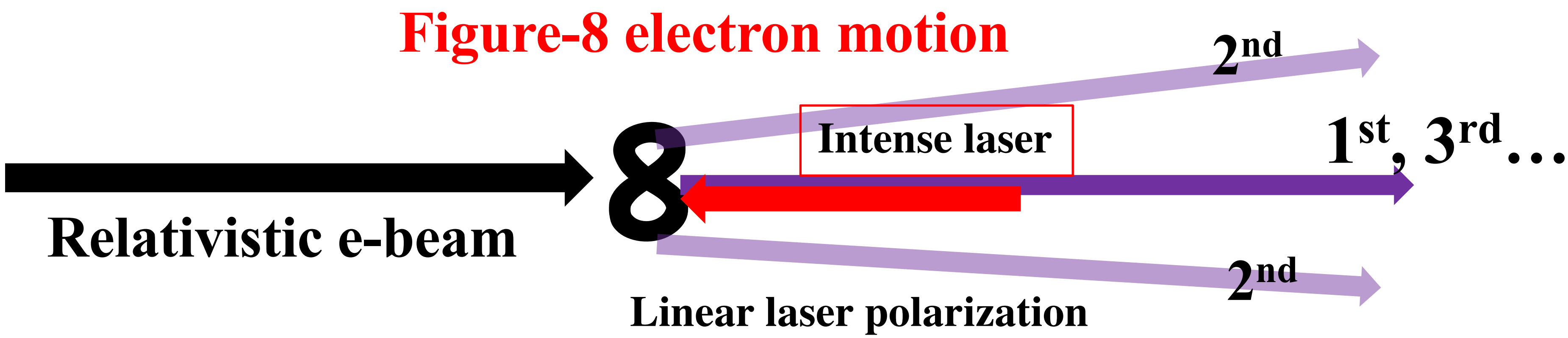






F.H. O'Shea, et al., Phys. Rev. ST-Accel Beams 15, 020702 (2012)

Nonlinear ICS physics "observables"



Nonlinear ICS: a_L~1, transverse motion relativistic, nontrivial longitudinal oscillation

★**Red-shifting *and* BW increase:**

$$h\nu_{X\text{-ray}} \Rightarrow h\nu_{X\text{-ray}} / (1+a_L^2/2),$$

***a_L not* constant during interaction**

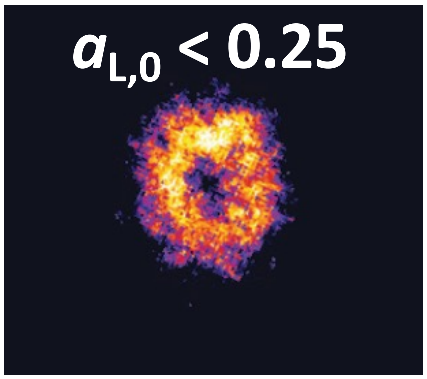
★ **Harmonic generation/angular dependence:**

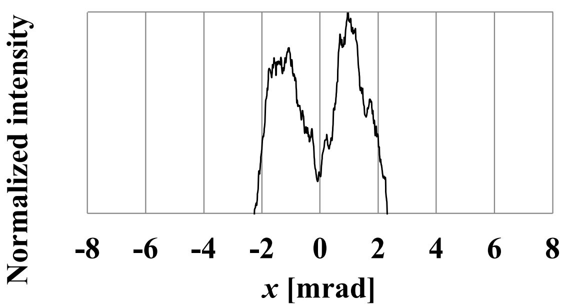
(*Multi-photon process in dense photon field*)

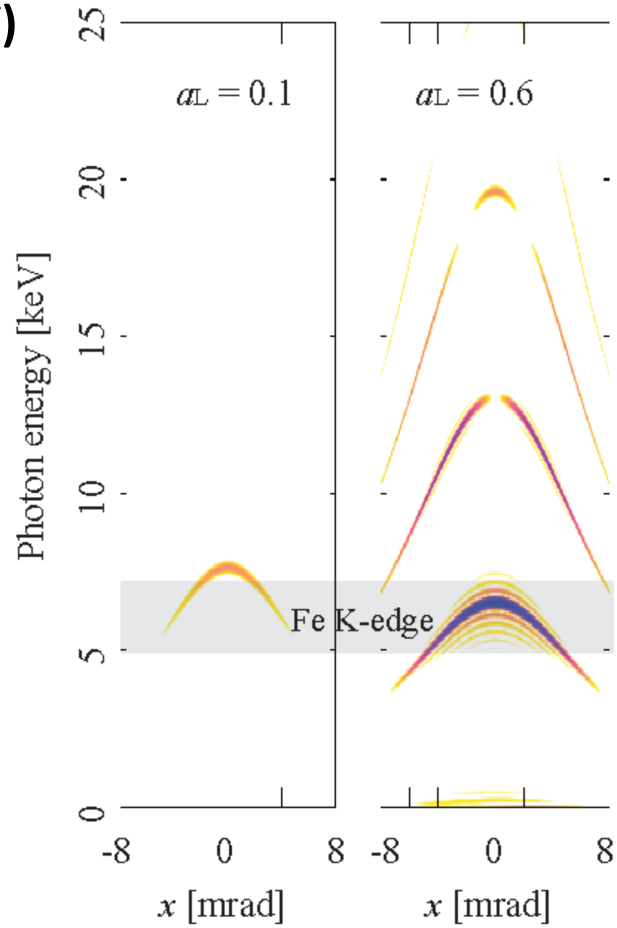
$$h\nu_{X\text{-ray}} = 4\gamma^2\, h\nu_L n$$

Observation of nonlinear red-shift in fundamental

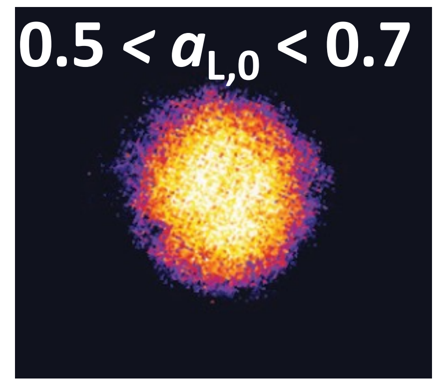
7.6 keV < Fe k-edge (at 5-7keV)
On-axis components is cut

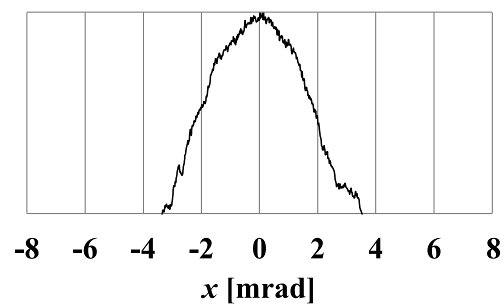






Red-shifting to 5-6 keV



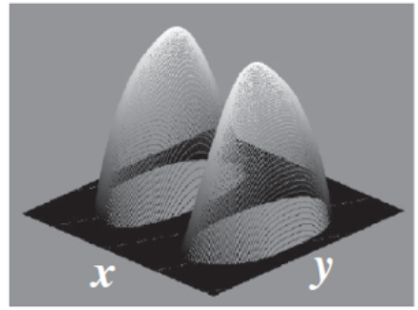


$$h\nu_{ICS,\,1^{st}} = 4\gamma^2 \nu_L/(1+a_{L,0}^2/2) \rightarrow \therefore 0.5 < a_{L,0} < 0.7$$

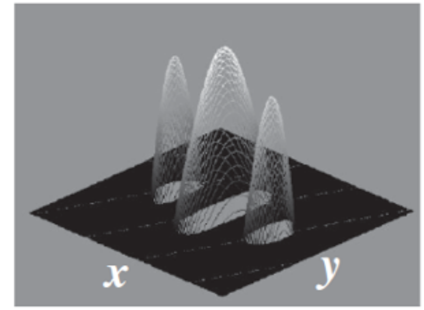
Y. Sakai, et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

2nd & 3rd harmonics with *linear polarization*

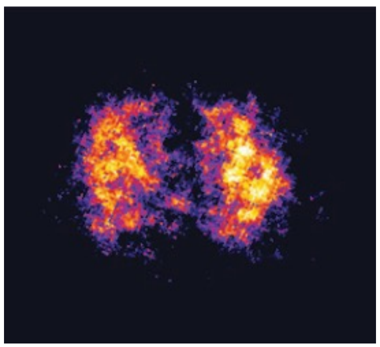
2nd

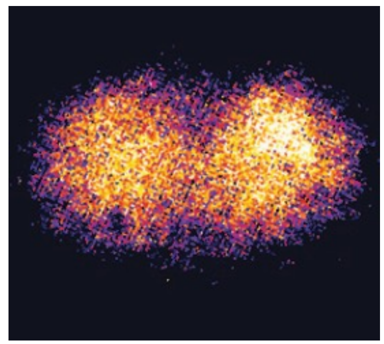


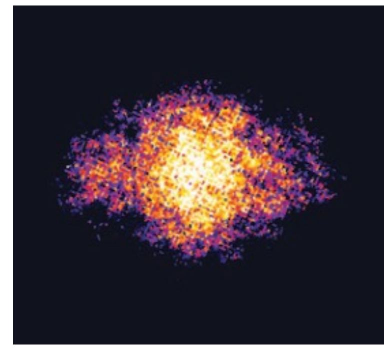
3rd

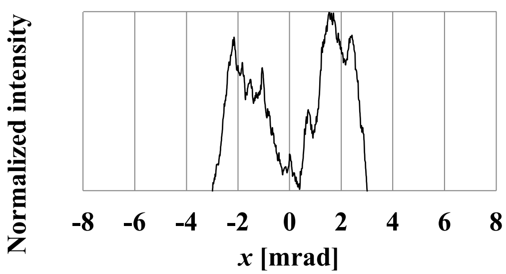


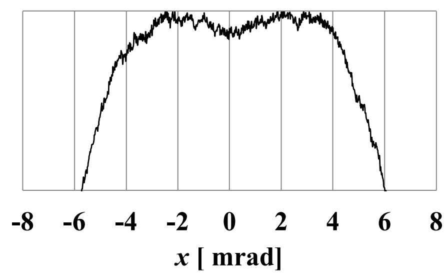
Au L-edge (12 keV)	Al 250 μm > 10 keV	Al 1000 μm > 15 keV

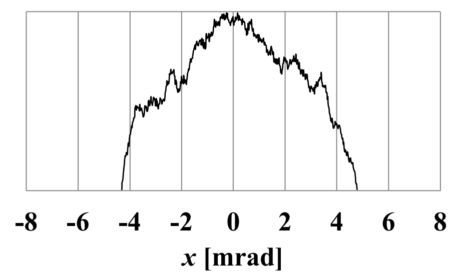












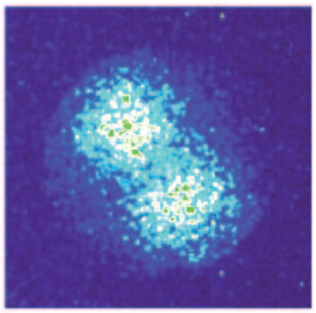
Narrow band 2nd	2nd + 3rd	3rd (On-axis & lobes)

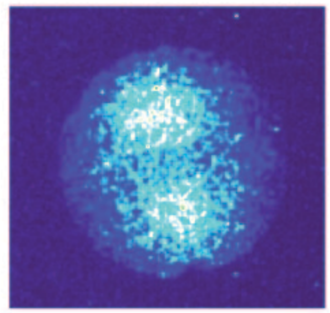
Y. Sakai, et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

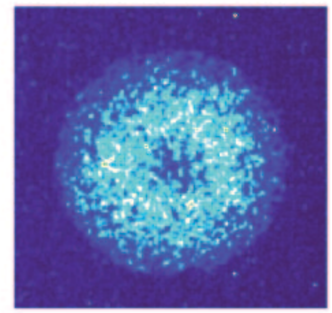
Circularly polarized harmonic radiation

¼ wave plate between regenerative and TW amplifier

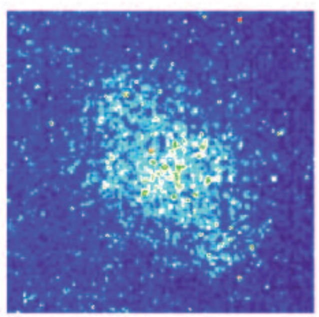
Al 250 μm | **Linear, 2^{nd}** | **Elliptical, 2^{nd}** | **Circular, 2^{nd}**

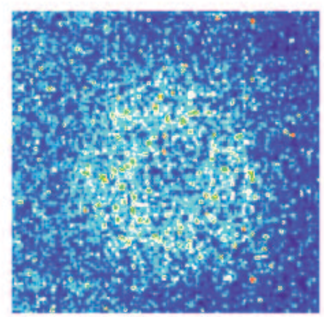






Al 1000 μm | **Linear, 3^{rd}** | **Circular, 3^{rd}**





Much attention to this result-

Demonstration of orbital angular momentum?

V. Petrillo, G. Dattoli, I. Drebot, and F. Nguyen, PRL 117, 123903 (2016)

Orbital angular momentum in short wavelength light

- Can make OAM X-rays using FEL, ICS scenarios

Nature Photonics (2019)

X-RAY OPTICS

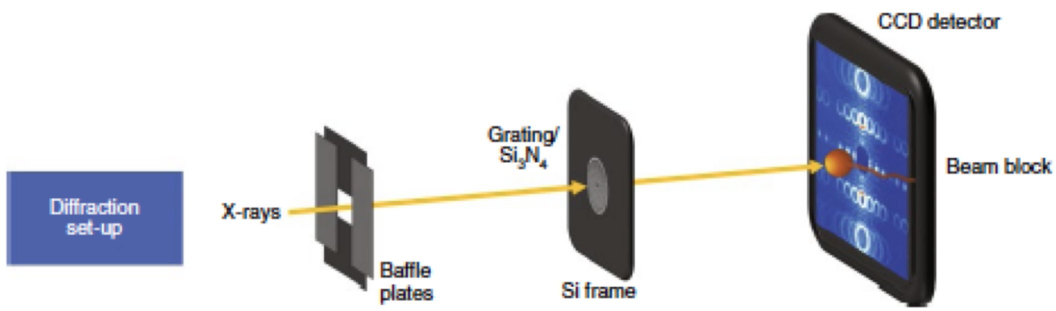
Twisted light beyond the visible

Orbital angular momentum is a property of light that has many emerging applications, but has been poorly appreciated until recently. The wavelength frontier of orbital angular momentum sources is extending beyond the ultraviolet thanks to research in fields ranging from nanostructures to free-electron lasers.

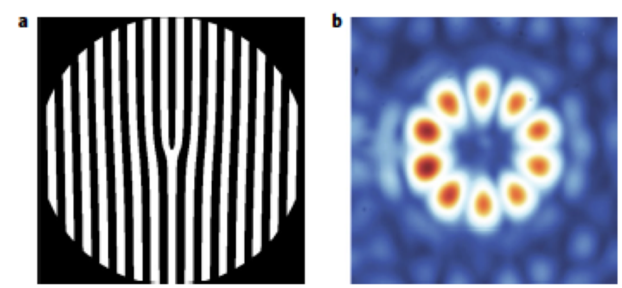
James B. Rosenzweig

https://journals.aps.org/prab/speced/FACET2

- Recent results obtained in soft X-ray techniques



Nanolithography based gratings for OAM creation and analysis (J.C. Lee, et al., Nature Photonics (2019))

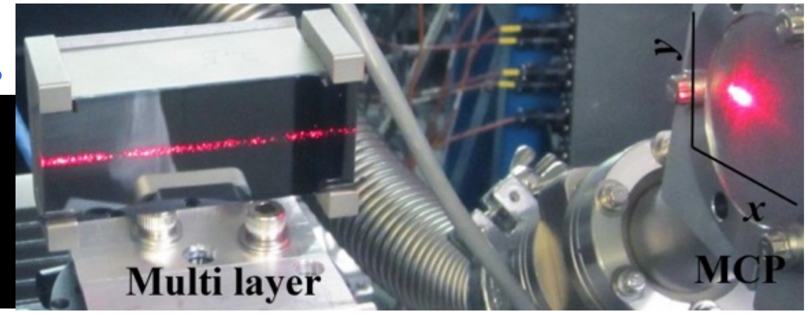


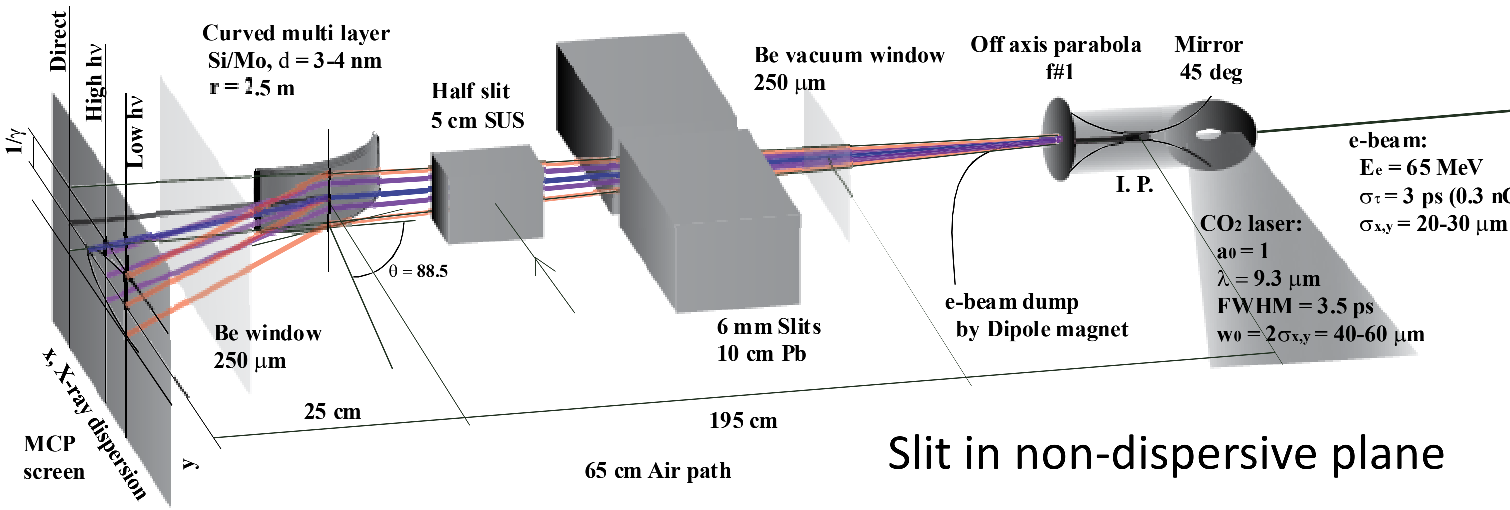
Binary diffraction fork, OAM mode structure

- What physical systems can be probed w/OAM X-rays?

Seeing *details* of the ICS X-ray spectrum…

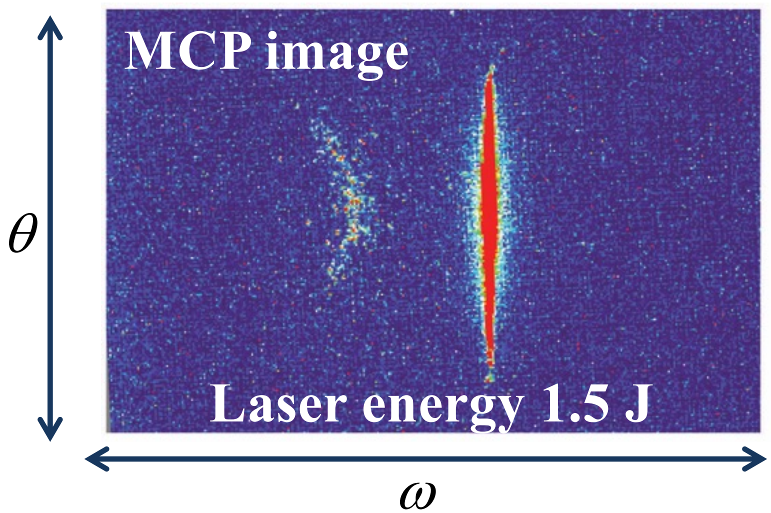
Single-shot bent multi-layer crystal X-ray spectrometer

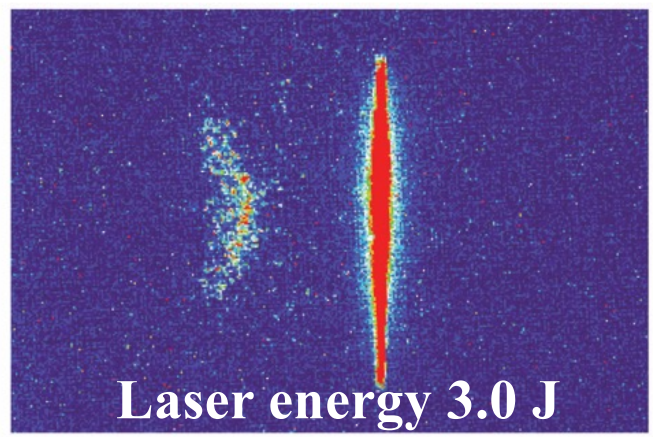




- ✡ Mo-Si multi-layer thickness: $d \approx 3.3$ nm
- ✡ Bragg angle: ~ 25 mrad
- ✡ Angle acceptance : ~ 50 mrad
- ✡ Reflectivity ~ 15% @ NSLS X15A

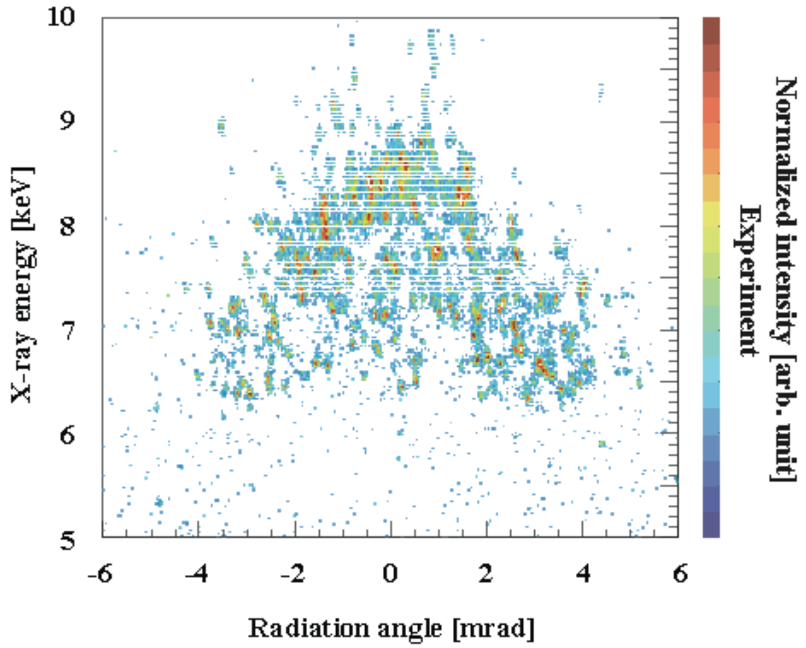
Slit in non-dispersive plane

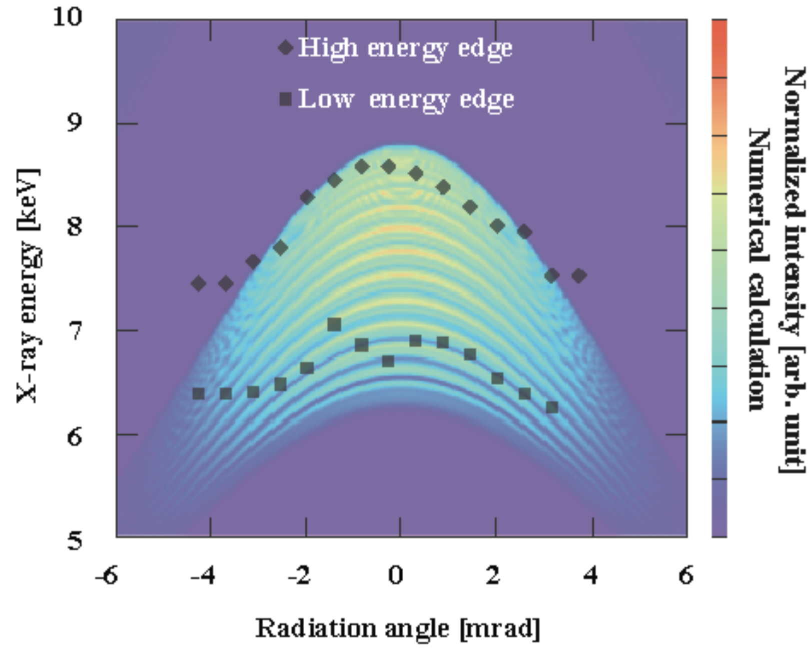




Y. Kamiya, T. Kumita and P. Siddons et al., X-ray spectrometer for observation of nonlinear Compton scattering, Proc. Joint 28th Workshop on Quantum Aspects of Beam Physics (World Scientific), 103 (2003)

Single shot, *double differential* spectrum
$a_0 = 1$ case





What are these fringes?

Width/shape of spectrum yields information on laser-electron beam overlap

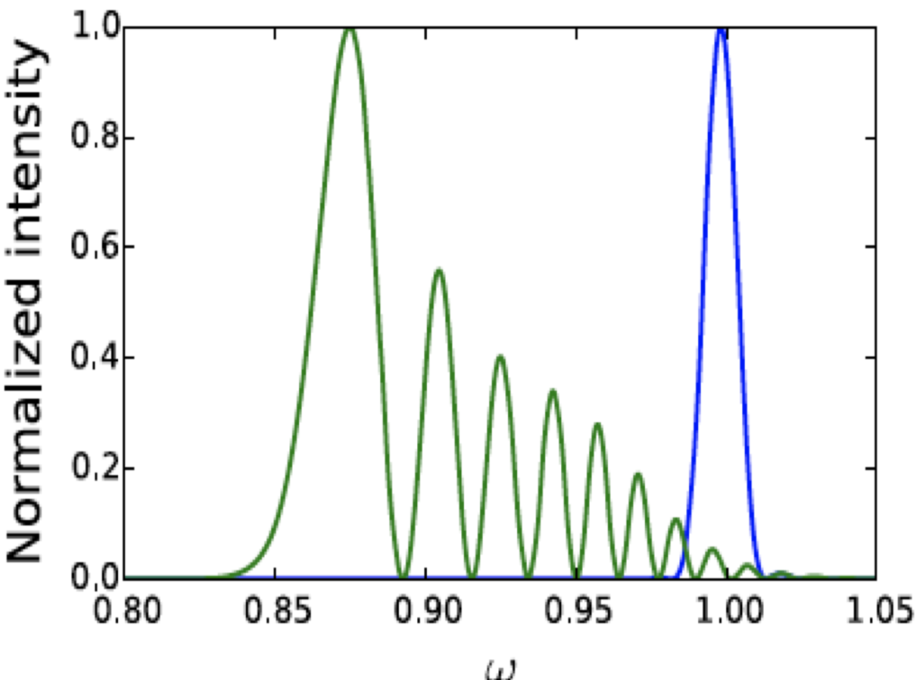
Near-axis spectral broadening in nonlinear ICS

- ✶ **Probability model (no wave phase effects)**
- ✶ **Temporal variation: high red-shift emphasis P_1**
  - ✶ **Wave *self-interference* effects from a_L occurring twice**
- ✶ **Transverse effect displays more *low red-shift* P_2**

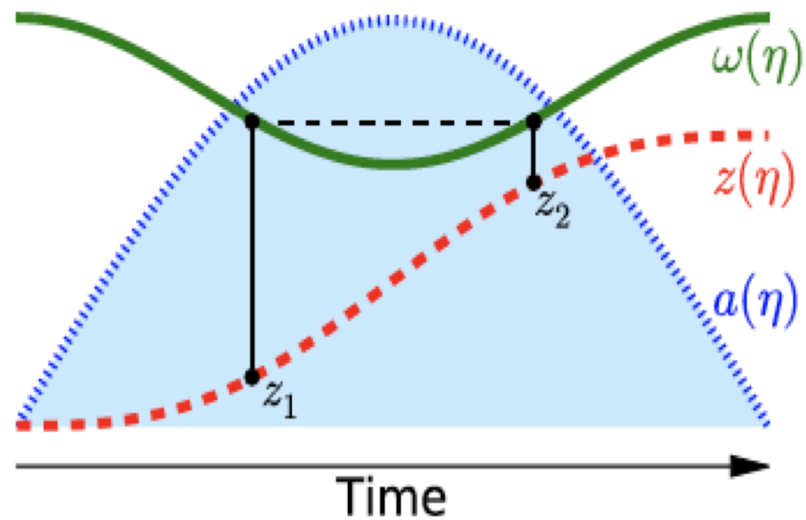
$$P_1(\Delta\lambda) = \frac{C_1}{\sqrt{\ln(\Delta\lambda_{max} / \Delta\lambda)}}$$

$$P_2(\Delta\lambda) = C_2\left(\frac{\Delta\lambda}{\Delta\lambda_{max}}\right)^{\kappa-1}$$

$$\kappa = \sigma_l / \sigma_e$$



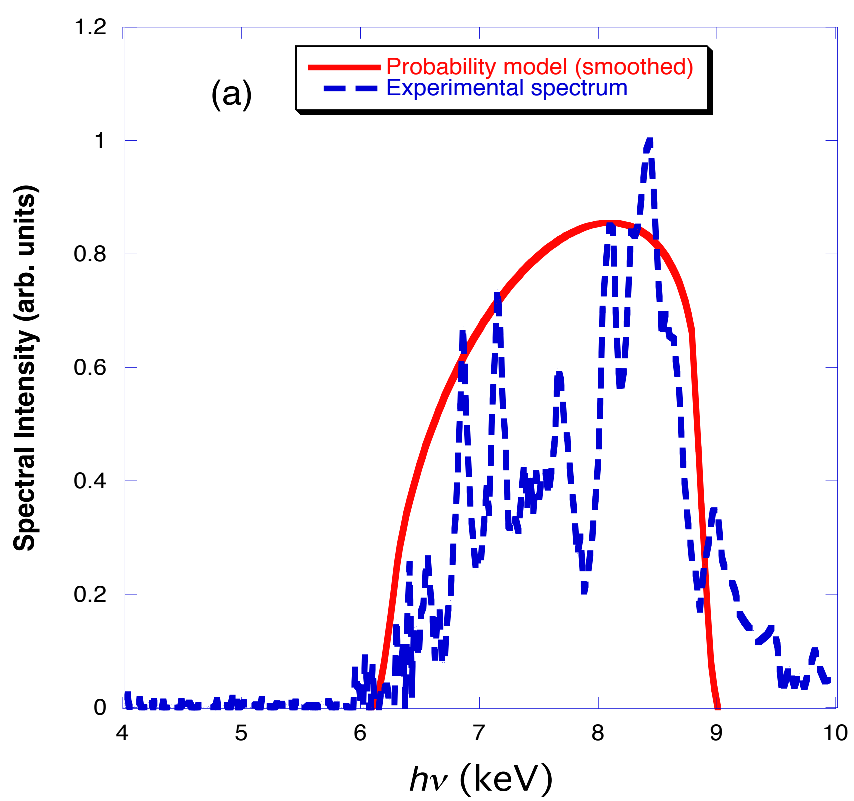
L-W numerical model shows interference fringes



All effects, κ dependence

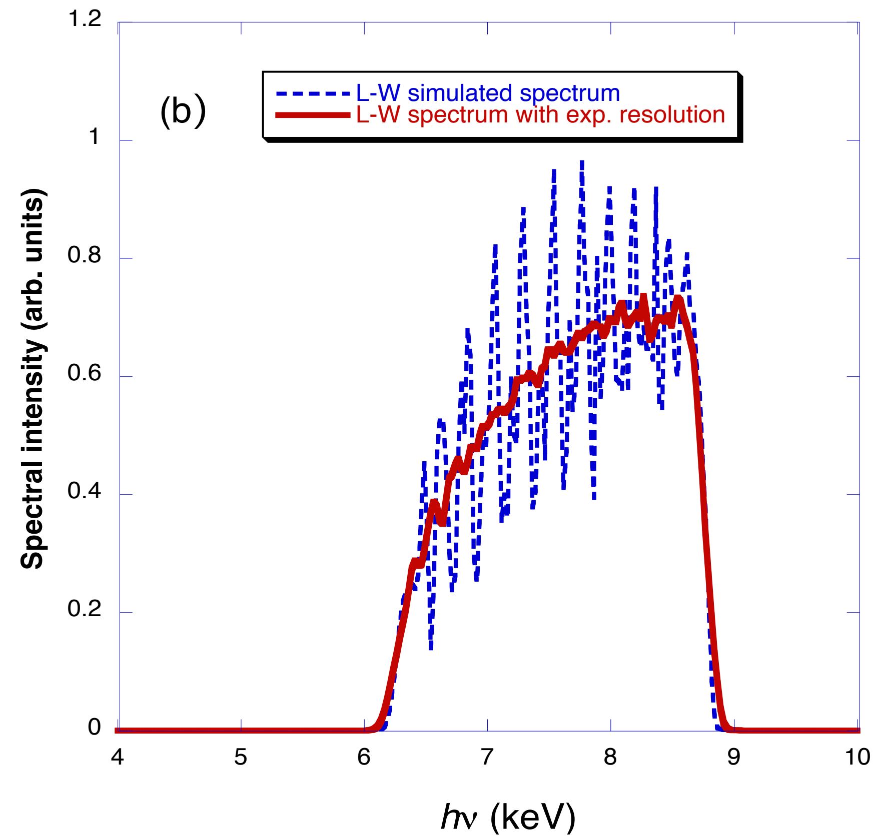
Evaluation of Experimental Results

- Shape similar to model but more peaked
- Peak position is non-destructive method for determining laser-electron beam overlap
- Fine structure present (but inconclusive). **Must revisit.**



Is structure due to self-interference?

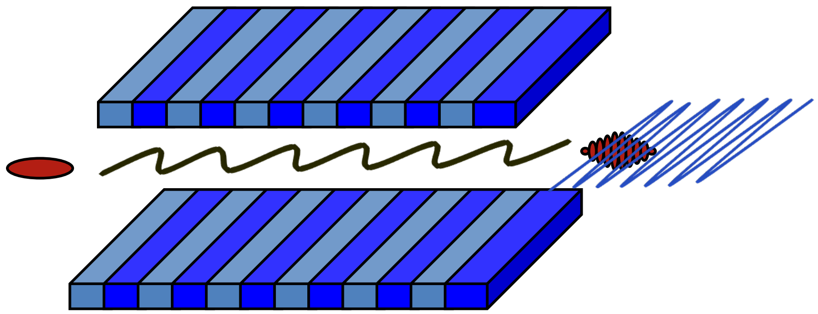
Y. Sakai, et al. *Phys. Rev. Accel. Beams* **20**, 060701 (2017)



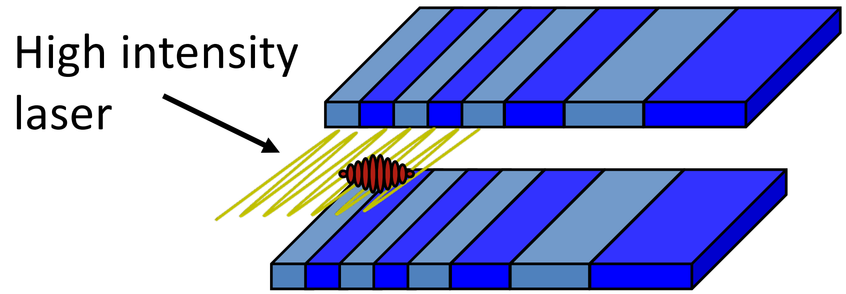
Simulated spectrum (blue)
With resolution effects (red)

Compact *optical* accelerator: IFEL

In an FEL, energy is transferred from an electron-beam to a radiation field



In an IFEL the electron beam absorbs energy from a radiation field.



$$\lambda_{r,n} = \frac{\lambda_u}{2\gamma^2 n}\left(1 + \frac{K^2}{2}\right)$$

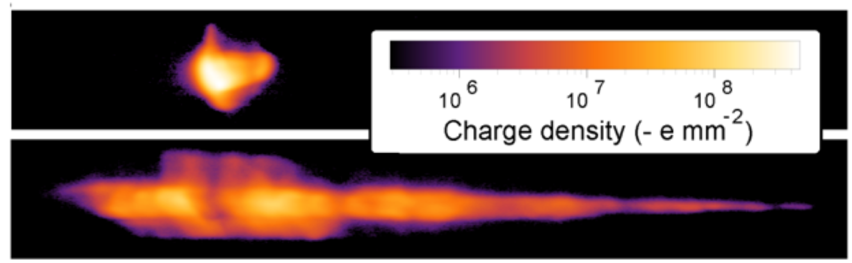
R.B. Palmer, *J. Appl. Phys.* **43**, 3014 (1972).

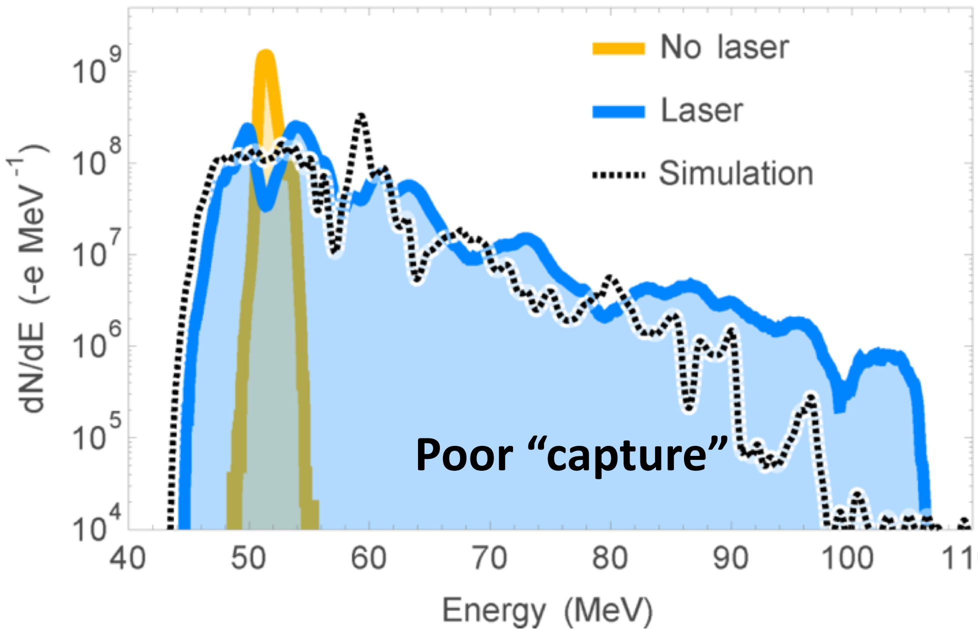
E. D. Courant, C. Pellegrini, and W. Zakowicz, *Phys. Rev. A* **32**, 2813 (1985).

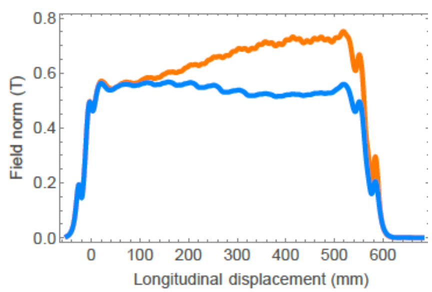
- IFEL well suited for 50 MeV – ***up to few GeV*** (due to SR limits)
- ***Plane wave*** accelerator: minimal 3D effects
- ***Vacuum*** accelerator - not dependent on boundaries
  - ***High rep rate, low losses***
  - ***Preserves e-beam quality/emittance***
  - ***Stable energy output***: static undulator field sets resonant energy
- Requires ~10 TW laser for GeV/m; *same laser* is optimal for ICS

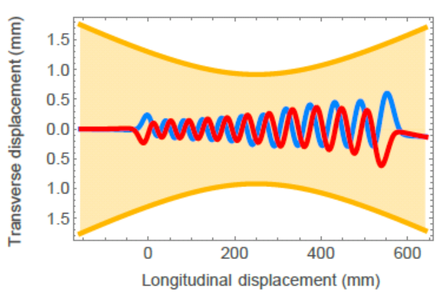
Rubicon IFEL experiment

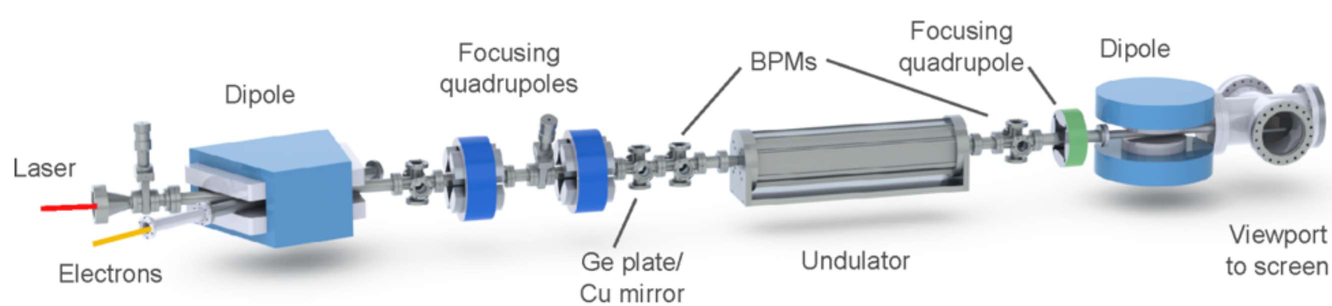
- Helical geometry, high gradient IFEL
- Strongly tapered helical Halbach undulator
- High gradient(>100 MeV/m demonstrated



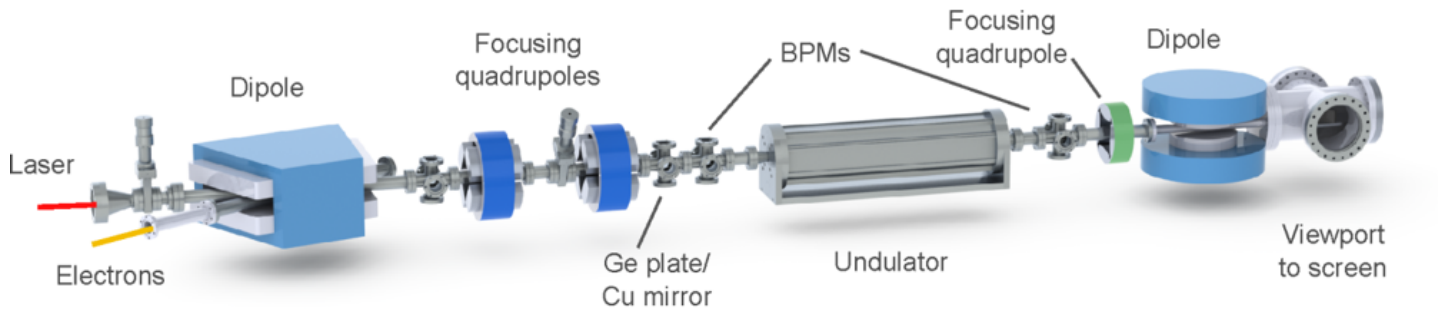






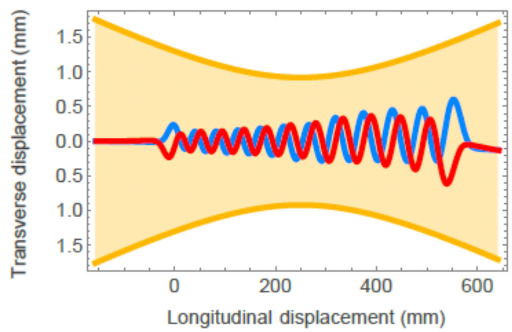


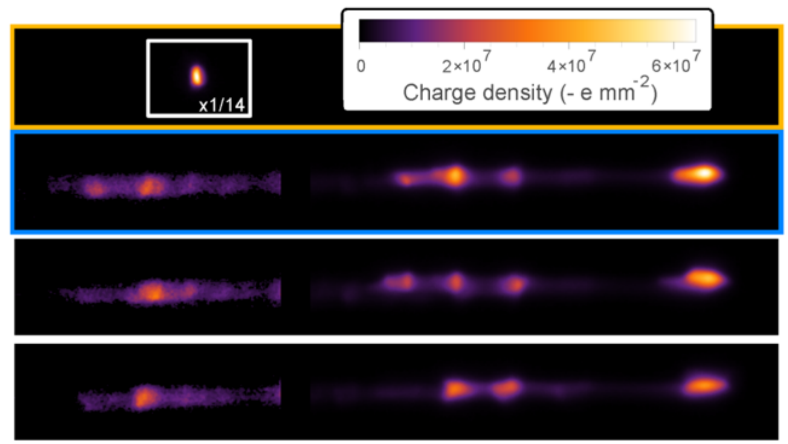
Rubicon: high quality IFEL-accelerated beams



Rubicon IFEL layout

Tapered undulator beam trajectory

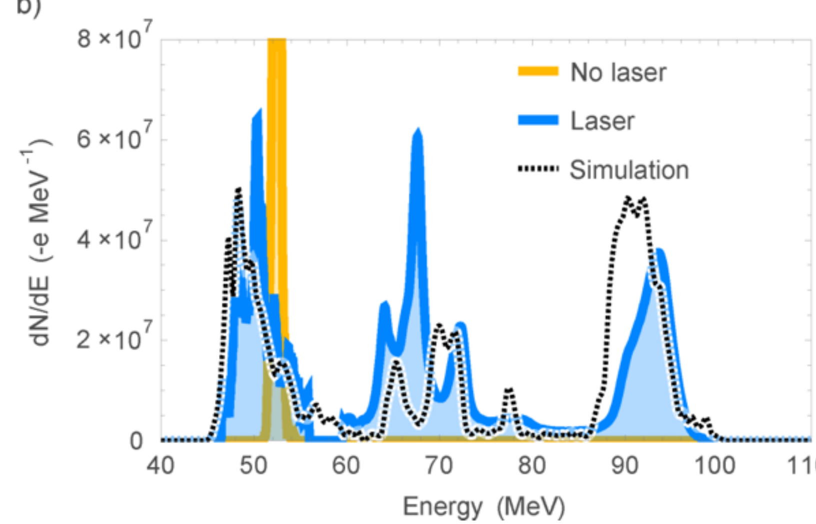




- 93 MeV – 1.8 % energy spread
- **Reproducible spectra** (σ_E < 1.5 %) with 30% rms laser fluctuations
- Since superseded by "double buncher"

Laser on shots

b)



nature COMMUNICATIONS

ARTICLE

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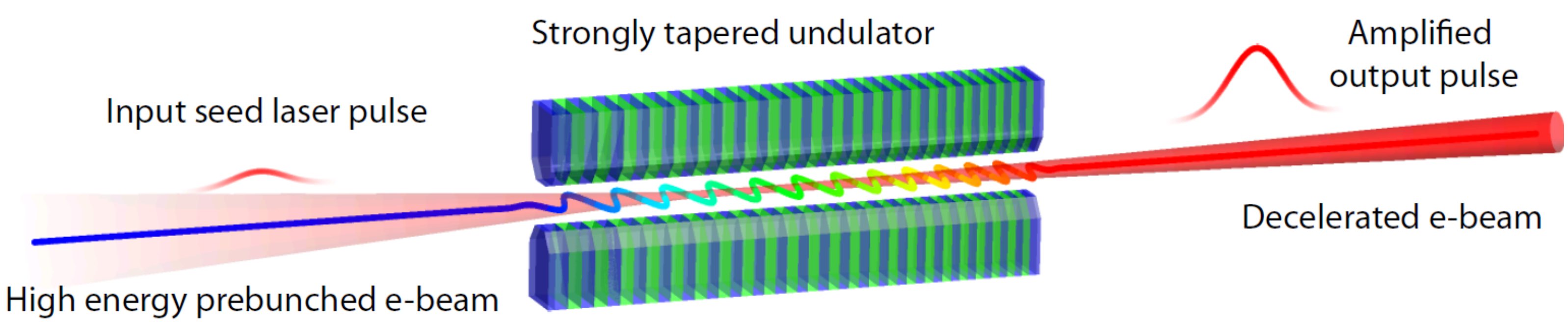
High-quality electron beams from a helical inverse free-electron laser accelerator

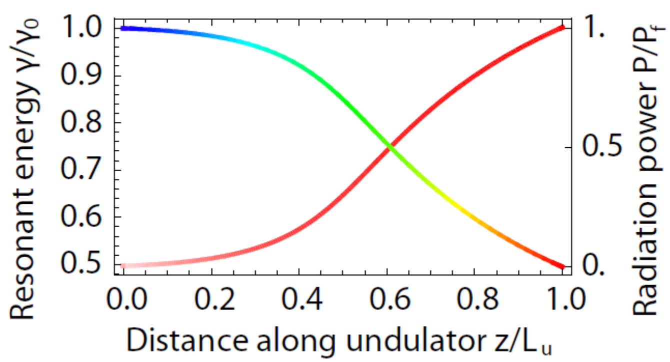
J. Duris[1], P. Musumeci[1], M. Babzien[2], M. Fedurin[2], K. Kusche[2], R.K. Li[1], J. Moody[1], I. Pogorelsky[2], M. Polyanskiy[2], J.B. Rosenzweig[1], Y. Sakai[1], C. Swinson[2], E. Threlkeld[1], O. Williams[1] & V. Yakimenko[3]

Can IFEL run in reverse?

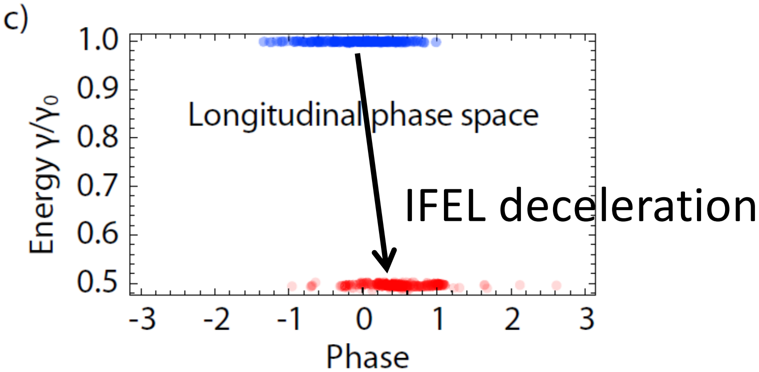
Tapering Enhanced Stimulated Super-radiant Amplification (TESSA)

- Reverse the laser-acceleration process, extract large fraction of energy from an electron beam, given:
  - A high current, micro-bunched input e-beam
  - **Intense input seed**
  - Gradient matching to exploit growing radiation field



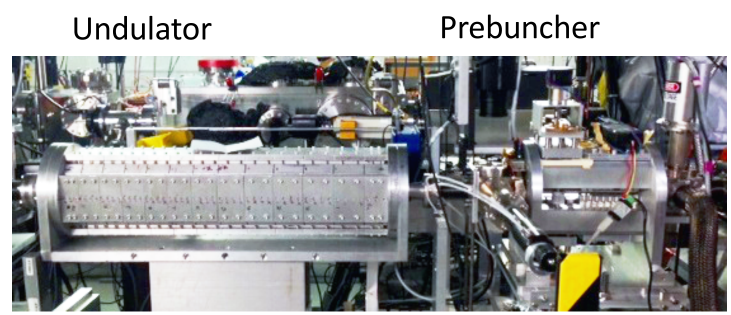


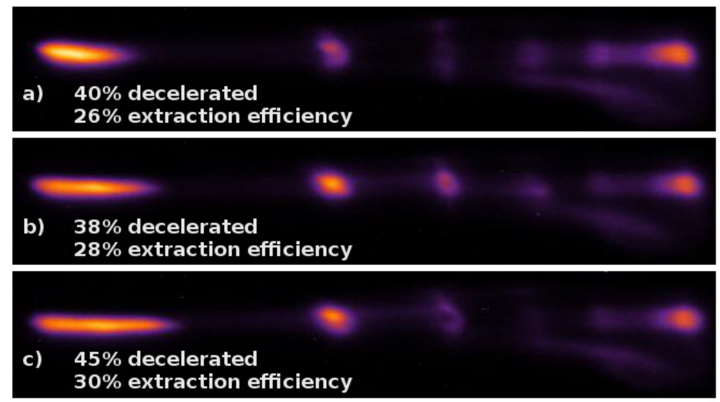
c)

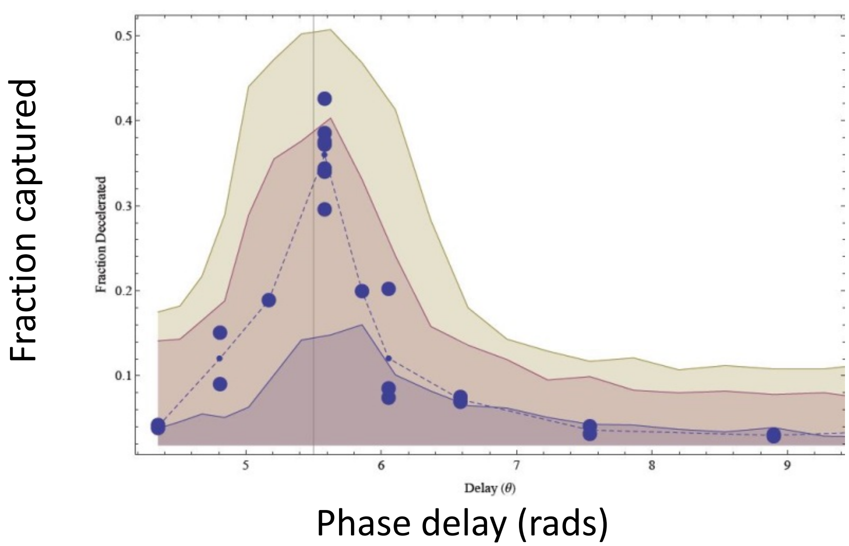


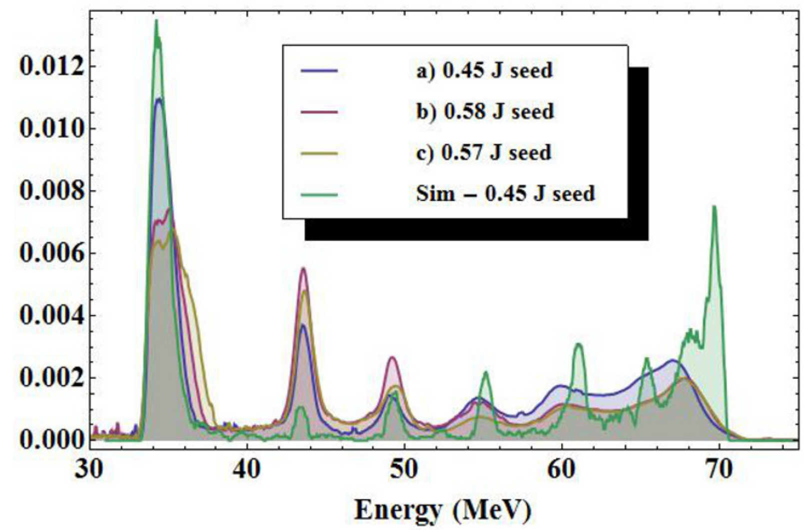
NOCIBUR IFEL deceleration experiment

- Maximized capture with variable field chicane
- 45% of the 100 pC beam captured and decelerated
- 30% extraction efficiency (2 mJ)
- Spectra agree with simulation







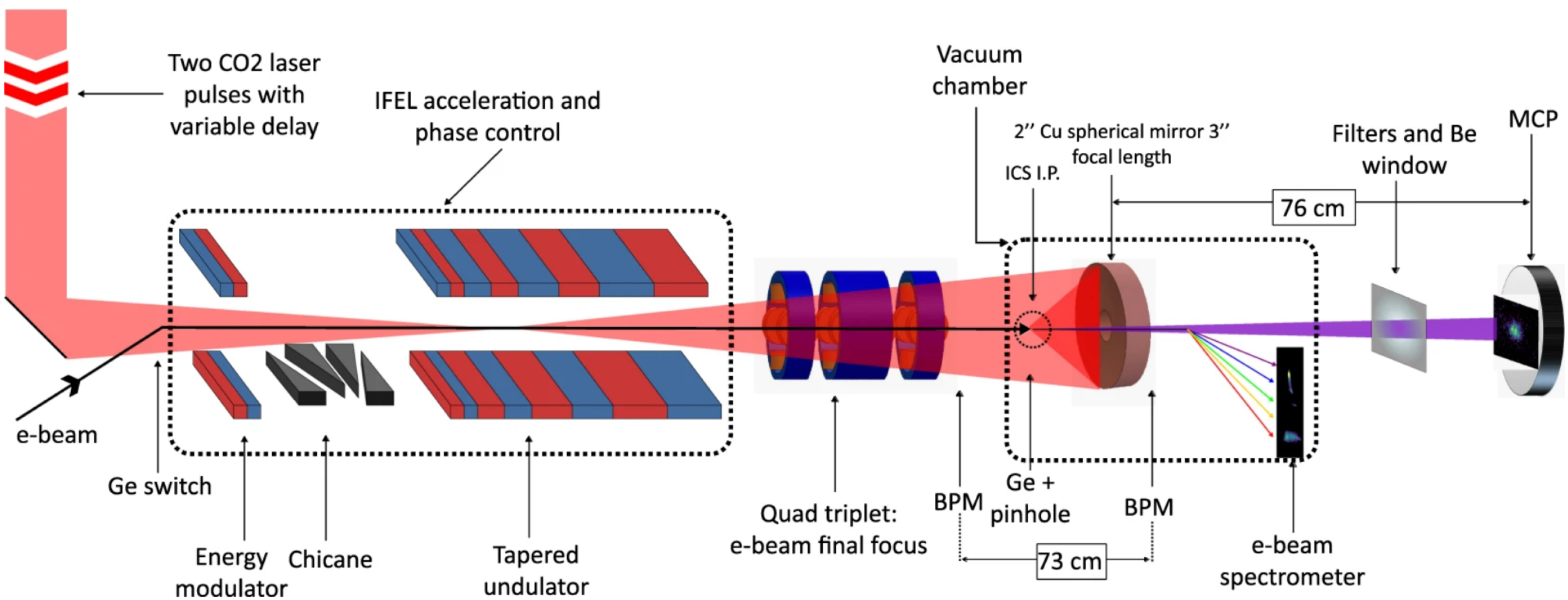


N. Sudar, *et al., Phys. Rev. Lett.* 117, 174801 (2016)

Merging IFEL and ICS

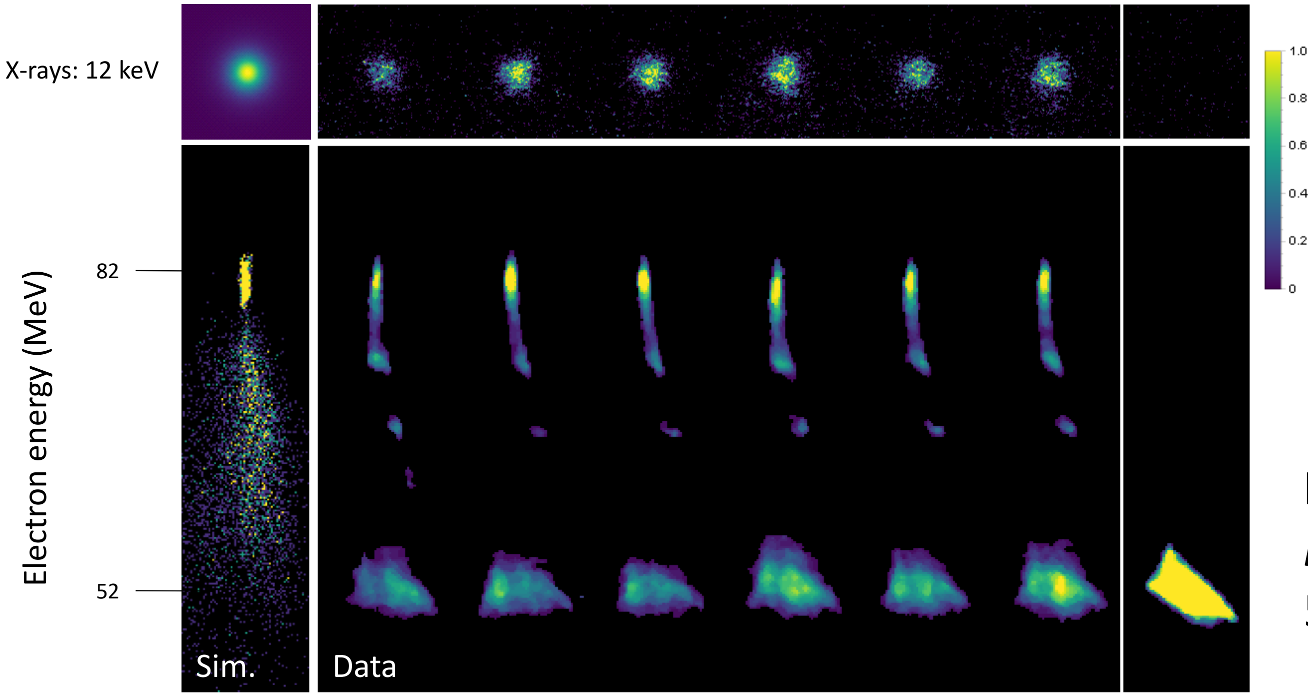
- Success of IFEL, combined with ICS physics and experimental methods…

RUBICONICS: pre-bunched IFEL for ICS



Two-pulse CO_2 laser, separated by 2x focal length of retro-reflector (0.5 ns)

RUBICONICS scattered photons

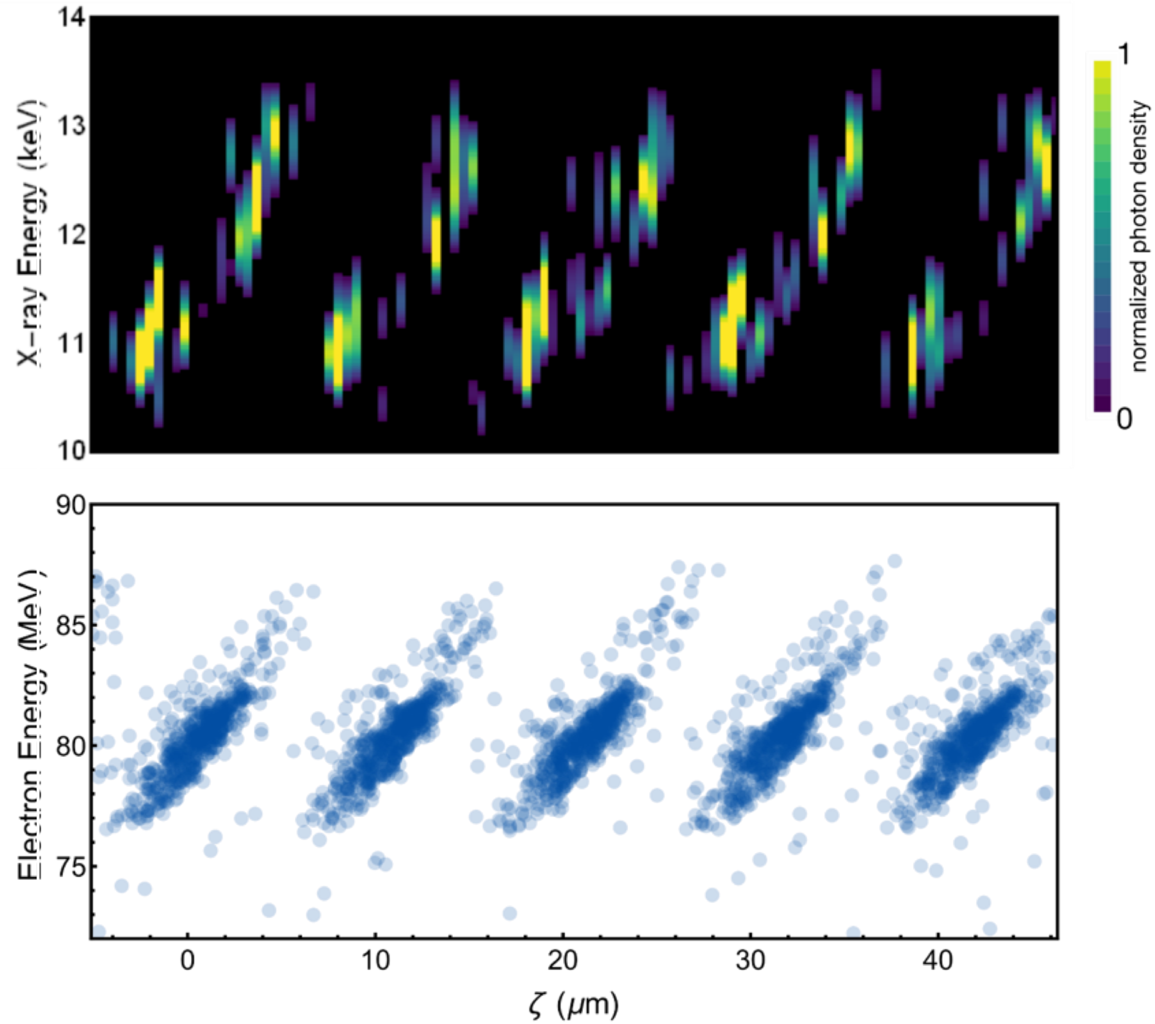


I. Gadjev, *et al.*, in *Nature Scientific Reports* 9, 532 (2019)

- Six sequential shots with highly stable beam
- Al filter attenuates ICS from 52 MeV beam
- 12 keV X-rays obtained
  - 34 fs pulse train, unique format

RubiconICS Future Directions

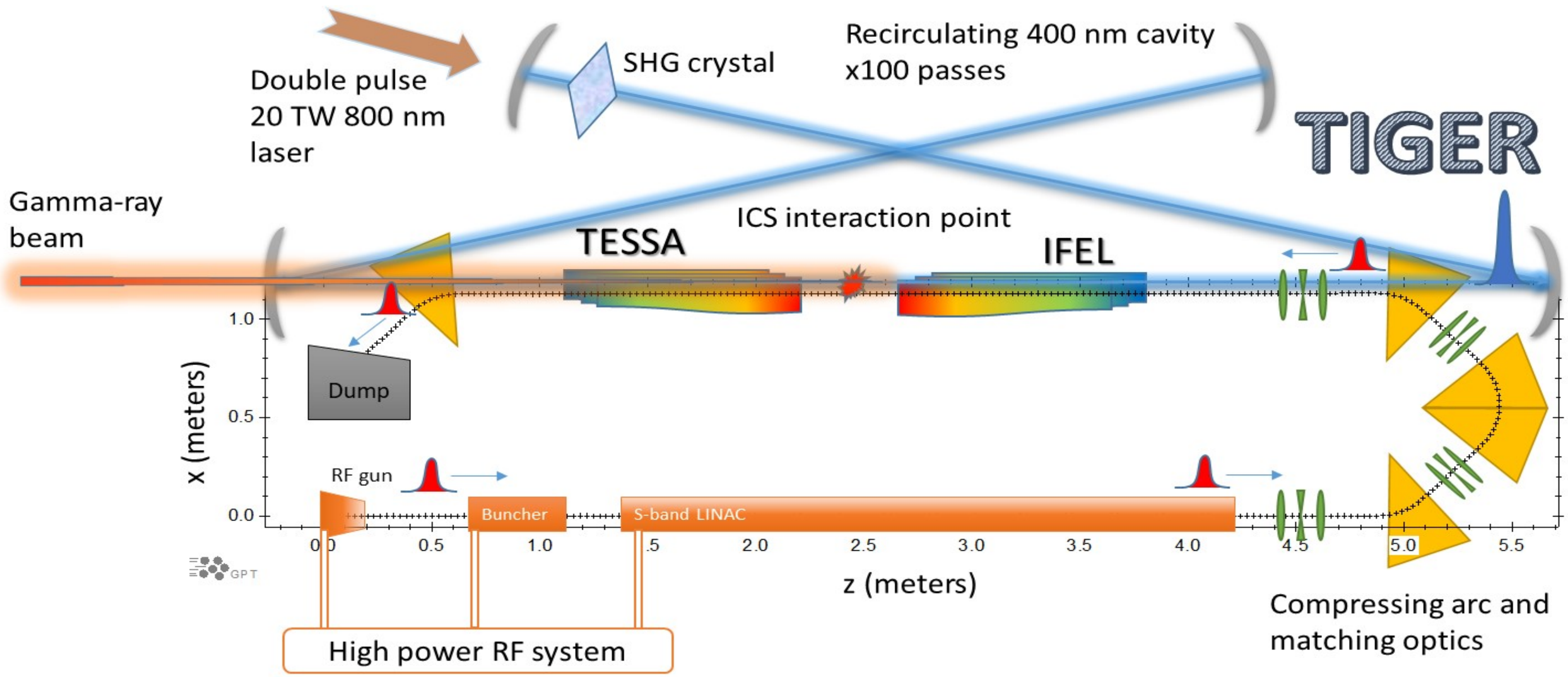
- First 5th generation light source gives *fsec* bursts of X-rays
- Micro-bunched e-beam
  - Bunching at laser wavelength $\lambda_L = 10.3$ μm
  - Translates to $\Delta T = 34.4$ fs pulse-to-pulse separation
- Application to pump probe
  - CO_2 pumped system, synchronized X-rays
- Development of integrated system with optical energy recovery



Electron pulse structure at ICS IP

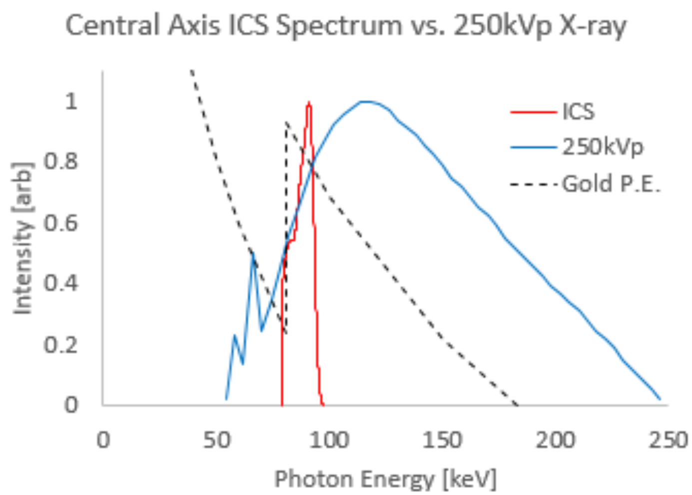
TIGER High Flux MeV ICS Source

- Full recirculating IFEL system – multi TW laser



TIGER Schematic. RF photoinjector, linac generates train of 100 MeV e- pulses. A 180 deg arc redirects and compresses the beam to a subpsec levels. Bend allows injection of co-propagating high power laser pulse for IFEL acceleration. A 1 m IFEL undulator driven by 5-10 TW laser pulse accelerates e-s up to 0.6 GeV energy for MeV ICS photons. The laser wavelength is 400 nm, lowering the e-beam energy needed, Downstream of the interaction, the laser beam energy is fully recovered, by an IFEL decelerator section.

1 μm ICS-Driven Photon Activated Therapy by with non-reactive AuNP (*K*-edge = 81 keV)



Goal ICS spectrum: 81 keV < *hv* < 95 keV

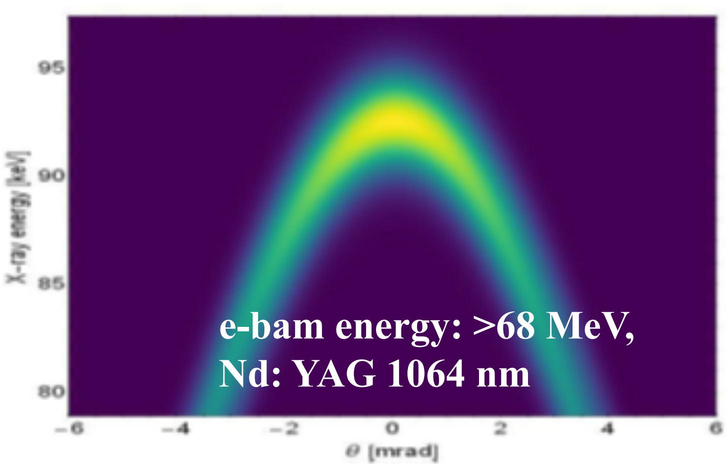
Enhanced dose with ICS monochromatic photons

Process: *Hard X-ray absorption by Au K-shell electrons*

Emission of Auger electron from outer shell,

Dose enhancement adjacent to nano-particle surface

Linear ICS Spectrum



[I. Gadjev]

AuNP size ~ 10 nm

Penetration depth of Auger e- ~ 10 μm (function of hv_{ICS})

Au nanoparticle is also a *diagnostic* for > 81 keV photons

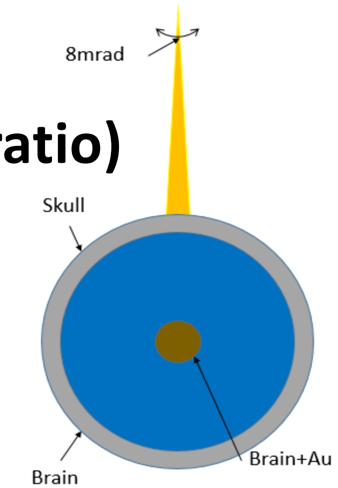
Transparent for surrounding low *Z* material:

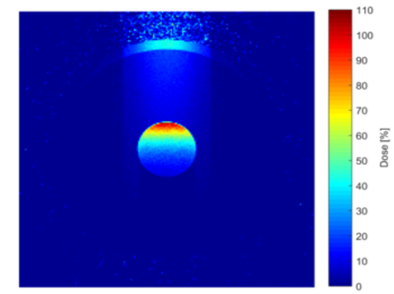
***K*-edge (resonant energy) for C, O, H is lower << 10 keV**

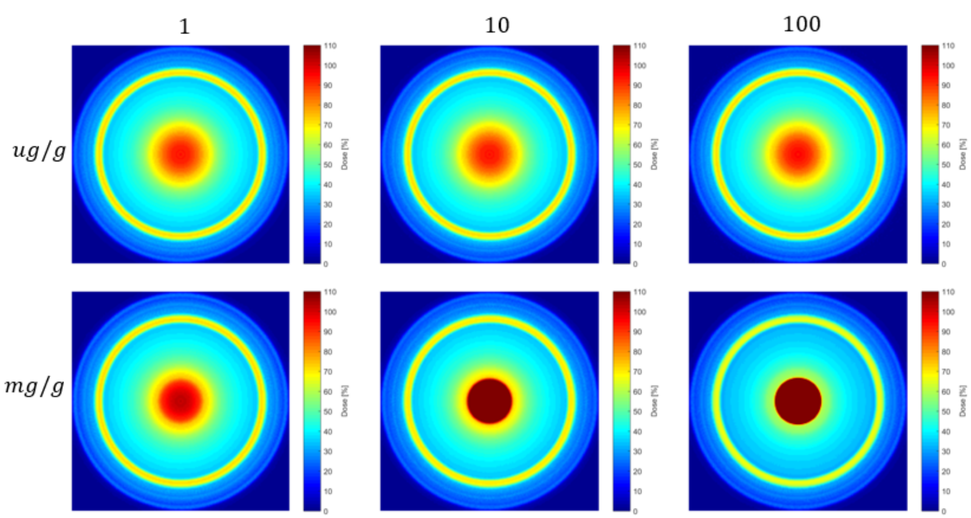
Example of dose enhancement by ICS source Monte Carlo simulation

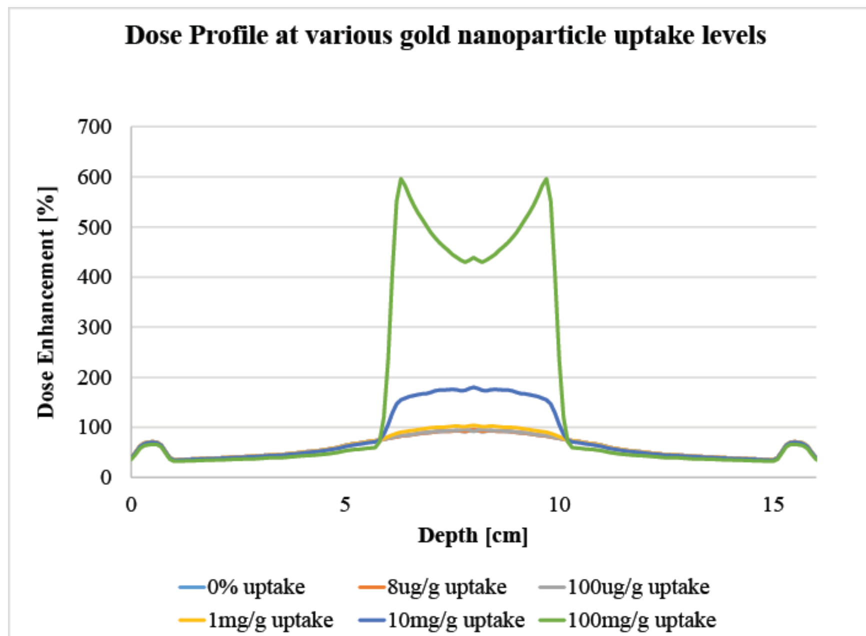
AuNP 100 mg/g uptake (<0.2% volumetric ratio) for cm size target shows dose saturation

- ✪ Density of Au: 19.7 g/ml
- ✪ Corresponds to few 100's μm thick Au filter



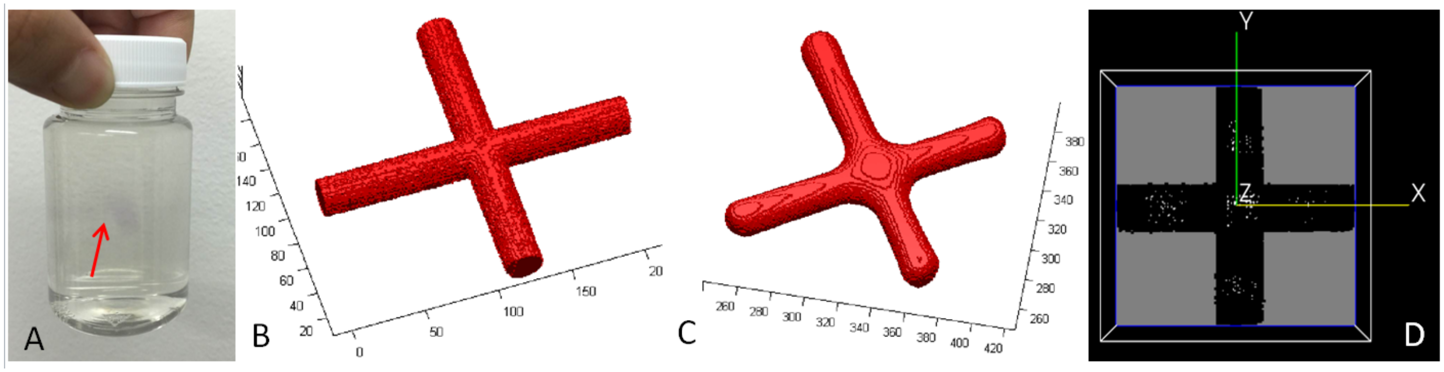






Y Yang, I Gadjev, J Rosenzweig, K Sheng "Gold Nanoparticle Dose Enhancement of Inverse-Compton Based Monoenergetic Photon Beams: A Monte Carlo Evaluation" *Int. J. Rad. Oncol.* **99**, E744 (2017)

3D gel dosimetry validation test using optical CT scanner in UCLA medical school

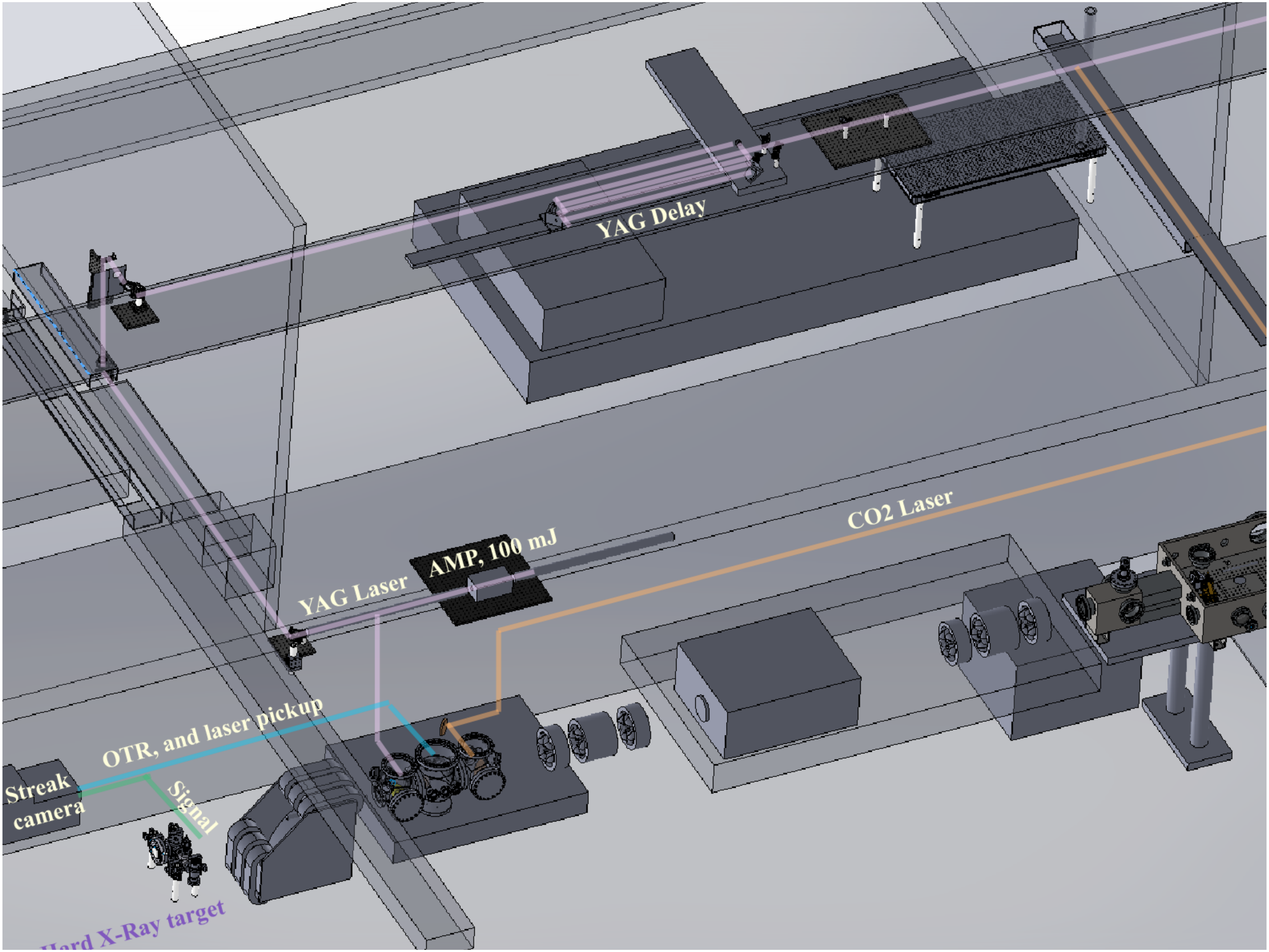


3D gel dosimetry validation test:

Two pairs of 5 mm circularly collimated orthogonal beams were projected on a 3D gel dosimeter. The change in optical density is visible as a purple hue in the irradiated gel bottle (A) and quantified by an optical CT scanner. After conversion to dose using a calibration curve, the measured dose (C) was compared against the calculated dose (B). (D) Gamma calculation.

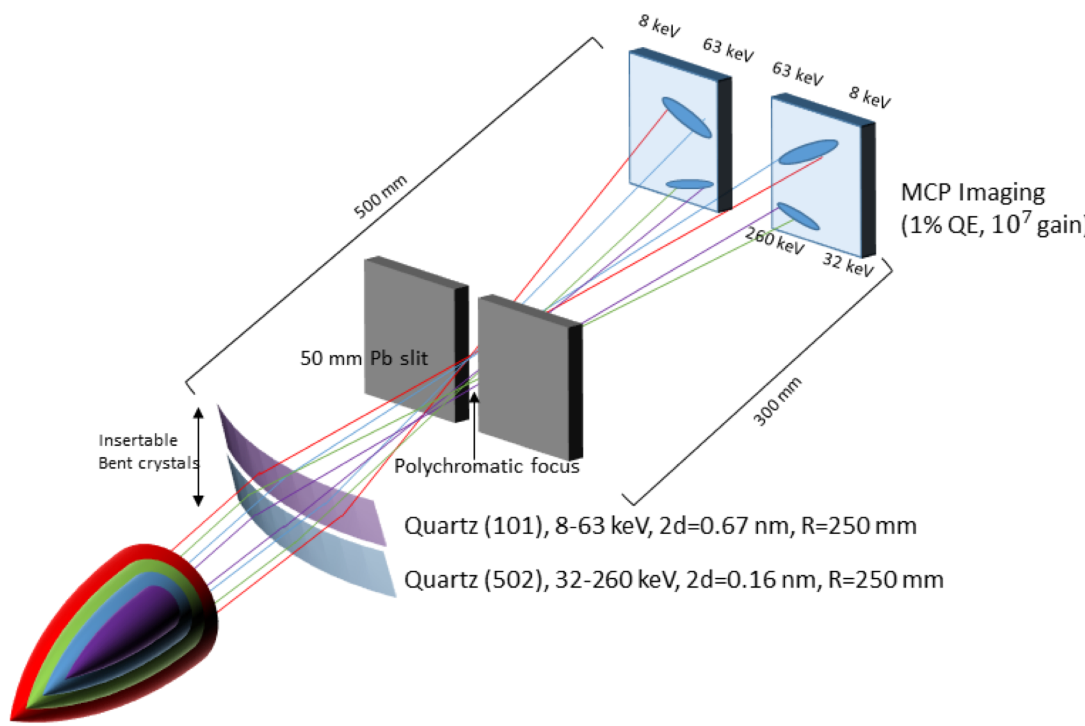
[K. Sheng et. al.]

Also developing fluorescence imaging of Au NP with Stanford Medical School


YAG Delay
CO2 Laser
AMP, 100 mJ
YAG Laser
OTR, and laser pickup
Streak camera
Signal
Hard X-Ray target

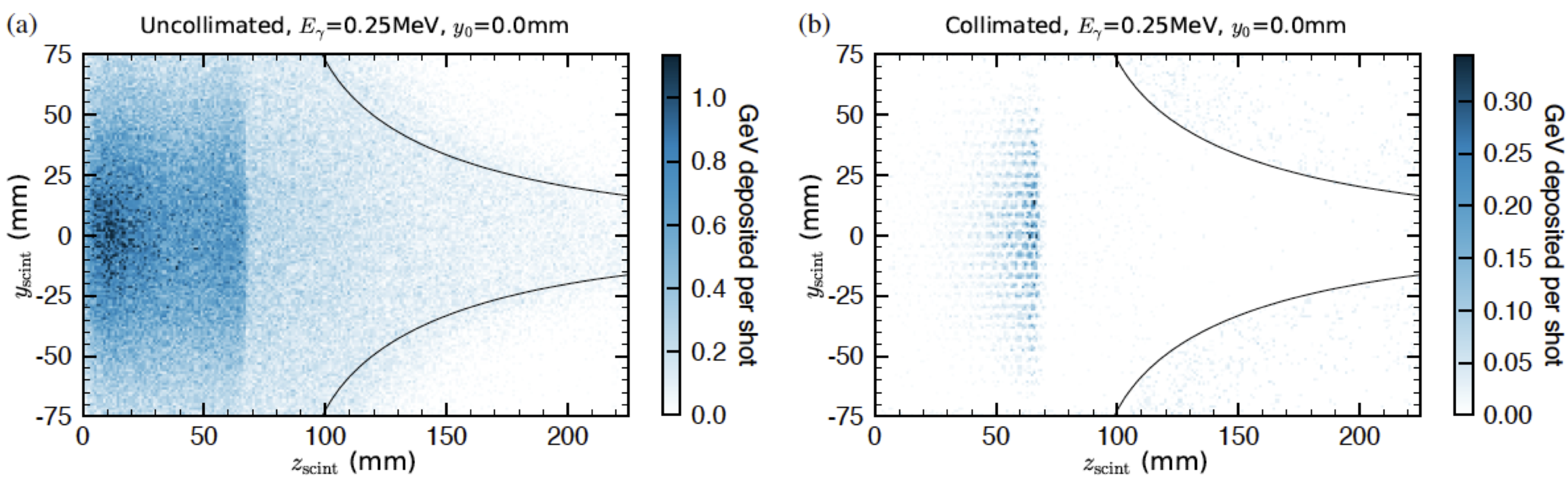
Spectral characterization

- For >81 keV photons, Au K-edge based diagnosis
  - Au foils, AuNP gel
- Bent crystal spectrometers now under development
  - Transmission geometry
  - Synergy with FACET-II betatron radiation



Higher energy photons

- Compton spectrometer 0.25(!)-20 MeV
  - Covers DARPA and FACET-II (betatron/*Compton* needs
  - Characterize at ATF with 3rd harmonic laser



Collimator allows only "good" electrons to be measured
Extend utility from 1 MeV minimum down to 250 keV

Summary

- ✶ **UCLA developed basis for all-optical IFEL/ICS system for high average flux MeV γ's**
  - ✶ **Transition to other funding agency**
- ✶ **5^{th} generation light source with unique characteristics**
  - ✶ **Come back for pump-probe in the future**
  - ✶ **Applications to MeV γ's – SNM detection**
  - ✶ **AuNP-ICS therapy urgent (Stanford, UCLA Medical)**
- ✶ **Fundamental ICS physics investigated**
  - ✶ **Nonlinear red-shift, harmonics. Self-interference!**
  - ✶ **Novel behavior of 1 um/10 um ICS spectra**
  - ✶ **Orbital angular momentum needs to be explored**
- ✶ ***Other system architectures* for very narrow band…**

DARPA GRIT Program Initializing

- Burst mode high flux γ output through pulse stacking laser cavity
- Cryo-cooled hybrid photoinjector, ultralow emittance, short pulse
  - Emittance permits low bandwidth
- C-band RF linac to enable compactness (~10 m) and high flux
- **Develop up to 200 keV ICS capabilities at UCLA during project**