UCLA

Particle Beam Physics Lab

Inverse Free-Electron-Laser based Inverse Compton Scattering: an All-Optical 5th Generation Light Source

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BROOKHAVEN NATIONAL LABORATORY

UCLA-RadiaBeam-BNL Collaboration

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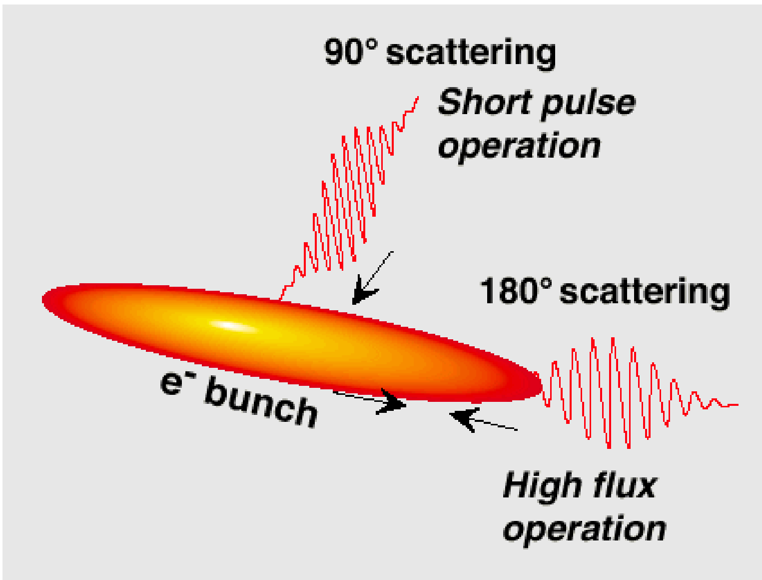
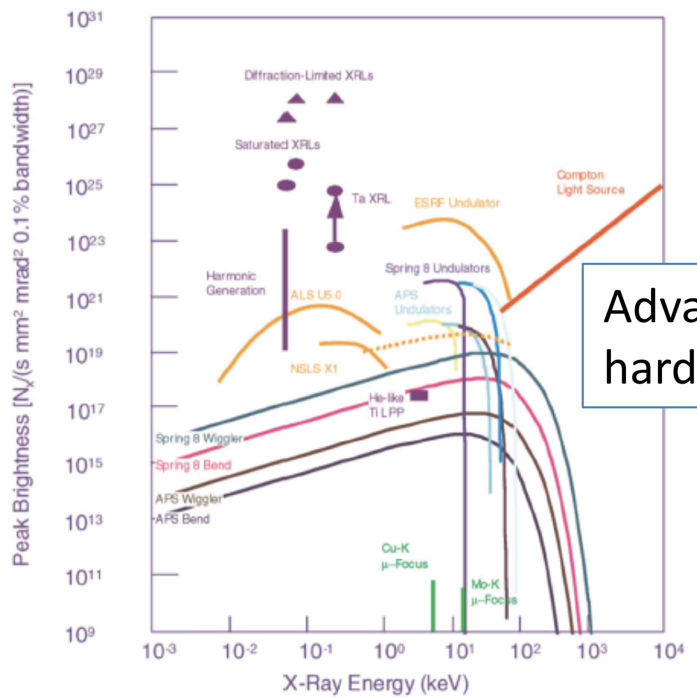
keV-to-MeV Photon Production: Inverse Compton Scattering (ICS)

- Collision of *relativistic* electron beam bunch with intense laser pulse
- Source is directional, *ultra-fast – to* sub-100 fs
- Scattered light is *quasi-**monochromatic***
- **Tunable wavelength** (relativistic Doppler, like FEL)
- Many new projects worldwide (*e.g.* ELI-NP)
  - Combined with novel e- accelerators: **5th generation light sources**

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

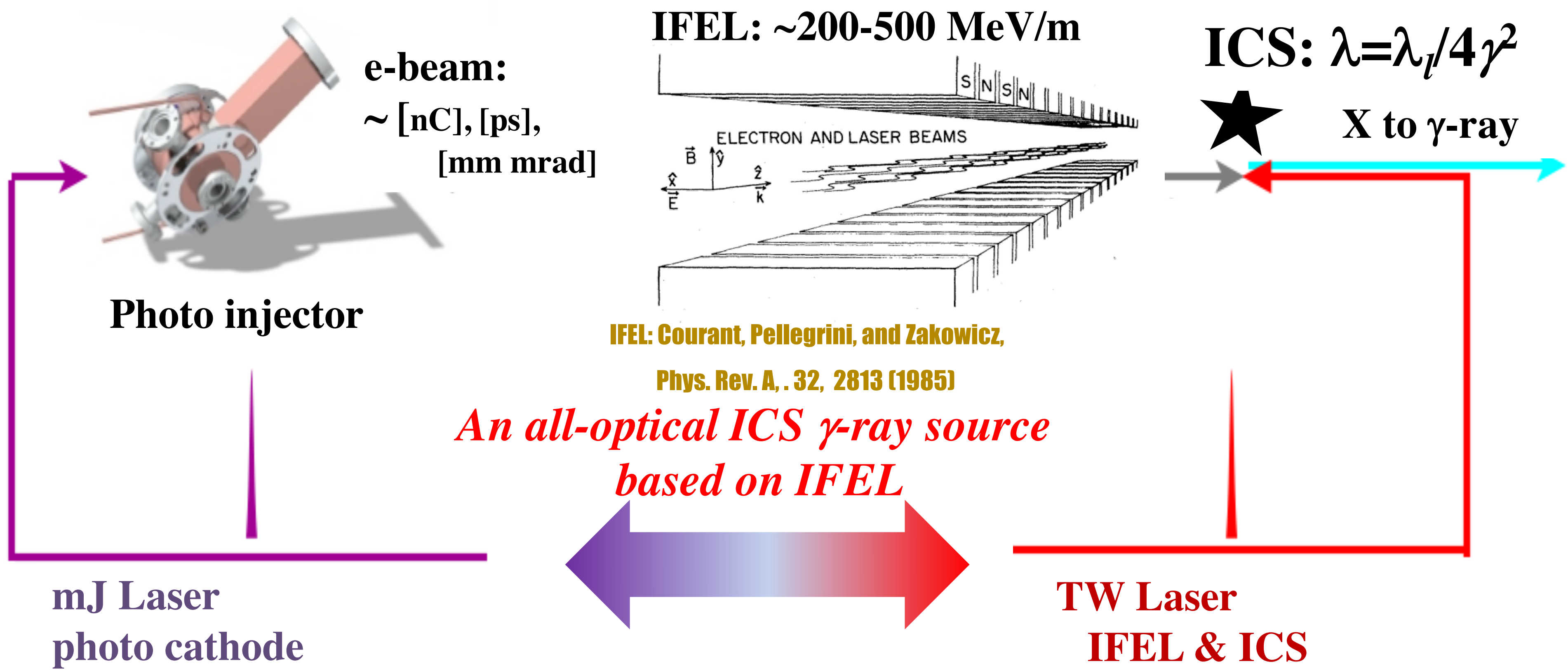




Advantages in hard γ's

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

UCLA-BNL ATF project *RUBICONICS*:
Compact γ-ray source enabled by lasers and electron beams



ICS permits compact undulator, access to MeV photons

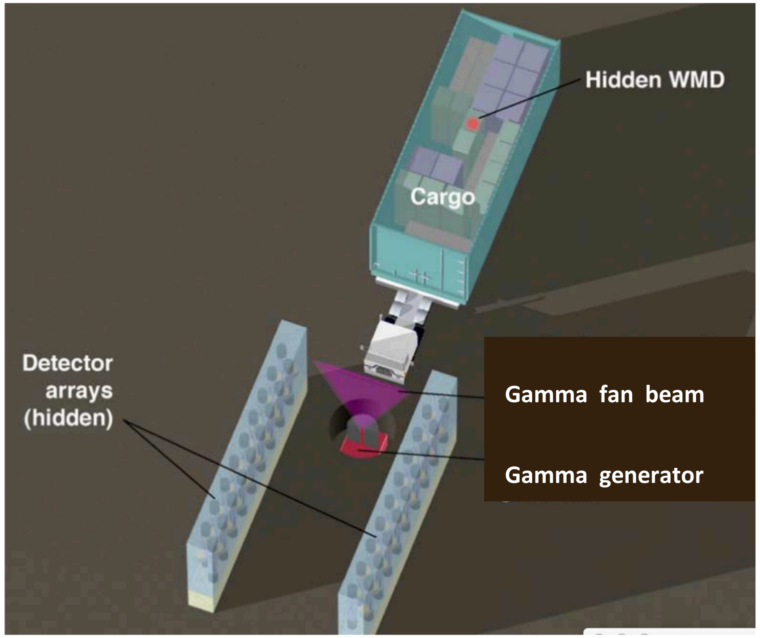
IFEL: high gradient laser-based, free-space acceleration scheme

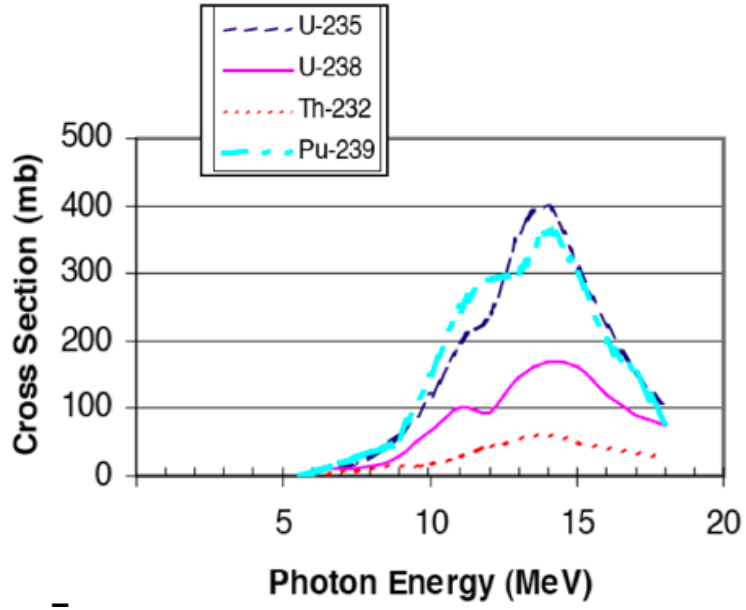
* Low collective e-beam effects
* Laser can be recirculated (unlike, e.g, in plasma)

Applications of narrow-spectrum MeV photons

★Active detection of special nuclear materials

National security priority: Active detection of nuclear materials via photo-fission (also nuclear fluorescence)



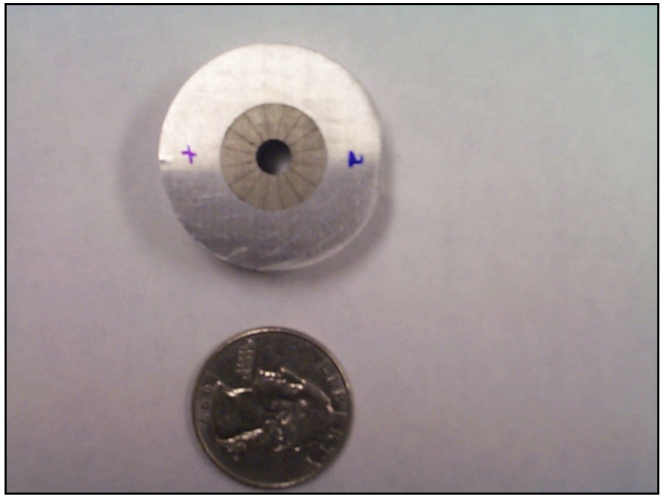


- ★ **Directed γ's, U~10-15 MeV**
- ★ **Required photon number > 10^{12} /sec**
- ★ **Similar requirements for keV γ's in medicine, semiconductors**

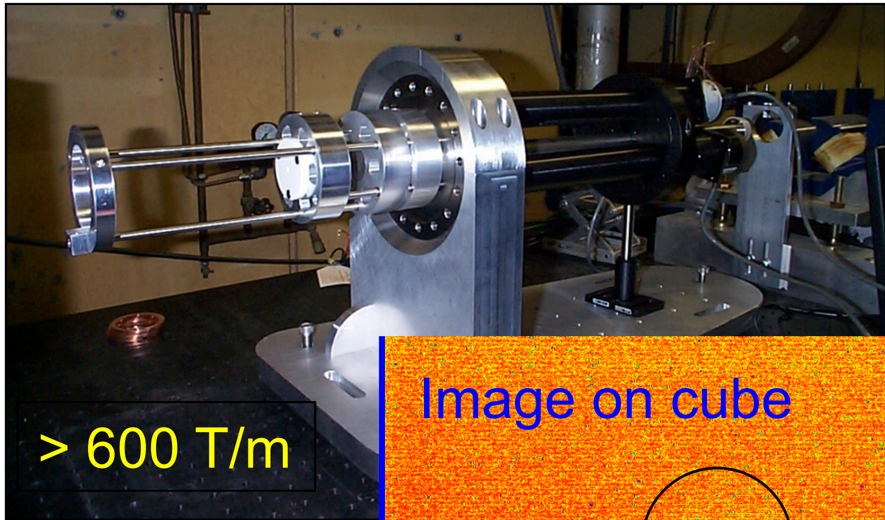
ICS Demands High Collision"Luminosity"

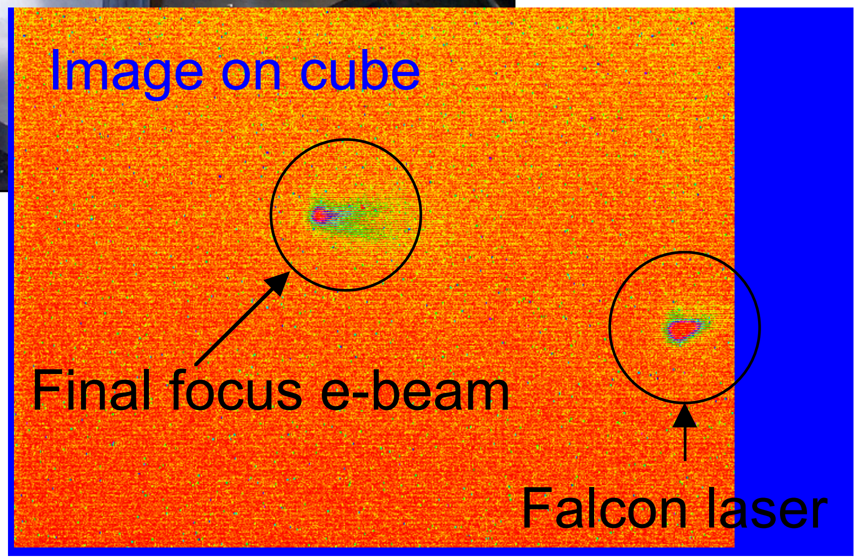
- **Like HEP collider: timing, pointing, *focusing***
- Ultra-strong e- focusing (<10 μm e- spots)
- Innovation: ultra-strong PMQs, "camera" triplet

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



Designed and built at UCLA





But there is a *limit* on focusing…

Intense, focused beams increase X-ray flux

High brilliance

Luminosity/pulse

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

$$N_\gamma = 0.6\alpha\left(k_L\sigma_z\right)a_L^2 N_{e-} \propto a_L^2 \qquad a_L = \frac{eE_L\lambda_L}{2\pi m_e c^2}$$

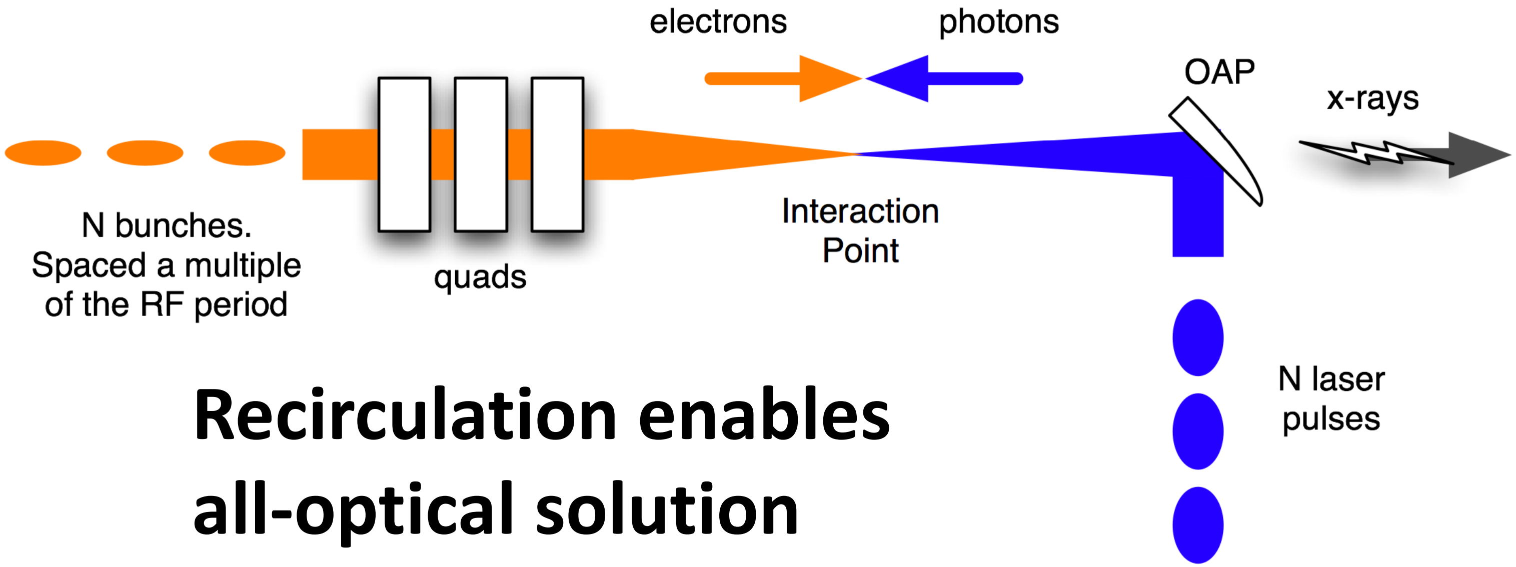
J. B. Rosenzweig, O. Williams, *Inter. J. Mod. Phys*. A 23, 4333 (2007)

Focused laser produces nonlinear electrodynamic effects – increased bandwidth and harmonic generation; lower brightness

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

Multi-bunch ICS Interaction

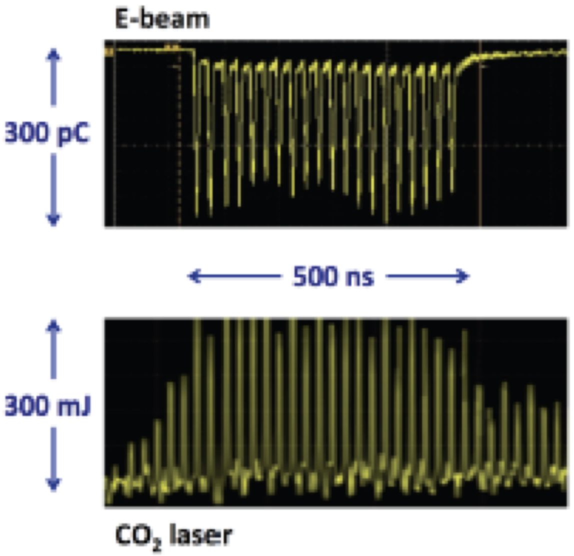
- Optimized ICS source produces ~10^8 photons *per pulse*
- Cargo interrogation requires >10^{12}-10^{13} photons/s
- State of the art accelerator and laser systems ~500 pps
- Few laser photons used up in ICS interaction
- Solution: re-use photons, interact *N* time per RF pulse
  - Produce *N* e- bunches per pulse and recirculate laser *N* times



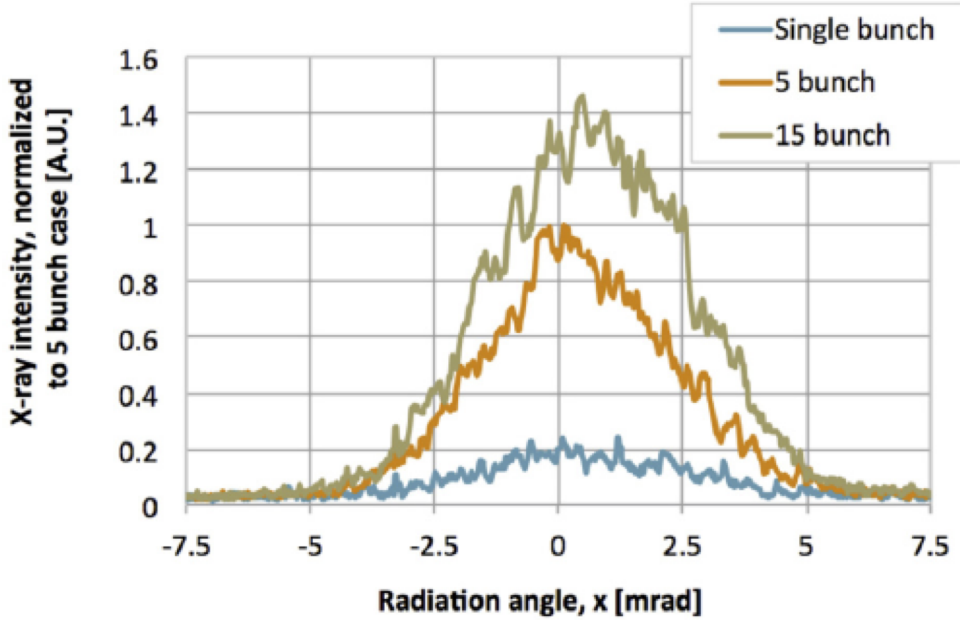
Recirculation enables all-optical solution

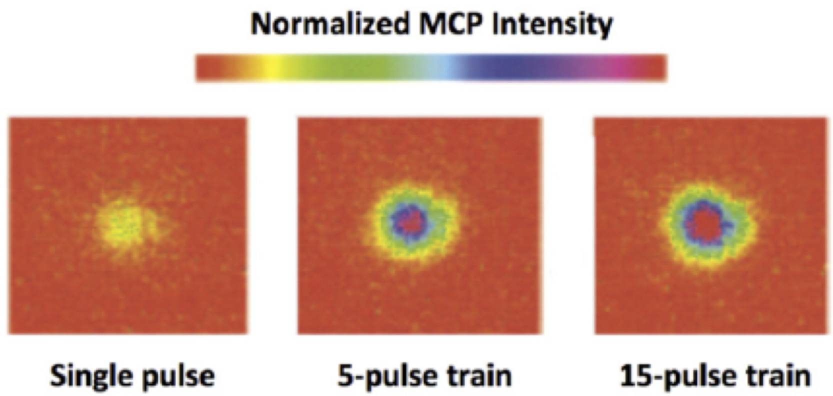
Recirculating ICS interaction demonstrated

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



- Recirculation of IFEL...



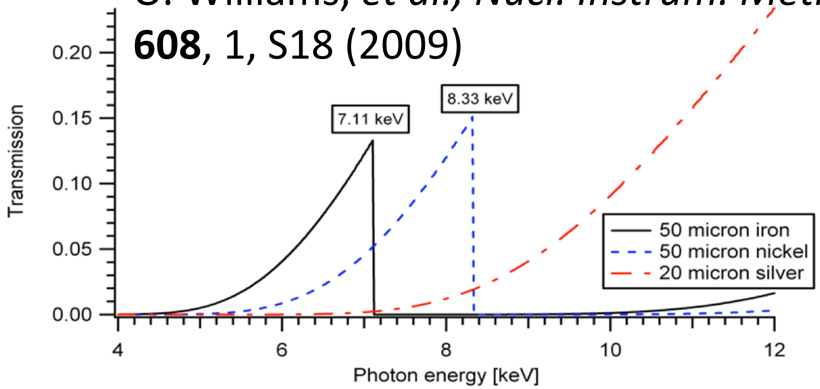


A. Ovodenko, *et al. Appl. Phys. Lett.*, 109, 253504 (2016)

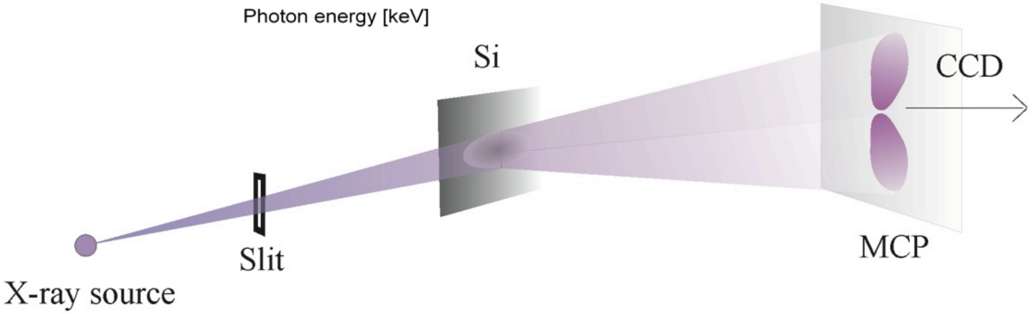
Inverse Compton Scattering: Experimental Context

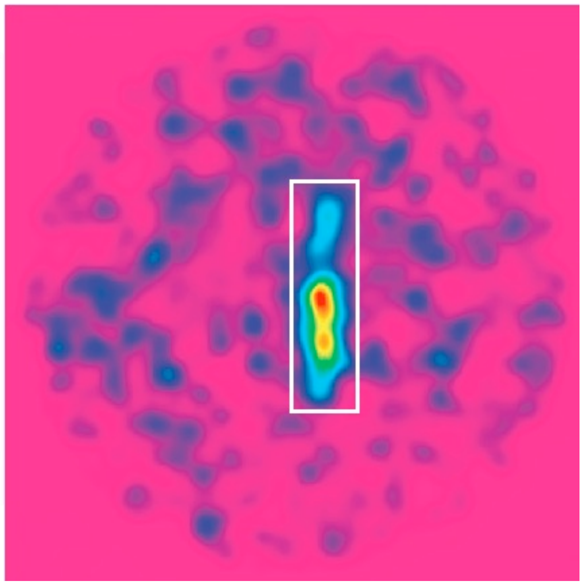
- K-edge filtering diagnostics
- Single-shot phase contrast imaging
- Single-shot diffraction

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



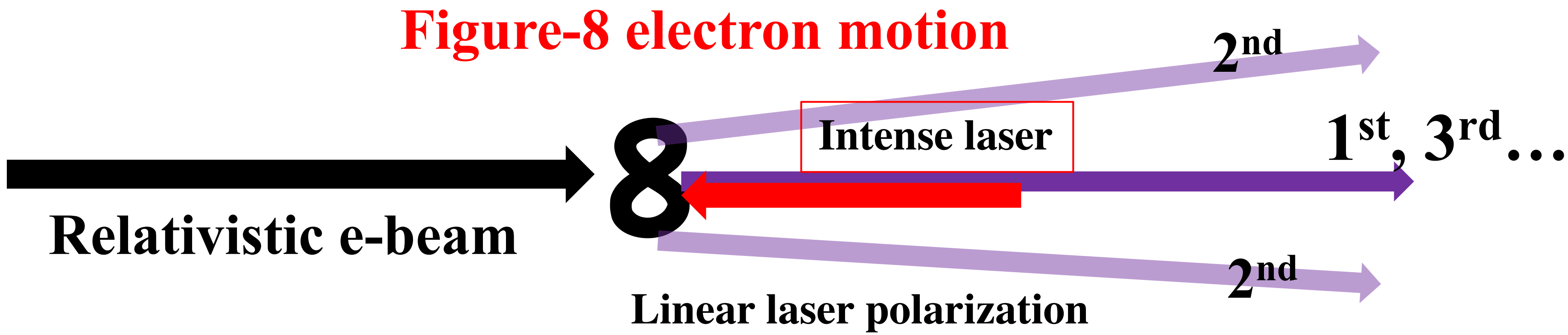
P. Oliva, et al., Appl. Phys. Letters 97, 134104 (2010)





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

Experimental emphasis: nonlinear ICS physics



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:**

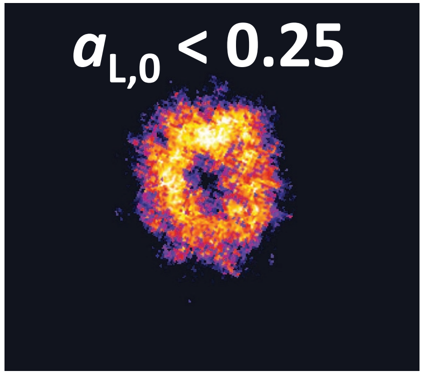
(*Multi-photon process in dense photon field*)

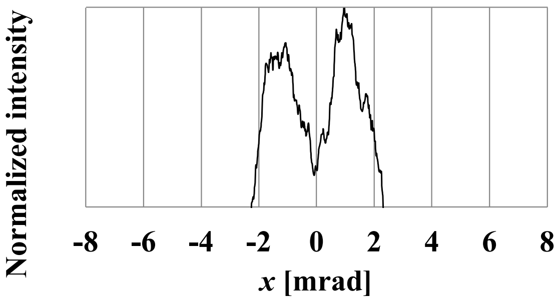
$$h\nu_{X\text{-ray}} = 4\gamma^2\, h\nu_L\, n$$

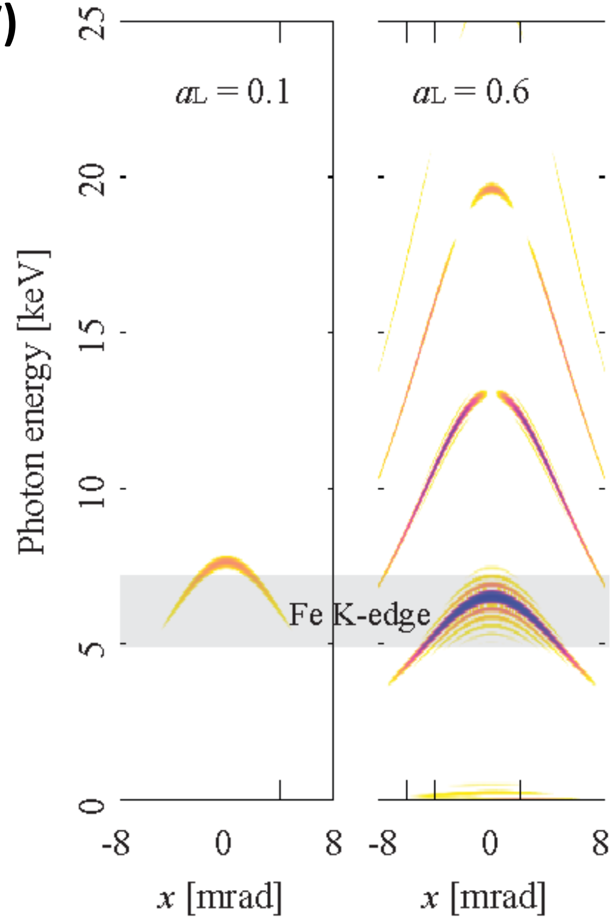
Observation of nonlinear red-shift in fundamental

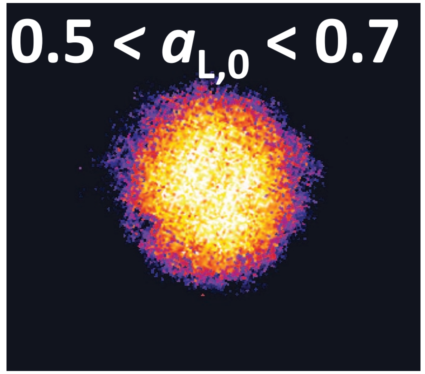
7.6 keV < Fe k-edge (at 5-7keV)
On-axis components is cut

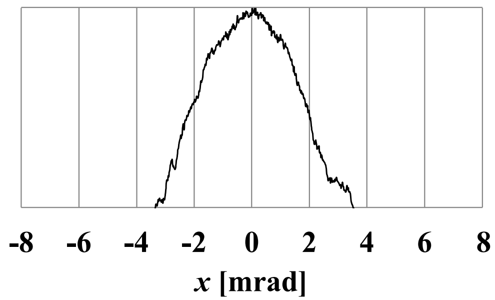
Red-shifting to 5-6 keV









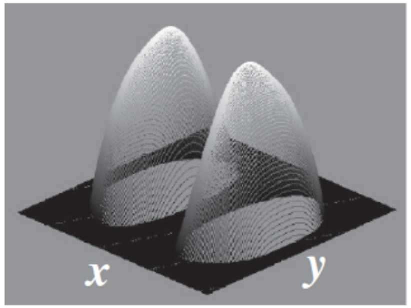


$$h\nu_{ICS,\,1^{st}} = 4\gamma^2 \nu_L/(1+a_{L,0}^2/2) \rightarrow \therefore 0.5 < a_{L,0} < 0.7$$

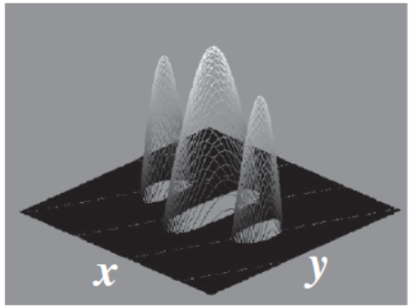
Y. Sakai, et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

2^{nd} & 3^{rd} harmonics with *linear polarization*

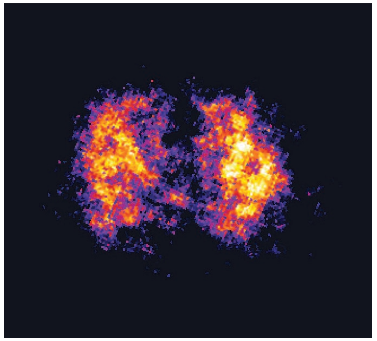
2^{nd}

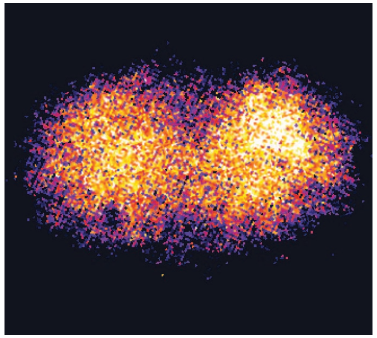


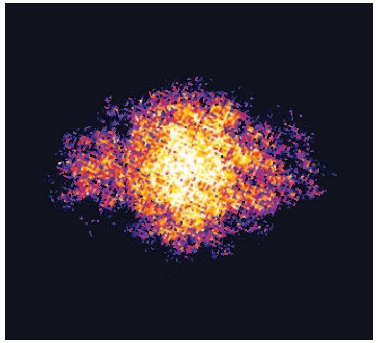
3^{rd}

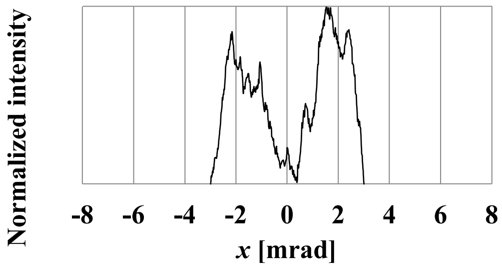


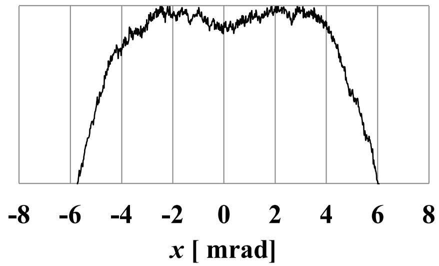
Au L-edge (12 keV) | Al 250 μm > 10 keV | Al 1000 μm > 15 keV

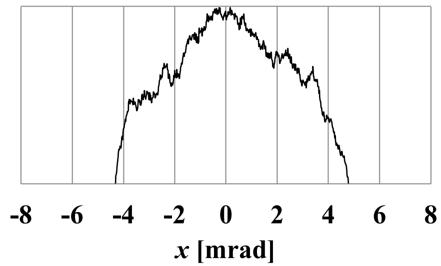












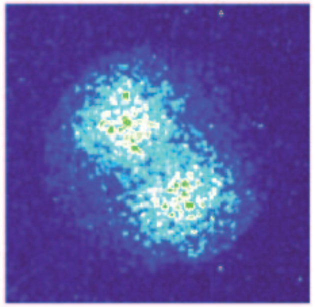
Narrow band 2^{nd} | 2^{nd} + 3^{rd} | 3^{rd} (On-axis & lobes)

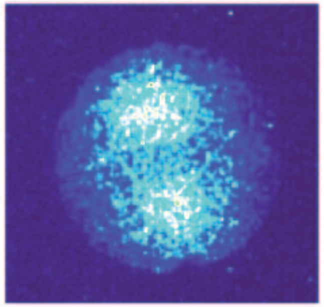
Y. Sakai, et. al, Phys. Rev. ST Accel. Beams 18, 060702 (2015)

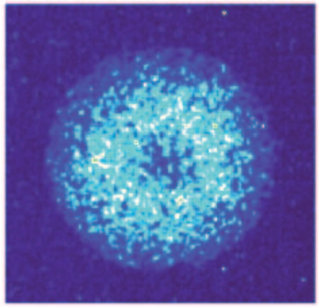
Circularly polarized harmonic radiation

¼ wave plate between regenerative and TW amplifier

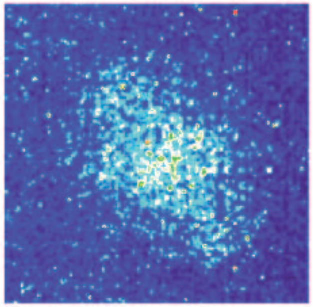
Al 250 μm Linear, 2nd Elliptical, 2nd Circular, 2nd

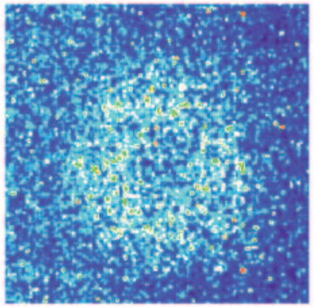






Al 1000 μm Linear, 3rd Circular, 3rd



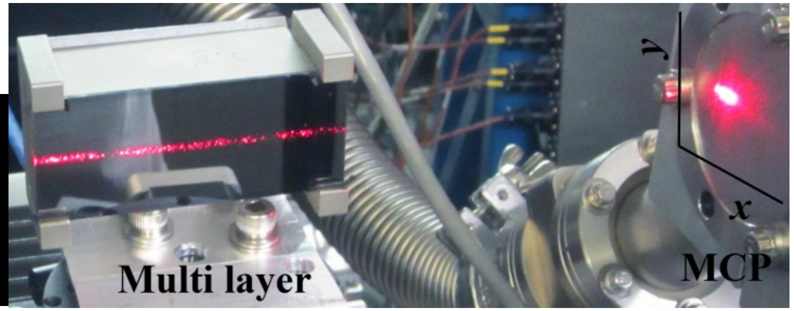


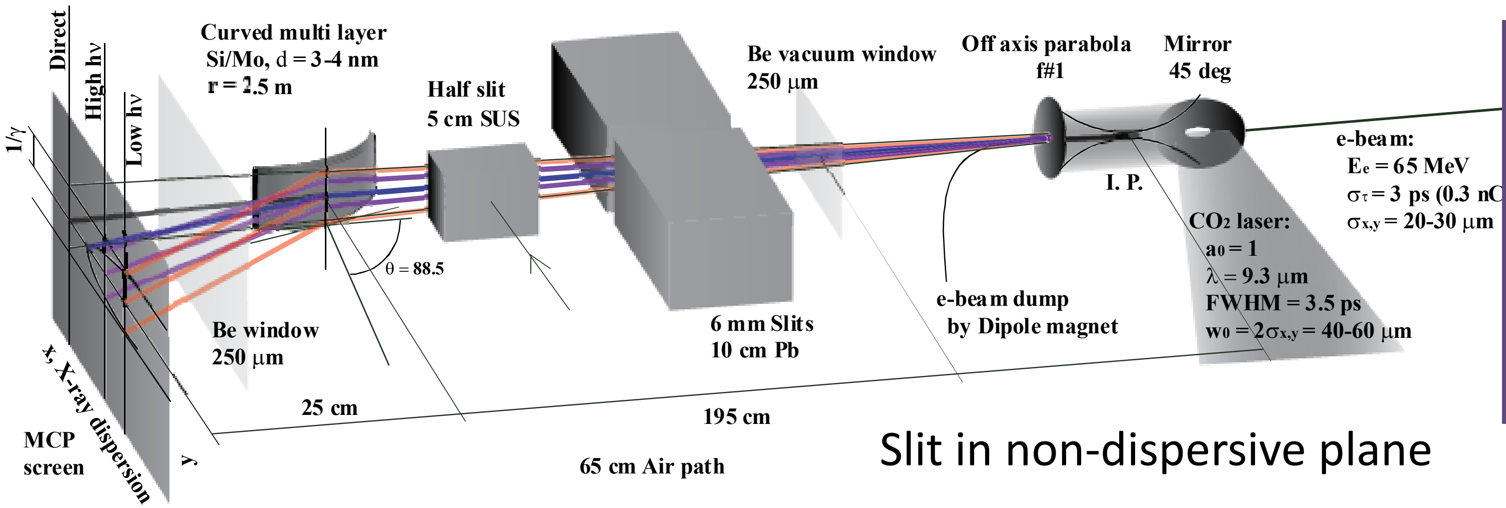
Much attention to this result-
Demonstration of orbital angular momentum?

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

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

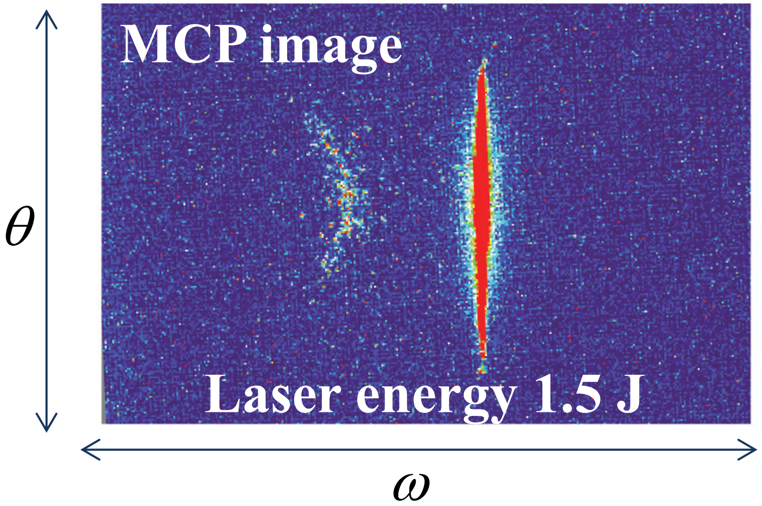
Single-shot bent multi-layer crystal X-ray spectrometer

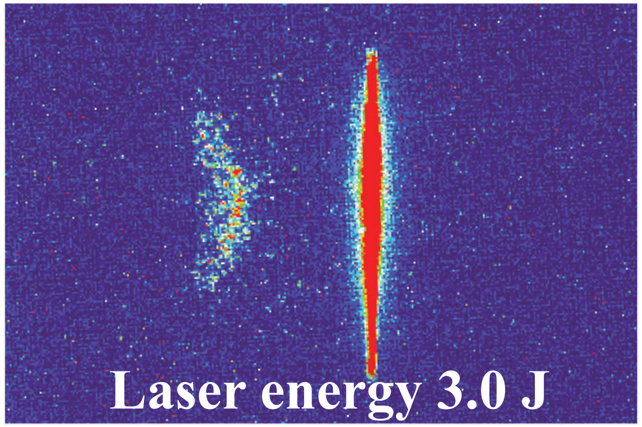




Slit in non-dispersive plane

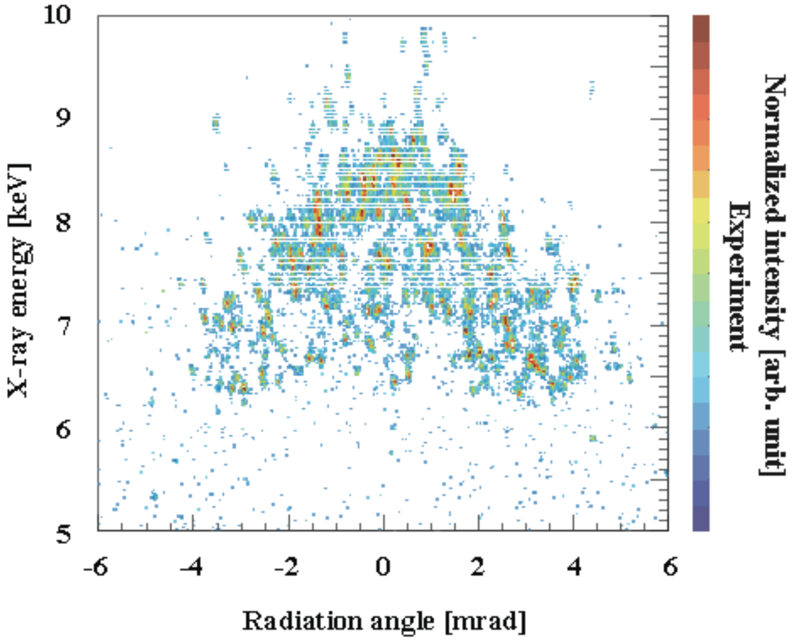
- ✡ Mo-Si multi-layer thickness: $d \approx 3.3$ nm
- ✡ Bragg angle: ~ 25 mrad
- ✡ Angle acceptance : ~ 50 mrad
- ✡ Reflectivity ~ 15% @ NSLS X15A

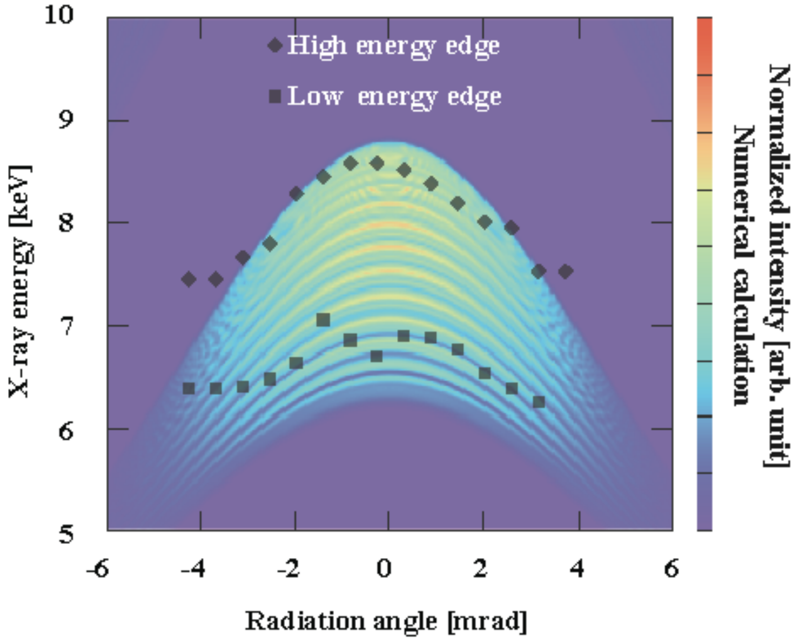




Y. Kamiya, T. Kumita and P. Siddons et al., X-ray spectrometer for observation of nonlinear Compton scattering, Proc. Joint 28th Workshop on Quantum Aspects of Beam Physics (World Scientific), 103 (2003)

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





What are these fringes?

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

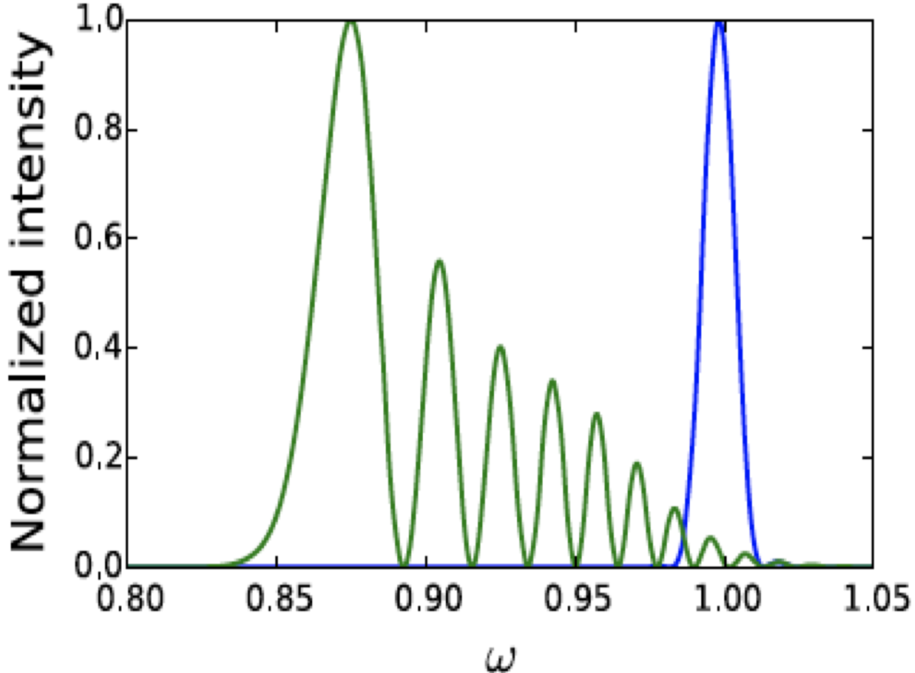
Analysis: near-axis spectral broadening in nonlinear ICS

- ✶ **Probability model (no wave effects)**
- ✶ **Temporal variation: high red-shift emphasized**
  - ✶ **Wave *self-interference* effects from a_L occurring twice**
- ✶ **Transverse effect emphasizes *low red-shift***

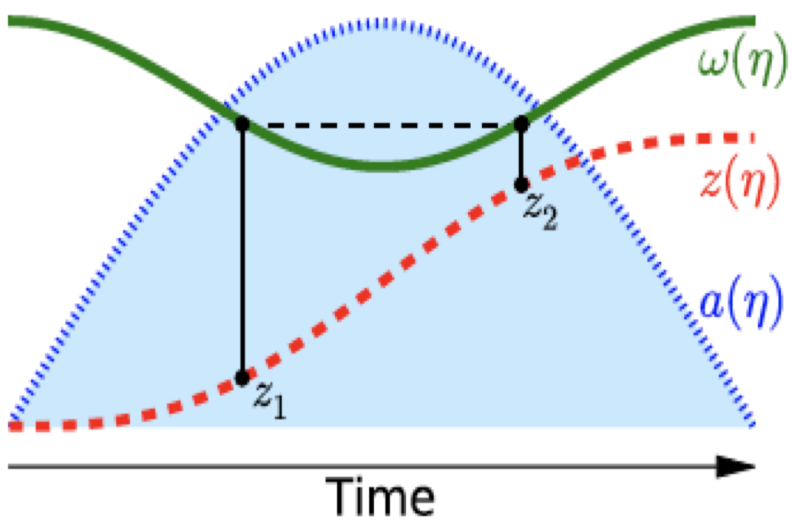
$$P_1(\Delta\lambda) = \frac{C_1}{\sqrt{\ln(\Delta\lambda_{max} / \Delta\lambda)}}$$

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

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



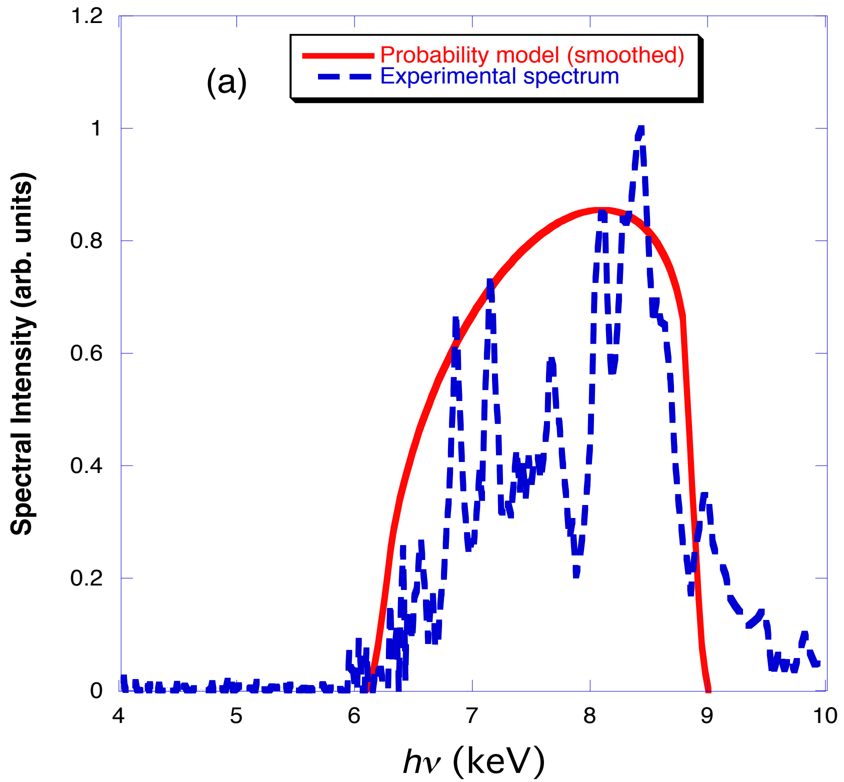
L-W numerical model shows interference



All effects, κ dependence

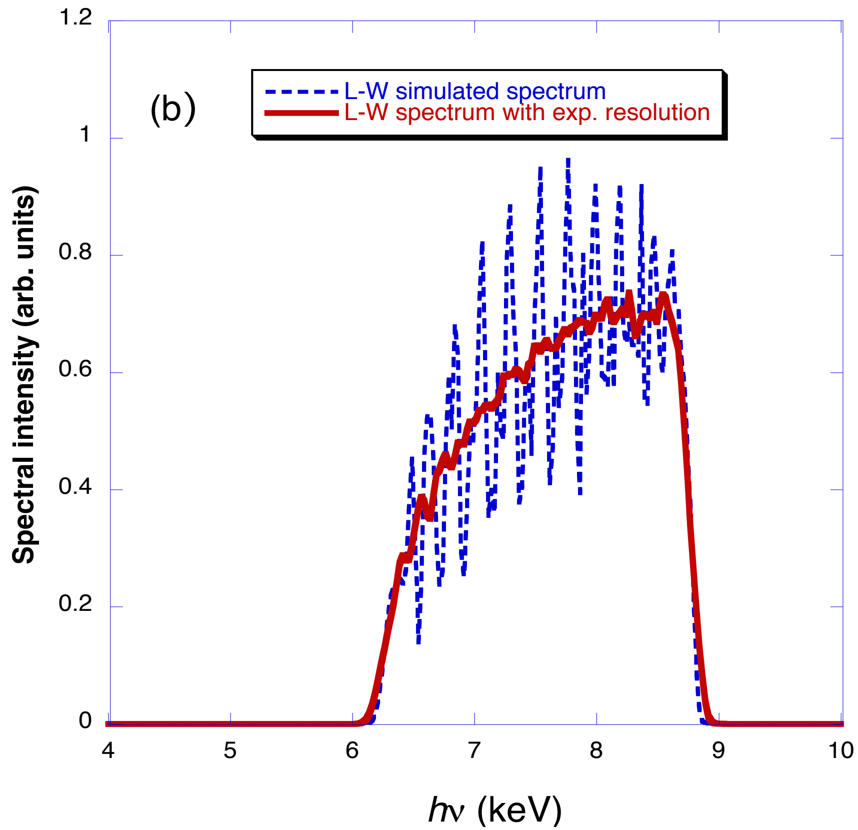
Evaluation of Experimental Results

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



Is structure due to self-interference?

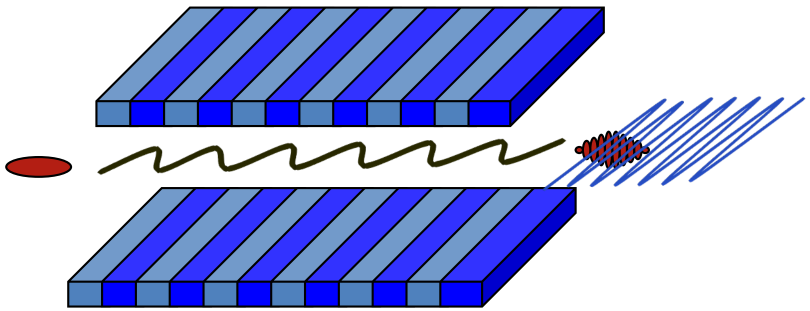
Y. Sakai, et al. *Phys. Rev. Accel. Beams* **20**, 060701 (2017)



Simulated spectrum (blue)
With resolution effects (red)

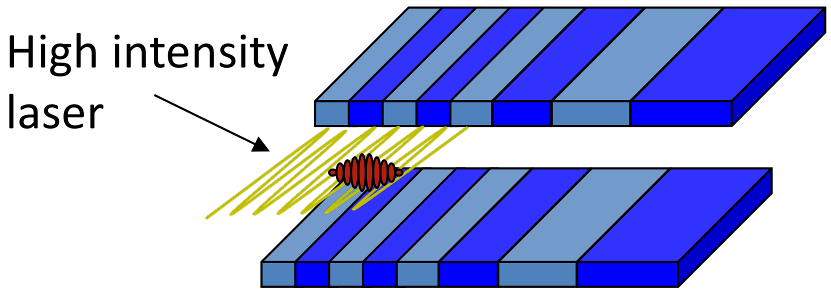
Compact *optical* accelerator: IFEL

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



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

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



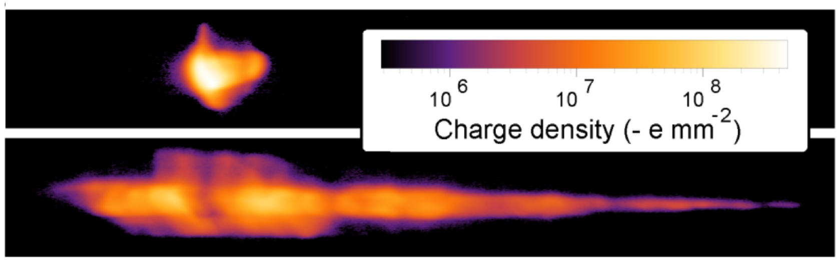
R.B. Palmer, *J. Appl. Phys.* **43**, 3014 (1972).

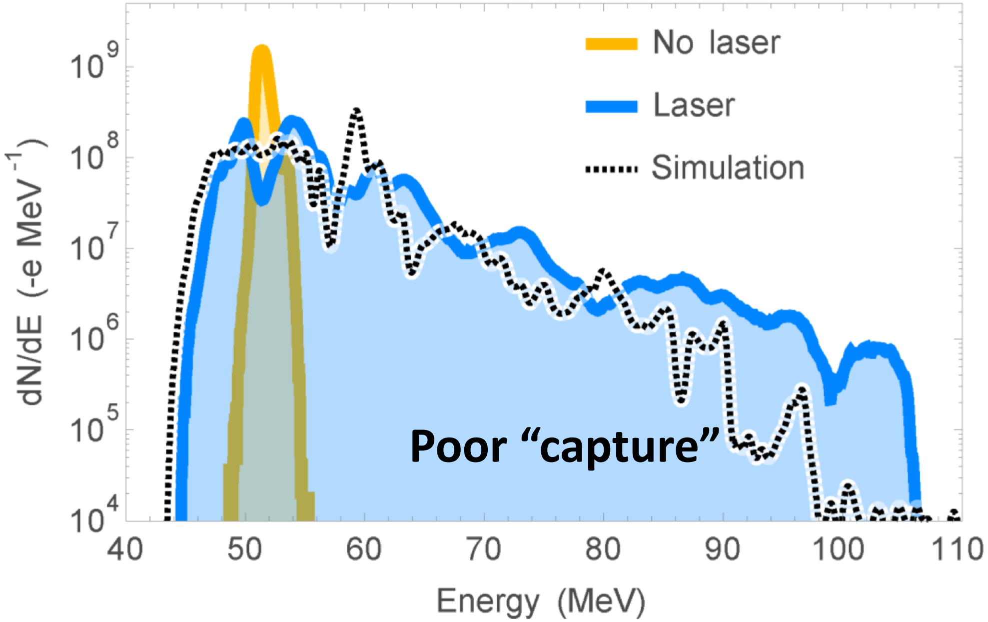
E. D. Courant, C. Pellegrini, and W. Zakowicz, *Phys. Rev. A* **32**, 2813 (1985).

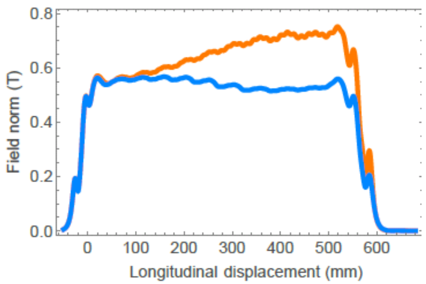
- IFEL well suited for 50 MeV – ***up to few GeV*** (due to SR limits)
- ***Plane wave or far field*** accelerator: minimal 3D effects
- ***Vacuum*** accelerator - not dependent on boundaries
  - ***High rep rate, low losses***
  - ***Preserves e-beam quality/emittance***
  - ***Stable energy output***: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

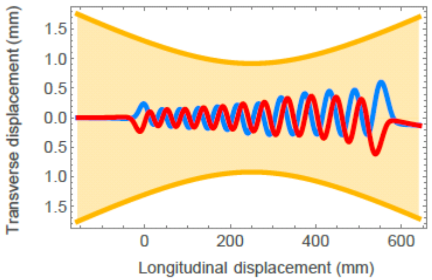
Rubicon IFEL experiment

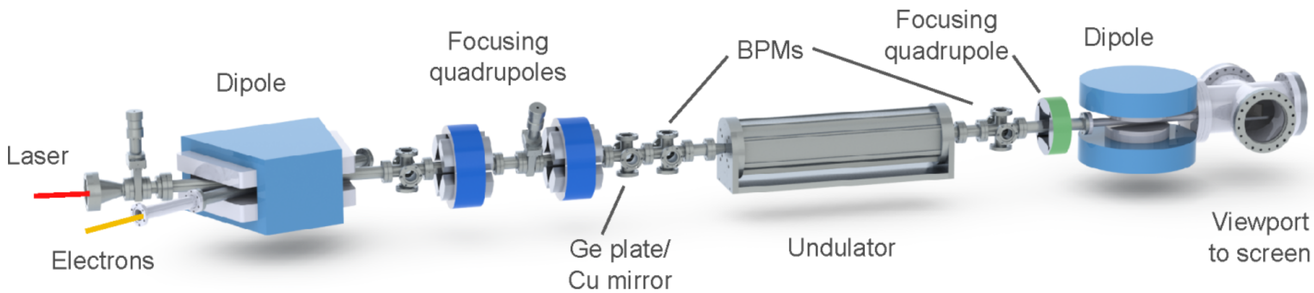
- Helical geometry, high gradient IFEL
- Strongly tapered helical Halbach undulator
- High gradient(>100 MeV/m demonstrated





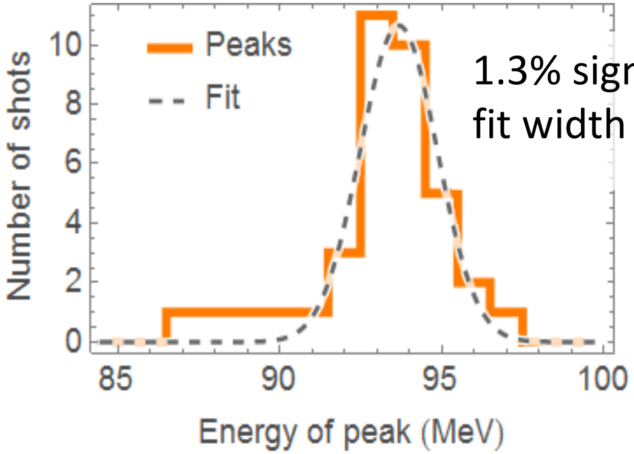


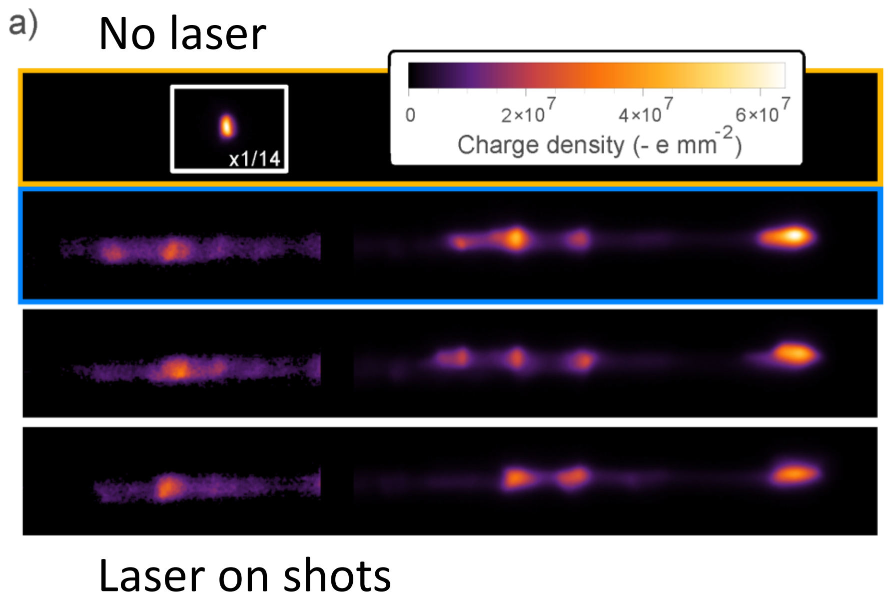


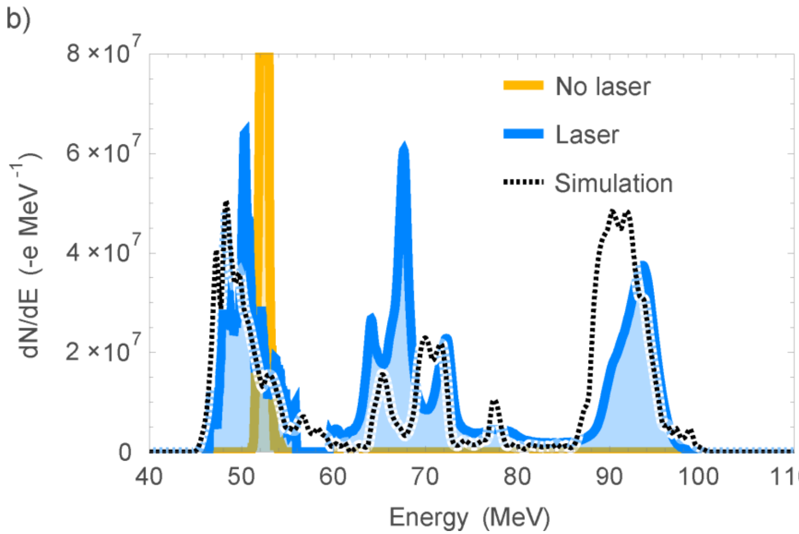


High quality IFEL accelerated beams

- 93 MeV – 1.8 % energy spread
- **Reproducible spectra** (σ_E < 1.5 %) with 30% rms laser fluctuations







nature COMMUNICATIONS

ARTICLE

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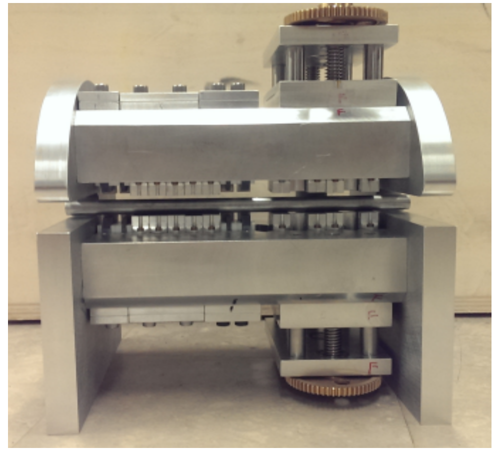
High-quality electron beams from a helical inverse free-electron laser accelerator

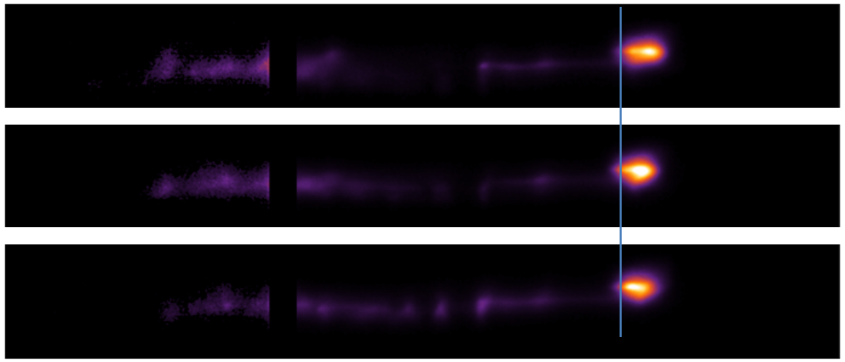
J. Duris[1], P. Musumeci[1], M. Babzien[2], M. Fedurin[2], K. Kusche[2], R.K. Li[1], J. Moody[1], I. Pogorelsky[2], M. Polyanskiy[2], J.B. Rosenzweig[1], Y. Sakai[1], C. Swinson[2], E. Threlkeld[1], O. Williams[1] & V. Yakimenko[3]

IFEL with prebuncher

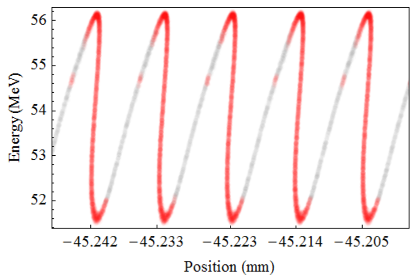
- UCLA permanent magnet based pre-buncher
- Permanent magnet chicane with adjustable R_{56}
- Achieved **> 50% capture**

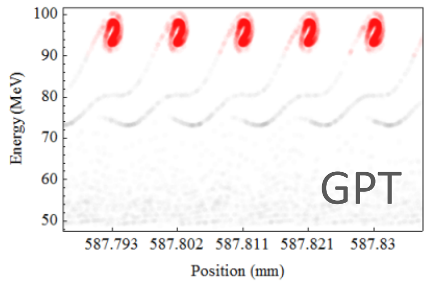
~30 cm

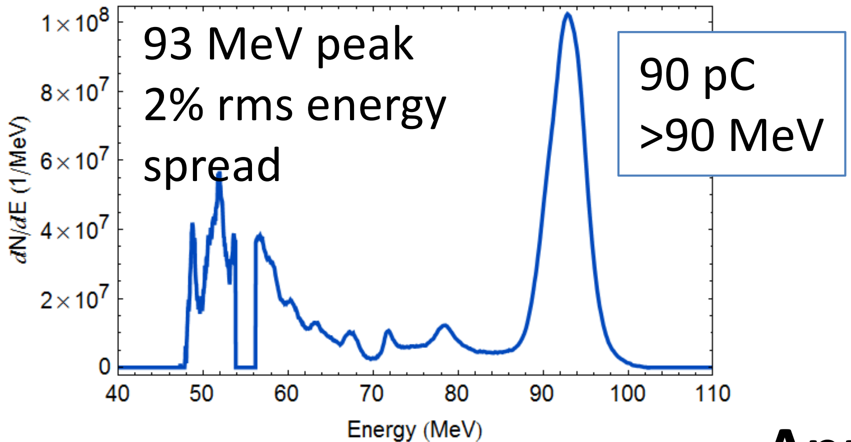




First experiment using a CPA CO2 laser

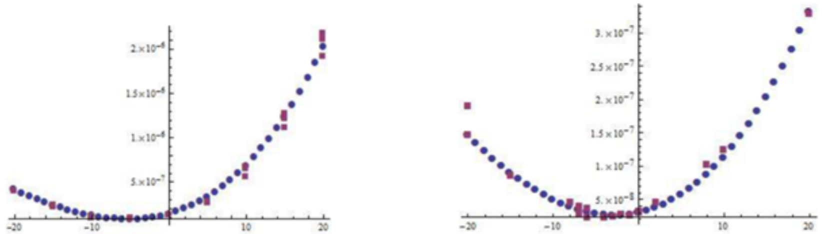






Unaccelerated emittance 2.3 um

Accelerated emittance 2.4 um

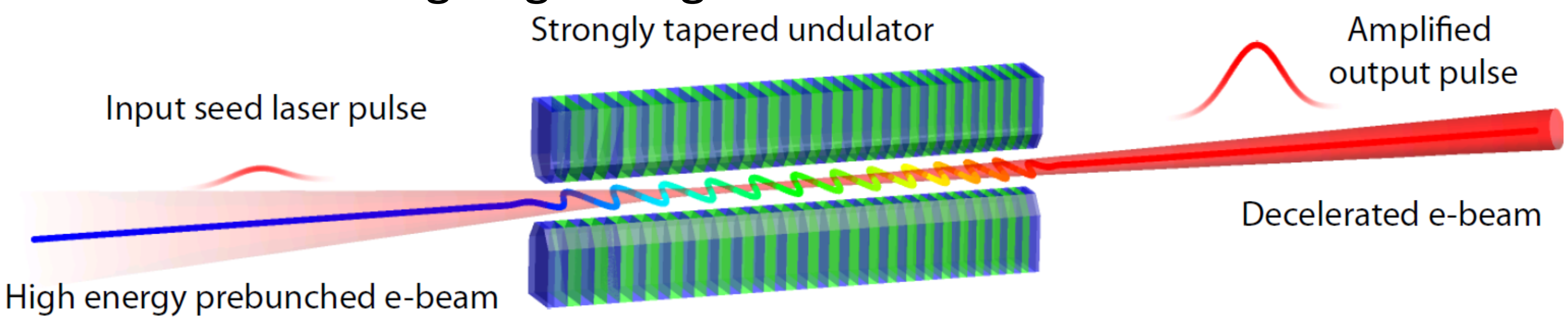


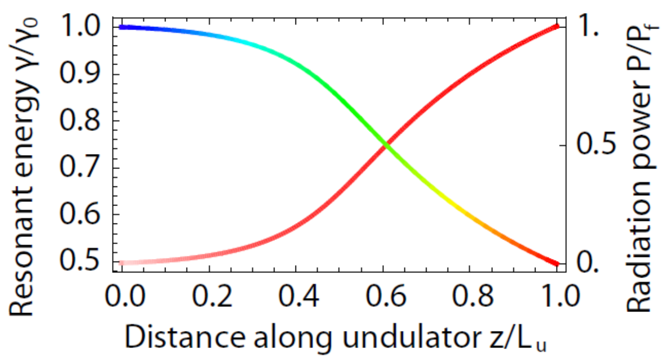
Apply this beam in ICS experiment…

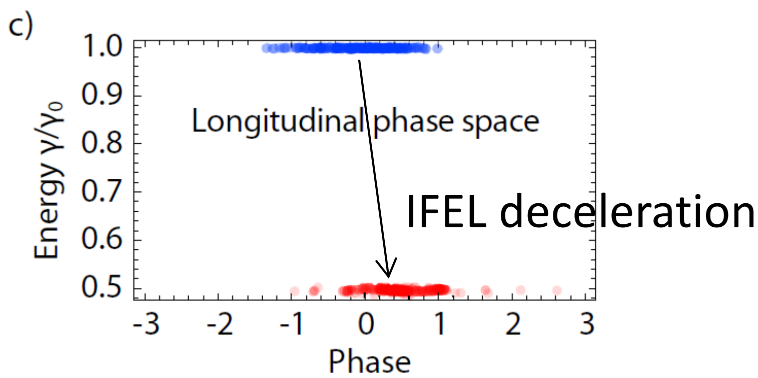
Can IFEL run in reverse?

Tapering Enhanced Stimulated Super-radiant Amplification (TESSA)

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



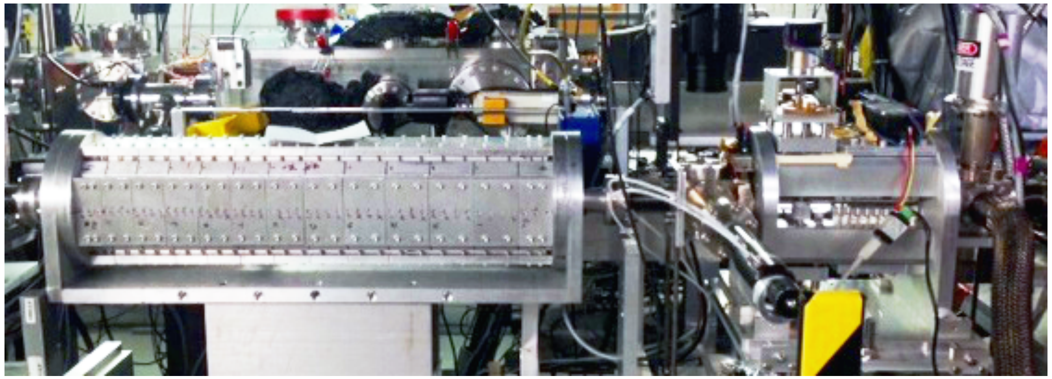


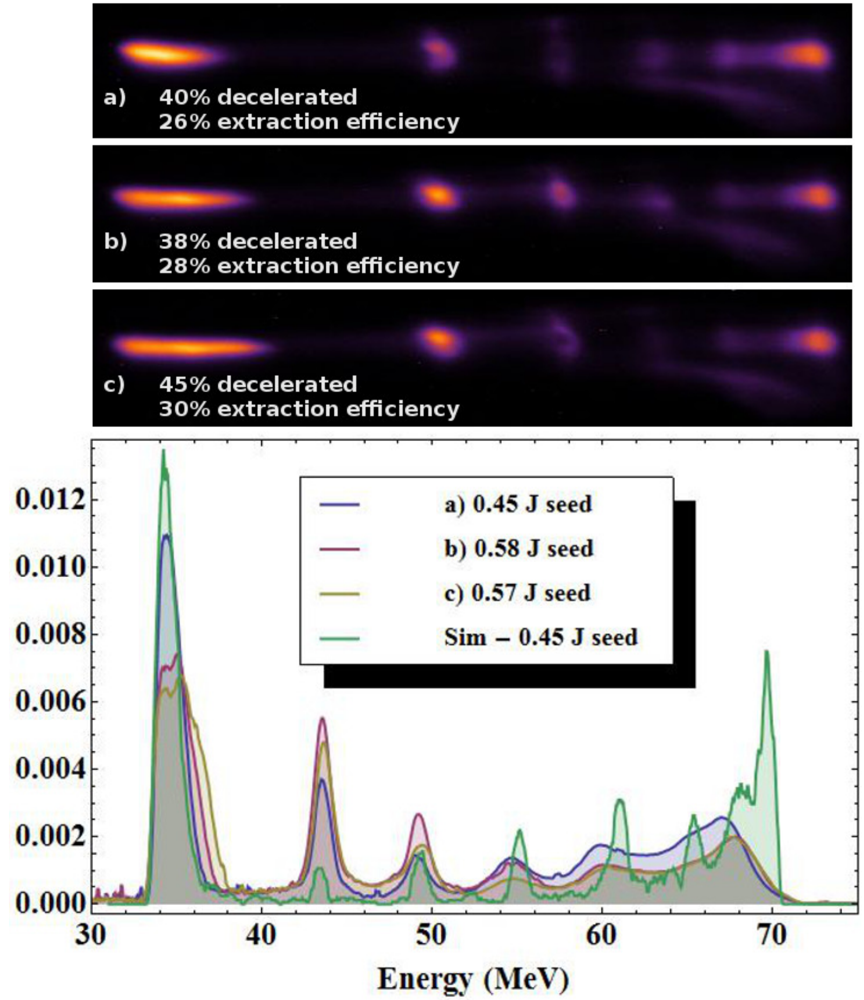


NOCIBUR IFEL deceleration experiment

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

Undulator Prebuncher



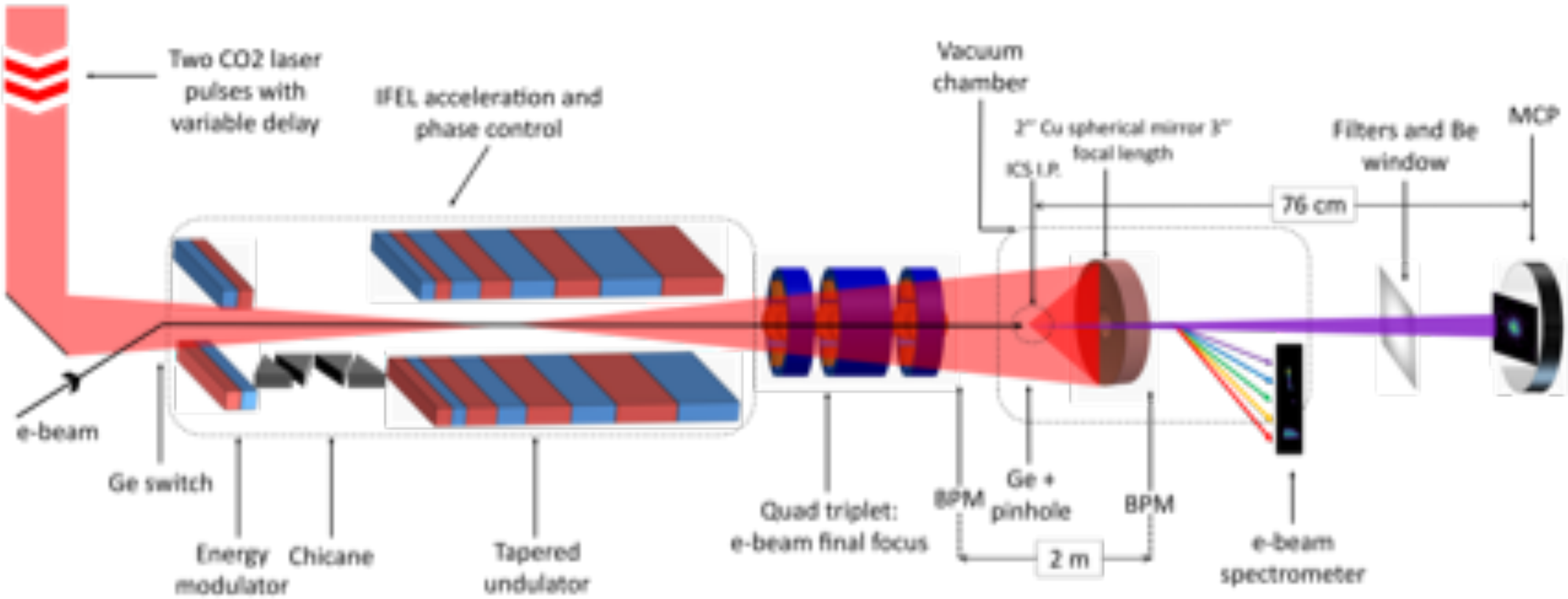


N. Sudar, *et al., Phys. Rev. Lett.* 117, 174801 (2016)

Merging IFEL and ICS

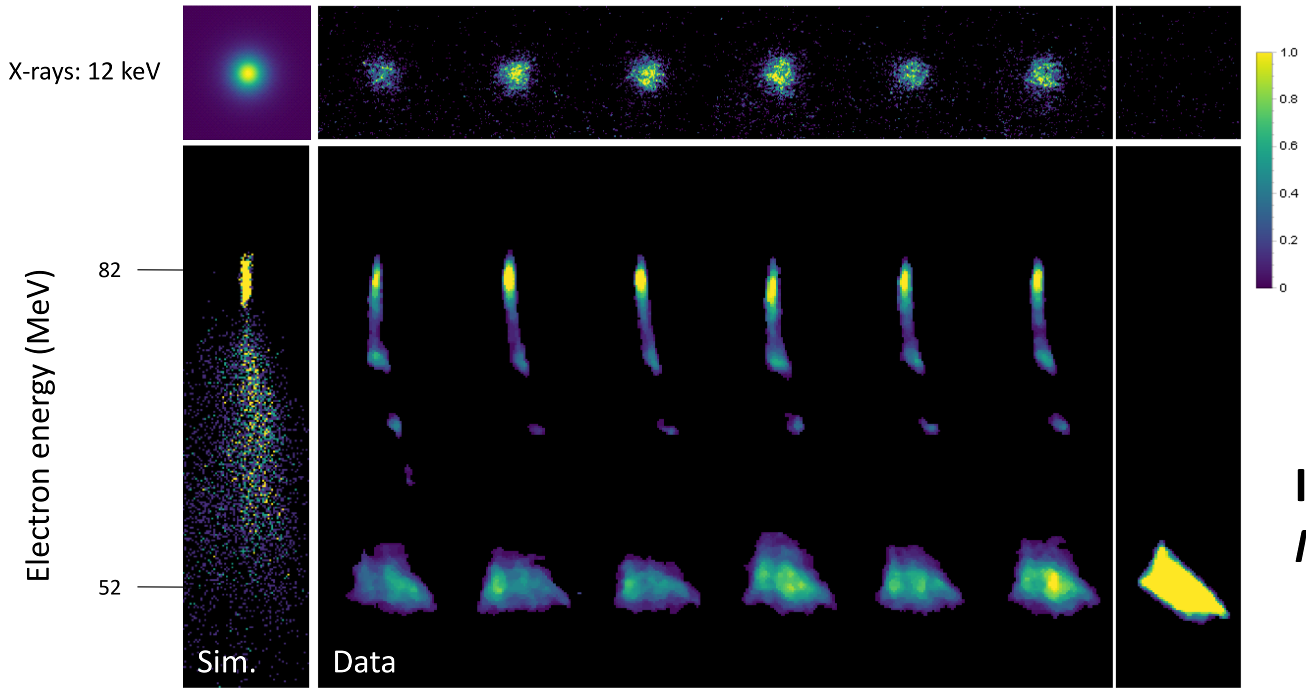
- Success of IFEL, combined with ICS physics and experimental methods…

RUBICONICS: pre-bunched IFEL for ICS



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

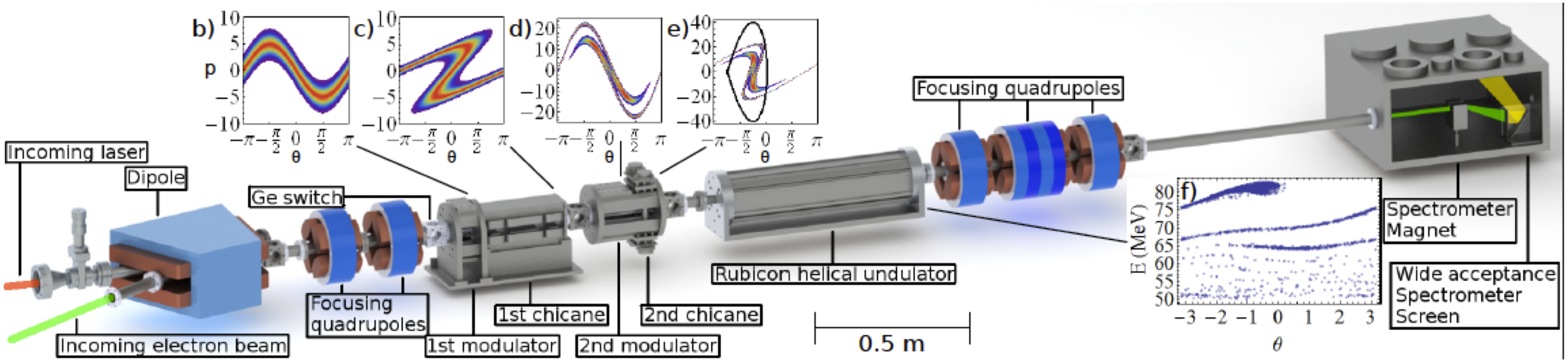
RUBICONICS scattered photons

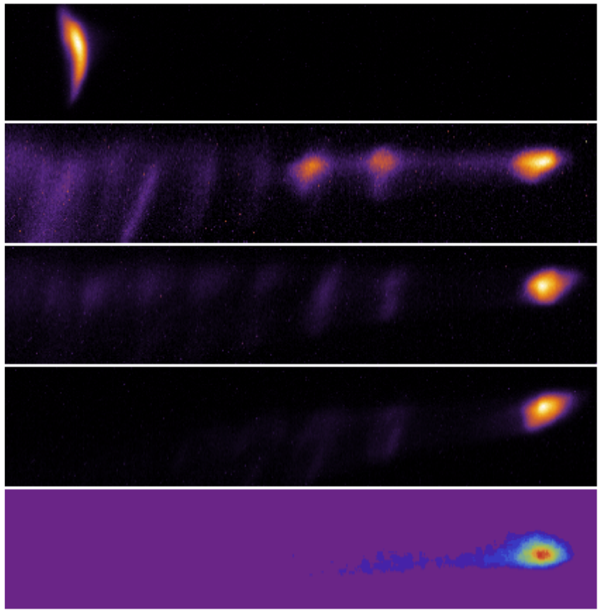


I. Gadjev, et al, to appear in *Nature Scientific Reports*

- 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

Improving the source: double buncher





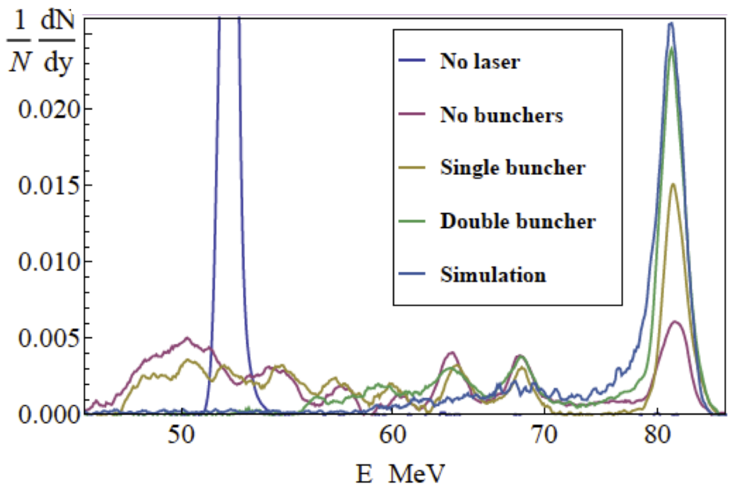
No laser

No bunchers

Single buncher

Double buncher

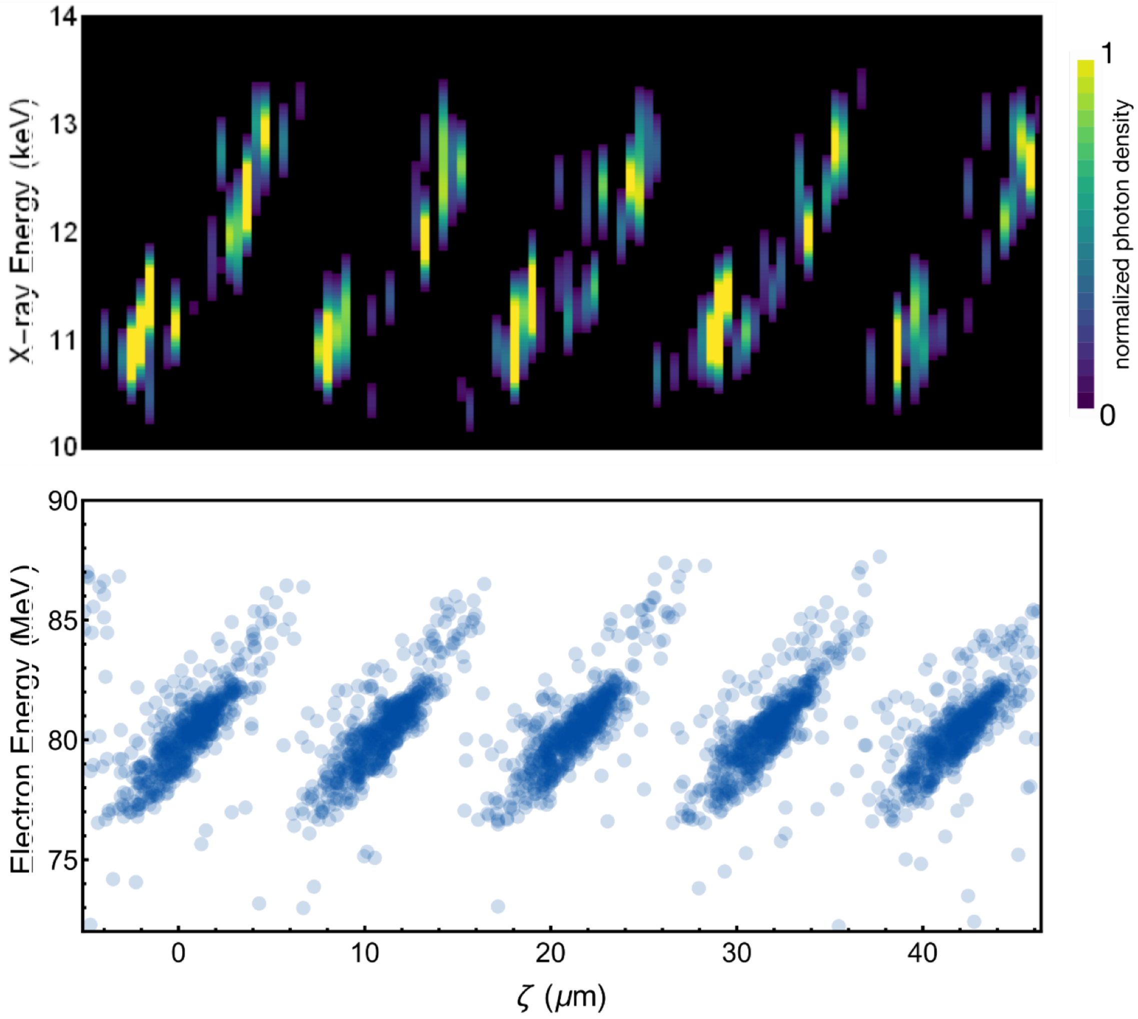
Simulation



- 96% captured
- 78% accelerated to final energy

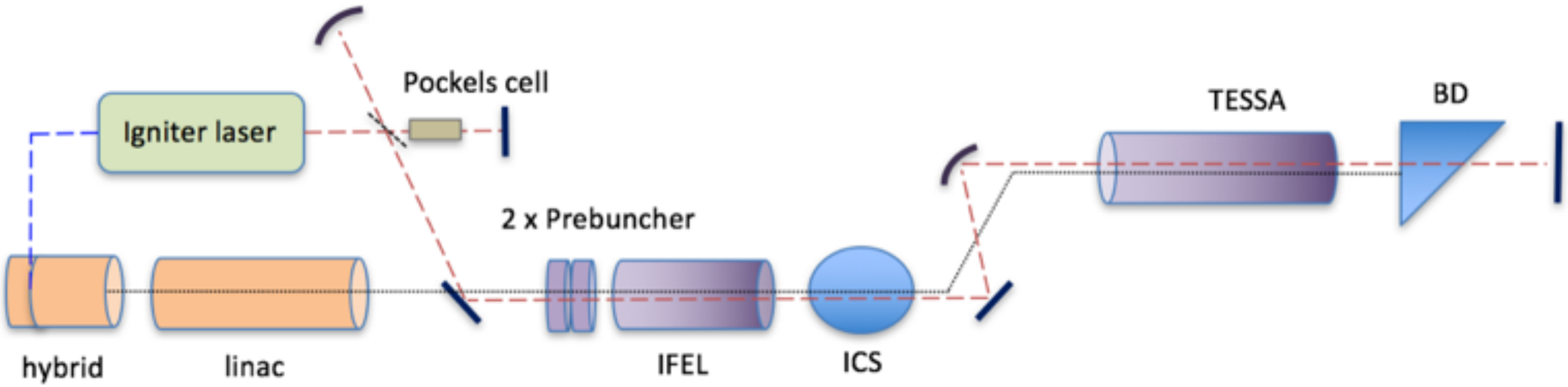
Current and Future Directions

- Femtosecond 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
- Measure e-s with RF deflector
- Currently working on *IFEL* recirculation
- On to main application… *CONTROL*



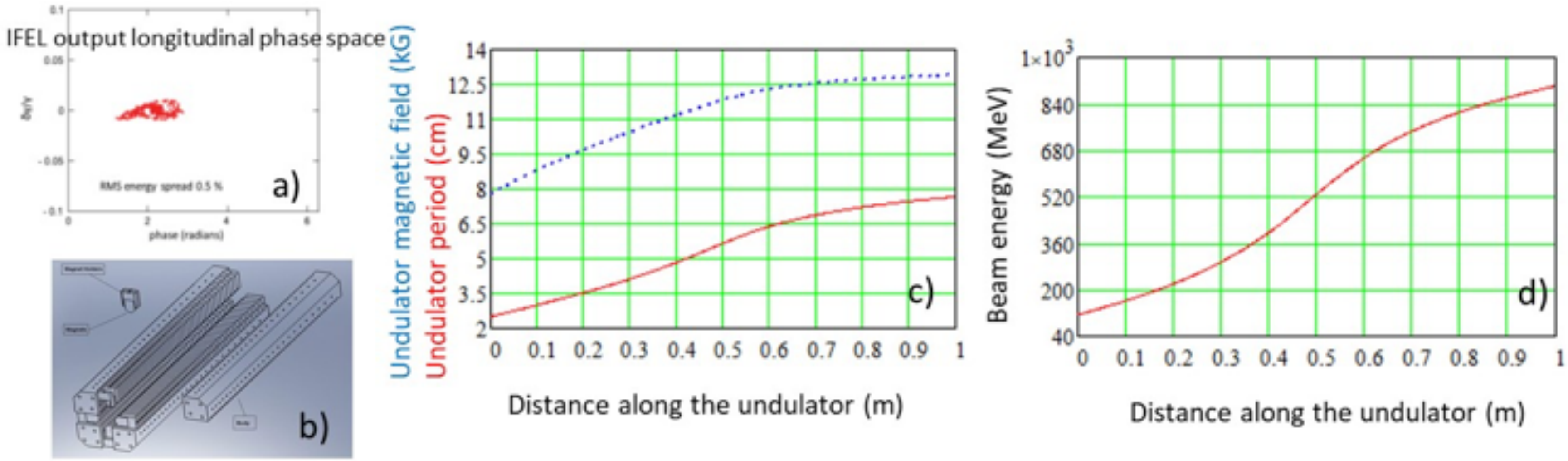
Electron pulse structure at ICS IP

CONTROL: COmpton-based Nuclear probe using Tapered, Recirculating Optical



- **High repetition rate gun**
- **Optimized IFEL bunching**
- **Energy recovery using TESSA**

UCLA-RadiaBeam proposal (DARPA)



Summary

- ✶ UCLA developing all-optical IFEL/ICS system for high average flux MeV γ's
- ✶ Fundamental ICS physics investigated: nonlinear red-shift, harmonics, orbital angular momentum
- ✶ IFEL compact accelerator optimum for <GeV energy
  - ✶ Excellent performance, high quality microbunched beam
  - ✶ Spin-off to FEL - TESSA; also use for e- energy recovery
- ✶ *Recirculation* for high average flux
  - ✶ Advantage over other advanced acceleration schemes
  - ✶ ICS demonstrated; IFEL underway
- ✶ 5^{th} generation light source with unique characteristics