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

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March 8, 2018

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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 *bright* (directional, *ultra-fast – to* sub-100 fs)
- Scattered light is *quasi-**monochromatic***
- **Tunable wavelength** (relativistic Doppler, like FEL) $\boxed{\lambda_{sc} \approx \lambda_L / 4\gamma^2}$
- Many new projects worldwide (e.g. ELI-NP)
  - **Also with novel e- accelerators: 5th generation light sources**

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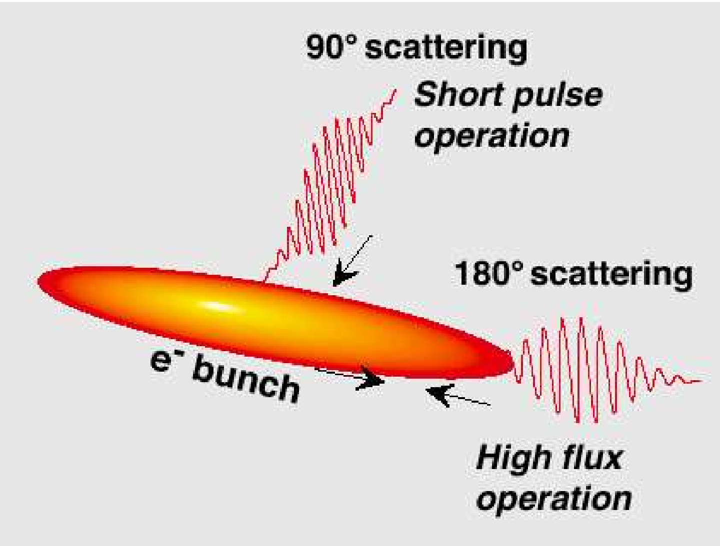
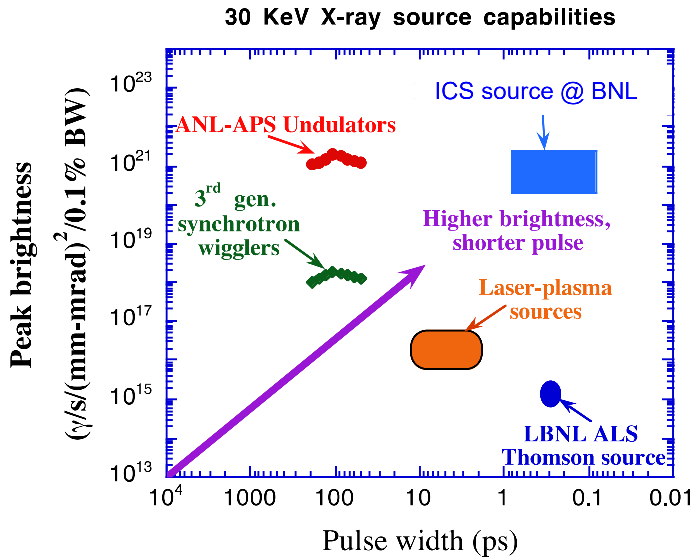
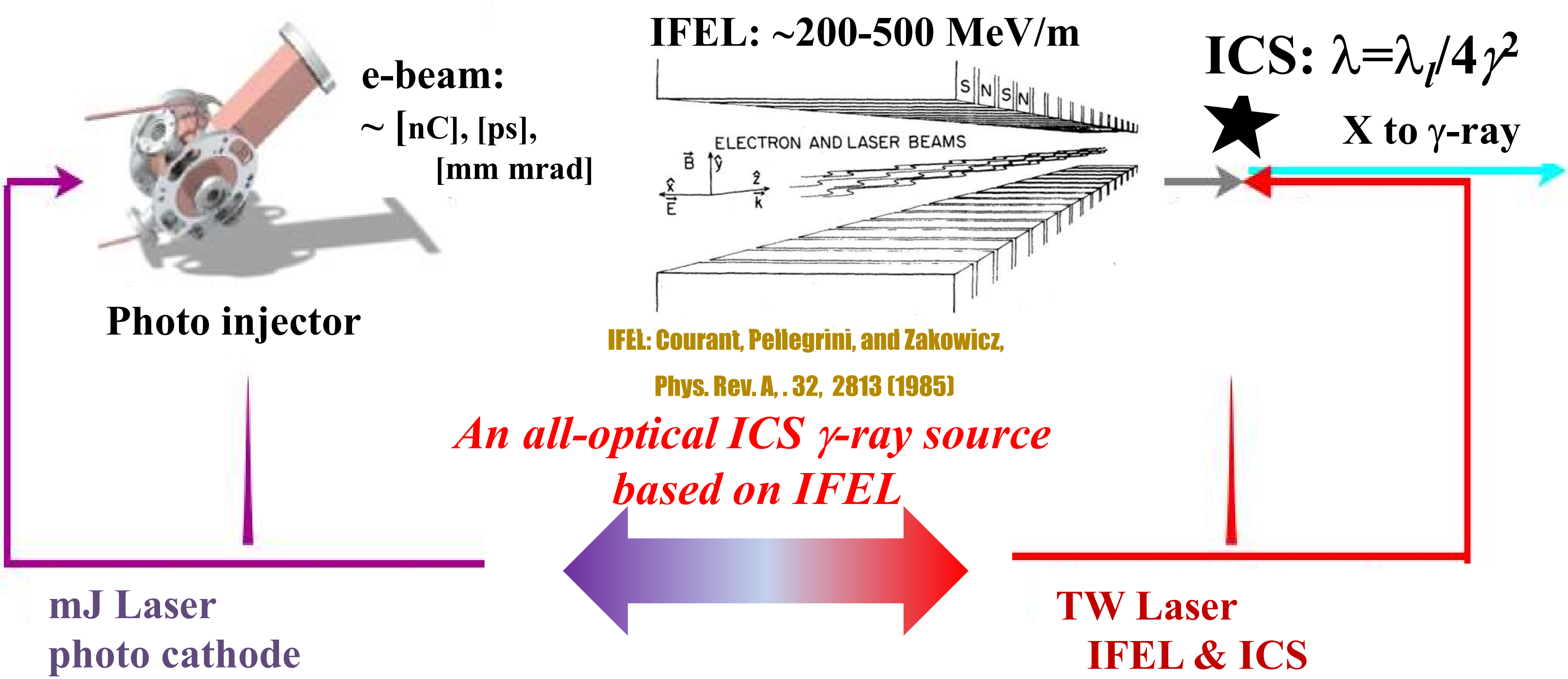
$$\boxed{\lambda_{sc} \approx \lambda_L / 4\gamma^2}$$





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

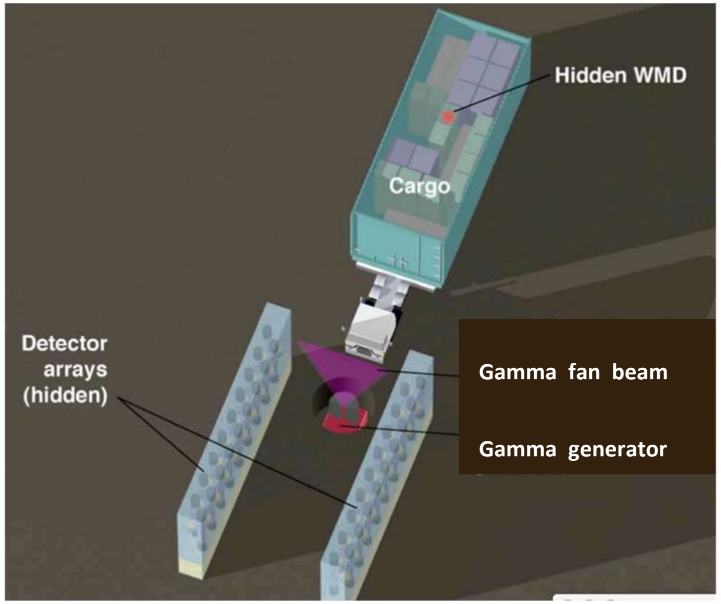
↔ Low collective e-beam effects

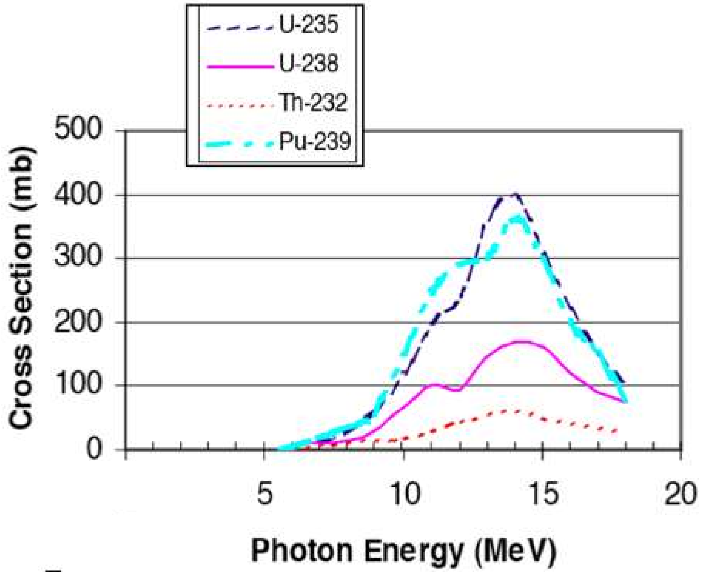
↔ Laser can be recirculated (not in plasma)

Applications of MeV photons

✶Active detection of special nuclear materials

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



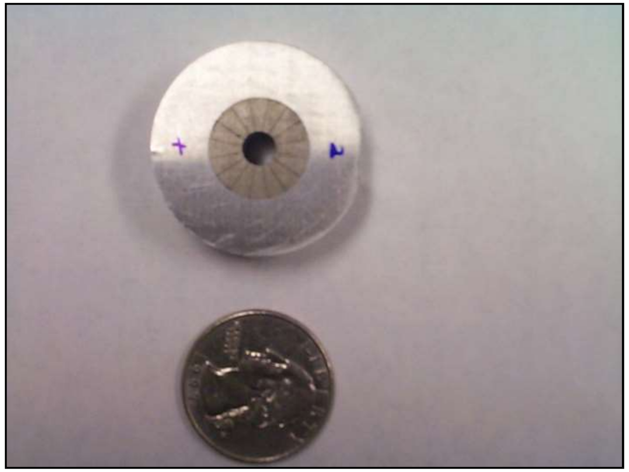


- ★ **Directed γ's, U~10-15 MeV**
- ★ **Required photon number > 10^{12} /sec**
- ★ **Similar requirements for keV γ's in medicine, semiconductors**

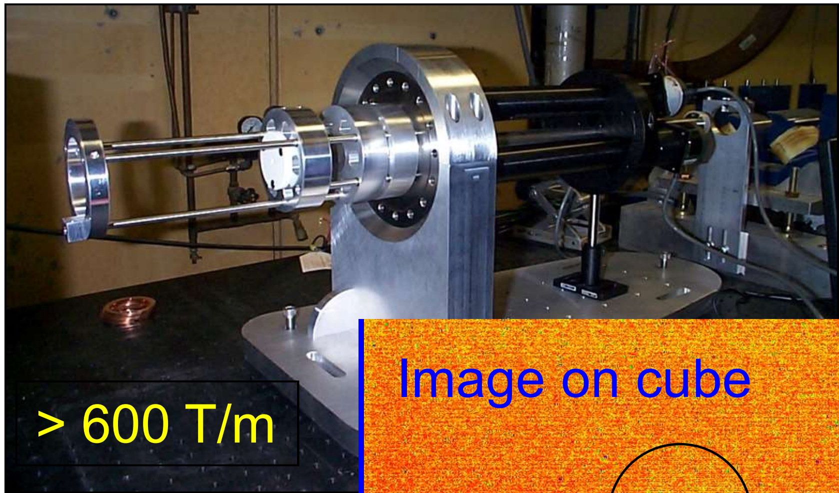
ICS Demands High Collision"Luminosity"

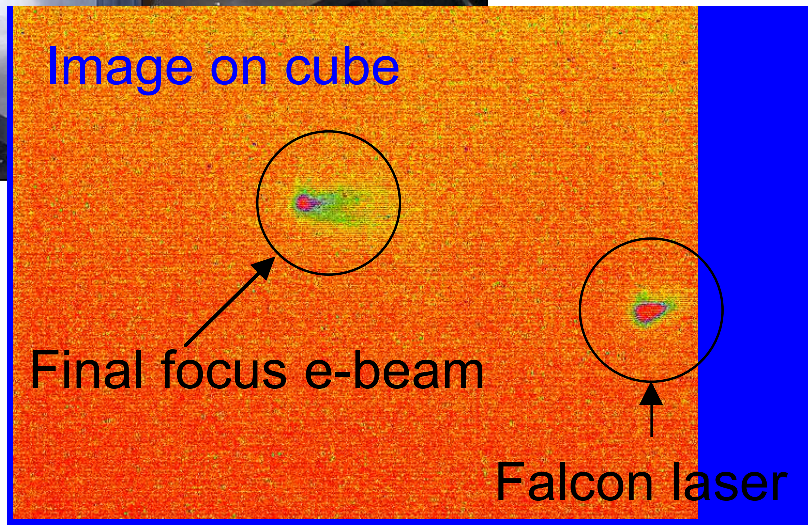
- **Like HEP collider: timing, pointing, *focusing***
- Ultra-strong e- focusing (<10 μm e- spots)
- Innovation: ultra-strong PMQs, "camera" triplet

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

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

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

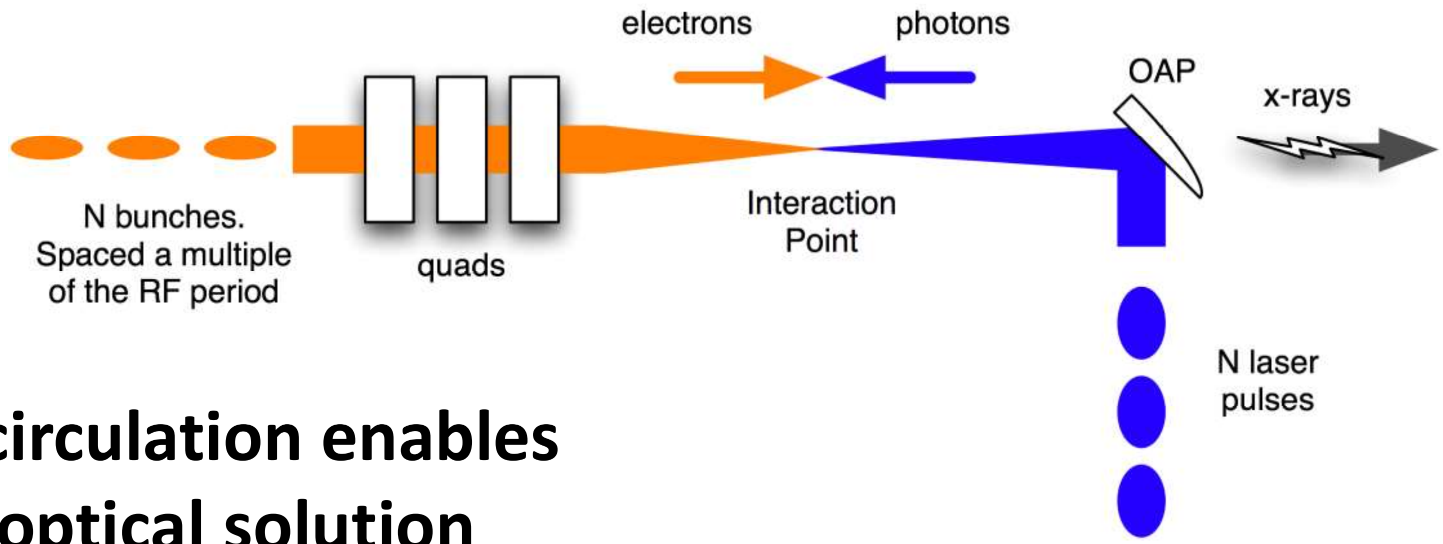
J. B. Rosenzweig, O. Williams, *Inter. J. Mod. Phys*. A 23, 4333 (2007)

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

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

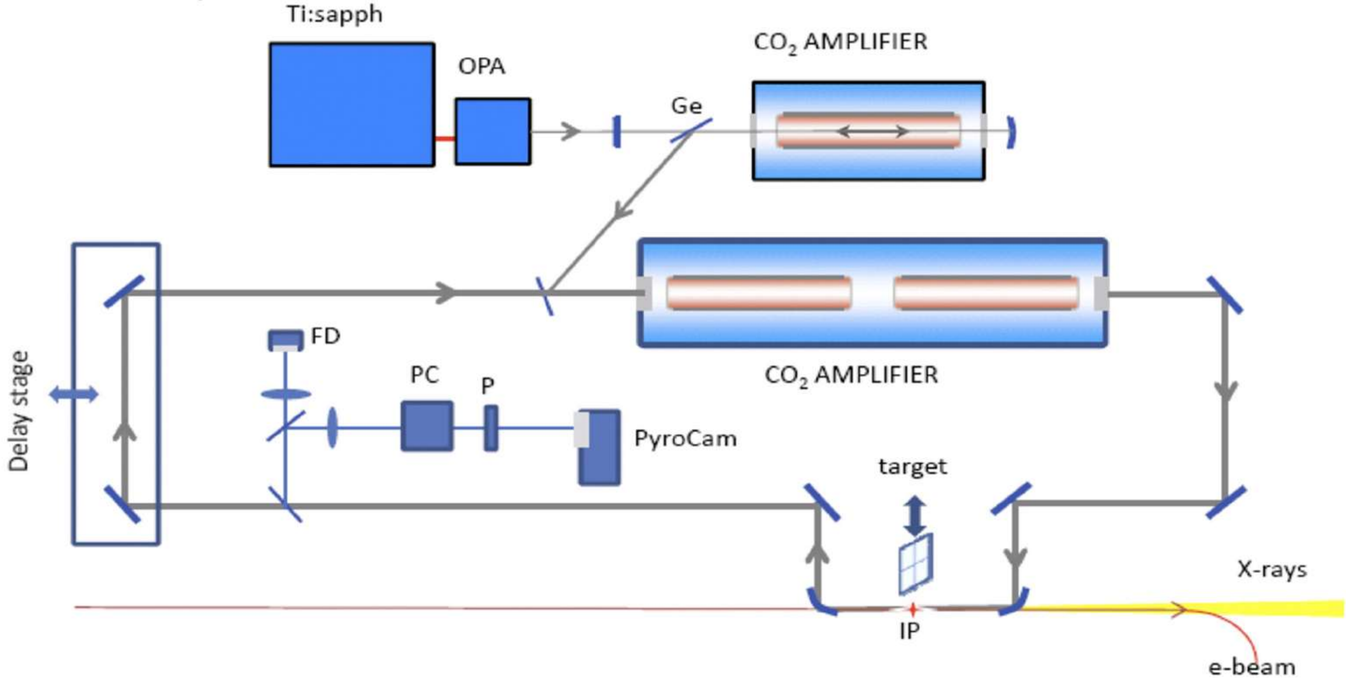
Multi-bunch ICS Interaction

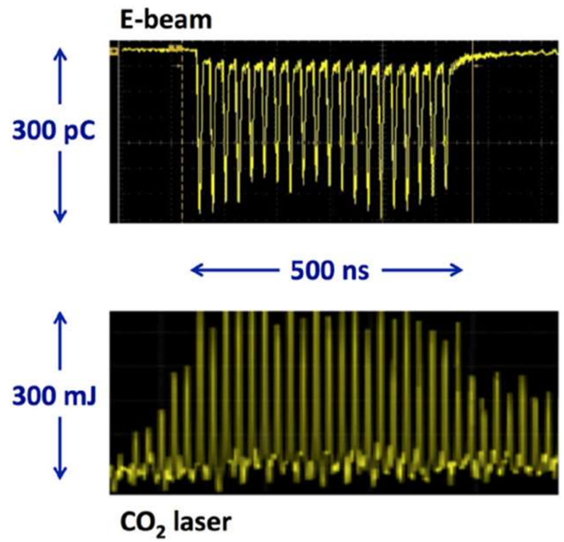
- Optimized ICS source produces ~10^8 photons *per pulse*
- Cargo interrogation, e.g., requires >10^{12}-10^{13} photons/s
- State of the art accelerator and laser systems ~500 pps
- Few laser photons scattered (*used up*) in ICS interaction
- Solution: re-use photons, interact *N* time per RF pulse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



Recirculation enables all-optical solution

Laser Recirculation with multi-pulse electrons

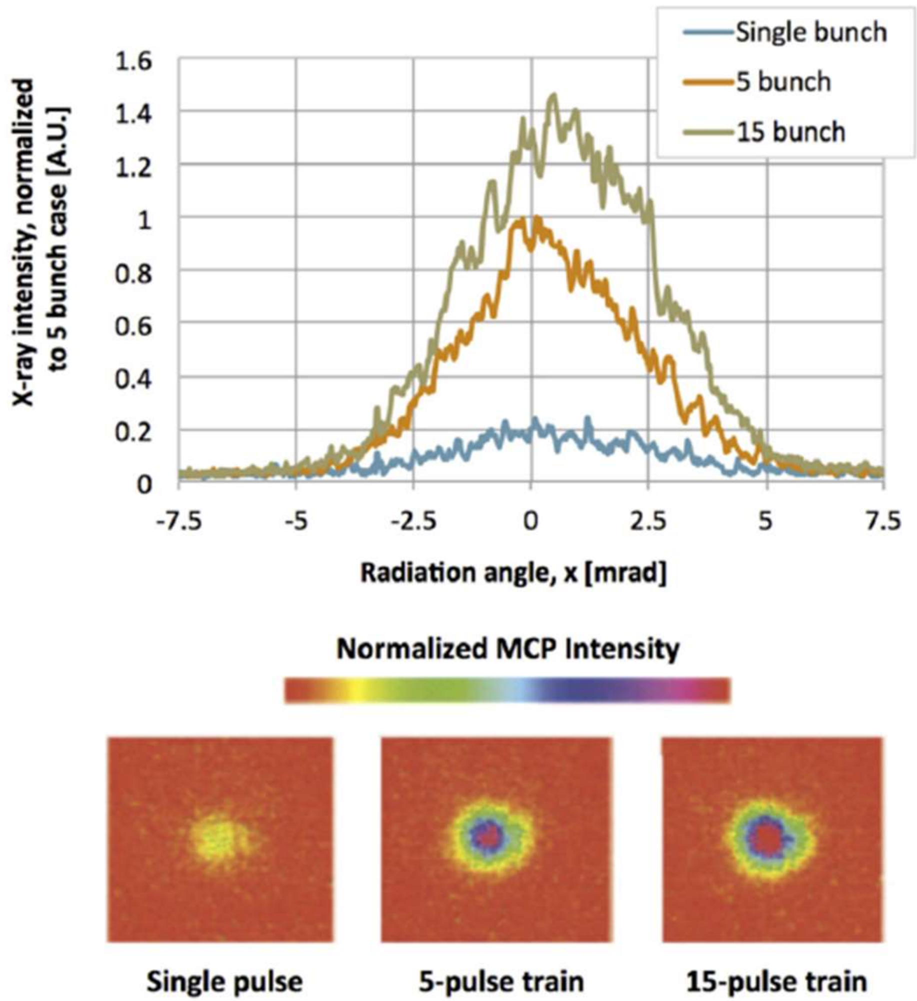




- Pulsed ICS using CO_2 laser pulse-train
- Active medium recirculating cavity
  - Passive solutions also (*e.g*. ELI-NP)

Recirculating ICS interaction demonstrated

- Output fluctuations stabilized
- Multiple pulse performance limited by CO2 laser degradation
  - Correction now in place
- Recirculation of IFEL...

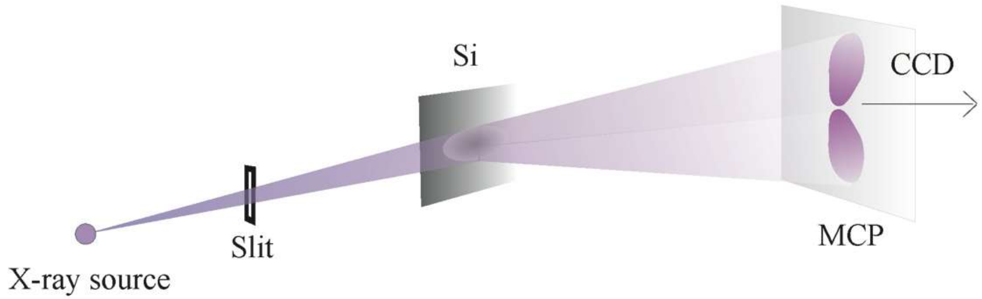


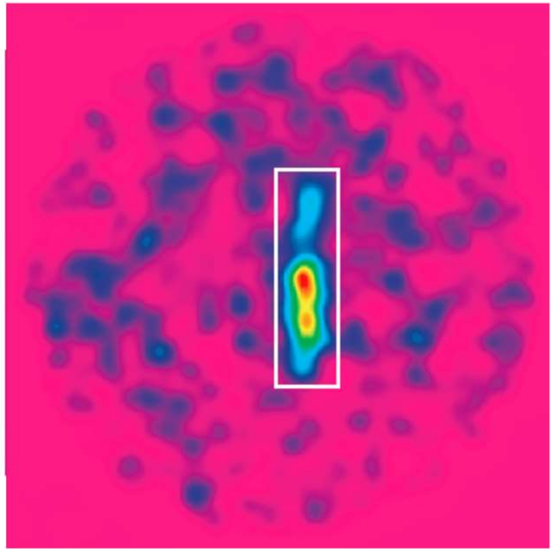
A. Ovodenko, *et al. Appl. Phys. Lett.*, 109, 253504 (2016)

Inverse Compton Scattering: Experimental Context

- *Prehistory* illuminates methods
- PLEIADES (UCLA/LLNL) diffraction
- K-edge filtering at BNL ATF
- Single-shot phase contrast imaging
- Single-shot diffraction

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





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

X-ray spectrum from *K-edge filtering*

Nuclear Instruments and Methods in Physics Research A 608 (2009) S18–S22

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

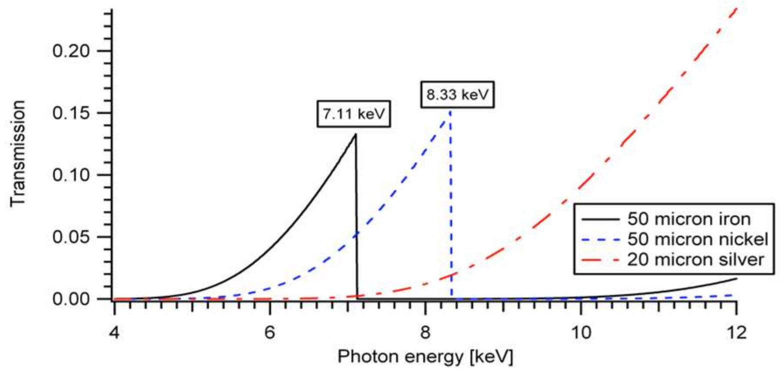
journal homepage: www.elsevier.com/locate/nima

Characterization results of the BNL ATF Compton X-ray source using K-edge absorbing foils

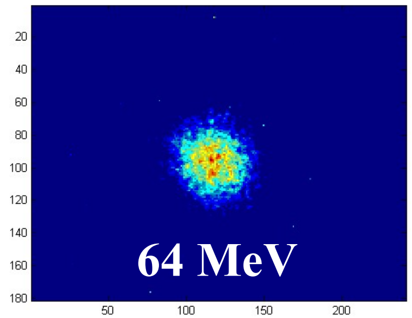
O. Williams[a,*], G. Andonian[a], M. Babzien[b], E. Hemsing[a], K. Kusche[b], J. Park[b], I. Pogorelsky[b], G. Priebe[c], J. Rosenzweig[a], V. Yakimenko[b]

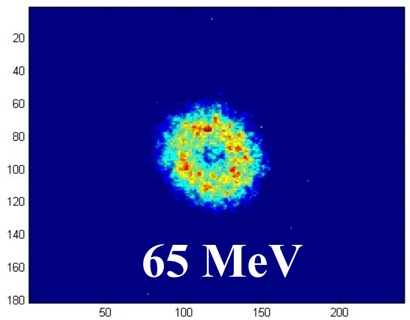
Characterizing X-rays via K-edge foil
ICS photons have angular-energy correlation (as in FEL):

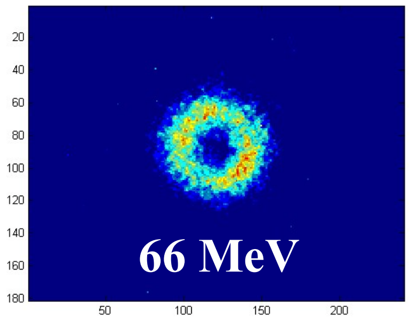
$$\hbar\,\omega_{\text{x-ray}} = \frac{4\gamma^2\hbar\omega_{\text{L}}}{1 + a_{\text{L}}{}^2/2 + \gamma^2\theta^2}$$



Crude band-pass filter – must improve!

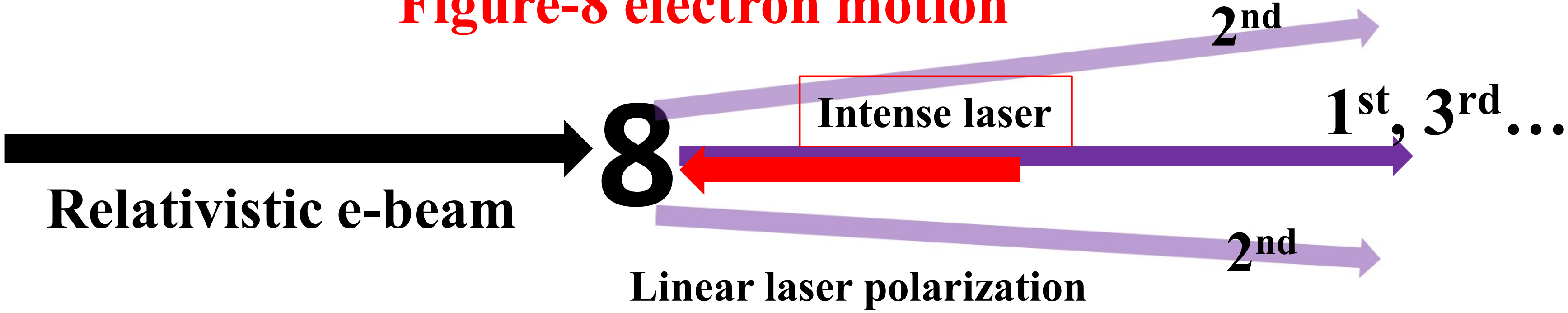






Current experimental emphasis: nonlinear ICS physics

Figure-8 electron motion



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

★**Red-shifting *and* BW increase:**

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

a_L *not* constant during interaction

★ **Harmonic generation/angular dependence:**

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

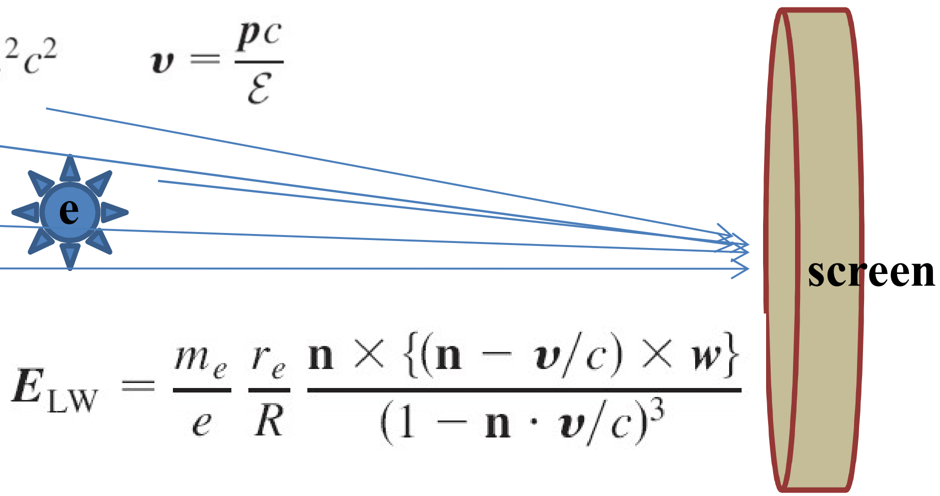
$$h\nu_{\text{X-ray}} = 4\gamma^2\, h\nu_L\, n$$

Calculating Nonlinear Electrodynamics in ICS: Lienard-Wiechert Field Solver

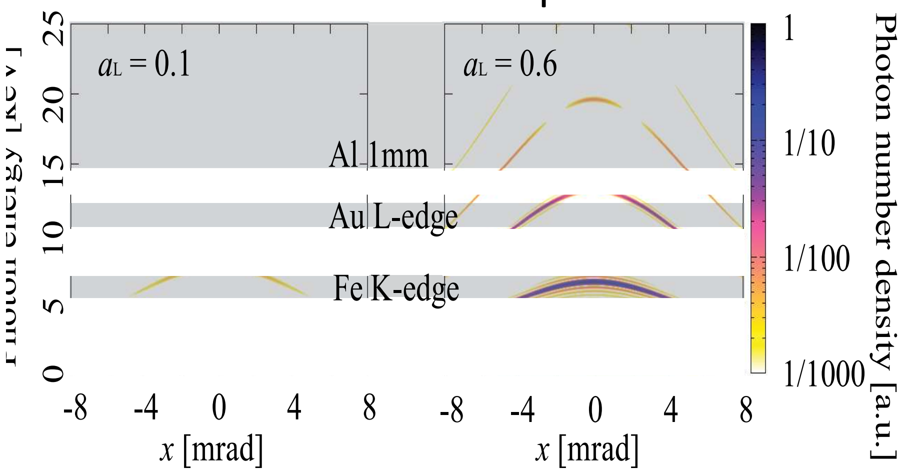
Angular-wavelength spectra for nonlinear ICS experimental scenarios

$$\frac{d\boldsymbol{p}}{dt} = e\boldsymbol{E} + e\left(\frac{\boldsymbol{v}}{c}\right) \times \boldsymbol{H} \qquad p_\mu p^\mu = m_e{}^2 c^2 \qquad \boldsymbol{v} = \frac{\boldsymbol{p}c}{\mathcal{E}}$$

$$E_x = E_{0,s} \sin(k_s z - \omega_s t)$$



Linear and nonlinear spectra

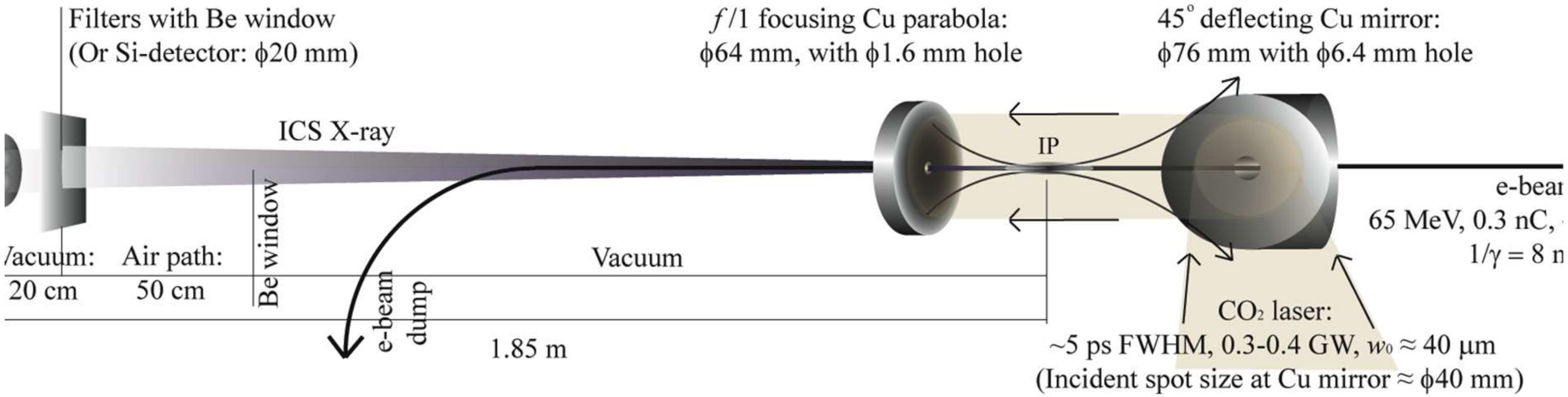


$$E_{\mathrm{LW}} = \frac{m_e}{e}\frac{r_e}{R}\frac{\mathbf{n} \times \{(\mathbf{n} - \boldsymbol{v}/c) \times \boldsymbol{w}\}}{(1 - \mathbf{n} \cdot \boldsymbol{v}/c)^3}$$

$$E_{\mathrm{LW},x}(\omega) = \left| \int_{-\infty}^{\infty} E_{\mathrm{LW},x}(t) e^{i\omega t} dt \right|$$

Essential tool for experimental analysis

Nonlinear ICS Experiments 2014-16



✦ CO_2 laser: $a_L \approx$ **0.6 to 1.0**

FWHM ≈ *3.5* – 5.0 ps, 10.6 μm, $w_0 \approx 40$ μm

✦ **Electron beam: *E*=65 - 70 MeV**

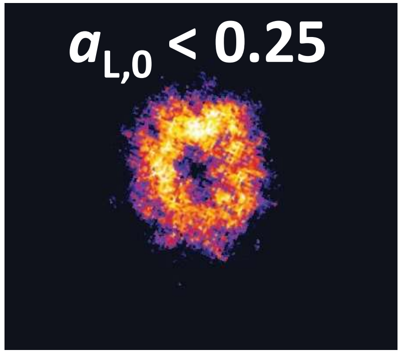
Q **≈ 0.3 nC, $\sigma_z \approx 300$ μm, $\sigma_x \approx 30$ μm**

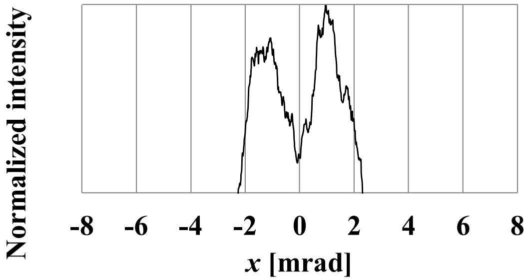
★Compton edge: $h\nu = 4\gamma^2 E_L \approx 7 - 10$ keV

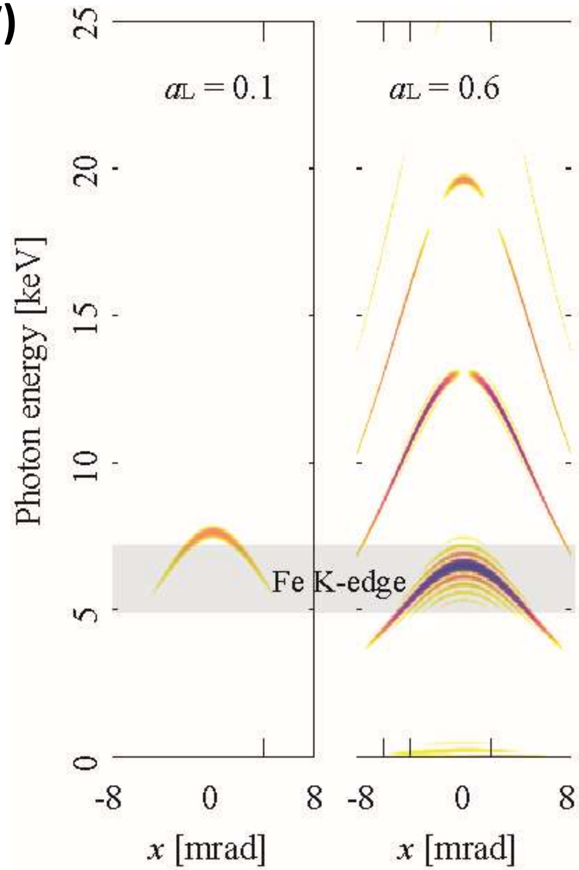
★Photons/pulse from IP : $N_g \approx \underline{10^9}$

Observation of nonlinear red-shift in fundamental

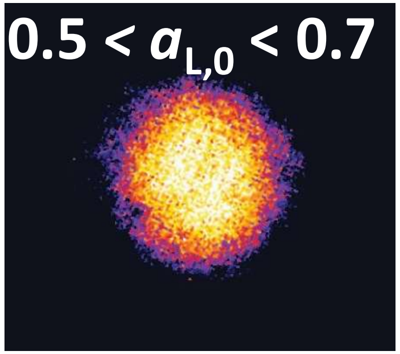
7.6 keV < Fe k-edge (at 5-7keV)
On-axis components is cut

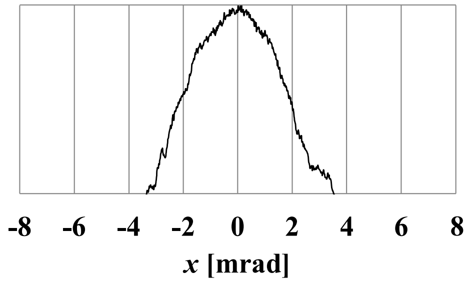






Red-shifting to 5-6 keV





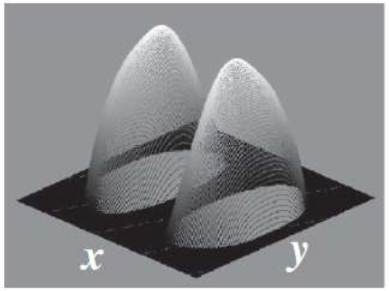
$$h\nu_{ICS,\,1^{st}} = 4\gamma^2\nu_L/(1+a_{L,0}^2/2) \rightarrow \therefore 0.5 < a_{L,0} < 0.7$$

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

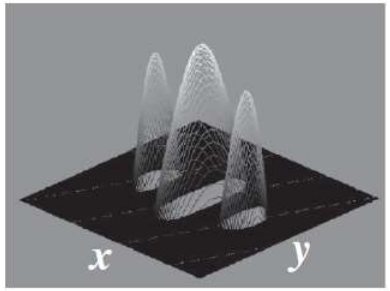
Radiation distribution
Linear polarization

2nd & 3rd harmonics

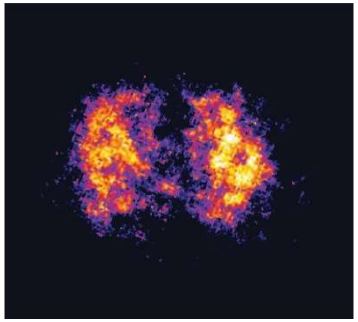
2nd

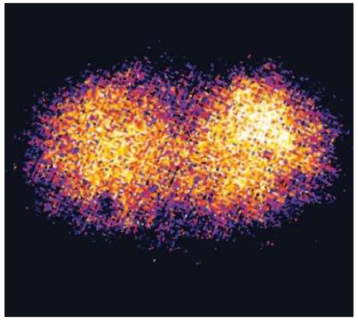


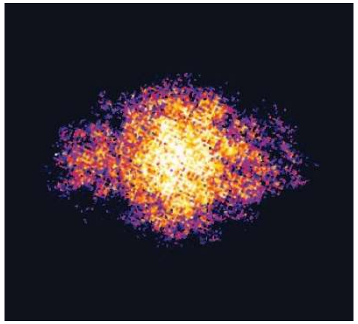
3rd

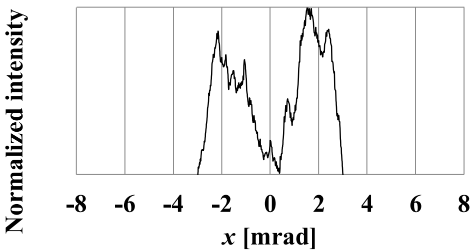


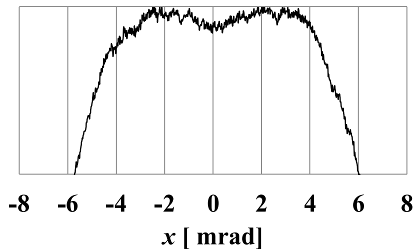
Au L-edge (12 keV) | **Al 250 μm > 10 keV** | **Al 1000 μm > 15 keV**

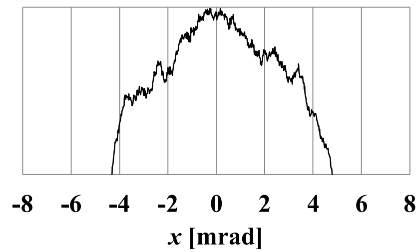












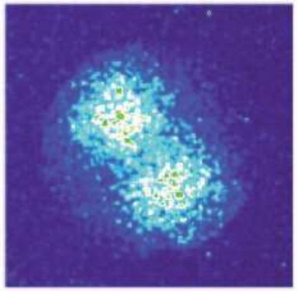
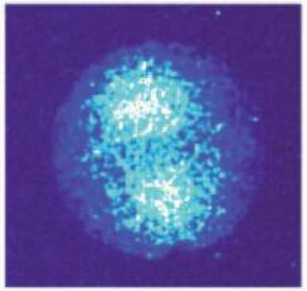
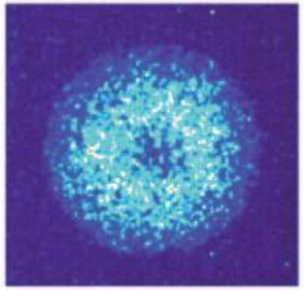
Narrow band 2nd | **2nd + 3rd** | **3rd (On-axis & lobes)**

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

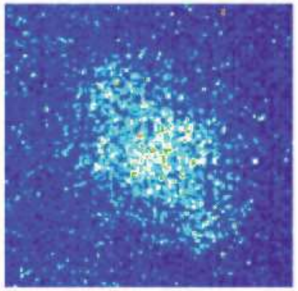
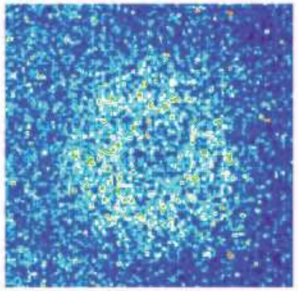
Circularly polarized harmonic radiation

¼ wave plate between regenerative and TW amplifier

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

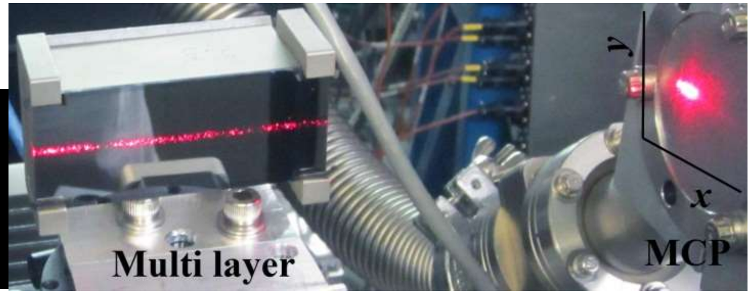
Al 1000 μm **Linear, 3rd** **Circular, 3rd**

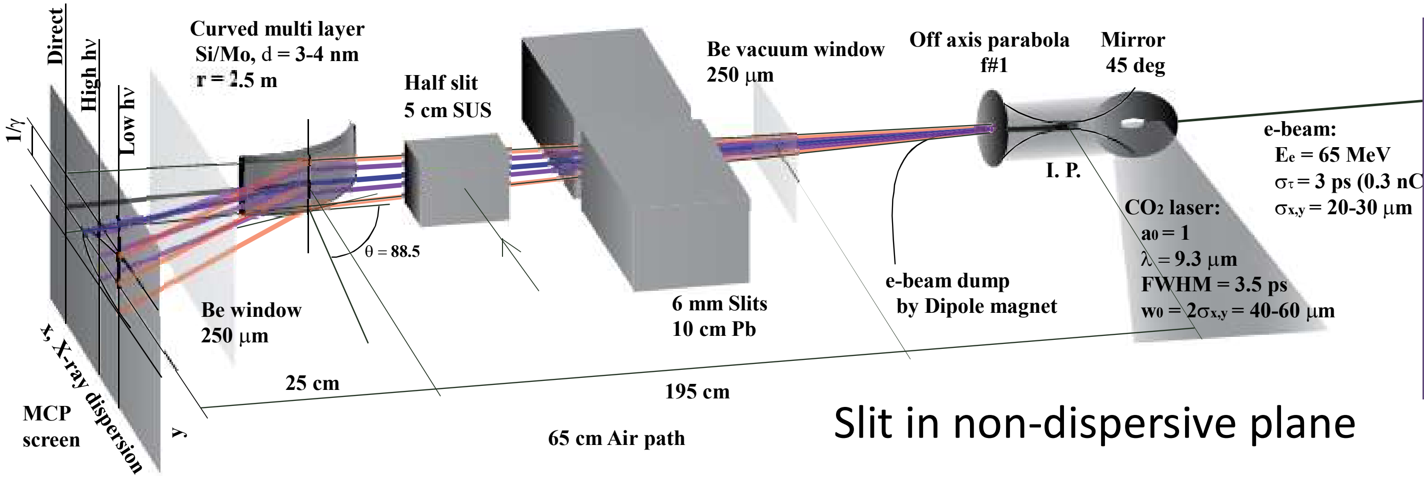



Much attention to this result-
Demonstration of orbital angular momentum?
V. Petrillo, G. Dattoli, I. Drebot, and F. Nguyen, PRL 117, 123903 (2016)

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

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





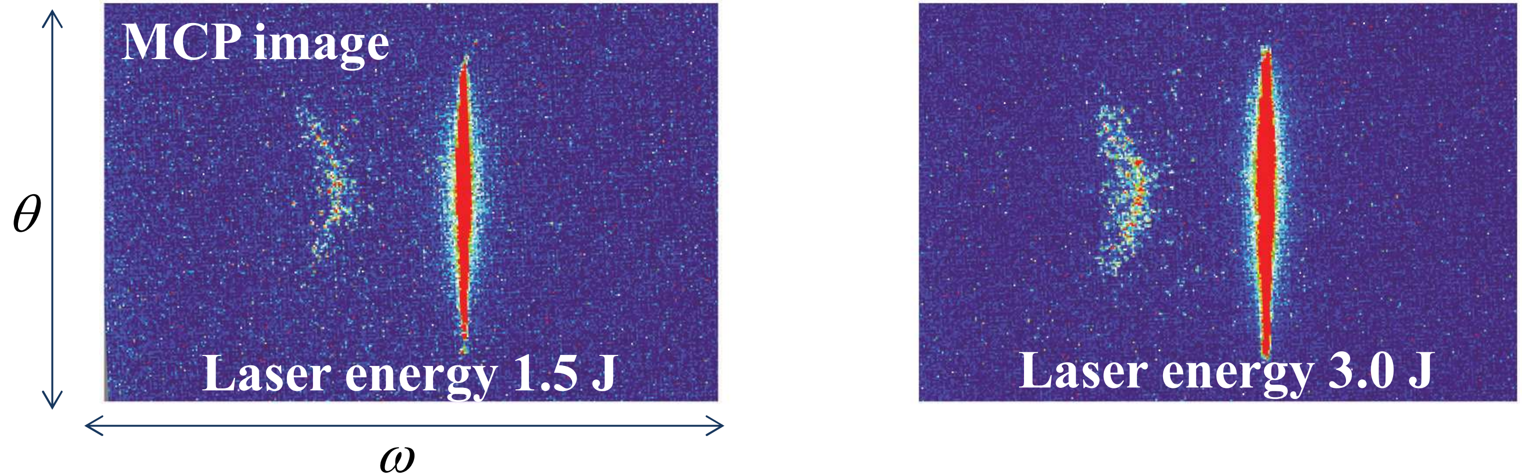
✡ Mo-Si multi-layer thickness: $d \approx 3.3$ nm

✡ Bragg angle: ~ 25 mrad

✡ Angle acceptance : ~ 50 mrad

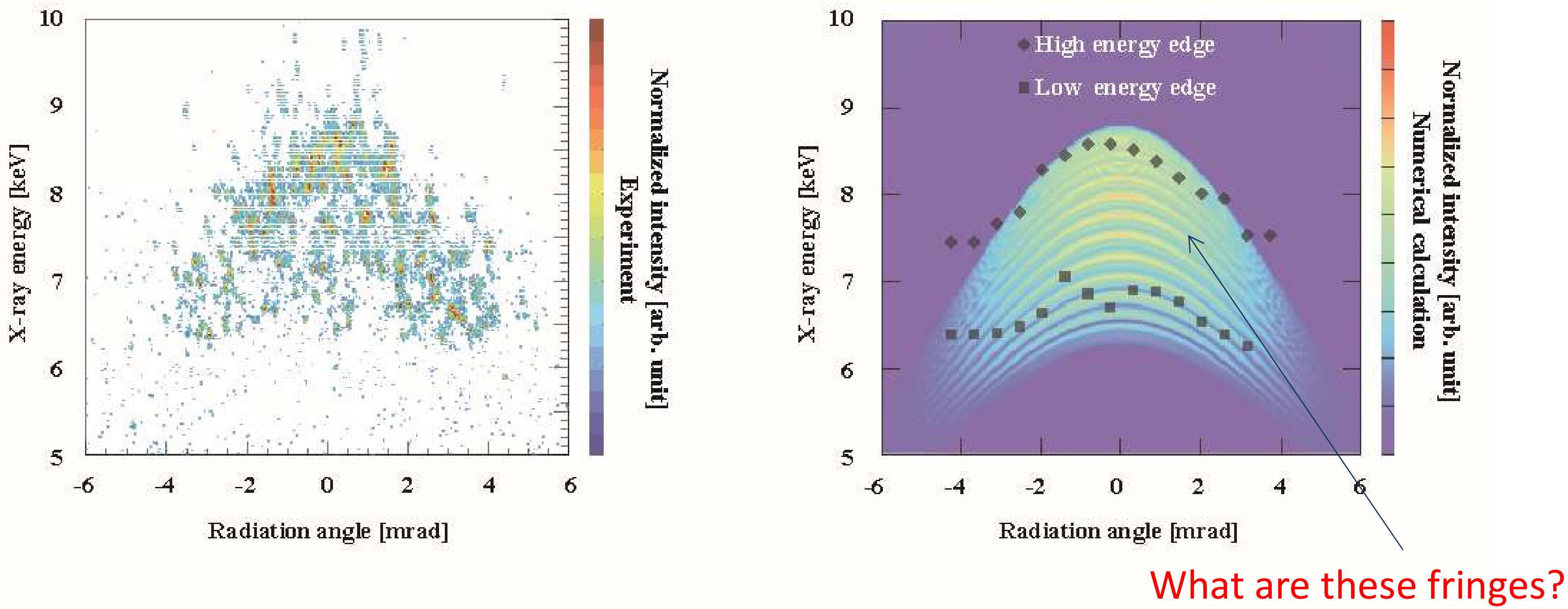
✡ Reflectivity ~ 15% @ NSLS X15A

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



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

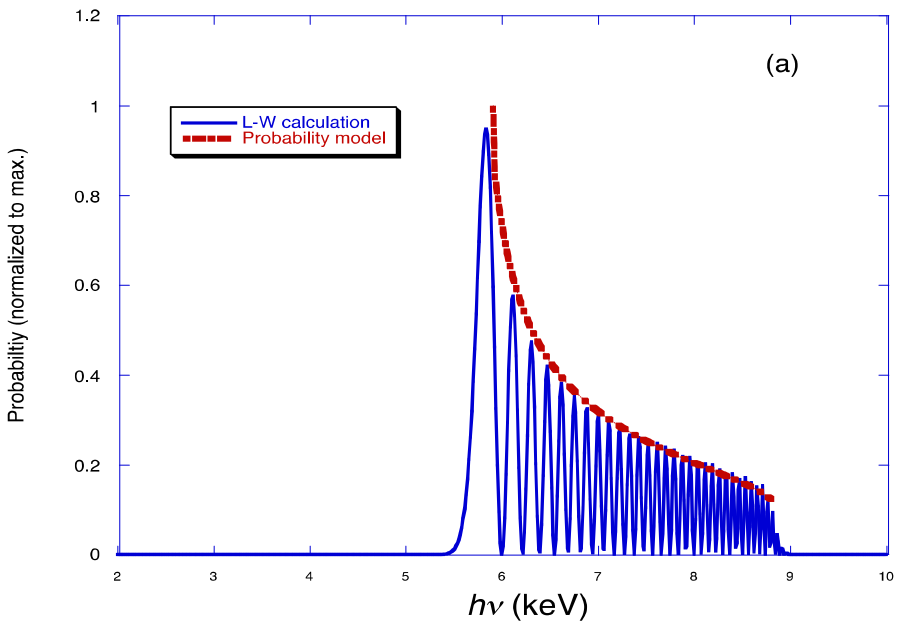
Analysis: near-axis spectral broadening in nonlinear ICS

- ✶ **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***

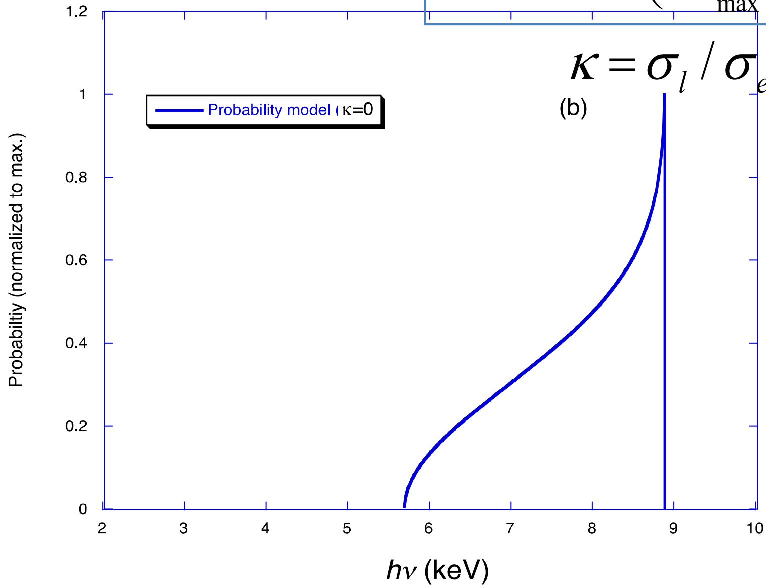
$$P_1(\Delta\lambda) = \frac{C_1}{\sqrt{\ln(\Delta\lambda_{\max}/\Delta\lambda)}}$$

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

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



Only temporal effects
L-W numerical model shows interference



Only transverse shift

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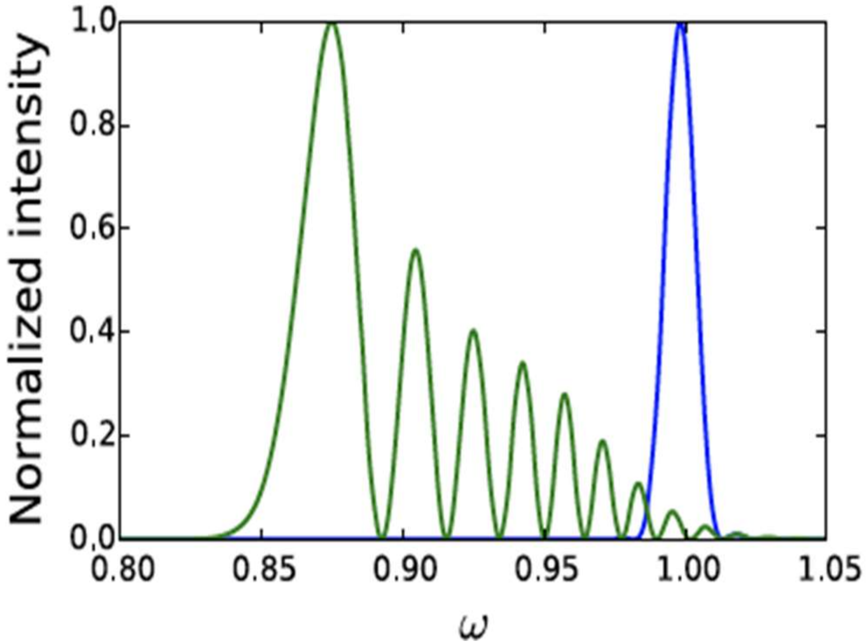

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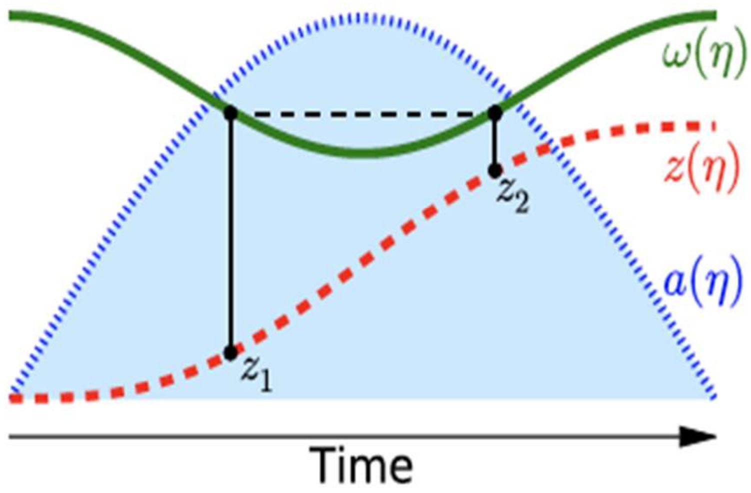

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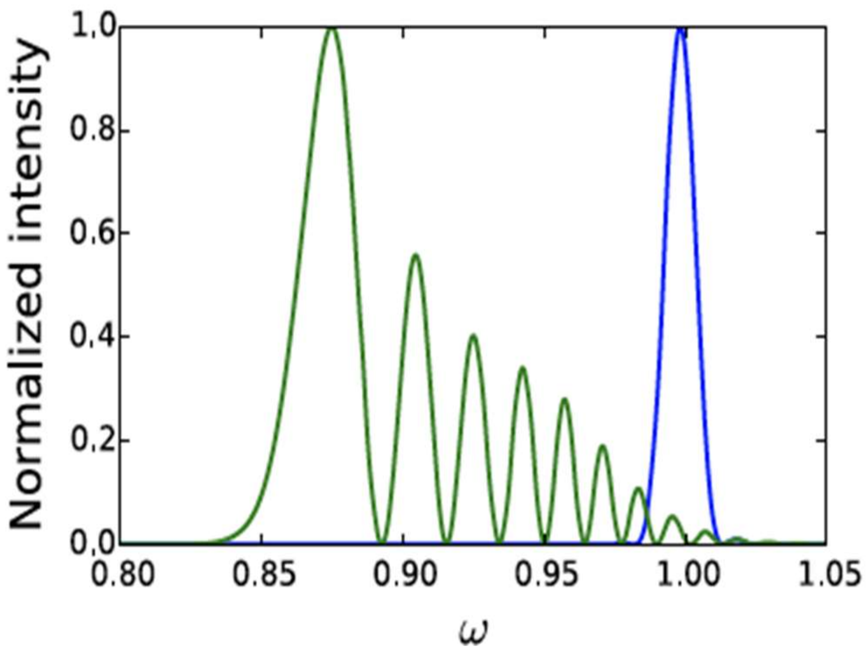
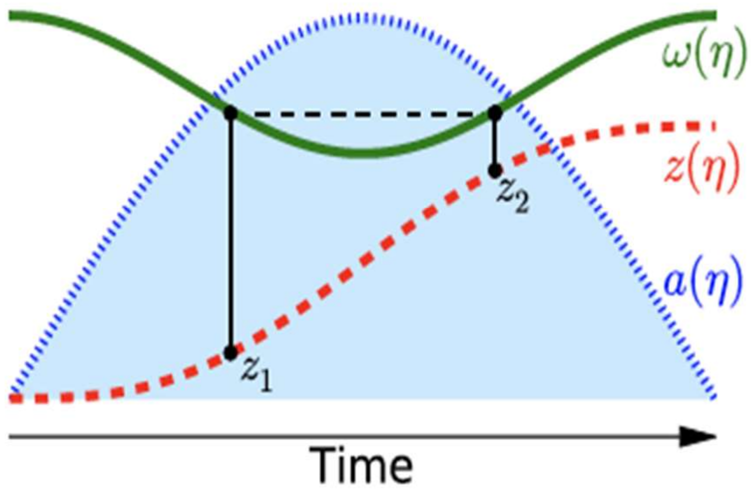
$$P_1(\Delta\lambda) = \frac{C_1}{\sqrt{\ln(\Delta\lambda_{\max} / \Delta\lambda)}}$$

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

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



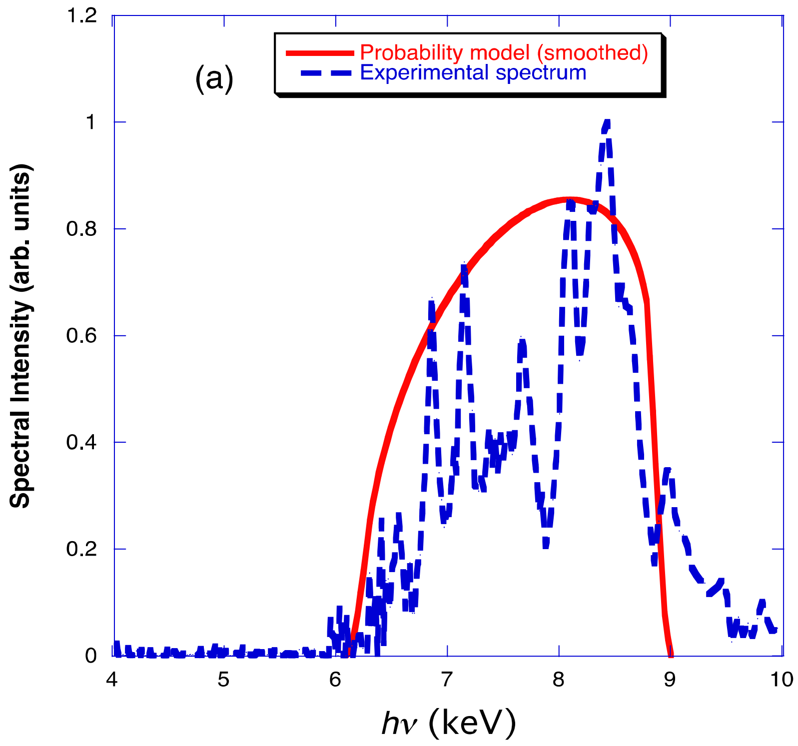
L-W numerical model shows interference



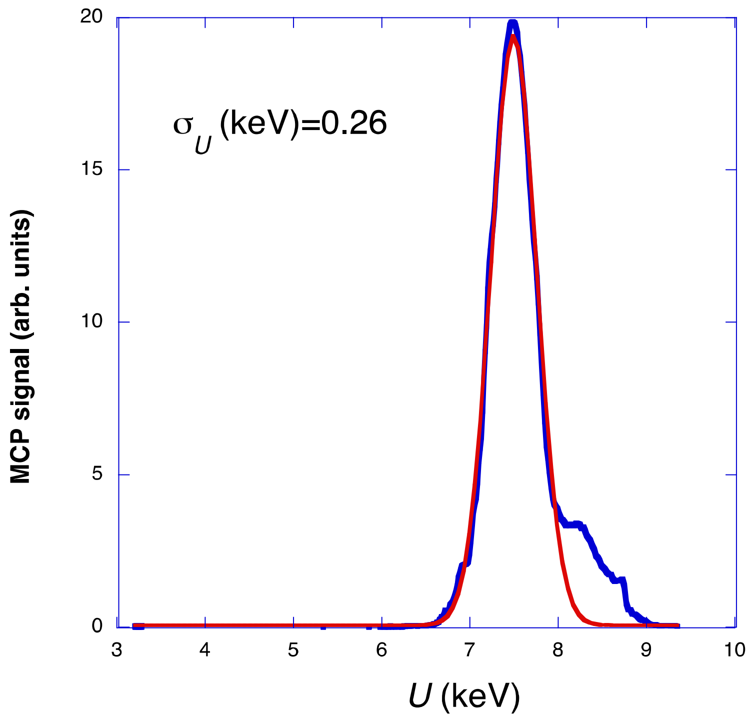
All effects, κ dependence

Evaluation of Experimental Results

- Shape similar but more peaked
- Fine structure present, due to what?



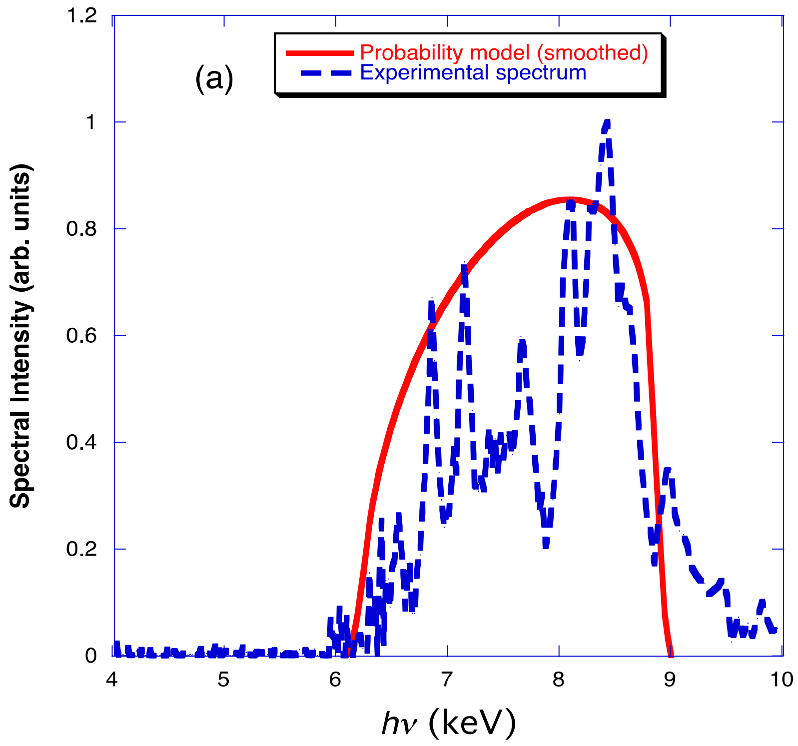
Is structure due to self-interference?



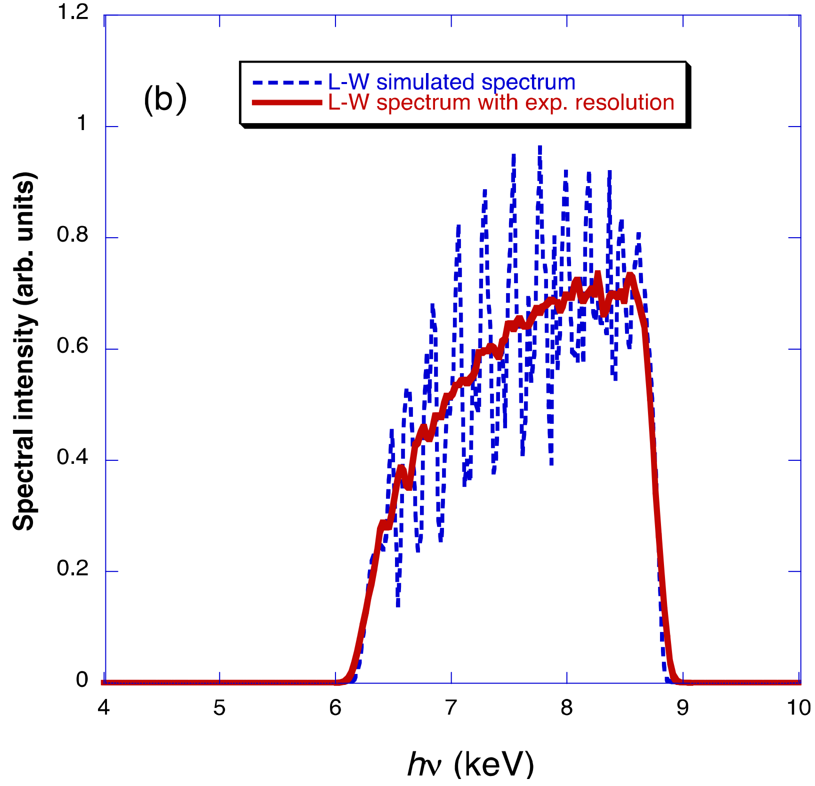
Measured spectral resolution (NSLS)

Evaluation of Experimental Results

- Shape similar but more peaked
- Fine structure present, due to what?



Is structure due to self-interference?



Simulated spectrum (blue)
With resolution effects (red)

Self-interference in the literature

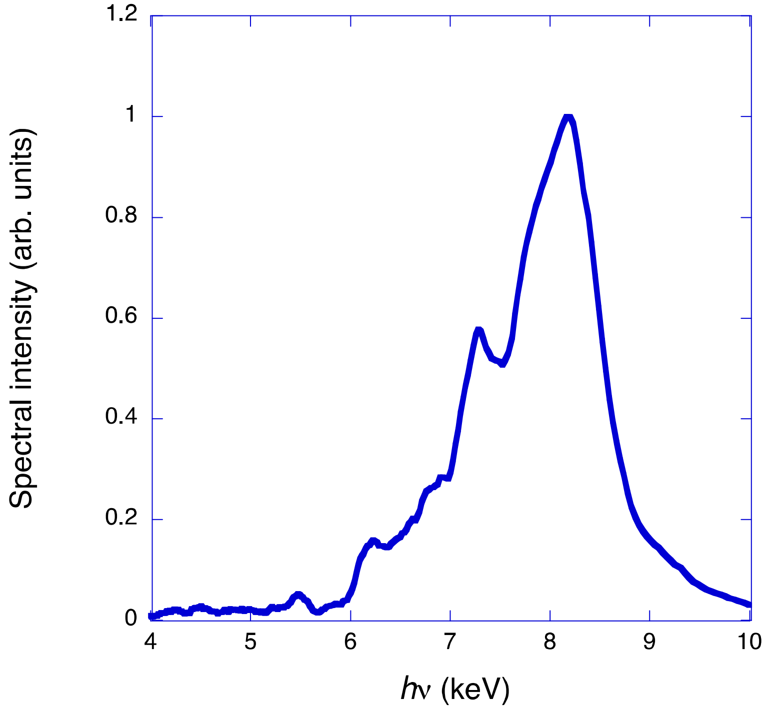
- G. A. Krafft *Phys. Rev. Lett.* **92**, 204802 (2004)
- C. A. Brau Phys. Rev. ST Accel. Beams **7**, 020701 (2004)
- G. A. Krafft, A. Doyuran and J. B. Rosenzweig, *Phys. Rev. E* **72**, 056502 (2005)
- T. Heinzl, D. Seipt, and B. Kämpfer, *Phys. Rev. A* 81, 022125 (2010)
- B. Terzić, K. Deitrick, A. S. Hofler, and G. A. Krafft *Phys. Rev. Lett.* 112, 074801 (2014)
- B. Terzić, Cody Reeves, and Geoffrey A. Krafft, *Phys. Rev. Accel. Beams* **19,** 044403 (2016)
- S. G. Rykovanov, et al., *Phys. Rev. Accel. Beams* 19, 030701 (2016)
- G. A. Krafft, et al, *Phys. Rev. Accel. Beams* 19, 121302 (2016)
- B. Terzić and G. A. Krafft, Phys. Rev. Accel. Beams 19, 098001 (2016)

Two comments:

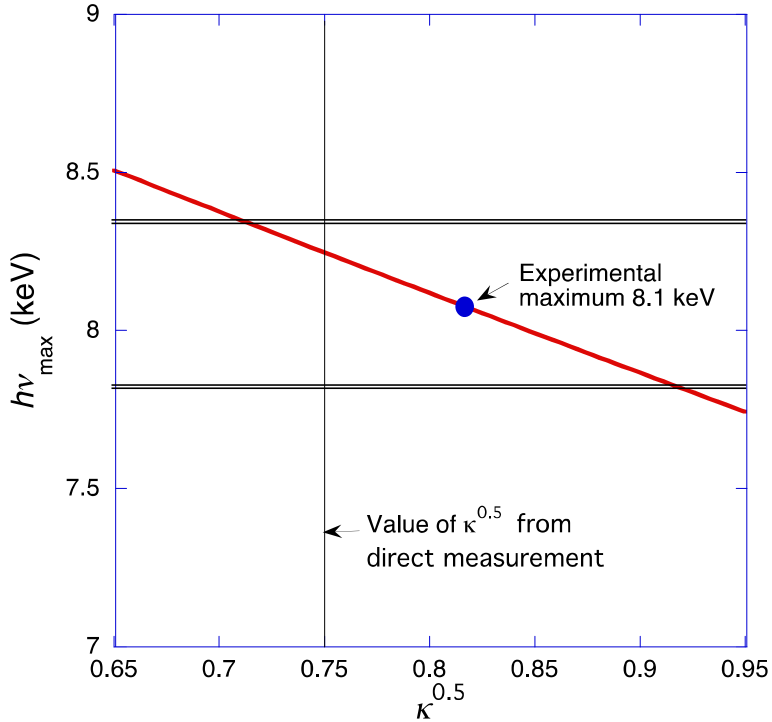
- ***We need to observe this effect.*** **Optimize resolution**
- **Theorists lived in a a 1D world until now (only t-dependence)**

Determination of beam-beam overlap

- Use multi-shot average for *peak* location
- $\kappa^{0.5}$=0.75 is obtained within experimental error



Spectrum slightly narrower,
less redshifted (pedestal, satellites)

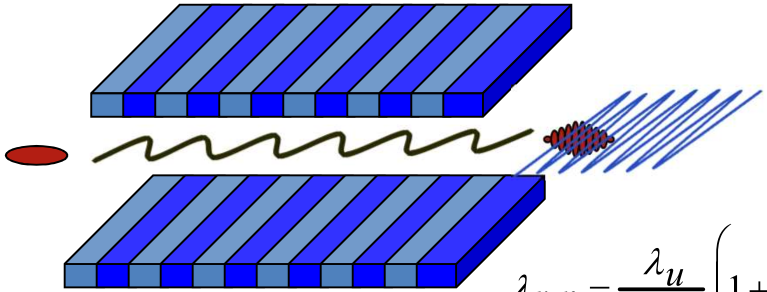


Y. Sakai, et al. *PRAB* in press 2017.

More sophisticated analysis can permit details of interaction to emerge

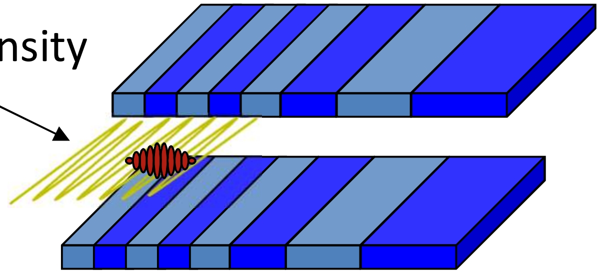
Compact *optical* accelerator: IFEL

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.



Undulator magnetic field couples high power radiation with relativistic electrons

$$\boxed{\gamma_r^{\,2} \cong \frac{\lambda_w}{2\cdot\lambda}\cdot\left(1+\frac{K^2}{2}\right)} \qquad K = \frac{eB}{mck_w} \quad >> \quad K_l = \frac{eE_0}{mc^2 k}$$

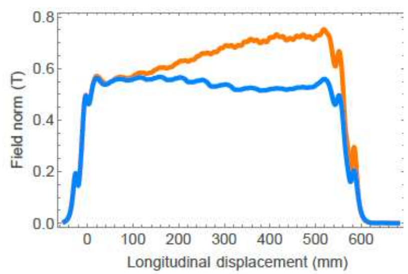
Energy exchange when resonance condition obeyed

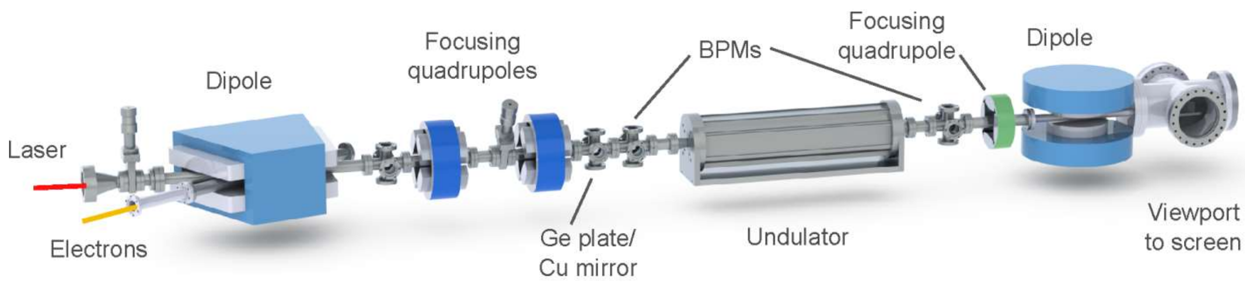
- IFEL well suited for 50 MeV – ***up to few GeV*** (due to SR limits)
- ***Plane wave or far field*** accelerator: minimal 3D effects.
- ***Vacuum*** accelerator - not dependent on boundaries
  - ***Preserves e-beam quality/emittance***
  - ***Stable energy output***: <u>static undulator field sets resonant energy</u>

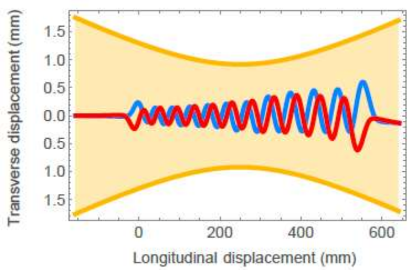
Rubicon IFEL experiment

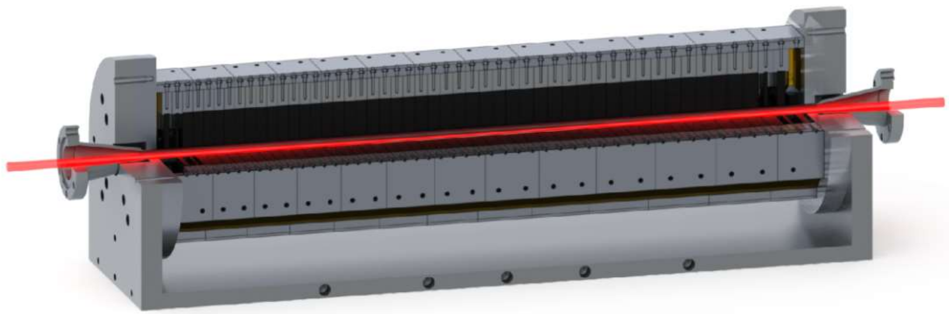
- Helical geometry, high gradient IFEL
- **Strongly tapered helical Halbach undulator**
  - Tunable system

Input e-beam energy	50 MeV
Average accelerating gradient	**100 MeV/m**
Laser wavelength	10.3 µm
Laser power at interaction point	**500 GW**
Laser focal spot size (w)	980 µm
Laser Rayleigh range	30 cm
Undulator length	**54 cm**
Undulator period	4 – 6 cm
Magnetic field amplitude	5.2 – 7.7 kG



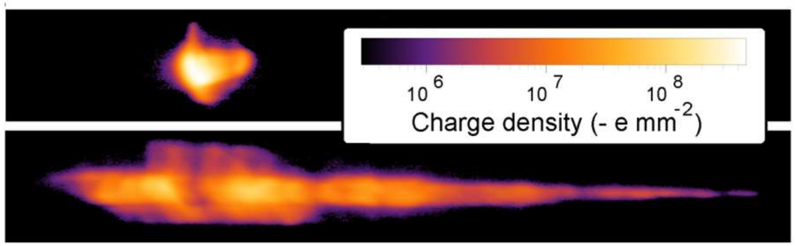


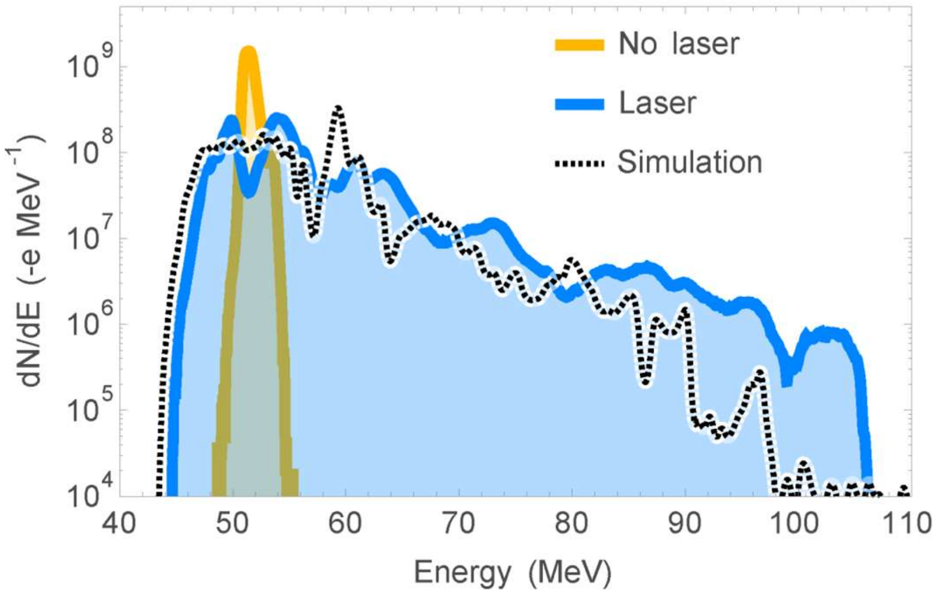




High gradient acceleration

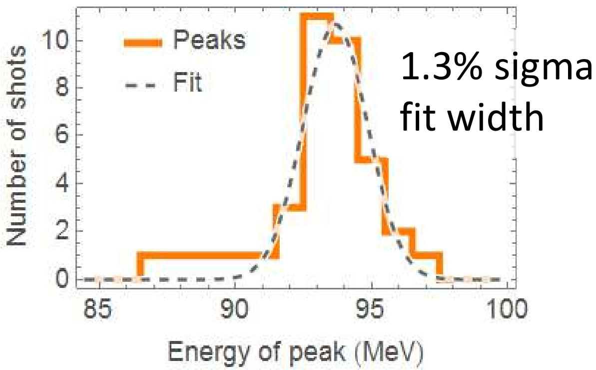
- **52 to 106 MeV in 54 cm**
  - **100 MeV/m average accelerating gradient**
- **Aperture demands relaxes laser focus, reduces available gradient**
- **Undulator retuning to improve *capture***





High quality accelerated beams

- 93 MeV – 1.8 % energy spread
- **Reproducible spectra** (mean energy std < 1.5 %) with 30% rms laser energy fluctuations
- **Laser intensity 5 orders of magnitude lower than LWFA**



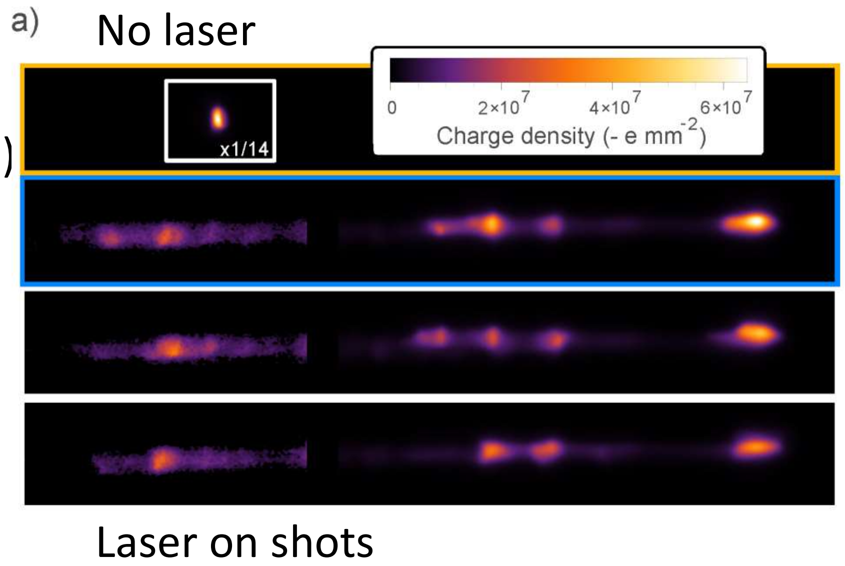
nature COMMUNICATIONS

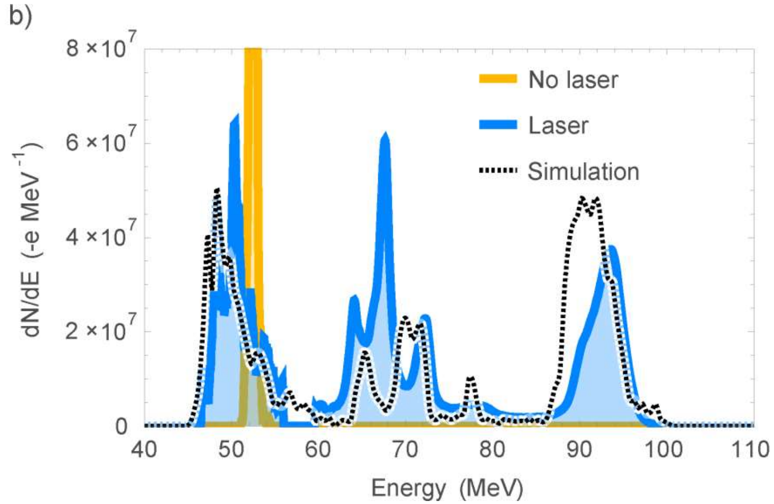
ARTICLE

Received 3 Jun 2014 | Accepted 8 Aug 2014 | Published 15 Sep 2014 DOI: 10.1038/ncomms5928

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]

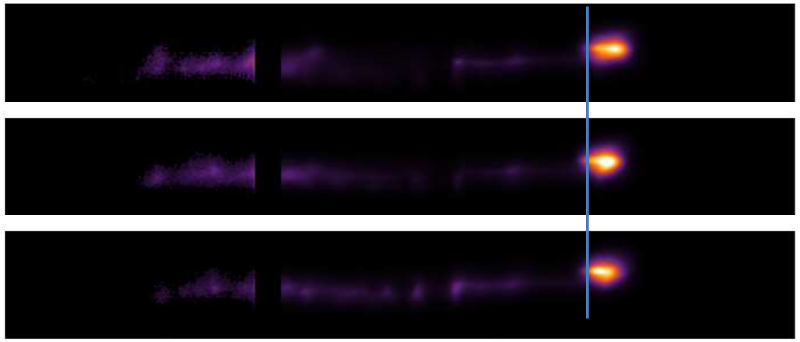




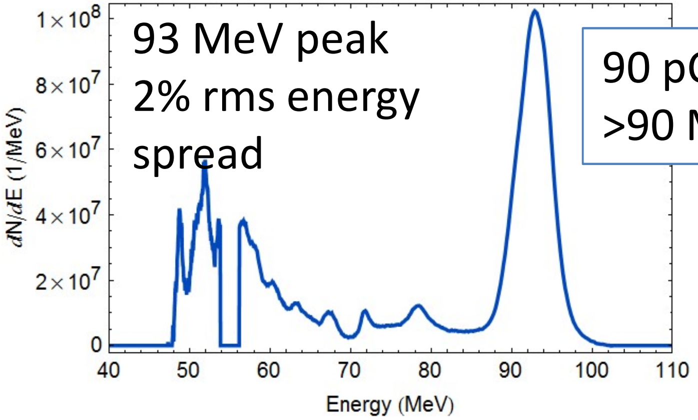
IFEL with prebuncher

- UCLA permanent magnet based prebuncher
- Permanent magnet chicane with adjustable R_{56}
- Achieved **> 50% capture**
- IFEL acceleration **preserves emittance**

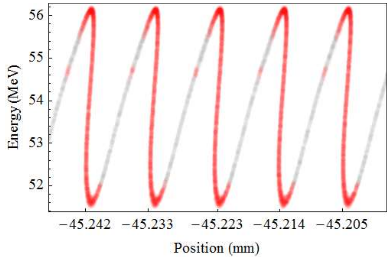
~30 cm

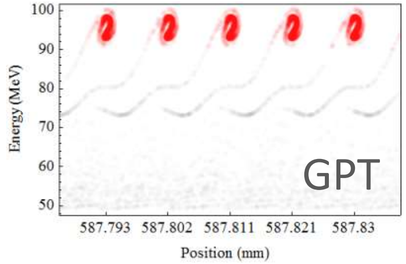


First experiment using a CPA CO2 laser

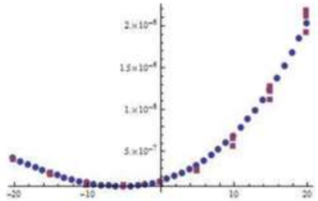


90 pC
>90 MeV

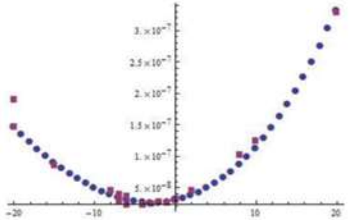




Unaccelerated emittance 2.3 um



Accelerated emittance 2.4 um

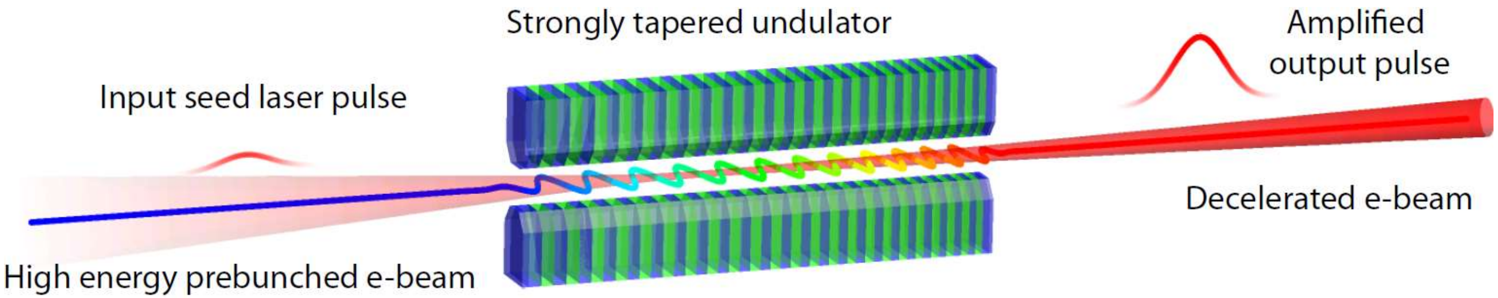


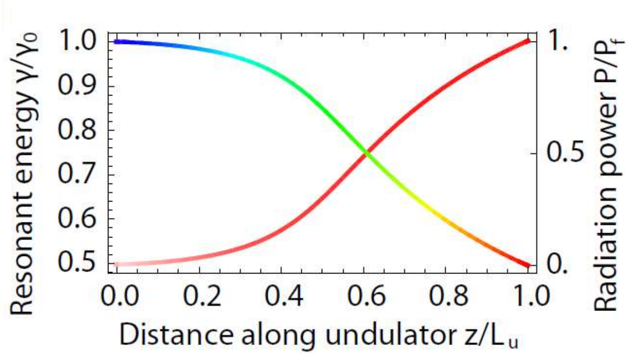
Apply this beam in ICS experiment…

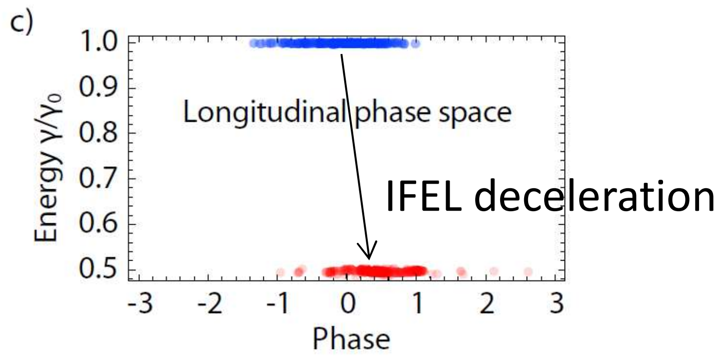
Can IFEL run in reverse?

Tapering Enhanced Stimulated Super-radiant Amplification (TESSA)

- 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



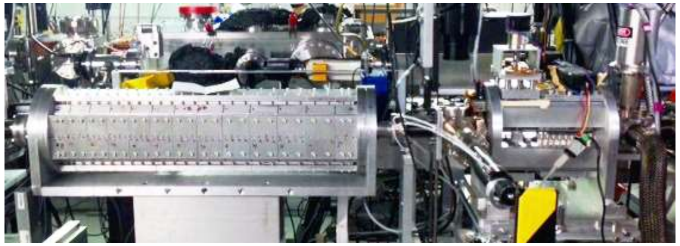


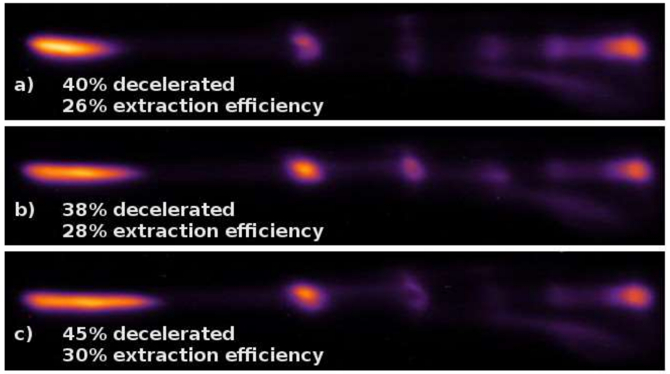


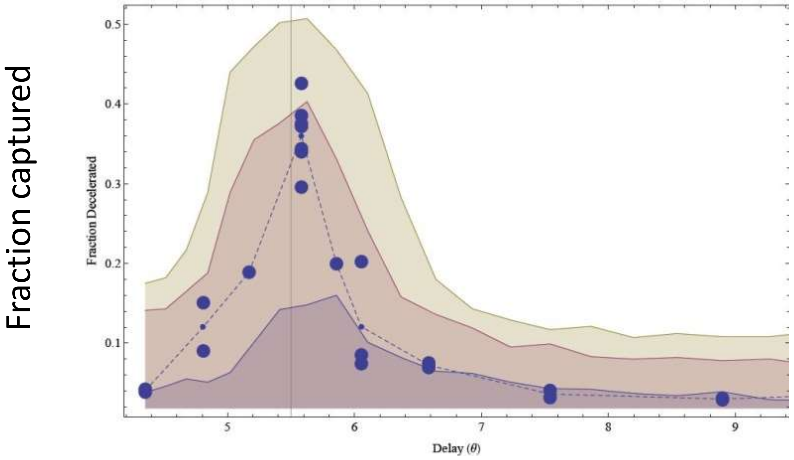
NOCIBUR IFEL deceleration experiment

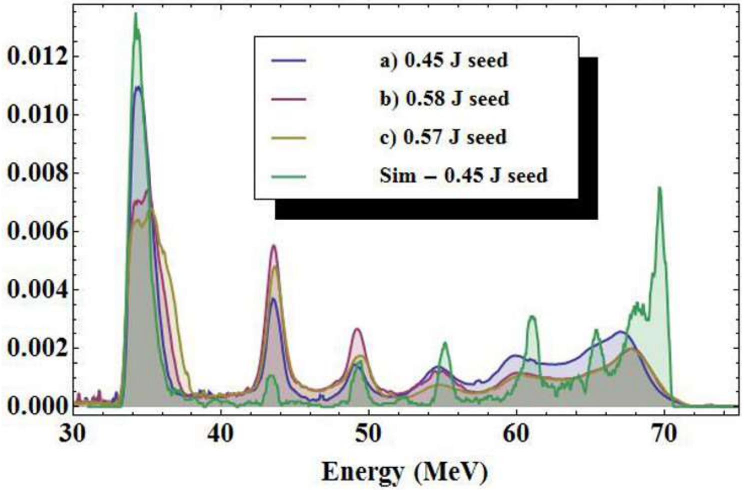
- Maximized capture with variable field chicane
- 45% of the 100 pC beam captured and decelerated
- 30% extraction efficiency (2 mJ)
- Spectra agree with simulation

Undulator Prebuncher







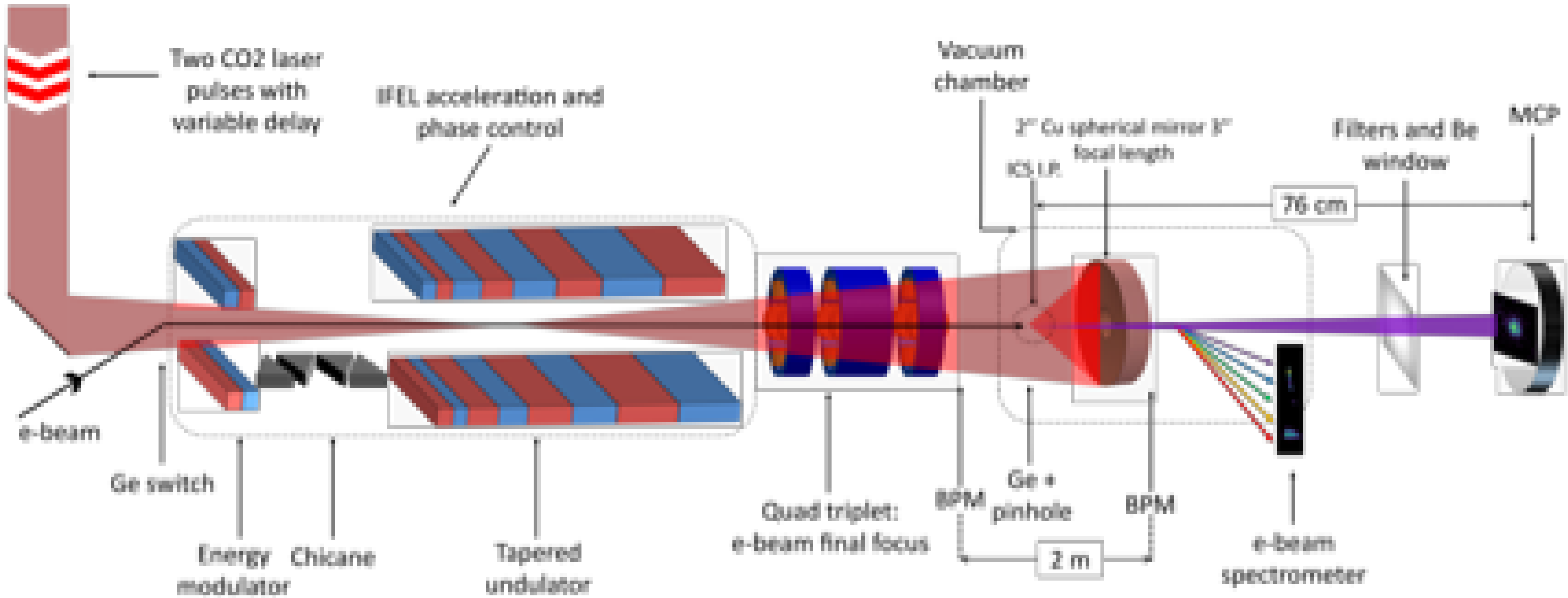


N. Sudar, *et al., Phys. Rev. Lett.* 117, 174801 (2016)

Merging IFEL and ICS

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

RUBICONICS: pre-bunched IFEL for ICS



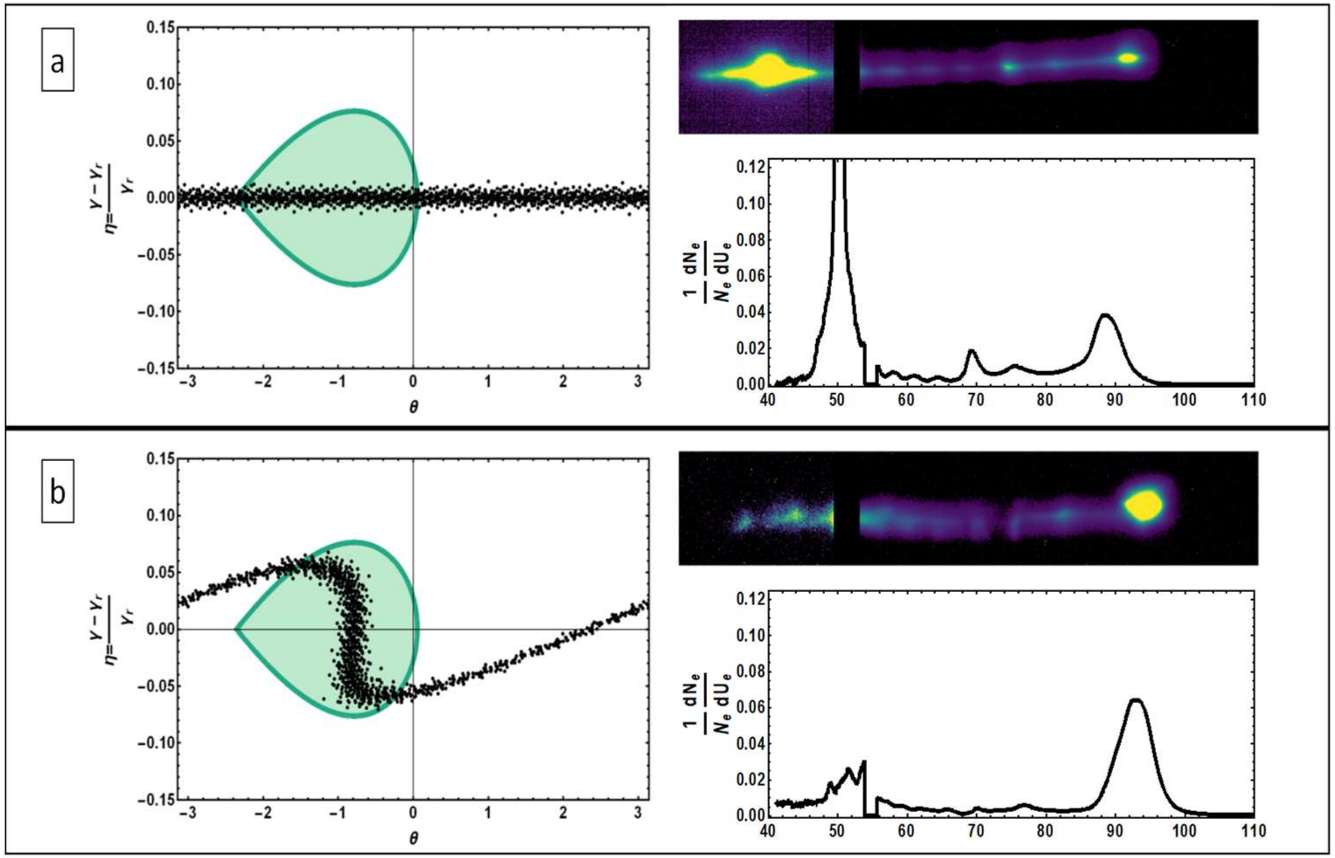
Two-pulse CO_2 laser, separated by 2x focal length of retro-reflector (0.5 ns)

Retuned RUBICON for stable operation

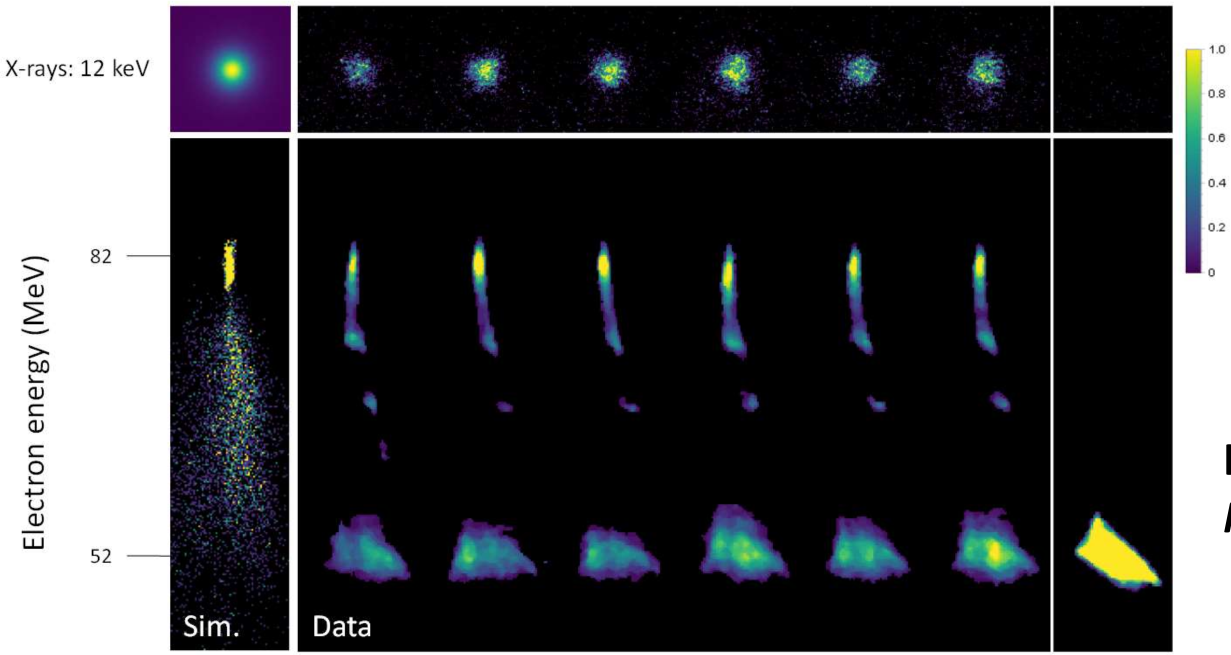
- Efficiently bunched beam accelerated to 82 MeV
  - Negligible emittance growth

No pre-buncher

Pre-buncher



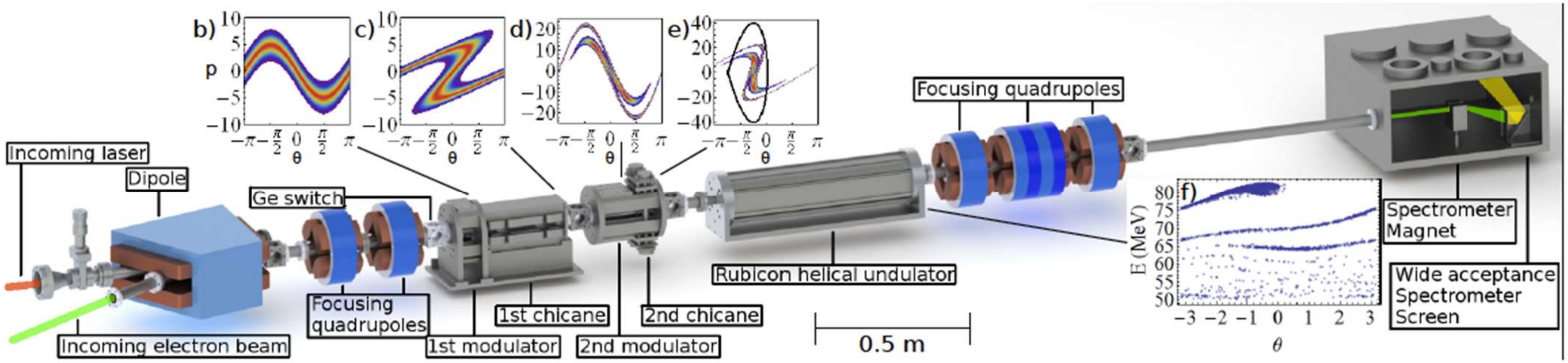
RUBICONICS scattered photons

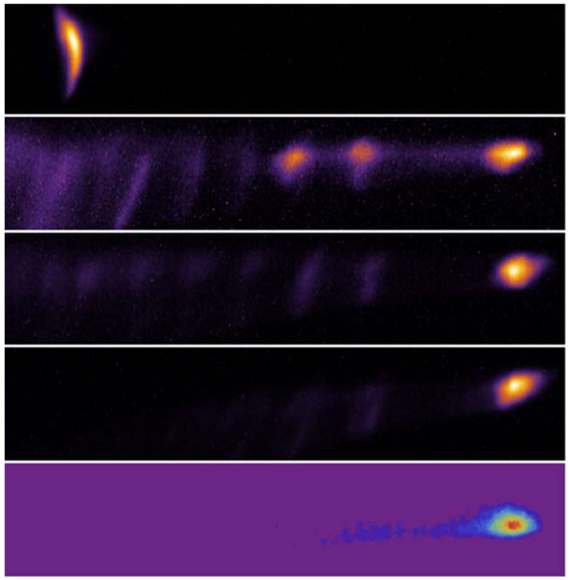


I. Gadjev, et al, to appear in *Nature Scientific Reports*

- 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





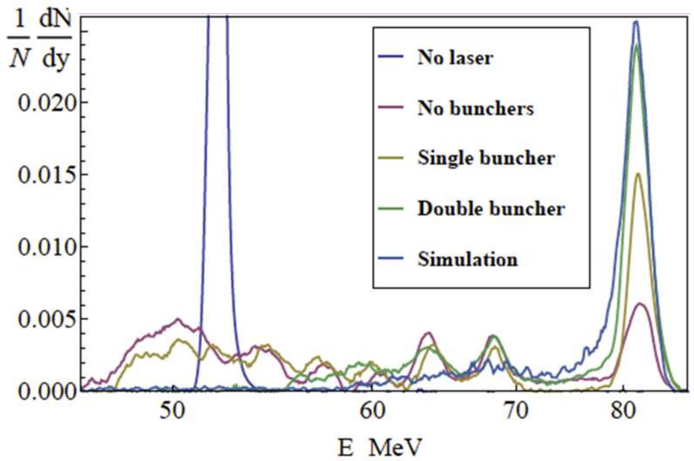
No laser

No bunchers

Single buncher

Double buncher

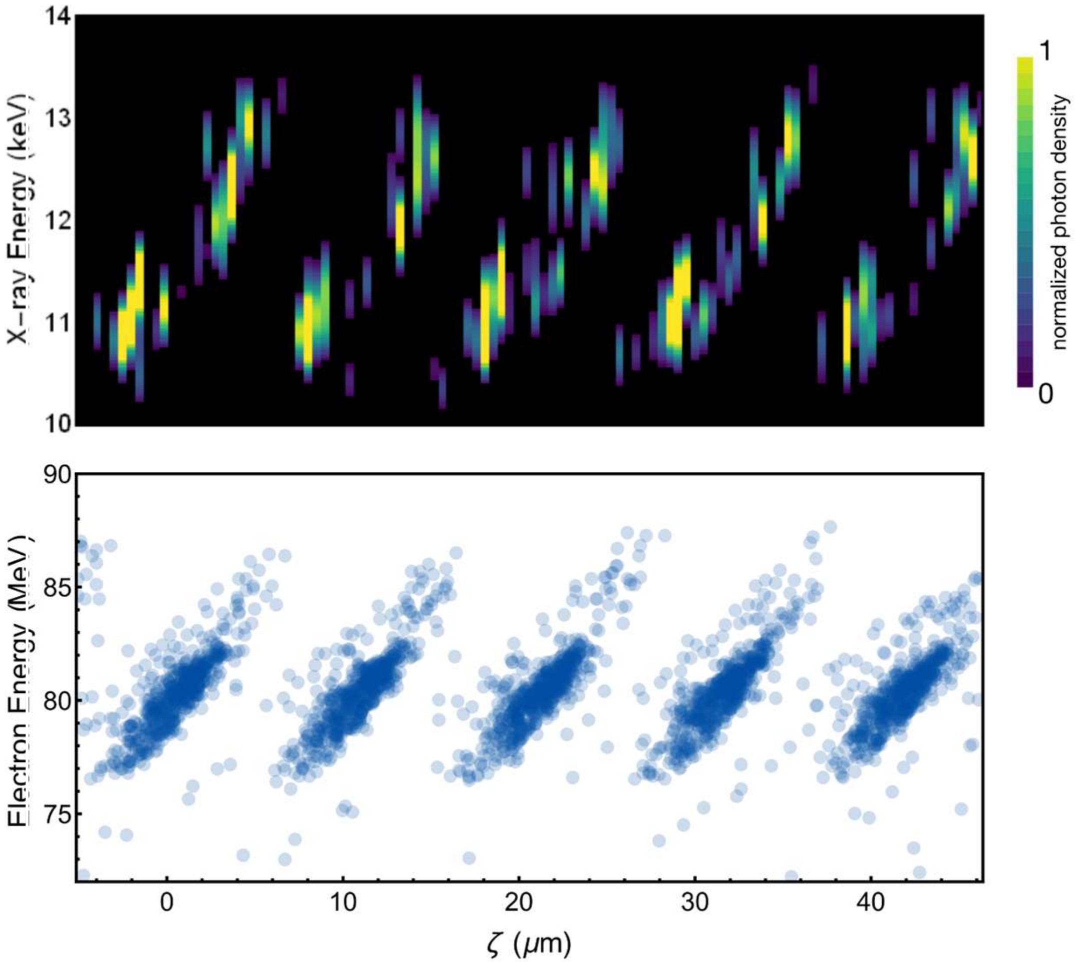
Simulation



- 96% captured
- 78% accelerated to final energy

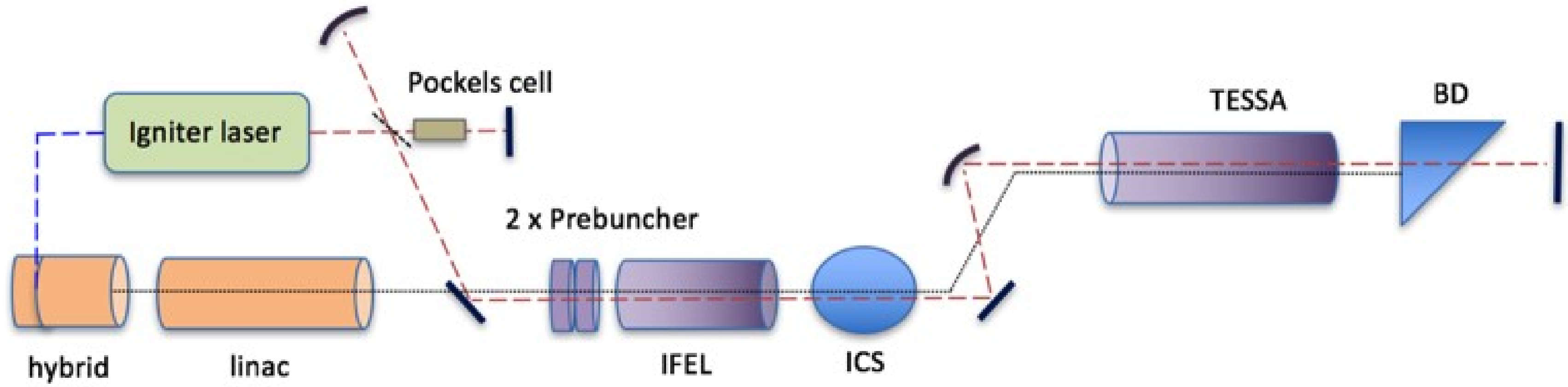
Current and Future Directions

- **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***



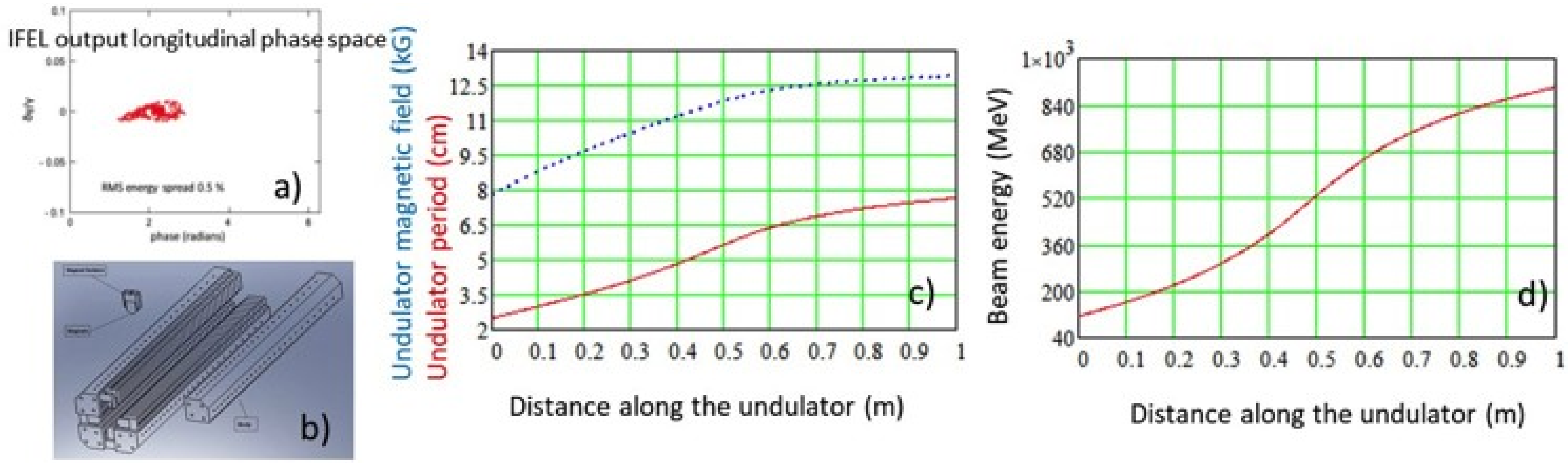
Electron pulse structure at ICS IP

CONTROL: **CO**mpton-based **N**uclear probe using **T**apered, **R**ecirculating **O**ptical



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

UCLA-RadiaBeam Proposal
(DNDO->DARPA)



Summary

- ✶ UCLA developing all-optical IFEL/ICS system for high average flux MeV γ's
- ✶ Fundamental ICS physics investigated: nonlinear shift and harmonics, OAM
  - ✶ Insight into spectral shape from single shot spectrometer
- ✶ IFEL compact accelerator optimum for <GeV energy
  - ✶ Excellent performance, high quality microbunched beam
  - ✶ Spin-off to FEL - TESSA; use for e- energy recovery
- ✶ *Recirculation* for high average flux
  - ✶ Advantage over other advanced acceleration schemes
  - ✶ ICS demonstrated; IFEL underway
- ✶ 5th generation light source with unique characteristics