Ultrafast Compton Scattering X-Ray Source Development at LLNL

F.V. Hartemann, A.M. Tremaine, S.G. Anderson, C. P. J. Barty, S. M. Betts, R. Booth, W. J. Brown, J.K. Crane, R.R. Cross, D.J. Gibson, D.N. Fittinghoff, J. Kuba, G. P. Le Sage, D.R. Slaughter, A.J. Wootton, E. P. Hartouni, P.T. Springer

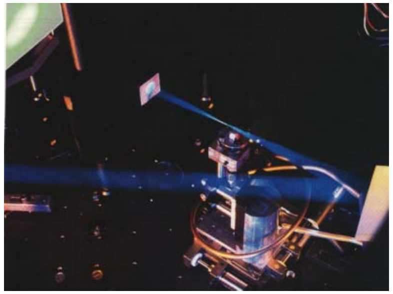
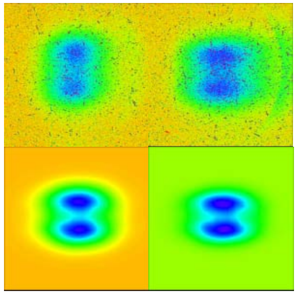
J. Rosenzweig, M. Bastea, R. Soufli, J. Belak, A. Jankowski, A. Kerman

- Introduction, Motivation & Background
- Experimental Setup: Laser & E-Beam
- Experimental Results
- Dynamic Diffraction
- Nonlinear Regime

Currently, No Bright Sources > 50 keV, < 50 ps

- 3^{rd}-Generation: < 50 keV, > 50 ps
- LCLS: max. energy 24 keV
- K-α: energy limit ~ 100 keV, 4π

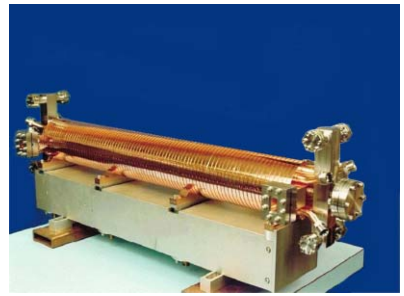


- PLEIADES: has already established record brightness at 140 keV

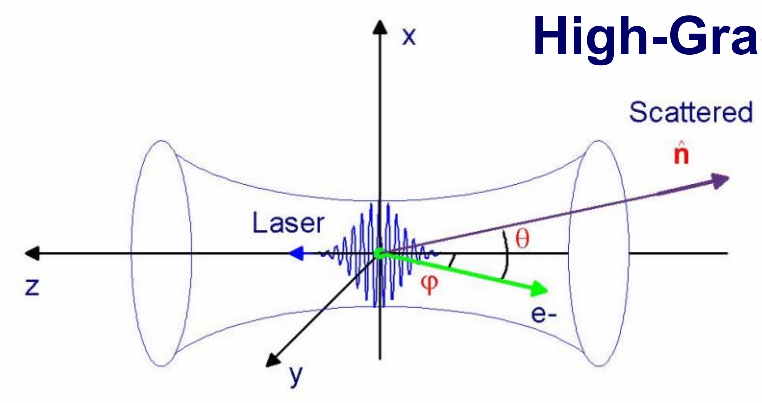
Compton Scattering X-Ray Source

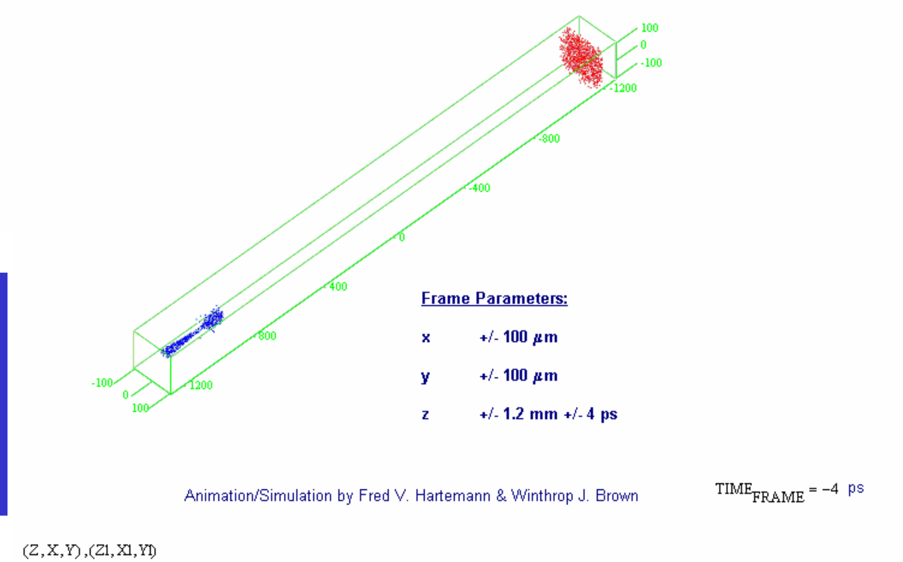
High-Brightness RF Gun



TW-Class CPA Laser

High-Gradient Linac





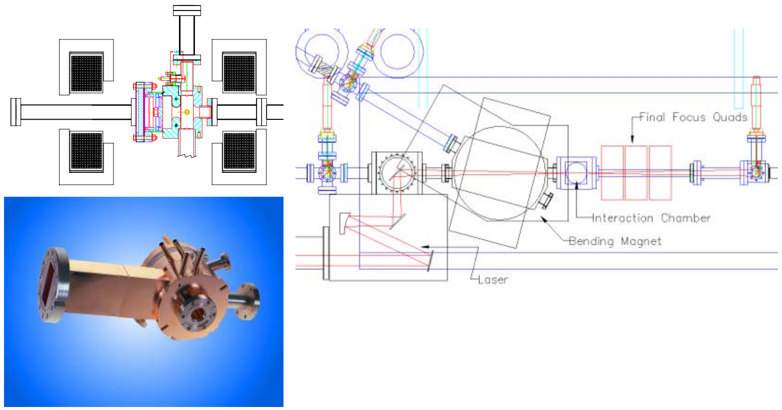
$$\omega_x \cong \frac{\omega_0}{\left(1+A_0^2\right)\left(\frac{1+\sigma^2}{2}\right)} \frac{\gamma - u\cos\varphi}{\gamma - u\cos\theta}$$

Radiation Pressure

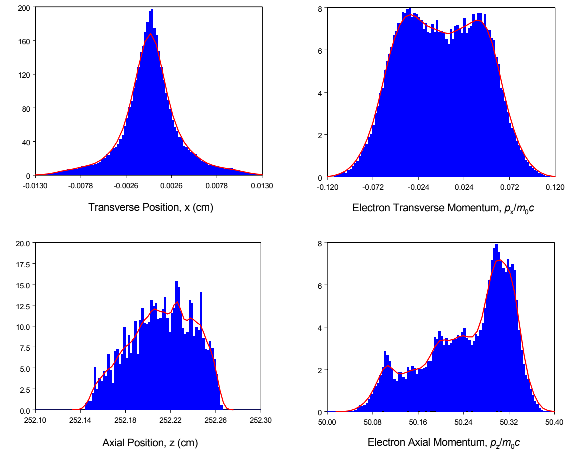
Polarization

PLEIADES Modeling Capabilities

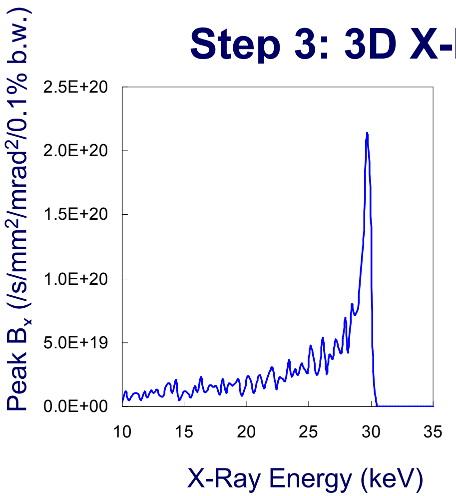
Step 1: PARMELA-SUPERFISH Design

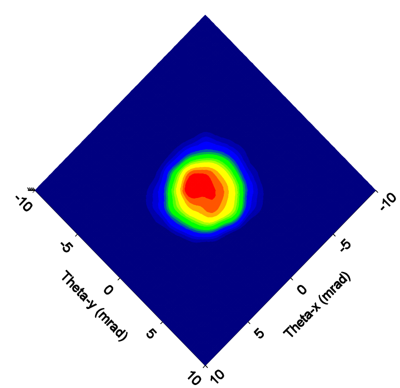


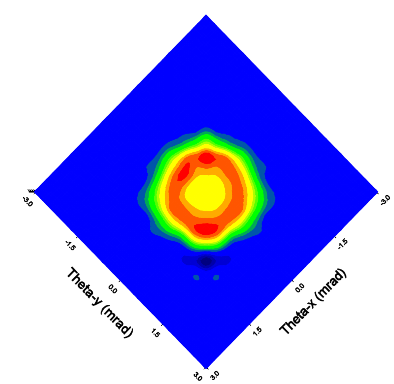
Step 2: Phase Space



Step 3: 3D X-Ray Simulations



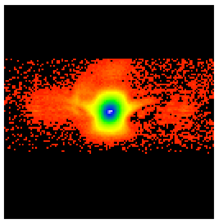




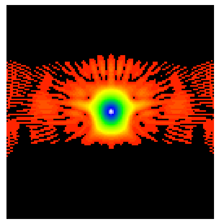
FALCON Laser Overview

Pulse Duration

GRENOUILLE Traces

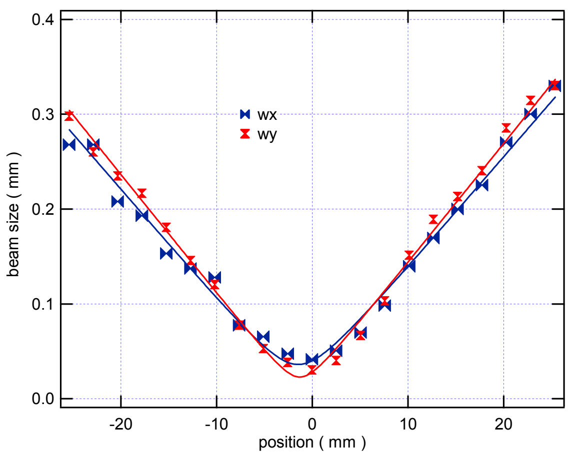


Measured



Retrieved

Δt = 54 fs



Ti:Al_2O_3 OPCPA Hybrid

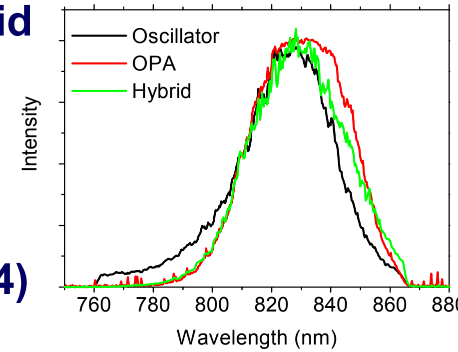
800 nm

500 mJ (compressed)

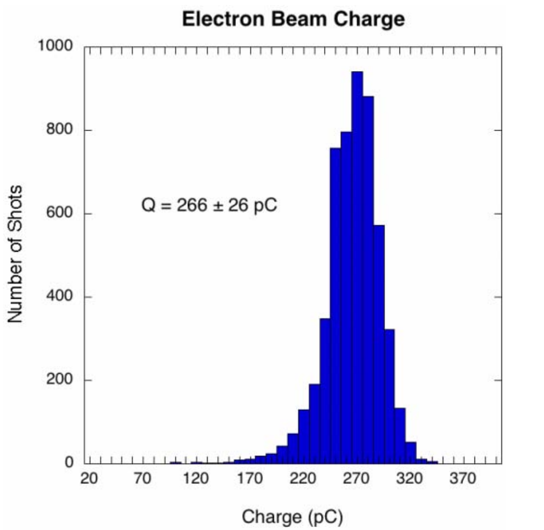
50 fs FTL

20 μm FWHM (M^2 ~ 1.4)

10 Hz

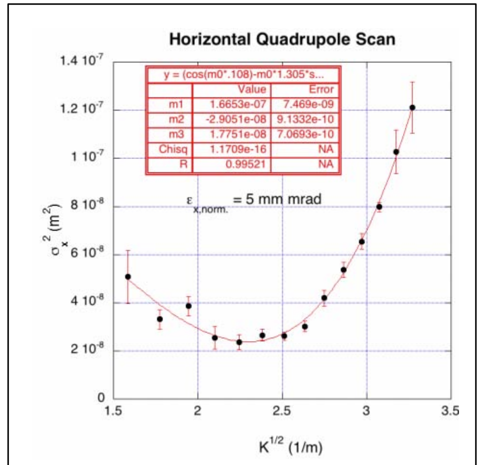


PLEIADES Electron Bunch Measurements

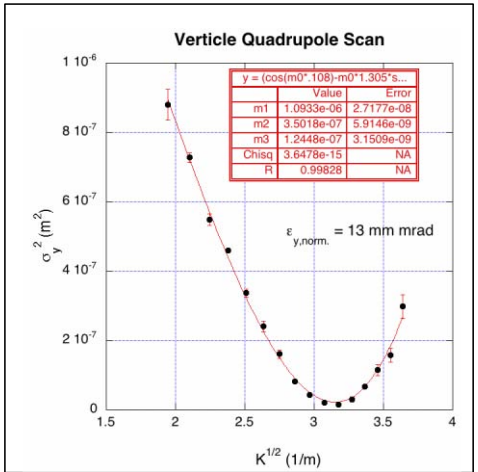


$<q> = 266$ pC

Emittance



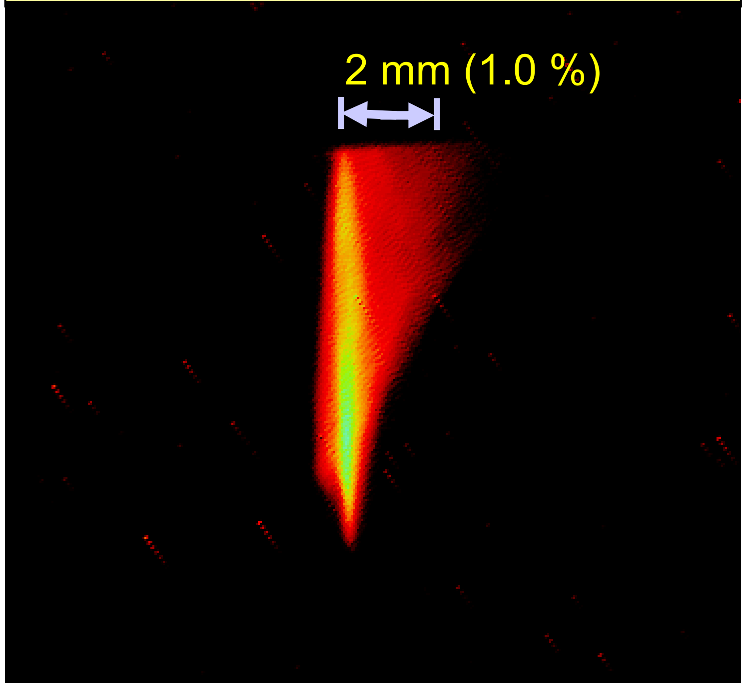
$\varepsilon_x = 5$ mm mrad



$\varepsilon_Y = 13$ mm mrad

PLEIADES Electron Bunch Measurements

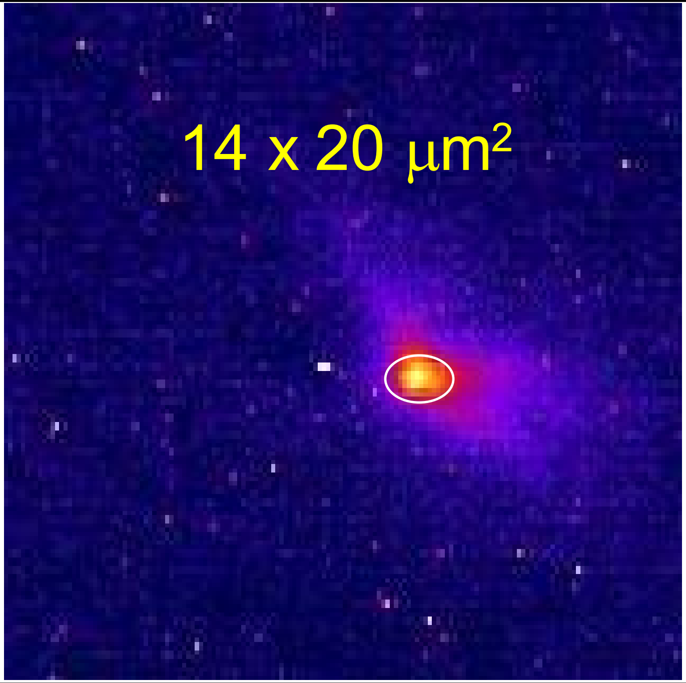
Energy Spectrometer



$E = 59.2$ MeV

$\sigma_E = 0.2$ %

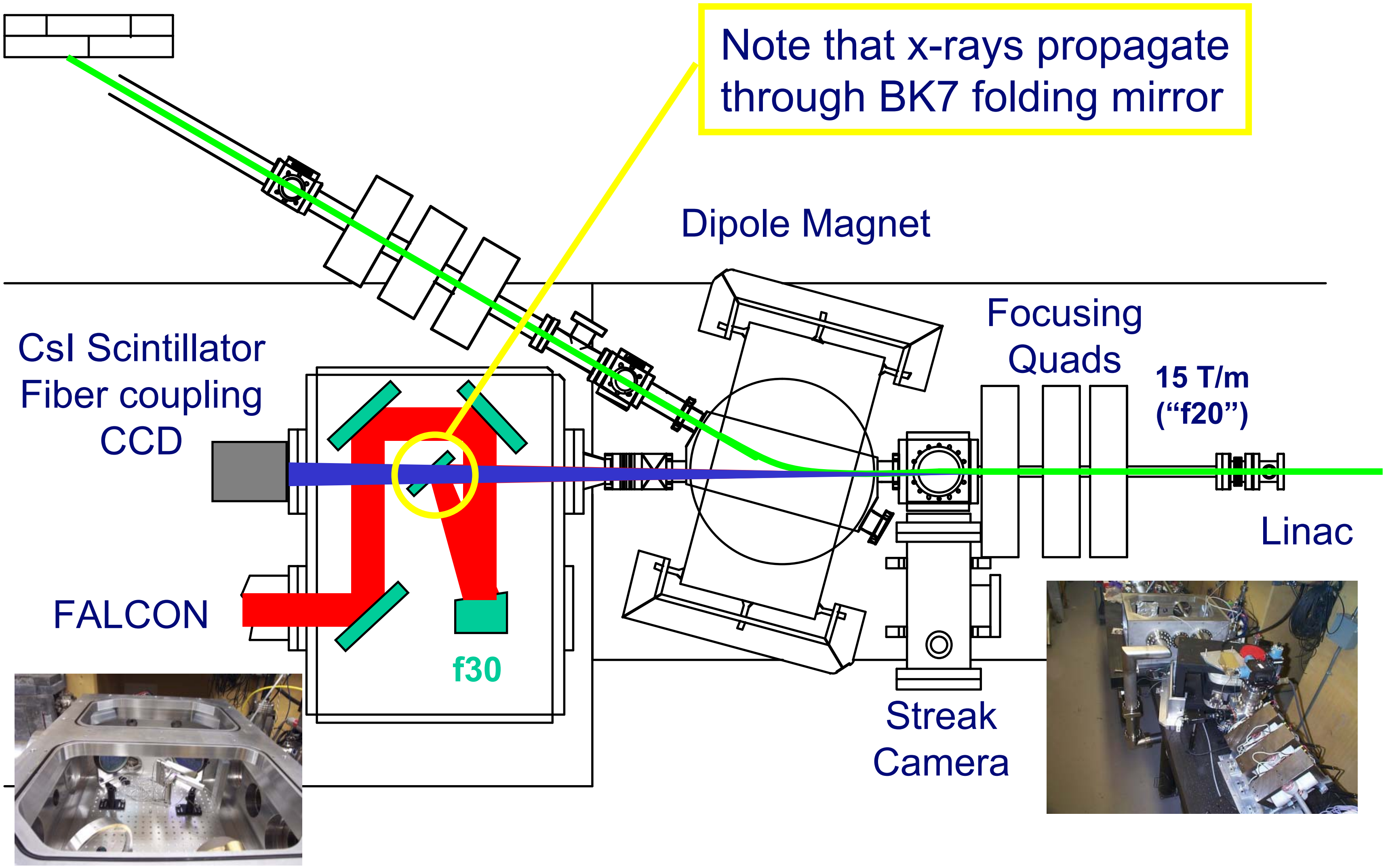
Beam Spot At Interaction



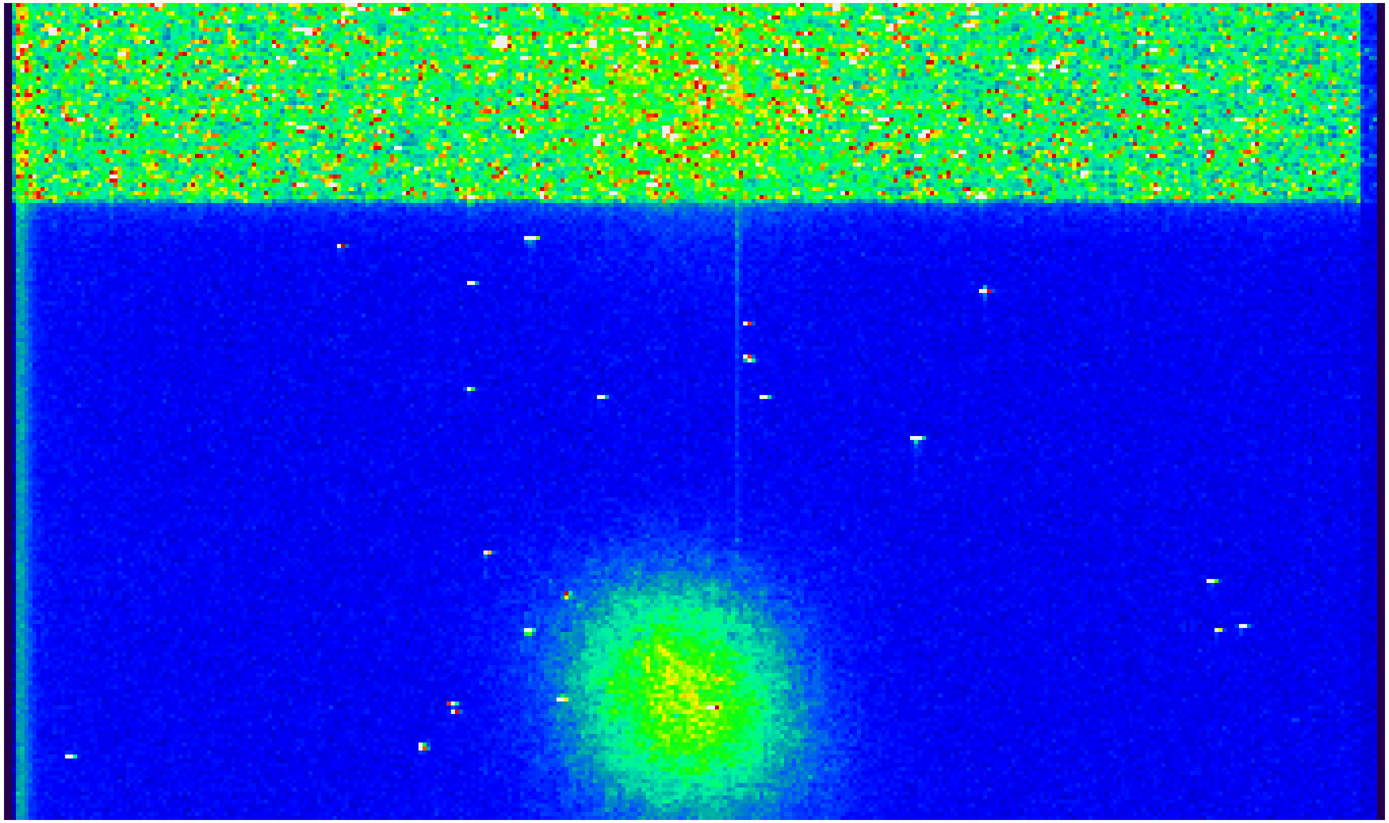
$\sigma_x = 14\ \mu m$

$\sigma_y = 20\ \mu m$

PLEIADES 180-Degree Interaction Region

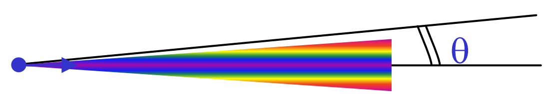


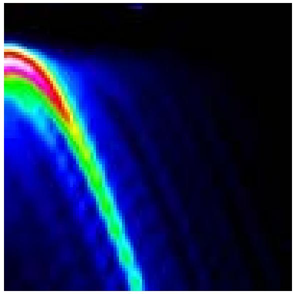
First Light: 200 ms X-Ray CCD Capture



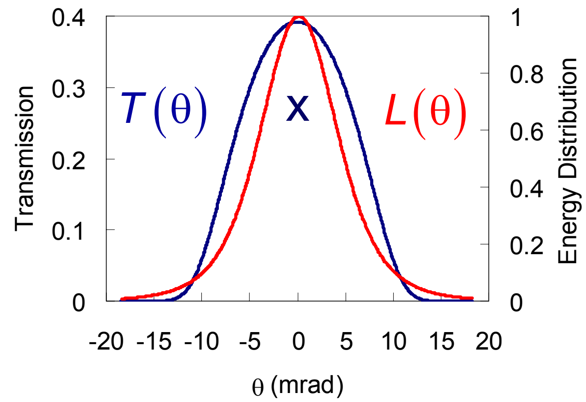
PLEIADES: Theory and Experiment

- BK7 flat (800 nm fold mirror) attenuates x-rays according to their energies (higher att. at low energy)
- Angular correlation between scattering angle & energy results in narrowing of the angular distribution





- X-Ray energy distribution is given by: $L(\theta) \sim 1/\left[1+(\gamma\theta)^2\right]^3$



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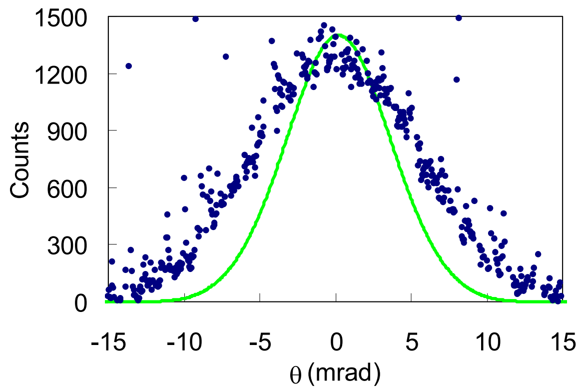
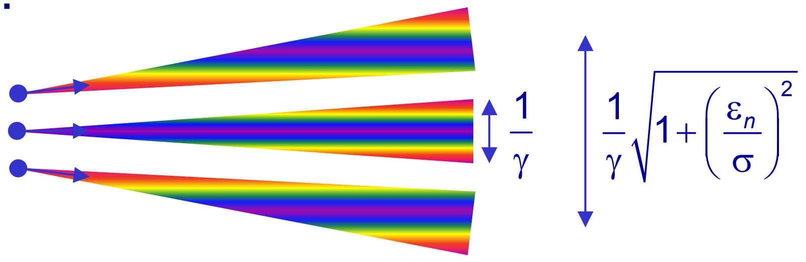
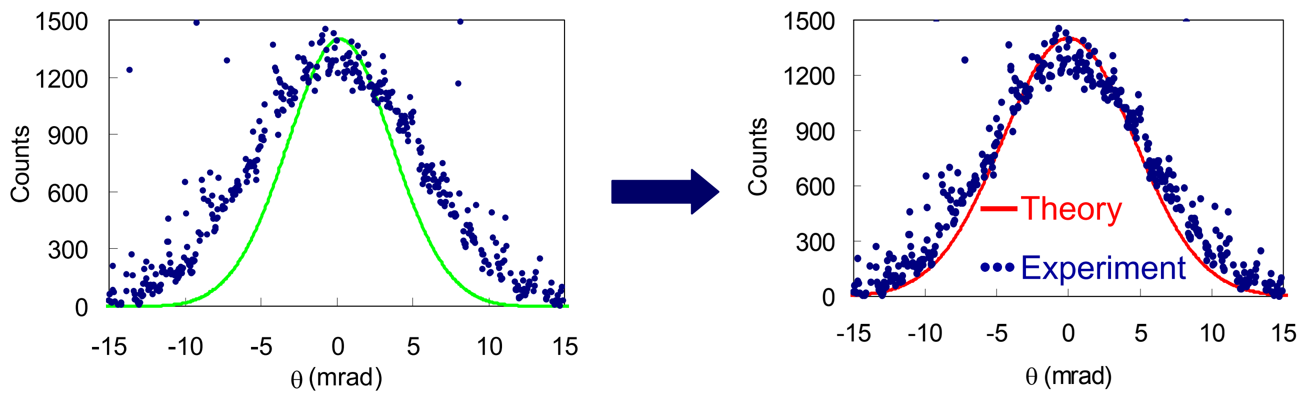


PLEIADES: Theory and Experiment

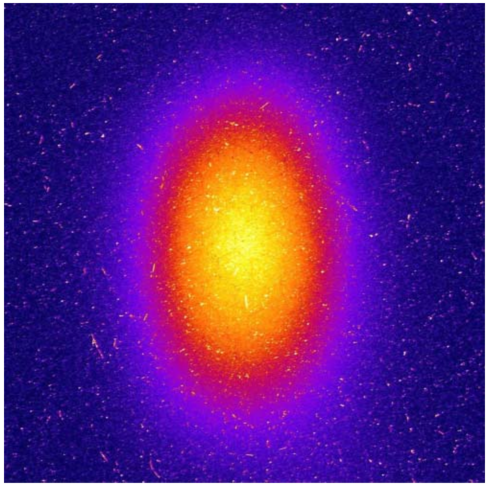
- However, emittance and 3D focusing broaden angular distribution:

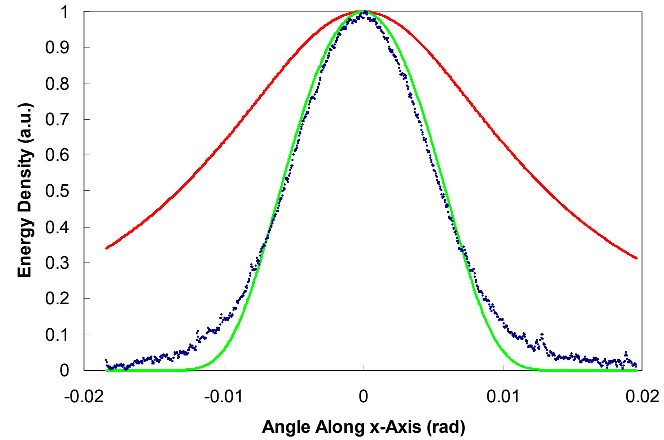


- All these effects must be accounted for to match data

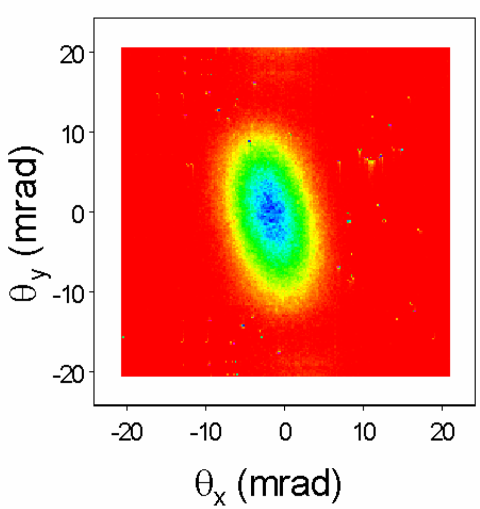


X-Ray Dose per Shot: > 2 x 10^7

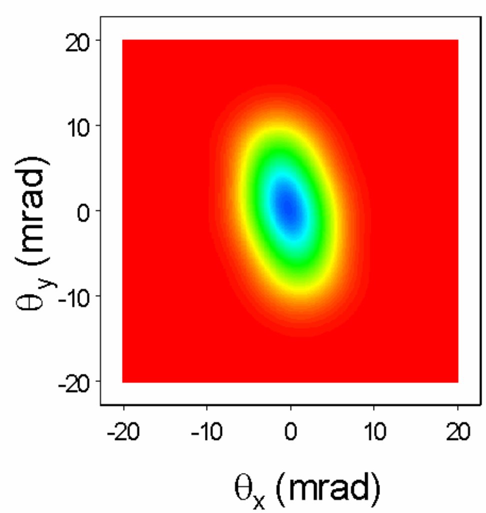




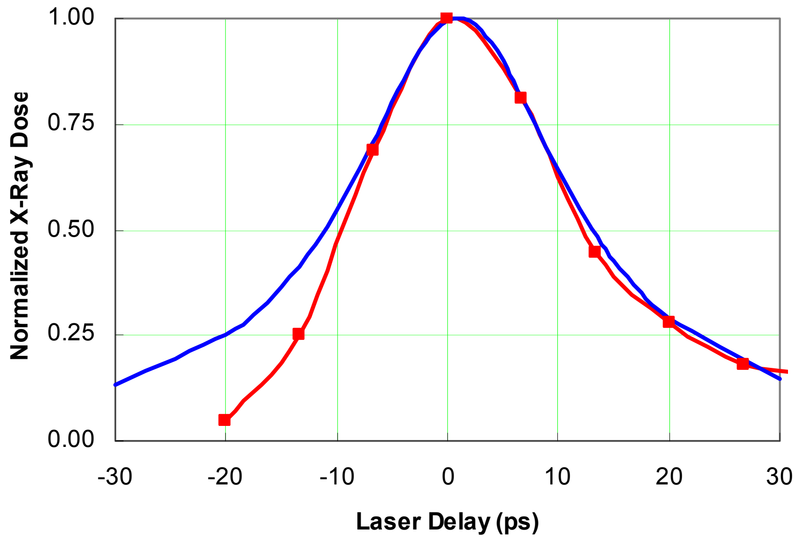
Measured Profile



Calculated Profile



PLEIADES Normalized Dose Versus Delay



$$N_x \propto \frac{1}{1+\left(z/z_0\right)^2} = \frac{1}{1+\left(\frac{c\Delta t\lambda_0 M^2}{\pi w_0^2}\right)^2} = \frac{1}{1+\left(\Delta t/\tau\right)^2}$$

$\lambda_0 = 800$ nm

$w_0 = 36\ \mu$m

$M^2 = 1.4$

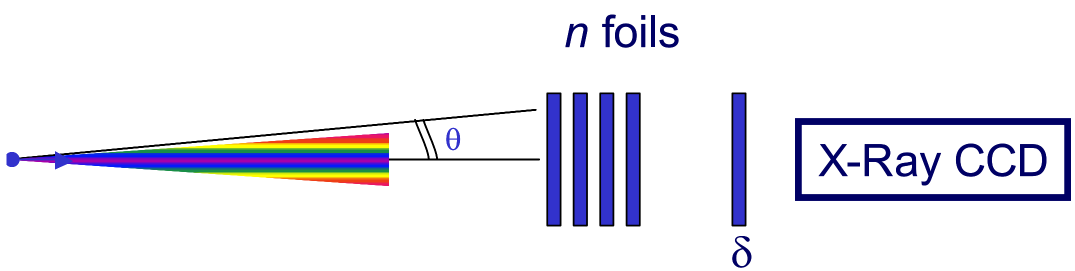
$\tau = 12.1$ ps

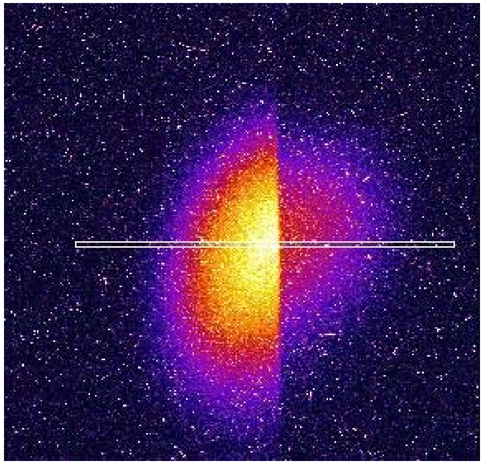
Red: experimentally measured data

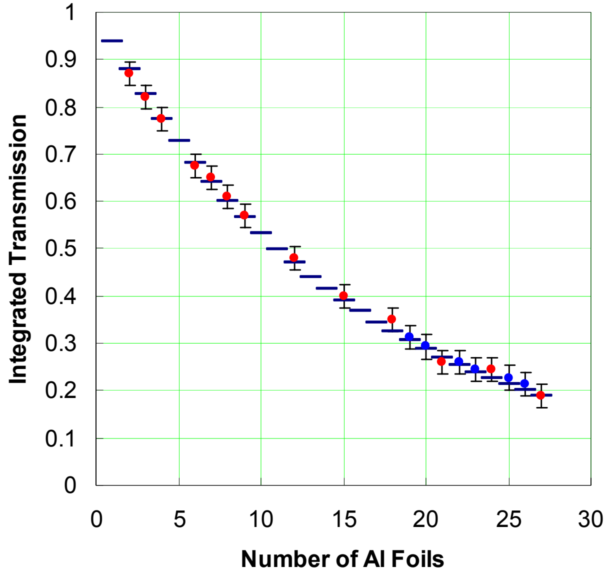
Blue: theoretical Lorentzian profile for Gaussian pulses, using the measured laser parameters

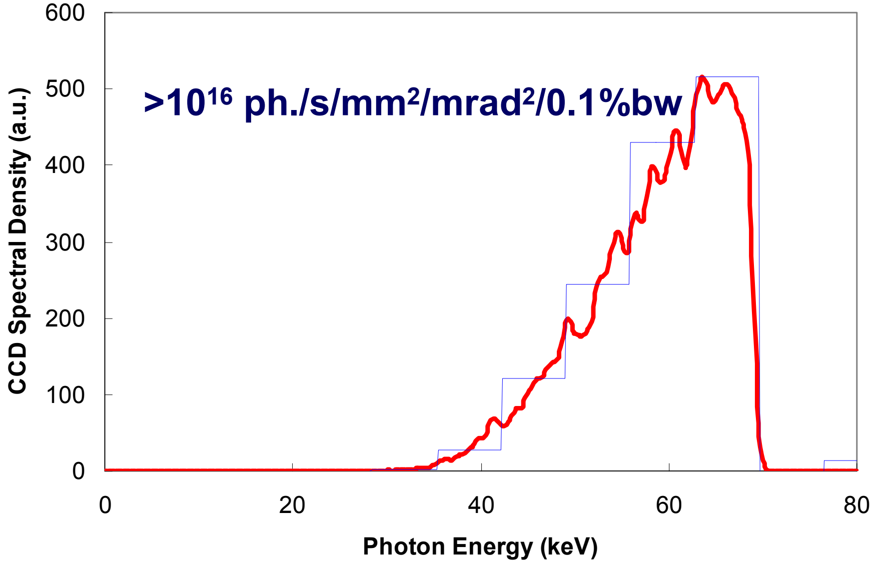
The asymmetry reflects the fact that the electron beam current is higher at the tail than at the front: for positive delays, the bunch tail is closer to the focus where the highest photon density is reached

On-Axis Spectral Brightness



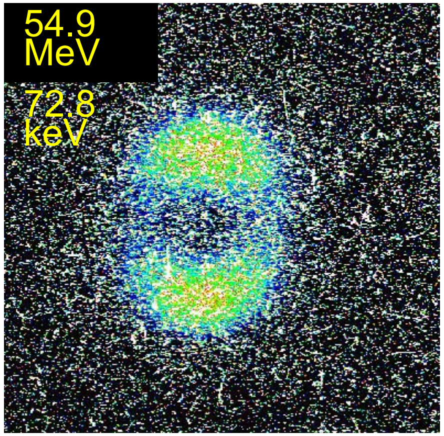


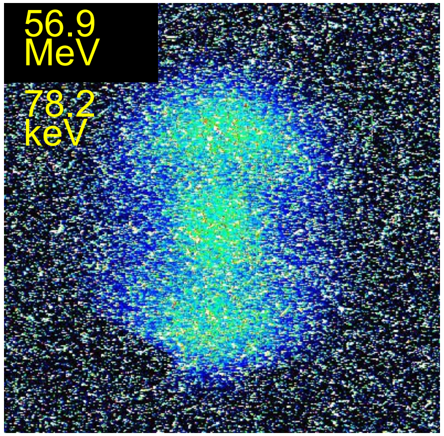


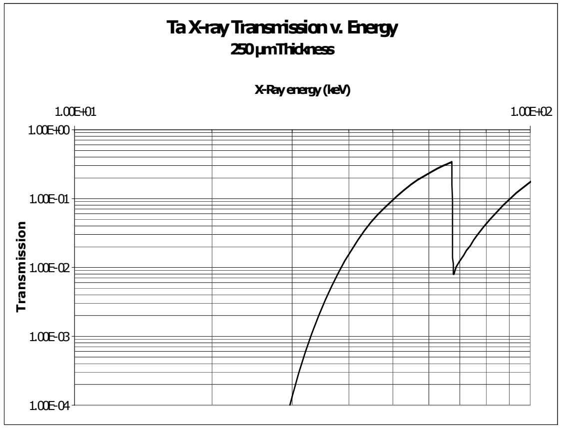


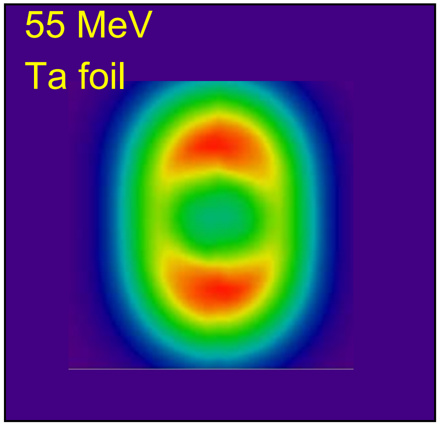
Radiography and Tunability

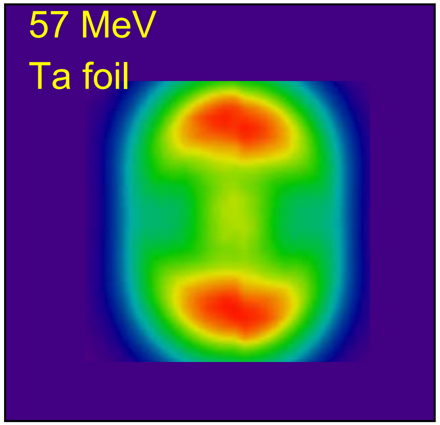
0.005” Tantalum foil; K-edge @ 67.46 keV

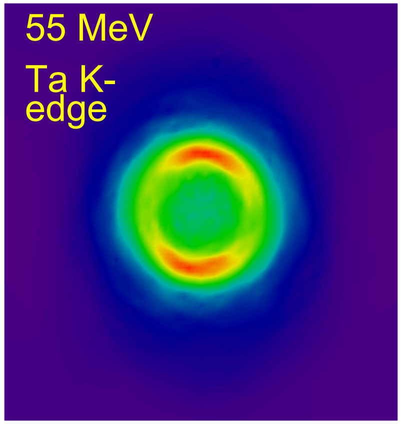






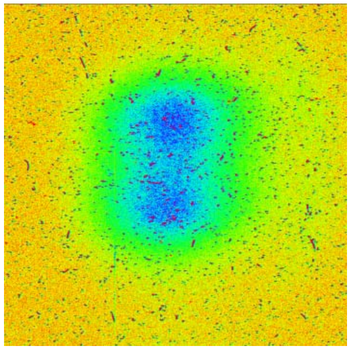






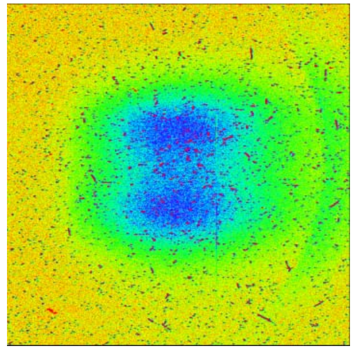
U K-Edge 115.6 keV

73.5 MeV, 15 mil



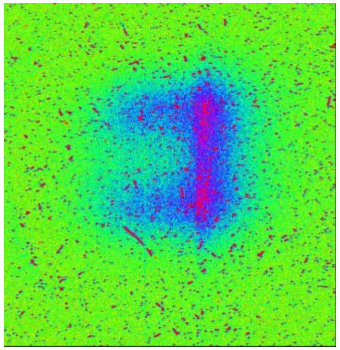
800 x 800 pixels

71.5 MeV, 15 mil



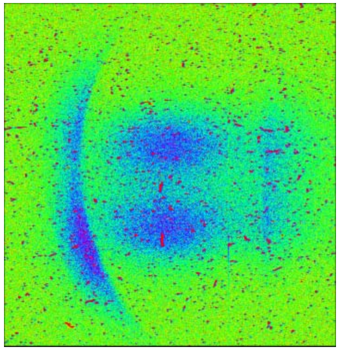
800 x 800 pixels

73.5 MeV, 33 mil

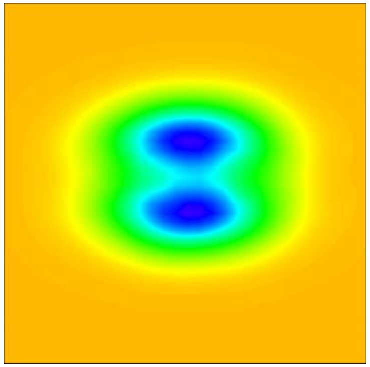


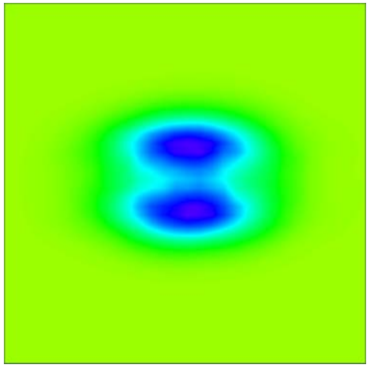
800 x 800 pixels

71.5 MeV, 33 mil

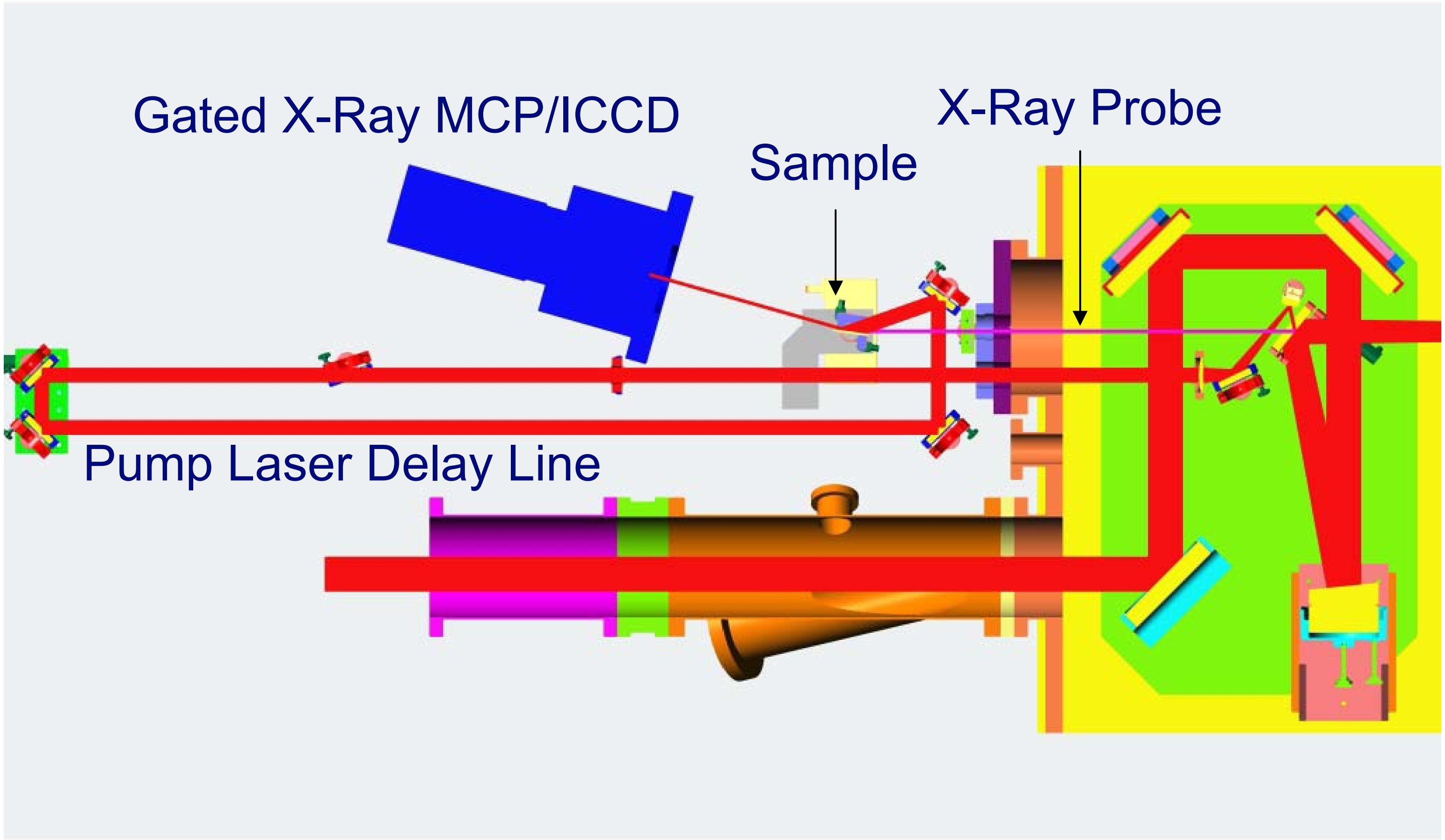


800 x 800 pixels

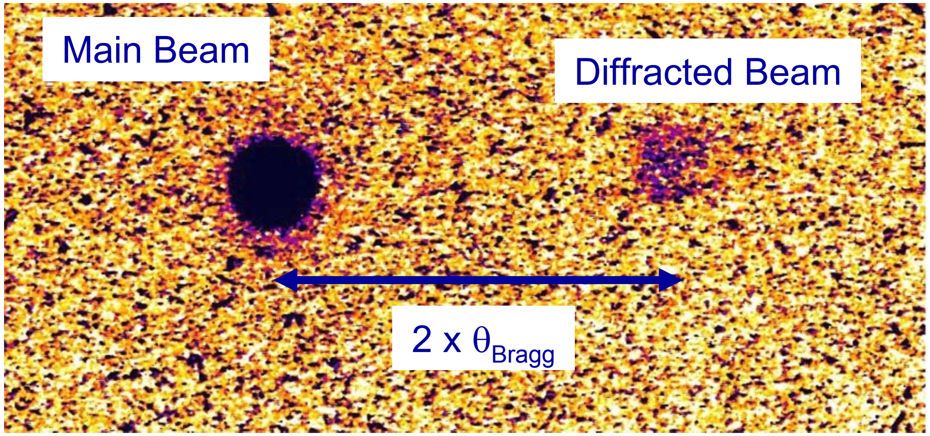


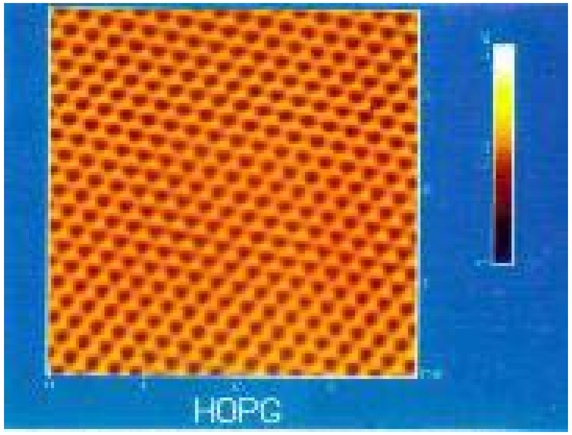


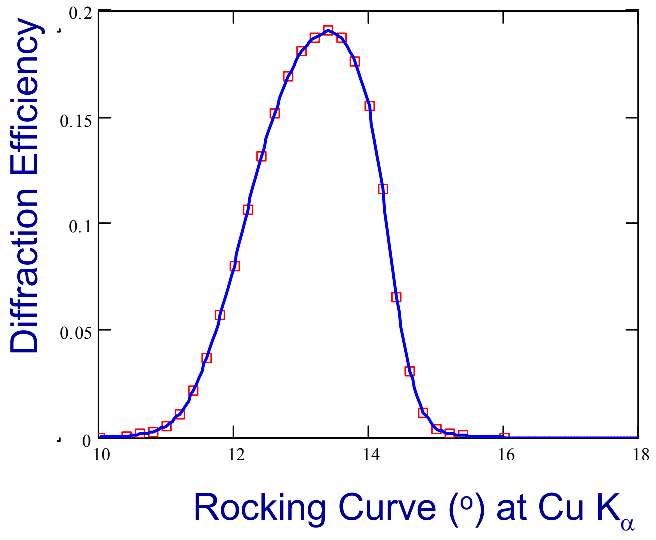
Dynamic Diffraction Experimental Setup

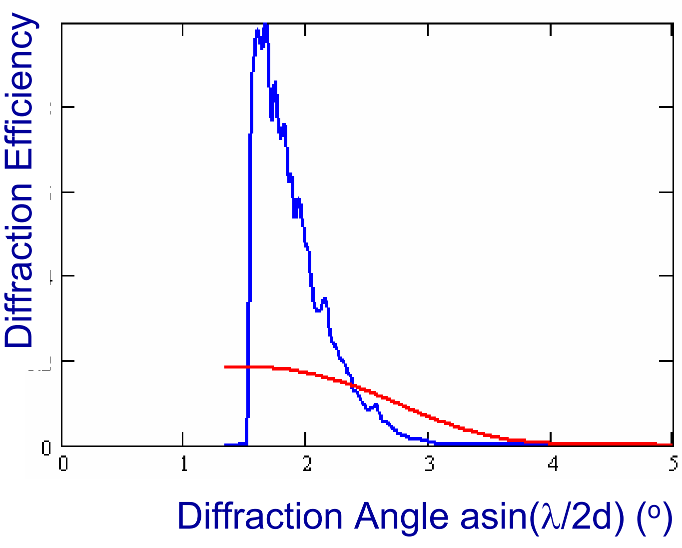


HOPG Static Diffraction

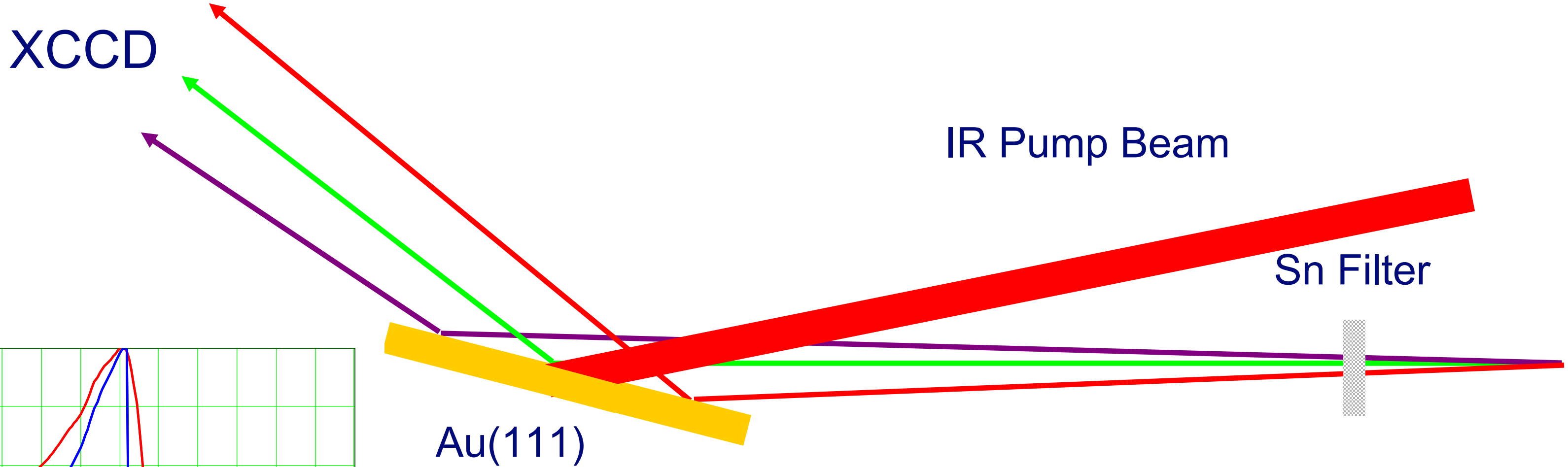


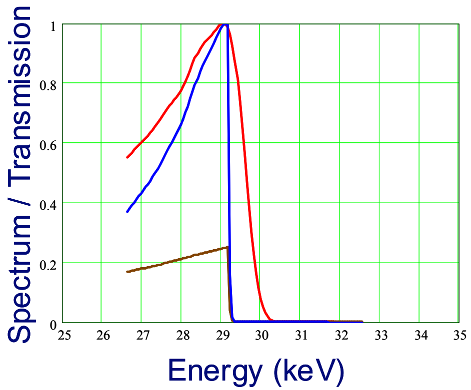






High-Contrast Dynamic Diffraction



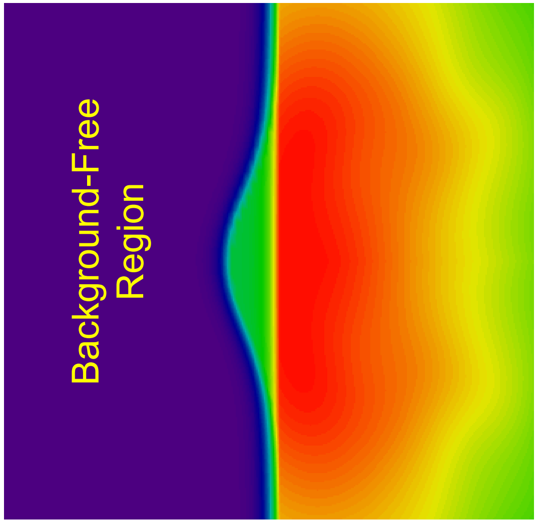


Au from Room Temperature to Melting: 1.5% Increase of 2*d*

Ultrafast (Non-Thermal) Melting: Fluence 5-20 mJ/cm^2

Gaussian Shape is Due to Pump Laser Illumination on Crystal

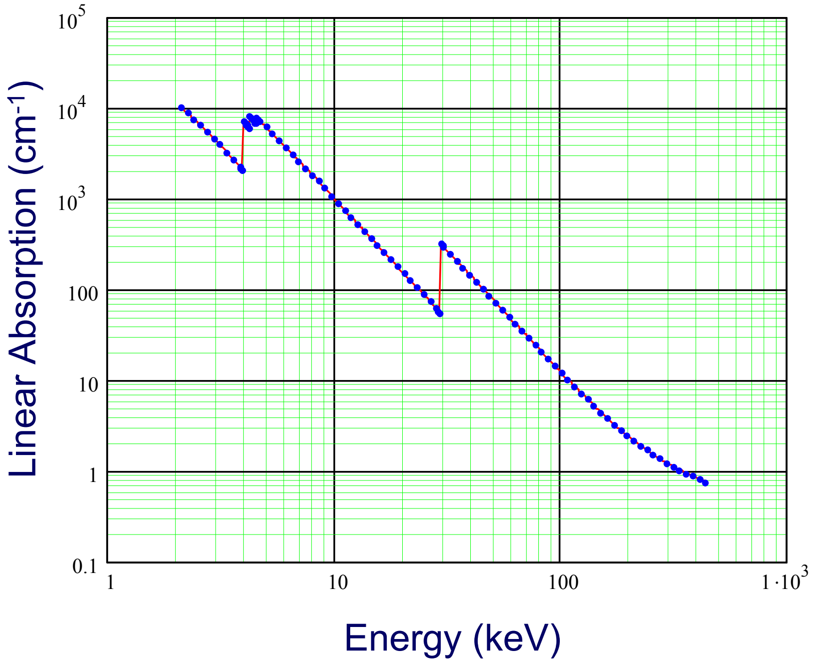
Edge Shift is a Direct Measurement of 2*d*-Spacing

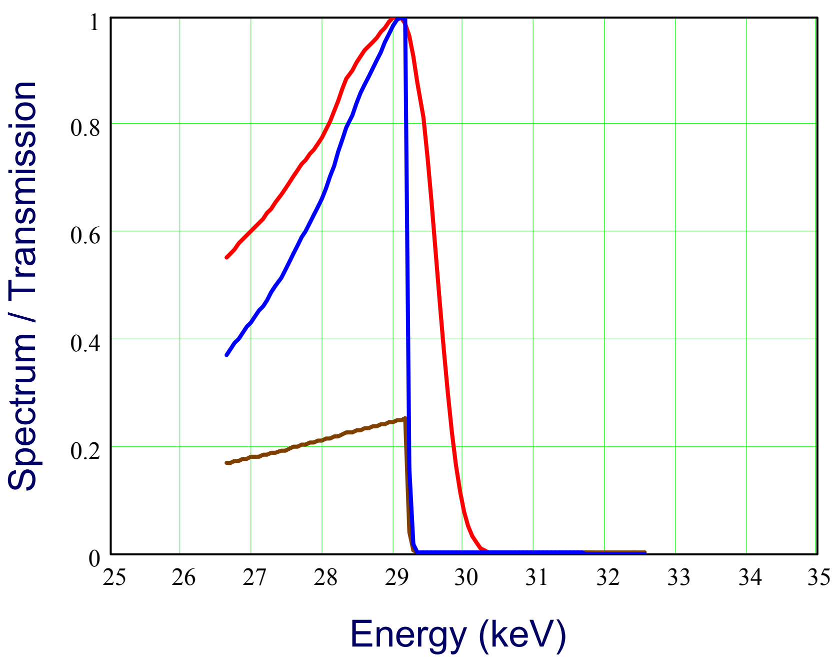


Diffraction Angle +/- 2.5 mrad

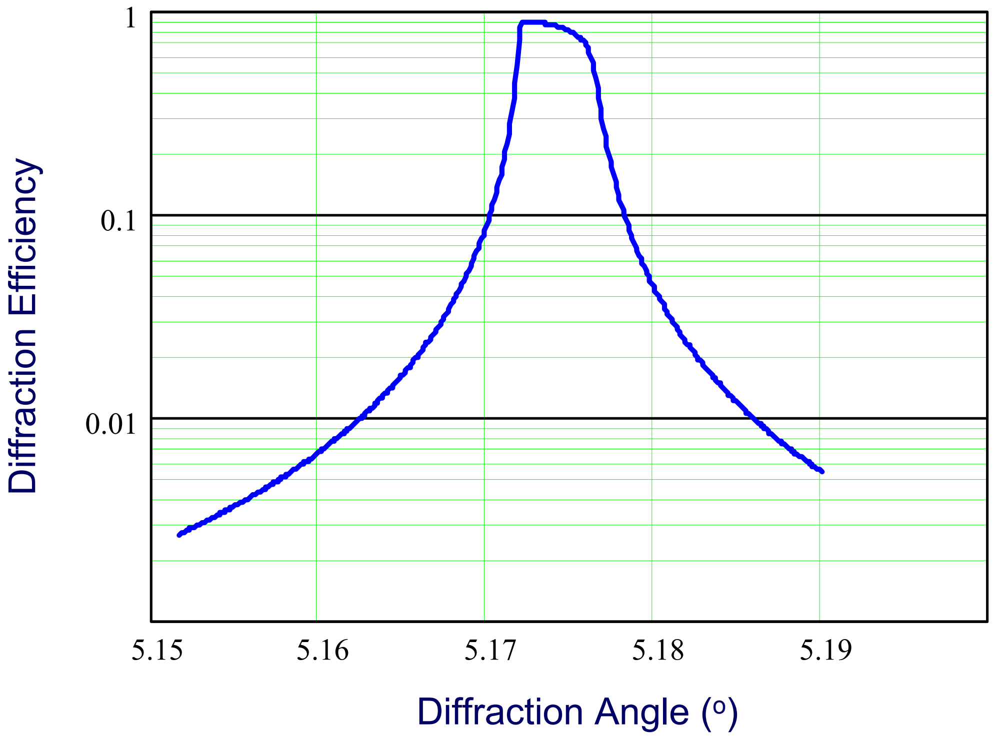
K-Edge Tagging: 250 μm Sn

By using K-edge tagging, one can considerably improved the data collection technique used by LBNL on InSn



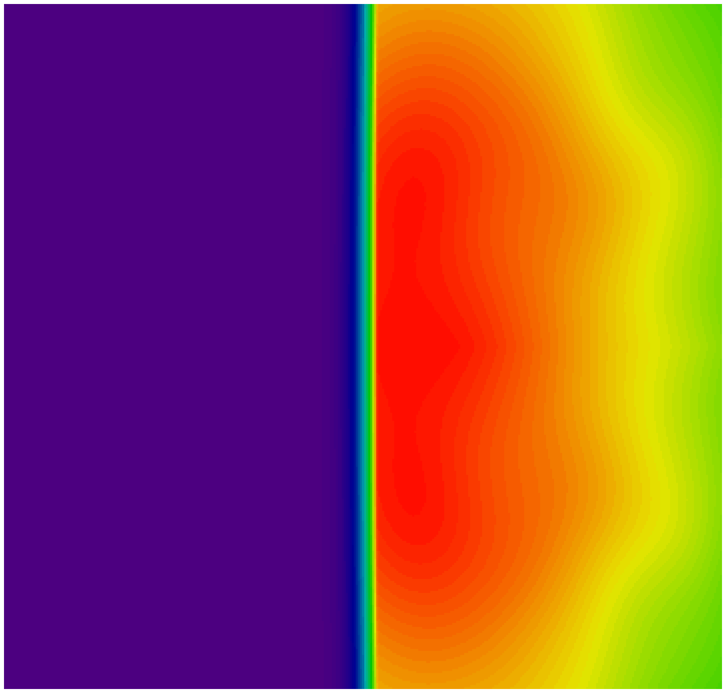


Darwin Curve Au (111)

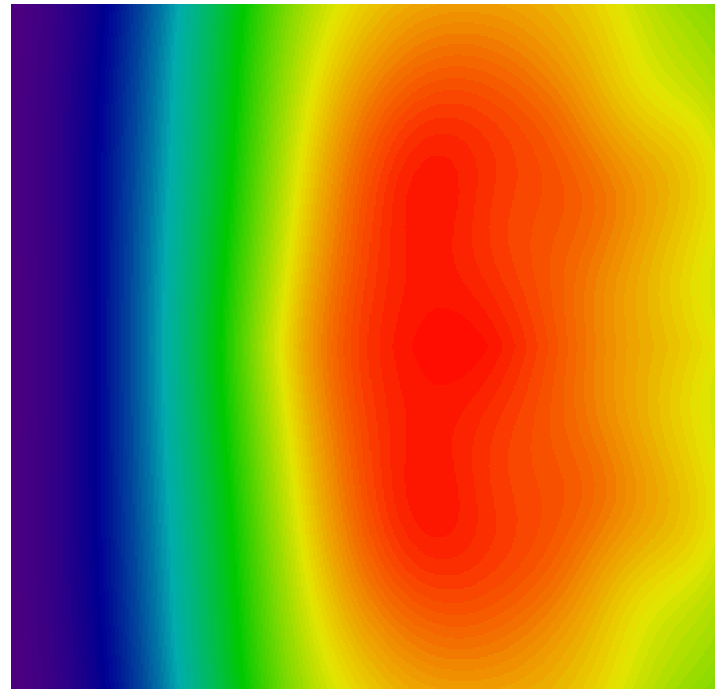


Au (111) High-Contrast Static Diffraction

$\theta > \theta_{Bragg}, \lambda > \lambda_{Sn}$



Diffraction Angle



Diffraction Angle

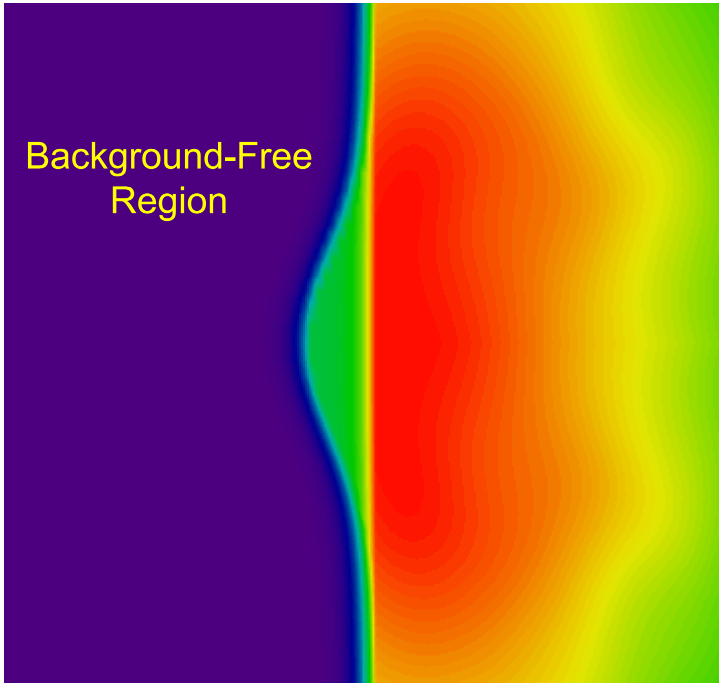
$5 \times 5\ \text{mrad}^2$

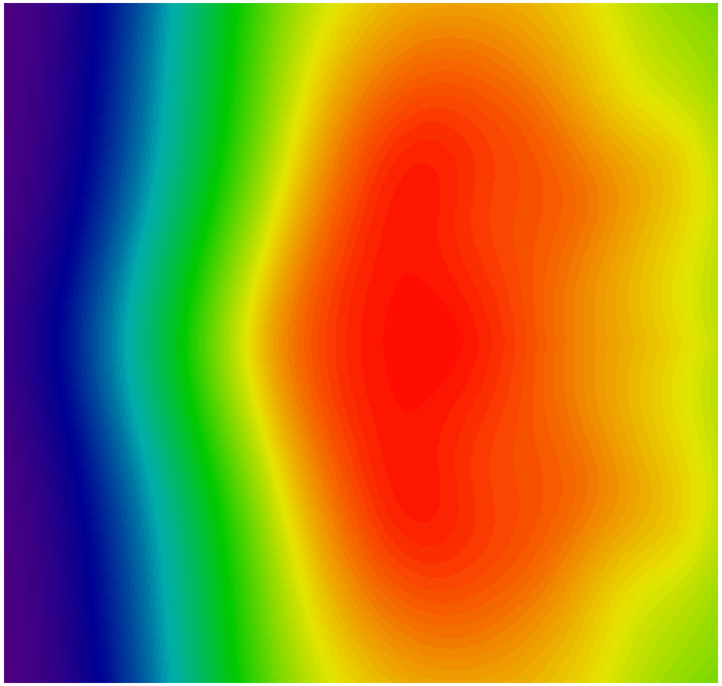
$$hc / e\lambda_{Sn} = 29.2001\ \text{keV}$$

$$2d_{Au(111)} = 4.7092\ \text{Å}$$

$$2d \sin\theta = \lambda$$

Au (111) High-Contrast Dynamic Diffraction





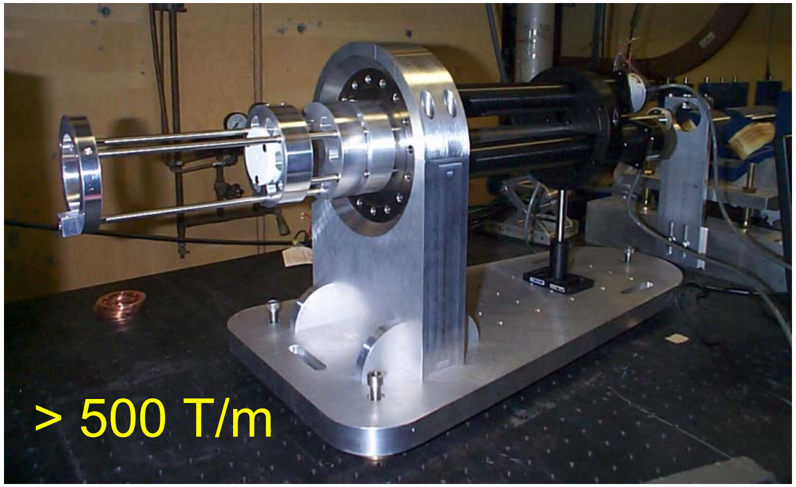
Au from Room Temperature to Melting: 1.5% Increase of 2*d*-Spacing

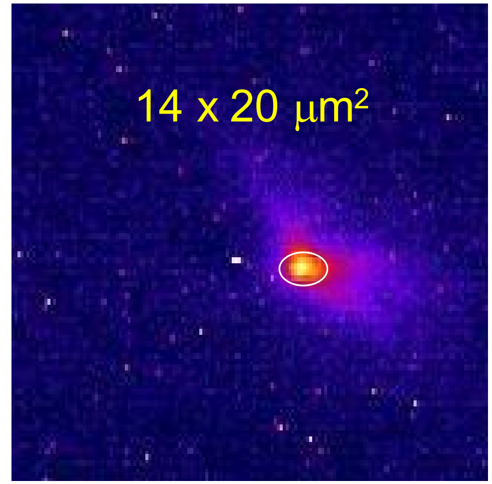
Ultrafast (Non-Thermal) Melting: Fluence 5-20 mJ/cm^2

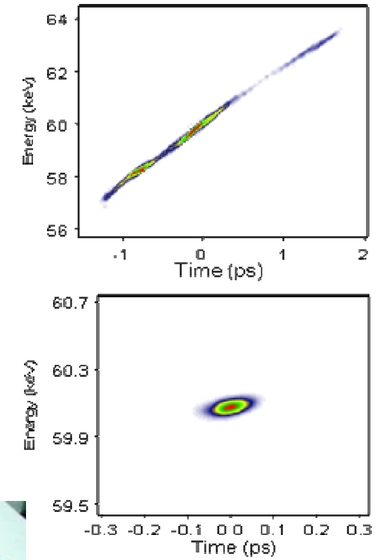
Gaussian Shape is Due to Pump Laser Illumination on Crystal

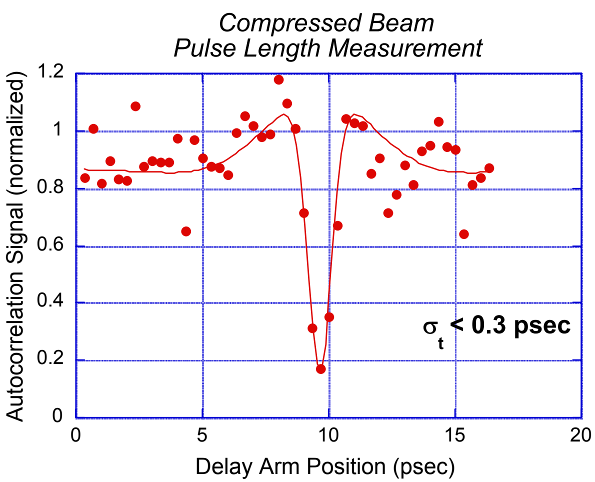
Edge Shift is a Direct Measurement of 2*d*-Spacing

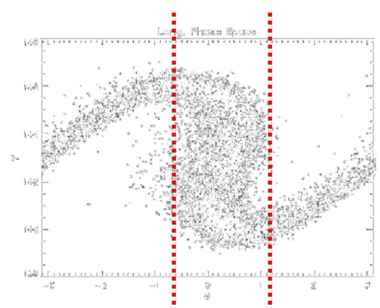
Pushing Toward μm, fs/as Beams



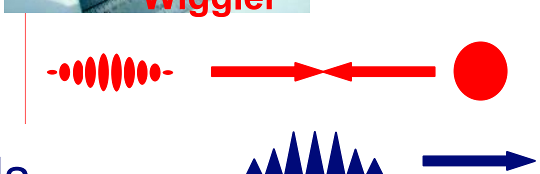








700 attoseconds
(after 1' wiggler!)

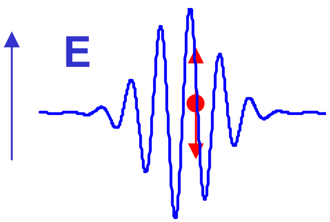


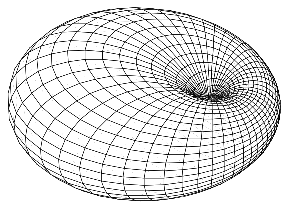
Attosecond
X-ray strobe light

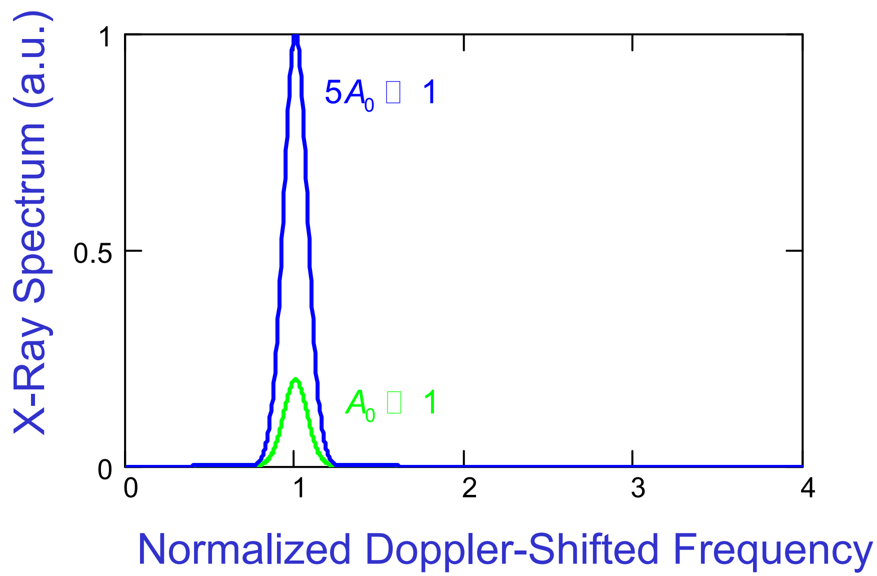
Linear & Nonlinear Compton Scattering

$$A_0 = \frac{eE}{\omega m_0 c} \Leftrightarrow K = \frac{eB_w}{m_0 k_w c}$$

$< 10^{17}$ W/cm^2

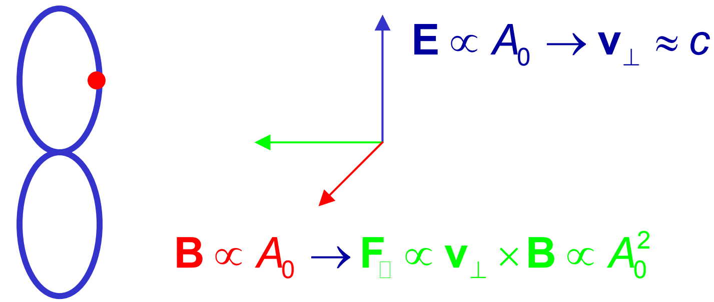


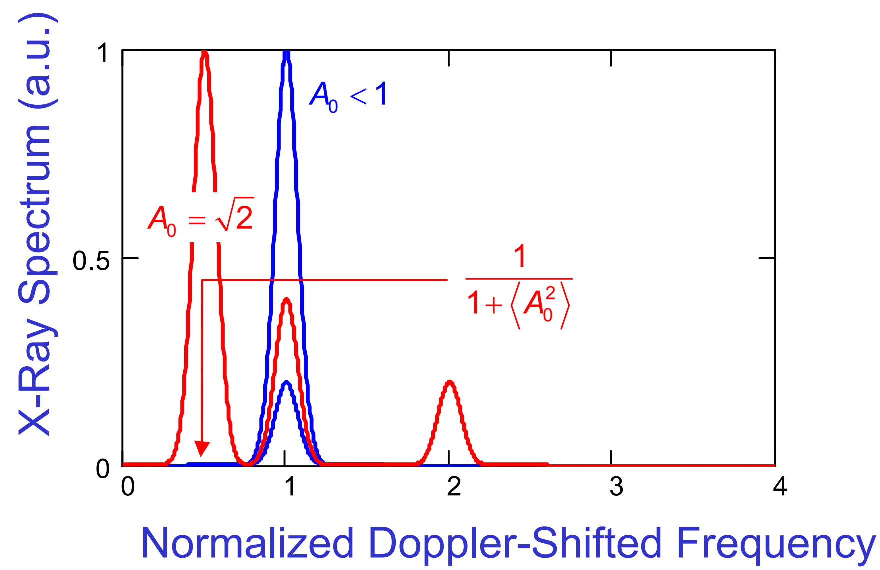




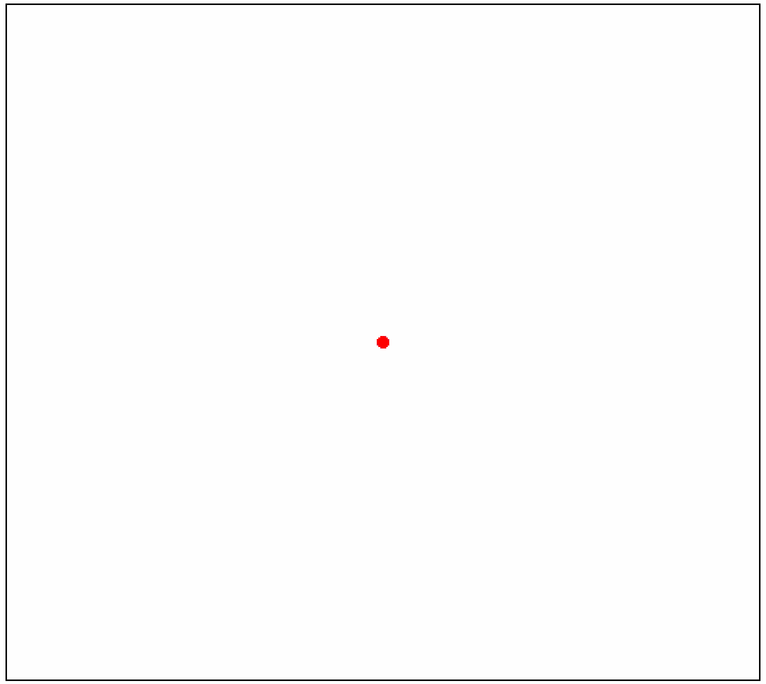
Analogy: Strong Wiggler Field

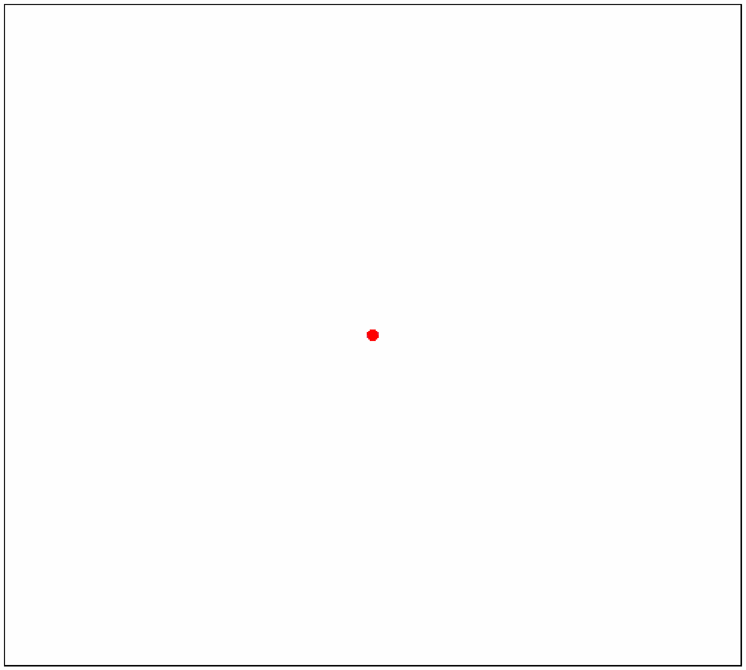
X-Ray Harmonic Production



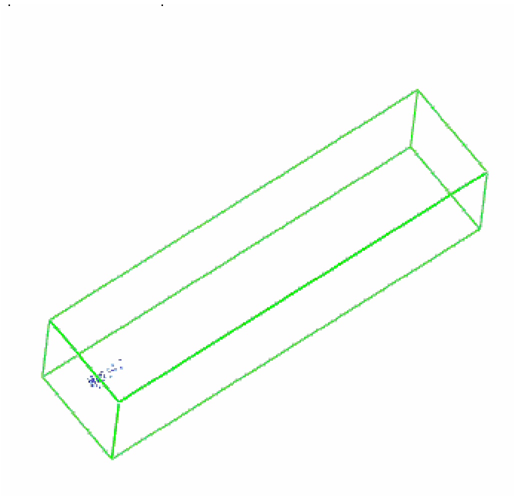


Linear & Nonlinear Compton Scattering





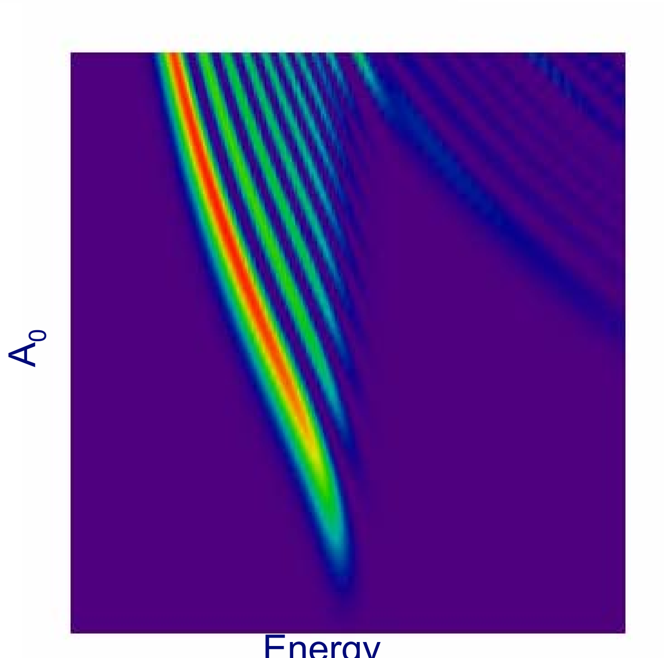
3D NL Code: Linear Polarization

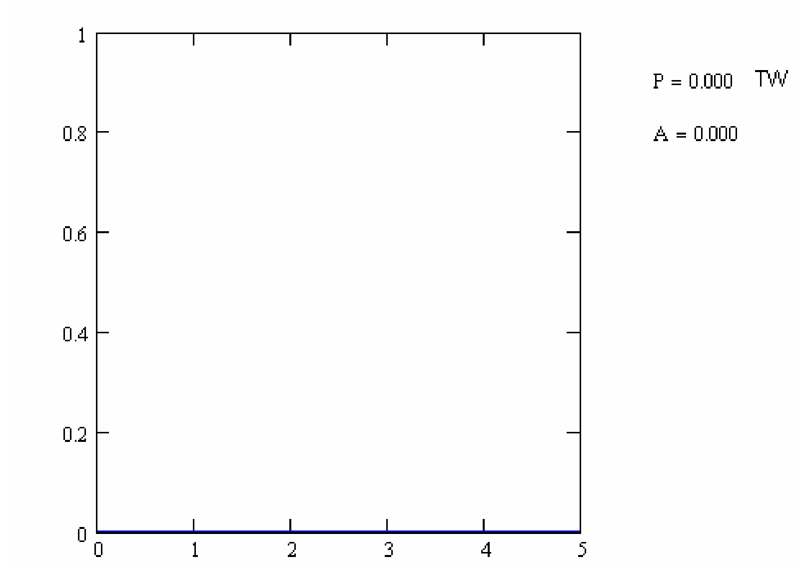


$\theta_x = \theta_y = 0$ $\qquad w_0 = 30\ \mu m$

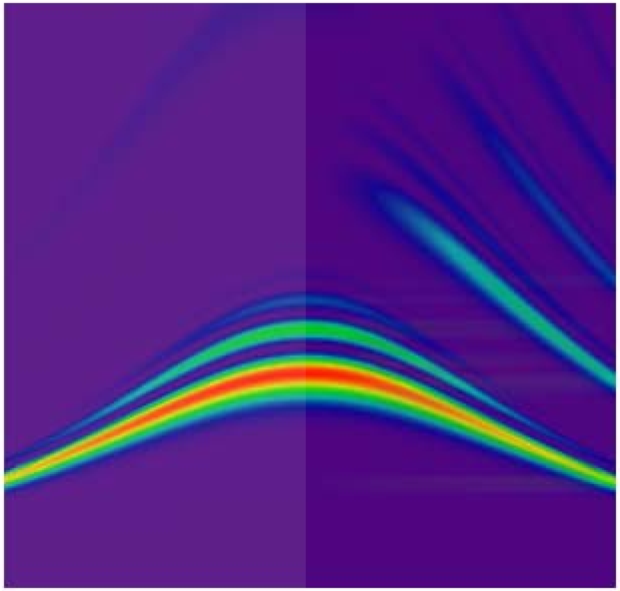
$\Delta t = 10$ fs $\qquad$ 30 MeV

$A_0 = 0 - 2$ $\qquad \dfrac{\omega_x}{4\gamma_0^2} = 0 - 2$





NL Compton Scattering: Off-Axis Spectrum



$\left(\theta, \omega_x, S_x\right)$

$A_0 = 1$

$w_0 = 30\ \mu\text{m}$

$\Delta t = 10\ \text{fs}$

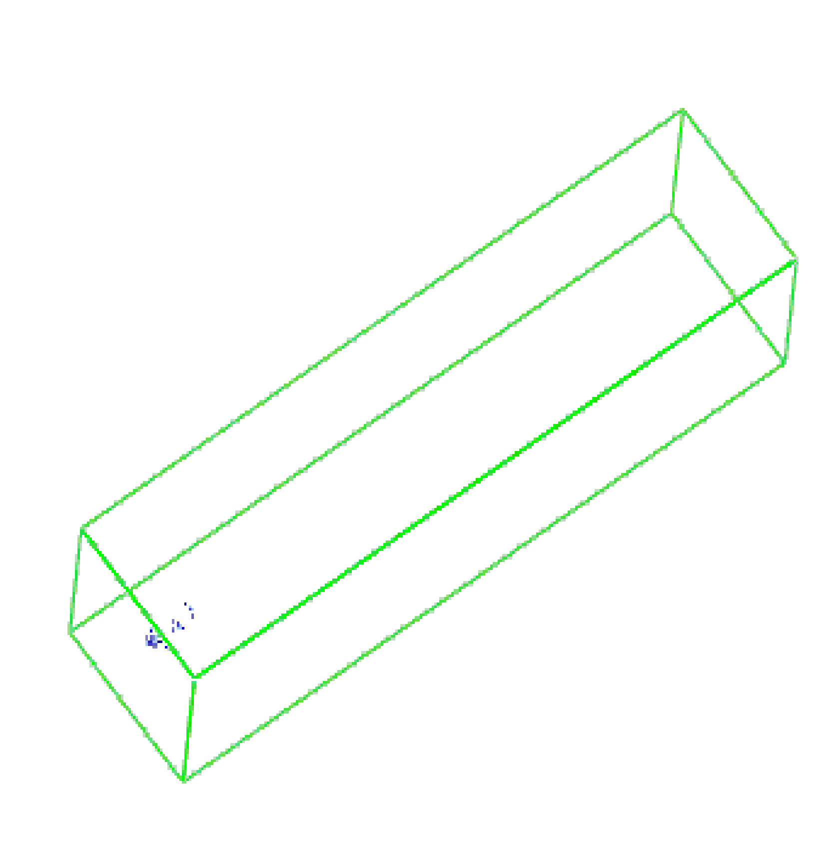
30 MeV

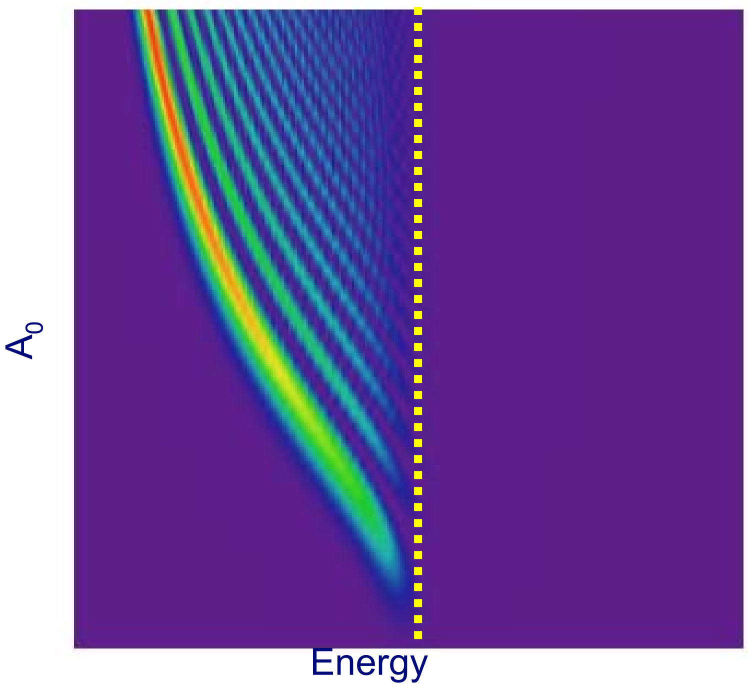
$\theta_x = 0 - 20$ mrad, $/\!/$ polarization (right)

$\theta_y = 0 - 20$ mrad, $\perp$ polarization (left)

$$\frac{\hbar\omega_x}{4\gamma_0^{\ 2}\hbar\omega_0} = 0 - 2$$

3D NL Code: Circular Polarization



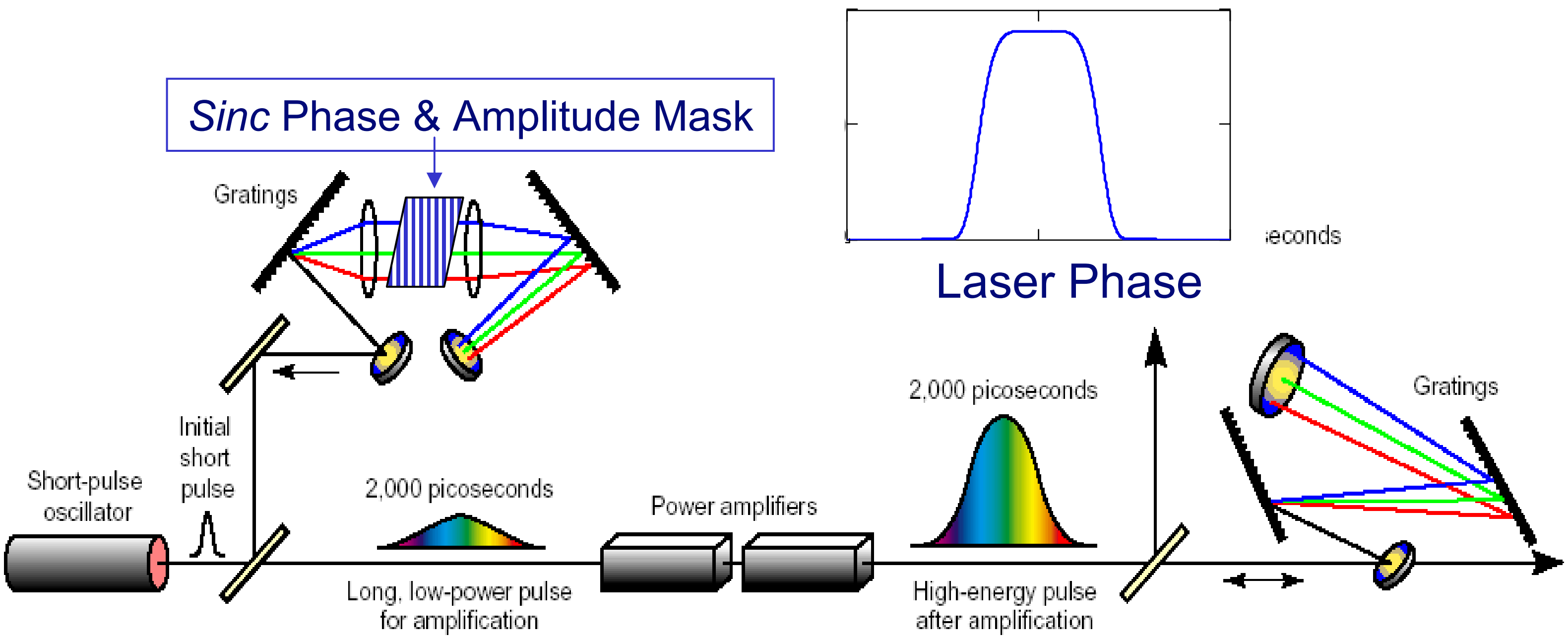


Spectral Control: Laser pulse Shaping

Approach:

1) Circular Polarization, to Eliminate High Harmonics

2) Temporal Pulse Shaping, to Eliminate “Transient” Lines (Dazzler)



High Brightness NL Compton Scattering

$$\lambda_x = \frac{\lambda_w \left(1 + A_0^2\right)}{4\gamma^2}$$

Increase Laser Intensity

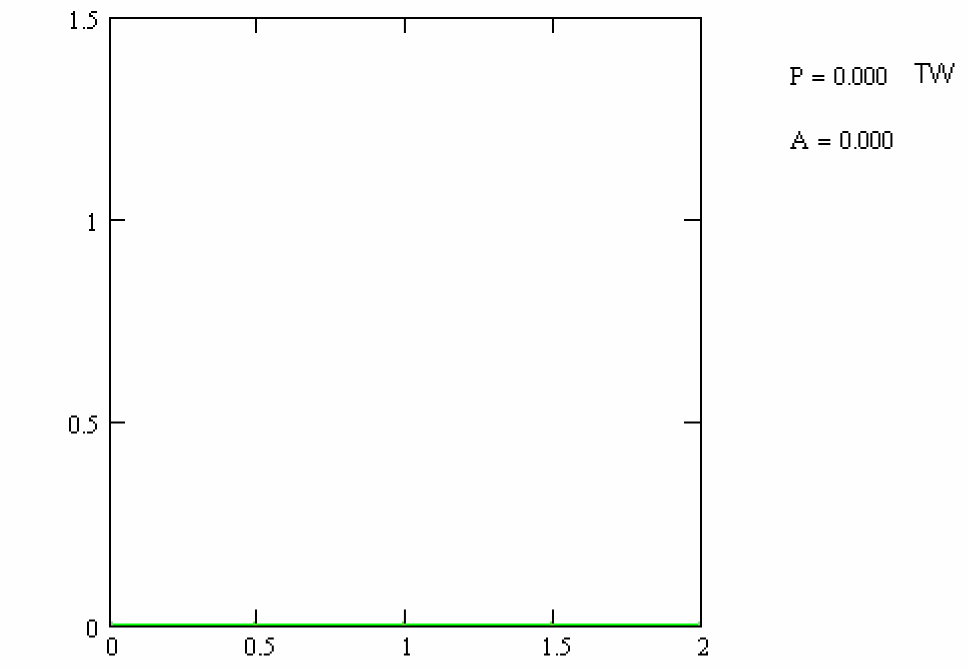
Increase E-Beam Energy

$\frac{\varepsilon_n}{\gamma}$ Decreases: Much Smaller Spot Size

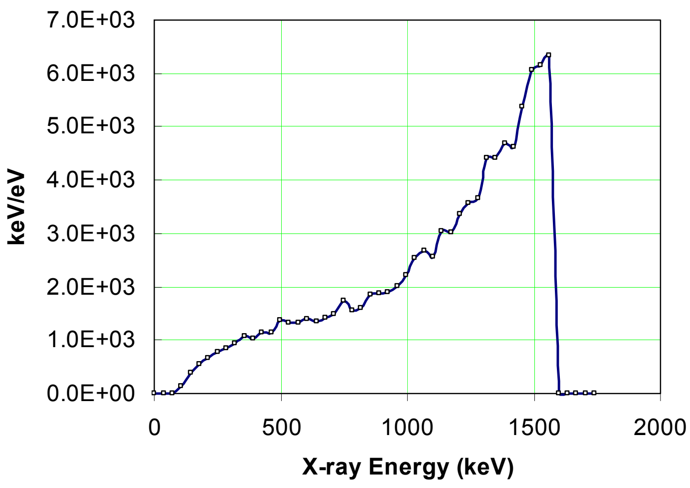
Circular Polarization, Gaussian

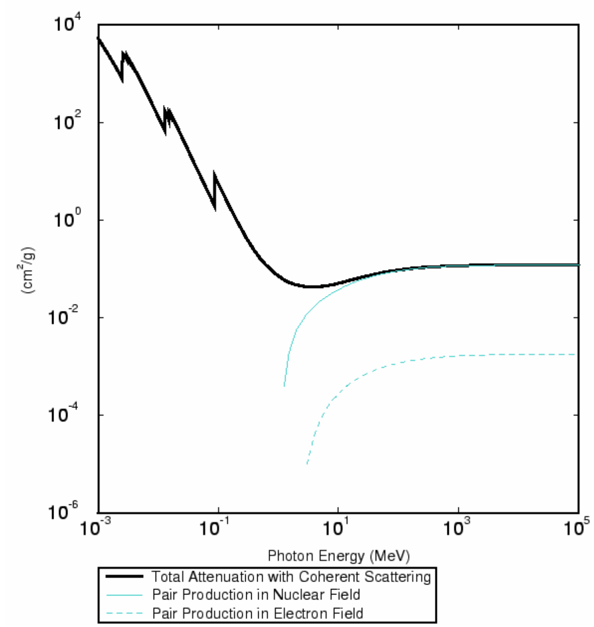
Circular Polarization, Square

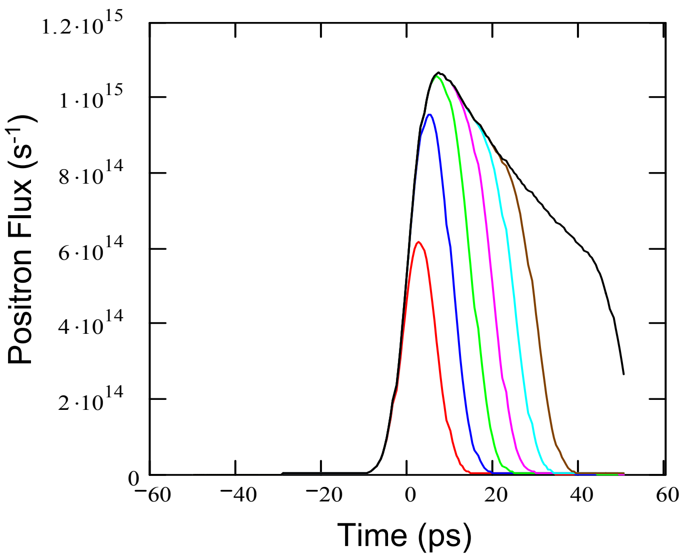
Circular Polarization, Square
X-Ray Energy Fixed



Picosecond Positron Pulse Production at PLEIADES







Linac Beam at 150 MeV
FALCON at 3 ω, 10%
Pb Target

- 10^7 Above State-of-the-Art
- Time-Resolved Positron Annihilation Spectroscopy