Inverse Compton Scattering Sources from Soft X-rays to γ-rays

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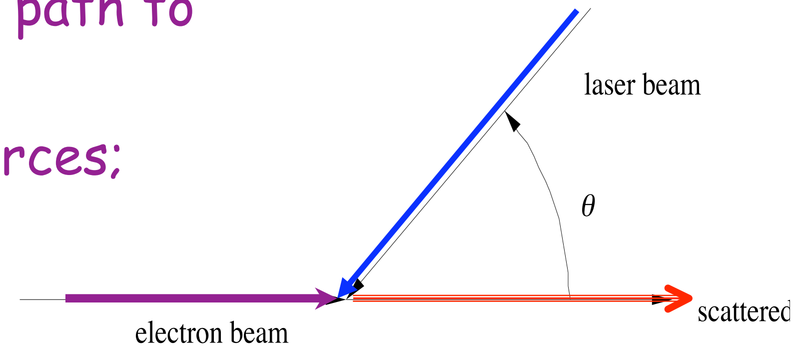
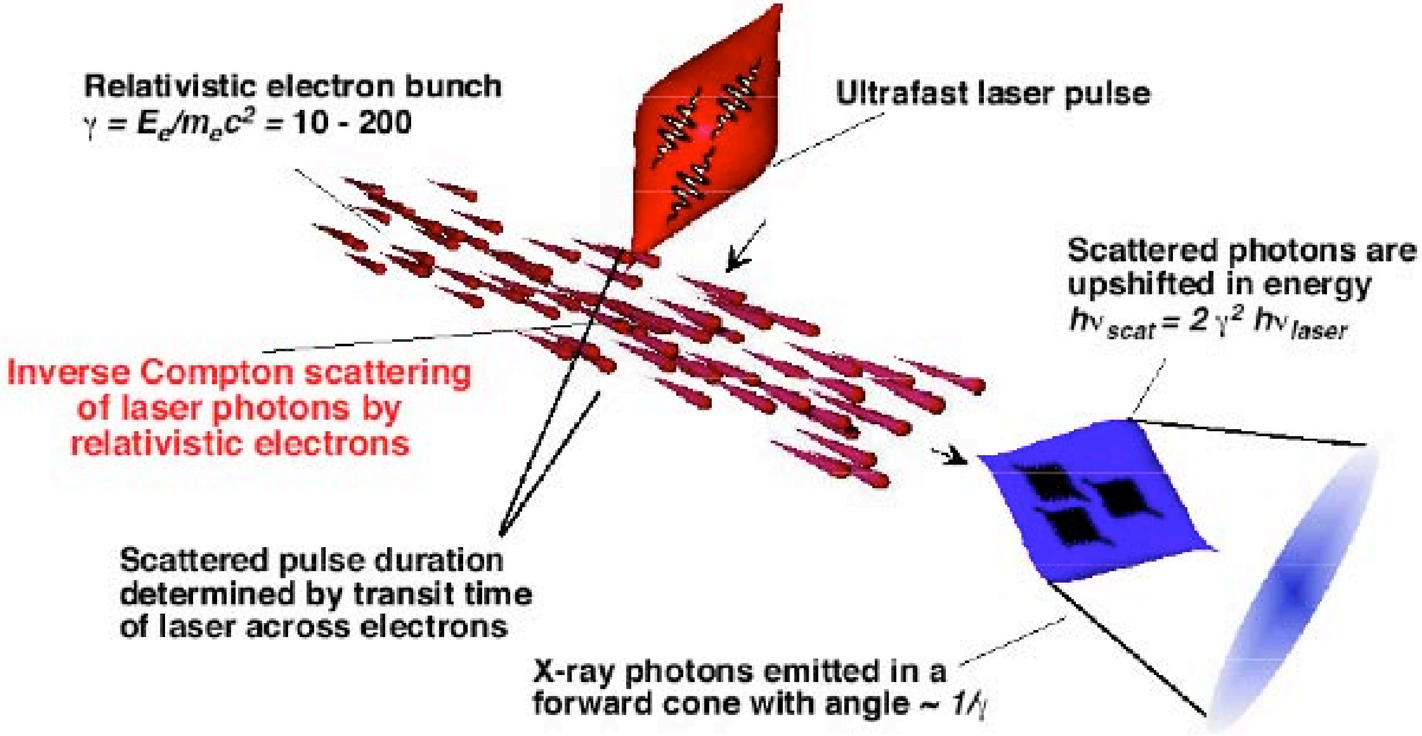
Introduction

- Inverse Compton scattering provides a path to 4th generation x-ray source
- Doppler upshifting of intense laser sources; "monochromatic" source
- Intense electron beam needed
- Extremely diverse uses
  - High energy density physics (shocks, etc.)
  - Material sciences
    - Cool positron production
  - High energy physics
    - Polarized positron sourcery
    - Gamma-gamma colliders
  - Medicine
    - Diagnostics (dichromatic coronary angiography)
    - Enhanced dose therapy



$$\lambda_\gamma \cong \lambda_L / 2(1+\cos(\theta))\gamma^2$$

Inverse Compton process



Relativistic electron bunch
$\gamma = E_e/m_e c^2 = 10 - 200$

Ultrafast laser pulse

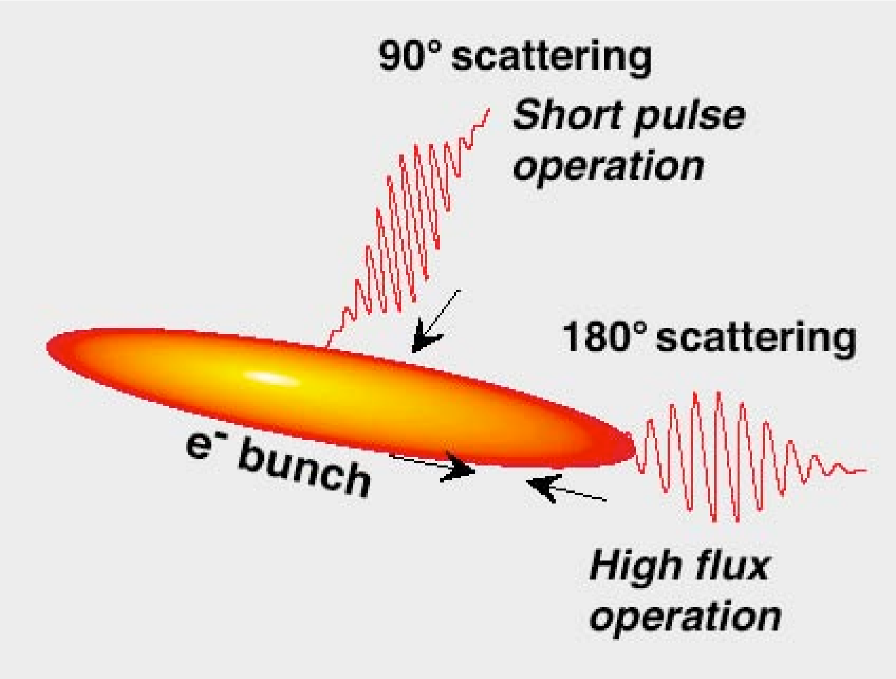
Scattered photons are upshifted in energy
$h\nu_{scat} = 2\gamma^2 h\nu_{laser}$

Inverse Compton scattering of laser photons by relativistic electrons

Scattered pulse duration determined by transit time of laser across electrons

X-ray photons emitted in a forward cone with angle ~ $1/\gamma$

Choice of time structure



90° Scattering	180° Scattering
10 - 100 keV 50 - 100 fs pulse width ~10^8 γ/pulse (10% bandwidth)	20 - 200 keV < 10 ps pulse width ~10^9 γ/pulse (10% bandwidth)

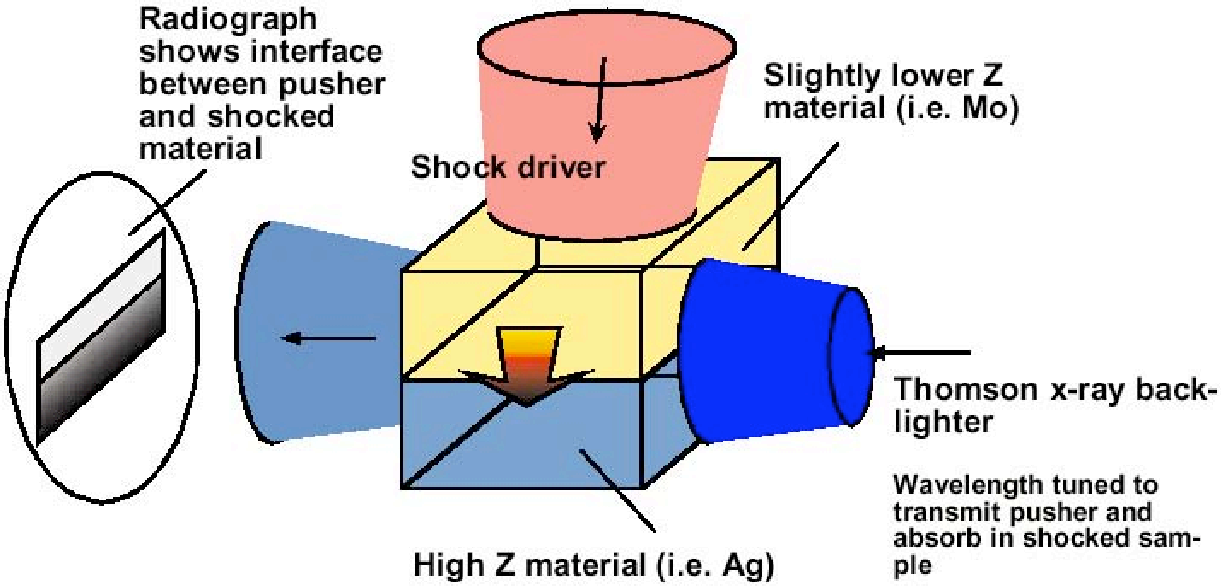
The luminosity problem

$$N_\gamma = \left[\frac{N_l N_{e-}}{4\pi\sigma_x^2}\right]\sigma_{th}$$

- Photon creation as in HEP colliders
- Very tight foci (σ_x^2) needed for both laser and e-beam
- Laser problems:
  - Large "emittance" ($\lambda/4\pi$),
    - short Rayleigh range (depth of focus)
    - Large angles (initial condition variation)
  - Final mirror damage; laser "exhaust" handling
  - Large N_l means high power, large field - nonlinear scattering
- Electron beam problems:
  - Achieving ultra-short beta-functions
  - Chromatic aberrations

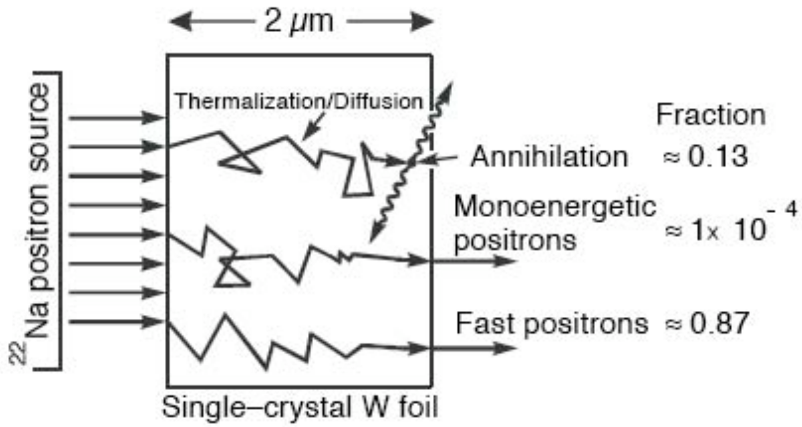
Shock physics

- Fundamental material studies for ICF, etc.
- Pump-probe systems with high power lasers
- EXAFS, Bragg, radiography in fsec time-scale.

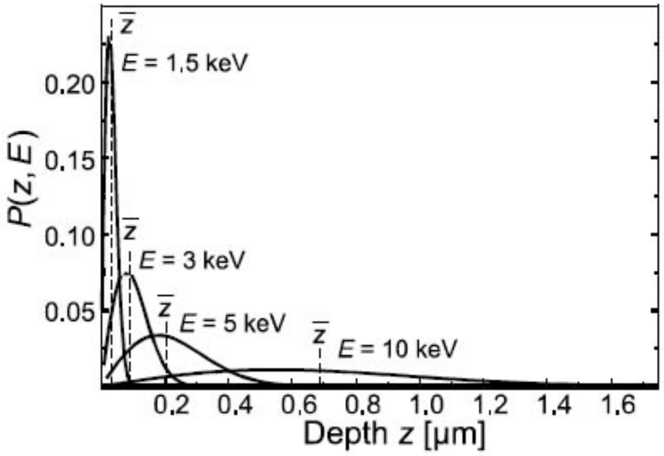


Pair Production

- Pair production for photon energies above threshold
- Moderate positrons
  - produce ultra-cold beam, or
  - Use directly for probing material defects
- Fast, intense sources
- Threshold is 260 MeV for SPARC (800 nm light)
  - Double the light=> 180 MeV



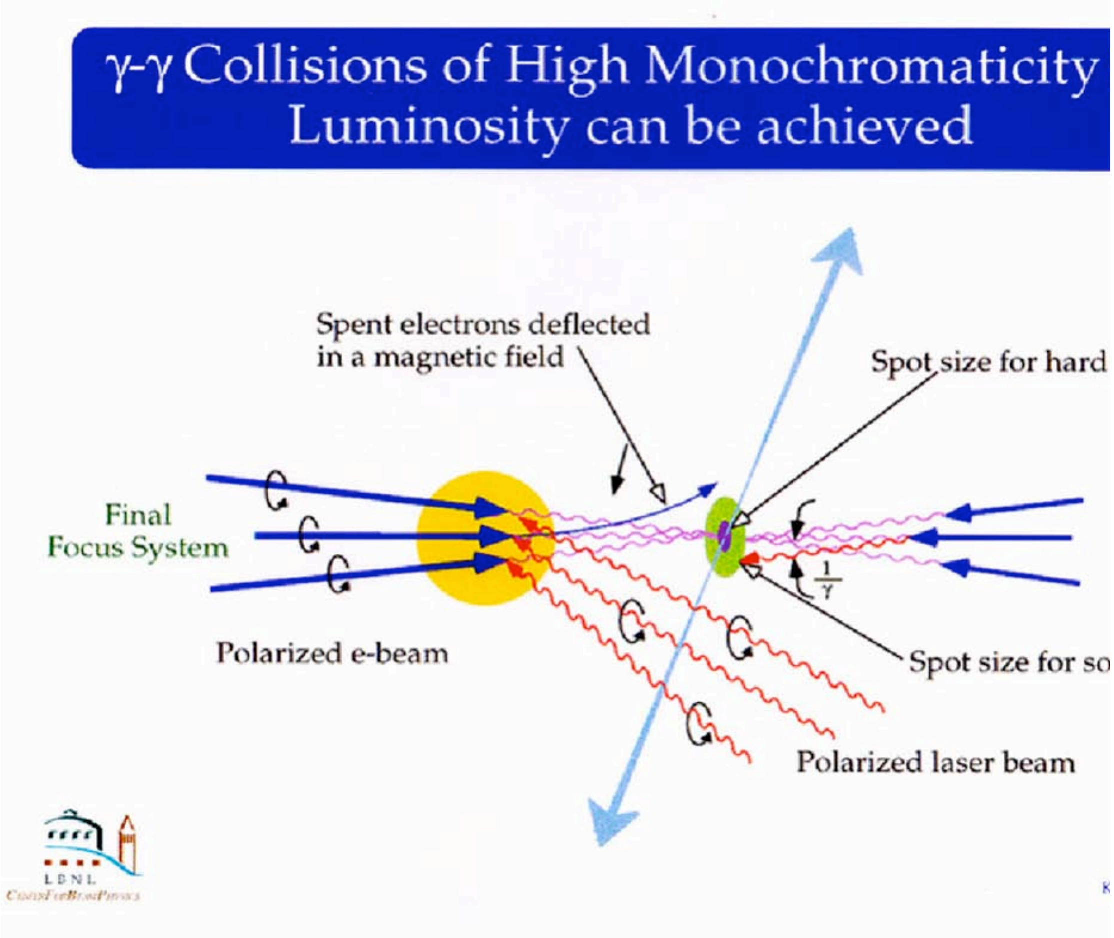
Positron moderation with standard source



Positron depth for defect profiling

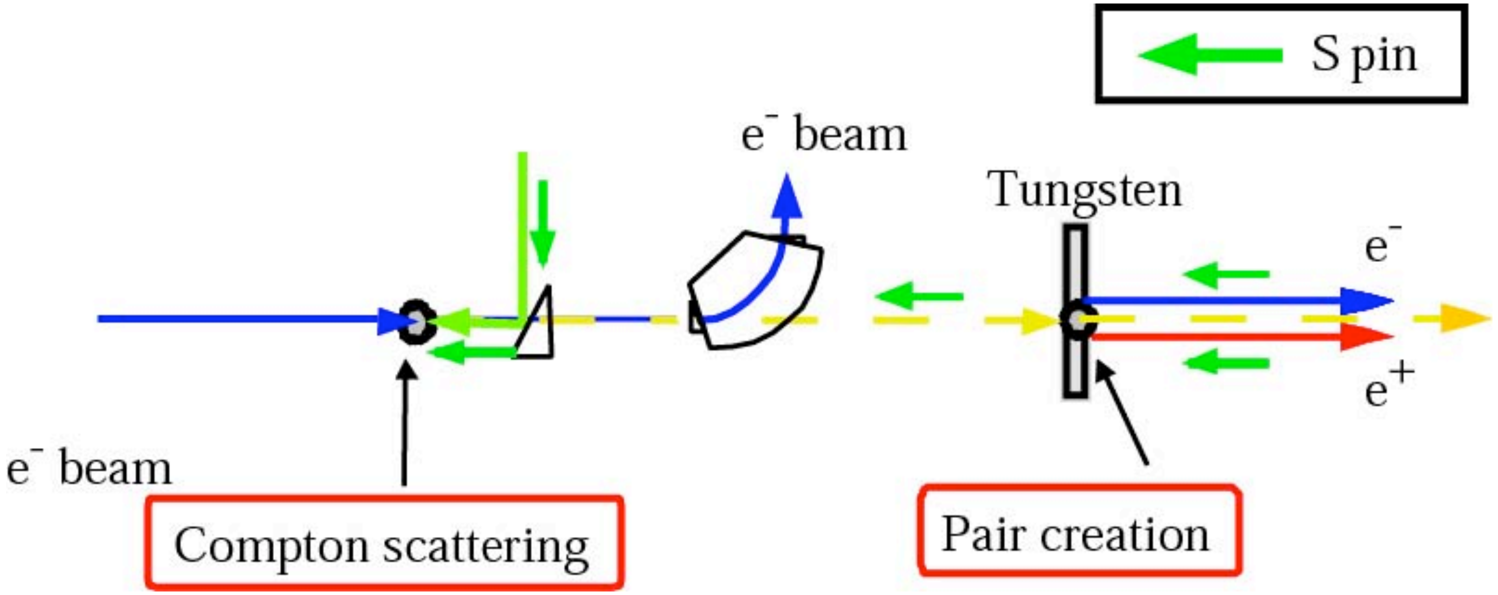
HEP 1: Gamma-Gamma collisions

- Start with an electron linear collider
- Collide the electron bunches with a laser pulse just before the IP to produce high energy photons (<u>100's GeV</u>)
- Requires:
  - Lasers
    - Pulses of 1J / 1ps @ 11,000 pulses / second
    - Helical polarization
  - Optics
    - Focus pulses inside the IR without interfering with the accelerator or detector



γ-γ Collisions of High Monochromaticity Luminosity can be achieved

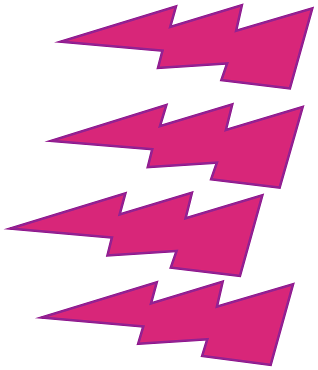
HEP 2: Polarized Positron Sourcery



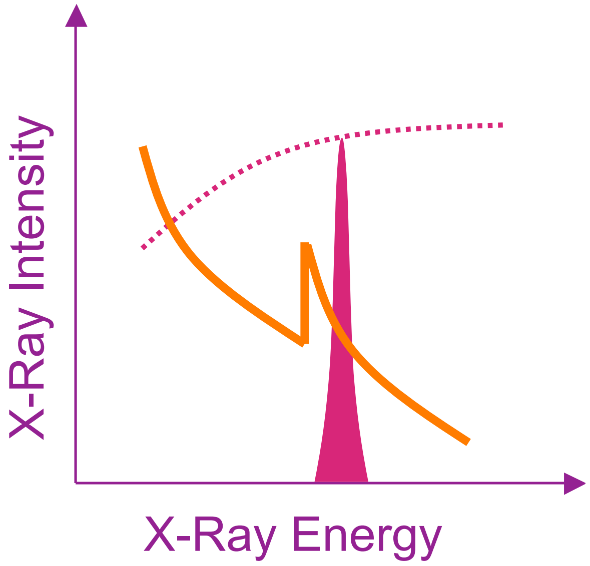
- Start with an 2-7 GeV electron linac (dependent on photon choice)
- Collide the electron bunches with a circularly polarized laser pulse to produce high energy photons (<u>100 MeV</u>)
- Convert gammas W target to obtain the positrons
- Requires:
  - Lasers
    - Pulses of 1J / 1ps @ 11,000 pulses / second

Medical uses :Monochromatic cancer therapy

Tagged Agents Imaged by Noninvasive X-Ray Absorption or Diffraction Spectroscopy



Intensity Increased to Deliver Localized Radiation Dose



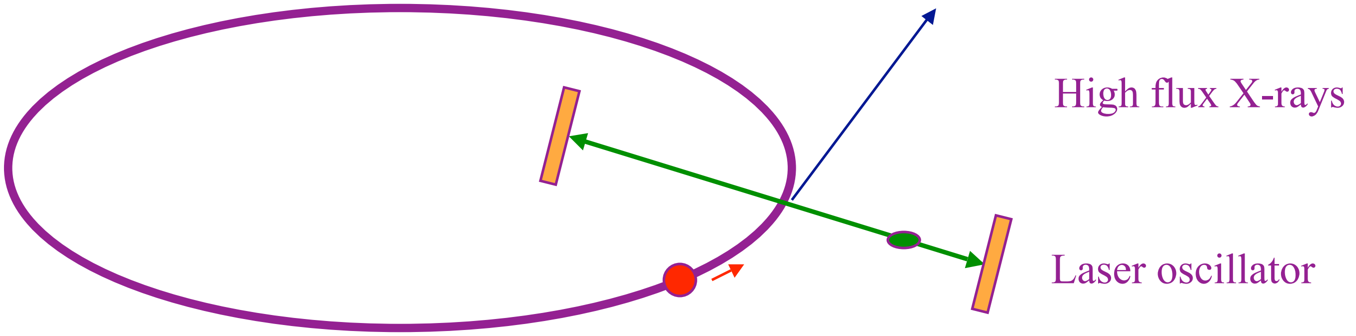
K-edge (~30 keV)

Also can use for dichromatic coronary angiography

Time structure is certainly not an advantage…

Storage ring-oscillator geometry

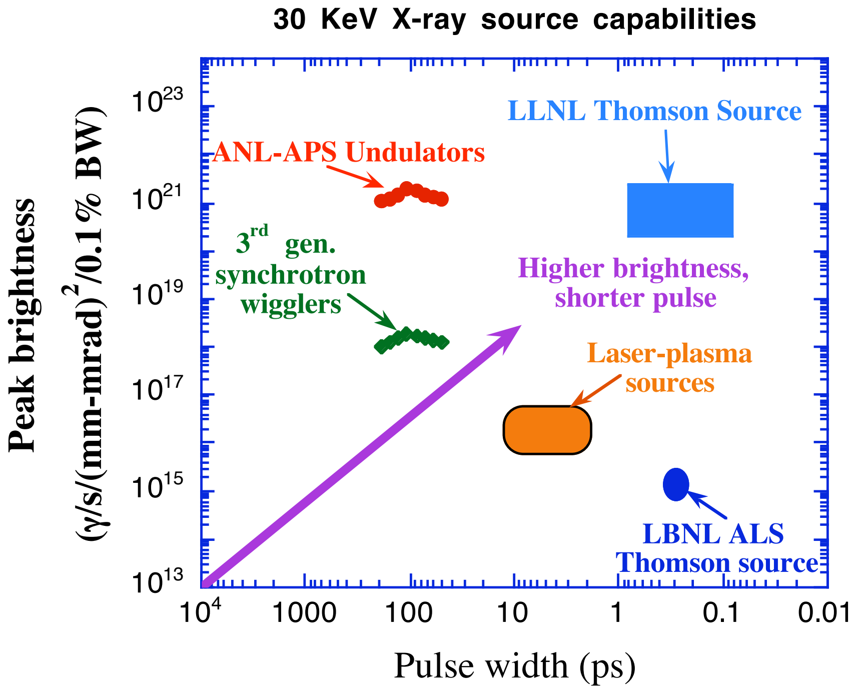
- Laser oscillator
- Compact 50-75 MeV storage ring
  - Poor lifetime
  - Radiation damping with *laser*
- Low peak flux (1000 photons/pass)
- ~100 MHz collision frequency: high average flux
- Private company initiative in Palo Alto



UCLA ICS activities

- PLEIADES at LLNL
  - Very mature experiment
  - Velocity bunching, ultra-short focal length PMQ FF
  - First physics: dynamic diffraction
- Neptune 10 micron experiment
  - nonlinear ICS, polarization
- Future activities
  - PEGASUS ICS for nanoscience
  - SPARC opportunities?
  - SLAC FFTB?

The PLEIADES source

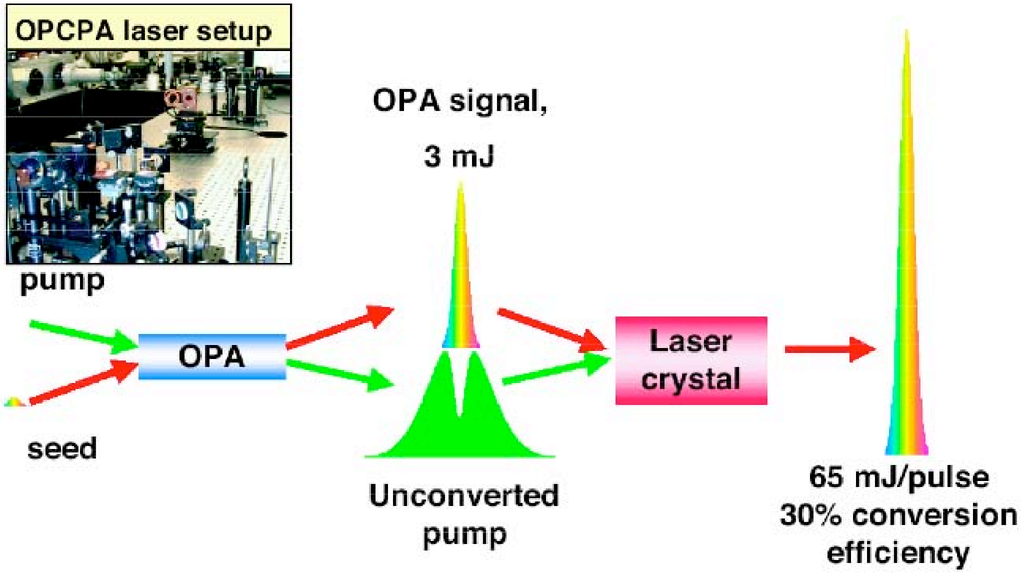


$$\lambda_{sc} = \frac{\lambda_l}{2\gamma^2(1-\beta\cos\psi)}\left[1+a_l^2+(\gamma\theta)^2\right]$$

Brightness limited by energy?

- **P**icosecond **L**aser-**E**lectron **I**nter**A**ction for **D**ynamic **E**valuation of **S**tructures
- Joint project: LLNL and UCLA
- High brightness photoinjector linac source
  - 1 nC, 1-10 ps, 35-100 MeV
- **FALCON** laser
  - 10 TW, >50 fs, 800 nm source
- Up to 1E9 x-ray photons per pu
  - Not yet…
- Photon energy tunable > 30 kV

The FALCON laser



OPCPA laser setup

pump

seed

OPA

OPA signal,

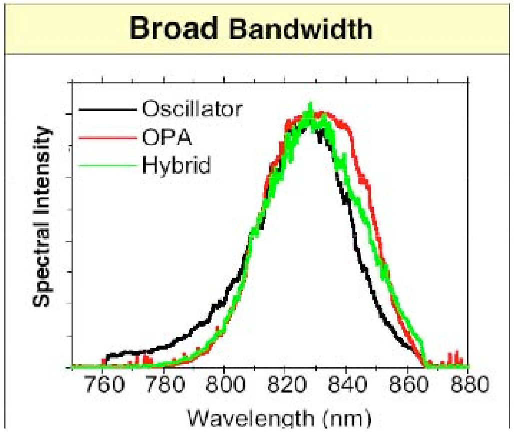
3 mJ

Unconverted pump

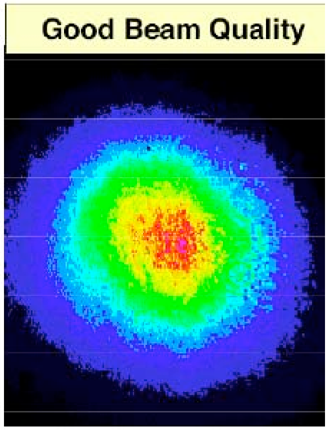
Laser crystal

65 mJ/pulse
30% conversion efficiency

LLNL advanced technology



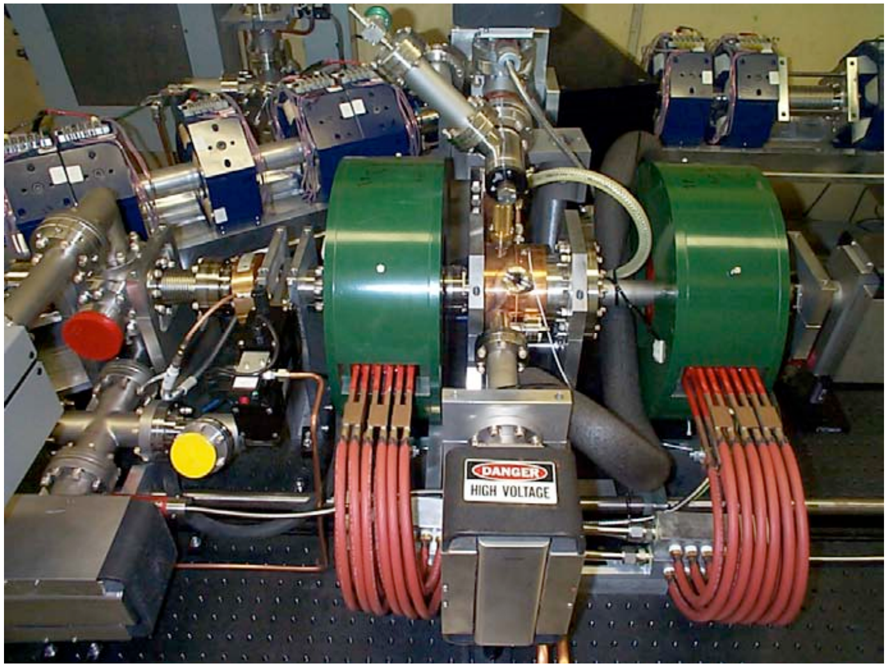
Broad Bandwidth



Good Beam Quality

RF Photoinjector and beamline

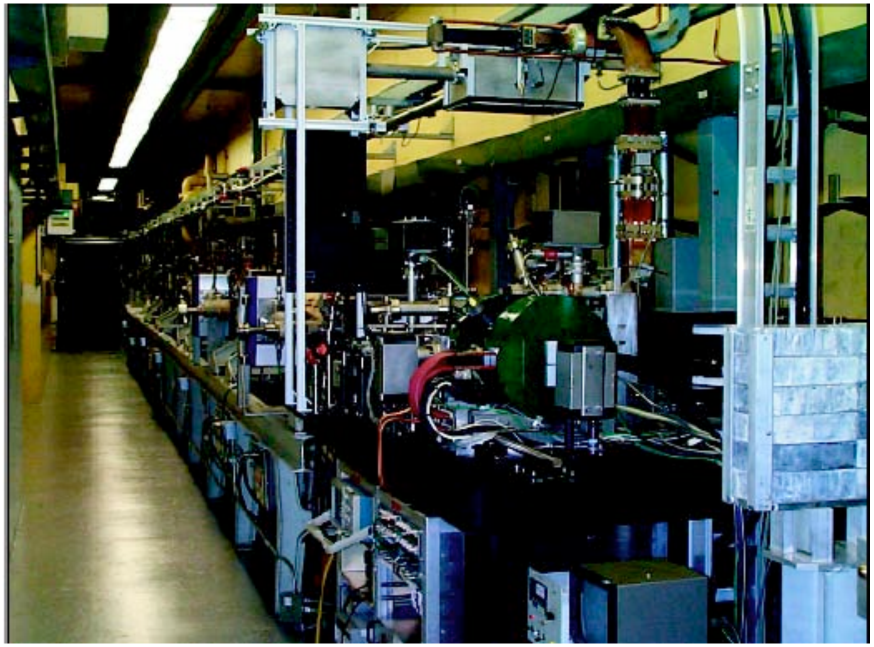
- UCLA responsibility
- 1.6 cell high field S-band (a la SPARC)
  - 2854.5 MHz(?!)
  - Run up to 5.2 MeV
- All magnets from UCLA
  - Solenoids
  - Bypass quads/dipoles
  - Final focus
    - High field electromagnets
    - PMQ system!



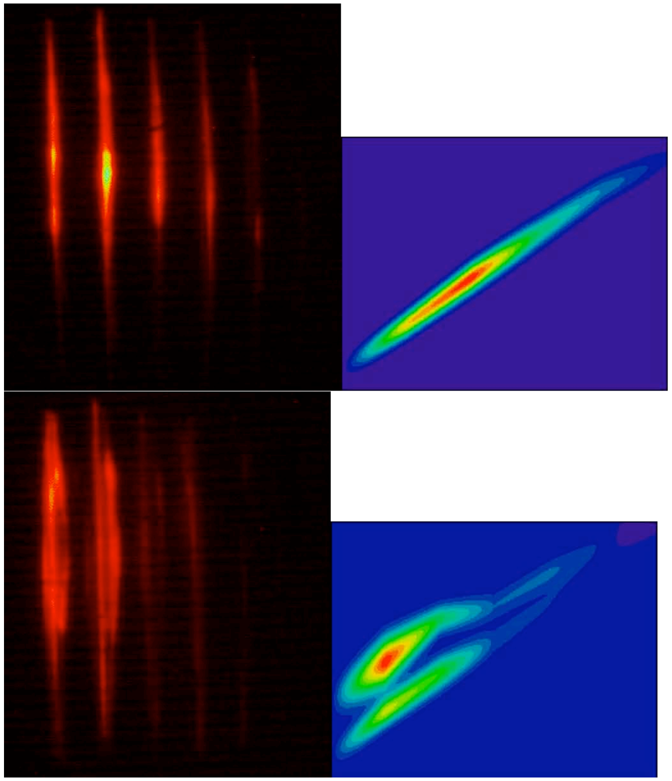
Photoinjector and bypasss

Electron linac

- 35 year old 120 MeV travelling wave linac
- 4 linac sections
  - *Adjustable phases for velocity bunching*
- Solenoid focusing around each section



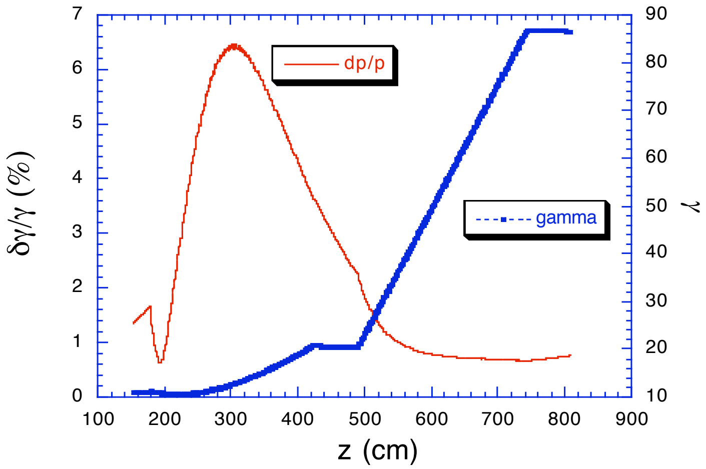
Velocity bunching for shorter pulses…

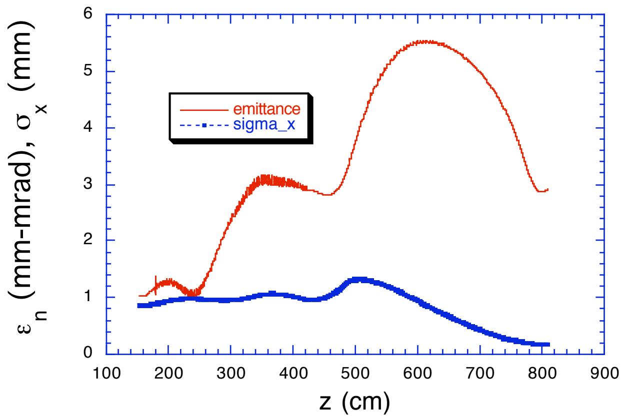


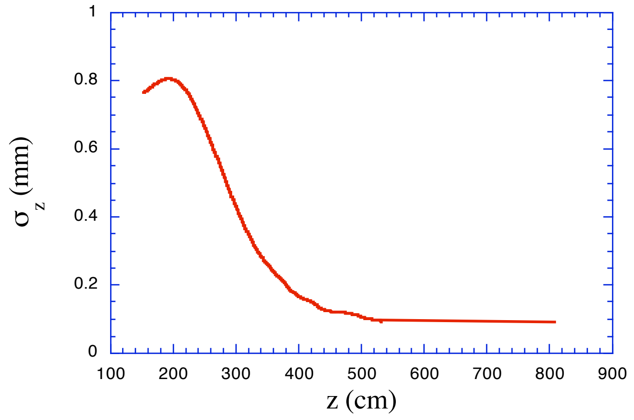
Multi-slit phase space measurement at Neptune showing bifurcation in chicane

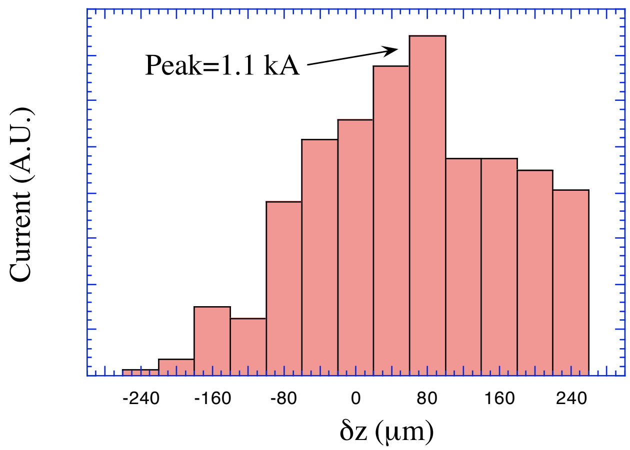
- Enhanced photon brightness
- Avoid problems of magnet chicane bunching
- Emittance control *during bunching* using solenoids around linacs
- Bunching effectively at lower energy
  - Lower final energy spread
  - Better final focus… still have chromatic aberrations!

PARMELA simulations of velocity bunching



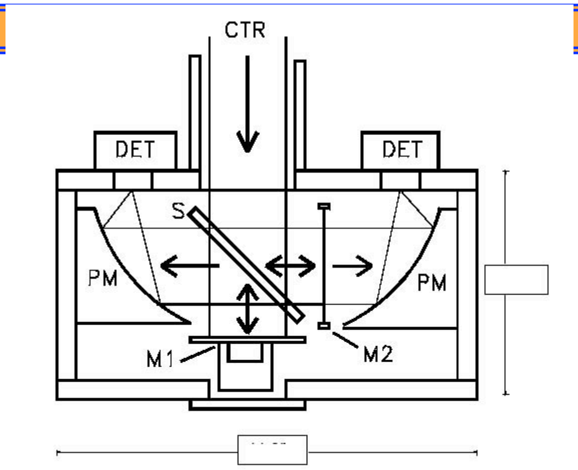


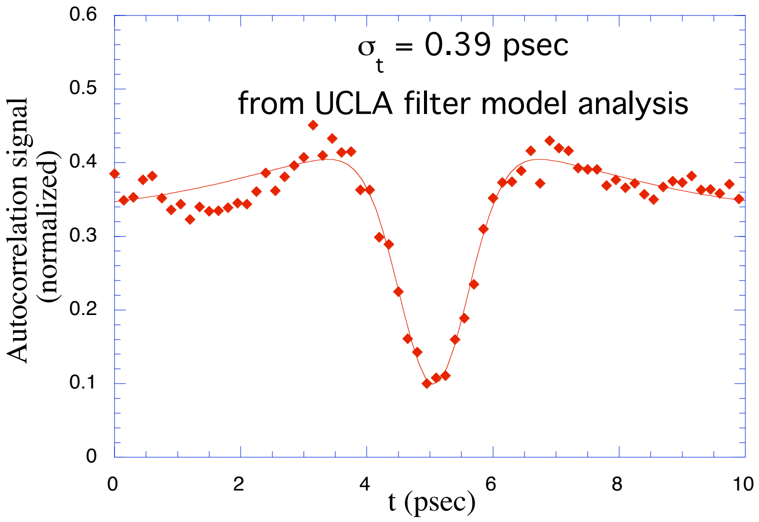




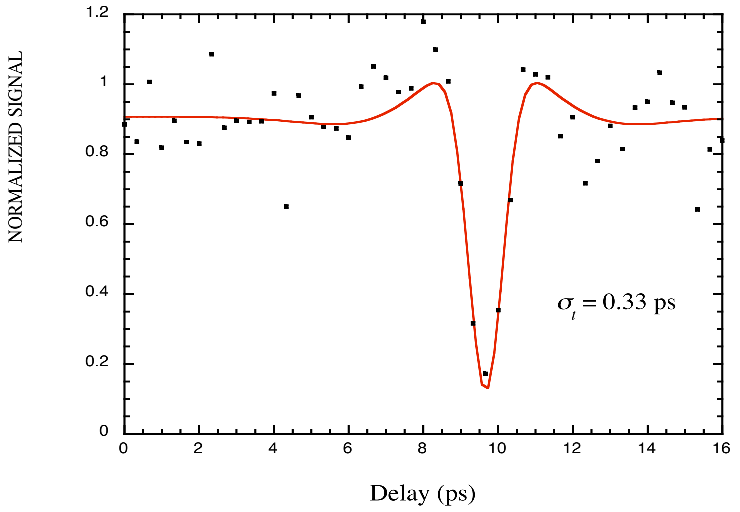
Velocity bunching measurements

- Over factor of 15 bunching shown in CTR measurements
- Better than Neptune “thin-lens” performance
- Next measurements: emittance control



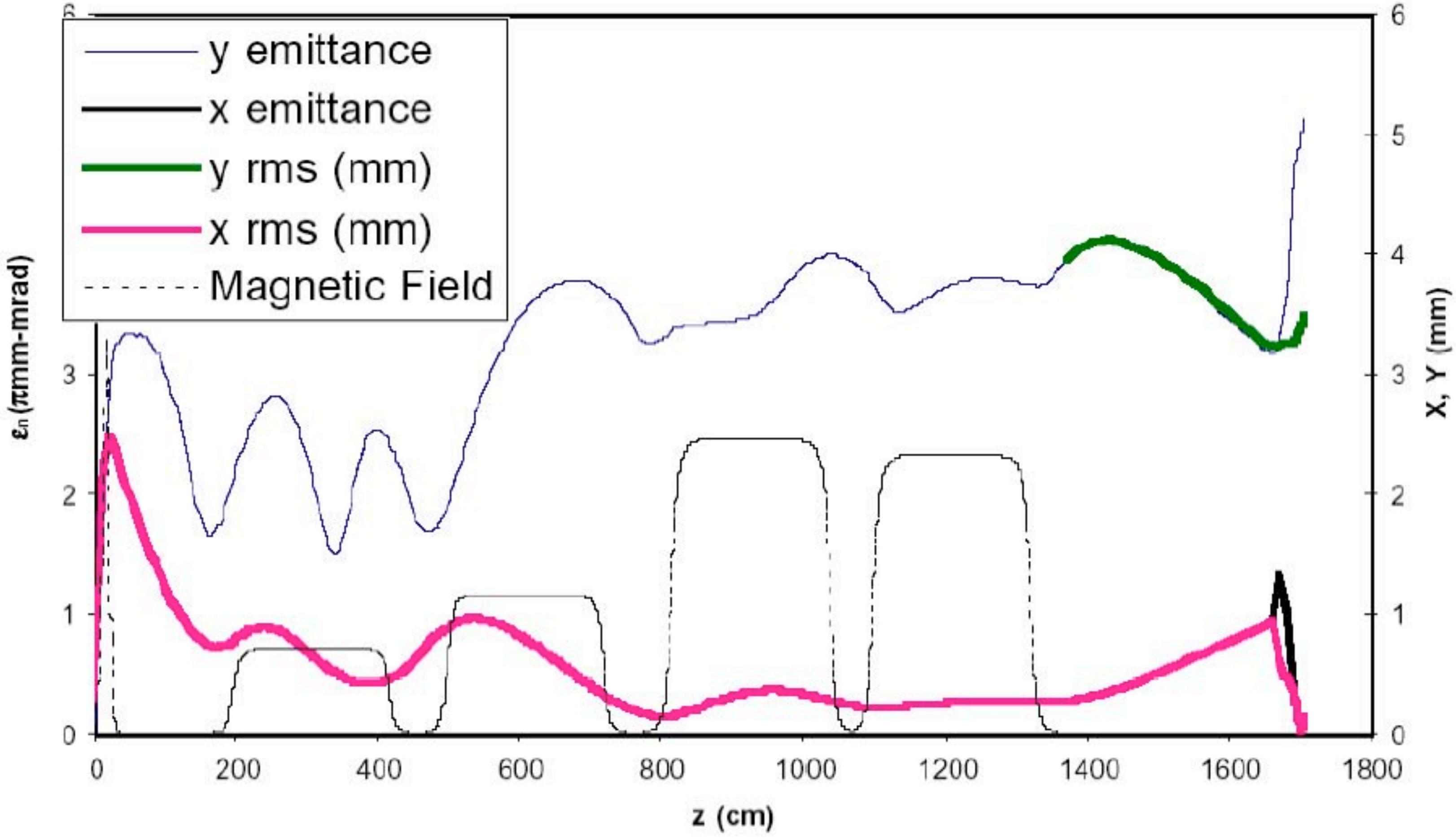


Neptune measurements (PWT “thin lens”, no post acceleration)



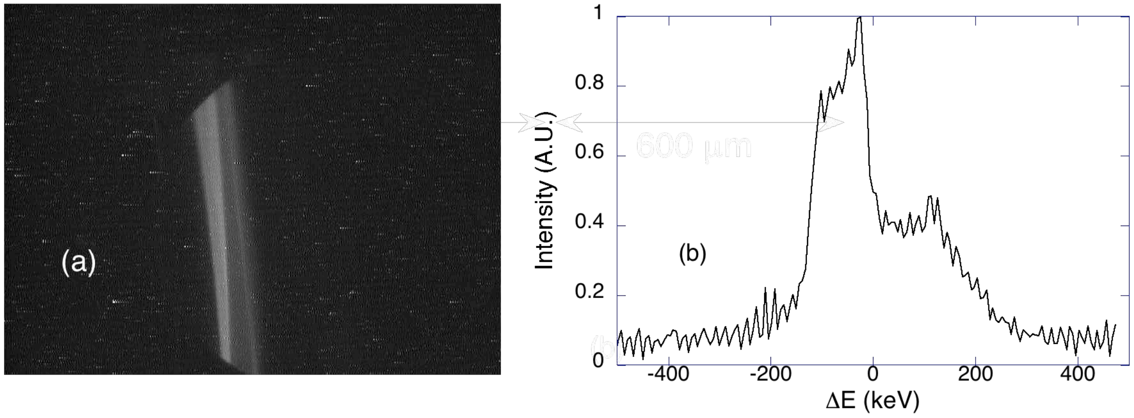
Recent measurement of velocity bunching at LLNL PLEIADES

Start-to-end simulations with final focus…

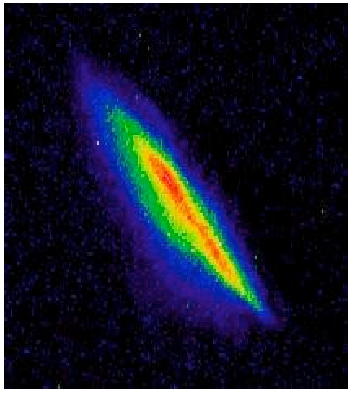


How did it really work?

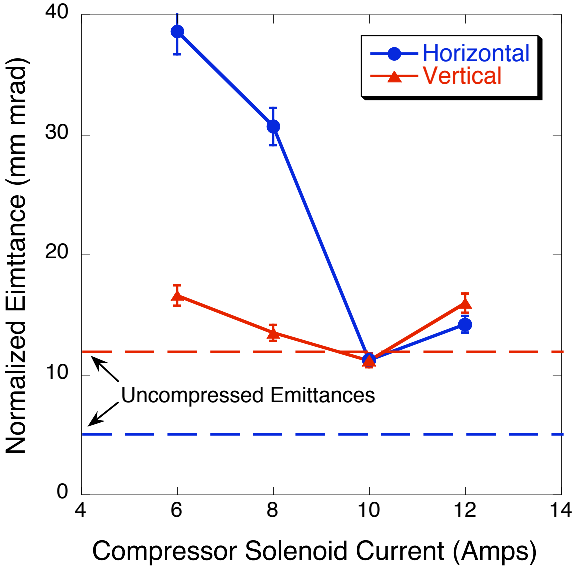
ICS Collisions with velocity bunching: beam quality



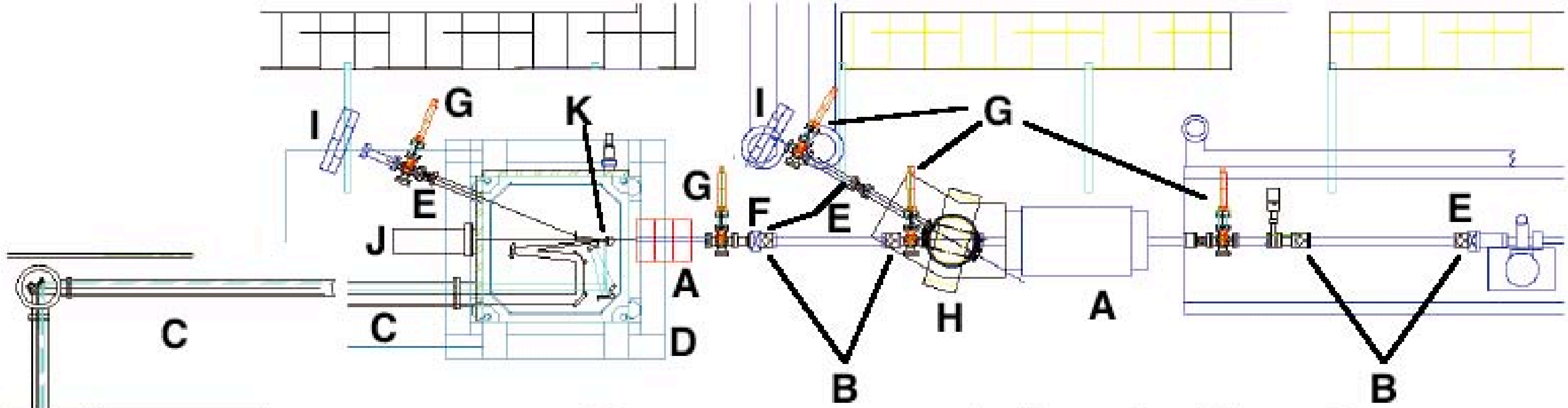
0.5% energy spread

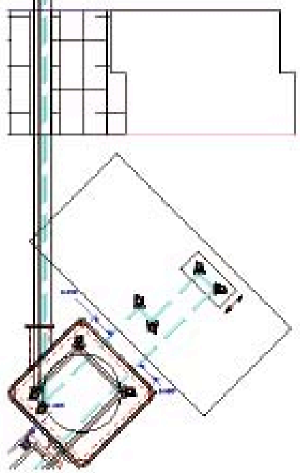


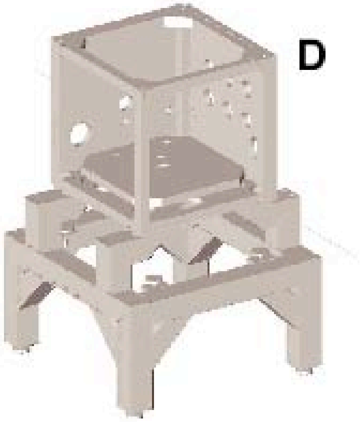
Transverse emittance compensation limited by x-y correlations



Interaction region

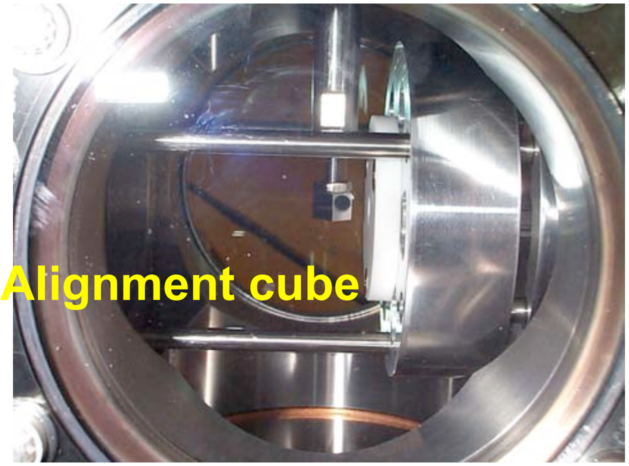


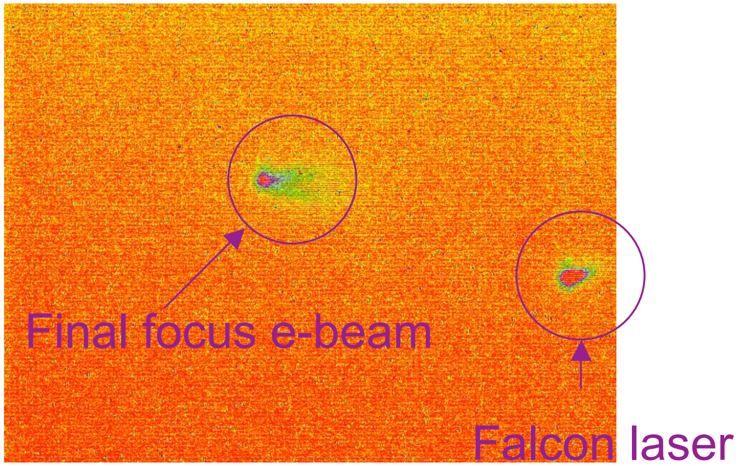




A	Focusing Magnets
B	Steering Magnets
C	Laser Transport
D	Interaction Chamber
E	Beam Current Monitors
F	Beam Position Monitors
G	Pop-Ins
H	Electric Dipole
I	e-Beam Dumps
J	X-ray CCD
K	OTR foil
L	Bend Magnets

Timing and alignment

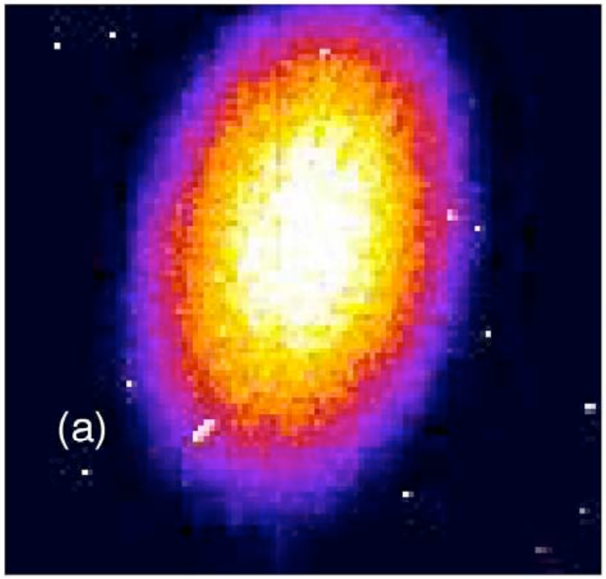




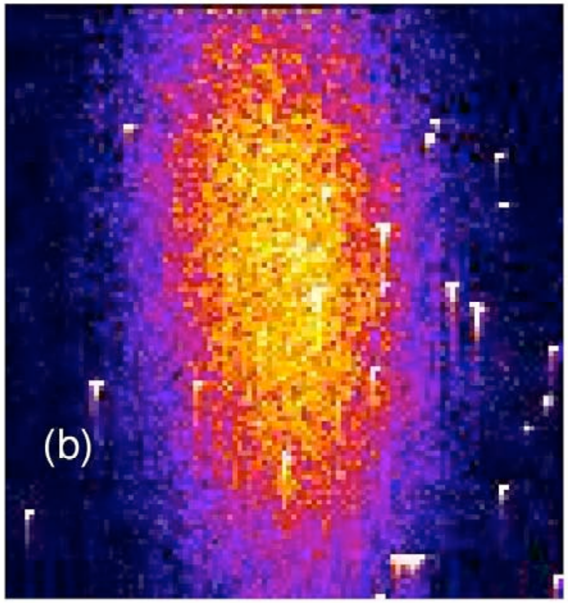
- Polished aluminum cube gives *<u>for laser and e-beam</u>*
  - Spatial alignment (CCD): few micron
  - Timing (streak camera): 1 ps

Photon production

- W/O velocity bunching: 5E6 photons/pulse
- With velocity bunching: 1.2E6 photons/pulse
- Increase brightness by factor of >4!



W/O VB



W/VB

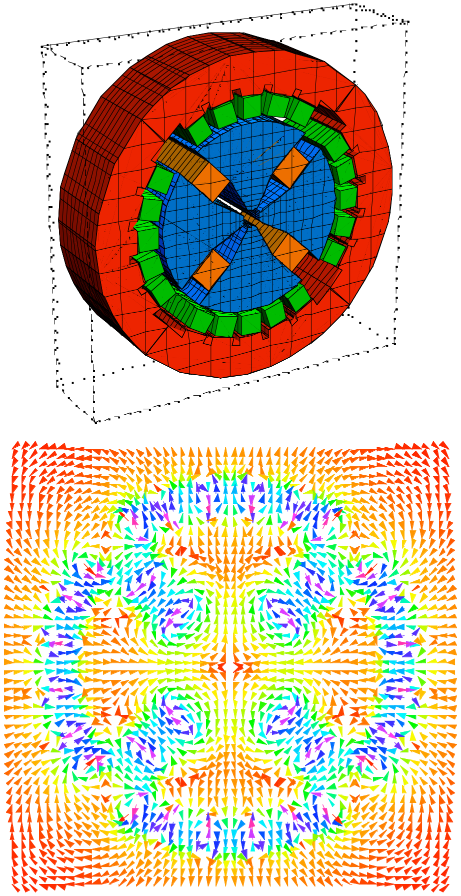
The problem of the final focus

- Luminosity demands small beams
- Compression gives large energy spread
  - Chromatic aberrations
  - Demagnification limit
  - Cannot remove chromatic aberrations with sextupoles, etc. Transport too long, costly…

$$\frac{\sigma^*}{\sigma_0} = \sqrt{\frac{1+\left(\frac{\beta_0}{f}\right)^2\left(\frac{2\sigma_{\delta p}}{p}\right)^2}{1+\left(\frac{\beta_0}{f}\right)^2\left[1+\left(\frac{2\sigma_{\delta p}}{p}\right)^2\right]}} \underset{\left\{\frac{\beta_0}{f} >> \frac{p}{\sigma_{\delta p}}\right\}}{\cong} \frac{2\sigma_{\delta p}}{p}$$

- Quadrupole strength problem
  - Cannot expand beam; space-charge “decompensation” (also with sextupoles)
  - Solution: permanent magnet quadrupoles

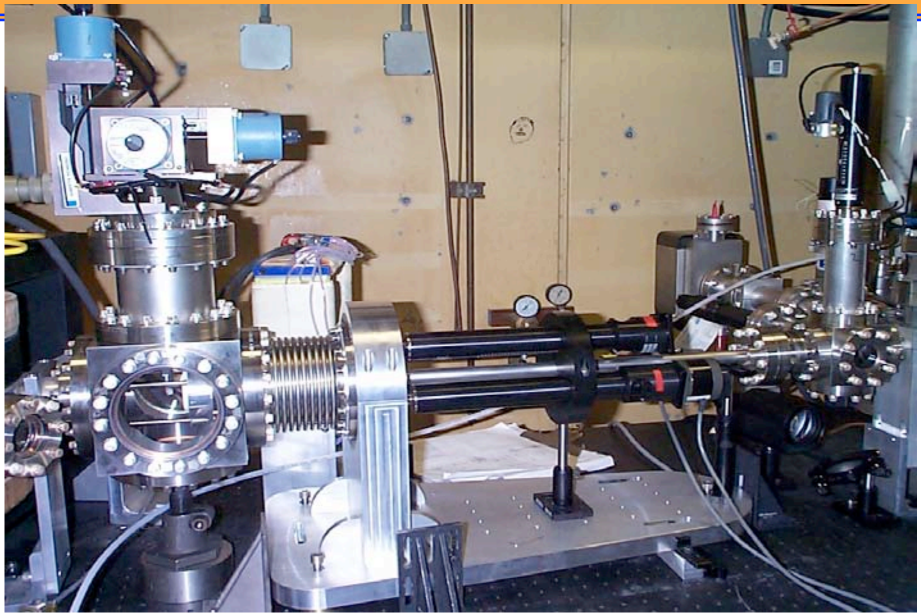
Permanent magnet quadrupoles



Halbach ring-tuned quad for NLC (UCLA/FNAL/SLAC project), with field map

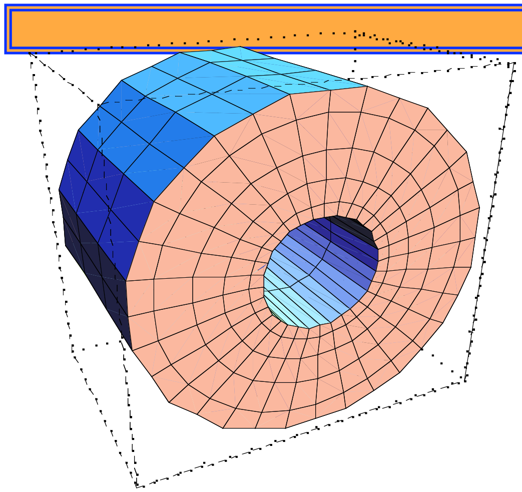
- PMQs stronger than EMQs
  - >600 T/m v. <25 T/m
- PMQs are quite difficult to tune
  - Need to tune system from 35 to 100 MeV!
  - Tradeoffs between tunability, strength, centerline stability
- We decided to *not adjust strength* of PMQs… only *change longitudinal position*

UCLA PMQ Final Focus System



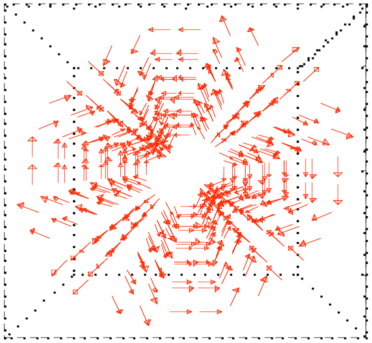
- Tunable through longitudinal positioning (like camera optics)
- FODO lattice configuration
- High precision stepper motor linear actuators
- Beam pipe through the center axis of the final focus system

PMQ Simulation (600T/m)

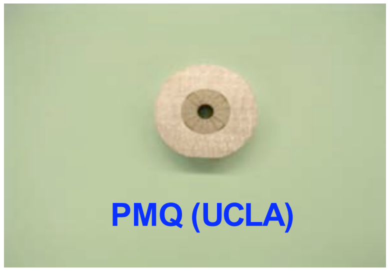


10mm in length, 2.5mm in bore radius, 7.5mm in outer radius

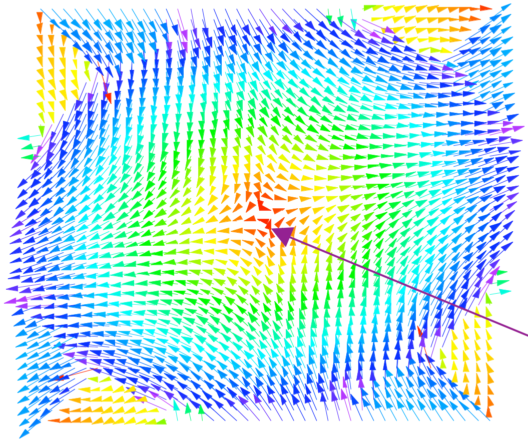
- Magnetic remnant field: 1.2T
- Permanent magnet material: NdFeB
- Expected magnetic field gradient:570T/m



The magnetic easy-axis direction in each magnet block 22.5°

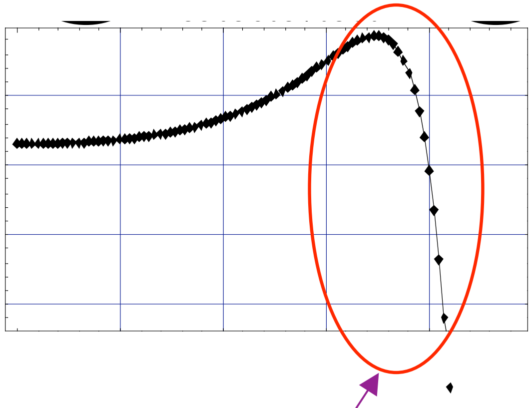


x40 improvement over 15T/m EMQ



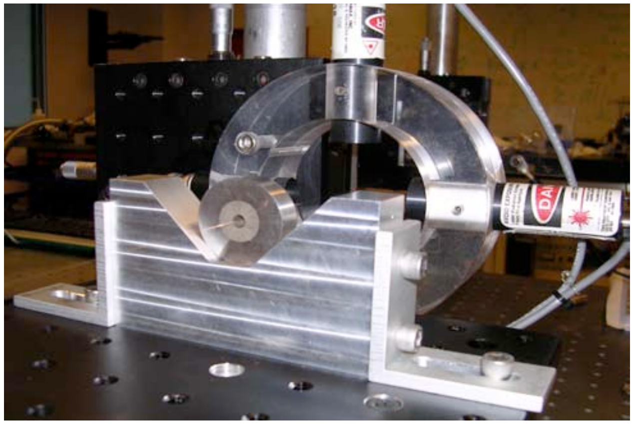
Magnetic center

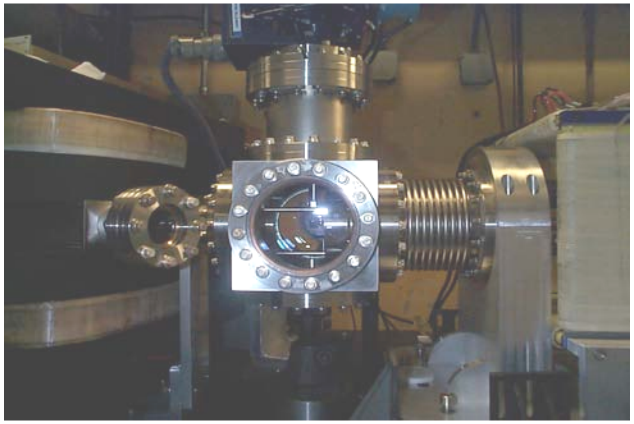
2D representation of magnetic fields



B-field near bore surface

Final Focus System Project Stage





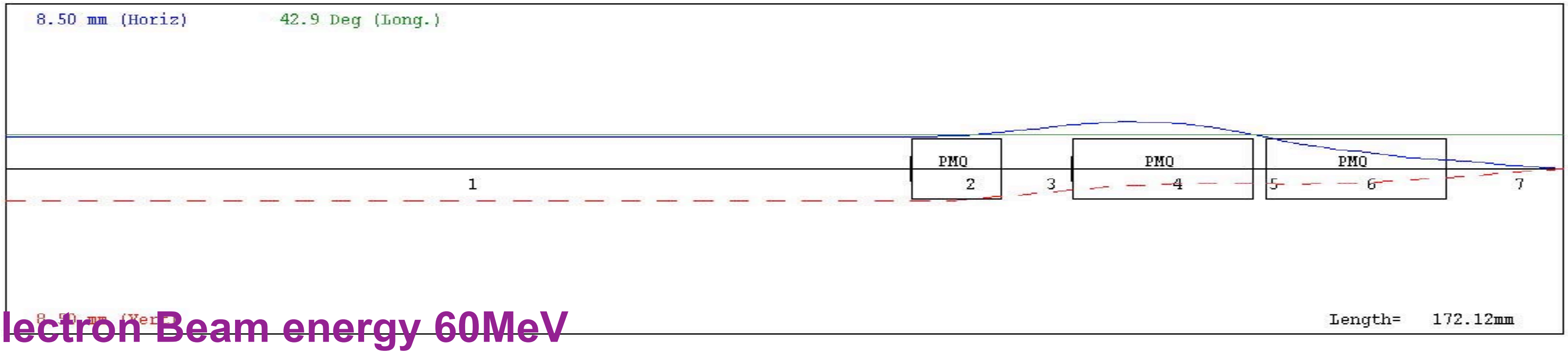
- Extremely challenging engineering
- 16-piece Halbach PMQ designed at UCLA & manufactured at a local magnet vendor
- PMQ magnetic properties measured with both Hall sensor (field gradient) & pulsed-wire technique (center alignment & linearity)
- Mover system designed to meet with LLNL experimental set-up criteria
- The system assembled & installed in the facility in December, 03
- Motion-VI control software enabling live-time control remotely in the linac control room

Beam Transport Simulation

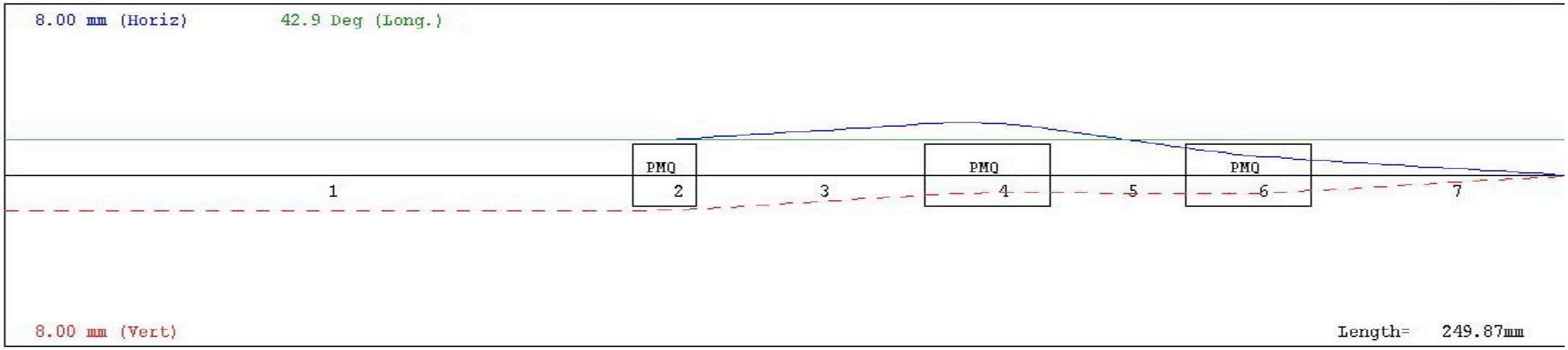
Electron Beam energy 30MeV

TUNABILITY of PMQ final focus system

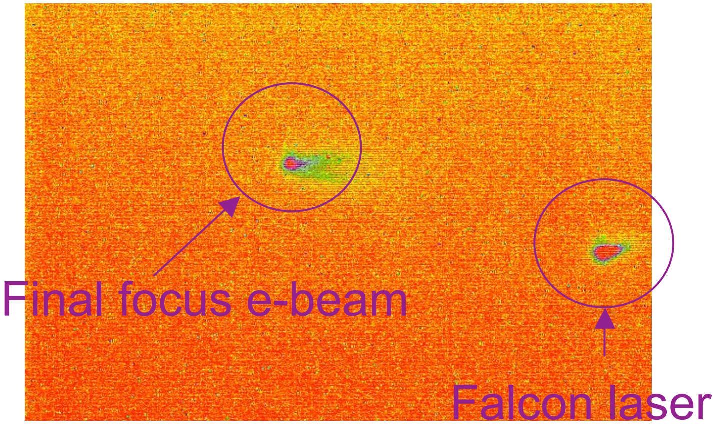
β_x~1 mm, σ_x ~10μm spot size

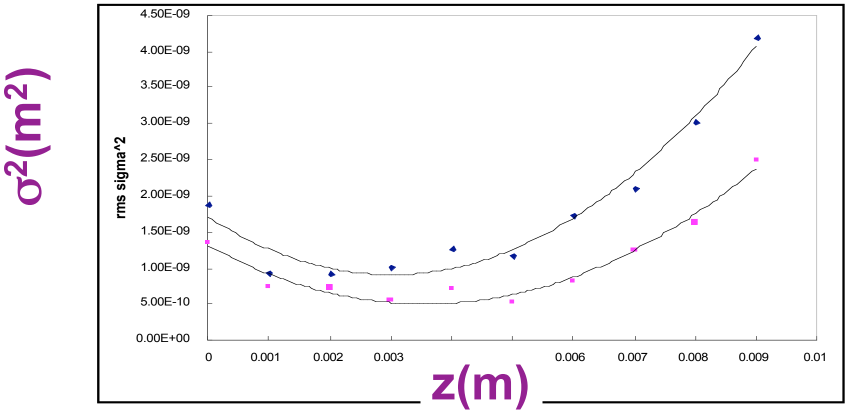


Electron Beam energy 60MeV



Beam Measurements

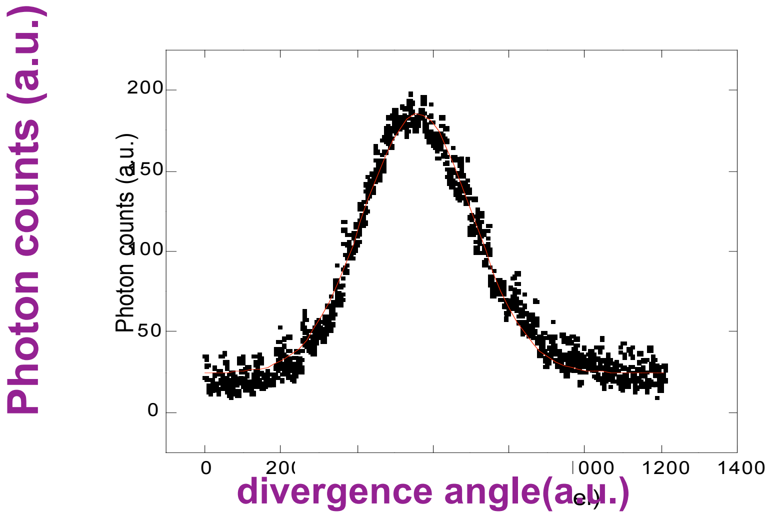


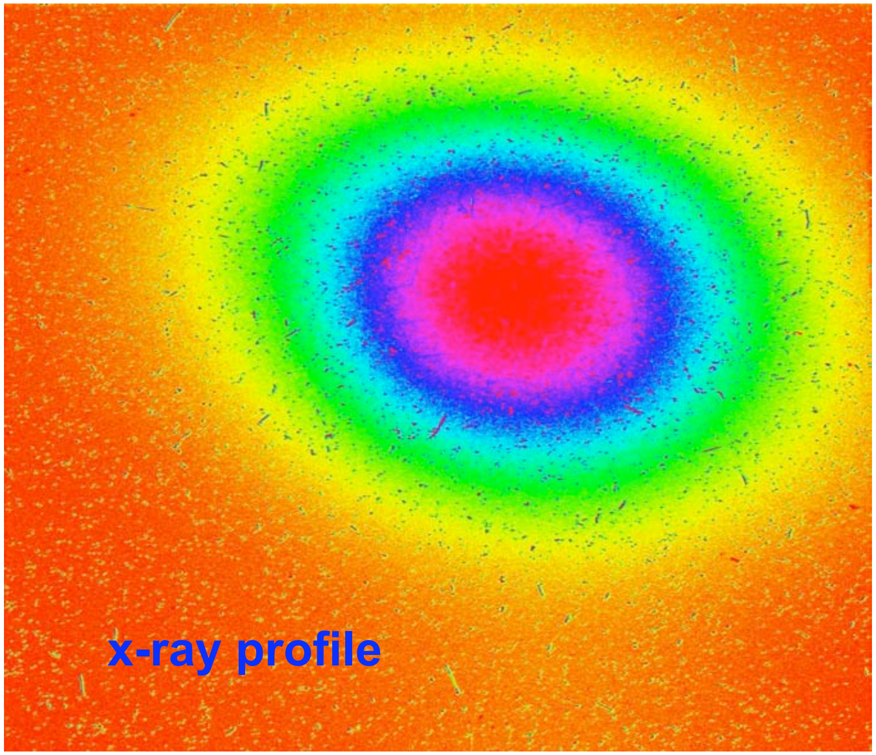


- CCD used to obtain beam images at alignment cube
- $E_{electron}$=74.1MeV,Q=300pC, $\varepsilon_{x,y}$=(9.24,10.9)mm-mrad, $\beta_{x,y}$=(3.69,5.16)mm/mrad
- $\sigma_{rms} \approx 15 \times 20\ \mu m$ electron beam spot size obtained at I.P. for 59-79MeV
- Quad scan performed with PMQ → larger emittance measured: 25-30 mm-mrad
- Minimum spots 18x18 micron

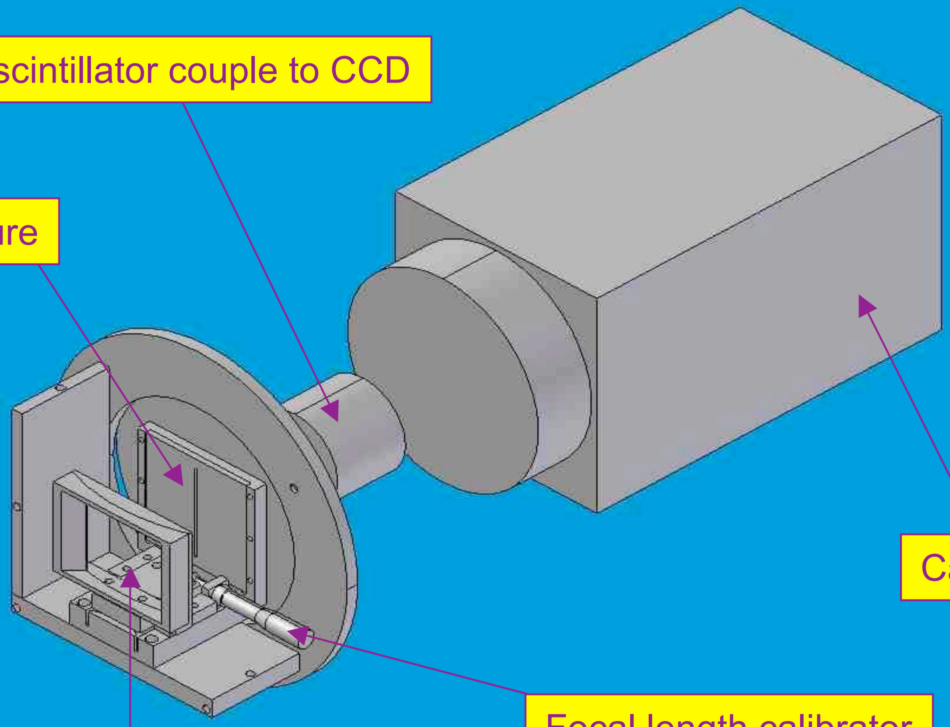
Inverse Compton X-rays with PMQ Final Focus

4.4 x 10^6 photons (75 keV peak)
ps pulse duration





Transmission X-ray Spectrometer

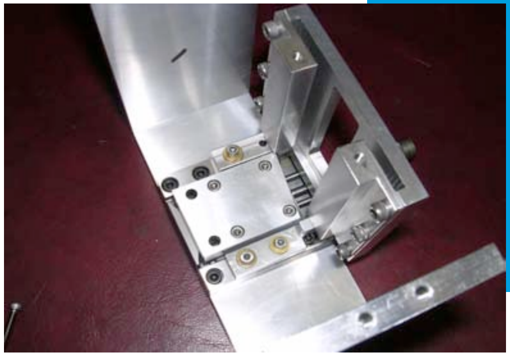

CsI scintillator couple to CCD

Slit aperture

Camera electronics

Focal length calibrator

LiF bent crystal



ICS Positron Source Physics Issues

- Need high Compton luminosity
- Need very small electron/laser beams
- Need very high charge/laser energy
- Polarization has strong angular dependence
- Polarization dictates avoiding harmonics

$$\lambda_\gamma \cong \frac{n\lambda_L}{4\gamma^2} \cdot \left[1 + \frac{K_L^2}{2} + \right.$$

  - Laser vector potential must be limited

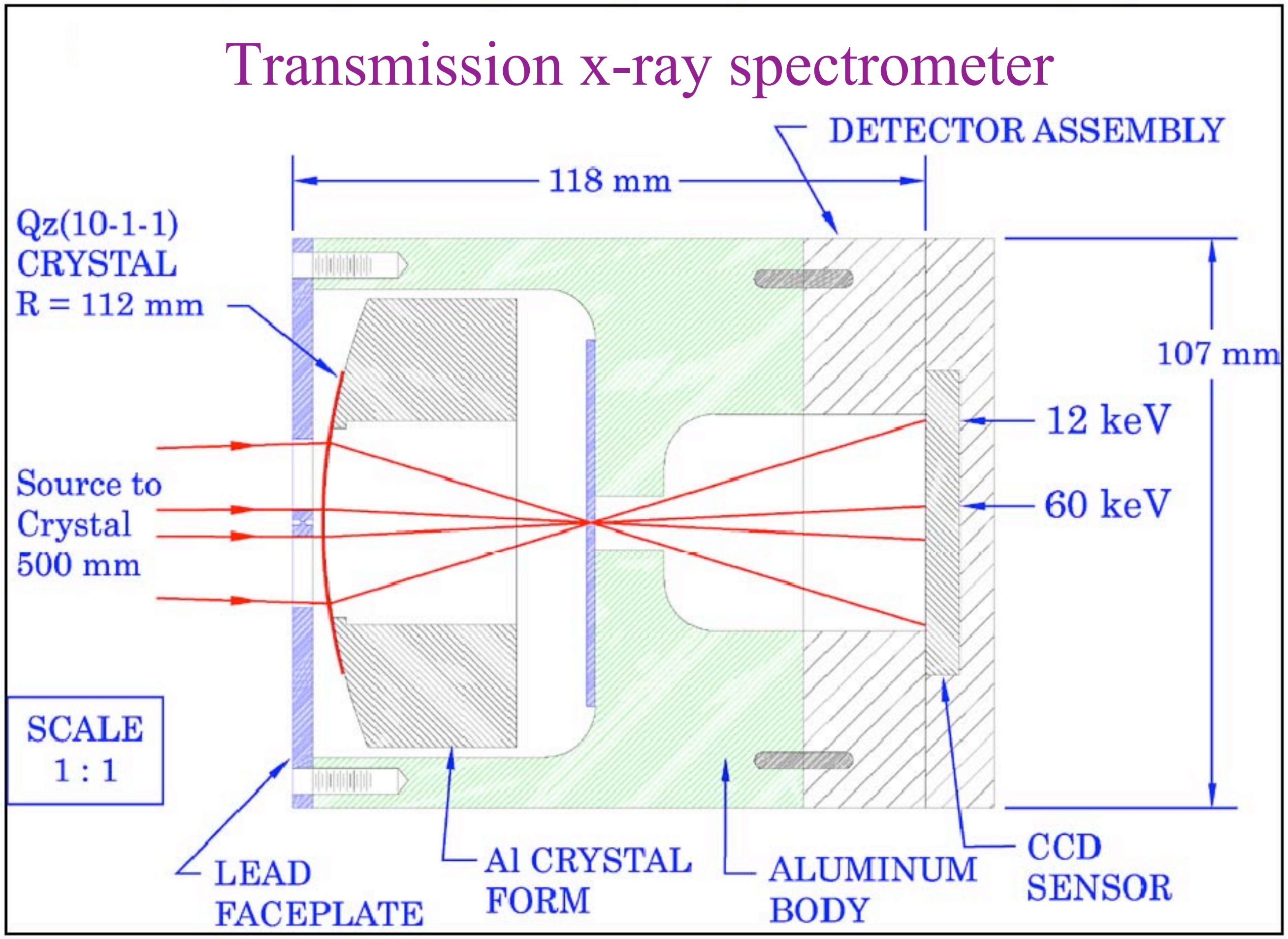
$$a_L \equiv eE_L / k_L m_e c^2 < 0.2$$

  - Do NOT use long λ (10 mm)
  - USE long λ for nonlinear physics

$$N_\gamma \propto U_L N_{\gamma,L} \propto E_L^2 \lambda_L$$

$$\propto (a_L / \lambda_L)^2 \lambda_L \propto \lambda_L^{-1}$$

Spectrometer for nonlinear ICS…

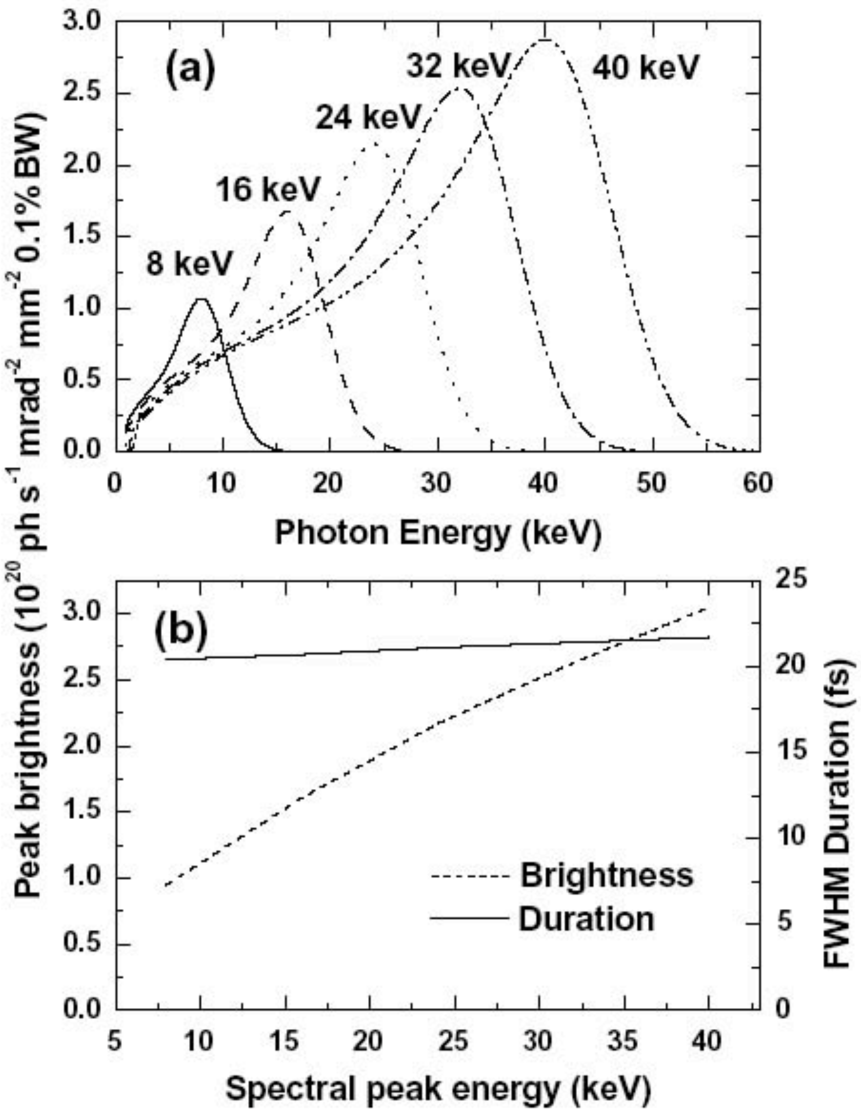


-Transmission spectrometer

-Aiming also for LCLS work

New directions: SAICS

- Need higher brightness with short pulse length
- Specific problem SPARC is at too high energy
- Small Angle Inverse Compton Scattering
- Small angle gives
  - Lower photon energy with high energy e-beam; small angle x-rays!
  - Luminosity challenges, but *higher brightness*
  - fs pulse lengths
  - Larger spectral width



Example for SPARC

- "Medical" photons (33 keV)
- Moderate energy is excellent regime

Input:

Beam $U_{e-} = 200 \text{ MeV}$ $\beta_{e-} = 5 \text{ mm}$ $\varepsilon_n = 2 \text{ mm-mrad}$ $\sigma_t = 0.5 \text{ ps}$

Laser $\lambda_L = 800 \text{ nm}$ $U_L = 1 \text{ J}$ $\tau_L = 100 \text{ fs}$ $Z_r = 0.4 \text{ mm}$

Crossing angle $\boxed{\phi = 21.5 \text{ deg}}$ (not that small…)

Output $\tau_{sc} = 106 \text{ fs}$ $N_{sc} = 7 \times 10^7$ $\left(dE/E\right)_{sc} = 3.4$

Very high brightness at this energy!