Production of femtosecond pulses and micron beam spots for high brightness electron beam applications

Scott G. Anderson[*], D. J. Gibson, F. V. Hartemann,
J. S. Jacob, A. M. Tremaine — LLNL

J. K. Lim, P. Frigola, J. B. Rosenzweig, G. Travish
— UCLA

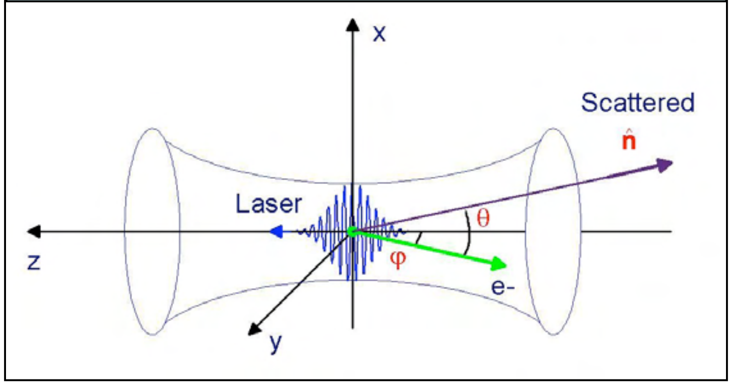
This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48, and by the University of California, Los Angeles under contract numbers DE-FG-98ER45693 and DE-FG03-92ER40693

[*]e-mail: anderson131@llnl.gov

Advanced applications require high-brightness, *dense* beams

Scaling of applications to higher performance requires shorter bunch dimensions; examples: advanced accelerators, next generation light sources.

Collision of ultra-relativistic electron with focused laser pulse



Hard x-rays (10-80 keV) use only moderate energies:

$$\lambda_w \approx 0.8\ \mu\text{m}, \quad \frac{hc}{e\lambda_w} \approx 1.55\ \text{eV}, \quad \gamma m_e c^2 \approx 20 - 60\ \text{MeV}$$

Performance depends on intensities of overlapping beams:

Flux: $$\frac{dN_x}{dt}(t) = \sigma c[1 - \beta \cdot \mathbf{k}] \iiint n_\gamma(\mathbf{x},t) n_e(\mathbf{x},t)\, d^3\mathbf{x}$$

Total dose: $$N_x = \frac{\sqrt{2} N_e N_\gamma \sigma}{\pi(2r_b^2 + w_0^2)}$$

Source brightness: $$B_x = \frac{N_x}{(2\pi)^{5/2}\, \sigma_\tau \underbrace{\sigma_x^2 \sigma_{x'}^2}_{\varepsilon_{geom}^2} (.1\%\text{BW})}$$

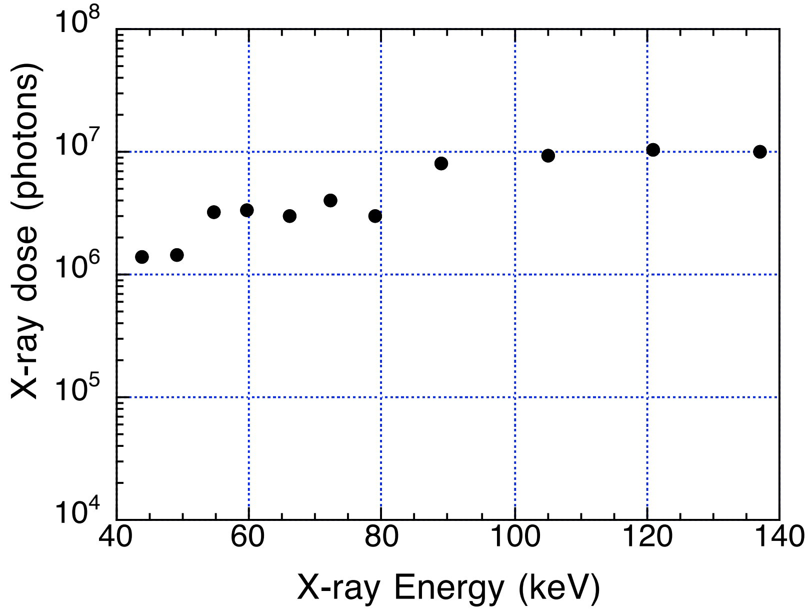
X-ray applications need bright beams with short β-functions and sub-ps duration.

The PLEIADES x-ray source uses velocity bunching and PMQ focusing

- LLNL-UCLA collaboration
- Tunable, bright, ICS hard x-ray source
- 1.6 cell S-band photo-gun + 4 × 2.5 m SLAC sections gives 20-80 MeV, 250 pC, 3 ps (rms), 10 mm-mrad
- 800 nm, 250 mJ, 50 fsec, Ti:Sapphire laser

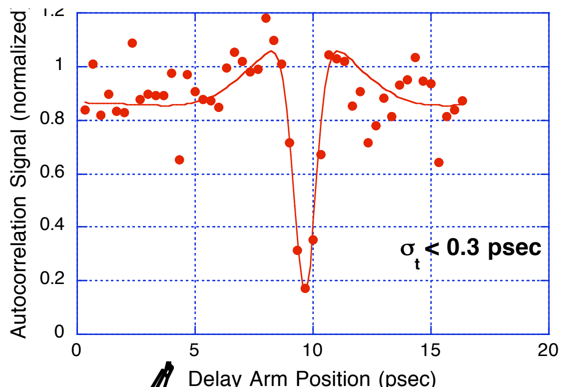
- Compress ps photo-beam using velocity bunching
- Use ultra-strong permanent magnet focusing at ICS interaction point

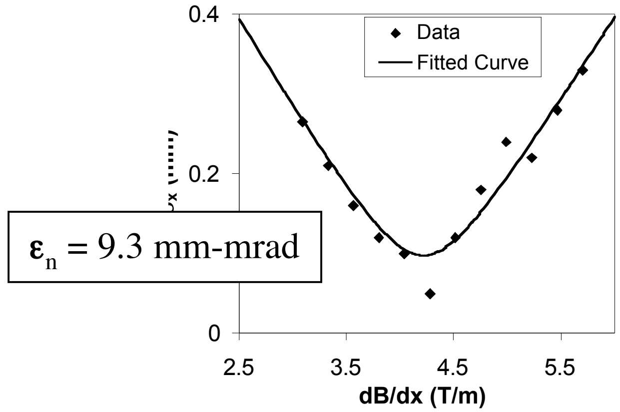
Measured x-ray flux vs. energy

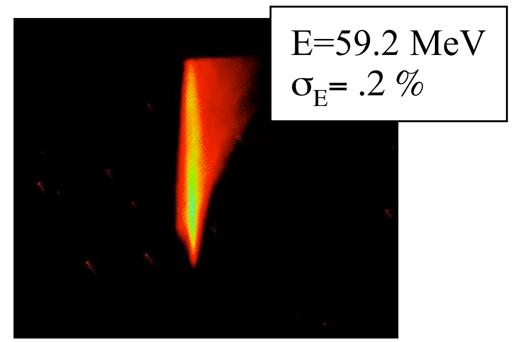


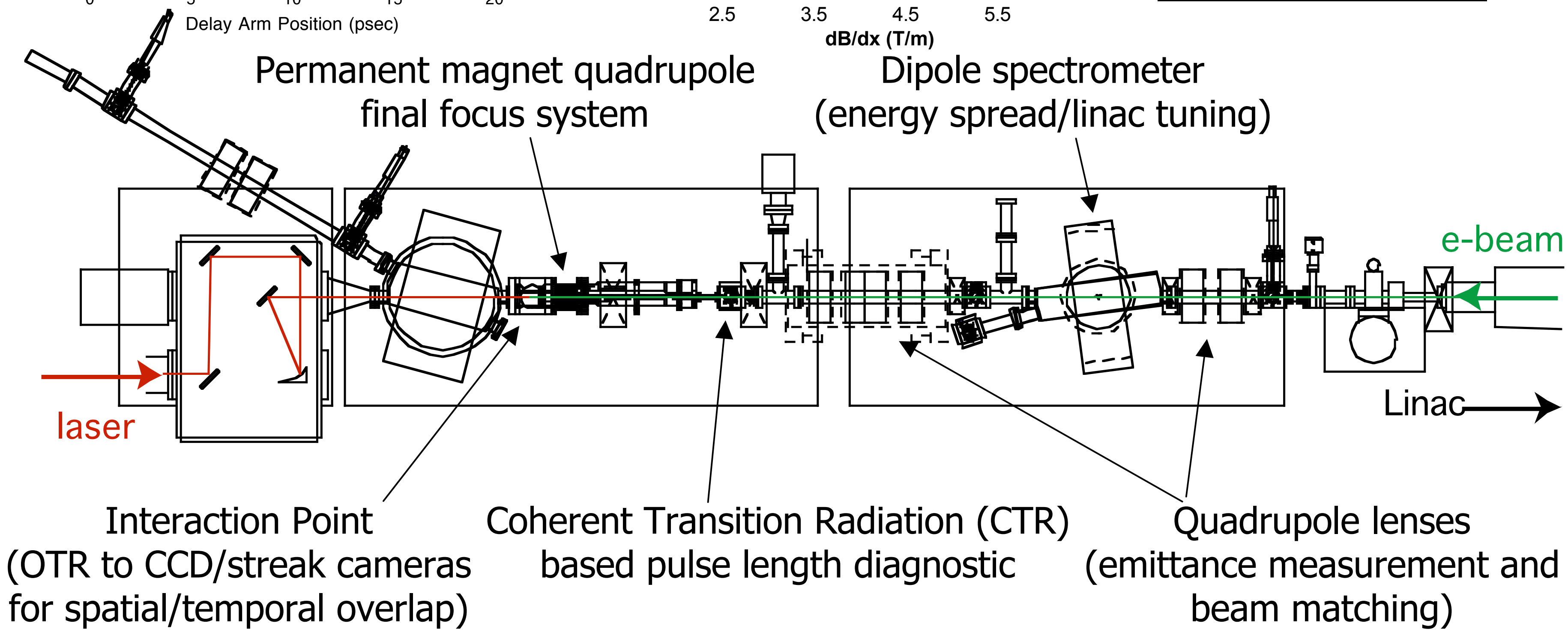
E-beam compression and PMQ focusing have significantly increased source flux and brightness.

PLEIADES interaction beamline





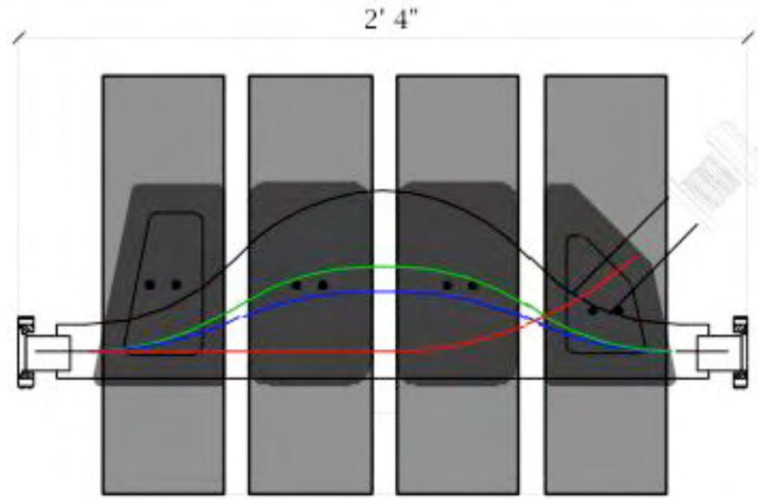


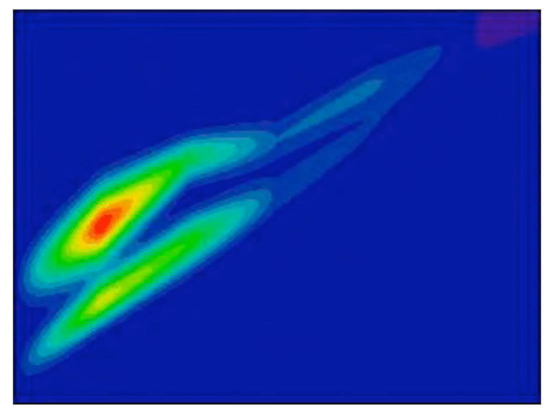


Magnetic compression of photoinjector beams gives emittance growth

UCLA

- Magnetic chicane compressors produce sub-picosecond beams
- Collective effects in chicane cause phase space distortions
  - CSR at moderate/high energies
  - Space-charge at low energies
- Resulting emittance growth and energy spread are a major concern for applications





Transverse phase space low energy (space-charge) effect

Velocity compression as an alternative

- Beam is injected ahead of peak accelerating phase, and compresses as it slips back in phase.

Particle equations of motion in traveling-wave field:

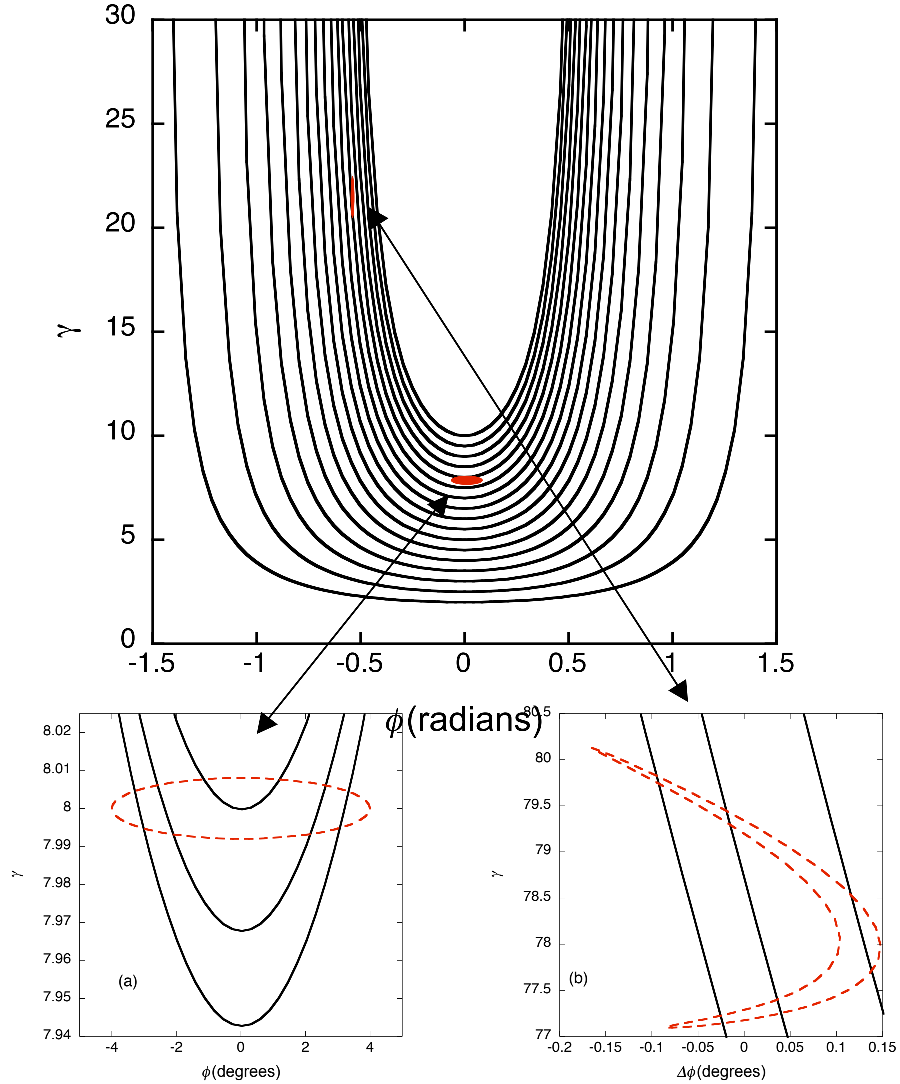
$$\frac{d\gamma}{dz} = -\alpha k \sin\phi,$$

$$\frac{d\phi}{dz} = k\left[1 - \frac{\gamma}{\sqrt{\gamma^2 - 1}}\right]$$

Final bunch length:

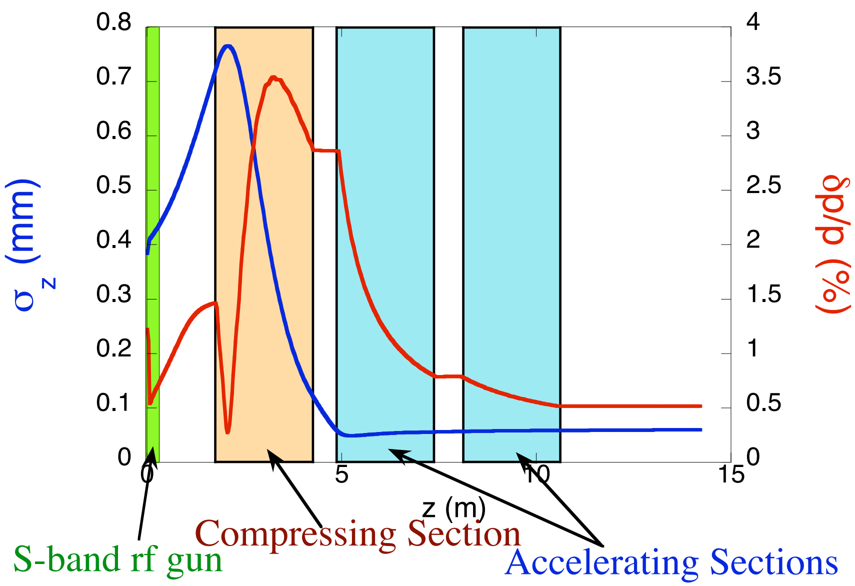
$$\Delta\phi_\infty = \frac{\sin\phi_0}{\sin\phi_\infty}\Delta\phi_0 + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\Delta\gamma_0 + \frac{1}{2}\left[\frac{\cos\phi_0}{\sin\phi_\infty} - \frac{\cos\phi_\infty\sin^2\phi_0}{\sin^3\phi_\infty}\right](\Delta\phi_0)^2.$$

Longitudinal phase space during compression

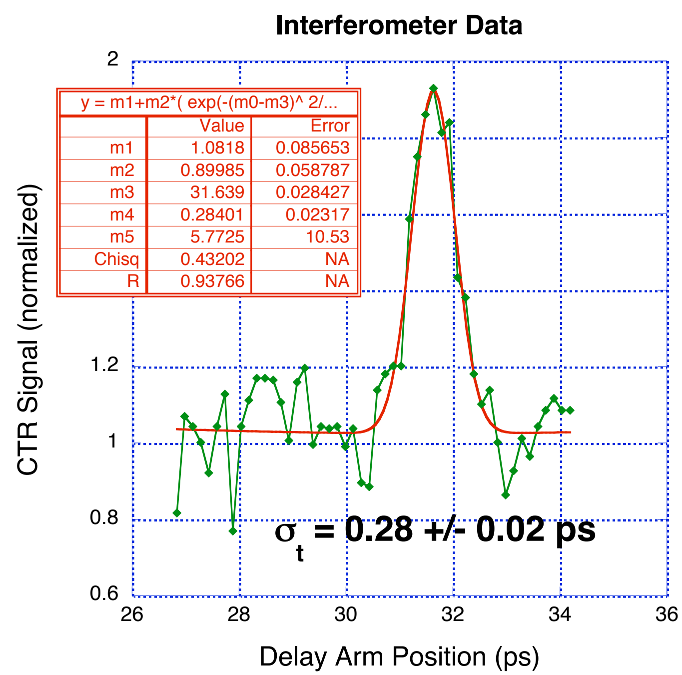


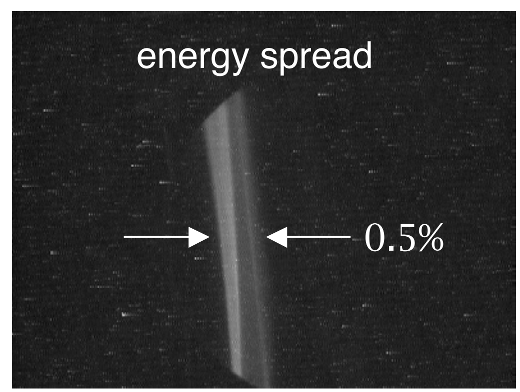
Velocity bunching results: longitudinal dynamics

Simulation



Measurements



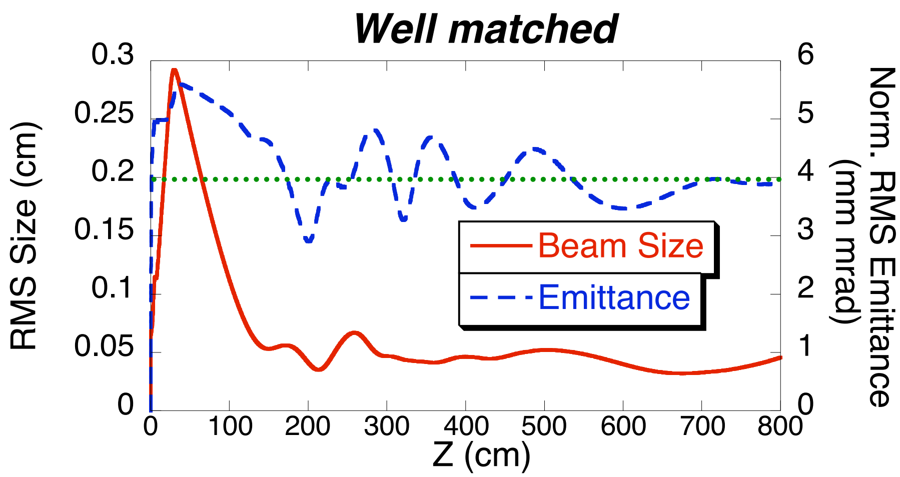


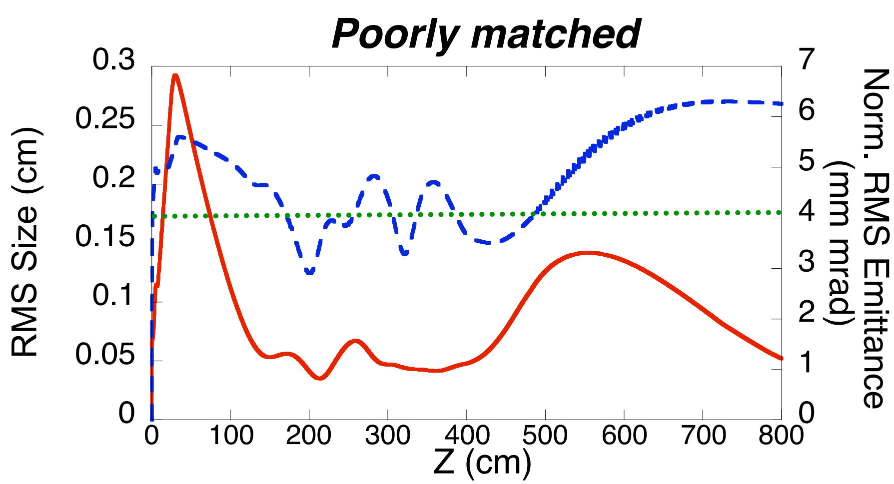
Final beam parameters:

compressed	nominal
$E = 50\,MeV$	$E = 59\,MeV$
$\frac{\sigma_\gamma}{\gamma} = 0.5\%$	$\frac{\sigma_\gamma}{\gamma} = 0.2\%$
$\sigma_t = 200\,fs$	$\sigma_t = 3\,ps$

Velocity bunching results: transverse dynamics

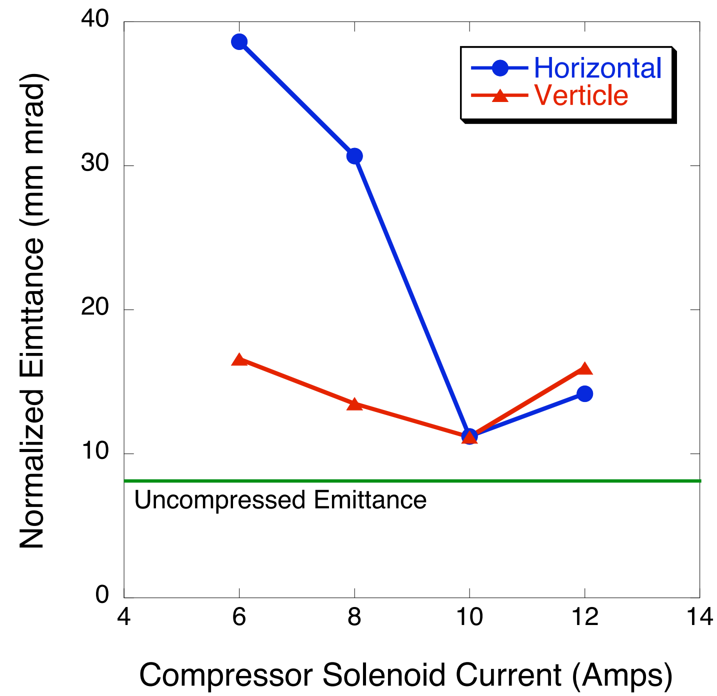
Simulated beam matching





- Simulations predict matching critical for emittance conservation
- *Quad scan measurement agrees!*

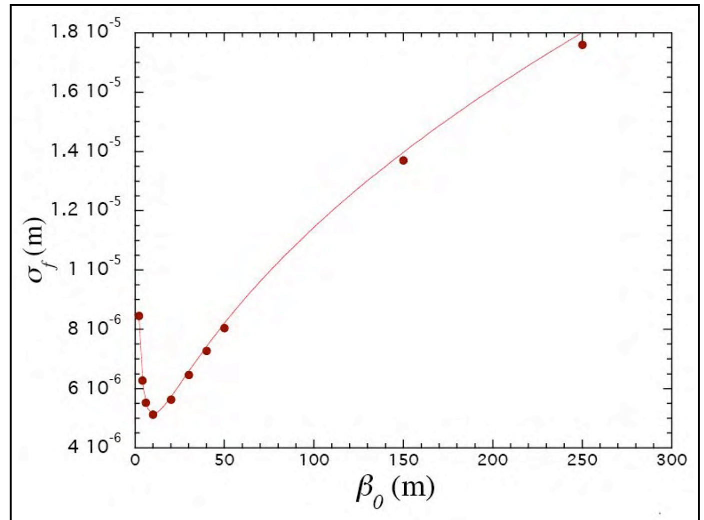
Measured emittance



Permanent magnet quadrupoles achieve ultra-high field gradients

- Chromatic aberration limits demagnification; need increased B’

$$\sigma_{0,opt} = \sqrt{\varepsilon_0 f \frac{p}{\delta p}}; \quad \sigma^*_{\min} = \sqrt{2 f \varepsilon_0 \frac{\delta p}{p}}$$



Final spot size vs initial β

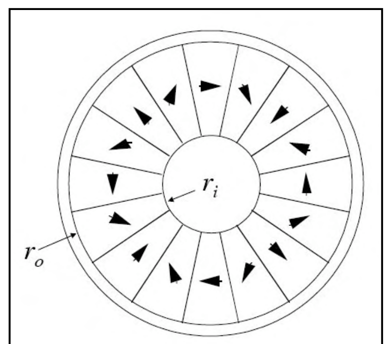
- Idealized, cylindrical PMQ achieves field gradient:

$$B' = 2B_r\left(\frac{1}{r_i} - \frac{1}{r_o}\right)$$

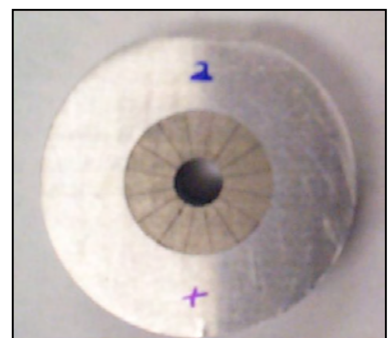
with $B_r = 1.22\text{T (NdFeB)}, r_i = 2.5\text{mm},$

and $r_o = 7.5\text{mm}, B' = 640\frac{\text{T}}{\text{m}}$

$$kl_q = \left(\frac{B'}{BR}\right) l_q \leq 0.5 \Rightarrow l_q \approx 1 \text{ cm}$$



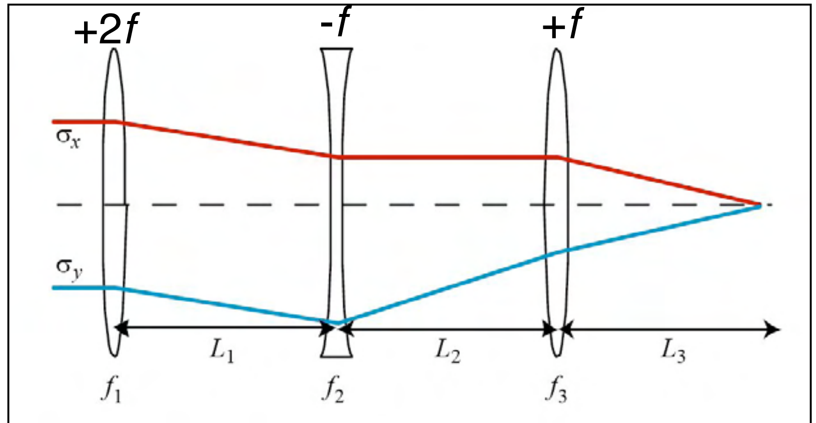
Segmented Halbach design



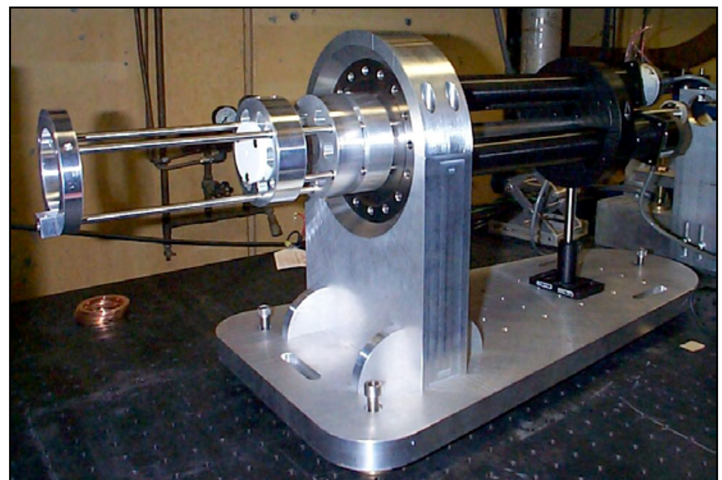
Built PMQ

Adjustable PMQ final focus system

- Final focus modeled as simple thin lens triplet
  - For PMQ focal length, f_{PMQ}=BR/B'l_q, strongest triplet focusing is in F-DD-FF configuration
- System adjusted by magnet spacing; L_1, L_2, L_3
- Trace3D (and experiments) verify system tunable to focus 50-90 MeV beams; *final β-functions in 3-5 mm range*



Asymmetric triplet model

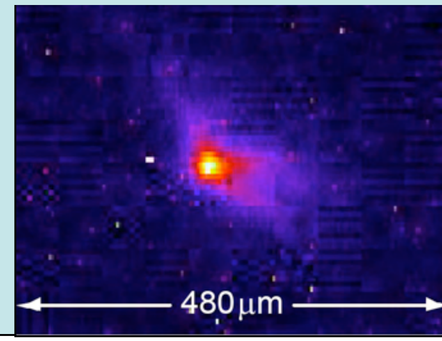


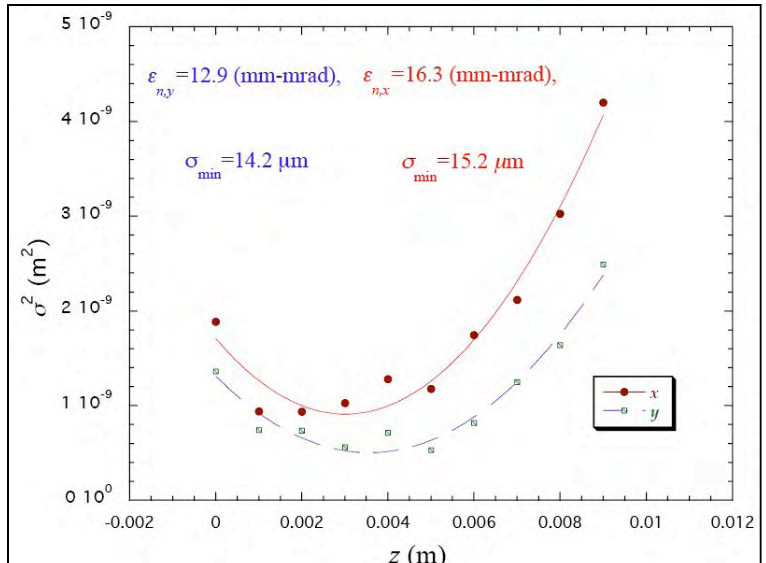
PMQ mover assembly

Final focus performance is enhanced with PMQ system

- Final focus procedure:
  - Perform quad scan with up-stream magnets
  - Use Trace3D to compute EM quad settings for ~ few meter β_0 and PMQ positions for best focus
- IP spot measured with OTR + 3 μm/pixel video camera
  - Measurement problematic; sensitive to aberrations in camera lens
  - < 20 μm spots directly measured
- PMQ scan indicates σ^* = 15 μm

OTR image of 70 MeV, 200pC, 20 μm (rms) final focus



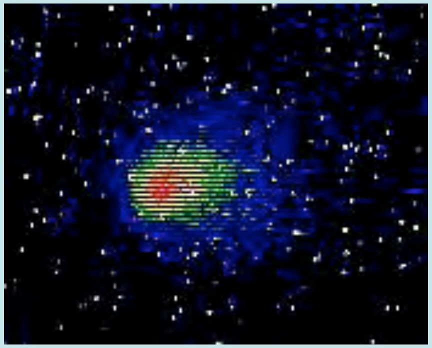


PMQ scan shows β^* = 3 mm

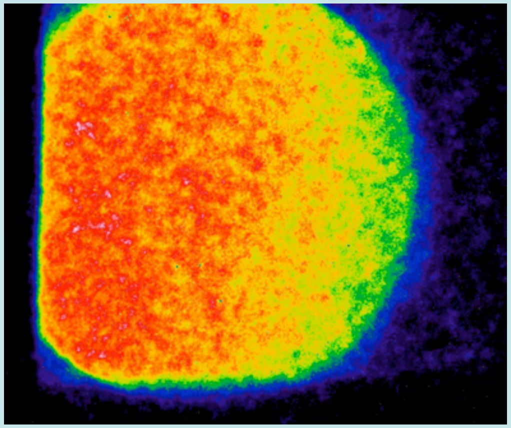
X-ray generation using velocity bunched, PMQ focused beam

- X-ray generation issues:
  - Final focus spot size increase due to increased emittance, energy spread of compressed beam
  - Shot-to-shot jitter and short term drift (~minute scale)

X-ray Beam Properties	
Parameter	**Value**
Photon energy	65 keV (300 fs), 30-140 keV (3 ps)
Number of photons	10^6 - 10^7
Source dimensions	20 μm × 5-10 mrad
Peak Brightness	> 10^{16} γ/(s-mm^2-mrad^2-0.1%BW)



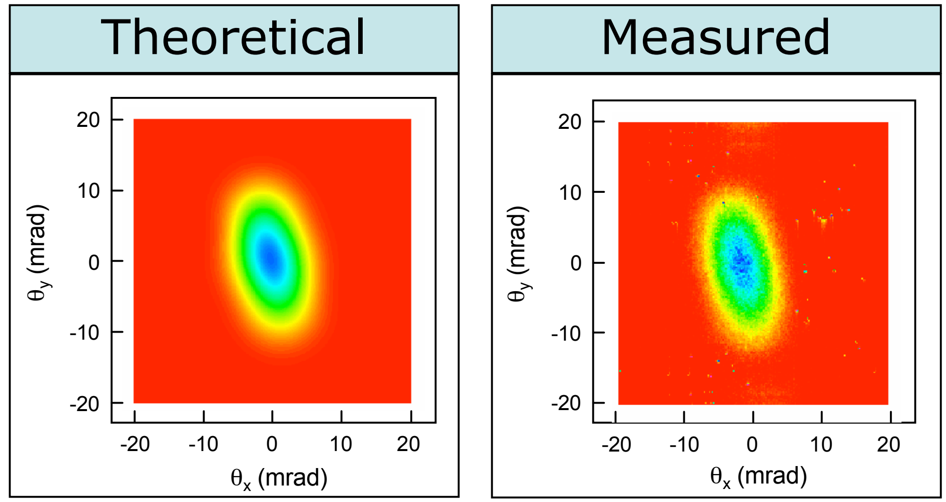
OTR image of velocity bunched beam; 30 μm (rms) final focus

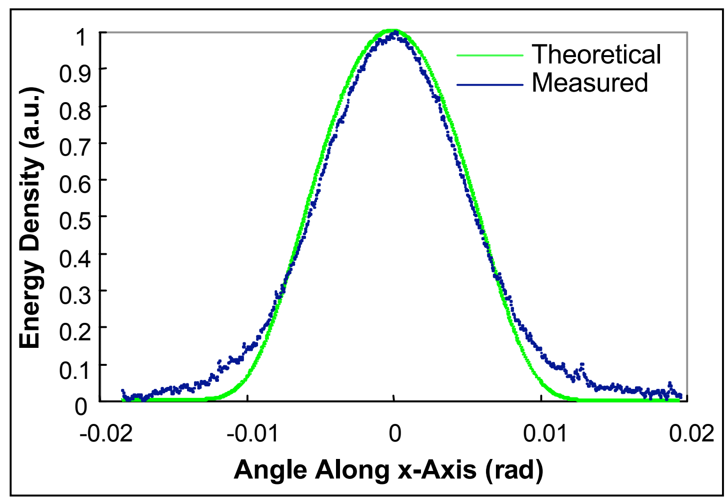


X-ray CCD image of 300 fs, 65 keV, ICS photons

The PLIEADES X-ray source is well modeled

- 3-D time and frequency domain code developed to model source.
  - W.J. Brown, *et al., Phys. Rev. ST Accel. Beams*, **7** p. 060702 (2004).
- The x-rays measured with the PLEIADES system matched the theoretical flux and profiles very well, once all the electron and laser beam parameters, material transmission, and CCD response were taken into account.

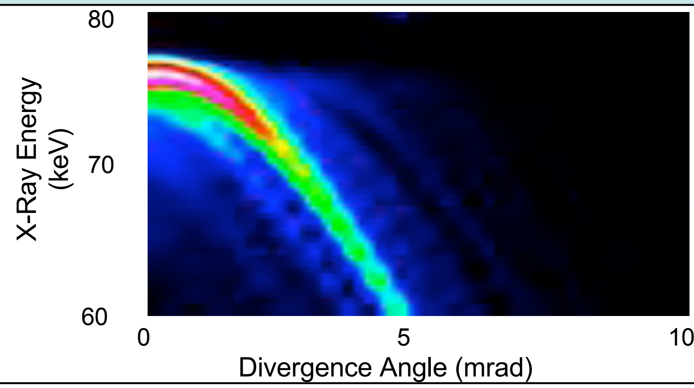


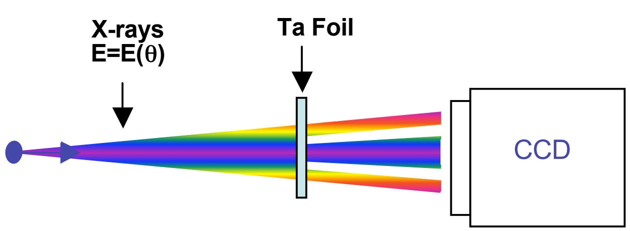


Spectral–Angular Correlation

The dependence of x-ray energy on emission angle was observed using filter absorption edges.

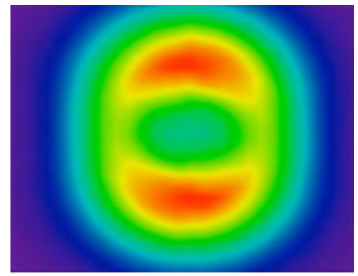
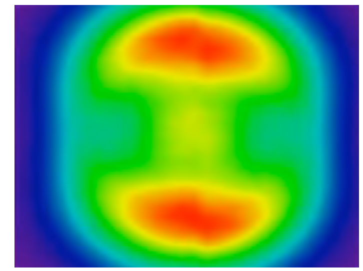
Simulated Spectral Dependence on Divergence





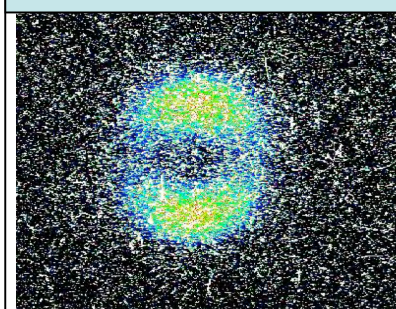
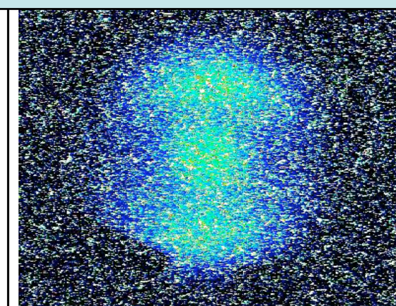
0.005” Tantalum Foil

Theoretical Transmission (K-edge 67.46 keV)

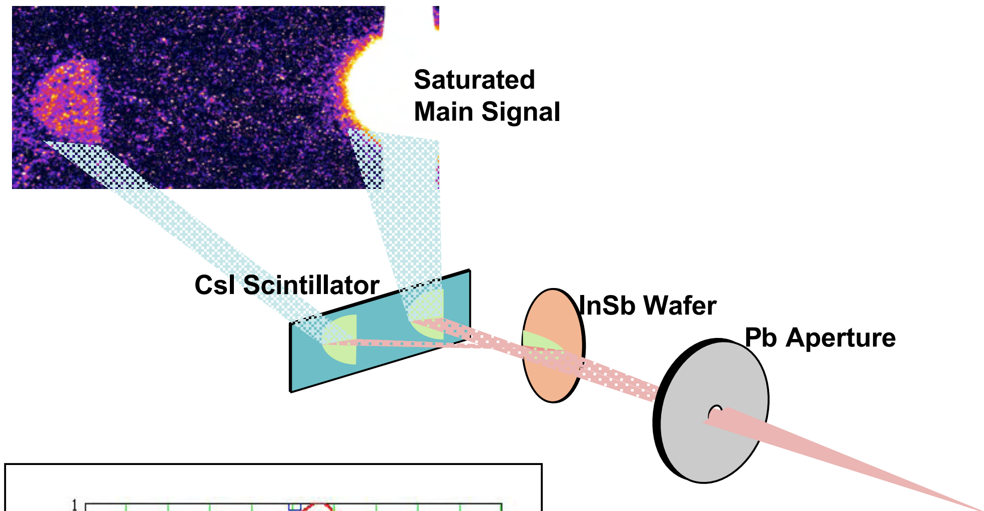
	
$E_{electron}$=55 MeV $E_{x\text{-}ray,peak}$=73.1 keV	$E_{electron}$=57 MeV $E_{x\text{-}ray,peak}$=78.5 keV

0.005” Tantalum Foil

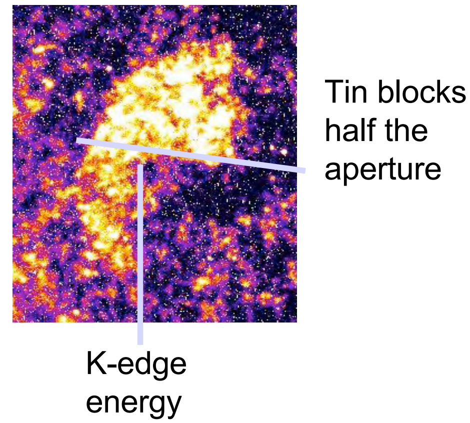
Measured Transmission (K-edge 67.46 keV)

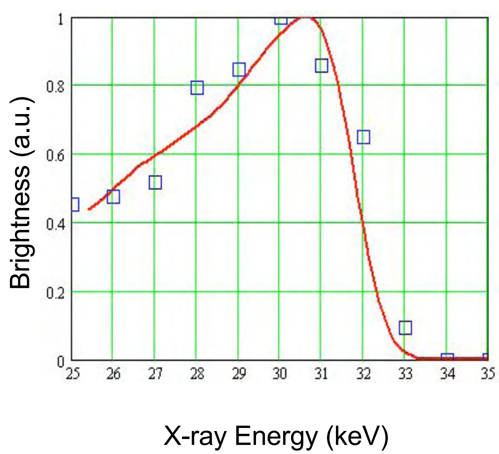
	
$E_{electron}$=54.9 MeV $E_{x\text{-}ray,peak}$=72.8 keV	$E_{electron}$=56.9 MeV $E_{x\text{-}ray,peak}$=78.2 keV

Diffraction Measurements



X-Ray Diffraction from InSb showing Sn K-edge (round aperture)





The x-ray spectrum was measured by looking at the diffraction intensity as a function of angle of incidence upon an InSb (111) crystal.

Diffraction of the x-ray beam has been observed off several crystal materials, including graphite (C), gold (Au), and indium antimonide (InSb). Because of the small source size, the divergent x-ray beam that reflects off the crystal has a strong correlation between the position on the CCD detector and the energy of the x-ray photons. Placing a foil with a K-edge in the range of the energy of the diffracted electrons creates a notch in the diffracted image. It is the dark region produced this way that can allow for observation of dynamic diffraction effects.

Summary

UCLA

- Velocity bunching is a very effective compression technique at moderate energies.
  - ≤ 300 fsec, 250 pC bunches produced; stability sufficient for PLEIADES experiment
  - Emittance control possible with solenoid focusing, but not perfect; *needs more study with low emittance system.*
- A Halbach type PMQ final focus system has been developed [J. K. Lim, *et al.*, *Phys. Rev. ST Accel. Beams*, **8**, p. 072401 (2005).]
  - Ultra-high field gradient — 560 T/m
  - ≤ 20 μm spots, 3-5 mm β-functions routinely generated

Both techniques enhance PLEIADES performance

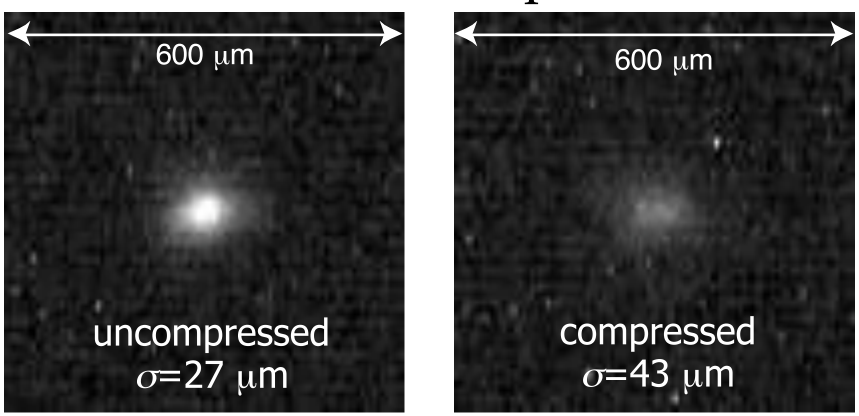
Beam density in 10^{15} cm^{-3} range; ~10^4 higher than at gun exit

Compton x-ray production

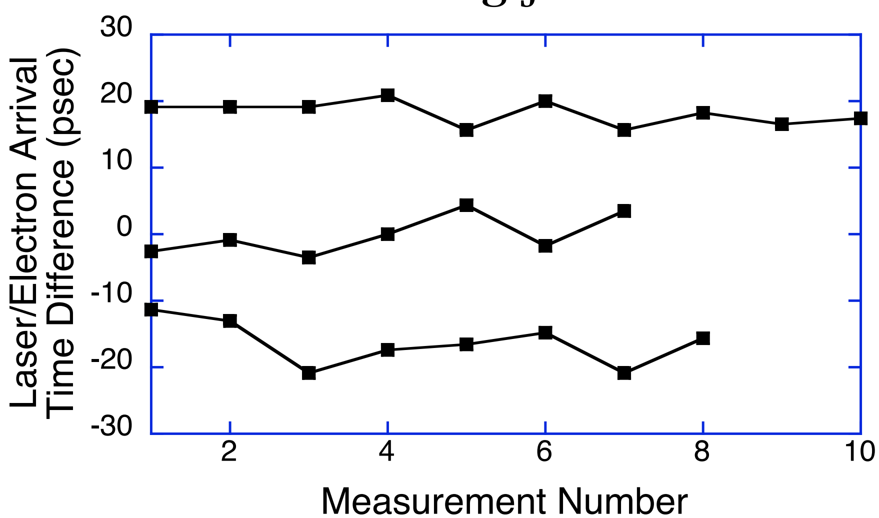
E-beam issues for x-ray generation:

- Focused spot size
- Timing stability

Final focus spots

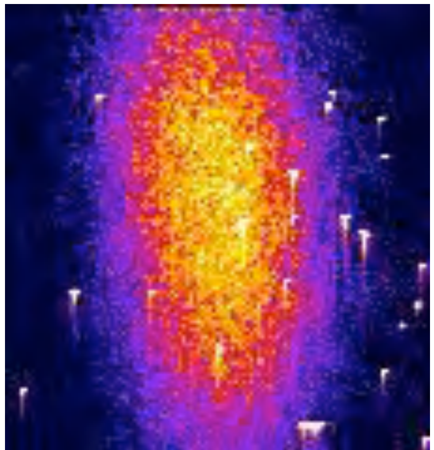


Timing jitter

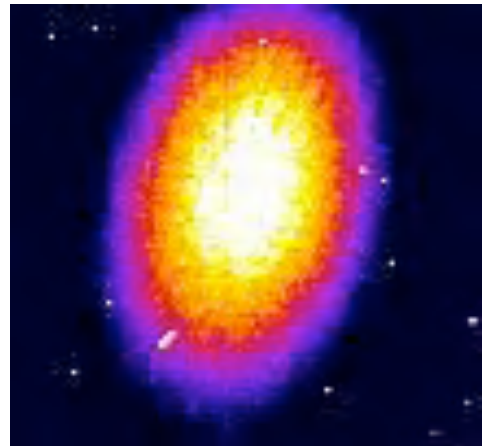


X-rays generated

X-ray CCD Images



Compressed electrons



Uncompressed electrons

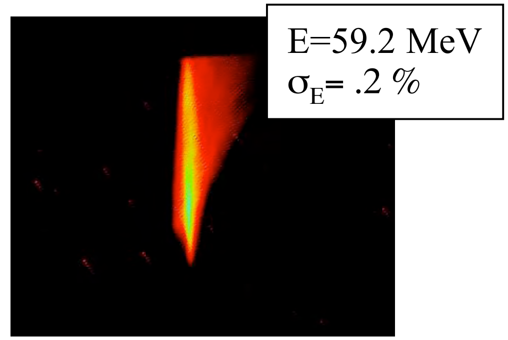
X-ray brightness: $B_x = \dfrac{N_\gamma}{(2\pi)^{5/2}\sigma_t\sigma_x^2\sigma_{x'}^2(0.1\%\mathrm{BW})}$

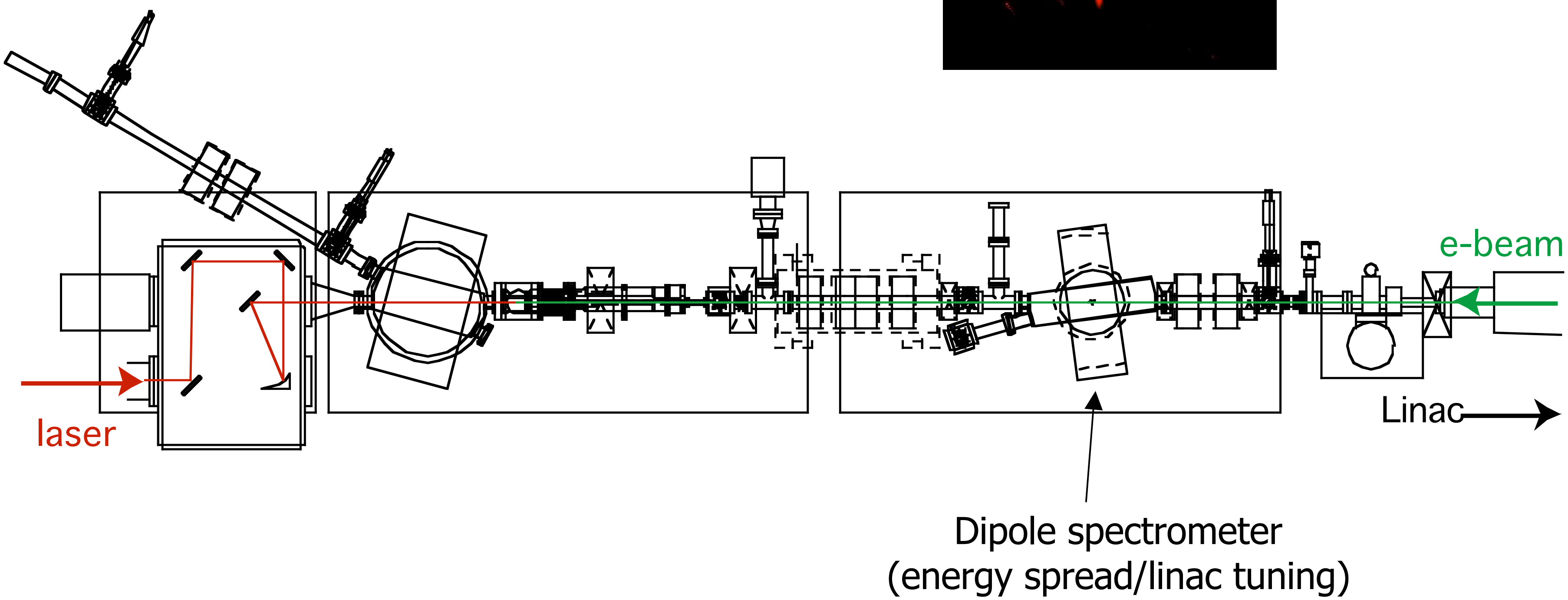
N_γ & $\sigma_t \downarrow$

$\sigma_{x'} \uparrow$ $\Longrightarrow$ *Brightness increase 70%*

PLEIADES experimental beamline

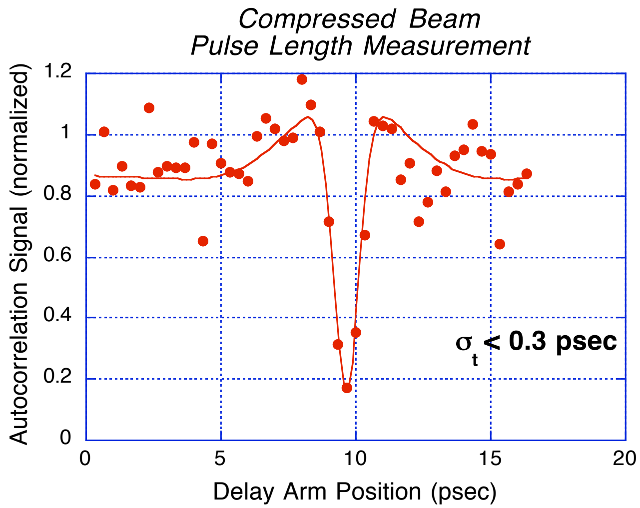
Energy spread measurement

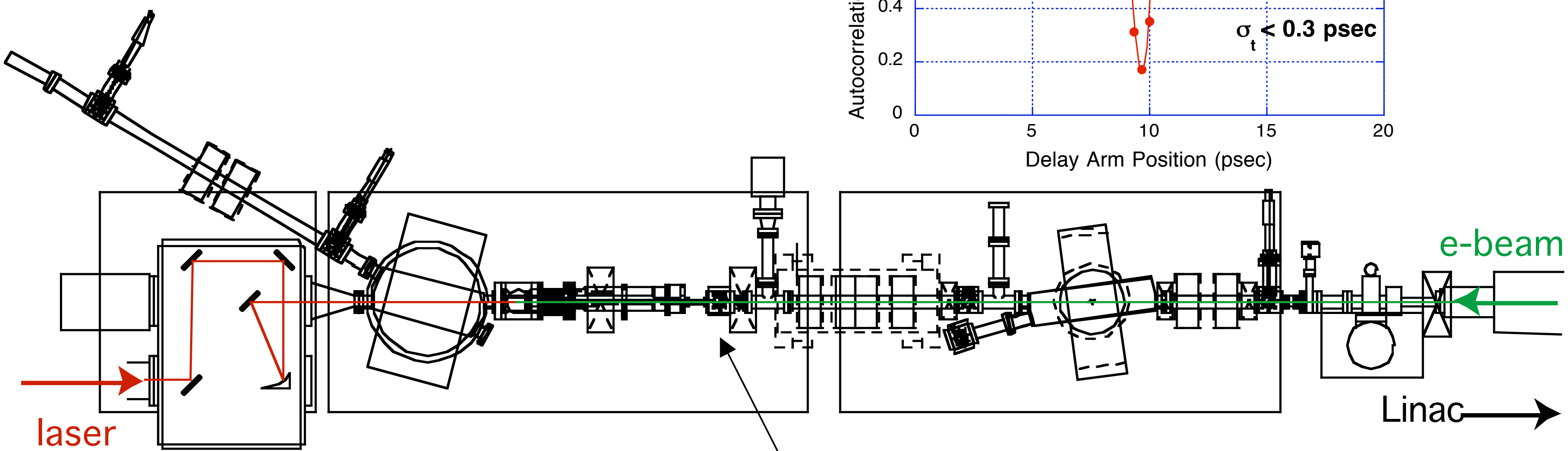




PLEIADES experimental beamline

Bunch length measurement

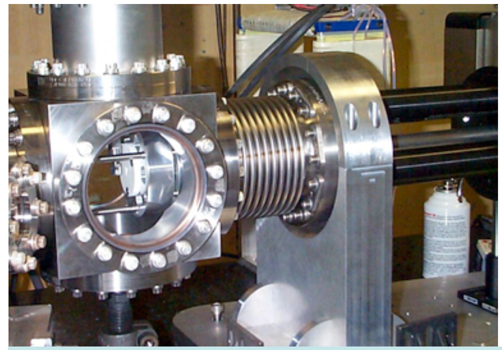




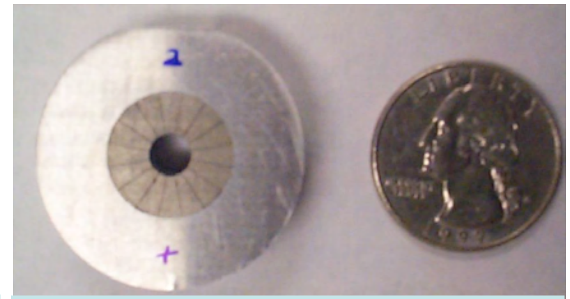
Coherent Transition Radiation (CTR)
based pulse length diagnostic

PLEIADES experimental beamline

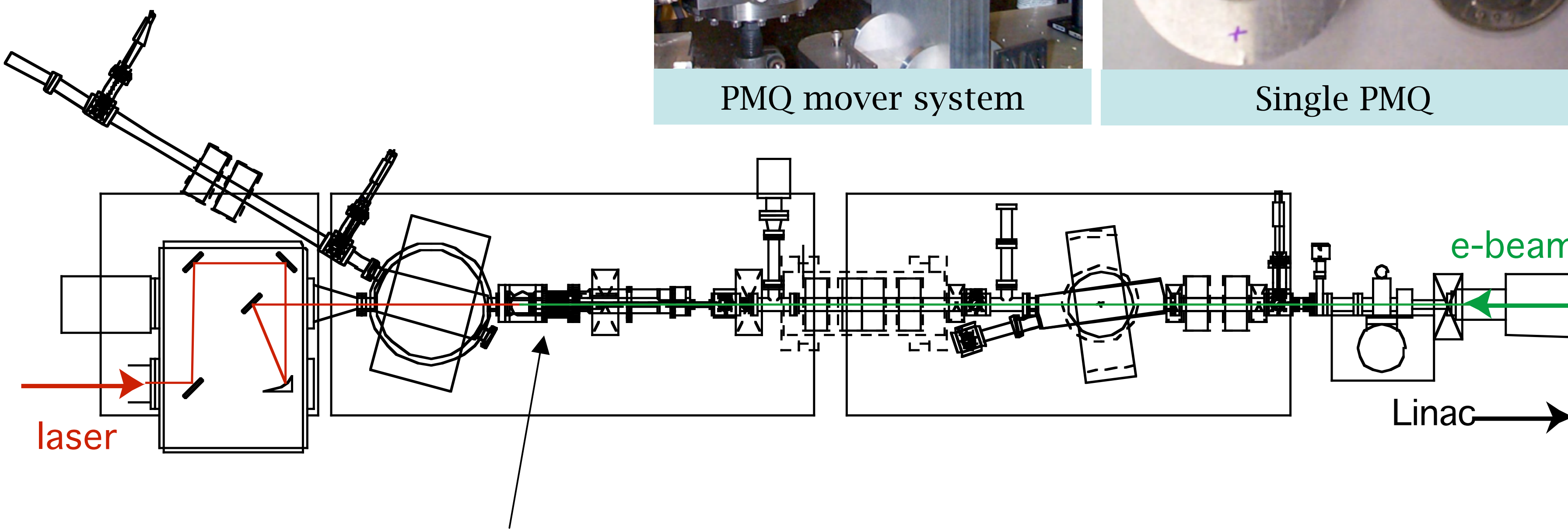
560 T/m field gradient!



PMQ mover system



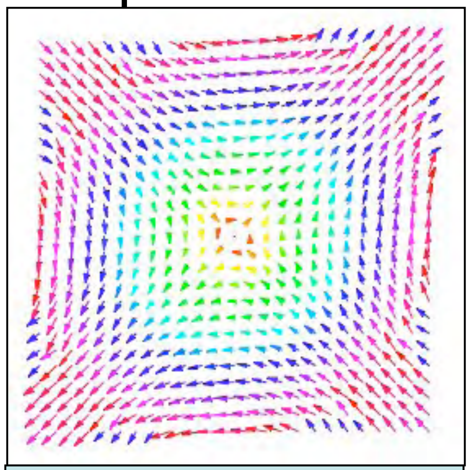
Single PMQ



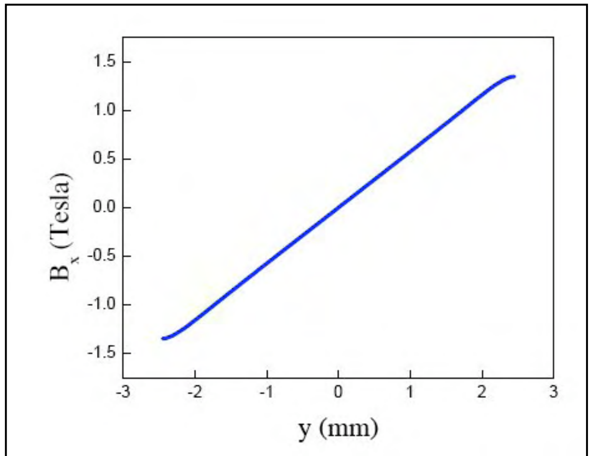
Permanent magnet quadrupole
final focus system

3D simulations quantified design tolerances

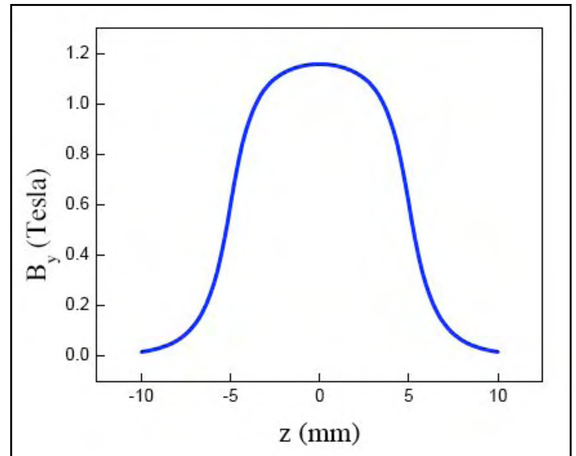
- RADIA — 3D magnetostatic field solver simulate design parameters: ID = 5 mm, OD = 15 mm, L = 10 mm, and B_r = 1.22 T



Vector field plot in bore region



Linearity good to r ~ 2 mm
B' = 573 T/m

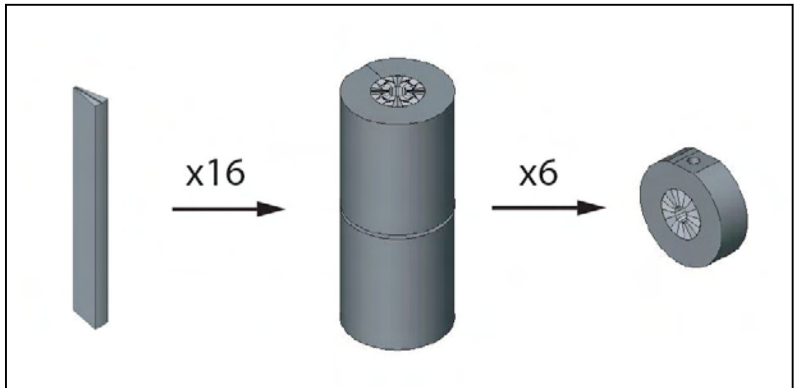


l_{eff} = 10.4 mm

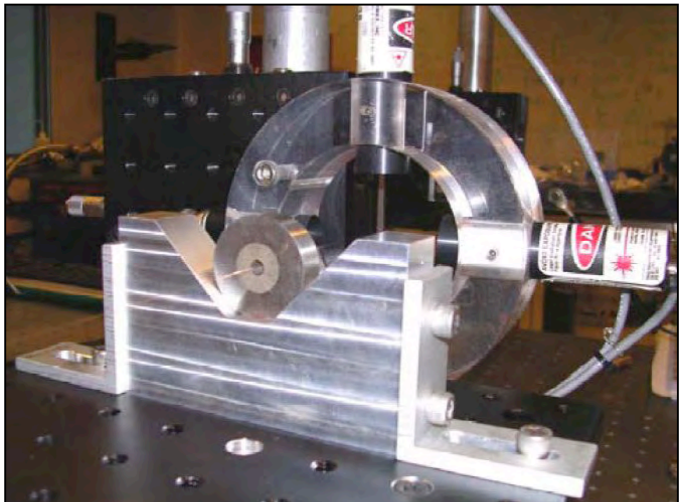
- RADIA + ELEGANT error studies performed to find manufacturing tolerances
  - ± 50 μm bore radius error ⇒ ± 3% B' variation
  - 2% wedge shape and easy axis orientation allowable
  - *10 mrad rotation (skew) error produces significant emittance growth*

Measurements of built PMQs agree with RADIA simulations

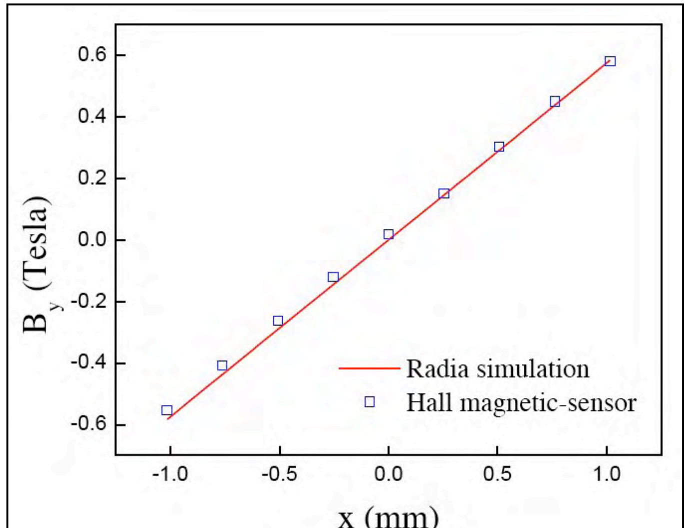
- Manufacturing process ensures consistency between PMQs, minimizes skew errors.



PMQ construction steps



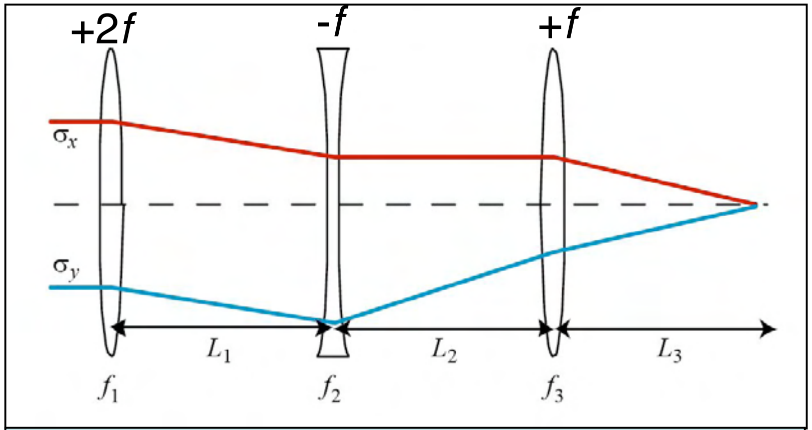
Pulsed-wire scan verifies field linearity to r ~ 2 mm. Magnetic and mechanical centers within 25 μm



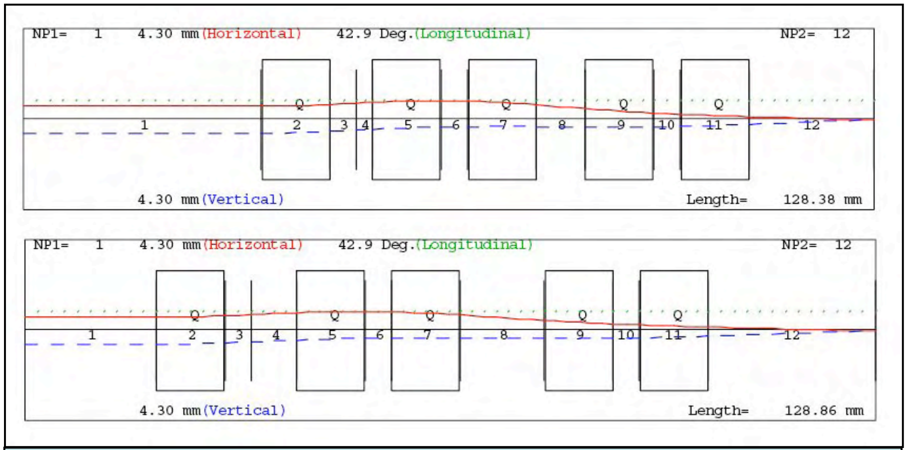
Hall probe measurement gives B' = 560 T/m

Adjustable PMQ final focus system

- Final focus modeled as simple thin lens triplet
  - For PMQ focal length, f_{PMQ}=BR/B'l_q, strongest triplet focusing is in F-DD-FF configuration
- System adjusted by magnet spacing; L_1, L_2, L_3
- Trace3D (and experiments) verify system tunable to focus 50-90 MeV beams; *final β-functions in 3-5 mm range*



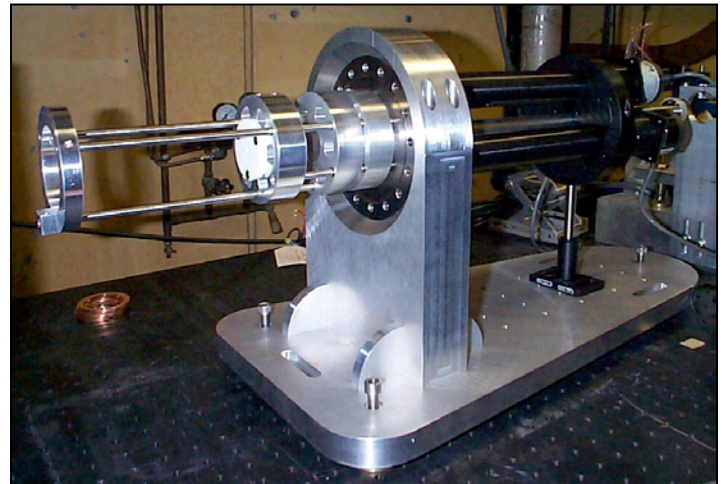
Asymmetric triplet model



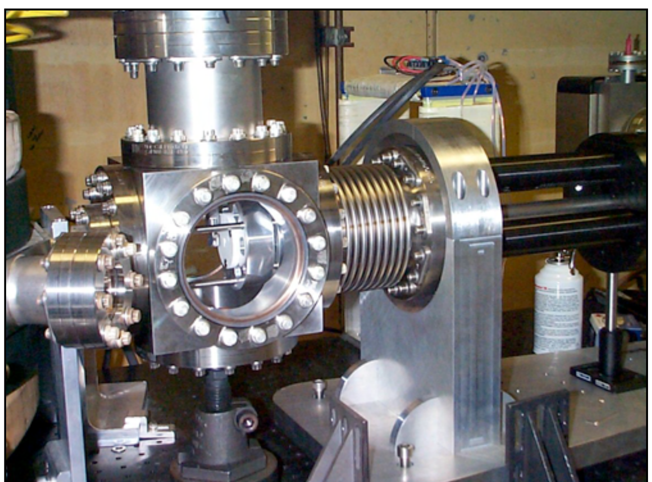
Trace3D tunes at 70 & 90 MeV

The PMQ mover system meets experimental requirements

- CNC machined “PMQ holders” constrained by rail system
  - < 1 mil PMQ to system center-line throughout range of motion
- Push-rods + stepper motors + LabVIEW for on-line, < 50 μm resolution longitudinal positioning



PMQ mover assembly



PLEIADES PMQ final focus

- Alignment verified optically (theodolite) in PLEIADES beamline

Advanced applications require high-brightness, *dense* beams

- Scaling of applications to higher performance requires shorter bunch dimensions; examples: advanced accelerators, next generation light sources.
- Plasma wake-field accelerator (PWFA) scaling:

Wave-breaking field

$$E_{WB} = m_e c^2 k_p / e$$

Efficiently excited wake amplitude

$$E \propto k_p^2 N_b \quad \text{if} \quad k_p \sigma_z < 1$$

Ultra-strong focusing

$$\beta_{eq} = \sqrt{2\gamma}\, k_p^{-1}$$

PWFA longitudinal field