The LLNL/UCLA High Gradient Inverse Free-Electron Laser Experiment

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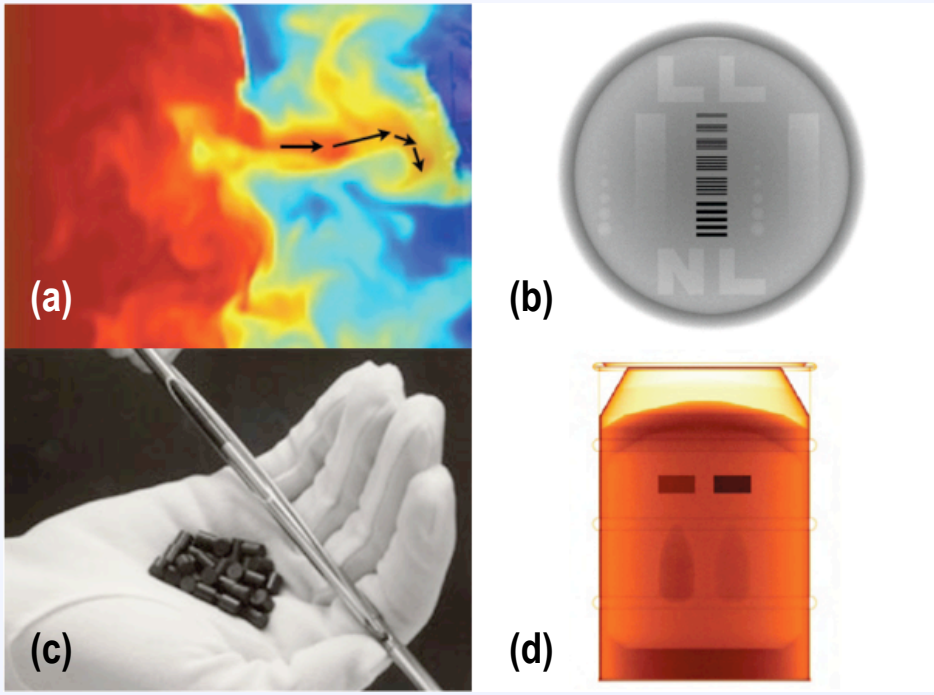
Lawrence Livermore National Laboratory

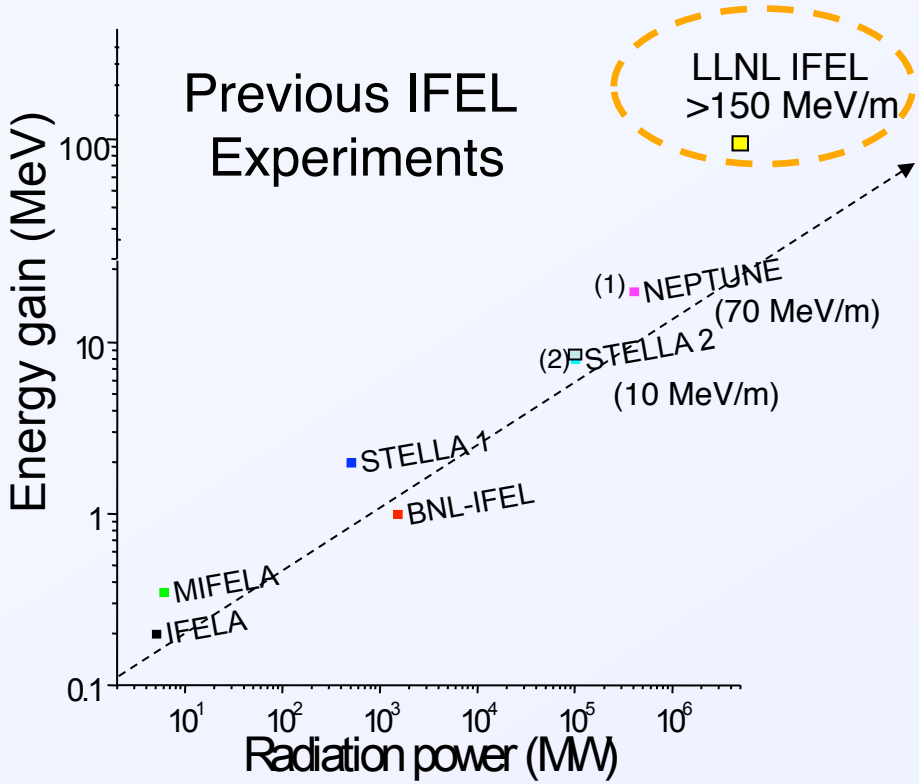
LLNL programs benefit from compact, high brightness, high average power accelerator technology development



Illustrations of potential applications: (a) Flash HED plasma imaging, (b) Imaging/assay of stockpile components, (c) Assay of fission products, (d) Detection/imaging legacy waste or transport containers

- One application: narrow-band, intense γ-ray sources for DHS and NNSA missions
- Compton scattering + Nuclear Resonance Fluorescence (NRF) detection enables isotope-resolved applications
  - Detection
  - Quantitative Assay
  - Imaging
- Light source needs low emittance, average current, and compact accelerators!

Why pursue IFEL?



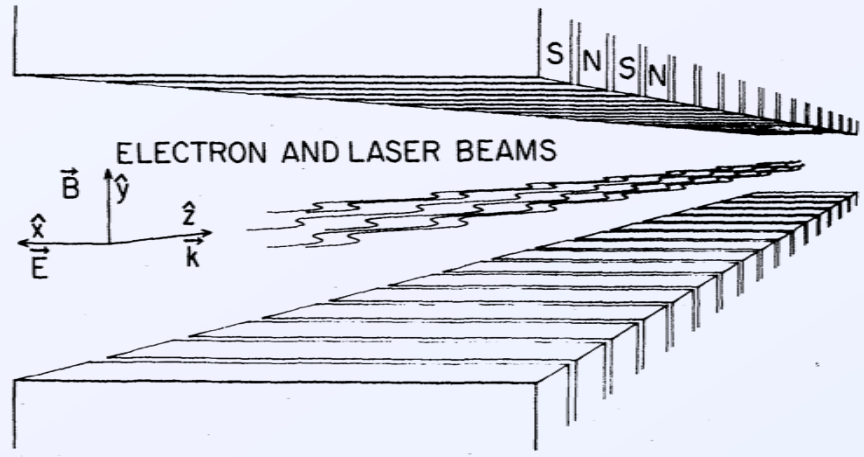
(1) UCLA, P. Musumeci*et al.*, Phys Rev Lett 94, 154801 (2005)
Demonstrated 70 MeV/m over 50 cm, 10% capture

(2) BNL, W. Kimura *et al.*, Phys Rev Lett 92, 0584801, (2004)
Demonstrated 10 MeV/m, 80 % capture

- **Compact, GeV injector for:**
  - **Compton γ-ray sources**
  - **FELs**
  - **Polarized positrons**
- ***Rep. rate scales with Joule-class laser tech – leverages LLNL programs***
- **IFEL tech ideally suited for 100 MeV – few GeV accelerators:**
  - **High power, 1 μm/800 nm lasers**
  - **Permanent magnet undulators (cm periods)**
- **High gradient *and* beam quality preservation**
- **Other IFEL advantages:**
  - **No RF structure**
  - **Mitigates dark current, breakdown, and wakefield issues**
  - **Efficient acceleration**
  - **Micro-bunched beams**

What is an Inverse Free-Electron Laser (IFEL)?

- IFEL is a high gradient, laser-based acceleration scheme.
- IFELs use magnetic undulators to couple energy between laser radiation and relativistic electrons.
- A periodic, transverse magnetic field is used to induce a 'wiggle' motion in the electrons, which allows energy transfer to (or from) the laser field.



From: Courant, Pellegrini, and Zakowicz, Phys. Rev. A, vol. 32, p. 2813 (1985).

Sets up transverse 'wiggle' motion

Couples energy from radiation to electrons; IFEL seeks to maximize this term!

Lorentz force:

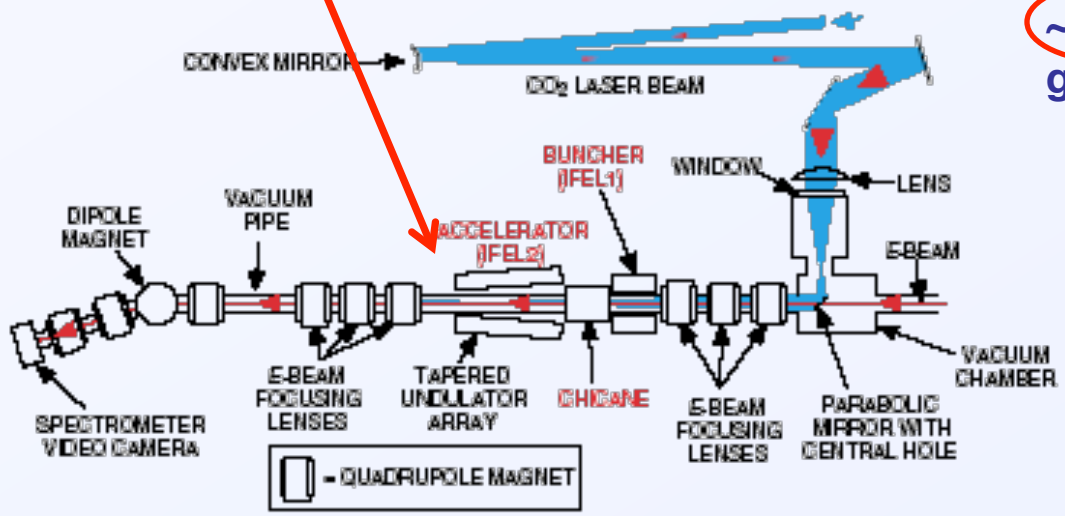
$$\frac{d\vec{p}}{dt} = e\left[\left(\vec{v}\times\vec{B}_w\right) + \vec{E}_L\left(1-\frac{v_z}{c}\right) + \hat{z}\left(\vec{v}\cdot\frac{\vec{E}_L}{c}\right)\right]$$

Wiggler Field

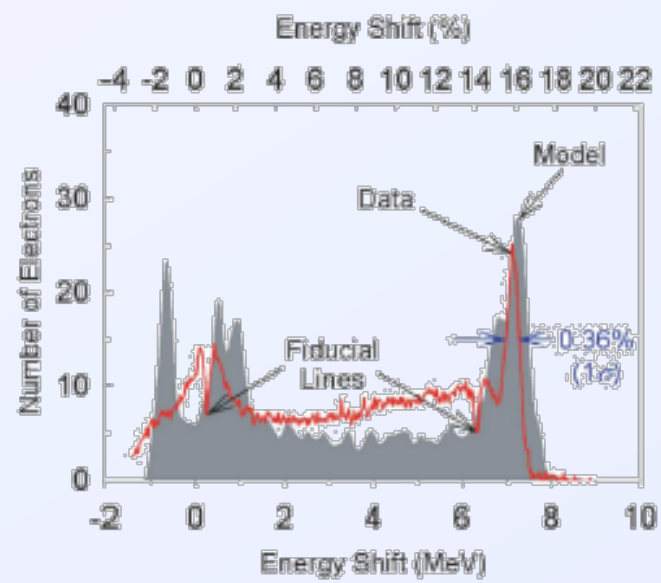
Laser Field

STELLA2 experiment

Gap-tapered planar undulator
(no period tapering).



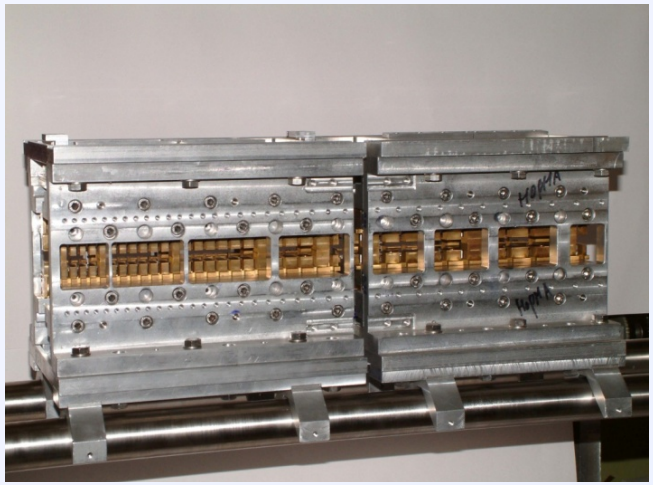
80 % of electrons accelerated,
energy spread less than 0.5 % FWHM
~30 GW@ λ = 10.6 μm,
gain up to 17 % of initial beam energy

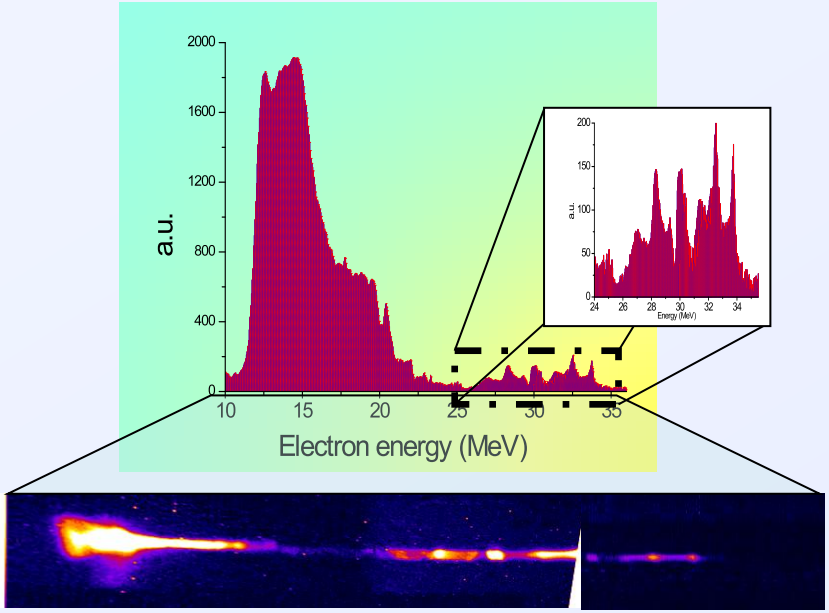


W. Kimura et al. First demonstration of high trapping efficiency and narrow energy spread in a laser accelerator, PRL, 92, 154801 (2004)

UCLA Neptune IFEL

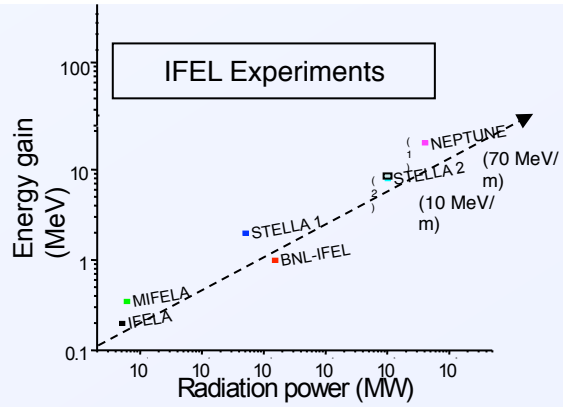
- 0.5 TW 10.6 μm laser
- Strongly tapered (period and amplitude) Kurchatov undulator
- Highest recorded IFEL acceleration
- 15 MeV beam accelerated to over 35 MeV in ~25 cm
- Accelerating gradient ~70 MeV/m !
- Observation of higher harmonic IFEL interaction !





IFEL research offers path to compact, moderate energy, high repetition rate machines

Previous IFEL proof of principle:
- BNL – acceleration + high capture
- UCLA – high gradient



Capability
Technology development

LLNL
- *Emittance preservation, high rep. rate, compact*
- Application of Ti:Sapph, 10 Hz, short pulse

UCLA
- *GeV/m gradient*
- Helical Undulators
- IFEL theory

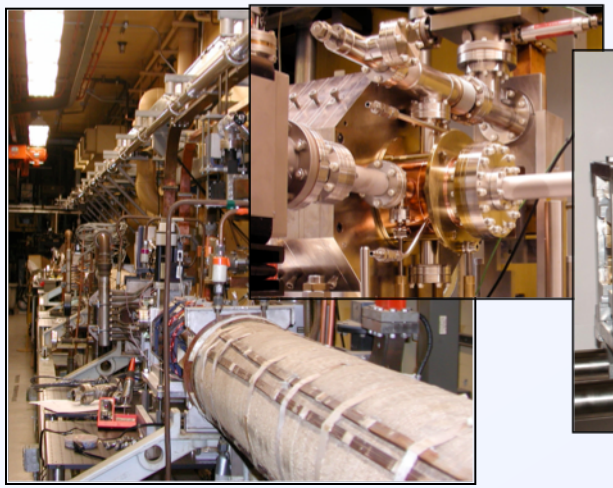
BNL
- *Laser recirculation*
- Undulator inside CO_2 laser cavity

Table-top GeV, high brightness, high current

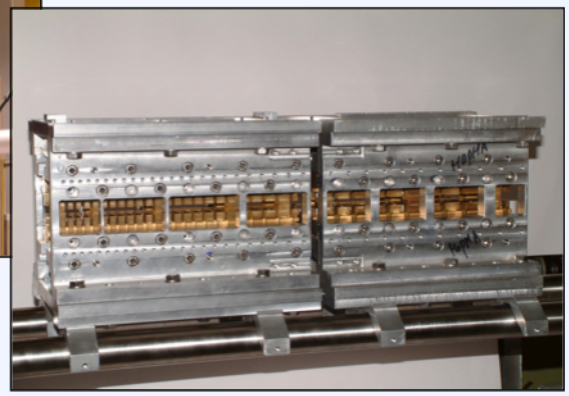
Applications:
- Compton gamma-sources – stand-off detection, nuclear physics
- Soft X-ray FEL, polarized positrons, other rad. sources

LLNL IFEL uses B194 linac and UCLA undulator

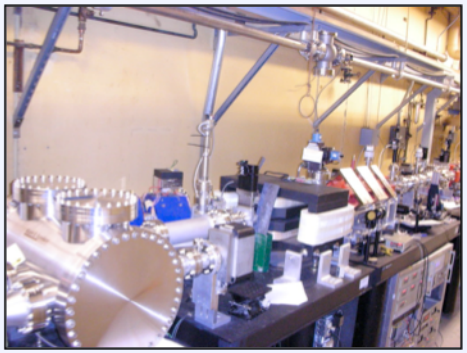
LLNL 120 MeV high brightness photoinjector and S-band accelerator



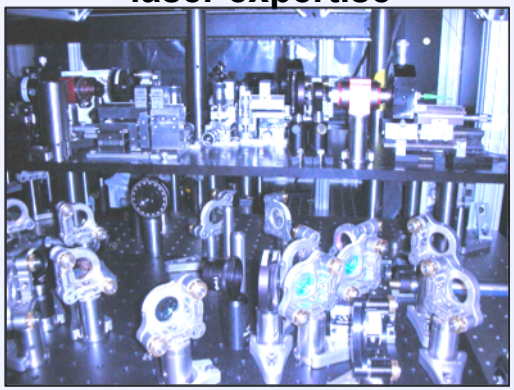
UCLA/Kurchatov 50 cm undulator



laser/electron interactions demonstrated with T-REX



LLNL high power laser expertise



Goals of 2nd Gen IFEL

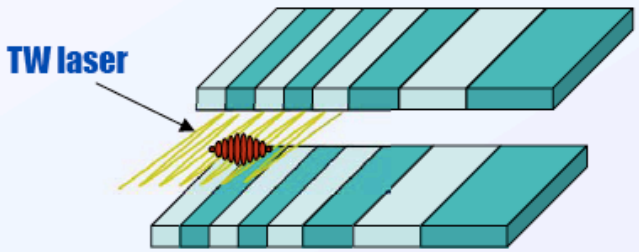
1. Compact (>200 MeV/m), high rep. rate (10 Hz) accelerator
2. Demonstrate e-beam quality preservation

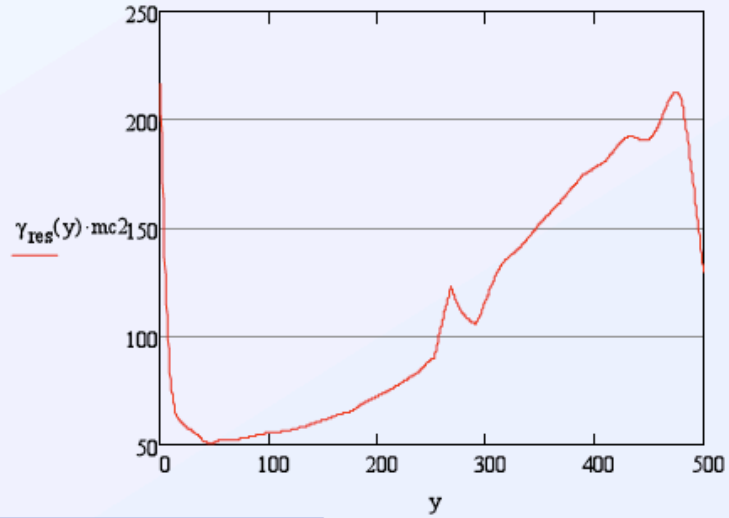
Challenges of LLNL/UCLA Expt.

1. Adapting Ti:Sapph technology to IFEL
2. Ramifications of ultra-short laser pulses

Ti:Sapphire technology offers >> TW @ 10 Hz, but must match laser to undulator (and budget!)

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





FEL equation: Resonance Condition:

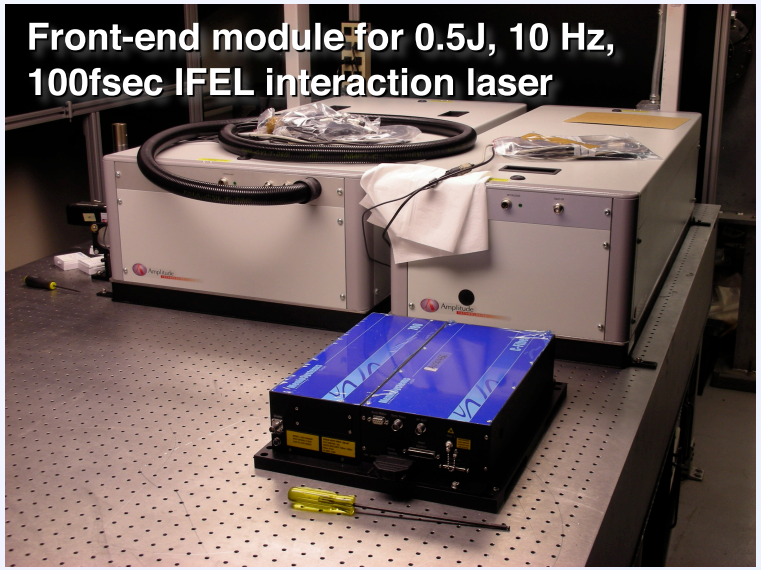
$$\gamma_r^{\,2} \cong \frac{\lambda_w}{2\cdot\lambda}\cdot\left(1+\frac{K^2}{2}\right)$$

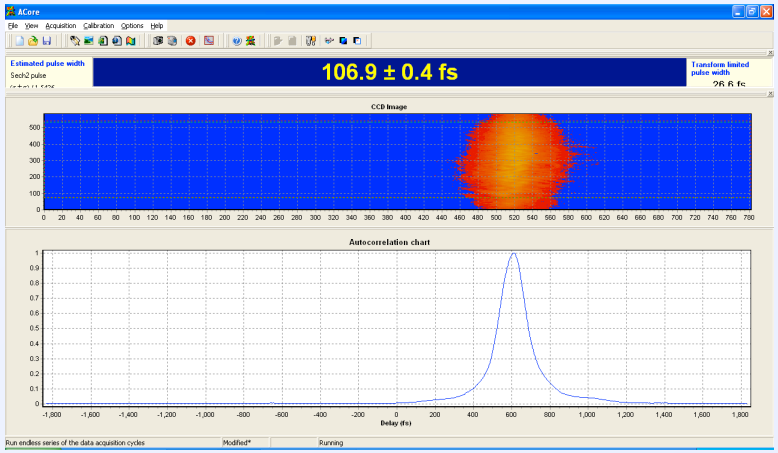
- UCLA undulator tapers λ_w from ~ 1.5-5 cm and K from 0.2-3
- Need at least ~4 TW to maintain γ_r, i.e., **4 J/ps**
- But, pulse length matters; undulator has 19 periods ⇔ 50 fs of 800 nm light

✓ **Need >= 4TW and >= 100 fs**

Amplitude Technologies was chosen as laser vendor

- Amplitude Technologies specializes in TW to PW Ti:Sapphire laser systems for experimental science market
- Ti:Sapphire laser system specs:
  - <120 fs, > 500 mJ, 10 Hz, 800 nm
  - Fiber laser oscillator
- Laser built from 'standard' modules
- Upgradable with additional amp stage to > 4J
- Amplitude recommended by colleagues
- Compatible with LDRD-ER budget
- Amplitude engineers installed last week!





Factory measurement of compressed pulse

We have extended IFEL theory to include short pulse, strongly focused (diffraction dominated) lasers

- **1-D theoretical analysis seeks to write 'accelerator equations' – energy and phase evolution on accelerator axis**

- **Original plane-wave analysis**

$$\vec{E}_L = E_0 \sin(kz - \omega t)\hat{x}$$
$$\vec{B}_W = B_0 \sin(k_W z)\hat{y}$$

$$\frac{d\gamma}{dz} = \frac{1}{2}\frac{kK_L K_W \cdot JJ}{\gamma}\sin\psi$$
$$\frac{d\psi}{dz} = k_W - k\frac{1 + K_W^2/2 + K_L^2/2 + K_W K_L JJ\cos\psi}{2\gamma^2}$$

$$\psi = (k + k_W)z - \omega t$$

- **In our case, laser field and phase vary significantly over interaction length (but not over single oscillation – SVEA)**

$$\vec{E}_L = E_0 \frac{w_0}{w(z)} e^{-\frac{(kz-\omega t)^2}{(\omega\tau)^2}} \sin\left(kz - \omega t - \tan^{-1}\left[\frac{z}{z_R}\right]\right)\hat{x}$$

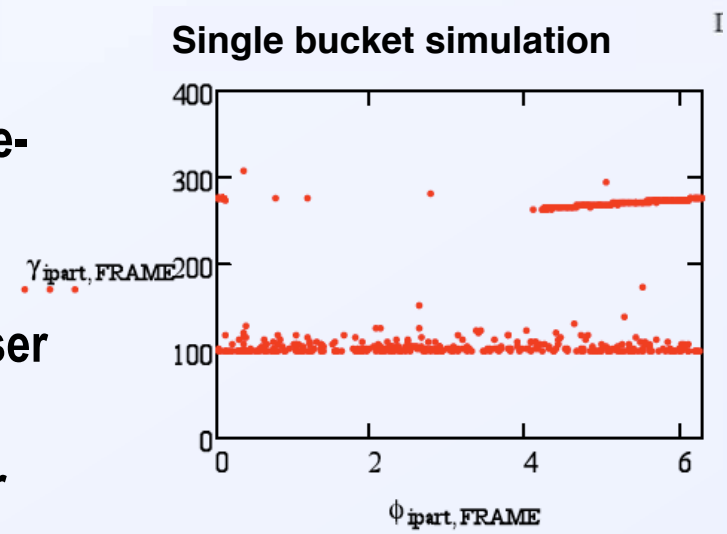
$$\frac{d\gamma}{dz} = \frac{1}{2}\frac{kK_{L,eff} K_W \cdot JJ_{eff}}{\gamma}\sin\psi$$
$$\frac{d\psi}{dz} = k_W - k\frac{1 + K_W^2/2 + K_{L,eff}^2/2 + K_W K_{L,eff} JJ_{eff}\cos\psi}{2\gamma^2} - \frac{1}{z_R\left[1 + \left(\frac{z}{z_R}\right)^2\right]}$$

$$\psi = (k + k_W)z - \omega t - \tan^{-1}\left[\frac{z}{z_R}\right]$$

$$K_{L,eff} = K_L \frac{w_0}{w(z)} e^{-\frac{(\psi - k_W z)^2}{(\omega\tau)^2}}$$

3D simulations required to fully understand short laser pulse ramifications, and to model this experiment

- Previous experiments used CO_2 lasers; analysis assumed constant amplitude over e-bunch – simulation of one accelerating 'bucket'
- Need to track particles over full length of laser pulse to simulate short pulse effects
- Code written to solve Lorentz force in 3D for input electron distribution



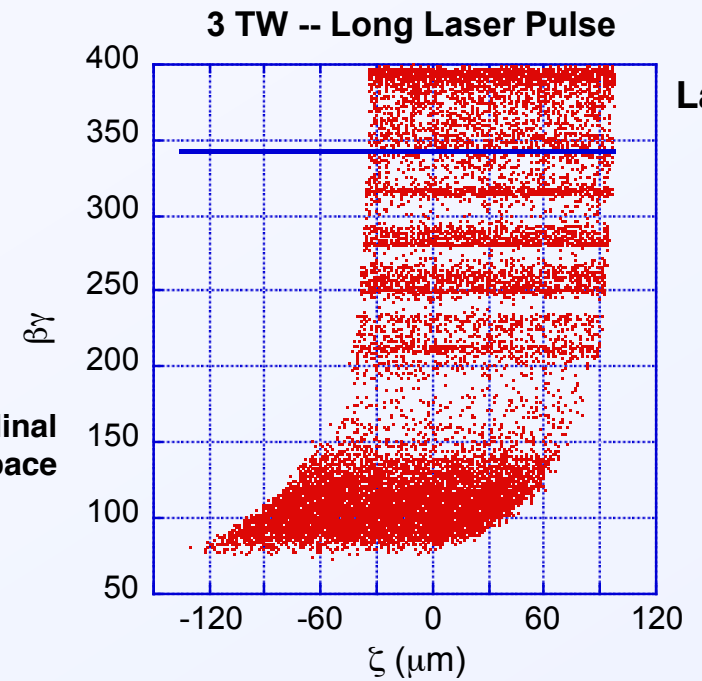
$$\frac{d\vec{p}}{dt} = e\left[\left(\frac{\vec{v}}{c}\times\vec{B}_w\right) + \vec{E}_L\left(1-\frac{v_z}{c}\right) + \hat{z}\left(\frac{\vec{v}}{c}\cdot\vec{E}_L\right)\right]$$

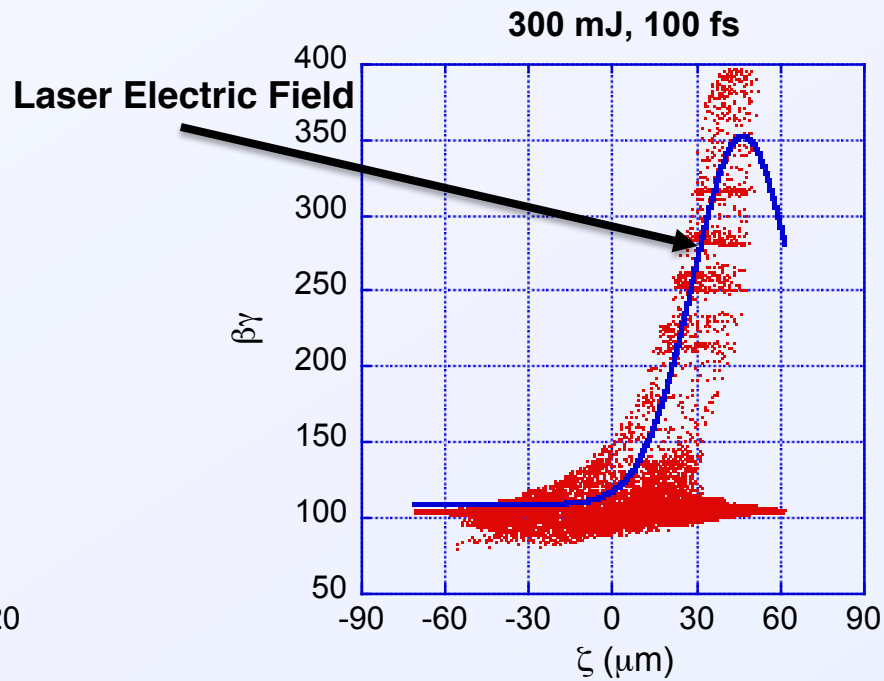
Wiggler field imported from measured data

Laser field computed assuming Gaussian pulse; includes phase fronts, Gouy phase shift

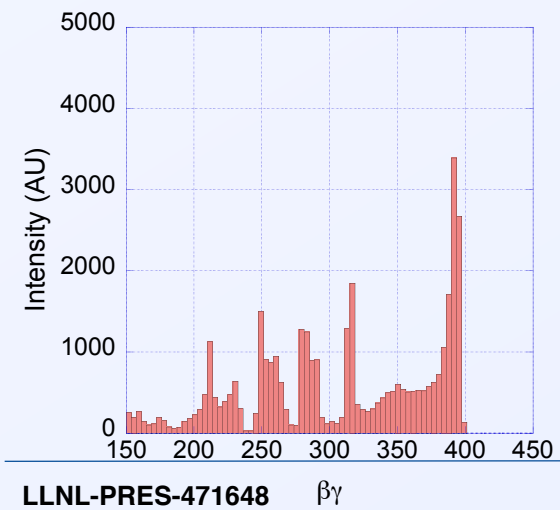
Long pulse versus short – short requires higher peak power

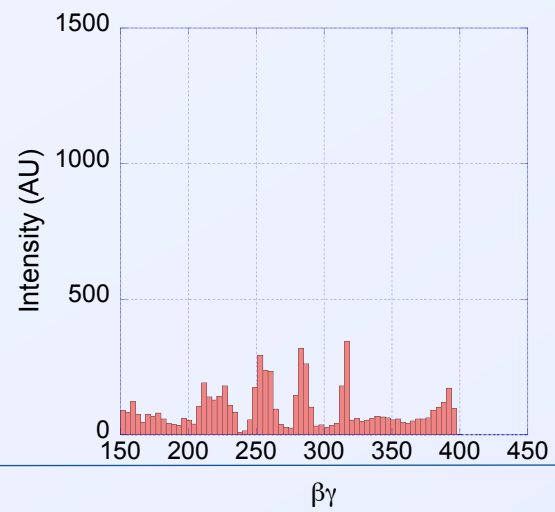
Longitudinal phase space



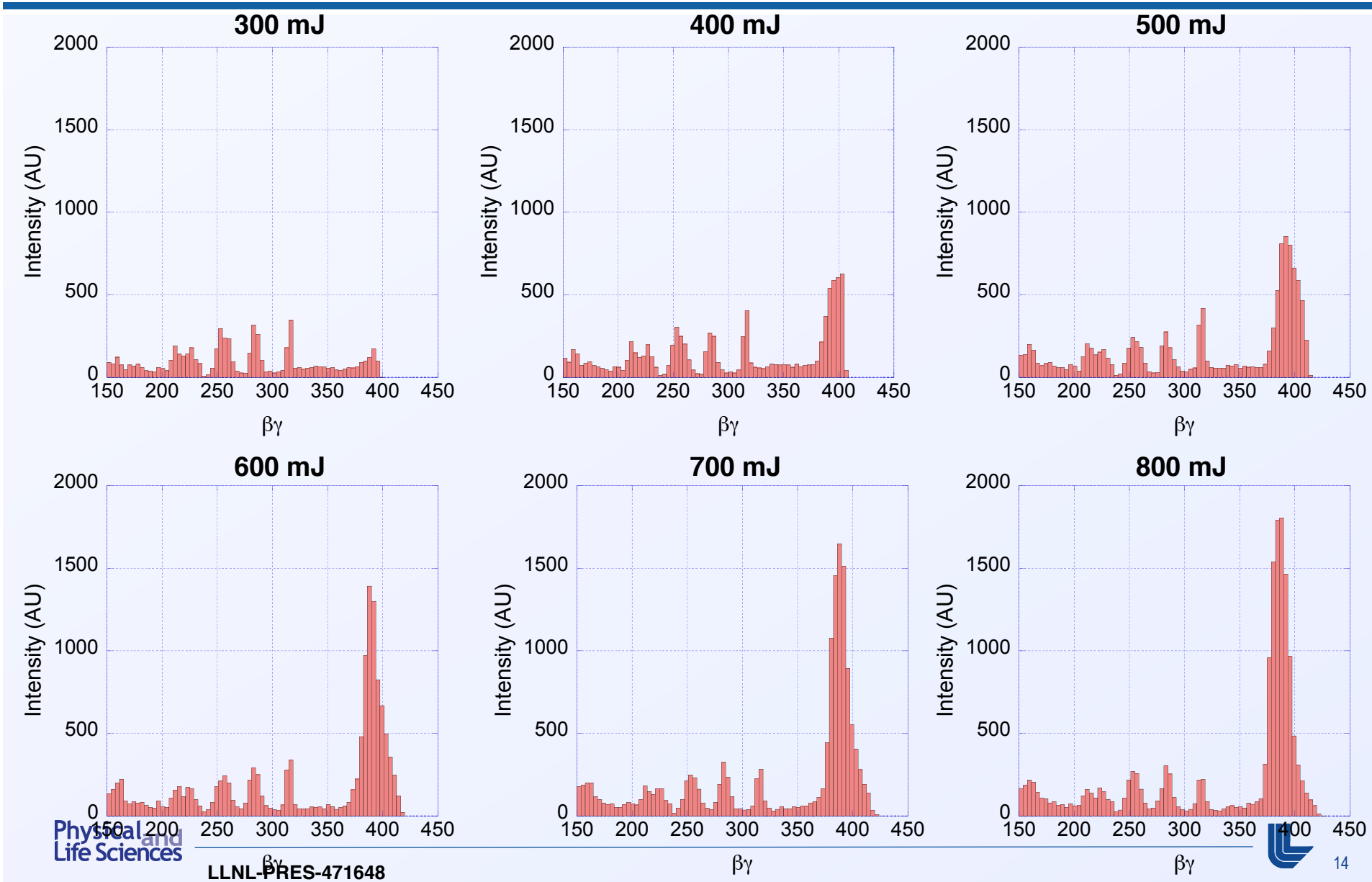


Momentum spectrum

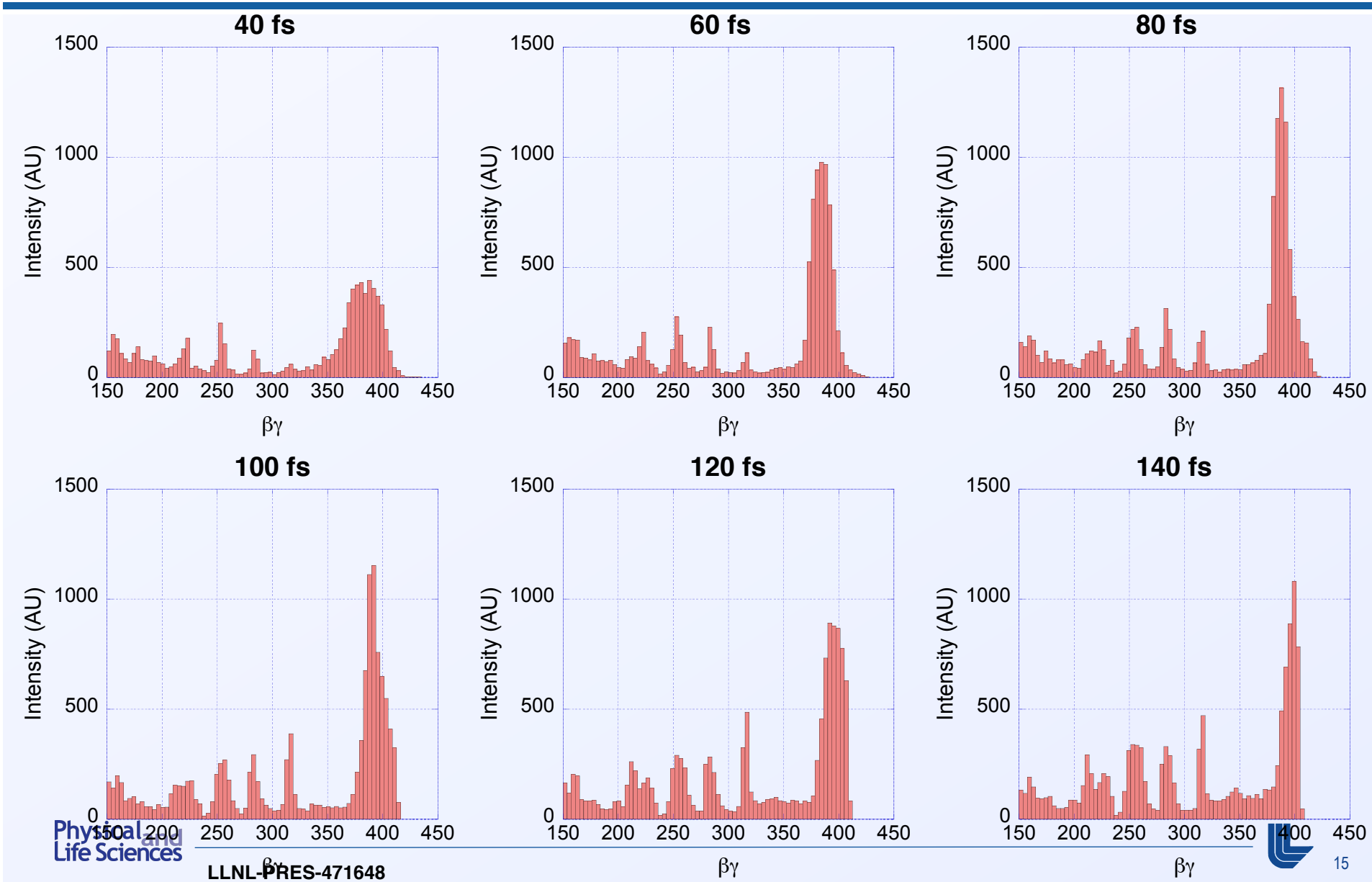




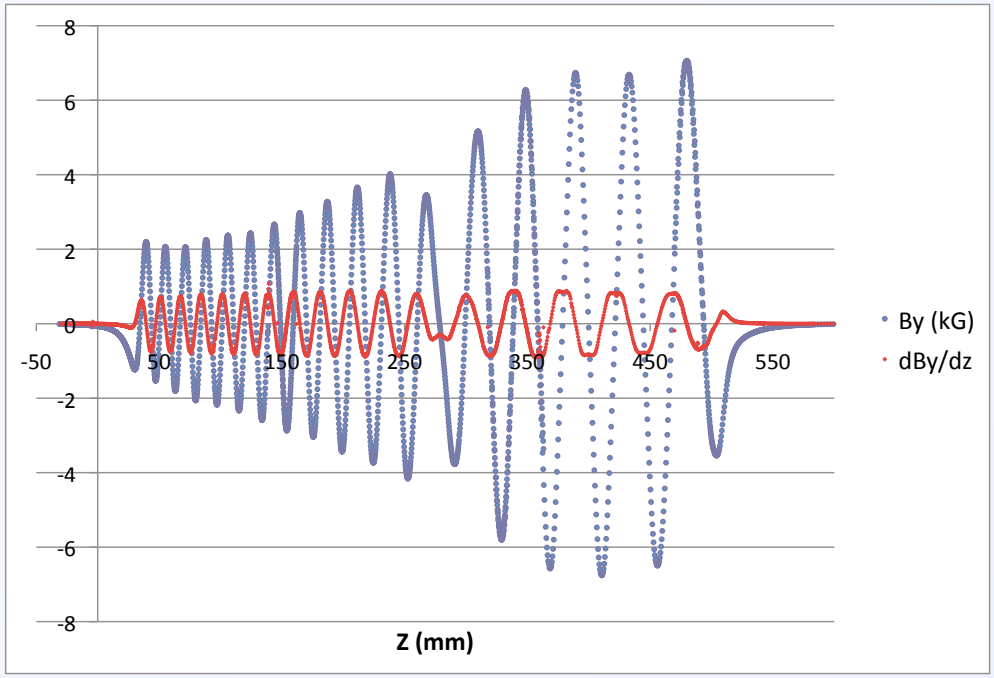
Spectrum versus laser energy @ 100 fs – final e- energy does not change, 'bucket' size does



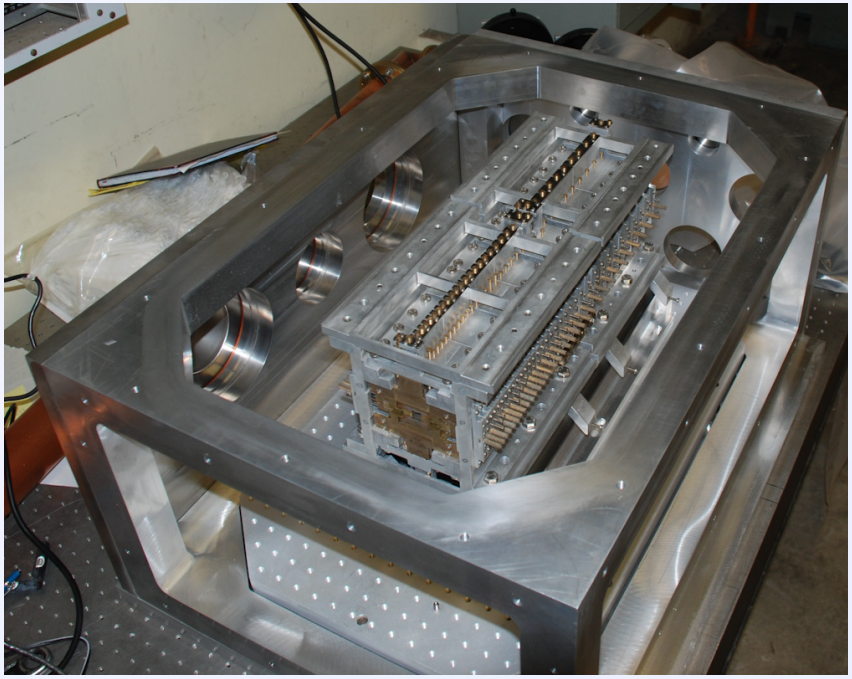
Laser pulse length dependence @ 550 mJ – 100 fs is roughly optimal



UCLA undulator is ready to be installed

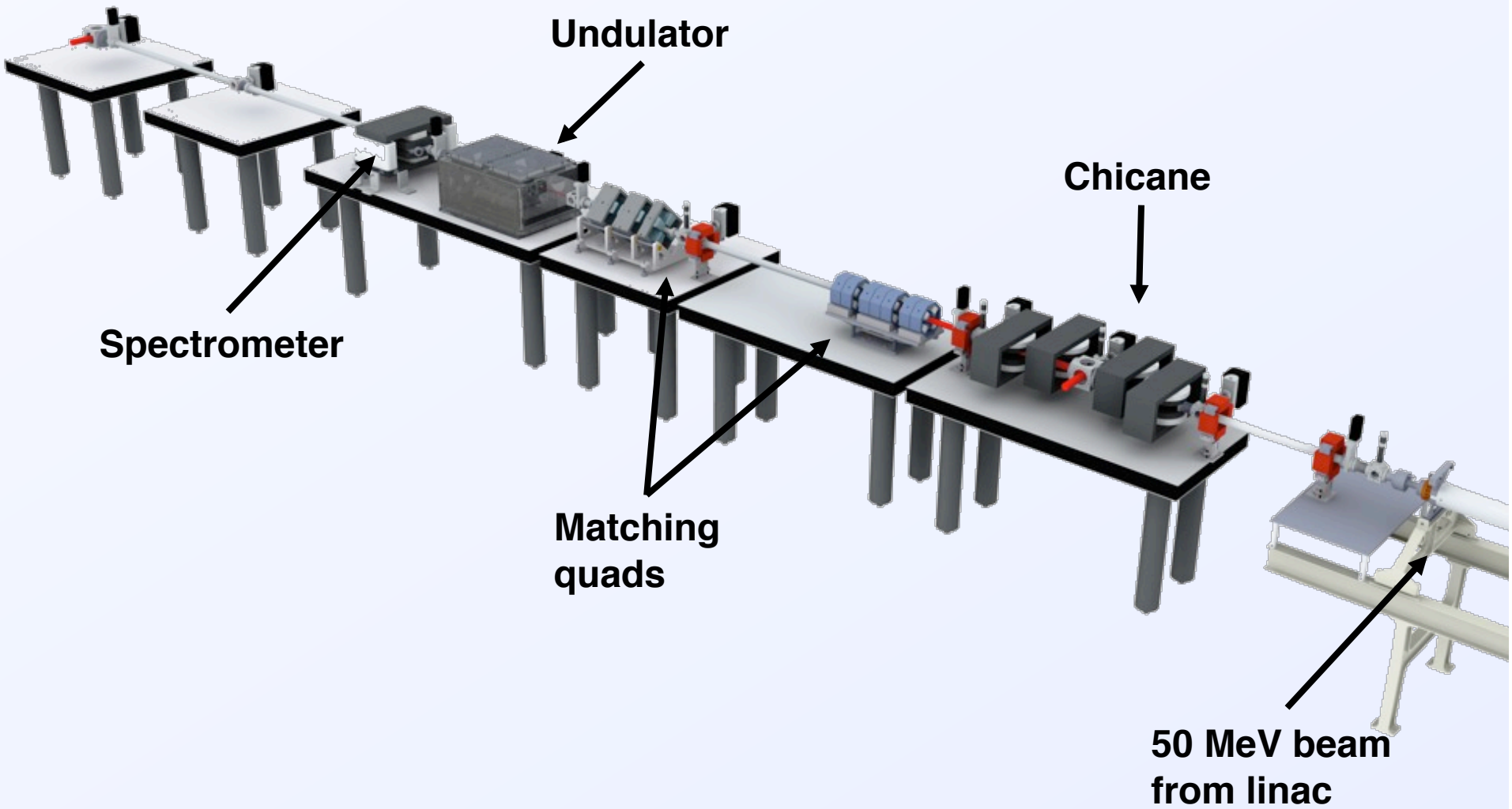


Measured undulator field. Data imported into simulation code



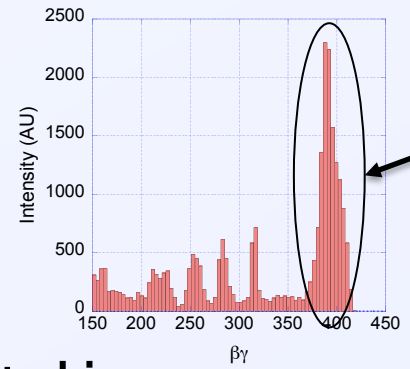
Undulator in vacuum chamber

IFEL beamline layout



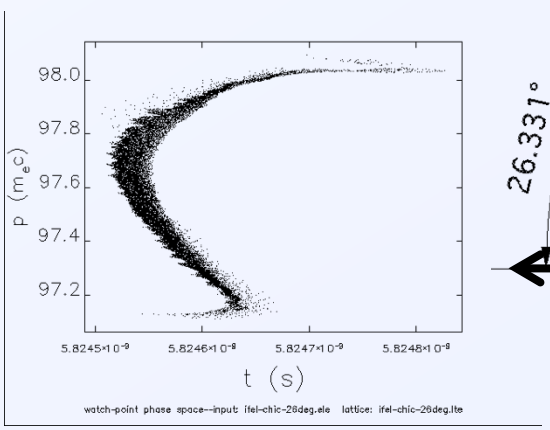
Electron bunch compression will be used to increase the amount of accelerated charge

- Requirements of injected e- beam:
  - 50 MeV (2 sections of B194 linac)
  - Only ~ 100 fs slice will be accelerated
- Cathode drive laser can be 100 fs
- Use novel 'blow-out' mode bunch generation + chicane compression for ultra-short e- bunch



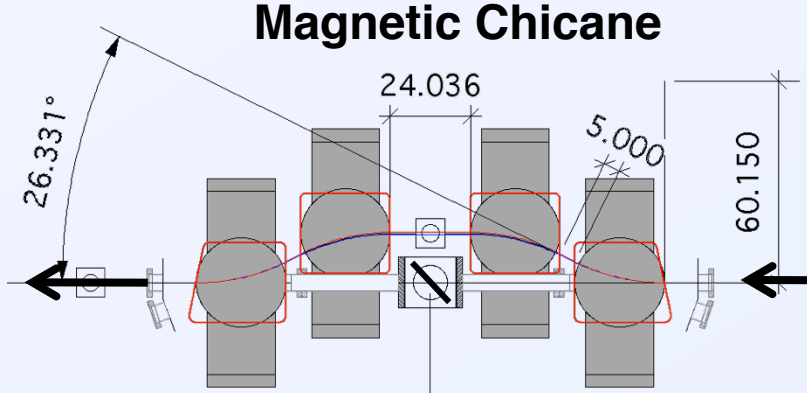
3.5pC per 100 Amps of beam current

Δt = 100 fs



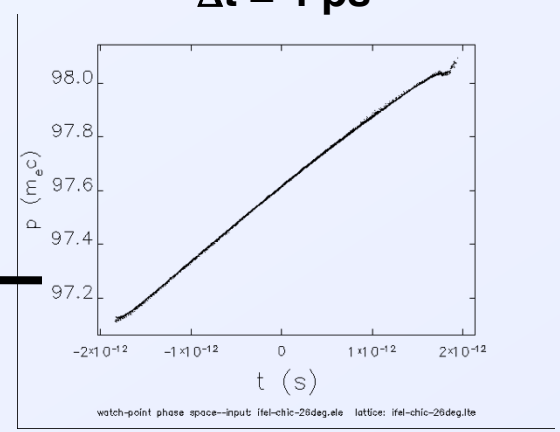
Longitudinal phase space after compression

Magnetic Chicane



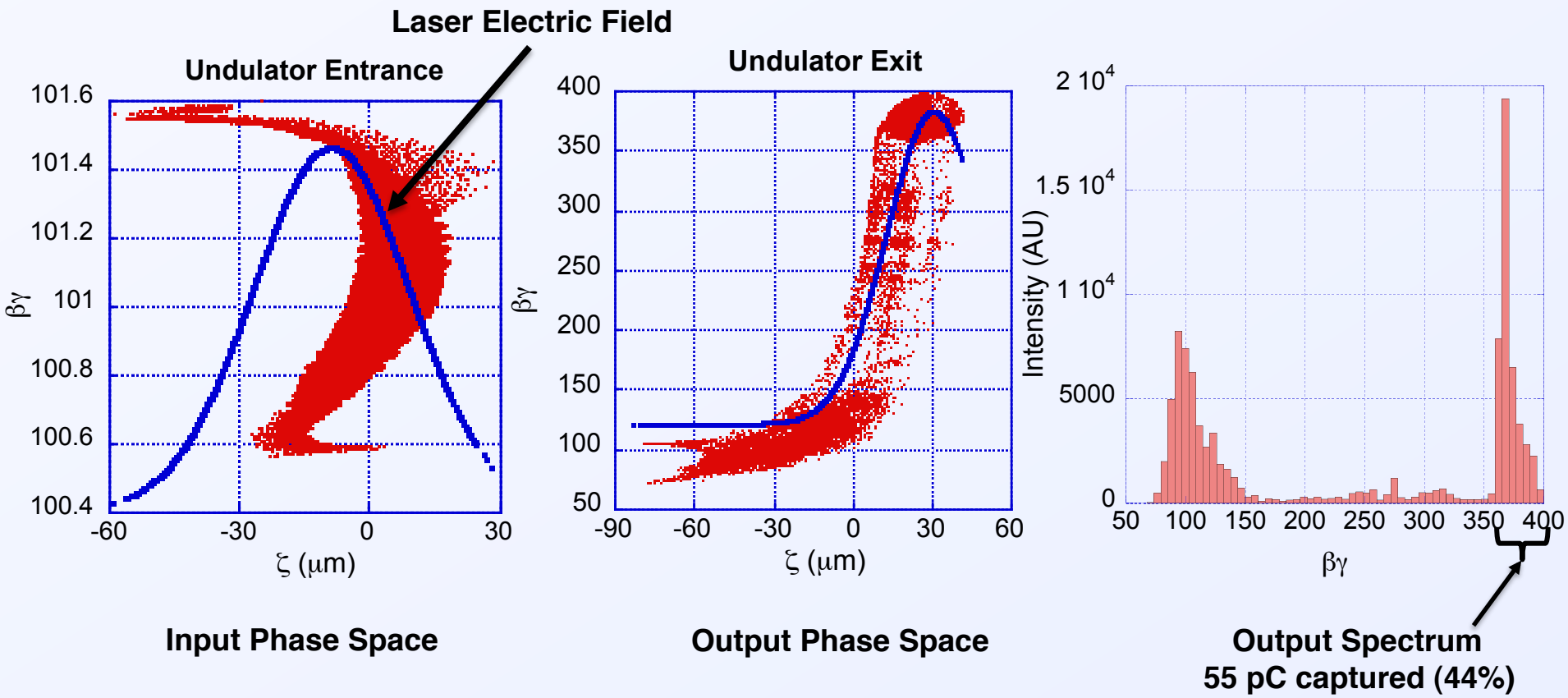
IFEL laser input port

Δt = 4 ps



Longitudinal phase space exiting linac

IFEL acceleration of the compressed e- beam



Input Phase Space

Output Phase Space

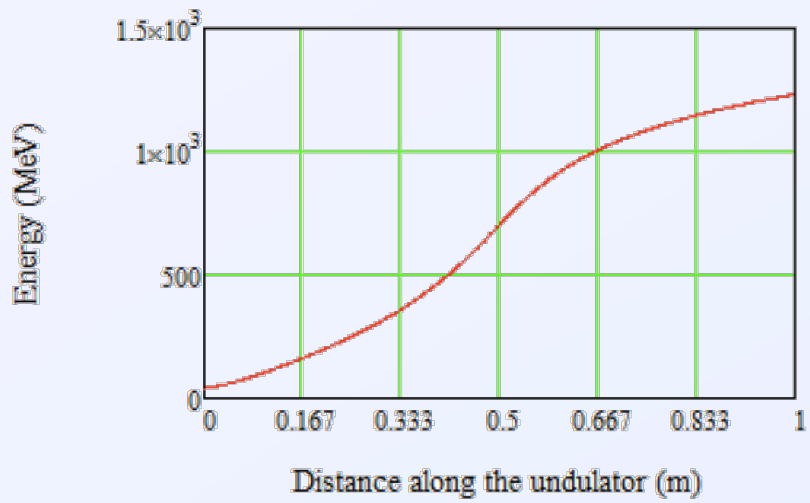
Output Spectrum
55 pC captured (44%)

Experimental Plan

- FY10
  - Install laser (front end + UV arm)
  - Procure vacuum compressor chamber
  - Finalize design of laser transport beamlines
  - Begin IFEL beamline installation
- FY11
  - Purchase/install laser (high power arm)
  - Complete beamline and laser transport construction
  - Perform e- beam blow-out mode + compression expts.
  - Plan and design IFEL diagnostics (overlap + spectrum meas.)
- FY12
  - Build/procure IFEL diagnostics
  - Perform IFEL acceleration expts.

Follow-on R&D needed for table-top, GeV, IFEL accelerators

- **IFEL beam dynamics studies**
  - UCLA novel 'linear' pre-buncher
  - 0.1%-level energy spread
- **500 MeV/m Helical IFEL**
  - Using existing laser
- **Ti:S IFEL recirculator**
- **3rd generation IFEL**
  - 1 GeV in 1 meter
  - Upgrade Amplitude laser to 4J ($2M)
- **High rep. rate, 0.5-1 GeV applications**
  - Compton scattering 10-20 MeV γ-rays
  - Stand-off detection
  - Polarized e+/e- pair creation
  - Soft X-ray FEL



Energy gain in preliminary GeV/m design