Demonstration of a cascaded optical IFEL

E. Hemsing

On behalf of

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SLAC National Accelerator Laboratory

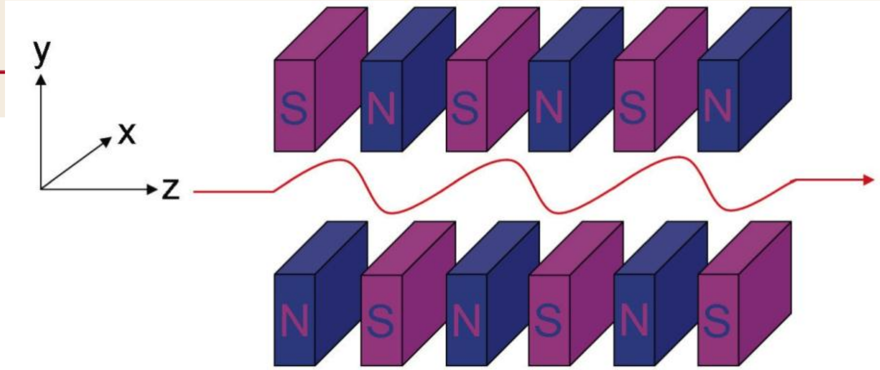
Outline

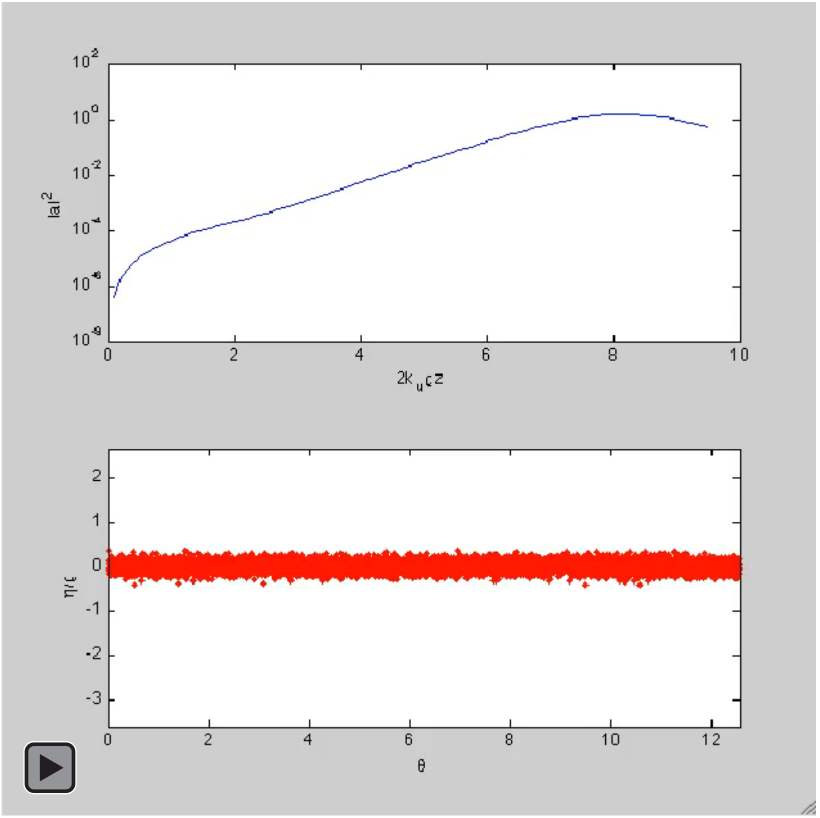
- IFEL Basics
- Relationship to FELs
- IFEL Tapering/Scaling
- Previous IFEL Experiments
- Improvements through cascading
- Potential Upgrades
- Applications in modern light sources

Free Electron Laser

- Wiggling electron beam exchanges energy with radiation field in undulator
- Radiation feeds back onto beam, modifying particle phase space distribution
- High-gain instability develops, e-beam develops microbunching at resonant wavelength
- Radiation power grows exponentially,

  E-beam loses energy





Radiation Power

Phase space

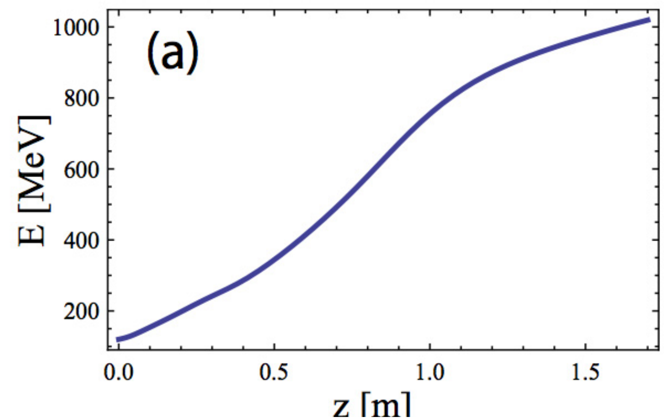
Inverse FEL

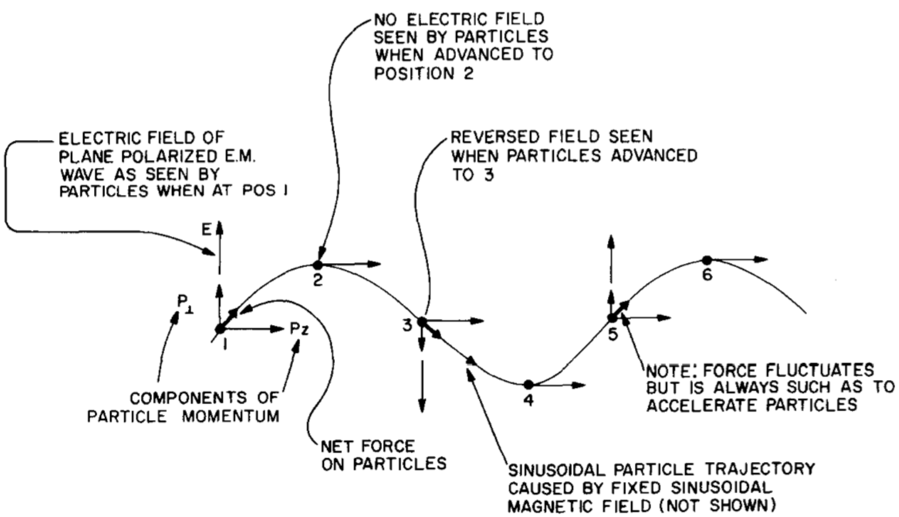
Relativistic electrons continuously accelerated by EM fields in undulator

Interaction of Relativistic Particles and Free Electromagnetic Waves in the Presence of a Static Helical Magnet*

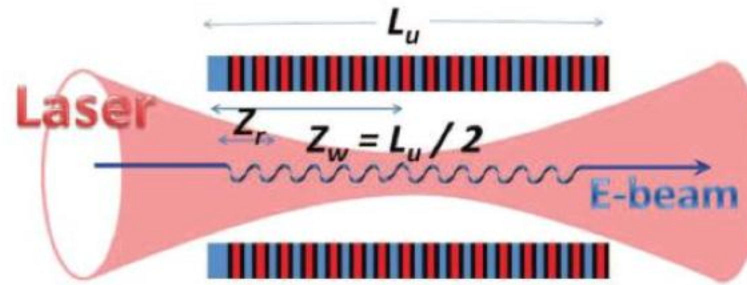
Robert B. Palmer
Brookhaven National Laboratory, Upton, New York 11973
(Received 23 December 1971)

It is shown that a particle passing along the axis of a helical magnet (in which the field is perpendicular to the axis and rotating as a function of position along the magnet) can be continuously accelerated by its interaction with circularly polarized radiation passing in the same direction. An example is given in which an electron is accelerated to 10 GeV, using a laser of 10^{14} W. A second example shows how pions and kaons might be separated at momenta over 1000 GeV. It is further shown that bunched charged particles passing down the helical magnet will radiate coherent circularly polarized electromagnetic waves, and it is speculated that the required bunching may under some circumstances be self-generating. An example is shown in which a 10-A current of 15-MeV electrons is used to generate a 75-MW beam of 10-μ radiation





J. Appl. Phys., Vol. 43, No. 7, July 1972



(Courtesy J. Duris - UCLA)

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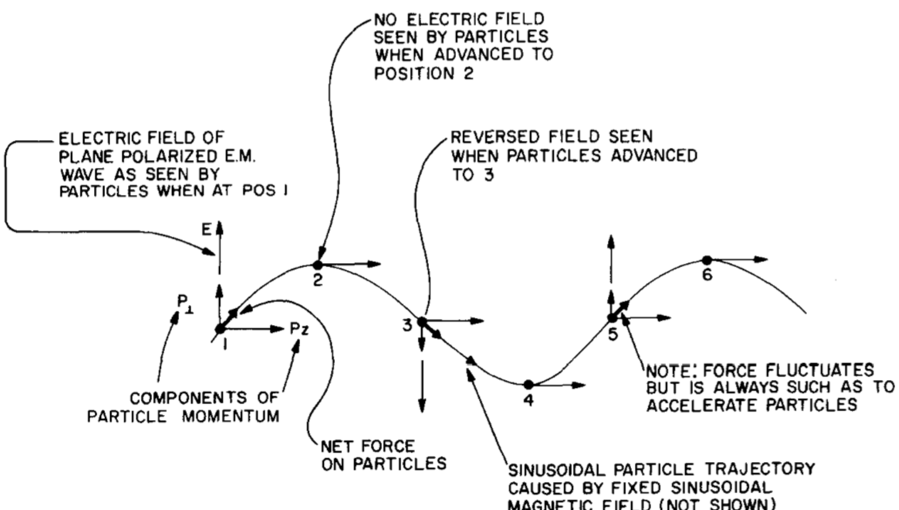

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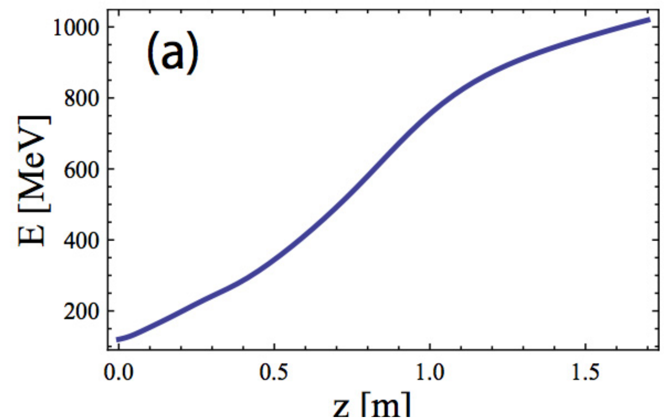

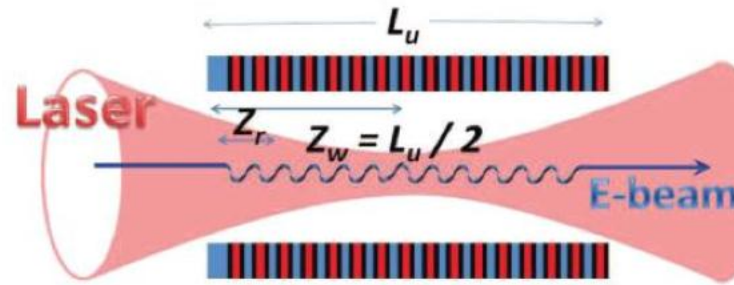

(Courtesy J. Duris - UCLA)

IFEL basics

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- As beam energy change, tuning of undulator must also change to maintain resonance.
- Optimal tapering is obtained by matching resonant energy change with available driving field gradient

Undulator strength

$$K = \frac{qB\lambda_u}{2\pi mc}$$

Laser strength

$$K_l = \frac{qE\lambda}{2\pi mc^2}$$

Resonance condition

$$\gamma^2 = \frac{\lambda_u}{2\lambda}\left(1 + \frac{K^2}{2}\right)$$

Energy change

$$\frac{d\gamma^2}{dz} = \frac{2\pi K K_l}{\lambda}\sin\phi$$

Eg: Taper undulator K

$$\frac{dK}{dz} = \frac{4\pi K_l}{\lambda_u}\sin\phi$$

IFEL scaling

SLAC

PHYSICAL REVIEW A VOLUME 32, NUMBER 5 NOVEMBER 1985

High-energy inverse free-electron-laser accelerator

E. D. Courant
Brookhaven National Laboratory, Upton, New York 11973
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Brookhaven National Laboratory, Upton, New York 11973
(Received 14 June 1984; revised manuscript received 28 June 1985)

We study the inverse free-electron-laser (IFEL) accelerator and show that it can accelerate electrons to the few hundred GeV region with average acceleration rates of the order of 200 MeV/m. Several possible accelerating structures are analyzed, and the effect of synchrotron-radiation losses is studied. The longitudinal phase stability of accelerated particles is also analyzed. A Hamiltonian description, which takes into account the dissipative features of the IFEL accelerator, is introduced to study perturbations from the resonant acceleration. Adiabatic invariants are obtained and used to estimate the change of the electron phase-space density during the acceleration process.

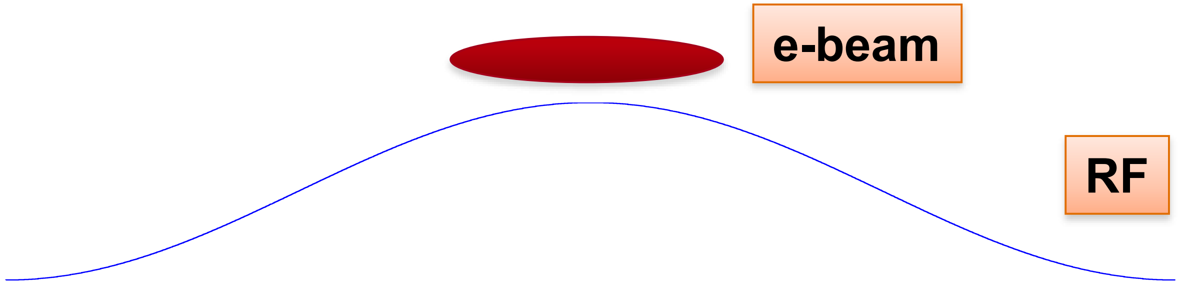
Several methods to taper, each with different scaling

- Constant K
- Constant λ_u
- Constant B

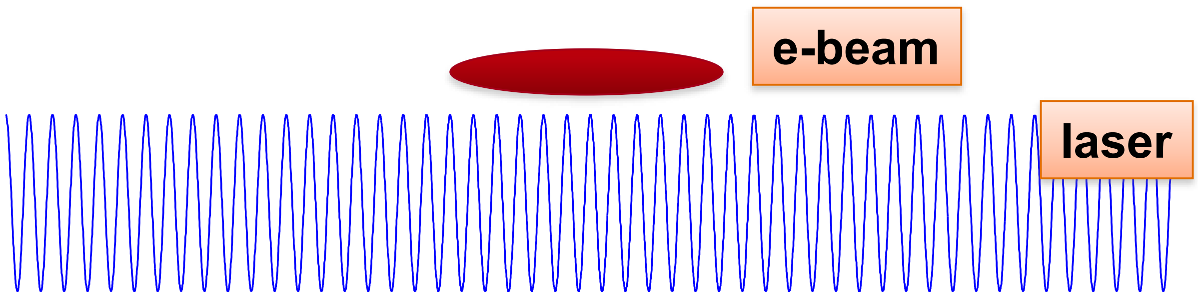
- Including the effects of radiation losses, it turns out that only constant K has no maximum in obtainable electron energy.
- Practically difficult: λ_u must increase while B decreases
- A modest energies (~<1GeV), radiation losses are more limited and more aggressive tapering can be used.

RF vs Laser Acceleration

- Entire ~ps e-beam sits within RF wavelength
- All electrons see similar accelerating fields



- e-beam sits over many laser wavelengths
- electrons see all phases - both accelerating and decelerating fields



Phase space evolution during IFEL acceleration

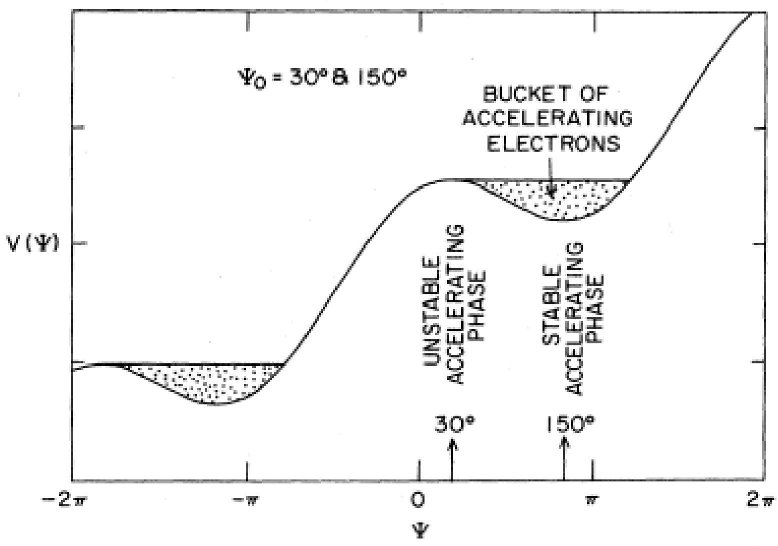
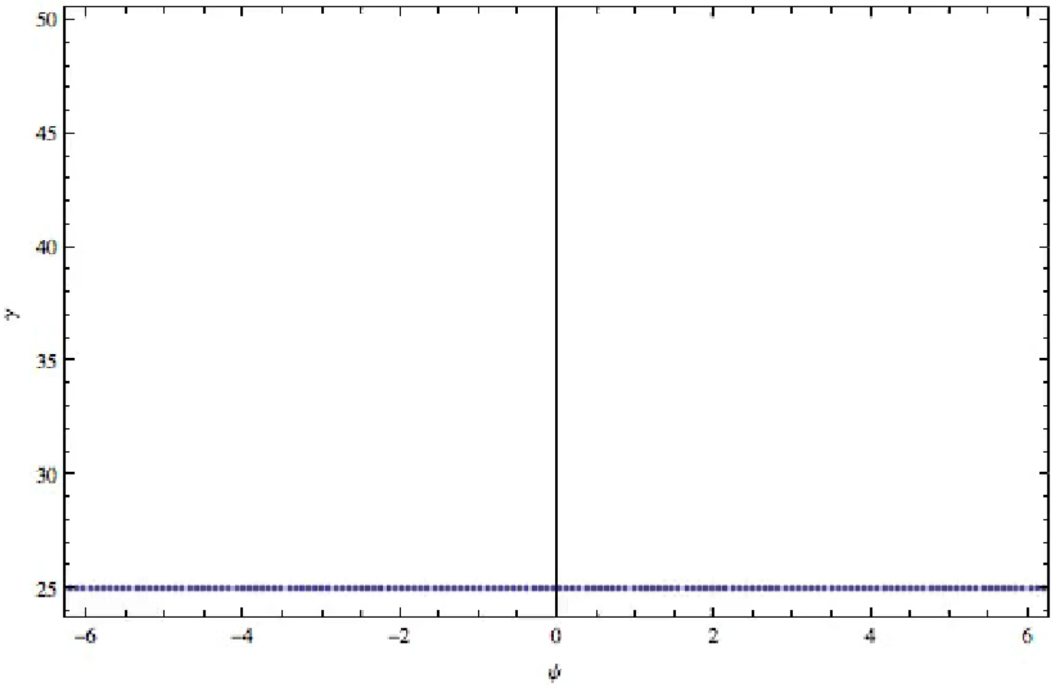


FIG. 5. Binding potential $V(\phi)$ for accelerating electrons.



Some historical IFEL experiments

- @1.6 mm: *Wernick, I., and T. C. Marshall, Phys. Rev. A 46, 3566 (1992)*
- @microwaves: *Yoder, R. B., T. C. Marshall, and J. L. Hirshfield, Phys. Rev. Lett. 86, 1765 (2001)*
- @10.6 um: *van Steenbergen, A., J. Gallardo, J. Sandweiss, and J.-M. Fang, Phys. Rev. Lett. 77, 2690. (1996)* & *Musumeci, P., et al., Phys. Rev. Lett. 94, 154801 (2005)* [2nd undulator harmonic]
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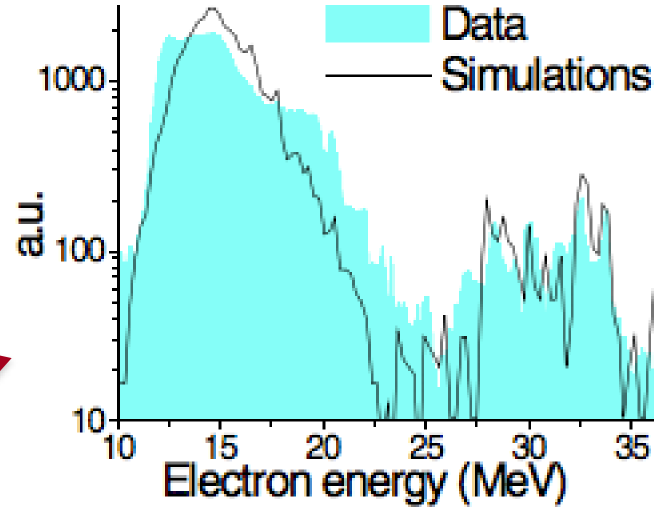
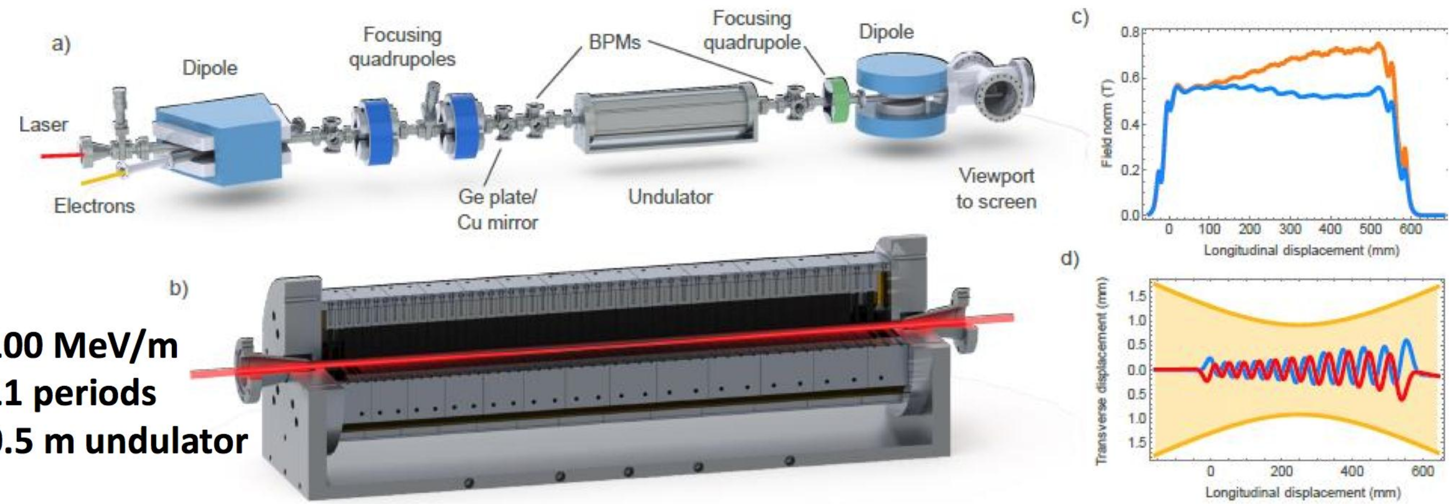
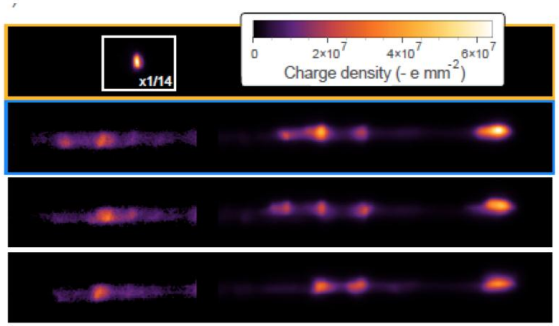


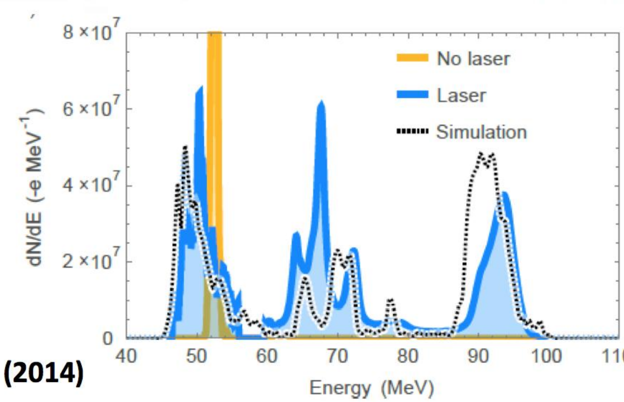
Recent Rubicon IFEL experiment@BNL-ATF

- Rubicon IFEL experiment recently demonstrated high quality acceleration of 50 MeV e-beam at BNL ATF in a strongly tapered helical undulator



100 MeV/m
11 periods
0.5 m undulator

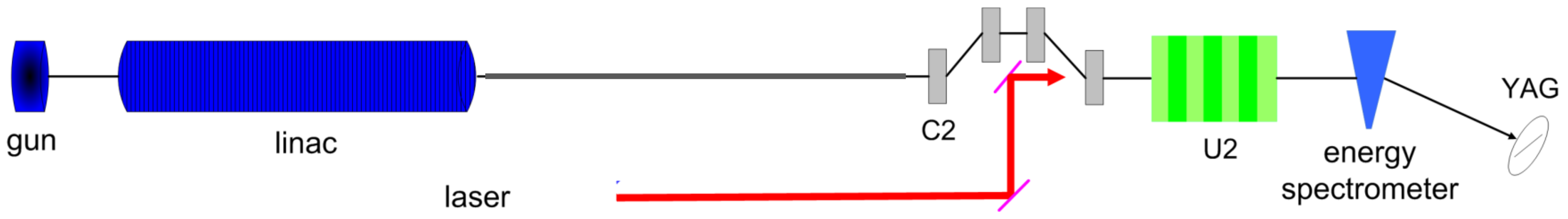




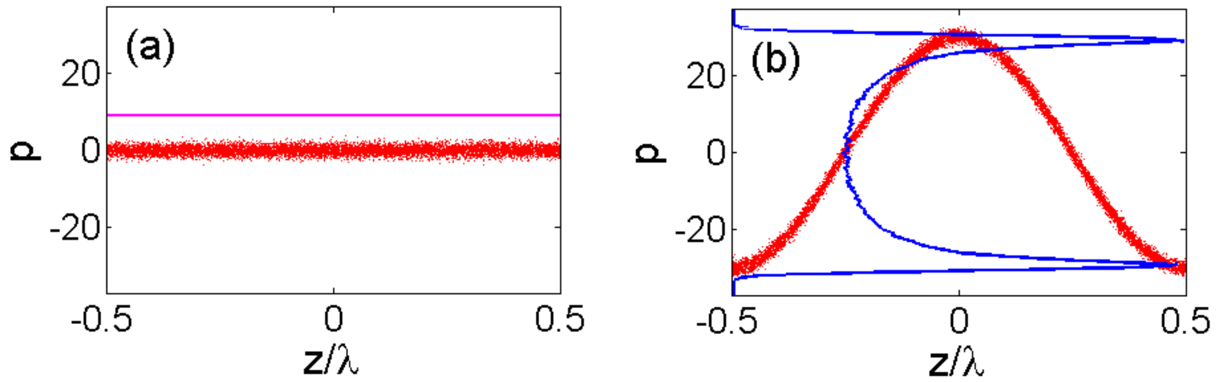
Nat. Commun. 5:4928 doi: 10.1038/ncomms5928 (2014)

(Courtesy J. Duris - UCLA)

Cascaded IFEL for improved efficiency



• Single Stage



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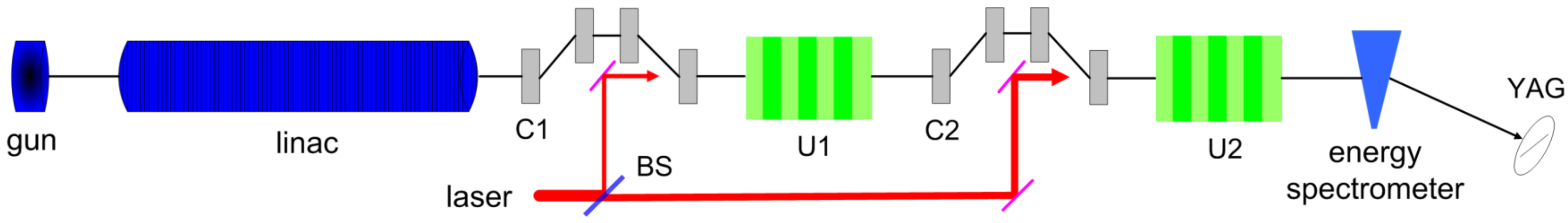
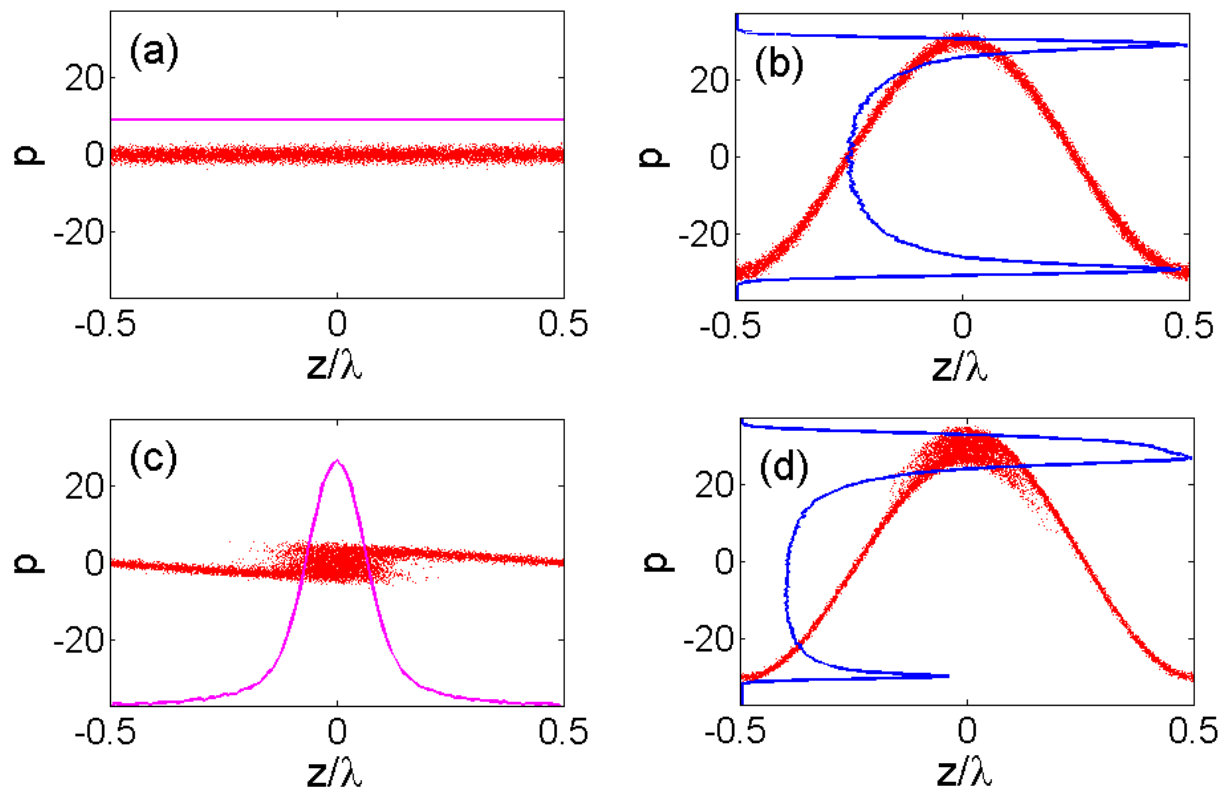
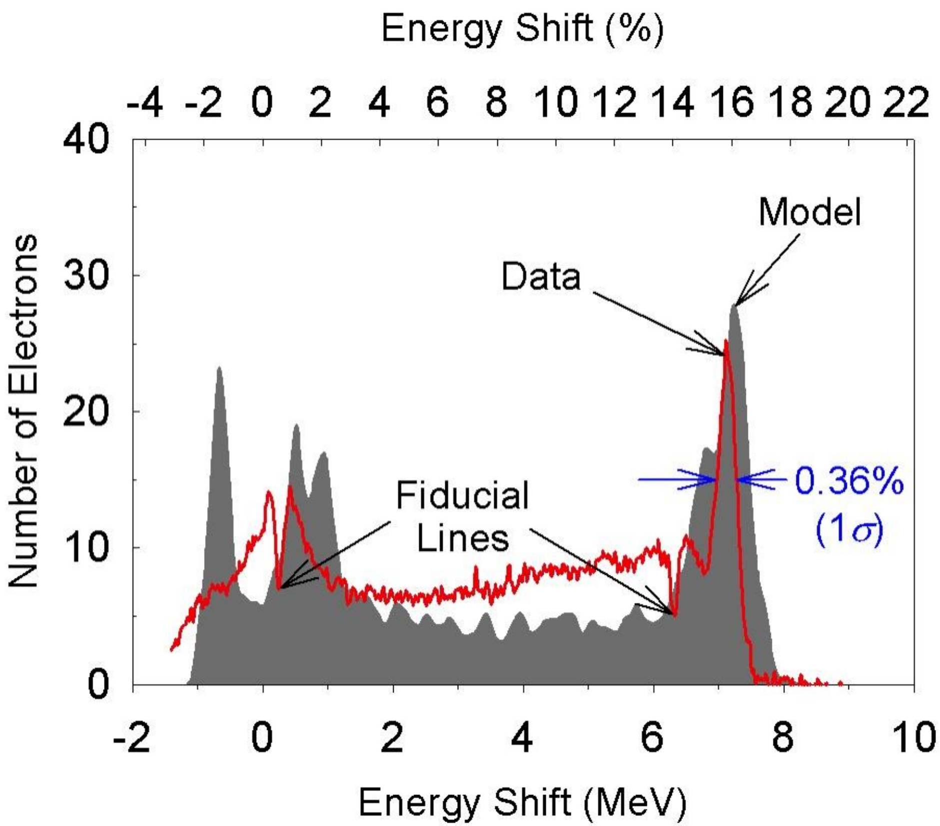


- Single Stage
- Double Stage



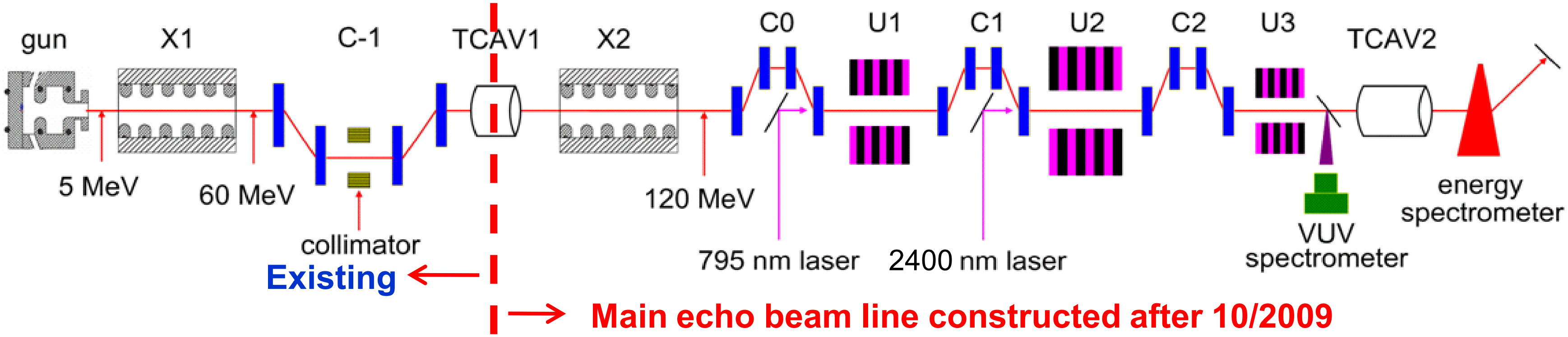
Two stage IFEL at 10.6 um



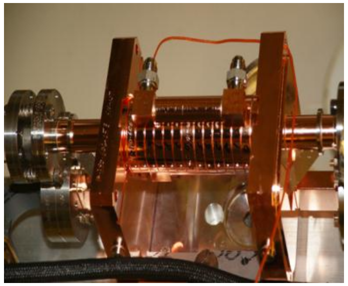
- ~80% of the electrons captured and accelerated
- 14% boosted by 7 MeV with a 0.36% relative energy spread

Kimura, W. D, et al., Phys. Rev. Lett. 92, 054801 (2004)

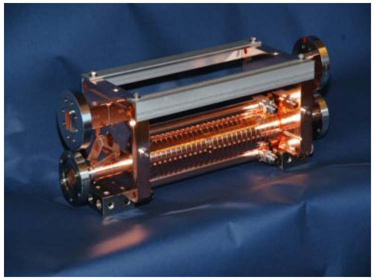
Echo Experiment at SLAC's NLCTA

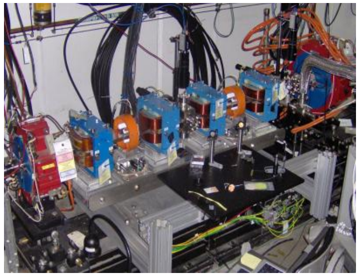


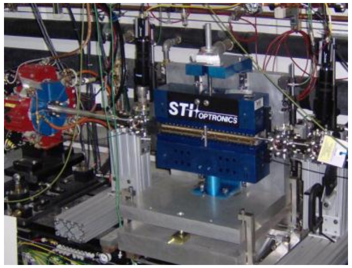

C-1


TCAV1


X2

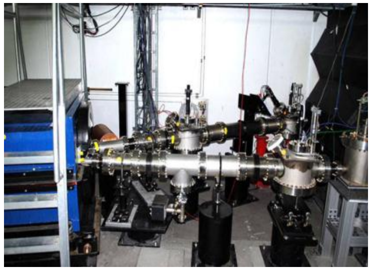

TCAV2


C1



U1

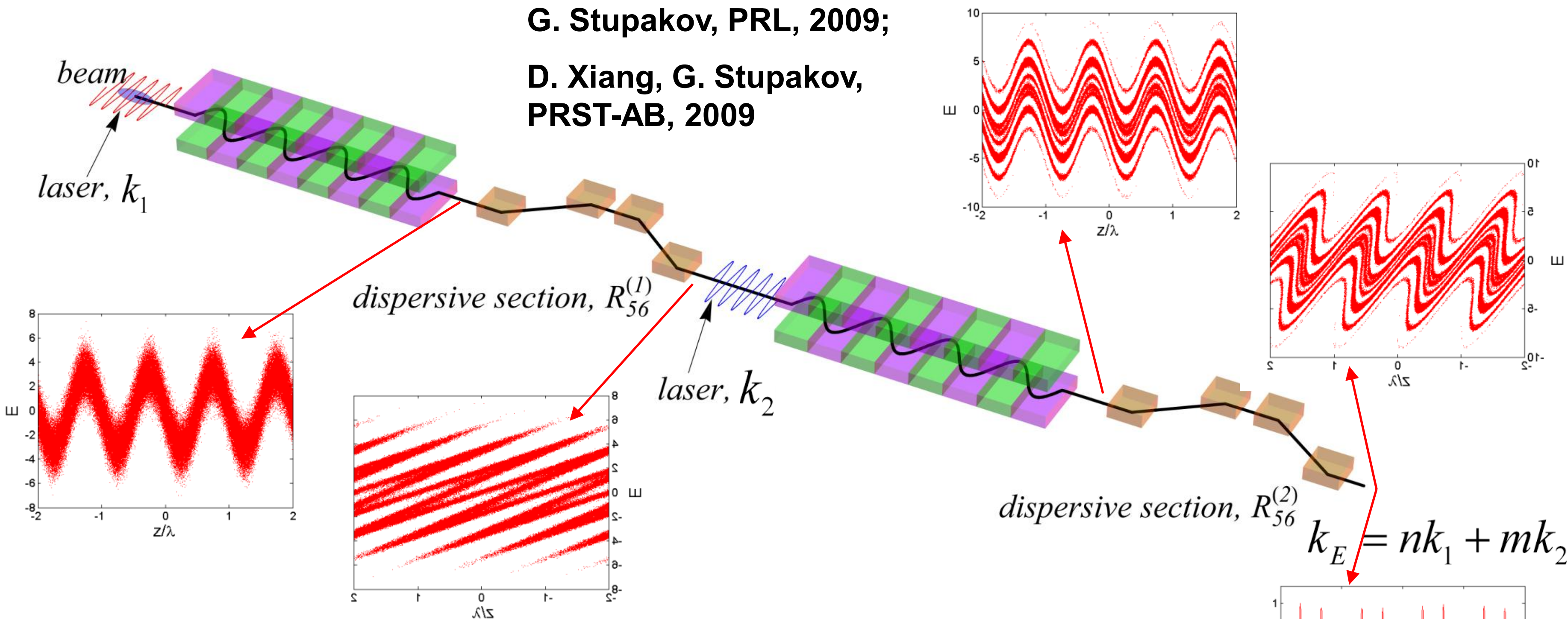
U2


spectrometer

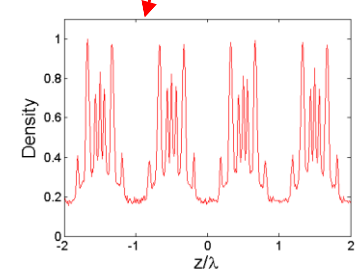
Echo-Enabled Harmonic Generation (EEHG)

G. Stupakov, PRL, 2009;

D. Xiang, G. Stupakov, PRST-AB, 2009

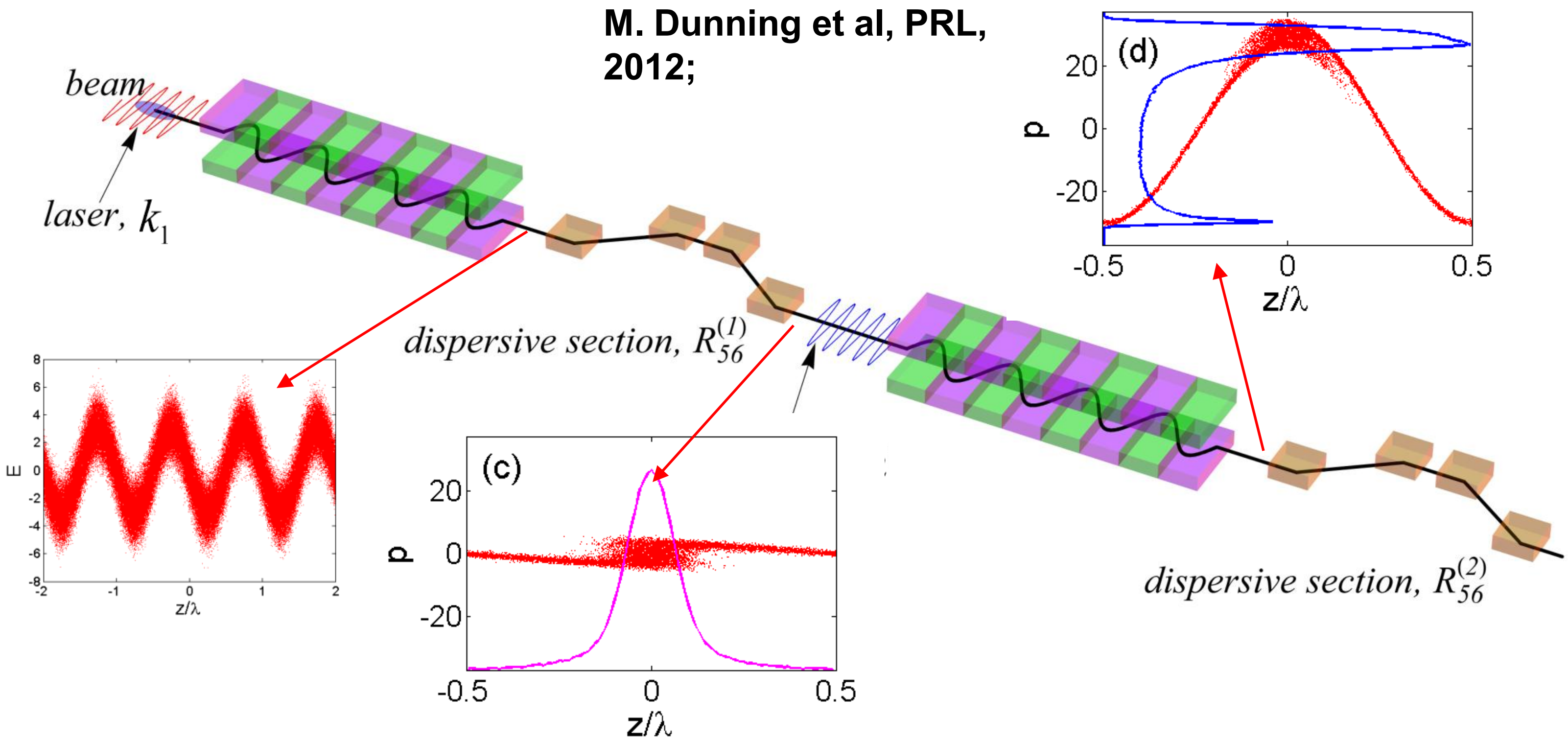


- First laser generates energy modulation in electron beam
- First strong chicane stratifies the longitudinal phase space
- Second laser imprints energy modulation
- Second chicane converts energy modulation into harmonic density modulation



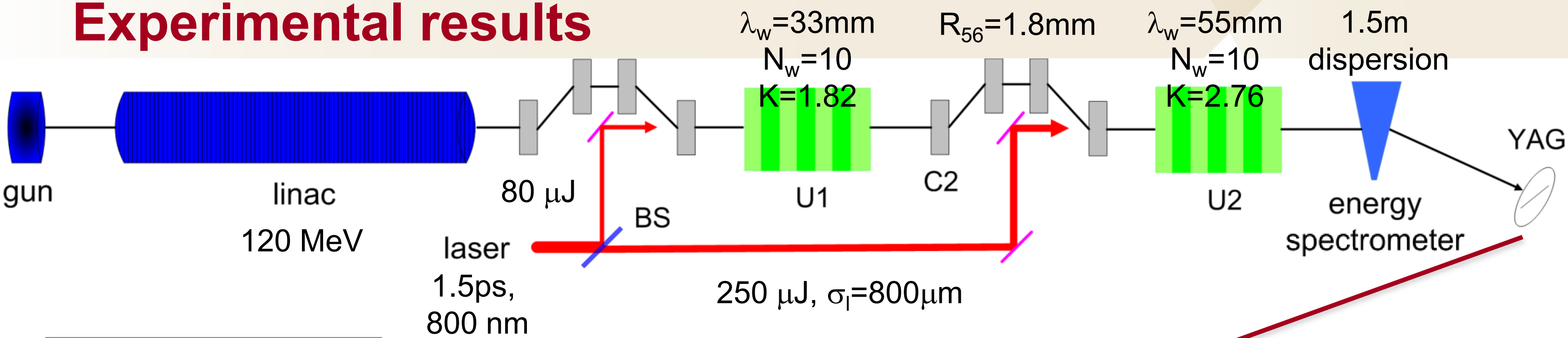
Cascaded Optical IFEL

M. Dunning et al, PRL, 2012;

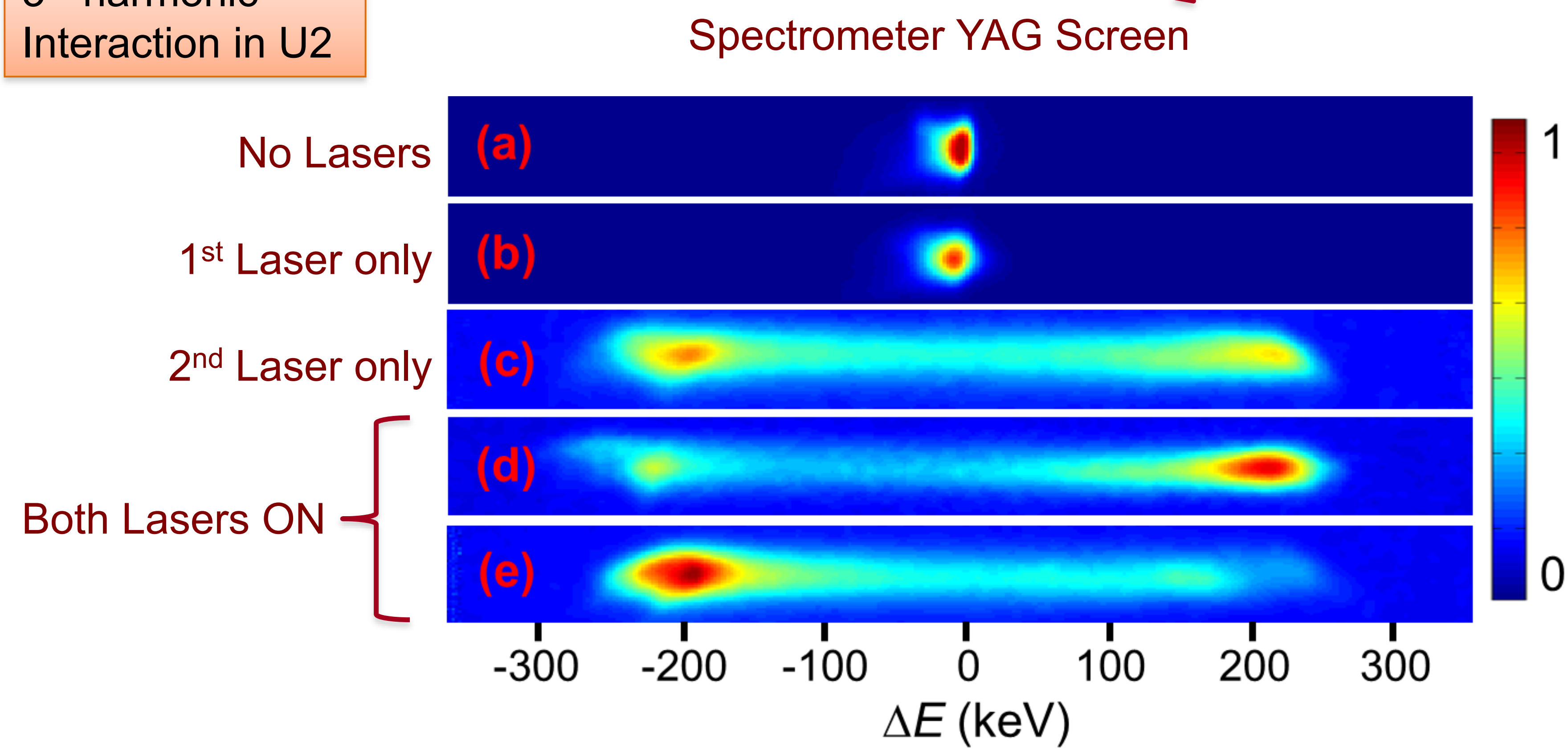


- First laser generates energy modulation in electron beam
- First chicane generates density bunching
- Second laser imprints large energy modulation

Experimental results



3rd harmonic
Interaction in U2

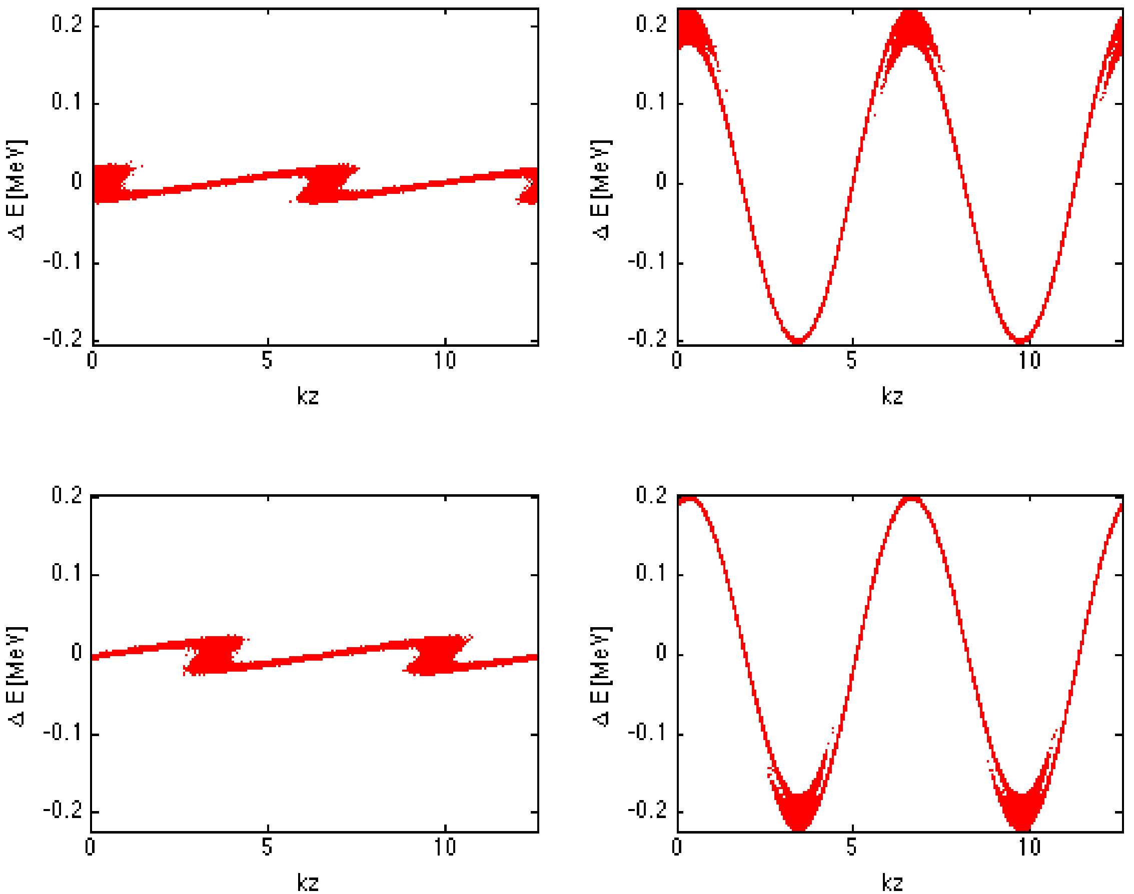


Acceleration/Deceleration Jitter

After chicane | After Laser 2

Accelerating Phase

Decelerating Phase



Stability

- Energy jitter plus dispersion leads to jitter in particles' longitudinal position

$$\Delta z = R_{56}\Delta E_j / E$$

- The dispersion is set to optimize bunching from first laser modulation

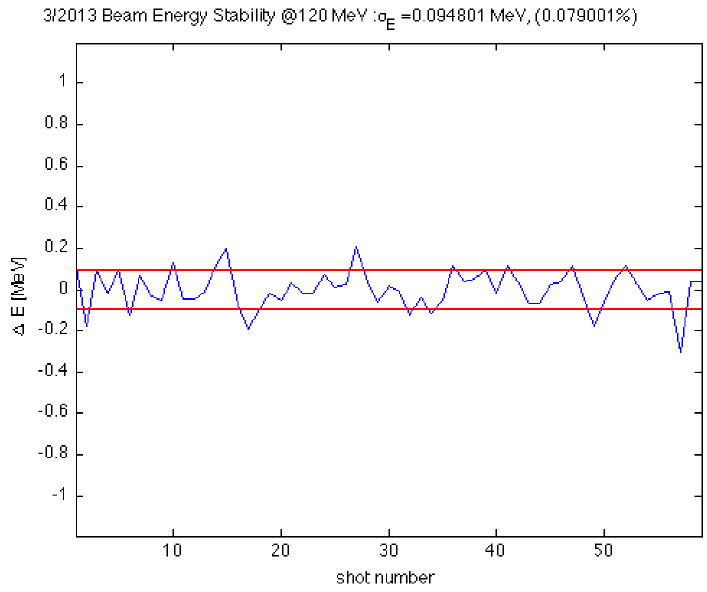
$$R_{56}\frac{\Delta E_{LM}}{E} = \frac{\lambda}{4}$$

- Desirable to keep position jitter much less than λ/4 to maintain IFEL acceleration

$$\Delta z = \frac{\lambda}{4}\frac{\Delta E_j}{\Delta E_{LM}} < \frac{\lambda}{4}$$

- Thus, laser modulation must be larger than intrinsic system energy jitter

$$\Delta E_j < \Delta E_{LM}$$



NLCTA: $\Delta E_j/E \leq 0.1\%$
$\Delta E_j \approx 100$ keV
$\Delta E_{LM} \approx 20$ keV

Not the case in the experiment

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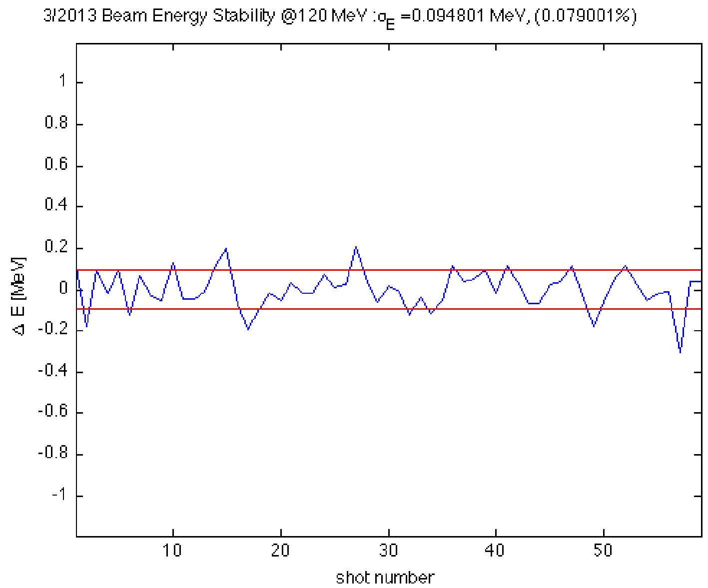

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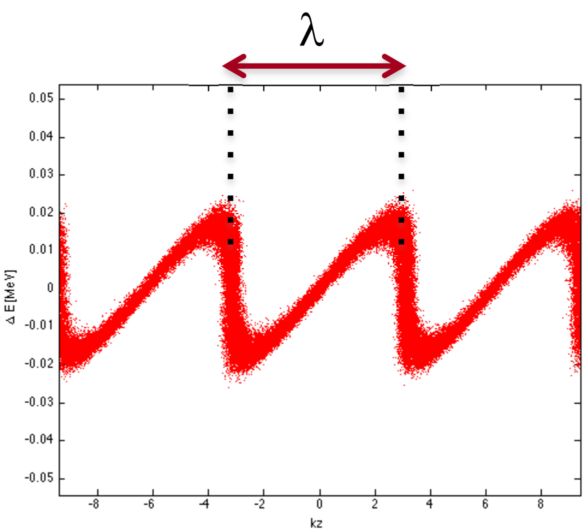
Phase Space Structure Effects

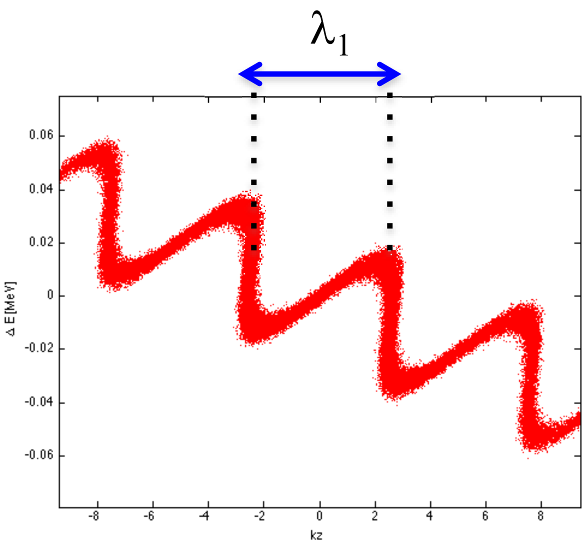
Linear energy-time chirp on beam leads to shift in bunching wavelength after R_{56}

$$\lambda_1 = (1 + hR_{56})\lambda$$

Chirp:

$$h = \frac{d\delta}{dz}$$





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Chirp:

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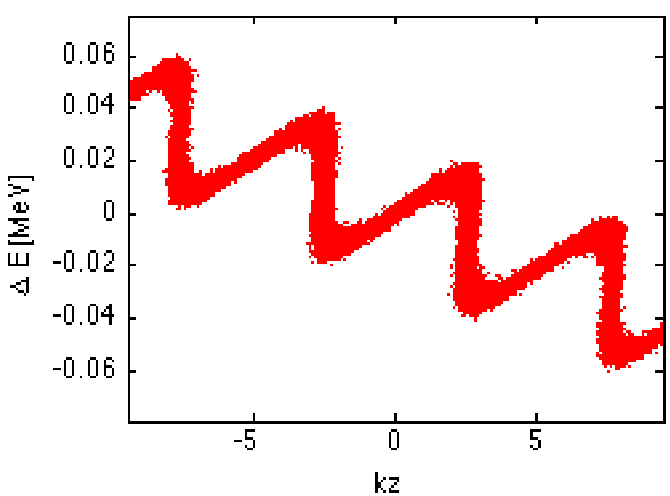
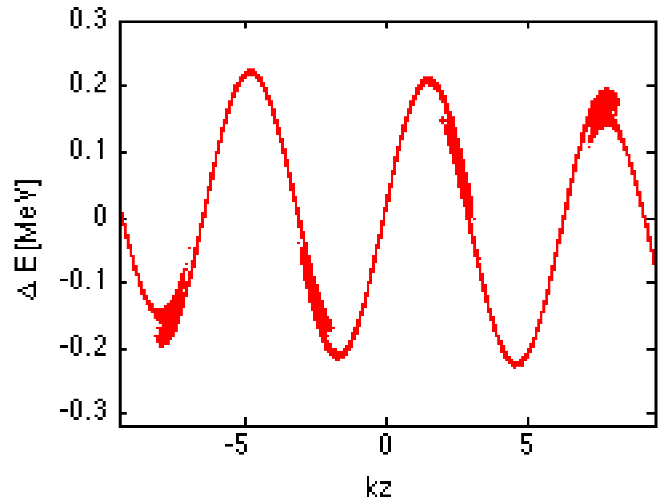
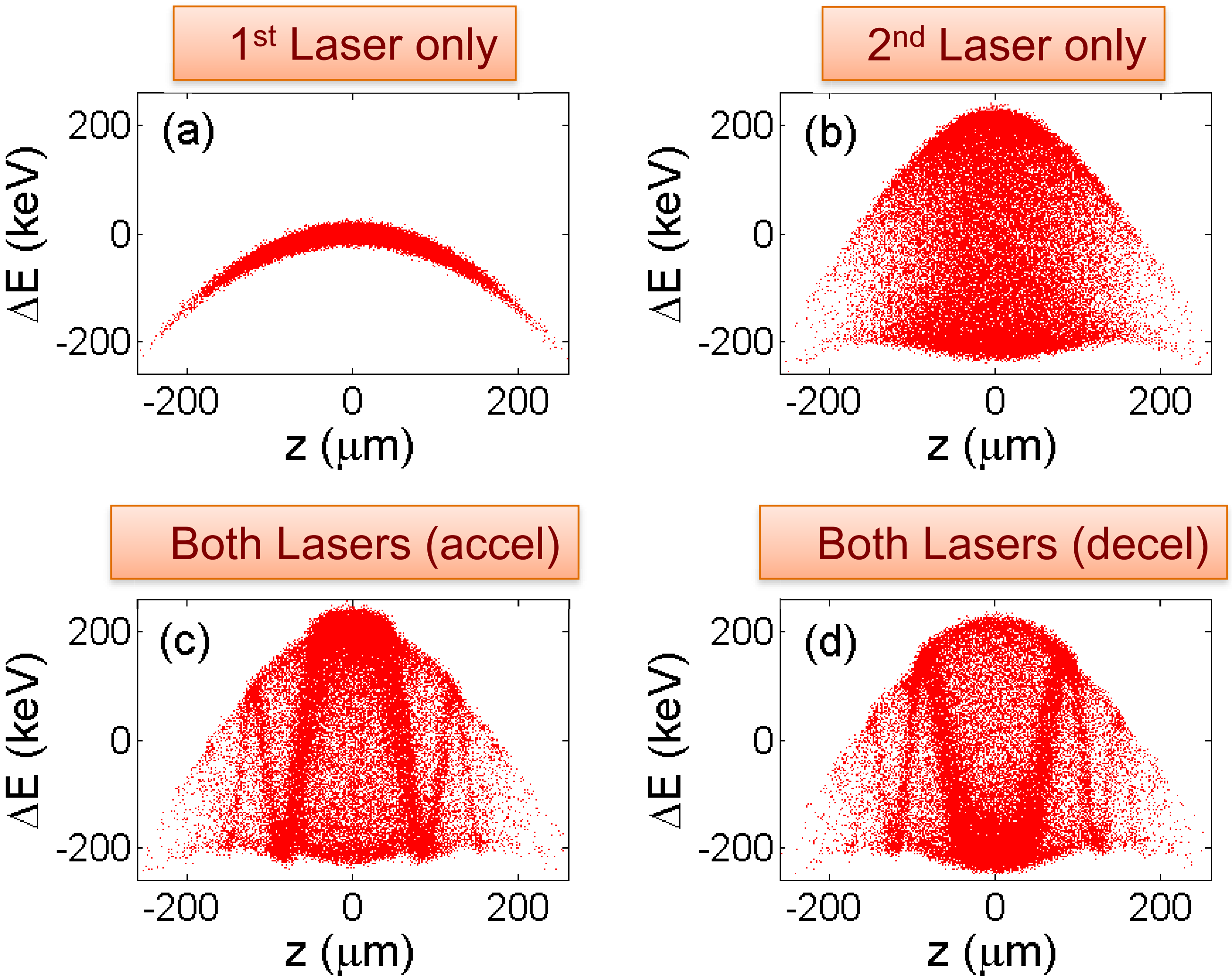
As a result, the bunching has different periodicity than drive laser fields, so bunches sample different phases in the IFEL laser field





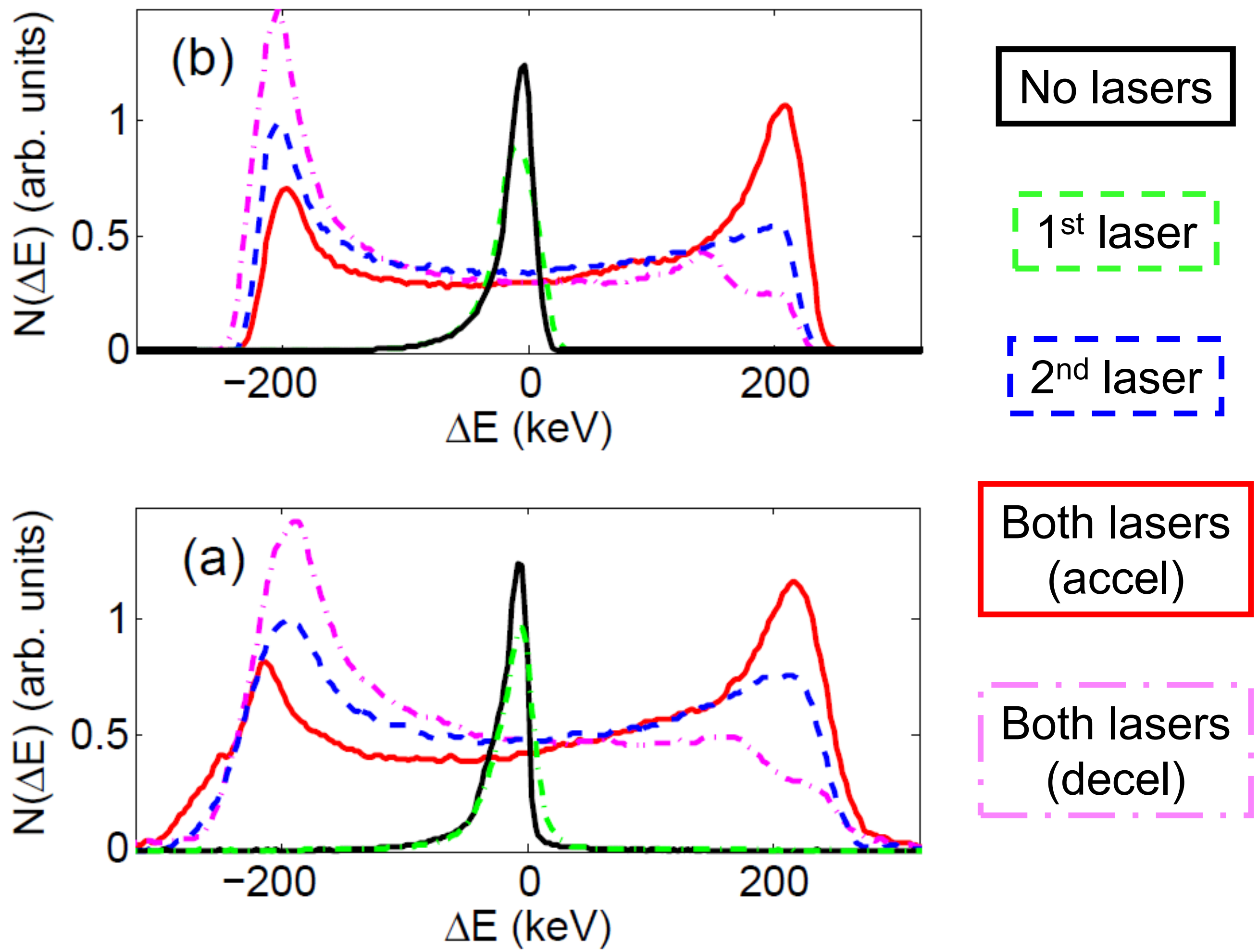
Effects of Phase Space Curvature



Benchmarking Simulations

Simulations

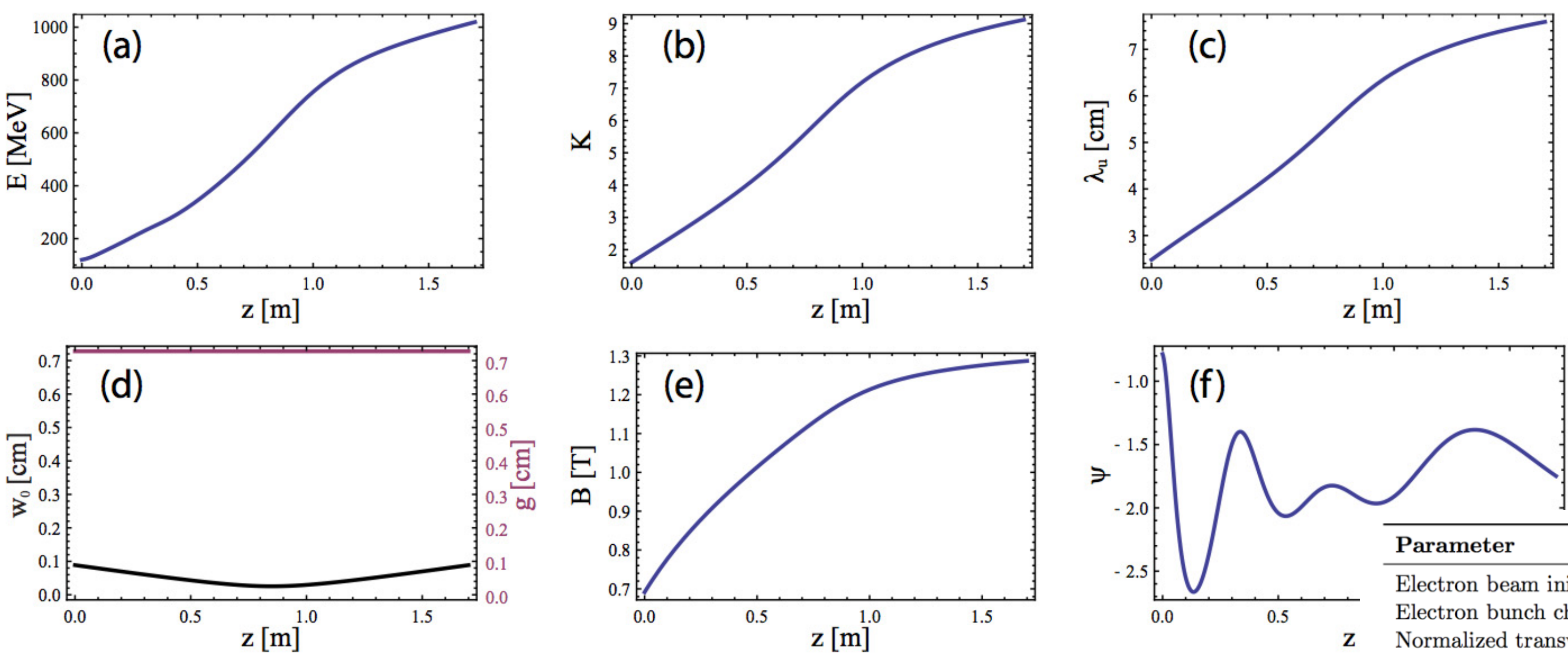
Experiment



Improved energy gain through upgrades

Our setup optimized for EEHG studies, not IFEL

Dedicated laser upgrade and tapered undulator could conceivably yield 1GeV in < 2m



Parameter	Value
Electron beam initial energy	120 MeV
Electron bunch charge	20 pC
Normalized transverse emittance	2 μm
FWHM electron bunch length	0.25 ps
FWHM laser pulse width	100 fs
Laser pulse energy, U1	500 μJ
Laser pulse energy, U2	2 J
Undulator period, U1	3.3 cm
Undulator period, U2	2.5-7.5 cm
Undulator parameter K, U1	1.82
Undulator parameter K, U2	1.6-9.3
RMS electron beam size, U2	100 μm
RMS laser beam size, U2	250 μm

Resonant particle evolution in ~1TW 800 nm laser pulse: ~***500 MeV/m***

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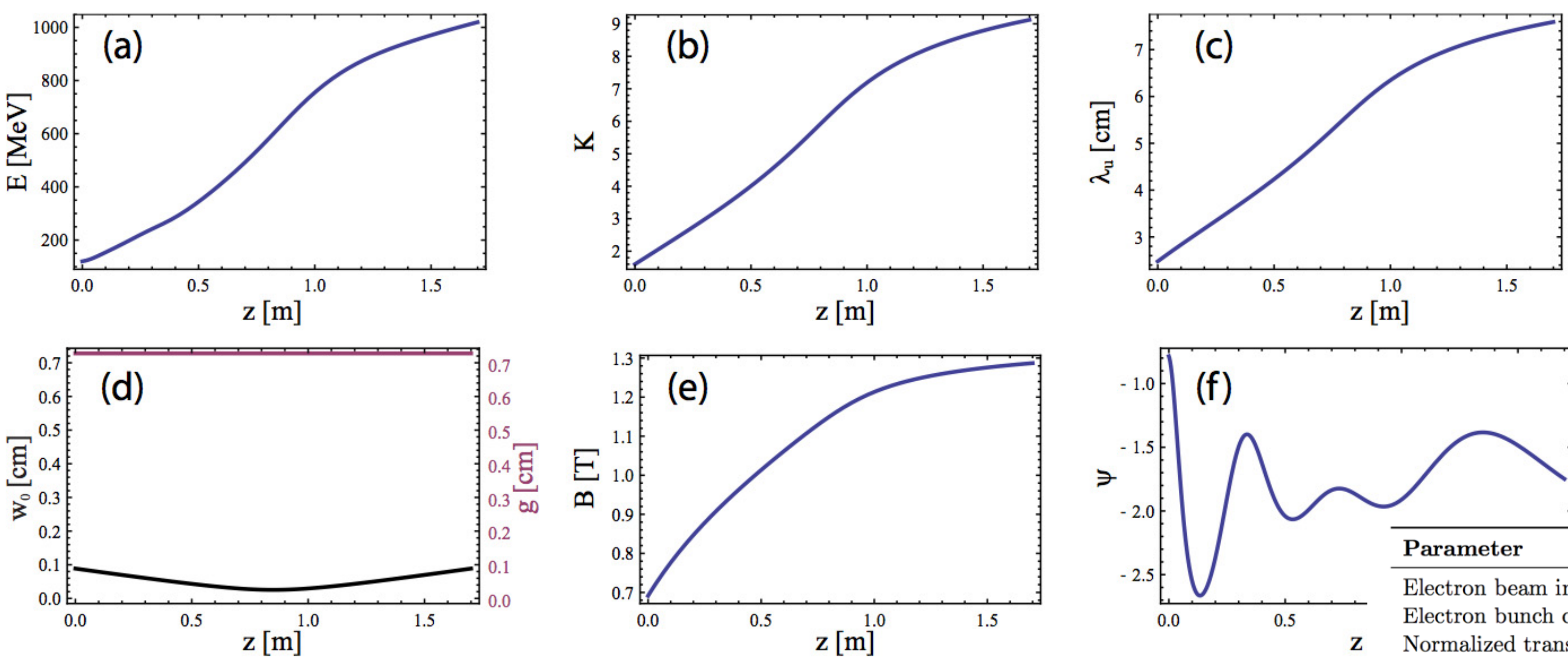

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RMS electron beam size, U2	100 µm
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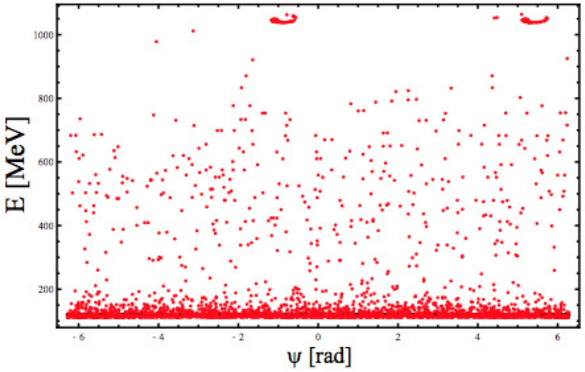
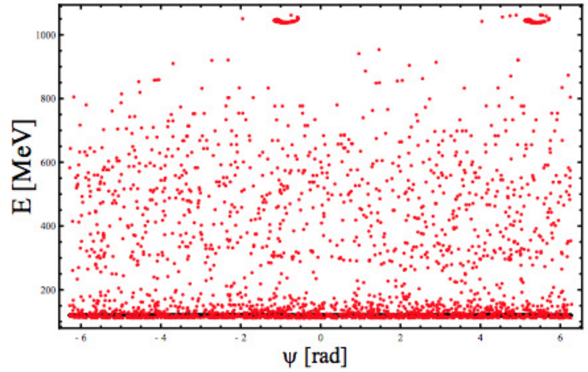
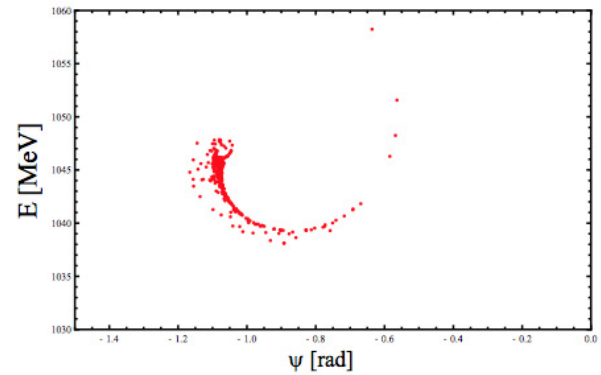
High-gradient IFEL



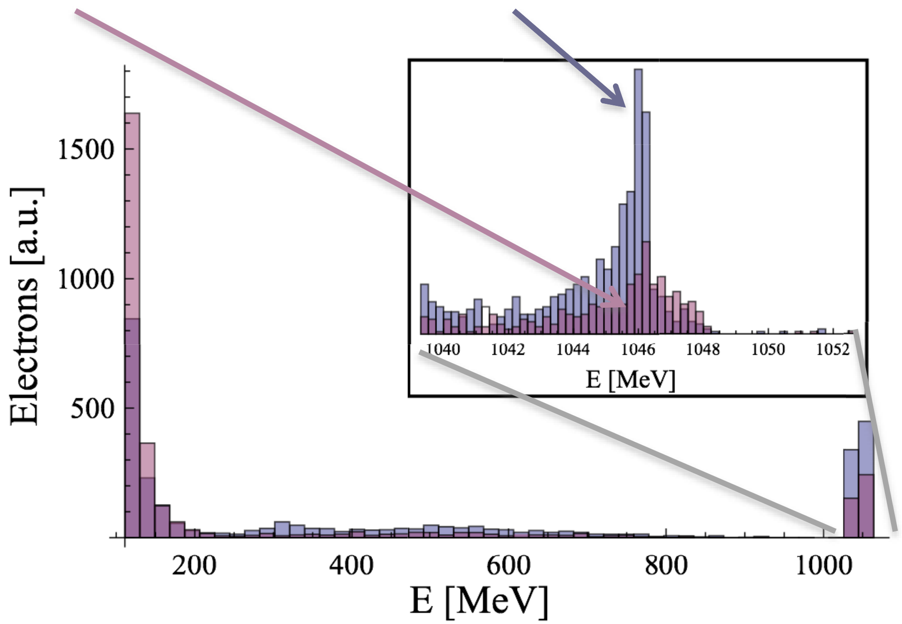
(a) Final electron phase space for an unbunched beam.



(b) Final electron phase space for a pre-bunched beam.

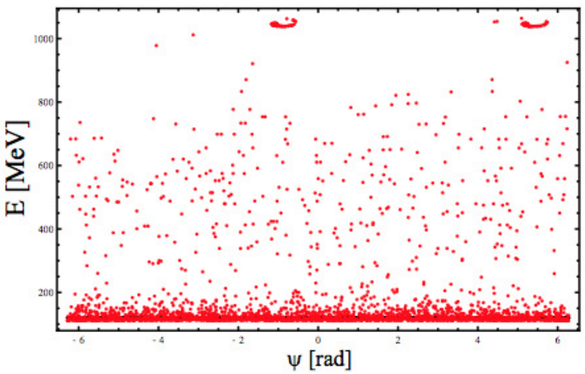


(c) Close-up of the particles that are fully trapped and are accelerated to more than 1 GeV.

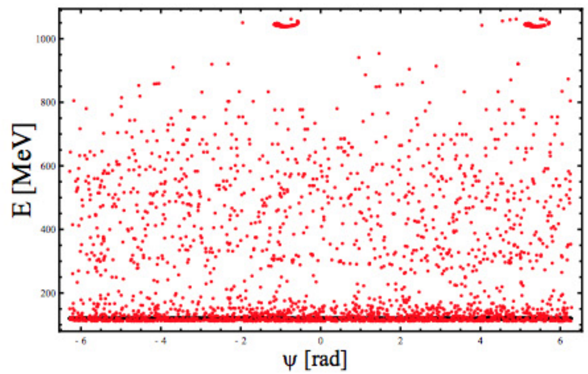


Optimizing for high field gradient does not generally optimize the capture efficiency!

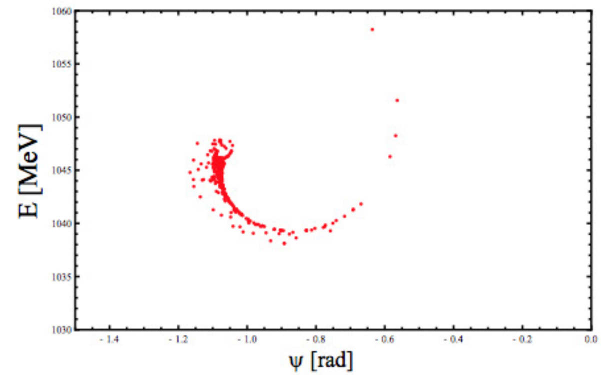
High-gradient IFEL



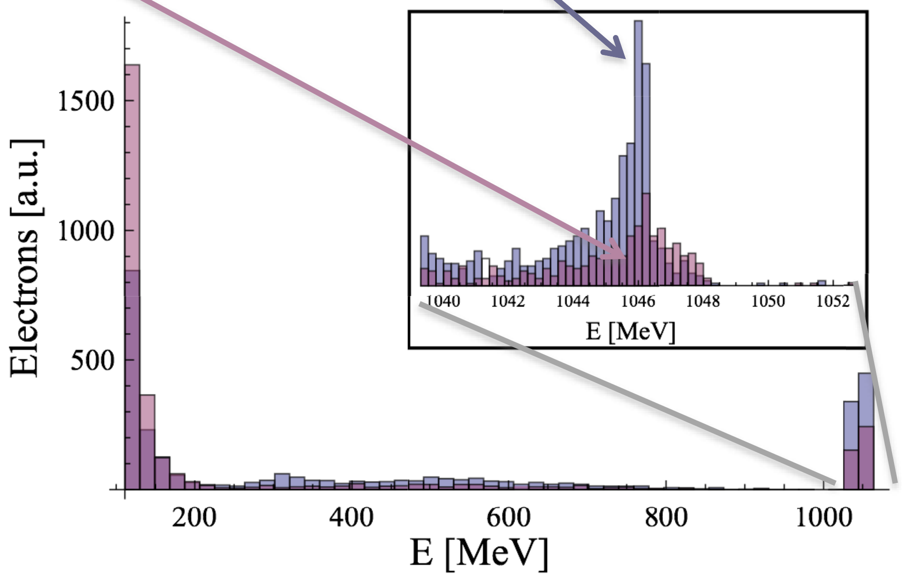
(a) Final electron phase space for an unbunched beam.



(b) Final electron phase space for a pre-bunched beam.



(c) Close-up of the particles that are fully trapped and are accelerated to more than 1 GeV.



Optimizing for high field gradient does not generally optimize the capture efficiency!

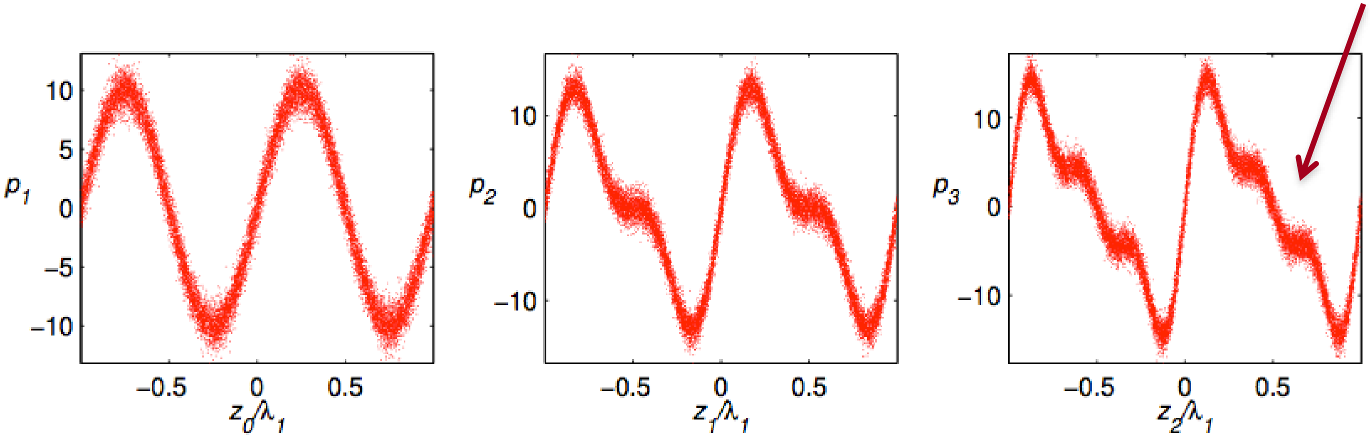
Improving capture efficiency

Multiple stages for tailoring e-beam phase space prior to IFEL

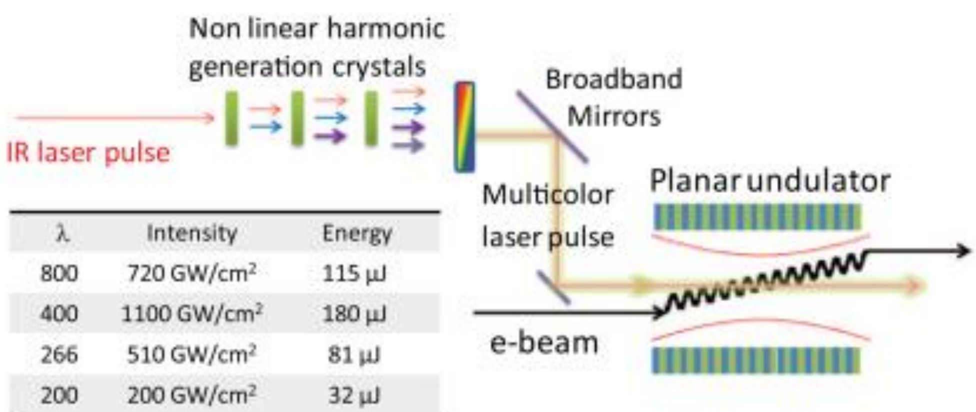
Ex: Successive harmonic modulations to generate sawtooth distribution

$$\Delta E_{LM} = \frac{2\Delta E}{\pi} \sum_{h=1} \frac{\sin hkz}{h}$$

Linearized

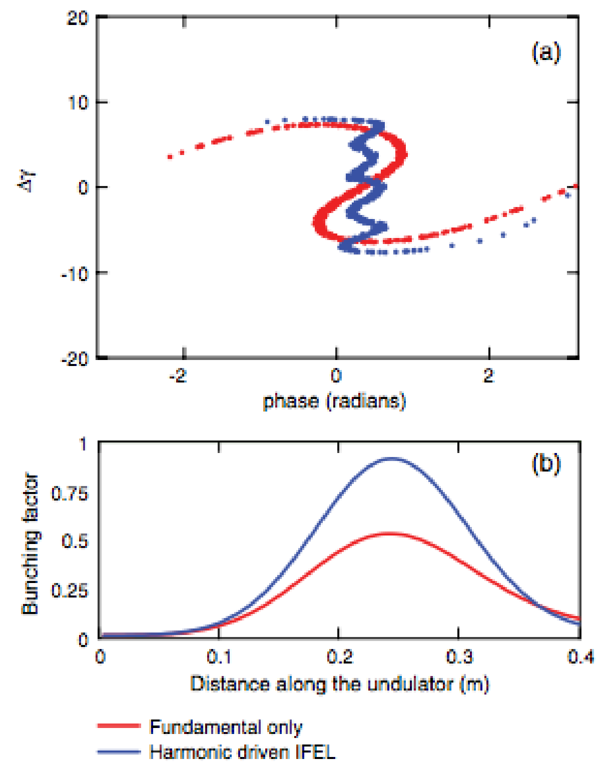


Harmonic buncher concept

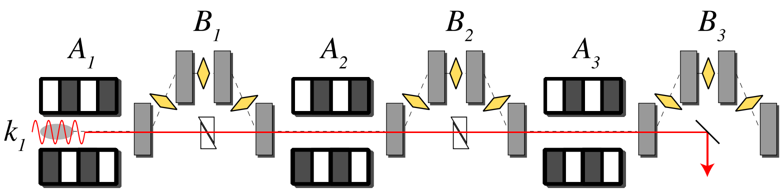


λ	Intensity	Energy
800	720 GW/cm²	115 μJ
400	1100 GW/cm²	180 μJ
266	510 GW/cm²	81 μJ
200	200 GW/cm²	32 μJ

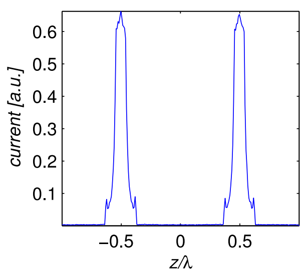
from J. Duris, et al, Phys. Rev. ST Accel. Beams 15, 061301 (2012)

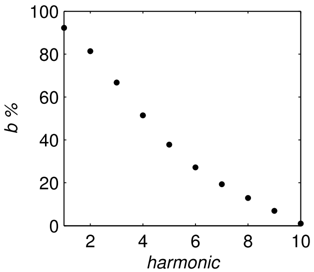


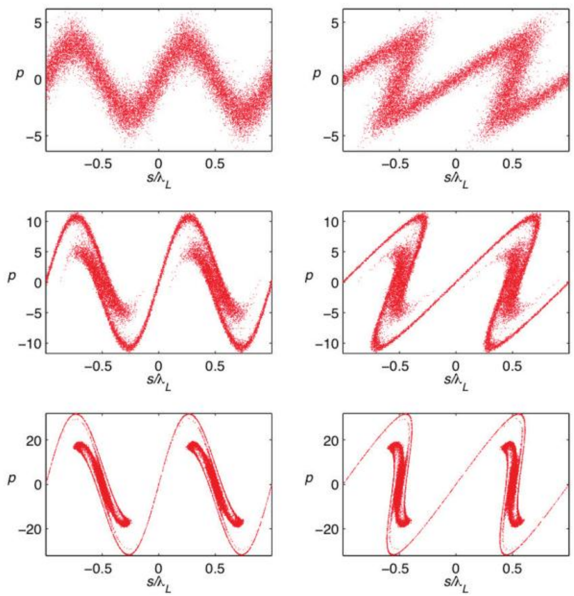
Adiabatic Buncher concept



one laser, >90% bunching







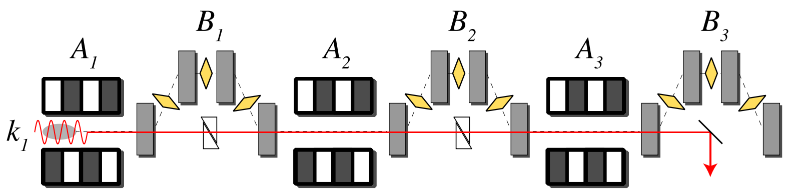
After first chicane

After second chicane

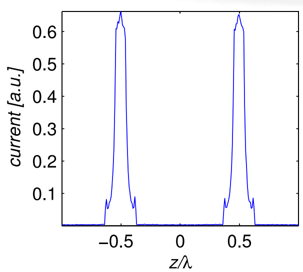
After third chicane

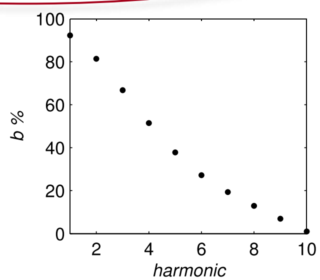
...

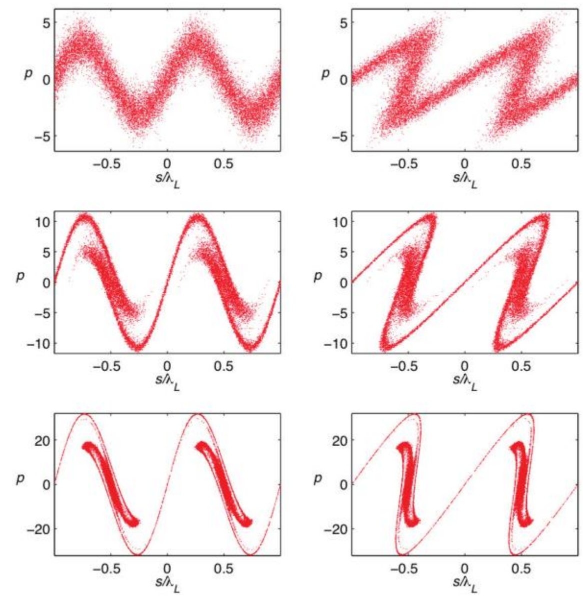
Adiabatic Buncher concept



one laser, >90% bunching







After first chicane

After second chicane

After third chicane

...

Successive energy modulation and chicane sections “coil up” beam into accelerating buckets.

Applications: Managing large energy spreads

Relatively large IFEL longitudinal emittances also common in DWAs and LPAs

For high-gain FELs, a Transverse Gradient Undulator (TGU) can be used

PRL 109, 204801 (2012) PHYSICAL REVIEW LETTERS week ending 16 NOVEMBER 2012

Compact X-ray Free-Electron Laser from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator

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[1]*SLAC National Accelerator Laboratory, Menlo Park, California 94025, USA*
[2]*Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
(Received 13 July 2012; published 12 November 2012)

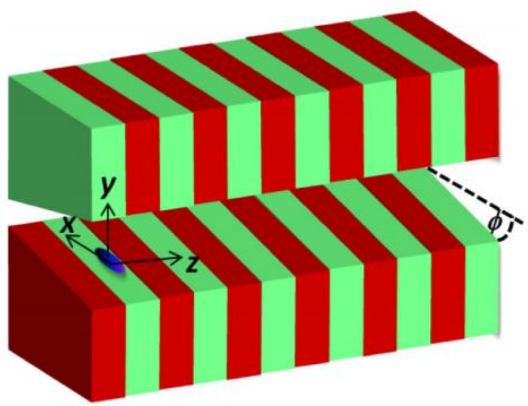


FIG. 1 (color online). Transverse gradient undulator by canting the magnetic poles. Each pole is canted by an angle ϕ with respect to the xz plane. The higher energy electrons are dispersed to the higher field region (positive x) to match the FEL resonant condition.

Canted pole faces generate x-dependence of undulator field:

$$\frac{\Delta K}{K_0} = \alpha x$$

Dispersing beam horizontally by

$$x = \eta \frac{\Delta\gamma}{\gamma_0} = \frac{K_0^2 + 2}{\alpha K_0^2} \frac{\Delta\gamma}{\gamma_0}$$

Removes energy spread dependence because change in energy is compensated by change in K. All e's in resonance.

Lasing in TGU with large energy spread

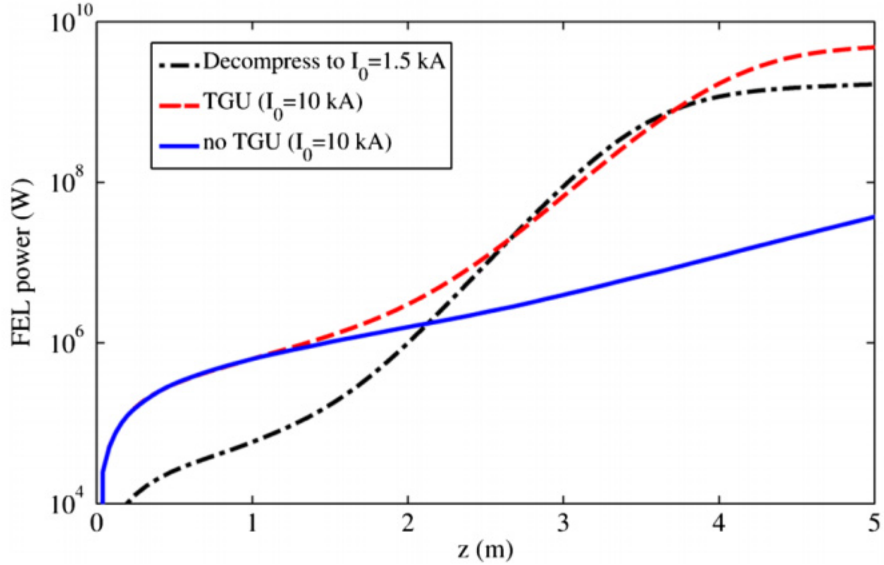
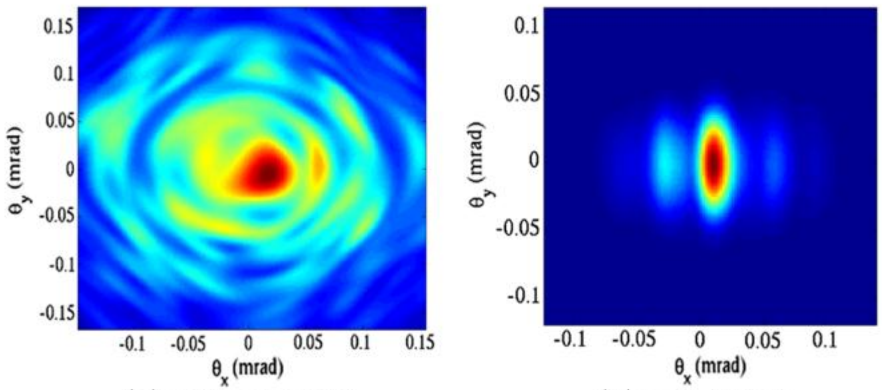


FIG. 6 (color online). FEL power around 3.9 nm for a normal undulator without decompression (solid blue), with a factor of 7 decompression (dashed doted black), and for a transverse gradient undulator without decompression (dashed red).

Compared with simply decompressing beam, TGU gives:

- Shorter x-ray pulse length
- Higher peak power
- Smaller bandwidth
- Central wavelength stable to energy jitter



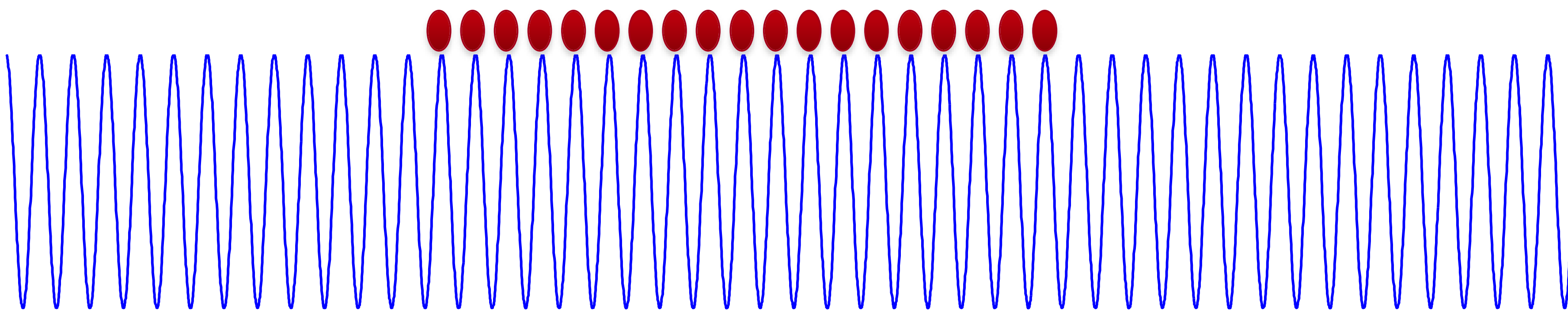
(a)without TGU. (b)with TGU.

Z. Huang, et al PRL 109, 204801 (2012)

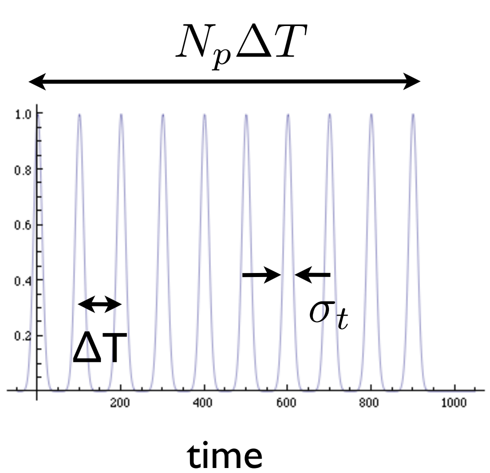
Photon production schemes

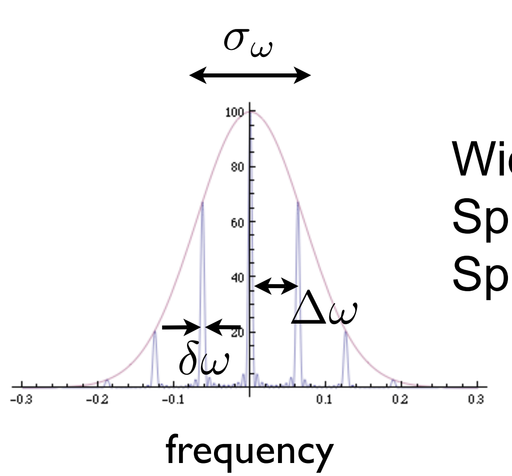
SLAC

IFEL beams are naturally bunched at the laser wavelength (b~100%)



Could have applications in driving x-ray pulse trains





Width of envelope: $\sigma_\omega = 1/2\sigma_t$

Spike separation: $\Delta\omega = 2\pi/\Delta T$

Spike width: $\delta\omega = 2\pi/N_p \Delta T$

Enhanced SASE

SLAC-PUB-10713
September 2004

CURRENT-ENHANCED SASE USING AN OPTICAL LASER AND ITS APPLICATION TO THE LCLS*

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P. Emma, Z. Huang, G. Stupakov, SLAC, Stanford, CA 94309, USA
S. Reiche, UCLA, Los Angeles, CA 90095-1547, USA

Periodically density modulated beam drives pulse train of FEL pulses with uniform spacing.

Duration of each spike can be less than cooperation length, so each is temporally coherent

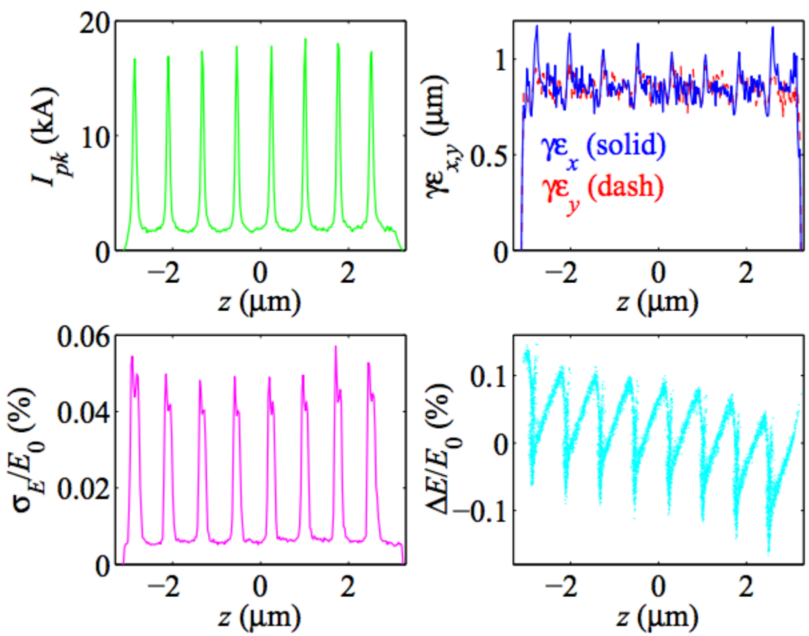

Figure 3: Same plots as in Fig. 2, but at a z-position immediately following the DL2 beamline. Strong current modulation and CSR effects are now apparent.

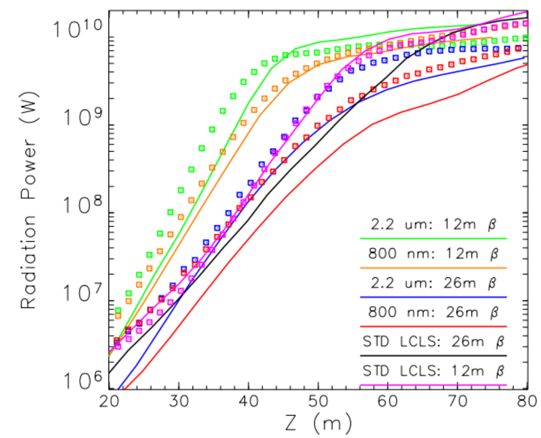

Figure 4: $\langle P \rangle$ plotted versus z for ESASE and standard LCLS configurations. The solid lines and boxes represent *GINGER* and *GENESIS* results, respectively.

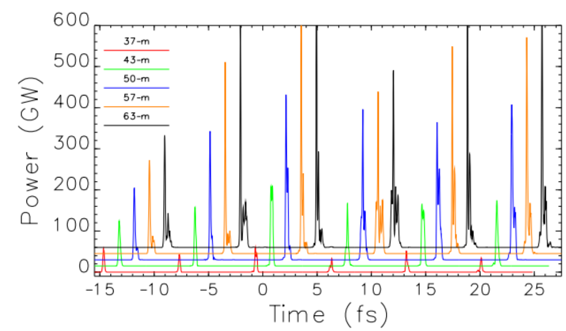

Figure 5: $P(t)$ snapshots at 5 different z-locations for a 2.2 μm-energy-modulated ESASE pulse with $\langle\beta\rangle$ =12 m, plotted with staggered offsets of 1.5 fs in time and 15 GW in power. For legibility, the z =37 m data has been multiplied by a factor of 2.0.

Slippage Boost FEL configurations

SASE

Mode-Coupled

Mode-Locked

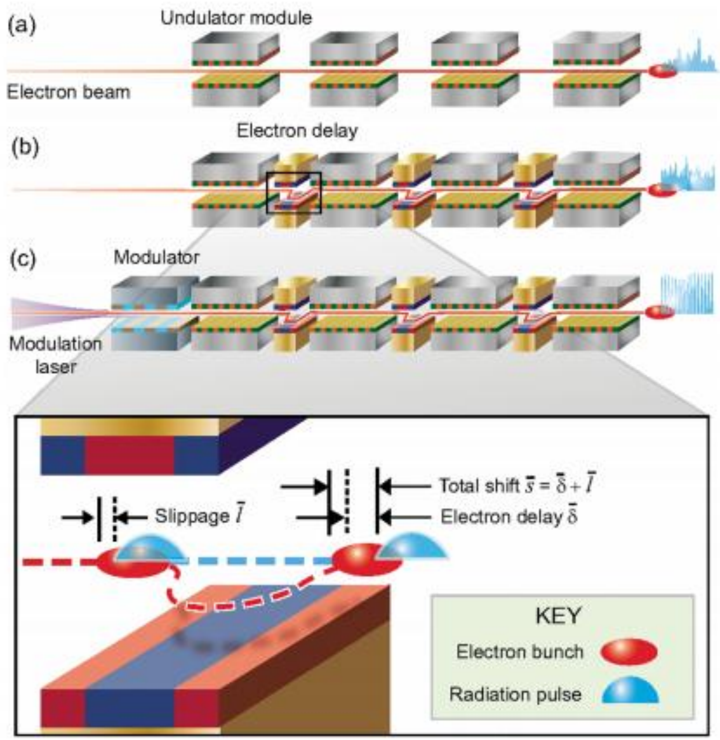

FIG. 1 (color). Schematic of three regimes of FEL interaction: (a) SASE regime (b) Mode-coupled SASE regime and (c) Mode-locked SASE regime. The inset shows a detail of the electron delay.

Thompson and McNeil, PRL (2008)

SASE FELs have limited temporal coherence because the phase information does not propagate over the whole beam

Periodic delays can be used to artificially increase the slippage and improve coherence

Mode-Locked xFEL

SLAC

- Time domain consists of many ultrashort pulses equally separated by the IFEL laser wavelength.
- Many sharp spectral lines within a wide bandwidth
- Examine the dynamics of a large number of atomic states simultaneously.

New Journal of Physics
The open-access journal for physics

A wide bandwidth free-electron laser with mode locking using current modulation

E Kur[1], D J Dunning[2,3], B W J McNeil[2], J Wurtele[1,4] and A A Zholents[5,6]

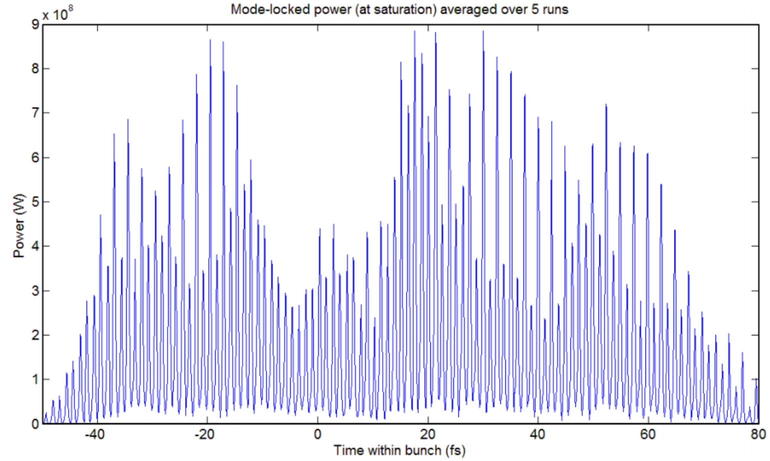

Figure 5. The mode-locked FEL output power averaged over five runs. Mode locking was obtained by an energy modulation of the beam.

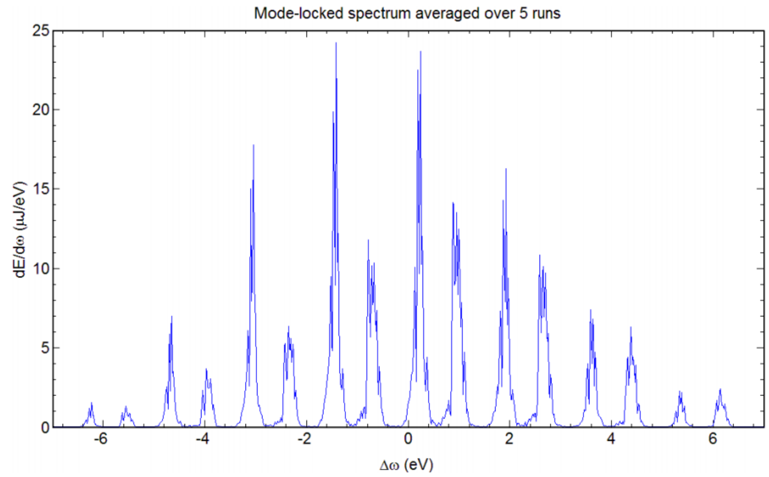

Figure 6. The mode-locked FEL output spectrum averaged over five runs. Mode locking was obtained with energy modulation of electrons.

Enhanced Self-Seeded X-ray FELs

SLAC

Beamlets are mode locked by FEL self-seeding

- E-beam with density modulation at long wavelengths (eg, IR) lases in FEL
- Radiation is monochromatized, sent back onto e-beam and amplified
- Density modulated beam radiates x-ray pulse train that is mode locked.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 050707 (2012)

Mode-locked multichromatic x rays in a seeded free-electron laser for single-shot x-ray spectroscopy

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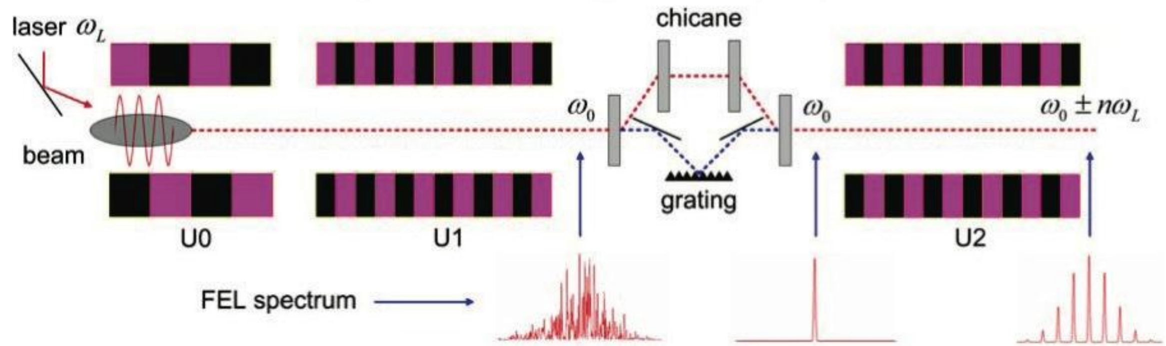
(Received 12 March 2012; published 14 May 2012)



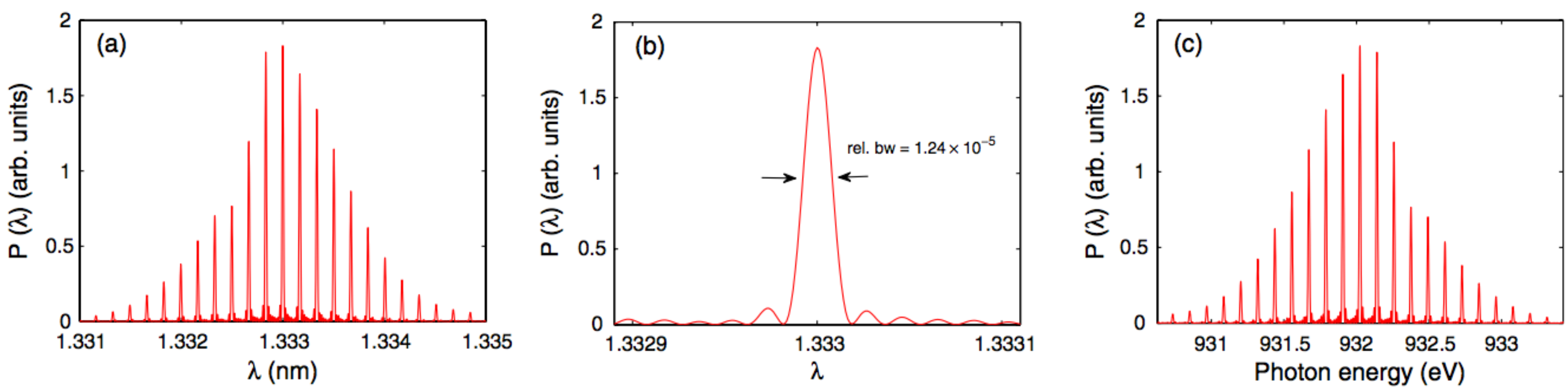


FIG. 3. FEL power spectrum as a function of x-ray wavelength (a); enlarged view of the central frequency line (b); FEL power spectrum as a function of x-ray photon energy (c).

Summary

- IFELs can obtain large (0.5-1GeV) accelerating gradients
- Cascaded IFELs improve capture efficiency
- Demonstrated proof-of-principle Two-stage IFEL at 800 nm using 3rd harmonic undulator resonance
- New phase space manipulation schemes can further increase efficiency
- TGUs provide method of high-gain FEL operation with large energy spread beams
- Periodic structure of IFEL beams can be harnessed to produce pulse trains in modern light sources

Thanks!