High gradient IFEL acceleration and deceleration in strongly tapered undulators

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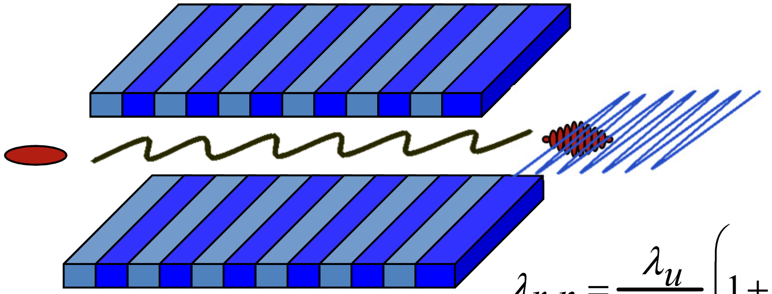
UCLA

Outline

- IFEL – acceleration
  - Background
  - Rubicon IFEL experiment at ATF
  - Designs for GeV/m IFEL
  - Genesis informed tapering scheme (GITS)
- TESSA – deceleration
  - EUV afterburner simulations
  - Low gain - Nocibur IFEL decelerator experiment
  - High gain - UV amplifier experiment @ ATF2
- GITS applied to x-rays

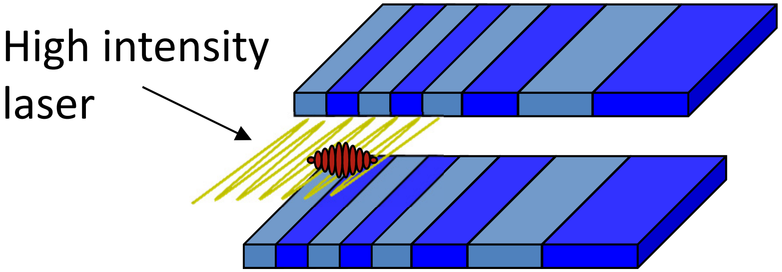
IFEL Interaction

In an FEL energy in the e-beam is transferred to a radiation field



$$\lambda_{r,n} = \frac{\lambda_u}{2\gamma^2 n}\left(1+\frac{K^2}{2}\right)$$

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



Undulator magnetic field to couple high power radiation with relativistic electrons

$$K_l = \frac{eE_0}{mc^2 k} \qquad K = \frac{eB}{mck_w}$$

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

Significant energy exchange between the particles and the wave happens when the resonance condition is satisfied.

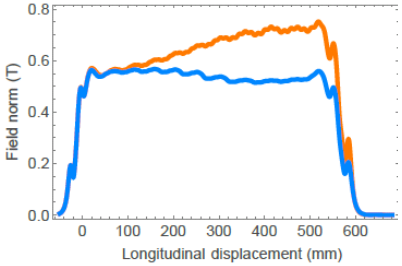
Why are we interested in IFELs?

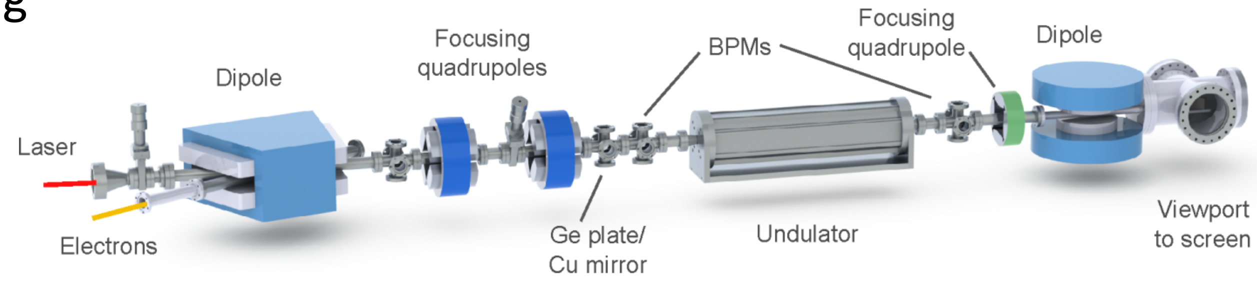
- IFEL well suited for mid-high energy ranges (50 MeV – ***up to few GeV***)
  - High power laser wavelengths available (10 μm, 1 μm, 800 nm)
  - Mature permanent magnet undulator technology (cm periods)
- ***Plane wave or far field*** accelerator: minimal 3D effects.
  - Transverse beam dimensions can be mm-size for μm-scale accelerating wavelength.
- ***Vacuum-based*** accelerator
  - ***Efficient*** mechanism to transfer energy from laser to electrons
  - Simulations show high energy, high quality beams with ***large gradient ~GeV/m*** achievable with current technology!
  - ***Preservation of e-beam quality/emittance*** and high capture.
- ***Stable energy output***: static undulator field sets resonant energy.
- Potential for compact GeV-class accelerators for light sources

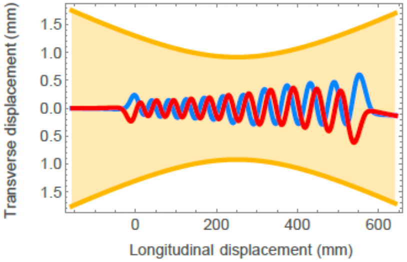
Rubicon IFEL experiment

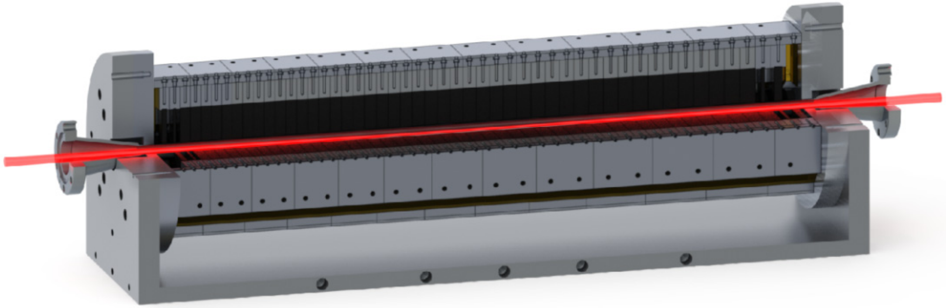
- Helical geometry high gain high gradient IFEL
- First strongly tapered helical undulator
- Two different tapers used
  - Demonstrate control of the final beam properties by undulator tuning

Input e-beam energy	50 MeV
Average accelerating gradient	**100 MV/m**
Laser wavelength	10.3 µm
Laser power	**100-300 GW**
Laser focal spot size (w)	980 µm
Laser Rayleigh range	30 cm
Undulator length	**54 cm**
Undulator period	4 – 6 cm
Magnetic field amplitude	5.2 – 7.7 kG



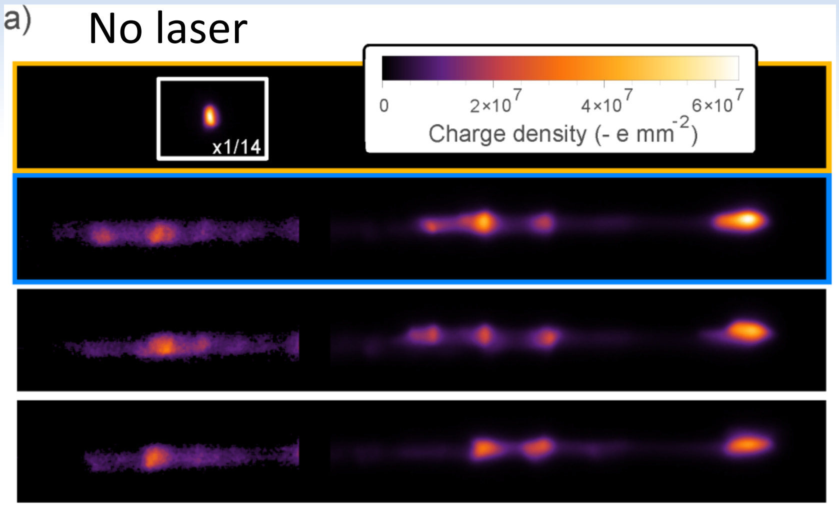






High quality output beams

- 93 MeV – 1.8 % energy spread
- Very reproducible (mean energy std < 1.5 %) despite 30% rms laser power fluctuations
- Laser intensity 5 orders of magnitude lower than LWFA



Laser on – consecutive shots

ARTICLE

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High-quality electron beams from a helical inverse free-electron laser accelerator

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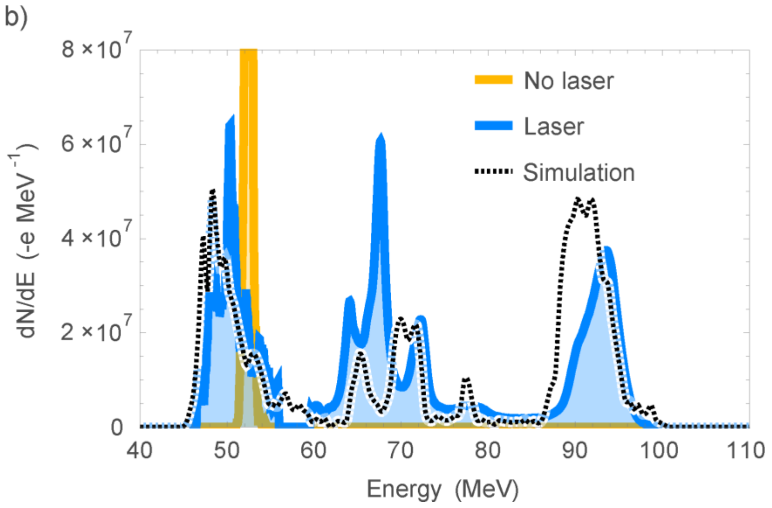
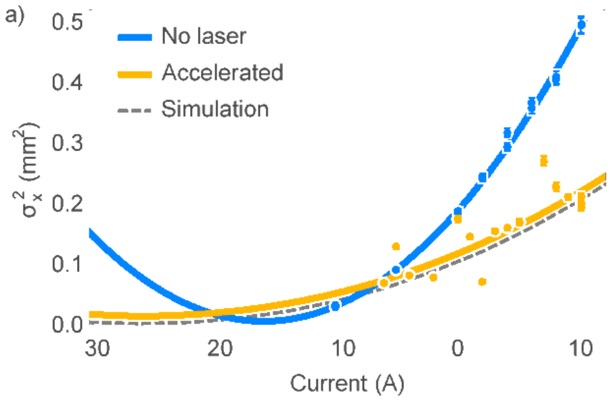


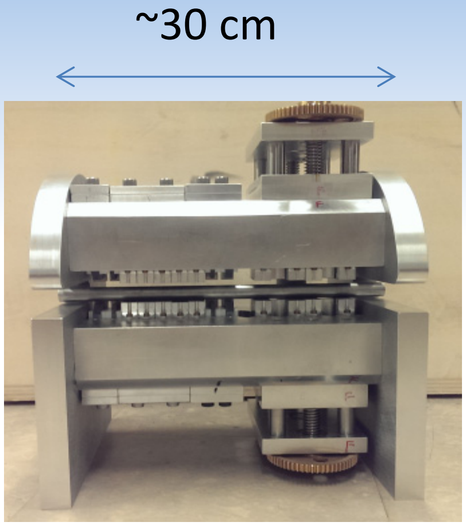


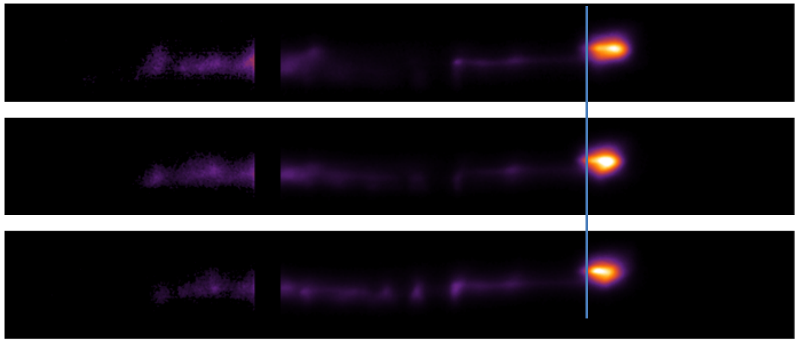
Emittance measurement

- Quad scan on energy dispersed beam
- Emittance growth (from 2 μm -> 3 μm) is due to mismatching in the undulator

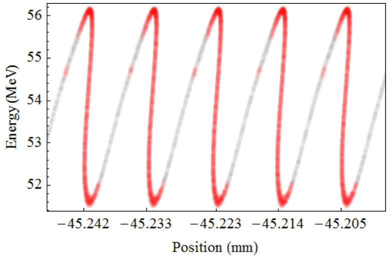
Most recent Rubicon run

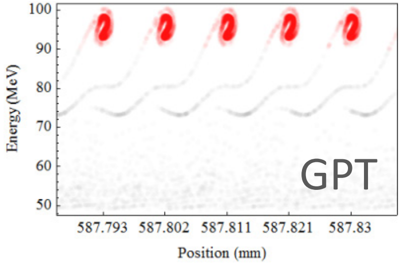
- UCLA permanent magnet based prebuncher
- Permanent magnet chicane with adjustable R_{56}
- Achieved **> 50% capture**
- Better matching into undulator **preserves emittance**

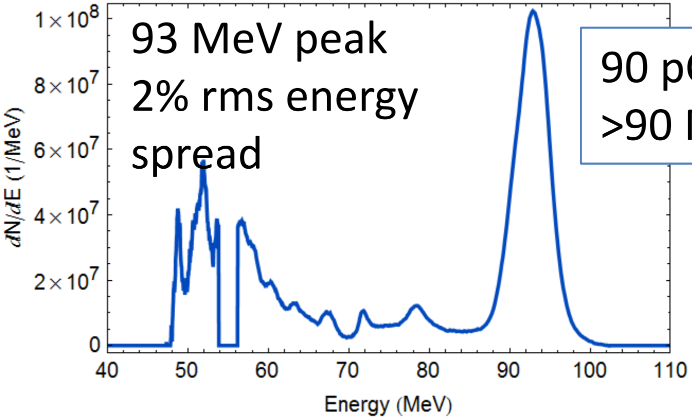




First experiment using a CPA CO2 laser



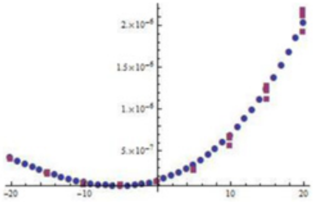




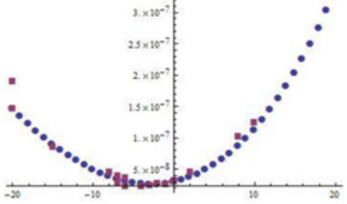
93 MeV peak
2% rms energy spread

90 pC
>90 MeV

Unaccelerated emittance 2.3 um



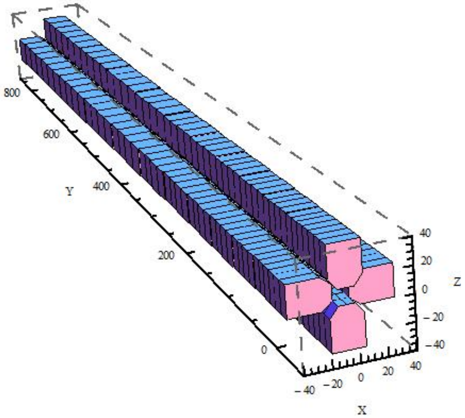
Accelerated emittance 2.4 um

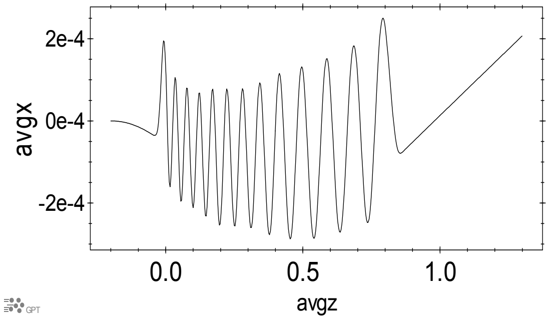


0.5 GeV IFEL at ATF2

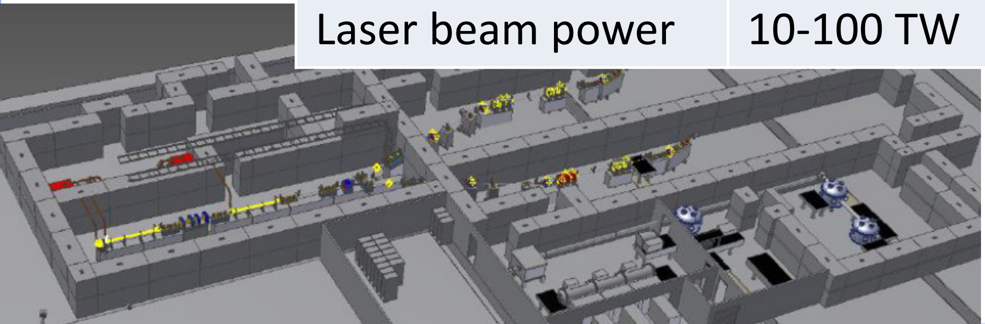
- Demonstrate GeV/m gradients
- Demonstrate GeV-class energy gain
- Design aiming at 0.5 GeV output energy
- Flexibility : undulator can be retuned

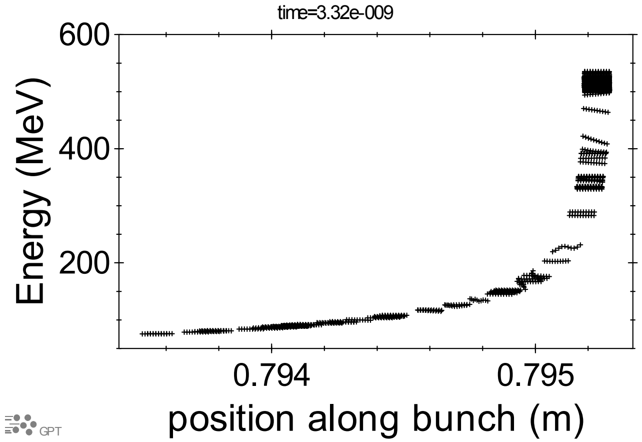
Parameter	Value
Laser power	**25 TW**
Laser pulse length	> 0.5 ps
M^2	**1.5**
Gap	**10 mm**
Input energy	90 MeV
Output energy	500 MeV
Energy spread	2 %
Undulator length	75 cm
Gradient	> 0.5 GeV/m





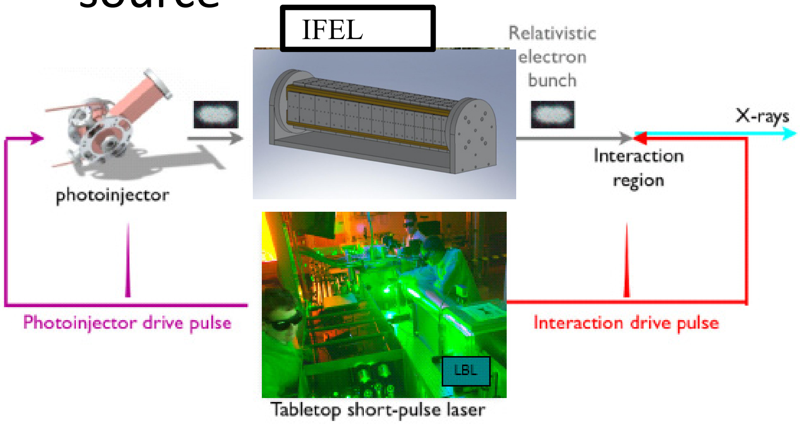
ATF2 stage 1 upgrade parameters	
E-beam energy	50-150 MeV
Laser beam power	10-100 TW



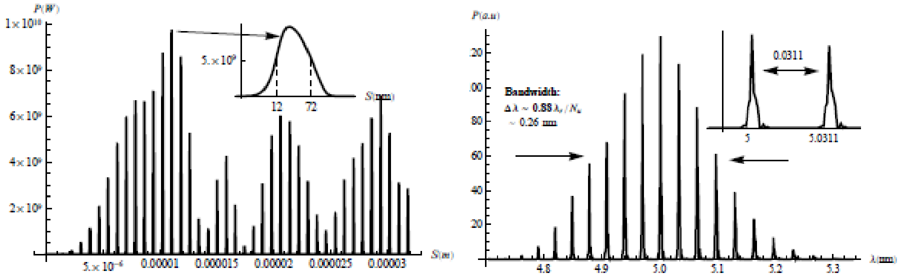


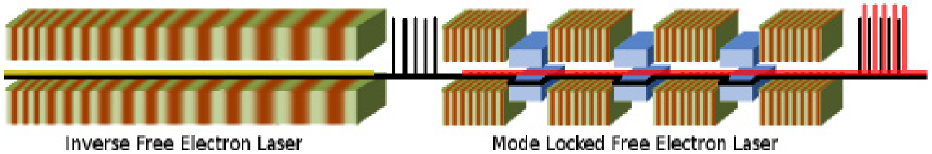
Applications

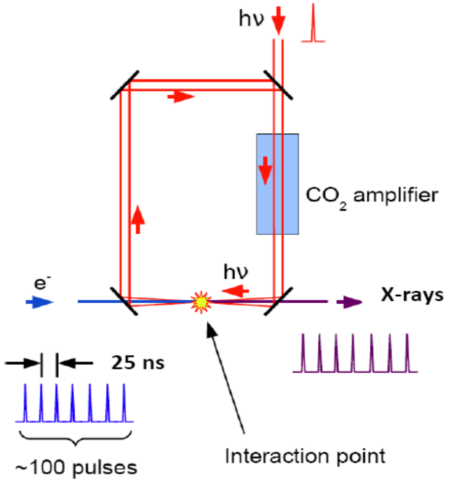
- Inverse Compton Scattering-based compact gamma-ray source



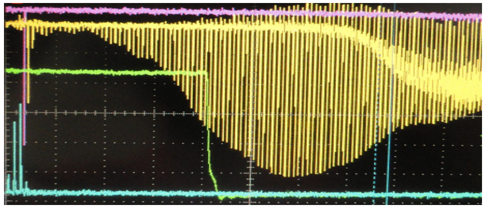
- Compact Modelocked soft-X-ray FEL
  - Take advantage of current increase
  - Use chicane to realign radiation spikes with e-beam modulation





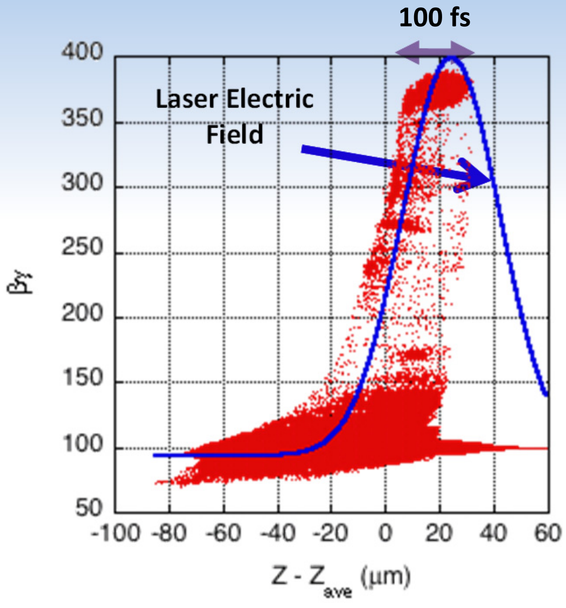


- Recirculate drive laser for IFEL to increase repetition rate and average flux of ICS photons

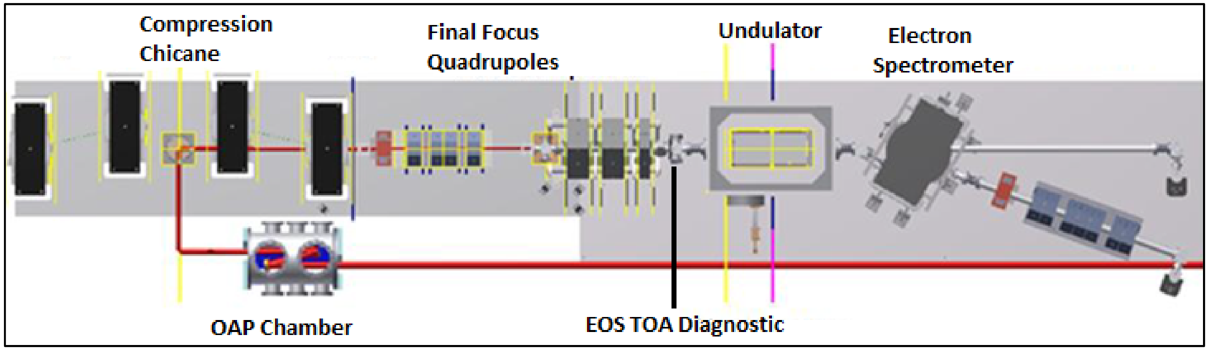


LLNL Ti:Sa IFEL accelerator

- First TW-class laser driven IFEL
- Strongly tapered undulator for diffraction-dominated interaction
- Short pulses (sub-ps) interaction
- 77 MeV – 122 MeV in 22 cm
- > 200 MV/m gradient !
- Sub-ps synchronization and timing



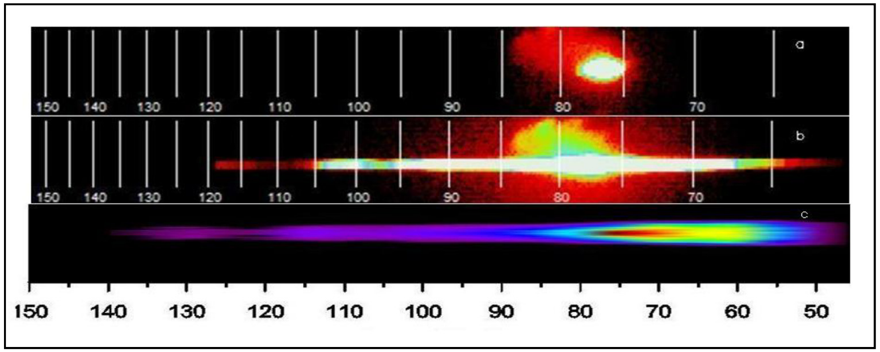
Courtesy of J. Moody

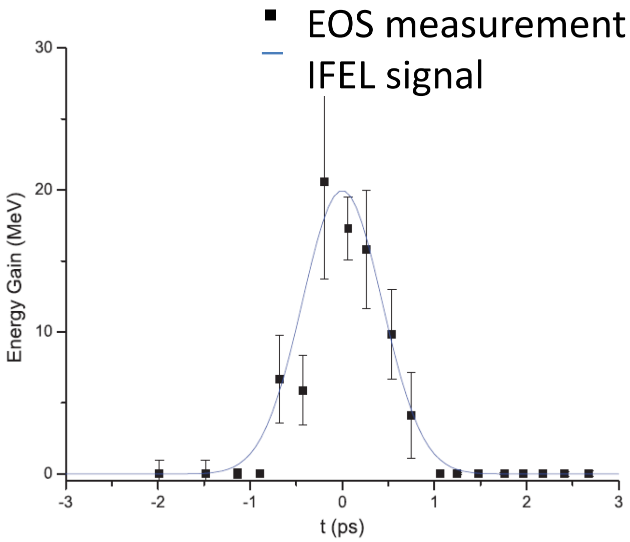


Laser off

Laser on

Simulations

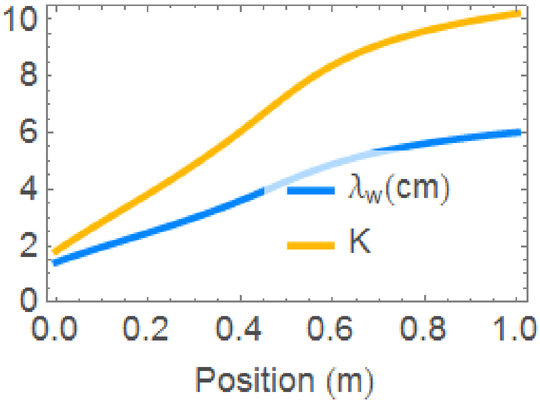


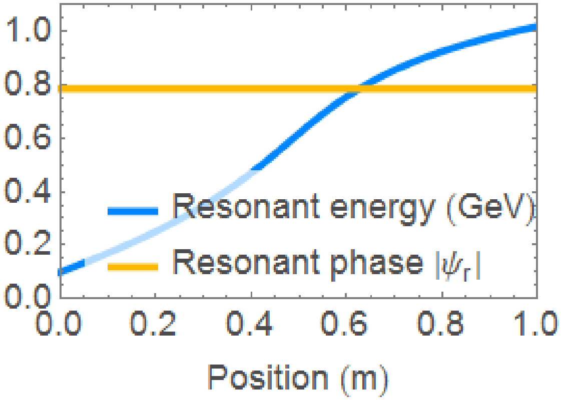


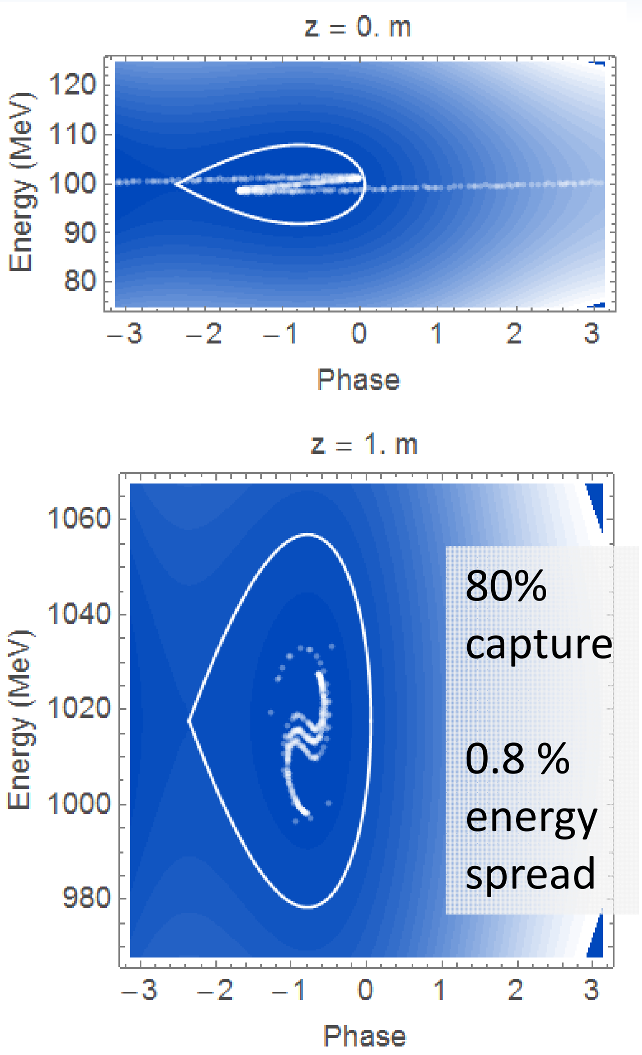
GeV IFEL concept

Achieve GeV/m gradient with commercially available Ti:Sa laser

- 20 TW, 800 nm laser
- 100 MeV e-beam prebunched
- 1m long permanent magnet undulator
- Constant resonant phase –π/4
- **920 MeV energy gain in 1 m undulator**







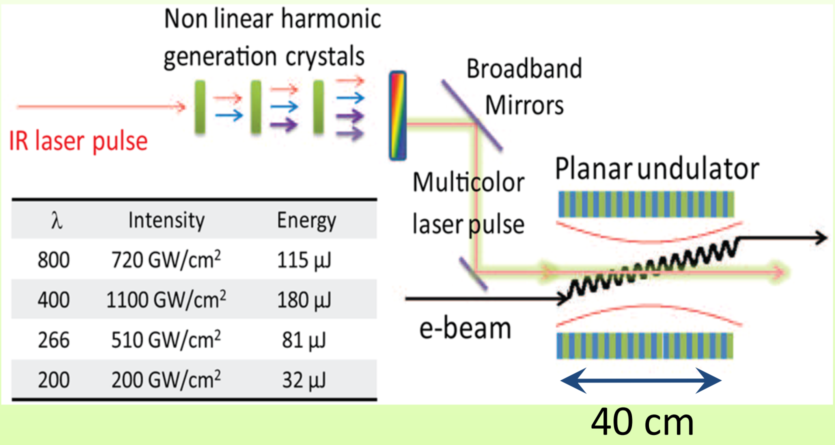
80% capture

0.8 % energy spread

Improved bunching schemes

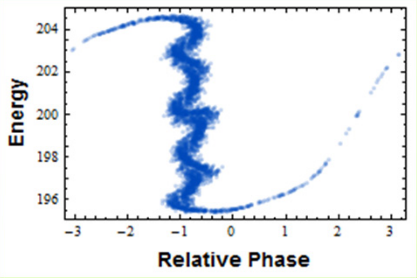
Harmonic prebuncher

Linearize ponderomotive gradient using harmonics



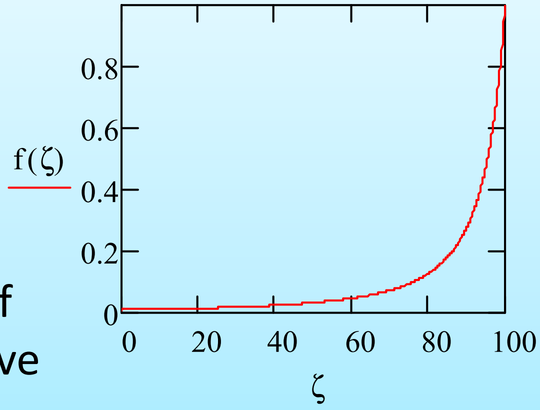
λ	Intensity	Energy
800	720 GW/cm²	115 μJ
400	1100 GW/cm²	180 μJ
266	510 GW/cm²	81 μJ
200	200 GW/cm²	32 μJ

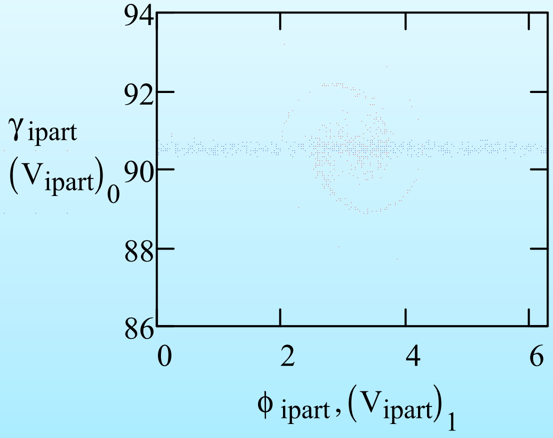
b = 0.95 @ 800 nm



Adiabatic prebuncher

Ramp up the field to capture all of the input phase space and preserve longitudinal emittance



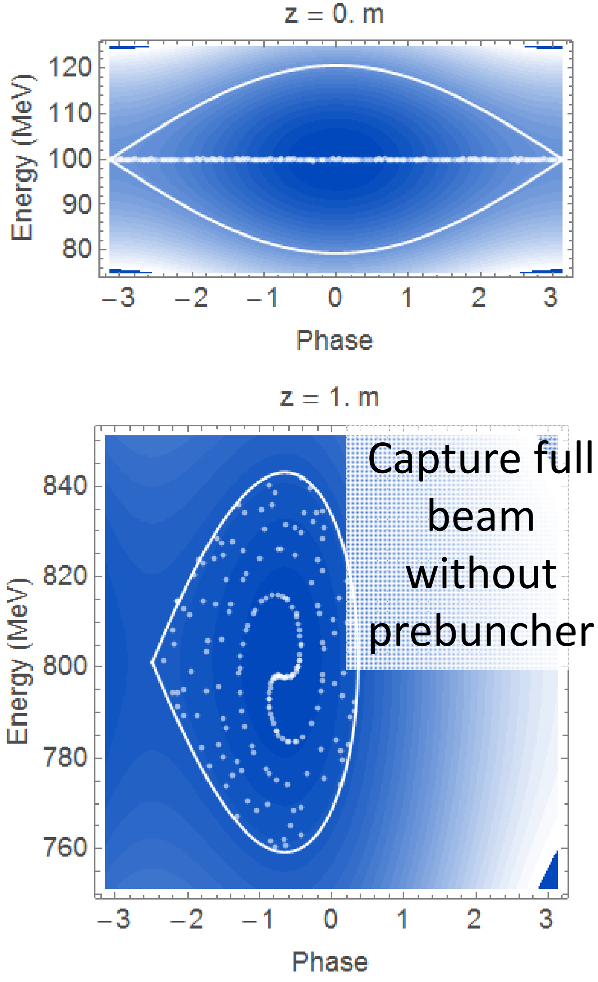


Put laser focus at the end of long undulator

Adaptive resonant phase

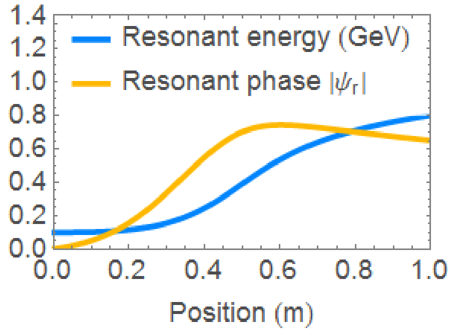
Vary resonant phase to keep action constant as separatrix grows (KMR)

Uniform beam

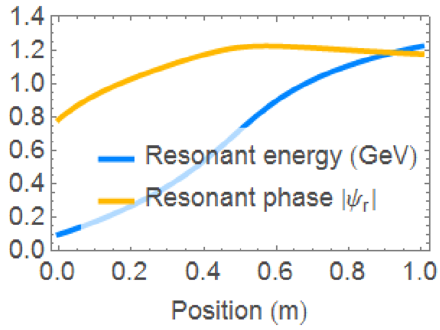


Capture full beam without prebuncher

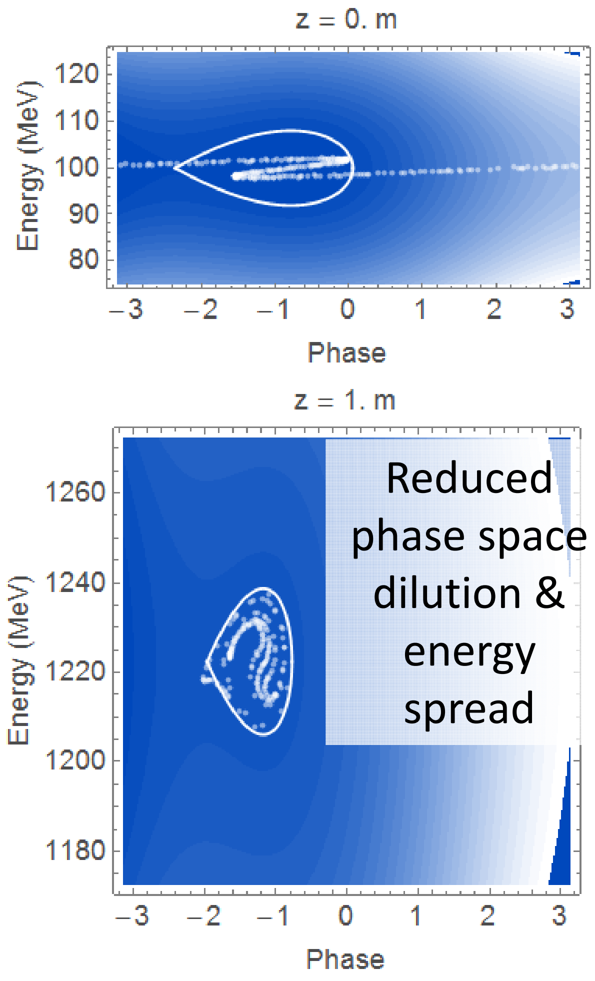
Initial resonant phase 0



Initial resonant phase −π/4



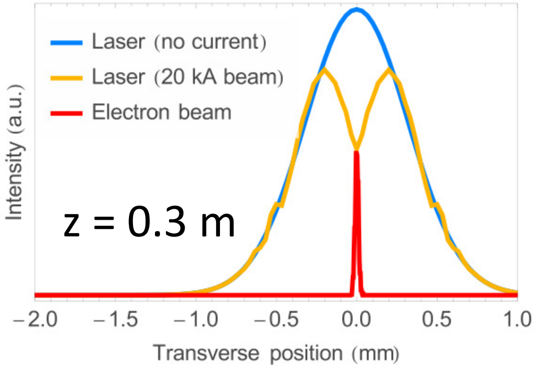
Prebunched beam

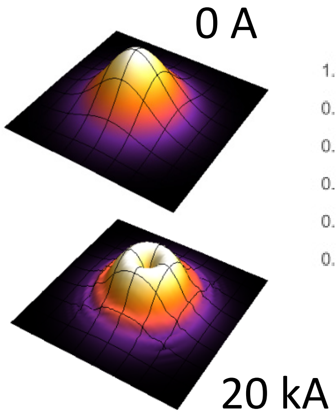


Reduced phase space dilution & energy spread

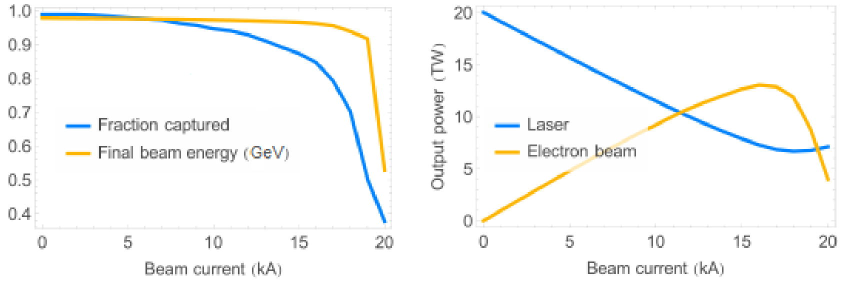
Beam loading effects

- Fully self-consistent IFEL model
  - Self-consistent treatment of EM fields
  - Period-average and SVEA approximations
  - GENESIS-based
  - Diffraction included
  - Beam loading





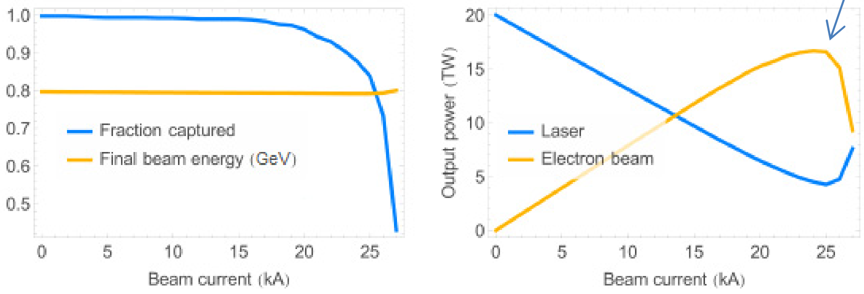
Laser depletion limits acceleration



Compensate laser power absorption in taper design

$$P_{abs}(z) = \eta I m_0 c^2 (\gamma(z) - \gamma_0)$$

>80% conversion!



Genesis Informed Tapering Scheme

Solve tapering equations with help of 3D FEL code Genesis

$$\frac{d\lambda_w}{dz} = -\frac{8\pi K_l K \operatorname{Sin}[\psi_r]}{1 + K^2 + 2\lambda_w K \frac{\partial K}{\partial \lambda_w}} \qquad K_l = \frac{e\lambda}{2\pi m c^2}\sqrt{2 Z_0 I_{\mathrm{crit}}}$$

Solve tapering period-by-period

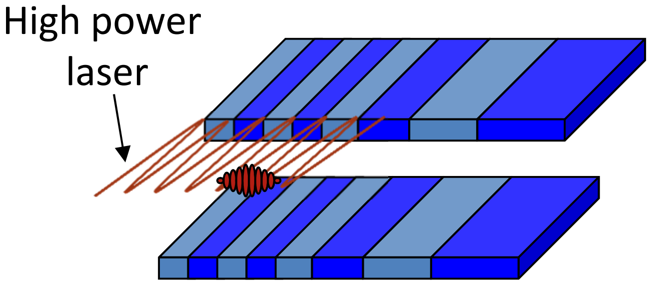
- Run Genesis on a period
- Select capturable particles (within the ponderomotive bucket)
- Measure min intensity seen by particles => threshold for capture
- Calculate new period and undulator parameter
- Saves taper as well as simulated data

GITS offers options to dynamically optimize different simulated e-beam and radiation parameters: maximize power transfer, minimize detrapping, play with resonant phase, etc.

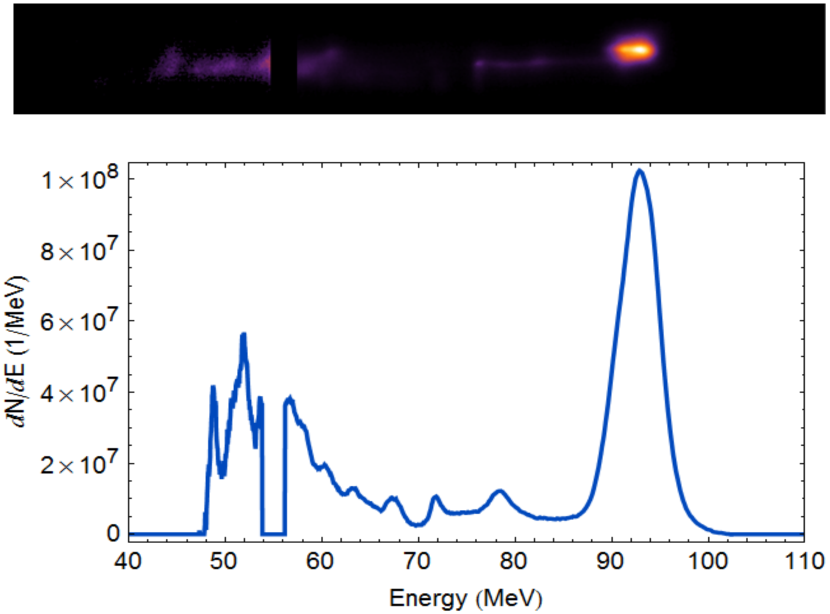
Useful for loaded IFEL design.

Lessons from Inverse FEL

- FEL beam-laser energy exchange is usually < 1 MeV/m
- IFEL demonstrated energy exchange rate ~ 100 MeV/m
- Design studies indicate possibility of GeV/m gradients
- Beam loading compensation: 10 kA beam absorbs 50% power
- ***Can we run IFEL in reverse?***



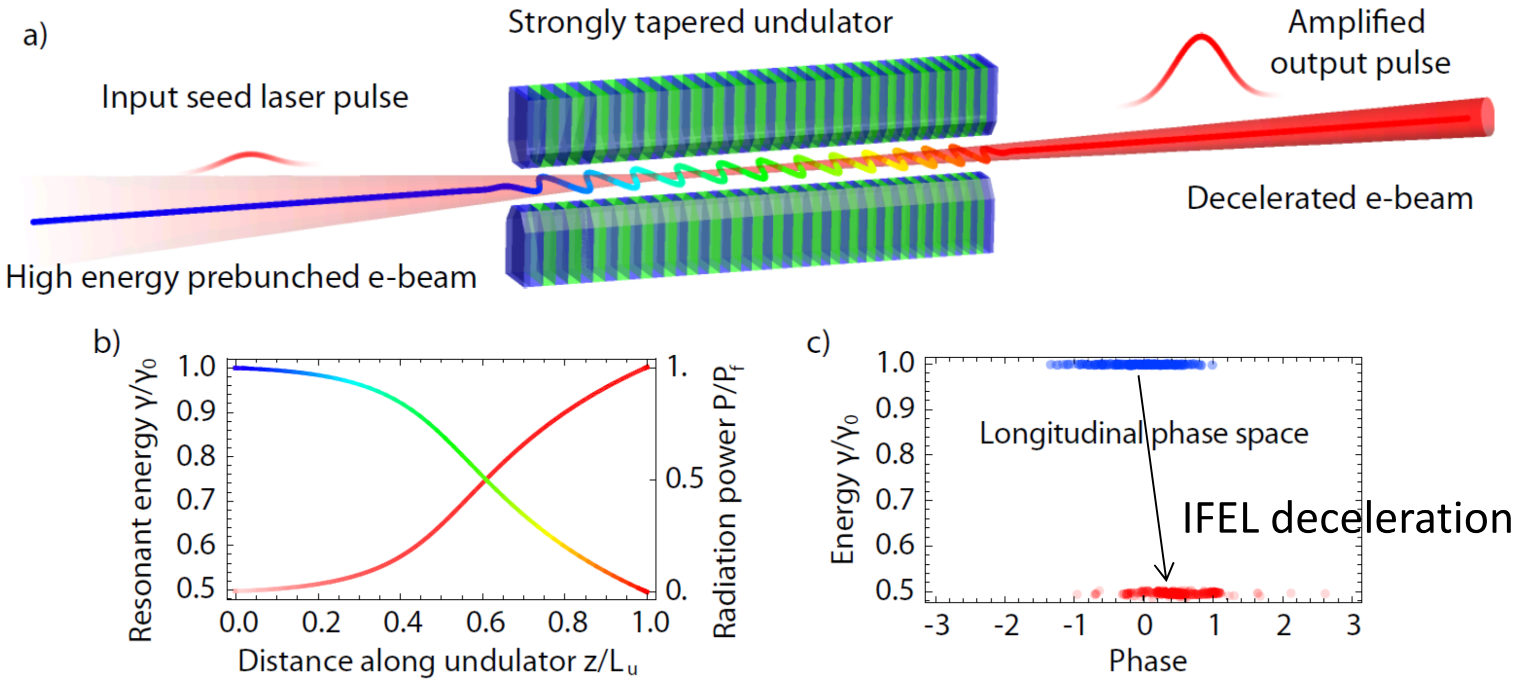
In an IFEL the electron beam absorbs energy from a radiation field.



UCLA results from prebunched RUBICON

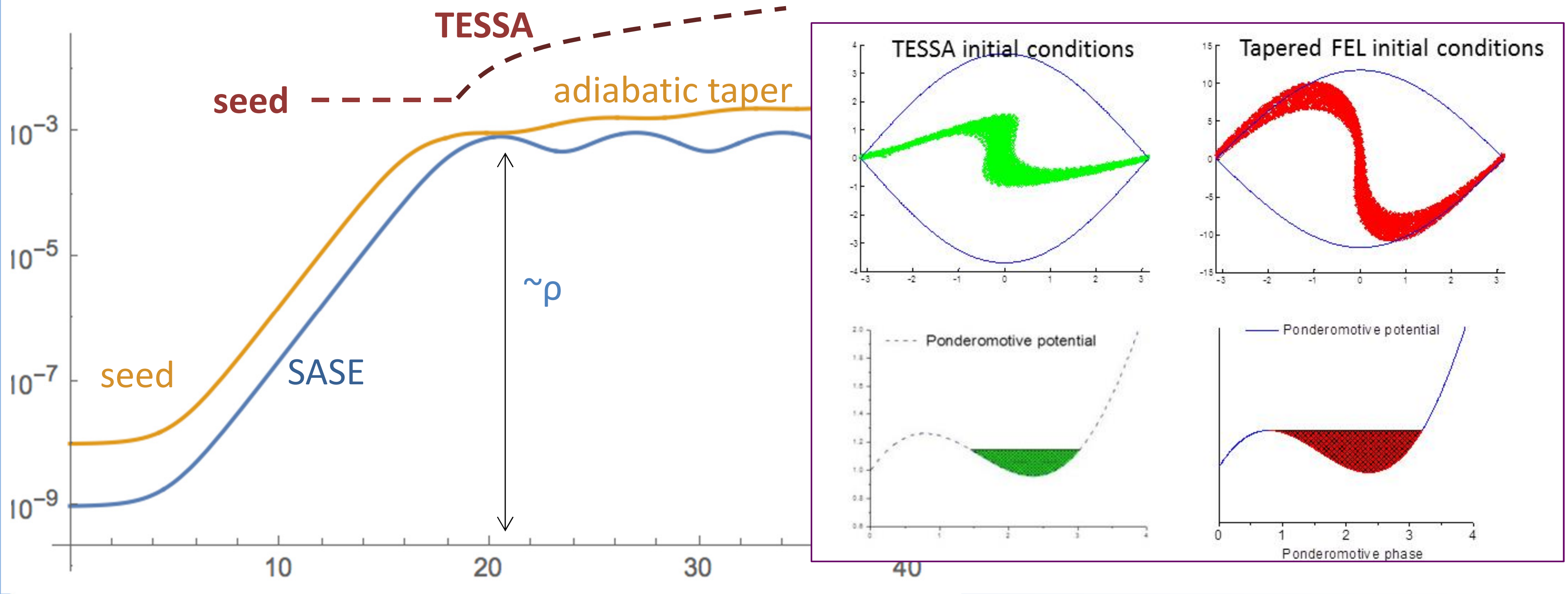
Tapering Enhanced Stimulated Superradiant Amplification

- Reversing the laser-acceleration process, we can extract a large fraction of the energy from an electron beam provided:
  - A high current, microbunched input e-beam
  - An **intense input seed**
  - Gradient matching via GITS to exploit growing radiation field



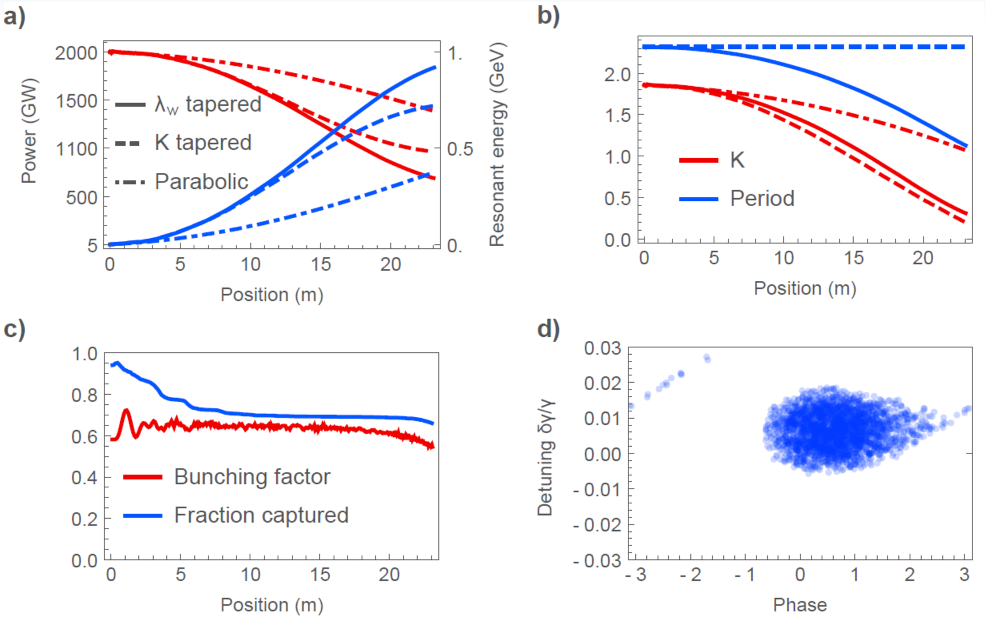
TESSA

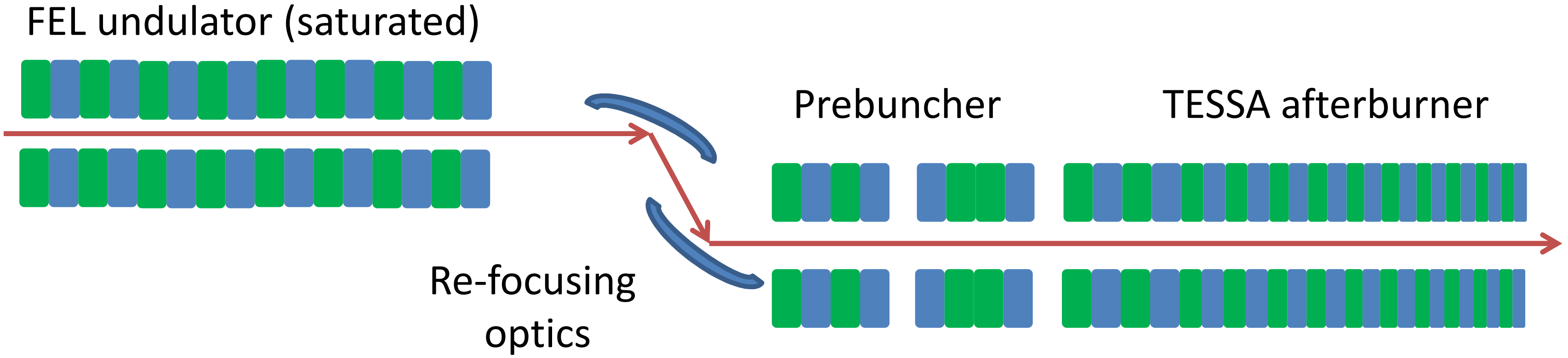
- Reach *IFEL gradients* with **large laser intensity** => input seed > FEL saturation intensity
- Aggressive tapering
  - Use tapering equations with radiation field sampled by capturable particles simulated with Genesis (GITS)
- **Rapid deceleration** with minimal beam losses
  - Prebunch beam => smaller longitudinal emittance (**smaller beam**)
  - Focus laser => greater acceptance (**larger bucket**)



TESSA afterburner at 13.5 nm

- Refocusing SASE (~GW) to recreate high intensity condition
- 4 kA @ 1 GeV = 4 TW beam power available
- Achieved **45% efficiency** in 23 meters!
- High rep rate => high average power





FEL undulator (saturated)

Prebuncher

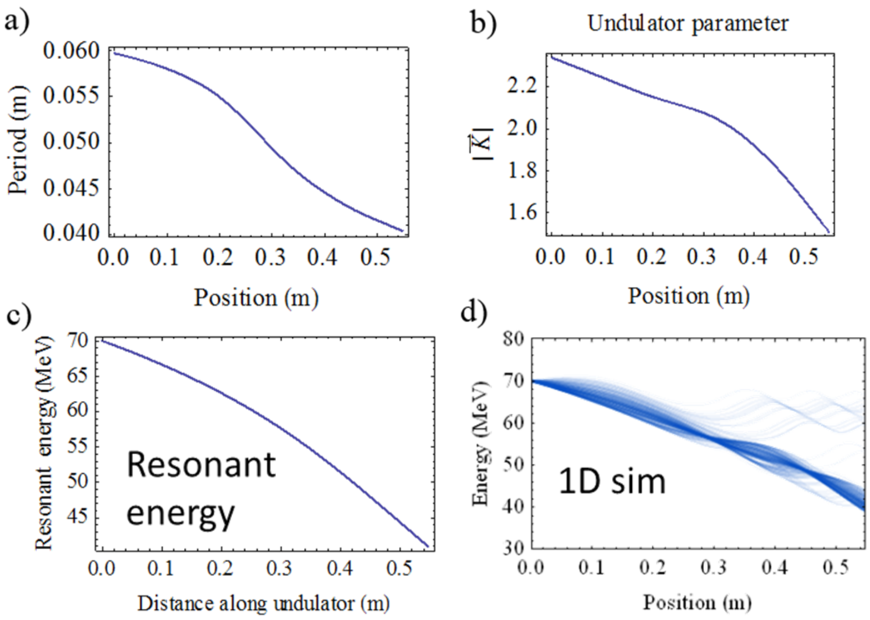
TESSA afterburner

Re-focusing optics

NOCIBUR IFEL deceleration experiment

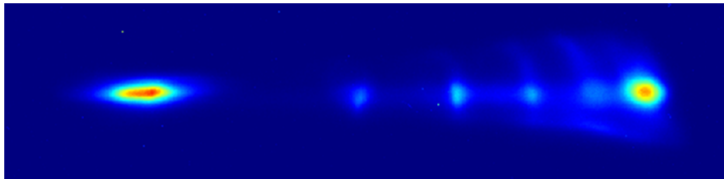
- Use RUBICON IFEL set up in reverse at ATF/BNL
- Retapered the 0.5 m undulator for deceleration
- Potentially extract 40 % of energy from a relativistic electron beam in half a meter

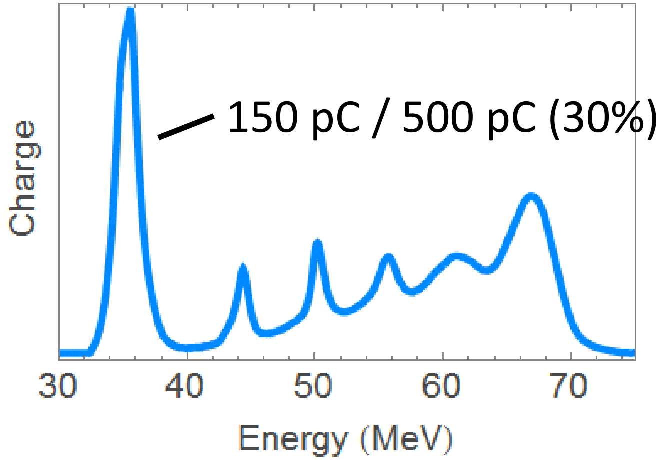
Parameter	Value
E-beam energy	65 to 34 MeV
E-beam current	100 -> 400 A
Laser focal intensity	4 TW/cm^2
Laser wavelength	10.3 µm
Rayleigh range	30 cm
Laser waist	1.0 mm
Input peak power	100 GW
Output peak power	130 GW



IFEL decelerator experiment at ATF/BNL

- First results (see N. Sudar TUP074)
- Next step:
  - compress input beam + prebunch for higher capture
- Hard to measure radiation: few mJ on top of 1 J seed
  - Use spatial cuts & time resolved diagnostics
- Performance scales with beam power



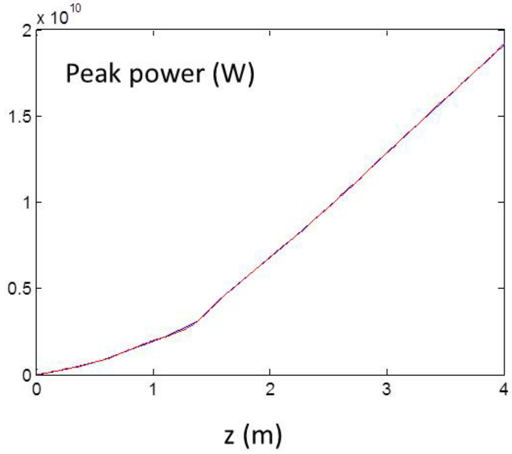


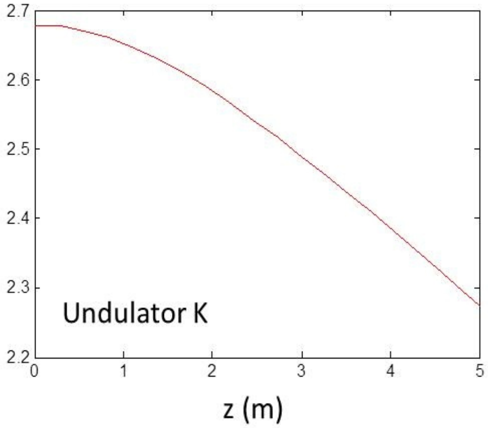
150 pC / 500 pC (30%)

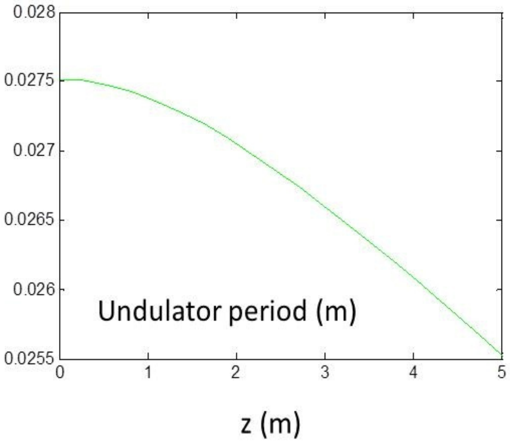
Preliminary results

Seeded TESSA Amplifier

- Nocibur limitation: deceleration experiment (low gain), laser beam is much longer than e-beam, amplification is hard to measure
- To demonstrate orders of magnitude amplification (high gain), we plan to use 266 nm laser as a seed, focused to a small spot size with a 350 MeV beam at 1 kA at ATF2
- Preliminary studies indicate over 3 orders of magnitude amplification in 4-5 meters undulator at 266 nm, with energy extraction in the range of 10-30 % depending on the e-beam parameters.

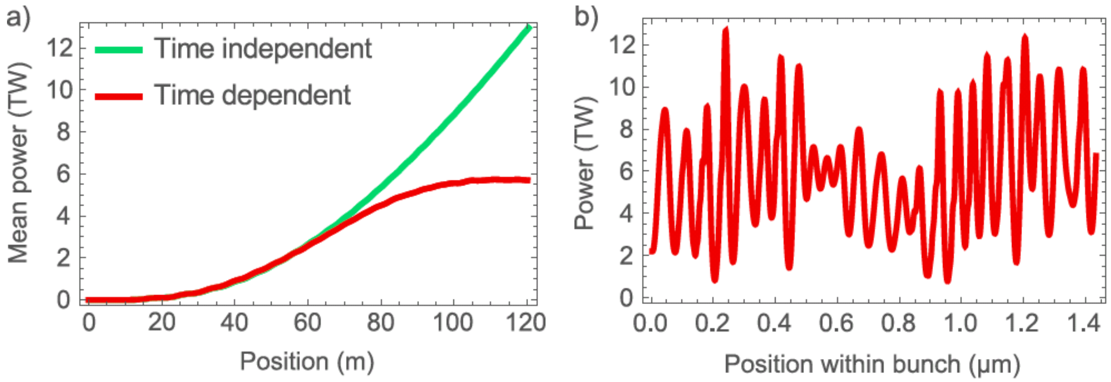


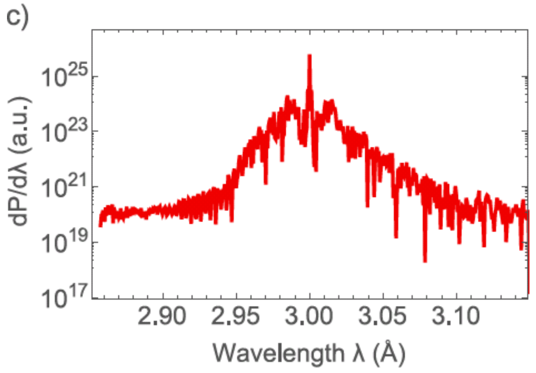




GITS applied to X-ray production

- **GITS formalism** also useful for tapering x-ray FEL's
- Relation to other tapering approaches
  - Tapering enhancement to stimulated superradiance (A. Gover, PRSTAB'05)
  - Local dynamics vs global optimization (Y. Jiao, et al. PRSTAB'12; C.Emma, et al. PRSTAB'14)



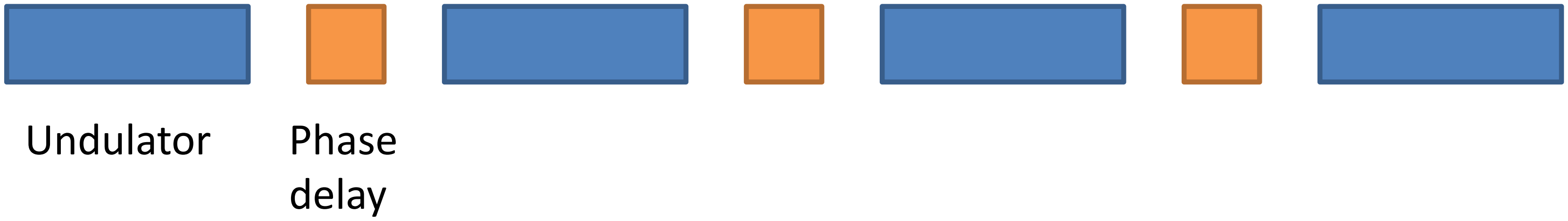


- No easy source of x-rays => self-seeding
- No high-power x-ray mirrors so decelerating gradient reduced for x-ray production
- Sideband growth limits interaction to ~80 m

Parameter	Value
Wavelength	0.3 nm
Self-seeding power	5 MW
Energy	14.35 GeV
Current	4 kA
Bunching	Shot noise
Spot size (rms)	11 μm
Norm. emittance	0.3 um

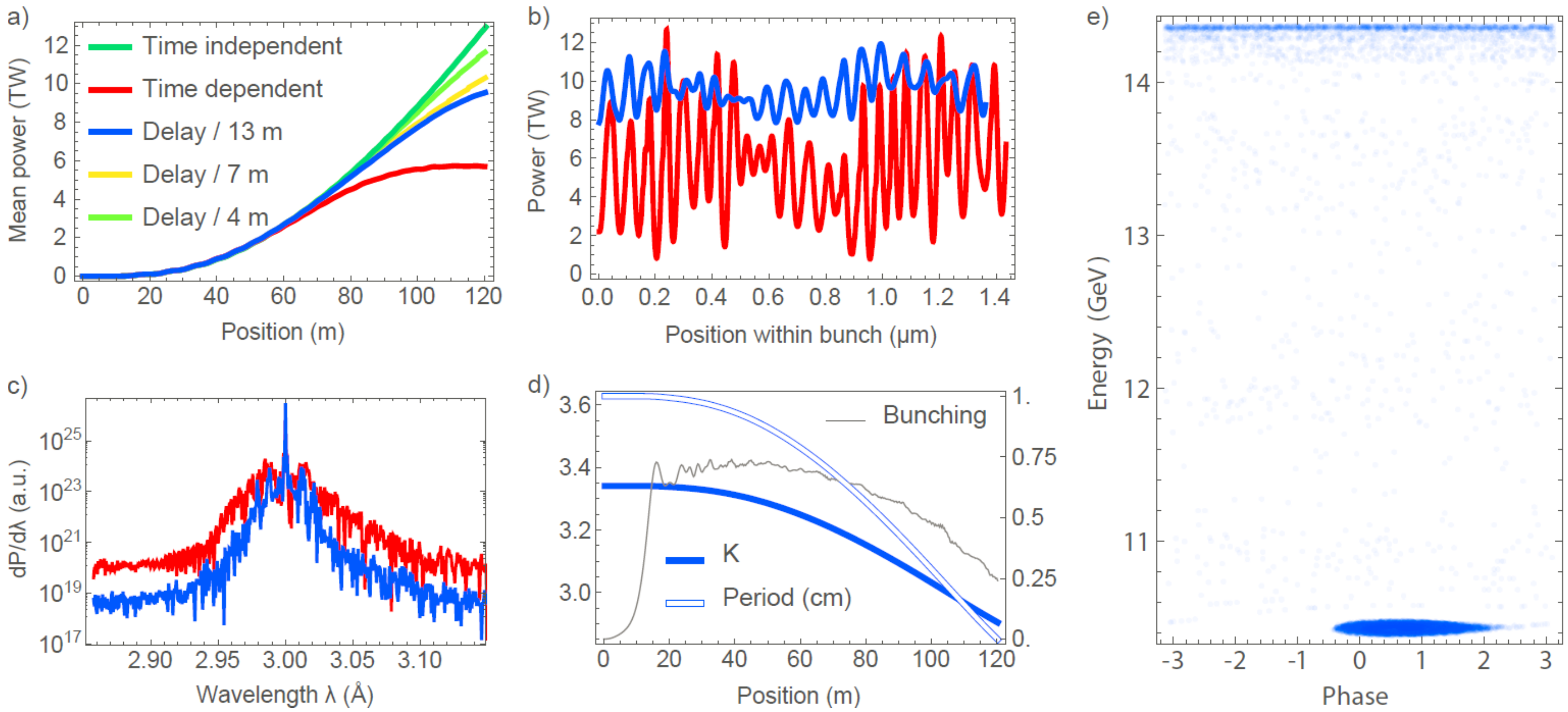
Sideband instability management

- Shot noise suppression reduces starting power in sidebands (Gover & Dyunin PRL’09; Ratner, Huang & Stupakov PRSTAB’11)
- Uniformly fill bucket to prevent growth (KMR)
- Taper hard to change synchrotron period
- **Actively suppress with phase shifters**
  - Phase shift peak sideband by π for deconstructive interference while preserving fundamental
  - Challenge to make nearly isochronous chicanes



Sideband suppression

- Periodically add phase delays to shift the peak sideband by π and recover more power
- Required delays on the order of $z_s(1+K^2)/4\gamma^2$ or 30 - 100 nm



Conclusion

- Experiments point to IFEL as mature and reliable laser-based high gradient accelerator technology
- Push to GeV/m gradient and GeV energy gain
- Enable laser-driven compact accelerator applications
- High gradient IFEL deceleration: TESSA can achieve over an order of magnitude improvement to FEL efficiency with high intensity seed laser
- GITS algorithm useful for hard x-ray FELs, but lack of intense seed necessitates sideband growth management

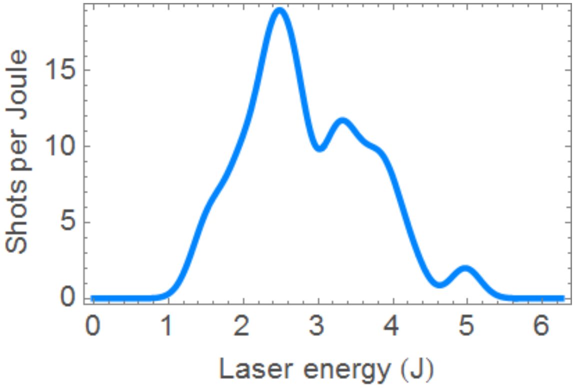
IFEL stability

IFEL output remarkably stable considering input fluctuations

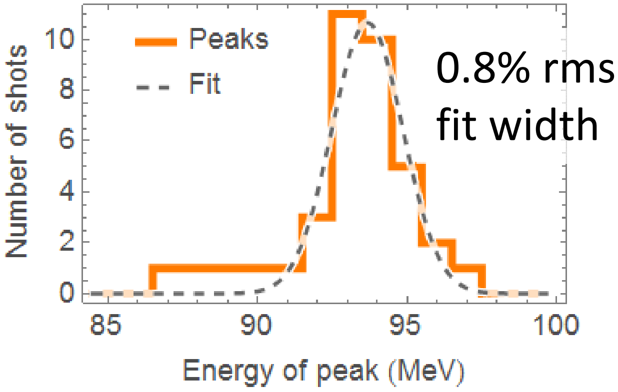
- Resonant energy laser intensity independent
- Energy spread and jitter set by ponderomotive bucket height which scales as fourth root of the laser intensity
  - => $\delta\eta/\eta \sim \frac{1}{4}\, dI/I$

Source of error	Fluctuations
Laser power	**30 % rms**
Laser position dx/w_0	15 % rms
E-beam time of arrival jitter	~1 ps (20% of laser duration)

Input laser energy



Energy of peak charge density of accelerated beam



0.8% rms fit width

Adaptive resonant phase

As suggested in KMR, resonant phase may be chosen to keep the action constant as the separatrix grows.

$$J_b = J_{b,0}$$

$$\psi_r = \mathrm{sgn}(\psi_{r,0})\, f_J^{-1}\left(\sqrt{\frac{\lambda_{u,0}K_{l,0}K_0}{\lambda_u K_l K}}\, f_J(\psi_{r,0})\right)$$