Advances in Inverse Free Electron Laser accelerators and implications for high efficiency FELs

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Noce workshop, Arcidosso, September 20th 2017

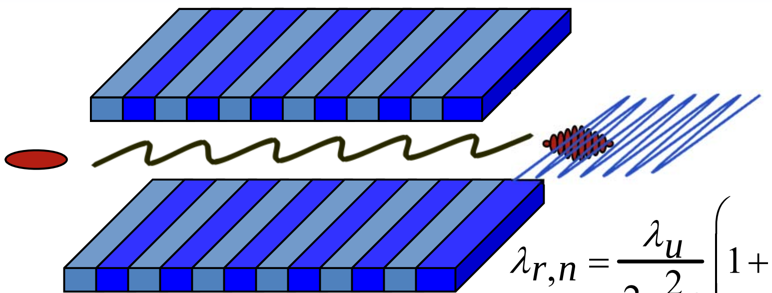
UCLA

Outline

- Introduction to ponderomotive interaction in strongly tapered undulators
- IFEL acceleration experiments
  - LLNL IFEL – 800 nm laser
  - Rubicon – 10 um laser
  - RubiconICS
  - Double buncher
- Future directions
  - Recirculated IFEL
  - GeV-class IFEL experiments at ATF/ATF2
- TESSA, an inverse IFEL: high gradient laser decelerator
- TESSA experiments and roadmap

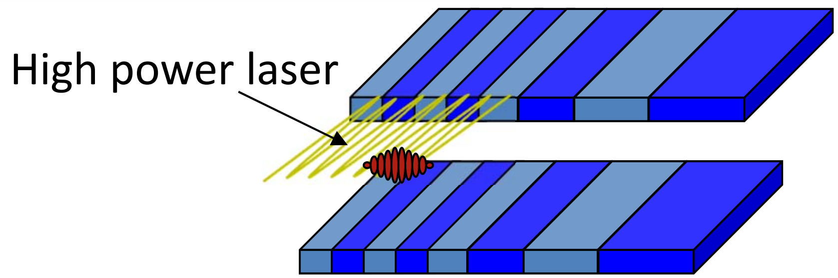
IFEL Interaction

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

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

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

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

IFEL research overview

IFEL scales ***ideally well*** for mid-high energy range (50 MeV – ***up to few GeV***) due to

- high power laser wavelengths available (10 μm, 1 μm, 800 nm)
- permanent magnet undulator technology (cm periods)

Plane wave or far field accelerator : minimal 3D effects.

Transverse beam dimensions can be mm-size for μm accelerating wavelength!

Vacuum-based accelerator

Efficient mechanism to transfer energy from laser to electrons

Simulations show high energy/ high quality beams with gradients ~GeV/m achievable with current technology!

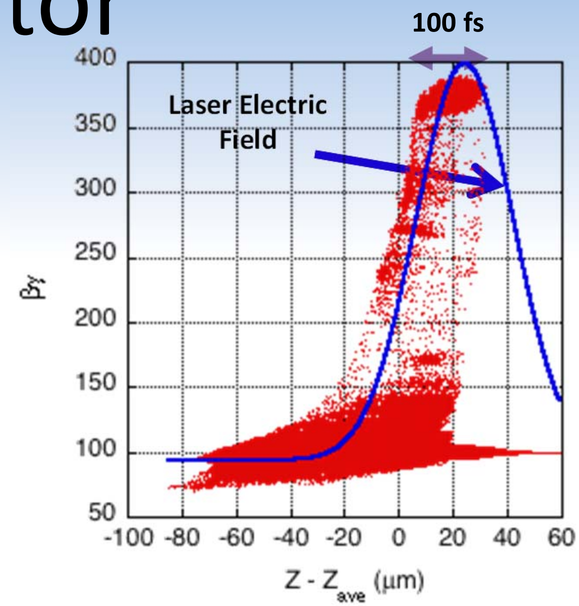
Preservation of e-beam quality/emittance and high capture.

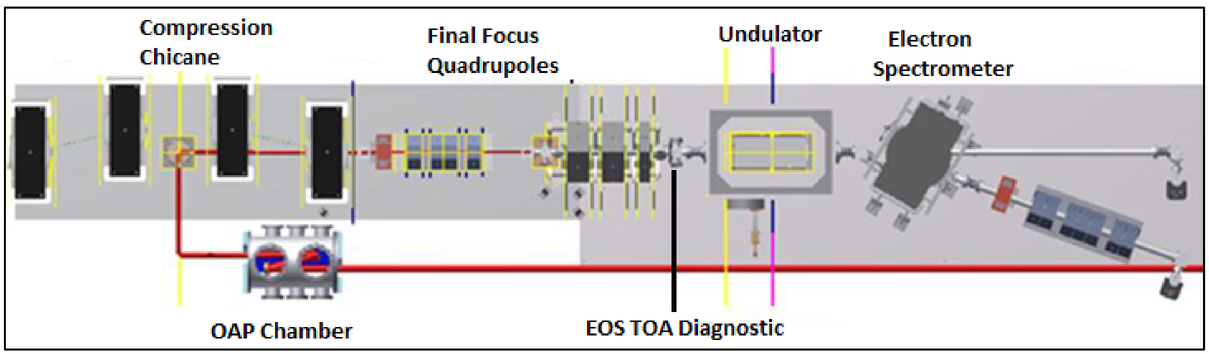
Microbunching: longitudinal phase space manipulation at optical scale

<u>Viable technology for compact laser-driven 1-2 GeV injector</u>

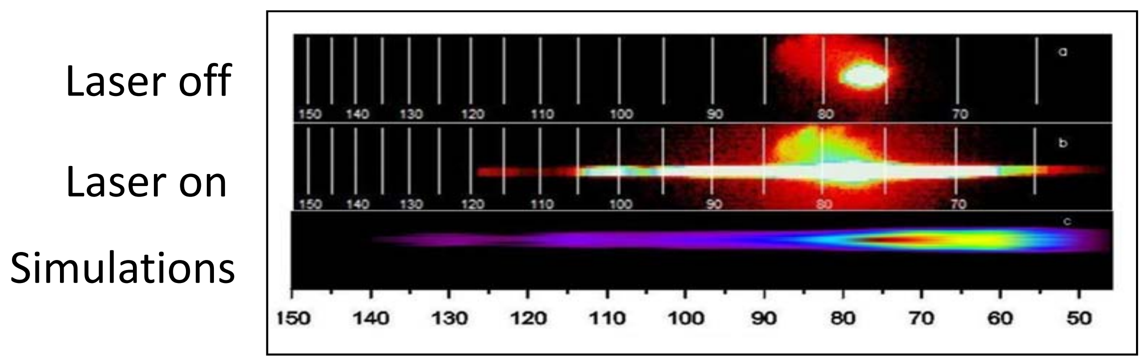
LLNL Ti:Sa IFEL accelerator

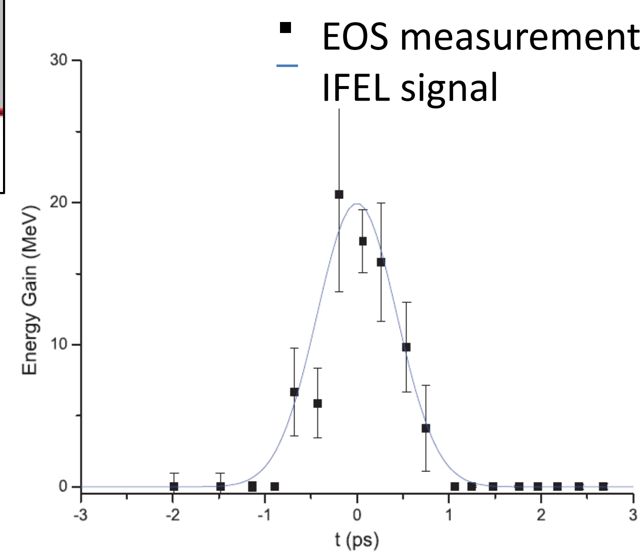
- First TW-class laser driven IFEL
- Strongly tapered Kurchatov undulator for diffraction-dominated interaction
- Short pulses (sub-ps) interaction
- 77 MeV – 122 MeV in 22 cm
- > 200 MV/m gradient !
- Sub-ps synchronization and timing





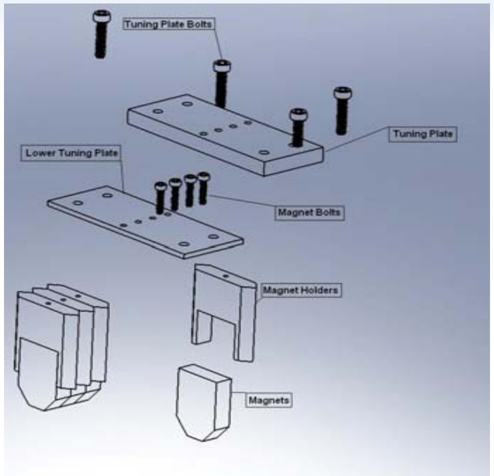
J. T. Moody, et al. Physical Review Accelerators and Beams 19, 021305 (2016)

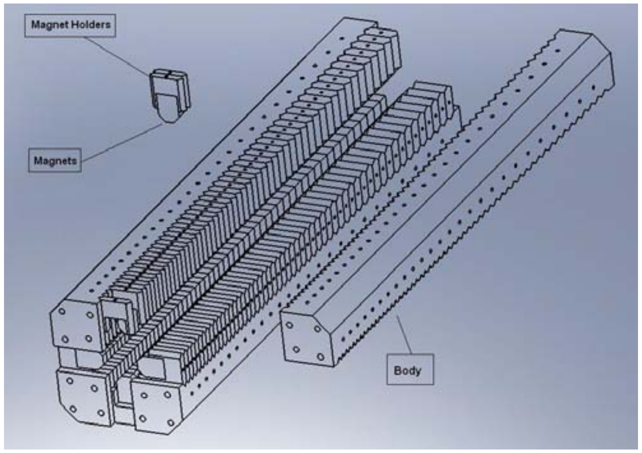




Strongly tapered helical undulator technology

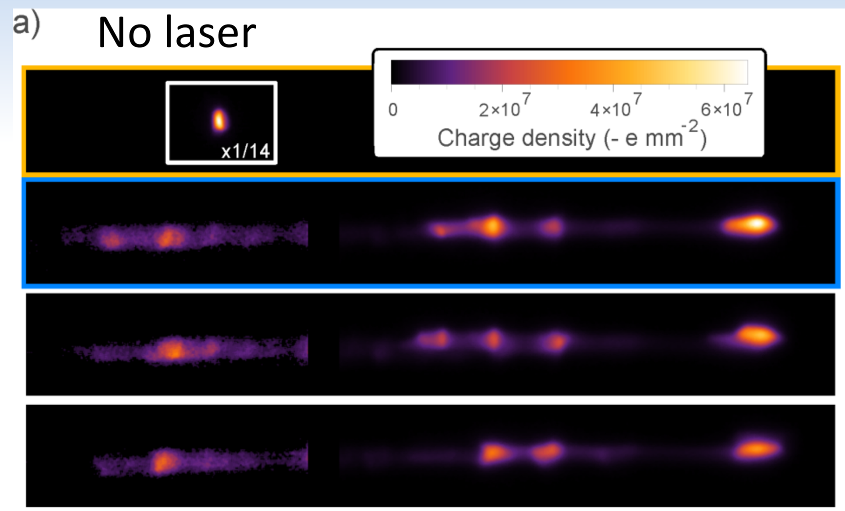
- Advantage of helical geometry
- UCLA Halbach-style undulator: scalable and affordable
  - NdFeB magnets
  - Orthogonal Halbach undulators with varying period and field strength
  - Entrance/exit periods keep particle oscillation about axis
  - Beam pipe or vacuum box to allow smaller gap
  - Fully tunable



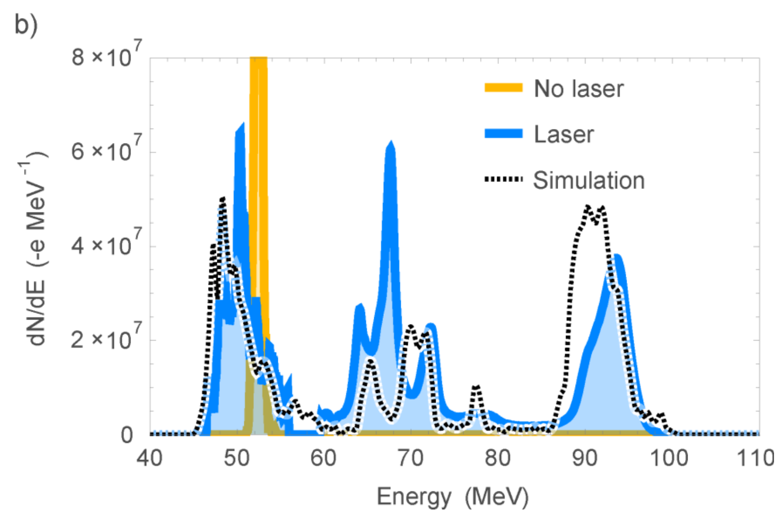


High quality output beams: Rubicon experiment

- Input: 50 MeV e-beam, 400 GW CO_2 laser, 54 cm long tapered helical undulator
- Output: 93 MeV – 1.8 % energy spread
- Very reproducible (mean energy std < 1.5 %)
- Laser intensity 5 orders of magnitude lower than LWFA
- Good agreement with simulation prediction



Laser on – consecutive shots



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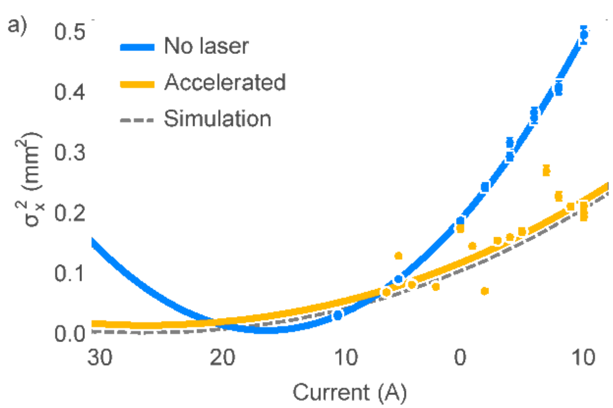
High-quality electron beams from a helical inverse free-electron laser accelerator

J. Duris[1], P. Musumeci[1], M. Babzien[2], M. Fedurin[2], K. Kusche[2], R.K. Li[1], J. Moody[1], I. Pogorelsky[2], M. Polyanskiy[2], J.B. Rosenzweig[1], Y. Sakai[1], C. Swinson[2], E. Threlkeld[1], O. Williams[1] & V. Yakimenko[3]



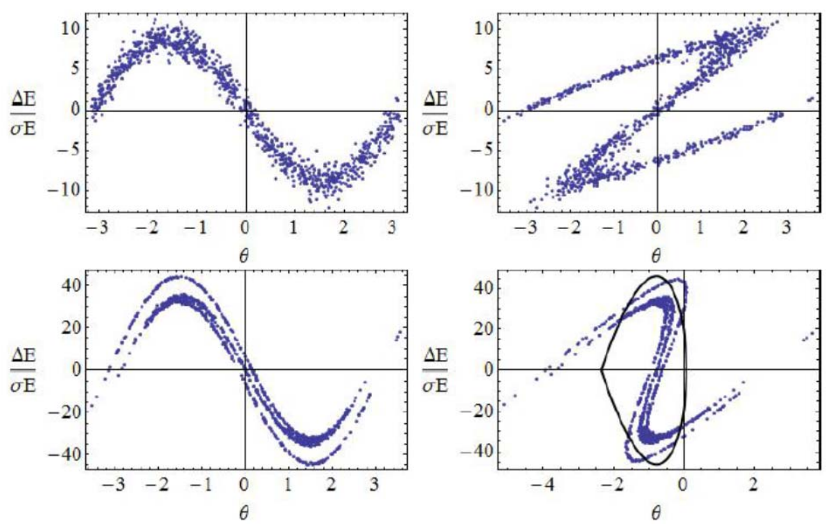
Emittance measurement

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

Double buncher. Adiabatic capture

- Beam quality strongly dependent on fraction of particles captured
- Single buncher + R56 is first step to improve capture, but severely limited by non-linearities of cos-like potential
- Putting together two ideas:
  – Diffraction-based adiabatic capture
  – Piece-wise bunching

Use two stage modulator + chicane to slowly compress all the particles Cascade microbunching [Hemsing and Xiang, PRSTAB 2012]

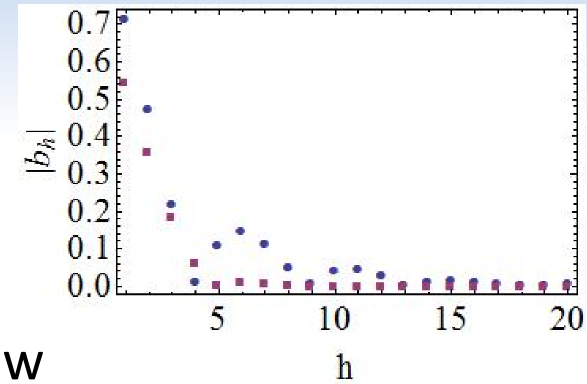


Cascaded pre-bunching

- Modulator: $p' = p + A\sin(\theta)$ $\theta' = \theta$
- Chicane: $\theta'' = \theta' + Bp'$ $p'' = p'$
- $p \equiv \delta\gamma/\sigma_\gamma$ $\theta \equiv kz$ $A \equiv \Delta\gamma/\sigma_\gamma$ $B \equiv k R_{56} \sigma_\gamma/\gamma_r$
- Modulator 1 (**I**): small energy modulation
Modulation amplitude **A1**
- Chicane 1 (**II**): large dispersion **B1**
Over rotate energy modulation ($-\pi/2 \rightarrow \pi/2$)
- Modulator 1 (**III**): large energy modulation
Modulation amplitude **A2**
- Chicane 1 (**IV**): small dispersion **B2**
Rotate energy modulation into density modulation ($-\pi/2 \rightarrow 0$)

Applications of double buncher

- Improve capture in laser accelerator (DLA and IFEL)
- Increase peak current (ESASE)
- Maximize bunching factor
- Increase harmonic content in the beam
- Favorable comparison with single buncher for low induced energy spreads



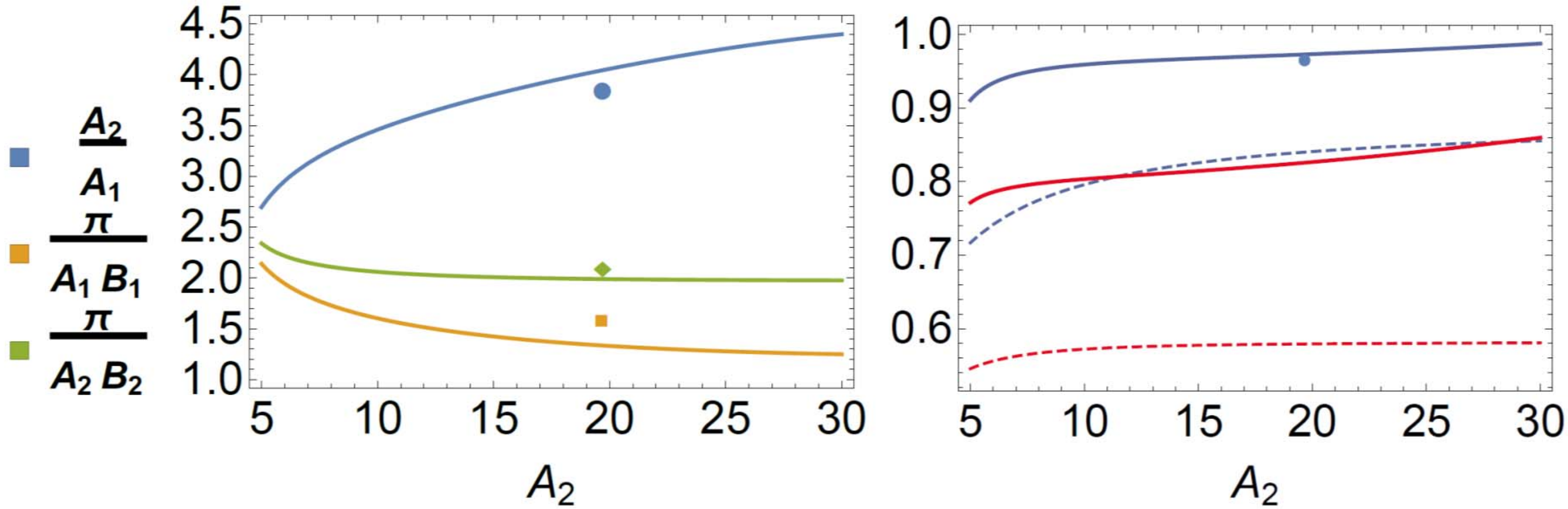
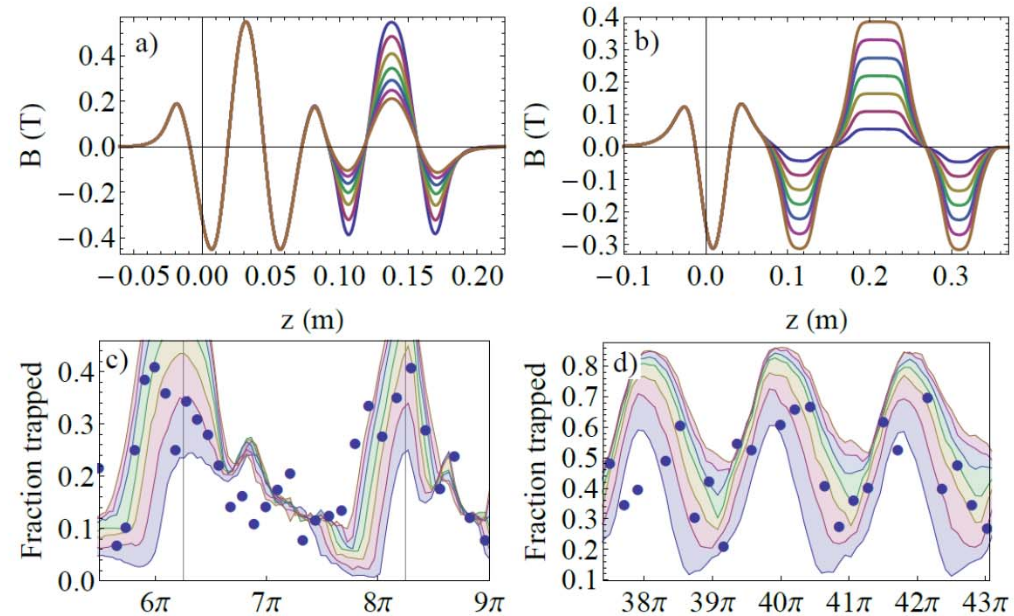
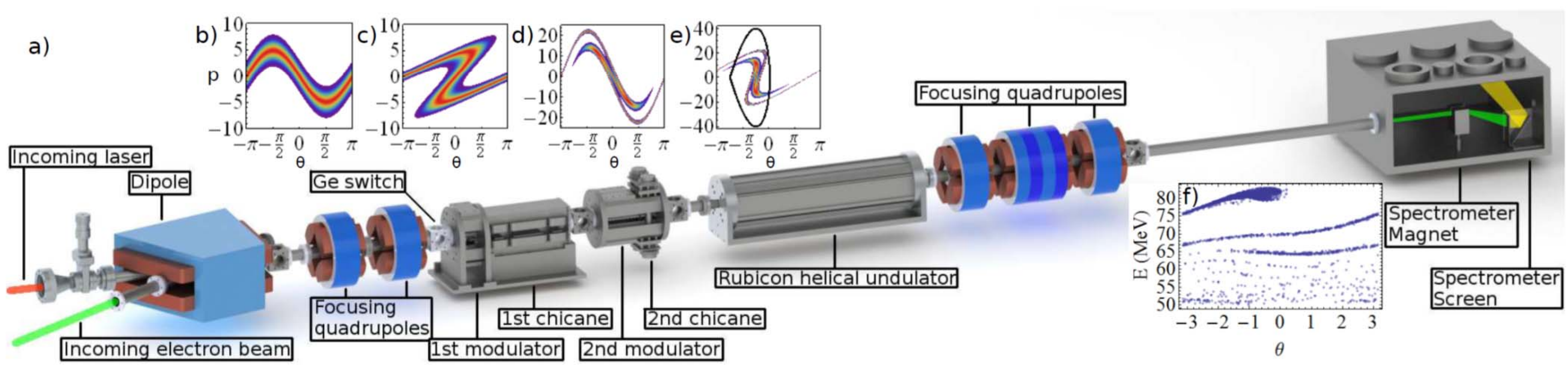


FIG. 2. (left) optimal double buncher parameter values maximizing trapping. (right) Double buncher fraction trapped and bunching factor (blue, dashed) and single buncher fraction trapped and bunching factor (red, dashed). Points at A_2 = 20 are experimental values.

ATF experimental demonstration

- 2 modulator-chicane pre-bunchers in series
- Use single high power 10 um laser pulse
- IFEL accelerator as bunching diagnostic





IFEL accelerator with double buncher

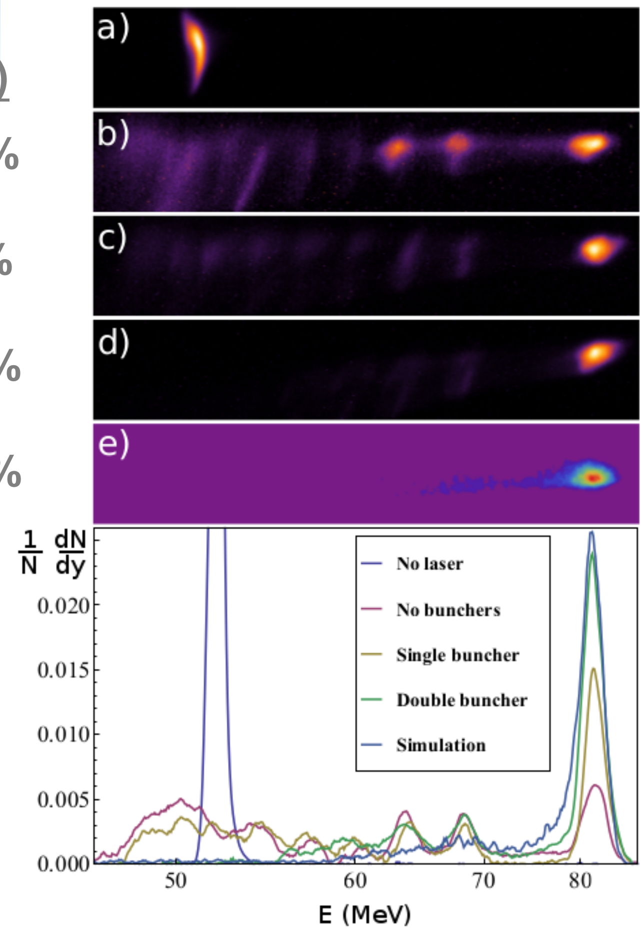
<u>Fraction trapped (E>77 MeV)</u>

No bunchers: 25%

1 buncher: 40%

2 bunchers: 70%

2 bunchers (GPT): 75%



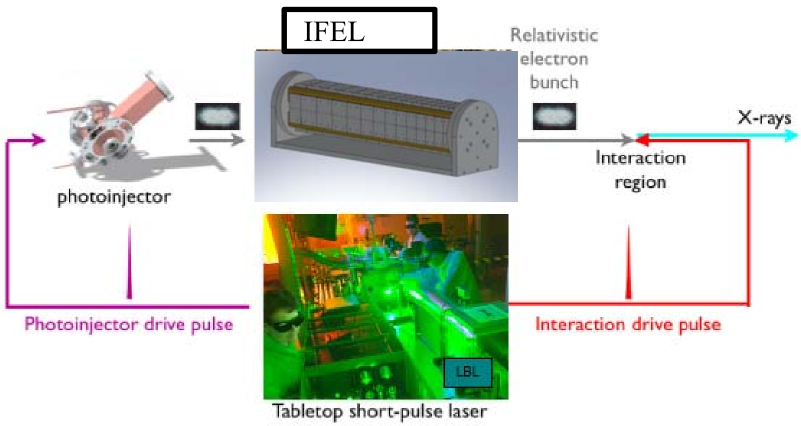
- > 90 % captured !
- Good agreement with GPT simulations
- Can directly measure microbunching with RF deflector (Fall 2017)

Arxiv: Sudar et al. Demonstration of cascaded modulator-chicane micro-bunching of a relativistic electron beam

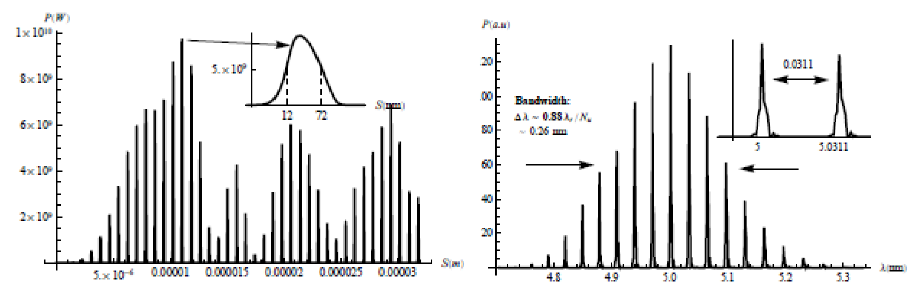
Acknowledgement of SCGSR support for N. Sudar

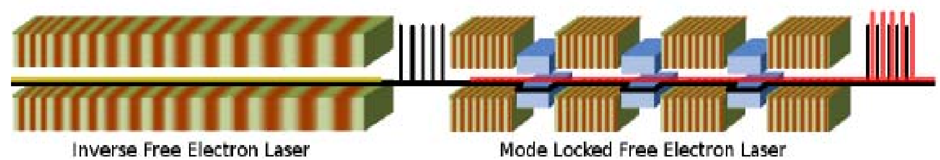
IFEL Applications

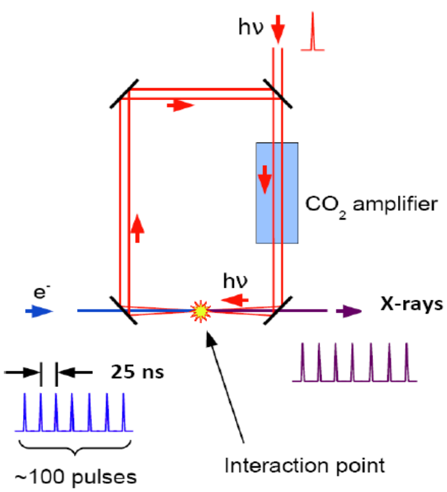
- Inverse Compton Scattering-based compact gamma-ray source
  - DNDO – DTRA interest



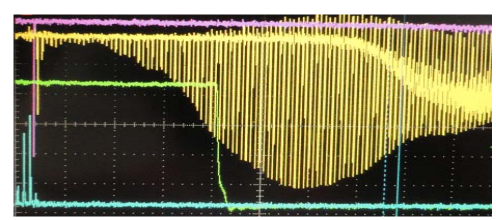
- Compact Modelocked soft-X-ray FEL
  - Take advantage of current increase
  - Use chicane to realign radiation spikes with e-beam modulation





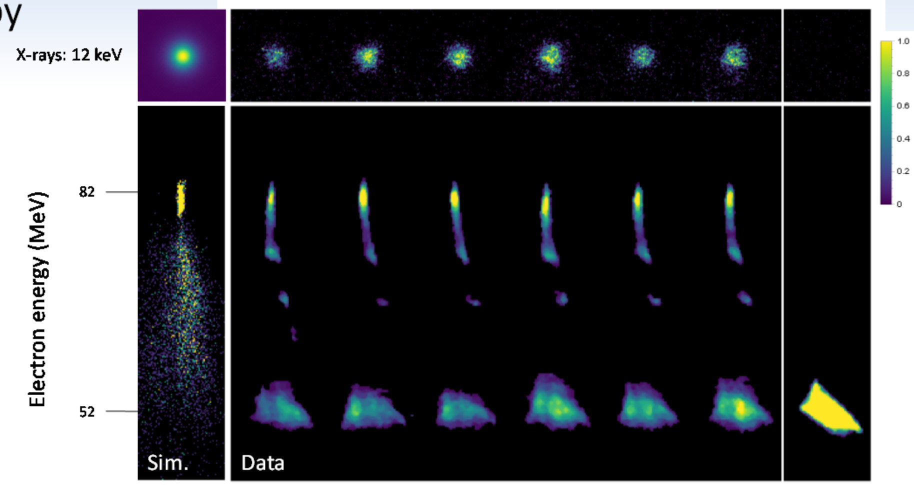


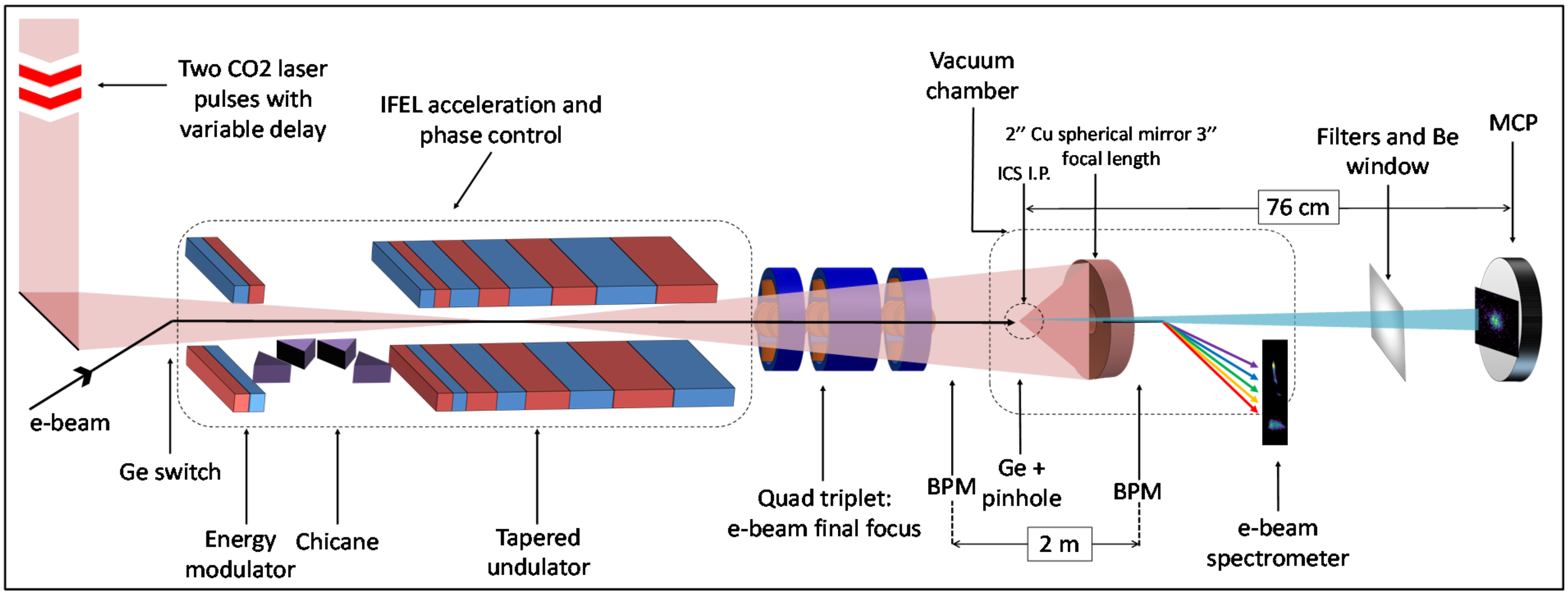
- Recirculate drive laser for IFEL to increase repetition rate and average flux of photons



RubiconICS

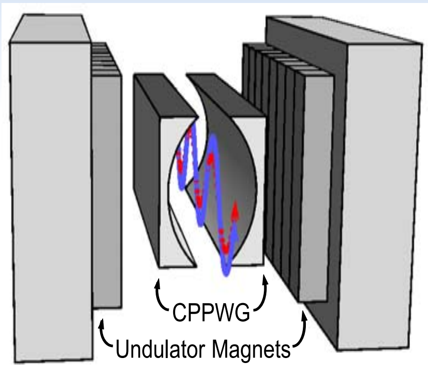
- Inverse Compton Scattering x-rays from a beam accelerated in an inverse free electron laser
- Use two 1 J 10.3 μm amplified pulses separated by ~0.5 nS
- 1st pulse drives IFEL - electron beam accelerated from 52 to 80 MeV in ~0.5 m
- 2nd pulse is back reflected and focused at ICS interaction point
- Filter is used to spectrally analyze radiation
- Femtosecond scale X-ray temporal structure

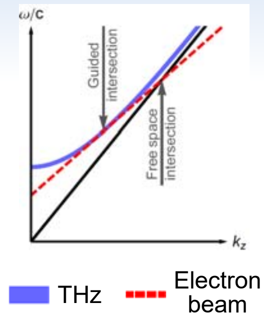




Group and phase velocity matching in THz IFEL interaction

Courtesy of E. Curry

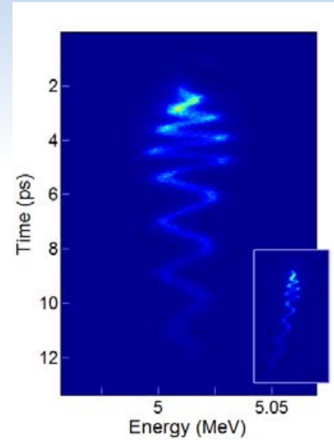


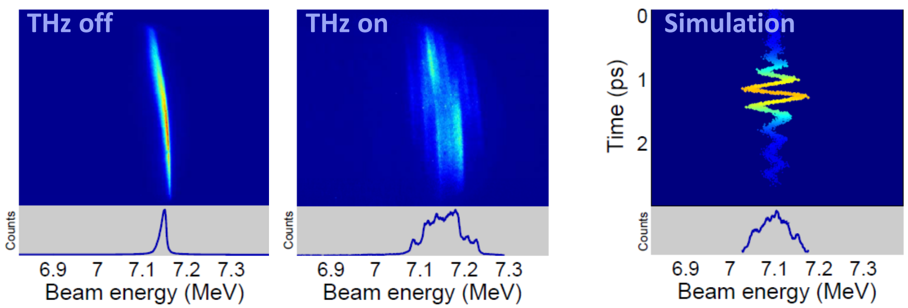


$$\omega/c = \beta_z(k_z + k_u)$$

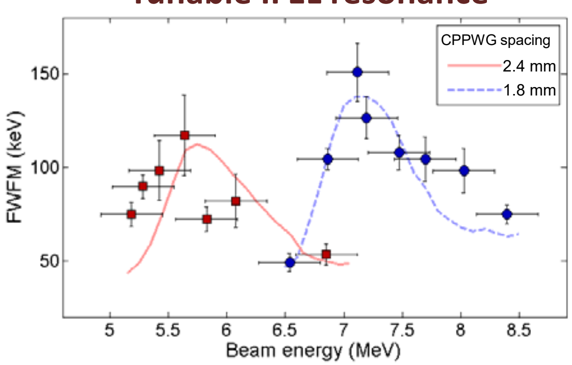
$$\beta_g = \frac{\partial(\omega/c)}{\partial k_z} = \beta_z$$

Beam Parameters	
Bunch energy	4-9 MeV
Undulator period	3 cm
Undulator parameter, K	1.27
# of undulator periods	10
CPPWG spacing	1.8-2.7 mm
Plate curvature radius	2 mm
Peak frequency	.84 THz
Pulse energy	1 μJ

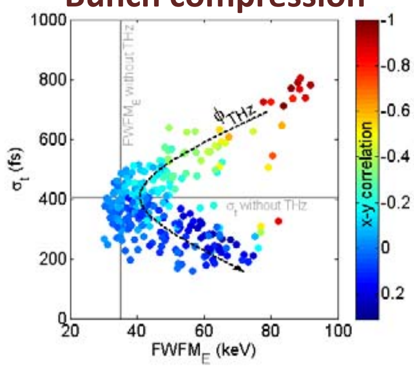




Tunable IFEL resonance



Bunch compression



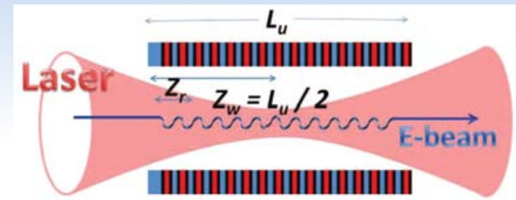
- Broadband interaction with near-single cycle THz pulse
- Group and phase velocity matching allows a meter-scale broadband interaction
  - Measured up to 150 keV energy modulation
- Longitudinal phase space measurements show well-defined sinusoidal energy modulation
  - Time-stamping with energy modulation
  - Scales linearly with THz field
  - Bunch compression by factor of two

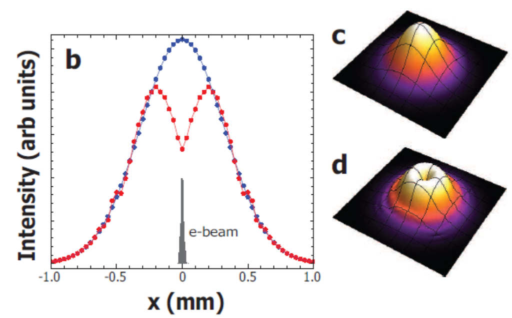
Future Directions

- THz-driven longitudinal profile diagnostic
- THz amplification via FEL interaction

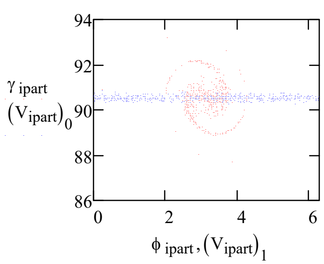
What's next in IFEL acceleration ?

- GV/ m gradient and GeV energy gain
- Recirculation of laser power
- Hollow waveguide IFEL to beat diffraction limit
- Beam loading in IFEL
  - Self consistent IFEL modeling
- Control of ponderomotive phase
- Evaluate other advanced bunching schemes

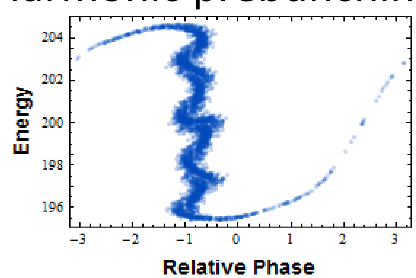


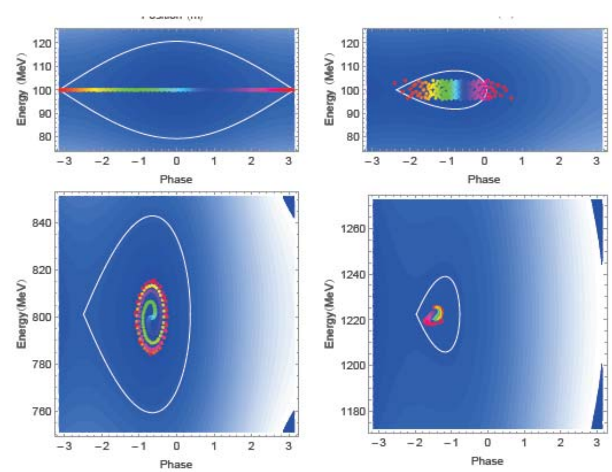


Adiabatic capture



Harmonic prebunching

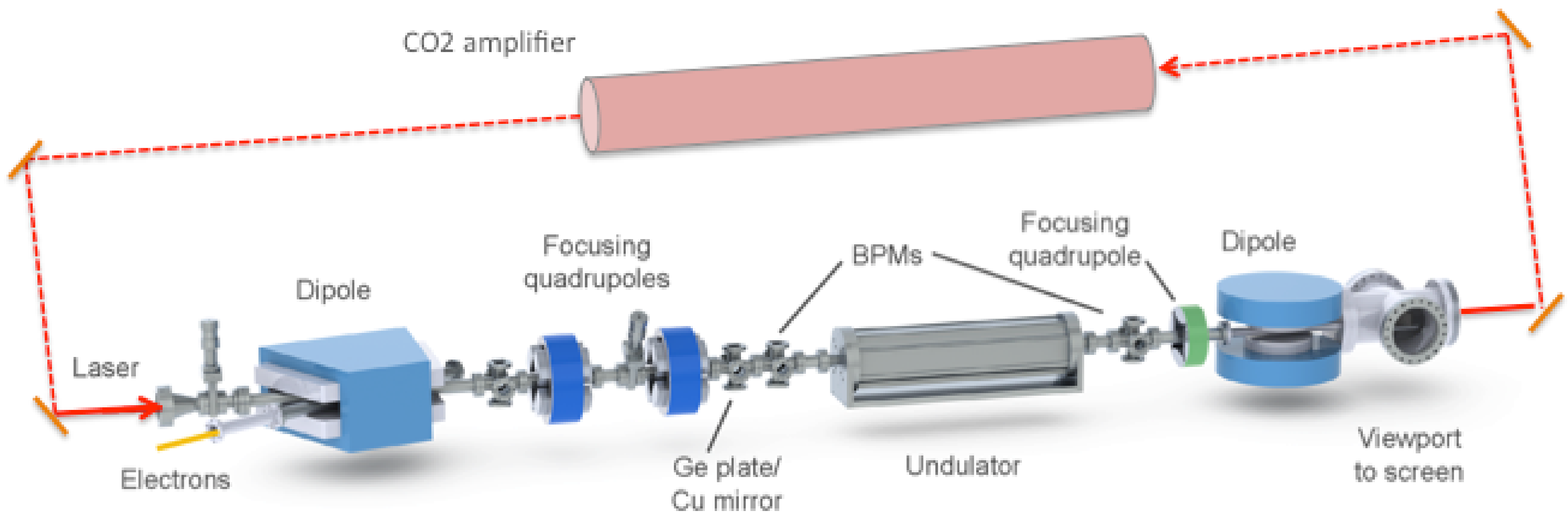




High duty cycle IFEL

- E-beam dyamics in a pulse train mode
- CO2 recirculated system upgrade
- IFEL optimization and integration

- Objective: to demonstrate intracavity IFEL operation in a pulse train regime
- Phase I: System design (2015-6)
- Phase II: Proof of concept demonstration (2017)

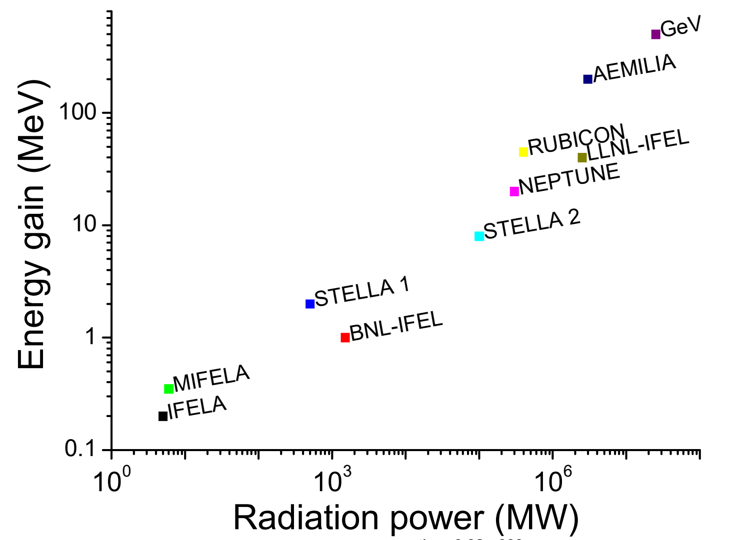


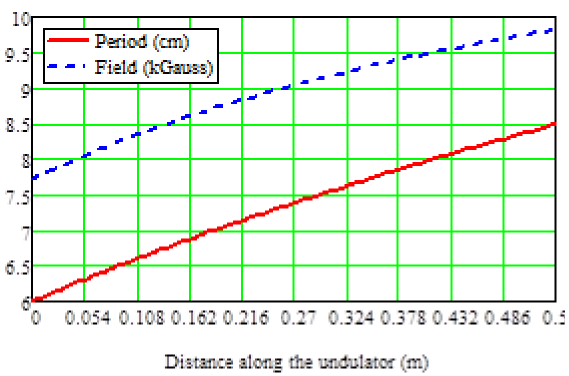
GeV-class IFEL accelerator

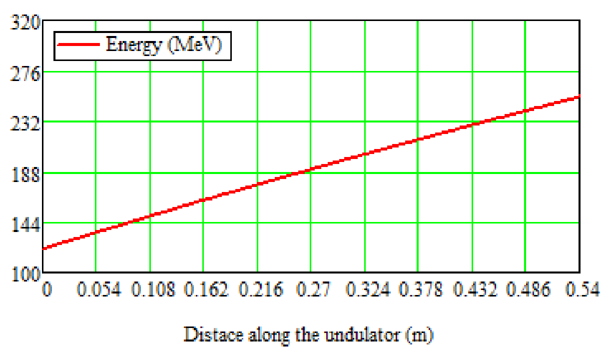
- Take advantage of ATF/ATF2 TW peak power laser upgrade.
- Demonstrate GeV/m gradients and GeV-class energy gain
- Enable IFEL applications
  - Gamma-ray production by Inverse Compton Scattering
  - FEL radiation in soft-X ray region

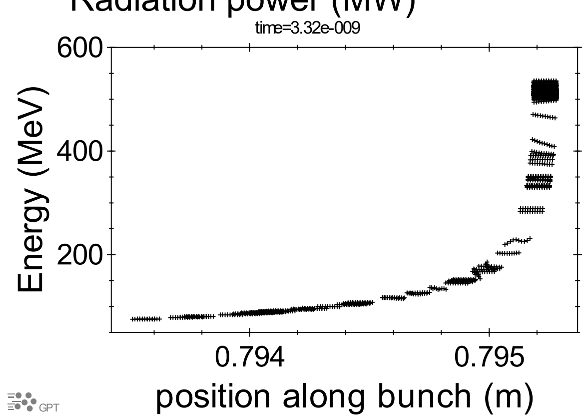
	AEMILIA	ATF-2 IFEL
Laser power	2 TW	25 TW
Undulator length	1.08 m	75 cm
Input energy	50 MeV	90 MeV
Output energy	250 MeV	500 MeV
Energy spread	1.5 %	2.5 %
Undulator period	4 – 8.5 cm	5-12 cm
Magnetic field	0.5 – 0.9 T	0.7-1.2 T

- Inverse Free Electron Laser experiments



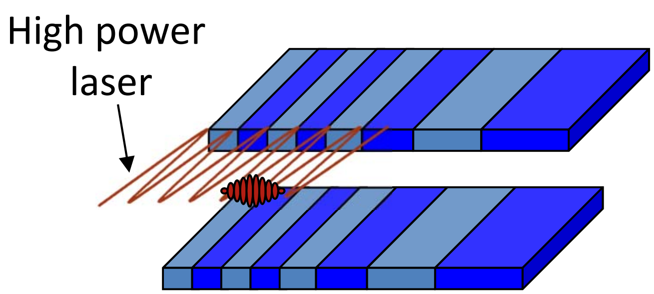




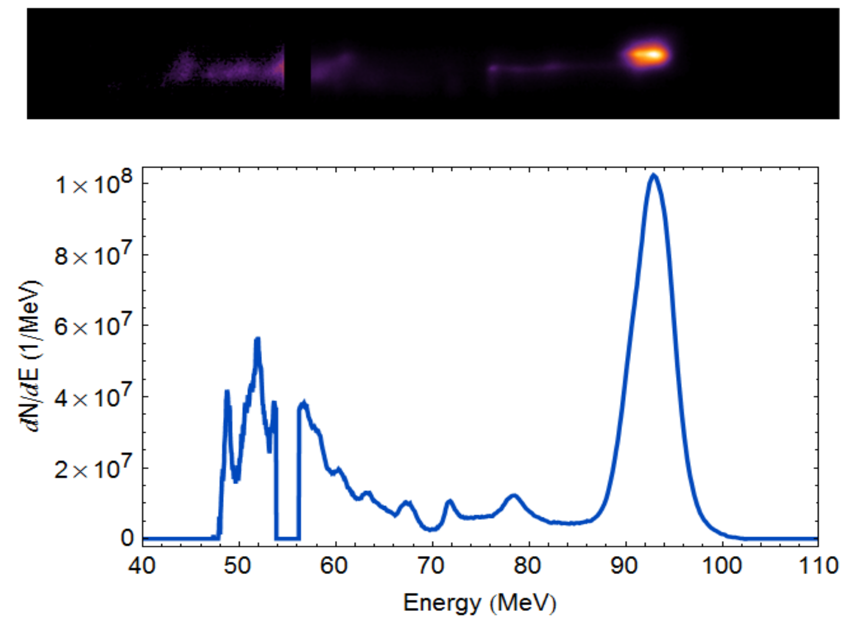


Lessons from Inverse FEL

- FEL beam-laser energy exchange is usually < 1 MeV/m
- IFEL demonstrated energy exchange rate ~ 100 MeV/m
- Design studies indicate possibility of 1 GeV/m
- ***Can we run IFEL in reverse?***



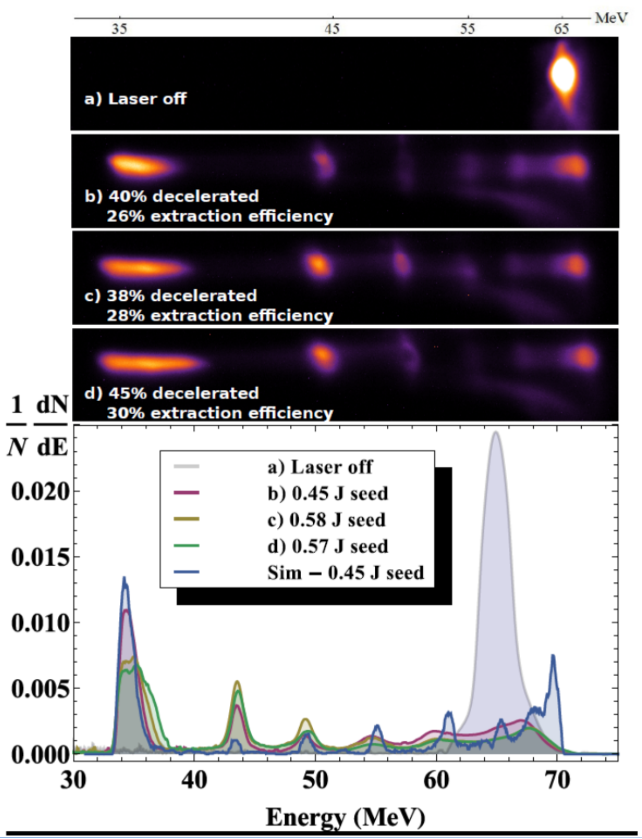
In an IFEL the electron beam absorbs energy from a radiation field.

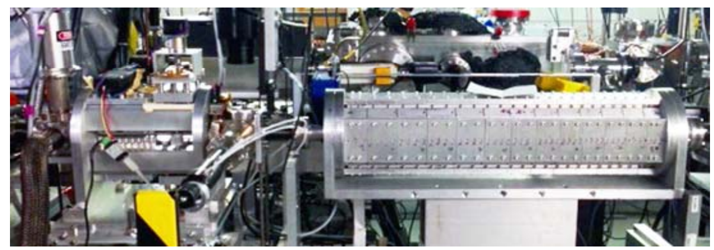


UCLA results from prebunched RUBICON.
J. Duris et al, *Nature Comm*. **5**, 4928, 2014

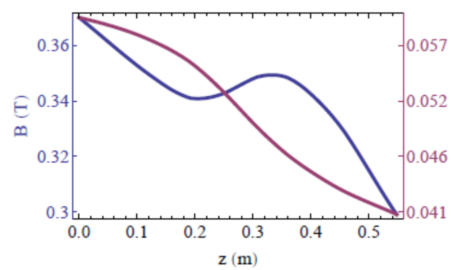
High efficiency interaction: NOCIBUR deceleration

- Use RUBICON IFEL set up in reverse at BNL ATF
- Reversed and retapered the 0.5 m undulator for high gradient deceleration
- Up to 45% of 100 pC beam captured and decelerated
- Demonstrated >30% efficiency from a relativistic electron beam in half a meter (2mJ)

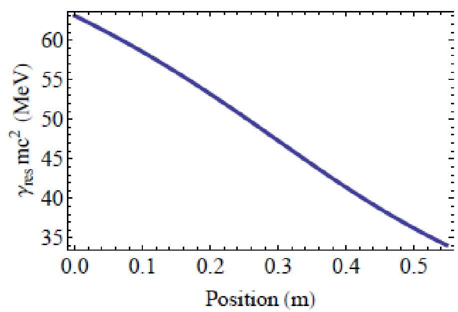




Undulator parameters



Resonant energy



PRL 117, 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

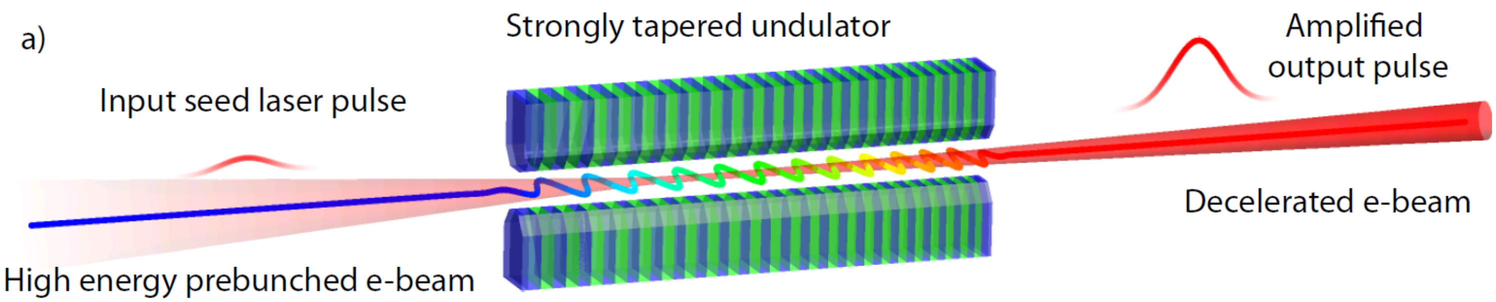
High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

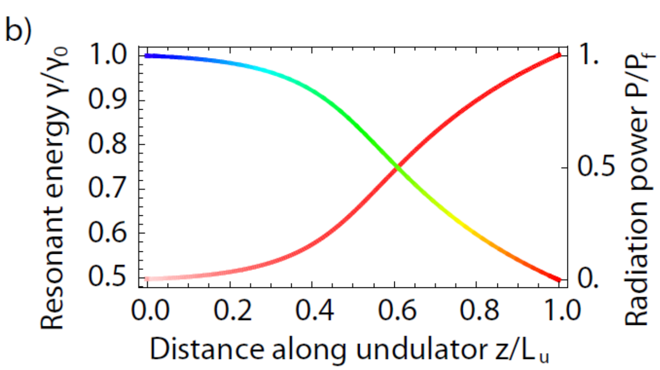
N. Sudar, P. Musumeci, J. Duris, and I. Gadjev
Particle Beam Physics Laboratory, Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA

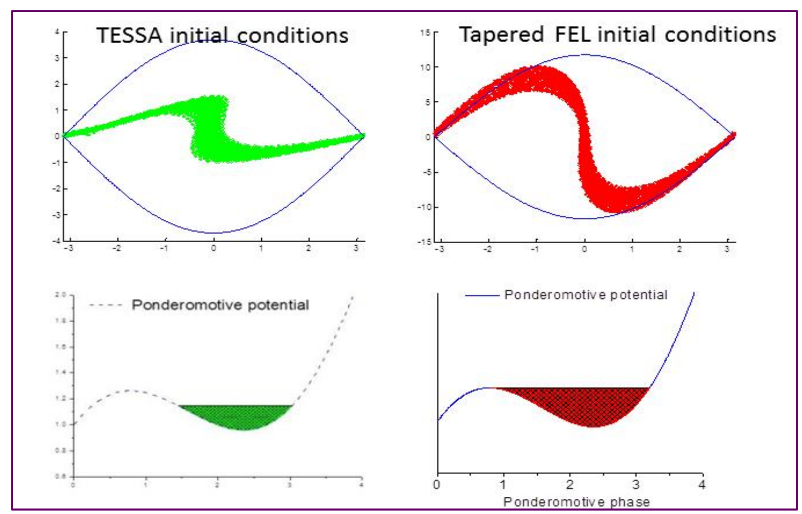
Tapering Enhanced Stimulated Superradiant Amplification

- 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 to exploit the growing radiation field

  GIT algorithm @ UCLA, but many others around (SLAC, DESY, Lund)







J. Duris et al. New Journal of Physics (2015)

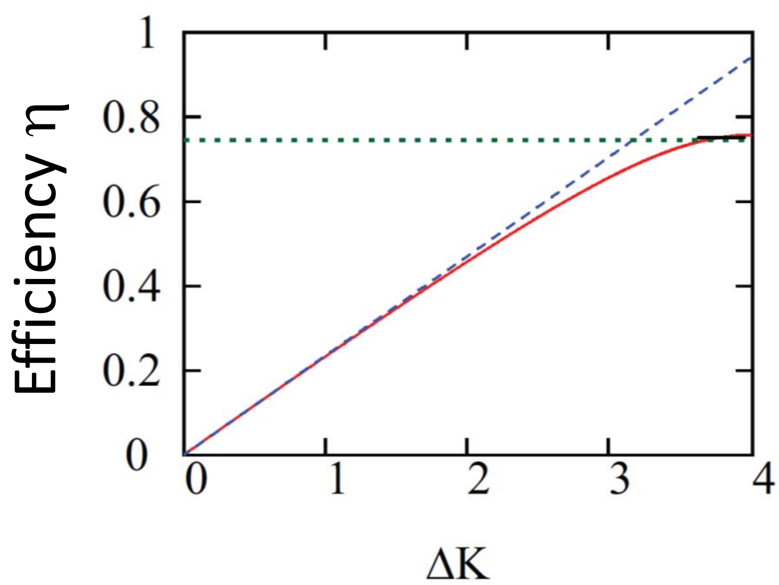
TESSA efficiency

- KMR physics: Match undulator gradient and ponderomotive gradient
- Numerical implementation. GIT Genesis-informed tapering.
- Once tapering (ΔK) is known, then efficiency is just proportional to relative energy loss of particles
- Low gain - $\Delta K = 4\pi K_l \sin\psi_r N_w$
- High gain – Radiation evolution

$$\frac{d{\gamma_r}^2}{dz} = \frac{2e_0E_0}{mc^2} K \sin\psi_r$$

$$\frac{d{\gamma_r}^2}{dz} = \frac{\lambda_w}{\lambda} K \frac{dK}{dz}$$

$$\frac{dK}{dz} = -2k_w K_l \sin\psi_r$$



$$\eta = 1 - \frac{\gamma_f}{\gamma_i} = 1 - \sqrt{\frac{1+(K_0-x)^2}{1+K_0^2}} \approx \frac{K_0 x}{1+K_0^2}$$

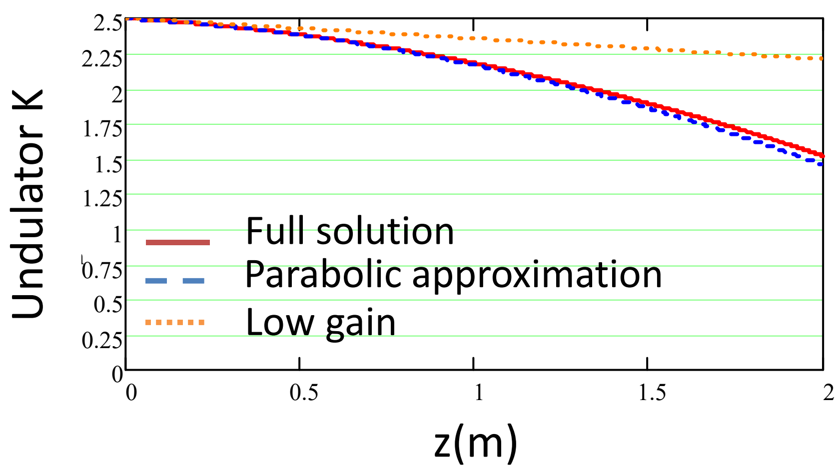
High gain TESSA

Include evolution of radiation field

$$\frac{dK}{dz} = -\frac{2\lambda}{\lambda_w}\frac{eE(z)}{mc^2}\sin\psi_r \qquad \frac{dE}{dz} = \frac{Z_0\, I}{2A_e}\frac{b(\psi_r)}{\gamma_r}\sin\psi_r$$

$$\frac{d^2K}{dz^2} = -\left(\frac{2\lambda}{\lambda_w}\right)^{3/2}\frac{eZ_0}{mc^2 2A_e}\mathrm{I}\, b(\psi_r)(\sin\psi_r)^2\frac{K}{\sqrt{1+K^2}}$$

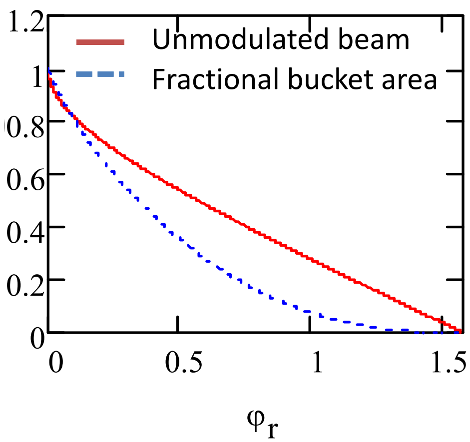
$$K(z) \approx a_0 + a_1 z + \frac{a_2 z^2}{2}$$



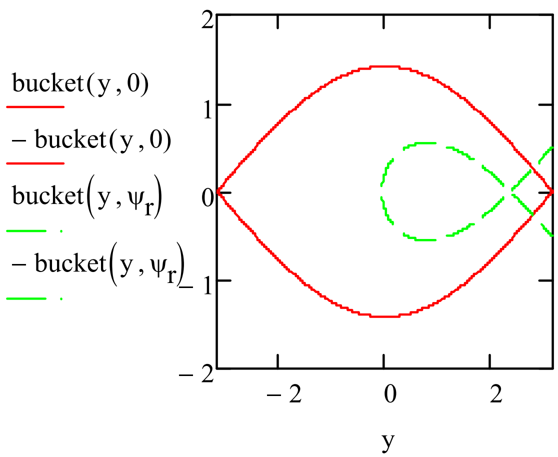
266 nm
375 MeV beam
1 kA
1 GW seed

Trapping and choice of resonant phase

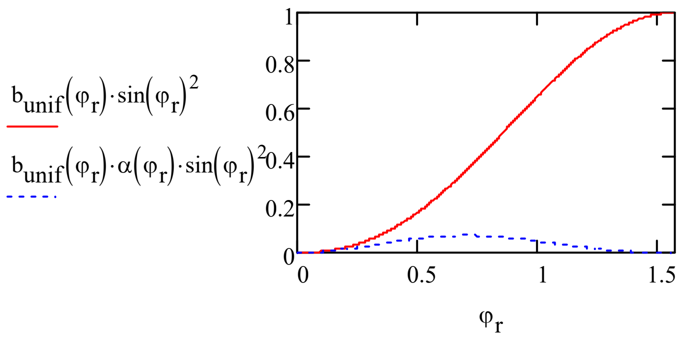
- Bunching factor = $b(\psi_r) \cdot trap(\psi_r)$
- Trapping is strongly dependent on resonant phase
- It also depends on initial beam conditions
  - Unmodulated beam
  - Prebunched beam
  - Saturated FEL



Ponderomorive bucket for
$\psi_r = 0$ and $\psi_r = \pi/4$



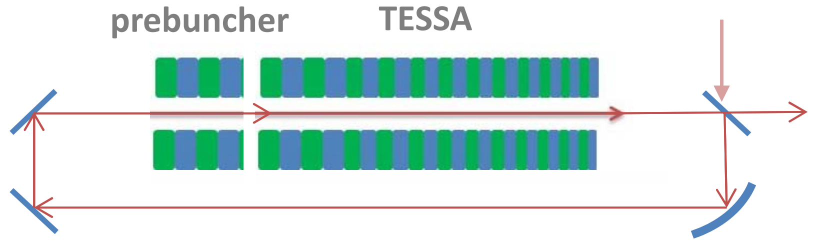
There is a lot to gain
from prebunching !



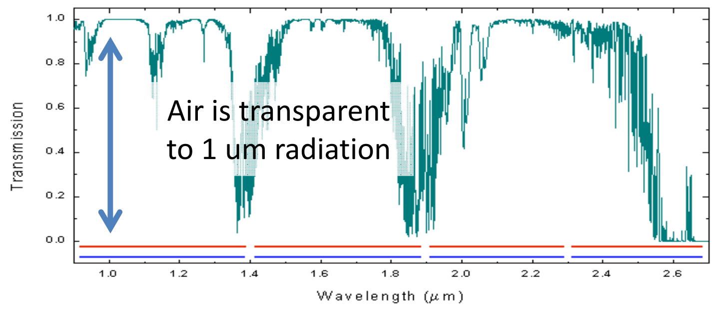
Towards high average power coherent tunable radiation sources

~50% efficiency * high average power e-beams
=> high average power laser

- Where do you get the high power seed?
- Oscillator configuration
  - – Starting from noise : start-up analysis
  - – Starting from igniter pulse Ignition feedback regenerative amplifier (IFRA) (Zholents et al. Proc. SPIE'98).



- Applications
  - Atmosphere is transparent to 1 um radiation
    - – Power beaming to high-bandwidth satellites
    - – Deorbit burning of space trash
    - – Boosting satellites to higher orbits
  - EUV Lithography



From: Gemini observatory
http://www.gemini.edu/?q=node/10789

TESSA experiments & roadmap

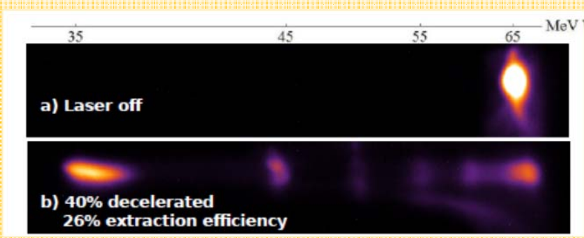
Nocibur

Completed

Proof-of-principle agreement 100 GW 10 um driver. Deceleration from 65 -> 35 MeV

Validation of the model and the simulation tool

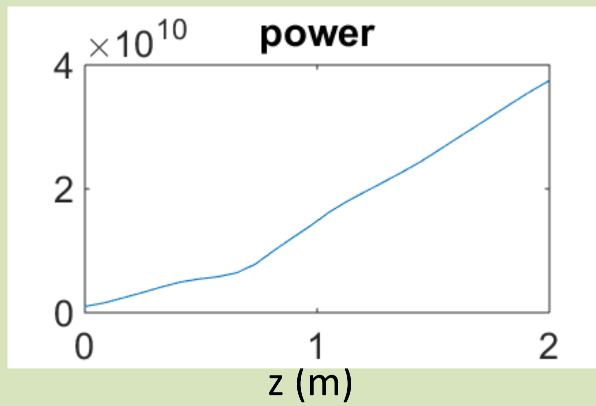
Relative gain is inversely proportional to efficiency so no measurement of radiation amplification



266 nm single pass

375 MeV 1000 A
>10 % efficiency in 4 m long undulator

Next experimental demonstration @ 266 nm



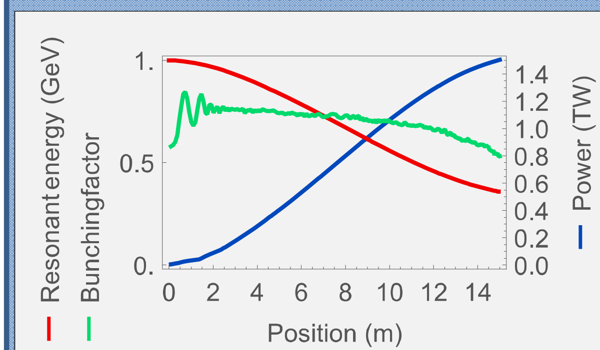
Requires high energy high brightness beamline
TESSA266 @ LEA !

13.5 nm for EUV

3 kA @ 1 GeV = 3 TW beam power available

Use high intensity input seed (from refocusing seeded FEL. GW afterburner)

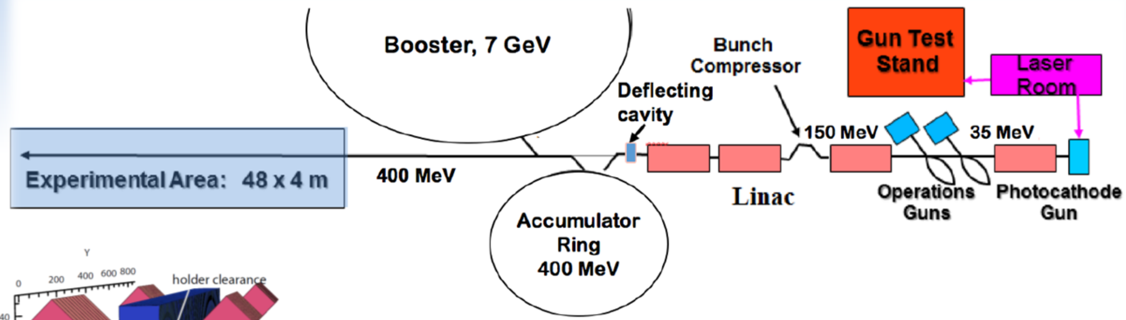
Duris et al. NJP (2015)

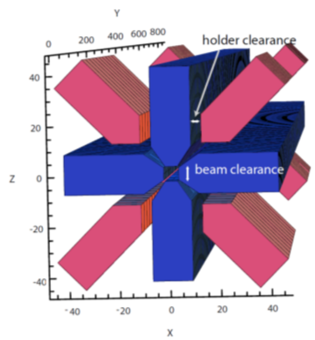


Very high gain regime
45% efficiency in 15 m.

TESSA266 @ LEA

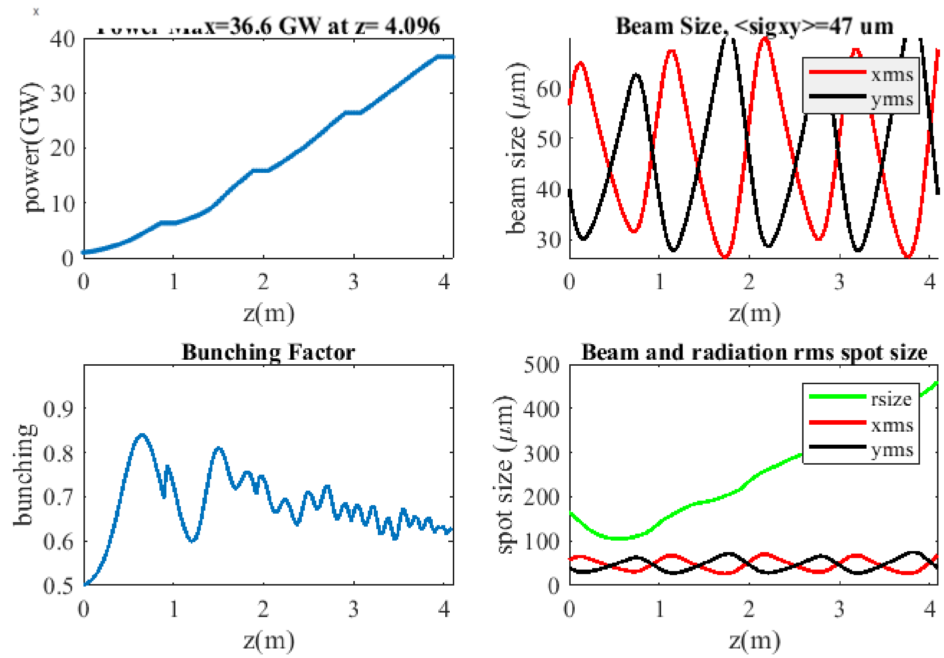
- ANL-UCLA-RBT collaboration
- Use APS linac to demonstrate high efficiency at 266 nm
- Goal: measure spectral and transverse properties of TESSA radiation
- Strong focusing undulator





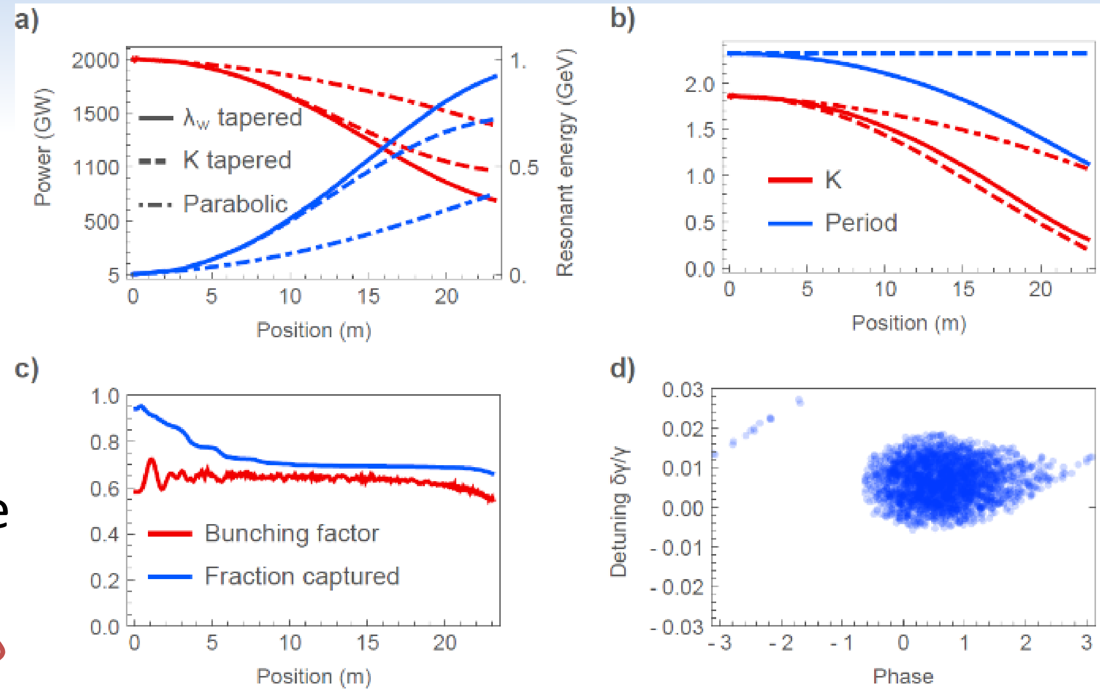
Integrated FODO channel in Halbach-style undulator

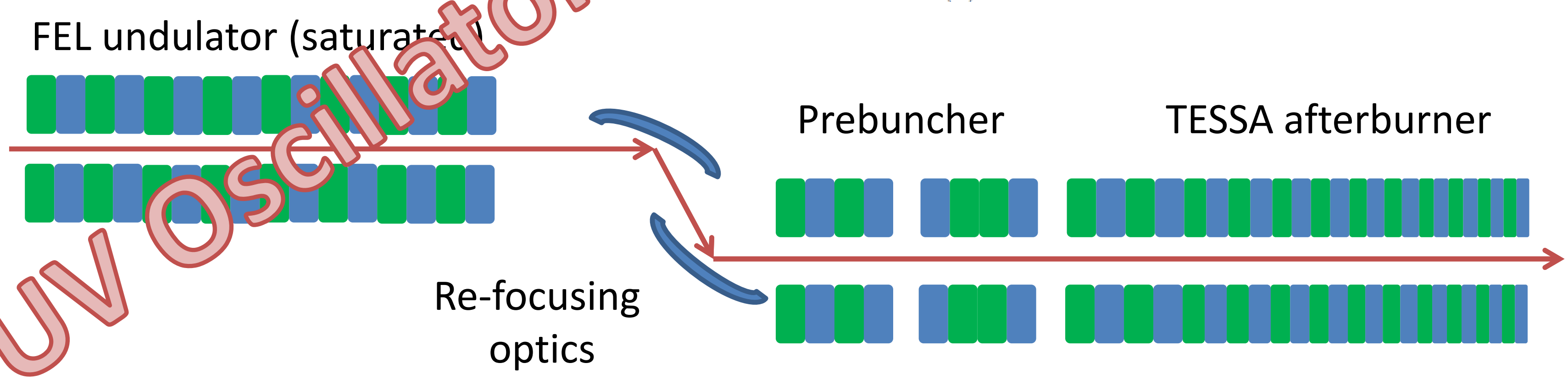
Beam Energy	375 MeV
Peak current	1 kA
Emittance	2 um
Energy spread	0.1 %
RMS spot size	45 um
Undulator length	4 m
Radiation wavelength	266 nm
Seed power	1 GW
Interaction geometry	helical



TESSA at 13.5 nm : Afterburner concept

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

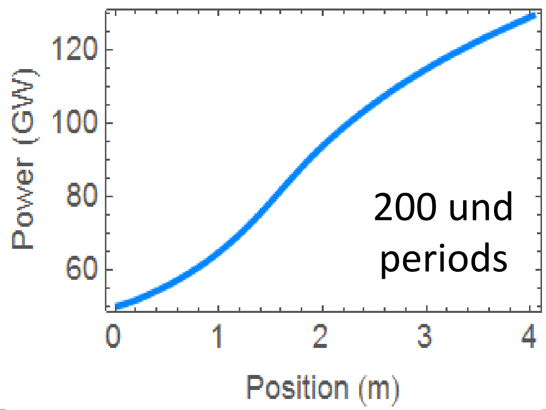




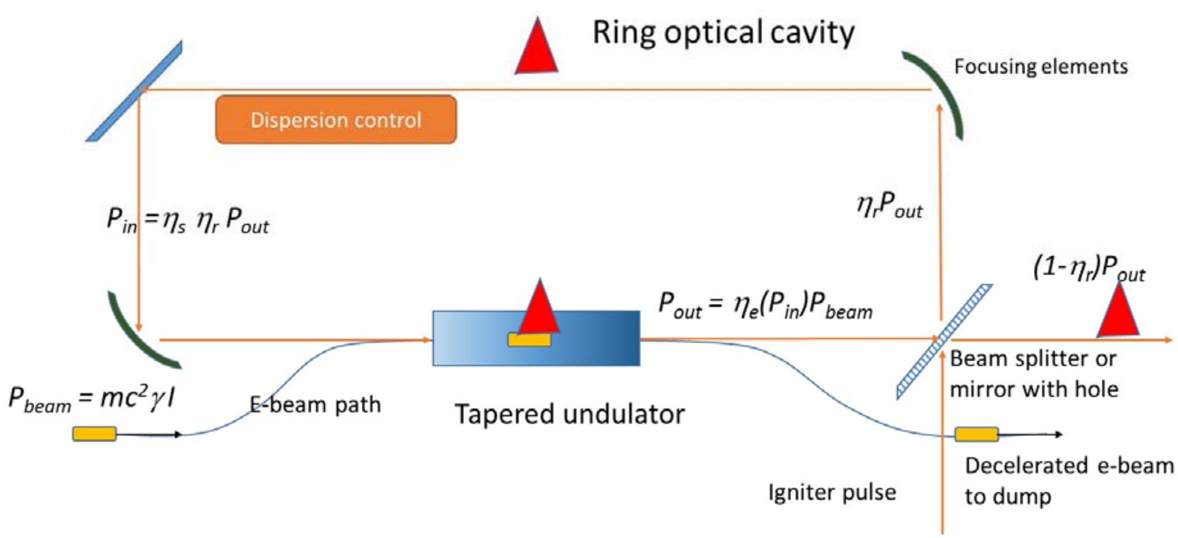
EUV Oscillator?

TESSA Oscillator – TESSO
High power 1 μm oscillator design

Parameter	Value
E-beam energy	250 MeV
Current	500 A
Charge	1 nC
Emittance	1 μm
Undulator length	4 m
Laser wavelength	1 μm
Rayleigh range	48 cm
Laser waist	1.8 m
Input peak power	50 GW
Output peak power	127 GW
Net efficiency	54%

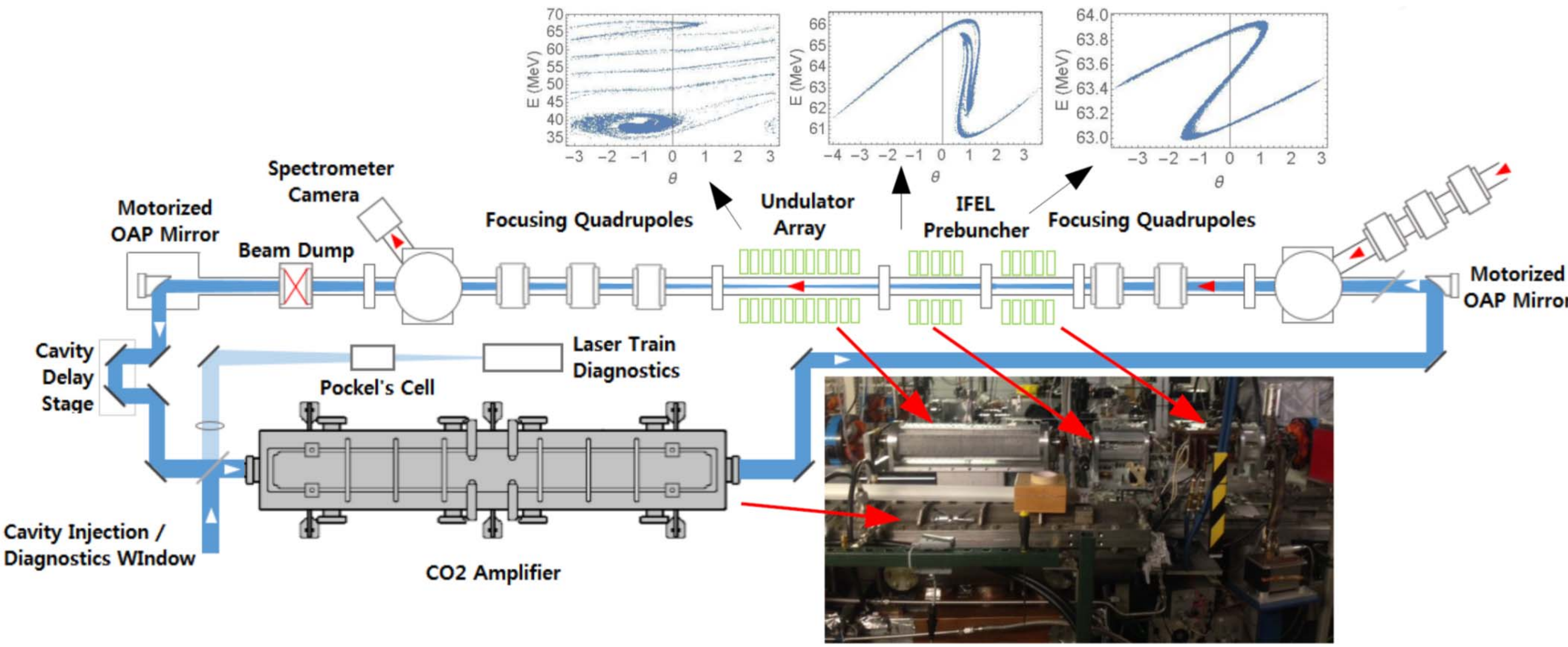


- 250 MeV * 500 A = 125 GW beam power
- Seed power is 50 GW (40% of beam power)
- Diffraction of stimulated radiation limits undulator length to 4 m to keep undulator gap small
- Prebunching to capture more (nearly all) charge increases net efficiency to 50%



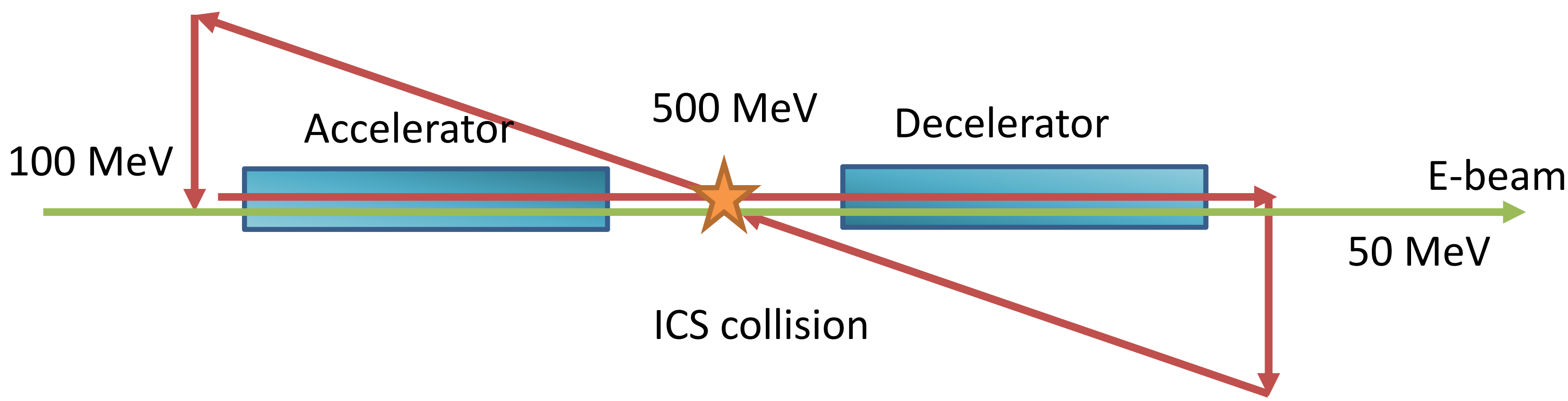
High duty cycle IFEL -> Recirculated Nocibur

- Use IFEL recirculation experiment as a test-bed for recirculated TESSA
- Observe gain in oscillator configuration



Inverse FEL driven ICS source

- Number of photons scattered in ICS is negligible
- Laser is unperturbed and can be used to accelerate electrons
- TESSA-like decelerator can be used to replenish energy
- Potentially very high repetition rate incoherent x-ray and gamma ray source



Physics and Application of High Efficiency Free Electron Lasers

Increasing the efficiency of Free-Electron Laser amplifier will enable tunable very high peak and average power radiation sources with breakthrough potential in a variety of applications, ranging from TW-class x-ray laser pulses to single molecule imaging and high field QED to EUV sources for lithography, to high energy lasers for industrial and space applications.

Typical FEL efficiency in the infrared and shorter wavelength are well below 1 %. A series of recent papers in the community shows the renovated interested for improving on the energy extraction from an electron beam beyond the exponential gain saturation level and increase the efficiency up to the 10 % level.

In this workshop we want to bring together the growing interest of the community in expertise of the community together to understand the application and the limits of tapering. In particular we will focuse on the needs for very high efficiency FELs, undulator tapering schemes, simulation techniques, theoretical limits in efficiency and other innovative approaches

The workshop will be held at UCLA April 11-13th 2018.

Claudio Pellegrini and Pietro Musumeci, co-chairs

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A. Murokh. (Radiabeam Technologies)

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Conclusion

- IFEL is one of the most efficient way to couple electron and laser beams
- Long series of successful IFEL experiments – entering the regime of laser-accelerator application .5th generation light source.
- Upcoming IFEL efforts
  - Recirculated IFEL and recirculated TESSA
  - Extend energy reach for applications:
- TESSA builds up on decade-long experience from IFEL/ tapered undulator and has the promise to achieve very high electrical-to-optical energy conversion efficiencies.
  - Nocibur experiment recently demonstrated 30 % energy extraction
  - Scaling of low gain and high gain TESSA demonstrates advantages of prebunched beam and large input seed powers (Benefit to sideband instability see C. Emma talk on Friday)
  - TESSA roadmap well marked