Tapering Enhanced Stimulated Superradiant Amplification

How to achieve the highest energy extraction efficiency from relativistic electron beams?

P. Musumeci
UCLA Department of Physics and Astronomy

SSMB Workshop 12.8.2020

UCLA

Acknowledgements

*J. Duris, N. Sudar, **Y. Park, A. Fisher** Graduate Students (UCLA)*

A. Gover (Tel Aviv University)

A. Murokh, T. Campese, I. Gadjev, R. Agustsson (Radiabeam Technologies)

I. Pogorelsky, M. Polyanskiy, M. Fedurin, M. Babzien, K. Kusche, C. Swinson (ATF, Brookhaven National Laboratory)

A. Zholents, J. Byrd, W. Berg, Y. Sun, K. Wootton, J. Dooling, A. Lumpkin (ANL)

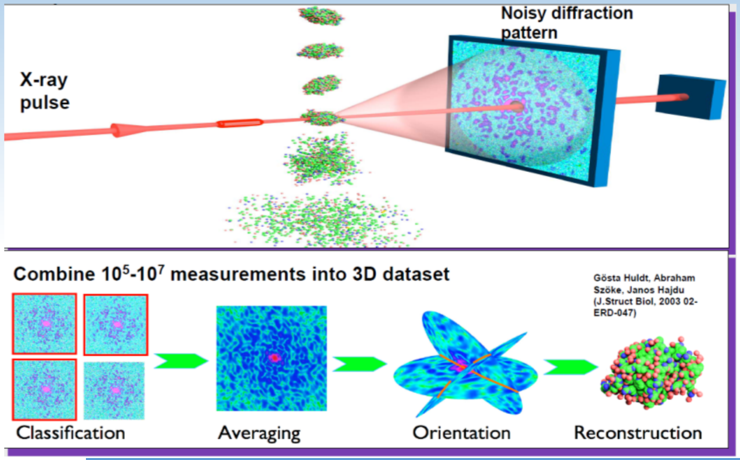
Funding agencies : DOE BES, DOE Stewardship, DOE SBIR/STTR program

Outline

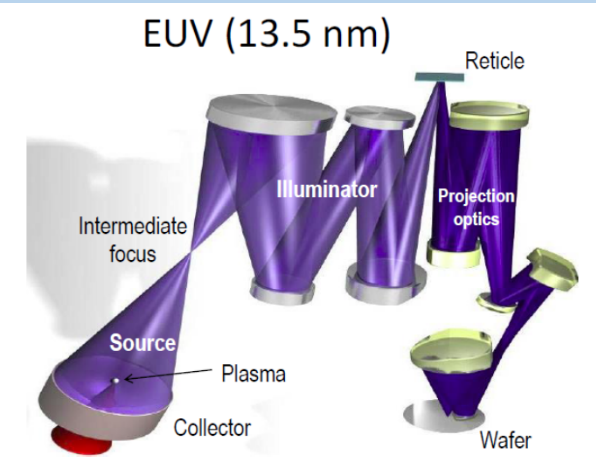
- Motivation
- Background
- Theoretical considerations and scaling laws
- TESSA266 at ANL
- TESSA in an optical cavity : TESSO

High efficiency enables high average and peak power light sources

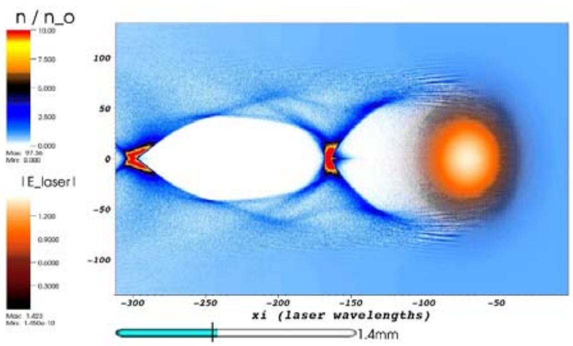
Single molecule imaging



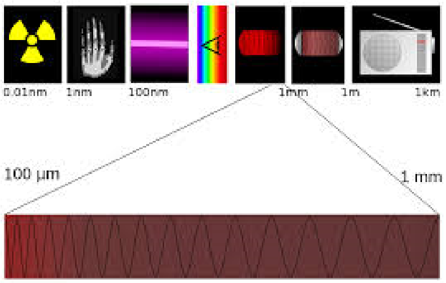
EUV lithography



High energy lasers



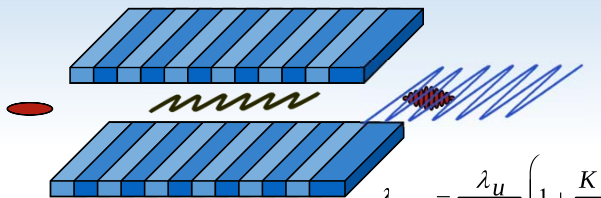
High power THz sources



Unique characteristics of ponderomotive interaction in magnetic undulator

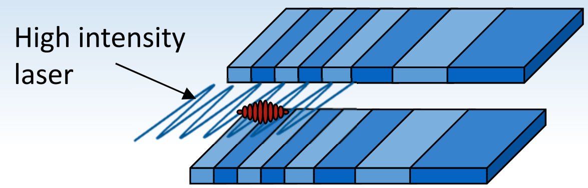
Particle acceleration - Radiation generation

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



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

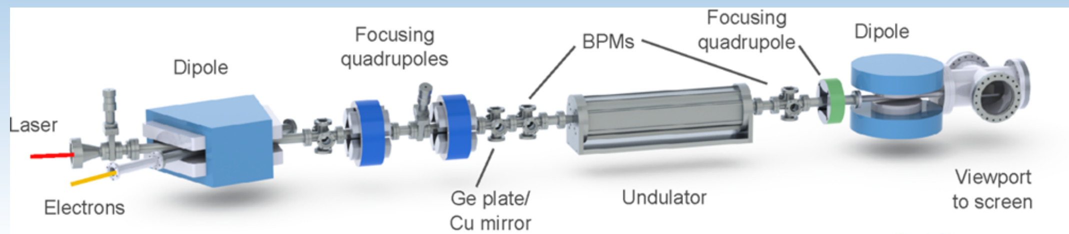
In an IFEL the electron beam absorbs energy from a radiation field.



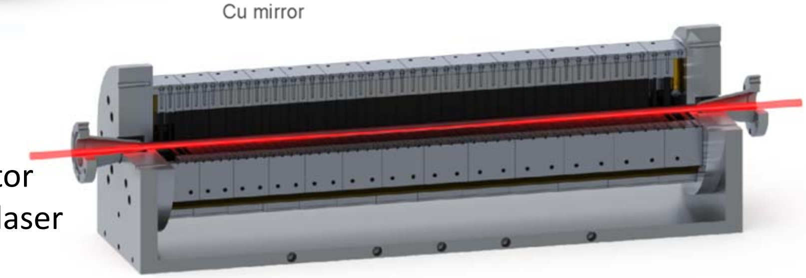
- “Without radiation there is no acceleration”
- “To be efficient an accelerator must be able to operate in reverse”
- IFEL/FEL is a particularly advantageous interaction scheme in this regard
  - ***Vacuum-based*** accelerator. No mechanism for energy loss. ***Efficient energy exchange***
  - ***Tunability.*** Resonance can be adjusted using undulator parameters and beam energy (from FIR to X-rays)
  - ***Plane wave or far field*** accelerator: minimal 3D effects. Transverse beam cross-section can be mm-size for μm-scale radiation wavelength.

Lessons from IFEL research

- Rubicon IFEL experiment demonstrated high quality acceleration of 50 MeV e-beam at BNL ATF
- Strongly tapered helical undulator
- Prebuncher to maximize fraction of particles captured in laser accelerator
- Monochromatic output < 2 % energy spread
- Stability <1.5% energy jitter
- Emittance preservation



100 MeV/m
11 periods
0.5 m undulator
300 GW CO_2 laser



Laser off energy spectrum

IFEL output energy spectrum

nature COMMUNICATIONS

ARTICLE

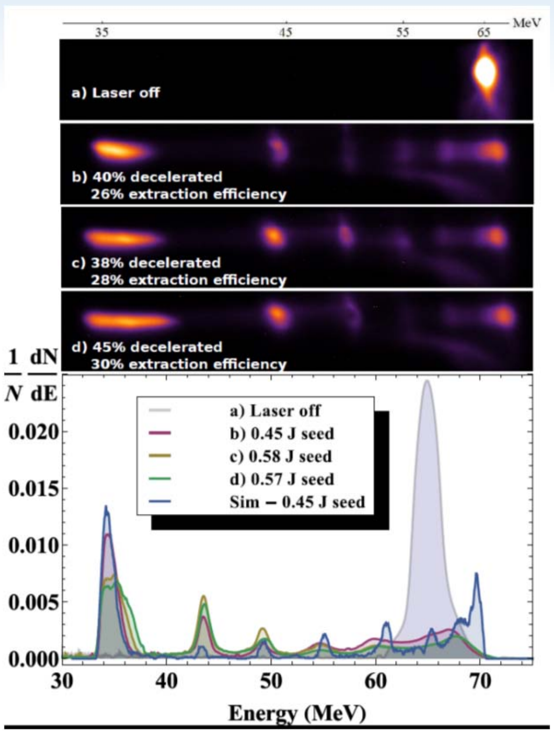
Received 3 Jun 2014 | Accepted 8 Aug 2014 | Published 15 Sep 2014 DOI: 10.1038/ncomms5928

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

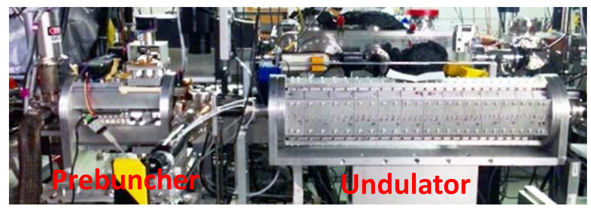
J. Duris[1], P. Musumeci[1], M. Babzien[2], M. Fedurin[2], K. Kusche[2], R.K. Li[1], J. Moody[1], I. Pogorelsky[2], M. Polyanskiy[2], J.B. Rosenzweig[1], Y. Sakai[1], C. Swinson[2], E. Threlkeld[1], O. Williams[1] & V. Yakimenko[3]

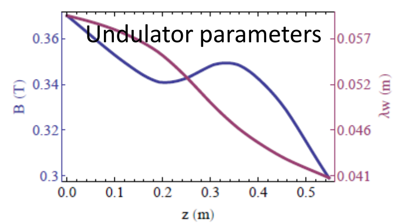
NOCIBUR IFEL deceleration experiment

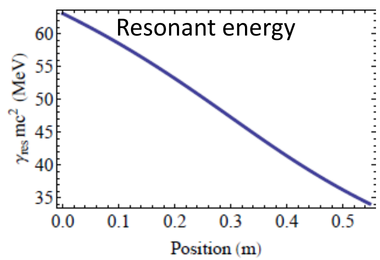
- Use RUBICON IFEL set up in reverse at BNL ATF
- Retune tapering profile for 0.54 m long helical undulator for high gradient deceleration
- Demonstrated >30% conversion efficiency from a relativistic electron beam



- Maximized capture with prebuncher modulator + chicane
- Up to 45% of 100 pC beam captured and decelerated





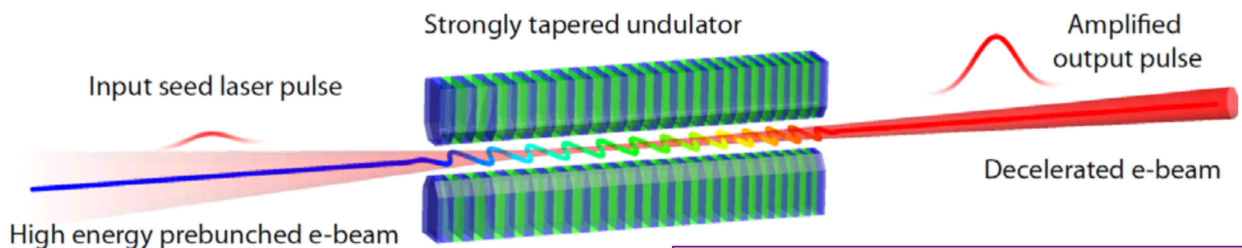


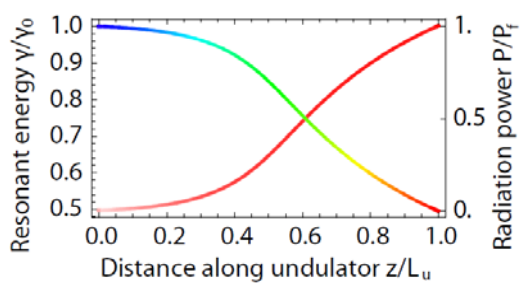
PRL **117,** 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

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

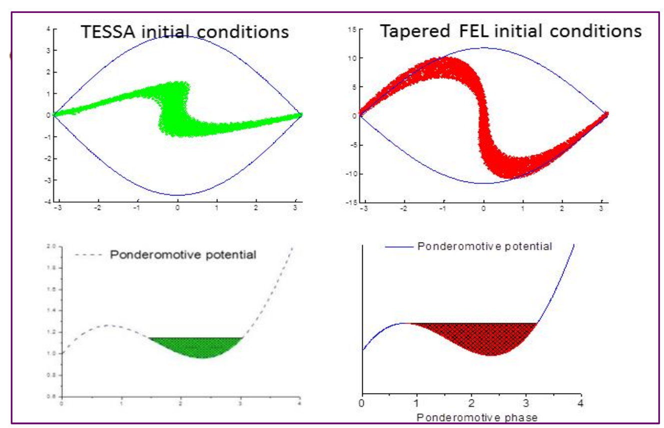
Tapering Enhanced Stimulated Superradiant Amplification

- 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**
  - High gain regime: matching decelerating gradient to growing radiation field amplitude





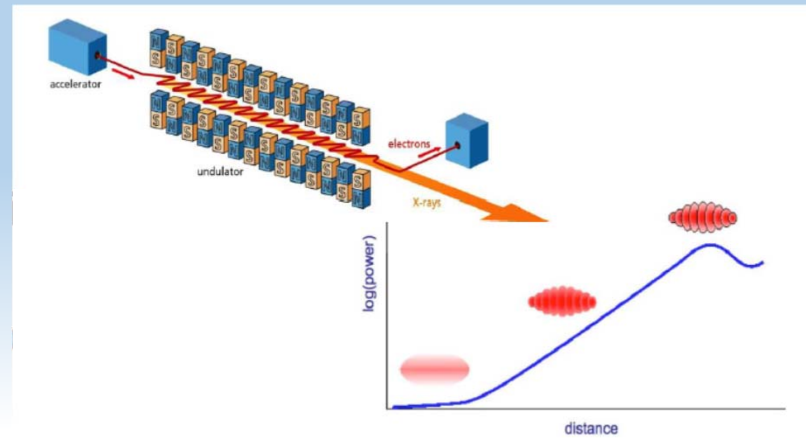
J. Duris et al. New Journal of Physics, 17 (2015)

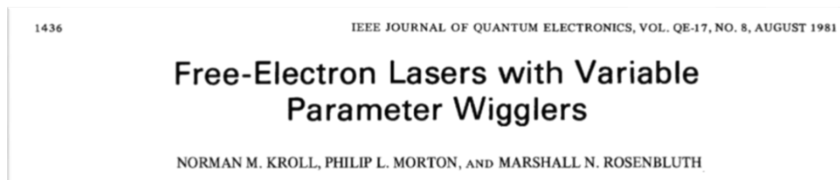


Tapered FEL

- ρ is the dimensionless FEL parameter, at EUV it is ~ 0.1%
- High gain FEL
  - Exponential growth (L_G~ $1/\rho$)
  - **Saturation** (P_s~ ρP_b)
- 1981 KMR seminal paper on undulator tapering
  - Hamiltonian model
  - Concept of resonant phase
  - Instabilities
- Old and renewed interest
  - ELF, Paladin experiment in ‘80s @ LLNL
  - TESSA
  - Self-seeded cases for TW X-FEL
  - High Efficiency Free Electron Lasers workshop - UCLA– April, 11-13 2018

W. Fawley : “Before big $$$ are spent on a TW-class x-ray FEL undulator, we need systematic, well diagnosed experimental studies of best tapering strategies”

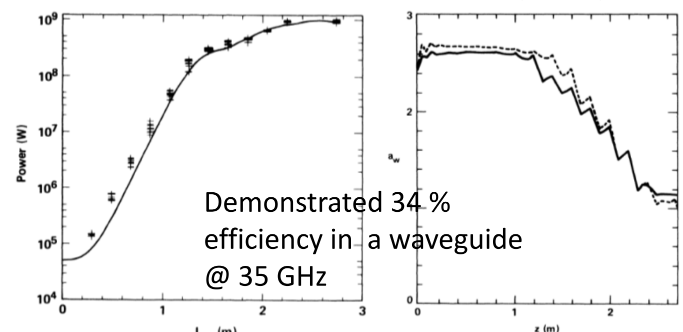



1436 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-17, NO. 8, AUGUST 1981

Free-Electron Lasers with Variable Parameter Wigglers

NORMAN M. KROLL, PHILIP L. MORTON, AND MARSHALL N. ROSENBLUTH

Orzechowski et al., PRL 57, 2172 (1986).



Demonstrated 34 % efficiency in a waveguide @ 35 GHz

FIG. 3. Amplified signal output as a function of wiggler length for tapered wiggler field. Crosses indicate experimental values and the solid line is the results of the numerical evaluation.

FIG. 2. Optimum wiggler field profile for tapered wiggler. The dashed line corresponds to empirical evaluation and the solid line is the numerical prediction.

TESSA examples & roadmap

Low gain regime

Nocibur

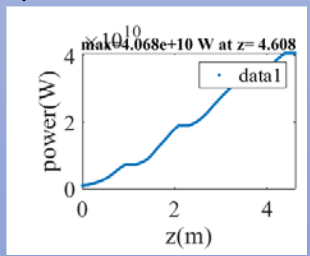
Proof-of-principle test
Simulation benchmark.
35 % efficiency @10 um
Deceleration from 65 - > 35 MeV

Sudar et al. PRL 2016

High gain regime

TESSA-266

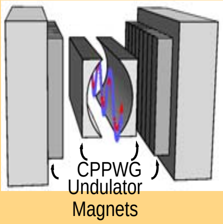
Obtain first measurements of spectral and spatial properties of amplified radiation



High energy high brightness beamline LEA @ Argonne

TESSATRON at Pegasus

10 % efficiency
THz range
Zero-slippage waveguide FEL
Prebunched e-beam

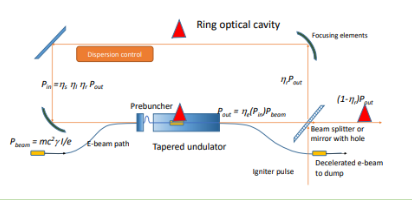


Snively et al. Optics Express 2019
Planned @ UCLA Pegasus 2021

Optical cavity

TESSO

No intense input seed available
Optical cavity and recirculating scheme
Igniter pulse / RAFEL configuration

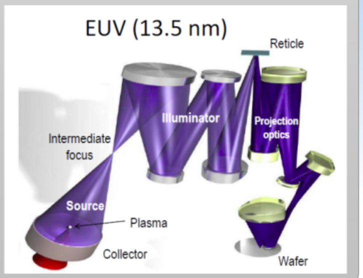


J. Duris et al. PRAB 2018

Applications

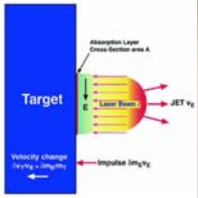
EUV lithography

LCLS2-like injector 4 kA @ 1 GeV = 4 TW beam power available
MHz-reprate yields 10-20 kW of radiation power
Duris et al. NJP 2015



Laser ablation propulsion

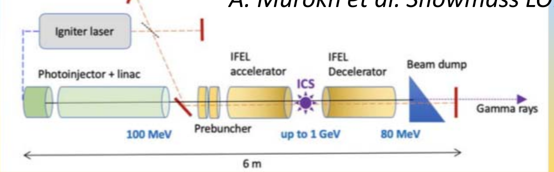
1 um MW-average power laser with TW-peak power
SRF accelerator driver
Atmospheric transparency window. *Phipps et al. JOSAB 2018*



High flux Gamma-Ray source

High rep-rate IFEL acceleration
Inverse Compton Scattering

A. Murokh et al. Snowmass LOI



TESSA examples & roadmap

Low gain regime

Nocibur

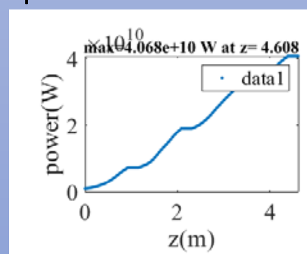
Proof-of-principle test
Simulation benchmark.
35 % efficiency @10 um
Deceleration from 65 - > 35 MeV

Sudar et al. PRL 2016

High gain regime

TESSA-266

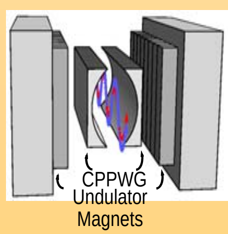
Obtain first measurements of spectral and spatial properties of amplified radiation



High energy high brightness beamline LEA @ Argonne

TESSATRON at Pegasus

10 % efficiency
THz range
Zero-slippage waveguide FEL
Prebunched e-beam

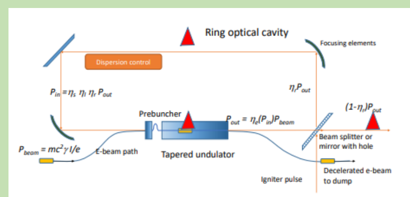


Snively et al. Optics Express 2019
Planned @ UCLA Pegasus 2021

Optical cavity

TESSO

No intense input seed available
Optical cavity and recirculating scheme
Igniter pulse / RAFEL configuration

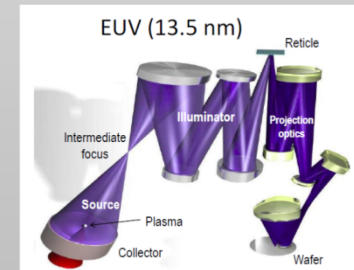


J. Duris et al. PRAB 2018

Applications

EUV lithography

LCLS2-like injector 4 kA @ 1 GeV = 4 TW beam power available
MHz-reprate yields 10-20 kW of radiation power
Duris et al. NJP 2015



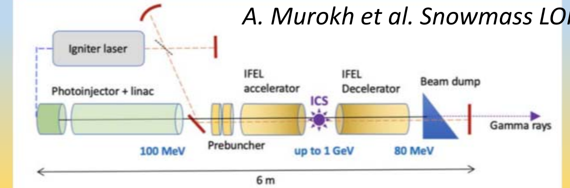
Laser ablation propulsion

1 um MW-average power laser with TW-peak power
SRF accelerator driver
Atmospheric transparency window. *Phipps et al. JOSAB 2018*

High flux Gamma-Ray source

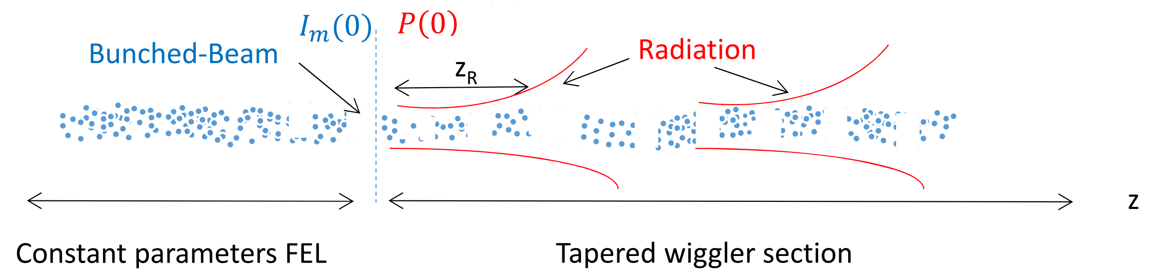
High rep-rate IFEL acceleration
Inverse Compton Scattering

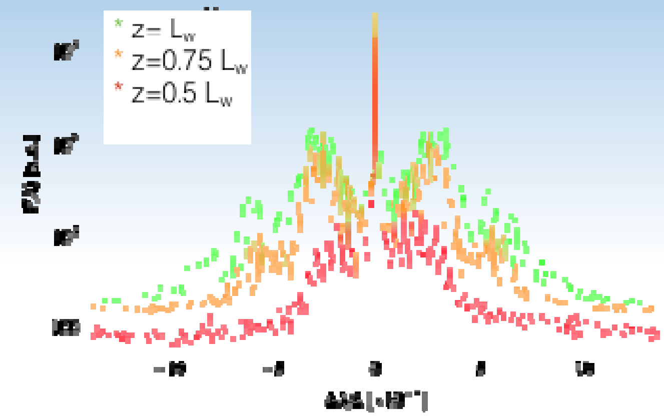
A. Murokh et al. Snowmass LOI



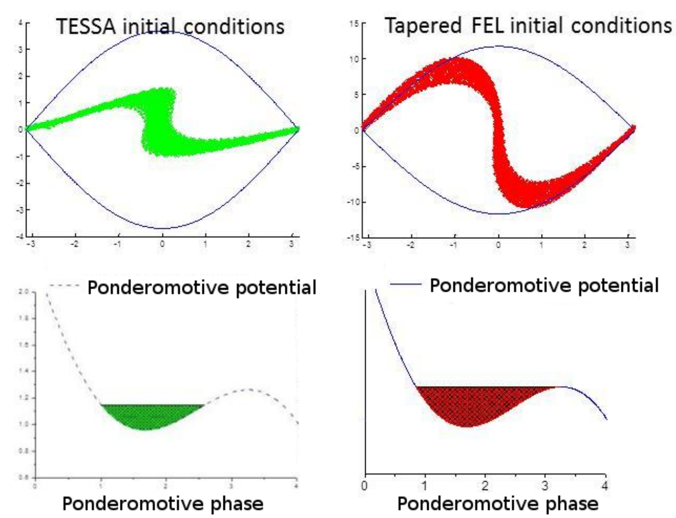
Tapered wiggler optimization in seed injected FEL

D. Prosnitz et al PRA (1981); Scharlemann T. et al., PRL (1981)





Duris, Murokh, and Musumeci (2015)



<u>Effects degrading the fundamental processes:</u>

- 1d theory [1]
-Diffraction[2-7]
-Sideband instability [1,3,4,7,…]
-Spectral effects; Shot-Noise [9,10]
-Phase space spread of injected beam [3,7,8]

<u>Evolving solutions:</u>

-Fresh bunch scheme [11,12]
-Phase shifter [13,14]
-Gain modulation [8]
-Shot-noise suppression [9,10]
-Experimental tests [15]

[1] KMR (1981); Bonifacio, Casagrande (1988) [2] Fawley (1996); [3] Jiao et al (2012); [4] Emma, Pellegrini (2014); [5] Schneidmiller, Yurkov (2015); [6] Tsai, Wu et al (2018); [7] N.Sudar (2019) [8] Emma, Sudar (2017) [9] Gover and Dyunin (2009); [10] Ratner, Huang, Stupakov (2011) [11] Ben-Zvi et al (1992) [12] Emma C. et al (2017) [13] Ratner, D., et al., 2010 [14] Duris, Murokh, and Musumeci (2015) [15] Wu (2017); N. Sudar et al., (2018)

Extensive reference list: Gover et al Rev. of Mod. Phys. Vol/EID: 91/035003 (2019)

High Gain TESSA: 1D efficiency

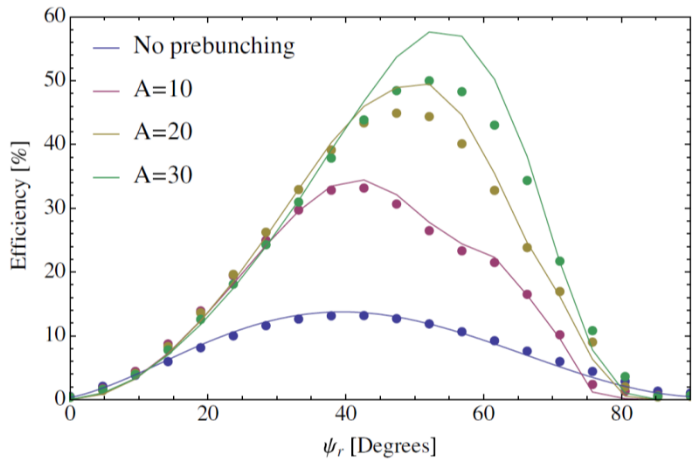
Fundamental approximation : tapering maintains constant bunching

Use tapering equation + Maxwell equation

Efficiency proportional to peak beam current

Role of trapped fraction

Time-dependent effects and side-band effects



C. Emma et al., PRAB, 20, 110701 (2017)

$$\frac{dK}{dz} = -\frac{2\lambda}{\lambda_w}\frac{eE(z)}{mc^2}\sin\psi_r$$

$$\frac{dE}{dz} = \frac{Z_0}{2A_e}\frac{I\,b(\psi_r)}{\gamma_r}\sin\psi_r$$

$$\eta \cong \frac{K_0 f_T}{1+{K_0}^2}(a_1 z + a_2 z^2/2)$$

Low gain efficiency

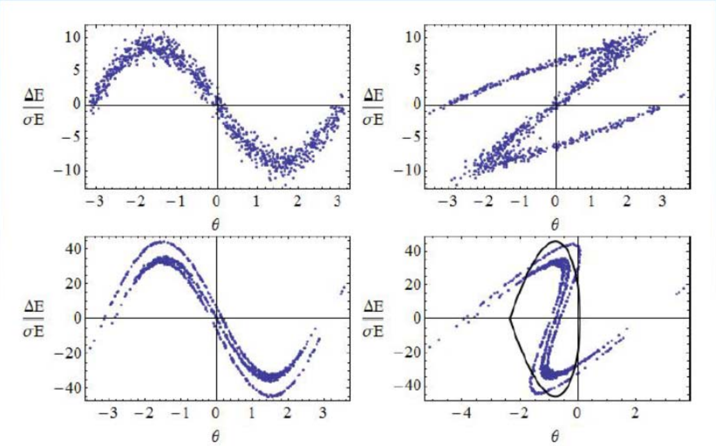
$$a_1 = 2k_w K_l(0)\sin\psi_r$$

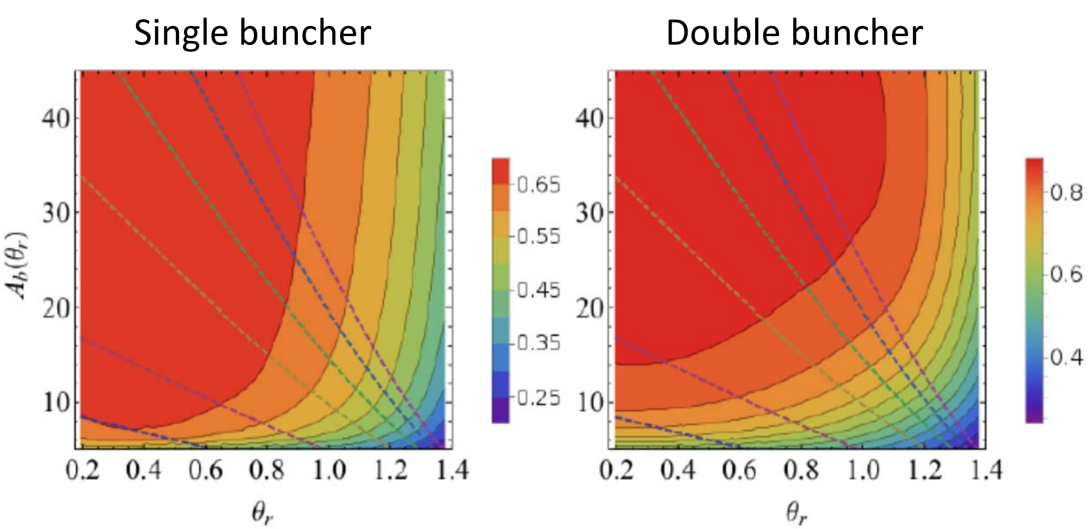
High gain

$$a_2 = \left(\frac{2k_w}{k_l}\right)^{3/2}\frac{eZ_0 I f_T}{8\pi\sigma^2}\sin{\psi_r}^2$$

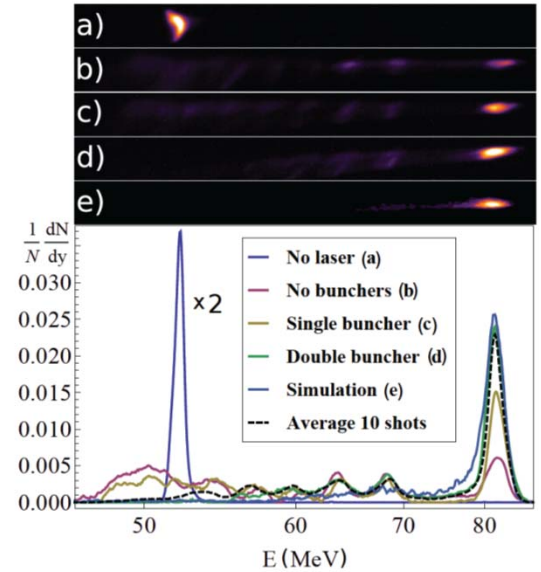
Bunching to get highest efficiency

- Efficiency strongly dependent on fraction of particles captured and decelerated
- Single buncher + R56 is first step to improve capture, but severely limited by non-linearities of cos-like potential
- Use double-buncher to get > 90 % captured (N. Sudar et al. PRL 2018)





Fraction trapped vs. normalized ponderomotive bucket amplitude and resonant phase



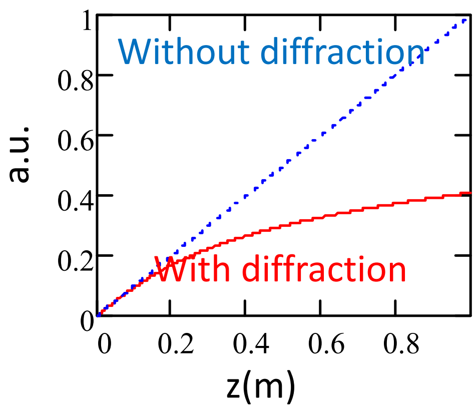
Add diffraction (3D effects)

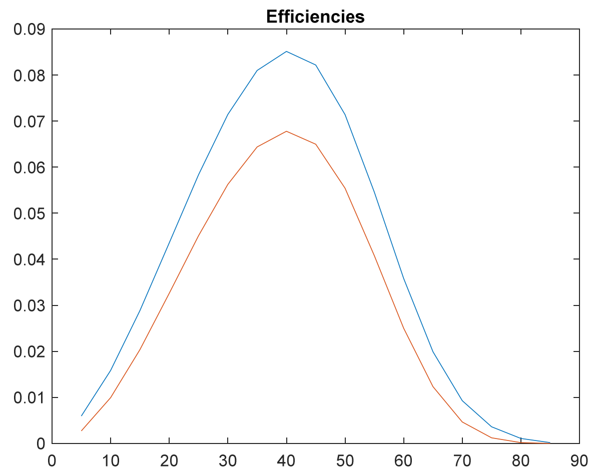
- 1D analysis highlights critical need for strong focusing channel (i.e. minimize σ_e)
- At the small beam limit diffraction takes over and limits efficiency
- Electron beam Fresnel number $N = \frac{k\sigma_e^2}{\lambda}$
- Use Saldin, Schneidmiller, Yurkov NIM 539,499 (2005) Green's function approach to solve field equation with transverse dependence
- Assuming constant bunching source term we can get a (semi-)analytical estimate for efficiency
- Cross term (seed x bunching field) enhances efficiency

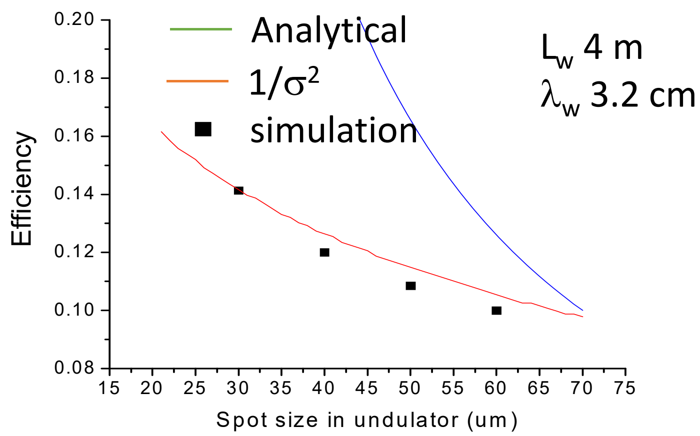
$$E_{SM}(z,0) = \frac{K\omega b I_0}{4\pi\epsilon_0 c^2\gamma}\left[\arctan\frac{z}{N} - \frac{i}{2}\ln(1+\frac{z^2}{N^2})\right]$$

Schnedmiller, PRAB 2015

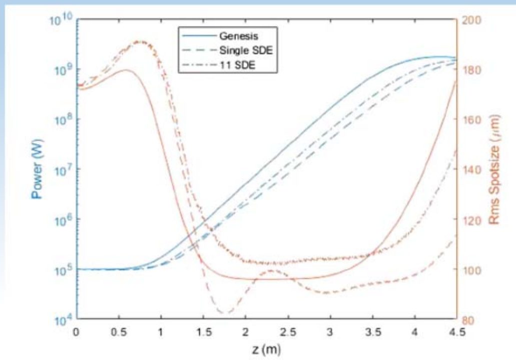
On axis field (266 nm, σ_e = 45um)



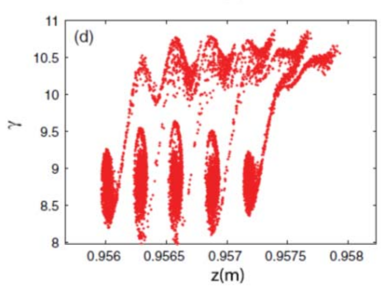




Self-consistent FEL modeling with GPT particle tracking code



Comparison of evolution of radiation power and spotsize along the undulator (Genesis vs. GPT FEL with SDE and multimode).



Example of final phase space simulation output for a high efficiency (> 10% in this case) THz FEL running in the zero-slippage regime obtained with GPT-FEL waveguide mode set.

Develop a simulation tool based on widely used 3D particle tracking code GPT to self-consistently calculate the interaction of relativistic electron beams with a finite set of electromagnetic modes.

Significance and Impact

Expand reach of FEL simulation to include transverse and longitudinal space charge interaction, dispersive properties in FEL and coherent undulator radiation effects, full entrance and exit effects of undulator magnet.

Research Details

GPT-based module calculates the evolution of the mode amplitudes and their effect on the particle motion.

Source-dependent expansion can be used to minimize the number of modes required.

Quiet-loading enables low number of particles/modes in the simulation

First application of the new code in collaboration with SLAC to study emission of MA-class beams in short undulators

Full publication record: A. Fisher, P. Musumeci and B. Van Der Geer, “Self-consistent numerical approach to track particles in free electron laser interaction with electromagnetic field modes”. *PRAB*, **2020**, *23*, 110702.

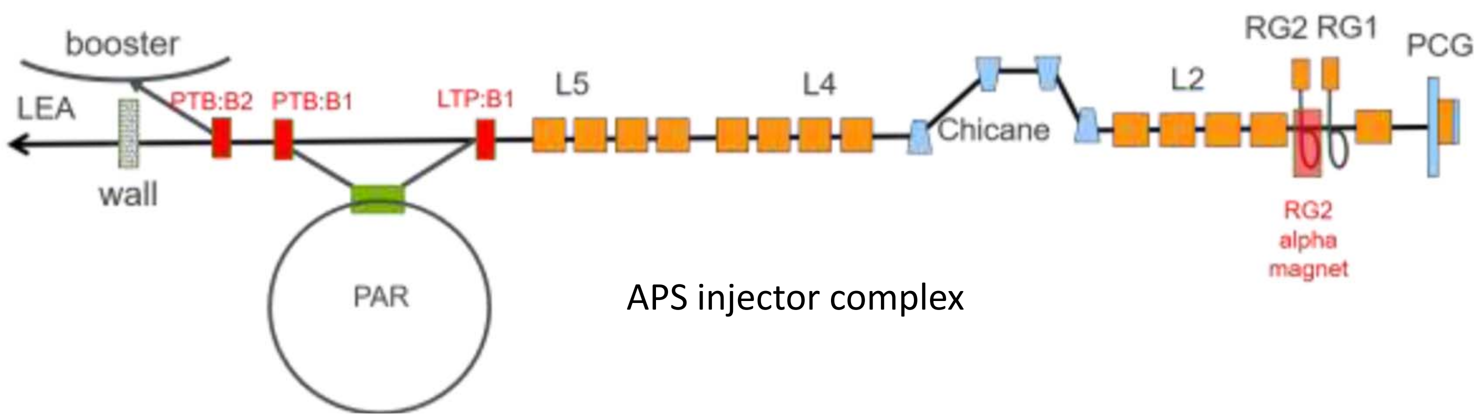
U.S. DEPARTMENT OF ENERGY | Office of Science

UCLA

TESSA-266 project

- UCLA – RadiaBeam– ANL collaboration
- Two stated scientific goals:
  - First experimental measurements of spectral and transverse profile characteristics of the radiation amplified in the TESSA regime of operation.
  - Demonstration of single pass record high energy extraction efficiency from a relativistic electron beam in the UV region of the electromagnetic spectrum.
- Opportunity offered by high brightness APS RF photogun and LEA tunnel availability
- Requires new TESSA beamline including Theseus undulator, seed laser system and longitudinal phase space diagnostics

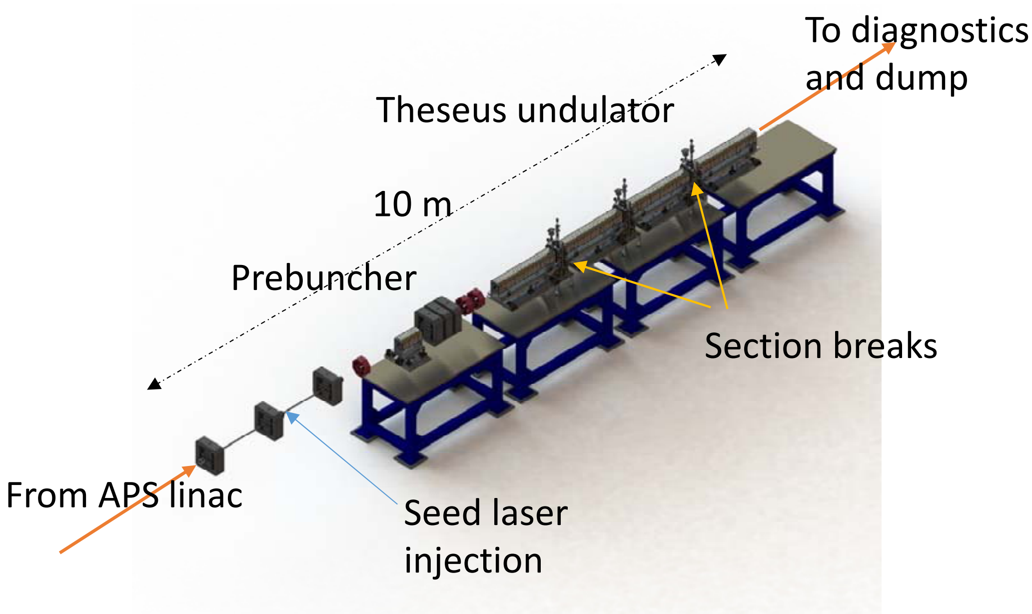
Beam Energy	375 MeV
Peak current	1 kA
Emittance	2 um
Energy spread	0.1 %
RMS spot size (avg)	47 um
Undulator length	4 m
Radiation wavelength	266 nm
Seed power	1 GW
Interaction geometry	helical

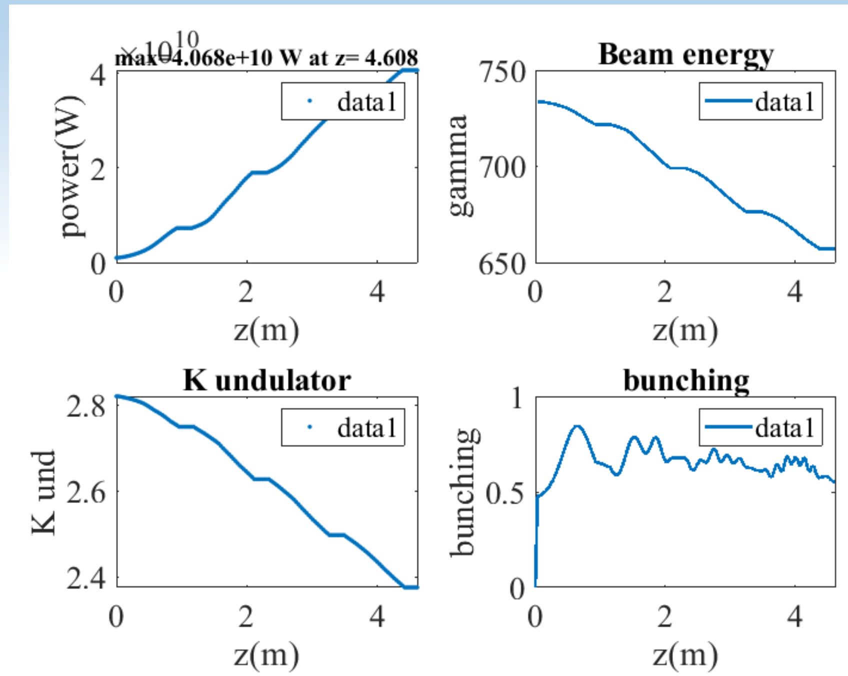


APS injector complex

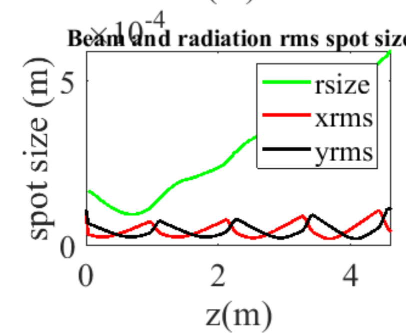
TESSA266 experiment at LEA

- Experiment setup
  - Use photocathode gun and APS linac to inject 375 MeV 1 kA high brightness beam
  - 1 GW UV laser seed power
  - Prebuncher and 4 m long tapered helical undulator under construction at UCLA and RBT





Time-independent simulations
- 10 % efficiency
- Doublet quadrupole to keep small spot size
- 40 GW output power

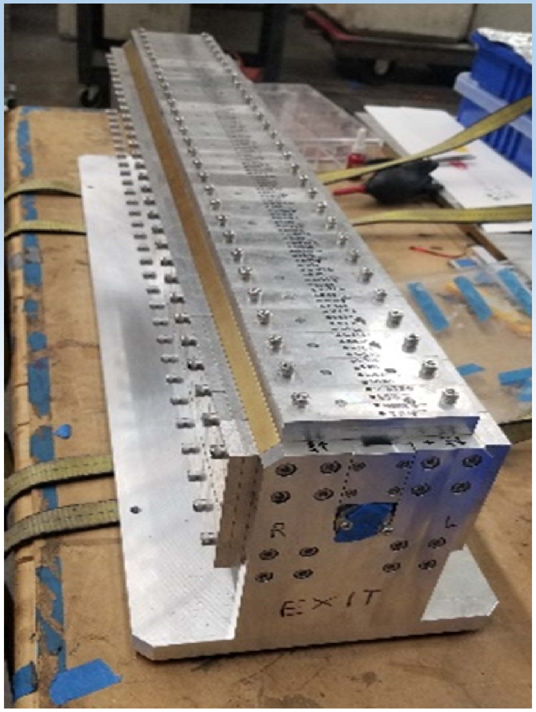


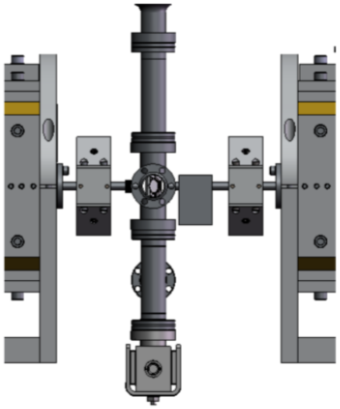
Argonne NATIONAL LABORATORY

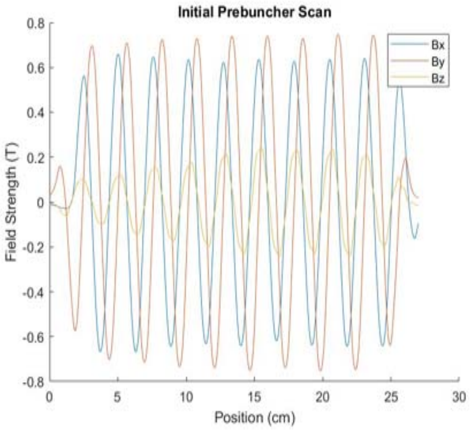
Theseus strongly tapered helical undulator

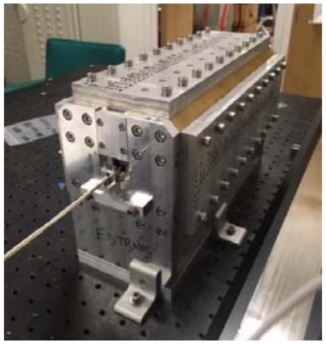
- 2 orthogonal Halbach undulators with varying period and field strength
- 3.2 cm period / 0.9 T field. 266 nm resonant energy 375 MeV
- Prebuncher and first section completed
- Tuning and fiducialization ongoing

- **Break section in between undulators**
  - Needed for diagnostics + vacuum, but length is critical
  - Quadrupole doublet to tightly focus e-beam – inspired by future LCLS plans
  - Adjustable hybrid quadrupole design
  - Electromagnetic dipole for adjusting phase-shift

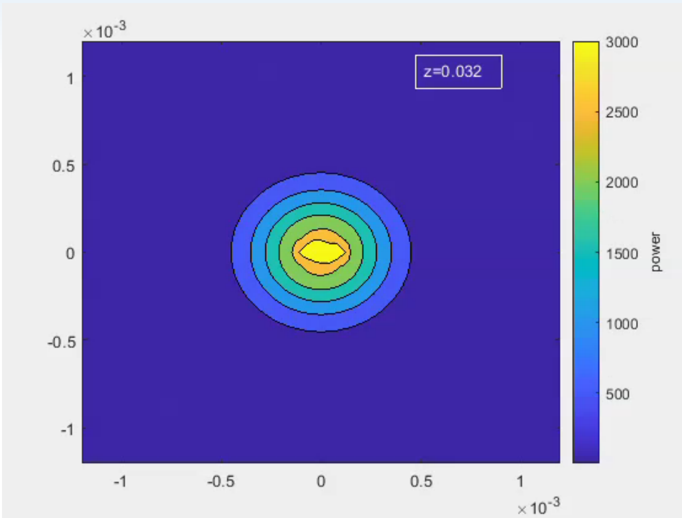


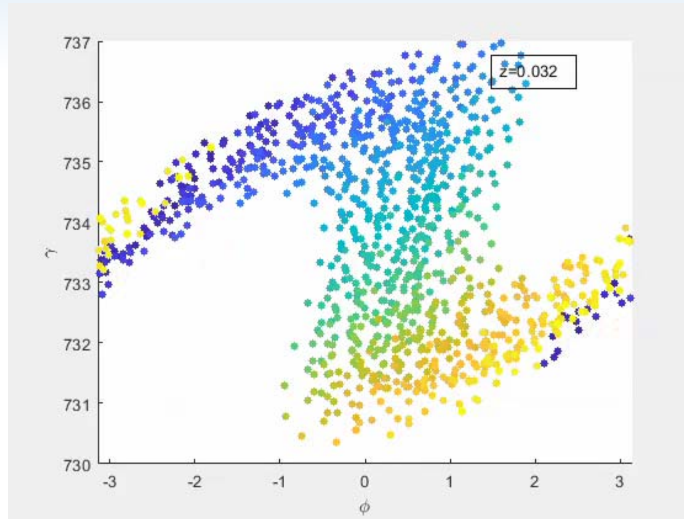






Experimental outputs:
Radiation and LPS evolution





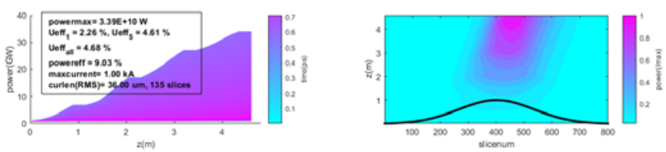
Longitudinal phase space matching

For same pulse charge, flat-top current distribution shows higher energy efficiency and higher peak power than gaussian profile

Studies of APS linac to linearize LPS ongoing

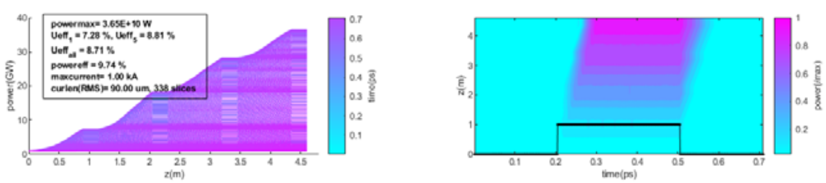
Gaussian, Peak current 1kA, current length (RMS)36um, charge 300pC

Ueff=4.7%, pmax = 34GW

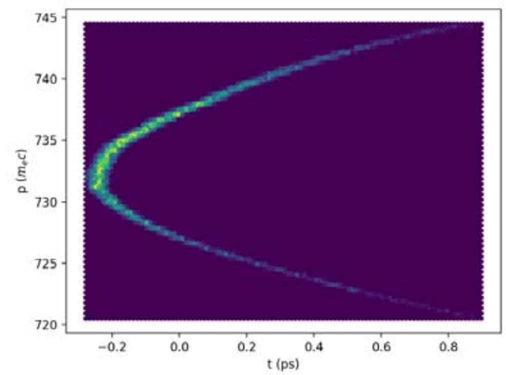


Rectangular, Peak current 1kA, current length 90um, charge 300pC

Ueff=8.7%, pmax = 37GW



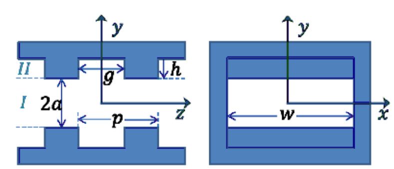
Strongly non-linear compression



Sextupole in dispersive region
Hard to control emittance growth

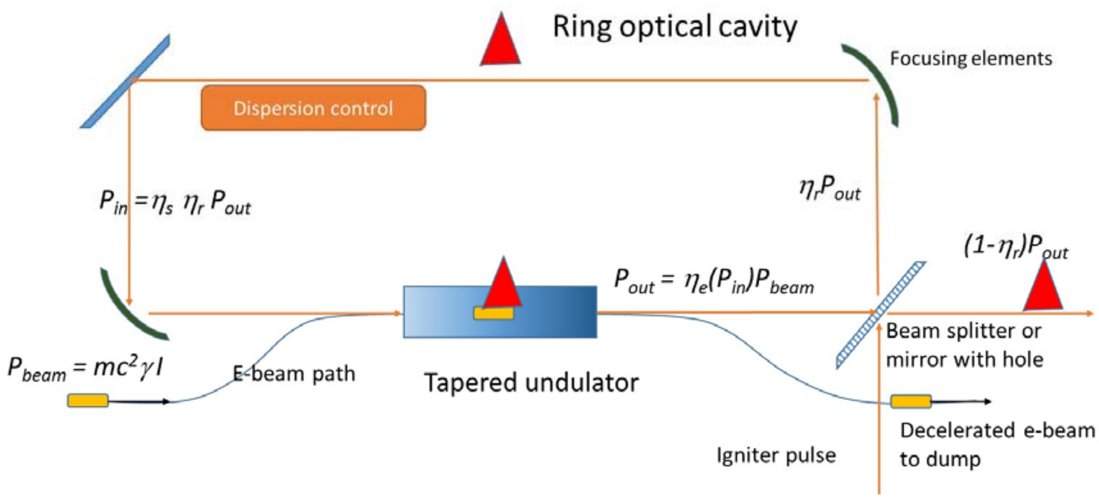
Wakefield linearizer

Wake function for corrugated pipe (Zhang, PRAB 2015)



TESSA Oscillator = TESSO

- Oscillator is needed whenever high intensity seed is not available
- Embed TESSA oscillator in laser cavity
- Reach very high average power with high rep-rate SRF accelerators
- Oscillator start-up : an open problem



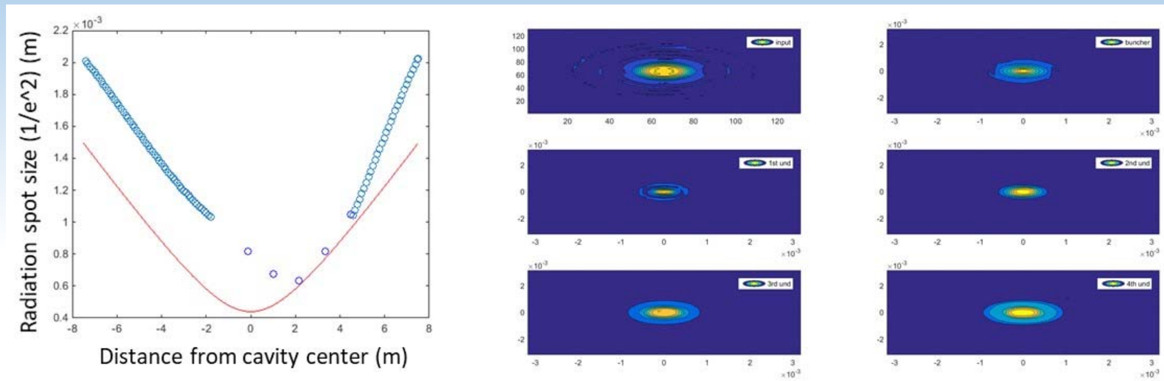
J. Duris, P. Musumeci, N. Sudar, A. Murokh, A. Gover. Tapering Enhanced Stimulated Superradiant Oscillator. Physical Review Accelerators and Beams 21, 080705 (2018)

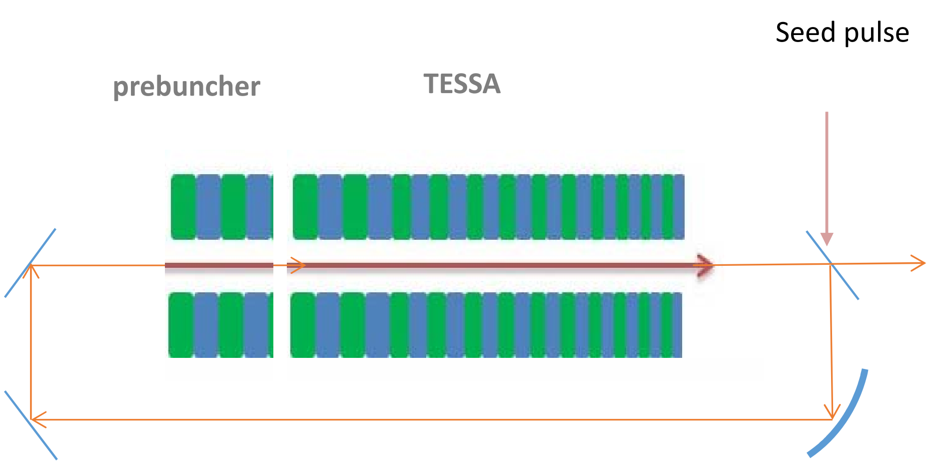
Impose that at steady state the recirculated power is constant $N_{ph} \approx \alpha\ N_e^2$

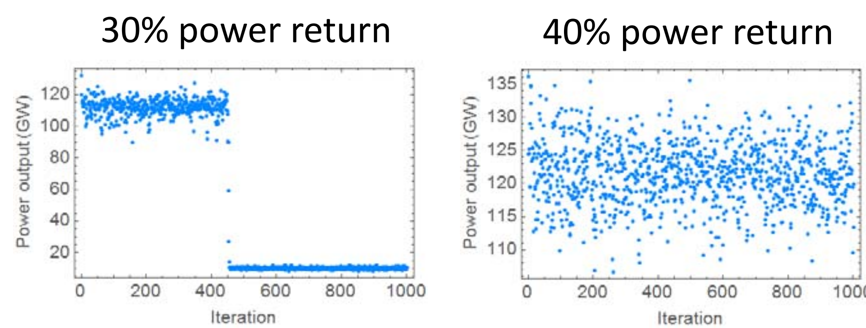
Important overlap with RAFEL/XFELO research efforts at SLAC and ANL

Full simulation model of oscillator

- Use field propagator + GENESIS to simulate multi-pass in cavity
- Optimize focusing mirrors
- Optimize return fraction
- Transverse active cavity eigenmode
- Study stability to e-beam current fluctuations



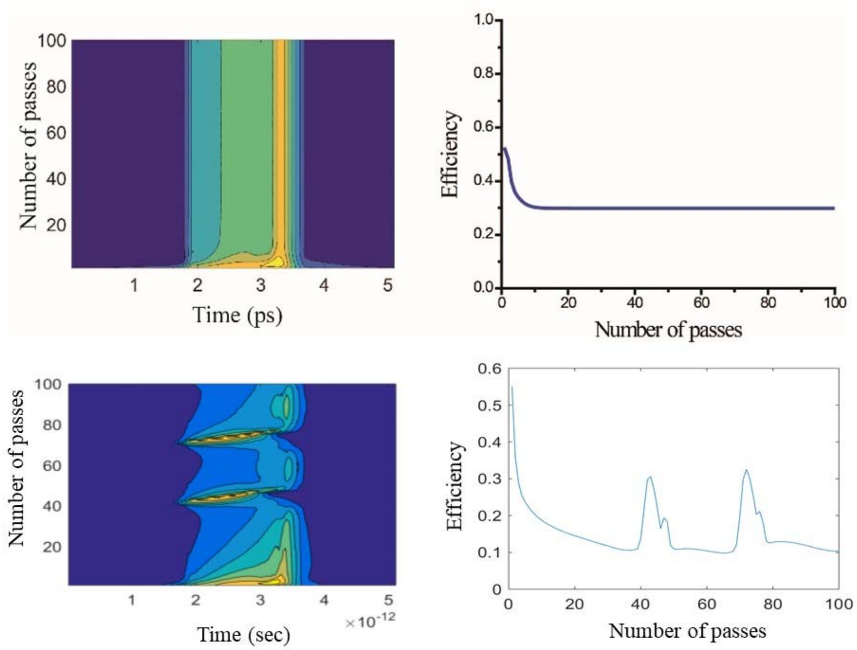


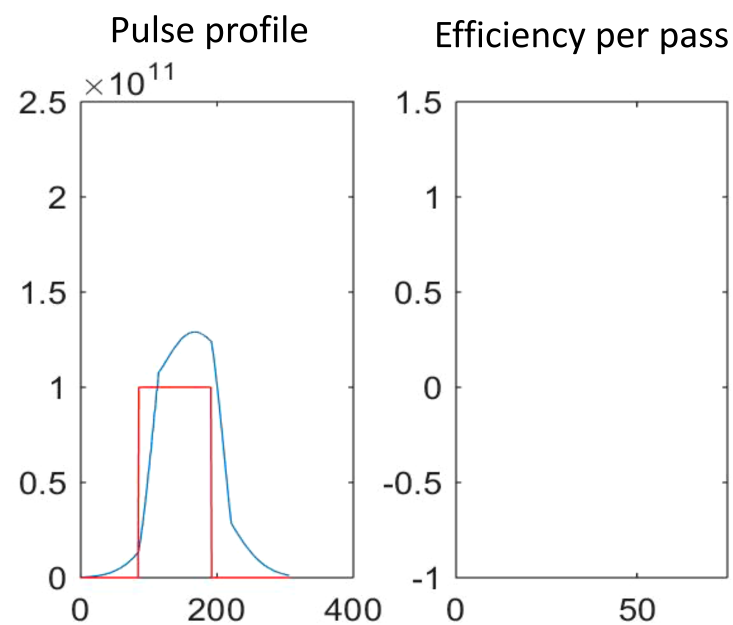


5% rms current fluctuations

TESSO as extension/follow up for TESSA-266 at ANL

- Use pulse train in linac to study igniter-assisted oscillator start-up
- 20 electron pulses @ 50 ns separation to fit within 1 us of RF macropulse
- 1D simulations show existence of longitudinal eigenmodes in high extraction efficiency cavity
- Cavity detuning is critical to select optimal longitudinal mode
- 3D simulation model computational intensive





Conclusion

- High gradient IFEL-like deceleration can achieve electrical-to-optical energy conversion efficiency in the tens of percent !
  - Nocibur experiment recently demonstrated 30 % energy extraction
- High peak power + high average power laser can take advantage of mature electron beam technology
- TESSA in an oscillator configuration (TESSO) can be used when no seed wavelength or only low-rep rate seeds are available
- Long range experimental program and various end-applications
  - TESSA266/ TESSO @ ANL
  - TESSATRON @ UCLA Pegasus
- Many issues to consider such as
  - Sidebands build up
  - Oscillator startup from small/zero seed power
  - Dispersion control in cavity needed to compensate for slippage in undulator
  - Mirrors and stretcher optics may require cooling