Tapering Enhanced Stimulated Superradiant Amplification experimental program

P. Musumeci
on behalf of TESSA collaboration

TESSA-FAST collaboration

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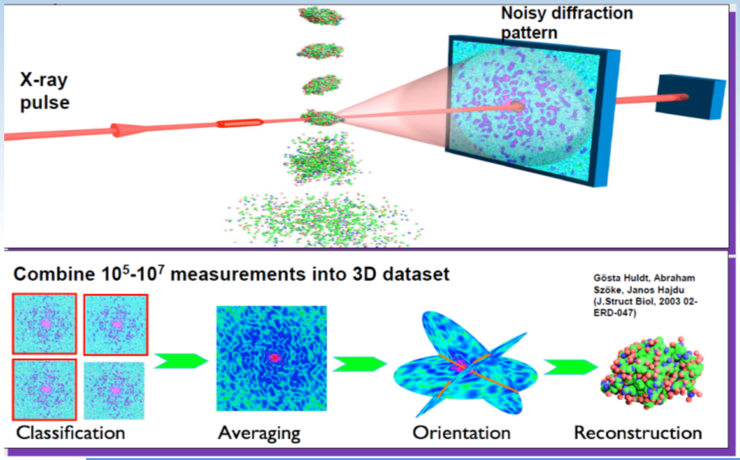
Funding agencies : DOE SBIR/STTR program, DOE BES (SCGSR + UCLA)

Outline

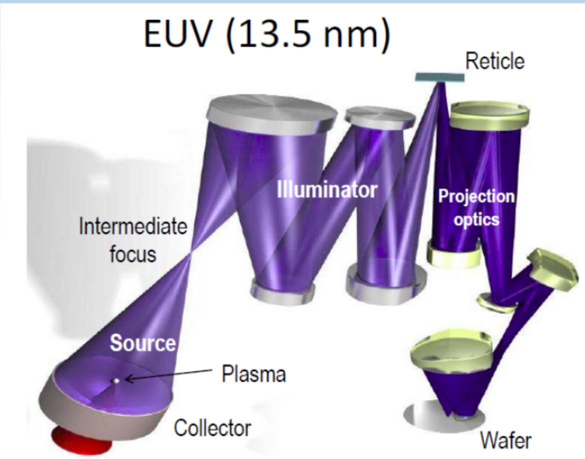
- Electron beam-based high efficiency radiation sources
- TESSA roadmap
- Near term proposal.
  - Single-pass TESSA – FAST experimental plans
- Long term program.
  - TESSA oscillator.
  - ICS-based gamma ray source
  - Polarized positron production

How to efficiently extract energy from relativistic e-beams?

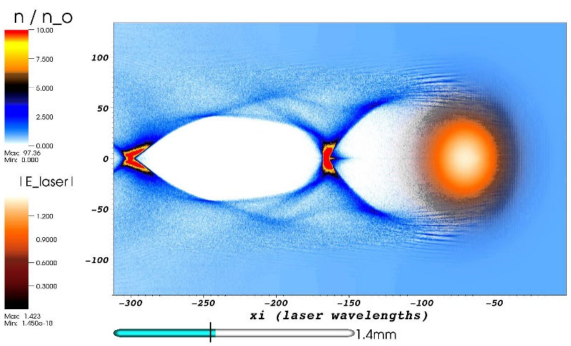
Single molecule imaging



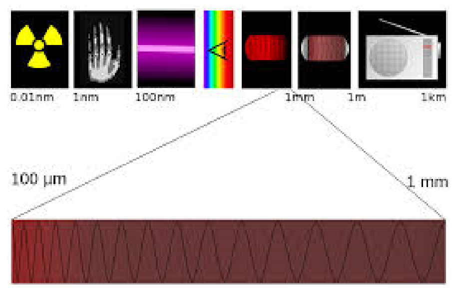
EUV lithography



High energy lasers



High power THz sources

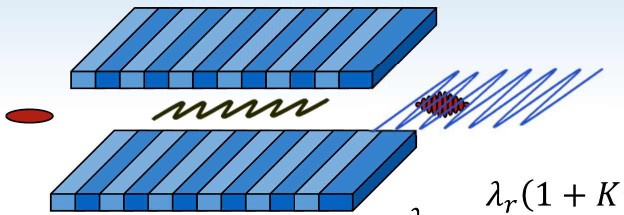


High efficiency enables high average and peak power light sources

Unique characteristics of ponderomotive interaction in magnetic undulator

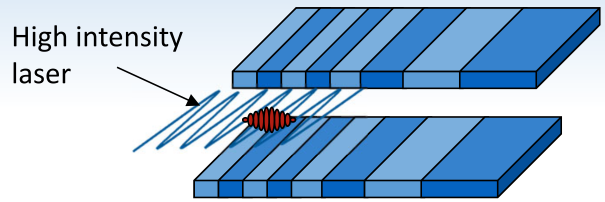
Particle acceleration - Radiation generation

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



$$\lambda_r = \frac{\lambda_r(1 + K^2)}{2\gamma^2}$$

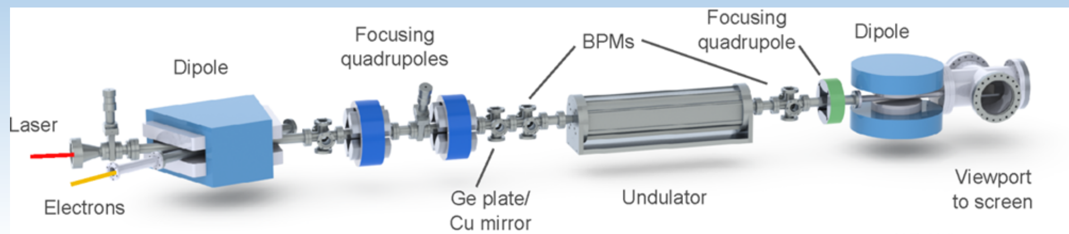
In an IFEL the electron beam absorbs energy from a radiation field.



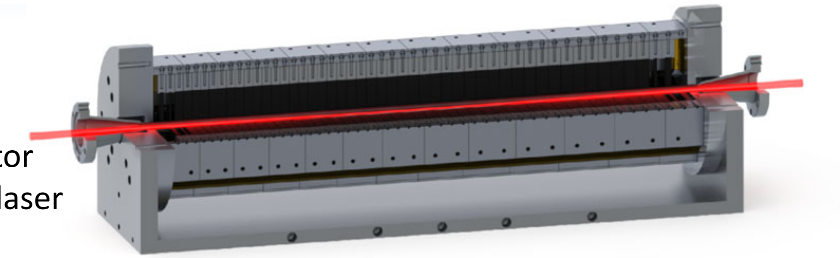
- “Without radiation there is no acceleration” – R. Palmer
- “To be efficient an accelerator must be able to operate in reverse”
- IFEL/FEL is a particularly advantageous interaction scheme in this regard
  - ***Vacuum-based*** accelerator. **No** mechanism for energy loss. ***Efficient energy exchange***
  - ***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

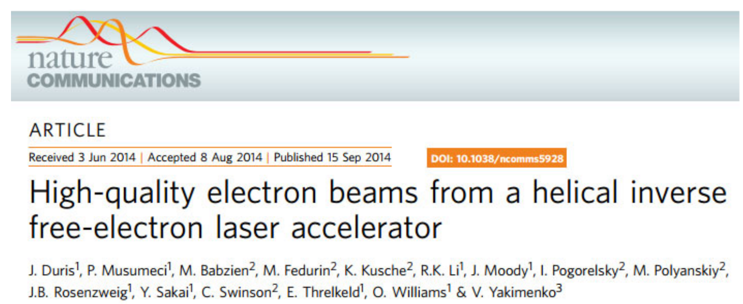


100 MeV/m
11 periods
0.5 m undulator
300 GW CO2 laser



Laser off energy spectrum

IFEL output energy spectrum


nature COMMUNICATIONS

ARTICLE

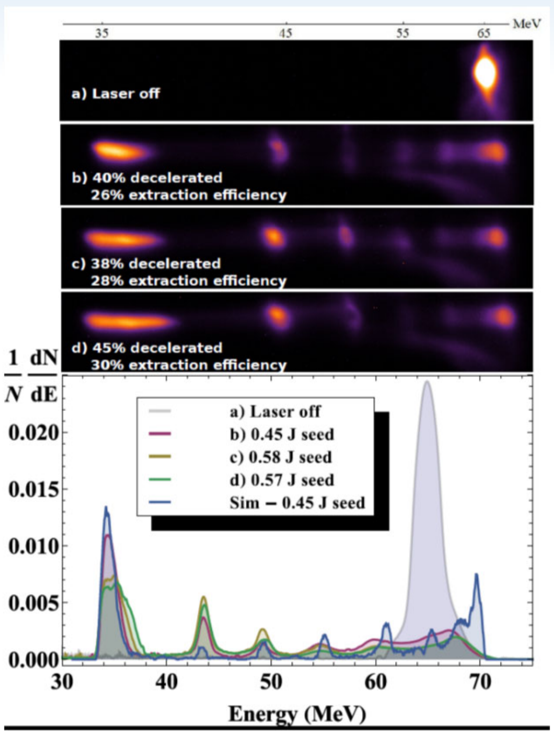
Received 3 Jun 2014 | Accepted 8 Aug 2014 | Published 15 Sep 2014 DOI: 10.1038/ncomms5928

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

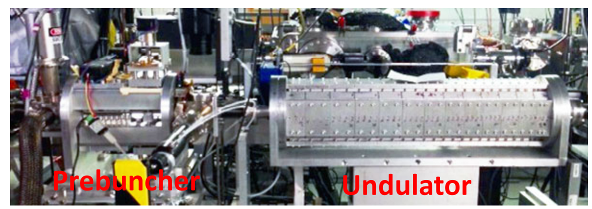
J. Duris[1], P. Musumeci[1], M. Babzien[2], M. Fedurin[2], K. Kusche[2], R.K. Li[1], J. Moody[1], I. Pogorelsky[2], M. Polyanskiy[2], J.B. Rosenzweig[1], Y. Sakai[1], C. Swinson[2], E. Threlkeld[1], O. Williams[1] & V. Yakimenko[3]

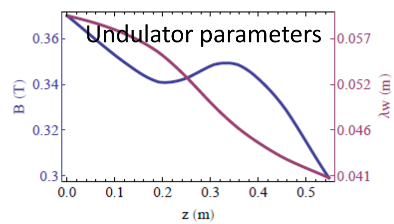
NOCIBUR IFEL deceleration experiment

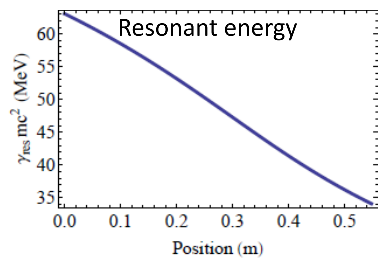
- Use RUBICON IFEL set up in reverse at BNL ATF
- Retune tapering profile for 0.54 m long helical undulator for high gradient deceleration
- Demonstrated >30% conversion efficiency from a relativistic electron beam



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





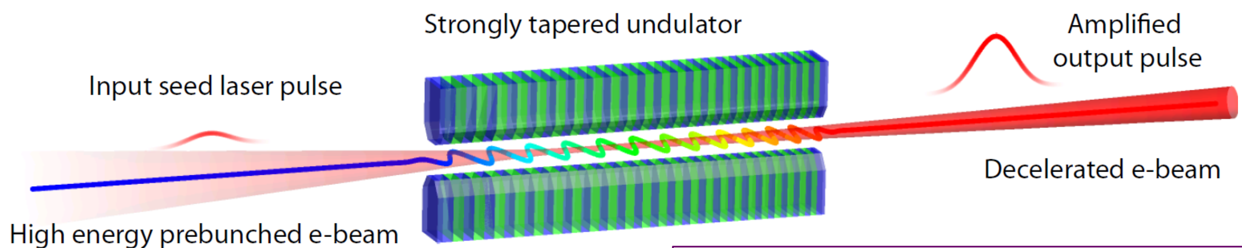


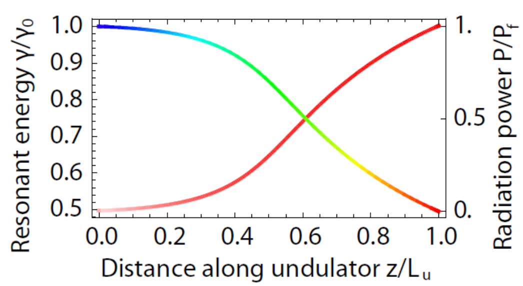
PRL **117,** 174801 (2016) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2016

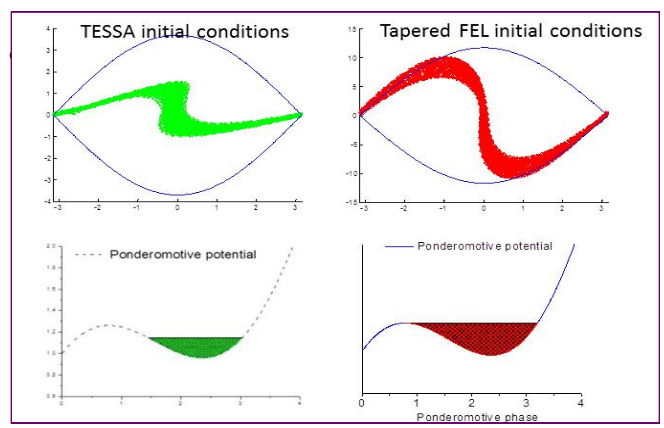
High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

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: strong tapering matches decelerating gradient to growing radiation field amplitude

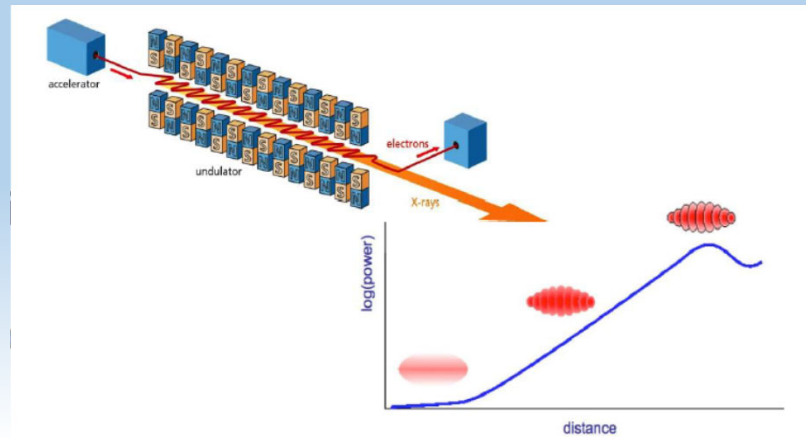




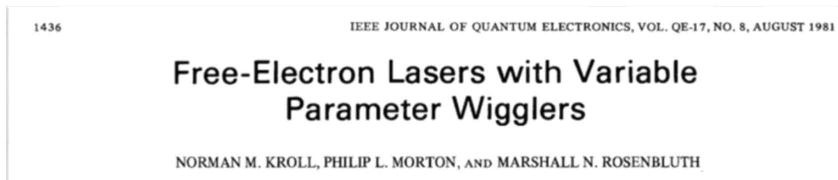


J. Duris et al. New Journal of Physics, 17 (2015)

Tapered FEL



- ρ is the dimensionless FEL parameter, for short wavelength typically ~ 0.1% or less
- 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

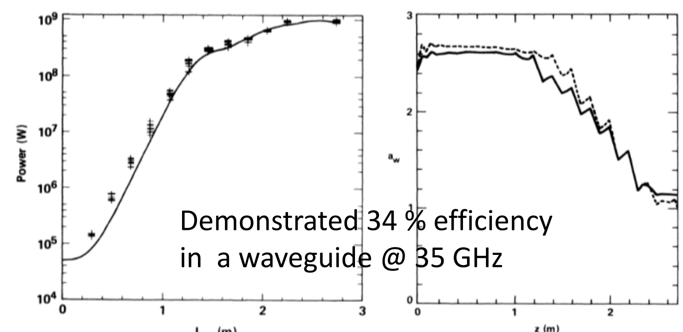

1436 IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-17, NO. 8, AUGUST 1981

Free-Electron Lasers with Variable Parameter Wigglers

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

- Old and renewed interest
  - ELF. Waveguide FEL @35 GHz
  - Paladin experiment at 10 um
  - Nocibur / TESSA
  - Self-seeded cases for TW X-FEL

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

High gain regime

Optical cavity

Applications

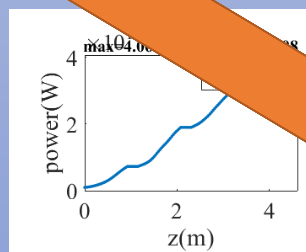
Nocibur

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

Sudar et al. PRL 2016

TESSA-FAST

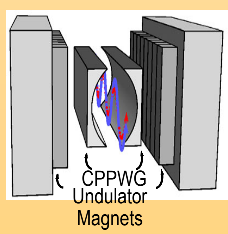
Obtain first measurements of spectral and spatial properties of ampli... diation



High energy high brightness beamline

TESSATRON at Pegasus

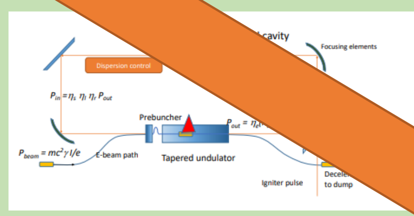
10 % efficiency
THz range
Zero-slippage waveguide FEL
Prebunched e-beam



In operation at UCLA Pegasus !!!

TESSO

No intense input seed available
Optical cavity and recirculating scheme
...er pulse / RAFEL
...tion



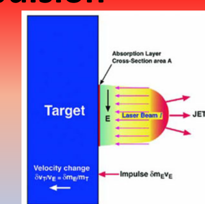
J. Duris et al. PRAB 2018

EUV lithography

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

Laser ablation propulsion

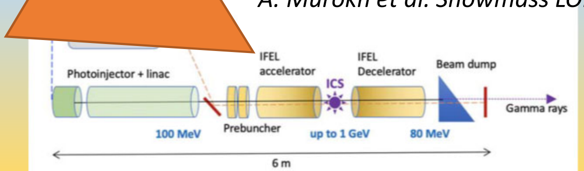
SRF accelerator driver
1 μm MW-average power laser with TW-peak power
Atmospheric transparency window. *Phipps et al. JOSAB 2018*



High flux Polarized Gamma-Ray source

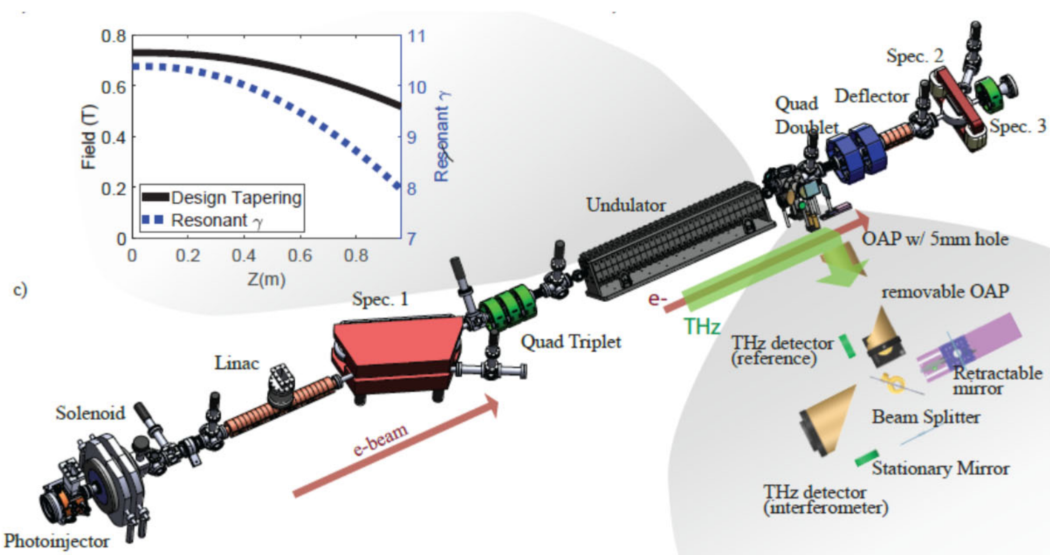
...rse Co... ton Scattering
...EL acceleration to boost photon ene...

A. Murokh et al. Snowmass LOI

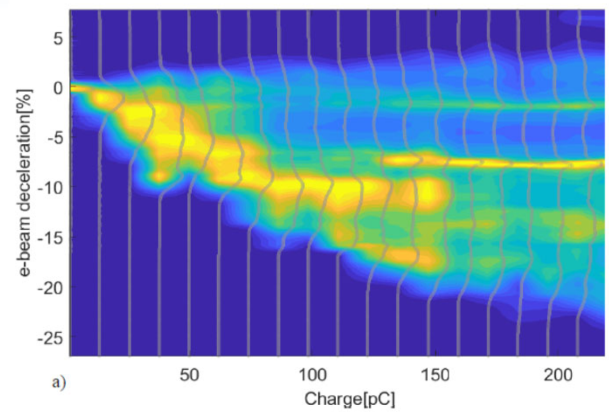


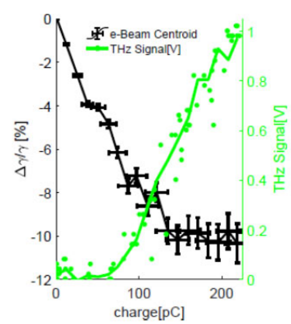
TESSATRON

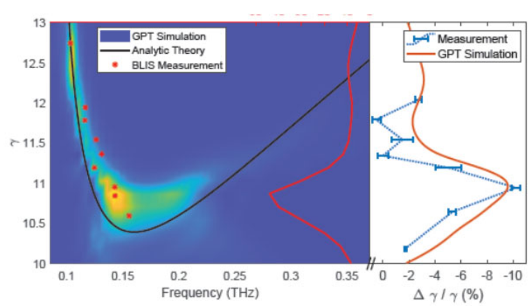
- Strongly tapered helical Theseus undulator installed at UCLA Pegasus (5-8 MeV beamline)
- Zero-slippage FEL physics. Use of waveguide to match e-beam and radiation group-velocity + satisfy FEL resonant condition
- Measured record 10 % efficiency



E-beam spectrum







TESSA-FAST project

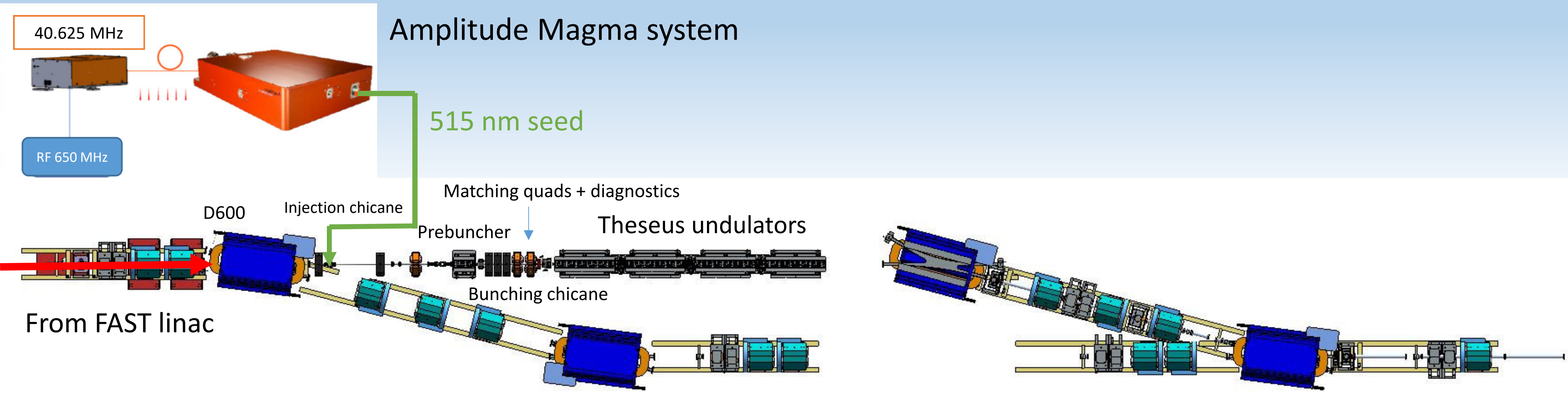
- UCLA – RadiaBeam – ANL – FNAL – collaboration
- Main scientific goals:
  - First experimental **measurements of spectral and transverse profile characteristics** of the radiation amplified in the TESSA regime of operation.
  - Demonstration of single pass **record high energy extraction efficiency** from a relativistic electron beam in the VIS region
  - Open the path to MHz-rep rate Tapering Enhanced Oscillator multi-kW high power lasers
  - Enable high rep-rate Inverse Compton Scattering based polarized gamma-ray sources for nuclear physics/polarized positron production

Beam Energy	**220 MeV**
Peak current	0.6 kA
Emittance	3 um
Charge	1 nC
Energy spread	0.1 %
Undulator length	4 x 0.96 m
Radiation wavelength	**515 nm**
Seed power	1 GW
Interaction geometry	Helical

Motivations for TESSA at FAST

- *UCLA workshop on High Efficiency FELs. 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"*
- Experiment originally designed for 340 MeV in LEA tunnel at APS linac, tuned for 266 nm wavelength. Not a good match due to APS-U schedule
- Scarcity of available high brightness beam facilities in the 200-400 MeV range. Leverage availability (time and space) of FAST linac
- **Extend TESSA to SRF-linac is a stepping stone towards high average power radiation sources.**
- Enable very high flux ICS-based polarized gamma-ray source. Nuclear physics / Polarized Positron Production
- Convergence of interests from University-National Laboratory-Industry.

TESSA-FAST experiment setup

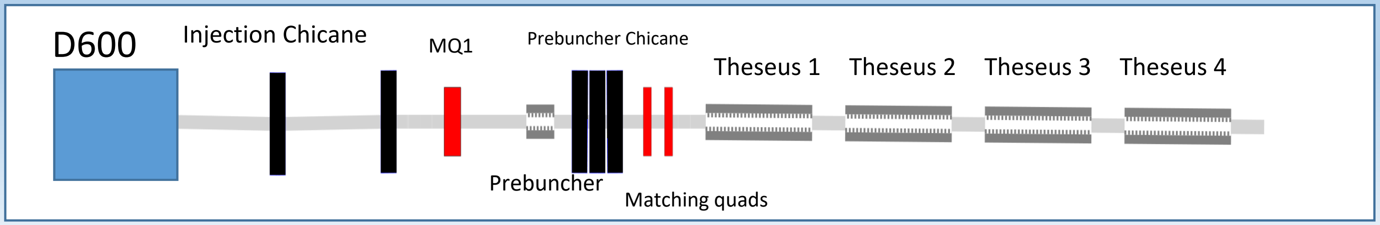


Requires installation of TESSA beamline components including :

- Seed laser system (at company, waiting to be shipped)
- Prebuncher (in hand, tuned)
- Injection and Bunching chicane (in hand, ready to be shipped)
- 4 undulator sections (2 ready, 2 to be built using latest round of SBIR funding)
- 3 break sections (1 prototype built)
- Matching quadrupoles (missing)
- Radiation and beam long. phase space diagnostics (partially developed in collaboration with ANL)

Also needs:
Beamline supports
Power supplies
Vacuum pump and controllers
Control system integration

TESSA simulations



Time-independent simulations

- ~9 % power efficiency
- Doublet permanent magnet quadrupole (112 T/m) channel
- 75 um average rms size in undulators
- 13 GW output power

Beam Energy	**220 MeV**
Peak current	0.6 kA
Emittance	3 um
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Energy spread	0.1 %
Undulator length	4 x 0.96 m
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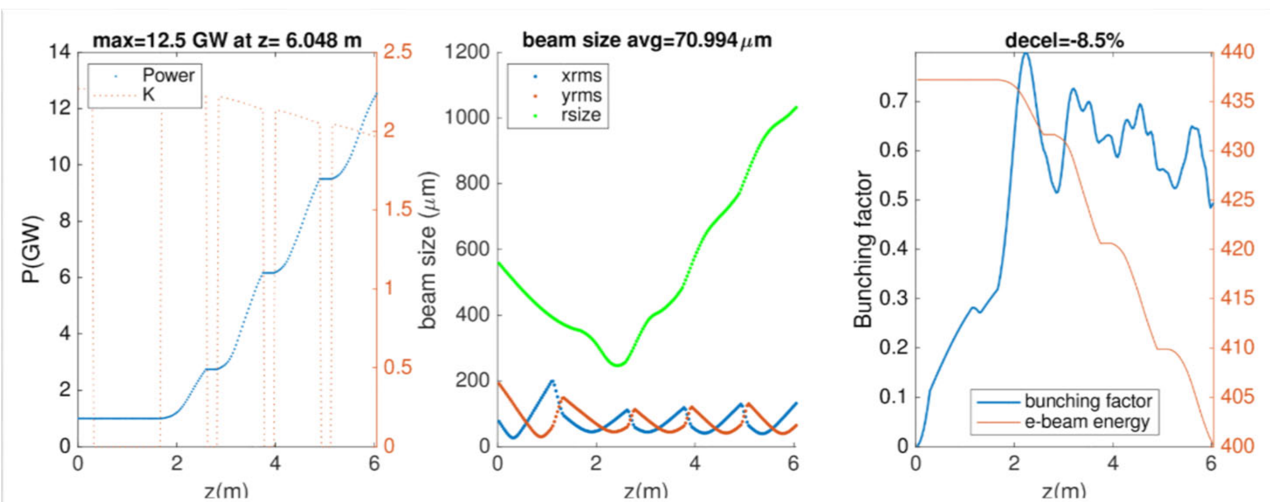
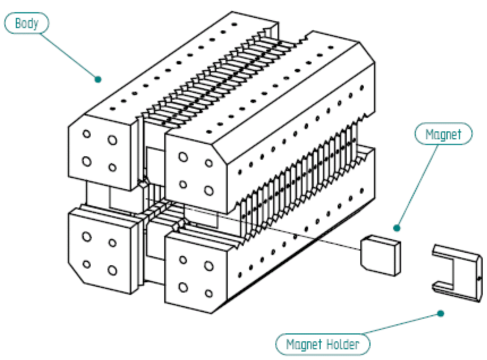
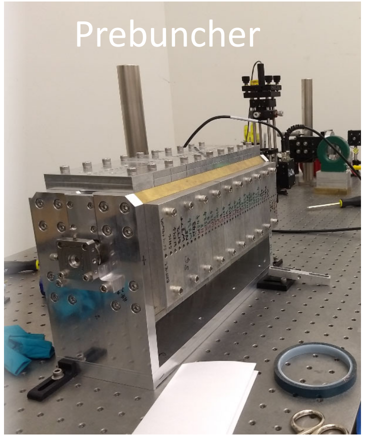


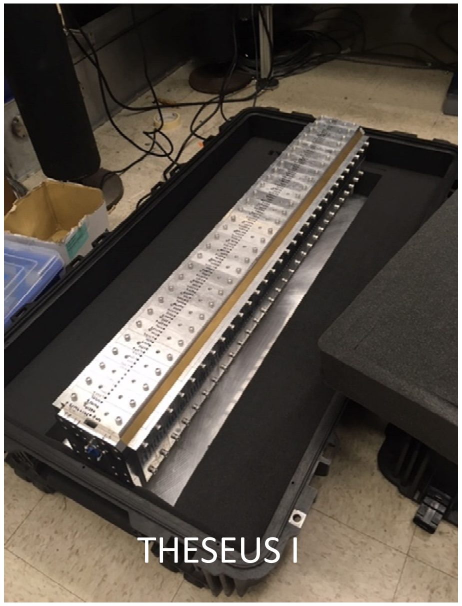
Theseus: Tapered HElical SEgmented Undulator System

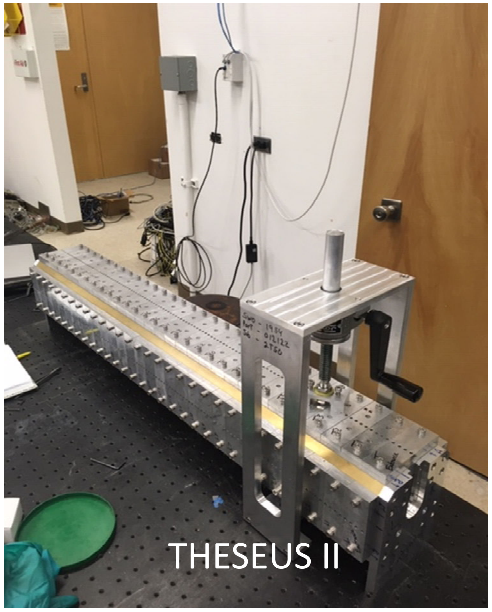
- 2 orthogonal Halbach arrays with constant period and adjustable gap
- Improved design from Rubicon undulator
- 1 m long sections
- Completed prebuncher (8 periods) and two undulator sections (28 periods)
- Entrance and exit sections add ~ 1 period per section to FEL interaction (GPTFEL)
- Measurements, tuning and fiducialization ongoing

Undulator period	3.2 cm
Peak field	0.75 T
K_max	2.3
Resonant energy @ 515 nm	220 MeV
Gap (min/max)	5.5 mm / 7.5 mm









Hall probe scans

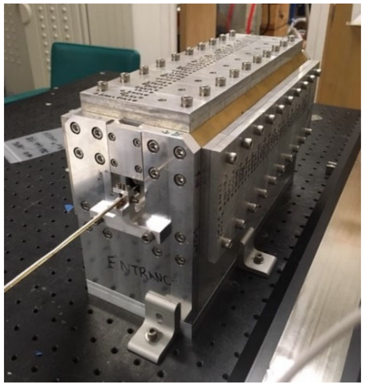
3D mini Hall probe (Senis-GMW)

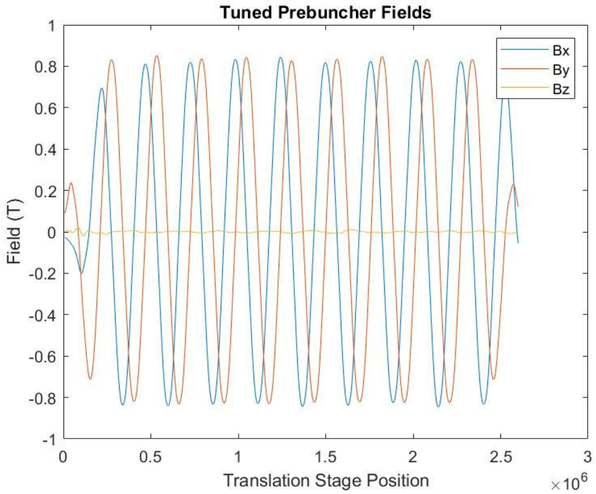
1 m translation stage

Mounting system for centering Hall probe in undulator (u-beam+carriage)

Need to keep/register the probe on the undulator axis within 200 um and 2 degrees.

Linear system allows Matlab optimization for magnet insertion





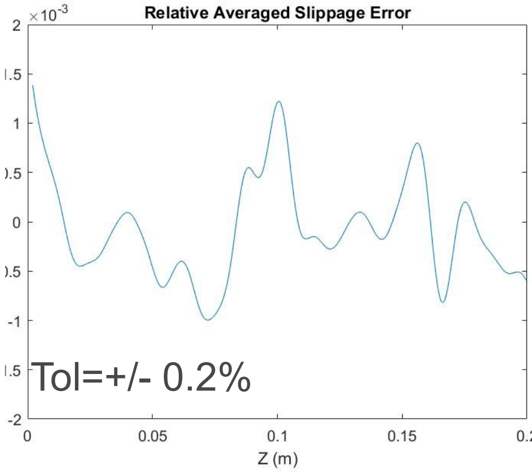
Pulse wire

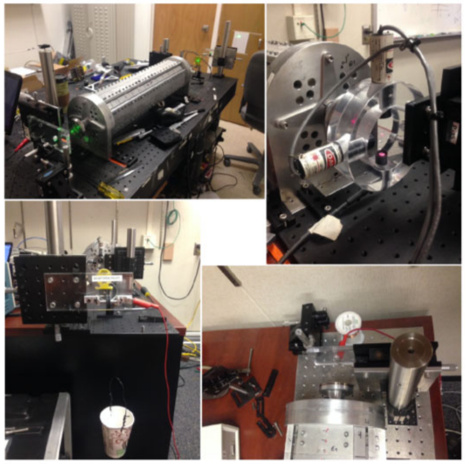
Final trajectory adjustment

Entrance and exit magnet tuning

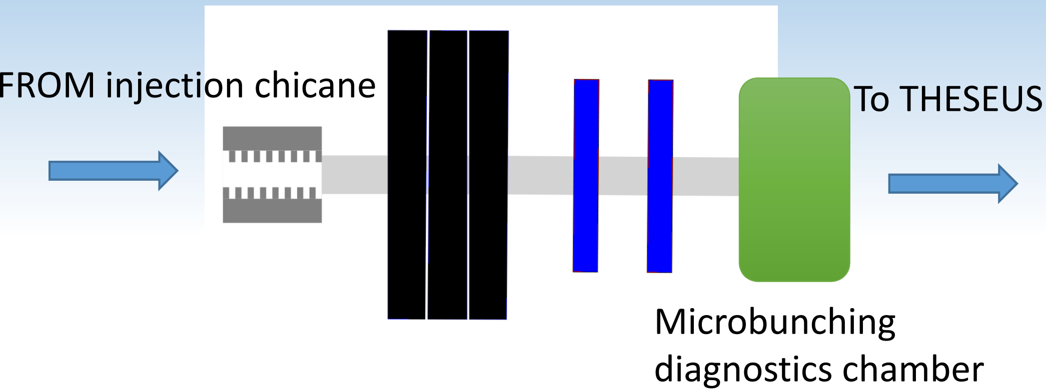
Trajectory axis references to alignment monument on undulator body to < 40 um

Consider checking trajectory after shipping?



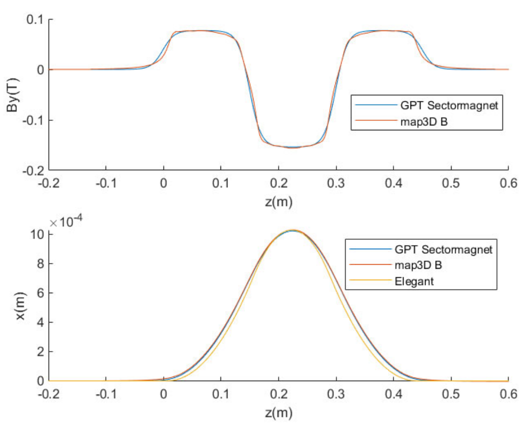


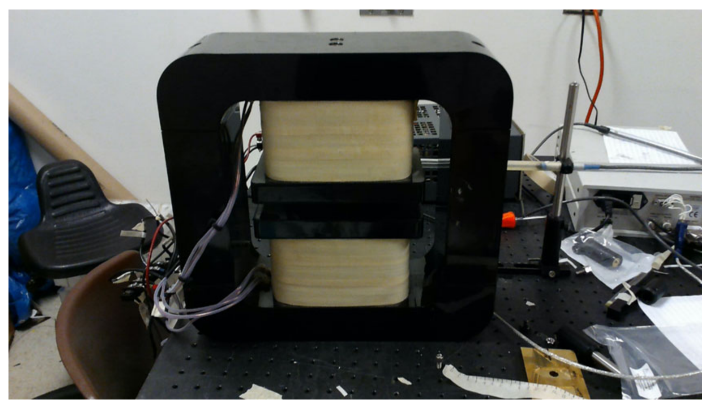
Prebuncher chicane



3 magnet bunching chicane parameters	
Dipole Strength	0.078T, 0.16 T (center)
Bend Angle	.009 rad, .018rad (center)
Magnetic Length	146mm
Physical Chicane Length	410 mm
Prebuncher to Theseus I entrance length	1.368 m
R56	< 18 um

Field and e-beam Trajectory





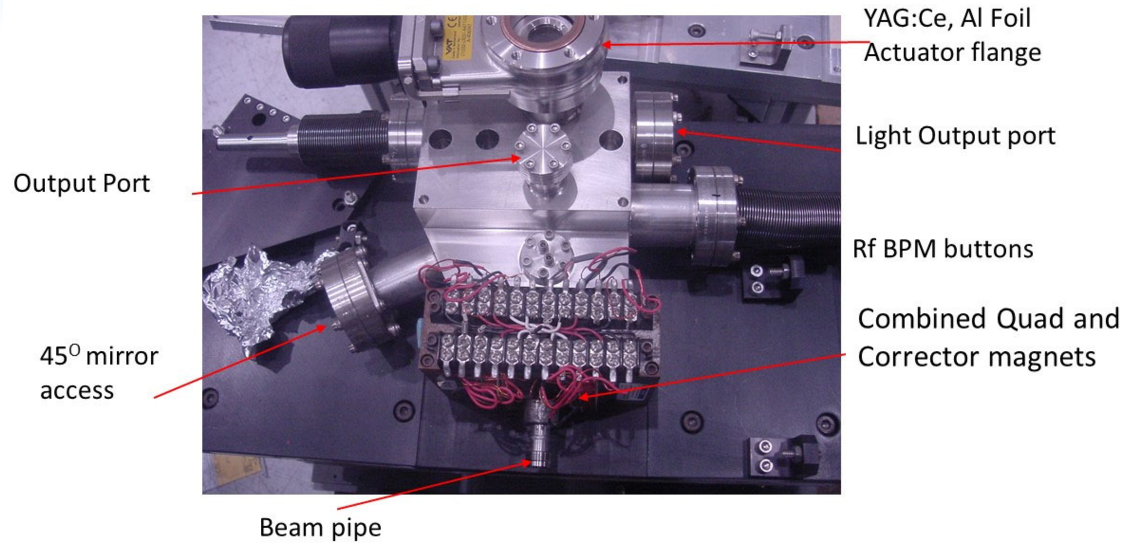
Same dipole as injection chicane

Old Neptune chicane.

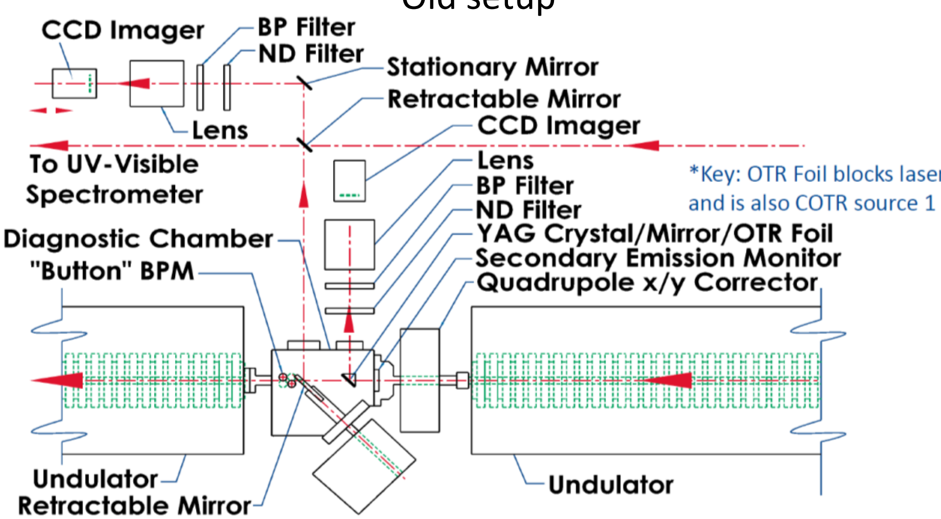
Thanks to Jamie Roseznweig

Microbunching Diagnostics Chamber

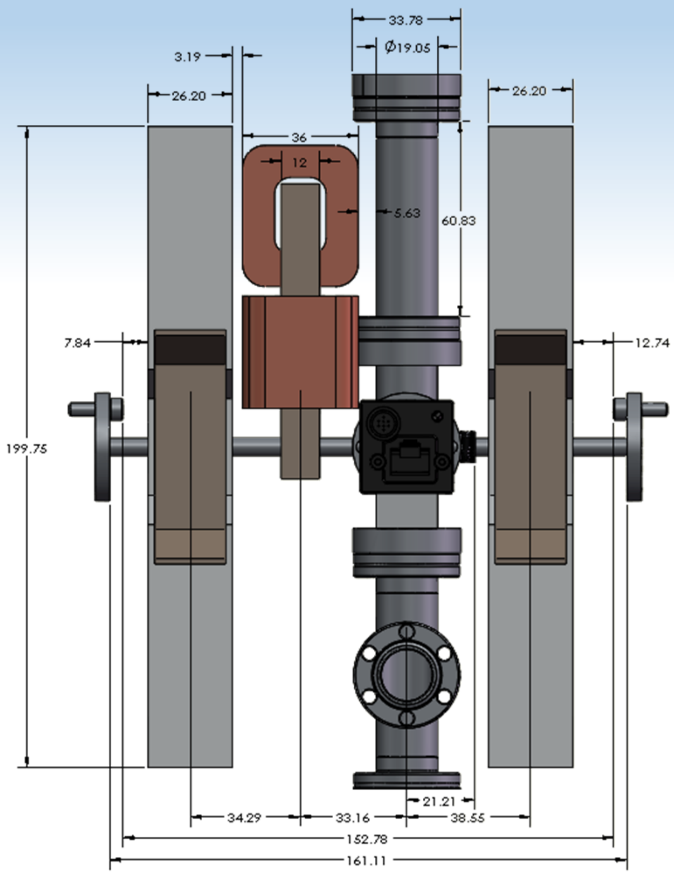
- 2 stations in storage at ANL from A. Lumpkin
- FEL light and COTRI station with L=6.3 cm between foils.
- 50 um foil to block laser and preserve microbunching



Old setup

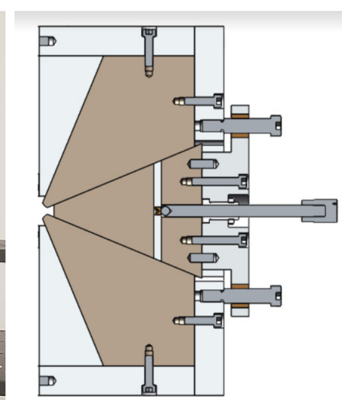


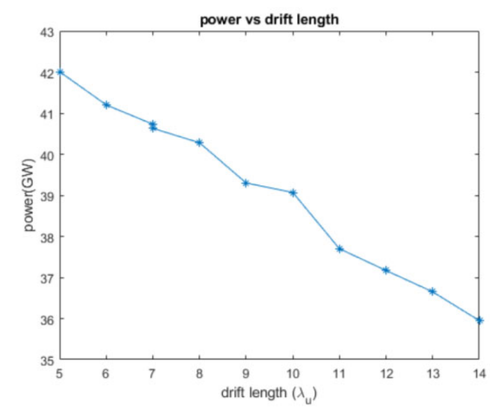
THESEUS Break Section Design



*EMD design and position in the figure is not updated

- One of the most critical section of the experiment
- 162.6 mm long
- Physics requirement: minimize inter-undulator distance where radiation is quickly diffracting and losing intensity.
- Quadrupole doublet to refocus beam
- Phase shifter design based on offset quadrupoles + electromagnetic dipole
- GPT model to evaluate dispersion effects
- Vacuum + diagnostics

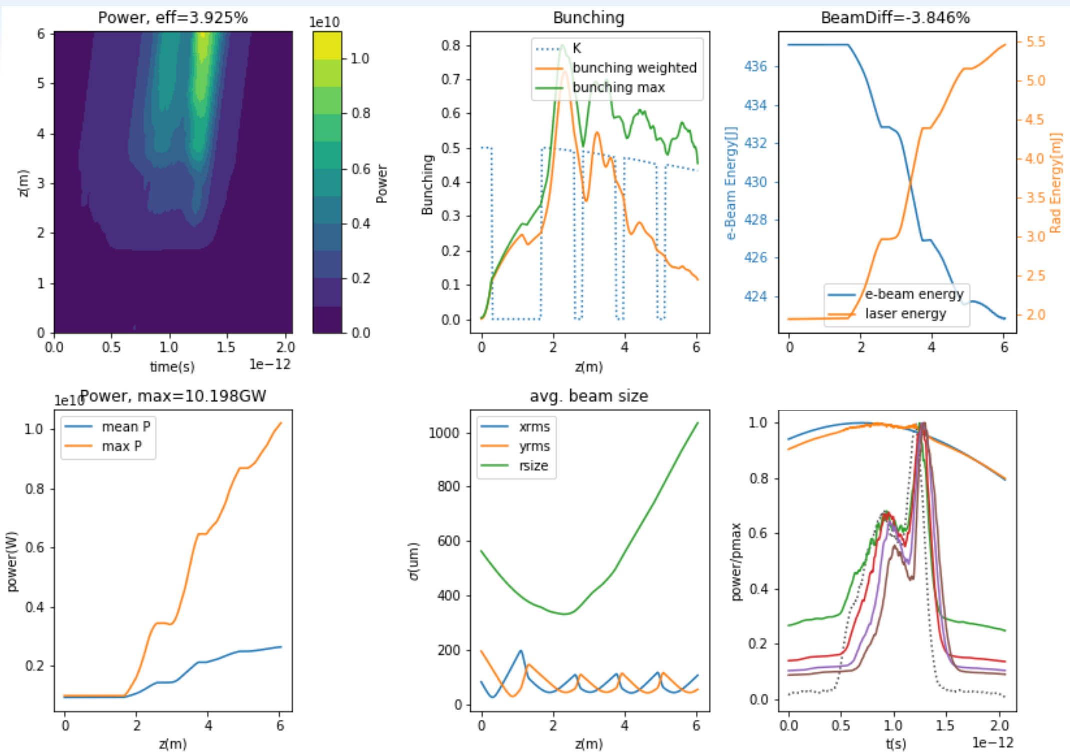




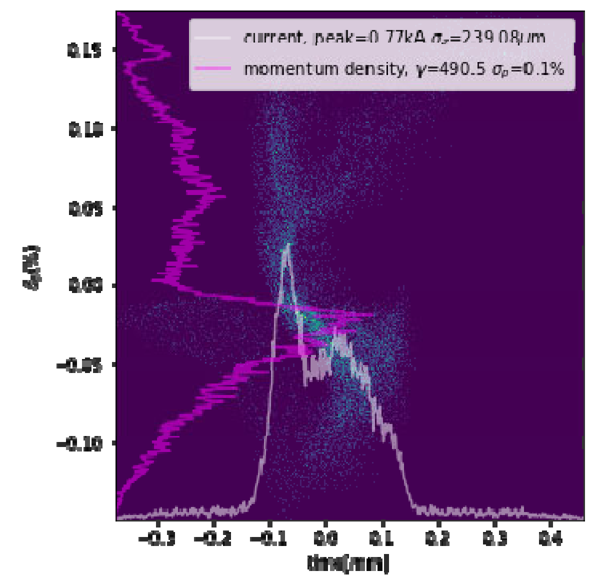
UCLA

Time-dependent simulations

For equal bunch charges, a flatter current distribution yields higher energy efficiency due to slippage
Necessary to correct linac compression nonlinearity (no linearizer compared to advanced FEL beamlines) to better control current distribution for four-undulator setup



Longitudinal phase space from LINAC



radiasoft

TESSA Oscillator = TESSO

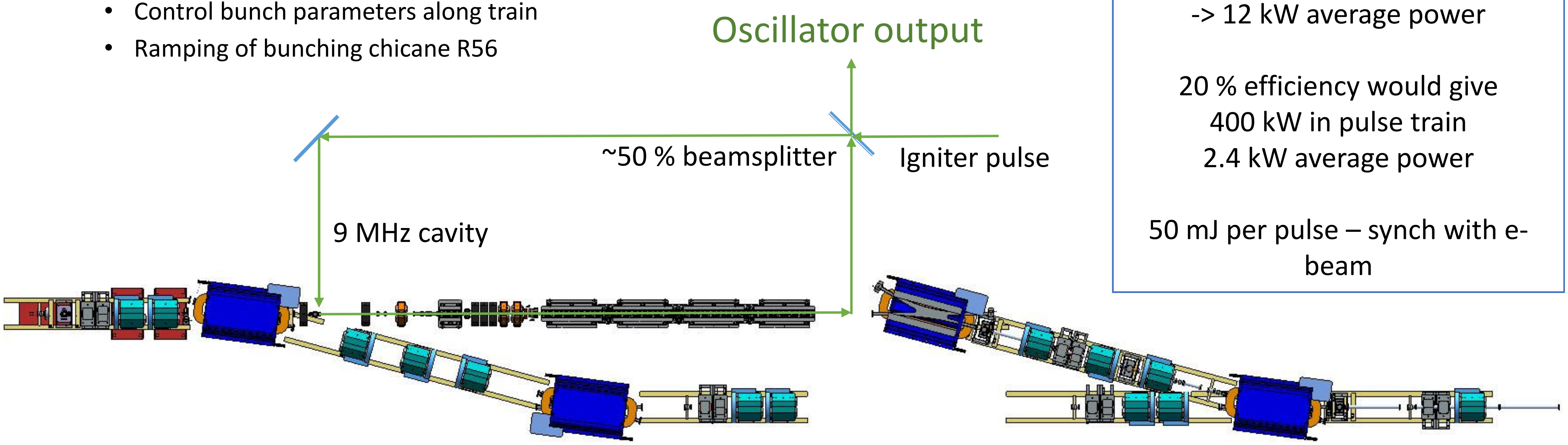
J. Duris, P. Musumeci, N. Sudar, A. Murokh, A. Gover. Tapering Enhanced Stimulated Superradiant Oscillator. Physical Review Accelerators and Beams 21, 080705 (2018)

- Oscillator is needed whenever high intensity seed is not available
- Solution: embed TESSA in optical resonator
- Reach very high average power with high rep-rate CW SRF accelerators
  - Exploit 3 MHz (or 9 MHz if available) pulse train capability at FAST
- Oscillator start-up : an open problem. Various possibilities.
  - **Igniter pulse**
  - Control bunch parameters along train
  - Ramping of bunching chicane R56

9 MHz 220 MeV 1.2 nC
-> 12 kW average power

20 % efficiency would give
400 kW in pulse train
2.4 kW average power

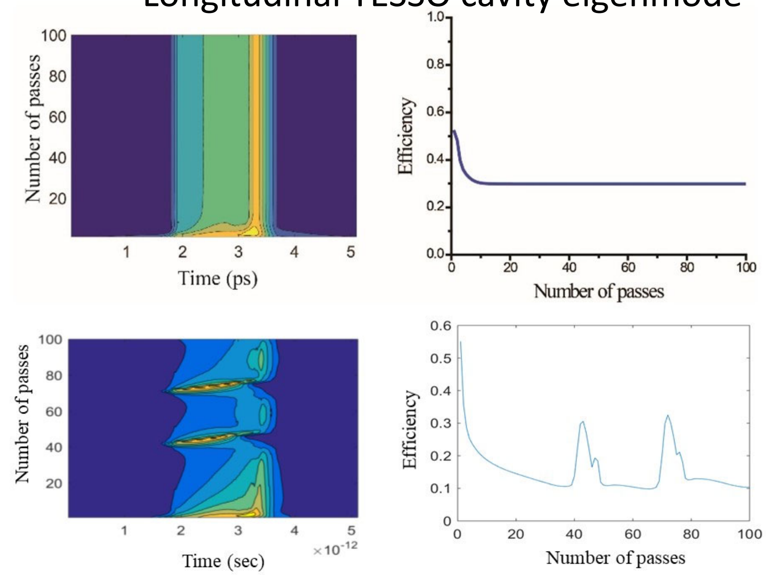
50 mJ per pulse – synch with e-beam



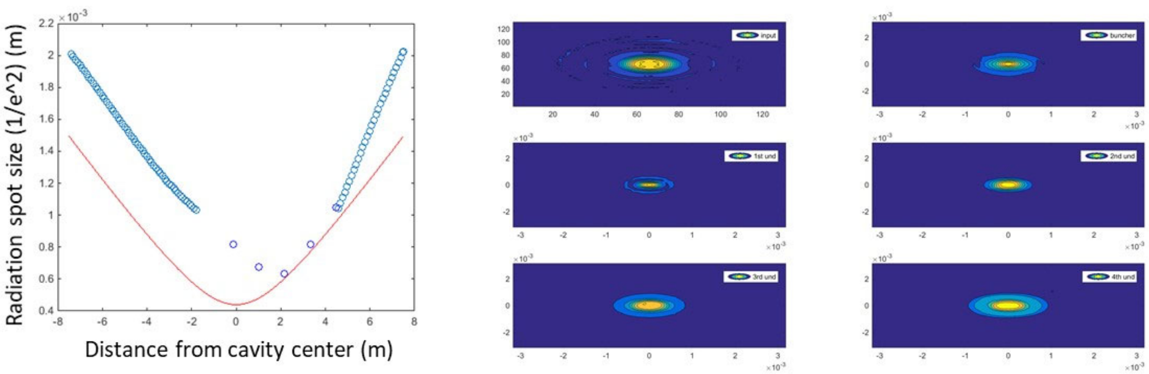
Oscillator transverse and longitudinal modes

- Lots of work to do: Optimize focusing optics. Optimize return fraction. Study stability to e-beam current fluctuations
- Modeling tools in hand. Use field propagator + GENESIS/GPTFEL to simulate multi-pass in cavity
- Important connection with RAFEL and XFELO program at SLAC
- Longitudinal and transverse active cavity eigenmodes established after < 10 passes. Short pulse train would be sufficient for first studies
- Cavity detuning/ spectral filtering is critical to select optimal lasing modes
- Mirrors and stretcher optics may require cooling at very high average powers

Longitudinal TESSO cavity eigenmode



Transverse TESSO cavity eigenmode



ICS-based Gamma-ray production

For high flux gamma ray production via Compton the main issue is the laser rate. Hiγs @ TUNL/Duke uses an FEL + storage ring to generate ~10^10 ph/sec

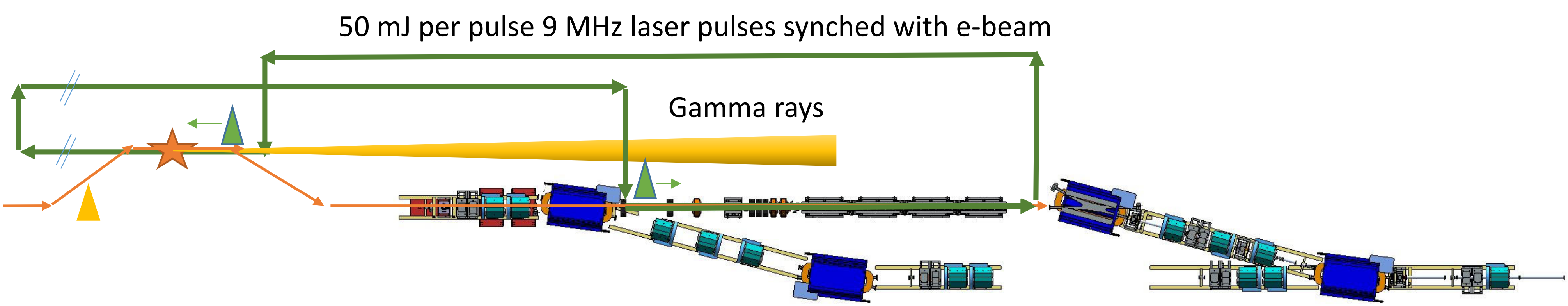
Tunability (limited by optics) scales as γ^4

@ 9 MHz train / 5 Hz -> 5·10^11 photons/sec – ps pulses

Synchronization scheme. A possibility is two light pulses in a 2x longer cavity

Helical geometry - > Circularly polarized gammas

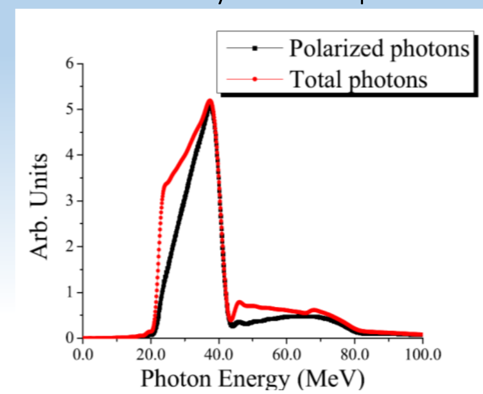
Parameter	Value
E-beam energy	220 MeV
E-beam charge	1.2 nC
Laser energy	50 mJ (20% efficiency)
Laser wavelength	515 nm
Gamma ray energy	1.8 MeV
Gamma ray flux	>10^7 per shot

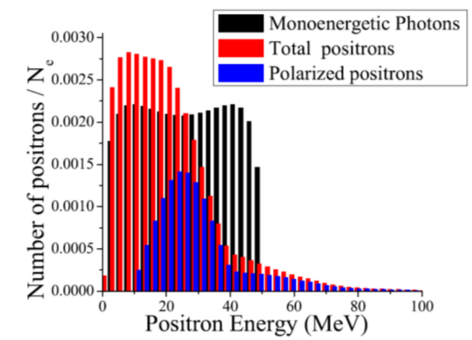


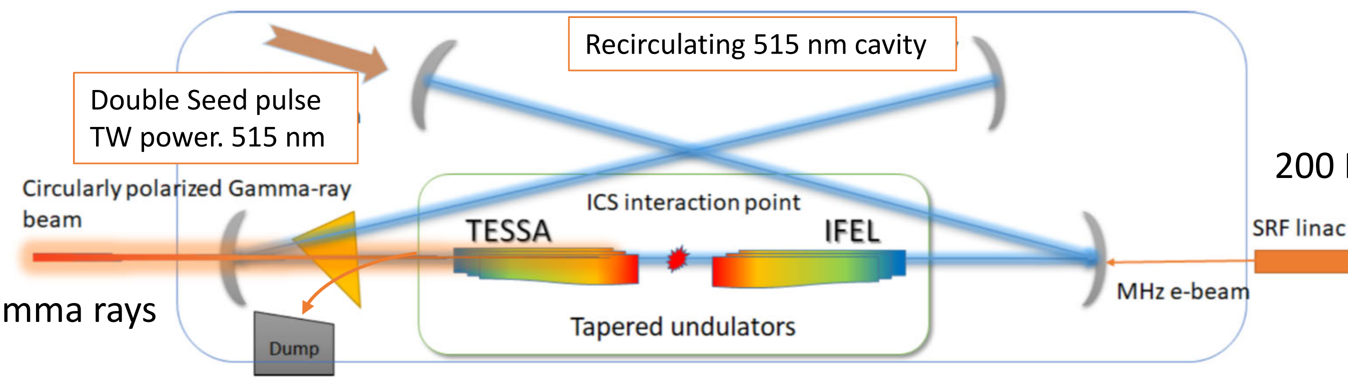
Polarized positron production for e+/e- linear collider

- ILC/Higgs factory really benefits from polarized positron source
- Current scheme uses 200 m long undulator (K = 1) and 120 GeV beams to get the required gamma ray flux (10^14 ph/sec) at 10 MeV.
- ICS-based source considered, but laser-power limited
- Murokh, Musumeci et al. Snowmass 21 LOI. Compact source proposed based on IFEL acceleration + ICS + TESSA deceleration
- Optical energy recirculation
- Note: for ILC, with laser-based Compton source it is hard to get close to 1 ph/e- so in order to get as many e+ as e-, one would need to start with much higher e- current

Case study for 40 MeV ph







200 MeV

10 MeV gamma rays

IFEL acceleration to 500 MeV

Conclusions

- High gradient FEL interaction can achieve electrical-to-optical energy conversion efficiency up to the tens of percent !
  - BNL Nocibur experiment demonstrated 30 % energy extraction
  - UCLA TESSATRON results shows 10 % efficiency and high gain in THz regime
- TESSA mechanism provides direct path to high peak power + high average power radiation sources
  - FAST is the only available high energy SRF accelerator beamline in US
  - Leveraging significant investment in hardware from UCLA/RBT in the last 5 years
- Long range research program and various end-applications
  - TESSA-FAST – First experiment targeting single pass high efficiency at 515 nm.
  - TESSO – optical resonator cavity. build-up. High average power lasing.
  - Application developments (ICS-based gamma ray source, SLAP, EUV-lithography, TW-XFEL)
- Formal proposal to FAST/IOTA facility to be submitted soon !!!