Dinner at 6.30 pm
Napa Valley Grille

1100 Glendon Ave Ste 100, Los Angeles

Tapering Enhanced Stimulated Superradiant Oscillator

Towards very high average power free-electron based radiation sources

P. Musumeci

High efficiency FEL Workshop

UCLA April 11-13th 2018

Acknowledgements

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

A. Gover (Tel Aviv University)

A. Zholents (ANL)

A. Murokh. (Radiabeam Technologies)

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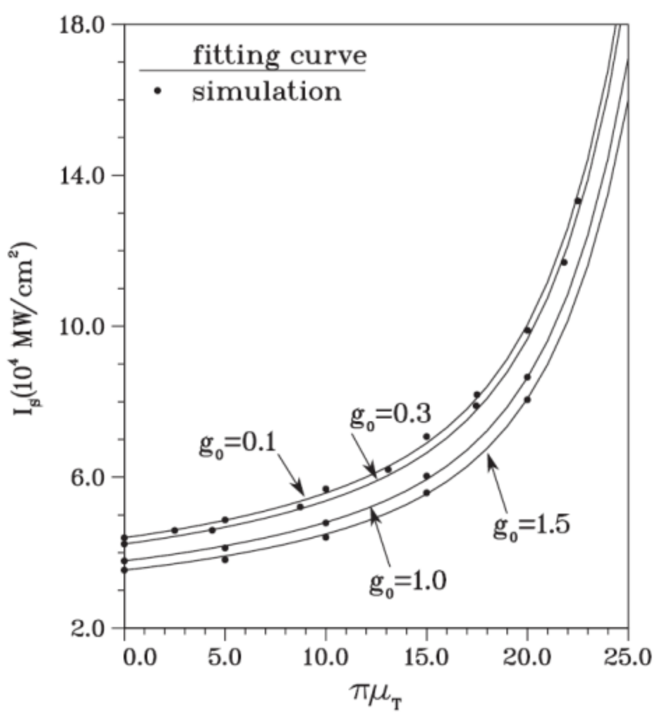
Outline

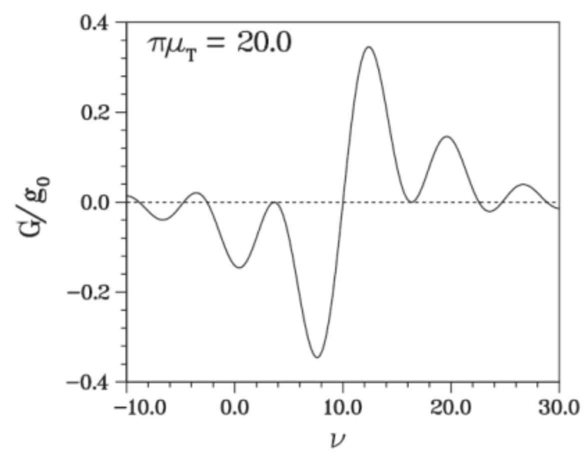
- Introduction
  - Tapered undulators in FEL oscillators
  - TESSA approach. Strongly tapered helical undulator experiments at BNL
- What are the critical elements to get high extraction efficiency?
- TESSO, high efficiency oscillator
  - A 1 μm test-case
  - Optical cavity and stability study
  - Slippage and pulse propagation effects
- Conclusions

Tapered undulators in FEL oscillators

- Old idea with interesting literature and surprising results
- Small signal formalism and only mild linear tapering
- Start-up analysis
- Benefits of reverse tapering !
- Pulse propagation effects considered

$$\mu_T = 2N\frac{\Delta B}{B}\frac{K_0^2}{1+\frac{K_0^2}{2}},$$



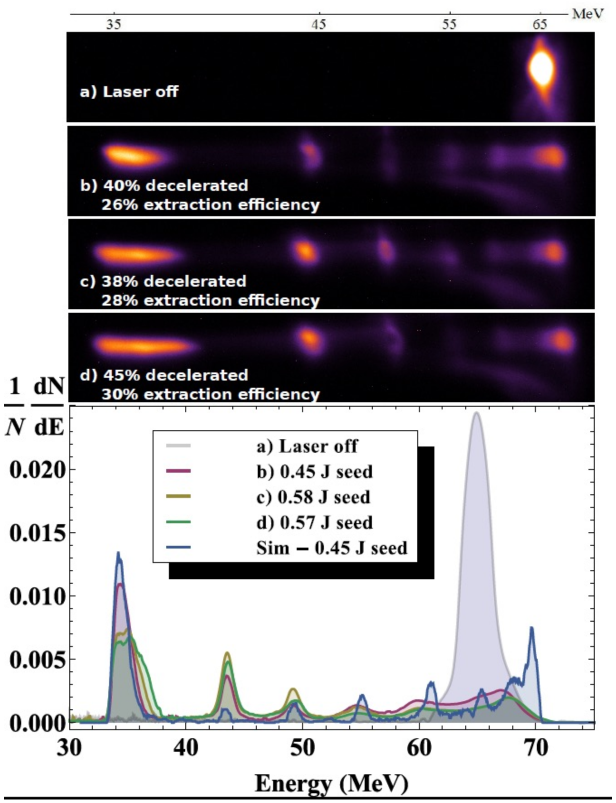


E. L. Saldin, E. A. Schneidmiller and M. Y. Yurkov. Optics Communications 103 297 (1993)

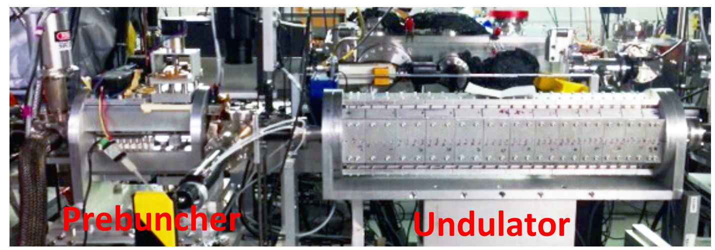
G. Dattoli, S. Pagnutti, P. L. Ottaviani and V. Asgekar. Phys. Rev. STAB, 15, 030708 (2012)

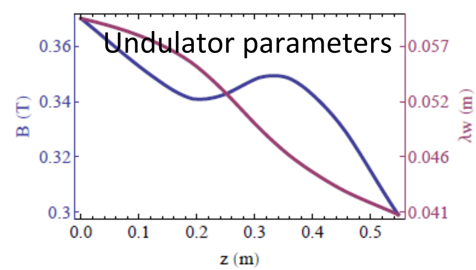
NOCIBUR IFEL deceleration experiment

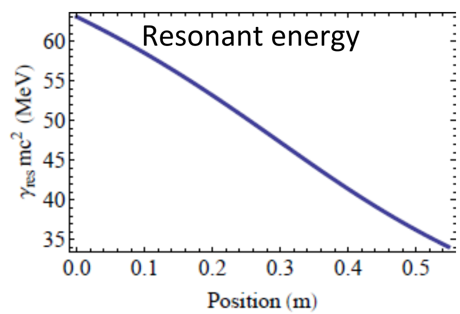
- Use RUBICON IFEL set up in reverse at BNL ATF
- Reversed and retapered the 0.5 m undulator for high gradient deceleration
- Demonstrated >30% efficiency from a relativistic electron beam in half a meter



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







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

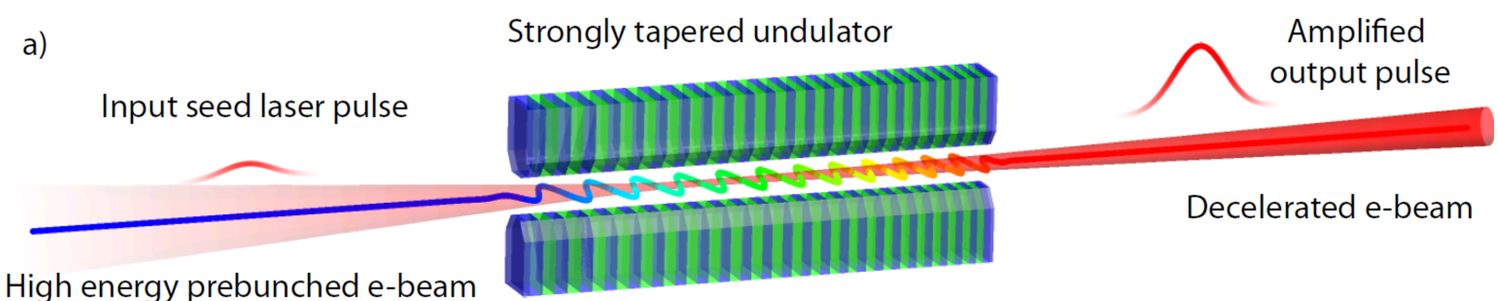
High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

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**
  - Gradient matching to exploit the growing radiation field

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

a)



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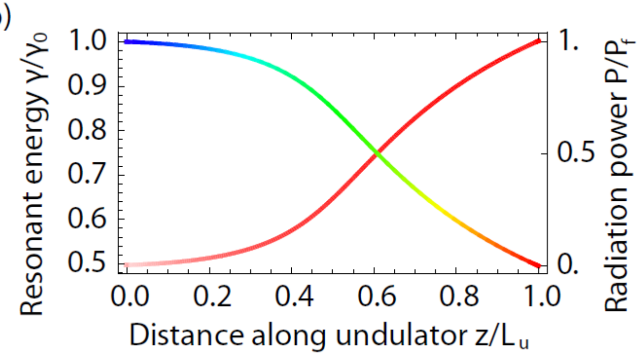
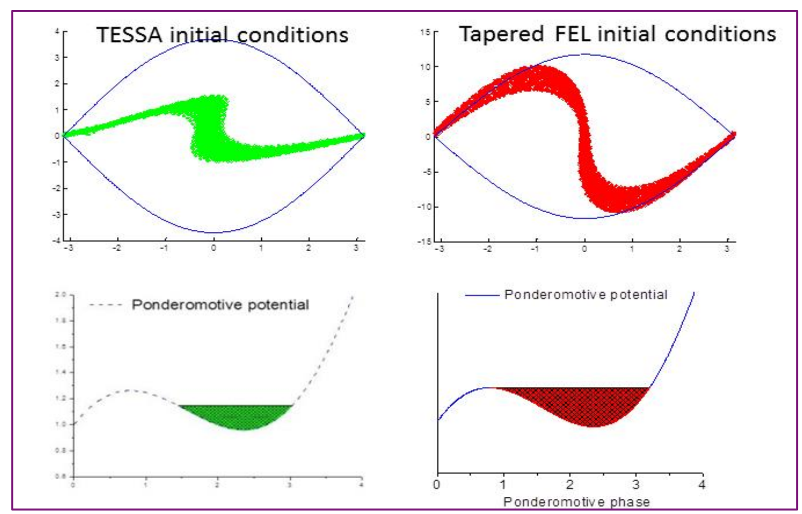




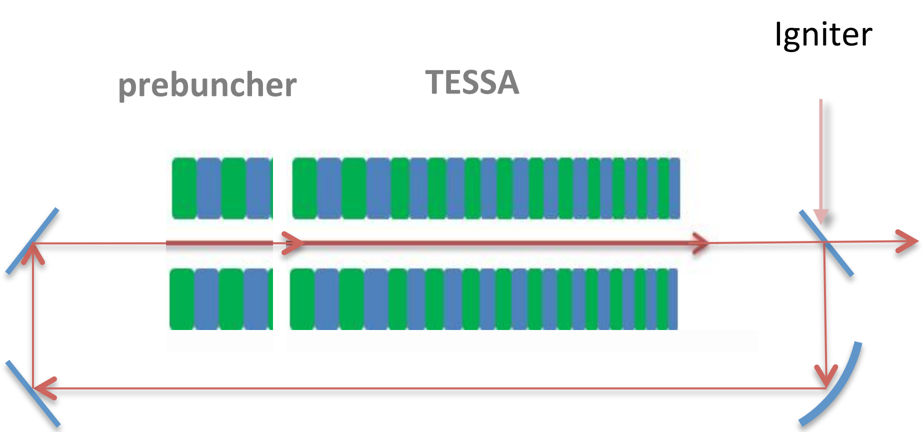
J. Duris et al. New Journal of Physics, 17 (2015)

TESSA in conjunction with high rep-rate electron beams

>30% efficiency * high average power e-beams
=> high peak **AND** average power laser

- Where to get the high repetition rate high intensity seed pulse?
- Oscillator configuration
  - Starting from noise : start-up analysis
  - Ramp-up undulator tapering
  - **Starting from igniter pulse**

    Ignition Feedback Regenerative Amplifier (IFRA) (Zholents et al. Proc. SPIE'98).

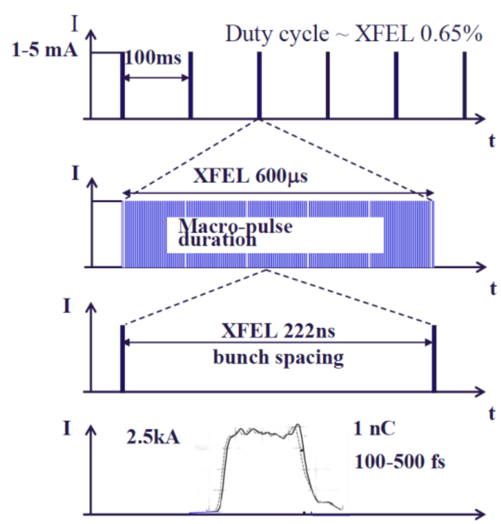


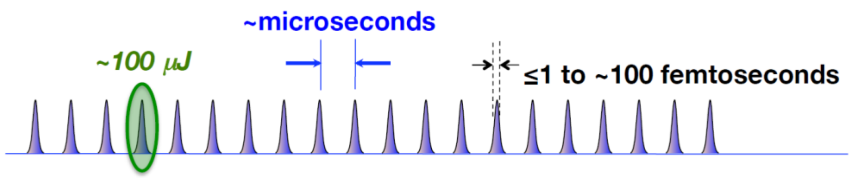
TESSO. J. Duris et al.
Under review in PRAB
arXiv:1704.05030v2

High average power electron beams

	XFEL	LCLS2	FAST
Bunch charge	1 nC	200 pC	1 nC
Bunch spacing	200 ns	1 us	>10 ns
Bunch train duration	600 us	CW	1 ms
Reprate	10 Hz	1 MHz	5 Hz
Transverse emittance	1 mm-mrad	0.5 mm-mrad	1-100 mm-mrad
Bunch length	100 fs	40 fs	1 ps
Beam energy	17.5 GeV	8 GeV	300 MeV
Peak power	30 TW	20 TW	300 GW
Average beam power	**500 kW**	**1 MW**	**300 kW**

- Repetition rate
- Macro-pulse
- Bunch
- Slice



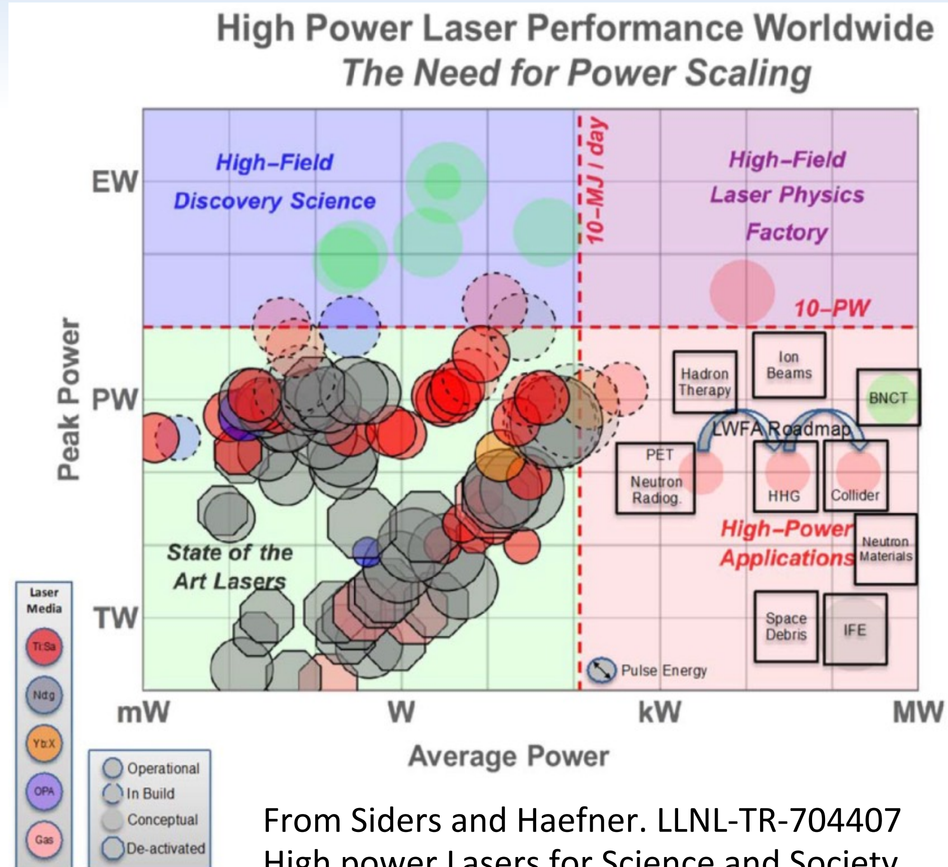


Applications

- Power beaming – 1 um wavelength
  - Deorbit burning of space debris
  - Boosting satellites to higher orbit
  - MW average power, pulse format ?
- EUV Lithography – 13.5 nm wavelength
  - >10 kW average power

- Laser acceleration (see next talk from A. Murokh)

- Longer wavelength (THz?)

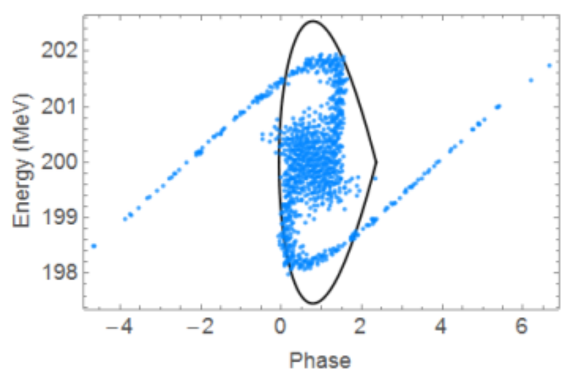


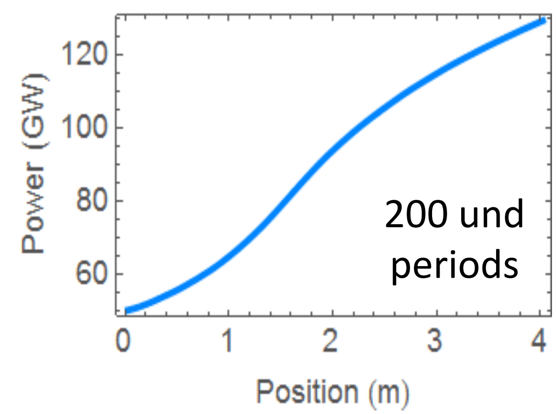
From Siders and Haefner. LLNL-TR-704407
High power Lasers for Science and Society.

High power 1 μm oscillator design

Parameter	Value
E-beam energy	250 MeV
Current	500 A
Charge	1 nC
Emittance	1 μm
Repetition rate	1 MHz
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%
Average power	**120 kW**

- 250 MeV * 500 A = 125 GW peak beam power
- 250 MeV * 1 mA = 250 kW average beam power
- Seed laser power is 50 GW (40% of beam power)
- Diffraction of stimulated radiation limits undulator length to 4 m to keep gap small
- Prebunching to capture more (nearly all) charge increases net efficiency to 50%



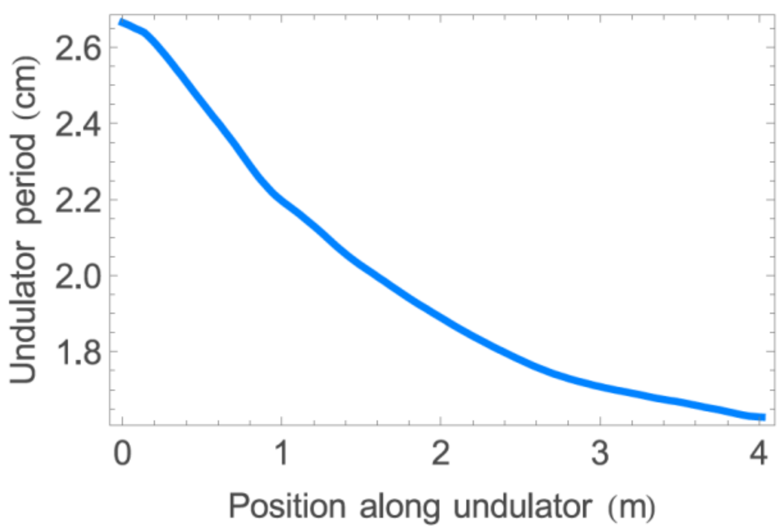


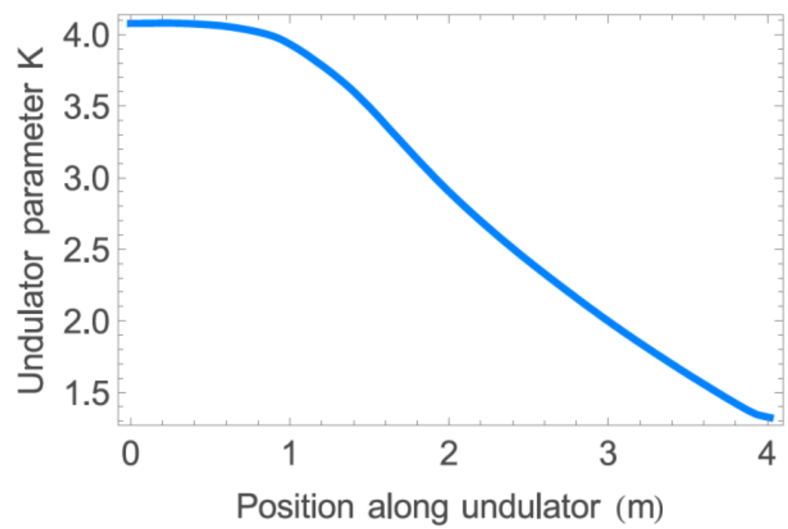
TESSO undulator

Helical geometry

Tapering both period and amplitude to maximize efficiency

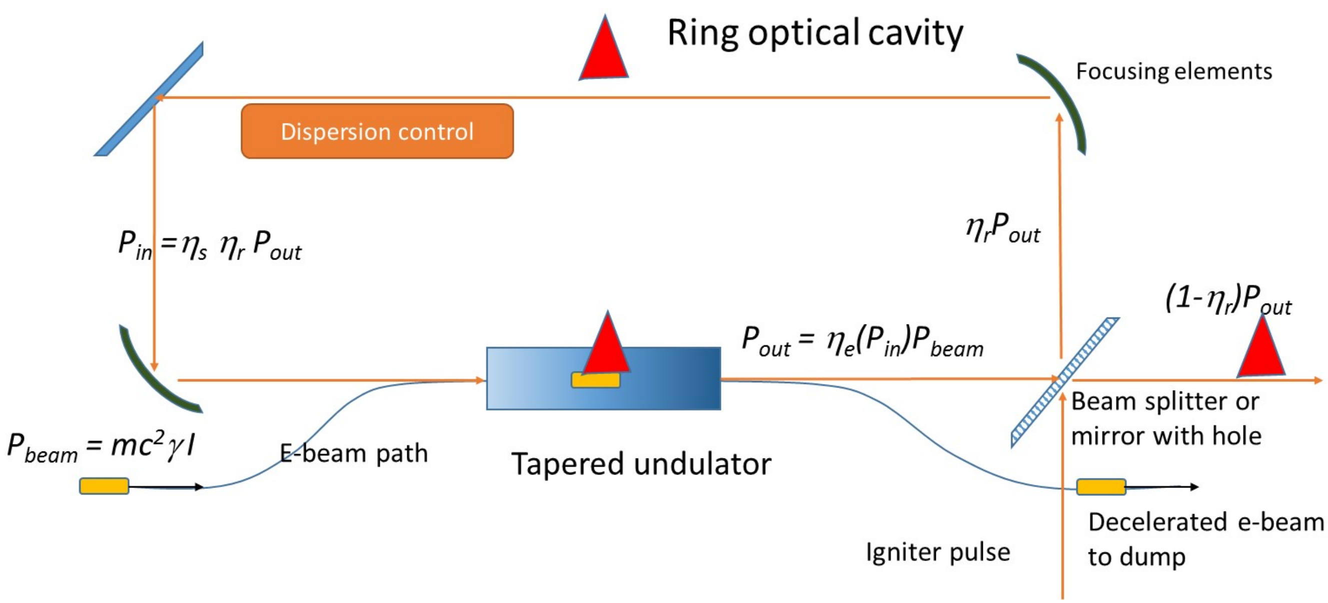
Parameters consistent with Halbach permanent magnet undulator technology with 5 mm gap





Oscillator cavity design

- Assuming LCLS2-like 1 MHz injector c / 1 MHz = 300 m
- Calculate steady state efficiency (input power dependent).
- Analyze stable resonator design using two spherical mirrors and a beam splitter for outcoupling.
- Intensity on optics → spot size → cavity length → rep rate

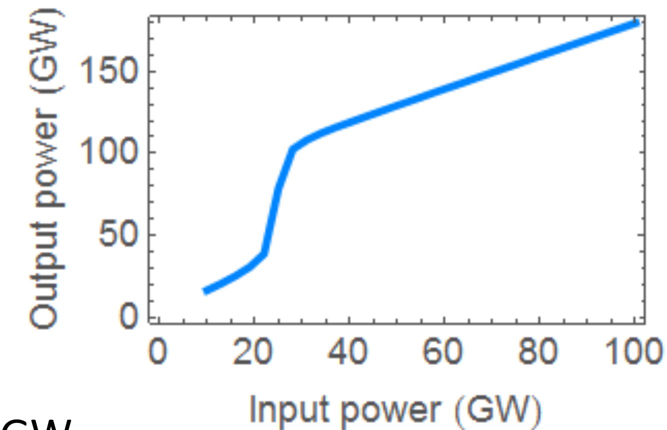


Impose that at steady state the recirculated power is constant

Interestingly, if one computes the total amount of output energy $N_{ph} \approx \alpha\ N_e^2$

Simulation model of oscillator

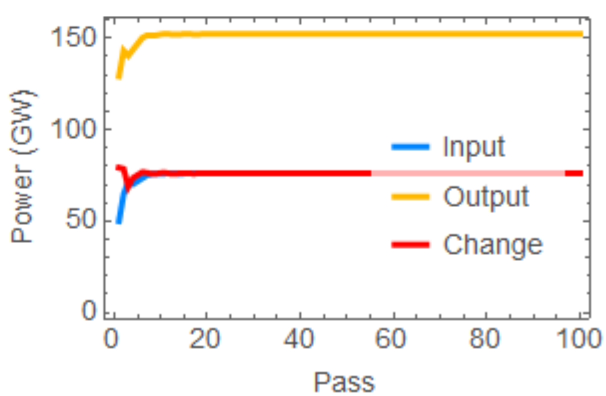
- Use field propagator + GENESIS to simulate multi-pass in cavity
- Optimize output coupler / return fraction



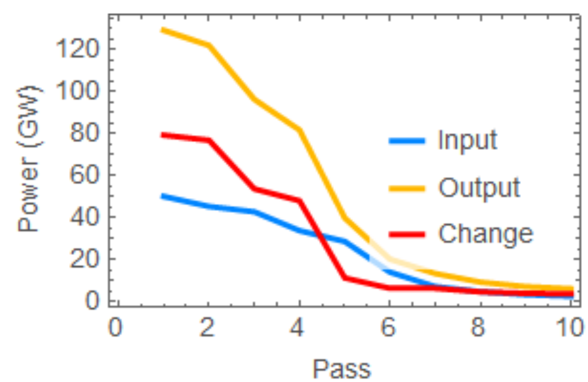
Steady state response function of tapered undulator

Assume first seed pulse 50 GW

50% return fraction



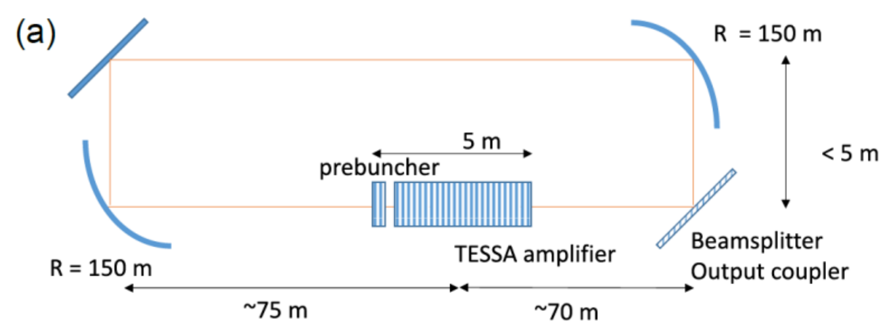
35% return fraction

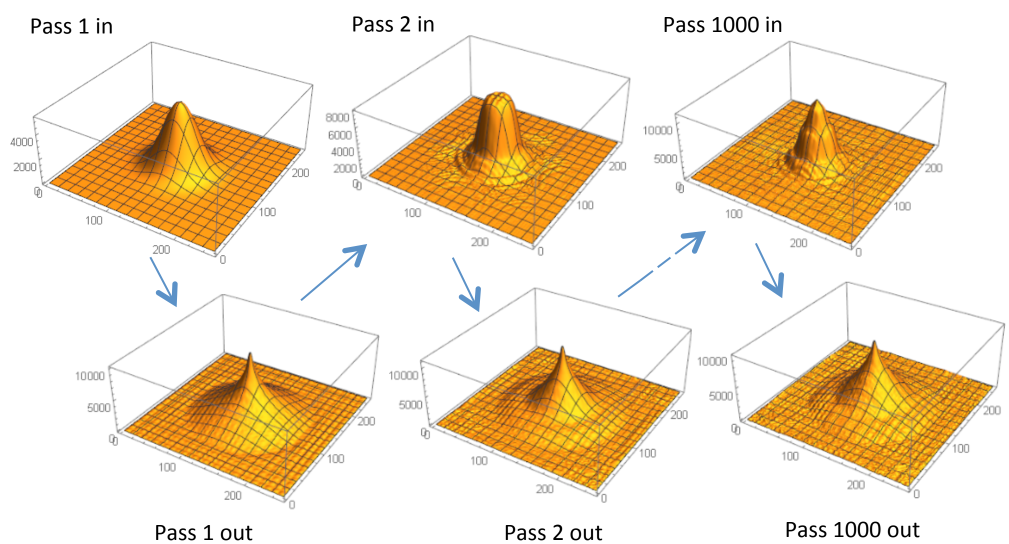


76 GW output coupled / extracted
96% of power generated in first pass

Full 3D simulations
Transverse mode quality

- Loop Genesis simulations + numerical radiation propagation (Huygens integral method)
- Output converges to steady state mode in a few passes



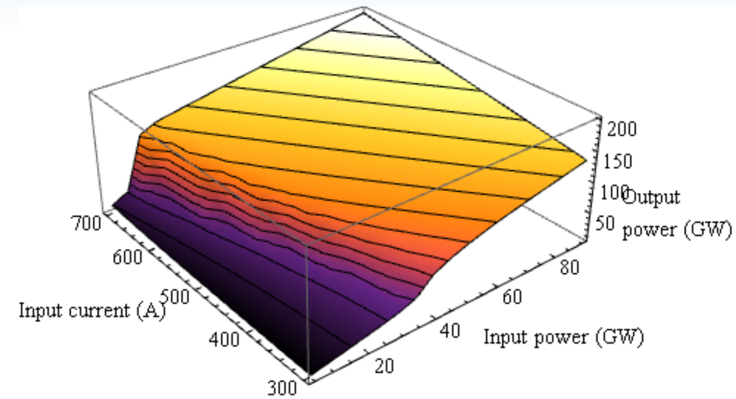


- Mode quality not perfect.
  - Adjust beam focusing in undulator.
- Mirrors may require cooling depending on absorption losses
  - > 1 kW/cm2 average incident intensity

E-beam current stability analysis

E-beam current will vary. How much variation can the design tolerate?

- Investigate with combined current and power map (assuming output radiation mode is same as seed)
- Randomly draw subsequent currents from a normal distribution

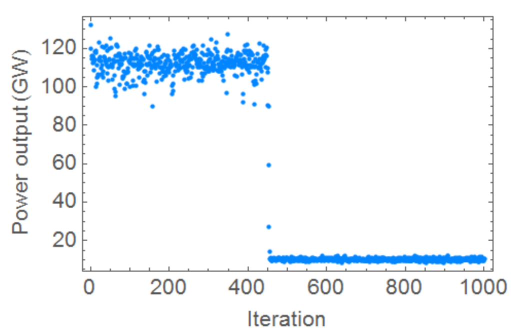


For 5% rms current fluctuations:

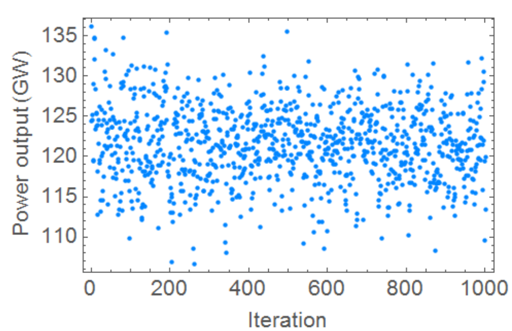
- stable operation with > 40% return

Average output after 1000 passes of 100 oscillators

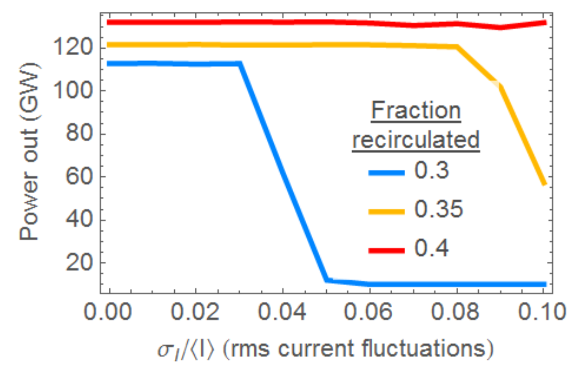
35% power return



40% power return



5% rms current fluctuations



More resilient with increased cavity power

Slippage effects

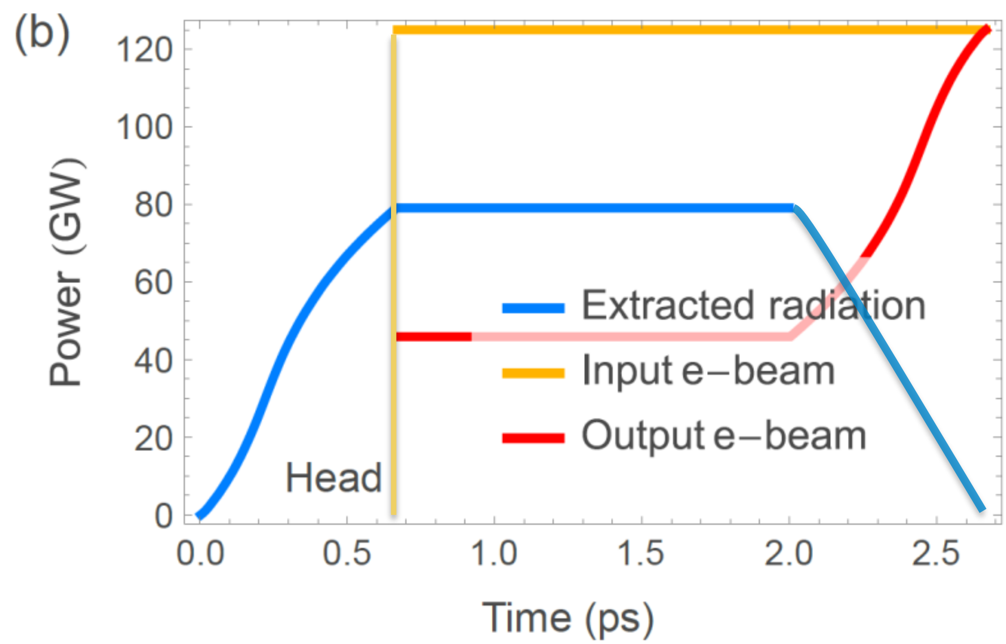
For flat-top electron current distribution

Consider pulse propagation
200 periods @ 3 fs = 600 fs

Need to re-stretch output pulse to fully cover electron beam before next pass

Absorption / dispersion filter

30 % losses taken into account in efficiency calculation



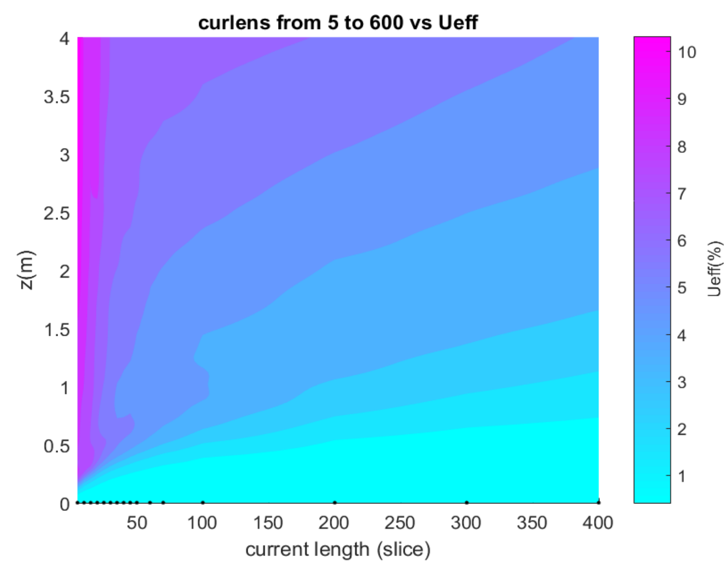
In the oscillator study bunch length was set by 500 A max current achievable with high rep-rate linac at 250 – 300 MeV energy, but....

Aside: What happens as we increase the compression ratio of the beam before TESSA ?

- Efficiency in high gain is proportional to current, but at some point slippage will play a role.
- In exponential gain regime, the cooperation length provides a temporal scale to measure the e-beam
- In post-saturation regime, gain length is no longer a fundamental scale length for the system. Dynamics occurs on different scales: what is the relevant quantity ? Slippage in a synchrotron period, …. ?

Y. Park
TESSA-266 nm simulation study

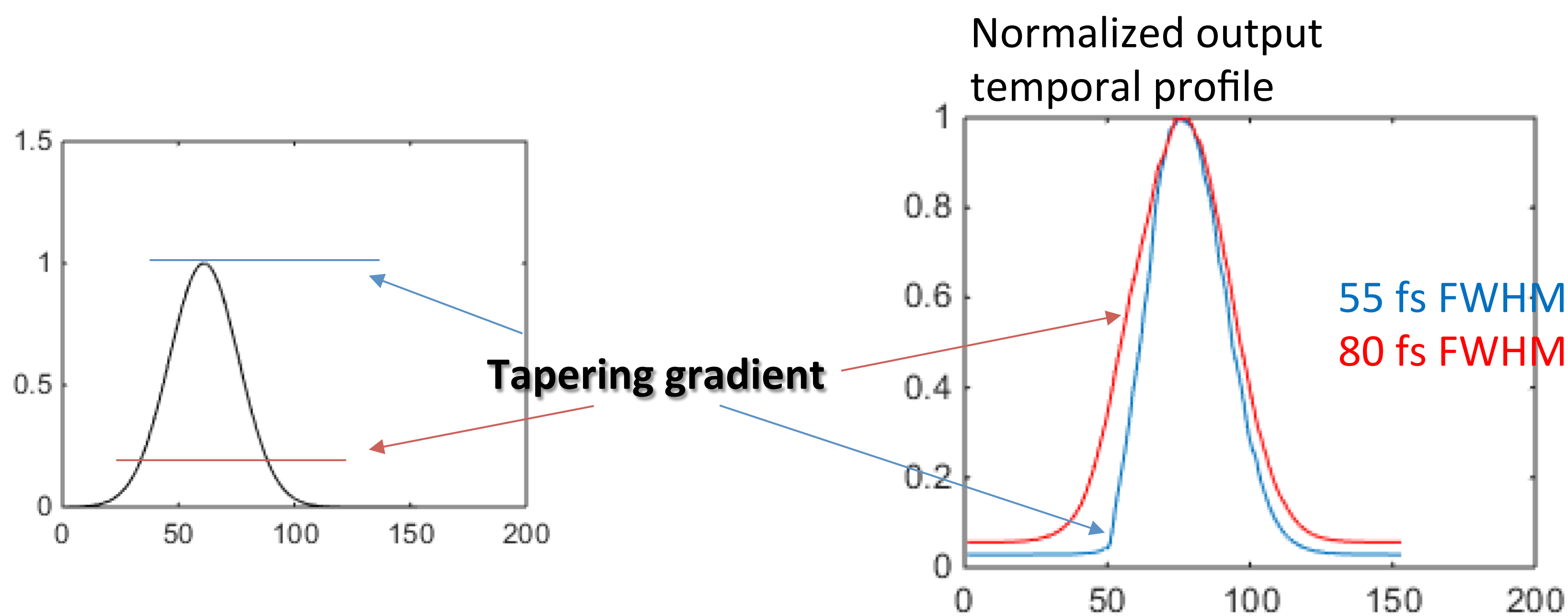
Efficiency vs. FWHM electron bunch length (constant charge)



Slippage effects in post-saturation regime

- Coupled non linear equations $\left(\frac{\partial}{\partial z} - \frac{1}{c\beta_z}(1-\beta_z)\frac{\partial}{\partial t}\right)a = \frac{k}{2}$
- The design tapering steepness can be used control trapping along the beam and therefore radiation pulse length.

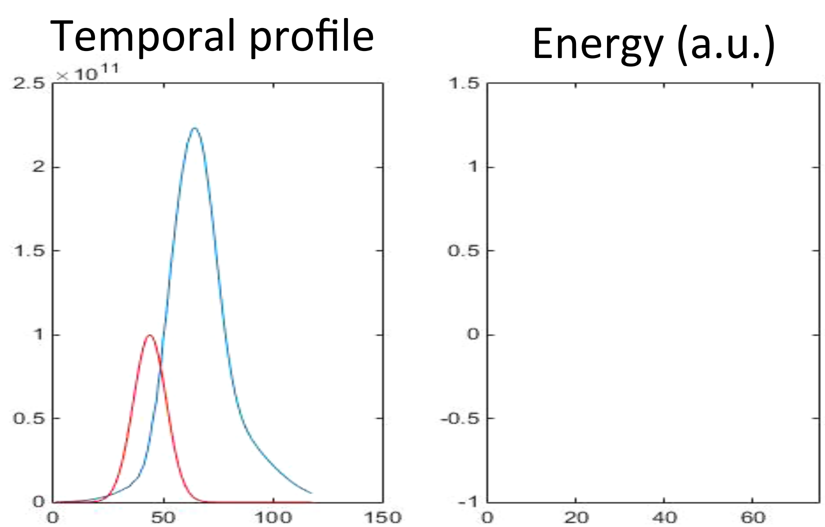
$$H = \frac{k_w \delta\gamma^2}{\gamma_r} - \frac{kKa(z,t)}{\gamma_r}\cos(\psi) + \psi\frac{\partial\gamma_r}{\partial z}$$



Perave simulation results. TESSA 266 nm parameters

Time-dependent TESSO simulation

- We can take advantage of this intrinsic pulse-lengthening to avoid the introduction of stretching/ dispersive elements in the cavity
- Note that it is still required to filter out sideband power to avoid ripple on pulse intensity
- *Perave* animation of time-dependent oscillator simulation



Conclusion

- High gradient IFEL deceleration can achieve very high electrical-to-optical energy conversion efficiency.
  - Nocibur experiment recently demonstrated 30 % energy extraction
- Exploit mature high rep-rate beam technology for high peak power + high average power lasers
- TESSA in an oscillator configuration (TESSO) has potential for > 50% efficiency for high average power light sources
- Many issues to consider such as
  - Dispersion control in cavity
  - Mirrors and stretcher optics may require cooling
  - Sidebands build up over hundreds of passes
  - Startup from smaller seed power (ramp up undulator field)