Tapering Enhanced Stimulated Superradiant Amplifier

IFEL decelerator

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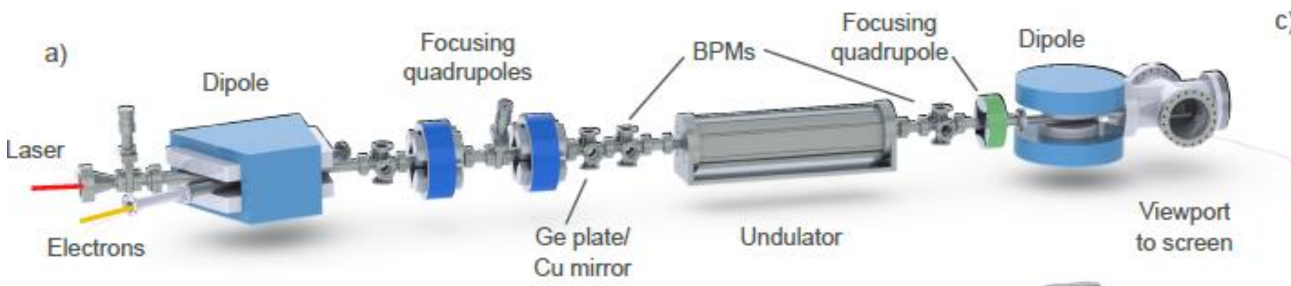
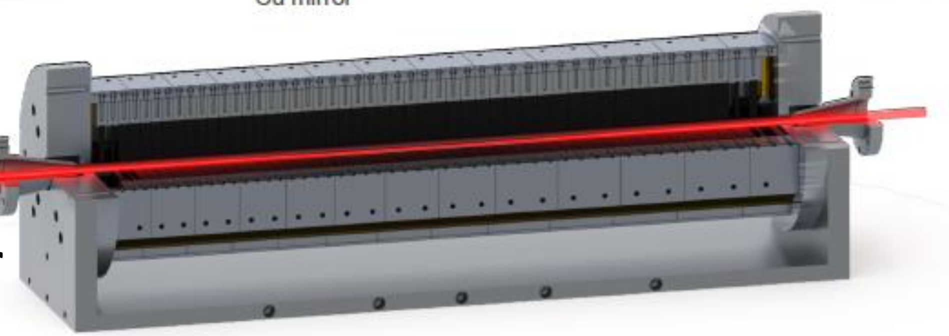
Outline

- IFEL background
- Tapering Enhanced Stimulated Superradiant amplifier
- Low gain regime
- High gain regime
- Few case studies
  - 10.6 micron proof of principle experiment at ATF
  - X-rays amplification at LCLS
- Conclusion

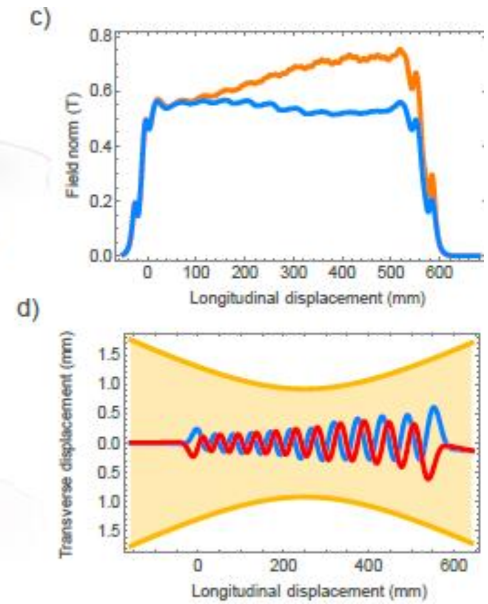
Inverse FEL Background

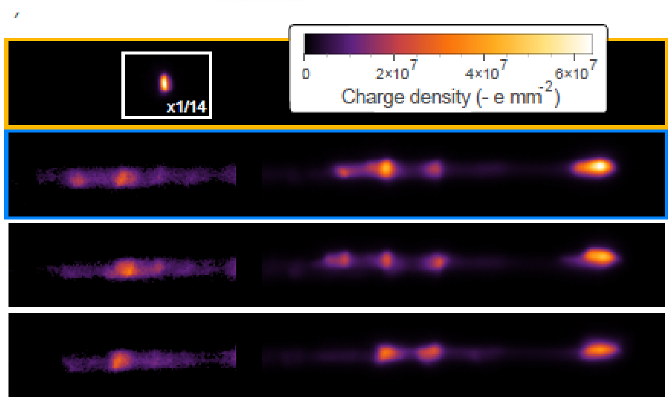
- Rubicon IFEL experiment recently demonstrated high quality acceleration of 50 MeV e-beam at BNL ATF in a strongly tapered helical undulator

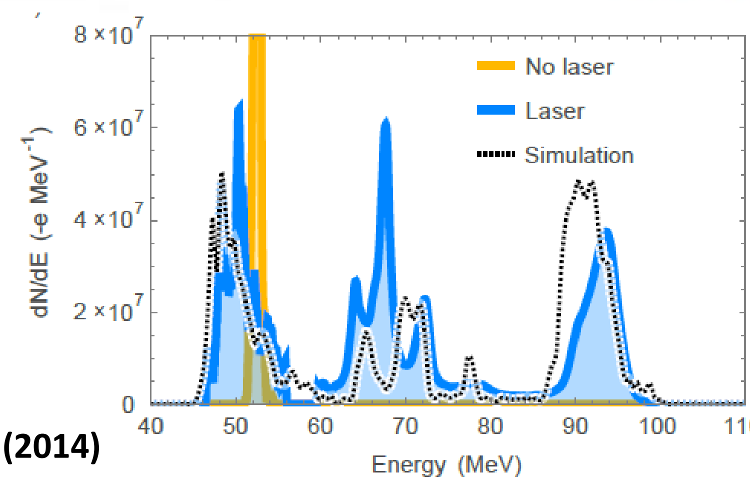




100 MeV/m
11 periods
0.5 m undulator







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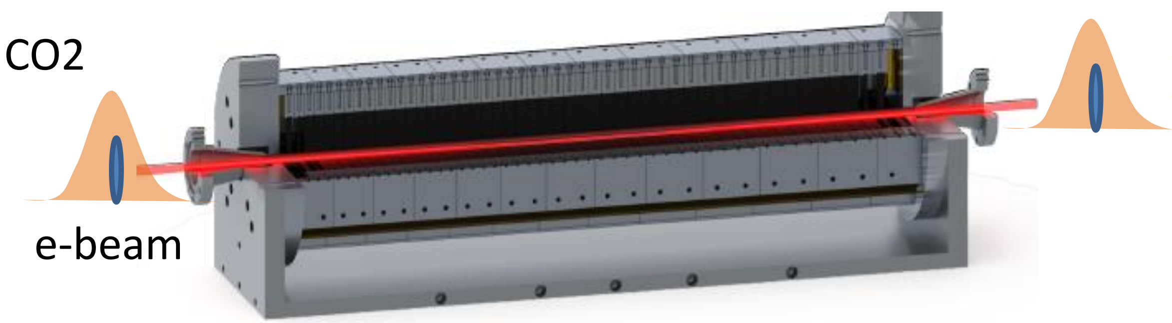
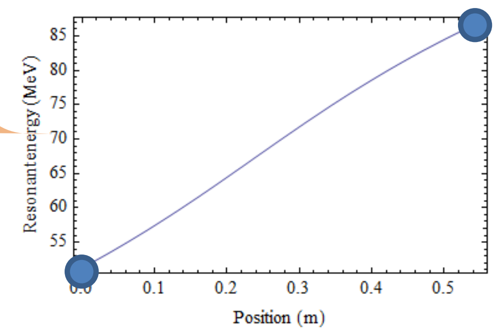
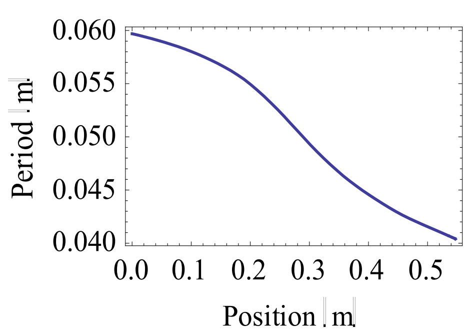
What happens if we do the same experiment in reverse ?

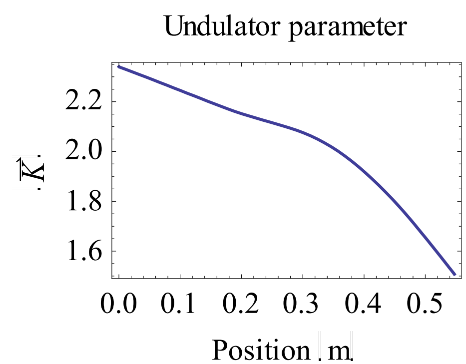
- 10.3 um-driven IFEL decelerator.
- Decelerate 90 MeV to 50 MeV using 100 GW input power.
- Potentially demonstrate ~40 % (!!!) energy extraction from a relativistic electron beam
- For comparison, FEL's typically get efficiencies of ~0.1%

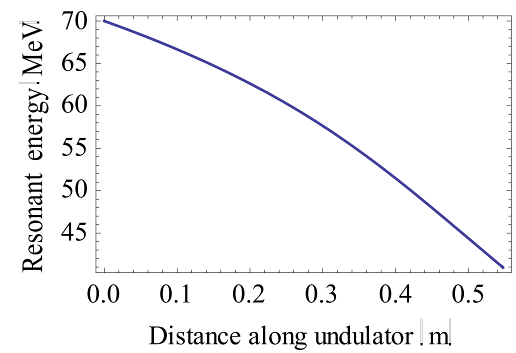




Slight re-tuning of the undulator since ATF max energy after compression is < 70 MeV



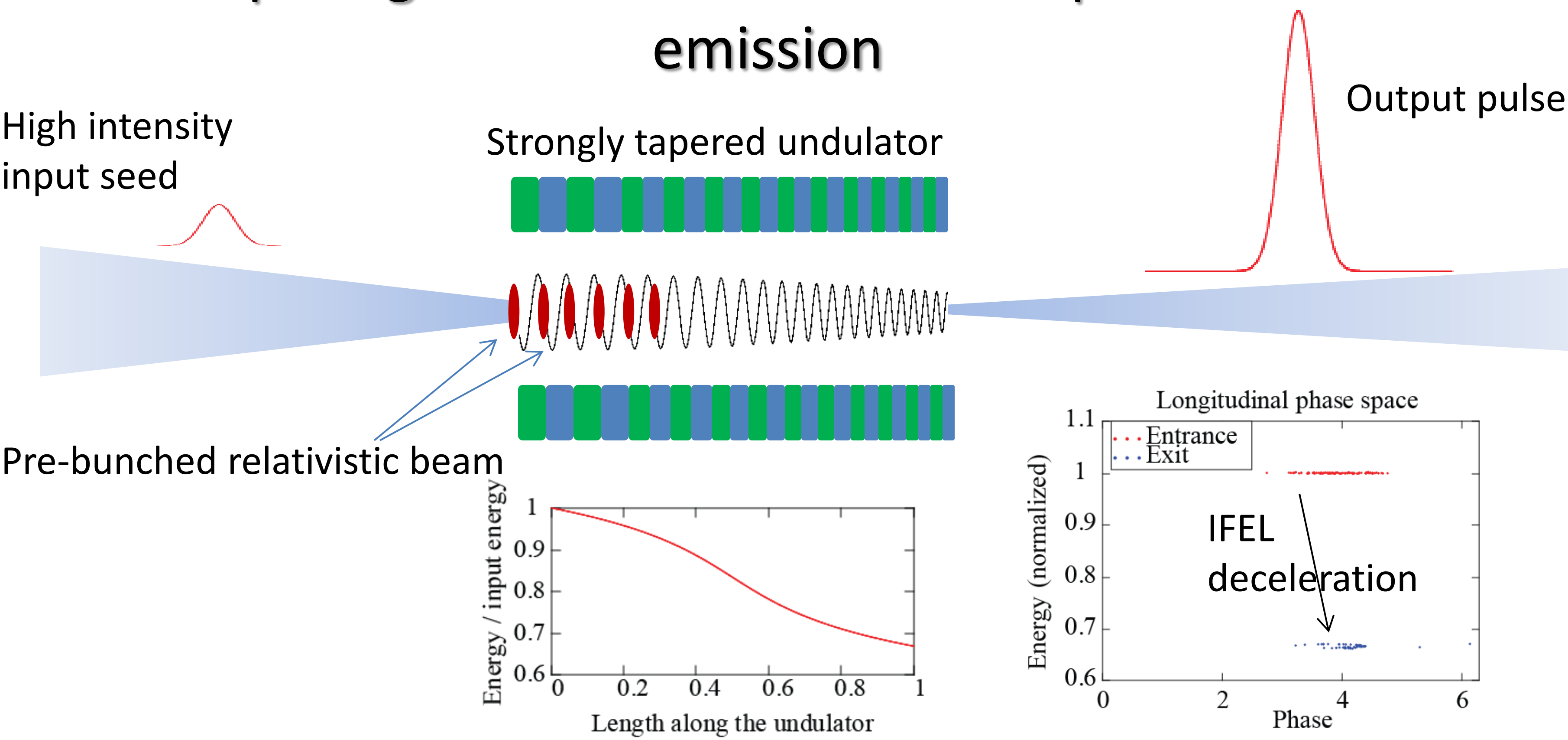




TESSA concept

- Reversing the laser-acceleration process, we can extract most of the energy from an electron beam provided:
  - A microbunched input e-beam
  - An intense input seed

Tapering-Enhanced Stimulated Superradiant emission



Applications

- High efficiency conversion of electron beam energy to coherent radiation opens door to very high average power light sources.

- Wavelength set by e-beam energy and resonant condition -> wide tunability
  - High average power IR and visible lasers.
  - X-rays.
  - EUV-L applications.

- LLNL Paladin experiment in the ‘80s showed large conversion efficiency using tapered undulator and waveguide at 250 GHz

- Differences from current optimization tapering schemes for short wavelength FEL
  - Strong tapering (both period and amplitude)
  - large seed intensity - much above FEL saturation level –
  - Higher initial input energy (so that at the decelerated output energy undulator is still feasible)

TESSA theory: tapering optimization

- First approximation. Frozen field, small gain regime
  - Do not compensate for radiation emission.
  - For constant period there is an analytical solution varying only the magnetic field amplitude (larger gap, weaker permanent magnets, smaller current, etc.)
  - Varying also period allows more flexibility and might be technologically simpler.

- Optimum tapering is obtained by matching resonant energy gradient to the available ponderomotive gradient

$$\gamma_r^{\,2} = \frac{k}{2ku}(1+K^2)$$

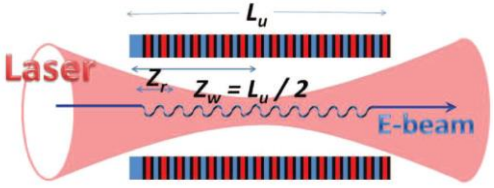
$$\frac{d\gamma_r^{\,2}}{dz} = 2kKK_l \sin\Psi_r$$

$$\frac{dK}{dz} = 2kuK_l \sin\Psi_r$$

- Efficiency proportional to number of periods and laser normalized vector potential.

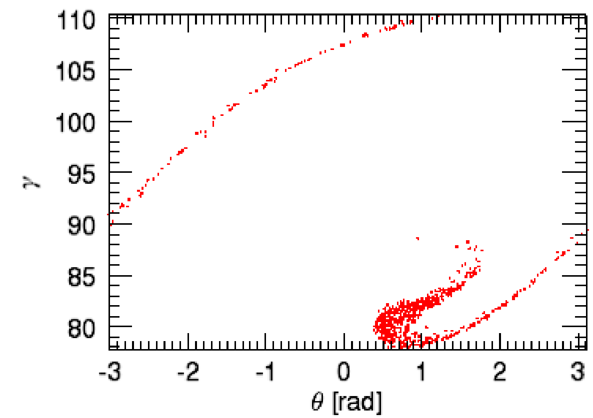
$$\eta \cong 2\pi N_u K_l \sin\psi_r$$

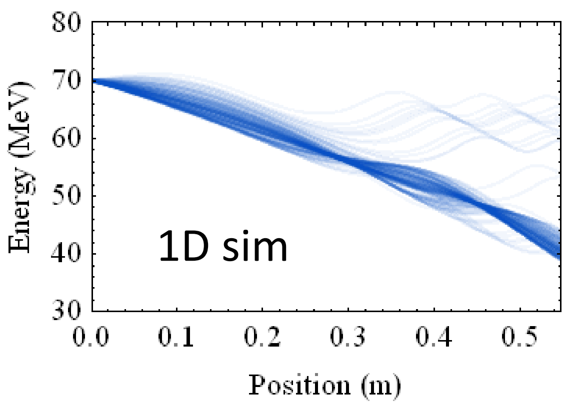
- Including diffraction
  - higher intensity smaller spot size
  - shorter interaction length longer Rayleigh range

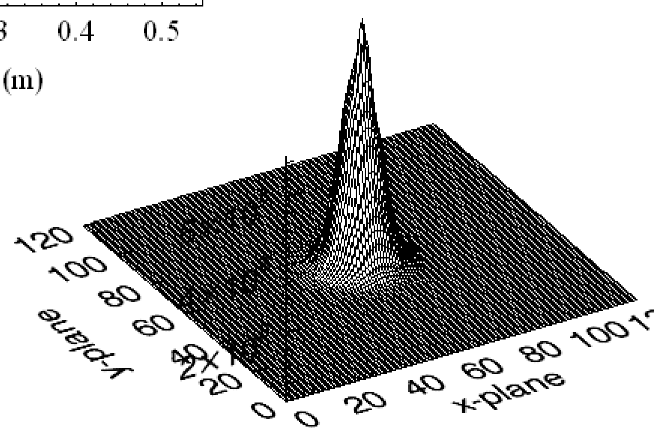


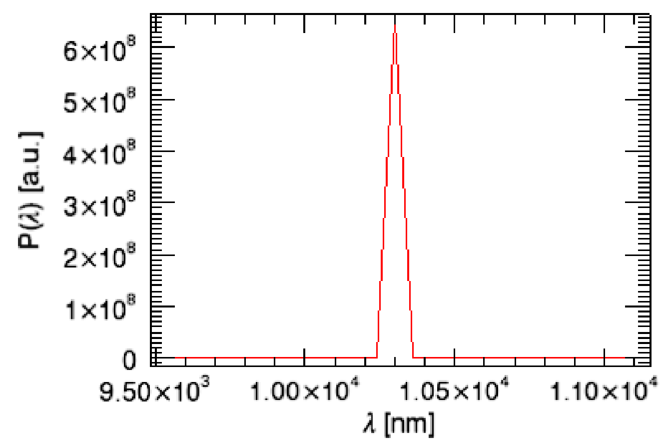
Nocibur Genesis simulation

- Input power: 100 GW
- Output power: 127 GW
- 1 kA input beam @ 70 MeV
- Decelerated to ~40 MeV



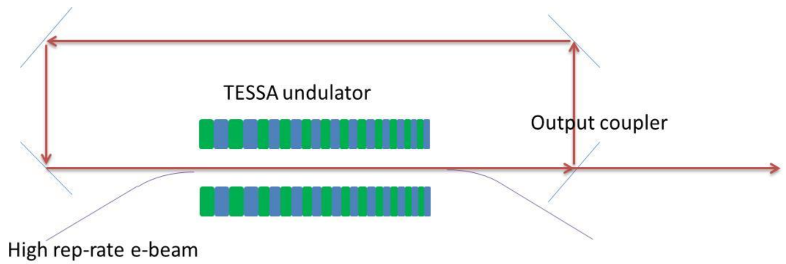




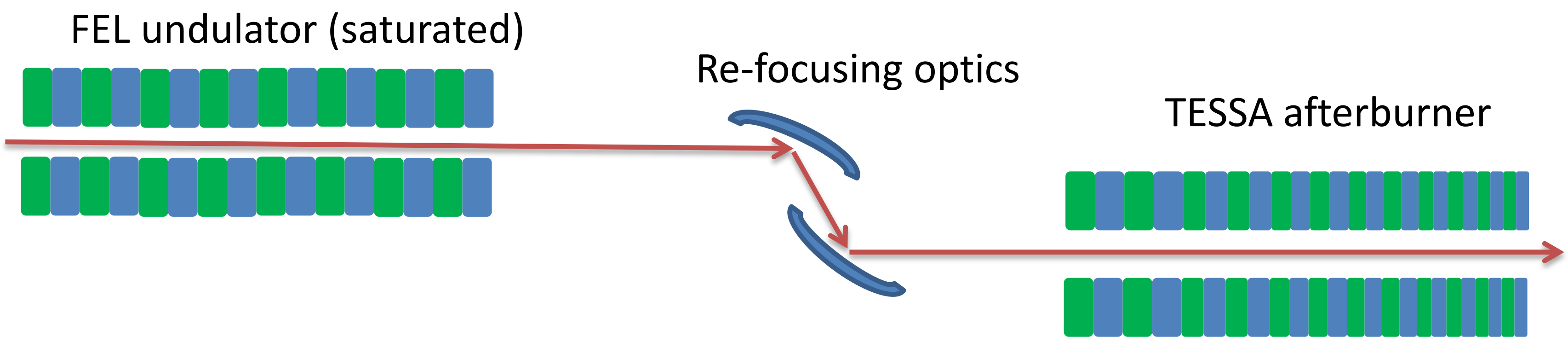


Application to short wavelengths: Where to get the high **intensity** seed?

- Oscillator configuration
  - Low gain regime
  - Build-up is complex problem
  - Could use low rep-rate igniter pulse



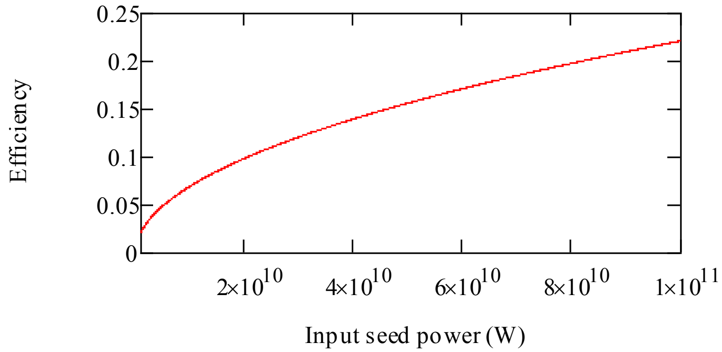
- Afterburner following FEL amplifier
  - Simpler
  - Use mirrors to refocus radiation (issues of damage on mirrors?)
  - Efficiency limited by seed power…. but



Low gain vs high gain regime

- **Low gain**
  - Neglect radiation power increase along the undulator.
  - Trapping and deceleration will work for any beam current.
  - Beam-independent efficiency.
  - Proportional to sqrt (input seed power)

$$\eta \cong 2\pi N_u K_l \sin\psi_r$$



- **High gain regime**
  - As the radiation power increases we can taper and extract energy more efficiently ! Power grows along the undulator as the particles are decelerated.
  - Tapering depends on amplitude of ponderomotive potential $\propto \sqrt{I}$
  - But some of the generated power diffracts away (3D effects)
  - How to optimize?

High Gain TESSA
Genesis Informed Tapering optimization Scheme

Due to strong diffraction, and external seed laser, gain guiding single-mode formulas not sufficient to describe laser driving intensity

$\Rightarrow$ Solve numerically with help of 3D FEL code -- Genesis!

$$\lambda_w = \frac{8\pi K_l K \sin\psi_r}{(1+K^2)\,\lambda_w\, 2K \frac{dK}{d\lambda_w}} \qquad I_{te}K_l = \frac{e}{2\pi m c^2}\sqrt{2 Z_0 I_{crit}}\ 2 \quad 2 \quad \sigma_x^2$$

$\Rightarrow$ Genesis Informed Tapering Scheme (GITS) optimization

Solve tapering period-by-period

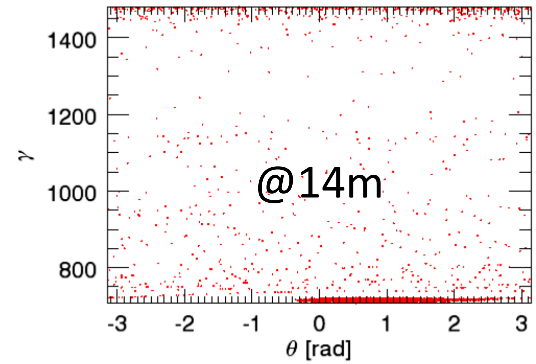
- Run Genesis on a period
- Measure min intensity seen by particles => threshold for capture
- Calculate new period and undulator parameter
- Saves tapering as well as simulated data

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

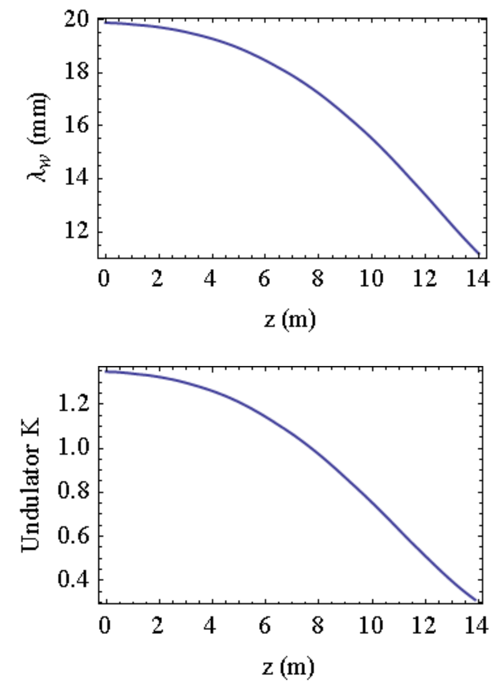
Single stage TESSA 14 m long @ 13 nm

- Input energy: **750** MeV
- Input current: 3 kA
- Gap const 7.5 mm
- Beam size 20 um (emittance 0.5 um)
- Resonant phase: 0.5 to 1.0
- Lu = 14 m,   zw = 3 m , zr=1 m

- Input power: 5 GW
- Output power: 1.0 TW (**44**% conversion)

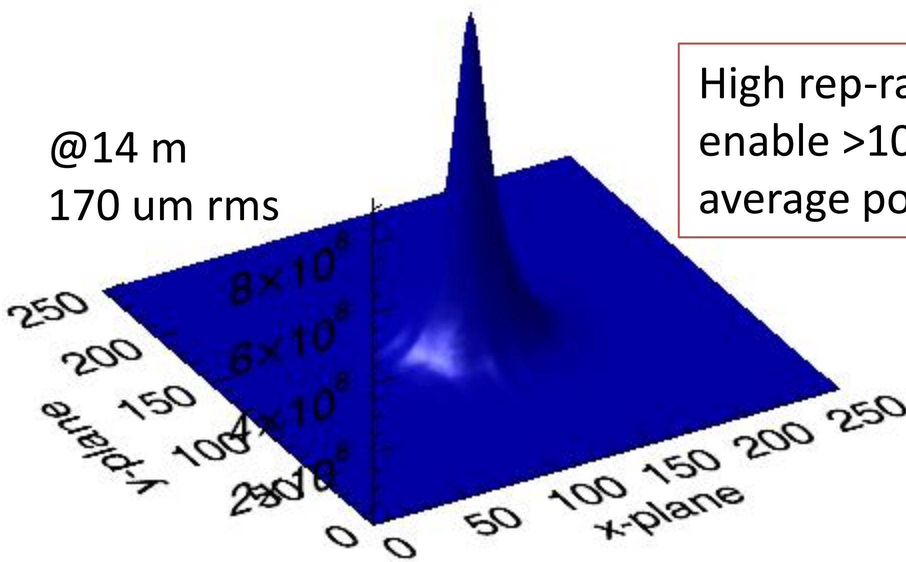


14 m optimization case



High rep-rates could enable >10kW average power EUV

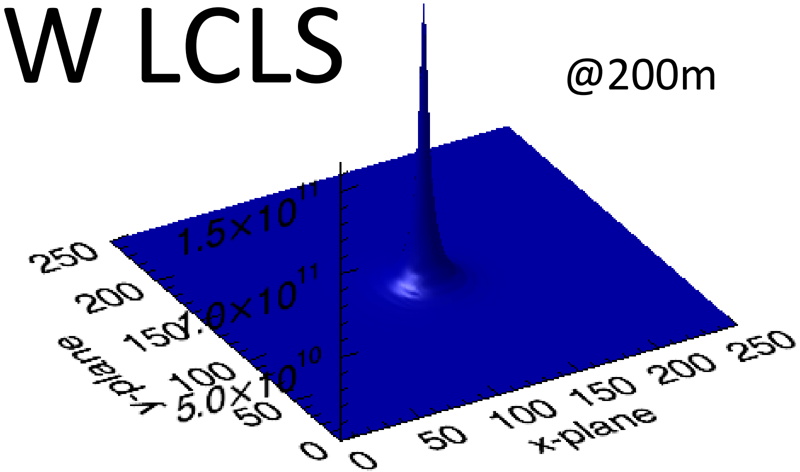
@14 m
170 um rms

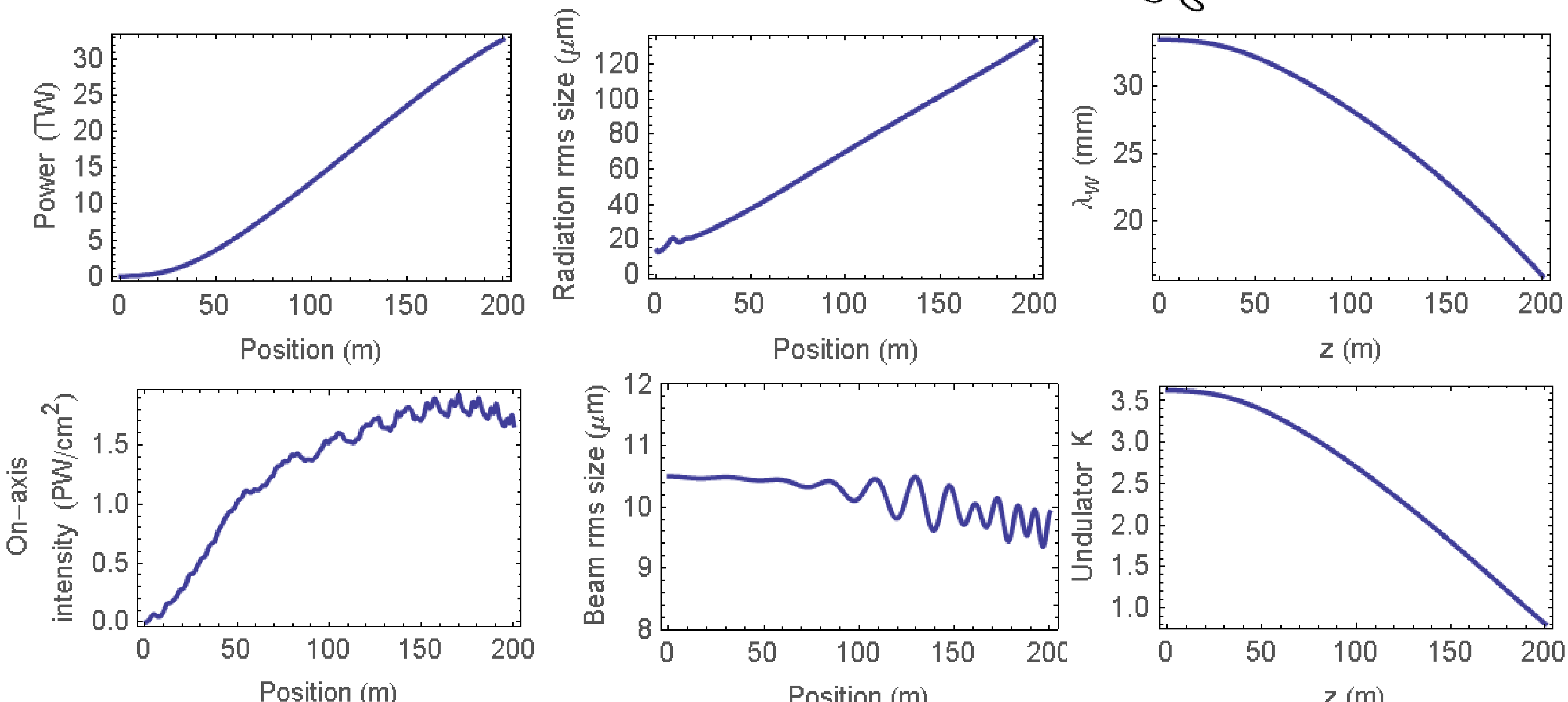


X-ray : Multi TW LCLS

- Beam: 14.35 GeV, 4 kA, and 0.3 um emittance
- Seed: 5 MW
- Realistic permanent magnet Halbach undulator (Br=1.32T)

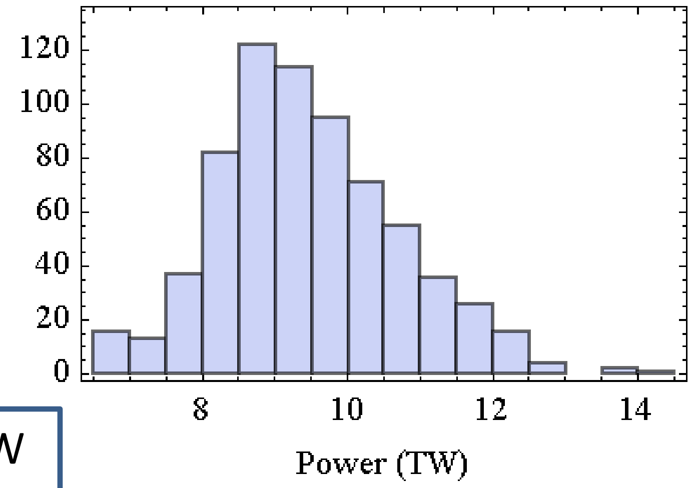
@200m

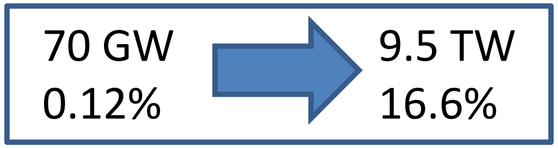


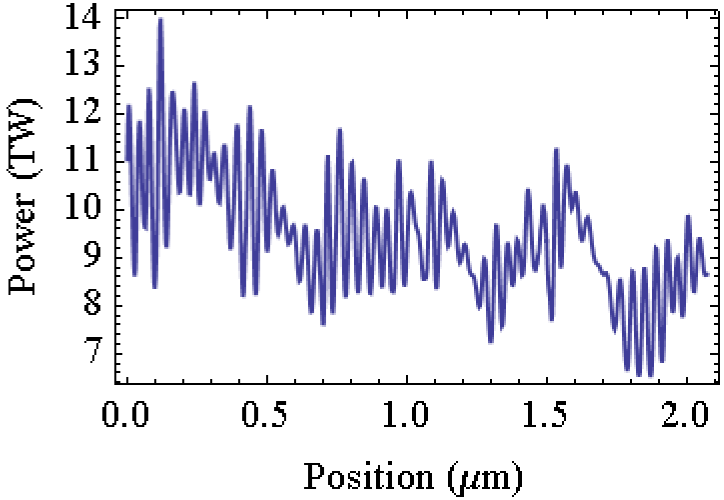


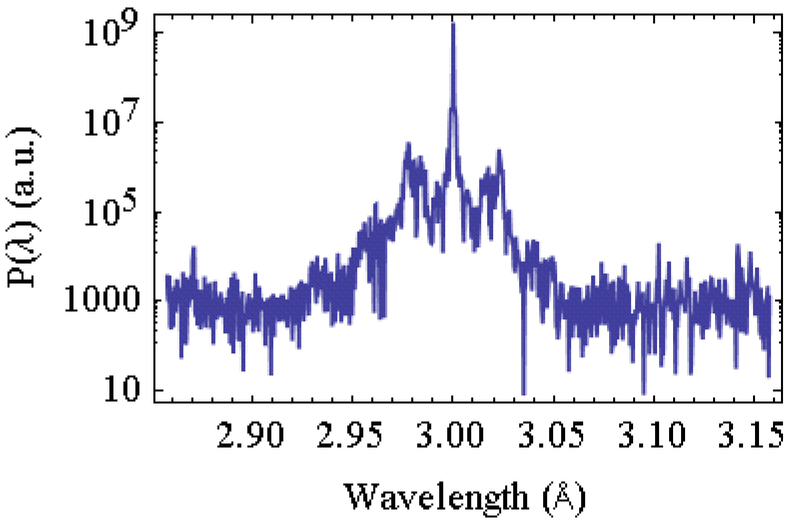
Time dependent simulation

- Optimized time dependent simulation
- Sideband instability causes particles to detrap @ ~100 m
- Peak power = 14 TW
- Mean power = 9.5 TW (16.6 % conversion)
- Final beam energy: 10.5 GeV







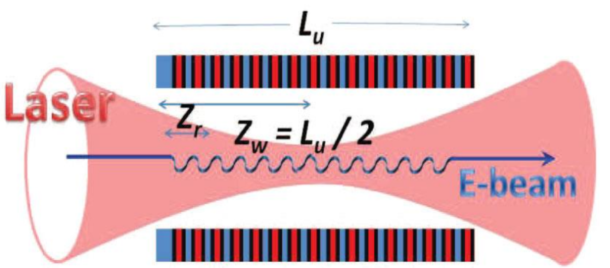


Conclusion

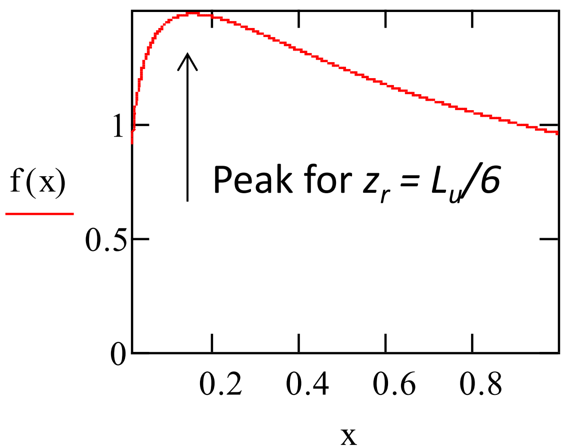
- TESSA - tapering enhanced stimulated superradiant amplifier
  - Strongly tapered helical undulator
  - Refocus FEL radiation to drive beyond FEL saturation
  - 3D simulation guided tapering
- "Nocibur" low gain demonstration at ATF will be first step.
  - Measure energy beam spectrum, CO_2 output power, mode quality, spectrum.
  - All hardware required for the experiment already in hand !
- Strongly driven system: effects of energy spread and emittance reduced compared to SASE FEL.
- Applications in various spectral ranges
- Many interesting points
  - Mirrors to refocus radiation
  - Start-up in oscillator configuration
  - Side-band supression

Efficiency estimate: Low gain regime

- Define $\eta = \frac{\gamma_0 - \gamma}{\gamma_0}$
- For constant K_l and small efficiency $\eta \cong 2\pi N_u K_l \sin\psi_r$
- Taking into account diffraction, we need to find a compromise between:
  - higher intensity smaller spot size
  - shorter interaction length longer Rayleigh range



$$\frac{\partial}{\partial z_r}\left[\int_0^{L_u} \sqrt{\frac{1}{z_r}\frac{1}{1+(\frac{z-\frac{L_u}{2}}{z_r})^2}}dz\right] = 0$$



Plug-in numbers for Nocibur

P	100 GW
λ	10.3 um
w_0	1 mm
K_l	0.016
N_u	11
η	**0.45**

Reasonable estimate !