High efficiency energy extraction from high brightness beams

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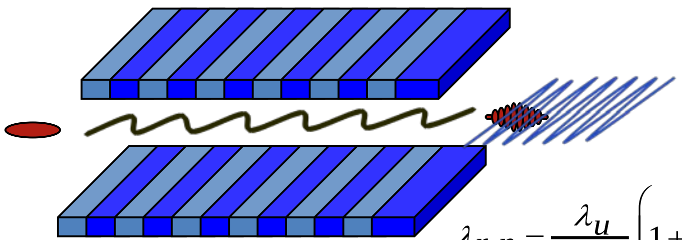
UCLA

Outline

- Background
  - Tapered FEL
  - IFEL experiments
- TESSA, estimate and limits to single pass deceleration efficiency
  - Low gain + diffraction
  - High gain 1D
- Trapping and choice of resonant phase
- Sideband instability
- TESSA experiments and roadmap
- TESSO, high efficiency oscillator
  - Igniter pulse: 1 μm. No seed: EUV
  - Recirculating cavity stability, slippage, radiation refocusing

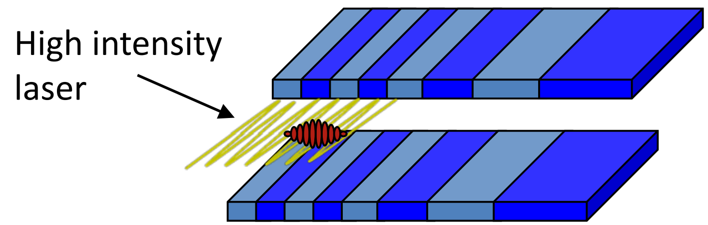
Particle acceleration // Radiation generation

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.



- “To be efficient an accelerator must be able to operate in reverse”, R. Ruth (SLAC)
- Note that one of the schemes widely discussed in AAC notably violates this principle. (LWFA)
- IFEL is on the other hand a particularly advantageous accelerator scheme in this regard
  - ***Plane wave or far field*** accelerator: minimal 3D effects. Transverse beam cross-section can be mm-size for μm-scale accelerating wavelength.
  - ***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)

Early days of FEL tapering

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

- KMR seminal paper
  - Hamiltonian model
  - Concept of resonant phase
  - Instabilities
- At that time extracting energy from e-beam was attractive to Star-Wars program
- ELF experiment circa 1985 LLNL

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

35 GHz (up to 250 GHz) waveguide FEL.
Up to 35 % efficiency
empirical optimization very close to KMR-style self-design taper
Good matching with simulations

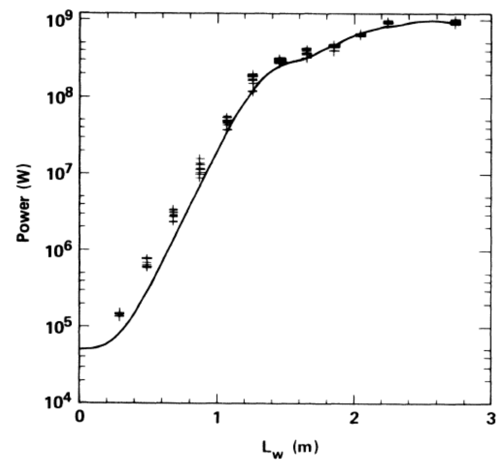


FIG. 3. Amplified signal output as a function of wiggler length for tapered wiggler field. Crosses indicate experimental values and the solid line is the results of the numerical evaluation.

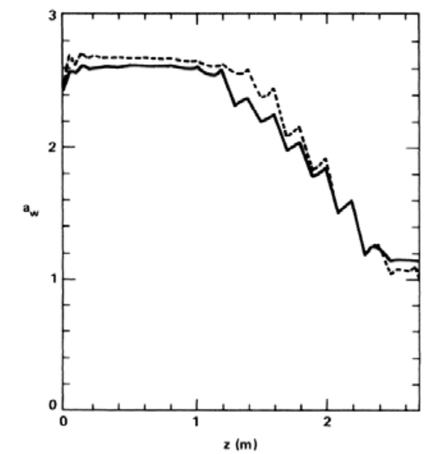


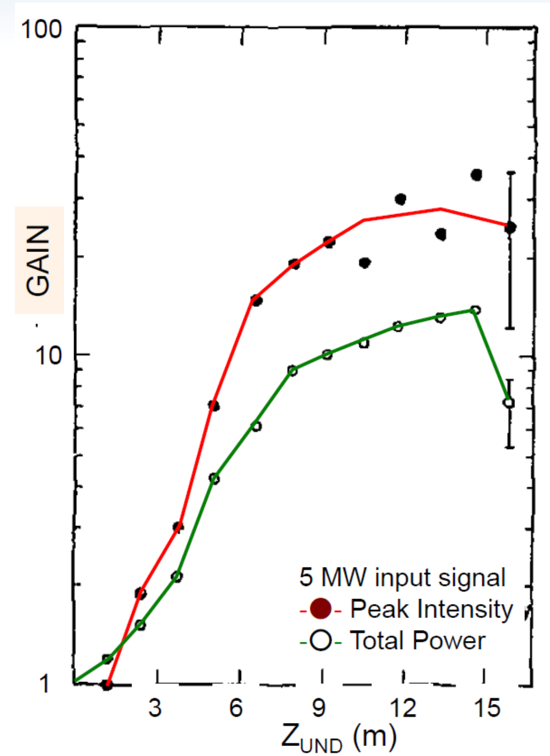
FIG. 2. Optimum wiggler field profile for tapered wiggler. The dashed line corresponds to empirical evaluation and the solid line is the numerical prediction.

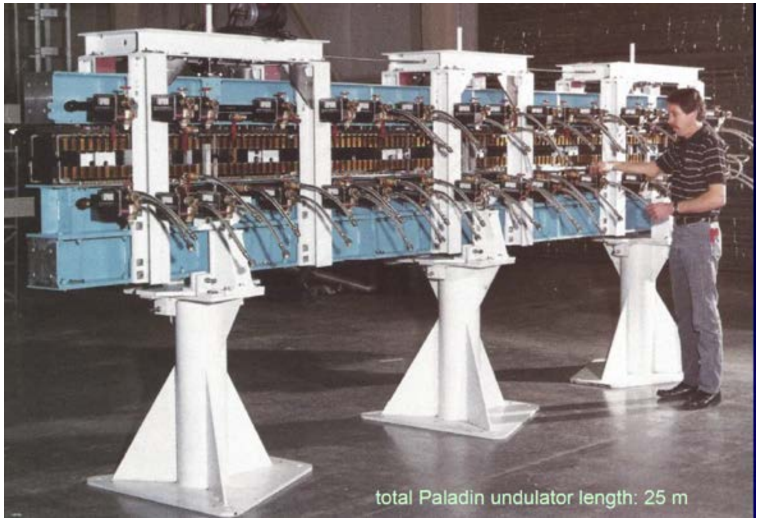
Paladin experiment

- Shorter wavelength 10 um follow up of successful ELF tests @LLNL
- Based on 45-MeV Advanced Test Accelerator

  designed for 10-kA induction linac for charged particle beam propagation experiments, not for 1-2 kA high brightness applications

- Original hope: 2+ kA & 30 dB gain relative to 5 MW seed
- Results were: 0.5 kA & 14 dB gain, saturation @12-15 m

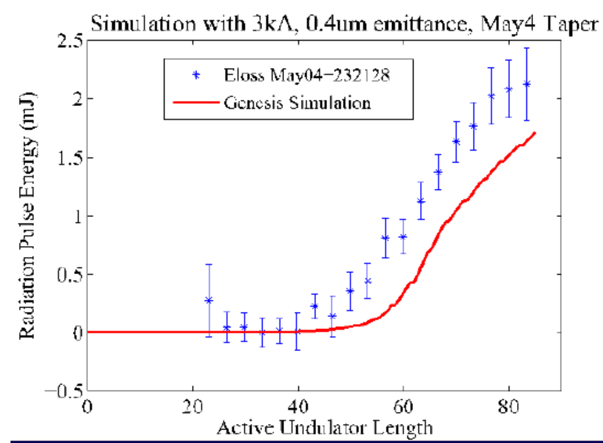




Disappointing results !
Insufficient beam brightness

Renewed interest from the FEL community in tapering in 2010s

- Reverse tapering + chirped beam for single spike generation
- Mostly driven by TeraWatt XFEL quest
- SASE Tapering: ~3X output pulse energy gain relative to saturation

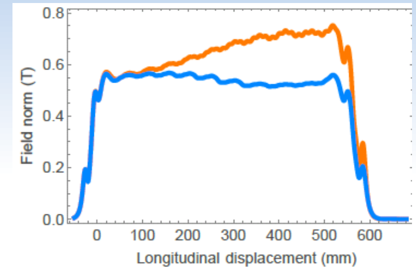


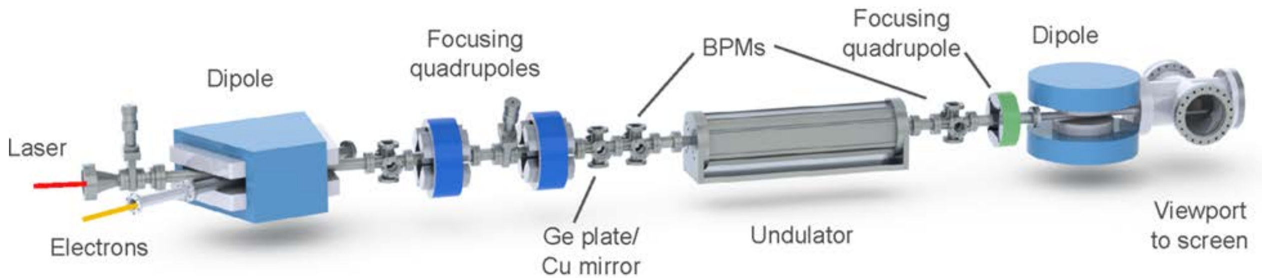
- Self-seeded cases
  - Jiao et al. (2011+/SLAC)
  - Mak-Curbis-Werin (2014+/Lund)
  - Schneidmiller&Yurkov (2014+/DESY)
  - C. Emma & C. Pellegrini (2015-2016:UCLA/SLAC)

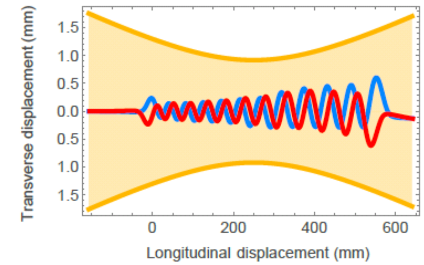
Always starting from exponential gain initial conditions
No discussion of sidebands !

Rubicon IFEL experiment

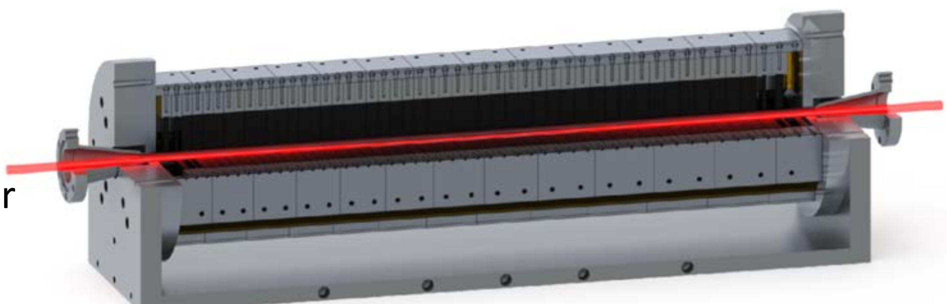
- Rubicon IFEL experiment demonstrated high quality acceleration of a 50 MeV e-beam at BNL ATF in a strongly tapered helical undulator



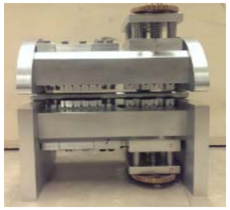




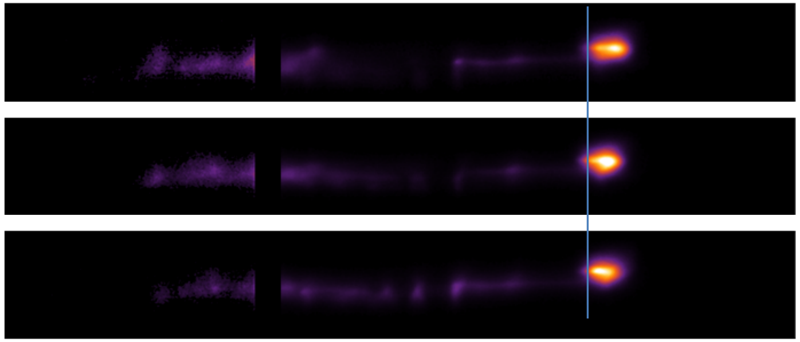
100 MeV/m
11 periods
0.5 m undulator
300 GW CO2 laser

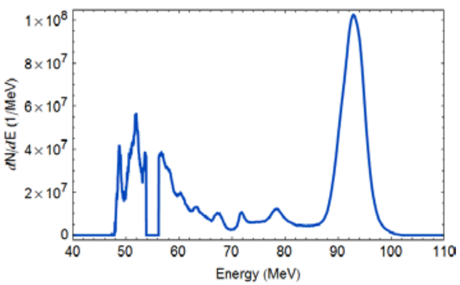


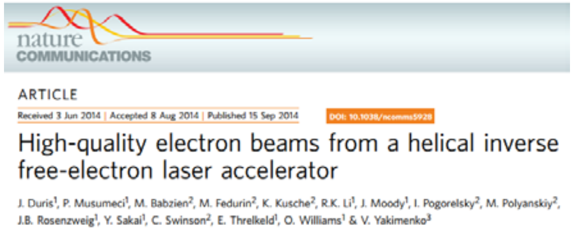
93-100 MeV peak (tunable)
< 2 % energy spread
<1.5% energy jitter
Emittance preservation



Prebuncher






nature COMMUNICATIONS

ARTICLE

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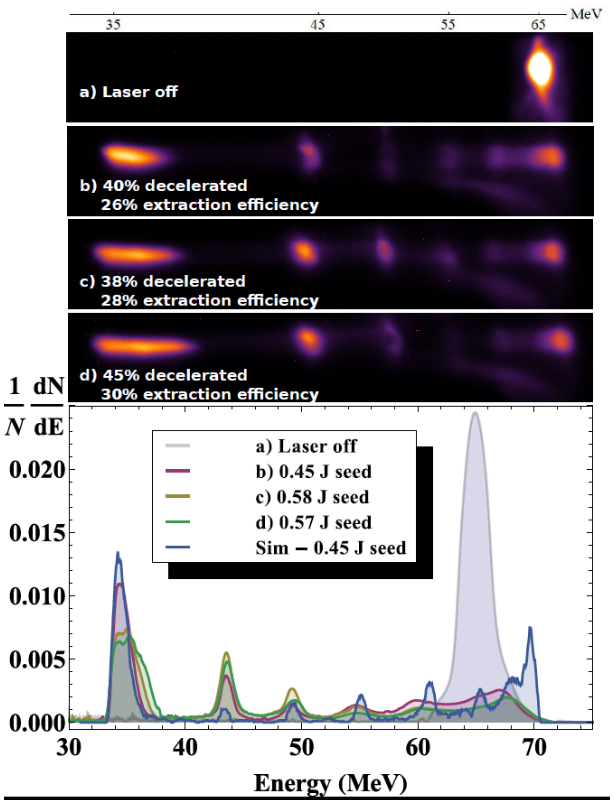
High-quality electron beams from a helical inverse free-electron laser accelerator

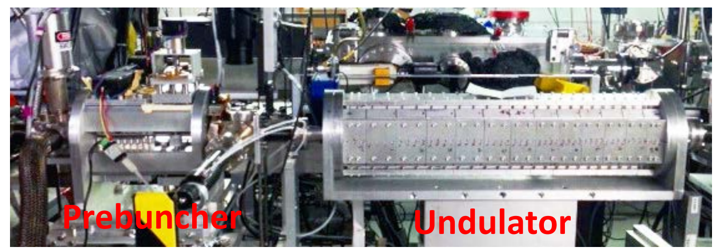
J. Duris[1], P. Musumeci[1], M. Babzien[2], M. Fedurin[2], K. Kusche[2], R.K. Li[1], J. Moody[1], I. Pogorelsky[2], M. Polyanskiy[2], J.B. Rosenzweig[1], Y. Sakai[1], C. Swinson[2], E. Threlkeld[1], O. Williams[1] & V. Yakimenko[3]

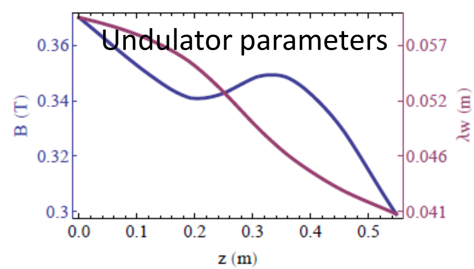
NOCIBUR IFEL deceleration experiment

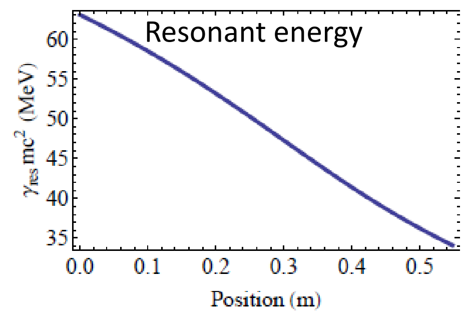
- Use RUBICON IFEL set up in reverse at BNL ATF
- Reversed and retapered the 0.5 m undulator for high gradient deceleration
- Demonstrated >30% efficiency from a relativistic electron beam in half a meter



- Maximized capture with variable gap prebuncher chicane
- Up to 45% of 100 pC beam captured and decelerated
- 30% energy extraction efficiency (2 mJ)







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

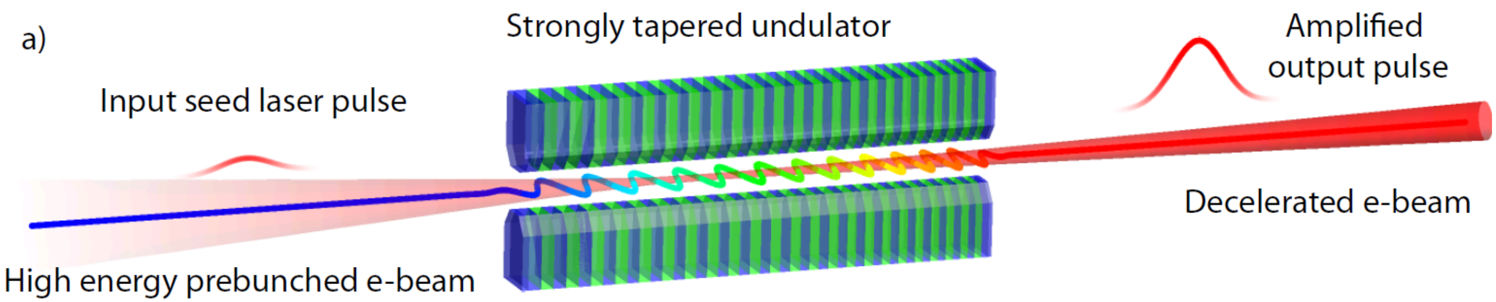
High Efficiency Energy Extraction from a Relativistic Electron Beam in a Strongly Tapered Undulator

Tapering Enhanced Stimulated Superradiant Amplification

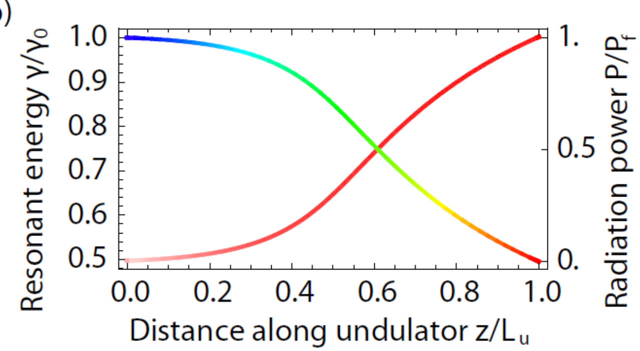
- Reversing the laser-acceleration process, we can extract a large fraction of the energy from an electron beam provided:
  - A high current, microbunched input e-beam
  - An **intense input seed**
  - Gradient matching to exploit the growing radiation field

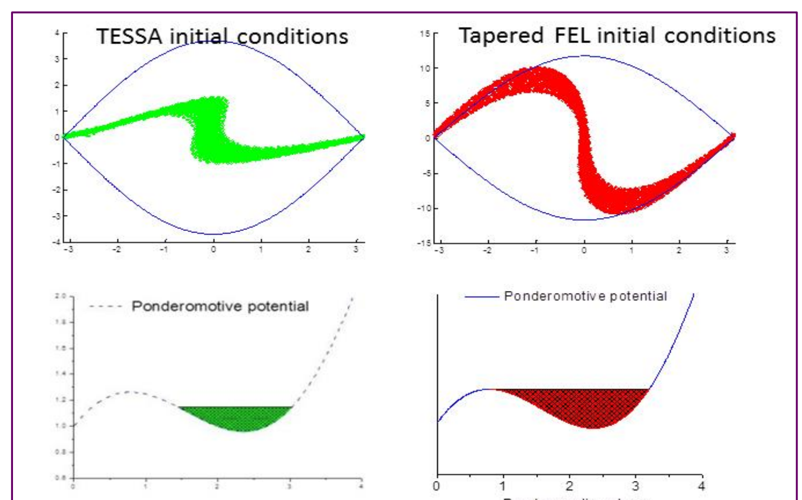
  GIT algorithm @ UCLA, but many others around (SLAC, DESY, Lund)

a)



b)





Duris et al. NJP (2015)

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Matching undulator tapering to ponderomotive gradient

From the ponderomotive interaction in an undulator with an EM wave having peak field E_0

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

From the resonance condition, assuming constant period undulator

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

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

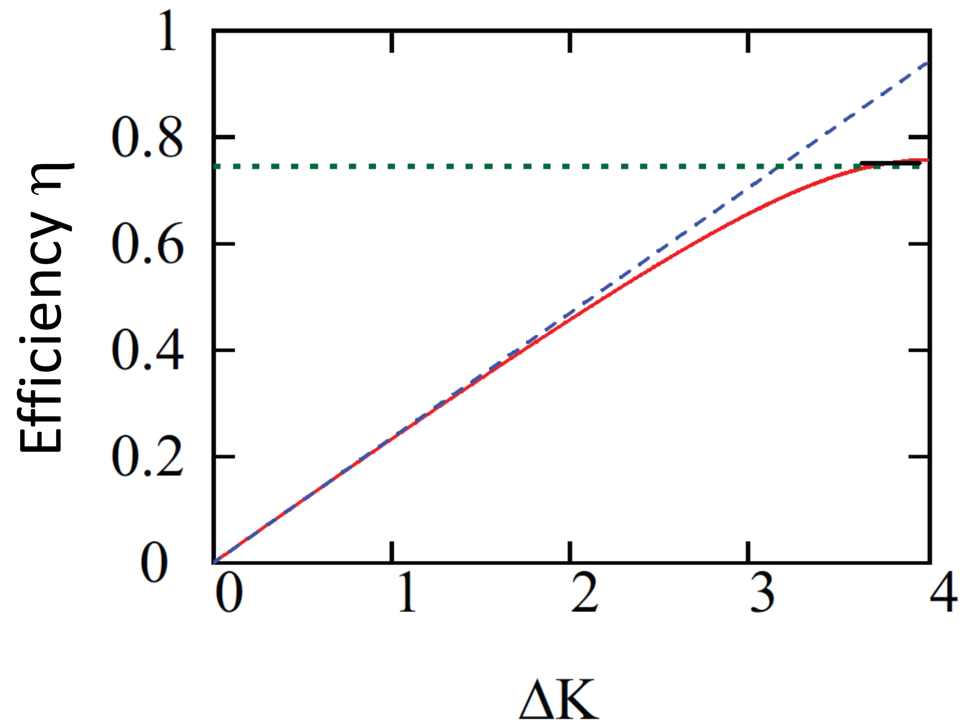
❖ Recipe to determine undulator tapering (constant period case)

- Numerical implementation.
- Allow for analytical estimates
  - Assume constant (or analytical + diffraction) field – low gain TESSA
  - Include radiation gain 1D only – high gain TESSA

Efficiency of single pass for constant undulator period

Once tapering (ΔK) is known, then efficiency is just proportional to relative energy loss of particles

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



Max efficiency

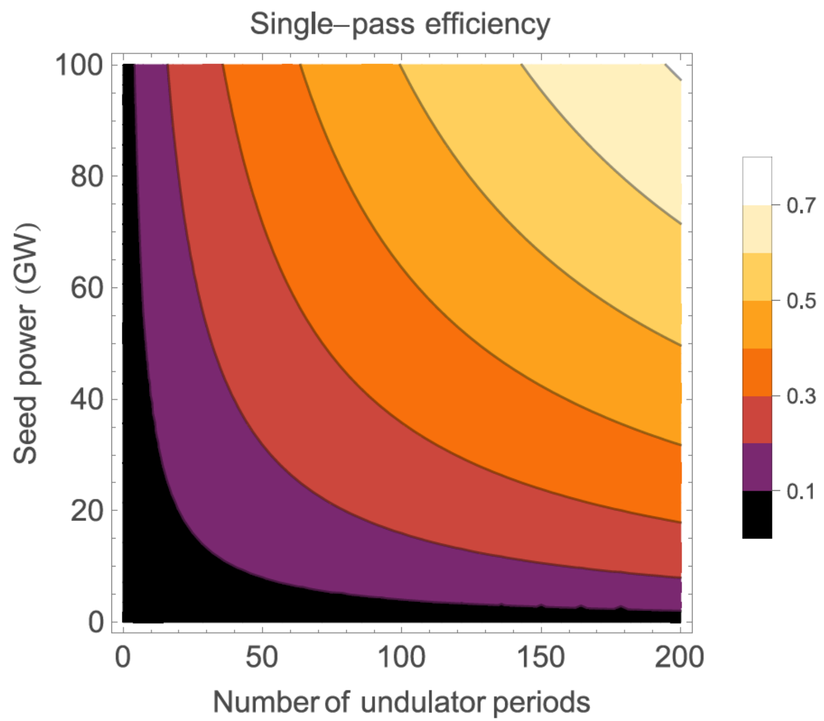
$$\eta_{max} \cong 1 - \frac{1}{K_0}$$

Low gain – Assume frozen field

Assuming constant period undulator and low gain (lower bound estimate)

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

$$\Delta K = 4\pi K_l \sin\psi_r N_w$$



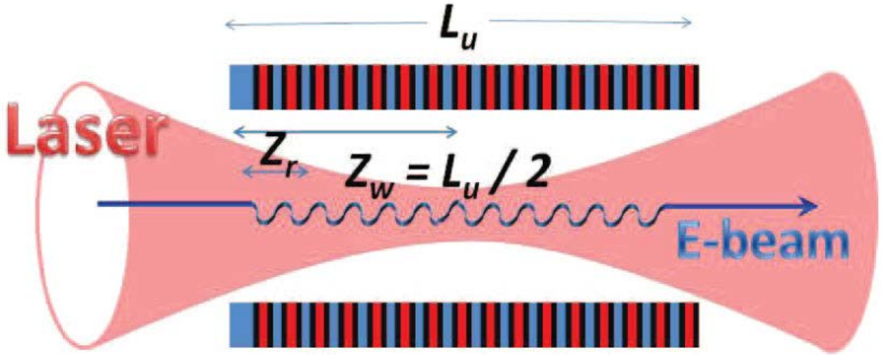
250 MeV, 1 um radiation, $K_0 = 4$

Diffraction effects

Assume Gaussian mode seed with Rayleigh range z_r
and waist in the middle of undulator

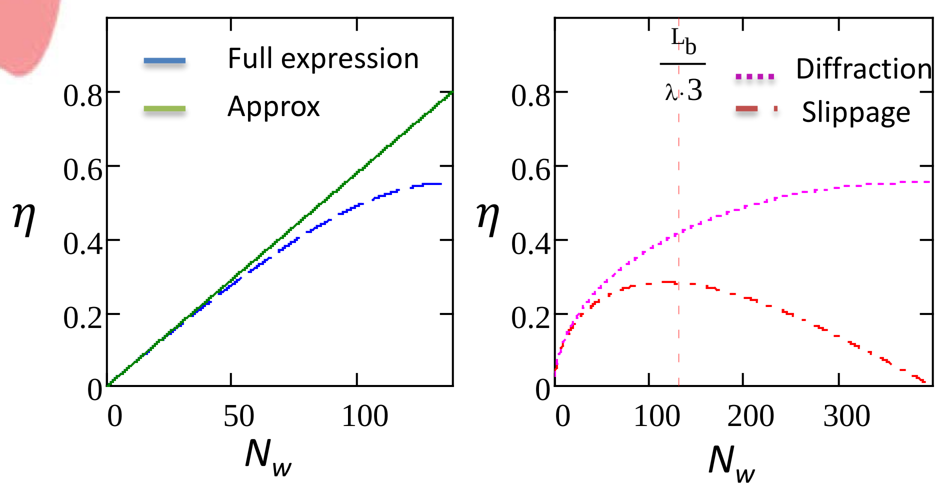
$$\Delta K = 2k_w K_{l0} \int_{-\frac{L_w}{2}}^{\frac{L_w}{2}} \frac{1}{\sqrt{1+\left(\frac{z}{z_r}\right)^2}} dz$$

$$\Delta K = 2k_w K_{l0} 2z_r \sinh^{-1}\frac{L_w}{2z_r}$$



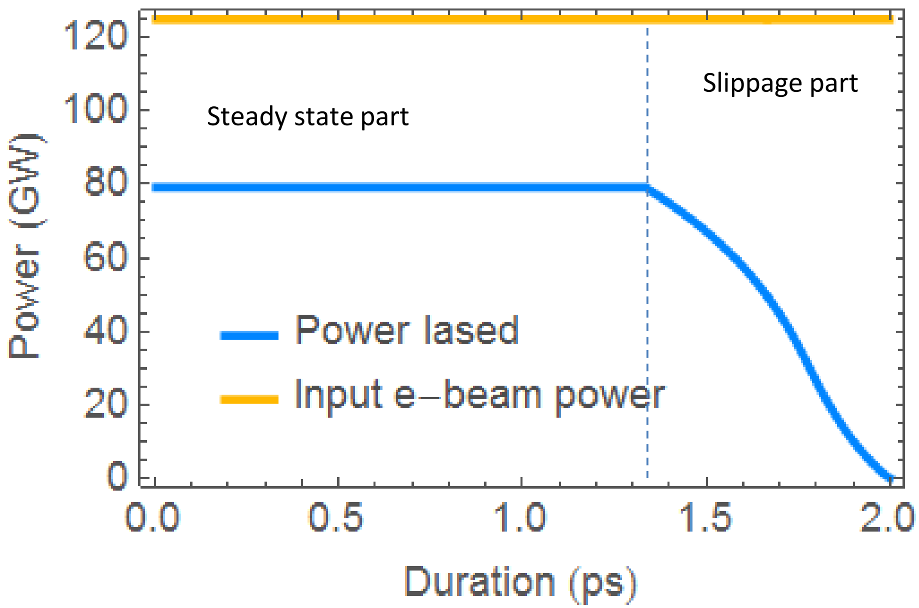
- Including diffraction effects, optimize
  - Gradient
  - Interaction length

$$L_w \approx 6\, z_r$$



Slippage effects

- Every undulator period radiation slips forward one wavelength
- The tail of the beam doesn't fully decelerate => decreased energy efficiency



$$\eta_{energy} \propto \left(1 - \frac{N_w \lambda}{2L_b}\right)$$

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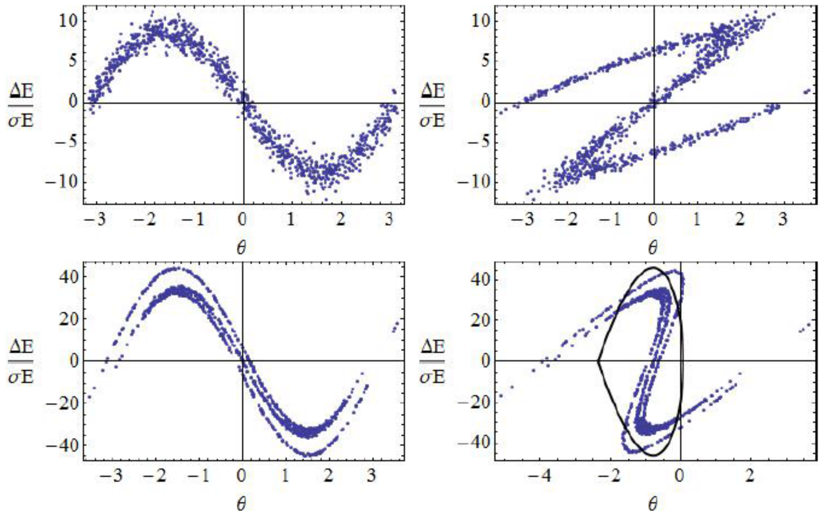
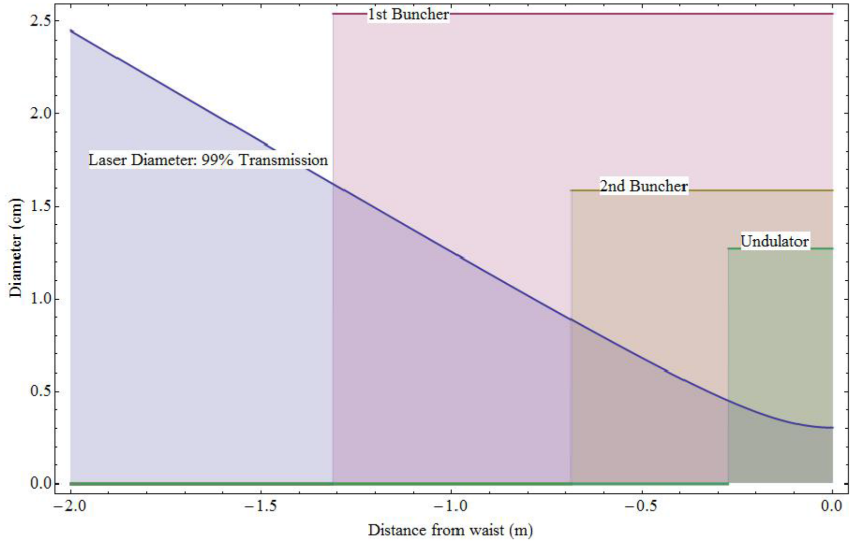
Double buncher. Adiabatic capture

- 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
- Putting together two ideas:
  - Diffraction-based adiabatic capture
  - Piece-wise bunching





Use diffraction to increase strength

Use two stage modulator + chicane to slowly compress all the particles

BNL recent results to be discussed in next talk by N. Sudar !

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So... what about sidebands?

- Sidebands well-known to KMR, oscillator community in 1980's
- Basic cause is synchrotron motion by trapped particles in ponderomotive well
- Shot noise growth in exp. gain regime *always* provides an initial broadband seed for sidebands
- Some detuning due to power growth
  - but weak since $\Omega_{SYN} \sim P^{1/4}$
- Check out poster WEP076 by Emma&Pellegrini: "Tapering Studies for TeraWatt Level X-Ray FELs with a Superconducting Undulator and Built-in Focusing"
- My personal opinion: this is a problem we want to have!

Perave: a 1-D period-averaged, time-dependent FEL code

Basics of the code

✶Electron E.O.M. (1) and (2) integrated via RK-4

✶Includes shot-noise via quiet loading

✶Field equation (3) solved in SVEA approx. including slippage

(1) $$\frac{d\gamma_j}{dz} = -\frac{\chi_1 K_1 E}{\gamma_j}\sin\psi_j$$

(2) $$\frac{d\psi_j}{dz} = k_w \times \left(1-\frac{\gamma_j^2}{\gamma_r^2}\right)$$

(3) $$\frac{dE}{dz} = \chi_2 K_1 \left\langle \frac{\sin\psi_j}{\gamma_j}\right\rangle$$

Motivation for code

Physics

✶Study time-dependent physics of tapered FELs in absence of diffraction & 3-D effects

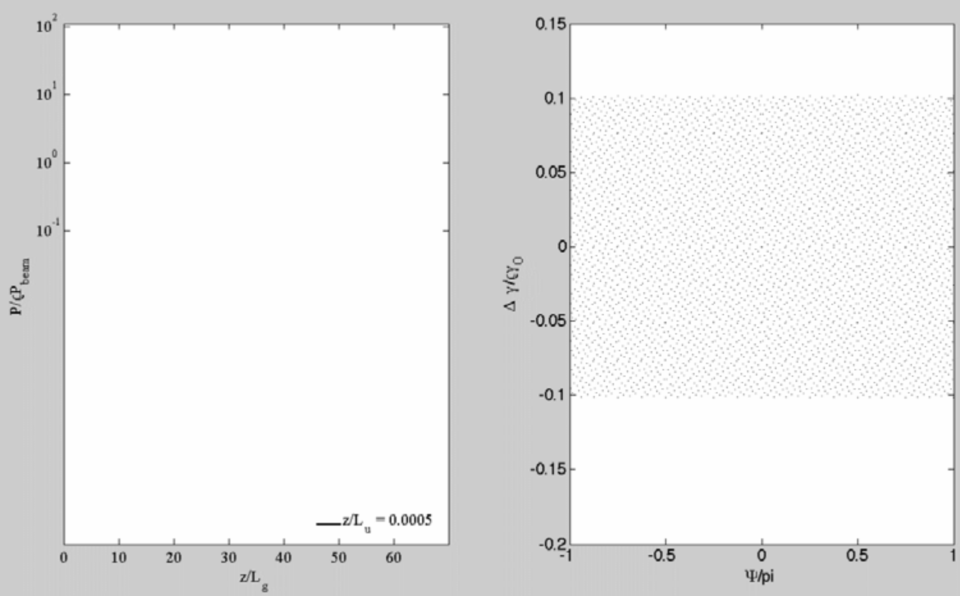
✶Study the impact of the sideband instability on tapered FELs

✶Determine the effectiveness of methods of sideband suppression

Practical

✶Fast compute time: single bucket simulation runs in ≈1s

Example run: Radiation power and particle dynamics



C. Emma (UCLA)

Perave: first results, benchmarking KMR theory

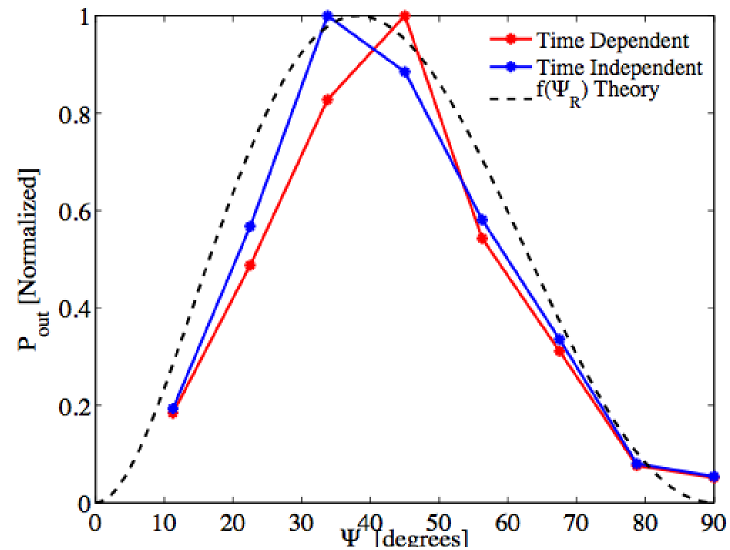
Testing theoretical Predictions

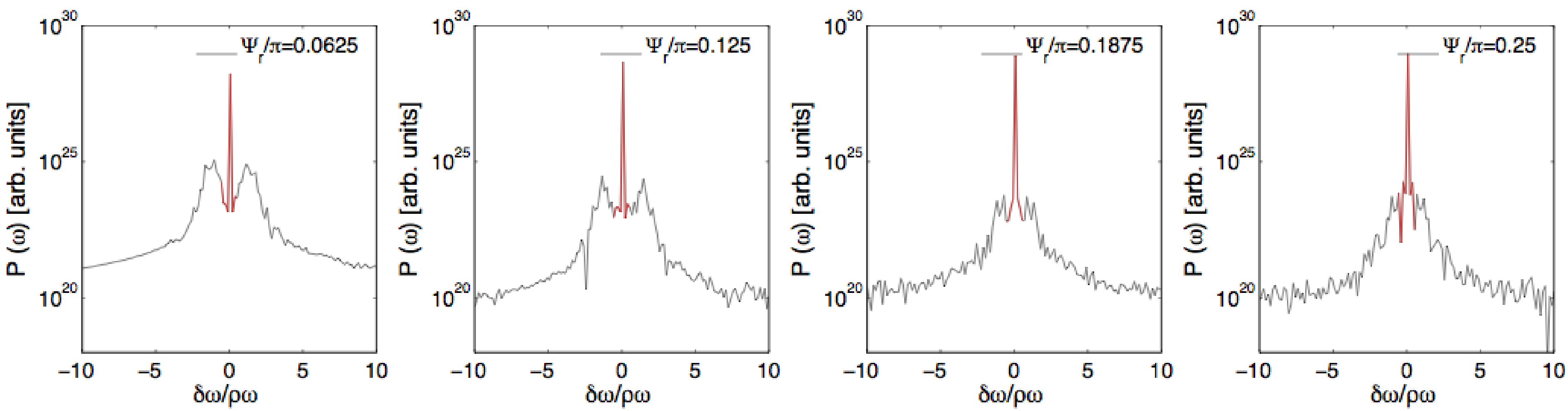
(1)Efficiency is proportional to product of deceleration gradient and bucket area $f(\psi_R)$ ✔ ☐

(2)Sideband Gain is inversely proportional to ψ_R ✔ ☐

(3)Relative sideband growth length is inversely proportional to ψ_R ✔ ☐

(4)To do: Gain modulation/detuning can be used to suppress sidebands





C. Emma (UCLA)

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Empirical/numerical tapering optimization: Genesis Informed Tapering Scheme

Solve tapering equations with help of 3D FEL code Genesis

$$\frac{d\lambda_w}{dz} = -\frac{8\pi K_l K \,\mathrm{Sin}[\psi_r]}{1 + K^2 + 2\lambda_w K \frac{\partial K}{\partial \lambda_w}}$$

Use Halbach formula to relate undulator period and amplitude

Solve tapering period-by-period

- Run Genesis on a period
- Select capturable particles (within the ponderomotive bucket)
- Measure min intensity seen by particles => threshold for capture
- Calculate new period and undulator parameter
- Saves taper as well as simulated data

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

TESSA experiments & roadmap

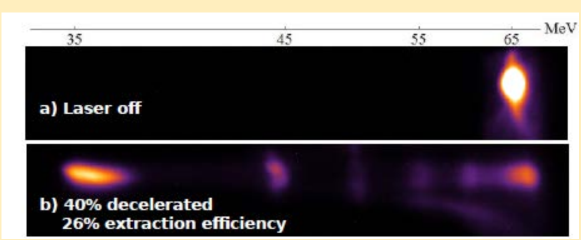
Nocibur

Completed

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

Validation of the model and the simulation tool

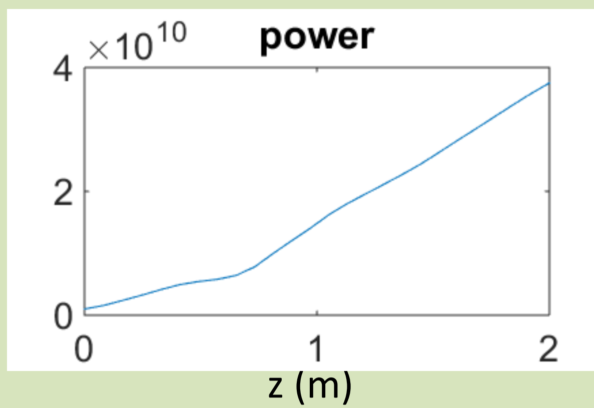
Relative gain is inversely proportional to efficiency so no measurement of radiation amplification



266 nm single pass

300 MeV 1000 A
10-15 % efficiency in 2 m long undulator

Next experimental demonstration @ 266 nm



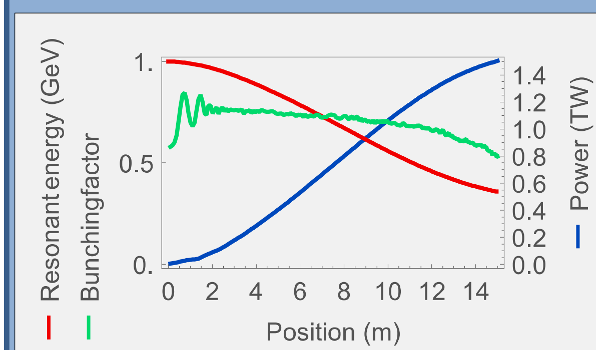
Requires high energy high brightness beamline
TESSA-LEA !

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)

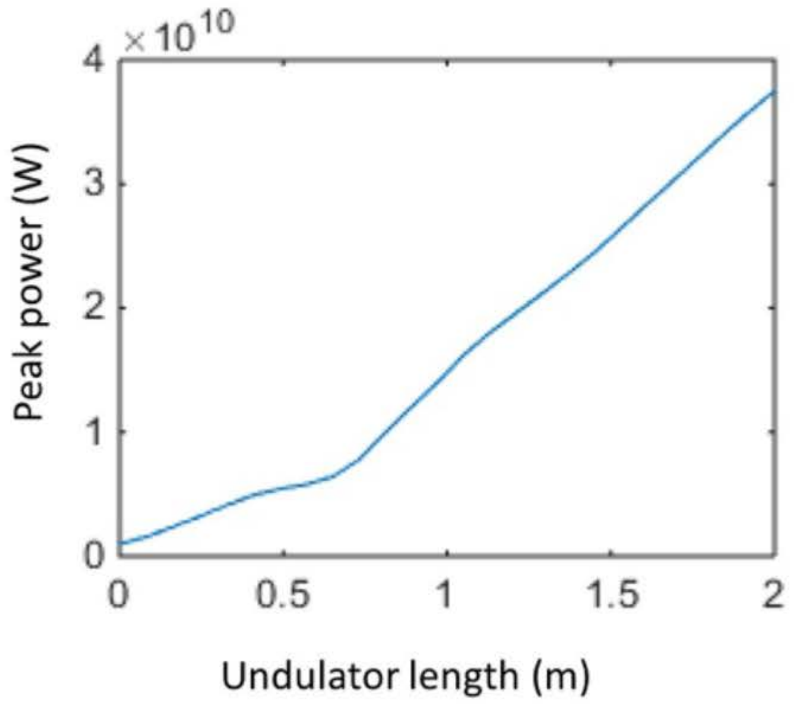
Duris et al. NJP (2015)



Very high gain regime
45% efficiency in 15 m.

TESSA @ LEA

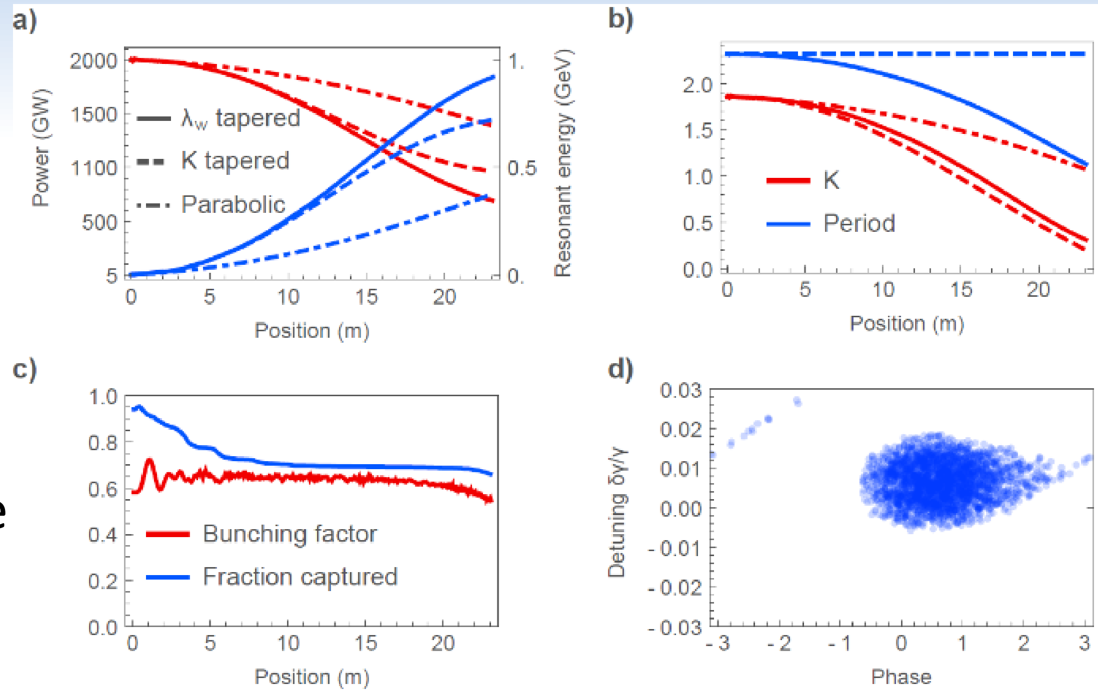
Beam Energy	300 MeV
Peak current	1 kA
Emittance	2 um
Energy spread	0.02 % - 0.1 %
RMS spot size in undulator	30 um – 40 um
Beta function	54 cm – 1 m
Undulator length	2 m
Radiation wavelength	266 nm
Seed power	1 GW
Interaction geometry	helical

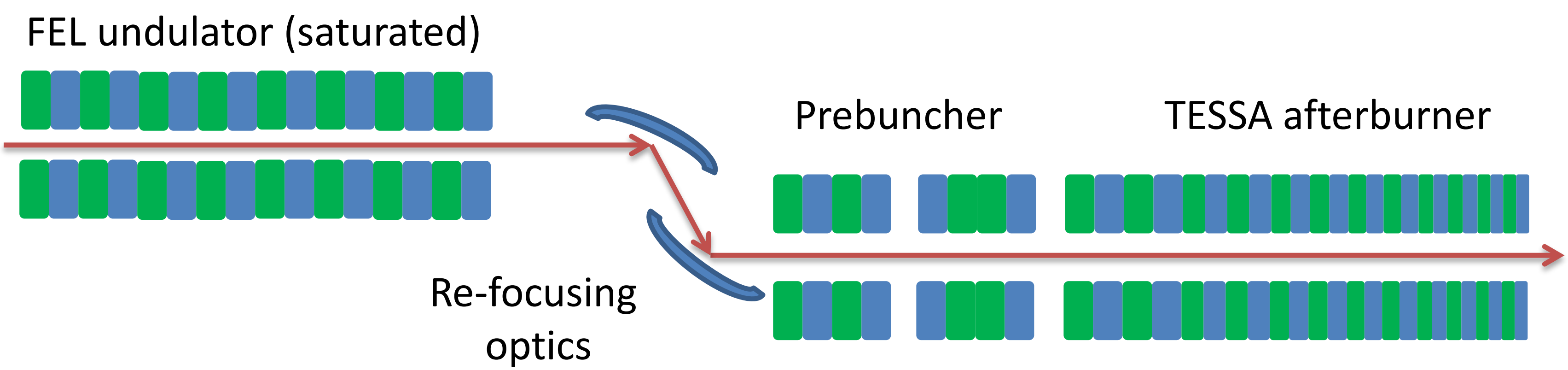


Detailed discussion in this afternoon talk !

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

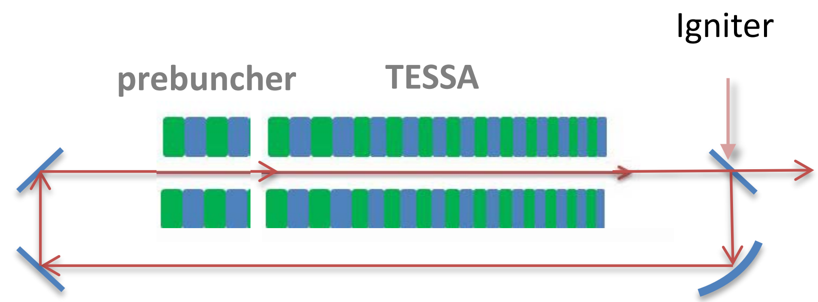




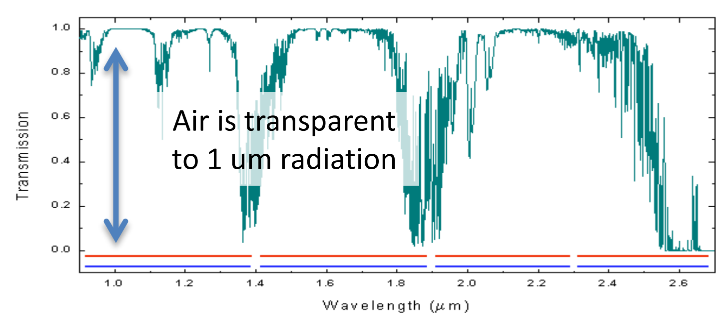
Towards high average power coherent tunable radiation sources

~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).



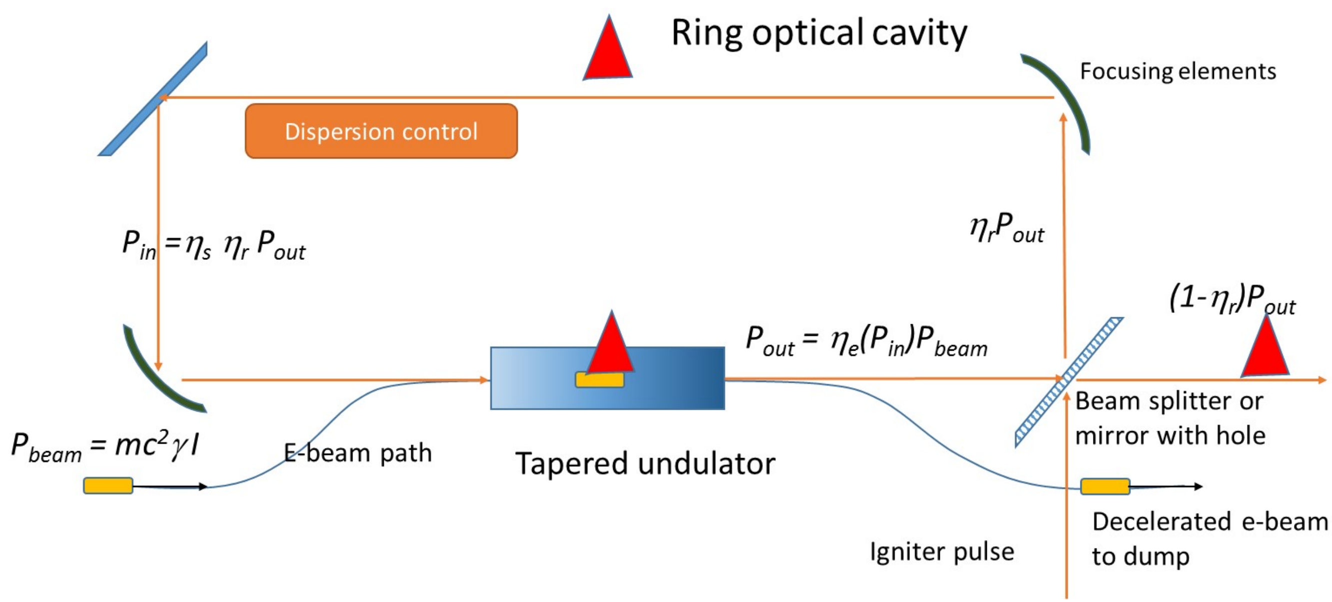
- Applications
  - Atmosphere is transparent to 1 um radiation
    - Power beaming to high-bandwidth satellites
    - Deorbit burning of space trash
    - Boosting satellites to higher orbits
  - EUV Lithography



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

TESSA Oscillator = TESSO

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

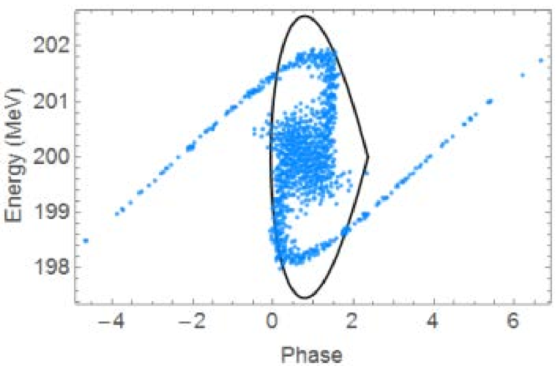


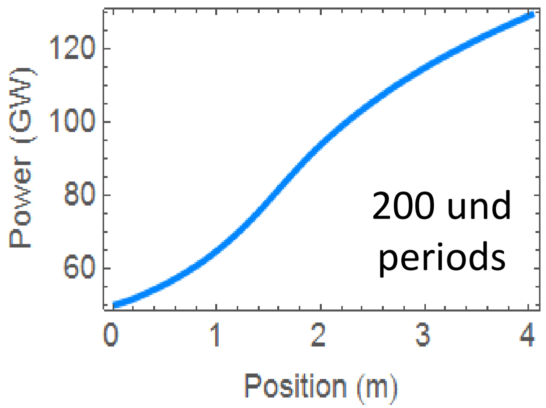
Impose that at steady state the recirculated power is constant
Maximizing efficiency, η_r = 50 %
Interestingly if one computes the total amount of output energy $N_{ph} \approx \alpha N_e^2$

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%

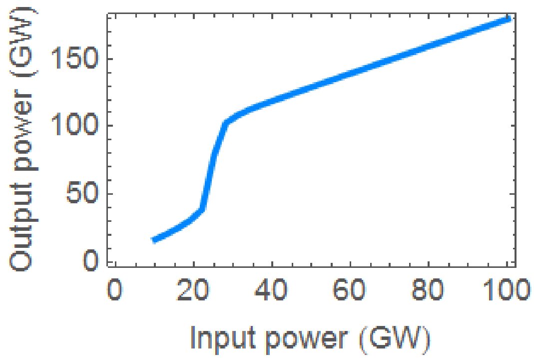
- 250 MeV * 500 A = 125 GW beam power
- Seed power is 50 GW (40% of beam power)
- Diffraction of stimulated radiation limits undulator length to 4 m to keep undulator gap small
- Prebunching to capture more (nearly all) charge increases net efficiency to 50%

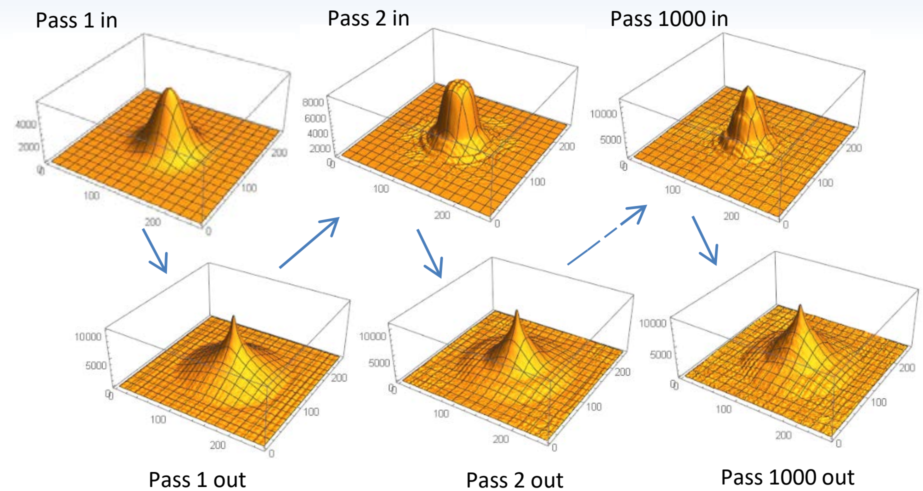




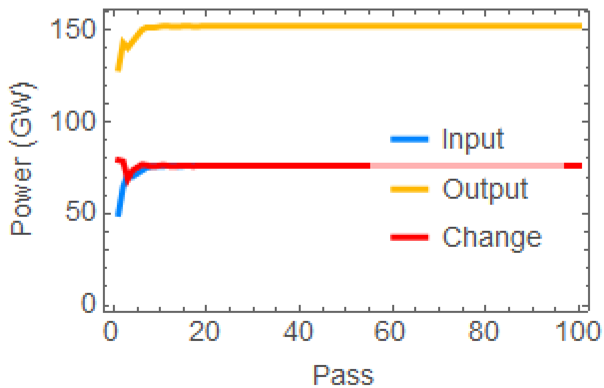
Full simulation model of oscillator

- Use field propagator + GENESIS to simulate multi-pass in cavity
- Optimize focusing mirrors
- Optimize return fraction



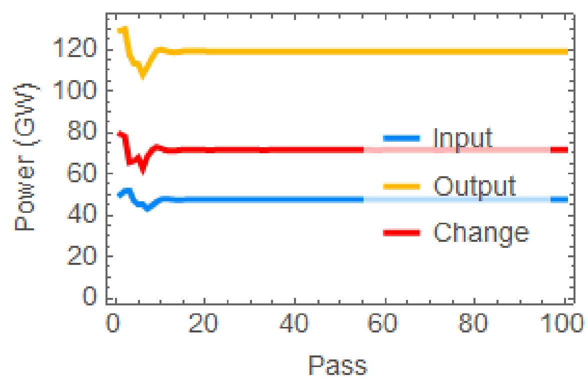


50% output coupler



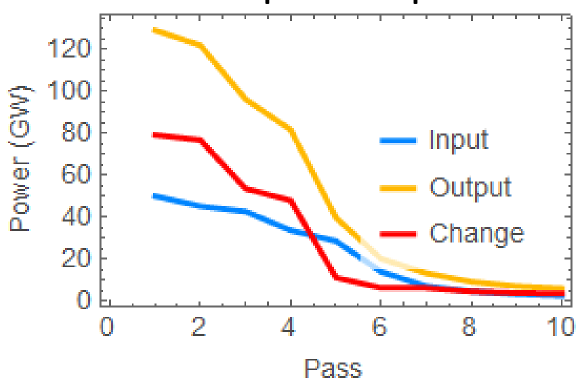
76 GW extraction
96% of first pass

60% output coupler



72 GW extraction
91% of first pass

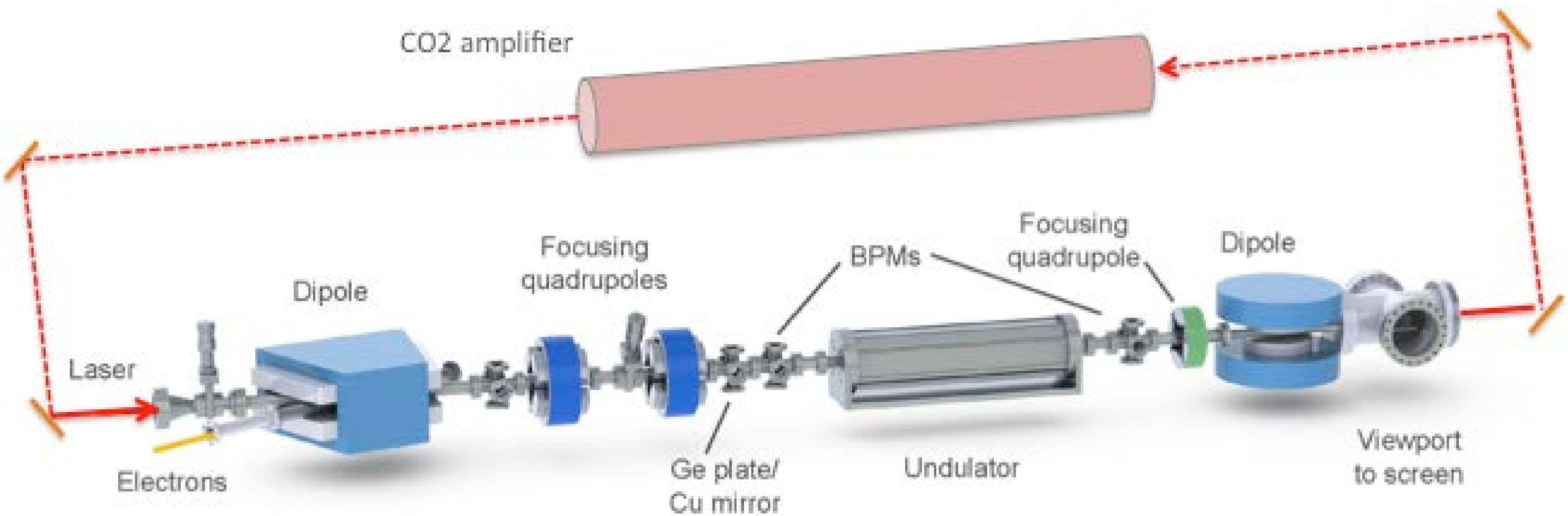
65% output coupler



High duty cycle IFEL -> Recirculated Nocibur

- 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 (2016-2017)



Conclusion

- TESSA builds up on decade-long experience from IFEL/ tapered undulator
- High gradient IFEL coupling can 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
- TESSA roadmap well marked
  - Short wavelength single pass
  - TESSA in an oscillator configuration (TESSO) has potential for > 50% efficiency for high average power light source.