High efficiency FEL

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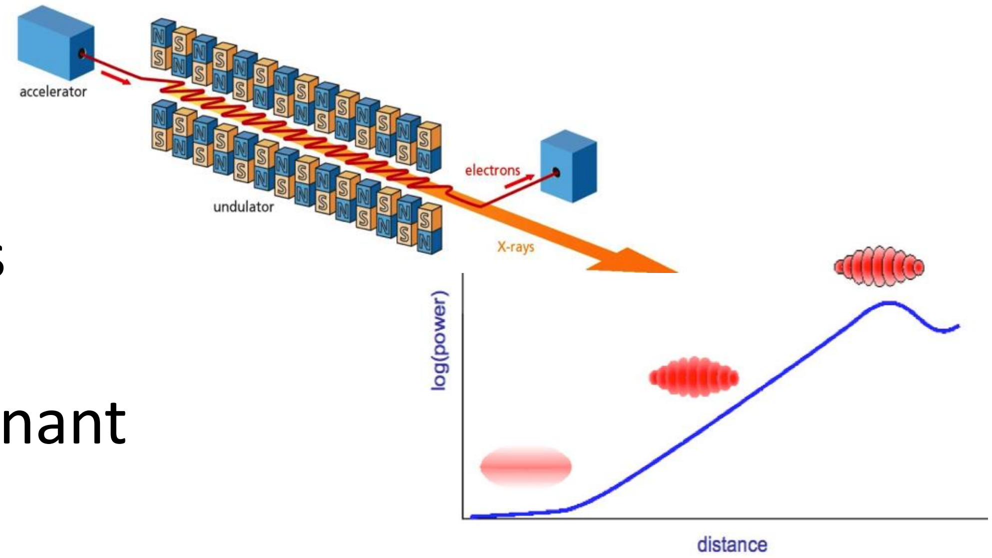
RadiaBeam Technologies, LLC.

EUVL workshop, LBNL, June 15 - 2016

Outline

- **FEL at 13 nm**
- **Tapered FELs**
- **TESSA**
- **TESSA deceleration experiment**

FEL at 13 nm



- In a high gain FEL the exponential field growth is achieved via e-beam microbunching at the resonant wavelength
- Beam quality control throughout acceleration and radiation is critical for FEL to work
- For optimized FEL system at 13 nm, e-beam energy is ~ 1 GeV

$$P[\mathrm{kW}] = I_a[\mathrm{mA}]E[\mathrm{MeV}]\eta_e$$

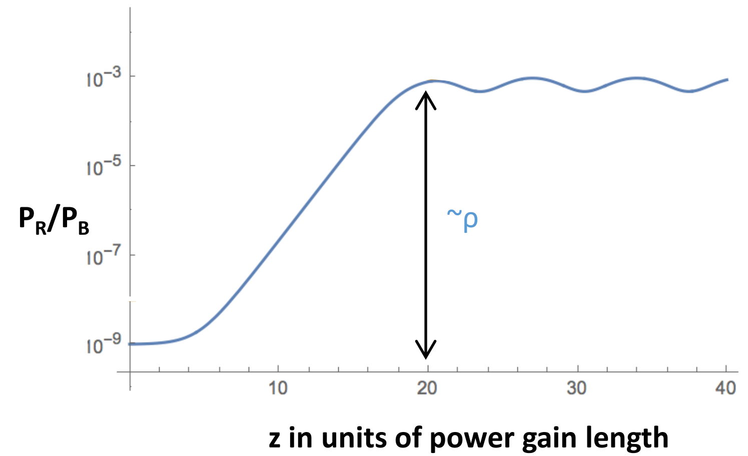
~ 1 GeV

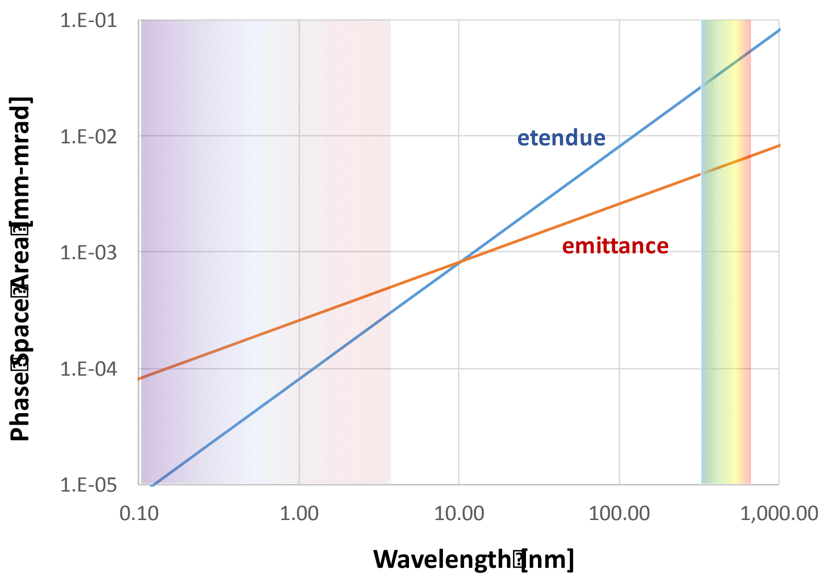
$$P[\mathrm{kW}] = 10\ I_a[\mathrm{mA}]\eta_e\ [\%]$$

FEL efficiency limitations

- ρ is a dimensionless FEL parameter, at EUV it is ~ 0.1%
- High gain FEL has 3 regimes:
  - Lethargy (~ 3 L_G)
  - Exponential growth (L_G~ $1/\rho$)
  - **Saturation** (P_s~ ρP_b)
    - FEL bandwidth ~ ρ
- If 3D effects (i.e. diffraction) are taken into account it can be even smaller

$$\rho_{1D} \sim \lambda_r{}^{1/2} n_e{}^{1/3}$$

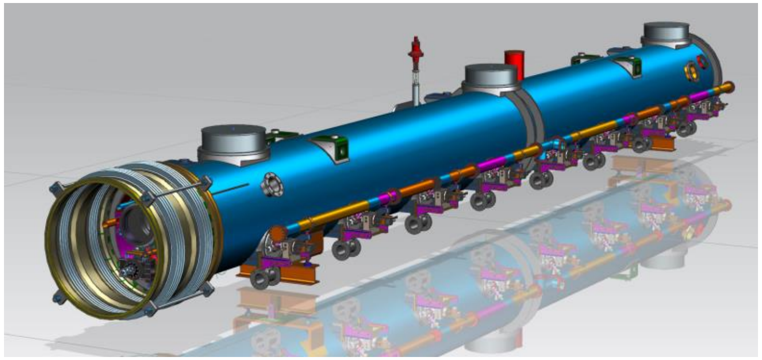




High power FEL challenge

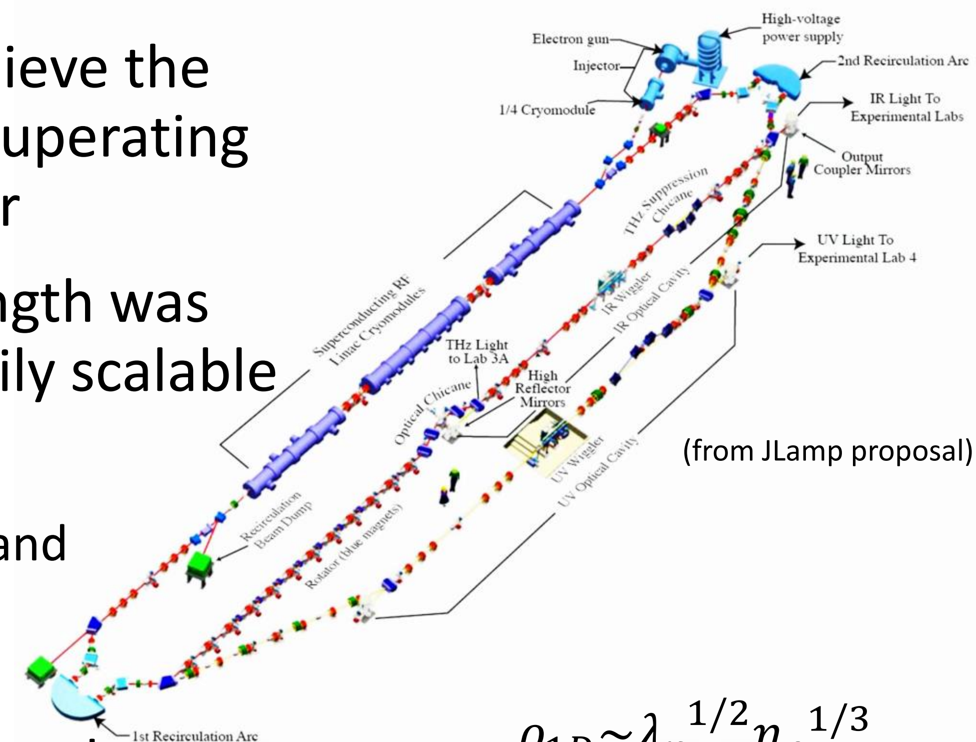
- A single pass SASE FEL energy efficiency is limited by Pierce parameter ($\eta_e \sim \rho_{3D} \sim 10^{-3}$ for EUV and soft X-rays)
- A 10 kW EUV FEL needs ~ 10 mA average current
- For such rep. rate we need superconducting accelerator
- State of the art high duty cycle FEL:
    - FLASH FEL < 50 μA
    - LCLS-II < 0.3 mA

$$P[\mathrm{kW}] = 10\, I_a[\mathrm{mA}]\eta_e\, [\%]$$



Energy Recovery Linac (ERL)

- SCRF ERL can economically achieve the desired ~ 10 mA current by recuperating the spent electron beam power
- 10 kW FEL power at IR wavelength was demonstrated, but it is not easily scalable
- IR→ EUV ERL FEL requires
  - > 10 larger e-beam average power, and
  - > 1000 improvements in brightness (challenging beam dynamics)
- ERL EUV FEL requires a lot of development
- **An alternative to ERL is to look into possible improvements to FEL efficiency**



(from JLamp proposal)

$$\rho_{1D} \sim \lambda_r^{1/2} n_e^{1/3}$$

$$P[\mathrm{kW}] = 10\ I_a[\mathrm{mA}]\eta_e\ [\%]$$

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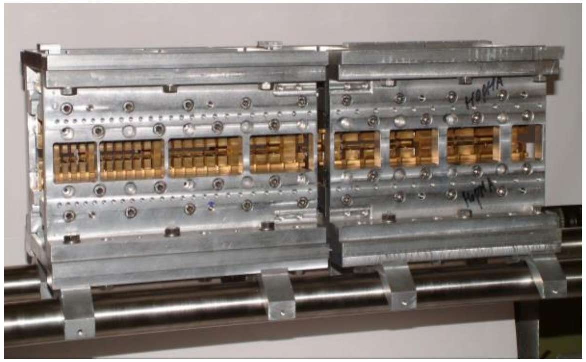
Tapered FELs

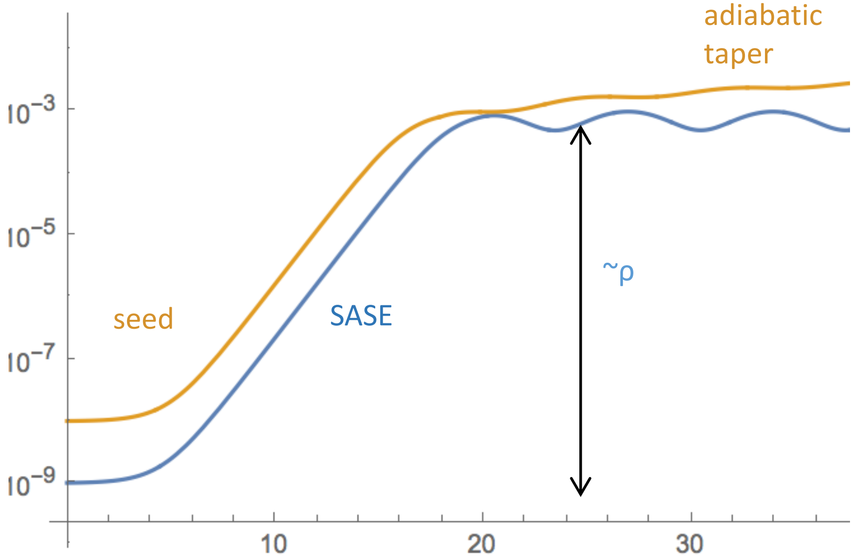
- Energy loss can be compensated by adjusting wiggler strength (tapering)
- Kroll-Morton-Rosenbluth developed 1D tapering model (1981)



$$\gamma_R(z) = \sqrt{\frac{\lambda_w}{2\lambda}\left[1 + a_w^2(z)\right]}$$

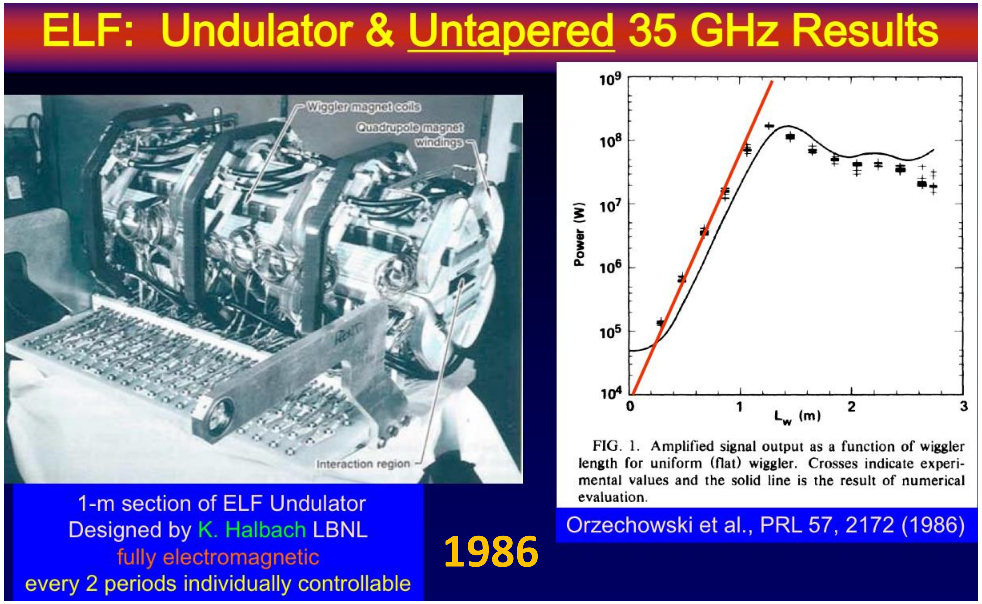
$$\frac{d\gamma_R}{dz} = -\frac{e}{\sqrt{2}m_e c^2}\frac{a_w(z) f_B(z) E_0(z)}{\gamma_R(z)} \sin[\psi_R(z)]$$

N. M. Kroll, P. L. Morton, and M. N. Rosenbluth, Free- electron lasers with variable parameter wigglers, IEEE J. Quantum Electron. 17, 1436 (1981).



Tapered FEL demonstration

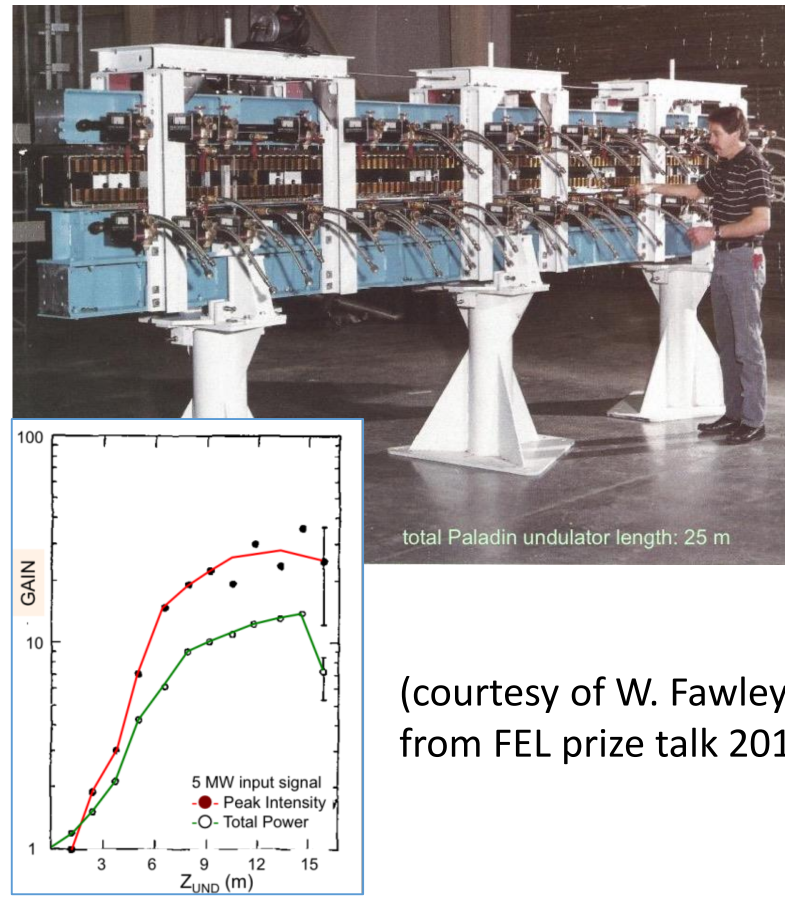
- Tapered waveguide FEL at Livermore demonstrated 34% efficiency @ 8 mm wavelength (50% energy extraction, 70% beam capture)
- Only factor of 5 increase over fixed period FEL (at 8 mm wavelength FEL parameter can be ~ 0.1)



(courtesy of W. Fawley, from FEL prize talk 2015)

Extrapolating to 10 μm

- PALADIN experiment at LLNL @ 10.6 μm (1989)
- Failed to achieve sufficient beam brightness, and resulted in a very limited FEL gain (no advantage from tapering)
- PALADIN failure contributed to the demise of Strategic Defense Initiative
- Also, nearly destroyed FEL program in the US (lost decade)



(courtesy of W. Fawley, from FEL prize talk 2015)

New interest (TW X-rays)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 040702 (2015)

Model-based optimization of tapered free-electron lasers

Alan Mak,[*] Francesca Curbis, and Sverker Werin
MAX IV Laboratory, Lund University, P.O. Box 118, SE-22100 Lund, Sweden
(Received 18 December 2014; published 23 April 2015)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 030705 (2015)

Optimization of a high efficiency free electron laser amplifier

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Deutsches Elektronen-Synchrotron (DESY), Notkestrasse 85, D-22607 Hamburg, Germany
(Received 4 September 2014; published 9 March 2015)

PHYSICAL REVIEW ACCELERATORS AND BEAMS **19,** 020705 (2016)

High efficiency, multiterawatt x-ray free electron lasers

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(Received 28 October 2015; published 26 February 2016)

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 050704 (2012)

Modeling and multidimensional optimization of a tapered free electron laser

Y. Jiao,[1,2,*] J. Wu,[1,†] Y. Cai,[1] A. W. Chao,[1] W. M. Fawley,[1] J. Frisch,[1] Z. Huang,[1] H.-D. Nuhn,[1] C. Pellegrini,[1,3] and S. Reiche[4]
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(Received 12 March 2012; published 3 May 2012)

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PAPER

Tapering enhanced stimulated superradiant amplification

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Keywords: laser particle acceleration, free electron laser, sideband suppression, extreme ultraviolet lithography, x-ray diffraction

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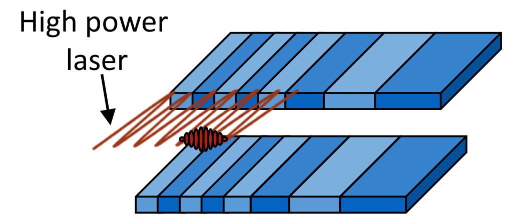
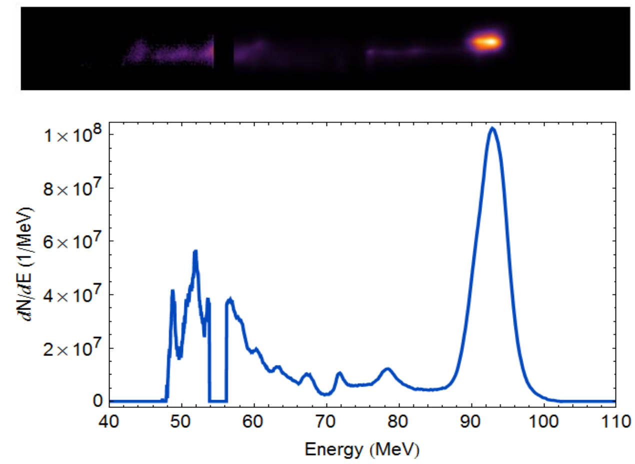
Inverse FEL

- Broader view of undulator interaction: laser and e-beam, when at resonance inside the wiggler exchange energy)
- FEL is an amplifier and decelerator (laser absorbs energy from e-beam, albeit at a moderate rate < 1 MeV/m)
- IFEL is an accelerator: e-beam absorbs energy from the high power laser
- IFEL demonstrated energy exchange rate ~ 100 MeV/m, and design studies indicate possibility of 1 GeV/m
- ***Can we run IFEL in reverse?***

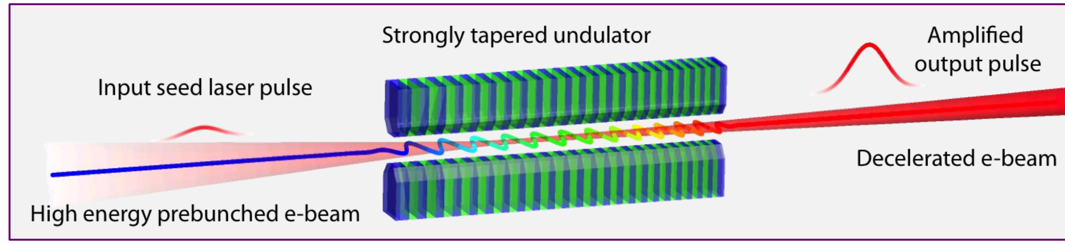


In an IFEL the electron beam absorbs energy from a radiation field.

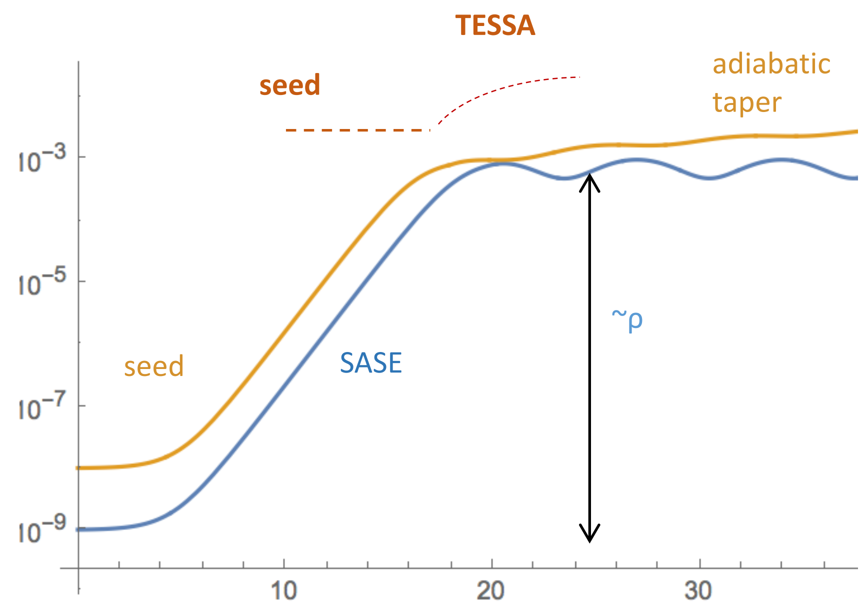


UCLA results from RUBICON experiments
J. Duris et al, *Nature Comm*. **5**, 4928, 2014

TESSA

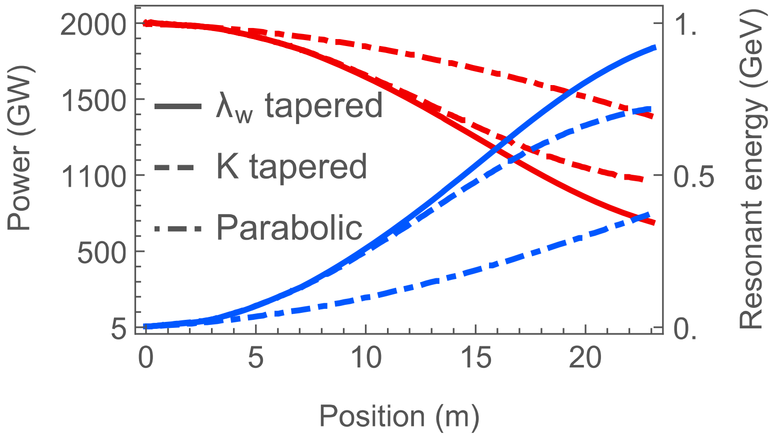


- Inverse IFEL = ~~FEL~~ TESSA (**T**apering **E**nhanced **S**timulated **S**uperradiant **A**mplification)
- E-beam rapid deceleration → laser amplification
- Requires seed pulse of high intensity (larger than P_{SAT})
- Tapering is optimized using proprietary GIT algorithm (Genesis Informed Tapering)



TESSA at EUV

- GIT simulations of TESSA at EUV
- E-beam decelerates from 1 GeV to 320 MeV in 23 m undulator,
- Laser power increases from ~ 5 GW seed to ~ 1 TW
- W/capture ~ 80% the overall energy extraction efficiency **> 50%**
- Sensitive to peak current (4 kA for this working point).



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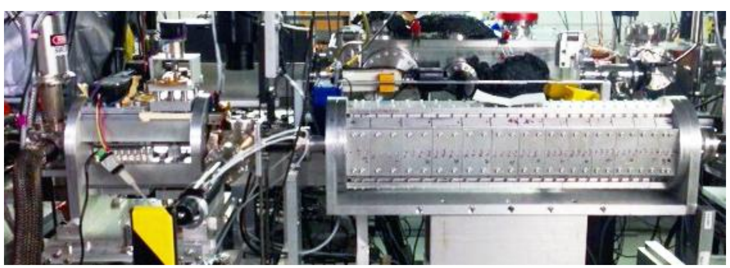
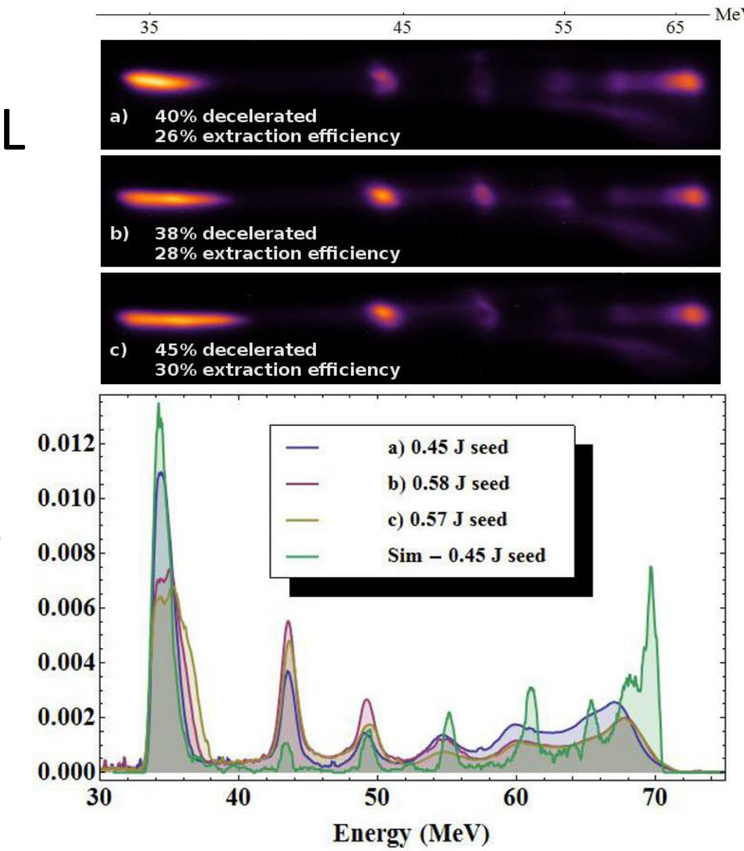
Proof of concept experiment

- IFEL accelerator program at BNL is called RUBICON (**R**adiaBeam **U**CLA **B**NL **I**FEL **Co**llaboratio**n**)
- The IFEL decelerator (TESSA) was termed Nocibur (Rubicon in reverse)
- Demonstrated 30% efficiency at 10.3 µm (~ 50% deceleration, close to 70% capture)

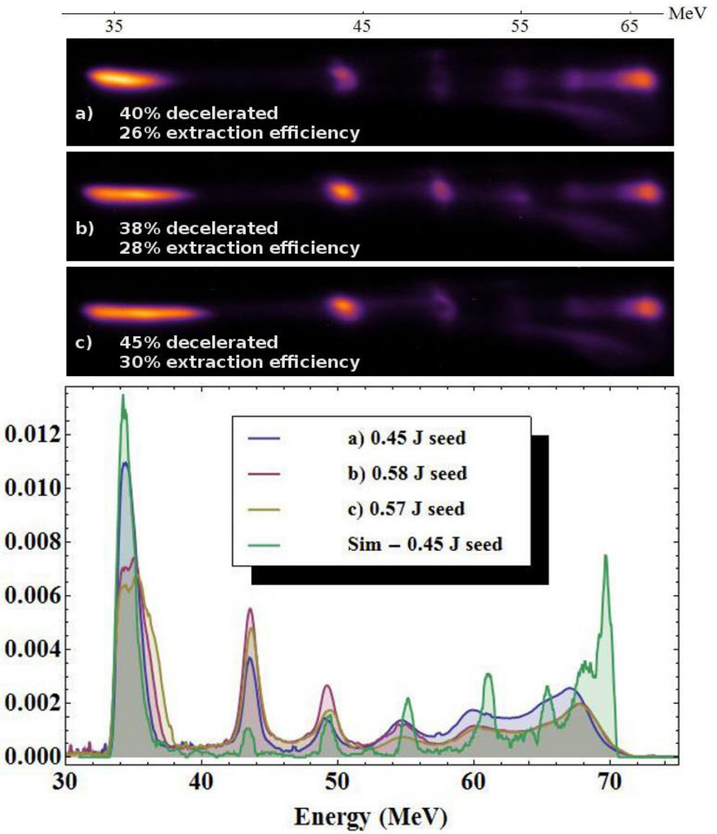




N. Sudar et al. https://arxiv.org/pdf/1605.01448v1.pdf (2016).

Nocibur conclusions

- TESSA deceleration is demonstrated with the energy exchange rate ~ 100 MV/m
- Laser seed ~100 GW (but only few GW overlapped w/e-beam)
- Results support TESSA design approach and GPT numerical tools
- Next step is to demonstrate TESSA amplifier at visible or UV range



General conclusions

- Industrial EUV FEL is a source of excitement, but also a challenge for the FEL community
- High efficiency tapered FEL theoretically exists, and can be perceived as an alternative technological path vis-à-vis ERL FEL, in the context of 13.5 nm source
- TESSA proof of concept demonstration @ 10 μm was a success (30% efficiency), and we need to follow up with experiments at shorter wavelengths
- Thank you!

- Acknowledgement: Nocibur experiment was designed, and carried out by UCLA (P. Musumeci, J. Duris, N. Sudar, et al) with full support of BNL ATF