Modeling and Operation of an Edge-Outcoupled Free- Electron Laser

Michelle Shinn*, Stephen Benson, George Neil, and Anne Watson
TJNAF, Newport News, VA 23606
Peter van der Slot
LPNO, Mesa+ Institute for Nanotechnology, University of Twente,
P.O. Box 217, 7500 AE Enschede, the Netherlands
Ramin Lalezari
Advanced Thin Films, Boulder, CO 80301

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Outline

- The challenge to achieving wide tunability with high outcoupling efficiency
  - Discussion of previous techniques
- Introduction to Edge-outcoupling
  - Design
- Experimental results
  - Gain & Loss
  - CW power
- Model results (3D Genesis 1.3/OPC)
- Discussion
- Conclusions

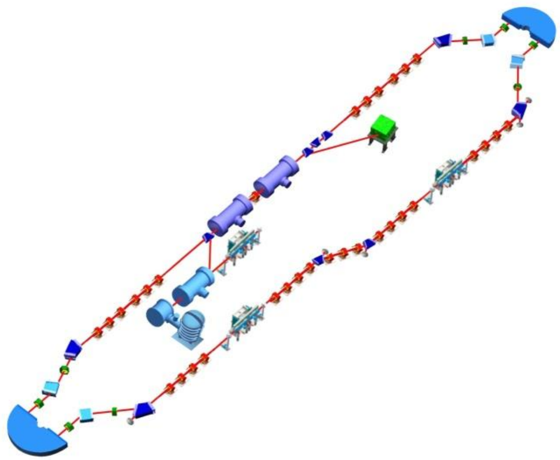
Outcoupling techniques

- The goal is to realize a feature of FELs, the ability to quickly tune the wavelength over a wide range.
- Ways to do this:

- Hole outcoupling
  - The most common FEL outcoupling technique. Very poor efficiency (only ~ 5% of that anticipated geometrically.
  - At Jlab we discovered some issues with heating about the hole causing mode-hopping when running cw.
- Brewster window
  - Employed at Stanford on the Mark III. Abandoned due to
    - Need to adjust angle as a function of wavelength
    - Laser-induced damage.
- Scraper outcoupling
  - A mirror with a hole in the middle, placed near one of the end mirrors of the cavity. Good (~ 90%) outcoupling efficiency.
  - Diffraction from the double pass through the hole must be managed.

Edge-outcoupling: a fresh look at an old idea

- Edge-outcoupling is a variant of the usual near-concentric resonator.
- Both mirrors have broadband (usually metal) HR coatings.
- Outcoupling takes place by making the downstream mirror smaller in diameter than the optical mode, so the outer portion of the mode passes around the edge of the mirror.
- Can be deployed on existing FELs.
- Two new FELs where it can be used are shown below:



BigLight at Florida State Univ.
3 FELs spanning 2.5-1500 microns

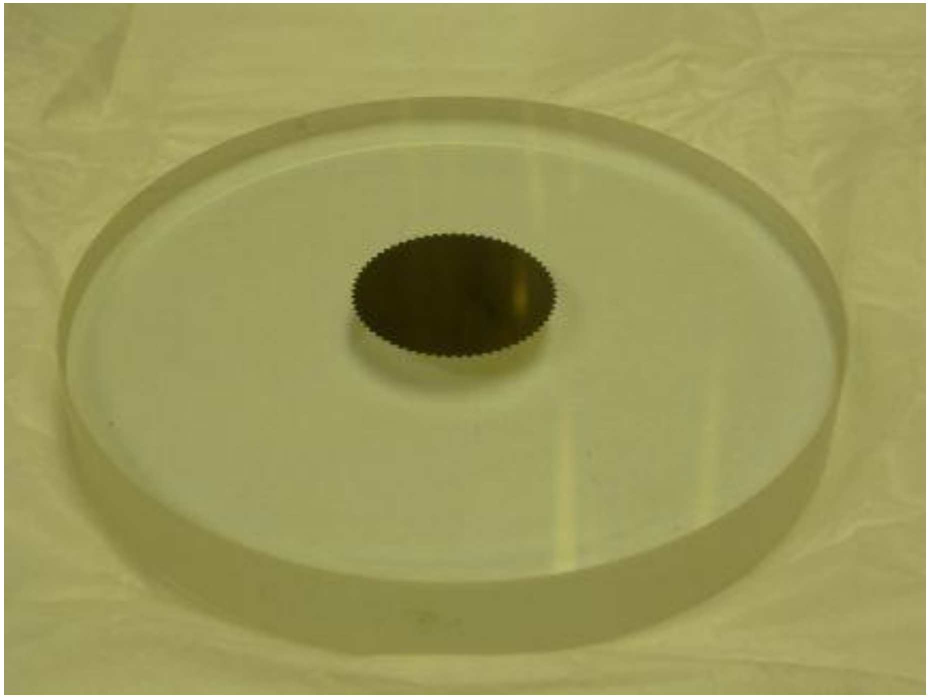
JLAMP at Jlab
12-124 nm

Modeling

- To determine the downstream mirror diameter, one must keep the outcoupling (the majority of the loss) roughly 1/3 the small signal gain over the wavelength region of interest.
- The geometric loss = 1 – mirror area/mode area can be determined using the formulae published by Kogelnick and Li (1966)
- The gain can be estimated using formulae (*e.g.*, Dattoli or M. Xie) or computer simulations (*e.g.* PERSEO, Genesis 1.3 or Medusa)
- The design of the outcoupler was done using analytical formulae for both gain and loss to provide continuous operation from 1-3 μm.
- After data was collected, more sophisticated modeling was done using Genesis 1.3 in 3D mode (currently only works in 3D mode with OPC version 0.7.4

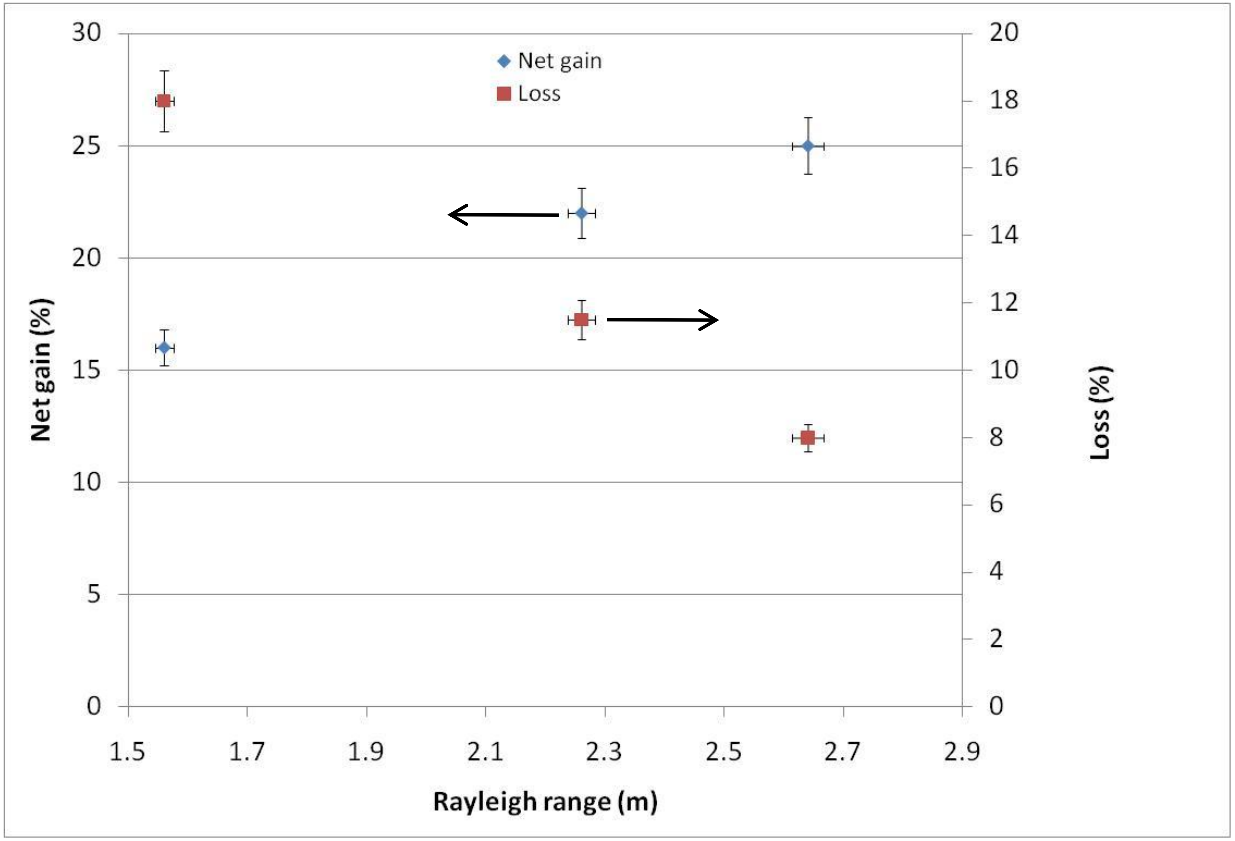
Edge-outcoupling implementation on the JLab IR FEL

- Mirror was constructed on a 7.62 cm dia. planoconcave (16.0 m ROC) sapphire substrate.
- The concave side has a 1.93 cm enhanced aluminum HR coating , apodized to mitigate intensity spikes in the far field output as well as the near field .
- The concave side of the substrate not covered by the HR coating was coated with an AR coating (1-3 μm).
- The plano side was AR coated as well.



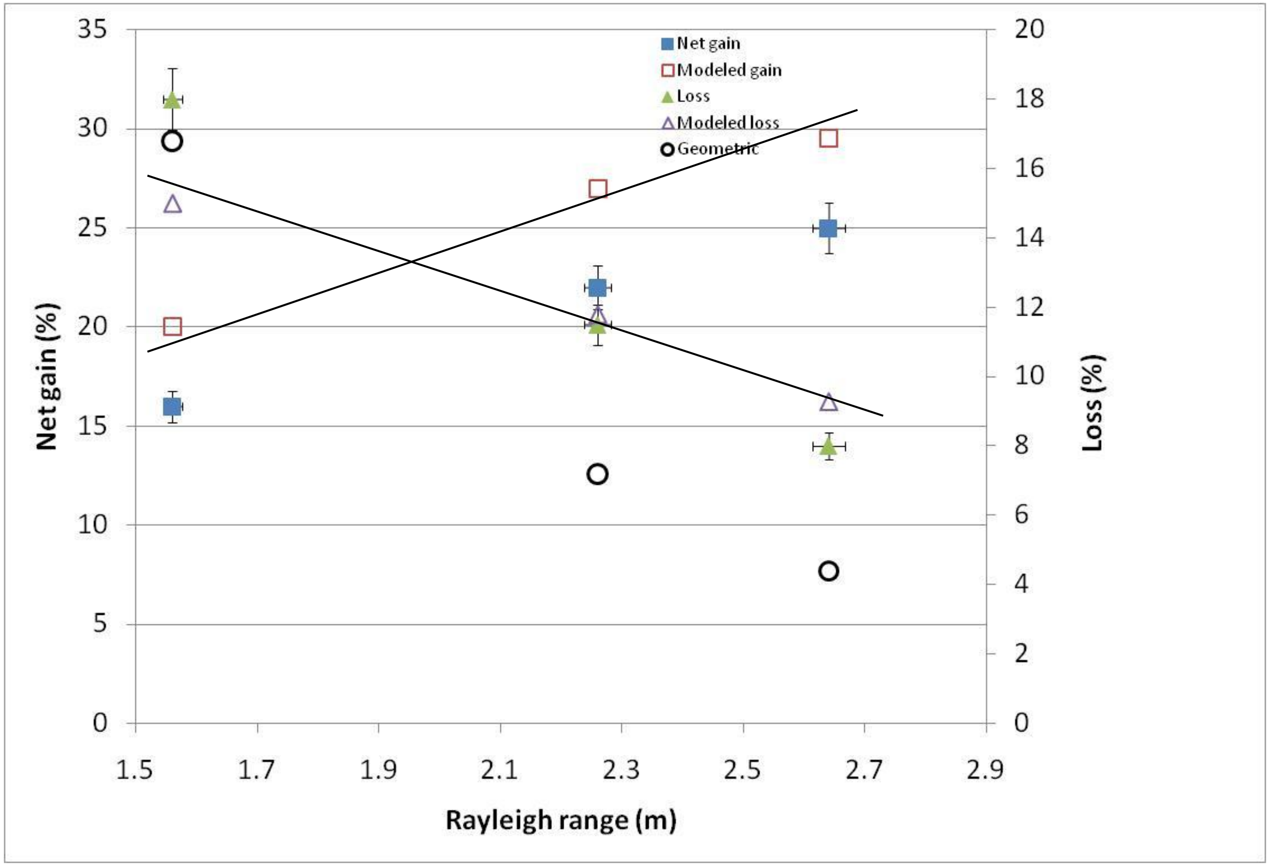
Gain and loss data

- Gain and loss data were taken over two shifts
- Data shown below is for 4.68 MHz, 2Hz, 250 μs macropulses at 2μm.
- The linear trend for both gain and loss were anticipated; the former from filling factor, the latter from the properties of Gaussian mode propagation.



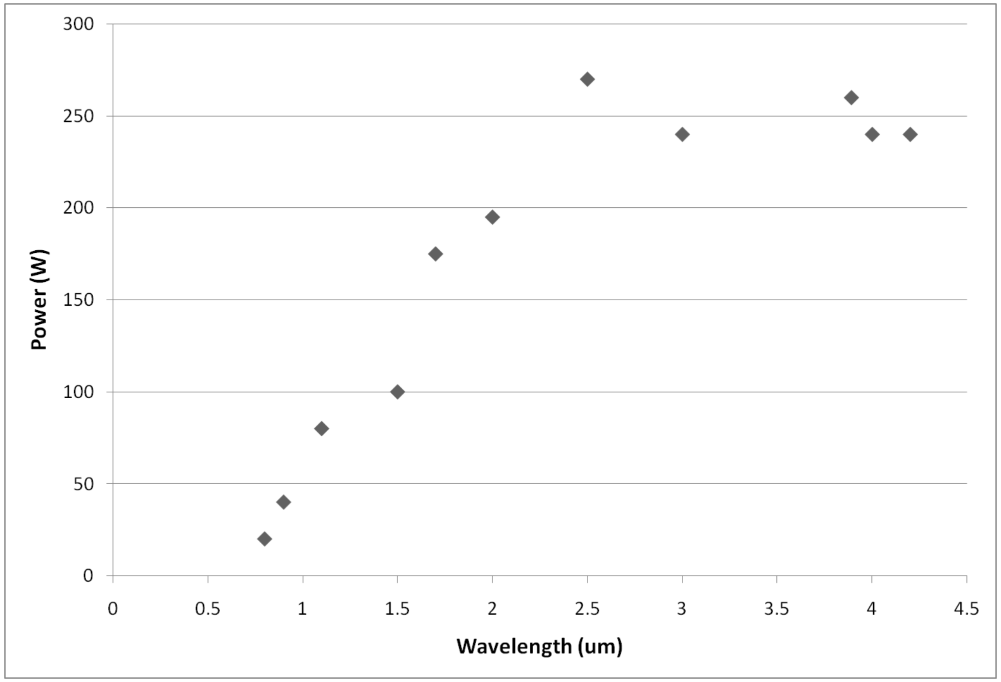
Modeling results

- E-beam parameters (energy, emittance, etc) were determined using our beam-based diagnostics .
- The radii of curvatures of the mirrors were determined both in and *ex-situ*.



CW Performance

- We optimized the outcoupling at each wavelength to obtain this data
  - This was done by changing the HR mirror ROC, and hence the Rayleigh range of the resonator. There was no evidence of mode hopping at any wavelength.
  - Wavelength limits:
    - Short λ end – gain/loss ratio & Rayleigh range (mode too small at outcoupler)
    - Long λ end – gain/loss ratio at 3rd harmonic more favorable, 3rd harmonic lased preferentially.



Discussion

- The linear trends for the gain and loss are reasonably well-reproduced.
- The calculated net gain is about 25% higher than measured, but since the calculation ignores the details of the pulseshape or slippage, this is not too surprising.
- The measured loss is within 10% of the calculated loss, except at the longest Rayleigh range.
- Of great importance is to estimate the outcoupling efficiency, as we want a system that performs better than a hole outcoupler.
  - The fact that the predicted loss and measured loss are in good agreement indicate the outcoupling efficiency is high.
- One can also determine the best fit x-intercept to the loss data to derive an estimate.
  - If the outcoupling efficiency is high then zero outcoupling implies a mirror diameter that is ~ 3 or more times the mode radius.
    - The x-intercept implies a mirror diameter/mode radius ratio of 2.9 – again suggesting a high outcoupling efficiency.
- The predicted power followed the trend in wavelength, but was higher than measured, by about a factor of two.
  - We need to do 4D simulations and look again at beam parameters.

Conclusions

- We have designed and used for the first time edge outcoupling.
  - For convenience, we used a transmissive substrate to mount the mirror
  - In general, one would use a suspension mount.
- For systems with modest single pass gain (of order 40%), the outcoupling efficiency is high, of order 90%, similar to that for the annular scraper.
  - Wavefront encounters the edge one time, not twice, so diffractive losses are lower.
- We produced high average power over a wide wavelength range:
  - Over 100W from 1.5-4.3μm, with no mode hopping.
  - We have already been using this technique for user experiments
- The use of a gain code, like Genesis or Medusa, with OPC has better predictive power than can be obtained with a purely analytical approach.
- Continuing simulations with Medusa/OPC in both 3D & 4D, as we wish to do a comparison, and better predict the power.
  - Genesis/OPC will be available in a 4D version soon.

The Jefferson Lab FEL Team

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