# Beam Line Commissioning of a UV/VUV FEL at Jefferson Lab *

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For the FEL Team

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# Outline

- Initial specifications and simulations
- Design and construction
- Results
  - 700nm
  - 400nm
  - Comparison with simulation
- Setup for 3rd harmonic (~ 10eV) photon detection
- VUV measurements
- Future plans

# INITIAL UV FEL SPECIFICATIONS

**Specification (from UV Demo proposal - 1995)**

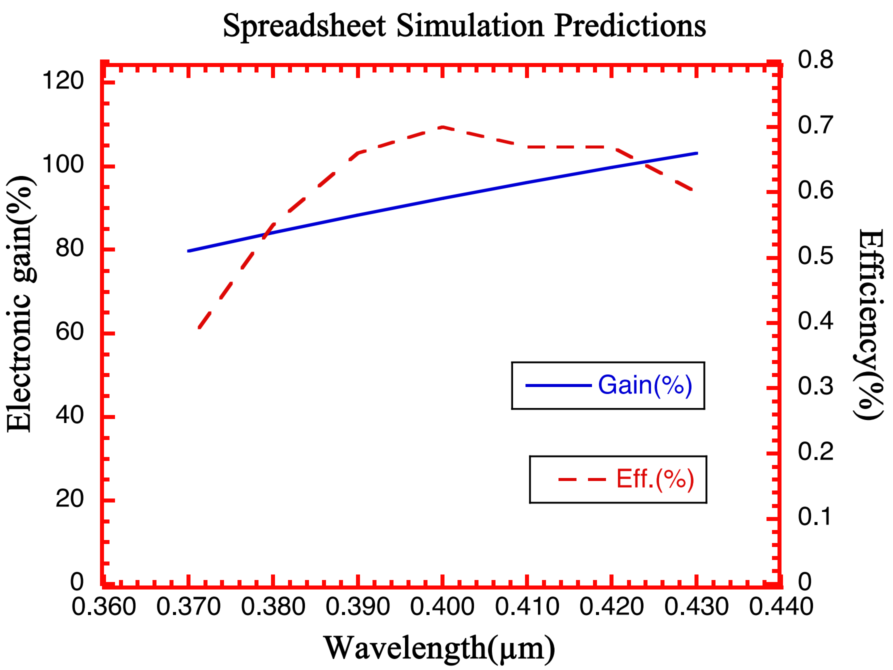
| | |
|---|---|
| • Average Power | > 1000 W |
| • Wavelength range | 1–0.25 μm |
| • Micropulse energy | ~25 μJ |
| • Pulse length | ~0.1-1 ps FWHM nominal |
| • PRF | 74.85, 37.425, 18.7, 9.36, 4.68 MHz |
| • Bandwidth | ~ 0.2–1.5 % |
| • Timing jitter | < 1 ps |
| • Amplitude jitter | < 2 % p-p |
| • Wavelength jitter | 0.02% RMS |
| • Polarization | linear, > 100:1 |
| • Transverse mode quality | < 2x diffraction limit |
| • Beam diameter at lab | 2 - 3 cm |

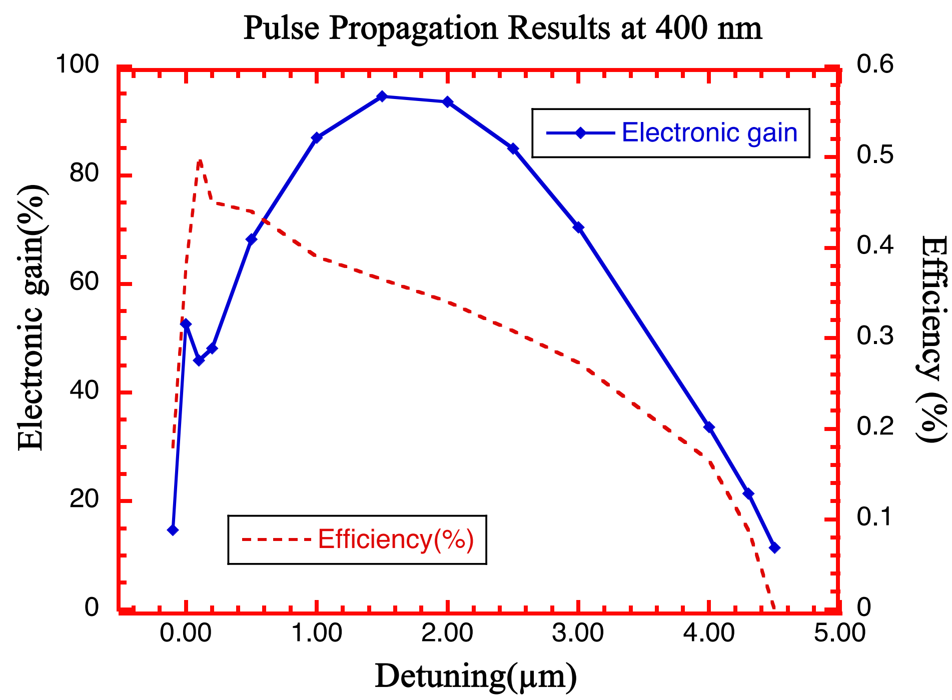
# Electron Beam and Optical Requirements

- Short wavelengths require higher electron beam energies. The higher the better. For 250 nm we need 150 MeV. For 120 nm we need 250 MeV.
- The transverse emittance and energy spread should be lower by ~ 2X compared to the IR Upgrade.
  - Achieve this by operating at ½ the IR Upgrade FEL charge/bunch and raising the energy to 135 MeV.
- UHV vacuum is required for stable, long-term operation.
- Manufacturing mirrors with $\lambda/10$ figure in the UV is challenge.
- UV coatings are more lossy than those in the visible, although exact numbers are hard to pin down. They may be only a few 100 ppm
- **The OC mirror will absorb ~ 1/3 of the incident THz power. The absorbed power limit is proportional to the wavelength so we can't afford much absorbed power.**
- **Note: No mirror degradation seen in these experiments! Spontaneous radiation is very soft compared to SRFELs.**

# Estimates of FEL performance

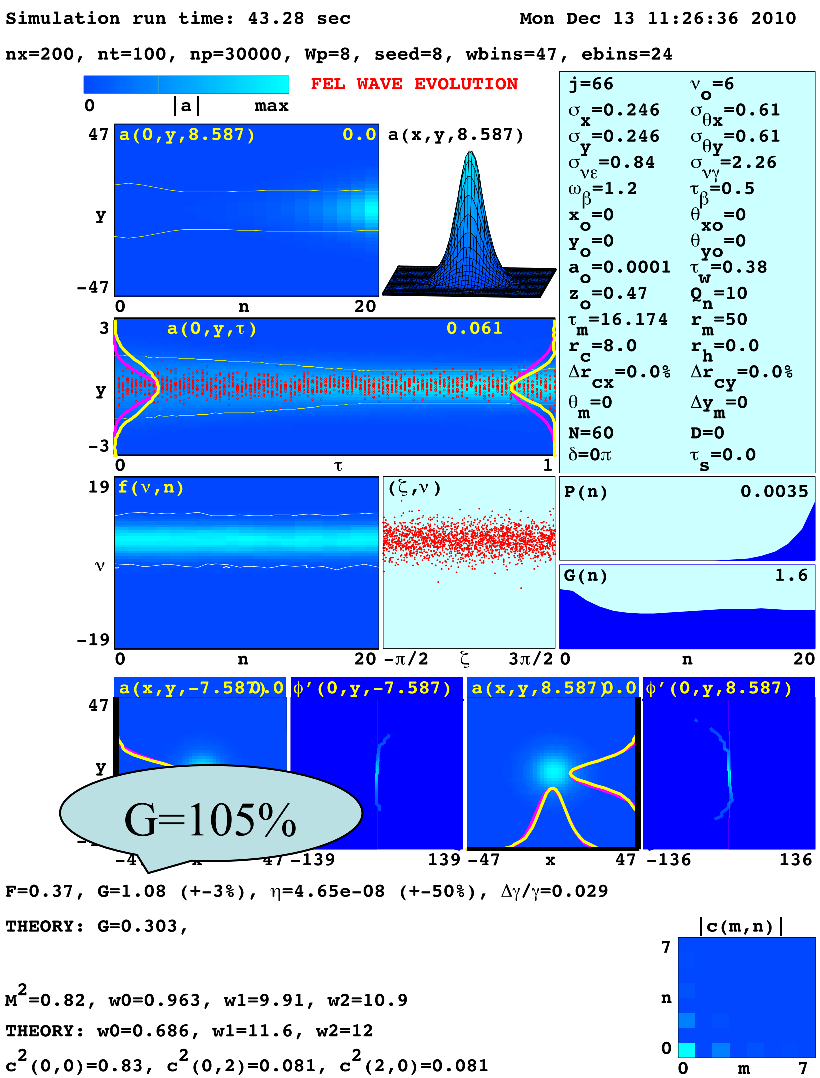
- Both pulse propagation and one-dimensional spreadsheet models are first used to estimate the gain and power.

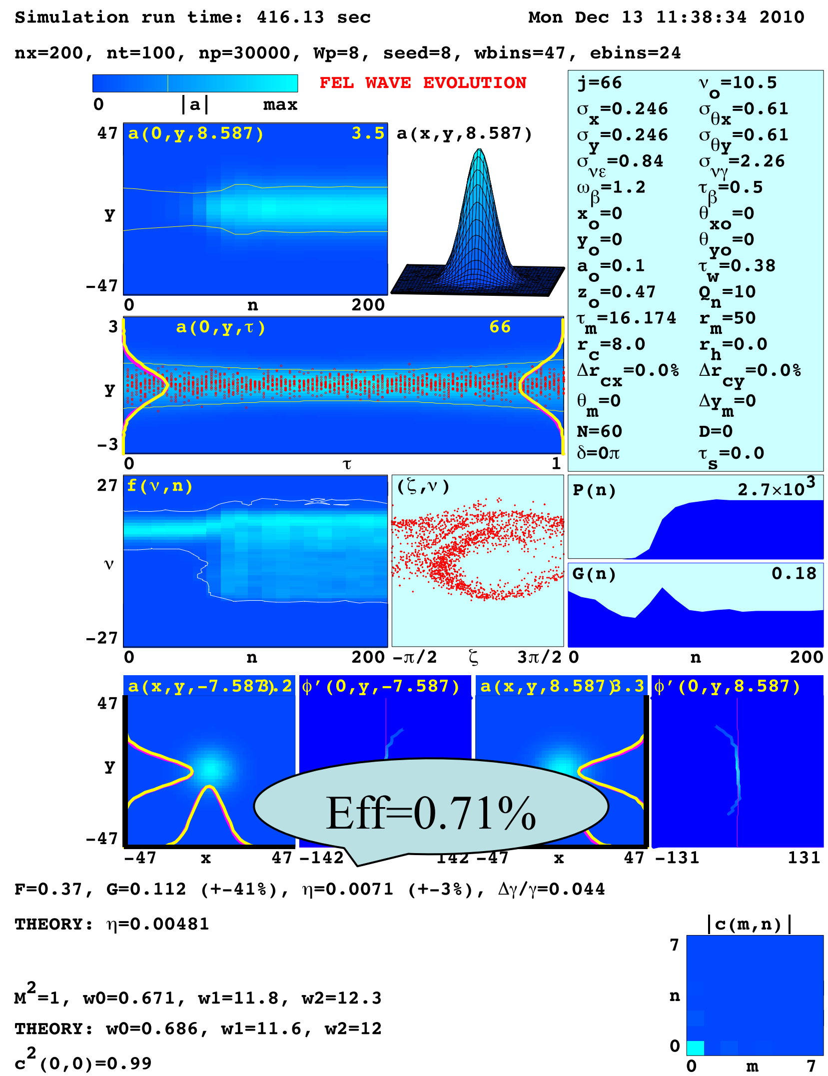



Note: Both models assume perfect mirrors with a 93 cm Rayleigh range and 10% transmissive output coupling.

# Three Dimensional Simulations



# Expected Power Output with Room Temperature Mirrors

**Absorbed THz And Fundamental Power Set The Power Limit For Initial Operation With Water Cooled Mirrors. We analyzed this in August 2008:**

- At half the charge, but twice the rep rate, the THz power generated will be about half that in the IR Upgrade before the THz chicane was installed.
  - That value was measured as 15W absorbed per mA of beam current.
- So, for this machine we would expect 7.5W launched/mA, but 1/3 is absorbed, yielding 2.5W /mA
  - At 0.56mA (9.36 MHz), assuming 15% OC a mirror heating model shows an output of ~ 120W (assumes perfect mirrors)
  - Assuming 0.1% absorption, we have a total absorbed power of 2.2W, comparable to the limit of ~ 3W absorbed.
  - So, we can expect, at least initially, ~ 100W at 400nm.

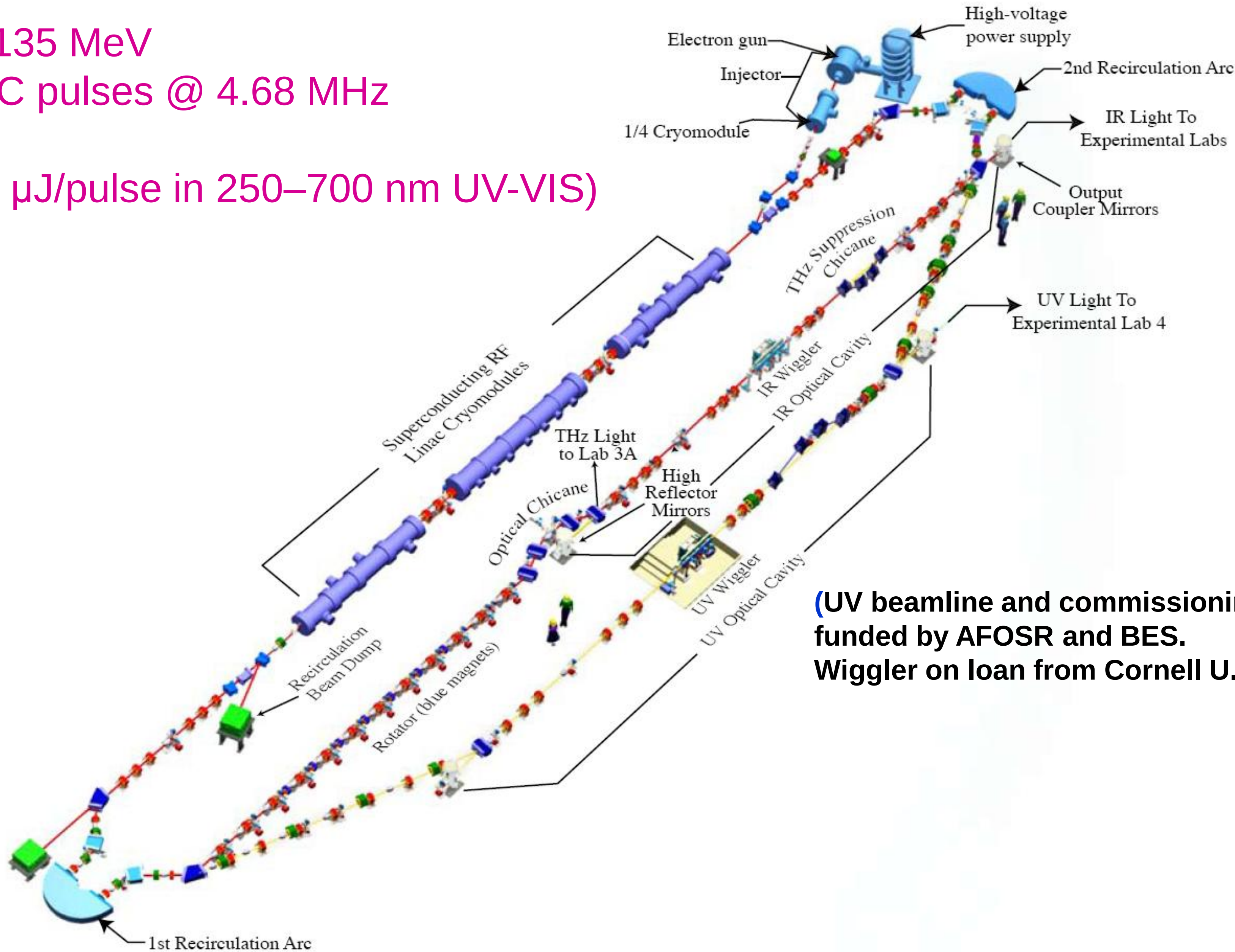
# Initial Implementation

- Funding limitations led to some compromises to lower costs.
- The high pump rate afforded by the NEG pumps was deferred
  - Might have faster degradation due to carbon build up on mirrors
- The cryocooling was deferred.
  - Limits power due to thermal aberration from power loading.
- The deformable mirrors were deferred.
  - We cannot optimize the Rayleigh range for VUV production.
  - Also limits power due to thermal aberrations.
- The THz chicane was not installed, leading to higher absorbed power from the downstream dipole.

# UV Demo Beamline Layout

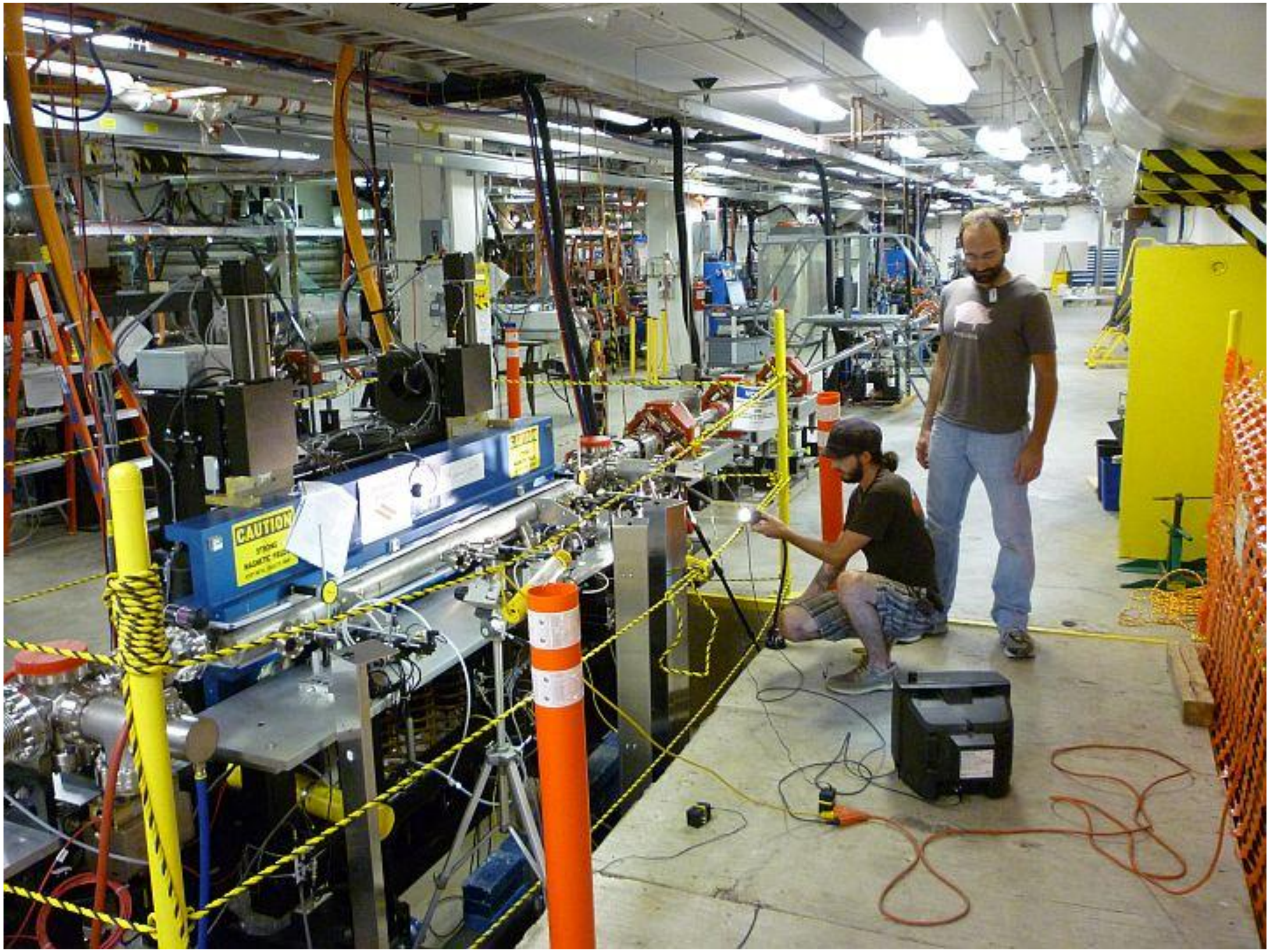
E = 135 MeV
67 pC pulses @ 4.68 MHz

(>20 μJ/pulse in 250–700 nm UV-VIS)




(UV beamline and commissioning funded by AFOSR and BES. Wiggler on loan from Cornell U.

# Cornell Undulator A Prototype

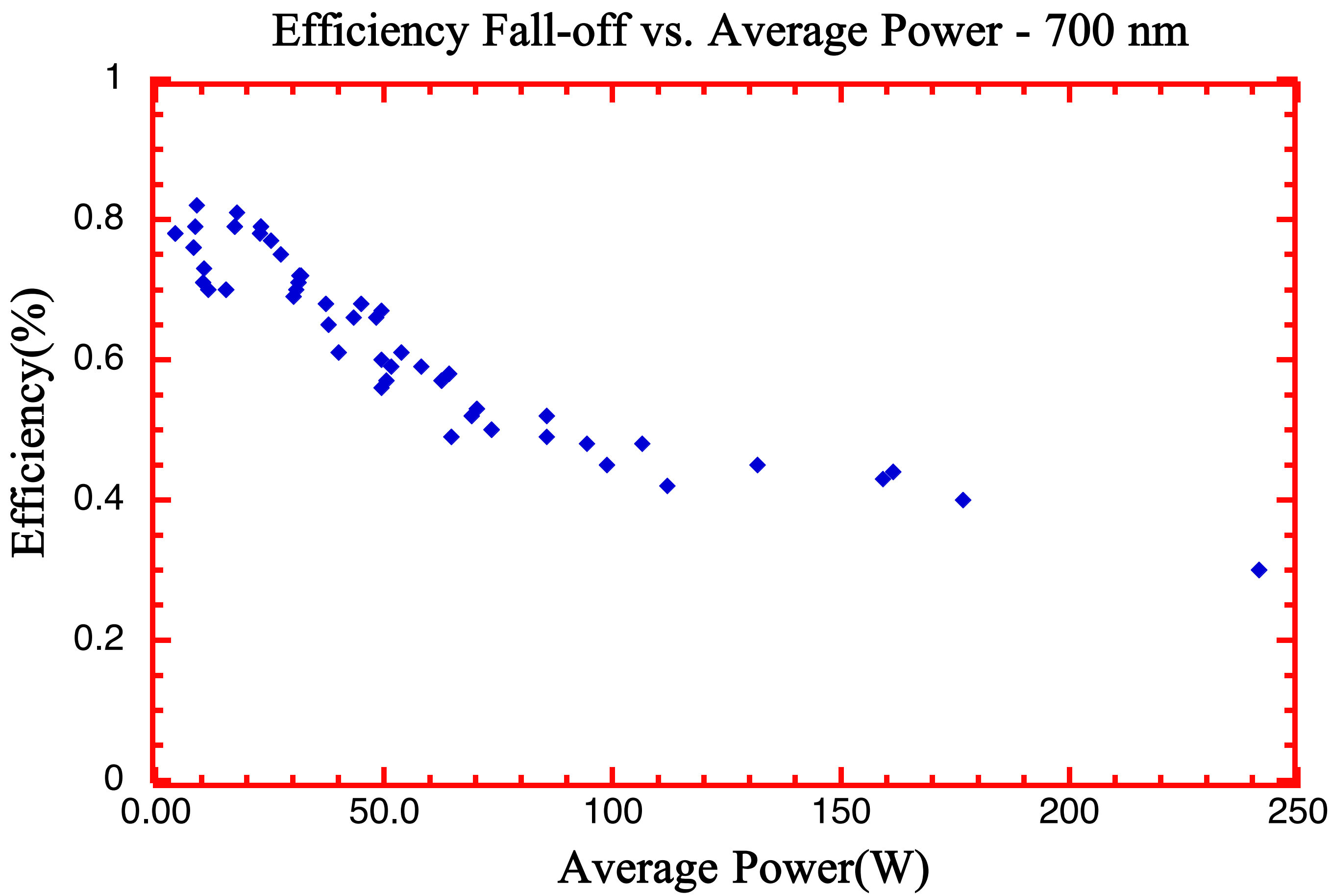


# Accelerator performance

| Parameter | IR Upgrade performance | UV line performance |
|---|---|---|
| Energy | 115 MeV | 135 MeV |
| Charge | 135 pC | 60 pC |
| Pulse length | 150 fsec rms | 100–140 fsec rms |
| Energy spread | 0.5% rms | 0.3–0.4% rms |
| Emittance | 7-8 mm-mrad | 5-6 mm-mrad |

Note: Energy spread and emittance are macropulse averages.

# FEL performance at 700nm

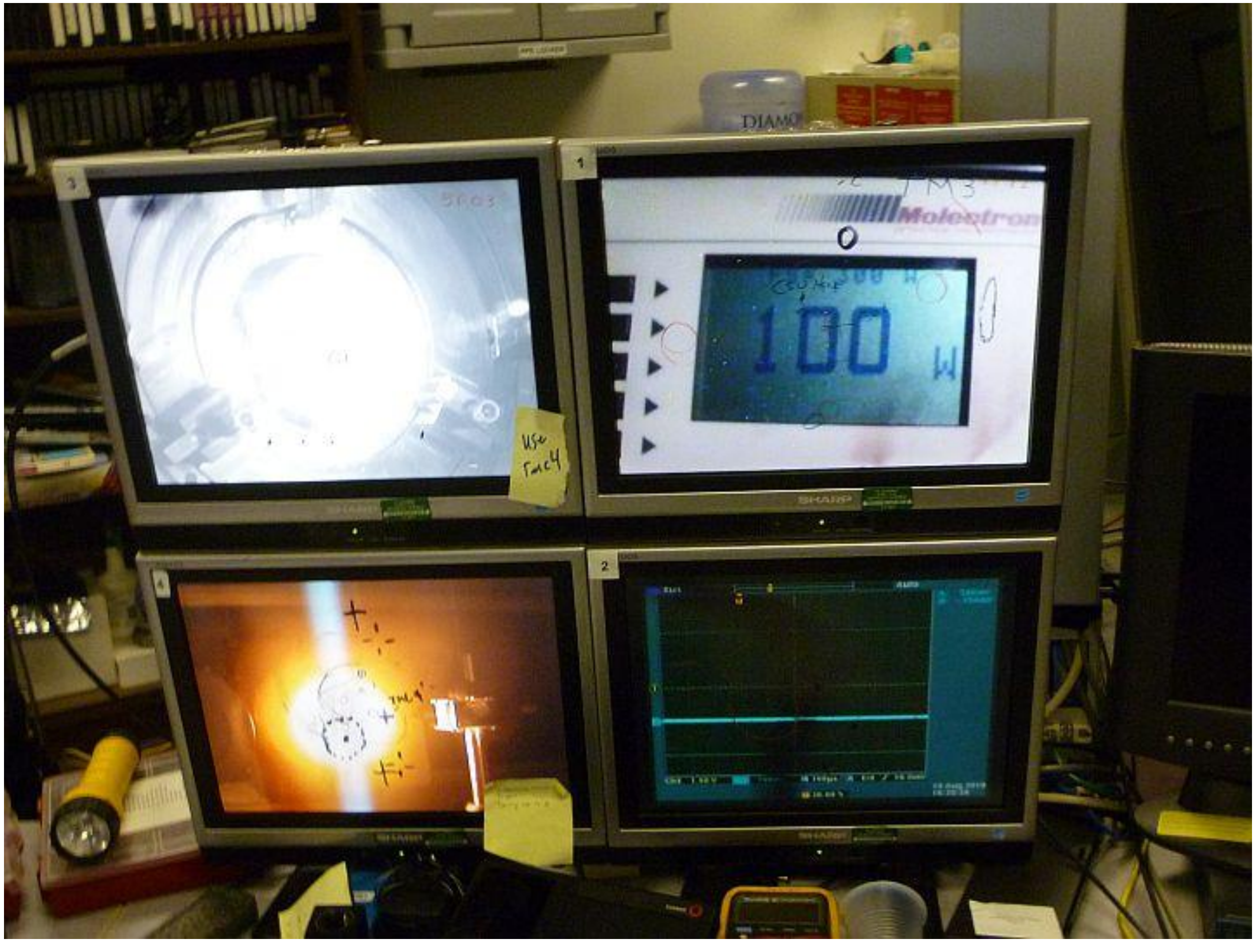



Gain at low power is ~100%, detuning curve is 12.5 μm in length

# Images while lasing at 100W

Light scattered from HR mirror

Light scattered from power probe

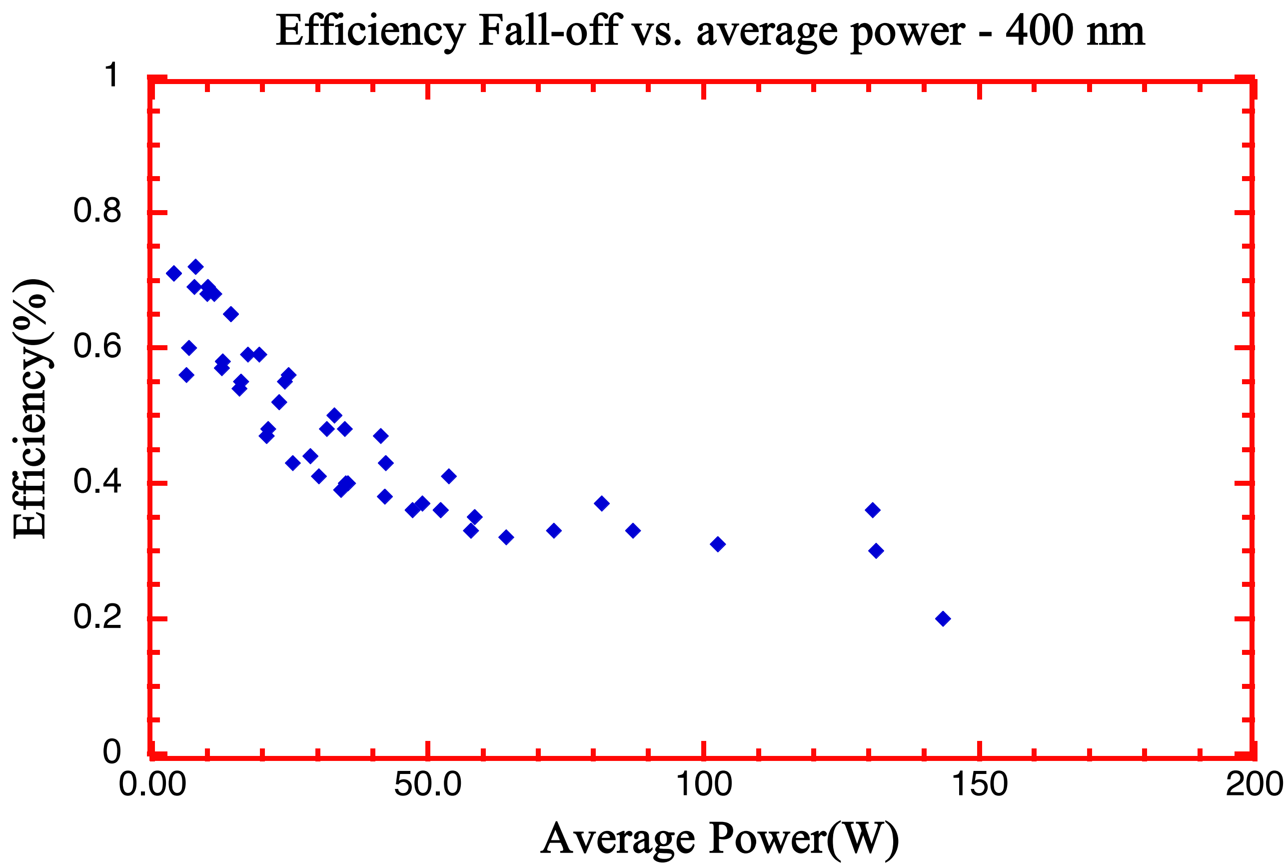



Power meter

Time dependent diagnostics

# FEL performance at 400nm

- We had to run with the OC mirror de-centered, as the metallization technique created a damage spot at the mirror center.



# Very High Gain Seen at 400 nm

# Performance of the UVFEL Has Greatly Exceeded 1D and 3D Predictions

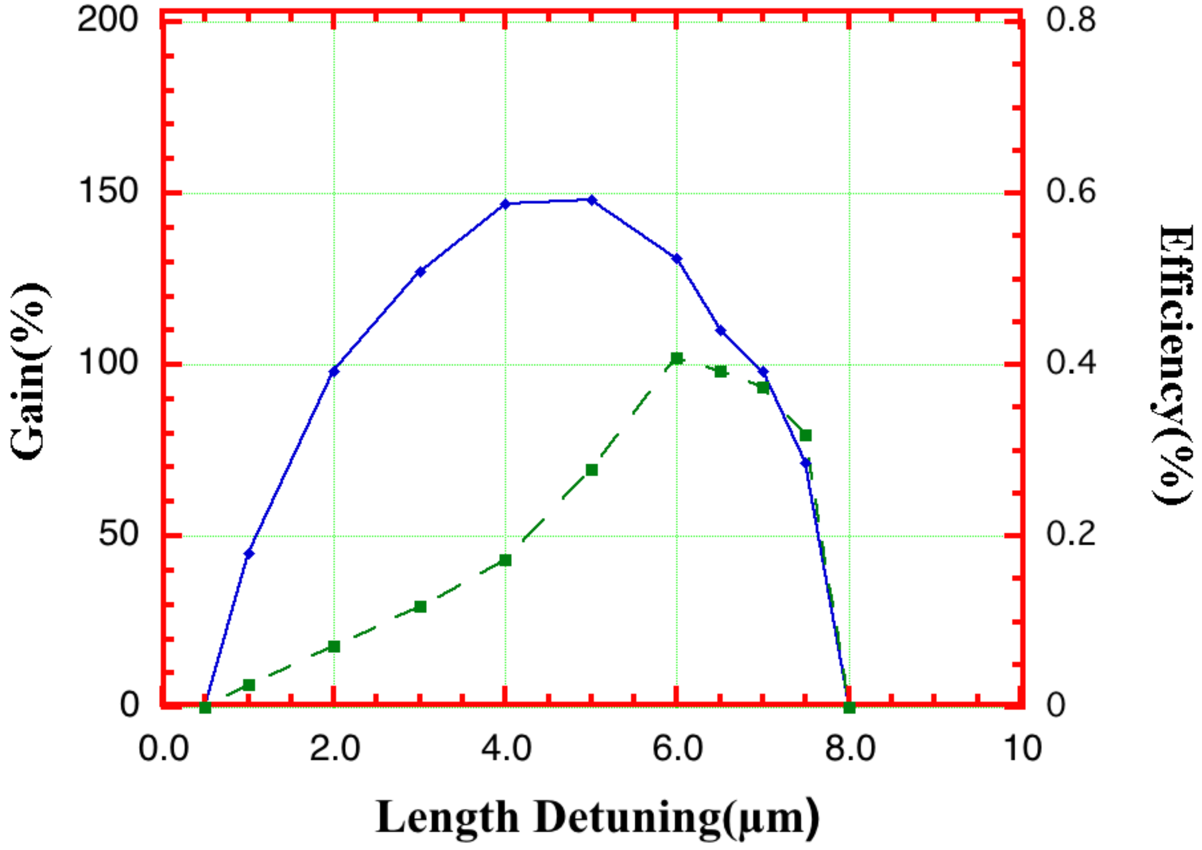
| ***Parameter*** | ***Simulations*** | ***Experiment*** |
|---|---|---|
| Turn-on time | 8.6 μsec. | 5 μsec. |
| Net Gain | ~70% | ~150% |
| Detuning curve | 4.5 μm | >7 μm |
| Efficiency | 0.5-0.7% | 0.73±0.05% |

| | Net gain (%) | Lasing eff. (%) |
|---|---|---|
| JLab spreadsheet | 75 | 0.7 |
| Genesis/OPC (3D) | 88 | 0.67 |
| Wavevnm(NPS-3D) | 88 | 0.72 |
| Medusa/OPC (3D) | 168 | 0.63 |
| Medusa/OPC (4D) | 119 | 0.41 |
| Expt | 145±10 | 0.73±0.05 |

3D codes are close on efficiency but 4D is low. Medusa 3D, modified by slippage factor is close to experiment.

# Medusa/OPC 4D simulation

- 4D Simulations using Medusa/OPC, which tends to underestimate power is shown here. Detuning curve length is correct.



# Why is the Performance so Good?

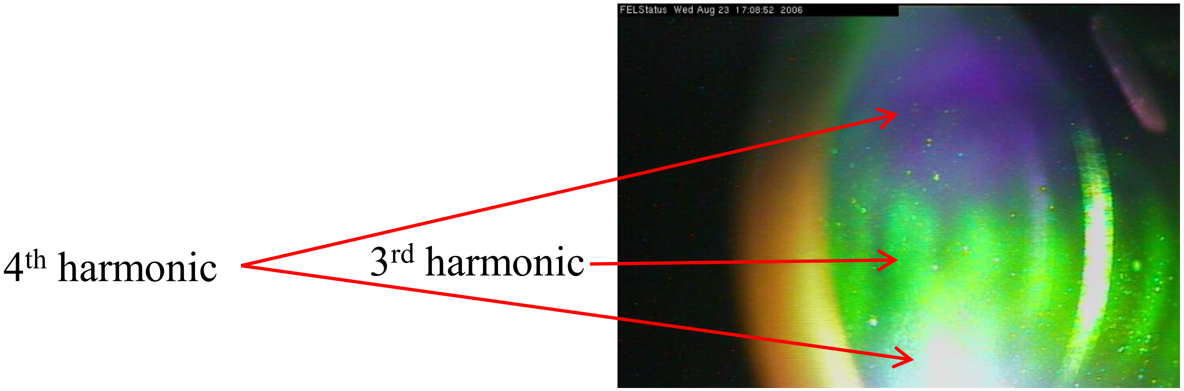
Almost all experimental imperfections reduce gain or efficiency. What might increase the gain and/or efficiency?

- Already assuming perfect wiggler and mirrors. Can one have a wiggler or mirror design that is better than perfect?
- Chirp enhances efficiency and doesn’t hurt the gain much?
- Wiggler taper? Should decrease gain if efficiency increases.
- Energy spread and emittance are projected. Slice values might be lower.(must be much lower but not hurt efficiency)
- Non-Gaussian distribution has much better performance than Gaussian distribution with the same moments?

We want to try some other 4D codes (Genesis/OPC for example) to see if they have performance closer to the experiment. We will use an S2E distribution as well.

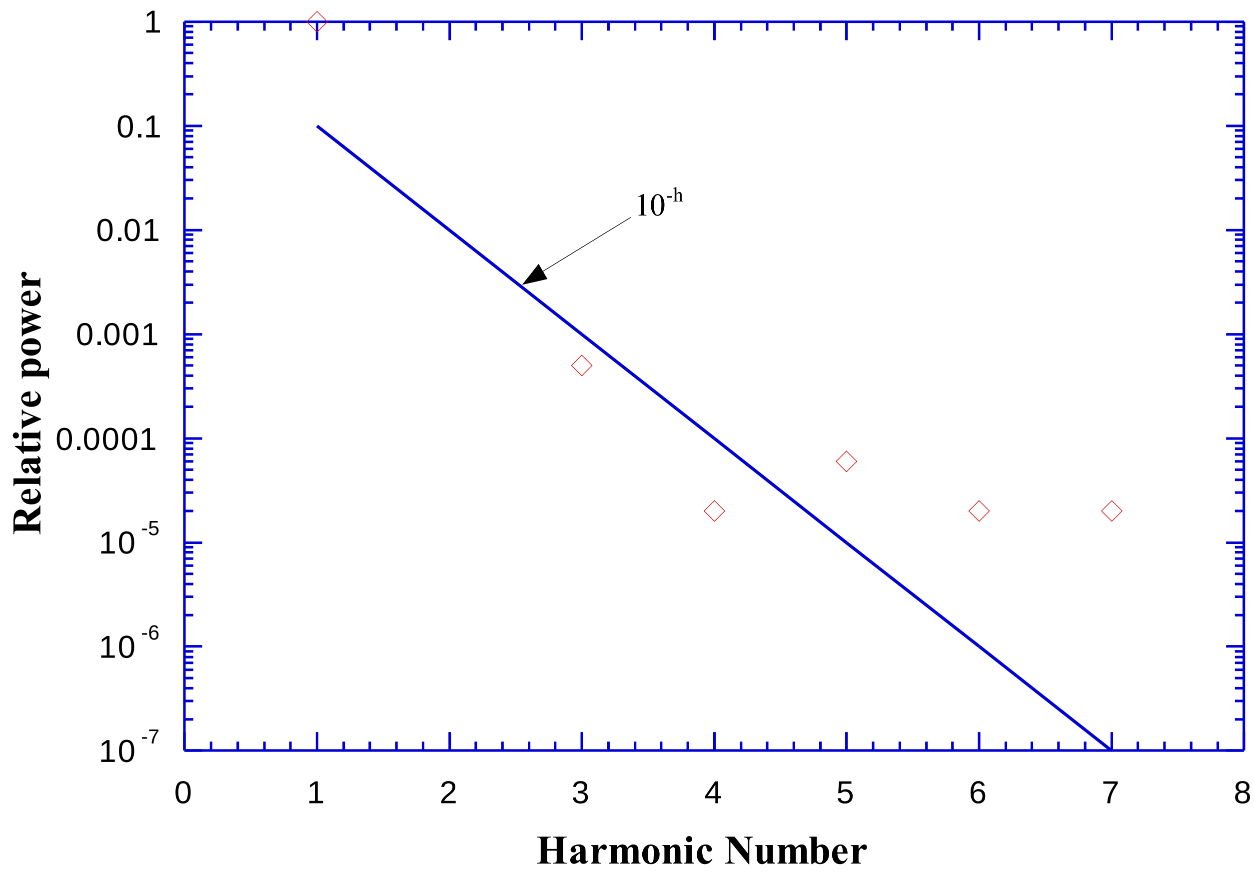
# We can generate coherent harmonics at useful levels

- Harmonics are produced through the electron bunching process that creates gain at the fundamental.
- This bunching has Fourier components at harmonics of the fundamental frequency and in our case extends into the vacuum ultraviolet.
- First few harmonics can be many 10’s of watts.
- We performed measurements in the IR Demo
    - “Coherent Harmonics in the Super-Radiant Regime from an FEL”, S.V. Benson, J.F. Gubeli, and M.D. Shinn, Proc. PAC 2001
- Performed preliminary measurement in late August 2005
    - Ratio of 3rd-7th harmonics to the fundamental




Harmonics on OC Mirror while lasing at 1.6 micron

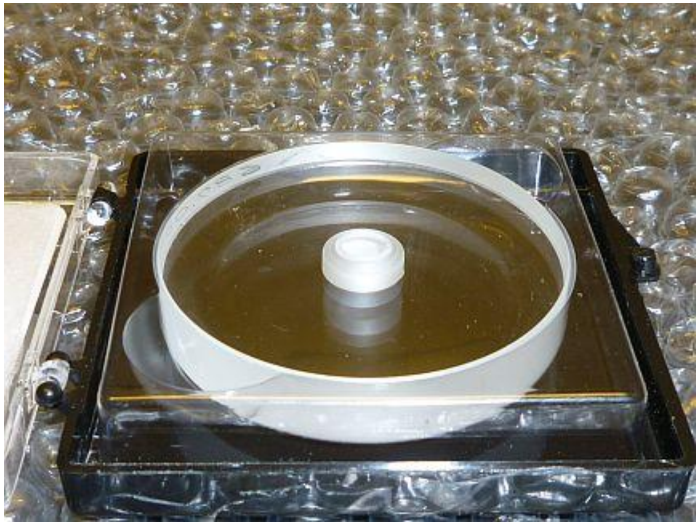
# IR Demo harmonic power measurements

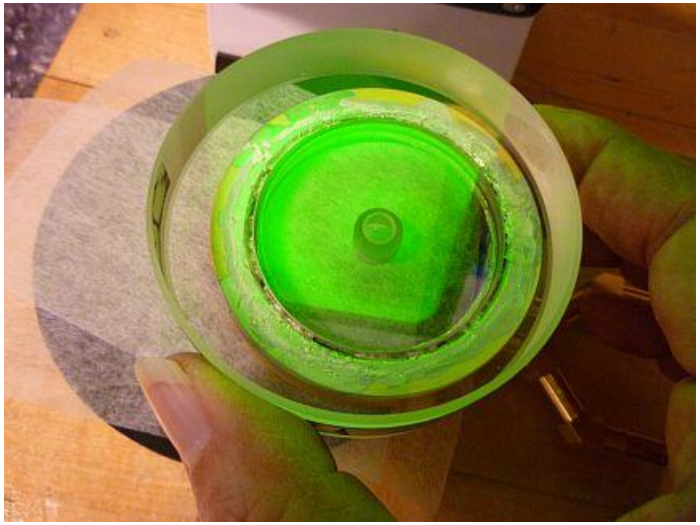



Third harmonic power is down by about a factor of 1000. We get about 50 W at 372 nm so we expect about 50 mW of VUV light.

# Get the VUV out Through a Hole

- Hole was drilled in an already fabricated sapphire substrate
  - This is nontrivial – a larger hole was mechanically drilled through the plano (back) side to within 1mm of the front surface. Front was drilled with an ultrashort-pulsed laser.
- It was then coated for max R at 372nm, then metalized and brazed into a cooled mirror holder and installed.

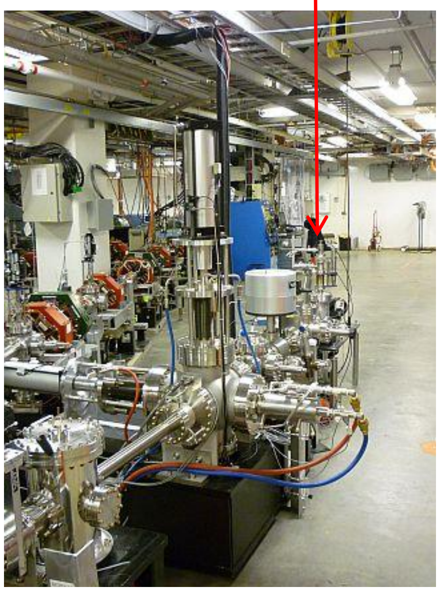


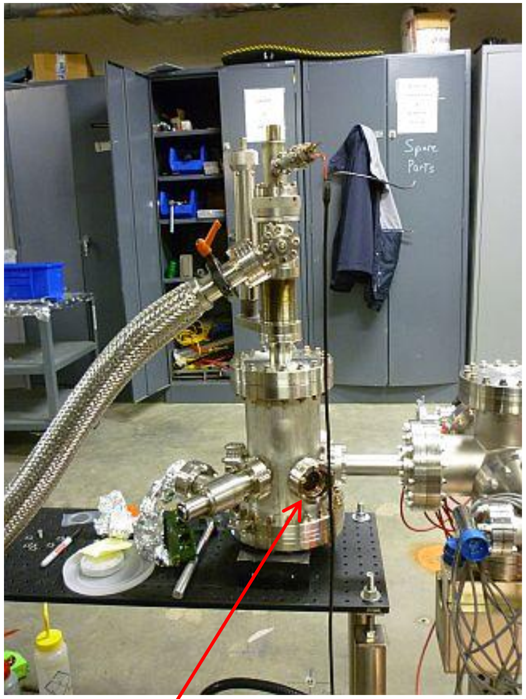


# Initial Characterization of 10eV photons

- Bob Legg had built a chamber for the SRC at Univ. Wisconsin that we adapted for our purposes:

VUV Chamber



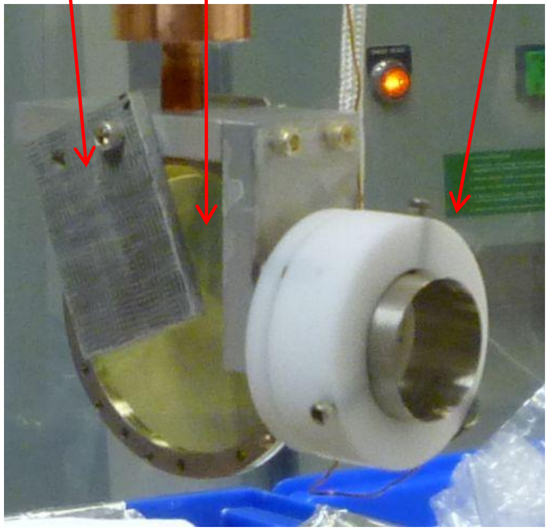


Viewport

10eV viewer

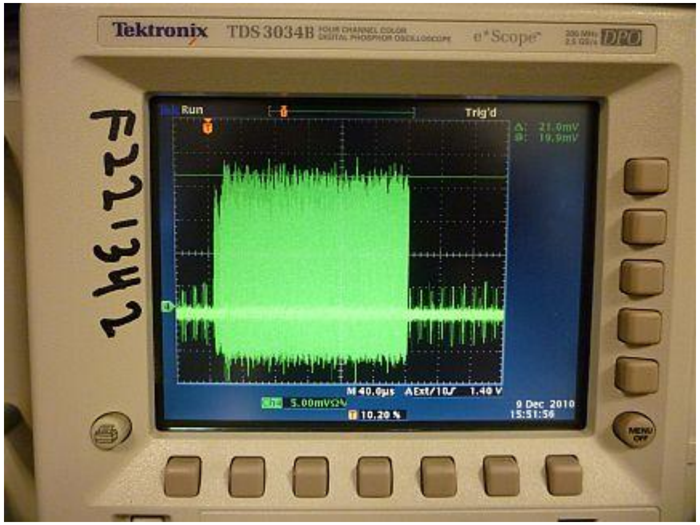
Ce:YAG viewer

VUV photodiode

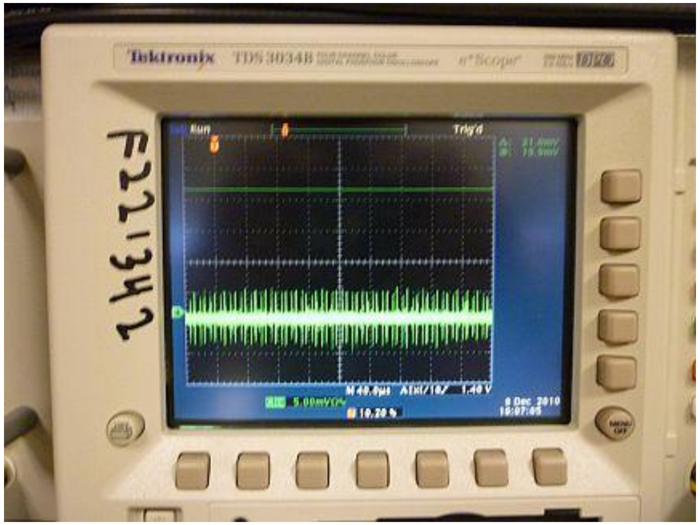


# We detected the higher harmonics on 12/09

- The output through the hole was dominated by the fundamental and 3rd harmonic
  - The 5th harmonic is approximately $10^2$ weaker.
  - By closing a windowed vacuum valve, we effectively inserted a long pass filter – blocking the 10eV but not the fundamental, and proving the detector only responded to the higher energy photons.

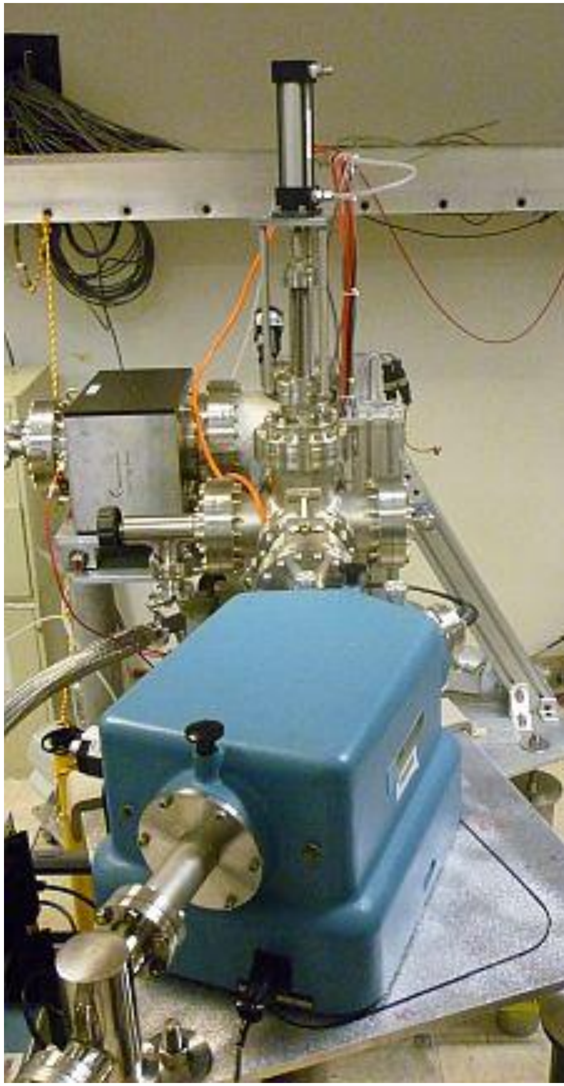


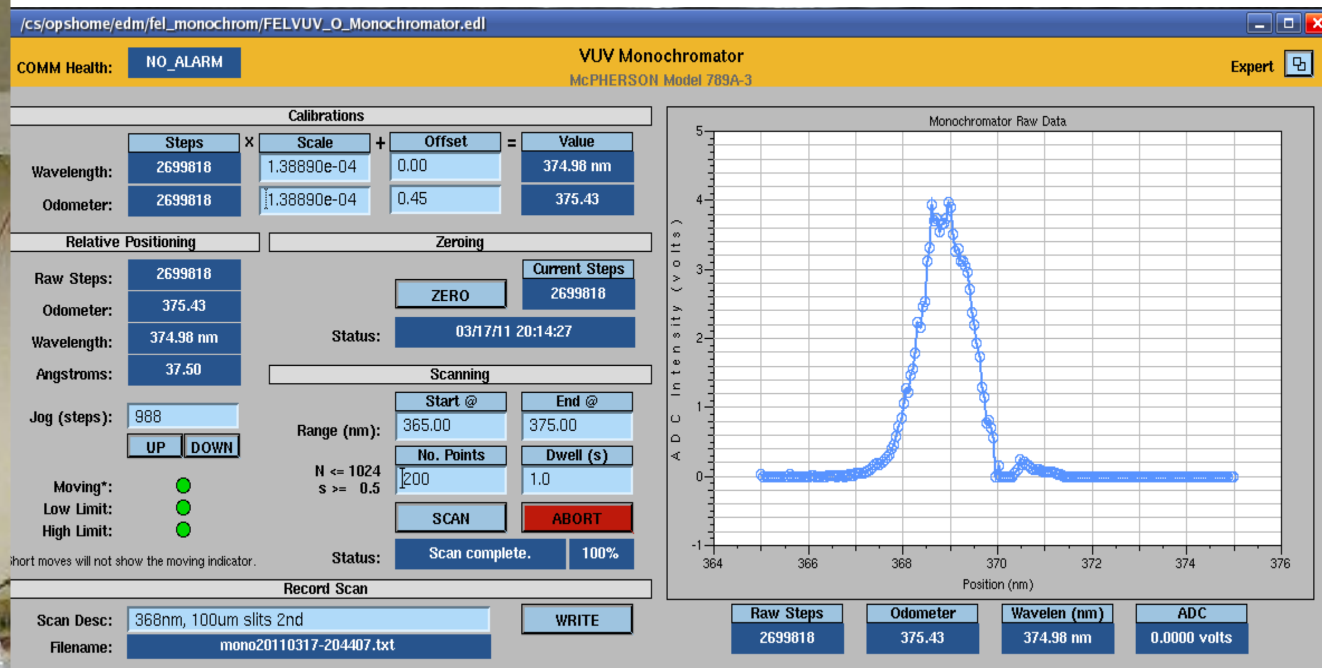

Windowed valve open




Windowed valve closed

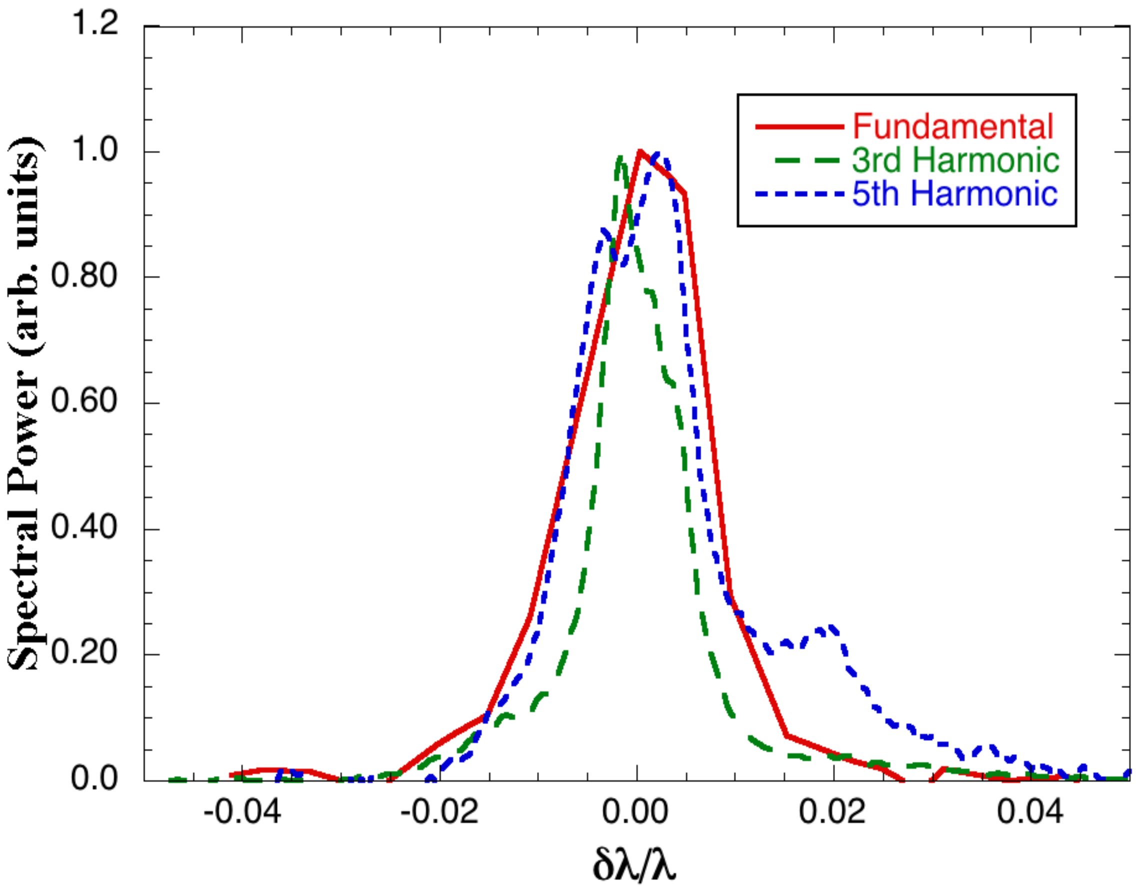
# Spectrum of UV in User Lab 1






Scattered UV light in the monochromator prevented a clean measurement of the VUV spectral bandwidth.

# Relative Spectral Bandwidth of Harmonics




Measurements on the IR Upgrade FEL at 2.25 microns indicate a third harmonic relative bandwidth 60% of the fundamental relative bandwidth.

# 10 eV measurements

- We measured a maximum photocurrent of 0.46 μA for a train of 240 μs pulses at 60 Hz (1.4% duty factor)
  - The amplitude fluctuations were small, of order ± 3%
- This corresponds to 4.8 x $10^{12}$ ph during the macropulse.
- If the efficiency were unchanged when going cw, this is ~ 2 x $10^{16}$ ph/sec
- We still need to measure the bandwidth of the 3rd harmonic to make an accurate comparison to storage rings. An estimate derived from 2.2 μm lasing is 0.2% FWHM.
- In User Lab 1 we measured a conversion efficiency of 3x$10^{-4}$. This was with a non-optimized laser and a damaged transport mirror so it is a lower limit.

# Plans for the future

- Install new undulator using LEUTL jaws (Thanks Argonne!)
- Add radius of curvature control to the HR cavity mirror to optimize the FEL output as well as the production of harmonics.
- Install mirrors optimized for harmonic production.
    - This uses silicon rather than sapphire substrates.
- Upgrade optical transport to better separate UV and VUV photons.
- Install cryogenic mirrors to allow lasing at the 1 kW level.
- Install THz chicane.
- Raise energy to push to shorter wavelengths.

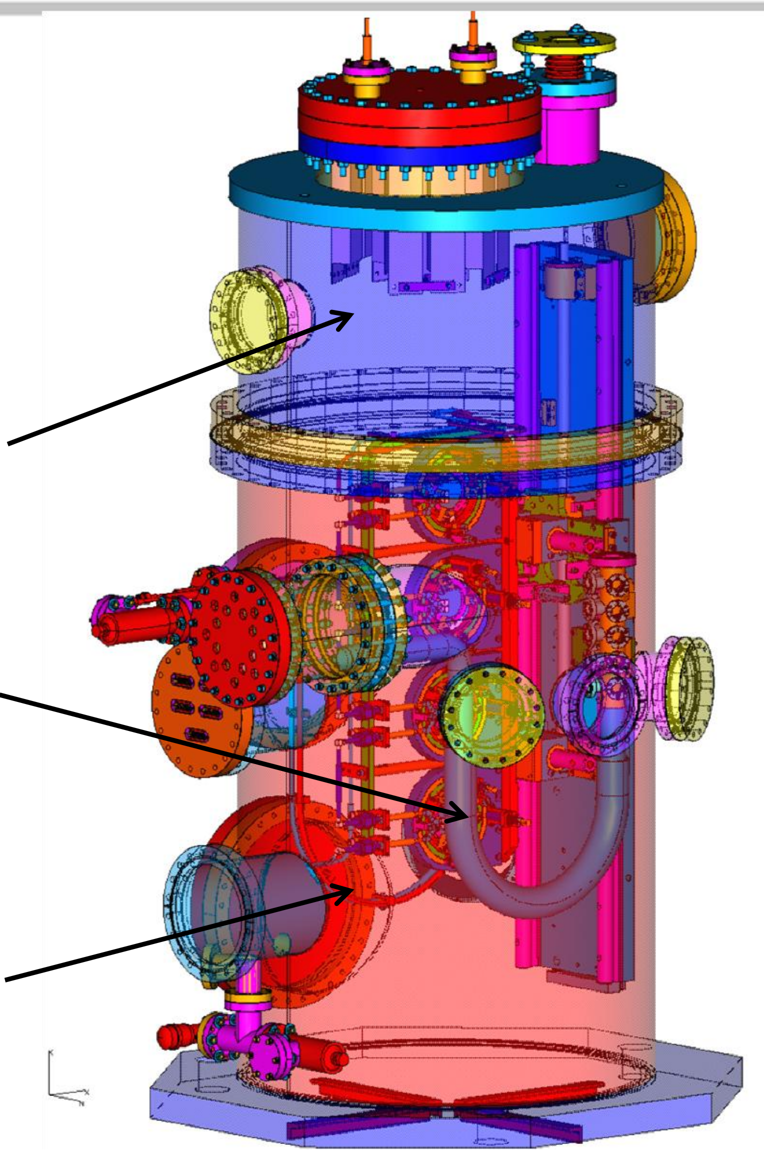
# Acknowledgments

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.

- Ramin Lalezari – Thin Films (coating design and deposition)
- Univ. of Wisconsin (SRC) – VUV chamber with aluminum photodiode

# The UV FEL cavity has evolved from the IR Upgrade

- Gimbaled mirrors have high first resonance (> 200 Hz)
- Angular control using piezos
- NEG strips for higher pumping speed
- Majority of wiring contained in a separate vacuum enclosure to lower out-gassing.
- Designed for cryo-cooling with well-separated cooling lines and Macor thermal isolators.



# UV Demo Commissioning Timeline

- January 2006 - Install and commission Cornell wiggler with new gap mechanism.
- Spring and Summer 2009 – Install beamline components except for optical cavity and wiggler chamber.
- Fall 2009 – CW beam through UV beamline.
- Spring 2010 – Install new zone 3 module and commission.
- June 2010 – Lase at 630 nm, 67 pC in IR laser with 135 MeV beam.
- July 2010 – Recirculate laser quality 1 mA CW beam through wiggler sized aperture.
- August 17, 2010 – First electron beam through wiggler.
- August 19, 2010 – First lasing, 150 W CW at 700 nm.
- August 31, 2010 – First lasing in UV, 140 W @400 nm, 68 W @372 nm
- December 9, 2010 – First measurement of 124 nm light