

Status of the JLab ERL

George R. Neil, C. Behre, S. V. Benson, G. Biallas, J. Boyce, J. Coleman, D. Douglas, H. F. Dylla, R. Evans, P. Evtushenko, C. Gould, A. Grippo, J. Gubeli, D. Hardy, C. Hernandez-Garcia, C. Hovater, K. Jordan, M. J. Kelley, M. Klopff, W. Moore, T. Powers J. Preble, M. Shinn, R. Walker, G. P. Williams, and S. Zhang

**Jefferson Lab
Newport News, Virginia**

**ICFA FLS Workshop
Hamburg
May 16, 2006**

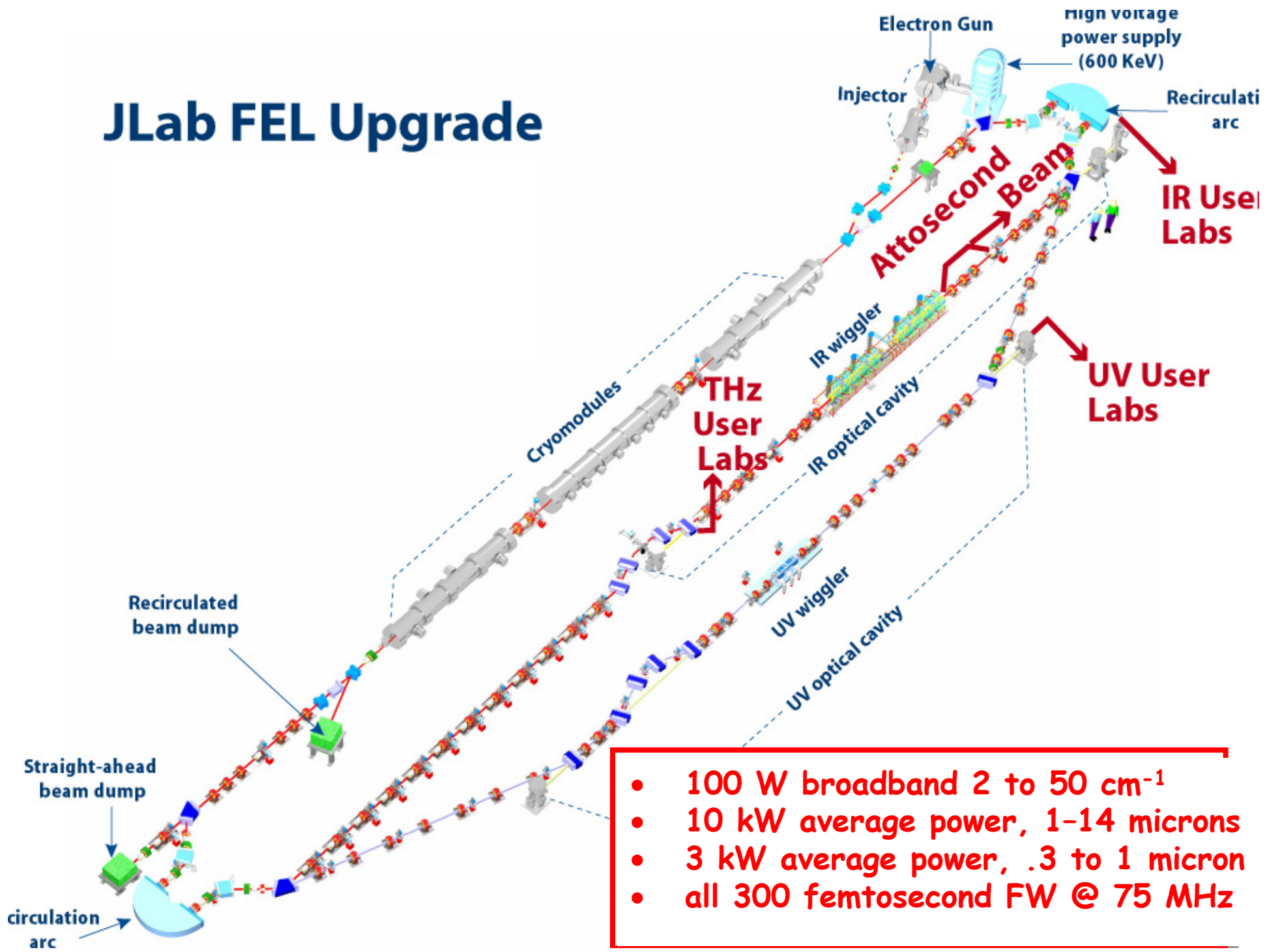


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JLab FEL Upgrade



- 100 W broadband 2 to 50 cm^{-1}
- 10 kW average power, 1-14 microns
- 3 kW average power, .3 to 1 micron
- all 300 femtosecond FW @ 75 MHz

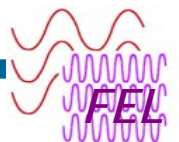
IR Upgrade Specifications

- **Average Power** > 10,000 W
- **Wavelength range** 1 to 14 μm
- **Micropulse energy** > 100 μJ , in pulse train 50 μs to CW, arbitrary
- **Micropulse length** $\sim 0.1\text{-}2$ ps FWHM (adjustable)
- **PRF** 74.85 MHz $\div 2x$ down to 4.68 MHz
- **Bandwidth** $\sim 0.2\text{-}3$ % (always Fourier transform limited!)
- **Position/Angle jitter** < 100 μm , 10 μrad
- **Polarization** linear, > 1000:1
- **Transverse mode** < 2x diffraction limit. Gaussian profile
- **Beam dia. at lab** 2 - 6 cm, wavelength dependent

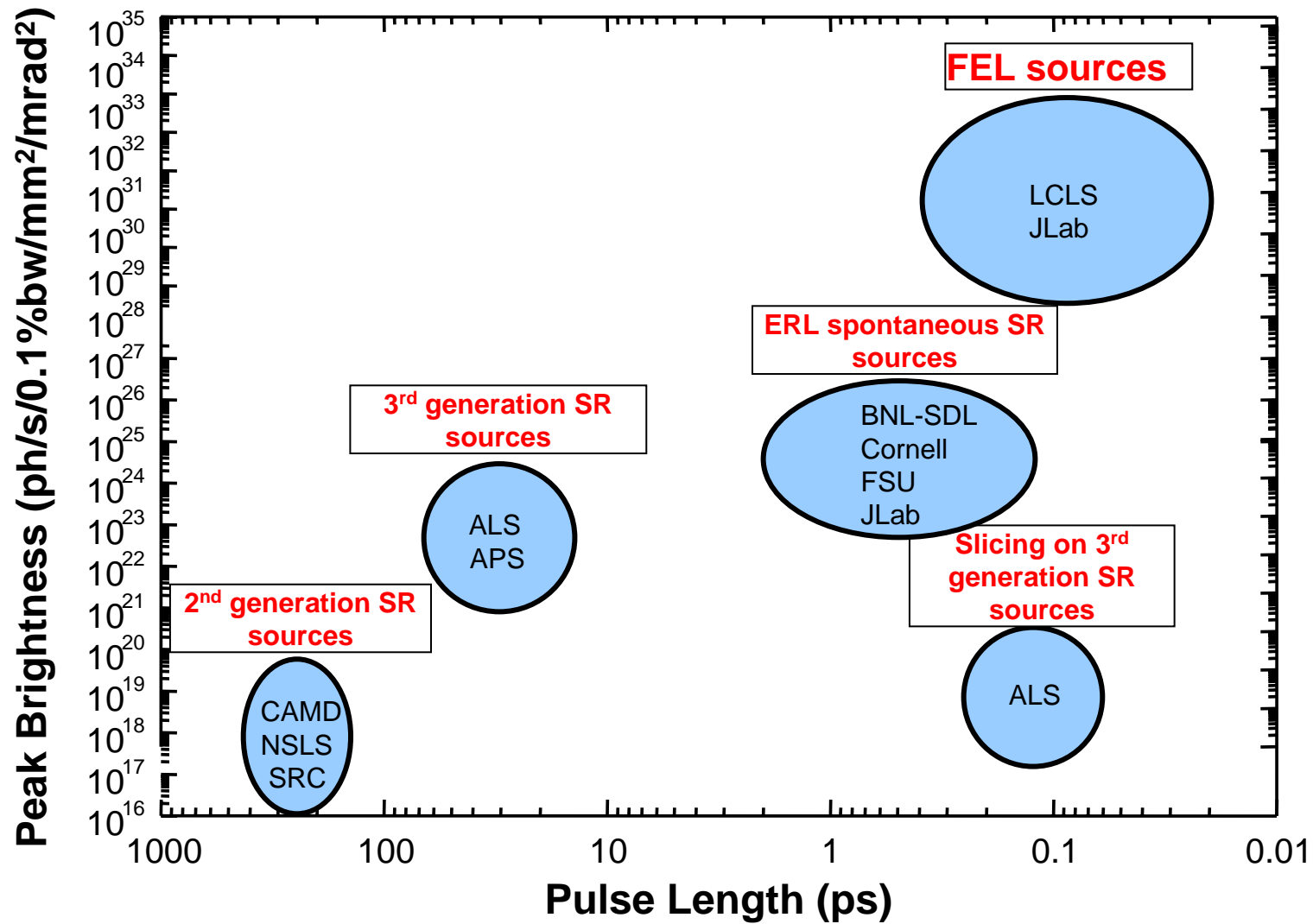


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Light Source Landscape

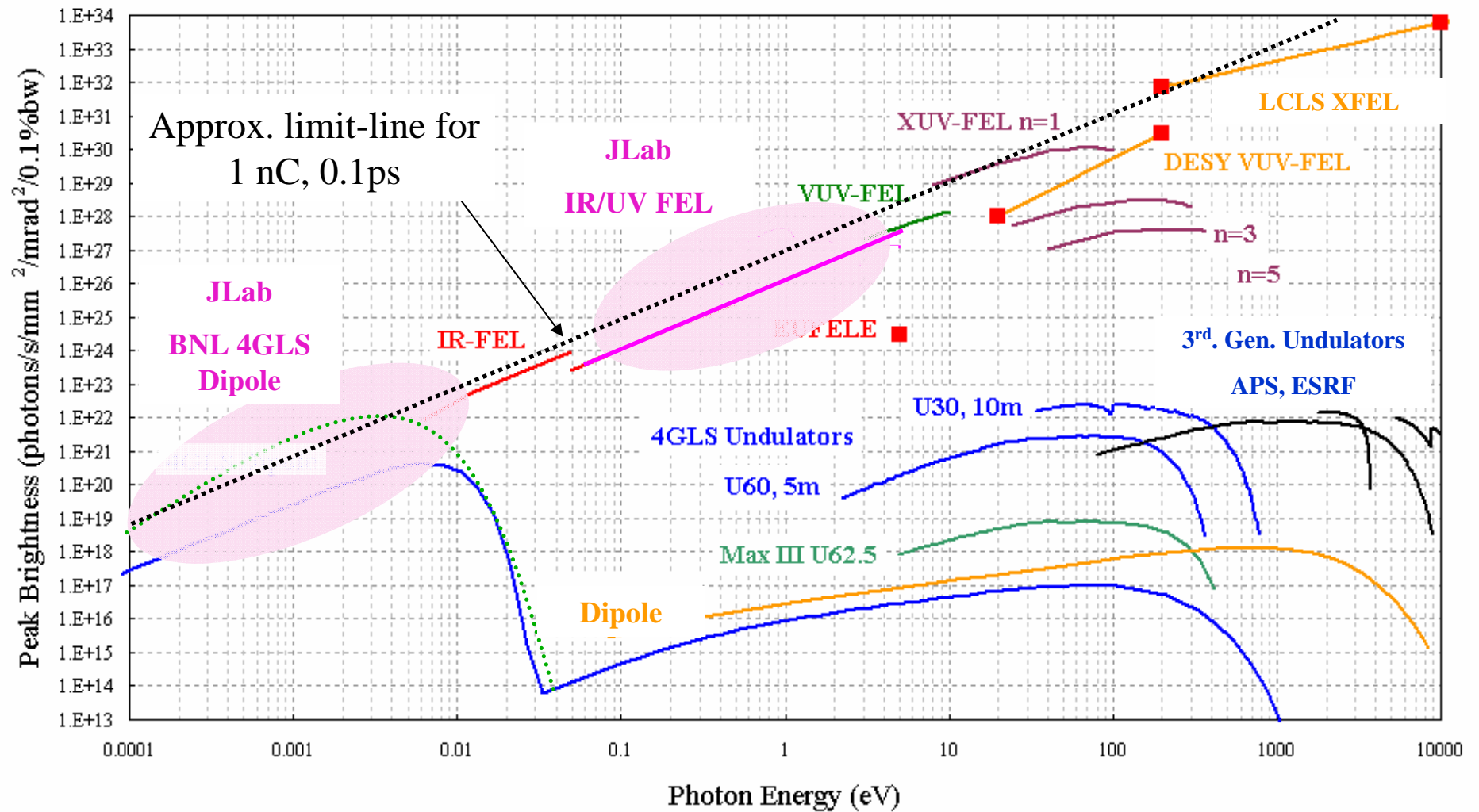


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Light Source Landscape



All data is approximate for illustrative purposes

Wendy Flavell Manchester University UK



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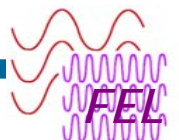
JLab ERL Status

- . **IR Upgrade FEL running up to 10 kW**
 - . **10 kW average power lasing achieved at 6 microns**
 - . **Lased 2 to 7 kilowatts at 1.0, 1.6, 2.8 microns with narrowband mirrors**
 - . **Lased at 20-100 W from 0.7 to 4.8 microns, tuning over the full band in seconds using hole outcoupler**
 - . **User experiments have begun: nanotubes, fat cell necrosis**
- . **THz system installed and has begun user experiments**
 - . **Power, spectrum, and noise being characterized**
- . **UV installation deferred due to loss of funding in FY06**
- . **UV FEL project hardware is in-hand and 90% complete**
 - . **Attempting to re-establish program support for FY07**



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What have we learned in the last six months?

Accelerator

- **Stable, reproducible operation at 115 MeV**
- **Very short pulses at the wiggler (<350 fsec FWHM) that are maintained at currents > 5 mA CW for hours**
- **Excellent beam quality**
 - Transverse core beam emittances in x and y ~6-8 mm-mrad but halo emittances 3-5x larger with significant envelope mismatch**
 - Longitudinal emittance typically ~90 kV-psec**
 - $dp/p \sim 0.5\%$ at 115 MeV/c, $\sigma_t \sim 0.15$ psec at wiggler**
- **Strong laser performance**
 - Extraction efficiencies >1.7%**
 - (have observed up to 2.6kW/mA=2.25%)**
- **Stable, robust, trouble free, long-lived gun operation**



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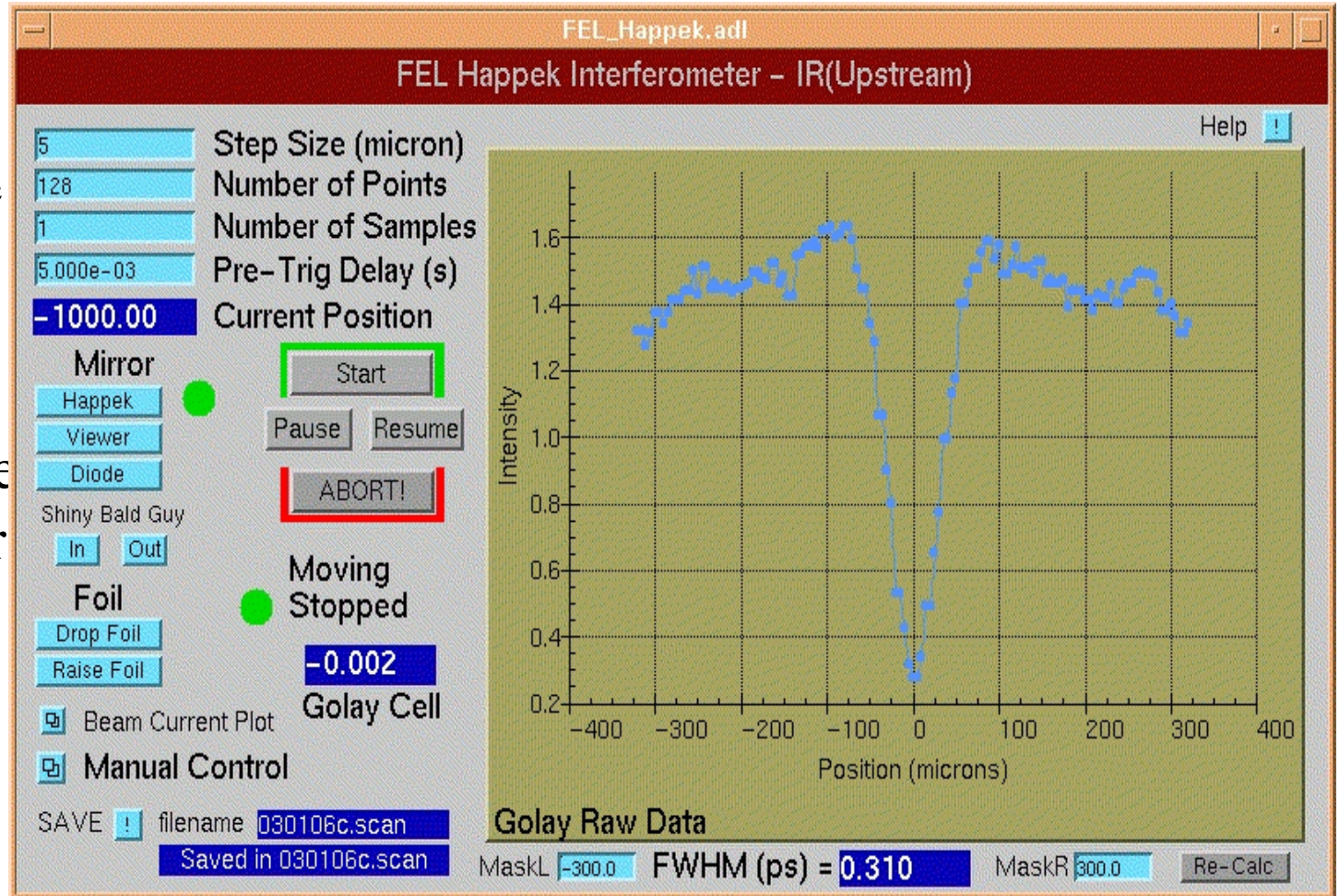
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Linac produces stable ultrashort pulses

We now regularly achieve 300 fs FWHM electron pulses

Optical pulses are of the same order at zero desynchronism when measured by FROG



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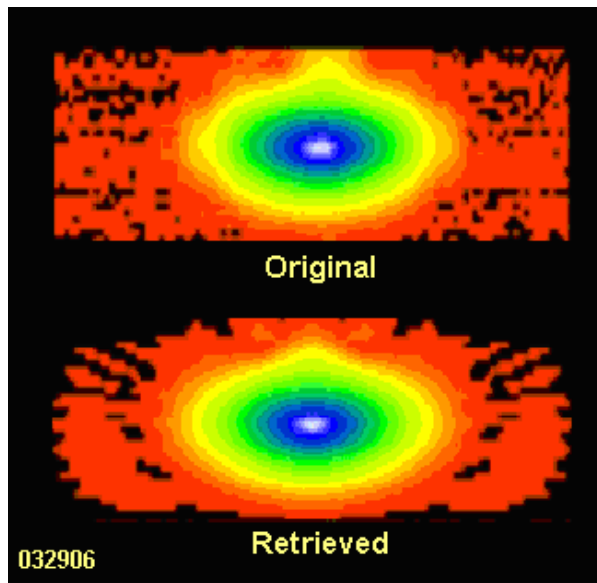


FROG Analysis of JLAB FEL Pulses

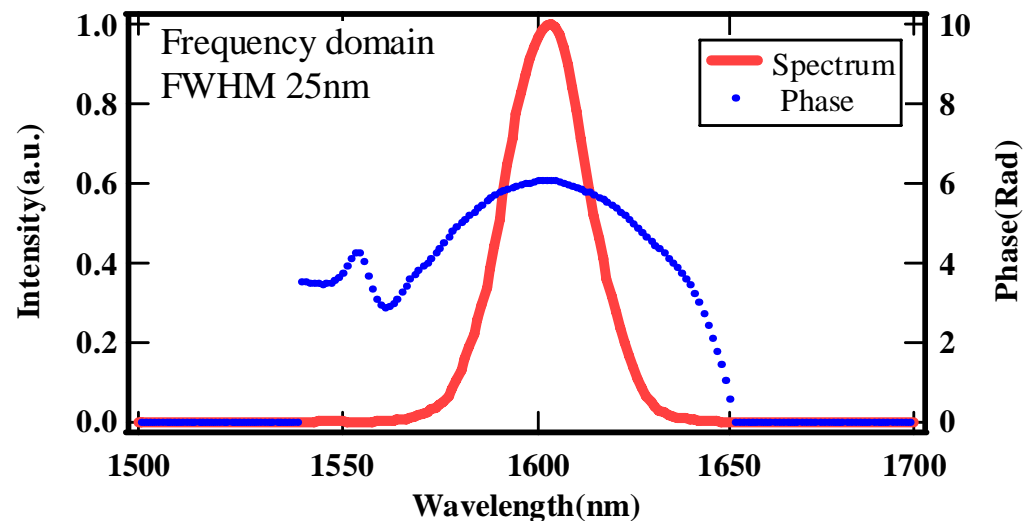
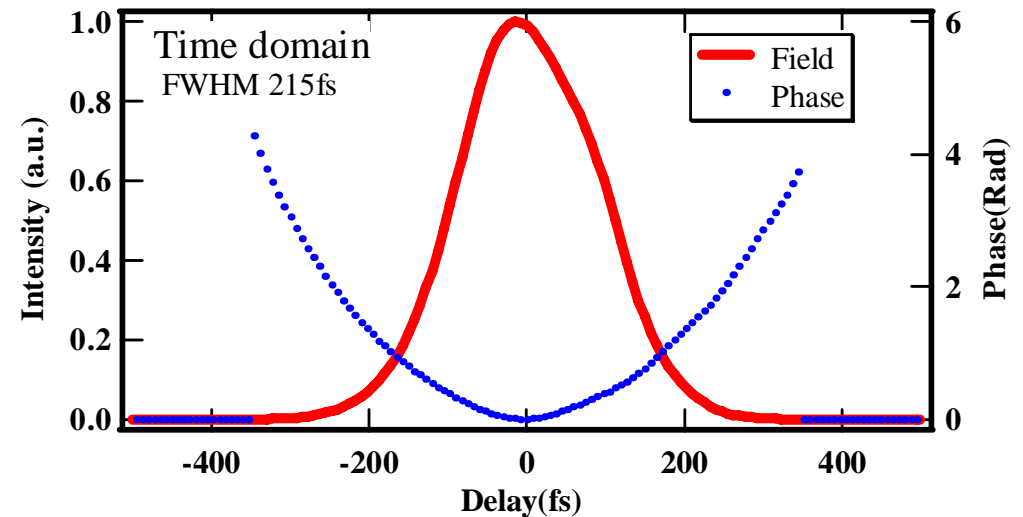
Courtesy S. Zhang

- Laser: CW 1KW in 9MHz
- Wavelength: 1.6 μ m

SHG FROG Traces



FROG error is 0.0015



Phase space out of linac from streak camera

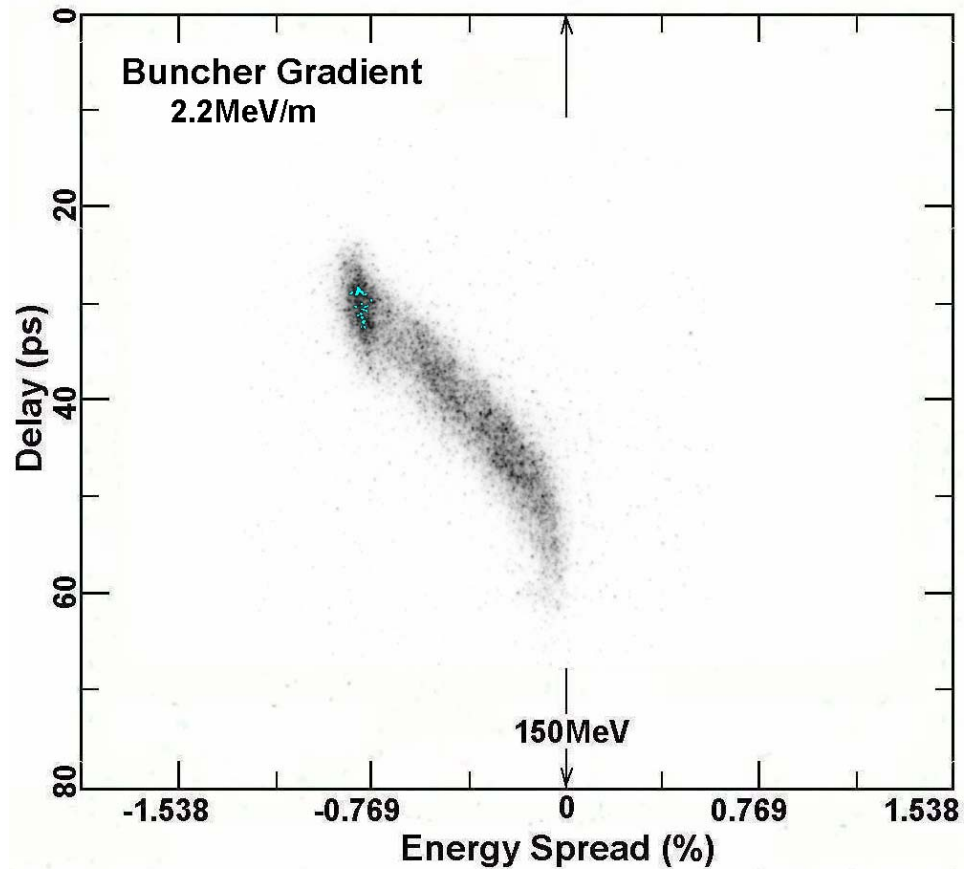
Beam Conditions:

150MeV

60Hz, 1 ms

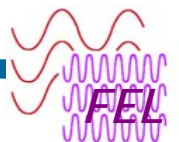
9MHz

110pC

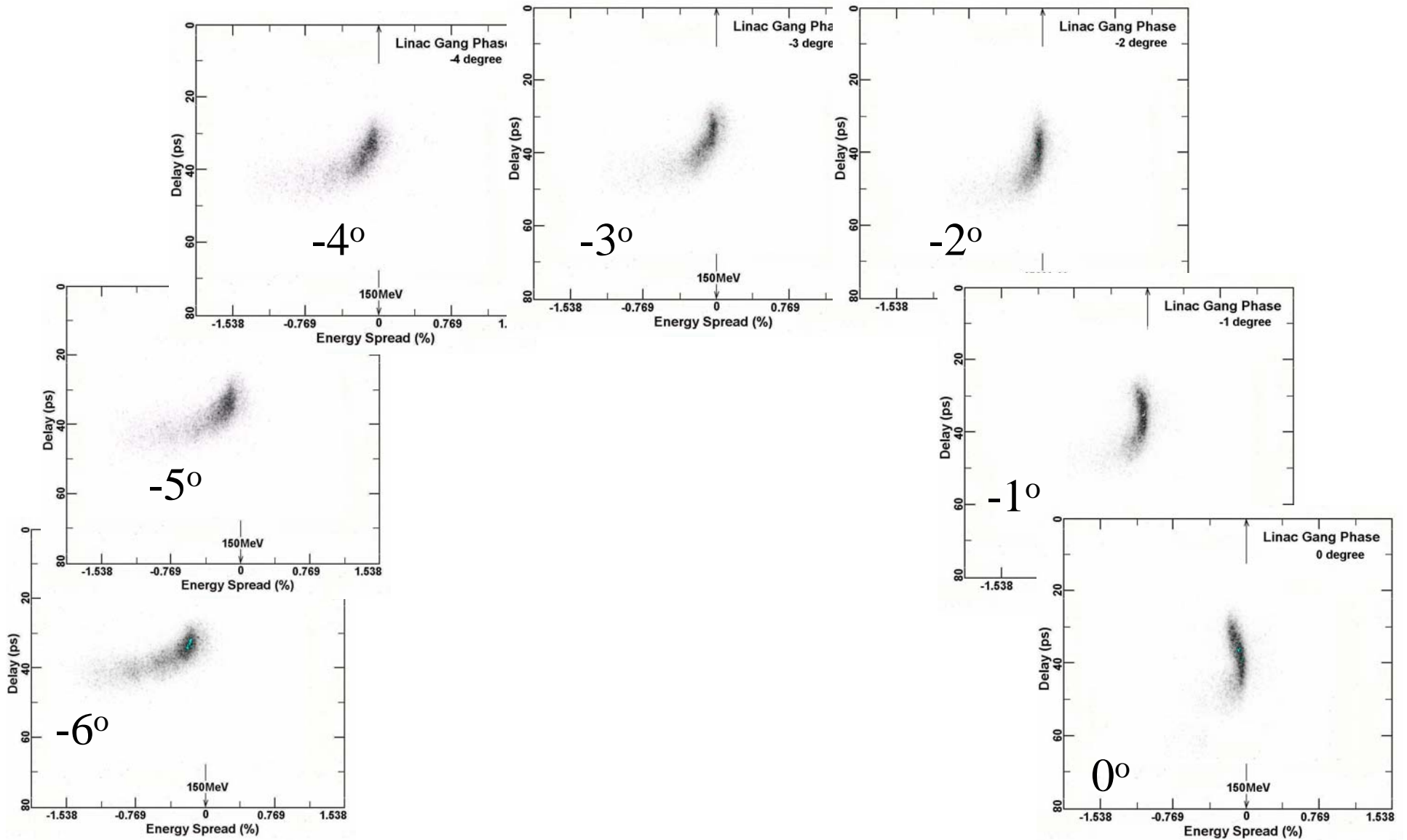


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Phase variation between injector and linac

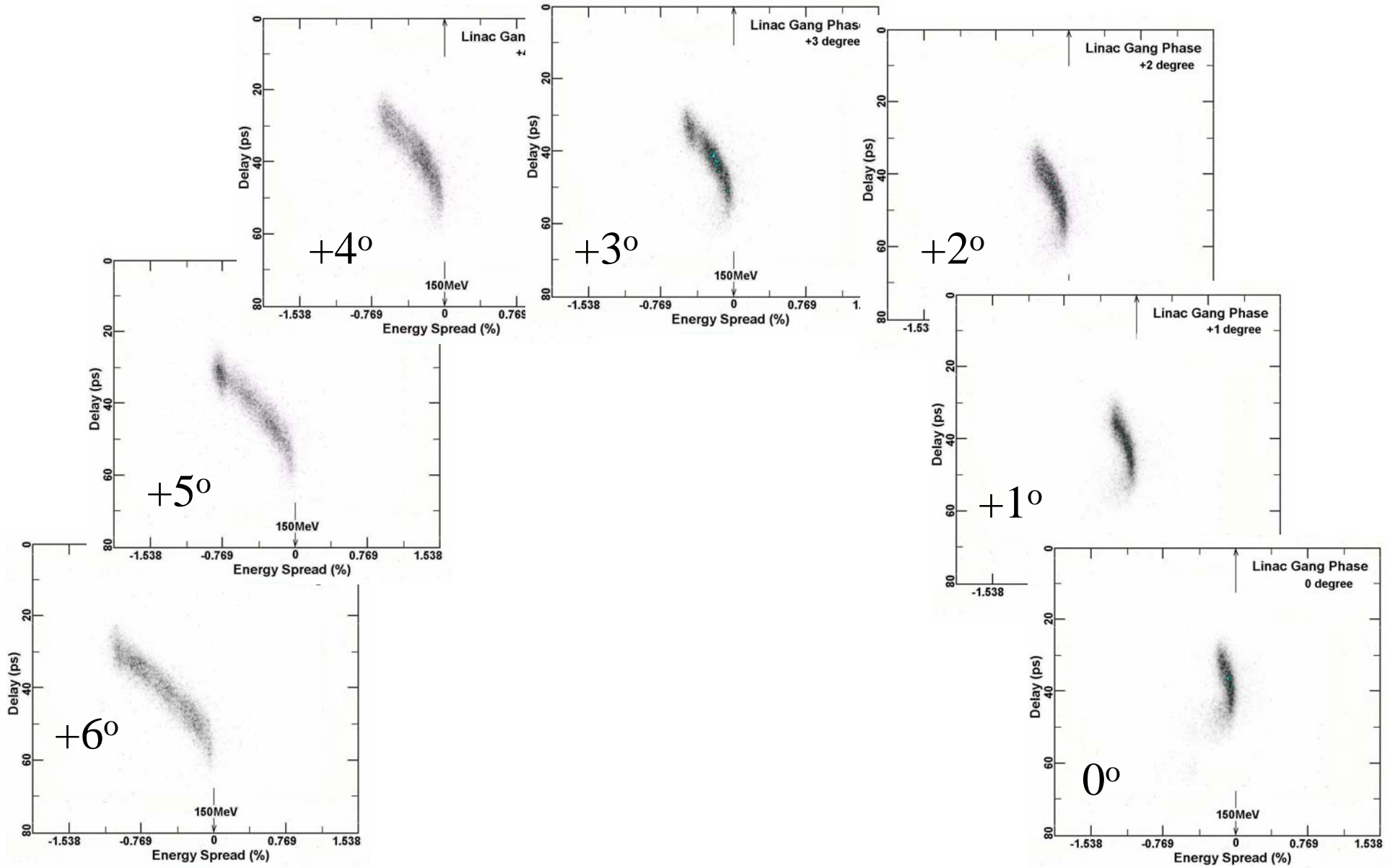


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Phase variation between injector and linac

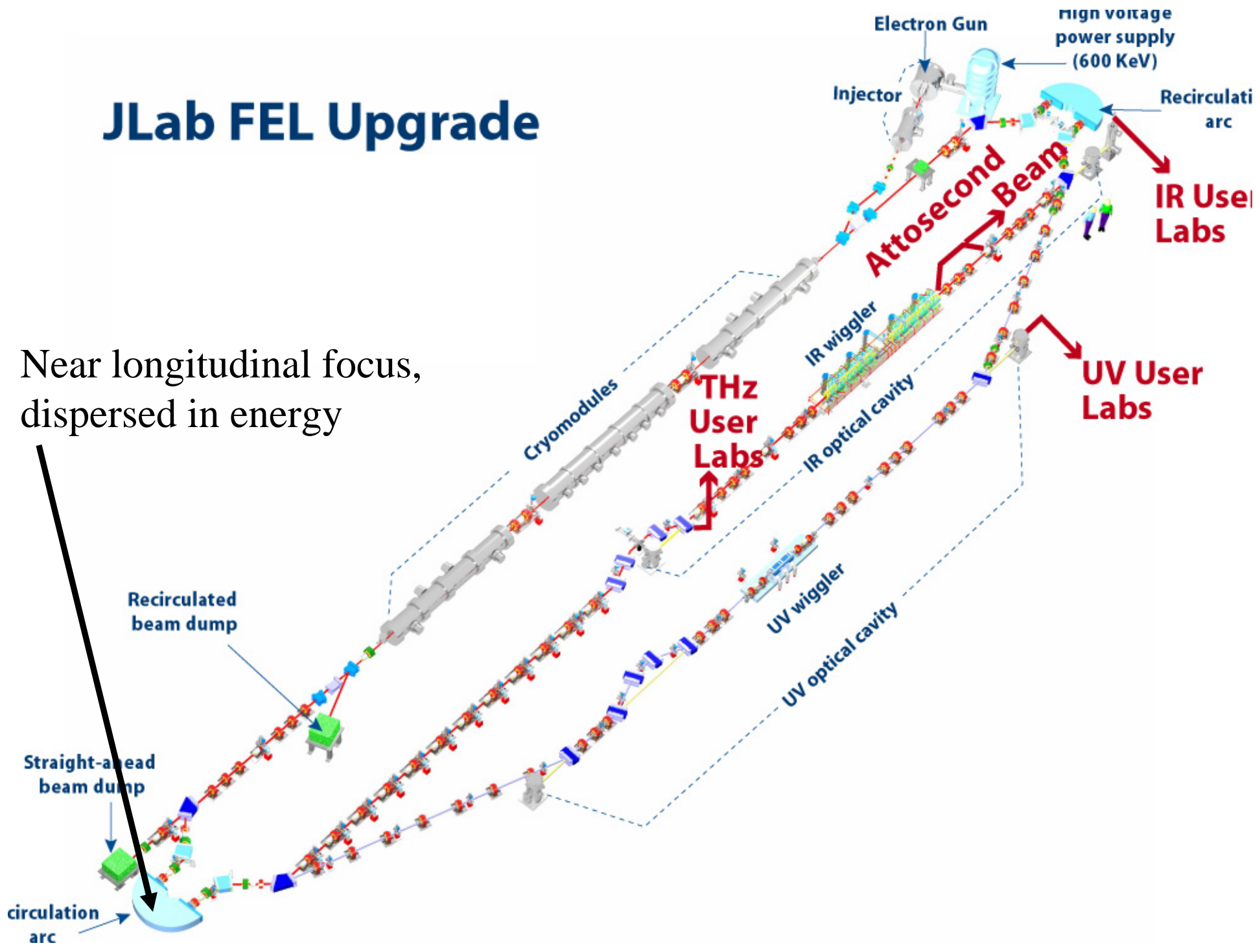


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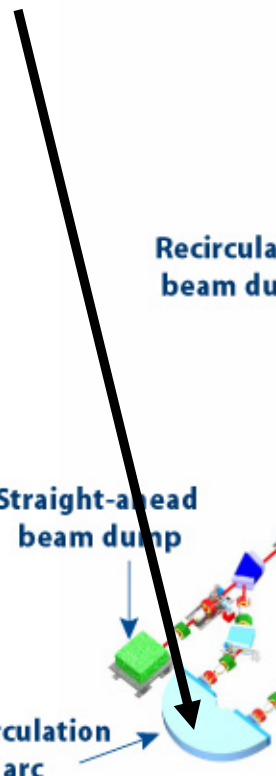
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JLab FEL Upgrade



Near longitudinal focus,
dispersed in energy



What have we learned? (cont.)

Wigglers

- **Have now demonstrated efficiency of over 1.7% with three different wigglers.**
- **All three wigglers have demonstrated the ability to tune continuously over the bandwidth of the mirrors while lasing at high power.**
- **The gain-efficiency product of the pure wigglers is higher than for an optical klystron.**
- **Operating a high current beam with a small gap wiggler is more difficult than one might imagine. Losses need to be less than one part in one million for amp class ERLs. This is really hard to do. We often have losses 10 times this with a 13 mm clear aperture.**



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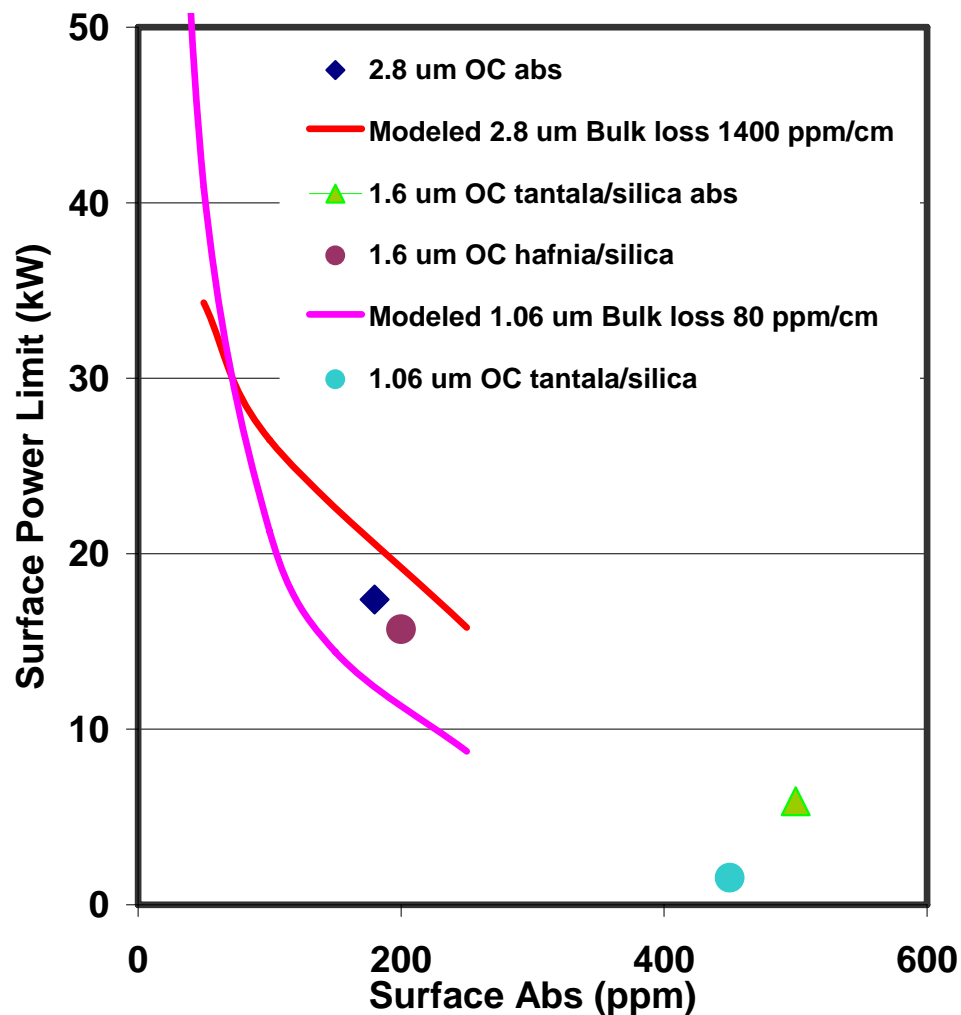
What have we learned? (cont.)

Optics

Hafnia/silica coatings have now eliminated UV induced losses previously seen in tantala/silica coatings.

Losses so low we can only say they are at or below 200 ppm

Output power limits due to mirror absorption at 20K



What have we learned? (cont.)

Optics

- **Lasing can suppress BBU!**
- **THz loading on optics must be considered and dealt with**
- **High magnification oscillators are sensitive to astigmatism**
- **Minimization of aberration is essential. Careful engineering of mounting has now allowed us to meet spec at 1 micron and eliminated previous issues.**
- **Preparations underway on installation of cryogenically cooled outcoupler in FEL: helium cooling line to mirror can under construction for installation by summer. This will eliminate thermal distortion power limits**



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What have we learned? (cont.)

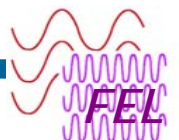
FEL Physics

- **Using best estimates for electron beam and cavity parameters the calculated gain and efficiency compare well with the experimental values (for moderate Rayleigh ranges).**
- **At high power the FEL sometimes shows mode hopping behavior. This may be a transition to the non-Gaussian mode seen in simulations for short Rayleigh range systems.**
- **We continue to get shorter cavity length detuning curves than expected for the measured gain.**
- **The FEL is capable of harmonic lasing near the synchronous point (this is due to the behavior of the optical coating)**
- **We have also lased at 1 micron on the fundamental, third, and fifth harmonic of the wiggler settings**



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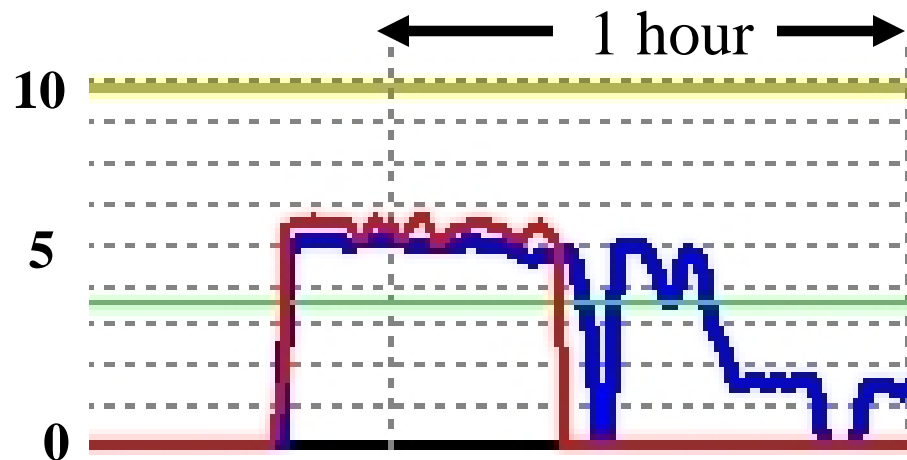
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What have we learned? (cont.)

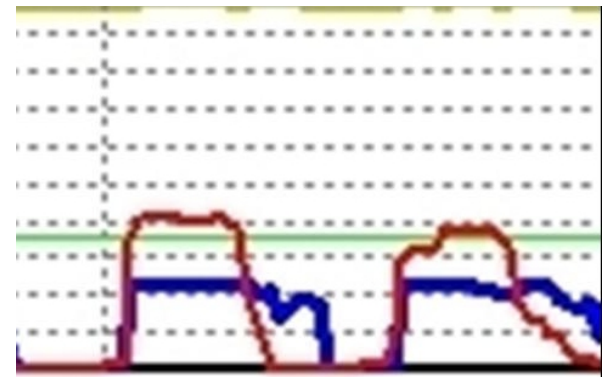
FEL Physics

- Power has been limited due to a roll off in efficiency at high powers. The cause of this is still under investigation



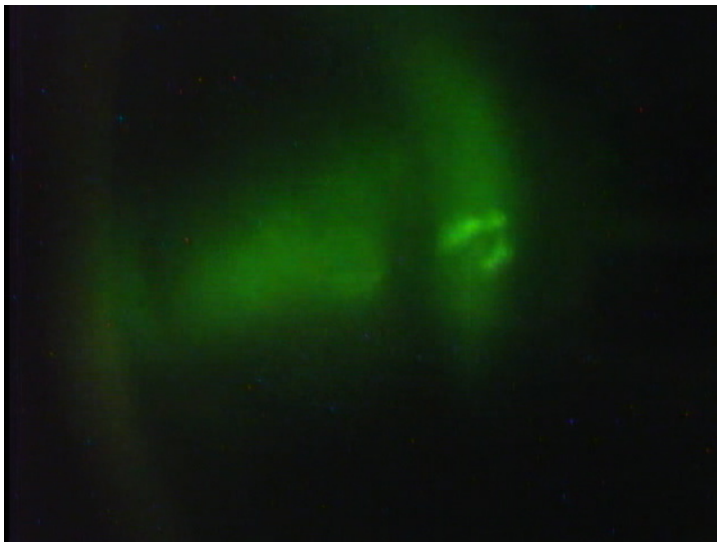
— Current (mA)
— Power (kW)

High Current: 1.1 kW/mA

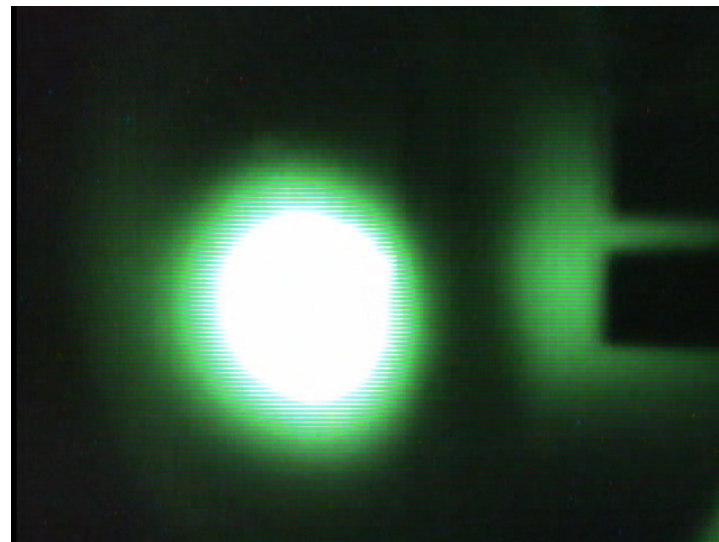


Low Current: 1.7 kW/mA

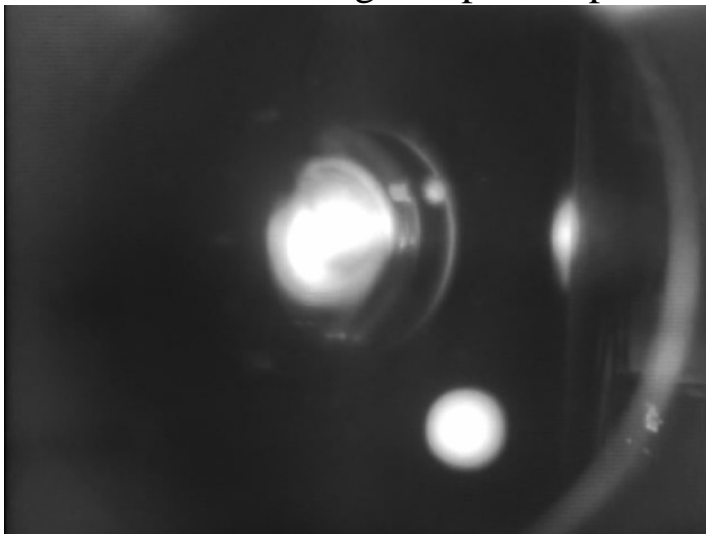
Harmonic vs. fundamental lasing



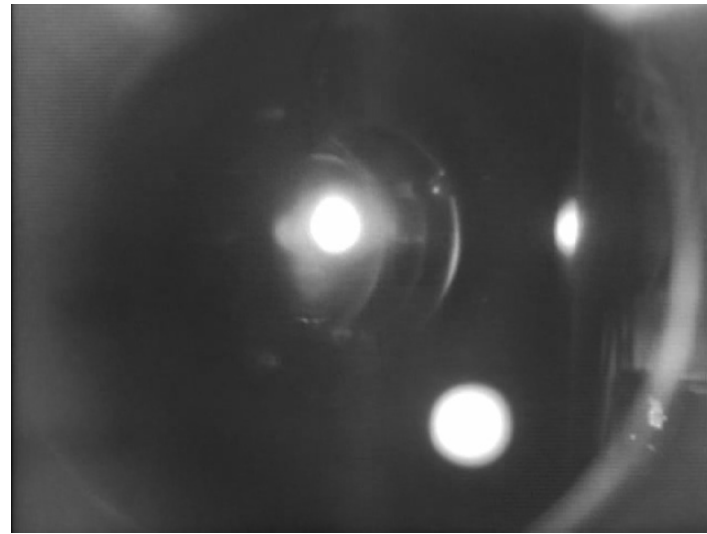
Fundamental lasing, Output coupler



Harmonic lasing, Output coupler

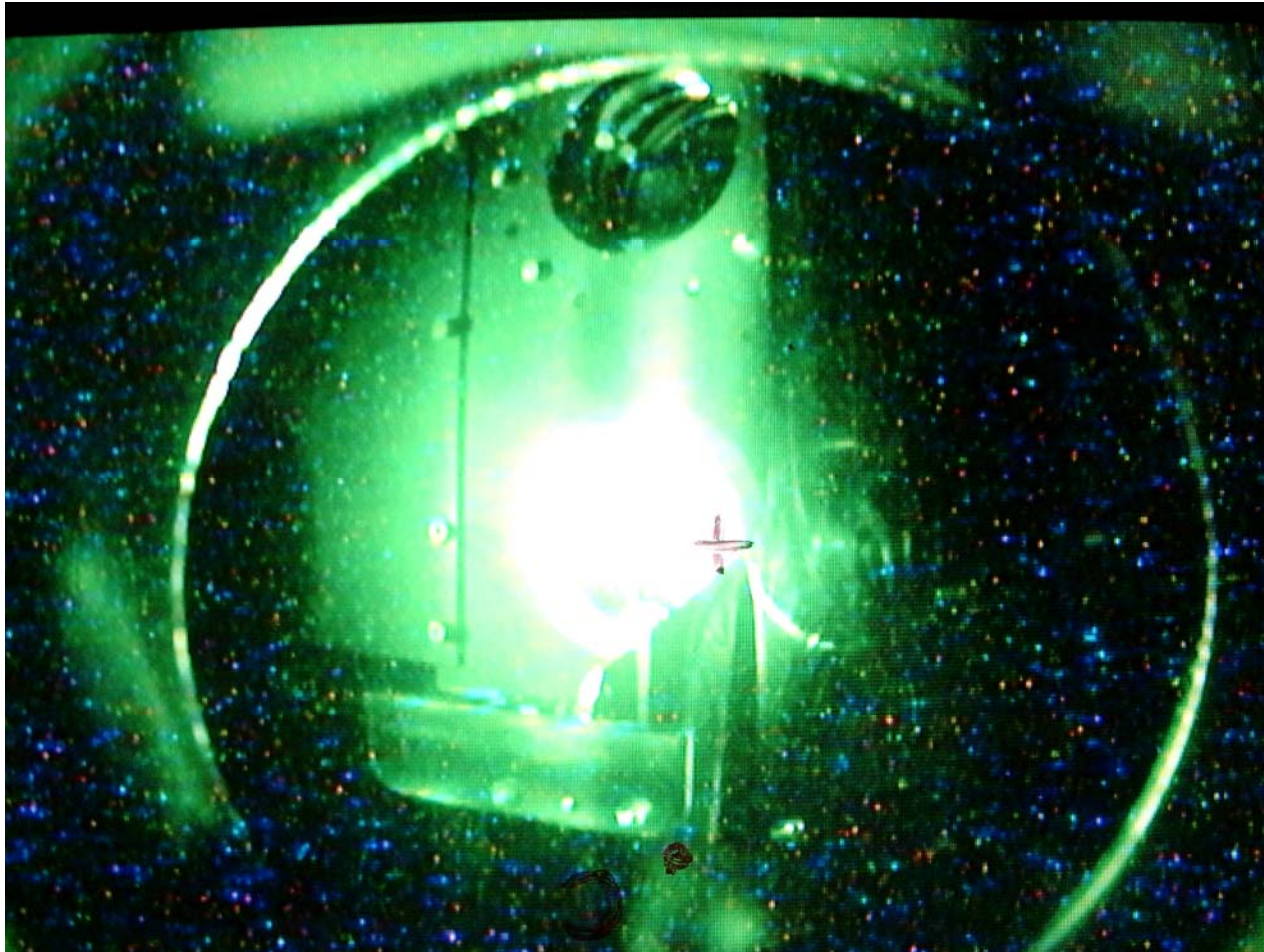


Fundamental lasing, High reflector

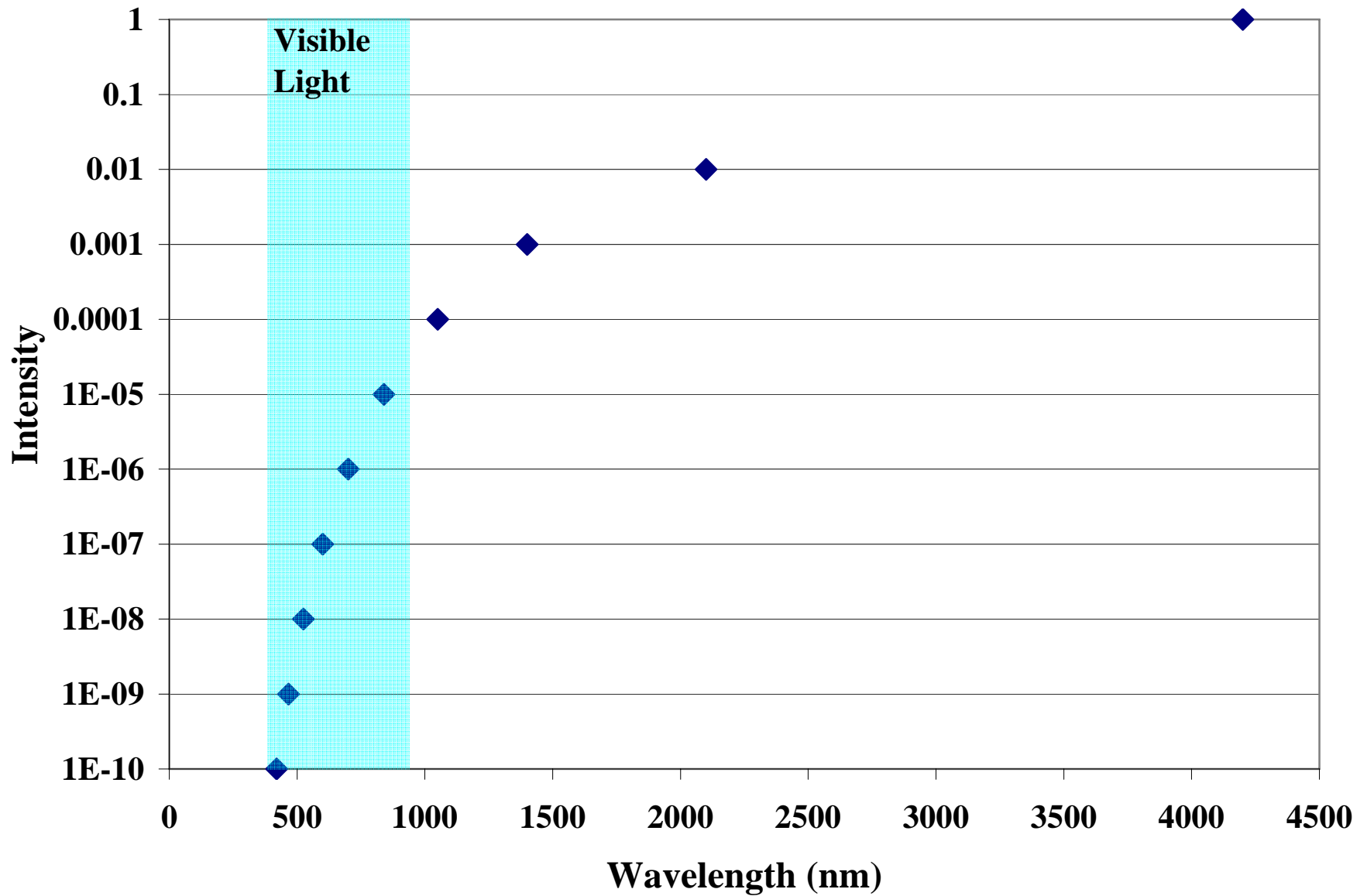


Harmonic lasing, High reflector

Third Harmonic Radiation (530 nm) while lasing at 1.6 microns

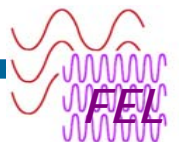


Harmonic Radiation while lasing

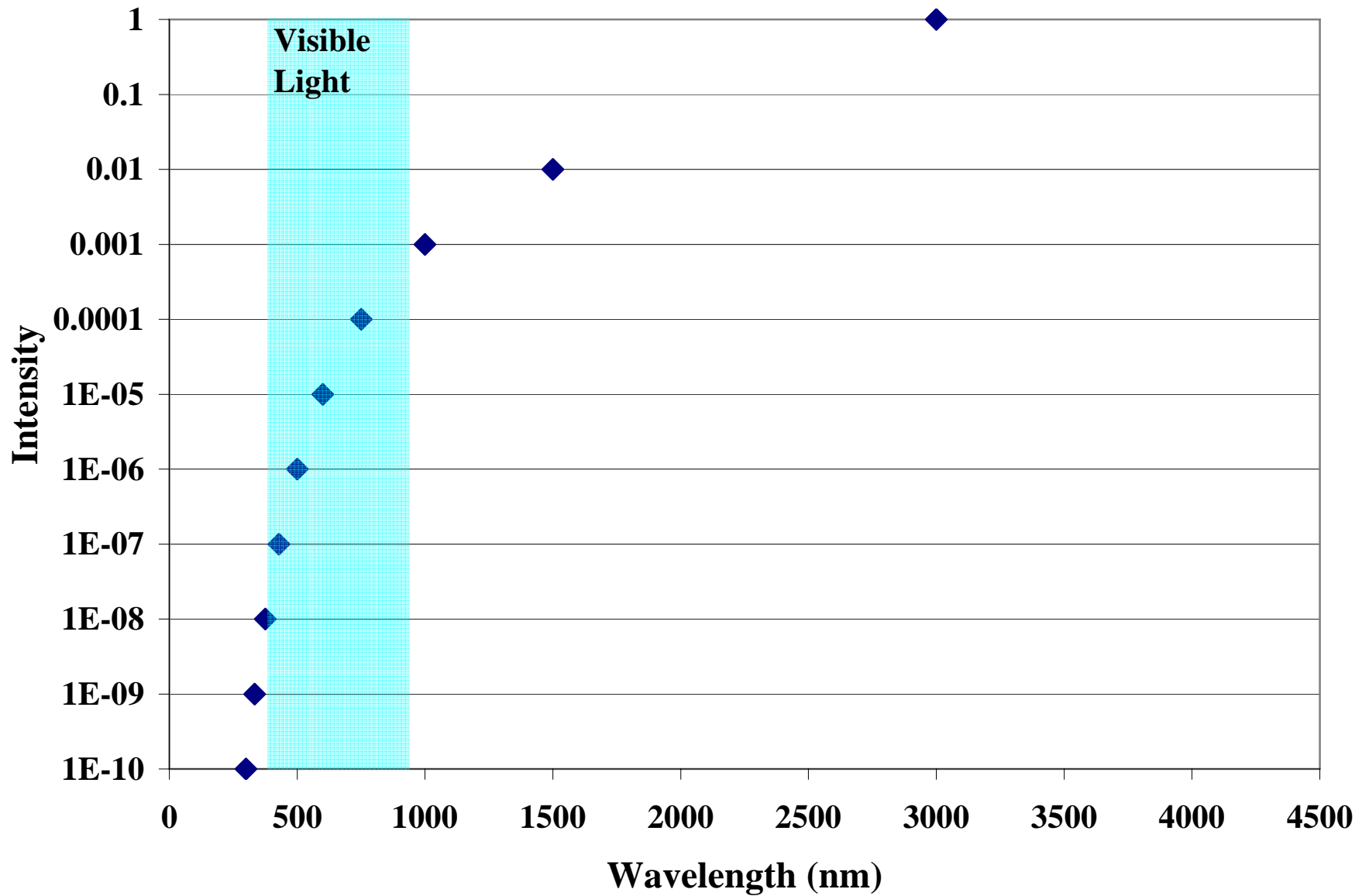


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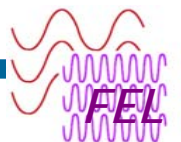


Harmonic Radiation while lasing

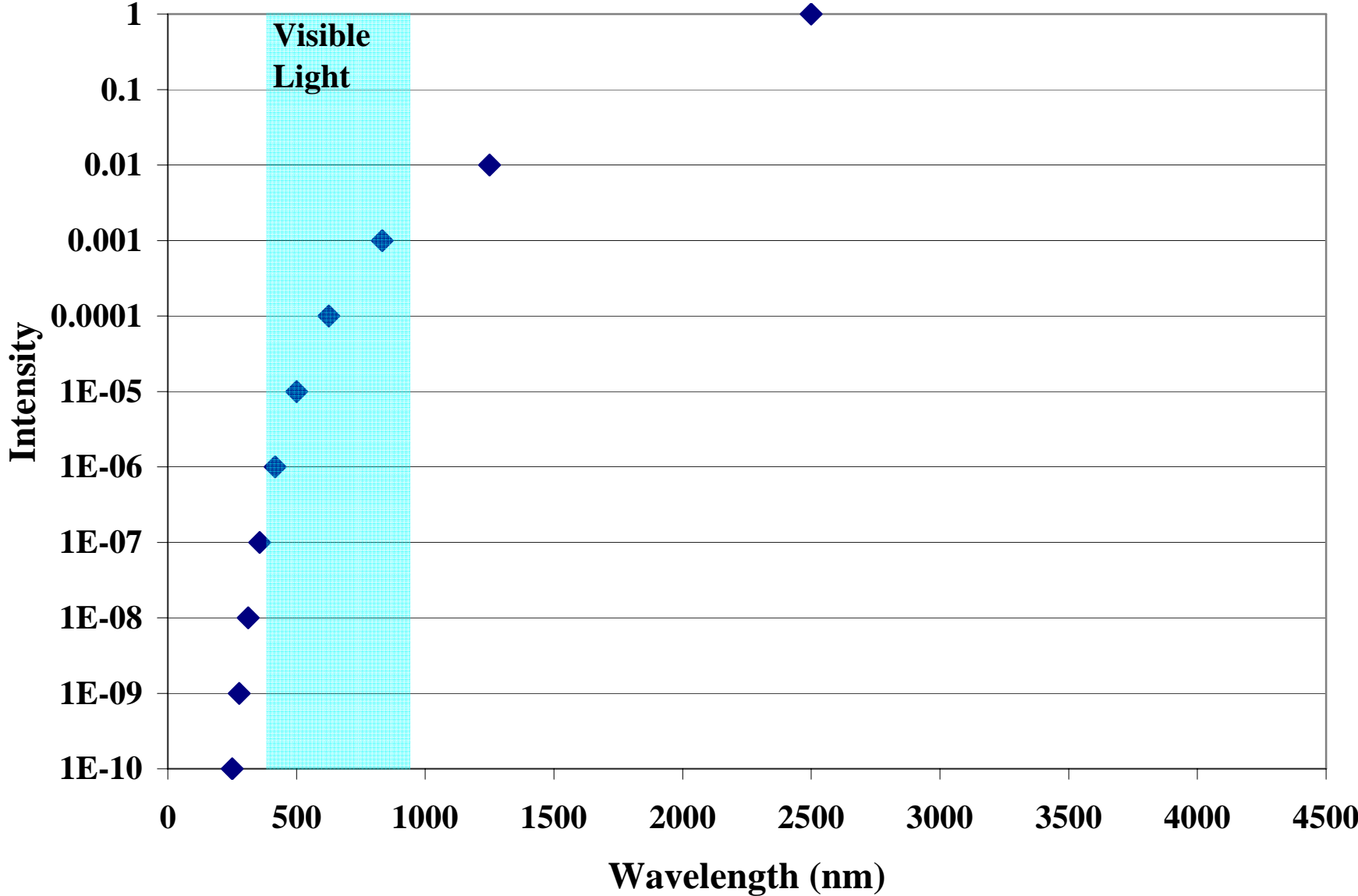


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Harmonic Radiation while lasing

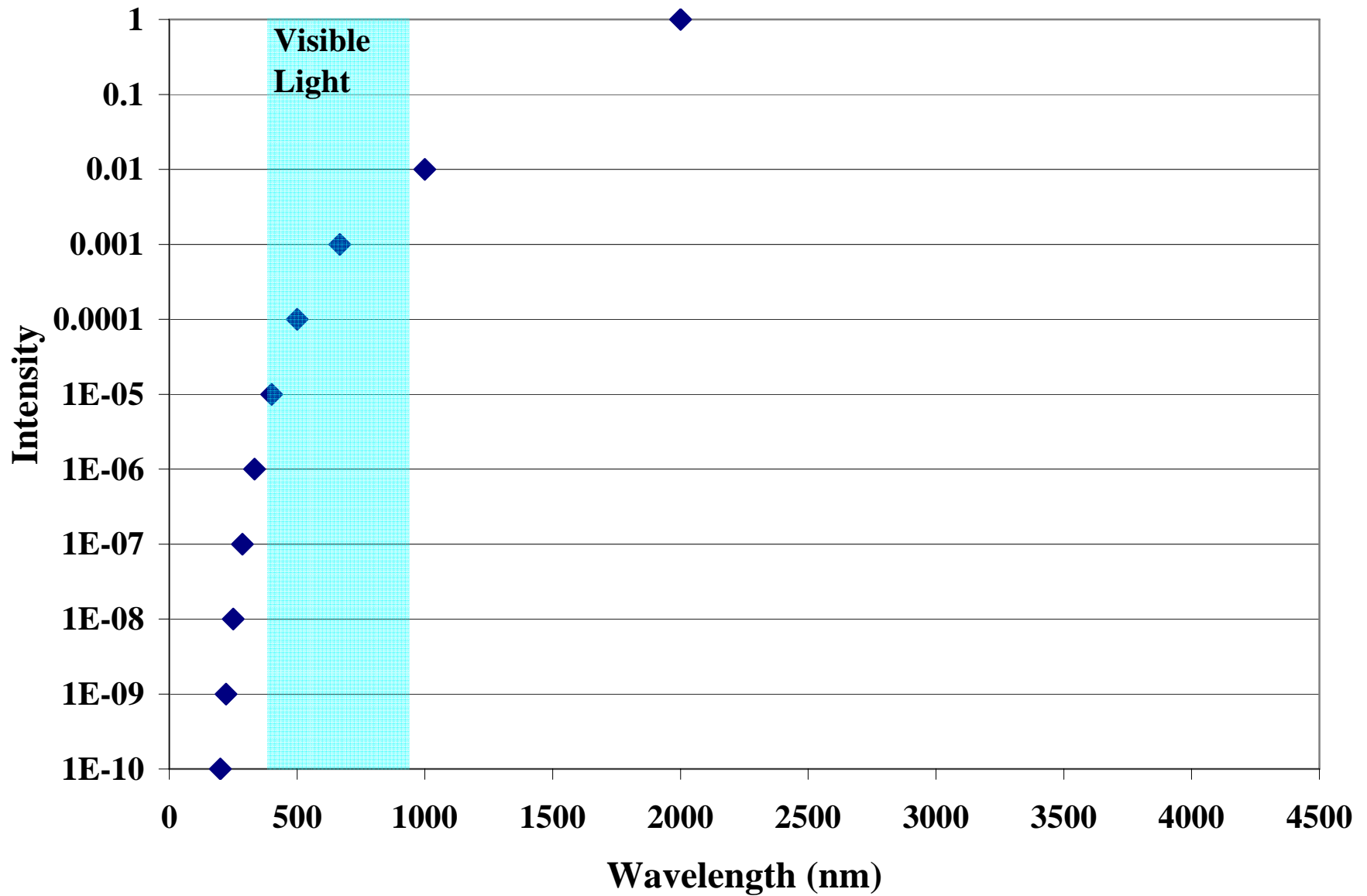


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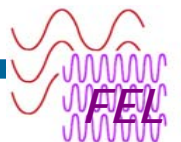


Harmonic Radiation while lasing

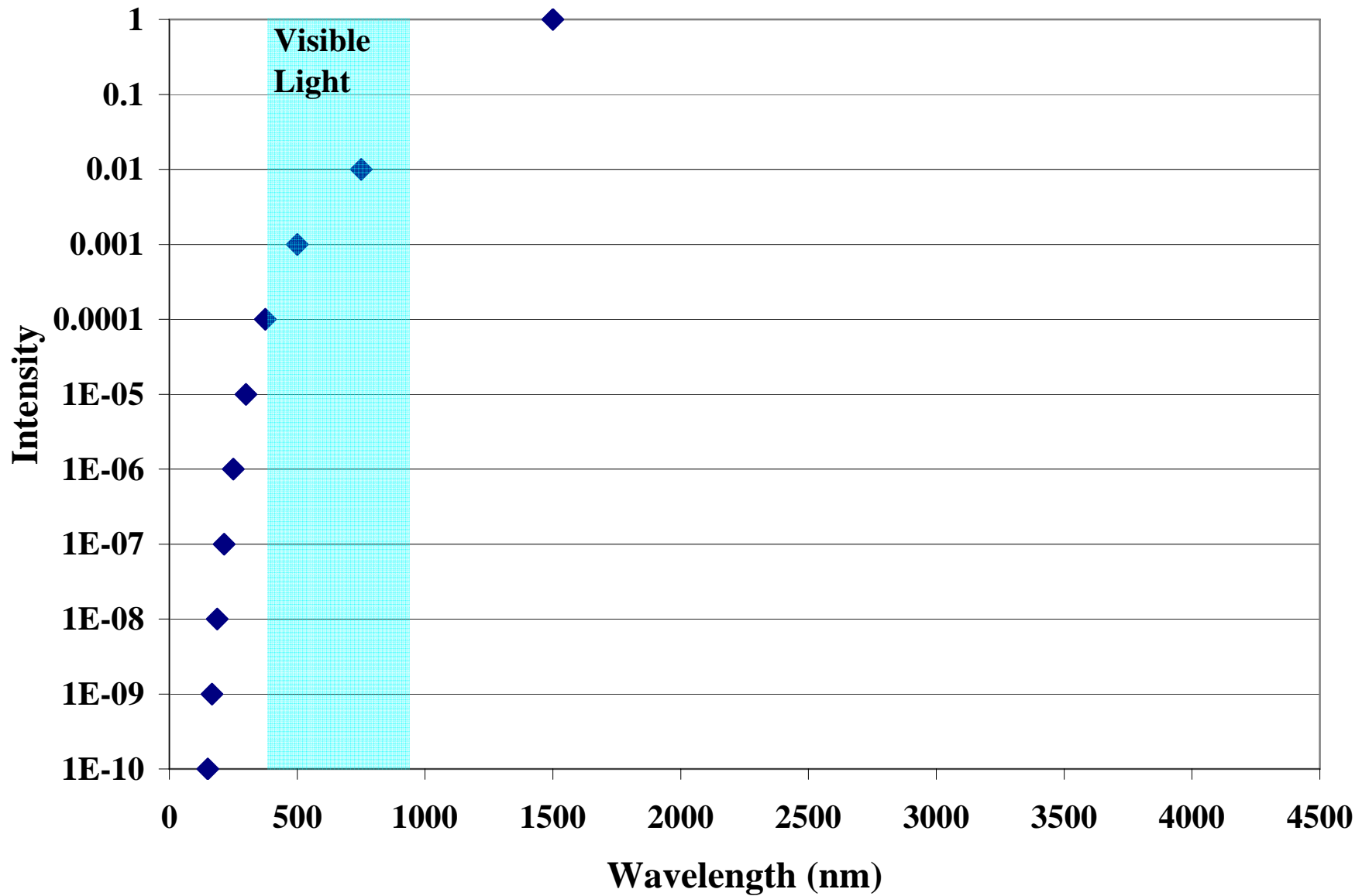


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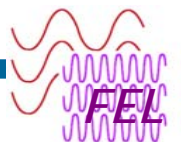


Harmonic Radiation while lasing

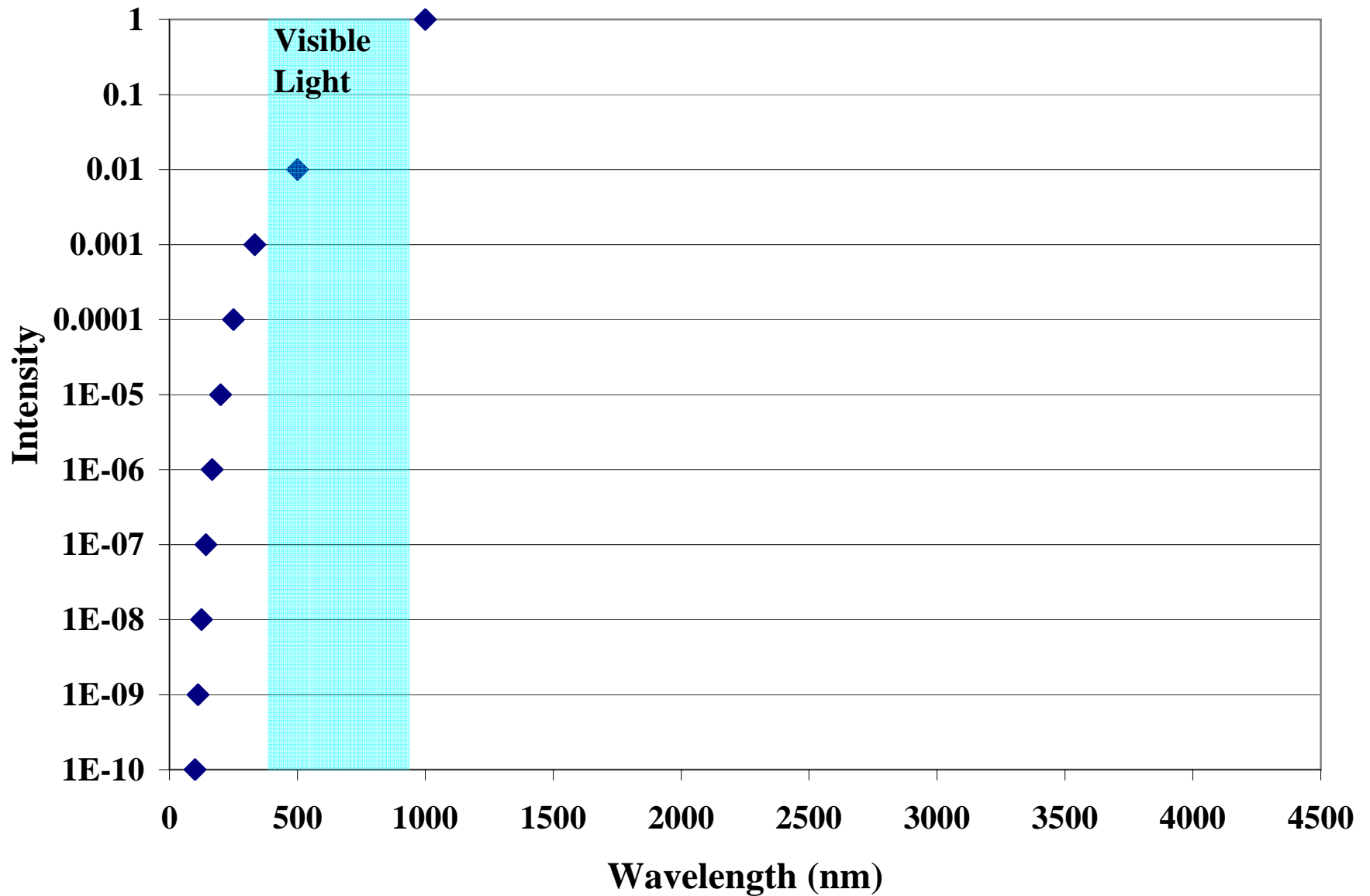


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Harmonic Radiation while lasing

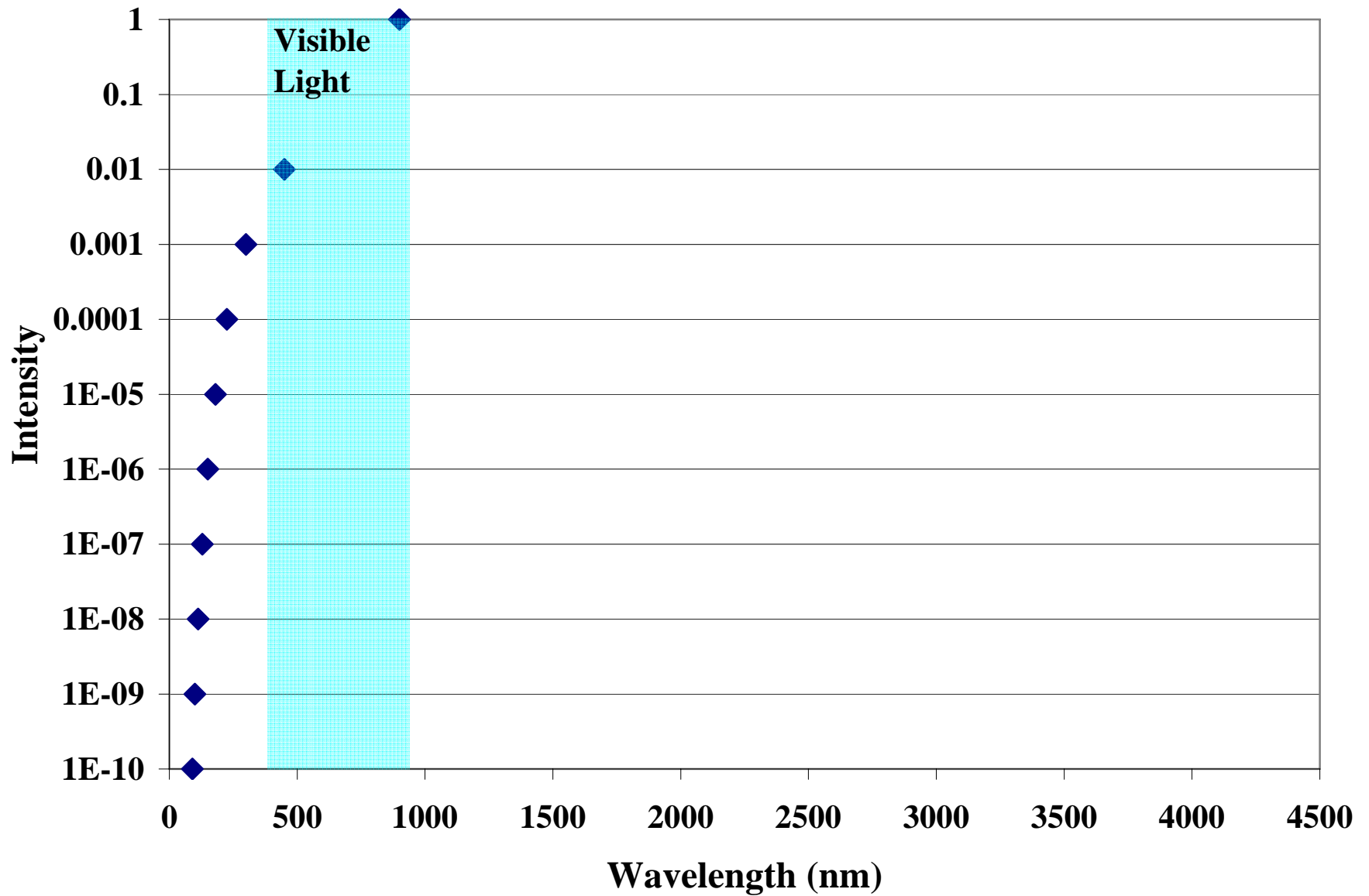


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Harmonic Radiation while lasing

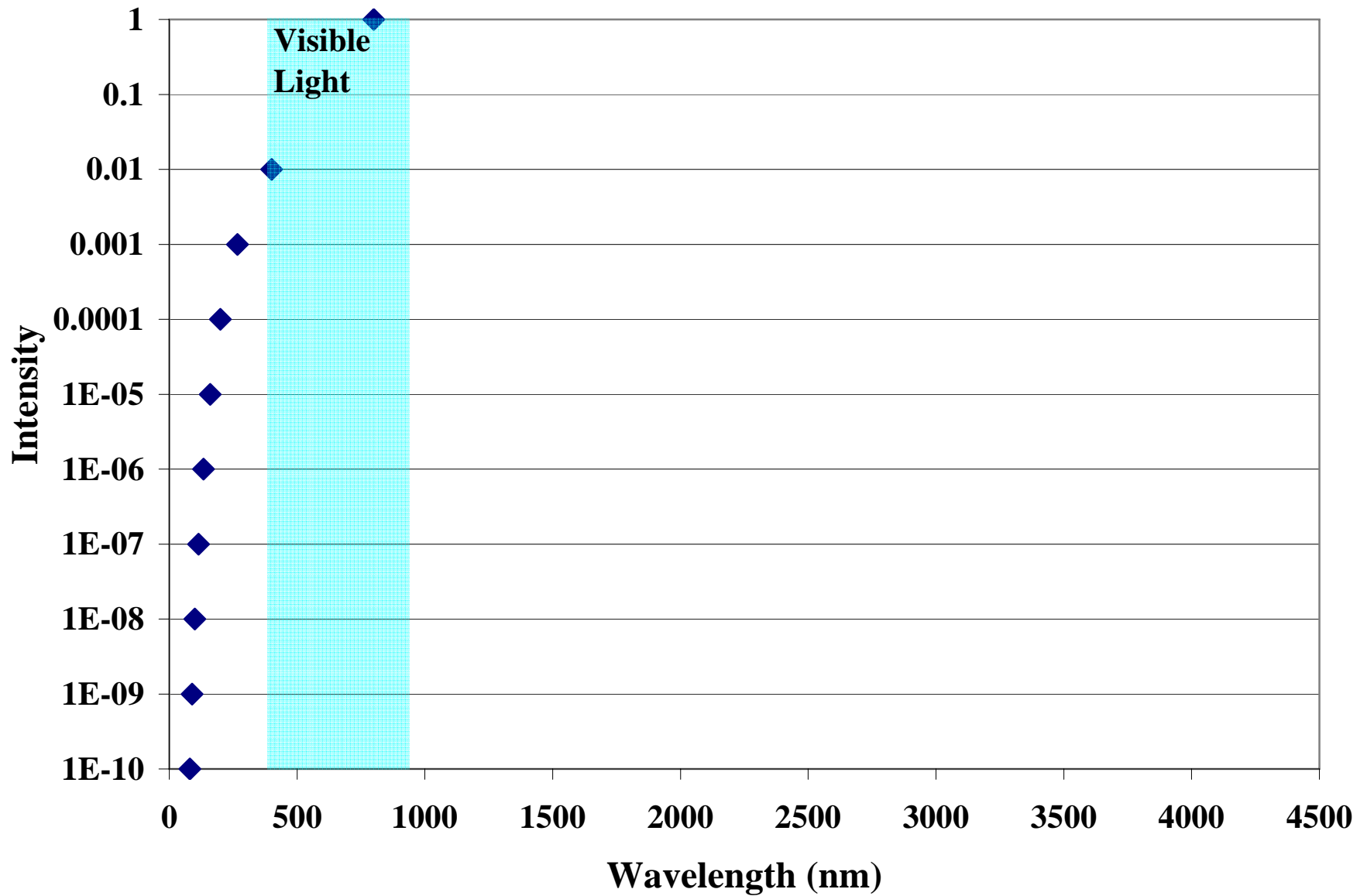


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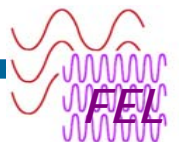


Harmonic Radiation while lasing



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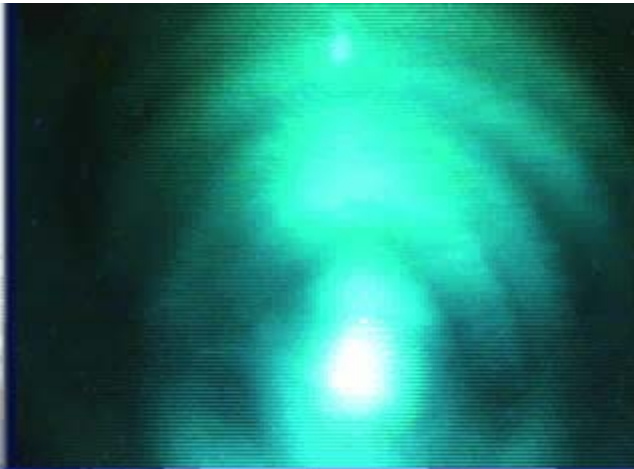
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Harmonic Radiation while lasing

Tuning movie

Wiggler
gap



High
Reflector

Hole
Outcoupler



Beam in
control
room

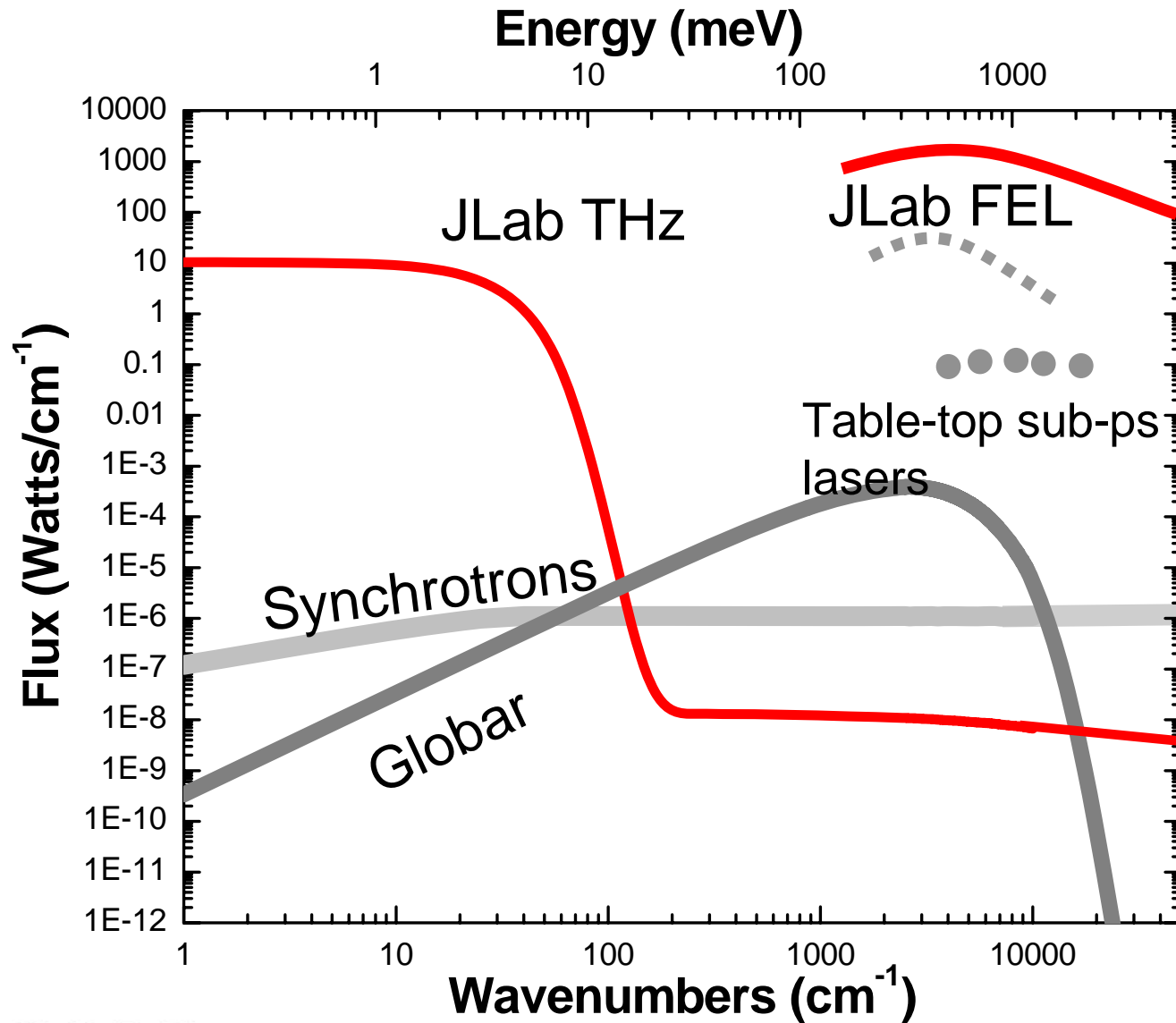


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High power THz with sub-picosecond pulses is produced parasitically from electron beam



FEL proof of principle:
Neil et al. Phys. Rev.Letts **84**, 662 (2000)

THz proof of principle:
Carr, Martin, McKinney, Neil, Jordan & Williams
Nature **420**, 153 (2002)

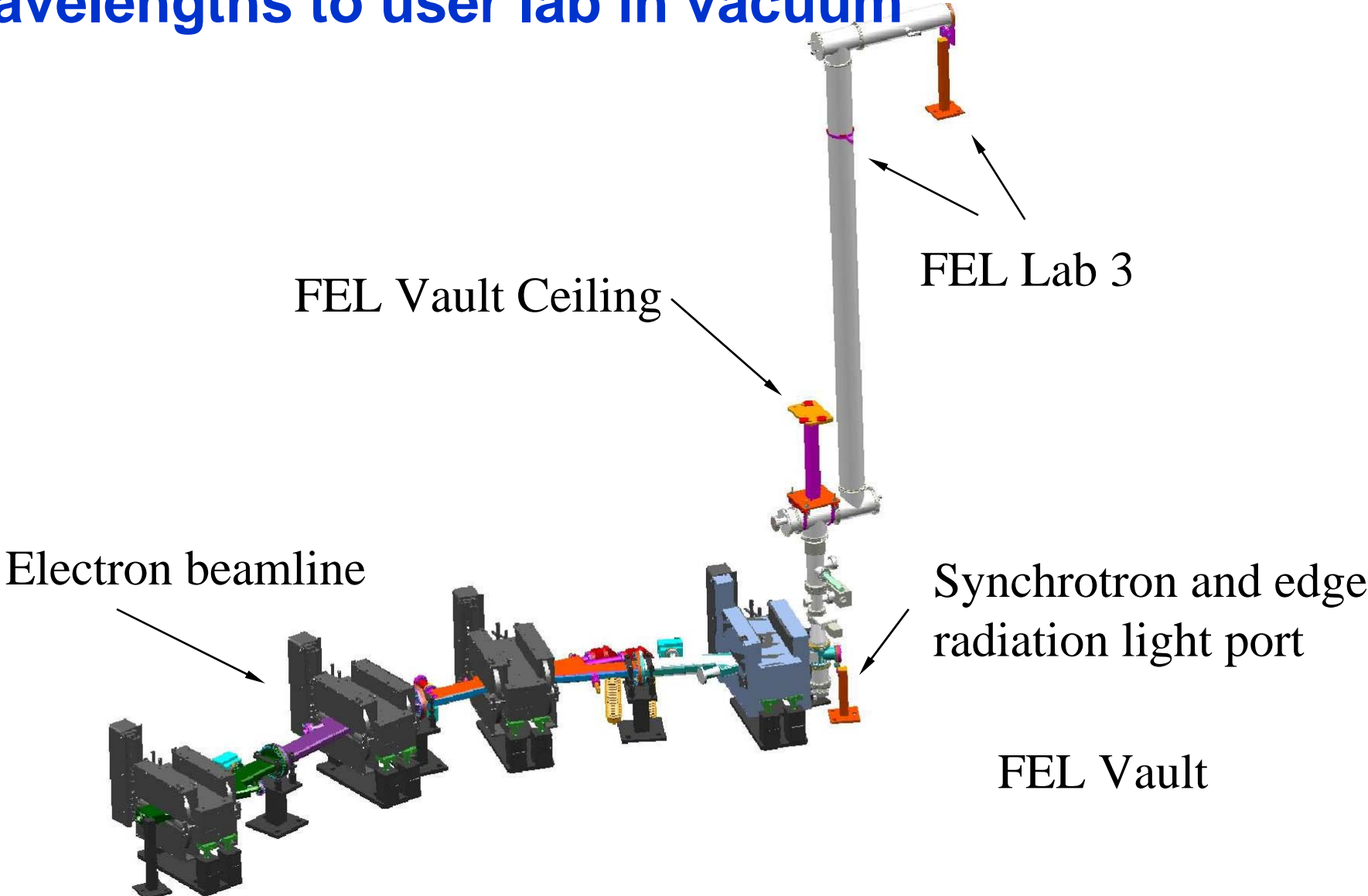


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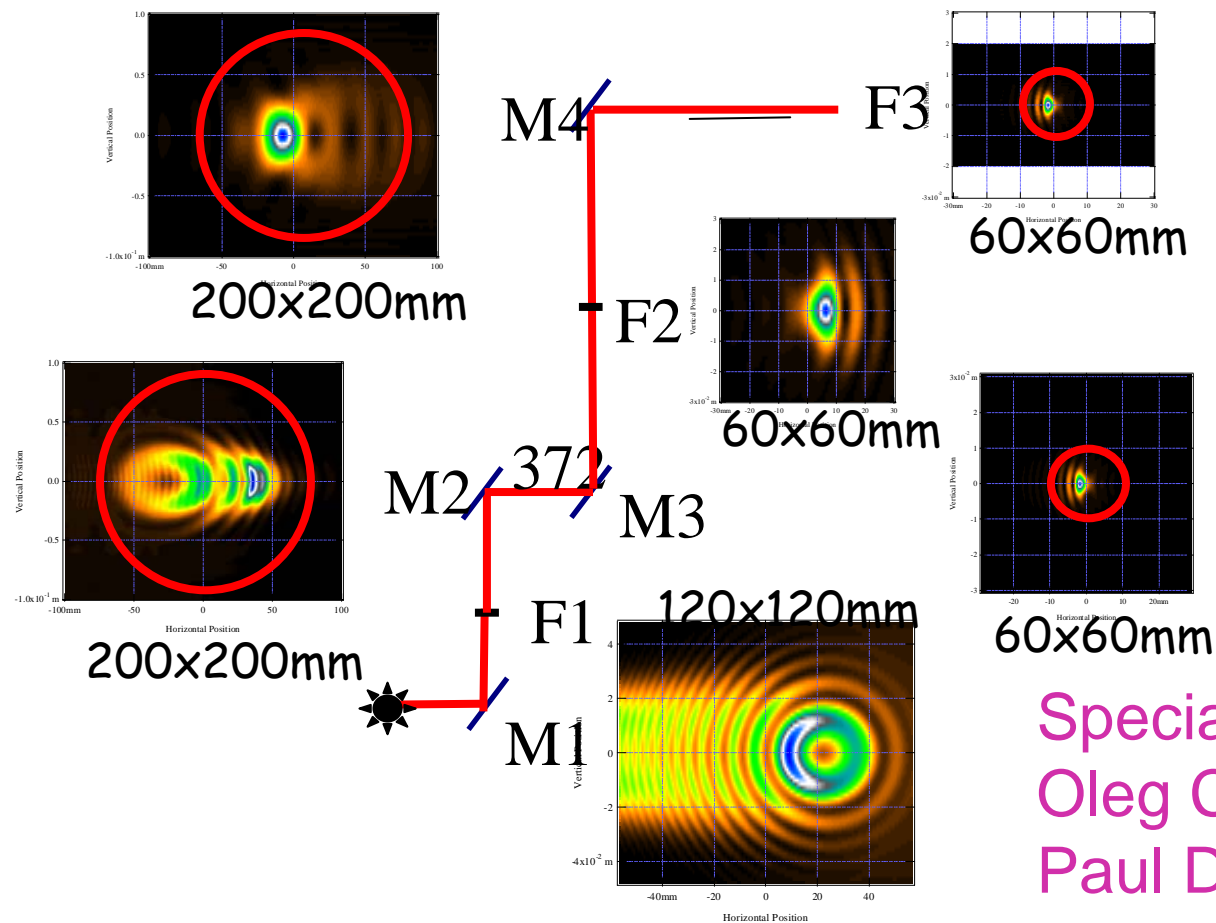
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Terahertz beamline transports visible to 5 mm wavelengths to user lab in vacuum



JFEL THz Beamline Calculated Optical Beam Patterns



Special thanks to
Oleg Chubar,
Paul Dumas.



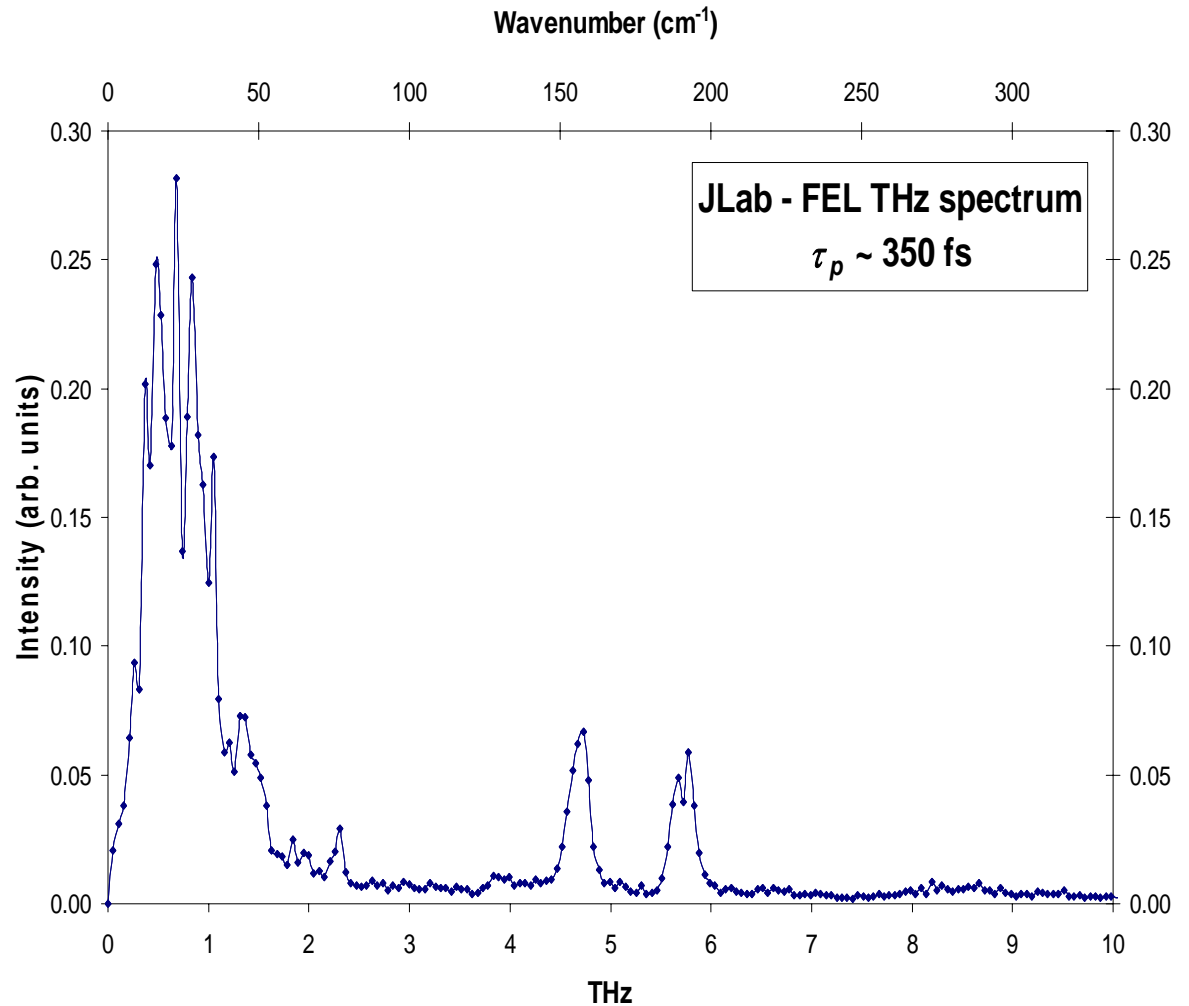
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JFEL THz as measured through our FTIR spectrometer (through air so shows H₂O lines)

Serves as excellent beam diagnostic
Requires FTIR spectrometer modification for pulsed measurement



Courtesy M. Klopff



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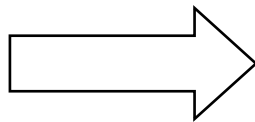
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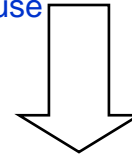
NASA/Jlab Nanotube Synthesis - Research to Production



New and used target



From Target to Product, 100% In-House



Product, ~1 hour of beam time

- Production with 750 W at 1.6 micron is now routine.
- Production rate of 2-6 g/hour of as-grown, high quality, “research grade” raw material is already cost competitive in \$400/g market.
- Nanotube diameter is strong function of laser parameters, suggesting the possibility of “designer” tubes (selectable diameter likely... chirality, maybe?)
- Experimental trends indicate improved gross and net yield with soon-to-be-available shorter FEL wavelengths and higher power (no scale-up issues).

Mike Smith NASA LaRC



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The benefits of high power, tunability and short pulses



6 NEWS

Fat-busting laser revolutionises

A technique developed by American scientists could lead to fat-related conditions, including arterial heart disease, being melted away by high-intensity beams, says Sam Lister

ACNE, cellulite and excess fat zapped with the flick of a switch? It may sound like the sci-fi dream of teenagers and the middle-aged, but scientists have developed a laser technique that can target and melt fat under the skin.

A team of researchers have used a machine called a free-electron laser (FEL), which can produce very specific beams, to heat and break down fat without damaging other body tissue.

The breakthrough paves the way for laser use on various fat-related conditions, including lipid build-up linked to arterial heart disease, cellulite and acne.

Rox Anderson, a dermatologist at Massachusetts General Hospital, led the experiment using pig fat and skin samples about 2in (5cm) thick. He said that the results were proof of the principle for heating tissue with light.

The success of the study, which was conducted at a unit of the US Department of Energy, could herald a precision laser treatment for acne within years.

The condition, as with cellulite, has confounded most efforts to combat it. Questions remain over the current most effective acne drug, isotretinoin (known as Accutane), which has been linked to birth defects in children whose mothers used it while pregnant.

Cellulite—deposits of subcutaneous fat and fibrous tissue that cause a dimpling effect on the overlying skin—and other surface body fat could be targeted, as well as the fatty plaques



"But you're a leopard..."

that form in arteries, leading to heart attacks, Dr Anderson said. "We can envision a fat-seeking laser, and we're heading down that path now."

Using the FEL, which is much more powerful than a conventional laser, the scientists were able to choose selective laser wavelengths that could heat up the fat, which was then broken down and excreted by the body.

"They found that the process, called selective photothermolysis, did not affect the area of skin that was exposed to the beam."

Dr Anderson added that he was particularly excited by the technique's potential as a treatment for severe acne. He said that researchers wanted to see if sebaceous glands could be directly targeted with a particular laser wavelength, isolating the source of spots.

The sebaceous glands secrete a fatty substance called sebum through the hair follicles, which lubricates and protects

the skin. However, excess sebum can collect and form deposits, which are associated with acne.

The results of Dr Anderson's study, which also involved researchers from Harvard Medical School, were presented yesterday at the annual meeting of the American Society for Laser Medicine and Surgery (ASLMS) in Boston, Massachusetts.

In the first part of the study the team used human fat obtained from surgically discarded, normal tissue. The tissue was exposed to a range of wavelengths of infrared laser light (from 800 to 2600 nanometres) using the FEL, and the effects were recorded.

The researchers measured how selected wavelengths heated the fat and compared the results with those of an experiment to heat water. At most wavelengths, water is more efficiently heated by infrared light. However, the researchers found three wavelengths—965, 1210 and 1210 nanometres—where the effects were much more pronounced on fat.

The researchers then exposed fresh samples of pig skin and fat about 2in thick, to free-electron infrared light using the two most promising wavelengths, 1208nm and 1210nm.

To imitate surgical conditions, the pig skin was placed next to a window, which mimicked the application of a cold compress to a patient's skin. The researchers zapped samples with beams of infrared laser light from 8mm to 12mm for about 10 seconds.

They found that the 1210nm wavelength heated the pig fat up to 1cm deep without damaging the overlying skin. At this particular setting, the fat was heated to a temperature more than twice that of the overlying skin.

"The root cause of acne is a blocked sebaceous gland, the sebaceous gland which sits a few millimetres below the surface of the skin," Dr Anderson said. "We want to be able to selectively

Seeing the light in hi-tech revolution

By Sam Lister

The invention of laser technology, first envisaged by Albert Einstein in the early 20th cent-

uries created by, for instance, a light bulb.

While the light given off by bulbs and other common light sources usually covers a wide

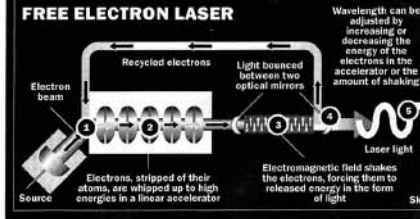
ZAPPING THE FAT

Using a free electron laser, which can provide intense and highly accurate beams of light, scientists have discovered a means of melting fat under the skin. They believe the technique could be a solution to problems caused by localised areas of fatty deposits.

● Acne, right, is caused by an inflammation of the sebaceous glands. It is common in adolescence and results in pimples, black heads and pustules that can appear on almost any part of the body, but are usually on the face. It can result in scarring.



● Cellulite, left, forms when the thin layer of tissue between the fat cells, often just a few cells thick, becomes more fibrous—like a scar. These areas then start to pull together around the fat, causing the tiny dimples and irregularities typical of cellulite.



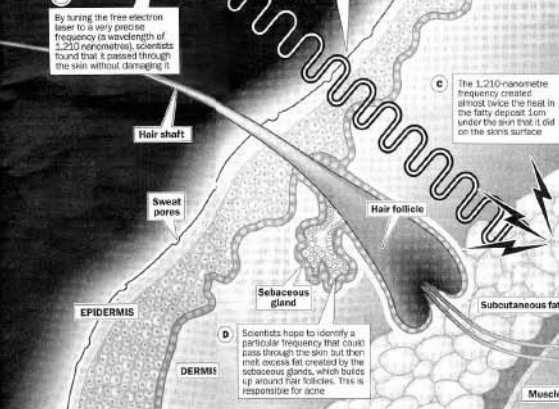
THE TIMES MONDAY APRIL 10 2006

treatment for acne and cellulite

DR THOMAS STUTTFORD MEDICAL BRIEFING



● Rox Anderson, right, and colleague Steve Barnes, left, discuss laser beam wavelengths.



NEWS 7

Trivial? Spots can truly blight teenagers' lives

DR THOMAS STUTTFORD MEDICAL BRIEFING

ACNE and cellulite are the two conditions that the free-electron laser (FEL) may be able to help by targeting the layers of skin or subcutaneous tissue in which both have their origins. If FEL proves effective, and as yet the laser has not undergone clinical trials in human beings, its most likely assured market would seem to be acne.

Acne is a skin problem that is too easily trivialised: it can have profound effects on some people's lives. It may be so socially ergative that it causes secondary infections. Several antibiotics prove inadequate, and there are no contraindications to its use, such as the chance of pregnancy or a history of psychiatric problems, isotretinoin is usually recommended if there is any chance of chronic cysts, craters or scarring. Unfortunately, once this is prescribed, the patient needs supervision so that side-effects may be avoided.

Cellulite is the deposition of excess fat in the deeper layers of the skin and the superficial layers of subcutaneous tissue. There is no way really, other than liposuction.

The third suggested use of the FEL would be for its application to skin problems that are not too great, and debris does not block the skin pores, the oil is spread thick across the skin and is either rubbed or washed away. If the sebum does not drain easily through a

skin pore, the sebaceous gland is likely to become enlarged and may cause a pustular cyst. When the cyst eventually subsides, it often leaves an unsightly crater or scarring.

Acne is more of a problem in men than it is in women as testosterone is the hormone that is chiefly responsible for it. However, in women mild degrees of acne are more likely to continue throughout life. It tends to be worse in the week before menstruation, during pregnancy or in women taking the pill.

Hitherto there has nothing available to prevent acne, but it can and should be treated. Mild cases usually respond to local measures applied to the skin, but any severe acne requires antibiotics to prevent secondary infections. Several antibiotics also reduce the quantity of sebum produced.

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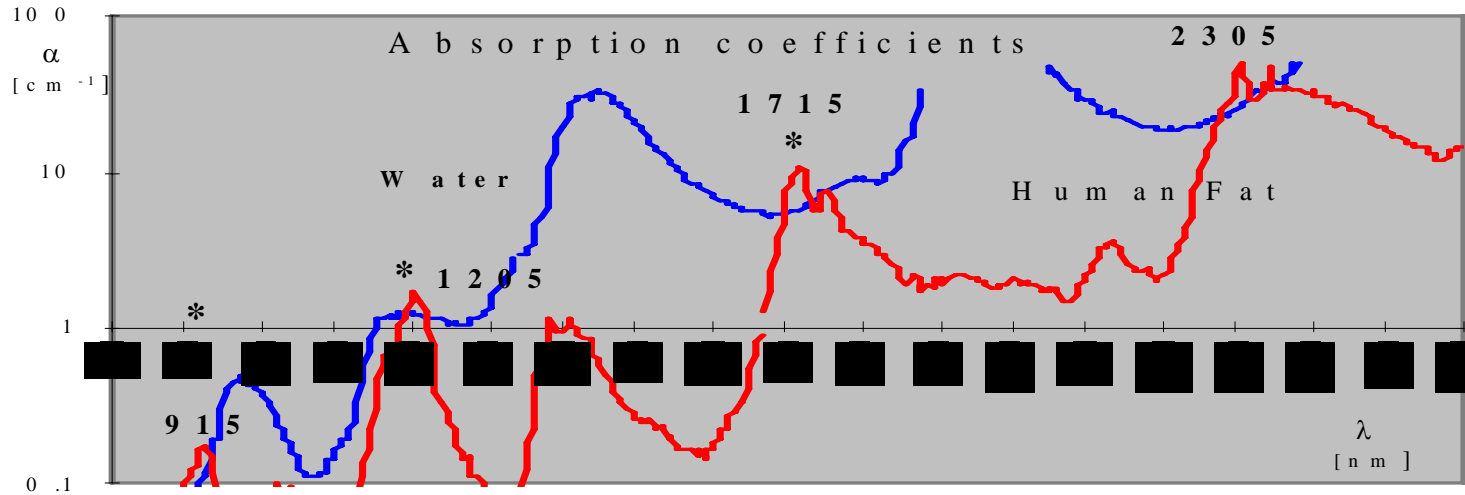


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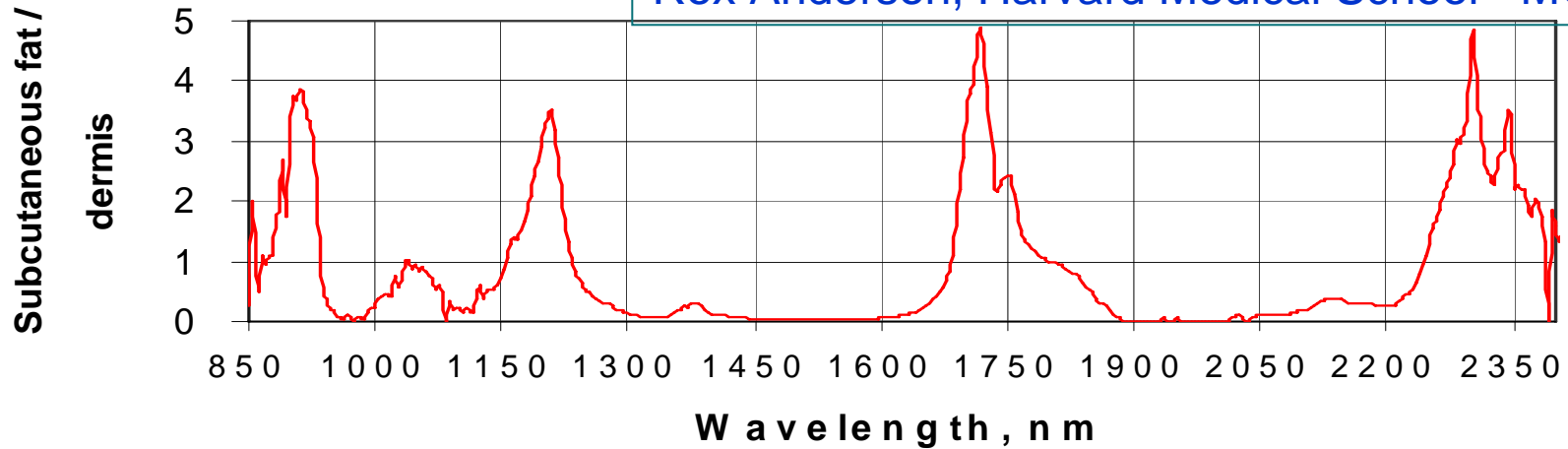
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The benefits of high power, tunability and short pulses



Rox Anderson, Harvard Medical School - MGH

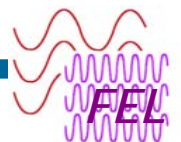


Fat and Water have nice “colors” in the NIR



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With the help of lots of others at JLab

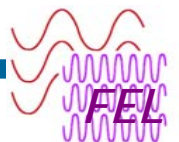


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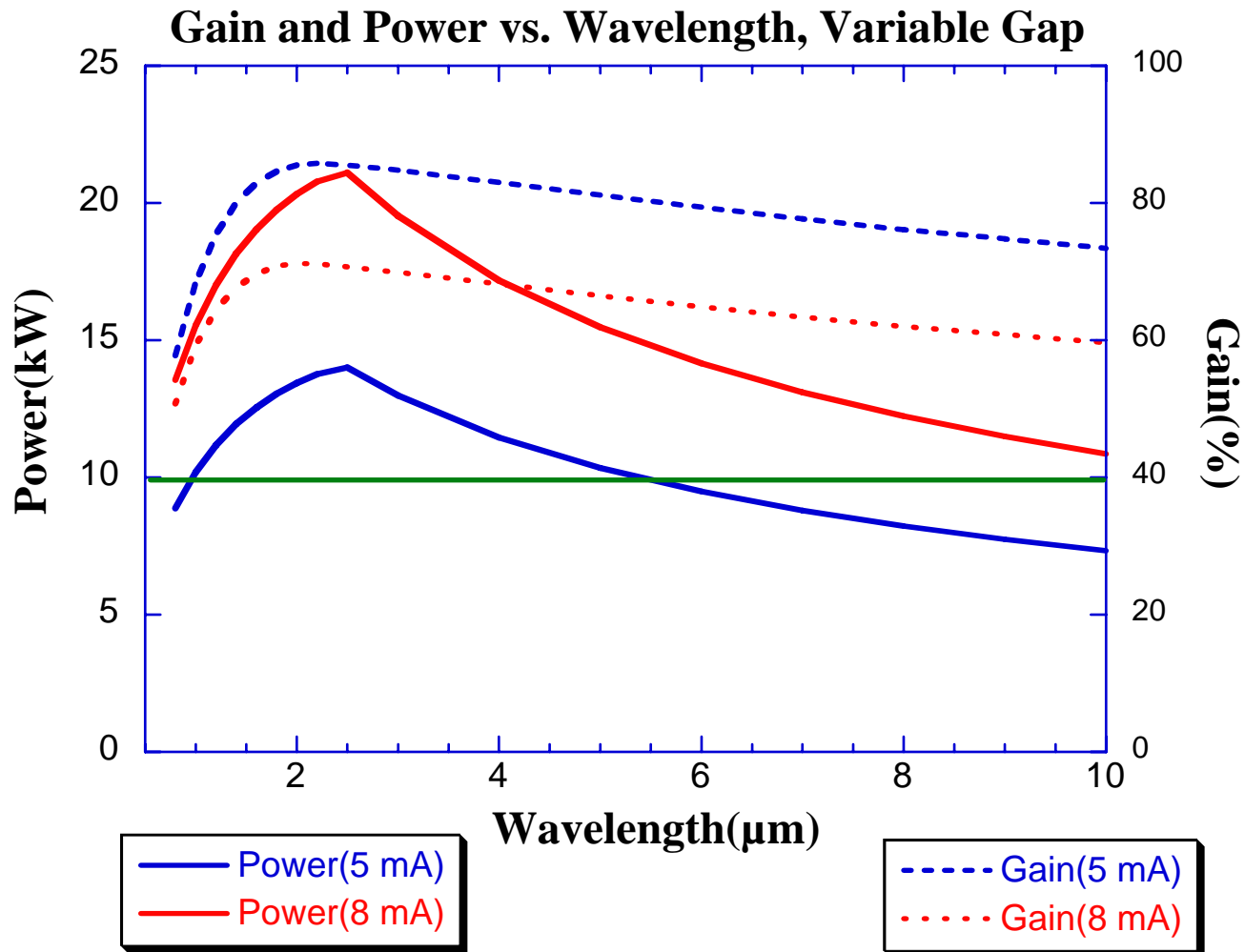


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Performance with Variable Gap PM Wiggler

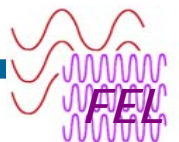


Minimum beam energy=80 MeV, Energy <160 MeV. Energy spread constant

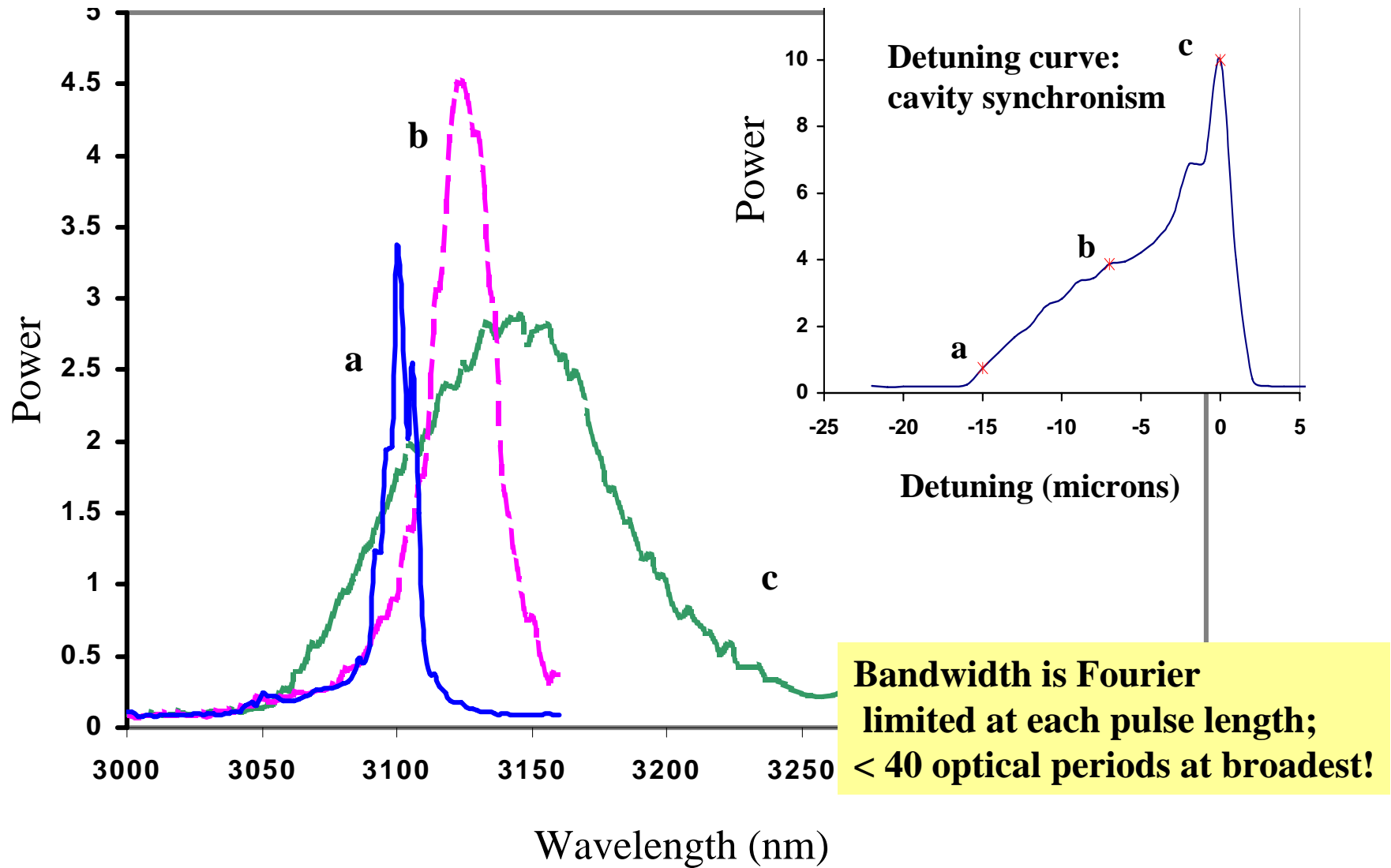


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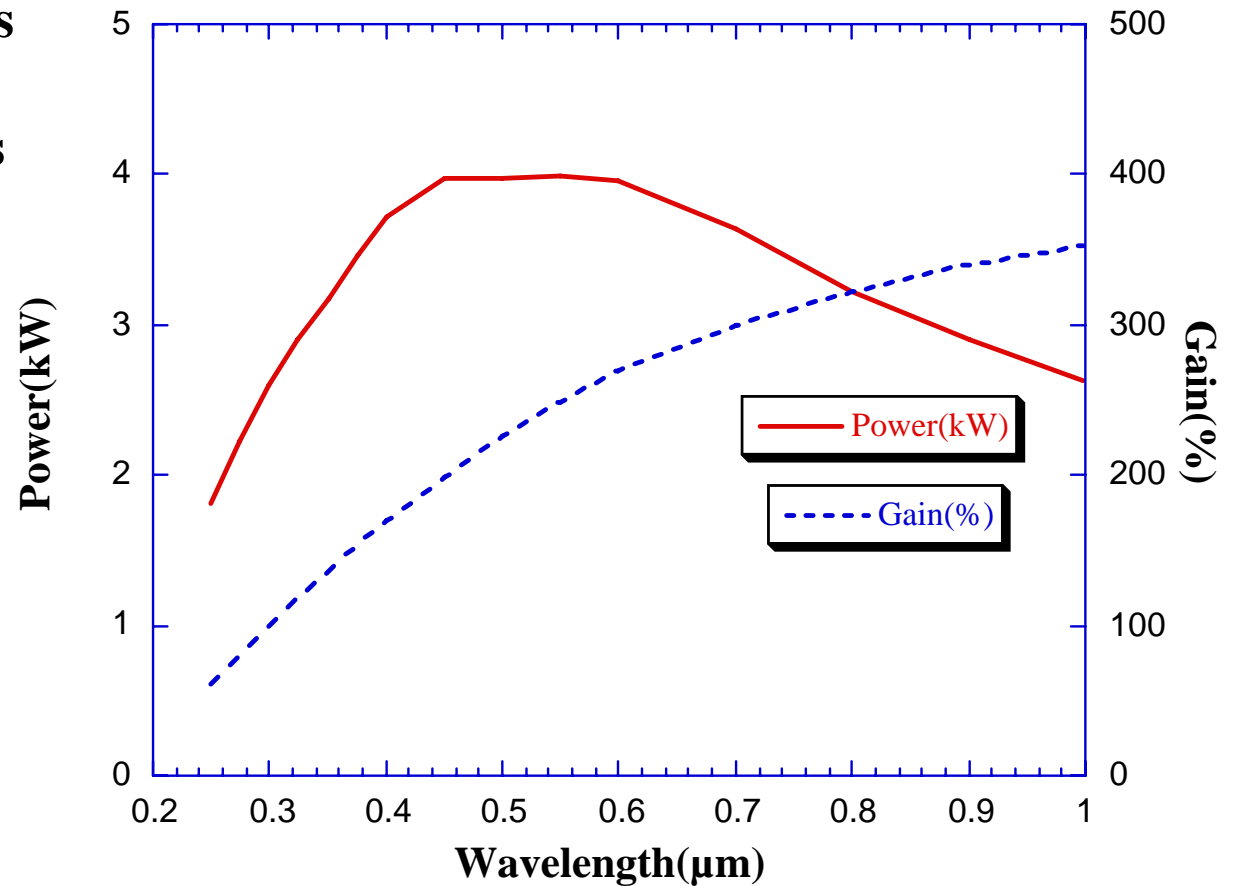
IR Demo measured bandwidth varied as a function of optical cavity length



UV Upgrade Performance: Installation TBD

- Tunable pulse energy to saturate electronic transitions
- Drive non-linear field effects
- High rep rate for S/N: e.g., molecular beams, gas phase

UV Upgrade Power and Gain



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