# FEL Program Update

## FEL Users /LPC Meeting
## March 9-10, 2005

**H. F. Dylla for the FEL Team**

# Building and Using the World's Most Powerful Tunable Laser

***developed by the***

**Laser Processing Consortium**

***managed by***

**Thomas Jefferson National Accelerator Facility**

**(Jefferson Laboratory)**

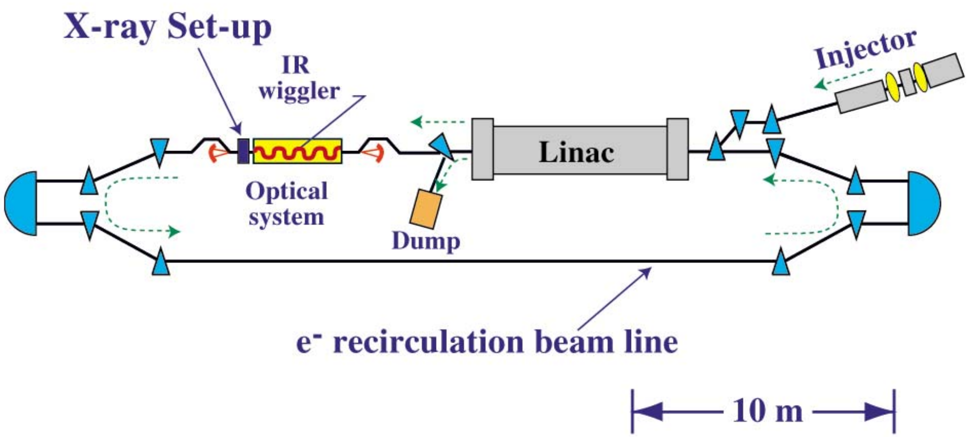
Aerospace Corporation
Advanced Energy Systems
Dominion Power
Dupont
IBM
Northrop Grumman
PLD, Inc.
Siemens
3M

Office of Naval Research
Naval Research Laboratory
NASA Langley Research Center
Southeastern Universities Research Association
Optoelectronics Research Center, Southampton University
Fraunhofer Institutes
Air Force Research Laboratory
US Dept. of Energy
Virginia Center for Innovative Technology

# FEL Program Goals

- Development, demonstration and application of high average power and energy efficient lasers (superconducting accelerator driven FELs) for applications of interest to:

IR Demo Layout




  1. Science
  2. Industry
  3. Defense

- Key attributes of the JLab FEL
  - High average power (1 - 10 - 100 kW)
  - Broad tunability (0.25 μm - 15 μm)
  - Unique time structure (75 MHz, sub piosecond)

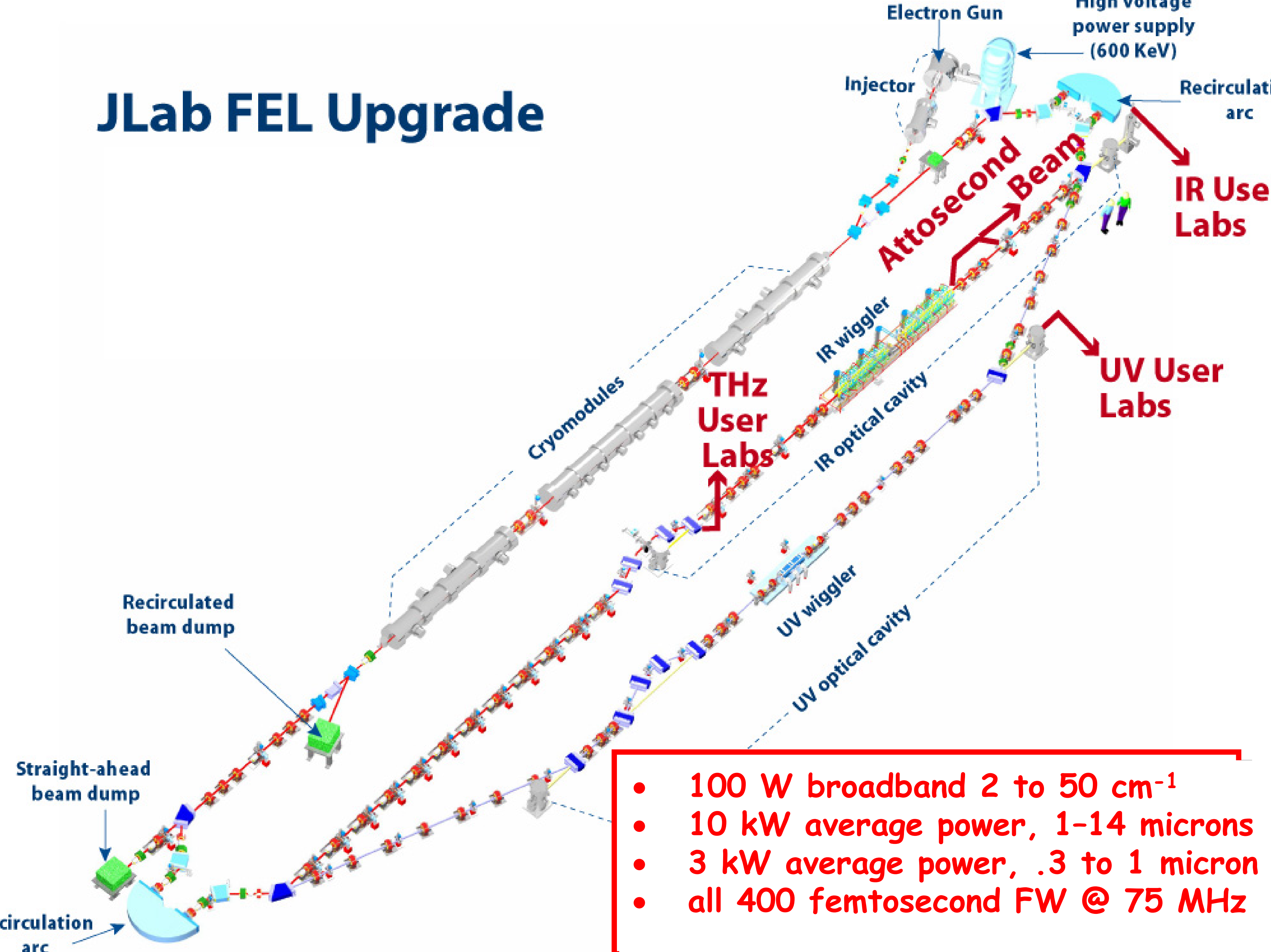
# FEL Program Timeline

| | |
|---|---|
| **Evolution of Design:** | |
| • 1 kW IR FEL Demo | 1996–1998 |
| • IR Demo operations | 2000–2001 |
| • 10 kW IR Upgrade | 2000–2003 |
| – 10 kW IR Upgrade operations | 2004– |
| • 1 kW UV Upgrade | 2002–2005 |
| – 1 kW UV Upgrade operations | 2005– |
| **In planning stage:** | |
| • 50—100 kW technology development | 2004–2006 |
| • User Lab Expansion | 2006(?) |

# FEL Program Stakeholders

- Scientific community (FEL Program Advisory Committee – FEL PAC)
  - **Always new frontiers when any parameter of a scientific tool improves by 10x**
  - **The 1 kW Demo was the most powerful tunable laser in the world by:**
    - **10 (UV)**
    - **$10^2$ (IR)**
    - **$10^5$ (THz)**
- Defense community (Maritime Technical Advisory Committee – MTAC)
  - **Navy: technology demonstration for directed energy applications (all electric drive tunable to atmospheric windows)**
  - **Air Force: high volume UV laser microfabrication**
  - **Army: THz beam line for land mine detection studies**
- Industrial Community (Industrial Advisory Board-IAB)
  - **Materials processing at 10-100 kW where cost per photon is commercially viable - (1-10¢/kJ)**
    - **Surface modification**
    - **Microfabrication**
    - **Pulse laser deposition/ablation**

# 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 400 femtosecond FW @ 75 MHz

# JLab FEL Upgrade: Highlights since March 2004 User's Meeting

**Successes:**

- IR Upgrade FEL completed and 10 kW milestone achieved on July 21, 2004
  - Characterization has begun : 10 kW average power lasing achieved at 6 microns
  - Lased at moderate powers at 2.8 - 3microns with broadband mirrors
  - User experiments getting ready; have provided alignment beam into Lab 1
- UV Upgrade FEL installation occurring this year
  - User experiments late next fall

  - THz system installed and ready to begin user experiments

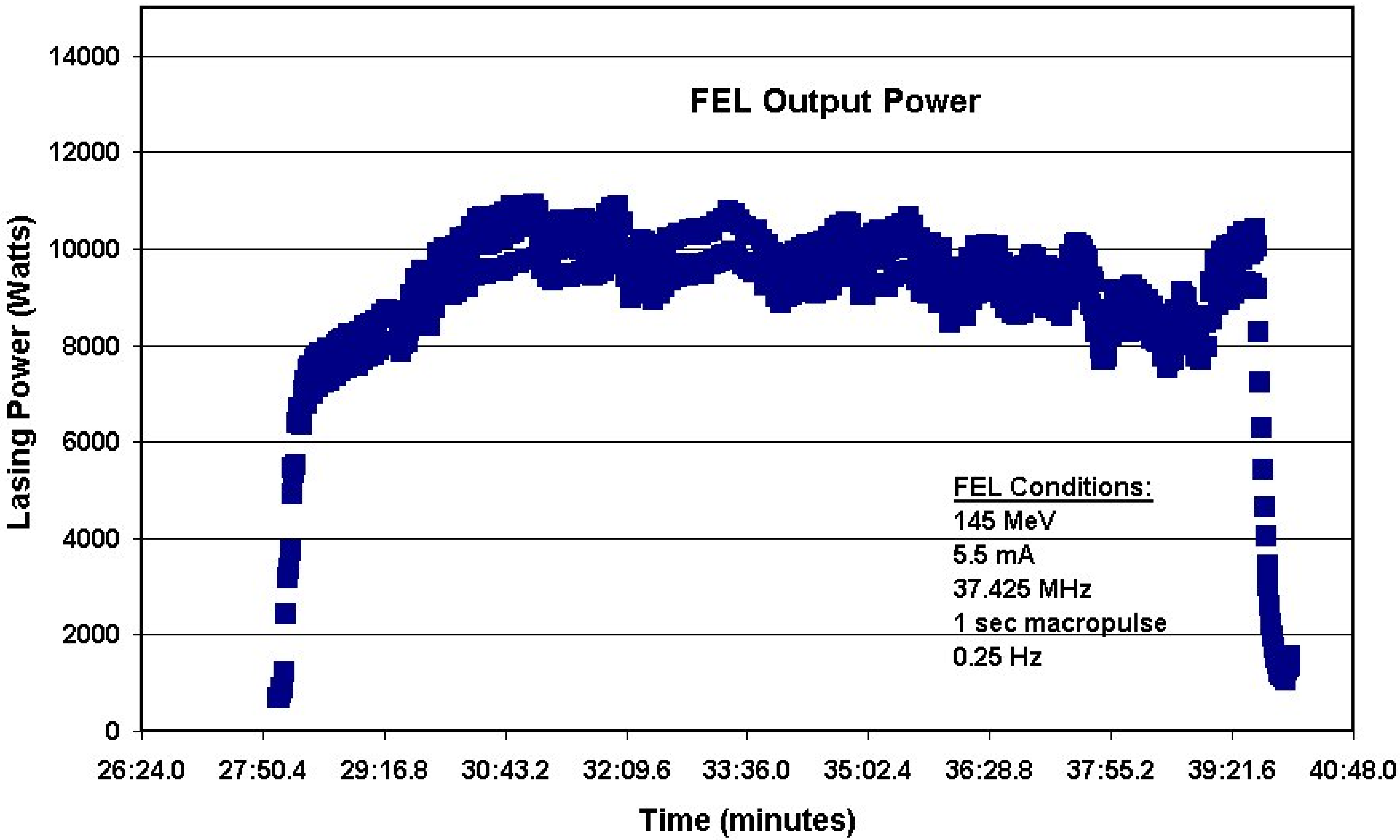
**Some setbacks**: lost some voltage capability in linac; may not be able to make 1 micron at full power (2005 Goal) or UV lasing on fundamental until replacement linac module is ready.

**User program will start up**:

- Third harmonic 1 micron lasing
- 700 nm lasing and doubled

# Timeline for Achieved Power

| Date | Wavelength | OC loss(PPM) | Pulsed efficiency | CW Power (W) |
|---|---|---|---|---|
| Aug. 27 | 10 µm | 7000 | 0.3% | 300 |
| Jan. 13 | 10 µm | 4000 | 1.25% | 700 |
| Switch to 88 MeV | | | | |
| Mar. 17 | 6 µm | 600 | 0.8% | 2300 |
| Apr. 23 | 5.75 µm | 250 | 1.1% | 4100 |
| Switch to 145 MeV, 2 sextupole families in first arc | | | | |
| June 15 | " | " | 1.6% | 6100 |
| Swap output coupler and high reflector | | | | |
| June 24 | " | " | 1.6% | 8500 |
| July 21 | " | " | 1.6% | 10600(1 sec) |



FEL Output Power
Lasing Power (Watts)
14000
12000
10000
8000
6000
4000
2000
0
FEL Conditions:
145 MeV
5.5 mA
37.425 MHz
1 sec macropulse
0.25 Hz
26:24.0
27:50.4
29:16.8
30:43.2
32:09.6
33:36.0
35:02.4
36:28.8
37:55.2
39:21.6
40:48.0
Time (minutes)

# Specifications: FEL Upgrade Design vs. Achieved

| Driver Accelerator | Design Spec. | Achieved Jul. 21 | UV Upgrade (2005) |
|---|---|---|---|
| Linac Energy | 80 MeV (145) | 160 | 160 |
| Linac Ave. Current | 10 mA | 9.1 | 5 |
| Charge | 135 pC | 150 | 135 |
| Transverse Emittance | 30 mm-mrad | <15 | 11 |
| Energy Spread | 0.3% | 0.3 | 0.3 |
| Bunch length * | 0.5ps | 0.5 | 0.5 |
| Longitudinal Emittance | 50 kV-ps | 80 | 50 |

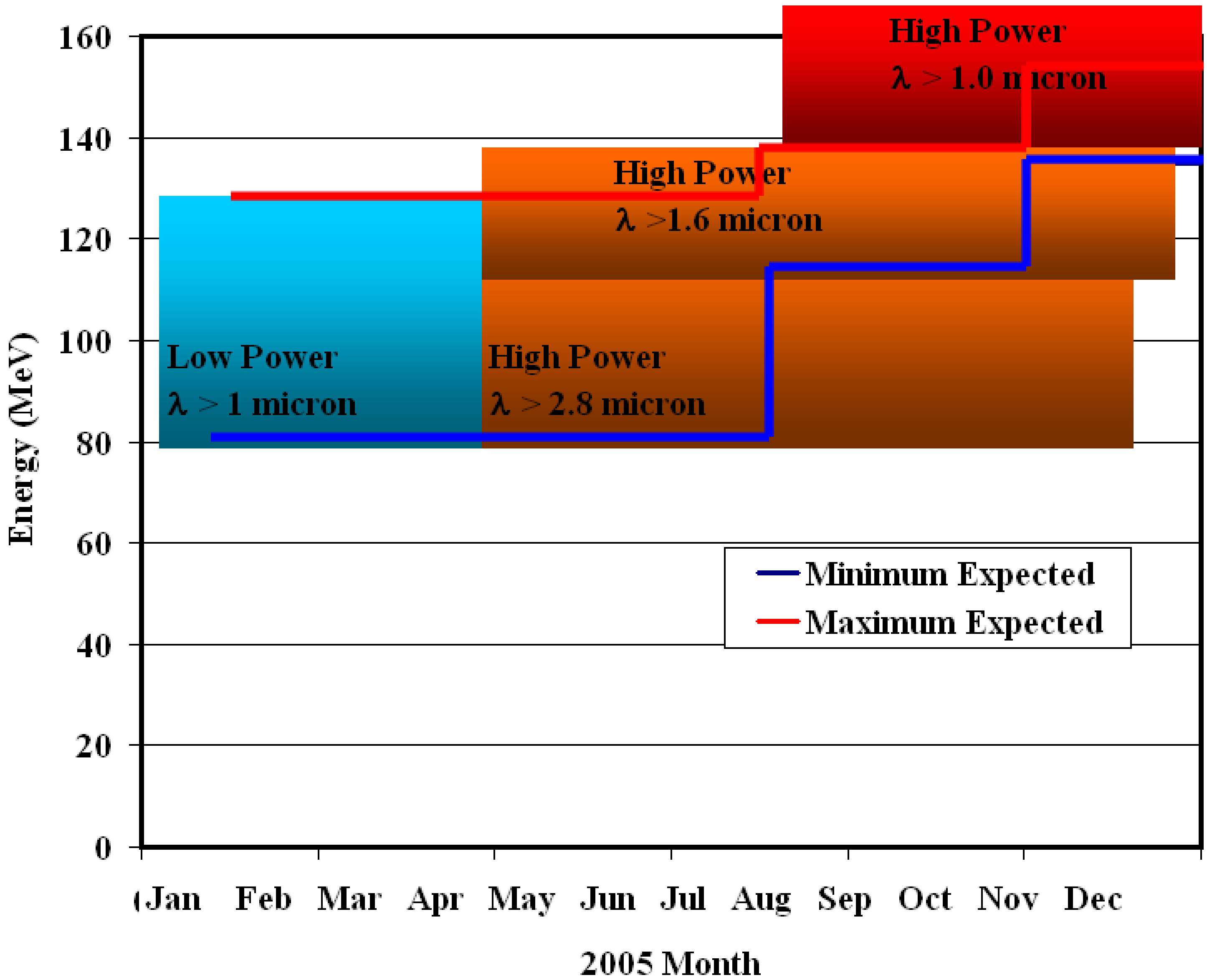
*FEL System*

| | | | |
|---|---|---|---|
| Ave. Power (cw) | 10 kW | 8.5 | 1 |
| Ave. Power (pulsed) | n/a | 10.6 for 1s | |
| Lasing efficiency | 1 kW/mA | 2.6 | |
| Stored Optical Power (@6um) | | 132 kW | |

*at desired energy spread

# It’s Time for Wine!

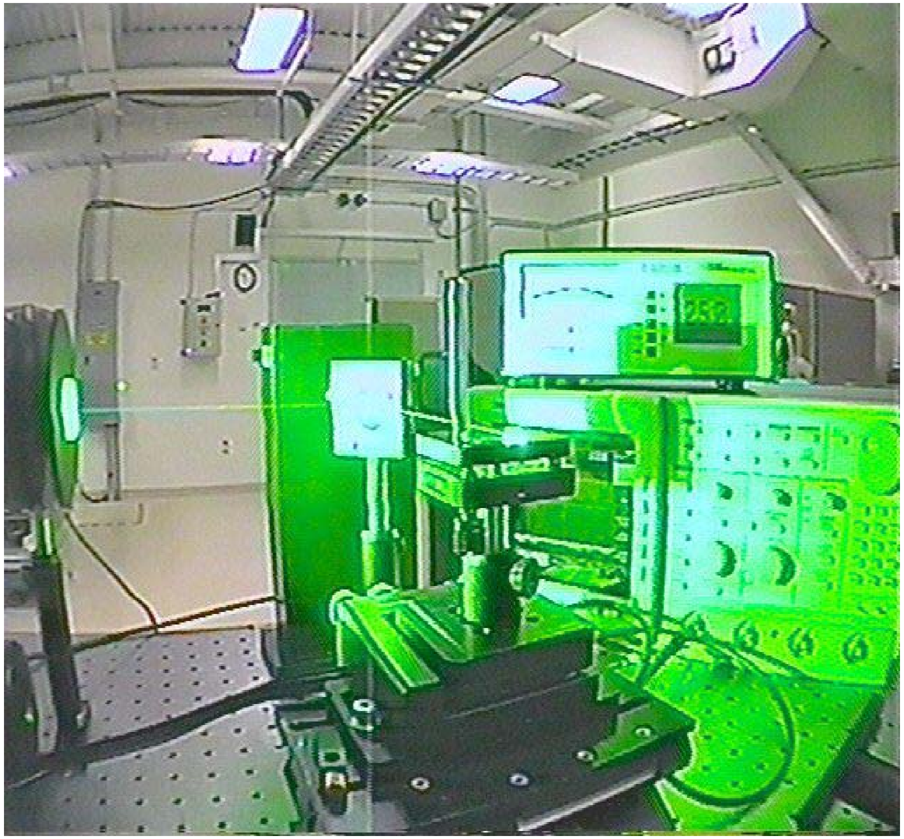
# Lasing Capability – IR Upgrade



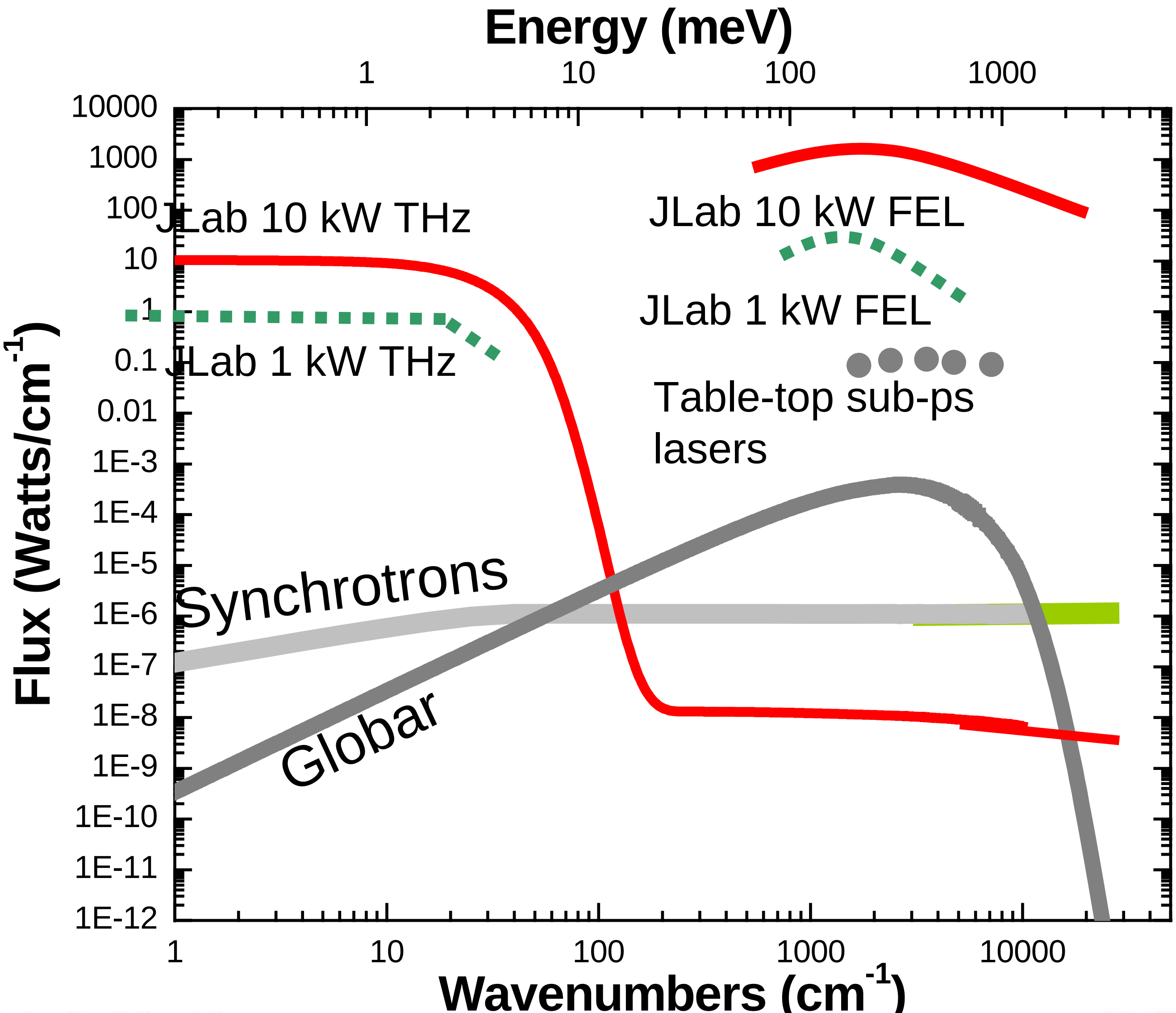
# JLAB FEL Harmonic Generation

| Wavelength | Conversion efficiency | CW Power (Watts average) |
|---|---|---|
| **Fundamental** 3.165 mm | 1.6% (ebeam:light) | 2100* |
| **Lasing 3rd Harmonic** 1.055 mm | 0.7% (ebeam:light) | 350* |
| **2x** 528 nm | 40% | 56* |
| **3x** 352 nm | 9% | 12* |
| **4x** 264 nm | 8% | 17 (pulsed) |

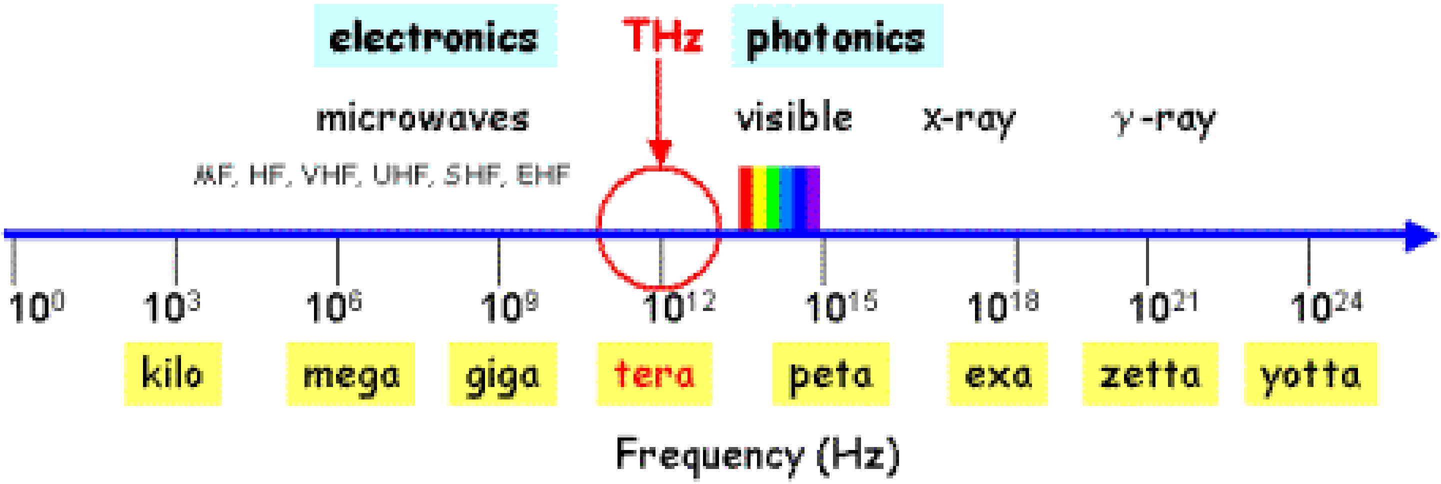
*World record for picosecond laser



# JLab FEL Power vs Conventional Sources



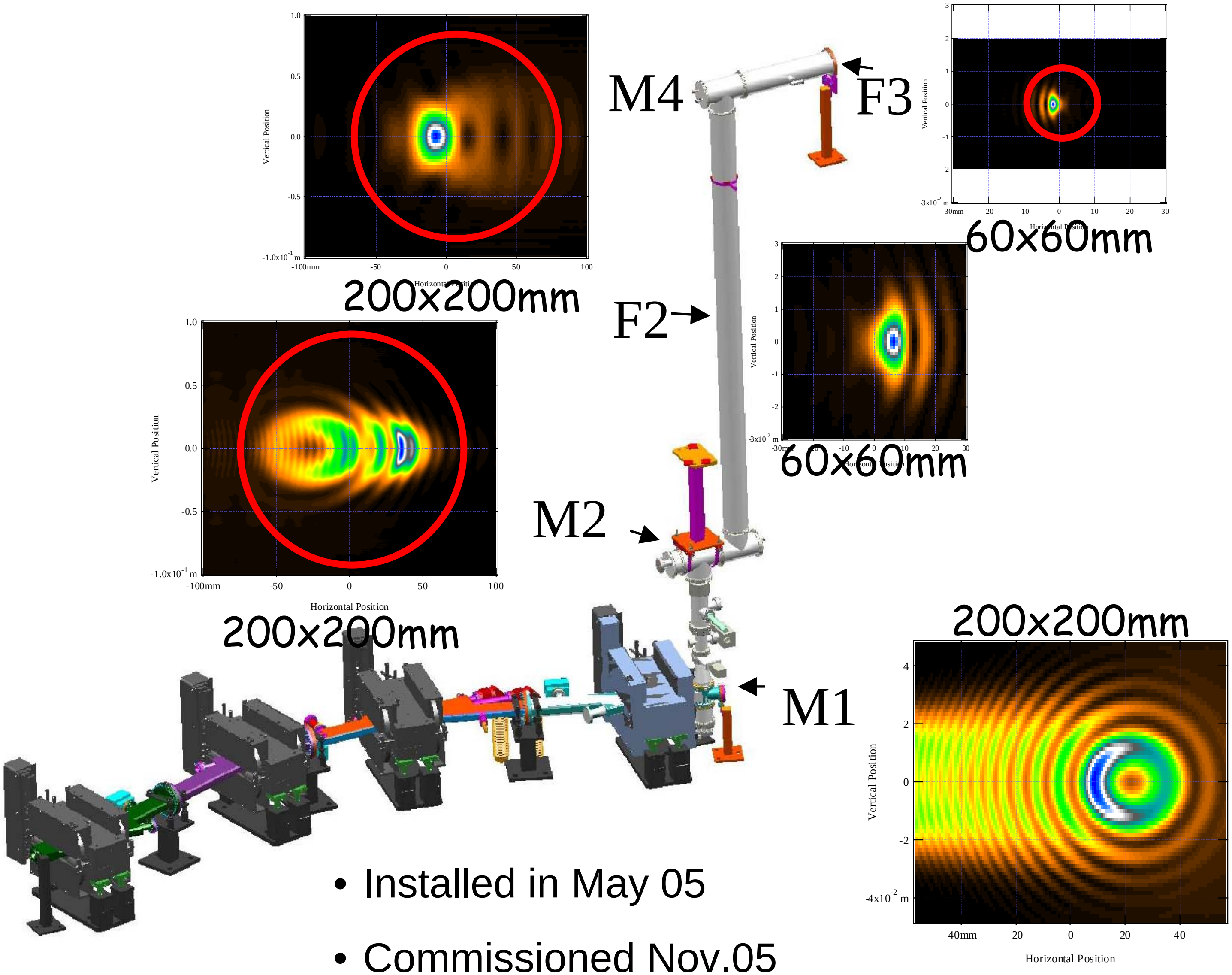
# THz: a Frequency Range with Rich Science but Limited Technology




1 THz ~ 1 ps ~ 300 μm ~ 33 $cm^{-1}$ ~ 4.1 meV ~ 47.6 °K

http://www.rpi.edu/~zhangxc

# Terahertz Beam Schematic with Optical Beam Ray-tracing




- Installed in May 05
- Commissioned Nov.05

# JLab THz Beamline Users on Deck

- Users with preliminary proposals, or who have indicated interest:

  ***Tatiana Globus, UVa***, spectroscopy of biological materials including DNA, polynucleotides and tissue, to establish dynamical processes and contrast mechanisms for imaging.

  ***X.-C. Zhang, RPI***, large area real-time imaging development using electro-optic detection methods and large imaging crystals.

  ***G. Williams, JLab, and L. Carr, BNL***, spectroscopy and scattering of particulate matter relevant to army program, initial experiments in June 2004 at Brookhaven.

  ***A. Sievers, Cornell***, non-linear dynamical studies of iron oxides, generation of localized modes. Development and testing of novel "shear" wavelength multiplexing interferometer.

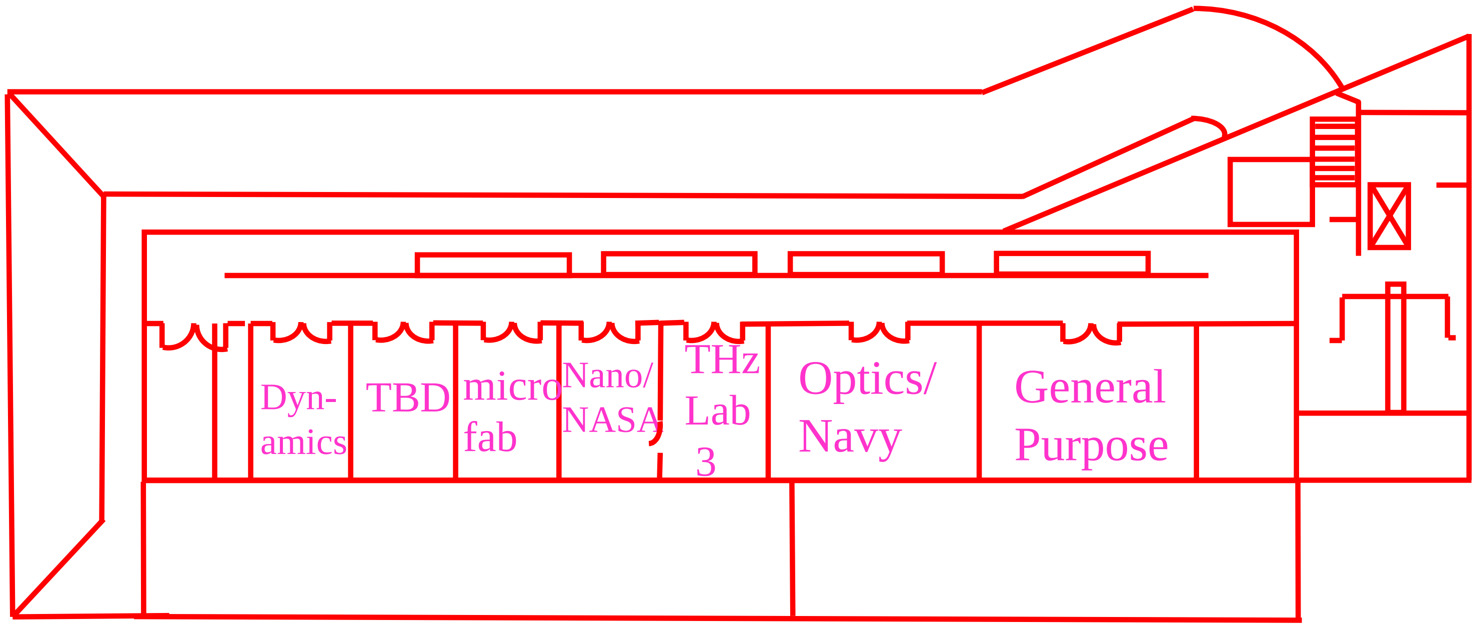
  ***Bob Jones, UVa***, creation of Rydberg atoms and dynamical studies.

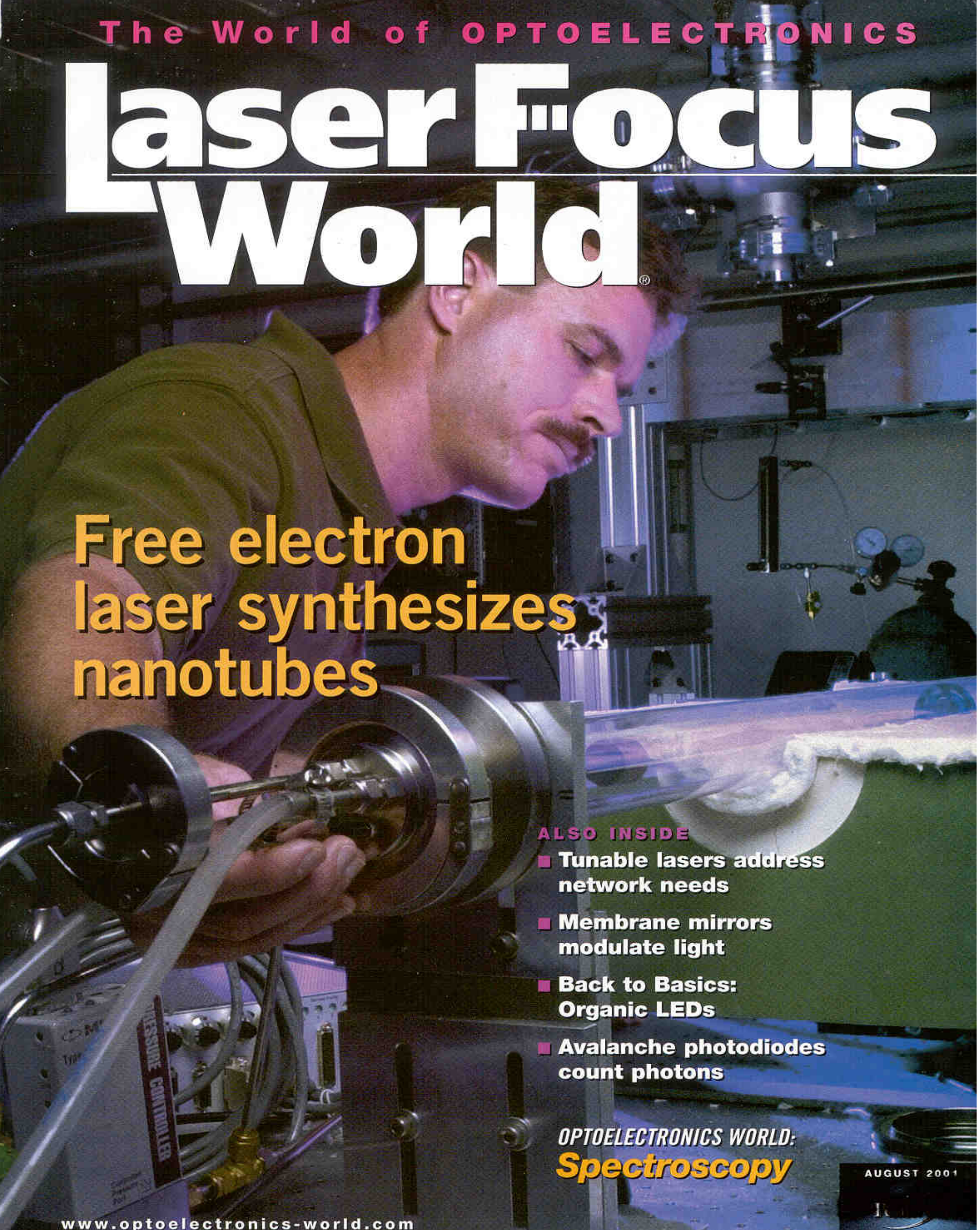
  ***Martyn Chamberlin, Durham, UK***, use of high power THz light to bleach water absorption in biological samples.

  ***Dan Mittelman, Rice U***., use of high power THz for imaging modality studies.

  ***Bob Austin, Princeton***, energy transport in biomolecules

# JLab FEL User Lab Layout






Jefferson Lab

# *FEL Science Research 2000/2001*

***Interactions of Hydrogen in Group IV Semiconductors with Intense Infrared Resonant Radiation*** G. Lüepke, CWM , L. Feldman, N. Tolk, and M. Budde, Vanderbilt

***Laser Target Interactions in PLD*** A. Reilly, M. Kelley, CWM, and M. Shinn, JLab

***FEL Polymer Ablation for Reflective Sails*,** M. Kelley, CWM, J. Clarke and S. Reich, Northrop Grumman

***Long lived Amide I Vibrational Modes in Myoglobin*,** R. Austin, Princeton

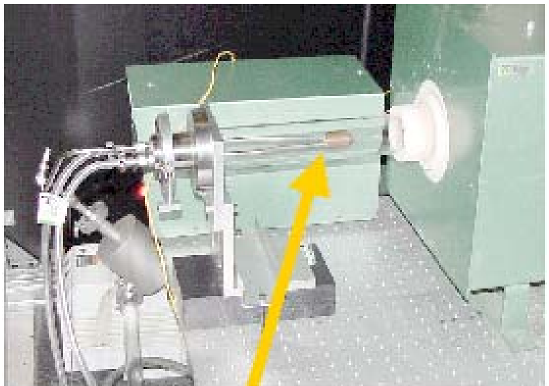
***Synthesis and Characterization of carbon nanotubes and Si and Ge nanowires for use in NLO Composites*,** B. Holloway, CWM, M. Smith, NASA, Langley, P. Ecklund et al. Penn. St.

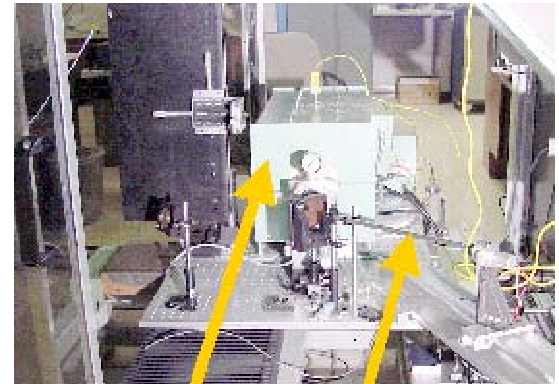
***Laser-Plasma Material Interactions in Dense and Reactive Gas Atmosphere*,** P. Schaaf, U. Gottingen, Germany

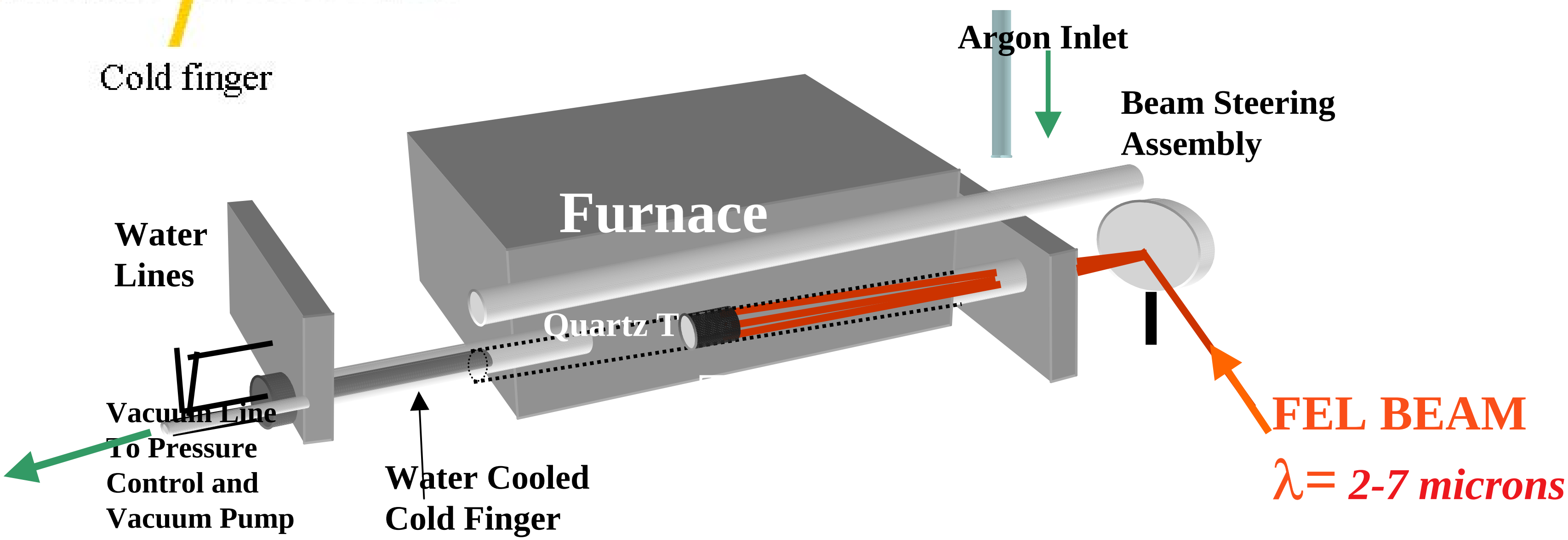
# Synopsis of FEL User Results: 2000-2001

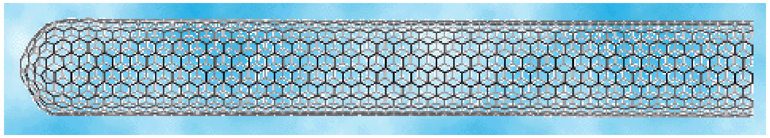
- Spectroscopy
  - H-Si (Luepke, CWM)
  - Amide-I in myoglobin (Austin, Princeton)
- Ablation
  - Resonant PLD of polymers – (Kelley, CWM; Haglund, Vanderbilt)
  - Non-resonant, high quality magnetic/SC films – (Reilly, CWM; Shinn, JLab)
- Micro/nano-fabrication
  - C-nanotubes – (Holloway & Smith, CWM, NASA, PSU)
  - UV/visible micro structuring of glasses (Helvajian, Aerospace Corp.)
- Surface processing (Kelley)
  - Laser nitriding of metals (Schaff, Göttingen)
  - Laser amorphization of metals (Kessel, Dominion Power)

# Reaction Chamber for laser fabrication of C-nanotubes



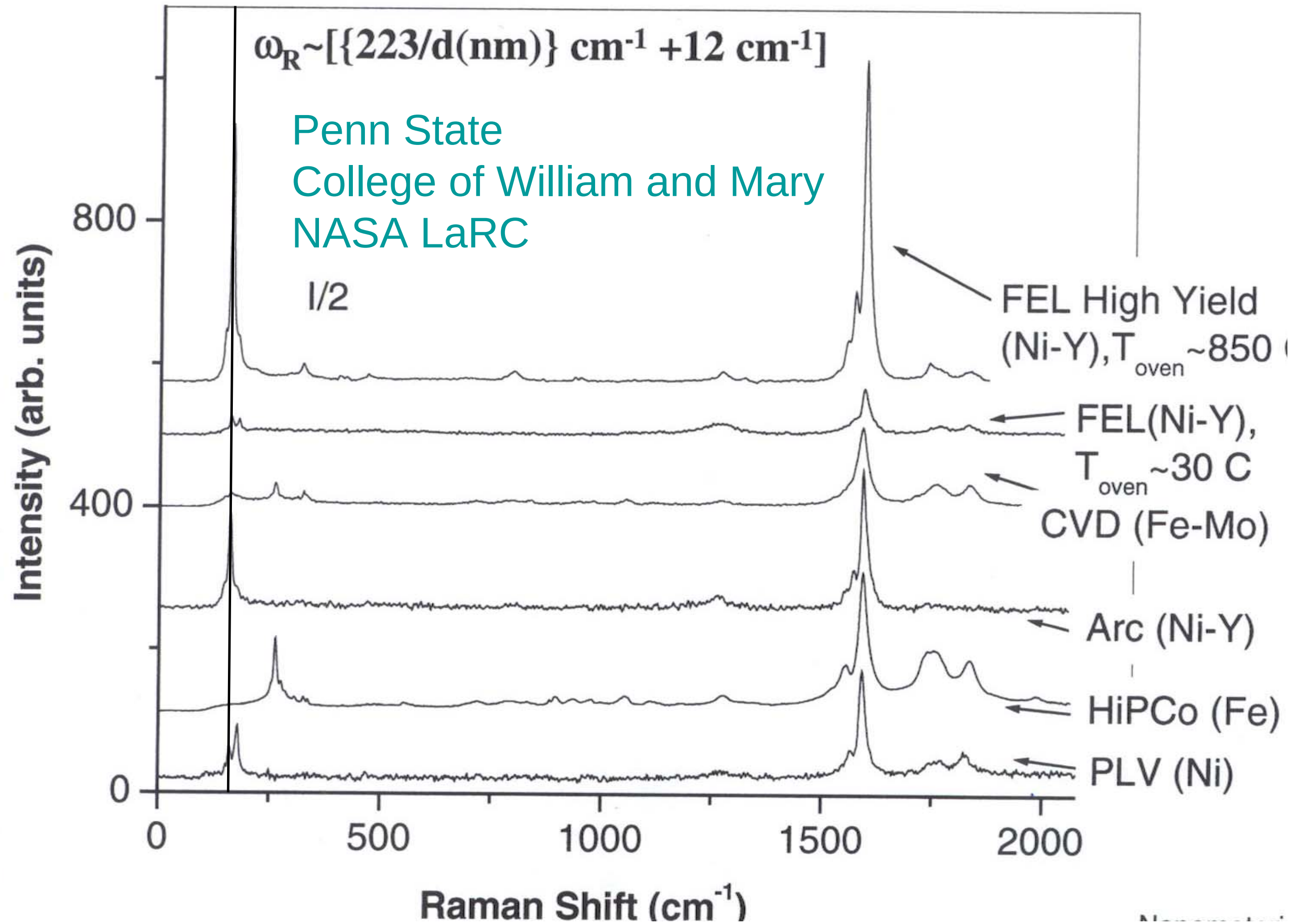





# Nanotubes at the JLab FEL

Penn State
College of William and Mary
NASA LaRC



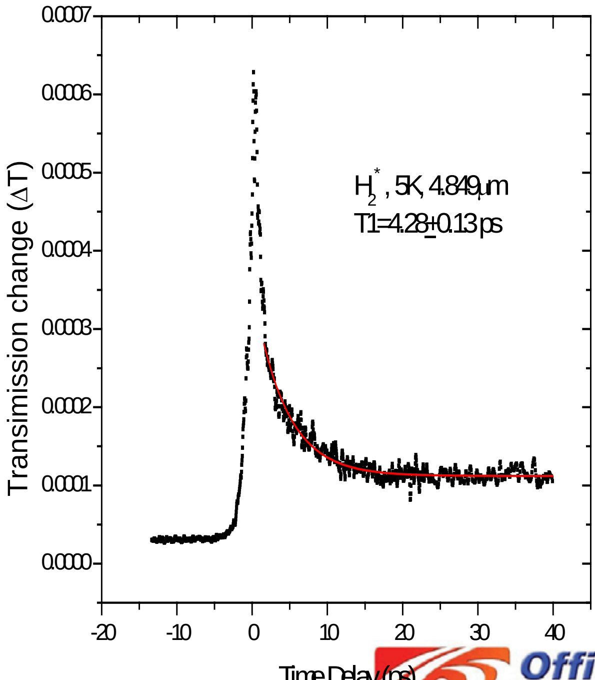
# Vibrational Lifetimes of Hydrogen in Silicon

**Physical Review Letters -- August 14, 2000 -- Volume 85, Issue 7 pp. 1452-1455**

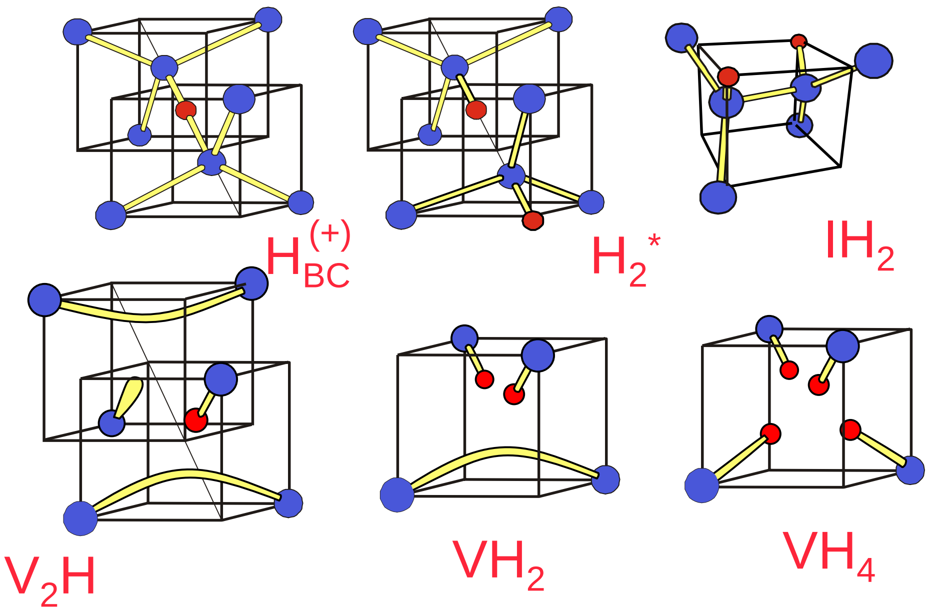
**Vibrational Lifetime of Bond-Center Hydrogen in Crystalline Silicon**

**M. Budde,[1] G. Lüpke,[2] C. Parks Cheney,[1] N. H. Tolk,[1] and L. C. Feldman[1,3]**
*[1]Department of Physics and Astronomy, Vanderbilt University, Nashville, Tennessee 37235*
*[2]Department of Applied Science, The College of William and Mary, Williamsburg, Virginia 23187* *[3] Solid State Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831*

- **Hydrogen is a common impurity in crystalline silicon**
- **Vibrational lifetimes of the hydrogen can be measured by a pump-probe of bleaching decay**



# Science at the JLab FEL - H/Si



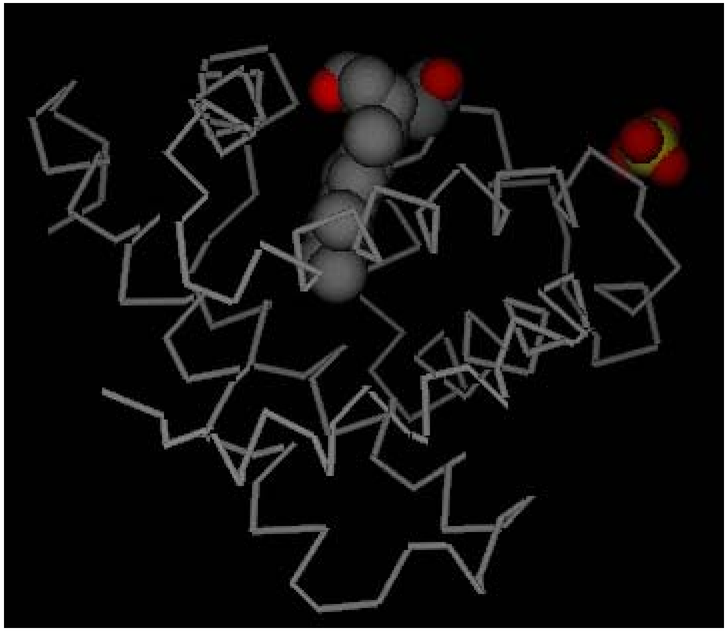

**Luepke et al. CWM**
**Feldman et al. Vanderbilt**

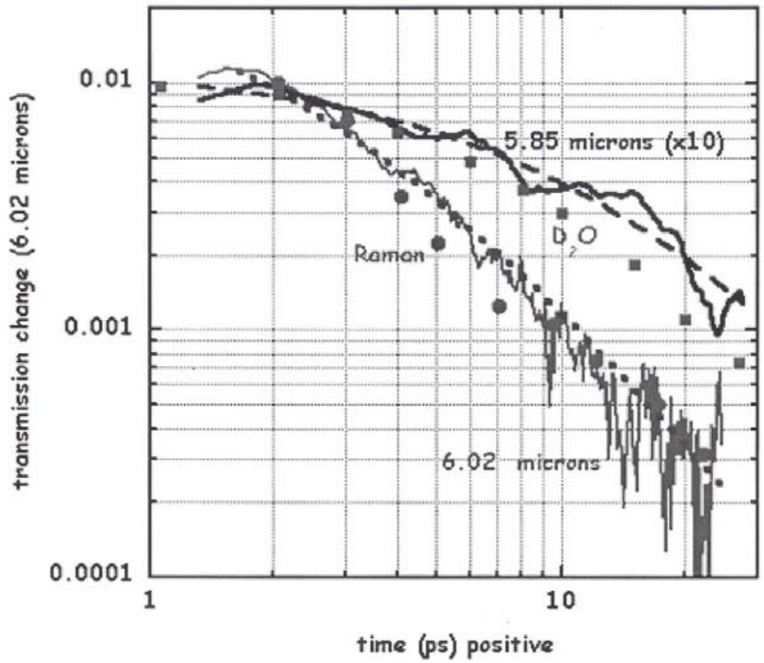
Phys. Rev. Lett. **88**, 135501, 2002
Phys. Rev. B. **65**, 035214, 2002.
Phys. Rev. Lett. **87**, 145501, 2001
Phys. Rev. Let. **85**, 1452 2000
J. Appl. Phys. **93** 2316 2003

Major program in hydrogen vibrational dynamics

| Defect | $\omega_H$ ($cm^{-1}$) | $T_1$ (ps) | $T_1$ (ps) | $\omega_D$ ($cm^{-1}$) |
|---|---|---|---|---|
| $H_2^*$ | 2062.1 | 1.9 | 4.8 | 1500.1 |
| $IH_2$ | 1987.1 | 12 | 20 | 1446.5 |
| $IH_2$ | 1990.0 | 11 | 18 | 1448.7 |
| $VH_2$ | 2122.3 | 60 | 70 | 1547.9 |
| $VH_2$ | 2145.1 | 42 | 55 | 1565.1 |
| $VH_4$ | 2223.0 | 56 | 143 | 1617.5 |
| $HV{\cdot}VH_{(110)}$ | 2072.5 | 295 | 93 | 1510.4 |

# Protein dynamics



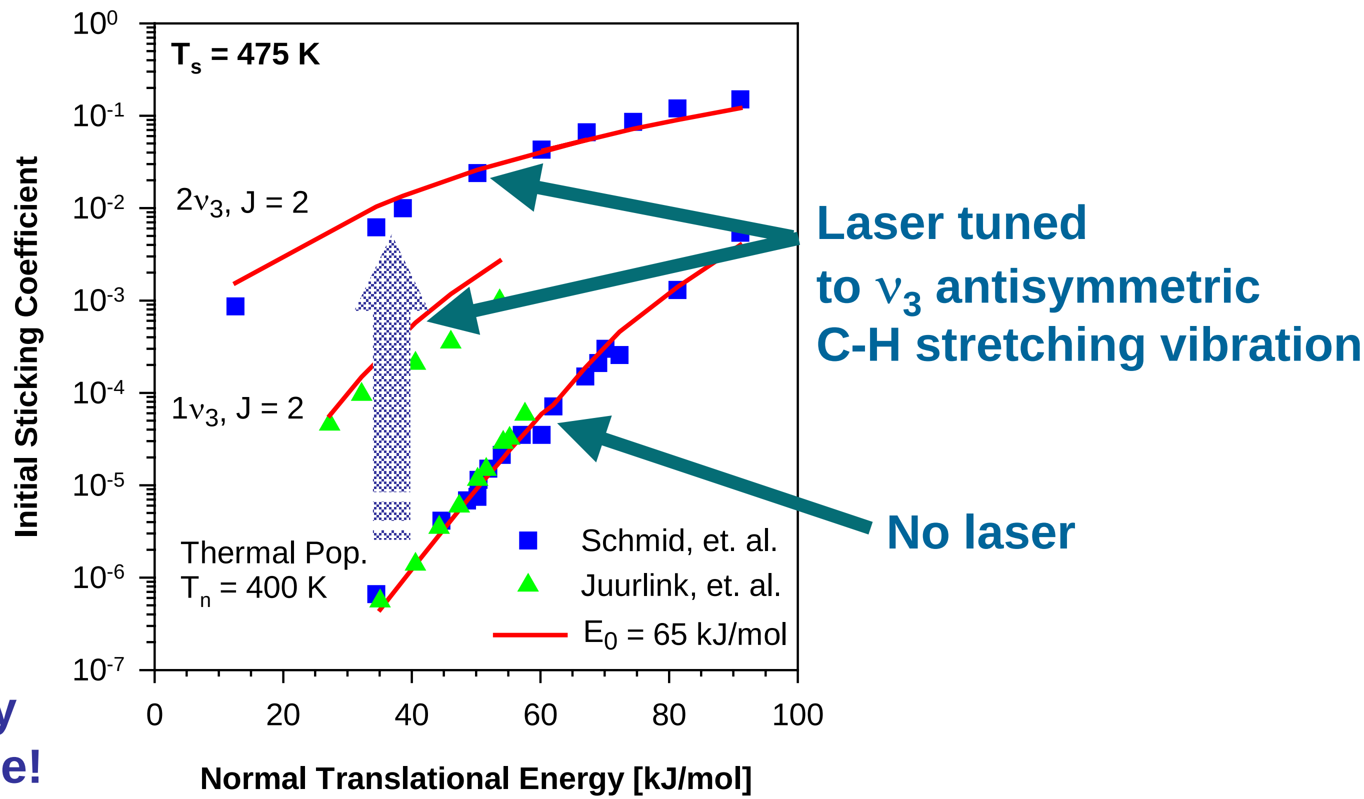



powerlaw decay: $(t/\tau)^{-2}$, $\tau$ = 2.1 ps at 6.02 um, 15 ps at 5.8

**Dynamics of myoglobin Amide I ($CONH_2$) band.**
**Felix FEL replicated at J-Lab.**

**A. Xie, L. van der Meer, W. Houff, R.H. Austin Phys. Rev. Letts. 84 5435, 2000 at FELIX repeated at JLab**

# The benefits of high repetition rate and tunability




**IR-laser pumping increases reaction probability by many orders of magnitude!**

Dissociative chemisorption of a $CH_4$ molecular beam incident on a Ni(100) surface with and without laser excitation of the.

Ian Harrison et al, UVa

Microcanonical Unimolecular Rate Theory at Surfaces – IR Photochemistry in Catalysis

# Potential Industrial Application

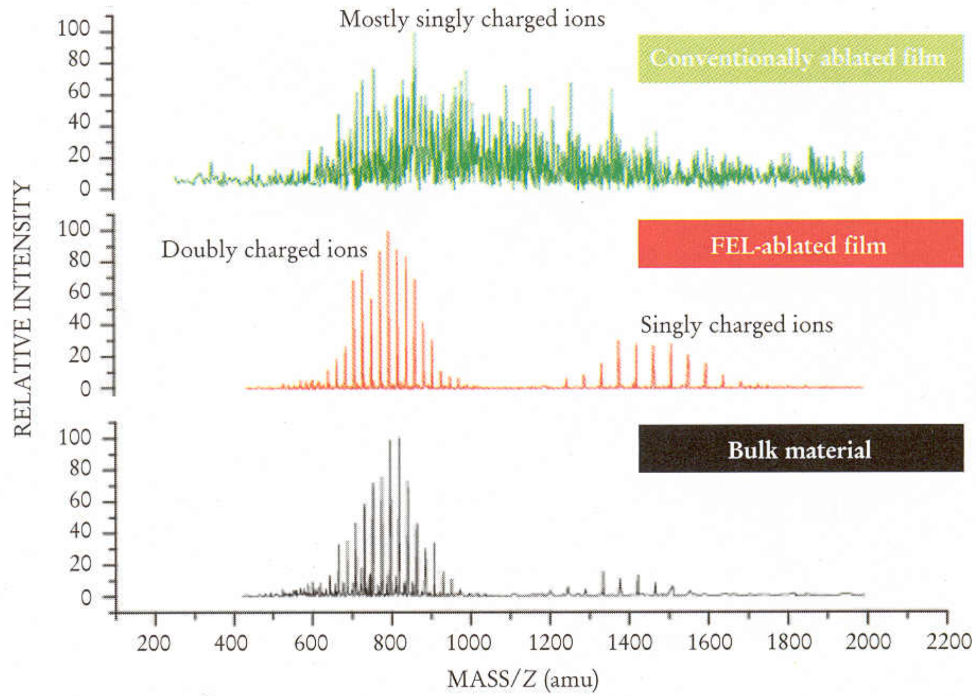
**Example**: IR resonant ablation shown in JLab and Vanderbilt FELs

Select wavelength to deposits energy into the link: 2.9 μm for poly(ethylene glycol)

Find molecularly-faithful materials transport and degradation-free cutting

Opportunity to coat "anything on anything"

D.M.Bubb et al.; J.Vac.Sci.Technol. A 19 (2001) 2698 cited in W.B.Colson et al. Physics Today 55 (2002) 35.

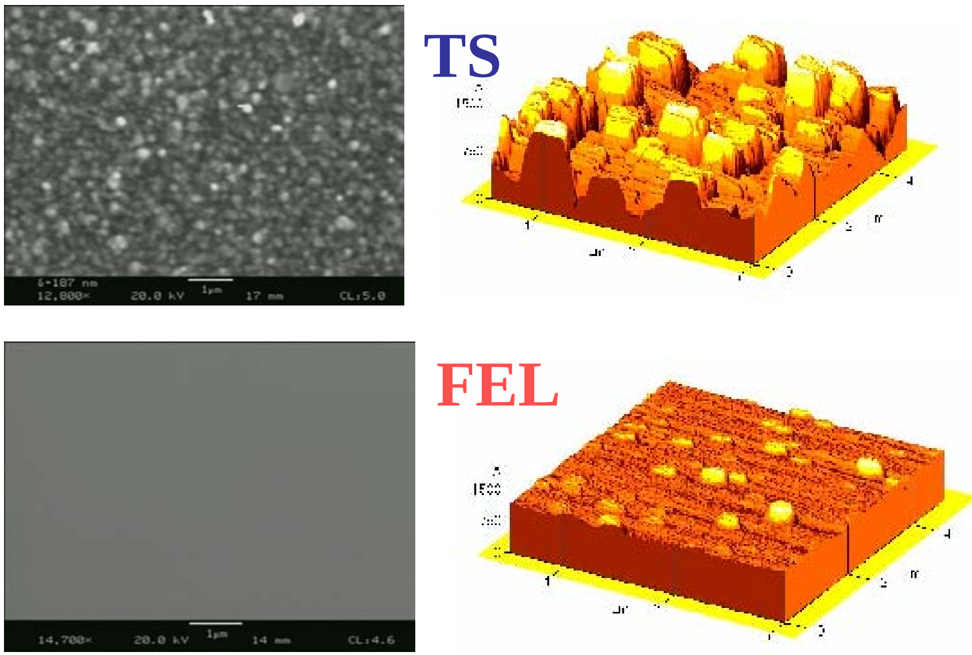


# Pulsed Laser Deposition with the JLab-FEL:Benefits of Picosecond Pulses, High Average Power and High Repetition Rate

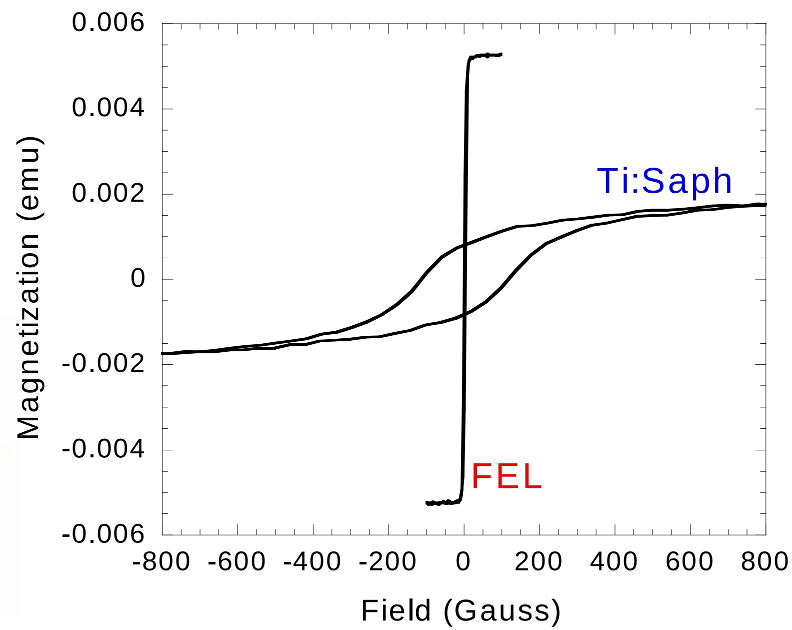
Deposition of metals with high rate (up to 200 Å/sec)

A. Reilly et al. CWM

Particulate free films (< 1 $cm^{-2}$) of high quality compared to low repetition rate Amplified Ti:Sapphire deposition

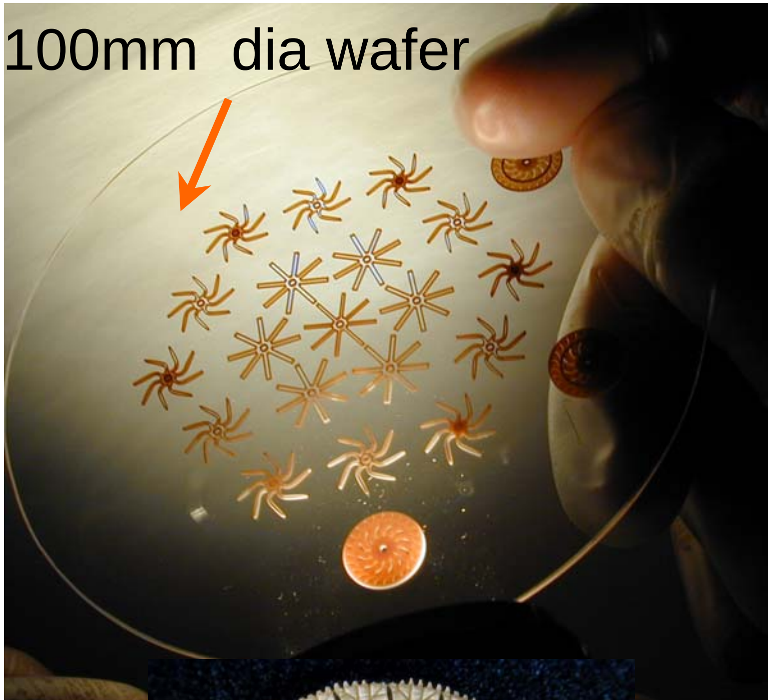



SEM (left) and AFM (right) of NiFe films grown with an amplified Ti:Saph (top) and the FEL (bottom).

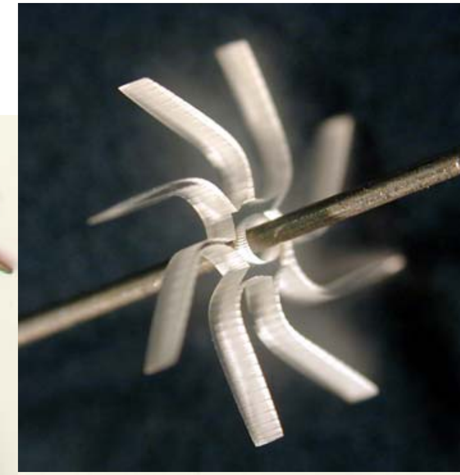


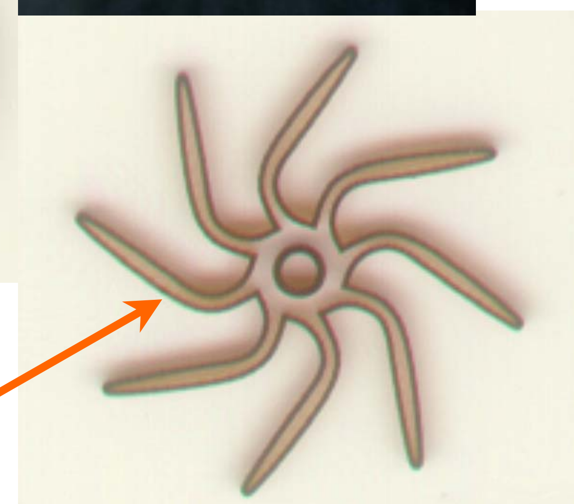

Magnetization of NiFe films grown with amplified Ti:Saph and FEL. Note high quality, low coercivity (~ 5 Gauss) of FEL film.

# An example of UV microfabrication for satellites:
# 3D Test Turbines Patterned via Laser Exposure



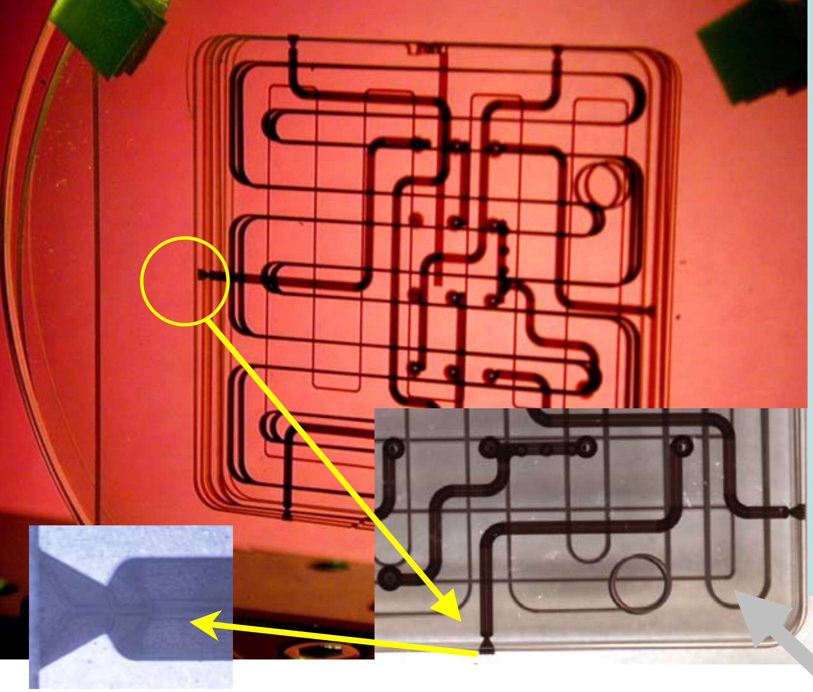


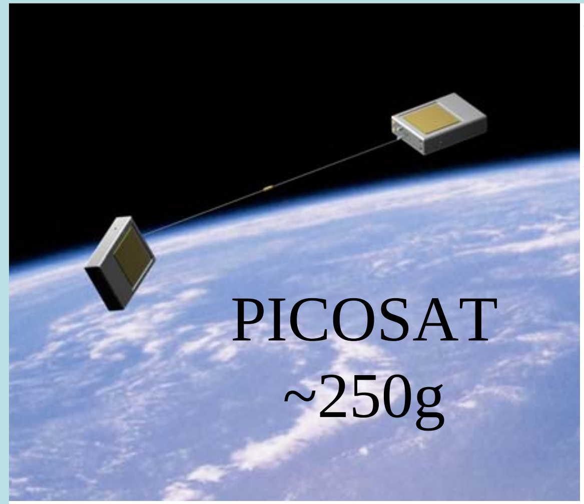




1 mm thick
Pattern 200 μm

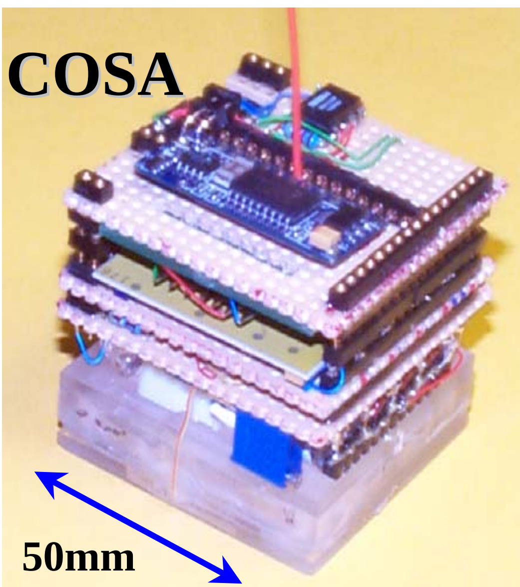
Henry Helvajian, Aerospace Corp.

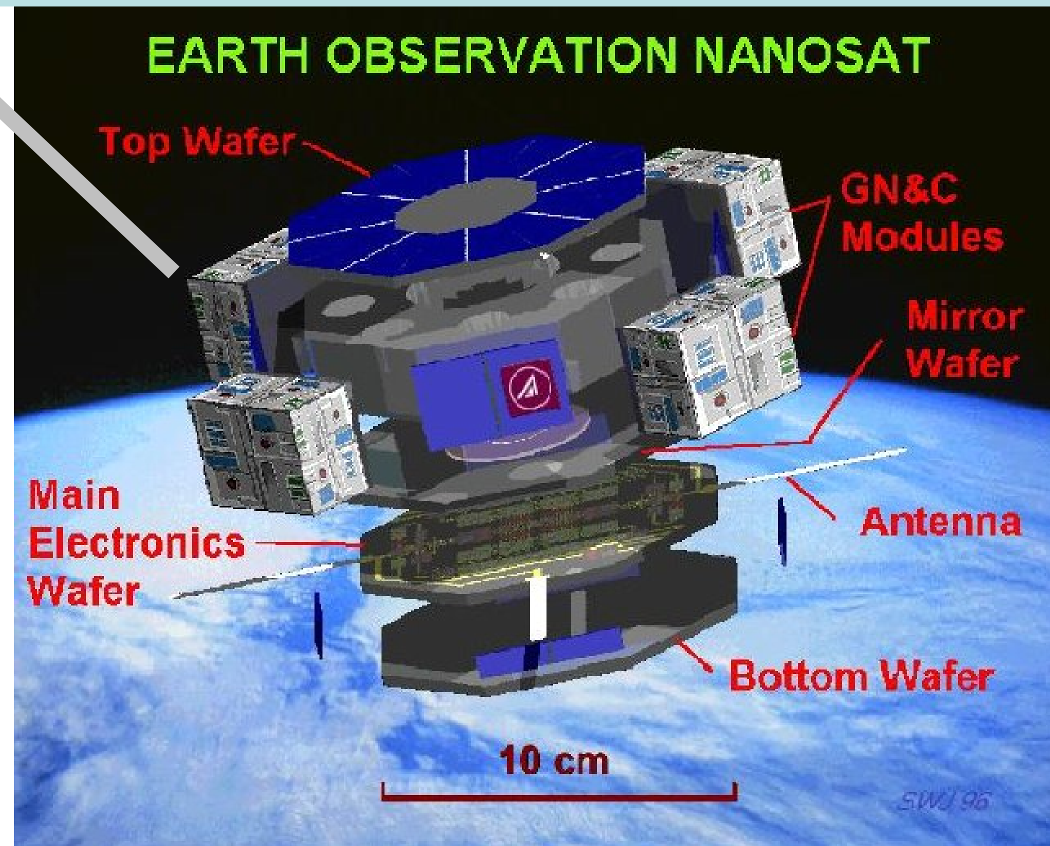





DARPA/Aerospace/AFRL

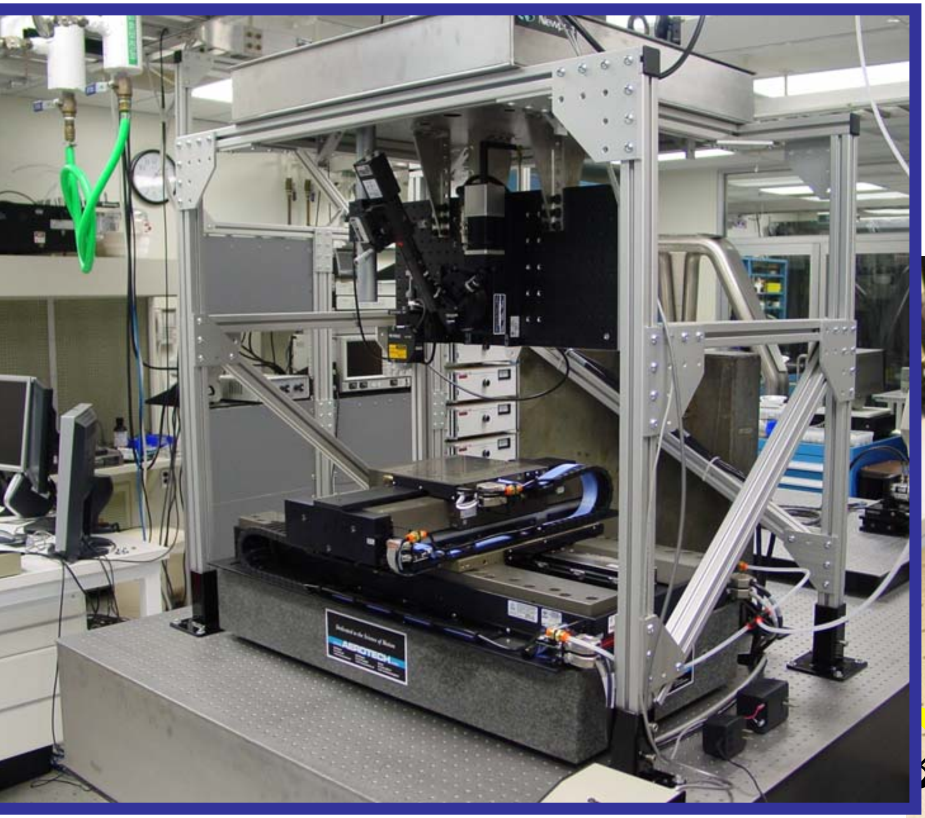
**Picosat1**
Launched 1/26/00
**Picosat2**
Launched
12.44 PDT 9/7/01
after more than a year storage inside a larger satellite

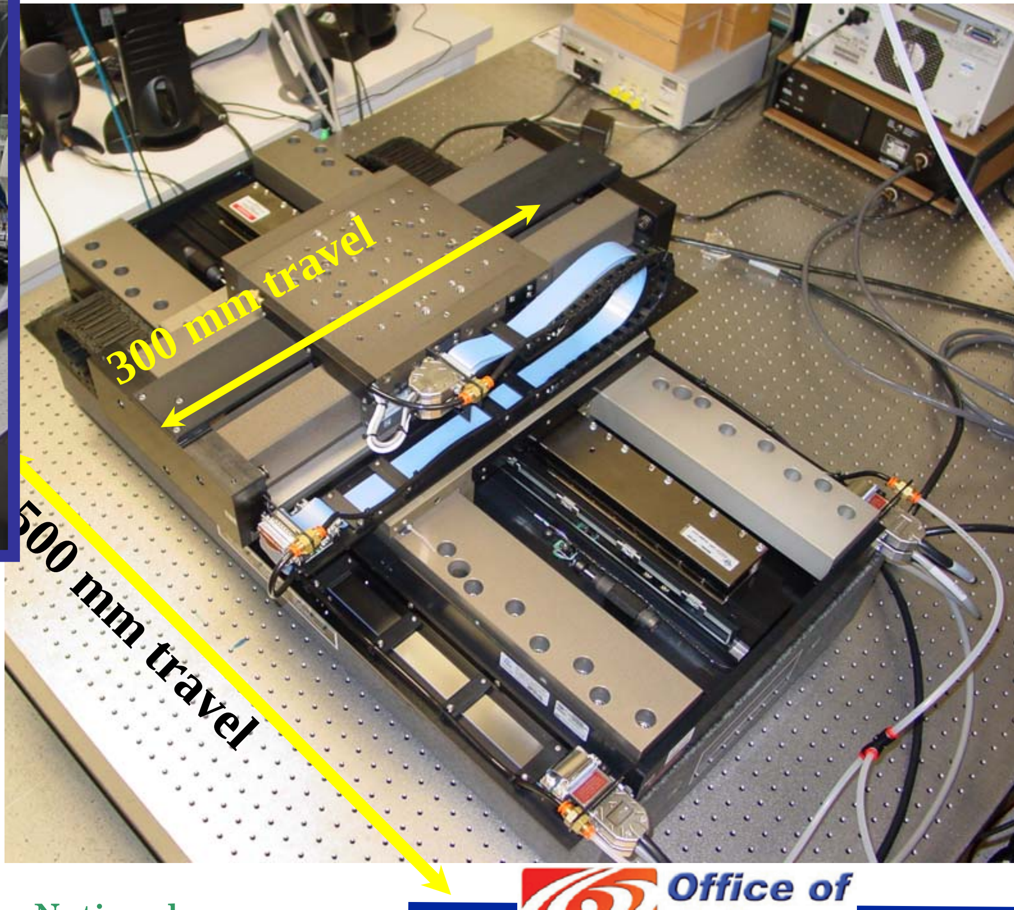


# Prototype Laser Microengineering Station for UV FEL

- First 3D laser microfab. station
- State-of-art speed, resolution, and processing area (+/- 0.25m)



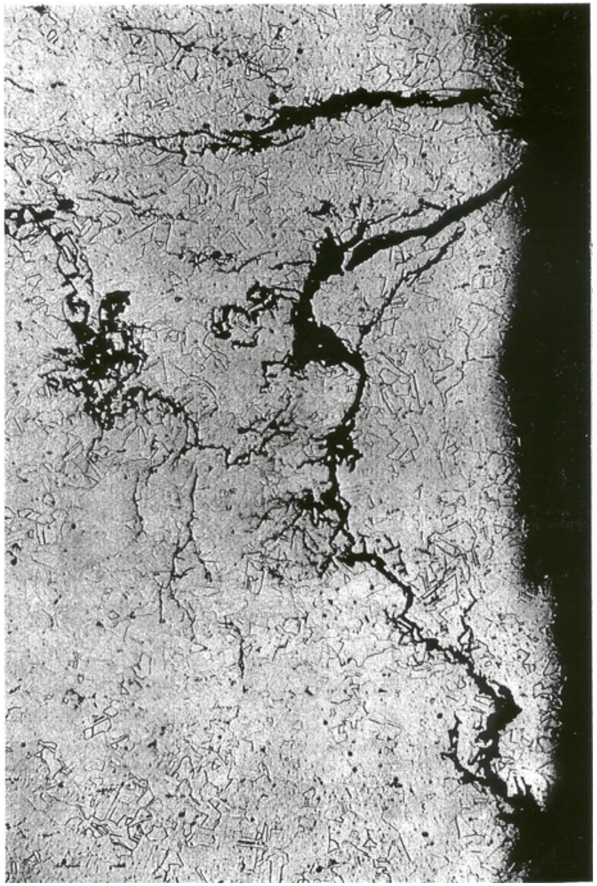



- Designed and built by Aerospace Corp. (due May 05)
- Installation in User Lab 4

# Achieving Amorphization

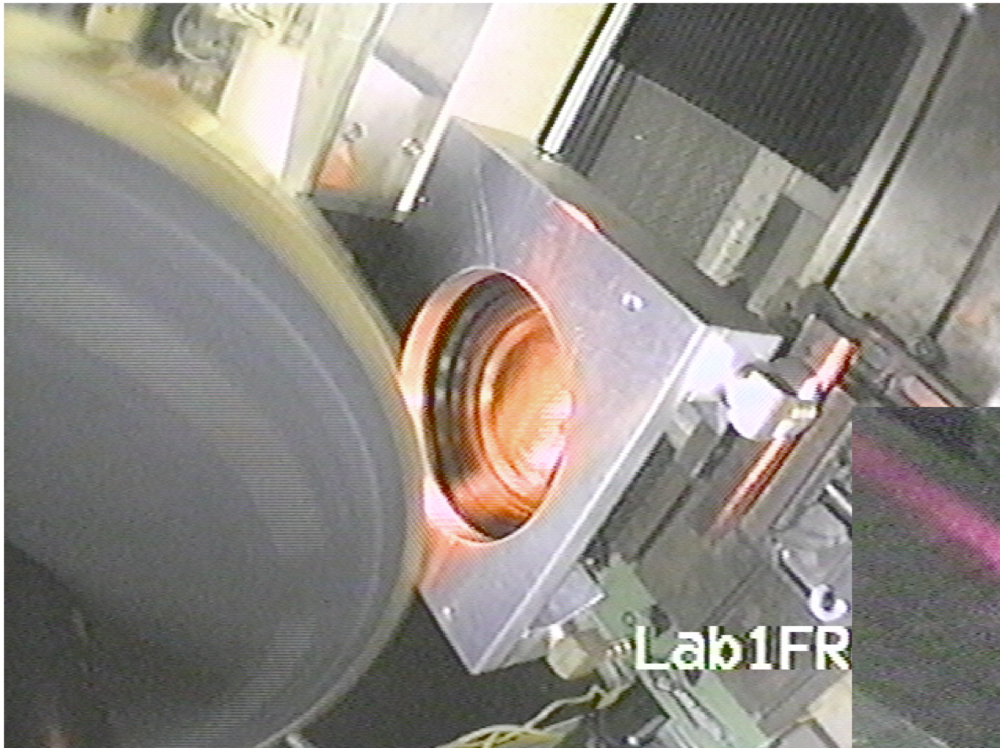
- Special alloying compounds are required to minimize crystal growth
- Picosecond FEL pulses provide high surface cooling rates that amorphize ordinary metals: crystals don't have time to form

| Laser Process | Cooling Rate (K/sec) |
|---|---|
| FEL | $10^{15}$ |
| Excimer | $10^{10}$ |
| CO2 | $10^{6}$ |
| Rapid Quenching | $10^{6}$ |

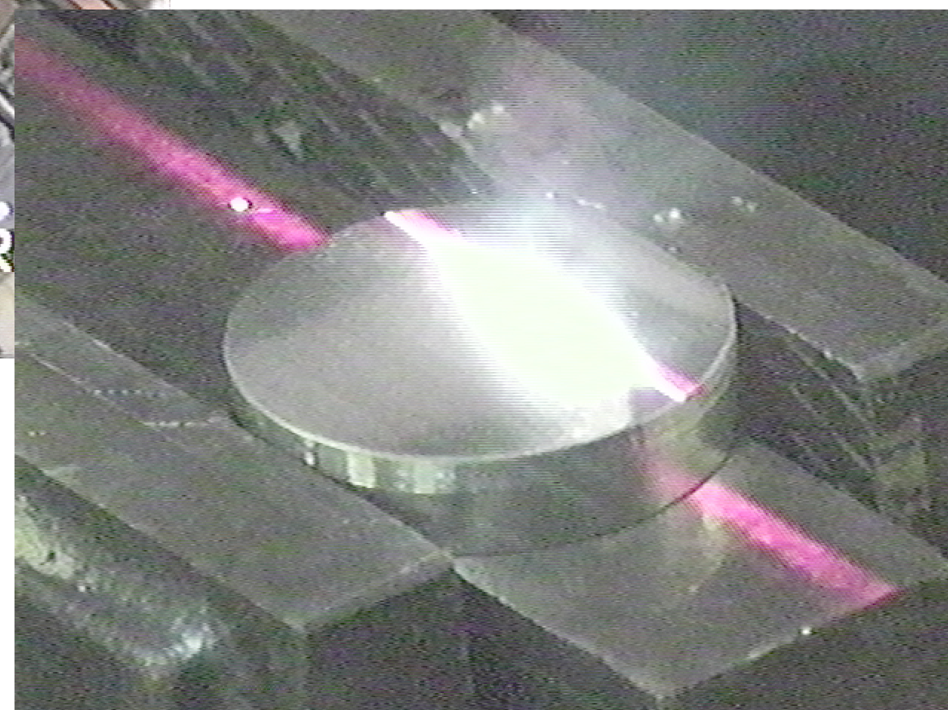


Micrograph of corrosion attacking grain boundaries on an ancient Japanese sword

# Metal Surface Processing




Successful FEL surface amorphization of steels (Kessel, Dominion Power)

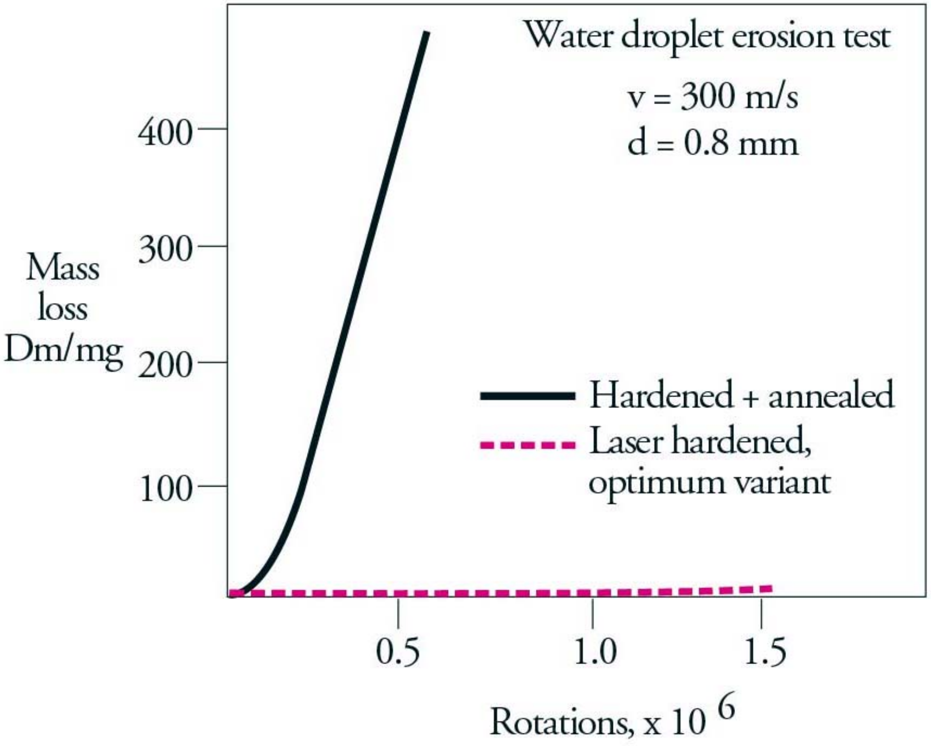


Have also achieved in situ nitriding for surface hardening (Schaaf, Göettingen)

# Surface Amorphization of Metals

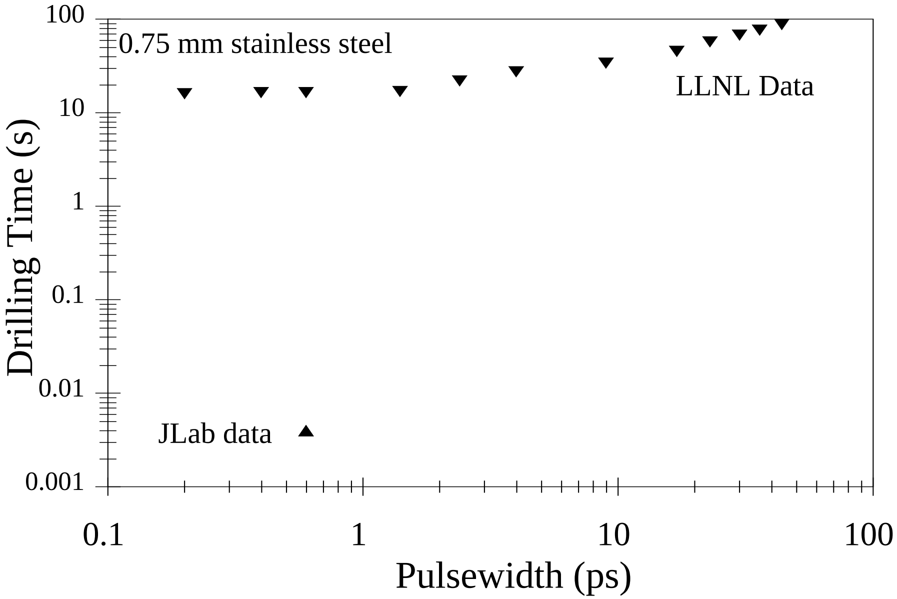
Amorphous metals exceed their crystalline counterparts in

- Strength
- Wear resistance
- Toughness
- Corrosion resistance




Applications in turbine blades, tooling, structures for marine environments, etc.

# Laser microdrilling of fuel injector orifices (Siemens)





***Tests show FEL has ideal pulse structure for high volume production***

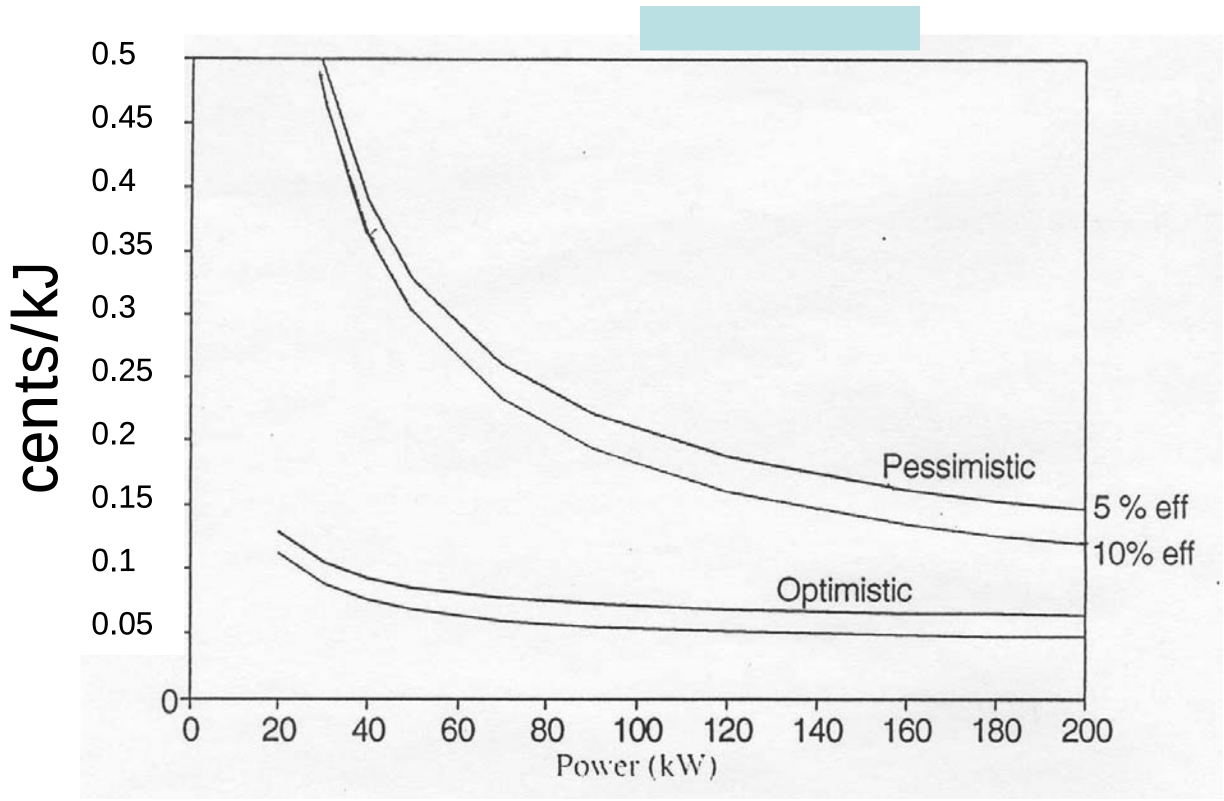
**An application with difficult requirements for ordinary lasers**

- **high reproducibility**
- **shape control**
- **high repetition rates**

# High Power FEL Cost Analysis

**the FEL: an interesting industrial tool at 10-100kW**

IR FEL: depreciation, utilities, maintenance, operators




Alternatives costs, c/kJ

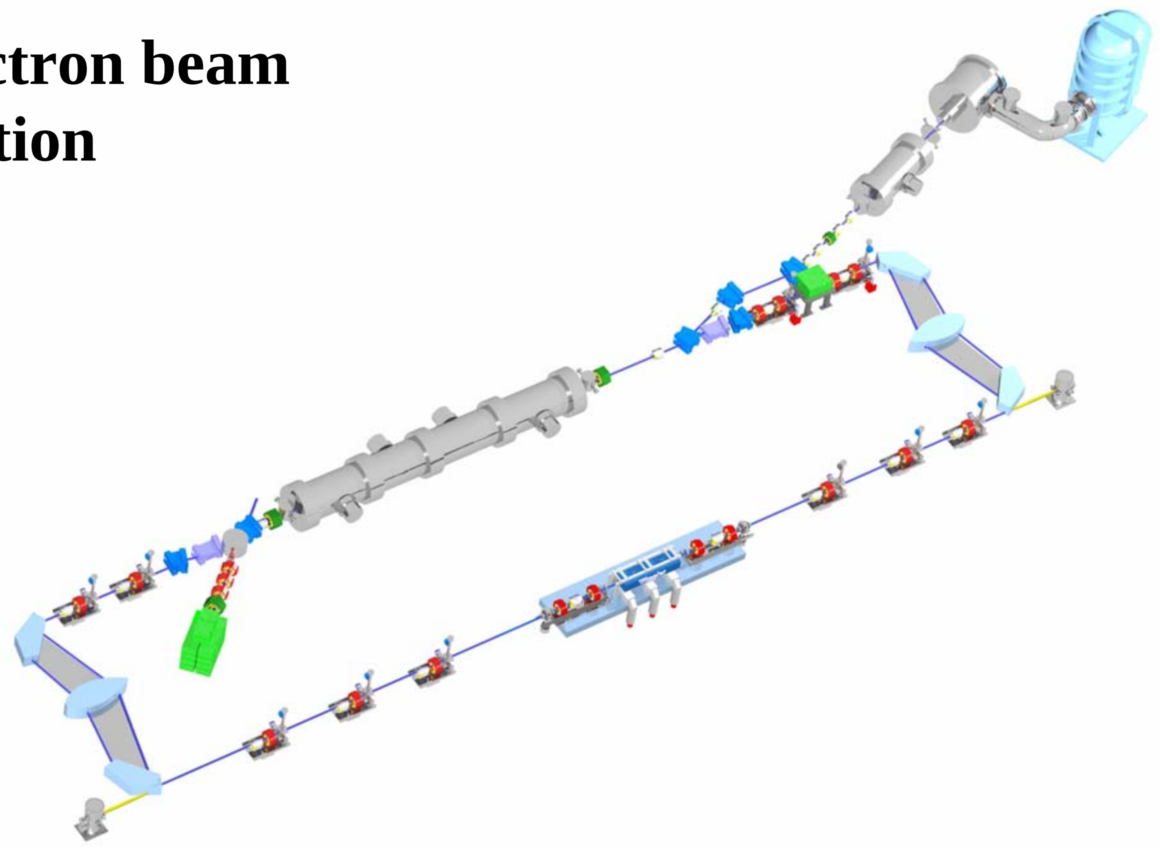
$CO_2$: 0.15

Nd:YAG: 0.37

Excimer: 9

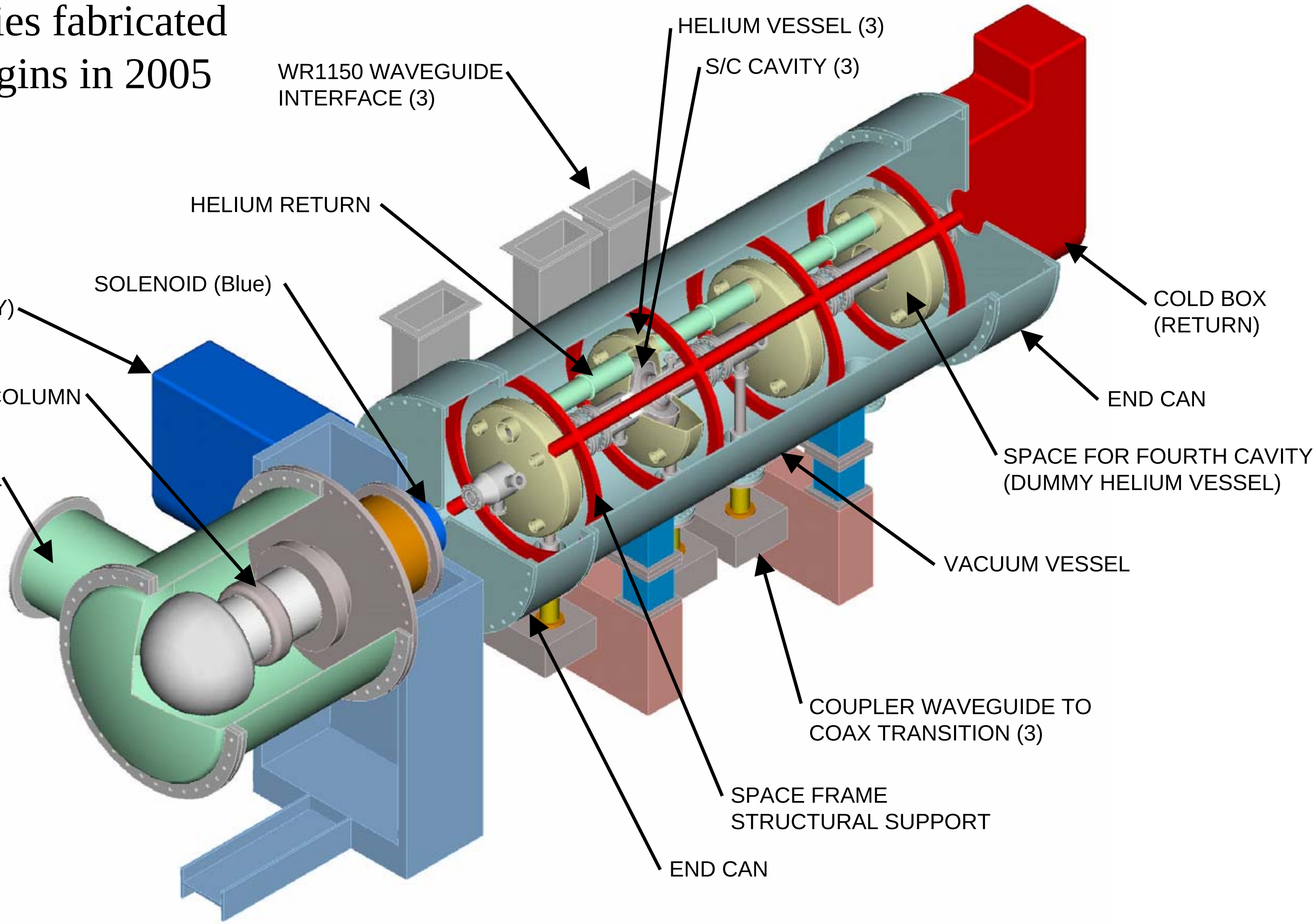
# Conceptual Layout for a 100kW$^{+}$ Compact FEL (courtesy D.Douglas)

**150 MeV, 0.1-1A electron beam**
**100 kW initial operation**
**1 to 2.2 microns**



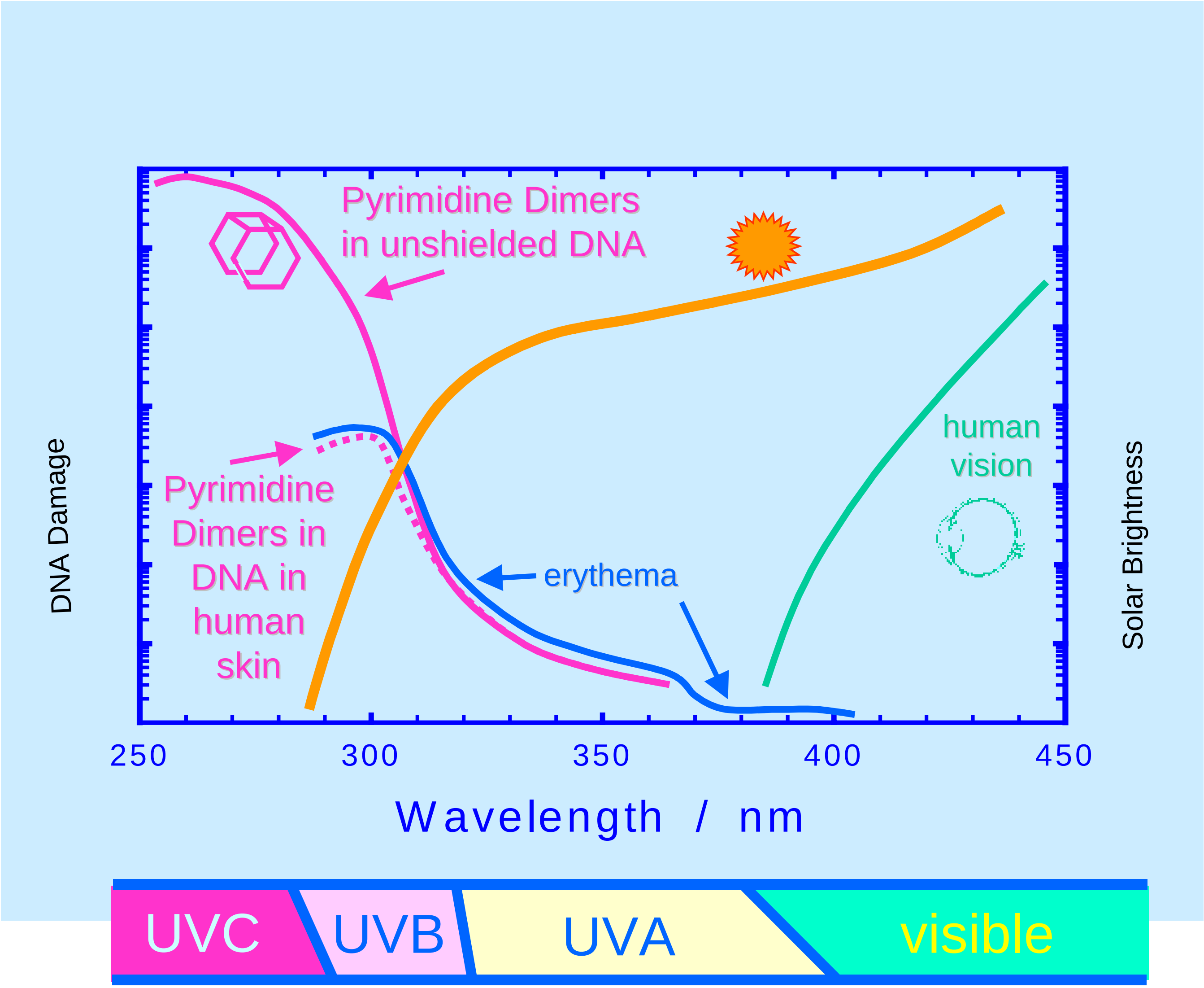
# 100 mA JLab/AES Injector Cutaway

Status: Cavities fabricated
Assembly begins in 2005



# FEL Applications to Photobiology and Photomedicine

- Protein sorting, gene expression studies with laser-mass spectroscopy
- UV and near UV Photodamage to biological systems
  - - Important for the “ozone” problem; sunscreen development
- Photodynamic Therapy (PDT)
  - - Expansion of a promising and simple cancer therapy
- Ballistic Imaging in the Visible – IR
  - - A new non-ionizing (i.e., zero consequence) medical imaging, technique
- Infrared microscopy
  - - An expanded microscopic technique which gives chemical identification



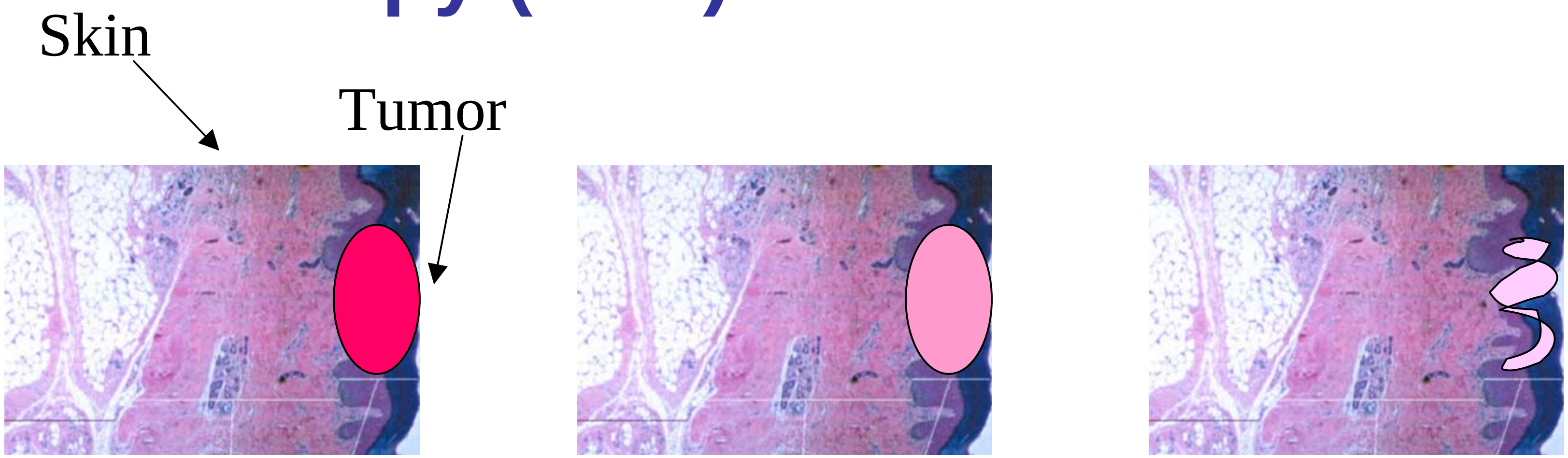

Courtesy of John Sutherland, East Carolina University

# Photodynamic Therapy (PDT)

- Well-established cancer treatment for accessible, non-metastatic tumors
  - Match-up of laser output wavelength (color) with absorption line of a vital biological dye
  - Dye must be preferentially absorbed by target organ (typically skin and lung cancers)
  - Dye must have no other serious health effects and be FDA approved
  - very few dyes meet all requirements (i.e., “photofrin”)

Courtesy of Harvard and EVMS

# Photodynamic Therapy (PDT)




Preferential absorption of dye by tumor

Irradiation by laser absorbed by dye

Tumor cells preferentially killed

Courtesy of Harvard and EVMS

# Laser Bioscience Center Proposal Collaborators

- A. Gomez, University of Virginia (Co- PI)
- R. Anderson, Harvard Mass. General Hospital (Co- PI)

- R. Austin, Princeton University
- J. Sutherland, East Carolina University
- J. Semmes, Eastern Virginia Medical School
- W. Cooke, The College of William and Mary
- D. Manos, The College of Williams and Mary
- W. Wasilenko, Eastern Virginia Medical School
- W. Gibbons, Eastern Virginia Medical School
- L. Beach, Hampton Roads Research Partnership

# Initial User Proposals for the FEL Upgrade (2004-5)

- Vibrational dynamics of hydrogen
  (***Luepke, CWM***)
- Carbon nanotubes and other nanostructures
  (***Smith, NASA and Holloway, CWM***)
- Pulsed laser deposition
  (***Reilly, Kelley, CWM with NRL, UVA, Vanderbilt, PLD, Inc.***)
- Non-linear localized modes (THz)
  (***THz Working Group***)
- Atomic/Molecular/Optical (AMO) experiments
  - intramolecular vibrational energy transfer
  - induction & control of surface chemical reactions
  - dynamics within Bose-Einstein condensate
  (***Jones, Harrison, UVa; Cooke, CWM and Sukenik, ODU***)
- UV and IR photobiology and photomedicine
  (***Austin, Princeton; Anderson, Harvard; Semmes, EVMS; Sutherland, ECU***)

# Summary

- The FEL Upgrade has re-established new world's records for output laser power (10 kW) and energy recovered power (1.1MW)
- The FEL user program is set to re-start in the next few months with returning and new user groups
- The Navy IR FEL program over the next decade is demanding and exciting:
  - minimum of ~$10M/yr of support over FY05-08 for both FEL technology development and FEL applications
- AF UV FEL program will be launched with an exciting new light source (>1kW UV) and world class end-station (3D LMES) for industrial interest
- THz beamline facility is unique and credentialed users have been lined-up
- Bioscience applications proposal under development should lead to expanded capabilities, user base and user support funds
- Scientific interest in the FEL Facility continues to grow and the funding base is becoming more diversified

# Acknowledgements

We thank all who allow us to pay our bills and bring you the FEL:

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SURA

City of Newport News

Laser Processing Consortium

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Linda Williams
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Mark Wiseman
Byung Yunn
Joseph Zhang
Harvey Rutt
Gwyn Williams

Many others from JLab also contributed greatly to the project.

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Harvey Rutt, University of Southampton, Materials Science

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**Alan Todd, IAB Chairman, Advanced Energy Systems**
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