Applications of Free Electron Lasers

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Applications of Free Electron Lasers

Outline

- **Background**
- **Example Potential Industrial Applications**
- **Economic Drivers**
- **Conclusion**

Background

The JLab FEL program was initiated in 1995 based on the idea that at sufficiently high powers there would be economically viable applications for industrial activity - nominally 100 kW @ < 1.0 ¢/kJ

see ***"A Cost Model for High Power FELs" George R. Neil, Proceedings of the 1995 IEEE Particle Accelerator Conference (Dallas, 1995).***

Progress in FEL technology has pushed us closer to the point where industrial applications would be viable: 14 kW @ ~ 5¢/kJ

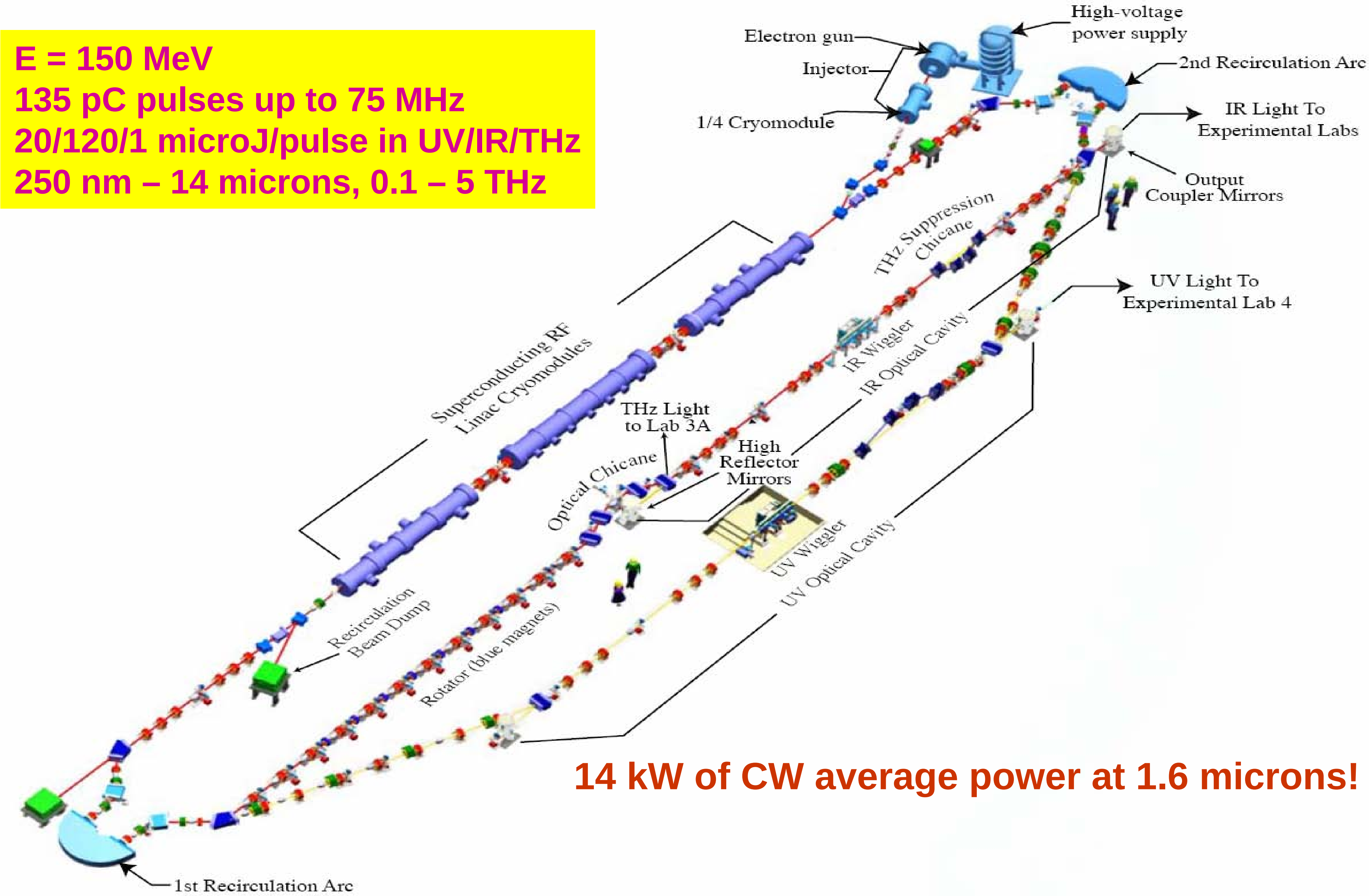
New applications have been identified. Lab scale benchmarking is in progress.

Still more work to both scale the FEL and to validate the applications technically. Still working for industry buy-in.

Cost estimates still support original idea of economic viability

JLab Energy Recovered FEL

E = 150 MeV
135 pC pulses up to 75 MHz
20/120/1 microJ/pulse in UV/IR/THz
250 nm – 14 microns, 0.1 – 5 THz



14 kW of CW average power at 1.6 microns!

Industrial applications

Does it make sense to use a high power FEL in an industrial setting?

It needs an application that works better/cheaper than any existing approach

It must be something that people are willing to pay enough for to make a profit over the costs

You have to be able to make and sell enough of the product to cover the economics

- *Need an FEL of sufficient power to make enough product to satisfy a market.*
- *FEL must be simple to operate, reliable, efficient,...*

Example Industrial applications

Nanotube production
Metal surface amorphization for corrosion resistance
Metal nitriding for hardness
PLD of metals
PLD of organics
Microengineering of components

Nanotube production

Process: FEL light produces carbon nanotubes on graphite target

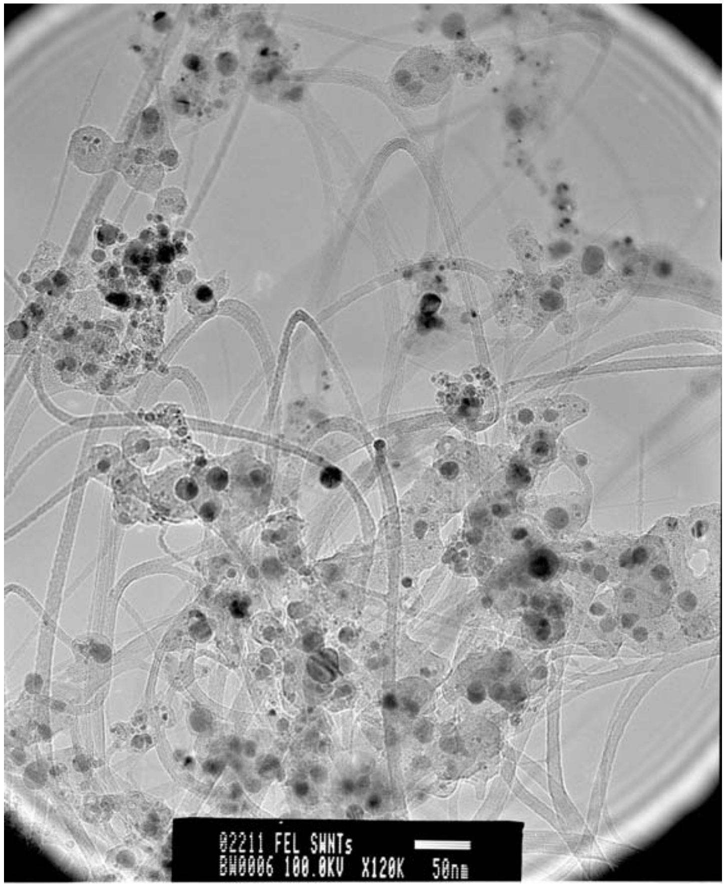
Technical status: process works at tabletop level, we know some of the parameters for optimum output, collection system is bottleneck, presently a batch process

Figure of merit: Wavelength 1 to 3 microns, < 1 kW of FEL light produces 8 gm/hour. Value is ~ $600/gm

Required to move forward: Need development of collection system and continuous process. Market analysis required to validate investment. Economics presently works for $0.01/kJ

Dangers: High production rates would likely lead to drop in price due to limited market although long term demand for composite industry is for very high volume.

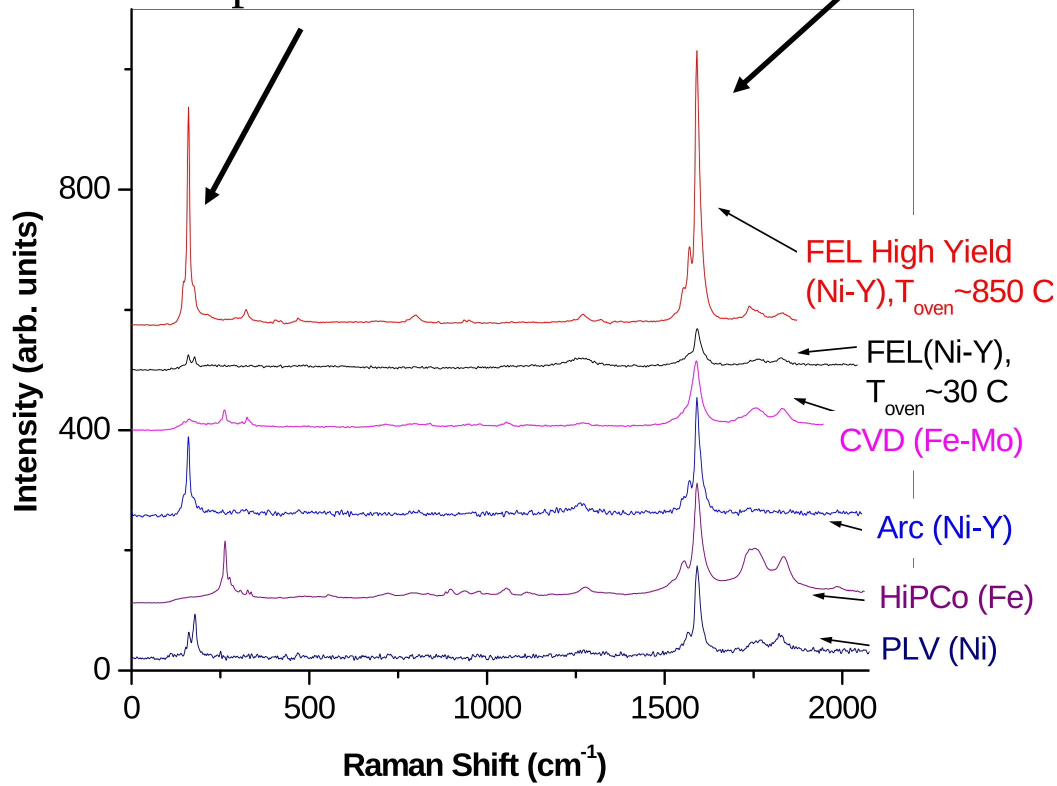
Transmission Electron Microscopy shows high quality carbon nanotube production



TEM indicates tube dia (~1.4 nm) and small bundle size (~12 nm)

TEM images by D. Luzzi and B. Smith, UPenn

Spectroscopic data shows yield is high and pure



FEL peak is 4x next best process

Courtesy: B. Holloway, M. Smith

Metal Amorphization

Process: ***FEL light produces amorphizes steel surface providing 3x improvement in corrosion resistance.***

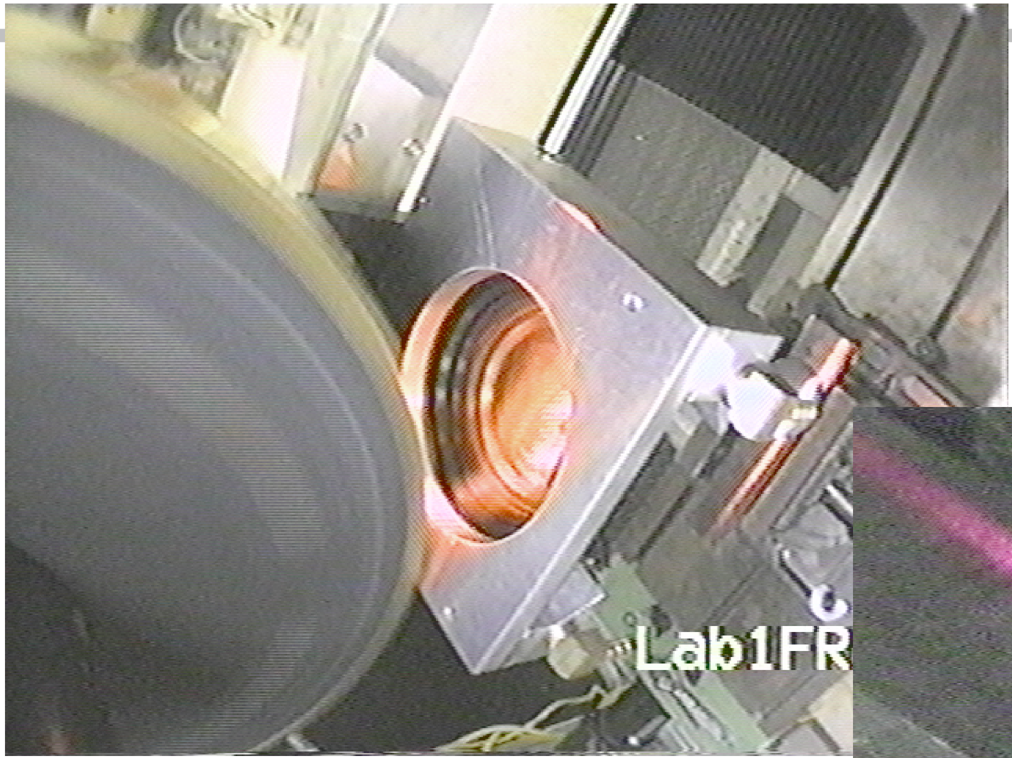
Technical status: process works at scientific level, we know the parameters for optimum output

Figure of merit: Need ~ 1J/cm^2 scanned over the metal surface. Short wavelengths are better but < 2 microns works.

Required to move forward: Need good scanner technology. Market analysis required to validate investment. Economics positive for high value targets such as turbine blades at < $0.01/kJ

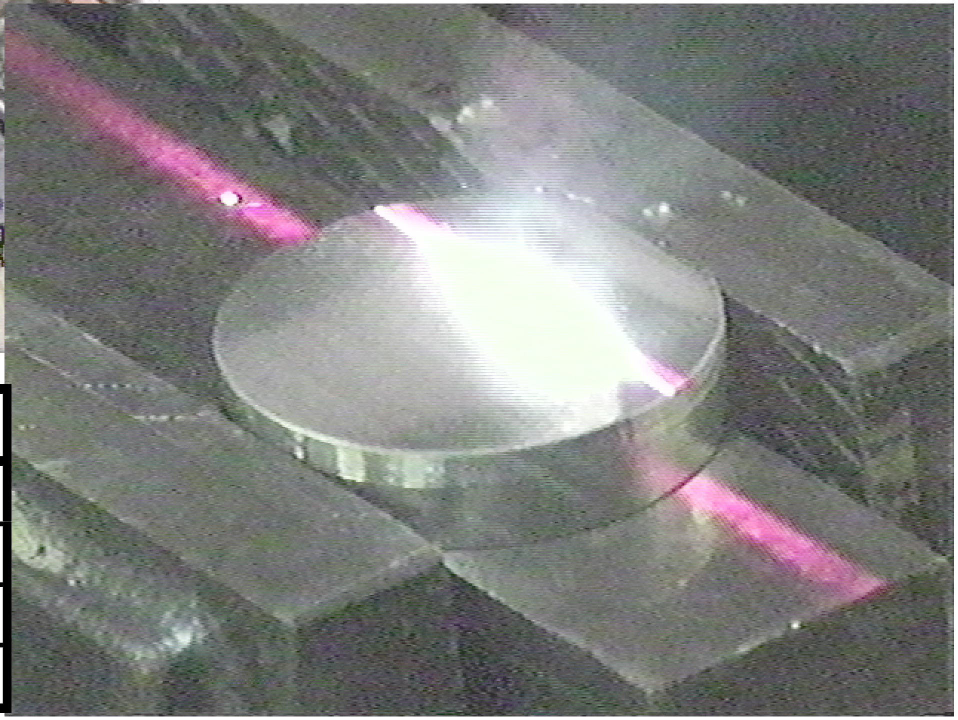
Dangers: Must demonstrate to industry value added. Difficult scanning geometries are a problem. No industrial activity at present and present suppliers do little R&D.

Metal Surface Processing



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

Short pulse melting by FEL cools at more than 10^{15} K/sec



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

Metal Nitriding

Process: ***FEL light is used to create nitride coatings on metal surfaces. Commercial plasma method requires vacuum to work. Competing laser methods don't produce the same quality coatings***

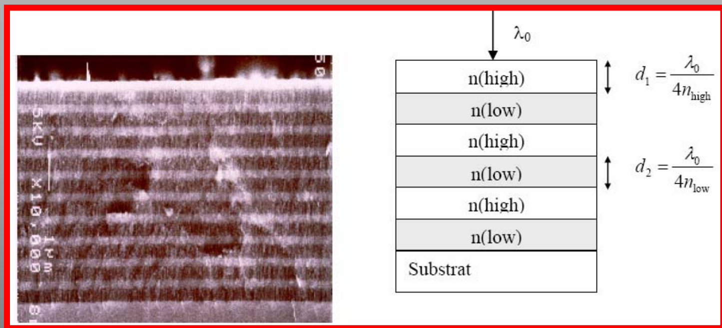
Technical status: A scientific demonstration of approach at JLab was a very successful initial step and produced several publications. Process optimization has not yet been done.

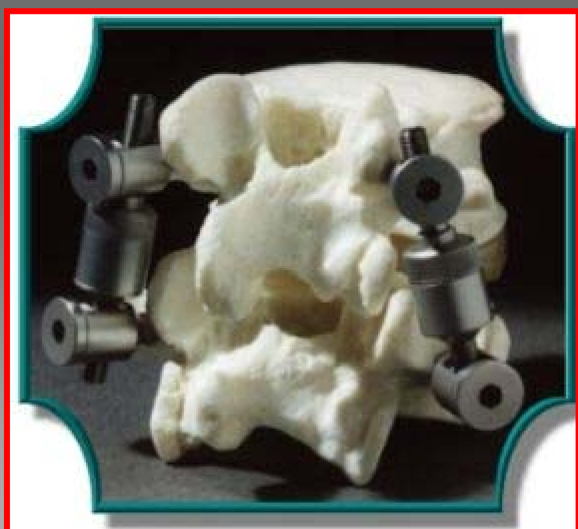
Figure of merit: Need ~ 0.1 to 1J/cm^2 scanned over the source material at short IR wavelength. We don't expect strong wavelength dependence but shorter is probably better.

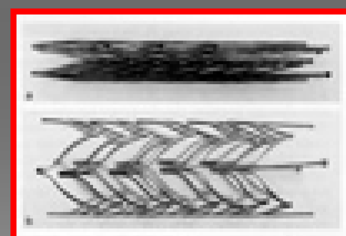
Required to move forward: Need optimization of process parameters and demonstration of specific application. Market analysis required to validate investment. Economics unknown at present but there are likely high value coatings which provide an entry to market at < 1¢/kJ, maybe < 10¢/kJ

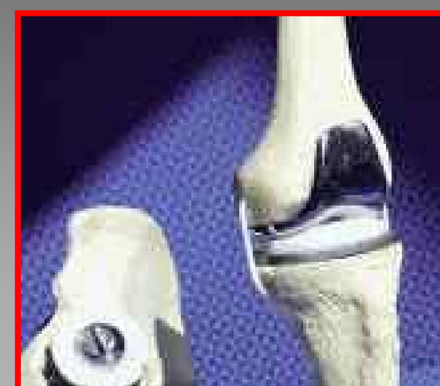
Dangers: Process parameters may be difficult to control. Must compete in existing market

Applications of Thin Films and Coatings

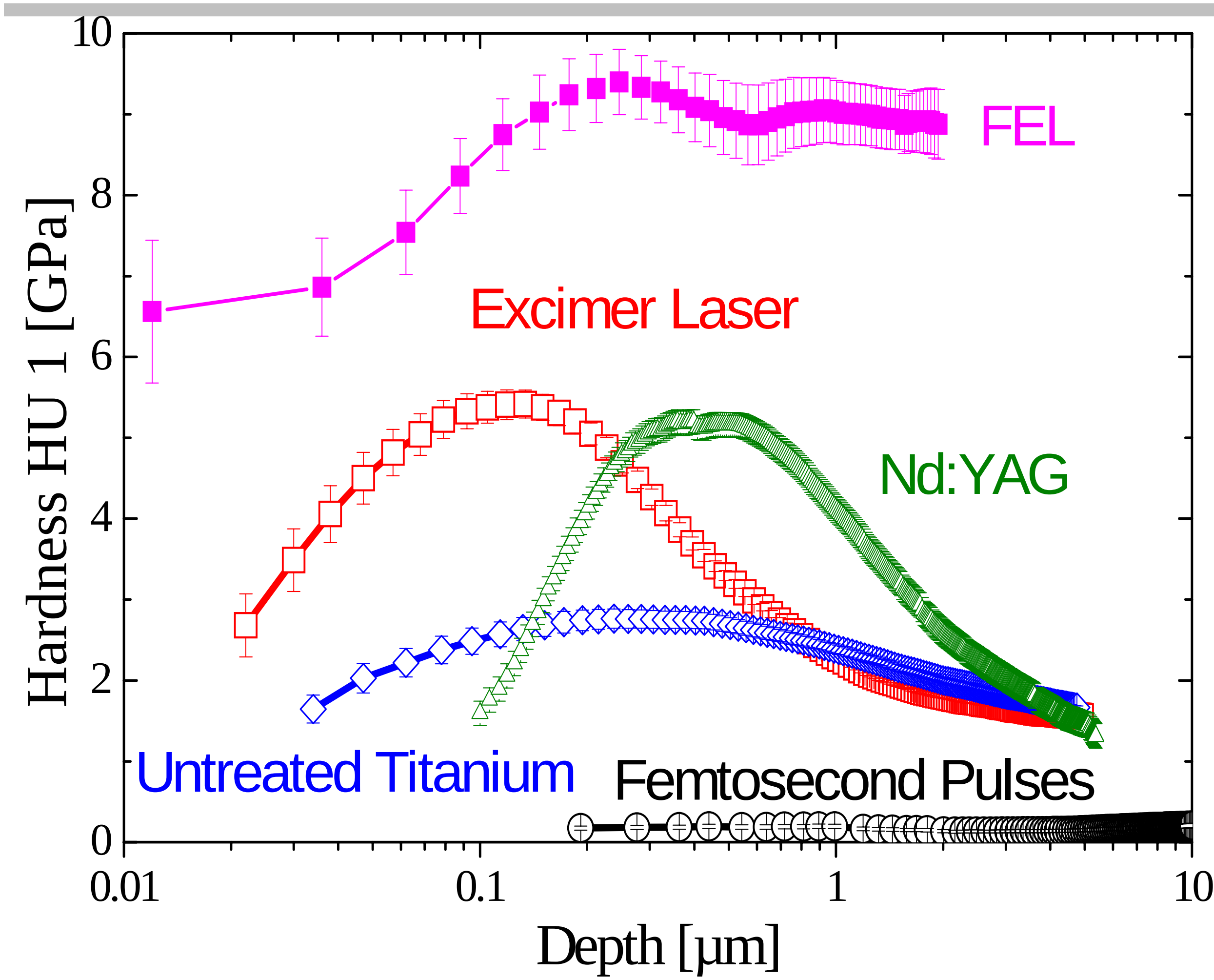








TiN: hardness – comparison by laser



Femtoseconds – very soft (nanocluster)

FEL highest hardness and thickest coating (>5 µm)

P. Schaaf, Gottingen

E. Carpene, PS, *MRS Proc.* 780 (2003) Y5.8.1
E. Carpene, M. Shinn, PS, Appl.Phys. A (2005) i

PLD of Metals and Organics

Process: ***FEL light is used to deposit metal or organic coatings on essentially any desired surface. Many different coatings possible. No competing method is available for organics application***

Technical status: Some scientific demonstrations of approach at Vanderbilt. We are presently installing a SOA PLD apparatus

Figure of merit: Need ~ 0.1 to 1J/cm^2 scanned over the source material at molecular resonance wavelength for organics, typically ~ 3.2 microns. Need >1J/cm^2 scanned over the material at short IR to UV wavelengths for metals

Required to move forward: Need optimization of process parameters and demonstration of specific application. Market analysis required to validate investment. Economics unknown at present but there are likely high value coatings which provide an entry to market at <$ 0.01/kJ.

Dangers: Process parameters may be difficult to control. Must develop new market

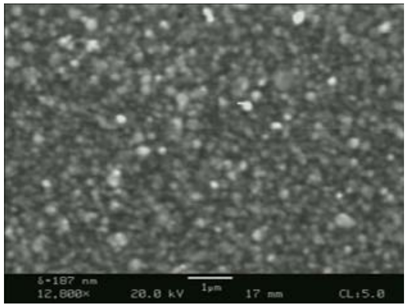
Benefits of short pulses and high rep. rate

Pulsed laser deposition with the JLab-FEL

A. Reilly et al. CWM
J. Appl. Phys. <u>95</u> 3098 (2003)

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

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



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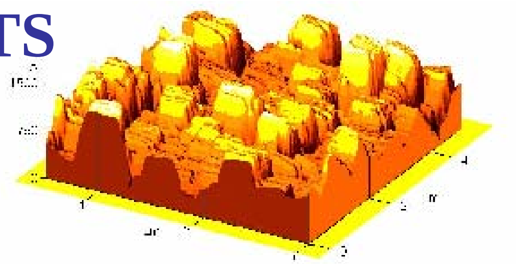
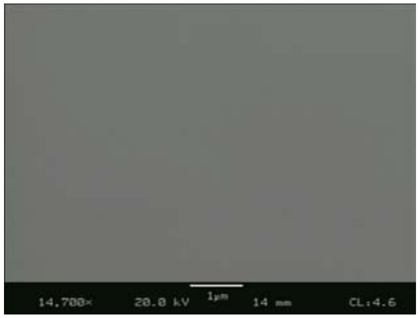
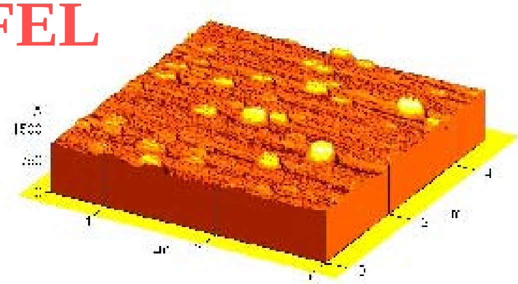
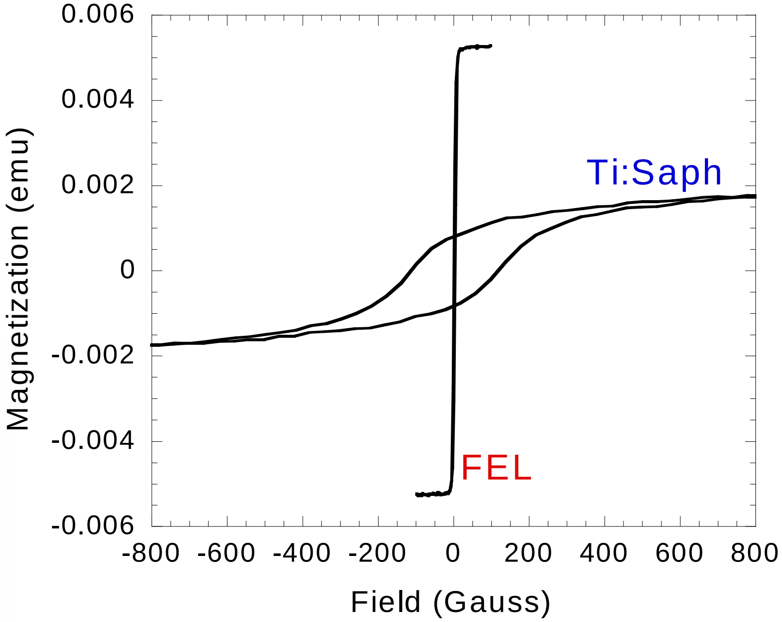




FEL

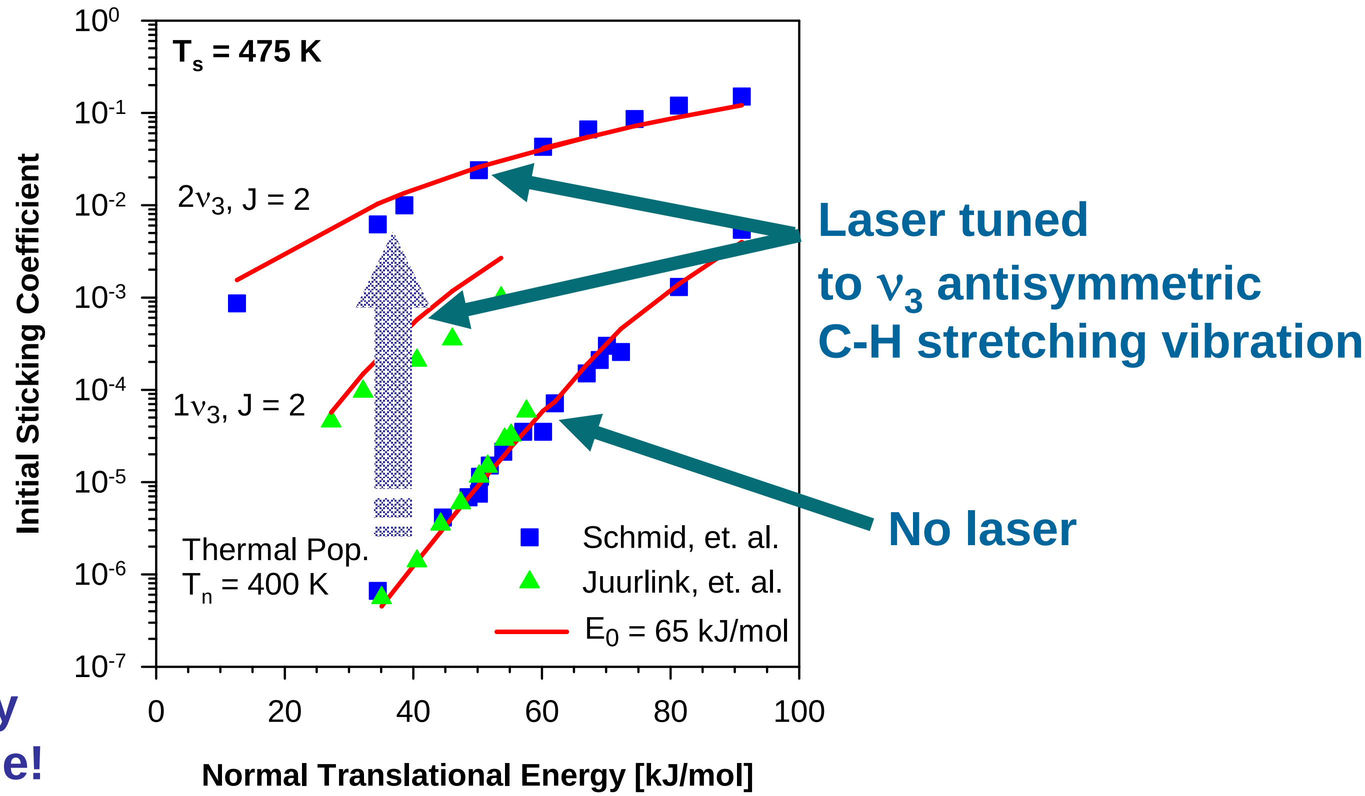




SEM (left) and AFM (right) of NiFe films grown with an amplified Ti:Saph (top) and the FEL (bottom).

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

Laser Deposition: 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.

Ian Harrison, UVa

Microcanonical Unimolecular Rate Theory at Surfaces – IR Photochemistry in Catalysis

Microengineering

Process: ***FEL light is used to micromachine and microengineer components from ceramics, glasses, etc.***

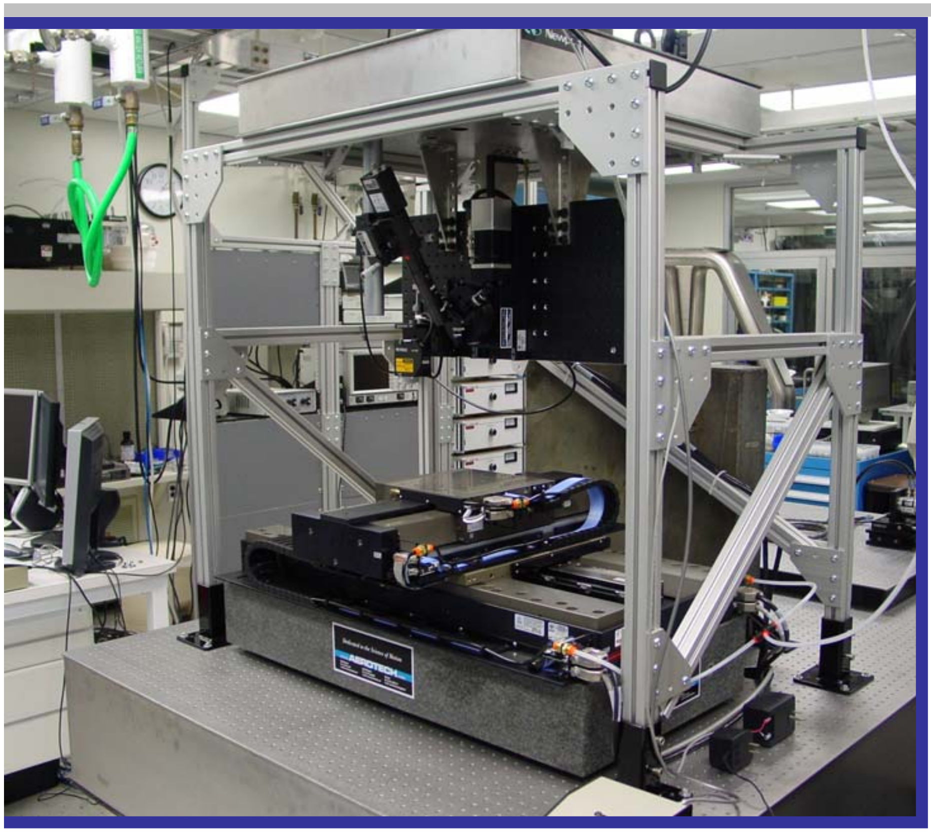
Technical status: Three satellites have been produced using excimer lasers. FEL should work better due to short pulse length. We have machining station installed and in commissioning in Lab 4. Optimum use requires UV from FEL by IR upconversion or lasing.

Figure of merit: Need ~ 0.1 to 1J/cm^2 scanned over the source material but only 50 W total required

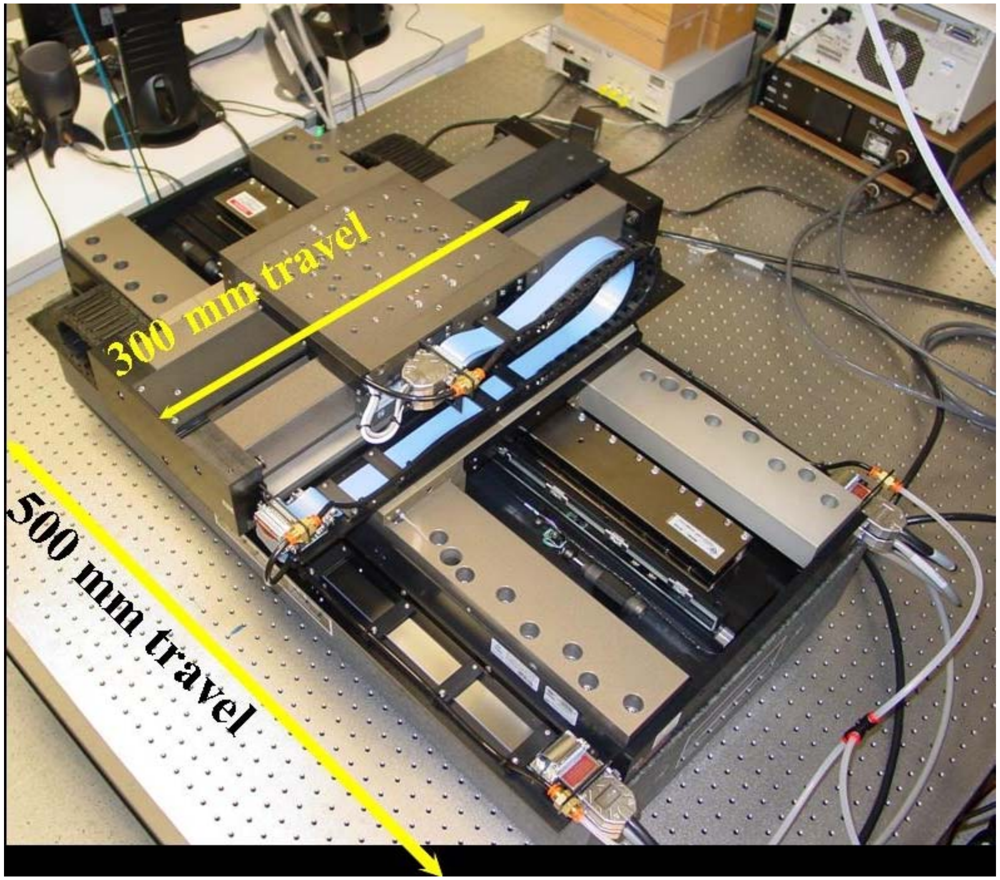
Required to move forward: Need demonstration of specific application which includes UV production from FEL. Market analysis required to validate investment but believed to be extremely favorable for high value targets (produce a satellite every 3 hours) at even $0.10/kJ.

Dangers: Other lasers may eventually take over this application because of low power required. FEL may be ultimately relegated to lower value higher volume production

Laser Microengineering Station for JLab FEL

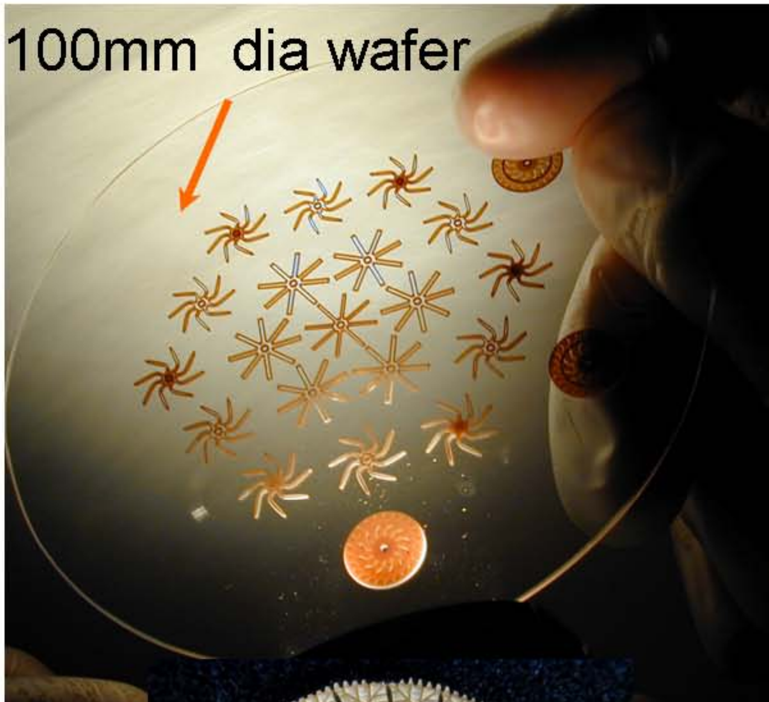


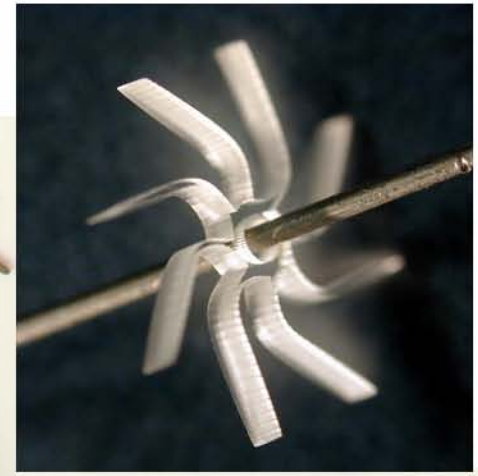
- First 3D laser microfab. station
- State-of-art speed, resolution, and processing area (+/- 0.25m)

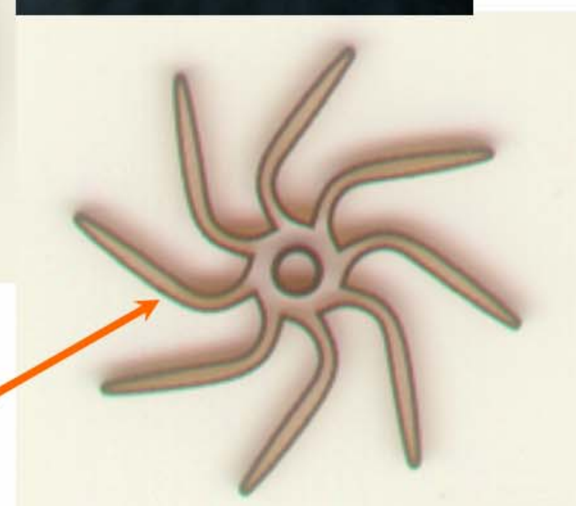


- Designed and built by Aerospace Corp. , H. Helvajian

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

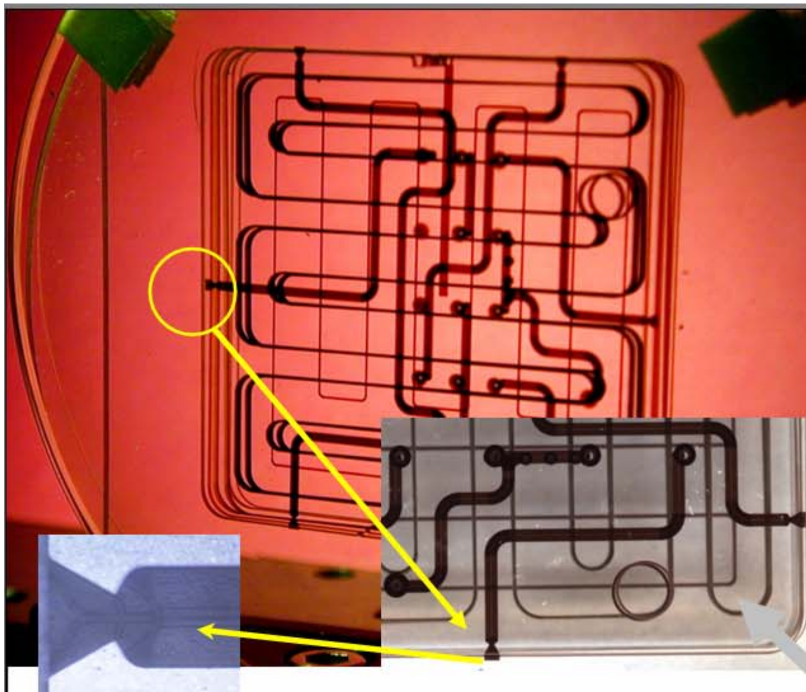


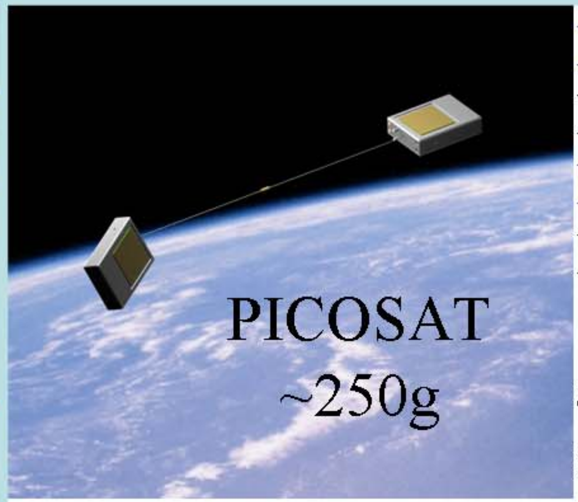




1 mm thick
Pattern 200 μm

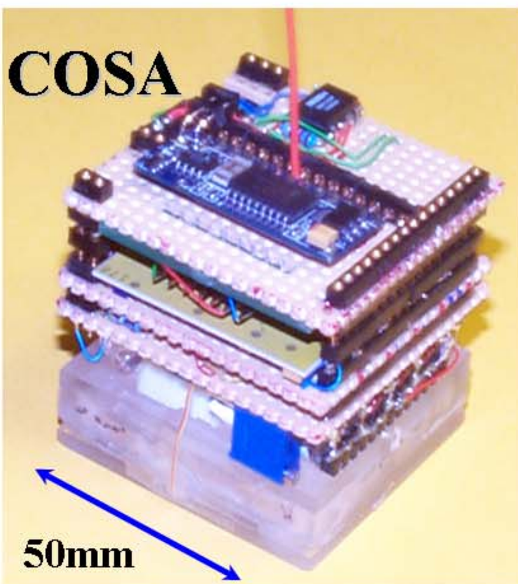
Henry Helvajian, Aerospace Corp.

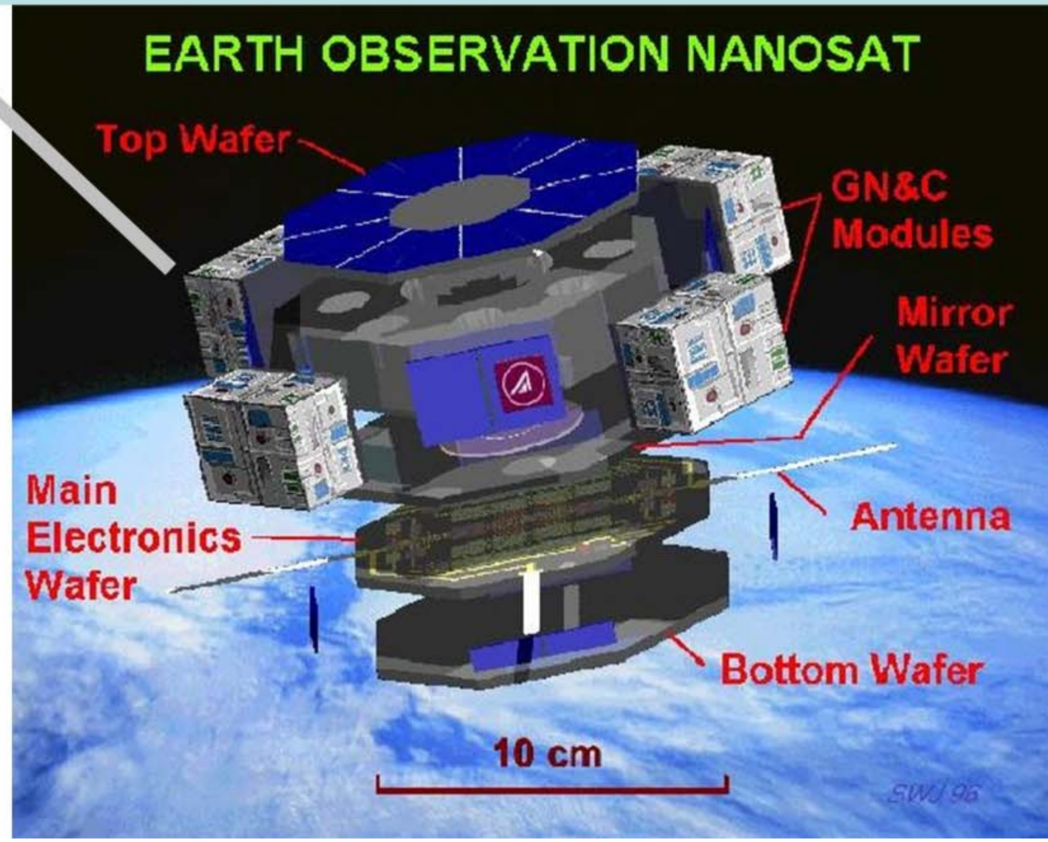




DARPA/Aerospace/AFRL

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





FEL Economics

What is cost of light production permissible to meet FEL economics?

10¢/kJ for low volume, high value added process: microengineering?

1¢/kJ for medium volume, modest value added process: PLD of magnetic coatings for hard disks?, nitriding? organics deposition?

0.1¢/kJ for high volume, low value added process: polymer surface amorphization?

n.b.: commercial excimers cost 50¢/kJ, solid state lasers 1-10¢/kJ , CO_2 lasers 0.1-0.5¢/kJ to run in an industrial setting

FEL Economics

How much product might you make? What can it cost?

Mid-Value production example:

An industrial system running at 10 kW for only 5000 hours/year produces $1.8x10^{11}$ Joules.

At 1 J/cm^2 this treats or covers 18 Mm^2

This process would have to charge \$0.55/m^2 to sell \$100M/yr. This is borderline profitable for some high value added processes

(Note: You pay \$1/yd^2 at Carpet City for anti-stain treatment)

FEL Economics

What does it cost to build a high power FEL?

Analysis and experience at JLab indicate that 10x in power costs < 2x more

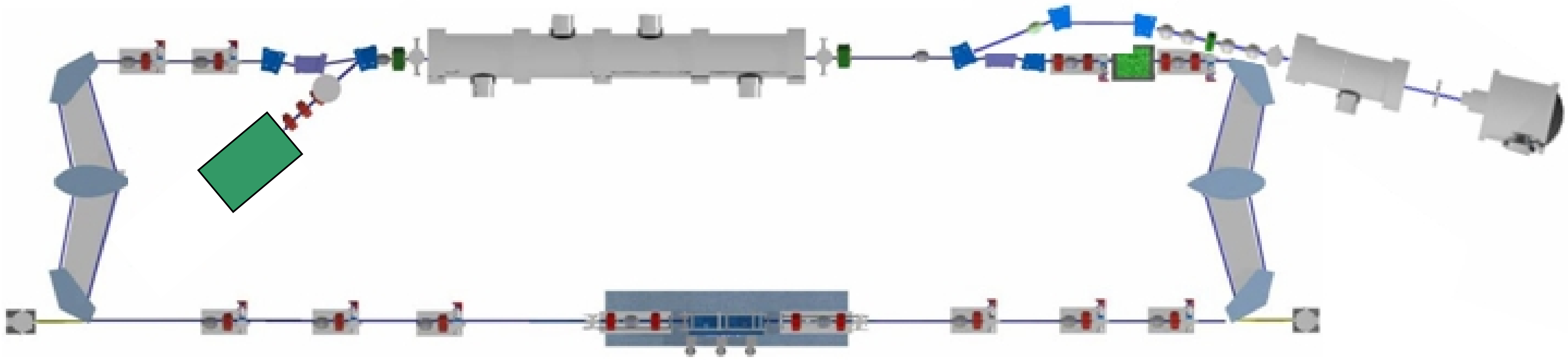
JLab and AES independently estimate first article 100 kW system at ~ $70M. The JLab IR Upgrade cost ~ $30M and has lots of bells and whistles undesirable in an industrial system

Latest research indicates reducing injection energy to as low as 5 MeV is possible; this is very helpful in reducing costs and improving wallplug efficiency. IOTs now under development also help with wallplug efficiency

For < $0.01/kJ delivered need 100 kW for $35M for multiple copies. We believe this is very achievable for IR, and not far off for UV.

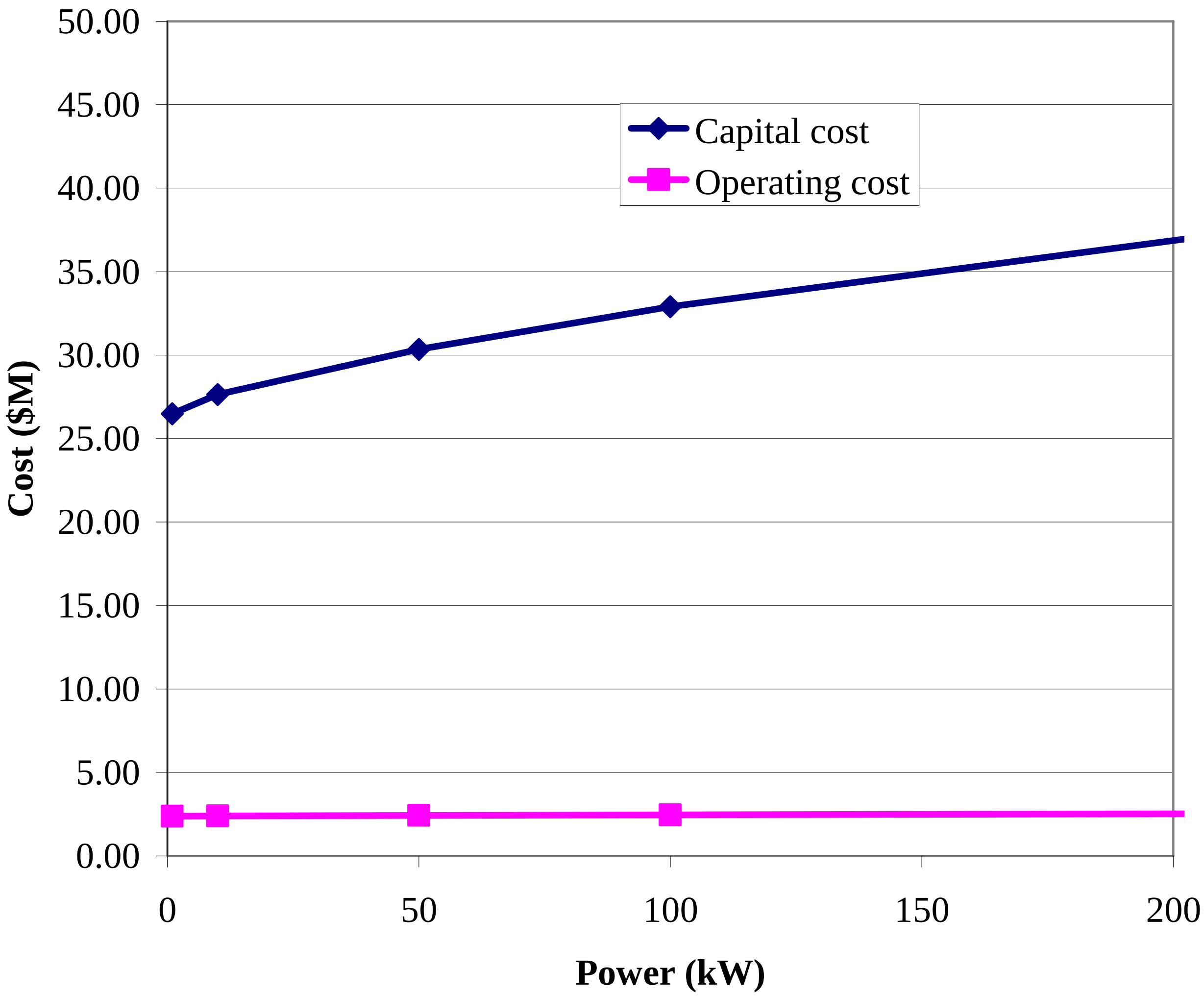
Compact 100 kW IR Oscillator

120 MeV
<100 mA, 130 pC at 750 MHz
4m x 20m
Low part count, robust operation



- **Originally proposed in 2003 for a cost estimate of $75M**
- **Estimated cost still valid: simplified 2006 design counterbalances inflation**

Cost analysis shows weak dependence on power



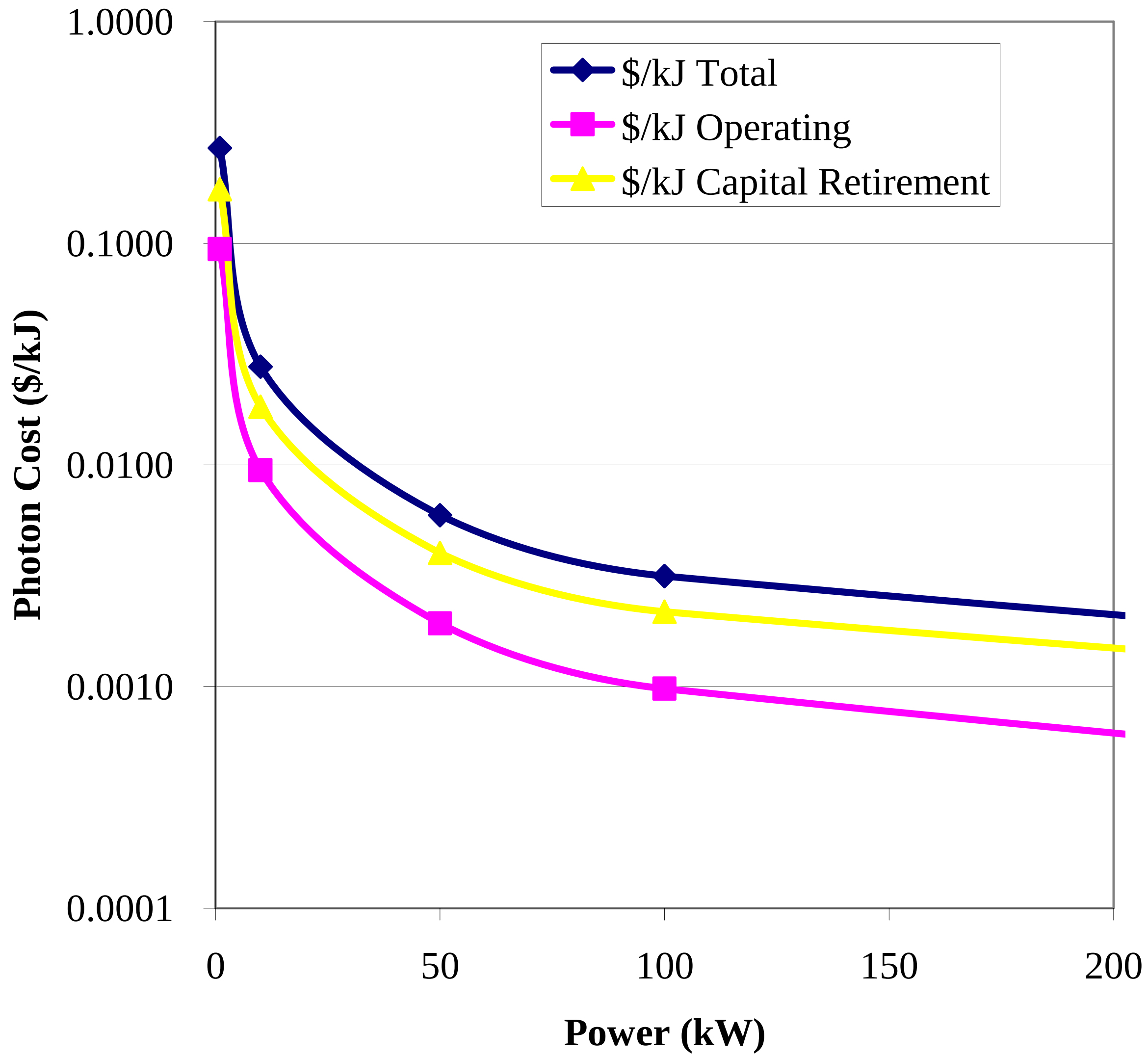
Capital cost:

- **No NRE, IR output.**
- **Add ~ $7500k for UV**

Operating cost:

- **Electric cost @ 0.08/kWH, 8000 hrs/yr**
- **6 year flat capital amortization**
- **Operators**
- **Maintenance contract**
- **Cryogens**
- **No material handling**

Estimated cost per photon meets requirements



Cost estimates appear to meet entry level goals of < 1¢/kJ at > 40 kW output

Summary

FELs are now at a technical maturity level where one can consider industrial applications requiring 10-100 kW

A number of potential applications have been identified and are under investigation; many others possible

FEL economics looks favorable for mid and high value added processes

We intend to carry forward these ideas and establish lab-industry partnerships to validate and commercialize these technologies in parallel with improving FEL performance

Acknowledgements

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

- **Office of Naval Research**
- **Naval Sea Systems Command, PMS 405**
- **Air Force Research Laboratory**
- **Air Force Office of Scientific Research**
- **Army Night Vision Laboratory**
- **Department of Energy**
- **Department of Defense, Joint Technology Office**
- **Commonwealth of Virginia**
- **SURA/JSA**
- **City of Newport News**
- **Laser Processing Consortium**

JLab FEL Team

Backups

Wallplug efficiency also improves with power