Jefferson Lab Free Electron Laser Program

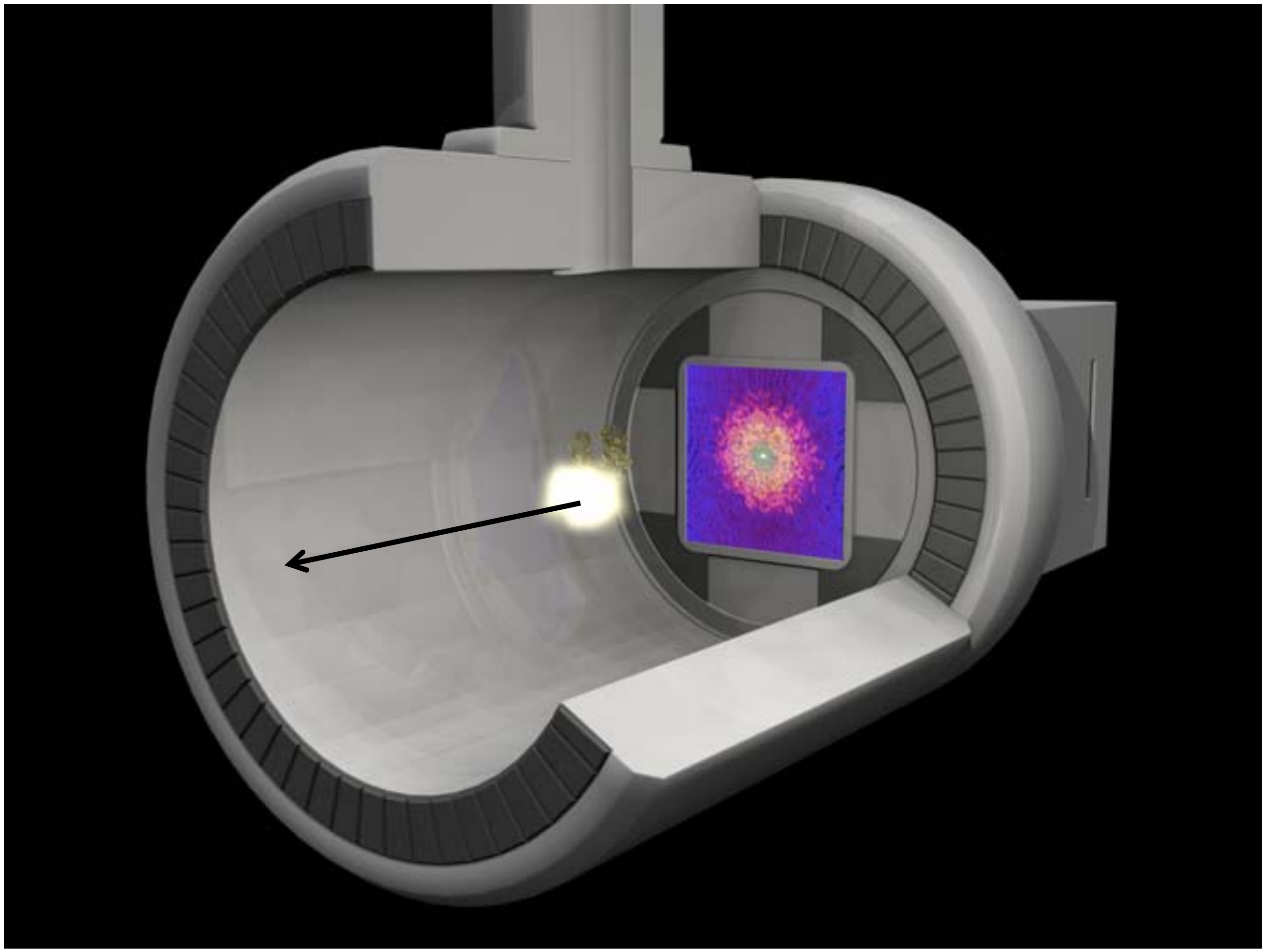
Carlos Hernandez-Garcia

XII Mexican Workshop on Particles and Fields

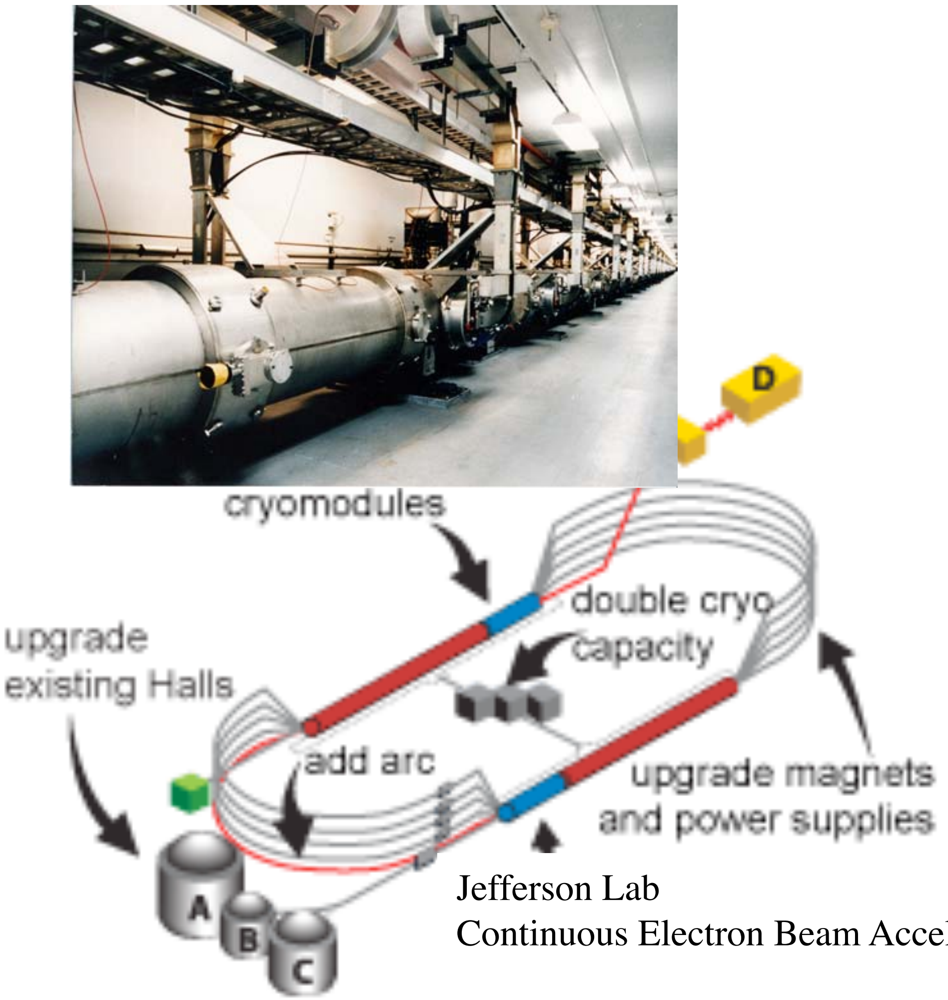
Mazatlan, Mexico

(**Distribution Statement A: Approved for public release; distribution is unlimited.**)

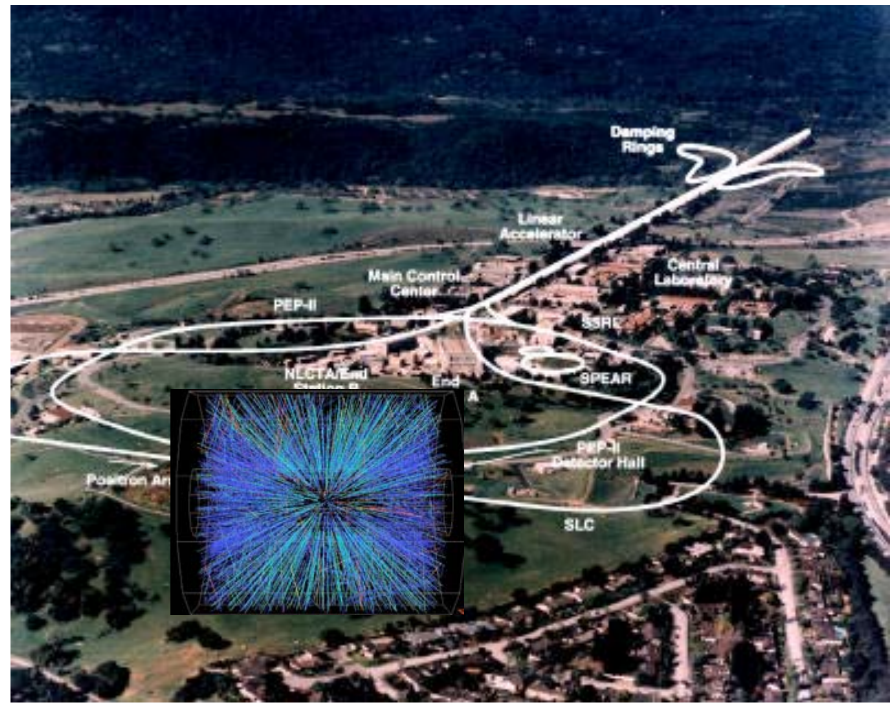
Electron beams in accelerators find two main uses



As a point-like probe in the form of ***Polarized*** electrons for High Energy and Nuclear Physics research



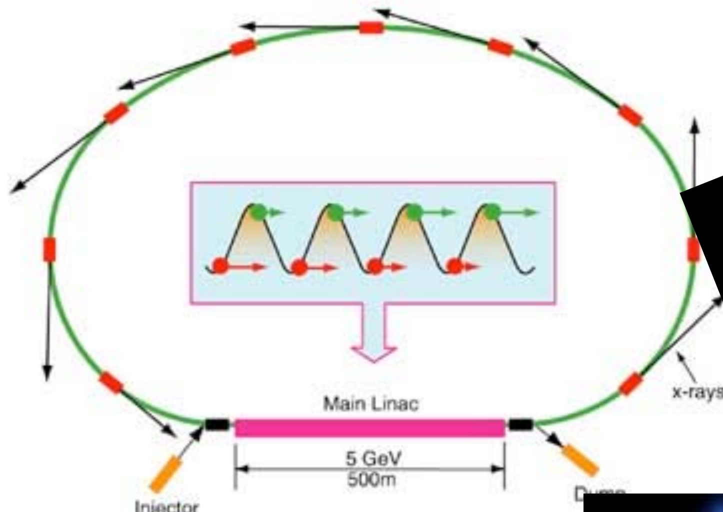
Jefferson Lab
Continuous Electron Beam Accelerator Facility

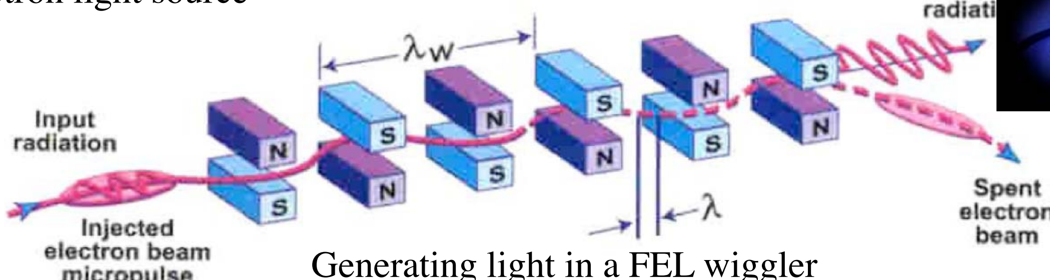


Stanford Linear Accelerator

As a source in the form of *<u>Un-polarized</u>* electrons for producing IR to X-ray photons in machines like Storage Rings, Synchrotrons and Free Electron Lasers

Argonne National Lab
Synchrotron light source





Generating light in a FEL wiggler

The 10 DOE "Basic Research Needs" Workshops

10 workshops; 5 years; more than 1,500 participants from academia, industry, and DOE labs

BESAC - Basic Research Needs to Assure a Secure Energy Future

- Basic Research Needs for the Hydrogen Economy
- Basic Research Needs for Solar Energy Utilization
- Basic Research Needs for Superconductivity
- Basic Research Needs for Solid State Lighting
- Basic Research Needs for Advanced Nuclear Energy Systems
- Basic Research Needs for the Clean and Efficient Combustion of 21st Century Transportation Fuels
- Basic Research Needs for Geosciences: Facilitating 21st Century Energy Systems
- Basic Research Needs for Electrical Energy Storage
- Basic Research Needs for Catalysis for Energy Applications
- Basic Research Needs for Materials under Extreme Environments

Slide courtesy Pat Dehmer

DOE BES Science Grand Challenges

Directing Matter and Energy; 5 Challenges for Science & the Imagination (Report - Graham Fleming and Mark Ratner, Chairs)

1. **How do we control materials processes at the level of the electrons?**
2. **How do we design and perfect atom- and energy-efficient synthesis of new forms of matter with tailored properties?**
3. **How do remarkable properties of matter emerge from the complex correlations of atomic and electronic constituents and how can we control these properties**
4. **How can we master energy and information on the nanoscale to create new technologies with capabilities rivaling those of living things?**
5. **How do we characterize and control matter away -- especially very far away -- from equilibrium?**

Ultrafast, ultrabright, tunable THz/IR/UV/X-Ray light

Free Electron Laser Development at Jefferson Lab

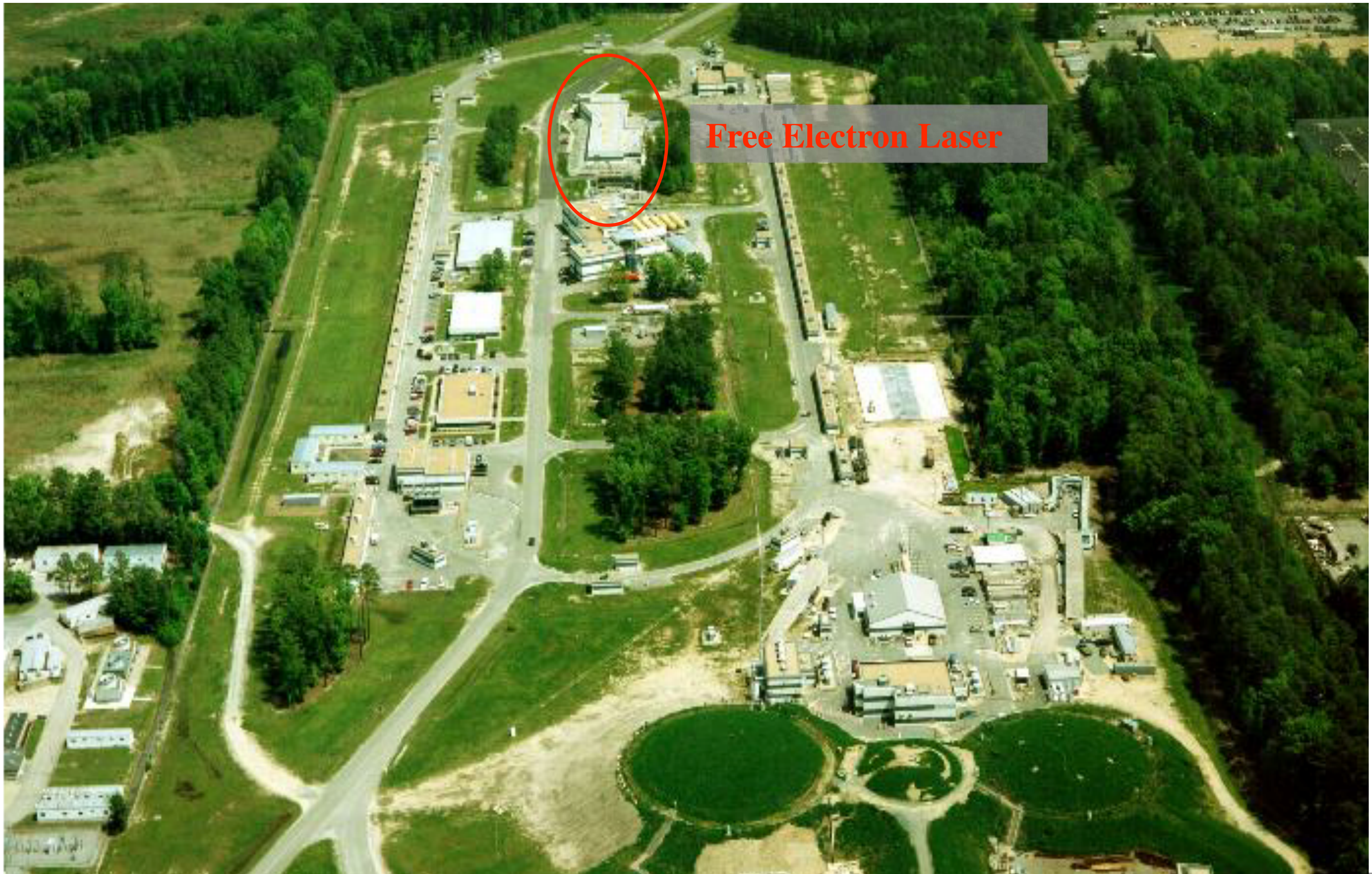
- **Designed, built and commissioned highest average power FEL (IR Demo) in 1996-98**
  - achieved **2.1 kW** at 3.1 microns (previous world record, 11 watts)
  - demonstrated power efficiency by lasing at 2.1 kW while recirculating and recovering more than 75% of the input linac energy, enabling energy recovered linacs (ERLs)
  - World class powers in the FIR (THz), visible, UV and x-ray
- **Established a versatile User Facility for the IR Demo FEL in 1999-2001:**
  - used by 30 research teams in 1999-2001
- **IR Upgrade to 10 kW completed in July 2004:**

-demonstrated sustained operation 14.2kW at 1.6μm in Oct. 06

-continuing high power FEL development

-operating for scientific users and other sponsors

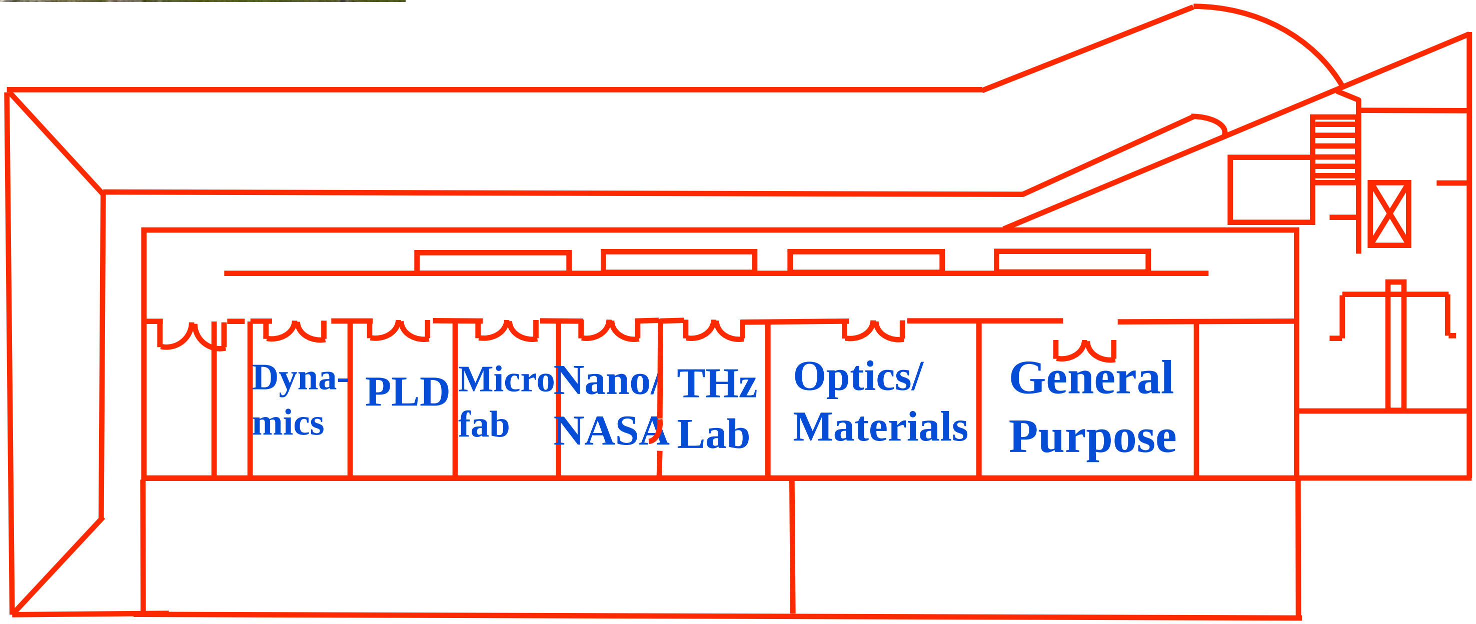
Continuous Electron Beam Accelerator Facility and Free Electron Laser at Jefferson Lab



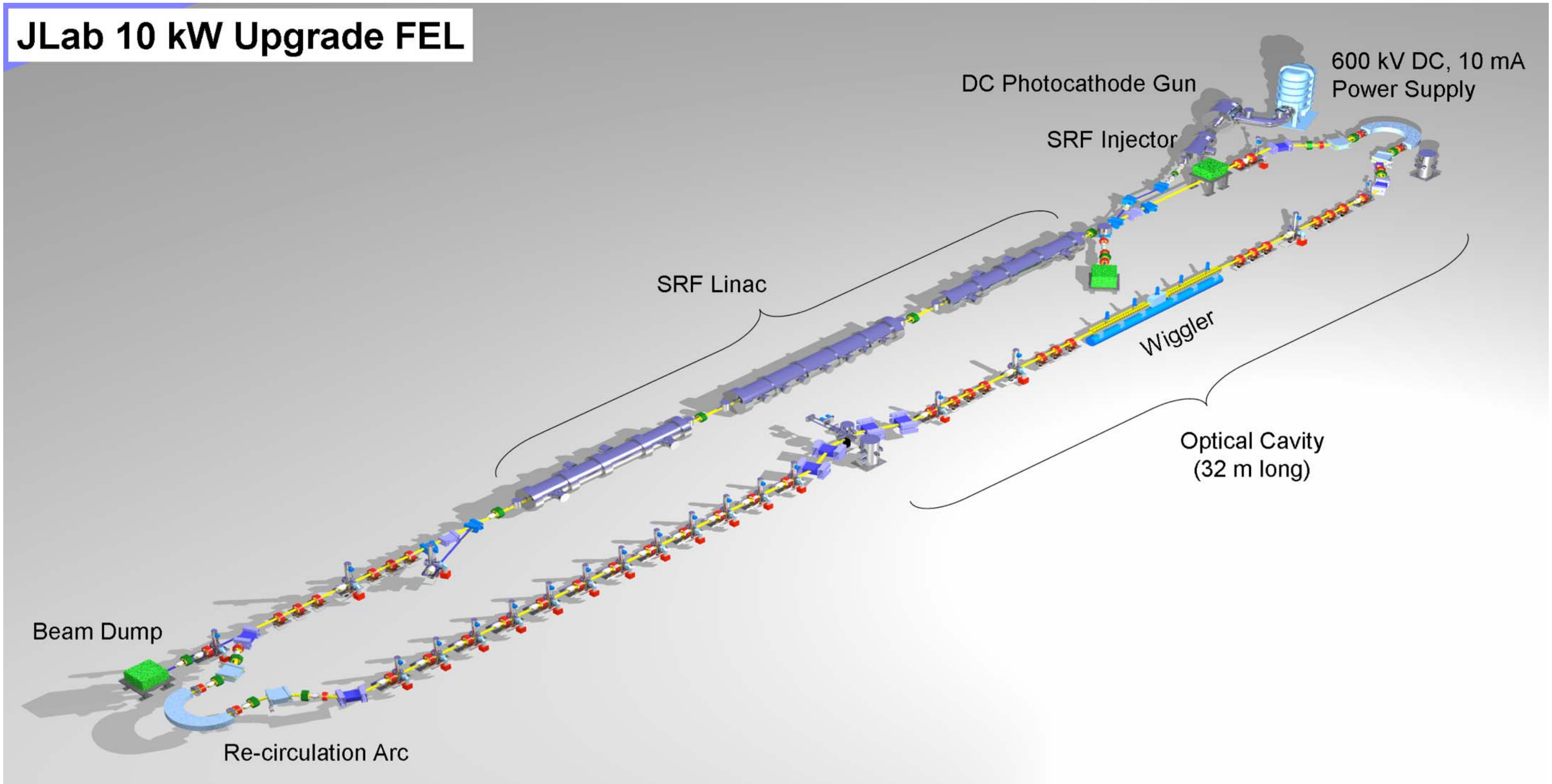
The Free Electron Laser User Facility

Current User Facility has 7 Labs

- Lab1 General set-ups and prototypes
- Lab 2 Materials studies
- Lab 3 THz dynamics and imaging
- Lab 3a NASA nanofab
- Lab 4 Aerospace LMES
- Lab 5 PLD
- Lab 6 FEL + lasers for dynamics studies

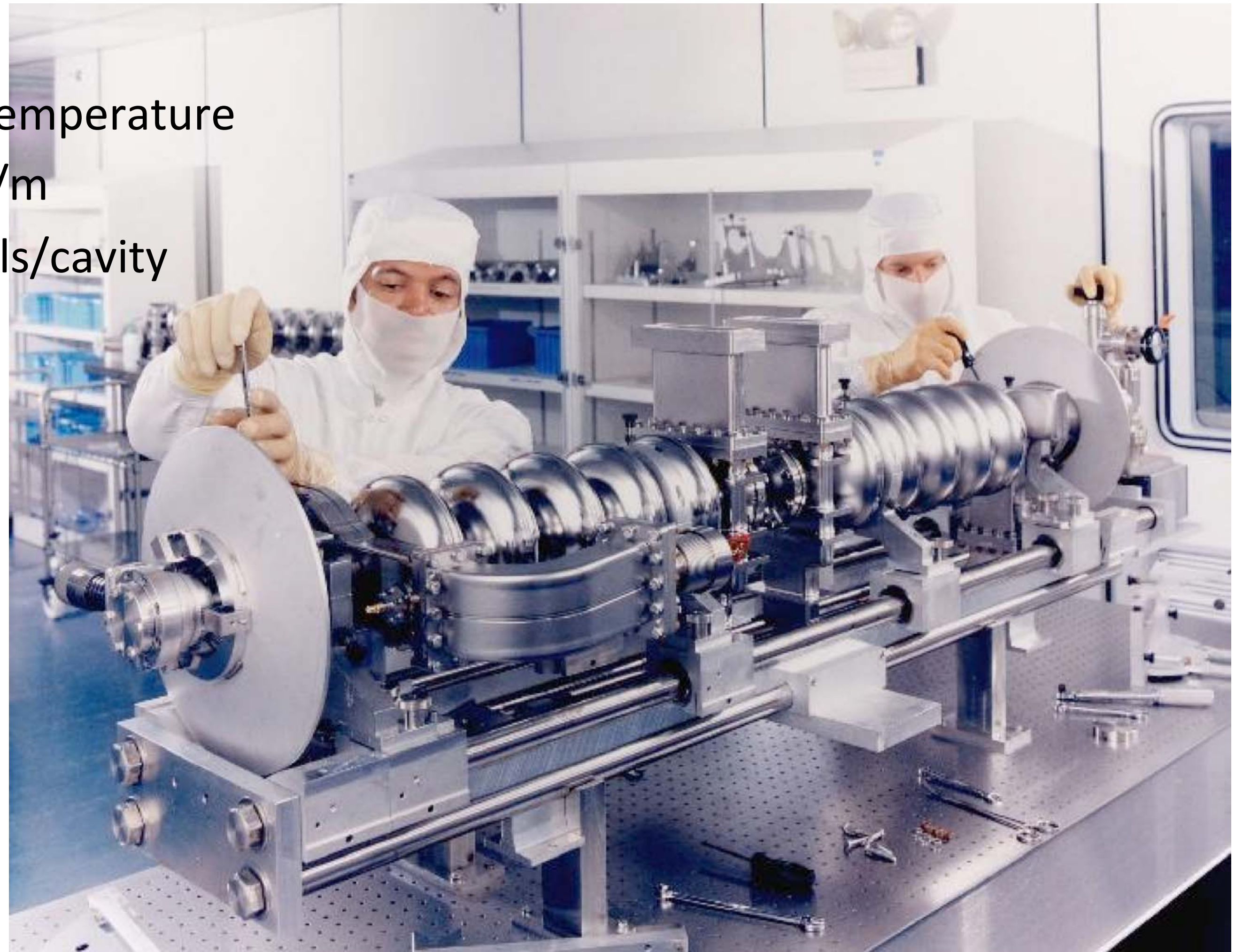


The 10 kW IR Upgrade Free Electron Laser…

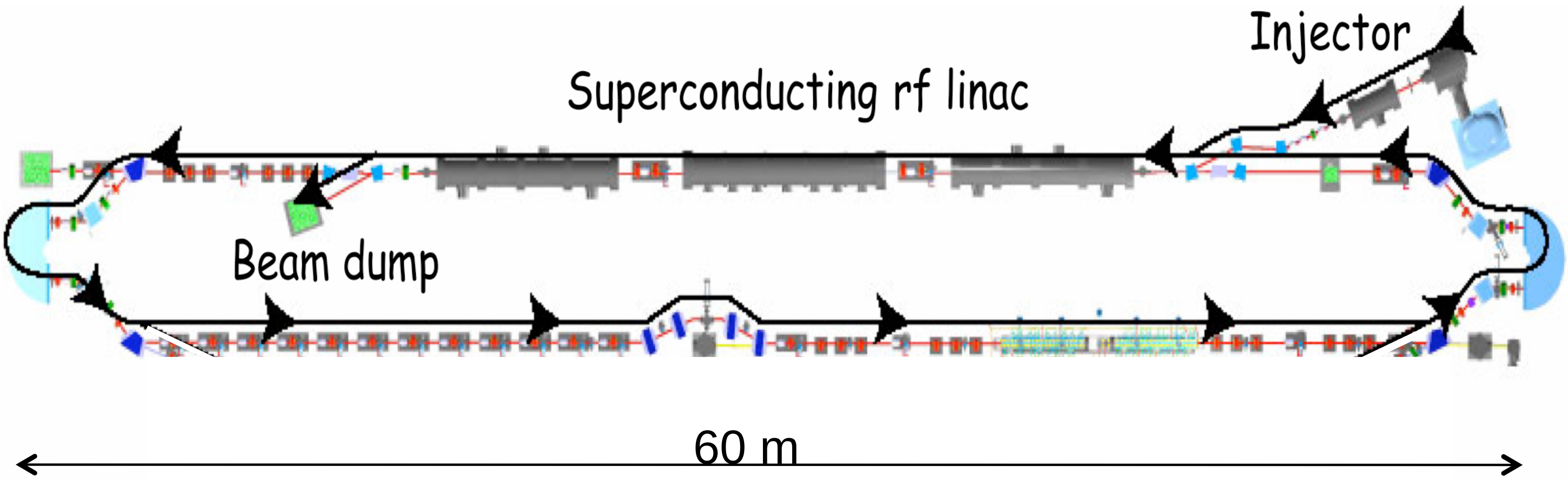


…utilizes superconducting linac technology…

- CEBAF has 338 five cell cavities
- FEL has 26
- 1497 MHz
- 2.2 Kelvin operating temperature
- Operate up to 20 MV/m
- New version has 7 cells/cavity

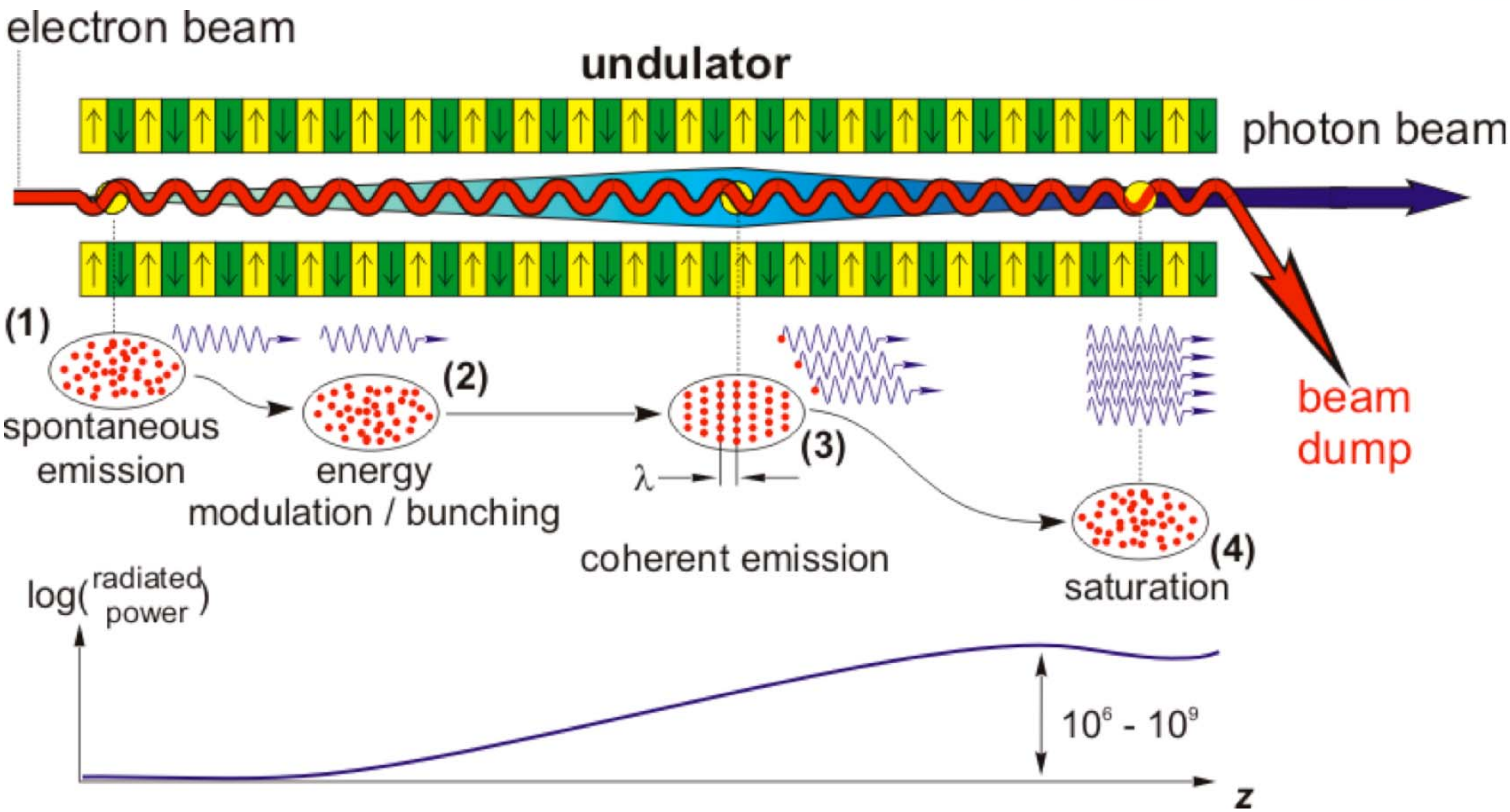


…and Energy Recovery Linac concept…



JLab IR FEL Electron Beam Parameters	Design	Achieved
Energy (MeV)	145	160
Bunch charge (pC)	135	270
Average current (mA)	10	9.1
Bunch length* (fs)	500	150
Norm. emittance* (mm-mrad)	30	7
Max. Bunch rep. rate (MHz)	74.85	74.85
Max. extracted charge (Coul)	-	7000

...to generate Laser light
SASE (Self Amplified Spontaneous Emission) operation

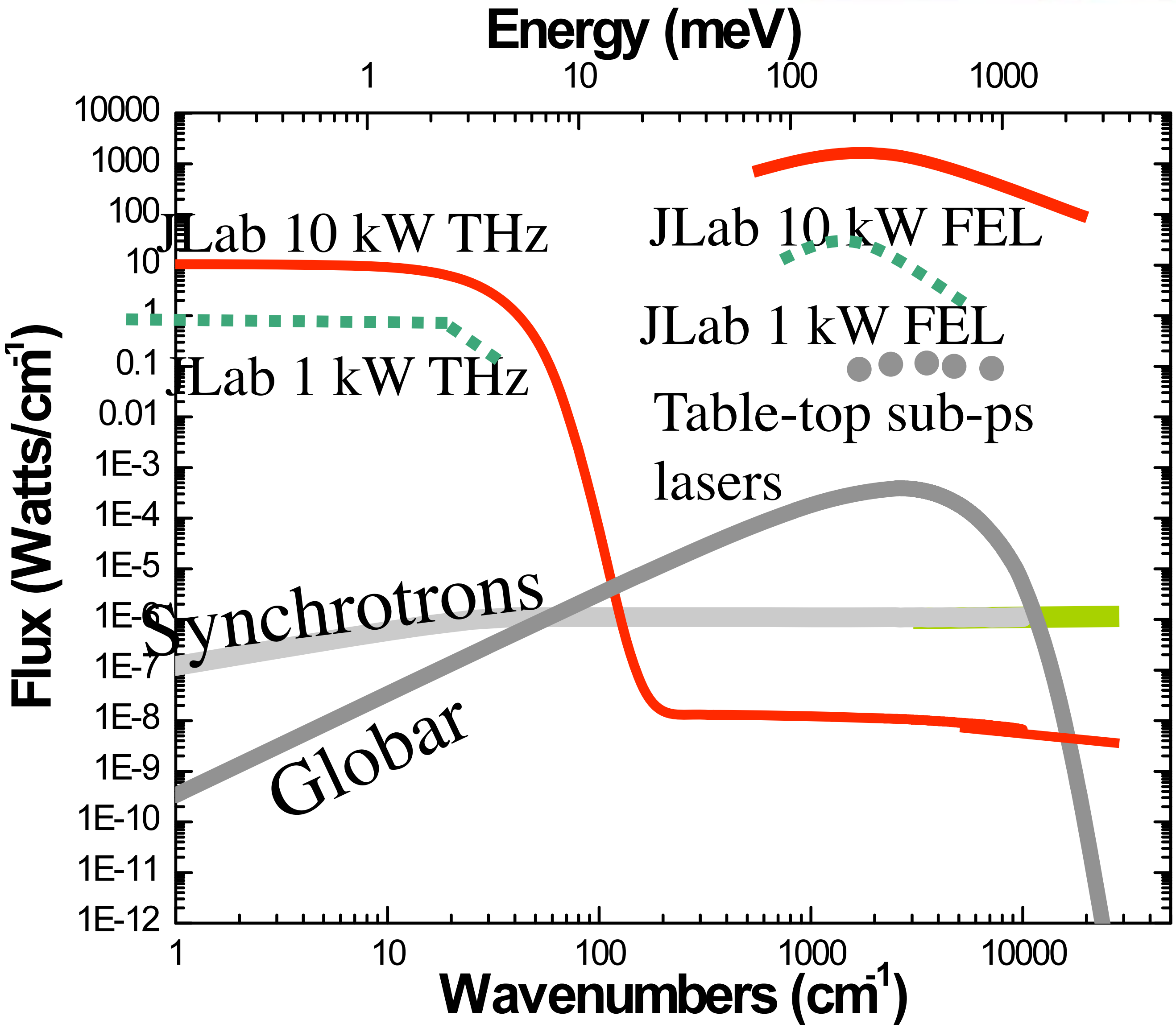


All electrons emit coherently ---- brilliance proportional to n_{el}^2

extremely high peak brilliance ----- fully coherent beam ----- fs pulses

W. Eberhardt, BESAC Feb. 2009

JLab FEL Power vs Conventional Sources



Key FEL Program Accomplishments in 2006-2009

- Very long carbon nanotube (CNT) production runs for NASA-LaRC at >1 kW on target at 1.6 microns; record production (>7 g/hr) and purity levels (> 80% single wall CNT) for laser ablation.
- Laser nitriding of titanium experiments for the Univ. of Göttingen
- Pioneering experiments completed on differential heating of fat tissue at 1.2 and 1.7 microns; resulting in best paper for Harvard PI at International Conference of Lasers in medicine and Surgery (Boston, April 2006).
- New type of THz interferometer and vacuum THz spectrometer demonstrated on THz beamline; World's first THz movies.
- Physics beyond the standard model: LIPSS Dark Matter Particle Searches

NASA/JLab Nanotube Synthesis - Research to Production

New and used target

From Target to Product, 100% In-House

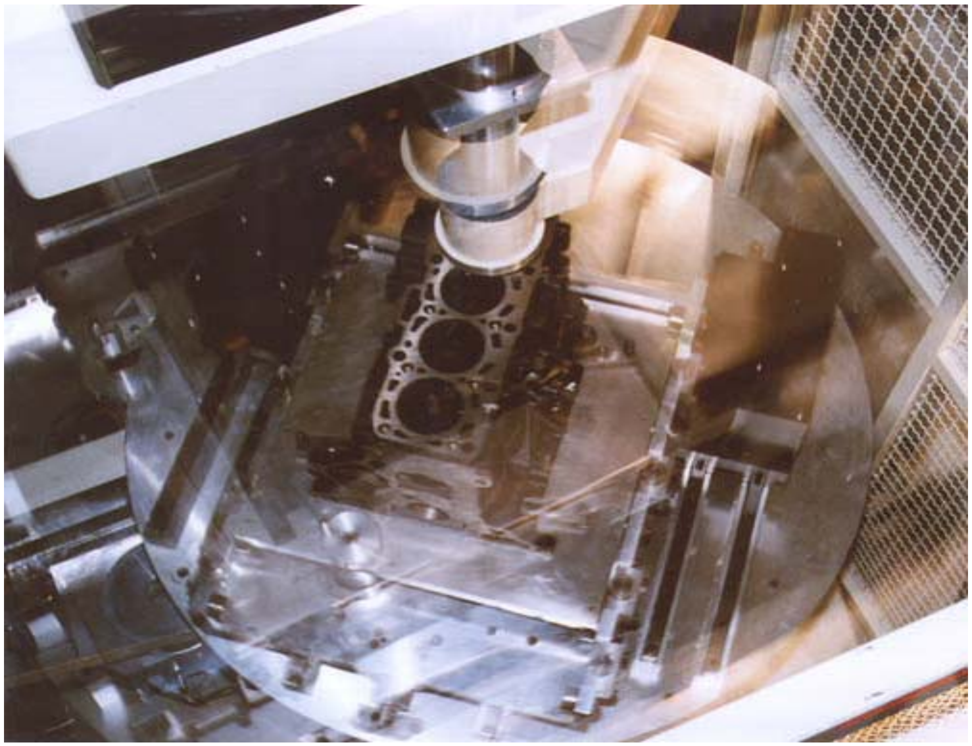
Product, ~1 hour of beam time

- 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).

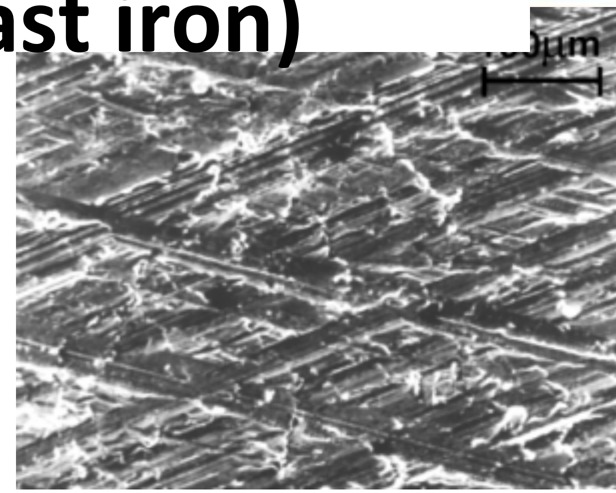
Mike Smith NASA LaRC

Application: Laser nitriding automobile cylinder liners (grey cast iron)

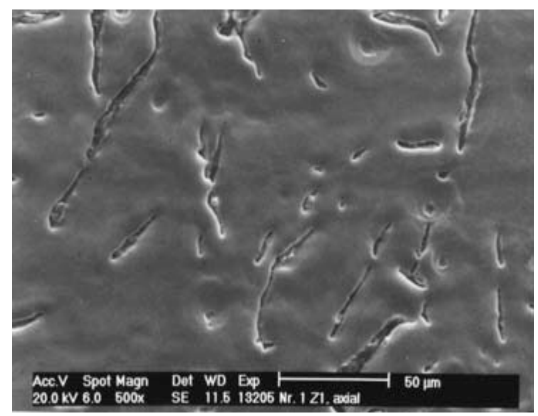
J. Lindner, AUDI AG



Treatment: mirror inside cylinder; rotating engine block in series production, 5 simultaneous excimer lasers



After honing



After laser treatment

Slide courtesy of P. Schaaf - U. Göttingen

Reduction of oil consumption (30x)

The benefits of high power and tunability - differential heating of fatty tissue

THE TIMES 60p
No 68620 • MONDAY APRIL 10 2006 • NEWSPAPER OF THE YEAR

Fat-burning laser will treat acne

Scientists have developed a laser technique that can melt fat under human skin. The breakthrough could herald selective laser treatment for various fat-related conditions, including lipid build-up linked with arterial heart disease, cellulite and acne.

A team of researchers from the US Department of Energy used a free-electron laser, which can produce very specific beams, to heat and break down fat without damaging other body tissue.

NEWS pages 6, 7

Jefferson Lab
Exploring the Nature of Matter

Fat-busting laser revolutionises treatment for acne and cellulite

A technique developed by American scientists could lead to fat-related conditions, including arterial heart disease, being melted away by high-intensity beams, reports **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 selected 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 infra-red laser light (from 800 to 2,600 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 infra-red light. However, the researchers found three wavelengths — 915, 1,210 and 1,720 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 infra-red light using the two most promising wavelengths, 1,210nm and 1,720nm.

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 infra-red laser light from 8mm to 17mm for about 16 seconds.

They found that the 1,210nm 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 lipid-rich 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 evolution of laser technology, first envisaged by Albert Einstein in the early 20th cent-

sions created by, for instance, a light bulb.

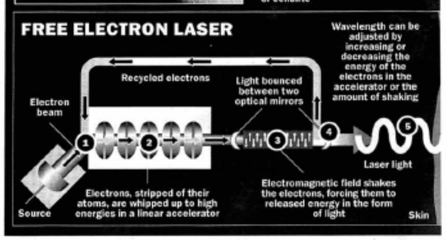
While the light given off by bulbs and other common light sources usually covers a wide

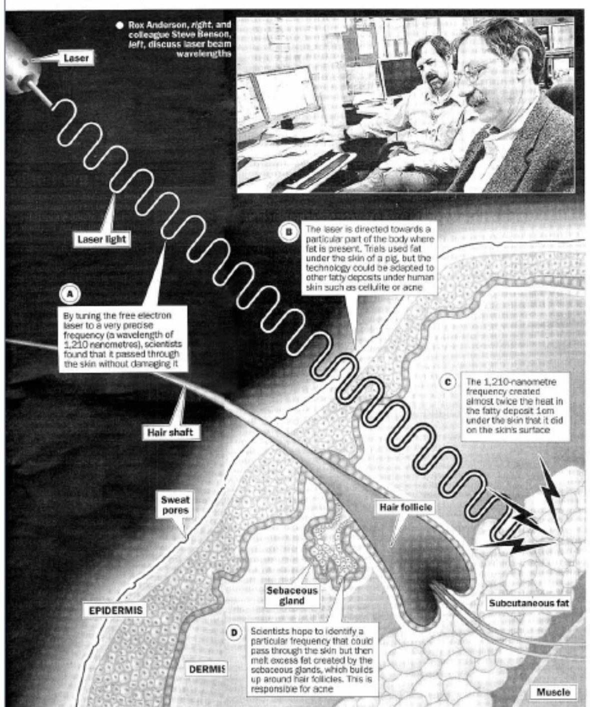
ZAPPING THE FAT

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, become more fibrous — like a scar. These areas then start to pull together around the fat, causing the tiny dimples and irregularities typical of cellulite





Trivial? Spots can truly blight teenagers' lives

DR THOMAS STUTTAFORD
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 crippling that in severe cases it not only blights emerging social and sex lives but is also a not uncommon factor in adolescent depression and suicide.

Eighty per cent of adolescents suffer from acneform spots, an appreciable number of people continue to have them until middle age, and in women they can last until the menopause.

Acne may occasionally appear for the first time in the mid-twenties or thirties. When acne starts in adolescents, it is the almost inevitable result of the hormonal surge that occurs in puberty, which causes the skin to produce greater quantities of sebum, the oil from the sebaceous glands attached to the hair follicles, than in childhood.

Provided that the quantity of sebum produced is not too great, and debris does not block the skin pores, the oil is spread thinly across the skin and is either rubbed or washed away. If the sebum doesn't drain easily through a skin pore, the sebaceous gland is likely to become enflamed 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.

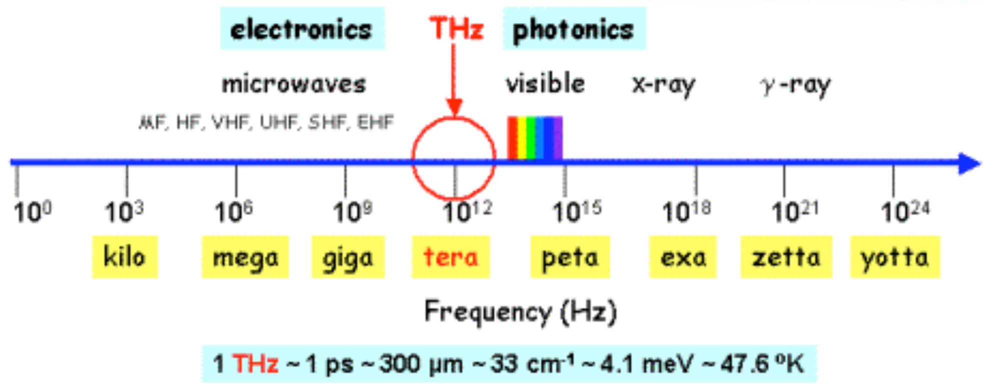
Hitherto there has nothing available to prevent acne, but it can and should be treated. Mild cases usually respond to local measures applied to the skin, but any severe acne requires antibiotics to prevent secondary infection. Several antibiotics also reduce the quantity of sebum produced.

If antibiotics prove inadequate, and there are no contraindications to its use, such as the chance of pregnancy or a history of psychiatric problems, isotretinoin by mouth is highly effective and 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 easy remedy, other than weight loss.

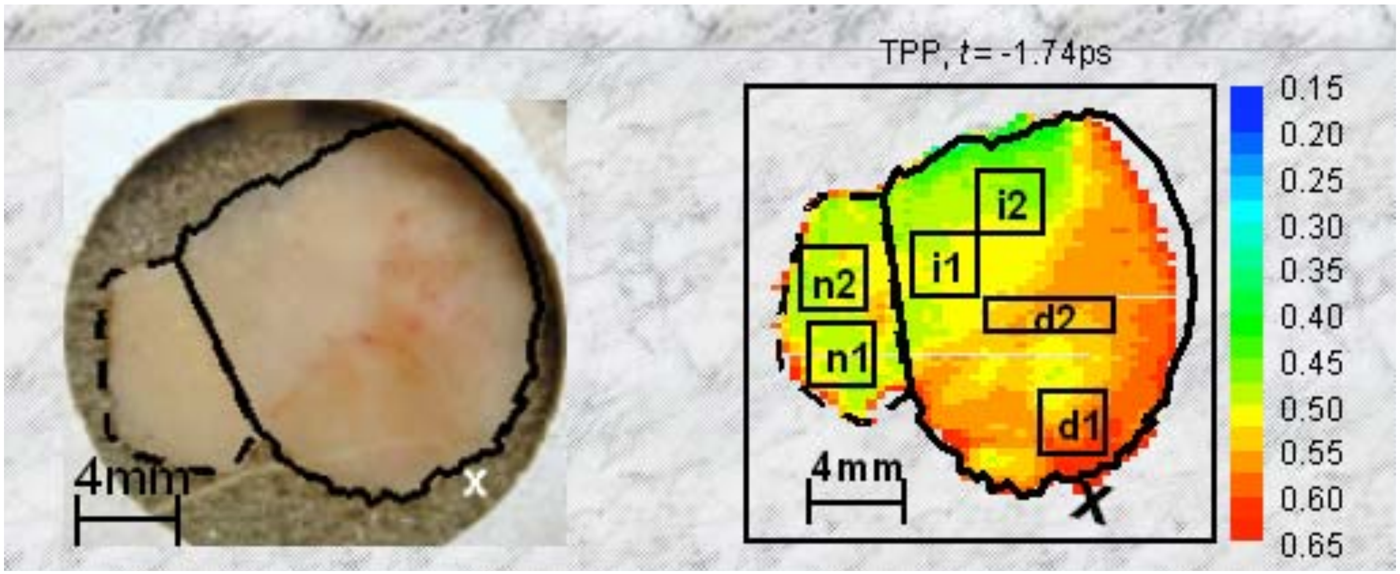
The third suggested use of the FEL would be for its adaptation so that it might destroy atheromotous plaques in arteries. This has been done before with other means but problems have arisen with distribution of debris when the plaques have been eradicated.

THz Programs at JLab FEL



- THz lies between electronics and photonics.
- THz broadband user facility constructed (world's highest power).
- Tissue interactions and safety limits.
- Imaging, movies.
- Magnetism, dynamics of quasiparticles, spin.
- Quantum coherence and control.
- Fundamental optical physics.
- Localization effects.
- Coherent Half- and Few-Cycle Sources for Nonlinear and Non-Equilibrium Studies.

Imaging / bio-medical cancer screening



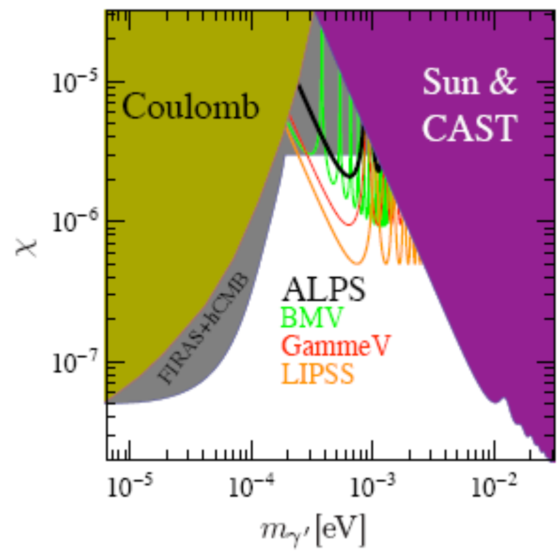
Basal cell carcinoma shows malignancy in red. Teraview Ltd.

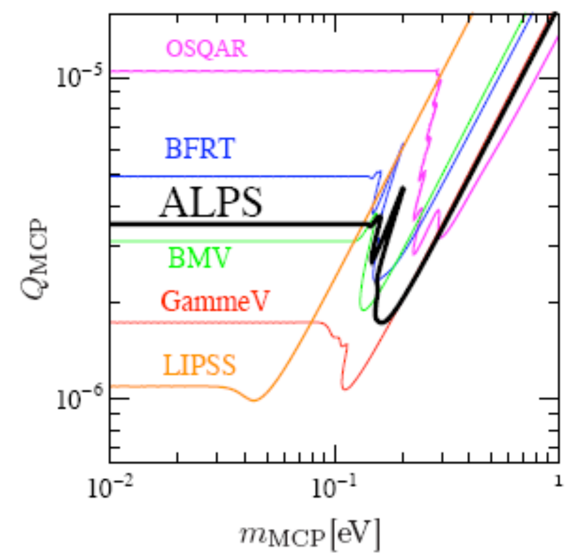
1 mW source images 1 cm^2 in 1 minute

100 W source images whole body (50 x 200cm) in few seconds

Physics Beyond the Standard Model
LIPSS[1] Dark Matter Particle Searches

The Universe:
0.5% stars/galaxies
<10% neutrinos
~5% e- & protons
~30% dark matter
~65% dark energy

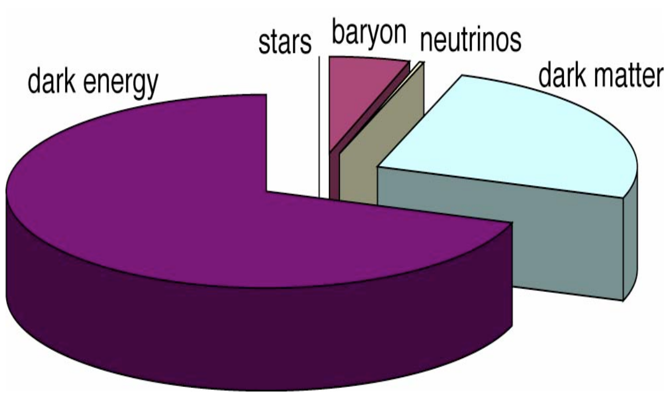




Exclusion Limits

paraphoton-photon mixing

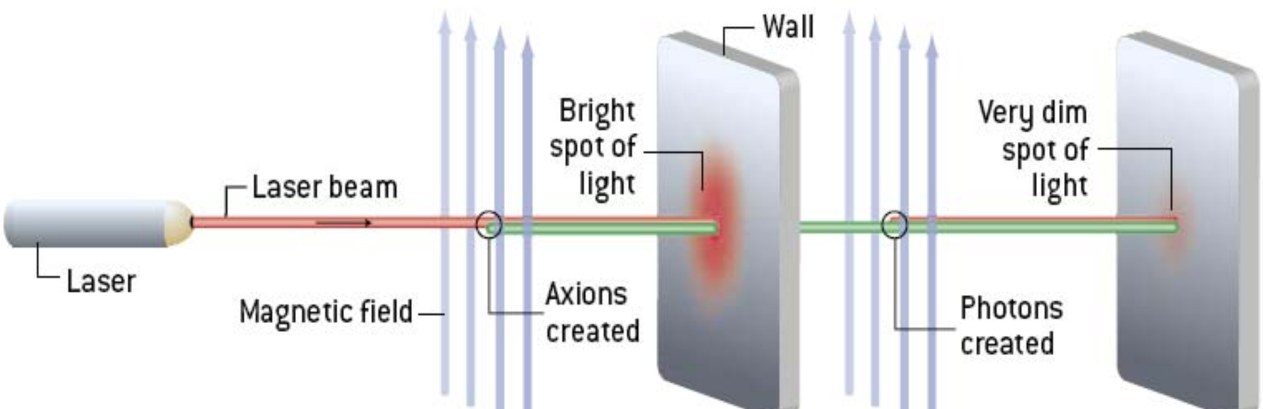
milli-charged fermions



[1]**<u>LI</u>**ght **<u>P</u>**seudoscalar and **<u>S</u>**calar **<u>S</u>**earch Collaboration
Yale Univ., Hampton Univ., Jefferson Lab, Muons, Inc.

"Light Shining through Wall" technique to search for:

- Light Neutral Bosons (LNB) 10^{-6} eV < mass < 10^{-3} eV
- Photon/paraphoton oscillations (string theory test)
- Milli-charged fermions



Reference:
A. Afanasev et al., (LIPSS Collab.),
Phys. Lett. B 679, 317 (2009).

We also perform accelerator physics research

- Use Maximum Entropy algorithm

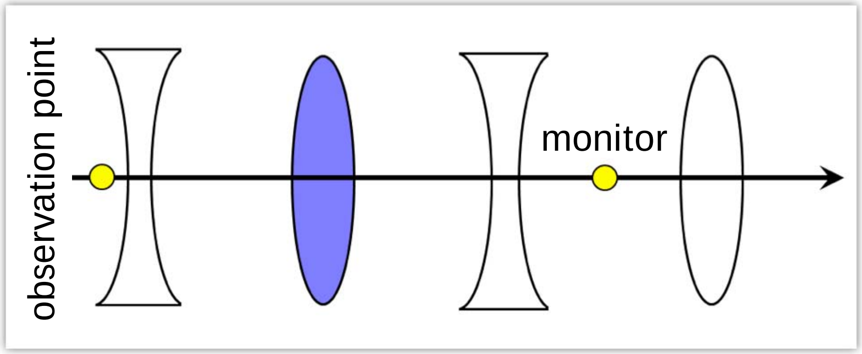
  (J. Scheins, TESLA 2004-08)

  - Most likely solution consistent with data while minimizing artifacts

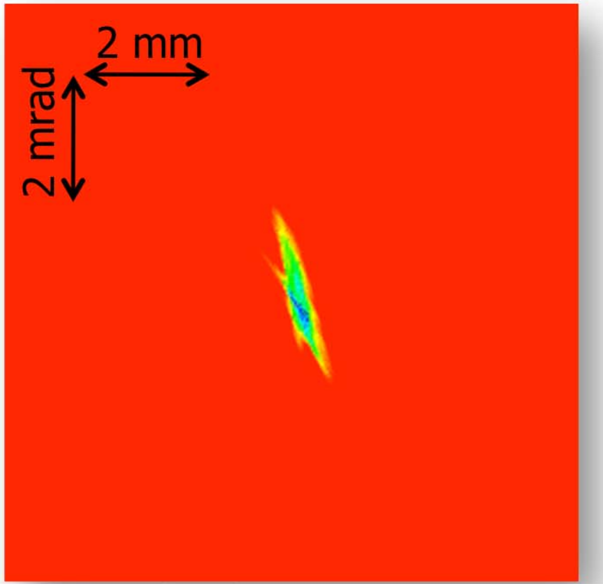
- Reconstructed horizontal phase space at 115 MeV

- Extracted parameters:

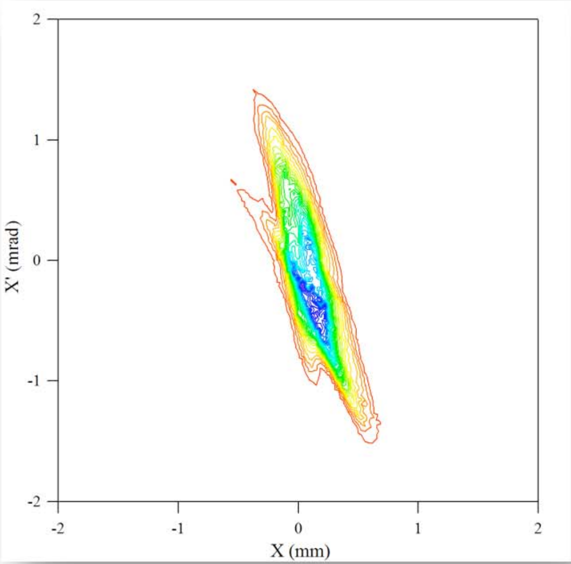
  ε_n = 15.36 mm-mrad
  β_x = 0.48 m
  α_x = 1.14



Tomography

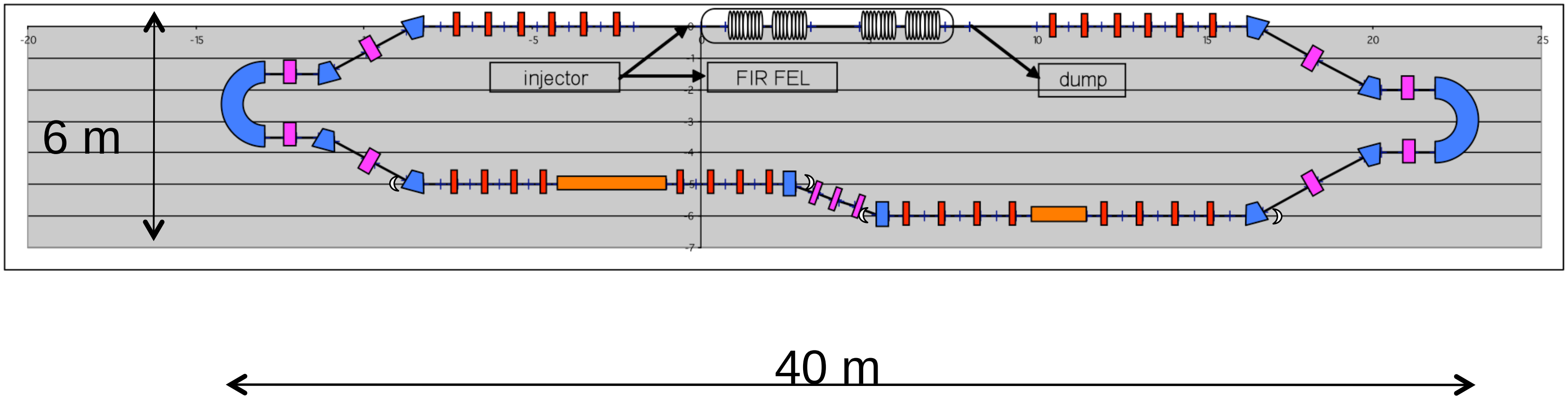


Reconstructed phase space



C. Tennant et al., JLAB-TN 09-021

And have developed compact FEL design for Florida State University/ NHMFL

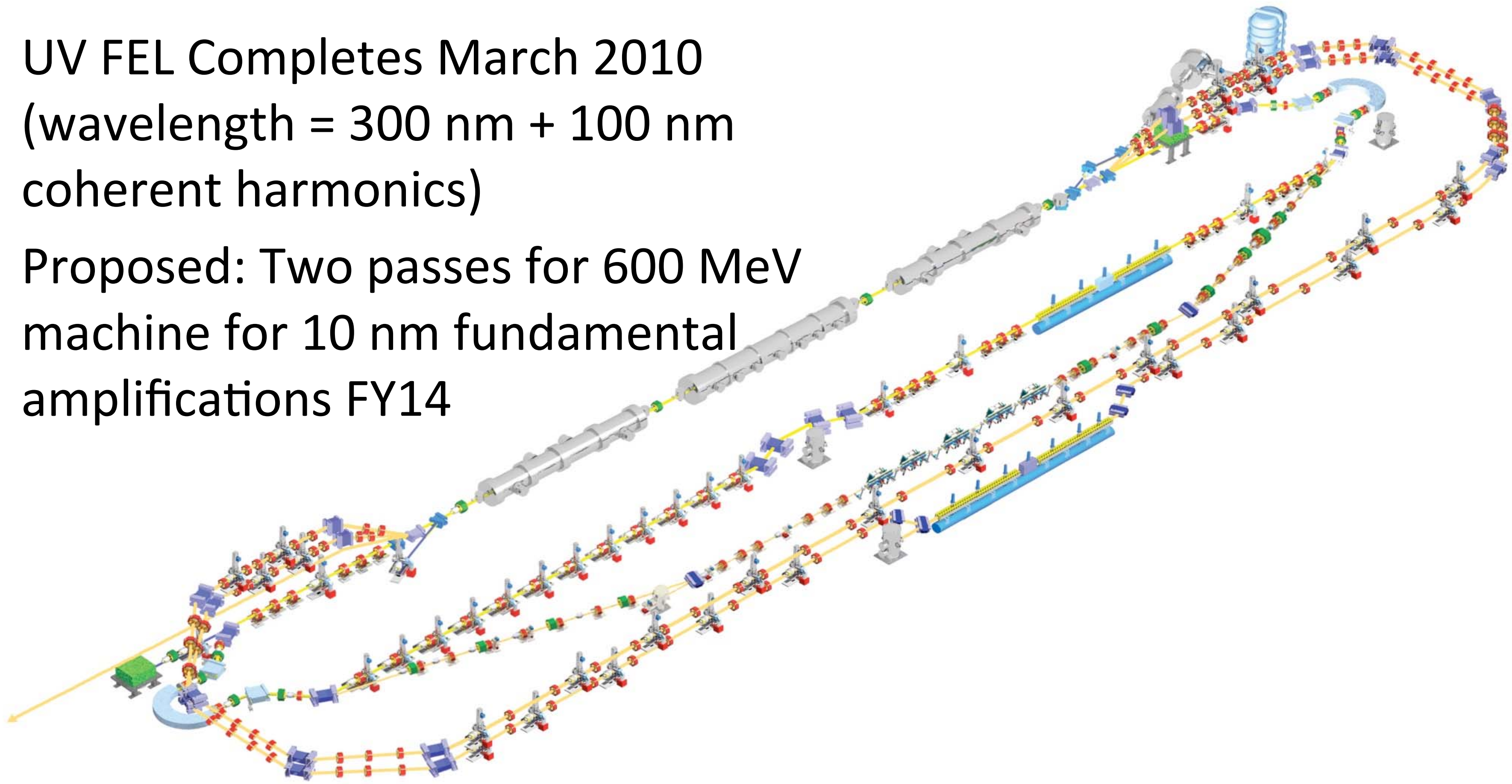


- Would be first user-dedicated ERL FEL
- 60 MeV ERL with injector/FIR & beam dump interior to recirculator
- Linac based on two 1.3 GHz 9-cell cavity pairs

Courtesy, D. Douglas, JLab

The next step at Jefferson Lab towards 4th generation light sources in the VUV and soft X-Ray

- UV FEL Completes March 2010 (wavelength = 300 nm + 100 nm coherent harmonics)
- Proposed: Two passes for 600 MeV machine for 10 nm fundamental amplifications FY14



JLAMP X-ray Amplifier/Oscillator on Jlab FEL

Summary

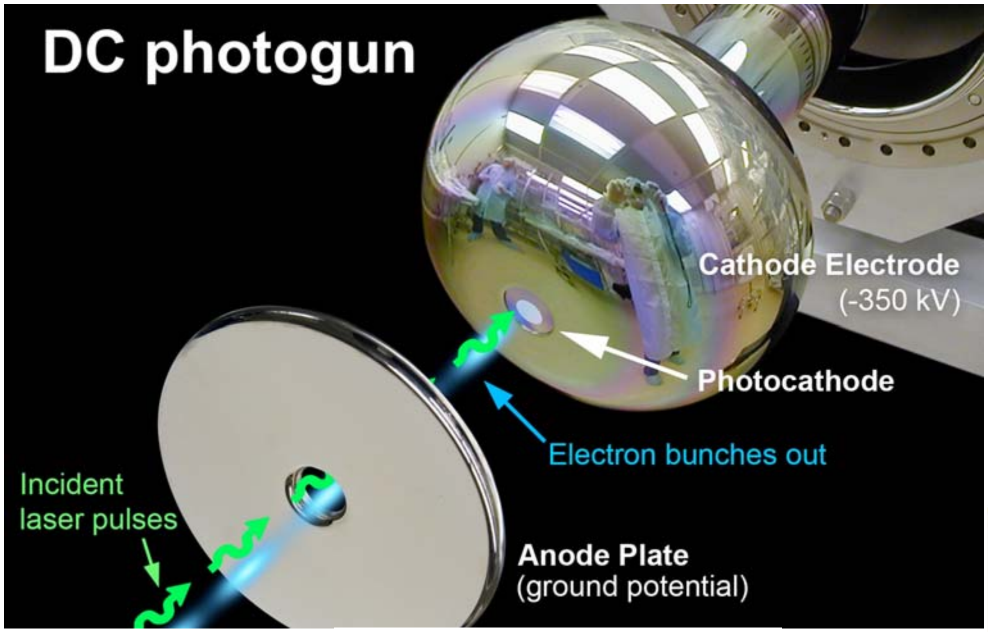
- A large scientific community utilizes accelerator based light sources to exploit capabilities unmatched by conventional sources

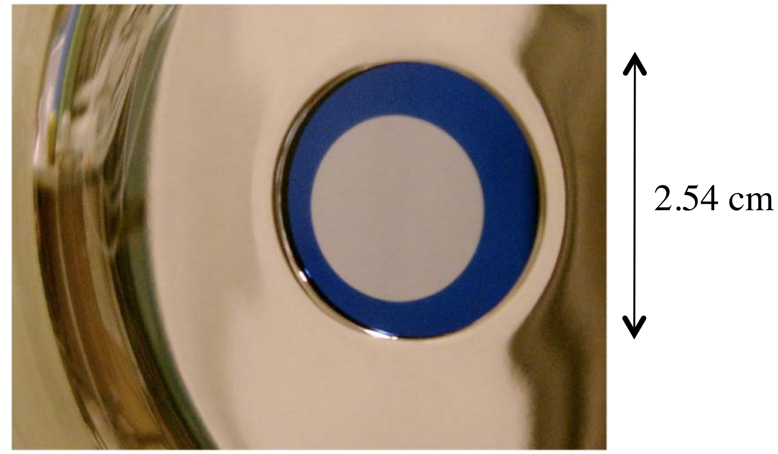
- Development of new 4th generation light sources will further expand this activity into higher brightness, shorter wavelength, and shorter pulse length photonic R&D

THANK YOU on behalf of he Jefferson Lab FEL team

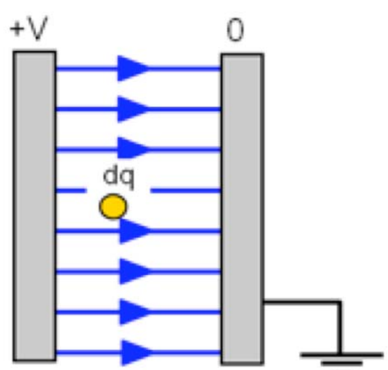
BACKUP SLIDES

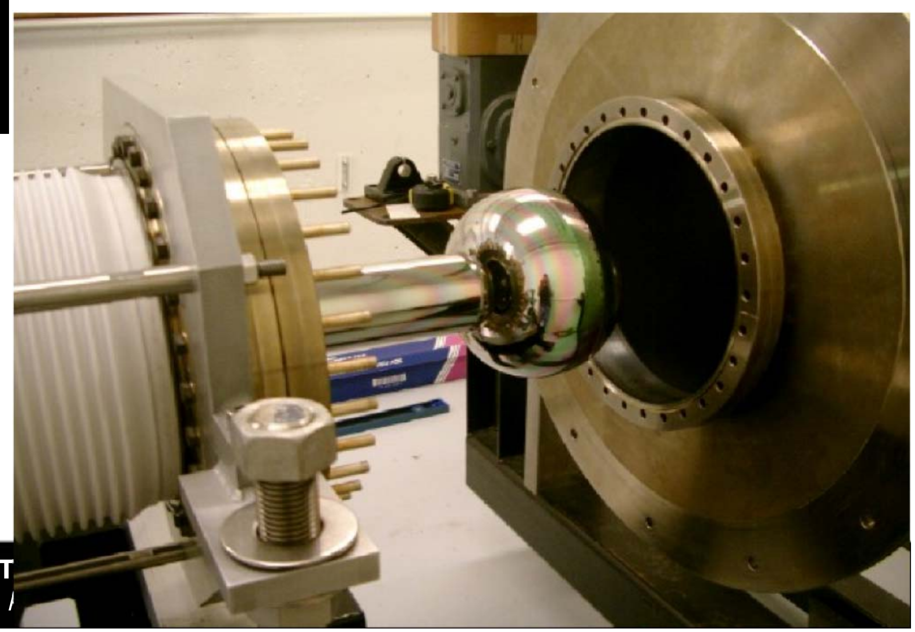
The electrodes in a DC gun hold the photocathode inside a vacuum chamber and are electrically insulated by a a large ceramic



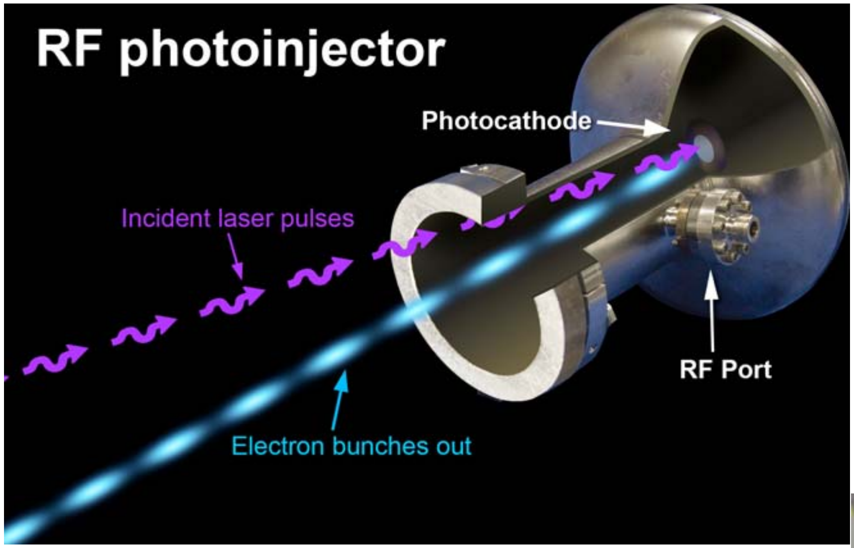


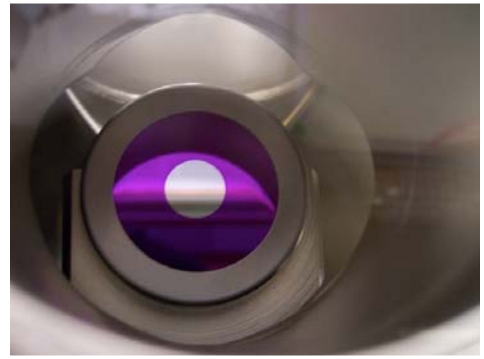
Anodized GaAs photocathode





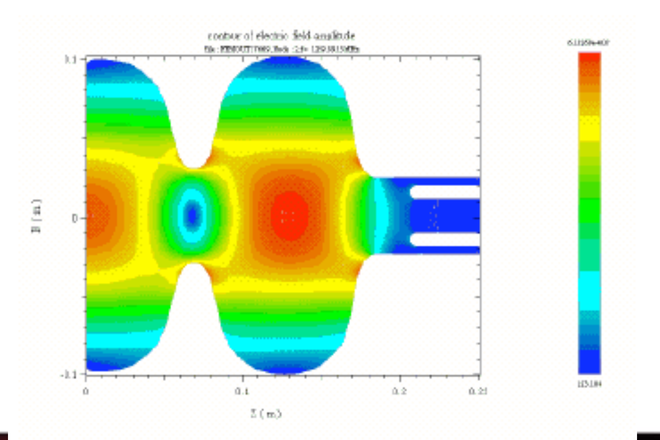
In Radio Frequency guns the vacuum chamber is a cavity shaped to maximize the longitudinal component of the RF field on the cathode

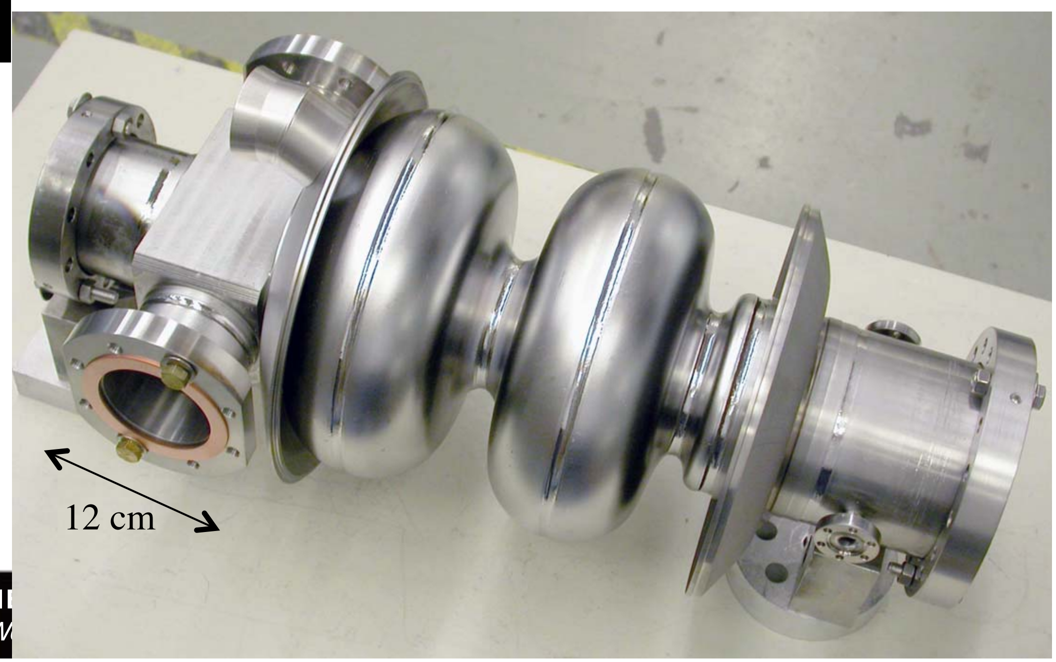




Semiconductor photocathode

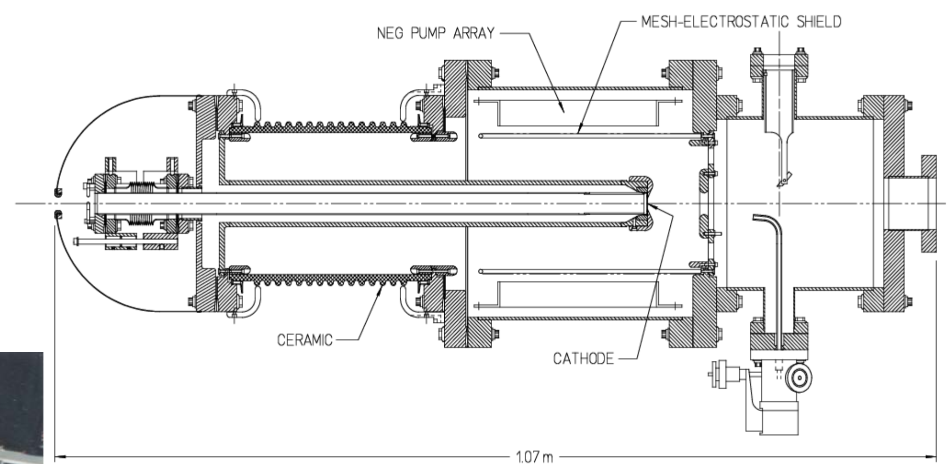
INFN superconducting injector

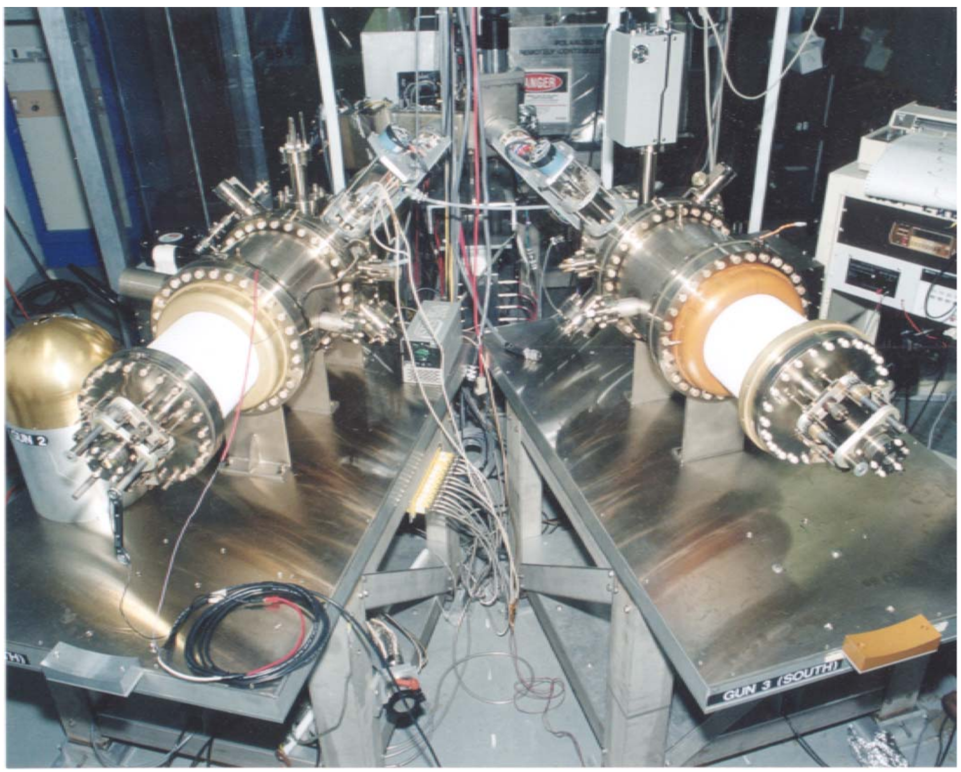




CEBAF 100 kV polarized electron source*

- Two-Gun Photoinjector - One gun providing beam, one "hot" spare
- vent/bake guns – 4 days to replace photocathode (can't run beam from one gun while other is baking)





- Activate photocathode inside gun – no HV breakdown after 7 full activations (re-bake gun after 7th full activation)
- 13 mm photocathode, but use only center portion, 5 mm dia.
- Extract ~ 2000 Coulombs per year
- Beam current ~ 100uA, laser 0.5mm dia., lifetime: ~ 100C, 1x10^5 C/cm^2

* Courtesy of Matt Poelker. CEBAF Polarized Source Group.

Making laser light with electrons

- A Free-Electron Laser (FEL) provides intense, powerful beams of laser light that can be tuned to a precise color or wavelength. Free-electron lasers absorb and release energy at any wavelength, because the electrons are freed of atoms. This key feature enables the FEL to be controlled more precisely than conventional lasers to produce intense powerful light in brief bursts with extreme precision. The lack of a lasing medium in the cavity allows the laser to operate at very high power levels without the usual cavity heating problems.