JLab FEL Overview

The upgraded JLab free-electron laser (FEL) is on-line as a wavelength-tunable, subpicosecond, >10 kW infrared light source offering a combination of high repetition rate and high power per pulse. **The JLab FEL operates in regimes unattainable by subpicosecond tabletop lasers, even at a specific wavelength.** It builds on the successes of JLab's principle-proving, kilowatt-scale "Infrared Demo" FEL. The IR Demo operated for scientific users from 1999 to late 2001.

An aggressive program is in place to shorten the FEL's light pulses down to the **attosecond regime** to explore frontiers of time as well as high field in a fully wavelength-tunable device. The upgraded FEL soon will also incorporate a **kilowatt-scale ultraviolet capability.**

"Driving" the FEL is a superconducting ERL. This Energy-Recovering Linac—linear accelerator—is a small, higher-current cousin of JLab's huge CEBAF electron accelerator for nuclear physics. This ERL has demonstrated the production of **broadband terahertz light over four orders of magnitude brighter than achieved anywhere before.** The upgraded FEL's ERL is configured for further advances in this underexploited region of the electromagnetic spectrum, which lies between electronics and photonics.

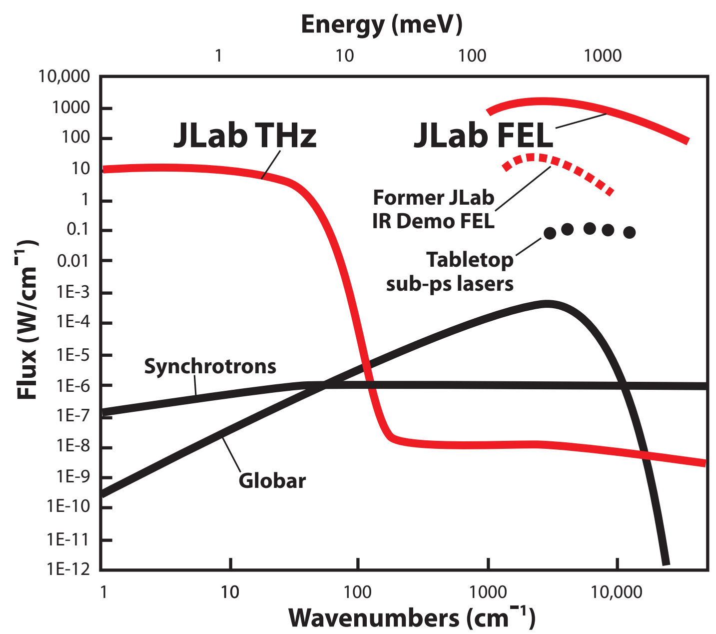
JLab's ERL-driven FEL is the first of a new generation of accelerator-based light sources in which each electron circulates only once rather than being stored, as it would be in a typical synchrotron light source. Each electron's energy is recovered and almost immediately imparted to another electron in the ERL.

JLab FEL results have begun changing scientists' thinking about linear and nonlinear dynamical processes. JLab's earlier kilowatt-scale FEL delivered light with subpicosecond time structure at enormously high repetition rates. **A comprehensive bibliography of resulting publications appears on the FEL pages at www.jlab.org.** The papers derive from only 1872 hours of funding-limited operation for some 30 user collaborations at JLab's then-nascent light-source facility—an output comparable to those of established light sources. Moreover, in basic accelerator, beam, and photon physics, the FEL and ERL are opening regions of promising study for developing future research tools.

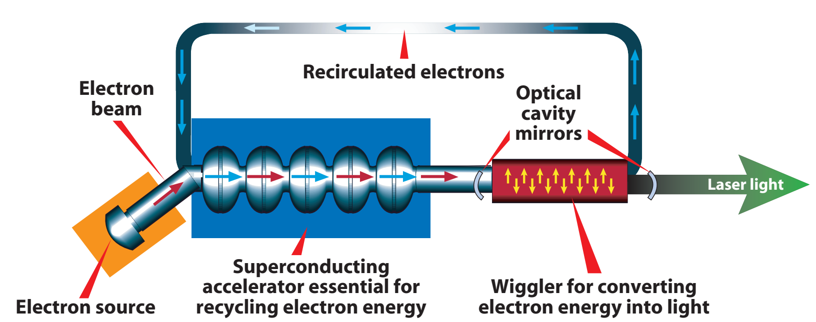
JLab Upgraded FEL Performance

Wavelength range (IR)	1–14 µm
Power/pulse*	120 µJ
Pulse repetition frequency	Up to 75 MHz
Pulse length	500–1700 fs FWHM
Maximum average power	>10 kW
Wavelength range (UV/VIS)	250–1000 nm
Power/pulse	20 µJ
Pulse repetition frequency	Up to 75 MHz
Pulse length	300–1700 fs FWHM
Maximum average power	>1 kW

**>1 mJ with stacking cavity*



Spectral range comparisons.

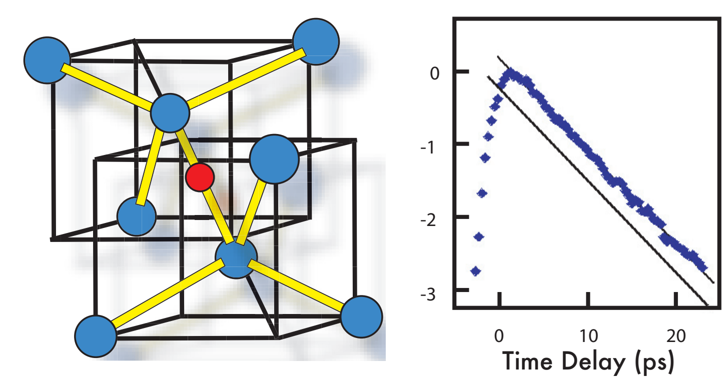


Generic conceptual layout of an FEL (free-electron laser) driven by an ERL (energy-recovering linear accelerator). Wavelength-tunable light is extracted from electrons that "slalom" through the wiggler, an array of opposed magnets.

IR Demo Highlights: Linear Dynamics

Hydrogen defects in silicon

Though elastic x-ray scattering yields important structural information, the function of materials can only be measured via experiments which probe the dynamical interplay between the electrons and phonons with high precision in both energy and time. Experiments at the JLab IR Demo FEL by scientists from the College of William and Mary yielded critical information about the poorly understood ways in which hydrogen defects fundamentally limit the use of silicon. In these two-photon experiments, the FEL pump pulse was tuned to the frequency of the defect, and the subsequent energy relaxation processes were studied by a second photon at a matched frequency. Seven substitutional, interstitial, and vacancy defects were measured as a function of temperature for both hydrogen and deuterium. Surprisingly, relaxation rates varied by orders of magnitude even for defects close to each other in energy.



Bond-center H in Si and its dynamical decay as measured at the JLab IR Demo FEL.

Amide-1 vibrational energy relaxation in myoglobin

Experimenters from Princeton University have been using the JLab FEL to learn how myoglobin, the "engine-of-life" protein, works. Myoglobin in muscle tissue takes oxygen from hemoglobin in the blood. Yet the energetic pathways are not understood. By tuning the FEL to specific molecular (amide-1) vibrational modes, the researchers learned more precisely how energy is transmitted within the molecule. One interesting and unexpected finding was that the dynamical processes differ drastically even for closely spaced vibrational modes.

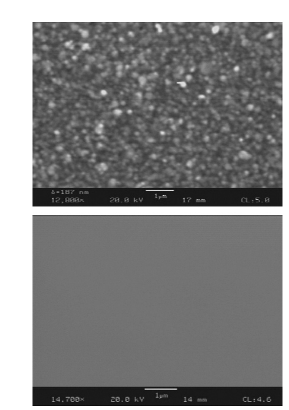
IR Demo Highlights: Nonlinear Dynamics

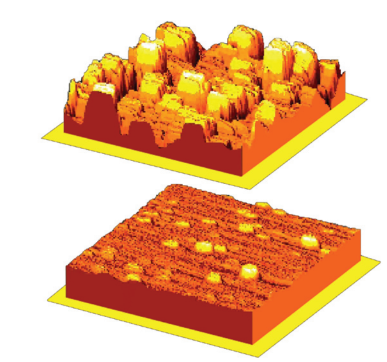
Single-walled carbon nanotubes

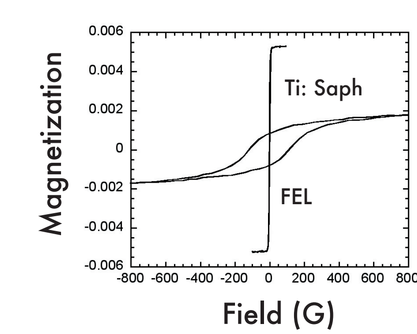
Intense peak electric fields (up to 10^{13} V/m), combined with the 75 MHz repetition rate, allowed experiments in an entirely new regime, the production of carbon nanotubes via the excitation of graphite in the presence of a catalyst. High yields of exotic carbon molecules were attributed to excitations within the excited plume that itself came from multiphoton absorptions. More work is needed to characterize and hence understand these nonlinear interactions on subpicosecond time scales.

Pulsed laser deposition of magnetic thin films

Magnetic thin films are an example of novel but difficult materials preparation. In another JLab FEL experiment by researchers from the College of William and Mary, unique magnetic thin films were produced by excitations of bulk NiFe films. The multiphoton absorption process led to the creation of hot material without the electronic excitation typically observed with tabletop lasers. Hysteresis curves were found to be identical to those of the native material. This has major technological implications and marks the beginning of a major program.







Three comparisons of thin NiFe films as grown with an amplified Ti-sapphire laser (TS) and with the JLab IR Demo FEL. (*Above*: scanning electron microscope. *Top right*: atomic force microscope. *Right*: hysteresis curves.)

Jefferson Lab's Free-Electron Laser User Facility

Research Opportunities

In the **structure and dynamics of materials**, the JLab FEL User Facility offers research opportunities extending far outside the confined spectral regions available elsewhere, both in photon energy and electric field. Thus **nonlinear as well as linear** spectral response functions can be determined for materials in equilibrium and out of equilibrium.

Specifically, the FEL presents unprecedented opportunities for studies of **material behavior,** from protein folding and protein specific function (photosynthesis, metabolic pathways) to complex materials, non-Fermi metals, superconductors, and semiconductors. The source enables studies of **chemical reaction dynamics** and energy partition and flow. Although average powers are expected to be raised to tens of kilowatts, an external cavity will allow 100 pulses to be combined to increase the power per pulse at the expense of the repetition frequency. Peak electric fields are 10^{13} V/m at 1 μm wavelength. Terahertz light with fields of 10^{7} V/m will be available from 0.1–5 THz, allowing—for the first time—nonlinear optical studies of critical materials in this regime.

In **condensed-matter physics** an understanding of correlated effects, described by various theoretical formalisms such as the Luttiger liquid formalism, can be obtained from frequency-dependent conductivity measurements for both ground and excited states. In principle, issues of key importance such as the behavior of complex materials can finally be fundamentally understood, for instance for materials exhibiting giant magneto-resistance and high-temperature superconductivity. Similarly enabled are experiments relevant for the revolution occurring in **nanotechnology.**

Biology profits from increasingly sophisticated measurements of protein and genomic form, but functional dynamics experiments require sophisticated tools that can tune to specific protein intramolecular vibrational modes since these likely determine folding and functional behavior. The FEL user facility will enable an understanding of energy transfer mechanisms in protein molecules.

In **chemistry** the FEL user facility will offer unprecedented opportunities for studies of Bose-Einstein condensates in a novel way in which the condensate is held by the pulsed high field but can be examined between pulses. With enhanced stacking schemes, the FEL will provide boosted single-pulse energies to a level suitable for gas-phase chemistry. At the forefront of theoretical and experimental inquiry in the gas phase are nonadiabatic dynamics and underlying factors controlling product branching, angular momentum, and energy disposal. The study of radical-molecule reaction dynamics in crossed beams, which has been beyond the capability of other probe techniques, promises detailed insight into these issues. Similar methods can be used to probe complex kinetics in multicomponent systems. The frontier of chemical kinetic investigations is the study of interacting systems of chemical reactions, whether in atmospheric, combustion, or industrial processing applications. Additionally the intramolecular excited-state energy pathways for both ground-state and excited-state Rydberg and even ionized atoms and molecules is central to our understanding of effects ranging from **Earth-based chemistry** to **combustion dynamics** to the **evolution of the universe.**

For more detailed information about conducting scientific research at the Jefferson Lab Free-Electron Laser User Facility, please consult the FEL pages at www.jlab.org.

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Science with Light

at Jefferson Lab

The Jefferson Lab Free-Electron Laser User Facility offers research opportunities without parallel anywhere.

The superconducting technology that Jefferson Lab pioneered for nuclear physics research with electron beams now also serves science conducted at JLab with light: biology, medicine, chemistry, environmental science, materials science, condensed-matter physics, nanotechnology. Because JLab's initial, principle-proving light-source capabilities exceeded those of established conventional sources, initial experiments yielded some 100 papers in leading journals. **Then, in 2003, substantially upgraded light-source capabilities became available at the JLab Free-Electron Laser User Facility, offering research opportunities without parallel anywhere.**