Storage-ring free-electron laser operates in the visible

The successful generation of a 6500-Å free-electron laser beam this summer at the French electron storage ring ACO represents a number of firsts. This culmination of a three-year effort by an Orsay–Stanford collaboration at Orsay's LURE (Laboratoire pour l'Utilisation du Rayonnement Electromagnetique) synchrotron-light laboratory is the first operation of a free-electron laser oscillator at a visible-light wavelength. It is, furthermore, the first operation of a free-electron laser oscillator *at any wavelength* using the circulating electron beam of a storage ring. The Orsay–Stanford FEL is also the first device to achieve laser oscillation with an "optical klystron"—a modified wiggler design suggested by N. A. Vinokurov and Alexander Skrinsky at Novosibirsk (in 1977) for enhancing the gain of free-electron lasers.

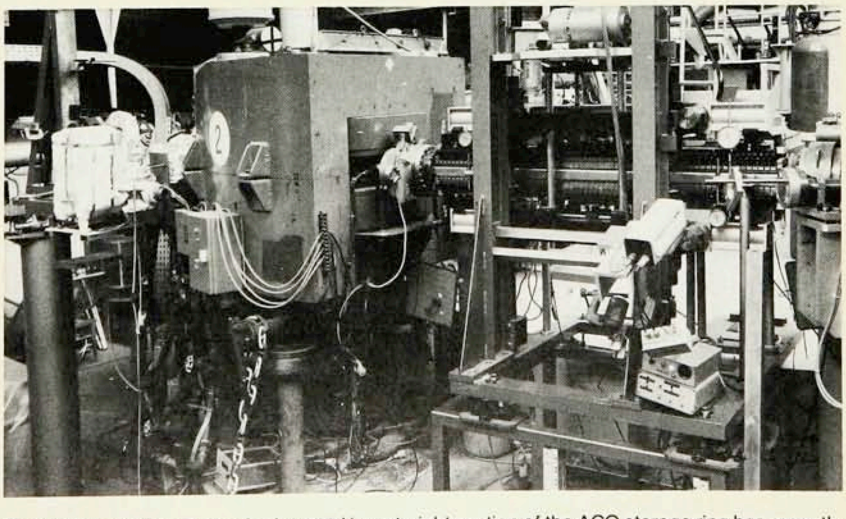
Although many experiments have successfully demonstrated the free-electron laser as an *amplifier* of laser light since the idea of using an undulating electron beam as a laser medium was introduced by John Madey at Stanford in the early 1970s, the ACO experiment is only the third to surpass the gain threshold for actual laser *oscillation* in a mirrored optical cavity. In an FEL amplifier, one simply observes the amplification of an external laser beam as it interacts with an undulating electron beam passing through the periodic magnetostatic structure of a "wiggler." A true free-electron laser oscillator, on the other hand, produces a laser beam without the need for an external laser. The spontaneous radiation generated by undulating electron bunches in the wiggler is reflected back and forth between a pair of end mirrors, generating enough stimulated emission in successive electron bunches to produce and sustain a laser beam.

The first such FEL laser oscillator was successfully demonstrated by Madey and his Stanford colleagues in 1976, employing the electron beam from a superconducting linac at Stanford to produce infrared laser beams with wavelengths around three microns. Shortly thereafter, a Columbia–Naval Research Lab collaboration used a pulsed-diode electron beam to achieve FEL oscillation at 400 microns in the far infrared—a wavelength so long that lasing is facilitated by electron–electron plasma interactions that are not useful at shorter wavelengths.

Since the recent Orsay–Stanford experiment at 6500 Å in the visible,[1] there has been one more demonstration of an FEL laser oscillator. A TRW–Stanford group, passing the electron beam of the Stanford superconducting linac through a tapered wiggler built at TRW, has achieved[2] laser oscillation at 1.6 microns in the near infrared. The tapered wiggler configuration, in which the spacing between successively alternating magnet poles is gradually decreased toward the downstream end of the wiggler as the electron beam gives up energy to the radiation field, is nowadays the principal approach toward the achievement of very-high-power, high-efficiency FELs in the near infrared. Its theoretical underpinnings were provided by Norman Kroll (University of California, San Diego), Philip Morton (SLAC), and Marshall Rosenbluth (then at the Institute for Advanced Study) in 1979.

Extensive experimental efforts at Los Alamos and Mathematical Sciences Northwest with strongly tapered wiggler amplifiers have already lent support to the theory of Kroll, Morton, and Rosenbluth; but these groups have yet to attempt laser oscillation with tapered wigglers. Because the TRW–Stanford laser has only a very modest taper (about 2%), Rosenbluth (now at the University of Texas) told us, its successful operation in the oscillator mode does not yet provide a severe test of the theory. The high power promised by the tapered-wiggler FEL scheme makes it particularly interesting for industrial and military applications. The TRW–Stanford group, headed by John Edighoffer and George Neil at TRW, and by Alan Schwettman and Tod Smith at Stanford, reports a 10-watt laser output at 1.6 microns, extracting energy from the electron beam in the tapered wiggler with an efficiency of better than 1.2%. This power level and efficiency, Neil told us, exceeded that of the previous FEL oscillators (except in the far-infrared plasma regime) by an order of magnitude.

Visible wavelengths. After the Stanford group had achieved infrared FEL oscillation in 1976, they began looking at the problem of how to do the same thing at visible wavelengths, and eventually even in the ultraviolet. The



The Orsay–Stanford wiggler inserted in a straight section of the ACO storage ring has recently achieved free-electron-laser oscillation at 6500 Å (red–orange). The 160-MeV electron beam emerges from the storage-ring bending magnet at left to undulate through the 1.3-meter-long wiggler. This alternating-polarity array of permanent magnets originally had seventeen 7.8-cm-long periods. The laser gain has been greatly enhanced by replacing the three central periods with a dispersive section of double-width magnets, making the wiggler an "optical klystron."

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essential issue as one moves to shorter wavelengths in a free-electron laser is the need for electron beams of higher current density. The gain of an FEL depends on the number of electrons per optical wavelength. Thus for shorter wavelengths one requires more electrons per unit length along the beam. The angular spread of the beam must also decrease. Thus, overall, one needs to reduce the phase-space density, or emittance, of the beam to achieve FEL oscillation in the visible.

Madey and his colleagues David Deacon and Kem (*sic*) Robinson concluded that to achieve the requisite beam current densities for FEL oscillation in the visible and ultraviolet one would have to go to electron storage rings; linacs, they felt, would not do. What limits the current density of linacs, Madey argues, can be understood in terms of Liouville's theorem, which tells us that, in the absence of dissipative forces, the phase-space density of an electron beam is conserved, remaining at the low level with which it emerges from the initial accelerating stage. One can concentrate the beam spatially only at the cost of increasing its angular and energy spread.

Storage rings, by contrast, circumvent this restriction because their synchrotron radiation, being velocity dependent, is a quasi-frictional dissipative force. In fact, one makes use of this effect in synchrotron-radiation-damping storage rings to concentrate the phase-space distribution of positrons before injecting them into e^+e^- colliders. A well designed storage ring can achieve current densities four to six orders of magnitude greater than a linac of the same beam energy.

Some of the other groups striving for free-electron lasing in the visible regard Madey's dismissal of linacs as premature. A Math Sciences Northwest–Boeing collaboration led by Jack Slater and John Adamski has built an rf linac for their tapered-wiggler program that has recently demonstrated[3] sufficiently high beam phase-space density to encourage their hope that the system will be able to operate in the visible.

Although Stanford has two high-energy storage rings of world renown, the newer one, PEP, is dedicated entirely to the high-energy physics of e^+e^- collisions, and SPEAR, its lower-energy predecessor, will soon be fully occupied as the synchrotron light source of the Stanford Synchrotron Radiation Laboratory. Furthermore, neither of these storage rings is designed to function efficiently at the low energies (a few hundred MeV) required for a visible-light FEL. The Stanford group therefore approached a group at LURE that had been developing wigglers (undulators, strictly speaking) to intensify and concentrate the synchrotron light from its ACO storage ring. One must distinguish between the *incoherent* synchrotron radiation that emanates from any circular electron ring much like the headlight of a train on a circular track and the spatially fixed, *coherent* light beam from a free-electron laser. But the wigglers used in both technologies—linear arrays of alternating magnetic poles that impart an undulatory perturbation to the electron beam—are in essence quite similar. Yves Petroff, a pioneer of synchrotron wiggler development at LURE, is now the director of LURE and a member of the Orsay–Stanford group.

The Orsay–Stanford collaboration finally got under way in 1979, with the intention of using a recently built one-meter-long superconducting wiggler designed by Petroff. The other physicists in the Orsay contingent are Michel Billardon, Jean-Michel Ortega and Pascal Elleaume.

ACO is a venerable colliding-beam storage ring, 22 meters around, built in the mid 1960s to study e^+e^- collisions. The plan was to run a 240-MeV electron beam through the superconducting wiggler installed in ACO, doing FEL amplifier experiments first and then putting in mirrors to attempt laser oscillation. The setup was not ideal for FEL experimentation, Madey explains. The 10-ampere peak electron current of ACO was lower than one would have liked. Furthermore, because it was built so long ago, the ACO design does not include more recently developed features to counteract various sources of beam instability. It was feared that having an FEL in the ring would exacerbate such instabilities. Also, the crowded ring magnet structure limits the length of the wiggler to one meter. Because the gain of an FEL scales as the cube of its length, there was concern that the gain might be marginal for FEL oscillation.

The resonant effect by which the radiation field extracts energy by stimulated emission from the undulating electron beam requires that the electrons, in the beam rest frame, see a wiggler periodicity equal to that of the radiation. Thus the lasing wavelength is proportional to the wiggler wavelength divided by the square of the electron beam energy, with a proportionality constant that increases as one raises the magnetic field strength of the wiggler. One tunes the laser by varying either the electron beam energy or the wiggler field strength. With a wiggler periodicity of 4 cm, the Orsay–Stanford group set its magnetostatic field strength so that a 240-MeV circulating beam would yield a green lasing wavelength of 4880 Å. This wavelength was chosen to match the output of the external argon ion laser to be used in the initial amplification experiments.

In 1981 the group reported the successful amplification of the 4880-Å external laser beam in the FEL. They also measured the effect of the FEL on the energy spread and bunch length of the circulating electron beam. Here they found a surprise. One expects the external laser beam (and the intrinsic beam of an FEL oscillator) to have an adverse effect on the energy spread and thus on the bunch lengths. A small energy spread is essential to maintaining tight electron bunches that concentrate the electrons in those parts of the radiation field that decelerate rather than accelerate them. If the energy spread becomes too large, electrons are scattered uniformly at all phases and there would be no net transfer of energy from the beam to the radiation. At low beam currents the group found the expected adverse "laser-induced beam heating." But the surprise came at higher currents, where the energy spread and bunch lengths were actually decreased by the external laser beam passing through the wiggler. In the recent FEL oscillator experiment, this encouraging effect has persisted beyond expectation in the intrinsic laser field of the FEL, contributing to the laser's gain and the stability of the circulating beam.

Laser oscillation. After the completion of the initial amplifier experiments, the superconducting wiggler burned out. "This turned out to be something of a blessing in disguise," Madey told us. This wiggler had not been built with FEL operation in mind. Its loss now impelled the Orsay group to build a new wiggler with permanent magnets in place of the superconducting coils, better tailored to needs of the FEL experiment. But with the installation of mirrors at both ends of the new wiggler, fresh problems arose. The gain of the FEL oscillator proved to be disappointingly low, in part because the stored current density in ACO was a factor of five below initial expectation. The gain was insufficient to make up for the reflectivity losses in the mirrors (seven parts in 10^4 per round trip). Furthermore, the reflectivity of the mirrors was observed to deteriorate severely with time. This was caused by ultraviolet harmonics of the spontaneous synchrotron radiation generated in the wiggler. Similar mirror degradation has presumably been responsible for the failure of the FEL experiment at Novosibirsk's VEPP III storage ring to function as a laser oscillator in the visible.

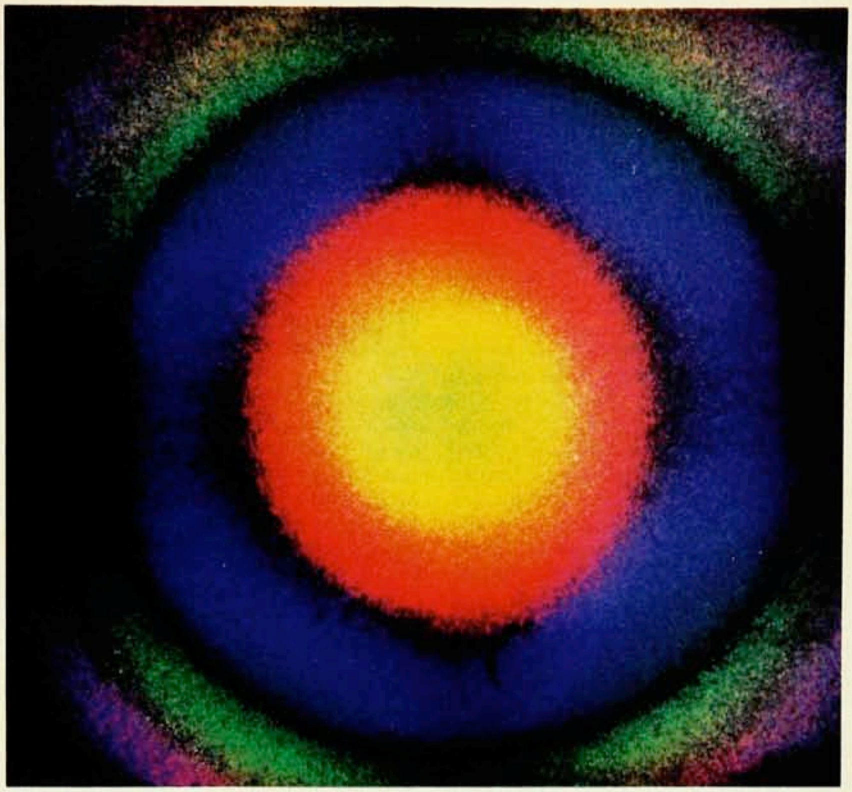
Attempts at LURE to produce mirrors better than the original layered TiO_2–SiO_2 mirrors were unsuccessful. A twofold solution finally did the trick: First of all, the group lowered the beam energy to 160 MeV, reducing the intensity of the offending ultraviolet harmonics to negligible levels. This solution, however, had its costs in terms of stored current in the ring; ACO functions better at higher energies. A further adverse effect on gain resulted from the corresponding reduction of wiggler field intensity required to maintain the lasing frequency at 6500 Å, the wavelength at which the layered-dielectric mirrors are designed to have maximum reflectivity.

The second trick, the modification of the wiggler into an optical klystron, saved the day. It enhanced the gain of the laser by a factor of four to about 1.5×10^{-3}—more than enough to compensate for the losses in the mirrors, which were now no longer suffering ultraviolet degradation. The group converted the wiggler into an optical klystron simply by removing one of its central magnet pole pairs. The double-length central wiggler period thus created serves the function of converting the velocity modulation generated in the first half of the wiggler into a beam density modulation in the downstream half (hence the klystron analogy). The more energetic electrons, experiencing less deflection in the central wiggler period, traverse a shorter path length than their less energetic brethren. The resulting density modulation improves the microbunching of the electrons in the decelerating parts of the radiation field.

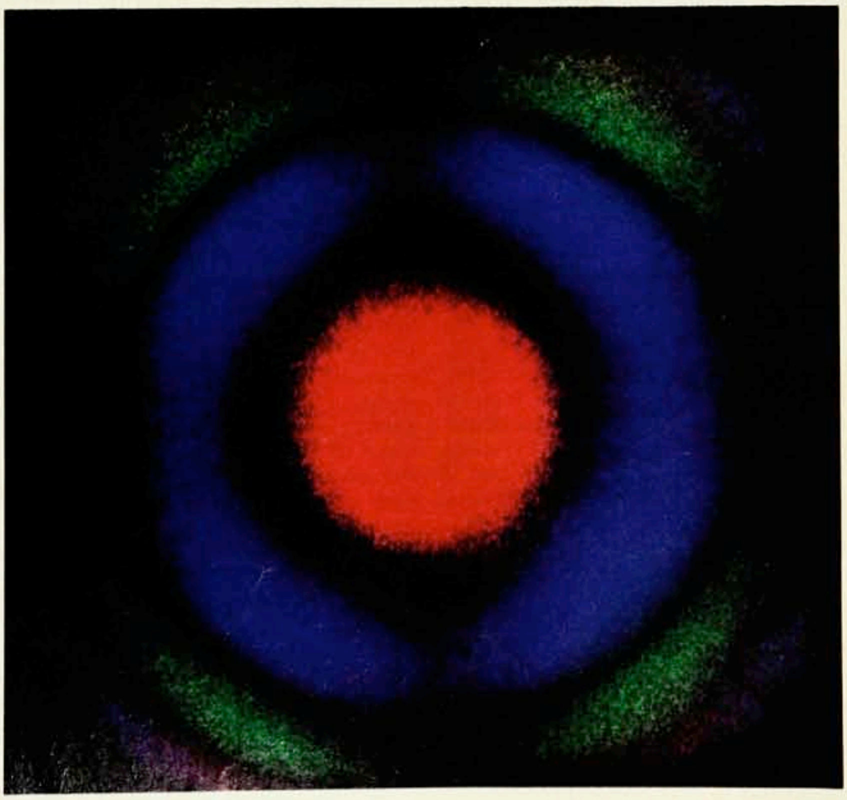
With the optical klystron in place and the beam energy at 160 MeV, laser oscillation was finally observed. As the wiggler field was increased by bringing its pole faces closer together, the colorful pattern of concentric rings indicating incoherent synchrotron harmonic generation in the wiggler suddenly vanished and the intensity of the central red-orange 6500-Å spot increased dramatically by a factor of 10^4. The FEL was operating as a laser oscillator. The laser beam persists for periods of about half an hour, limited only by the beam storage time of the ACO ring.

The average optical power density inside the optical cavity of the Orsay–Stanford FEL oscillator is 50 MW/cm^2, six orders of magnitude higher than the power density in the group's earlier amplifier experiments. "The electrons are really being driven quite hard by the optical field," Madey comments. Despite this high power density of the FEL in the ring, the ACO beam remains stable. The unanticipated laser-induced beam cooling effect—decrease of energy spread and bunch lengths—though not yet well understood, may eventually contribute significantly to the stability of practical storage-ring FELs.

The gain of the FEL oscillator at LURE is now about 10% above lasing



Spontaneous, incoherent synchrotron radiation from the wiggler of the Orsay–Stanford free-electron laser moves from shorter wavelengths (top photo) to longer wavelengths (below) as the magnetic field intensity in the wiggler is increased toward the design value at which laser oscillation will occur. On axis we see the fundamental wavelength, with longer wavelengths emitted at larger off-axis angles. Superposed on this fundamental spectrum is the second-harmonic spectrum, which first becomes visible as the violet ring at larger angle because its central region is in the uv. When the central spot reaches 6500 Å (orange–red), the wavelength at which the mirrors are most reflective, the intensity of the central spot suddenly increases ten-thousand-fold and the surrounding ring pattern vanishes. Coherent laser oscillation has begun.



threshold. A quite general theorem limits the efficiency of an FEL in a storage ring to the fractional energy acceptance of the ring—perhaps 3% in an optimally designed storage ring. The Orsay–Stanford group was gratified that its oscillator efficiency (2.4×10^{-5}) comes close to the limit set by this theorem for the less than optimal ACO ring. The use of optical klystrons also limits the energy acceptance of an FEL and thus its efficiency in a storage ring.

Tapered-wiggler lasers, it is hoped, will eventually operate with efficiencies closer to 20%. But these high-power devices are probably too disruptive for storage ring beams. Restricted to linacs, they may perhaps be limited to infrared applications, though the goal of the rf linac development program by the Math Sciences Northwest–Boeing groups is a tapered wiggler lasing in the visible. Efficiency is of course a much more important issue for the industrial and military uses one has in mind for tapered-wiggler FELs than it is for storage-ring-based visible and ultraviolet FELs. These latter are sought primarily as research tools.

Prospects. In the coming months we can expect a number of other FEL oscillators to become operational. Charles Brau and his colleagues at Los Alamos are in the process of converting its tapered-wiggler amplifier into an oscillator. Claudio Pellegrini's Brookhaven group is building a storage-ring-based uv oscillator. Don Prosnitz and coworkers at Livermore are preparing to apply an alternative linac technology—the ETA and ATA high-current induction linacs—to tapered-wiggler FELs.

Other electron-beam sources under development for infrared FELs are a microtron (a kind of mini-cyclotron) to be used by a group at Bell Labs led by Kumar Patel and Earl Shaw,ε and an electrostatic accelerator employed by Luis Elias and his colleagues at the University of California, Santa Barbara. The Santa Barbara group hopes to establish a user facility for condensed matter studies with its FEL providing far-infrared laser light tunable from 100 microns to 1 mm, with an average power of several kilowatts. The Orsay–Stanford group is planning to use a positron beam in place of electrons in ACO. Positrons remove one source of storage-ring beam instability—the trapping of positively charged residual gas ions by electrons.

Future plans at LURE call for the building of a "super ACO ring," optimized for free-electron lasers. A 1-GeV storage ring under construction at Stanford will house a 20-meter-long wiggler with which Madey's group hopes to achieve FEL oscillation down to 500 Å in the extreme ultraviolet. At Frascati's storage ring, Sergio Tazzari and his colleagues are planning to operate an FEL oscillator in the visible. The gain measurements they have already performed in the amplifier mode have yielded results similar to those achieved at LURE. —BMS

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Second heavy-fermion superconductor

The recent demonstration of superconductivity in uranium beryllide (UBe_{13}) by an ETH–Los Alamos collaboration provides us the second example of an exotic and potentially instructive new class of materials, the "heavy-fermion superconductors." Four years ago, Frank Steglich and his colleagues at Darmstadt and Cologne reported the discovery of the first of these unconventional and somewhat puzzling new superconductors—$CeCu_2Si_2$. The unearthing of UBe_{13} is important not only because it shows that $CeCu_2Si_2$ is not a unique abberation. Until recently, investigations of $CeCu_2Si_2$ have been plagued by the difficulty of fabricating stoichiometrically clean, reproducible samples of this material; different samples were giving distressingly different results. With the advent of UBe_{13}, where one does not have this metallurgical problem, and with new techniques for making crystalline $CeCu_2Si_2$ samples of high quality, one now has two sources of reliable data on the heavy-fermion superconductors.

The superconducting transitions of these two materials—$CeCu_2Si_2$ at 0.65 K and UBe_{13} at 0.85 K—come as a great surprise. The Curie–Weiss increase of their magnetic susceptibilities as they are cooled clearly indicates the strong presence of localized magnetic moments at temperatures above about 10 K. Magnetic interactions are anathema to the usual Cooper-pairing mechanism necessary for superconductivity, because the opposite spins of the two pairing electrons would perceive a magnetic perturbation with opposite signs. Furthermore, both materials exhibit enormous electronic specific heats at low temperatures, indicating the presence of delocalized electrons with effective inertial masses in the lattice two to three orders of magnitude greater than that of a free electron. One would expect such extraordinarily "heavy" electrons to condense to a magnetically ordered or charge-ordered state rather than a superconducting one.

The presence of these heavy fermions is further confirmed by the observation of unprecedentedly high values of the rate of increase of the critical magnetic field with falling temperature at the superconducting transition. It was, in fact, this extraordinarily high value of $-dH_c/dT$ at the critical temperature T_c that led Ernst Bucher and his colleagues at Bell Labs astray in 1974. Having observed a critical-field derivative of about 300 kG/K, they concluded that the superconducting transition they were apparently seeing in UBe_{13} must be due to some filamentary impurity in the sample. Interest in UBe_{13} then subsided until its recent reawakening under the impetus of Hans Ott at the Eidgenossische Technische Hochschule in Zurich.

Cerium and uranium have in common the fact that both possess partially filled inner shells of f (orbital angular momentum of 3) electrons. Cerium is the first of the lanthanides, a sequence of elements characterized by the sequential filling of the inner 4f shell while the further-out 5s, 5p and 6s shells are already occupied with fixed configurations. Uranium is the third of the actinides, the analogous heavier series characterized by sequential filling of the 5f shell. A simpler and more familiar example of this sort of inner shell filling while the outer configuration of valence electrons remains fixed is the series of transition elements such as iron, cobalt and nickel, where the partially filled 3d shell plays a central role in ferromagnetism.

The heavy fermions apparently responsible for superconductivity in $CeCu_2Si_2$ and UBe_{13} are these f electrons. The enormously high electronic specific heats observed in both materials indicate that these f electrons move through the lattice with effective inertial masses as much as a *thousand* times the mass of a free electron. Unlike ordinary conduction band electrons, which move freely through the lattice with effective masses close to the free electron mass, taking almost no notice of each other, these inner-shell f electrons spend most of their time inside the electron cores of the lattice atoms. Thus they experience strong mutual repulsion and they are highly correlated with one another. It is these strong interactions between f electrons that greatly impede their