Matter That Matters

CREATING the stuff of stars—this was the goal of a team of experimental researchers from Lawrence Livermore and Texas A&M University.

Using the Laboratory's electron-beam ion trap (EBIT) as an ion source and a cryogenic Penning ion trap (RETRAP) to capture, confine, and cool the ions, these experimenters produced a form of matter that is the thermodynamic analog of the matter found in white dwarf stars. "This development has exciting astrophysical ramifications," says Dieter Schneider, EBIT program leader. "Understanding the cooling process of white dwarf stars will help us determine their age and the age of the universe."[1]

Making Ions to Order

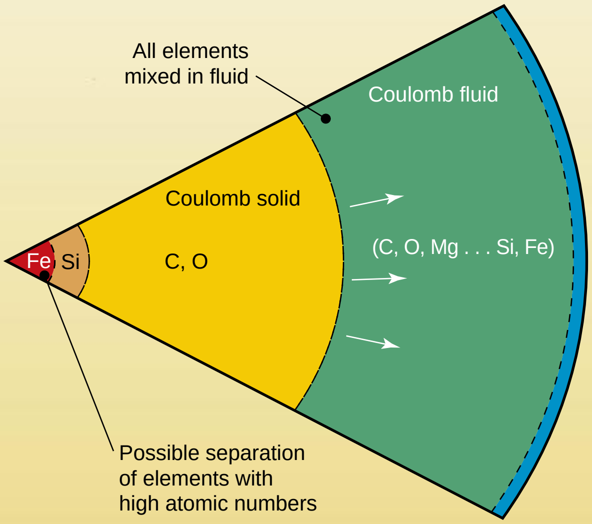
Originally developed and built at Lawrence Livermore by physicists Mort Levine and Ross Marrs in 1985, EBIT uses a tightly focused and energy-tunable electron beam to create and trap highly charged ions. (An ion is an atom or molecule that has become charged by gaining or losing one or more electrons. A completely ionized atom is one stripped of all of its electrons.) Virtually any charge state of any element in the periodic table can be studied using EBIT. It is the only ion source in the world that can create the highest charged ions at rest; other sources able to produce such highly charged ions involve accelerators that increase the velocity of the ions to extremely high energies.

The Livermore EBIT consists of a high-current-density electron beam (up to 5,000 amperes per square centimeter) passing through a series of three drift tubes that hold in place ions of the element being studied. These positively charged ions are confined radially by being attracted to the center of the electron beam and are trapped axially by voltages applied to the end drift tubes. As the electrons in the beam collide with an ion, they strip electrons off the ion until the energy required to remove the next electron is higher than the beam energy.

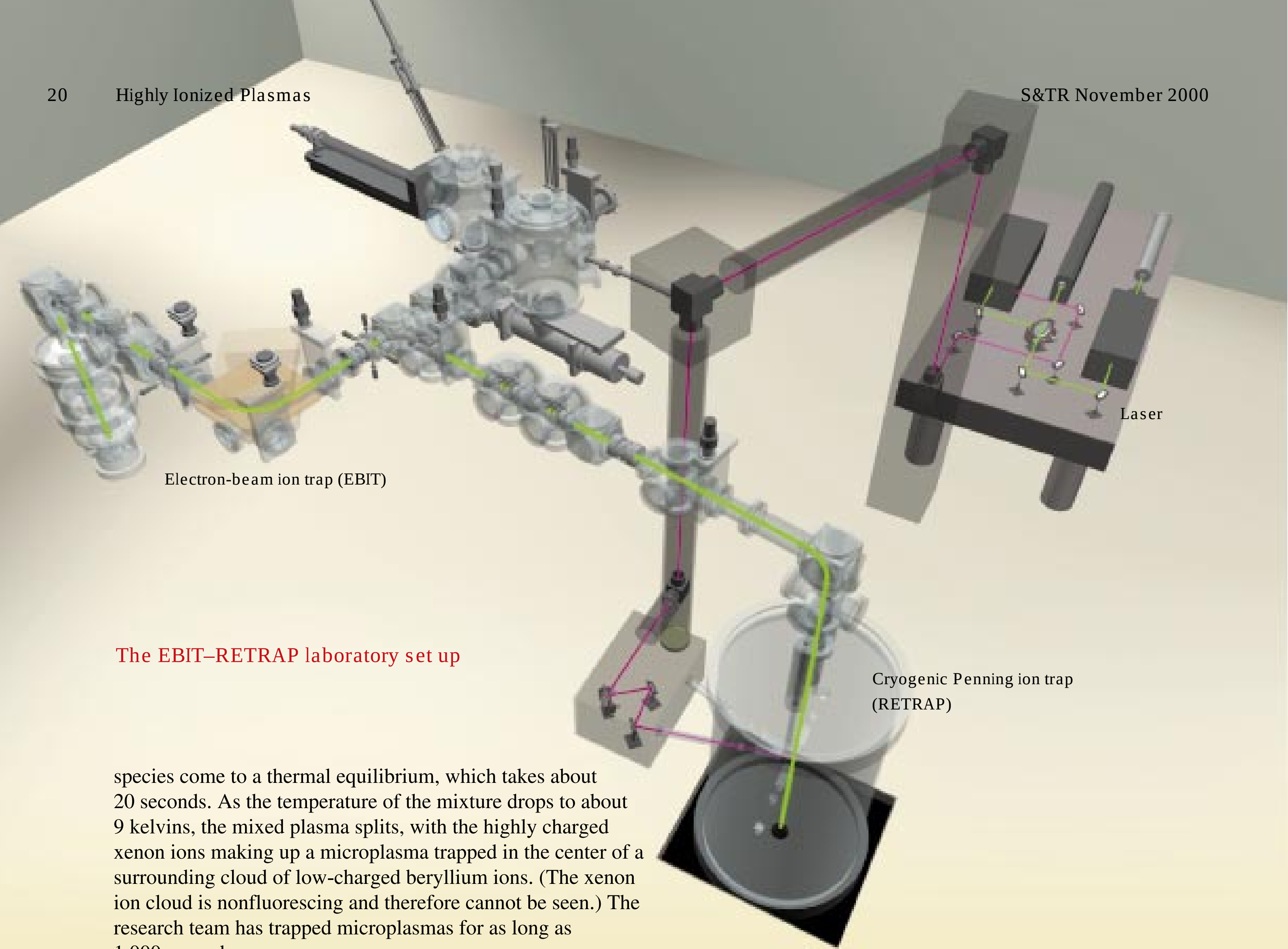
The original EBIT had a peak electron-beam energy of about 30 kiloelectronvolts, enough to make uranium ions with the same number of electrons as neon (U^{82+}). The Super-EBIT can achieve an electron beam energy of 220 kiloelectronvolts, enough to make bare uranium (U^{92+}). Uranium has the highest atomic number among the naturally occurring elements, and therefore, Super-EBIT is sufficiently powerful to serve as the ion source for all of these elements.

Once the highly charged ions are created in EBIT, they are extracted to RETRAP, where they are cooled, stored, and studied. (One of several types of ion traps, the Penning trap uses static electric and magnetic fields to hold the ions.) RETRAP allows researchers to control the temperature and the relative position of the ions. In particular, it allows cooling the ions (reducing their kinetic energy by slowing down their random motion) to the near-zero temperatures needed to create strongly coupled, crystallized plasmas.[2]

The cooling is accomplished in a two-step cooling scheme developed at Lawrence Livermore. (See the figure on p. 21.) First, the cloud of light, singly charged beryllium ions (Be^+) in the ion trap is illuminated with laser beams whose frequency has been selected so that only those ions moving away from the beam absorb the laser light. As the ions reemit the light in a random direction and return to their ground state, they (on average) lose kinetic energy. The process cools the ion cloud to temperatures of a few kelvins. Highly charged xenon ions (Xe^{44+}) are extracted from EBIT and moved to the RETRAP. The beryllium ions, which continue to be cooled by the laser, sympathetically cool the xenon ions, slowing them down. The temperature (energy) of the xenon ions drops until both ion



Structure of the interior of a white dwarf star, showing how the elements are distributed. EBIT–RETRAP recreates the thermodynamic conditions shown in the yellow section, where the ion plasmas crystallize.



The EBIT–RETRAP laboratory set up

species come to a thermal equilibrium, which takes about 20 seconds. As the temperature of the mixture drops to about 9 kelvins, the mixed plasma splits, with the highly charged xenon ions making up a microplasma trapped in the center of a surrounding cloud of low-charged beryllium ions. (The xenon ion cloud is nonfluorescing and therefore cannot be seen.) The research team has trapped microplasmas for as long as 1,000 seconds.

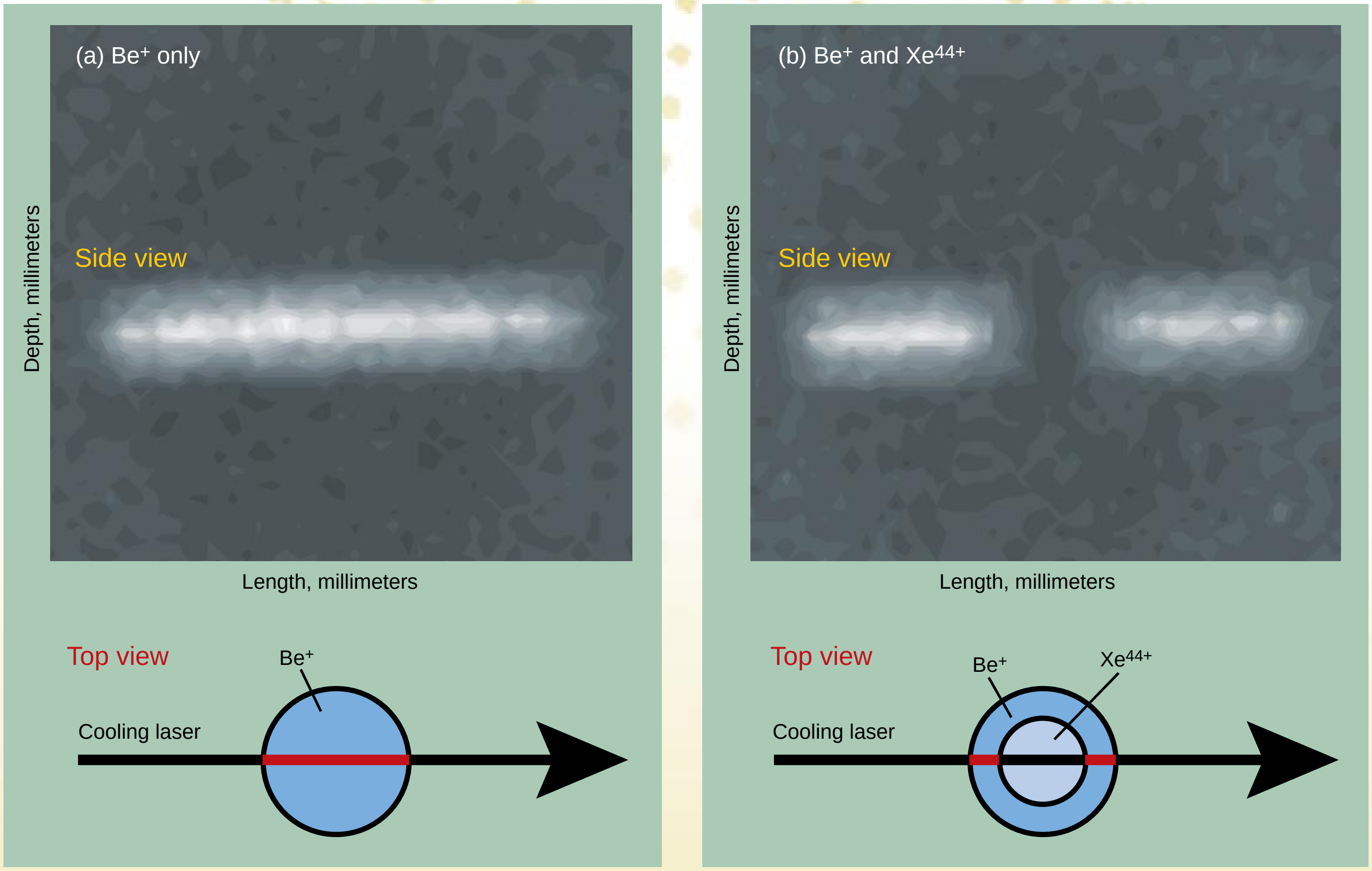
The densities of the microplasmas created with EBIT and RETRAP reach about 100 million (10^8) ions per cubic centimeter, with the distance between the ions being a few micrometers. (Normal, room-temperature liquids and solids have densities of about 10^{23} atoms per cubic centimeter and distances between atoms of a few nanometers.)

Cool and Thin Equals Hot and Dense

At these ultracold temperatures and at certain densities, the microplasmas condense to form an ionic crystal in which the individual ions lock into place relative to each other yet retain their individual identities. “Unlike a noncharged or neutral plasma,” says Schneider, “these highly charged plasmas can exist at thermal equilibrium.”

What’s more, these microplasmas are thermodynamically equivalent to certain exotic high-density plasmas found in white dwarf stars. That is, these two plasmas, at opposite ends of the temperature and density spectrums, have the same thermodynamic properties—for example, specific heat and phase transitions. The reason for this strange parallelism lies in the definition of a single, dimensionless parameter called the Coulomb coupling parameter. This parameter is determined by the density and temperature of the plasma as well as the amount of attraction or repulsion felt by neighboring ions because of their charge (the Coulomb force). Schneider says, “In the EBIT–RETRAP system, we create a strongly coupled, highly charged plasma that crystallizes and has the same Coulomb coupling parameters as those found in the plasmas of white dwarf stars. As long as the parameter is the same, the thermodynamic properties of the plasmas are analogous, even though, in the trap, the ion densities are 20 orders of magnitude and the temperatures 9 orders of magnitude lower than those found in white dwarf stars.”

The extreme conditions in white dwarf stars lead to highly ionized plasmas that are essentially bare nuclei of mostly carbon and oxygen, stripped of all their electrons. The electrons form a uniform background of negative charge, confining the star plasma much as the microplasma is confined by electric and magnetic fields in the RETRAP. Another big plus for researchers who seek to understand these plasmas better is that the EBIT–RETRAP system can be used to create microplasmas consisting of a mix of ion species,



(a) Side view and top-down diagram of a cold (about 9 kelvins) beryllium ion cloud illuminated by a laser beam passing through the center of the cloud. (b) Side view and top-down diagram of the cold beryllium ion cloud displaced radially by a microplasma of highly charged xenon ions, which are chilled by the cold beryllium ions using a sympathetic cooling scheme developed at Livermore. (The xenon ions cannot be seen because they are nonfluorescing.)

just like those in the stars themselves. The system is unique because not only can researchers choose the concentration of different ion species they want in the plasma mix, but they also can control the density and the temperature of the plasma. "This capability exists nowhere else in the world," says Schneider.

Future in the Stars

Studies of these exotic plasmas are helping researchers understand and model the cooling of hot, dense stars and the evolution of our galaxy.

Other intriguing research directions are possible, notes Schneider, including the possibility of creating quantum-computing gates based on ions in crystals stored in traps. A quantum computer could exponentially reduce the time required to complete a complex computation.

—Ann Parker

References

1. Stringfellow, G. S., et al., "Equation of State of the One-Component Plasma Derived from Precision Monte Carlo Calculations," *Physical Review A,* **41**(2), 1105–11 (1990).
2. Steiger, J., et al., "Coulomb Clusters in RETRAP," *AIP Conference Proceedings* (No. 457), Trapped Charged Particles and Fundamental Physics, Asilomar, CA, 31 August–4 September 1998, (American Institute of Physics, 1999), pp. 284–289.

Key Words: Coulomb coupling parameter, cryogenic Penning ion trap (RETRAP), electron-beam ion trap (EBIT), highly ionized plasmas, microplasmas, white dwarf stars.

For further information contact Dieter Schneider (925) 423-5940 (schneider2@llnl.gov).

New Imaging Technique Gets under the Skin . . . Deep

USING a combination of simple optical techniques, plain old white light, and image processing, two Lawrence Livermore researchers and a colleague from the City College of New York (CCNY) have developed a technique for imaging tissue structures—tendons, veins, tumors—deep beneath the skin. The ultimate goal of this research is to dramatically improve the ability to perform minimally invasive cancer detection.

"With a technique called spectral polarization difference imaging [SPDI], we use different wavelengths of light to reach different depths. We also use the polarization properties of the light to help us select the light that penetrates into the tissue and is reflected back out of the tissue as opposed to the light that bounces off the tissue surface," says Livermore physicist Harry Radousky, acting Director of University Relations. "We then image the tissue structures at the different depths, based on how these structures absorb, scatter, and depolarize light. This technique, combined with fiber optics, charge-coupled-device cameras, and image enhancement calculations, allows us to image up to 1.5 centimeters inside tissue, far deeper than the millimeter depths managed by other existing optical techniques."

The basic research to develop this technique was funded by the Department of Energy through one of its centers of excellence in laser medicine—the DOE Center for Laser Imaging and Cancer Diagnostics directed by Robert Alfano, M.D., at CCNY. A branch of this center is hosted at the Laboratory within the Materials Research Institute.

Optical Trickery

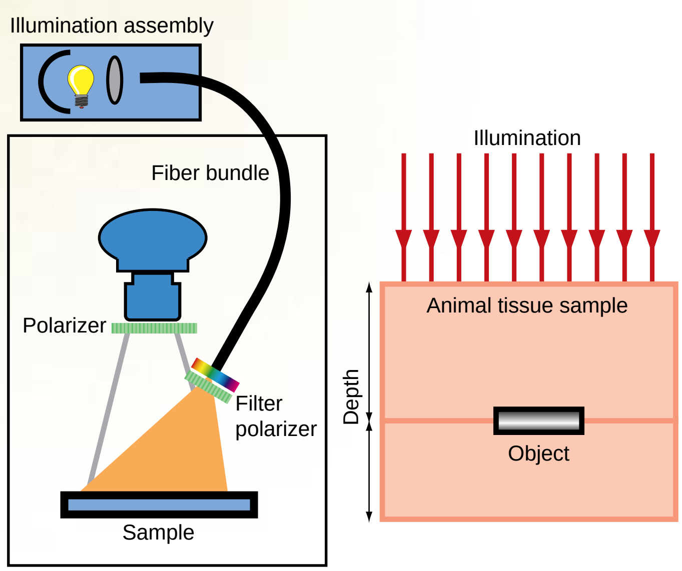
The SPDI system developed by the Livermore–CCNY team depends on simple and inexpensive instrumentation, including a white light source, fiber optics, a filter, two polarizers, and a camera lens coupled to a charge-coupled device (CCD).

The low-power, white-light source is coupled to a fiber-optics bundle that delivers the light to a filter. This filter selects the desired wavelength of light. With this setup, the research team conducted experiments using different bandwidths at the visible to near-infrared portion of the white-light spectrum.

"Longer wavelengths penetrate tissue more effectively," explains physicist Stavros Demos. "Think of what you see when you hold an ordinary white-light flashlight to your hand. The light that shines through your hand is red, which is at the longer wavelength end of the visible spectrum; the other wavelengths in the visible spectrum are scattered and absorbed within the tissue. For even longer wavelengths—those in the near-infrared spectral region—scattering and absorption of the photons is even further reduced."

The light that passes through the filter then passes through a polarizer. The light that finally hits the tissue sample is thus not only of a given wavelength but also of a selected polarization. As photons penetrate the tissue, they interact with various tissue structures that may have optical properties different from those of the host tissue. Finally, some of the injected photons emerge from the tissue in the backscattering direction. The intensity of the backscattered light depends on the optical characteristics of the tissue at the sample's surface as well as below its surface at a particular location.

Light that reflects from the surface (known as a spectral reflection) is polarized and can be removed with a second polarizer set to reject this light. This phenomenon is similar to the way sunglasses work to remove the polarized glare from surfaces, such as the water surface in a swimming pool. The light that backscatters from somewhere below the surface of the tissue is depolarized and consequently can pass through this second polarizer. This remaining light passes through a 50-millimeter camera lens, which is coupled to a CCD detector that captures the image in an exposure of a few milliseconds.

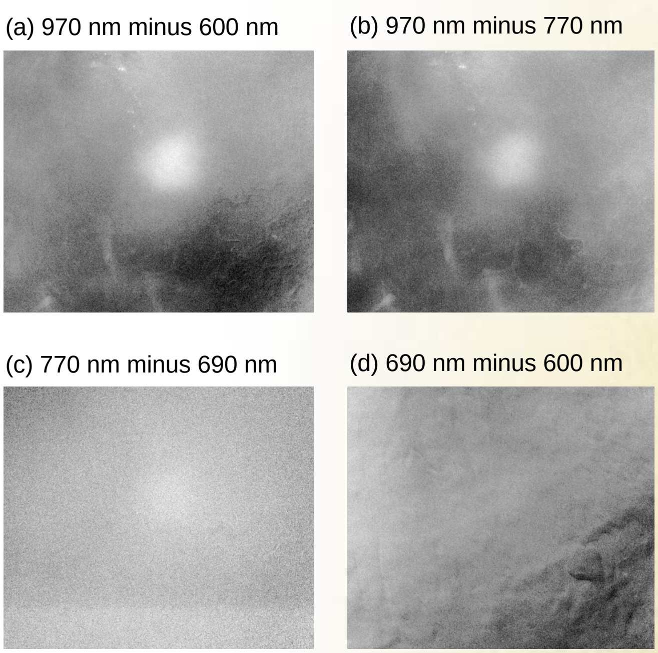


Schematic diagram of the spectral polarization difference imaging setup.

First Chicken, Then Beef

To prove their technique, the researchers attempted to image a small ceramic disc buried in a chicken breast (tissue) bought from a local supermarket. The disc—about the size of a small slice of pencil eraser (4 millimeters in diameter and 1 millimeter thick)—was placed on top of a 1-centimeter-thick slab of chicken breast and topped with an equally thick slab. This "chicken sandwich" was placed between two glass plates and slightly compressed to a uniform thickness.

Four images were recorded using light at 600, 690, 770, and 970 nanometers. The exposure time of the CCD camera was adjusted so the intensity of each image at an arbitrary point was about the same. The researchers took pairs of these digital images—one from a longer wavelength that reaches the disc, the other from a shorter wavelength—and digitally subtracted one from the other. By combining this subtraction technique with the elimination of specular reflections, researchers can remove the image information from the outer tissue layers. In the resulting images, structures deep within the tissue are more visible than they would be if the images were made with light at a single wavelength. "It's like looking for stars in the daylight," explains Radousky. "By 'subtracting' light from the sun, you're able to see the stars."



Four final images of an object 1 centimeter below the surface produced by the spectral polarization difference imaging technique. The images were produced by digitally subtracting images derived from photons at different illumination wavelengths (in nanometers, nm) that reach different depths within the tissue. Using the right combination of wavelengths of light is important to the clarity of the resulting image. The wavelength combinations in (a) and (b) allow the subsurface object to be seen with better contrast than in (c) and (d).

"Once we proved the basic technique," adds Demos, "we imaged the tendons in bovine tissue as well as the veins in the arm of one of the researchers."

More Details Coming

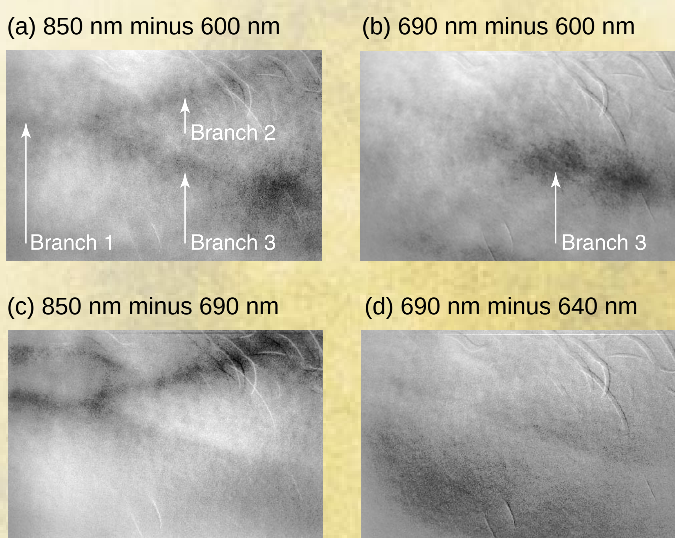
All in all, the researchers say, SPDI looks to be a promising technique that, once refined and developed into a system, could help the medical community in its fight against cancer.

The next step in this DOE-sponsored project, notes Radousky, is to develop mathematical models that will reconstruct the object in more detail and also provide the object's precise size, something that isn't yet possible. "We're going to work to enhance the images and get as much information out of them as possible. That, of course, is the goal of any cancer-detection system used in a clinical setting—to get as much information about the tumor to the clinicians as possible, in real-time."

—Ann Parker

Key Words: cancer detection, Center for Laser Imaging and Cancer Diagnostics, Materials Research Institute, spectral polarization difference imaging (SPDI).

For more information contact Stavros Demos (925) 423-3388 (demos1@llnl.gov).



Four subsurface views of the arm of a human male with well-developed muscle structure and deep veins. The different nanometer-wavelength combinations reveal different details of the subsurface. For example, (a) the image created by subtracting the 600-nanometer (nm) wavelength from the 850-nm wavelength reveals three vein branches, while (b) the 690-nm minus 600-nm subtraction shows only one vein branch, which is closer to the surface than the other two.