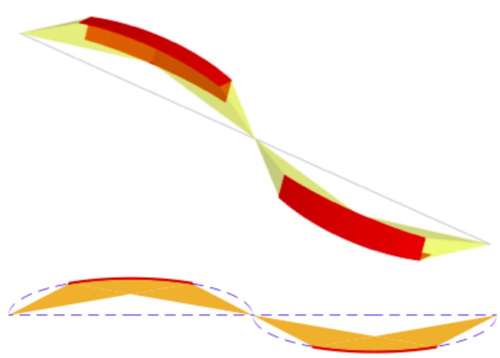
Estia, A Truly Focusing Reflectometer

NOV 10, 2014

Reflections on previous research focus the future of neutron optics for large-scale facilities in Europe.

LUND, COPENHAGEN and VILLIGEN — The European Spallation Source (ESS) will produce neutrons in quantities estimated at 100 times greater than existing sources. This brightness, or flux, together with the long-pulse structure of the beam and real-world sample environments present a distinct challenge to instrument scientists: how to guide the neutrons precisely and in quantities optimized for the sample type and its environment. Too many neutrons in the wrong places and the result is over-exposure; too few in the right sample area and the data is insufficient.

To meet the challenge, the Swiss-Danish Instrument Consortium, comprised of Dr. Jochen Stahn's team at the Paul Scherrer Institut (PSI) in Switzerland and Dr. Marité Cardenas' team at the University of Copenhagen (KU), have called on the gods: Estia, the hearth and focal point for both the family and the house itself, and Selene, the moon incarnate. Estia, or Εστία, is a focusing reflectometer designed for ESS that specializes in measuring small samples. Selene is its guide.



Graphic representation of the Selene guide concept. "For neutrons, the lens has to be replaced by a reflecting device, here a planar-elliptic mirror. Like all focusing optical devices this suffers from aberration, which is largest in this case for reflections close to the focal points. Avoidance of these regions and compensation of the coma aberration by a second, identical reflector results in the optical path as sketched on the right for the vertical plane (red: reflectors, gold: beam). This is applied also in the horizontal plane..."
-Estia instrument proposal

'The neutron guide for Estia is truly focusing," says Stahn. 'It acts like a burning glass in light optics." That is, it takes a divergent light beam, like the sun's rays, and focuses it onto a designated area. A neutron beam, however, is not focused with lenses, but with mirrors. To create the guide, Stahn paired two elliptically shaped reflectors in opposite orientations—one pair situated horizontally and the other vertically. As the neutron beam passes through the mirrored guides, each reflector normalizes the inherent optical aberrations produced by the other and directs the focused beam to the sample. Adjustments to the guide allow for unusually precise hand tuning of the neutron beam's intensity and focal area. This is the Selene guide.

Small samples, giant leap

The focusing optics of Estia is an entirely novel concept among neutron instruments in present-day operation. By allowing the user to easily control both the beam's footprint and its divergence, the Selene guide gives Estia the tool it needs to exploit the unique brightness of ESS. '[The Estia instrument] uses an innovative guide concept—based on optics already introduced for x-rays, but new for neutron beamlines—which will help answer many academic questions and make possible new industrial applications," says Associate Professor Beate Klösgen from the University of Southern Denmark, a consulting scientist on the instrument team.

Neutron reflectometry has a large European user community, and it is expected that ESS will build two or three reflectometers as part of its instrument suite. The technique is used to gather information about the density, thickness, roughness, and magnetization of a thin film surface when the intensity of neutrons reflected off the material is measured as a function of the incidence angle. Estia will outperform other neutron reflectometers with its ability to finely probe very small samples of biological membranes, curved or bent surfaces, and to image the magnetic profile of thin films—such as surface coatings—at an atomic level.

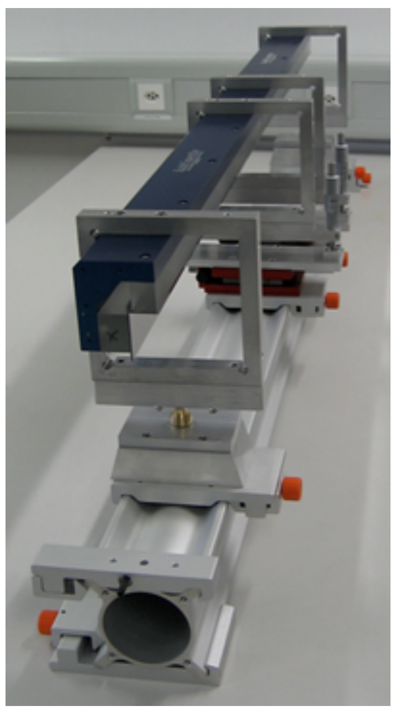
'Any reflectometer constructed at ESS would be expected to improve performance over existing instruments by at least an order of magnitude," says Dr. Robert Dalgliesh, instrument scientist at ISIS in the UK, and chair of the ESS Scientific and Technical Advisory Panel (STAP) for reflectometry. 'The unique Estia concept was recommended for construction by the STAP because it goes further than this. The design makes use of truly focusing neutron optics, which will provide performance gains of more than two orders of magnitude for samples smaller than one square centimeter. This represents a huge step forward for neutron reflectometry as many samples are currently artificially manufactured at sizes larger than one square centimeter because of the limited flux available on existing instruments."

Two are better than one: Selene and Estia, Villigen and Copenhagen

The idea for the focusing reflectometer was born in the PSI laboratory. While investigating add-on functionality for AMOR, his reflectometer at PSI, Stahn turned to a paper by Dr. Frédéric Ott of Laboratoire Léon Brillouin in France.

'He suggested to use an elliptic reflector with a laterally graded multilayer coating for energy-disperse reflectometry, using the detector for angular resolution, rather than an initial slit," explains Stahn. Taking his cue from this concept, Stahn modified it to accommodate his needs for instrument design. Having based his calculations on a theoretical source size, and discovering this workable source was far too small for real-world beam sizes, Stahn's design began to falter late in its development. Scaled up to the size of an ESS beam line, the optical aberrations would dominate the image. Stahn's breakthrough moment came while taking a head-clearing bike ride: use two elliptic reflectors rather than one, a well-established focusing principle in light-based optics.

The Selene guide became the key element for more than one instrument proposal being developed for ESS. While Stahn's group was designing its reflectometer optimized for small magnetic samples, Cardenas, Klösgen, and research assistant Ursula Bengaard Hansen, were developing a complementary reflectometer concept in Copenhagen. It was also dependent on Stahn's Selene guide concept, and the two teams had been exchanging information on their projects from the beginning. Eventually, the two pooled their research and manpower in support of Stahn's concept and the Estia proposal.



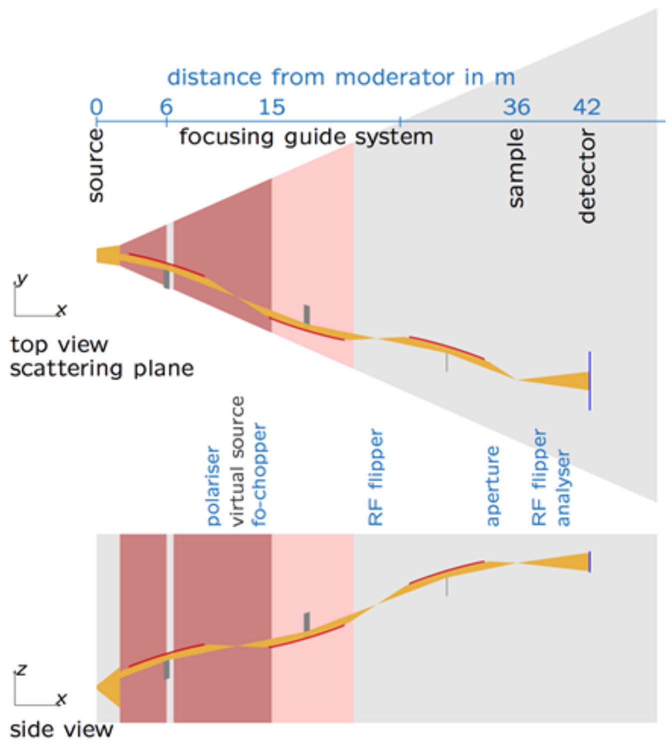
The Selene guide on supports.

Time and money

The high-precision Selene guide maintains constant resolution on a sample without the need for pulse shaping choppers. It allows scientists to tune the brightness of the source beam, preventing over-illumination of the sample and strong coma aberration (similar to optical distortion in a camera lens), which causes poor focus in existing neutron guides.

The performance gain over a similar reflectometer at a continuous source facility, assuming the same average power, is a factor of 30.

'Unlike many other guides, the geometry and performance of the Selene guide can be calculated with a quite high accuracy by hand. This allows one to analyze problems or to design components, like a polarizer, in an analytic way. Geometry, beam, and expected performance are clear," says Stahn. 'I am still often surprised by some features of Estia. A good example is the alignment of the sample. On normal reflectometers one often spends up to hours to 'find' the sample. Especially the angular accuracy has to be very good—below 1/100th of a degree. In contrast, an initial misalignment of the sample on Estia by up to one degree will still lead to a signal on the detector, allowing one to quickly discover the error."



Layout schematic of the Estia instrument.

Samples must often be kept small in reflectometry experiments due to time restrictions and the complexity of preparing materials such as single crystals and thin films grown by pulsed laser deposition. Cost is another factor, for example, to procure isotopes necessary to study slow diffusion processes in solids or carry out selective deuteration, a contrast variation technique for labeling groups in molecules. Estia will greatly increase efficiency relative to these constraints.

The application of data resulting from improved reflectometry methods is expected to improve the design and optimization of materials used in medical implants and a wide variety of devices for sensor technology, energy and data storage, and electronics. Better understanding of the basic nano-scale structure of small samples will allow for breakthroughs in drug delivery systems and more efficient solar cell and display screen technologies.

###