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HOTLINE

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X-ray Crystal Spectrometer Makes Debut at C-Mod

New Technique a Major Advance for ITER

By Anthony R. De Meo

A PPPL-MIT collaboration on the Alcator C-Mod machine has resulted in the demonstration of a greatly improved X-ray crystal spectrometer for application to ITER and fusion reactors. Alcator C-Mod is a fusion experiment at the MIT Plasma Science and Fusion Center. Experiments conducted by a PPPL-MIT team in April mark the beginning of a new era in the ability of such devices to determine radial profiles of the ion temperature and the rotational velocity of high temperature plasmas without the need for diagnostic beams. Their success will benefit substantially ITER and other advanced fusion energy systems.

X-ray crystal spectrometers measure X-rays emitted by plasma impurities when these foreign ions collide with the plasma. Remarkably this radiation shows, with exquisite detail, the temperature and rotation of the plasma. While spectroscopy in the visible range has been used for years, X-ray spectroscopy has been difficult to develop because of the lack of mirrors, lenses, and fiber bundles

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From left are MIT's Alex Ince-Cushman, PPPL's Ken Hill and Manfred Bitter, MIT's John Rice, and Christian Broennimann of the Paul Scherrer Institute in Switzerland.

Granstedt Wins Stix Prize

Prize Joins the Past, Present, and Future of Plasma Physics

Erik Granstedt at the Eiffel Tower.

By Patti Wieser

Princeton University graduate student Erik Granstedt was among 78 international students attending the first ITER Summer School, thanks to a fund created in memory of plasma physics giant Tom Stix.

Granstedt, winner of the 2007 Thomas H. Stix '54 Plasma Physics Prize, used the award to participate in the week-long summer school, "Turbulent Transport in Fusion Plasmas." The school was held in Aix-en-Provence, France: about an hour from Cadarache, the future site of ITER.

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Spectroscopy

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— which are available for optical spectroscopy but not for X-ray spectroscopy.

Due to the large size of crystal spectrometers and the precious real estate around major tokamaks, typically only one such instrument has been installed, usually with a central sightline through the plasma to measure the ion temperature and rotation speed at the plasma center. TFTR, a tokamak at PPPL that operated from 1982 to 1997, and Alcator C-Mod managed to install multiple spectrometers that provided up to five sightlines through the plasma. Information on the ion temperature profile obtained from those measurements was inadequate for detailed comparisons with theoretical predictions of plasma transport from modern computer codes.

With the mission of overcoming these limitations, PPPL physicists Manfred Bitter and Ken Hill initiated work on the new spectrometer several years ago. The X-ray imaging crystal spectrometer, which has now been installed on Alcator C-Mod, is based on a new concept. The new device uses spherically-bent quartz crystal to separate the frequencies of X-ray light emanating from the plasma. A 150-micron-thick slice is cut from 50-mm-diameter cylindrically-shaped quartz crystal. After polishing on both sides, the circular quartz disk is placed on a precisely machined spherically-shaped concave surface, much like that of a reflecting telescope. The surfaces stick together like two glass plates. Molecular forces hold the crystal — without glue — on the substrate.

The resulting spherically-bent crystal serves as a diffraction grating. When X-ray light strikes the surface of the crystal, it is broken up into its constituent frequencies much the same way white light passing through a prism is separated into the colors of the spectrum. The imaging properties of the spherically-bent crystal permit physicists to observe simultaneously X-ray spectra from multiple sightlines through the plasma and to obtain radial profiles of the ion temperature and plasma rotation velocity from these spectral data.

The development effort has continued a long-standing and successful collaboration between PPPL researchers and the Alcator C-Mod team. "Ken and I worked very closely with C-Mod's John Rice and his graduate student, Alex Ince-Cushman, who has made very essential contributions to the design, testing, and installation of the spectrometer," said Manfred Bitter.

With only one sightline available, physicists needed only a one-dimensional detector. With the new devices, two-dimensional detectors are needed to image the whole plasma. When the new spectrometer was ready for proof-of-principle testing in 2003, the team was able to obtain a multi-wire proportional detector, built for use on KSTAR, from Sang Gon Lee of the Korean Basic Sciences Institute. This device did not have the count rate capability required for the new spectrometer. Nevertheless, such a detector was used to demonstrate successfully the fundamental principles of the new crystal spectrometer, first on NSTX, and later on the Alcator C-Mod, thanks to the assistance of MIT's John Rice and Earl Marmar, who made a horizontal port available on C-Mod.

Fortunately, in 2005 while visiting Europe, Bitter heard about an advanced two-dimensional X-ray detector, PILATUS II, in use at a synchrotron radiation facility in Switzerland. The only drawback seemed to be the cost of each unit: $80,000. At the time, Bitter did not have sufficient funds to purchase one, so he tactfully arranged a collaboration with Christian Broennimann and Eric Eikenberry of the Paul Scherrer Institute in Switzerland.

Subsequently a PILATUS II detector was tested on C-Mod in May 2006. The results were so good that everyone agreed that the PILATUS II detectors were ideal to fully exploit the potential of the spectrometer. As Bitter noted, "It's a wonder of modern electronics, since each tiny (0.172-mm x 0.172-mm) picture element or 'pixel' of this detector includes a pulse-shaping amplifier, comparator, and counter, so that you can do single photon counting. And the whole thing works at room temperature. You don't have to cool it off." PPPL's Steve Scott, currently managing the PPPL-MIT C-Mod collaboration, added, "Currently multi-wire proportional counters have a count rate of 400,000 counts per second. The PILATUS II can count up to 10^{11} photons per second. That's more than five orders of magnitude improvement." Bitter and his colleagues expect other detectors currently under development to also be available for the new X-ray crystal spectrometer. These will be of special interest for ITER.

With $500,000 in costs for the new X-ray crystal spectrometer shared between PPPL and MIT, the team was able to proceed with the first experiments on C-Mod

Hotline

Editor/Writer: Patti Wieser **Graphic Artist:** Greg Czechowicz
Photographer: Elle Starkman **Layout:** Patti Wieser and Greg Czechowicz

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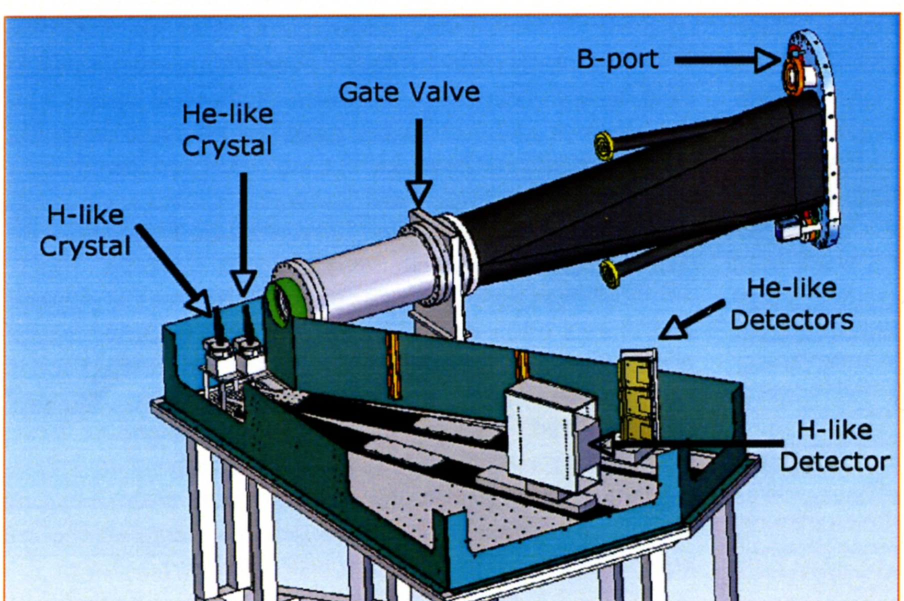
in April of this year. The new spectrometer can look at the entire 72-cm height of the plasma with at least 150 sightlines. The system consists of two spherically-bent crystals and four PILATUS II detector modules and is considered a prototype for the crystal spectrometers that will be used on ITER. The dimensions and layout of the ITER spectrometers will be very similar to those of the new instrument on C-Mod.

In the C-Mod experiments, physicists deliberately inject argon atoms into the plasma. At sufficiently high temperatures, 16 of argon's 18 electrons will be stripped from each atom. Physicists call this "helium-like" argon, because like a helium atom, the argon ion has two electrons. But the two electrons are in a field of 18 protons, not just two protons as in ordinary helium. This results in a helium-like spectrum shifted into the X-ray region. Ordinary helium ions would emit visible light. When all but one electron is taken from the argon, a "hydrogen-like" X-ray spectrum results. With its two crystals, the new spectrometer can measure spectra from helium-like and hydrogen-like species.

The entire plasma actually spins in the toroidal direction, i.e., the "long way" around the donut. If the plasma is spinning toward the observer, the frequency of the X-rays emitted by the argon will be higher than those from a stationary plasma. If the plasma is spinning away from the detector, the frequencies will be lower. This "Doppler Shift" is the same phenomena involved in the change of the pitch of a train whistle heard when the train passes a station. Steve Scott said, "If all the ions were moving toward you, you would see a narrow spectrum shifted in one direction. If they are all moving away from you, it's shifted in the other direction. If the ions are moving and have temperature, the line is shifted and broadened. By the shift you get the rotation. By the broadening you get the temperature — two measurements for the price of one."



X-ray Crystal Spectrometer layout

Ideal for ITER

Charge-exchange Recombination Spectroscopy, CHERS, has been the standard method for determining plasma temperature. It has been used extensively on NSTX, TFTR and earlier tokamaks. CHERS is a beam-based system that takes advantage of the widespread carbon impurity in magnetically confined plasmas. Carbon enters the plasma from the wall of the vacuum vessel. As Bitter explained, "Carbon is totally ionized in the plasma and therefore cannot emit any light. However, if a hydrogen neutral-beam is injected into the plasma, the electron of the hydrogen atom is captured by the fully stripped carbon ion, and it cascades down in the carbon atom and emits (visible) light that can be used for ion temperature measurements, with better spatial resolution than that available with the older X-ray spectrometers. However, we can only do the CHERS measurement along the beam-line and the injection of the beam affects the rotation of the plasma."

But an even more serious problem looms for larger experiments such as ITER. Current CHERS diagnostics use beams with energies in the range of 100 KeV, which is ideal for producing photons in a charge-exchange system. But researchers predict that ITER and other future devices will require 1000-KeV beams to allow adequate penetration into their larger plasmas. "Without Manfred and Ken's perseverance in developing the new X-ray crystal spectrometer, we would have to rely on difficult and limited beam-based measurements on ITER. Their innovation is ideally suited for larger, more advanced systems," said Raffi Nazikian, Deputy Head of PPPL's Off-site Research Department.

Bitter and Hill noted the importance of the continued support they receive from the DOE Office of Fusion Energy Sciences. Bitter said, "Darlene Markovich was instrumental in providing $200,000 each year since 2002. This funding was vital for our project because we would not have been able to accomplish anything without it." They also expressed appreciation for the technical and financial assistance provided by Earl Marmar and Rice at C-Mod and from the PPPL-MIT C-Mod Collaboration managed by Steve Scott and Randy Wilson. ●

PPPL Summer Program Empowers Next Generation of Plasma Scientists

Story by Chad Boutin • Photos by Denise Applewhite

The future of nuclear fusion and its promise of limitless, clean energy has arrived at PPPL in the form of 28 budding scientists, many of them still in their teens.

This contingent of top-notch university and high school students from across the country has gathered for a summer of intensive lab work in plasma physics, the field that could someday provide a way to create power the way the sun does — by pressing two uncommon forms of hydrogen together until they combine to form helium atoms, releasing a burst of energy in the process. Fusion energy, which does not produce greenhouse gases, has the potential to help mitigate global warming.

Because a practical fusion reactor may still be decades away, the current generation of fusion experts is already preparing to pass their nuclear torch on to the next, and the lab's research internship program aims to provide a smooth handoff.

"As a lab, just as at the University, we want to train the next generation of scientists," said Andrew Zwicker, head of the Laboratory's science education program. "The point is to give them a real lab experience, with nothing canned, from the initial research to presenting the results at a national conference. We want to give them the most hands-on training we possibly can."

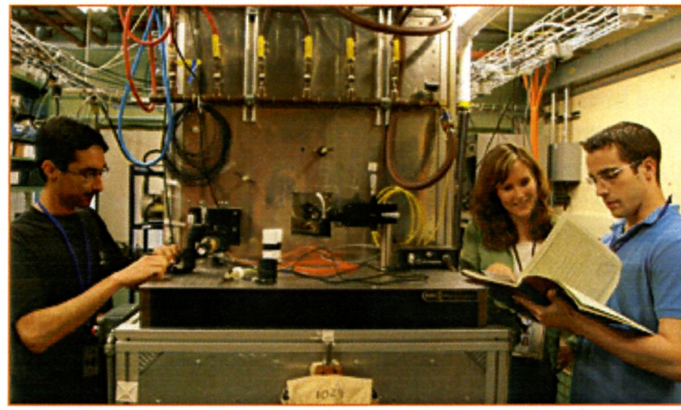
Providing this experience requires the joint commitment of a score of lab scientists, who mentor the students; Princeton University, which provides room and board; and the U.S. Department of Energy, which funds the internship program. This marks the 16th year that student groups have come to the Lab for summer training, which Zwicker said is crucial to the future of the field.

"We track our students for up to eight years after they finish the program, and it turns out it makes a big difference in their career choices," he said. "We find that if we don't expose bright students to plasma physics when they are getting started, we lose them to other fields."

The university students arrived first for a week-long intensive introduction to the physics of plasmas. Even for physics majors, the 25-hour course is often their first exposure to the substances' inner workings.

"Undergraduate physics majors don't get plasma physics as a rule," Zwicker said. "So we give them a crash course in everything from the beginning to the most advanced topics. Then they have the theoretical background to work here for the summer."

A plasma is simply a gas that has been heated to such high temperature that electrons whirling about each of its atoms escape their orbits, leaving behind positively-charged



Abbas Haider (left), a senior at South Brunswick High School, works with his lab partner, David Newby, a senior at Drew University, under the supervision of their mentor, PPPL Collaborator Jill Foley. Through close one-on-one interaction with their mentors, program participants rapidly gain insight into the fundamentals of plasma physics.

ions. This excited cloud has such unusual properties — such as the abilities to conduct electricity and to respond to magnetic fields — that scientists consider plasma to be a state of matter distinct from solids, liquids and gases.

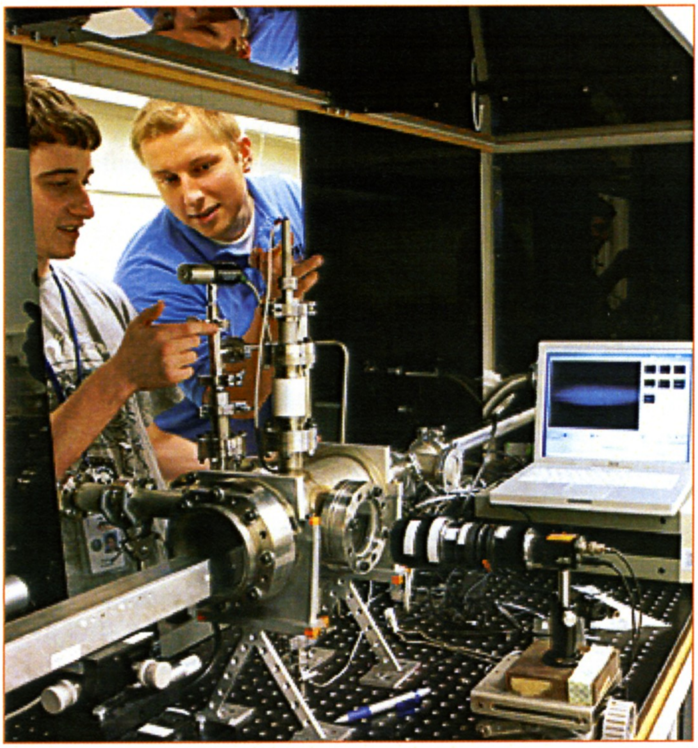
It is within pressurized plasmas in the interior of the sun that natural nuclear fusion takes place, and recreating these distinctly un-Earthlike conditions will be necessary to create a working reactor. But plasmas are not so exotic as to be unrecognizable to the Earthbound observer: They form candle flames, they fill the interiors of fluorescent light bulbs, and they are mixed with the dust in the tails of comets.

In fact, though the Lab's overarching mission is to develop a working fusion reactor, the need to understand the behavior of these ionized gases has led some scientists to explore plasma behavior in fields such as astrophysics. Mike Hvasta, a college senior who Zwicker is mentoring, said he was excited to spend his summer in Princeton with a dusty plasma chamber.

"Most of the universe is either empty void or plasma, and there's often dust there too," said Hvasta, a physics major at the College of New Jersey. "Learning about dusty plasmas helps us understand things like the rings of Saturn."

Hvasta, who intends to go on for an advanced degree in physics, said he grows more comfortable with his career choice as he spends time with the Lab's state-of-the-art equipment.

"I'm having a great time with the responsibility Andrew has given me," he said. "Five days after I got



Ruslan Fridman (left), a senior at Livingston High School, works on a dusty plasma chamber with his research partner, Mike Hvasta, a senior at the College of New Jersey. Dusty plasmas, which form the tails of comets, are a subject of interest to astronomers, and the students will have an opportunity to present their findings to the physics community at a scientific conference later this year.

here, he turned me loose and let me fix a key component of a machine that we use for experiments. It's rewarding knowing what we're doing will contribute to the scientific body of knowledge, and tinkering with these machines helps me to really learn about them."

Two weeks after the university students arrived, an additional 10 high schoolers joined them in the Lab. Ruslan Fridman, Hvasta's Lab partner, said that even after four days at the Lab, he could tell the experience would be unlike anything he had done in high school.

"In school, you have a project and the teacher knows what's supposed to happen," said Fridman, now entering his senior year at New Jersey's Livingston High School. "Here, we have absolutely no idea what's supposed to happen, and we have to figure it out. Things happen all the time that defy logic."

Fridman and Hvasta will spend the next eight weeks figuring out the behavior of dusty plasma so they can make an original contribution to physics. They will have a chance to present their findings in November at the national conference of the American Physical Society, to be held this year in Orlando, Fla.

Kelly Greenland, who just finished her senior year at Loch Haven University of Pennsylvania, said she remains undecided about the specific topic she will pursue in graduate school, but that the summer program was giving her more perspective on her options.

"It's definitely helping," said Greenland, a physics major. "I love the hands-on aspect of my work here but I'm also very into theory, so I hope between this and graduate school it will help me decide which route I want to take."

Zwicker said the research process is rigorous, but the numbers show it gives students the background they need to continue in the field.

"Of the students who finish the summer program, about two-thirds go on to get an advanced degree in physics, math or engineering, and a fifth of those specialize in plasma physics," he said. "A third of those specialists over the past four years have been women, which is a fact we're particularly proud of, especially because in physics graduate programs overall, women constitute only about half that amount."

The program has also seen its share of students return to Princeton for further schooling. Joshua Kallman, who finished the summer program in 2005, is now in his second year of graduate school in plasma physics.

"I wasn't sure at that point what subfield of physics I wanted to study, and my time here inspired me to choose plasma physics as my career path," Kallman said. "I like the connection to fusion, to creating power. But it's also because I liked the work. I had a really great mentor, and the experience has led me to a great Lab here at the Forrestal Campus too."

Kallman is currently working with Leonid Zakharov, a principal research physicist at the Laboratory, on issues concerning plasma when it is at equilibrium, and is growing interested in developing the lithium walls that might form a blanket to shield the reactor from hot plasma. He said he might like the opportunity to continue these investigations in his professional career.

"A lot of this sort of research goes on right here at the Laboratory, and they have a machine here I'd like to work on," Kallman said. "I could definitely see myself here." ●

PPPL's research internship program draws top-notch university and high school students from across the country, including Kelly Greenland (foreground) and Lauren Chilton. Greenland just finished her senior year at Loch Haven University of Pennsylvania, and Chilton is entering her senior year at Bernards High School. The summer program is designed to train the next generation of plasma physicists.

Granstedt

Continued from page 1

ITER (Latin for "the way") is a large international fusion experiment aimed at demonstrating the scientific and technological feasibility of fusion energy. Seven partners, including the U.S., are participating in the project, with operations expected to begin in 2016.

"We listened to lecturers from all over the world whose talks focused on science issues related to ITER," Granstedt said, adding that PPPL's Roscoe White and T.S. Hahm were among 21 presenters.

He said the students got a chance to talk to the school's speakers during coffee breaks and at a dinner reception. One day they took a side trip to Tore Supra, the French tokamak at Cadarache. They also visited lavender fields and found out about the distillation process for lavender oil.

Although the talks were in English, novice European visitor Granstedt benefited from striking up friendships with fellow students. "On the first day I arrived, I met a student from Russia who helped me get my bearings because he spoke some French," he said.

Once the school concluded, Granstedt took a side trip to the plasma physics lab at Ecole Polytechnique and ended his trip sightseeing with his wife in Paris. PPPL's Nat Fisch had gotten in touch with a friend at Ecole Polytechnique about hosting Granstedt's visit to the plasma physics experiments.

A second-year graduate student, Granstedt spent his first year at PPPL conducting research on Hall thrusters with Fisch and Yevgeny Raitses. "Cross-field turbulent transport is common to both," he said of his summer school education and his year's work on the thruster.

The prize winner, who grew up in Honduras and Ecuador before his family settled in San Diego, came to Princeton after receiving bachelor's and master's degrees in applied physics from Caltech in 2004 and 2005. "I deferred for a year to go to Japan with my wife for Christian work," he said.

When he found out about the Stix Prize, he submitted a two-page proposal outlining how he would use the prize money and describing why it would be beneficial for him to participate in the ITER summer school program.

Granstedt had heard about Stix when he began studying physics. "Stix was one of a generation of great leaders in plasma physics, and I knew of his waves book [*The Theory of Plasma Waves*]," he said. "I see him as one of the founding fathers of plasma physics."

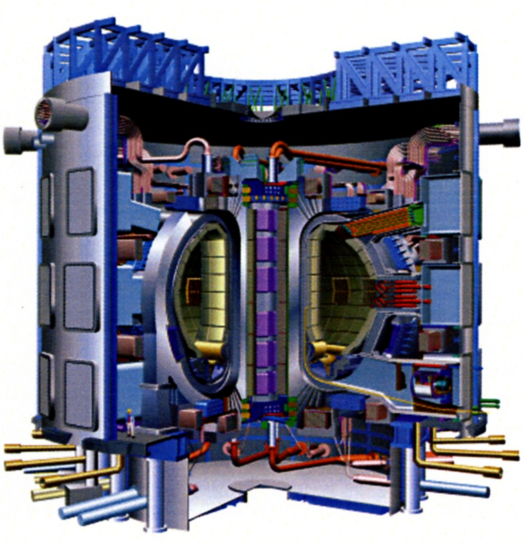
Stix was the founder and longtime director of graduate studies for the University's Program in Plasma Physics and a leader in the development of plasma physics. He died in 2001. A fund, co-organized by PPPL's Greg Hammett, was created in his memory to establish a prize for first and second-year graduate students studying plasma-related topics. The prize would enable international travel for conferences or research. PPPL's Hong Qin and Randy Wilson made up the selection committee in 2007.

This year's prize brings together a plasma physics great from the past, a student of the present, and a plasma physics project of the future: Stix, Granstedt, and ITER.

Of receiving the prize, Granstedt offered, "I feel really honored." He said it was fitting that the prize be used to support an international trip for a plasma physics student because he understood that Stix appreciated science's role in promoting international dialogue and understanding. By using it to attend international conferences, students establish connections with others around the world involved in similar research. Granstedt's experience at the ITER summer school enabled him to connect with others in the field — from student peers to researchers.

He said he believed the ITER summer school was meant to foster the interest of future fusion scientists and educate them about key ITER issues.

So might he end up being a researcher at ITER when it begins operating around 2016? "Perhaps." ●



First ITER Summer School

The emphasis of the first school was on the physics of turbulent transport and its implications on confinement. A series of lectures and informal discussions included an introduction to the theoretical and phenomenological framework of turbulent transport in fusion devices, and current theoretical models of frontier physics, as well as an overview of the main diagnostics used in experiments.

— ITER web site

PPPL's Anderson Has Spent Lifetime *Being Prepared*

You could say PPPL's Glenn Anderson was born with sea legs. By the time he was 11 they were well developed. "I grew up with the Sea Scouts. We cruised boats instead of pitching tents like the Boy Scouts," said Anderson, who came on board in 2006 as an electrical safety representative for the ES&H group.

His fascination with the sea and boating continued as an adult. This summer, the Point Pleasant resident retired from the U.S. Coast Guard with 20 years of service, including fours years on active duty and 16 on reserve. He was activated for 9-11 and Operation Restore Iraqi Freedom in 2003.

"I joined the Coast Guard when I graduated from high school and traveled all over aboard the Icebreaker Glacier — Antarctica, the Arctic, Fiji, Tahiti, American Samoa, New Zealand, Australia, and South America," said Anderson.

While enlisted he attended electricians school at Governors Island. Anderson is a N.J. licensed electrical contractor and N.J. electrical sub-code official. At the Lab he comments on electrical safety issues concerning peer labs, and is involved in PPPL design reviews and final electrical inspections.

After active duty, Anderson married Lisa Adams. "Basically on the weekends we are on the water," he said. The family has a Boston Whaler, kayaks, paddleboats, and sailboats, and both daughters, Kristen and Allyson, have their boating licenses. The latest acquisition for the Anderson fleet is a 24-foot Sea Ray. "It was idle for about three years, but the engine is in great shape," he said.

The sea and all things nautical have always entranced Anderson. "There was a scout unit three blocks from my house when I was growing up and a buddy of mine had joined. I went down to the unit when I was 11 and never left until the unit folded," he recalled, noting that nearly every weekend was spent there as a teen. "I was never home when I was a kid. I was always working on the engines and maintaining the boat."

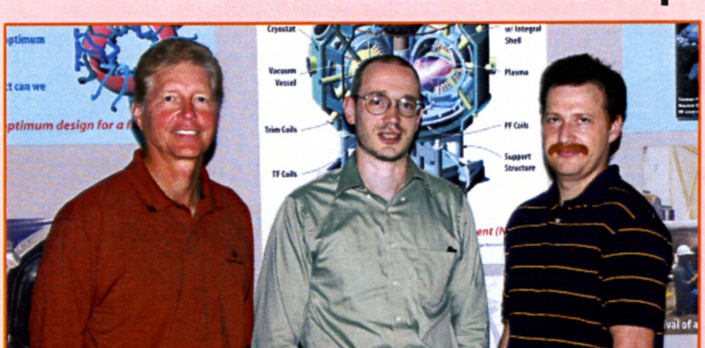
Glenn Anderson and his wife, Lisa, and daughters Kristen and Allyson, attend Anderson's Coast Guard retirement ceremony.

The unit, with adult leadership, restored a 1954, 63-foot Aviation Rescue boat used by the Corps of Engineers' as an officers' party boat. The boat was completely restored to original specifications. "As teen scouts, we cruised the boat to Canada and North Carolina, and also used it to practice Army ROTC maneuvers with local colleges. It had been used as an Air Force rescue boat to rescue downed pilots," he said.

After his military stint, he sailed as a civilian electrician with the U.S. Navy's Military Sealift Command and did a couple of tours of duty in the Mediterranean, and the North and South Atlantic. Shortly after Desert Storm he re-enlisted with the Coast Guard Reserve and was a qualified small boat engineer. He said being a reservist required spending two weeks each summer and one weekend a month on the boats.

Anderson was honored for his years of Coast Guard service in July during a flag ceremony at the U.S. Coast Guard Station in Point Pleasant. Retiring from the Coast Guard, however, will not mean less time on the sea. "I'm more comfortable on boats. I can navigate better on water than on land," Anderson said. ●

2007-2008 PPPL Colloquium Committee Named



The PPPL 2007-2008 Colloquium Committee includes, from left, Steve Baumgartner, Stefan Gerhardt, and Igor Kaganovich. Please feel free to contact them about possible speakers and topics for future colloquia.

Baumgartner can be reached by phone at ext. 2820 or by e-mail at sbaumgartner@pppl.gov, Gerhardt at ext. 2823 or at sgerhard@pppl.gov, and Kaganovich at ext. 3277 or ikaganov@pppl.gov.

Avast, me Hearties!  and come to the

PIRATES of PPPL PICNIC

Monday, September 10

PPPL FRONT LAWN

11:30 A.M. to 2:00 P.M.

FOOD, FUN, BUCCANEER GAMES, ARRR!

Boatloads of Fun! Ships Ahoy!

· Volleyball · Palm Reading · Putting Green · Ball Tosses ·

· Basketball · Music and more!

Shiver Me Treasure Prizes!

· Hamburrrrgers · Hot Dogs · Sausage & Peppers · Salads ·

· Pirate Chips · Beverages · Funnel Cakes ·

· Italian Ice ·

Rrrain date is Wednesday, Sept. 12