*Volume 6, No. 1*
*April, 2003*

# VLT News

*The Newsletter for the Virtual Laboratory for Technology*

*Volume 6, No. 1*
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# VLT News

*The Newsletter for the Virtual Laboratory for Technology*

## CPI 140 GHz Gyrotron for Wendelstein 7X Achieves 154 Second Pulsed Operation at 500 kW Power Level

The Virtual Laboratory of Technology has an intensive program of research and development of megawatt power level gyrotrons and related technology needed for ECH plasma heating in the US and international fusion research programs. Research in the VLT ECH Technology program is conducted by a consortium of Communication and Power Industries, Inc. (CPI) of Palo Alto, CA; General Atomics (GA); MIT; Univ. MD; and Univ. WI. Calabazas Creek Research and Diversified Technologies participate through the Small Business Innovative Research (SBIR) program.

CPI is under contract from IPP Garching, Germany to develop a 1 MW, 140 GHz gyrotron for heating the W7X stellarator being built in Greifswald, Germany. The CPI program is under the direction of Kevin Felch, and includes Monica Blank, Philipp Borchard, Pat Cahalan, Steve Cauffman, Sam Chu and Howard Jory. The 140 GHz gyrotrons will be used for start-up and heating of the stellarator. The reliable operation of the gyrotron system is absolutely necessary for the proper performance of the W7X machine.

The CPI 140 GHz gyrotron is shown in the Figure below. It operates at up to 80 kV, 45 A for 1 MW of output power. The collector voltage can be depressed by 20 kV to increase the gyrotron overall efficiency. The design operating resonator mode is the $TE_{28,7,1}$ mode. The output window is an 88 mm CVD diamond disk and the output radiation is in the form of a Gaussian ($TEM_{00}$) beam.

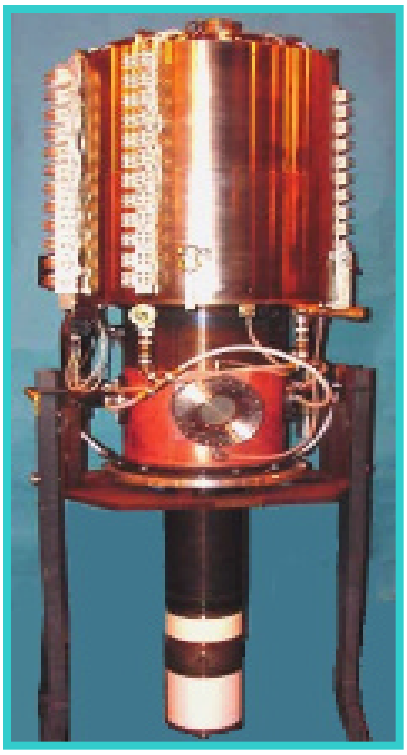

*Figure: 1 MW, 140 GHz Gyrotron*

The 1 MW, 140 GHz gyrotron first went on test in 2001 - 2002. The gyrotron was able to produce a full power electron beam but the desired operating mode of the cavity, the $TE_{28,7,1}$ mode, was found to be very difficult to excite. Mode competition from nearby modes was blocking the efficient excitation of the desired operating mode.

In late 2002, CPI worked with several other members of the VLT ECH consortium in analyzing the mode competition effects. Of great importance was the use of a multi-mode, time-dependent code developed by Tom Antonsen and coworkers at Univ. MD and recently improved by Gregory Nusinovich and Alexander Vlasov of the Inst. Res. Electron. Appl. Phys. (IREAP) at Univ. MD. Runs of this code were crucial in redesigning the gyrotron cavity to avoid mode competition. Additional theoretical research on mode competition effects in the linear regime was conducted at MIT by a graduate student, James Anderson, working with Michael Shapiro and Richard Temkin.

The redesigned gyrotron was put on test in early 2003. In short pulse (up to 5ms) tests at 80 kV and 45 A, 930 kW of output power was obtained. The collector voltage was depressed by 20 kV in these tests, giving an effective beam voltage of 60 kV. In long pulse operation, the CPI power supply is limited to currents of 25 A or less, thus limiting the output power of the gyrotron to well below 1 MW. In operation with pulses of up to 154 seconds at 80 kV, 25 A, with 25 kV of collector depression, output power of 500 kW was demonstrated. This is the longest pulse operation achieved so far at such a high power level in the US gyrotron development program.

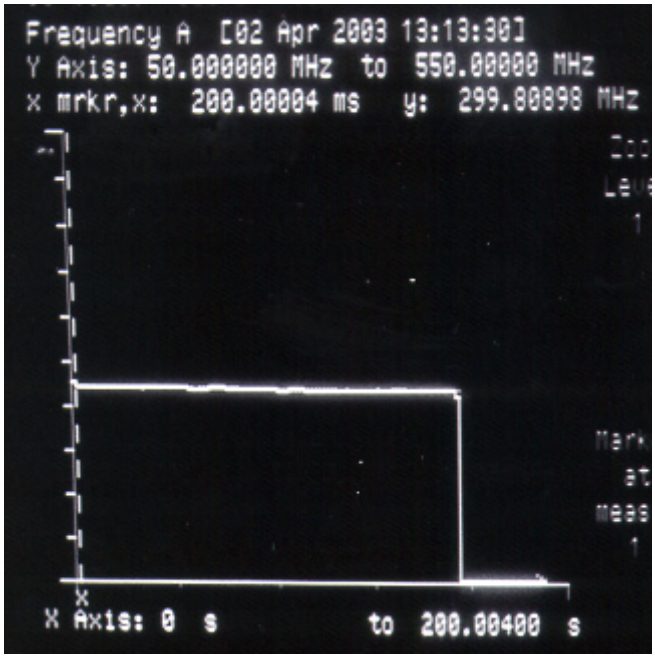


**Figure 2: Frequency change (50 MHz per division) vs. time in a 154 second pulse of the 500 kW, 140 GHz gyrotron. The observed good frequency stability indicates that thermal equilibrium has been achieved in the gyrotron resonator.**

The tube will eventually be shipped to Germany for testing at the 1 MW power level in pulse lengths of several minutes.

These new results are very promising for extension of gyrotron power and pulse length capability. Similar or better results will be expected when CPI tests its 1.5 MW, 110 GHz gyrotron with a single stage depressed collector in 2004. In the long run, the US program hopes to develop the 1 MW, 170 GHz gyrotrons needed for ITER.

***Contributed by K. Felch, CPI and R. Temkin, MIT***

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# Liquid-Metal Experimental Work at the University of Illinois at Urbana-Champaign

The Plasma-material group at the University of Illinois at Urbana-Champaign has done extensive work in the area of liquid-metal erosion, particle retention, diffusivity and surface physics. In the past five years the PMI group at UI has pioneered work in the measurement of erosion from liquid lithium [1-4]. Recently work on erosion studies continue and include work with liquid tin. In addition a new facility known as FLIRE (Flowing Liquid Surface Retention Experiment) has just been built and measurements of retention of free surface flowing liquid lithium have just been completed [5,6]. Following is a brief summary of these experiments and their recent results.

**FLIRE (Flowing Liquid Surface Retention Experiment)**

The Flowing Liquid Surface Retention Experiment (FLIRE) has been designed to provide fundamental data on the retention and pumping of He, H and other species in flowing liquid surfaces. Figure 1 shows a schematic of the new facility at the University of Illinois.

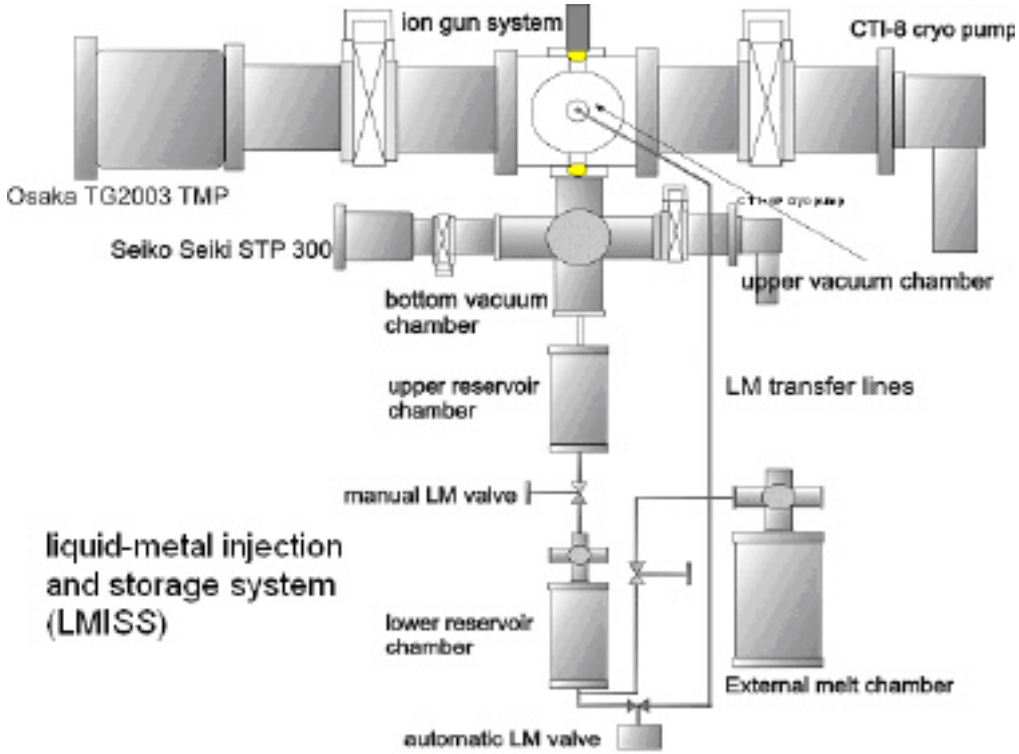


**Figure 1. Schematic of the main components of FLIRE.**

The FLIRE facility currently uses an ion beam source, which injects ions into a flowing stream of liquid lithium. Its design allows the liquid lithium to flow between two vacuum chambers that become isolated from each other when the lithium flows. Flow velocities between 0.5-3.0 m/s down two ramps inside the upper vacuum chamber can be achieved. The ramps and lines where the liquid lithium flow are heated to temperatures ranging from 250 to 500 °C to prevent any possible freezing. A dual residual gas analyzer system monitors the partial pressure of the implanted species in both vacuum chambers. The release rate of gas atoms in the second chamber is directly related to the mechanisms of transport within the metal bulk and also the process of desorption from the surface. For the case of helium, an effective diffusion coefficient was calculated to be $4.5 \times 10^{-3}$ $cm^2/s$ at 250 °C, with an uncertainty of ± $1.75 \times 10^{-3}$ $cm^2/s$. Helium retention coefficients on the order of $10^{-4}$ were obtained based on the experimental data. Future work includes further tests with He and H particle bombardment with variation of flow velocity, liquid-metal temperature and incident particle energy. In addition, a new thermal desorption spectroscopy (TDS)/Purification system will be implemented for hydrogen isotope studies with flowing liquid lithium as well as a moderate flux hollow cathode source to provide plasma-liquid interaction studies.

**IIAX (Ion-surface Interaction Experiment)**

The Ion-surface Interaction Experiment (IIAX) has pioneered work in measurements and modeling of liquid-metals from low-energy charged particles. Erosion measurements in IIAX utilize quartz crystal microbalance technology for reliable measurements of erosion processes including sputtering and evaporation. In the past five years research has mainly focused on erosion studies of solid and liquid-phase lithium, solid and liquid-phase tin-lithium and solid and liquid-phase tin. Figure 2 shows a schematic of the IIAX facility with the capability to measure erosion from solid and liquid surfaces. In addition, surface physics studies of liquid-metals include the measurement of secondary sputtered ion fraction from liquid lithium and other candidate liquid-metals. Recently liquid erosion measurements from tin in the solid and liquid phase have been completed and are shown in Figure 3. The data is also shown with modeling using VFTRIM-3D a variant of the TRIM-SP binary-collision simulation code. Results conclude that a thin oxide layer on solid-phase tin could lead to enhancement in tin erosion [7].

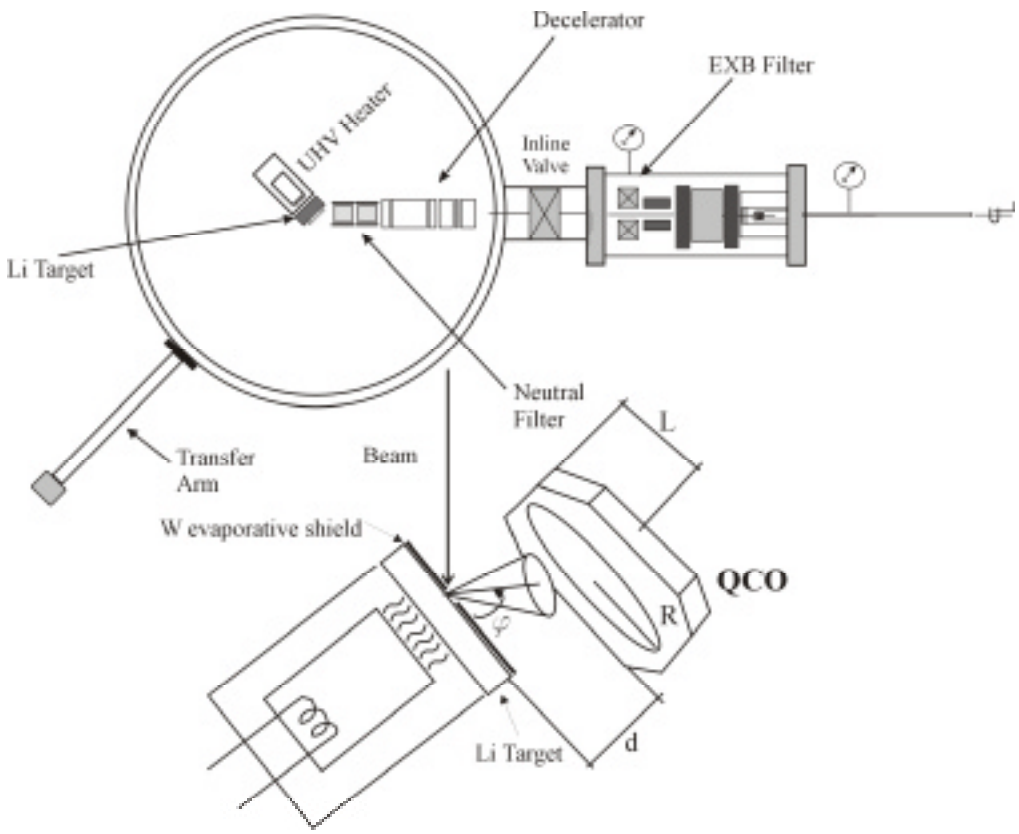


**Figure 2. Experimental set-up schematic of the Ion-surface Interaction Experiment (IIAX).**

Oxides are typically known to reduce physical sputtering in most metals. However, some metals do exhibit enhancements in their erosion with moderate oxide coverage including tin oxide. Further studies will look at how melting the tin layer may lead to a reduction in erosion due to the subsequent reduction in oxide coverage. These studies will also address erosion enhancements of liquid-metals under low-energy bombardment, which have been measured recently in several liquid-metal systems. Future work will focus on developing a self-consistent model to understand erosion enhancement from liquid lithium as the temperature is increased beyond the melting point. Figure 4 shows liquid lithium temperature-dependent data showing evidence of this enhancement and consistent with plasma/material interaction measurements in PISCES-B [8,9]. Models will include recent work using molecular dynamics and semi-analytical theory.

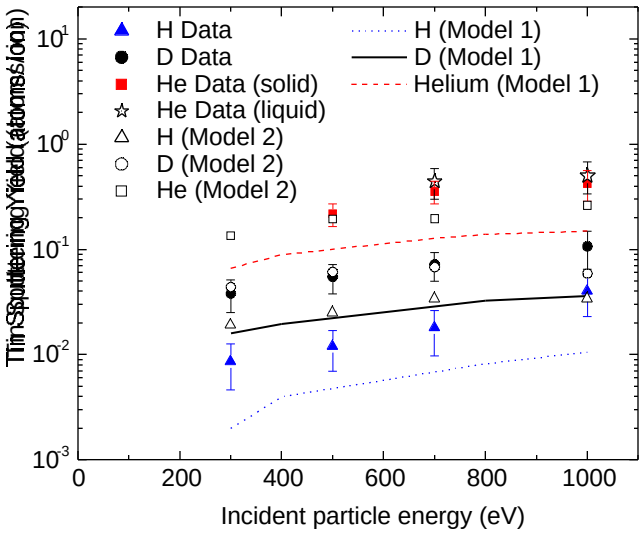


**Figure 3. Tin sputtering data and VFTRIM-3D modeling in the solid and liquid phase by H, D and He charged particles at oblique incidence measured in IIAX (Ion-surface Interaction Experiment).**

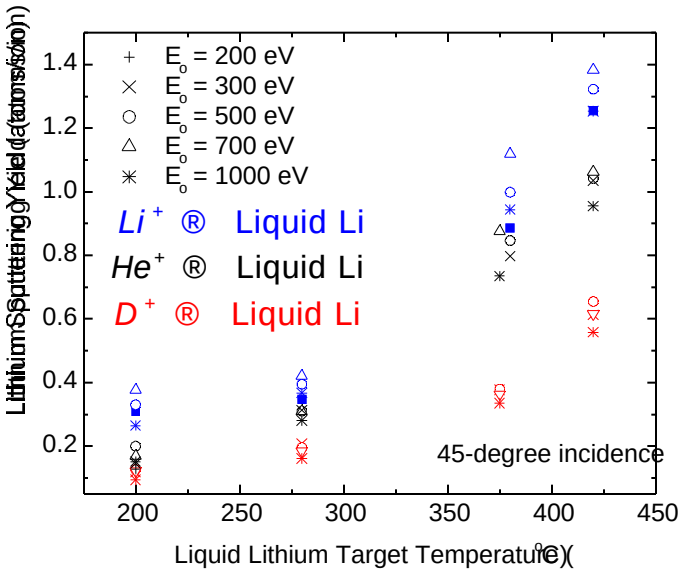


**Figure 4. Temperature-dependent sputtering data of liquid-lithium by D, He and Li charged particles at oblique incidence measured in IIAX (Ion-surface Interaction Experiment).**

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## *Enabling Technology Program Highlights for July 2002 - March 2003*

The VLT News has been given permission from the Office of Fusion Energy Sciences to publish Enabling Technology program highlights that are delivered monthly to the Director of the Office of Science (SC-1).

These highlights from laboratories and institutions participating in the Enabling Technology Program report on accomplishments or events from the program that are significant enough for reporting to SC-1, focusing on long-term research that is relevant to improving the vision for fusion energy, and near term experiment support that improves performance and accomplishes tasks such as enabling new physics regimes. The impact on other OFES activities and international fusion R&D efforts is an important part of highlight reporting, as are the contributions of various laboratories and other facilities to multi-institutional efforts.

The highlights which follow have been sent to SC-1 from July 2002 to March 2003, with the most recent highlight noted first:

### *March 2003*

**Completion of fabrication of the JET High Power Prototype Antenna**

Researchers at Oak Ridge National Laboratory (ORNL) and Princeton Plasma Physics Laboratory (PPPL) in collaboration with the European Fusion Development Association (EFDA) have completed the fabrication and begun testing a high power prototype (HPP) antenna. It is an advanced "ITER-Like" antenna designed to heat plasmas to high temperature with radio-frequency (rf) waves. The antenna is a full-scale quarter section of the "ITER-Like" design planned for installation on the EFDA Joint European Torus (JET) tokamak in 2005. The JET antenna will operate at up to 9 $MW/m^2$. It will incorporate design features that should simplify the control and improve the reliability of launching rf waves into JET and other high performance fusion plasmas. This includes the ability to maintain operation despite rapid changes in plasma edge conditions ("load tolerance") that tend to degrade performance of current antenna launchers. The HPP will test critical elements of the design including current and voltage limits and verification of the characteristics of the load tolerant impedance matching network, which is integral to the antenna itself. Testing will be conducted by ORNL, PPPL and EFDA staff at the ORNL Fusion Energy Division Radio Frequency Test facility (RFTF). The HPP will be tested from 30- 55 MHz, the frequency range of the actual ITER-Like Antenna. The additional rf heating power will allow EFDA-JET and collaborating US researchers to study the physics and technology challenges encountered in high fusion yield plasma regimes which are close to those expected in a fusion reactor.

**US - EU Collaboration to Investigate Tritium Retention in ITER Plasma-Facing Materials**

The accumulation of tritium in plasma confinement devices can negatively impact many aspects of burning plasma experiments, from limiting operating time to tritium inventory issues that can affect licensability. A major influence on tritium accumulation is retention

by codeposition of tritium with materials that have been eroded from plasma-facing surfaces. There are now large uncertainties in the prediction of codeposition rates due to the limited understanding of how mixtures of eroded plasma-facing materials react to plasma bombardment and how that reaction influences the codeposition of hydrogen isotopes with eroded mix materials.

To increase this understanding for ITER conditions, the US is collaborating with the EU to investigate mixed-material erosion and codeposition with plasma-facing materials to be used in ITER (i.e., carbon, beryllium, and tungsten). Experiments are being conducted in an edge plasma simulation facility, called PISCES-B, located at the University of California, San Diego. Earlier research with PISCES-B, which is unique in its ability to operate with beryllium materials, has provided important data on plasma erosion of beryllium and carbon materials and has identified the conditions for formation of carbonaceous films on beryllium surfaces.

Since hydrogen isotope retention in beryllium/carbon mixed material layers and carbonaceous redeposited films can significantly increase tritium accumulation, the ability to mitigate these retention processes will be very important for ITER. In the first phase of collaborative experiments, studies are being conducted on beryllium-seeded deuterium plasma interaction with graphite and tungsten surfaces to guide development of computational tools for predicting erosion and redeposition processes. The most recent PISCES-B experiments, carbonaceous deposits were reduced when beryllium impurities suppressed chemical erosion of graphite plates which could significantly reduce film formation and tritium retention. This and the understanding gained from future experiments can potentially be used to identify means for mitigating formation of carbonaceous deposits to a degree that tritium retention and accumulation will not be a major interference with ITER operations or licensing.

***October 2002***

**Progress in Plasma Current Drive with Radio-Frequency Waves**

Researchers at Oak Ridge National Laboratory (ORNL) and Princeton Plasma Physics Laboratory (PPPL) have recently made significant progress in using radio-frequency (rf) waves to drive plasma current in the National Spherical Torus Experiment (NSTX) at PPPL. The ability to drive plasma current in such a way could potentially provide the means to achieve long-duration pulses in future spherical torus plasma experiments.

The NSTX uses a 12-element rf antenna array that provides much better control in launching rf waves than is possible with the 4-element antennas used in most other plasma experiments worldwide.

The NSTX antenna makes it possible to launch rf waves in directions that would increase the plasma current or in opposite directions to decrease the plasma current. Experiments were carried out with NSTX plasma conditions being kept nearly identical except for changes in the direction of the launched rf waves. Results of these experiments provided encouraging indications that the plasma current can be effectively driven by rf waves and that it may

be possible to control the profile of the plasma current with rf waves.

While calculations by researchers from PPPL, ORNL, University of California, San Diego and the Massachusetts Institute of Technology have predicted that NSTX might be able to create plasma current profiles that are centrally-peaked, which would be beneficial to achieving improved plasma performance, more analysis of time-dependent current profile evolution is needed to confirm this capability. The NSTX experiments were performed with 3 megawatts (MW) of rf power at a frequency of 30 MHz.

Plans for the next year are to increase the rf power up to 6 MW and to repeat the rf current drive experiments with higher power and improved diagnostics. The goal of this research is to demonstrate the ability to achieve long-duration pulses in spherical torus plasmas with current drive methods such as rf waves. The usual method of driving current by voltages induced in the plasma can sustain currents for only relatively short durations.

***September 2002***

**Fusion Materials Program Planning**

As a result of restructuring during the past three years, the fusion materials program has increased the role of universities (from 5% to 12% of budget), expanded work on theory and modeling (from 8% to 20% of budget), formed multi-institutional teams addressing cross-cutting materials science issues, enhanced community roles in program governance, and made strong connections to fusion technology and design communities.

With restructuring goals successfully completed, the community met recently to plan future research activities based on prospects for each of the three classes of candidate low-activation structural materials: ferritic steels, vanadium alloys, and silicon carbide composites (i.e., SiC fibers in SiC matrix). For vanadium alloys, the only promising design concepts use lithium as a coolant, requiring electrical insulator coatings on structural surfaces to limit magnetohydrodynamics-induced pressures from liquid metal flow through magnetic fields.

Given the difficulties experienced thus far in research on coatings for lithium-cooled vanadium alloy systems and the challenges foreseen in developing coatings for high-temperature fusion environments, a programmatic shift will be made to reduce research efforts on vanadium alloys, an area which has been receiving 50% of fusion materials funding. Resources will be redirected to increase research on advanced ferritic steels that have the potential, through nanoscience approaches to microstructural engineering, for excellent fusion performance and lifetime, but with much lower levels of development risk than those foreseen for vanadium alloys.

Relative to SiC/SiC composites, research efforts will continue at the same level (about 25% of fusion materials research funding) or slightly higher during the next few years.

***August 2002***

**New Test Stand to Study Liquid Surface Technology for Plasma Experiments**

Liquid surface technology may provide promising long-term concepts for plasma

facing components in fusion reactors, with the potential for greater lifetimes and surface heat removal capacities than is possible with solid surfaces. Opportunities have been identified for nearer-term deployment of liquid surface technology, such as plasma particle removal, or "pumping", in the NSTX. The NSTX team is evaluating this approach, along with more conventional cryogenic techniques, to meet particle pumping needs in future facility upgrades. Particle pumping with liquid surfaces would be achieved in NSTX by exposing the plasma edge directly to a flowing lithium surface, which is known to be an excellent absorber of edge plasma particles.

A new test stand at Sandia National Lab called LIMITS (**LI**thium **M**etal **I**ntegrated **T**est **S**tand) has been assembled to study feasibility issues for deploying a flowing lithium surface in the NSTX. LIMITS, which has several magnet sets that simulate edge magnetic field conditions in NSTX, will study magnetohydrodynamic effects of NSTX's edge magnetic fields on the flow of lithium jets under vacuum conditions. Shakedown testing is now being conducted with water to test a circular jet nozzle and high speed liquid jet catcher prior to the introduction of lithium.

Diagnostic systems compatible with flowing lithium are also being installed and checked out. Experiments with flowing lithium, which

will begin in September, will study a variety of flow approaches (films and jets) to determine an optimal liquid surface design for NSTX conditions. With its e-beam system that can be focused onto flowing lithium, LIMITS will also study surface heat flux handling capabilities of liquid lithium without magnetic fields. LIMITS experiments will be conducted on a schedule to support a decision in late 2003 on whether or not to deploy a liquid lithium system in NSTX for particle pumping.

***July 2002***

**Promising Technology for Mitigating Effects of Plasma Disruptions**

A sudden loss of plasma confinement or "disruption" in magnetic confinement devices can cause the stored energy of the plasma to be rapidly dumped into surrounding components, resulting in damage by localized heating from particle fluxes and by mechanical forces from magnetic field transients. It is therefore essential to develop techniques that can mitigate the effects of disruptions potentially severe enough to cause such damage.

In collaborative experiments on the DIII-D National Fusion Facility in San Diego, researchers from General Atomics, Lawrence Livermore National Lab, Oak Ridge National Lab (ORNL), and the University of California, San Diego have demonstrated the feasibility of using high-pressure gas jets to mitigate the damaging effects of disruptions without the deleterious side effects of previously explored techniques.

Using a fast acting valve developed at ORNL, the injection into D-IIID plasmas of high-pressure jets of helium, neon, and argon gas was able to benignly dissipate stored plasma energy through radiation processes, with forces transmitted to the vacuum wall reduced by typically a factor of

4 and heat fluxes on key in-vessel components reduced by up to a factor of 10.

In addition, there have been successes with initial experiments in D-IIID to detect certain types of plasma disruptions, which could provide the technical basis to develop diagnostics that can send signals to trigger this mitigation technique in realistic situations. Experiments and computer modeling are in progress to verify the physics model of gas jet penetration for the conditions of higher temperature burning plasmas. This disruption mitigation technology now appears to be promising for use in next step burning plasma experiments and future fusion power reactors where damage to components from unmitigated disruptions is can be a serious limiting factor on device lifetime.

**For more information on the Office of Fusion Energy Sciences Program, visit their website at:** http://www.ofes.science.doe.gov/

**For more information on the Enabling Technology Program participating institutions, visit the VLT website at:** http://vlt.ucsd.edu

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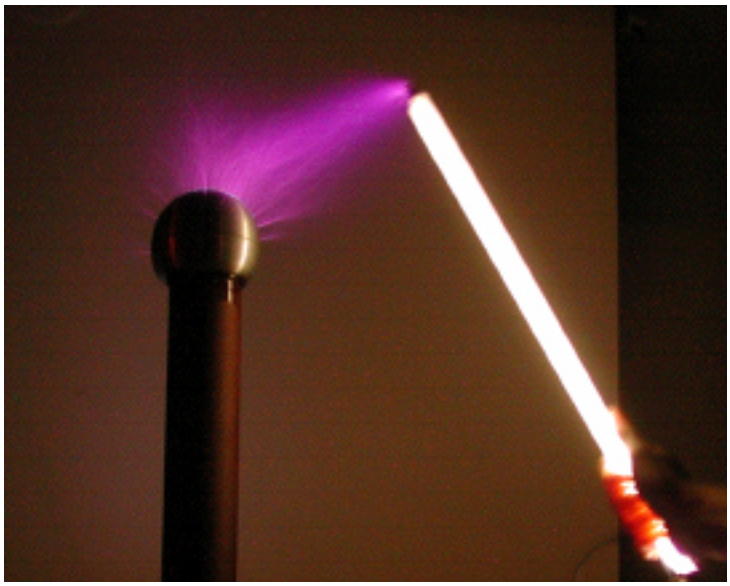
# VLT Lab Notes

The annual Teachers' Day and Plasma Expo for 2002 was held in Orlando, Florida on November 12-15 as part of the American Physical Society's Division of Plasma Physics yearly meeting. The Princeton Plasma Physics Laboratory was the lead institution in organization of this year's educational outreach event which is sponsored by APS and the U.S. Department of Energy. Sixty-five teachers from the Orlando area participated in the Teachers' Day workshops and over 1,000 people attended the Expo.



**May the Force Be With You--**
***Students experiment with Tesla coil and plasma filled light saber at Plasma Expo 2002.***

Teachers Day presented a day of workshops for middle and high school teachers that presented various topics in plasma physics research. The teachers who attended had the opportunity to meet and talk with research physicists from research centers, laboratories, academia, and industry and participated in workshop presentations designed especially for middle and high school science teachers. A variety of resource materials such as plasma balls and video tapes about plasma physics were given to the teachers to be used in the classroom. Workshops presented by scientists from participating institutions included plasmas and fusion science, fluid instabilities, NASA's Dynamic Sun presentation, the electromagnetic spectrum, radioactivity, and the nature of matter.

The Plasma Expo is held as an adjunct to Teachers' Day and is also open to members attending the APS/DPP meeting and the general public. This exhibition focuses on hands-on science education and ttendees can participate in science activities and talk with scientists in the field of plasma physics.

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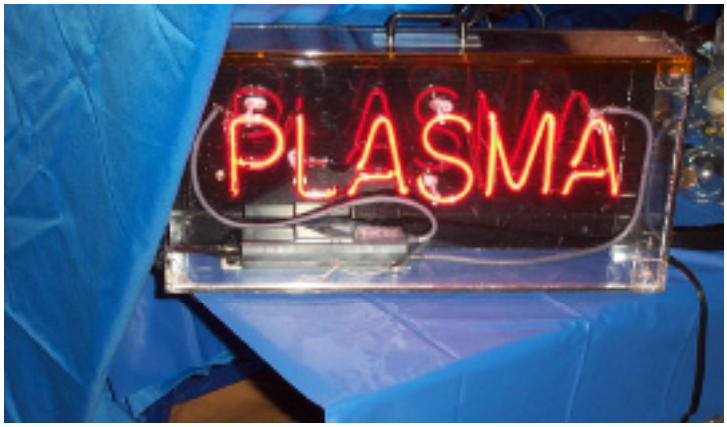
More than 2000 students attended the San Diego Science Alliance's sixth San Diego County Educational Technology Fair on Wednesday, February 19, 2003 at the Del Mar Fairgrounds. Students from 38 regional middle and high schools met with high-technology, science- and space- related exhibitors from 46 regional companies and organizations as they showcased current and future technologies through interactive displays. In addition to educational and corporate exhibitors, students had the opportunity to meet California Congressional Representative Susan Davis to discuss their interests in high-tech careers and their educational goals to support those aspirations.




***Entrance to UC San Diego's exhibit tent at February 2003 Tech Fair***

The University of California, San Diego's fusion energy research program presented a variety of interactive demonstrations including experiments in fluid dynamics and the electromagnetic spectrum, a portable plasma experiment demonstrating the action of magnetic fields on confined plasma, and experiments using the electromagnetic spectrum.

***P. Stewart, UCSD***

***Contributors to this issue may be reached via e-mail and telephone for further information on their programs:***

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# *VLT CALENDAR*

## *April 2002 - June 2005*

| DATE | MEETING | LOCATION | CONTACT |
|---|---|---|---|
| **7-11 April 2003** | APEX/ALPS Mtgs. | Xanterra Parks & Res., Grand Canyon, Arizona | youssef@fusion.ucla.edu |
| **8-16 April 2003** | ITER Meetings | Toronto, Canada | |
| **5-6 May 2003** | Town Mtg on IFE Liquid Wall Chamber Dynamics | Hilton Garden Inn Hotel, Livermore, CA | wmeier@llnl.gov, raffray@fusion.ucsd.edu |
| **5-6 May 2003** | NRC BP Assessment Committee Meeting | National Academies Bldg., Washington, DC | mmoloney@nas.edu |
| **5-9 May 2003** | ARIES Meeting | Hilton Garden Inn Livermore, CA | lester.m.waganer@boeing.com, or knecht2@llnl.gov |
| **12-16 May 2003** | ITER Model Coils Workshop | Brolo, Sicily | karin.grau@tech.efda.org |
| **22-25 June 2003** | 2003 ASEE Annual Conference & Expo | Nashville, TN | gom@intleng.org |
| **3-5 Sept 2003** | 9th Plasma Edge Theory Meeting | Center for Magnetic Recording Research, UCSD, San Diego,CA | http://cerfe.ucsd.edu/pet9.html |
| **3-5 Sept 2003** | ARIES Meeting | Georgia Tech | lester.m.waganer@boeing.com |
| **7-12 Sept 2003** | 2003 IFSA | Doubletree Hotel, Monterey, CA | http://www.llnl.gov/nif/ifsa03/ |
| **14-17 Oct 2003** | 20th SOFE/03 | Bahia Hotel, San Diego, CA | http://d3dnff.gat.com/sofe03/ |
| **7-12 Dec 2003** | ICFRM-11 | Kyoto Int'l Conference Hall, Kyoto, Japan | http//icfrm.iae.kyoto-u.ac.jp |
| **12-17 Sept. 2004** | 7th Int'l Tritium Conf. | Baden-Baden, Germany | |
| **May/June 2005** | ISFNT-7 | Kyoto, Japan | sekim@fusion.naka.jaeri.go.jp |

***Editor's Note:***

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