Volume 5, No. 2
August, 2002

VLT News

The Newsletter for the Virtual Laboratory for Technology

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The Newsletter for the Virtual Laboratory for Technology

New ORNL Pellet Injection System Installed and Operated on MST

A compact pellet injection system (Fig. 1) that was designed and constructed at the Oak Ridge National Laboratory (ORNL) has been installed on the Madison Symmetric Torus (MST) at the University of Wisconsin-Madison and used in some preliminary plasma experiments. The system, referred to as a "pellet injector in a suitcase," is a pipe gun device with a four-barrel capability (1- to 6-mm bore), and it uses a cryogenic refrigerator for in-situ hydrogen pellet formation. To minimize costs and expedite construction, the initial injector configuration only included two barrels (1.0- and 1.8-mm bores) and two high-pressure propellant valves for pellet acceleration (speeds of ~1000 m/s). For the MST application, two pellets are considered adequate for present plasma experiments. The injector design facilitates the change-out of gun barrels for different pellet diameters, and this can easily be completed within a few hours. The stand-alone instrumentation and controls, as well as the data acquisition system, are personal-computer-based and housed in one standard instrument cabinet.

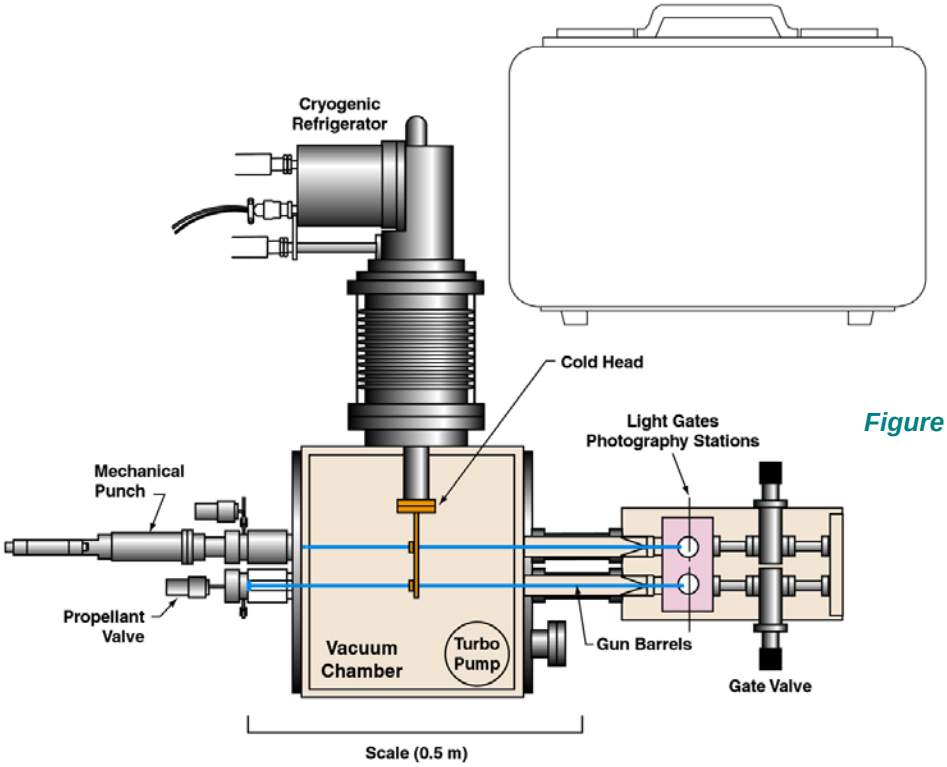

Figure 1

A three-man team of ORNL researchers visited MST and assisted MST staff in the installation and commissioning of the injection system. The ORNL injector and pellet injection line were fitted to an existing MST test stand, and the entire assembly was lifted into place and connected to MST. Remarkably, the installation and checkout were completed in four days. A photograph of the injection system on MST is shown in Fig. 2. The injector is mounted near MST and is aligned such that pellets are injected radially at an angle of 15 degrees above the outboard midplane. Images of 1-mm-diameter D_2 pellets (~1000 m/s) ablating in MST plasmas are shown in Fig. 3. Recorded with a CCD camera, the view shown here is from a port toroidally displaced from the pellet injection port.

Each image from the CCD camera is integrated over about 1 ms, thereby capturing in a single image the entire pellet flight (starting on the left of the image) across the 1-meter-diameter plasma. In Fig 3a, the pellet makes it part of the way across the plasma; and in Fig. 3b, the pellet clearly makes it all the way across the plasma to the inner wall.

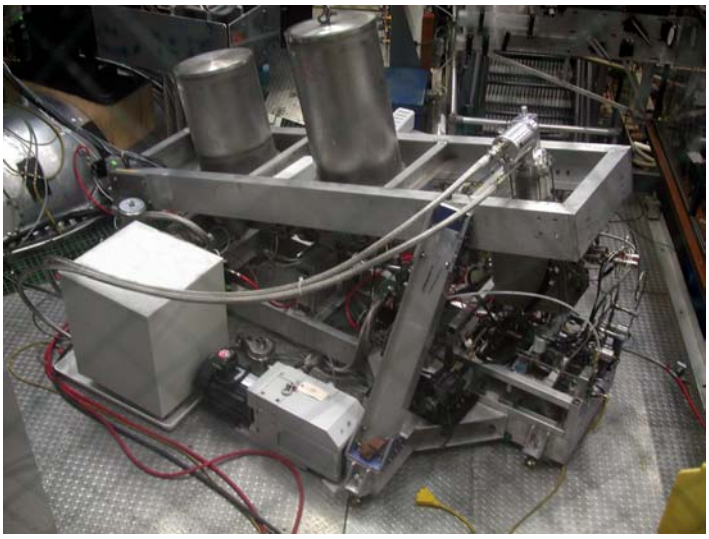

Figure 2

The injector has already produced useful results on MST. During improved-confinement plasmas, for example, the line-averaged density has been increased by almost 100%, and the increase lasts several milliseconds, consistent with improved particle confinement in these plasmas. In addition, it appears that pellet injection successfully peaks the density profile in these plasmas. The density profile is usually flat, and previous attempts to increase the central density with gas puffing have failed. The puffed fuel merely accumulated in the plasma edge, causing the density profile to become hollow.

Over the next year, the injector will be used in a variety of targeted MST experiments. Pellet injection will be applied to standard-confinement plasmas in an attempt to suppress confinement-degrading sawtooth crashes. Such suppression is observed with pellet injection in tokamaks due to a favorable change in the current density profile. Pellet injection will also be applied further to improved-confinement plasmas with the initial goal of surpassing the usual density limit in these plasmas. In addition to these fueling experiments, the injector will also be used to inject impurities into the plasma core. Similar to gas-puff fueling, impurity gases puffed into the plasma edge do not penetrate to the plasma core. Reliable core impurity injection will allow studies of, e.g., highly-radiative plasmas and impurity particle transport.

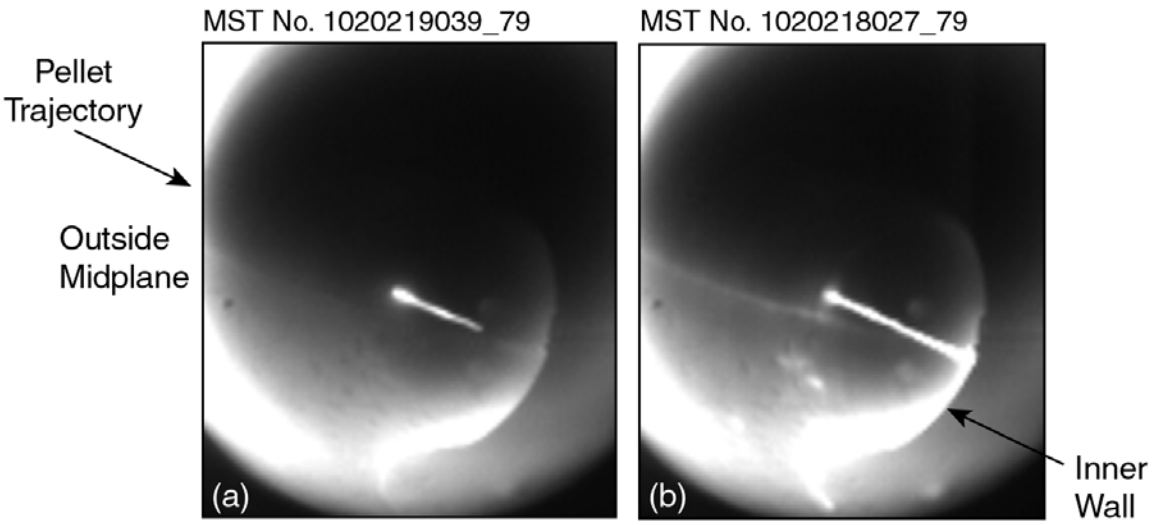

Figure 3.

Important to these planned experiments are a few scheduled modifications/upgrades to the injector, which will provide MST with the maximum operational reliability and flexibility. The first upgrade was completed by ORNL researchers recently (August 1, 2002), with the 1.8 mm gun replaced with a smaller 1.0 mm gun; the 1.8 mm pellets proved to be too large for present plasma parameters. The capability was also added to inject pellets at a variety of speeds (100 to 1000 m/s). To achieve the minimum pellet speed, a pellet punch (or pusher rod) was added to one gun and is used to initiate pellet motion. To achieve speeds above the minimum, a small burst of propellant gas can be used to supplement acceleration. Fueling with slow pellets (100 - 300 m/s) will be tested as soon as possible. If slow pellets are effective, this will have multiple benefits. First, it will allow fueling through virtually any port on MST, since slow pellets can be routed through curved guide tubes. In addition, it will allow the injector to be placed further away from the MST vessel, freeing up valuable space around the machine. Although presently equipped to provide two pellets per plasma, the injector and injection line were designed to accommodate a total of four gun barrels, which would allow injection of up to four pellets per plasma pulse. Each gun barrel can be fitted with close-coupled propellant valve for high-speed pellets or a pusher rod in combination with a propellant valve for slow to intermediate pellet speeds. In the next upgrade, two additional gun barrels will be added for the full complement of four.

This new, portable pellet injection system was developed to provide a flexible means of plasma fueling on a wide variety of magnetic confinement devices. The system also features a relatively low cost, both for installation and operation. This injector (or a clone) is being considered for use on the National Spherical Torus Experiment (NSTX).

Contributed by S. Combs, ORNL

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DIII-D Collaboration Demonstrates High Pressure Gas Jet Mitigation of Disruptions

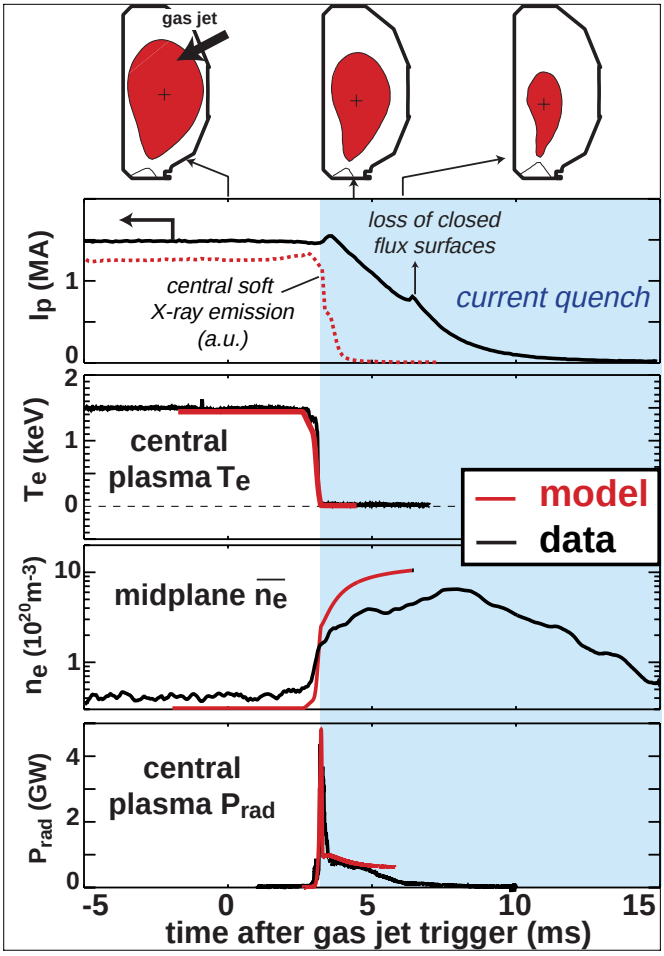
In collaborative experiments on the DIII-D National Fusion Facility in San Diego, researchers from General Atomics, the University of California San Diego, Oak Ridge National Laboratory and Lawrence Livermore National Laboratory have demonstrated the feasibility of using a high-pressure gas jet to mitigate the damaging effects of disruptions. These tests are very encouraging for next-step burning plasma experiments and future fusion reactors where disruptions, which result in rapid uncontrolled loss of the plasma energy to wall surfaces, are predicted to be a serious limiting factor on device lifetime.

Using a fast acing valve developed at ORNL for the Fusion Technology Fueling Development Program, high-pressure jets of helium, neon, and argon have been injected into the DIII-D core plasma. The high-pressure jet has been found to penetrate efficiently through the lower pressure plasma, increasing the particle content of the plasma by a factor of 50. The injected species then effectively dissipate the plasma energy to the entire wall surface by line radiation in a few milliseconds, achieving instantaneous radiation rates greater than 2 GW. This uniform energy dissipation results in a reduction of local power flux to the divertor surfaces of up to a factor of 10. Furthermore, the experiments demonstrated that the rapidly cooled plasma dissipated the confining poloidal magnetic field energy (i.e plasma current) while simultaneously maintaining the position of the plasma away from the wall surfaces. Thus, the electromagnetic forces transmitted to the vacuum wall of the tokamak were dramatically reduced by at least a factor of four. The generation of runaway relativistic electrons was also avoided because of the large plasma and neutral density caused by the gas jet injection.

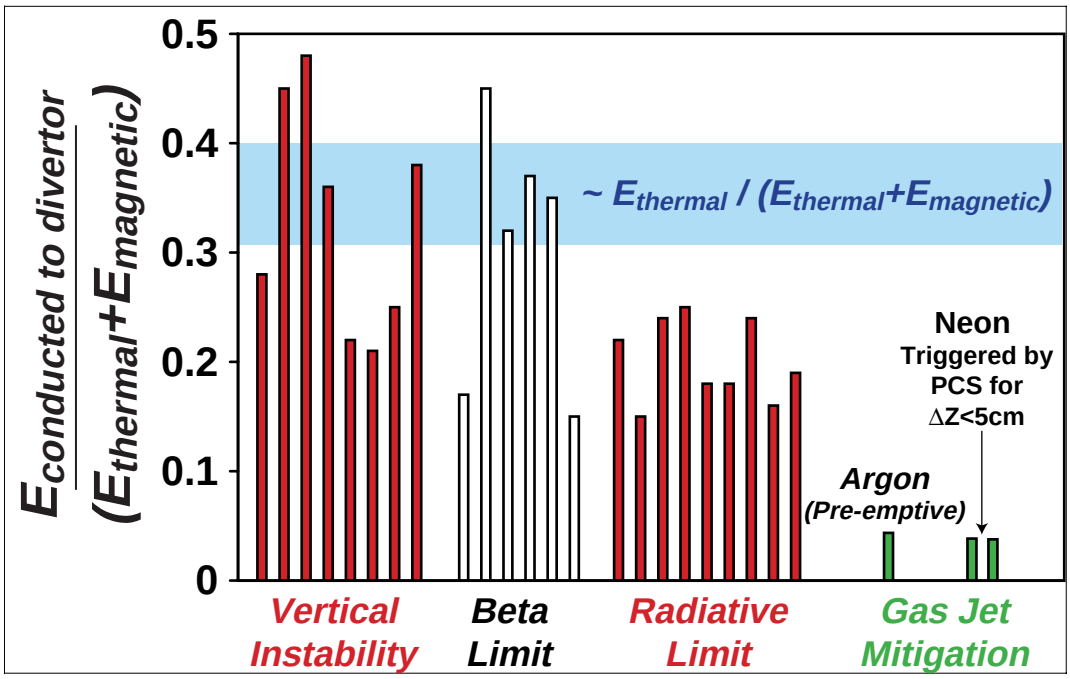
Real-time plasma control detection and triggering of the gas jet has been demonstrated. The early detection and understanding of the evolution of disruptive plasmas is a critical aspect of using disruption mitigation in future devices. The DIII-D plasma control system was equipped with an algorithm to detect the unstable vertical movement of the plasma toward the walls. The algorithm successfully detected 2 cm vertical displacement of the ~2.5 m height plasma and triggered the fast-valve gas jet injection. As a result, the plasma was safely terminated by the gas jet before it moved into the vessel wall.

Experiments on DIII-D are continuing to test various techniques to reliably detect various types of disruptions. In addition, experiments and computer modeling are in progress to verify the physical model of the gas jet penetration into the higher temperature and pressured burning plasmas.

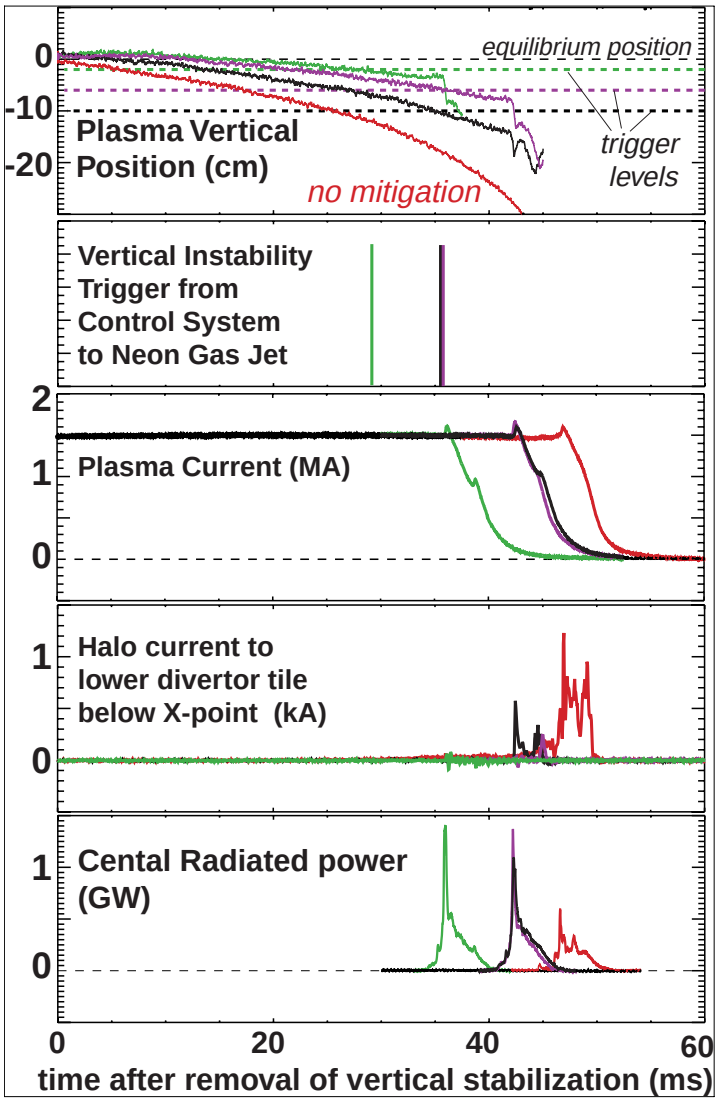
Contributed by
D. Whyte, UC San Diego



A neon gas jet radiative termination of the DIII-D plasma for disruption mitigation. The gas jet reaches the DIII-D central plasma ~4 ms after the valve is released. The neon radiates away the plasma energy in a few milliseconds (P_{rad}) and increases the density (n_e) by a factor of 10. Consequently the central plasma temperature (T_e) decreases from ~2000 eV to ~2 eV in 100 microseconds. These features are matched by a radiation model (red lines). The plasma current (I_p) decays exponentially with no sign of runaway relativistic electrons, while the core plasma remains well-centered in the vessel as it is quenched (top).



In unmitigated DIII-D disruptions of all types (vertical, Beta (pressure) or radiative), ~50-100% the plasma's thermal energy ($E_{thermal}$) is carried to the divertor in about a millisecond. In a burning plasma experiment, this would result in severe damage to the divertor components. However the neon or argon gas jet mitigation releases the plasma energy by radiation to the entire wall structure and thus alleviates divertor damage from local heating.



Tests of the vertical instability disruption detection algorithm on DIII-D have been successful. The plasma control system (PCS) detects in real-time the displacement of the plasma away from its equilibrium position. The PCS is set to various displacement threshold levels for the disruption detection (e.g. green traces: 2 cm,) while the red traces show a vertical instability disruption with no mitigation. The PCS triggers the neon gas jet sufficiently early that the plasma movement toward the wall is slowed resulting in less halo current and vessel stresses in the divertor, while simultaneously dissipating plasma energy by radiation.

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Enabling Technology Program Highlights for February - June 2002

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 February - June 2002.

February, 2002

New Experiment to Study Liquid Metal Flows in Magnetic Fields

An experiment system called MTOR, for Magnetic Torus, has begun operation at UCLA. Built from 24 electromagnets, each about 1 meter in diameter and capable of about 1 Tesla, MTOR simulates key magnetic field features of toroidal approaches to magnetic confinement of plasmas. MTOR will be used to study free-surface liquid metal flow magnetohydrodynamics (MHD), a feasibility issue for plasma-facing components that would have liquid metals in direct contact with plasmas. This liquid surface technology is under investigation for use in plasma experiments as an innovation to achieve levels of particle control and heat flux handling that are beyond present-day capabilities. Upgrades to MTOR, which now uses a gallium alloy flow loop to study drag and stability effects on liquid metals flows across magnetic field gradients, are planned to achieve MHD parameters closer to those expected for plasma experiments. Data from MTOR will guide development of 3-D MHD models and computational fluid dynamics codes for design, analysis, and prediction of first-generation liquid surface systems. For the longer-term, this research contributes to resolving feasibility issues of "liquid wall" concepts that could improve prospects for performance and reliability of fusion systems since plasma-facing surfaces are flowing liquids that never wear out.

March 2002

Record Levels of Operation for Microwave Technology

Electron cyclotron resonance heating with microwaves is a leading approach in magnetic fusion experiments to reach fusion-relevant plasma temperatures and to drive currents for plasma control and sustainment. The devices used to produce the microwaves are called gyrotrons. For the first time, a gyrotron has sustained 110 GHz microwave operation at a one megawatt power level for 5 seconds, the longest reported continuous operation of a gyrotron at such a frequency and power level. The gyrotron, which was operated in

the D-IIID tokamak, is being conditioned to operate for a full 10 seconds. The breakthrough performance for this gyrotron, which was designed in a collaboration between several US universities, national labs, and industrial firms, was enabled in part by improvements to the window that transmits microwave power out of the gyrotron tube.

These windows, made of optical quality artificial diamond, can convert to graphite during high temperature brazing in gyrotron fabrication, causing high local heating that results in window failure. To avoid the failures that have been observed in these windows, an improved brazing/fabrication process was developed in a collaboration between a US industrial firm, a US national lab, and a European lab. This improved process was used for the window in the record-breaking gyrotron.

The temperatures measured in the window indicated that it should be capable of long pulse or even continuous operation. It is now planned to bring two additional gyrotrons up to operation at the one megawatt level and to use them for up to 10 seconds of operation. The ability of these gyrotrons to deliver focused high power microwaves to localized regions in the D-IIID plasma will enable the control of current profiles needed to achieve plasma stability during long pulse operation.

US-Japan Collaboration on Fusion Materials

Experiment plans have been completed for the next phase of the long-standing collaboration between the fusion materials research programs of DOE and the Japanese Atomic Energy Research Institute (JAERI). JAERI and DOE each provide $1M per year to conduct irradiation testing in ORNL's High Flux Isotope Reactor (HFIR) of materials that are candidates for structures in fusion power systems.

The irradiations examine the effects of neutron bombardment, a key factor in the behavior and lifetime of fusion materials, on microstructural evolution, damage accumulation, and property changes of materials that produce only modest long-term radioactivity from transmutations and that can operate at high temperatures with slow and predictable degradation.

The next phase of the collaboration will focus on the irradiation responses at varying temperatures and neutron doses of specimens made from ferritic steels alloys that are elementally tailored for fusion environments. Data from the irradiation campaigns, which will begin in mid-2002, will be obtained in post-irradiation examinations by Japanese and US materials scientists and used to develop models and computer codes for fusion materials response prediction and simulation and for designing advanced materials that can operate for extended periods at very high temperatures for improved fusion economic attractiveness.

April 2002

Advanced Steels for Fusion Energy

An international workshop was hosted by the US to review the status and plans for research on advanced steels for structures in the plasma chambers of fusion energy systems. Internationally, the leading

candidate materials for such fusion applications are "reduced activation ferritic steels" or RAFS, which are modified versions of ferritic steels developed for fission power cores. Alloying elements that produce significant long-lived radioactive products by activation (i.e., transmutation by fusion neutrons) are replaced in RAFS with elements that produce much lower levels of activation without degrading properties, performance, or lifetime.

Although the prospects for successfully developing RAFS appear good, operating temperature limits of less than 600 C pose constraints on the economics of fusion power plants. While it has been known that the ability to operate RAFS up to 800 C could significantly improve the economics of fusion by enabling efficient thermal cycles, research on advanced RAFS that can operate at such temperatures is a relatively new field, employing nano-scale materials science techniques that are rapidly emerging. The 40 scientists that attended the international workshop reviewed design approaches to effectively use advanced RAFS and identified key technical issues to that need to be addressed in research programs. The workshop identified a number of interests in collaborative research that will be carried out under established bilateral and multilateral agreements.

Spallation Neutron Sources for Fusion Materials Research

A meeting under the IEA Implementing Agreement on Fusion Materials was hosted by the US to discuss the use of spallation neutron sources for irradiation testing of candidate fusion materials. This meeting was held in response to a request from the IEA Fusion Power Coordination Committee to assess the extent to which spallation neutron sources available now and in the foreseeable future could contribute to, and possibly accelerate, the development of fusion materials.

Agreement was reached at this meeting to hold an international workshop on this subject in September 2002. Among the topics to be addressed at this workshop will be (a) relevance of spallation source neutron characteristics to fusion materials research and the impact of non-prototypical features (e.g., differences between the neutron spectra of fusion devices and spallation sources), (b) access by fusion users to desired regions of spallation sources, (c) ability to achieve important irradiation testing parameters (e.g., control over temperature of irradiation specimens), (d) potential needs for facility modifications to improve usefulness for fusion testing, and (e) the role of modeling and simulation in interpreting data from spallation sources. It is expected that the September workshop will lead to a report by the end of this year on the use of spallation sources for fusion materials research.

May 2002

Record Performance by High Heat Flux Components for Burning Plasma Experiments

The ability of plasma facing components to reliability remove high levels of surface heat deposited by burning plasmas, while not deteriorating rapidly or contaminating the plasma with impurities, is a major technology issue for burning plasma

experiments. One of the greatest challenges is in the "divertor", which provides plasma particle exhaust by magnetic field lines being "diverted" so that particles in the edge of the plasma can exit, striking surfaces that must handle the high heat flux deposited by large currents of energetic plasma particles. The levels of surface heat flux expected in the divertors of ITER and FIRE (the international and US burning plasma experiment designs, respectively) are up to 20 MW/m2, a level usually associated with rocket nozzles.

A significant advance was recently made in the development of divertor components that can sustain such high levels of heat flux. Sandia National Lab, in a collaboration with the Japan Energy Atomic Research Institute and a US small business, completed testing of divertor component mockups that use tungsten rods joined to copper alloy. The tungsten rods, which can sustain the high temperatures produced by energetic plasma particle bombardment, would face the plasma and protects the underlying copper alloy that serves as a heat sink with water-cooled channels.

This concept was developed over several years based on earlier work done by the US on ITER divertors. Using recent advancements in design and fabrication techniques based on research supporting the FIRE divertor, tungsten-copper mockups tested at a Sandia heat flux simulation facility were able to sustain over 20 MW/m2 without damage for 3000 heating periods of at least 30 seconds, the amount of time needed to achieve thermal equilibrium during a heating period. This testing demonstrates the viability of this tungsten-copper concept for the high heat flux components of divertors in burning plasma experiments. Future research will be aimed at extending performance limits and testing tolerances to off-normal events.

June 2002

Successful Test of High Temperature Superconductor Coil

The fusion program's first high temperature superconductor coil recently completed preliminary testing with good results. This technology will be used in the Levitated Dipole Experiment (LDX), which is being developed by Columbia University and the Massachusetts Institute of Technology as an innovative concept to investigate plasma confinement with a dipole magnetic field. LDX, which will be the first plasma confinement experiment in the US to use a high temperature superconductor coil, consists of a 5 m diameter vacuum vessel and three superconducting coils. Two of the three superconducting coils will use Nb_3Sn and NbTi, which are commercial low temperature superconductors.

In LDX, a floating coil (Nb_3Sn) provides the magnetic field for plasma confinement, a charging coil (NbTi) inductively charges and discharges the floating coil, and a levitation coil (high temperature superconductor) electromagnetically supports the weight of the floating coil and cryostat (about 1300 lbs) and controls the vertical position of the floating coil. The levitation coil, which contains about 7000 m of high temperature superconductor tape manufactured by a Phase II SBIR grantee, was successfully tested recently at a temperature of 77K (liquid nitrogen bath) to confirm its

superconducting behavior. When fully integrated into LDX, the high temperature superconductor will minimize both electrical and cooling power needs for the levitation magnet. Longer-term, high temperature superconductors offer the potential economic benefits of reduced cryostat complexity and cryogenic refrigeration costs.

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

Highlights of the Sixth International Symposium on Fusion Nuclear Technology

The Sixth International Symposium on Fusion Nuclear Technology (ISFNT-6) was held in San Diego on April 8-12, 2002. The Symposium is recognized as a major event for the international exchange of technical information on all aspects related to fusion nuclear technologies (FNT) and for the promotion of international collaboration. The total number of participants was about 250 (including 27 students) who came from approximately 16 countries.

The conference provided an excellent opportunity to report on recent technical progress, discuss key issues and identify means to resolve these issues. The conference covered both near-term fusion devices and long-term reactor technologies. Papers related to technology, experiments, facilities, modeling, analysis, and design were presented on the following topics:

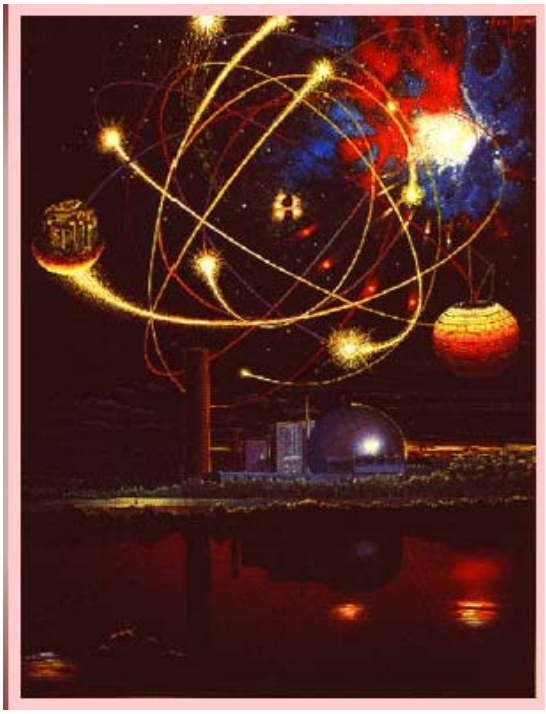
1. *First Wall Technology and High Heat Flux Components*
2. *Blanket Technology*
3. *Fuel Cycle and Tritium Processing*
4. *Material Engineering*
5. *Vacuum Vessel*
6. *Nuclear System Design*
7. *Safety Issues and Waste Management*
8. *Models and Experiments*
9. *Repair and Maintenance*
10. *Burning Plasma Control and Operation*
11. *Inertial Confinement Fusion Studies and Technologies*
12. *FNT Contributions to Other Fields of Science & Technology.*

ISFNT-6
San Diego, USA

Previous, current and planned meetings in this series are:

ISFNT-1	*Tokyo*	*April 1988*
ISFNT-2	*Karlsruhe*	*June 1991*
ISFNT-3	*Los Angeles*	*June 1994*
ISFNT-4	*Tokyo*	*April 1997*
ISFNT-5	*Rome*	*Sept. 1999*
ISFNT-6	*San Diego*	*April 2002*
ISFNT-7	*Tokyo*	*May 2005*

The conference had two noteworthy keynote speakers: Richard Rhodes, a Pulitzer Prize winner, and Stephen Baum, CEO of Sempra Energy. Rhodes addressed why rational introduction of new primary energy sources has been complicated and compromised historically by sociocultural barriers as well as technological, infrastructure and competitive challenges. His talk entitled "



A vision of the future from Richard Rhodes

"Energy Transitions: A History Lesson," explored past experience with transitions such as wood to coal, gas light to electric light, and especially fossil fuel to nuclear power that offer lessons for transitioning to fusion. Baum, Chairman, President and CEO of Sempra Energy, detailed his view of the role of nuclear power in the nation's energy roadmap in a talk entitled "Beyond the Crisis: Solutions for Our Energy Future." Geo-political uncertainty combined with the fallout of the California energy crisis and the Enron debacle has created a new reality for the energy industry.

The conference had three plenary sessions covering topics of broad interest. The closing plenary session on the last day of the conference included four overview papers highlighting the status of fusion nuclear technology in Japan, Europe, Russian Federation and the United States. There were 12 oral sessions which included 48 invited papers. A total of 173 contributed papers were presented in five poster sessions. Peer reviewed papers will be published in a special issue of Fusion Engineering and Design.

The ISFNT issued for the first time two awards (the Miya-Abdou Award named after the founding leaders on the ISFNT series of conferences) which acknowledge outstanding contributions to fusion nuclear technology by people relatively early in their careers. The awards were presented to Dr. Lance Snead (ORNL) and Dr. Neal Morley (UCLA).

The conference represents the combined effort of many hardworking people. Dr. Rene Raffray served as the Executive Secretary and co-editor of the proceedings and Mrs. Claudia Hennessy served as the Symposium Secretary and chair of the Local Organizing Committee.

Contributed by Charles C. Baker,
Conference General Chairperson
University of California, San Diego

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VLT CALENDAR
September 2002-June 2005

DATE	MEETING	LOCATION	CONTACT
9-13 Sept 2002	*22nd SOFT*	*Marina Congress Center Helsinki, Finland*	*soft@tsgcongress.fi* ***and/or*** *http://www.vtt.fi/val/soft2002*
11-12 Sept 2002	*FESAC Meeting*	*Mariott Gaithersburg, Gaithersburg, MD*	*albert.opdenaker@science.doe.gov*
17-18 Sept 2002	*ISOFS Workshop*	*General Atomics, San Diego, CA*	*dahlburg@fusion.gat.com*
2-4 Oct 2002	*ARIES Meeting*	*PPPL, Princeton, NJ*	*najmabadi@fusion.ucsd.edu*
22-24 Sept 2002	*4th Int'l Conf. Mat'ls Processing Defects*	*Cachan (Paris), France*	*http://www.lmt.ens-cachan.fr/mdp4/*
24-25 Sept. 2002	*FESAC Non-Electric Panel Meeting*	*Hilton Fisherman's Wharf, San Francisco, CA*	*haactj@inel.gov, km3@inel.gov*
14-19 Oct 2002	*IAEA Fusion Energy Conference*	*Lyon, France*	
28-31 Oct 2002	*Engineering Problems of Thermonuclear Reactors (EPTR-7)*	*St. Petersburg, Russia*	*EPTR@niiefa.spb.su* ***and/or*** *http://eptr7.niiefa.spb.su*
30 Oct-1 Nov 2002	*High Power Density Wkshop*	*PPPL, Princeton, NJ*	*kaita@pppl.gov, ying@fusion.ucla.edu*
4-8 Nov 2002	*APEX/ALPS Meeting*	*Prospect House, Princeton Univ., Princeton, NJ*	*tgreenberg@pppl.gov*
11-15 Nov 2002	*APS Div. of Plasma Physics Meeting*	*Orlando, FL*	*http://www.aps.org/meet/DPP2002/index.html*
12 Nov 2002	*APS Science Teachers Day*	*Orlando, FL*	*http://www.pppl.gov/aps_teachers/*

DATE	MEETING	LOCATION	CONTACT
14-15 Nov 2002	APS Plasma Expo	Orlando, FL	http://www.pppl.gov/aps_teachers/
17-21 Nov 2002	15th ANS Topical Mtg on Tech of Fusion Energy (TOFE)—Embedded in ANS Winter Meeting	OMNI Shoreham Hotel Washington, DC	sneadll@ornl.gov **or** http://www.ans.org/meetings/text.cgi?category=0
3-4 Dec 2002	Fusion Power Associates Annual Meeting	Capitol Hill Club Washington, DC	fpa@compuserve.com **and/or** http://fusionpower.org
7-12 Dec 2003	ICFRM-11	Kyoto, Japan	Icfrm.iae.kyoto-u.ac.jp **and/or** http://icfrm.iae.kyoto-u.ac.jp
May/June 2005	ISFNT-7	Kyoto, Japan	sekim@fusion.naka.jaeri.go.jp

Editor's Note:

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