VLT
PLASMA
TECHNOLOGIES
PROGRAM ELEMENT

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Budget Planning Meeting

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by
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Virtual Laboratory for Technology

VLT Plasma Technology Element Mission Statement

- **Mission**
  - *To provide the tools and understanding for creation, confinement and control of high-temperature plasmas*
- **Supporting mission statements for each sub-element**
  - *ECH*
  - *ICH*
  - *Plasma facing components*
  - *Magnets*
  - *Fueling and pumping*

Program element five-year goals follow from the Plasma Technologies top level goal: Achieve and sustain high performance—physics and operations

FUSION POWER DENSITY: $p_f \sim \langle\beta^2\rangle B^4$

BURN CONDITION: $nT\tau \sim (\beta/\chi)\, a^2\, B^2$

MAGNET TECHNOLOGY

- **High performance/low cost: technology for burning plasma or long pulse experiment**
  - **Improved strand, structural materials, measurement methods, design and analysis codes**
- **Develop fusion relevant high temperature superconducting (HTS) conductor and magnet technology**
- **Development of cost effective IFE-HIF focusing magnets**

HEATING AND CURRENT DRIVE

- **Higher power density heating/current drive technologies**
  - **Smaller ICRF antennas**
  - **2 MW, 200 GHz gyrotrons**
- **Improved system reliability, efficiency**
  - **Deliver high power to rapidly changing plasma conditions (ICH)**
  - **Multistage depressed collector high efficiency ECH mode convertors and transmission lines**
- **Real-time heating/current drive control**
  - **Tunable gyrotrons, steerable ECH launchers**
  - **ICH dynamic phase control**
  - ***EBW for heating, current drive and mode suppression***

Five-Year Goals (Cont'd)

FUELING

- **Develop the physics understanding and fueling technology for density and density profile control**
- **Develop low cost fueling physics "tools" for international collaboration and alternate confinement devices**
  - **JET, NSTX, MST, LHD and NCSX**

DISRUPTION MITIGATION

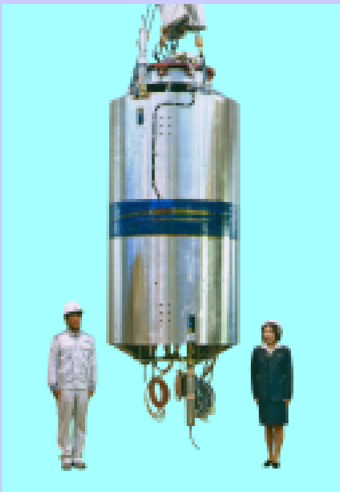
- **Develop massive gas puff and liquid jet technology for rapid plasma quench and disruption mitigation**

PFCs/PMI

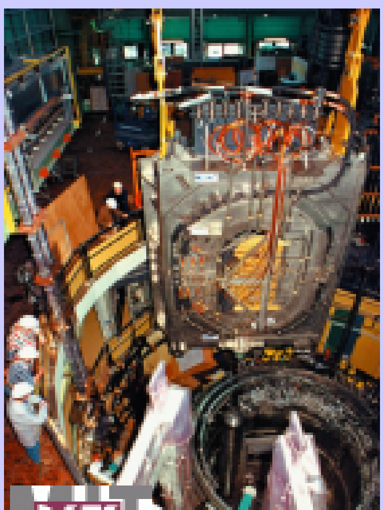
- **Develop integrated theoretical code that couples core plasma to first wall**
- **Demonstrate innovative PFC with 50% improvement in critical heat flux and erosion life time and deploy such a component on a fusion device**
- ***Prove the technical effectiveness of liquid surfaces as plasma facing components and deploy a divertor module on a major fusion device.***
- ***Educate a next generation of fusion scientists and engineers in the plasma facing component field***

Magnet technology Highlights

Model Coil Testing



Nb_3Al Coil Tested at JAERI



TFMC Tested at FzK

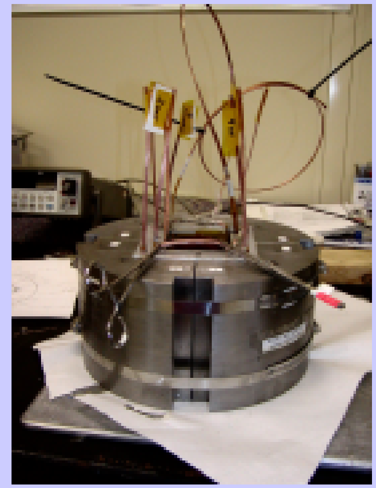
Superconducting Magnets for LDX

NbTi Charging Coil

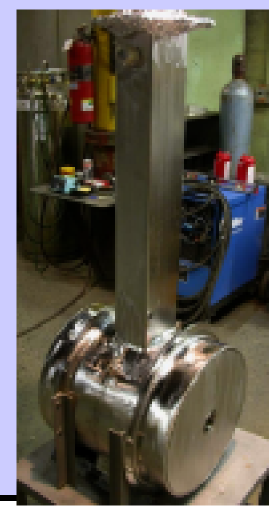
Nb_3Sn Floating Coil

HTS Levitation Coil

Quadrupole Magnets and Cryostat for HCX



Optimized Quadrupole



HCX Cryostat

The University of Wisconsin-Madison
Applied Superconductivity Center

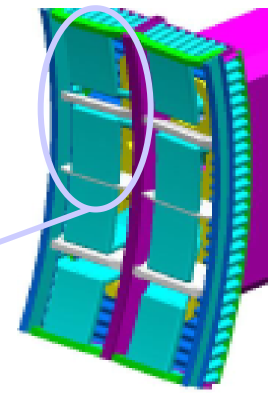
VLT Program Area: Plasma Technologies

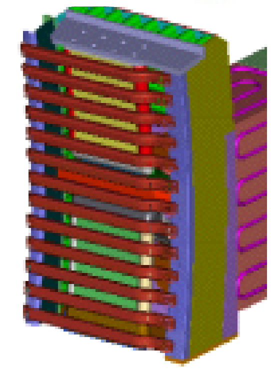
Element	Recent Accomplishments	FY04/05 Deliverables
Magnet Technology	• Completed test campaigns for Nb_3Al Insert Coil at JAERI and TFMC at FzK, and performed analysis of test results showing impact on ITER superconductor design criteria. • A 3D model for supercritical helium flow in 2-channel CICC has been developed and incorporated into a new analysis code: SOLXPORT3D. • Designed, fabricated and will test (April 03) unique cryostat for HCX doublet quadrupole coils for IFE-HIFD. • Completed design and fabrication of second generation, optimized quadrupole prototype focusing magnets for HCX (to be tested end of FY03). • Completed a study on wire drawing and hot isostatic pressing which increases J_c in MgB_2 by a factor of two at 20K. • Performed an irreversible filament cracking study that shows onset between 0.5 and 0.6% bend strain at room temperature for high J_c SMI-PIT Nb_3Sn strands. This indicates that high Jc strands need not be more sensitive to bend strains than CSMC generation strand. • Performed preliminary R&D of modified Incoloy® Alloy 908 showing reduced SAGO sensitivity for heats with Si addition.	• Test of the CICC samples w/ Ti conduit (fabricated in FY03) in the CRPP/SULTAN Facility (Switzerland) – late fall 2003 – early 2004: depends on facility availability. Analyze data and issue test report indicating impact on modified ITER Design Criteria (April 2004). • Participate in test of NbTi PF Conductor Insert (PFCI) at Naka – summer 2004. • Design an experiment to explore the possibility of using the Nb_3Sn strands produced by mixed technologies (including both high and low J_c) in CICC samples for future test in CRPP/SULTAN Facility – January 2004. (Note: Fabrication of mixed strands depends on increased funding to procure new generation of high J_c strands) • Detailed calibration of SOLXPORT3D against other thermohydraulic codes such as FLOWER and M&M (April 2004). • Fabrication and test of the third generation HIF quadrupole (fall 2004). • Testing of the mixed strands CICC in SULTAN (January 2005) depending on facility availability • Test of the second generation IFE doublet in cryostat (Fall 2005)

RF Technology Highlight:
The JET-EP ICRF Antenna and the High Power Prototype (HPP)

- **JET-EP antenna is an advanced ion-cyclotron launcher to be installed on JET in 2004.**
  - **Designed to couple ICRF power at high density (9 MW /m^2) into an ELMy H-mode plasma.**
- **ORNL & PPPL, in collaboration with the EU, are building and testing a high-power prototype of one quadrant.**
- **The JET-EP ICRF Launcher addresses most of the goals of the VLT Program Plan for ICH technology**:
  - **Use limited port space, with a high power density launcher**
  - **Run for long pulses, essentially steady-state**
  - **Work with rapidly varying plasma loads**
  - **Operate over a wide range of density and magnetic fields**
  - **Survive in a reactor environment**
- **This collaboration provides US participation in a test of cutting-edge rf technology in a cost-effective way**
- **The collaboration will continue with commissioning and operation of the full antenna on JET.**

JET-EP ICRF antenna
(Faraday shield not shown)





High-power Prototype antenna

ornl rf technology

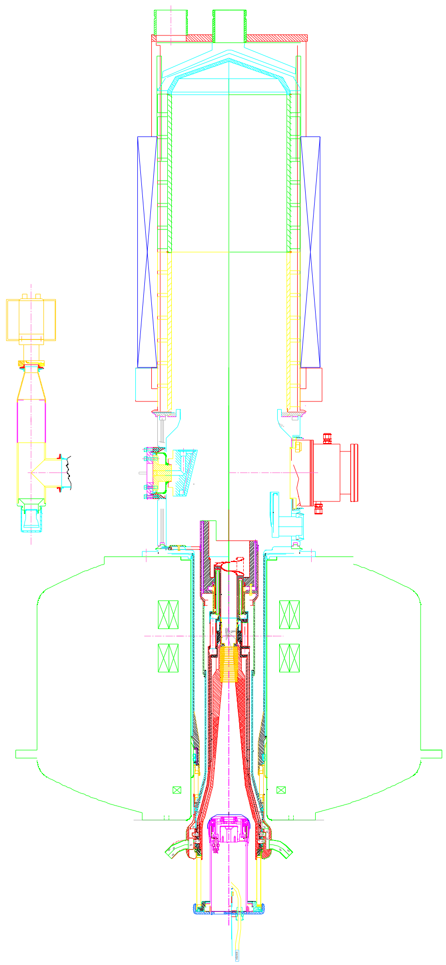
EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

PPPL PRINCETON PLASMA PHYSICS LABORATORY

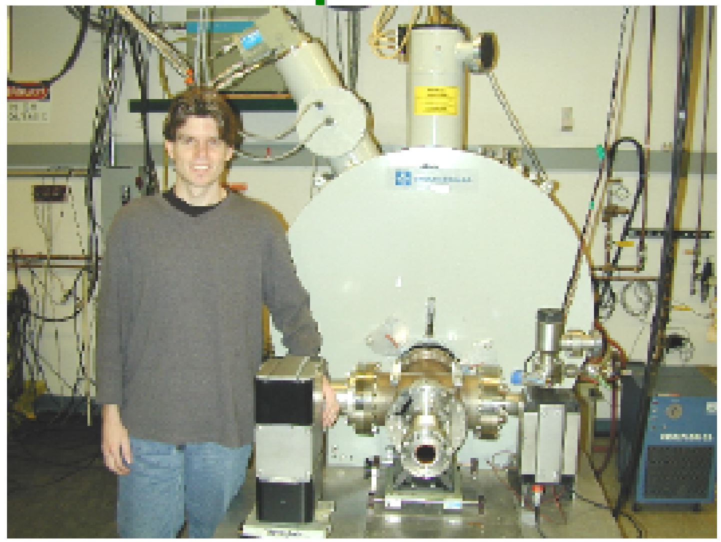
VLT Program Area: Plasma Technologies

Element	Recent Accomplishments	FY04/05 Deliverables
ICRF	• High-power prototype antenna for JET-EP built; testing will start soon. • NSTX ICRF operation raised from 3.5 to 5 MW. Real-time control of phase used to vary current-drive efficiency. • RF loading with significant asymmetry seen and explained on NSTX using RANT3D code and density profiles from ORNL reflectometer.	• Complete final design of advanced antenna for ET (03/04) • Complete modeling evaluation of possible NSTX antenna upgrades (08/04) • Complete fabrication of advanced antenna for ET (03/05) • Complete design review of high-density-plasma rf test facility (02/05) • Obtain data from instrumented antenna on NSTX, C-Mod, or other machine to improve antenna reliability and power handling (06/05)

ECH Highlight: 1.5 MW, 110 GHz Gyrotron Development



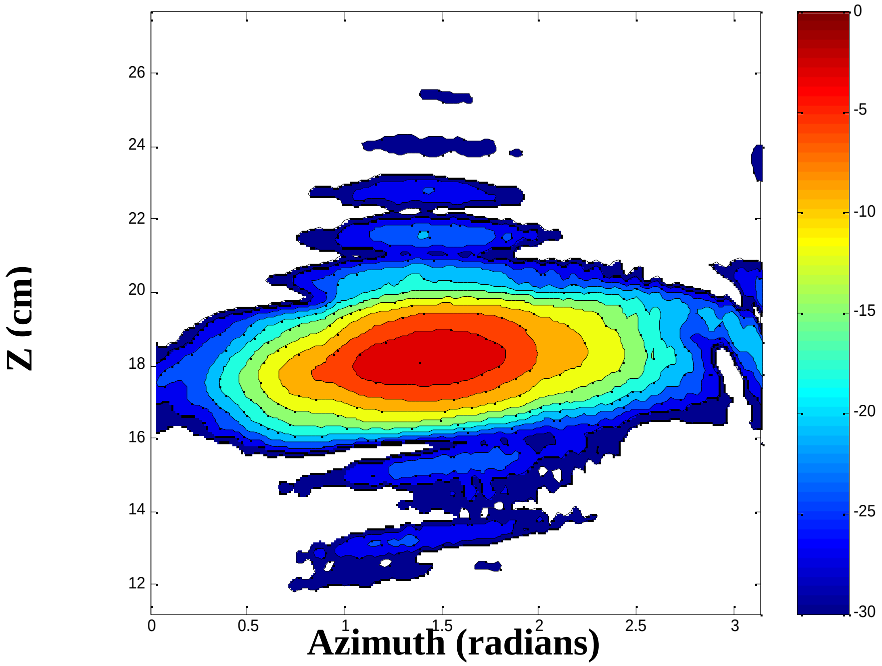
Completed layout of industrial (CPI) tube



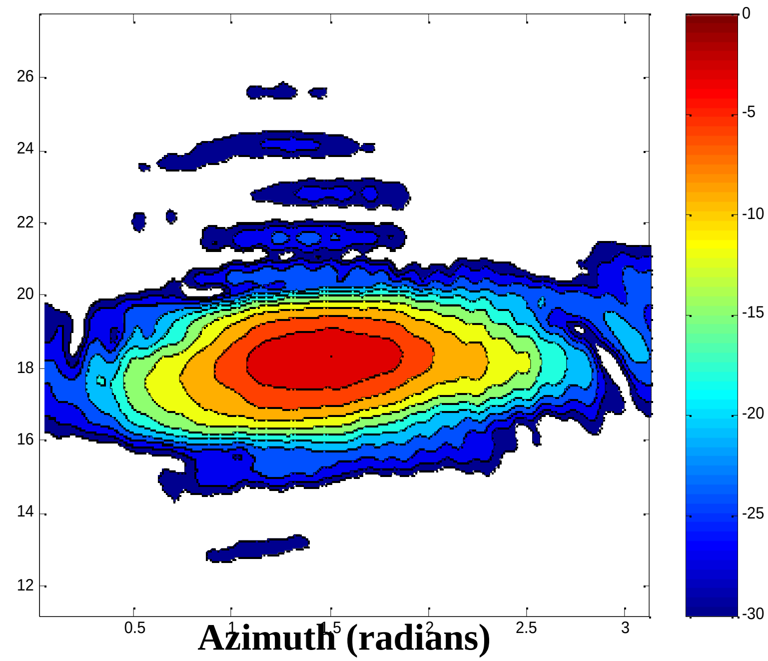
First megawatt power level results obtained in short pulse (3 μs) operation at MIT (James Anderson, graduate student)

- 1.5 MW gyrotron development is advancing.
- First megawatt results obtained at MIT in FY03.
  - Short pulse (3 ms) operation.
- Industrial (CPI) tube parts drawings are complete.
  - Test Results at CPI: March - June, 2004.
- Key issues: higher power, higher efficiency (depressed collector), and new layout concept.
- Supporting research at GA, Univ. MD, Univ. WI.
- Results on this tube are needed to pave the way for future gyrotron development, including ITER.

ECH Highlight: New Internal Mode Converter Theory



Calculated by J. Neilson, CCR Research



Measured at Univ. WI

•New calculation of gyrotron internal mode converter fields using surface integral method by J. Neilson, Calabazas Creek Research.

•Results are in excellent agreement with experiments at Univ. Wisconsin.

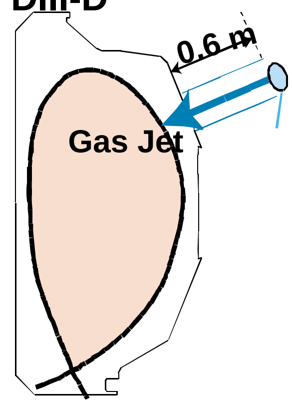
VLT Program Area: Plasma Technologies

Element	Recent Accomplishments	FY04/05 Deliverables
ECH	• Operation of CPI 110 GHz gyrotrons at GA to output power levels of 1 MW in 5-second pulses and 0.6 MW in 10-second pulses. • MW power level operation of prototype, improved reliability (1.5 MW) 110 GHz gyrotron in short pulse operation at MIT. • Advances in ECH launchers, including test of GA 170 GHz remotely steerable launcher at JAERI. • Measurement of cathode emission uniformity at MIT showing the separate contributions of global and local work function spread. • Calculation of microwave fields of a gyrotron internal mode converter using a surface integral technique at Calabazas Creek Research; in excellent agreement with experimental results of Univ. WI.	• Complete testing of prototype 1.5 MW, 110 GHz gyrotron at MIT with internal mode converter and depressed collector (10/03) • Complete fabrication of 110 GHz, 1.5 MW industrial gyrotron at CPI (3/04) • Complete testing of 110 GHz, 1.5 MW gyrotron with a single-stage depressed collector at CPI (6/04) • Design a two-frequency beam-shaping mirror system using a 3 reflector design algorithm, Univ. WI (7/04) • Advances in remotely steerable launcher design to permit steering at larger angles and with the incorporation of miter bends in the line at GA (9/04) • Analyze start-up scenarios for frequency tunable gyrotrons with the code MAGY at Univ. MD (9/04) • Implement two-stage depressed collector in 110 GHz, 1.5 MW gyrotron at CPI (12/04) • Complete testing of 1.5 MW, 110 GHz gyrotron with a two-stage depressed collector (3/05)

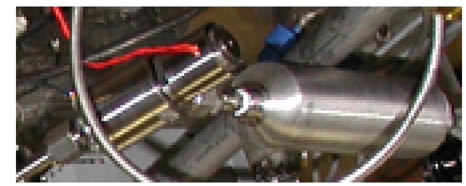
Plasma Fueling Highlights:

(1) Massive Gas Puff for Disruption Mitigation - Mainline Tokamaks
(2) Pellet Injector in a Suitcase - Alternative Confinement Devices
(3) Pellet fueling - H-mode fueling

- **Massive gas puff technology tested in experiments on DIII-D (ITER relevant)**
  - Mitigation of all major disruption effects with high-pressure impurity gas injection (D2, He, Ne, or Ar) has been demonstrated
  - Total plasma energy is radiated isotropically; runaway electrons are eliminated; and halo current stress is reduced by 75-100%

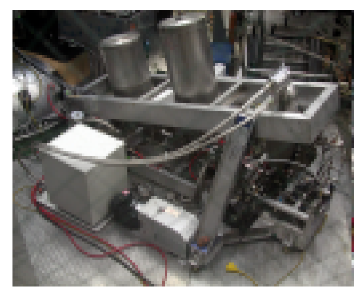


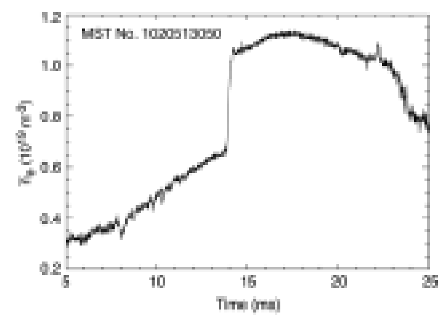
Valve and Reservoir



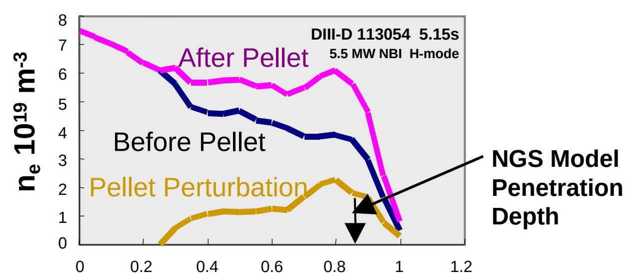
- **A new, portable, stand-alone pellet injection system provides flexible plasma fueling for wide variety of confinement devices**
  - Pipe gun with 4 barrels; cryogenic refrigerator simplifies operation
  - First application on MST, with significant increases (≈100%) in line average density observed in initial experiments

System installed on MST





- **Small (1.8 mm) slow (250 m/s) pellets injected into H-mode from HFS**
  - ≈100% fueling efficiency and deep mass penetration to $\rho = 0.4$

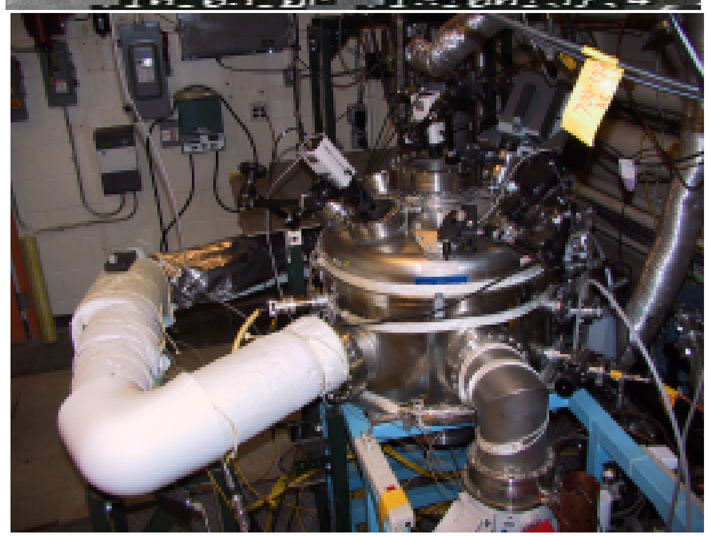


VLT Program Area: Plasma Technologies

Element	Recent Accomplishments	FY04/05 Deliverables
Fueling	• Developed compact pellet injector for alternates, installed/performed initial experiments on MST • Massive gas puff technology for disruption mitigation tested successfully in experiments on DIII-D • Achieved first cool down of hydrogen extruder apparatus with cryocooler • Tested curved guide tube design for vertical launch on JET (found speed limit of ~350 m/s) • Developed high throughput gas valve for IFE (to be used in acceleration of DT targets)	• Characterization of pellet survivability and gas loading with pumped curved guide tube (6/04) • Test of hydrogen extruder with cryocooler(10/03) • Characterization of massive gas puff through curved guide tubes for disruption mitigation(10/03) • Design high-speed compact vertical injector system for HFS fueling of burning plasma proof-of-principle test on DIII-D or JET; FIRE and ITER relevant (12/04) • High throughput guide tube test with ITER relevant pellet flow rates and pumping (4/05) • Complete conceptual design of centrifuge/twin-screw extruder for minimum inventory of tritium; optimum system for burning plasma experiment (7/05)

PFC Highlight: Free Surface Liquid Experiments(LIMITS)

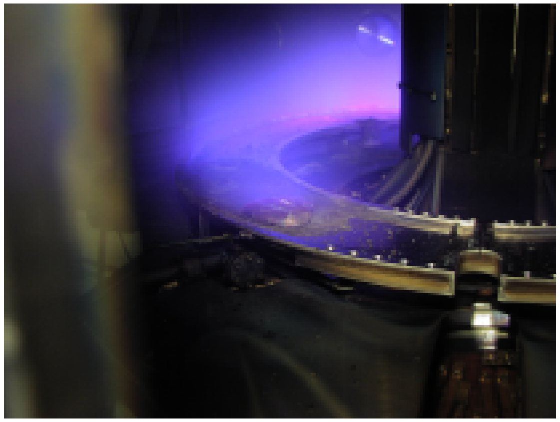
- **Constructed Liquid Metal Integrated Test System (LIMITS)**
- **Operated with a flowing liquid Li jet (5-mm diameter) at 10 m/s**
- **MHD experiments will start in 3/03**

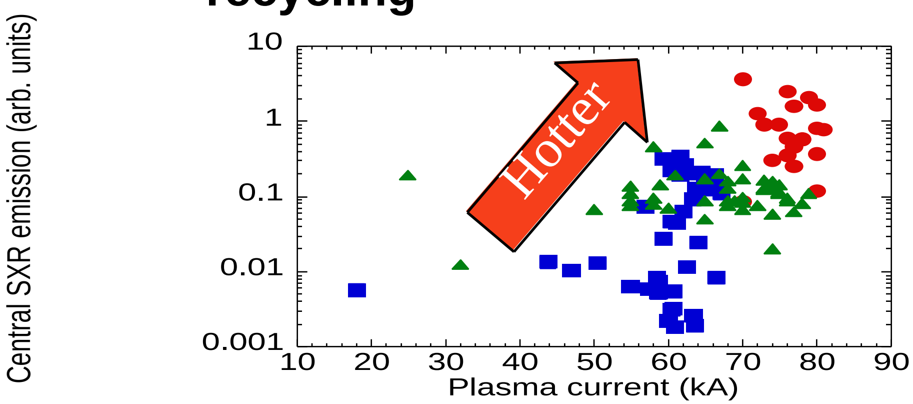


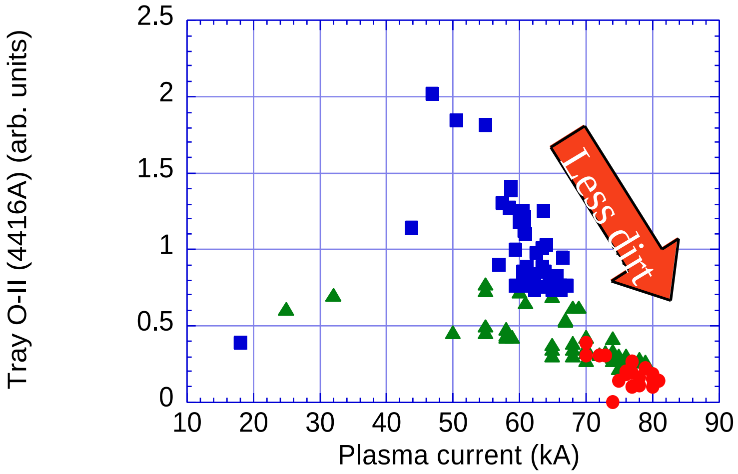
Sandia National Laboratories

PFC Highlight: CDX-U Lithium Technology for MFE

- **Lithium under argon glow discharge cleaning in stainless steel tray for fully toroidal lithium limiter**
- **Best plasma performance achieved with liquid lithium limiter:**
- **Highest core temperature and lowest impurities and recycling**







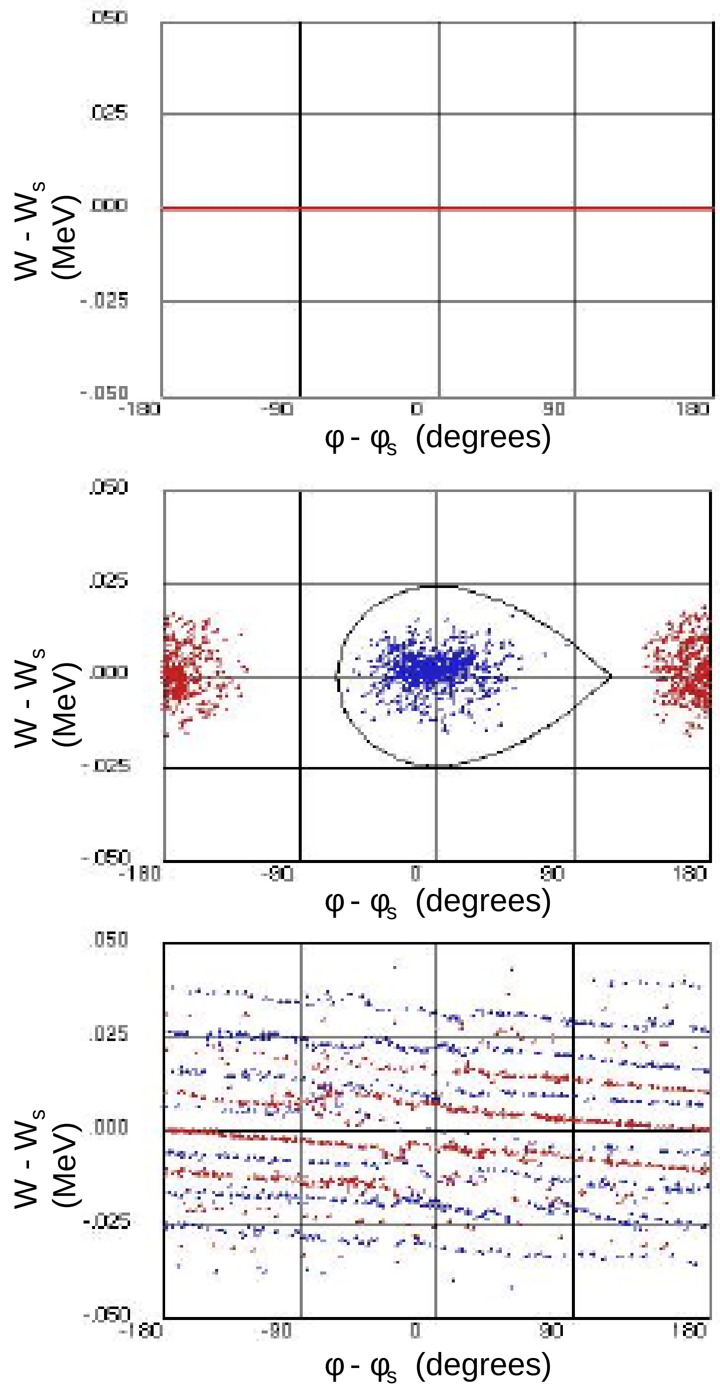
▲ Bare stainless steel tray ▲ Cold lithium ● Liquid lithium (250° C)

VLT Program Area: Plasma Technologies

Element	Recent Accomplishments	FY04/05 Deliverables
PFC/PMI	**Plasma Facing Components** • Completed the construction of LIMITS facility (SNL) • Concept development for liquid surface module in NSTX. (ORNL) • CDX-U operation with a liquid lithium tray limiter (PPPL). Developed techniques for production of large area clean liquid lithium surfaces for ALPS Program. (UCSD) **Plasma Materials Interactions** • Completed study of hydrogen refilling of the codeposited layer on graphite after depletion by annealing (SNL) • HEIGHTS model development and study of helium trapping in flowing liquid metal divertors. (ANL) • Construction of FLIRE and measurements of retention/diffusion of He in flowing liquid lithium (UIUC)	• **Complete MHD testing of free surface Li liquid flow in NSTX magnetic fields with externally applied currents (SNL) 9/04** • **Determine, through controlled experiments, hydrogen isotope adsorption/desorption properties of liquid metal materials proposed for use in ALPS components (Li, Ga, and Sn). Ion impact desorption cross sections will be measured to quantify recycling rates during plasma exposure. (SNL) 6/04** • **Carry out studies of redeposited carbonaceous films generated by beryllium seeded plasmas. PISCES-B in collaboration with IPP Garching and KFA Juelich laboratories. (UCSD) 9/04** • **Initiate R&D effort to support US role in ITER PFC fabrication (SNL) 6/05** • **Conduct final MHD tests in preparation for NSTX liquid module (SNL) 9/05**

VLT Program Area: Plasma Technologies

Element	Recent Accomplishments	FY04/05 Deliverables
PFC/PMI (continued)	**Plasma Materials Interactions** • Carried out beryllium seeding experiments in PISCES-B hydrogen plasmas. (UCSD) **Plasma Edge Measurements and Modeling** • Erosion/redeposition analysis of DIII-D/DiMES lithium experiments. (ANL) • In FY03 expose Li-DiMES experiment in DIII-D. (GA) • Predicted strong particle control and low core contamination from NSTX Li module (LLNL) • Molecular Dynamics modeling of low-energy hydrocarbon reflection from “soft” and “hard” carbon layers. (UIUC)	• **Complete studies of tungsten beryllium mixed material layer formation and redeposition in PISCES-B and SNL-TPE. (SNL & UCSD) 9/05**



PARMTEQ Simulation Demonstration of Feasibility of 1 MeV Neutralized Ion Beam Production

Input: 100 keV DC beam of 10 mA D^+ and 10 mA D^- injected into 1 GHz RFQ accelerator.

Acceleration: RFQ traveling wave bunches beam in alternating groups of positive (red) and negative (blue) ions. Beam energy is raised to 1 MeV as wave velocity increases.

Mixing: Longitudinal field is relaxed, and beam debunches. 1 MeV neutralized ion beam is attained. Final beam density is > 1 A/cm^2, and total accelerator length is < 1 m.