University of California Lawrence Livermore National Laboratory

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Summary of Preliminary Coordination Activities in Plasma Boundary Interfaces Research

V. A. Soukhanovskii for NSTX

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NSTX, C-Mod, and DIII-D National Tokamak Planning Workshop
Massachusetts Institute of Technology
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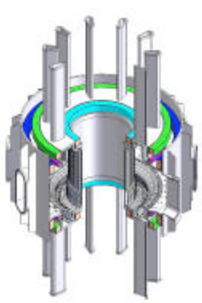
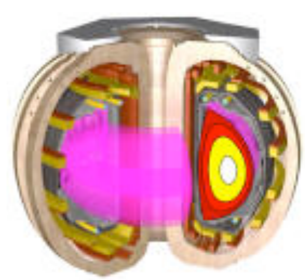
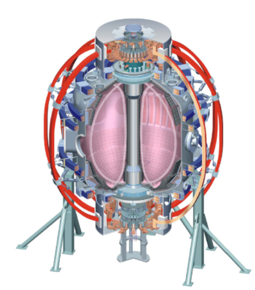
Boston, MA

FESAC Priorities Subpanel Report defined major research thrusts in Plasma Boundary Interfaces area

- **FESAC Priorities Subpanel Report on "Scientific Challenges, Opportunities, and Priorities for the U.S. Fusion Energy Sciences Program", April 2005**
  - » **Thrust 1: Pedestal**
  - » **Thrust 2: Scrape-off layer**
  - » **Thrust 3: First wall and divertor**
  - » **Thrust 4: Composition of divertor and first wall**

Alcator C-Mod, DIII-D, and NSTX provide facilities for both common and complementary Boundary studies

- **Alcator C-Mod - compact, high-field tokamak with Mo/W PFCs**
  - ✓ High parallel power density (500 MW/m^2)
  - ✓ Divertor plasma densities spanning that of ITER
  - ✓ Short mean free paths in SOL and divertor ideal for accessing ITER regimes
  - ✓ Bulk high-Z Plasma Facing Components

- **DIII-D**
  - ✓ All Graphite Wall, Density Control
  - ✓ Shape Flexibility- can match ITER's shape
  - ✓ Pedestal collisionalities spanning ITER's, core performance leading the way to ITER
  - ✓ Controlled/Suppressed ELM regimes
  - ✓ Pulse length approaching first order wall time constants

- **NSTX - spherical torus with novel power and particle handling techniques**
  - ✓ Low magnetic field, low aspect ratio configuration effects
  - ✓ Shape flexibility - wide ranges of triangularity and elongation
  - ✓ Novel lithium power and particle handling techniques for future devices
  - ✓ Unique edge plasma regimes (enhanced pedestal H-mode, type V ELMs?)
  - ✓ ITER-relevant divertor heat fluxes ($q_{perp} \leq 10$ MW/m^2)

Existing collaborations between Alcator C-Mod, DIII-D, and NSTX are extensive

- **Alcator C-Mod - DIII-D**
  - ✓ SOL radial transport
  - ✓ Disruption mitigation with massive gas injection
  - ✓ Deposition studies
  - ✓ Pedestal Scaling/Fueling
- **Alcator C-Mod - NSTX**
  - ✓ Blob structure, transport and origin, comparison with turbulence models
  - ✓ Comparison of small ELM characteristics
  - ✓ RF edge effects (RF-driven sheaths, SOL convective cell imaging)
- **DIII-D - NSTX**
  - ✓ ELM control with RMPs
  - ✓ Edge stability analysis and modeling
  - ✓ Edge turbulence studies

» **A number of collaborative efforts are also ongoing through ITPA PEP and DSOL groups**

ITPA PEP group activities

PEP-1+3	Dimensionless identity experiments in JT-60U and JET: studies of ripple effects and rotation	G Saibene, V Parail, J Lonnroth and A Loarte (EFDA JET); N Oyama, H Urano, K Kamiya, K Shinohara (JAERI)	JET, JT-60U
PEP-2	Pedestal gradients in dimensionally similar discharges and their dimensionless scaling	A. Loarte, M. Kempenaars, G. Saibene, M. Beurskens, (JET) T. Osborne, A.Leonard, M. Fenstermacher (DIII-D), L. Horton T. Eich, W. Suttrop, (AUG)	JET, **DIII-D**, AUG
PEP-4	Stability analysis with improved edge treatment	L Lao, Y Kamada	AUG, **DIII-D**, JT-60U, MAST
PEP-5	Dimensionless identity experiments with JT-60U type II ELMy H-modes in DIII-D	T Osborne, T Hatae	DIII-D, JT-60U
PEP-6	Pedestal Structure and ELM stability in DN (MAST, NSTX and AUG)	H. Meyer(MAST), L. Horton (AUG), I. Nunes(JET), R. Maingi (NSTX)	AUG, MAST, **NSTX**, JET
PEP-7	Pedestal width analysis by dimensionless edge identity experiments on JET, ASDEX Upgrade, Alcator C-Mod and DIII-D	G P Maddison*/ I Nunes† – JET, W. Suttrop, L. Horton (AUG), A Hubbard, J. Hughes (C-Mod), A. Leonard, T. Osborne, R. Groebner (DIII-D)	JET, AUG, **C-Mod, DIII-D**
PEP-8	Parameter similarity studies Quiescent H-mode regimes)	TBD	AUG, **DIII-D**, JET, JT60U
PEP-9	NSTX-MAST-DIII-D pedestal similarity	T Osborne, A Kirk, R Maingi	**DIII-D,** MAST**, NSTX**
PEP-10	The radial efflux at the mid-plane and the structure of ELMs (AUG and MAST)	Andrew Kirk, Albrecht Herrmann, J. Terry	AUG, MAST, **C-Mod**
PEP-11	Dimensionless comparison of L-H threshold and H-mode pedestals on C-Mod and ASDEX Upgrade	W Suttrop, F Ryter, A Hubbard	AUG, **C-Mod**
PEP-12	Comparison between C-Mod EDA and JFT-2M HRS regimes	K. Kamiya, N. Oyama, (JAERI) and A. E. Hubbard	**C-Mod**, JFT-2M
PEP-13	Comparison of small ELM regimes in JT-60U and AUG and JET	N. Oyama, H. Urano (JT-60U), L.D. Horton/ W. Suttrop (AUG), G. Saibene, A. Loarte (EFDA-JET)	AUG, JT-60U, JET
PEP-14	QH/QDB with Co/Counter Rotation Control IN JT-60U AND DIII-D	P. Gohil, L. Lao (DIII-D), N. Oyama, Y. Sakamoto (JT-60U)	**DIII-D**, JT-60U
PEP-15	Testing influence of particle source on pedestal density profile	R Groebner, L D Horton	MAST, JT-60U
PEP-16	C-MOD/NSTX/MAST SMALL ELM REGIME COMPARISON	A. Hubbard, R. Maingi, H. Meyer	**NSTX**,MAST,**C-Mod**
PEP-17	Small ELM regimes at low pedestal collisionality	N. Oyama, Y. Kamada, H. Urano, K. Kamiya (JT-60U), T. Osborne, A. Leonard (DIII-D)	JT-60U, **DIII-D**
PEP-18	Comparison of Rotation Effects on Type I ELMing H-mode in JT-60U and DIII-D	Y. Kamada (JT-60U), A. Leonard (DIII-D)	JT-60U, **DIII-D**
PEP-19	Edge transport under the influence of resonant magnetic perturbations in DIII-D and TEXTOR	T. Evans, M. Fenstermacher, R. Moyer, I. Joseph (DIII-D) B. Unterberg, H. Frerichs, D. Harting, M.W. Jakubowski, M. Lehnen, D. Reiter, O. Schmitz, D. Schega (TEXTOR)	**DIII-D**, TEXTOR
PEP-20	Documentation of the edge pedestal in advanced scenarios	Pedestal: C. Maggi (AUG), R. Sartori (JET), R. Groebner (DIII-D), Y. Kamada/ N. Oyama(JT-60U) SSO TG: G. Sips (AUG), R. Sartori (JET), T. Luce (DIII-D), S. Ide /T. Suzuki (JT-60U)	JET, **DIII-D**, AUG, JT60U

Table courtesy of A. Leonard (GA)

2007 Proposals for IEA/ITPA DSOL inter-machine experiment : 13 continue+2 new

DSOL-1 Scaling of Type-1 ELM energy loss and pedestal gradients through dimensionless variables (Loarte)
Proposal: JET, **DIII-D**, ASDEX Upgrade

DSOL-2 Hydrocarbon injection to quantify chemical erosion (Philpps)
Proposal: TEXTOR, JET, AUG, JT-60U, **DIII-D**

DSOL-3 Scaling of radial transport (Lipschultz)
Proposal: **C-Mod**, MAST, AUG, **DIII-D**

DSOL-4 Comparison of disruption energy balance in similar discharges and disruption heat flux(A. Loarte, D. Humphreys, G.Pautasso) Proposal: JET, **DIII-D**, ASDEX Upgrade, MAST

DSOL-5 Role of Lyman absorption in the divertor (Lisgo) Proposal: **C-Mod**, JET

DSOL-8 ICRF Conditioning for hydrogen removal (Ashikawa)
Proposal: LHD, HT-7, EAST, AUG, TEXTOR

DSOL-9 C-13 injection experiments to understand C migration (Philipps)
Proposal: JET, **DIII-D**, TEXTOR, ASDEX-Upgrade

DSOL-11 Disruption mitigation experiments (Whyte)
Proposal: **DIII-D**, Tore Supra, JET, **Alcator C-Mod**,TEXTOR, AUG

DSOL-12 Oxygen wall cleaning (Stangeby) Proposal: TEXTOR, HT-7, EAST, **DIII-D**

DSOL-13 Deuterium codeposition with carbon in gaps of plasma facing components (Krieger)
Proposal: data from AUG, TEXTOR, MAST, **DIII-D**, ToreSupra, **C-Mod**

DSOL-14 Multi-code, multi-machine edge modelling and code benchmarking (Coster)
Proposal: Codes only (Database in AUG, JET, **DIII-D**, **C-Mod**, JT-60U is required)

DSOL-15 Inter-machine comparison of blob characteristics (Terry)
Proposal: **C-Mod**, PISCES, **DIII-D**, JT-60U, VTF, JET, AUG, TJ-II, VINETA, **NSTX**, TEXTOR

DSOL-16: Determination of the poloidal fueling profile (Groth) Proposal: **DIII-D**, AUG, JET, MAST, **C-Mod**, JT-60U

DSOL-17: Cross-machine Comparisons of Pulse-by-Pulse Deposition (Skinner) Proposal: **NSTX**, AUG, JET, TEXTOR

DSOL-19: Impurity generation mechanism & transport during ELMs for comparable ELMs across devices (Loarte)
Proposal: JET, DIII-D, ASDEX-Upgrade, Alcator C-mod, JT-60U, MAST

List courtesy of M. Groth (LLNL @ GA)

Proposed themes for future research coordination and collaborative activities

1. Particle balance and inventory studies
2. Edge localized mode (ELM) control, with emphasis on ELM suppression using resonant magnetic perturbation (RMP)
3. Scrape-off layer heat flux distribution physics
4. Plasma-material interaction (PMI) diagnostic development

Collaboration in Particle balance and inventory studies would benefit all three facilities

» **Control of D/T fuel and retention is a critical issue for future devices**

- ✓ **Complementary studies** of
  - D recycling, retention mechanisms
  - pumping
  - fueling

  with various PFC materials (C, Li, Mo / W) and pumping techniques

- ✓ **Proposed joint Alcator C-Mod, DIII-D, and NSTX milestone in FY 2009**

- ✓ **Development of common approach to experiments and analysis**
  - impact of wall conditioning techniques (boronization, glow discharge cleaning)
  - particle (gas) balance models
  - interpretation of diagnostics (e.g. "window frame technique")

Proposed three facility FY 2009 milestone reflects importance of particle balance and inventory studies

"Experiments on Alcator C-Mod, DIII-D, and NSTX in FY09 will address the issue of understanding particle control and hydrogenic fuel retention in tokamaks. Used together, these facilities offer a unique opportunity to identify the fundamental processes governing particle balance by systematically investigating a combination of divertor geometries, particle exhaust capabilities, and wall materials. Alcator C-mod operates with high-Z metal walls, NSTX is pursuing the use of lithium surfaces in the divertor, and DIII-D continues operating with all graphite walls. Edge diagnostics measuring the heat and particle flux to walls and divertor surfaces, coupled with plasma profile data and material surface analysis, will provide input for validating state-of-the-art simulation codes. The results achieved at the major facilities will be used to improve extrapolations to planned ITER operation."

Collaboration in Particle balance and inventory studies would benefit all three facilities

- **Alcator C-Mod**
  - D/T retention and recovery studies with Mo (and W) PFCs ongoing
  - New upper divertor cryopump: particle throughput effect on retention?
  - Plans: enhance diagnostics --> better extrapolation to ITER / DEMO
- **DIII-D**
  - All-carbon PFCs, divertor cryopumps
  - Determination of the poloidal fueling profile ongoing
  - Role of poloidal drifts in particle exhaust
  - Hot Walls - the role of surface temperature on particle retention
- **NSTX**
  - Effect of lithium-coated carbon walls and liquid lithium divertor (LLD) on density, plasma performance, recycling, divertor heat flux
  - Advanced fueling techniques (supersonic gas jet, compact toroid injection)

Edge Localized Mode control with emphasis on Resonant Magnetic Perturbation

» **Control ELM particle and energy losses with minimal degradation in core and pedestal**

- ✓ Type I ELMs can limit divertor and first-wall PFC lifetime
- ✓ ELM control techniques include RMP, pellets, and development of small ELM regimes
- ✓ Implement common modeling / analysis tools across devices

ELM control with emphasis on RMP

- **Alcator C-Mod**
  - Considering installing non-axisymmetric perturbation coils
  - Emphasis on controlling / understanding particle flux across edge transport barrier
  - ELM effects: Use high C-Mod energy density to approach ablation limit of films
- **DIII-D**
  - I-coil for RMP, C-coil for EFC
  - Demonstrated Type I ELM suppression using n=3 RMP for a range of shapes and collisionalities, studied impurity transport, plasma rotation during RMP
  - New RMP high field side coils - edge localized high m,n modes
- **NSTX**
  - 6 external midplane coils for RWM/EFC/RMP, considering 2 to 4 rows of 12 internal off-midplane coils for RMP/RWM/EFC
  - n = 1-6 RMP for ELM control (high-n n=6 low field side unique capability)
  - Small ELM (Type V) regimes at lower collisionality and stronger shaping
  - Impact of ELMs on liquid lithium surface

Scrape-Off layer heat flux distribution

» **Understanding is critical for divertor and wall heat flux management in present and future devices**

- ✓ **Study q_{peak}, λ_q, λ_T, λ_n as functions of key plasma parameters (n_e, ν^*, P_{SOL}, I_p, B_t) to develop empirical scalings**
- ✓ **Study *e*-*i* equipartition and role of electron / ion conduction**
- ✓ **Steady-state SOL heat and particle radial transport and turbulence models**
- ✓ **Study the role of plasma flow and convective parallel transport**
- ✓ **Comparison of various experimental techniques for q_{peak}, λ_q, λ_T, λ_n measurements (e.g. IR cameras, Langmuir probes, thermocouples)**

Scrape-Off layer heat flux distribution

- **Alcator C-Mod**
  - » Improve diagnosis of heat flux pattern in divertor
  - » Main ion species upstream: role of ion conduction in heat removal

- **DIII-D**
  - » Install 3 IR/Visible TV periscopes for full toroidal/poloidal coverage
  - » Install thermocouple calorimeters (first set ready for 2008)
  - » Divertor Bolometer array
  - » High resolution SOL/pedestal profiles and fluctuation measurements
  - » Considering Gas puff imaging system for transport and turbulence studies

- **NSTX**
  - » Experimental data for λ_q, λ_T not consistent with Kallenbach $\lambda_T \sim R$ tokamak scaling - role of *a*?
  - » FY 2008 milestone - study variation and control of heat flux in SOL, substantiated by an excellent SOL/divertor profile diagnostic set and turbulence measurements
  - » Attempt to control SOL transport by induced poloidal electric field

Plasma - Material Interaction diagnostic development

» **Provide test environment for *in-situ* PMI diagnostics development**
  - ✓ **Accurate surface diagnostics critical for PFC erosion, retention, and deposition studies**
  - ✓ **Tritiated dust creation is a safety issue for future devices**

- **Alcator C-Mod**
  - » Surface-science station installed 2007: Extensive boronization studies
  - » Proof of principle new PSI diagnostics
    - accelerator (RFQ) in-situ ion beam analysis
    - Radio-isotope in-situ surface analysis (ARRIBA)
- **DIII-D**
  - » DiMES and MiMES probe program
  - » Quartz microbalance installation underway
  - » Improved detector for high resolution spectrometer
  - » Ongoing dust studies (DiMES, Video Imaging, Mie Scattering)
  - » Considering In-situ plasma facing surface deposition measurements
- **NSTX**
  - » Ongoing dust transport studies with unique dust diagnostics - stereoscopic imaging, electrostatic dust detectors
  - » Considering DiMES-like system
  - » Quartz microbalances

Proposed research themes address Scientific Priorities for the U.S. Fusion Energy Sciences Program

1. Particle balance and inventory studies
2. Edge localized mode control, with emphasis on ELM suppression using resonant magnetic perturbation
3. Scrape-off layer heat flux distribution physics
4. Plasma-material interaction diagnostic development

Note:

» **Process is starting, much work needed to coordinate diagnostic, experimental and theoretical activities in the four areas**

» **Theory and Modeling contributions TBD**

Appendices

Rational for Proposed themes for future research coordination and collaborative activities

- Criteria
  - » Opportunity for starting new proposals
  - » Research areas where all three facilities can contribute
  - » Research areas of US expertise
  - » Areas critical for burning plasma research

Tokamak λ_{Te} scaling

"Multi-machine comparisons of H-mode separatrix densities and edge profile behavior in the ITPA and Divertor Physics Topical Group", by A. Kallenbach, N. Asakura, A. Kirk, A. Korotkov, M.A. Mahdavi, D. Mossessian, G.D. Porter, Journal of Nuclear Materials 337–339 (2005) 381–385