International Activities

complementarity and synergy with the US domestic fusion program

presented at the DOE/OFES Budget and Planning Meeting

Wednesday, March 13, 2002

by Ned Sauthoff
on behalf of the US fusion community's participants in international collaborations

Basis for Strategy and Tactics in International Collaborations

- **"Technical Opportunities for International Collaborations by the U.S. Fusion Program" (11/97)**
  - and the resultant "DOE Strategic Plan for Fusion International Collaborations"
- **"Enhancing the Effectiveness of International Collaborations" (3/99)**
- **FESAC reports on goals and structure (1999)**
  - and the resultant DOE/OFES Strategic Plan
- **Integrated Program Planning Activity (12/2000)**
  - mostly
    - IPPA Goal 3 on high-performance plasmas (tokamaks) and
    - IPPA Goal 2 on innovative configurations (stellarators)

Programmatic Directions for International Collaborations

- **"Future international collaborations should be developed as an integral part of the overall US fusion program planning process --- not independently."**
- **" The activities should be guided by identification of the most promising opportunities for achieving US program goals by utilization of domestic and international facilities and by participation in foreign programs."**
- **" The formality of the planning process must be graded, with minimal oversight of the choices by individual investigators to pursue their research through international collaborations and with formal joint planning for the large-scale activities."**

Major Areas for International Collaborations ('99 report)

- **Tokamaks:**
  - burning plasmas, energetic particle effects, and size-scaling (JET, JT-60; ITER, IGNITOR)
  - long-pulse AT studies (JET, JT-60, ASDEX, ToreSupra; KSTAR, HT-7U)

- **Alternate concepts:**
  - stellarators (LHD, Wendelstein),
  - ST's, RFP

- **Inertial fusion (Japan, France, Britain, Russia):**
  - fast igniter, heavy ions, high energy density physics
  - ion bunching, plasma lens, laser drivers

- **Technology [~$1640k in FY02]:**
  - material irradiation,
  - RF (JET, KSTAR),
  - power/particle (JET, KSTAR, LHD),
  - blankets, magnets (ITER, KSTAR, MAST), operations and tritium (JET)

ITPA Topical Group Structure

Transport and Internal Barrier Physics

Edward Doyle (**US**) Vladimir Mukhovatov* (RF)

Confinement Database and Modelling

Wayne Houlberg (**US**) Alexei Polevoi* (RF)

Edge and Pedestal Physics

Yutaka Kamada (JA) Tom Osborne (**US**)

Scrape-off-layer and Divertor Physics

Nobuyuki Asakura (JA) Bruce Lipschultz (**US**)

MHD, Disruption and Control

Otto Gruber (EU) Yuri Gribov* (RF)

Energetic Particles, Heating and Steady State Operation

renamed “Steady State Operation and Energetic Particles”

Claude Gormezano (EU) Kenro Miyamoto (JA)

Diagnostics

Tony Donne (EU) Alan Costley* (EU)

ITPA's High-priority physics R&D for 2002

- **MHD, Disruption and Control**
  - NTMs (onset, hysteresis, stabilization by ECCD, impacts) at increased-δ; need for modulation feedback
  - RWM stabilization by plasma rotation (BP-relevant?), error-field reduction, and feedback coils
  - sawtooth control by ECRH and ECCD
  - tolerable ELMs
  - disruption mitigation by neutral point, disruption severity at lower-q_edge, killer-pellets/gas-puff
  - disruption database with pre-disruption-state and precursor inputs
  - real-time current profile control (LH, EC, NI)

- **Scrape-off-layer and Divertor Physics**
  - understanding the effect of ELMS and disruption on divertor and edge
  - tritium retention
  - understand SOL plasma interaction with main chamber
  - high-density separatrix density and divertor performance

ITPA's High-priority physics R&D for 2002

- **Transport and Internal Barrier Physics**
  - ITB-formation and sustainment with $T_e \sim T_i$, low rotation, high density, flat density profile, …
  - develop, manage and analyze the new ITB database (profile and global)
  - critical tests of simulations of ion transport

- **Confinement Database and Modelling**
  - identify experiments to improve the conditioning of the databases
  - identify additional variables needed in databases
  - unify definitions of database parameters
  - develop tools for submitting and accessing data
  - test sensitivity of 1-D models to magnetic and rotational shear
  - scaling of confinement saturation and degradation with density

- **Edge and Pedestal Physics**
  - predictive capability of pedestal structure through profile modeling
  - physics based empirical scaling of pedestal parameters
  - predictive capability for ELM control, ELM dynamics, small-ELM/Quiescent modes

ITPA's High-priority physics R&D for 2002

- **Steady State Operation and Energetic Particles**
  - assess in existing experiments potential for steady state burning plasma operation
  - systematic studies of fast-particle-induced collective modes at low/reversed magnetic shear
  - compare model predictions against experimental data (ECCD at r/a~0.4, ICRH coupling, off-axis NBCD)

- **Diagnostics**
  - q(r)-profile by MSE, polarimeter, or other technique
  - divertor-region diagnostic requirements and techniques
  - impacts of radiation-induced electromotive force on magnetic measurements (is this a problem for ITER or FIRE?)
  - lifetime of plasma-facing mirrors (erosion and deposition)
  - measurements of confined and escaping alpha particles

Observations on the ITPA

- **Recognized emergence of high-priority integration between groups:**
  - Special focus on Steady-State integration
  - Need for tools to integrate areas:
    - Integrated modeling (US a recognized leader)
    - US support for MDS-Plus databases

- **Party actions:**
  - US participation in ITPA meetings has been strong
  - In other parties, the ITPA's High Priority R&D plays a strong role in the planning of the programs

- **New ITPA web site: www.aug.ipp.mpg.de/itpa/**

Totals ($k) by facility

Facility	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
JET	2487	2691	2303	2691	2463
JT-60U	325	247	0	230	0
KSTAR	378	368	362	371	522
other tokamaks	519	527	200	527	682
stellarators	440	406	388	414	461
	4149	4239	3253	4233	4128

EU program status (D. Campbell)

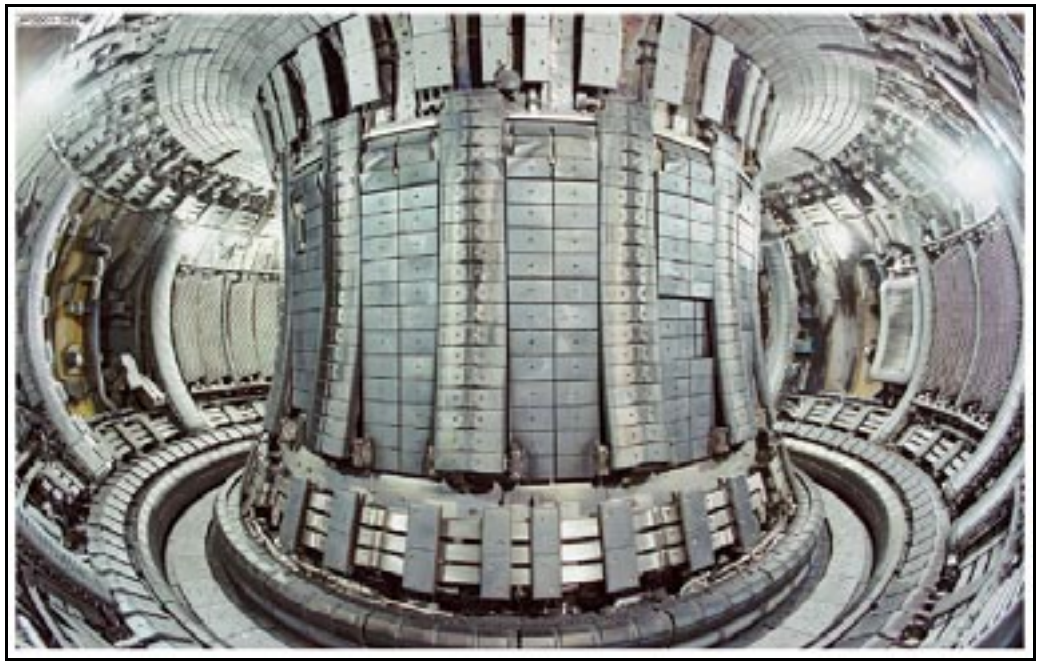
- **The procedure for approving the research budget for the 6th Framework Programme (FP6: 2003-2006) is nearing conclusion:**
  - fusion budget of 750MEuro expected
  - this includes contribution to expected start of ITER construction

- **The priorities within the EU fusion programme for FP6 will be more strongly focussed on ITER-relevant activities in physics and technology**

- **There is increasing level of collaboration between the European fusion laboratories to exploit the major facilities**
  - JET has run very effectively under EFDA for past two years with European Task Forces organizing the scientific programme
  - ASDEX Upgrade, FTU, TEXTOR and Tore Supra have all initiated the process of opening experimental programmes to other EU laboratories

EFDA-JET status and plans

- **MkIIGB divertor septum now removed**

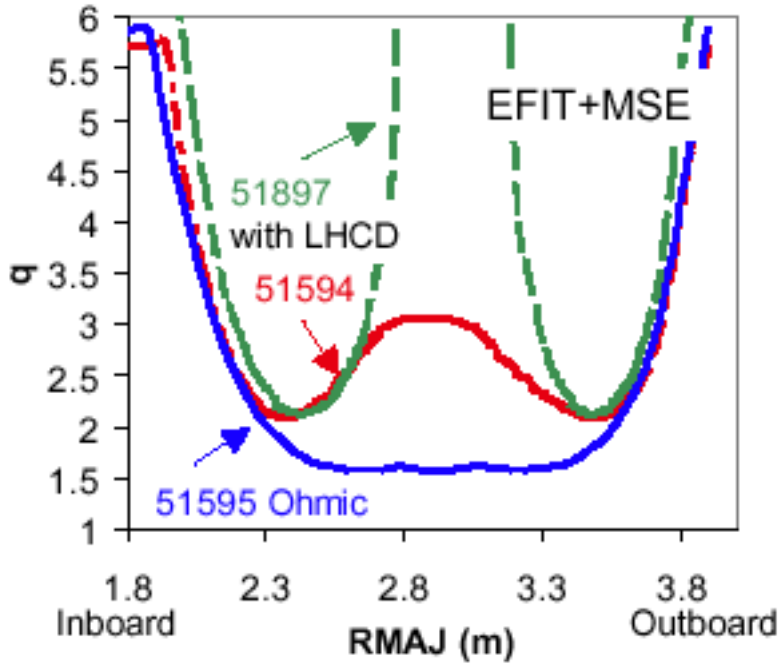


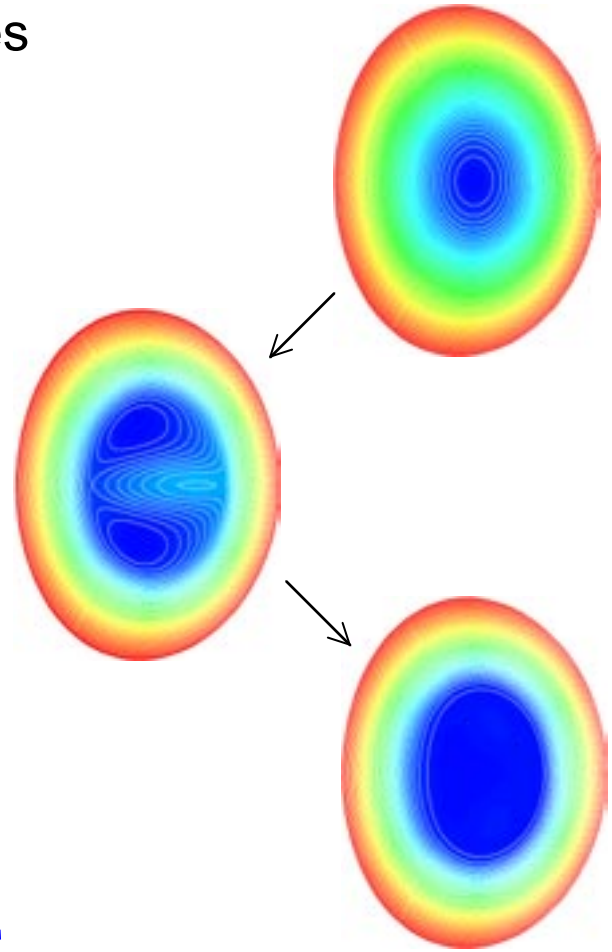
- **NBI power upgrade to ~25MW**

- **Numerous diagnostics also being upgraded**

JET Current-Hole Experiments Lead to New Insight on Current Evolution

MSE data: B. Stratton (PPPL), N. Hawkes

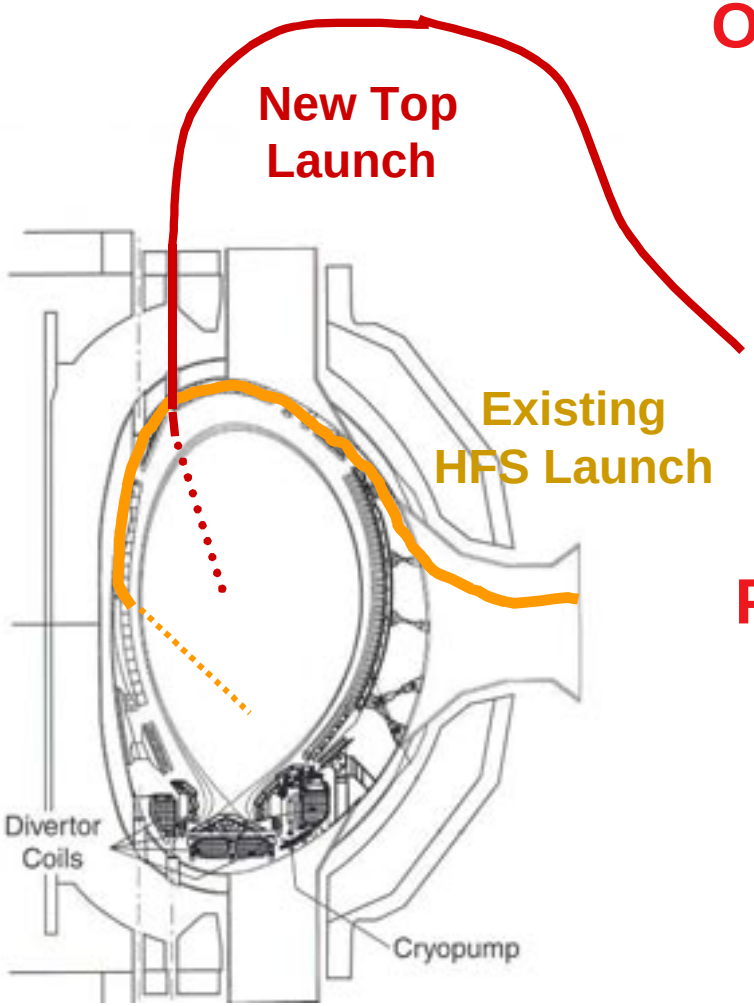




Breslau, et al ….PPPL

- Improved coupling of LH power in JET
- US-EU collaboration important to the understanding the physics

Optimization of Inside Pellet Launch on JET is a Critical Technology and Science Issue for Burning Plasma



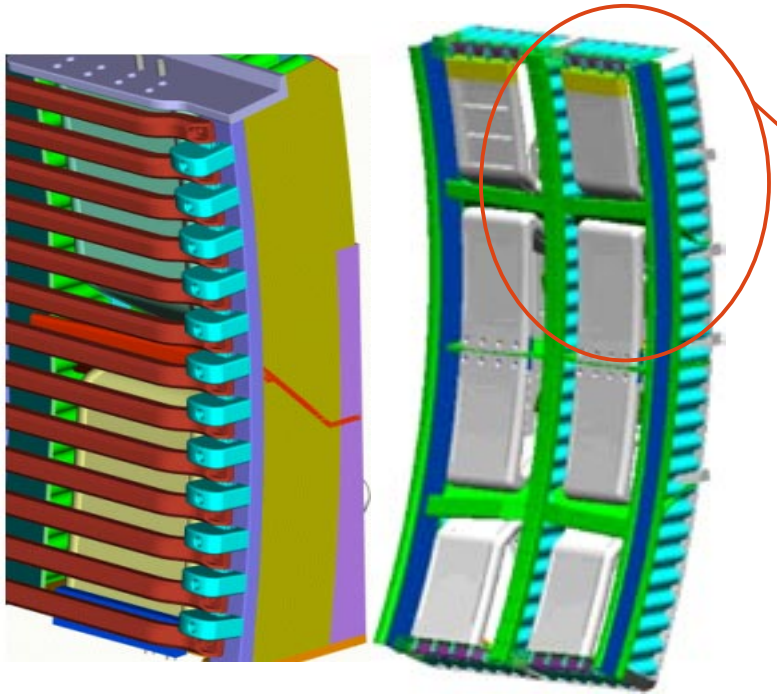
ORNL Mock-up of JET guide tube

PPPL Pellet Spectrometer for JET

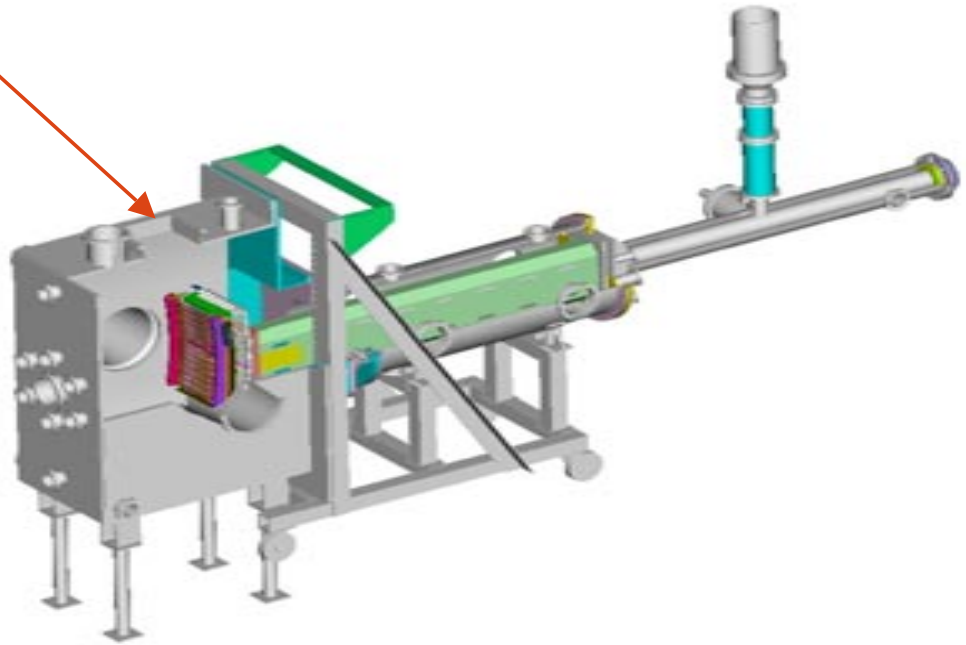
Significant opportunities for DIII-D participation in this activity

ORNL and PPPL Collaboration on JET High-Power Prototype Antenna

- JET-EP antenna aims for efficient coupling through ELMs
- Critical technology for all burning plasmas
- Experiments on JET-EP provide an ideal platform for burning plasma technology development



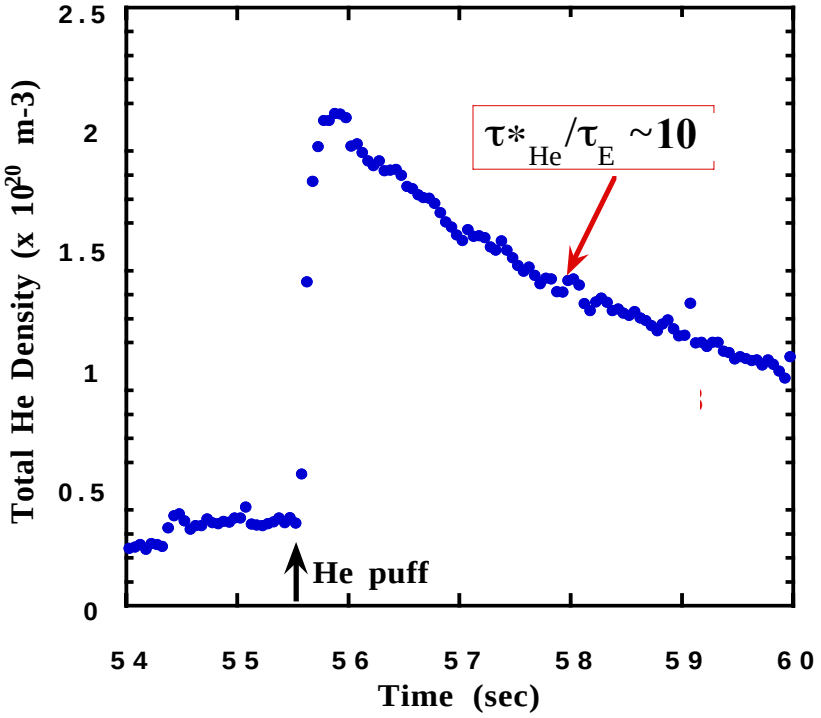
Prototype is one full quadrant of JET-EP antenna: to be tested in vacuum at high power



Helium Ash Removal Studies in JET-EP

Current JET Experiments FY01-FY02

JET Helium Exhaust via Ar frost Pumping
in ELMing H-mode



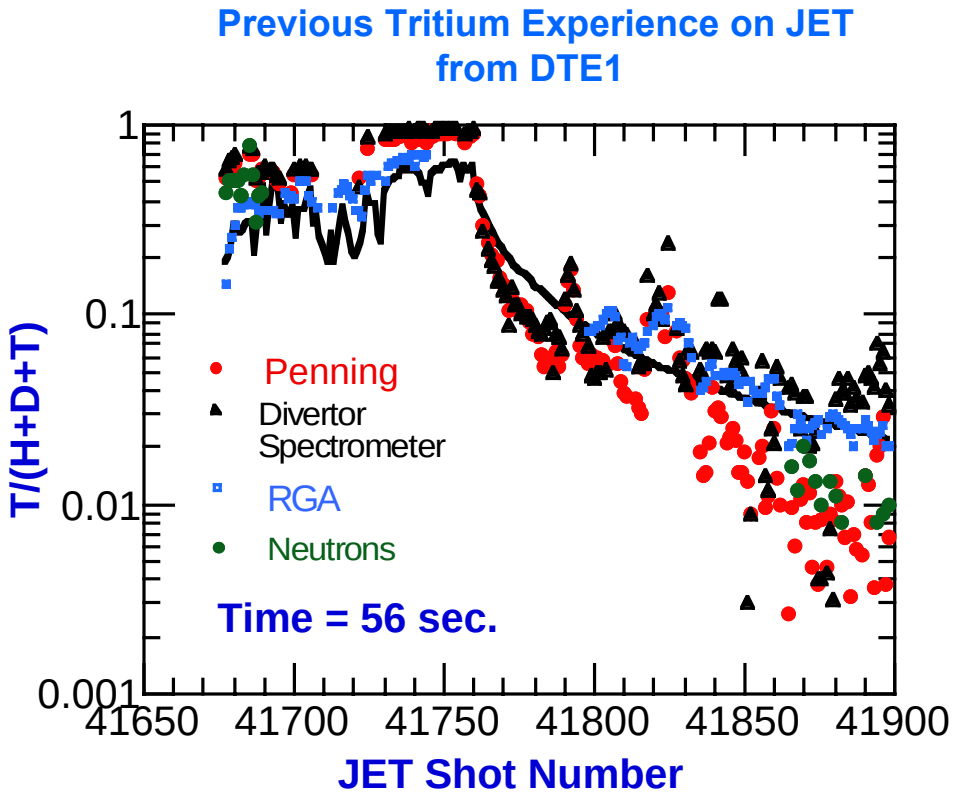
Helium Experiments performed in Collaboration with TEXTOR

Future He Ash Experiments
During 2005 JET DT Experiments
(Proposed)

- **Build and Construct Helium CXRS He Ash Spectroscopy System for JET DT**
  - **Provide increased sensitivity for detection of He produced in DT reaction**
  - **Increase number of radial spatial chords to 30 for investigating ITB changes in radial profile**
  - **improved time resolution**

- **Address Helium transport and exhaust issues for future Burning Plasma Experiments**
  - **JET is the only near term DT experiment**

Tritium Wall Retention addressed on JET-EP

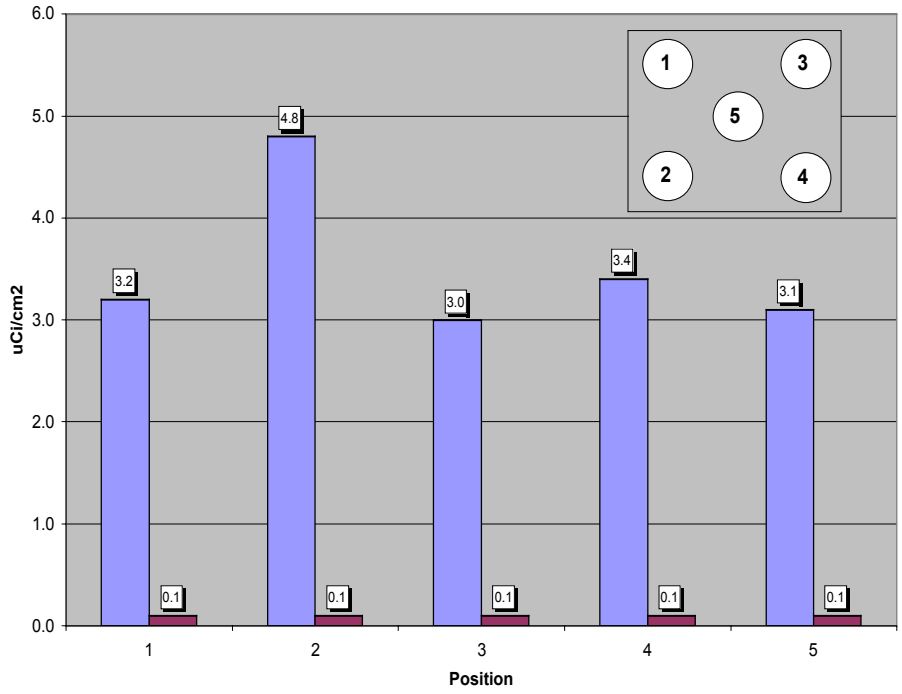


ORNL Designed Penning gauge provided Tritium Concentrations in Divertor of JET

JET is uniquely suited for international collaboration on carbon co-deposition, erosion and tritium retention

Tritium rich dust collects in divertor louvers on JET!
(J. Hogan ORNL & C. Skinner PPPL)

JET surface tritium content before/after laser treatment
(C. Gentile, C. Skinner PPPL)



Collaboration on JET involves ORNL, PPPL and Livermore
Opportunity exists for fully remote in-vessel test of tile detritiation proposed by the US

Lehigh - JET Collaboration

- **H-mode Pedestal Models**
  - Develop and apply pedestal model for predictive integrated modeling simulations of JET discharges
    - Implement model in BALDUR and JETTO predictive codes
    - Validate model by comparing with JET H-mode discharges

- **ITB Modeling**
  - Lehigh research group has published simulations demonstrating formation and motion of ITBs in JET
    - Finite beta and flow shear effects are used in the Multi-Mode transport model
  - Effort will focus on predicting dynamic behavior of ITBs
    - Simulations follow time evolution from Ohmic → L-mode → formation of ITB → H-mode → motion of ITB
  - Investigate link between the q profile and ITB formation
  - Simulate and analyze JET discharges with double ITBs
  - Examine JET ITB discharges with high density and deep pellet injection

On-going initiative on JET and JET-EP

- **EU participants in discussions:**
  - EFDA: K. Lackner
  - JET/EFDA: J. Paméla, M. Watkins

- **Key areas for focused research, arising from US meetings with EFDA/JET in February/March 2001:**
  - Internal Transport Barriers
  - Performance-Limiting Edge Phenomena
  - Energetic-Particle Driven Modes
  - Neoclassical Tearing Modes
  - Minimization of Tritium Inventory

Diagnostics elements of the US/JET Initiative (based on JET/DOE discussions)

High Resolution Thomson Scattering (GA)
He Spectrometer CXRS (ORNL)
Lost Alpha detectors (PPPL/Colorado)

Pellet Spectrometer (PPPL) [near completion]
TAE Antennas (MIT)
Microwave Access (PPPL)
Li-beam polarimetry (GA)
Bubble Chambers for Alpha Knock-on (GA) [detector development]

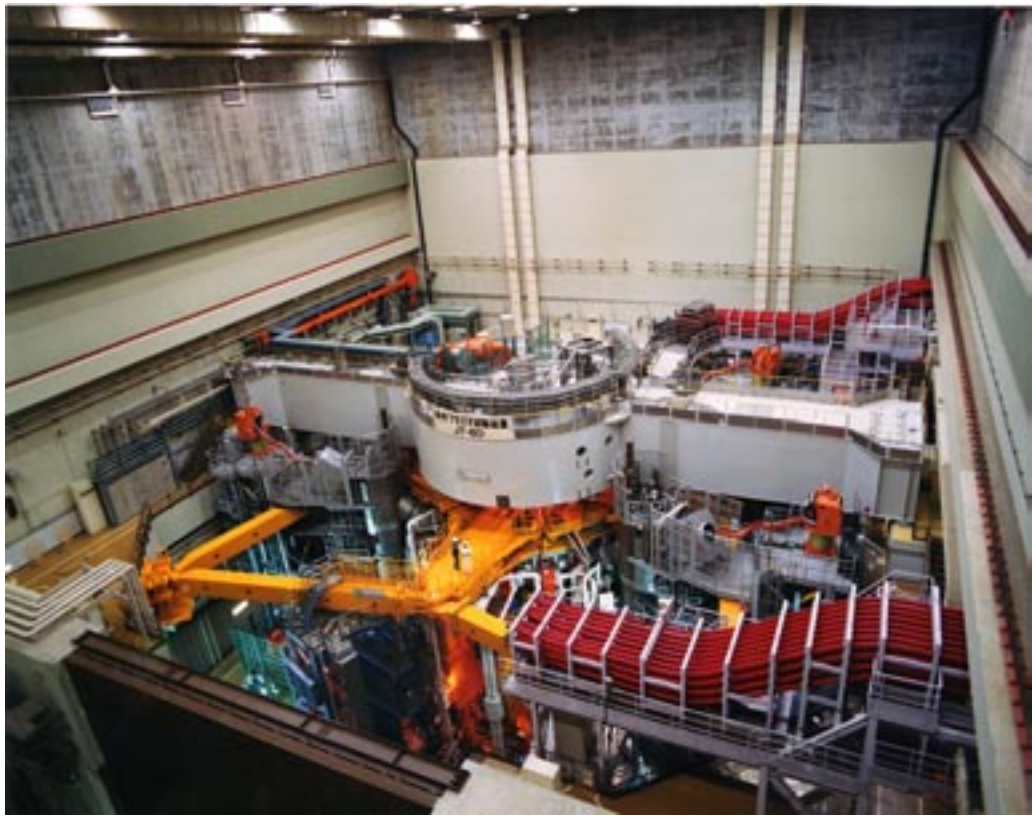
JET proposals ($k)

US Inst	Internat. Facility	U.S. Contact	Description of Activity	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
GA	JET	Carlstrom	Thomson Scattering	0	0	500	0	400
GA	JET	Thomas	Li Beam System	0	0	400	0	600
MIT	JET	Fasoli	TAE Alpha Studies	0	147	0	147	0
MIT	JET	Various	MIT Expt Part in various w/C-MOD funds	55	55	60	50	63
MIT	JET	A. Hubbard	Comparison of small ELM regimes	0	0	0	0	0
MIT	JET	J. Rice	ICRF driven ITB and rotation studies,	0	0	0	0	0
MIT	JET	B. Lipschultz	Cross-field SOL transport	0	0	0	0	0
MIT	JET	D. Mossessian	Enhanced D-Alpha H-mode studies	0	0	0	0	0
MIT	JET	J. Snipes	Combined LHCD and ICRF studies	0	0	0	0	0
ORNL	JET	Hillis	Experiment/Data Analysis	409	409	332	409	450
ORNL	JET	Goulding	Prototype antenna design	143	0	15	0	0
PPPL	JET	B. Stratton	MSE and current hole & RWM	270	270	0	260	0
PPPL	JET	J. Hosea	JET-EP/ITER prototype antenna for JET	150	250	33	100	34
PPPL	JET	R. Nazikian	Fast ion transport in AT regimes at small ρ*	340	470	333	730	150
PPPL	JET	C. Skinner	Tritium codeposition and	160	150	0	125	0
PPPL	JET	J. Strachan	Role of connection length in divertor performance	260	270	0	280	0
PPPL	JET	R. Budny	Comparison of RF and NBI plasmas: Role of rotation in confinement on JET	420	410	0	380	0
PPPL	JET	E. Mazzucato	Turbulence analysis in ITBs at small ρ*	120	120	630	90	766
PPPL	JET	G. Schmidt	Pellet fueling and particle transport	80	100	0	80	0
PPPL	JET	K. Young	Alpha diagnostics on JET	80	40	0	40	0
				2487	2691	2303	2691	2463

JT-60U for Size-scaling and AT

- **Progress:**
  - Improved plasma control system, with increased CD efficiency by N-NBI (1.55 1019 A/W/m2) and higher beam power and beam energy.
  - EC injection of 2.8MW for 3.6s.

- **JT-60U will operate 4 weeks in May/June 2002 (50% of 2001 budget)**
  - Focus: ITB-control by ECH and pellets.
  - JAERI will propose to continue JT-60U experiments.



JT-60U ($k)

US Inst	Internat. Facility	U.S. Contact	Description of Activity	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
PPPL	JT-60U	N. Gorelenkov	Energetic particle modes	100	60	0	55	0
PPPL	JT-60U	R. Nazikian	Microstability in large tokamaks	105	67	0	55	0
PPPL	JT-60U	L. Grisham	NNBI development	120	120	0	120	0
				325	247	0	230	0

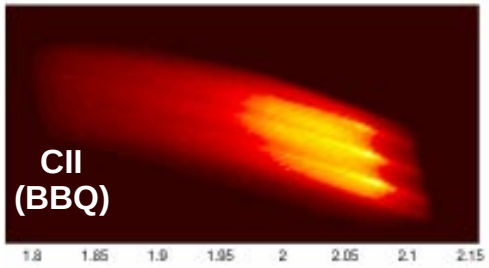
Current Tore Supra modeling collaborations

PLASMA-WALL PARTICLE EXCHANGE

Deuterium recycling model
A. Escarguel, R. Guirlet et al
[PPCF (to appear 2002)]

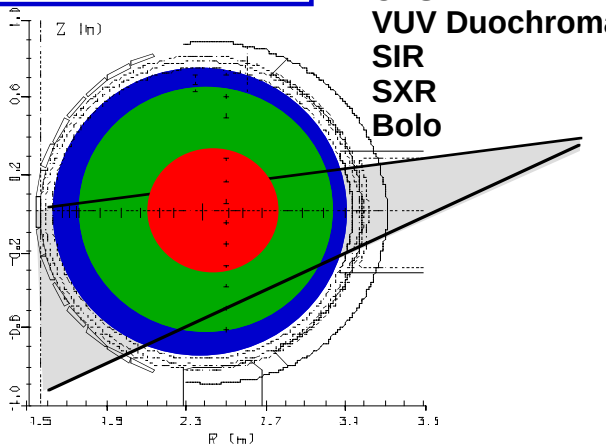
Particle-induced desorption in plasma-wall exchange
C. Grisolia, J. Hogan et al
*[J Nucl Mater **290** (863) 2001]*

ERGODIC DIVERTOR NEUTRALIZER TRANSPORT



R. Giannella et al
*[PPCF **43** (271) 2001]*
Y. Corre et al
*[J Nucl Mater **290** (250) 2001]*

Core transport
Ergodic zone
SOL transport



CXS
VUV Duochromator
SIR
SXR
Bolo

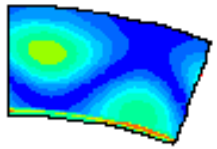
CIEL EROSION

Basic erosion processes:

chemical sputter comparison
R. Ruggieri, E. Gauthier, J. Hogan et al,
J. Nucl. Mater '99

chemical sputter vs T_{wall}
new topic:
A. Cambe, E. Gauthier, J. Hogan EPS 2002

Detailed CIEL erosion model
new topic: **J. Hogan, R. Guirlet, A. Cambe, E. Gauthier, R. Mitteau, D. Guilhem, EPS 2002**



SPUTTERED CI FLUX DENSITY
PHYSICAL SPUTTERING

Max. 6.84
Min 0.27 (10^{21} pt / m^2 / s)

HYBRID 3D - 1D TRANSPORT MODEL

- *duochromator simulation*
  J. Hogan, C. DeMichelis , P. Monier-Garbet et al
  [PPCF (to appear 2002)]
- *SOL / core decoupling : ergodic zone impurity expulsion*
  R. Guirlet, J. . Hogan et al
  *[J Nucl Mater **290** (872) 2001]*
  R. Guirlet, J. Hogan et al
  IAEA Sorrento 2000 (to be publ.)

CORE TRANSPORT

- *CXS profile C, Ne -> base ergodic transport model*
  W. Hess, V. Basiuk, J. Hogan APS 2001
- *non-ambipolar impurity transport & role in ITB impurity accumulation*
  . W. Hess, J. Hogan et al EPS 2002

Other Tokamaks ($k)

US Inst	Internat. Facility	U.S. Contact	Description of Activity	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
ORNL	ToreSupra	Mioduszewski	Experiment/Data Analysis	320	329	100	329	362
ORNL	ASDEX-U	Hogan	Modeling/Data Analysis	99	99	0	99	110
Texas	ASIPP, Hefei, PRC	K. Gentle	Provide improved diagnostics for HT-7 (ECE, CXRS, Impurity injection)	0	0	100	0	100
ORNL	TEXTOR	Hillis	Experiment/Data Analysis	100	99	0	99	110
				519	527	200	527	682

KSTAR (J. Wesley/GA)

- **Plasma schedule:**
  - First plasma by 2006;
  - "full performance" 20-s operation phase continues through 2010;
  - upgrade to 300-s operation in 2011

- **Research Program foci:**
  - "advanced" plasma performance and science basis in long-pulse/steady-state (full non-inductive drive) regime(s);
  - "prototyping" of reactor configuration and operation modes

- **Status:**
  - Tokamak hall and support facility construction complete (beneficial occupancy May 2002).
  - SC coil production facility and support infrastructure operational, first-article NbSn TF and NbSn PF coils wound and reacted;
  - torus vacuum vessel in fabrication;
  - NBI and IC prototype development in progress

Pictures of KSTAR construction

US Korea Bilateral Meeting participants. Upper front of nearly completed KSTAR facility is visible behind KBSI building

Discussions during the KSTAR Diagnostic Cassette design review meeting

The KSTAR program is especially inviting to the US

- **Facility making rapid progress**
  - first TF coil ready
  - prototype vacuum vessel segment complete
  - torus hall ready
- **Key areas of US involvement on long pulse operation:**
  - Control systems (GA)
  - Diagnostic cassette design (PPPL)
  - Auxiliary systems…
- **Workshops are essential for shaping the KSTAR program**

Torus Hall

KSTAR ($k)

US Inst	Internat. Facility	U.S. Contact	Description of Activity	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
GA	KSTAR	Wesley/Casper	Integration of Control Sys	109	108	137	108	152
LLNL	KSTAR	Wesley/Casper	Corsica Modeling	25	25	125	25	250
ORNL	KSTAR	Colchin	Diagnostic Design	15	15	0	15	20
PPPL	KSTAR	J. Hosea	RF Systems design	60	80	100	103	100
PPPL	KSTAR	H. Park	Diagnostic cassette design	109	100	0	80	0
PPPL	KSTAR	H. Park	Advanced diagnostic develp.	60	40	0	40	0
				378	368	362	371	522

Alternate Concepts ('99 Recommendations)

- **"…the prime focus for stellarator collaboration should be the Large Helical Device (LHD) in Japan, with participation on the more modest devices W7-AS and TJ-II;**

- **"…the US should plan participation in the European W7-X, which is under construction in Europe."**

- **"The US's spherical torus programs (NSTX, Pegasus, HIT-II and CDX-U) should coordinate with the world ST community (MAST in U.K., Globus-M in Russia, TS-4 in Japan, and ETE in Brazil), emphasizing their complementarity."**

- **"The US Reversed Field Pinch program should remain coupled to the world program, and should encourage foreign participation on the MST device in Wisconsin."**

Unique opportunities Exist to Advance 3-D Physics on LHD, W7-AS

- **W7-AS**
  - Joint experiments on W7-AS physics to assess stability of current-carrying stellarators
    - planned for summer 2002 (PPPL)
    - Alfvén Eigenmodes (ORNL)
    - divertor physics (Livermore)

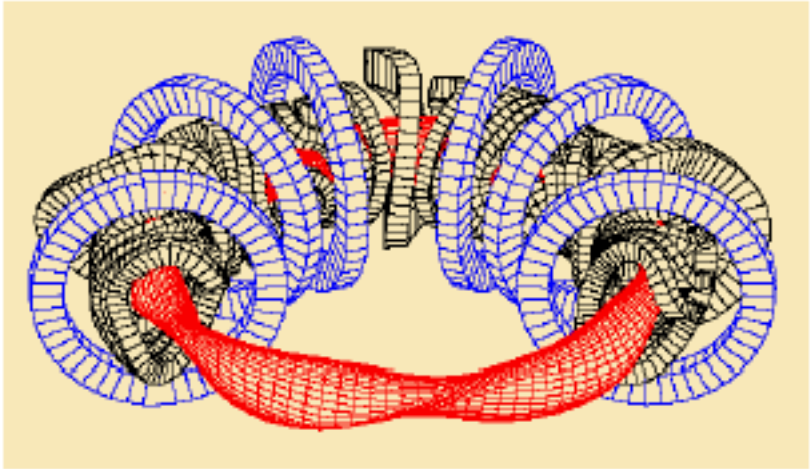


Fig. 3. Coil system and magnetic surface of Wendelstein 7-AS.

- **LHD**
  - collaboration provides opportunity for assessing low-n stability at high beta
    (LHD reached T_e~10keV, T_i~2-5 keV, 50msec confinement at low density (5 10^18m^-3) and Pulse lengths ~ 2 minutes duration
  - Ongoing areas of interaction :
    - energetic particles
    - microstability and transport
    - equilibrium & stability
    - RF physics

Stellarators ($k)

US Inst	Internat. Facility	U.S. Contact	Description of Activity	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
PPPL	LHD	R. Nazikian	Physics of Large Stellarators	220	256	56	364	60
PPPL	W7-AS	M. Zarnstorff	Stability of hybrid stellarators	220	150	0	50	0
LLNL	W7-X	Rognlien	Stellarator Modeling	0	0	332	0	401
				440	406	388	414	461

Some International Activities funded within US facility programs

US Inst	Internat. Facility	U.S. Contact	Description of Activity	FY 2002	FY 2003 Congr	FY 2003 Incr	FY 2004 Flat	FY 2004 Incrmnt
Texas	ASIPP, Hefei, PRC	K. Gentle	Joint experiments on HT-7 (Long pulse, MHD, transport)	20	15		20	
Texas	HUST, Wuhan, PRC	K. Gentle	Advise on installation of TEXT					
PPPL	Globus-M (Ioffe)	M. Peng	NSTX-Globus-M cooperation	0	0	0	0	0
PPPL	MAST (UKAEA)	M. Peng	ST Proof of Principle Physics	100	150		150	
PPPL		M. Peng	ST-Compact Tori Cooperation	20	20		20	
MIT	ASDEX-U	A. Hubbard	Dimensionless H-Mode Treshold & Pedstl	10	15		15	
MIT	ASDEX-U	P. Bonoli	RF modeling	20	10		20	
MIT	FTU	J. Snipes	Lower Hybrid Current Drive Studies			17		18
MIT	JT60-U	B. Lipschultz	Joint divertor studies	15	15			
MIT	LHD	J. Rice	Impurity and transport studies		10		10	
MIT	Tore-Supra	R. Parker	X-ray imaging spectrograph for C-Mod	10	10			
MIT	Tore-Supra	P. Bonoli	RF modeling	8	8		8	
MIT	various	M. Greenwald	MDSplus support	80	80		80	
LLNL	JET	Fenstermacher	Extended Jet Vists	100	100		100	
				383	433	17	423	18

Summary

- **International collaborations offer compelling opportunities for complementarity and synergy with the US domestic fusion program**
  - address key US program goals
  - uniquenesses/features: size, geometry/configuration, pulse-length, tritium, diagnostics and control tools
- **ITPA should enable US participation in joint assessments and planning, data bases, modeling and workshops on burning plasma issues for next step facilities**
  - ITPA High-Priority R&D Topics should be included in program planning process
- **JET and KSTAR are specific opportunities and near-term issues**

Now is the time…

- **To act on the near-term on-going US/EU JET/EFDA-initiative on the physics of energetic particles and larger-scale:**
  - Follow-through on the Lackner/Paméla-invitation / US/JET-EFDA coordination process
    - research foci (funded by both US international budget and US domestic budgets)
    - diagnostics (focused on US research foci and EFDA desires)
    - understanding of the future of JET in the EU's 6th Framework
  - Either
    - as part of the FESAC burning plasma charge, or
    - as part of a turbulence/diagnostics initiative, or
    - as an independent initiative

- **To develop the medium-term international part of the US approach to steady-state tokamaks:**
  - Consider US research roles on KSTAR and/or HT-7U
    - instrumentation
    - control
    - scenario-development