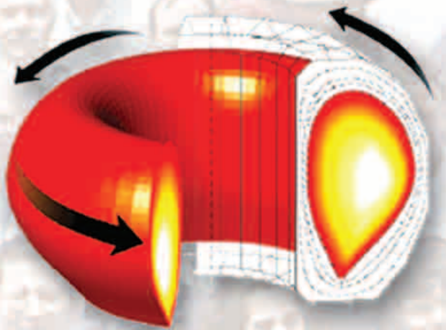
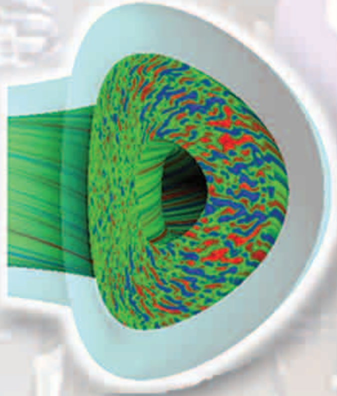
Edge and Boundary Topical Science Area

by
S. L. Allen

Presented to
DIII–D Program
Advisory Committee





January 31– February 2, 2006

DIII–D
NATIONAL FUSION FACILITY
SAN DIEGO

Outline - Boundary Topical Science Area Presentation

- **Review recommendations from 2005 PAC Meeting**
- **Review results from 2005 campaign (highlights)**
  - LTOA upgrades motivate new experiments
- **New capabilities provided by the LTOA**
- **ITPA and ITER physics research needs guide planning for experiments**
- **Summary of 2006-7 Experimental Planning**
  - Working groups: PSI, Heat flux control, Transport, AT Divertor
  - Boundary presentation to Research Council
- **Boundary Topical Science Area Response to Charge**
  - Impurity transport with (primarily) carbon walls
  - Rich boundary diagnostic set for comparison with codes (e.g. UEDGE, BOUT)

Recommendations from Previous PAC

- **Recognized ^{13}C migration and flow measurements in list of outstanding achievements**
- **"Excellent job in showing how .. research relates to ITER needs"**
  - ^{13}C experiments, ELM fluxes, wall gap experiments, UEDGE modeling
  - Emphases of past year are excellent and should be continued
- **Inner divertor modification is high leverage - PAC recommends**
  - New divertor diagnostic measurements: probes, Penning gauges, fibers
- **Wall flux measurements of ELMs expanded to disruptions**
- **Compatibility of AT scenarios with divertor operation not enough attention**
  - Puff and pump in hybrid started in 2005
- **"PAC was puzzled by the DIII-D position on O_2 bake"**
  - PAC recommends that it be reconsidered
  - Should be done at ITER wall temperatures
  - Under consideration, but may be 2007 (2006 short vent)

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Argon "Puff and Pump" enrichment is greater in the closed upper divertor - ITER "dome" issue

Enrichment = $(f_{EXH})/(f_{CORE})$

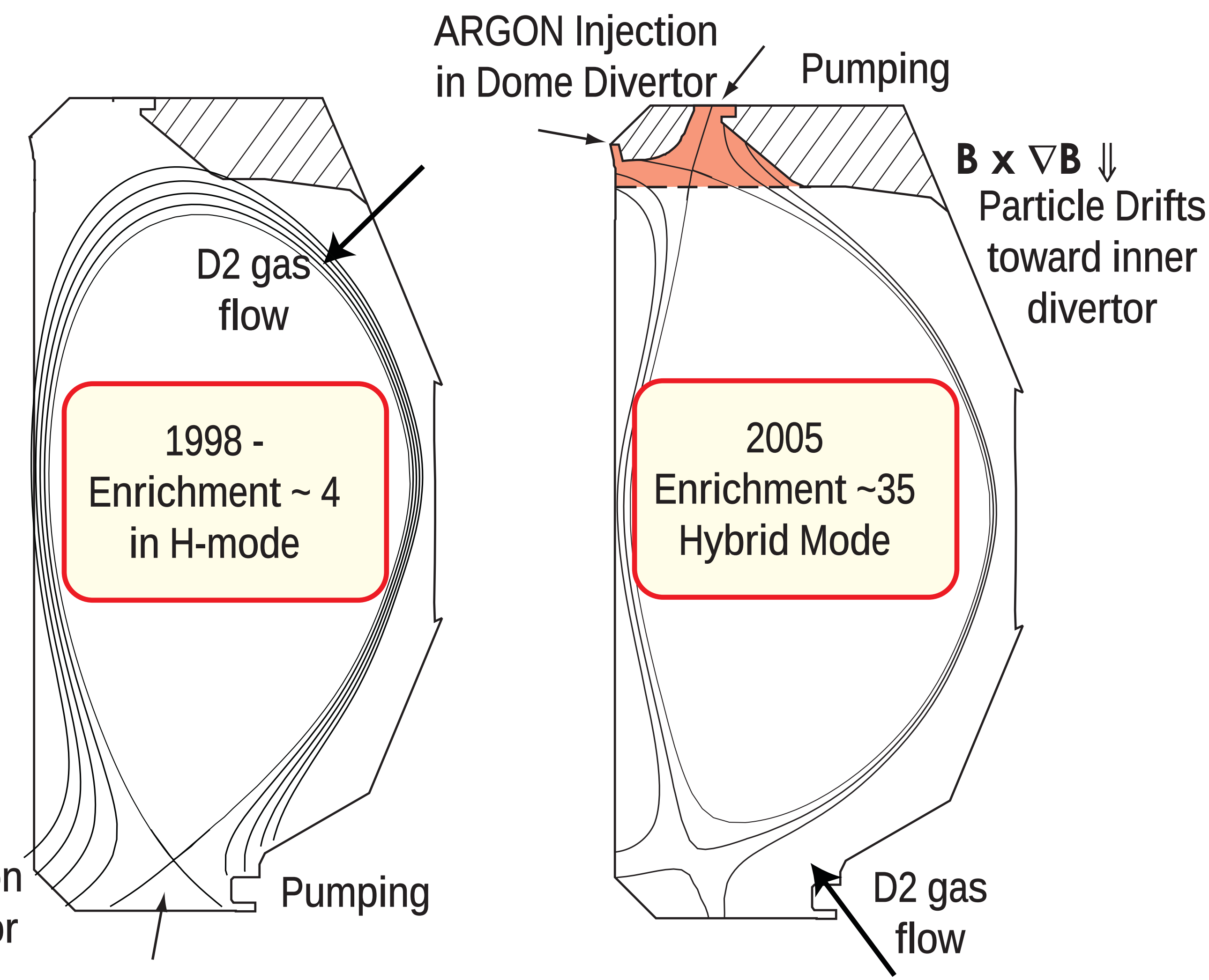
$f_{CORE} = (n_{Z,CORE})/(n_{e,CORE})$

(CER) (TS)

$f_{EXH} = (P_{Z,EXH}/(2 \times P_{D2,EXH})$

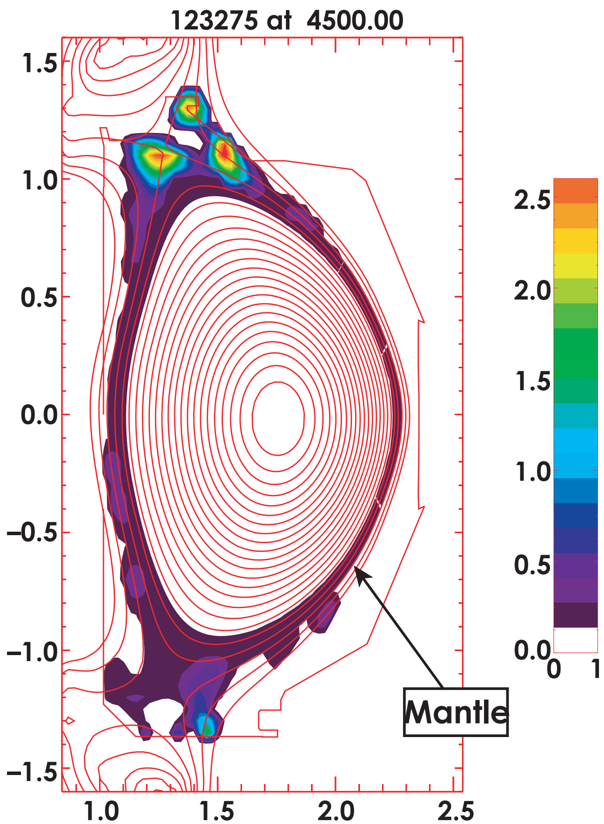
(Penning Gauge)

2006: Compare with and without DOME

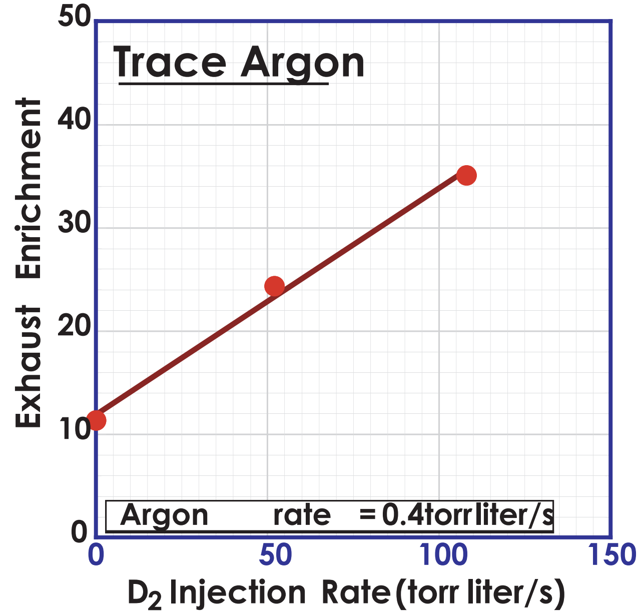


The Radiative Divertor was Successfully Applied to "Hybrid" Operation

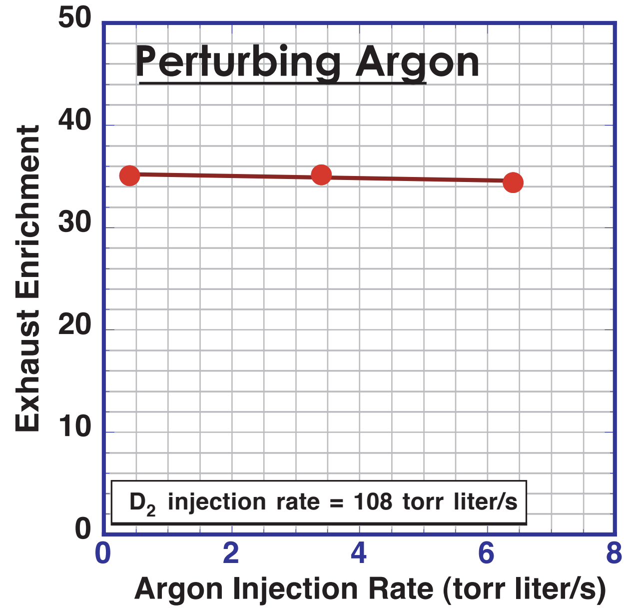
$$\text{Enrichment} \equiv \frac{f_{exh}}{f_{core}}$$



$P_{rad}/P_{tot} = 0.62$
$\beta_N = 2.5$
$H_{89P} = 2.0$



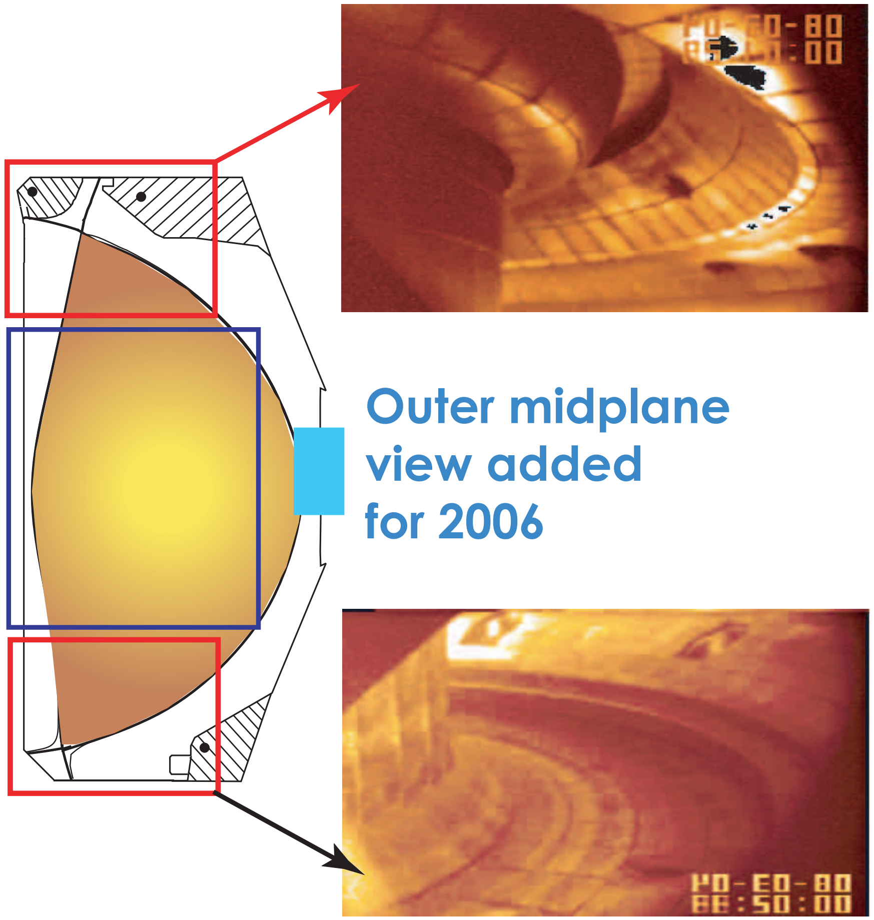
Enrichment of trace argon increased with Γ_{D2}



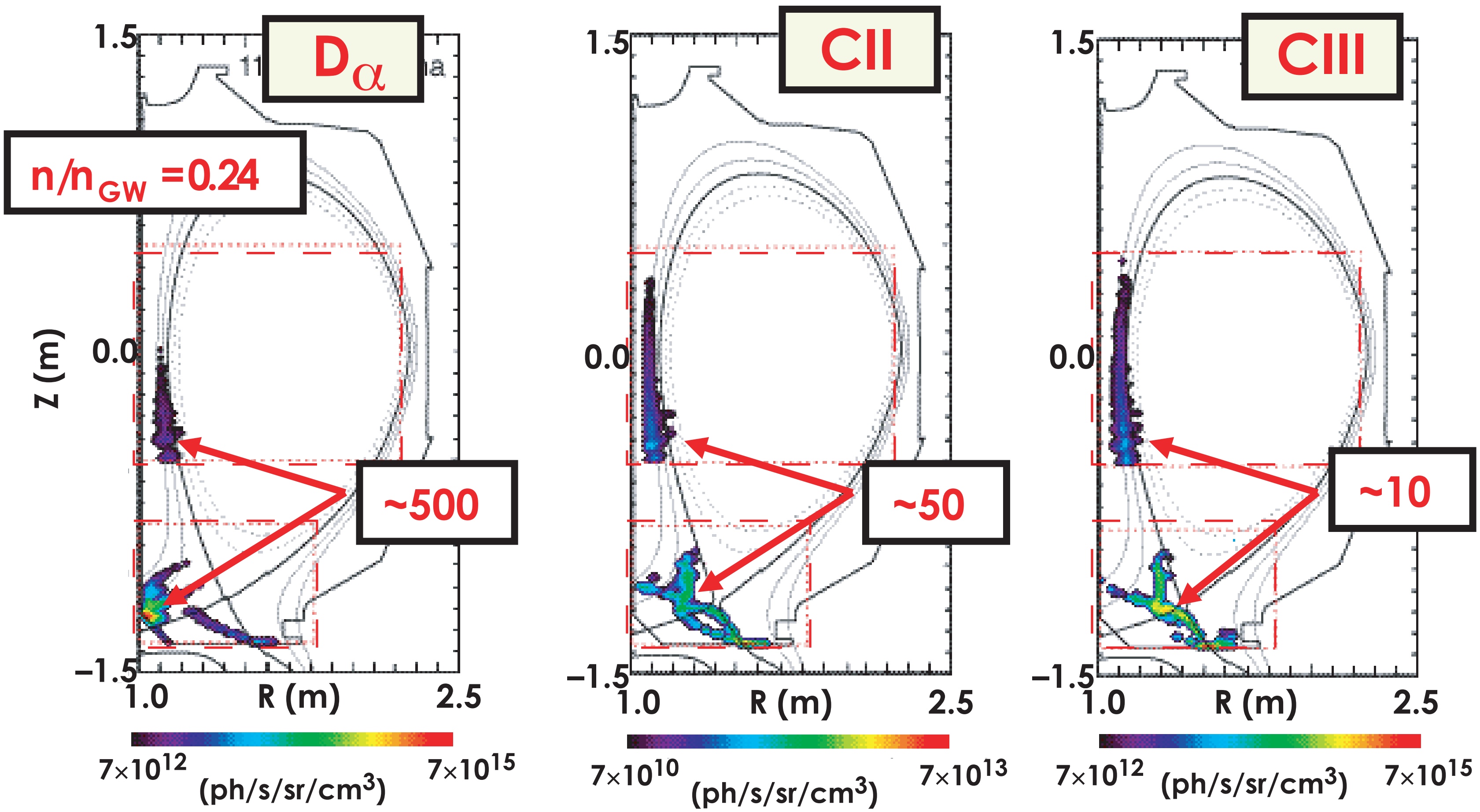
Enrichment was relatively insensitive to Γ_{AR}, with Γ_{D2} ~ constant

Direct Measurements of Recycling and Impurity Influx Compared With UEDGE Modeling are Important to Guide ITER Operation

- Deuterium neutral distribution can be explained by recycling at the divertor target plates and neutral transport into the main chamber
- Poloidal core plasma fueling profile is determined by fueling in the divertor X-point region and neutral leakage from divertor
- Carbon is produced mainly at the divertor plates and walls, due to chemical sputtering processes

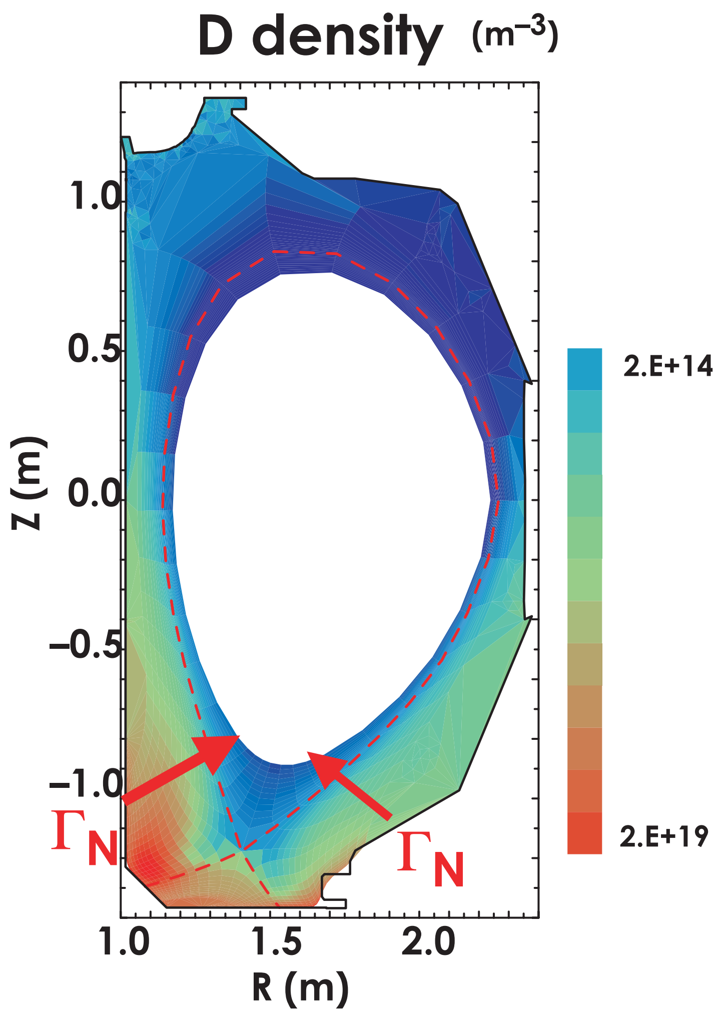


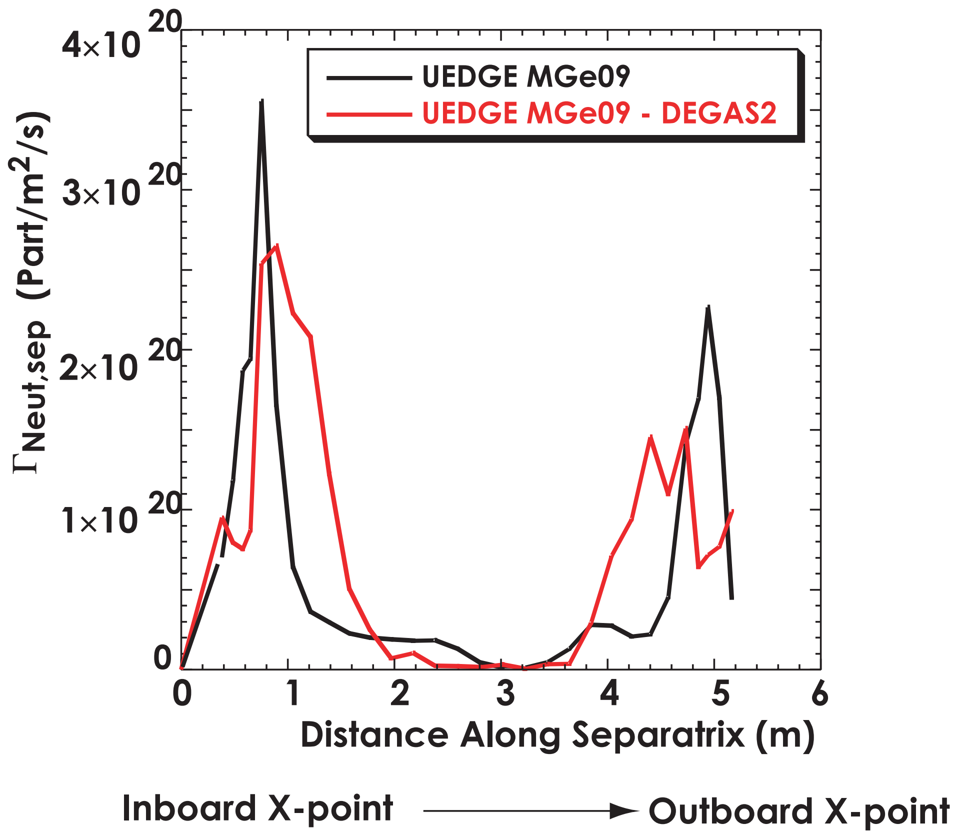
2-D DIII–D Data Shows Deuterium and Carbon Emission is Predominantly From The Divertor Region



- Plan: outer midplane views, high density operation, comparison with C-Mod picture frame data

UEDGE/DEGAS2: Core Plasma is Fueled Through Divertor X-Point Region and by Divertor Neutral Leakage





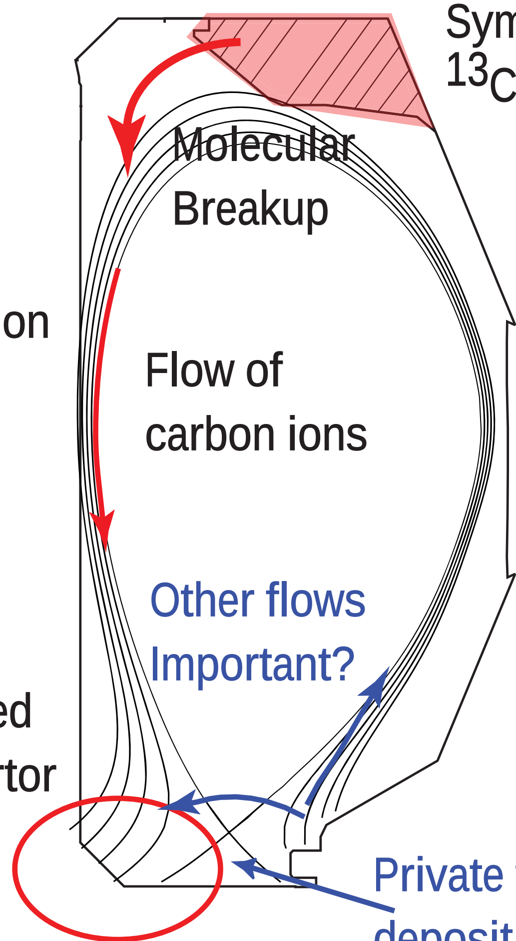
2006: New midplane views to measure main chamber interaction, also probes and MiMES

^{13}C tracer injection in DIII-D has proven to be remarkably revealing (ITER tritium inventory)

Toroidally Symmetric ^{13}C Injection

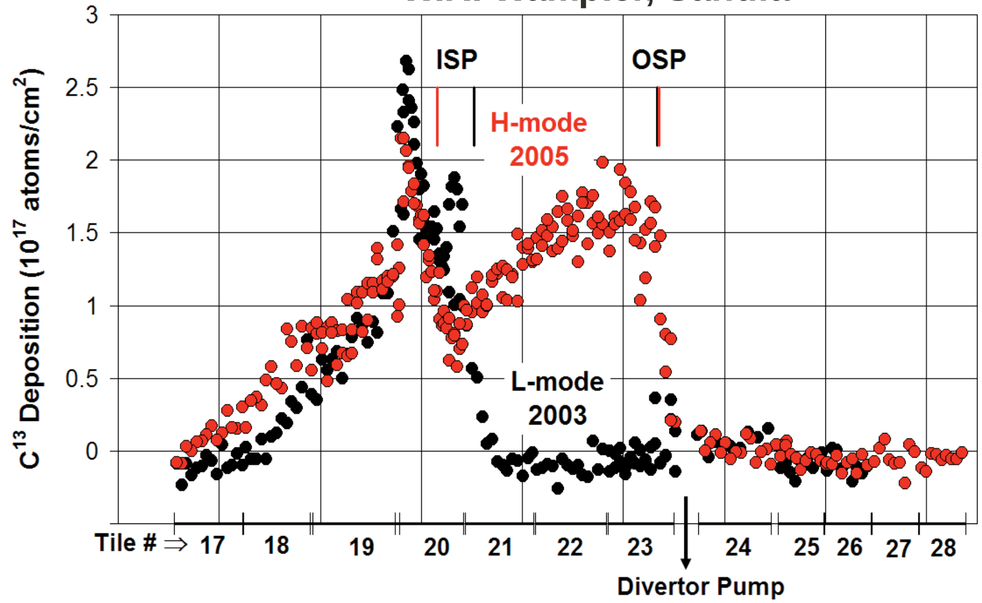
Low deposition elsewhere (~1/3 total if poloidal data is distributed)

Highly concentrated deposition in divertor region (~1/3 total)



Private flux zone has deposition in H-mode

^{13}C(^{3}He,p)^{15}N Nuclear Reaction Analysis
W.R. Wampler, Sandia



Low ^{13}C deposition found away from divertor

- Detecting main chamber ^{13}C deposition requires higher sensitivity
  - $^{13}C(p,\gamma)^{14}N$ nuclear reaction resonance at the U. Wis. (D.G. Whyte)
  - 10X lower detection limit
  - If small poloidal sample is representative, accounts for ~1/3 of total

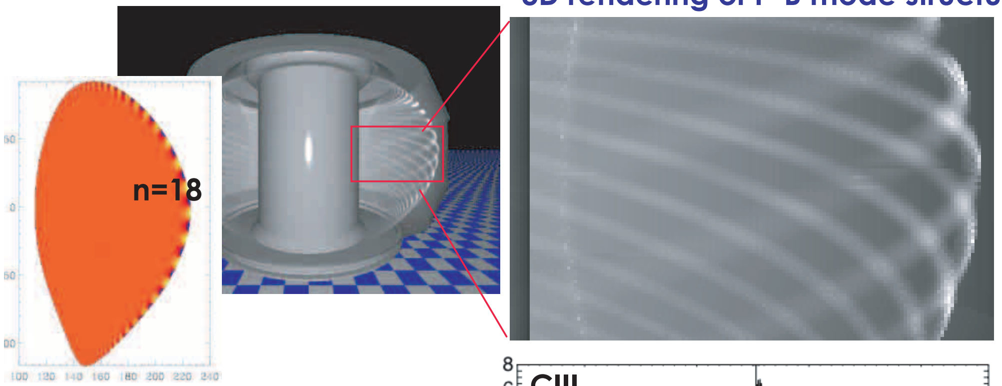
- ^{13}C thermal oxidation facility (J.W Davis) at U. Toronto (J.W. Davis)
  - 20 tiles planned to be tested

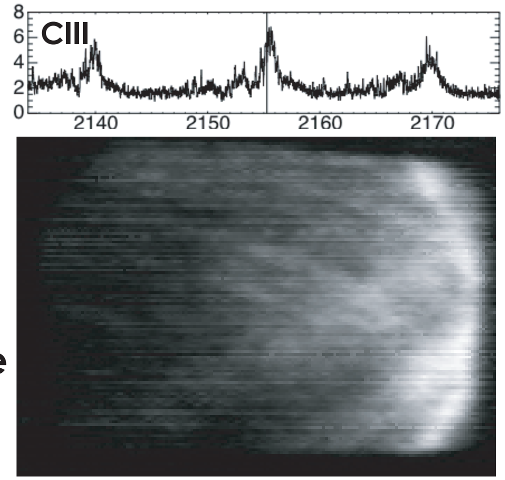
Ion beam analysis facility
University of Wisconsin

Oxidation facility
University of Toronto

ELMs show Peeling-Ballooning structure and expel bursts of density at main wall

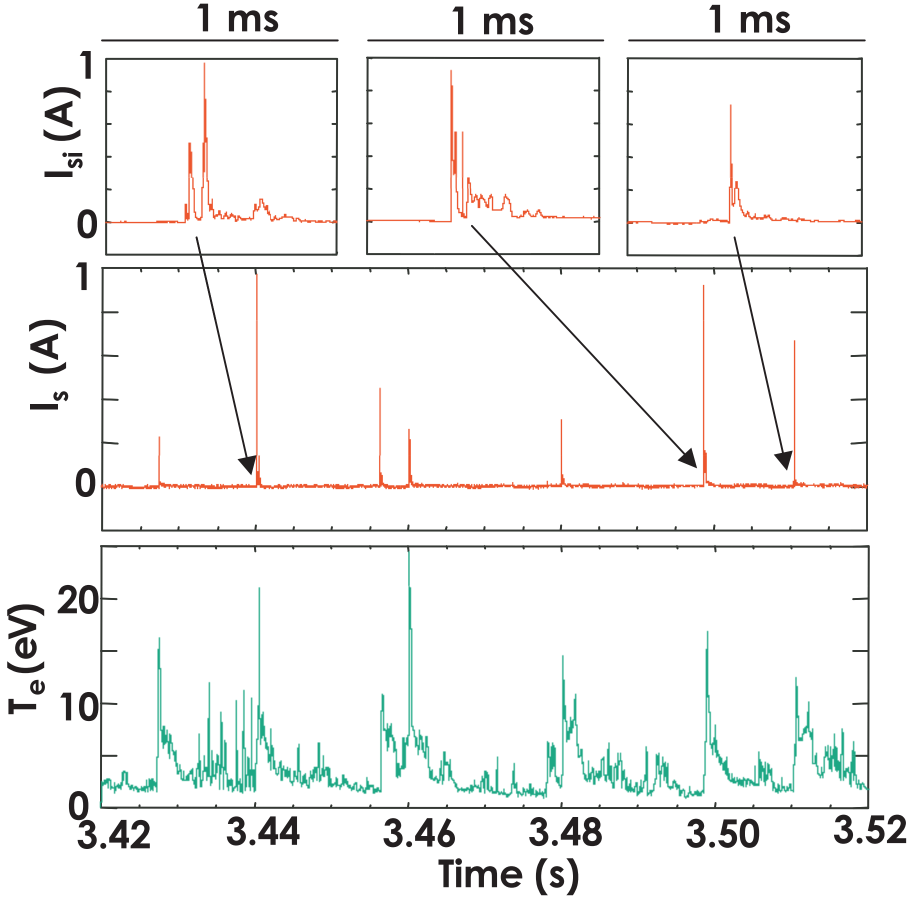
3D rendering of P-B mode structure





- Most unstable modes from ELITE linear P-B instability are $18 \le n \le 21$
- CIII emission structure suggests $n \sim 17$

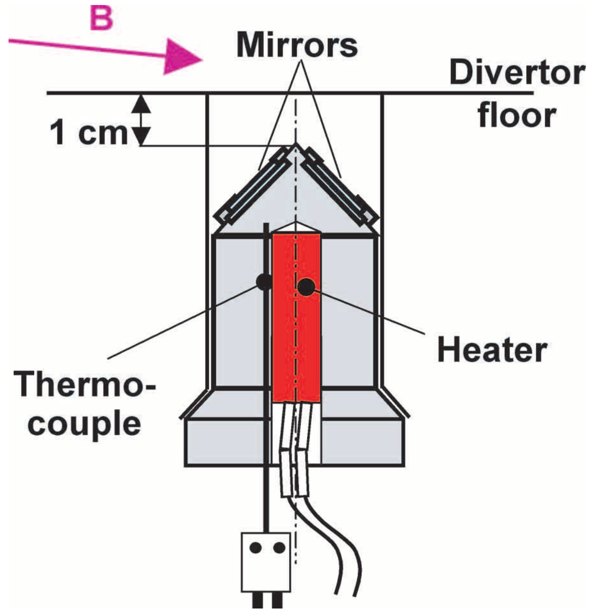
I_s and T_e midplane scanning probe



2006: New midplane MiMES with probe capabilities

Divertor mirror deposition is temperature sensitive (~100°)

- **Diagnostic plasma facing mirrors are listed as high-priority ITPA topic**
  – ITER divertor mirrors will have deposition
- **Mo mirrors were exposed in the Private Flux zone of Detached ELMing H-mode discharges**
  – Room temperature (6 shots, 25 s)
  – ~100°C (not constant) (17 shots, 70 s)



Visible deposits were observed on the mirrors exposed at room temperature

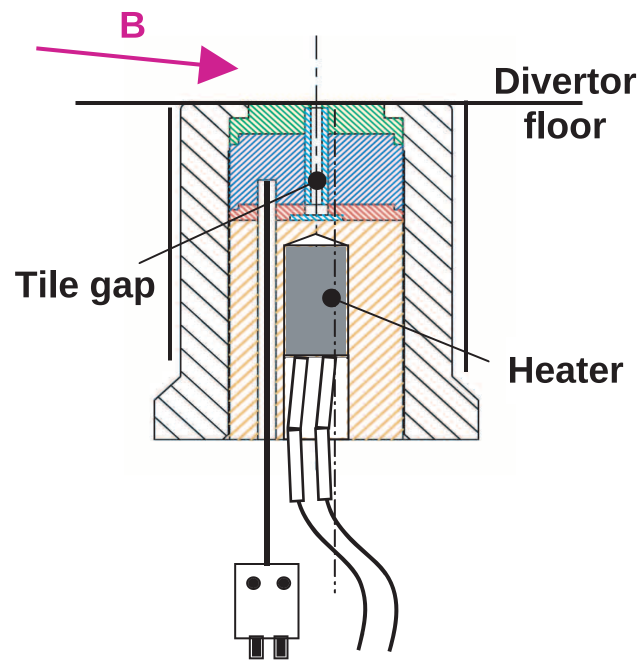
No deposits were observed on the mirrors exposed at elevated temperature !!

– Plan to repeat in 2006 with constant temperature

Deposition in tile gaps is reduced at higher temperature

- Tritium co-deposition with carbon in tile gaps is a serious potential problem for ITER
- DiMES sample with a simulated tile gap 2 mm wide and 15 mm near the detached OSP in two sets of identical L-mode discharges
- First exposure was performed at room temperature, second exposure was with sample heated to 200˚C
- C:D films deposited in the gap at room temperature were of the “soft” amorphous type with D/C atomic ratio of 0.3–0.6
- Amount of co-deposited deuterium in the heated exposure was an order of magnitude lower than at room temperature
- A rather high net carbon erosion rate of 3 nm/s was measured at the sample surface in heated exposure

2006: Repeat with controlled temperature

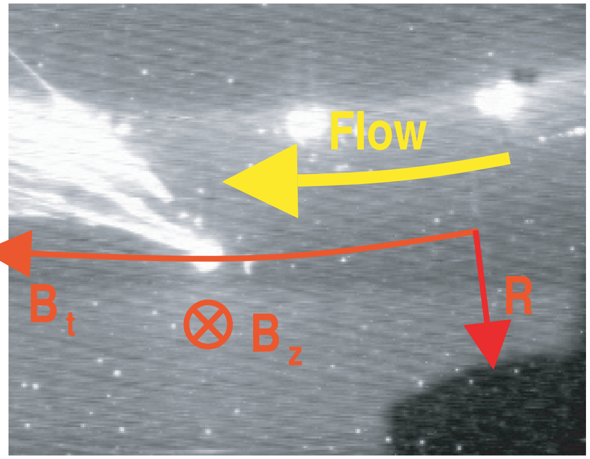


DUST is identified as an important ITPA topic

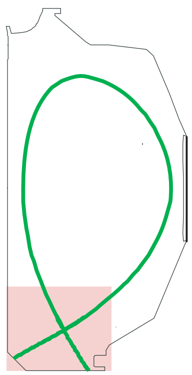
- During dust DiMES experiments cameras with near IR filters observed individual dust particles moving with velocities of 10–100 m/s
- Direction of the dust trajectories can be explained by a combination of the ion drag, Coulomb forces, and ion pre-sheath drifts

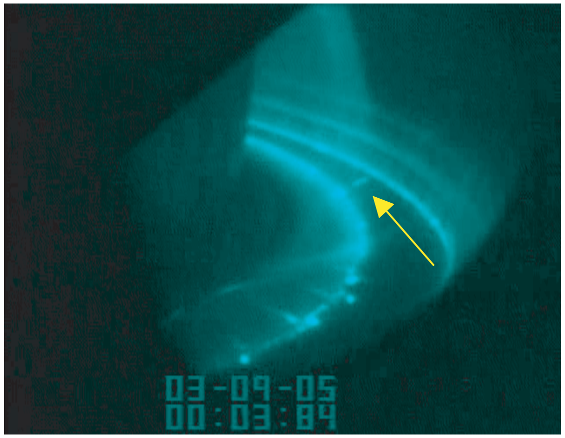
"Statistics" being developed
Thomson Scattering - 400/cubic meter, 80 nm average

Top view (DiMES TV)

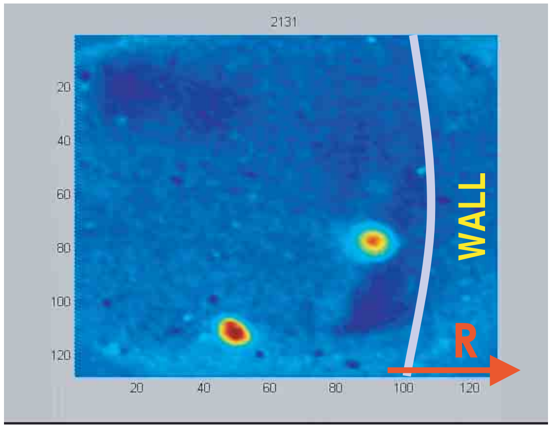


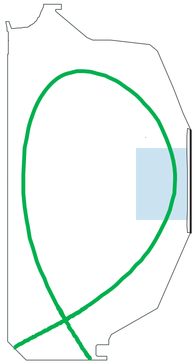
Tangential divertor camera (LLNL)





Fast-framing midplane camera (UCSD)





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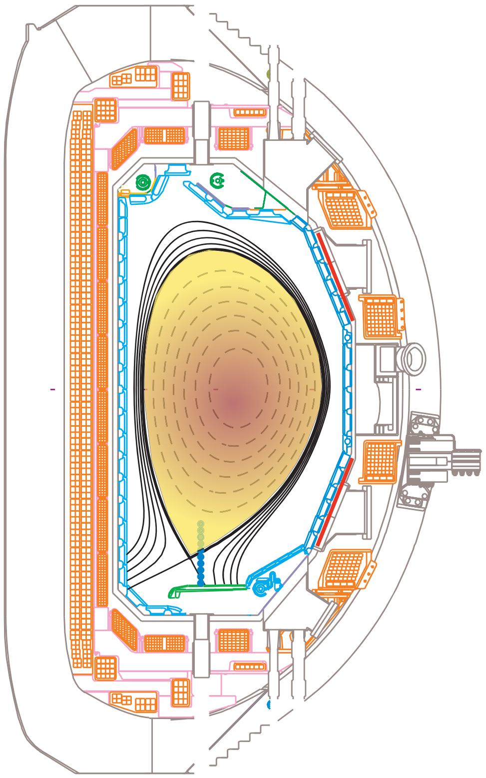
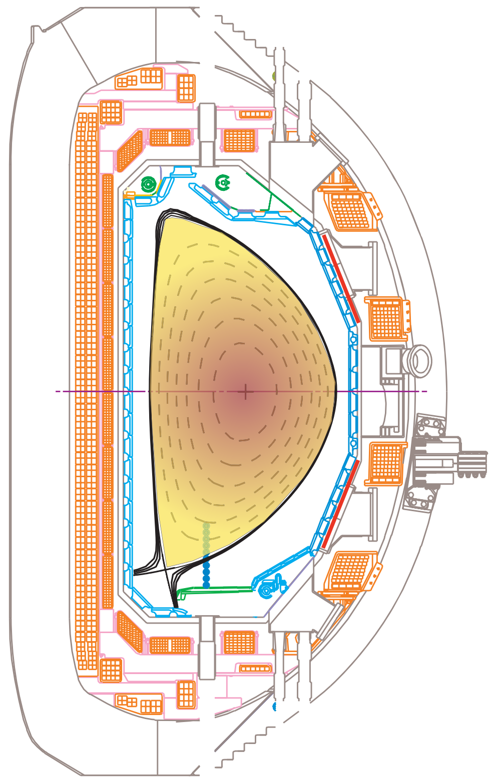
ITER-relevant boundary studies with the new AT divertor

Flexible Divertor Studies



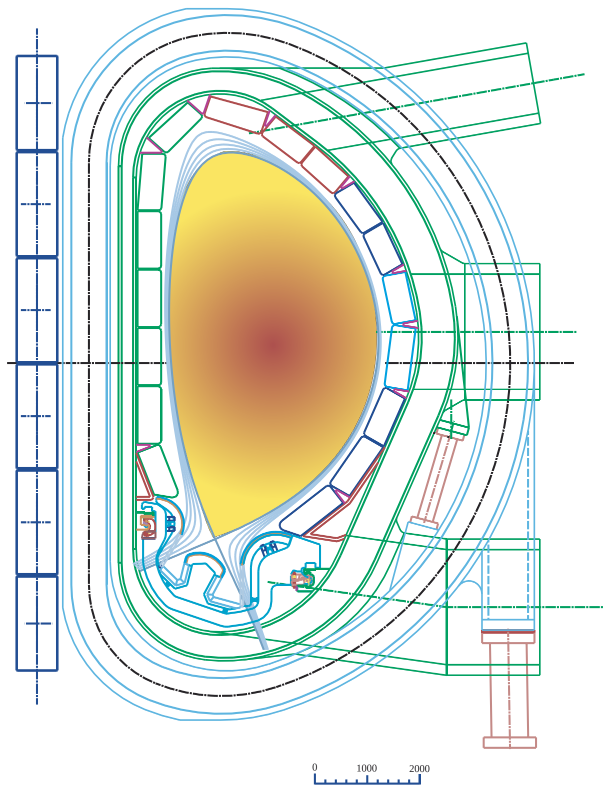
- Strike point on shelf
- Plasma sweeping
  for 2-D profile
- Baffle allows new views

SN ITER shape (also DN)

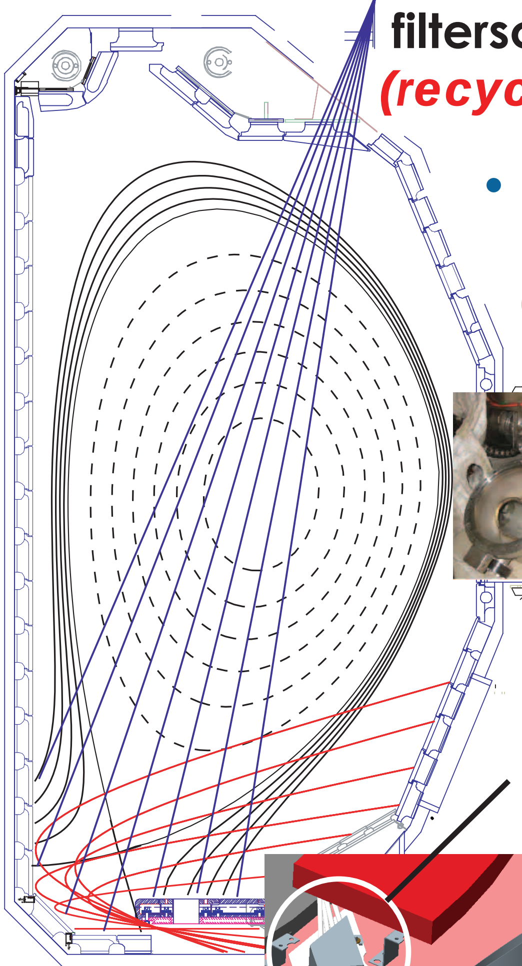


- Either SN (ITER) or DN (AT)
  shapes
- New probes and views for
  this shape

ITER (scaled)

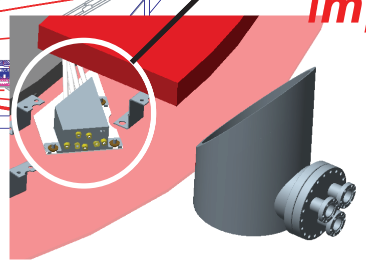


New divertor measurements in the DN AT divertor

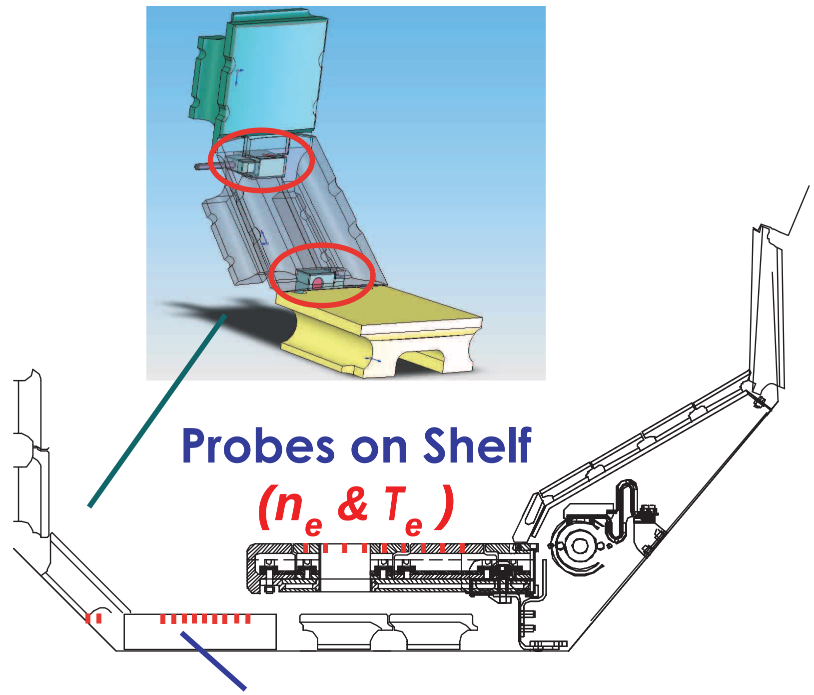


- New upper filterscope views *(recycling, impurities)*
- Midplane Probe and MiMES *(n_e, T_e, Surfaces, Fluctuations)*

- Baffle Filterscope views *(recycling, impurities)*

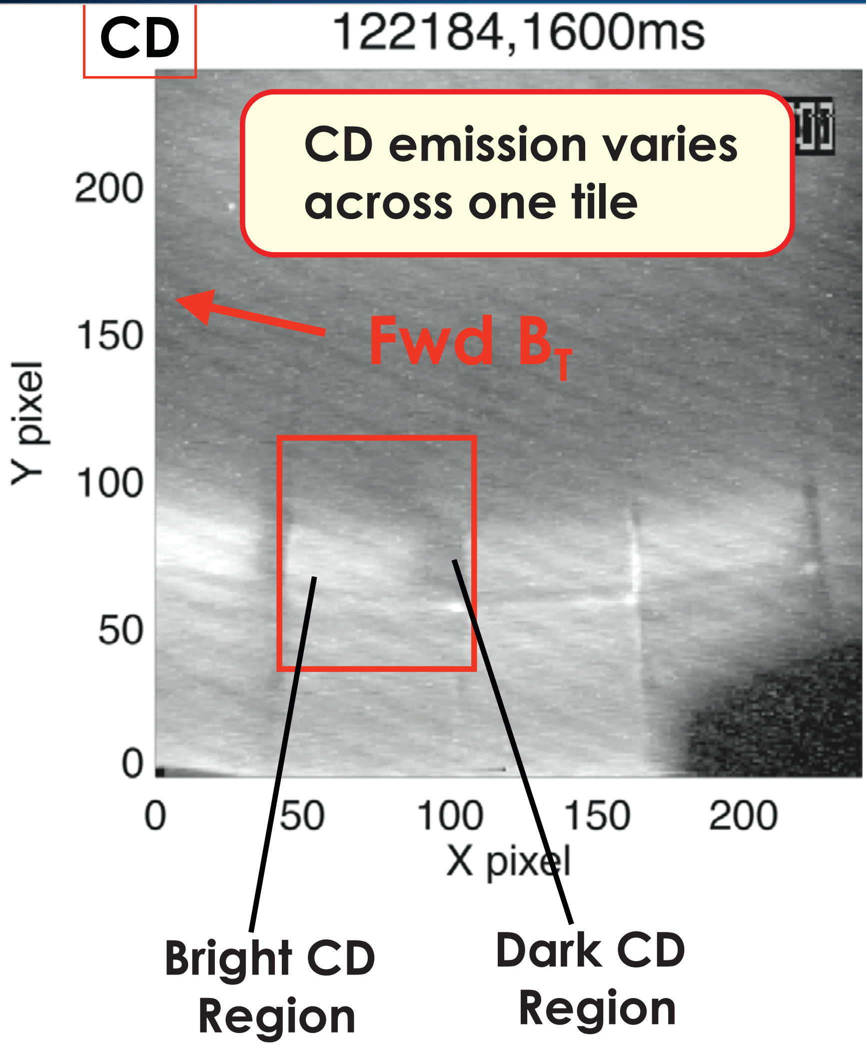


2 Quartz Microbalances
(Real time deposition)

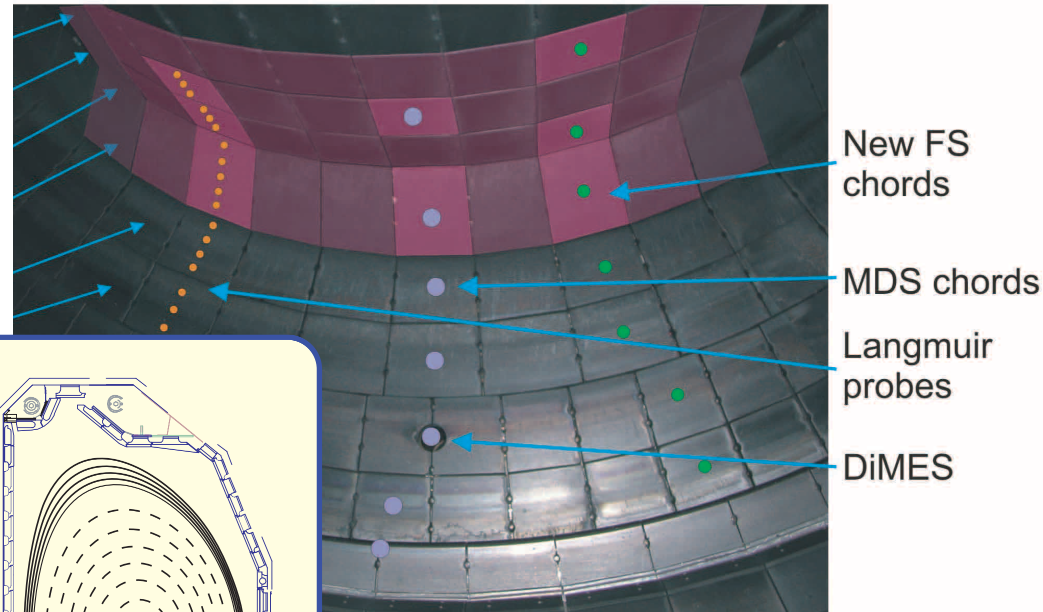


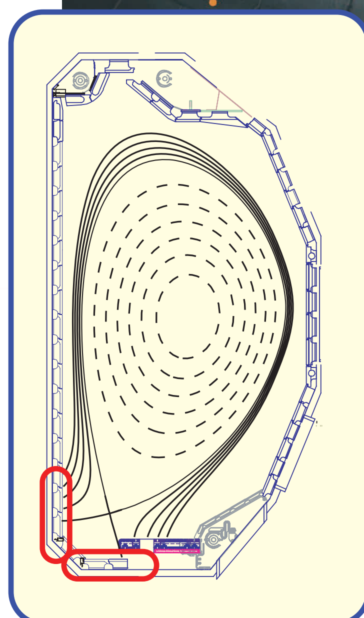
- High spatial resolution Langmuir probes in AT strike point region *(n_e, T_e, heat flux in shadowed areas)*

Diagnostic divertor area will have contoured tiles



New Divertor will have contoured tiles in lower divertor and up the centerpost





Contoured Tiles
Reduces carbon generation from gaps

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ITER needs : Design Issues and ITPA tasks

- **Design issues that need ITPA input (Shimada, IT)**
  - a. Heat load on first wall, especially due to ELMs
  - b. Carbon erosion/deposition/control of tritium inventory and material choice
  - c. Private region PFC and necessity of Dome
- **ITPA High Priority Research Tasks and ITPA/IEA Experiments 2005-6**
  - d. Understand the effect of ELM/disruptions and first wall structures
  - e. Improve understanding of Tritium retention & the processes that determine it and development of efficient T removal methods
  - f. Develop improved prescription of SOL perpendicular coefficients and boundary conditions for input to BPX modeling
  - g. Determine life-time of plasma facing mirrors used in optical systems
  - h. Development of measurement requirements for dust

Boundary TSA working groups are organized around ITER physics issues

- **Plasma Surface Interactions (Groth) b, e, f, g, h (ITER) 28**
  - Carbon transport - ITER tritium inventory
  - ITER mirror and tile gap tests
- **Heat Flux Control and Fueling (Petrie) a,c, d,c 8**
  - Heat load on first wall, AT divertors
  - Puff and pump in ITER Hybrid and AT plasmas
- **Transport & ELMs (Boedo) d, f 19**
  - Poloidal dependence of transport, ELM effects
- **AT Divertor (Mahdavi) c 5**
  - Commission new divertor in AT shape
  - Particle control in highly shaped AT DN plasma
  - Dome shape for ITER

(Assumes no ^{13}C exposure in 2006)

Example of organized proposals - PSI area

ITER Mirror - g

^{13}C - b,e

ITER "protoyping" or operations studies

735	Andrey Litnovsky	ITER Mirror test. Exposures of diagnostic mirrors in the divertor and in the midplane locations.
734	Andrey Litnovsky	Investigations of ITER-like castellated structures in DIII-D: carbon migration and fuel accumulation
1027	Michael J Schaffer	Minimum Bake Temperature for Expeditious Tokamak Operation
758	Peter C. Stangeby	Quantitative oxidation of DIII-D following 13C deposition
776	Peter C. Stangeby	Regular monitoring of the plasma conditioning of the new divertor tiles using a standard discharge

Sputtering b,d,

Chemistry and spectroscopy of sputtering

733	Adam McLean	Spectroscopic characterization of CH4, C2H4, and H2 in attached and detached divertor plasmas
983	Adam McLean	Simulation of wall chemical sputtering using methane puffing into USN plasmas with the PPI
987	Adam McLean	Simulation of wall chemical sputtering using strong methane puffing into LSN high density plasmas
745	Mathias Groth	Toroidal distribution of CD and C2 emission and chemical sputtering in DIII-D
547	Neil H Brooks	Study of fragmentation chemistry using porous plug to inject hydrocarbons into divertor strike pt.
947	Sebastijan Brezinsek	Deuterium injection for quantification of the recycling flux in the detached outer divertor of DIII-
946	Sebastijan Brezinsek	Hydrocarbon injection for quantification of erosion yields in the detached outer divertor of DIII-D

Wall Temperature - e,g

Effect of wall temperature on sputtering and migration

1075	Adam McLean	Studies of impurity flow and recycling in the SOL and divertor of plasmas with a hot vessel wall
604	Clement Wong	Material exposure at DiMES and MiMES locations and at different temperatures, with ELMs free H-mode.
1097	Dennis Whyte	Effect of divertor surface temperature on carbon chemical erosion
972	Dmitry Rudakov	Dependence of C deposition and D co-deposition rates on the surface temperature –
636	Neil H Brooks	13C tracer injection into DIII-D plasmas, with the vessel wall hot

^{13}C-b,e

Erosion and Material migration w & w/o tracer isotopes

920	Alexander Pigarov	Intrinsic dust migration and dust production rate evaluation. C13 tracer for dust
636	Neil H Brooks	13C tracer injection into DIII-D plasmas, with the vessel wall hot
758	Peter C. Stangeby	Quantitative oxidation of DIII-D following 13C deposition
655	William R. Wampler	Carbon Erosion with argon detached plasmas

Tile Gaps-b,e

Gaps

682	Karl W. Krieger	Measurement of deuterium and carbon deposition in gaps of plasma facing structures
765	Peter C. Stangeby	Measurements of the effects of small wall gaps
802	Sergei I Krasheninnikov	Plasma in shadow regions
768	Soren Harrison	Neutral particle erosion/deposition measurements between tile gaps.

Dust - h

Dust

917	Alexander Pigarov	The role of dust in impurity/tritium migration
919	Alexander Pigarov	Nanometer-size dust inventory measurements
920	Alexander Pigarov	Intrinsic dust migration and dust production rate evaluation. C13 tracer for dust
921	Alexander Pigarov	Carbon-dust shield for deep gas puffing and disruption mitigation
918	Alexander Pigarov	Observation of dust-blob and dust-ELM interactions
973	Dmitry Rudakov	Migration of micron size carbon dust in tokamak divertor and SOL

Example: Run time request in PSI area

		A	B	C
ITPA	**• Quantification of chemical sputtering in DIII-D**			
	– Fragmentation of hydrocarbon molecules	2x 1/2		
	– Characterization of D / D_2 recycling fluxes		1/2	
	– Helium plasmas			1
	• D and C deposition in tile gaps			
ITPA	– Heated vs. unheated DiMES tile gap sample, detached divertor conditions	2x 1/2		
	– Heated vs. unheated ITER-like, castellated DiMES sample, detached divertor conditions		2x 1/2	
	– QMB	P-B		
	• Heated diagnostic mirror test			
	– Mirror at constant temperature	1/2		
	– Differentially heated DiMES mirror			1/2
	• Wall chemical sputtering			
ITPA	– CH_4 injection into USN		1/2	
	– Strong CH_4 injection into LSN			1
	• Mainchamber erosion - new camera	1/2		
ITPA	**• Material erosion**			
	– Multi-sample exposure			1
	– Ar induced detached divertor plasma			1/2
	– Temperature dependence of erosion			1

Power and Particle Control Experiments Grouped

		∇B	dRsep	Gases	Time
ITER	Impurity Enrichment in DN H-mode	U&D	0	Ar + D_2	0.5 + 0.5
588 Petrie	Radiative Divertor Compatible with DN H-mode plasmas?	U&D	0	Ar + D_2	0.5 + 0.5
757 Leonard	Low n_e Radiative Divertor by pellet and impurity	D	+1	Ar + Pellet	1.0
ITPA e	Divertor Plasma With and Without Dome	U&D	+1,-1	Ar + D_2	0.5 + 0.5
592 Petrie	Optimal fueling in pumped DN: Inside vs. Outside	U&D	0	D_2	0.5
594 Petrie	Heat flux outside slot divertor be reduced?	U&D	-2	Ar + D_2	0.5 + 0.5
643 Ongena	Stationary feedback controlled Argon seeded H-mode radiative divertor	UorD	Any	Ar + D_2	06- piggyback
701 Baylor	Scaling of HFS pellet mass drift and comparison with theory			Pellet	1.0
921 Pigarov	Carbon dust shield for deep gas puffing and disruption mitigation			Need duster	piggyback

Power and Particle Consolidated run time request

	Topic	2006	2007
ITER	Radiative Divertor	2	1
	Feedback	Piggyback	2.0
	HFS pellet	1(b)	
	Carbon dust shield	Need duster, piggyback	piggyback

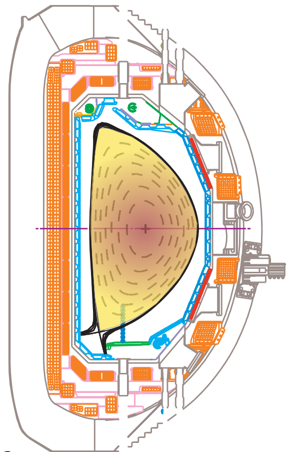
Boundary TSA working groups are organized around physics issues

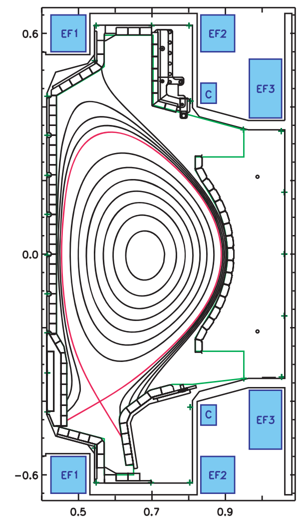
- **PSI group (Groth) 3/2/4 WG request/12wk/32 wk**
  - ITER tritium inventory and carbon transport
  - ITER mirror and tile gap tests
- **Heat Flux Control and Fueling (Petrie) 2/1/4**
  - Puff and pump in ITER Hybrid and AT plasmas
- **Transport & ELMs (Boedo) 1/0/2**
  - Poloidal dependence of transport, ELM effects
- **AT Divertor (Mahdavi) 2/2/4**
  - Commission new divertor in AT shape
  - Compare pumping with predictions
  - Dome shape for ITER

(Assumes no ^{13}C exposure in 2006)

DIII-D in the context of world tokamaks contributing to ITER

DIII-D
- Particle control in AT shape
- Carbon: erosion/redeposition
- ITER mirror and tile gap
- DN, divertor dome
- Simple flow diagnostics
- Modeling - Data comparison



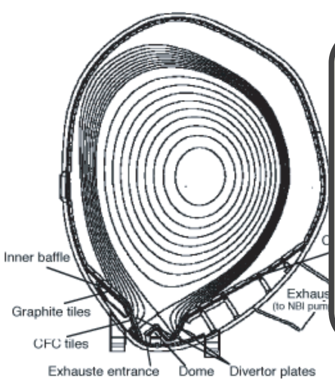


C-MOD
- High n_e and power density
- Moly walls, wall coatings
- Main chamber vs. divertor particle sources
- SOL transport
- Mixed materials studies

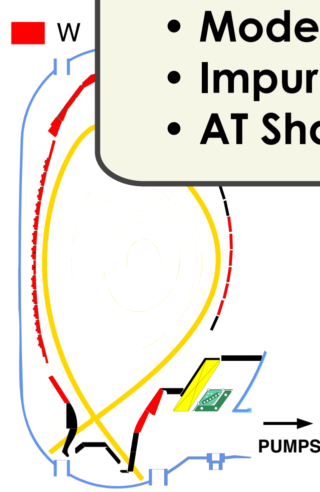
NSTX and MAST - comparisons of divertor detachment & ELMs

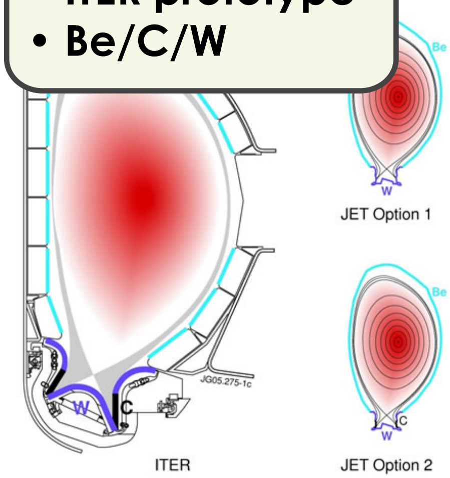
JET
- Major Wall program
- ITER prototype
- Be/C/W

ASDEX -U
- Extensive W
- Modeling gaps
- Impurity transport
- AT Shapes



JT-60U
- Divertor Dome
- Carbon Walls
- Extensive flow probes
- AT Plasmas





These are "icons" - not to scale

ITER site decision provides focus for DIII-D Boundary Program

– a. Heat load on first wall, especially due to ELMs
– d. Understand the effect of ELM/disruptions and first wall structures

Continued work with new diagnostics - probes, main chamber camera
Radiative divertor in Hybrid mode

– b. Carbon erosion/deposition/control of tritium inventory and material choice
– e. Improve understanding of Tritium retention, processes, and T removal

^{13}C experiments, DiMES, and modeling (DIVIMP, UEDGE), side lab O_2 bake

– g. Determine life-time of plasma facing mirrors used in optical systems
– h. Development of measurement requirements for dust

TS for dust, dust during commissioning)

– c. Private region PFC and necessity of Dome

New divertor geometry with and without dome, SN, DN - effect of drifts

– f. Develop SOL perpendicular coefficients and B.C. for input to BPX modeling

Comprehensive diagnostic set compared with computational models:
UEDGE, BOUT, DIVIMP, DEGAS-2, BOUT-Kinetic -- with particle drifts