THE ADVANCED TOKAMAK DIVERTOR

S.L. Allen and the DIII–D team

14th PSI

GENERAL ATOMICS
UCSD
ornl
DIII–D NATIONAL FUSION FACILITY SAN DIEGO
UNIVERSITY OF WISCONSIN MADISON
Department of Engineering Physics
PPPL PRINCETON PLASMA PHYSICS LABORATORY
UCLA

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Outline of Presentation

- Detached divertor solution
- Extend to "AT" Regime
  - → Particle control
  - → Profile control

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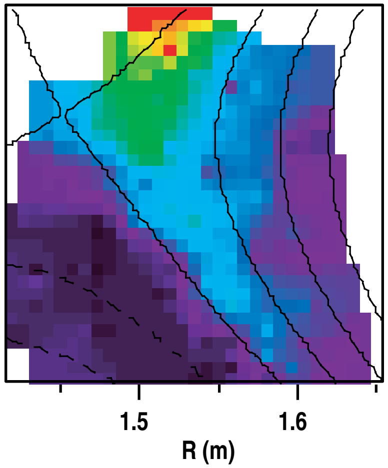
Detached divertors for particle and power handling

Data Shows Low T_e



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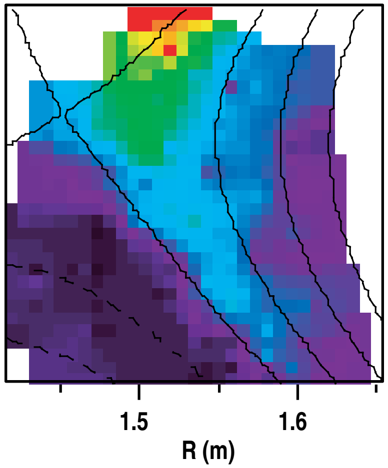

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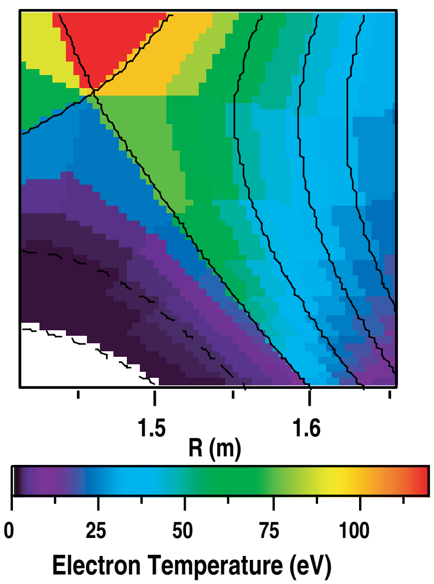

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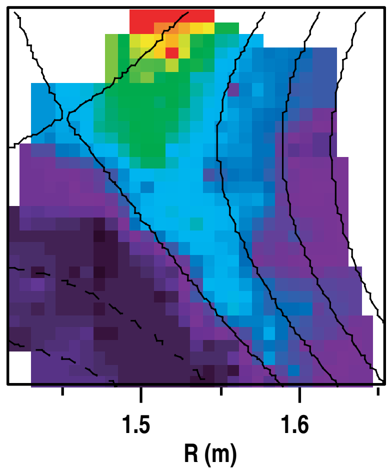

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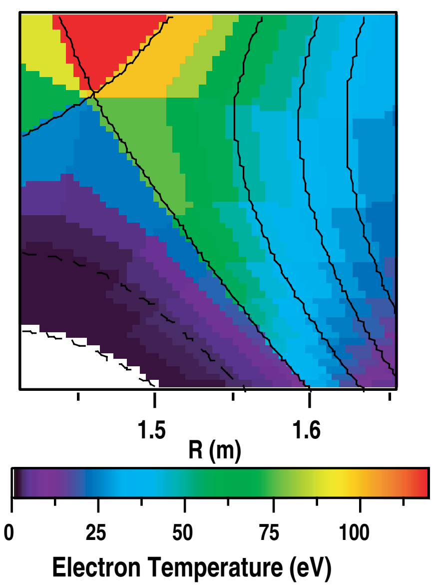
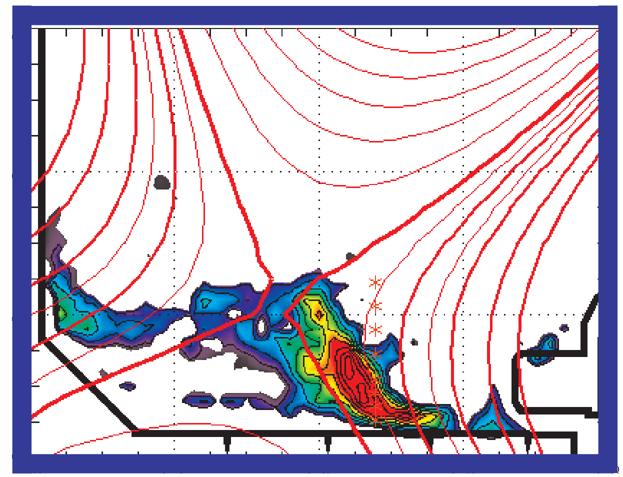


Recombining Plasma Near Plate (D_γ/D_α)



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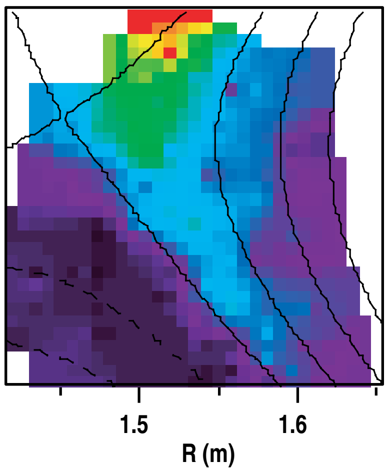

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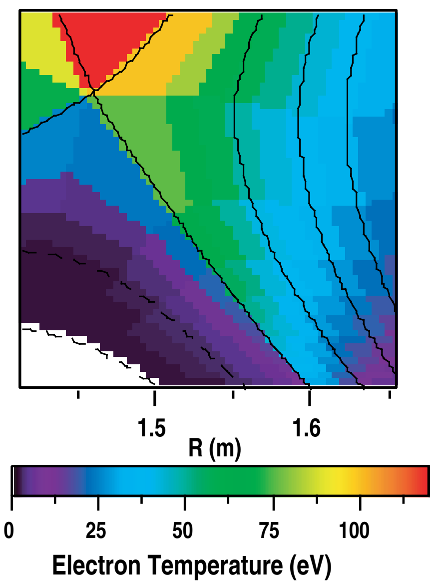

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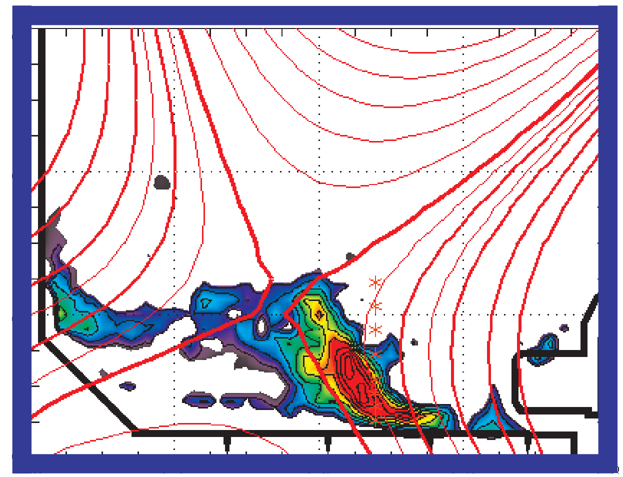
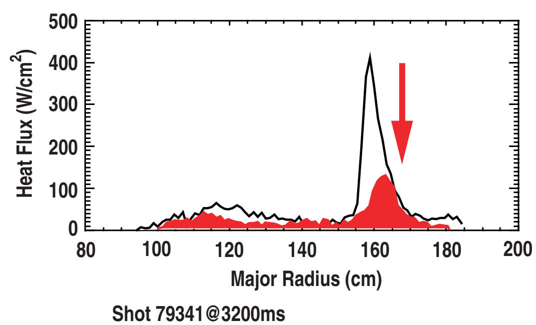
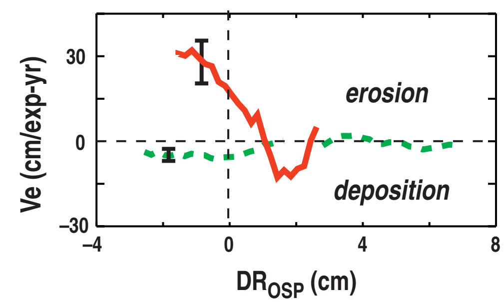


Divertor Heat Flux is Reduced



Erosion is Reduced



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We have a high density divertor solution

We have a reasonable scientific basis for a conventional long-pulse tokamak divertor solution at high density (collisional edge, detached)

- **Low Te recombining plasma leads to low heat and particle fluxes at wall**
- **Adequate ash control, compatible with ELMing H–mode confinement**
- **Appropriate for future tokamaks (e.g. to high density ITER-RC)**
- **Concerns about *simultaneously* handling disruptions/ELMs and tritium inventory which shorten divertor lifetime**

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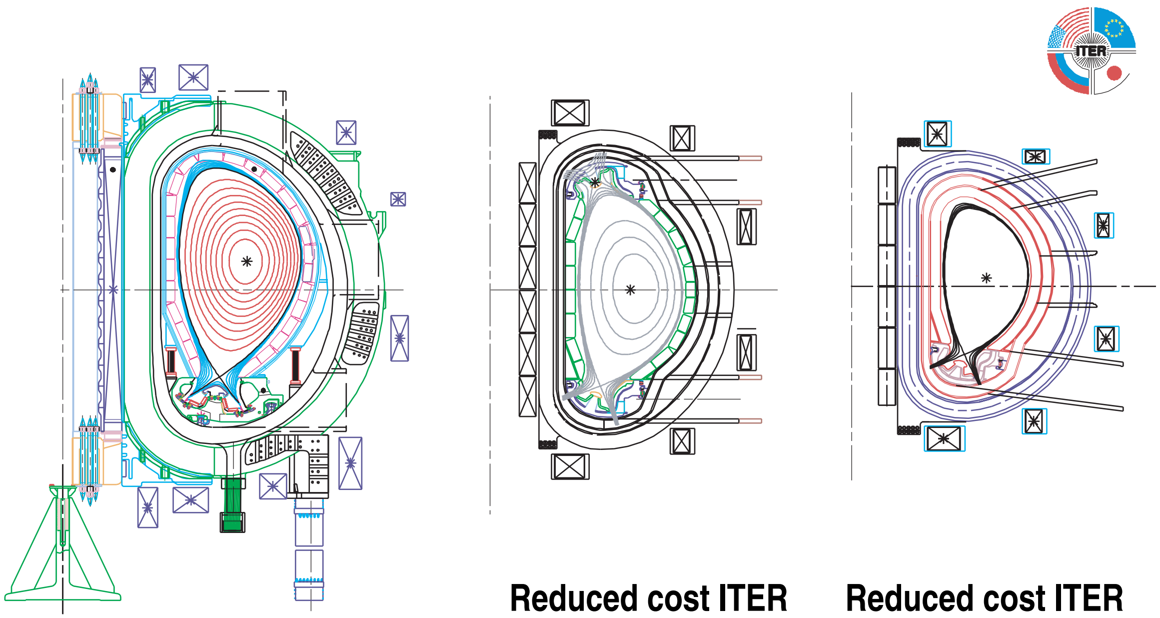
The challenge is to find self consistent operating modes for other configurations ...

(U.S. Snowmass working group, July 2000)

Improved confinement and stability can lead to more compact tokamak designs



ITER
final design report

Reduced cost ITER
LAM

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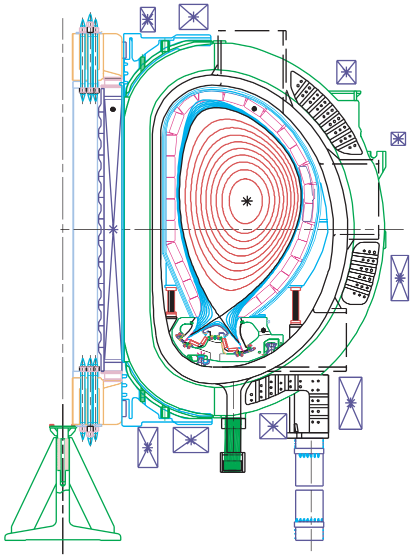

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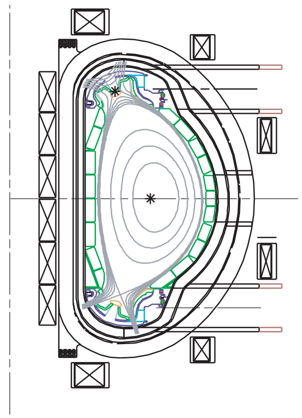

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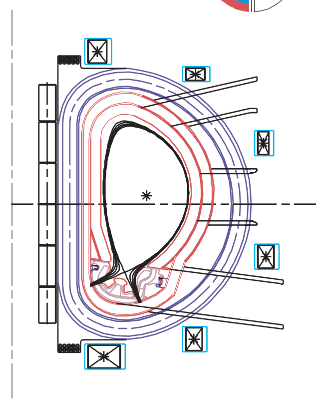

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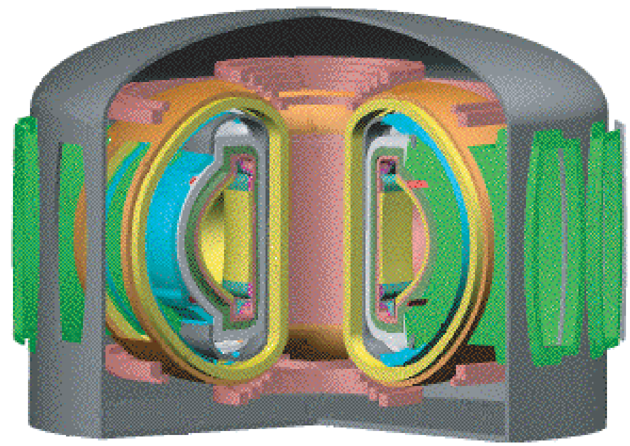
Advanced Tokamak



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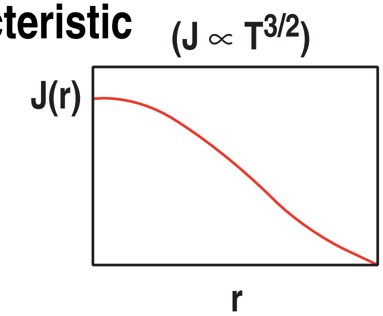
An AT operates at higher H (~3) and β_N (~5)

- Definition evolves as progress is made
  - Plasma shapes beyond circular were once "advanced," now standard
  - H–mode was "advanced," now standard

- A standard tokamak
  - Has a peaked current profile (q_0 = 1, sawteeth present) characteristic of ohmic heating
  - Therefore has a beta limit $\beta_N \leq 3$
  - Has standard confinement (L– or H–mode scaling)
  - Low bootstrap fraction



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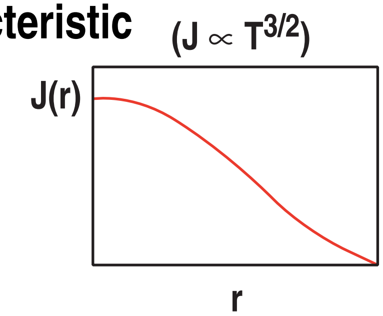
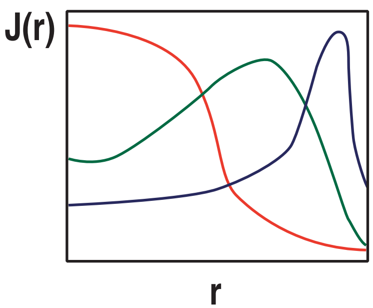
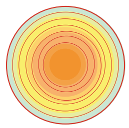
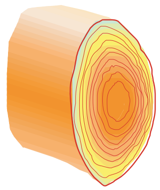
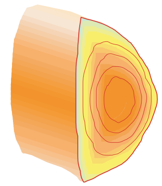
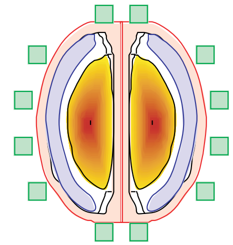


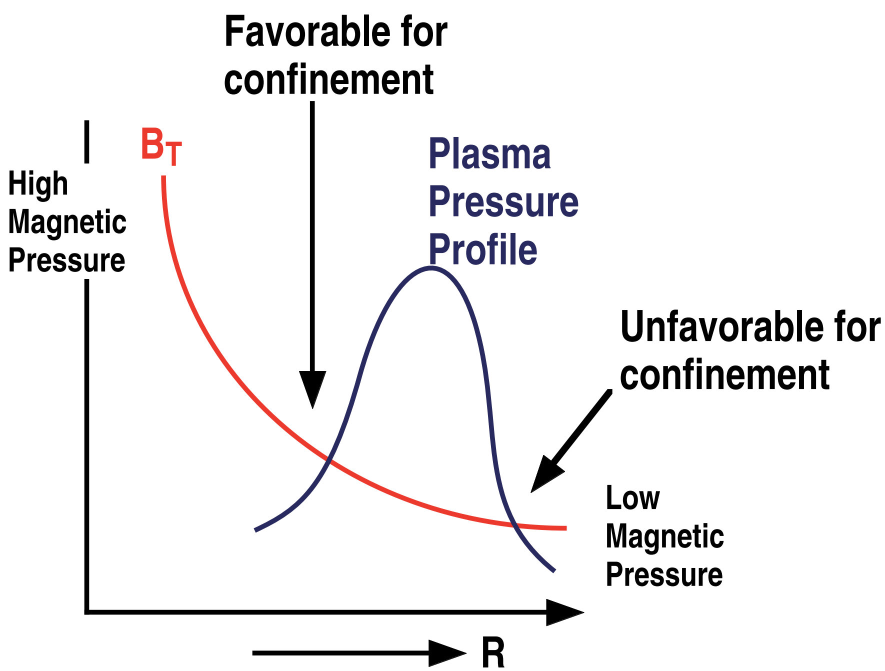
- **An advanced tokamak**
  - Frees the current profile from the ohmic constraint
  - With wall stabilization has potentially β_N up to 6
  - Exploits transport barriers for improved confinement
  - Has bootstrap fractions potentially $\rightarrow$ 100%
  - Potential for steady-state, reduced size fusion systems



Plasma shaping allows higher β_N AT operation, requires new divertor

- β  ~ 2.5%,  ~ 5%,  ~ 12.5%,  ~ 35%,

- Plasma shaping ($\kappa,\delta,\varepsilon$) increases the fraction of the total field line tragectory that is in the high magnetic field region resulting in improvement in the confinement concept



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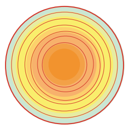
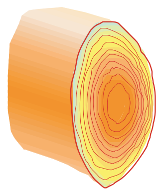
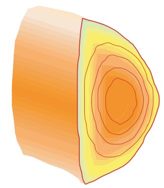
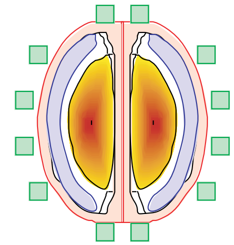
- β  ~ 2.5%,  ~ 5%,  ~ 12.5%,  ~ 35%,
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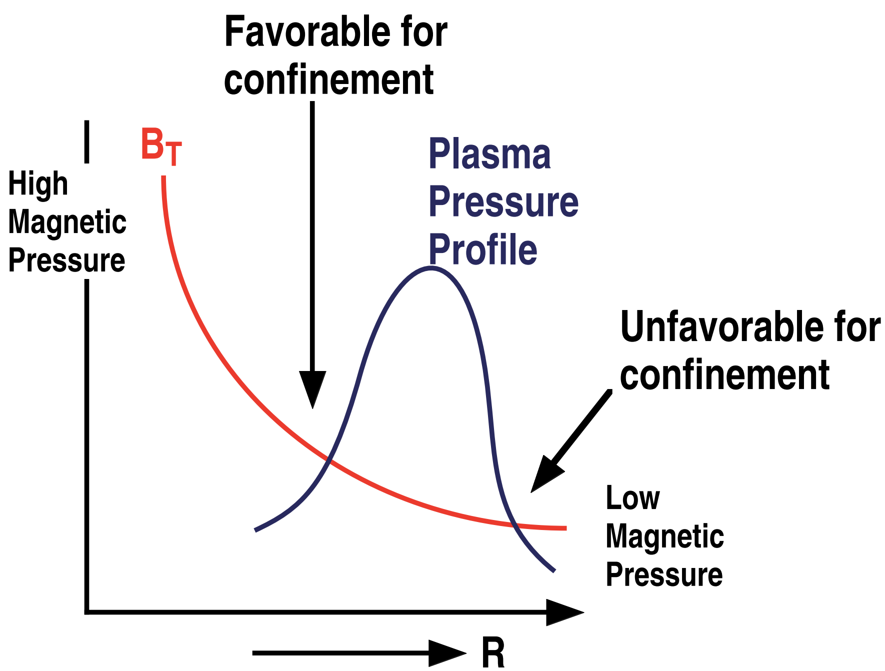
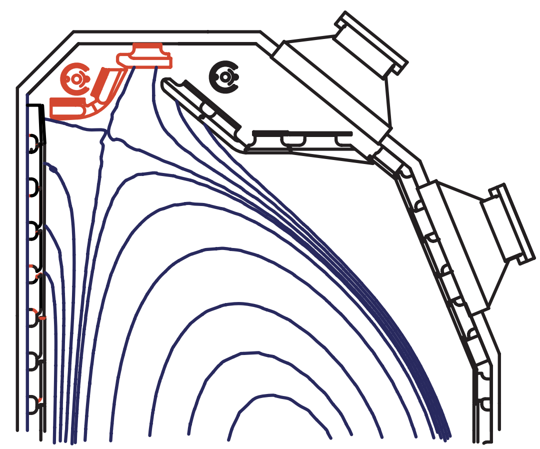
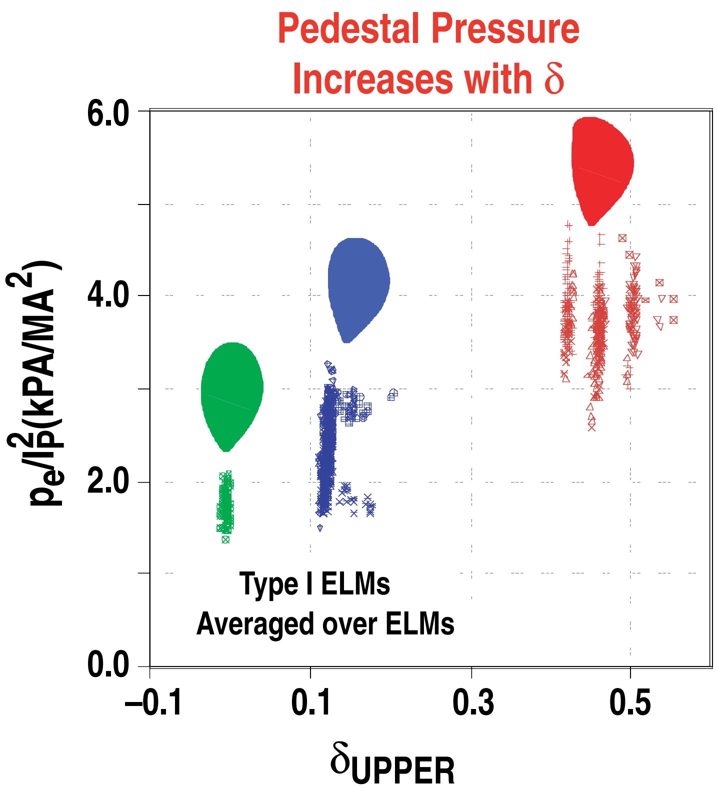


High - δ divertor



Shape is important for high pedestal pressure and good confinement



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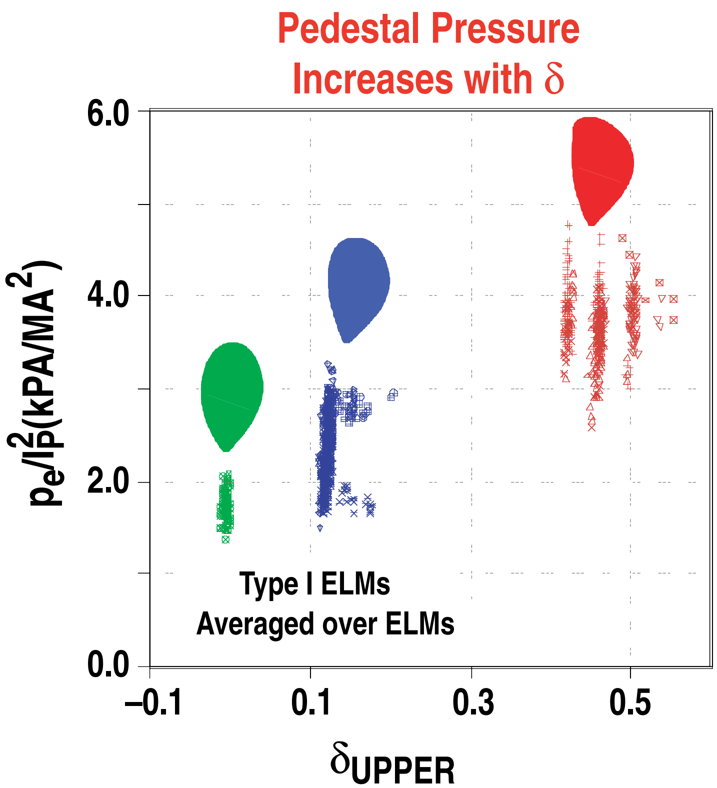

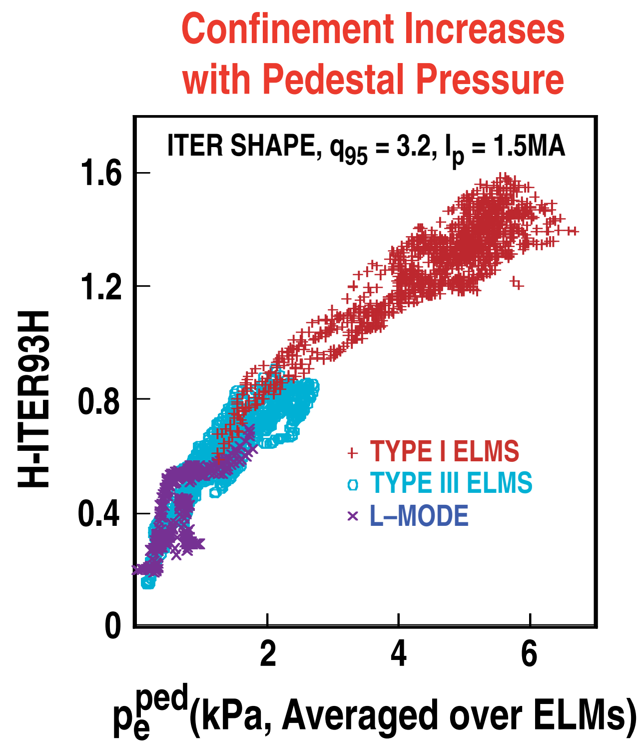

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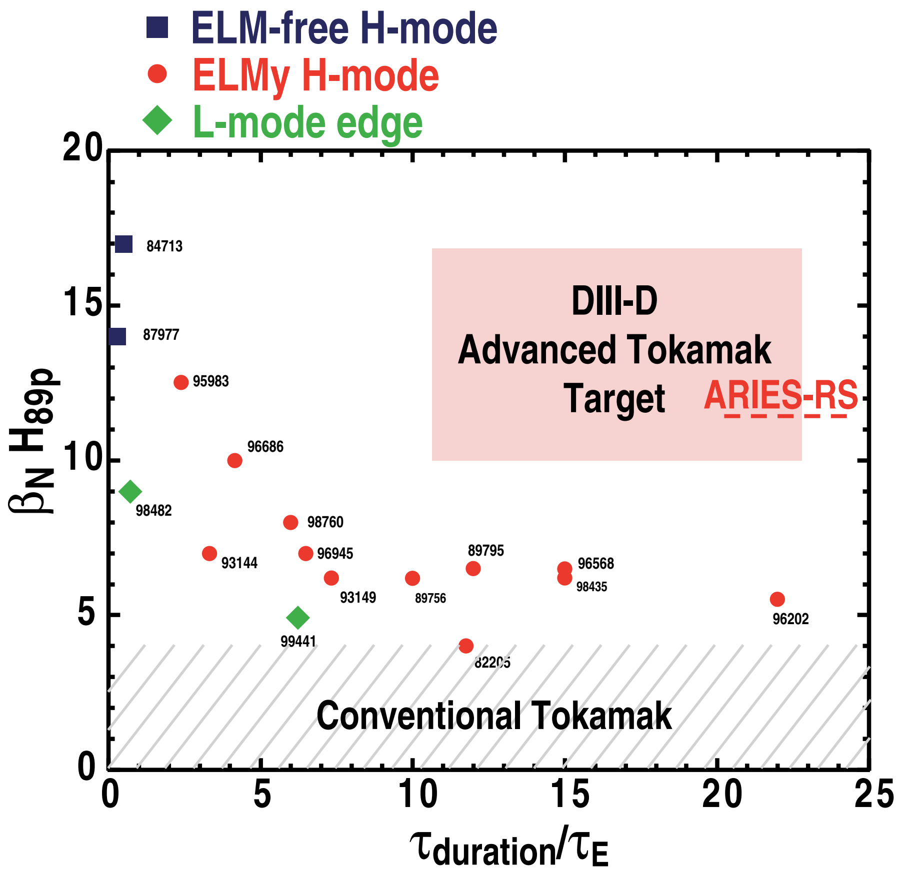
Significant progress has been achieved in long pulse AT operation



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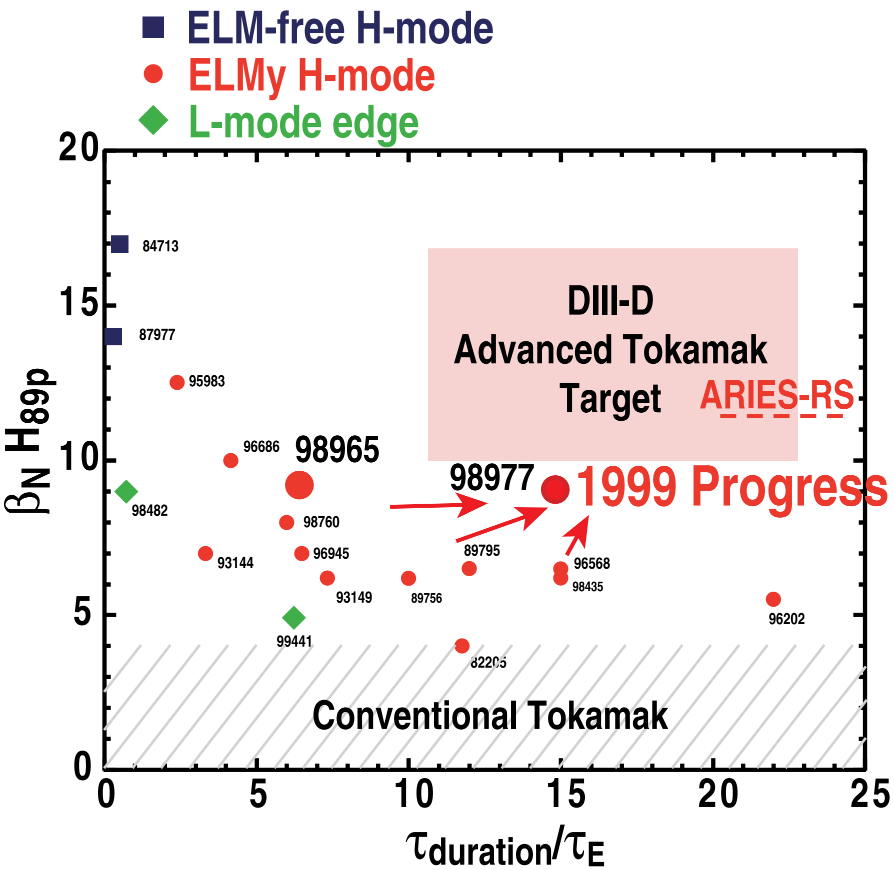

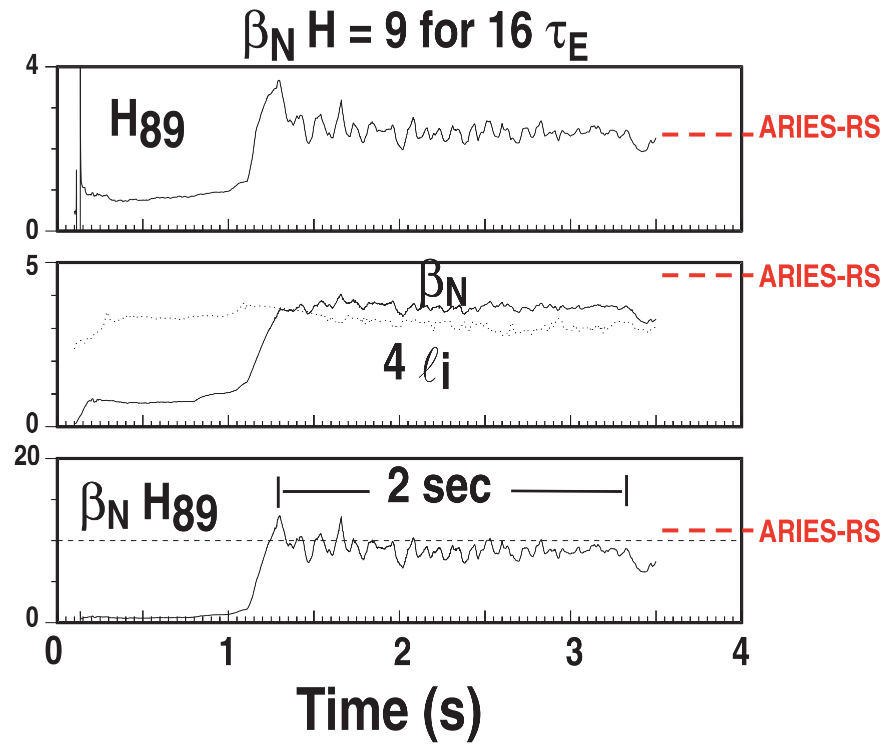

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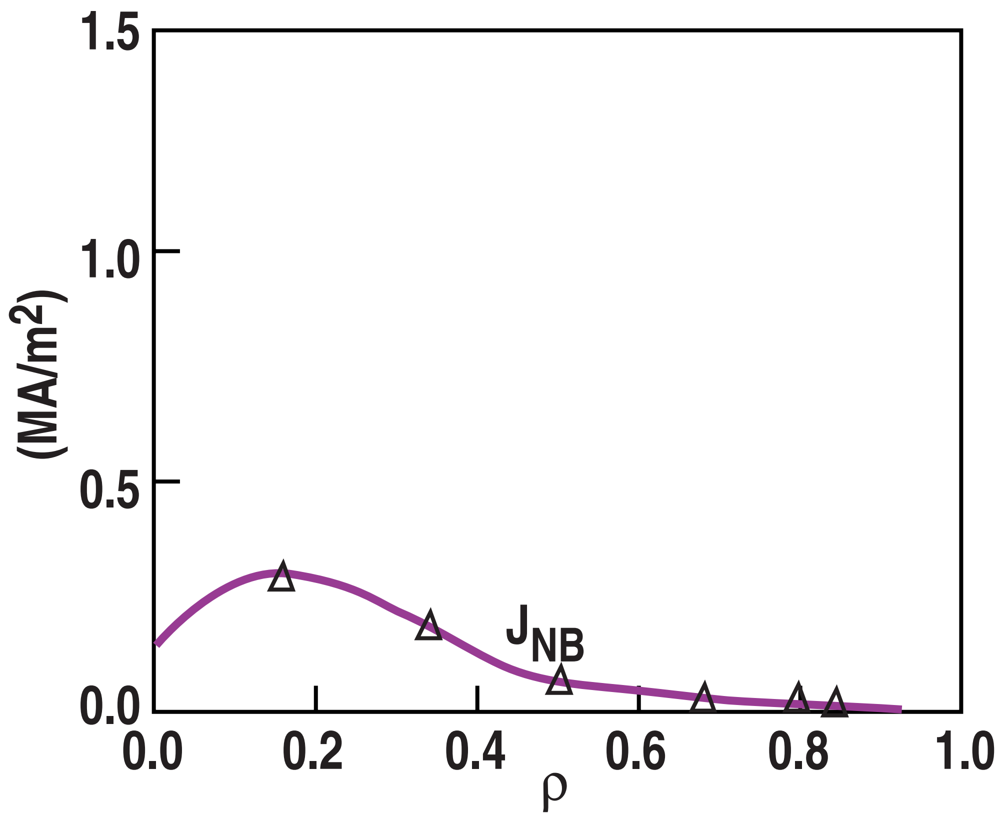
The DIII–D AT scenario with off-axis ECCD

	2001	2002	2003
P_{EC} (MW)	2.3	4.5	7.0
P_{FW} (MW)	3.5	3.5	6.5
P_{NBI} (MW)	4.1	3.8	6.5
β_N	4.0	5.3	5.7
H_{89P}	2.8	3.5	3.5
$\bar{n}/n_G$	0.3	0.4	0.4



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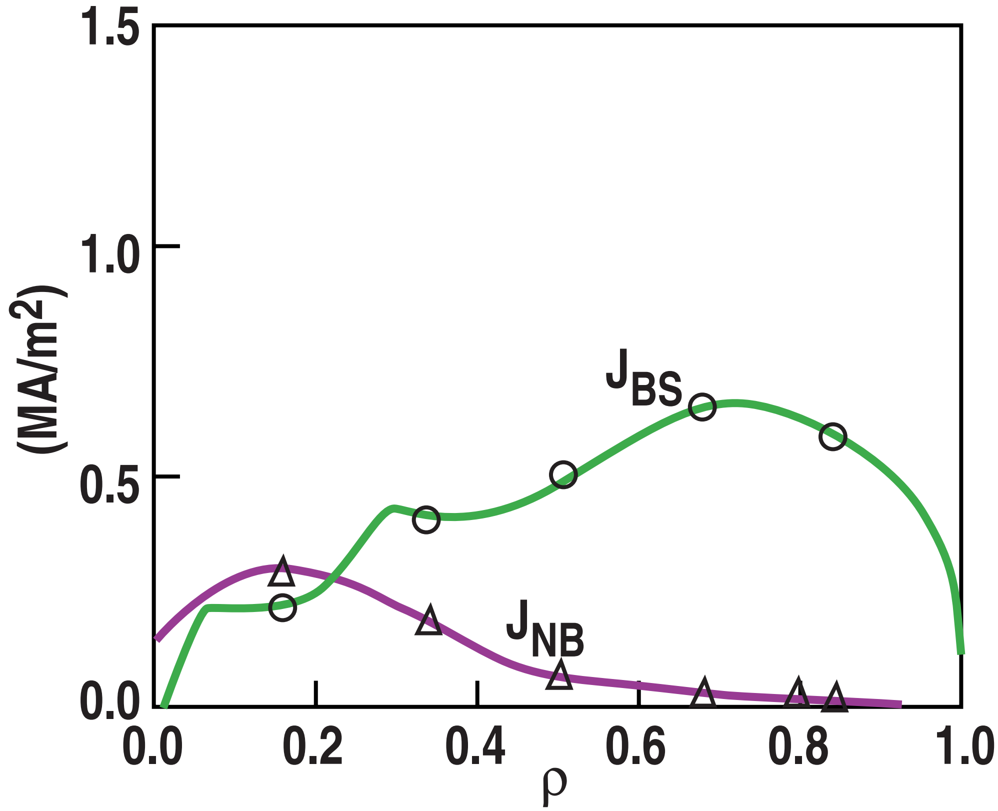

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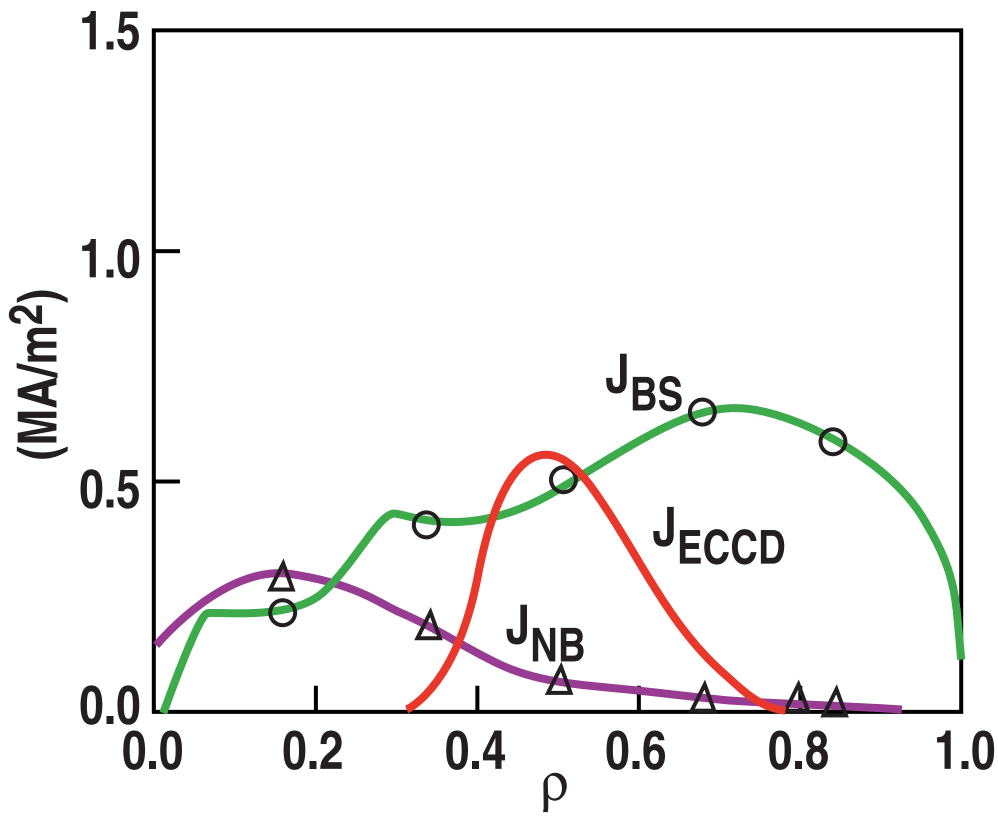

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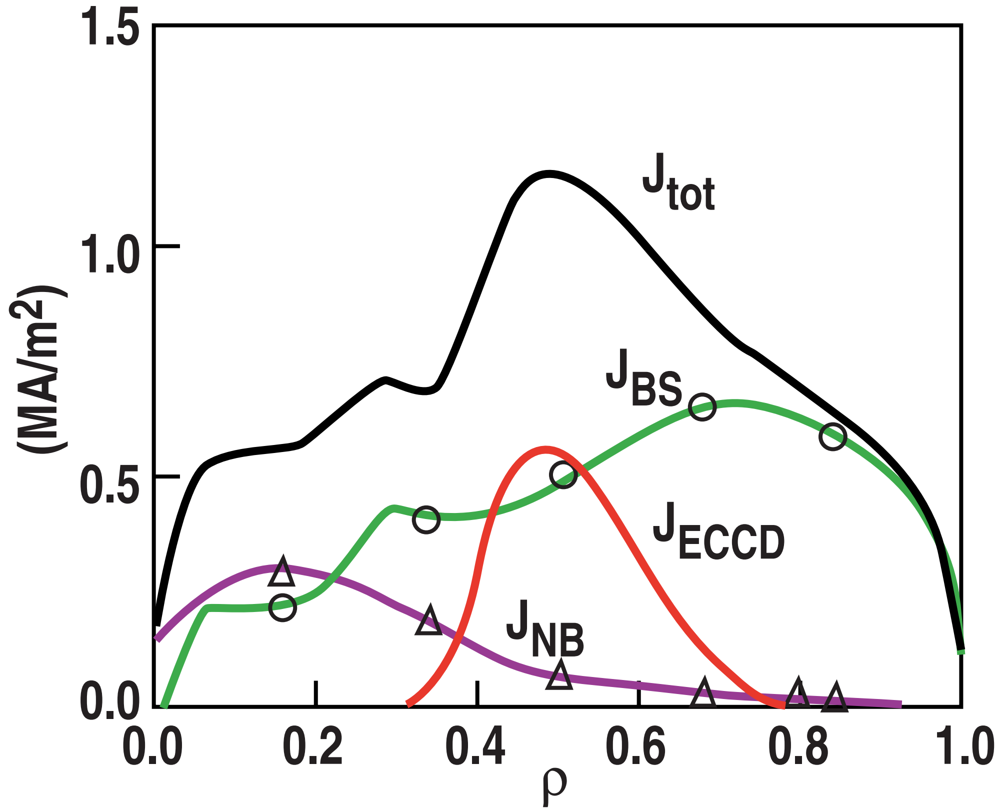
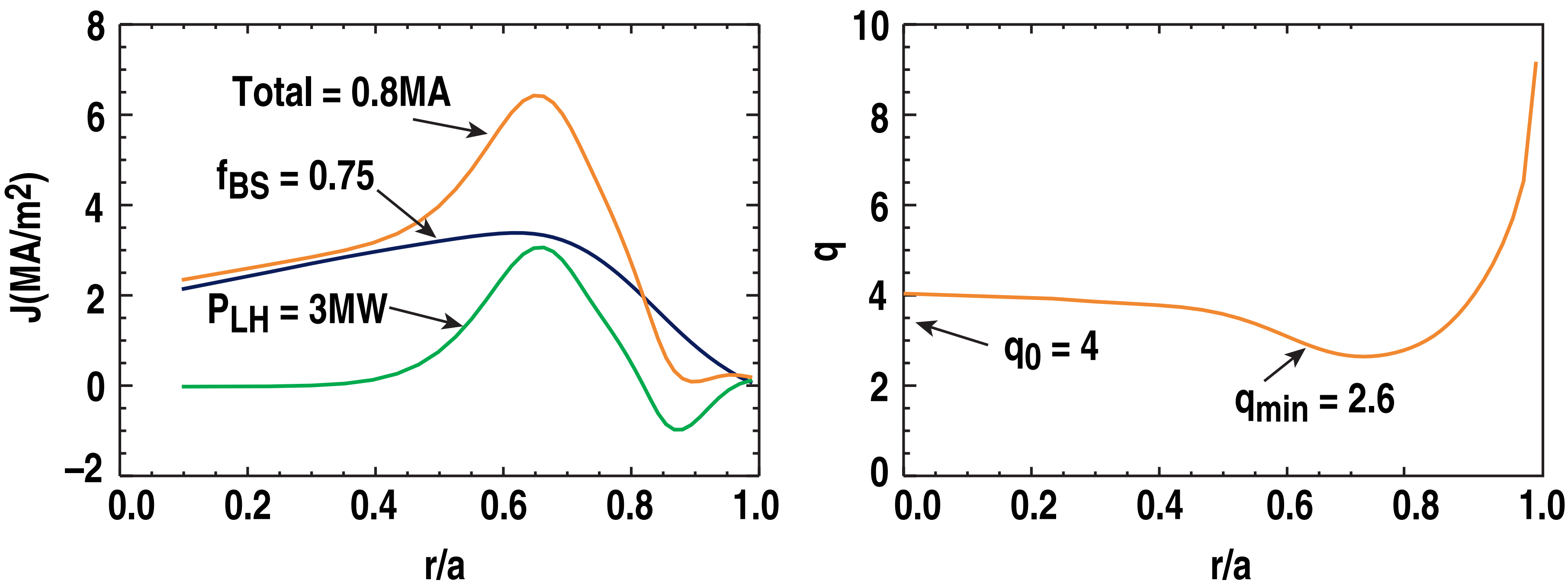


C–Mod AT operation at β_N ~3.5 (no wall stabilization necessary)



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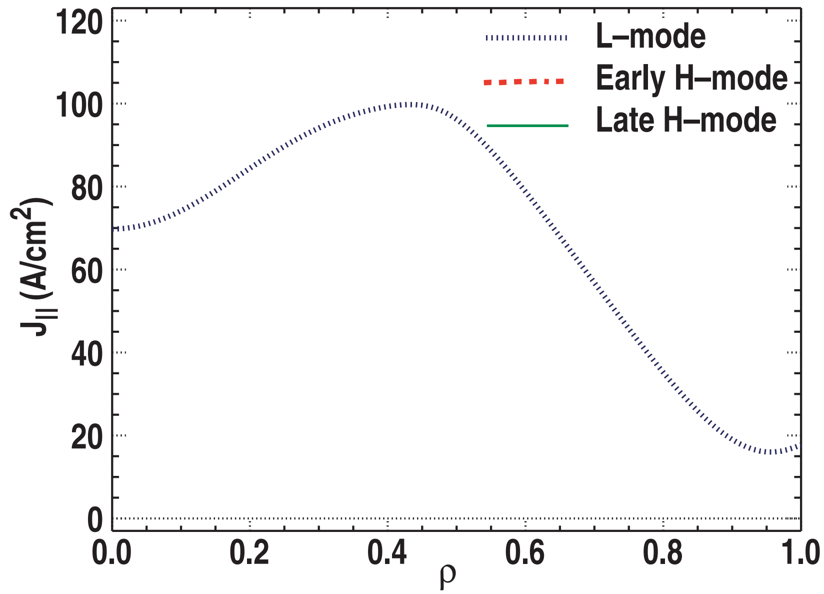
Density control and noninductive current sustainment are required for AT operation

- Current profile diffuses to unstable profile



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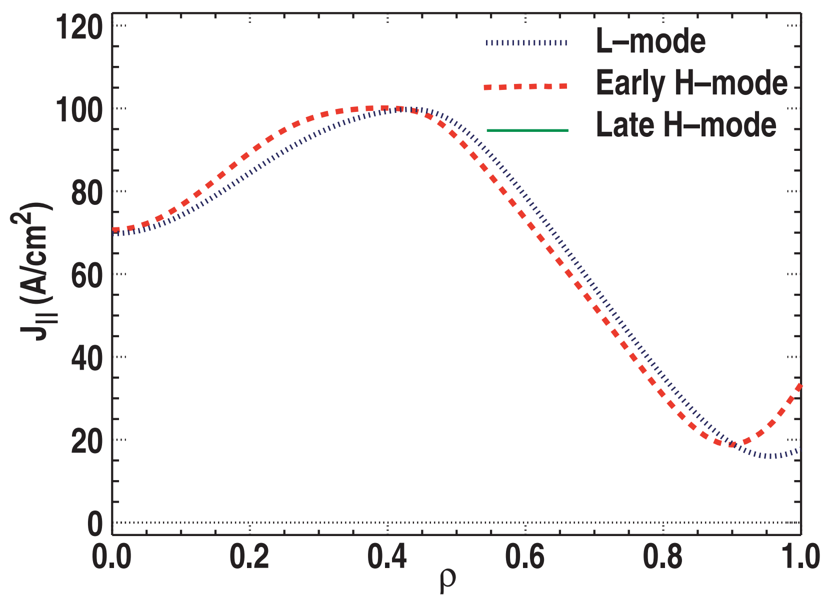

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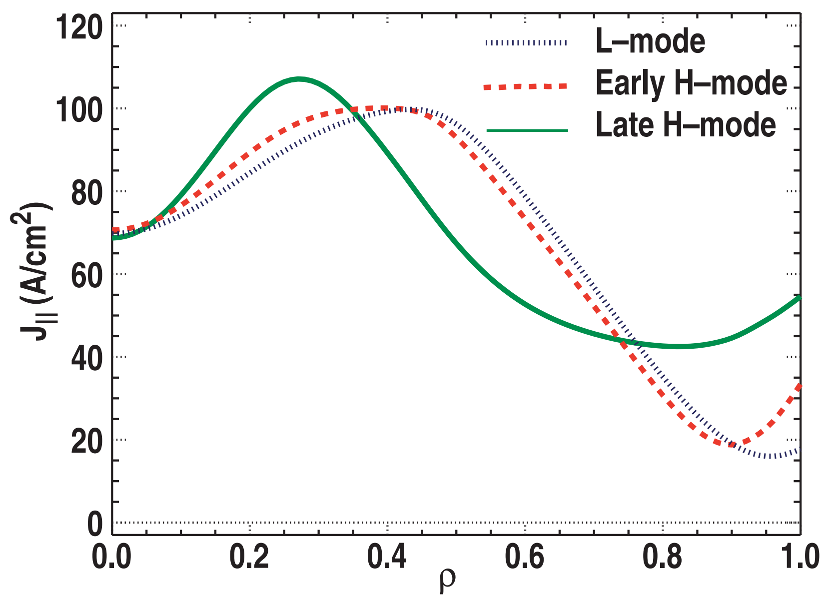

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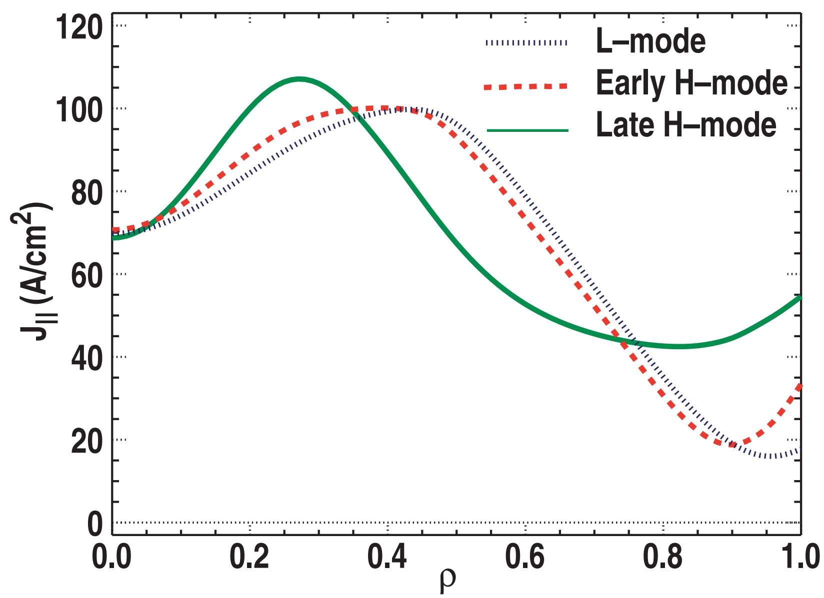
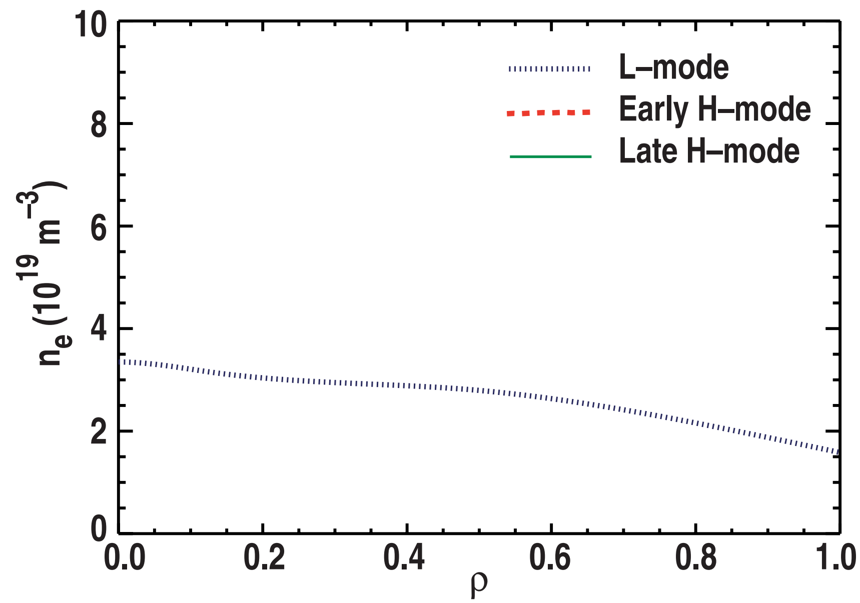


- Density continuously grows at constant β



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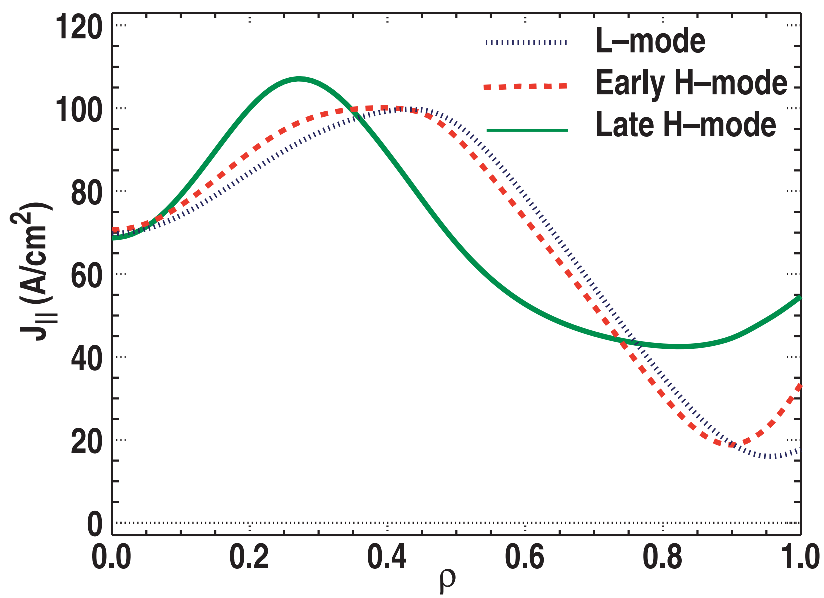

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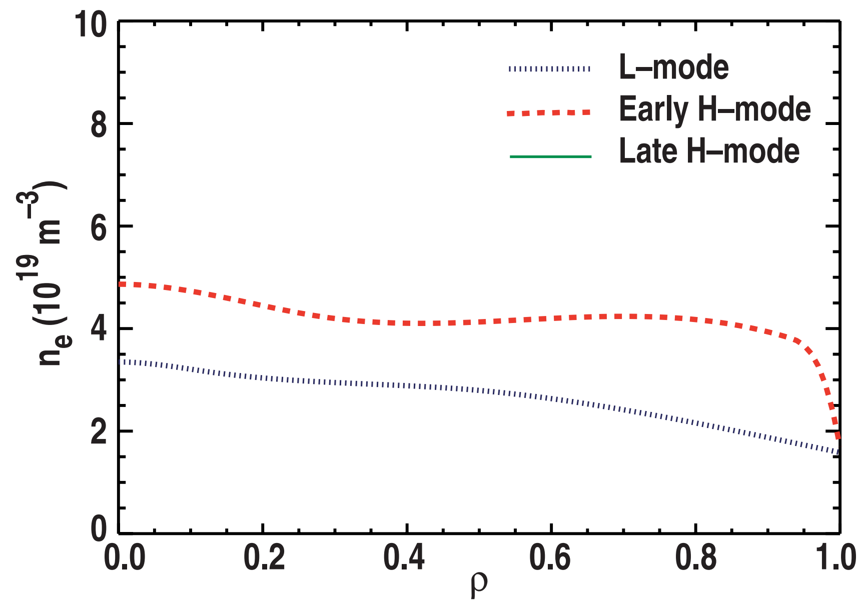

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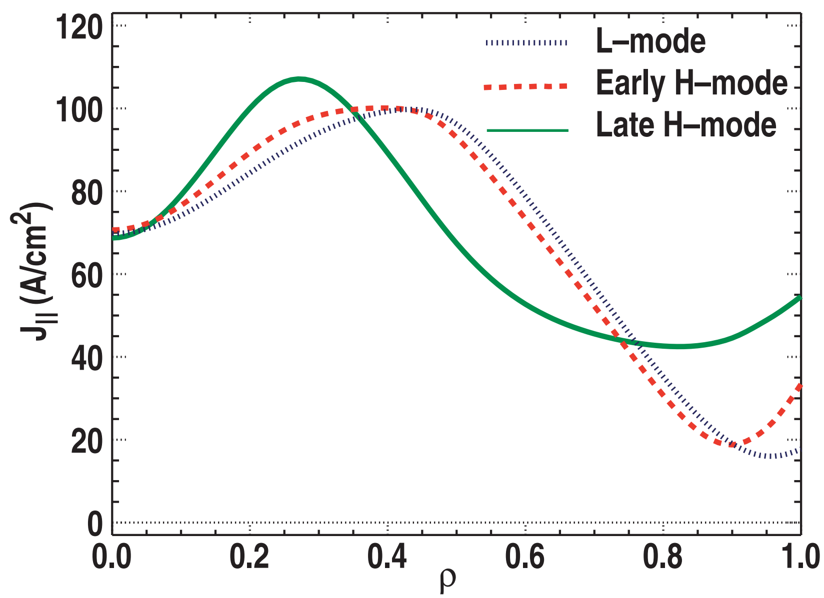

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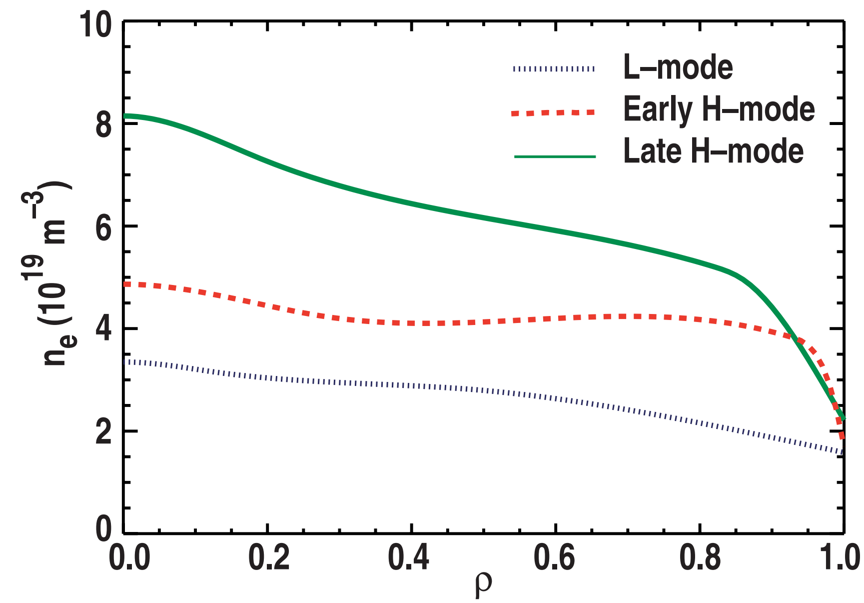

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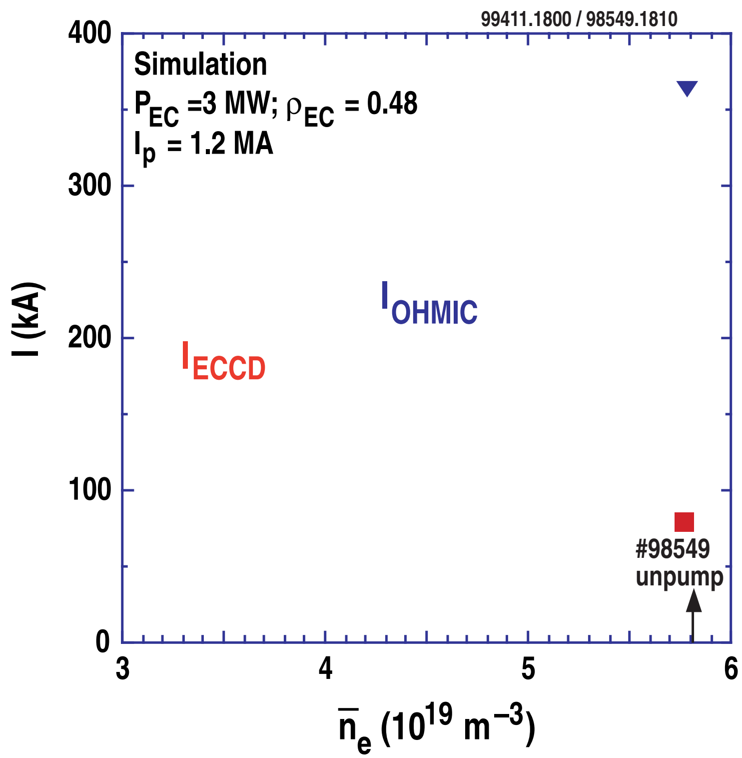

- $I_{CD} \propto \frac{T_e}{n_e} \frac{1}{(Z_{eff} + 5)}$

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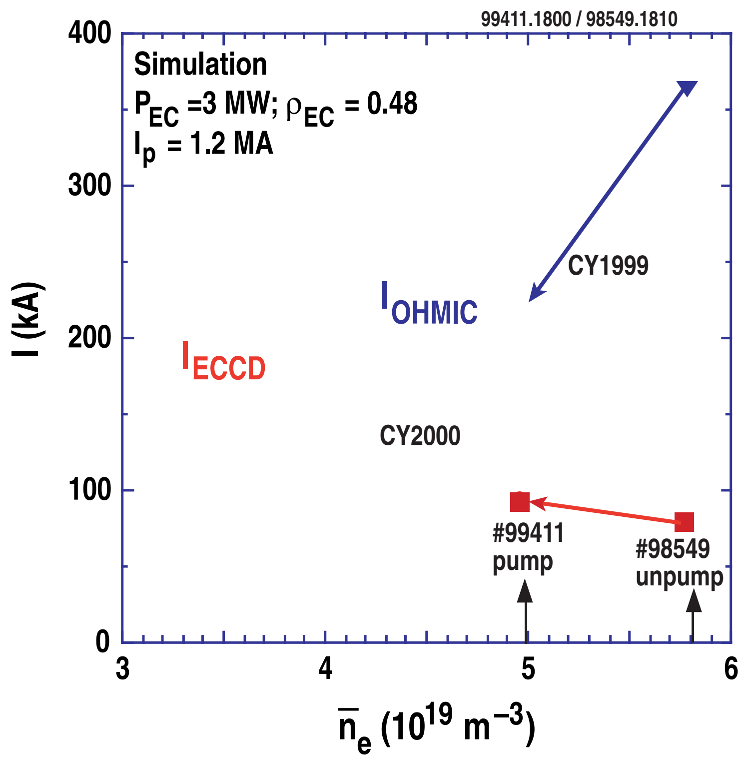

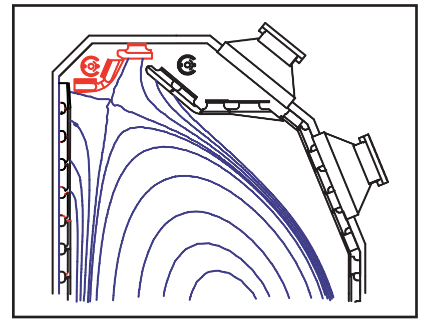

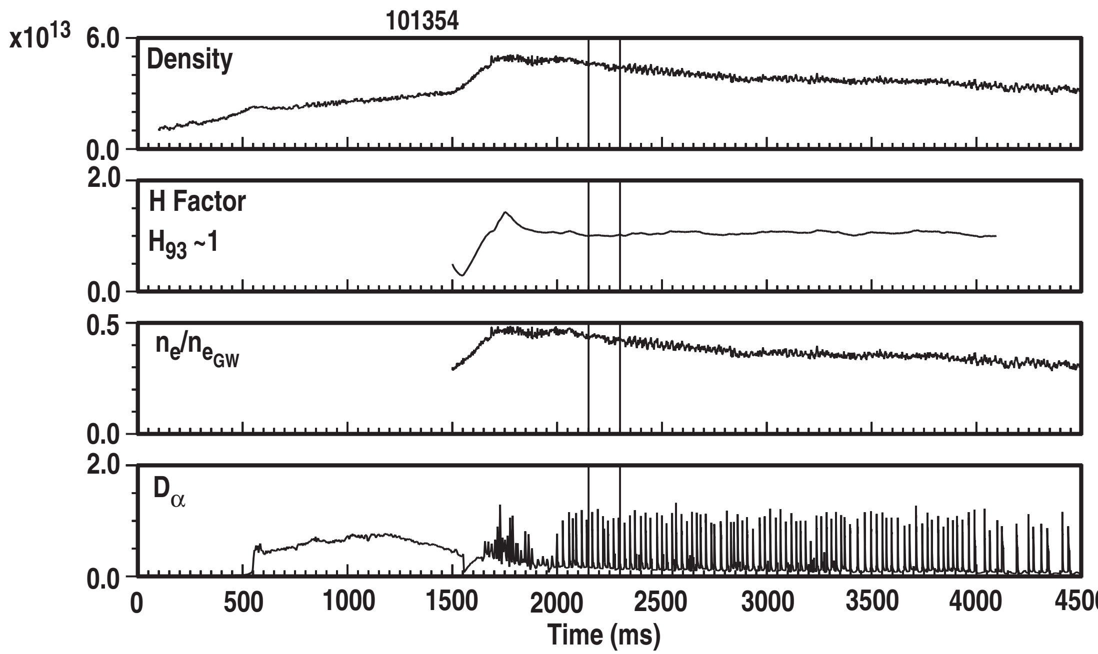

- $I_{CD} \propto \frac{T_e}{n_e} \frac{1}{(Z_{eff} + 5)}$

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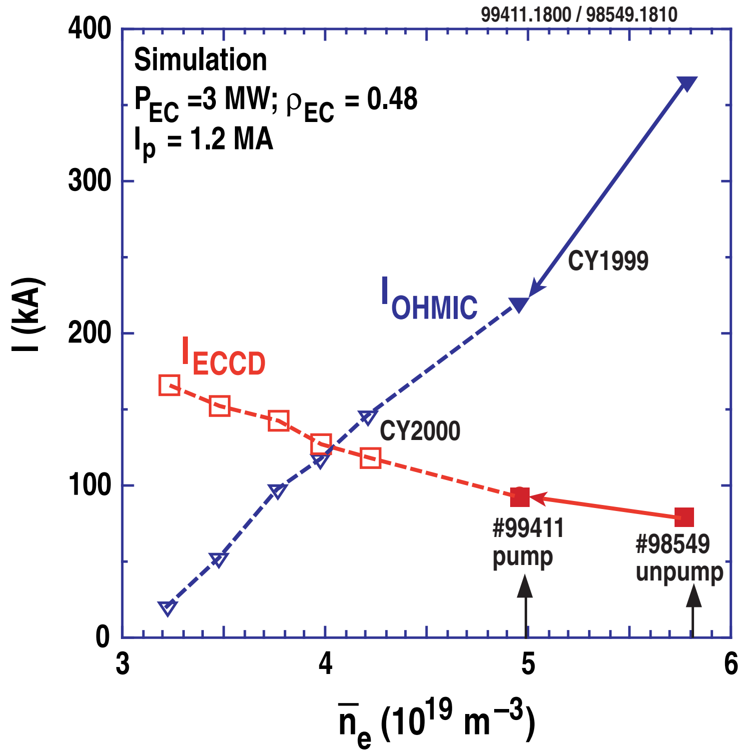
With available ECH power on DIII–D, density and impurity control are critical - these are provided by the divertor



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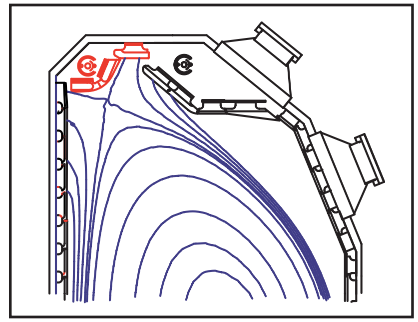

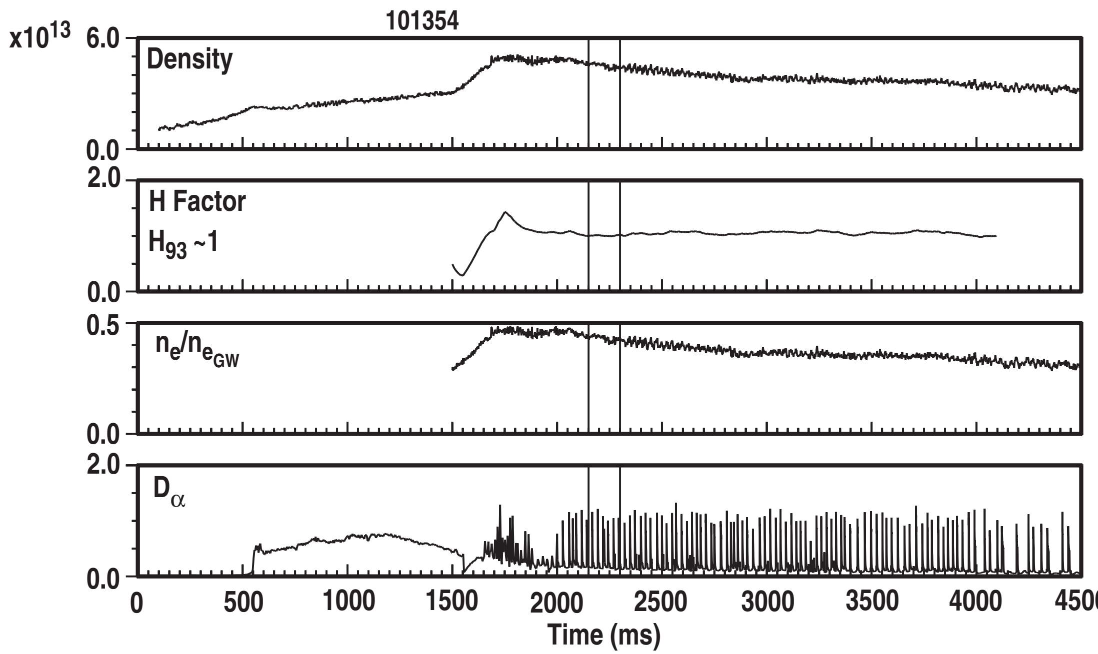

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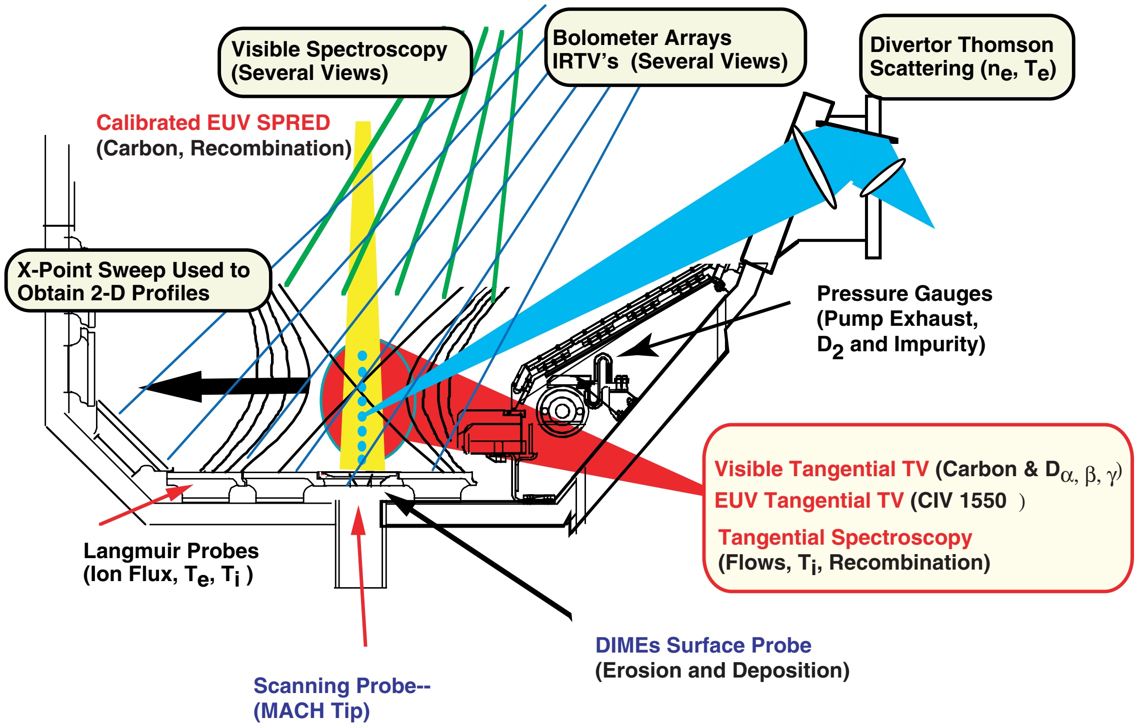
DIII–D divertors can compare open (low-δ) and closed (high-δ) operation with flexible pumping



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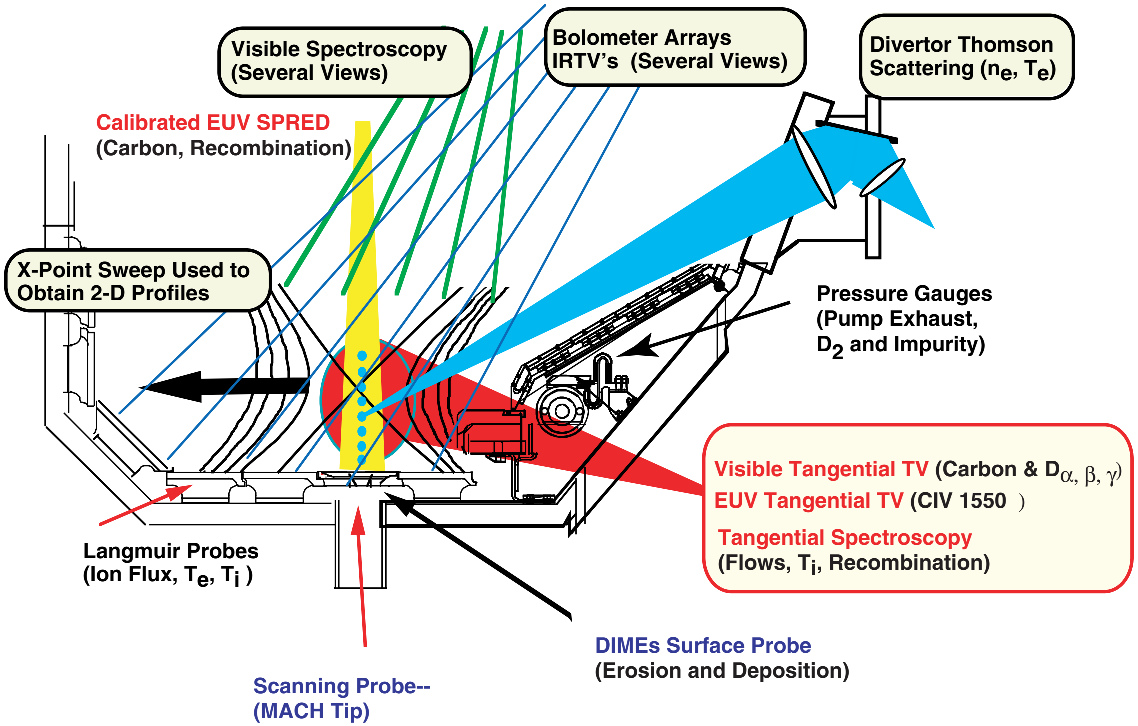

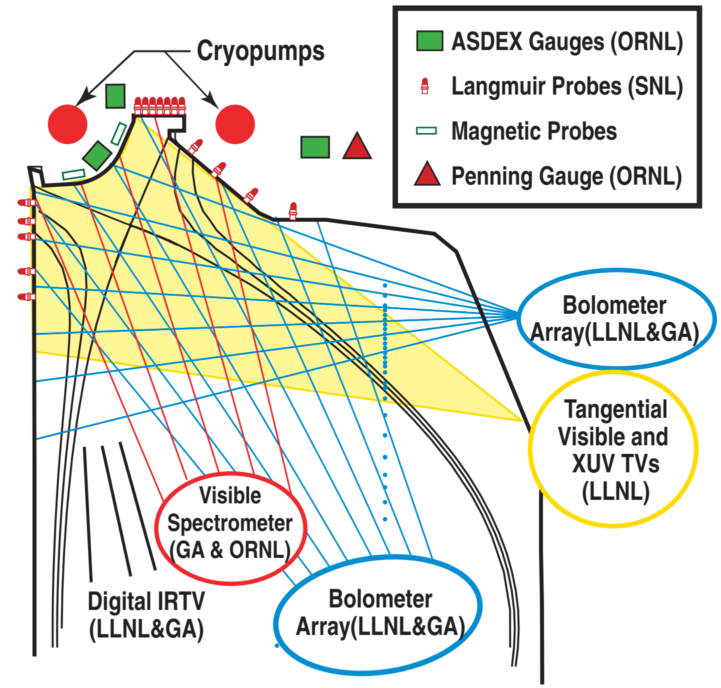

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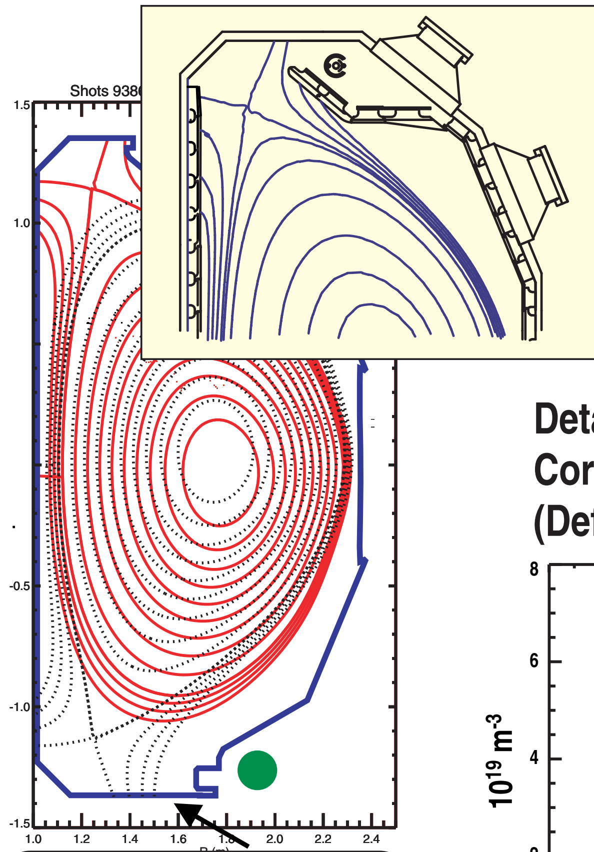
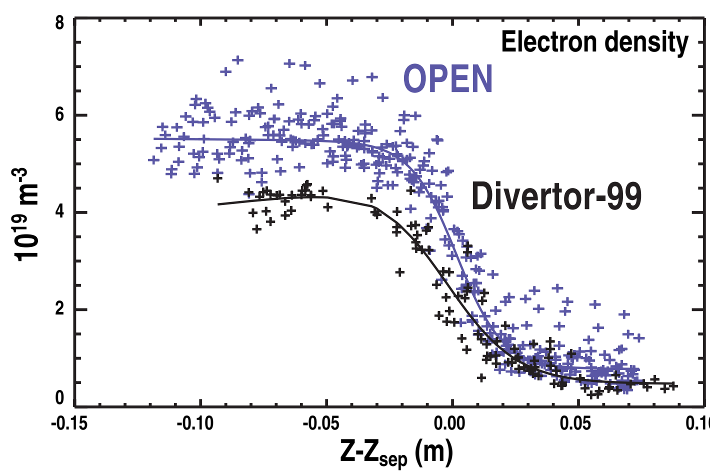
RDP 2000 is a closed divertor and reduces core ionization source (even without cryopumping)

RDP-1999
Data F = 2.5
UEDGE F = 3.5



Open Lower Divertor

Detailed n_e profile used to calculate Core Ionization Relative to Open Divertor (Defined to be F)



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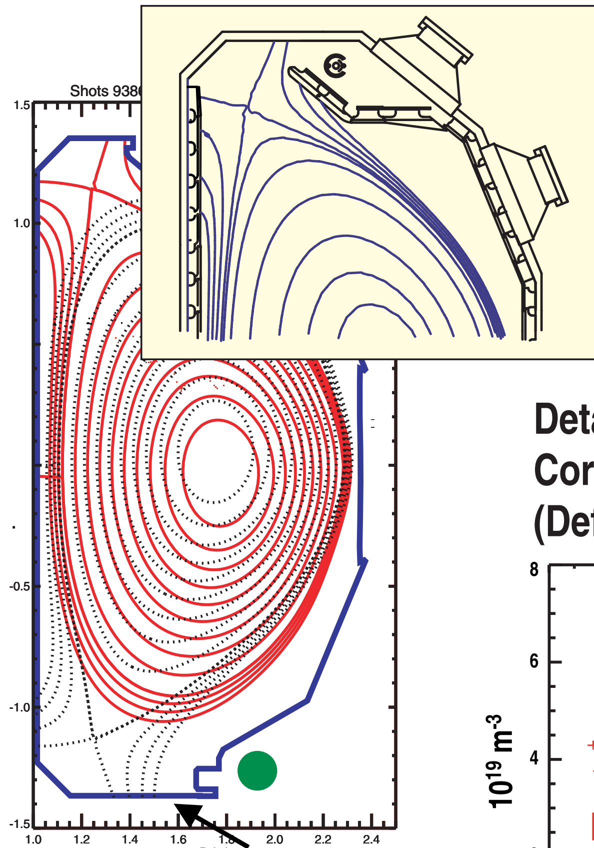
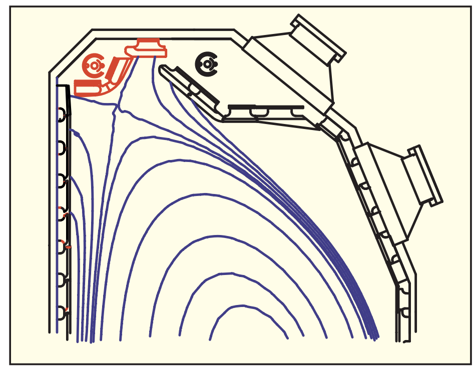


RDP-2000
Data (Prelim.) F ~ 5
UEDGE (Prelim.) ~ 6



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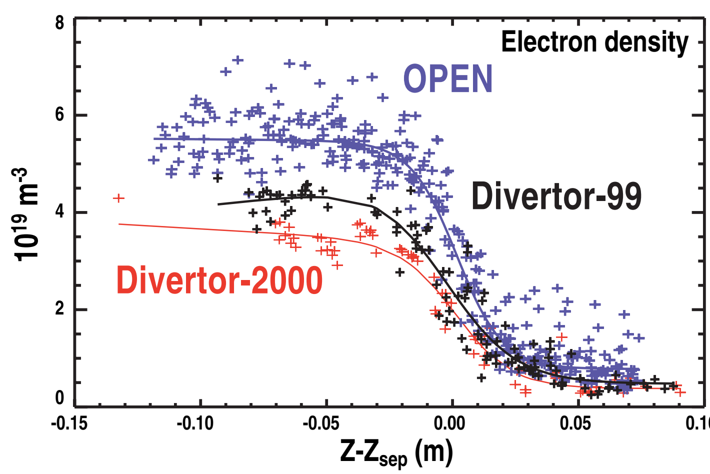

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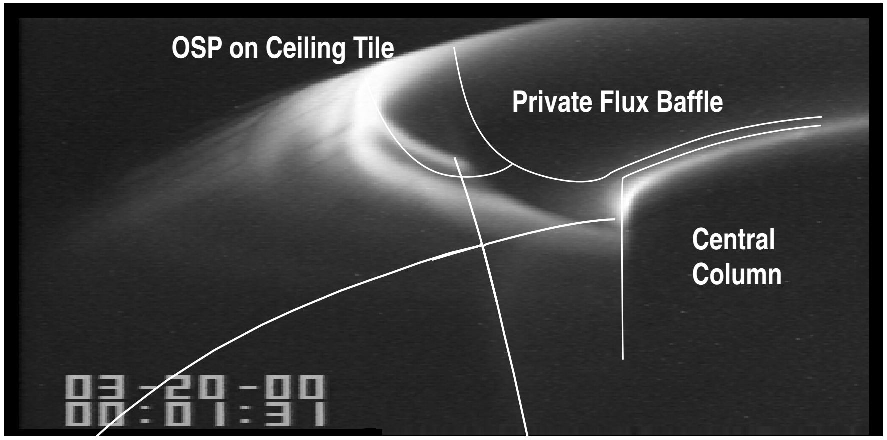
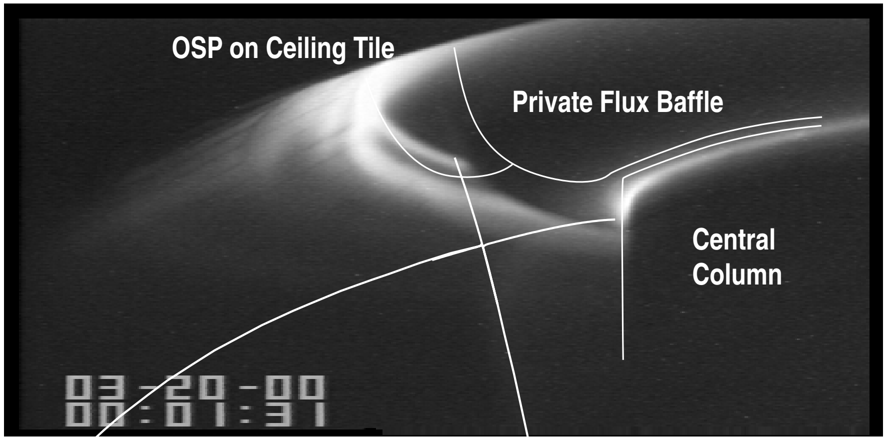
Experience gained in lower divertor (with DTS) is applied to upper divertor (with simplified diagnostics)

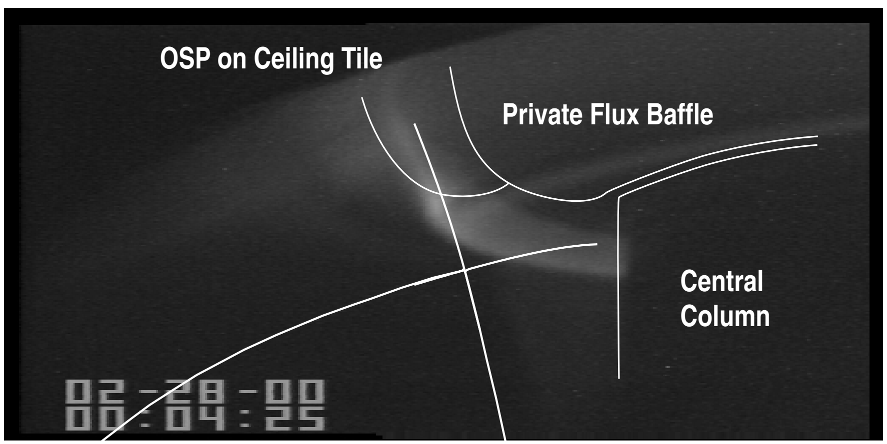


Attached Plasma
at Low Density

Experience gained in lower divertor (with DTS) is applied to upper divertor (with simplified diagnostics)



Attached Plasma at Low Density



Detached Plasma at High Density

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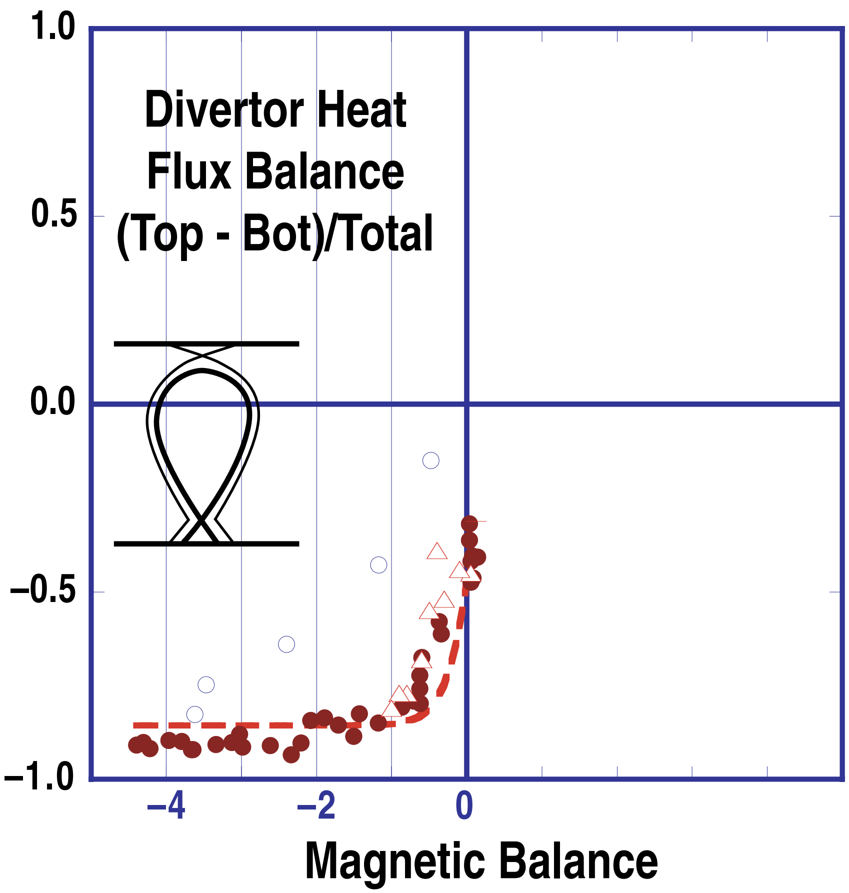
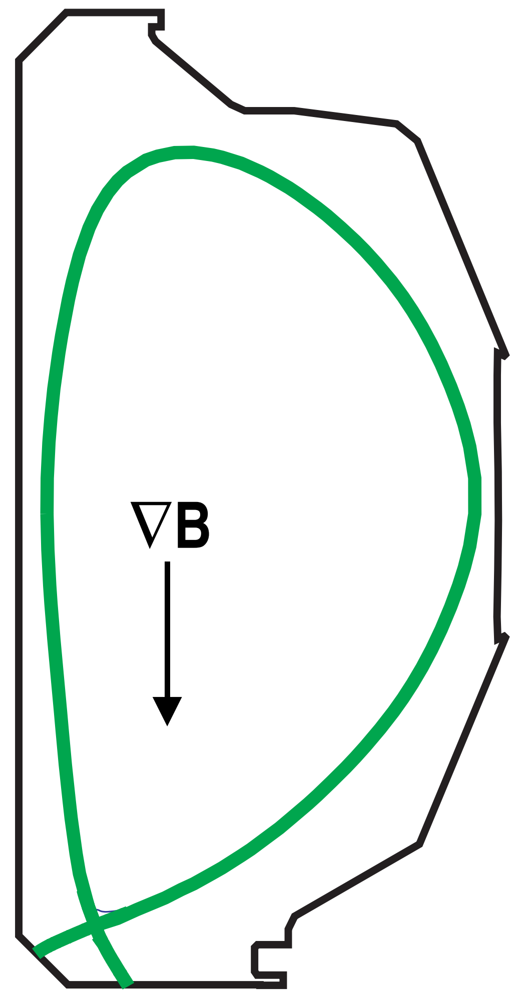
Magnetic balance can be used for power and particle control





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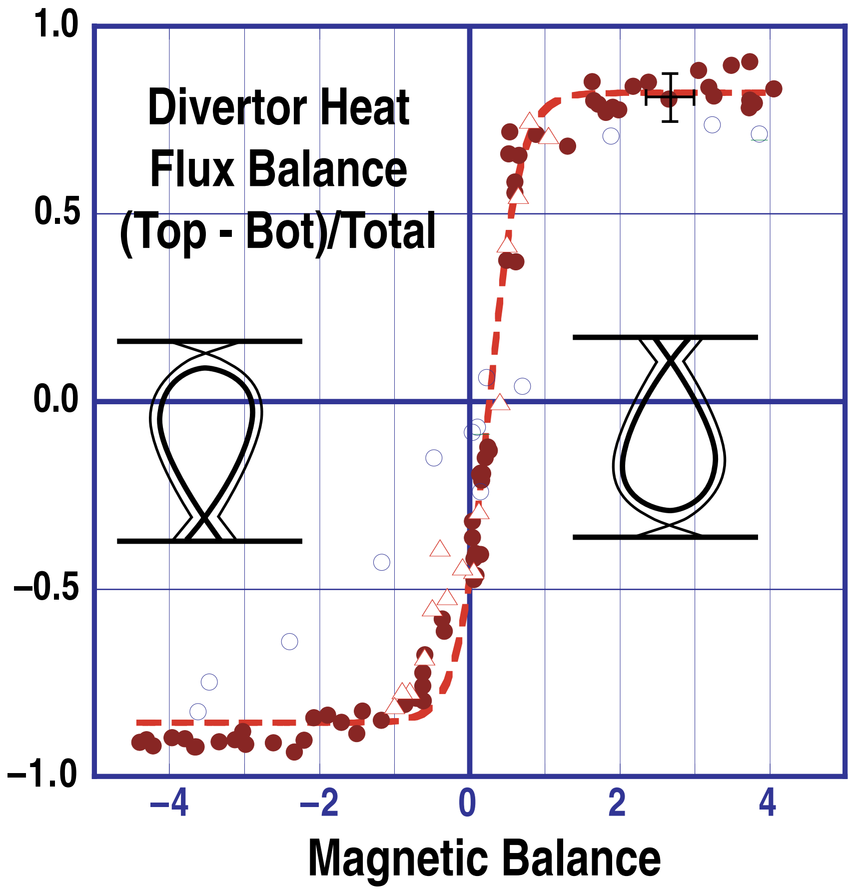
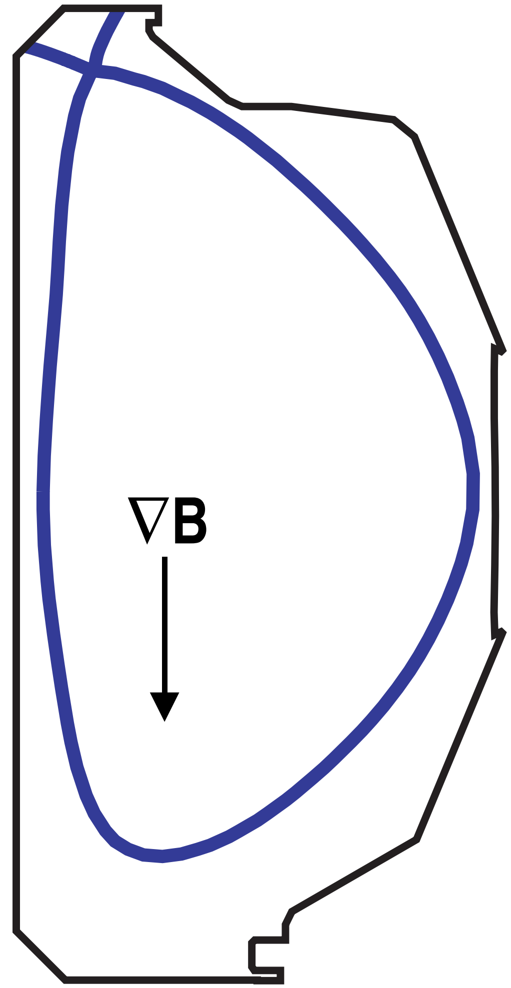
Magnetic balance can be used for power and particle control





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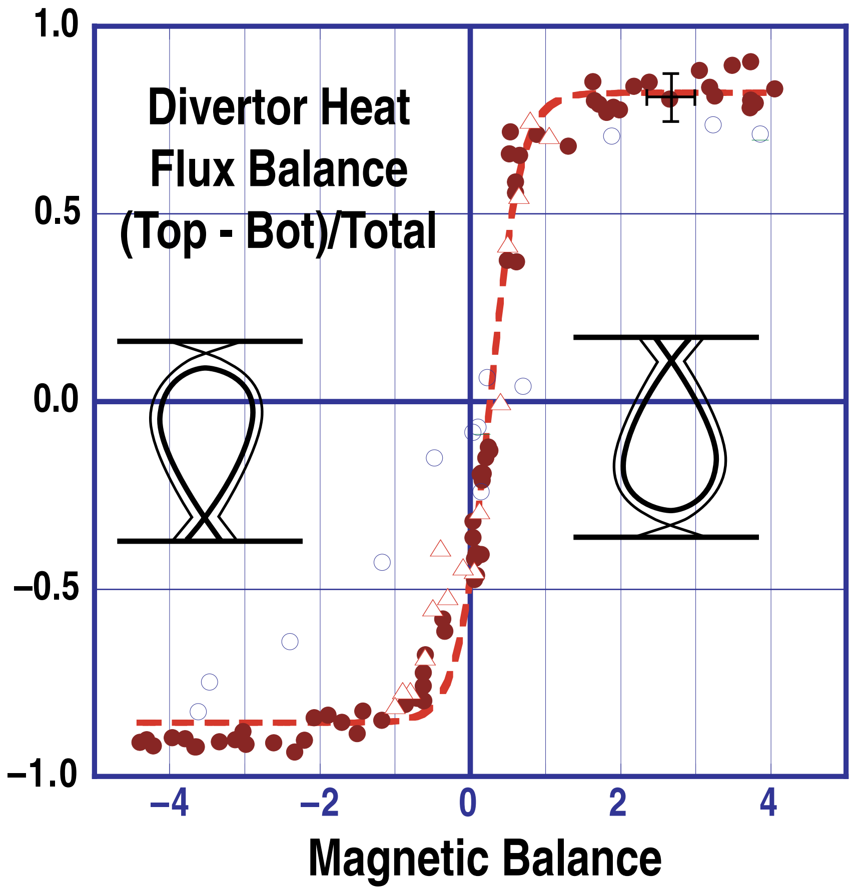

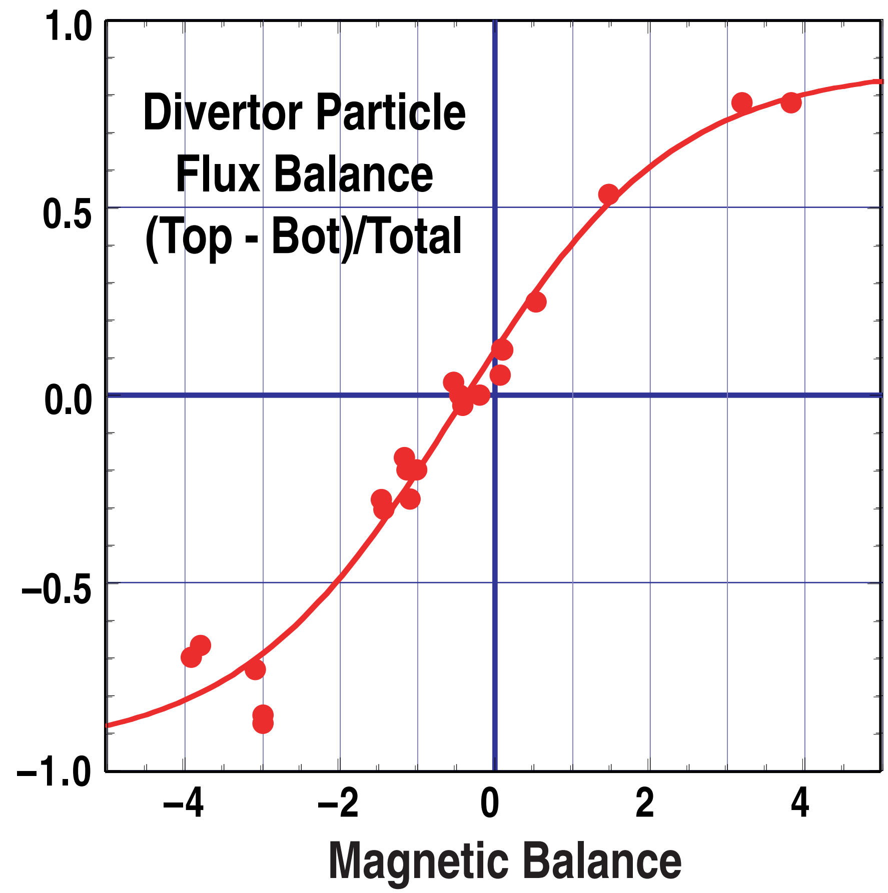

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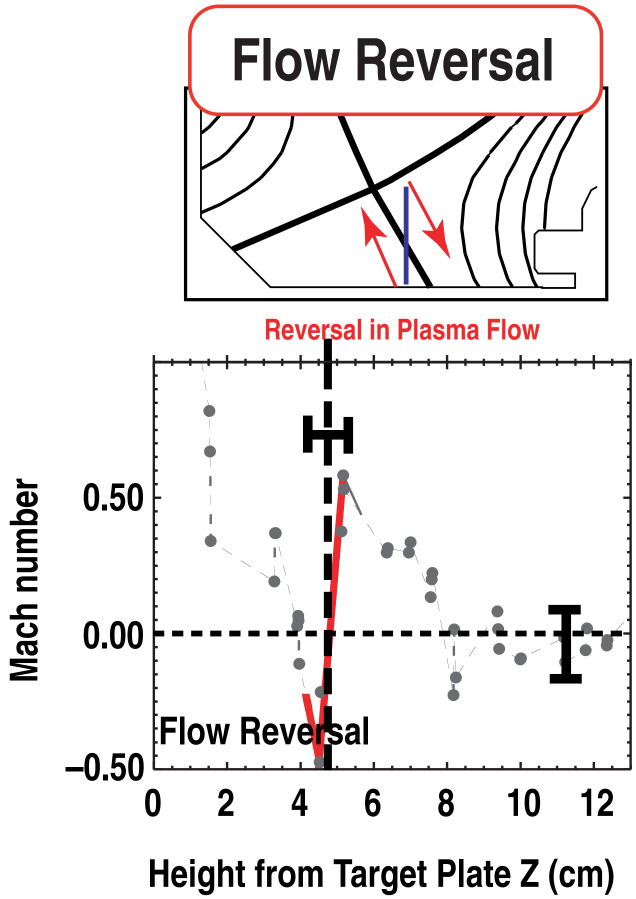
New physics in the x-point and private flux region



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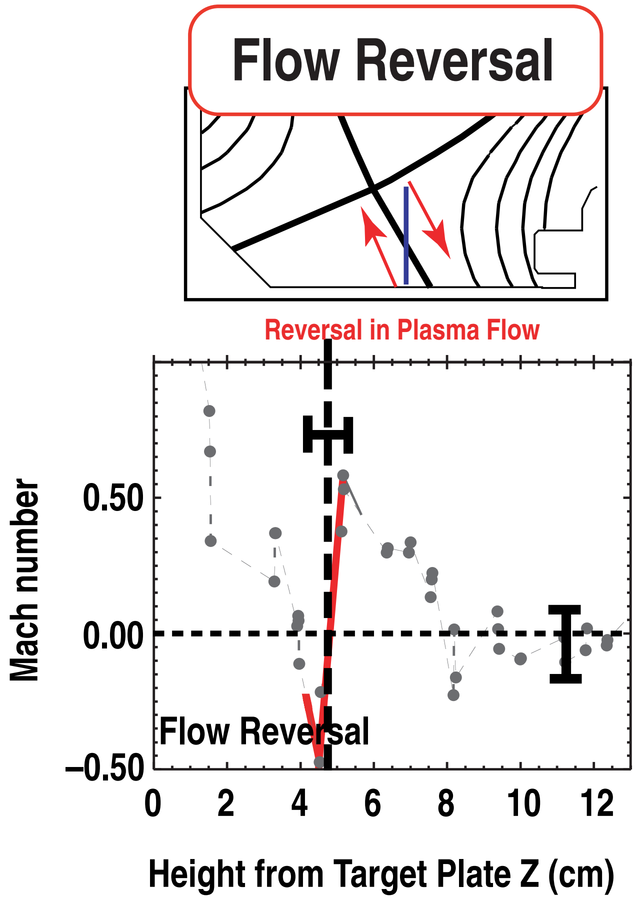

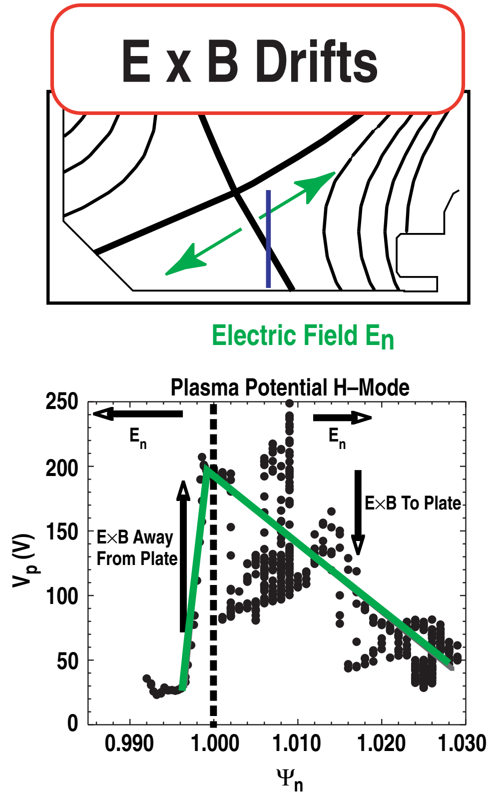

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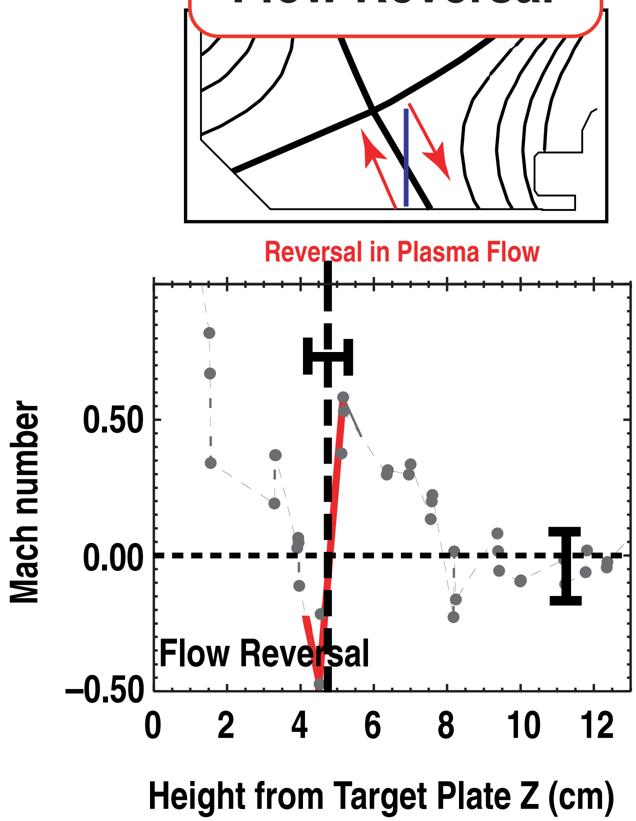
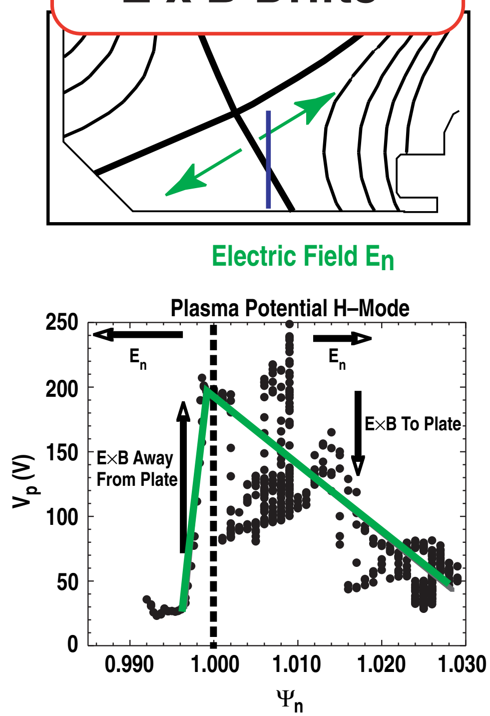
New physics in the x-point and private flux region

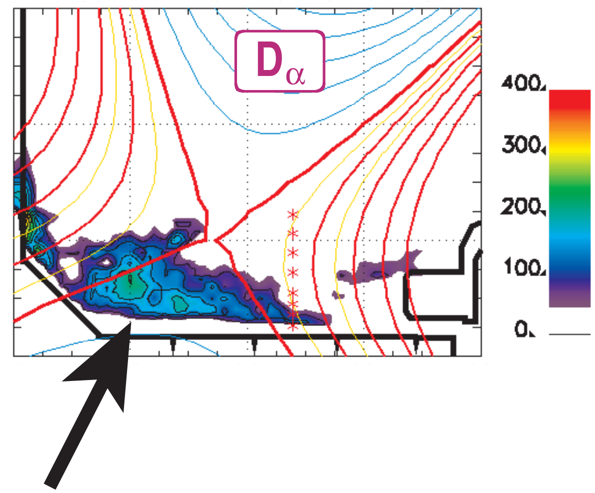
Flow Reversal



E x B Drifts



Recombination in “Private Flux”



Appreciable T_e, n_e In this Region

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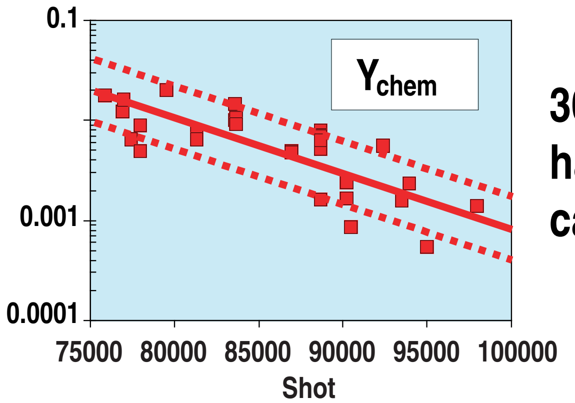
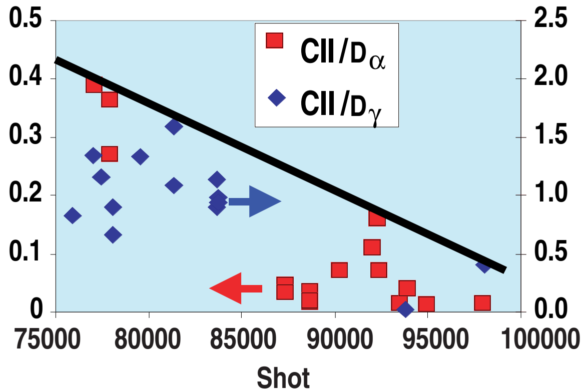
Divertor Carbon Source Is Reduced, Core Content Is Similar!



30 Boronizations have reduced the carbon sputtering yield



The divertor carbon source is reduced by a factor of 4

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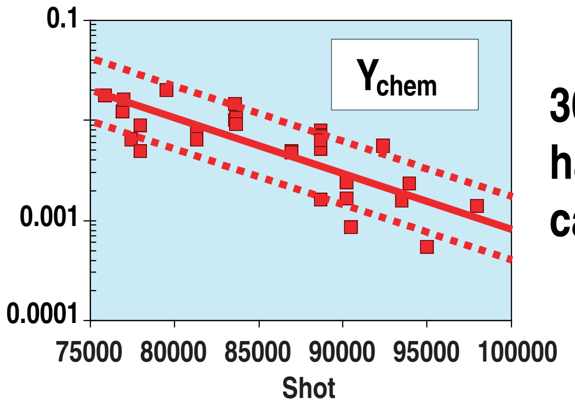

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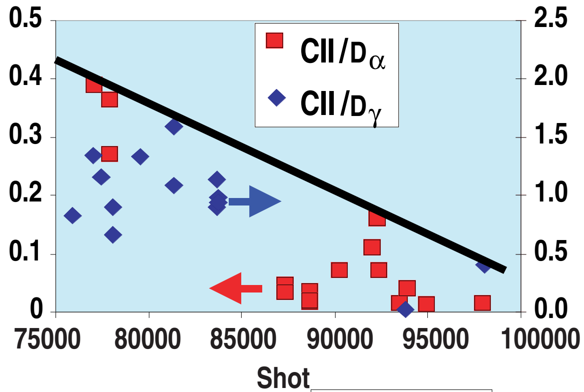

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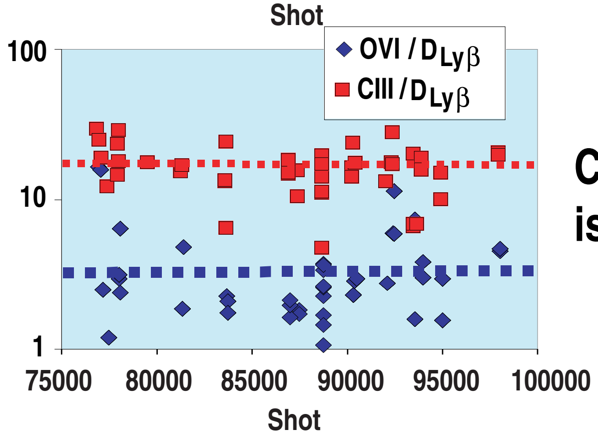

Core content is similar

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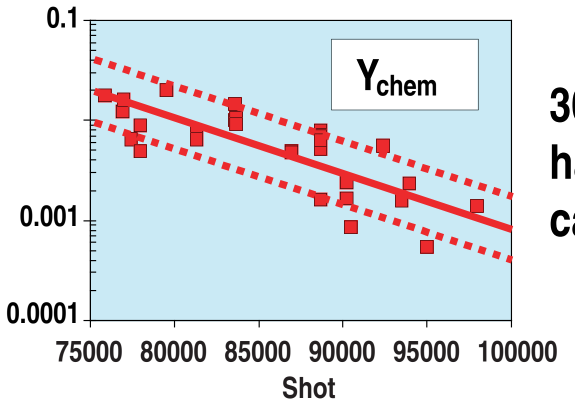
103-00 jy

Divertor Carbon Source Is Reduced, Core Content Is Similar!



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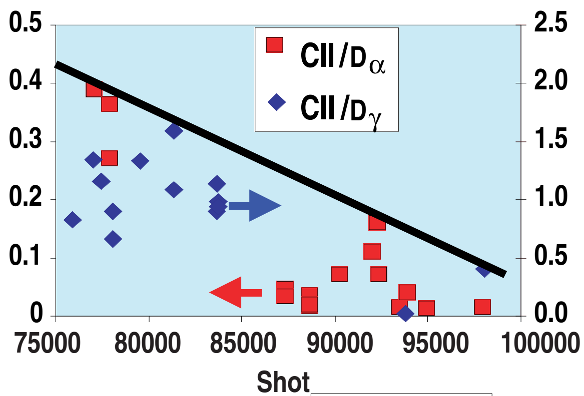

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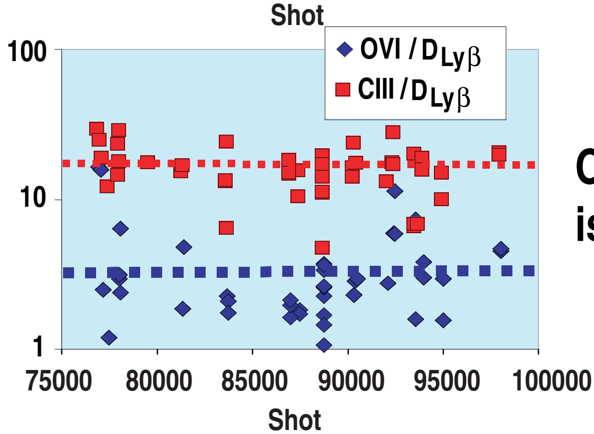
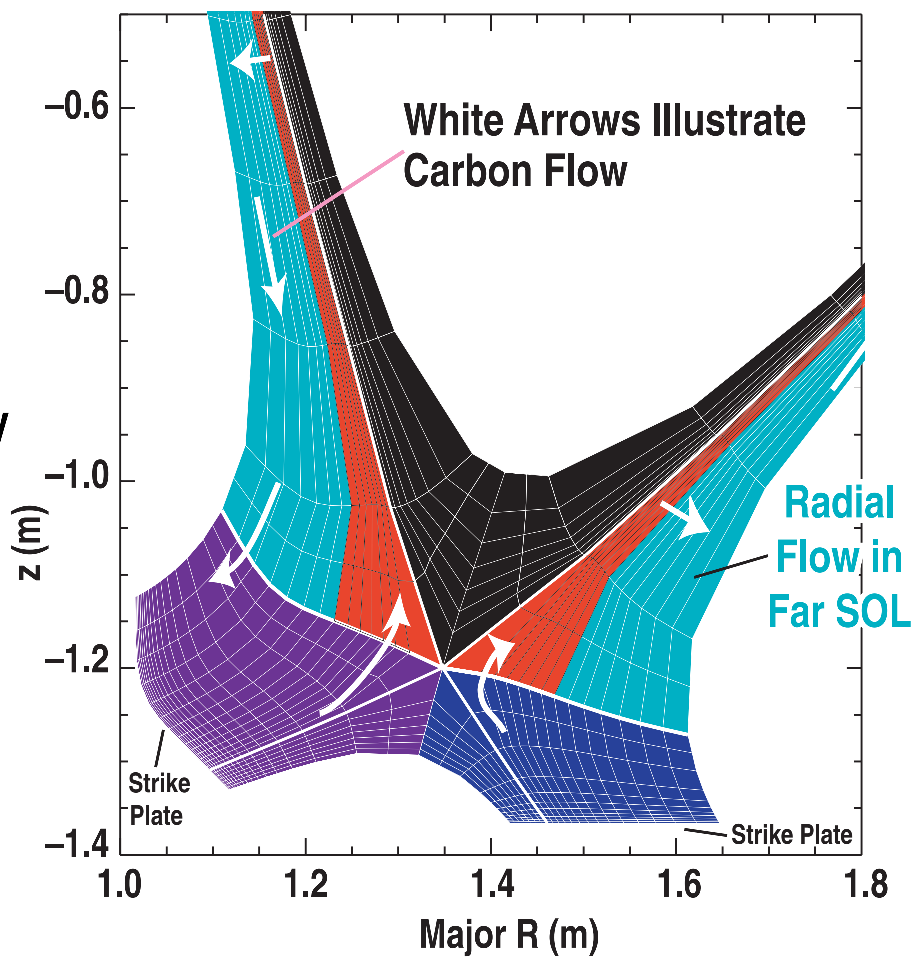


Core content is similar



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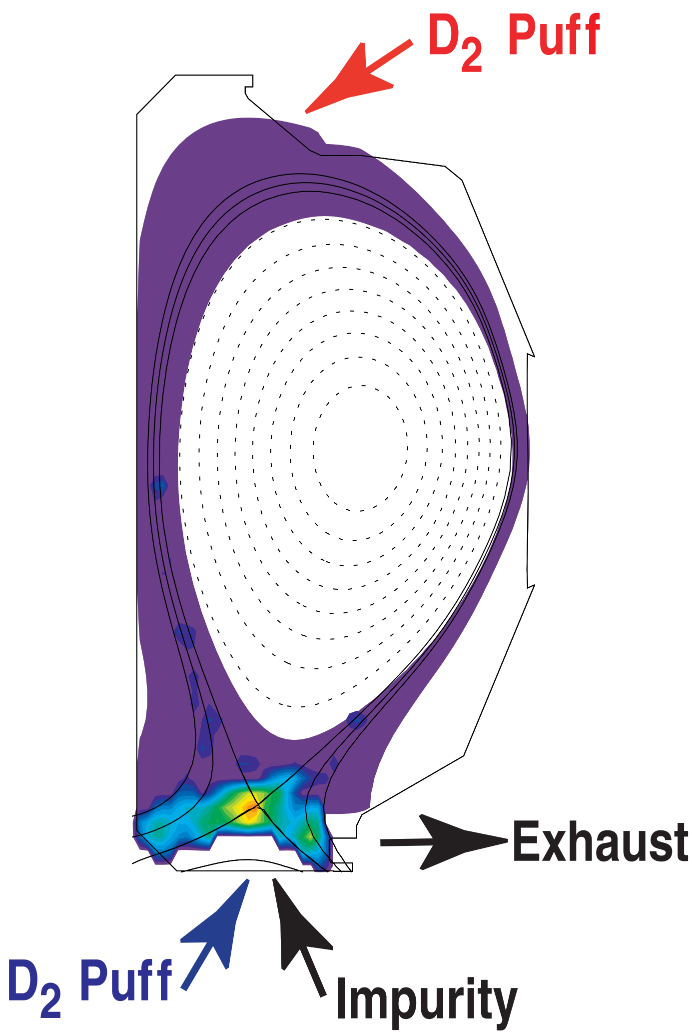
Puff And Pump In Both The Open And Closed Divertors



- Open Divertor
  - Argon Enrichment Divertor vs Core (D_2 puff)
  - Carbor and Argon Radiation Increase
- Closed Divertor
  - Also good enrichment

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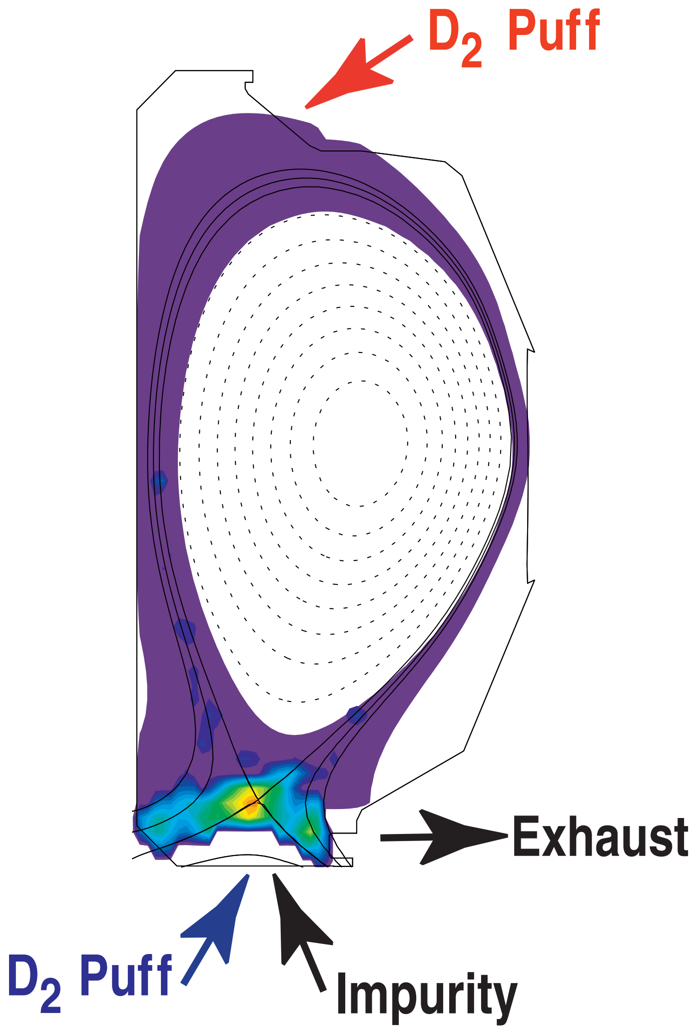
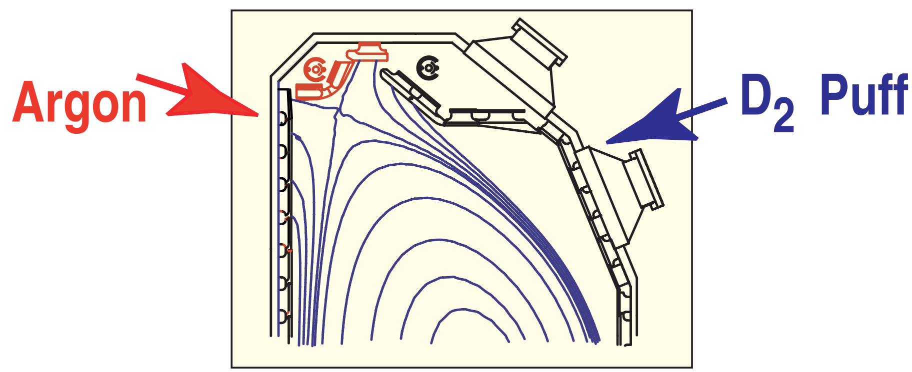
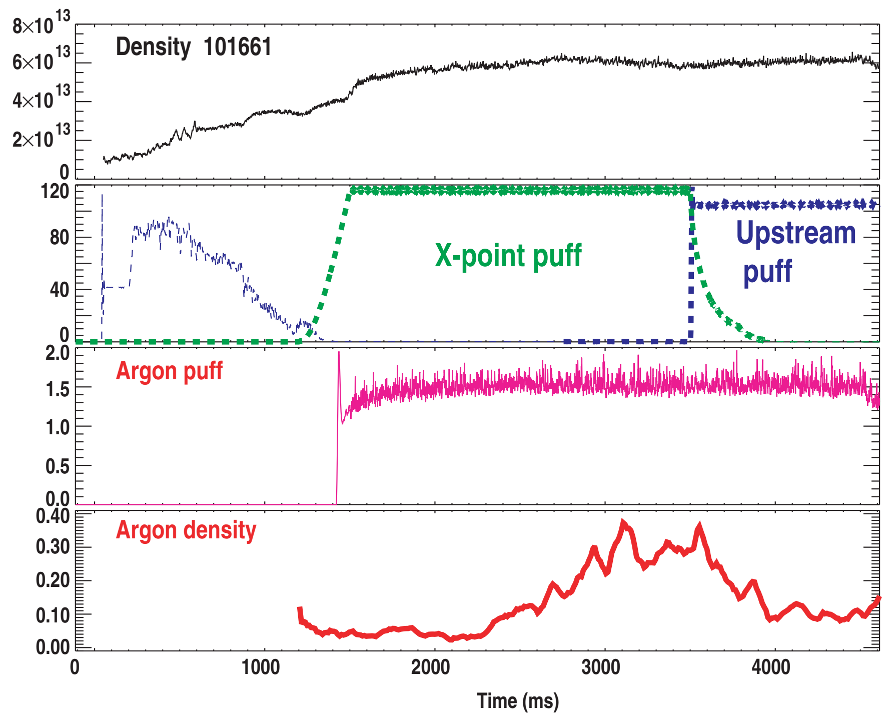
Puff And Pump In Both The Open And Closed Divertors







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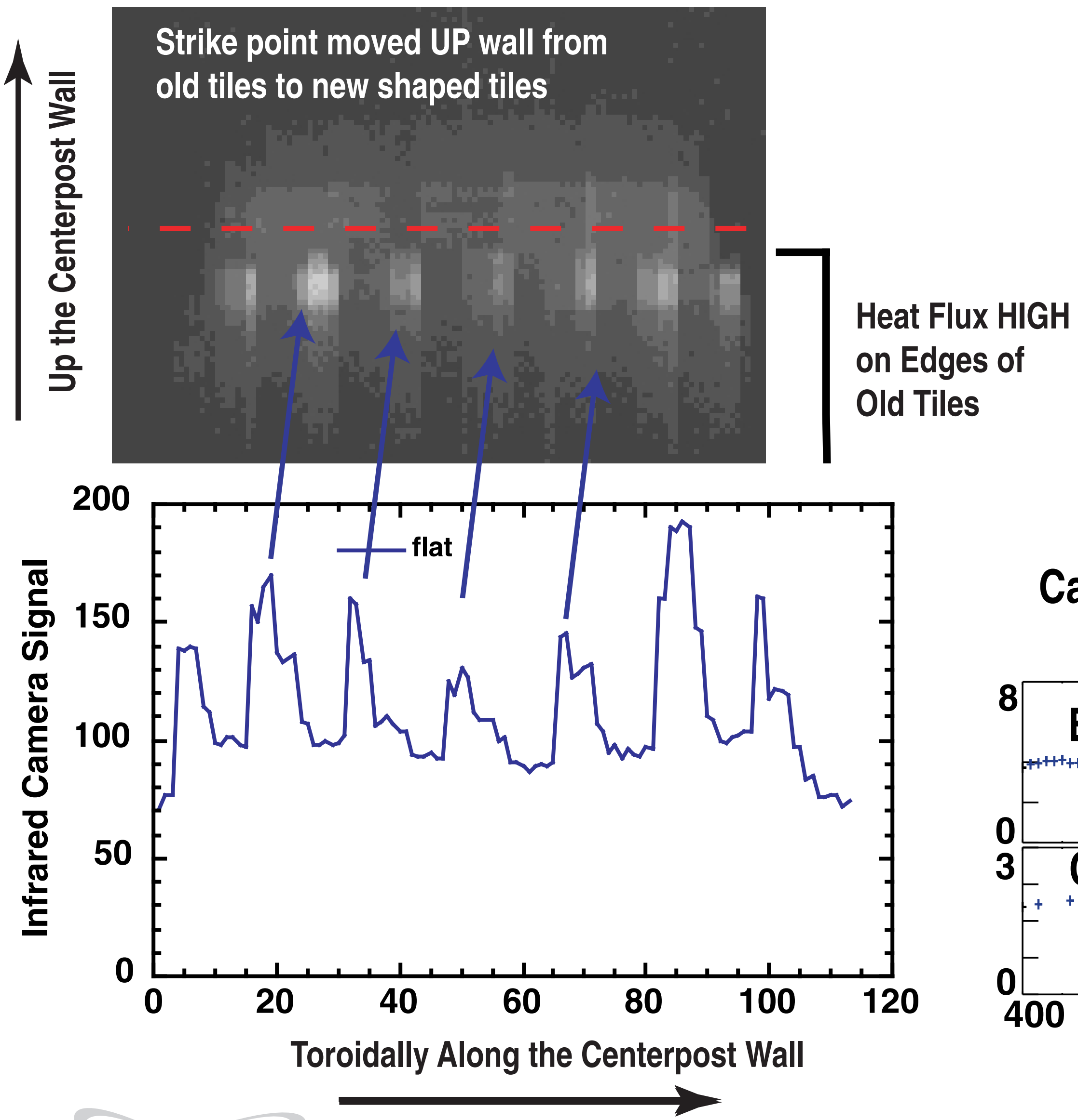
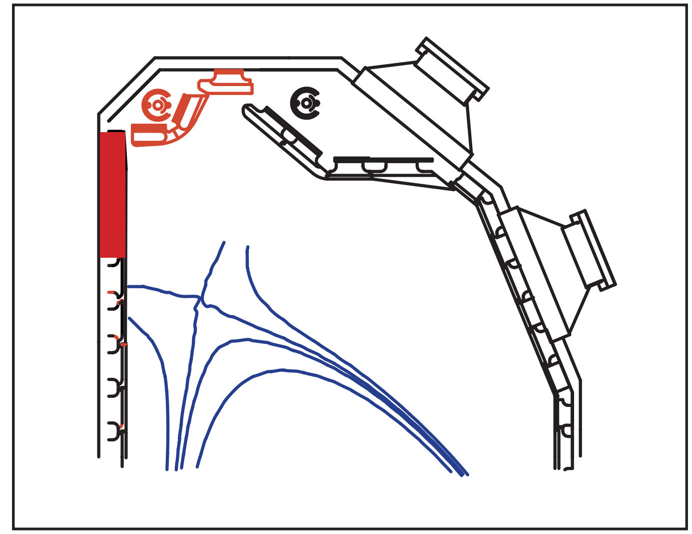
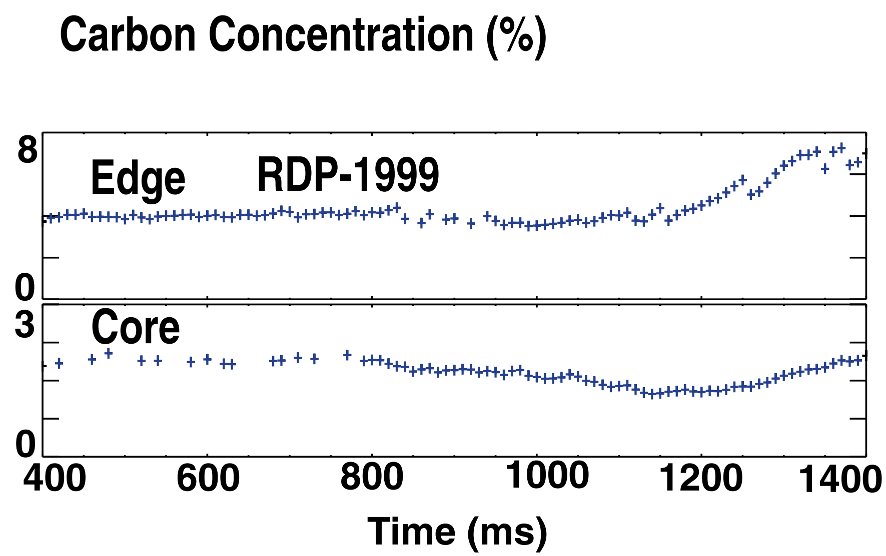
Impurity Control In AT Plasmas With Careful Tile Shaping







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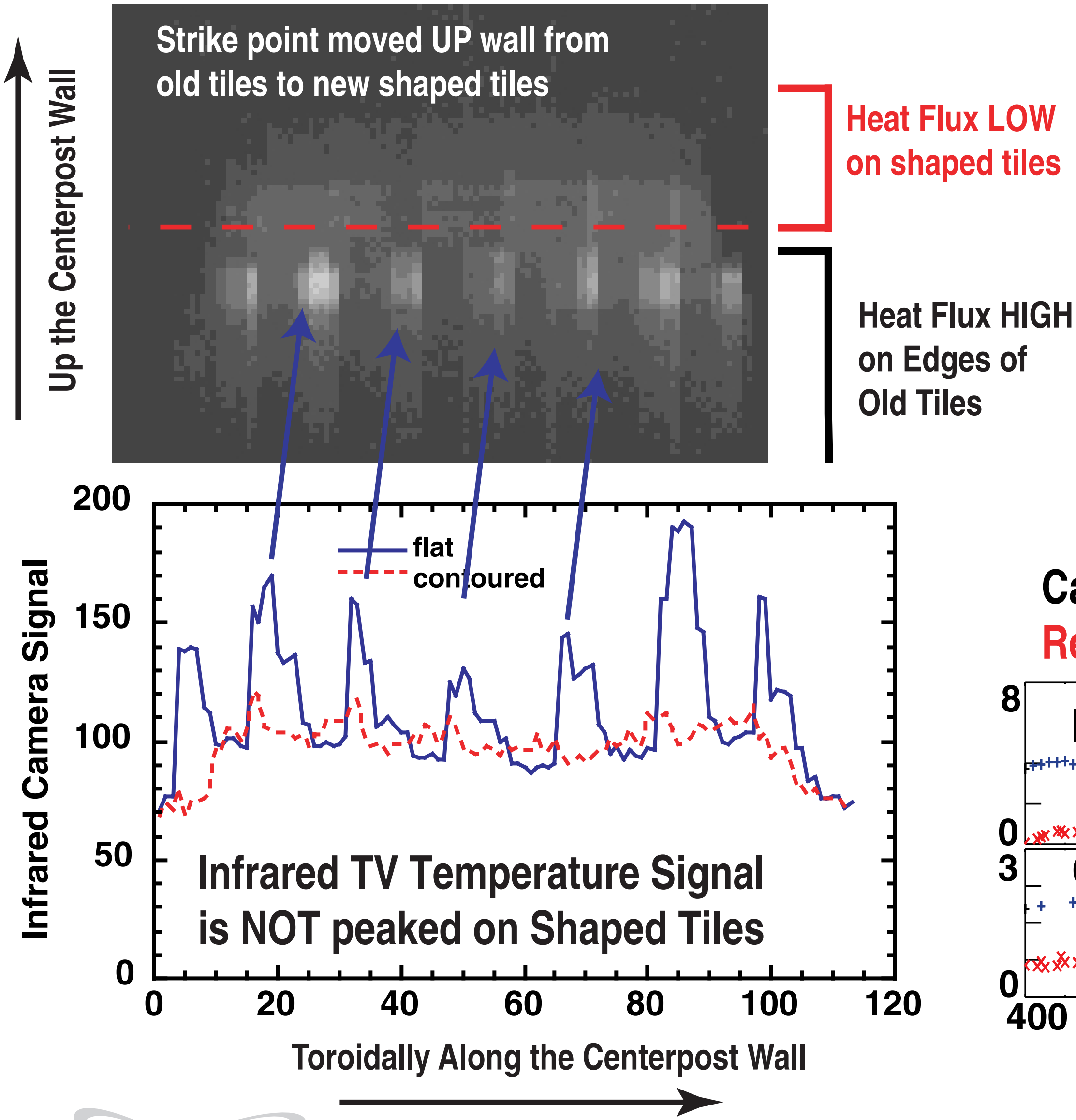
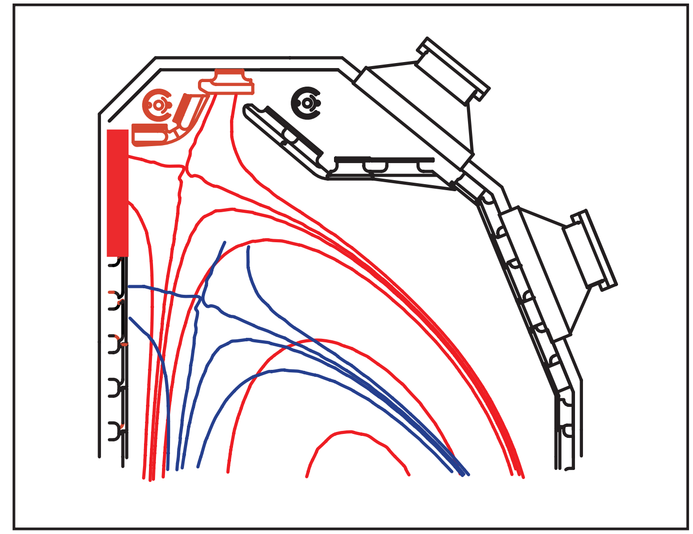
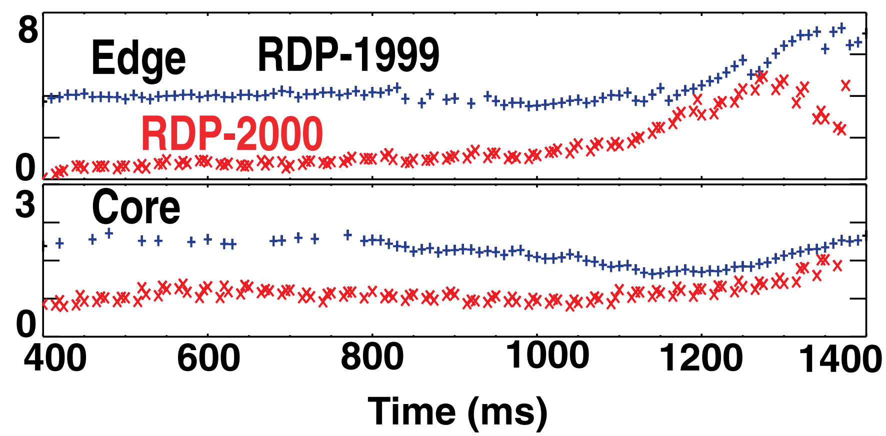




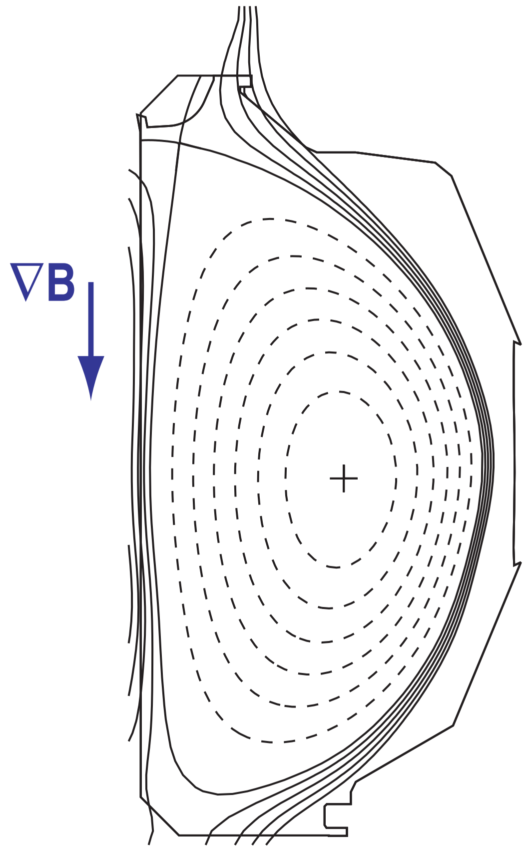
Carbon Concentration (%) is Reduced Compared to Previous Operation



AT Scenario Uses Divertor Shapes For Real-time Control

UN Pumped L–mode →

- Maintain ℓ_i in L–mode
- Density profile fw NBI absorption
- drsep +2 to raise H–mode threshold



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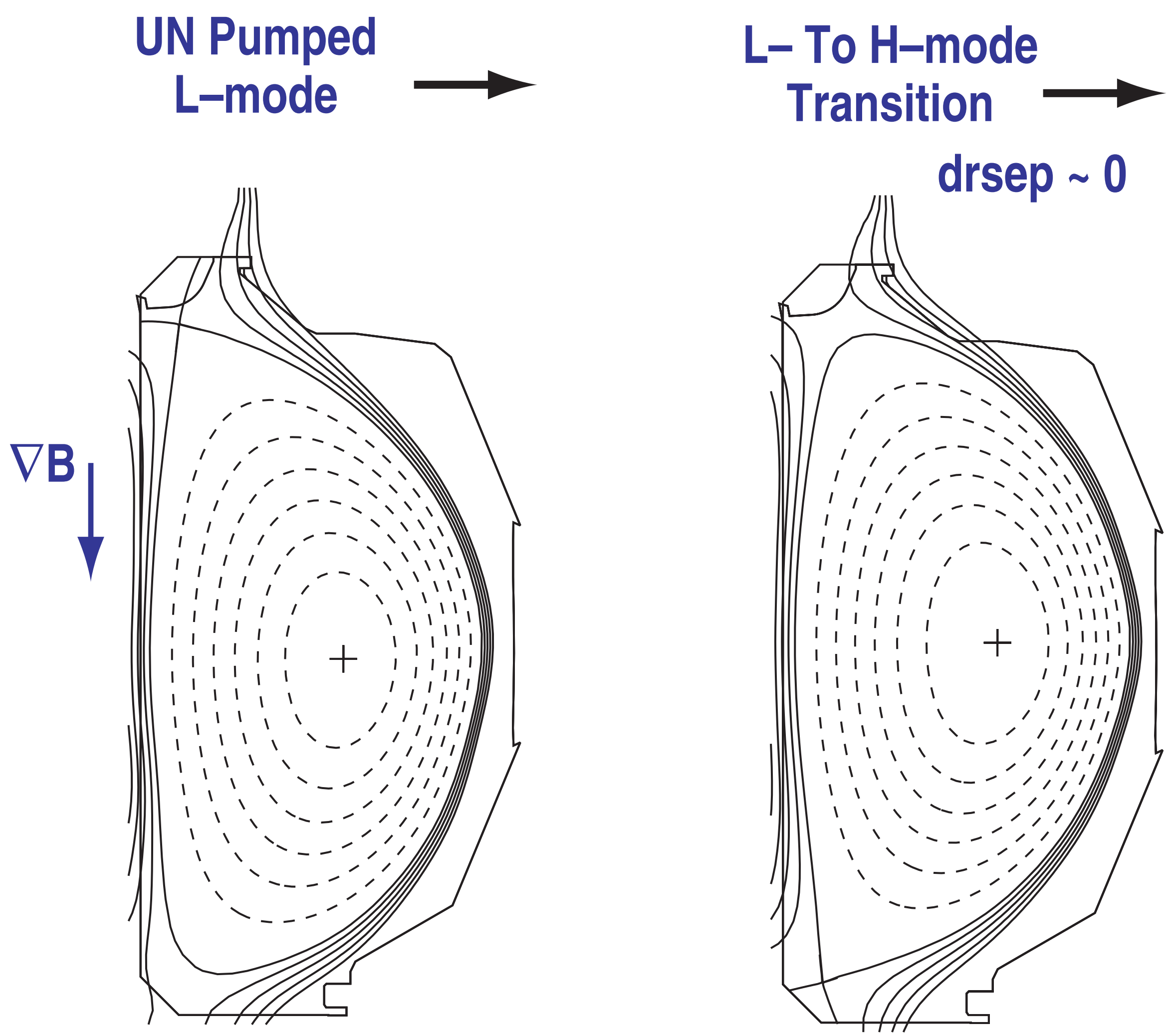
AT Scenario Uses Divertor Shapes For Real-time Control



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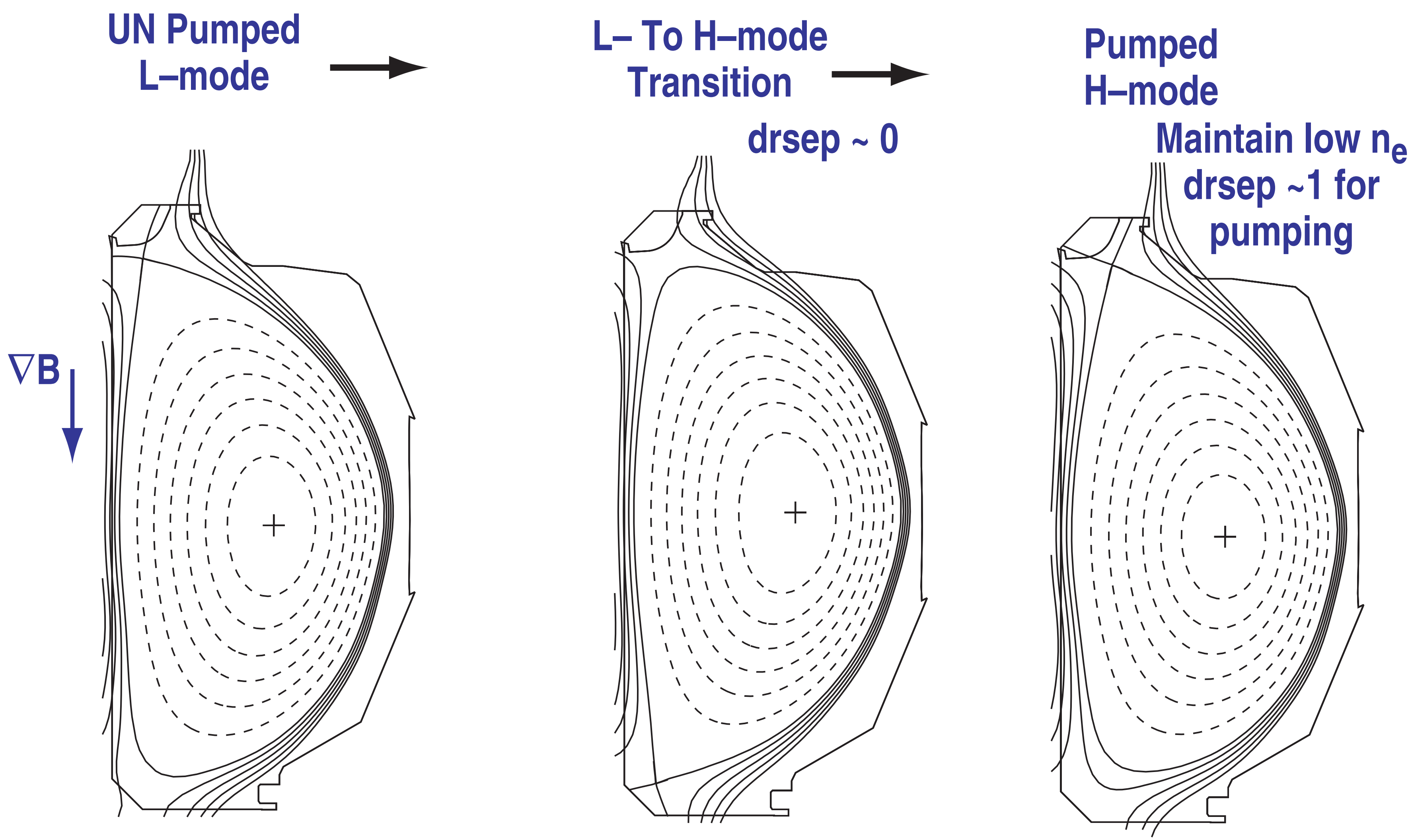
AT Scenario Uses Divertor Shapes For Real-time Control



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“AT Divertors are not just for heat flux reduction”

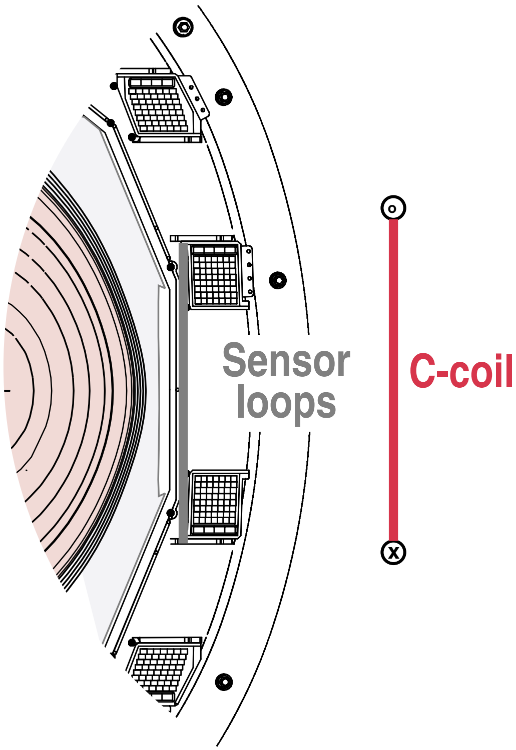
Advances in detached plasmas by this community have made possible a high density divertor solution (with some caveats, of course!) ...

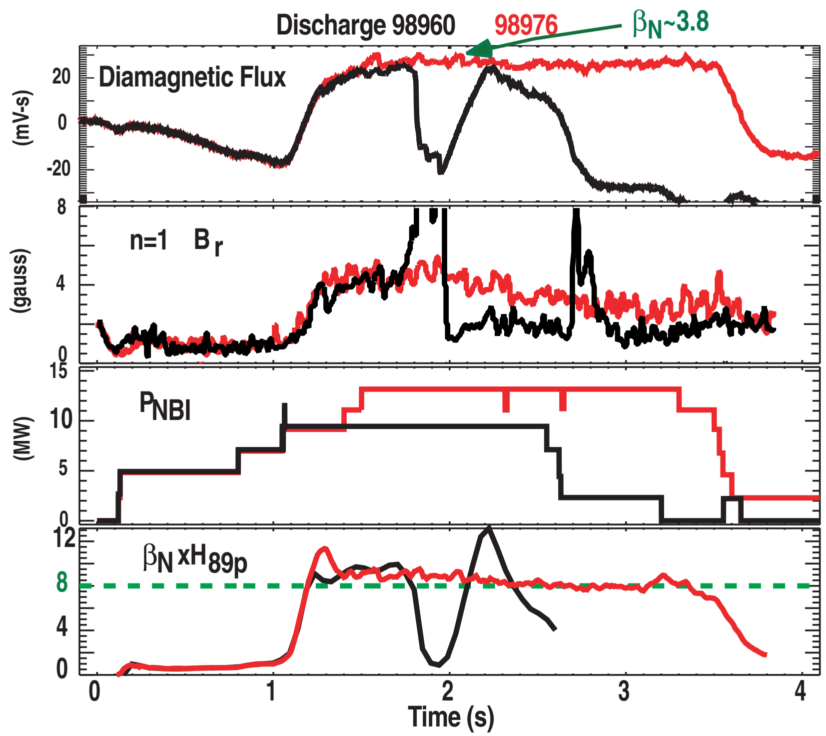
- Now divertor particle control is vital for AT modes
- Shaped plasmas are "standard", needed for high performance
- Real Time Shape control enables H-mode power threshold control, particle control
- Current profile control (ECCD) is at the heart of the AT, *Impurities* are important!

Heat flux control in AT plasmas is expected to require impurity flow control

- "Puff and Pump" or active flow control, need progress in understanding flows
- Lots of new, exciting physics in the pedestal and x-point region

Wall stabilization avoids the Resistive Wall Mode





- Ip=1.2 MA, Bt=1.6 T
  q_{min} ~1.7, q_{95}~5.5
- β_N limited to about 4li (no wall limit) by bursty RWM
- Higher NBI power improves stability and duration
- 75 % current non-inductive
  >50% bootstrap

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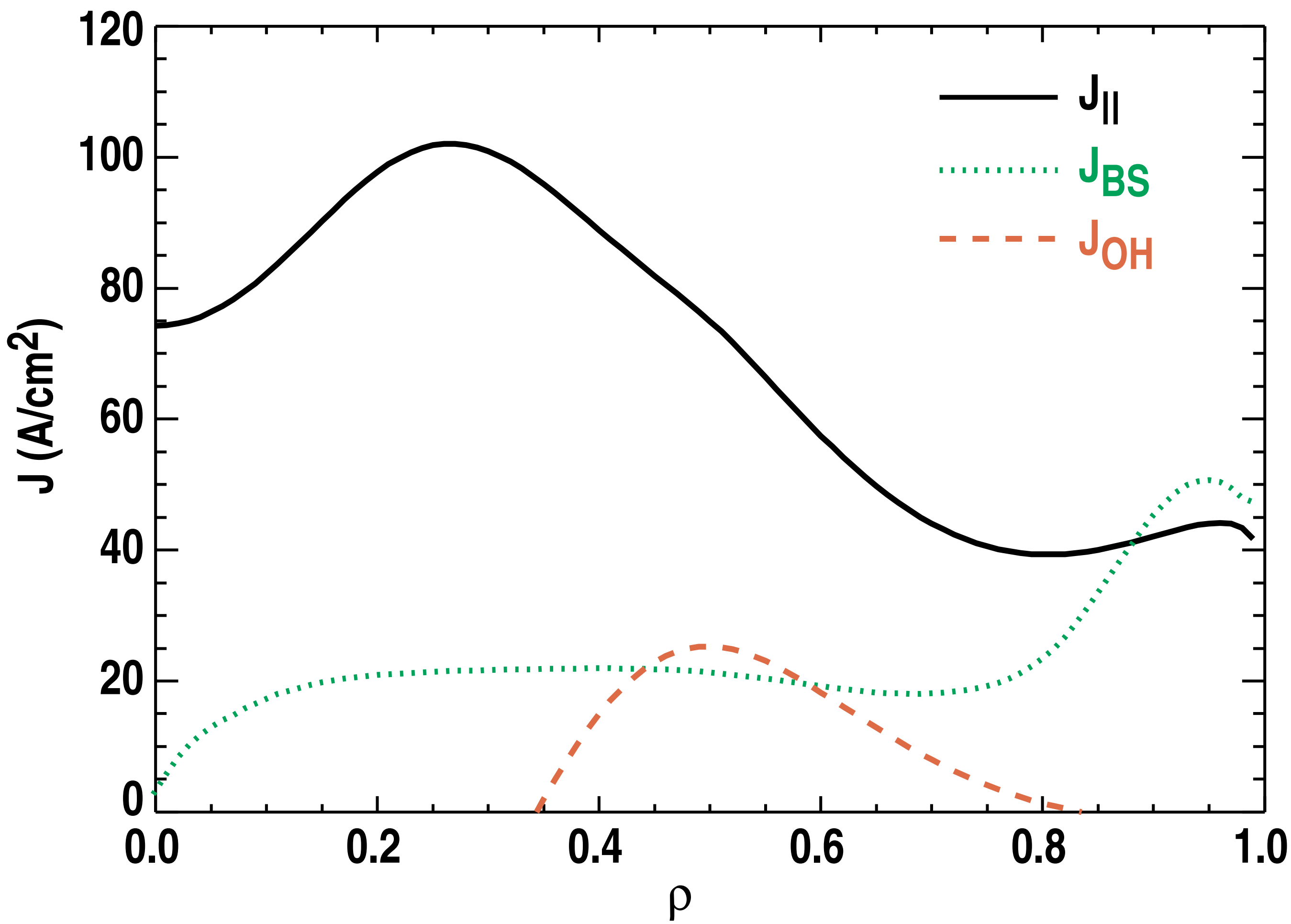
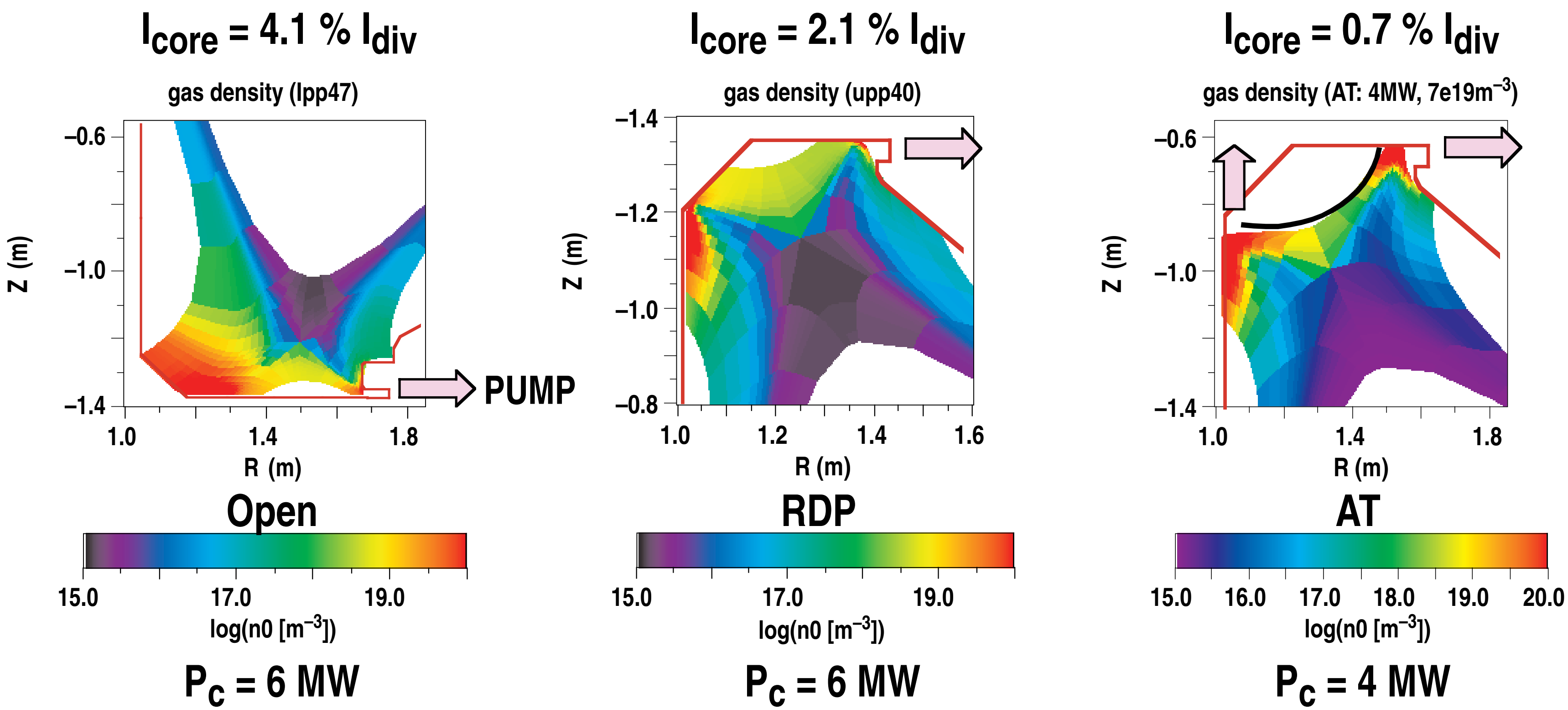
Non-inductive current is needed at the half radius for steady state operation



UEDGE shows core refueling fraction (I_{core}/I_{div}) is lower in closed divertors



- Neutrals are confined to divertor region by better baffling in RDP and AT divertors

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