Power and Particle Control in QPS

QPS

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Power and Particle Control in a CE-Experiment?

QPS

- **Experimental evidence clearly demonstrates that control of neutrals and impurity influx is a prerequisite for good plasma performance in any plasma device.**
- **Based on this experience, the plasma boundary program has two goals:**

Primary Goal

- **Support the mission and objectives of QPS and provide the best possible conditions for confinement, beta, and pulse length**

Secondary Goal

- **Contribute to the knowledge base of divertor physics for future compact stellarators** *(in collaboration with NCSX)*

What Are the Key Issues of Power and Particle Control in QPS ?

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1. **Boundary configuration**
   - Magnetic topology in the edge
   - Divertor/limiter configurations
   - Connection lengths
2. **Particle and impurity control**
   - Control of neutrals
   - Density control in bell jar
   - Impurity control
3. **Power Handling**
   - main issue is presumably the non-uniform pattern

Magnetic Configuration in the Plasma Boundary

QPS

- Stellarators don't necessarily have the well-ordered boundary structure we are used to from tokamaks.

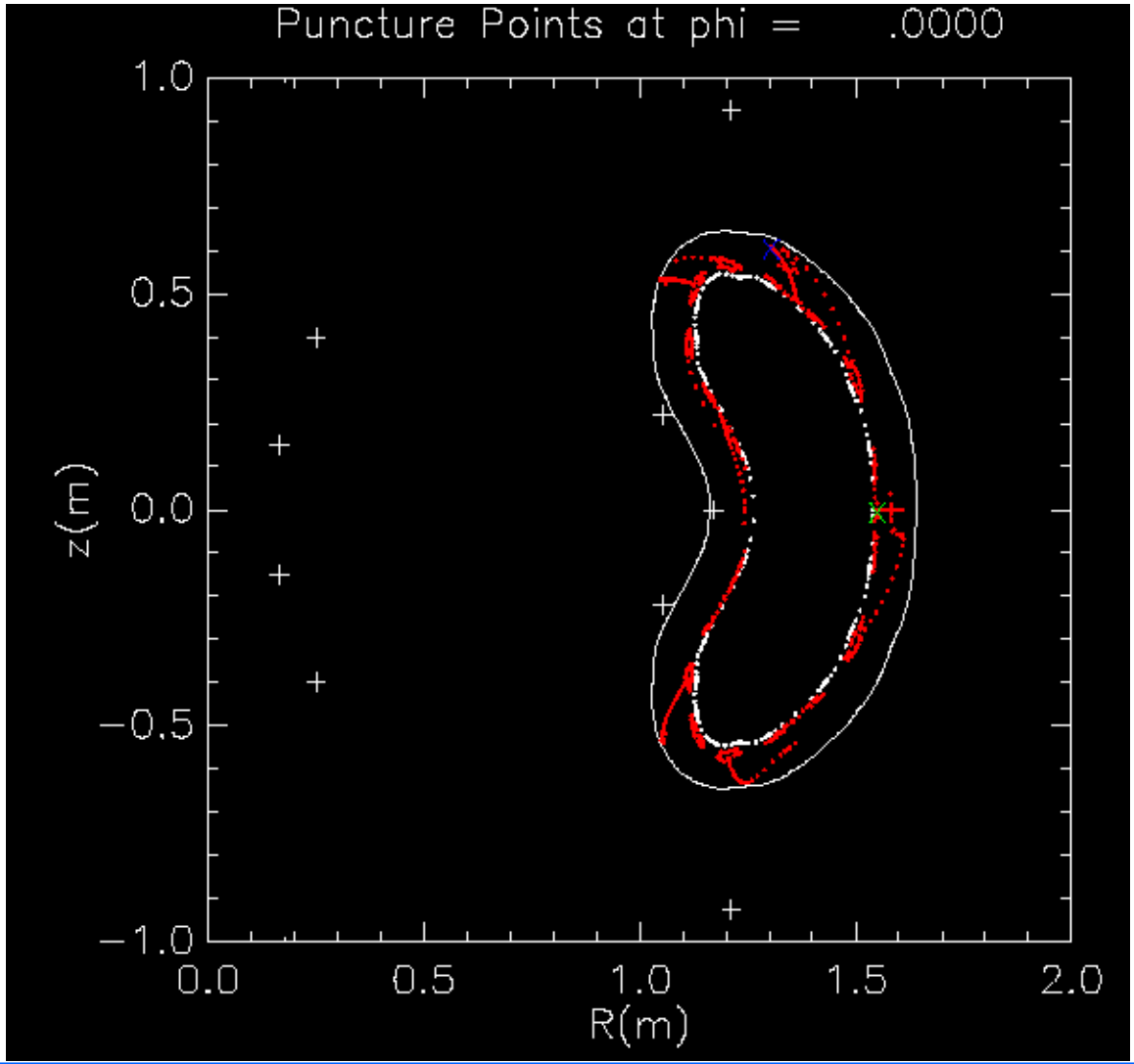
- However, present experience on modular stellarators (W7-AS, W7-X) indicates that the island divertor concept can be used for effective interception of power and particle fluxes.

- We have found island structures outside the LCMS of QPS - as well as NCSX - which appear to be suited for power and particle handling.

- First results of field-line tracing on QPS show also that the connection lengths of field lines launched within a few cm outside the LCMS are long, another prerequisite for effective divertor operation.

Poincaré Plot of Field Lines Outside the LCMS

QPS



30 field lines were launched, starting at the midplane/LCMS and moving out 2mm at a time.

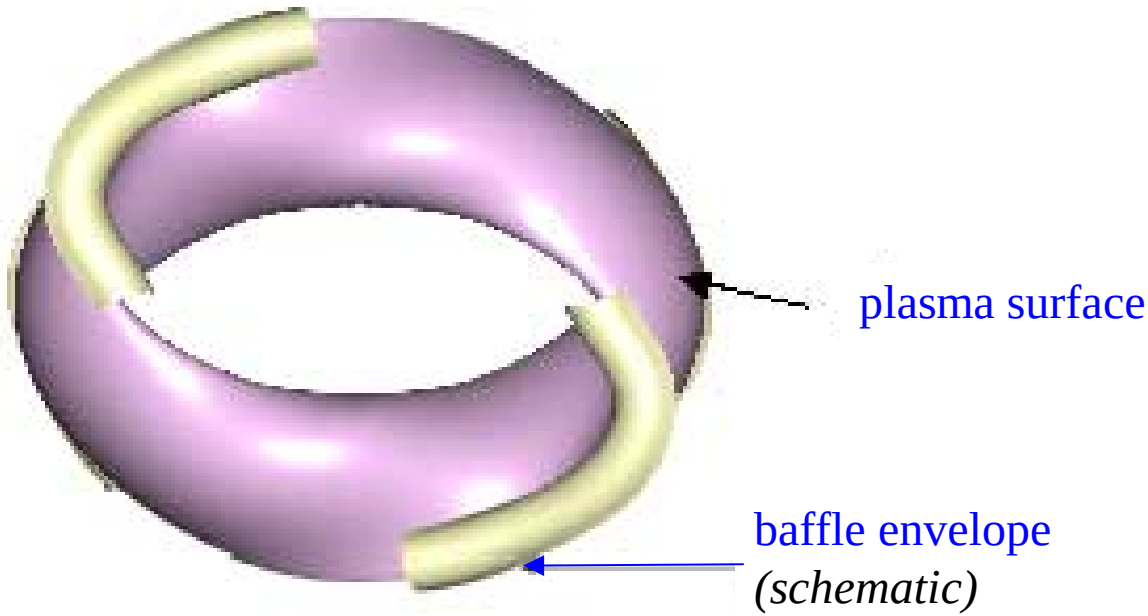
When the field lines are intercepted by a 10-cm conformal surface, they are stopped.

Island formation is clearly observed, especially in the top and bottom of the cross-section.

3-D View of the Divertor Baffles

QPS

- 4 divertor baffles total for power and particle handling
- The exact location, shape, size of the baffles will be determined with
  - field line following codes for optimum location, and
  - neutrals modeling for best shape/size for neutrals and impurity control

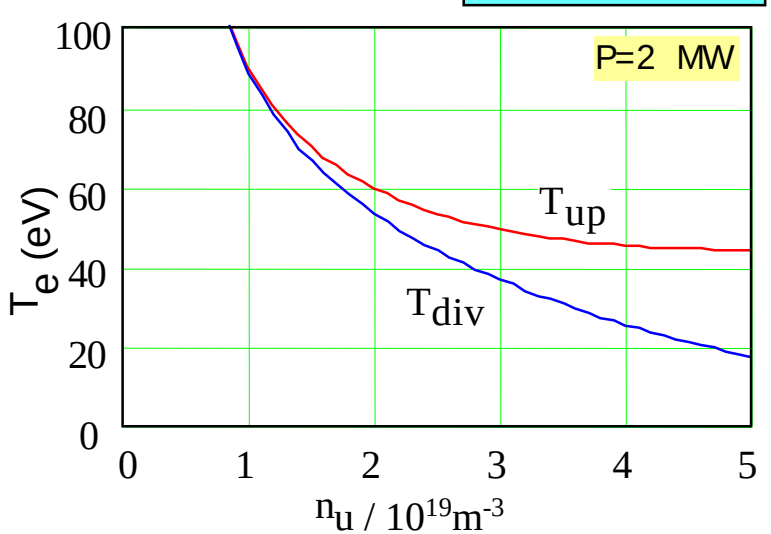


Importance of Connection Length

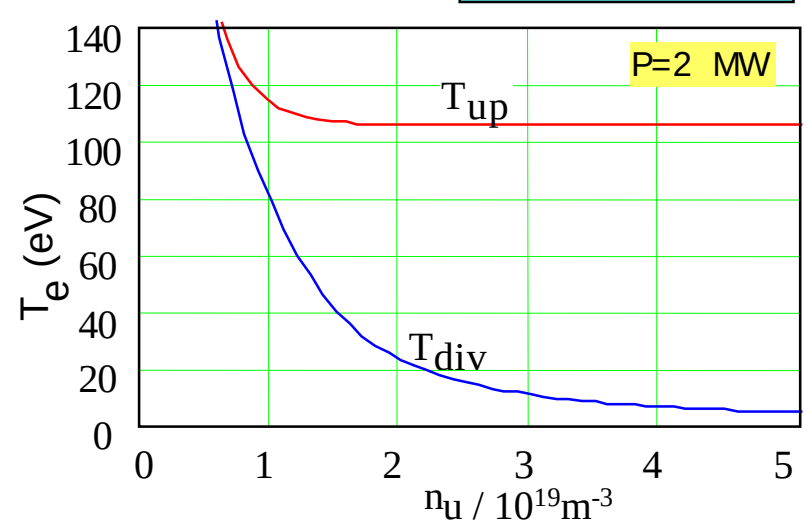
QPS

- **Ideal plasma is:**
  - **hot at the LCMS - high pedestal temperature, H-mode confinement**
  - **cold at the divertor plate - erosion/impurity control**
- **To achieve the necessary gradient between LCMS and divertor target, sufficiently long connection lengths are required.**
- **2-point divertor model calculates upstream and downstream temperatures for given connection length, separatrix density and power flux:**

connection length = one field period



connection length = 10 toroidal revol.



Control of Neutrals

QPS

1. **The build-up of neutral pressure in the vessel will be minimized through local concentration of recycling**

   - **Poincaré plots (and experiments on W7-AS) indicate that field lines (particles) leave the plasma predominantly at the top and bottom of the bean shape.**

   - **Here, recycling neutrals will be confined mechanically by baffles and and then have finite probability of re-ionization by the plasma.**

   - **Mechanical baffling and local recycling with re-ionization can lead to high-recycling divertor operation with low electron temperatures at the plate.**

2. **Additional neutrals control will be achieved by surface pumping**

   - **Boronization *(line-of-sight of plasma)***
   - **Large area titanium (or cryo-) pumping *(top or bottom, behind baffles)***

Density Control Strategy

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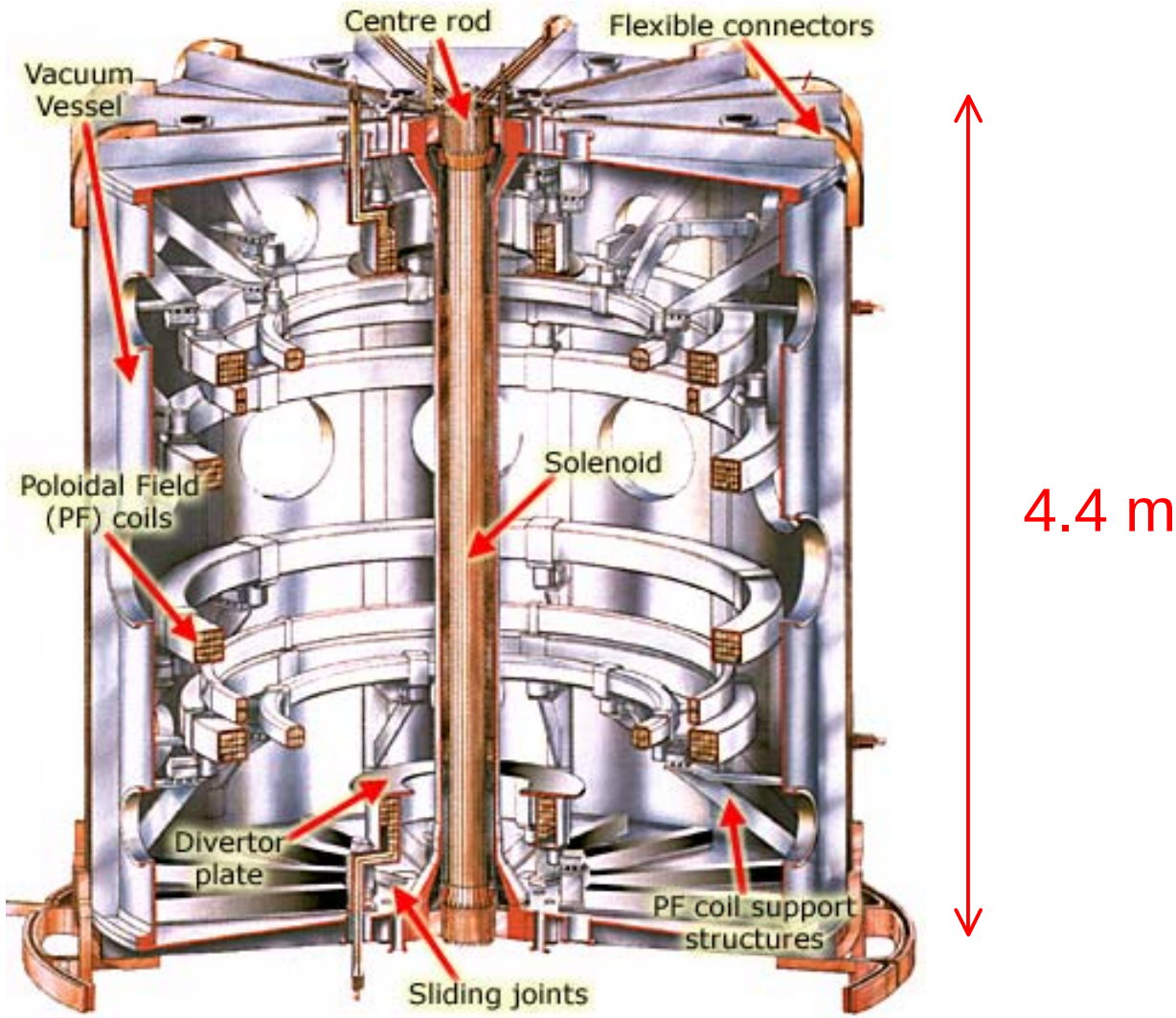
The QPS vacuum vessel is a bell jar with a volume of ~ 45m^3; it provides a large reservoir for neutral gas which can have a major effect on density control.

- We are developing multiple strategies for density control:
  1. Control of the neutrals sources through mechanical confinement with divertor baffles and re-ionization of neutral particles
  2. Recycling control through surface pumping via boronization of all plasma-facing components
  3. Large-area titanium (or cryo-) pumping of neutral gas: s=20,000 L/s per m^2 for molecular gas; need to evaluate possible conductance!
  4. Direct fueling of the core plasma with gas injectors at the divertor baffles

The "MAST" Device Has a Bell Jar Vacuum Vessel, With Multiple Internal Components

QPS

Size comparable to QPS bell jar



Impurity Control

QPS

- Wall conditioning is the key technique for impurity control, including
  - baking,
  - glow-discharge cleaning and
  - thin-film deposition (e.g. boronization)
- Control of plasma-surface interactions
  - the most intense impurity source will be at the baffles; we will optimize materials choice (C, B_4C), location, shape, conditioning
  - divertor plasma between baffle surface and LCMS will help shield main plasma from impurity source
- Leaks in coil casings
  - large number of coils inside the vacuum…large potential for leaks/virtual leaks…need first rate Q.A. during fabrication
  - gas cooling will make leaks more benign and will help to diagnose leaks

Power Handling

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- **Heating power:**
  - **P_{input} 1- 3 MW; pulse duration t ≤ 0.5s**
- **Plasma-facing components:**
  - **divertor baffles: assuming 80% of P_{input}, allowing max. of 20 MW/m^2 => 2.4 MW / 20 MW/m^2, need 0.12m^2 for uniformly wetted surface (the crucial question is non-uniformity/ peaking factor!)**
  - **the divertor baffles can easily provide an area 10-times larger**
- **Low power-density areas:**
  - **plasma surface = 15 m^2; assume 80% radiation and CX power: average surface power density: 0.16 MW/m^2**
    ***lower at winding surface, i. e.* coils: ≤ 0.16 MW/m^2**
  - **Bell jar (cylinder walls): 80% radiation and cx : 2.4 MW / 65m^2 ~ 0.037 MW/m^2**

Vacuum Considerations

QPS

- Bell jar vacuum:
  - goal is to achieve leak rate of $Q_{leak} \leq 10^{-5}$ TorrL/s; this should be possible with double seals (viton baked at 150 C) and differential pumping
  - assuming outgassing rates of stainless steel (Al) and an internal surface area 3-times the bell jar surface, total outgassing is ~2×10^{-6}TorrL/s after mild bake at 150 C
  - effective pumping speed of several 1000 L/s will lead to base pressure in the 10^{-8} Torr range

- Considerations for pre-cooled coils for longer pulse length:
  - analysis: adsorption/desorption equilibrium of CO on internal s.s. surfaces
  - result: 16-times higher coverage on surfaces at 273 K vs. surfaces at 300 K.
  - since surface conditions are not well defined, we conclude not to use pre-cooled coils or, if necessary, install temperature insulation

Summary and Plans

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- The goal of the power and particle control program on QPS is to support QPS mission.
- The boundary conditions, as we understand them so far, look favorable for island divertor* operation:
  - first results of magnetic field line modeling outside the LCMS indicate long connection lengths and island formation in the plasma boundary.
- Work between PVR and CDR includes:
  - detailed field line and foot print mapping of the plasma boundary
  - neutrals modeling of the baffle region to optimize recycling and neutrals control
  - modeling of power and particle fluxes on baffles
- Most issues of power and particle handling are similar between QPS and NCSX and we will largely benefit from the NCSX work.

* as developed for W7-AS

Estimate of Neutral Gas Density in Bell-Jar

QPS

$$n = \frac{\frac{N/\tau_p}{1-R} \cdot \frac{\lambda_{gas}}{\bar{v}_{gas}}}{V_{edge}}$$

the plasma efflux is assumed to be the only gas source!

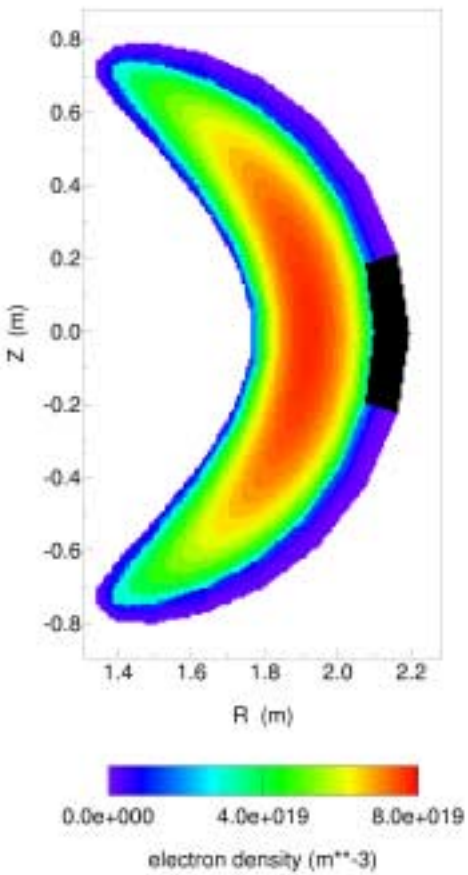
parameter	DIII-D	QPS
N (plasma)	1.2×10^{21}	1.2×10^{20}
τ_p [s]	.2	0.02
N / τ_p [s]	6×10^{21}	6×10^{21}
R	0.9	0.5
λ_{gas} [m]	0.1	1
v_{gas} [m]	1.2×10^{3}	1.2×10^{3}
V_{edge} [m^3]	7	10 *
n [m^{-3}]	7.1×10^{17} (2×10^{-5} Torr)	1×10^{18} (3.1×10^{-5} Torr)
$\frac{(\text{neutrals})\ n \cdot V_{edge}}{(\text{plasma})\ N}$	$\frac{4.9 \times 10^{18}}{1.2 \times 10^{21}} = 0.004$	$\frac{1 \times 10^{19}}{1.2 \times 10^{20}} = 0.08$

*** the bell-jar has a lot of structure inside, which reduces the open volume strongly!**

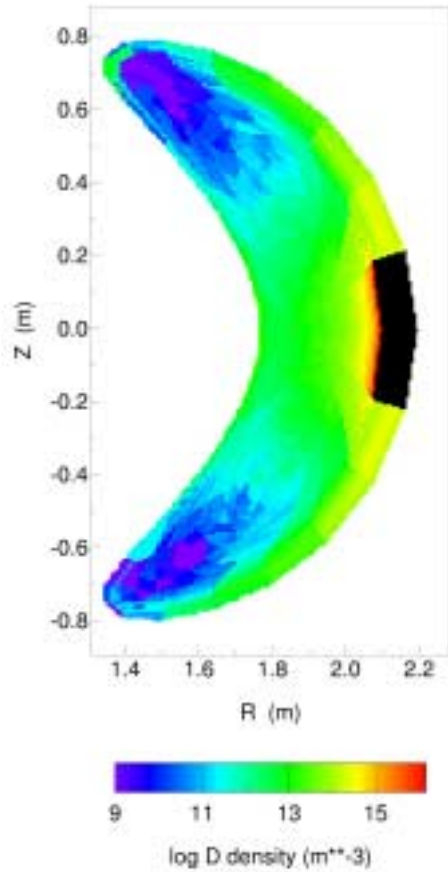
Initial 2-D Neutrals Calculations with DEGAS-2: Limiter at the Outboard Side or Baffle at the Bottom

NCSX

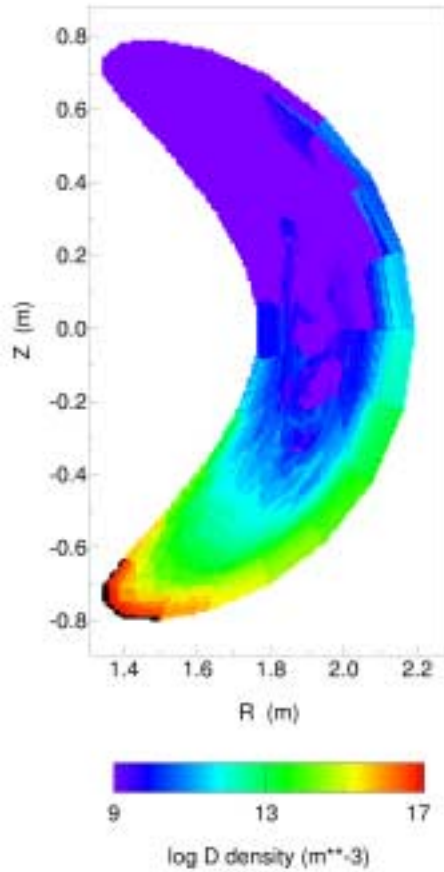
n_e (m^{-3})



n_0 (m^{-3})



n_0 (m^{-3})



D. Stotler

(assuming plasma profiles with: Te(0) = 3 keV, Ti(0) = 2 keV, ne(0) = $8 \times 10^{19} m^{-3}$)

Two-Point Divertor Model (1)

QPS

momentum balance: $n_d T_d = 0.5\, n_u T_u$ (1) (upstream:M=0; downstream:M=1)

heat conduction: $T_u^{7/2} = T_d^{7/2} + \frac{Q_{tot} L_c}{\kappa_0 A_{sol}}$ (2)

sheath condition: $q = \frac{Q_{tot}}{A_{sol}} = \gamma\, n_d T_d \sqrt{\frac{2T_d}{m}}$ (3)

Replacing $n_d T_d$ in the sheath condition with the momentum balance and T_u from the heat conduction equation, yields an implicit equation for T_d as a function of n_u, Q_{tot}, and L_c.

$$\frac{Q_{tot}}{A_{sol}} = 0.5\gamma\, n_u \left[T_d^{7/2} + \frac{7}{4}\frac{Q_{tot} Lc}{\kappa_0 A_{sol}} \right]^{2/7} \cdot \sqrt{\frac{2T_d}{m}}$$

Definition of Divertor vs. Limiter Operation

QPS

- **Divertor baffles intercept open field lines**
  - **This could be islands or stochastic regions outside the separatrix**
  - **Divertor baffles have some plasma as buffer between the solid surface and the main plasma**
  - **This is advantageous for neutrals re-ionization and high recycling as well as for impurity screening**
  - **For symmetric operation, we need one set of baffles per field period**

- **Limiters intercept closed field lines**
  - **Limiter provides the last closed magnetic surface**
  - **No separatrix operation**
  - **Major source of recycling neutrals in the main plasma**
  - **Major impurity source in the main plasma**