Power- and Particle Control and Vacuum Conditions in QPS

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for the QPS Boundary Group

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

- 1. Boundary configuration
  - Magnetic topology in the edge
  - Divertor/limiter configurations
  - Connection lengths
- 2. Particle and impurity control
  - Control of neutrals
  - Vacuum conditions and density control in external vessel
  - Impurity control
- 3. Power Handling
  - Pulsed load
  - Main issue is the non-uniform pattern

Magnetic Configuration in the Plasma Boundary

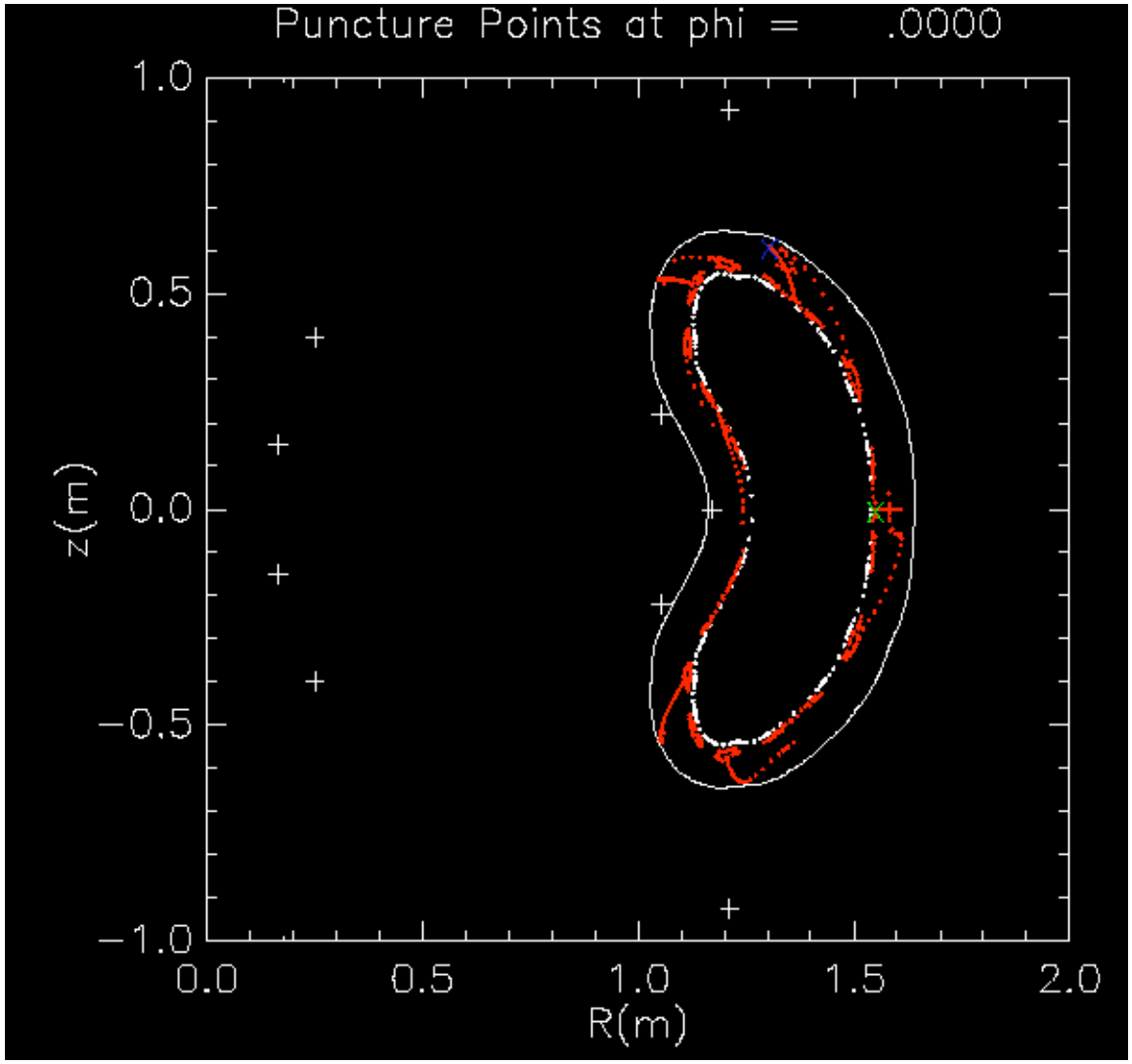
- **Stellarators don't necessarily have the well-ordered boundary structure we are used to from tokamaks.**

- **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-like 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



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

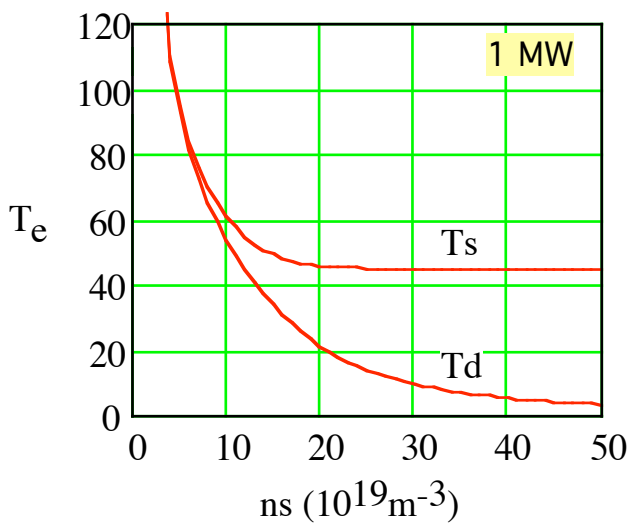
When the field lines are intercepted by a 10-cm conformal surface, they are stopped.

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

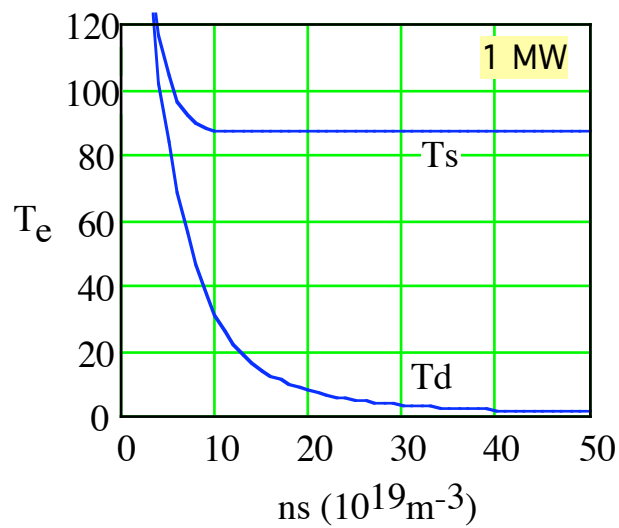
Importance of Connection Length

- **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 = 6 m



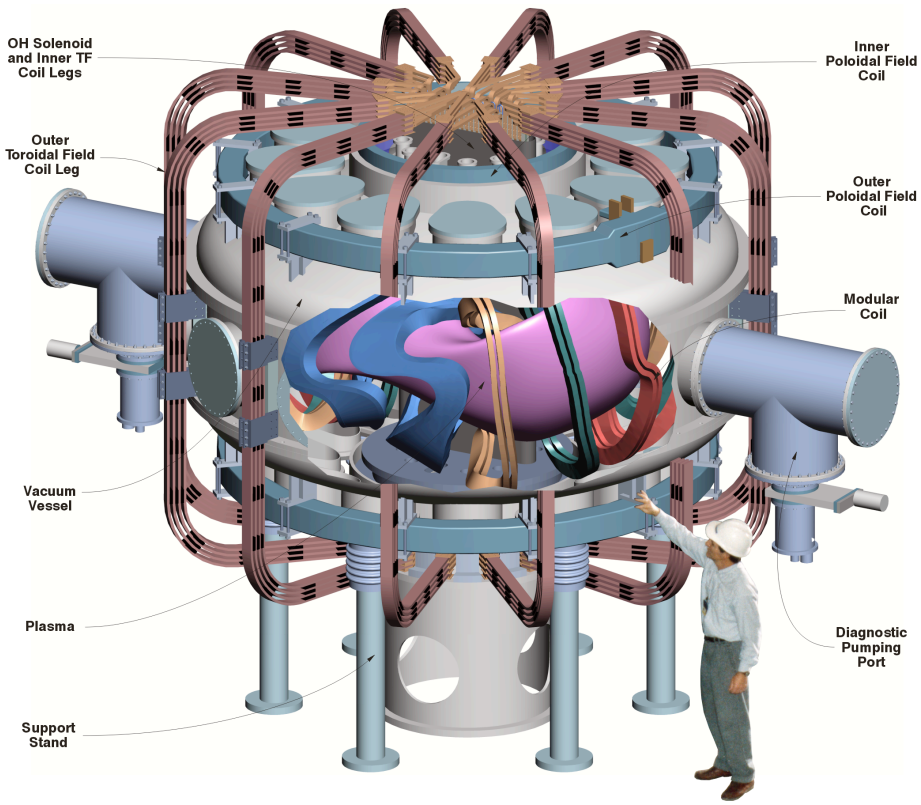
connection length = 60 m



External Vacuum Vessel Requires Special Attention to Vacuum and Particle Control Issues

- **Vacuum:**
  - **2 large viton o-rings with differential pumping (4 m diam.)**
  - **All other ports are conflat with copper seals**
  - **Large outgassing surface areas in vessel**
- **Density control**
  - **Large neutral gas reservoir**
  - **Recycling control**
  - **Pumping**
- **Neutrals control**
  - **Baffling**
  - **Pumping**
  - **Wall conditioning**

Coils and Stuctures Represent Large Internal Surface Areas



- **Vacuum vessel:**
  - $V_{vv} = 19.5\ m^3$
  - $A_{vv} = 65.7\ m^2$
- **Modular coils:**
  - $A_{mc} = \sim 46\ m^2$
- **Structure:**
  - $A_{ss} = \sim 53\ m^2$
- **Total Surface Area:**
  - $A = \sim 170\ m^2$

Vacuum Requirements: Outgassing and Leak Rate

- **Base pressure:** $p_0 = \frac{Q_{leak} + Q_{outgas}}{S_{TMP}} \leq 10^{-8}$ Torr **(goal !)**

- **Outgassing:**

  S.s. walls etc. Q_{walls} = 170 m^2 x 2x10^{-8} Torr-L/s m^2 = 3.4 x10^{-6} Torr-L/s

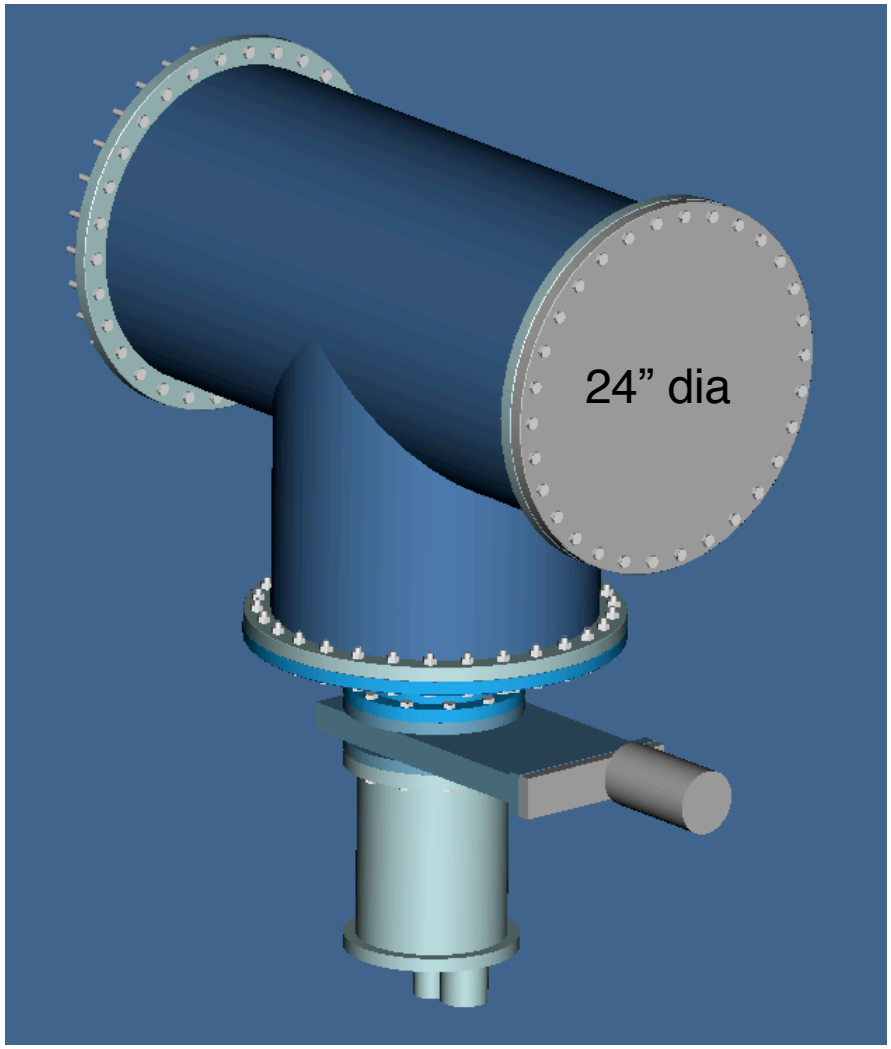
  Viton o-rings: Q_{viton}= 1 m^2 x 2x10^{-6} Torr-L/s m^2 = 2x10^{-6} Torr-L/s

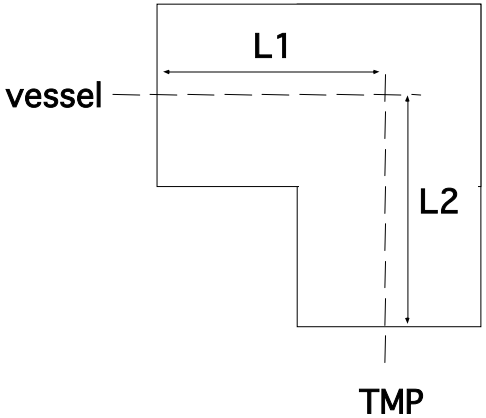
- **Leak rate:** $Q_{leak} \leq$ 1 x 10^{-5} Torr-L/s

Pumping speed: S_{TMP}^{eff} = 5000 L/s

Base pressure: p_0 = 1.1 x 10^{-9} Torr

Pump Ducts Have Large Conductance: TMP





$S_{TMP} = 3x10^{3}$ L/s

1. conductances of L1 + L2 :

$C_{air} = 1.7 \times 10^{4}$ L/s

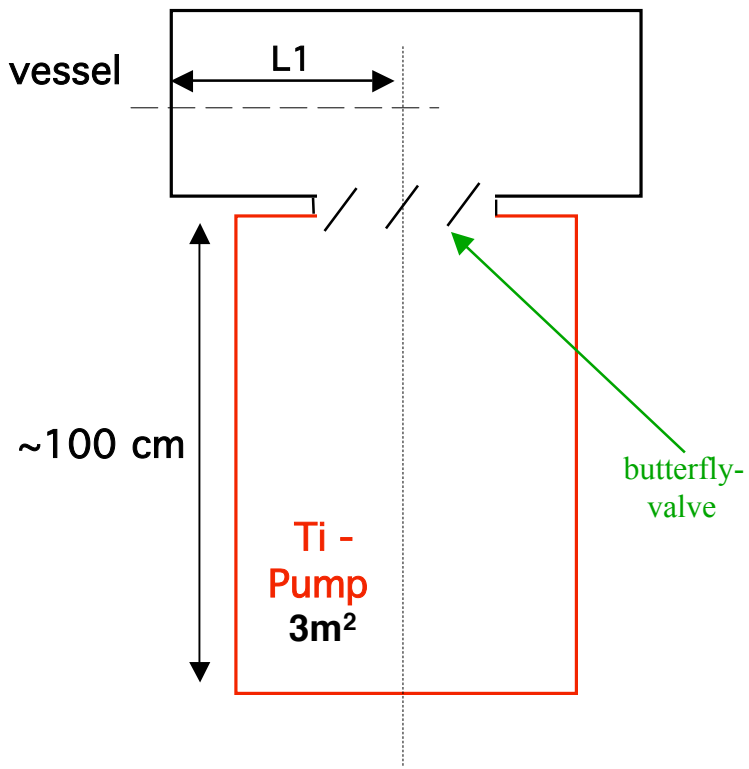
$C_{deut} = 3.9 \times 10^{4}$ L/s

2. effective speed on the vessel:

$S_{air} = 2.5 \times 10^{3}$ L/s

$S_{deut} = 2.7 \times 10^{3}$ L/s

Titanium Appendage Pumps



1. conductance of L1

$C_{air} = 2.42 \times 10^4$ L/s

$C_{deut} = 5.43 \times 10^4$ L/s

2. Ti-pump --> $A = 3 \times 10^4$ cm²

$S_{air} = 5.6$ L/cm² s x A = 1.7×10^5 L/s

$S_{deut} = 1.8$ L/cm² s x A = 5.4×10^4 L/s

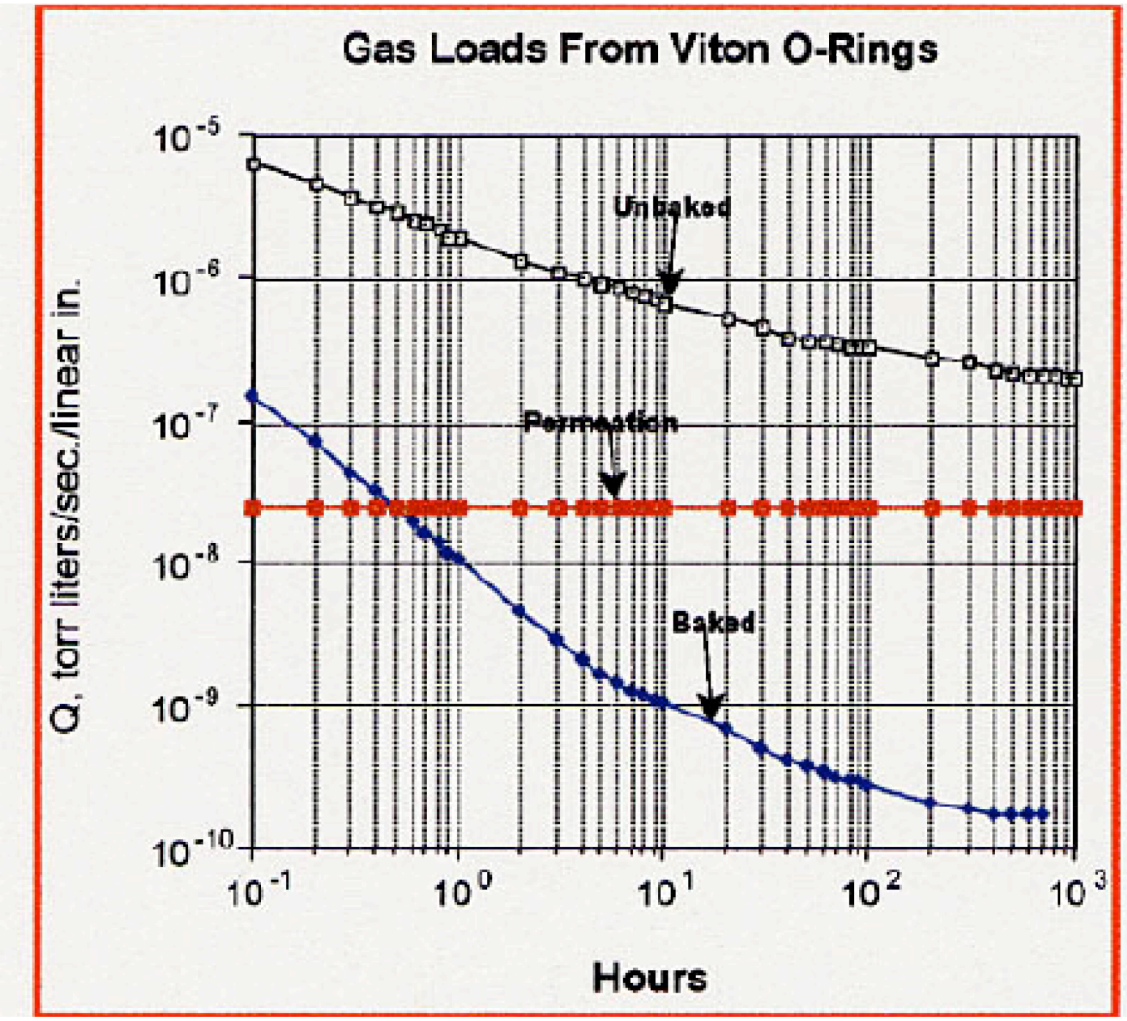
3. Effective pumping speeds:

$S_{air} = 2.1 \times 10^4$ L/s

$S_{deut} = 2.7 \times 10^4$ L/s

2 appendage pumps will provide 5.4×10^4 L/s for deuterium

Viton Gas Loads Consist of Outgassing and Permeation



Double o-rings with differential pumping reduces permeation by 2-3 orders of magnitude.

Baking can reduce the outgassing rates by more than 2 orders of magnitude

courtesy of an unknown vacuum researcher

Density Control with External Vacuum Vessel

- Due to the external vessel, we have a large active fuel reservoir !
- The ratio of the vessel to plasma volume is $V_{vv}/V_{pl} = \sim 10$
- Typical neutral pressure in the W7-AS vessel is: $p = 1\text{-}10 \times 10^{-5}$ Torr
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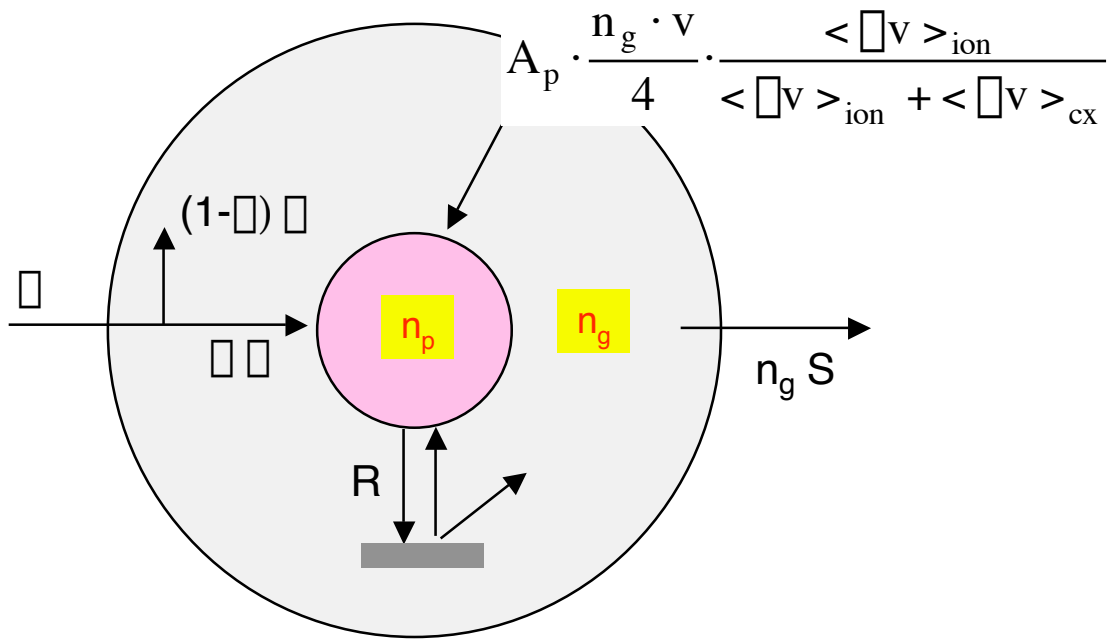
- For the QPS vacuum vessel, this would be $1\text{-}10 \times 10^{19}$ atoms, i.e. comparable to the plasma inventory
- This could present a problem for density control and we are going to implement the following remedies:
  - Gas puff nozzle close to plasma (divertor baffles)
  - Close-fitting divertor baffle
  - Extra pumping with titanium appendage pumps

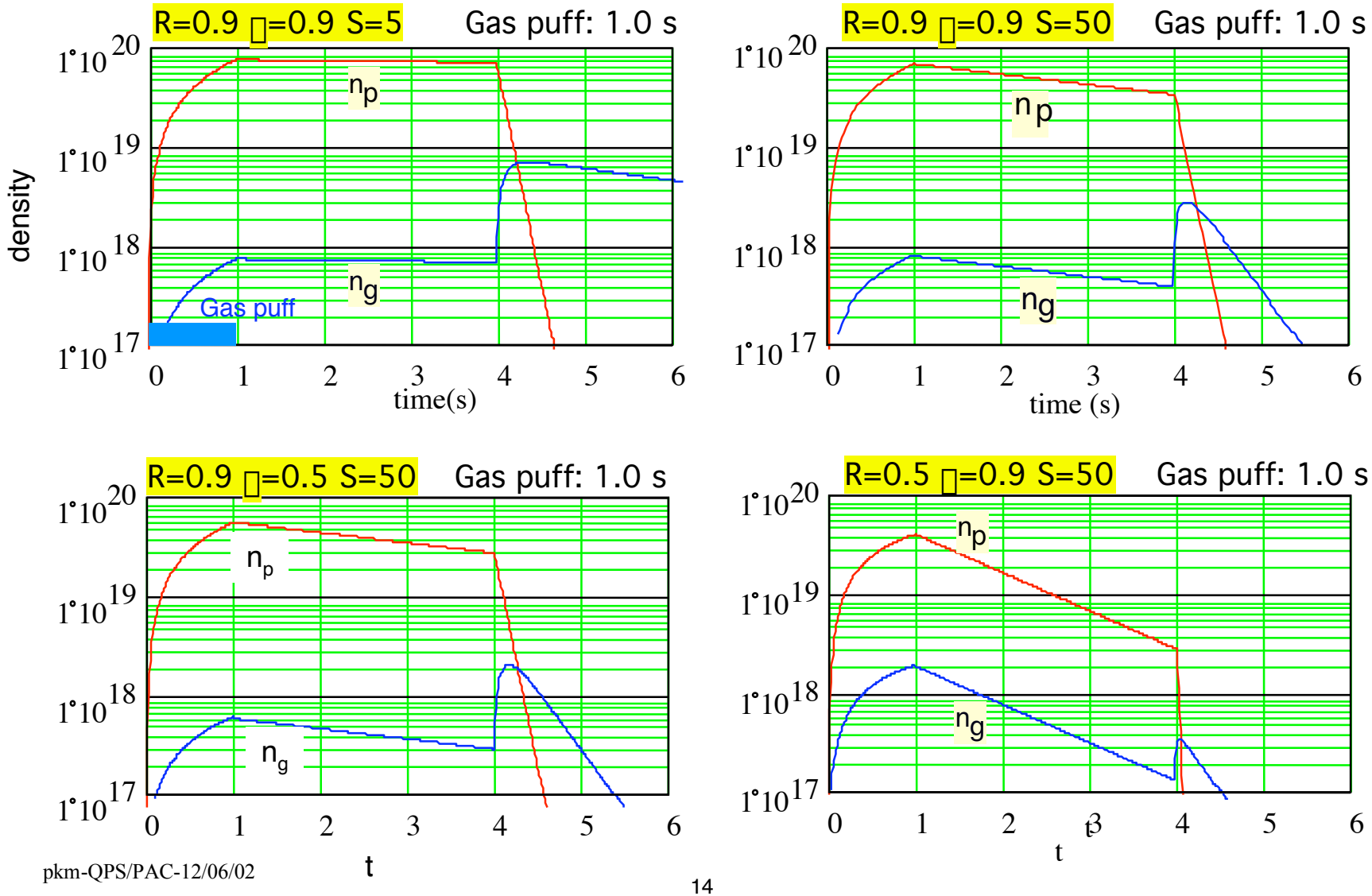
Particle Balance for Plasma and Vacuum Vessel



$$\frac{dn_p}{dt} = \Phi \cdot \frac{\Phi(t)}{V_p} \eta \frac{n_p}{\tau}(1 \eta R) + \frac{A_p}{V_p} \cdot \frac{n_g v}{4} \frac{<\sigma v>_{ion}}{<\sigma v>_{ion} + <\sigma v>_{cx}}$$

$$\frac{dn_g}{dt} = (1 \eta \eta) \cdot \Phi(t) + \frac{n_p}{\tau}(1 \eta R) \cdot \frac{1}{V_g} \eta \frac{A_p}{V_p} \cdot \frac{n_g v}{4} \frac{<\sigma v>_{ion}}{<\sigma v>_{ion} + <\sigma v>_{cx}} \eta n_g \cdot S$$

Density Control Through Gas Puff, Recycling, And Pumping



Control of Neutrals

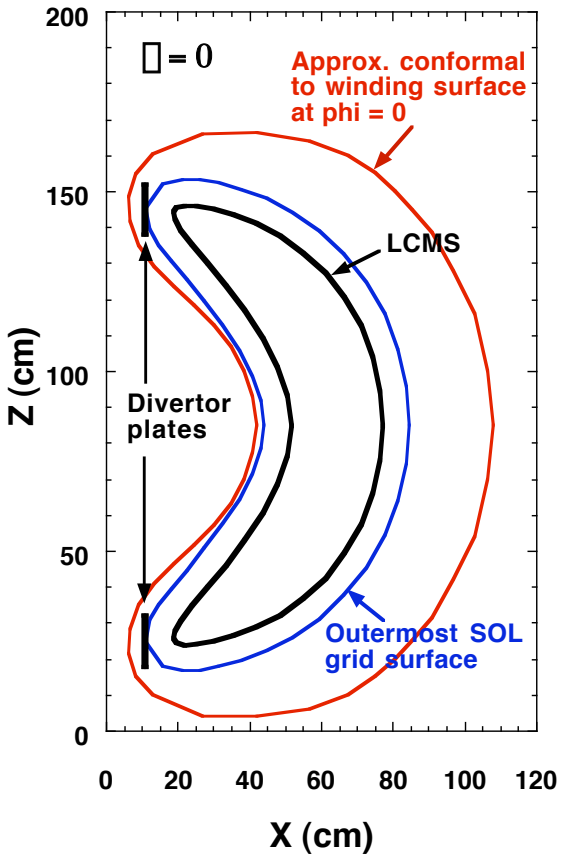
1. **The build-up of neutral pressure in the vessel will be minimized through local concentration of recycling**

   - **Poincaré plots (and experiments on W7-AS) indicate that field lines 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 a finite probability of re-ionization by the boundary plasma.**
   - **Mechanical baffling and local recycling with re-ionization can lead to high-recycling divertor operation with low electron temperatures at the plate.**

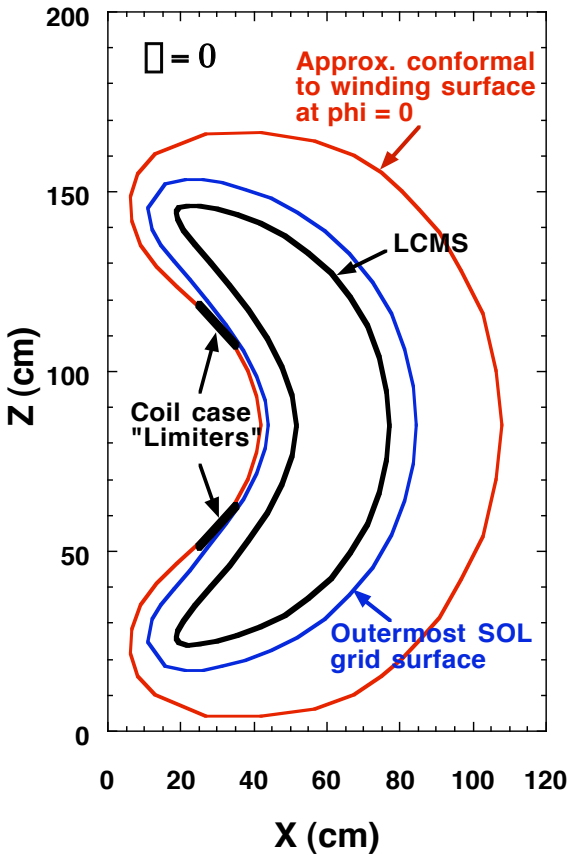
2. **Additional neutrals control will be achieved by surface pumping**
   - **Boronization *(line-of-sight of plasma)***
   - **Titanium appendage pumping**

2-D Neutrals Simulations In Toroidally Axisymmetric Geometry at f = 0

Toroidally axisymmetric geometry for simulations in which divertor plates are innermost plasma facing surfaces.

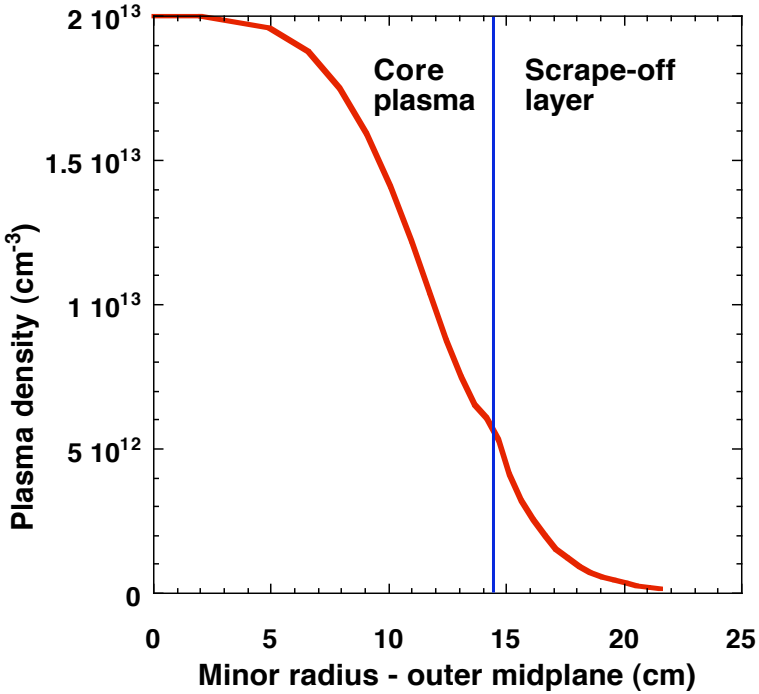


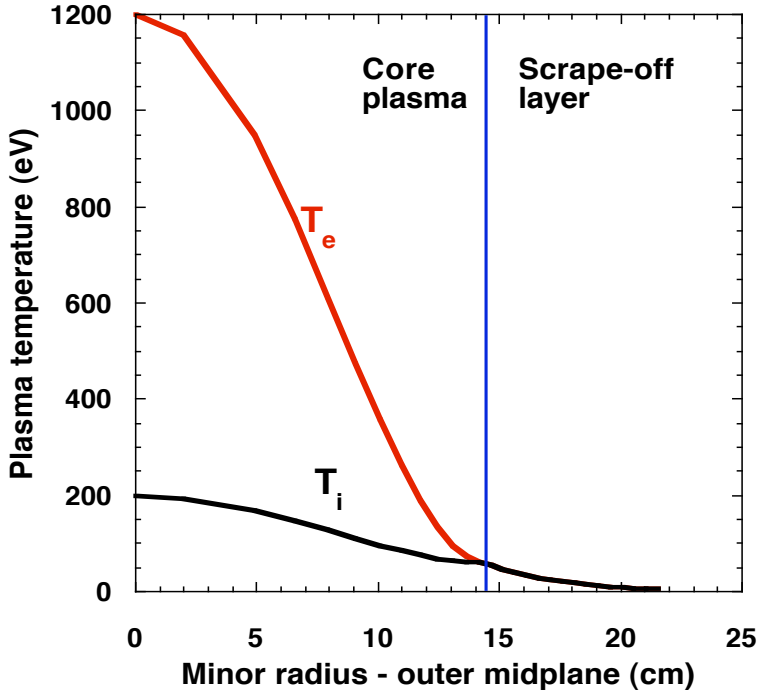
Toroidally axisymmetric geometry for simulations in which the coil case is the innermost plasma facing surface.



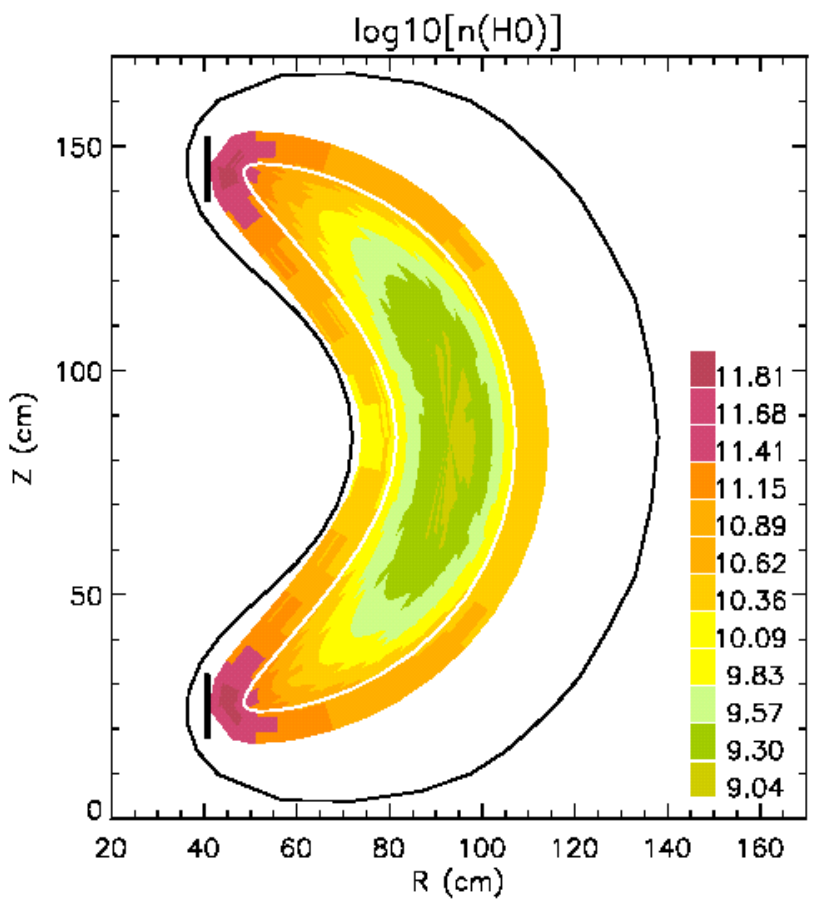
Background Plasma Density and Temperature Profiles Used in Monte Carlo Neutral Transport Simulations

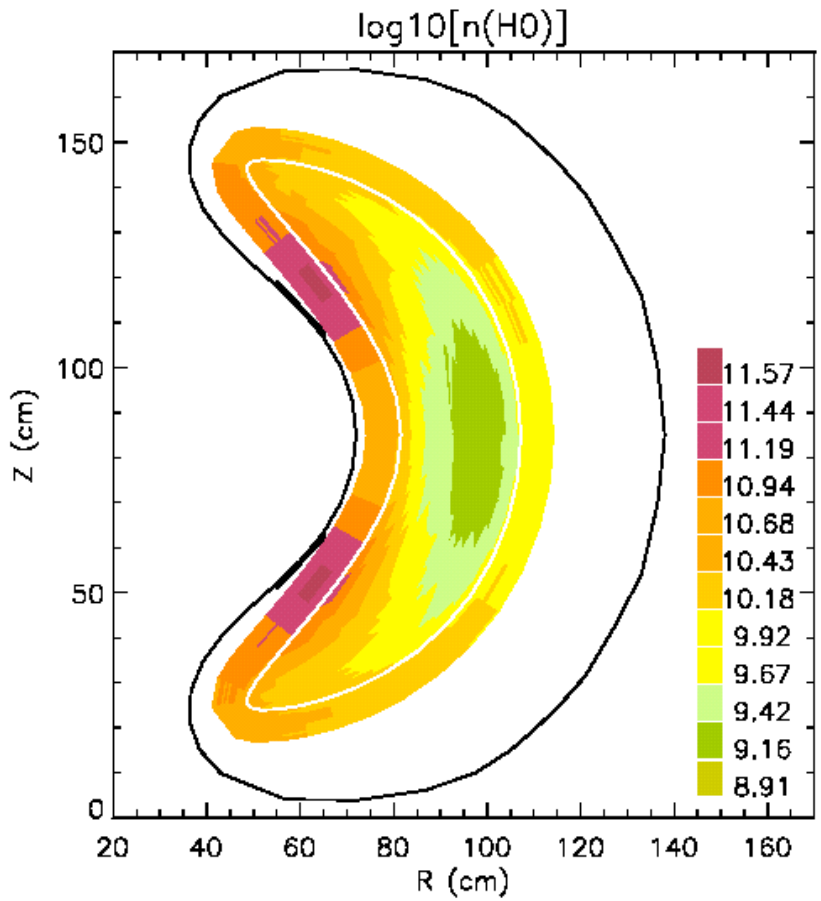
Assumptions: Particle flux to each divertor/limiter plate = 6.25 x 10^{21} ions/s. Recycling is simulated with gas puffs of 32% atoms (T=30.6 ev) and 68% molecules (T=0.026 eV). No wall or plate pumping. Plasma profiles are constant poloidally and toroidally (only radial variation). Core ions are cold relative to electrons but equilibrate in the scrape-off layer.



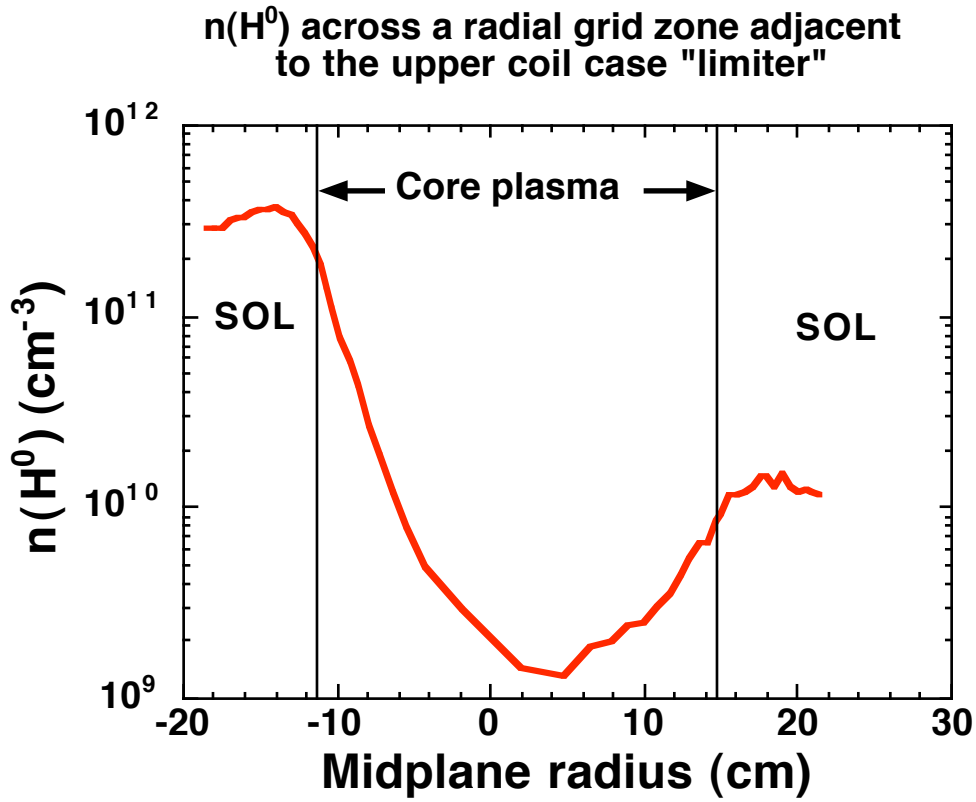


Even at Low Electron Density the Decay Length of the Neutrals in the Core Plasma Is Rather Short





Neutrals Distribution for Inboard Limiter



Impurity Control

- Wall conditioning is the key technique for impurity control, including
  - baking (150 °C)
  - glow-discharge cleaning and
  - thin-film deposition (e.g. boronization)
- Control of plasma-surface interactions
  - the most intense impurity source will be at the divertor 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

- **Heating power:**
  - **P_{input} 1- 3 MW; pulse duration t ≤ 0.5s - 4 s**
- **Start with low power and short pulse; IR camera measurements of power flux distribution**
- **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**
  - **Vacuum vessel (cylinder walls): 80% radiation and cx : 2.4 MW / 65m^2 ~ 0.037 MW/m^2**

Summary and Plans for CDR

- The necessary conditions for vacuum, plasma boundary, and density control can be achieved.
- 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 now 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
  - density control modeling
- Most issues of power and particle handling are similar between QPS and NCSX and we will largely benefit from the NCSX work.

* as in W7-AS