# Modeling of Alcator C-Mod Divertor Baffling Experiments

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# INTRODUCTION

- C-Mod divertor baffling experiments:
  - Change divertor - main chamber conductance by 2,
  - Divertor neutral pressure also changes by 2.
  - Infer that bypass current is constant!
  - Divertor plasma conditions and $D_\alpha$ do not change!
- Implies:
  - Atomic processes limit flow through bypass,
  - Divertor behaves as if it were completely open.
- Modeling requires:
  - Detailed treatment of geometry,
  - Kinetic treatment of neutrals.
  - $\Rightarrow$ use DEGAS 2 (Stotler 1992).
- Absence of effect on divertor plasma allows fixed plasma to be used,
  - Use Langmuir probe data,
  - And Two-Point model (Pitcher 1997).
- Find:
  - Insenstivity of bypass current for large conductances,
  - Dependence of pressure on conductance,
  - No change in $D_\alpha$.
  - However, quantitative differences arise.

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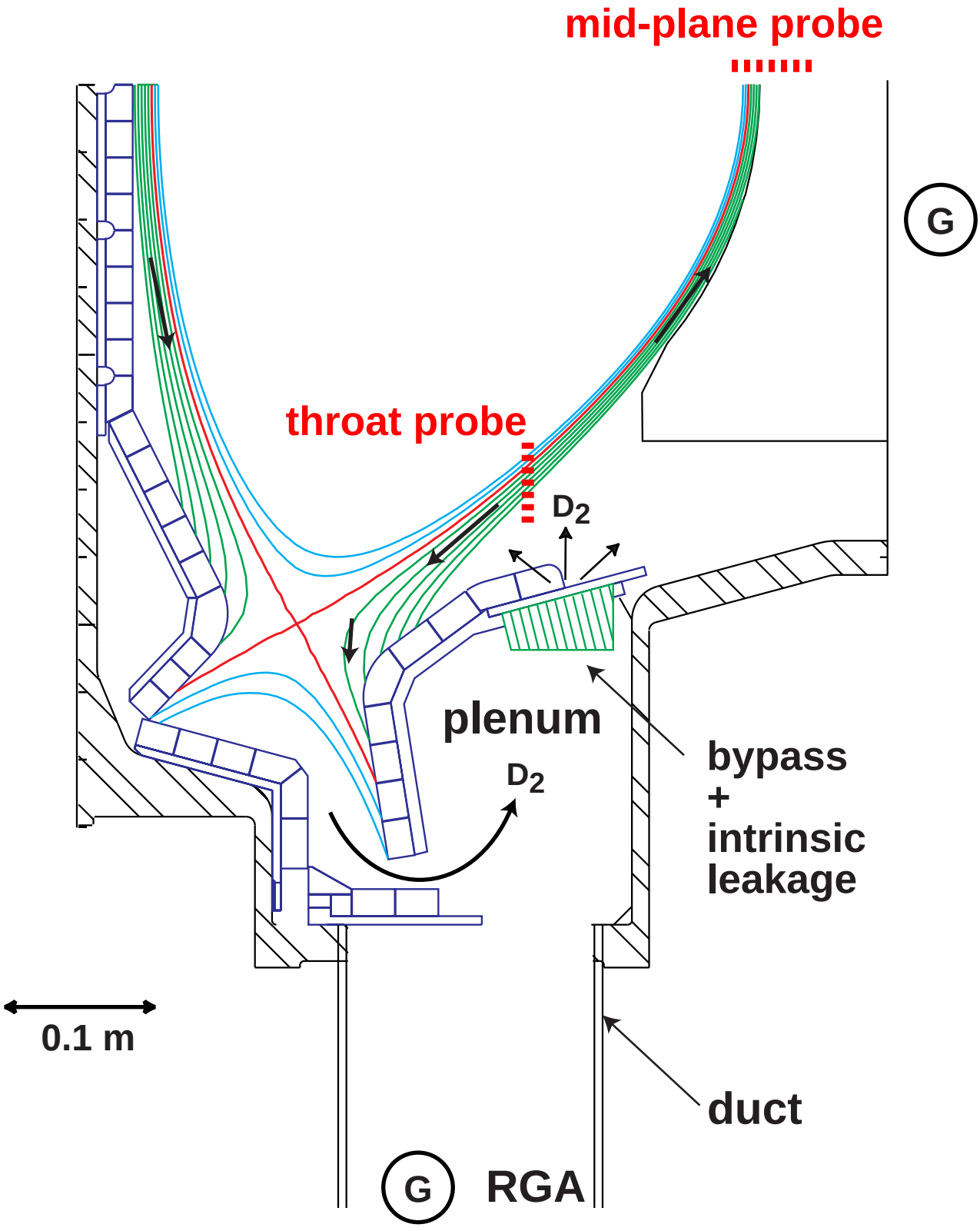
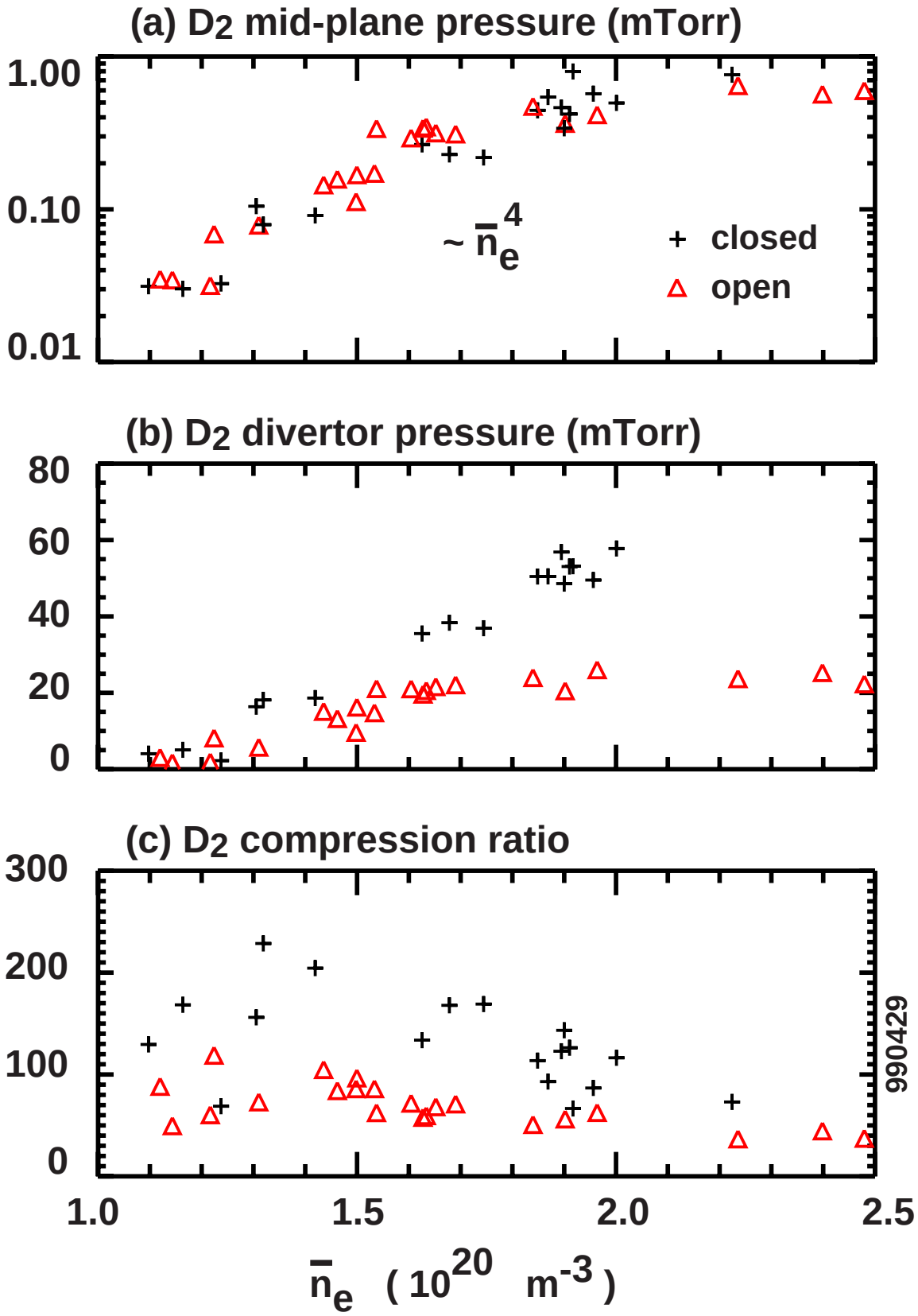
# Alcator C-Mod Divertor Bypass

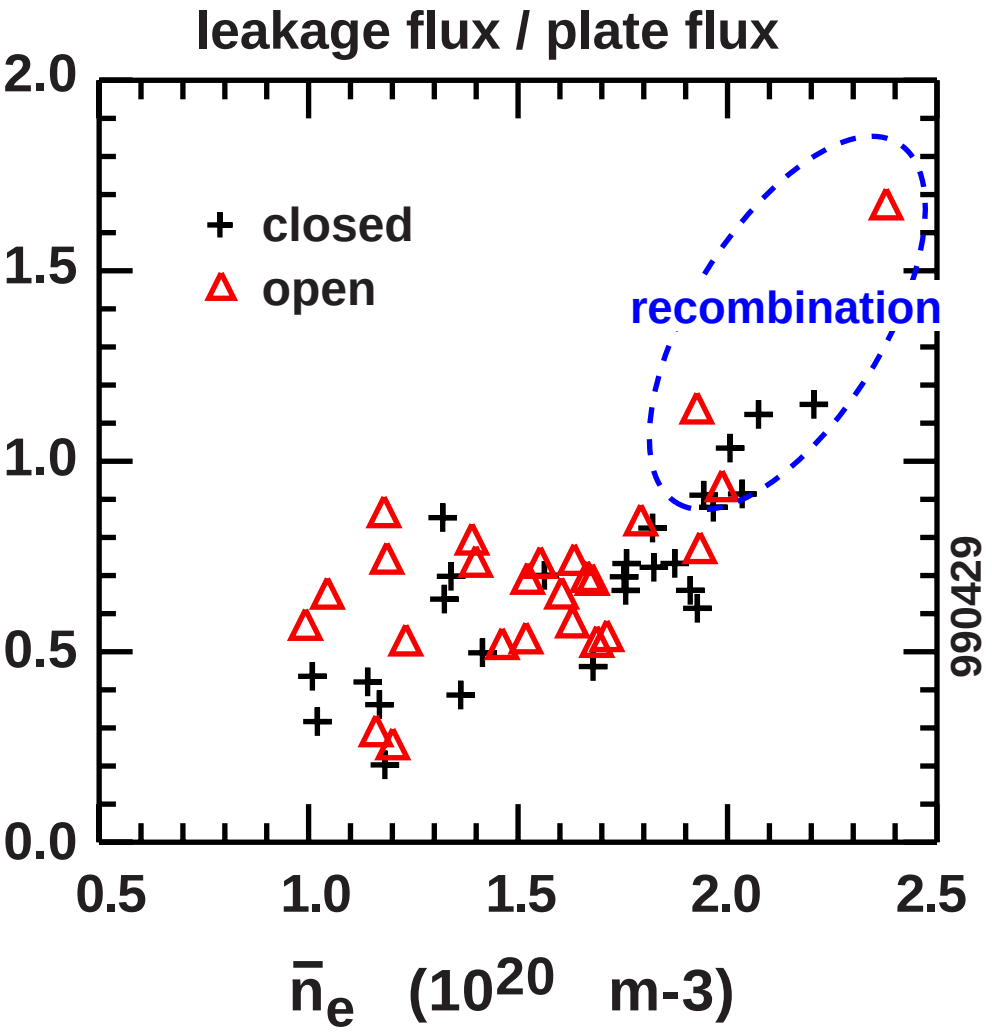


# Effect of Bypass on $D_2$ Pressures

**1 mTorr ~ 0.1 Pa = $10^{-3}$ mbar**



## Leakage Flux is comparable to ion flux to outer plate




**this is surprising given that the C-Mod baffling is relatively closed, f ~ 0.15**

## EXPERIMENTAL DATA

- Divertor bypass experiments described in (Pitcher 2000).
- Focus on shot 990429019, $t = 0.95$ s,
  - $\overline{n}_e = 1.46 \times 10^{20}$ m$^{-3}$,
  - Both targets in high recycling regime,
  - $P_{\rm div} = 15$ mTorr with bypass open,
  - $P_{\rm div} = 30$ mTorr with bypass closed.
- Plasma data from scanning probes at midplane & throat,
- Target data and fluxes from fixed Langmuir probes.
- Compare with divertor viewing $D_\alpha$ array
  - B-top, 63 detectors.

- Plasma for DEGAS 2:
  - 1-D "Two Point" model for variation between probes,
  - Plasma pressure constant along flux surfaces,
  - Except in recycling region near target,
  - Pressure drops to target value,
  - Size estimated for these simulations.
  - Parameters in PFR interpolated between inner & outer values.
  - $n_e = n_i$, $T_e = T_i$, no impurities.
  - Plasma outside computational mesh:
    - 4 cm radial density decay,
    - constant $T$.
- Main chamber source:
  - Simulate recycling on limiters in main chamber (Umansky 1998),
  - Calculate using

$$\Gamma = \frac{1}{4} n_{D_2} \sqrt{\frac{8 T_{\text{wall}}}{\pi m}},$$

  - With $n_{D_2} = P_{\text{main}} / T_{\text{wall}}$,
  - Use measured value $P_{\text{main}} = 0.15$ mTorr.

## DESCRIPTION OF SIMULATION

- Geometry
  - Outline of vacuum vessel, including
    - Divertor plenum,
    - Lower port,
    - RF limiter.
  - EFIT equilibrium,
  - Loaded into DG,
  - Generate plasma mesh with CARRE,
  - Transfer "elements" and plasma mesh to *definegeometry2d*,
  - Polygons broken up into triangles with *Triangle* (Shewchuk 1996),
  - Polygons labeled with zone number,
  - Converted to DEGAS 2's internal "surfaces" and "cells".
  - Conductance between divertor, duct, and plenum approximate.
- Bypass width $w$,
  - $w = 16$ mm $\rightarrow$ integrated area of 0.075 m$^2$,
  - Corresponds to bypass *closed*.
  - With bypass *open*, total area estimated 0.150 m$^2$, $\Rightarrow w = 32$ mm,
  - Also consider $w = 0$, 8, and 64 mm.
  - $w = 0 \leftrightarrow$ ideal of closed divertor.

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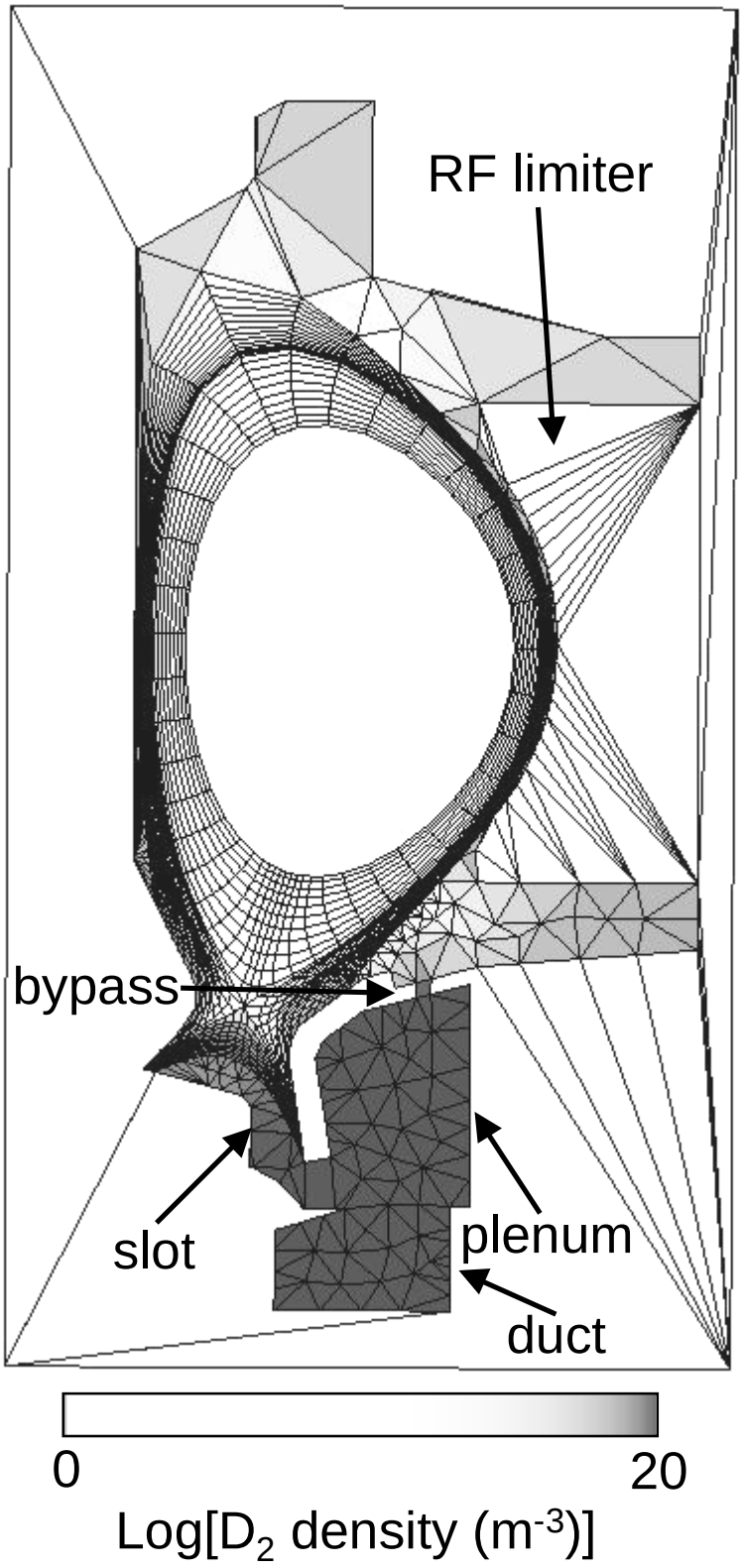
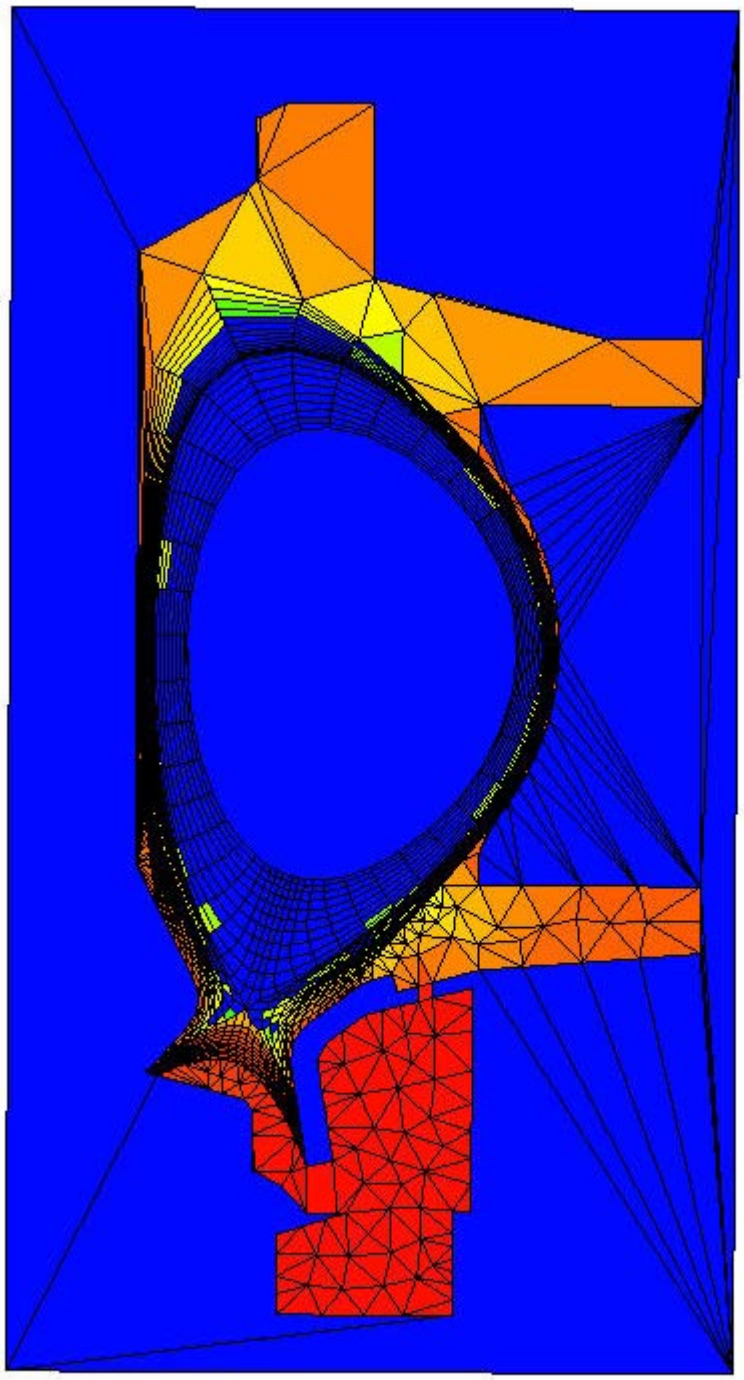



Fig. 1


0
20
Log[D2 density (m-3)]

- All surfaces assumed to be molybdenum,
  - Reflection coefficients from TRIM, 0.5–0.6.
  - Non-reflected atoms desorb as thermal molecules.
- Atomic Physics
  - Collisional-radiative model for D ionization & recombination,
    - Based on (Weisheit 1975),
    - Cross sections taken from (Janev 1993),
    - Optically thin,
    - Assess opacity effects later using escape factor (e.g., Terry 1998).
  - Molecular rates and kinetics as in (Stotler 1996),
    - No $D_\alpha$ from molecules ($10\%$ effect).
  - Ion-neutral scattering,
    - Differential cross sections computed using quantum mechanical techniques (Krstic 1998),
    - D + $D^+$ incorporates CX & elastic scattering,
    - Include $D_2$ + $D^+$,
    - Enforce minimum scattering angle,
      - But constrain momentum transport to not change (Kanzleiter 1999),
    - Use cumulative probability tables for cosine of scattering angle (Kanzleiter 1999).

- Neutral-neutral elastic scattering,
  - BGK treatment just as in (Reiter 1997),
  - Knudsen numbers,
    - $\sim 0.01$ for molecules in plenum,
    - $> 1$ for atoms in slot,
    - $\Rightarrow$ Need nonlinear kinetic treatment.
- Running on 18 processor PC cluster (Stotler 2000),
  - Single iterations $\sim$ few minutes,
  - Few to several iterations required.

## RESULTS

- Plot plenum pressure $P$ and bypass current $\phi$ vs. $w$,
- $\phi \ll$ ion current to target $= 1.60 \times 10^{22}$ s$^{-1}$
- Compare $D_\alpha$ with measurements,
  - Simulation results show no dependence on $w$,
  - Emissions dominated by regions far from slot,
  - And because $\phi$ small.
- Plenum pressures $\sim$ order of magnitude too small,
- $D_\alpha$ is a factor of 3 – 10 too small,
- Possible explanations:
  - No reason to suspect Langmuir probes off by $> 2$,
    - But, earlier neutral particle balance encountered similar difficulties (Niemczewski 1995).
  - Recombination in private flux region
    - $D_\gamma$ tomography indicates more than obtained with simple plasma model for PFR,
    - Assess effect by adjusting plasma to match peak,
      - Recombination source $\sim$ outer target current,
      - $D_\alpha$ plotted,
      - $P \uparrow$ from 0.97 mTorr ("closed" bypass) to 1.88.
      - Recombination nearer outer target may have larger effect.

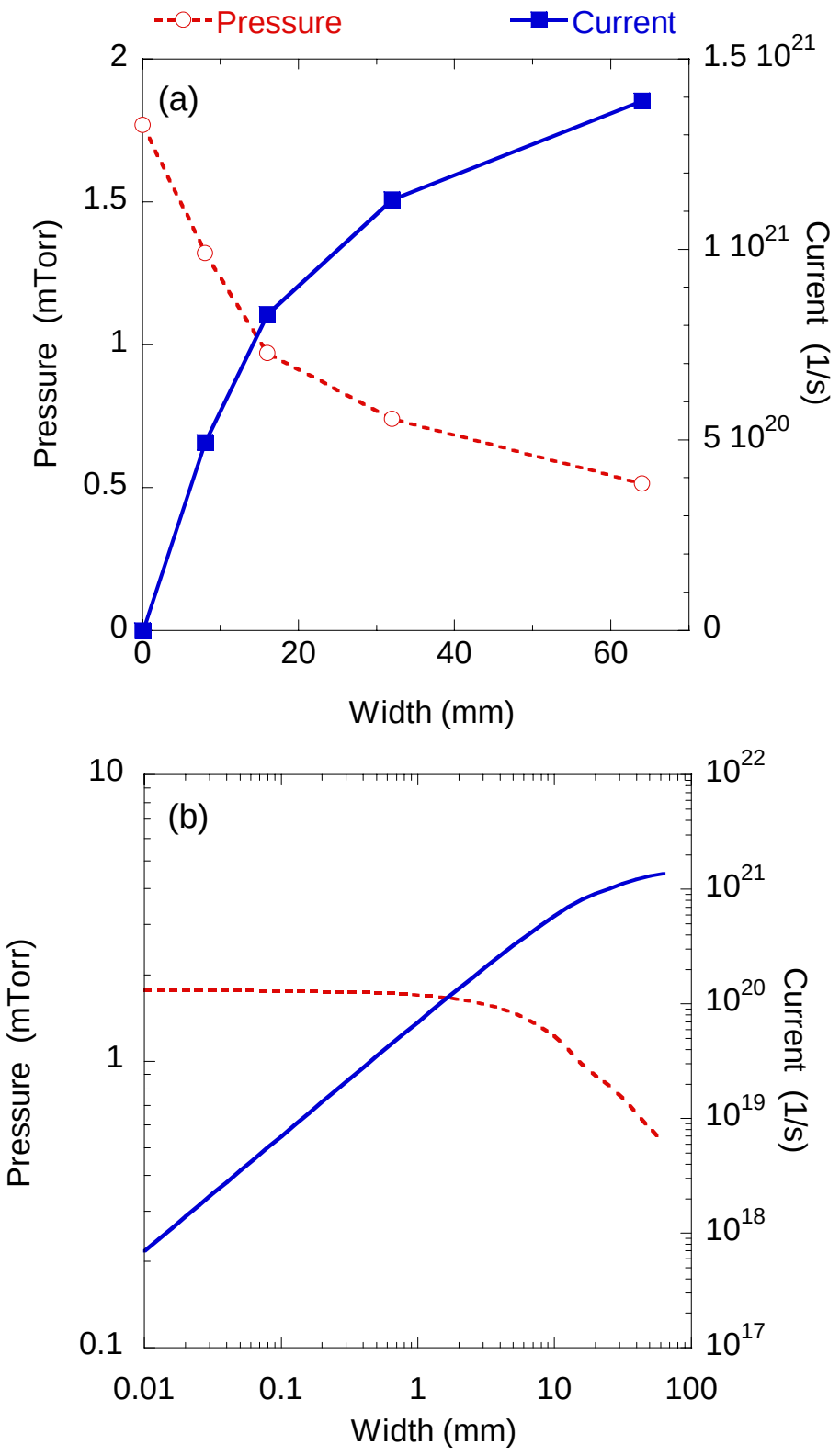
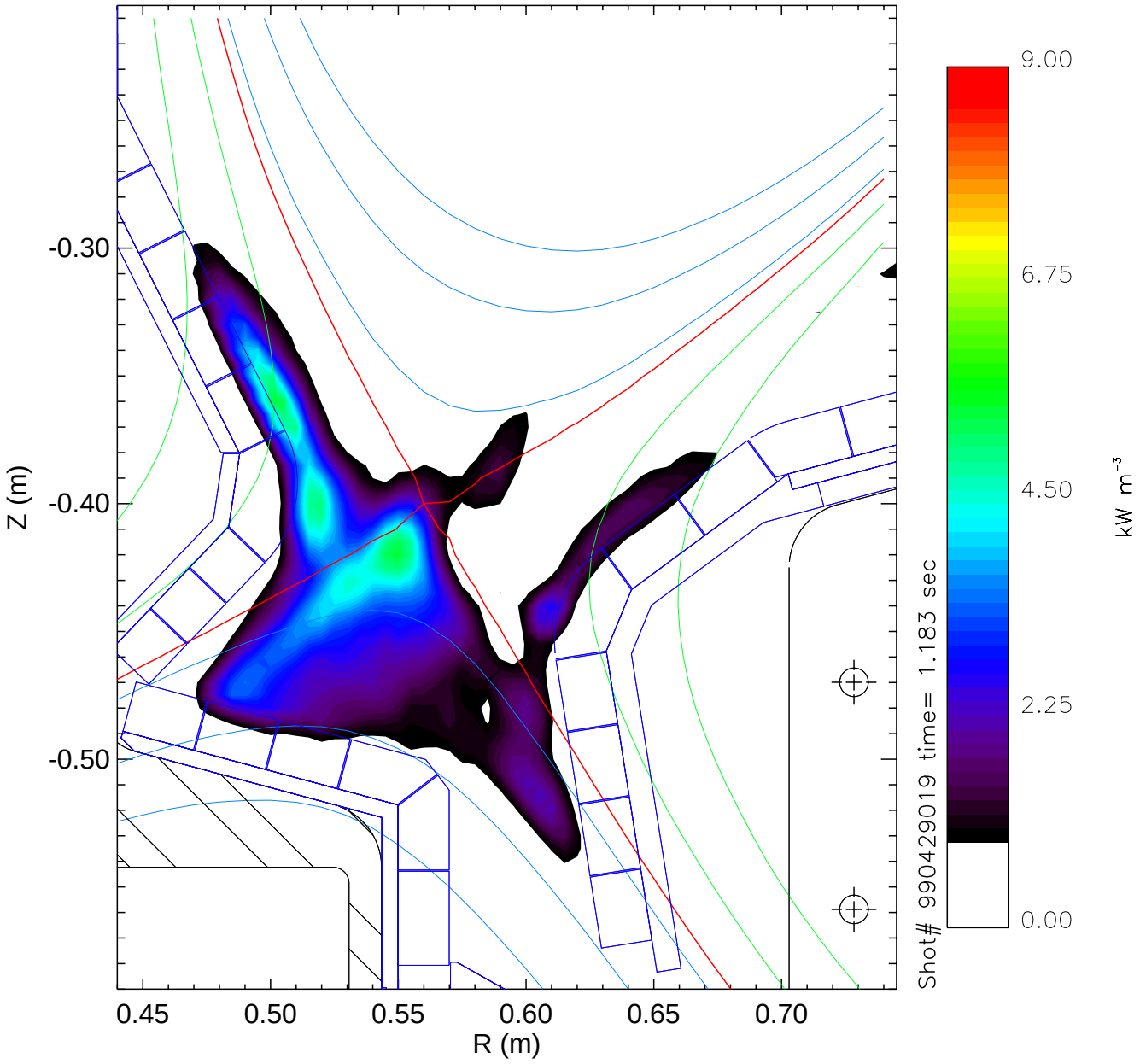
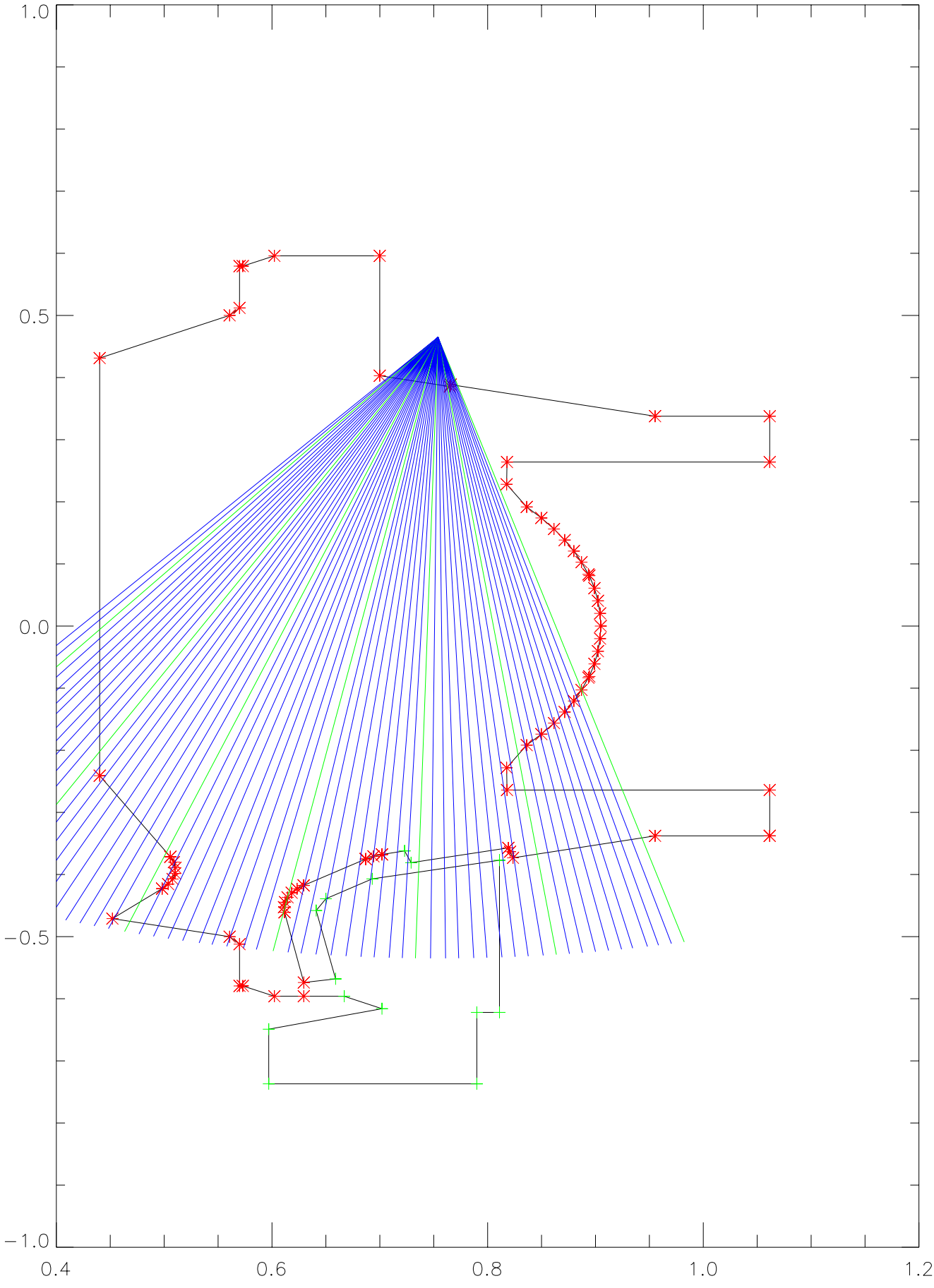
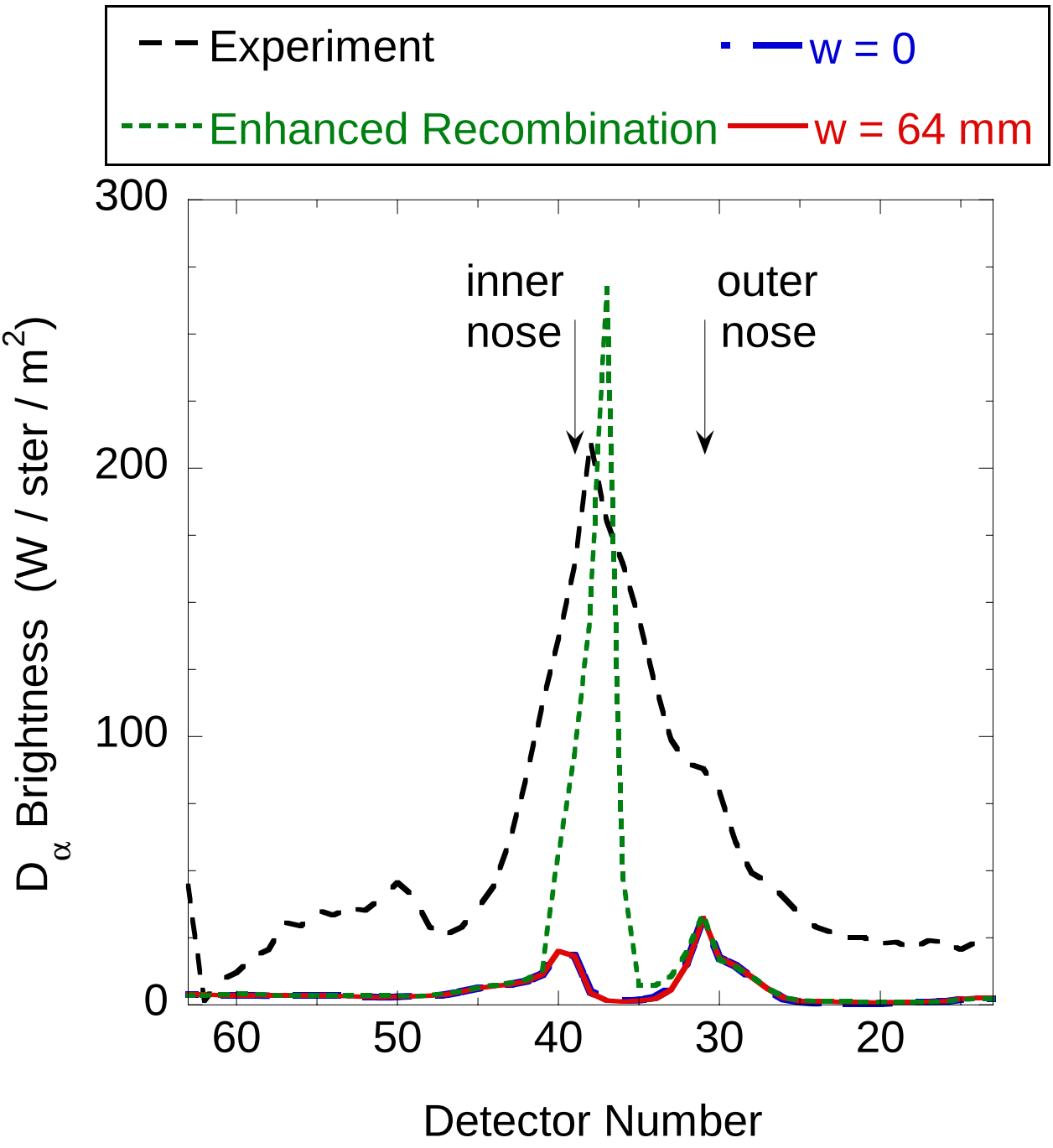

Pressure
Current
(a)
Pressure (mTorr)
Current (1/s)
Width (mm)
(b)
Pressure (mTorr)
Current (1/s)
Width (mm)

Fig. 2


-0.30
-0.40
-0.50
Z (m)
0.45
0.50
0.55
0.60
0.65
0.70
R (m)
9.00
6.75
4.50
2.25
0.00
kW m⁻³
Shot# 990429019 time= 1.183 sec


1.0
0.5
0.0
−0.5
−1.0
0.4
0.6
0.8
1.0
1.2


Experiment
w = 0
Enhanced Recombination
w = 64 mm
300
200
100
0
inner
nose
outer
nose
60
50
40
30
20
Detector Number
D α Brightness (W / ster / m2)

– Treatment of recycling region,
  * Size of region and density peak only estimated,
  * Errors could overemphasize ionization,
  * Should iterate DEGAS 2 & plasma model,
  * Bound magnitude of effect by capping $n$ and $T$ at $1 \times 10^{20}$ m$^{-3}$ and 4 eV,
    · $P$ and $\phi \uparrow$ by 2,
    · $D_\alpha$ less affected.
– Treatment of neutral-neutral scattering has not been adequately benchmarked,
  * Undetected problems may be preventing atom - molecule momentum transfer,
  * Is working correctly qualitatively,
    · Set up test simulation with target fluxes enhanced by 10,
    · $\Rightarrow P = 12.5$ mTorr,
    · Turn off neutral-neutral scattering: $P = 6.3$,
    · Turn off molecule-ion scattering: $P = 5.4$.

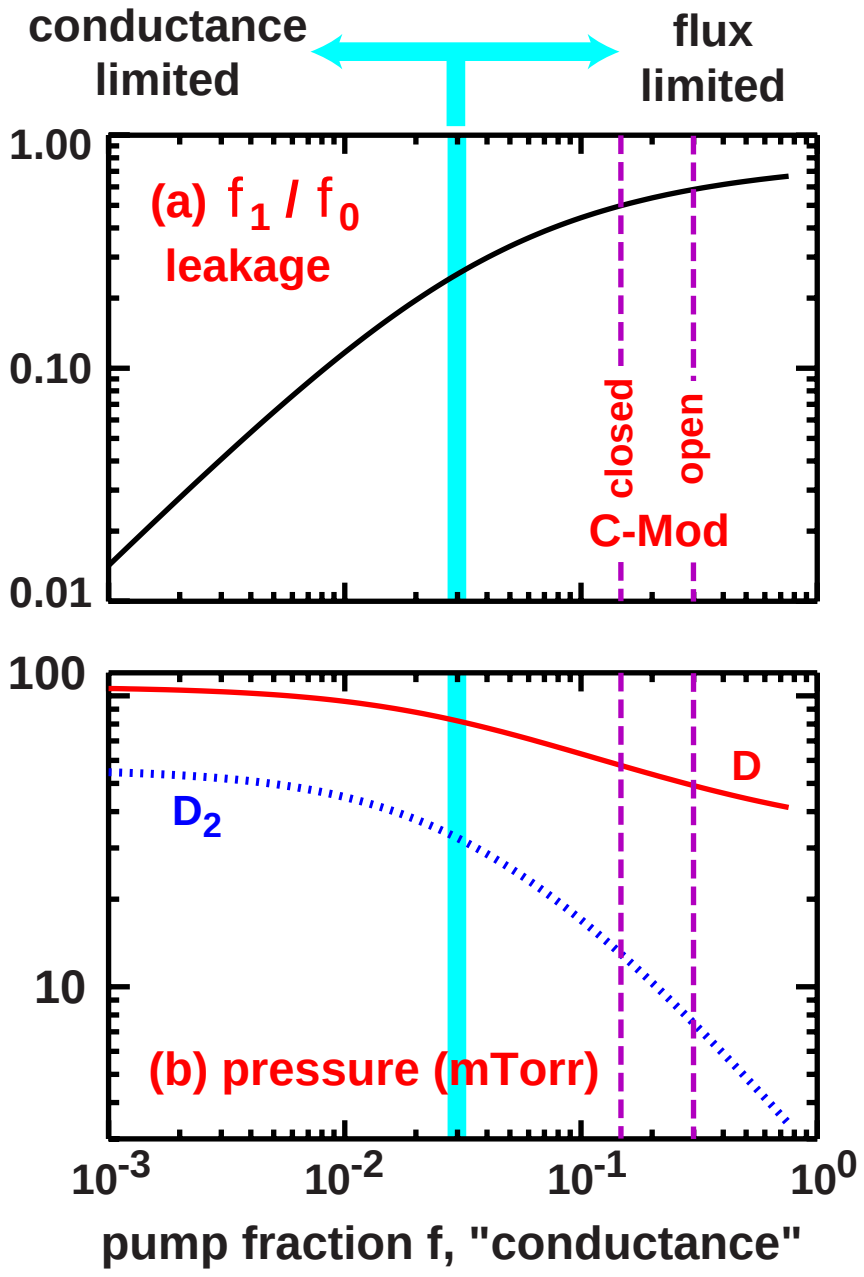
# Two Regimes of Operation

**(1) conductance limited**

leakage ~ f, pressure ~ const.

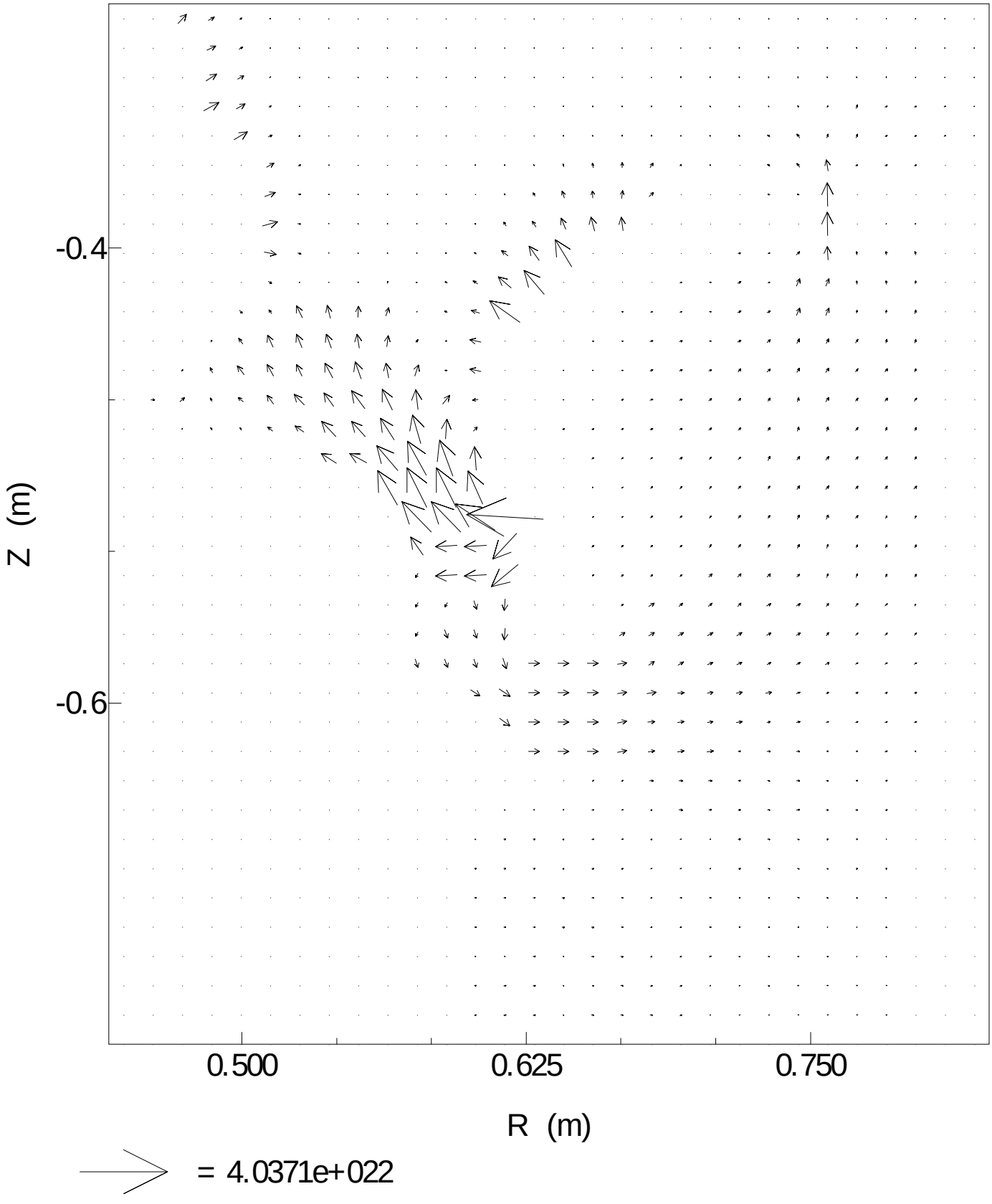
**(2) flux limited**

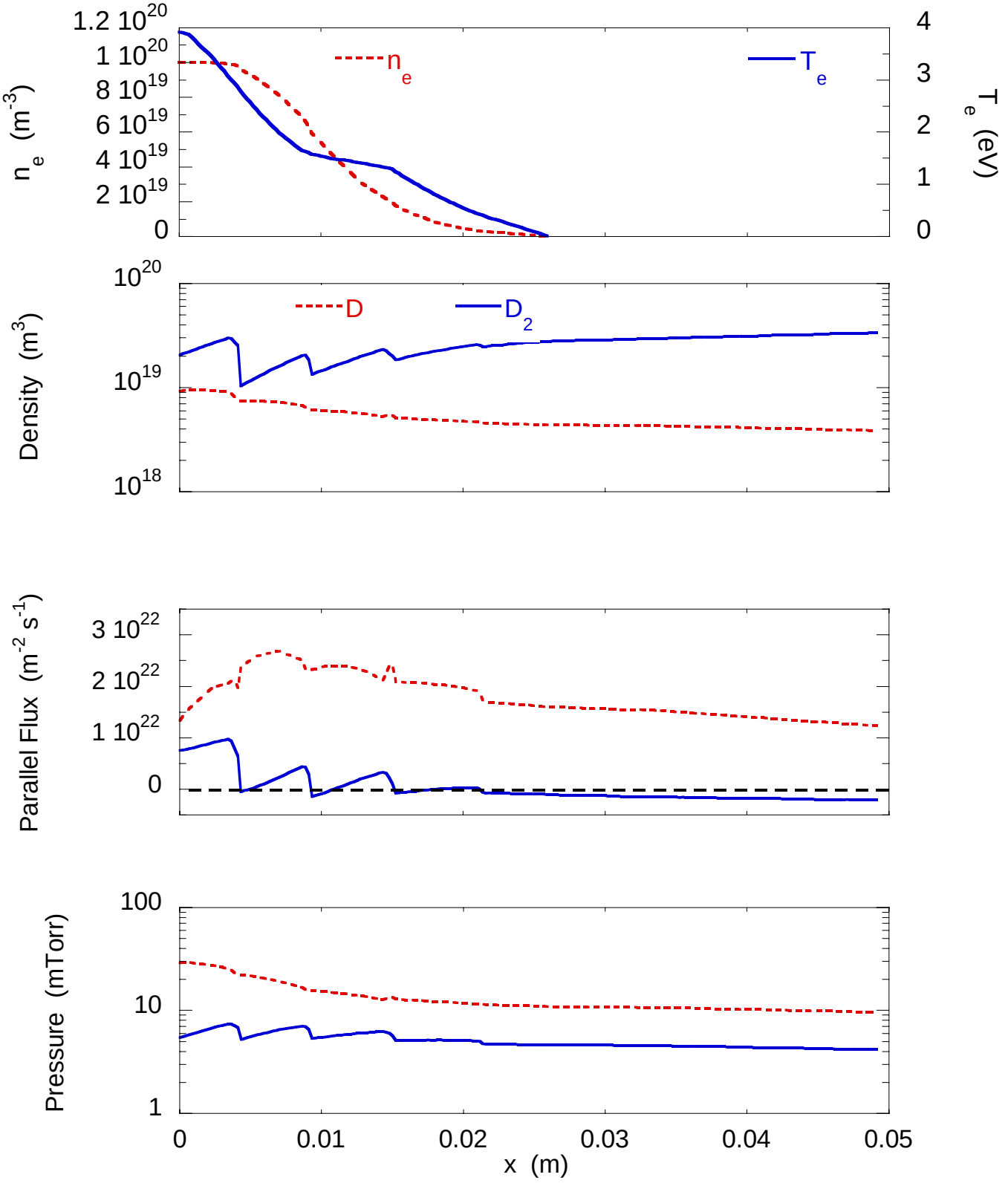
leakage ~ const., pressure ~ 1/f



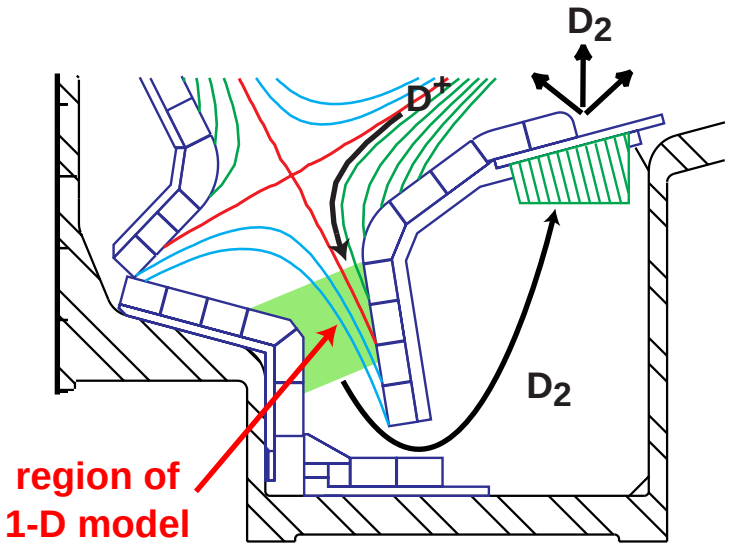

note: confirmed using DEGAS 2, see Stotler, P-2.59

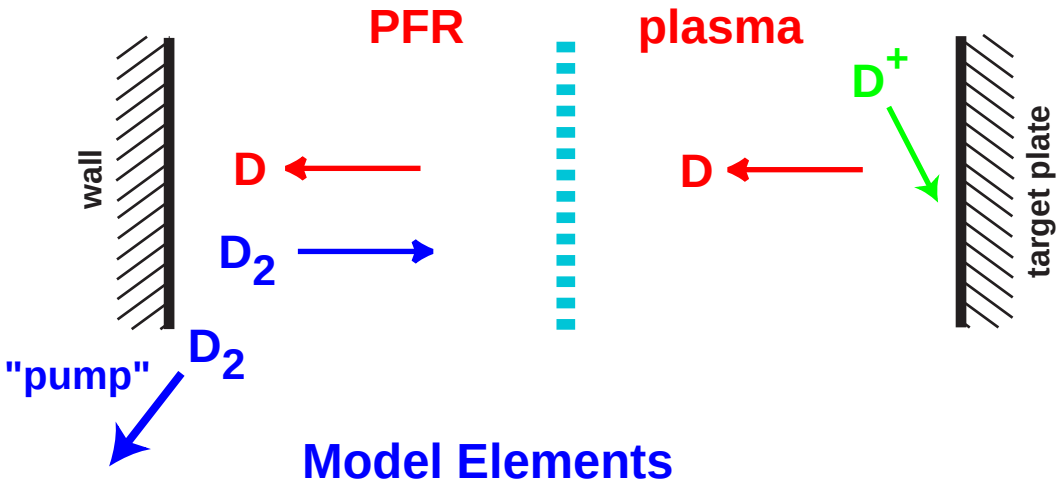
# Total D Flux Vectors in
# w = 16 mm Baseline Simulation




1.2 10^20
1 10^20
8 10^19
6 10^19
4 10^19
2 10^19
0
n_e (m^-3)
n_e
T_e
4
3
2
1
0
T_e (eV)
10^20
10^19
10^18
Density (m^3)
D
D_2
3 10^22
2 10^22
1 10^22
0
Parallel Flux (m^-2 s^-1)
100
10
1
Pressure (mTorr)
0
0.01
0.02
0.03
0.04
0.05
x (m)

# Simple 1-D Model



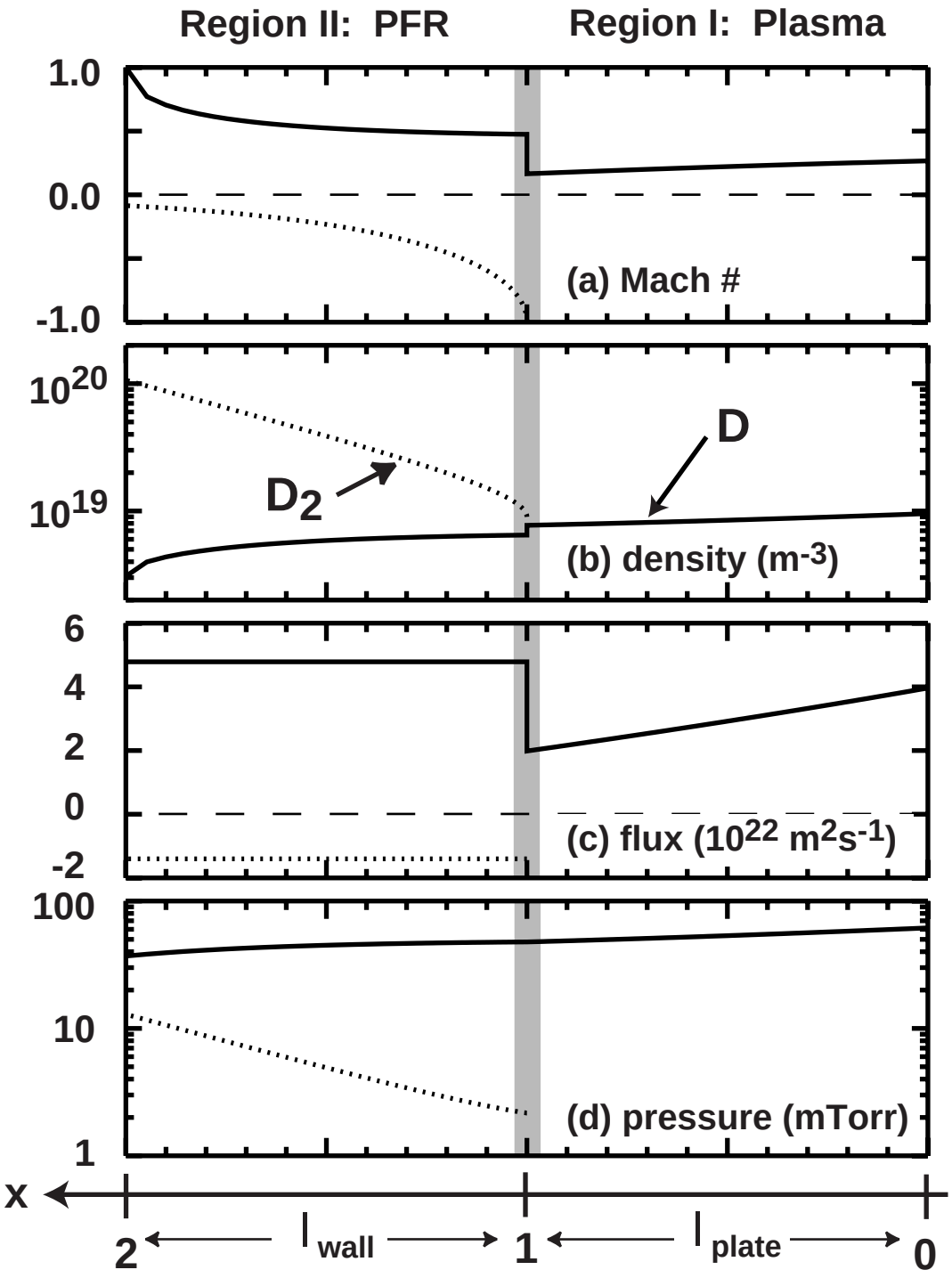

**Model Elements**

- atom, molecule: continuity, momentum
- plasma: ionization and CX
- PFR: momentum exchange between D and $D_2$

**Boundary Condition ("Pump Fraction" = f )**

$$f_{pump} = \frac{1}{4} n_{mol} \bar{c}_{mol} f$$

# Fig. 7


Region II: PFR
Region I: Plasma
1.0
0.0
-1.0
(a) Mach #
10^20
10^19
D2
D
(b) density (m-3)
6
4
2
0
-2
(c) flux (10^22 m^2s^-1)
100
10
1
(d) pressure (mTorr)
x
2
wall
1
plate
0

## CONCLUSIONS

- Experimental results:
  - Bypass strongly affects neutral pressure,
  - But not bypass current,
  - Plasma conditions and $D_\alpha$ do not change.
- Principal result here:
  - Reproduce same qualitative trends,
  - Decreasing sensitivity of $\phi$ with $w$ $\Rightarrow$ some other process limiting flow,
  - Conclude: divertor effectively open.
- Compare with 1-D model of (Pitcher 2000a):
  - Replot data on log-log scale,
  - Closely resembles Fig. 7 of (Pitcher 2000a),
  - Quantitative differences arise,
  - See also 1-D plots of DEGAS 2 data (bypass closed with capped $n$, $T$).
- "Flux limited" regime arises for $w \gtrsim 10$ mm,
  - $\phi$ determined by competition between divertor ionization and escape through bypass,
  - At large enough $w$ ionization & CX limit $\phi$,
  - $\Rightarrow$ open divertor.
- "Conductance limited" for $w < 10$ mm,
  - Linearly varying $\phi$ with $w$,
  - Insensitive pressures.

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