Three-Dimensional Simulation of Neutral Pressure Measurement Experiments on NSTX and Alcator C-Mod

D. P. Stotler, H. W. Kugel, B. LaBombard[1], R. Maingi[2],
R. Raman[3], and V. A. Soukhanovskii[4],

Princeton Plasma Physics Laboratory
Princeton University
Princeton NJ 08543

[1]MIT Plasma Science and Fusion Center, Cambridge MA 02139
[2]Oak Ridge National Laboratory, Oak Ridge TN 37831
[3]University of Washington, Seattle, WA 98195
[4]Lawrence Livermore National Laboratory, Livermore, CA 94550

Note: This poster is available on the Web at:
`http://w3.pppl.gov/degas2/`

Introduction

- NSTX considering options for 2006 particle control milestone, e.g.,
  - Cryopump,
  - Flowing liquid lithium module,
  - Lithium coatings.
- Validate 3-D DEGAS 2 Monte Carlo neutral transport simulation capability in preparation for evaluation of options.
- Progress to date:
  1. Simulate gas flow through a pipe,
     - Compare with expected conductance over range of Knudsen numbers.
  2. Benchmark against measurements of C-Mod gas conductances.
  3. Begin assembly of corresponding 3-D model of NSTX.

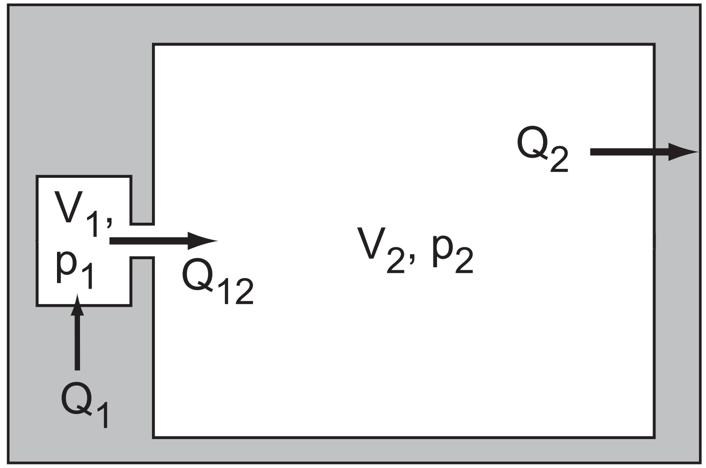
Summary

1. Pipe flow benchmark successful for molecular & transition regime,
   - Simulation of viscous flow limited by computational resources.

2. 3-D DEGAS 2 simulated C-Mod conductances match measured values to within factor of two.
   - Remaining differences may be due to details not simulated,
   - And / or inadequate spatial resolution.

3. Fully detailed 3-D simulations of molecular & transition regime gas flows in tokamaks possible,
   - In some case, practical with massively parallel computers.

Use Two Chamber Model To Relate Physical Quantities



$$U_{12} \equiv Q_{12}/(p_1 - p_2).$$

- Solve equations with constant U_{12}, initial p_1, p_2, and $Q_2 = 0$,
  - For $t \gg V_1 V_2 / U_{12}(V_1 + V_2)$, $p_1 - p_2 = \frac{1}{U_{12}} \frac{V_2 Q_1}{V_1 + V_2}$.
- If Q_2 due to pump of speed S, $Q_2 = S p_2$, have steady state solution

$$p_1 = Q_1 \left(\frac{1}{S} + \frac{1}{U_{12}} \right); p_2 = \frac{Q_1}{S}.$$

D_2 - D_2 Collisions Only - No Plasma

- Only treating D_2 - D_2 elastic scattering,
  - Iterative, BGK treatment with $\vec{v}$-independent $\langle \sigma v \rangle$,
  - Set $\langle \sigma v \rangle = kT/\eta$ using measured viscosities η.
- Molecules striking walls absorbed / desorbed with 100% recycling,
- Sample desorbed molecules with 300 K Maxwell flux distribution.
- Gas source also 300 K, Gaussian in energy, cosine in angle.

Use Simple Pipe Flow Case to Validate DEGAS 2 Physics & Illustrate Conductance Changes with Flow Regime

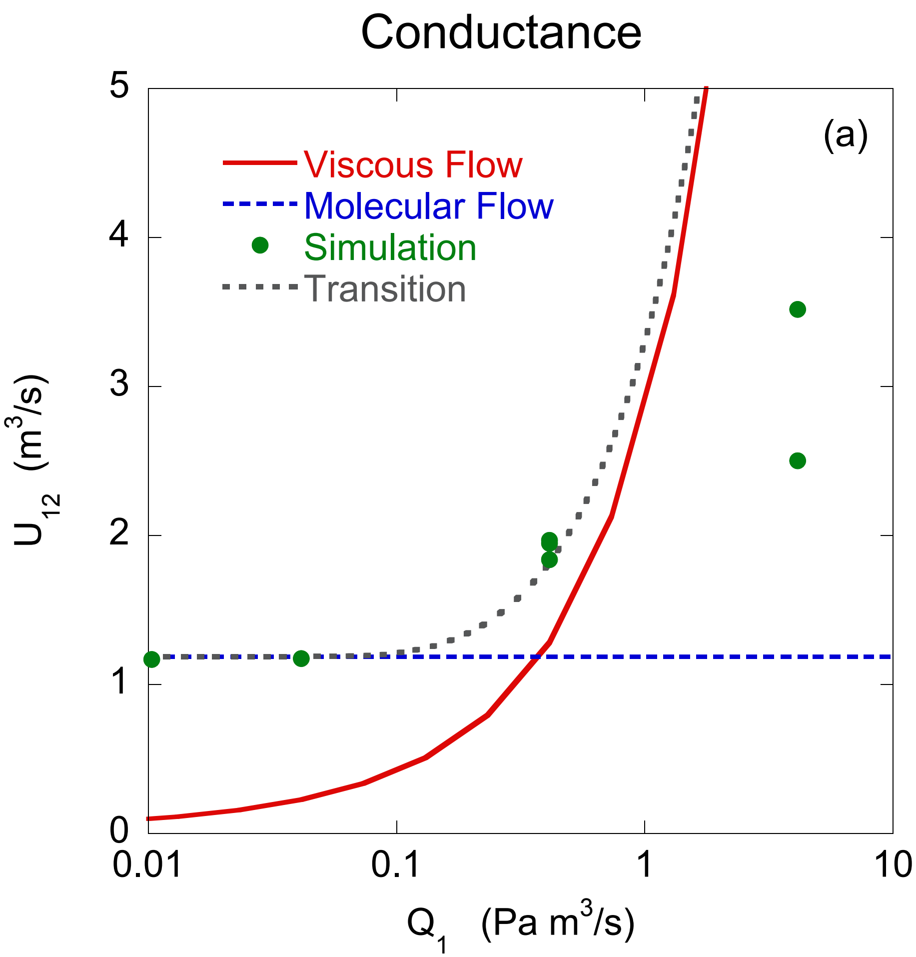
- Flow regime characterized by Knudsen number $K = \lambda / d$,
  - $K \gtrsim 1 \Rightarrow$ "molecular flow" regime, $U_{12} \propto p^0$,
  - $K \lesssim 0.01 \Rightarrow$ "viscous flow" or "continuum" regime, $U_{12} \propto p^1$,
    - Subdivided into "viscous laminar" ($\mathcal{R} < 1200$) & "turbulent".
  - In between: "transition" regime.

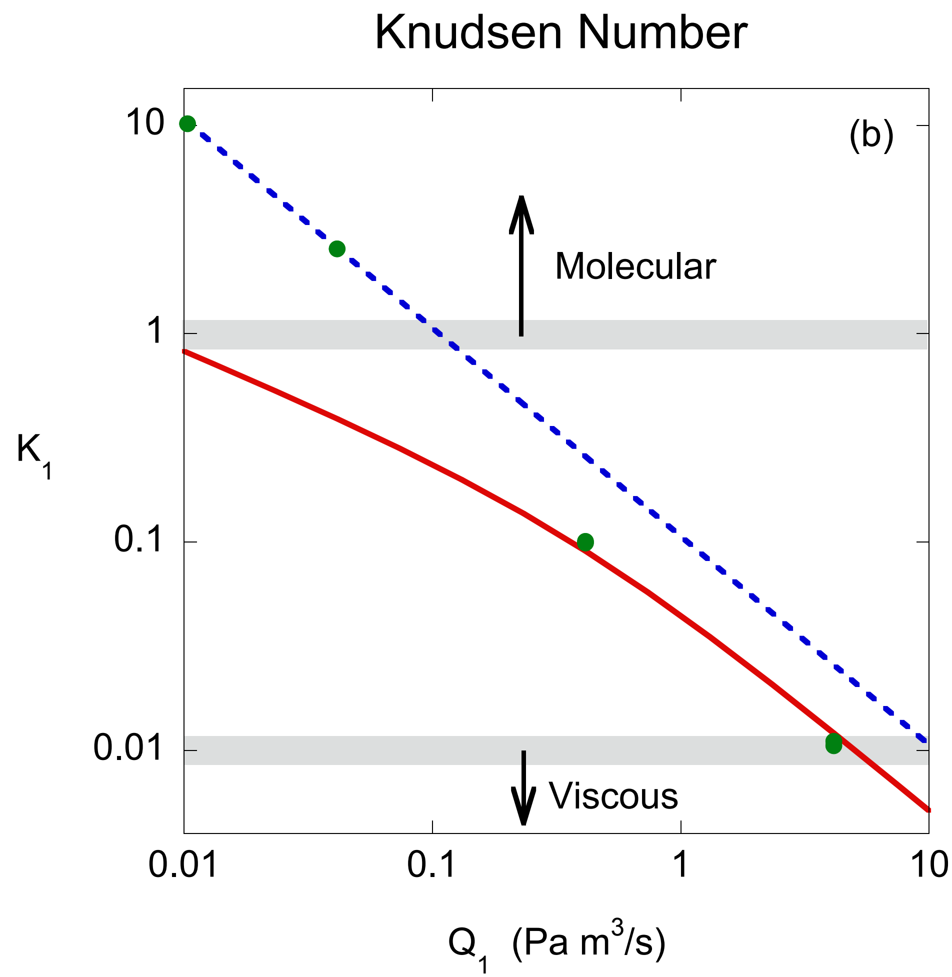
- Consider flow through 0.205 m long, 0.1 m square pipe,
  - Molecular flow: $U_{mf} = A\frac{\bar{v}}{4}W$,
  - Long pipe viscous flow governed by Poiseuille equation:

$$U_{vf} = \frac{1}{12\eta}\frac{a^2b^2}{L}\overline{p}Y.$$

    - Use U definition and $p_2 = Q_1/S$ to get $U_{vf}(Q_1)$.
    - For these simulations, correction for finite pipe length $\lesssim 15\%$.
  - Knudsen gave an empirical fit for transition conductance,
    - But, not directly applicable here,
    - Instead, plot shows smooth curve connecting limiting expressions.

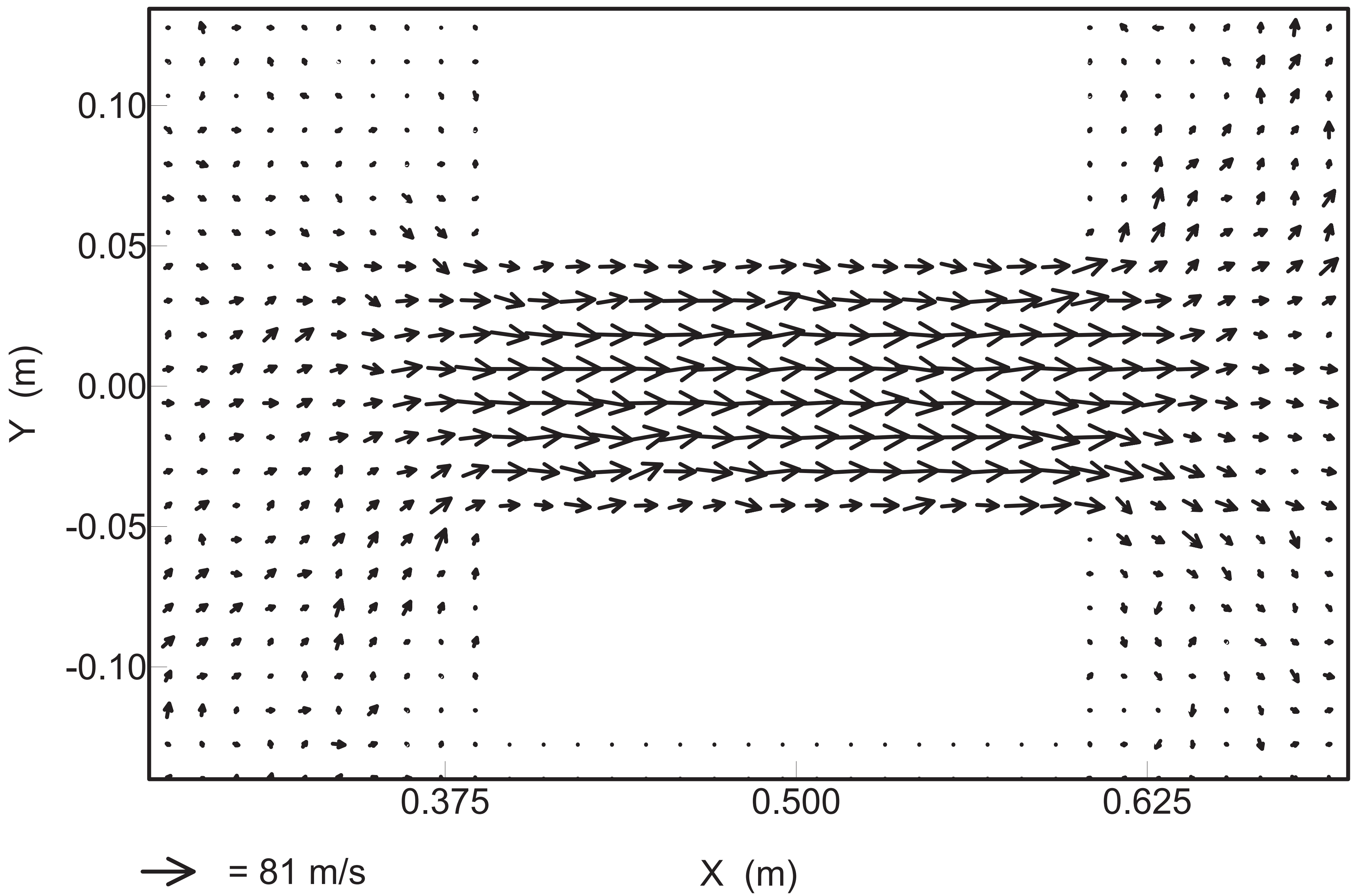
Comparison of Simulated & Predicted Pipe Conductances





Multiple points at a Q_1 show U_{12} increasing with spatial resolution

Velocity Shear Across Pipe Center in $Q_1 = 0.4$ Simulation



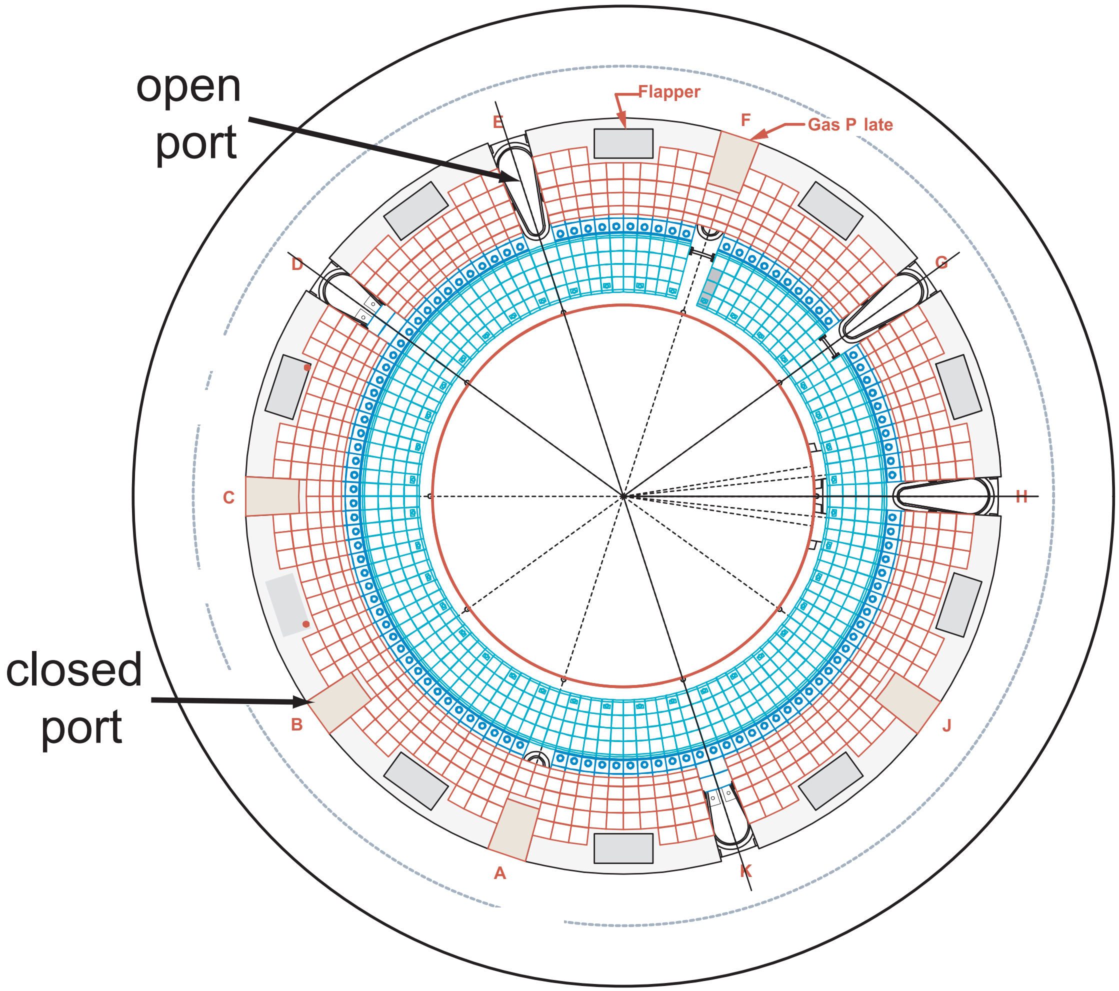
Code Works Well for Molecular Flow / into Transition Regime; Denser Flows More Difficult

- Low Q_1 results agree with U_{mf} to within 2%.
- Have viscous flow for $Q_1 > 40$ Pa-m^3/s.
- Points at $Q_1 = 0.4$ have 16, 64, and 256 zones spanning pipe cross section,
  - Impacts U because need to resolve flow shear across pipe,
  - Finer resolution runs do not differ significantly $\Rightarrow$ adequate resolution.
- Appears to affect $Q_1 = 4.$ case even more strongly,
  - Points shown have 64 and 256 zones, neither is adequate.

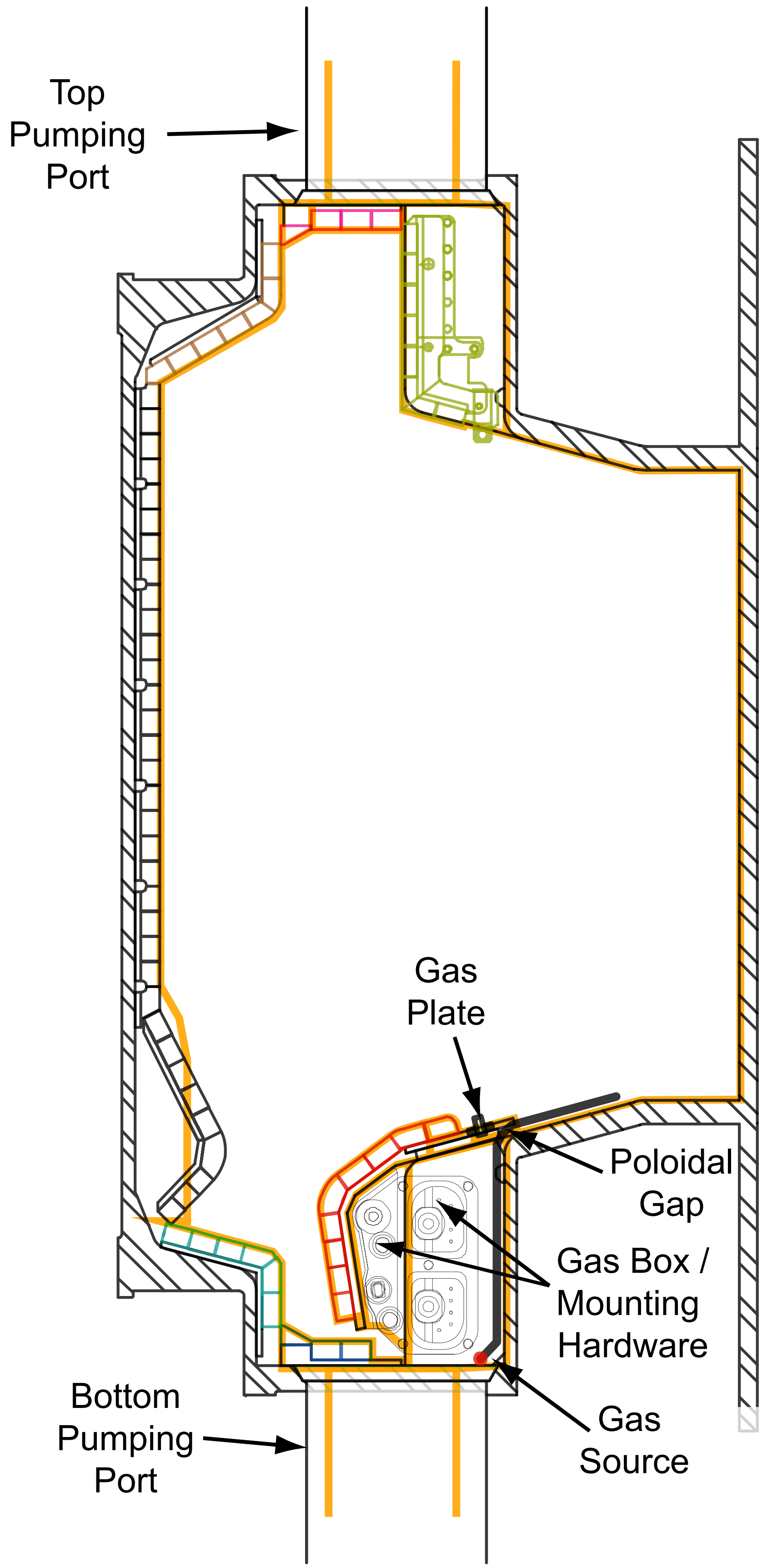
C-Mod Conductance Measurements Provide Good Validation Data

- Install gas capillaries & pressure gauges to measure flow out of “open” and “closed” divertor ports,
  - “Closed”: main flow through slot under outer divertor,
  - “Open”: divertor plate / tiles removed for diagnostic access.
- Puff gas into gas box,
  - Calibrate Q_1 from dp_2/dt in main chamber & known torus volume,
  - Measure p_1 at bottom of pumping port,
  - Take p_2 in main chamber,
  - $\Rightarrow$ compute U_{12}.
- Note that conductances hold steady as pressures rise.

Plan View of C-Mod Lower Divertor

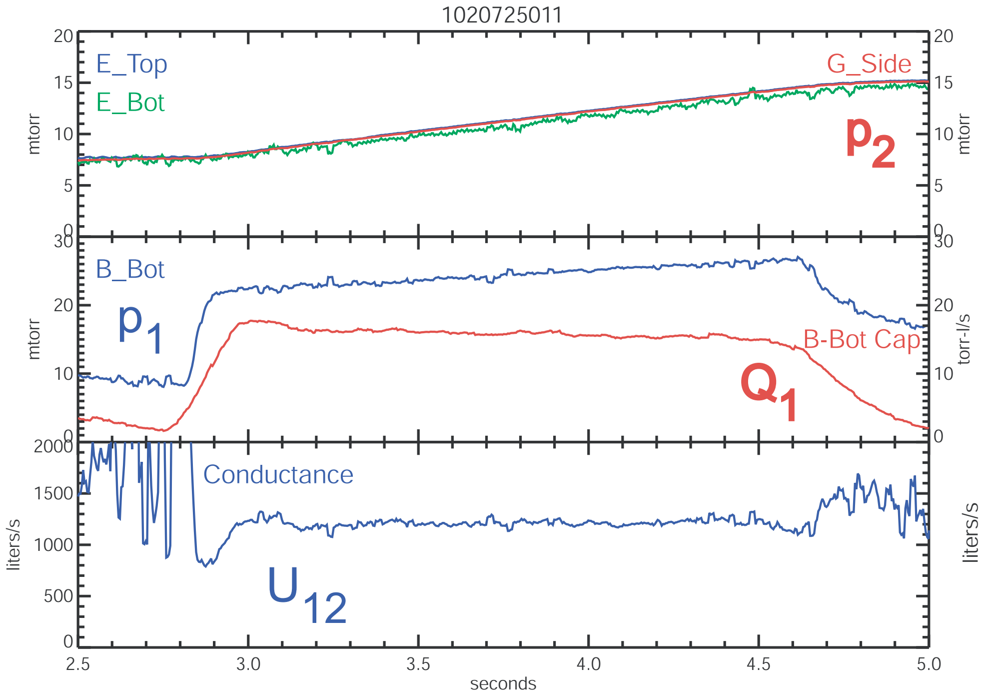


DEGAS 2 Polygons Overlaid on C-Mod Closed Port Cross Section

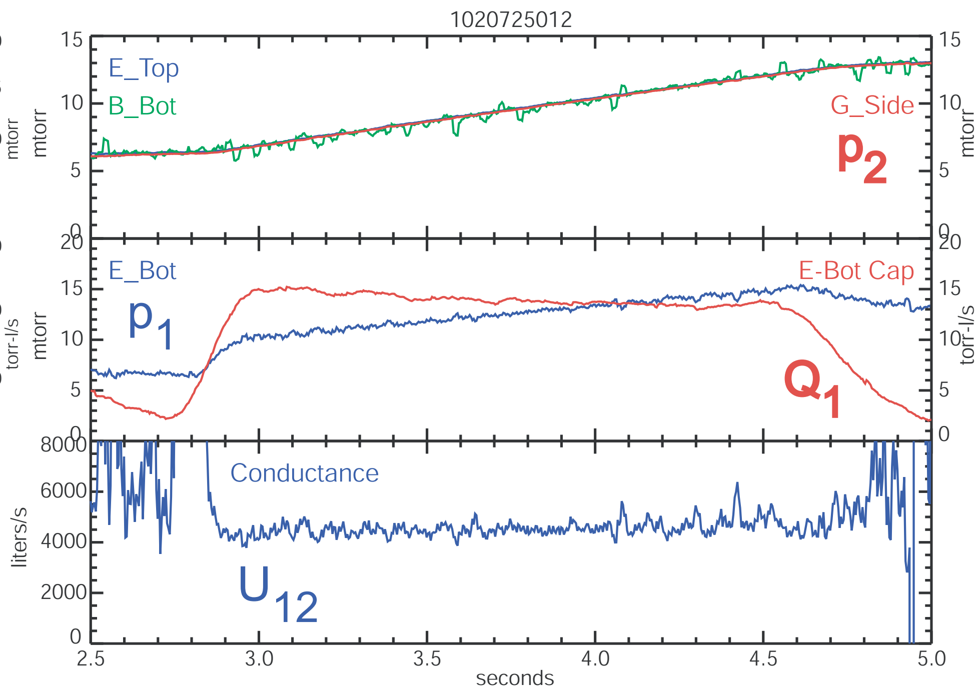


Experimentally Pressures Rise Linearly Conductances Hold Steady

Closed



Open



Use Pie Slice Model to Describe Toroidal Variation of C-Mod Hardware

- Represents modest extension of existing 2-D geometry setup tools.

- Principal toroidal variation:

  - Vertical pumping ports: 6° wide, to $Z = \pm 1.9$ m,

  - Divertor mounting hardware: 6° wide solid on either side of ports,

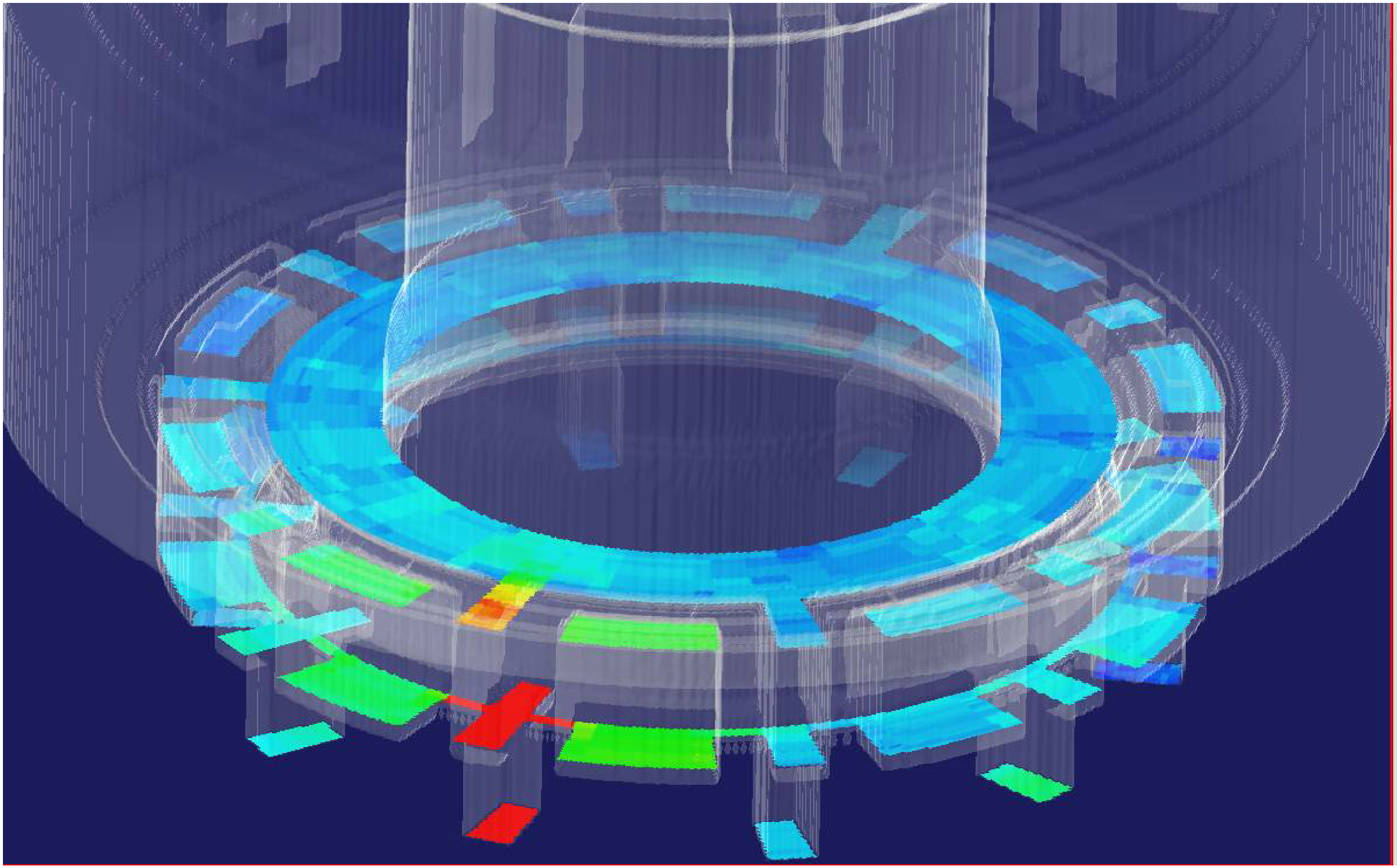
  - Vacuum elsewhere: gas box.

  - Outer divetor plate / tiles: solid except 6° gaps at "open" ports & 3 mm gaps at "closed" ports.

- Also have 0, 2, or 4 mm gap at top of gas box.

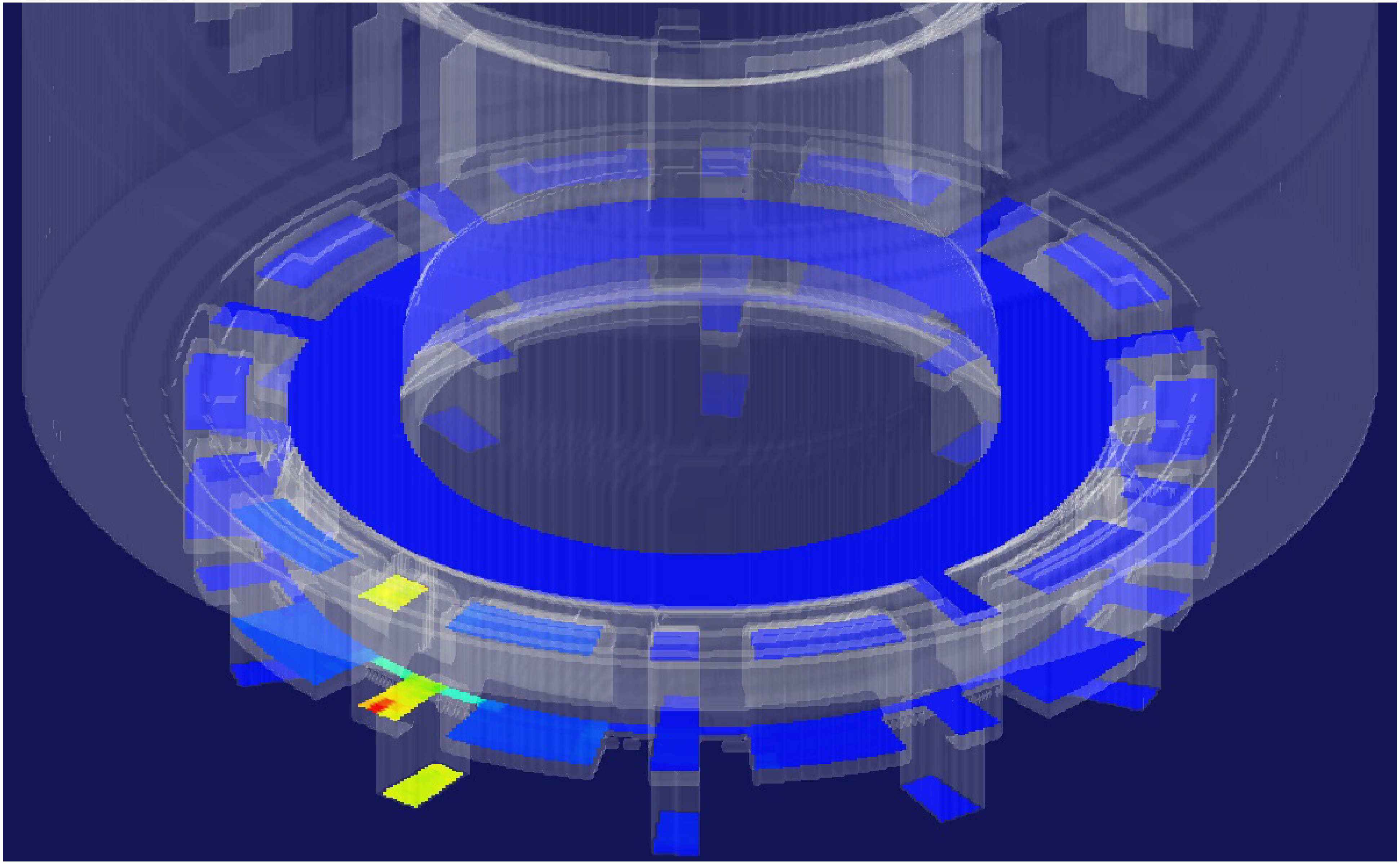
- 10% sink at top of upper ports $\Rightarrow$ steady state simulations.

Visualization of Open Port Simulated Neutral Pressure



Visualization by S. A. Klasky

Visualization of Closed Port Simulated Neutral Pressure



Visualization by S. A. Klasky

Compare Simulated & Measured Pressures & Conductances

Run	p_1 (Pa)	p_2 (Pa)	Q_1 (Pa-m^3/s)	U_{12} (m^3/s)	Error
Open	1.46	1.22	1.86	7.8	16%
Open - expt.	1.46	1.05	1.86	4.5	-
Closed (base)	3.7	1.29	1.99	0.83	8.6%
Closed - expt.	3.7	2.04	1.99	1.2	-
2 mm pol. gap	3.9	1.30	1.99	0.76	3.9%
Reduce source	0.26	0.085	0.124	0.71	2.8%

("Experimental" p_2 values computed from measured U_{12}, Q_1, and simulation p_1.)

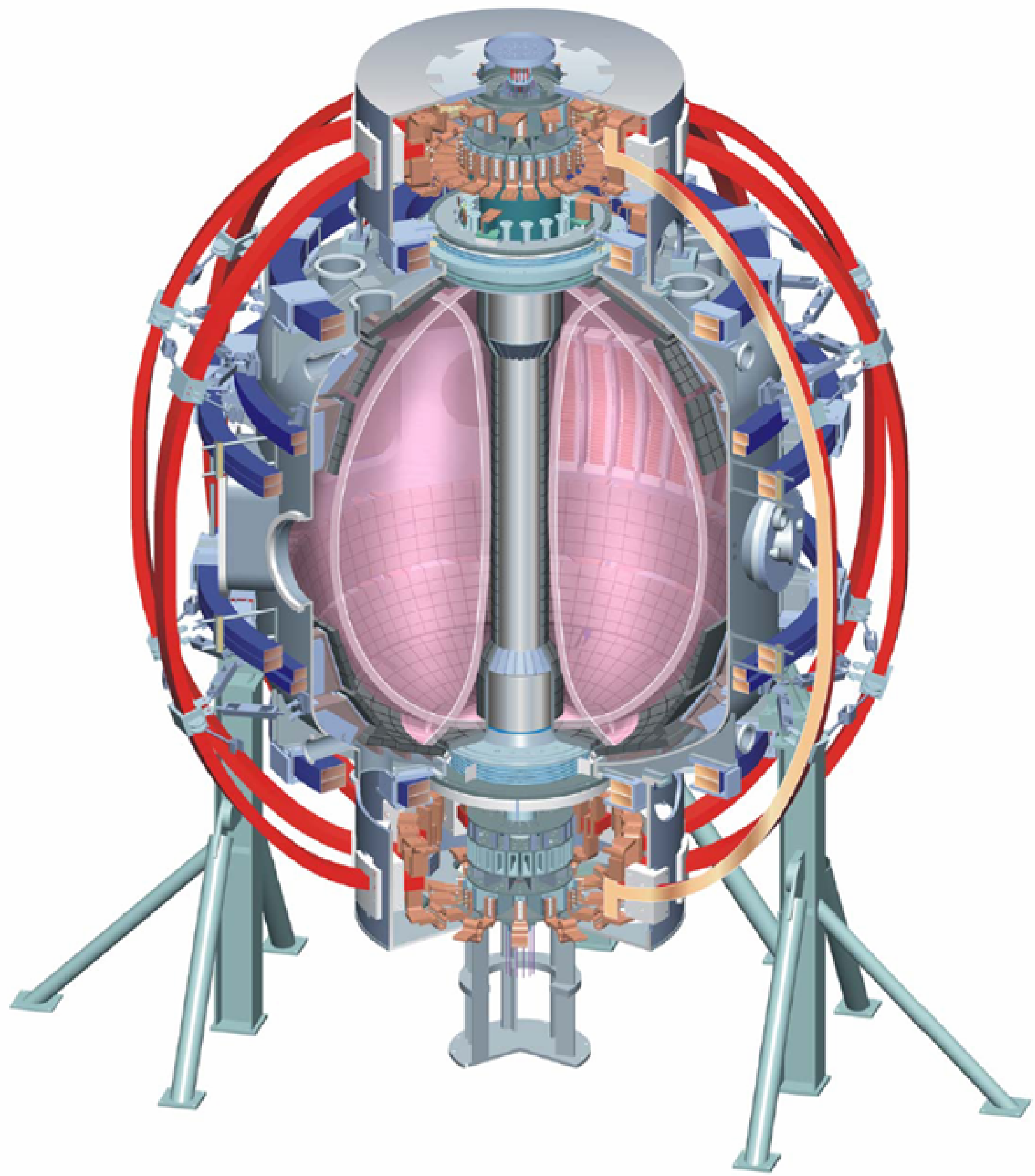
Discussion of C-Mod Benchmark

- Fully detailed 3-D simulations of molecular and transition regime gas flows in tokamaks possible,
- Practical given inexpensive CPUs: baseline closed port case took 41 hours on 30 1.7 GHz AMD Athlon processors,
  - $\leq 10^5$ flights, 56,659 zones.
- Simulated “open” & “closed” conductances agree with measurements to within factor of 2.
- Consider remaining differences,
  - One too high, one too low $\Rightarrow$ still missing important details in geometry & experimental arrangement?
  - Pipe flow results suggest examining spatial resolution in gaps.

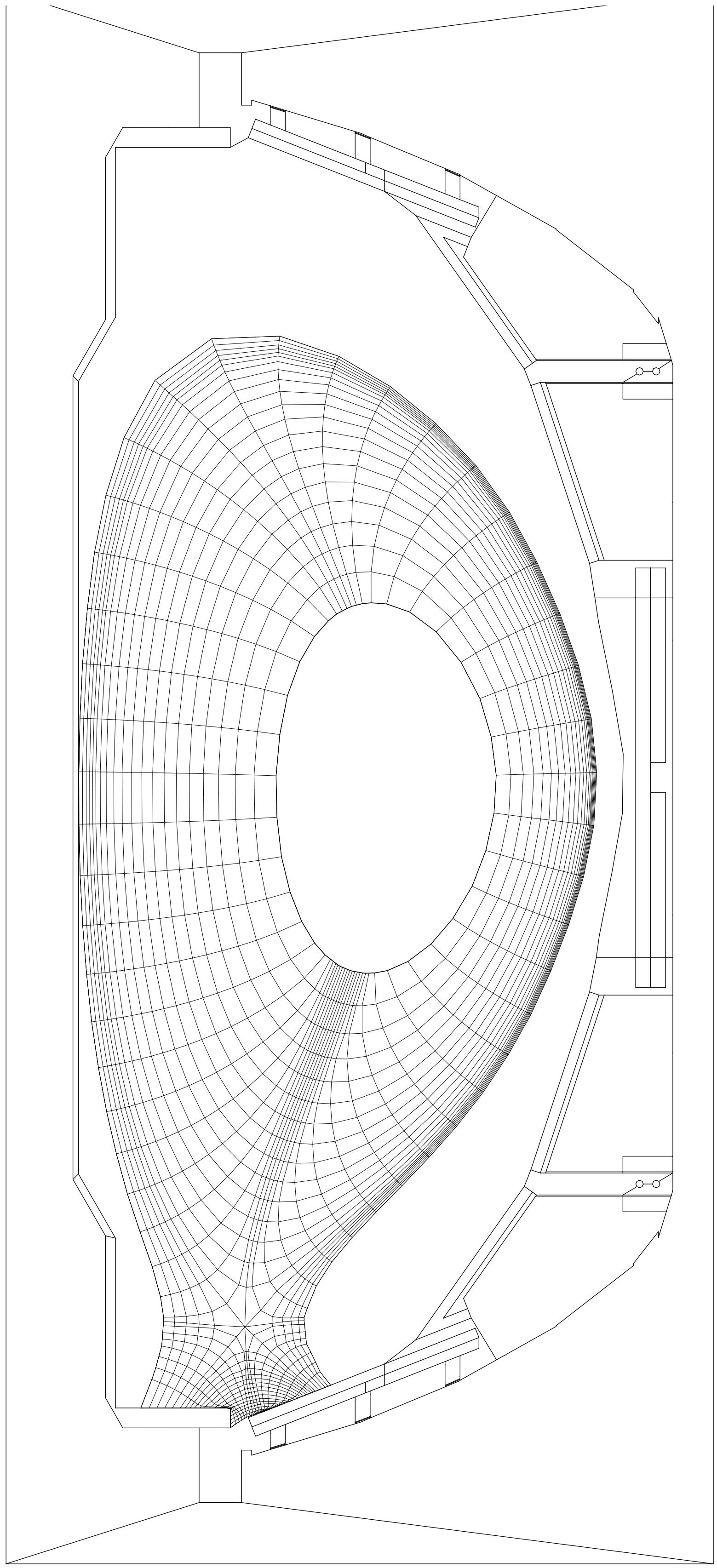
NSTX Simulations

- Neutral pressures surprisingly insensitive to plasma density,
- Begin examining 3-D gas conductance pathways in search of explanations.
- This work will feed into cryopump design effort.
- Have laid out on paper approximate 3-D component configuration,
  - Need more suitable engineering drawings!
- Have done initial axisymmetric simulation,
- Currently building 3-D DEGAS 2 geometry.

NSTX Vacuum Vessel
Full of 3-D Gas Pathways



DG File for DEGAS 2 Simulation of NSTX



Neutral Pressures in Axisymmetric NSTX Simulation