

Development of a High-Mach-Number CFD Model for Neutral Gas Injection in Pegasus-III

C. Billingham^a and R. Raman^a

Dept. of Aeronautics and Astronautics, University of Washington, Seattle, WA USA

Abstract

Transient coaxial helicity injection (CHI), a solenoid-free plasma startup method on Pegasus-III, requires rapid, controlled delivery of neutral deuterium into the vacuum vessel. A time-dependent compressible-flow model was developed in COMSOL Multiphysics® to simulate transport from a 5000 Torr plenum through 25 cm and 100 cm injector pipes into an initially 10^{-4} -Torr chamber at a restricted flow rate of approximately 1800 Torr·L/s. Increasing the pipe length substantially delays gas-front propagation and chamber pressurization, retaining the pressure disturbance near the injector for longer. Knudsen-number diagnostics show that although the undisturbed chamber extends beyond the continuum regime, the injected deuterium rapidly establishes a denser region where continuum modeling is more appropriate. These results quantify the influence of injector geometry on transient gas delivery and provide guidance for CHI injector design and CHI start-up initiation timing on Pegasus-III.

Keywords: CHI, transient gas flow, solenoid-free, plasma startup, helicity

Introduction

Spherical tokamaks (STs) offer a compact approach to magnetic confinement fusion, but their low aspect ratio constrains central-solenoid size and motivates non-solenoidal plasma startup. Transient coaxial helicity injection (CHI), demonstrated on HIT-II, NSTX, and QUEST [1], applies a voltage between electrically isolated electrodes to ionize neutral gas and drive current along open magnetic field lines. Above the “bubble burst” threshold, the resulting Lorentz force expands injector poloidal flux into the vessel; rapid termination of the injector current then permits magnetic reconnection and formation of closed poloidal flux. Pegasus-III, an ST at the University of Wisconsin–Madison, is investigating transient CHI using a double floating-biased electrode configuration.

Successful transient CHI requires rapid establishment of sufficient deuterium density in the injector region while keeping the remainder of the vessel comparatively rarefied. Excess gas can reduce electron temperature, increase radiative losses, and promote undesired electrical breakdown outside the injector. The gas pulse must therefore remain localized during the short CHI discharge. Previous work estimated that approximately 0.5–2.5 Torr·L of deuterium should be delivered as rapidly as possible and identified the advance of low-density gas ahead of the main pulse—the “leading-edge problem”—as an important design consideration for Pegasus-III [2].

The present study uses COMSOL Multiphysics CFD simulations to evaluate deuterium transport from the plenum through 25- and 100-cm delivery pipes into a vessel geometry representative of Pegasus-III. The goal is to determine whether the system can produce a transient region of elevated density near the injector while maintaining substantially lower density elsewhere in the vessel. In the planned Pegasus-III implementation, a piezoelectric valve will throttle the plenum flow to a maximum of approximately **1800 Torr·L/s**; the simulations therefore assess the evolution of the injected gas following valve opening under this flow constraint.

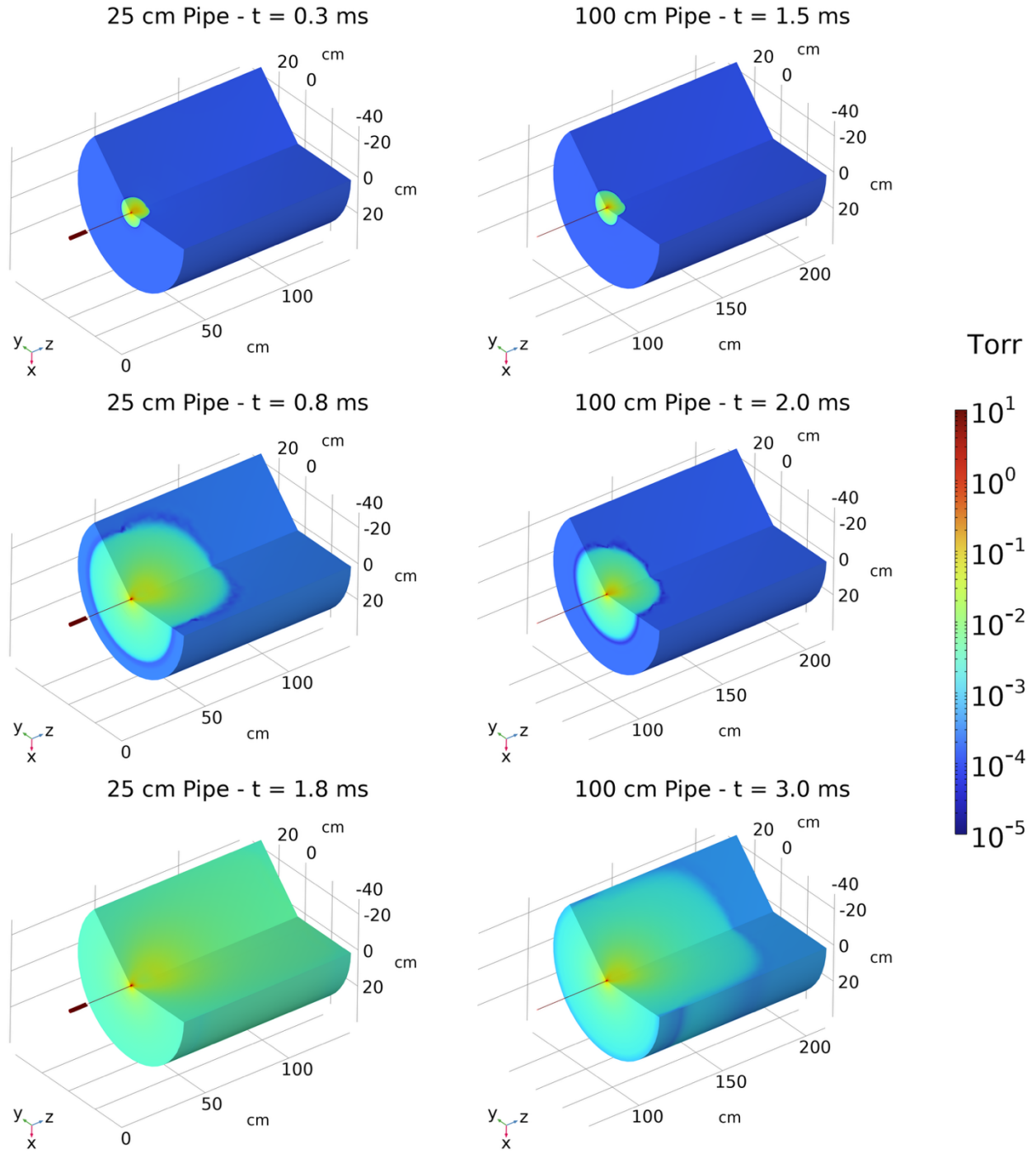


Figure 1. Time evolution of the deuterium pressure distribution for the 25 cm (left) and 100 cm (right) injector-pipe configurations. The 25 cm case is shown at (a) 0.3, (c) 0.8, and (e) 1.8 ms; the 100 cm case at (b) 1.5, (d) 2.0, and (f) 3.0 ms. Under identical plenum and flow-restriction conditions, the 25 cm pipe produces substantially faster expansion of the gas pulse into the chamber, whereas the 100 cm pipe keeps the pressure disturbance localized near the injector for longer.

Experimental Set Up

The gas-injection geometry was modeled in a two-dimensional axisymmetric r - z domain comprising a cylindrical plenum of radius 1 cm and height 10 cm, a 1.5 cm-long nozzle of radius 0.06 cm, and delivery pipes of radius 0.11 cm of lengths 25 or 100 cm. The plenum was initialized at 5000 Torr; the downstream domain, 10^{-4} Torr. The nozzle and pipe used rectilinear meshes with characteristic spacings of approximately 0.03 cm and 0.0275 cm, respectively, while the chamber employed a graded triangular mesh that was refined near the pipe outlet and became progressively coarse farther into the vessel. Transient calculations used an initial and maximum time steps of 10^{-10} s and a 2×10^{-7} s, respectively; the two pipe-length otherwise used the same geometry, mesh strategy, and boundary conditions. Fig. 1 shows the gas expansion into the chamber for both cases.

Governing Equations and Thermodynamic Model

The rapid expansion of deuterium into the evacuated vessel was modeled using the **High Mach Number Flow (HMNF)**, $\mathbf{k} - \epsilon$ interface in COMSOL Multiphysics®, which solves the fully compressible conservation equations for mass, momentum, and energy with a two-equation turbulence closure.

Conservation of mass and momentum are expressed as

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0 \quad (1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \tau_{eff} \quad (2)$$

where ρ , $\mathbf{u}$, and p are the gas density, velocity, and pressure, respectively; τ_{eff} includes both molecular and turbulent viscous stresses. Turbulence is represented by the standard k - ϵ model, with transport equations for turbulent kinetic energy k and dissipation rate ϵ . Their contribution to the effective viscosity is represented by the turbulent viscosity

$$\mu_T = \rho C_\mu \frac{k^2}{\epsilon} \quad (3)$$

Because the gas undergoes strong compressible expansion, the thermal state is obtained simultaneously from the total-energy equation,

$$\frac{\partial (\rho E)}{\partial t} + \nabla \cdot [(\rho E + p) \mathbf{u}] = \nabla \cdot (k_{th} \nabla T) + \nabla \cdot (\tau_{eff} \cdot \mathbf{u}) \quad (4)$$

where E is the total specific energy, T is temperature, and k_{th} is thermal conductivity. Deuterium was treated as an ideal gas with molecular mass $M = 4.028 \text{ g} \cdot \text{mol}^{-1}$, specific heat $c_p = 7.261 \text{ kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$, and heat-capacity ratio $\gamma = 1.397$. The initial gas temperature was 293.15 K. Dynamic viscosity and thermal conductivity were evaluated as temperature-dependent properties using the material relations implemented in COMSOL.

Extreme Pressure-Ratio Initialization

The initial condition spans an exceptionally large pressure ratio between the 5000 Torr deuterium plenum and the 10^{-4} -Torr background gas,

$$\frac{p_{plenum}}{p_{bg}} = \frac{5000}{10^{-4}} = 5 \times 10^7 \quad (5)$$

Direct initialization of this pressure ratio as a sharp Riemann-type discontinuity became numerically unstable, so a smooth initial pressure transition was introduced between the plenum and downstream domain:

$$p_{init}(z) = p_{bg} + \frac{p_{plenum} - p_{bg}}{2} \left[1 - \tanh\left(\frac{z - z_0}{\Delta z}\right) \right] \quad (6)$$

with $z_0 = 10$ cm and $\Delta z = 0.5$ cm. Here, z_0 defines the transition center and Δz its characteristic width. The regularization preserves the prescribed plenum and background pressures away from the transition region while replacing the initial discontinuity with a continuous pressure gradient. The initial velocity was zero throughout the domain. The regularized initial pressure profile is shown in Fig. 2c.

Simulation Results

Transient flow-rate oscillations. The nozzle- and pipe-outlet flow rates in Fig. 2(d) exhibit repeated transient depressions superimposed on the overall gas-delivery trends. Numerical diagnostics showed that these features persist under changes in mesh resolution, time stepping, pressure initialization, and flow formulation including a substantially refined model developed in consultation with COMSOL Technical Support. Their origin could not be conclusively identified; possible causes include transient compressible-wave interactions, geometric effects, and numerical sensitivity associated with the extreme pressure-gradient initial condition. The individual oscillations are not interpreted quantitatively here, but they do not seem to affect the overall system response. The robust large-scale result is that the 100 cm pipe substantially delays gas transport into the chamber, retaining more gas near the injector during the early transient relevant to CHI initiation. **As shown in Fig. 3, this may be advantageous because pressure in much of the vessel remains lower while near the injector it remains higher for longer.**

Continuum-Flow Applicability

Because the chamber is initialized at 10^{-4} Torr, portions of the domain lie outside the continuum-flow regime. To assess the applicability of the High Mach Number Flow formulation, three Knudsen diagnostics were evaluated using the hard-sphere mean free path,

$$\lambda = \frac{k_B T}{\sqrt{2} \pi p d^2} \quad (7)$$

with an effective deuterium molecular diameter of $d = 2.9 \times 10^{-10}$ m. Geometric Knudsen numbers were defined using characteristic lengths of 0.2 cm for the injector pipe and 5 cm for the chamber, while a gradient-length Knudsen number was used to compare the molecular mean free path with the local pressure-gradient length scale.

As shown in Figure 4, the diagnostics show that the undisturbed high-vacuum chamber can enter transitional or molecular-flow conditions, where a Navier–Stokes description is not quantitatively valid. However, the injected deuterium rapidly forms a denser region near the pipe outlet and within the expanding gas front, reducing the local Knudsen number substantially. Figure 3 shows that the principal pressure structures occur in regions where the mean free path is small relative to the local pressure-gradient scale. Accordingly, the HMNF k - ϵ model is interpreted primarily as a continuum approximation of gas transport through the injector and the dense expanding pulse, rather than as an accurate description of the undisturbed rarefied chamber background.

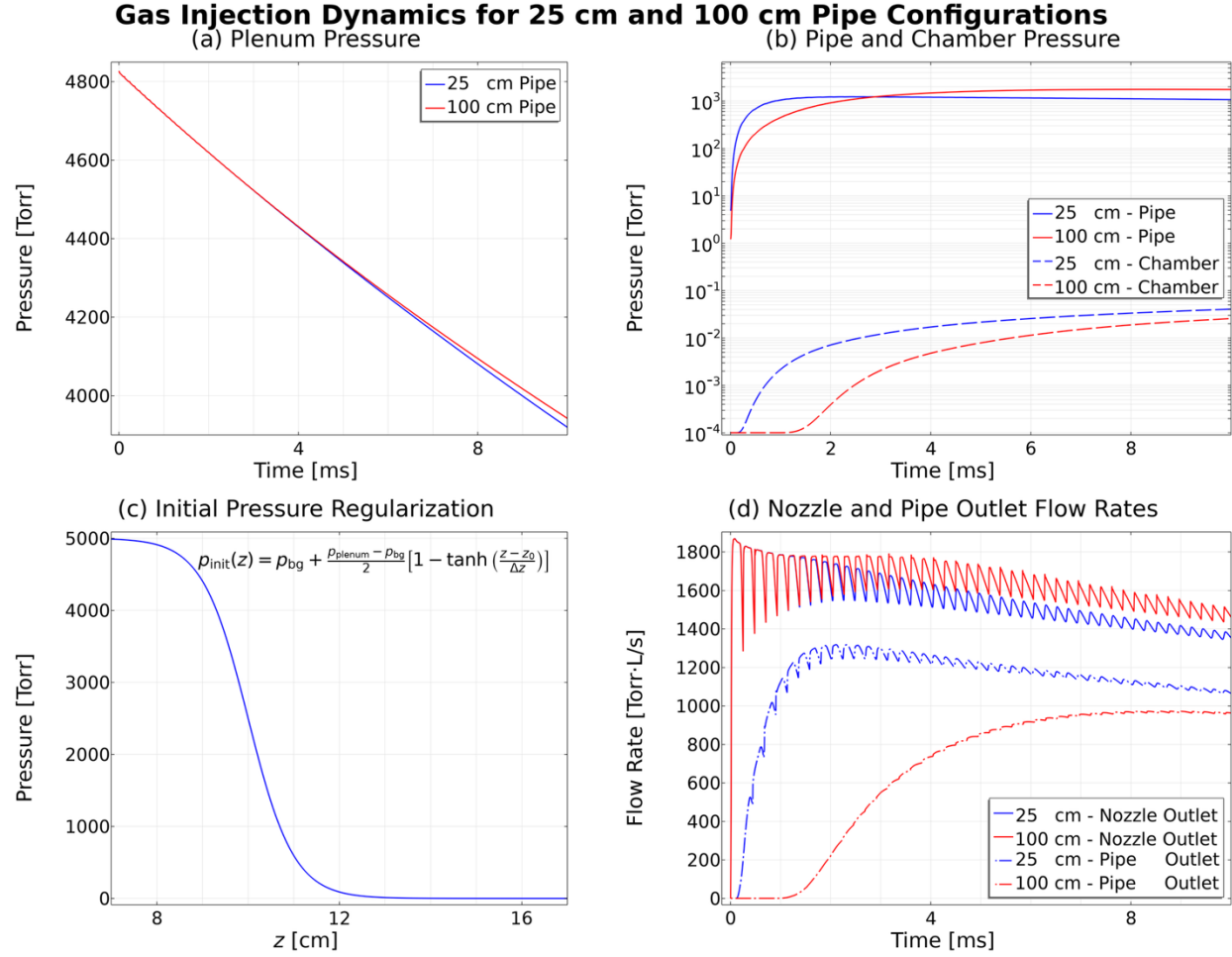


Figure 2. Transient gas-injection dynamics for the 25 cm and 100 cm injector-pipe configurations. (a) Average plenum pressure during the simulated injection. (b) Average pressure in the injector pipe and vacuum chamber. (c) Regularized initial pressure distribution used to transition smoothly from the 5000 Torr plenum to the evacuated downstream domain. (d) Deuterium flow rates at the nozzle and pipe outlets. The longer pipe produces a delayed rise in both chamber pressure and pipe-outlet flow rate compared with the 25 cm configuration.

Conclusions and Future Work

The present work demonstrates that a transient compressible-flow model in COMSOL Multiphysics can resolve the principal features of neutral-deuterium delivery relevant to transient CHI on Pegasus-III. Increasing the delivery-pipe length from 25 to 100 cm substantially delays gas arrival and expansion in the chamber, retaining the pressure disturbance near the injector longer while the shorter pipe pressurizes the chamber more rapidly. Transient oscillations in the calculated nozzle- and pipe-outlet flow rates do not alter this dominant effect of pipe length. Knudsen-number analysis further shows that, while the undisturbed 10^{-4} -Torr chamber lies partly outside the continuum regime, the injected deuterium rapidly forms a denser region where continuum modeling is better justified.

This gas-injection model is an initial element of a broader multi-physics representation, or digital twin, of transient CHI on Pegasus-III. The next stage is to reproduce the injector and vessel geometry more faithfully and couple the neutral-gas calculation to the time-dependent electromagnetic drive between the

injector electrodes. COMSOL's electromagnetic capabilities can represent the applied fields and external circuit, enabling subsequent modeling of deuterium ionization, plasma formation, and helicity injection. Ultimately, this will require a self-consistent magnetohydrodynamic treatment.

Pressure Evolution in the Vacuum Chamber

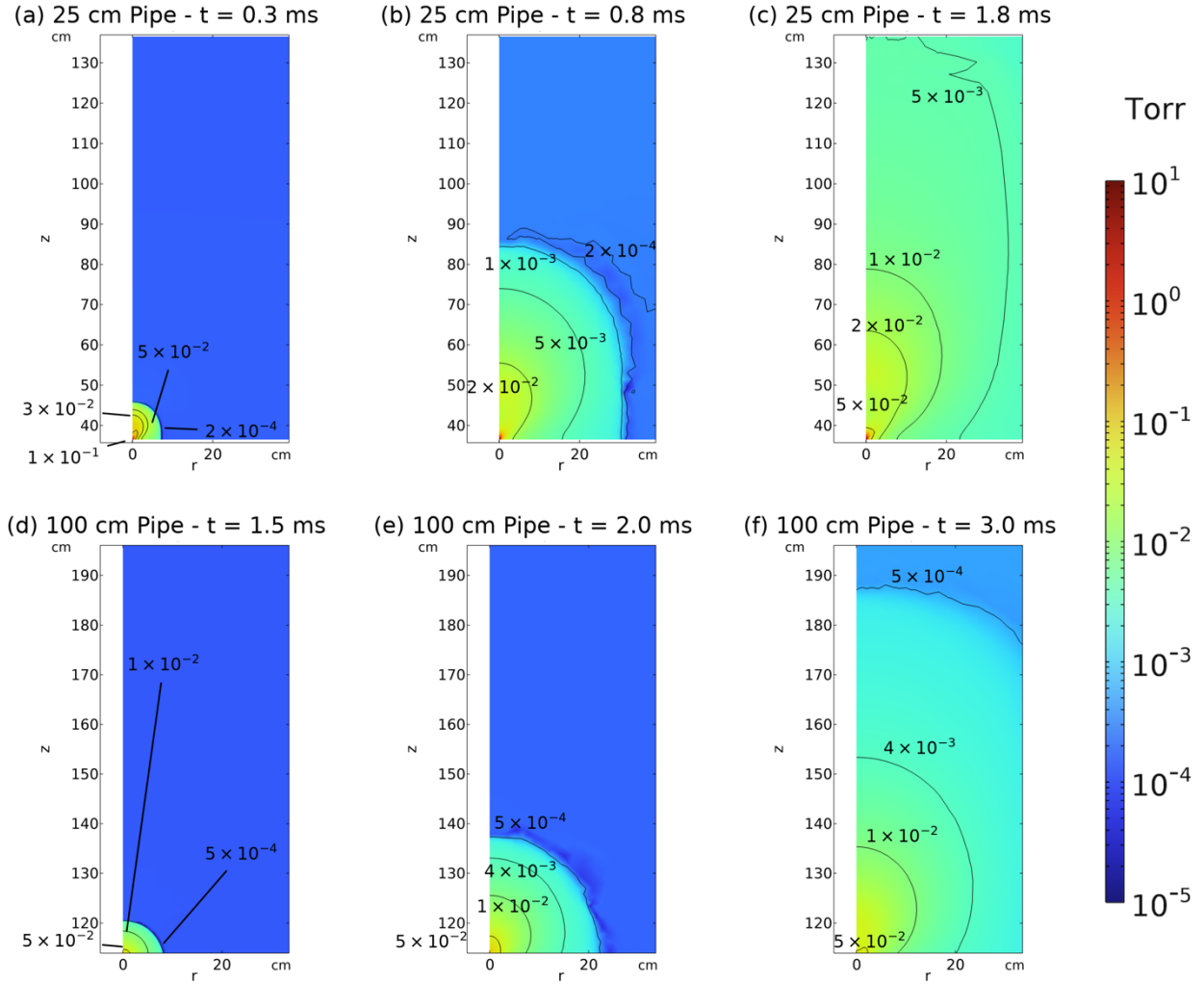


Figure 3. Pressure evolution in the vacuum chamber for the 25 cm and 100 cm injector-pipe configurations. The top row shows the 25 cm case at (a) 0.3 ms, (b) 0.8 ms, and (c) 1.8 ms; the bottom row shows the 100 cm case at (d) 1.5 ms, (e) 2.0 ms, and (f) 3.0 ms. Pressure is shown in Torr on a logarithmic color scale, with selected pressure contours overlaid to highlight propagation of the pressure disturbance through the chamber.

A longer-term objective is to implement CHI-relevant physics and numerical methods from established tokamak MHD tools within COMSOL. TSC evolves an axisymmetric free-boundary plasma coupled to external circuits and controls, while M3D-C1 solves extended-MHD equations for fusion-plasma equilibrium and dynamics. Reproducing selected functionality within a customized COMSOL framework could couple gas injection, electromagnetics, ionization, plasma dynamics, and engineering models in a common multi-physics environment tailored to transient CHI on Pegasus-III.

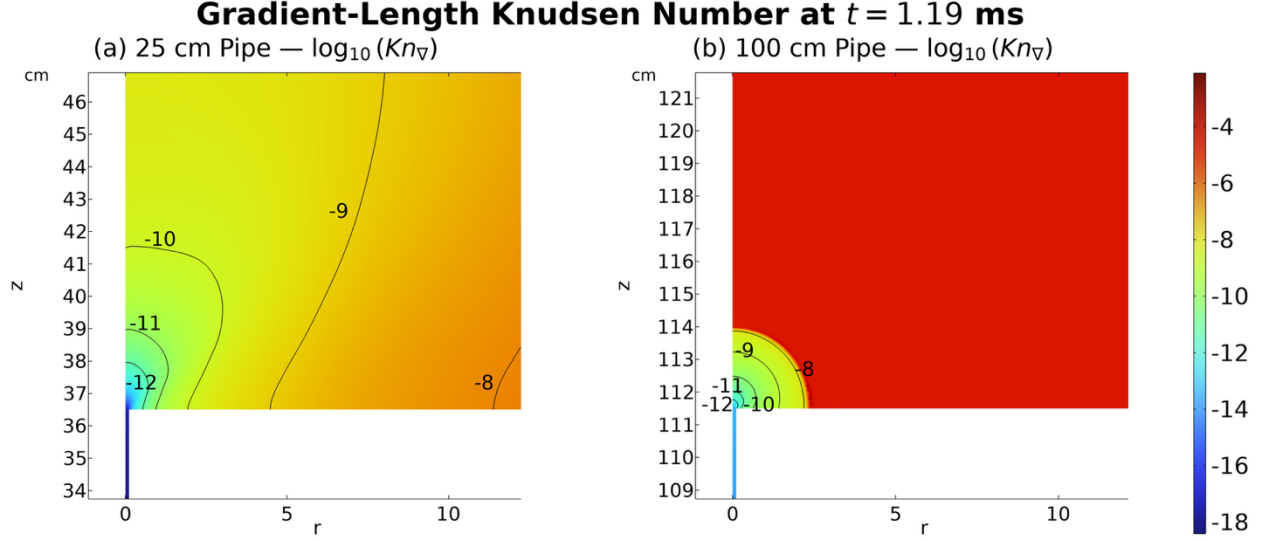


Figure 4. Gradient-length Knudsen number distributions at $t = 1.19$ ms for the (a) 25 cm and (b) 100 cm injector-pipe configurations. The plotted quantity is $\log_{10}(Kn_{\nabla})$, where Kn_{∇} compares the molecular mean free path with the local pressure-gradient length scale. As a guide, continuum flow corresponds approximately to $Kn_{\nabla} < 0.01$ [$\log_{10}(Kn_{\nabla}) < -2$], with $0.01 \lesssim Kn_{\nabla} \lesssim 0.1$ representing the slip regime, $0.1 \lesssim Kn_{\nabla} \lesssim 10$ transitional flow, and $Kn_{\nabla} \gtrsim 10$ molecular flow. The values shown near the injector exit are therefore well within the continuum regime, consistent with the increased density of the injected deuterium.

Such an integrated modeling capability may also have relevance beyond Pegasus-III. Following experimental demonstration and optimization of transient CHI on Pegasus-III, an important longer-term question is whether non-solenoidal startup techniques can contribute to the startup strategy of future spherical-tokamak power plants. The UK STEP program is developing a prototype spherical-tokamak fusion power plant, with a stated goal of demonstrating net energy and a path toward commercial fusion power [3]. COMSOL-based multi-physics modeling is already being used in the STEP program for electromagnetic and thermal analyses of its superconducting magnet system during plasma-initiation scenarios. Thus, development of a validated COMSOL-based transient-CHI model on Pegasus-III could provide both a tool for near-term injector design and a foundation for examining how CHI-related startup concepts might eventually be integrated into the broader multi-physics design environment of next-generation spherical tokamaks.

References

1. R. Raman, *et al.* (2025). Design considerations for optimizing the transient CHI injector on QUEST, *Plasma Physics and Controlled Fusion* **67** (2025) 095007
2. C. Billingham, *et al.* (2026). Considerations for Transient CHI Gas Injection System Design for Pegasus-III. *Fusion Science and Technology*, **82**(6), 1220–1236.
3. H. Meyer (2024). Plasma burn—mind the gap. *Philosophical Transactions of the Royal Society A* **382** (2024) 20230406.

Acknowledgements

We wish to express our sincere gratitude to Dr. Scott Dossa from COMSOL’s technical support team for his assistance. This work is supported by US Dept. of Energy Grant # DE-SC00119415.