PEGASUS-III
Experiment

Design Considerations for a Transient CHI Gas Injection System for PEGASUS-III

[1]R. Raman,[1]**J.A. Rogers***, [2]J.A. Reusch, [2]S.J. Diem

[1]University of Washington, Seattle, WA, USA
[2]University of Wisconsin, Madison, WI, USA
*Presenter

64th Annual Meeting of the APS Division of Plasma Physics, Spokane, WA
Presentation CP11.00053
17 October 2022

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

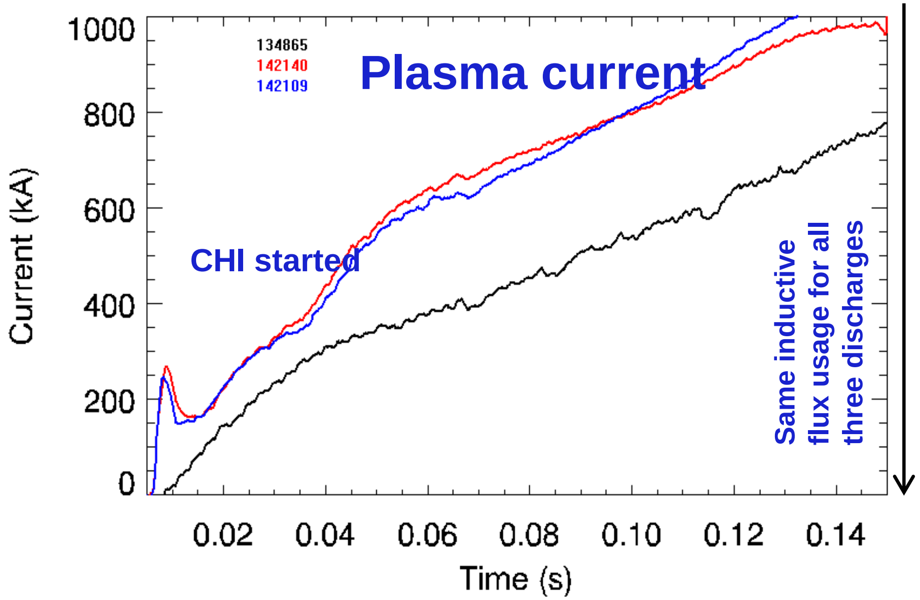
Abstract

Transient Coaxial Helicity Injection, a method first developed on the small HIT-II experiment and then validated on the much larger NSTX device is a method to initiate an inductive-like tokamak plasma discharge without reliance on the central solenoid. In both these devices, toroidal ceramic insulators were used to electrically separate the inner and outer vessel components so that magnetic flux that initially connects the inner and outer vessel components could be grown into the vessel using J x B forces to generate a closed magnetic field line configuration. In reactors, the installation of large toroidal insulators as part of the vacuum vessel boundary may not be possible. To address this design requirement, a first of its kind, a floating double biased reactor-relevant CHI configuration is being developed for PEGASUS-III. An equally important requirement for successful transient CHI discharge initiation is the need for injecting a relatively small amount of gas while simultaneously satisfying the requirements for gas breakdown in the injector region, while avoid breakdown in other parts of the vessel. This stringent requirement generally requires that a small gas plenum be located close to a toroidal gas manifold in the injector region in a high gas conductance configuration. Design aspects for a transient CHI gas injection system for the PEGASUS-III geometry will be described.

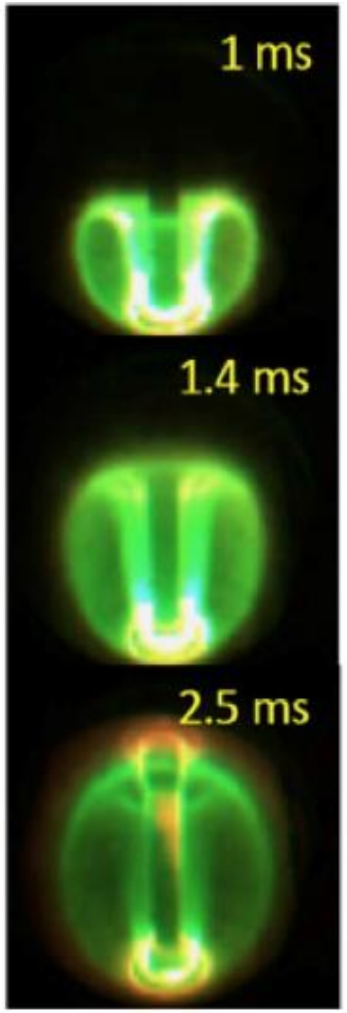
Work supported by US DOE grants DE-SC0019008 and DE-SC0020402, and DE-SC0019415

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

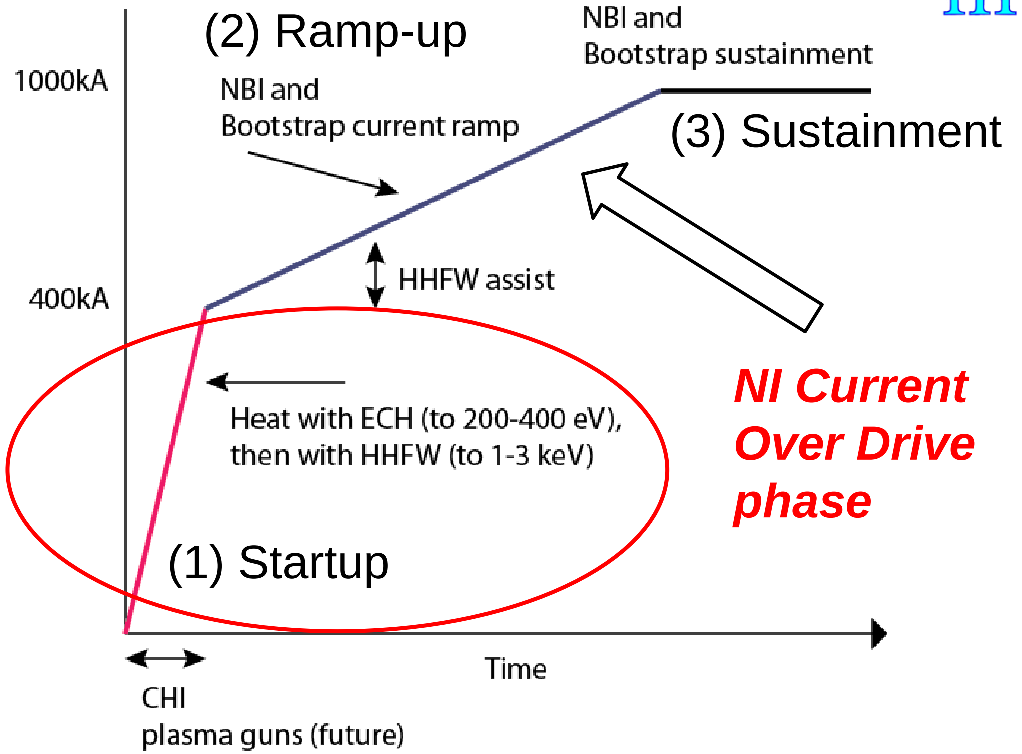
Plasma start-up in a ST involves three phases 1) solenoid free start-up, 2) non inductive current ramp, 3) non inductive current sustainment



- Transient Coaxial Helicity Injection on NSTX
  - 0.2 MA start-up currents ramped to 1 MA with inductive flux savings



Fast camera images of T-CHI discharge evolution in NSTX

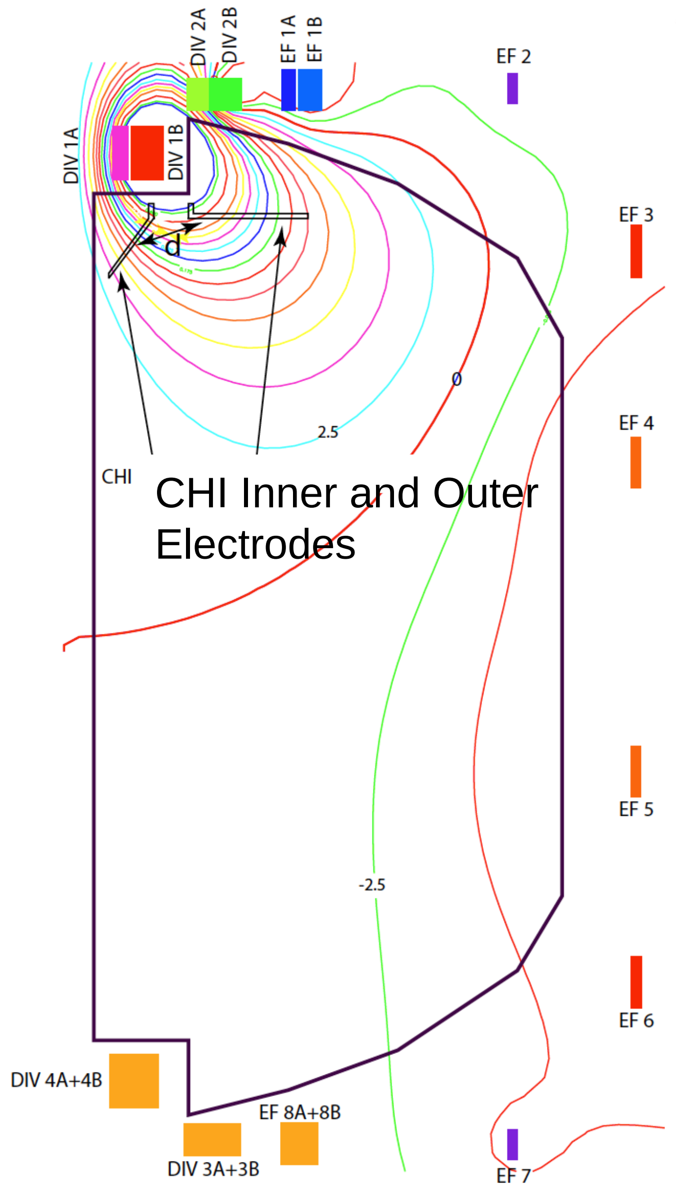


The three phases of plasma startup and sustainment

NSTX-U strategy
Poli et al, NF 55 (2015) 123011

Transient CHI Research Plan on PEGASUS-III

- Develop and test a double biased electrode configuration
  - Clearly defines current path
  - First ever test of concept to better control absorber arcs
- Initiate Transient CHI discharge and optimize it to understand requirements for implementing it on NSTX-U
  - Quantify the range of the flux footprint width parameter 'd' that maximizes conversion of open flux to closed flux
  - Extent of injector current overdrive that is possible in a double biased configuration
  - Study the requirements for CHI insulator gap location
  - Compare CHI discharge to MHD simulations
  - Heat CHI plasma using RF waves
  - Generate currents up to the external PF coil limits (~300kA)
- Drive a T-CHI discharge using LHI to study synergisms with LHI and EBW (eventually with ECH)



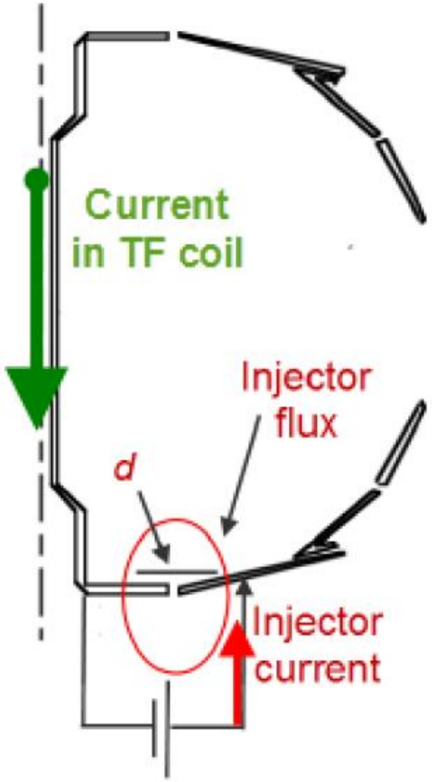
Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Scaling Relations for Transient CHI Based on Experimental Results From HIT-II, NSTX, and TSC Simulations

- Injector current* I_{inj} must meet *bubble-burst condition* for plasma to expand from injector to main vessel

- Toroidal current* generation is proportional to the ratio of toroidal flux ψ_{tor} to injector flux ψ_{inj}

- Capacity to generate plasma current I_p is proportional to ψ_{inj}



$$I_{\rm inj} \geq \frac{2\psi_{\rm inj}^2}{\mu_0^2 d^2 I_{\rm TF}}$$

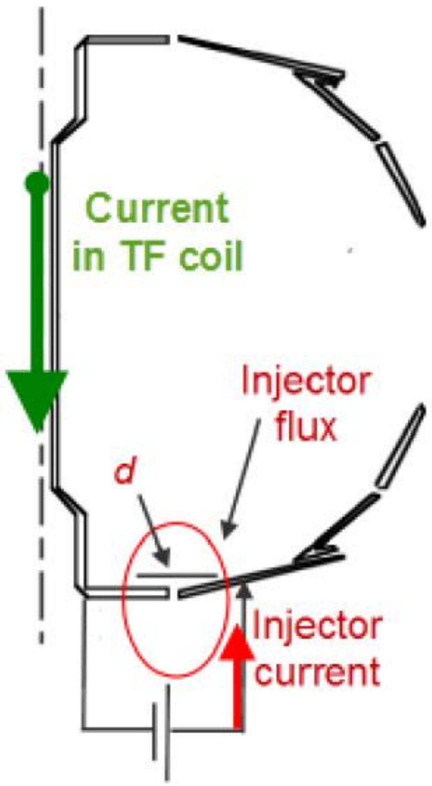
$$I_{\rm p} \leq I_{\rm inj}\frac{\psi_{\rm tor}}{\psi_{\rm inj}}$$

$$I_{\rm p} = \frac{2\psi_{\rm pol}}{\mu_0 R_{\rm maj} l_i} \qquad \psi_{\rm pol} \leq \psi_{\rm inj}$$

Department of Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

* T.R. Jarboe, Fusion Tech. 15, 7 (1989)

Studies on PEGASUS-III Will Optimize CHI by Improved Quantification of Scaling Parameters in Support of Future Studies on NSTX-U



$$I_{\mathrm{inj}} \geq \frac{2\psi_{\mathrm{inj}}^2}{\mu_0^2 d^2 I_{\mathrm{TF}}}$$

$$I_{\mathrm{p}} = \frac{2\psi_{\mathrm{pol}}}{\mu_0 R_{\mathrm{maj}} l_i} \qquad \psi_{\mathrm{pol}} \leq \psi_{\mathrm{inj}}$$

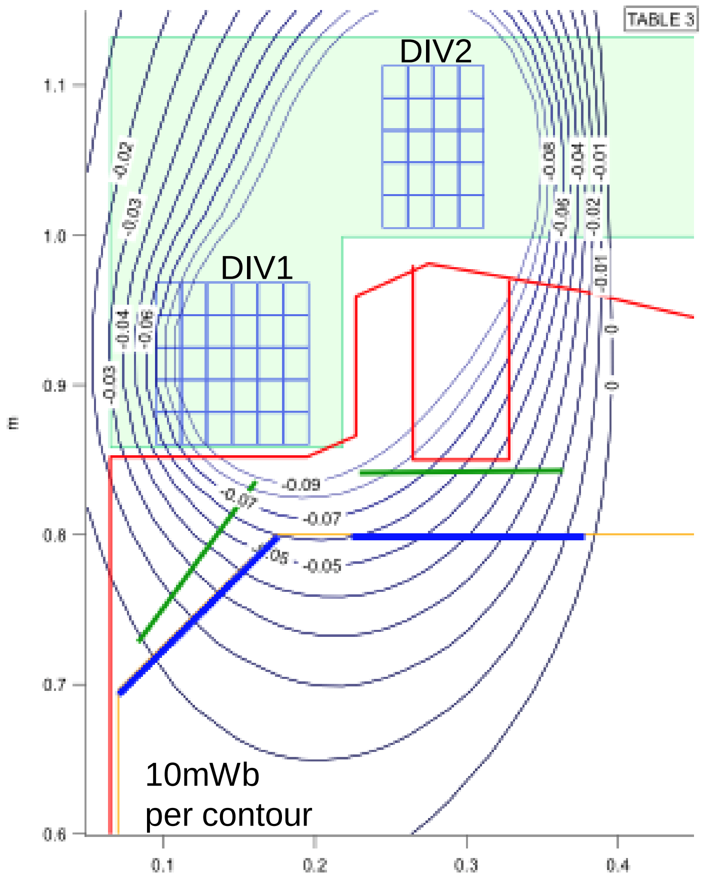
Parameter ‘d’, the injector flux footprint width, strongly determines required injector current and needs improved characterization

The attained plasma current is dependent on the plasma internal inductance, which is controlled by the edge current carrying open flux during CHI discharge initiation

External flux shaping coils will control the parameter ‘d’ and the width of the edge current channel

Close positioning of the divertor coils to the CHI electrodes would permit these important parameters to be studied on PEGASUS-III

Initial Studies to be Conducted with 10 to 25 mWb Flux Injection (~150 kA Current Generation)



DIV1/DIV2 = 16 kA
EF1-3 = 14.5 kA

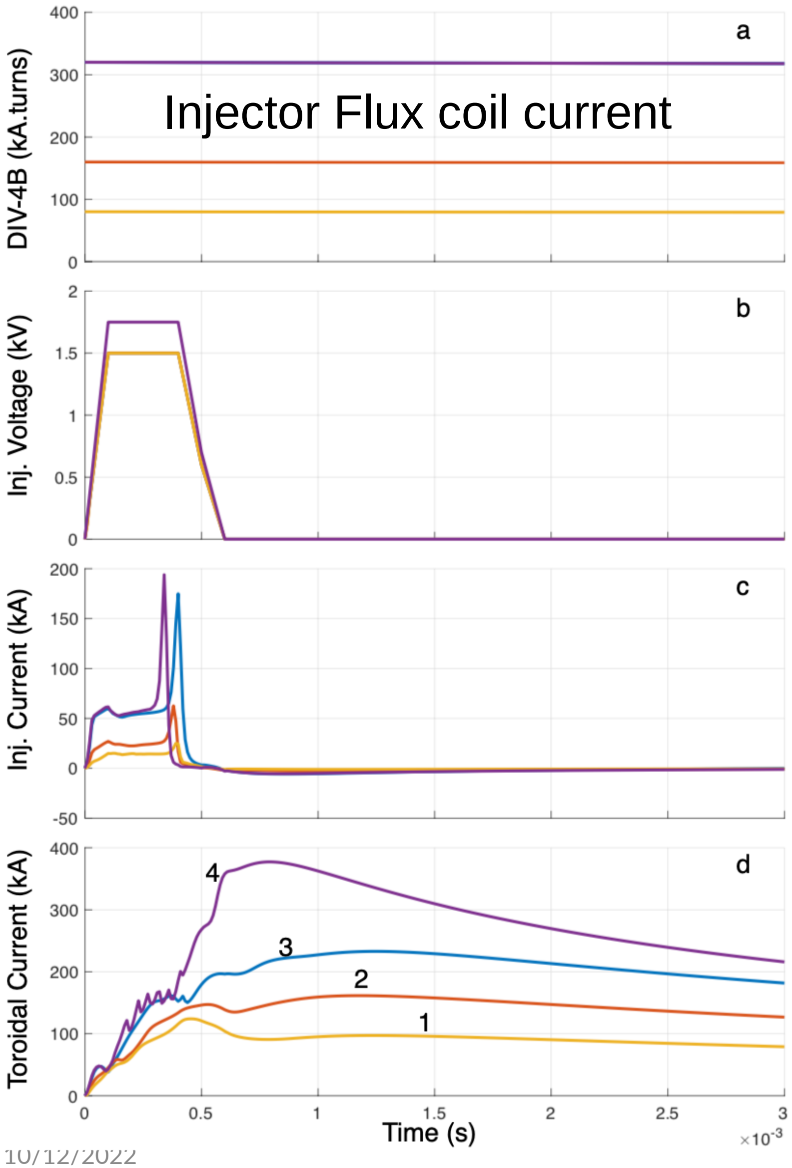
ψ_{inj} ~50mWb

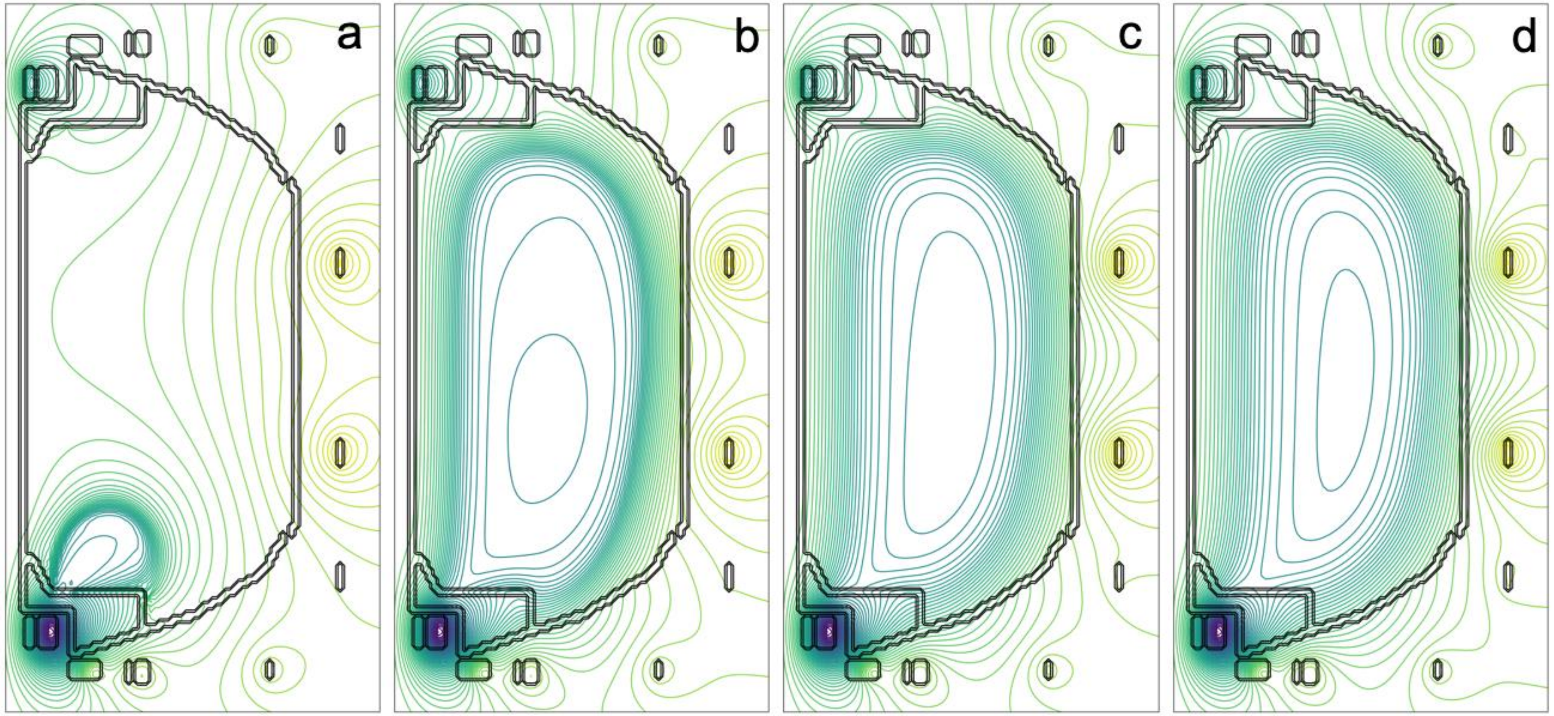
Ip (kA):	150.00
Rm (m):	0.45
B_T (T):	0.51
B_T @ CHI location (T):	0.82
Bt multiplier factor:	1.61
l_i - Plas normalized Inductance:	0.30
Enclosed Polo flux (mWb):	12.72
Flux conversion efficieny:	0.70
Injector flux (mWb):	18.18
Itf (kA):	1152.00
footprint width ‘d’ - (cm):	10.00
Injector Current (kA):	22.60
Plasma Inductance (uH):	0.08
Plasma inductive energy (kJ):	0.95

Increasing ‘d’ would allow more flux to be injected at same level of injector current

Department of Engineering Physics
UNIVERSITY OF WISCONSIN-MADISON

TSC Simulations of Transient CHI Startup on PEGASUS-III

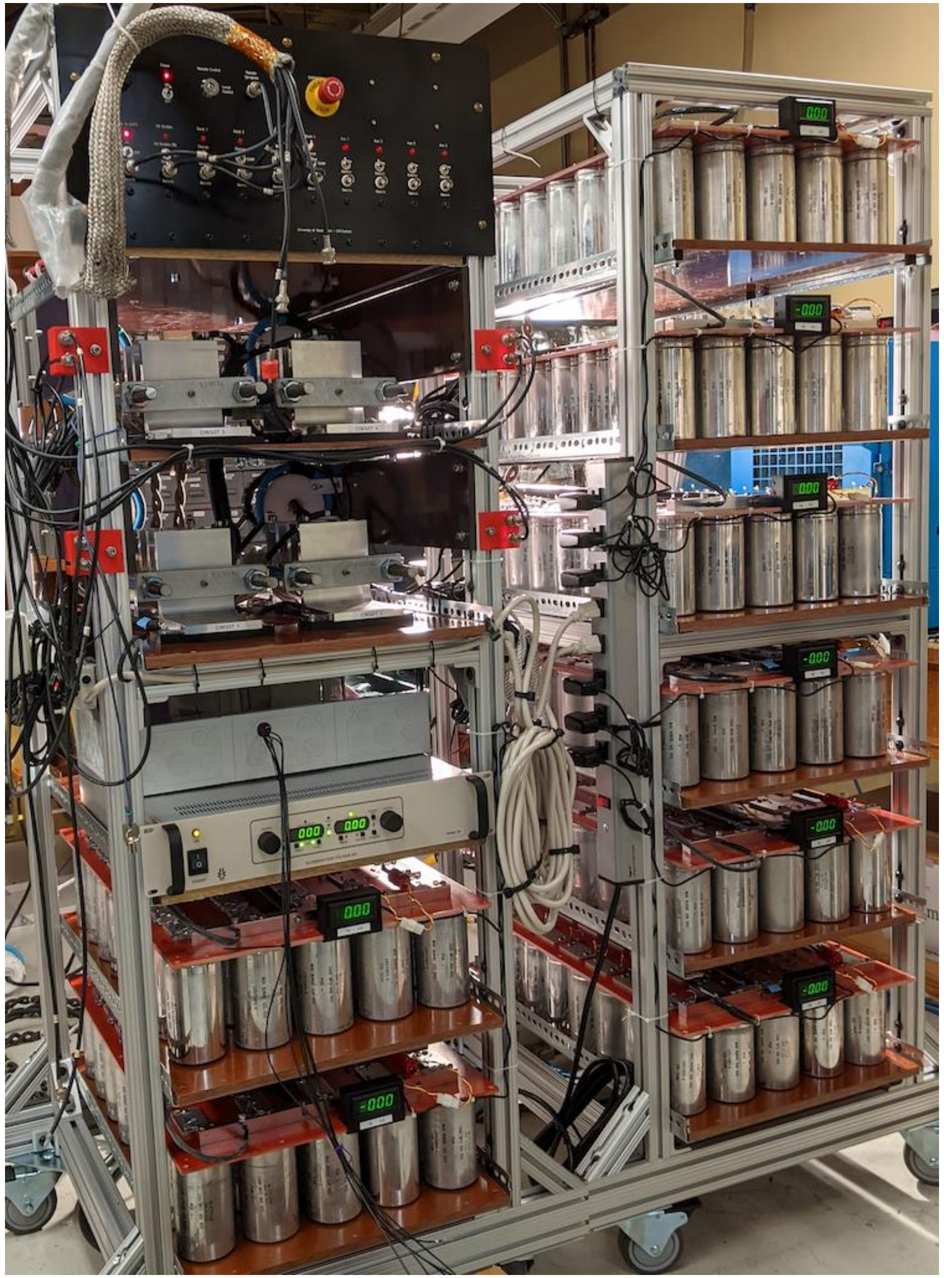


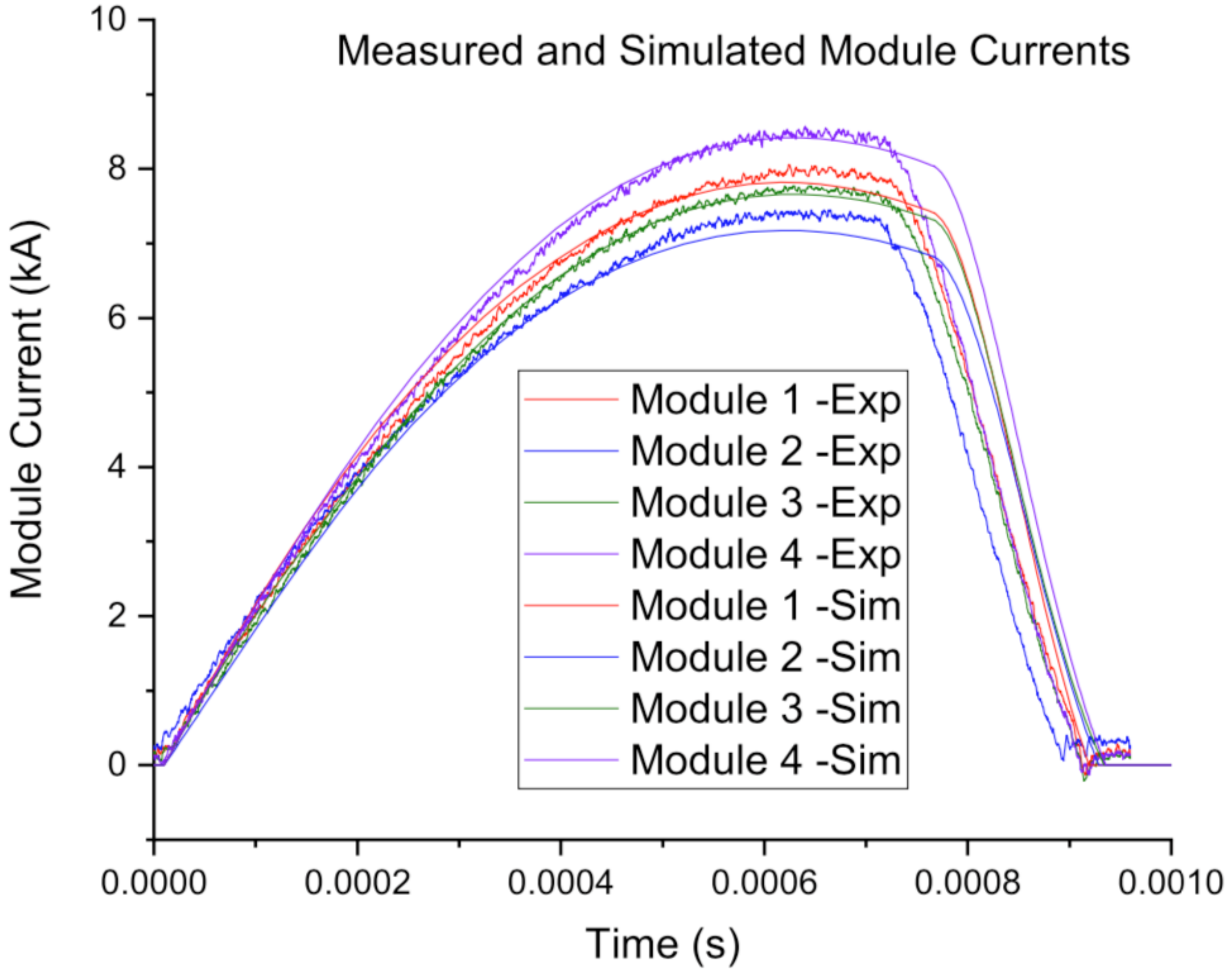


Poloidal flux at (a) t=0.1 ms, (b) 1 ms, (c) 2 ms, and (d) 3 ms for Case 2

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Transient CHI Power Supply

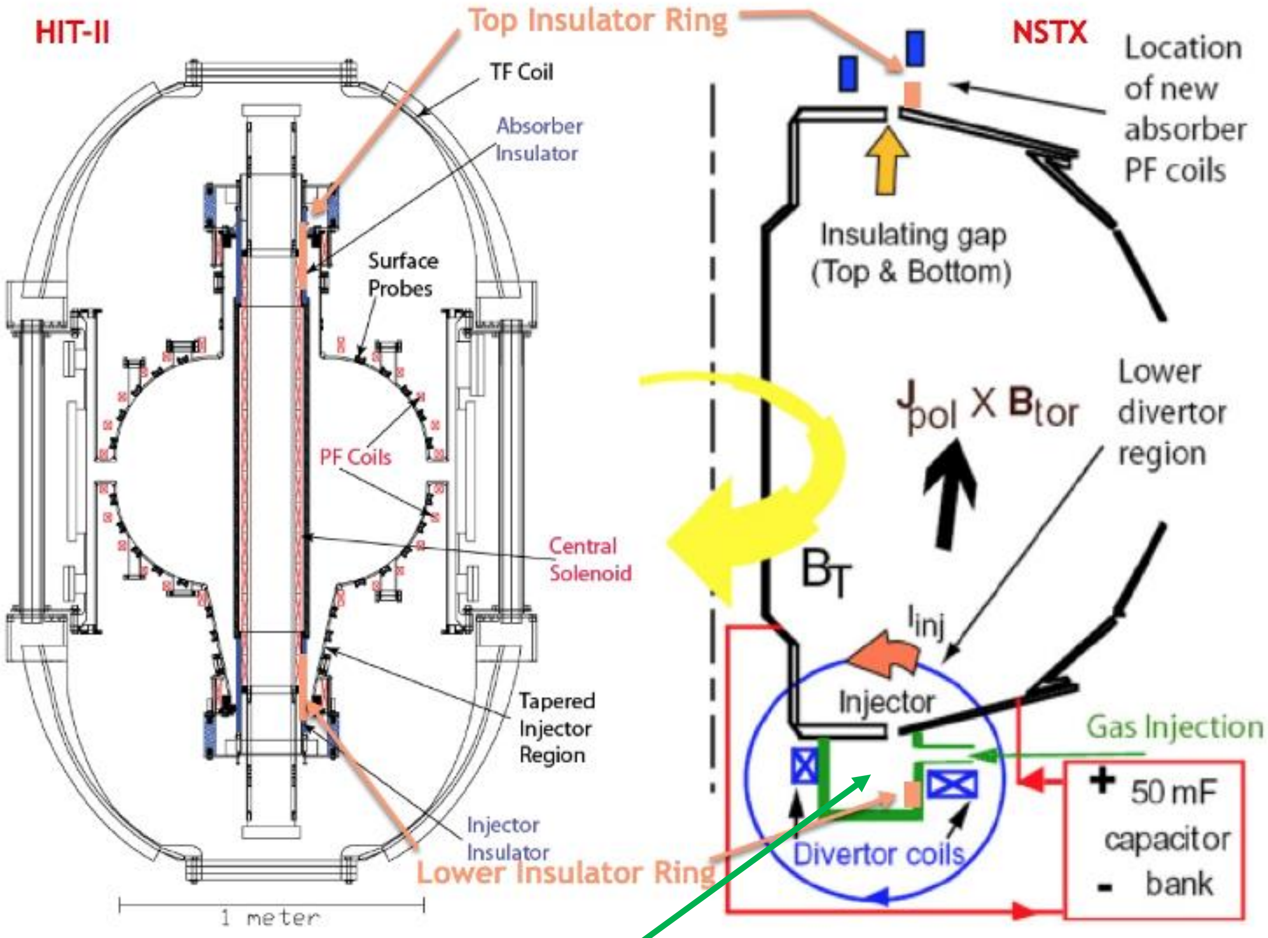




32 kA @ 2kV (as tested)
Potential for 55 kA @ 3kV and 6 modules

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

HIT-II and NSTX Used Insulators as Part of the Vacuum Break, QUEST Uses a Single Biased Electrode

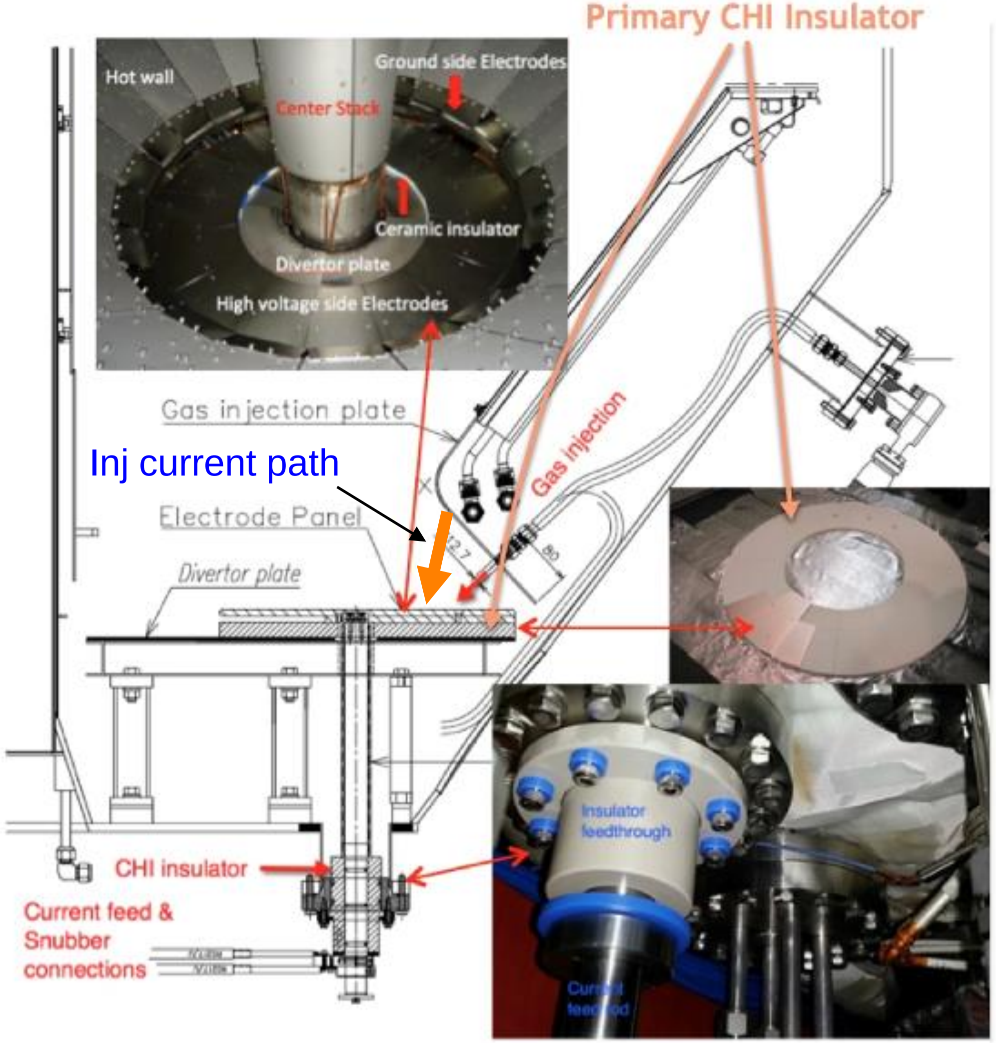


R/a = 0.3/0.2m, B_T = 0.5T

R/a = 0.86/0.66m, B_T = 0.55T

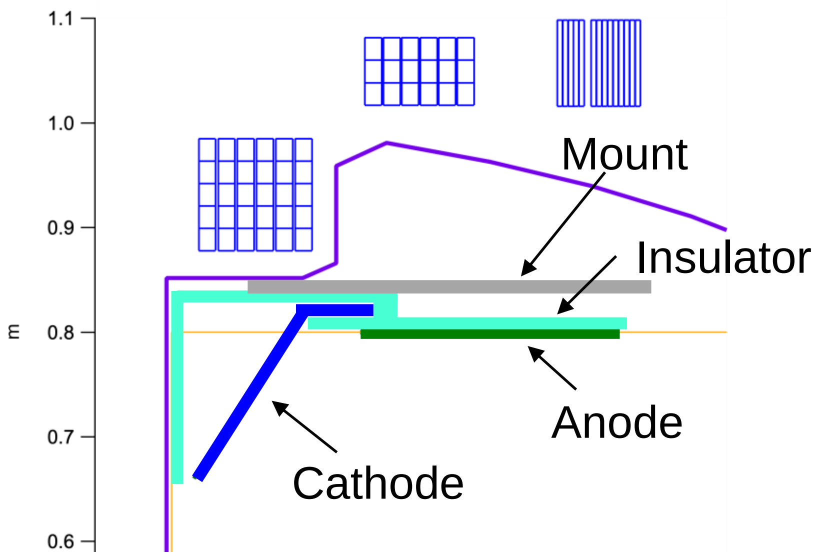
Gas manifold

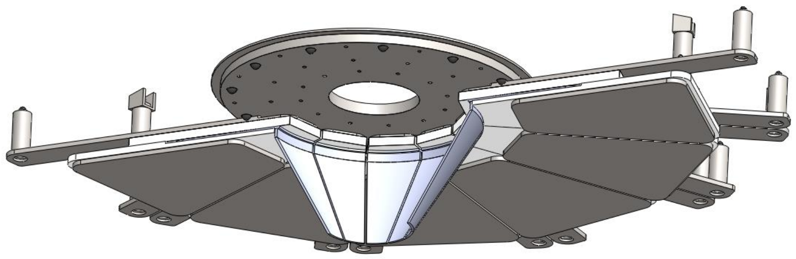
QUEST (Kyushu University, Japan)



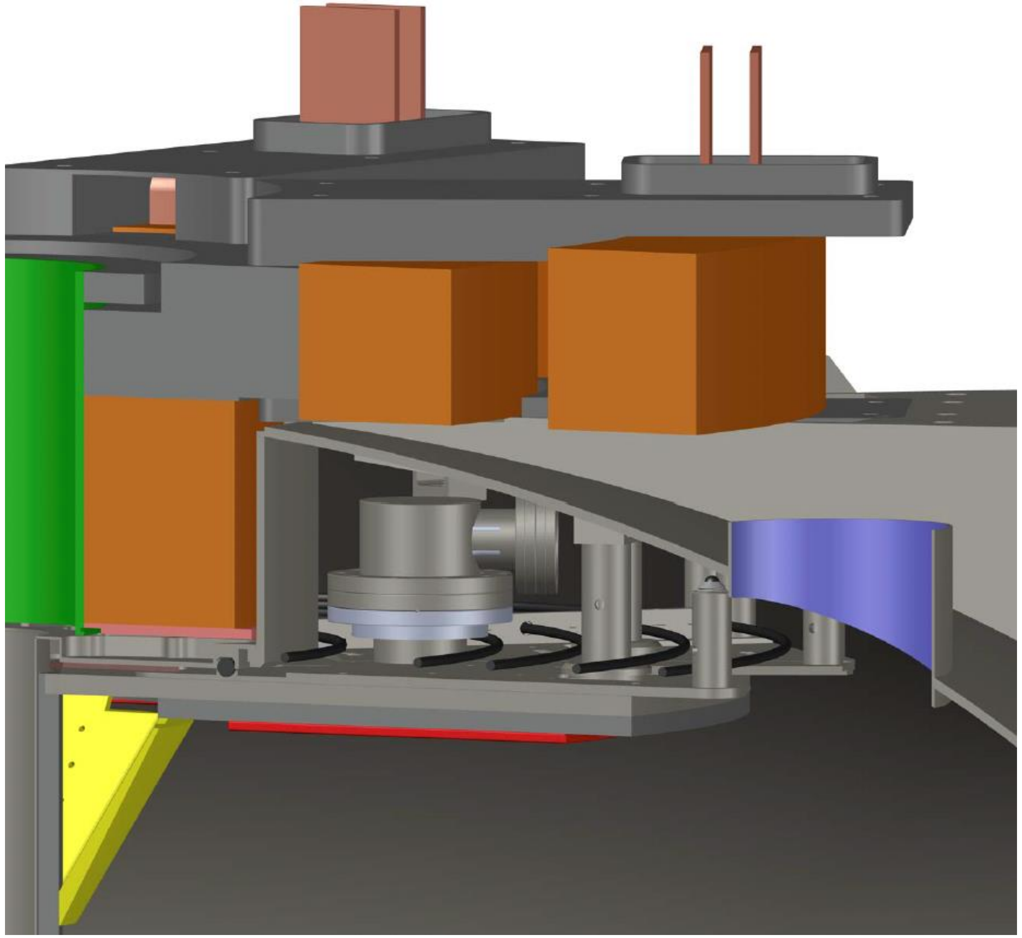
Robust Feeds Under Design to Provide Symmetric Low Inductance Path for CHI and LHI Injector Currents

2D Sketch of Electrode Plate Concept





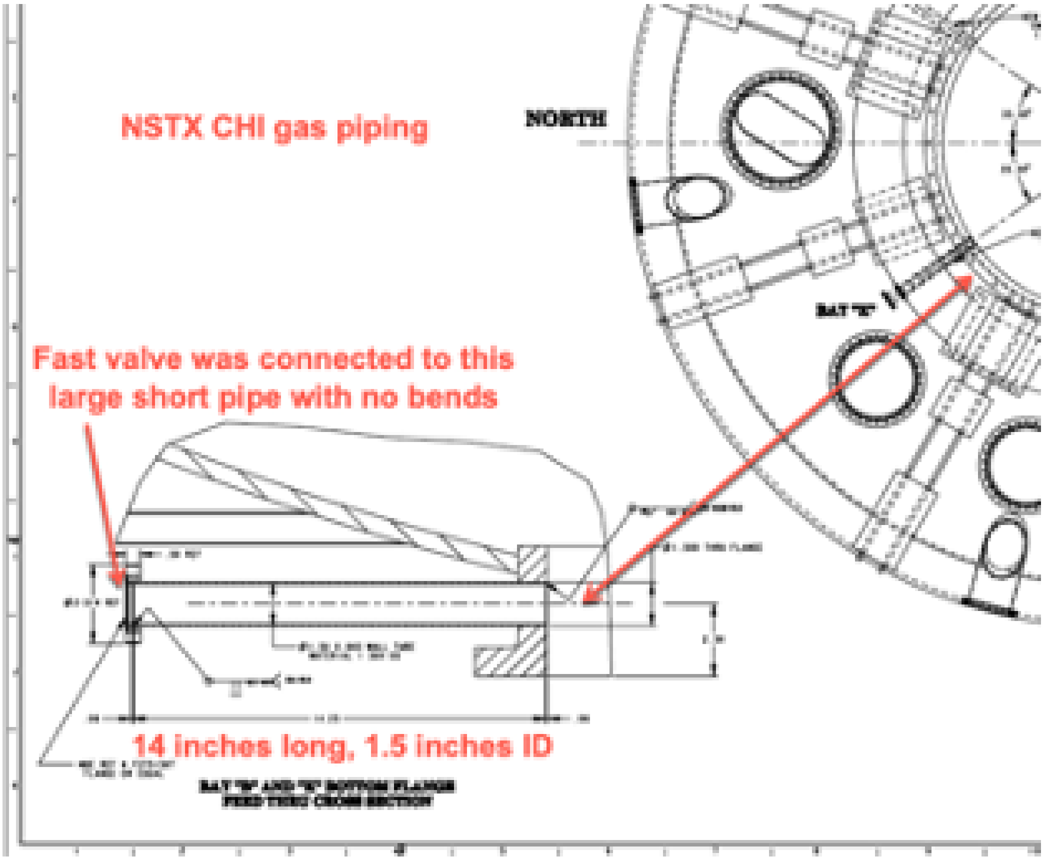
3D Sketch of Electrode Plate Concept

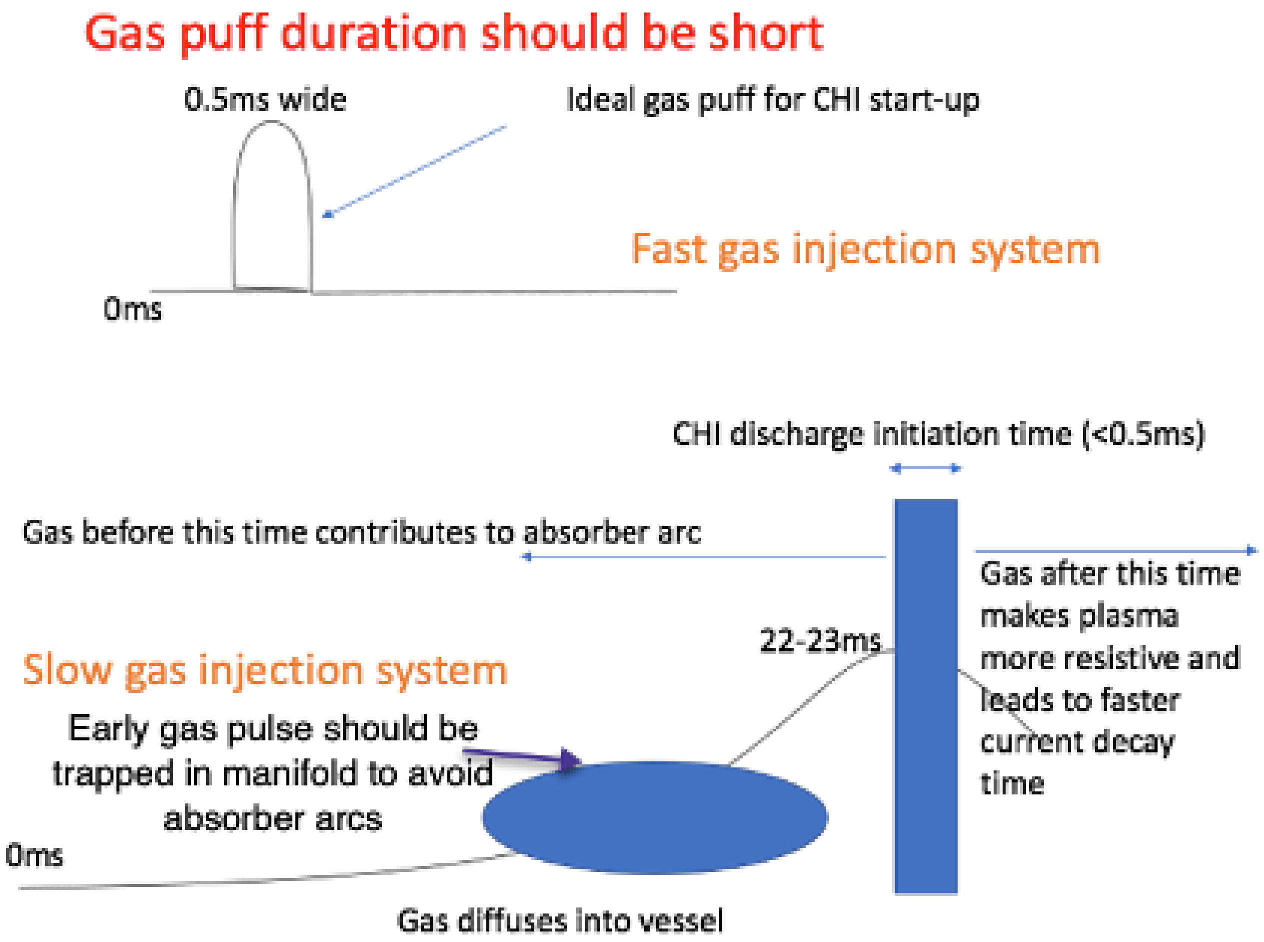


Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Transient CHI gas injection system needs to deposit needed gas on a short time scale to avoid absorber arcs and limit plasma density increase

NSTX Gas Injection Configuration

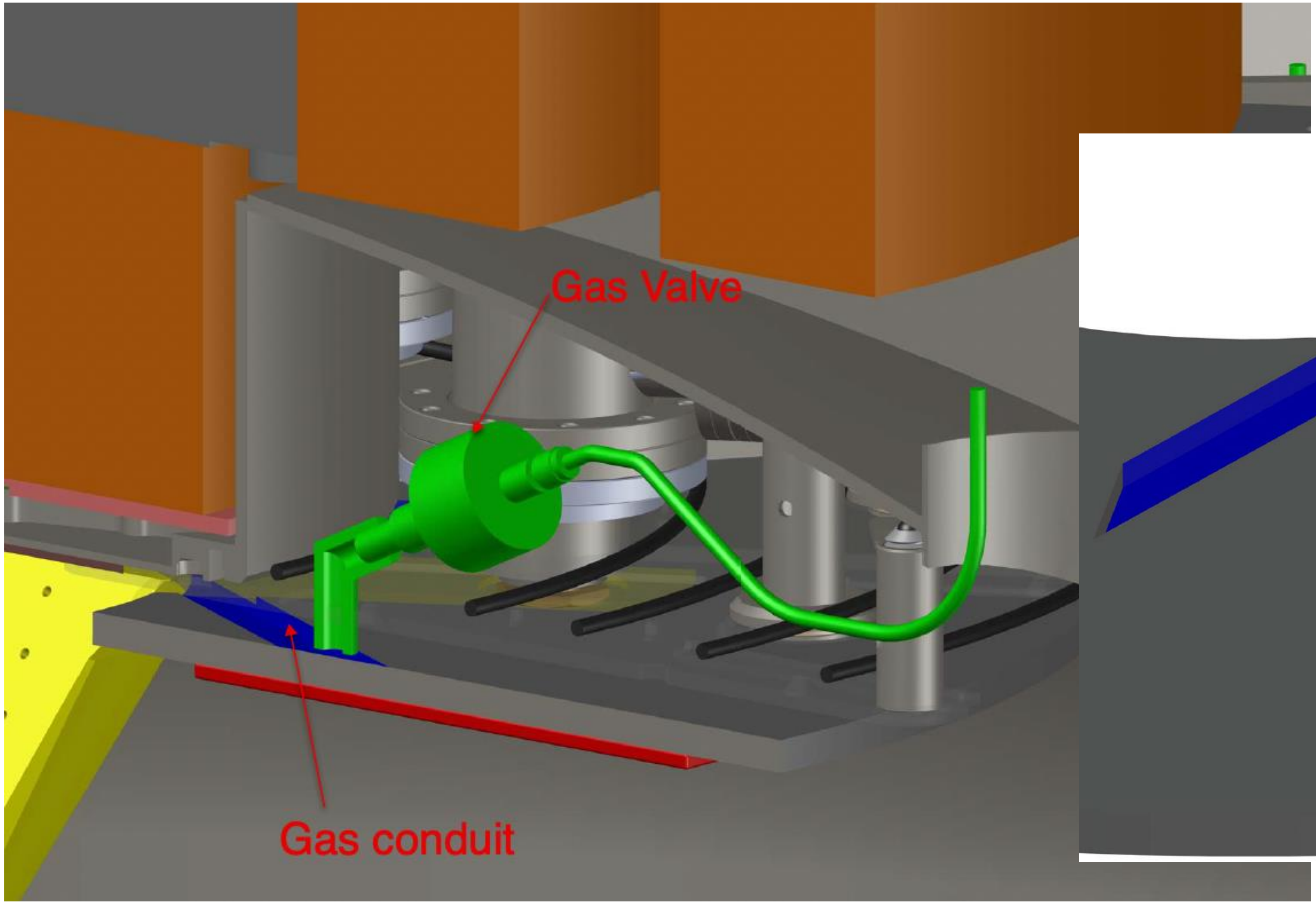


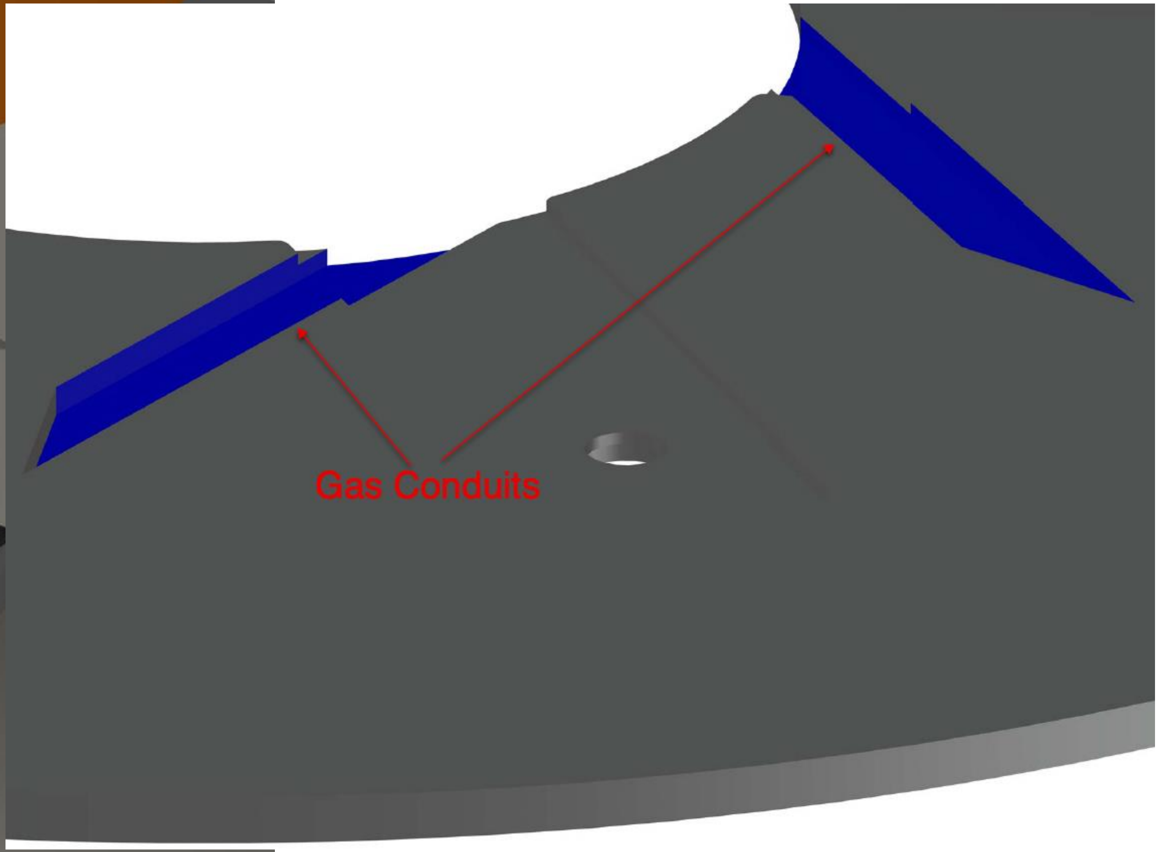


See NSTX gas manifold on slide 10

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

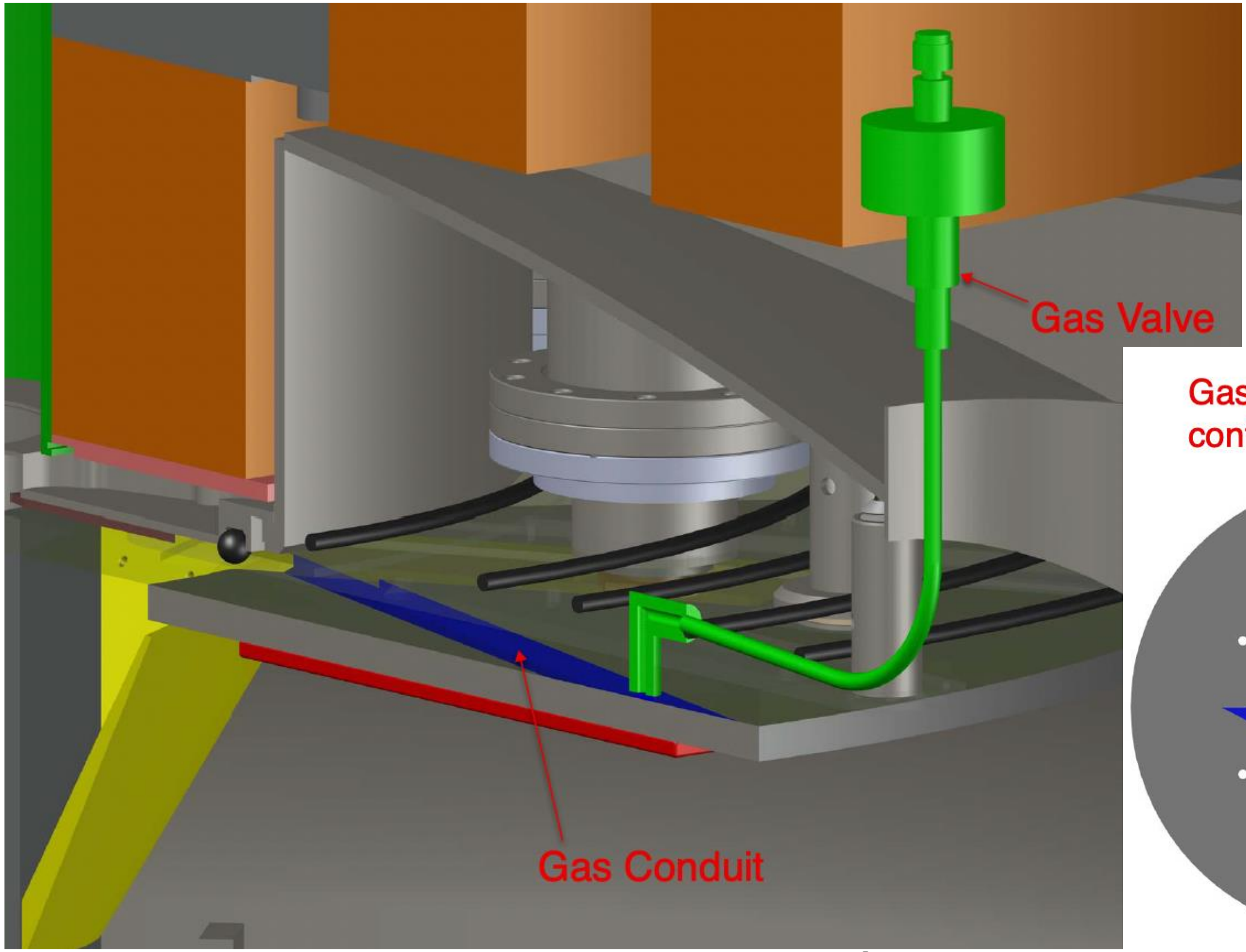
High Conductance Gas Injection with Gas Valve Positioned inside PEGASUS-III Dome





Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Low Conductance Gas Injection with Gas Valve Positioned outside PEGASUS-III Dome

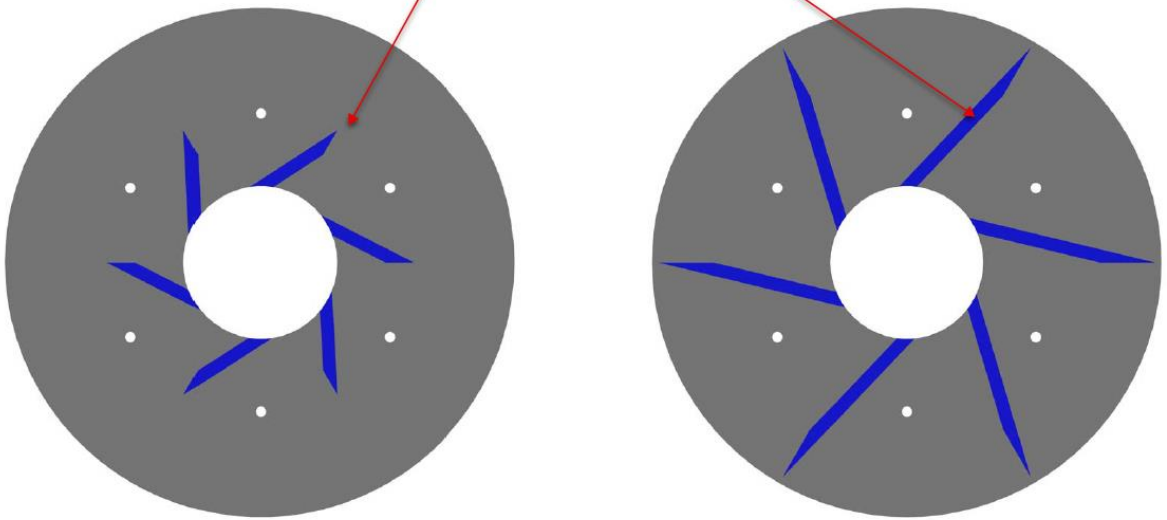


Conduit dimensions:

Low conductance:
2.45 cm wide x 7.6mm deep x 31cm

High conductance:
2.45 cm wide x 7.6mm deep x 16cm

Gas conduits for high (left) and low (right) gas conductance configurations

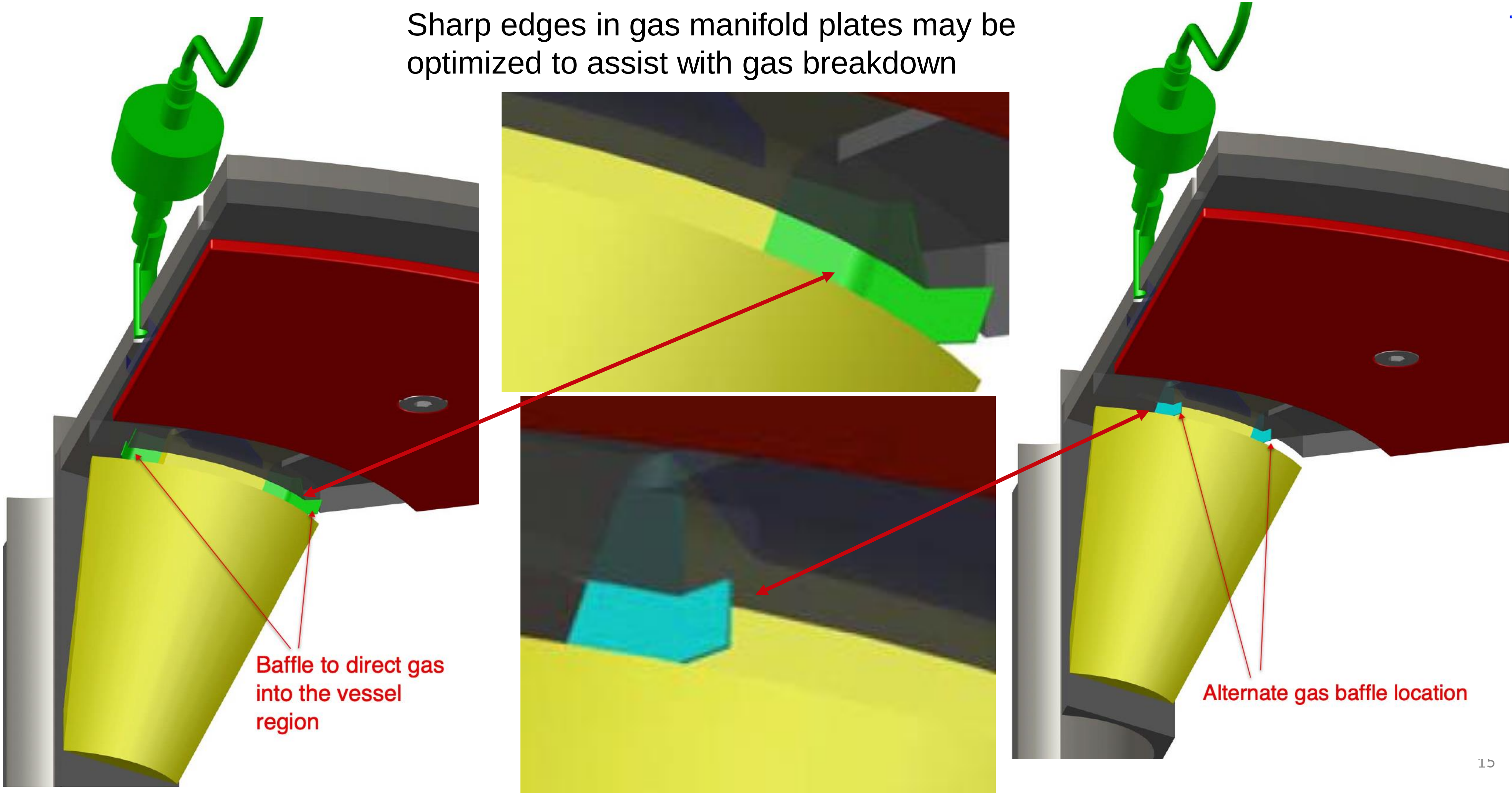


Conduit shaped as it is to avoid interaction with electrode current feed

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON

Baffles to redirect gas from the inner electrode to the outer electrode in a diffuse manner, analogous to that on NSTX

Sharp edges in gas manifold plates may be optimized to assist with gas breakdown



Transient CHI Studies on PEGASUS-III Will Improve Our Understanding of the CHI Scaling Relations for MA-class Startup

- Develop and test a double biased electrode configuration
  - First test of novel electrode geometry
  - Supports transient, sustained CHI experiments
- First CHI studies on PEGASUS-III seek to establish and optimize Transient CHI scenarios
  - Increasing high I_p up to external PF coil limits as B_T is raised (goal: 0.15 → 0.3 MA)
  - Quantify the parameter ‘d’, flux shaping effects, the sensitivity to the CHI insulator location and insulator gap width, on the plasma internal inductance and on the closed flux conversion efficiency
  - Compare CHI discharge to MHD simulations
- Future: exploration of synergistic effects
  - T-CHI-to-LHI sustainment scenarios
  - RF auxiliary heating of T-CHI discharges

Department of Engineering Physics
UNIVERSITY OF WISCONSIN–MADISON