NSTX-U

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CHI Research on NSTX-U

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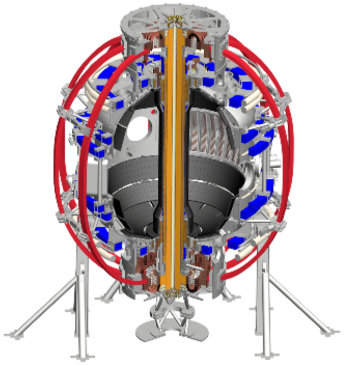
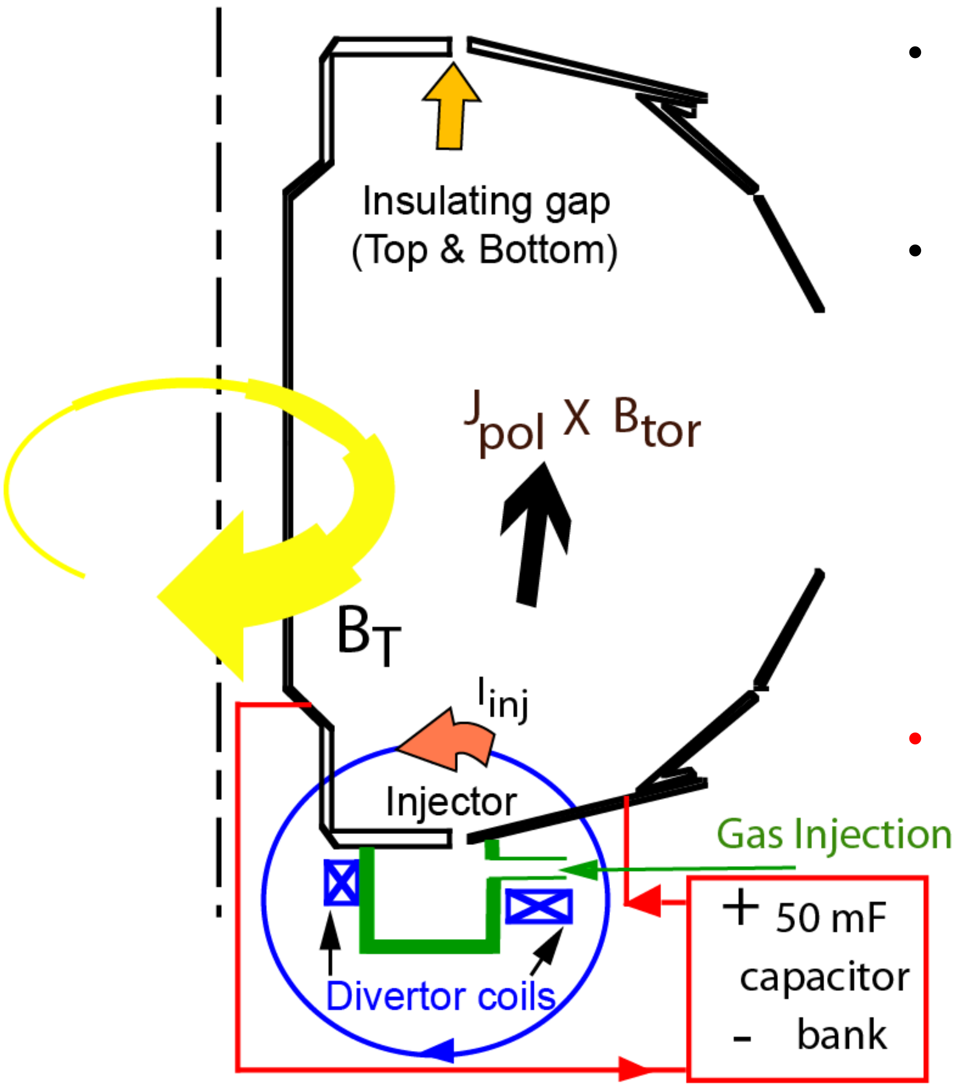


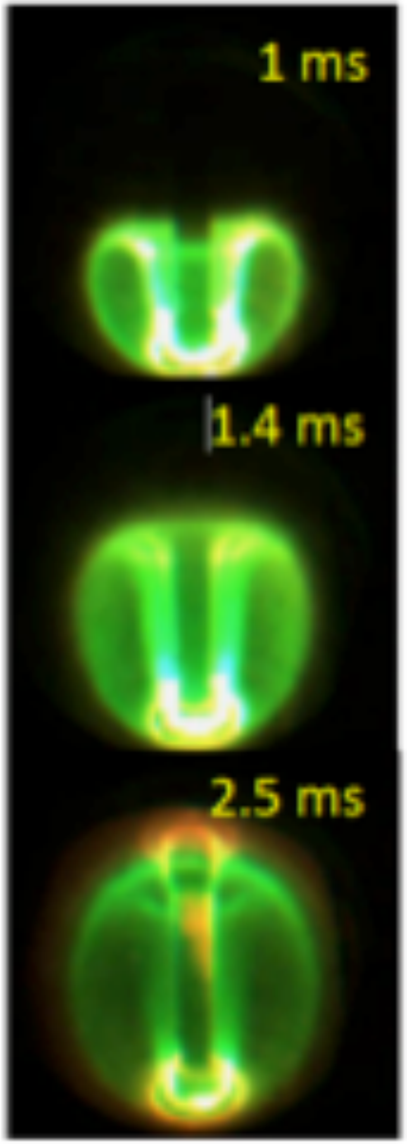
Objectives of Transient CHI Research

1. Introduction to Transient CHI Start-up
2. Minimize non-inductive current ramp-up requirements
3. Simplify electrode configuration for ST-FNSF
4. CHI on QUEST
5. Planned configuration for CHI on PEGASUS
6. TSC Simulations
7. NIMROD Simulations
8. Conclusions

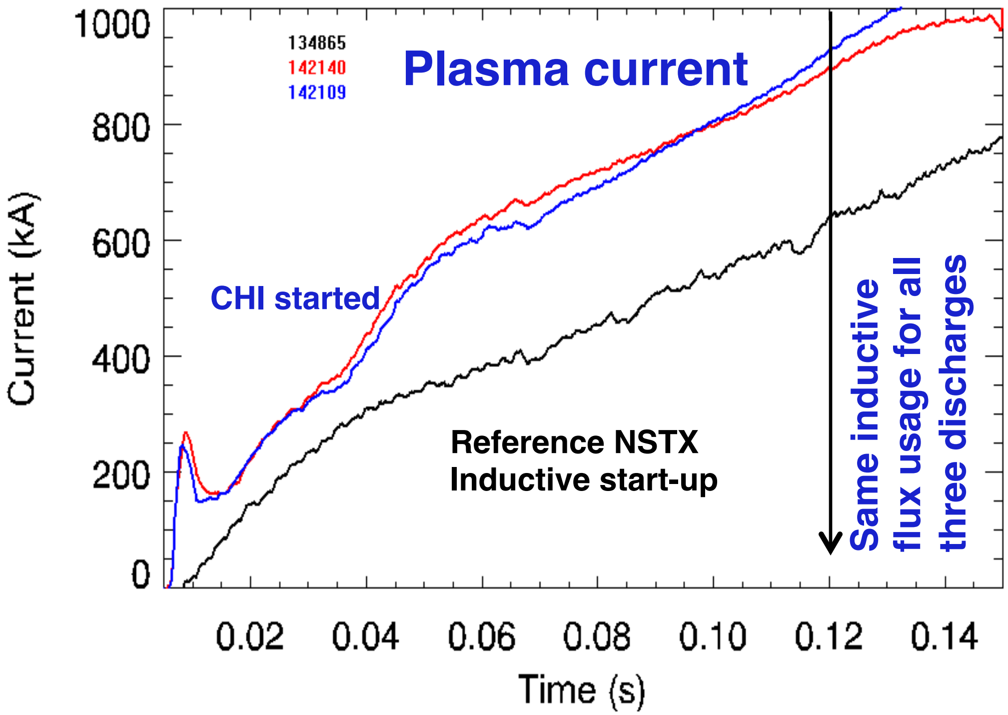
Transient CHI on NSTX: The injected open flux closes in on itself to a relaxed state containing >70% of initial injected flux

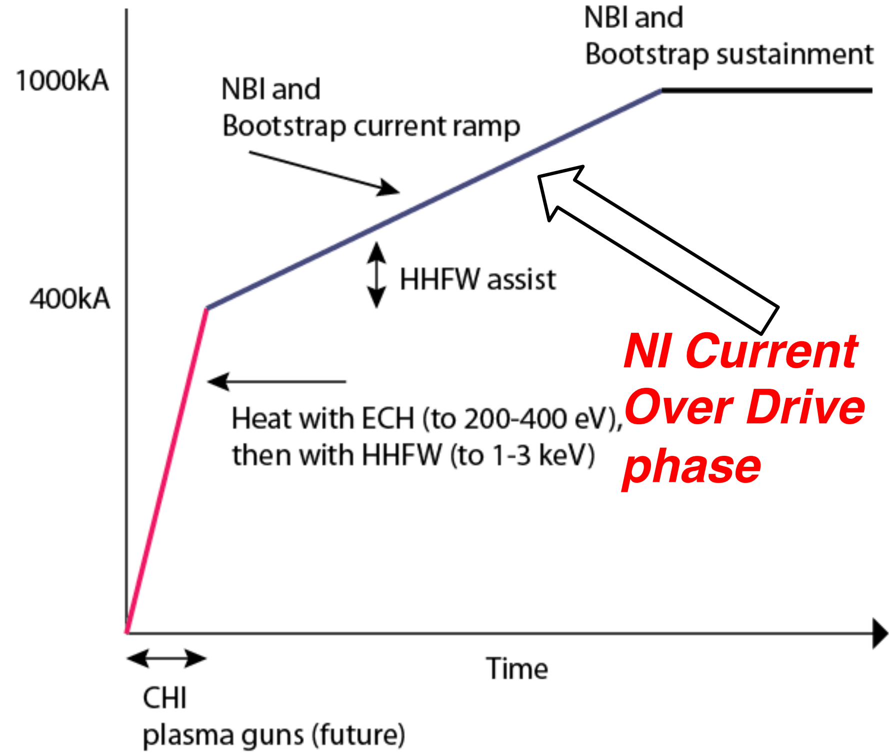


- Transient CHI does not rely on dynamo current drive
- Thus, T-CHI is simpler, as one need not develop scenarios for current overdrive in a magnetic configuration that is constantly changing in time
- Can T-CHI produce most of the initial current needed during sustained operation in a reactor?



Minimizing Non-Inductive Current Ramp-up Phase would Simplify Current Over Drive Needs in an ST-FNSF





- Transient Coaxial Helicity Injection (CHI) on NSTX
  - 200 kA start-up currents ramped to 1MA with inductive flux savings
  - Generating I_p ~ 1 MA by CHI would eliminate the need for the difficult non-inductive current ramp-up step

Externally Produced Toroidal Field makes CHI Efficient in an ST & Necessary for High Current Generation in an ST-FNSF

- Bubble burst current*: $I_{inj} = 2\psi_{inj}^2 / (\mu_o^2 d^2 I_{TF})$

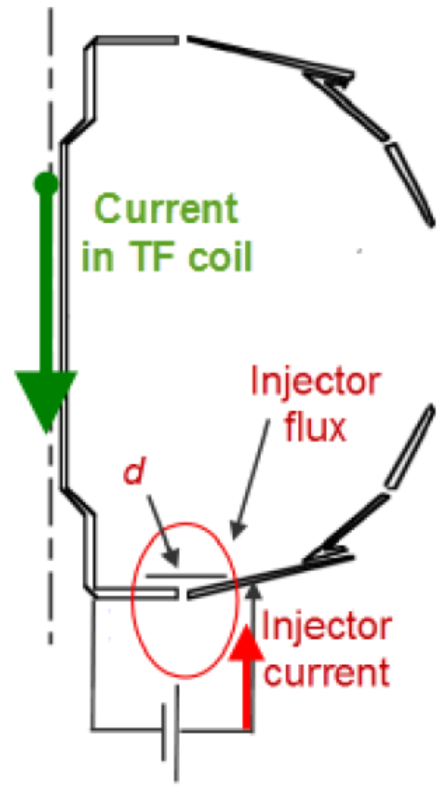
  ψ_{inj} = injector flux

  d = flux foot print width

  I_{TF} = current in TF coil

Injector current **Toroidal flux**

$$I_P = I_{inj}(\psi_T / \psi_{inj})$$



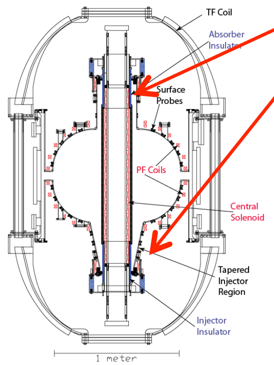
- Current multiplication increases with toroidal field
  - Favorable scaling with machine size
  - Increases efficiency (10 Amps/Joule in NSTX)
  - Smaller injector current to minimize electrode interaction

Closed flux current magnitude is proportional to injector flux, and this must be maximized while minimizing the injector current

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

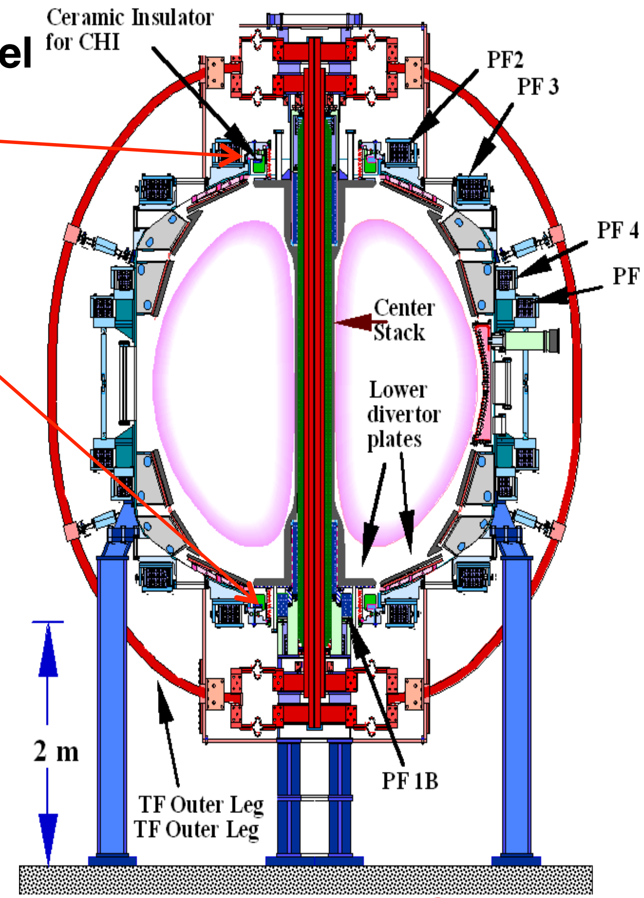
CHI Insulator On NSTX and HIT-II are part of Vessel Vacuum Boundary

HIT-II and NSTX use two toroidal insulators to insulate the inner vessel from the outer vessel components



Devices approximately to scale

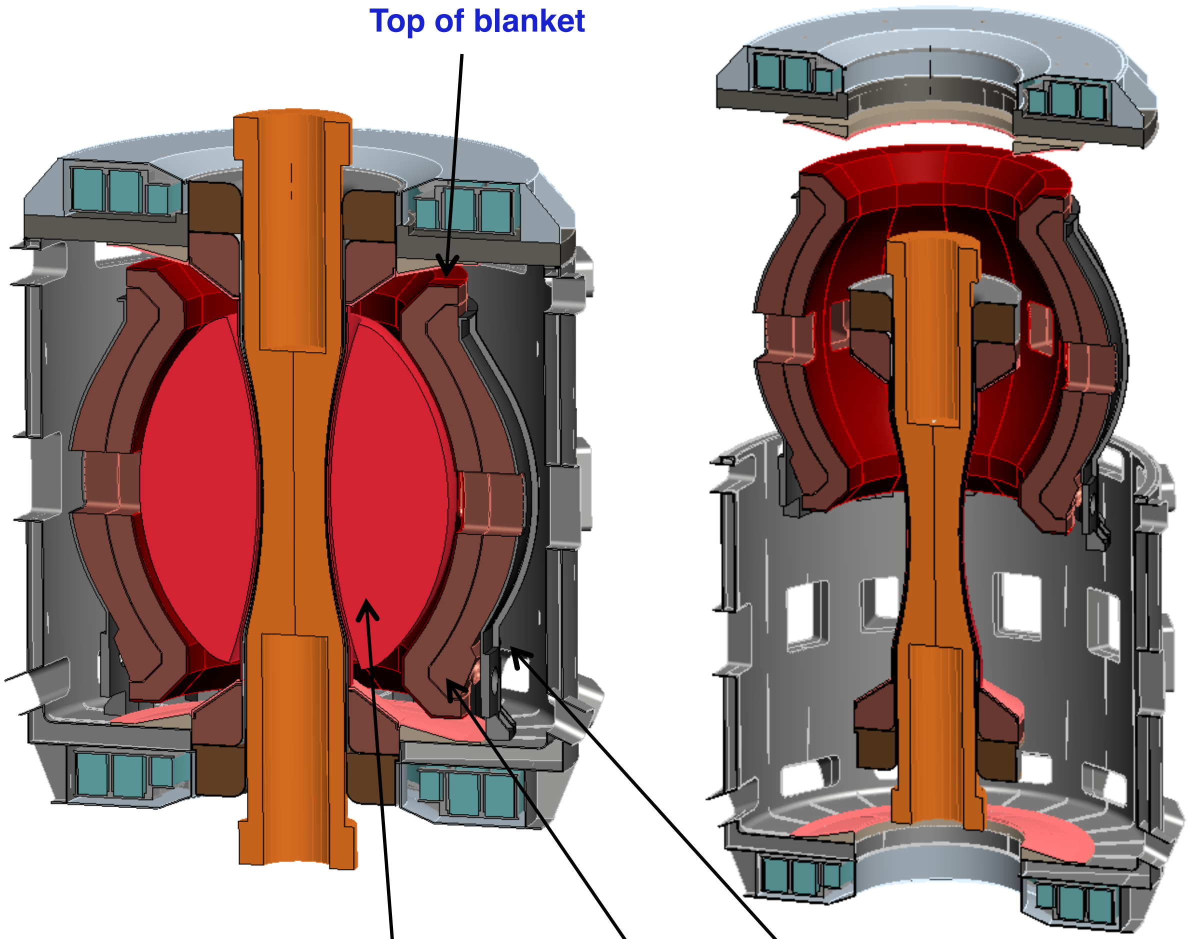
Concept exploration device HIT-II
- Built for developing CHI
- Many close fitting fast acting PF coils
- 4 kV CHI capacitor bank
- 16 mWb injector flux, produced I_p = 100 kA

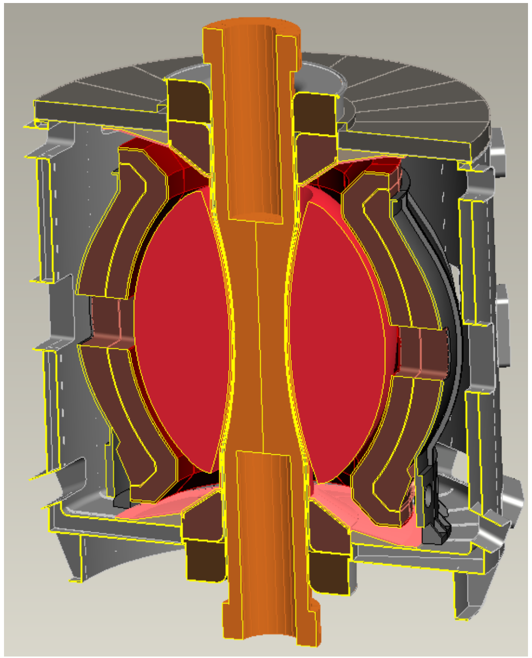


Proof-of-Principle NSTX device
- Built with conventional tokamak components
- Few PF coils
- 1.7 kV CHI capacitor bank
- 50 mWb injector flux, produced I_p = 200 kA

NSTX plasma is ~30 x plasma volume of HIT-II

ST FNSF Configuration
(R_{maj} = 1.7m, A=1.5, B_T = 3T, I_p = 10MA)



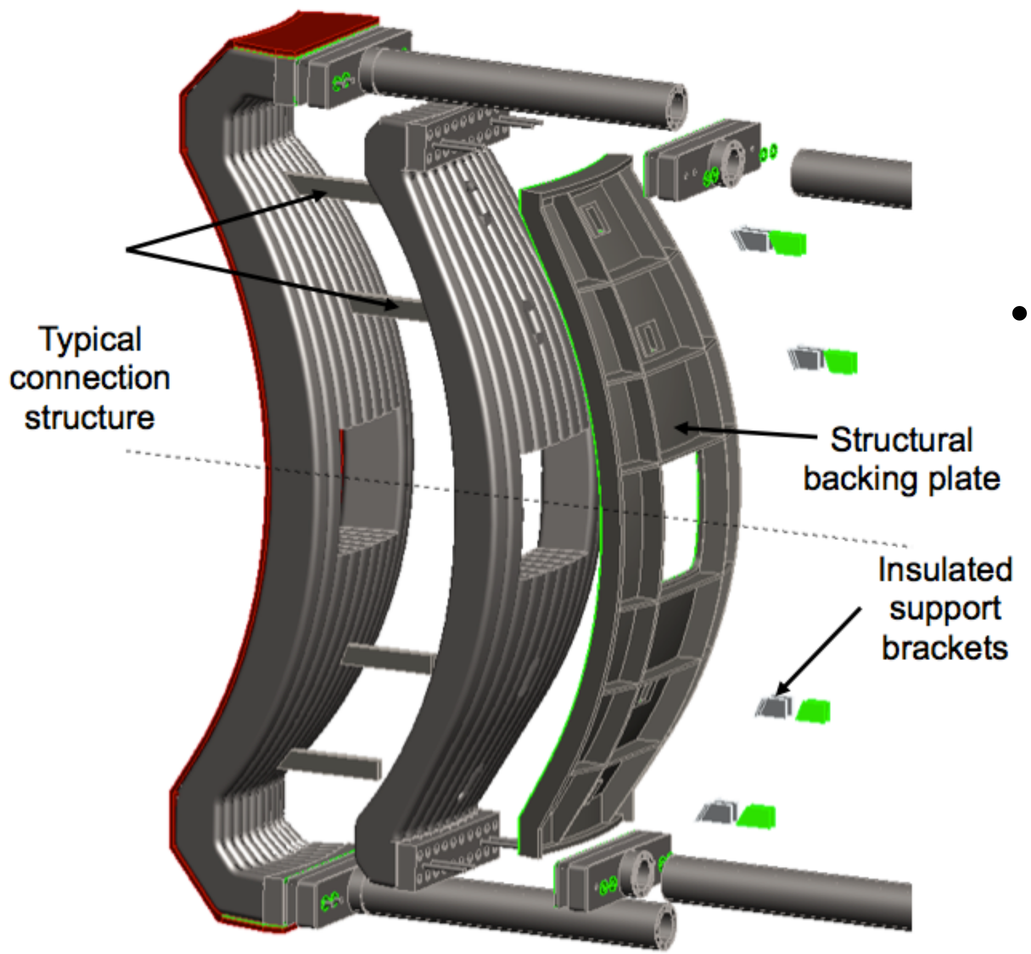


3-D Neutronics model

CHI Design Studies for ST-FNSF have Identified Two Designs with > 2MA Start-up Current Generation Potential

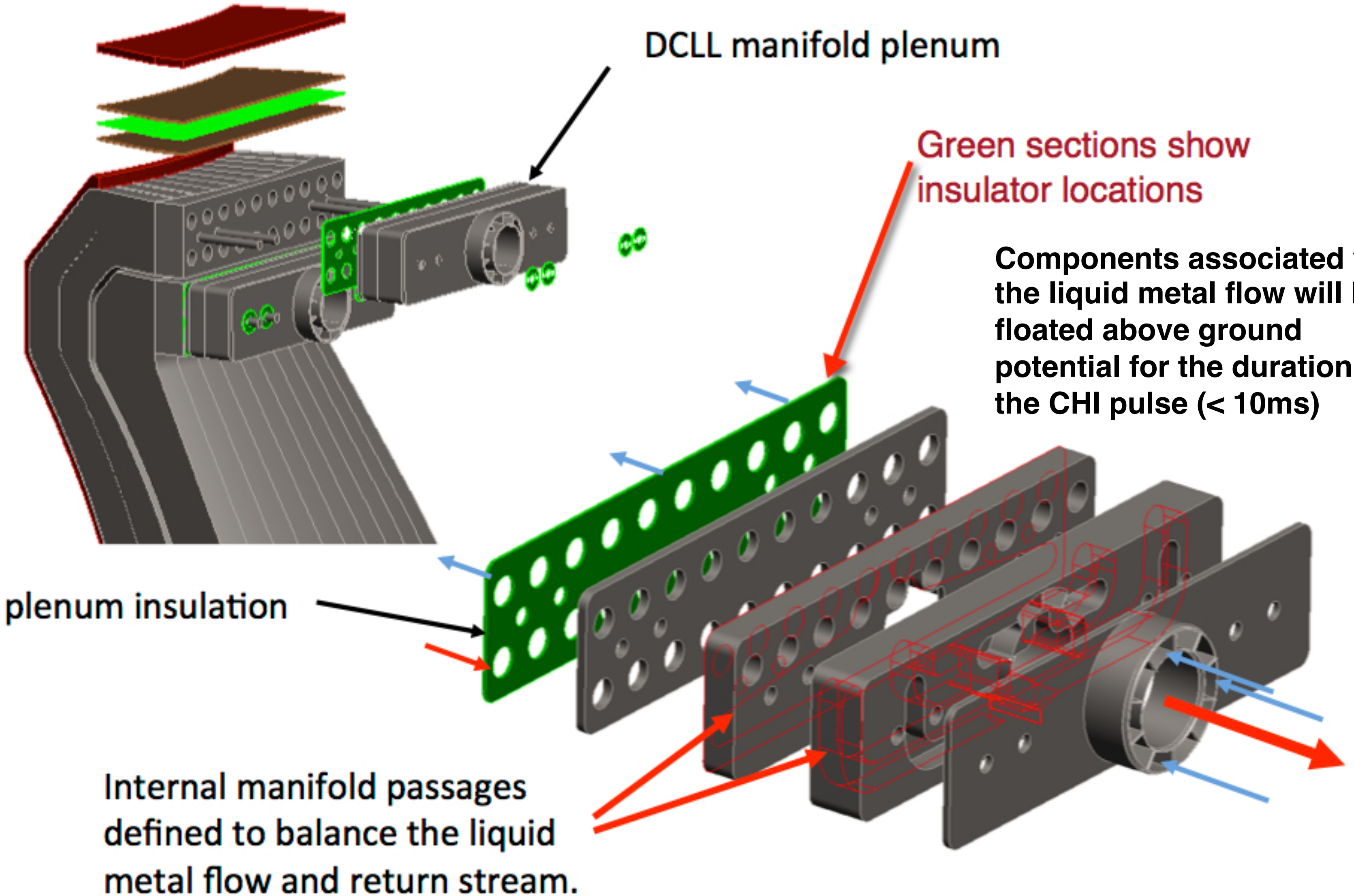
Concept – I (NSTX-like)

***Blanket modules and piping insulated from rest of vessel**



- On NSTX and NSTX-U entire inner vessel is electrically isolated from outer vessel
  - Injector flux connects inner divertor plate to outer divertor plate and outer vessel regions
- In ST-FNSF concept – I, entire blanket structure is electrically insulated from entire vessel
  - Injector flux connects lower portion of vessel to the lower portion of the blanket assembly
  - For CHI, the blanket is analogous to the inner vessel in NSTX/NSTX-U

Concept – I Requires All Piping to be Electrically Insulated



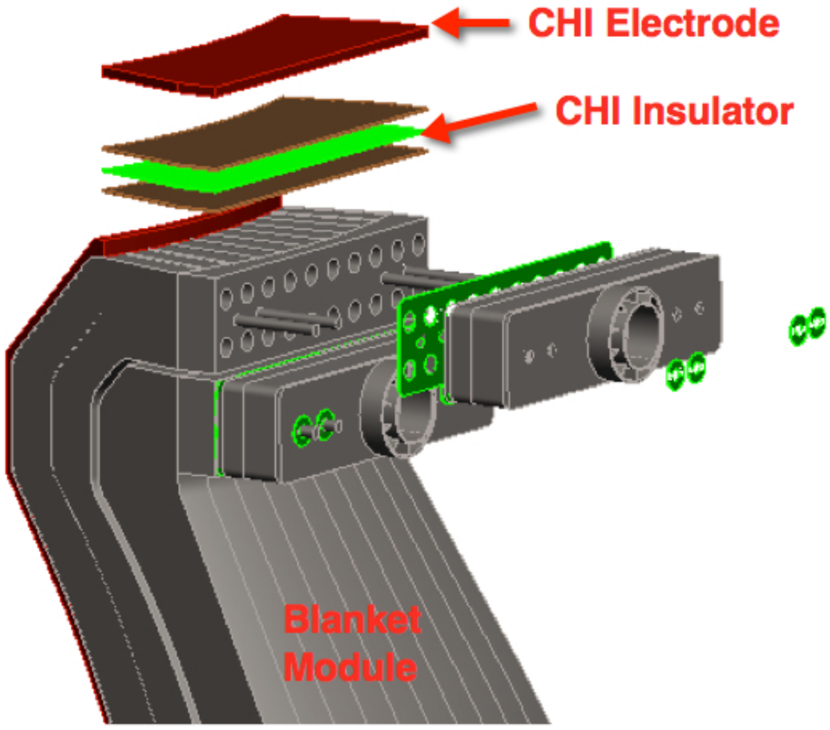
Components associated with the liquid metal flow will be floated above ground potential for the duration of the CHI pulse (< 10ms)

Concept – II is simpler, but Requires Additional Experimental Tests

- On DIII-D a Ring-Electrode was installed inside the vessel
  - Injector flux connects parts of the DIII-D vessel to the ring electrode
  - Concept successfully used to sustain 1kV voltages for over 1s with MA plasma present
- In ST-FNSF concept – II, a toroidal ring electrode is placed on top of the upper blanket section, insulated from the blanket using a insulator plate
  - Injector flux connects upper portion of vessel to the electrode plate on the upper portion of the blanket assembly
  - Because the insulator is largely shielded from direct neutron streaming, insulator dose issues should not be a problem, as noted by the 3-D neutronics calculation

Concept – II (DIII-D/QUEST-like)

Toroidal electrode on top of blanket structure, analogous to CHI ring electrode previously used on DIII-D



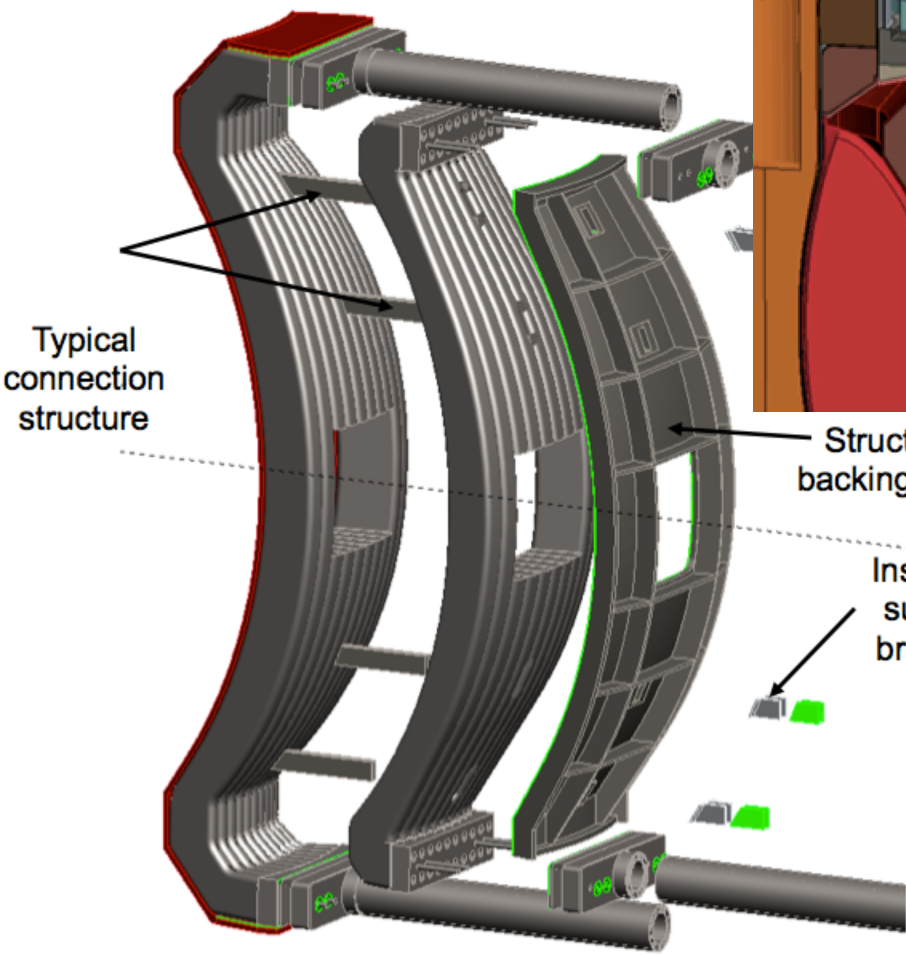
*Insulator dose: ~6×10^{9} Gy @ 6FPY < 10^{11} Gy limit

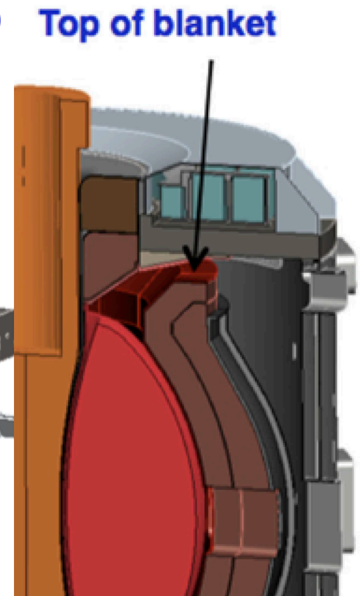
*** L. El-Guebaly, et al., MCNP Neutronics**

CHI Design Studies for ST-FNSF have Identified Two Designs with > 2 MA Start-up Current Generation Potential

Concept – I (NSTX-like)

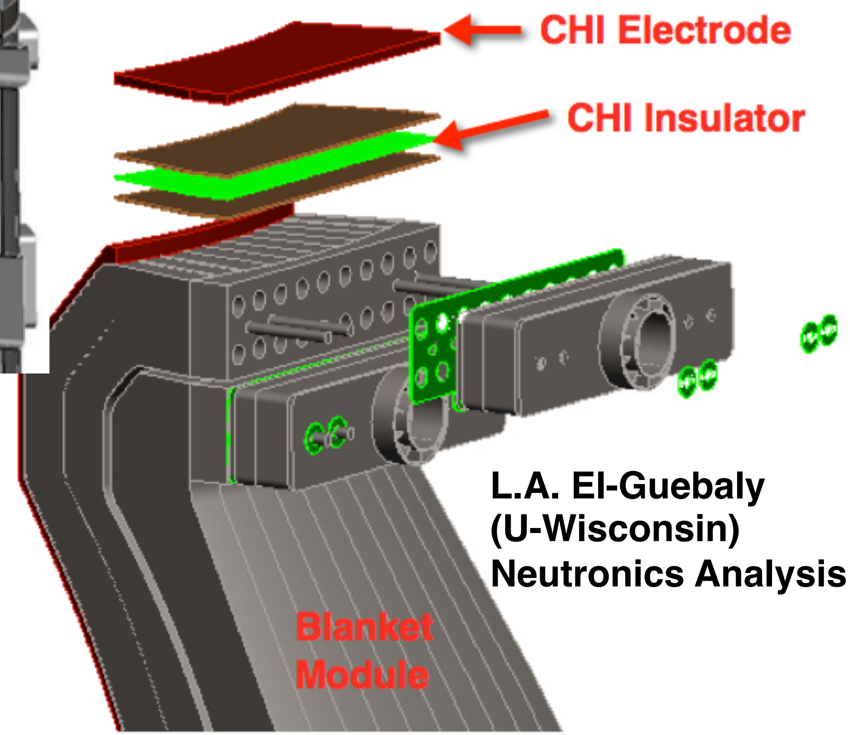
*Blanket modules and piping insulated from rest of vessel





Concept – II (QUEST-like)

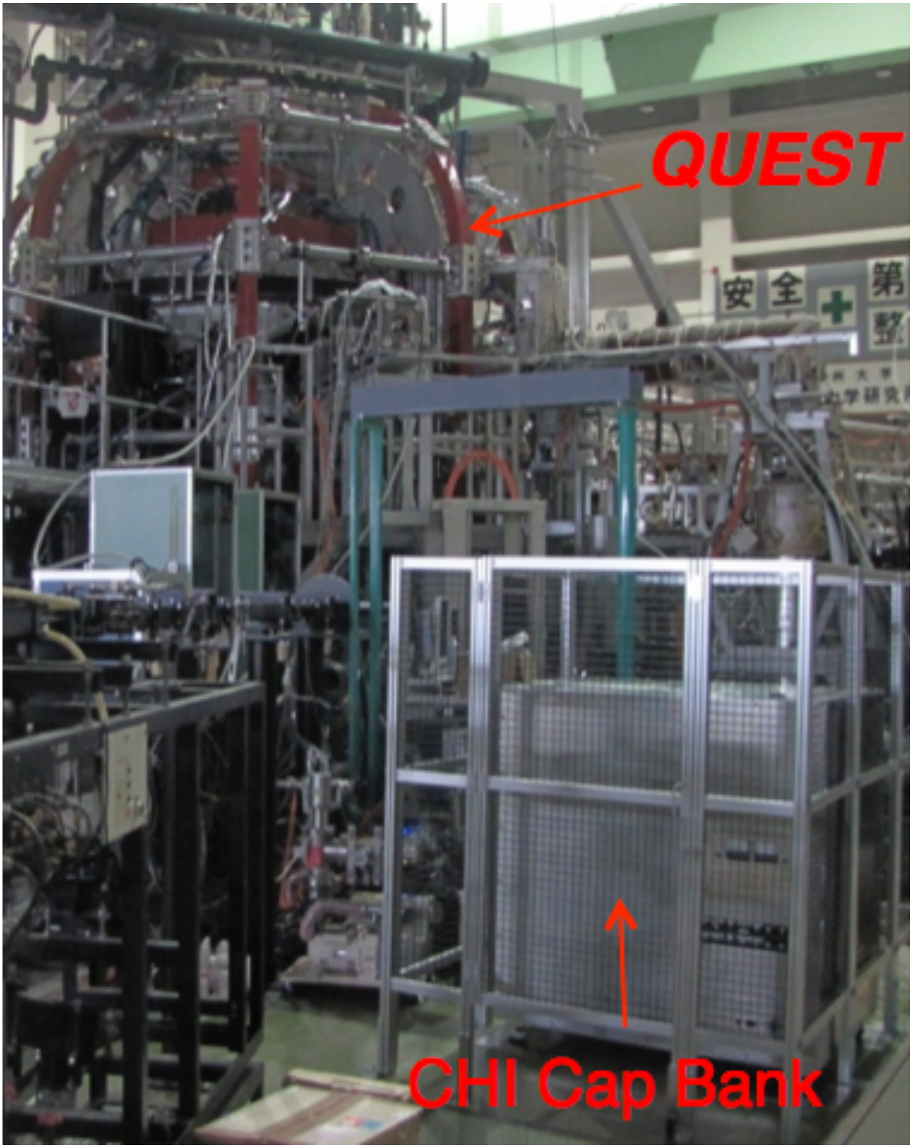
Toroidal electrode on top of blanket structure, analogous to CHI ring electrode previously used on DIII-D



L.A. El-Guebaly (U-Wisconsin) Neutronics Analysis

R. Raman, T. Brown, L.A. El-Guebaly, et al., Fusion Science & Technology (2015)

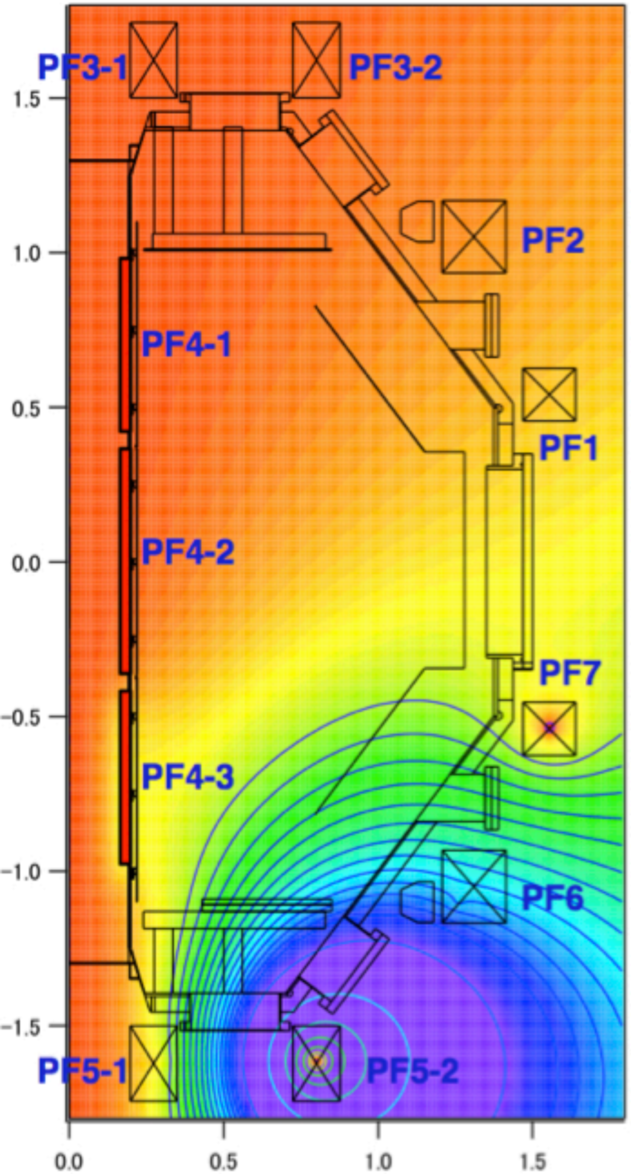
CHI Research on QUEST in Support of NSTX-U and ST-FNSF

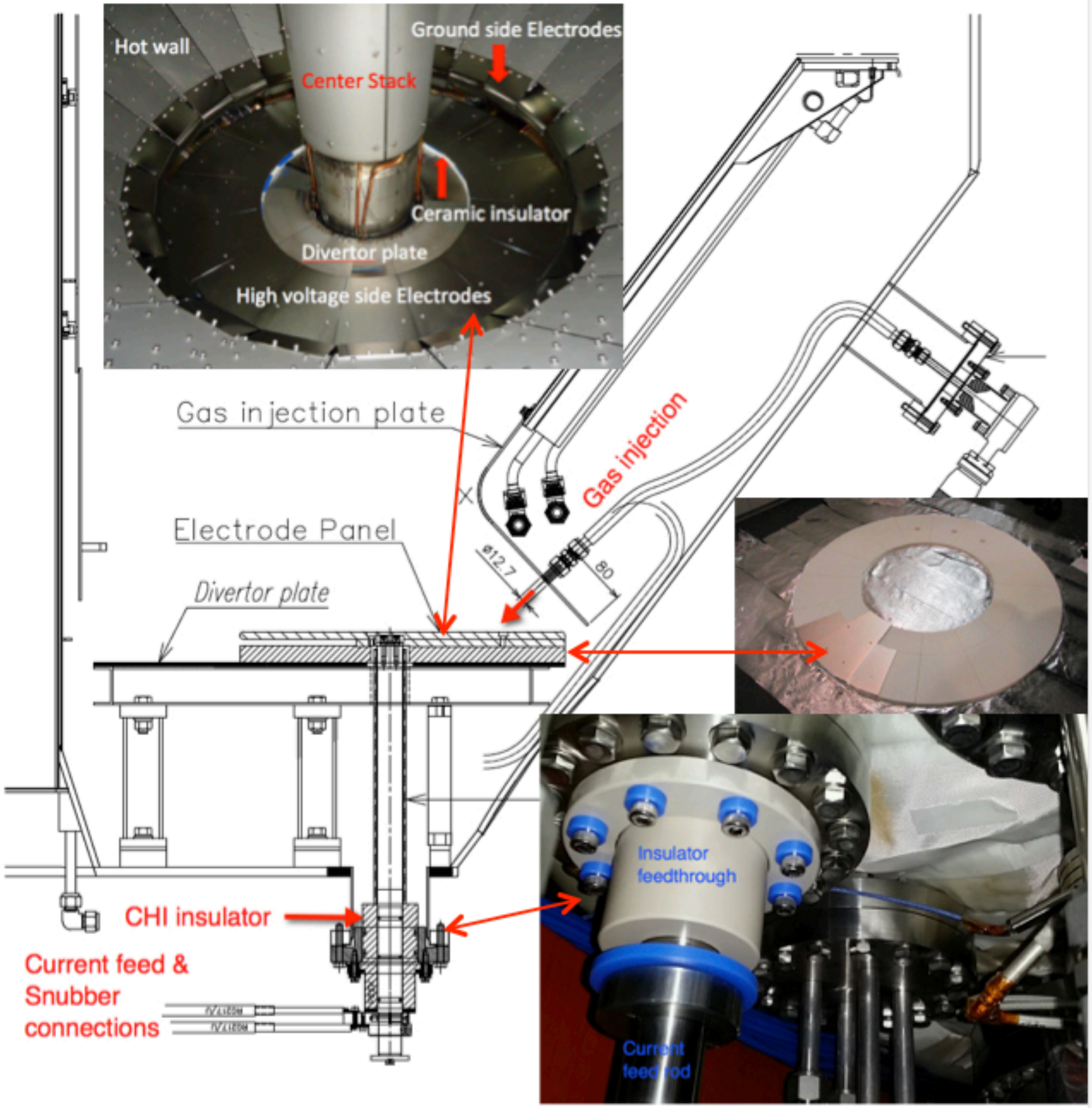


- Test ECH heating of a CHI Target
  - QUEST is equipped with ECH
- Test CHI start-up using metal electrodes
  - Clean metal electrodes should reduce low-Z impurity influx
- Test CHI start-up in an alternate electrode configuration that may be more suitable for a ST-FNSF installation
  - CHI insulator is not part of the vacuum vessel

Collaboration with Kyushu University:
K. Kuroda, K. Hanada, M. Hasegawa, T. Onchi, et al.,

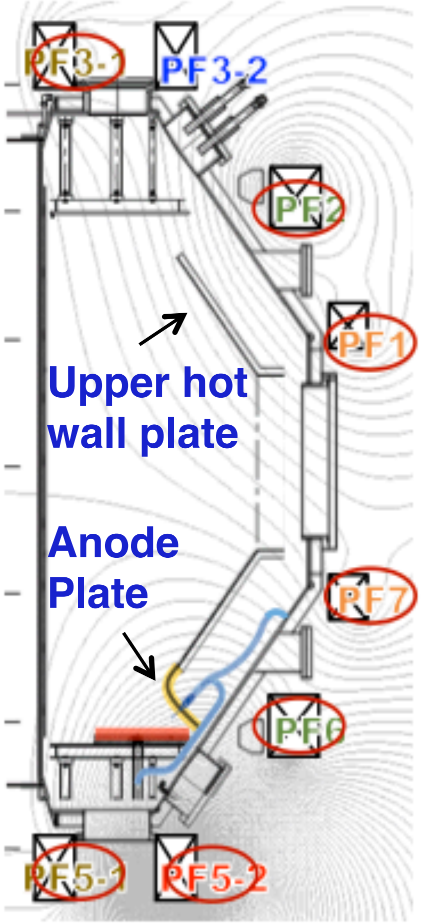
CHI Configuration on QUEST is Developing ST-FNSF Relevant Single Biased Electrode Design

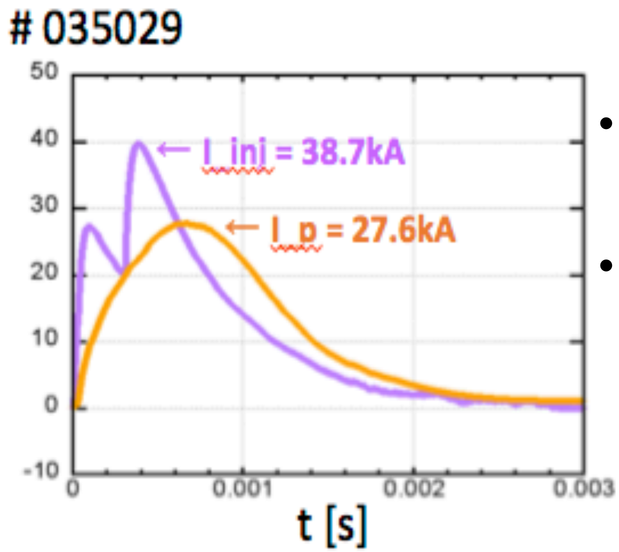


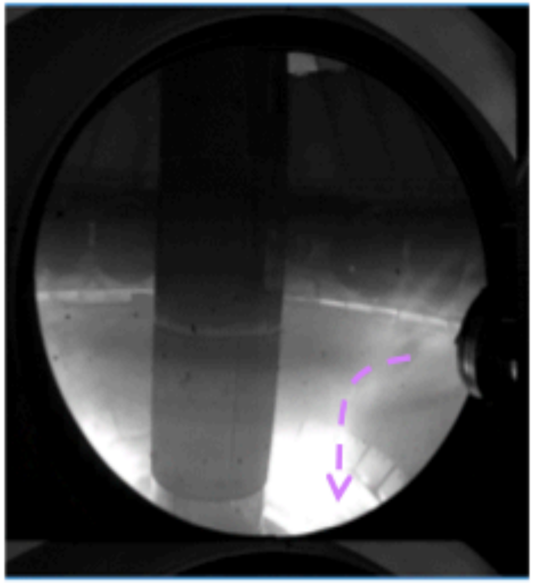


Reliable Discharge Initiation & Plasma Growth Obtained in the Single Biased Electrode Configuration on QUEST

Injector Flux Configuration on QUEST to reduce flux footprint width

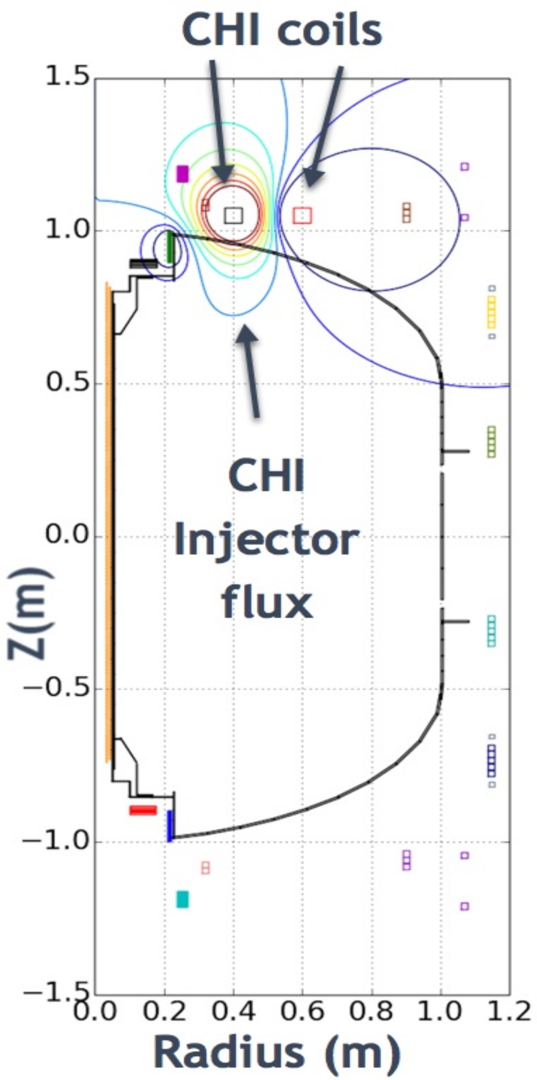


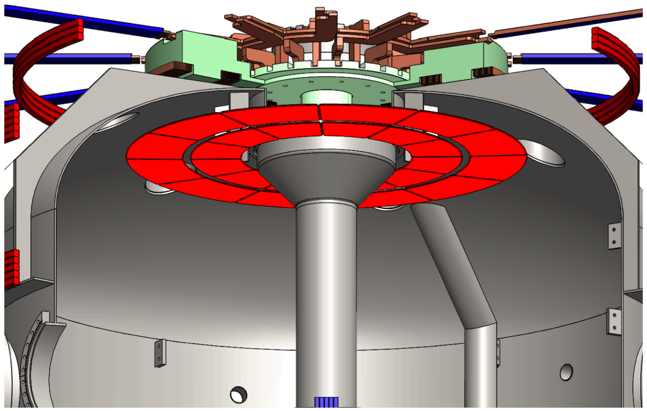


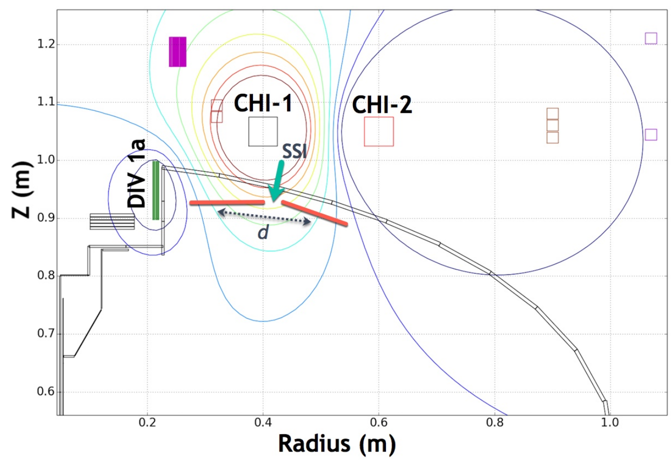


- At low I_p, current path is to the outer anode plate
- As current increases, and plasma fills the vessel, (not shown here) the discharge appears to contact the upper hot wall plates
- Improved diagnostics, plasma shaping, and capacitor bank programming to be implemented in future to improve discharge performance

CHI research on Pegasus plans to develop a <u>double biased</u> electrode configuration to better define the current path







Collaboration with Univ. of Wisconsin:
J. Reusch, R. Fonck, M. Bongard

Goals on Pegasus:

-High I_p ~300 kA (@ PF coil limits for I_p)

-Flux footprint width characterization

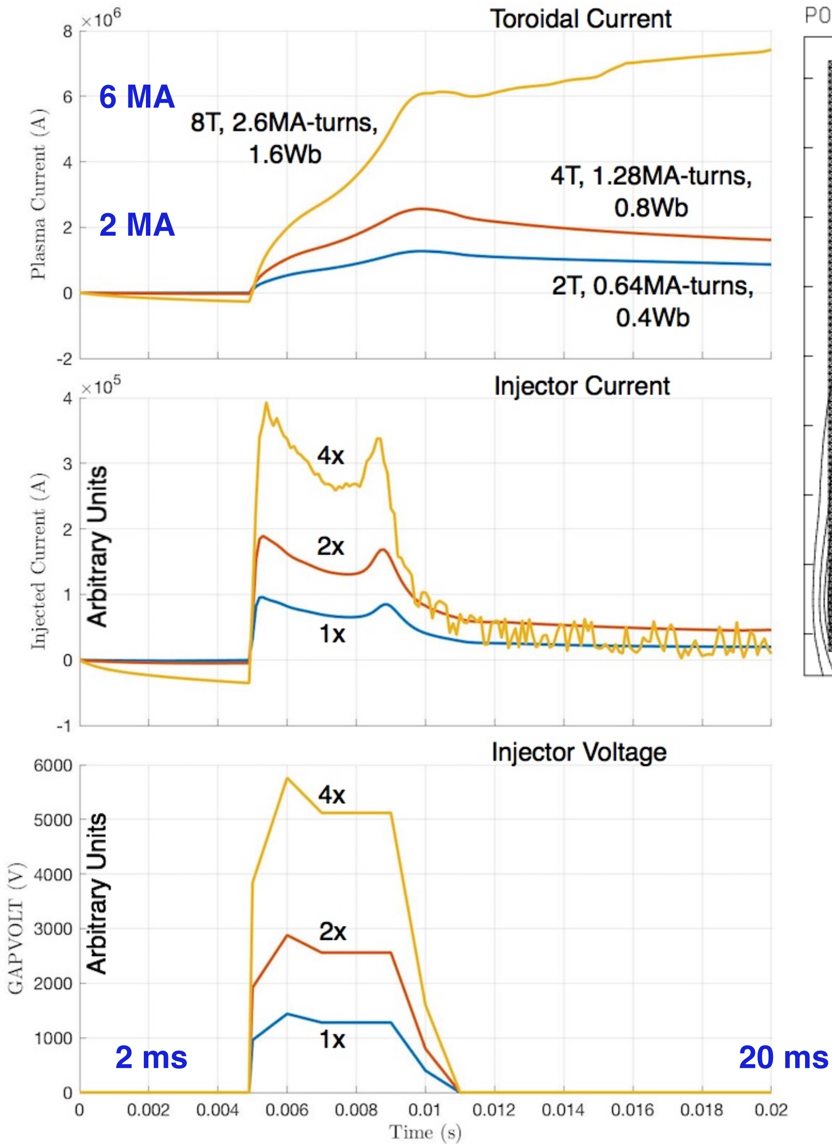
-Role of impurities

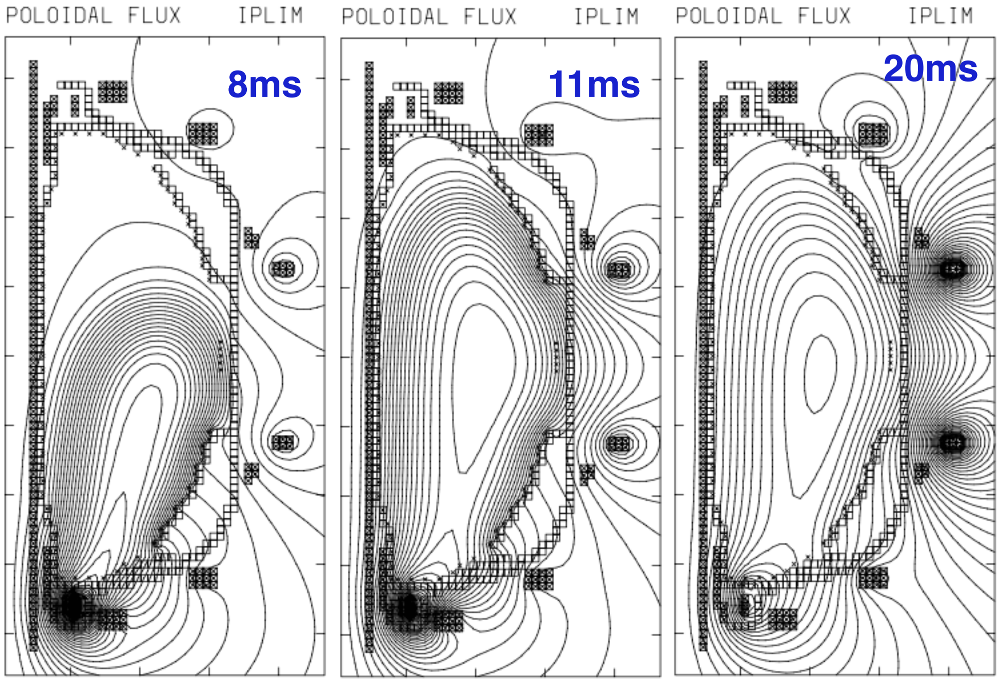
-Influence of current channel shape on reconnection

-Dynamo current drive enhancement

-ECH heating

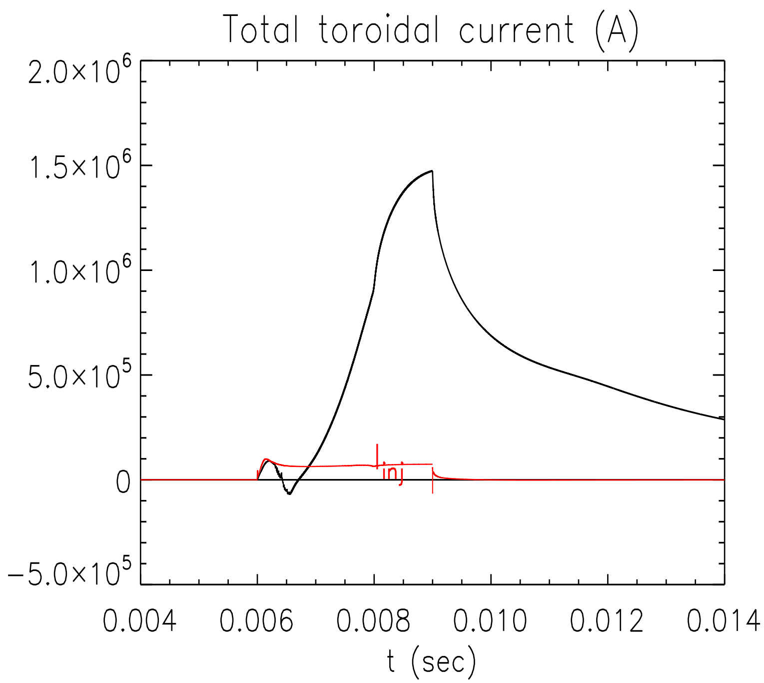
TSC Simulations in NSTX-U Geometry Show Toroidal Current Continuing to Increase with Injected Flux





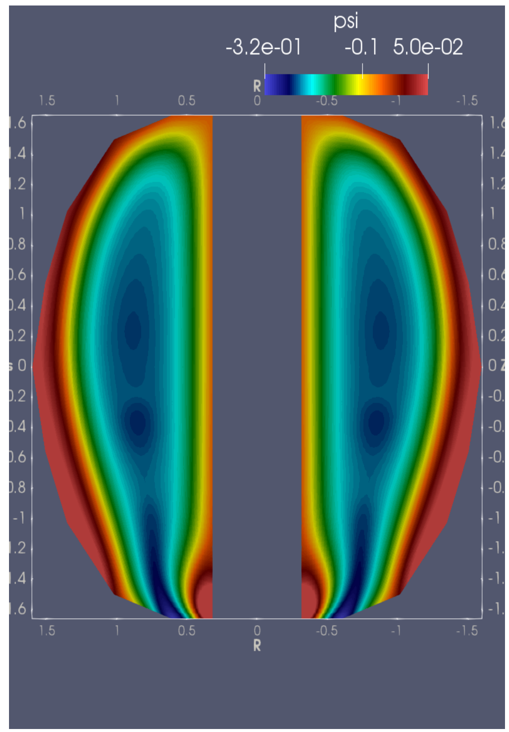
- Without increase in TF, required injector current would be 16x higher for a factor of 4 increase in injected flux
- TSC simulations provide good estimates for required injector current, and projected total currents, but in general always severely under predict closed flux current magnitude

First High-Flux NIMROD Simulations Show Peak Current Generation to Over 1 MA, Similar to TSC Results

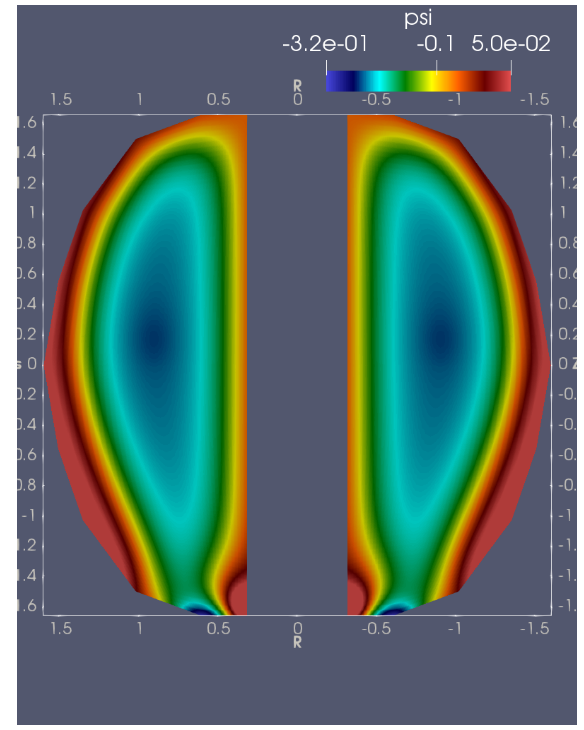


- Peak toroidal current ~1.5 MA
- Simulations are performed at high poloidal flux of 0.32 Wb and toroidal field of about 4 T
- Te limited to ~15eV, will be increased to 100 eV in future

t = 8 ms



t = 9.3 ms



- Poloidal fluxes during injection 8 ms and decay phase 9.3 ms.
- 0.5 MA closed flux (un-optimized run)

Representative Parameters for Transient CHI in STs

Parameters	HIT-II	NSTX	QUEST	Pegasus
Major radius [m]	0.3	0.86	0.68	0.45
Minor radius [m]	0.2	0.66	0.4	~0.3
B_T [T]	0.5	0.55	0.25 - 0.5	0.15 – 0.6
Injector flux (mWb)	16	50	28	~60
Projected Start-up current (kA)	100	200	<150	~300

Transient CHI is being studied to assess its potential for full current generation in a ST/AT – based fusion reactor

- Transient CHI has been very successful on HIT-II and NSTX
- 200 kA current generation on NSTX, and ramp-up to 1 MW with record low flux consumption when coupled to induction demonstrated the high current start-up capability of transient CHI
- Transient CHI does not rely on dynamo mechanism for current generation, so the scaling to larger devices is simpler (I_p is proportional to Injector Flux)
- QUEST has successfully generated significant toroidal currents in a new single biased electrode geometry
- Design studies are in progress to implement a double biased electrode configuration on PEGASUS
- As a result of rapid improvements in HTSC technology, the design and injector current requirements for full magnitude current generation in STs is investigated using TSC and NIMROD codes
    - TSC simulations show the toroidal current continues to increase with Injector Flux
    - NIMROD simulations show high open to closed flux conversion efficiency and is being used investigate maximum flux injection limits in a given vessel size