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Application of transient CHI plasma start-up to future ST and AT devices

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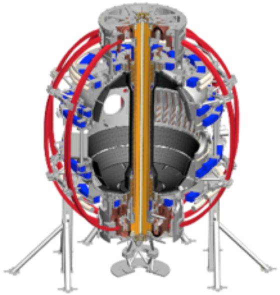


Motivation

- The ability to start up a tokamak plasma without a central solenoid is desirable for reactor design
- Multiple approaches pursued to date
  - Induction from poloidal field coils
  - Radio-frequency heating and current drive
  - Helicity injection (point-source, coaxial)
- Advantages of transient **C**oaxial **H**elicity **I**njection (CHI)
  - Successful implementation on HIT-II, NSTX, QUEST
  - Favorable scaling to larger devices

Motivation

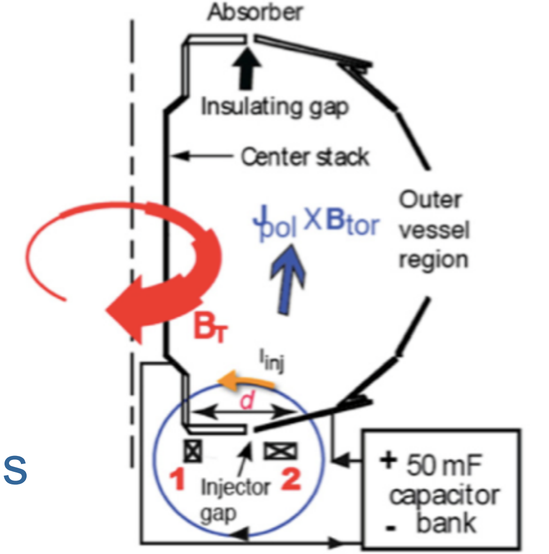
- Plasma breakdown requirements must be carefully considered for future CHI implementations
  - Plasma must break down in a particular location in order to work
  - Weaknesses of previous designs could become show-stopping issues
- In this talk: assessment of feasibility for next-step devices
  - Review of transient CHI start-up
  - Development model to predict CHI breakdown feasibility and location
  - Modeling of breakdown in two previously-successful configurations
  - Projections for attainable plasma parameters in larger devices

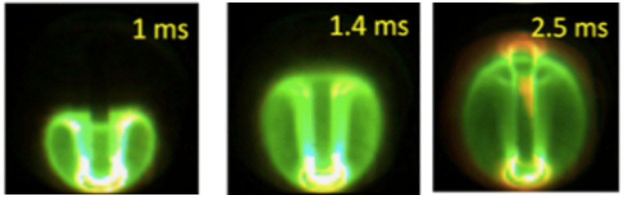
Outline

- Review of transient CHI start-up
- Model to predict CHI breakdown feasibility and location
- Assessment of different CHI electrode concepts
- Predictions for CHI in next-step devices

Transient CHI converts a brief DC plasma discharge to a toroidal plasma with closed flux surfaces

- Hardware requirements
  - Two axisymmetric electrodes
  - Toroidal field + poloidal flux between electrodes
  - Sufficient prefill gas for breakdown
- Plasma development
  - Current flows between electrodes along field lines
  - J × B forces expand plasma into vessel
  - Reconnection leads to closed flux surfaces
  - Fast reduction of injector current enables efficient conversion of injector flux to poloidal flux





Raman et al., *Phys. Plasmas* 2011

Key parameters for CHI

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

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

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

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

- Capacity to generate **plasma current** I_{p} is proportional to ψ_{inj}

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

Jarboe, *Fusion Technol.* 1989

Milestones for transient CHI

- HIT-II: closed flux surfaces and persistent I_p of 100 kA (Raman et al., *PRL* 2003)
- NSTX: 160 kA $I_p = 60 \times I_{inj}$ (Raman et al., *PRL* 2006)
- NSTX: Handoff to Ohmic heating with inductive flux savings (Raman et al., *PoP* 2011)
- NIMROD: confirms interpretation of flux surface formation (Ebrahimi et al., *PRL* 2015; *Nucl. Fusion* 2016)
- QUEST: startup with localized single divertor toroidal electrode (Kuroda et al., *PPCF* 2018)
- Pegasus (URANIA): double-biased toroidal divertor electrode

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Assessment of CHI breakdown applies the Townsend avalanche theory on a flux-tube-resolved basis in the tokamak cross-section

- Townsend avalanche theory
  - Key parameters: gas pressure p, electric field E, connection length L_c
  - Predictions: minimum E for breakdown, time τ_{bd} to break down (Lloyd et al., *Nucl. Fusion* 1991)
- Spatially-resolved analysis of the tokamak cross-section
  - Properties of each flux tube are considered independently
  - DIII-D: breakdown occurs closer to location of maximum flux-tube electric potential than to the poloidal field null (Lazarus et al., *Nucl. Fusion* 1998)
- Combined approach: apply avalanche theory to each flux tube
  - Should indicate where breakdown can occur and is most likely to occur
  - Helpful for Ohmic discharges; crucial for CHI

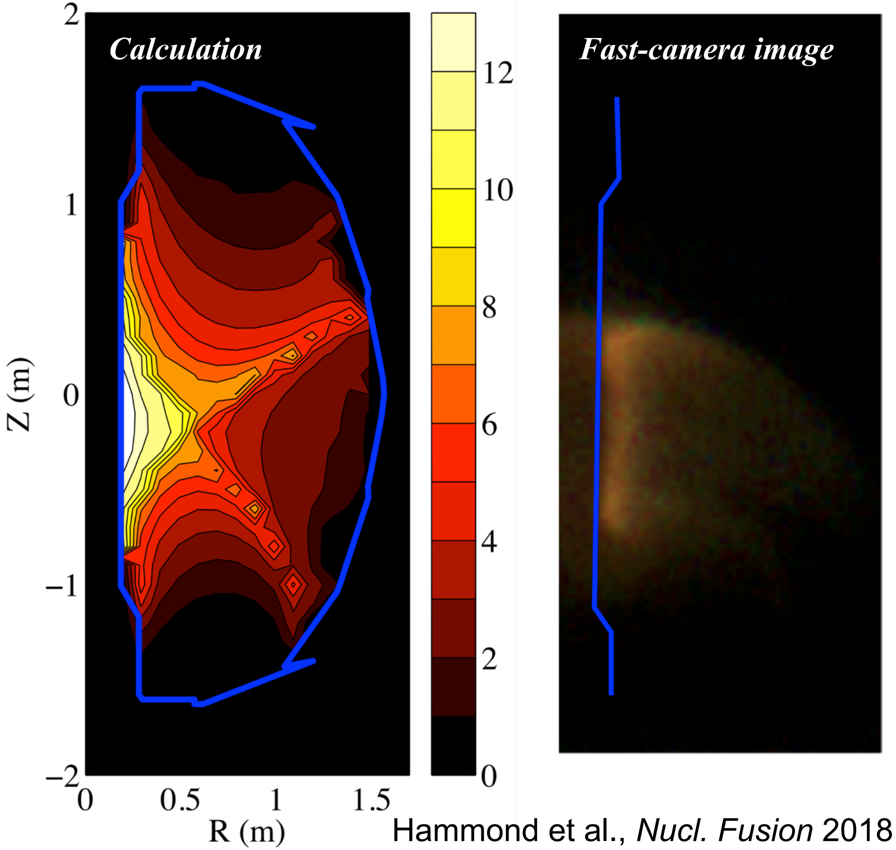
Flux-tube-resolved calculation successfully predicts breakdown location for Ohmic discharges in NSTX

- Plasma should form in flux tubes with greatest *relative electric field*, $E_{\mathrm{mean}}/E_{\mathrm{min}}$

$$E_{\mathrm{mean}}(r,z) = \frac{1}{L_c(r,z)} \int_{\mathbf{s}(r,z)} \frac{V_{\mathrm{loop}}(s)}{2\pi R(s)} ds$$

$$E_{\mathrm{min}}(r,z) = \frac{Ap}{\ln\left[BL_c(r,z)p\right]}$$

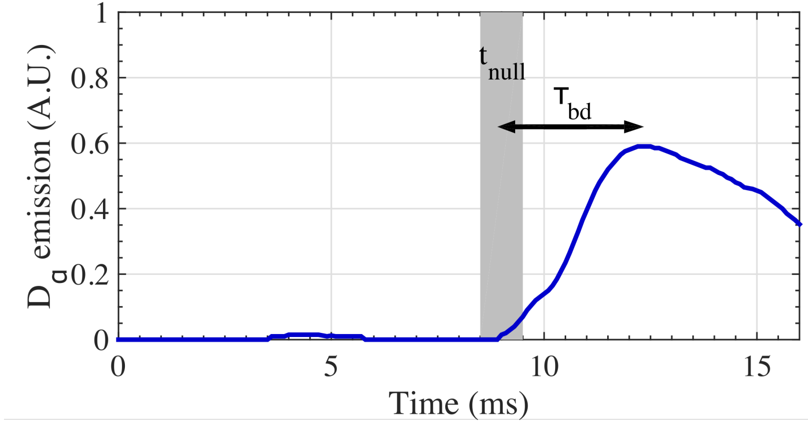
- E_{mean}, E_{min} parametrized by r, z in poloidal cross-section

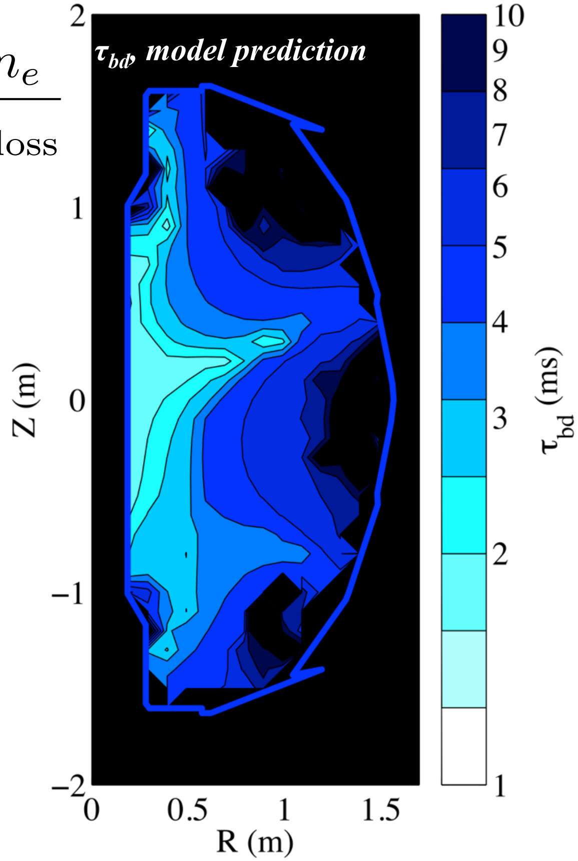


Hammond et al., *Nucl. Fusion* 2018

$E_{\mathrm{mean}}(r,z)$ can be used to predict the time required for breakdown

- Model avalanche by balancing ionizations with end losses: $\frac{\partial n_e}{\partial t} = \frac{n_e}{\tau_{\mathrm{ion}}} - \frac{n_e}{\tau_{\mathrm{loss}}}$
- Time to reach 50% ionization: $\tau_{\mathrm{bd}} = \frac{\ln\left(n_{\mathrm{bd}}/n_{e0}\right)}{\eta(E_{\mathrm{mean}}/p)(\alpha - 1/L_c)}$
- Predicted τ_{bd} agrees well with experiment:





Adapting the model to CHI discharges

- E_{mean} arises from electrode bias rather than loop voltage:

$$E_{\mathrm{mean}}(r,z) = \frac{V_{\mathrm{inj}}}{L_c(r,z)}$$

- Difficult to model experiments precisely
  - Breakdown occurs immediately after release of gas to injector
  - Distribution of gas $p(r,z)$ is non-uniform and time-varying
- Can still estimate requirements for CHI breakdown in future devices:
  - At what pressure can breakdown occur? $p_{\mathrm{min}} = \frac{1}{AL_c}$
  - What plasma temperatures are attainable with the amount of gas used?

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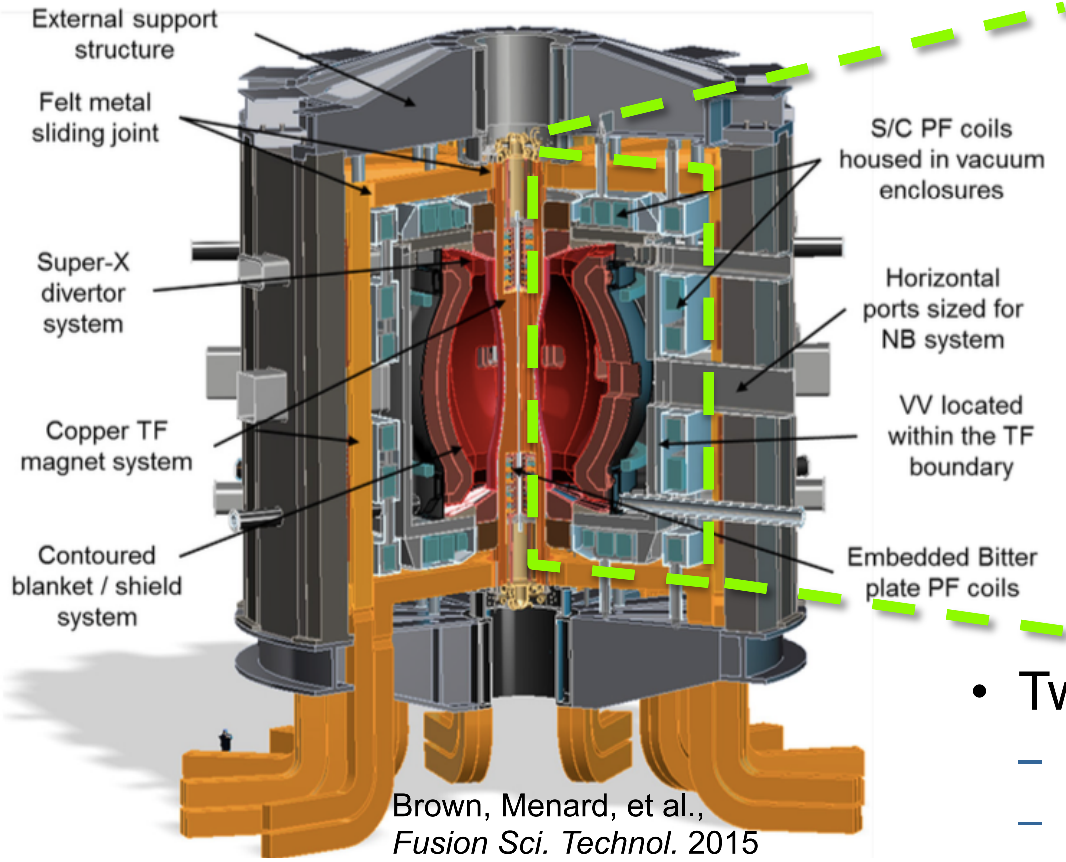
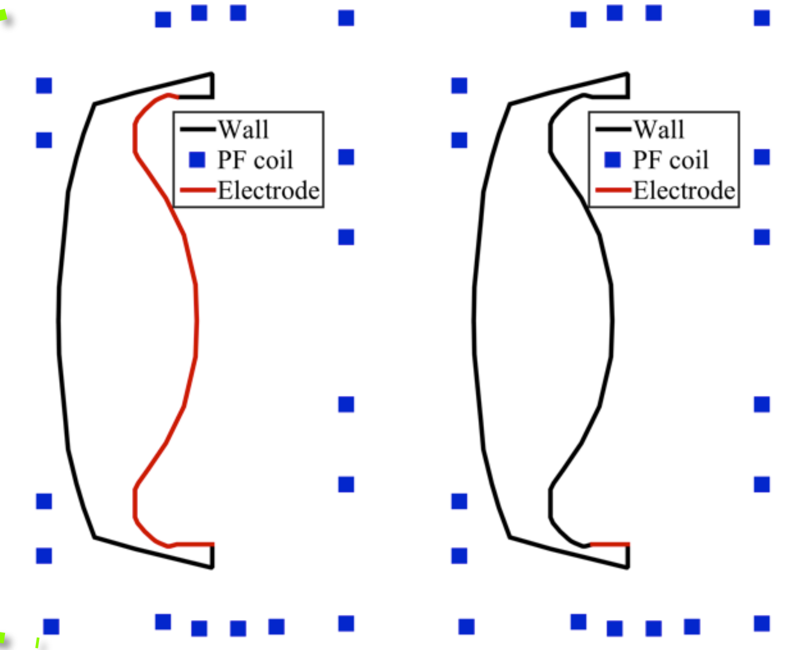
Electrode concepts will use the geometry of a ST-FNSF



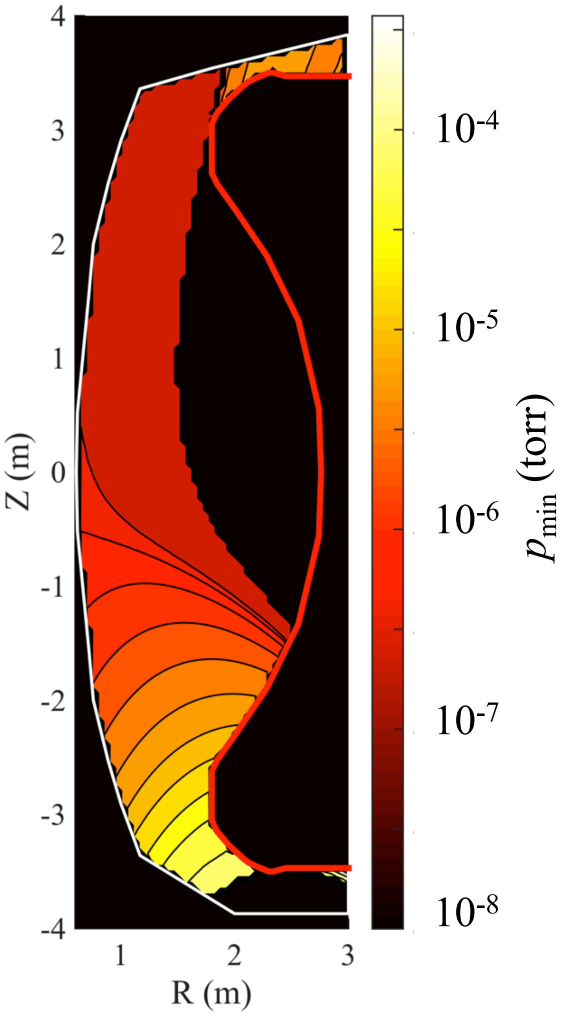
Brown, Menard, et al., *Fusion Sci. Technol.* 2015



- Two concepts for CHI electrodes:
  - “NSTX-like”: entire outer wall is biased
  - “DIII-D-like”: axial ring in lower divertor

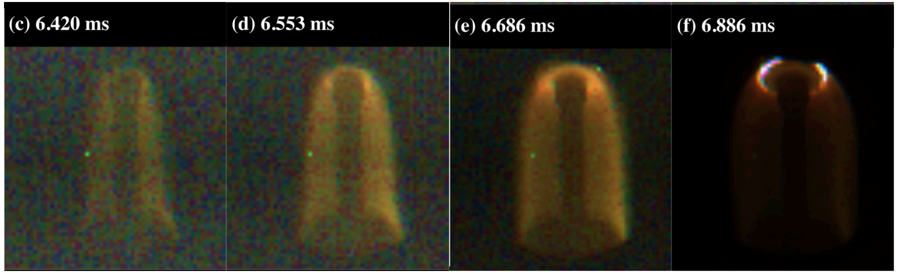
NSTX-like electrode concept is vulnerable to parasitic breakdown in main vessel

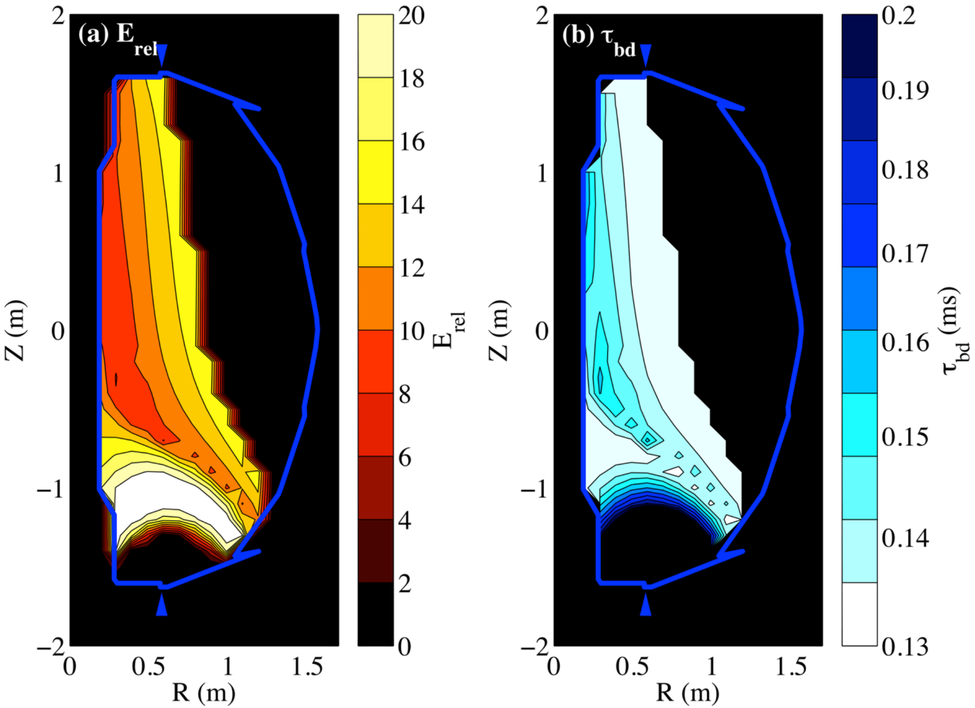
- Breakdown is intended to occur in the divertor area
- Longer connection lengths in main vessel could permit breakdown at $p \sim 10^{-7}$ torr, where as $p_{\mathrm{min}} > 10^{-4}$-$10^{-5}$ torr in injector
- Breakdown in main vessel would prevent efficient injection of current and flux



This effect was observed sometimes in NSTX, but NSTX was less vulnerable

- Similar effect is predicted if sufficient gas fills vessel
- This was observed in some cases where breakdown failed in lower divertor



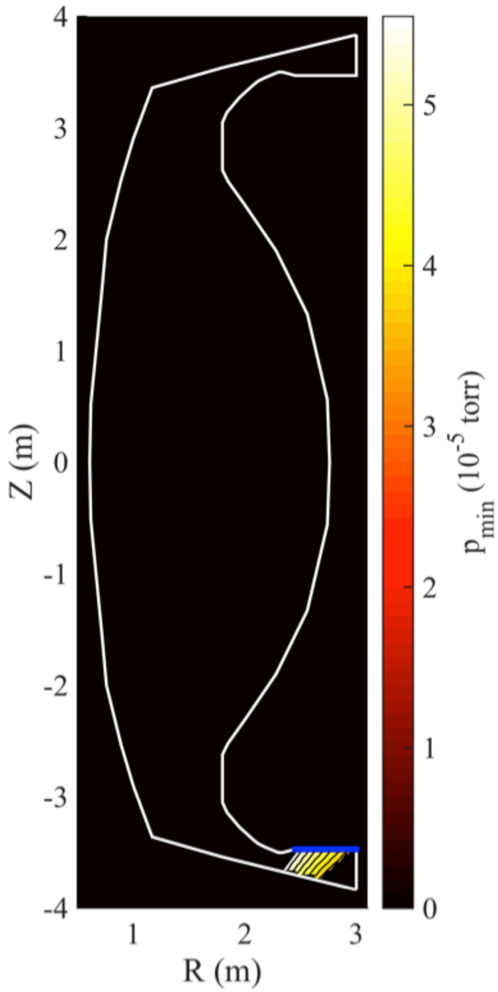


Hammond et al., *Nucl. Fusion* 2018

- Occurrences were rare due to higher p_{min} in main vessel

Localizing the biased electrode to the lower target eliminates this risk

- In the “DIII-D-like” concept, breakdown is restricted to the lower divertor area
- Minimum pressure still relatively low with comparable injector flux smaller devices



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Configuration comparison

- Injector flux will be much higher than previously used
  - Permissible due to higher toroidal fields
  - More injector flux will permit attainment of higher closed-flux currents (I_p)

$$I_p = \frac{2\psi_{\mathrm{pol}}}{\mu_0 R_{\mathrm{maj}} l_i} \qquad \psi_{\mathrm{pol}} \approx 0.7\psi_{\mathrm{inj}} \qquad l_i \approx 0.6$$

  - More poloidal flux means more stored energy for Ohmic self-heating

$$P_{\mathrm{self}} = \frac{\Delta\psi_{\mathrm{p}}}{\Delta t} I_{\mathrm{p}}$$

Key expected quantities

Quantity	ST, B_0 = 3 T	ST, B_0 = 6 T	AT, B_0 = 6 T	AT, B_0 = 9 T
R_{maj}	1.7 m	1.7 m	2.4 m	2.4 m
ψ_{inj}	1.0 Wb	1.0 Wb	1.0 Wb	1.0 Wb

Key expected quantities

Quantity	ST, B_0 = 3 T	ST, B_0 = 6 T	AT, B_0 = 6 T	AT, B_0 = 9 T
R_{maj}	1.7 m	1.7 m	2.4 m	2.4 m
ψ_{inj}	1.0 Wb	1.0 Wb	1.0 Wb	1.0 Wb
I_{inj}	310 kA	160 kA	110 kA	73 kA
PF coil current	780 kA turns	780 kA turns	610 kA turns	610 kA turns
V_{min}	310 V	310 V	310 V	310 V
$p(V_{min})$	4.0×10^{-3} torr	2.0×10^{-3} torr	1.5×10^{-3} torr	1.0×10^{-3} torr

Key expected quantities

Quantity	ST, B_0 = 3 T	ST, B_0 = 6 T	AT, B_0 = 6 T	AT, B_0 = 9 T
R_{maj}	1.7 m	1.7 m	2.4 m	2.4 m
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V_{min}	310 V	310 V	310 V	310 V
$p(V_{\mathrm{min}})$	4.0×10^{-3} torr	2.0×10^{-3} torr	1.5×10^{-3} torr	1.0×10^{-3} torr
I_p	1.1 MA	1.1 MA	0.77 MA	0.77 MA
n_{plasma}	6×10^{18} m^{-3}	3×10^{18} m^{-3}	2×10^{18} m^{-3}	1×10^{18} m^{-3}

Key expected quantities

Quantity	ST, B_0 = 3 T	ST, B_0 = 6 T	AT, B_0 = 6 T	AT, B_0 = 9 T
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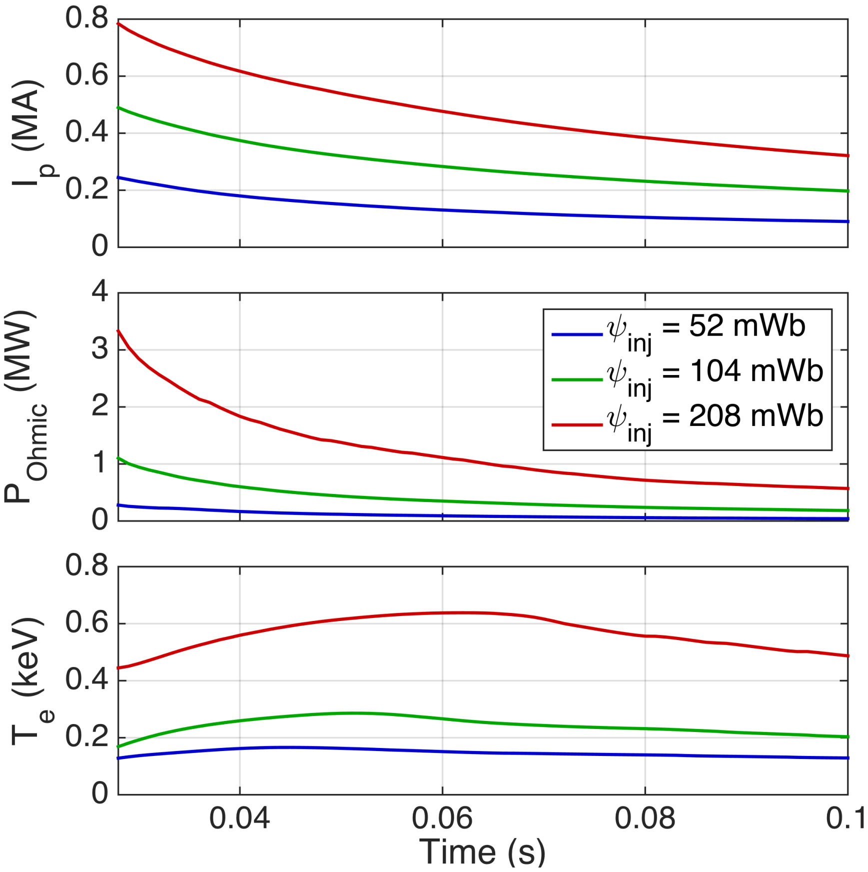
I_p	1.1 MA	1.1 MA	0.77 MA	0.77 MA
n_{plasma}	6×10^{18} m^{-3}	3×10^{18} m^{-3}	2×10^{18} m^{-3}	1×10^{18} m^{-3}
P_{self}	4 MW	4 MW	3 MW	3 MW
n_{co} for ECRH	9×10^{19} m^{-3}	35×10^{19} m^{-3}	35×10^{19} m^{-3}	78×10^{19} m^{-3}

Simulations with TSC support expectations of higher current, self-heating power, and temperatures with increased injector flux

- Tokamak Simulation Code (TSC)
  - Time-dependent, free-boundary equilibrium and transport solver
  - Solves MHD/Maxwell's equations coupled to transport and Ohm's law
- Initial study: NSTX config. with increasing levels of injector flux:
  - 52 mWb (typical NSTX experiment), 104 mWb, and 208 mWb
- Supports main predicted trends
  - I_p increases in proportion with ψ_{inj}
  - Heating power, T_e increase faster

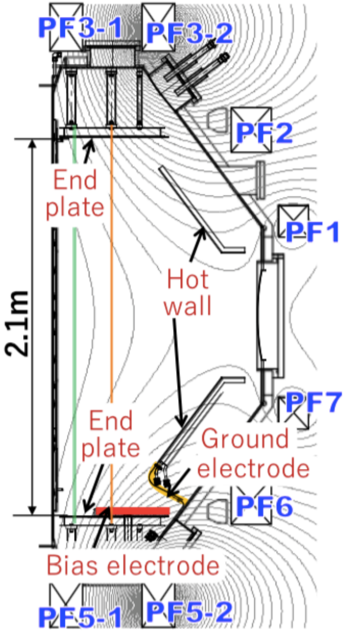


Conclusions

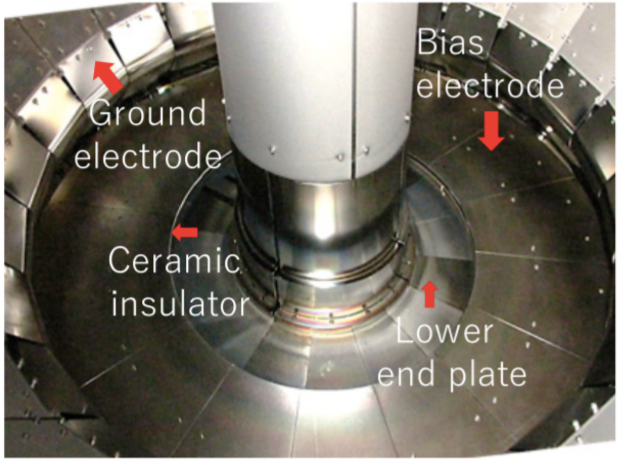
- Requirements for attaining plasma breakdown must be considered for future CHI implementations
  - Breakdown modeling must be spatially resolved
  - A simple model for assessing these requirements has been developed, which applies the Townsend avalanche theory to each flux tube
- CHI systems in future reactors should avoid large electrodes and instead use toroidal rings localized to the divertor
- Next-step devices will be able to use much more injector flux, permitting MA-level plasma currents and higher temperatures

Upcoming CHI experiments in QUEST and URANIA will test concepts to be implemented in fusion reactors

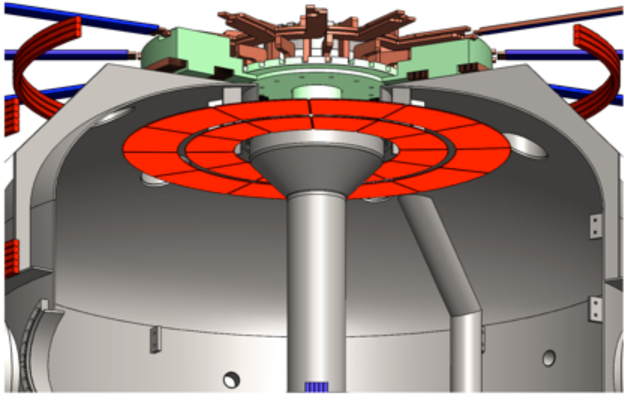
- Localized toroidal electrodes
  - QUEST: single biased electrode
  - URANIA: dual biased electrode
- Low-field side injection
- Coupling to ECRH heating



QUEST



Kuroda et al., *Plasma Fusion Res. Rapid Comm.* 2017



URANIA (currently Pegasus)

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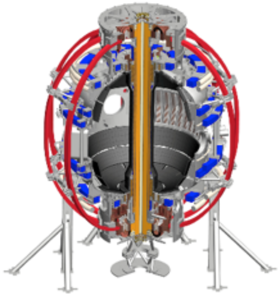


Supplement: assumptions about the effective secondary electron emission coefficient for CHI breakdown calculations

- E_{min} for tokamaks is a special case of Paschen's Law with secondary electron coefficient $\gamma = 0.58$

Tokamak model

$$E_{\min} = \frac{Bp}{\ln\left(AL_c p\right)} \quad V_{\min} = \frac{BL_c p}{\ln\left(AL_c p\right)}$$

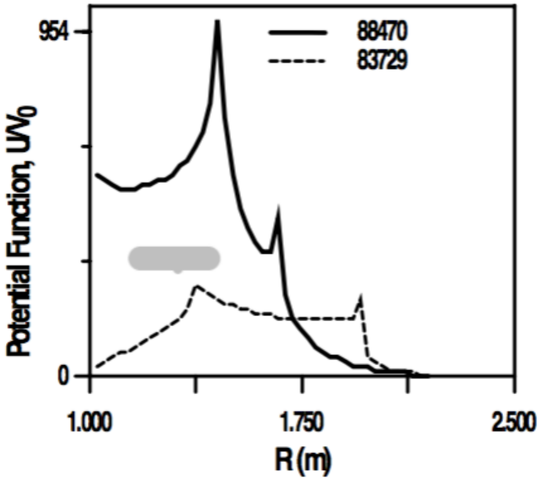
Paschen's Law

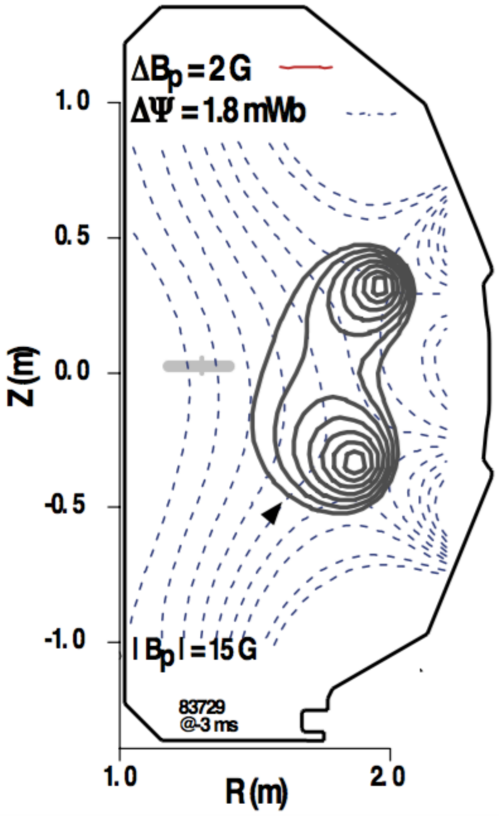
$$V_{\min} = \frac{BL_c p}{\ln\left(AL_c p\right) - \ln\left[\ln\left(1 + 1/\gamma\right)\right]}$$

- Measurements for parallel plates indicate $\gamma = 0.05$ for D_2
- Larger value may be valid in main vessel where L_c is large and particle paths make many revolutions
- In the injector gap, less "enhancement" of γ is expected
  - $\gamma = 0.01$ assumed for injector region (pessimistic for our purposes)

Supplement: spatially-resolved calculation assisted interpretation of breakdown in DIII-D

- Breakdown location found to not coincide with poloidal field null
- Better agreement found with maxima in electric field integrated along flux tubes

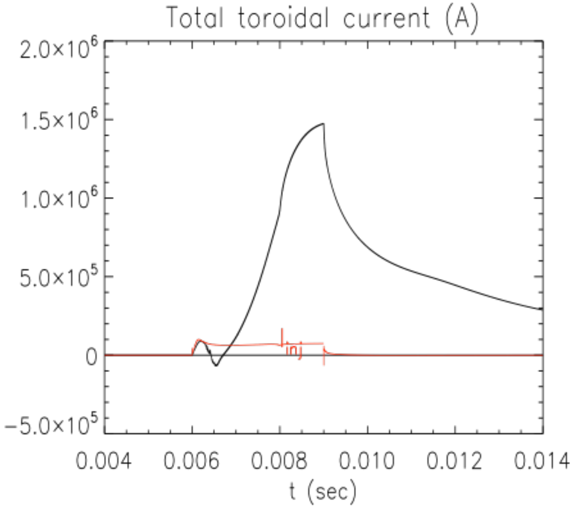


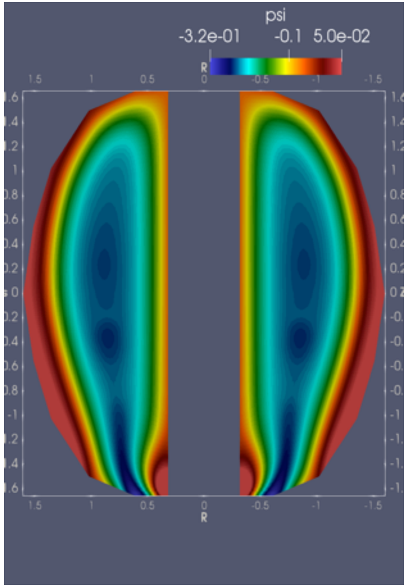


Lazarus et al., *Nucl. Fusion* 1998

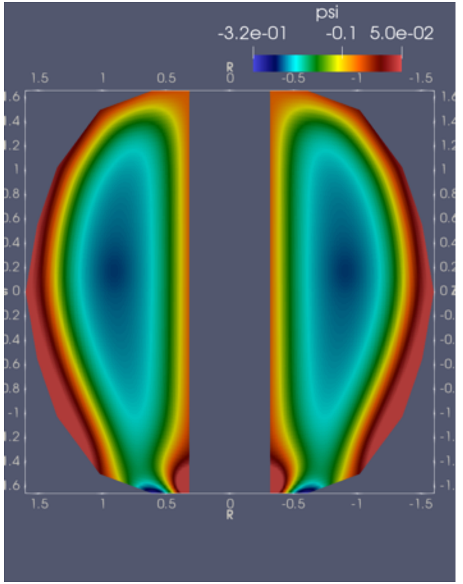
Supplement: NIMROD simulations with high ψ_{inj} show peak current generation over 1 MA

- Simulations performed assuming ψ_{inj} = 0.35 mWb, B_0 = 4 T
- T_e limited to 15 eV but will be increased to 100 eV in the future





8 ms
(injection phase)



9.3 ms
(decay phase)

Ebrahimi, *Nucl. Fusion* 2016

Supplement: additional values from the parameter comparison table

```
|-------------|----------------|-------------------------------------|
|    Quantity |      Dimension |     ST34     ST64     AT64     AT94  |
|-------------|----------------|-------------------------------------|
|      r_axis |              m |     1.70     1.70     2.40     2.40 |
|      aspect |                |     1.70     1.70     2.40     2.40 |
| max_pf_curr |             kA |   782.42   782.42   610.21   610.21 |
|    inj_flux |            mWb |  1000.00  1000.00  1000.00  1000.00 |
|    tor_flux |             Wb |    30.08    60.17    55.67    83.50 |
|       gamma |                |     0.01     0.01     0.01     0.01 |
|     pAtVmin |   10^{-5} torr |   397.33   204.85   148.34    99.17 |
|        vMin |              V |   307.48   307.48   307.48   307.48 |
|  bubbleCurr |             kA |   310.42   155.21   109.94    73.29 |
| currMultFac |                |    30.08    60.17    55.67    83.50 |
|         I_p |             MA |     1.09     1.09     0.77     0.77 |
|    pol_flux |            mWb |   700.00   700.00   700.00   700.00 |
|   vol_ratio |                |    22.50    22.50    25.75    25.75 |
|      P_self |             MW |     3.82     3.82     2.71     2.71 |
|    n_plasma | 10^{17} m^{-3} |    56.74    29.25    18.51    12.37 |
|        n_o1 | 10^{17} m^{-3} |   873.68  3494.46  3494.24  7861.98 |
|        n_x2 | 10^{17} m^{-3} |  1747.36  6988.92  6988.47 15723.95 |
|        fec1 |            GHz |    83.87   167.72   167.72   251.58 |
|        fec2 |            GHz |   167.73   335.45   335.44   503.16 |
|-------------|----------------|-------------------------------------|
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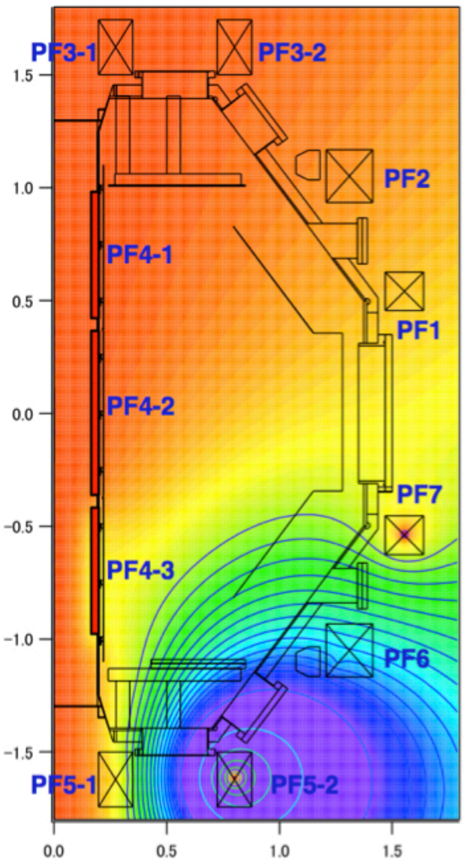
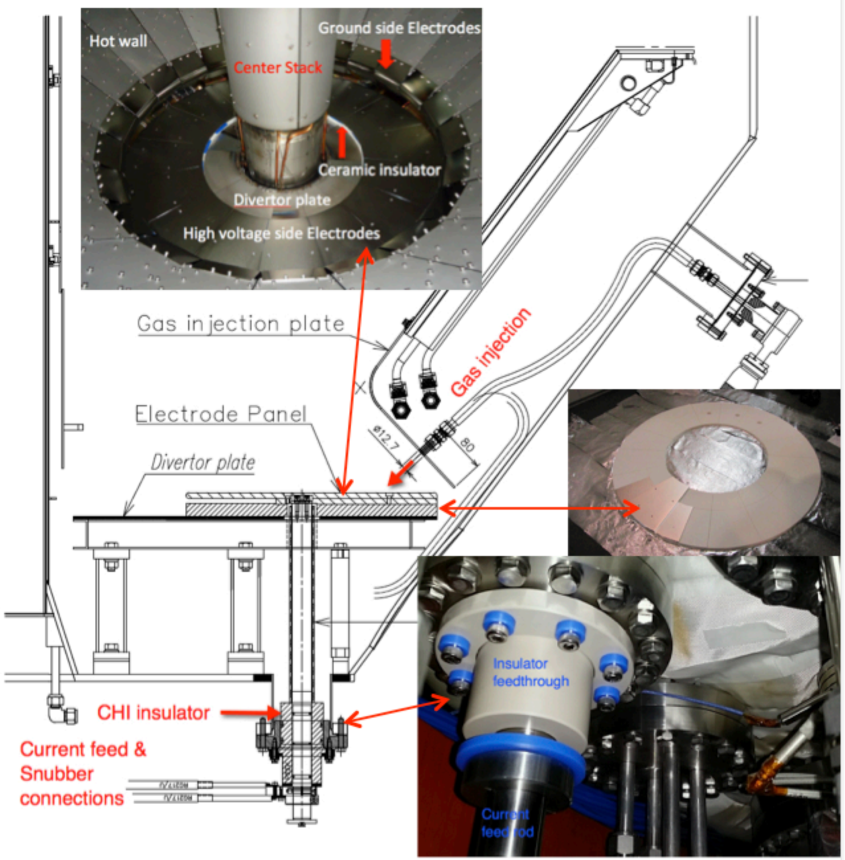
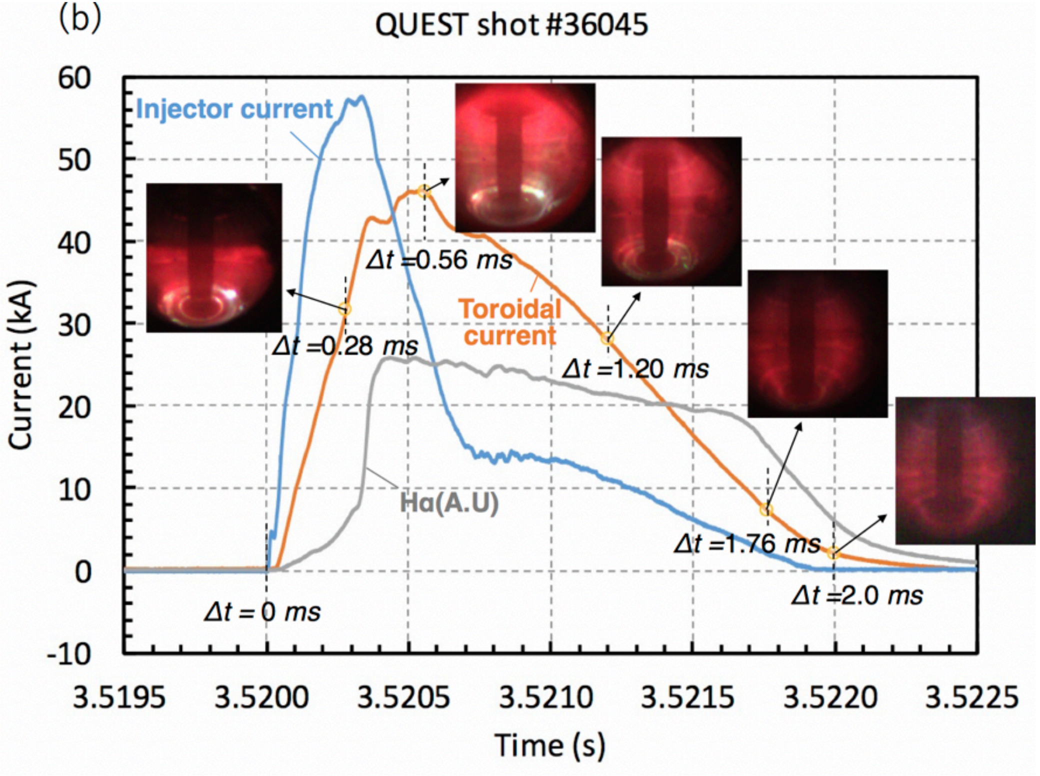
Supplement: CHI configuration on QUEST is developing ST-FNSF relevant single-biased electrode design





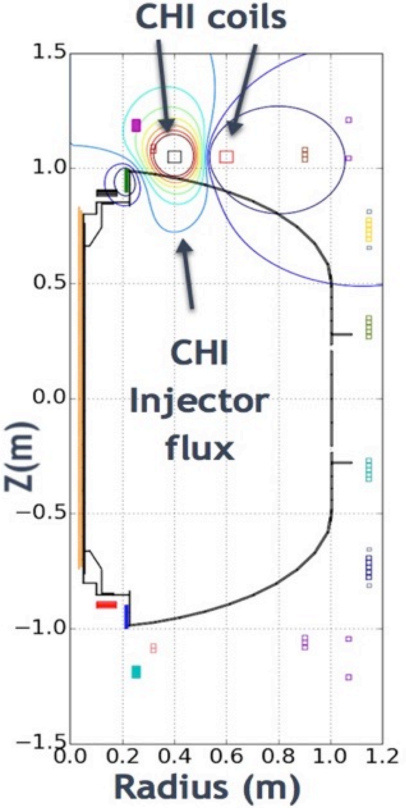
Kuroda et al.

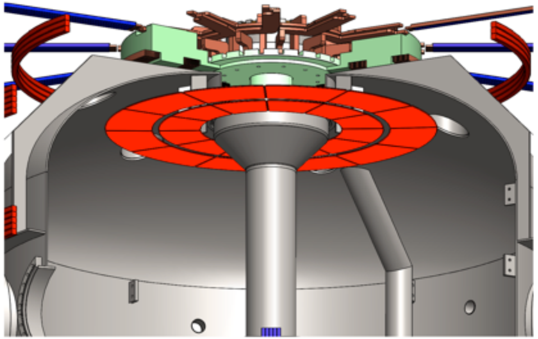
Supplement: Transient CHI start-up on QUEST

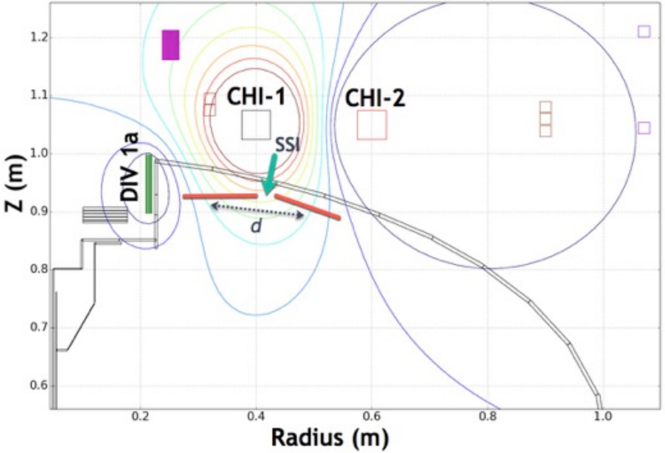


Kuroda et al., *Plasma Phys. Control. Fusion* 2018

Supplement: CHI research on PEGASUS plans to develop a double-biased electrode configuration to better define current path







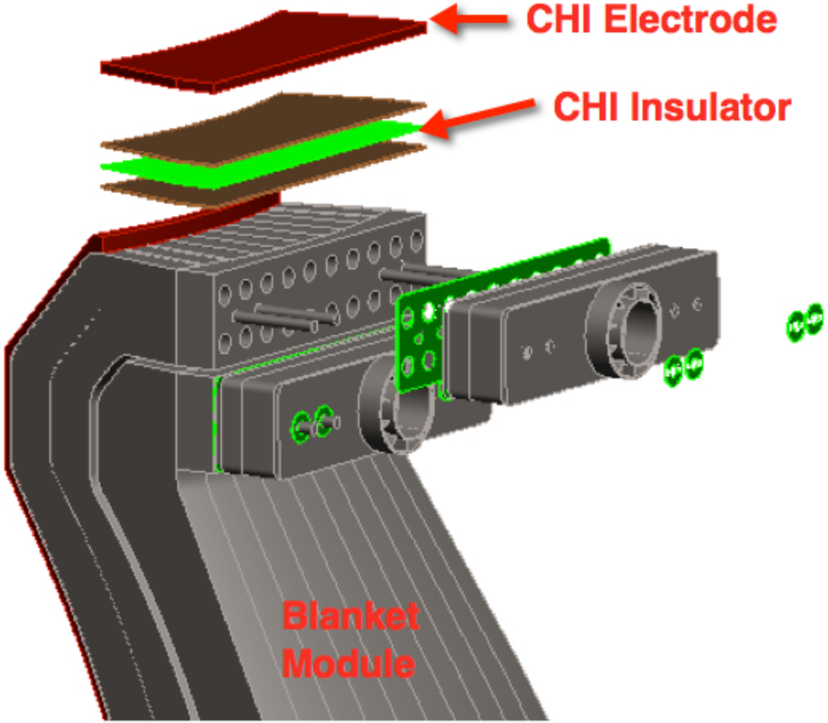
Goals on Pegasus:

- -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

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

Supplement: implementation of a ring electrode in a ST-FNSF

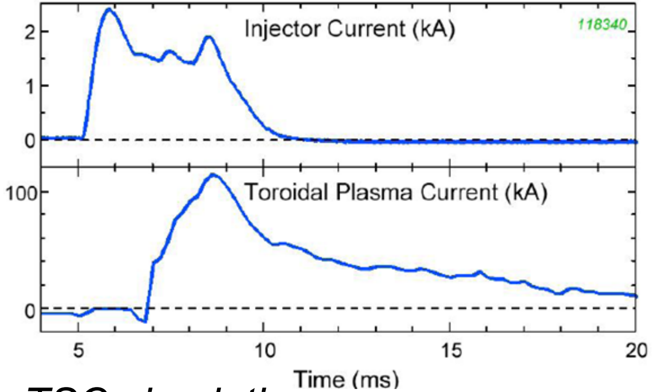
- Ring electrode is placed on top of the upper blanket section
  - Insulator plate isolates electrode from blanket
  - Injector flux connects upper portion of the vessel to the electrode plate on the upper portion of the blanket assembly
  - Electrode is largely shielded from direct neutron streaming



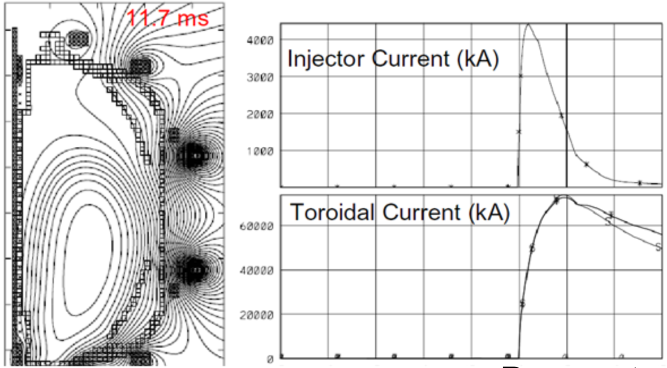
Raman et al., *Fusion Sci. Technol.* 2015

Supplement: Tokamak Simulating Code (TSC) simulations can help understand CHI scaling with machine size

NSTX experimental result



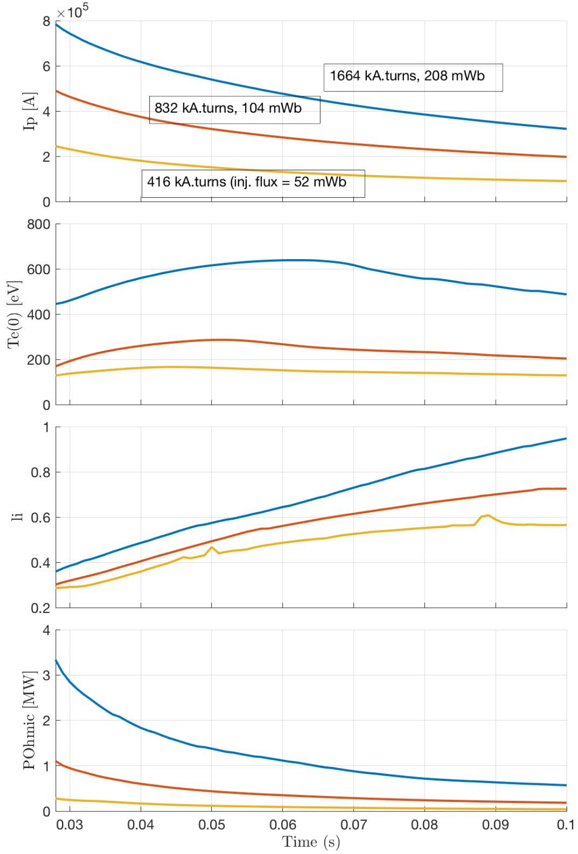
TSC simulation



Raman et al.

- Time-dependent, free-boundary, predictive equilibrium and transport
- Solves MHD/Maxwell’s equations coupled to transport and Ohm’s law
- Requires as input:
  - Device hardware geometry
  - Coil electrical characteristics
  - Assumptions concerning discharge characteristics
- Models evolutions of free-boundary axisymmetric toroidal plasma on the resistive and energy confinement time scales
- NSTX vacuum vessel is modeled as a metallic structure with poloidal breaks
  - An electric potential is applied across the break to generate a desired injector current

Supplement: further details on new TSC work



- Time-dependent, free-boundary, predictive equilibrium and transport
- Solves MHD/Maxwell’s equations coupled to transport and Ohm’s law
- Transient CHI discharge initiated with injector flux values of 52, 104 and 208mWb (B_T = 1T)
  - At the end of the CHI phase, injector current is reduced to zero
  - Transport equations solved to calculate input power & heating
  - Plasma allowed to decay without any additional external heating sources
  - Transport parameters maintained same for all cases
- Simulations show an initial low normalized inductance plasma, consistent with current being driven in the edge by the CHI process
  - Inductance increases as current diffuses radially in
  - Transient CHI naturally produces a low initial inductance discharge needed for high-performance ST and AT discharges (we may want to remove this frame and associated text – to not spend too much time on this – think about it)
- The Ohmic input power increases with increasing injector flux
- Electron temperatures for the 208 mWb cases increases to over 500eV on its own
  - 1 Wb plasmas may heat to the 1keV level on their own? (can delete sub bullets)
  - Requires experimental verification

Supplement: required experimental developments

- Experiments in QUEST and URANIA will test CHI with relevant properties:
  - Localized toroidal electrodes
  - Injection from the low-field side
  - Coupling to ECRH heating

Parameters	HIT-II	NSTX	QUEST	*URANIA (to be finalized)*
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*