Transient CHI Plasma Start-up and Non-inductive Current Ramp-up in NSTX-U

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Presented by Brian A. Nelson

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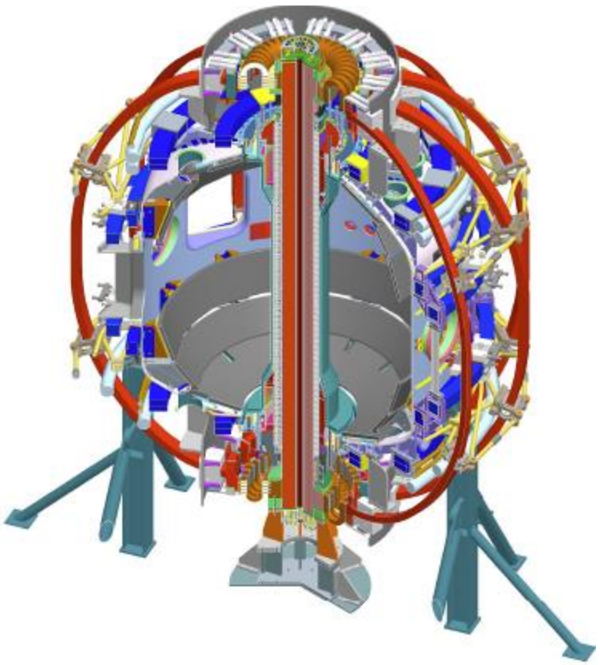
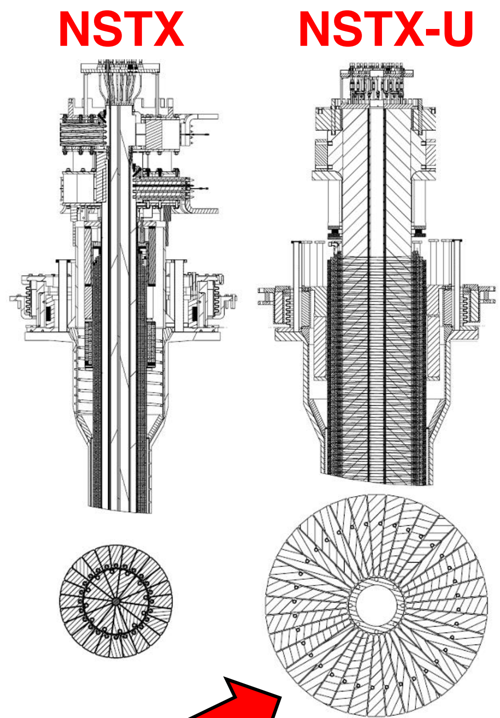
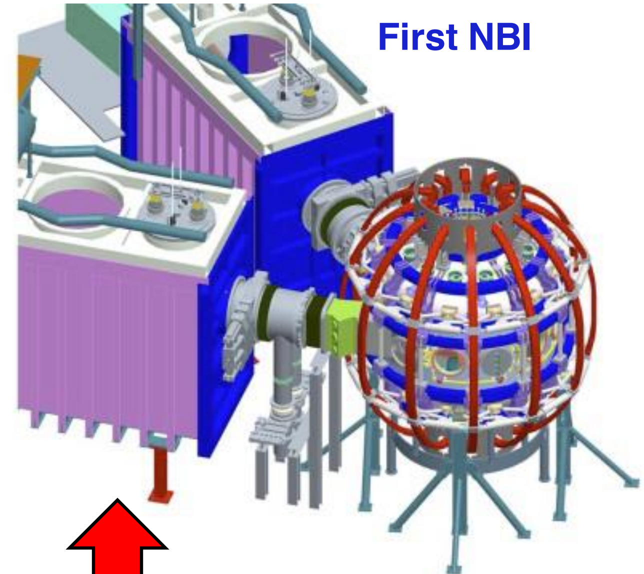
NSTX-U Research will Advance the ST as a Candidate for a Fusion Nuclear Science Facility (FNSF)







New large center stack in NSTX-U enables

- B_T: Increases from 0.55 to 1 T
- Plasma current: 1 to 2 MA
- Discharge pulse duration: 1 s to 5 s

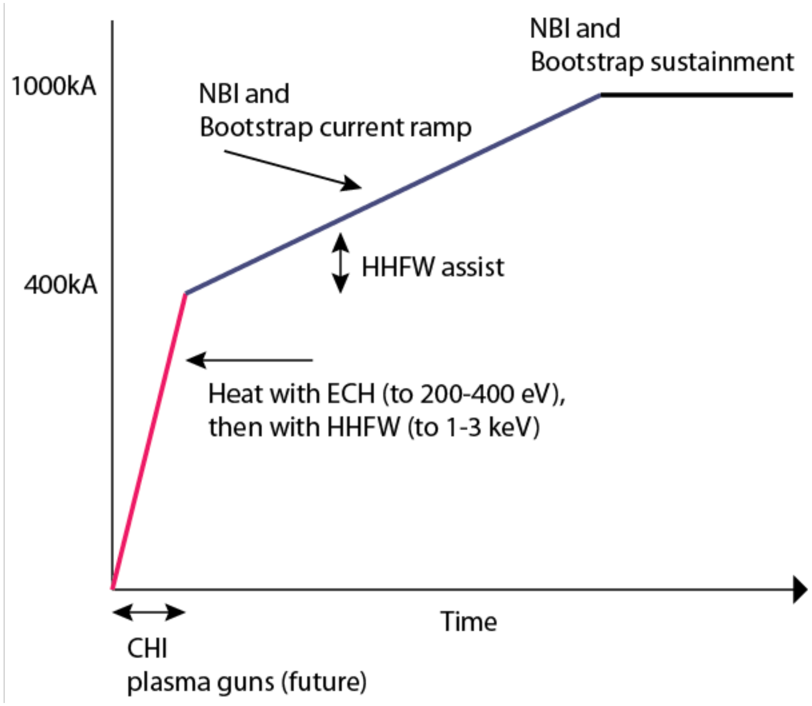
Second tangential neutral beam in NSTX-U enables development of

- Non-inductive current ramp-up and 100% NI sustained operation

NSTX-U Aims to Develop and Understand Non-inductive Start-up/Ramp-up to Project to ST-FNSF Operation

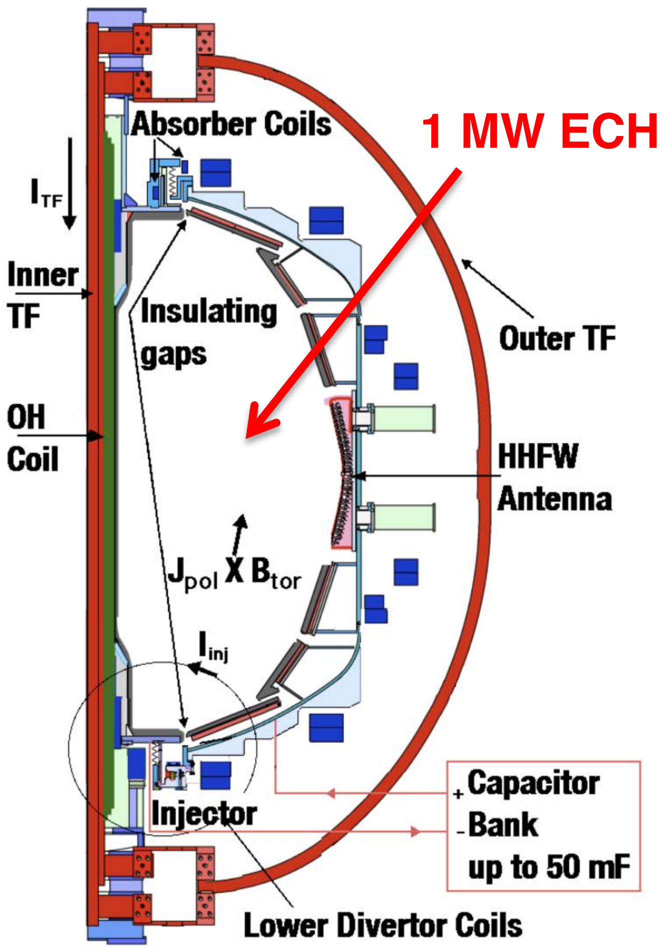
- Establish physics basis for ST-FNSF, and non-inductive start-up is essential in ST
  - Simplify the tokamak concept to reduce cost
- NSTX-U is striving for fully non-inductive operations
  - Transient Coaxial Helicity Injection (CHI) start-up is the front end of that objective
  - Plasma guns and EBW will be tested after those systems are technically ready

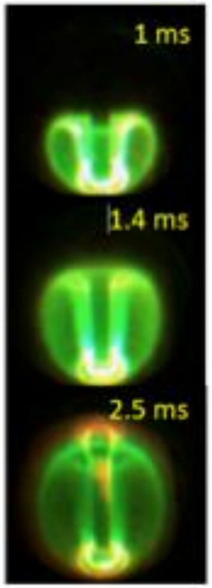
NSTX-U Start-up and Ramp-up Strategy



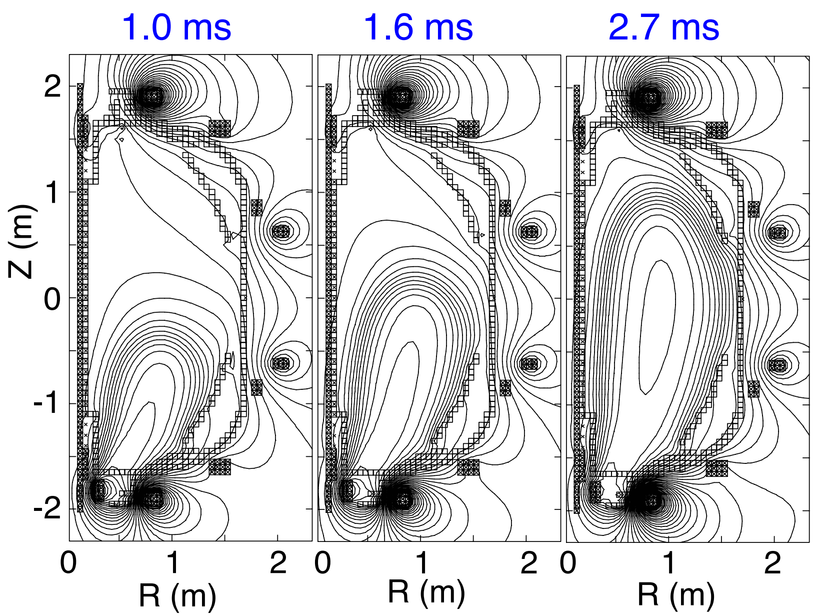
CHI is Planned to be Used as Initial Current Seed for Subsequent Non-inductive Current Ramp-up in NSTX-U

CHI in NSTX/NSTX-U





TSC (axisymmetric 2D) simulation of CHI startup

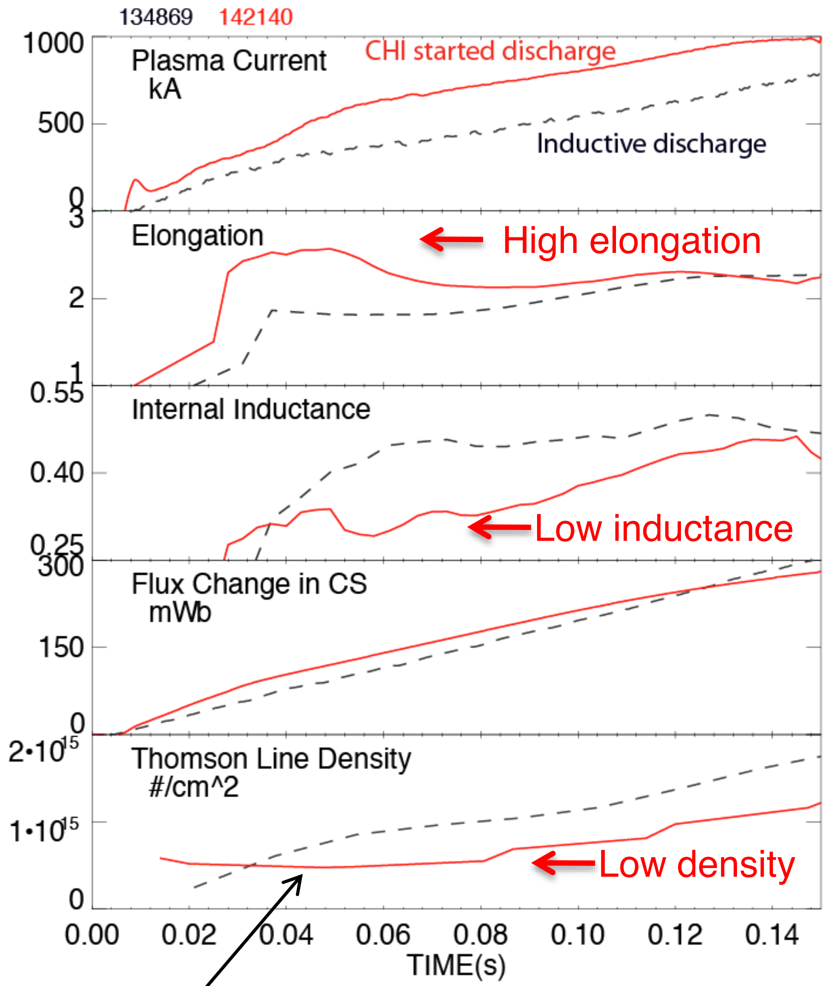


New Tools for CHI

- > 2.5x injector flux (proportional to I_p)
- TF = 1 T (increases current multiplication)
- ECH (increases T_e)
- > 2 kV CHI voltage (increases flux injection)
- Full Li coverage (reduces low-Z imp.)
- Metal divertor, cryo pump (increases T_e)

Plasma Discharge Ramping to 1 MA Required 35% Less Inductive Flux when Coaxial Helicity Injection (CHI) is Used

CHI assisted startup in NSTX



CHI generates plasmas with low n_e so that ECH could be used to heat these plasmas

27 kJ of stored capacitor bank energy used for CHI plasma start-up

CHI produced plasma is clean

(Discharges have transitioned to H-mode after coupling to induction)

Externally Produced Toroidal Field makes CHI much more Efficient

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

  ψ_{inj} = injector flux

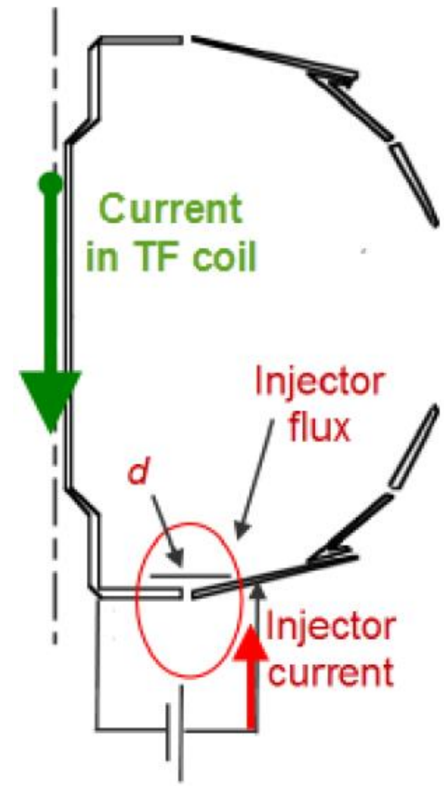
  d = flux foot print width

  I_{TF} = current in TF coil

Injector current → Toroidal flux ↓

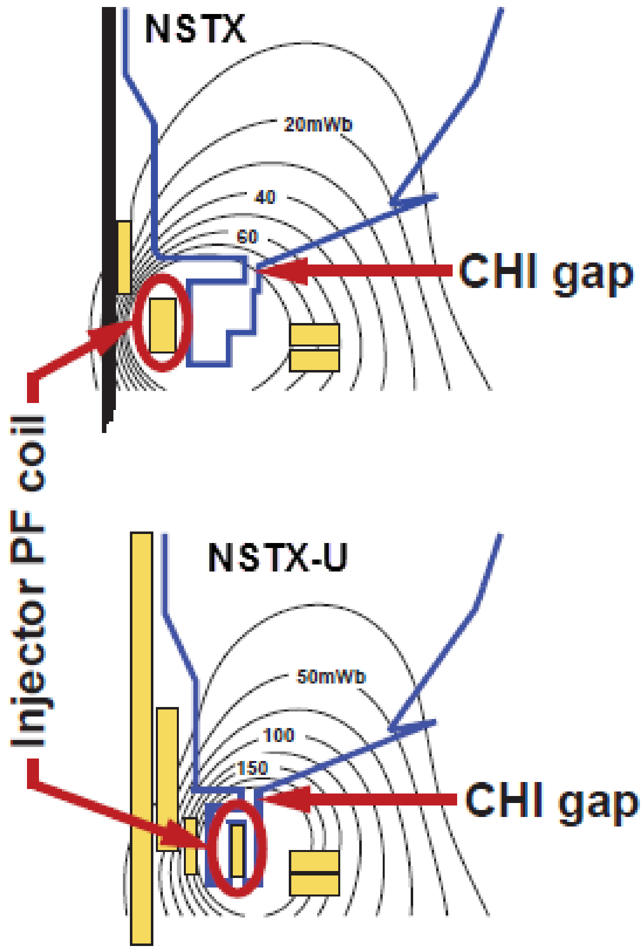
$$I_P = I_{inj}(\psi_T / \psi_{inj})$$

- 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



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

CHI Start-up to ~0.4 MA is Projected for NSTX-U, and Projects to ~20% Start-up Current in Next-step STs

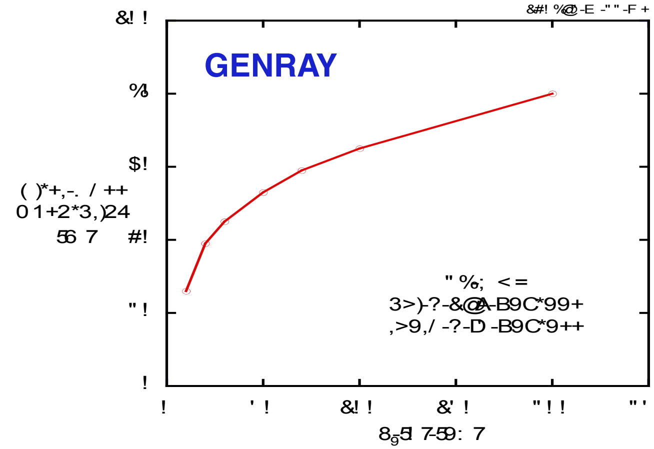


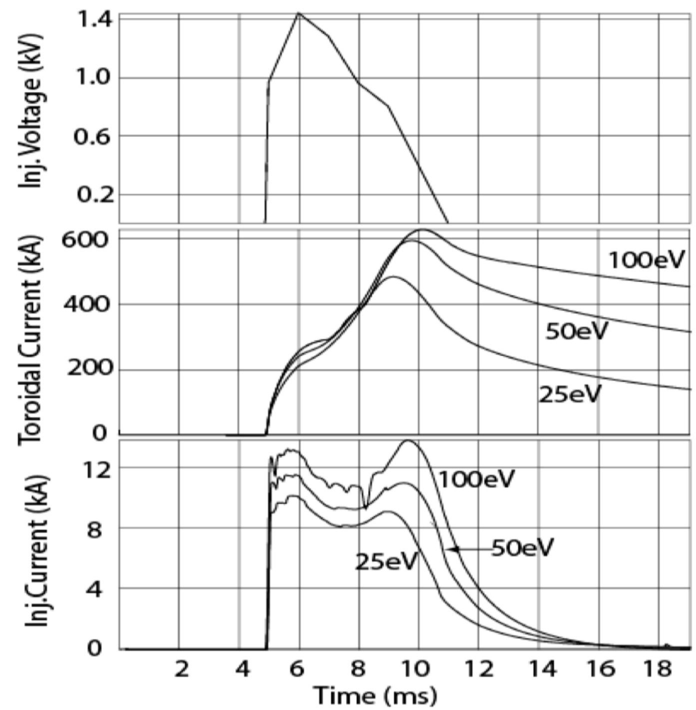
Parameters	NSTX	NSTX-U	ST-FNSF	ST Pilot Plant
Major radius [m]	0.86	0.93	1.2	2.2
Minor radius [m]	0.66	0.62	0.80	1.29
B_T [T]	0.55	1.0	2.2	2.4
Toroidal flux [Wb]	2.5	3.9	15.8	45.7
Sustained I_p [MA]	1	2	10	18
Injector flux (Wb)	0.047	0.1	0.66	2.18
Projected start-up current (MA)	0.2	0.4	2.0	3.6

Injector flux in NSTX-U is ~ 2.5 times higher than in NSTX → supports increased CHI current

Ramp-up Strategy Significantly Benefits from 1-2 MW ECH to Heat CHI Plasma

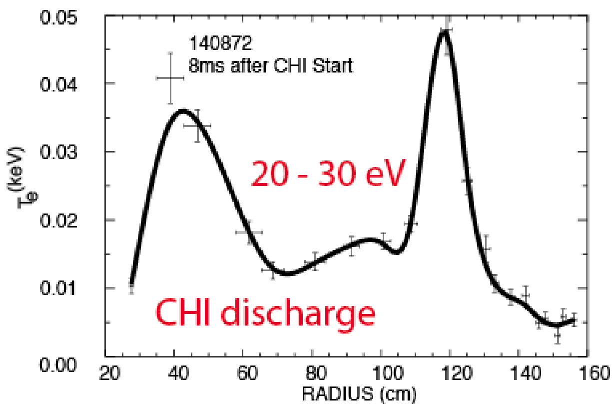
- In a 500 kA decaying inductive discharge, TSC* simulations indicate 0.6 MW of absorbed ECH power could increase T_e to ~400 eV in 20 ms (with 50% ITER L-mode scaling)
  - ECH absorption and deposition profile being modeled using GENRAY
  - CHI discharge densities at T_e = 70 eV would allow 60% first-pass absorption by 28 GHz ECH in NSTX-U
- Increased T_e predicted to significantly reduce I_p decay rate
  - ECH heated plasma can be further heated with HHFW
  - Maximum HHFW power < 4 MW, higher B_T in NSTX-U would improve coupling
  - HHFW has demonstrated heating a 300 kA / 300 eV plasma to > 1 keV in 40 ms



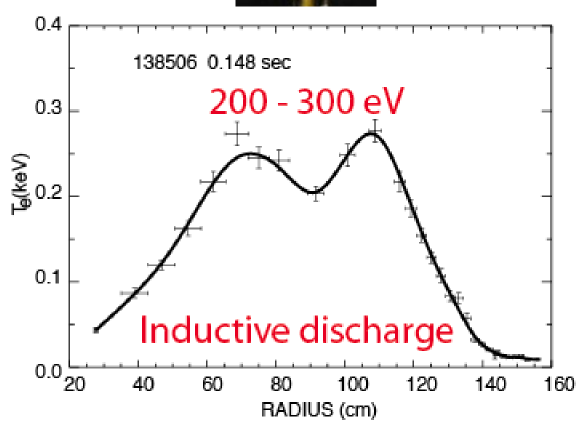


S.C. Jardin et al., J. Comput. Phys. 66, 481 (1986)

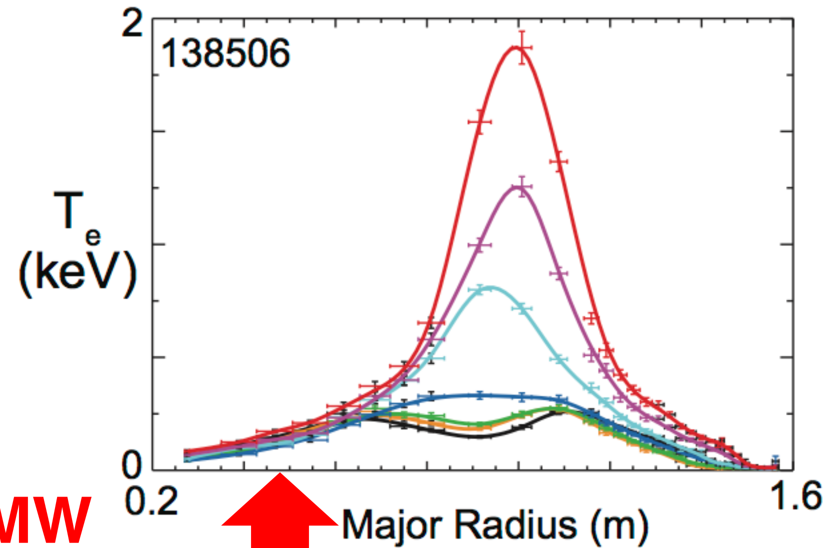
Bridge Electron Temperature Gap Between CHI Start-up and Current Ramp-up Requirements with ECH Heating

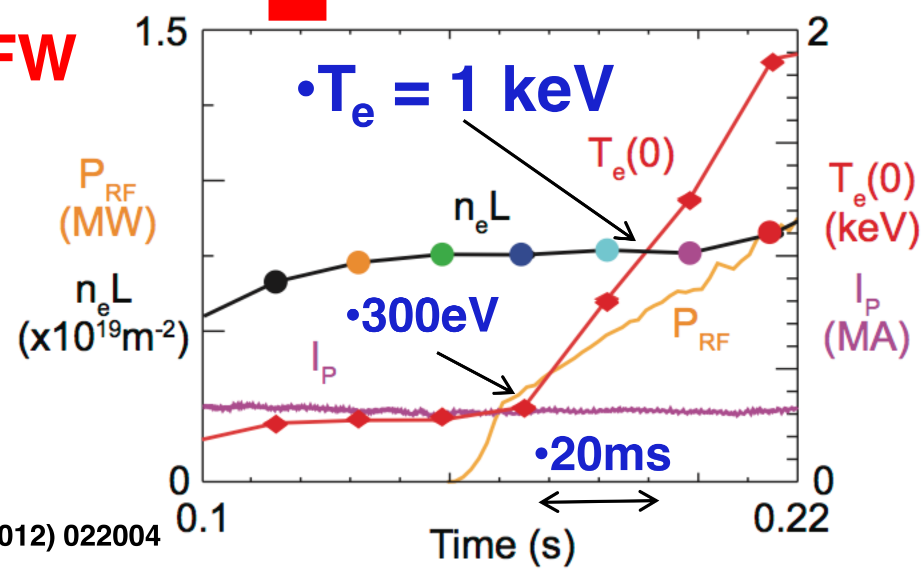


1MW
ECH



1-2 MW
HHFW





G. Taylor et al.,
Phys. Plasmas 19 (2012) 022004

CHI Injector and Absorber Poloidal Field Coil Parameters (NSTX and NSTX-U)

Coil	R (cm)	# Turns	L (mH)	R (mΩ)	kA-Turns (min)	kA-Turns (max)	kA.Turns/ms and Voltage (kV)
NSTX							
PFAB1	43.06	48	3.93	129.7	-48	48	+/- 4.8 [1 kV]
PFAB2	63.18	48	6.46	190.2	-48	48	+/- 4.8 [1 kV]
PF1B	30.5	32	0.673	3.15	0	+320	+19 [2 kV]
PF2L	80	28	1.98	7.32	-560	+560	+/- 25.3 [2 kV]
NSTX-U							
PF1AU,L	32.4	64	2.03	8.93	-460	1172	56.2 [2 kV]
PF1BU,L	40.4	32	1.14	9.19	-192	416	+45.8 [2 kV]
PF1CU,L	55.05	20	0.72	4.49	-100	318	+41.1 [2 kV]
PF2L	80	28	1.98	7.32	-308	420	+25.3 [2 kV]

Injector coil is positioned much closer to CHI gap (R = 57-61.6 cm) in NSTX-U

Absorber buffer coils have much higher current slew rates

TSC Simulations are Being Used to Develop Initial Start-up Scenarios for NSTX-U

- Time-dependent, free-boundary, predictive equilibrium and transport

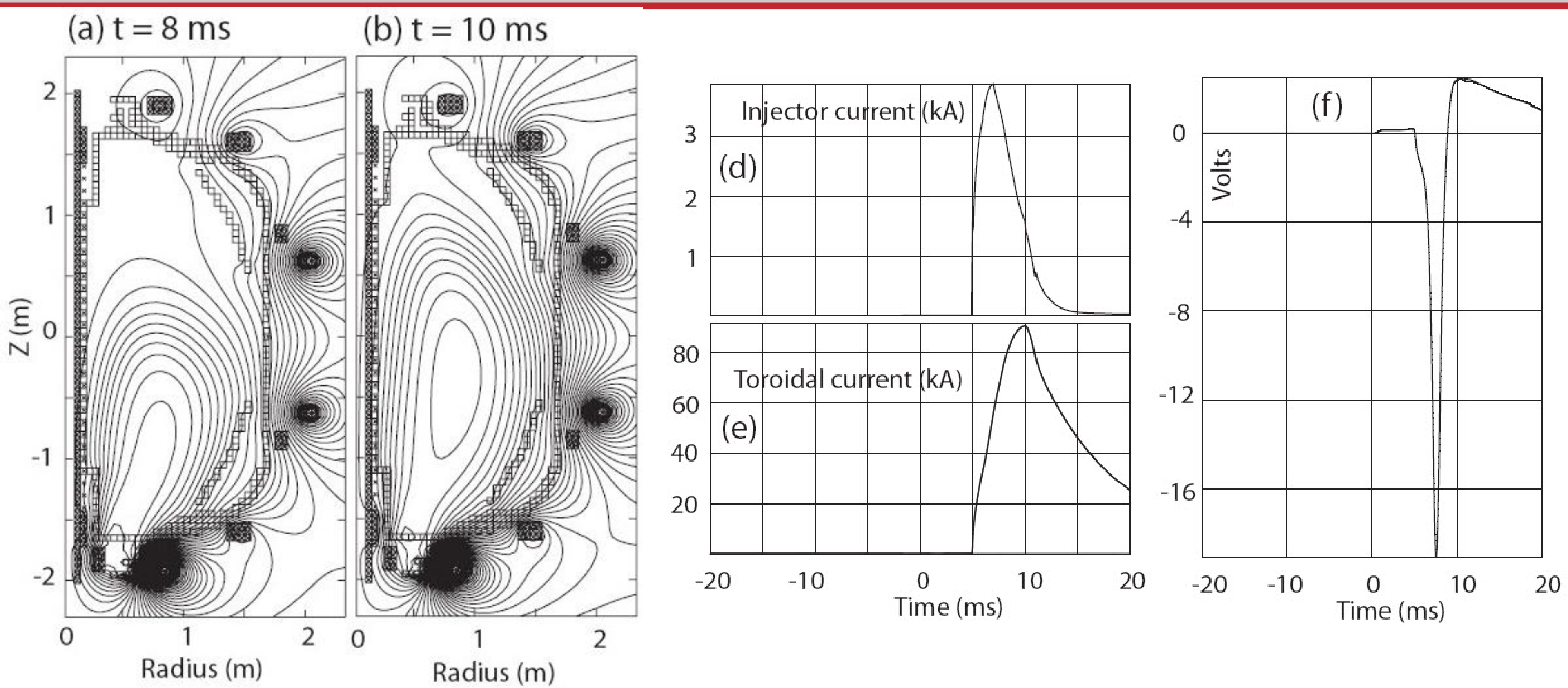
- Solves MHD/Maxwell's equations coupled to transport and Ohm's law

- 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 modeled as a metallic structure with poloidal breaks
    - An electric potential is applied across the break to generate the desired injector current

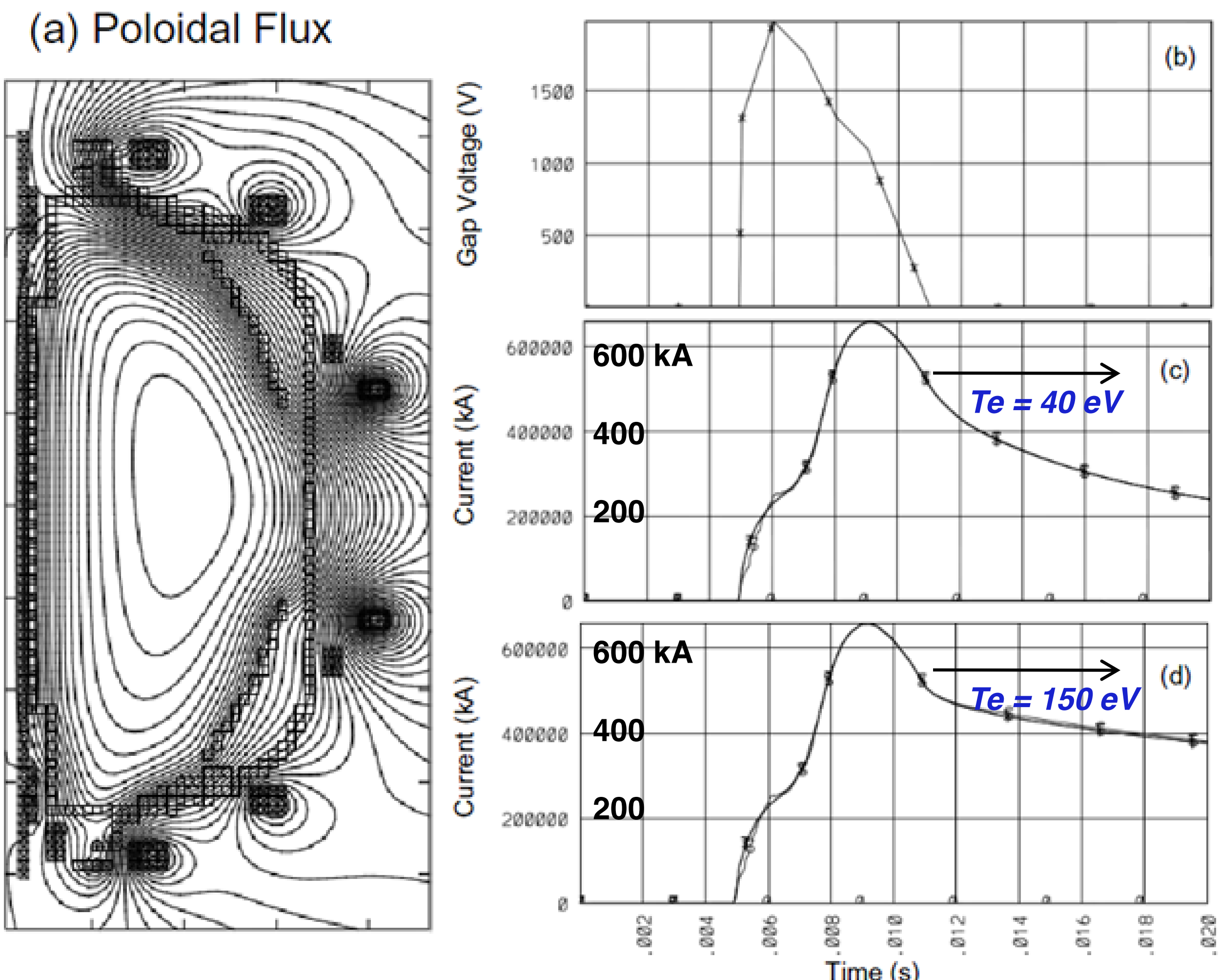
Closed Flux Surfaces Begin to Form after a Positive Loop Volatge is Induced by the Decaying Poloidal Flux



Simulation of a 60 kA NSTX Transient CHI discharge with the TSC code. For these simulations, the coil currents used in the experiment were used as input parameters. The CHI voltage is applied at 5 ms. Shown area (a-b) poloidal flux contours, (d) the injector current, (e) the plasma current and (f) the induced loop voltage at Z = -0.3 m along the inner vessel during the growth and decay of the CHI plasma discharge.

R. Raman, S.C. Jardin, et al., Nucl. Fusion 51, 113018 (2011)

TSC Simulations Show Slower Current Decay as the Electron Temperature is Increased

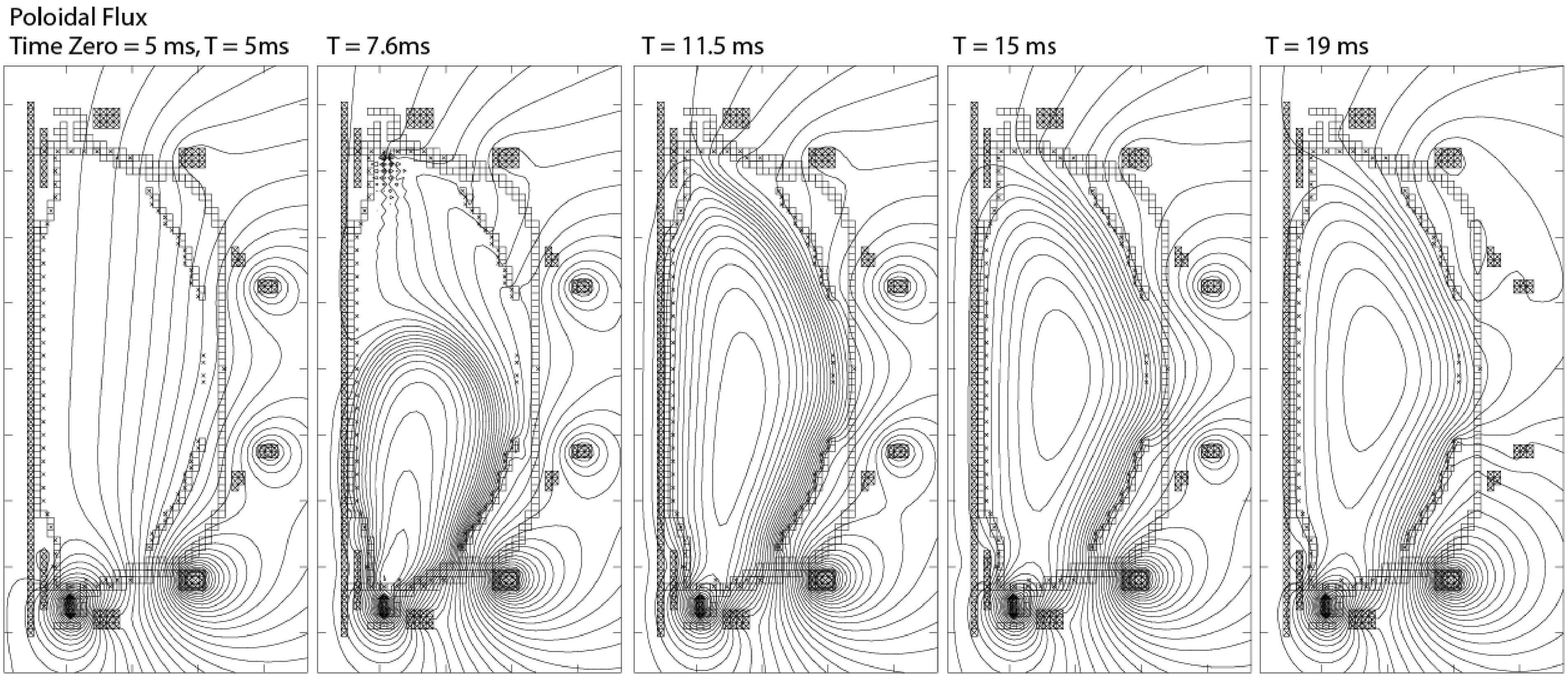


Projected plasma current for CTF >2.5 MA [$I_p = I_{inj}(\psi_{Tor}/\psi_{Pol})$]

- Based on 50 kA injector current (1/5th of the current density previously achieved)
- Current multiplication of 50 (achieved in NSTX)

- **Consistent with present experimental observations in NSTX that attain >300 kA at 0.5 T**
- **NSTX-U will have B_T = 1 T capability, ST CTF projected to have B_T about 2.5 T**

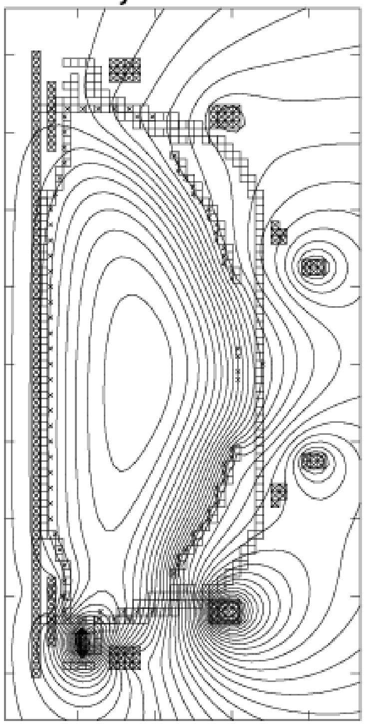
Initial CHI Start-up Scenario in NSTX-U
(TSC Simulations in NSTX-U Geometry – Static Coil Currents)



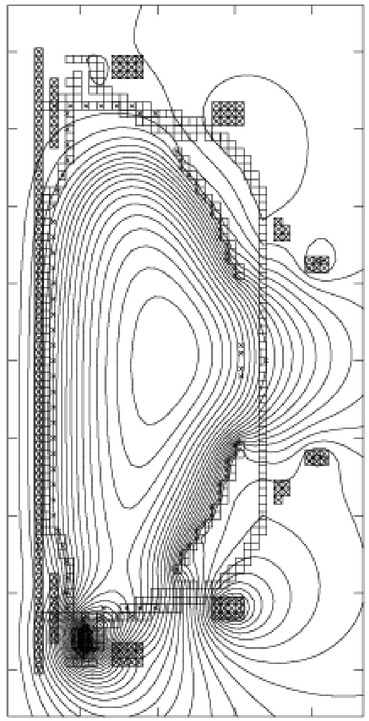
- Initial Transient CHI discharges in NSTX-U will start with low levels of current in the Primary PF1CL injector coil
- CHI discharge will be grown into a magnetic well suitable for the final CHI plasma equilibrium
- Poloidal flux evolution (shown above) is for for constant (in time) coil current values of:
    - PF1CL (2 kA, max available 15 kA), PF1AL (-0.4 kA), PF2L (-0.35 kA), PF3L (-0.5 kA),
    - PF5 (-0.15 kA), PF3U (-0.07 kA), and zero current in the other coils
    - Absorber arc suppression may require low levels of current in the PF1CU coil

CHI Produced Toroidal Current Increases with Increasing Levels of Current in the CHI Injector Coil (NSTX-U)

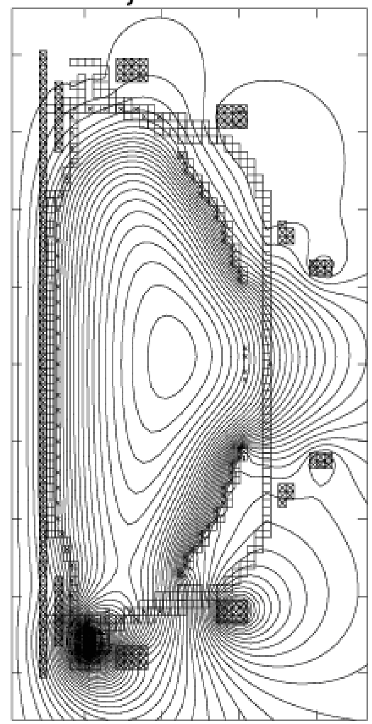
Poloidal Flux at 15 ms
2 kA in Injector Coil



4 kA in injector Coil

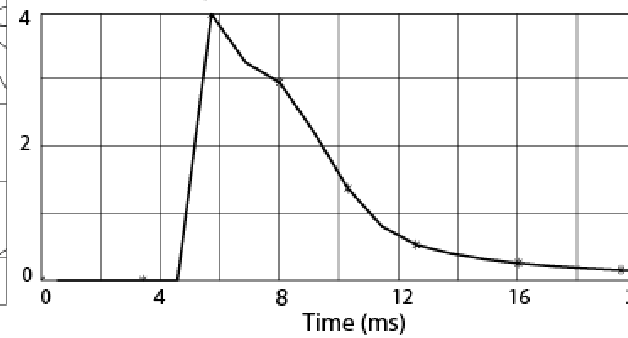


8 kA in Injector Coil

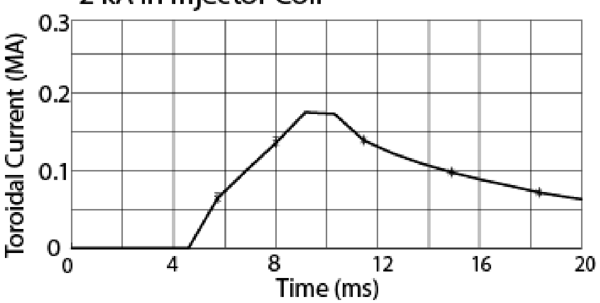


Representative Injector Volatge Waveform (Arbitrary Units)

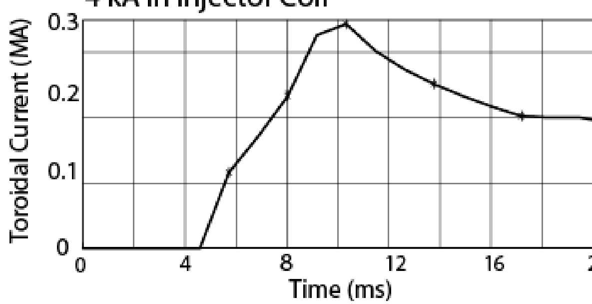
Representative Injector Current Waveform (Arbitrary Units)



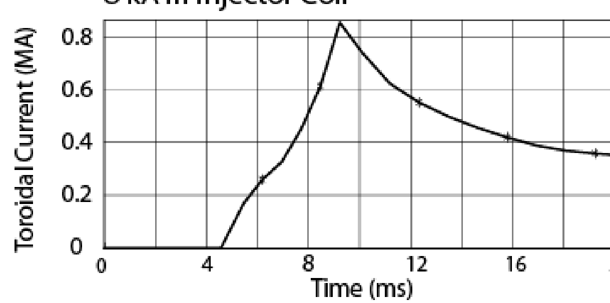
2 kA in Injector Coil



4 kA in injector Coil



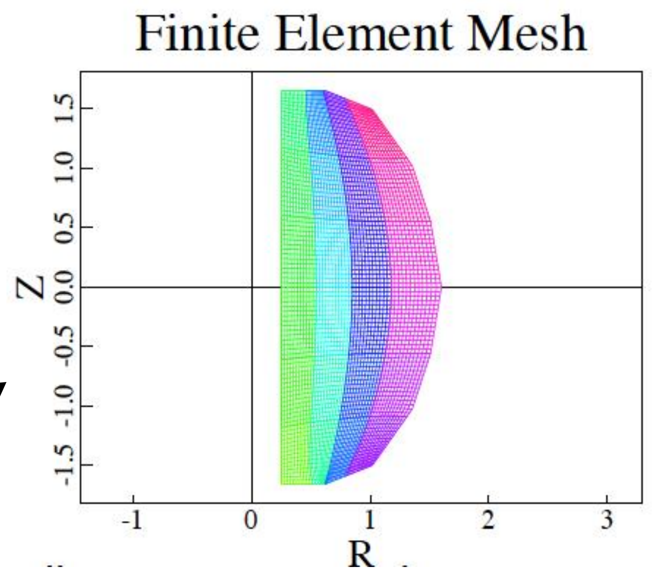
8 kA in Injector Coil

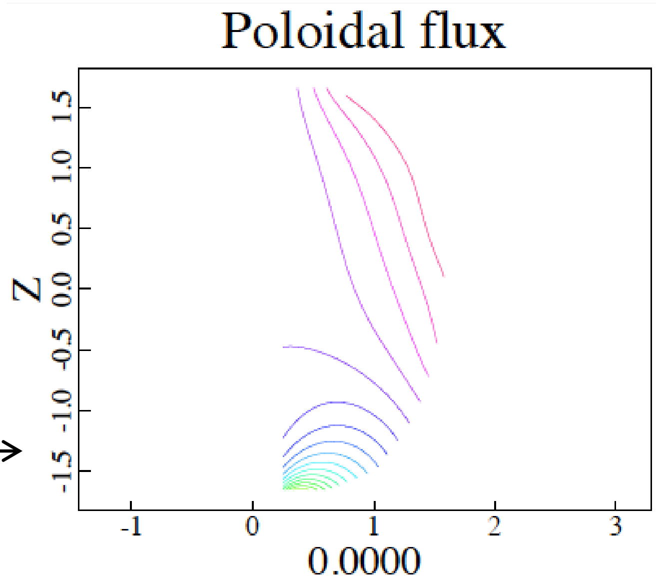


R. Raman et al., IEEE Transactions on Plasma Science, Vol 42, No. 8 2154 (2014)

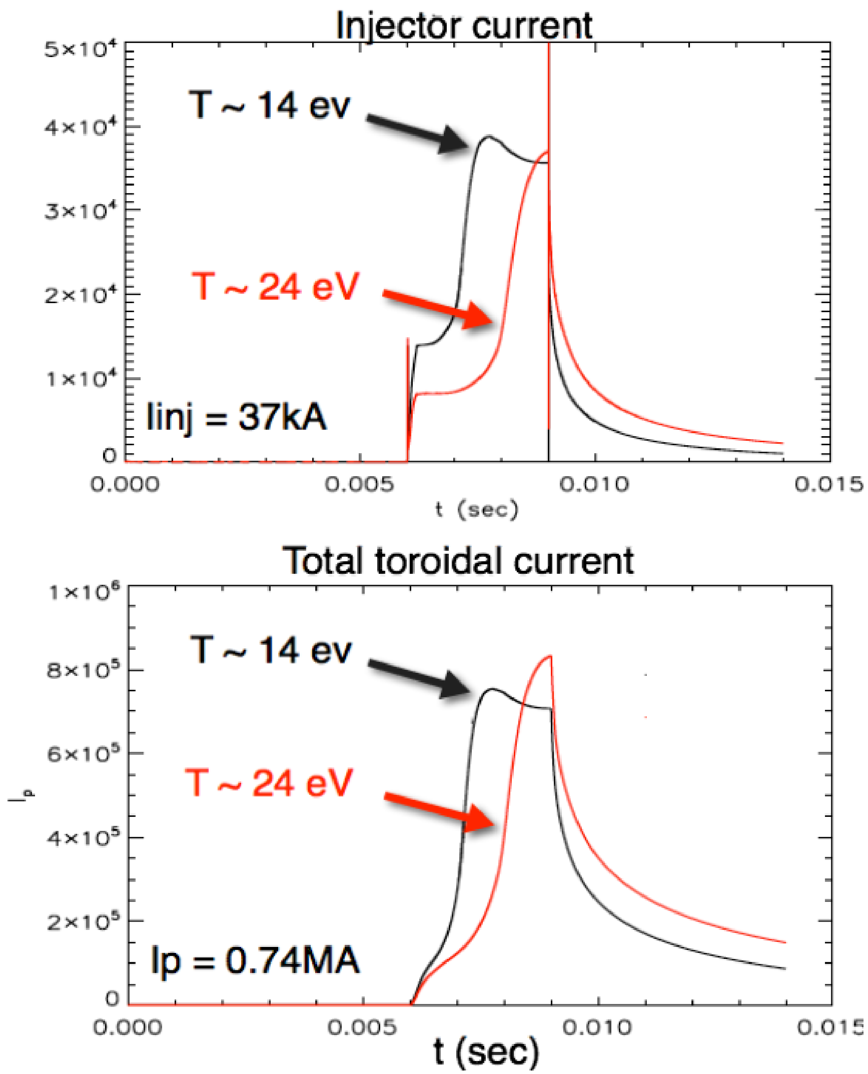
Axisymmetric Simulations are Performed Using the Resistive MHD Code NIMROD

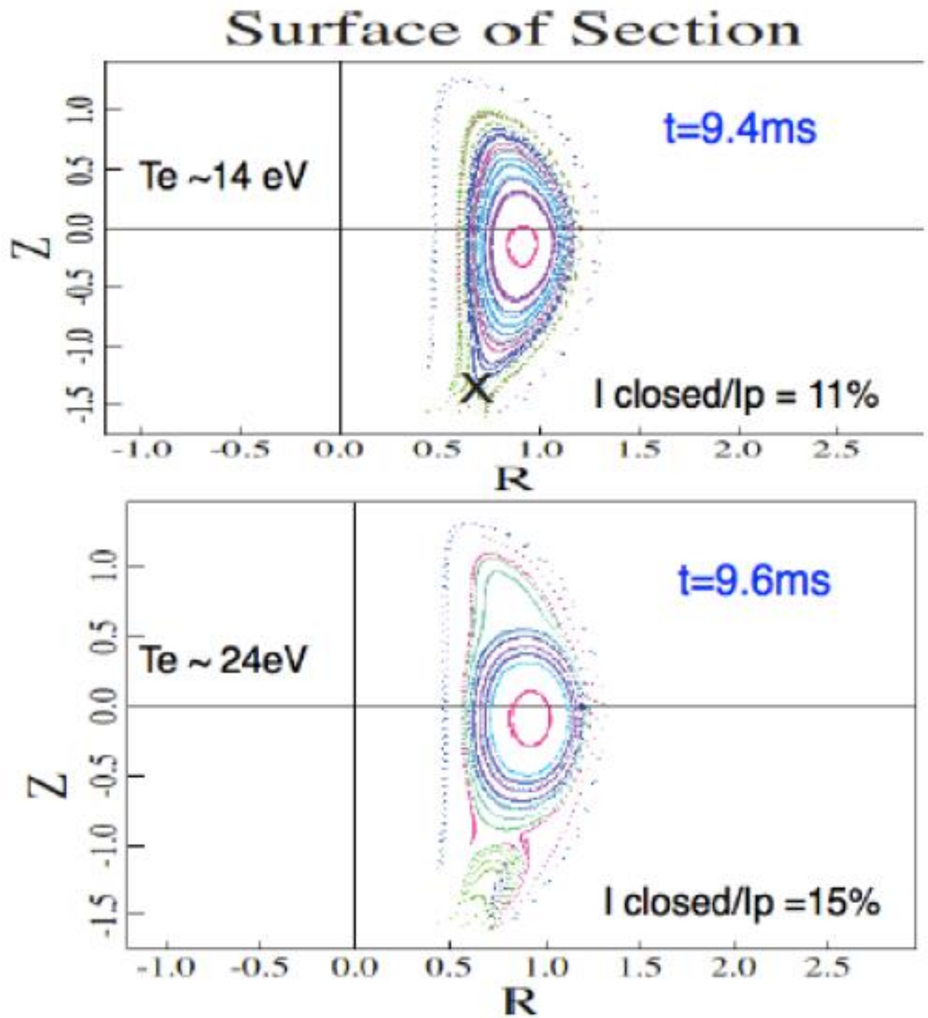
- Simulations provide an understanding of the physics of injection, flux-surface closure in transient CHI discharges
- The computational model is similar in geometry to the NSTX vessel with a narrow gap of 4 cm between the inner and outer divertor plates
- Axisymmetric (n=0) with poloidal grid (45 x 90) fourth or fifth order finite elements
- Voltage is applied across the injector gap (V_{inj}), and no current is allowed on the absorber gap by setting $\Delta B_\phi=0$
- E x B normal flows at the injector and absorber gaps is allowed
- Initial injector poloidal flux is produced by including currents in the NSTX poloidal field coils





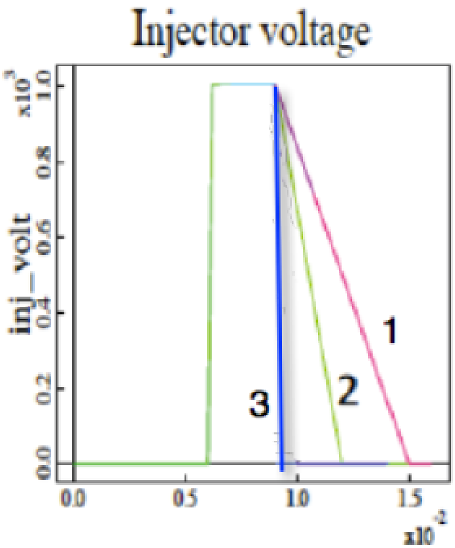
Flux Closure Obtained Only at Low Magnetic Diffusivity and at Levels Similar to that in the Experiment

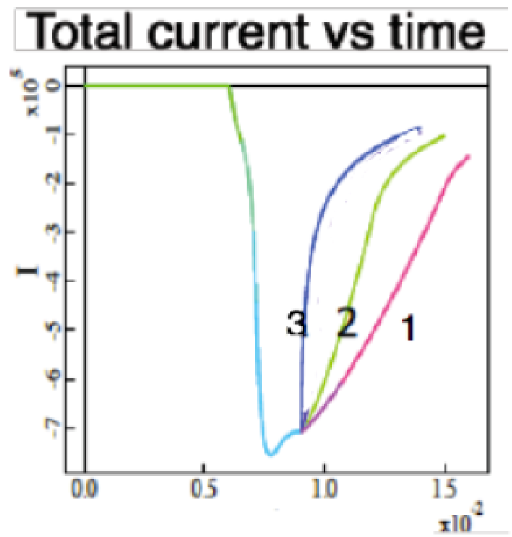


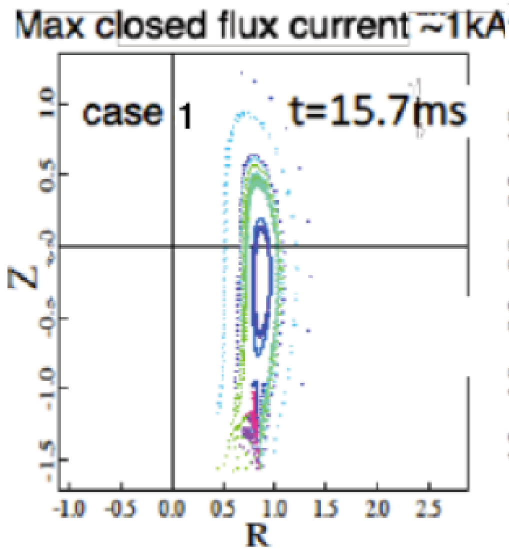


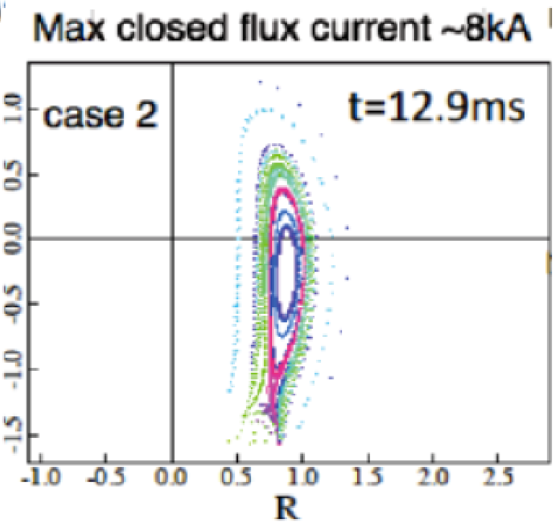
Closed flux fraction increases as the magnetic diffusivity is reduced

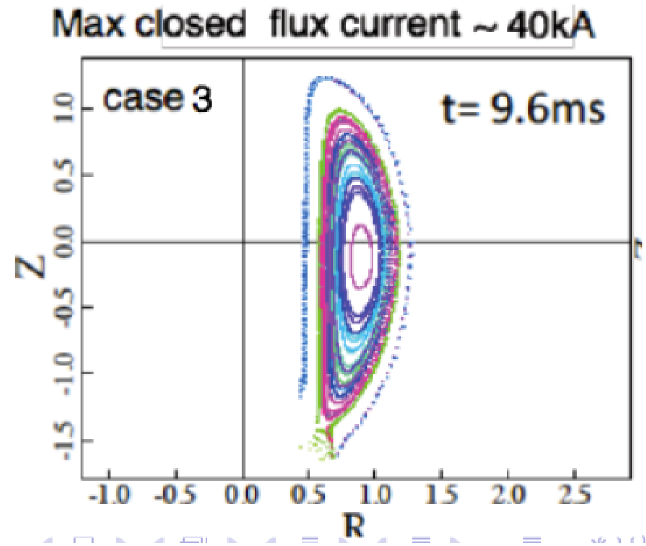
Rapidly Reducing the Injector Voltage (and Current) Increases the Closed Flux Fraction



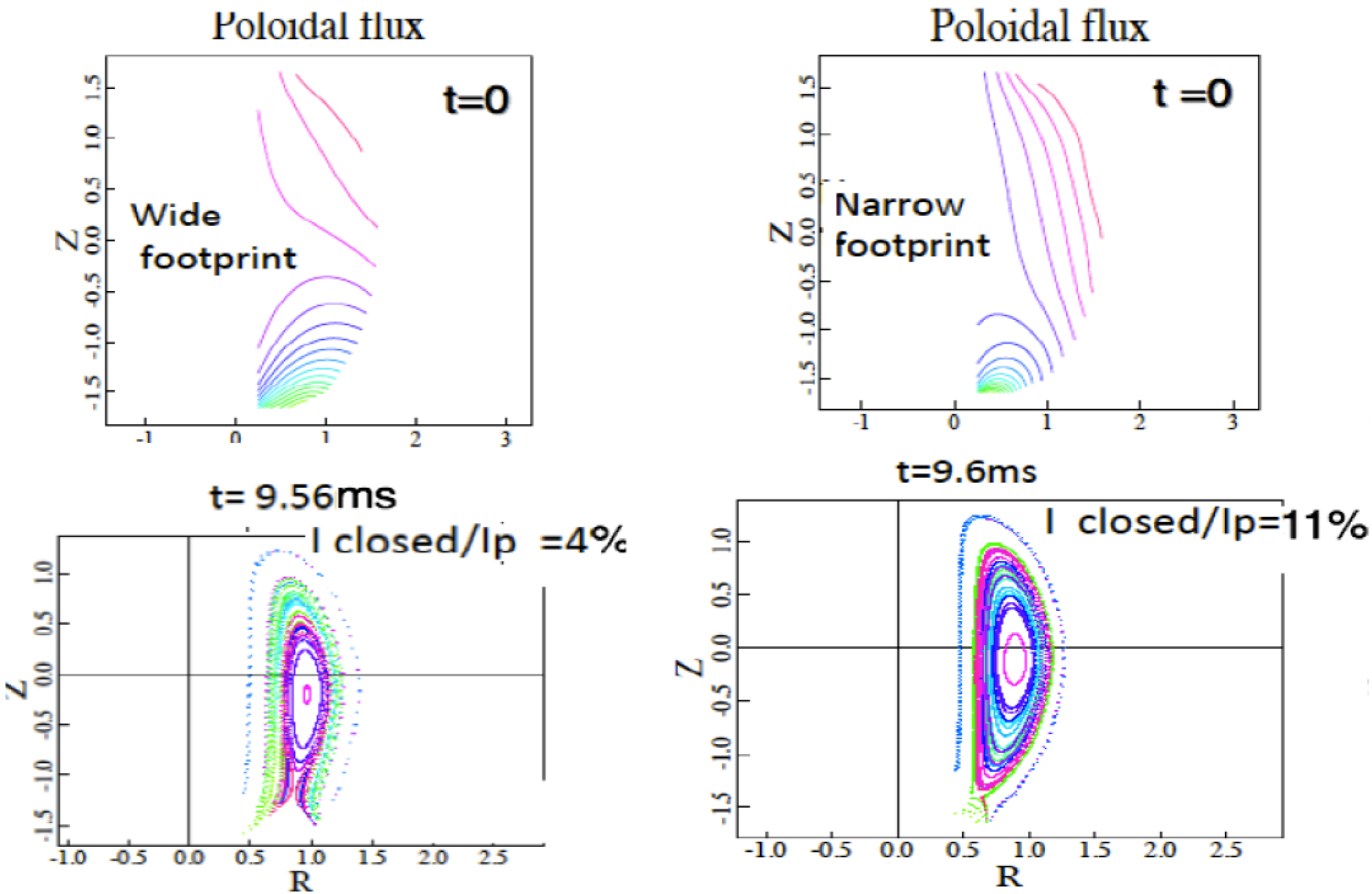






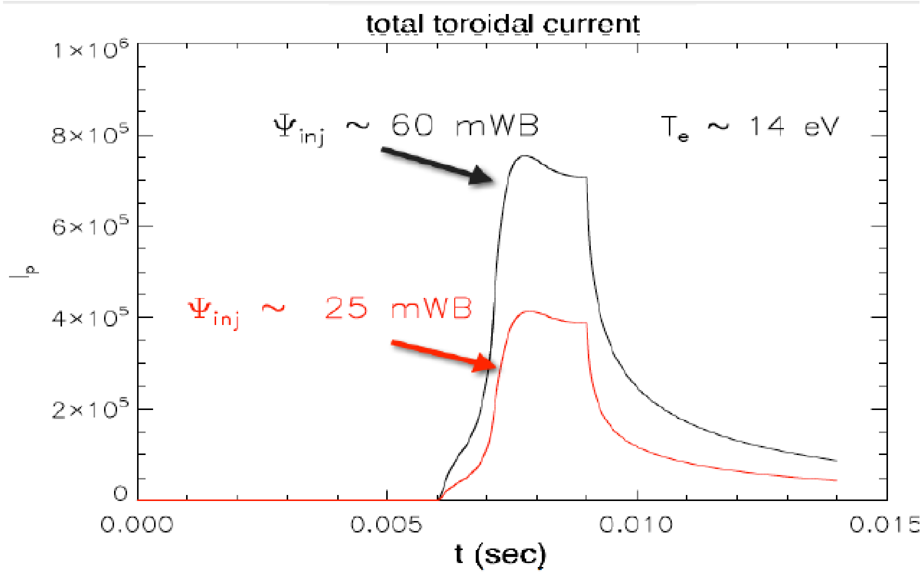


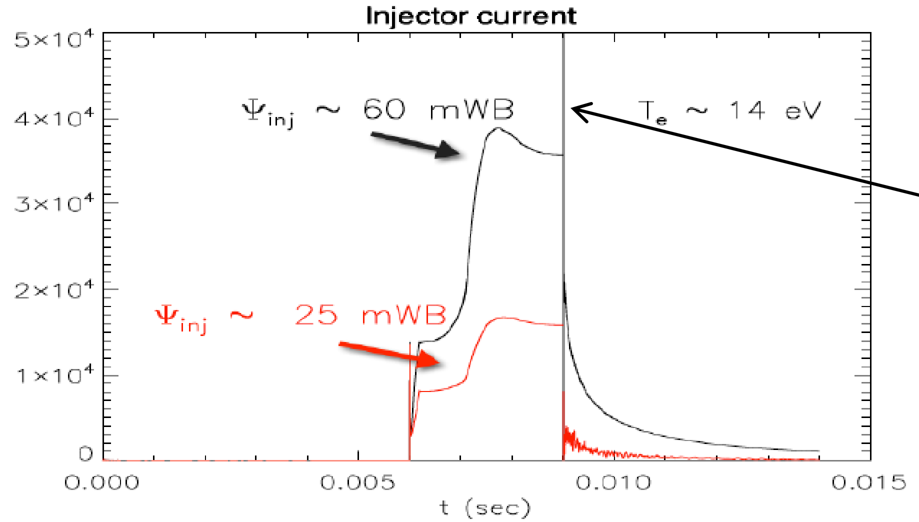
Closed Flux Fraction Increases as the Injector Flux Footprint Width is Reduced



F. Ebrahimi et al., Phys. Plasmas 21, 056109 (2014)

Generated Toroidal Current Scales with Injector Flux





Reducing the injector coil currents, to reduce the injector flux from 60 to 25 mWb, proportionally reduces the closed flux fraction following injector voltage turn-off

What Triggers Magnetic Reconnection?

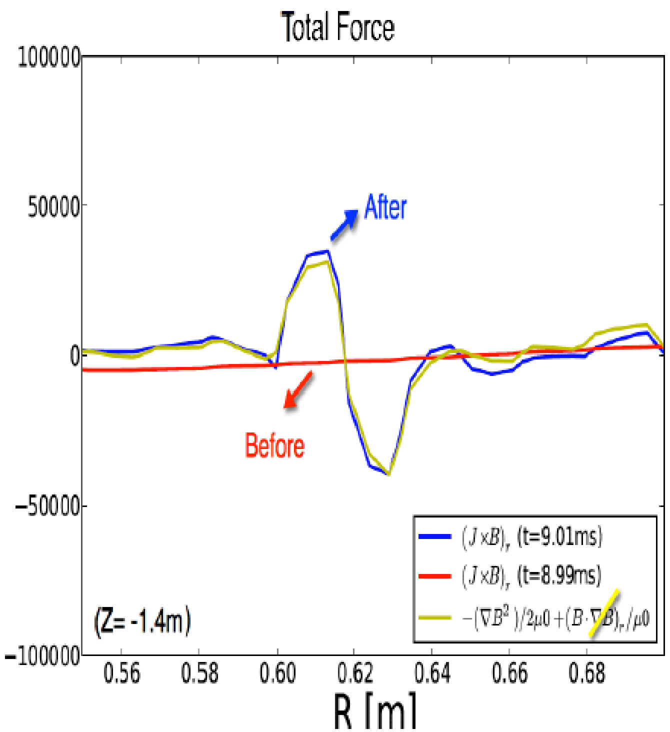
The system is almost in equilibrium before reconnection, and when voltage is turned off and B_ϕ drops around the injector region, magnetic compression exerts a radial force and system is imbalanced

- Total field consists of a fixed background field and evolving axisymmetric fields ($\mathbf{B} = \mathbf{B}_0 + \widetilde{\mathbf{B}}$).

$$(\mathbf{J} \times \mathbf{B})_r$$

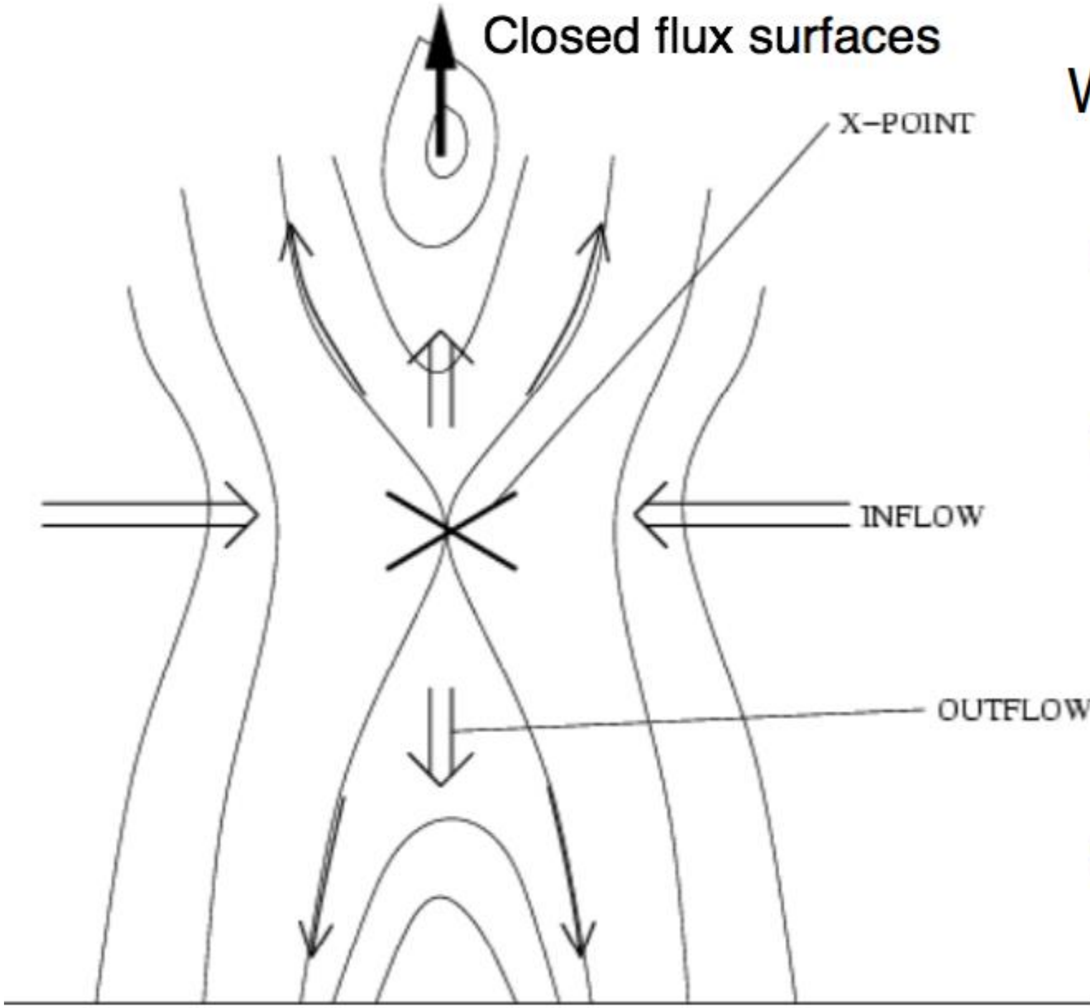
$$= \underbrace{-\nabla(B_z^2 + B_\phi^2)/2\mu_0}_{\text{magnetic compression}} \underbrace{- B_\phi^2/r\mu_0 + B_z dB_r/dz\mu_0}_{\text{curvature}}$$

$$B_\phi^2 \approx B_{0\phi}\widetilde{B_\phi}$$



F. Ebrahimi et al., Phys. Plasmas 20, 090702 (2013)

Reconnection is 2-D Sweet-Parker-like, and 3-D Effects do not Seem to Play a Role in These Early Simulations

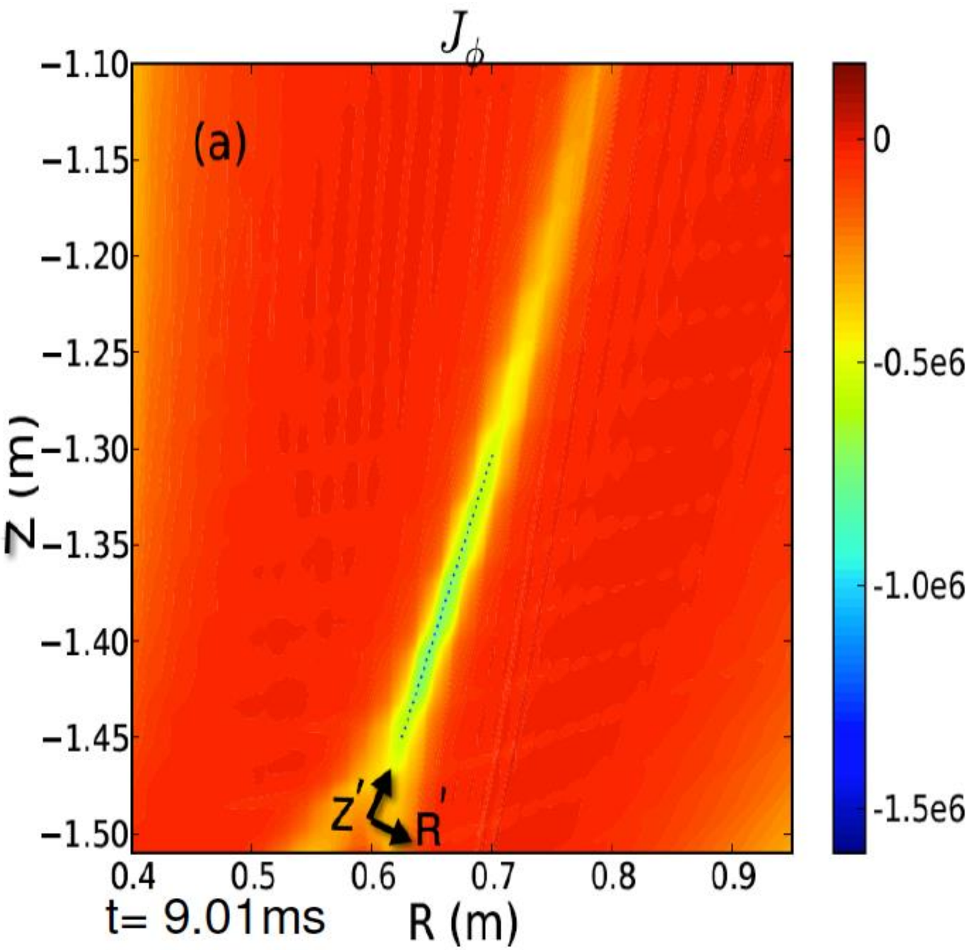


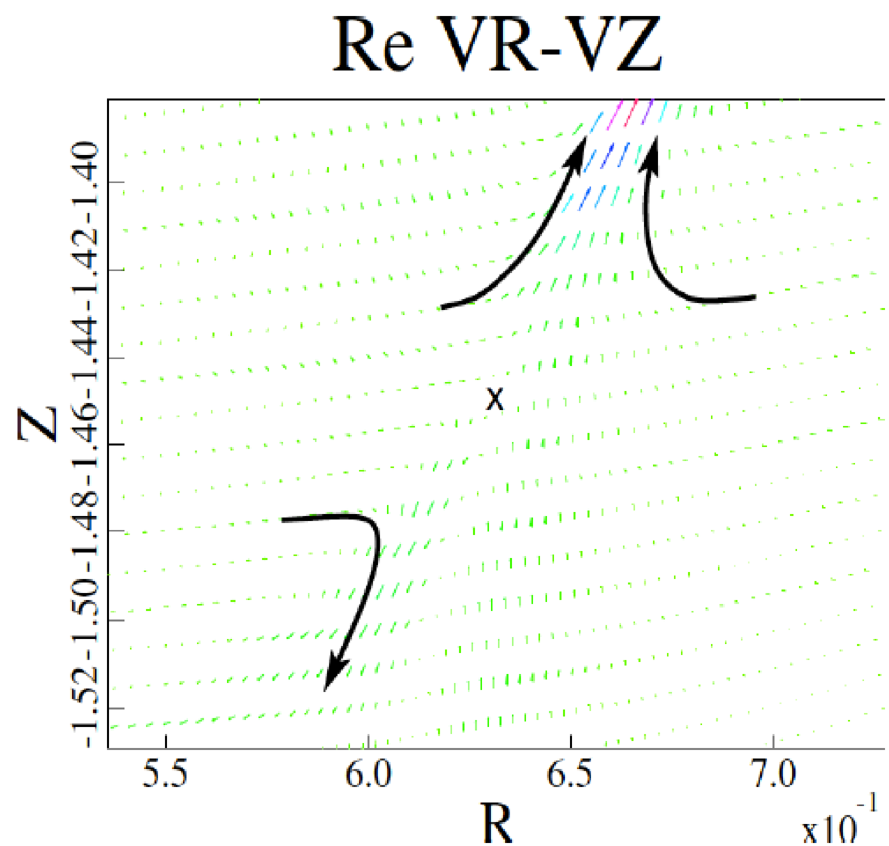
What are the signatures?

1. Elongated current sheets, $L > \delta$.
2. Scaling of the current sheet width $\delta/L \sim S^{-1/2} \sim V_{in}/V_{out}$ $(S = \mu_0 L V_A/\eta)$
3. Pinch inflow and Alfvénic outflow

F. Ebrahimi et al., PoP 2013

Elongated Current Sheet forms near the Injector Region and is Accompanied by Inflows and Outflows





A coordinate transformation to coordinates aligned with the current sheet (shown with dotted line)

Poloidal flow is zero around the X-point at (R = 0.63 m, Z = -1.445 m)

Simulation Results Summary

- TSC simulations show that closed flux surfaces begin to form soon after a positive toroidal loop voltage is generated. Physically, this loop voltage is generated due to the decaying poloidal flux on open field lines, and is analogous to the large loop voltage that is predicted to form in ITER immediately following a thermal quench, as the poloidal flux in ITER begins to decay.
- NIMROD results also show the formation of a toroidal electric field in the injector region. The NIMROD simulations offer greater insight by showing that this electric field acts on the poloidal injector flux and brings oppositely directed field lines closer together and allow them to reconnect, forming closed flux surfaces.
- NIMROD simulations provide a more complete picture of magnetic reconnection processes during transient CHI. Both ideal Alfvenic and resistive time scales are resolved in NIMROD. Local and global characteristics of magnetic reconnection, including flows and current sheet formation, are elucidated.
  - The greater the amount of injected poloidal flux, more field lines reconnect and the closed flux magnitude increases.
  - The closer the oppositely directed field lines are in the injector region, less time is required for them to come together. Both of which are desirable for increasing the closed flux fraction.
  - Finally, they show that T_e must be above some threshold value, suggesting that at too low a value of T_e any closed flux plasma that may have formed would decay at a rate faster than it is being formed.

NSTX-U Aims to Develop Full Non-inductive Start-up and Current Ramp-up in support of FNSF and next step Tokamaks

- 0.2 MA closed flux current generation in NSTX validates capability of CHI for high current generation in a ST
- Successful coupling of CHI started discharges to inductive ramp-up & transitioning to an H-mode demonstrates compatibility with high-performance plasma operation
- Favorable scaling with increasing machine size (from two machines of vastly different size, HIT-II and NSTX and in TSC and NIMROD simulations)
- NIMROD simulations show X-point and closed flux formation, 0.5 ms after the injector voltage (and current) is reduced
- A bi-directional pinch force causes the field lines to reconnect near the injector region, allowing closed flux surfaces to form
- Closed flux formation during transient CHI is consistent with 2-D Sweet-Parker type reconnection, and 3-D modes do not seem to be important
- NSTX-U is well equipped with new capabilities to study full non-inductive start-up and current ramp-up (2x higher TF, 1 MW ECH, second tangential NBI for CD, 2x higher CHI voltage, >2.5x more injector flux, improved upper divertor coils)