LLNL-POST-594093

Flux-surface closure during resistive-MHD simulations of Coaxial Helicity Injection (CHI) in NSTX

Bick Hooper, LLNL
Carl Sovinec, Univ. of Wisconsin
Roger Raman, Univ. of Washington
Fatima Ebrahimi, Univ. New Hampshire
Jon Menard, PPPL

Division of Plasma Physics
American Physical Society
Providence, RI, Oct. 29-Nov. 2, 2012

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, by Princeton Plasma Physics Laboratory under Contract DE-AC02-09CH11466, and by the PSI Center (University of Wisconsin) under Grant DE-FC02-05ER54813

ABSTRACT:

CHI in STs offers considerable promise for generating startup plasmas, with NSTX experiments demonstrating coupling to Ohmic drive with magnetic flux savings [1]. Success in these experiments depends in part on the achievement of flux closure following CHI voltage crowbarring. Flux closure is demonstrated here in whole-device, resistive MHD simulations using the NIMROD code. In axisymmetric plasmas significant closure due to resistive effects requires the injection slot to be narrow (e.g. 4 cm vs. 11 cm) in agreement with experiment. In simulations reduction of the applied injector flux following the crowbar forms an X-point close to the bottom of NSTX that significantly enlarges the closed volume; closure is not seen if the flux is held constant. The physics of closure will be discussed and applied to maximizing the volume. Effects of a background plasma in simulations of flux formation and closure will also be described.

[1] R. Raman, et al., PRL 104, 095003 (2010).

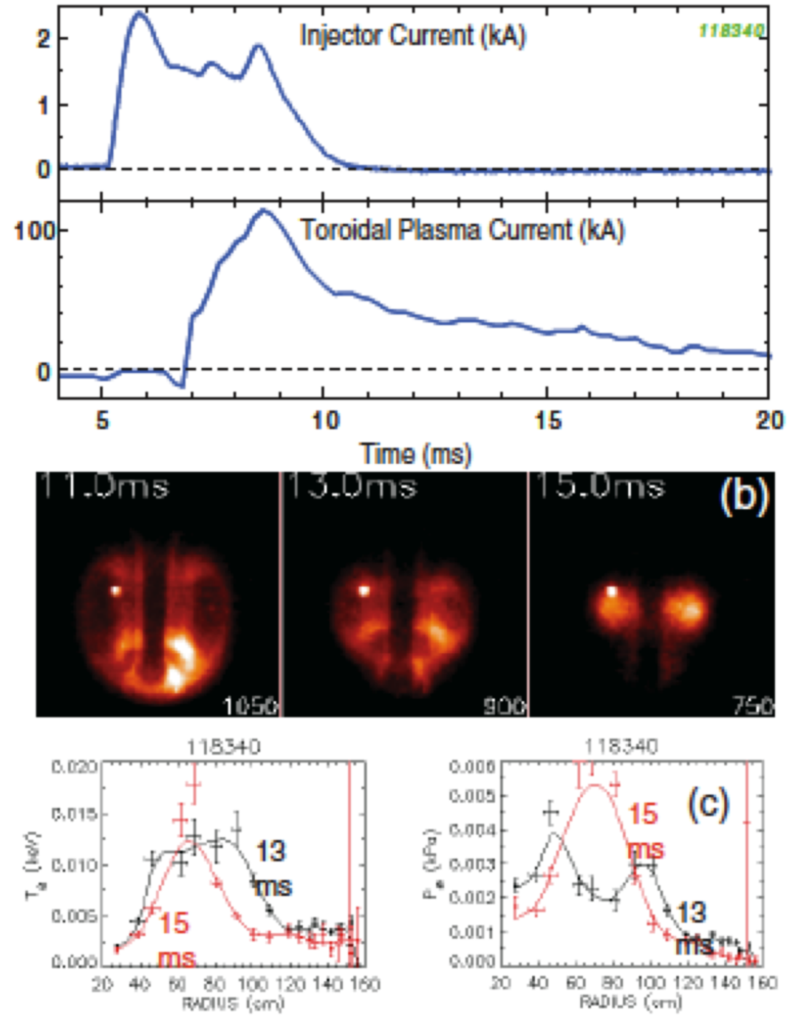
Accomplishments and Status of work in progress

- The model used for CHI into NSTX compares well with experiment during the injection phase. A power-supply model drives the injection
  - Voltage across the injection gap
  - Injected current — measured from R^*B_φ at the gap
  - Injected plasma and toroidal current and flux
  - The model includes time evolution using NSTX time-dependent boundary conditions (including wall eddy currents)
  - Ohmic heating and thermal conductivity (along open field lines) have been implemented
  - Simulations show an n=1 mode
- Closure is observed in three cases
  - During injection when ohmic heating inside the injected flux is weak
  - "Fast" closure – when the applied voltage is rapidly reduced
  - "Driven" closure – when the external, applied poloidal field evolves towards a divertor configuration and forms an X-point near the bottom of NSTX

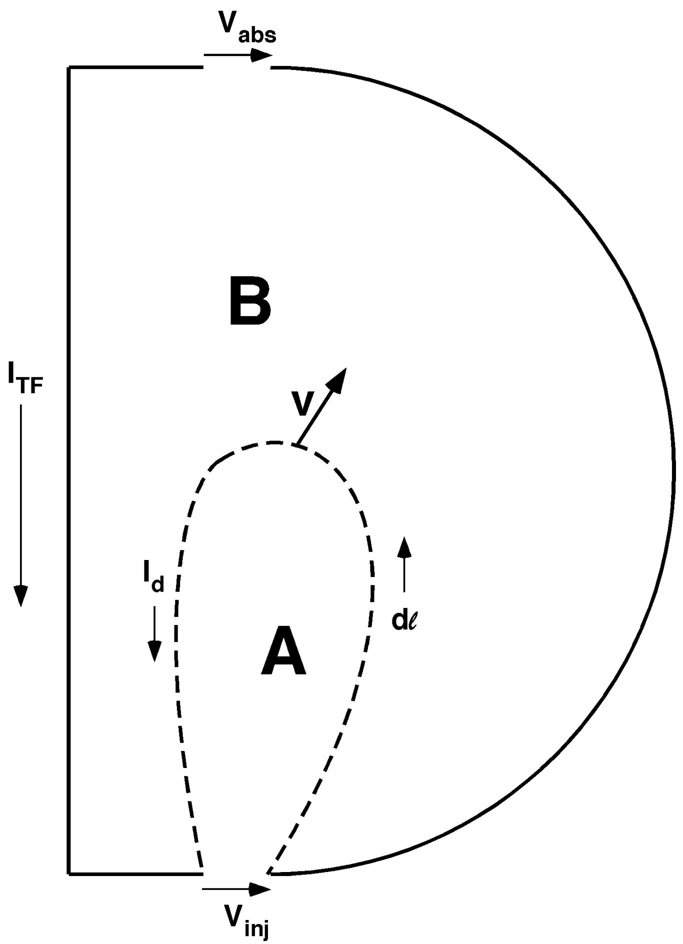
Closure during injection followed by "fast" reduction of voltage generates surfaces similar to those in the experiment

NSTX: Shots shows expanding flux bubble

See R. Raman, et al. Phys. Rev. Letters 97, 175002 (2006)



Boundary conditions for helicity injection

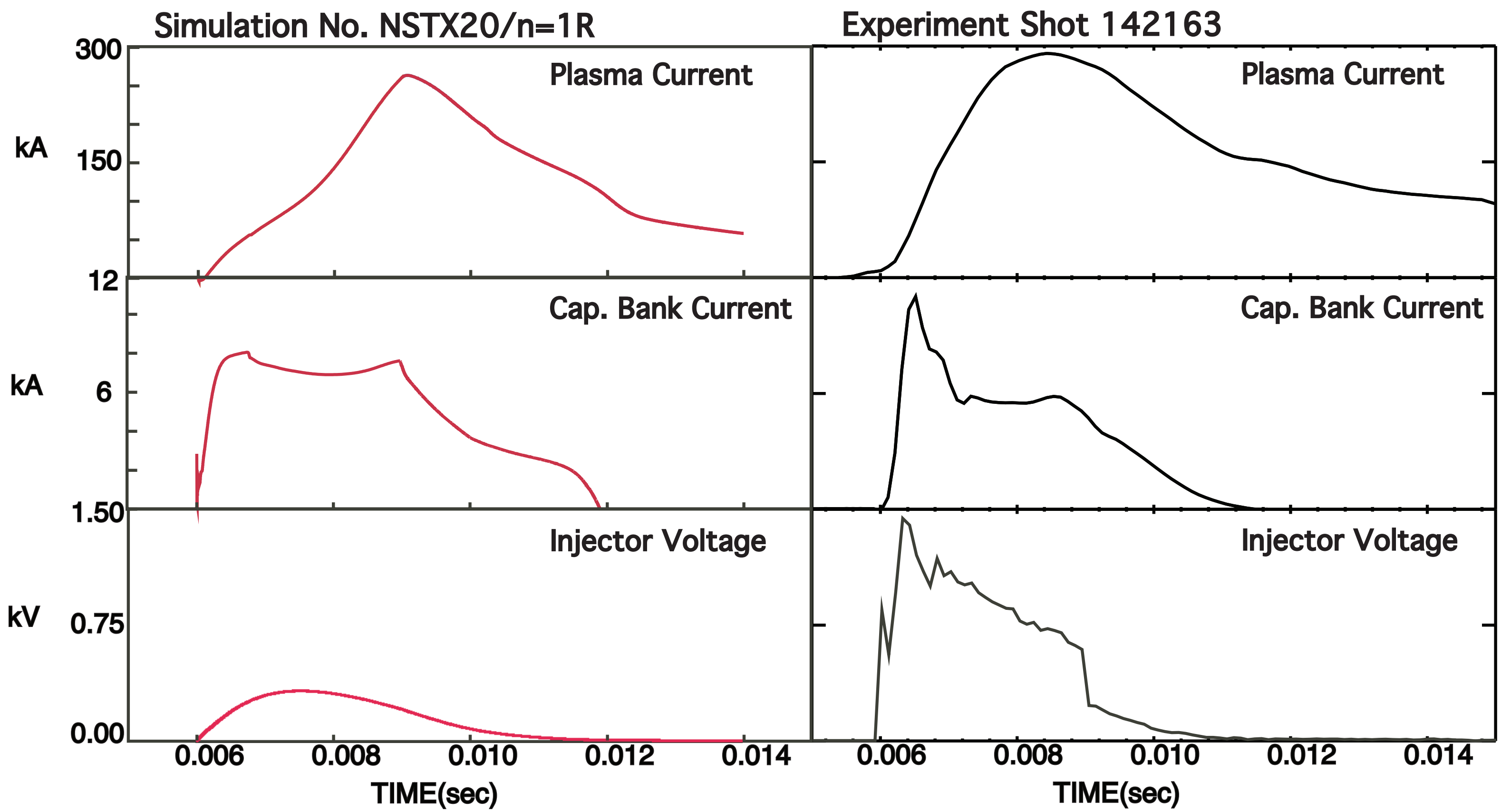


- Rate-of-change of toroidal flux — equals $V_{inj} - V_{abs}$
- Absorber voltage — determined by requiring the total vacuum toroidal flux to be constant, corresponding to a constant I_{TF}
- Discharge (injector) current — measured by the change in RB_φ just above the injector slot
- Toroidal flux — carried in by ExB flow at the injector and out by ExB flow at the absorber
- Equating flows of *vacuum* toroidal flux yields

$$E_r^{abs} = E_r^{inj} \frac{r_{inj,\min}}{r_{abs,\min}} \frac{\displaystyle\int_{r_{inj,\min}}^{r_{inj,\max}} dr \frac{B_\varphi}{r^2 B^2}}{\displaystyle\int_{r_{abs,\min}}^{r_{abs,\max}} dr \frac{B_\varphi}{r^2 B^2}}$$

This generalizes the model used in HIT-II: R.A. Bayliss, C.R. Sovinec, and A.J. Redd, Phys. Plasmas 18, 094502 (2011).

Previous simulations — injection but no flux-surface closure (last APS, ICC conferences)



There was no flux-surface closure after the injection ended

Flux-surface closure has now been demonstrated

Experimental results:

- Flux surfaces — close in experiment during or following removal of injection voltage
- Closure is important for a start-up plasma — toroidal current increases as inductive current drive is applied

Simulation results:

- Flux surface closure — observed in three cases

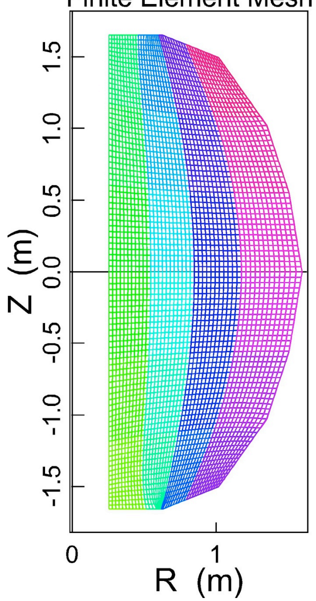
  A) Fast reduction of applied voltage — low temperature plasma with radiation cooling
  B) Fast reduction of applied voltage — high temperature without radiation cooling
     - Closure starts during the injection phase
  C) Slow reduction of applied voltage — closure driven by variation in external poloidal flux
     - Closed volume is small — leans against central column

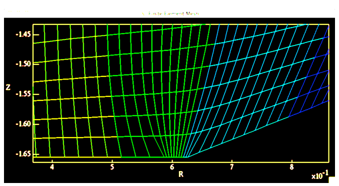
- **Fast reduction of voltage at high temperature generates the largest enclosed volume — closest to the experimental observations**

Simulation — A narrow injection slot narrows the injected current – required for flux-closure

A narrow slot was found to be important in the experiment — guided the simulations

Finite Element Mesh

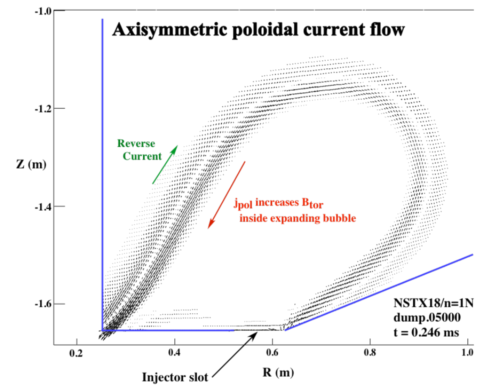




Injection slot

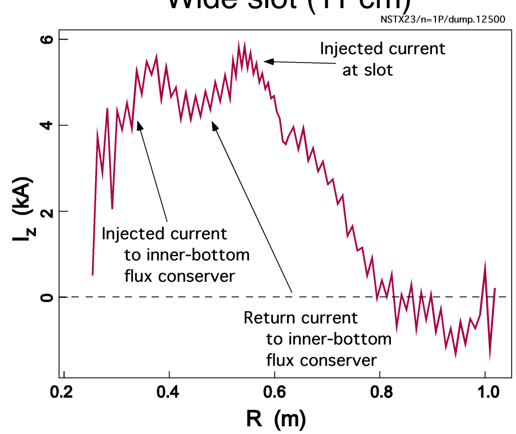
Finite elements generate additional resolution

Current flow in flux bubble

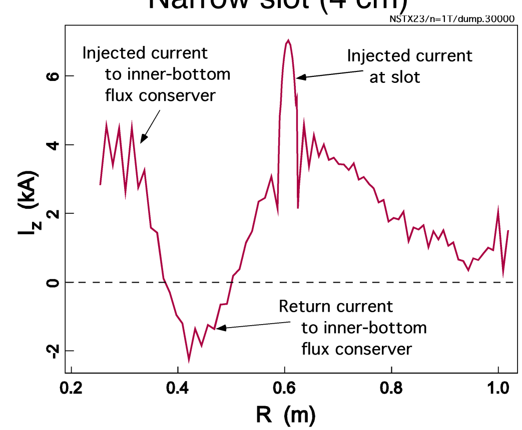


Vertical current inside radius R at the bottom of the flux conserver

Wide slot (11 cm)



Narrow slot (4 cm)



The narrow slot generates a narrow distribution of injected current

Simulations without Absorber Coils are a better model of the experiment than those with them

ISSUE: The absorber slot boundary condition requires an outward EXB flow

ExB out-flow at the extractor slot — generates plasma flows in plasma outside the flux bubble

- Absorber coils *energized* — Problem as the bubble approaches NSTX top
  - Flows forced to small R by absorber magnetic fields — cross B-field to reach absorber
  - Flows interact with bubble – Result – injector current not fully localized in surface layer

- Absorber coils *not energized* — Flow reaches absorber slot along B
  - Negligible interaction with bubble
  - Injector and toroidal currents largely localized in the bubble
  - Experimental problems with breakdown do not occur in simulations

Conclusion: Simulations without absorber coils are used in present closure simulators

High spatial resolution is required for accurate simulations

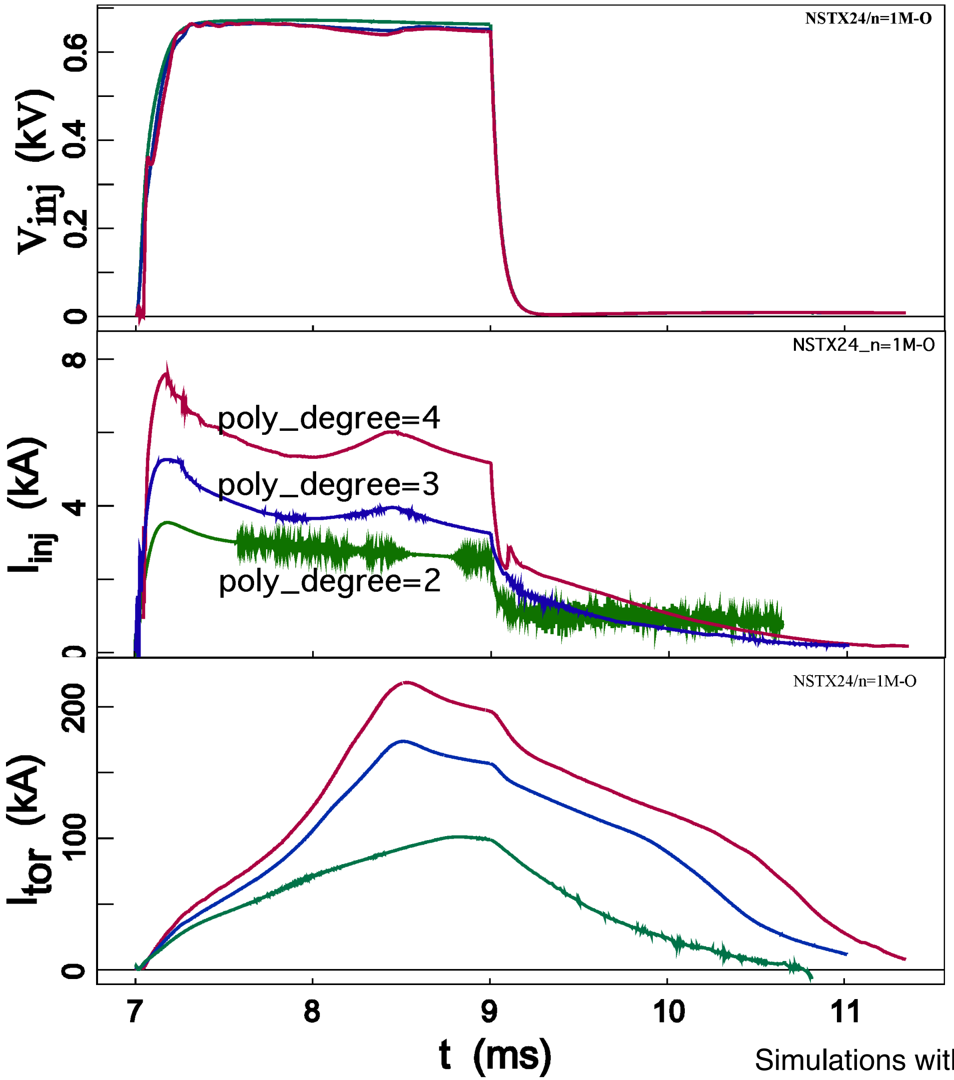
Spatial resolution is improved by using finite elements within the grid

Shown are comparisons of polynomial degree 2, 3, 4

Flux surfaces with polynomial degree 2 did not close

Conclusion: High resolution is needed for an accurate simulation

(Higher degrees have not been tested.)



Simulations with fast closure, radiation cooling, and n=1 mode

Case A: Flux surface closure at low temperatures

An “atomic” radiation term was used to keep T < 100 eV

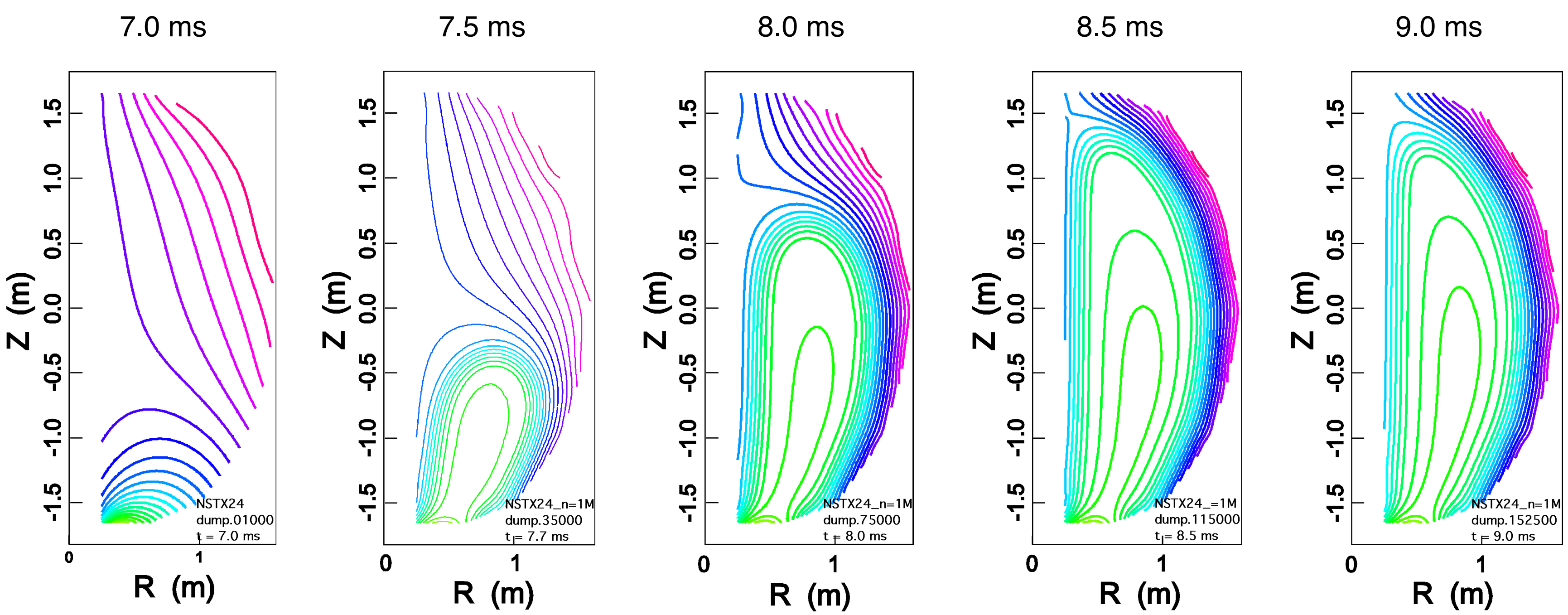
- The temperature dependence of the radiated energy approximated that of a low-Z impurity but without the possibility of “burnout”

- A model of oxygen including “burnout” has been added to Nimrod — simulations have started using it

A 4 cm injection slot and poly_degree = 4 were used for the following results

- The simulation time history is shown in the previous slide

Poloidal flux contour plots expand during injection

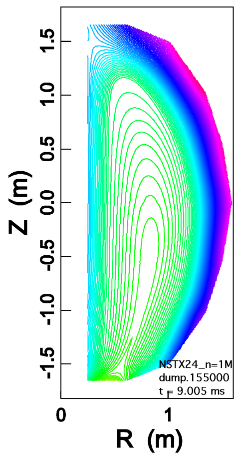


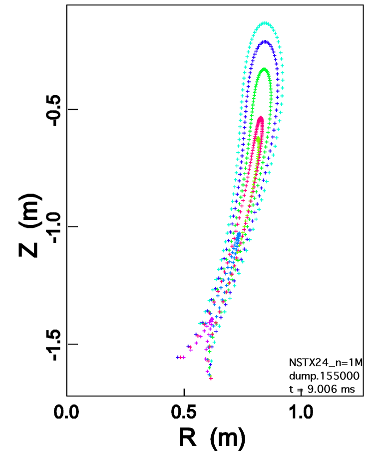
Contour spacing
$\Delta\psi \approx 4.3$ mWb

Poloidal flux closure starts within 10-s of microseconds after the voltage starts to drop (9 ms)

Poloidal flux **Poincaré puncture plots**

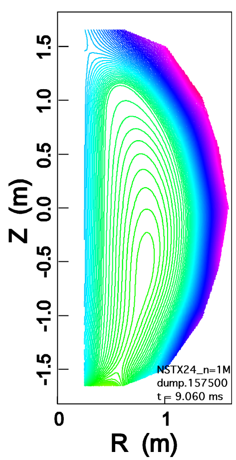
t = 9.006 ms

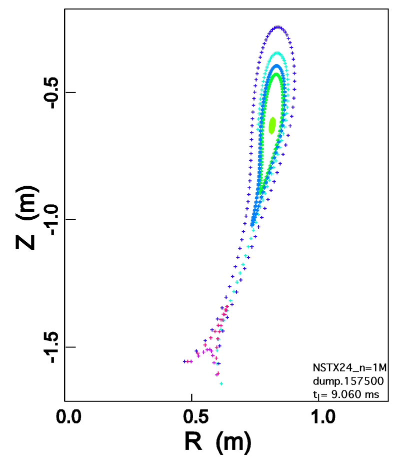




No flux closure

t = 9.060 ms

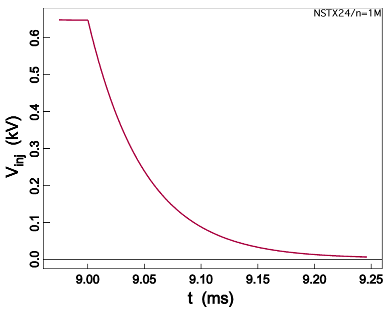


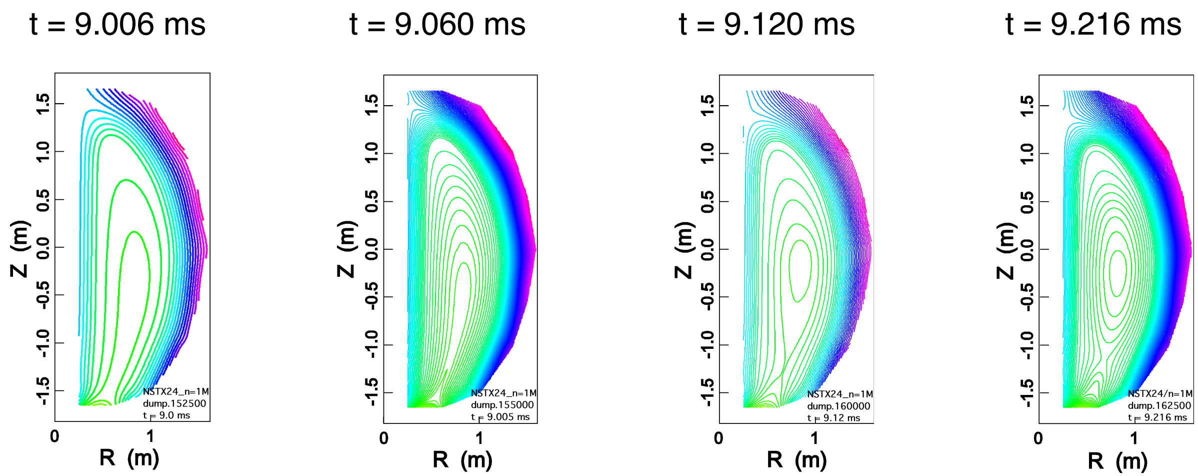


Flux closure starts along narrow neck of flux from the injector slot

$\Delta\psi \approx 1.1$ mWb

Plasma flow reduction and flux surface closure



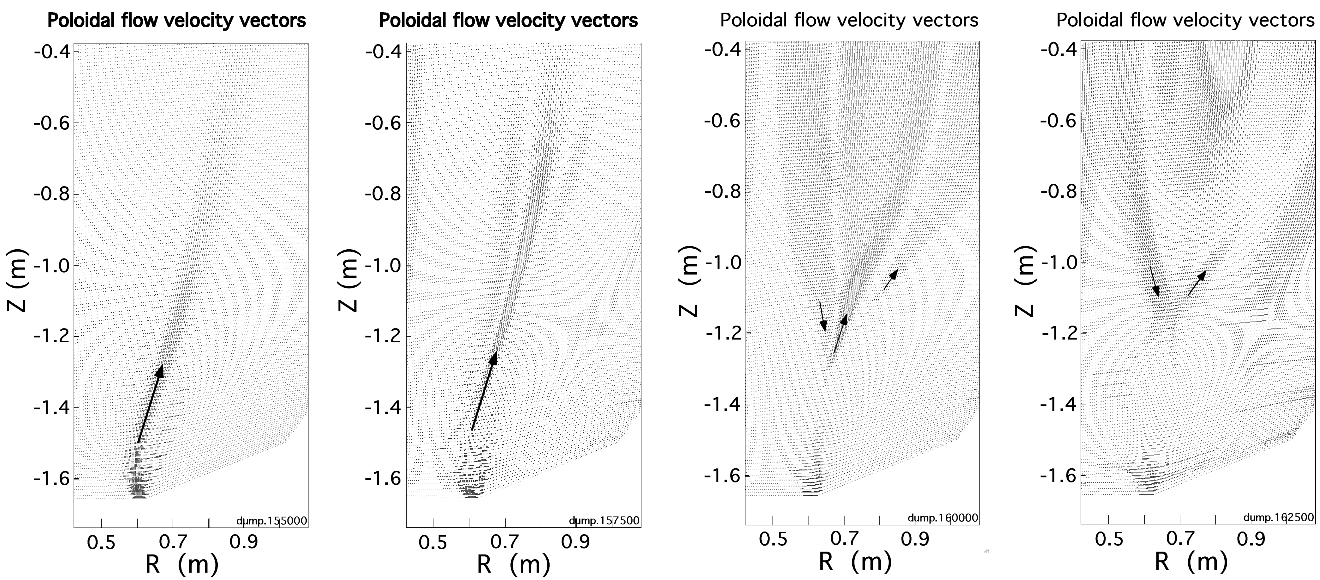


Poloidal flow-velocity vectors

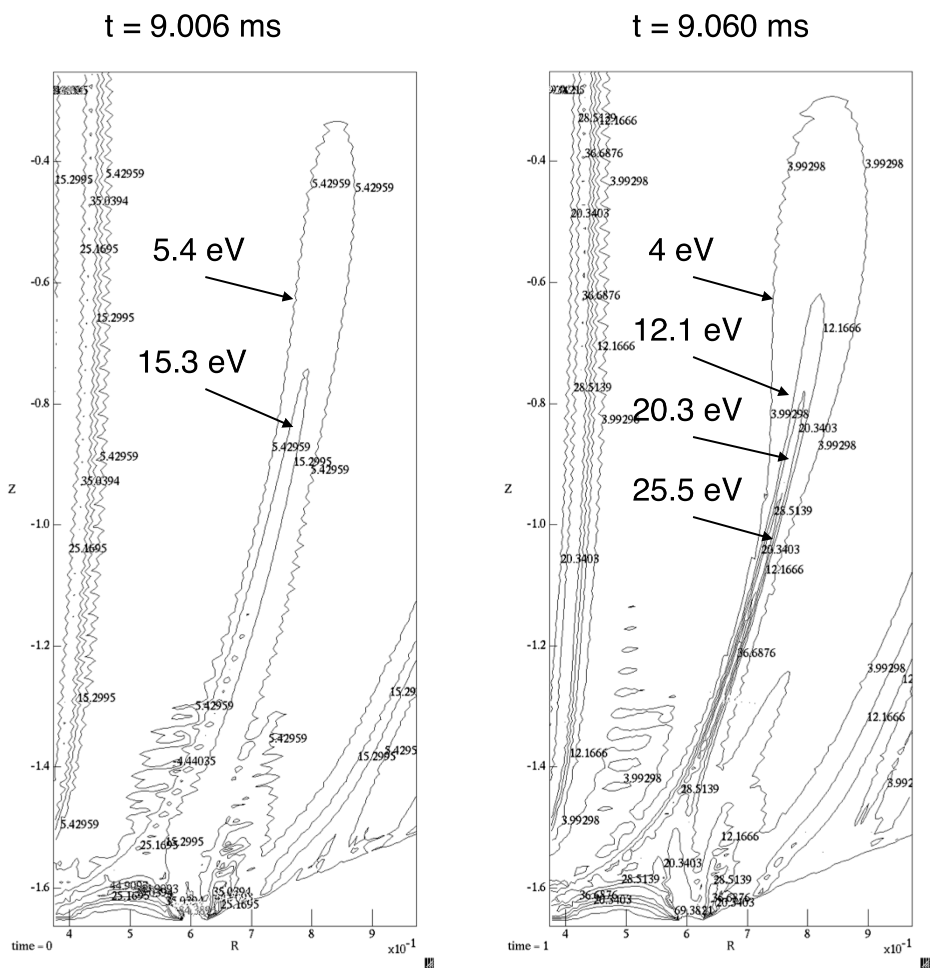
As injection voltage drops, flow drops allowing flux-surfaces to pinch, speeding reconnection

At low voltage, flow continues from outside the closed surface, carrying toroidal flux across the X-point into the surface

Finally, flow becomes small and closed surface area grows before resistively decaying



Temperatures are low in flux plume — flux closure heats plasma locally



Magnetic diffusion

$$D_m = 411 / T_e^{3/2}$$

$$\approx 5 \ \mathrm{m}^2/\mathrm{s} \ \text{at } 20 \ \mathrm{eV}$$

$$\approx 40 \ \mathrm{m}^2/\mathrm{s} \ \text{at } 5 \ \mathrm{eV}$$

Diffusion distance in 50 μs is

$$\Delta x \approx 0.01 \ \mathrm{m} \ \text{at } 20 \ \mathrm{eV}$$

$$\approx 0.04 \ \mathrm{m} \ \text{at } 5 \ \mathrm{eV}$$

Distances are similar to those in the plume

Conclusion: Resistive diffusion closes flux surfaces at these temperatures and dimensions

Case B: Flux surface closure at high temperatures

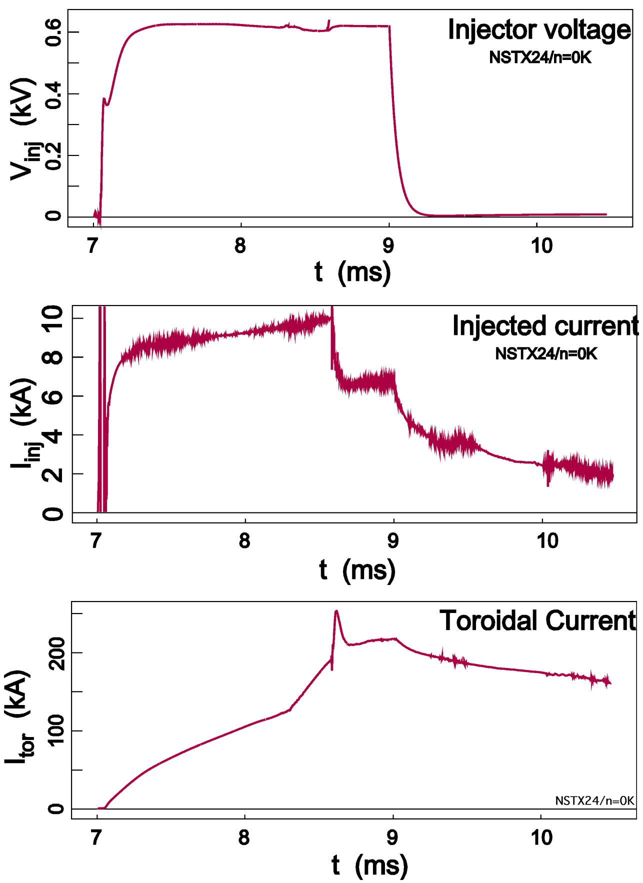
No atomic radiation in the simulation

- Temperatures well above 100 eV were generated

A 4-cm injection slot and poly_degree = 4 were used as in the low-temperature simulation

The simulation studied here was axisymmetric (no n=1 mode)

High-temperature, flux-surface closure



Comments on the structure in the currents:

Closed flux surfaces form during the injection

Before the upward bend in the toroidal current (t = 8.30 ms) — a region near the nose of the flux bubble has closed surfaces

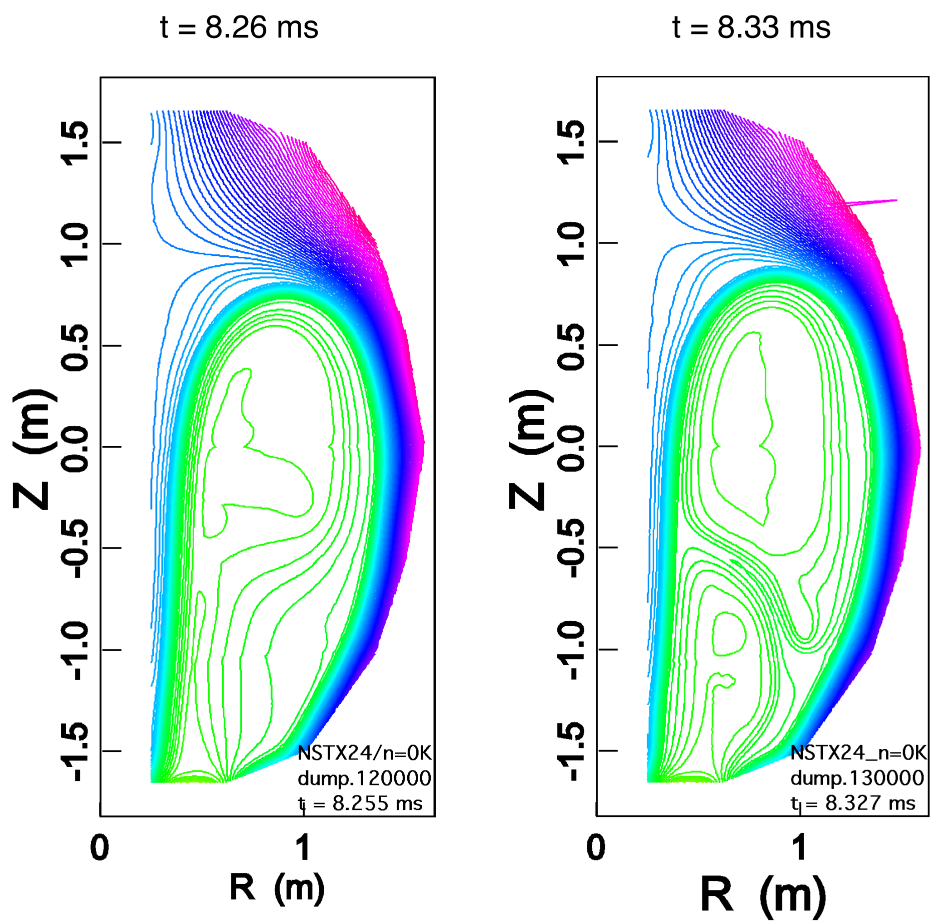
After the bend —closed volume increases but with two separated regions (next slide)

Peak in the toroidal current and drop in injected current — the inner leg of injected-current path moved away from the central column

Noise in injected current (measured by RB_ϕ above the injector slot), is apparently numerical. Effect on flux-surface closure is uncertain.

- Including an n=1 mode may reduce or prevent this noise

Flux-surface closure during injection



Flux-surface spacing: poloidal flux = 1.1 mWb;
Total applied flux = 84 mWb

Before t = 8.3 ms – a single region of closed flux; afterwards, two regions

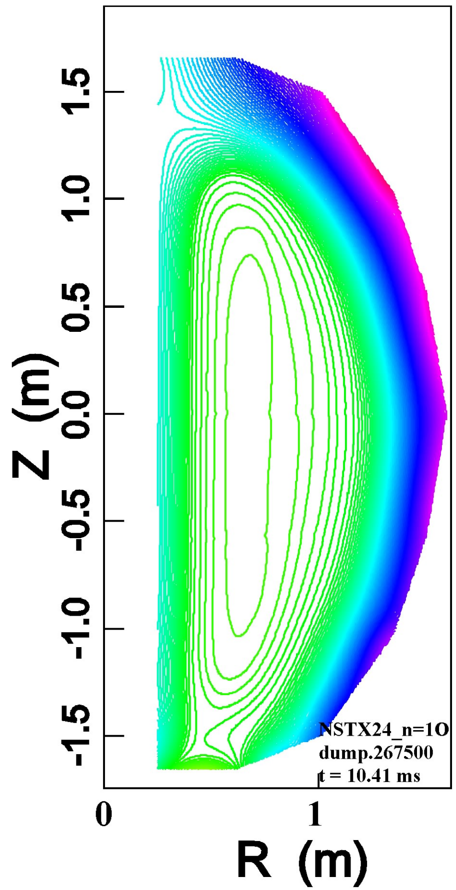
- Verified by field line tracing

Temperatures are high (100-300 eV) in the current channel at the surface of the flux bubble

BUT – temperatures are low inside the bubble (10 – 30 eV) allowing closure to occur

The total closed flux is ≈ 7 mWB, <10% of the total bias flux

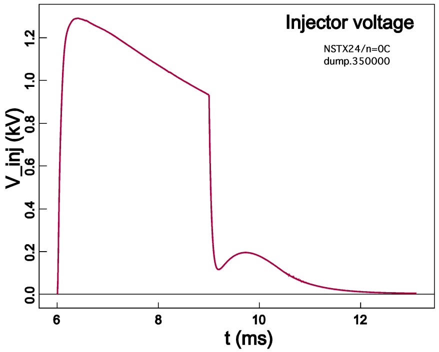
Flux-surface closure following injection

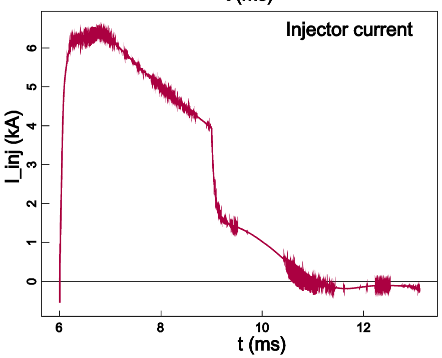


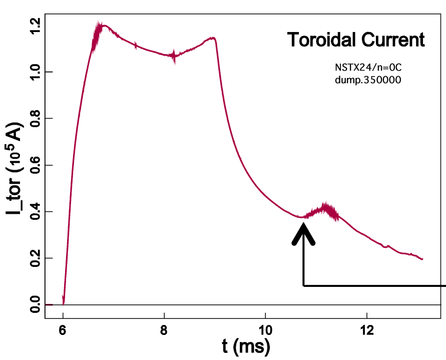
After injection voltage ends — closed-flux regions coalesce and grow somewhat in volume

Enclosed poloidal flux (≈ 5 mWb) and toroidal current (estimated ≤ 50 kA) are smaller than in NSTX experiment

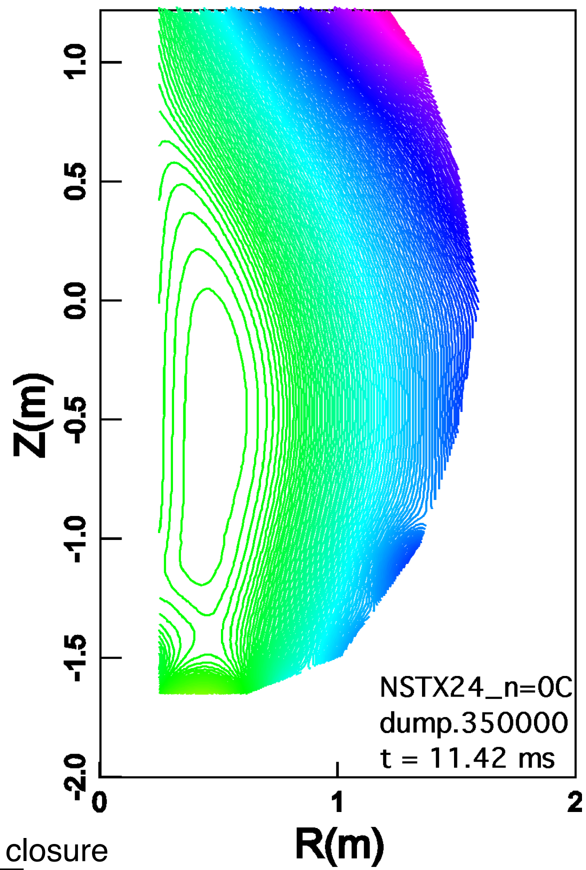
Case C: Flux-surface closure driven by external flux changes







Flux closure starts



Comments

Closure verified by field-line tracing

X-point in poloidal flux occurs after the (measured) injector current reaches zero. The toroidal current has dropped below 40 kA

X-point does not form if bias poloidal magnetic field is constant

As toroidal current decays — closed flux region leans on the central column and shrinks in volume

Summary of flux-surface closure results

Closure is seen in several simulations

- A narrow injection slot is required
- High spatial resolution is required

The "fast voltage reduction, high-temperature" case compares the best to experiment

Ongoing simulations include:

- Including the n=1 mode in high-temperature simulations
  - Needed to minimize numerical noise
- Using a better atomic radiation model to more fully determine effects of temperature on closure
- Exploring the physics of generating surfaces to enclose a larger fraction of the toroidal current
  - Presently, much toroidal current flows outside the closed flux

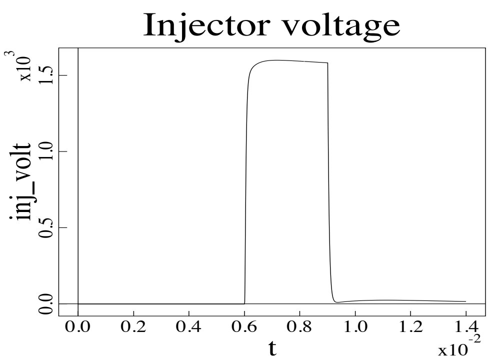
Simulations with constant flux

Simulations are also being run to study the physics of flux closure with a simpler model than in the previous viewgraphs

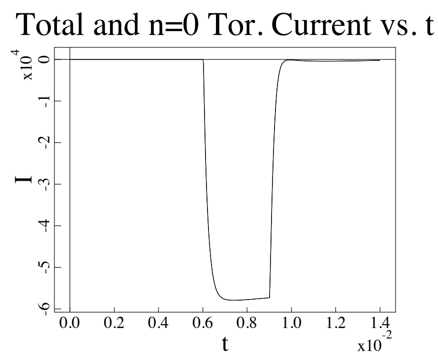
- Simulations started with fixed boundary fields (including NSTX poloidal coil currents) for a narrow slot of 4cm.
- Two sets of simulations are performed, 1) at zero pressure and 2) including a pressure model
- Simulations at zero pressure (similar to Carl's HIT-II simulations) started with a constant high voltage of 1.3kV at 6ms which drops sharply at 9ms.
- Second set of simulations also include pressure and resistivity models and ohmic heating.

Simulations at zero pressure

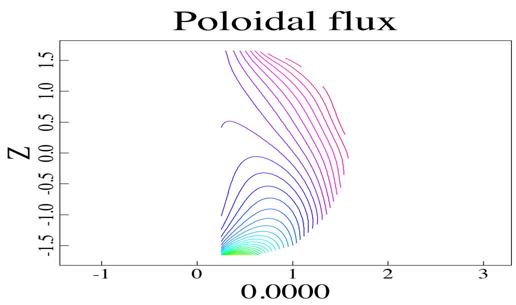
- A simple waveform of injector voltage is used. High resolution of poly-degree=3 is used.

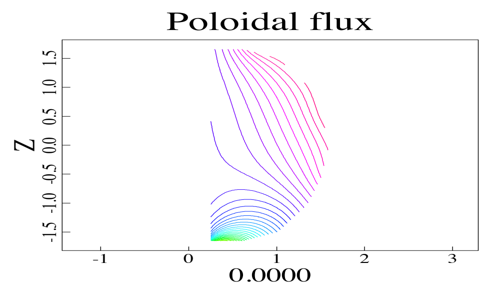


t=9.1ms



t=9.6ms

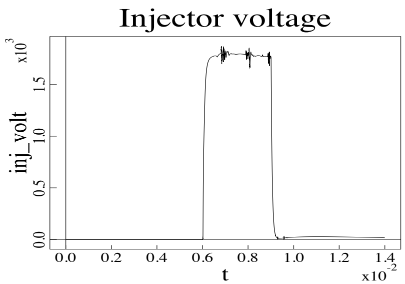


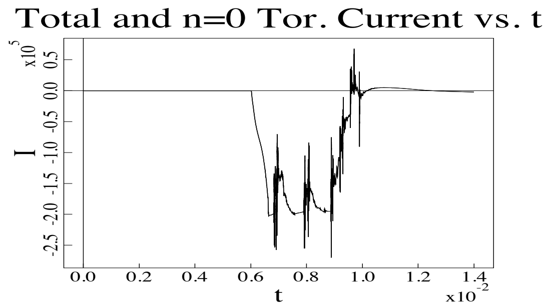


- *No flux closure is obtained during the sharp decrease of the voltage at 9ms.*
- *A this voltage of 1.5 kV not enough large current is produced to pull up enough flux and cause closure with zero pressure mode (similar to HIT-II case). Simulations at higher voltage are underway.*

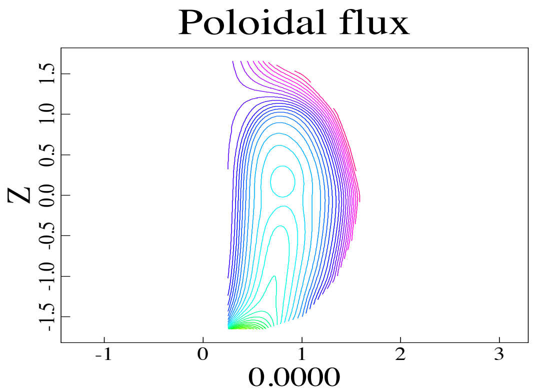
Simulations with pressure model

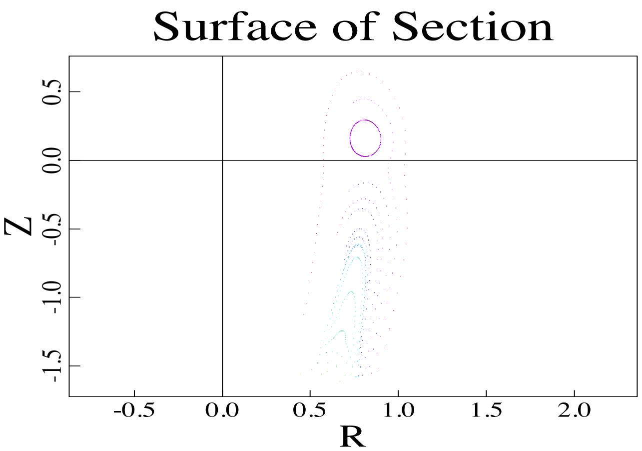
- *Similar voltage and boundary fields are used with resolution of poly_deg=2. However, higher total current is obtained with pressure.*





t= 9.1ms





- *Small flux closure is obtained as shown in the puncture plot. This simulation at higher resolutions poly_deg=3 is running.*

Summary of simulations with constant flux

- Simulations with constant flux show a very small volume flux closure only when pressure model is included and voltage is sharply decreased. For this case, higher resolution simulations are underway.
- Simulations at zero pressure similar to HIT-II so far have not produced the flux pull-up and closure (at the voltage used). Also, for this case, simulations at much higher voltage are underway.

Plasma outside the expanding flux bubble differs from the experiment

MHD simulations include a plasma throughout NSTX that affects helicity injection

Absorber-slot boundary condition imposes an outward flow — supplied by flow from plasma throughout the machine

- Flows couple to current generation via Ohm's law
- Absorber-coil currents are zero to minimize effects of cross-field transport near the top of NSTX

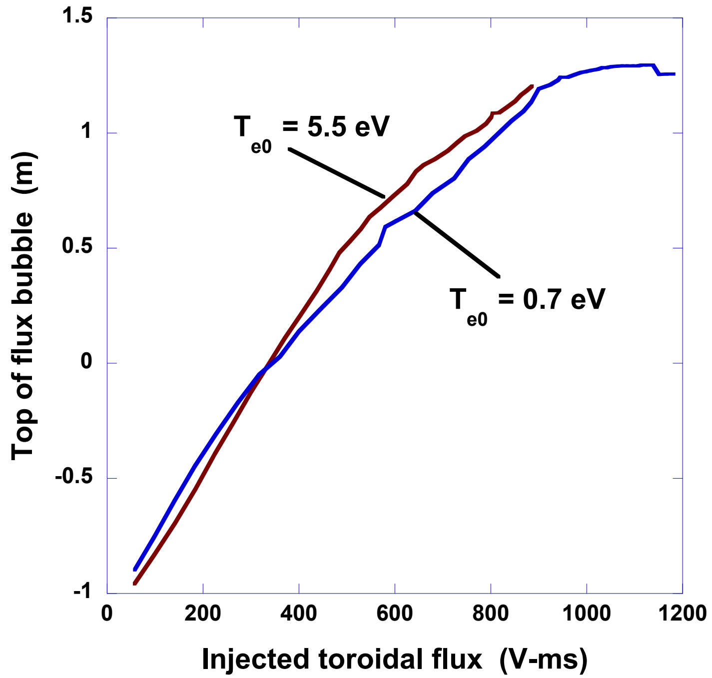
Bubble expansion compresses and bends magnetic field between it and the top of NSTX

- Unconstrained plasma temperature — strong currents generated locally
- Local plasma heating —currents increase ("run-away" to high T)
- "Run-away" current densities can be comparable to injected and toroidal currents in the bubble

Partial "fix":

- Temperatures in several grid rows near the top are held at background value to minimize flow-generated currents
- Temperature increases limited outside the flux bubble

Good news: Plasma expansion is determined by the injected toroidal flux – weak external temperature effects



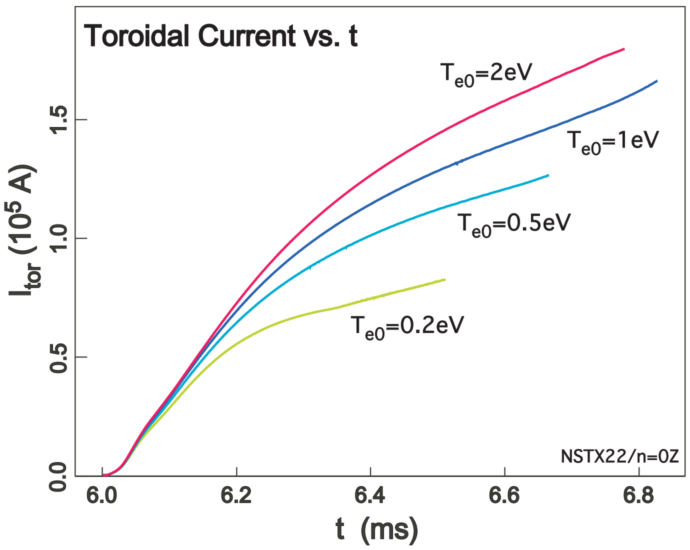
In the absence of magnetic reconnection, injected toroidal flux is proportional to helicity

External plasma has only a small effect on the toroidal flux

Plasma outside the expanding flux bubble affects toroidal current generation

In the experiment – ionization, radiation, and other effects limit plasma temperature

- In the calculation shown here we “clamp” external temperatures



Perturbed magnetic field — generated by plasma-flow and diffusion

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times \frac{\eta}{\mu_0} \nabla \times \mathbf{B}$$

At 0.2 eV, diffusion dominates ($\eta \sim T^{-3/2}$)

At 2 eV, flows are more concentrated and dominate field evolution

External temperature in the experiment is not known

Summary of external plasma effects

Plasma flows and currents are generated in the plasma outside the flux bubble

- Injection is not significantly affected — the flux bubble forms and closure occurs
- However — these flows and currents change details of the injection history

The effects of these flows and currents have been minimized by:

- Maintaining a low temperature at the top of the machine near the absorber slot
- Turning the absorber coils off
- Preventing temperature excursions in the external plasma

Further effort is planned to fully minimize the effects of the external plasma