LLNL-PRES-550052

Resistive MHD simulations of Coaxial Helicity Injection (CHI) in NSTX

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This work — done with support from and in collaboration with:

Carl Sovinec	**University of Wisconsin and PSI Center, University of Washington**
Roger Raman	**University of Washington and NSTX (PPPL)**
Jon Menard	**Princeton Plasma Physics Laboratory**

Motivation and goals

Startup of tokamaks typically uses loop voltage generated by the central solenoid

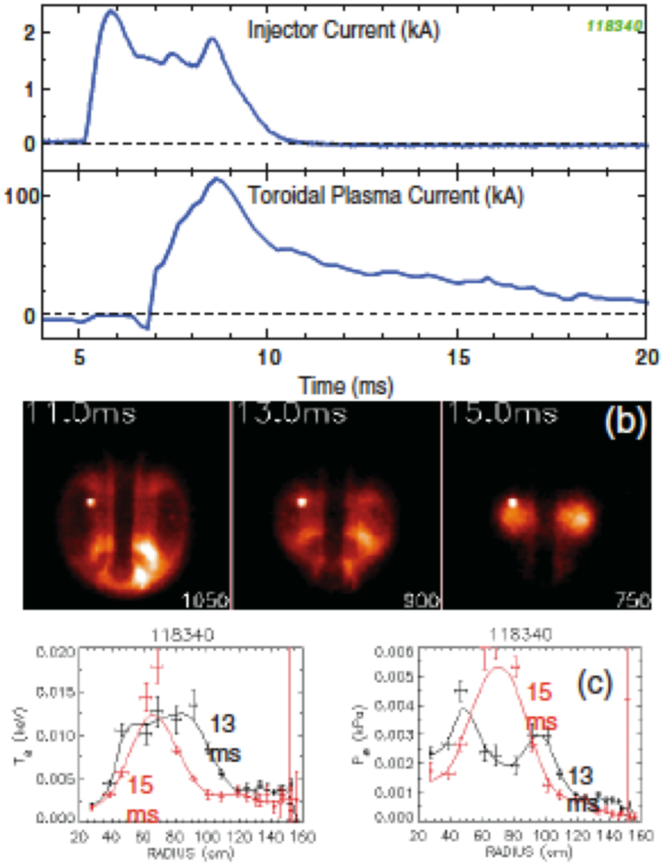
- Can consume considerable volt-seconds
- The spherical torus — with a small central column — is sensitive to this problem

Roger Raman — experiments on HIT-II and NSTX demonstrate coaxial helicity injection (CHI) to generate a startup plasma

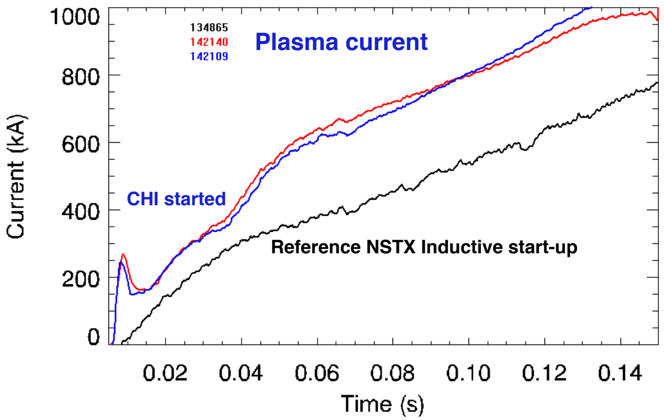
Present study —resistive MHD simulations of CHI in the NSTX geometry

- Understand the physics and injection optimization
- Model injection in NSTX-U — prepare for experiments
- Prepare for simulations and experiments using non-inductive current drive starting from CHI

NSTX: Shots demonstrate expanding flux bubble, ramp-up by induction with volt-sec savings



R. Raman, et al., Phys. Rev. Letters <u>97</u>, 175002 (2006)



Experiments using induction demonstrate ramp-up of toroidal current following CHI startup

R. Raman, et al., 53rd Meeting of Div. Plasma Physics, Salt Lake City, November 14-18. 2011

MHD model — NSTX startup includes density and temperature

- Equations include temperature and number-density evolution

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{V}) = \nabla \cdot D \nabla n$$

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v}\right) = \mathbf{j} \times \mathbf{B} - \nabla p + \nabla \cdot \rho \nu \nabla \mathbf{v}$$

$$\frac{3}{2} n \left(\frac{\partial}{\partial t} + \mathbf{V} \cdot \nabla\right) T = -nT \nabla \cdot \mathbf{V} + \nabla \cdot \left[(\kappa_{\|} - \kappa_{\perp})\hat{\mathbf{b}}\hat{\mathbf{b}} + \kappa_{\perp}\mathbf{I}\right] \cdot \nabla T + \eta J^2$$

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

- Transport coefficients — $\kappa_{||} \sim T^{5/2}$; $\eta \sim T^{-3/2}$; $\kappa_{\perp}$, ν = const.
- D — large for these simulations
- Boundaries — perfectly conducting

Vacuum poloidal magnetic field – needed for CHI

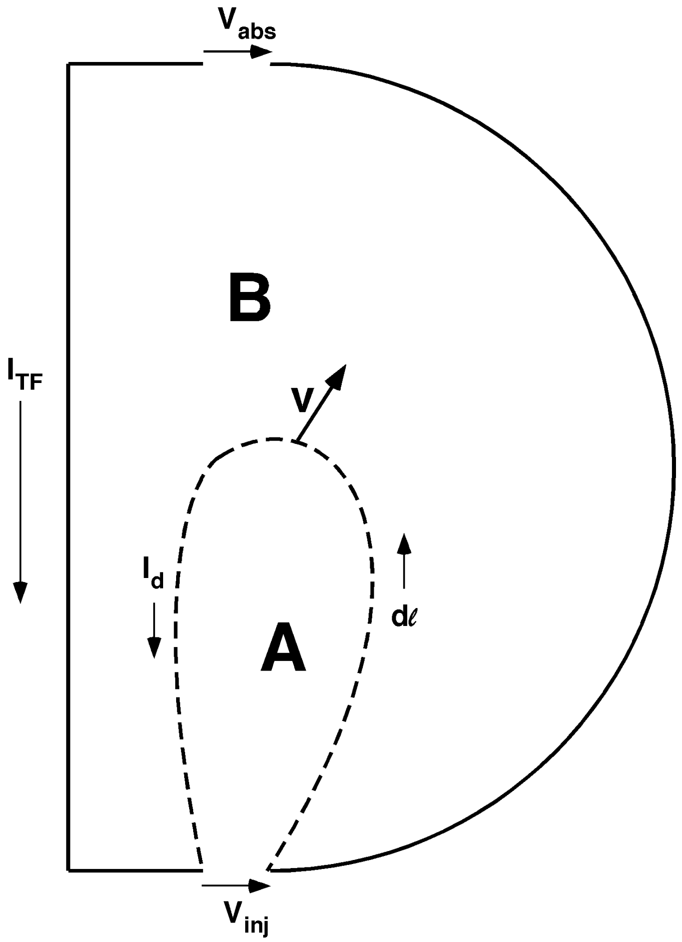
Two options:

(1) External magnetic coils, e.g. with currents from the experimental run

(2) Time-varying vacuum fields on the boundary — calculated using the PPPL "LRDFIT" code (Jon Menard)

- **Includes eddy currents in the NSTX structure and conducting (passive) plates (ms time scale)**
- **This option is used in the work presented here**
  - **Important for flux-bubble reconnection at end of CHI**

Boundary conditions for helicity injection

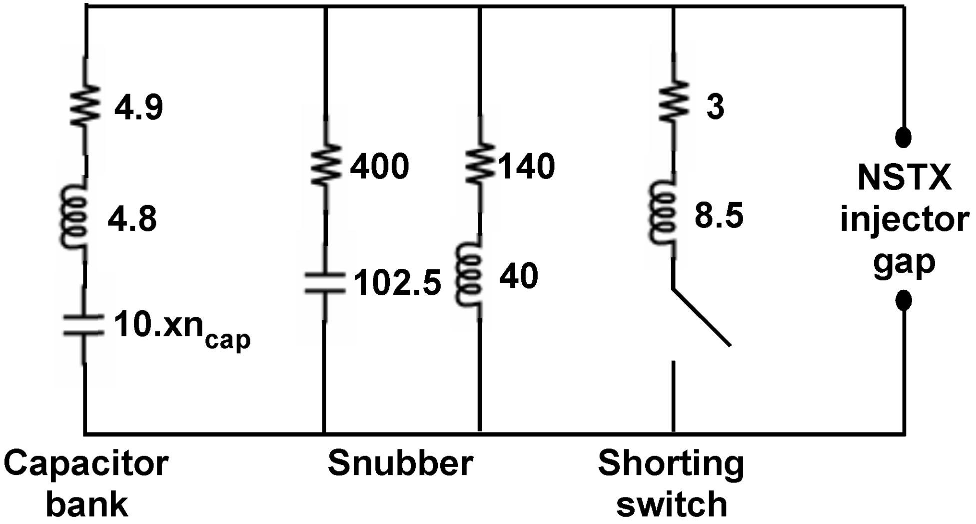


- Rate-of-change of toroidal flux = $V_{inj} - V_{abs}$
  - Toroidal flux — carried in by ExB flow at injector and out by ExB flow at absorber
- Absorber voltage — determined by requiring constant total vacuum toroidal flux (constant I_{TF})
  - Prevents "pile-up" of flux above "bubble" (would resist bubble expansion)
- Discharge (injector) current — measured by change in RB_φ above injector slot
  - Injector current satisfies bubble-burst condition: magnetic pressure drop across bubble exceeds poloidal-field tension

$$I_{inj} > I_{BB} = K\psi_{inj}^2 / \mu_0^2 I_{TF} d^2$$

Generalizes HIT-II model: R.A. Bayliss, C.R. Sovinec, and A.J. Redd, Phys. Plas. 18, 094502 (2011)

A model of the NSTX helicity-injection capacitor bank generates a time-dependent injection voltage

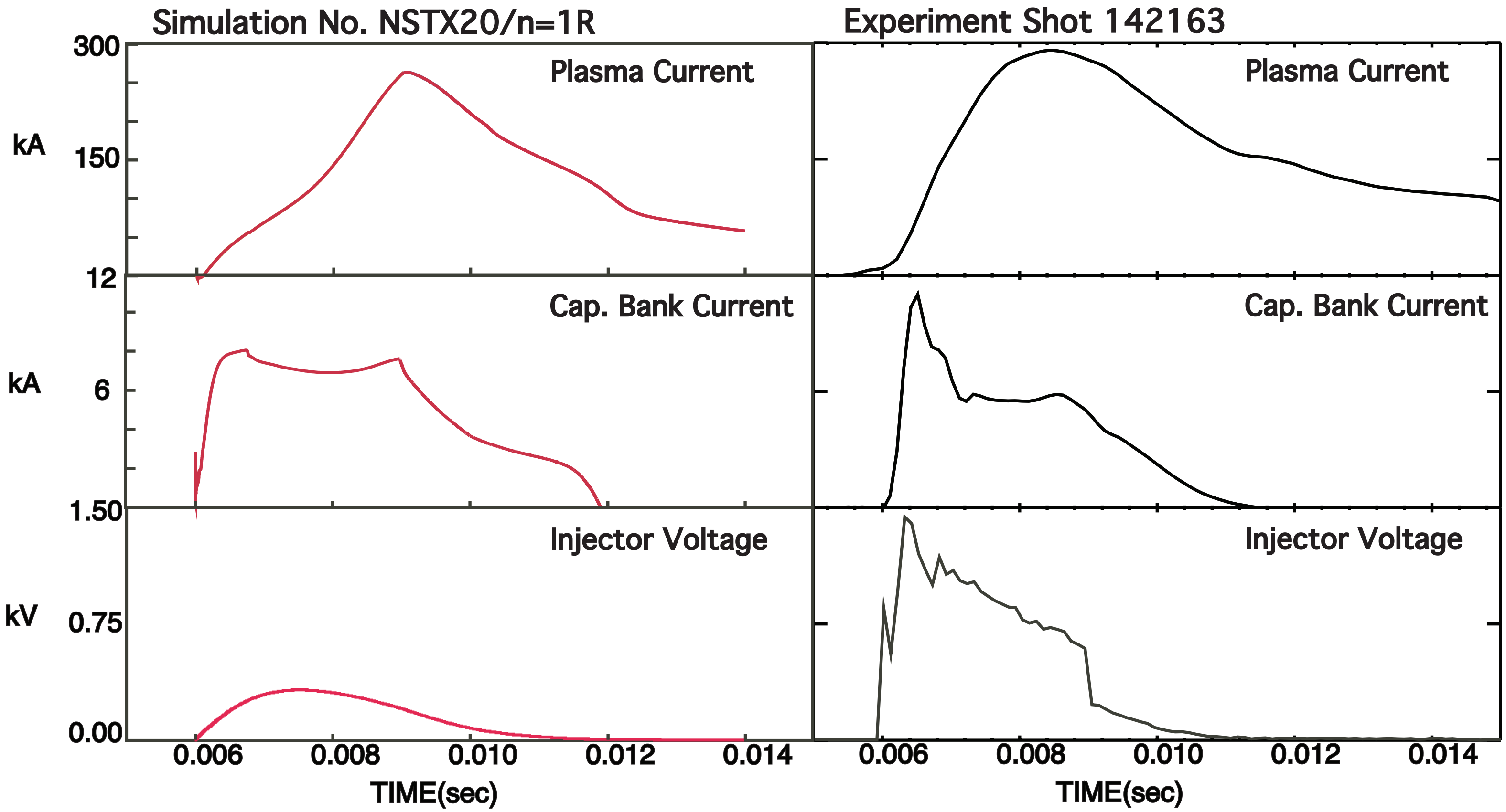


Resistances in mΩ
Inductances in µH
Capacitors in mF

- Initial voltage — applied to the capacitor bank.
- Discharge current
  - equals measured current
  - decreases the capacitor voltage (as determined by the circuit)

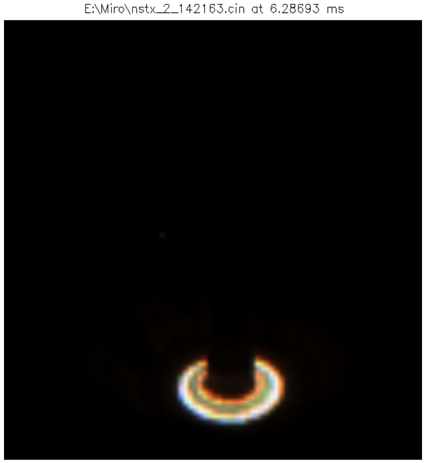
Other voltage models – e.g. constant in time – can be used

Simulation and experiment — Shot 142163

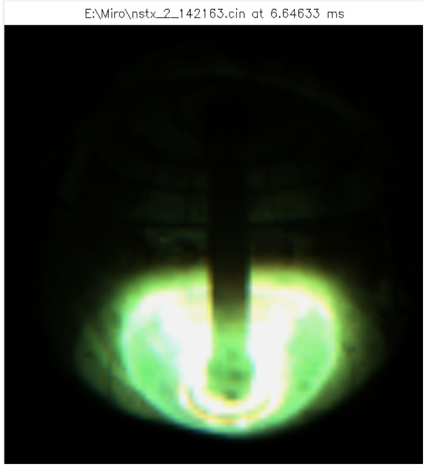


Notes:
- Power supply capacitor charging voltage: simulation = 0.75 kV; experiment=1.5 kV.
- dV/dt is damped for stability reasons

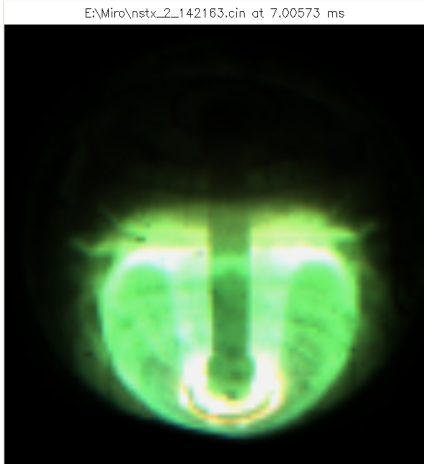
NSTX discharge 142163 — flux-bubble expansion and contraction during CHI



6.29 ms

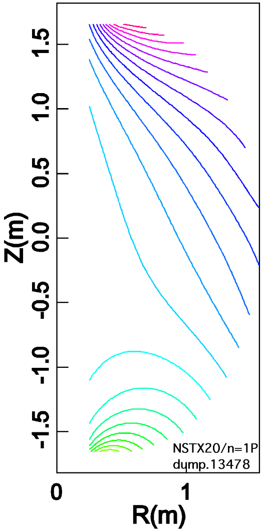


6.65 ms

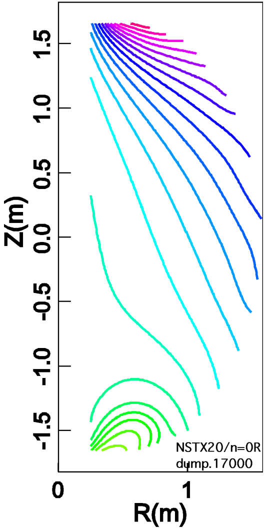


7.01 ms

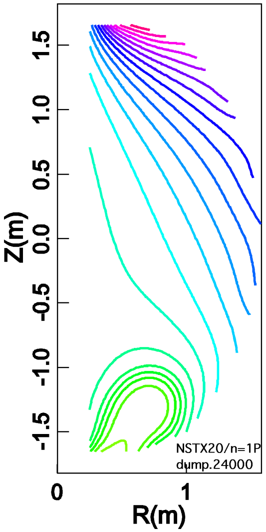
Pol. flux, t=6.00 ms



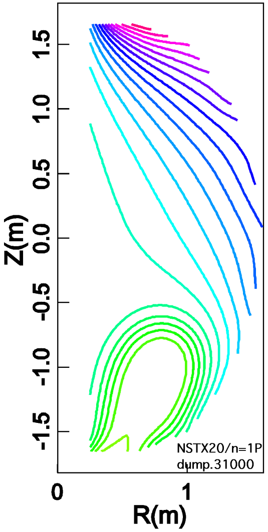
Pol. flux, t=6.28ms



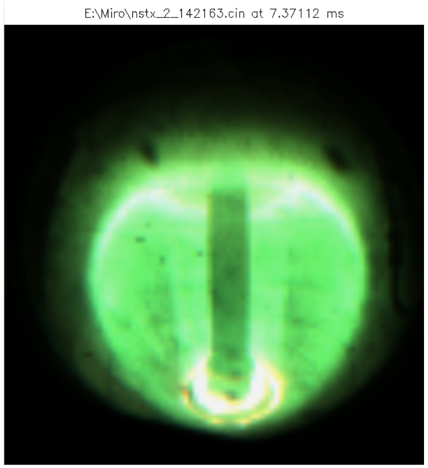
Pol. flux, t=6.66 ms



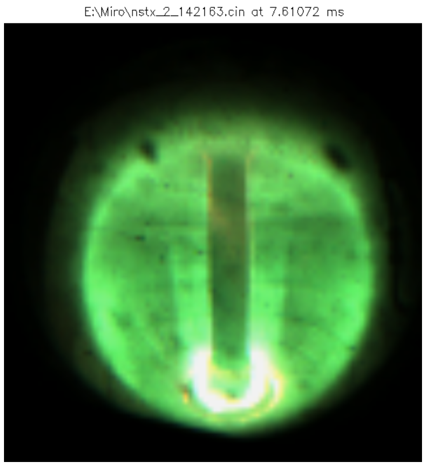
Pol. flux, t=7.00ms



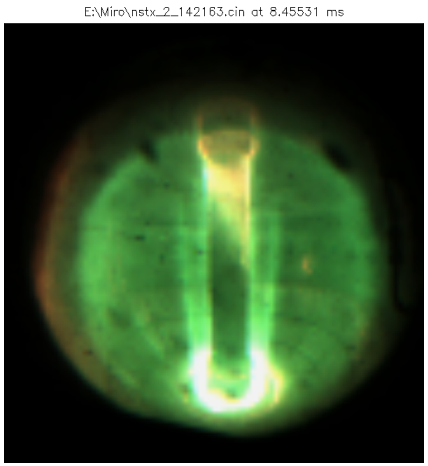
NSTX discharge 142163 — flux-bubble expansion and contraction during CHI (2)



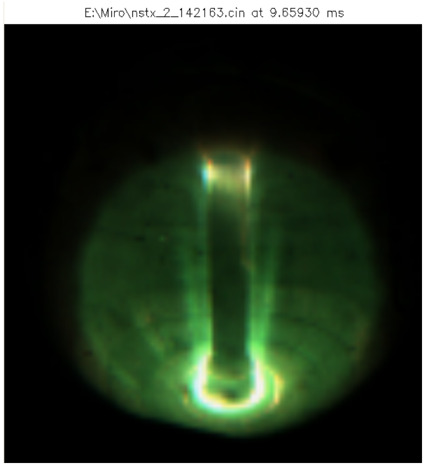
7.37 ms



7.61 ms

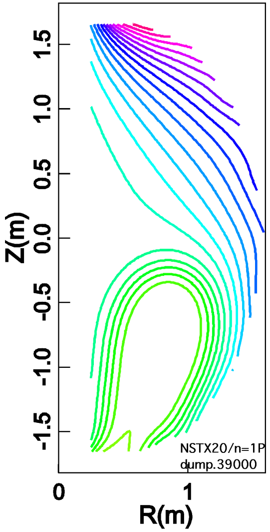


8.46 ms

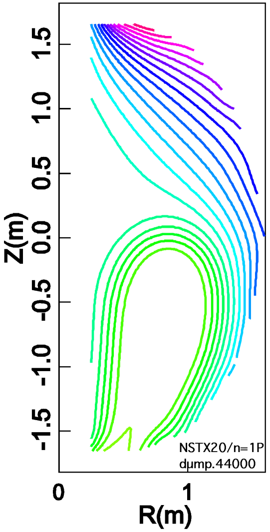


9.66 ms

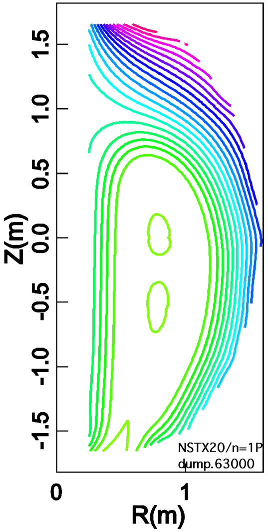
Pol. flux, t=7.37ms



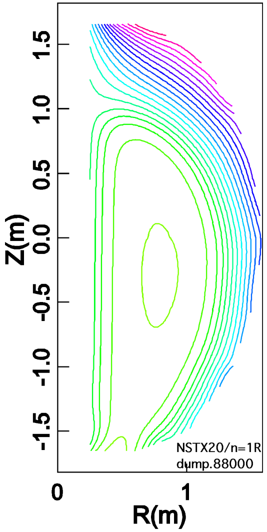
Pol. flux, t=7.61ms



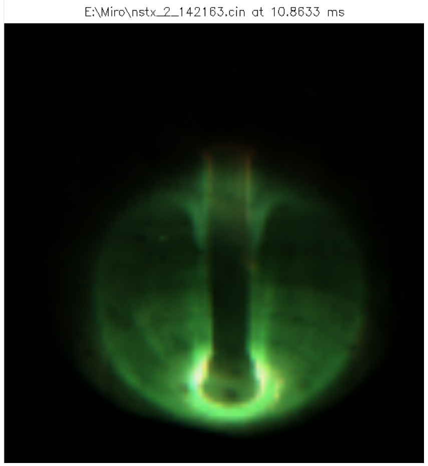
Pol. flux, t=8.46ms



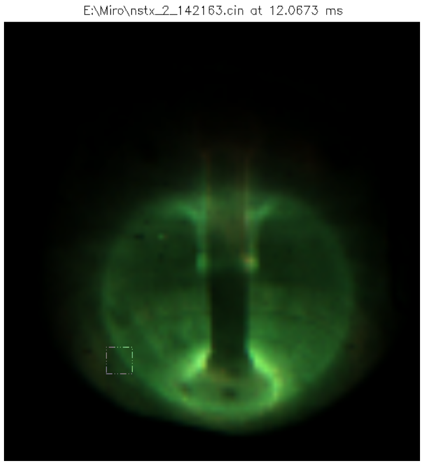
Pol. flux, t=9.65ms



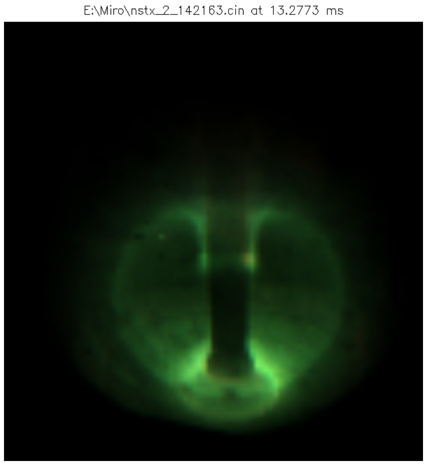
NSTX discharge 142163 — flux-bubble expansion and contraction during CHI (3)



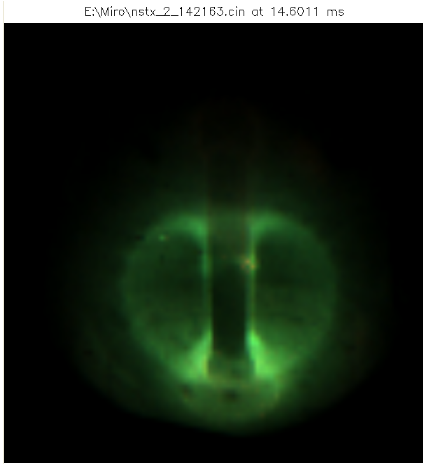
10.86 ms



12.07 ms

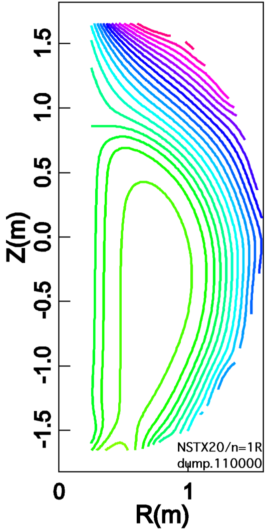


13.28 ms

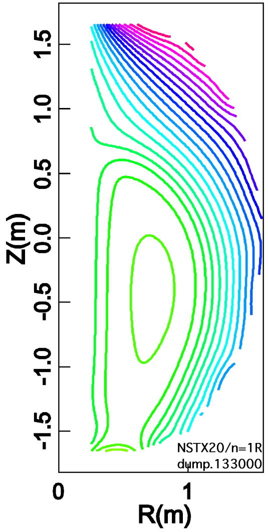


14.60 ms

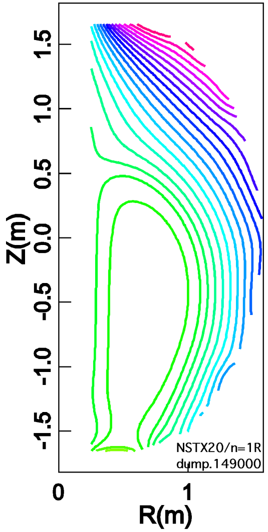
Pol. flux, t=10.86 ms



Pol. flux, t=12.06ms



Pol. flux, t=13.23ms



Note: Field-lines are very long (> 10^5 m).

But – No closed flux surfaces.

Injection physics

- Temperature: Ohmic heating and energy losses
- Current distribution at the front of the poloidal-flux bubble
- n=1 mode
- Effects of external plasma (outside the bubble)
- Flux-surface closure at end of the current drive (ongoing research)

Temperature: Computed electron temperature is consistent with experimental measurements

Plasma temperature — determined primarily by:

- ***ohmic heating***
- ***thermal losses along open field lines to the wall***

$$3n\frac{dT}{dt} \approx \nabla_{\parallel}\left(\kappa_{\parallel}\cdot\nabla_{\parallel}T\right)+\eta_{\parallel}j_{\parallel}^{2}$$

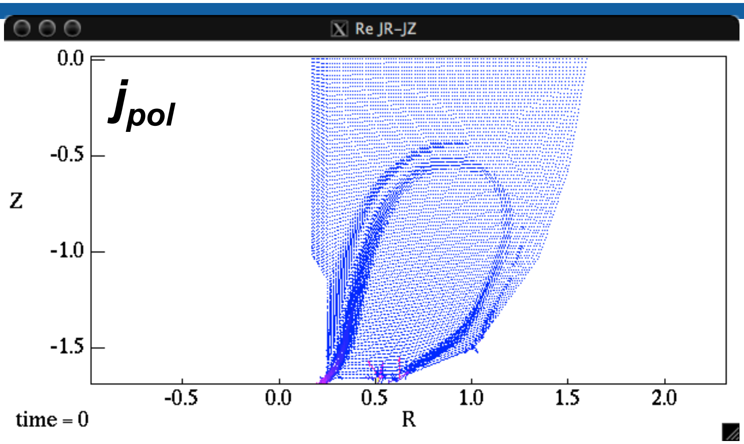
$$\kappa_{\parallel}\sim T^{5/2}\big/Z_{eff}$$

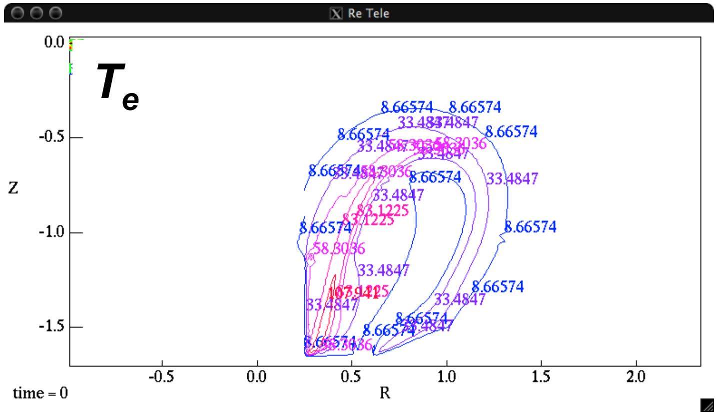
$$\eta_{\parallel}\sim Z_{eff}\big/T^{3/2}$$

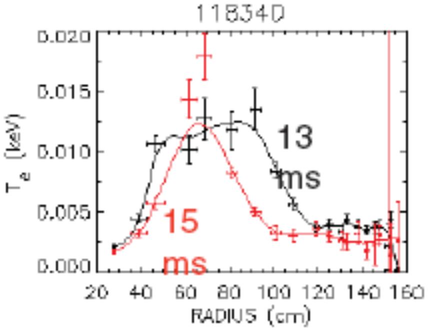
so

$$T\sim\left(Z_{eff}\,j_{\parallel}\ell\right)^{2/5}$$

with ℓ ***an effective scale length***





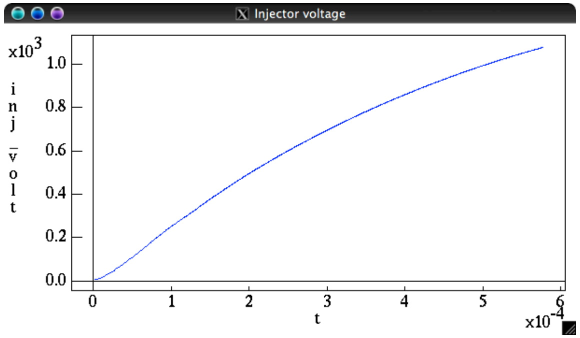


Experiment at midplane (Thomson-scattering measurements of **T_e** are not available for shot number 142163)

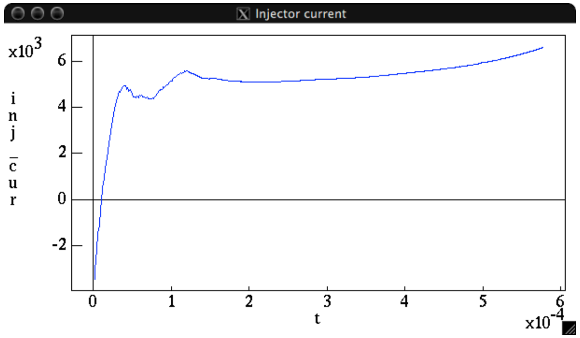
<u>Simulation at 0.52 ms: Z_{eff}=1.</u>
T_e is highest (126 eV) near the lower left corner (small R) where poloidal flux tube areas (2πRw) are small and $j_{\parallel}$ is large

<u>Simulation temperatures</u>
T_e is consistent with experiment

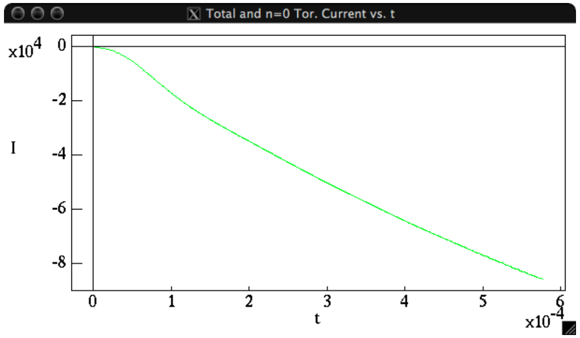
Current distribution — Poloidal flux "piles-up" in the "flux-bubble" surface layer



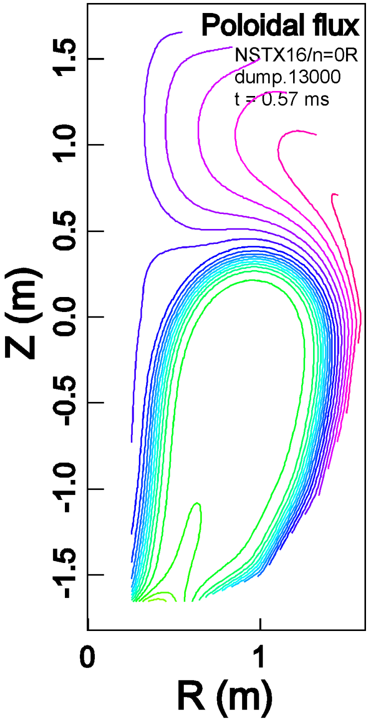
Discharge Voltage



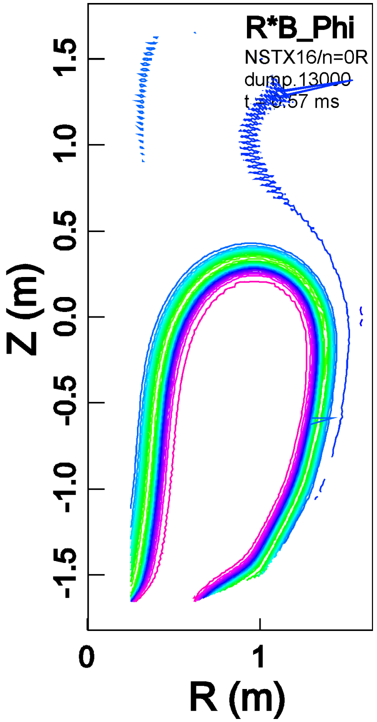
Discharge Current



Toroidal Current



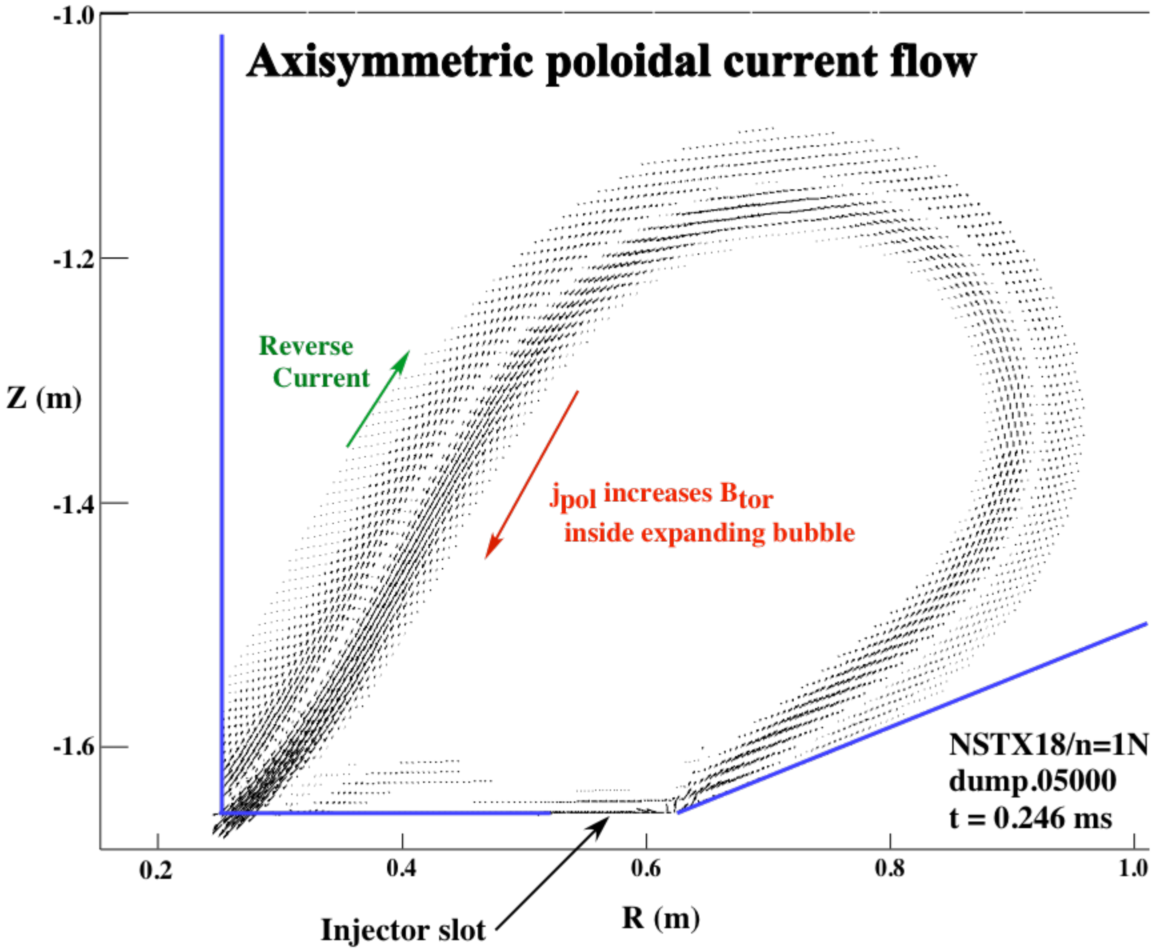
Poloidal flux at 0.57 ms



RB_φ at 0.57 ms

NSTX16/n=0R

A reversed poloidal current layer develops at the surface of the expanding flux-bubble



Poloidal field first increases then decreases across the current layer

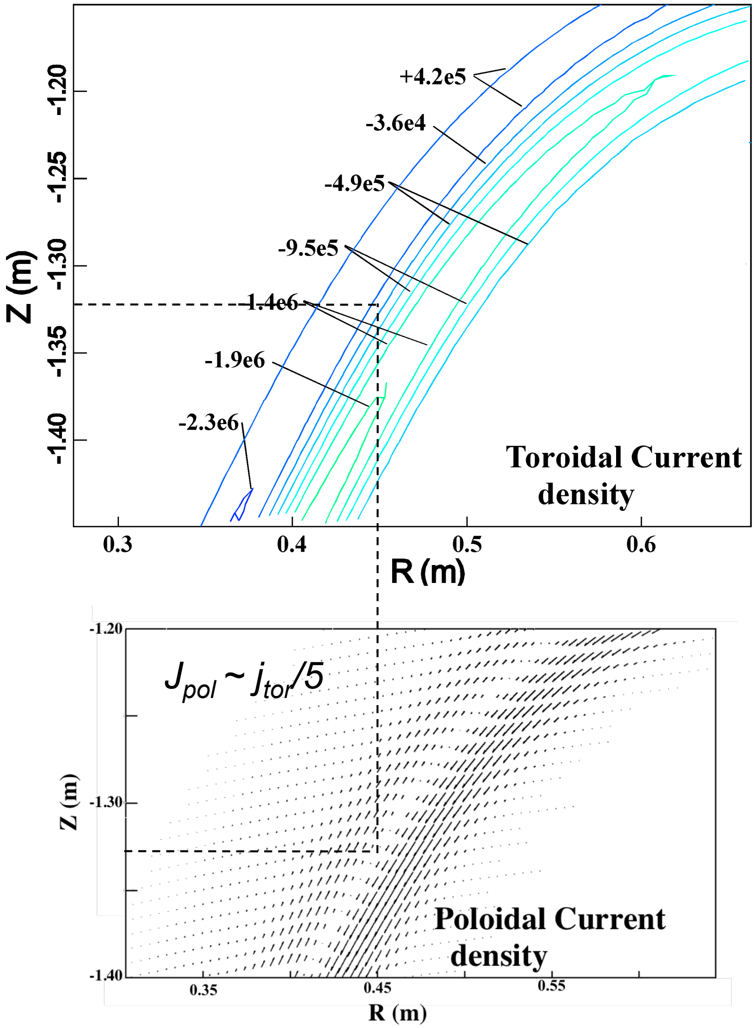
$$\frac{\partial \psi}{\partial t} + \mathrm{v} \cdot \nabla \psi = \eta j_{\varphi}$$

(axisym. approx.)

Reversed toroidal current results from “pileup” of poloidal flux near the surface of the bubble

Current is approximately force-free; toroidal and poloidal currents behave similarly

The axisymmetric toroidal current density reverses due to poloidal-flux pile-up

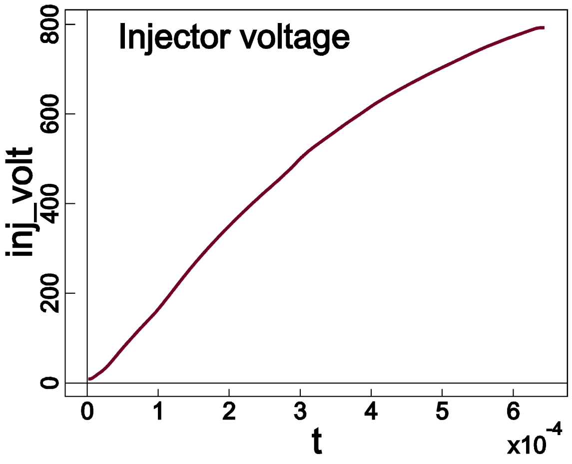


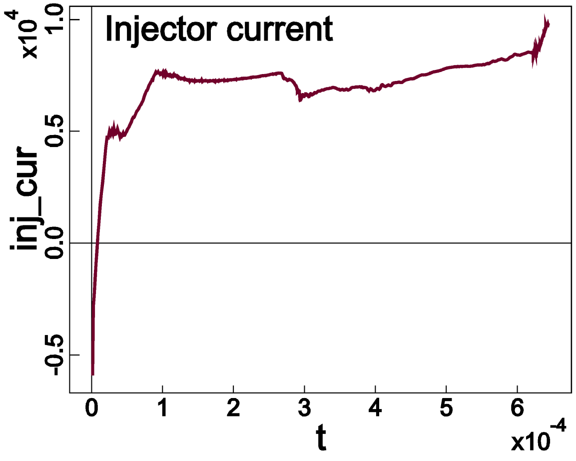
Toroidal and poloidal current nulls occur on or close to the same surface.

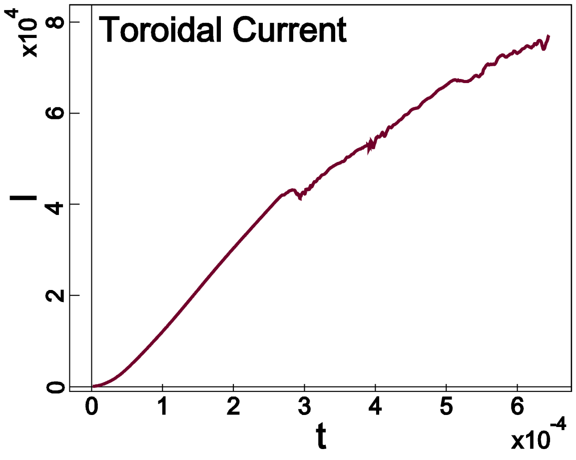
The toroidal current peaks ~ ± 1.0 MA/m^2 near the top of the flux bubble.

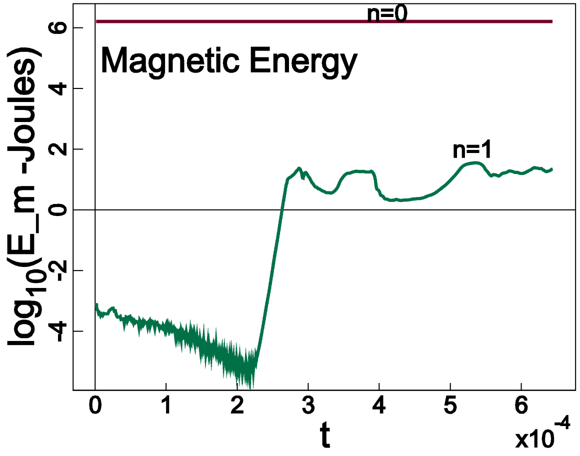
NSTX18/n=1N

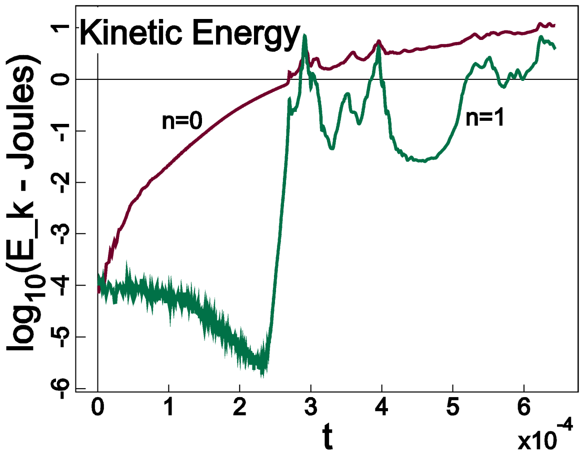
An n=1 toroidal mode develops as the flux-bubble expands









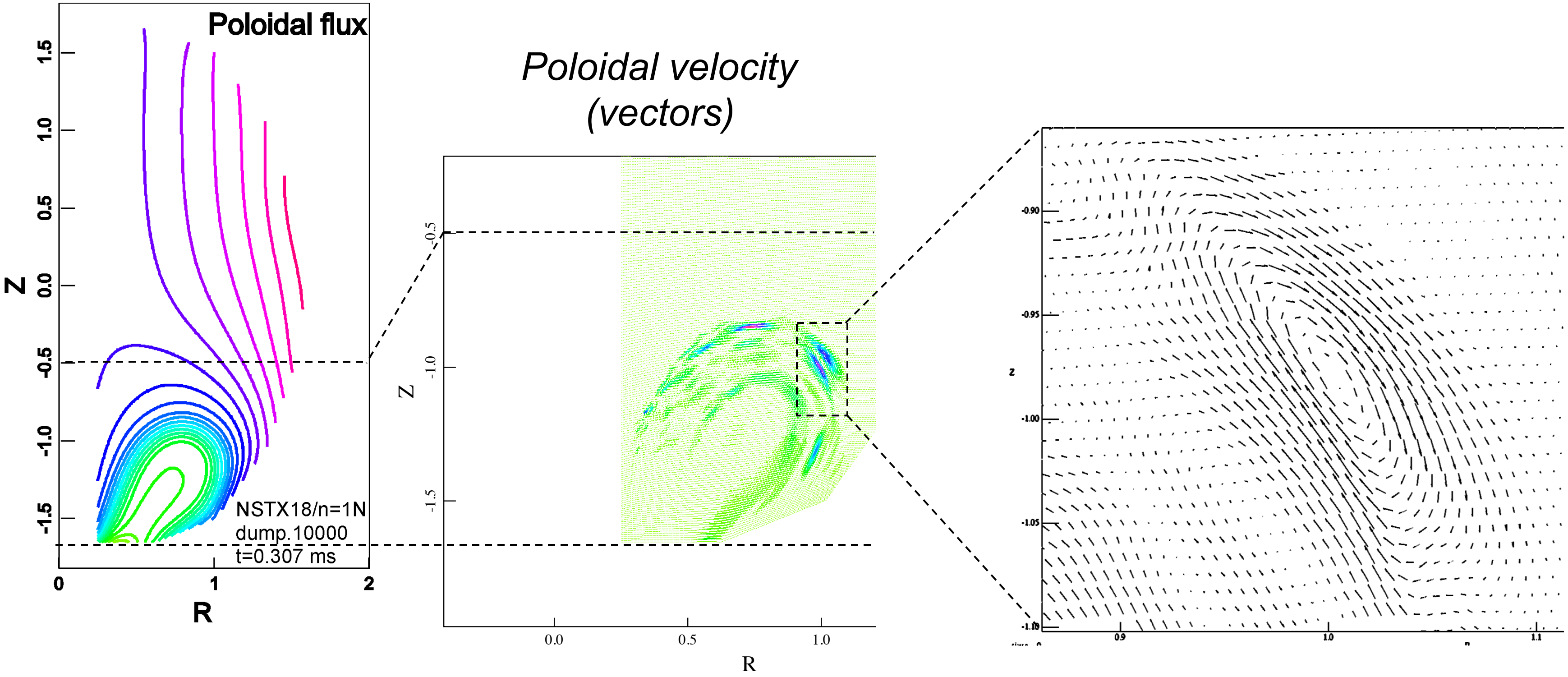


Kinetic (flow) energy in n=1 mode grows rapidly — approximately equals axisymmetric kinetic energy.

A series of relaxation events follow.

NSTX18/n=1N

Velocity field after first large MHD event: symmetry-breaking perturbation lies on the expanding bubble



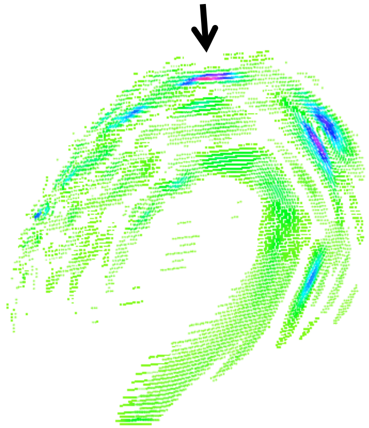
Axisymmetric poloidal flux.

Plasma flow velocity (n=0 plus n=1) includes surface-layer structure

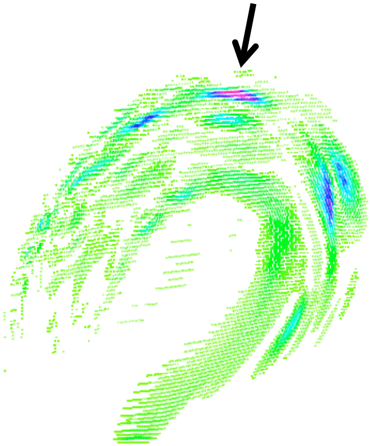
Velocity structures form poloidal vortices

NSTX18/n=1N

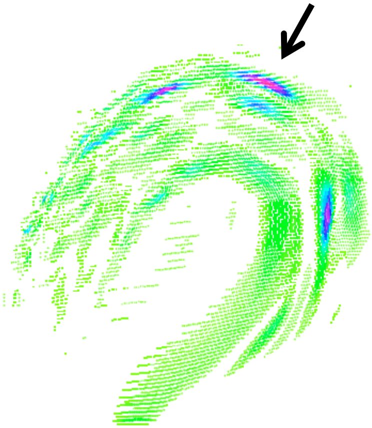
The velocity vortices form an helical structure aligned with the axisymmetric field — confirmed in a 3D view



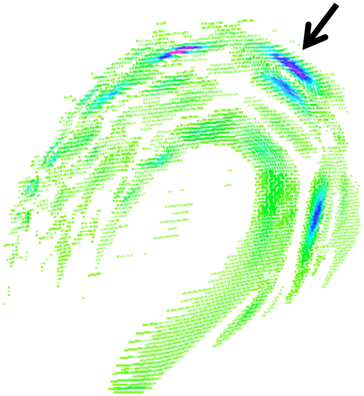
$\varphi = 0$



$\varphi = \pi/2$

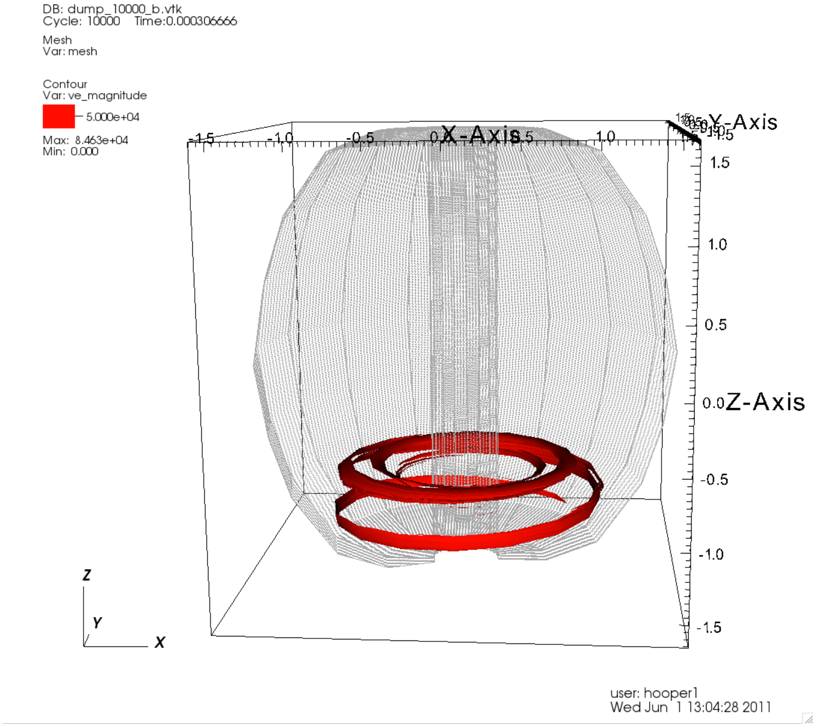


$\varphi = \pi$



$\varphi = 3\pi/2$

Shown is a surface with a constant magnitude of the velocity, $|\mathbf{v}| = 5\mathrm{x}10^4$ m/s



DB: dump_10000_b.vtk
Cycle: 10000 Time:0.000306666

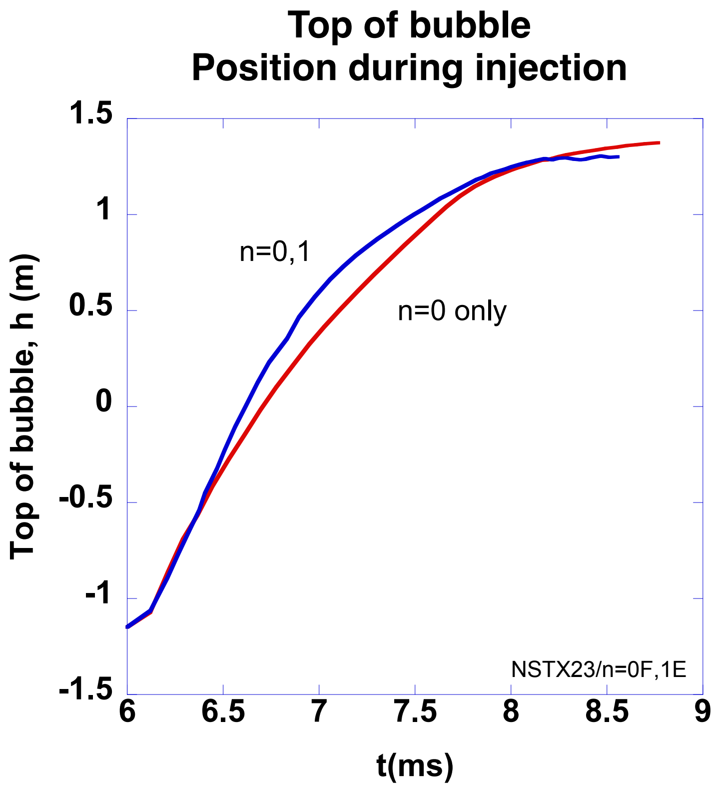
Mesh
Var: mesh

Contour
Var: ve_magnitude
🟥 5.000e+04
Max: 8.463e+04
Min: 0.000

user: hooper1
Wed Jun 1 13:04:28 2011

NSTX18/n=1N

The n=1 mode has only a minor affect on the n=0 evolution



- **n=1 mode broadens n=0 current distribution**
- **Results in a slightly faster evolution of the bubble, but otherwise has little affect**

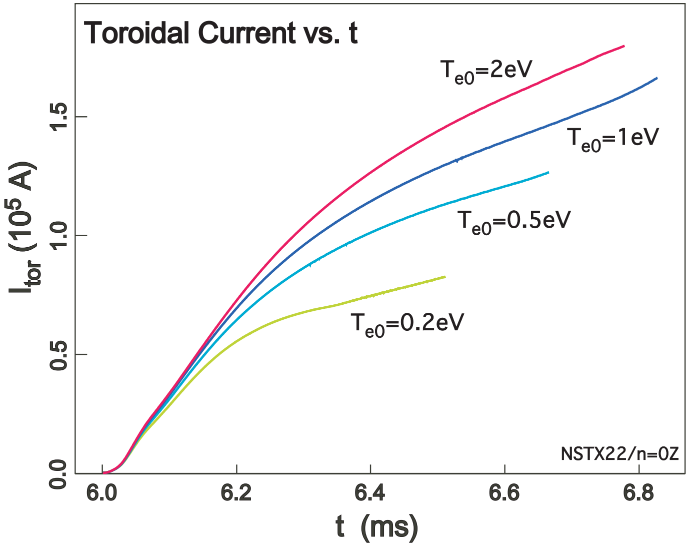
Plasma external to the expanding flux bubble affects its evolution

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

- **Unconstrained plasma temperature — strong currents generated locally where the effect is strong**
- **Local plasma heating —currents increase**
- **“Run-away” currents can be comparable to injected and toroidal currents in the bubble**

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

- **Rather than model this physics, we “clamp” external temperatures**



Perturbed magnetic field — generated by plasma-flow and diffusion

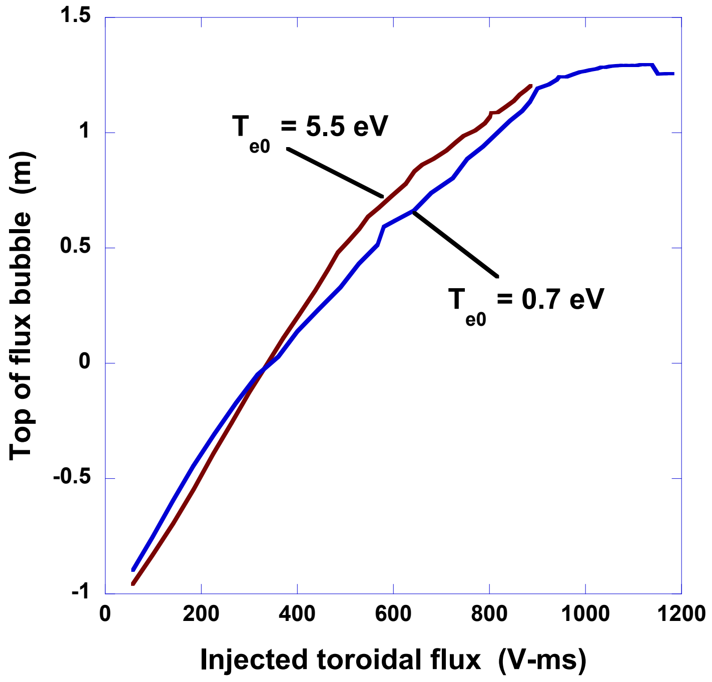
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\mathbf{v} \times \mathbf{B} \right) + \nabla \times \frac{\eta}{\mu_0} \nabla \times \mathbf{B}$$

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

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

The experimental temperature is not known

Plasma expansion is primarily determined by the injected flux (axisymmetric approximation)



Helicity (2x linked toroidal and poloidal fluxes) can be used instead of injected flux

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

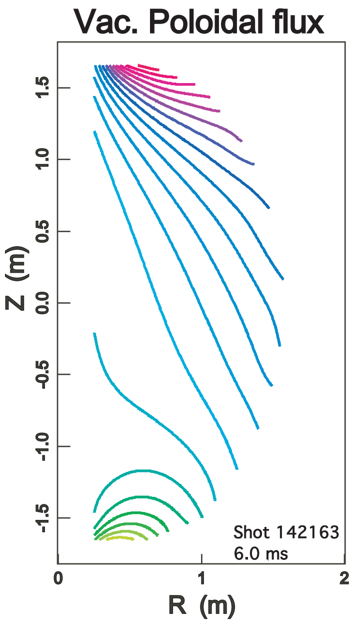
Flux-surface closure at end of injection – Bias flux programming

Flux surface closure — necessary to transition to non-CHI current drive

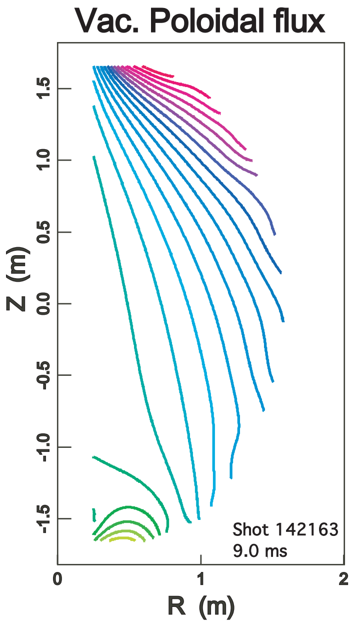
In experiment — generated by

- **Short-circuiting applied voltage**
- **Removing bias poloidal field — see below**

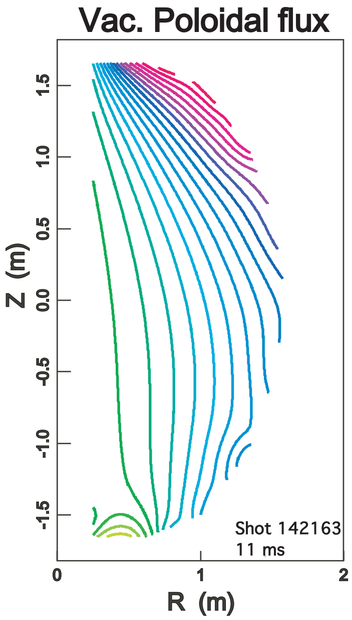
6 ms



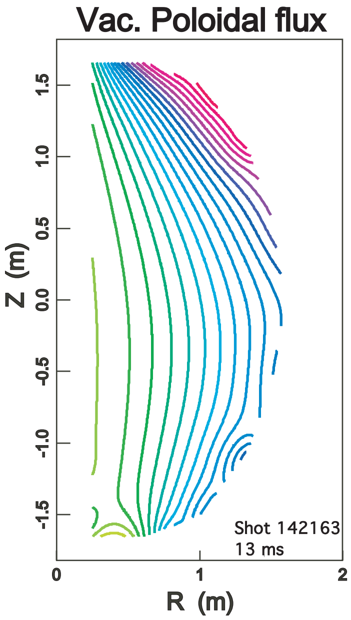
9 ms



11 ms



13 ms



Closure — possible magnetic reconnection mechanisms

Magnetic reconnection can occur via:

- Resistive diffusion (possible in axisymmetric system)
- Symmetry-breaking fluctuations

Experiment does not observe fluctuations — suggests resistive diffusion

- Diffusion time for spatial distance x is $t_{diff} \sim \frac{\mu_0}{\eta} x^2 \approx \frac{T^{3/2}}{411} x^2$

  At 10 eV and 0.1 m — $t_{diff} \sim$ 0.1 ms – consistent with closure times observed in experiment

- But — relatively high temperature must be maintained in the current channel to minimize flux decay

Other effects also may be important

- If the injected current returns in the central column reconnection is apparently impeded

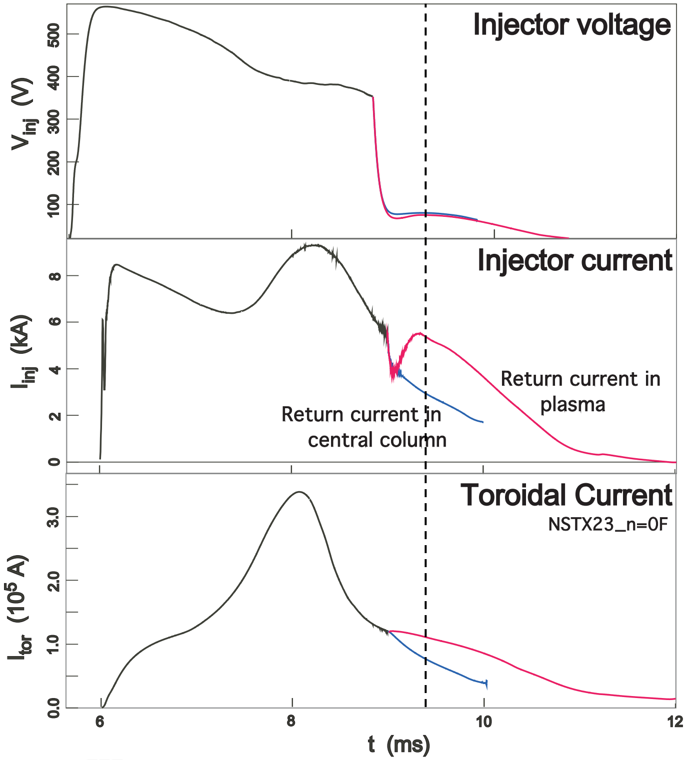
Effect of injector current return path on flux closure

Over-driven injection — Injector current returns in central column

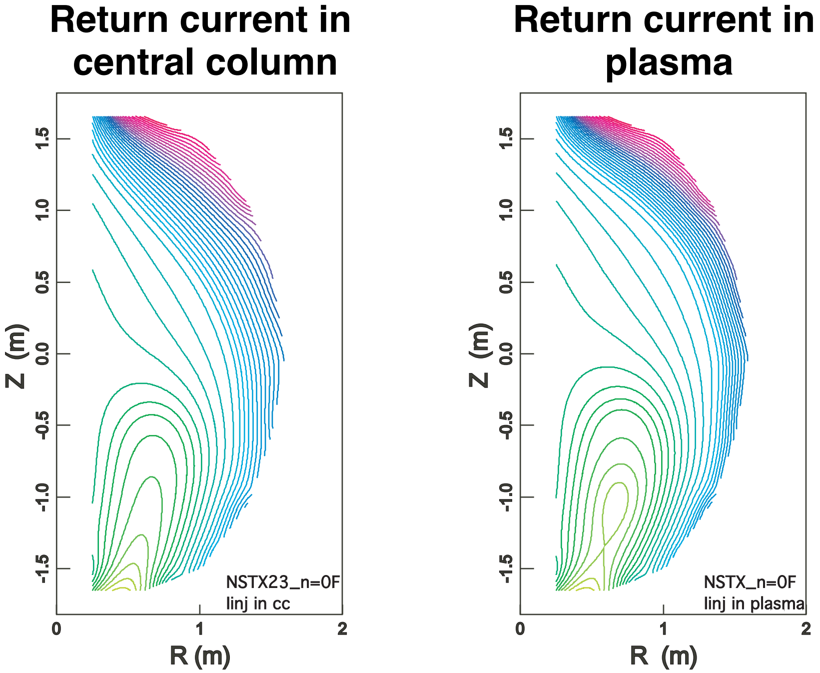
- No flux surface closure

Clamping temperature (0.7 eV) at top of flux bubble forces current to return in the plasma

- Flux surface closure



t = 9.4 ms


Return current in central column

Return current in plasma

T ~ 20 eV near x-point; similar for both cases
Temperatures in current channel = 5-15 eV

Summary – Results of resistive MHD simulations of CHI in NSTX

- **Reproduce most experimental features of CHI**
  - **The shape and evolution of the flux bubble are in good, semi-quantitative agreement with experiment**
  - **Temperatures are in approximate agreement with experiment**

- **Detailed current density and velocity distributions are analyzed**

- **An n=1 mode impacts details of the injection but apparently has no major consequences**

- **Temperature of the plasma outside the bubble affects flux evolution**

- **Flux-surface closure has been demonstrated**
  - **The volume of closed surfaces is small in present simulations**
  - **External plasma effects appear to be important**
  - **Understanding closure physics and optimizing the closed volume is “work in progress”**