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Comparing resistive MHD simulations and experiments of Coaxial Helicity Injection (CHI) in NSTX

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ABSTRACT:

NSTX generates CHI plasmas with current, density, and temperature appropriate for ST startup.[1] Whole-device simulations of CHI using the NIMROD MHD code[2] extend the HIT-II model.[3] A model power supply generates time-dependent voltage and current at the injection gap. Absorber gap voltage maintains a constant vacuum toroidal flux. Simulation physics includes ohmic heating and thermal conductivity along and across the magnetic field and generation of non-axisymmetric fields and flows. A flux bubble expands in the simulation with current and plasma temperature similar to experiment; an n=1 mode is observed to generate an helical ribbon of current and velocity vortices on the flux bubble surface. Time-dependent poloidal-field boundary conditions for interesting NSTX discharges are used for quantitative comparisons with experiments.

[1]R. Raman, et al., PRL 104, 095003 (2010).
[2]C.R. Sovinec, et al., J. Comp. Phys. 195, 355 (2004).
[3]R.A. Bayliss, C.R. Sovinec and A.J Redd, Phys. Plasmas 18, 094502 (2011);
C.R. Sovinec, E.C. Howell, and A.J. Redd, this meeting (JP9.00136).

Accomplishments and Status of work in progress

- The model used in simulations of HIT-II has been generalized
  - Voltage across the injection gap — determined by a model of the NSTX power supply (capacitor bank)
  - Current — measured from R^*B_φ at the gap and determines the evolution of the capacitor charges and voltages
  - Injected plasma and toroidal flux — extracted at the absorber gap by ExB flow

- Time evolution using NSTX time-dependent boundary conditions (including wall eddy currents) — demonstrated

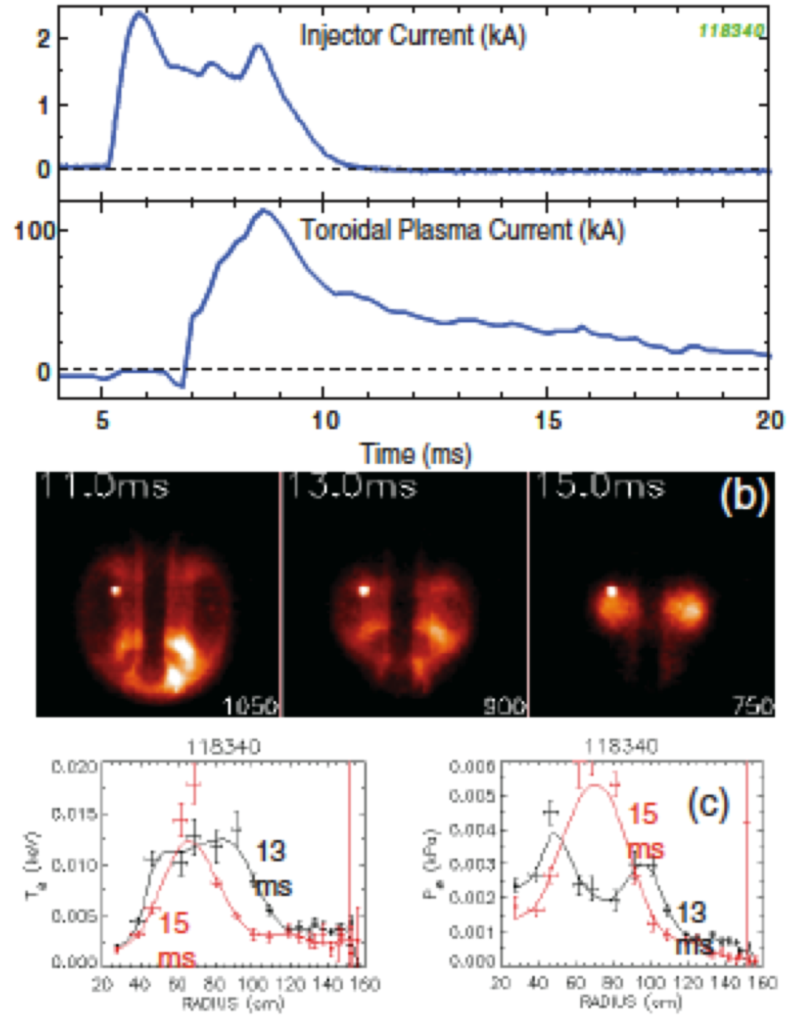
- Discharge currents and current amplification (toroidal current/discharge current) — current and amplification in approximate agreement with experiment

- Ohmic heating and thermal conductivity (along open field lines) have been implemented — temperatures in approximate agreement with experiment

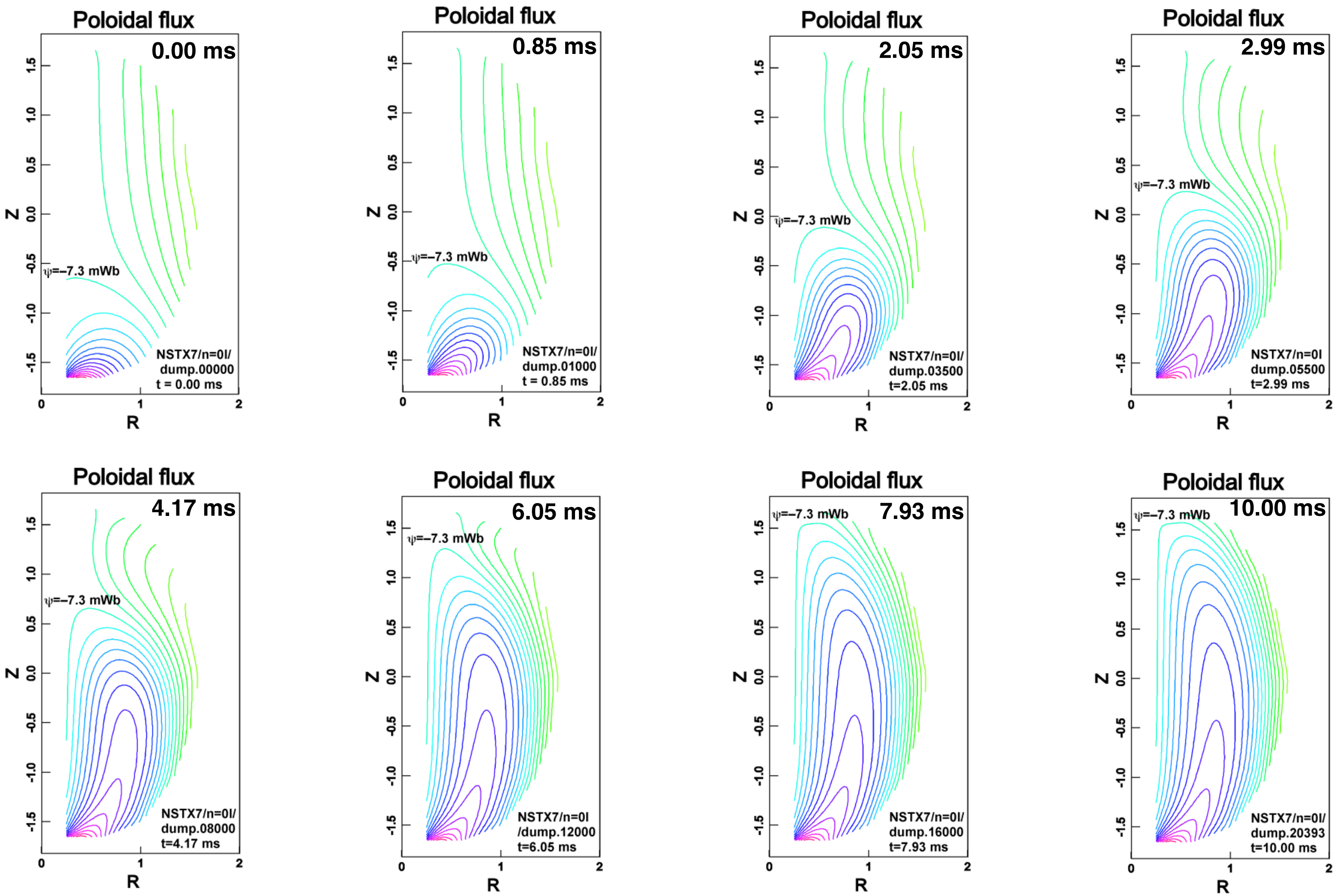
- Simulations show an n=1 mode — an instability in the current channel with poloidal wavelength 0.1-0.3 m, results in an helical structure in the current layer at the surface of the expanding flux bubble

NSTX: Shots shows expanding flux bubble

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



Simulation: Poloidal flux contour plots expand during injection



MHD model applied to NSTX startup includes density and temperature

- The system of equations includes temperature and number-density evolution.

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

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

- Transport coefficients are T-dependent: $\kappa_{||} \sim T^{5/2}$; $\eta \sim T^{-3/2}$.

- Detailed modeling of the injector bank controls the injector voltage (see below).

- The injector and absorber boundary conditions are swapped with respect to modeling for HIT to obviate the need for iterating parameters.

Vacuum poloidal magnetic field

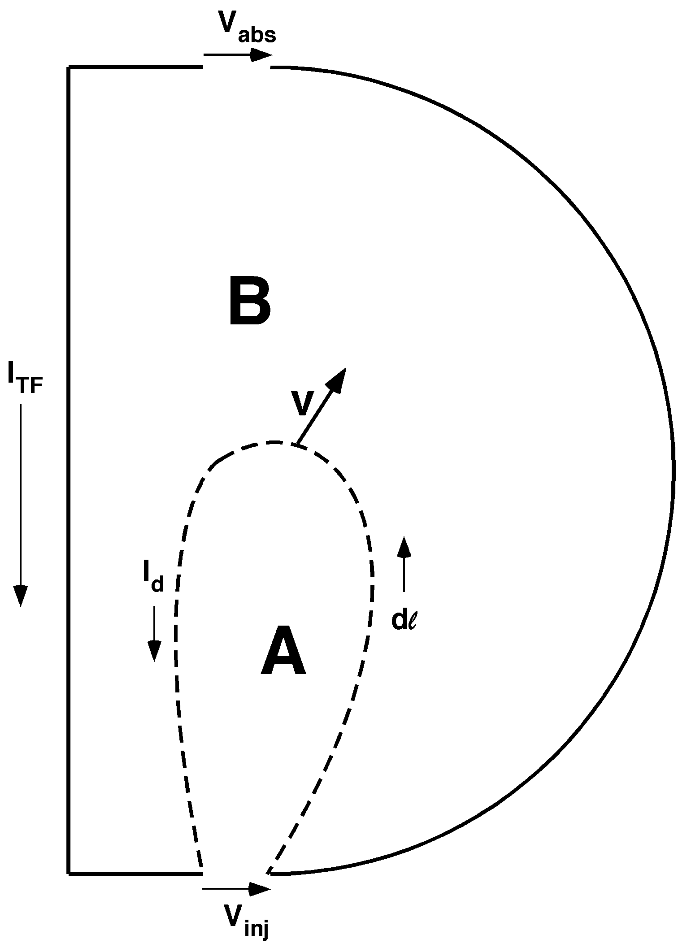
Two options are available for applying the vacuum poloidal magnetic field

(1) External magnetic coils with currents at t=0 from the experimental run

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

- **This option includes eddy currents in the NSTX structure and conducting (passive) plates**

Boundary conditions for helicity injection

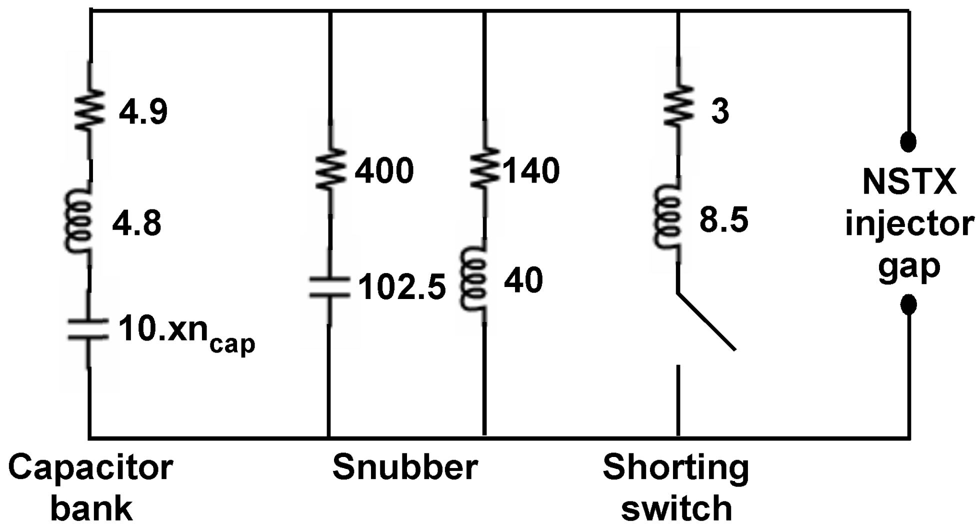


- Rate-of-change of toroidal flux — equals $V_{inj} - V_{abs}$
- Absorber voltage — determined by requiring the total vacuum toroidal flux to be constant, corresponding to a constant I_{TF}
- Discharge (injector) current — measured by the change in RB_φ just above the injector slot
- Toroidal flux —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

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

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

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

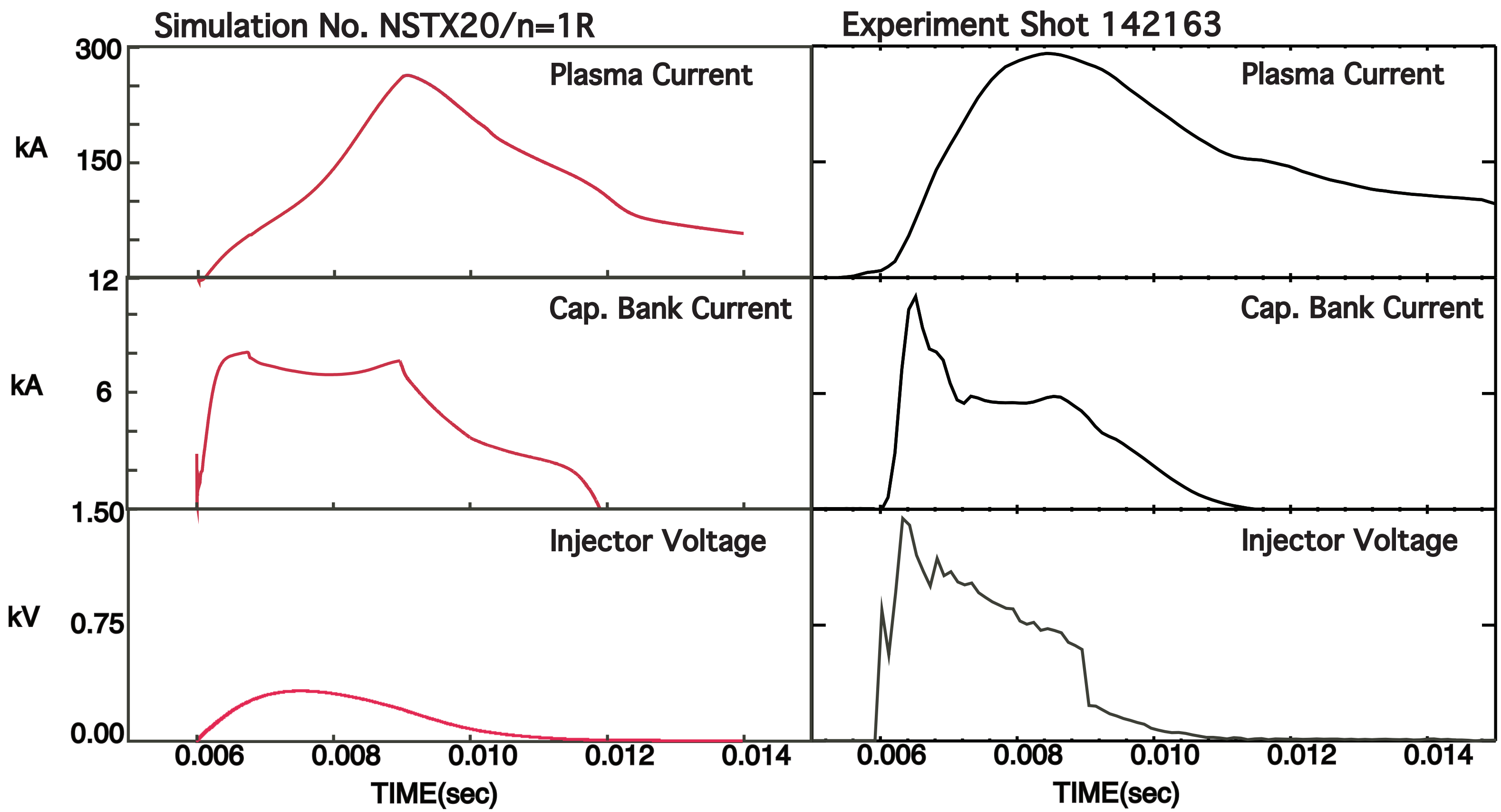


Resistances in mΩ
Inductances in μH
Capacitors in mF

- Initial voltage — applied to the capacitor bank.
- Discharge current — equals measured current and decreases the applied voltage as determined by the bank, snubber, and shorting switch

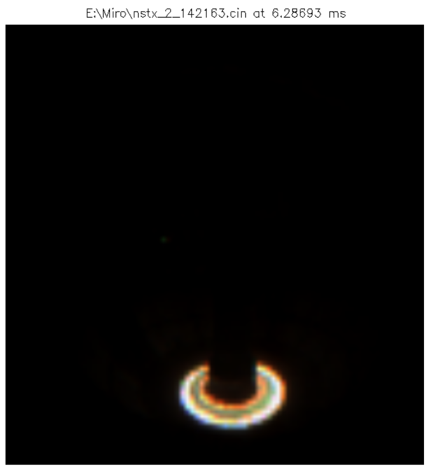
Other voltage models – e.g. constant in time – are also used

Simulation and experiment — Shot 142163

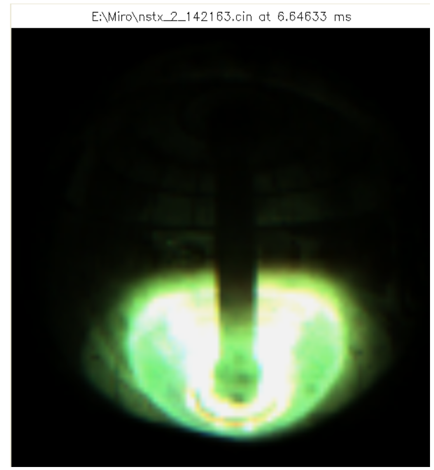


Notes:
- Power supply capacitor charging voltage: simulation = 0.75 kV; experiment=1.5 kV.
- The voltage rise time in the simulation differs from the experiment in part as there is no pre-electrical breakdown period; thus the power supply inductance limits the rate of rise. Also, there is added power-supply damping for stability reasons.

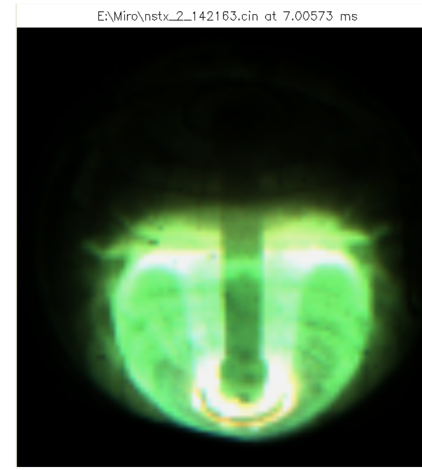
NSTX discharge 142163 — flux-bubble expansion and contraction during CHI



6.29 ms

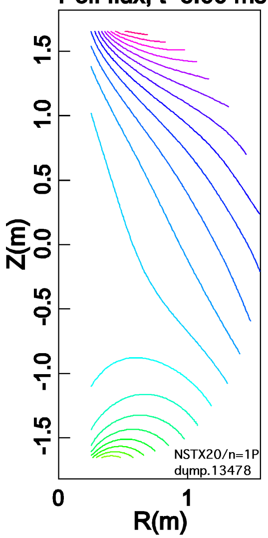


6.65 ms

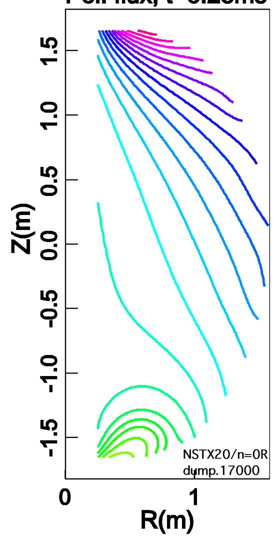


7.01 ms

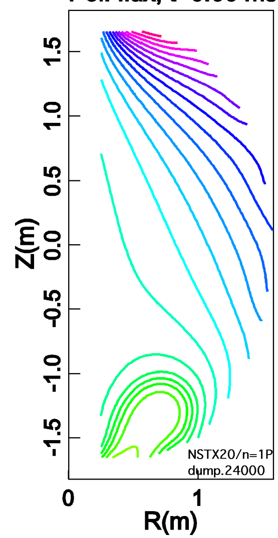
Pol. flux, t=6.00 ms



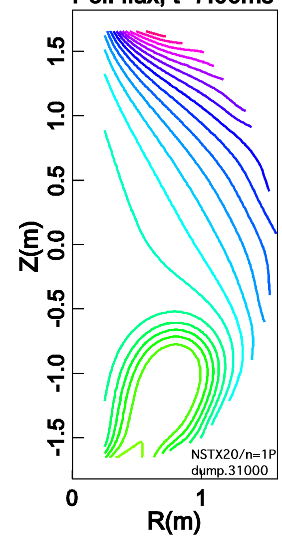
Pol. flux, t=6.28ms



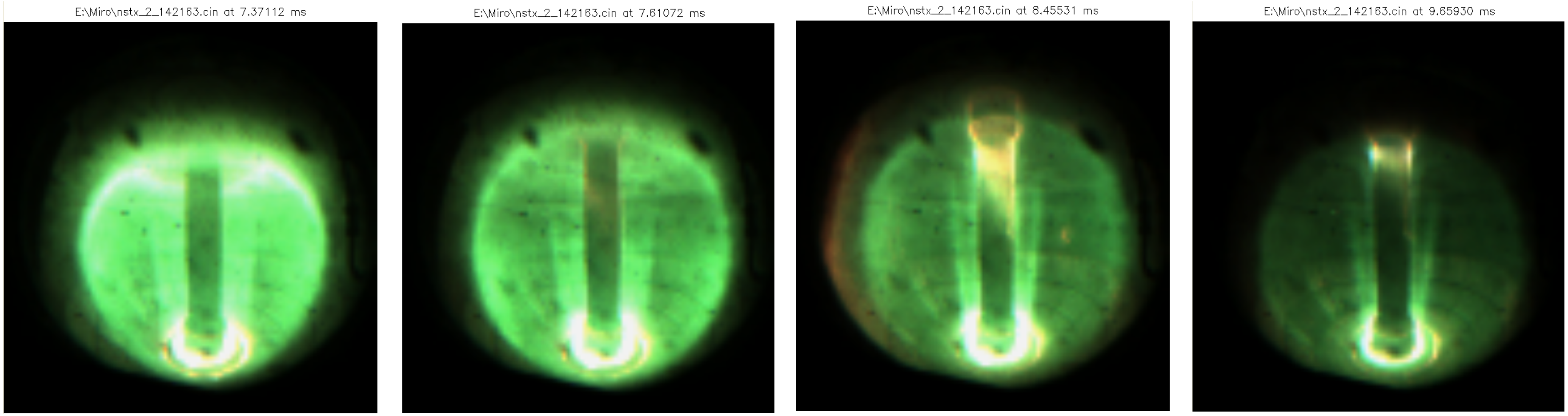
Pol. flux, t=6.66 ms



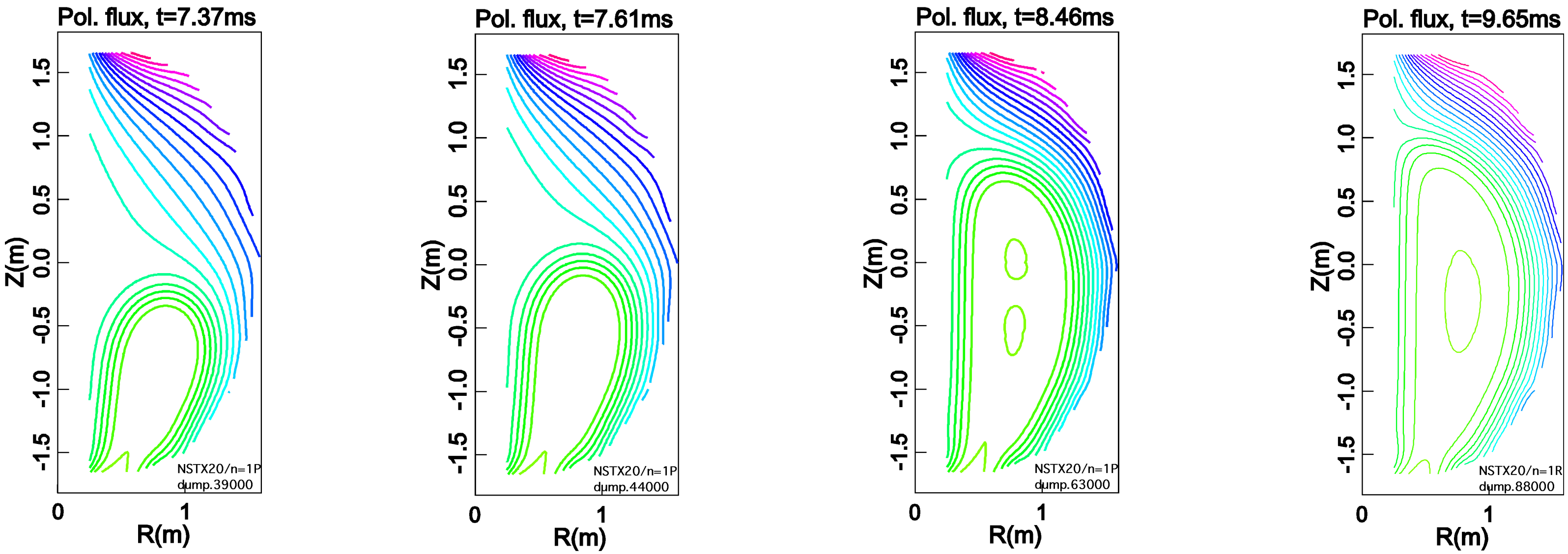
Pol. flux, t=7.00ms



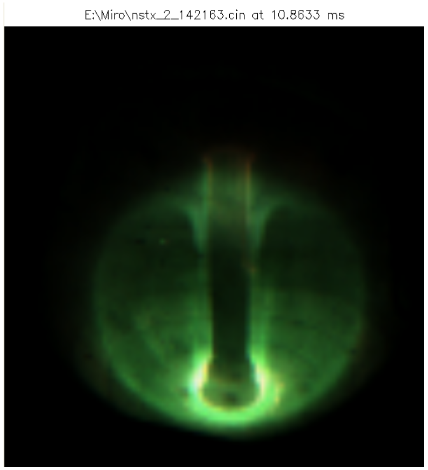
NSTX discharge 142163 — flux-bubble expansion and contraction during CHI (2)



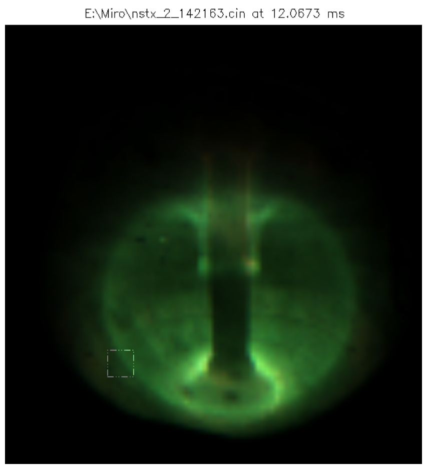
7.37 ms | 7.61 ms | 8.46 ms | 9.66 ms



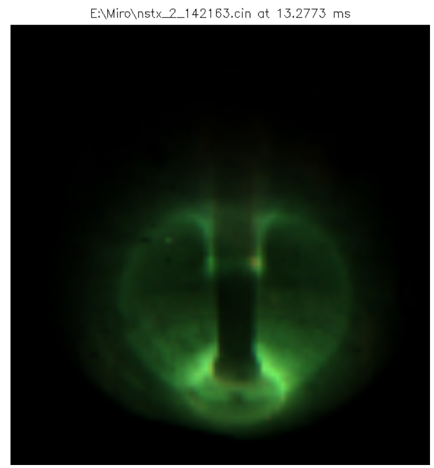
NSTX discharge 142163 — flux-bubble expansion and contraction during CHI (3)



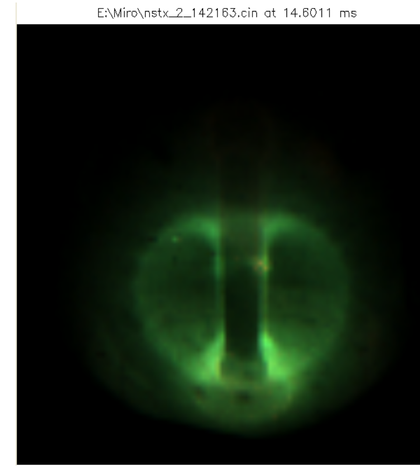
10.86 ms



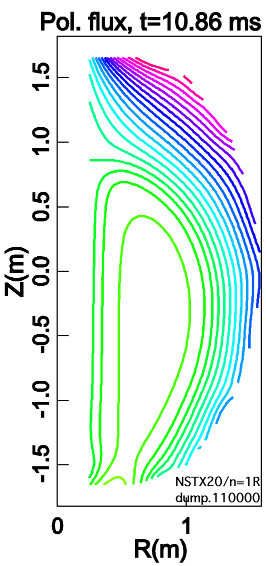
12.07 ms

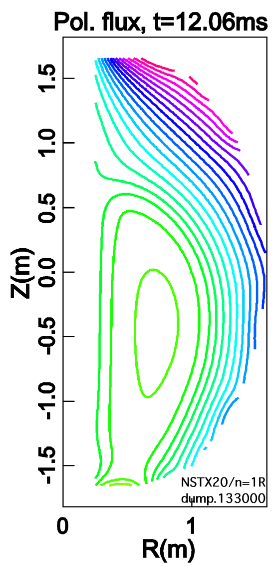


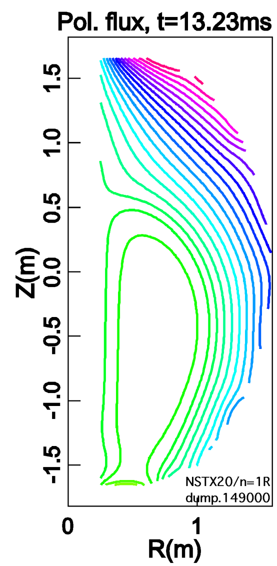
13.28 ms



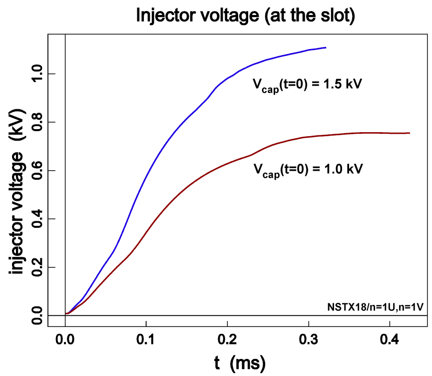
14.60 ms

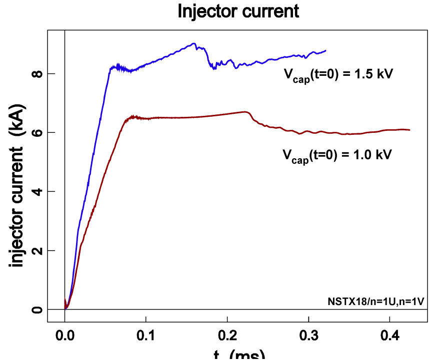


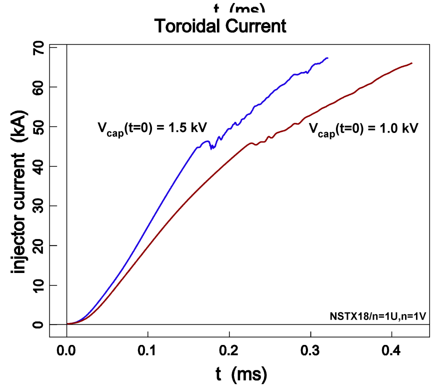




Discharge voltage: Physical effects not represented in the MHD modeling affect voltage requirements







The simulation finds lower injector voltages than the experiment to drive similar currents and flux-bubble expansion rates

The experiment includes physics which is not modeled in the simulations:

- Sheath drops, especially at the negative voltage (cathode) plate
  - In SSPX these were much larger than the "useful" voltage
- Impurity effects due to desorption of vapor and surface sputtering
- $Z_{eff} > 1$

Charging voltage in the figure: blue –> 1.5kV, red –> 1kV

Plasma heating: Computed electron temperature is consistent with experimental measurements

Plasma temperature — determined primarily by:

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

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

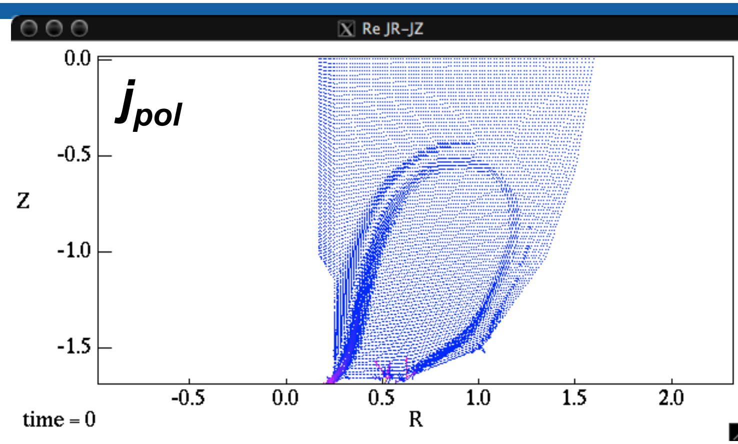
$$\kappa_{\|} \sim T^{5/2}/Z_{eff}$$

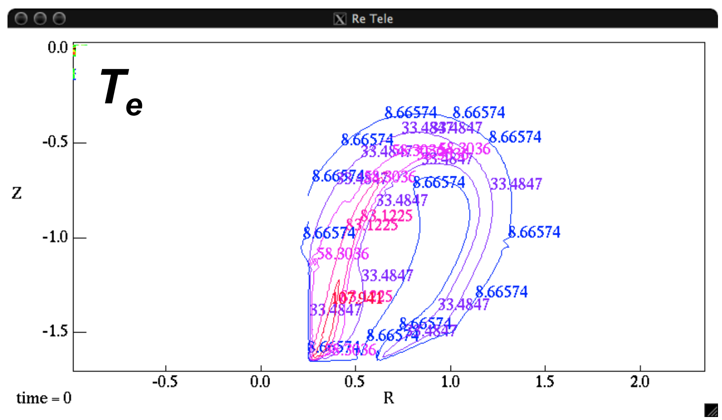
$$\eta_{\|} \sim Z_{eff}/T^{3/2}$$

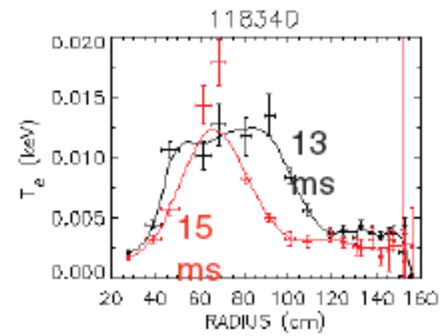
so

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

with ℓ an effective scale length





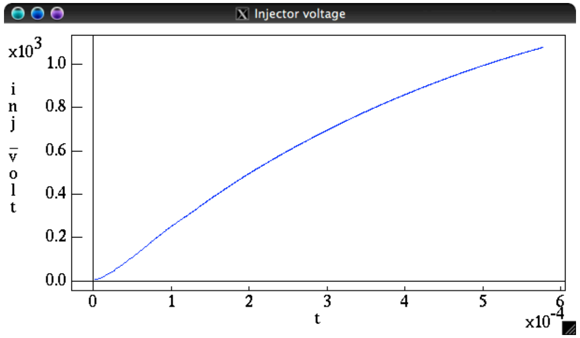


Experiment at midplane (Thomson-scattering measurements of T_e are not available for shot number 142163)

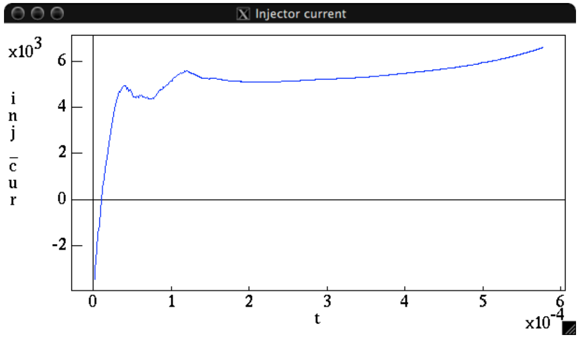
Simulation at 0.52 ms: Z_{eff}=1.
T_e is highest (126 eV) near the lower left corner (small R) where poloidal flux tube areas (2πRw) are small and $j_{\|}$ is large

Simulation temperatures
T_e is consistent with experiment

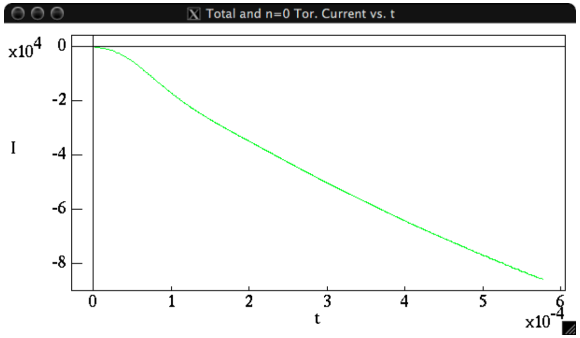
Poloidal flux "piles-up" in the "flux-bubble" surface layer



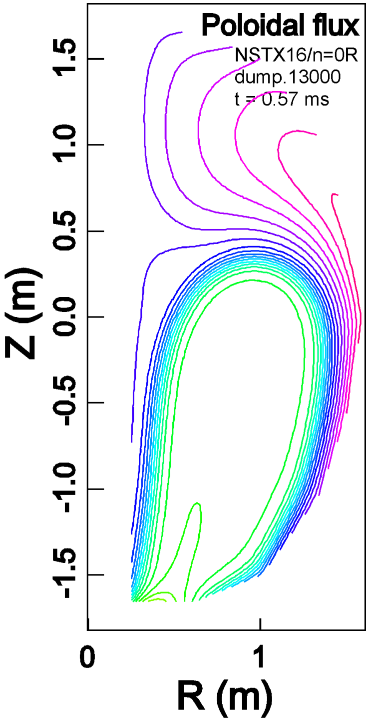
Discharge Voltage



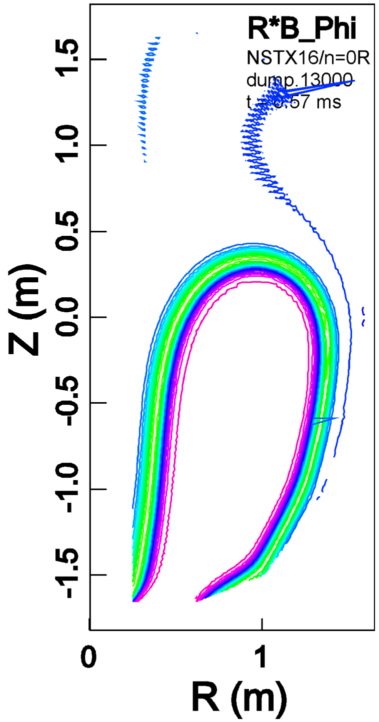
Discharge Current



Toroidal Current



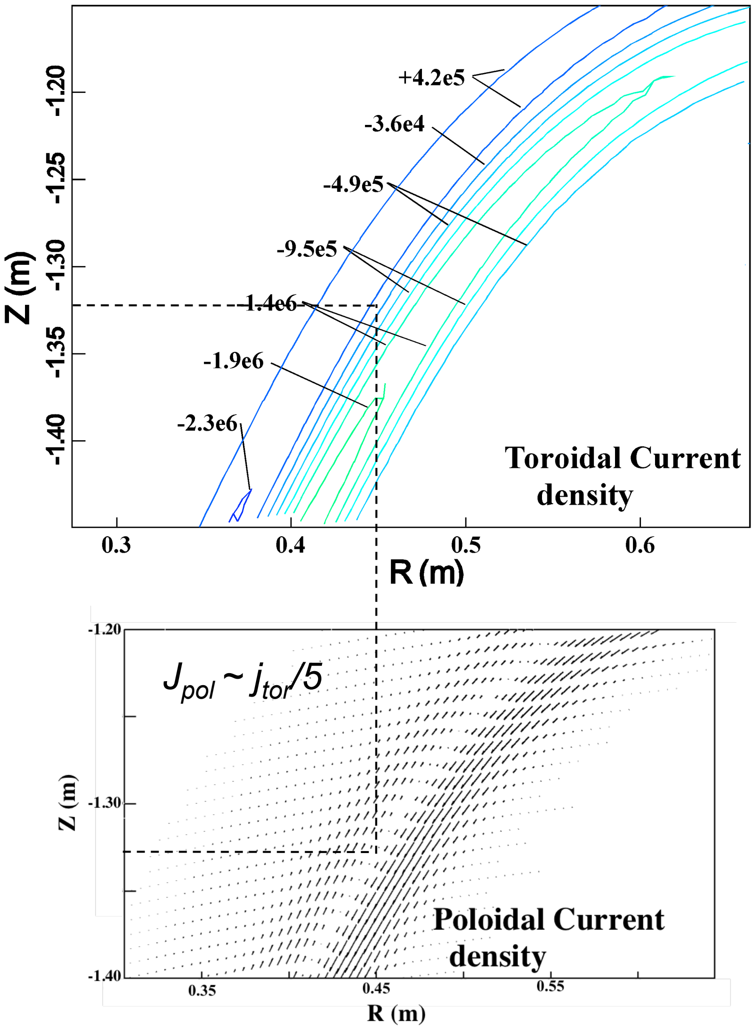
Poloidal flux at 0.57 ms



RB_φ at 0.57 ms

NSTX16/n=0R

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



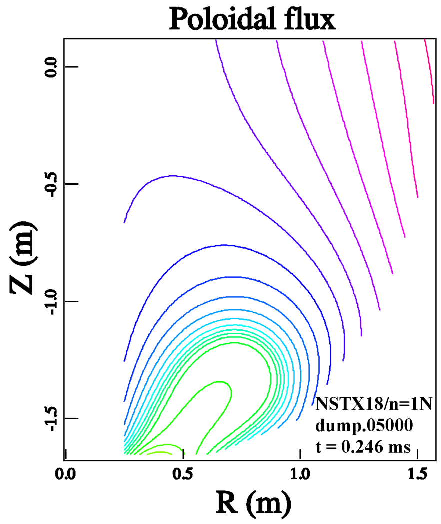
The reversed toroidal current results from the "pileup" of poloidal flux near the surface of the bubble. The poloidal field first increases then decreases as you cross the current layer.

The 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.

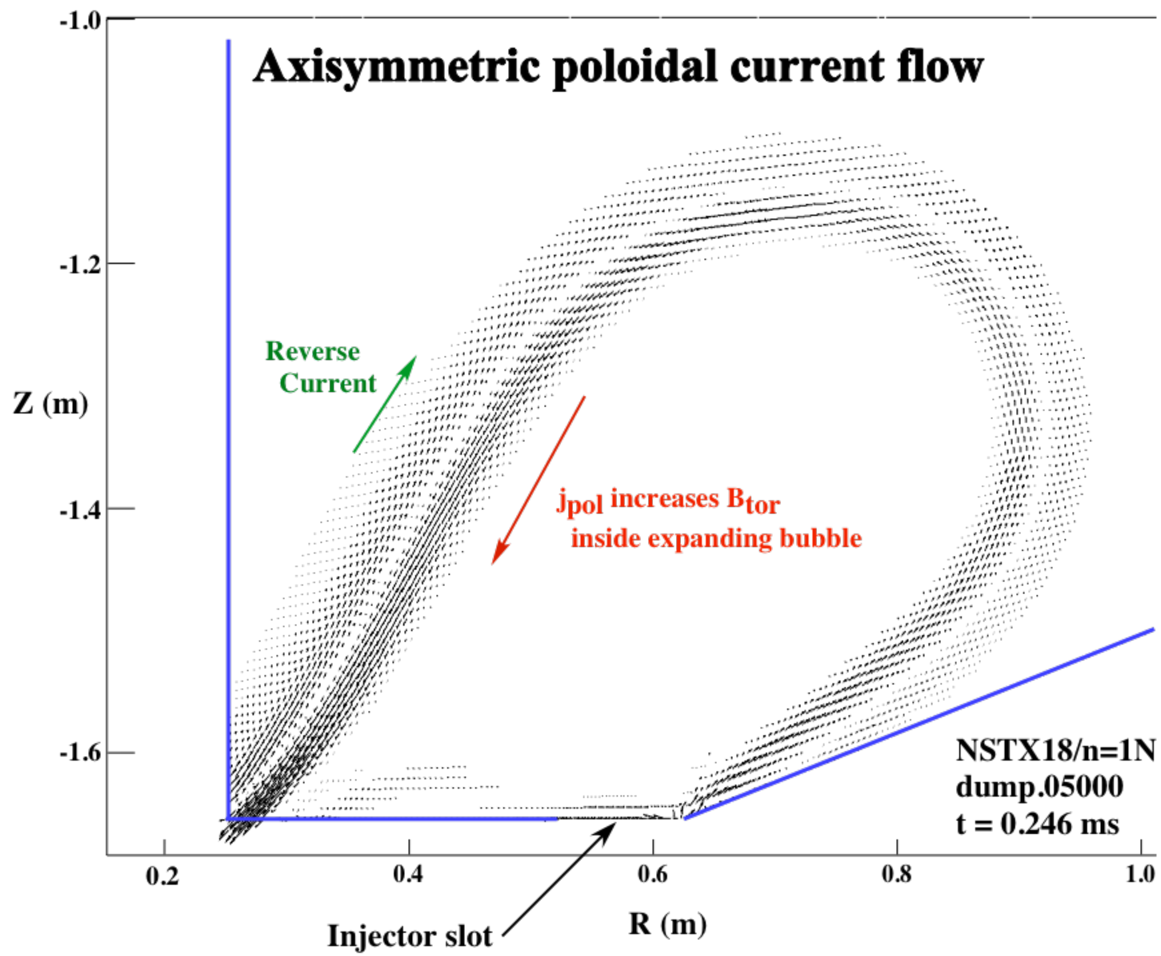
NSTX18/n=1N

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

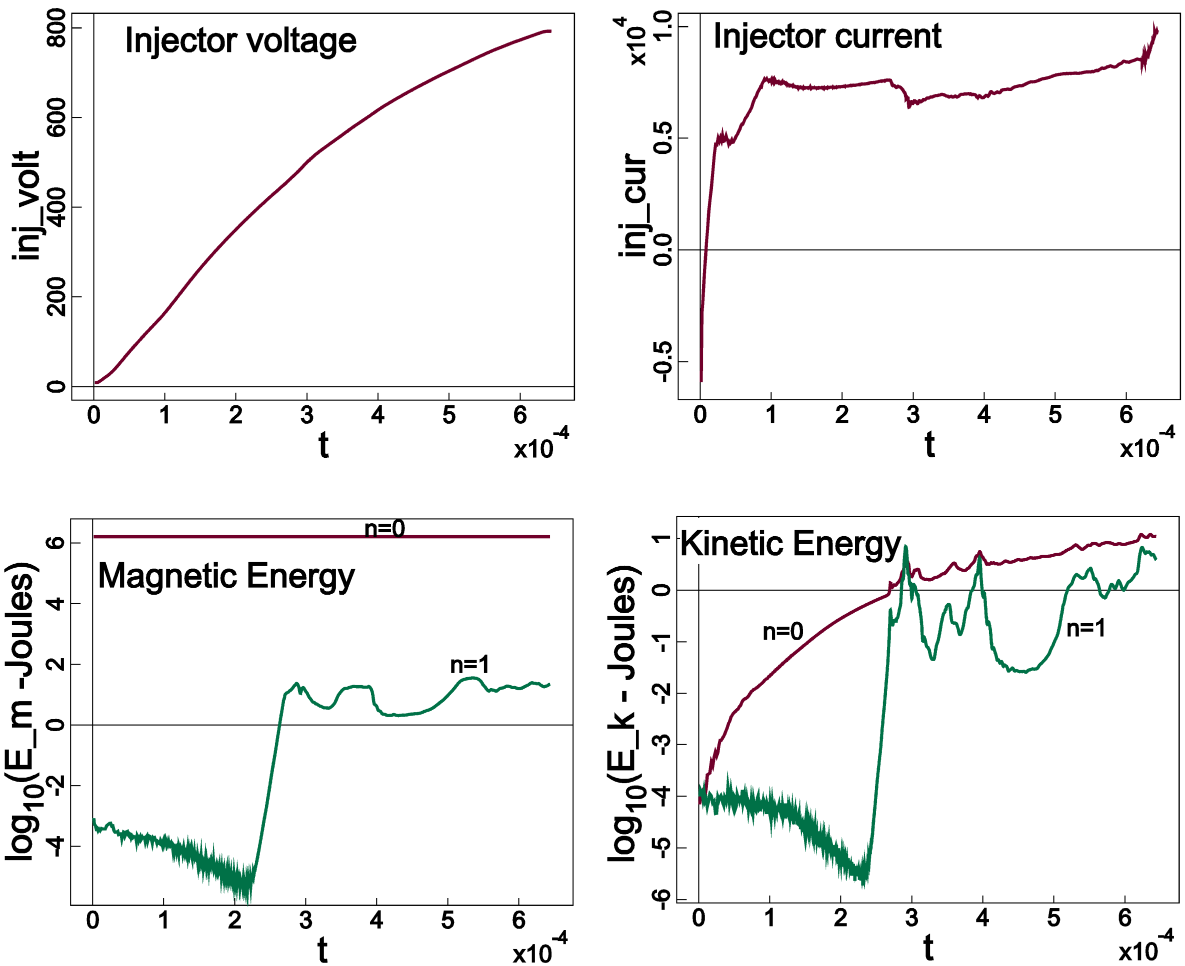


As the flux-bubble expands, poloidal flux "piles up" in a surface layer — The sign of $\partial B_{pol}/\partial t$ reverses as the bubble passes a given point

The toroidal and poloidal velocities vary smoothly through the layer



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

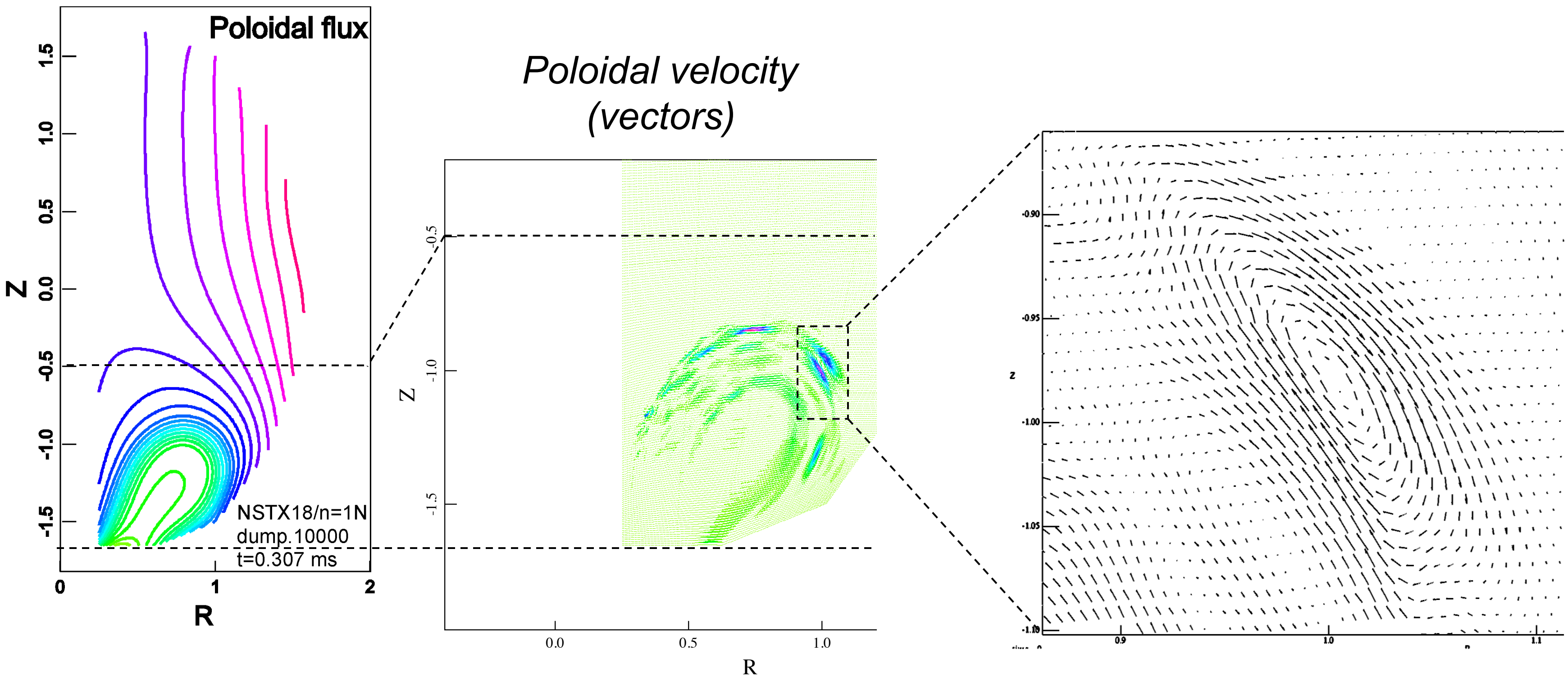


The total kinetic (flow) energy in a n=1 mode grows rapidly until it approximately equals the axisymmetric kinetic energy. A series of relaxation events follow.

In the next few slides examine the structure of the resulting configuration and the linear mode

NSTX18/n=1N

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



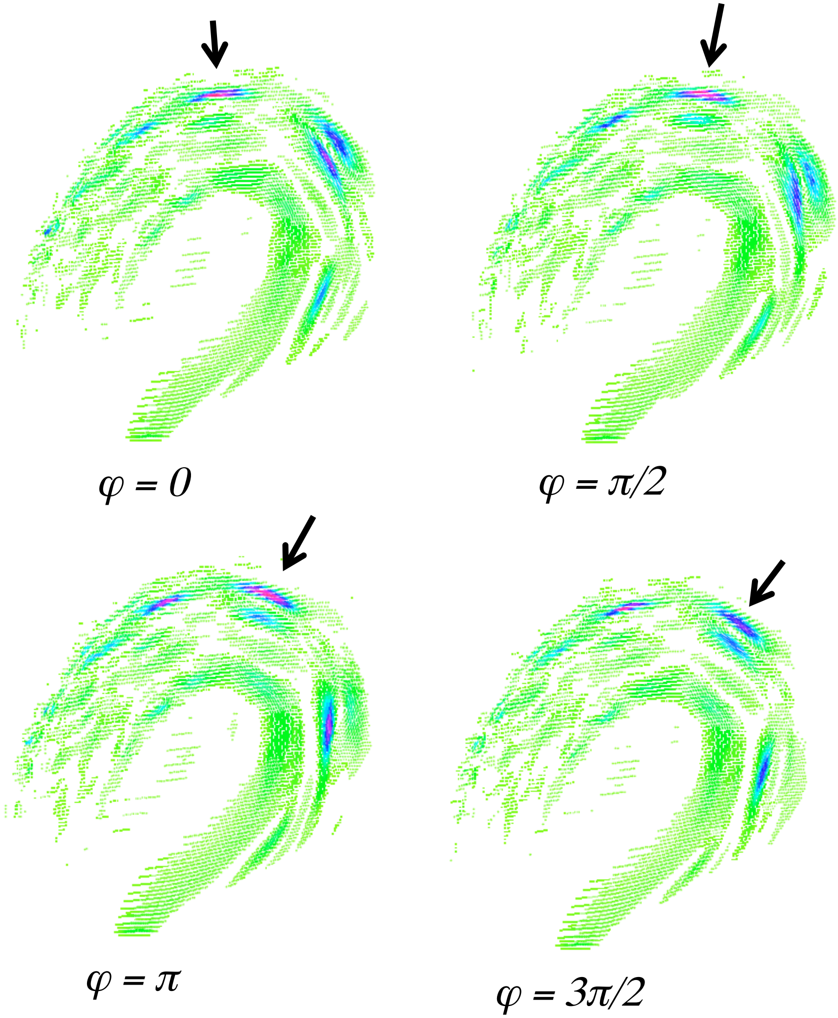
Axisymmetric poloidal flux. Note the pileup of flux in a layer at the bubble surface

*T*he total plasma flow velocity (n=0 plus n=1) includes structure in the layer

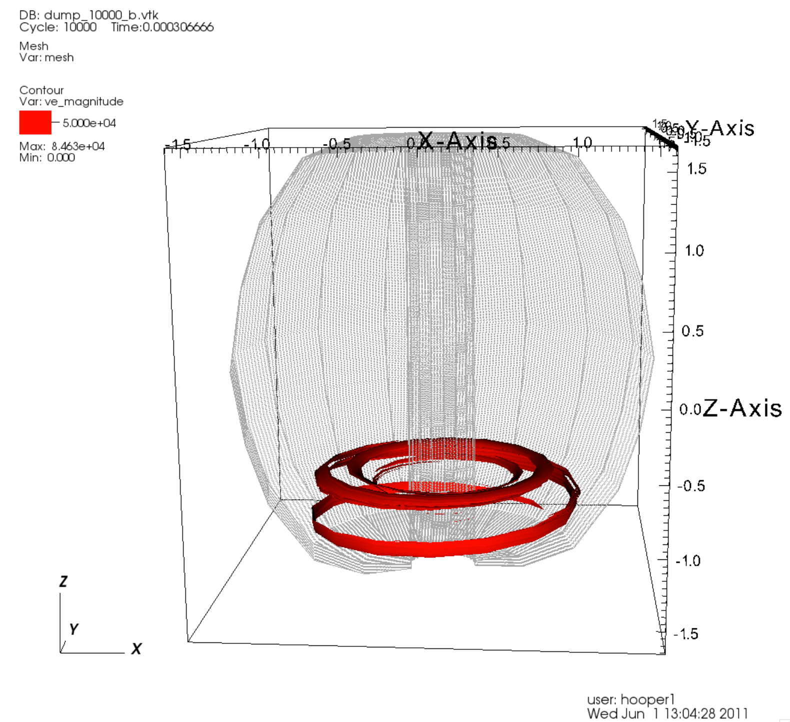
The velocity structures include poloidal vortexes

NSTX18/n=1N

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



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



NSTX18/n=1N

Summary

In the simulation:

- *Helicity injection generates an expanding flux bubble*
- *The injection model has been extended from that used for HIT-II*
- *Coupling to a model of the NSTX power supply has been implemented*
- *As more physics has been added to the simulations, improved handling of the downstream plasma (between the bubble and the top of NSTX) has been required*

Comparison with experiment:

- *The time-dependent flux-bubble expansion is similar to experiment*
- *Simulations require less injection voltage, perhaps due to the neglect of sheath voltages and other effects*
- *Injector and toroidal currents are similar to experiment*
- *Plasma heating is similar to experiment*
- *An n = 1 mode forms a helical structure on the surface of the flux bubble. It has sufficient amplitude to perturb the measured injector and toroidal currents*
  - *It is unknown whether the mode is present in the experiment*

Work continues on the model development and comparison with experiment