LLNL-POST-645794

Comparison of resistive MHD simulations and experimental CHI discharges in NSTX

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Division of Plasma Physics
American Physical Society
Denver, CO — November 11-15, 2013

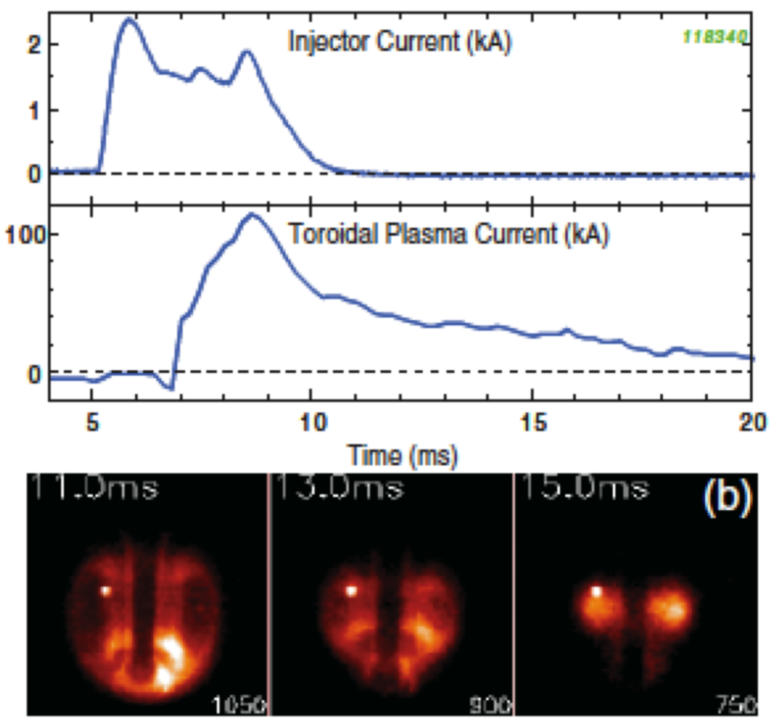
This work was performed under the auspices of the U.S. Department of Energy under contracts DE-AC52-07NA27344 at LLNL and grants DE-FC02-05ER54813 at PSI Center (U. Wisc.) and DOE-FG02-12ER55115 (at Princeton U.)

ABSTRACT:

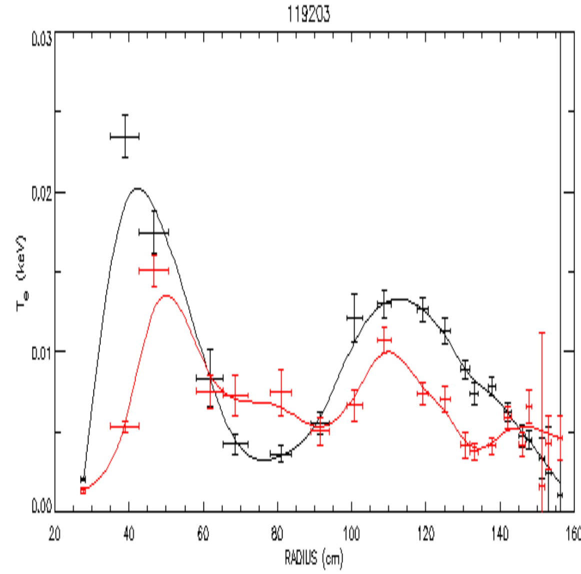
Resistive MHD simulations using NIMROD [1] simulate CHI discharges for NSTX startup plasmas [2]. Quantitative comparison with experiment ensures that the simulation physics includes a minimal physics set needed to extend the simulations to new experiments, e.g. NSTX-U. Important are time-varying vacuum magnetic field, ohmic heating, thermal transport, impurity radiation, and spatially-varying plasma parameters including density. Equilibria are compared with experimental injector currents, voltages and parameters including toroidal current, photographs of emitted light and measurements of midplane temperature profiles, radiation and surface heating. Initial results demonstrate that adjusting impurity radiation and cross-field transport yields temperatures and injected-current channel widths similar to experiment. These determine the plasma resistance, feeding back to the impedance on the injector power supply.

[1] E. B. Hooper, et al., Phys. Plasmas 20, 092510 (2013)
F. Ebrahimi, et al., Phys. Plasmas 20, 090702 (2013); also, invited talk this conference
[2] R. Raman et al., Phys. Rev. Letters 104, 095003 (2010).

NSTX: The goal of this study is to model the NSTX discharge 118340, one of the first to show flux closure



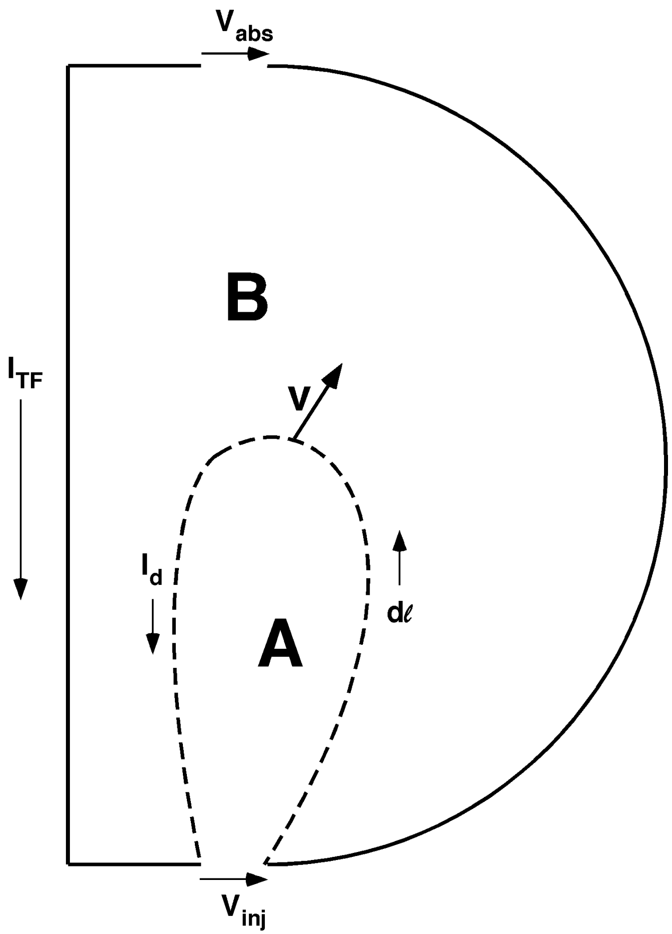
See R. Raman, et al. Phys. Rev. Letters <u>97</u>, 175002 (2006)



Temperature measurements:
  Black — 8 ms
  Red — 10 ms
Measured on a chord at the NSTX midplane

Discharge 119203 was similar to 118340

Boundary conditions for helicity injection



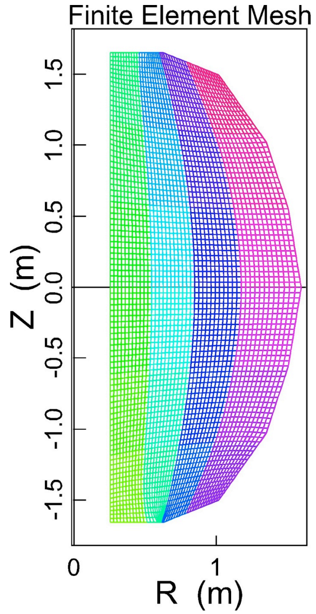
- Rate-of-change of toroidal flux — equals $V_{inj} - V_{abs}$
- Absorber voltage — determined by requiring the total vacuum toroidal flux to be constant, corresponding to a constant I_{TF}
- Discharge (injector) current — measured by the change in RB_φ just above the injector slot
- Toroidal flux —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

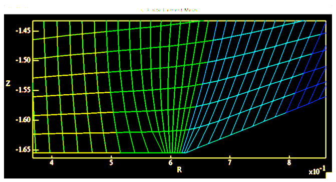
$$E_r^{abs} = E_r^{inj} \frac{r_{inj,\min}}{r_{abs,\min}} \frac{\int_{r_{inj,\min}}^{r_{inj,\max}} dr \frac{B_\varphi}{r^2 B^2}}{\int_{r_{abs,\min}}^{r_{abs,\max}} dr \frac{B_\varphi}{r^2 B^2}}$$

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

Simulation — A narrow injection slot narrows the injected current, allowing easier flux-closure

A narrow footprint on the bottom was important in the experiment — guided the simulations

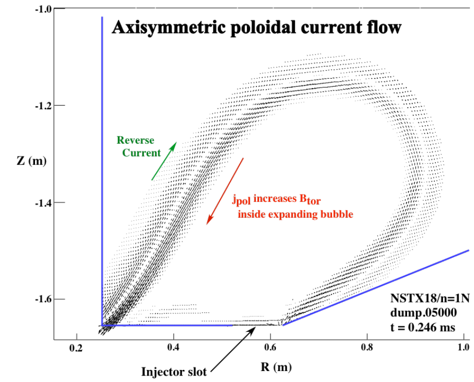




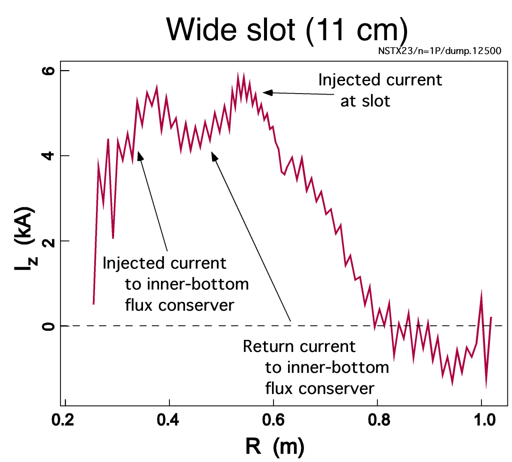
Injection slot

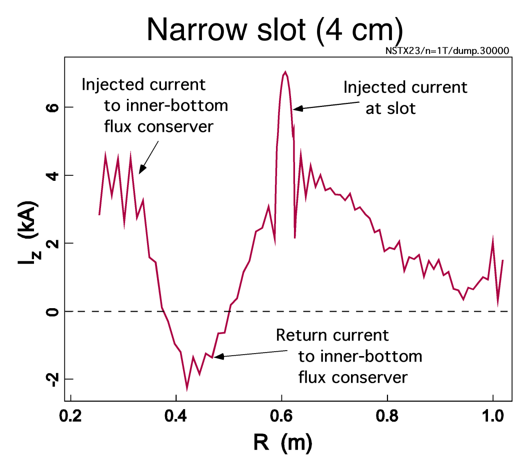
Finite elements generate additional resolution

Current flow in flux bubble



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





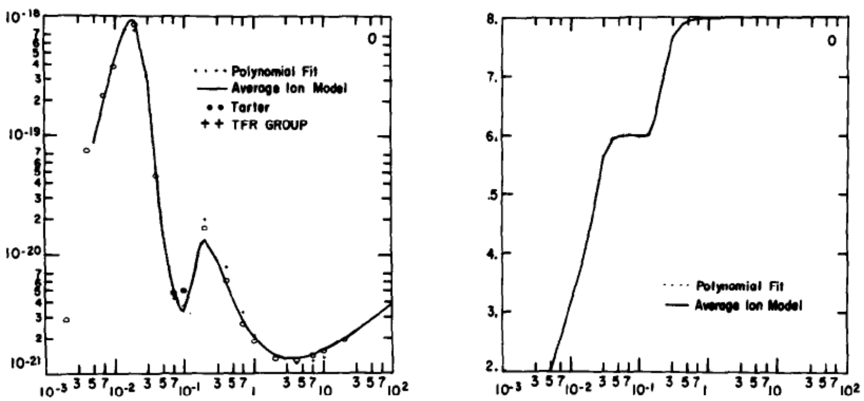
The narrow slot generates a narrow distribution of injected current and a strong flow of current along the bottom plate

Impurity radiation limits T_e

Simulations without impurity radiation generated temperatures well above 25 eV whereas discharge 118340 had temperatures < 25 eV

Model radiation losses were added to the power balance:

The radiation term assumed oxygen in coronal equilibrium — based on calculations by Post, et al.*



(Left) — cooling rate, L_z (ergs-cm^3/s)

Radiative losses = $n_e n_z L_z$ ergs/cm^3-s

(Right) — Average Z

No explicit terms were added to account for recycling, ionization, – the impurity fraction was treated as a parameter — adjusted to fit the experimental temperature

Density was fit (approximately) to experiment — no explicit correction for Z_{eff} was used

*D. E. Post, et al., Atomic data and Nuclear Data Tables 20, 397-439 (1977)

Simple models of impurity radiation – needed to match experimental T_e

In the experiment, impurity radiation was strongest near the return-current plate in the lower-inside corner of NSTX.

Simulations found that adjusting the impurity level to match the temperature at small radius yielded temperatures that were too low at large radius

A spatial distribution of impurity radiation was added:

$$\exp\left(-\left(r/r_{imp}\right)^2 - \left(z/z_{imp}\right)^2\right)$$

$r_{imp} = 0.45$ m, $z_{imp} = 1.0$ m matched the experimental observations

Impurity pump-out following the end of injection was included as an exponential decay:

$$\exp\left(-\left(t - t_{inj}\right)/t_{imp}\right)$$

Results shown in later slides demonstrate that $t_{inj} \approx 8$ ms, $t_{imp} \approx 1$ ms fit the experiment temperature measurements well

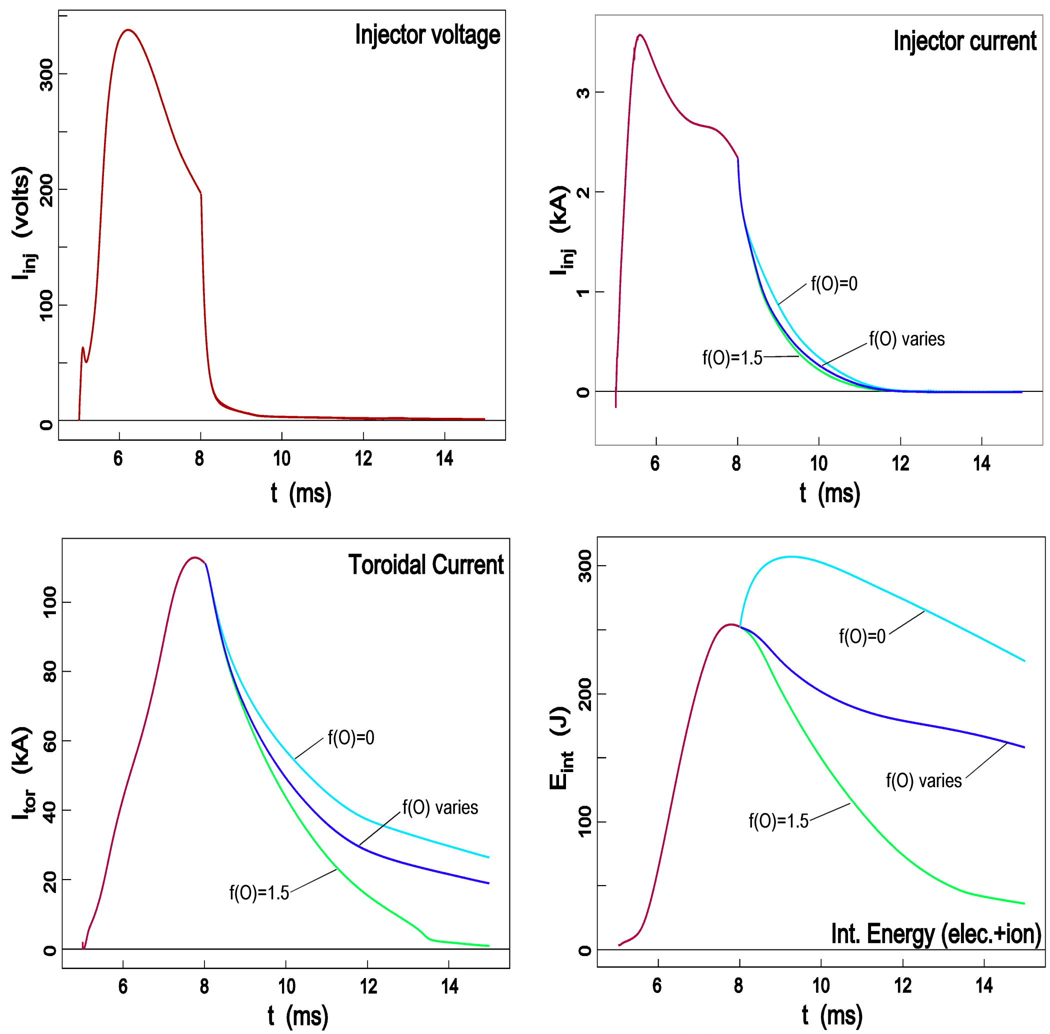
Parameters used in the simulation that best fits the experiment

<u>Parameter</u>	<u>Simulation sensitivity</u>
Power supply capacitance and capacitor voltage	discharge current
Plasma density	temperature
Thermal diffusivity (across B)	peak and width of temperature
Impurity fraction	temperature
Impurity spatial dependence	temperature spatial dep.
Impurity decay time	temperature and tor. current variation after t_{inj}

The magnetic diffusivity and the thermal diffusivity along B are the Braginskii values. Other parameters for the simulation presented here include:

Power supply cap. and voltage	40 mF and 500 V
Plasma density	3×10^{18} m^{-3}
Thermal diffusivity	20 m^2/s
Impurity fraction (Oxygen)	1.5 during injection; following inj. = 1.5, 0, or decaying from 1.5
r_{imp}	0.45 m
z_{imp}	1.0 m
t_{imp}	1.0 ms

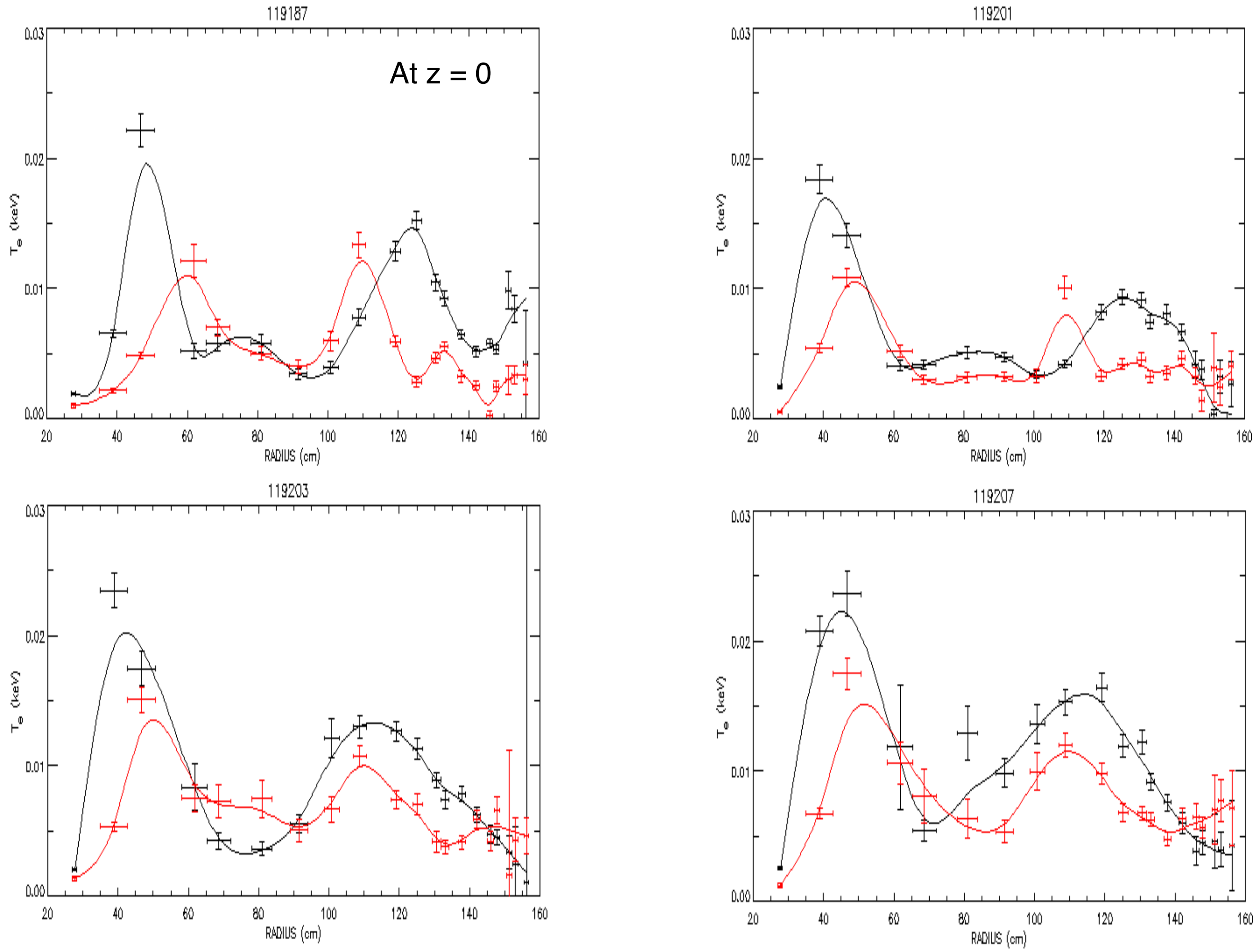
The decay of toroidal current following injection is sensitive to the impurity fraction



- Injection voltage and current are insensitive to f(O), the impurity (oxygen) fraction (=1.5) during injection
- Simulated injection voltage (left) is greater than experiment (≈1200 V0 and injected current is greater (exp. ≈ 2 kA)

  This may be due to plasma sheaths and ionization in the experiment
- Pump out of impurities is needed to match the time evolution of experimental toroidal current following injection

Experimental temperature at 8.0ms (during injection) exhibits shot-to-shot variation



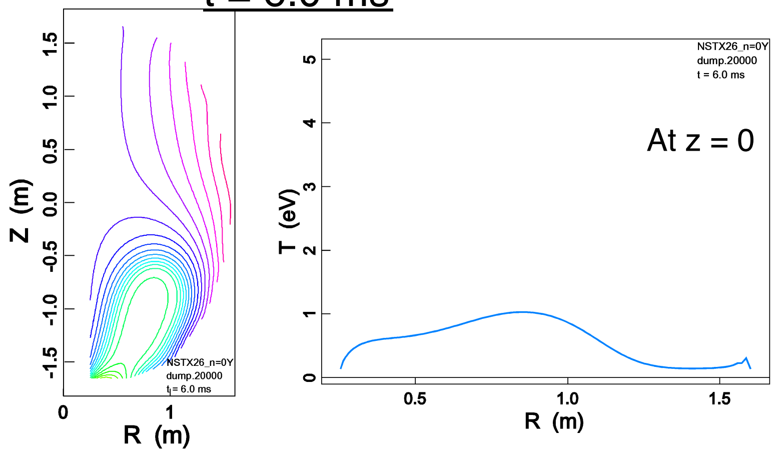
Black traces at 8 ms

Red traces at 10 ms

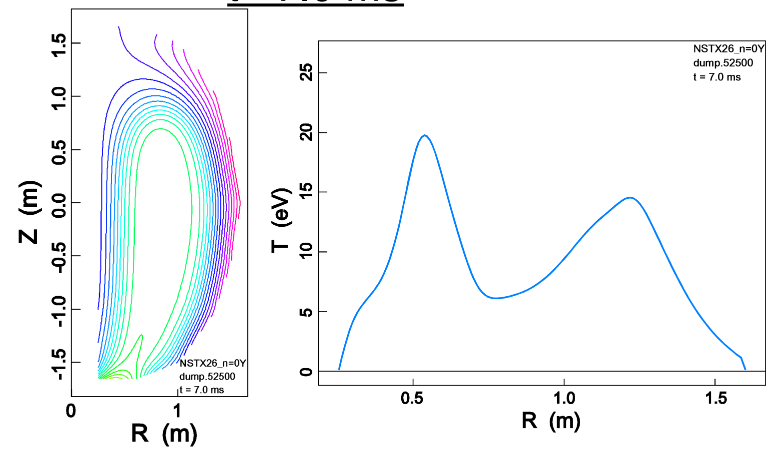
The simulation lies within the experimental shot-to-shot variability

Simulated poloidal flux and temperature during injection — consistent with experiment

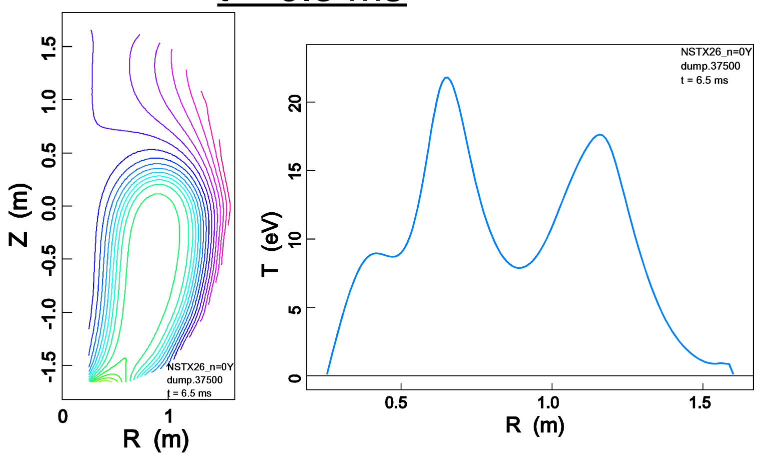
t = 6.0 ms



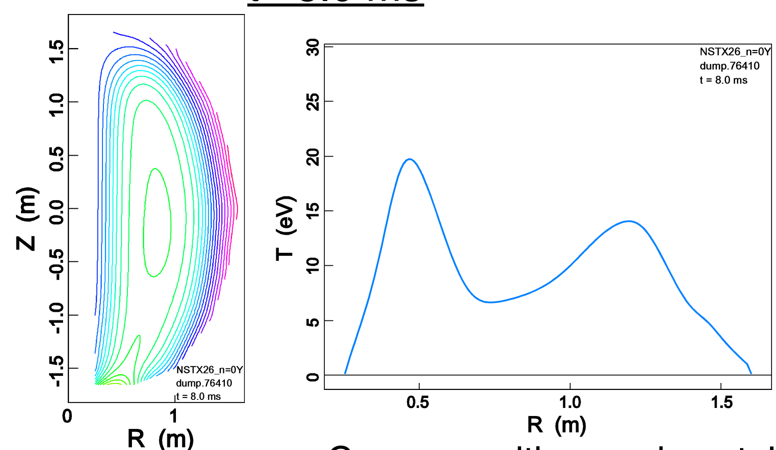
t =7.0 ms



t = 6.5 ms



t =8.0 ms



Compare with experimental temperatures (below)

Poloidal flux following injection vs impurity level — decay rate depends on impurity level

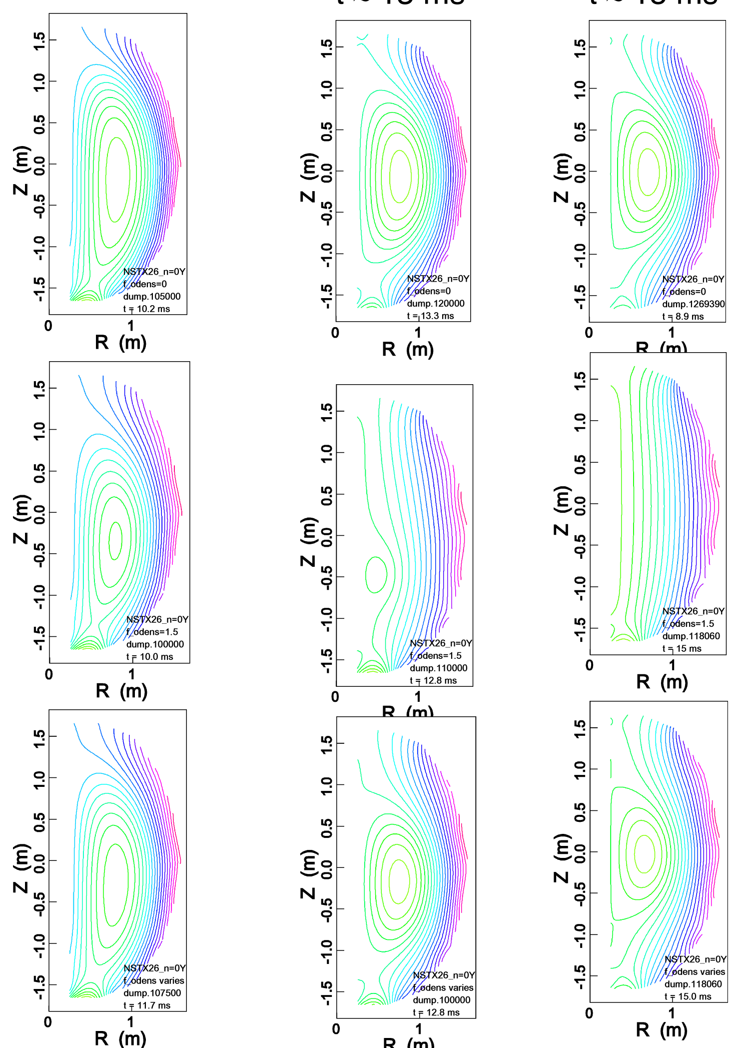
Impurity level, f(O)

0.0

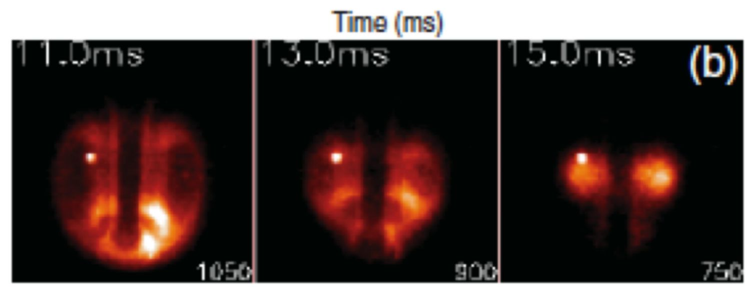
1.5

decays

t ≈ 10 ms | t ≈ 13 ms | t ≈ 15 ms



Experiment (light emission)



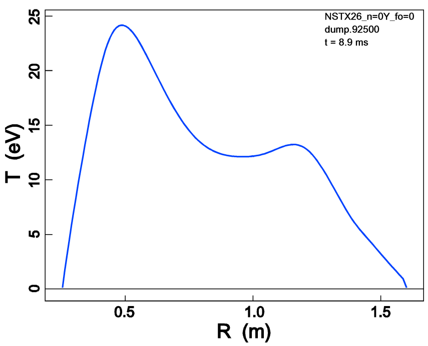
Simulation results for a decaying impurity level compare best with shape from fast camera images

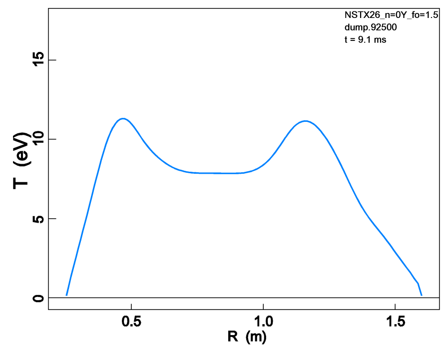
Impurity fractions
t = 10 ms, f(O) = 0.14
t = 13 ms, f(O) = 0.01
t = 15 ms, f(O) =0.001

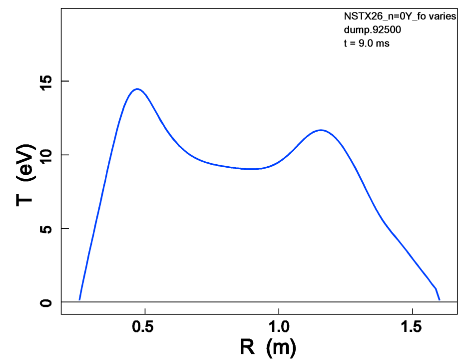
Temperature profile following injection vs impurity level — decay rate depends on impurity level

f(O) = 0 | f(O) = 1.5 | f(O) decays

t ≈ 9 ms

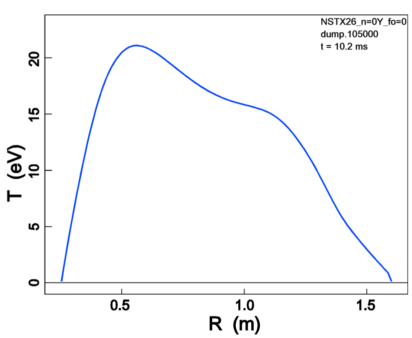


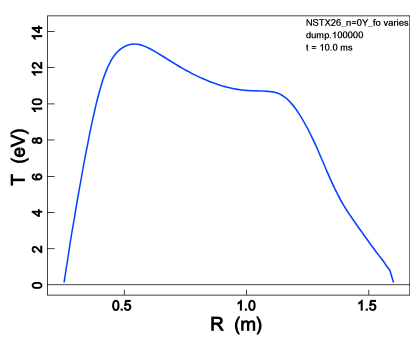


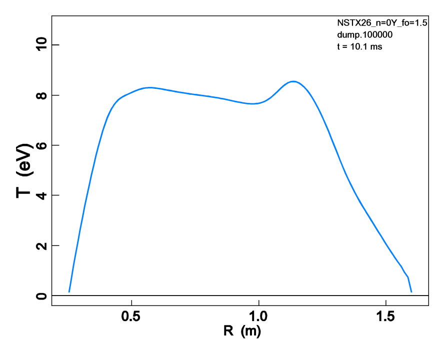


No experimental measurements

t ≈ 10 ms



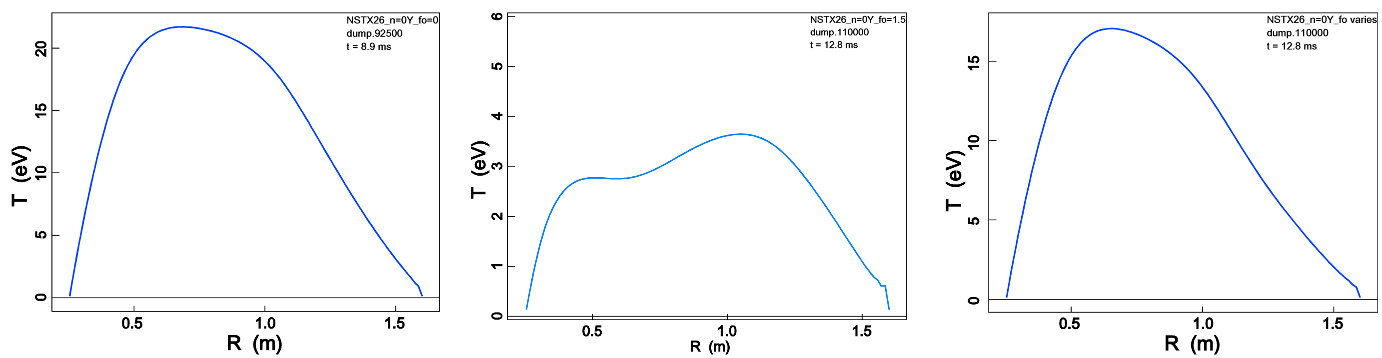




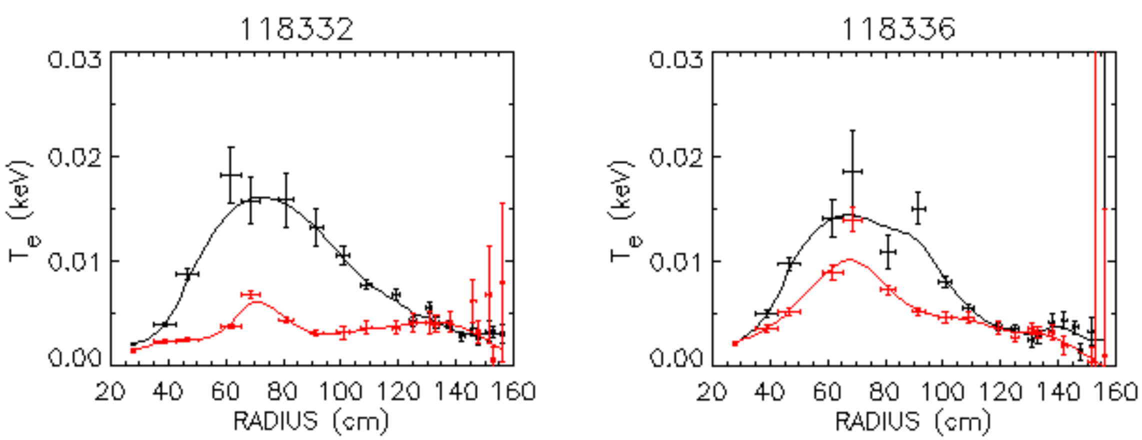
See slide on “Experimental temperature at 8 ms” (#11)

Temperature profile at 13 ms following injection vs impurity level — peak temperature drops to ≈ 15 eV

f(O) = 0 f(O) = 1.5 f(O) decays



Simulation



Experiment
(black traces)
Note consistency
with simulation
for "f(O) decays"

Summary — comparing simulation to experiment

- Including spatial and time dependence of impurities is required to match experiment
  - If impurities immediately drop to zero — the temperature rises rapidly due to ohmic heating in the current channel
  - Maintaining the impurity level unchanged — drops the temperature too far
    - Toroidal current enclosed in the surfaces decays
    - Surfaces disappear by 15 ms.
- The major difference is the discharge current-voltage relation
  - In simulations the injection current is higher than experiment and the injection voltage lower
  - Despite the difference, the flux bubble extends to the full height of NSTX in the simulation within the same time period as the experiment
  - The toroidal current peaks somewhat before the end of injection — as observed in many experimental discharges.