Modeling of the NSTX First Plasmas with the Tokamak Simulation Code (TSC)

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in collaboration with

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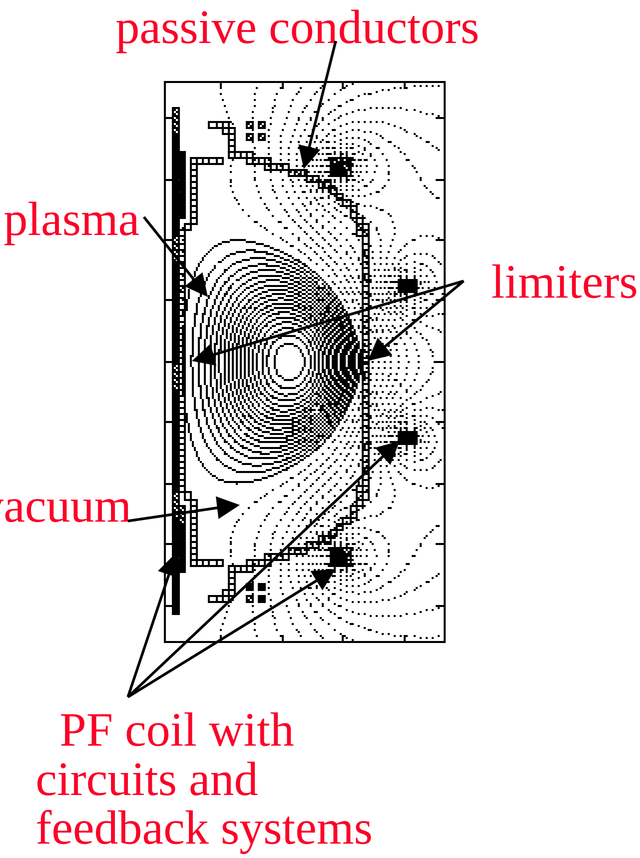
PPPL

Tokamak Simulation Code (TSC)



- TSC models the evolution of a free-boundary axisymmetric toroidal plasma on resistive and energy confinement time scales.
- The plasma equilibrium and field evolution equations are solved on a two-dimensional Cartesian grid….fluxes are continuous
- The surface-averaged transport equations for the pressures and densities are solved in magnetic flux coordinates using matrix implicit method
- An arbitrary transport model can be used,
- Neoclassical-resistivity, bootstrap-current, auxiliary-heating, current-drive, alpha-heating, radiation, pellet-injection, sawtooth, and ballooning-mode transport models are all available.
- As an option, circuit equations are solved for all the poloidal field coil systems with the effects of induced currents in passive conductors included.
- Realistic feedback systems can be defined to control the time evolution of the plasma current, position, and shape.
- A halo-region can be included, and the halo current is computed as part of the calculation

TSC can be run in several modes

Either	Or
p(ψ,t) input	• p(ψ,t) calculated from transport equation
n(ψ,t) input	• n(ψ,t) calculated from density evolution equation
Z(ψ,t) input	• Z(ψ,t) calculated from impurity ionization physics
I_i (t) input or read from experimental data file	• I_i (t) calculated from circuit equations with feedback
full device with no up/down symmetry	• impose symmetry about the midplane

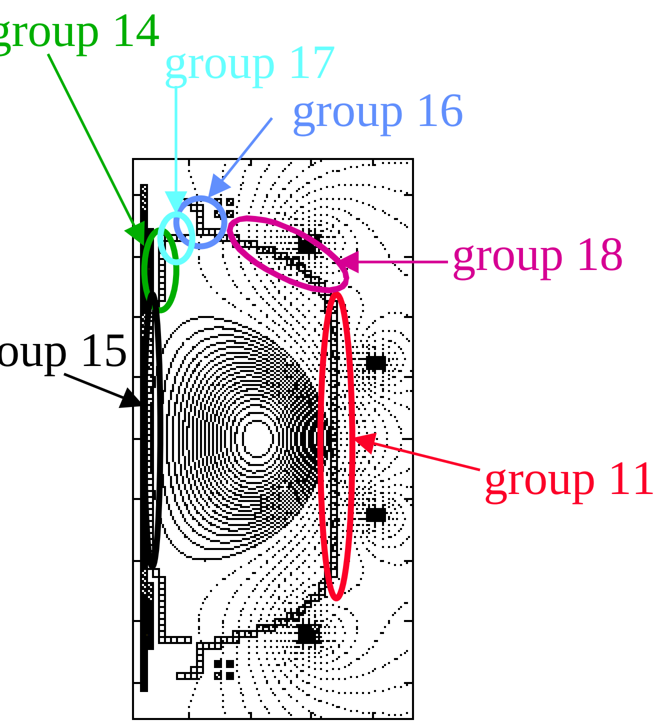
Refs: NF **33** (1993) p. 371 NF **34** (1994) p. 1145

Tokamak Simulation Code (TSC)

TSC has always been project driven. Each capability was added because there was no other code available to provide the needed result:

- S-1: inductive formation of spheromaks using flux core
- PBX- the effect of strong shaping on plasma axisymmetric stability, disruption forces on the passive stabilizers, volt-second benchmarking, CD experiments
- TCV- design of a tokamak with a flexible shaping system, doublet formation
- CIT/Ignitor - volt-second consumption, disruption effects, transient ignition
- DIII-D - shape control, VDEs, volt-second benchmarking
- BPX - burn control feedback, divertor sweeping
- TPX - vertical control, shape control, plasma scenarios
- ITER - volt-second consumption, shape control, plasma disturbances
- TFTR - volt-second benchmarking, impurity injection experiments

NSTX Vessel model in TSC



• vessel subdivided into 6 different groups with different resistances

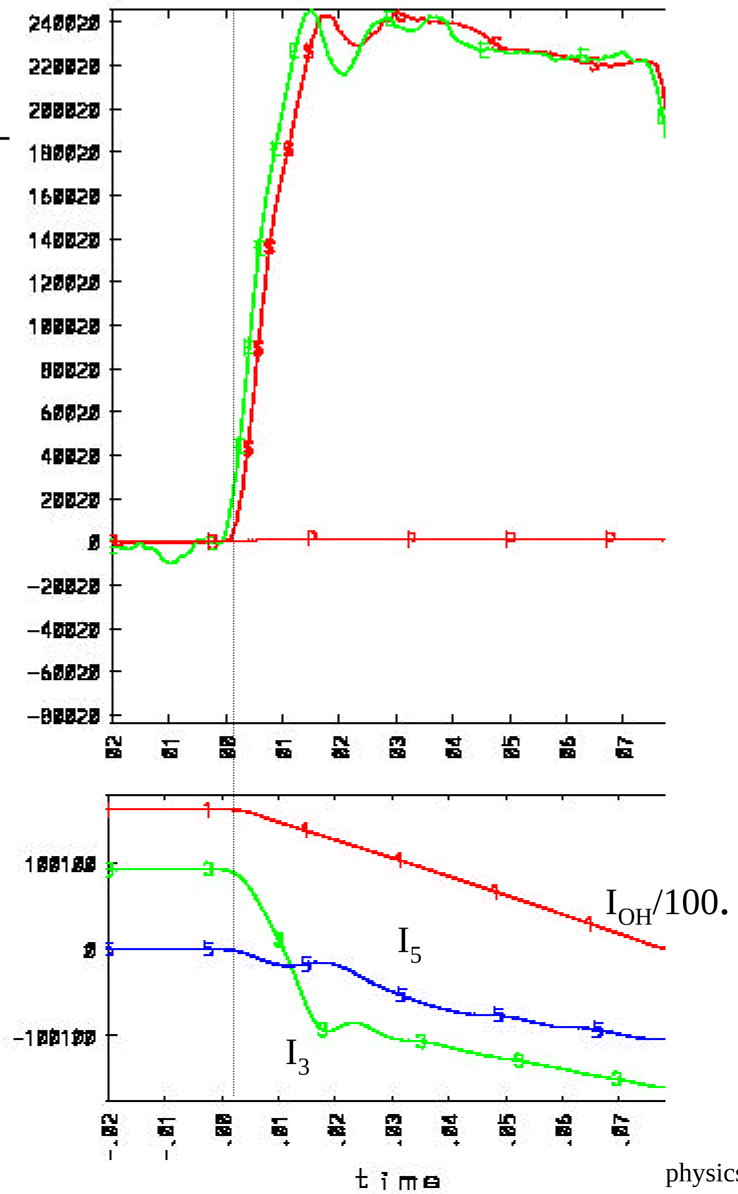
• conductivities matched with more detailed vessel model of Menard to give correct current distribution in steady state

• good agreement with vessel current vs time for shots without plasma

• reasonable agreement with flux loops…looking into calibration

NSTX shot 100194

- no plasma
- pre-programmed coil currents in OH, PF3, PF5 (same as plasma shot 100193)
- measurements of total vessel current, coil currents, 23 flux loops vs time
- agreement with simulation to about 5%..some question about synchronization



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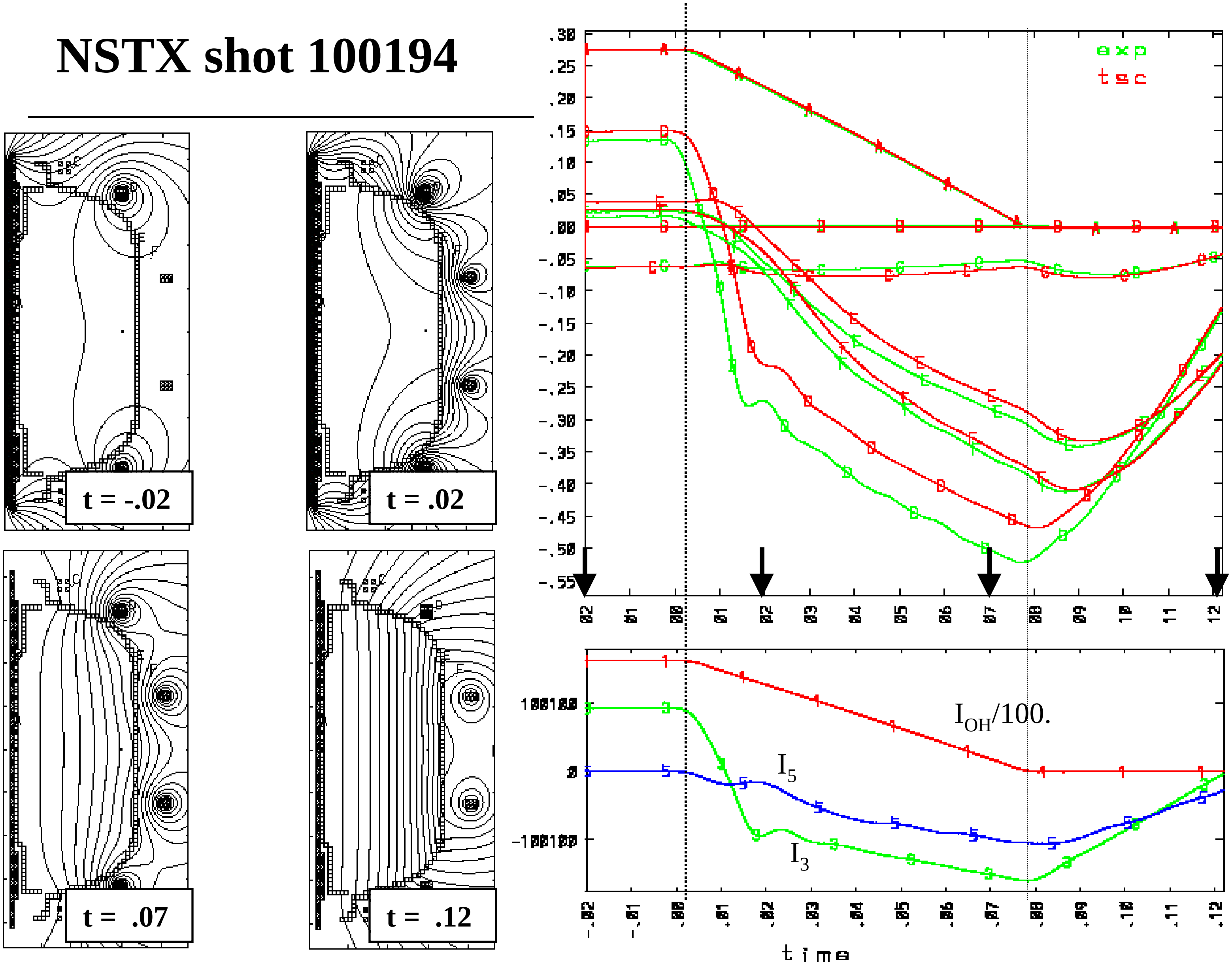
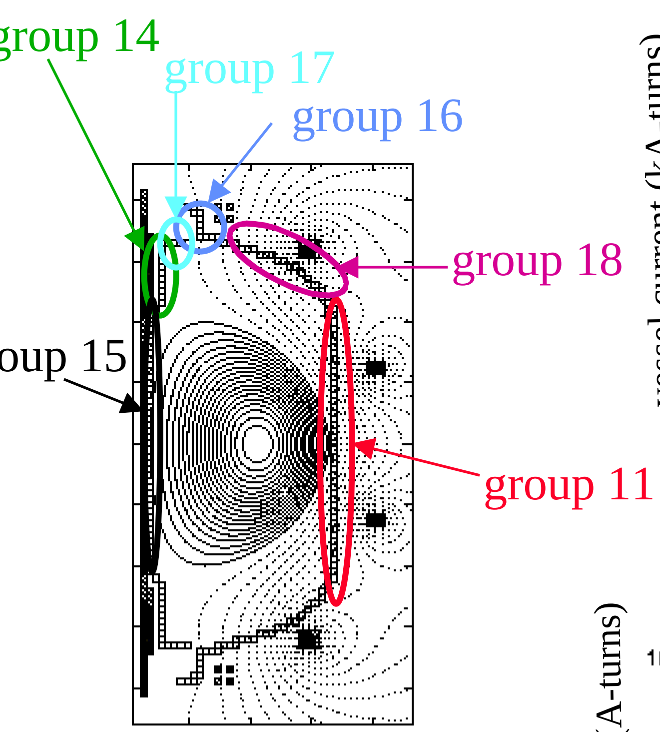
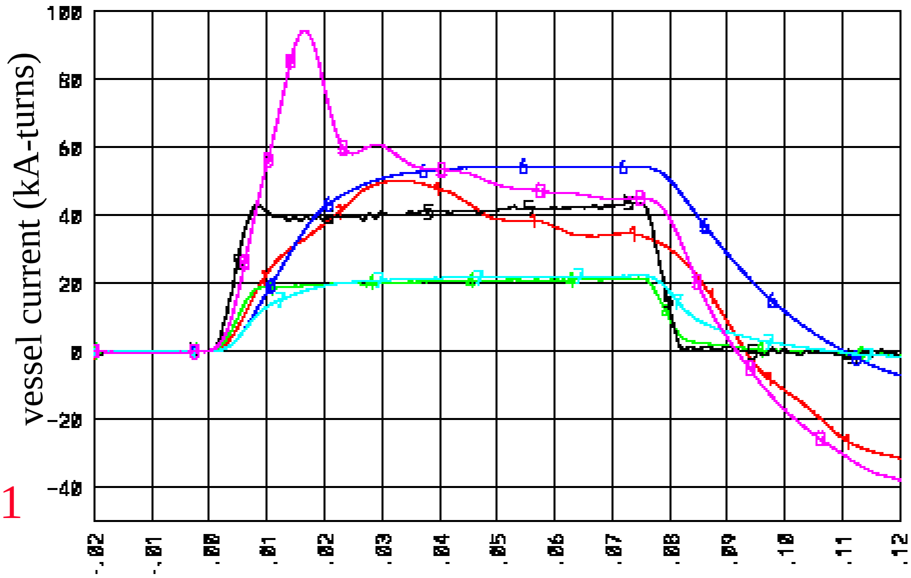
NSTX shot 100194

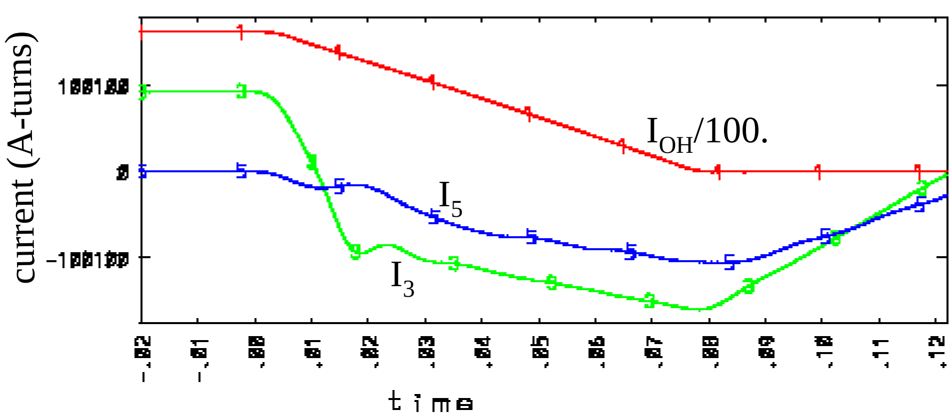


SC

NSTX Vessel currents without plasma







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NSTX shot 100193

- with plasma

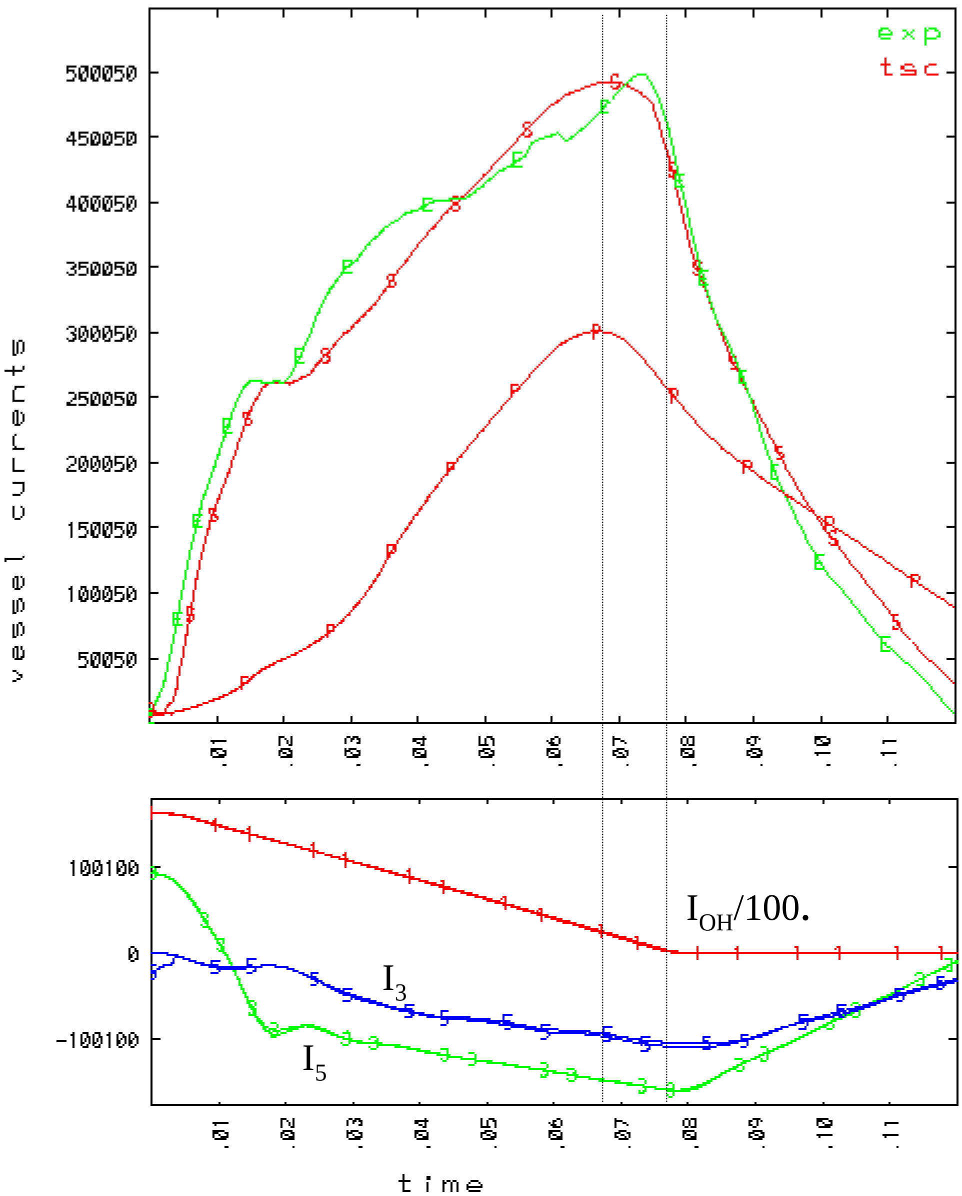
• pre-programmed coil currents in OH, PF3, PF5 (same as no-plasma shot 100194)

• measurements of total vessel current, coil currents, 23 flux loops vs time

• some offset in the timing of the coil and vessel currents

• differences in simulation/exp may be due to MHD or runaways

• note plasma current peaks ~10ms before end of OH ramp



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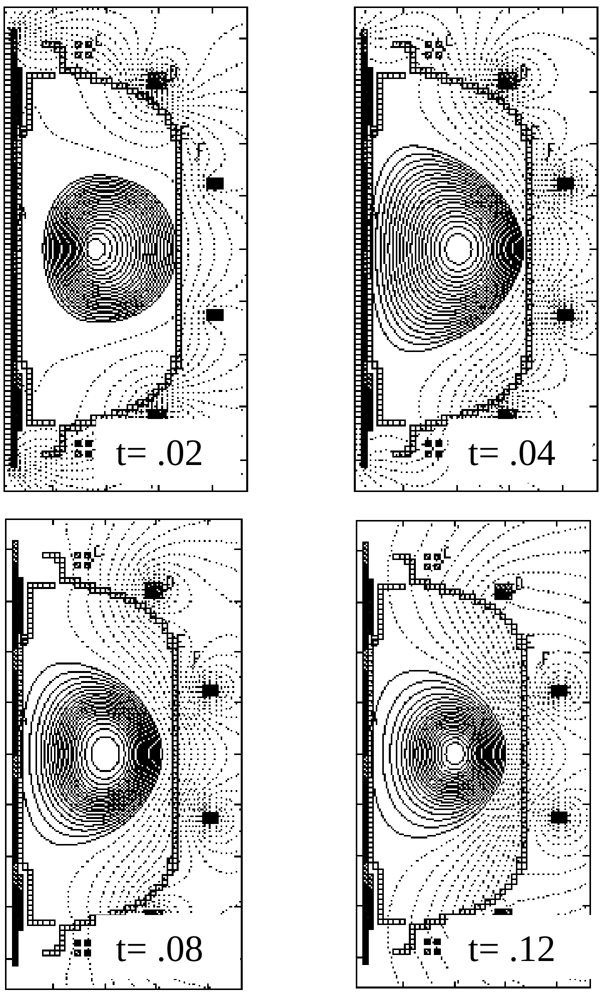
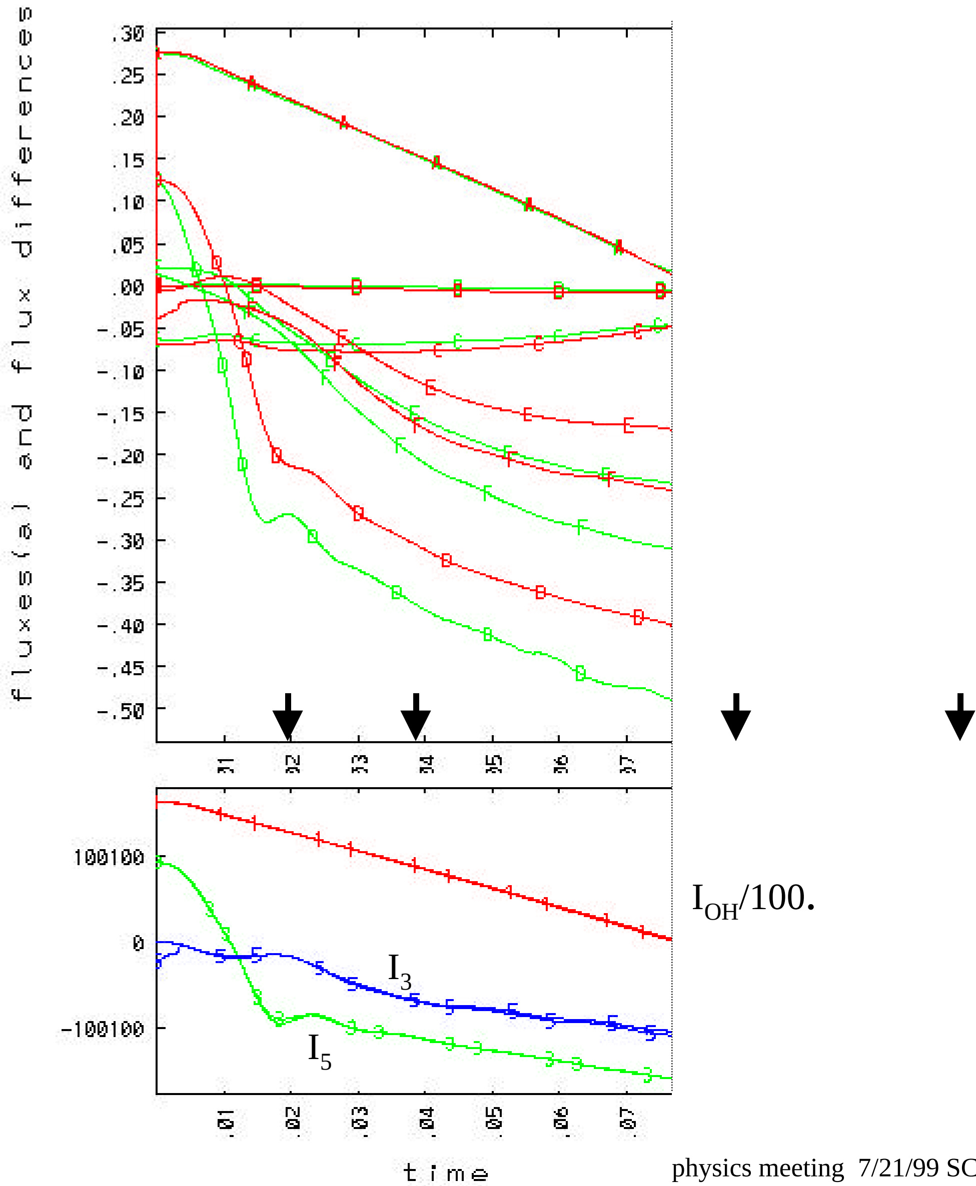
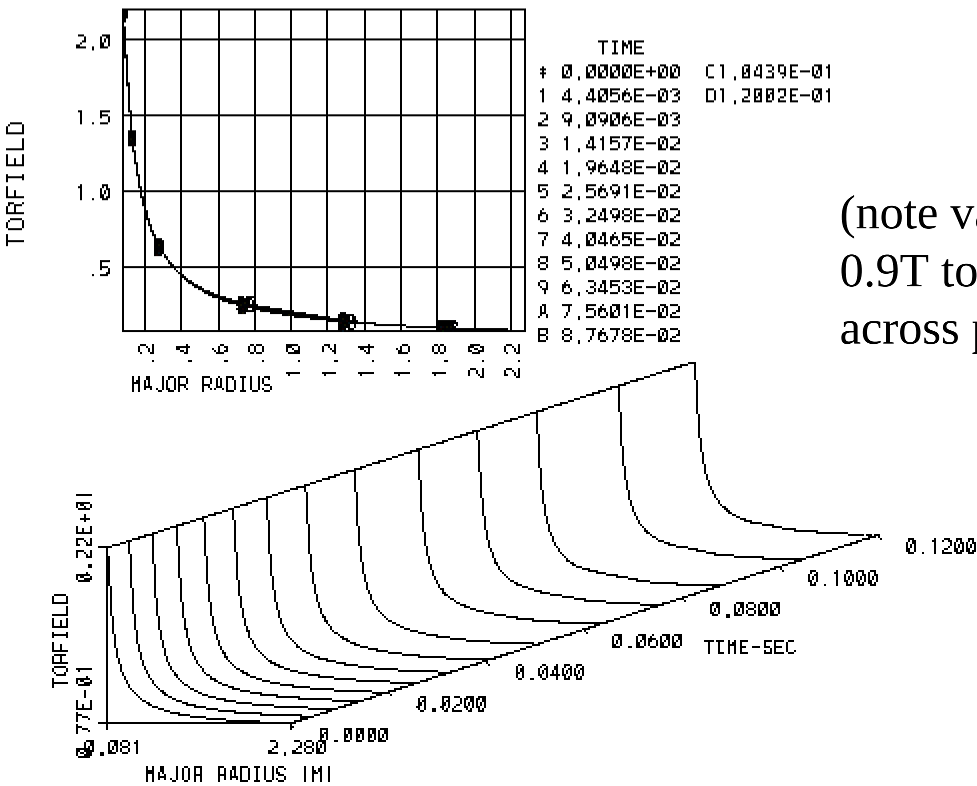
NSTX shot 100193



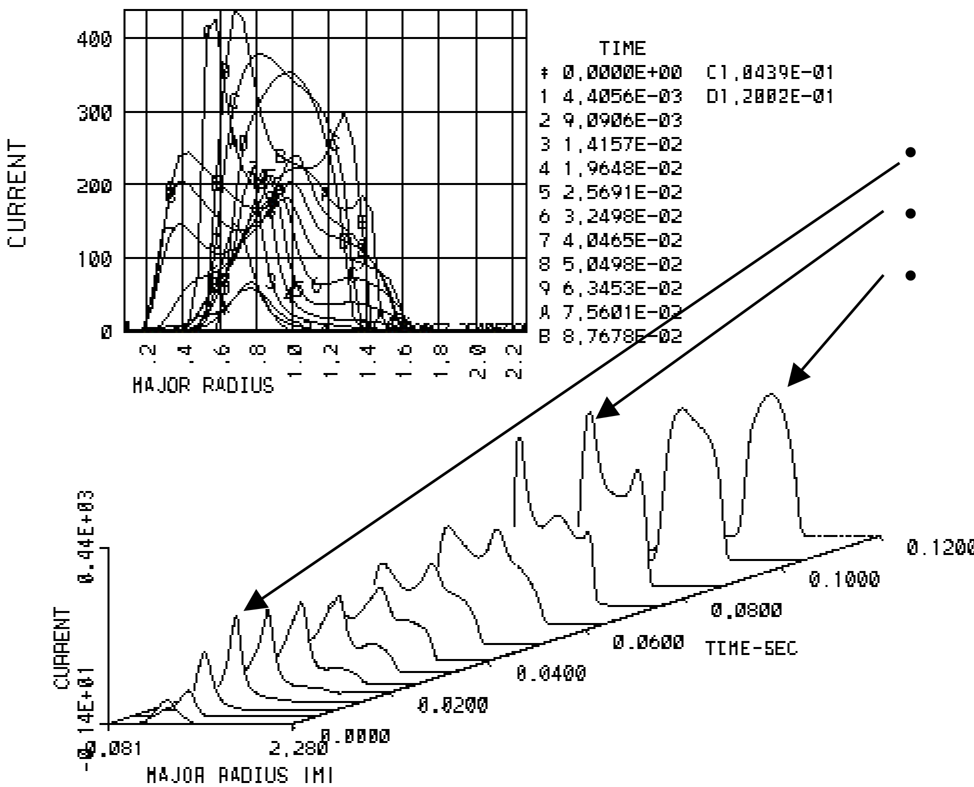


NSTX shot 100193: Toroidal field constant in time.



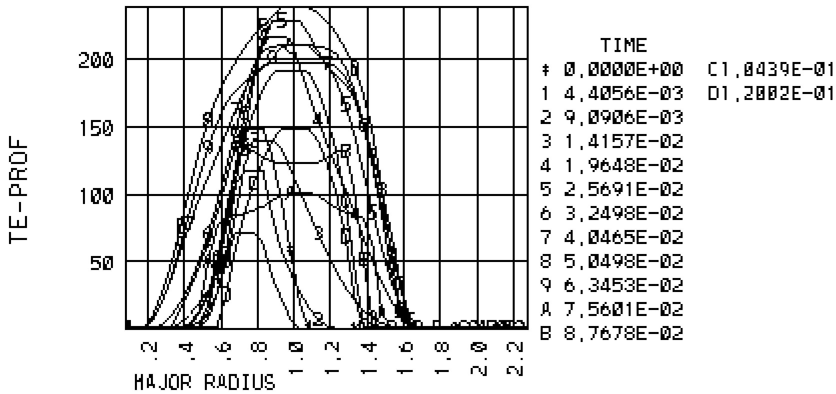
(note varies from 0.9T to 0.1T across plasma)

NSTX shot 100193: Current density



- **Initially peaked**
- **hollow during rampup**
- **peaked during decay**

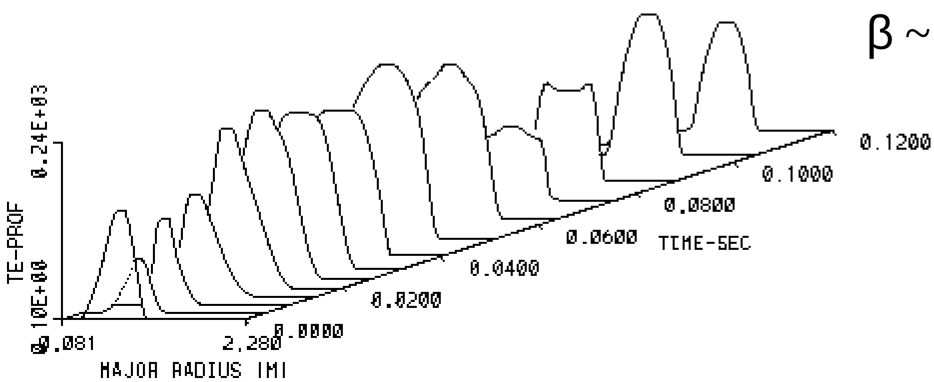
NSTX shot 100193: T_e profile



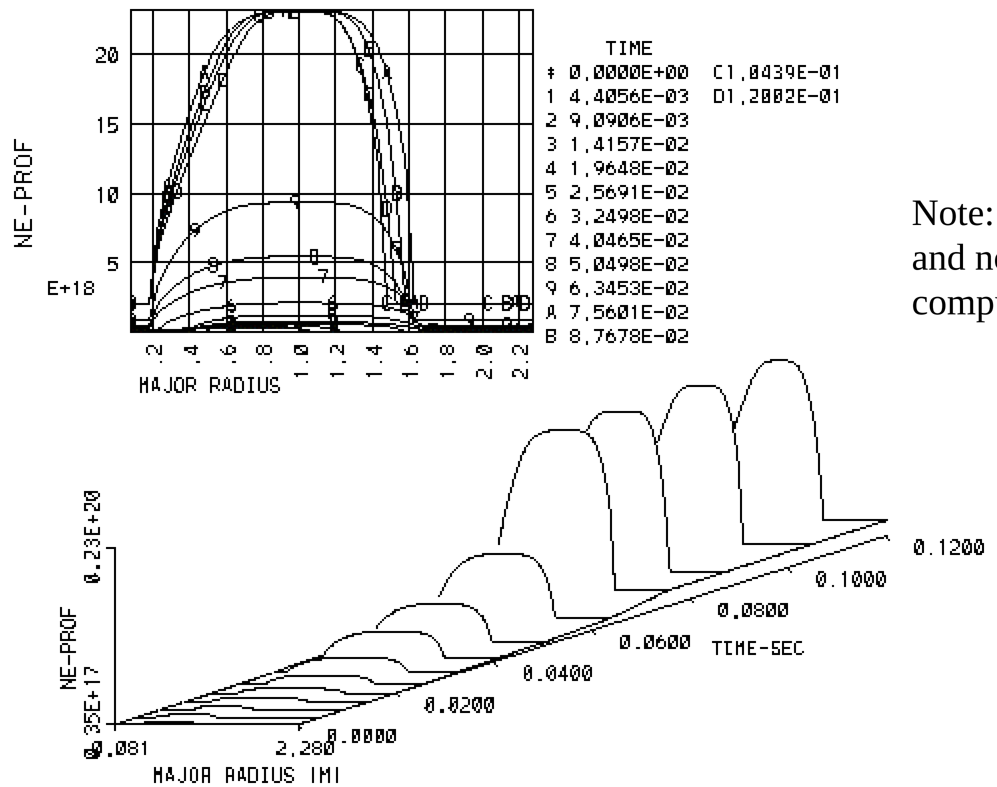
Te(0) ~ 200 - 250 ev

Note: actual value depends on density assumed

β ~ 2%

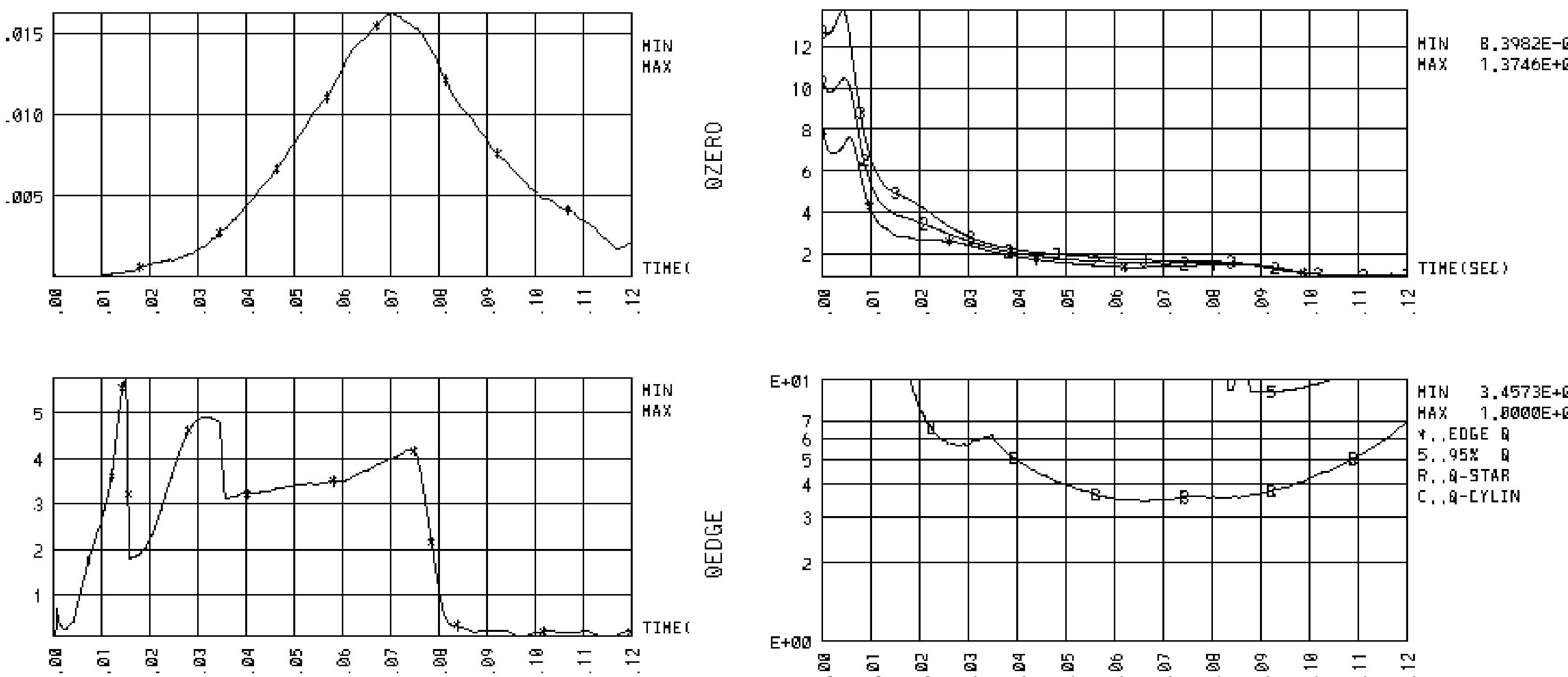


NSTX shot 100193: Electron Density

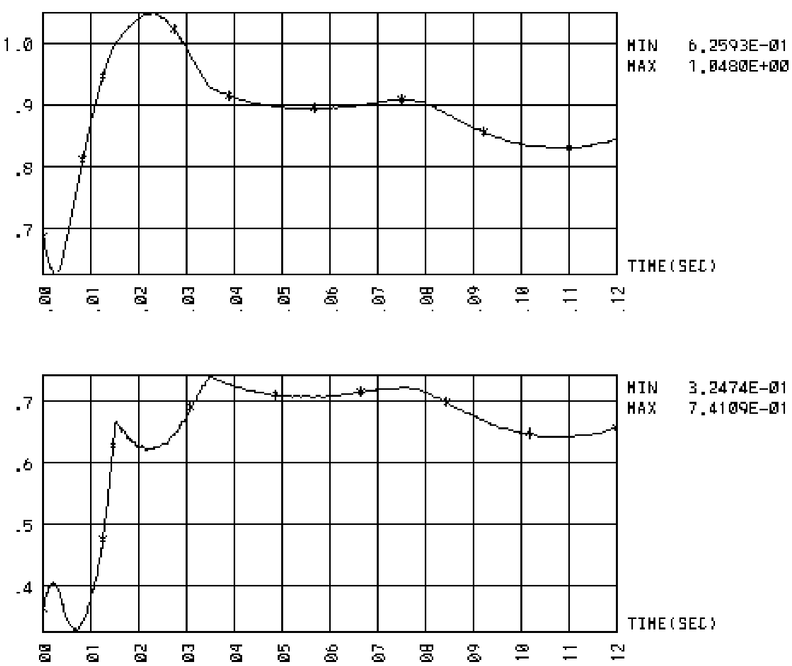


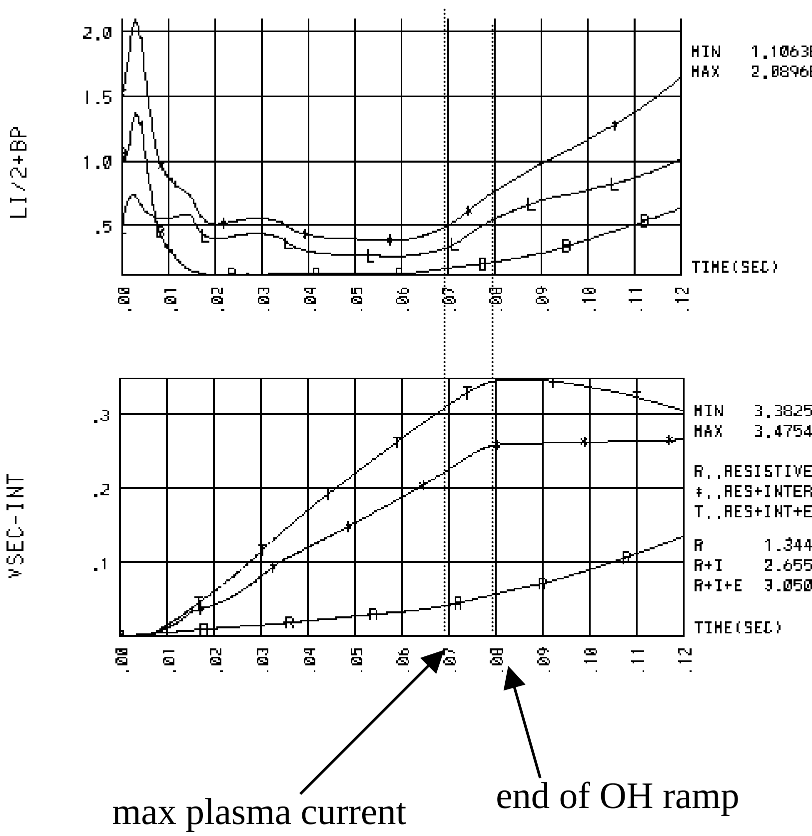
Note: This was assumed and not measured or computed

NSTX shot 100193:



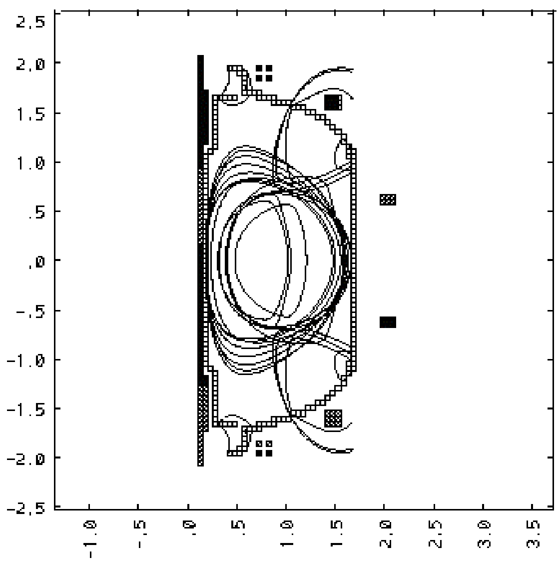
NSTX shot 100193:



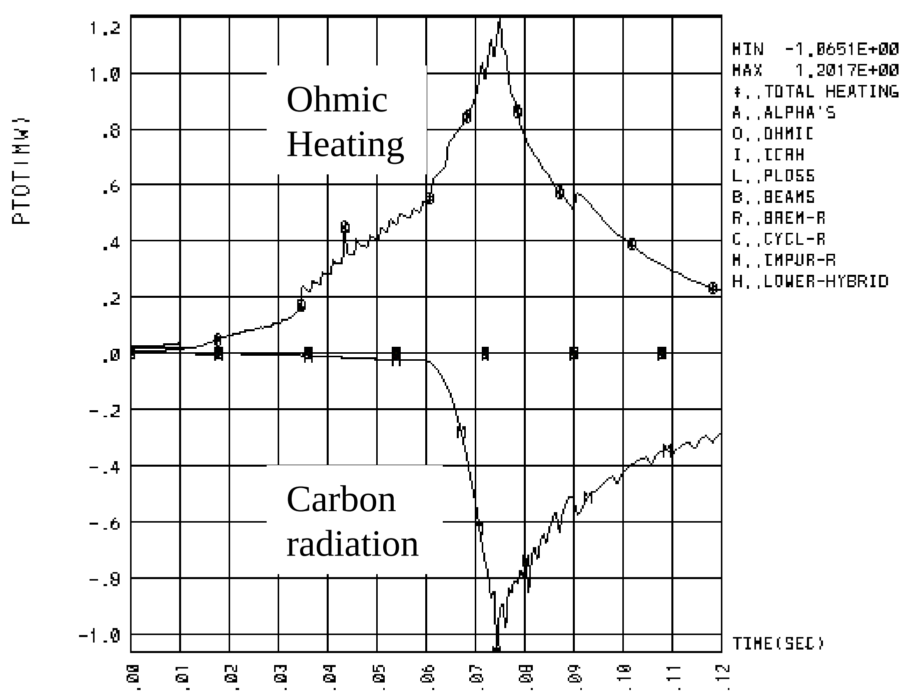


Note: no radial control!

NSTX shot 100193:



Superposition of
plasma/vacuum interfaces
for 0.0 < t < 0.12 sec



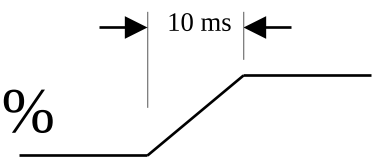
Some Physics Highlights of the TSC Modeling

- Some questions about calibration and timing of flux and current measurements
- Resistive volt-sec consumption was “small” due to rapid current rise time
  - $\Delta\Phi_R$(poynting) = $C_E \mu_0 R_0 I_P$
  - here C_E = .35 at end of current ramp (normally > .45 for full resistive profiles)
  - corresponds to hollow current profile with l_i still increasing
- No radial control was needed!
  - Implications for radial control system ←
- Plasma current resistive decay set by carbon radiation
  - insensitive to concentration
- Predictions for full flux-swing 1MA ohmic shots

Numerical experiments to study radial control in NSTX:

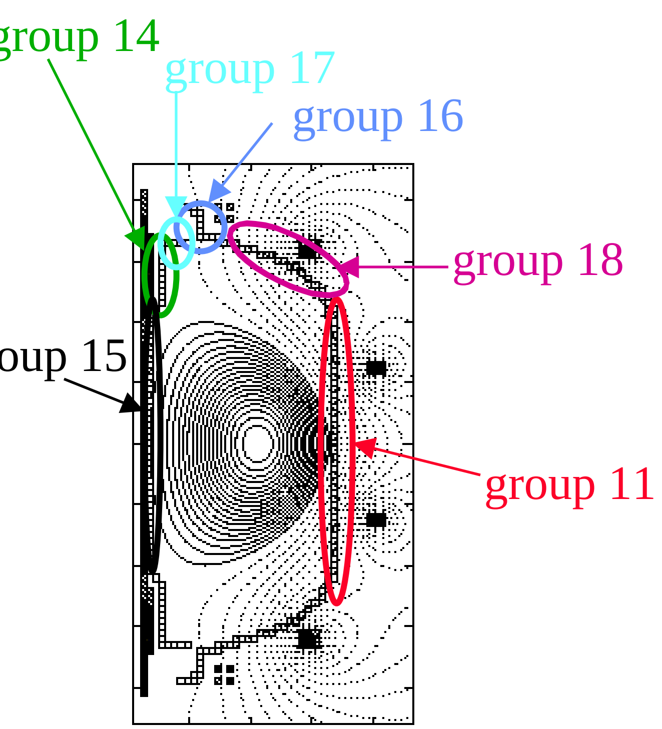
- Start with 300 ka equilibrium NSTX plasma centered in VV
  - turn on “plasma current feedback system” to keep current constant (maximum loop voltage 3.0 V)
  - change current in PF5 linearly over 10 ms to new value

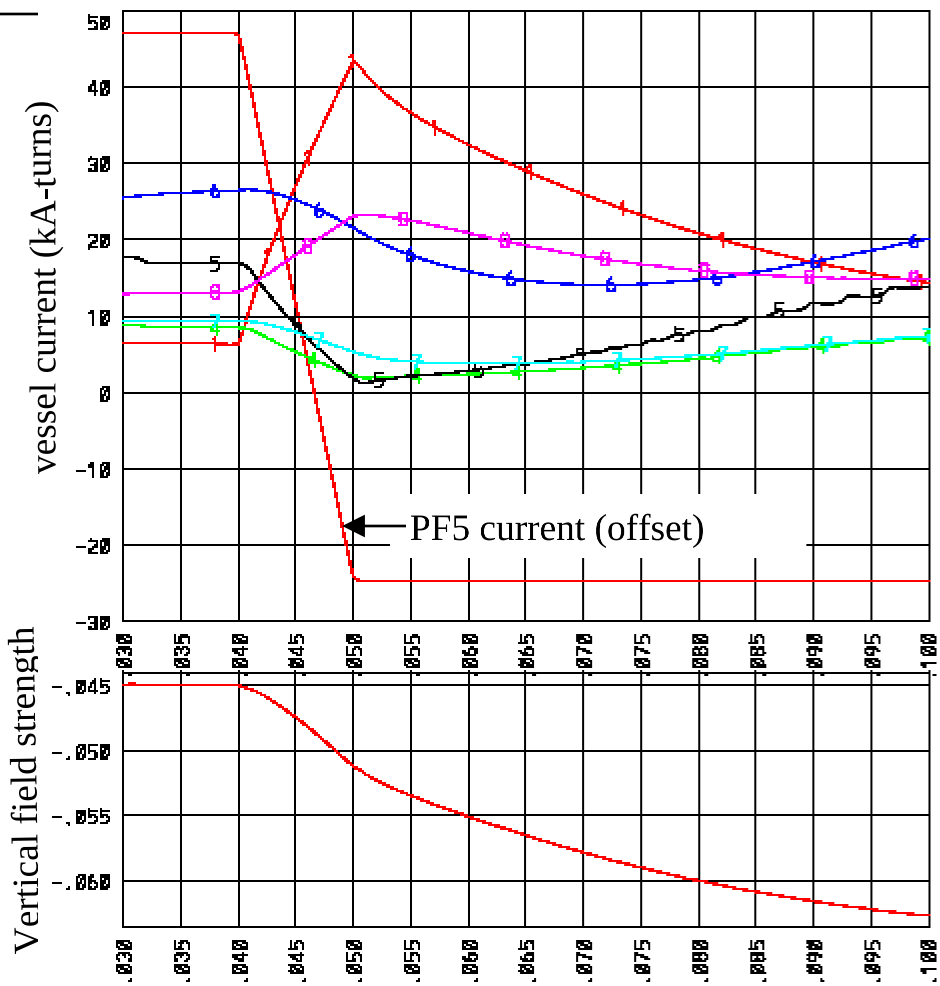
(1) increase vertical field strength by ~ 40%



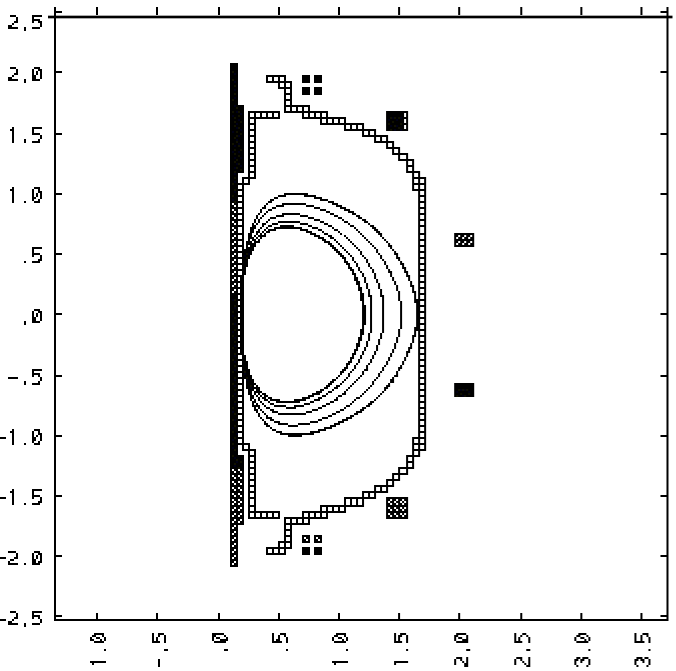
(2) repeat but decrease vertical field strength

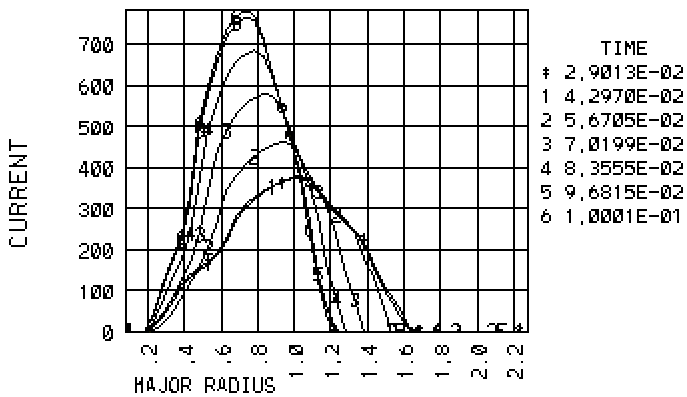
(1) increase vertical field strength by ~40%

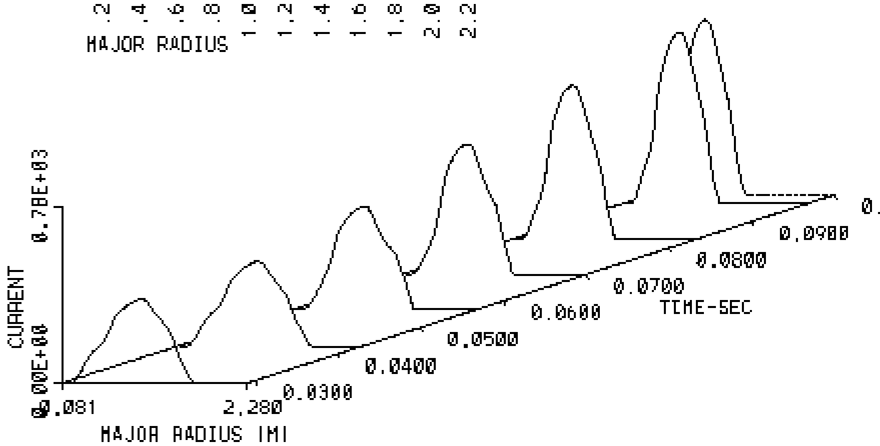




(1) increase vertical field strength by ~40% (cont.)







- j(0) increases by over 100% !
- I_P, q(0) stay fixed , p(0) up by 50%
- R_0, a decreases by 25% and 29%

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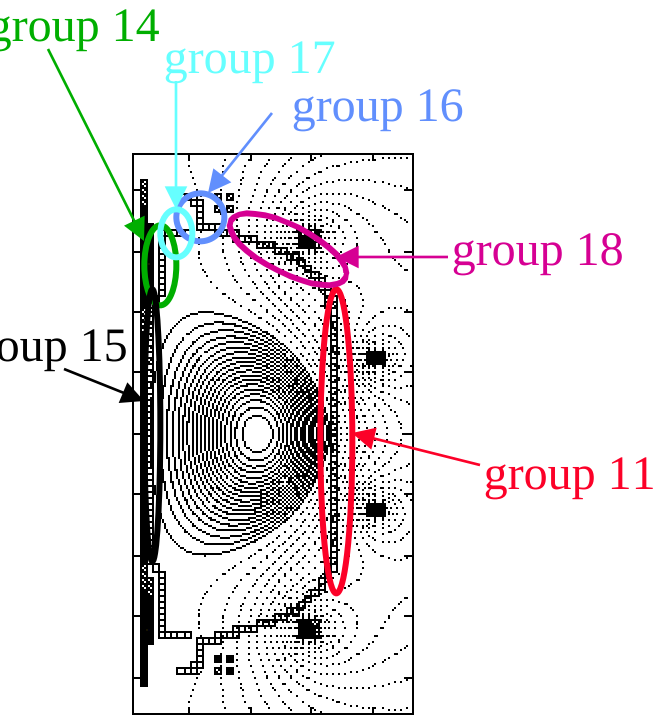
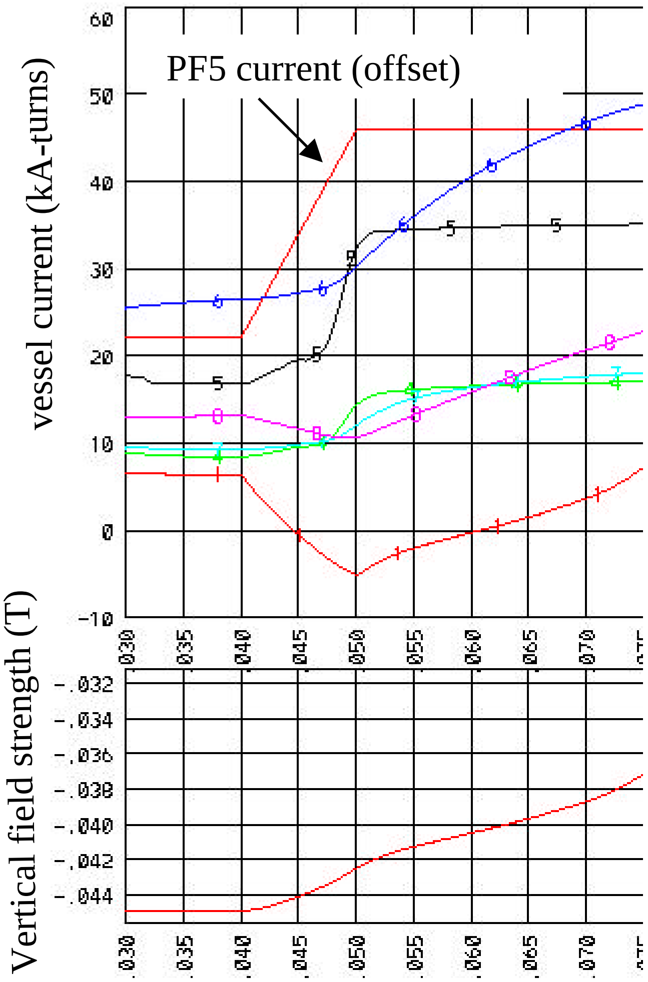
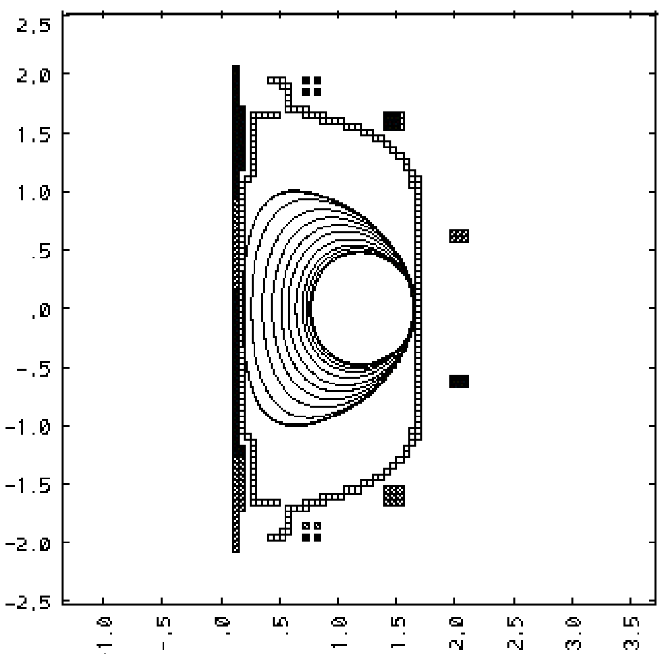
(2) decrease vertical field strength by ~25%

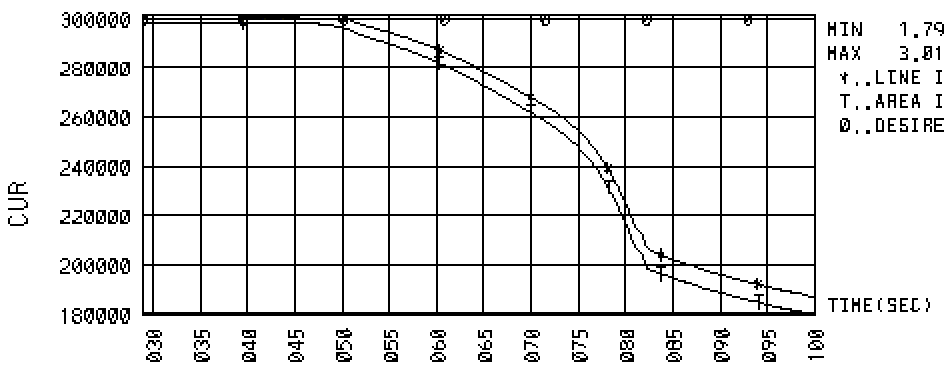




(2) decrease vertical field strength by ~25% (cont.)



- R_0, increases by > 32% ,
- a decreases by > 62%



- I_P decreases without limit!

  (even with current feedback on and V_L allowed to increase to 3 V)

- plasma termination ?

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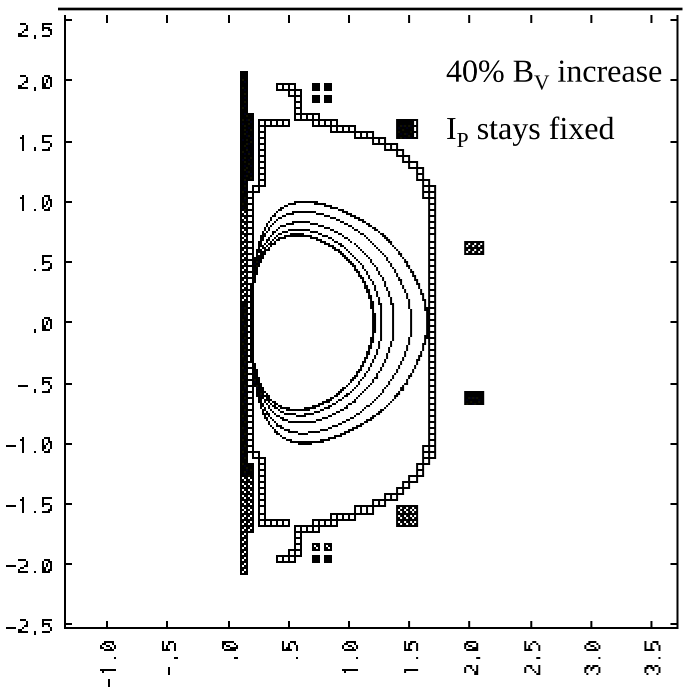
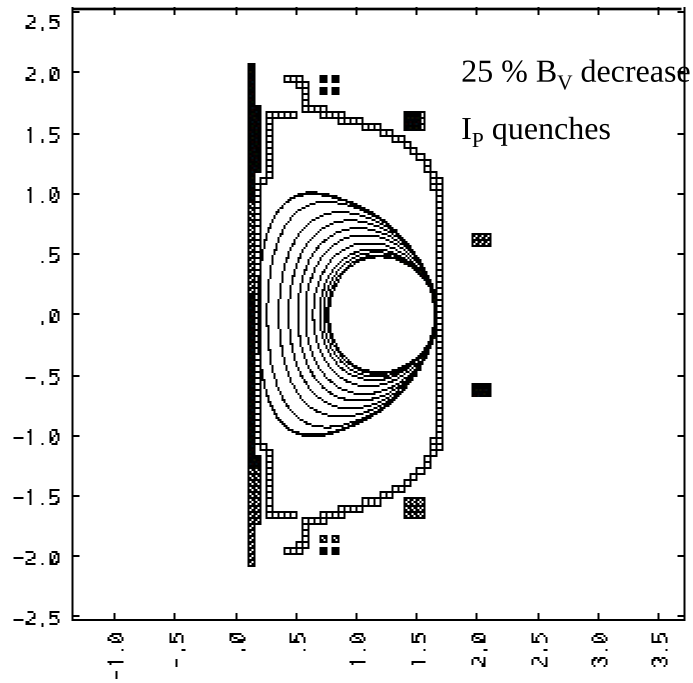
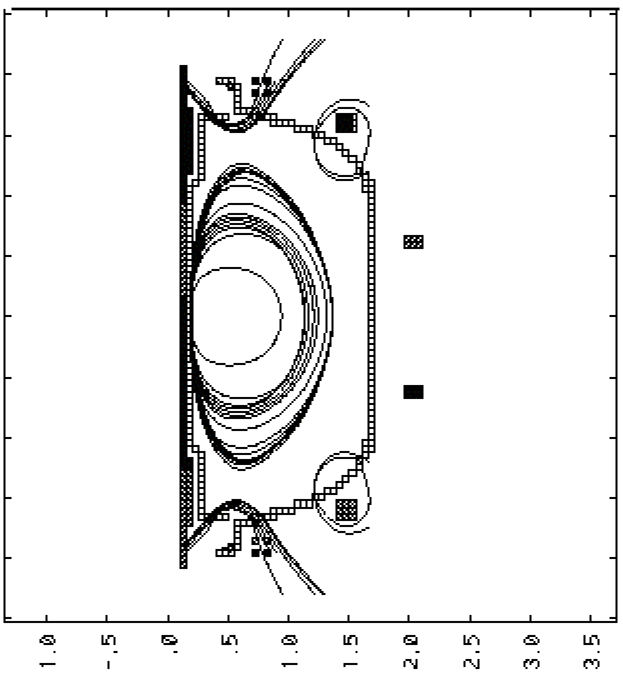
Summary of radial control experiments:

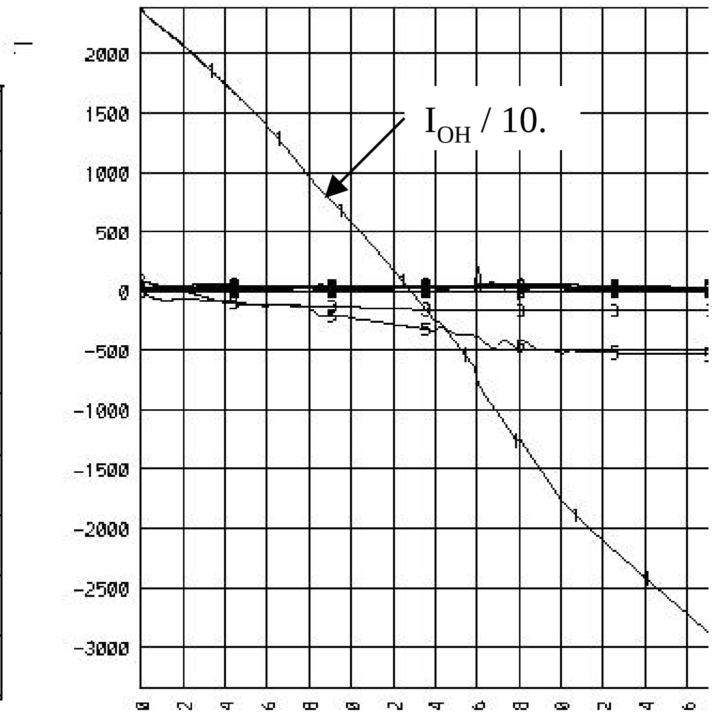


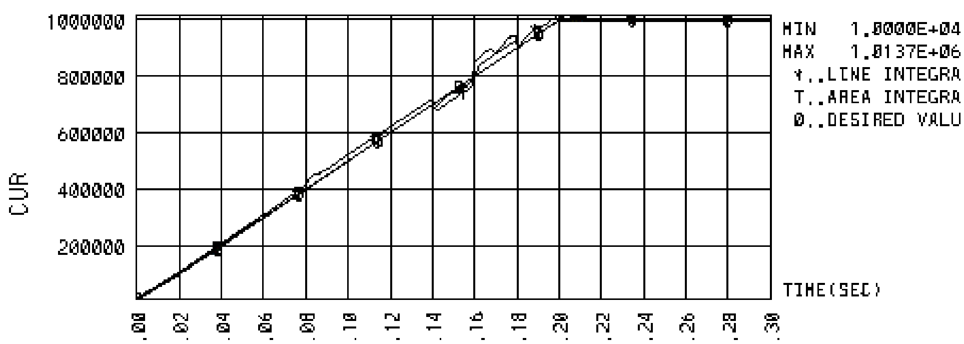


→ NSTX should be much easier to control on inside limiter

Predictions for full flux-swing 1 MA ohmic shots

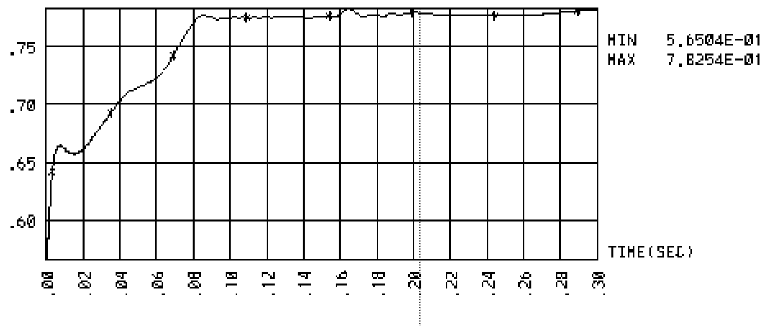


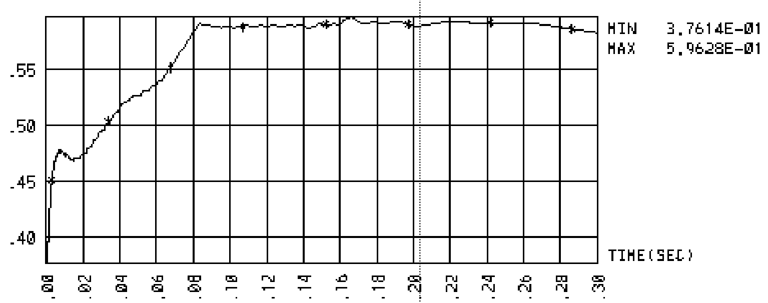


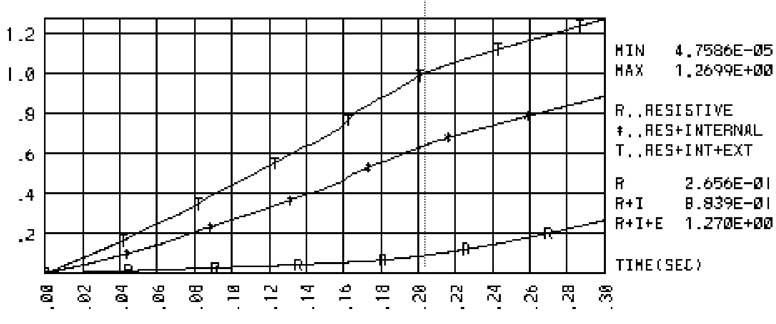


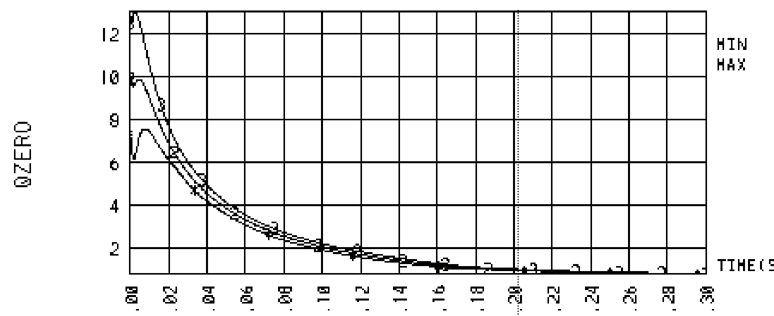
- Te(0) ~ 800 ev
- n(0) ~ 5 × 10^{19} =0.5 n_{GW}
  β_T = 8%, <β> = 4%
- ℓi ~ .7, Zeff ~ 1.2,
- C_E ~ .45 at t = 0.3

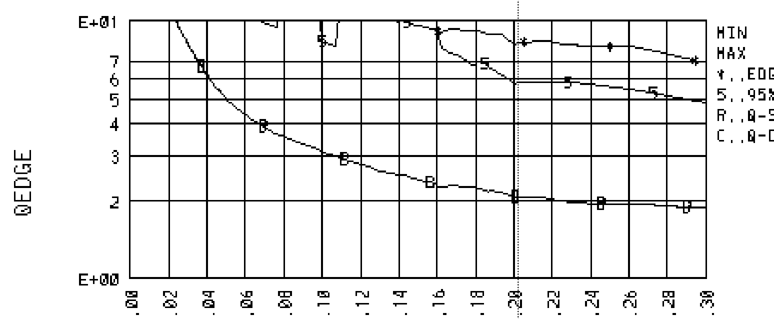
Predictions for full flux-swing 1 MA ohmic shots

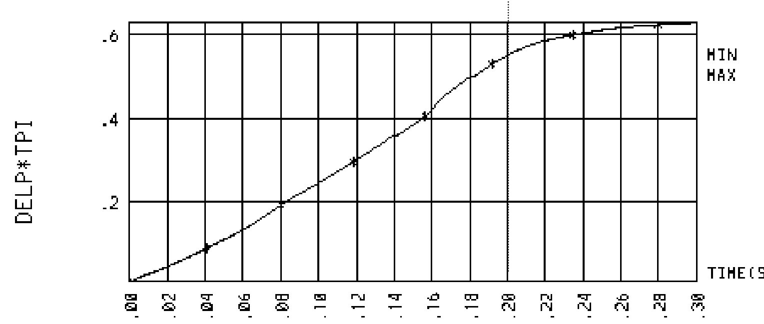












Predictions for full flux-swing 1 MA ohmic shots

Conclusions:

- NSTX should get 1 MA purely inductively if OH coil can swing from +25 kA to -18 kA
- Fully relaxed current profile with 0.6 W in plasma takes a larger OH swing (+25 kA to -30 kA)
- NSTX “natural” current ramp time for 1 MA is about 300 ms
  - faster will lead to hollow current profiles
  - slower will consume excess V-Sec