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Steady State Operation and Current Ramp-up Research on NSTX

Presented by D. A. Gates
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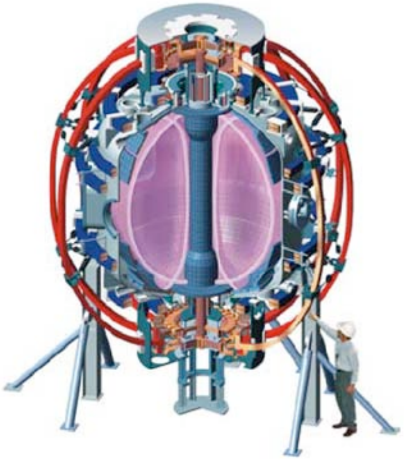

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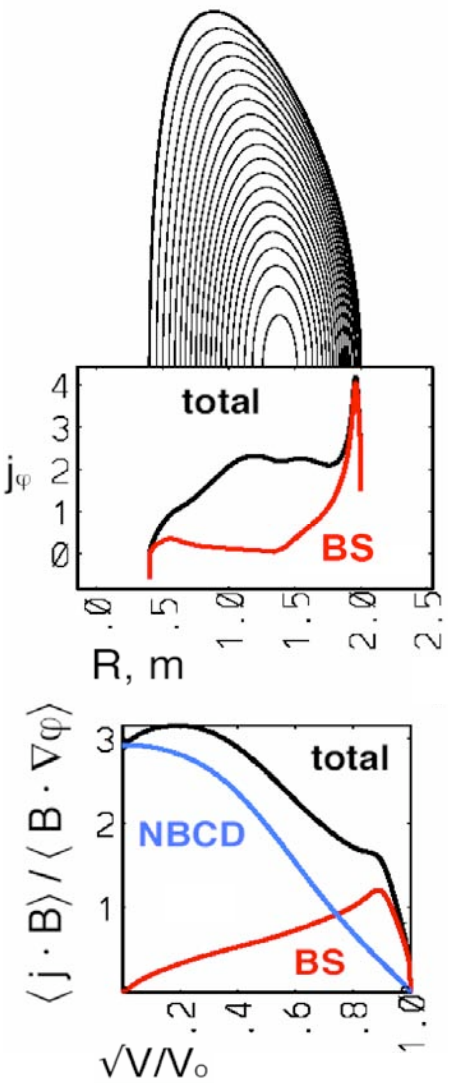
NSTX steady state operation and ramp-up research aims to provide physics basis for CTF

- CTF target definition
- Steady state
  - Progress on steady state operation
  - Run plan 2006
  - Strategic plan 2007-2008
- Ramp-up
  - Ramp-up paradigm
  - Run plan 2006
  - Strategic plan 2007-2008

CTF target defines research issues for both steady state and ramp-up

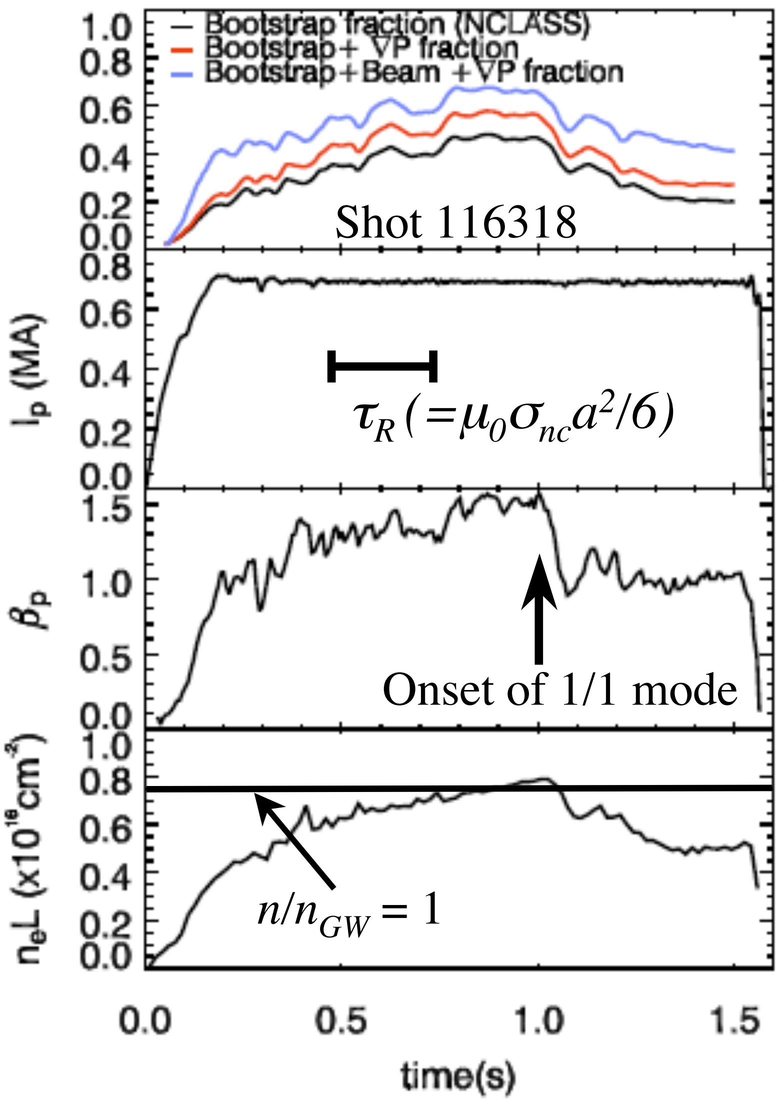


- Many CTF parameters already achieved on NSTX
- Primary difference are
  - higher elongation $\kappa \approx 3.2$ in CTF
  - fraction of beam driven current due to higher density in NSTX

Parameters	**CTF** **($\tau \gg \tau_{skin}$)**	**NSTX so far** **($\kappa \le 2.7$, $\tau \le 6\tau_{skin}$)**
I_p (MA)	10	≤1.5
B_t (T)	2.5	≤0.6
I_{BS}/I_p, I_{CD}/I_p	0.43, 0.57	0.5, 0.15
$\mu_0 \ell_i R I_p$ (Wb)	≥3.8	~0.13 (goal)
n_e/n_{GW}	0.16	0.7
β_N (%·m·T/MA)	3.5	5.5

Plasma with CTF q_{95} sustained for $6\tau_R$

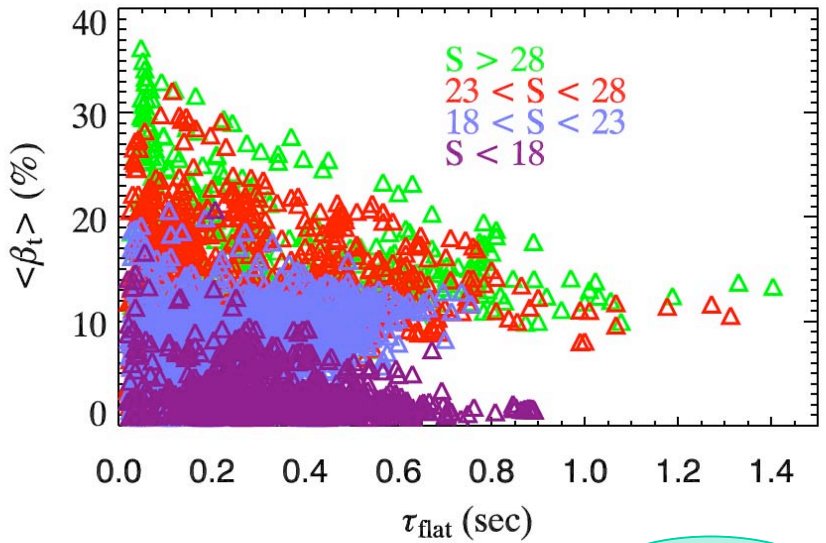
- Improved plasma shape control has enabled progress
- Discharge lasting ~1.6s
  - – Flattop for ~ 50τ_E and ~ $6\tau_R$
  - – Limited by TF coil temperature
- Non-inductive fraction reaches 65% with 85% of non-inductive current pressure driven
  - – Finite collisionality on NSTX reduces bootstrap by 20-30%
- Onset of 1/1 mode reduces confinement as $q(0) \rightarrow 1$
- $q(0) > 1$ sustained
  - – hybrid like mode - ITER relevant
- Issue: density ramps continuously

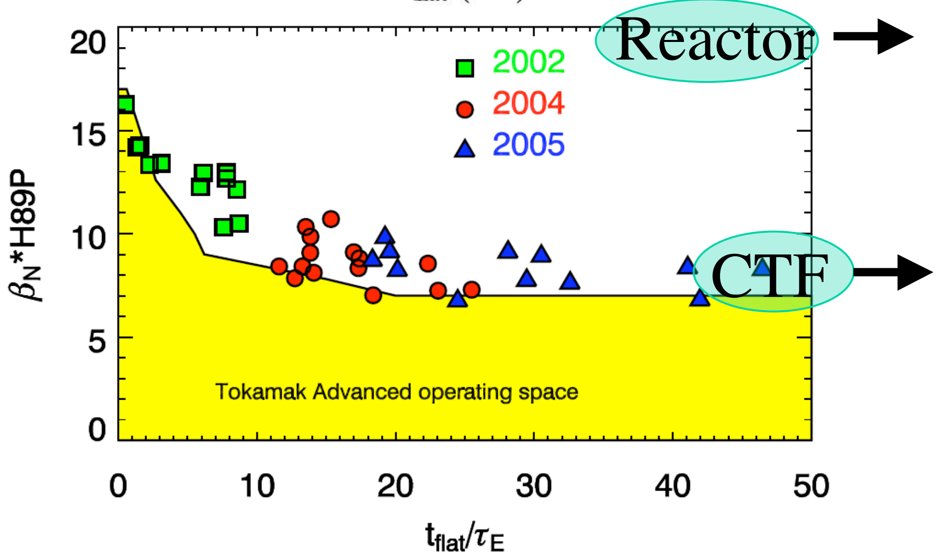


Progress towards steady state has been substantial

- Shaping is associated with both increased time averaged β_t ($\equiv <\beta_t>$) and increased pulse length
- Pulse length has been extended to ~50*τ_E while maintaining high confinement and β_N
- β_N*H_{89} saturates with pulse extension, similar to tokamak performance

$<\beta_t>$ versus pulse duration (β_t is averaged over τ_{flat}) sorted by shape factor $S \equiv q_{95}*I/aB_t$





Sustained β scales with increasing shape factor

- TRANSP calculations verify f_{bs} scales according to approximate relationship

$$f_{bs} \sim \sqrt{\varepsilon}\beta_p$$

- Define shape factor S

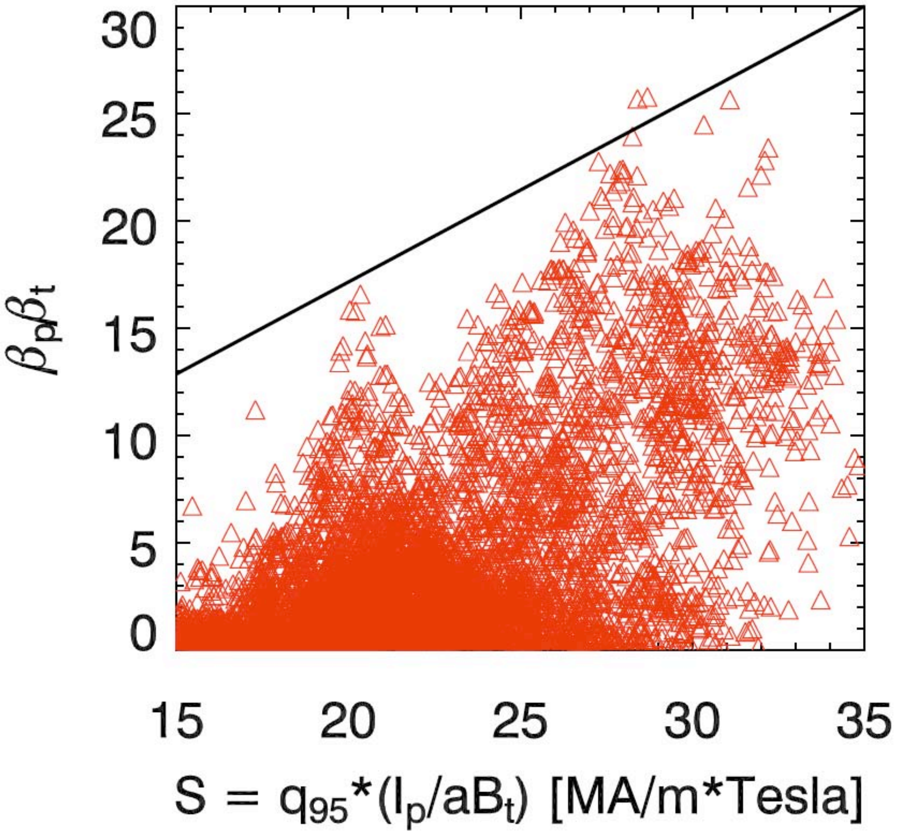
$$S = q_{95}(I_p/aB_T)$$

and “sustained β”

$$\beta_{sus} \equiv f_{bs}\beta_t \sim \sqrt{\varepsilon}\beta_p\beta_t \sim C\varepsilon^{-1/2}S\beta_N^2$$

- Expression shows expected scaling with shape factor
  - ➢ Gives confidence in scaling to larger devices at higher S

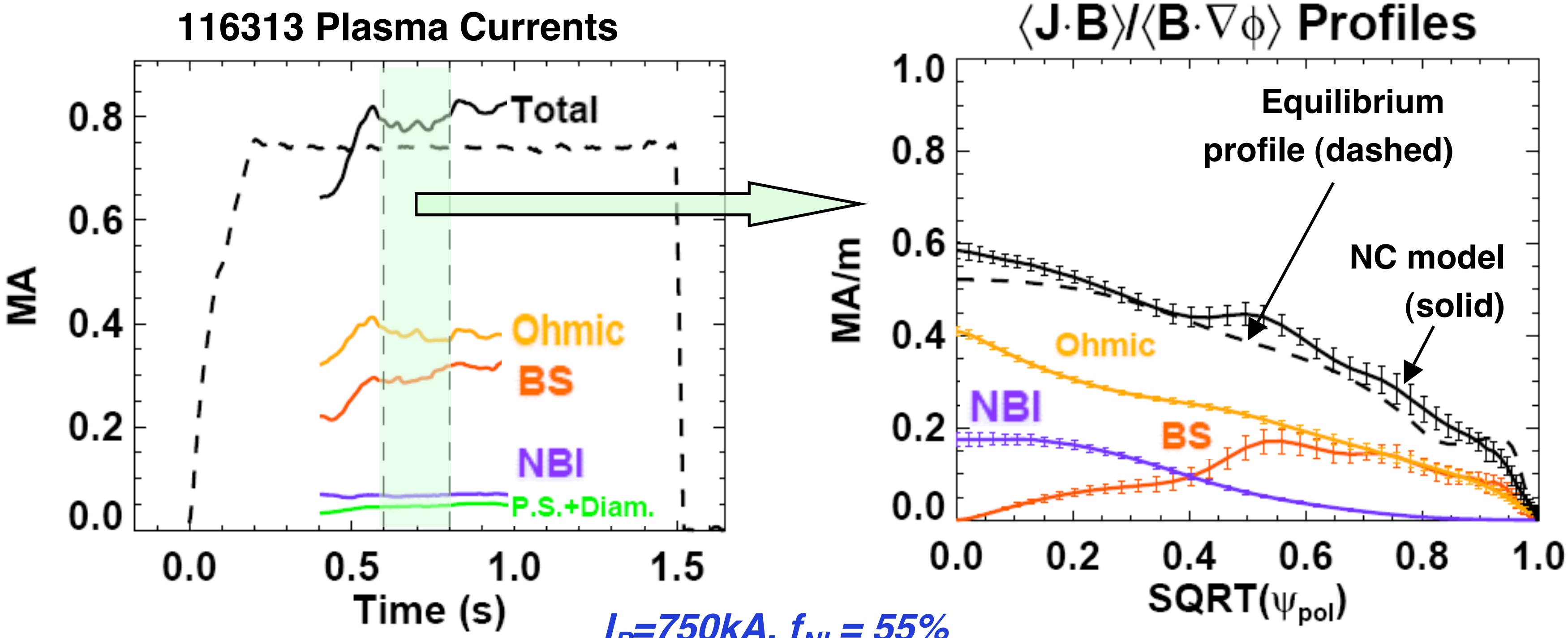
Pulse averaged approximate scaling β_{sus}vs. S (S averaged over the same time window as $\beta_p\beta_t$)



Predicted current profile in good agreement with MSE measurement for quiescent discharges

- Compute V_{LOOP} distribution/evolution directly from MSE-constrained fits
  - – Long pulse-length and quiescent discharges needed for analysis
- Fit T, p, Z_{eff} to ψ, compute σ_{NC}, J_{OH} & J_{BS} (Sauter model), add TRANSP J_{NBI}

Sauter collisional NC model consistent with experimental I_P and $J_{||}$

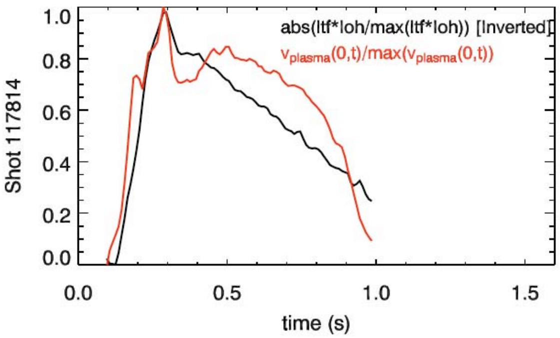


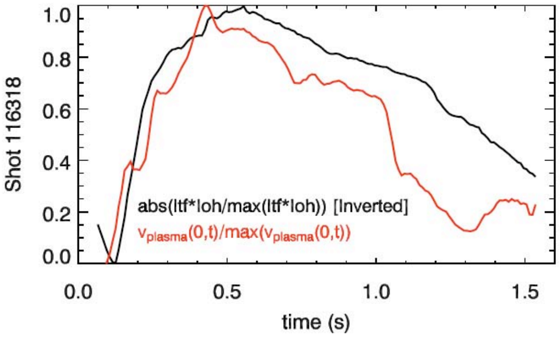
I_P=750kA, f_{NI} = 55%

Comparing Sauter to NCLASS models to assess role of aspect ratio, impurities, etc...

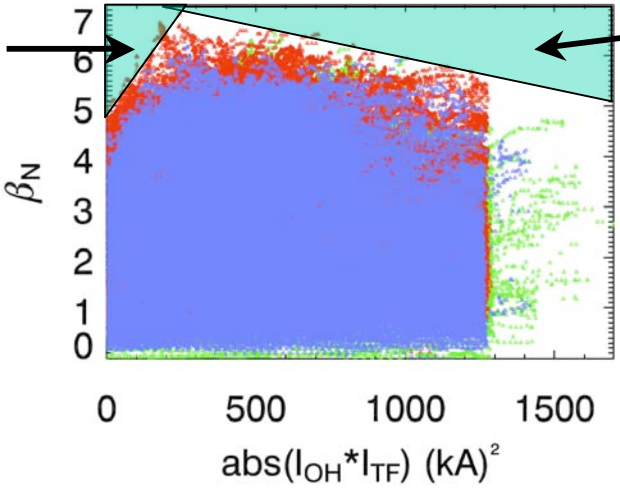
Error field reduction holds promise for pulse extension

- Error field scales with $I_{oh}*I_{tf}$ (with a time delay - inertia?)
- Achievable β_N decreases with increasing $I_{oh}*I_{tf}$
- Measured core rotation correlates with inferred error field amplitude
- Indicates that error field determines rotation speed
- Error field may be important in determining the maximum I_p ramp rate
  - Faster ramp could prevent onset of internal modes
- Investigate error field mitigation proportional to $I_{oh}*I_{tf}$



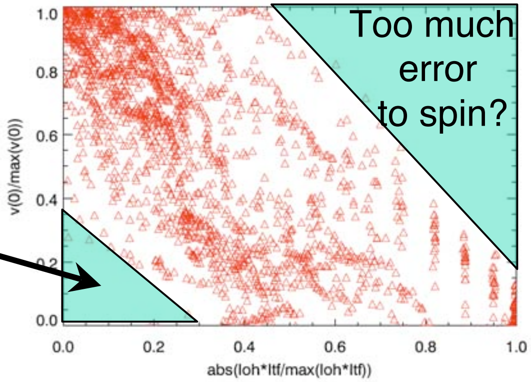


Inertia term?



Error field reduces maximum β?

Not enough error to brake?



Too much error to spin?

Run plan 2006 - Steady State development

- Investigate long-pulse operation with density control using lithium
- Propagate early H-mode and rtEFIT boundary control to all long-pulse scenarios
- Investigate effect of error field correction on long-pulse plasma behavior
- Investigate HHFW sustainment with improved voltage feedback to avoid trips

Research goals 2007-2008 - Steady State development

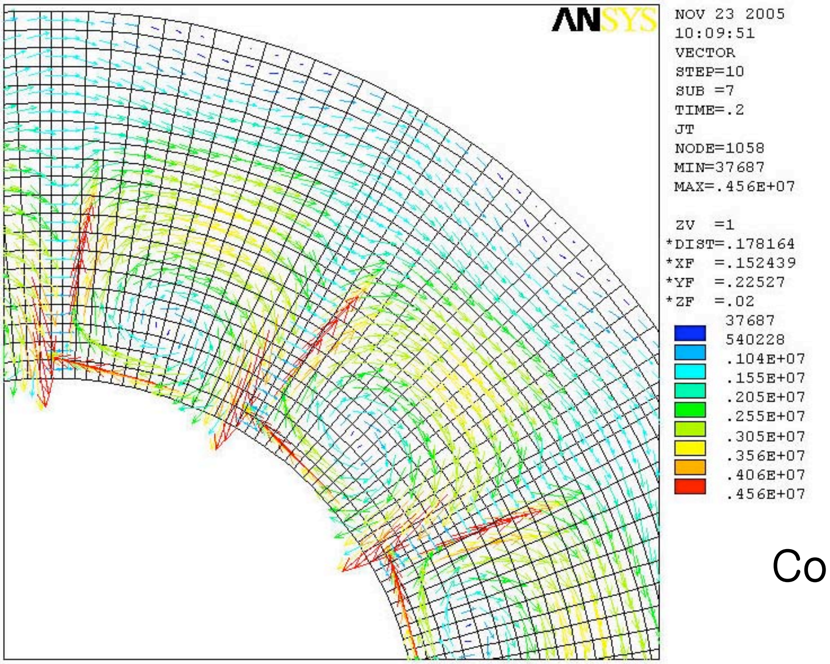
- Research milestone (2008): Perform long pulse plasmas in conditions relevant to CTF
- Investigate NB current drive physics in low density plasmas with high non-inductive fraction dominated by neutral beam driven current
  - Motivated by CTF design and by
  - Important issue for ITER
  - ASDEX-U observation of limitation of NB current at high powers
- Demonstrate higher $\kappa \sim 2.8$ operation
- Participate in MAST EBW experiments
- Modeling studies
  - Investigate possibilities for off axis current drive using neutral beams
  - Investigate EBW current drive

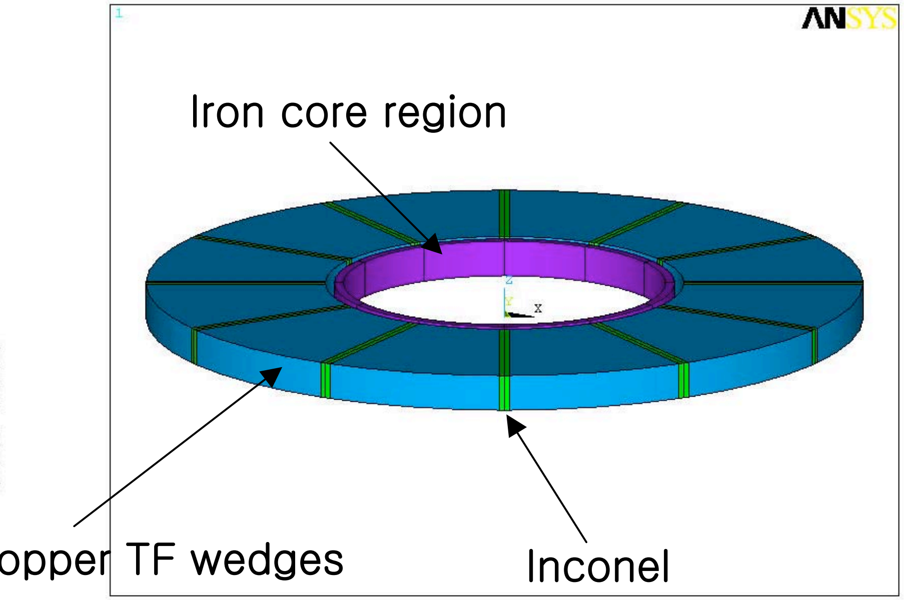
Possibilities for Current Ramp-up in CTF

- Assume initial plasma formation from CHI or ECH assisted PF startup
- Add in neutral beams giving three terms
  - NBI current
  - Bootstrap (+other pressure driven currents)
  - Vertical field ramp flux
    - Time history of the vertical field must match that required for equilibrium
- Use transformer for plasma startup and/or to provide current control during ramp independent of vertical field

Iron core concept changes CTF ramp-up paradigm

- If design is successful, 100% current ramp no longer required for CTF
- Iron core surrounded by copper wedges with Inconel separators which reduce eddy currents
- Eddy currents calculated to be acceptable
- Uses ~35% of center stack area to provide 1MA of plasma current
  - Does not eliminate need for startup scheme (CHI or PF assist) or non-inductive current drive (CHI, NB, bootstrap, EBW, etc.) during ramp-up



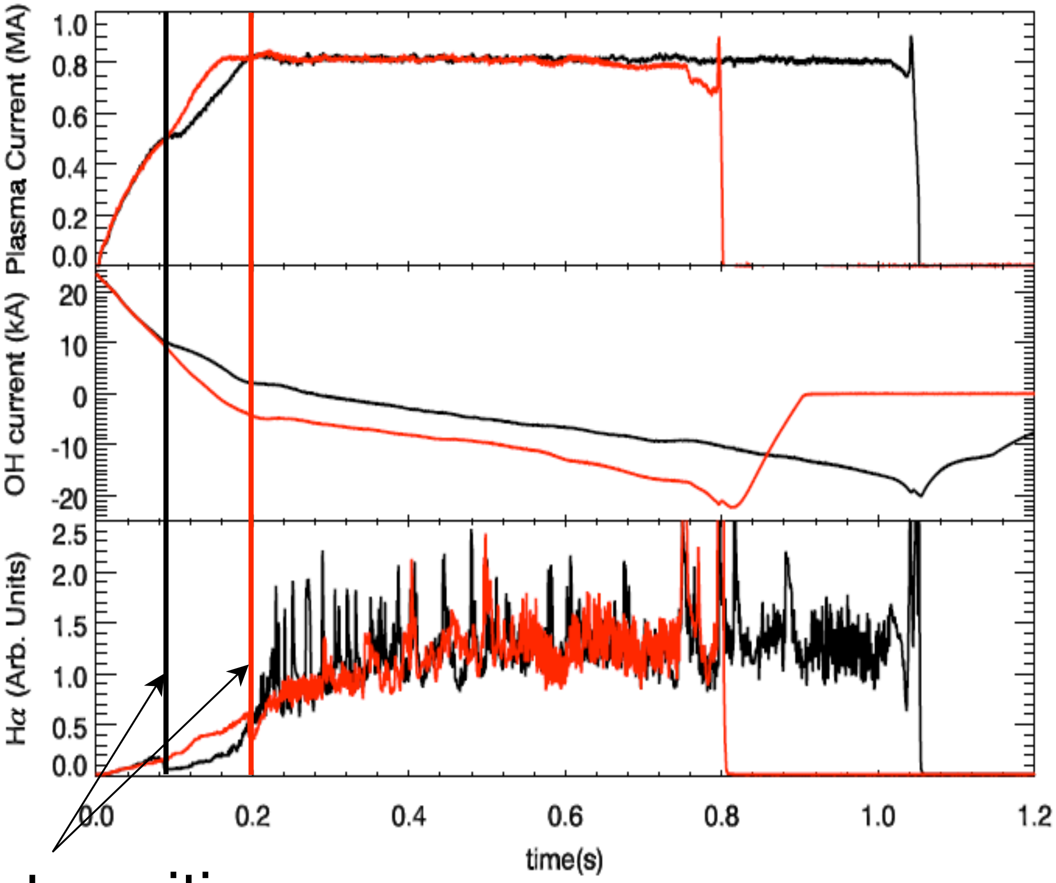


Early H-mode has reduced flux consumption

- I_p “flat-spot” induces early H-mode
- Lowers internal inductance
  - delays MHD onset (presumably due to increased q_{min})
  - Raises elongation/ bootstrap current (for fixed field curvature)
- Clear example of flux usage minimization

Shot 112546 - early H-mode

Shot 111964 - No early H-mode



H-mode transition

Run plan 2006 - Ramp-up optimization

- Further optimize flux consumption during startup
  - Early H-mode
  - Early shaping
  - Early heating
  - Flux optimization of null
- Explore HHFW for ramp-up with improved voltage feedback
- Develop low density operating scenario using lithium
  - Investigate locking behavior at low density

Research goals 2007-2008 - Ramp-up optimization

- Continue flux reduction studies
- Investigate flux-optimized initial null configurations
- Investigate flux consumption and current drive during current ramp
  - Low voltage NB injection during ramp-up
  - MSE to measure current profile
- Address possible mode-locking behavior at low density
  - Operational limits will be identified in 2006

Improvements in shape control and operational scenarios have enabled longer pulses

- At q_{95} required for CTF, NSTX has simultaneously achieved
  - Non-inductive current fraction ~ 65%
  - Pressure driven current fraction ~ 50%
  - 1.6s pulse length with flattop lasting $\sim 6\tau_R, \ \sim 50\tau_E$
- New iron core transformer concept for CTF adds impetus to research on NSTX to enhance flux utilization through
  - Error field reduction
  - Flux optimized null formation
  - Density control with lithium
  - Further shape optimization
  - Earlier H-mode in more scenarios
  - HHFW current-ramp assistance