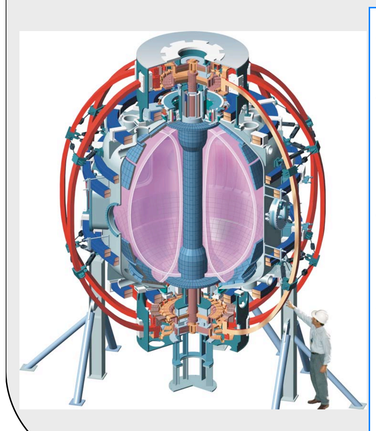
Physics Results from the *National Spherical Torus Experiment**

M.G. Bell, Princeton Plasma Physics Laboratory
on behalf of the NSTX Research Team

* *Work supported by US DOE Contract No. DE-AC02-76CH03073*

Supported by

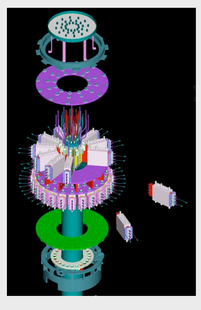
NSTX Designed to Study High-Temperature Plasmas at Low Aspect-Ratio

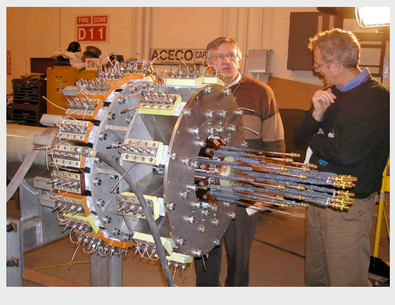


Aspect ratio A	1.27
Elongation κ	2.5
Triangularity δ	0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.6T
Pulse Length	1s
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 3 keV

Now Operating With a New Center Bundle for Toroidal Field Coil

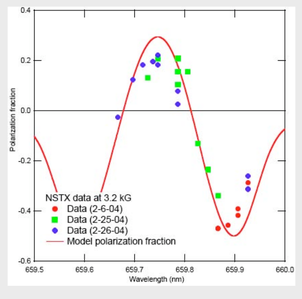
- Original damaged by joint failure in February '03
- New bundle constructed after redesign, modeling and review

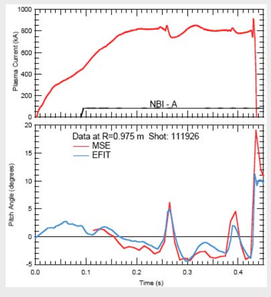




- Joints now monitored continuously
- Operating stably at 0.45T for ~ 1200 shots

New Diagnostics & Capabilities Developed, Including MSE Measurements of q-Profile

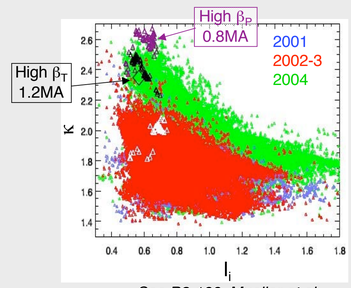


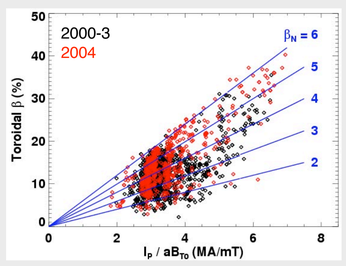


- Low field presents severe challenges for MSE technique
- First two channels now operating, more being installed this run
- Also new this run:
  - Fast tangential x-ray cameras
  - Fast divertor visible camera
  - Solid pellet injector
  - 51-channel CHERS & edge flow
  - RWM detection coils
  - RWM control coils (1 pair)

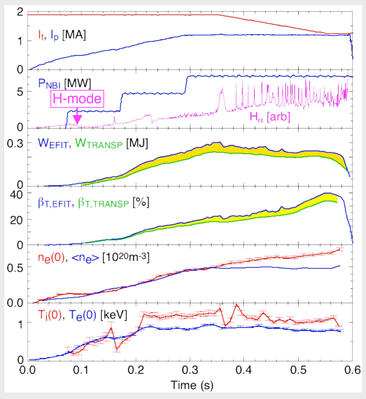
Long H-modes with High Elongation and Triangularity Provide Route to High β This Year

- Reducing error fields & H-modes improved performance in 2002
- Improved vertical position control & earlier H-modes opened operating window this year
  - Propagation latency in digital control system reduced to ~700μs
  - Lower internal inductance in H-mode allows higher elongation
  - Capability for higher κ, δ allowed higher I_P/aB_T



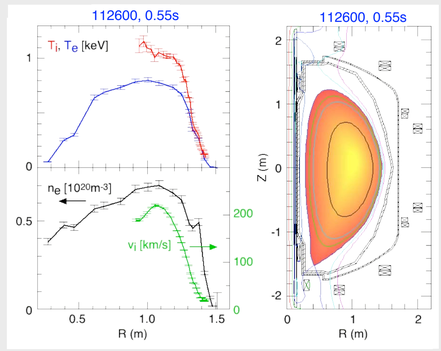


See P2-199, Mueller et al.



- Use He pre-conditioning to control recycling
- Initiate plasma at high B_T ($\propto I_t$) for most quiescent ramp-up
- Early NBI and pause in I_p ramp trigger H-mode
- High T_e & low l_i allow high κ, I_p
- Stage P_{NBI} increase to avoid β_N limit & excessive density
- Reduce B_T to increase β_T
- ELMs develop as B_T falls
  - ELMs reduce edge density
- β_T maximum as $I_t = I_p$ ($q_{95} \approx 4$)

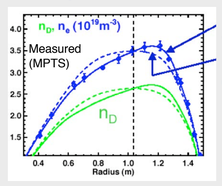
High-resolution Charge-Exchange Spectroscopy Measures High Rotation & Large Gradients in T_i, v_i



- A = 1.5
- κ = 2.3
- δ_{av} = 0.6
- q_{95} = 4.0
- l_i = 0.6
- β_N = 5.9%·m·T/MA
- β_T = 40% (EFIT, $<p_{||}+p_\perp>/2$)
  34% (TRANSP, $<p_{||}+2p_\perp>/3$)

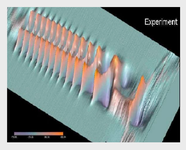
High v_ϕ/v_A Affects Equilibrium & Stability

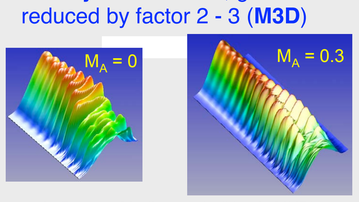
- Density shows in-out asymmetry
  - Effect of high Mach number of driven flow



$n_e(\psi,R)$ (MHD model with centrifugal effects)
$n_e(\psi)$ (assuming density a flux function)

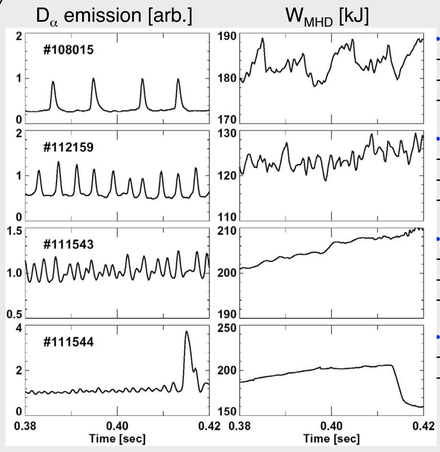
- **Experiment**: kinks do not grow but saturate
- **Theory**: with rotation, growth rate reduced by factor 2 - 3 (**M3D**)





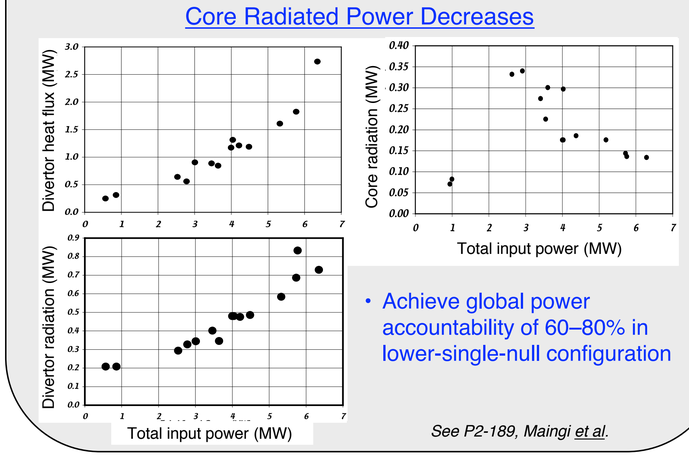
See P2-193, Sontag et al., (macrostability); P2-162: Redi et al. (microstability); P2-196, Gorelenkov et al., P2-200, Medley et al., (kinetic MHD)

Control of ELMs Critical to Optimizing β



- **Type I**
  - Mid ΔW_{MHD}
  - Magnetic signature
  - No precursor
- **Type III**
  - Small ΔW_{MHD}
  - Magnetic signature
  - High frequency precursor
- **NEW, Type V**
  - Imperceptible ΔW_{MHD}
  - Magnetic signature
  - No precursor
- **Mixed Type V + 'Giant ELM'**
  - Large ΔW_{MHD}
  - May couple to core mode

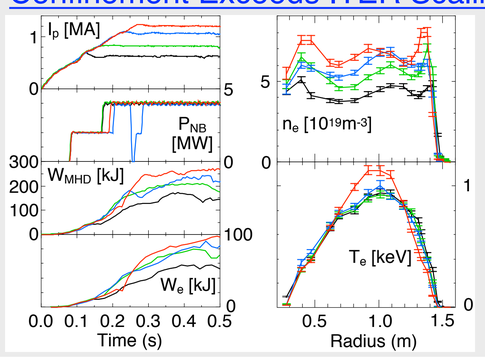
Divertor Heat Flux and Radiation Increase With NBI Power but Core Radiated Power Decreases

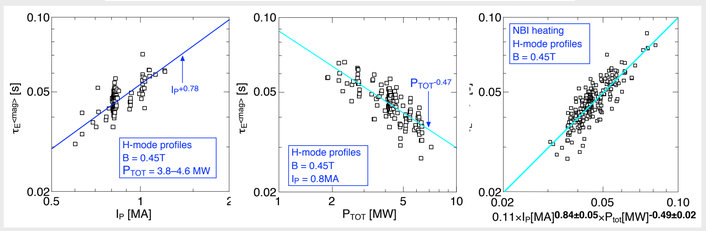


- Achieve global power accountability of 60–80% in lower-single-null configuration

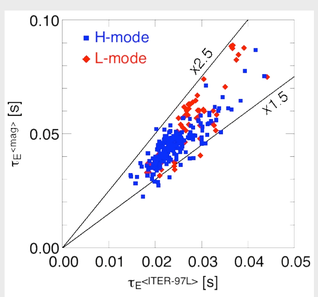
See P2-189, Maingi et al.

With NBI, Tokamak Trends Reproduced but Confinement Exceeds ITER Scalings

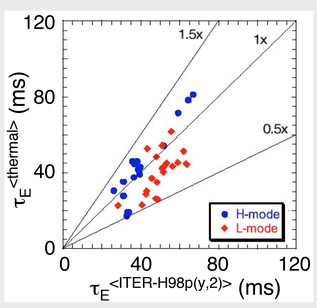




- Data for D-NBI heated H-modes at time of peak stored energy
- B_T = 0.45T, R_0 = 0.84 – 0.92 m, A = 1.3 – 1.5, κ = 1.7 – 2.5
- EFIT analysis using external magnetic data
  - Includes up to ~30% energy in unthermalized NB ions



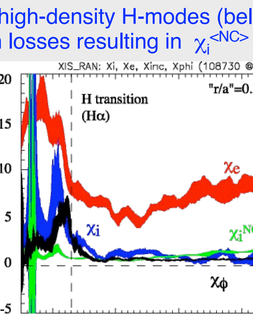
- Compare with ITER scaling for total confinement, including fast ions

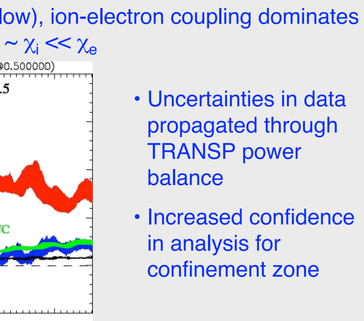


- TRANSP analysis for thermal confinement
  - L-modes have higher non-thermal component and are more transient

Power Balance Analyzed with TRANSP

- Use measured profiles of T_e, T_i, n_e, n_{imp}, P_{rad}
- Monte-Carlo calculation of classical NBI thermalization



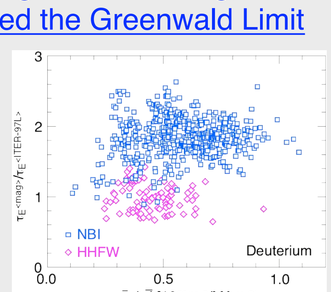


- In low-density L-modes (above) $\chi_i^{<NC>} << \chi_i < \chi_e$ in gradient region
- In high-density H-modes (below), ion-electron coupling dominates ion losses resulting in $\chi_i^{<NC>} \sim \chi_i << \chi_e$

- Uncertainties in data propagated through TRANSP power balance
- Increased confidence in analysis for confinement zone
- Some high-density H-mode shots show anomalously high T_i in region r/a ~ 0.6 – 0.8, yielding $\chi_i < \chi_i^{<NC>}$

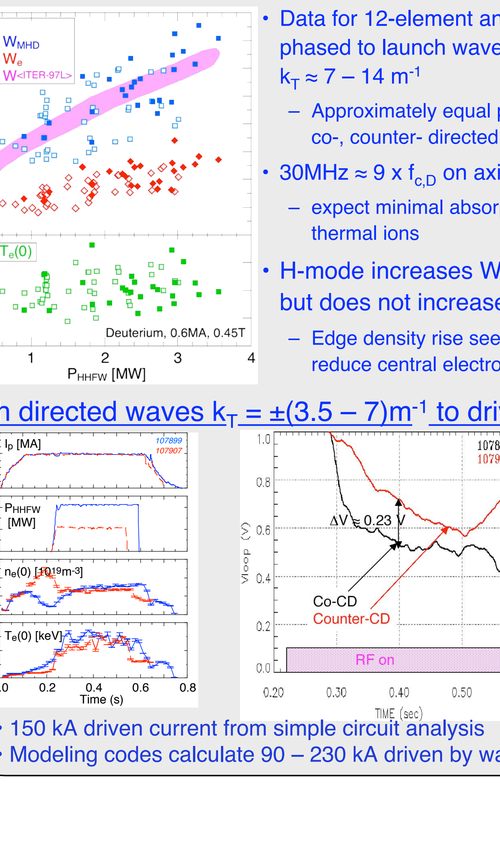
With Gas Fueling & NBI Heating, Densities Can Exceed the Greenwald Limit

- Observe little degradation in confinement at high density
- Regression to dataset shows
  - Incremental efficiency of deuterium gas is low
    - $dN_e/dN_{D,gas}$ = 5 – 10 %
  - NBI fueling is very efficient
    - $dN_e/dN_{D,NBI}$ = 95 – 105 %



See P2-190, Soukhanovskii et al.

RF Power at High Harmonics of Ion Cyclotron Frequency Heats Electrons and Can Trigger H-mode



See P2-198, Biewer et al.

Confinement Times Variable but Cluster About L-mode

- Data for 12-element antenna phased to launch waves with $k_T \approx 7 – 14$ m^{-1}
  - Approximately equal power in co-, counter- directed waves
- 30MHz ≈ 9 x $f_{c,D}$ on axis
  - expect minimal absorption by thermal ions
- H-mode increases W_{tot}, W_e but does not increase $T_e(0)$
  - Edge density rise seems to reduce central electron heating

Launch directed waves $k_T = \pm(3.5 – 7)$m^{-1} to drive current

- 150 kA driven current from simple circuit analysis
- Modeling codes calculate 90 – 230 kA driven by waves