NSTX

Supported by

Office of Science

Overview of results from the National Spherical Torus Experiment (NSTX)

D. A. Gates, PPPL

For the NSTX Research Team

22nd IAEA Fusion Energy Conference
Geneva, Switzerland
October 13-18, 2008

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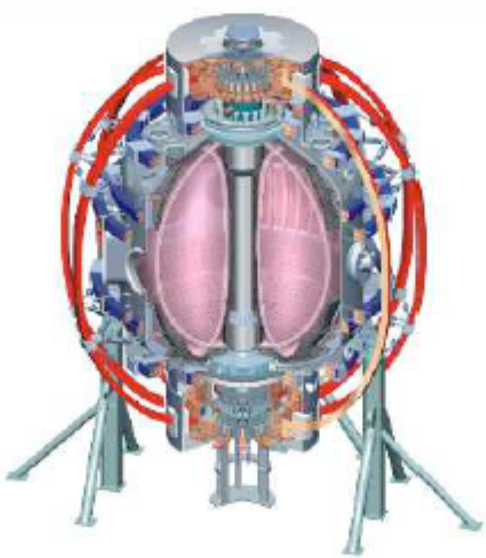

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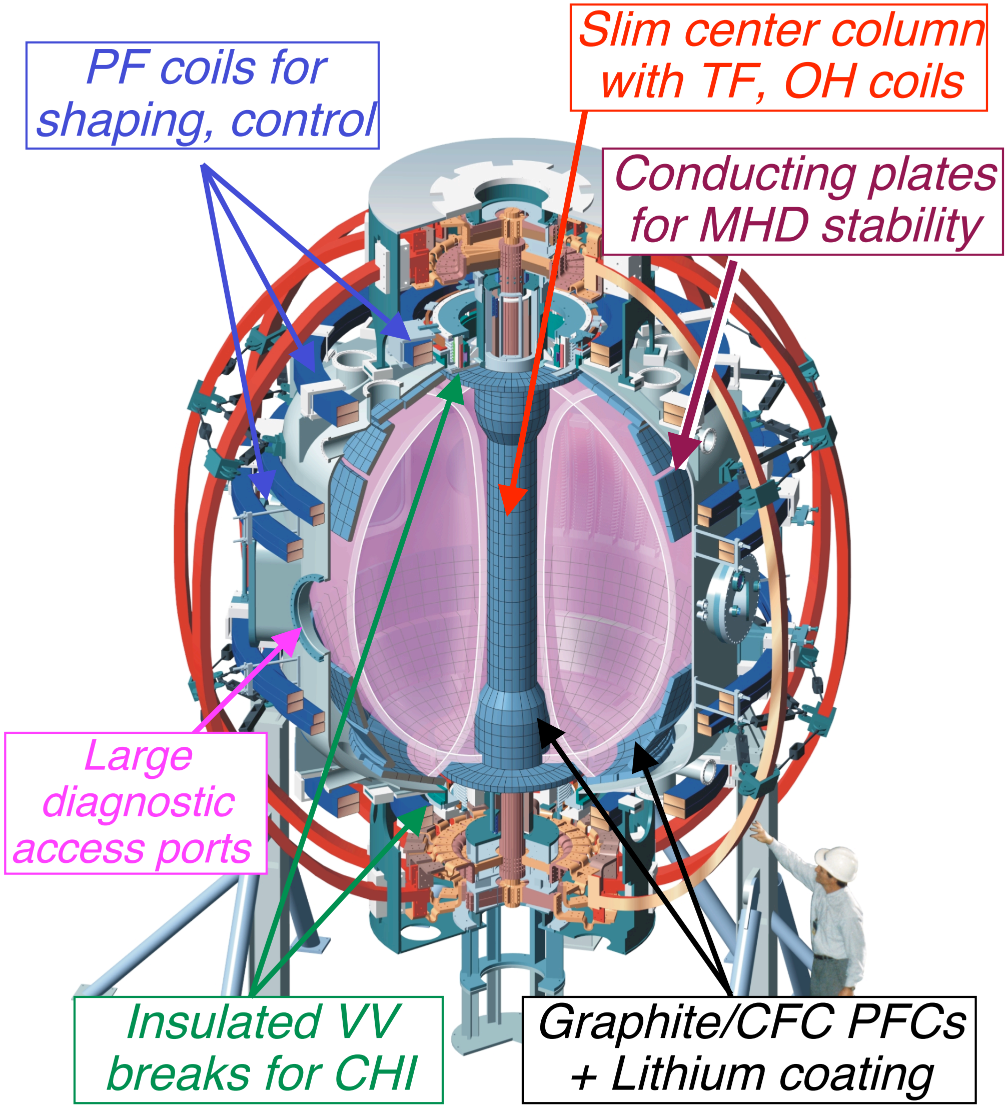
NSTX has made leading contributions in many areas of toroidal fusion science

- NSTX Mission is to:
  - Establish attractive ST operating scenarios & configurations
  - Complement tokamak physics and support ITER
  - Understand unique physics properties of the ST (in red) ⇒ basis of all the elements of the NSTX mission

<u>Outline</u>

- In support of this mission, NSTX has made significant progress in the areas of:
  - Transport and Turbulence
  - Plasma/wall interactions
  - MHD
  - Waves
  - Non-inductive startup
  - Advanced scenarios and control
  - Direct ITER support

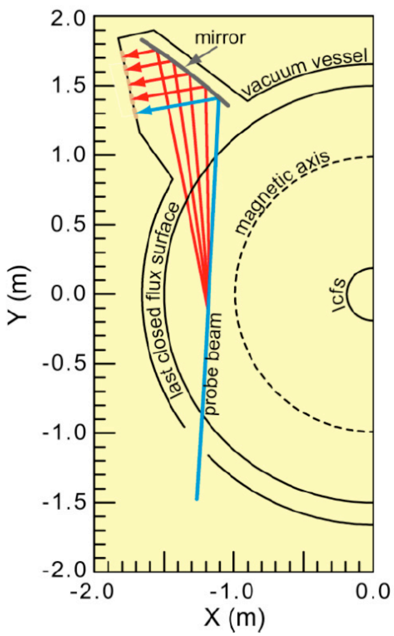
NSTX Designed to Study High-β Toroidal Plasmas at Low Aspect-Ratio



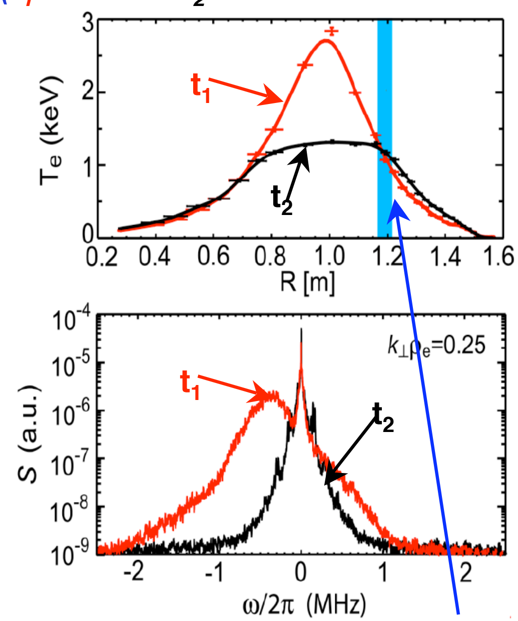
Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius R_0	0.85m
Plasma Current I_p	1.5MA
Toroidal Field B_{T0}	0.4 – 0.55 T
(Pulse Length	~2 – ~1 s)
Auxiliary heating:	
NBI (100kV)	5 – 7 MW
(Pulse Length	5 – 2 s)
RF (30MHz)	6 MW (5 s)
Central temperature	1 – 5 keV
Central density	$\leq 1.2\times10^{20}m^{-3}$

Observed onset of high-*k* electron turbulence consistent with ETG

- NSTX ideal experiment for electron turbulence measurements -
  - relatively large ρ_e*, large magnetic shear gives strong spatial localization
- Using High Harmonic Fast Wave heating to modify Te profiles, observed turbulence
  - scales with R/L_{Te}, rotates in electron direction, has large $k_\perp \rho_i >> 1 \rightarrow$ Inconsistent with ITG turbulence
- GS2 calculations of ETG critical gradient show agreement with the onset of turbulence
- Have begun quantitative assessment of observed fluctuations on transport

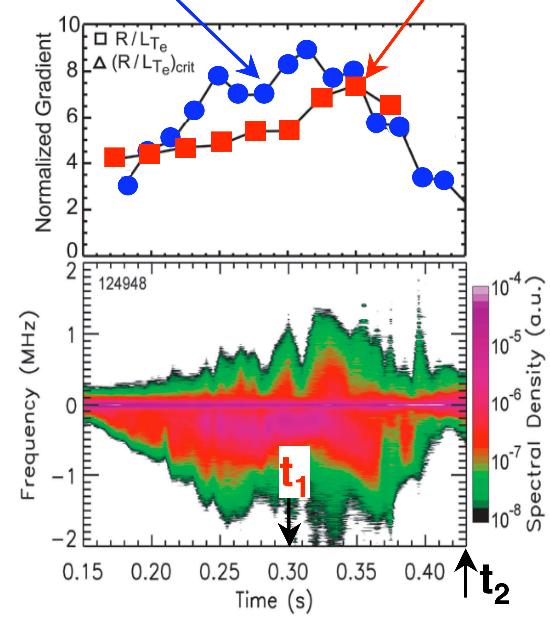


- ***Spectrum of fluctuations and electron temperature profiles with different R/L_{Te} (t_1 with and t_2 without HHFW heating)***



- ***Radial location of turbulence measurement***

- ***Measured R/L_{Te}***
- ***GS2 critical R/L_{Te}***



- ***Spectral density for $k_\perp \rho_e$ ~ 0.2-0.4***

See talk by E. Mazzucato EX/10-2

Also, *Phys. Rev. Letters* **101**, (2008) 075001

Also see poster by H. Yuh EX/P3-1

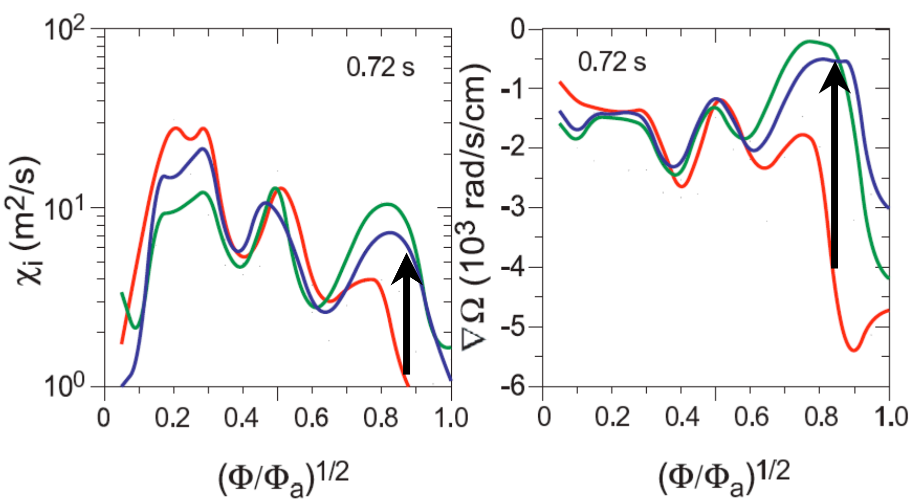
Non-resonant *n=3* magnetic braking capability is used to probe effect of *ExB* shear on confinement

- During beam injection, NSTX typically operates with γ_{ExB} ~ *1MHz* ~ *4-5*γ_{ITG}
  - Expect routine flow shear suppression of ion scale turbulence on NSTX

Energy

- n=3 braking reduces the magnitude of edge velocity shear
- Leads to an increase of edge ion thermal diffusivity

Ion Thermal Diffusivity **Velocity shear**

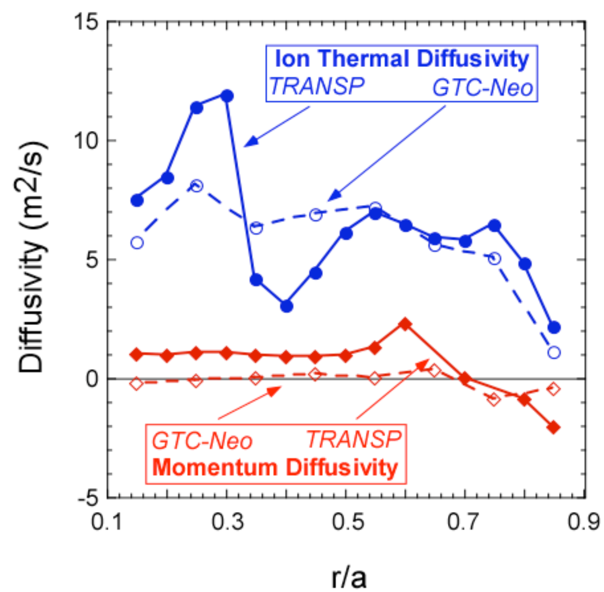


See talk by S. Kaye EX/3-2

Also, W. A. Solomon, et al. , *Phys. Rev. Letters* **101**, (2008) 065004

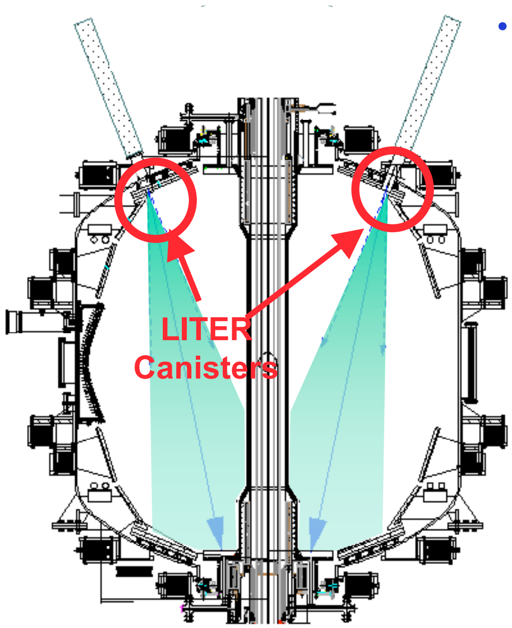
Momentum

- TRANSP analysis of rotation data from charge exchange $\chi_\phi >> \chi_{\phi\_neo}$
- Indicates residual low-k turbulence

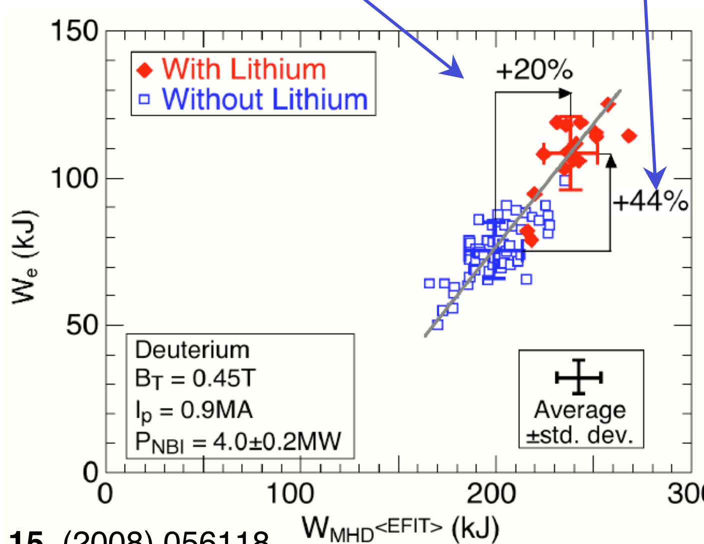


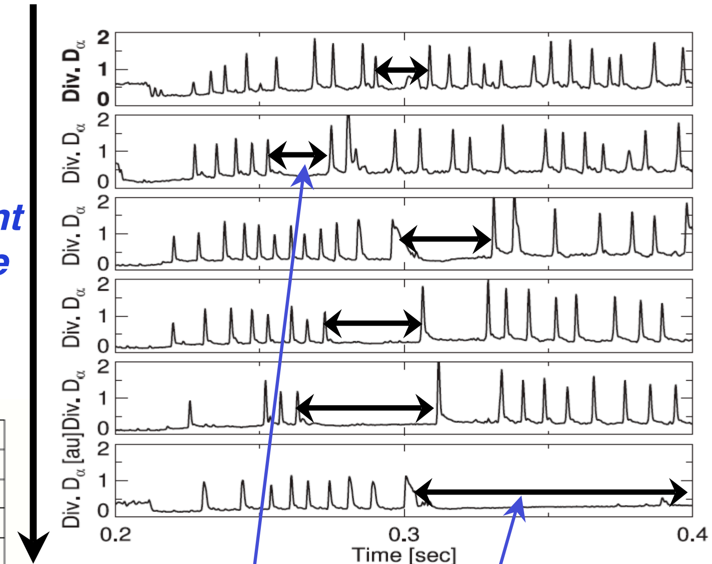
Lithium coating increases confinement and suppresses ELMs

- Lithium evaporation capability greatly improved
  - Redesigned evaporator with higher temperature, better alignment
  - Second evaporator added in 2008



- ***Stored energy increases 20% with Lithium***
- ***~2/3 of the improvement in confinement is in the electron channel***





Increasing lithium coating thickness

- ***Lithium extends ELM free periods***

See poster by R. Kaita EX/P4-9

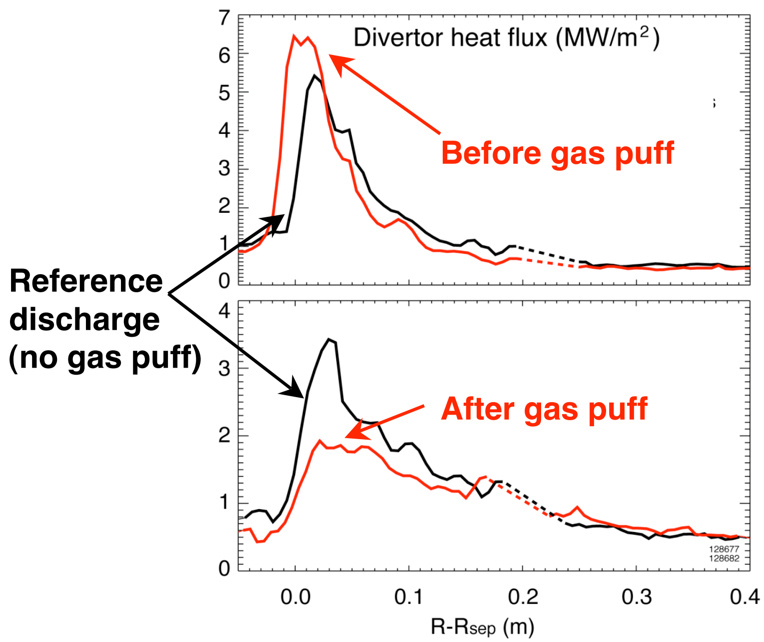
Also, H. Kugel et al., Phys. Plasmas **15**, (2008) 056118

Edge studies investigate scalings and mitigation of large SOL power flows

- Because of low-A effects, NSTX routinely operates with peak divertor heat fluxes ~ 10MW/m^2
  - Similar in magnitude to ITER heat divertor heat flux
- Important to mitigate heat flux and understand scaling to future low aspect ratio devices

Mitigation

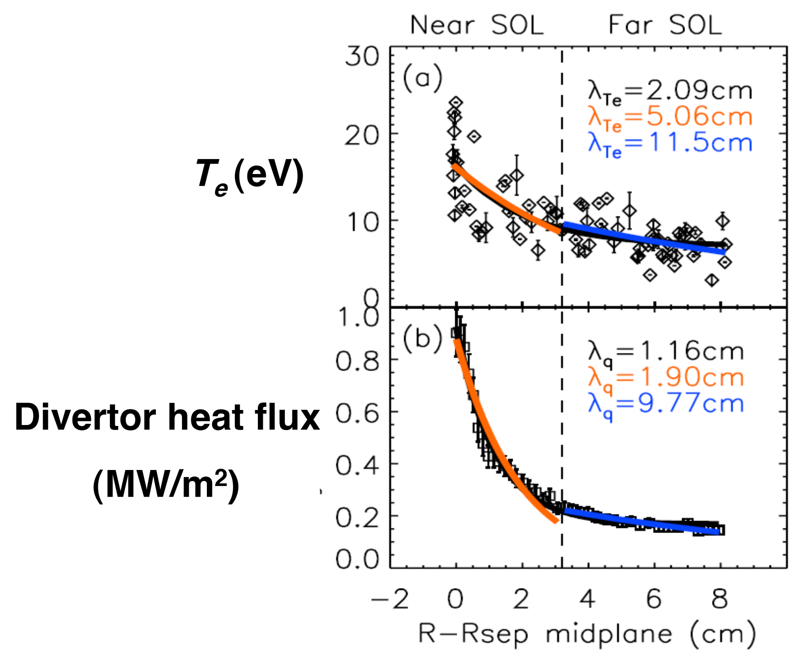
- ***Divertor gas puffing reduces peak heat flux to 1.3MW/m^2***
- ***Plasma performance maintained during gas puff***



See poster by V. Soukhanovskii EX/P4-22

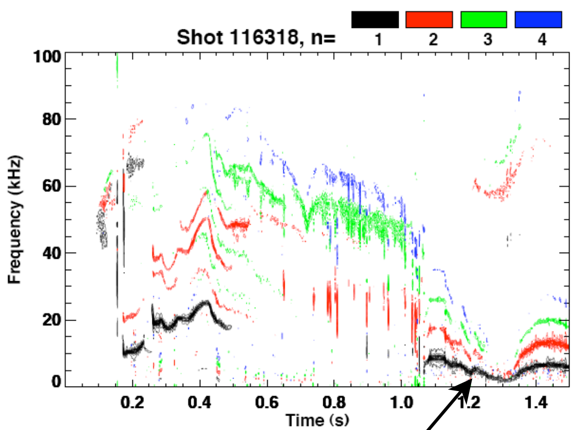
SOL width scaling

- ***Near SOL: λ_{Te}/λ_q ~ 2.5, closer to electron conduction dominant case (λ_{Te}/λ_q = 3.5) than sheath limited case (λ_{Te}/λ_q = 5)***
- ***Far SOL: λ_{Te}/λ_q ~ 1.2, suggesting other dominant process***

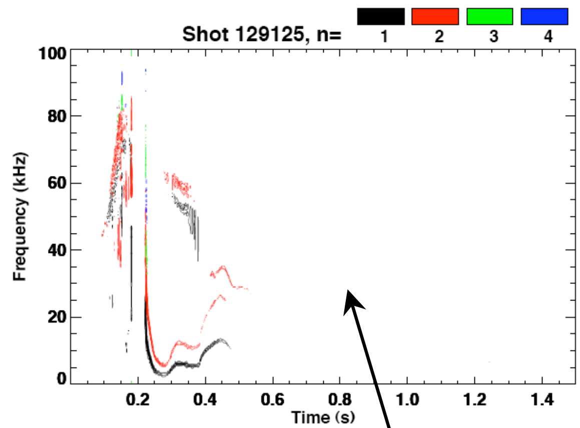


n=1 RFA/RWM control combined with n=3 error correction increases β and extends pulse

- ***MHD spectrogram w/o n=1 feedback and n=3 correction***

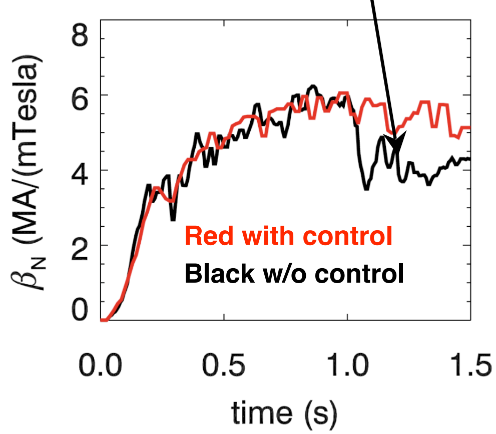


- ***MHD spectrogram with n=1 feedback and n=3 correction***

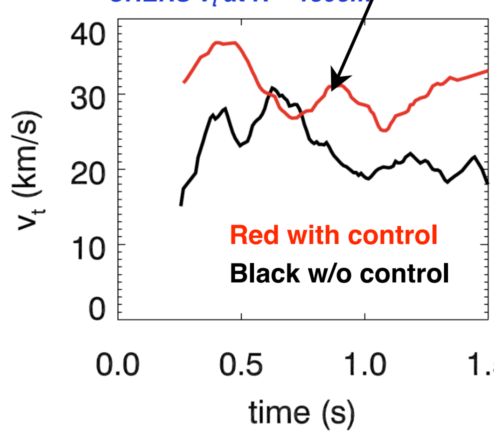


n=1 mode drops β

No MHD, β and rotation maintained



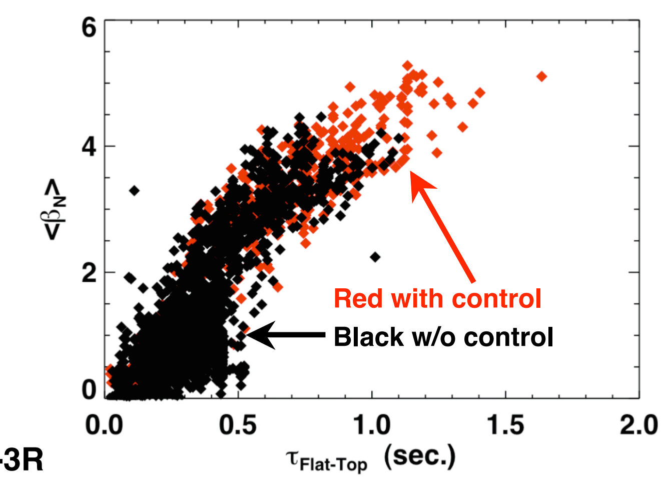
CHERS v_t at R = 139cm



See talk by S. Sabbagh EX/5-1 See also talk by H. Reimerdes/J. K. Park EX/5-3R

- Non-axisymmetric feedback algorithm has been developed using unique feedback training scheme
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge
- Control statistically raises β and increase pulse length

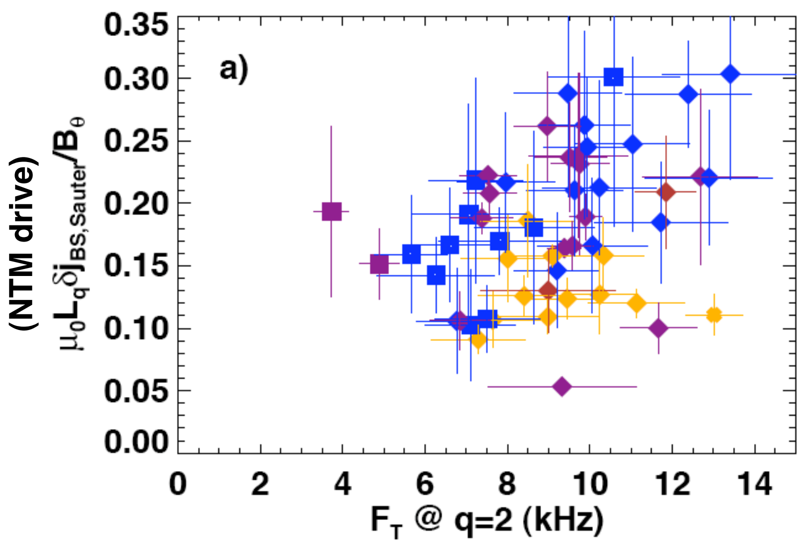
Pulse averaged β_N vs. current flat-top



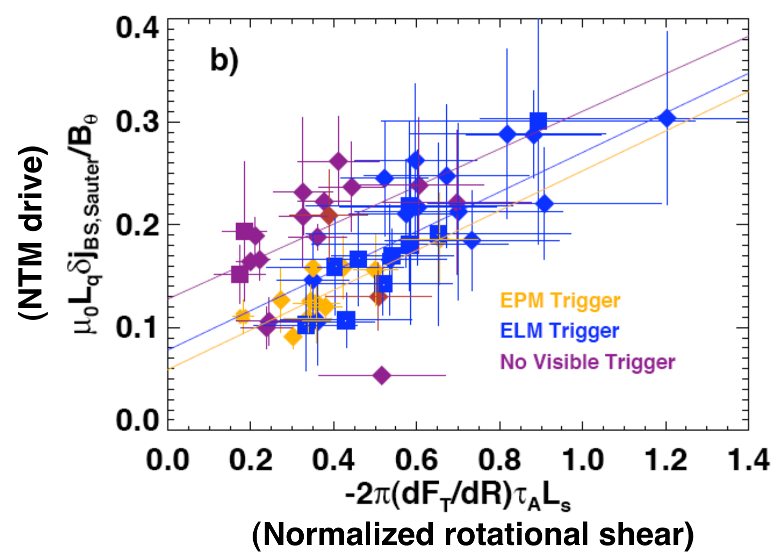
n=3 braking enables investigation of effects of rotation and rotational shear on MHD stability

- Neoclassical island drive is measured at onset of 2/1 NTM
  - Shows clear increase with rotation shear, no clear trend with rotation
  - Also clear increasing trend in required island drive with type of trigger with EPM → ELM → no visible trigger
- Indicates role of flow shear in stabilizing NTMs
- Will impact NTM stability in ITER

- ***Neoclassical island drive vs. rotation frequency at the q=2 surface***



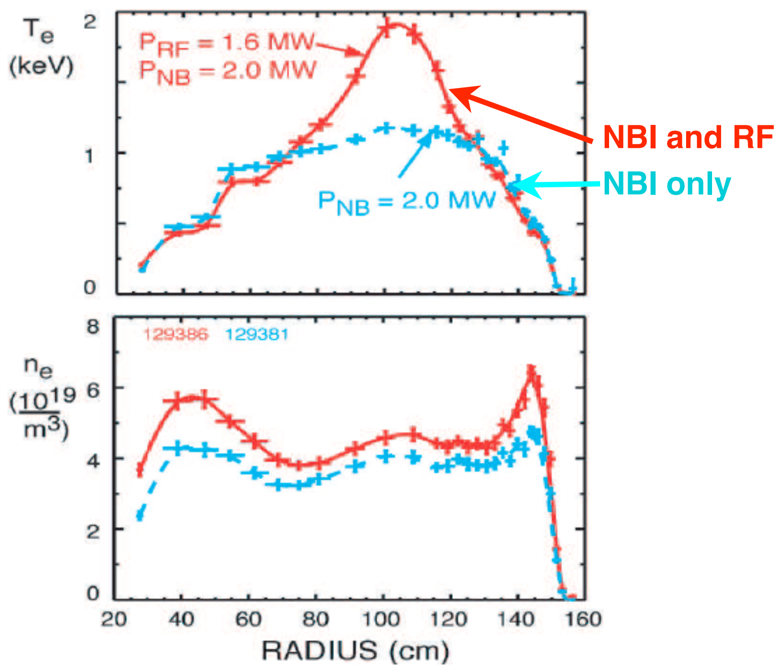
- ***Neoclassical island drive vs. normalized rotational shear at the q=2 surface***



See ITER poster by R. Buttery IT/P6-8

Edge density control using lithium coating has improved coupling efficiency of both HHFW heating and EBW emission

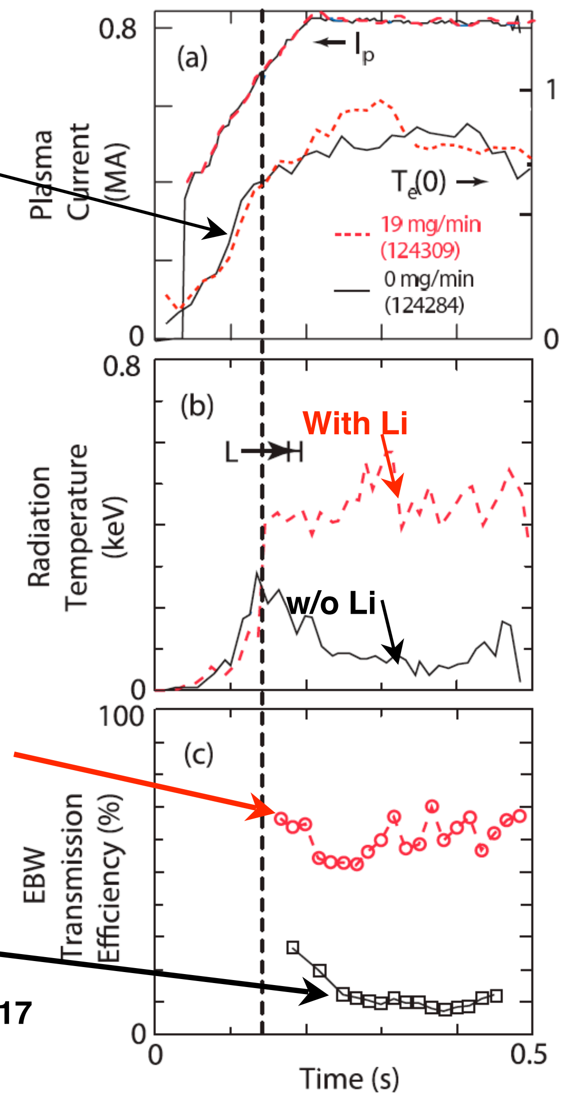
- NSTX explores the wave physics of overdense plasmas
  - ***HHFW heating efficiency improved by operating below the critical density for coupling to surface waves***
    - $n_{e\_crit} \sim Bk_{||}^2/\omega$
  - ***HHFW heats electrons in beam heated deuterium H-mode for first time***



See poster by C. Phillips EX/P6-25

- ***EBW emission efficiency improved by reducing the collisionality at the mode conversion layer***
- ***Transmission efficiency increased to ~70% with lithium from ~10% without lithium coating***

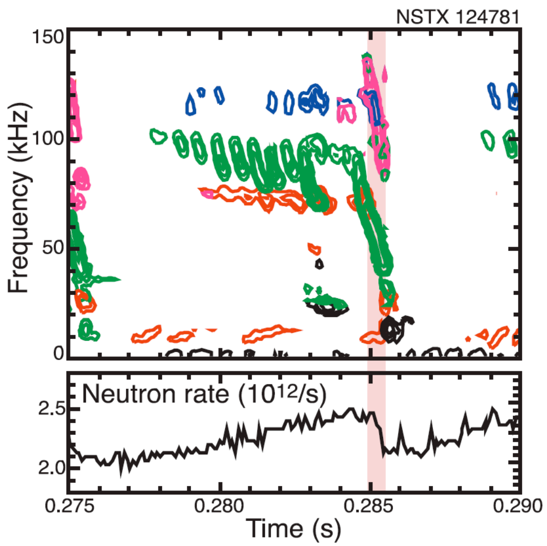
See poster by S. Diem EX/P6-17



Multi-mode TAE avalanches are observed to induce fast particle loss on NSTX

- Because of its low toroidal field and high neutral beam voltage, NSTX routinely operates with $v_{fast}/v_{Alfvén} > 1$
- Avalanches show modes with multiple n-numbers
  - TAE mode internal structure and amplitude are measured
  - Avalanche threshold also measured with beam voltage scan
- Particle losses are modeled using data, NOVA, and ORBIT
  - Good agreement found between measured and predicted losses
- Important physics for ITER and burning plasmas

Magnetic spectrogram of multi-mode TAE avalanche on NSTX showing ~20% neutron loss

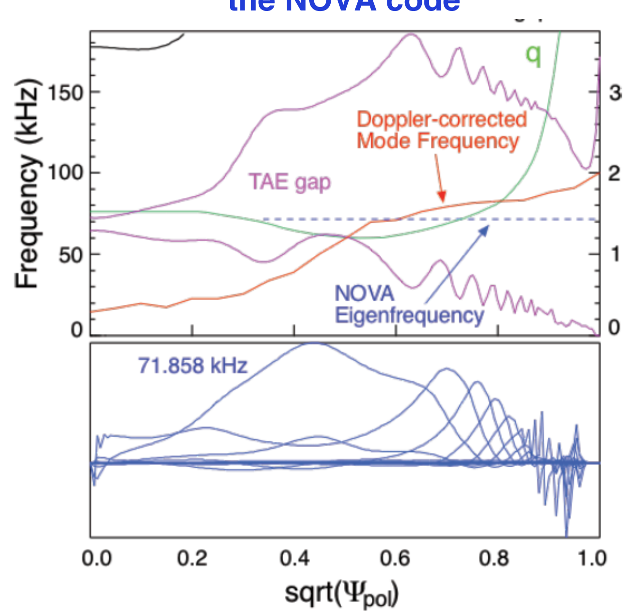


black n=1, red n=2, green n=3, blue n=4, magenta n=6

See talk by E. Fredrickson EX/6-3

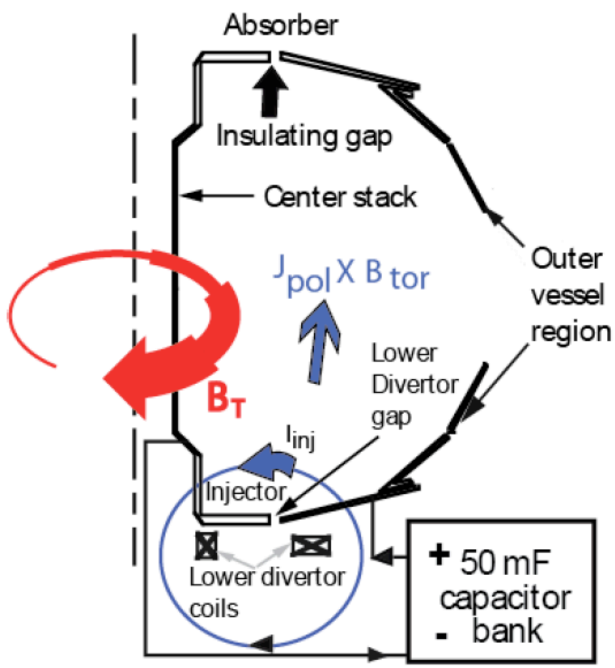
See talk by N. Gorelenkov TH/5-2

Calculated n=3 radial eigenfunctions from the NOVA code

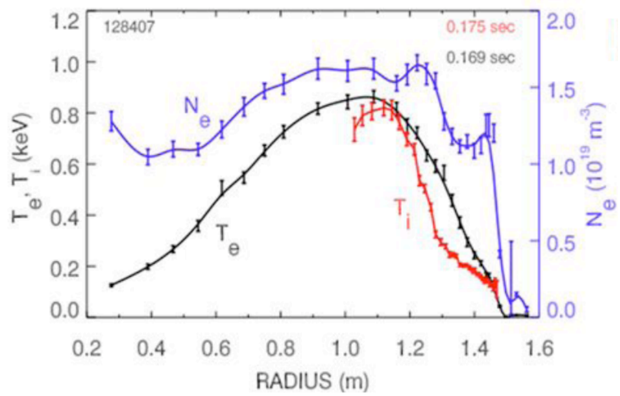


Ohmic ramp-up coupled to CHI startup plasma

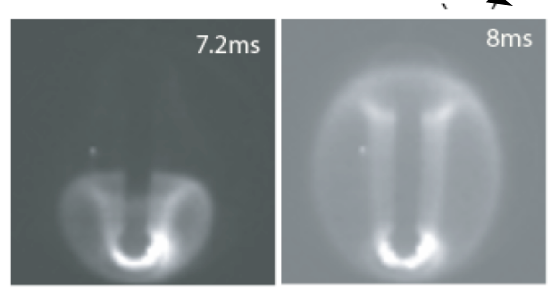
- Because of low aspect ratio, NSTX has very limited inductive flux ~0.7Vs
- CHI ramps current from 0 to ~100-150kA of closed flux current
  - Current multiplication = I_{inject}/I_p ~ 70
- Fixed loop voltage applied - current ramped to ~0.7MA
- NBI heating applied, plasma often enters H-mode



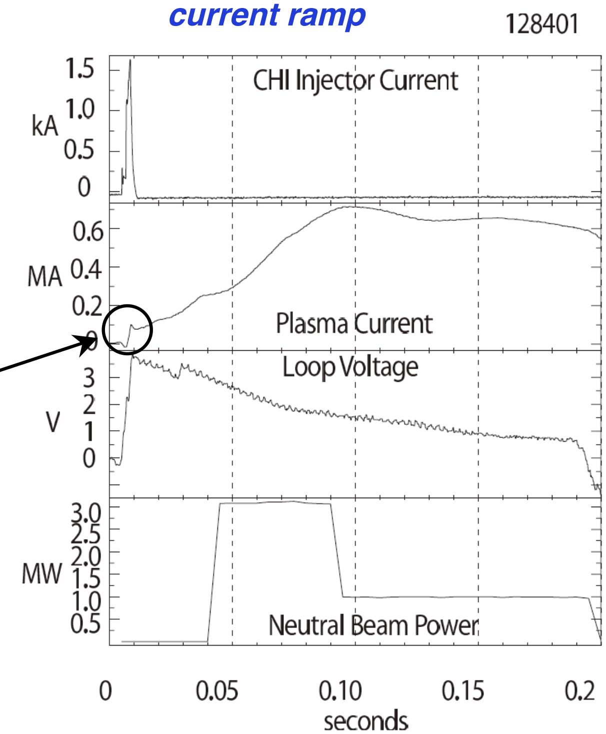
See poster by R. Raman EX/P6-10



- *CHI plasma*



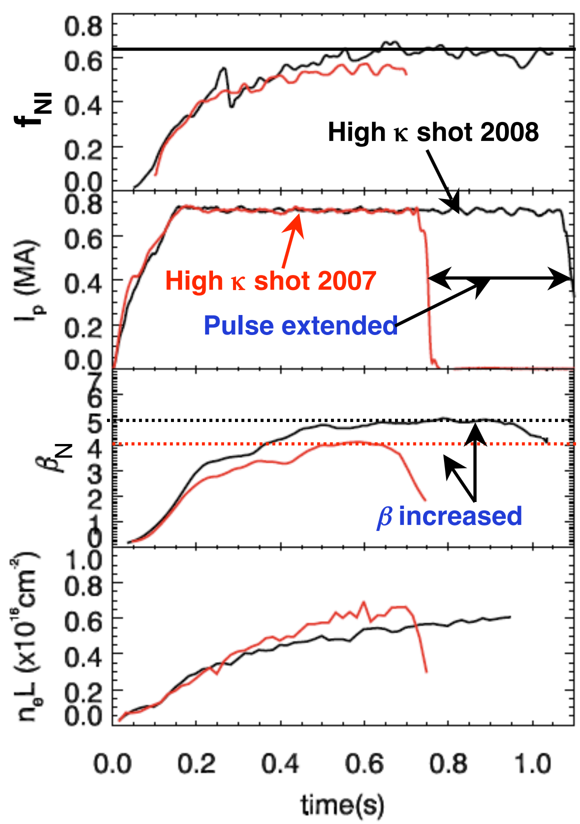
- ***Time history of CHI startup coupled to inductive current ramp***



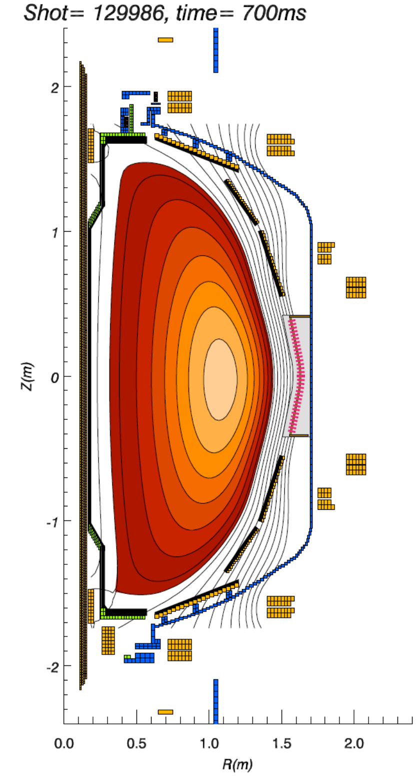
NSTX accesses long pulse at high β with extreme plasma shaping scenario

- Because of improved vertical stability at low aspect ratio, NSTX can access very high elongation $\kappa \sim 3$
  - $f_{bs} \sim (1+\kappa^2)/2$
- β maintained well above the no-wall limit, $\beta_N \sim 5$
- Pulse extended - maintained non-inductive current fraction $f_{NI} \sim 65\%$ for 1-2τ_{CR} - limited by TF coil heating limit
  - Uses n=3/n=1 control described earlier
  - Also uses lithium coating to improve confinement

Time history of global parameters and non-inductive current fraction as determined by TRANSP, constrained by MSE

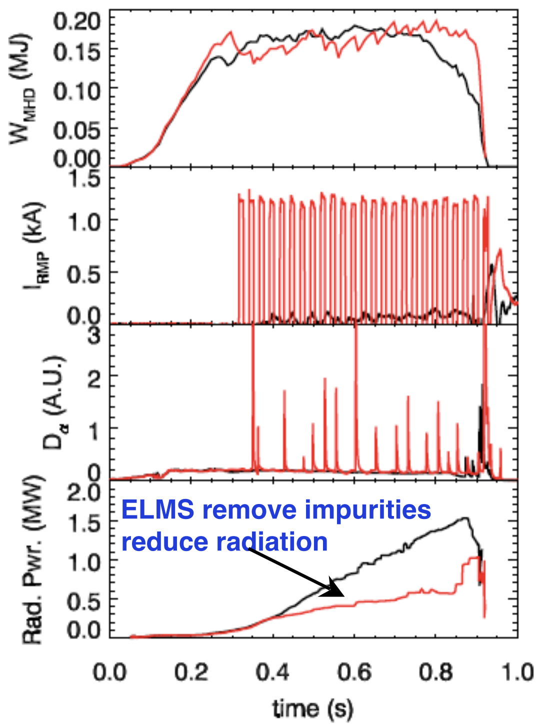


Cross-section of $\kappa \sim 2.7$ equilibrium



NSTX is improving understanding of RMP ELM control and vertical stability for ITER

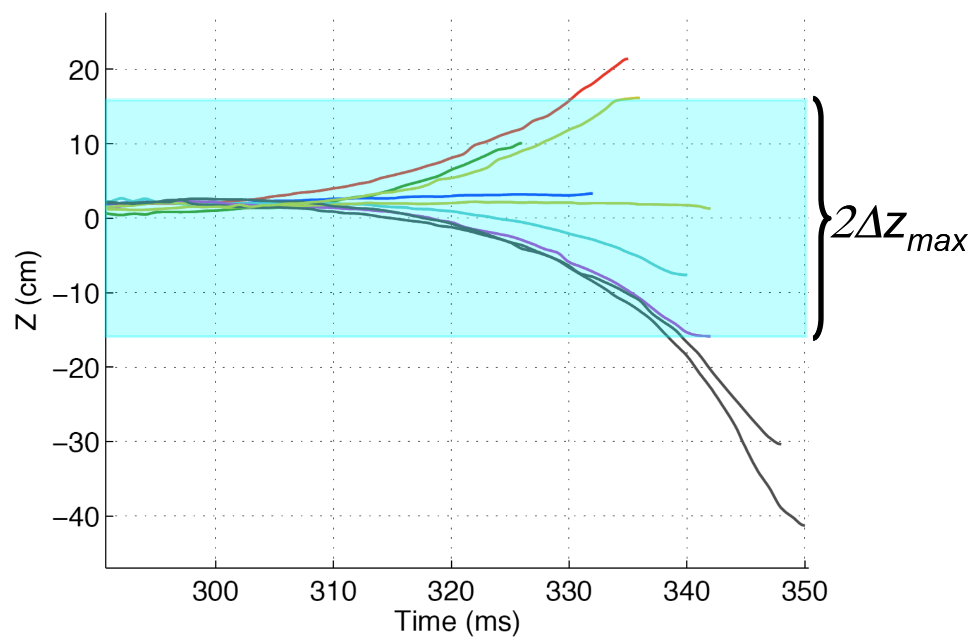
- Experiments using external n=3 fields with single row of midplane coils did not suppress ELMs
- Pulsed n=3 error fields triggered ELMs in discharges with lithium ELM suppression
  - ELM pacing with RMP coils?



See post-deadline paper by J. Canik

- Experiments using induced VDEs have measured Δz_{max}
- Results consistent with $\Delta z_{max}/a > 0.1$ for robust control
- Crucial that ITER has robust vertical control - internal control coil added

- ***Typical induced VDE Evolution on NSTX***



See rapporteured talk by A. Portone/D. Humphreys IT/2-4

NSTX has advanced the science of toroidal confinement and the ST concept across a broad spectrum of topics

- NSTX has progressed towards understanding the unique physics properties of the ST
  - Measured electron-scale turbulence consistent with ETG
  - Improved confinement with lithium
  - Measured and controlled edge and divertor power flows
  - Increased β and pulse length with RWM/RFA control
  - Improved wave coupling in over-dense plasmas with lithium
  - Observed and modeled TAE avalanches - important for burning plasmas and ITER
  - Coupled inductive ramp-up to CHI plasma
  - Achieved high β simultaneous with extreme plasma shaping
  - Investigated ELM RMP control and vertical stability for ITER
- These results are very promising for proposed future STs, such as NHTX and ST-CTF

See NHTX poster by R. Goldston FT/P3-12

See ST-CTF poster by Y. -K. M. Peng FT/P3-14

NSTX related posters at this conference

Talks

Wednesday

"Momentum Transport in Electron-Dominated Spherical Torus Plasmas" S. Kaye EX/3-2

Thursday

"Advances in Global MHD Mode Stabilization Research on NSTX" S. Sabbagh EX/5-1

"Effect of Resonant and Non-resonant Magnetic Braking on Error Field Tolerance in High Beta Plasmas" H. Reimerdes/J. K. Park EX/5-3R

"Toroidal Alfven Eigen-mode Avalanches" E. Fredrickson EX/6-3

"Theory and Observations of Low Frequency Eigen-modes due to Alfvén Acoustic Coupling in Toroidal Fusion Plasma" N. Gorelenkov TH/5-2

Friday

"ITER Plasma Vertical Stabilization" A. Portone/ D. Humphreys IT/2-4

Saturday

"Turbulent Fluctuations with the Electro Gyro-scale in the National Spherical Torus Experiment" E. Mazzucato EX/10-2

Posters

Tuesday		
Electron transport	H. Yuh	EX/P3-1
NHTX	R. Goldston	FT/P3-12
ST-CTF	Y. -K. M. Peng	FT/P3-14
Wednesday		
Lithium performance	R. Kaita	EX/P4-9
Edge turbulence	D. A. D'Ippolito	TH/P4-17
Divertor flux	V. Soukhanovskii	EX/P4-22
Thursday		
Small ELMs	R. Maingi	EX/P6-4
ITER NTMs	R. Buttery	IT/P6-8
CHI	R. Raman	EX/P6-10
EBW emission	S. Diem	EX/P6-17
HHFW heating	C. Phillips	EX/P6-25
Friday		
Gyrokinetics	W. X. Wang	TH/P8-44
Post deadline		
ELM triggering	J. Canik	