NSTX Contributions to Burning Plasma Studies

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Under the Auspices of
The IEA Large Tokamak Implementing Agreement
NSTX Is Contributing Actively to Physics Topics of Interest to Burning Plasmas

• Super-Alfvénic ion driven modes and associated losses
• Co-linearities in confinement scaling
• Active MHD mode control to raise $\beta$ limit
• 2-D x-ray crystal spectrometer
Low-A Studies of Super-Alfvénic Ion Driven Modes and Associated Losses Are of Interest to ITER

• **ITER Topic**: Prediction of fast particle induced instabilities and associated fast particle losses

• **High priority for 2005-2006**: Understand intermediate-n AEs; losses of fast particles from AEs; and perform theory-data comparisons on damping and stability.

• NSTX operating conditions overlap ITER in normalized fast particle velocity and $\beta$

• New modes by super-Alfvénic ions were discovered and identified—likely important in ITER

• Diagnostics & modeling readied to elucidate modes and transport of super-Alfvénic ions
NSTX Operating Conditions Overlap ITER in Normalized Fast Particle Velocity and $\beta$

- NSTX overlaps with ITER in $v_{\text{fast}}/v_{\text{Alfven}} \geq 1$ and $\beta_{\text{fast}}/\beta_{\text{tot}} \leq 0.2$
- Identify and characterize modes unique to super-Alfvénic ions
- Large $\beta_{\text{fast}}$ reveals potential nonlinear physics of wave-particle resonance overlap
- Strong test bed for simulations and validations of fast ion physics models by going beyond ITER parameters
- Caution: $\rho_{\text{fast}}^*$ different from ITER
New Modes by Super-Alfvénic Ions Were Discovered and Identified – Likely Important in ITER

ITER-Relevant Modes

- Multiple TAEs with resonant overlap / chirping
- Super-Alfvénic driven:
  - CAEs (nonlinear heating of thermal ions?)
  - GAEs
  - Hole-Clump
- Fisch (α-channeling)
- Gorelenkov (ITER beam and α profile relaxations)

High-f modes: energy transport

Low-f modes: fast ion transport

Multiple modes Relevant to ITER

New modes predicted to be present on ITER

New mode - likely unique to ST?
Diagnostics & Modeling Are Readied to Elucidate *AE Modes and Transport of Super-Alfvénic Ions

Measurements
- Fast particle loss
  - Fast Lost Ion Probe
  - Scanning FLIP
  - Neutral Particle Analyzer
  - Solid State NPA
- Fluctuations
  - Reflectometer
  - Tangential FIR polarimeter
  - High-freq Mirnov coils ($\omega \sim \omega_{ci}$)
  - Fast soft x-ray camera

Equilibrium Modeling
- EFIT + MSE at low B

Identify Lost Ions
- MSE + EFIT $\Rightarrow J(r,t) + q(\psi)$
- MSE (rms error ~ 0.4)

Locate *AE Mode
- sNPA & TRANSP Measure & Model Distribution
 ITER Topics: Resolve differences in $\beta$ scaling in H-mode confinement; resolve which is a more significant confinement parameter: $\nu^*$ or $n/n_{GW}$.

High priority for 2005-2006: Joint experiments on the above topics; improve global scaling by adding Low A database.

Low-A data provides leverage in determining scaling dependence for ITER

 Offers clarifying views into plasma transport and turbulence

Initial analysis of NSTX data suggests favorable $\beta$ exponent

New and planned turbulence diagnostics will enable contributions, jointly with DIII-D and C-Mod
Low-A Data Provide Leverage in Determining Scaling Dependence for ITER

- Firming up confinement scaling may expand ITER operating space and improve performance
- NSTX data helps remove collinearities ($\beta$, $\rho^*$, $\nu^*$) in moderate $R/a$ data
  - ITER operating point lies within range of NSTX data
  - NSTX provides a factor of 5 increase in range of $\beta$ and will help resolve this issue

- Probe and challenge toroidicity physics through expanded $R/a$
  - Trapped particles, mode coupling, magnetic shear
  - Similarity experiments with DIII-D, identity experiments with MAST
Low-A Plasmas Offer Clarifying Views Into Plasma Transport and Turbulence Properties

- **Low $B_T$**
  - Larger scale sizes ($\rho$), turbulence amplitudes → *electron-scale turbulence more measurable*
  - Large rotational shear ($\propto E_r/B$) → *reduce or suppress long-$\lambda \mu$-instabilities?*

- **Wide range in $\beta_T$ (≤ 40%)**
  - NSTX spans the range from *electrostatic* (low $\beta_T$) to *electromagnetic* (high $\beta_T$) → *Impacts electron transport?*

- **Greater toroidicity (lower R/a)**
  - Theory: non-linear saturation of short-$\lambda$ (ETG) turbulence due to poloidal coupling, parallel variation → *generation of radial streamers?*

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**GS2 Flux Tube Simulations of NSTX Turbulence**

U. Maryland
Initial Analysis of NSTX Confinement Data Suggests Favorable $\beta$ Dependence

Dimensionless confinement scalings derived from normal R/a data contain some ambiguity.

Different assumptions and methods produce different $\beta$ exponent:

\[
\begin{align*}
B_\tau E &\sim \rho_*^{-2.7} \beta^{-0.51} \nu_*^{-0.31} \\
&\sim \rho_*^{-2.7} \beta^0 \nu_*^{-0.15} \\
&\sim \rho_*^{-2.83} \beta^{0.48} \nu_*^{-0.42}
\end{align*}
\]

(_cordey-IAEA '04)

NSTX data suggests a favorable dependence of confinement on $\beta_T$ from statistical analysis

- Additional dedicated scans in $\beta$, $\nu_*$ are planned in NSTX
- Identity experiments with MAST

NSTX data submitted to ITPA database – full analysis underway
Active MHD Mode Control to Raise $\beta$ Limit Can Substantially Improve ITER Performance

- **ITER Topic**: Active control of MHD instabilities via conducting structures and additional coils

- **High priority for 2005-2006**: Enhance understanding and mitigation of the effects of RWMs by analysis, experimental verification of control, determination of role of plasma rotation and error fields. Determine control system requirements for diagnostics.

- NSTX provides low-A data to help understand the dissipations that rotationally stabilize RWM

- Study of equilibrium, stability, and control of high $\beta$, q-shear & rotation plasmas can contribute

- ITER RWM model may also benefit from NSTX conductor configuration
NSTX Provides Low-A Data to Help Understand the Dissipations that Rotationally Stabilize RWM

- Insight from drift-kinetic theory:
  - Trapped-particle effects at finite $\varepsilon$ significantly weaken ion Landau damping, but...
  - Toroidal inertia enhancement modifies eigenfunction when $\Omega_\phi / \omega_A > 1/4q^2$

- Experimental $\Omega_{\text{crit}}$ consistent with scaling $\propto \varepsilon / q^2$ – why?
- Is dissipation localized to resonant surfaces, or more global?
  - Addressing questions above w/ NSTX / DIII-D similarity experiments, and hi-res CHERS
- ST has uniquely high $\omega_{\text{sound}} / \omega_A \rightarrow$ distinguish between $\omega_s$ and $\omega_A$ scaling

*Needed for predicting control requirements for RWM stabilization in ITER*
Study of Stability and Control of High $\beta$, $q$-Shear & Rotating Plasmas Can Contribute

- Sustained operation above the no-wall limit at high $\beta$ motivates study of shape, RWM, and NTM control physics
  - Potential for improving steady-state $Q>5$ scenarios in ITER
  - Requires understanding + integration of both passive and active mode control
  - Important for achieving goal of non-inductive operation in NSTX

Effects of high $\beta$ & edge $q$-shear may be important

**Old PF1A**

**New PF1A**

- 24 in-vessel sensors
- 6 ex-vessel control coils

**MSE:** $q$ profile;
**CHERS:** $V_\phi$ profile

**VALEN (Columbia Univ.)**
ITER RWM Feedback Models May Also Benefit from NSTX Conductor Configuration

ITER AT scenario requires stabilized n=1 RWM
Baseline external coils can only increase $\beta_N$ from 2.4 to 3

U.S. proposal:
6 coils in ports
(VALEN – Columbia Univ.)

VALEN $\Rightarrow$ blanket increases ideal-wall limit $\beta_N$ from 3.5 to 5 ($C_\beta = 0.9$)

• Possibility of higher $\beta_N$ operation in ITER with active feedback control of RWM

Complex passive conducting structures that require 3D modeling

$\Rightarrow$ NSTX – good test-bed for this research

Present NSTX RWM coil will validate stabilization model up to $C_\beta = 0.68$
2D X-Ray Crystal Spectrometer on NSTX for $T_e$ and $T_i$ Profiles Are Being Considered for Use in ITER

- Collaboration: NSTX, C-Mod, KSTAR, LLNL, Columbia U
NSTX Is Contributing Actively to Physics Topics of Interest to Burning Plasmas

• Low-A studies of super-Alfvénic ion driven modes and associated losses are of interest to ITER
• Low-A database can shed new light on confinement scaling uncertainties in $\beta$ and $\nu^*$
• Active MHD mode control to raise $\beta$ limit can substantially improve ITER performance
• 2-D x-ray crystal spectrometer to measure $T_e$ and $T_i$ on NSTX are being considered for use on ITER