The NSTX Research Program and Collaboration Opportunities

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Alcator C-Mod Ideas Forum
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In reaching for high beta & long pulse through advanced control, NSTX provides scientific leverage

Assess high $\beta$, low A physics with passive control

Control tools to test physics & increase operating space

Innovative diagnostics

Inter-device studies

Optimize long-pulse, high $\beta$

Strengthen physics understanding

Test theory by isolating important physics and challenging models at their extremes of applicability
40% $\beta_T$ with $\sim$100% $I_{NI}$, $\tau_{\text{pulse}} >> \tau_{\text{skin}}$, demands development of new tools and understanding their underlying physics

- NBI + EBW CD.  
  *Ongoing partnership with MIT*
- Mode control + rotation are key  
  *Common elements with C-mod error field & locked mode avoidance research*
- Fast ion transport & MHD important for understanding $J_{NB}$  
  *Complementary *AE research with very different $V_{ion}/V_{Alfvén}$*
- Turbulence studies to form basis for confinement understanding  
  *Build on joint edge turbulence studies, towards high $k$ studies in the core.*
- Edge optimization & particle control required  
  *Pedestal studies with very different $B_p/B_T$ & $\rho_i$. MIT originated Li studies at PPPL*
- Successful HHFW w/ NBI ==> more $J_{BS}$. Also high value in NI-startup  
  *Wave physics opportunity?*

40% $\beta_T$, $I_{NI} = 100\%$, $\tau_{\text{pulse}} >> \tau_{\text{skin}}$

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*Kessel, TSC IAEA 2004*
Rotation effects are strong in NSTX plasmas

\[ M_S = \frac{v_\phi}{v_{\text{sound}}} = 0.4-0.8, \quad M_A = \frac{v_\phi}{v_A} = 0.2-0.4 \]

Flow shear stabilization a potentially important effect on internal modes \Rightarrow high \( V_\phi/V_A \) challenges theory at new extremes
Differences & similarities in plasma parameters may allow comparative studies in MHD mode control & mode locking

- Mode damping/locking mechanisms likely depend on $C_s/ V_A$, or $V_\phi/ V_A$, or other dimensionless variables
  - These differ between the two devices --> mode damping/locking mechanisms might be distinguishable

- Likely source of complementarity: error field and mode locking studies

Can an understanding of the deviation of the low A Compass-D results be developed with joint experiments?

Wolfe, APS ‘04

Contact jmenard@pppl.gov, ssabbagh@pppl.gov.
Alfven Eigenmodes Studies: Active and Passive

- Magnetics and Phase Contrast Imaging measurements reveal Alfven cascades
  - Fast ions from ICRF minority heating (E ~ 200 keV)
  - Can also be used as $q_{\text{min}}$ diagnostic with negative shear (as on JET)

- Active MHD spectroscopy antenna optimized to drive moderate $n$ (4<n<12), ITER relevant modes
- Used to drive and study stable modes
NSTX’s large population of super-Alfvénic fast particles enables an important branch of nonlinear MHD physics to be studied

- \( V_{\text{fast ion}} / V_{\text{Alfvén}} \sim 3 \), similar to ITER values of \( \sim 2 \).
- Access to multimode Alfvénic turbulence in nearly every NBI discharge on NSTX.
- MSE commissioned, with goal of routine EFIT constraints next run.
- Features for scientific leverage between C-Mod & NSTX include
  - similar shape, different R/a
  - Different driving mechanisms

Already joint XPs with DIII-D. Contact efredrickson@pppl.gov
Understanding electron thermal transport will be a focus for ‘05 - ‘07

- The dominant energy loss channel & a topic of broad importance to fusion & burning plasmas, including ITER.

- Potentially important for RF & CD

- While $\chi_e$ transport is rapid, it can be modified
  - Why the flat center?

- Collaborative core transport similarity experiments through ITPA (MAST, DIII-D)
High k scattering measurements will be developed in FY’ 05

- Initial system will allow range of k measurements in select locations (2 - 20 cm\(^{-1}\)) with good spatial resolution & \(\Delta n/n < 0.01\%

- Major installation this opening.

Contact hpark@pppl.gov

Luhmann (UC Davis), Munsat (U. Colorado)
Mazzucato, Park, Smith (Princeton U.)
HHFW Absorption Depends on Antenna Phasing

HHFW modulated to assess % absorption

Absorption

\[ k_{||} = 14 \text{ m}^{-3} \] 80%

\[ 7 \text{ m}^{-1} \text{ (ctr)} \] 75%

\[ -7 \text{ m}^{-1} \text{ (co)} \] 40%

\[ 3 \text{ m}^{-1} \] 10%

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Edge ion heating, parametric decay of HHFW

Evidence for parametric absorption processes found in spectroscopy, RF probes
Can overdense C-Mod plasmas be created so that fast waves can be launched and diagnosed?

- Need for NSTX: validate fast wave physics
  - Core deposition to be sampled with modified edge reflectometer (ORNL) up to $n_e = 6 \times 10^{12} \text{ cm}^{-3}$

- Opportunity for C-Mod program: Clarify & test FW deposition theory with PCI deeper into the core
  - Perhaps 80 MHz, high density operation will yield an appropriate overdense condition for the RF?
ST properties and recent experiments make EBW attractive & high priority

- Ongoing research effort with MIT theory

- EBW current drive takes advantage of high ST electron trapping fraction via Ohkawa effect. The ST is perfect for exploring this science.

- Recent NSTX emissions evaluating EBW coupling are promising

- Mode current drive

Contact gtaylor@pppl.gov
Improved diagnostics are allowing details of ELM characteristics to emerge

- Diagnostics (e.g. fast camera) now allow detailed documentation of ELM dynamics, tests of theory

- On NSTX, Type V ELMs: small, with little change in stored energy
  - So far, found in high $n_e$ regimes
  - Possible platform for comparative study with benign regimes on C-Mod

Type V
![Type V image]

Type I
![Type I image]

Small, filamentary, perturbation

Larger low $n$ perturbation

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NSTX is in a good position to contribute to edge & core transport & stability studies

- CHERS: resolution surpasses carbon ion gyroradius near the edge (51 channel system)
- MPTS: additional channels will be added in edge and core during the run (20 --> 30).
- Edge reflectometry for $n_e$

Contact for pedestal studies: rmaingi@pppl.gov
Imaging & probe measurements provide a powerful test bed for edge turbulence codes

- Already a strong collaborative effort with the C-Mod program

- L-H transition physics, turbulence structure and dynamics are all possibilities

- NSTX may be revealing new class of turbulence not seen in DIII-D or C-Mod
  - BOUT simulations point to “electrostatic shear Alfvén eigenmodes” (Umansky, LLNL).

- Can we better understand the limits of edge codes through this sort of comparative study?

BOUT simulations underway based on measured profiles & NSTX geometry (preliminary)
Lithium edge flux control studies start with pellets, and may culminate in a powerful edge control approach

- Li pellets: injector commissioned in ‘04
  - Develop deposition techniques in ‘05
- e-beam for Li coatings in ‘06
  - Li coatings: localized, 1000 Å before every shot
- Liquid lithium module: decision following coatings studies
  - Under ALIST group of VLT
  - Would represent a revolutionary solution for both power and particle handling

Contact hkugel@pppl.gov, rkaita@pppl.gov, boedo@fusion.gat.com
NSTX research run plan extends to 18 run weeks

• Scheduled to start in late winter

• Contacts: myself, Jon Menard (this run’s run coordinator), ET leaders, Stan Kaye, Mike Bell

  – MHD: Steve Sabbagh, Dave Gates
  – Transport: Stan Kaye, Dan Stutman
  – Boundary: Bob Kaita, Jose Boedo
  – HHFW/EBW: Cynthia Phillips, Randy Wilson
  – Integrated scenarios: Rajesh Maingi, Chuck Kessel
There are many opportunities for additional, high leverage collaborative research

• A key aspect of our research approach is to use similarities & differences between different devices to challenge theories & models at their extremes

• Scientific progress is colinear with demonstrations of advanced scenarios

• Improved diagnostics and control capability will enable more sophisticated comparative studies this run

• We welcome joint research as part of a continuing constructive dialogue between the two programs
MHD & macroscopic plasma behavior

**Passive stability limits & mode characterization**
- Error field studies
- Fast ion physics
- Edge stability (discussed later)

**Active feedback coils**
- Strong shaping
- Helicity injection

**Physics of active control**
- Expand operating space

**Flows**
- Nonlinear fast ion MHD
- Dynamo physics

**Optimize stability of high $\beta$**
- Develop startup techniques
- Deepen physics understanding of stability & reconnection

**NSTX characteristics include**
- Strongly driven rotation, with $V_{flow}/V_A \rightarrow 1$
- $V_{fast ion}/V_A > 1$
- Broad $q(r) \rightarrow$ potential of plasma/wall coupling of low $m/n$ modes
- Large $B_p/B_T$ & strong shear at edge

**C-Mod/NSTX opportunities include**
- Error field studies
- Fast ion physics
- Edge stability (discussed later)
Transport & turbulence (core)

Global scalings
Local $\chi$
Edge turbulence

Particle control: lithium
q profile & reverse shear
NB vs HHFW heating

Confinement optimization
Role of $\beta + E_r$ in $\chi$ & turbulence

Electron thermal transport: High k scattering
e-m effects, low & hi k
Ion, electron transport: low k imaging

Optimize confinement + $J_{BS}$ in long-pulse, high $\beta$
Extend physics understanding of turbulence to unity $\beta$

NSTX transport physics
- Role of $\beta$: onset of electromagnetic effects broadens theory/experiment comparisons
- Electron transport: Broad range of k for theory tests

C-Mod/NSTX research opportunities
- High k comparisons at low & high $\beta$ and the onset of e-m effects
- Core ITBs with RF
- Dimensionless similarity?
Waves & energetic particles

HHFW heating, phasing, & CD
EBW emissions

Coupling startup techniques to ramp-up
Wave physics in overdense plasmas

Heat low $I_p$ plasmas for ramp-up
NBI at modest $B$
EBW tube, Launcher development

Reduce $V_s$ through $J_{BS}$ and direct CD
Extend physics understanding of waves in overdense plasmas

HHFW wave physics from antenna to core
Super-Alfvénic particles & MHD
EBW physics: mode conversion & $f(v)$ modification

NSTX wave-particle physics

- HHFW, EBW: wave coupling, propagation & deposition for overdense plasmas (for ST, RFP)
- EBW: Ohkawa current drive with high trapping fraction

Opportunities with MIT/ C-Mod program

- Strong RF theory & modeling effort at present, including ongoing EBW theory research
- Direct measures of fast wave deposition
Plasma boundary interfaces

Boundary physics opportunities

- Advanced heat and particle flux management techniques relevant to all toroidal confinement concepts
- SOL transport: intermittency & shear Alfvénic turbulence

C-Mod/NSTX opportunities

- Different edge $B_p/B_T$
- Different values of $B, n_e, T_e$...
An important aspect of NSTX research is providing scientific leverage through high beta and low aspect ratio.

**Strengthen the scientific basis for fusion energy**

- **Core transport & turbulence**
- **Edge transport & stability**
- **MHD: stability & helicity injection**
- **Wave/particle interactions**

*Test theory by isolating important physics and challenging models at their extremes of applicability.*
NSTX research for ‘05 - ‘07 is well aligned with the fusion program’s scientific priorities and supports strategic goals

**FESAC Theme:** Understand the role of magnetic structure on confinement, & plasma pressure limits

*Stability pressure limits & magnetic reconnection vs. A, shape, profile, q & flows, for internal & external modes with $V_{\text{flow}}/V_A \leq 0.4$ & unity $\beta$; helicity transport*

**FESAC Theme:** Learn to use energetic particles & e-m waves to sustain and control high temperature plasmas

*EM waves in overdense plasma; Phase space manipulation with high electron trapping; energetic ions with large orbits; Alfven eigenmodes and turbulence with $V_{\text{fast}}/V_A \gg 1$*

**FESAC Theme:** Understand & control the processes that govern confinement of heat, momentum, and particles

*Microscopic ion, electron, and tearing turbulence measurement & theory comparison over wide range in $\beta$, flows, and magnetic shear, with good average curvature and high trapping*

**FESAC Theme:** Learn to control the interface between a 100 million degree plasma and its room temperature surroundings

*Physics of ELMs, pedestal, SOL turbulence & high divertor heat flux, with large in/out asymmetry; Li coatings & liquid surface interactions with plasma.*

**FESAC Theme:** Demonstrate Feasibility with Burning Plasmas

**FESAC Theme:** Develop Understanding and Predictive Capability

**FESAC Theme:** Determine Most Promising Configurations

**FESAC Theme:** Develop New Materials, Components, & Technologies
Plasma flows will be a focal point of research through ‘07

- Understanding momentum transport a national transport priority

- Motivated by observations
  - Counter-directed flow with co-injection
  - $V_\theta$, $V_\phi$ with HHFW & prior to ohmic H modes

- Needed to reconstruct $E_r$ & profile

- $V_\theta$ measurements deeper in the core will be developed for ‘06
Differences & similarities in plasma parameters may allow comparative studies in MHD mode control & mode locking

- Compared to moderate aspect ratio,
  - ~ similar sound speed, C-Mod has smaller \( V_{\text{Alfvén}} \). NSTX has larger \( V_{\text{flow}}/V_{\text{Alfvén}} \).
  - Implications for mode damping/locking?

- Likely source of complementarity: error field and mode locking studies

**RWM: camera image & DCON code**
NSTX research led to an expansion of operating space in 2004

Reduced latency improved vertical control at high-κ, high-β_T

More routine high κ, δ
Longer current flattop duration
\[ \tau_{\text{pulse}} = \tau(>0.85 \, I_{p,\text{max}}) \]

Capability for higher κ, δ allowed higher \( I_p/aB_T \)
Significantly more high-β_T
(β_N=6.8 %·m·T/MA achieved)

\[ \text{Time of peak } \beta_T \]

\[ \text{Toroidal } \beta(\%) \]

\[ \text{Elongation} \]

\[ \text{I}_p/aB_T \text{ (MA/m·T)} \]
NSTX research is entering a phase of advanced diagnostic implementation and advanced control

- Assess high $\beta$, low A physics with passive control
- Strengthen physics basis with advanced measurements & control at high $\beta$ & low A
- Innovative diagnostics
- Control tools to test physics & increase operating space
- Inter-device studies
- High $\beta$ impact on turbulence, waves, MHD
- Unique edge $B$ structure
- High $V_{\text{flow}}/V_{\text{Alfvén}}$
- Large super-Alfvénic $n_i$

- Focus for FY ‘05-‘07

- Optimize long-pulse, high $\beta$
- Strengthen physics understanding

- Take maximal scientific advantage of ST plasma characteristics through novel diagnostics and new control tools, and targeted inter-device studies