Experiments on the National Spherical Torus Experiment - Latest Results

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These are preliminary lecture notes, intended only for distribution to participants.
Experiments on the National Spherical Torus Experiment – Latest Results

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National Spherical Torus Experiment (NSTX)
and
Professor Rob J. Goldston, Director,
DOE Princeton University Plasma Physics Laboratory

October 16, 2001
NSTX research is uncovering high beta, low aspect ratio physics central to the ST mission

• In this talk: discussion of run plan, execution, and topical science, framed by the milestones we are pursuing

Outline
• Overview of goals, plan, and usage
• Core transport
• HHFW
• MHD
• Boundary physics
• Non-inductive startup
• Summary
Increase in range of operating scenarios enabled topical research

- Reproducible operating scenarios underly all of the research
  - 25% $\beta_T$ achieved
  - Routine and effective HHFW heating

- Topical studies
  - **MHD**: characterizing $\beta$-limiting and pulse-length-limiting modes
  - **Transport** with NBI and HHFW, core and edge
  - **HHFW**: heating, wave-particle and initial CD studies
  - **CHI**: MHD activity generated that is needed for flux closure
  - **Boundary**: Heat fluxes. Wall prep tools

- Cross-discipline studies
  - Beam-induced MHD and heating
  - H mode access requirements, expanded operating space
NSTX milestones and decision points are derived from its proof-of-principle mission

Recall IPPA 2.1: Assess the attractiveness of the ST concept

Milestones are checkpoints towards this assessment

- **FY '01 Milestones:**
  - Measure confinement properties with auxiliary heating
  - Assess HHFW heating; achieve 6 MW

- **Progress reports on FY '02 Milestones:**
  - MHD: Global stability without external control
  - Transport: Role of high beta and flow shear on confinement
  - CHI, EBW: Innovative startup techniques
  - HHFW CD physics & effectiveness

- **Upcoming decision points:**
  - MHD
    - FY '02: Mode stabilization: scientific assessment
    - FY '03: Mode stabilization: technical assessment
  - Advanced particle pumping/fueling, FY '03
We planned an emphasis on topical research, with some time for enabling activity.

Division of experimental time, FY '01.

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<th>ET Group, Leaders</th>
<th>Plan</th>
<th>Actual</th>
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<td>MHD (Sabbagh, Menard)</td>
<td>15%</td>
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<td>Transport and Turbulence (Kaye, LeBlanc)</td>
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<td>HHFW (Wilson, Swain)</td>
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<td>CHI (Raman, Gates)</td>
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<td>Boundary Physics (Maingi, Skinner): heat flux</td>
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<th>Program Enabling/cross-cutting</th>
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<td>e.g. 1st NBI, control commissioning, boron, calibration</td>
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Highlights

- HHFW: success and broad impact resulted in giving significant contingency time
- Program enabling/cross cutting work also received additional time
- CHI: ~ 2x more days attempted; system setbacks (TF water leak, gas programming)
- Boundary: IR camera repair delayed start
Activities supporting a broad portion of the program are high priority

- NBI long-pulse work
  - Startup optimization

- Diagnostic development & cross-checking
  - $T_\text{i}(R,t), V_\text{a}(R,t)$: Background array installation and calibration for CHERS.
  - $T_e$ from 3 different techniques

- H mode search: dedicated run days to explore operating space

- HHFW & early heating in the pulse
  - Modify the current profile; use as a control tool

- Boronization
  - TMB established; plasma boronization being developed
Diagnostics are maturing and being confirmed

- $T_i$, $V_\phi$: development of direct background measurement
  - Required for time-dependent measurements
  - Required cross-calibrations performed; analysis techniques being developed

$T_e(0)$ confirmed by 3 independent measurements
Diagnostics are maturing and are being confirmed (2)

- TS high throughput, small error bars. $n_e$ consistent with reflectometry
- $T_i$: CHERS, NPA consistent with each other

**Total Stored Energy Comparison**

**Kubota, Gilmore, Peebles (UCLA); LeBlanc, R. Bell**

**S. Medley, R. Bell**
Outline

• Overview of plan, usage, and goals

• Core transport
  – NBI heating, $\tau_E$ scaling, and power balance; puzzles
  – Possible role of fast-ion MHD
  – Perturbative particle transport
  – Microstability analysis

• HHFW

• MHD

• Boundary physics

• Non-inductive startup

• Summary

FY '01 Milestone: Measure and analyze the confinement of auxiliary-heated NSTX plasmas

FY '02: Assess the effects of beta and sheared flow on plasma heat loss
Profile measurements give first indication that favorable confinement with NBI may be due to ion channel

- Broad $T_i$ profile (compared to $T_e$), even though $\sim 2/3$ of beam energy expected to go to electrons
- Large $T_i - T_e$ seen routinely
- High $V_\phi$ in core & edge
Power balance analysis reveals puzzles

- With NBI: apparent anomalous source of heat to ions, or a heat pinch
  - New heating physics?
  - Small A changes in basics?
  - Requires vigilence in diagnostic calibration
Astrophysics and observed MHD may hold one clue to the power balance puzzle

- Being investigated: Compressional Alfven Eigenmodes
- Modes excited by fast ions; waves transfer energy to thermal ions
- Theory of stochastic wave heating of corona developed (White)
- Application of theory to ST has begun
- $V_{\text{beam}} \gg V_{\text{Alfven}}$ key

Fredrickson (PRL 2001)

Gates, Gorelenkov, White
Beam-driven Compressional Alfven Waves may heat ions on NSTX

- Simulations of compressional Alfven modes give stochastic ion heating.

- e.g.-- $\delta B/B = 0.001$ with 20 modes centered at half Alfven frequency

- Possible relevance to interpretation of ion-heating on NSTX

D. Gates, N. Gorelenkov, R. White (PRL, 2001)
Impurity transport rates are small in the core

- After puff, almost no neon penetrates the core until MHD event near 260 ms

- Modelling suggests core diffusivity $< 1 \text{ m}^2/\text{s}$, rivaling neoclassical theory

- Low ion particle transport consistent with low ion thermal transport

He-, H-like Ne lines (USXR)

He-, H-like Ne lines (USXR)

Fully ionized Ne (SXR)

Fully ionized Ne (SXR)

Signals from difference of similar plasmas w/ and w/o neon

Transport solution

Diffusion coefficient $D$ (m$^2$/s)
Theory: short wavelength modes may dominate transport; long wavelength modes may be suppressed

- Long wavelengths: growth rate lower than $\mathbf{E}_x\mathbf{B}$ shear rate
  - Large $\lambda$ associated with ion thermal transport

- Short wavelengths: growth rates large
  - Responsible for electron thermal transport?
  - Non-linear simulations begun

Growth rates, $k_p \rho_i >> 1$ (Short $\lambda$)

C. Bourdelle (PPPL), W. Dorland (U. MD)
Outline

- Overview of plan, usage, and goals
- Transport
- HHFW
  - Heating results
  - Source calculations & electron thermal transport
  - Fast ion interactions and early current drive studies
- MHD
- Boundary physics
- Non-inductive startup
- Summary

**FY '01 Milestone:** Measure and analyze how HHFW with slow propagation velocity (14 m⁻¹) interacts with and heats high-temperature ST plasmas

**FY '02:** Assess the efficiency of HHFW to drive current via direct interactions with the electrons and/or fast ions
HFFW heating observed in a wide variety of conditions

- Fast phasing nearly as good as slow
- Heating similar in D and He$^4$
  - Previous differences seem related to discharge, not species
- Modulated rf used to measure deposition profile
  - Complicated by electron energy transport physics
Strong central peaking of $T_e$ observed in some cases
Power balance analysis reveals that reduced electron transport correlated with high $\nabla T_e$

- Core $\chi_e$ drops as high $T_e$ develops
  - Steep gradients due to transport changes, not source
  - Conductivity still very high!

- Heating source from HPRT ray tracing (Rosenberg)
Turbulence theory suggests testable trend for transport experiments

Conduct a theory experiment: vary $T_i/T_e$, keeping other profiles constant

- Theory indicates:
  - high $T_i/T_e$ stabilizes ion modes
  - high $T_e/T_i$ stabilizes electron modes

- Do we see signatures of this in measured confinement trends?
Recent data is the foundation of important tests of wave-particle interactions theory

- HHFW turns off at t=200ms
- D⁺ tail extends to 140keV
- NBI Source A on throughout
- Tail saturates in time during HHFW

HPRT code:
50% of rf power absorbed on beam ions

May explain reduction in effective electron heating when NBI is combined with early HHFW

Rosenberg, Medley, Menard
HHFW-driven H modes found

- LSN
- Lower current (350 - 500 kA)
- He and D
- ELMy, ELM-free
- $\beta_p = 1$ observed
  - Large bootstrap?
  - Large dip in surface voltage

Starting scenario for future CD work?
High power phasing tests for current drive begun

- Co, counter, balanced fast phasing investigated (7 m⁻¹)

- Similar heating, reproducible matching for all phasings

- Not obvious differences in loop voltage evolution
  - Difficult to obtain a long steady shot: H mode target a possibility
  - Need MSE

- Closed loop phase feedback from antenna started
  - Two transmitters in vacuum

- Fast particle interactions studies key part of CD assessment
Outline

• Overview of plan, usage, and goals

• Transport

• HHFW

• MHD: beta-limiting
  – Range of operations
  – Towards assessing physics of RWM's
  – Locked mode coils/error field detection
  – NTM's
  – Current driven kinks

• Boundary physics

• Non-inductive startup

• Summary

FY '02 Milestone: Measure and analyze the global stability at high beta without active external control

Active feedback decision points:
FY'02: Scientific
FY'03: Technical
Profile variations have been performed to map out operational space for stability studies.

- Maximum $\beta_N$ increases, then saturates with increased current profile peaking.
- Fast beta collapses observed at all values of $I_i$.
- High pressure peaking.
- Beta saturation coincident with tearing activity at higher $\beta_N$, $\beta_p \sim 0.45$.  

\[ \beta_N = 4I_i \]
Taking a step towards an MHD control strategy: identifying the Resistive Wall Mode

- Dedicated experiments; continued active discussion

- Goals
  - Operate at or above the ideal no-wall beta limit: candidate plasmas have ideal kink-driven collapses
  - Critical rotation frequency test: measure the plasma rotation leading up to the instability
  - Plasma/wall coupling test: Vary the outer gap: determine variation of mode stability

- Techniques
  - Operate with $l_i \sim 0.6, \beta_N > 3$
  - Operate clear of sawteeth and low n islands

Sabbagh, Columbia U.
USXR data shows a mode structure resembling a global kink in RWM candidate shots

- RWM Candidate
- Fast collapse
- No core islands and no 1/1 mode before reconnection event (RE)
  - More likely a kink mode onset

- Plasma with island activity
  - Reconnection event leads to 1/1 mode at 237 ms
  - Less likely a kink mode onset

D. Stutman
Candidates for RWM have a fast collapse when rotation frequency is below a small value

- "Critical" rotation frequency $< 2$ kHz at the plasma core at time of collapse, consistent with DIII-D observations of RWM and theory

- Rotation decrease occurs across the entire plasma (preliminary CHERS analysis)
Locked mode coils have been installed, calibrated, and used

- **6 large B_r sensors**
- Opposing sensors are differenced in analog, then integrated
  - MDS+ tree archives uncompensated $\delta B_r$
    - J/K-D/E, A/L-F/G, B/C-H/I
  - Remaining calibration done in software (IDL)
- B_r sensors are mounted on PF5 coils
  - PF5 generates large apparent $\delta B_r$ caused by:
    - Sensor misalignment
    - PF5 non-circularity
RWM candidate driven unstable by greater NBI heating

- Control plasma: small outer gap, 1 NB
  - Plasma stable until q(0) = 1 (sawtooth)
    - Fast increase of locked mode signal

- Pressure-driven mode: small gap, 3 NB's
  - Beta collapse observed 15 ms after $\delta B_r$ excursion
Wall-plasma gap scan, $\delta B_r$, and rotation measurements reveal clues regarding RWM

- Smaller gap $\Rightarrow$ longer time between start of rapid growth phase of $\delta B_r$ and beta collapse $\Rightarrow$ stronger wall mode interaction

- With clear tearing activity, no observed $\delta B_r$ precursor to collapse

At least two possible complications

- Theory suggests $\delta B_r$ largest on inboard side for these $\beta_N$'s, $\Rightarrow$ weaker wall interactions compared to DIII-D

- Locked mode coils $\Rightarrow$ large field error from PF 5
PF5 is apparently responsible for a large $n=1$ field error

- Error field is localized to lower PF5 coil
- 30-50 Gauss $n=1$ error field for typical PF5 current and 0 cm gap
- 20-30 Gauss peak error field for 10 cm gap
Ohmic shots: often early and prolonged locking

- "Reconnection event" collapse occurs near $t=220\text{ms}$
- Mode growth starts near $t=160\text{ms}$
- Mode persists for 100ms after collapse event
Slow-growing, $\beta$-limiting internal modes are likely NTM's.

- Coincident with saturation of beta
- Limits $\beta_p \sim 0.4$
- Modes appear near $\beta_{\text{crit}}$
- Further analysis required

D. Gates, E. Fredrickson
Current-driven kinks observed on NSTX

- $B_T$ ramp-down, $I_p$ ramp-up key elements of XP
- SXR array shows growth of edge kink structure

Manickmam, Fredrickson, Okabayashi
Outline

- Overview of plan, usage, and goals
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- MHD

- Boundary physics
  - H modes and turbulence characteristics
  - Heat and particle flux measurements
  - Wall preparations

- Non-inductive startup

- Summary

In addition to transport milestones,

FY '03 B.P. Milestone: Measure and analyze the dispersion of edge heat flux and assess the impact on plasma facing component requirements
Both ELM-free and ELMy H-modes have been observed in NSTX

• HHFW and NBI
• Exploration for scenario development, transport, and boundary physics
Theory indicates complex turbulent structures may exist in NSTX edge

- **BOUT code**: turbulence modeling
  - 2-fluid, 3D Braginskii equation code

\[
\langle \Gamma(\psi, \theta) \rangle \times 10^{20} / \text{M}^2 \text{s}
\]
Influx data being obtained with 1-D CCD arrays
IR camera being used for heat flux studies

Heat flux peaks during auxiliary heating

Maingi (ORNL)
Boronization consistently reduced impurity influxes, improved performance

- TMB Boronization now a routinely used tool

- Plasma boronization implemented for first time
  - Lower radiated power in ohmic shots
  - Reduced V-s consumption, longer pulse

Na (KBSI); Maingi (ORNL), Skinner, Kugel
Outline

- Overview of plan, usage, and goals
- Transport
- HHFW
- MHD
- Boundary physics
- Non-inductive startup
  - Higher currents; $n = 1$ activity
  - Spectroscopy
  - EBW
- Summary

'02 Milestone: Demonstrate innovative techniques for starting up plasma currents in toroidal fusion devices
High currents, strong MHD observed in CHI start-up studies

- Up to 390 kA of toroidal current was produced, with 14 times current multiplication
- Discharges sustained for 330 ms
- Strong $n = 1$ oscillations observed
Spectroscopy used to measure $T_i$ and edge plasma rotation in CHI plasmas

- Direction of rotation is clockwise (same as HIT-II)

- $T_i \sim 30 - 50$ eV, midplane view

- $V_\phi \sim -10$ to -20 km/s
Flux closure is being assessed via further analysis of magnetics and spectroscopy.

Array that looks down

- USXR emission increases at the higher CHI currents
- MFIT consistently shows modest closed flux regions when CHI-driven current is sufficiently high
  - Not seen in absence of n=1 MHD
  - Encouraging, but is not proof of closed mean-field surfaces

Stutman, JHU

Schaffer, GA
A next step for CHI on NSTX is feedback control & handoff with other current drive mechanisms

- Control challenge: currents not on flux surfaces play a role in the equilibrium
- Absorber arcs reduced, but still limit experiment efficiency
- EFIT analysis with $I_{\text{inj}}$ fitting required

⇒ Likely an increase in the fraction of run time required for CHI and control system work
EBW mode conversion efficiency increases at L-H transition when edge density increases

- Mode conversion of EBW from core occurs in scrapeoff in H mode

- Measured EBW conversion efficiency agrees relatively well with calculated values

- On CDX-U, limiter inserted to control $L_n$ demonstrates conversion efficiency can be controlled

- Possible tool for plasma startup, island healing

- Joint research with U. Wisconsin
Physics central to the ST mission is being investigated

- Transport: confinement picture intriguing and potentially important
  - New heating physics specific to the ST?
  - Electron thermal channel may dominate
  - Edge turbulence measurements made; comparison to modelling begun

- HHFW: effective heating in all regimes
  - Fast ion interactions observed
  - CD studies begun; no obvious signatures of HHFW-CD yet

- MHD: Beta-limiting modes being investigated
  - RWM studies underway: well along towards '02 Milestone
  - Importance of locked mode uncovered
  - NTM’s, current-driven kinks both being studied
Physics central to the ST mission is being investigated (con’t)

- Boundary physics extended to heat and particle flux studies
  - Comparisons to modelling begun
  - Enabling techniques extended: plasma boronization
  - H mode power threshold established for one condition: ~ 10x usual scaling

- CHI research produced record toroidal current, observed critical MHD activity
  - $T_i$ of 30 - 50 eV measured
  - MFIT analysis consistent with closed flux, not conclusive
  - Absorber arcs reduced, but continue to be an issue
  - First CHI-to-ohmic, ohmic-to-CHI experiments performed; technical exploration stage
This was an exciting run for the NSTX Team

- The group worked well in a limited amount of time

- For FY '02: day-to-day run coordination duties are handed over to Rajesh Maingi
  - The run scheduling is in good hands!
Detailed orbit calculations being performed to benchmark heat source models.

Heidbrink, UC Irvine

Neutron Rate (a.u.)

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80 keV D beam ion orbits

Divertor plates

Passive stabilizer plates

Beam ion strike on HHFW antenna

D. Darrow
NSTX has achieved $\beta_{t0} \sim 25\%$ plasmas

- Data shown below:
  - EFIT reconstructions using external magnetics only
  - $\beta_N \leq 3-4$ at peak $W_{TOT}$
- $I_p/aB_{t0} = 2-6$
- $\beta_P \leq 0.55 \Rightarrow$ paramagnetic
- Original Troyon definition of $\beta$ better fit to present data

![Graphs showing $\beta_{t0}$ and $\langle \beta \rangle$ vs. $I_p/aB_{t0}$](image)

EFIT - S. Sabbagh