The Near-Term NSTX Program Plan and Research Development

E.J. Synakowski

NSTX Program Advisory Committee Meeting

February 8 - 9, 2001

The NSTX Program is quickly moving towards assessing local high beta physics

In this talk:

- How we develop the program
  - Experimental Task (ET) groups and how plan is made
  - Experiments that impact the entire program

- For each ET, their milestones and physics goals
  - Mid-FY ‘01 highlights
  - Plans for rest of ‘01
  - Outline for ‘02
  - Responses to PAC comments and concerns

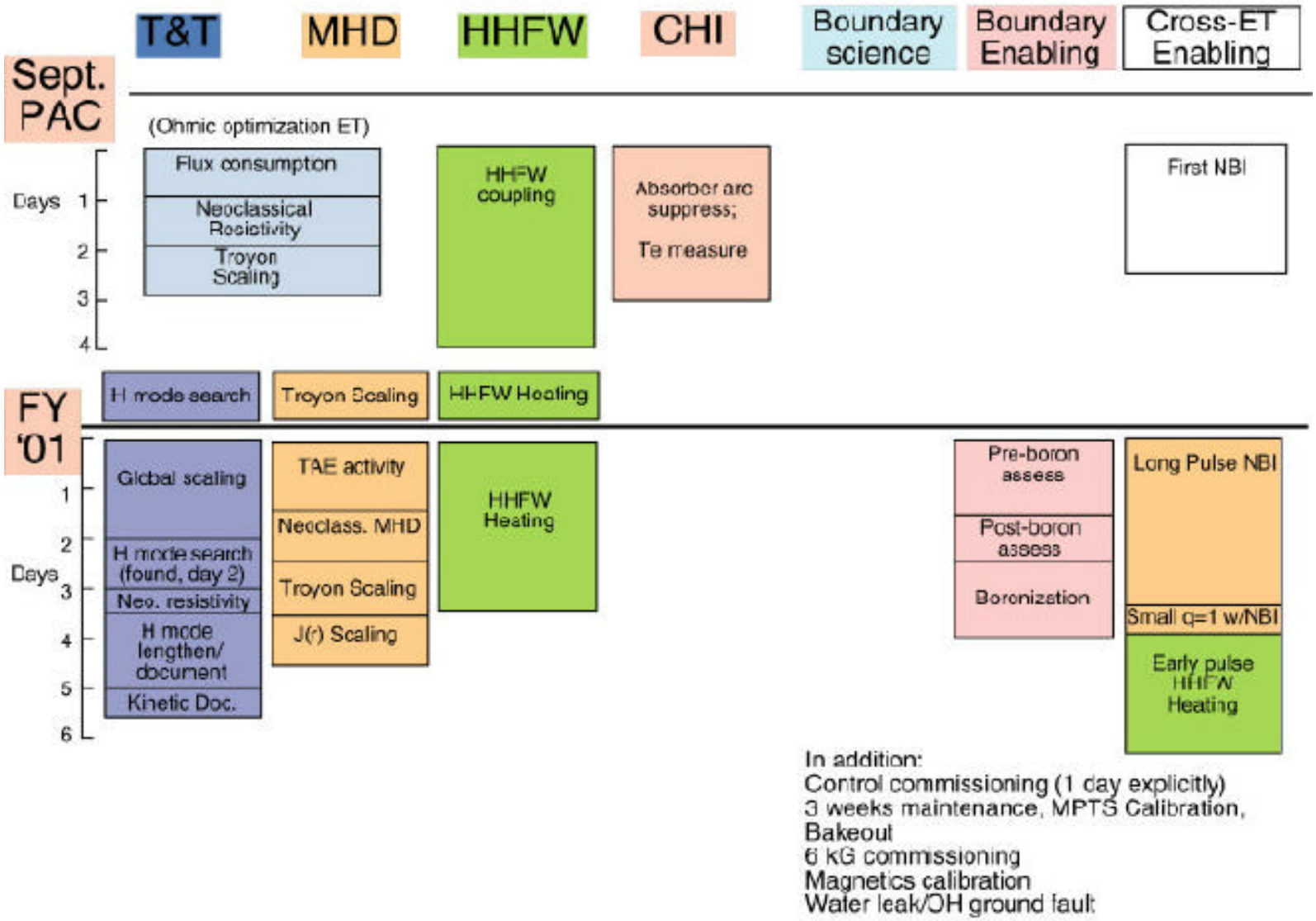
- Summary

In the last PAC, the research plan emphasized topical research and enabling activity

ET Group, Leaders	Plan, FY '01
– MHD (Sabbagh, Menard)	15%
– Transport and Turbulence (Kaye, LeBlanc)	15%
– HHFW (Wilson, Swain)	13%
– CHI (Raman, Gates)	13%
– Boundary Physics (Maingi, Skinner)	6%
Program Enabling	
– 1st NBI	6%
– Commissioning (control,calibration, boronization)	12%
Contingency	20%

- XMP's (machine proposals) executed for commissioning, control work
- Fast ion physics in Transport and MHD ET's
- ET divisions will be assessed annually

Run Usage Since the September 2000 PAC



In addition:
Control commissioning (1 day explicitly)
3 weeks maintenance, MPTS Calibration, Bakeout
6 kG commissioning
Magnetics calibration
Water leak/OH ground fault

The pace of change half-way through FY '01 has been rapid

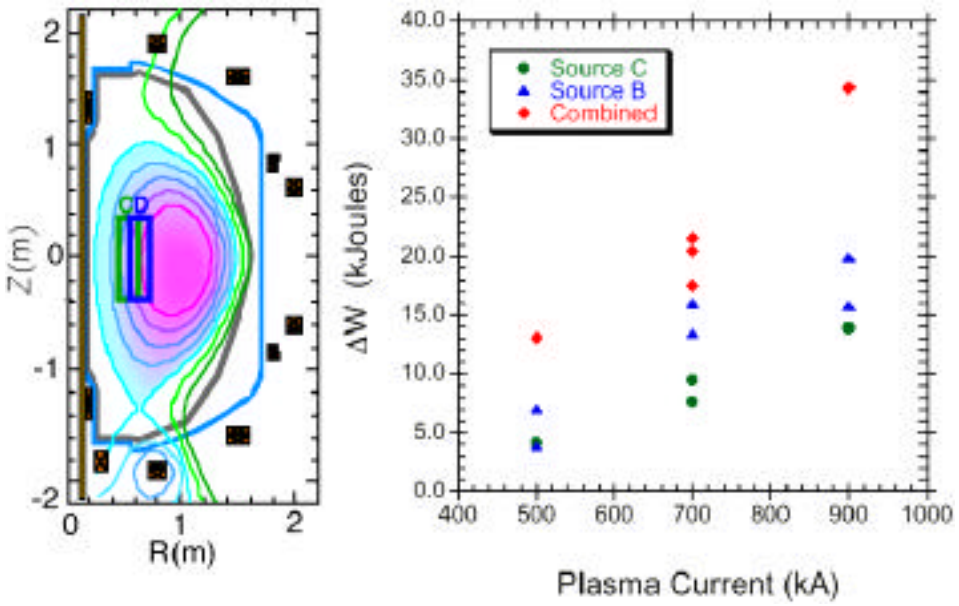
- Beams started near the last PAC (Sept. 00)
  - Now routine at 80 keV/source
- More cross-ET work than anticipated
  - Of benefit to entire group
- Operational advances are significant
  - Boronization, between-shots glow, control capability
- Local measurement capability improving rapidly (LeBlanc talk)
  - First T_i, V_φ profiles emerging
  - Thomson T_e, n_e essential
  - Reflectometry (UCLA, ORNL)

Each ET is developing research to reach and go beyond milestones

- FY '01 Milestones
  - Transport and turbulence: global scaling
  - HHFW: assess heating physics
- FY '02: Milestones
  - MHD: global limits without external feedback control
  - CHI: innovative startup and maintenance (CHI + Ohmic)
- FY '03 Milestones
  - Boundary Physics: edge heat fluxes, plasma facing component needs
  - Integration: the whole package for $t_{pulse} > \tau_E$
- Milestones only part of the story. We are working to articulate the local physics goals and put these on an equal footing
  - Explicitly speak to science component of program.

Some of the program has depended on research that crosses ET lines

- First neutral beam injection experiments
  - Grisham, Gates, Darrow:
    - NB injection operational constraints consistent with expectations
  - Faster than linear increase in ΔW_{tot} with I_p better fast ion confinement with I_p?
- Long pulse development with NBI: born in MHD ET, but of benefit to entire group
  - Gates
    - Early NBI helps slow down current evolution,
    - In conjunction with XMP work



Experiments that cross ET lines help enable rest of research program (con't)

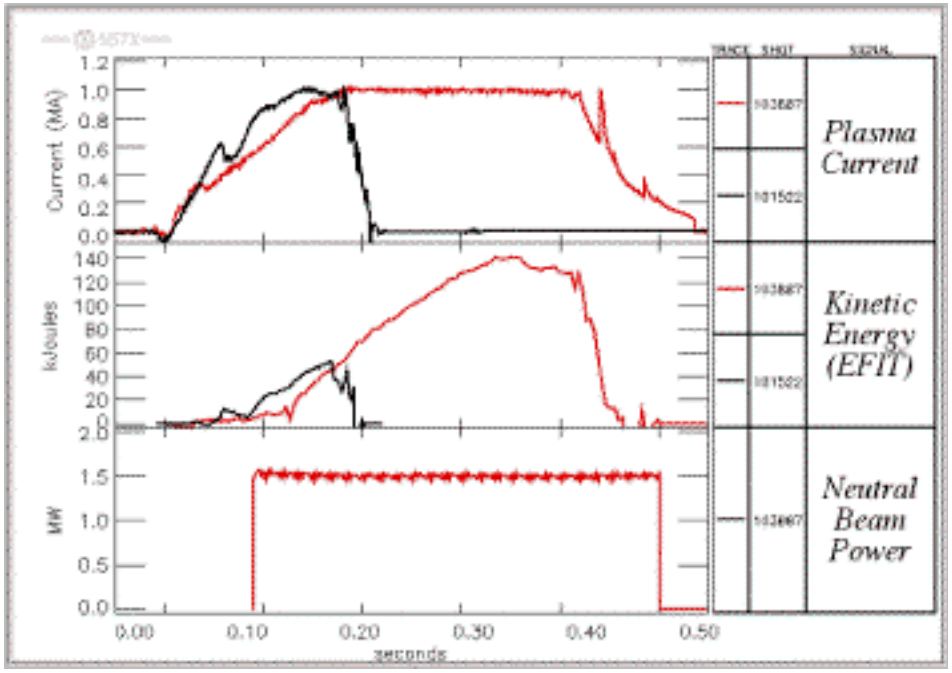
- Early RF injection (Menard)
  - Aim: Develop RF as a tool to heat early, modify q(r,t)
  - Surprising results, not clearly understood
  - Already used as a tool
- H mode search and characterization (Maingi)
  - Certainly a strong transport research area
  - Also, development of H modes potentially a win from broad pressure profiles
    - Not at the "tool" stage yet, but will receive additional run time with this and transport physics in mind

Time will continue to be allocated for control system and boundary physics tool development

- Control work already absolutely key; additional work aimed at rtEFIT control (deploy FY ‘02)
- Control essential for CHI development if startup is to be connected with ohmic and HHFW (FY ‘01 - FY ‘02)
- Boundary physics tools already essential and key
  - TMB: used several times already (Kugel)
  - More routine introduction of boron?
  - Between-shots HeGDC now routine

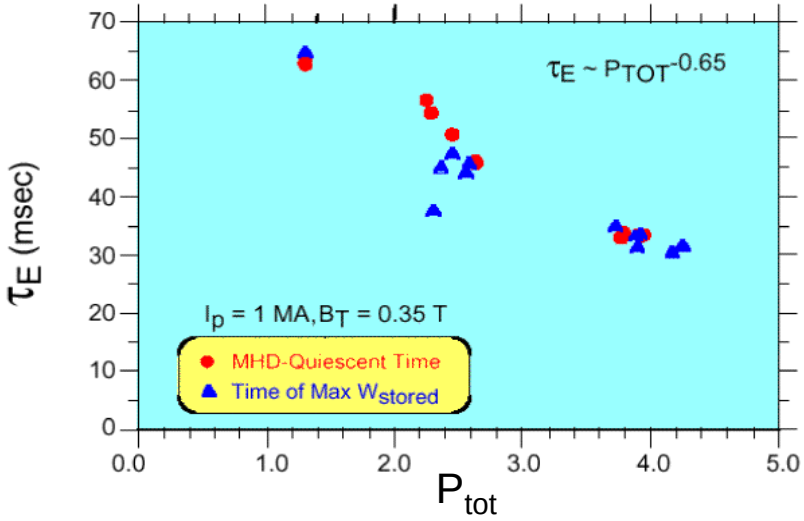
Cross-ET XP's and XMP's, control commissioning, boundary prep have all led to a much-improved baseline scenario

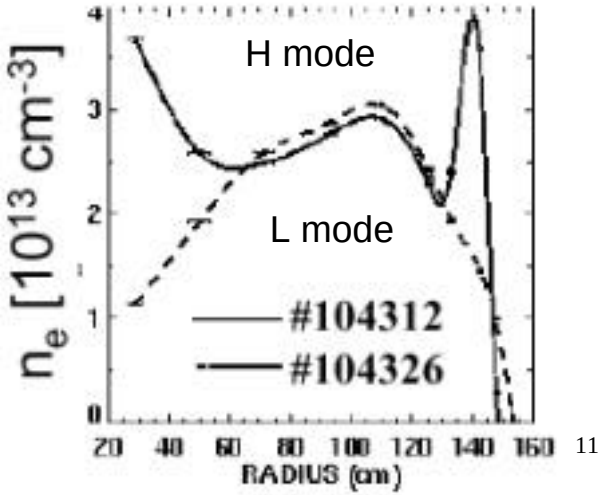
- 1 MA now routine; intend to strike for higher I_p soon
- Pulse length increased; reproducibility improved
- Inner-wall limited, LSN, DN all have been developed
- Will have 6 kG capability for experiments that need it; 4.5 kG routinely used
- L mode plasmas routinely exceed L- and H-mode scalings



In FY '01, transport studies have made progress on milestone and local physics

- Global scaling studies aided by scenario development (Kaye)
- H mode found - operating space being identified (Maingi,Leblanc)
- Neoclassical resistivity assessment underway (Menard)
- Edge turbulence imaged (Maqueda (LLNL), Zweben)
- CHERS has seen first light; initial T_i, V_φ profiles produced
  - First power balance being assessed for high β_T





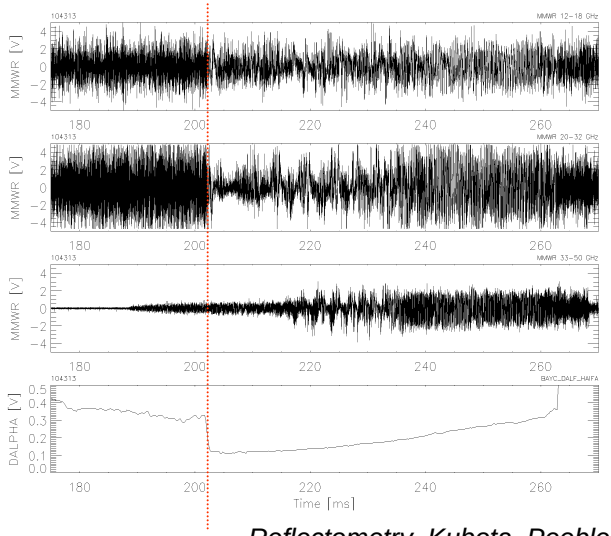
In rest of FY '01, transport studies should meet global milestone, extend studies of core and edge

- Global scaling: FY '01Milestone
  - Will benefit from recently developed operating scenarios
- Local physics: core
  - First χ_i, χ_e, χ_φ over NSTX operating range
    - Low & high β_T;low & high n_e (LeBlanc)
  - RF/NBI at a similar β_T, n_e
    - Gyrokinetics for high β benchmarked: GS2 & FULL (Bourdelle)
  - Initial DIII-D/NSTX aspect ratio studies (with Greenfield, Petty)
  - Neoclassical resistivity (Menard)
  - Fast ion transport/beam blips (Heidbrink,Darrow)
  - Search for core enhanced confinement modes (Efthimion) *
  - Perturbation studies with EBW, SXR array (Stutman, Efthimion) *
- Local physics: edge
  - H mode threshold/operating space (LeBlanc, Maingi)
  - Edge turbulence imaging, (Maqueda, Zweben); probe (Boedo) *

* explicit run time in question with present schedule

FY ‘02 Transport studies will demand increasing local measurement capability

- Extended diagnostic capability
  - Thomson scattering: 30 points, 90 Hz
  - CHERS: 75 points using MSE optics
  - Edge reflectometry (UCLA; ORNL)
  - Edge probes (UCSD; begin in FY ‘01)
  - MSE (see Levinton talk, Friday)

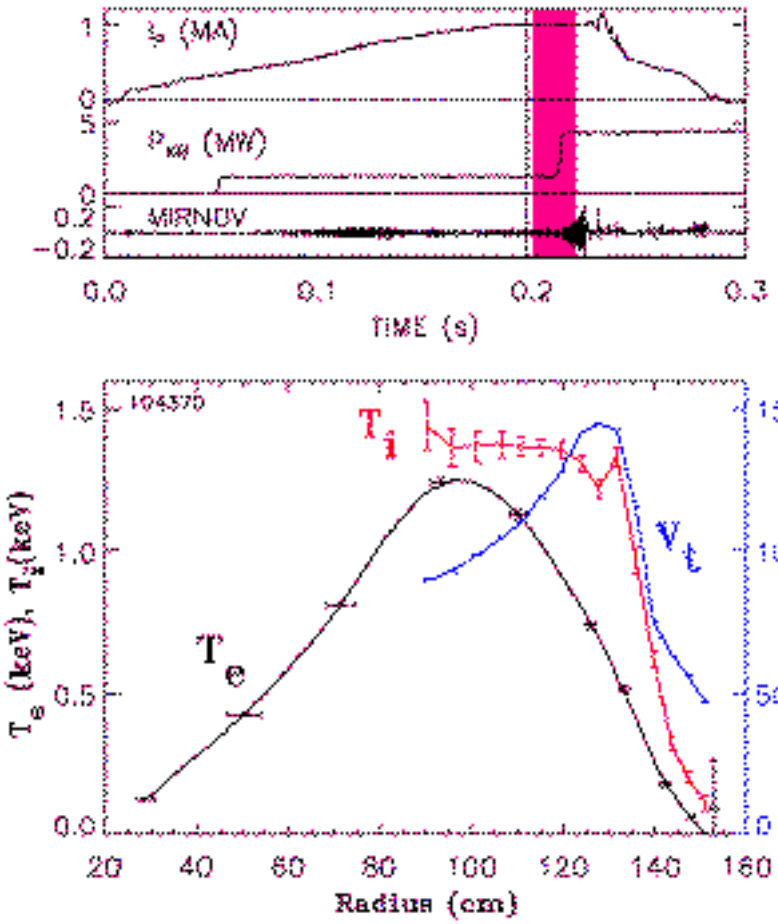


Reflectometry Kubota, Peebles UCLA

- FY ‘02 experimental priorities
  - Systematic scans: Extend local transport at low & high beta, n_e, B_T
    - RF/NBI over a similar range of low and high β_T & n_e
  - Aspect ratio scaling: DIII-D/NSTX - complete DIII-D portion. Also intra-NSTX.
  - Core enhanced confinement
  - H mode pedestal characterization/operating space
  - Edge fluctuation/correlation lengths (UCLA; UCSD)
- Develop and solicit proposals for core fluctuation diagnostics

PAC concern: Increase focus on local transport

- Strongly agree: ion and electron kinetic diagnostics revealing an interesting story
- Data in hand includes 20% β_T with NBI. Also RF, ohmic
- Gyrokinetic codes benchmarked at high beta, ready for data
- Details on diagnostic status and plans: LeBlanc (Friday)



Preliminary data!

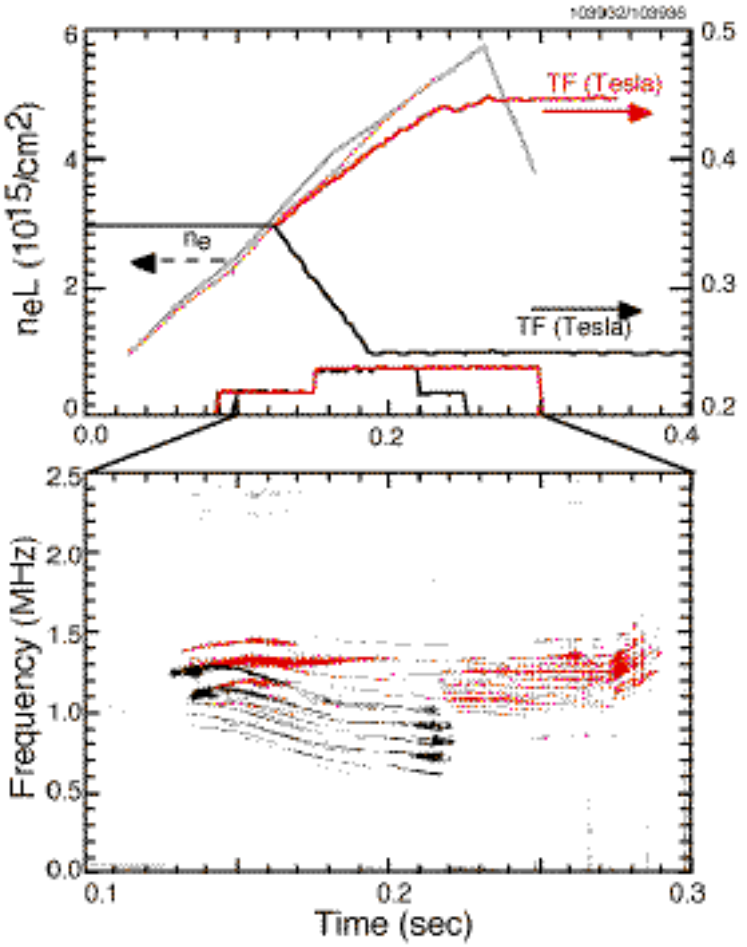
R. Bell, B. LeBlanc

Turbulence Diagnostic Workshop held to develop key measurement strategy

- *Meeting goals of fusion science program demands a qualitative improvement and new investment in diagnostic capability*
  - *IPPA, Snowmass goals are ambitious*
- Workshop Charge: Identify elements for a turbulence research strategy
- Core: Two-part strategy identified
  - Survey capability (spatial and k) highly desirable
    - Low A, trapped particle effects can exaggerate in-out asymmetries
    - Collective scattering in an ST has improved spatial resolution over moderate A
    - Aim for high k capability for electron transport studies
  - Core imaging would provide unique info on low k modes (reflectometry)
  - Port design efforts being included in base program budget
- Edge: imaging, probe (UCSD) and mods for Reynolds, Maxwell stress
- Report being written; will be posted on Web, submitted to DOE

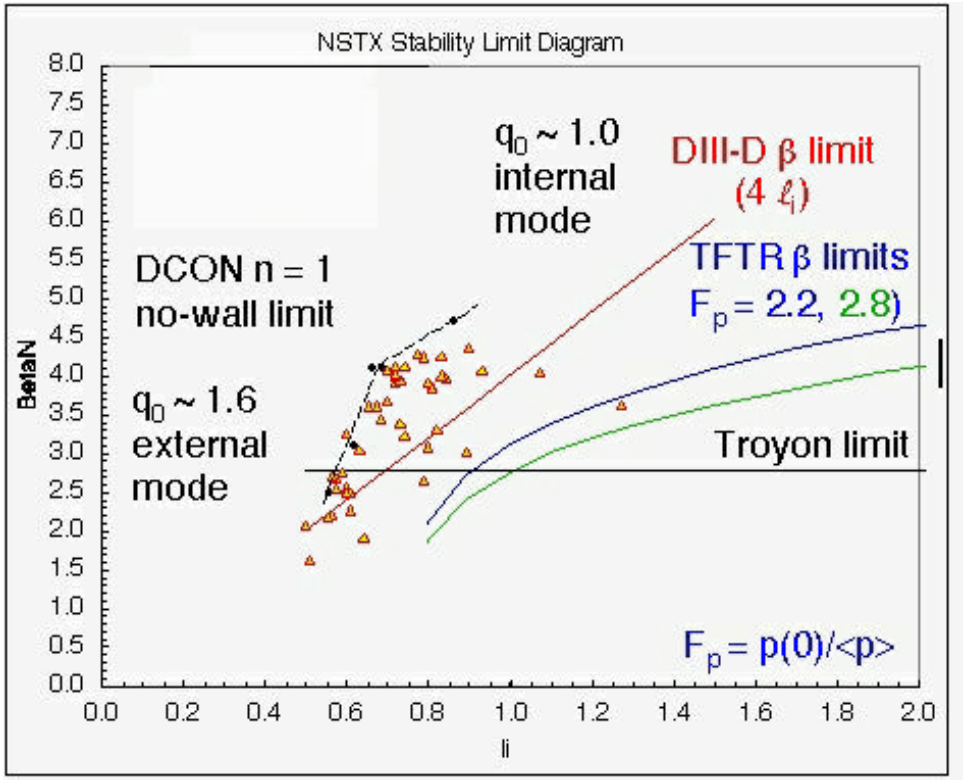
MHD studies have addressed 3 physics issues as well as facilitated scenario development

- Global stability:
  - Troyon scaling XP begun (Menard) in concert with stability study varying J(r) (Sabbagh)
- Beta-limiting mode identification
  - Search for NTMs started and will continue (Gates)
- Fast ion modes
  - Evidence for TAE-like modes seen (Fredrickson)
- Scenario development: Efforts born in MHD group and benefit entire group
  - Pulse extension work (Gates)
  - Enforce small q=1 (M. Bell)



Remainder of FY '01 will see continuation of global assessments, local MHD studies

- Global stability characterization
  - Troyon, J(r) scaling studies fundamental to milestone
  - Use HHFW as control tool (Menard)
- Physics of particular instabilities
  - Current driven kinks (Manickam)
  - Begin characterization of resistive wall modes (Sabbagh)
  - Ballooning mode stabilization at low A (Sabbagh)*
- Fast ion MHD
  - DIII-D/NSTX fast ion MHD comparison (Heidbrink, Fredrickson)



*explicit run time in question w/ present schedule

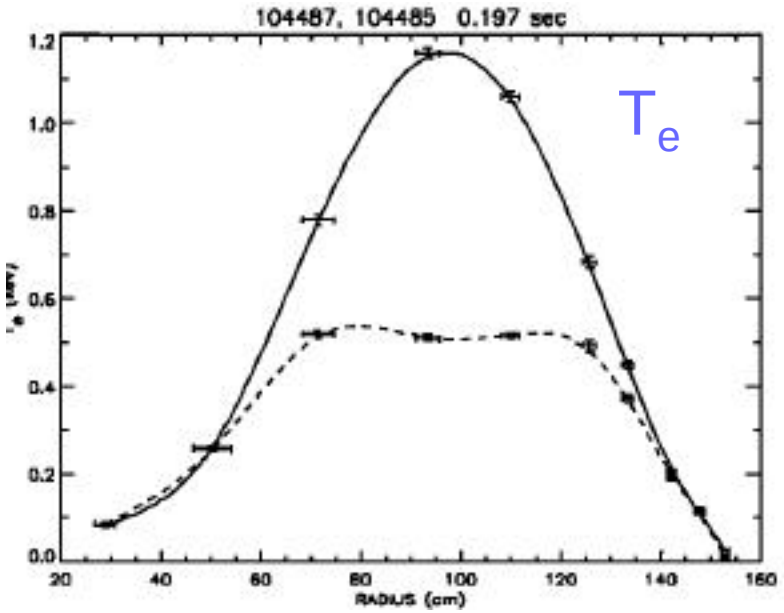
In FY '02, MHD studies can go beyond global stability milestone & into mode stabilization research

- A good database on global stability properties should be well in hand
- RWM stabilization vs. plasma shape and position
  - Increased control will improve effort started in FY '01
- Towards assessing need for active stabilization at end of FY '03
  - Scenario development: *run time beyond '02 likely required* to develop scenario that will be the likely target for long pulse work
  - New diagnostics being implemented
    - First complete locked mode coil measurements (6)
    - Improved poloidal Mirnov array (next opening)
    - Toroidally displaced SXR arrays to distinguished RWM from tearing mode
  - End of '02: consider electrical reconfiguration of passive plates

In FY '01, HHFW demonstrated heating; now moving to local studies and tool development

- FY '01 Milestone: Understanding heating with HHFW
  - 4 MW achieved
  - Electron heating demonstrated
  - Ti with RF being analyzed
  - Modeling of HHFW heating underway (Mau, Bonoli, Phillips)
  - NPA acquiring data

- HHFW already has demonstrated value as a tool for rest of program (Menard)



LeBlanc, R. Bell

Remainder of '01: HHFW research has three focal points

- Understanding electron component of damping
  - Deposition: 2nd laser for Thomson, 20 channels
  - Test theory of scattering of waves off of edge fluctuations
    - Reflectometry of fluctuations and at 30 MHz (the HHFW frequency). Vary working gas (He,D)
  - Asymmetric loading (Swain)

- Begin studies of ion interactions (Thesis: Rosenberg)
  - HHFW & Beam ions: Neutral particle analyzer data, fast MHD
  - Ion heating: Ti(R,t) from CHERS already obtained

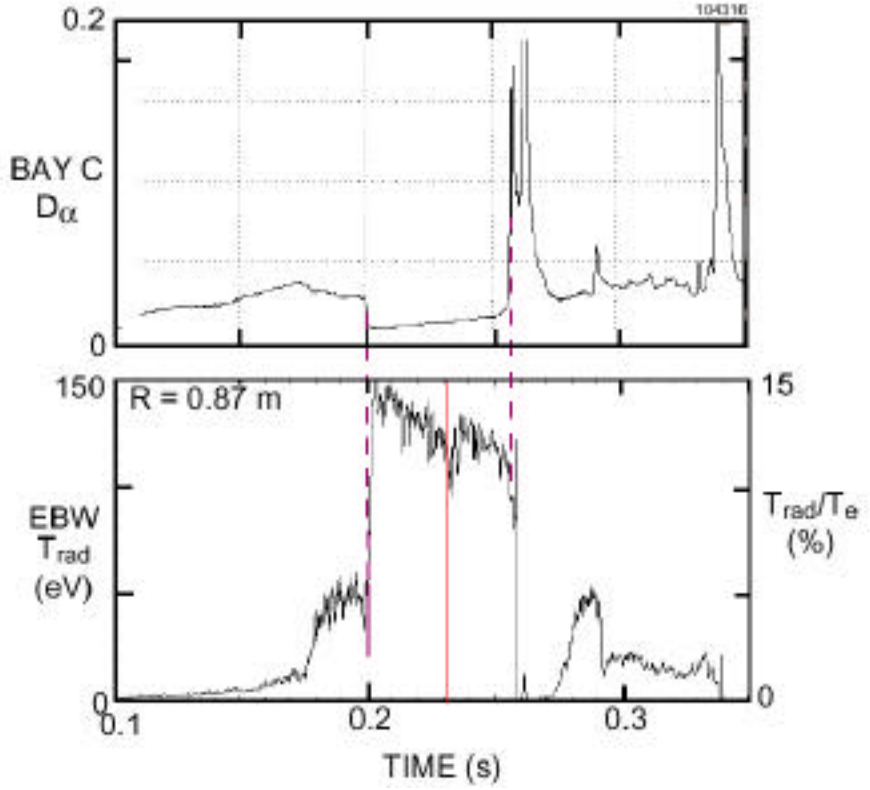
- Applications (Tools)
  - Develop further and understand early heating work (Menard): cross-ET
  - Start closed loop phase feedback development
  - Begin off-axis heating for P(R) broadening

HHFW for FY '02 emphasizes current drive, tool development, ion effects

- Current drive and modification
  - Further development of close loop phase feedback
    - e.g. use rtEFIT output to explore feedback on position or inductance
  - Further early heating work to modify J(R)
- Complete first generation of studies of interactions with ions
- Heat or drive current in a plasma started with CHI
  - Again, a control challenge. Handoff will be difficult

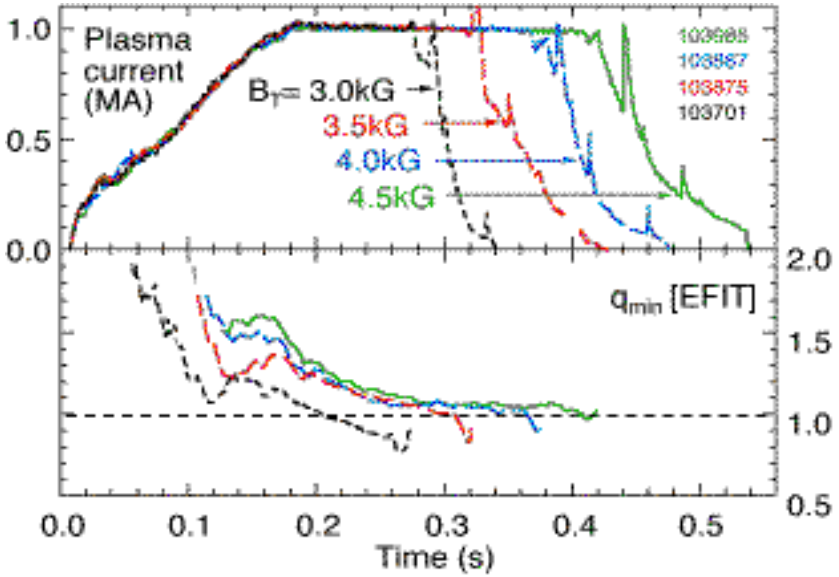
Studies are ongoing to assess viability of EBW for T_e measurements or heating

- This year: Piggyback experiments on EBW emission suggest low EBW transmission, need to steepen edge gradient
  - Exp't: Bigelow, Taylor; Theory: Ram
- Study limiter insertion of ECH/EBW hardware to enforce a steep gradient (Efthimion)
  - Possible installation next vacuum opening



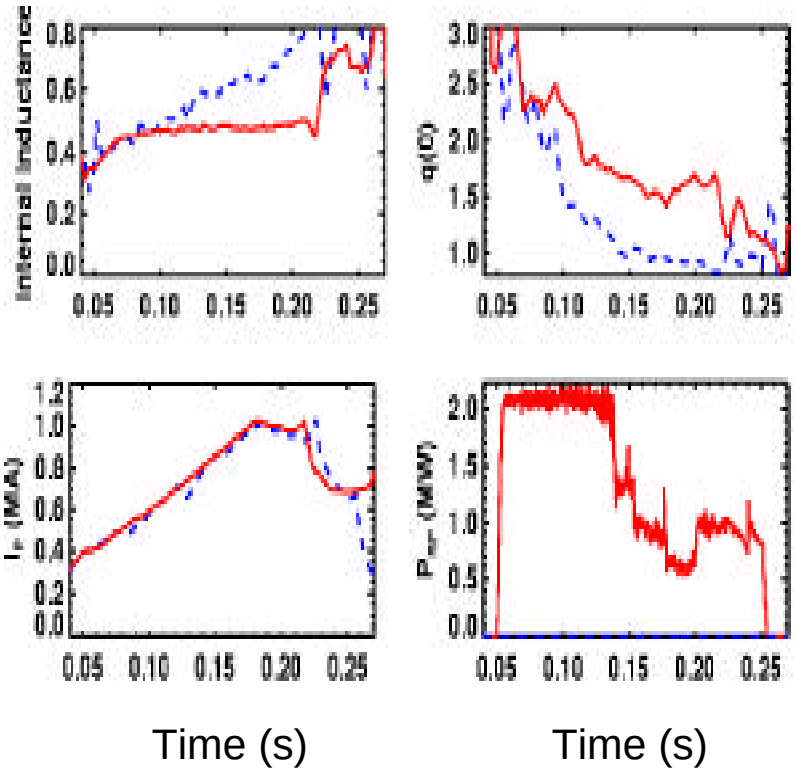
PAC concern: Don't isolate HHFW program

Issue: q(0) = 1 limits performance



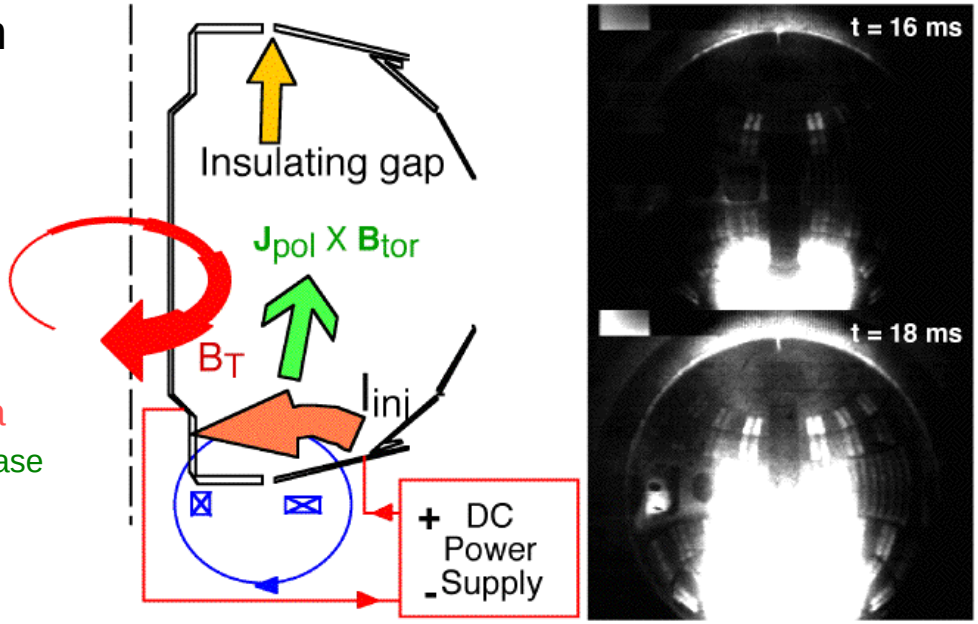
- Strongly agree
- HHFW already used as control tool (early heating: Menard)
- HHFW set the stage by being the first system to heat on NSTX

HHFW early in I_p ramp modifies J(r,t)



Non-inductive plasma startup: CHI has the challenge of assessing flux closure, developing control

- Coaxial Helicity Injection (CHI) a key research effort with U. of Washington
- Over 200 kA I_T achieved in FY '00; absorber arcs reduced
- FY '01 so far:
  - First look at flux closure
    - TS view could only graze CHI plasma
      - Absorber arcs limit attempts to increase plasma height
    - Wide/narrow footprint
  - Analysis tools being developed
    - EFIT, TSC; Kaye will discuss
  - Run in December lost due to TF cooling water leaks
    - Will make up time in 2nd half of FY '01



In rest of FY '01, CHI will make use of experimental runs and a focused assessment period

- Experimental plan: run CHI at start & finish of next FY '01 run period
  - Add CHI to Ohmic (Mueller)
    - Can learn much about control; Exploratory: look for confinement effects
  - Absorber arc suppression
    - Made power supply for PF1au Bipolar to create absorber field null
    - Simultaneously nulling field with PF1au and controlling boundary a question
    - Will attempt MPTS measurement of Te with improved target position
  - Assess/drive closed flux
    - Further absorber arc control, TF scan, gas puff scan
  - Initial feedback control experiments
- Analysis period (interim)
  - Assess what we learned with CHI + Ohmic
  - Identify elements for feedback control algorithms (B. Nelson, UWash)
  - Modify EFIT: private flux current, open field lines (Schaffer, Lao, GA)
  - Ask: do we need to add another PF control coil?

FY '02 CHI milestone requires improved control

- Milestone: Demonstrate coupling of CHI to ohmic
- CHI control requires conceptual development
  - Not as well formulated as Ohmic plasma control
- Elements of feedback scenarios have to be identified
  - Proposal to use injector voltage to feedback on I_T
  - Add sensors feeding into real time control computer
    - New Sky II control computer to be installed this April
- Use HHFW to heat a CHI plasma, stimulate flux closure

In addition to boundary prep work, FY '01 edge physics studies will address heat flux scaling and the role of influxes on confinement

- Boundary physics *science* component
  - Edge heat flux scaling studies highest priority (Maingi, Skinner)
    - 1D CCD array for Dα; IR camera for heat fluxes
  - Gas puffing and confinement/imaging of fluctuations (Maqueda, Zweben)
    - What is the L mode state on NSTX?
    - Shared time with T&T ET
- Boundary physics *enabling* component: Wall preparation work already essential
  - Boronization, spectroscopic assessments of influxes
  - Significant growth in spectroscopy capability
  - Wall coupons providing valuable data

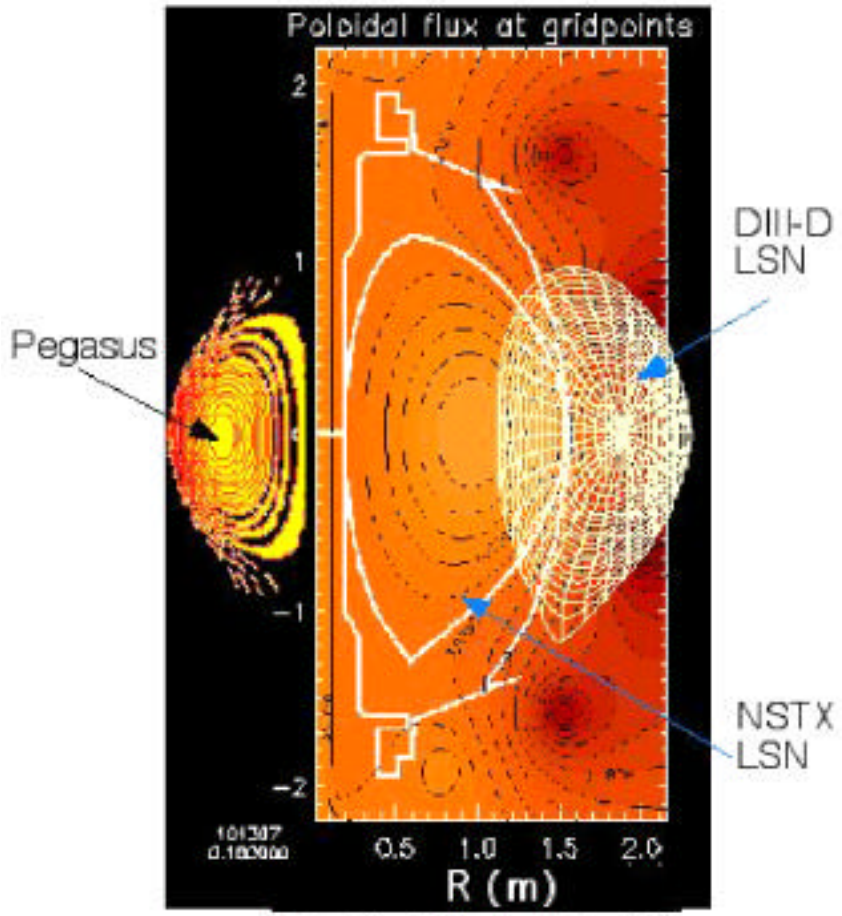
In FY '02, boundary physics will advance both enabling capability and edge physics

- Boundary Enabling activity
  - High temperature helium bake capability
  - Develop boronization into normal plasma discharge
  - Li pellet injector (slow pellets) to be installed
- Boundary Science activity
  - Begin to ask question for '03 milestone: Is the NSTX heat flux solution adequate?
  - Improved edge data for models
    - Edge probe (UCSD) and reflectometry (ORNL, UCLA)
    - Improved Thomson, CHERS coverage
    - 1D Dα CCD array

      Input to DEGAS2 and UEDGE (edge neutrals and transport; Stotler; Rensink, Rognlien), BAL (Myra), BOUT transport (Xu) models
  - Cross-machine: particle balance between NSTX/MAST (piggyback)

To highlight physics of high beta & aspect ratio, inter-machine research will add to scientific strength of the national program

- DIII-D: similar cross section shape, size
  - RWM assessment work in place
  - Transport: aspect ratio studies proposed
  - Beam-induced MHD proposed
    - Difference in gap structure predicted for *AE modes
- MAST: similar size and A, but wall is far
  - Wall/no wall influence on MHD, particle balance
  - Differences in neutral density
- Pegasus: aspect ratio can match at 1.25
  - Logical connection for studying physics of A



Approximate run time allocation

- Planning for 8 more weeks in FY '01; about 1/2 way through the year
- Approximate run time allocation for remainder of FY '01
  - Transport 5 days
  - MHD 5
  - HHFW 4
  - CHI 6
    - Pick up some days lost prior to holidays
    - 2nd run at end of FY '01 dependent on what is learned in 1st
  - Boundary science 4
    - Edge heat flux scaling; gas puffing
  - Operating scenario development (cross-ET) 4
    - Early HHFW to modify J(r,t)
    - P(r) broadening with off-axis HHFW
  - Commissioning (control, calibration, new boronization) 4
  - Contingency 8
- FY '02 will see an increase in HHFW, control work: 13 Weeks

The NSTX Program is on a fast pace, and has to be flexible

- Cross-ET enabling experiments and activities important
  - Already essential in obtaining high β_T
  - Tool development benefits entire program (early HHFW, H mode)
- Progress on milestones is substantial
- Local physics goals a high priority
  - Diagnostics investment is essential to deepen science component
  - Elements in place to exploit cross-machine experiments
- Reduced run time slows pace of MHD assessment
  - Scenario development/exploration likely rate limiting step

Boundary Physics Priorities

- **<u>Prioritization of Proposed Experiments</u>**
- ***'Science role'***
- 1. Edge Heat Flux scaling is highest priority - if available, make use of reciprocating Langmuir probe at midplane for complete dataset. It is recommended that piggyback opportunities should be used extensively to see if peak heat flux extrapolates to problematic regime for NSTX in particular and ST's in general. [2-3 days, NBI and RF heating]
- 2. Effect of gas puffing on confinement - begin study of different gas puffing techniques, and assess impact on confinement. [1 day]
- 3. Cross field transport and turbulence with gas puff imaging - continue experiments to look into structure of turbulence and how it changes with gas puffing [1-2 days, shared time with transport and turbulence]

- ***'Enabling technology' role:***
- 1. Pre 350 deg. C bake characterization: [two 1/2 days]
- 2. Coupons and boronization coupon probe [piggyback]
- 3. Characterize effect of plasma boronization on performance [1 day]
- 4. Particle balance in NSTX ohmic/NBI, including cross machine comparison of particle balance on MAST [piggyback]

Allotment assumes 8 more run weeks this FY, 15 run weeks in FY '02

- Control development time will likely increase over original plan
  - Includes commissioning, debugging rtEFIT
  - CHI milestone in large part a control development effort

- HHFW research not sacrificed in favor of NBI
  - Essential to the NSTX mission
  - Enabling tool development key

Each ET is developing research to reach and go beyond milestones

- FY '01 Milestones
  - Transport and turbulence: global scaling
  - HHFW: assess heating physics
- FY '02: Milestones
  - MHD: global limits without external feedback control
  - CHI: innovative startup and maintenance (CHI + Ohmic)
- FY '03 Milestones
  - Boundary Physics: edge heat fluxes, plasma facing component needs
  - Integration: the whole package for $t_{pulse} > \tau_E$

ET groups consider milestones, program guidance for run time, and then hear and prioritize XP ideas

The primary method for getting into the loop:

- ET group calls meeting before the run to hear ideas, considering program goals and milestones
  - Attempting to make generally available on Web
  - Prioritization should evolve with time
- ET leaders and group prioritize XP's
  - Iterate depending on facility capability
- ET groups develop an XP with discussions prior to XP review by NSTX Team

Weekly Program/Operations Update meeting used to help develop schedule

- An opportunity to be heard, either through your ET leader or directly through myself or the Run Coordinator (RC)
- RC (FY '00, M. Bell; EJS, FY'01; Maingi, FY '02) develops schedule and proposes it to ET leaders and Program Head at Program/Ops meeting, Wednesday at 3 PM
  - discussion with Diagnostics, Beam group representative to assess facility ability to support plan
- Input from ET leaders has been vital for optimizing the schedule

- **NSTX Research Forum 2001**
- **Recommendations from the Energetic Particles Topical Group (TG5)**

- W. Heidbrink (UC Irvine) and D. Darrow (PPPL)

- This Topical Group met on Wednesday afternoon, January 17, 2001. A total of 19 presentations were given, in four general areas relating to fast particles: orbit confinement (7 presentations), interaction with MHD modes (6 presentations), diagnostics (5 presentations), and HHFW interactions with fast ions (1 presentation). The talk titles, abstracts, and, in most cases, presentations themselves, may be found on the Forum website.

- All work discussed in the task group is worthwhile and will advance the understanding of energetic ion behavior in STs. Based on limited discussion, here is a prioritized list of new work with approximate time scales for each.

  - DIAGNOSTICS
  - 1) Energy & pitch-angle resolving escaping beam-ion diagnostic (2001)
  - 2) Scan capability for the neutral particle analyzer (NPA) (2001)
  - 3) Natural diamond detector NPAs (2001)
  - 4) Fusion source profile monitor (2002-2003)
  - 5) Antenna for MHD spectroscopy (2002-2004)

  - DEDICATED EXPERIMENTS
  - 1) Beam-ion confinement using beam blips (2001)
  - 2) MHz beam-driven instability (2001)
  - 3) DIII-D/NSTX Alfvén mode similarity experiment (2002)
  - 4) Beam ion acceleration by HHFWs (2002)
  - 5) Edge electron heating from CAEs (2002)
  - 6) Radial electric field generation from NB ion loss: vary inner gap & NB source at constant outer gap (2003)
  - 7) Alfvén modes in the 100 kHz frequency range (2003)

  - MODELING
  - 1) Develop a fast, full-orbit code with reasonably complete physics--probably the LOCUST code (2001)
  - 2) Improve the treatment of beam ions in TRANSP (2001)
  - 3) Adapt a zero-dimensional calculation of the neutron rate for control-room use and preliminary analysis (2001)
  - 4) COM-based beam-ion loss calculations (2001)
  - 5) Collisional and ripple-loss calculations (2002)

  - THEORY
  - 1) Cavity Alfvén Eigenmodes (the likely explanation of the observed MHz beam-driven instability) (2001)
  - 2) An analytical model of the diffusion rate associated with violation of the first adiabatic invariant, μ (2001)
  - 3) MHD-induced fast-ion transport (2001)
  - 4) Fishbone stability (2002)