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Issues Regarding Magnetics and Stability Limits

Working Group III
National Spherical Torus Experiment Research Forum
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A research forum was held for the NSTX project on Feb 5-7, 1997 at PPPL. Following the plenary sessions and Working Group (WG) introductory talks, parallel WG sessions were held. A summary of the results for the WG3 session and a joint session on diagnostics of WG3 and WG4 is given below.

The WGs have been asked to suggest the near-term goals of the NSTX scientific research and envision the tasks needed to accomplish these goals. The recommendations for Magnetics and Stability Limits are provided first in this summary.

The WG discussions did not attempt to address exhaustively all relevant issues covering the planned experimental lifetime of NSTX. Therefore, the summary below should be used as a starting set of recommendations for scientific research under this topic.

Working Group 3 (Magnetics and Stability Limits) Suggested Goals and Tasks:

The NSTX PAC has advised that the NSTX scientific research should give priority to addressing physics features unique to the ST plasma. The NSTX stability working group has followed this advice.

Priority for Stability Physics of NSTX Plasmas:

1. Investigation of β limits and β-limiting phenomena in ST magnetic geometry
   - Scaling of the beta limit with plasma parameters, particularly the aspect ratio
   - Measurement of mode structures in ST magnetic geometry
2. Comparison of observed instabilities with conventional tokamak database
   - Neoclassical tearing
   - Disruption precursors
   - Resistive modes, IREs (Internal Reconnection Events)
   - Resistive wall modes, effect of conducting structure
3. Issues pertaining to future STs and reactor relevance
   - Alfven eigenmodes
   - Disruptions
     - Behavior of runaways
     - Effects of halo currents
   - Locked modes and active feedback
4. Successful diagnostics implementation and operation in ST geometry

Priority for Diagnostics of NSTX Plasmas:

1. Poloidal and toroidal plasma imaging, including the tangential soft X-rays.

2. Current profile measurement
   - For operations with $q \geq 1$ when sawteeth are absent, this measurement becomes all the more crucial
   - It is prudent to test new measurement methods in existing devices
   - Older ideas such as charge exchange polarization should be considered
3. Standard diagnostic set to permit reliable equilibrium reconstruction (T_i, T_e, n_e, Mirnov, flux loops, etc.)
   - This leads to important requirements on the Thomson scattering configuration. A single midplane Thomson chord may not be adequate for measuring the magnetic axis when it could be shifted off the midplane.

Key Subject Areas and Scientists to Contact for More Information

- Ideal MHD equilibrium / stability — Menard
- Free-boundary plasma modeling
  - startup dynamics — Pompherey
  - passive plates / resistive wall modes / active feedback — Paoletti, Garofalo, Sabbagh, Mauel
- Resistive MHD — Fredrickson/Park/Turnbull/Chu
- Neoclassical MHD — Chang/Kruger/Hegna
- Locked Modes — Ferron/Takahashi
- Error Fields — Ferron/LaHaye
- Alfven eigenmodes — Fu
- Experimental results (limiting modes, IREs, etc.) — Gartska/Choe/Ferron

Suggested Tasks and Scientists to Contact for More Information

- Clarify neoclassical MHD modes for realistic equilibria — Chang/Kruger/Hegna
- Measure effect of passive plates and resistive wall modes — Garofalo/Paoletti
- Design active feedback system — Mauel
- Develop adequate MHD imaging diagnostics — Fredrickson
- Maximize use of experimental data in modeling — Gartska/Sabbagh/Menard
- Measure tearing modes in ST plasmas — Fredrickson/Turnbull/Chu
- Clarify radial structure of Alfven eigenmodes — Fu
- Determine beta limit scaling with toroidal field — Fredrickson/Zakharov
- Clarify effect of ST geometry on locked modes — Ferron/Takahashi
- Determine error field correction requirements — Ferron/LaHaye
- Determine vertical stability of high k NSTX plasmas — Pompherey
- Measure MHD instabilities during startup via CHI
- Measure 2-D poloidal mode and 3-D mode structures
- Determine conflict among diagnostics systems
- Develop common or open database paradigm

These tasks can and should be addressed during the planned lifetime of NSTX. Contacts were not assigned since the people to assign were not clear.

Round-table Discussion of Goals and Tasks:

The WG members made the following comments on the above goals and tasks for Magnetics and Stability Limits, accounting for the presentations during the plenary sessions of the Forum:

Fredrickson:

- A study of the effect of passive plates and the importance of the resistive wall mode need to be considered.

The response was that Menard should be encouraged to expand his present work on MHD stability. In addition, it was added that the Columbia U. Collaboration is presently setting up free-boundary equilibrium reconstruction and stability studies for NSTX. The effects of the conducting plates and active feedback will be modeled.

- The design of feedback coils / smart shell configurations should be considered in the near-term design of NSTX

- The possibility that ECE (electron cyclotron emission) may not be effective on NSTX is a serious concern. Substitute systems, including the tangential soft X-ray viewing system, EBW (electron Bernstein wave), and other proposed systems need to be examined for possible development for NSTX as soon as possible.

- Suggestion to possibly bring diagnostics to START to help measure experimental ST plasma profiles, in support of NSTX research preparation.

Chang:

- Extend neoclassical MHD calculations, specifically in the short term by using more sophisticated equilibrium models.

Zuoyang suggested that Scott Kruger and Chris Hegna at UW are experts on this topic and might be able to participate in this regard.

Von Goeler:

- Resistive MHD should receive significant attention. The NSTX modeling of high beta plasmas is showing large edge gradients in the plasma profiles. What impact will this have on resistive stability?

- The NSTX data acquisition design should accommodate a large viewing data dump of the X-ray imaging systems.

Choe:

- Again, there has been little attention paid to resistive MHD at this meeting. However, START and CDX performance is limited by resistive MHD events. Additional modeling for NSTX in this regard is suggested.

The response suggested possible candidates who might participate in this analysis. Wonschull Park should be consulted as to what could be done with MH3D. Also, Turnbull and Chu at GA might be able to participate in this regard.

Gartska:

- Internal reconnection events (IREs) / resistive MHD are commonplace in ST experiments, and may be in NSTX. However, the data in this area is limited. Also, the effects of conducting plates and strong shaping - components of the NSTX design - on IREs is basically unknown.

Since IREs limit the performance of STs, attempting to determine their effect on the NSTX configuration could be important. Then again, we may find that in hot, strongly NBI heated NSTX plasmas, the limiting instabilities may change character. Can we use experience from conventional tokamaks to explore this? A suggestion was made that DIII-D might provide some insight, since resistive modes as well as ideal modes have been hypothesized to limit plasma performance in DIII-D.

Fu:

- The measurement of the radial mode structure of Alfven eigenmodes (AE) in ST magnetic geometry is important.
- How does the beta limit scale at the low toroidal field of NSTX? It is presently being hypothesized that conventional tokamak plasmas exhibit a toroidal field scaling of b_N . How would present models of this effect scale to NSTX?

Ferron:

- Very little has been said about locked modes in NSTX. What are the effects of low A on locked modes?

One of the only talks in the forum concerning locked modes was the talk given by Fredrickson on behalf of Takahashi. John’s concern perhaps strengthens Hiro’s proposal for installation of adequate diagnostics on NSTX to strengthen halo current studies in the device.

- What plans, if any, have been made for the implementation of error field correction coils on NSTX?

John continued by suggesting that Rob LaHaye might be able to help the NSTX design team through his extensive experience with the C coil on DIII-D.

- The calculations of the n=0 stability of NSTX should have greater exposure. It seemed from the presentations that only a limited range of kappa was considered. Have more extreme values of kappa been examined in this regard? Such extreme values of kappa might become experimentally interesting in future NSTX experiments.

Sabbagh:
- Much has been said regarding NSTX diagnostics. However, given that the machine is small, can all of the diagnostics envisioned for the machine be implemented in a complementary fashion?

- The field geometry of NSTX, the increase in Bp/Bt (~ 1 on the outboard midplane), and the importance of the destabilizing poloidal field curvature drive (for which there is no good curvature region) might change the poloidal structure of the instabilities in NSTX. Therefore, 2-D imaging of the plasma poloidal cross-section is highly desirable. In addition, the relatively recent realization of importance of 3-D modes in tokamaks (i.e. non-axisymmetric, intermediate-*n* ballooning modes which are disruption precursors in TFTR) suggest that similar modes should be measured in STs, particularly if islands are larger than in conventional tokamaks. Therefore, systems with 3-D mode resolution should be considered. (I.e. duplicate soft X-ray systems separated toroidally).

- A protocol for the common use of data, and the use of common software should be established. Analysis for important and timely data have been delayed at times for one or two diagnostic systems, resulting in reduced scientific productivity and inadequate peer review. An improved system should be adopted in NSTX to maximize quality and productivity of the analysis.

The responses to this included the comment that all data needs to be made available to the entire group, independently of the grouping of scientists according to conventional disciplines.

- Equilibrium/stability modeling should be expanded to include, to our best knowledge, experimentally probable profiles, rather than using only profiles optimized for maximum bootstrap current alignment and beta. Further, the effectiveness of conducting structure to reach the very high beta values, and the structure model are at present uncertain. The existing tokamak database is not strong enough to back such estimates.

Finally, a comment was made that CHI and non-inductive startup also contained many MHD issues. It was thought best that these groups therefore begin to overlap more in future NSTX studies, and that parallel sessions should not be scheduled for these groups in future meetings.

Summary of WG3 Session Presentations:

The main topics of the discussions in WG3 included the definition of the objectives for WG3 (ST stability issues), the importance of a well-planned diagnostic set with adequate bandwidth and resolution to allow detailed modeling of relevant instabilities, the present status of MHD studies performed in support of the NSTX design, and invitation to the national community to scrutinize and expand on this initial consideration on the NSTX scientific research.

1) Introduction (Fredrickson)

The emphasis of WG3 was divided into three topics: disruption limits, resistive/ideal instabilities, and fast-ion - MHD interactions. Modeling was combined with experimentation in the discussion. The identification of diagnostics set was of crucial importance to these topics. The "new" physics configuration (e.g., low aspect ratio, A, and reduced Bt) of NSTX, will require modified diagnostics and a fresh outlook on the physics issues. Topics of importance to present tokamaks including ideal instabilities, resistive wall modes, sawteeth, tearing/neoclassical tearing, density limit disruptions, TAE, fishbone, and trans-Alfvenic modes were mentioned. Some parallels with standard tokamak phenomena (i.e. instabilities) can be expected, but new behaviors may emerge due to the low A magnetic configuration.

2) Joint Diagnostics Session of WG3 & WG4

a) Multichannel interferometer and polarimeter: (Hyeon Park)

An interferometry system to measure density and internal magnetic field was proposed. The system is presently in use on TFTR, and many of the existing proponents can be transferred directly. Increased signal strength due to the increased path length from a system with vertical chords in an elongated device was mentioned. Accuracy of the system with respect to current density profile measurement was discussed. One issue raised was the inversion required for a Faraday rotation system. While adequate accuracy in principle can be attained for the direct measurement, the uncertainties due to the inversions were not addressed.

b) MSE diagnostic for NSTX: (Fred Levinton)

The motional Stark effect was discussed in general. Data from PBX was shown (Bt = 1.5 T). The broadening problems associated with low field operation of the diagnostic (Bt = 0.3T) were discussed. Signal to noise becomes unacceptable at the NSTX field magnitude. Techniques to attempt to work around this, such as viewing the inboard side of the plasma, and improving optics were considered.

Laser induced fluorescence (LIF) (optical pumping) might solve the low signal to noise problem. Measurement of Er with LIF might be possible. One positive aspect is that the view and the spatial resolution of the measurement (about 2 cm) should not be a problem.

c) MSE q-profile measurements for NSTX: (Brent Stratton)

View and spatial resolution (3-4 cm) should be fine. Problem is that σ and π-polarized components of beam emission at low Bt overlap strongly. Increasing integration times to 50-100 ms and increasing throughput of the system by a factor of two could produce pitch angle uncertainties of ~0.1 degrees. LIF was also mentioned (direct pumping of the one transition was considered), however the laser power required for this seemed prohibitive. This result differed from Fred Levinton's estimate.

Comment: (Buzz Jobes) Heavy ion beam probe diagnostic might be worth considering for internal magnetic measurement.

d) Impurity transport/MHD diagnosis of plasma edge (M. Finkenthal)

Emission of spectral lines were considered, giving access to the outer 5-10 cm of the plasma. Concepts of diagnosing MHD and impurity transport were proposed. For example, fluctuations of carbon line emission during MHD activity in CDX-U was shown. Systems of measuring line emission in the plasma edge with high resolution were sketched out. Resolutions of greater than 10 kHz (transport) and 100 kHz (MHD) temporally and less than 1 cm (low field side) and less than 2 cm (high field side) spatially, could be attained.

e) Imaging second harmonic interferometer for density measurement (Buzz Jobes)

Imaging second harmonic interferometer (two "color" laser interferometer) was proposed. Spatial resolution of 2-3mm is possible in principle, and a large number of channels (~ 100) is also possible. The return path of the laser is created by small retro-reflectors, making channel positioning relatively easy.

f) Electron temperature measurement using EBW (Phil Efthimion)

Electron cyclotron Berstein waves, generated in NSTX, are proposed to be used as a Te diagnostic. Accessibility in NSTX is an issue. Waveguides could be used to bring the RF to the machine. Plan would be to conduct a proof-of-principle on CDX-U and using existing components at PPPL and elsewhere.

g) Electron temperature / MHD measurements using soft X-rays (Ken Hill)

Diagnostic would allow imaging of internal MHD fluctuations. In addition soft X-ray may fill the void for Te(r,t) measurement if ECE is not possible in NSTX. Soft X-ray spectrometer was the primary proposal, based on the compact C-MOD design. Eighty channels of amplifiers, digitizers, and memory could be made available from TFTR for this application.

h) Edge MHD effects on transport (John Menard)

Possible transport effects due to edge MHD were discussed. Raising q(0) was proposed to change the high-*n* ballooning stability. Questions regarding the impact of an edge localized high-*n* ballooning unstable region and/or a region of high edge current density were raised. However, many of the questions raised have not yet been conclusively answered in existing tokamak experiments. It will be important to have high-resolution edge plasma diagnostics and the ability to measure intermediate-*n* values for modes near the plasma edge.

3) <u>WG3 Session</u>

a) Discharge control and real-time equilibrium reconstruction (John Ferron)

Plasma control technology was discussed with respect to what is now available in the community. Digital plasma control systems are now being used in DIII-D. Real-time equilibrium reconstruction has been recently implemented on DIII-D. Present control algorithm and software infrastructure is directly portable to NSTX. Hardware is machine specific, but new systems can be built analogously in many cases.

Real time equilibrium reconstruction as implemented in DIII-D is now fast enough (millisecond time scale) for feedback control of plasma parameters.

A question was asked regarding the adequacy of the existing design of the NSTX coil set for plasma shape and divertor control in a practical sense. The response was that if configurations could be modeled numerically, then they should also be able to be practically created. However, if NSTX will have a large edge current density (as computed by J. Menard), then dynamic divertor X-point control may be more difficult.

b) Neo-classical tearing modes in NSTX (Zouyang Chang)

The nonlinear island evolution equation was discussed. The ratio of the Glasser-Greene-Johnson term (finite βt stabilization) to the neoclassical term in the island equation is usually small in conventional tokamaks, but becomes large for STs. Neoclassical tearing for q(0) = 1 and q(0) = 2 scenarios were examined. For TFTR, the GGJ term is much smaller than the neoclassical term. The q(0)=1 NSTX case has a ratio of neoclassical/GGJ of about 2. However, the q(0)=2 case has neoclassical/GGJ $<<$ 1. The neoclassical destabilization term increases in the NSTX case compared to TFTR, however the GGJ stabilizing term may compensate for this effect. Estimates of the island width for the quick calculations of the NSTX scenarios were very large. Therefore, a more rigorous analysis for these modes in NSTX should be performed.

d) MHD phenomena in MEDUSA (Gartska)

MEDUSA, a small scale (R=0.1m, a = 0.07m, Bt = 0.1 - 0.4T) spherical tokamak, was discussed, particularly the equilibrium and stability during the current ramp, and internal reconnection events.

An internal magnetic probe is used to map B(R) in the plasma. The li(1) reaches 1 by the flat top of the current evolution. Analysis of the initial phases of the startup, based on the B(R) evolution, suggests that double tearing modes are present. Larger internal reconnection events (IREs) are observed later in the evolution of the discharge (near Ip flattop). The events have the normal signatures, including reduction of li (broadening of the current channel).

e) Measurement of neoclassical and diamagnetic currents using magnetic diagnostics (Eric Fredrickson for Hironori Takahashi)

The proposal is to mount tri-axial, densely packed probes to attempt to accurately reconstruct the current profile distribution in the edge plasma region. The presentation was conceptual, so that number of probes, spacing, etc. was not quantitatively discussed.

f) Measurements of halo currents intercepted by limiters (Eric Fredrickson for Hironori Takahashi)

The proposal is to mount a set of Rogowski coils at several places around the periphery of the vessel, including the center column, to measure halo currents crossing the appropriate limiter surfaces.

g) Disruption/Halo Current Study of ST Plasmas on NSTX (Wonho Choe)

Disruptions are a great problem for tokamaks, and if large STs suffer similar disruptive instabilities, J(halo) xB forces on the inner structure, and power handling might be a problem. Luckily, STs seem to have smaller J(halo) during induced VDEs, however, the physics of the halo current generation and distribution should be studied. The proposal is to install segmented Rogowski loops to measure the halo currents induced by VDEs or possibly disruptions in NSTX.

h) Tangential soft X-ray imaging (Eric Fredrickson for Schwick Von Goeler)

Tangential viewing can greatly improve the spatial resolution of soft X-ray pinhole cameras. The technique should be most effective on the outboard midplane, but views could be made flexible. The data would also be useful for equilibrium reconstruction.

i) Initial Considerations on Alfven Eigenmodes in NSTX (Gou-yong Fu)

The ellipticity (EAE) and triangularity-induced (NAE) Alfven eigenmodes are considered. The free energy that drives the instability comes from the fast ion pressure gradient. The smaller aspect ratio, increased beta, and strong shaping can each effect the Alfven eigenmode stability considerably. Ion Landau damping should be significantly different in NSTX vs. TFTR (should be larger). The particle gyro-radii are also much larger on NSTX. Compared to tokamaks, NSTX has wider continuum gaps due to the smaller A. Simulations for NSTX show additional core TAE's which occur in the same gap in radius, and higher frequency NAE's .