Working Group 2 - Heating, Current Formation and Sustainment by Fast Mechanisms

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1. Introduction

A great deal of new work has been done since last year in the areas related to our working group. Much study has been done on analysis of RF antennas for NSTX in preparation for the antenna Preliminary Design Review which occurred in early December. Assessments of heating RF core heating and current drive performance have also been carried out. There has also been much detailed modeling of energetic ion orbits and loss rates. This is of course a key issue for NSTX because of the low magnetic field and large gyro-radius beam injected or ICRF tail ions. The question of what is the effect of highly supra-Alfven ions on stability has begun to be addressed theoretically. The possibility for fully bootstrap operation (including current ramp) has been further explored, and bootstrap driven equilibria have been calculated, with $\beta(0)$ = 38% which are ballooning stable.

The working group met in two sessions (see agenda in the Appendix) 1) Heating and Current Drive Plans, Energetic particle Issues, Diagnostic Needs, and 2) ECH Possibilities, RF Modeling, Discussion. Much of our time was devoted to discussing diagnostics needs and prioritizing additions to the baseline set of diagnostics. The table below shows the WG2 perspective for diagnostic needs specific to the application of beam and wave heating. Provision of other measurements of broad interest such as magnetics is assumed. The table is organized into diagnostics existing in the baseline and those that are not, with the number of ticks in the priority column indicating order of importance.

The heating and current drive techniques now planned to be available on NSTX for the first three years of operation are:

- Low power ECH for preionization (18 GHz, 30 kW, 100 msec).
- High Harmonic Fast wave Heating and Current Drive (30 MHz, 6 MW for 5 sec, up to 12 MW of source power for 2 sec).
- Neutral Beam Injection (in Year 2) (5 MW at 80 keV, 5 sec).

The following two additional techniques have also been extensively discussed, in this Forum as well as other venues, as upgrade options:

- Electron Bernstein Wave techniques, to extend ECH techniques to the overdense ST plasma.

- Low frequency rf techniques (fast wave, mode conversion, direct launch IBW) as an alternate to HHFW or as a startup system.

Diagnostic Needs

	Measurement	Diagnostic	Priority
Baseline	Local antenna heating /lost particle heating	IR camera	44
	T_i (t), f(ε)	charge exchange/CERS	
	Rotation	magnetics (?)	
	Fluctuations	interferometer -> wide band	
Not in baseline	edge n_e, ϕ, T_e	reciprocating probe	4
	edge density profile at antenna	Reflectometer	44
	fast T_e measurement	(EBW emission?)	4
	T_i/lost ion distribution (poloidal resolution)	multi-purpose movable probe – SBD, foil detector, bolometer, SBD/diamond detector array	44
	Neutron Emission profile	neutron pinhole camera	
	MHD induced fast ion loss	fast neutron detector	(cheap)
	B measurement	pickup loops	

2. High Harmonic fast Wave (HHFW) program:

The HHFW system will be the only heating system on NSTX for the first year of operation. A discussion by Randy Wilson (PPPL) of the RF program for NSTX led off the Working Group discussion. The technical and scientific objectives for NSTX as discussed at the time are:

First 3 Months of Operation - Demonstrate Technical Capability of HHFW System

Scientific Objectives:

Demonstrate coupling into plasma at moderate power levels (~ 2 MW)

Hardware Requirements

Full complement of antennas and transmitters

Diagnostic Requirements

Total and diamagnetic stored energy, core and edge plasma density, core electron and ion Temperatures, rf probes, spectroscopic diagnostics

Code Requirements

Full wave and/or ray tracing analysis of HHFW performance at modest beta.
Basic TRANSP time-dependent analysis of discharge including rf power deposition

Begin late FY99 - High Power Operation

Scientific Objectives:

full power operation (~6 MW) with fixed phasing
rf-plasma coupling optimization
preliminary tests of HHFW CD scenarios
initial scoping studies for different target plasmas (shape, density, temperature, B field, etc.)

Hardware Requirements (additional)

add phasing control

Diagnostic Requirements (additional)

CX for energetic particles; reflectometry for instabilities
T_e (r,t) Thomson Scattering

Code Requirements (additional)

"SNAP"-like analysis of discharge available for between-shots analysis
More sophisticated, reliable RF analysis (including antenna coupling) for high beta targets.

Begin FY00 - Heating Scenario Optimization in RF Heated Plasmas

<u>Technical / Scientific Objectives:</u>

determine regimes with optimal electron heating (minimal ion heating)
plasma parameter scoping studies (density, temperature, shape, beta, B field, etc.)
detailed studies of power deposition profiles
map out regimes with strong ion damping
optimized plasma performance with HHFW heating
explore rf-driven instabilities
explore rf-quenching of instabilities
explore rf-driven rotation (if observed)

<u>Hardware Requirements</u>

active phase control

<u>Diagnostic Requirements</u>

fast Te ,Ti and V_ϕ diagnostics

<u>Code Requirements</u>

ability to include non-Maxwellian distributions

Mid FY-00; Demonstrate HHFW current drive

<u>Technical / Scientific Objectives:</u>

establish procedures for pre-programmed phasing variation
document CD profiles for various plasma regimes
determine CD scenarios for optimized plasma performance
localized CD for instability control

<u>Hardware Requirements</u>

same

<u>Diagnostic Requirements</u>

MSE, CHERS as soon as available

<u>Code Requirements</u>

current drive subroutines fully operational (parameterization routine for ST; full quasi-linear treatment if necessary)

Combined HHFW and NBI Injection

Technical / Scientific Objectives:

regimes for optimized plasma performance with combined HHFW and NBI (heating and CD scenarios)
detailed studies of interactions between HHFW and NBI ions
explore instabilities driven by combined HHFW + NBI
methods for instability control with combined HHFW + NBI
effects of rotation on plasma performance

Hardware Requirements

same

Diagnostic Requirements

neutron diagnostics
fast particle detectors

Code Requirements

routines for RF-NBI resonance effects

FY 01 and beyond: Advanced RF Studies
design / modify / install lower frequency ICRF system for:
- flow shear generation for transport barrier formation
- mode conversion for localized current profile control
design / modify / install ECRF system
explore heating and CD scenarios appropriate to next generation ST
modify HHFW system based on experience

RF design and modeling

A significant modeling effort has been mounted since the last Forum on HHFW heating, current drive, and antenna design. The antenna design effort, in particular, was driven by the need to conduct a Preliminary Design Review for the antenna, which was successfully completed in early December. Some of the advances in modeling reported since last year's Forum:

1. The effects of the antenna geometry on loading and wave launch were extensively modeled using PICES and RANT3D at ORNL. As a result, the antenna now in design for NSTX will be a single 12 strap unit (rather than 2 toroidally separated 6-strap units), with vertical current straps (rather than straps tilted to be approximately perpendicular to the toroidal field). Operating frequency will be 30 MHz.

2. A series of standardized EQDSK equilibria were produced (at 5, 25, and 40% β) for the purpose of "benchmarking" available full wave and ray tracing codes. These equilibria are available via anonymous FTP; for details contact Stan Kaye or Dick Majeski at PPPL.

Up until now, the codes primarily exercised in this fashion have been PICES (a full-wave code extensively used for NSTX analysis at ORNL) and CURRAY (a ray-tracing code in use at GA and UCSD). Although modeling results on heating and current drive agree at low beta, the predictions of the two codes begin to diverge for the 25% beta case. In particular, CURRAY predicts higher ion absorption than PICES. The reasons for this apparent difference are under active investigation; several possibilities were discussed at the Forum.

3. Detailed particle orbit calculations now indicate that fully bootstrapped operation of an ST may be possible, without an on-axis "seed current". The possiblity of fully bootstrapped startup was discussed.

4. Aside from HHFW, most of the rf modeling has focussed on electron Bernstein wave techniques as a substitute for conventional ECH. Even at modest parameters, the NSTX plasma should be optically thick to the EBW for the first 2-3 harmonics. Accessibility to the harmonic layers appears good, once the EBW has been excited. Analyses of two different approaches to mode-conversion from the X-mode to the EBW near the plasma edge indicated that high mode conversion efficiency was possible. Since the Bernstein wave propagates very close the the plasma edge the possibility of direct launch using a slow wave structure was also discussed. A critical issue here is the polarization of the EBW near the plasma edge, which will determine the optimum launcher design. In all cases, ray-tracing analysis of the Bernstein wave trajectory is needed. EBW techniques may have a role inheating low temperature startup plasmas.

The large expected optical thickness of the EBW may permit Bernstein wave emission to function as an electron temperature diagnostic.

Experiments in HHFW

Experiments performed in CDX-U at the 100 kW level have now demonstrated electron heating by HHFW. The effect of a variable angle between the magnetic field line and the antenna strap was examined and found to produce minimal modifications to HHFW launch, as long as the angle between straps and field line was greater than about 30^o.

The use of DIII-D for further testing of HHFW absorptivity was proposed. DIII-D operates at the highest harmonic number (typically 6-7 or more) of any present day large tokamak, and has also operated at relatively low toroidal field (~7 kG). Hence a test of the predicted high single pass absorption for HHFW can be performed on DIII-D, if a sufficiently high $n_{||}$ can be launched with the DIII-D antenna set.

Further modeling needs

The startup scenarios have not yet been adequately addressed. Initially this need can be addressed by iterating between TSC and PICES to evolve the early equilibria. However, there is a clear need to integrate an rf code capable of modeling HHFW heating and current drive into TRANSP. In the near term, there is a need for a “standard” set of equilibria and kinetics for NSTX to enable modeling uniformity between groups. Even in the case where modeling uniformity has been assured, there is an unresolved discrepancy between full-wave and ray-tracing results as to ion absorption.

Ray tracing of the EBW is needed in an ST geometry. For the direct launch option, there are as yet no launcher designs.

Debate on the viability of an edge reflectometer persists; the possibility needs to be examined in detail.

Operational needs

Position control for the outer plasma to control the edge density and therefore the antenna loading.

Identify placement of the ECRH antenna.

Diagnostic needs

Multichannel interferometry is needed for any rf modeling; at least one chord in addition to the plasma core.

Edge reflectometry, if feasible, will not be available on Day 1, hence a reciprocating probe in the midplane toroidally separated from the antenna by one port is needed.

An IR camera should be dedicated to the RF antenna from Day 1.

Wide bandwidth for the microwave interferometer is desired in order to detect HHFW driven density fluctuations.

Fast particle loss detectors (need is common to NBI; although the loss orbits may differ for RF-induced and NBI losses).

System to detect core Alfvenic (TAE, etc) fluctuations.

3. Energetic Ion Physics Issues on NSTX

This section on energetic ion physics issues on NSTX is a new addition to the WG2 summary. R. Nazikian of PPPL provided a new perspective on physics research elements in this area. The necessary measurements are largely similar to those from the previous forum, thought some new aspects are evident in the prioritized list of diagnostic needs. Supplementary written comments and/or expressions of interest from both domestic and international institutions are included in this report.

Energetic Ion Physics Elements

NSTX presents us with an entirely new regime for studying energetic ion confinement and transport. Some of the unique features of energetic ions in NSTX are: high energetic particle beta, large population of super Alfvénic ions, large Larmor radii and orbit width, large population of trapped ions even for co-beam injection, anisotropy induced by prompt loss of edge or counter going beam and/or RF ions, and existence of a deep magnetic well at high beta. A key question is whether we can predict and confirm experimentally the prompt loss, transport and heating profile of energetic ions in NSTX in this new parameter regime. Such information is required to: (a) determine the efficiency of NBI and HHFW heating/current drive, (b) determine plasma power balance and thermal transport and (c) determine the effect of energetic particle loss on plasma facing components such as stabilizer plates. Below are detailed discussions of various aspects of energetic particle physics on NSTX.

Auxillary heating and single particle orbit loss

The loss of beam ions or the possibility of an energetic ion tail excited by HHFW injection is key issues for immediate study. Orbit calculations indicate a significant loss fraction of beam ions near the plasma edge or in the counter direction. Although the beam ions will be injected in the direction of the plasma current, collisions during the slowing down time can lead to pitch angle scattering into lost orbits. Also, modeling of the distribution of energetic ions possibly driven by HHFW heating is needed, as well as the interaction of HHFWs on injected beam ions. The potential degradation of central HHFW heating due to coupling to beam ions or due to edge ion heating and prompt loss needs to be modeled and measured accurately. Similarly, the distribution of prompt loss beam ions needs to be modeled immediately for predicting the peak localized heating expected on the stabilizer plates.

Collective Energetic Particle Effects

A major challenge in the next 2-3 years is to determine the impact of collective fast ion effects on the internal redistribution and loss of energetic ions in NSTX, particularly in combination with other single particle transport processes. Theory and experiment have developed significantly in the understanding of energetic particle instabilities, particularly in relation to toroidal Alfvén Eigenmodes (TAEs). Although reasonable agreement exists between linear TAE theory and experiment in current devices, more effort is required to assess the impact of TAEs in spherical tokamaks.

At present, the non-linear behavior of energetic particle driven and the resulting particle transport is only poorly understood. Large prompt losses of super Alfvénic neutral beam and ICRH hydrogen minority ions have been observed previously under conditions of large central beta (~1%) in conventional tokamaks, and NSTX is expected to have much higher beam beta (up to 10%). Efforts to understand the nonlinear mechanisms that determine the saturation level and particle transport of TAEs have only just begun. Even less information exists on fast ion instabilities which may be relevant to NSTX such as fish-bones, kinetic ballooning modes (KBMs), resonant TAEs (RTAEs) or energetic particle driven modes (EPMs), and the velocity space modes that give rise to ion cyclotron emission (ICE).

To advance such studies, we required detailed internal measurements of plasma equilibrium, fluctuations and energetic particle distributions for comparing with theory. For theory, significant work is needed to produce a self-consistent non-linear quantitative model of TAEs and collective energetic particle instabilities.

MHD interaction with energetic particles

Another important area of study is the loss of energetic particles due to sawteeth, neoclassical tearing modes, disruptions, and other MHD activity, which introduce non-axisymmetric field perturbations. A major concern is the potential for sawteeth and other modes to redistribute fast ions to larger radii or to induce prompt loss and localized heating of the wall.

Large internal redistribution and even loss of energetic particles was observed during the saw-tooth crash in TFTR with the PCX and a-CHERS diagnostics. Fast ion detectors also showed large transient alpha particle losses during sawteeth, disruptions, and various types of MHD activity. Further measurements and modeling of such losses are important for NSTX as these effects may well be more severe in spherical tokamak geometry.

RF-wave fast ion interactions

Present and future devices require substantial RF for heating, pressure and current profile control in the plasma. These waves have all been observed to interact with fast ions in tokamak plasmas and one major concern is the interaction of HHFWs with beam ions in NSTX. Further study of interactions between RF waves and fast ions is warranted for several reasons. First, energetic particle wave absorption and subsequent behavior of the fast ions may affect heating and current drive efficiencies. Second, substantially enhanced losses of fast ions have been observed from such wave-particle interactions in TFTR. Third, it may be possible to apply wave-particle interactions to alter fast ion behavior in a number of useful ways. These include: transfer of the energetic particle energy to current drive or ion heating (so-called “alpha channeling”); driving energetic ions away from loss cones and transporting neutral beam ions from the edge to the center of a reactor-scale plasma for core fueling. To develop these ideas and assess their practicality, considerable experimental and theoretical efforts are needed.

Comments from Participants and Others

Emil Ruskov: PPPL

The principal objective of NSTX is creation of novel plasma regimes with high beta values and bootstrap currents. Initial ion heating will be with 6MW of High Harmonic Fast Waves (3-4MHz). In the latter phase of the project (year 2000) 5 MW of neutral-beam injection with up to 5 sec. pulse length is considered. The low value of the magnetic field (B=0.3T) points to existence of rich fast ion phenomena.

1. Single orbit effects

Gyro-orbit and guiding center code simulation of beam ions have found strange beam ion trajectories with large Larmor radii. For CTR injected D-beam ions at 80KeV, depending on the magnetic equilibrium details, 40-70% beam ion loss is calculated; for CO-beam ions, about 10% loss is calculated. This provides an excellent opportunity for testing theTRANSP and ORBIT code predictions for the localization and the amount of beam ion loss. The fusion product gyro-radii are of the order of the minor radius and they are expected to be promptly lost.

2. Collective effects

In NSTX beam ions are Supra-Alfvenic, which might lead to excitation of TAE modes and substantial beam ion loss. TRANSP simulations of NSTX plasmas calculate 30% beam driven current and neutron emission almost entirely originating from beam-target reactions. Significant beam ion loss will lower the experimental values. Beam blips and beam modulation can be used for testing various TRANSP fast ion loss models. These models must accurately reflect the loss levels in order to make any meaningful transport analysis. In other words, transport and fast ion confinement are very closely linked research topics in NSTX.

TRANSP modeling of recent experiments with tritium beam blips in TFTR reversed magnetic shear plasmas have indicated large (~40%) beam ion loss on a time scale much shorter than the beam ion slowing down time. This unexpected result could not decisively be confirmed with ORBIT code simulations. It was found that with the TRANSP calculated radial and pitch angle distribution of T-beam ions, ORBIT predicts at most a third of the implied loss. The ORBIT code loss predictions are particularly sensitive to the pitch angle distribution. A problem with accurate calculation of this distribution might exist in TRANSP. All these considerations point to a need for a detailed diagnostics of fast ion loss.

3. Fast Ion loss Diagnostics

In addition to fast infrared camera viewing a poloidal cross section of NSTX, an "integrated loss" diagnostics should be very useful. At several locations on the outer side of one poloidal cross section, and in between the stabilizing plates, retractable diagnostics heads with the following sensors are proposed:

1. Bolometer/Photo-diode combination for measurement of the total, and radiated energy flux.

2 . Silicon barrier or ion implanted detectors for neutral particle analysis. With liquid nitrogen cooling and pulse height counting techniques, they provide good energy resolution in the ~5KeV to 2-3MeV range (poster hTupP1 11 by Lyon, Oak Ridge, at the last Pittsburgh APS meeting)

3. Thin Faraday collector foils for beam ions (F. Cecil at the September meeting at JET responded that such collectors can be optimized for beam ion loss detection)

The advantage of having multiple loss diagnostics at the same location is obvious. Loss measurements can be cross checked and different types of losses can be more accurately identified.

Anatoli Krasilnikov: TRINITI

I hope you know about my and N.Gorelenkov proposal to use NDD for escaping energetic charged particles on NSTX. Nikolay Gorelenkov already discussed it with many physicists from NSTX and as I know this proposal has good perspectives. Nikolay will retern to Princeton 19 of December and you can discuss this point with him.

Another possibility on NSTX is to use NDD for energetic charge exchange atom spectrometry. As you know on TFTR we measured in the range 200 keV - 2.5 MeV. 200 keV limit was only due to ADC low level discrimination. I am sure that NDD with simular contacts can be used for charge exchange atom spectrometry with energy at least down to 50 keV. NDDs with special contacts could be developed for energy range ~ 10 keV. Of couse problem of noise due to gammas and neutrons should be estimated for NSTX conditions.

Michail Petrov: IOFFE Proposal for a Pinhole Neutral Particle Analyzer on NSTX

I. Justification

For low aspect ratio tokamaks, it is very important to study the loss and confinement of supra-thermal ions (E ~5-10 kT_i). Measurement of the radial profile of the ion energy distribution over a wide energy range is required both in steady state conditions (orbital losses) and during MHD activity (saw-tooth oscillations and other low frequency MHD events). During NBI, the ion energy distribution function can also be distorted by beam pressure gradient driven instabilities (TAE-like modes) because the Alfven velocity in the NSTX is ~ 10^8 cm/sec (which corresponds to ~50 keV ions). Measurement and modeling of the local ion distribution allows the study all these important effects in NSTX.

2. Diagnostic

We propose to use a radial viewing, multi-chord Pinhole neutral particle analyzer (NPA) to obtain passive charge exchange measurements of the local energy distribution of hydrogen ions in an energy range 0.5 -50 keV. The geometry of the experiment, shown in Fig. 1, views trapped ions, which are most sensitive to the effects noted above. Toroidal tilting of the instrument (if possible) will allow the study of trapped ions with different pitch angles.

A Pinhole NPA developed at the Ioffe Institute (St. Petersburg, Russia) has seven chords covering an angular range of +/- 30^o, an energy range of 0.5 - 50 keV, and uses either a gas chamber or a foil for neutral stripping. An electrostatic toroidal condenser is used for energy analysis and the detectors are channeltrons. The instrument is relatively compact (24 x 27 x 37 cm, weight 40 kg). Additional magnetic shielding of the analyzer (at least single layer and possibly double layer) will need to be provided by PPPL.

3. Expected Experimental Data

For typical NSTX discharge parameters during NBI, the estimated count rate of the NPA channels is ~ 10^5 s^{-1} in the energy range 2 - 20 keV which will allow the energy to be swept on a time scale of ~ 10^{-2} s. Without sweeping, measurement is at a selected energy common to all channels. The S/N due to the neutron and gamma background of xxx $cm^{-2}s^{-1}$ is estimated to be ~ xxx.

4. Status of Proposal

We are developing the analysis the possibilities of the PNPA for NSTX. PNPA can be installed a little bit more outside from the plasma machine (0.6 m outside of the toroidal coils). It will help to solve the problem of gas pumping. In addition we can use hydrogen or deuterium for stripping. PNPA in this case will be able to cover the angle range +/- 20 deg. In toroidal direction it will see both perpendicular and tangential particles and in poloidal will cover +/- 0.7 r/a. It is also will be possible to tilt the poloidal PNPA in toroidal direction, so you will see many kinds of orbits in one shot. A more detailed proposal will be delivered to NSTX in February 1998 upon my return to PPPL.

The Pinhole NPA can be delivered to PPPL six months ARO at a cost of $90k SIF US airport. However, the instrument needs detailed calibration with ions/atoms beams, which in principle could be done at either Ioffe or PPPL. The Pinhole NPA can be used on NSTX with the help of Ioffe experts that could stay at PPPL under the US/RF Exchange.

Summary of Issues and Recommendations from WG2 Presentations

• Need modeling of the expected charge exchange spectra.

• Need guidance from the RF group on what fast ion effects might be envisioned for HHFW and its interaction with energetic NBI ions.

• RF needs "fast" time resolved radial profiles of T_e (EBW), T_i (CHERS), $f_{NB,RF}$ (NPA) and toroidal rotation velocity (CHERS, X-ray Crystal) for understanding of RF performance (i.e. where is the power going and what is is coupling to). Other RF specific needs are

- n_e and T_e near the antenna (O-mode reflectometer, probes)

-RF pickup loops around the machine

- dedicated IR/Visible TV coverage

-j(r,t) with MSE will need beam blip during RF-only cases, but this data needed because the unexplored magnetic topology is a factor for NSTX

• Need standard set of equilibria for evaluation of physics/diagnostics issues.

• Points from Mikkelsen's talk

- NBI will always be unbalanced (counter injection is too lossy for balance) and we don't know if the rotation will be larger or smaller than equivalent scenarios on TFTR

- edge TF ripple is 0.5%...quite large so lost ion diagnostics gain importance. However, Mikkelsen claims ripple diffusion will not cause additional loss (except perhaps at the very outboard edge) because loss would occur due to orbit geometry anyway.

• Points from Gorelenkov's talk

- ICE generated by the magnetosonic cyclotron instability may be stronger than in tokamaks since all d ions in NSTX with E > 10 keV are superalfvenic ($v_A \sim 10^8$ cms^{-1}). In NSTX the eigenmodes are not at the edge, so external RF probe measurement as used on tokamaks may not work. The internal effect of ICE might possibly be detected with an interferometer if the bandwidth is sufficiently high (~ 5 MHz).

- passing/trapped boundary is "fuzzy" more so than in tokamaks due to large ion gyro-orbits

Appendix -Working Group 2 Agenda

Morning session – Heating and Current Drive Plans, Energetic Particle Issues, Diagnostic Needs

R.F. Heating and Current Drive Program for NSTX – R. Wilson

High Harmonic fast Wave quantification Experiments for NSTX – M. Carter

DIII-D capabilities at low field – R. Pinsker

Electron Cyclotron Emission Diagnostic for NSTX Utilizing Electron Bernstein Waves – P. Efthimion

Energetic Particle Confinement: Some Issues and Needs on NSTX – R. Nazikian

Energetic particle orbits in NSTX – D. Mikkelsen

Lost energetic particle measurements using thin foil Faraday collector – F. Cecil

Cyclotron instabilities in spherical tokamaks – N. Gorelenkov

Energetic particle Alfven wave excitation in NSTX – H. Berk

Beam-ion physics and diagnostics issues at NSTX – E. Ruskov

Neutral Particle analysis on NSTX – S. Medley

Afternoon Session – ECH possibilities, Modeling, Discussion

Electron cyclotron heating and current drive in NSTX – A. Ram

An electron cyclotron heating and current drive approach for low temperature startup plasmas using O-X-EBW mode conversion – D. Batchelor

HHFW current drive and profile control studies on spherical tokamak plasmas – T.K. Mau

A potential 100% Bootstrap Current Start-Up Method in NSTX – K. C. Shaing