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

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Working group 2 identified 5 basic objectives for our discussions (some of which were accomplished):

1) Identify the possibilities for various heating and current drive approaches
2) Identify the critical issues which must be resolved for the various approaches to be successful on NSTX
3) Identify elements of heating and current drive physics which can effectively be tested on NSTX (independent of their importance for the NSTX mission itself)
4) Identify hardware, diagnostic, or theory needs to test the various possibilities
5) Determine required plasma conditions for a given technique to function

Four types of technique were considered:

1) RF in the ion cyclotron range of frequencies:
   - High Harmonic Fast Wave ($\omega \sim 10\,\Omega_i$ - $20\,\Omega_i$)
   - Low Harmonic Fast Wave ($\omega \sim \Omega_i$ - $2\Omega_i$)
   - Alfven ($\omega < \Omega_i$)
   - RF helicity injection/other non-linear
2) Neutral injection
3) RF in the electron cyclotron range of frequencies:
   - Fundamental and 2nd harmonic Ω_e
   - Conversion to electron Bernstein Wave (EBW)
4) Current ramp by bootstrap

Although strictly speaking the last of these does not involve fast particle interactions, the success of the technique will rely on the ability to heat rapidly and to maintain a controlled pressure profile. It therefore fit appropriately within our working group.

RF in the Ion Cyclotron Range of Frequencies

The RF heating and CD technique which has been studied most for NSTX is high harmonic fast waves (HHFW). High power sources are available from TFTR at about 41 MHz. This translates to $f_{rf} \cong 4\,fD$ on the inside plasma edge up to f ~32 f_D on the outside edge. For fast waves the spatial damping rate on electrons $k_i = \mathrm{Im}\{k_\perp\}$ is proportional to $\mathrm{Re}\{k_\perp\}\beta_e$. Because of the low magnetic field in NSTX both

β and $k_\perp \propto \omega_p / \Omega_c$ tend to be quite large, leading to strong damping even at modest plasma conditions. We therefore anticipate being able to effectively heat over a wide range of plasma conditions. In conventional tokamaks which have considered fast wave current drive at $f \sim f_i - 2 f_i$ the electron damping is weak so that power absorption and driven current are highly peaked at the center. However in NSTX one can in principle control the radial deposition and current drive profile by adjusting the wave phase speed. Also relatively fast waves are well absorbed, $v_{phase} \sim 2 v_{thermal}$, so the current drive efficiency can be quite high. Calculations with a 2D full wave code have shown that by judicious choice of the launched toroidal and poloidal mode number, steering the absorption to the high field side of the magnetic axis where trapped particle effects are minimized, that 1 MA could be driven in NSTX at $n_e = 5 \times 10^{19} m^{-3}$ and $T_e = 2$ keV with $P_{rf} = 6$ MW. It will be difficult however to realize this with an actual antenna. Other applications for HHFW include: plasma and current buildup from relatively low performance plasmas provided by CHI or ECH startup. Strong electron absorption suggests possibility of buildup from very modest plasma conditions. Finally ICRF plasma initiation, as demonstrated on TEXTOR, should be considered.

The primary critical issues for use of HHFW in NSTX relate to compatibility of HHFW with neutral injection and antenna issues. Because of the large plasma dielectric constant (i.e. short wave length) fast waves can couple to energetic ions even up to quite high harmonics. For example in 2D full wave calculations including a hot ion component with $\eta_{hot} = n_{hot} / n_e = 0.1$, $T_{hot}(0) = 25$ kev and $T_{hot}(a) = 16$ kev up to 40% of the power was absorbed by the hot ion component. High bulk ion temperatures can also pose a problem from the standpoint of linear cyclotron harmonic absorption and conversion to high harmonic ion Bernstein modes. The degree to which this is a problem depends sensitively on the hot ion concentration, energy spectrum and profile, and requires further study. The concern is both that the electron deposition and current drive will be reduced and that the fast waves will produce trapped energetic ions and cause losses. There are however possibilities that synergies exist between the waves and energetic ions which can be beneficially employed.

The issues for antennas involve: 1) design to achieve maximum current drive efficiency and flexibility and, 2) issues related to antenna/edge plasma interactions such as sheath power dissipation. For both concerns the environment in NSTX will be substantially different from that in conventional tokamaks where our experience lies - in particular low magnetic field and the wide range in poloidal angle of the magnetic field near the antenna (0° at startup, ~ 45° at full current). Calculations with a 3D antenna code show that the lunched power in NSTX is very asymmetric with respect to toroidal and poloidal mode number. It is advantageous to launch long parallel wavelengths near the antenna in order to reduce edge absorption due to $k_{||}$ upshift and to direct power to the high field side where CD degradation from trapped particle effects is minimized. Two techniques have been studied so far to accomplish this: use of multiple, relatively phased poloidal straps, and poloidal placement of the antenna. It is found that factors of ~2 improvement in CD efficiency can be made by either of these approaches.

A major issue in ICRF antenna design for conventional tokamaks has been to minimize deleterious interactions between the antenna and the edge plasma. Theoretical modeling and comparison of theory and experiment on JET, TFTR and other tokamaks has shown that ions accelerated in the RF sheaths are responsible for RF-specific impurity generation, SOL density profile modification, and parasitic power dissipation. The power loss in the sheaths can, in extreme circumstances, cause greatly reduced heating efficiency and overheating of the antenna and limiter structures. There are several reasons why the sheath voltage V and associated sheath effects could be particularly large on NSTX. First, the fact that the field line pitch varies greatly between startup and full current operation makes it difficult to align the magnetic field with the antenna. For antennas with Faraday screens (FS), $E_{||} \propto \sin\theta$, where θ is the angle between the B field and the FS bars. On NSTX the mismatch angle θ will be unusually large during part of each discharge, which enhances $E_{||}$ and hence the sheath voltages. The spatial variation of the rectified sheath potential can drive $E \times B$ convection, which increases the perpendicular flux of plasma to the antenna and thus enhances the rate of impurity generation or local heating. Another unique feature of the NSTX configuration is the relatively low value of B near the outboard antennas. The convective enhancement of the perpendicular flux scales as $B^{-1/2}$, which further increases the edge interactions on NSTX relative to a standard tokamak.

Thus, one of the challenges of successful ICRF heating and current drive on NSTX will be to find means of controlling the RF sheath interactions. The standard techniques are 1) to use a particular choice of $d\phi$, the phase difference between adjacent current straps, to cause cancellation of the $E_{||}$ along a typical field line, and 2) to reduce the density at the antenna by the use of bumper limiters which are closely spaced in the toroidal direction. In any case, for a novel physics experiment like NSTX which is exploring a new heating regime, it would not be desirable to restrict the phasing *a priori*. The use of bumper limiters for sheath control works best when the RF convection is small and the plasma flux to the antenna is mainly diffusive. This is hard to achieve in most high power heating experiments. For the values of sheath voltage expected in NSTX, the RF convection dominates the diffusion and the large convective flux $\Gamma_{\perp} = nv$ of the plasma into the antenna ensures strong edge interactions, even though the local density at the antenna is low . Another possible technique for sheath reduction on NSTX is the use of insulating limiters. The basic idea is that the voltage V can be made to appear across the insulator rather than the plasma if the insulator impedance is large enough. Preliminary experiments using boron nitride limiters on Phaedrus were successful, but questions remain about the suitability of this material in a fusion plasma environment. Recent work to develop a new class of composite insulators shows promise for this application; recent calculations suggest that the new materials should be useful for RF sheath mitigation, and further tests under fusion plasma conditions are planned in the next two years. If successful, these materials would be available in time to be used on NSTX.

Use of low harmonic fast waves (LHFW) ($\omega \sim \Omega_i$ - $2\Omega_i$) was also considered. The advantage being that there are reasonable gaps in cyclotron layers allowing penetration to the core and is less susceptible to beam absorption This approach has not been much examined for ST so we need general reassessment (e.g.. at various β. Critical issues which are known include: availability of sources at the needed low frequencies (~5 MHz) and difficulty of spectrum control at such long wavelength.

Other possibilities for use of ICRF in NSTX: for Alfven waves, RF helicity injection and non-linear mechanisms such as rotating magnetic field current drive.

Opportunities for basic physics studies include: Physics of wave-particle interaction at large high $n\Omega_c$ and large $k_\perp \rho$

Research needs include a number of areas of theory and modeling:

Antenna analysis - launched spectrum optimization for various operating conditions, effect of strap angle, study of antenna/edge interactions $E_{||}$, sheaths, fast vs. slow excitation

Assessment of various ramp-up scenarios - determination of minimum target plasma requirements (DIII-D result suggest needed single pass absorption 5-10%, could be greater), evaluation of plasma and current ramp from initial ECH or CHI plasmas, assessment of ICRF plasma start-up

Assessment of performance capabilities and profile control in full performance plasmas - compatibility with NBI and high bulk temperature, compatibility with helicity injection

Code comparisons with standardized NSTX equilibria: full wave & ray tracing (even slab)

Assessment of common approximations: $\rho/L < 1$, $B \bullet \nabla B$ effect on $k_{||}$ (development may be needed)

Assessment of LHFW possibilities

Experimental research is also needed, particularly in the areas of antenna and edge plasma data base: CDX-U, DIII-D, PEGASUS (future)

Diagnostic needs include:

IR camera imaging antenna, visible light - imaging of the antenna is essential

Time resolved T_e: ECE, multi-pulse Thompson Scatt., EBW (new proposal), Soft X-ray camera (2D)

Diagnostics for SOL conditions: n_e, T_e (probes, reflectometer (not easy))

Fast ions: lost ion analyzer, CX

We suggest the following general question for both ICRH and NBI: Is there a credible non-inductive ramp-to-full-performance scenario, interfacing with either CHI or ECH startup?

Neutral Beam Injection

Neutral beams are a proven technique for heating and current drive in tokamaks of conventional aspect ratio. It is planned to install one TFTR neutral beam line on NSTX as early as possible. Not only does the NBI provide heating, current drive and some central fueling, but is also needed for diagnostics such as MSE and CHERS. The beam line will be operated at 80keV for 5 MW of total injected power. Modeling with TSC and TRANSP indicates ~300kA of beam current drive.

As with ICRF, neutral injection on NSTX differs from conventional tokamaks as a result of the low aspect ratio and low magnetic field. These two differences give rise to large trapped particle fractions, as well as large ion gyroradii, $0.06 \le \rho_i / a \le 0.5$, and trapped particle orbits. Hence, there is concern about orbit and ripple loss and the resulting localized heat loads on plasma-facing components. Specific loss mechanisms of concern for NSTX include:

- New loss cones due to unusual magnetic geometry - poloidally asymmetric trapped orbits have been observed
- Scrapeoff losses due to wide gyroradius and drift orbits
- Stochastic toroidal field losses
- Losses due to MHD modes
- Interaction with HHFW

NSTX is also new territory with respect to beam induced instabilities such as fishbones. Of particular concern is susceptibility to TAE instabilities since the Alfven speed for NSTX is so slow, $0.4 < v_{beam}/v_A < 5.$, and the low aspect ratio widens the Alfven eigenmode gaps. There is also the possibility, as yet unexplored, of velocity space instabilities due to the magnetic geometry.

With a single beam, central fueling is quite modest. It would therefore be desirable to have pellets for central fueling, density control and for shine-through reduction in target plasma. For purposes of optimizing bootstrap currents, density control and profile peaking may be particularly important.

The most immediate research needs for NBI include more modeling to choose a beam aiming angle which optimizes CD, beam ion confinement, and shine-through. Shine-through calculations are needed for wall armor design. There are also theory needs for validating guiding center codes against full Lorentz force equation orbit calculations for the low magnetic fields and aspect ratios of NSTX.

Initial estimates of the minimum target plasma density needed for NBI are central *(/volume average?)* $n_e = 2 \times 10^{19} m^{-3}$. This will however depend on profiles and wall armor design so more studies are needed.

A number of specific diagnostics will be required to assess fast ion confinement and loss:

IR camera

Fast ion loss detectors

Neutral particle energy analyzer

- Temperature profile diagnostics
- Internal fluctuation diagnostics
- Mirnov coils
- RF probes
- Neutron detectors
- Fast ion spectroscopy
- Diamagnetic loop

The importance of neutron diagnostics to determine the effectiveness of heating and current drive techniques and to verfiy the soundness of plasma modeling was pointed out. Neutron "shortfall" correlates closely with fast-ion loss, presence of beam injected or RF produced tails, and can be used to detect small changes in T_i. It has been proposed that the TFTR fission-chamber neutron detection system be used on NSTX with little modificaiton. It is estimated that rates down to 3×10^{10} n/s could be measured.

There are a number of basic beam/plasma physics issues which can be studied advantageously on NSTX. These include:

- Beam-driven TAE modes
  - larger gaps
  - mode possibly less damped
  - modes possible even into continuum
- Physics of super-Alfvenic beams with applications to negative-NBI and fusion alphas
- Physics relevant to alphas in low aspect ratio
- Test of ripple loss models
- Enhanced slowing down an heat transfer to bulk by fast ion emission of Alfven waves
- Any new orbit loss cones at low aspect ratio?
- Will velocity-space instabilities be driven by beam ions or RF ions (AIC, magnetosonic modes)?
- Interaction of fast ions with RF waves at high cyclotron harmonics

RF in the Electron Cyclotron Range of Frequencies

It appears feasible on NSTX to use ECH for pre-ionization, plasma and current buildup and even bulk heating and current drive. At present there are only plans to provide 15-20 kW of power at 18 GHz for 10-20 msec for pre ionization. However NSTX-relevant ECH hardware available from ORNL could provide significantly more power at minimal costs - two 28 GHz gyratrons providing up to 400 kW. These gyratrons could likely also be operated at lower frequency using a different cavity mode, 15.3GHz, although probably at lower power.

ECH pre-ionization is an established technique which will provide reliable initialization of NSTX plasma to control timing and location of the initial current channel. There are no significant issues related to that.

Although the magnetic field is low, fundamental and second harmonic resonances of the 28 GHz power exist respectively at the inside plasma edge, and at $\rho/a \sim 0.5$. The 15.3 GHz second harmonic resonance lies near the axis. Each of these is directly accessible during the low-density startup phase. The 28 GHz fundamental and second harmonics heat at densities up to 1.8×10^{13} cm^{-3}. A primary interest is in ECH driven startup. Pressure driven current startup has been demonstrated on CDX-U and DIII-D using ECH alone. On DIII-D current above 20 kA, sufficient to produce a core of closed flux surfaces, was produced with 1 MW of power. In both CDX-U and DIII-D plasma densities exceeding the ordinary mode cutoff were produced. Simple application of a scaling formula developed by Forest *et al* in conjunction with the DIII-D work indicates that 42 kA would be produced in NSTX with 350 kW of ECH power. However, since the results from DIII-D were obtained in a single day's run, with no attempt to grow or optimize the plasma using the poloidal field system, it is anticipated that substantially better than that can be achieved.

Another exciting possibility is to use Electron Bernstein Wave (EBW) for plasma buildup and current drive or for bulk heating and current drive during high density conditions. Absorptivity of 3 harmonics appears quite high. Three options for wave accessibility show promise but need further investigation:

- > Direct EBW launch using an electrostatic antenna similar to a lower hybrid waveguide grill
- > Conversion at the plasma edge of a launched wave in the X mode to an EBW which is damped on electrons
- > Conversion of a launched O-mode wave to X-mode at the plasma cutoff layer. The X-mode then propagates to a linear turning point and returns to the upper hybrid resonance layer where it is converted to an EBW. This technique has been experimentally demonstrated on W7-AS

Related to these techniques is a proposal to use radiated EBW as an electron temperature diagnostic in lieu of ECE. Again because of the large value of $\omega_{pe} / \Omega_{ce}$ the first 5 or so cyclotron harmonics are cut off and cannot be used for ECE. Estimates indicate that the EBW should be optically thick on NSTX. There are 2 approaches for detecting the EBW: 1) employ an electrostatic antenna to receive EBW propagating to the edge, 1) Detect X-mode which has been converted from EBW at the upper hybrid layer. This is essentially the inverse of the heating process proposed above.

A further option is to use fundamental absorption of the 28 GHz ECH at the inside plasma edge to drive an edge current by the standard Fisch-Boozer mechanism. Such an current is needed to in some of the NSTX scenarios to supplement the bootstrap current and provide edge stability. By absorbing the power on the inside edge, trapped particle effects are reduced. This technique would probably require a more elaborate launching system of reflectors to launch the power from the high field side.

The immediate research need is for detailed analysis with NSTX geometry to evaluate each of the above scenarios. In particular it is important to assess the various startup and current ramp techniques as an alternative or supplement to CHI. Further experiments on DIII-D, C-MOD, and CDX-U would also be helpful. It appears that a proof of principle for the EBW temperature diagnostic could be performed on CDX-U. Of course a critical issue is for high power ECH to me made available on NSTX.

Bootstrap Current Ramp

A spreadsheet level calculation was done to determine the feasibility of using heating and density control to ramp current in a Spherical Torus by means of the bootstrap effect (i.e. maintaining $I_{BS} > I_P$). The calculations were actually done for a 5 MA device but we expect to get results for NSTX soon. The spread sheet solves two-fluid power balance in time with assumed profiles and confinement time (typically H-mode with H~2). The bootstrap current is computed for the assumed profiles using Hirshman's single ion model (valid at arbitrary A) with a collisional correction from Hazeltine and Hinton. For the 5MA device considered an initial 200kA plasma was assumed ($q_{95} \approx 165$ with a flat profile, then density was ramped up with current to maintain a constant fraction of the Greenwald limit. The back EMF was evolved in time using a $\tau_{L/R}$ with self consistent T_e. Ramping power into electrons with I_P ($P_e = 5V \cdot I_P$) and maintaining $\langle n_e \rangle = 0.5 n_{Greenwald}$ gave a ramp rate of up to $\mathrm{d}I_P/\mathrm{d}t = 0.5$MA/s with I_P reaching 2.MA on 10s. The observations from the exercise were that the process can in principle work, it is much better to heat the electrons than ions, that density control during ramp-up is essential, that β_P tends to be high. Modeling of NSTX is needed and more comprehensive scenario calculations with a 1-1/2D transport model are needed.

Startup and Heating Using High Harmonic Fast Magnetosonic Waves (HHFW) for the PEGASUS Tokamak

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We describe the Radio Frequency (RF) auxiliary heating plans for the PEGASUS Extreme Low Aspect Ratio Tokamak (ELART). RF heating can facilitate access to high ße (=2$\mu_0$neTe/B2) PEGASUS plasmas, reduce the demand on ohmic core volt-seconds, and provide off axis electron heating for the fully developed high ße plasma. A kinetic analysis of the HHFW propagation indicates that there will be significant RF heating even at the lower electron temperatures and densities that occur during the first 10 msec of ohmic ramp-up of the plasma current channel. High ß can also be maintained by adjusting the antenna array phasing, after the ohmic start up evolution. The ion cyclotron absorbtion that would be expected to compete with the electron power absorbtion in a neutral beam heated high ß LART should not be a problem for PEGASUS. Since the relative fractions of Current Drive (CD) and electron heating necessarily coexist and depend on the antenna array spacing and phasing, CD and maintenance of large ß are mutually compatible.

Use of CDX-U to address RF issues on NSTX

Jon Menard

High frequency fast waves are to play an important role in heating and driving current in high beta NSTX plasmas. Of major concern is the effect of the extreme field line pitch (up to 60 degrees) of the equilibrium magnetic field on the coupling physics of the fast wave. First, one would like to know how (or if) the angle between the straps and magnetic field affects how much power goes into different wave branches. Second, even if most of the power goes into the fast wave independent of strap angle, there may be a loading resistance variation with both phasing and angle. Third, even if all the power goes into the fast wave and loading variations are moderate as the field-line pitch and/or phasing change, what happens to the heating/current drive deposition profiles as these parameters change?

To begin to address some of these concerns regarding high frequency fast waves on NSTX, a 2 strap antenna which can be manually rotated between shots was installed in the CDX-U tokamak. Thus far, most of the RF experiments performed on CDX-U have concentrated on the loading issues mentioned above. In particular, it has been observed that the plasma loading resistance is nearly independent of strap angle with respect to the equilibrium magnetic field for 0-pi phasing. This is in agreement with a coupling code used for modeling fast wave loading on CDX-U (ANT1D). This code does, however, predict a significant increase in FW loading for 0-pi/2 phasing (i.e. current drive phasing) as the straps become increasingly parallel to B. This loading dependence on phasing and angle has not yet been tested on CDX-U, but will be in the near future. If there is a significant loading dependence on phasing and strap angle, using fast waves for both startup and current sustainment in NSTX may be difficult due to different matching requirements during different parts of the discharge.

Thus, while this may already be obvious to everyone else, these considerations only highlight the obvious need for controlled FW experiments on NSTX which test the phasing and angle dependence of the coupling physics. The phasing variation is trivial, while the angle dependence is more difficult, since one would like to vary the current to change the poloidal field magnitude while keeping the temperature and density profiles fixed at the edge. Thus, B-dot probes might be very useful for measuring wave polarization, loading can be determined from the usual power balance and strap currents, and edge profile diagnostics are very important here as well if any modeling is to be pursued.

RF Sheath Issues and Control on NSTX

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One of the strongest interactions between fast wave (FW) antennas and the edge plasma is the formation of RF sheaths.[1-4] RF sheath potentials arise from the requirement to confine electrons, which otherwise would be accelerated out of the plasma by the RF electric field. On field lines which intersect a material boundary and are immersed in plasma, the voltage driving the sheaths is given by $V = \int ds\, E_{||}$, where $E_{||}$ is the component of the RF electric field parallel to the equilibrium B field, and the integral is taken along the field line between the contact points. Sheath voltages during high power ICRF heating can easily be in the range of kilovolts. Theoretical modeling and comparison of theory and experiment on JET, TFTR and other tokamaks has shown that ions accelerated in the RF sheaths are responsible for RF-specific impurity generation, SOL density profile modification, and parasitic power dissipation. The power loss in the sheaths can, in extreme circumstances, cause greatly reduced heating efficiency and overheating of the antenna and limiter structures. It is generally accepted that sheath control is necessary to achieve optimal ICRF antenna operation.

There are several reasons why the sheath voltage V and associated sheath effects are expected to be particularly large on NSTX. First, the fact that the field line pitch varies from 30 to 60 degrees between startup and full current operation makes it difficult to align the magnetic field with the antenna. For antennas with Faraday screens (FS), $E_{||} \propto \sin\theta$, where θ is the angle between the B field and the FS bars. On NSTX the mismatch angle θ will be unusually large during part of each discharge, which enhances $E_{||}$ and hence the sheath voltages. A second unusual feature of NSTX is the use of high harmonic fast wave (HHFW) heating, which introduces another source of $E_{||}$. The ratio of the off-diagonal to diagonal elements of the plasma dielectric tensor ($\varepsilon_X/\varepsilon_\perp$) scales as $\varepsilon_X/\varepsilon_\perp \propto \omega/\Omega_i$, which is large in the HHFW regime. This has two effects: a small $E_{||}$ contribution to the fast wave polarization ($E_{||}/E_y \propto \varepsilon_X^2/\varepsilon_\perp\varepsilon_{||}$) and a potentially larger contribution to the slow wave polarization that is proportional to the density gradient ($E_{||}/E_y \propto \varepsilon_X'/\varepsilon_\perp$). Thus, NSTX is likely to have large sheath voltages. The spatial variation of the rectified sheath potential can drive $E \times B$ convection,[5] which increases the perpendicular flux of plasma to the antenna and thus enhances the rate of impurity generation or local heating. Another unique feature of the NSTX configuration is the relatively low value of B near the outboard antennas. The convective enhancement of the perpendicular flux scales as $B^{-1/2}$, which further increases the edge interactions on NSTX relative to a standard tokamak.

Thus, one of the challenges of successful ICRF heating and current drive on NSTX will be to find means of controlling the RF sheath interactions. The standard techniques are 1) to use a particular choice of $d\phi$, the phase difference between adjacent current straps, to cause cancellation of the $E_{||}$ along a typical field line, and 2) to reduce the density at the antenna by the use of bumper limiters which are closely spaced in the toroidal direction. The optimal phase difference is found to be π for 2-strap antennas, but for larger antennas the improvement is not as noticeable. The sheath cancellation is imperfect for antennas with many current straps (e.g. the 6-current strap design of NSTX), because there are many asymmetric field line connections. In any case, for a novel physics experiment like NSTX which is exploring a new heating regime, it would not be desirable to restrict the phasing *a priori*. The use of bumper limiters for sheath control works best when the RF convection is small and the plasma flux to the antenna is mainly diffusive. This is hard to achieve in most high power heating experiments. For the values of sheath voltage expected in NSTX, the RF convection dominates the diffusion and the large convective flux $\Gamma_\perp = nv$ of the plasma into the antenna ensures strong edge interactions, even though the local density at the antenna is low .

Another possible technique for sheath reduction on NSTX is the use of insulating limiters.[6] The basic idea is that the voltage V can be made to appear across the insulator rather than the plasma if the insulator impedance is large enough. Preliminary experiments using boron nitride limiters on Phaedrus were successful,[6] but questions remain about the suitability of this material in a fusion plasma environment. Recent work[7] to develop a new class of composite insulators shows promise for this application; recent calculations[7] suggest that the new materials should be useful for RF sheath mitigation, and further tests under fusion plasma conditions are planned in thenext two years. If successful, these materials would be available in time to be used on NSTX.

In conclusion, a number of techniques exist for controlling RF sheaths and experiences on other experiments indicate that some effort should be expended in this area in order to have optimal FW heating and current drive.

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High Harmonic Fast Waves for Current Profile Control in NSTX

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Non-inductive current drive (CD) is required during plasma initiation and for current sustainment in NSTX. Current profile control is also desirable for experiments related to transport and turbulence. The operational and experimental possibilities for NSTX using high harmonic fast waves (HHFW) have been analyzed with the PICES[1] and RANT[2] codes. The CD efficiency is calculated using the Ehst, Karney empirical fit . The results indicate that the theoretical CD efficiency for HHFW can be very high, exceeding 1 MA for 6 MW of launched power for high density ($5x10^{19}m^{-3}$), full current scenarios. The current drive potential is much higher at low plasma densities ($\sim 1x10^{19}m^{-3}$). Current profile control may also be attainable with a HHFW system because of the strong absorption in NSTX. These theoretical possibilities can only be approached if sufficient flexibility is built into the HHFW antenna system. The system must be designed to reduce the effects of trapped particles if high CD efficiency is to be obtained for high density scenarios.

An appropriately designed HHFW system can allow experiments to be conducted with significantly different current profiles for turbulence and transport studies. Substantially different current profiles are possible for some plasma regimes by alternatively driving the HHFW system in the direction of, or opposite to the direction of the bootstrap current. Toroidal phase control for the antenna system can also provide current profile control in plasma regimes that produce moderately strong first pass absorption.

The use of HHFW should scale very well with future possible increases in the magnetic field strength for NSTX because of the scaling of parasitic ion absorption on $k_{\perp}\rho \sim \omega \upsilon_t / \Omega \omega_{a} \sim 1 B^2$ and because of the electron absorption scaling with β. Thus, raising the magnetic field strength greatly reduces parasitic ion absorption, and allows deeper penetratrion for high density operation.

The results to date can be summarized as follows: (1) The theoretical current drive efficiency for HHFW can be very high, and this study provides a good target for the actual antenna design. Non-zero poloidal mode excitation provides the best efficiency because of improved penetration to the high field region where trapped particle effects are reduced. However, limitations on antenna placement and phase control can substantially reduce the efficiency. (2) During plasma initiation, the primary issue for HHFW is loading since the CD capability is good. More profile information during start-up is needed to complete this study. (3) Standard launch from the equatorial plane leads to marginal CD performance at high density and full current, but advanced antenna designs exploiting the theoretical results show promise. For example, poloidal phasing with equatorial launch can add roughly 30% to the CD efficiency. Placement of the antenna away from the equatorial plane near the top or bottom of the tokamak can improve efficiency by about 100%. Other issues that have been addressed include the variation in strap loading during the current ramp and the strap-to-strap loading required for stable phase control of the antenna.

Perhaps the most important issue to still address is the edge phenomena that may limit the power handling capability of the antenna. HHFW produces, and in fact requires substantial electric field components parallel to $\boldsymbol{B}$. These parallel fields may require careful consideration when designing the lateral protection for the antenna to avoid sheath rectification and heating. Large parallel fields may also lead to substantial ponderomotive effects because of the relatively low confining magnetic field.

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NSTX RESEARCH FORUM

Improved Modelling of HHFW Current Drive Scenarios for Low-Aspect-Ratio Tokamaks

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Current drive and profile control in the off-axis region is a challenging issue facing tokamak concepts with attractive features like high β and high self-driven current fraction. For the low-aspect-ratio tokamak, such as NSTX, the high-harmonic fast waves (HHFW) [1] appear to be the most feasible candidate for off-axis current generation. To determine the driven current, the trapped electron degradation of the normalized local current drive (CD) efficiency must be accurately calculated. Present modelling codes make use of empirical CD effciency formulas based on fairly large aspect ratio ($\varepsilon<0.3$) plasmas. For accurate evaluations, a CD efficiency model that is valid for $0<\varepsilon<1$ and takes into account paramagnetic effects must be used. Such a model has recently been implemented in the CURRAY [2] ray tracing code, and is based on the adjoint technique [3] to solve the relevant Fokker Planck equation in a realistic equilibrium. The CURRAY code also has the capability of calculating the high-harmonic wave absorption by energetic ions represented by a slowing down distribution function. These capabilities appear to be quite suitable for exploring and analyzing proposed scenarios of current drive and profile control on NSTX using the HHFW and neutral beam injection, and for extrapolation of these scenarios to burning devices. To complement ray tracing modelling, it is proposed to upgrade the TORIC [4] full wave code to similar capabilities in order to investigate the effect of various antenna configurations on the CD scenarios.

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RF HELICITY AND NONLINEAR CURRENT DRIVE IN NSTX

by Paul Moroz, Univ. Wisconsin-Madison

Spherical tokamaks (ST) normally feature relatively high density, low magnetic field, and low temperature regimes of operation. Moreover, the trapped particle effects are very significant. As a result, many standard RFCD methods and neutral beam injection become not very efficient. CD methods via the fast waves at high harmonic (HHCD) frequencies, presently proposed for use in NSTX, although possible are still difficult and tricky especially in providing an efficient current profile control.

This proposal is focused on theoretical analysis and full-wave numerical simulation of a few non-standard CD techniques that can be applied to NSTX and will supplement the so far leading methods of HHCD and NBI. The idea is to search and investigate the CD methods that fit specifically to the unique ST geometry and parameters. In particular we are planning to focus on RF methods that are due to wave interaction with the bulk plasma and not only with the narrow region (in velocity space) of the resonant particle population. Some of these methods have been discussed in literature although presently none of them is developed enough to be directly used for NSTX. Among them are RF helicity current drive, rotating magnetic field current drive, current drive due to ponderomotive effects, or magnetic field generation due to nonlinear effects. Some other novel CD techniques might be found during the course of research. Such methods might be less affected by the trapping effect and might actually work in an ST better than the standard CD methods.

Our proposal includes theoretical and numerical parts. Also, active collaboration is proposed with NSTX engineers and scientists for development of CD techniques and appropriate antenna systems. For numerical calculations, we are planning to extend the ALFA code for correct treatment of the novel CD methods under investigation. The ALFA code [1-11] has been developed by the author during a number of years and has been used mostly for the analysis of FWCD or Alfven wave CD. We believe that the ALFA code is advantageous for use in calculations for ST configurations. ALFA features fully toroidal geometry, arbitrary shaped plasma, and arbitrary strong poloidal magnetic field effects. This is the hot-plasma code with the full dielectric tensor which includes the Bessel functions. This feature is important when the finite Larmor radius effects are substantial, which is relevant to the NSTX parameters. The ALFA code computes a 3D picture of RF wave fields and absorbed power. Transient processes of current diffusion are included in the model as well [7-8]. The code has an extended diagnostics with the possible output of up to 300 various plots during a single run of the code. The code has been used for RF heating and current drive analysis in TPX [1-4], Phaedrus-T [5-8], IGNITOR [9], JET [10-11], and ITER [6-7]. Our past theoretical studies of RF helicity CD [12-15] add to a solid starting base for the proposed research.

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Fast ion confinement and orbit losses from NSTX plasmas and techniques by which losses could be measured.

Doug Darrow

Theoretical and experimental studies of fast ion confinement are of importance to all magnetic fusion plasmas, and these subjects have a direct bearing on the efficiency of auxiliary heating and current drive in STs. The subject has been extensively studied in conventional aspect ratio tokamaks, but a number of unique physics issues are raised by the geometry of ST plasmas. These include: a large gyroradius in comparison to the plasma size, large trapped particle fractions, the potential for strong drive of Alfven eigenmodes due to the low toroidal field, the prospect of velocity space instabilities transporting fast ions into loss cones, and new loss cones developing at high beta due to asymmetric trapping of ions.

Measurements needed to address these issues include: IR imaging of the walls, fast ion loss detectors, Mirnov coils, rf probes, spectroscopic or pellet-based measurements of the fast ion distribution, neutron fluctuations, and internal fluctuation diagnostics.

Fast ion measurements will be applicable to discharges with neutral beams and possibly also to rf heated discharges. High beta discharges are likely to be especially interesting.

Electron Cyclotron Emission and Absorption Physic for NSTX Utilizing Electron Bernstein Waves

P. C. Efthimion

I am interested in investigating the physics of measuring electron temperature and the heating of electrons on NSTX using electron Bernstein waves (EBW). The experimental results from START indicate the achievement of high density ($n_e \geq 3e13$ cm^{-3}) with a modest toroidal magnetic field. Similar conditions are expected for NSTX. Such conditions translate into $\Omega_{pe}/\Omega_{ce} >> 1$. Consequently, electromagnetic radiation is not generated from at least the first five cyclotron harmonics in NSTX. Although very high harmonic electromagnetic radiation is accessible it will be far from the blackbody condition necessary for the measurement of temperature or for effective electron heating with microwave frequencies.

On PLT, Electron Cyclotron Emission measurements indicated that the extraordinary mode (X) fundamental electron cyclotron emission, $\omega \approx \Omega_{ce}$, is capable of determining the electron temperature [1]. The explanation invoked EBW emitting at blackbody levels, propagating to the Upper Hybrid layer, and mode converting into extraordinary mode (X) emission. From the electrostatic dispersion relation, ray tracing can be conducted to study the wave propagation, and the wave absorptivity can be calculated at the cyclotron layer. For $\omega \approx \Omega_{ce}$, I have calculated the optical thickness, τ, to be ≈ 3000 for NSTX, and ≈ 300 for CDX. For NSTX, the entire plasma diameter is highly absorptive to EBW, and the cyclotron emission easily meets the blackbody condition for measuring electron temperature, $\tau > 2$. The optical thickness for the second harmonic should also be optically thick for these machines. The high absorptivity makes EBW extremely attractive for ECRH on these machines.

Simple accessibility arguments indentify two potential means of accessing EBW from the electron cyclotron layer. One scenario is for EBW to propagate to the plasma edge and to employ an electrostatic antenna to couple the radiation into a conventional microwave receiver. The waves may not be accessible from both sides of the plasma because of the upper hybrid resonance and the X-mode cutoff layers. EBW should propagate to the edge of the inner half of the plasma. An electrostatic antenna can be placed oblique to the horizontal plane of the machine either above or below the midplane. Another scenario is for the EBW to mode convert into an electromagnetic wave at the upper hybrid layer, to tunnel through the X-mode cutoff, and to propagate out the low field side [2].

The optical thickness calculations indicate that the EBW physics, and the proof-of-principle for the electron temperature diagnostic and EBW electron heating regime can be done on CDX. One can verify the EBW absorptivity and accessibility by measuring emission and absorption of EBW. Launching waves and following their ray path would also be useful in verifying the theory. Typical parameters required are $T_e \approx 100$ eV and $n_e \approx 4e12$ cm^{-3}. The range of frequencies are ≤ 8 GHz. A successful program on CDX this year may allow for the development of a temperature diagnositic and a plasma heating regime that could be available during the first year of NSTX's operation.

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ECH on NSTX

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A key research objective of the NSTX Program plan is to develop advanced non-inductive plasma startup techniques to extend the operating regime of the baseline NSTX device and to eliminate the difficulties associated with inductive startup windings in future low aspect tokamak devices [1]. Electron cyclotron heating offers a well-proven capability for plasma initiation and has provided continuous low-level pressure driven currents in a number of experiments [2]. High Harmonic Fast Wave (HHFW) current drive is expected to provide adequate current in high β regime on NSTX. Due to poor coupling in the low density startup phase, an additional current drive and heating mechanism will clearly be required for non-inductive startup of NSTX. A current level of 100 kA is expected to be adequate for sustaining a suitable background plasma for further current drive using HHFW [1].

A number of possible Electron Cyclotron current drive (ECCD) mechanisms are available. Ad hoc scaling of previous ECH pressure-driven current drive results indicate that a 400 kW ECH system may be capable of driving as high as 60 kA with this mechanism. There are two direct ECCD mechanisms that may be applicable to NSTX- the Doppler shifted Fisch-Boozer technique and mode conversion to electron Bernstein waves from X-mode launch [3,4]. NSTX offers an excellent opportunity to further test and optimize these ECCD modes provided an ECH system with the required flexibility to be optimized for a particular process. Additionally, the synergistic effects between ECH and other current drive systems such as helicity injection, RF and inductive transformer action should be fully investigated.

The availability of existing ECH hardware at ORNL and power supply hardware at PPPL makes this research effort particularly attractive due to the significant cost and schedule reductions possible. Sufficient hardware exists to install 400 kW of ECH power at 28 GHz (two 200 kW, 100 ms pulse gyrotrons). A preliminary design for the ECH hardware and several launcher options has been completed. These gyrotrons are also expected to be operable at ~15.3 GHz in the TE_{01} mode which adds additional experimental flexibility for both startup and heating functions. An 18 GHz, 15-30 kW ECH pre-ionization system is also under consideration for startup assistance in the initial operating phase. The requirements and capabilities of this system have been addressed in a preliminary design.

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ELECTRON CYCLOTRON HEATING AND CURRENT DRIVE IN NSTX

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ABSTRACT:

Heating and current drive by electron cyclotron waves in high magnetic field tokamaks is commonly done by exciting the O-mode from the low-field side. However, for NSTX, where for most of the plasma the electron plasma frequency is greater than the electron cyclotron frequency, the O-mode is cutoff near the edge of the plasma and does not propagate into the core. For NSTX-type plasmas we find that, if power is coupled to the X-mode at the edge of the plasma, there can be a subsequent mode conversion to the electron Bernstein wave (EBW) which then propagates towards the plasma core. Since the upper-hybrid layer is followed by a cutoff of the slow X-mode, a triplet mode-conversion scenario (cutoff-resonance-cutoff) exists which can, ideally, lead to 100% mode conversion [1] to EBWs. The EBW could damp on the electrons by Landau damping due to the upshift in the magnitude of the parallel (to the magnetic field) wavenumber and/or at the Doppler-shifted electron cyclotron (or its harmonic) resonance. In this talk we introduce the mode conversion scenario, suggest possible test scenarios on present tokamaks, and outline our planned/ongoing studies on the excitation of EBWs in NSTX.

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NEUTRON DIAGNOSTICS FOR THE NSTX

Dan Jassby

Scientific issues being addressed

A key test of the ability of plasma simulation codes such as TRANSP to describe plasma performance depends on their prediction of fusion neutron rate, as the latter is sensitive to all plasma parameters including fast ion loss, density and temperature profiles, RF-induced tails, beam deposition profiles, and fast ion loss. Confidence in a simulation code is tentative unless neutron rates can be predicted to within 10-20%.

Measurement of neutron rate is also important for detecting small changes in ion temperature or production of ion tails when RF is applied, where other diagnostics are insensitive to changes (eg. recent IBW work on TFTR).

Relevance to ST fusion and plasma science

The very low aspect ratio of ST results in a large fraction of trapped particles, including beam-injected ions, RF-induced tails, and the tail of the thermal-ion distribution. Many of these ions will be on loss orbits and thus result in reduced heating, current sustainment, and fusion rates. Neutron measurements will reflect these phenomena. To get agreement with the neutron rates requires accurate calculation of beam-ion deposition, tail formation, slowing-down distribution, and loss processes including ripple loss.q

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Measurements needed

The time dependence of the neutron rate must be monitored. This task can be accomplished with the existing TFTR fission-chamber system (called NE for "Neutron Epithermal"). These detectors can be installed outside NSTX with no impact on NSTX construction or operation. The detectors must be calibrated absolutely by moving a Cf-252 source within the NSTX vacuum vessel.

Plasma parameters and operating conditions required

The NE system on TFTR can measure neutron rates down to 1xE11 n/s. When installed at NSTX, the detectors will be closer to the plasma and the neutron flux per source neutron much larger, so that rates down to 3xE10 n/s or even lower can be measured accurately. The detection system will be effective when any RF or neutral beam at all is applied, and during high-density ohmic discharges as well.

Bootstrap Current Ramp-Up on NSTX

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A critical issue for the development of fusion applications based on spherical tokamaks is the development of a reliable current ramp-up scenario in the absence of a central solenoid. One candidate scenario is to heat the plasma in the low-current phase of the discharge in order to maintain high $\beta_{poloidal}$. The neoclassical bootstrap effect might then generate a current in excess of the instantaneous value of the plasma current, resulting in a bootstrap-driven current ramp-up. We have investigated bootstrap current ramp-up scenarios for NSTX. An initial target plasma at 50 kA with $\beta_{poloidal}$˜2.5 requires about 110 kW of heating power in H-mode (a reasonable assumption since this exceeds the H-mode power threshold at the low density envisioned) if one assumes an energy confinement time of twice $\tau_{ITER89-P}$. Initiation of the bootstrap ramp-up at lower currents is limited by collisionality (we require a minimum value of ν* no larger than 0.25) and density control (satisfying the ν* constraint requires $\langle n_e \rangle$˜$0.3\times n_{GR}$ at 50 kA in NSTX). The bootstrap current is initially about 2.5 times the plasma current, resulting in a current ramp-up rate of about 1 MA/s. However, as the current approaches 150 kA the plasma reaches the β-limit (which we take to be β_N=3). Adjusting the heating power to maintain β_N=3 causes $\beta_{poloidal}$ to decrease below 2.5, resulting in a decrease in the ratio of the bootstrap current to the plasma current, and a consequent reduction in the rate of current ramp-up. Ultimately, this β-limit leads to a termination in the bootstrap current ramp-up at I_p˜250 kA (see figure below).