PPPL-CFP--3871

Heating and Current Drive on NSTX and HHFW Experiments on CDX-U

CONF-980130--

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Abstract. The NSTX (National Spherical Torus Experiment) device to be built at Princeton is a low aspect ratio toroidal device that has the achievement of high toroidal beta (~45%), and non-inductive operation as two of its main research goals. To achieve these goals significant auxiliary heating and current drive systems are required. Present plans include ECH (Electron cyclotron heating) for pre-ionization and start-up assist, HHFW (high harmonic fast wave) for heating and current drive and eventually NBI (neutral beam injection) for heating, current drive and plasma rotation. In support of the NSTX program, experimental tests of HHFW physics have been performed on CDX-U.

INTRODUCTION

The NSTX device is a small aspect ratio (R/a ~ 1.25) toroidal device with a minor radius, a=0.64 m, a major radius, R= 0.8 m, and an elongation, κ=2.2 [1]. Initially it will have a toroidal field of 0.38 T and a plasma current of 1 MA. While one goal of the NSTX program is to demonstrate that small aspect ratio devices do not require an ohmic heating system,NSTX will posses an ohmic heating solenoid capable of providing a 0.5 s pulse at full current. Extension to 5 s operation requires that substantial non-inductive current be driven. The large values of beta achievable in small aspect ratio devices induce a large bootstrap current, but even so, ~300kA of current drive will be required for full sustainment at I_p =1 MA. In the initial phase of NSTX operation, it is proposed to get this current from HHFW [2]. Subsequently, plasma heating with NBI is expected. The goal of totally noninductive operation requires plasma initiation and densification without the ohmic system. Presently, ECH in conjunction with coaxial helicity injection are proposed for this application.

A consequence of the low toroidal field and high plasma density is that the plasma dielectric constant $\omega_{pe}^2/\omega_{ce}^2$ is ≥50. Such a large value precludes the use of conventional ECH and lower hybrid heating due to the lack of accessibility of the wave to the plasma interior. This has not precluded several mode conversion schemes for ECH from being suggested [3]. Heating at ICRF frequencies is left as the most reasonable rf scheme for plasma heating and current drive.

HHFW for NSTX

Heating via the normal ICRF scenarios is possible in NSTX but would require frequencies around 3-5 MHz. The existence of a high power rf system previously used on TFTR gives motivation to find a heating scenario in the 30 MHz range. This frequency is greater than five times the hydrogen cyclotron frequency and ten times the deuterium cyclotron frequency. Direct electron heating via Landau damping/TTMP is possible for the fast wave at any frequency. The unusual properties of NSTX make this in fact a quite strong and attractive scenario. At high toroidal beta, the electron damping is significant and at high

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harmonic number the usual cancellation of the cross and TTMP terms does not take place. Single pass absorption on the electrons is easily achievable in NSTX. Interestingly enough however, ion absorption at high harmonics may be a problem in NSTX. For low ion temperatures, $T_i < 1$ keV, ion absorption is small, but for larger temperatures $k_\perp \rho_i$ can be large and ion absorption increases. For example, at $n_e(0) = 3\times10^{19}\text{m}^{-3}$, $T_e = 1.5$ keV and $T_i = 0.8$ keV an examination of the dispersion relation shows that the imaginary part of $k_\perp$ indicates significant ion harmonic absorption for $k_\parallel = 3\ \text{m}^{-1}$ but dominant electron absorption for $k_\parallel = 10\ \text{m}^{-1}$.

Electron damping can be adequate even for the startup plasma. A calculation for the NSTX plasma at 0.1 s with $T_e(0) = 0.35$ keV $T_i(0) = 0.3$ keV and a density, $n_e(0) = 3\times10^{19}\ \text{m}^{-3}$ performed with the METS95 code [4] gives a single pass absorption of 46%. The single pass absorption is 16% for a density $n_e(0) = 1\times10^{19}\ \text{m}^{-3}$.

The magnetic field line tilt at the outer midplane varies from 0^0 at startup to 45^0 at full current and high beta. In spite of this it has been decide, on the basis of modeling and the CDX-U experiments describe below, to not tilt the twelve antenna straps of the HHFW antenna. Each strap will be mounted individually and a simple modification to tilt the array is possible. Each strap is expected to handle 500 kW for a total power of 6 MW applied. The straps will be fed from six transmitters and be independently phasable.

CDX-U

To investigate antenna coupling issues relevant to NSTX and attempt to observe electron heating using high frequency fast waves, a two strap rotatable antenna with arbitrary strap current phasing has been installed in the CDX-U spherical torus - the only ST experiment presently capable of studying fast wave coupling and heating physics. Detailed density profile measurements and loading calculations indicate that most of the observed loading can be accounted for by fast wave excitation until the straps are less than approximately 30 degrees of being parallel to the edge magnetic field. This bodes well for the future application of high frequency fast waves in the upcoming NSTX experiment, provided the density in front of the antenna is sufficiently high to exclude the lower hybrid resonance layer, as is the case in CDX-U. Through the use of insulating antenna limiters as in the Phaedrus-T ICRF experiments [5], parasitic loading and impurity generation are observed to be modest and insensitve to variations in strap phasing and angle. Both of these observations support the use of a simple (non-tilted) antenna for the initial NSTX experiments. Lastly, signs of direct electron heating have been observed in hydrogen plasmas with ω/Ω_H=8 and deuterium plasmas (ω/Ω_D=16) using a triple Langmuir probe.

ECH and NBI

While conventional ECH will not penetrate in NSTX during the high density portion of the discharge, a preionization system is planned for day one operations and a higher power system could be used in fully non-inductive operation to provide the target for HHFW current ramp up and heating with densification. The preionization system proposed is 15-20 kW at 18 GHz. The startup system would be comprised of two 200 kW 28 GHz gyrotrons and will heat up to densities of $\sim 1.5 \times 10^{19}$ m $^{-3}$.

NBI heating and current drive offers several other attractions as well. Unidirectional injection can provide plasma rotation for increased plasma stability. Several extremely useful plasma diagnostics, such as CHERS and MSE, make use of the energetic neutrals.

The initial neutral beam injection configuration for NSTX will use a single TFTR beam line aimed in a CO-tangential direction. The beamline will be constructed from the former test stand, which was never exposed to tritium. The beamline will have 3 TFTR ion sources arranged in a horizontal array with angles of 4.2 degrees between the neutral beam centerlines. The ion sources will be ones previously employed on TFTR, and will have been decontaminated of tritium.

Initial plans call for operation at beam energies of about 80 keV to achieve about 5 megawatts of injected neutral power for pulse lengths of up to 5 seconds. Without additional modifications, the NSTX beam line can be operated at beam energies of 95 keV (about 7 megawatts) for a 5 second pulse length, or at 110 keV (about 8.5 - 9 megawatts) for 1.5 seconds. Without modification, the ion sources are capable of 30 second operation. The beam power versus pulse length relationship for the beamline arises from the power loading on the inertial ion dumps, which are not actively cooled on the time scale of a beam pulse.

If full power 110 keV operation for 5 second pulse lengths is eventually needed, this can be accommodated with a modest, relatively inexpensive upgrade of the dumps for the unneutralized residual ions. We have a design for a beamline top hat allowing the dumped ion energy to be spread out over a longer expanse of copper which is inertially cooled on the time scale of a beam pulse. Three additional TFTR beamlines and their 9 ion sources are available for future upgrades to NSTX or a successor. These additional beamlines will require tritium decontamination. The three ion sources on the NSTX beamline operate from entirely separate power supplies and controls. Thus, they can be turned on and off at independent times. At 80 keV, this means that the injected beam power can be varied in increments of about 1.2 - 1.3 megawatts. If one of the sources is operated at lower voltage, this adjustment increment can be made lower.

Using signals provided by NSTX, the accelerators of the ion sources can be turned on and off repeatedly (modulated) for feedback control of the energy content and pressure of the plasma. During the rise and fall of the acceleration voltage at the beginning and end of each modulation cycle, the electric field strength is mismatched to the ion source plasma density, resulting in poor beam optics during the rise and fall. The practical limit on the reliable modulation rate will be governed by the heat loading on the grids as they experience mismatched optics a larger fraction of the time. Based upon TFTR and General Atomics experience, this practical limit is likely to lie in the range of 20 to 50 Hz. If it should prove desirable to fire into the NSTX plasma at power levels significantly less than a megawatt, the beam from one ion source can be modulated independently to inject a lower power (averaged over the on and off periods of the beam).

For the beam modulation to represent a reasonably smooth power flow to the plasma, it is necessary that the beam off time between modulations be appreciably shorter than a beam ion slowing down time. In order for a modulated beam to smoothly feed the stored energy of the thermal plasma, it is also necessary that the thermal energy confinement time be significantly longer than the period between modulations. The beam slowing down time (50 ms) and the thermal energy confinement time (tens to 100 ms) for an established NSTX plasma will probably satisfy the requirements for beam modulation to produce a reasonably smooth temporal response in the plasma's beta. If low average power using modulation of an ion source should be desired for a startup plasma with shorter beam ion slowing down times and shorter thermal energy confinement times, then the power to the plasma may not be smooth with time.

This power in conjunction with that from HHFW will provide enough to test the beta limit under most reasonable confinement scenarios. One interesting feature of NBI on NSTX is to look at the confinement of fast ions in such a low field device. For CO injection the ions are well (>90%) confined. For counter injection, however, the ion orbits are such that as much as 70% of the ions can be lost on the first orbit [6]. Simulations of the current driven by 5 MW of injection indicate that ~300 kA of current can be driven. This is a similar value to that driven by HHFW. An additional area of interest for such energetic beam injection is that of beam driven instabilities. The injection velocity is in excess of the Alfven velocity and some excitement might be expected.

SUMMARY

NSTX provides a challenge to heating and current drive techniques. The goal of total noninductive operation is challenging but appears achievable with a combination of ECH startup, HHFW rampup and NBI plus HHFW sustainment. Initial operation with HHFW and ohmic will establish much of the character of small aspect ratio torus performance and set the stage for a demonstration of combined noninductive operation that will go a long way towards establishing the reactor capability of the small aspect ratio toroidal approach to fusion energy production.

ACKNOWLEDGMENTS

This work performed under USDOE contract number DE-AC02-76CH03073.

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