

High Harmonic Fast Wave Heating and Current Drive on NSTX — System and Experimental Plan

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Abstract. For the National Spherical Torus Experiment (NSTX) device, High Harmonic Fast Wave (HHFW) heating has been selected for its strong single pass absorption on electrons as the initial heating and current drive scenario. A frequency of 30MHz has been selected ($f \sim 16 f_{cd}$). The waves will be launched into the plasma from a twelve element phased antenna array. Six transmitters will feed the elements in pairs of six independently phasable subsections. Modeling predicts strong single pass damping (>40%) for temperatures as low as 250 eV. As the ion temperature is increased ion damping may compete with the electron absorption for ion temperatures > 1.5 keV. Experiments will be aimed at demonstrating HHFW heating of a small aspect ratio device leading towards the goal of fully non-inductive operation. In the first year of operation the HHFW system will be brought into operation and plasma heating under a variety of plasma conditions will be explored. In the second year, when current drive diagnostics are expected to be available, an exploration of HHFW current drive will begin.

INTRODUCTION

Small aspect ratio tokamaks offer a higher beta route to a fusion reactor. A major stumbling block of this approach, compared to a conventional tokamak is the lack of sufficient space in the center for an Ohmic heating system. The use of radio frequency waves to heat and drive currents in plasmas is well established. Radio frequency heating and current drive in a low field, small aspect ratio toroidal device faces several challenges due to the large value of the plasma dielectric constant and the unusual magnetic topology. With a value for the dielectric constant, ω_{pe}/ω_{ce} of ~ 5 conventional heating and current drive techniques such as those utilizing lower hybrid waves or electron cyclotron waves will not work because the waves involved will not propagate. Conventional fast wave heating via ion minority or second harmonic ion resonance should be feasible but at the low values of magnetic field required for spherical torii, especially for NSTX (~ 3 kG) a very low ICRF frequency (~ 4 MHz) would be required. Fortunately, it has been pointed out by Ono (1), that the damping on electrons of a high harmonic fast wave in high electron beta plasma is quite strong. NSTX will utilize the same rf frequency, 30 MHz, as that employed previously on TFTR. This frequency corresponds to $\sim 16 \omega_{ci}$ for deuterium ions near the magnetic axis. Complete single pass damping on electrons is expected for electron temperatures > 500 eV. In the sections following a description of the HHFW system is given as well as details of the experimental goals and plans.

HHFW SYSTEM

The NSTX HHFW system has been designed to make maximum use of the legacy ICRF system from TFTR. The six rf transmitters will be phase controlled electronically via low level electronics. To deliver the specified 6 MW to the plasma each transmitter will be required to deliver ~ 1.2 MW for up to 5 s. Each of the six transmission lines will have its own line stretcher and stub tuner for final impedance matching. Pre matching will be performed in the NSTX test cell via a quarter-wave transformer transmission line. The power will be split in two for each line to feed the twelve antenna elements. The six transmission lines will also be cross-connected with decoupling loops consisting of a high impedance connection and a stub (2). This will allow arbitrary phasing to be applied between transmitters with equal power levels in each feed. Data acquisition and control will be adapted from the TFTR systems. All control functions are passed through a programmable logic controller (PLC), while data acquisition is done via a CAMAC network.

Antenna

One component of the HHFW system that had to be designed and constructed from scratch was the antenna system. Efficient current drive was a high priority requirement for the HHFW system; therefore, the antenna system was designed to satisfy this constraint. Initially, two six element arrays on opposite sides of the machine were proposed. The constraints imposed by the inclusion of a neutral beam injector, beam dump and beam based diagnostics resulted in a single twelve element array. Each antenna element is a modular unit consisting of vacuum feedthrough, antenna radiating strap, backplate, Faraday shield and Boron nitride (BN) protective tiles. BN tiles were chosen for their electrical insulating properties, since, due to its low value of magnetic field, NSTX is susceptible to rf sheath formation. The antenna strap is solid copper for good electrical and thermal conductivity. Disruption forces are not severe on NSTX due to the low value of the magnetic field. The Faraday screen is a single layer of solid Molybdenum elements with ~50% coverage. Molybdenum was chosen for its high temperature properties along with good electrical and thermal conductivity. The shield is coated with a thin (10 μm) layer of Titanium carbonitride (TiCN), a low sputtering coefficient material.

Power Splitting and Phasing

To feed the twelve-element array from six transmitters the power from each transmission line must be split in two and the proper phase relationships maintained between antenna elements. Tying together the n th and $n+6$ elements of the array in a resonant loop will accomplish this goal. The attachment point also serves as the feed point and the attachment point for the decoupling loops. To facilitate this a five way cross has been fabricated. This element will be a one-ft cube with five faces accepting a 6 in coaxial line and the sixth face the 9 in input line. Two ports for the resonant loop and two ports for the decoupler loop. The sixth port will be used for assembly and to accommodate a diagnostic voltage coupler. At full power each antenna element will deliver 0.5 MW to the plasma.

TABLE 1. Variation of Loading and Driven Current with Antenna Phasing

Case/phase	Loading (Ω/m)	Driven Current (kA)
Startup/ 90°	7.9	300
5% beta / 60°	5.2	420
25% beta / 30°	8.3	320
25% beta / 90°	7.8	90

The maximum voltage on each antenna circuit should be less than 30 kV. This maximum occurs in the pressurized transmission line. Active phasing control between the elements will be required to maximize plasma loading and driven current as the plasma beta increases (see Table 1). As can be seen, to maximize the driven current as the plasma beta increases the phase angle between transmitters must be reduced from 90° to 30° .

EXPERIMENTAL PLAN

The NSTX device has been constructed with the goal of demonstrating the potential of the spherical torus as an attractive fusion reactor. Advantages of this approach are the high values of plasma beta that are theoretically achievable and its small size. A potential liability of the design is its need for external steady state current drive and the difficulty of plasma startup due to the small amount of space available in the center column. The NSTX experimental plan is designed to address these issues. The HHFW system will be utilized to heat the plasma up to challenge the theoretical beta limit. While predictions of the energy confinement time for a new device are risky, extrapolating from a variety of tokamak global scaling laws gives reasonable confidence that the six megawatt HHFW system should provide adequate heating power to reach an $\sim 40\%$ toroidal beta value. The ability of the HHFW system to provide directed electron drive should allow a reasonable amount of current to be driven. One advantage of the high plasma beta values of a spherical torus is the large bootstrap current that is driven. The combination of bootstrap current and HHFW driven current should be able to sustain the 1 MA of plasma current envisioned in the high performance phase.

The NSTX research plan is divided into a series of phases. The first phase, which will commence in August of 1999, will be devoted to establishing plasma start-up, ohmic plasmas of short (~ 0.5 s flattop) duration, beginning HHFW operation, including plasma heating, and investigating coaxial helicity injection (CHI). During this phase the HHFW system will be brought into operation. Initial investigations will concentrate on understanding the wave coupling properties of the antenna system, including characterization of the radiation resistance as a function of plasma parameters and antenna phasing, interaction between the

antenna and the edge plasma. The second goal will be to begin heating experiments. First, magnetic measurements will be used to verify that the wave energy is being absorbed in the plasma. Second, soft x-ray and Thomson scattering will be used to establish the radial location of the heating and verify that this location can be varied in a controlled fashion. Third, the question of ion absorption will be addressed. A charge exchange analyzer and fast particle probes will be employed to estimate the fraction of the power going into ions. Approximately fifteen weeks of experimental time is planned for this phase with about one third of that time being allocated for rf experiments.

The second phase of operations commences in June 2000. During this phase the full power, 6 MW, of the HHFW system should be routinely available for plasma heating. Current drive experiments will begin in this phase with the addition of MSE for q profile measurement. With the addition of the HHFW the current flat top will be extended to >1 s. HHFW will be used in conjunction with a breakdown scenario to explore fully non-inductive operation. The HHFW system should be able to drive current at electron temperatures as low as 300 eV. A target plasma of at least this temperature and a density of $\sim 1 \times 10^{19} \text{ m}^{-3}$ will need to be provided by some other technique such as CHI or ECH assisted breakdown.

During the third phase of operations, beginning in October 2001, NSTX will be pushed to its full performance parameters - average beta $\sim 40\%$, plasma current of 1 MA and a pulse length of 5 s.

SUMMARY

HHFW heating and current drive has been selected as the initial auxiliary heating and current drive scenario for NSTX. An rf system consisting of six generators feeding a twelve-element antenna array has been assembled. Active phase control of the antenna spectrum is planned. Early experiments will concentrate on establishing an understanding of how the HHFW antenna system performs in NSTX, evaluating HHFW heating efficiency and localization as well as power split between electron and ion absorption. Later experiments will focus on current drive and the ability of HHFW to allow fully non-inductive operation of a ST device.

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