ECH on NSTX

T. S. Bigelow, D.B. Batchelor, M.D. Carter, M. Peng
Oak Ridge National Laboratory, Oak Ridge, TN 37831-8071

J. R. Wilson
Plasma Physics Laboratory, Princeton University, Princeton, NJ 08544

Abstract. Electron Cyclotron Heating has been proposed for plasma initiation, startup assistance and non-inductive startup on NSTX. One physics goal of NSTX will be to establish entirely non-inductive plasma operation by utilizing ECH to provide a sufficient start-up plasma to support further current drive from other heating systems. Scaling of previous ECH-only startup experiments on CDX-U and DIII-D indicate that 400 kW of ECH should be capable of driving 42 kA of pressure driven current on NSTX and possibly higher levels after optimizing the process. Due to the low NSTX magnetic field, over-dense plasmas exist during most of the discharge so conventional ECH operation is limited to the low density startup phase. To extend the useful operating range for ECH, a scheme involving mode conversion to the electron Bernstein Wave (EBW) from either O or X mode launch is being investigated for bulk heating and current drive applications at higher density. Microwave equipment, including 18 GHz klystrons and 28 GHz gyrotrons are available at ORNL and appear ideal for use on NSTX. Preliminary pre-ionization and startup system configurations are presented here along with discussions on various operation modes.

INTRODUCTION

Electron cyclotron heating is being investigated for a number of missions on the NSTX small aspect ratio tokamak device under construction at PPPL. Some applications include plasma preionization, startup assistance, current drive and vessel wall conditioning. Previous inductive startup experiments have shown ECH capable of producing reliable, prompt, low voltage startup independent of error field level, with reduced resistive loop voltage and faster current ramp during the early portion of the discharge. Current drive and startup assistance have received considerable attention on small aspect ratio tokamak (ST) experiments due to the desire to minimize aspect ratio and therefore minimize or eventually eliminate the central solenoid ohmic heating coils on future ST experiments. Experiments investigating non-inductive ECH startup have demonstrated significant pressure driven currents using ECH alone. High Harmonic Fast Wave (HHFW) heating is being installed on NSTX and is expected to be capable of driving significant current during high density portions of a discharge where sufficient antenna loading exists. ECH is being investigated for generating a non-inductive startup plasma for HHFW antennas and as a target plasma for NBI. Although ECH is well proven for plasma preionization and startup assistance and has reasonable current drive efficiency in large high field devices, the low field of NSTX limits the density range available for conventional ECH heating and current drive to the startup phase. To extend the density range on NSTX, two advanced ECH scenarios are being investigated that involve mode conversion to electron Bernstein wave (EBW) in an overdense plasma core. The success on either of these mechanisms will lead to greater ECH capability on NSTX and provide interesting physics results to support further ECH work in this regime.
A number of ECH system configurations have been investigated for NSTX. The utilization of existing hardware has been mandated whenever possible due to cost constraints on the overall project and initial lower priority for ECH missions. Some lower frequency ECH hardware relevant to NSTX is available at ORNL. For pre-ionization, a system of two 18 GHz 15 kW klystrons is proposed and has received tentative approval for installation. A 400 kW, 28 GHz (two gyrotrons) system has been proposed for startup assist and current drive experiments and is tentatively scheduled to be available in the first 1-2 years of operation. A suitable power supply to drive the gyrotrons is available at PPPL near NSTX.

**BASIC ECH PHYSICS ON NSTX**

The low aspect ratio of NSTX generates a wide magnetic field range in the plasma. Table 1 shows the various resonance locations and O-mode cutoff density for a number of frequencies that match available high power equipment. The fundamental resonance for 28 GHz exists close to the inboard edge of the plasma and the 15.3 GHz second harmonic resonance is located near the plasma center. The frequency of 15.3 GHz is included in the table due to the possibility of operating the 28 GHz gyrotrons at a lower frequency as discussed in a later section.

<table>
<thead>
<tr>
<th>Frequency/harmonic #</th>
<th>Resonant field (T)</th>
<th>Major radius (m)</th>
<th>Minor radius (normalized)</th>
<th>Critical density ((x10^{12} \text{cm}^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>28 GHz/fund.</td>
<td>1.0</td>
<td>0.26</td>
<td>-0.9</td>
<td>9.2</td>
</tr>
<tr>
<td>2nd</td>
<td>0.5</td>
<td>0.52</td>
<td>-0.5</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>0.33</td>
<td>0.78</td>
<td>-0.1</td>
<td></td>
</tr>
<tr>
<td>18 GHz/fund.</td>
<td>0.64</td>
<td>0.40</td>
<td>-0.7</td>
<td>3.8</td>
</tr>
<tr>
<td>2nd</td>
<td>0.32</td>
<td>0.80</td>
<td>-0.07</td>
<td></td>
</tr>
<tr>
<td>15.3 GHz/fund.</td>
<td>0.55</td>
<td>0.47</td>
<td>-0.58</td>
<td>2.7</td>
</tr>
<tr>
<td>2nd</td>
<td>0.27</td>
<td>0.94</td>
<td>+0.15</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Location of ECH resonances and density limits for available frequencies

Since fundamental and second harmonic resonance locations are both present inside the plasma, absorption can occur at both locations at some point during the initial startup. With low field launch, the use of a polarization controlled beam launcher will provide control over the absorption location. The use of high field launch with 28 GHz can provide a density limit of nearly \(1.8x10^{13}\text{cm}^{-3}\) although the heating will be near the inner edge of the plasma using this scheme. Despite limited access, a small launcher could direct the power toward the center stack where it will be ducted into the high field region after a few bounces.

**CURRENT DRIVE MODES ON NSTX**

A goal of ECH startup assistance for NSTX is to achieve >100 kA of plasma current. This level of current is expected to provide an adequate plasma for loading the HHFW antenna for further heating and current drive at higher density. Conventional Fisch-Boozer "asymmetric-resistivity" ECCD will be limited on NSTX during the startup phase due to the low temperature and density although there may be some intermediate density and temperature window where current can be driven through this mechanism. The ECH bootstrap or pressure driven ECCD mechanism\(^3\) applies well to NSTX. Scaling results from CDX-U and DIII-D to NSTX indicate that 42 kA of current can be generated using 350 kW of ECH
power. Current drive will be possible at either the second harmonic or fundamental resonance locations with varying degrees of efficiency.

Any efficient current drive scheme requires a high degree of control over the launch beam to optimize first pass absorption at a central location. Oblique launch capability is necessary for the Fisch-Boozer technique. High mode purity transmission and polarized launch are required for efficient current drive.

**EBW MODE CONVERSION OPERATION**

Two mode conversion schemes\(^\text{4,5}\) are being investigated to overcome the low density limit for ECH on low field devices. These schemes involve coupling between the extraordinary mode and the electron Bernstein wave (EBW) near the turning point for the reflected X-mode wave. Power converted to the EBW wave can propagate toward the plasma center and is efficiently damped near harmonic surfaces including 3rd harmonic or higher. One scheme,\(^\text{4}\) which has been demonstrated experimentally, involves the launch of the ordinary mode (O-mode) which at a critical angle is converted to the X-mode then EBW. The other scheme\(^\text{5}\) uses direct X-mode launch. Both schemes require a narrow, polarized launch beam to be successful. An oblique launch is required for these schemes which requires optimization to handle major radius growth during the startup phase\(^\text{4}\).

**18 GHz PRE-IONIZATION SYSTEM**

A low-cost ECH preionization system will be installed to provide a reliable plasma startup mechanism and possibly provide some control of the initial current channel during the startup phase. Additionally this system will assist the plasma buildup during helicity injection current ramp experiments. A power level of 30 kW at a frequency of 18 GHz was selected due to the availability of 18 GHz klystron systems at ORNL which can be setup fairly inexpensively in time for first plasma operation. As indicated in Table 1, a fundamental resonance is located at normalized \(\rho=-0.7\) and a second harmonic resonance is located at \(\rho=0.07\) for 18 GHz. The required pulse length for pre-ionization is fairly short so a 100 ms or less pulse length was specified to simplify the power supply requirements even though the klystrons are rated cw. Two klystrons will be used with a common power supply and drive source. The klystrons will be located near the NSTX device to simplify the transmission line requirements. Individual slightly oversized, straight rectangular waveguide runs will deliver the power to the device with minimal loss. A vacuum window and open waveguide launcher for each waveguide will be located near the NSTX midplane. Two options are being considered for the klystron beam power supply which must supply \(-25\text{ kV at }3.5\text{ A per tube. A capacitor bank with a small charging supply and series pass regulator is the simplest option. A HVDC transformer/rectifier system is also available at the NSTX site and, although it is quite oversized for this application, could easily be adapted for use.**

**28 GHz ECH SYSTEM**

A high power ECH system constructed from existing gyrotron hardware has been proposed for NSTX. Two 28 GHz 200 kW 100 ms pulse gyrotrons are available from ORNL and long pulse/cw gyrotrons that are nearly interchangeable
with the pulse tubes are also available (with some repair work) if a longer pulse upgrade is warranted. A number of transmission line components are on hand as well as a beam launcher that is well matched to NSTX and could handle 2-3 gyrotrons simultaneously. A -80 kV, 20 A HVDC power supply is available at PPPL that can power 2-3 gyrotrons. A series pass modulator/regulator system to interface the HVDC supply to the gyrotrons is available from ORNL.

A narrow, slightly elliptically polarized beam with oblique launch is required for efficient current drive which can be provided with a focused beam launcher. Utilizing a beam launcher system from the ATF experiment at ORNL will provide this capability and permits 2 or 3 gyrotrons (and 18 GHz pre-ionization power) to be launched into a single mid-plane port as shown in figure 1. A transmission line with high mode purity and appropriate mode conversion is required to transmit the gyrotron power to the launcher.

Figure 1. Proposed NSTX ECH transmission and low-field launching system

A drawback to the use of 28 GHz on NSTX is the inboard location of the fundamental and second harmonic resonances. A lower frequency provides a more centralized location for full plasma size. It is likely that the TE_{02} mode 28 GHz pulse gyrotron model can be operated in the TE_{01} mode at ~15.3 GHz by lowering the gyrotron magnetic field. The internal configuration of this model of gyrotron is amenable to this change although the system efficiency may be slightly lower. Some adjustment will be required to switch between frequencies. This option provides some experimental flexibility for very little investment.

ACKNOWLEDGMENTS

*Oak Ridge National Laboratory, managed by Lockheed Martin Energy Research Corp. for the U.S. Department of Energy under contract number DE-AC05-96OR22464.

1 Ono, M., et al., this proceedings
4 Batchelor, D.B., et al, this proceedings
5 Wu, K., et al, this proceedings
DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.
DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.