Electron Bernstein Wave Experiment on the Madison Symmetric Torus

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Abstract.
A system to heat electrons and possibly drive off-axis field-aligned current is under development on the Madison Symmetric Torus RFP. Staged experiments have reached an input power of 150kW at 3.6GHz and have produced a localized increase in SXR emission during rf injection. This measured emission is consistent with modeling in its location, energy spectrum and dependence on radial diffusion within the plasma. The emission is strongest in the region where ray tracing predicts deposition of the injected power. The multi-chord SXR camera used is sensitive to 4-7 keV photons. Enhanced emission in this energy range is consistent with Fokker-Plank modeling of EBW injection. The enhanced SXR emission vanishes quickly when radial diffusion in the plasma is high (as indicated by m=0 magnetic activity); this is also consistent with Fokker-Plank modeling. An increase of boron emission (and presumably boron within the plasma) is also observed during EBW injection. This presents an alternative explanation to the enhanced SXR emission. Subsequent experiments with a different antenna at 100kW input showed a small increase in SXR emission near 3 keV. A higher frequency experiment (5.5 GHz) with more input power available is currently under construction. Initial tests are centered on a circular waveguide launcher which requires only a 5 cm circular port in the vacuum vessel and has a target launch power of 400 kW.

INTRODUCTION

The electron Bernstein wave (EBW) may facilitate localized heating and current drive in the over-dense plasma found in the reversed field pinch (RFP). The historically poor confinement of the RFP is governed by magnetic fluctuations driven by core-resonant tearing modes. Inductive application of a poloidal emf to drive stabilizing off-axis current, although transient and non-localized, is a well-established way to decrease dramatically these fluctuation levels and thereby increase energy confinement. The optimal current profile control technique for RFP plasmas is expected to be rf generated as it offers the possibility of steady and precise modification.

EBW heating and current drive has been demonstrated in the stellarator, toka-

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mak, and spherical torus, however the RFP presents unique challenges to rf heating and current drive[1]. The plasma is very over dense, with $\omega_{pe} > \omega_{ce}$ within a few cm of the plasma boundary. The low magnetic field strength in the Madison Symmetric Torus (MST) places the ECRF in the microwave range and the relatively low frequency leads to larger characteristic antenna size. The close-fitting conducting shell on MST is essential to equilibrium and limits the port size to a 4.5" diameter.

A staged experimental approach is underway toward EBW current drive on MST, first motivated by the measurement of thermal EBE from the MST plasma. Adequate efficiency is achieved in coupling to the EBW from a phased waveguide grill[2]. Topical experiments (at 10^5 W) are aimed at demonstrating heating and verifying models before proceeding to current drive experiments, where 10^6 W are expected to be required. Recent measurements in MST show toroidally and poloidally localized soft x-ray emission is caused by rf injection. The data are preliminary and cannot definitively claim plasma heating through the electron Bernstein wave, however the measurements are in qualitative agreement with modeling of the deposition region and spectrum.

EXPERIMENT ON MST

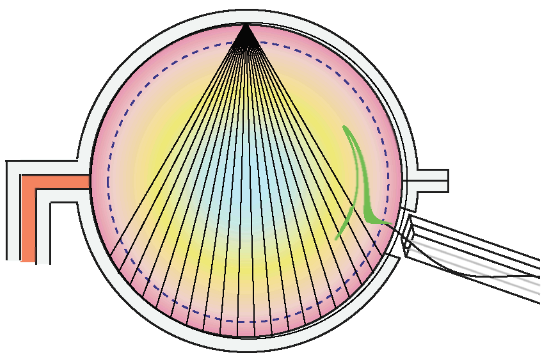

Figure 1: 20 chord pinhole camera monitoring SXR emission at the same toroidal angle as the EBW antenna. The green line is the GENRAY ray tracing result for a 3.6 GHz Bernstein wave launched in the target plasma.

Figure 1 is an illustration of the recently-installed SXR diagnostic and its location with respect to the EBW antenna which is delivering about 150 kW to the plasma (with coupled power around 80 kW). The camera consists of a 400 μm Be filter in front of a 35 μm Si photodiode which restricts the measured emission to about 4-7 keV. The outboard chords of the camera intersect the GENRAY predicted path of the EBW shown as the green line. The target plasma is a discharge with 250 kA of plasma current, a central magnetic field of about .25T, an edge magnetic field of about .1T, a line-average density of about 1x10^{13} cm^{-3}, and central electron temperature of about 500 eV. The antenna is oriented to excite the X-mode at the plasma boundary and mode conversion to the EBW takes place within a few cm. The EBW propagates to the Doppler-shifted electron cyclotron resonance where its power is deposited. Optimal coupling to the plasma requires particular phasing of the waveguide grill. Further, a boron nitride dielectric endcap is on the antenna acting as a limiter and preventing plasma from contacting the copper antenna.

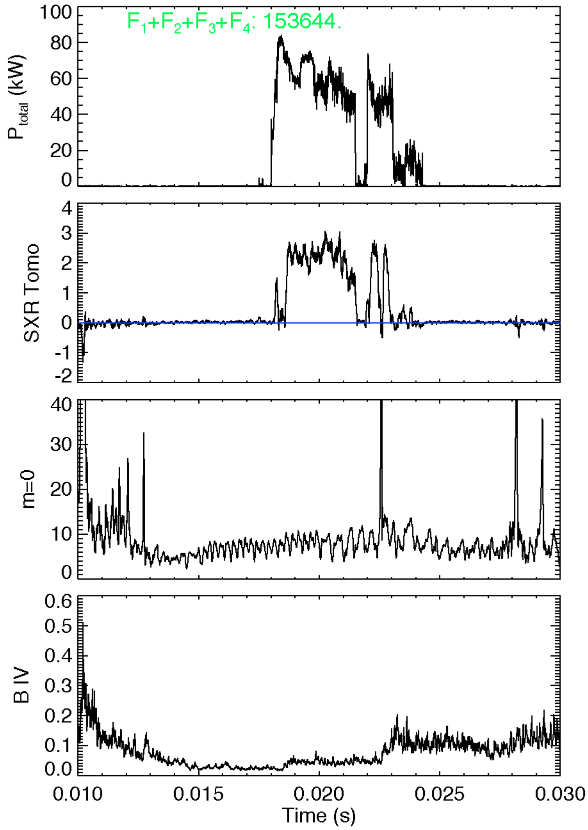

Figure 2: Injected RF causes an increase in SXR emission in the absence of m=0 activity. Boron emission is also enhanced by rf.

Measurements confirm that the increase of soft x-ray emission (4-7 keV) is caused by rf injection but the mechanism responsible for x-ray production is still under investigation as shown in Figure 2. Fig. 2a is the net power (forward going minus reflected) in the waveguide arms leading to the antenna and is surmised to go into the Bernstein mode. The 500 μs dropout in power at 21.5 ms is a programmed modulation; the drop in power at t= 23.2 msec is an indication of imperfect antenna behavior. The measured soft x-ray signal (Fig. 2b) on chord 19 (second from the outboard edge) is coincident with rf injection. The m=0 mode activity (Fig. 2c) demonstrates that measurable 4-7 keV emission requires both rf injection and electron confinement (bursts in the m=0 activity correspond to rapid confinement loss). This consequence is loosely predicted by Fokker-Plank modeling where increasing radial diffusion in the code from ~zero to 100 m^2/s decreases the predicted emission.

The time evolution of the SXR signal illustrates the effect of the rf on emission. From an experimental point of view it is convenient that there is effectively zero background emission: no signal when the rf is off. Coincident with rf turn-on the

SXR emission becomes measurable. As the antenna delivers power, the SXR emission remains quite high; substantially above the noise level. At the programmed gate (21.5 to 22 ms) the emission goes quickly to zero. After the rf resumes, the SXR emission is large until a loss of confinement (as indicated by the m=0 burst at 22.5 ms). At this time, the SXR signal again vanishes quickly; in fact here the SXR signal goes through zero to a negative value (due to rf pickup opposing the sxr signal in this diagnostic). Although the measured emission is consistent in its location with ray tracing and consistent with Fokker-Planker modeling in the spectrum and trend with confinement, causality has yet to be established, complicated mainly by the time evolution of the boron emission (Fig. 2d). The boron nitride antenna cover has been useful in improving coupling to the plasma (decreasing reflected power into the transmission line) but it does act as a source of impurities. The period of time leading up to the rf injection in this discharge is marked by low fluctuation amplitude (an extended burst-free period in Fig 2c exists from 13 to 23 msec). The BIV light decreases during the burst-free time to a low baseline value achieved by about 15 msec; it remains at this low level until the rf injection commences. There is a small but noticeable increase in BIV caused by the rf injection. It should be noted that this enhancement is small compared to the light observed at and immediately following an m=0 burst. The data obtained so far cannot rule out the possibility that locally high Z_{eff} values in front of the antenna contributes to the measured SXR emission increase.

SUMMARY

Electron Bernstein waves are being pursued as a method of heating and driving current in the overdense RFP plasma. In recent experiments, 100+ kW of rf power is injected and a localized increase of SXR (4-7 keV) emission is observed. The data are consistent with the target scenario: the launched X-mode converts to the Bernstein mode and propagates to the Doppler-shifted cyclotron resonance. However, due to complicated impurity source behavior during the rf injection, the mechanism leading to the SXR emission has not been experimentally identified. A higher power experiment at 5.5 GHz is under development and is hoped to deliver power more reliably to conduct a thorough experimental investigation of EBW heating effects.

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