Overview of MST LHRF Experiments

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Abstract. Lower Hybrid current drive has been offered as a means of improving confinement in the reversed field pinch by reducing tearing fluctuations. Modeling suggests that a slow wave launched at 800MHz and an $n_{\|}$ of 7.5 will penetrate near the region of maximum magnetic stochasticity and significantly reduce core tearing mode activity. The particular constraints of MST lead to the use of an interdigital-line structure rather than the traditional waveguide grill antenna. While there are several drawbacks to this type of antenna including the lack of phasing control, the launched spectrum displays good directivity, and loading studies indicate that the antenna operates well in a variety of plasma conditions. Toroidally localized hard x-rays in standard plasmas with energies up to 50 keV have been observed. This emission is likely the result of edge interaction with the near field of the antenna. Preliminary measurements in the soft x-ray regime are also consistent with this hypothesis.

Keywords: LHRF, antenna, interdigital, RFP, MST
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INTRODUCTION

Large tearing mode fluctuations generated by the dynamo have been shown to result in anomalous energy and particle transport in the reversed field pinch (RFP). By driving current at the edge through inductive techniques, fluctuations can be reduced and confinement times can be increased ten-fold[1]. The rf physics program on MST has up to now focused on the proof-of-concept of improving confinement with a steady state rather than a transient approach. Modeling indicates that lower hybrid waves at $n_{\|} \sim 7.5$ and 800 MHz can drive current and improve confinement in the RFP[2, 3].

EXPERIMENTAL OBSERVATIONS

The damping length is defined as the characteristic decay length of the electric field strength as the wave travels down the antenna structure and couples power to the plasma. It can be used as the figure of merit for the amount of antenna/plasma coupling. The damping length is relatively insensitive to the magnetic field pitch and strength, but has been found to correlate strongly with density[4].

The sawtooth cycle is a characteristic phenomenon of standard RFP plasmas. The sawtooth is an MHD relaxation event which generates toroidal flux and leads to a degradation in overall confinement from increased radial transport[5]. For rf physics, the more important sawtooth effect is the increased plasma-wall interaction. The injection of impurities into the edge and the associated increase in edge density has the potential to affect the antenna's coupling. If so, then we should see the damping length co-vary with the sawtooth cycle.

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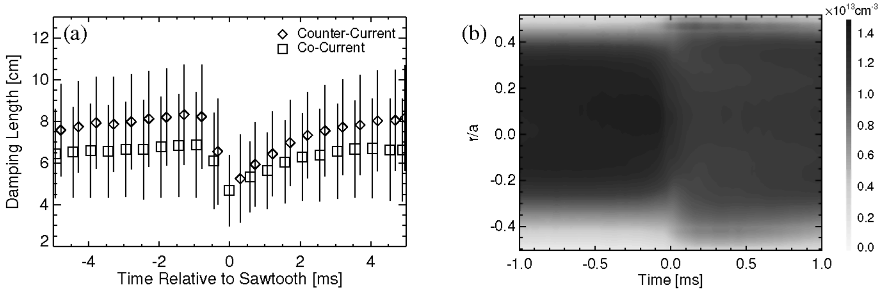

Figure 1. (a) The antenna damping length relative to the sawtooth cycle in 400 kA plasmas for both antenna phasings. (b) The density profile at the midplane for these plasmas. Zero milliseconds corresponds to the sawtooth crash.

Figure 1a shows the damping length as it varies relative to the sawtooth crash for a large ensemble of 400 kA plasmas with nominal line-averaged densities of $1 \times 10^{13}\,\mathrm{cm}^{-3}$. Figure 1b shows an ensembled density profile through the sawtooth. The sawtooth cycle has a significant effect on the loading of the antenna. At the crash the damping length drops by almost a factor of two even as the line-averaged density remains constant. The density showing a peaked profile becomes flattened directly before the crash with the edge density commensurately increasing. The behavior of the damping length is consistent with the vacuum gap between the antenna and plasma decreasing at the crash[6].

Although changing plasma conditions can affect antenna performance, the reverse is not true: at the current rf power levels, no plasma profile modification is expected or observed. On the other hand, at power levels $> 100\,\mathrm{kW}$, both soft x-rays (SXR) and hard x-rays (HXR) are found at toroidal views away from the antenna. A radial detector array 60° toroidally away from the antenna shows fairly flat profile out to r/a of ~ 0.8 which is the expected absorption region.

Two sets of observations dispute the hypothesis that the HXR flux we see is a verification of lower hybrid waves being absorbed. The first is shown in Figure 2. A set of HXR detectors at the same toroidal location of the antenna shows that the flux from chords intersecting the feed end of the antenna aperture is four orders of magnitude higher than chords off the antenna. In a related experiment the rf power was square-wave modulated in an effort to determine the fast electron decay time and consequently the fast electron diffusion. A representative shot is shown in Figure 3. When rf power turns off, the x-ray flux falls off to zero within about a microsecond, about the resolution of the detector.

The conventional mechanism for producing a high energy bremsstrahlung spectrum is for electrons to become decoupled from the bulk by Landau damping and then accelerated by the Ohmic electric field. With an Ohmic field of $\sim 0.5\,\mathrm{V/m}$ in standard plasmas, and the Landau resonance at $\sim 3\,\mathrm{keV}$, an electron achieving the the observed energies of $> 30\,\mathrm{keV}$ would have to remain in the plasma for more than half a millisecond. This consideration, given the measured fast electron confinement is $\sim 1\,\mu\mathrm{s}$ and the localized

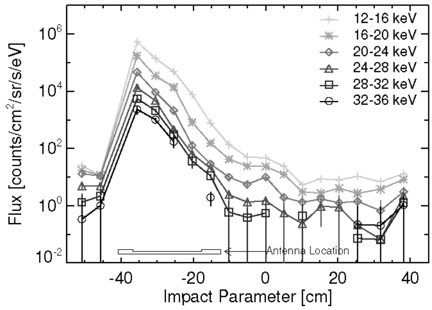

Figure 2. Radial profile of HXR flux looking at the face of the antenna with 85 kW of input power.

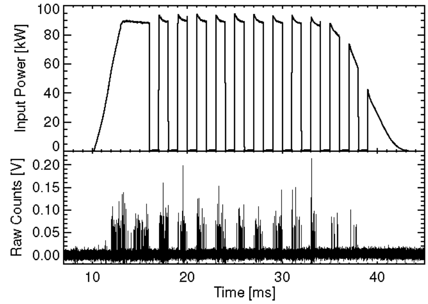

Figure 3. The rf power modulated at 500 Hz and the HXR response.

peaking indicates an alternate mechanism for fast electron production must be involved.

Previous work with grill antennas[7] has hypothesized that bulk electrons in the diffuse edge will Landau damp on the higher-$n_{\|}$ components of the fields directly in front of the antenna. These models, however, produce fast electrons that have energies well below those seen on the MST antenna, despite slightly higher field strengths. The MST antenna's principal spectral lobe is $n_{\|} \simeq 7$ rather than $2-4$ on current LHCD grill antennas, so more power can be easily transferred to the bulk electrons, but a simple 1D analytic model reveals that the maximum energy that an electron can achieve for 85 kW of rf power is on the order of 18.5 keV, much less than the >30 keV observed.

To further test the hypothesis that antenna near fields are responsible for high energy HXR flux, a three dimensional Monte Carlo code has been developed that uses the antenna vacuum fields as calculated by CST Microwave Studio™. The test electrons are chosen from a 40 eV Maxwellian velocity distribution, and are injected along the 1500 G background guide field. Each particle is followed for one million timesteps with a timestep of 2 ps. The fields were given a random phase at $t = 0$ for each particle.

Figure 4 shows the results from a set of runs using the Monte Carlo code. The Monte Carlo reproduces the 1D model well with a tail pulled out in the parallel (to the guide field) direction to almost 20 keV. Adding a realistic damping length to the model as in Figure 4c reduces the length of the tail as expected since the electron's potential well is not so deep.

The significant feature of the final velocity distribution is that a perpendicular tail forms extending above 40 keV, above what is required for the observed HXR flux. Adding damping reduces the strength of the tail somewhat, but still provides enough high energy electrons for the observed bremsstrahlung spectrum. This result is interpreted as the gyro-orbit interacting with gradients of the antenna's perpendicular electric field components. Increasing the guide field strength reduces the fraction of particles in the high energy tail, presumably because the smaller Larmor radius reduces the effective force — via the field gradient — averaged over a gyro-orbit. As such, the result requires at least a 2D model for gyromotion and a field model that accounts for the aperture function of a finite antenna.

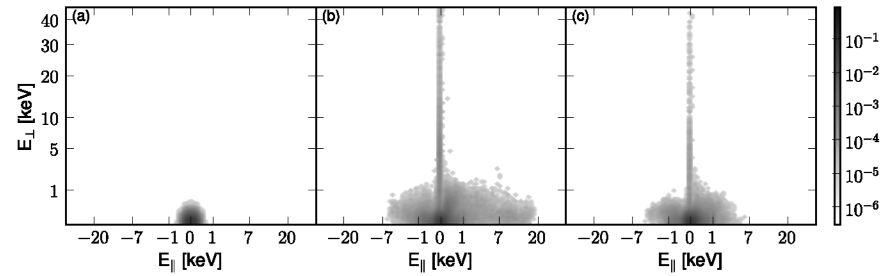

Figure 4. Results from Monte Carlo calculation. (a) Initial 40 eV distribution. (b) Final distribution for 85 kW input power and guide field pitch angle 8° relative to the antenna axis. (c) Same as (b) but with a power damping length of 5 cm on the antenna.

CONCLUSIONS

The MST lower hybrid antenna is shown to be sensitive to the changing edge conditions induced by the dominant sawtooth cycle in standard MST plasmas, but the change in the damping length is not significantly detrimental to the antenna/plasma coupling. The toroidally localized HXR flux[8] and recent SXR toroidal measurements are consistent with a local source of fast, poorly confined, electrons generated at the antenna. Monte Carlo modeling confirms that the gradients in the antenna near field can accelerate electrons to the requisite energies within the measured confinement time.

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