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Auxiliary Heating and Current Drive Systems for the Madison Symmetric Torus Reversed Field Pinch

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Control of the current density profile in MST has led to reduced magnetic fluctuations and transport, and much improved confinement. In addition, external heating of the plasma will allow for exploration of the beta limit in the RFP and its effects on transport and confinement. Techniques to apply controlled auxiliary power to the MST plasma and explore these physics issues are now being developed. These methods include pulsed parallel current drive (PPCD), oscillating field current drive (OFCD), neutral beam injection (NBI), lower hybrid waves (LH), and electron Bernstein waves (EB).

Both LH and EB wave injection are being developed to explore the physics issues of current drive in the RFP. Antenna design for both techniques poses significant challenges in the MST environment. A traveling wave LH antenna has demonstrated a power handling capability of 80 kW with a good impedance match to the plasma over a wide range of conditions in standard plasmas. Hard x-ray emission has been observed when sufficient power flows through the antenna (see Figure 1). For EB wave injection, a rotatable twin waveguide antenna that launches electromagnetic waves at power levels up to 150 kW has been developed. Studies performed at high power (≤100 kW) have identified the optimal launch angle for coupling to the EB wave near the plasma boundary (see Figure 2).

PPCD is an inductive current drive method and has been used to improve plasma performance. A system to correct field errors has recently been installed on MST, thus allowing for operation at higher plasma currents. The addition of variable inductors to the PPCD circuit will allow for optimization of the method at these higher currents (see Figure 3). OFCD is a helicity injection method being tested as a way to drive net current or to alter the current density profile. A moderate power system (~250 kW) applies poloidal and toroidal loop voltages inductively at 250 – 500 Hz. To date, OFCD has demonstrated current drive of 10% of the toroidal plasma current (see Figure 4). Feasibility tests of NBI as an effective way to heat RFP plasmas are underway [see G. Fiksel, *et al.,* this conference, poster 2P.100]. A nominal 1 MW – 1.5 ms neutral beam, either hydrogen or deuterium, is being used on MST. Initial studies indicate that fast ion confinement may not be degraded by the stochasticity of the RFP magnetic field (see Figure 5).

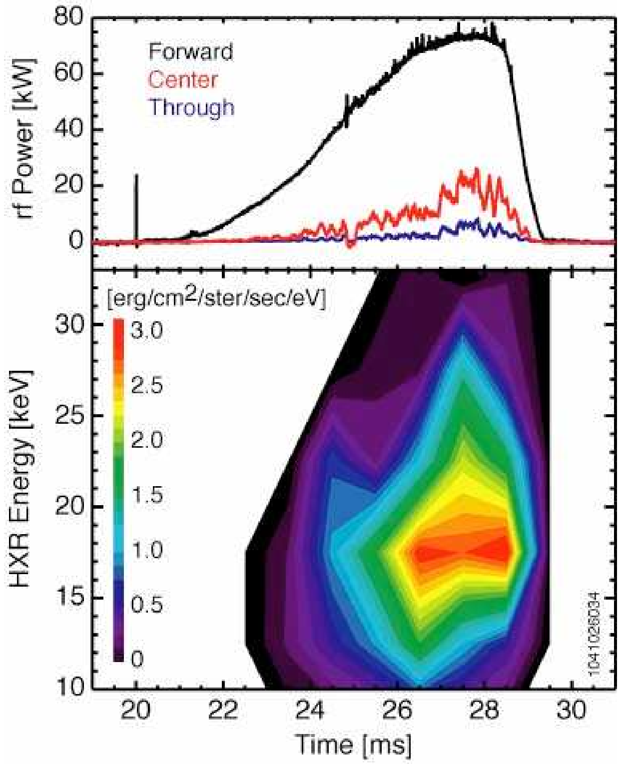

FIGURE 1. Hard x-rays up to 25 keV in energy are observed during lower hybrid wave injection on MST. The x-ray production is best correlated with rf propagation along the antenna. HXRs are measured when power flows in either direction through the antenna.

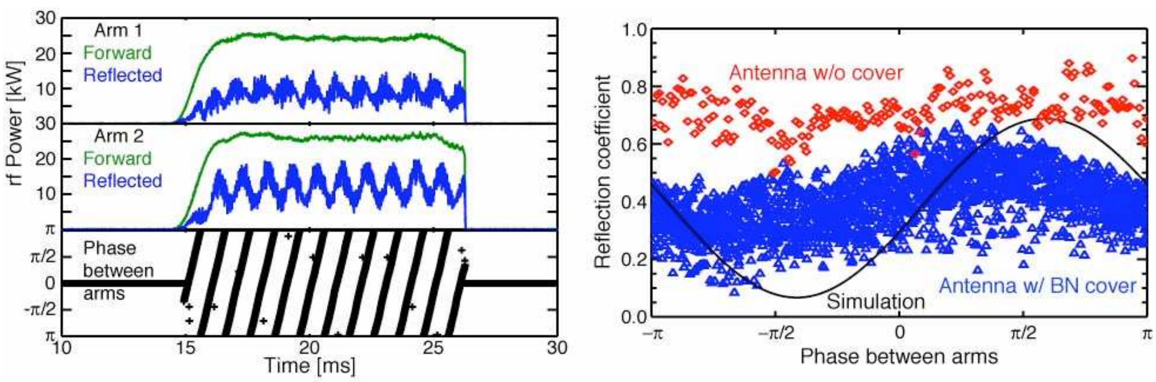

FIGURE 2. Tests of a twin-waveguide antenna designed to launch waves to couple to the EBW have been performed on MST. The reflected power in each waveguide changes with the applied phase between arms. The optimal phase has been determined and compared to that calculated from full-wave theory. The slight difference in optimal phase may be due to the boron nitride antenna cover.

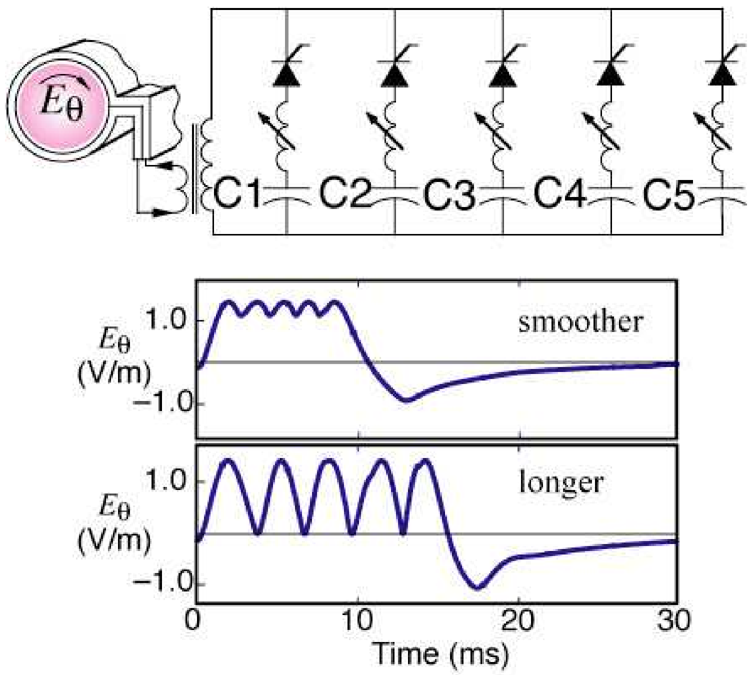

FIGURE 3. Diagram of the upgrade to the poloidal electric field circuit used for PPCD on MST. The addition of variable inductors allows for the choice of a longer or smoother E_θ waveform. A design for active control of E_θ using programmable power supplies is underway.

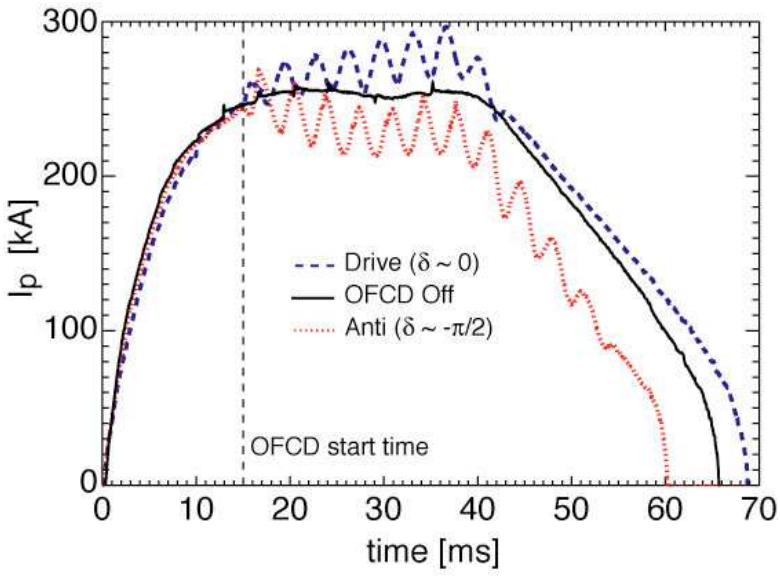

FIGURE 4. OFCD has been used to drive up to 10% of the plasma current in MST. Phase scans have been performed to determine the optimal phase between oscillators for maximum and minimum current drive. The amount of current driven does not increase with baseline current. Magnetic field penetration has been measured during OFCD. A rich variety of MHD effects, including sawtooth entrainment, mode amplitude changes, and ion heating, have been seen and are under active investigation.

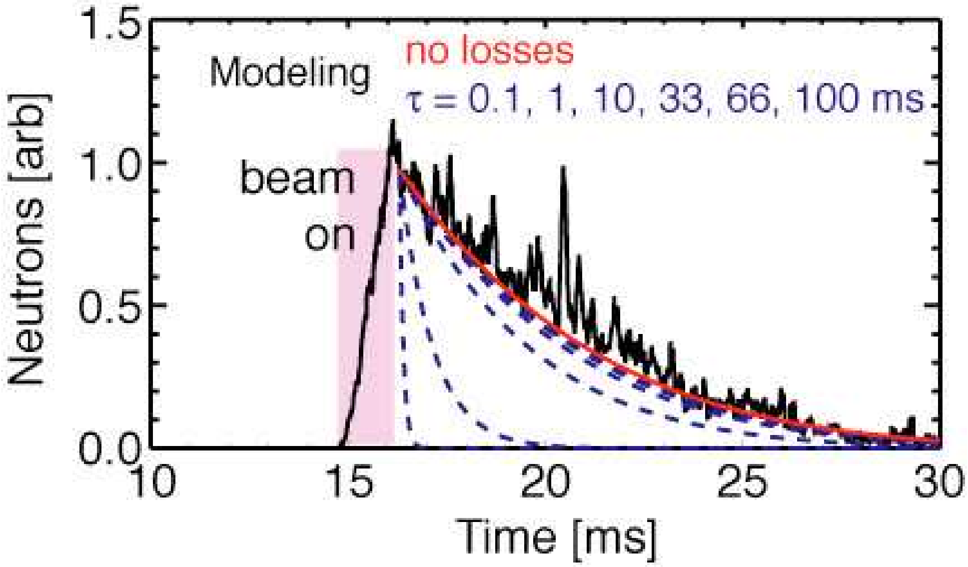

FIGURE 5. Neutrons generated from beam-plasma interactions are measured during neutral beam operation on MST. The fast ion confinement time inferred using modeling of the slowing down time and the fusion cross section is good: $\tau \geq 30$ ms. Fast ion confinement studies are ongoing as are plans to upgrade to a long pulse neutral beam suitable for heating and current drive experiments.