*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.114 (2002)*

Auxiliary Heating and Current Drive in the MST Reversed Field Pinch

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Until recently, reversed field pinch (RFP) plasmas have been created purely by inductive electric fields and heated Ohmically. Application of auxiliary power in the form of heating and current drive by neutral beams, RF waves, etc. was not practical in early RFP experiments because the Ohmic input power was too large. In present day RFP experiments, however, losses have been greatly reduced and resistivity lowered to the point that the addition of auxiliary power systems of modest scale is attractive for sustainment and control of plasma profiles as well as the exploration of beta limits. In the Madison Symmetric Torus, we are now applying auxiliary power of four types: (i) Oscillating Field Current Drive, (ii) Neutral Beam Injection, (iii) Lower Hybrid Waves, and (iv) Electron Bernstein Waves. In this paper, we present low power results in each of these areas.

Oscillating Field Current Drive

Oscillating Field Current Drive (OFCD) has long been considered as a means of sustaining the current in RFP plasmas.[1,2] The fundamental principle is that by oscillating the axisymmetric poloidal and toroidal loop voltages with a 90 degree relative phase, net helicity is delivered to the plasma. The plasma then relaxes via fluctuations and the injected helicity is distributed in such a way as to maintain a steady magnetic field with a small modulation. The first experimental test of OFCD was carried out in the ZT-40 device [3] and demonstrated that current could be driven or suppressed (I_{OFCD} ~ 5% I_p) by application of oscillating loop voltages with different relative phase. Although the applied power was substantial, the resistance of the plasma and severe plasma-wall interaction prevented full current sustainment by this method. In MST, the plasma resistance is much lower with Lundquist number (ratio of resistive time to Alfven time) above 10^7. First-time 3D nonlinear MHD computation with OFCD has also been carried out and verifies that sustainment of the plasma current is possible with this technique.

We have tested OFCD at low power (partial current drive) in MST and have confirmed that oscillating loop voltages with various relative phases have a predictable effect on the plasma current. Figure 1 shows I_p waveforms for cases with toroidal and poloidal voltages phased to produce co, counter, and no current drive along with a reference case without any oscillating voltages. A robust feature of these experiments is the entrainment of sawtooth crashes to the oscillating voltages so that crashes always occur in a particular phase of the oscillation. One surprising result in these experiments is the appearance of oscillations in the ion temperature of about 20% which are synchronized to the oscillating voltages and not explained by classical heating processes. These accompany oscillations in magnetic fluctuations, perhaps suggesting that the applied voltages repeatedly stabilize and destabilize fluctuations which then heat ions through an unknown process.

Neutral Beam Injection

Neutral beam injection has proven to be a very effective method for heating, driving current, and imparting momentum to plasmas in other configurations. In the past year, we have injected neutral beam power for the first time using an injector developed by the Budker Institute for Nuclear Physics in Novosibirsk, Russia. The design parameters of the beam are 60 A and 25 keV giving a power of 1.5 MW with 1.2 ms duration. To date, we have injected 40 A at 23 keV for a duration of 1.5 ms. Measurements of fast ion confinement time give ~ 1 ms, similar to the bulk ion confinement time, and the measured slowing down time is classical. Comparison with modeling of fast ion transport in a stochastic magnetic field is underway as well as detailed measurements of the heating, current drive, and rotation drive efficiency.

Lower Hybrid Waves

Lower Hybrid Current Drive (LHCD) has been successful in tokamaks but has never been attempted in the RFP. Theory has shown that lower hybrid waves are suitable for current profile modification and heating and may be able to suppress tearing instabilities in MST at moderate power levels (> 1 MW).[4] An interdigital line antenna is being developed for MST. The first prototype was able to launch power at the 2-3 kW level with less than 10% reflected power. RF probe measurements have detected the launched wave in the plasma. A second prototype, capable of higher power and more fully instrumented has recently been installed. Although testing has just begun, 10 kW has been injected with low reflected power. Fig. 2 shows the forward and reflected power along with the power transmitted through to the end of the antenna during a typical shot. The radiated power is evidently a large fraction the applied power. We anticipate proceeding to as much as 200 kW within the next year. At this level an observable effect on the plasma is expected allowing the physics of LHCD in the RFP to be addressed including measurement of the current drive efficiency, density limit, fast electron transport, and wave scattering by density fluctuations.

Electron Berstein Waves

Electron Bernstein Waves (EBW) have been proposed as a good candidate for heating and current drive in overdense plasmas like the RFP.[5] A mode conversion process allows EBW and electromagnetic waves to couple at the plasma boundary, providing a scenario for coupling to the EBW from an antenna. EBW emission has been measured in MST at close to blackbody levels, implying the mode conversion efficiency can be high. Low power tests (< 4 W) with a single waveguide antenna show good coupling to the plasma. During periods with favorable (steep) edge density gradients, reflection coefficients can be as low as 0.2 as shown in Fig 3. Short pulse, higher power experiments have begun at the 25 kW level and, although not yet optimized, have successfully injected power for 2 ms with a reflection coefficient of ~ 50%. Low power tests have also begun using a twin waveguide antenna. Here, the phase between the two halves can be adjusted to optimize the coupling. Extension of the power supply to the 150 kW level is planned in the near term. Detailed comparisons between experiment and theory are ongoing and RF probe measurements of the wave in the plasma along with hard x-ray measurements of the deposition profile will be conducted. One attractive feature is that the coupling appears to be more favorable during periods of improved confinement, opening the possibility for further improvements with more detailed current profile control.

This work is supported by the U.S.D.O.E.

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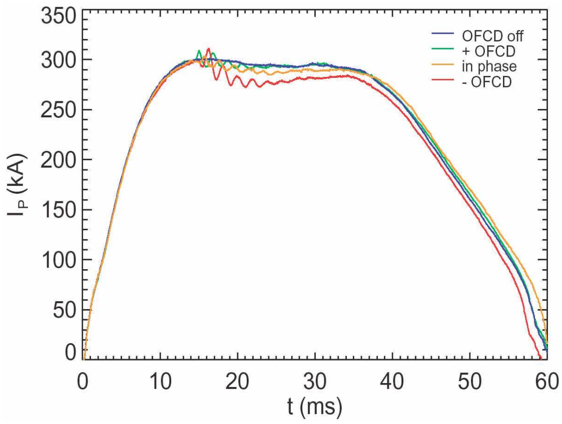

Fig. 1. Toroidal plasma current with different phasing of applied oscillating poloidal and toroidal loop voltages

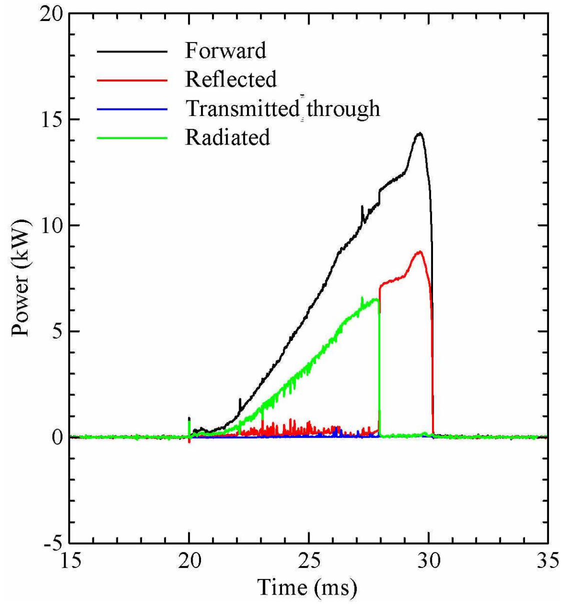

Fig. 2. Forward, reflected, transmitted, and radiated power for antenna launching waves in the lower hybrid range of frequencies

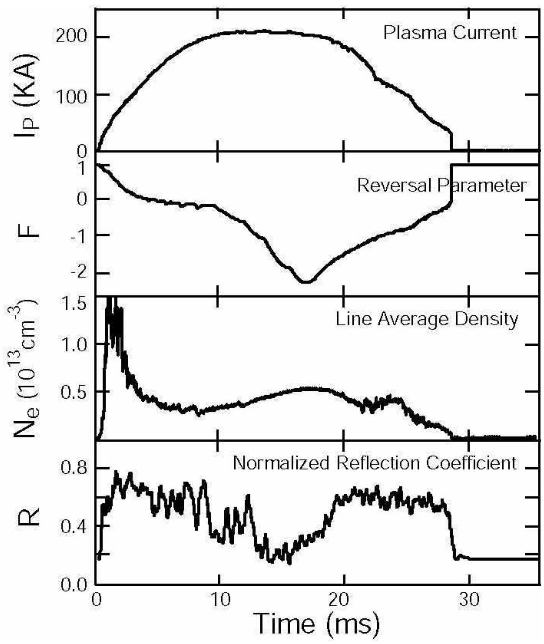

Fig. 3. Plasma current, reversal parameter, line-averaged density, and reflection coefficient for single waveguide launching power in the electron cyclotron range of frequencies