Ion Heating and Magnetohydrodynamic Dynamo Fluctuations in the Reversed-Field Pinch

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Ion temperature measurements, time resolved to 10 μs, have been made in the Madison Symmetric Torus (MST) reversed-field pinch with a five-channel charge-exchange analyzer. The ion temperature, $T_i \approx 300$ eV for $I=360$ kA, increases by as much as 100% during discrete dynamo bursts in MST discharges. Magnetic-field fluctuations in the range 0.5-5 MHz were also measured. Structure in the fluctuation frequency spectrum at the ion cyclotron frequency appears as the bursts terminate, suggesting that the mechanism of ion heating involves the dissipation of dynamo fluctuations at ion gyro-orbit scales.

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Reversed-field pinch (RFP) experiments with ion temperature diagnostics have reported ion temperatures clearly exceeding that which would be expected from simple collisional equilibration with the Ohmically heated electrons [1-4], and some authors have suggested the dissipation of magnetohydrodynamic (MHD) dynamo fluctuations as a mechanism for energy transfer to the ions [3-6]. The MHD dynamo [7-9] model for RFP field sustainment requires a substantial fluctuation level to generate the reversed toroidal flux. These fluctuations should be strongly coupled to the plasma via the small resistivity. Ion viscosity or wave-particle resonances can then convert the flow fluctuations into ion thermal energy. Arguments to support this hypothesis have typically focused upon the amount of Ohmic power that does not appear in electron heating [2,4,5], which is assumed to be stored in the fluctuations. Magnetic-field fluctuations as large as a few percent are present in RFP's and previous results have shown a clear dependence of the ion temperature on the fraction of non-Ohmic power [2,4,5]. Recently there have been some attempts to correlate ion heating and soft x-ray fluctuations in REPUTE-1 [4]; however, no direct measurements of dynamo fluctuations have been available.

As reported elsewhere [10], the toroidal flux in the Madison Symmetric Torus (MST) reversed-field pinch is generated in both a continuous fashion and during discrete events (Fig. 1). The self-generation of magnetic field in the RFP is attributed to an internal dynamo mechanism; therefore, the observed discrete flux-generating events in MST can be interpreted as periods of increased dynamo activity [11]. The measured nonlinear coupling of $m=1$ tearing modes to $m=0$ modes supports the "MHD dynamo" picture of equilibrium toroidal field generation in the RFP [10]. The magnetic-field mode structure during the discrete dynamo bursts changes dramatically, with energy flowing rapidly from small wave numbers to the largest wave numbers resolvable [10]. These dynamo events in the MST discharges present an unparalleled opportunity for a careful examination of the ion heating question, and in this Letter we report the first measurements of ion temperature and high-frequency magnetic-field fluctuations during discrete dynamo events.

The effective ion temperature was measured using a newly developed scanning, charge-exchange analyzer (CXA) (Fig. 2). The analyzer uses five continuous electron multipliers and an electrostatic bending field for energy analysis. Background plasma light was kept to a minimum and the background ion signal was eliminated by using a high-voltage deflecting system upstream from the nitrogen stripping chamber. The detectors were used in a current, rather than pulse-counting, mode. The time resolution of the analyzer was limited by available neutral flux to 10 μs. The measured signal-to-noise ratio of each channel exceeded 20:1 for discharges reported in this Letter, and the typical energy range analyzed was 200 to 2500 eV. The ion temperatures were determined by a nonlinear fit to the five-point neutral energy spectrum produced by the CXA.

On a limited number of discharges a graphite pellet was injected into the plasma. A seven-channel Doppler measurement of the *CV* 227.1-nm line was then possible, and the calculated Doppler ion temperature was in good agreement with the CXA hydrogen ion temperature: $T_i^{\rm Dopp}=75\pm 15$ eV, $T_i^{\rm CXA}=90\pm 20$ eV.

We find that average ion temperature during the first 10 ms of the discharge greatly exceeds that which would

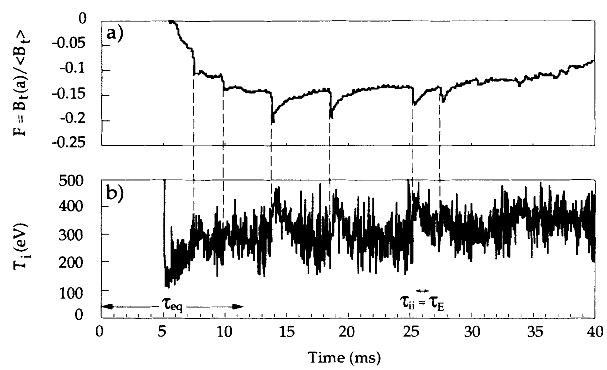

FIG. 1. (a) Reversed edge toroidal field is generated continuously and in discrete bursts. (b) Ion temperature "bursts" correlate with dynamo activity and $T_i \approx 150$ eV within 5 ms of start-up. The ion-ion collision time τ_{ii} and the ion energy confinement time τ_E are shown for reference.

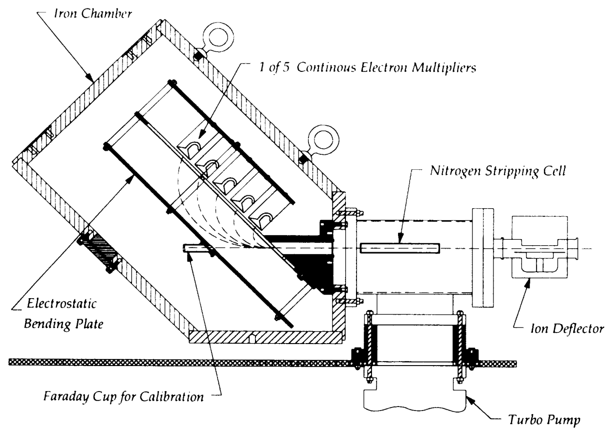

FIG. 2. Schematic of the five-channel charge-exchange analyzer.

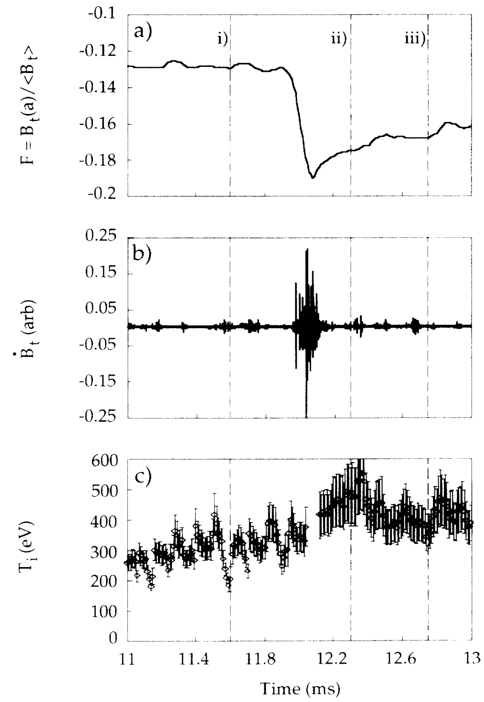

FIG. 3. (a) Enlarged view of reversal parameter during a dynamo burst (not the same discharge as Fig. 1). (b) High-frequency, 0.5–5.0 MHz, toroidal magnetic-field fluctuations during the same time interval. (c) Ion temperature from CXA during the same interval.

be expected from simple electron-ion collisional energy transfer (for MST, $\tau_{\text{equil}} \approx 10$ ms and $T_e < 100$ eV during the same period) (Fig. 1). Low signal levels prevent accurate measurements of T_i before 5 ms. This result confirms the anomalous character of the ion temperature as a general feature of the RFP as reported by other groups [1–6]. We also find that the measured ion temperature increases by as much as 100% during a discrete dynamo event (Figs. 1 and 3). This result clearly indicates a correlation between ion heating and dynamo fluctuations in the RFP.

Charge-exchange measurements of the ion temperature are susceptible to changes in the neutral density and ion temperature profiles. The neutral flux simulation code NEUCGA [12,13] was used to model the neutral flux from MST, and attempts were made to reproduce the observed changes in T_i and total neutral flux by changing the T_i, T_e, and n_e profiles. The required profile changes were inconsistent with the line-integrated density measurements made with a CO_2 interferometer [14]. The simulation also indicated that typical MST plasma densities are too low to affect significantly the temperature calculations based on fits to the tail of the neutral energy spectrum (Fig. 4). Therefore, the measured changes in T_i represent actual changes in the plasma ion temperature.

Theoretical considerations [15] suggest that a turbulent MHD cascade to scales where $\omega \approx \omega_{ci}$ (ω_{ci} is the ion cyclotron frequency) can transfer $\tilde{B}$ energy directly to the ions. This encouraged us to investigate high-frequency magnetic fluctuations during the discrete dynamo events. The fluctuations were measured at the edge of the plasma using a single electrostatically shielded coil. The signals were bandpass filtered (0.5–5 MHz) and digitized at 10 MHz. During a dynamo burst the total power in the fluctuation signal increased by as much as 3 orders of magnitude (Fig. 5). As mentioned earlier, a cascade of energy to smaller scales during the dynamo bursts is seen in the lower-frequency (1–250 kHz) edge magnetic fluctuations [10]. After the peak generation of reversed toroidal field, a trough appear in the power spectrum at the edge ion cyclotron frequency, $f \approx f_{ci} \approx 2$ MHz (Fig. 5). At this point, the neutral flux emission peaks, as well as the ion temperature (Figs. 3 and 4). The time lag between the generation of toroidal field and the increase in ion temperature (Fig. 3) is not well understood. The trough feature appears in the power spectrum *after* the fluctuation amplitude begins to decay. The time lag may also result from comparing a central ion temperature to an edge fluctuation measurement. There is no *a priori* reason to assume that high-frequency edge mag-

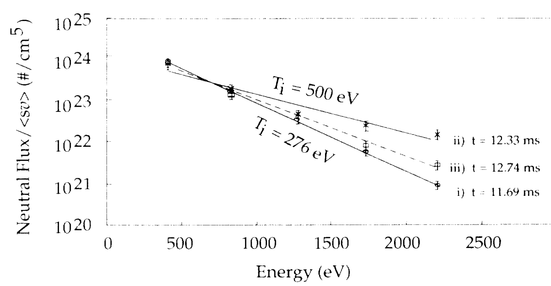

FIG. 4. Neutral energy spectra during a dynamo burst. Times indicated by lower-case roman numerals correspond to those in Fig. 3.

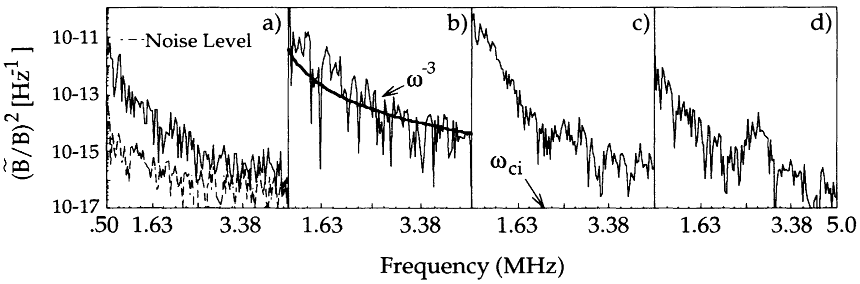

FIG. 5. Typical magnetic power spectra (a) before, (b),(c) during rise and decay, and (d) after a dynamo burst; each interval corresponds to 25 μs.

netic fluctuation characteristics are indicative of core fluctuation features. Numerical simulations designed to investigate this question are currently underway.

Qualitatively, our results support the turbulent MHD cascade scenario of Ref. [15], but a more quantitative comparison is desirable. Unfortunately, single-point probes can only measure the instantaneous energy spectrum, and a quantitative comparison to the model would require measurements of the spectral energy transfer rate. Spectral amplitude estimates from the theory of MHD inertial range turbulence (as in Ref. [15]) do not apply here, as the $\omega^{-3/2}$ theoretical spectrum clearly disagrees with the measured spectrum (Fig. 5). It *is* possible, however, to compare the energy associated with the excess loop voltage (non-Ohmic power) during the bursts, $\int_{t_0}^{t} I(V_L - V_{\rm Spitzer})/(\text{volume})$, with the energy gained by the ions during the same period, approximately $\frac{3}{2} n_i \Delta T_i$. For the dynamo events shown in Fig. 1, the non-Ohmic power associated each burst is 2 to 3 times the energy that would be required for the observed ion temperature changes of around 150 eV. We have assumed in this calculation that the ion heating occurs at a much faster rate than ion transport; the loss of energy via ion transport during heating or partial electron heating are just two possible explanations for the discrepancy.

In summary, the measured ion temperature in the MST appears dependent upon the level of dynamo activity. The rapid ion heating and the structure of the magnetic fluctuation power spectrum during the dynamo bursts suggest energy cascading and dissipation at $\omega \approx \omega_{ci}$ frequencies. These results are consistent with the hypothesis that dynamo fluctuations are damped by $\omega \approx \omega_{ci}$ resonances and are responsible for the observed ion heating in the reversed-field pinch. Experiments designed to measure changes in the electron temperature and density during dynamo bursts are under way.

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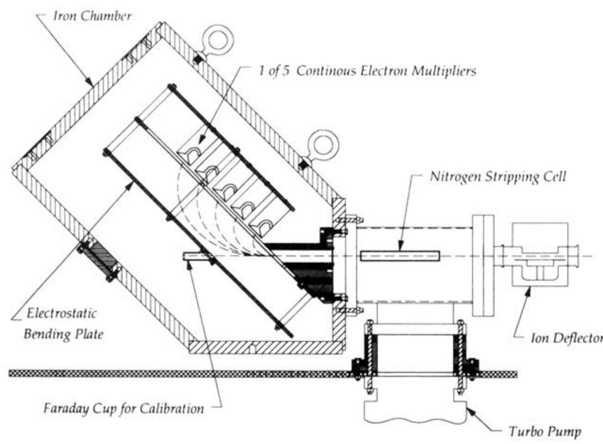

FIG. 2. Schematic of the five-channel charge-exchange analyzer.