INTERNATIONAL ATOMIC ENERGY AGENCY

FOURTEENTH INTERNATIONAL CONFERENCE ON PLASMA PHYSICS AND CONTROLLED NUCLEAR FUSION RESEARCH

Würzburg, Germany, 30 September – 7 October 1992

IAEA-CN-56/C-3-2

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DOE/ER/53198--203

DE92 041011

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Abstract

ANOMALOUS ION HEATING AND SUPERTHERMAL ELECTRONS IN THE MST REVERSED-FIELD PINCH.

Anomalous ion heating and superthermal electron populations have been studied in the MST reversed-field pinch. The ion heating is much stronger than that given by classical electron-ion friction, and is particularly strong during dynamo bursts. The heating displays a marked density dependence: in a 350-kA discharge with a maximum $\bar{n} = 0.9 \times 10^{13}$ cm^{-3}, T_i rises sharply as $\bar{n}$ drops below 0.4×10^{13} cm^{-3} late in the discharge. Superthermal electrons are produced in the core, with temperatures of $T_{eh} = 350$–700 eV while the bulk core temperature is $T_{e0} = 130$–230 eV. The fraction of superthermal electrons decreases with increasing density, from 40% at $\bar{n} = 0.5 \times 10^{13}$ cm^{-3} to 8% at $\bar{n} = 1.9 \times 10^{13}$ cm^{-3} at $I = 350$ kA. However, data with similar plasma parameters but higher oxygen impurity content had a lower T_{eh} and higher hot fraction. The edge superthermal electron distribution is well fit by a drifted bi-Maxwellian distribution with $T_{\|} \sim T_{e0}$ and relative drift speed $v_d/v_{th} = 0.4$. With the assumption that the parallel heat flux measured with a pyroelectric probe is carried by superthermal electrons, the measured electron current is consistent with $T_{\perp} \sim T_{ea} \sim T_{e0}/3$ and accounts for over half of the total edge parallel current measured with magnetic probes.

1. INTRODUCTION

Anomalous ion heating [1,2,3,4] and the presence of superthermal electrons both in the core [5] and edge [6,7] have been observed on several

RFP experiments. It has been proposed that the anomalous ion heating process involves viscous damping of fluid fluctuations produced by MHD 'dynamo' instabilities [8,9] or ion cyclotron resonance as the dynamo modes cascade to shorter wavelengths [10]. The core superthermal electrons resemble a classical slideaway population in the presence of the large value of E/E_{cr}, where E is the electric field and E_{cr} is the critical field for runaway. The edge superthermal electrons, which have temperatures comparable to the core bulk temperature and carry a substantial portion of the poloidal plasma current, may result from enhanced transport due to magnetic fluctuations [11,12] or may be generated locally by the effective dynamo electric field $\langle \tilde{V} \times \tilde{B} \rangle$.

These phenomena have been investigated on the MST reversed-field pinch using a five-channel charge-exchange analyzer (CXA) for central proton T_i, measurement of the Doppler-broadened CV 2271Å line for the C^{+4} ion temperature, central Thomson scattering for T_{e0} and n_{e0}, a Si(Li) x-ray spectrometer for the core superthermal electron temperature T_{eh} and fraction n_{eh}/n_e, an electrostatic electron analyzer (EEA) for measurement of the edge electron distribution, a pyroelectric for measurement of the parallel heat flux at the edge, as well as the standard diagnostics for plasma current, line-averaged density, etc.

2. ION HEATING

Both the CXA and CV measurements indicate that ion heating far exceeds that expected from classical electron-ion friction. Particularly strong ion heating is observed [3,4] during the periods of discrete dynamo events [13]. A recent theoretical model [10] proposes that this heating arises from ion cyclotron damping of dynamo fluctuations at wavelengths large compared to those required for efficient viscous damping of perpendicular flow fluctuations; edge fluctuating magnetic field spectra may indeed have a feature at $\omega \sim \omega_{ci}$ [3,4].

A strong increase of T_i has been observed to occur in the late portion of discharges in which the density is allowed to decrease. Figure 1 displays CXA spectra in different energy regions gathered from two similar discharges with peak $\bar{n} = 0.9 \times 10^{13}$ cm^{-3} and $I = 350$ kA. As $\bar{n}$ decreases, the high energy channels increase, resulting in an increase of T_i from 190 to 270 eV; this is also seen in the CV temperature, which rises from 100 to 130 eV. (The CXA spectrum shows a low energy component with $T = 40$ eV, due to charge exchange in the edge.) The rise in T_i is not enough to compensate for the decrease in $\bar{n}$; $\bar{n}T_i$ continues to decrease. Although the T_i rise may simply be the result of power balance with decreasing density and profile changes, there appears to be a critical density involved. Future radially resolved measurements will allow us to unfold profile changes that may be taking place.

3. SUPERTHERMAL CORE ELECTRONS

The effect of electric field strength, or E/E_{cr} on superthermal electron generation was investigated in a series of discharges at four density values $\bar{n} = 0.5\text{–}2.0 \times 10^{13}$ cm^{-3}, summarized in Table I. While T_{eh}/T_{e0} remained in the range 3–4, n_{eh}/n_e decreased from 40% to 7% and E/E_{cr}, calculated using T_{e0} from Thomson scattering, decreased from 0.14 to 0.04. In contrast, a 1% fraction of superthermal electrons was observed in much hotter HBTX plasmas ($T_{e0} = 600$ eV) with $T_{eh}/T_{e0} \sim 10$ and $E/E_{cr} = 0.9$ [5]. As Table I indicates, the inclusion of the hot component substantially increases the calculated core electron beta; however, the total beta still increases with increasing density.

It appears, however, that the superthermal component does not have a simple dependence on E/E_{cr}, as indicated by data taken under similar conditions on a different day (04July92). In this case, T_{eh} was lower and n_{eh}/n_e was higher than the comparable case quoted above. Three spectra, with two-temperature Maxwellian fits, are displayed in Fig. 2. The presence of 1.5 keV Al K radiation is evident, as well as an increase above the continuum below 0.8 keV thought to be due to oxygen K lines. The only known difference in the 04July92 set is a higher level of oxygen radiation, both visible and x-ray.

4. SUPERTHERMAL EDGE ELECTRONS

The distribution of electrons flowing along the magnetic field at the edge is measured with the EEA to fit a drifted bi-Maxwellian distribution with $T_{||} \sim T_{e0} \sim 115$ eV and relative drift speed $v_d/v_{th} = 0.4$ in low-density 220 kA discharges, accounting for roughly 10% of the local density. With the assumption that the parallel heat flux measured with the pyroelectric probe is carried by superthermal electrons, the measured current is consistent with $T_\perp \sim T_{ea} \sim 40$ eV and accounts for over half of the total edge current measured with magnetic probes. The superthermal current increases by as much as a factor of 5 during discrete dynamo events, at which time the toroidal magnetic flux increases sharply, implying that these electrons play a major role in the fast time-scale magnetic behavior. The ratio of electron currents parallel and anti-parallel to the total magnetic field remains constant during a dynamo burst, implying that the shape of the distribution is constant.

As superthermal electrons appear to play an important role in the energy confinement and magnetics, it is important to determine their production mechanism. We plan to measure the radial profile of superthermal electrons to distinguish between production in the edge region and enhanced transport from the core.

5. CONCLUSIONS

It appears that both anomalous ion heating and superthermal electron production are a consequence of strong MHD activity characteristic of the RFP. This results in large flow and magnetic fluctuations as well as enhanced resistivity leading to larger E/E_{cr} values than found in tokamaks with similar temperature and density. Since these fluctuations drive the poloidal current which sustains the RFP state, one might expect both effects to be a fundamental aspect of the RFP. However, as the results reported here show, both effects depend on plasma conditions, particularly on density: high density discharges have lower ion temperatures and a small core superthermal fraction, but a larger overall beta. Work will continue on MST to elucidate the heating processes via profile measurements and a wider range of parameter variation. The RFX experiment, now operating, will be able to investigate these effects at current and density values over four times higher than achieved on MST to help determine how these processes scale to a reactor.

This work was supported by the US Department of Energy.

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Date	$\bar{n}$ (cm^{-3})	T_{e0}	T_{eh}	n_{eh}/n_e	E/E_{cr}	β_{e0} (%)	β_e (%)
28May92	0.5×10^{13}	234	700	0.38	0.14	4.0	7.0
28May92	1.0×10^{13}	164	700	0.15	0.07	5.3	7.9
28May92	1.6×10^{13}	137	600	0.07	0.04	6.9	8.6
28May92	1.9×10^{13}	127	500	0.08	0.04	8.0	9.9
04July92	1.6×10^{13}	n.a.	350	0.19	n.a.	n.a.	n.a.

Table I: Results of analysis of Si(Li) spectra for a series of 350 kA discharges with different density, along with a similar set from a different date. β_{e0} is calculated using $\bar{n}$ and T_{e0} alone while β_e is calculated using T_{e0} and T_{eh} with the respective density fractions.

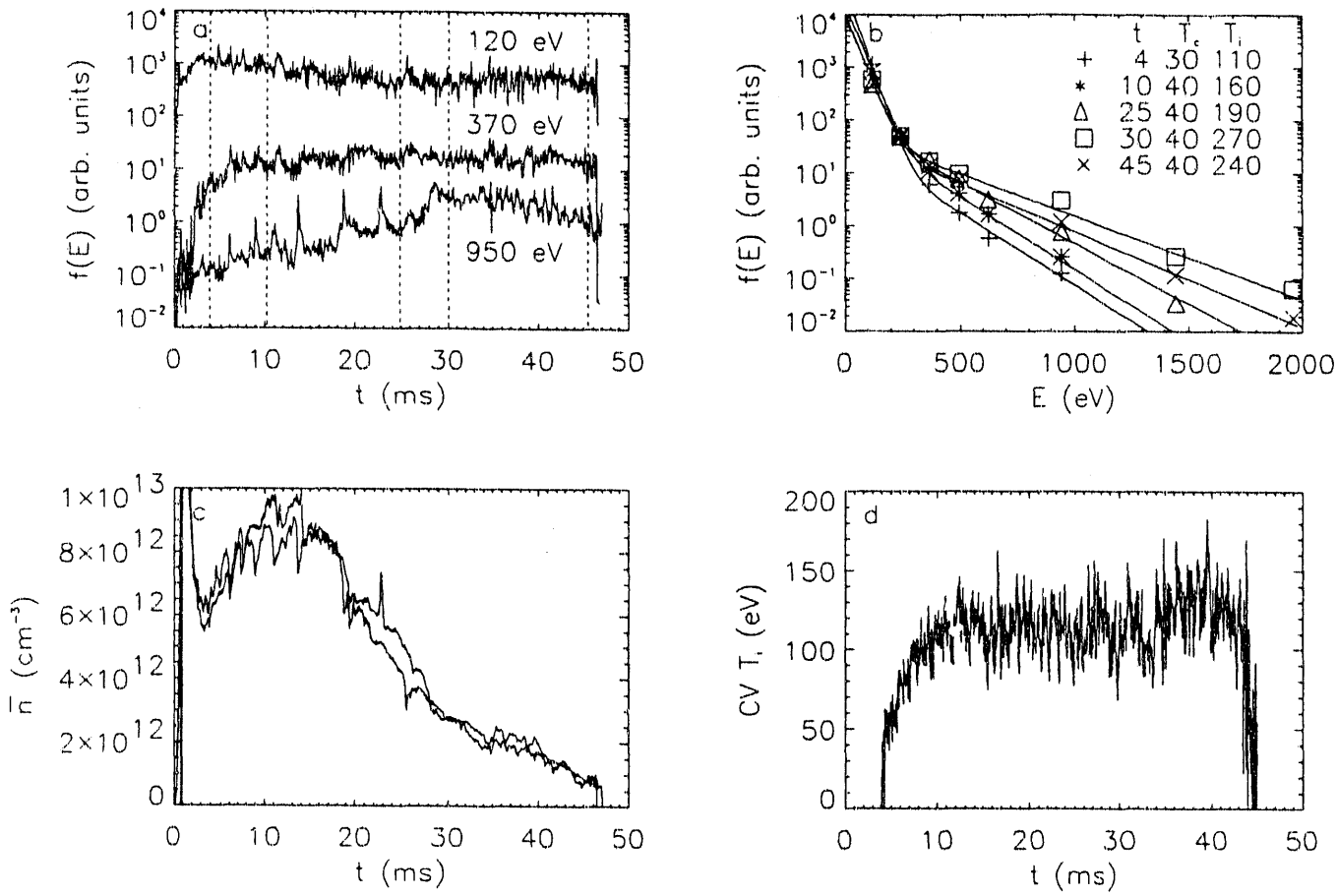


Figure 1 A rise in ion temperature during decay of density is seen via: a) time history of three CXA energy channels, b) CXA spectra at the times indicated with dotted lines in a), c) density for the two discharges used, and d) C^{+4} ion temperature (28May92 data).

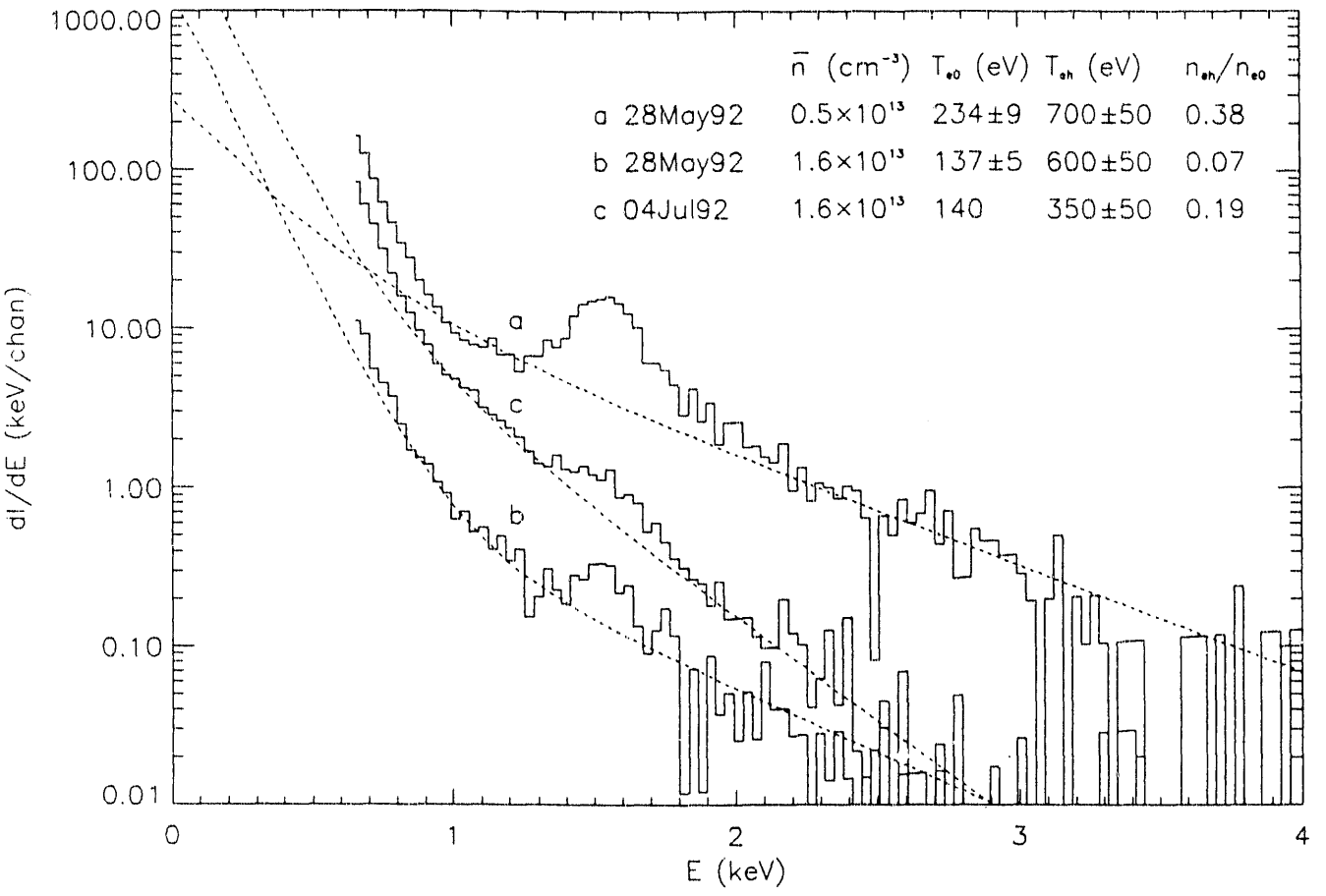


Figure 2 Si(Li) spectra, summed over the entire discharge, with two-temperature fits. Most counts are registered during the peak current portion. T_{e0} was not measured for the 04July92 set, but is expected to be similar to that of the corresponding 28May92 set.

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