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Mechanism of Radial Redistribution of Energetic Trapped Ions due to m=2/ n=1 Internal Reconnection in JET Optimized Shear Plasmas.

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INTRODUCTION

High performing plasmas are obtained in Optimized Shear (OS) configurations in JET due to formation of an internal transport barrier, with generally q(0)=1.5-2. In conditions where sawteeth are stable, other MHD modes arise to limit performance. The most common is pressure driven internal kink mode coupled to the plasma edge [1,2]. The unstable dominant m=2/n=1 mode leads to an internal reconnection('crash') at the q=2 surface. Some times the reconnection leads to a long-lived n=1 island with rapidly decreasing frequency ('chirping' due to plasma deceleration) and sometimes the mode grows to very large amplitude causing the plasma to disrupt. Using a high energy NPA, measurements were made of the energetic ICRF heated hydrogen ions. We have inferred large vertical transport of the ions from the plasma core during the MHD activity. When the 'chirping' island develops, the ions can be transported as far as the stochastic ripple diffusion domain at the top of the plasma[1].

OBSERVATION OF RADIAL REDISTRIBUTION OF ENERGETIC IONS

A description of the measurement set-up with a vertical line-of-sight was given in [1]. Figure.1 shows evolution of a deuterium OS plasma pulse with B_φ=2.5T, I_φ=2.3MA, and first harmonic D(H) ICRF heating giving the energetic ions. A burst of n=1 mode activity at t=4.724s destroys the transport barrier, degrades T_e, T_i, DD fusion rate R_{DD} and plasma rotation ω_{rot}. $q(r)$ was monotonic at the time, with $q_0 \cong 1.65$. Simultaneously with the n=1 burst a spike in the NPA flux Γ_H, by a factor 3÷10 larger than the ambient level, was seen in the whole measurement range $0.3 \leq E(\mathrm{MeV}) \leq 1.1$. We attribute NPA spike to redistribution of energetic ions from plasma core to location of greater neutralization along the Z axis. Ion expulsion from the core is evidenced also by abrupt extinction of energetic ion driven Alfvén eigenmodes. Subsequent to n=1 burst and NPA flux spike, an ELM is always observed, sometimes causing loss of ICRF coupling, as in fig.1. Evidence of reconnection is seen in ECE emission, locating it to the q=2 location. Magnetic fluctuations measured at the plasma edge[1] give that during the crash typically $\delta B_\theta/B \geq 3\times10^{-4}$, and for the island structure it is $\approx 2\times10^{-4}$. Comparison of deduced ion energy distribution function before, during and after the NPA flux spike, in the range $0.3 \leq E(\mathrm{MeV}) \leq 1.1$, shows that 10 ÷20% of the ICRF heated ions in the measurement phase-space are redistributed from the plasma core due to the crash, and that the affected ions are mostly those with toroidal precession time greater than the crash time τ_{cr}.

THE PROBLEM

Different mechanisms have been invoked to model ion redistribution during sawteeth. Before ~1995 the view was that ion motion was "frozen" into the equilibrium flux surfaces, and that during a sawtooth the ion motion along evolving flux surfaces gave mixing when field-line reconnection occurred. Kolesnichenko and Yakovenko[3] stressed that the $E_\perp \times B$ drift in the electric field generated by temporal evolution of the helical magnetic field perturbation must be taken into account. The resulting radial transport depends on relative magnitudes of the characteristic times associated with the process(precession, bounce, crash), allowing distinction to be made between thermal, supra-thermal, trapped and passing ions. In this model the interaction with $E_\perp$ leads to non-conservation of the ion toroidal momentum $P\varphi$. Gorelenkov [4] enhanced this model by noticing that the ion energy change is proportional to $< \upsilon_{pr} \cdot E_\perp >$, where υ_{pr} is toroidal precession speed and the brackets signify a bounce-orbit average. The latter approach was used to model radial redistribution of α-particles due to m=1/n=1 sawtooth reconnection in TFTR [4]. The same measurements in TFTR were modeled also by invoking, in addition to the above, magnetic field stochasticity due to overlapping multiple poloidal harmonics[5]. In the following we follow the formalism of Gorelenkov [4] to model ion redistribution due to reconnection at the q=2 location in JET OS plasmas. We make approximations to obtain analytic solutions which yield the main properties of ion mixing due to such reconnection. Comparing the modeling results with measurement, it is possible to exclude specific assumptions of modeling used in [4,5].

MODEL OF ION REDISTRIBUTION DUE TO M=2/N=1 RECONNECTION [6]

Following[4], the energetic ion distribution function is cast in variables $(\mu, P\varphi, p)$, $\mu = \varepsilon_\perp / B$ is the ion magnetic moment which is conserved during the reconnection, $P\varphi = \omega_{c0} B / 2\pi B_0 - \upsilon_{\parallel} R$ is not conserved, and the ion energy ε, or equivalently $p = \mu B_0 R_0 / \varepsilon$, are not conserved. The magnitude of p equals the major radius of the ion bounce point. The effect of reconnection on the ions is governed by destruction of equilibrium magnetic surfaces during the 'crash' phase of the oscillation. Kadomtsev's prescription, which invokes conservation of magnetic flux and number of ions, is used to invert the ion distribution function from before the crash to after it. Details of inversion of the distribution function for ions in real geometry and orbits of arbitrary radial width are given in [4]. Equations for evolution of ε and $P\varphi$ due to the electric field generated by plasma motion during the crash are [6]:

$$\frac{d\varepsilon}{dt} = z < \upsilon_{pr} \cdot E\perp > \text{ and } \frac{dp_\varphi}{dt} \cong \frac{d\bar{\psi}}{dt} < \nabla \bar{\psi} \cdot \upsilon_{E\perp} >.$$

where ψ is the poloidal flux. Analytic solutions are obtainable by making the assumption of ideal MHD electrostatic potential with one dominant mode *(m, n)*. The potential is written as $\varphi(\rho,t) = \varphi_0 \rho m \cos(m\theta - n\varphi - t)$, where $\rho = r/a$ is the normalized minor radius. With this simplification equations for evolution of radii ρ and ρ can be written as:

$$\frac{dp(P_\varphi)}{dt} = A\rho^{m-1} \sin(n\varphi + \omega t) \text{ and } \frac{dp}{dt} = C\rho^{m-1} \sin(n\varphi + \omega t).$$

$$\text{Coefficients } A = <-\frac{c}{B}\frac{m}{k}\varphi_0 \cos[(m-nq)\theta]> \text{ and } C = <-\frac{c}{B}\frac{m}{k}\varphi_0 \cos[(m-nq)\theta]>.$$

k is the trapping parameter, $k<1$ (trapped ions) and $k>1$ (passing ions). Solutions give postcrash minor and major radii (ρ_+ and p_+) of ion bounce-points in terms of the pre-crash radii (ρ_- and p_-). Then ($\rho_+ = p_- \exp[A\tau_{cr} \sin(n\varphi_0)]$ and $p_+ = p_- + (C/A)(\rho_+ - \rho_-)$. To illustrate conclusions of the model we have computed the ion bounce point trajectories due to the reconnection. We have specified the minor and major radius distribution of the ions before the crash as $f_{-} = (1-\rho^2)^4$ exp $[-p-R_c)^2\Delta_R^{-2}]$ a Gaussian with peaked spatial profile. R_c =3m is the position of the ICRF resonance,Δ_R = 0.1m is the radial width of the resonance layer, and R_0 m 3.1m is major radius of the axis. In fig.2 contours of initial spatial distribution of ICRF heated ions and vertical NPA line-of-sight are shown in red. Comparison is shown of postcrash ion bounce point motion(green) for two configurations, with core q(0)=1 and q(0)=2.

We see that as the pre-crash q in the plasma core occupied by the energetic ions increases from unity the ion orbit after the crash is stretched and becomes increasingly more elongated along the Z-coordinate. This is because the perturbed electric field seen by an ion moving along the helical field line has different polarization according to the value of q(0). Therefore the direction of $E_\perp \times B$ ion drift depends on the value of q where the pre-crash ions reside.

Before the crash the ions are distributed uniformly in toroidal angle φ. The effect of the crash depends on toroidal position of the ions at the crash. Thus the post-crash spatial distribution function of the ions is an integral over the pre-crash toroidal positions($\varphi\_$) of the ions.

$$f+(\rho(\rho\_,R\_),R(\rho,R\_)) = J^{-1}(2\pi)^{-1}\int f\_(\rho\_,R\_)J\_d\varphi\_$$
$$= J^{-1}\int f\_(\rho\ ,R+C(\rho-\rho)/A)G(\rho\ ,\rho)\ J\_\ d\rho$$

Coefficients A and C were defined earlier, J is the Jacobian of transition from the 6-D phase space to variables ($\mu, P\varphi, p$), and $G(\rho,\rho)=1/(2\pi\rho n\sqrt{\tau_{cr}^2 A^2-[\mathrm{In}(\rho/\rho)]^2})$

Spatial redistribution of energetic trapped ions is shown in Fig.3, using the initial distribution given earlier. A comparison of post-crash distribution is shown for core q(0)=1 and q(0)=2. Figure.3 illustrates a model prediction, that as the pre-crash core q(0) increases above unity, the number of ions redistributed into the vertical NPA line-of-sight also increases.

COMPARISON OF MODEL PREDICTION AND MEASURED ION TRANSPORT

The measured quantity is line-of-sight integral of atomic flux $\Gamma(E,Z)$ produced by neutralization of ions at their bounce points[1], $\Gamma(E) = \int F(E,Z,\mu^*)P_v(E,Z)\gamma(E,Z)dZ$. Here F is the local ion distribution function, P_v is neutralization rate, and γ is transparency of the plasma to the energetic atom travelling to the NPA. At fixed ion energy $P_v(Z)\gamma(Z)$ increases rapidly and monotonically with Z. Therefore a sharp spike in the NPA flux is interpreted as redistribution of ions to larger Z. The ratio of NPA flux in the spike to that before the spike, $\Gamma_+/\Gamma\_$, is then a measure of how far along Z the ions are redistributed due to the crash, or $\Gamma_+/\Gamma\_ \propto (Z_+ - Z\_$. Fig.4 shows measured $\Gamma_+/\Gamma\_$ for ions with E= 0.3MeV plotted against measured q(0). The result is consistent with the conclusion of the theory, that the direction of motion of ion bounce points due to the crash is determined by the value of core q(0), and that as the magnitude of q(0) increases from unity the ion bounce orbit becomes increasingly more elongated along the Z-coordinate.

CONCLUSIONS

(1) In Optimized Shear plasmas in JET with q(0)>1, NPA measurements show that internal reconnection at the q=2 location redistributes energetic trapped ions along the Zaxis.

(2) Modeling of the measurements is based on a theory of ion redistribution due to *E B* drift of the ions in the electric field generated by the evolving magnetic field perturbation, and the change in ion energy due to the electric field. This yields a result that ion redistribution is correlated with magnitude of q(0), and that as q(0) grows above unity the ion bounce points are distributed along trajectories that are increasingly vertical.

(3) NPAmeasurementsinJET are consistent with the modeling results. Correlation is found between pre-crash q(0) and ions redistributed into the NPA line-of-sight.

(4) The result allows the conclusion that distinctive features of Kadomtsev reconnection give the observed result and that stochasticity, invoked in modeling of α-particle measurements in TFTR[4,5], can be excluded.

(5) A test of the model, to determine anti-correlation in ion redistribution along the R- and Z-coordinates during q=2 reconnection, will be made during forthcoming JET operation.

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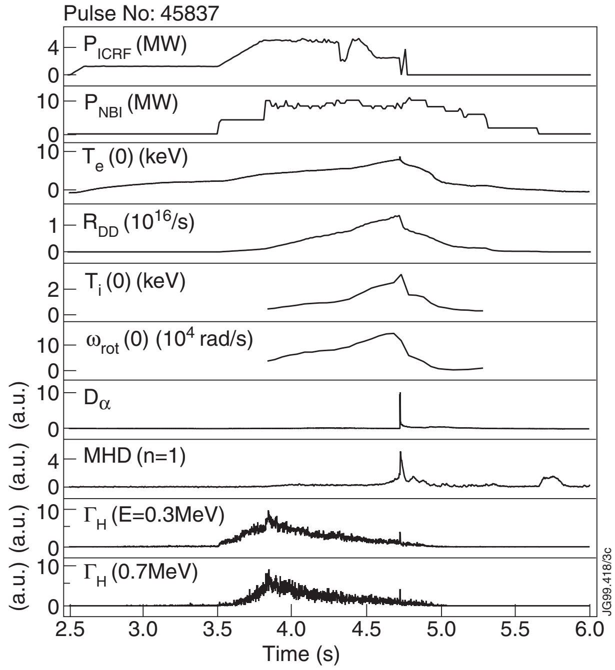

Figure 1

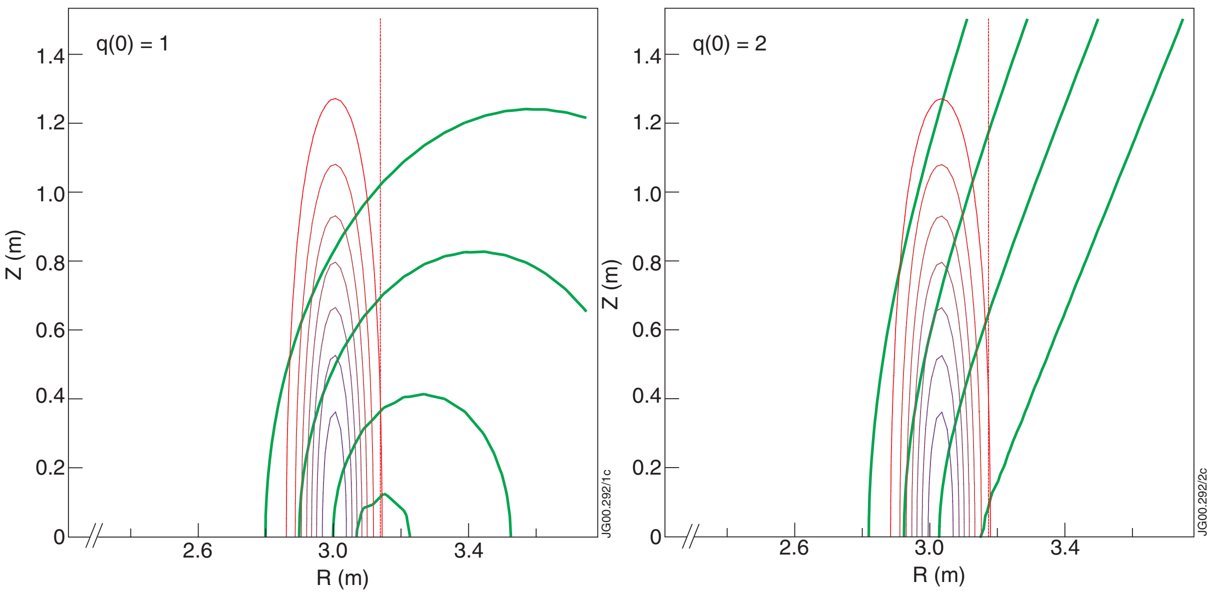

Figure 2

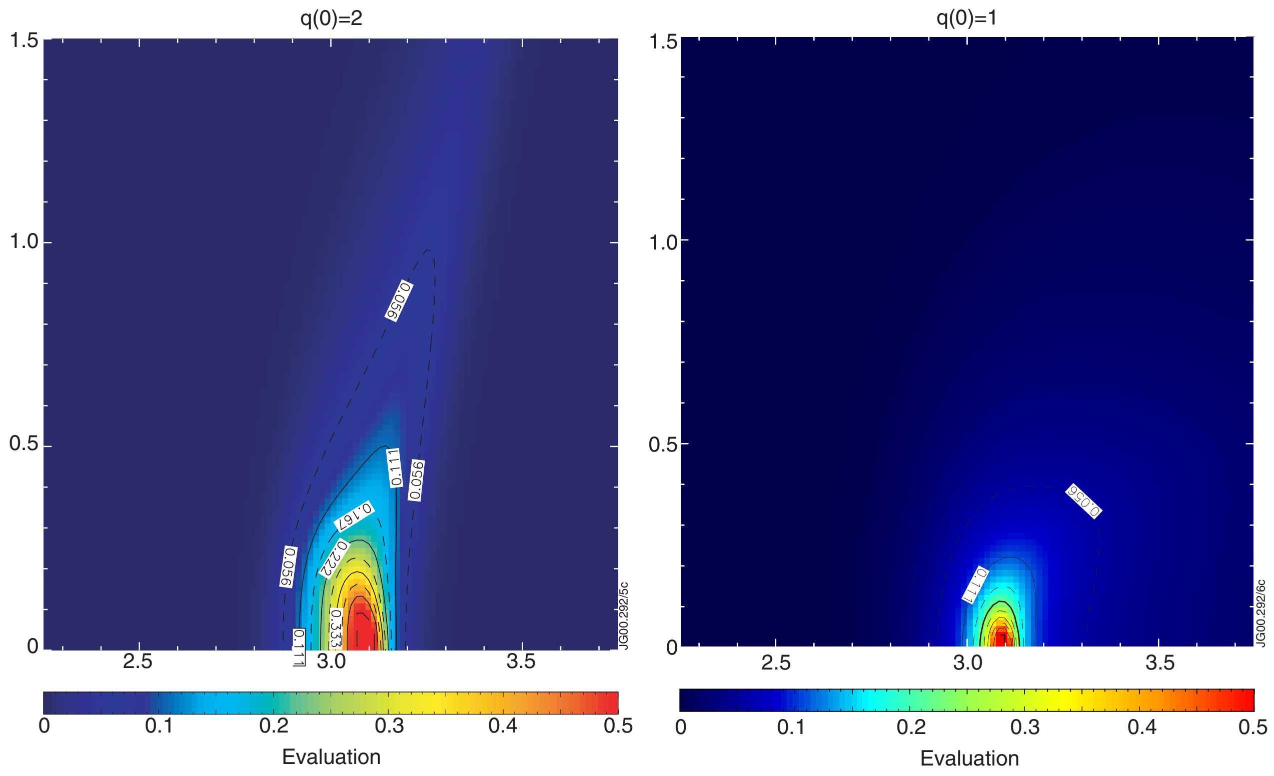

Figure 3

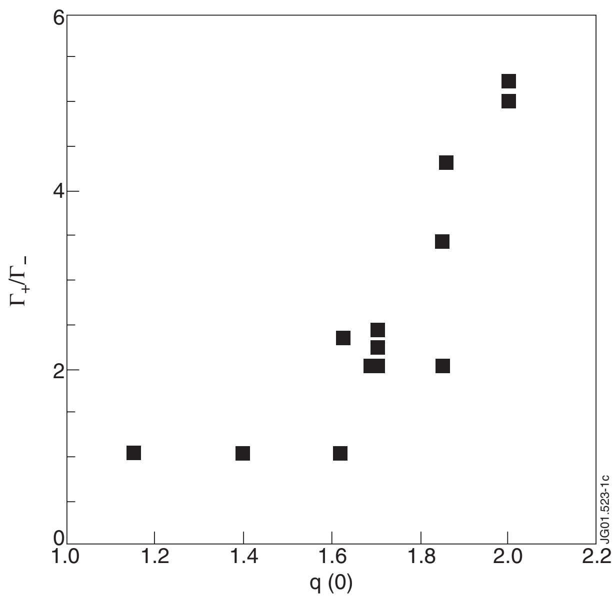

Figure 4