

Ion Acceleration during Reconnection in MAST

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Spontaneous acceleration of ions to suprathermal energies is observed during magnetic reconnection in the Mega-Ampere Spherical Tokamak (MAST). A high-energy tail is observed in the ion-distribution function following each internal reconnection event in Ohmic discharges. This phenomenon is explained in terms of runaway ion acceleration in the electric field induced by the reconnection.

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An important property of plasmas—both in the laboratory and in outer space—is that they sometimes have the ability to accelerate ions to very high energies. Spontaneous acceleration of ions is well documented in solar flares [1], astrophysical shocks [2], and reversed-field pinches [3]. The acceleration mechanism in these plasmas is usually uncertain; many theoretical possibilities have been put forward, but the experimental observations are often unable to discriminate between them. It is therefore somewhat unfortunate that in modern tokamaks, which tend to be very well diagnosed, no spontaneous acceleration of ions usually occurs. The only suprathermal ions that are ordinarily observed are the ones that are introduced deliberately for heating, such as neutral-beam injected ions, fusion products, and ions heated by radio-frequency waves.

However, as reported in this Letter, a high-energy tail is routinely observed to appear in the ion-distribution function in the Mega-Ampere Spherical Tokamak (MAST) following so-called internal reconnection events (IREs). The appearance of fast ions following IREs in MAST is interesting not only because it could shed light on ion acceleration in other plasmas, but also because it is so clearly associated with reconnection—an issue of fundamental importance in plasma physics. We find that the production of fast ions in MAST IREs can be explained as a manifestation of runaway acceleration in the parallel electric field associated with the reconnection. Ion runaway in tokamaks was predicted theoretically by Furth and Rutherford three decades ago [4] and it has been suggested that it is present in solar flares [5], but to our knowledge spontaneous runaway of thermal ions has not been identified before in a modern tokamak.

In order to investigate the behavior of both thermal and suprathermal ions, MAST is equipped with a neutral-particle analyzer (NPA) mounted in the vessel midplane. The NPA, which is on loan from PPPL, is of the type used in the Tokamak Fusion Test Reactor [6], comprising 39 hydrogen channels and 39 deuterium channels with a calibrated energy range of $1.0 \leq A(\text{amu})E(\text{keV}) \leq 150$.

The NPA thus facilitates diagnosis of the thermal ion distribution function for temperatures in excess of about 300 eV. In most discharges, the NPA had a line of sight oriented in the equatorial plane of the plasma with a tangency radius of 0.7 m (equal to that of the two codirected neutral-beam injectors) and observed particles moving in the direction of the plasma current. During quiescent Ohmic discharges, a clear Maxwellian spectrum is routinely observed. Extensive neutral-particle transport modeling on MAST indicates that flux detected by the NPA originates from the plasma center.

Internal reconnection events occur frequently in spherical tokamaks, including MAST. Presumably as a result of some plasma instability triggering the IRE, the current profile broadens, the total plasma current increases temporarily, and there is a negative voltage spike at the plasma edge; see Fig. 1. The duration of the IRE is about 1 ms, and the plasma recovers after the event. At the IRE the neutral-particle analyzer records a burst in each high-energy channel, which then decays approximately at the rate given by the ion slowing-down time. The ion-distribution function is Maxwellian before each IRE, but has a pronounced high-energy tail afterwards, extending to a few keV. Figure 2 shows the measured distribution function of ions moving in the parallel direction just before and just after a typical IRE. The solid line is the theoretical prediction from ion runaway theory, which will be discussed in detail below.

The toroidal electric field induced at an IRE must be substantial. A lower bound can be obtained by assuming that the reconnection occurs in an axisymmetric way, so that the loop voltage can be obtained from a standard EFIT equilibrium reconstruction of the current profile. Reconnection then takes place throughout the plasma, and the loop voltage exceeds 200 V in the plasma core; see Fig. 3. If the reconnection instead occurs in a more localized way, e.g., in a thin layer, the induced electric field would be even larger. Note that the electric field is much larger in the center of the plasma than at the edge,

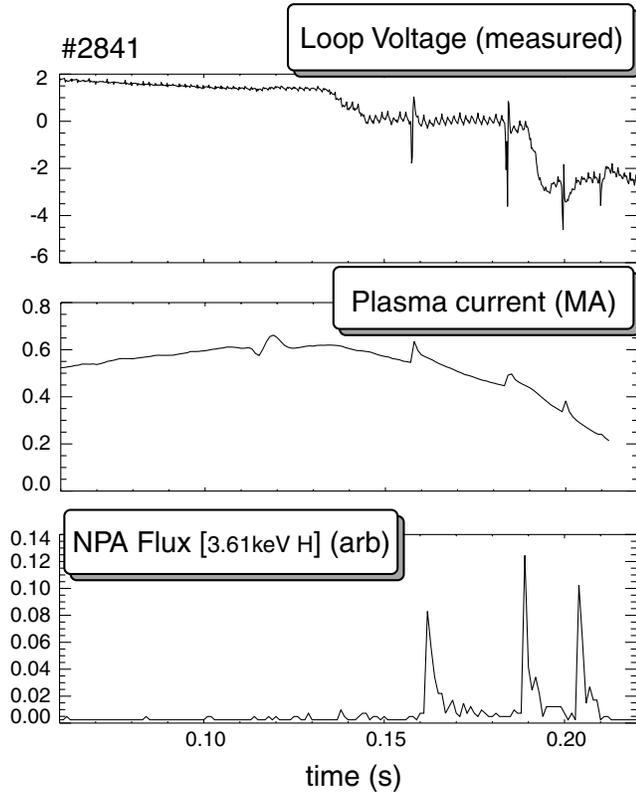


FIG. 1. Edge loop voltage, plasma current, and NPA flux at 3.61 keV in a MAST discharge with IREs.

and that the sign is different: it is in the direction of the plasma current in the center (where the current drops) but negative at the inboard edge (where the current rises).

As may be expected, this toroidal electric field generates runaway electrons. Hard x-ray detectors often record a burst during the first stage of the IRE, when the current increases and the induced electric field is largest. The detectors are situated outside the vessel, whose wall is so thick (9 mm) that only photons with energies exceeding 80 keV can be detected.

The acceleration mechanism for ions is different from that for electrons in several respects. First, as pointed out in Ref. [4] and discussed below, the friction force from electrons is highly important for the ion dynamics. It tends to cancel the electric force and must be accounted for accurately since the cancellation is complete in the simplest case of a pure plasma in a straight magnetic field. Second, the ions respond rather differently from electrons to a localized electric field. For electrons accelerated by sawteeth, it has been observed that the acceleration occurs in the small reconnection region at the X point of the magnetic island associated with this instability [7]. Ions, however, have much wider orbits than electrons and thus experience a smeared out electric field. The radial excursion of their orbits from magnetic surfaces enables the electric field even from an infinitely thin reconnection layer to accelerate ions over a region of width $\Delta r =$

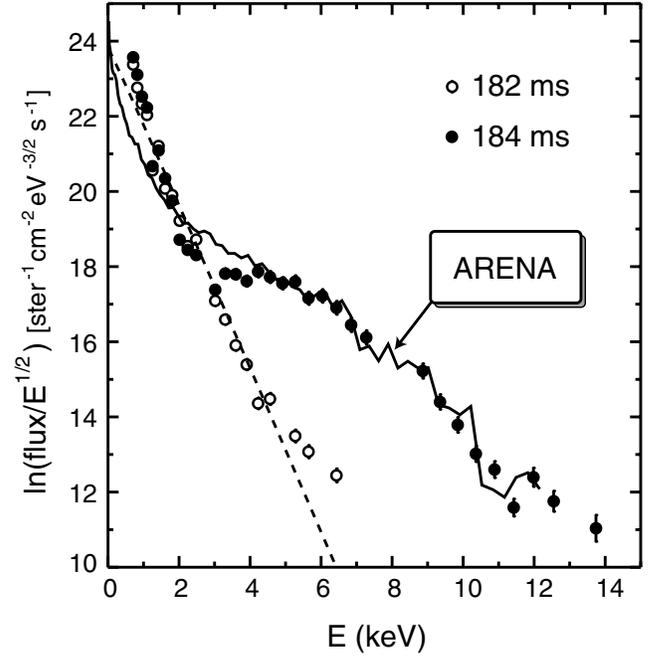


FIG. 2. Distribution function of fast ions before and after an IRE, as measured by the neutral particle analyzer and simulated with the ARENA Monte Carlo code.

$qm_i v/eB$, where q is the safety factor, m_i the ion mass, v the velocity, and B the magnetic field strength. In MAST, $\Delta r \sim 10$ cm is a significant fraction of the cross section. Furthermore, the ions drift from one field line to another at the precession frequency

$$\omega_\varphi = \overline{\mathbf{v}_d \cdot \nabla(\varphi - q\theta)} \approx m_i(v^2 + v_\parallel^2)q'(r)/2eBR,$$

where the overbar denotes a temporal average and the last, approximate, equality holds for particles well away from the trapped-passing boundary. In the duration $\tau_* \sim 1$ ms of an IRE, an ion explores the entire flux surface since $\omega_\varphi \tau_* \gg 1$. Therefore, for ions it does not matter whether or not the accelerating electric field is axisymmetric.

The ion kinetic equation is [4]

$$\frac{\partial f}{\partial t} + v_\parallel \nabla_\parallel f + \mathbf{v}_d \cdot \nabla f + \frac{eE_*}{m_i} \frac{\partial f}{\partial v} = C(f). \quad (1)$$

$C(f)$ denotes the Fokker-Planck operator for collisions between suprathermal ions and Maxwellian bulk ions and electrons,

$$C(f) = \frac{Z_{\text{eff}} v_c^3}{2v^3 \tau_s} \frac{\partial}{\partial \xi} (1 - \xi^2) \frac{\partial f}{\partial \xi} + \frac{1}{v^2 \tau_s} \frac{\partial}{\partial v} \left[(v_c^3 + v^3) f + (v_c^3 + v^3 T_e/T_i) \frac{T_i}{m_i v} \frac{\partial f}{\partial v} \right].$$

Here $\xi = v_\parallel/v$,

$$\tau_s = \frac{3(2\pi)^{3/2} \epsilon_0^2 m_i T_e^{3/2}}{n_e e^4 m_e^{1/2} \ln \Lambda} = \left(\frac{m_i}{m_e} \right)^{1/2} \left(\frac{T_e}{T_i} \right)^{3/2} \tau_{ii}$$

is the slowing-down time, and the critical velocity for slowing-down and pitch-angle scattering on ions is $v_c = (3\pi^{1/2}m_e/4m_i)^{1/3}v_{Te}$, with $v_{Te} = (2T_e/m_e)^{1/2}$ the electron thermal speed. The mean electron flow velocity is accounted for in Eq. (1) by the “effective electric field,” $E_* = E_{\parallel} + R_{ie\parallel}/n_i e$, which is the sum of the electric force and the average friction force on the ions from the electrons. In a plasma without impurities embedded in a straight magnetic field, these two terms cancel exactly, $E_* = 0$, and the ions do not “feel” the electric field; it is

exactly balanced by the friction force from the electrons since the electric force acting on the electrons must necessarily equal their friction against ions. However, as pointed out by Furth and Rutherford [4], the situation is different in a tokamak since the electric force on the electrons is balanced not only by friction against bulk ions, but also by the mirror force (causing trapping) and friction against any impurity ions present in the plasma. As a result of these effects, the effective electric field becomes [8]

$$\frac{\langle E_* B \rangle}{\langle E_{\parallel} B \rangle} \simeq \frac{\alpha}{1 + \alpha} + \frac{3.96 + 2.59x + \alpha(4.21 + 3.24x) + \alpha^2(1 + x)}{2.59(0.65 + x)(1.44 + x) + \alpha(3.24 + \alpha)(1 + x)^2} \frac{x}{1 + \alpha}, \quad (2)$$

where $\alpha = Z_{\text{eff}} - 1$ and $x = f_t/(1 - f_t)$, with f_t the effective fraction of trapped particles, which is $f_t \simeq 1.46\epsilon^{1/2}$ in a torus with small inverse aspect ratio ϵ . For realistic parameters in MAST, $\alpha \sim x \sim 0.5$, the bulk ions feel a large fraction of the induced electric field. The dynamic friction acting on a fast ion, $|\bar{\mathbf{v}}| \simeq (v + v_c^3/v^2)/\tau_s$, is a nonmonotonic function of velocity: for moderately high velocities, $v < v_m = 2^{1/3}v_c$, it falls off with increasing velocity, reaches a minimum at $v = v_m$, and increases at energies exceeding

$$\frac{m_i v_m^2}{2} = \left(\frac{9\pi m_i}{4m_e}\right)^{1/3} T_e \simeq 30T_e \quad (3)$$

in a deuterium plasma. Collisions with ions dominate for $v \ll v_m$, while slowing down on electrons is dominant for $v \gg v_m$. Ion runaway is possible if the effective electric field exceeds the minimum slowing-down force,

$$E_* > \frac{m_i(v_m + v_c^3/v_m^2)}{e\tau_s} = \left(\frac{3m_e}{2\pi m_i}\right)^{1/3} E_D, \quad (4)$$

where $E_D = n_e e^3 \ln\Lambda / 4\pi\epsilon_0^2 T_e$ is the Dreicer field. If this inequality is satisfied, as is always the case during IREs in MAST, ions can be accelerated to velocities exceeding v_m .

Equation (1) can be solved analytically in the limit of weak electric field, $\delta = E_* T_i / E_D T_e \ll 1$, and the steady-state solution was found in Ref. [4]. However, the duration of an IRE in MAST is not much longer than the ion collision time, so that a steady state is never established. To find the ion distribution function we must instead solve Eq. (1) as an initial-value problem. Full details of this calculation will be given in a separate publication, but we give a brief outline here. The kinetics of runaway ions with energies well below Eq. (3) is mathematically similar to that of runaway electrons, and the distribution function can be found by an expansion

$$F = \ln f = \delta^{-1} F^{(0)} + \delta^{-1/2} F^{(1)} + \dots$$

The solution of the kinetic equation is then constructed along lines laid out in a classic series of papers on runaway electrons [9], but now allowing the distribution function to vary in time. It is useful to rescale the independent variables by writing $\tau = 3\delta^{3/2}(\pi/2)^{1/2}(t/\tau_{ii})$ and $w = v(\delta m_i / T_i)^{1/2}$, so that $w = 1$ corresponds to the critical runaway velocity and that this velocity is reached at $\tau \sim 1$. In leading order, one then finds $F_{\xi}^{(0)} = 0$, while in next order we obtain

$$w^3 F_{\tau}^{(0)} + (w^3 \xi - w - F_w^{(0)}) F_w^{(0)} = \frac{Z_{\text{eff}}(1 - \xi^2)}{2} (F_{\xi}^{(1)})^2, \quad (5)$$

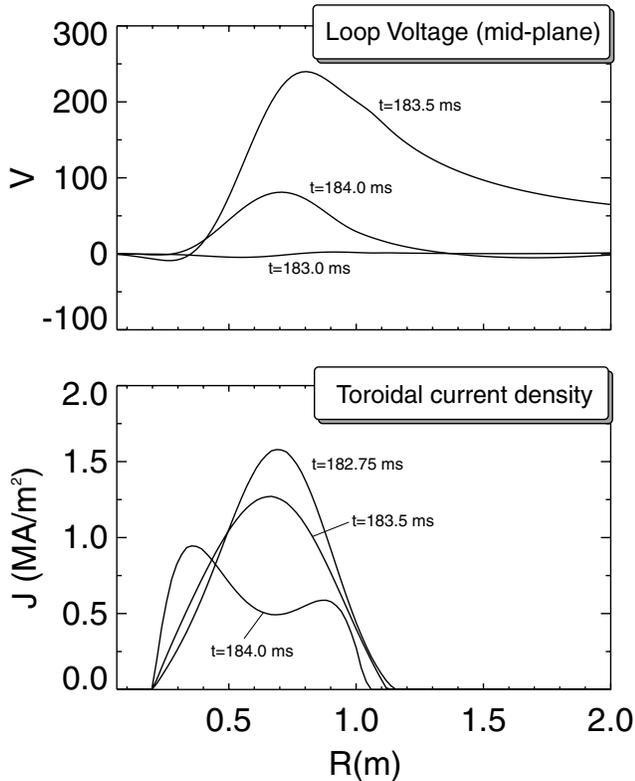


FIG. 3. Loop voltage and current profile from a magnetic reconstruction of MAST during the IRE occurring at $t \simeq 183$ ms in Fig. 1.

which at $\xi = 1$ reduces to

$$w^3 F_\tau^{(0)} = F_w^{(0)}(w - w^3 + F_w^{(0)}).$$

An approximate solution to this nonlinear equation can be found by noting that the initial condition that f be Maxwellian at $t = 0$ implies $F_w^{(0)} \simeq -w$ for $\tau \ll 1$, so that

$$w^2 F_\tau^{(0)} \simeq (w^3 - w - F_w^{(0)}).$$

This equation has the solution

$$F^{(0)}(w, \tau) = -\frac{w^2}{2} + \frac{1}{4}[w^4 - (w^3 - 3\tau)^{4/3}H(w^3 - 3\tau)],$$

where H denotes the Heaviside step function. This solution is valid not only for $\tau \ll 1$, but also for $\tau \gg 1$ if $w \leq 1$, and for $w \ll 1$ at all times. It is thus expected to be a uniformly good approximation to the exact solution, and it shows that the ion-distribution function develops an elevated tail at high energies. This tail is peaked in the forward direction, as follows from the solution of Eq. (5) for $F^{(1)}$, which is

$$F^{(1)} = 2w^2\sqrt{2(1 + \xi)/Z_{\text{eff}}} + C(w),$$

for $w \ll 1$, where $C(w)$ is an integration constant that is determined from the next-order equation. Hence, for $w \leq 1$, the distribution function is

$$f(w, \xi, \tau) \propto \exp\left[\frac{-2w^2 + w^4 - (w^3 - 3\tau)^{4/3}H}{4\delta} + 2w^2\sqrt{\frac{2(1 + \xi)}{\delta Z_{\text{eff}}}}\right],$$

and is thus strongly peaked around $\xi = 1$ if $\delta \ll 1$.

This analytical solution illustrates the main characteristics of the acceleration process, but is not accurate enough for a detailed comparison with experimental observations. For instance, the expansion parameter δ is not very small in MAST. Therefore, in order to compare the theory with experimental NPA data, numerical simulations have been carried out using the three-dimensional Monte Carlo code ARENA, originally developed for the study of runaway electrons [10]. This code solves the orbit average of the kinetic Eq. (1) in toroidal geometry, and has been applied to calculate the distribution function of fast ions in MAST following an IRE. The background plasma was represented by the density profile $n_e = n_0(1 - 0.9\rho^2)^{1/2}$ and temperature profile $T_i = T_0(1 - 0.9\rho^2)$, with $\rho = r/a$, $n_0 = 6 \times 10^{19} \text{ m}^{-3}$, $T_0 = 400 \text{ eV}$, and effective ion charge $Z_{\text{eff}} = 2$, all in accordance with experimental observations. The toroidal effective electric field was taken to be that inferred from the equilibrium reconstruction in Fig. 3 multiplied by Eq. (2). The simulation was thus performed without using any ‘‘free parameters.’’ The solid line in Fig. 2 shows the resulting theoretically expected distribution function of

fast ions moving in a cone around the forward direction, as observed by the NPA. Although some discrepancy between experiment and simulation is seen, the overall quantitative agreement found suggests that the proposed mechanism is indeed operative in MAST. Indeed, it is difficult to see how the ions could fail to be accelerated by the toroidal electric field that must accompany the current redistribution in an IRE.

Finally, it should be mentioned that the observed high-energy tail in the ion-distribution function could have other causes, but these appear less straightforward. The MHD instability causing the IRE could, for instance, couple to modes that Landau damp preferentially on fast ions [11]. Alternatively, runaway electrons accelerated at the IRE could excite a velocity-space instability that heats ions [12,13]. It is also possible that the IRE expels fast ions from the center to the far edge, where neutral particles are more abundant, thereby leading to a higher NPA signal. To rule out some of these possibilities, supplementary experiments were carried out in which the NPA was swung around 90° so that particles moving perpendicular to the magnetic field were detected. No significant tail formation was then observed, indicating that the acceleration occurs mostly in the forward direction, as expected for runaway ions. Of course, the sheer simplicity of direct acceleration and the quantitative agreement with experiment also speaks strongly for this mechanism.

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