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Energetic particle acceleration and transport by Alfvén/acoustic waves in tokamak-like Solar flares

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Abstract. Alfvén/acoustic waves are ubiquitous in astrophysical as well as in laboratory plasmas. Their interplay with energetic ions is of crucial importance to understanding the energy and particle exchange in astrophysical plasmas as well as to obtaining a viable energy source in magnetically confined fusion devices. In magnetically confined fusion plasmas, an experimental phase-space characterisation of convective and diffusive energetic particle losses induced by Alfvén/acoustic waves allows for a better understanding of the underlying physics. The relevance of these results in the problem of the anomalous heating of the solar corona is checked by MHD simulations of Tokamak-like Solar flare tubes.

Keywords. acceleration of particles, waves, (magnetohydrodynamics:) MHD, Sun: flares

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1. Introduction

The interplay of Alfvén/acoustic waves with energetic ions is crucial for energy and particle exchange in astrophysical plasmas (e.g., the Solar corona and wind) as well as to obtaining a viable energy source in magnetically confined fusion devices where the excitation of shear Alfvén waves such as Alfvén cascades (ACs), toroidal Alfvén eigenmodes (TAEs) and Alfvén-acoustic eigenmodes is of important for the fast-ion transport across field lines because of their potential to eject fast ions before their thermalization. Despite the very different values of plasma parameters, most of the normalized characteristic lengths and frequencies are often of the same order in Solar flares and Tokamaks.

2. Particle acceleration processes

A large wave-particle exchange of energy and momentum takes place if the resonance condition $\omega - k_{\|} \cdot v_{\|} - l\Omega_c \approx 0$ is fulfilled. Here, ω is the mode frequency, Ω_c the ion cyclotron frequency and $k_{\|}$ and $v_{\|}$ the parallel components of the wave vector and particle velocity. A high phase-space density of resonances leads to a phase mixing in a stochastic phase-space with non-linear exchanges of energy and momentum.

In Tokamaks, radial chains of overlapping Alfven/acoustic modes have been observed to cause strong coherent and incoherent fast-ion losses. Core-localized acoustic fluctuations have a severe impact on the overall fast-ion loss if the particle phase-space is covered by overlapping/crossing main and sideband resonances. Detailed *in situ* measurements of these losses, in particular of the MHD internal structures and particle distribution functions, performed at the Tokamak ASDEX Upgrade (Garcia-Munoz *et al.* 2008) can

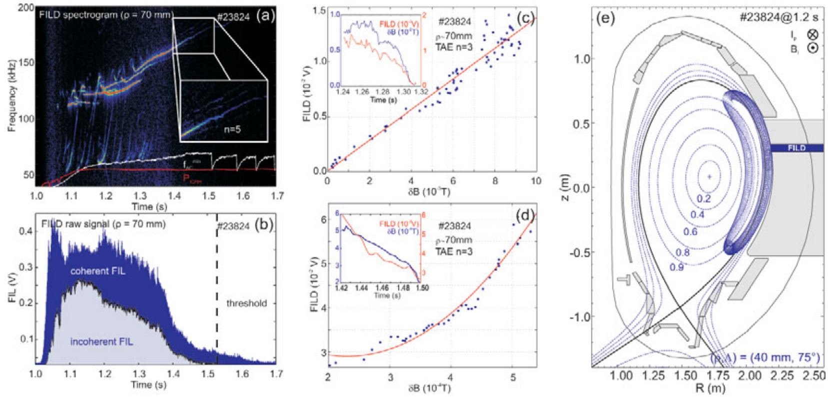

Figure 1. Left panel: Fourier analysis of the phase-space (energy and pitch angle) of fast-ion losses. Central panel: rate of the coherent and incoherent fast-ion losses as a function of the respective AE magnetic fluctuation amplitude. Right panel:Typical orbit of an escaping hydrogen ion with E ≈ 200 keV.

be used to study the underlying physical mechanisms. A Fourier analysis of the fast-ion loss signal Garcia-Munoz *et al.* 2010a allows us to identify the MHD fluctuations responsible for these losses (left panels of Fig. 1). The spectrogram reproduces the fast-ion losses correlated in frequency and phase with the related MHD fluctuation. The strongest coherent losses appear at the TAE frequencies and at the AC frequencies during their interaction with the acoustic branch near the f_{AC}^{min} (geodesic frequency) and during the AC-TAE transition. Diffusive fast-ion losses have been observed with a single TAE above a certain threshold in the local fluctuation amplitude.

The rate of the coherent and incoherent fast-ion losses as a function of the respective AE magnetic fluctuation amplitude is shown in Fig. 1, central panel. We can identify clear differences between particle ejection by single ACs and TAEs (directly proportional to the fluctuation amplitude, δB) and by the overlapping of multiple AC and TAE spatial structures and wave-particle resonances leading to a large diffusive loss that scales as $(\delta B/B)^2$. Simulations using the HAGIS drift orbit code (Pinches, 1998 show that the entire fast-particle phase-space in the energy range measured by the fast-ion loss detectors appear virtually covered by wave-particle resonances, enabling a stochastic fast-ion phase-space (Garcia-Munoz *et al.* 2010b). The right panel of Fig. 1 shows the typical trajectory of a detected escaping hydrogen ion with ≈ 200 keV.

3. Solar flares

We follow the evolution of a simplified model for Solar flares in MHD simulations (Mikic & Linker, 1994); Fig. 2 shows the model at different times. The initial conditions are a simple model of the solar atmosphere in magnetohydrodynamic equilibrium, permeated by a magnetic field emerging from a bipolar group of spots (left panel). A combined converging and shearing motion on the solar surface triggers the rise of magnetic loops (central panel) until an intense current sheet develops, and reconnection sets in, accelerating the emergence of the gas (right panel). A magnetic island disconnects from the surrounding field lines. In 3d, this corresponds to an extended flux rope anchored in the solar surface–a configuration resembling the geometry of the plasma in a tokamak.

To study resonant interactions between waves and particles, we compare Alfvén wave frequencies and particle orbital frequencies (left and central panels of Fig. 2) in the background field of the flare. We integrate the guiding-centre motion of particles gyrating

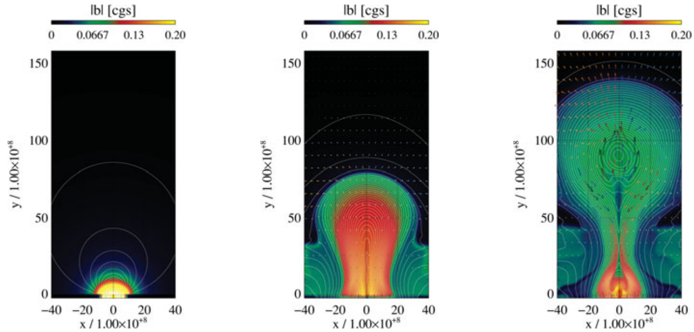

Figure 2. Snapshots of the MHD simulation of a solar flare showing the magnetic field strength (colours), field lines (white), and velocity vectors at (left to right) $t = 0$, $t = 3000$ s, $t = 4000$ s.

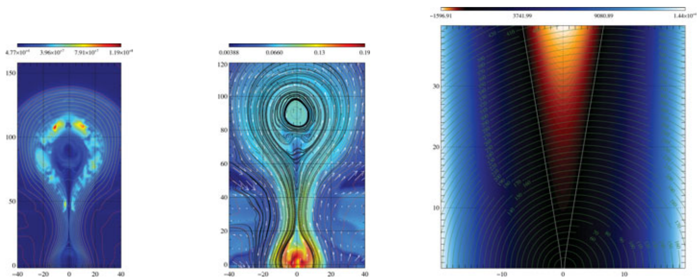

Figure 3. Left panel: frequencies of Alfvén (colour coded) propagating along sample field lines. Central panel: particle orbits in the flare model. Right panel: a resonance diagram for particles orbiting in the flare.

around the field lines of the model including the $\vec{E} \times \vec{B}$ drift; the vectors plotted show the velocity field of the guiding-centre drift.

We compute resonance diagrams (Karimabadi *et al.* 1990) in the phase space of particle momentum parallel and perpendicular to the wave vector, $p_{\|}$ and $p_{\perp}$. For a given particle energy, pitch angle and wave frequency, we compute the intersections between R surfaces fulfilling the condition for resonance, and H (Hamiltonian) surface defined by an energy equal to the particle energy. Resonance is possible if these surfaces intersect; if the intersections lie close to each other, the particle can gain energy by successive interactions in adjacent resonances. In the right panel of Fig. 3, the colours show the Hamiltonian function H for a proton of 1 MeV energy; white lines show the H surfaces where the particle is located. Green lines show R surfaces. The densely distributed interaction points indicate a high potential for resonant acceleration of the particle.

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