Abstract

Although the mechanism behind anomalous ion heating during periodic magnetic reconnection events in the RFP is not yet fully understood, many features of the energization process or processes have been identified. Recent neutral particle analyzer (NPA) measurements of the acceleration of NBI-born ions on MST provide new information about at least one of these energization processes. Modeling shows that the tangentially viewing NPA primarily measures the parallel component of high-energy, core-localized beam ions. The fast test ions are injected at energies between 8-25 keV and gain between 3-7 keV during a reconnection event. Higher initial energies correspond to higher energy gains, which can be explained by a runaway process in which a parallel electric field is indiscutably generated by changes in the equilibrium magnetic field. The magnitude of the measured ion acceleration is consistent with a 60 V/m, 100 μs core electric field calculated from equilibrium reconstructions. Ion acceleration of comparable magnitude is observed during counter-current beam injection in which the inductive electric field opposes the fast ion motion. The NPA will be moved to a radial viewport so that the perpendicular ion velocity can be sampled to gain further insight into the mechanisms at work. This work is supported by the US DOE and NSF.

Motivation: Anomalous ion heating during RFP sawteeth

The RFP is susceptible to a periodic “sawtooth” relaxation cycle that redirects magnetic flux to flatten the peaked, ohmically driven current profile.

This sawtooth cycle is a source of anomalous ion heating - the magnetic field is the ultimate energy source, but the mechanism is not yet fully understood.

Fast particle diagnostics enable new studies of sawtooth-driven ion energization

A 1-MW NBI can inject fast ions between 10-25 keV (background T_e < 2 keV). Injected ions are core-localized and high pitch (v_∥/v_⊥).

An EIB Neutral Particle Analyzer (NPA) measures fast hydrogen and deuterium between 5-45 keV (10 Hz, 10 D channels).

Modeling and experimental results indicate that despite large edge neutral density, the passive tangential view primarily measures the core-localized NBI population.

NBI-born ions energized during sawtooth reconnection events

A sample of an NPA data from a single MST discharge:

- Full- and half-energy beam components are observed during NBI.
- Slowing tail after beam turn-off matches classical slowing calculated from neutron measurements.
- Ion energization is clearly seen at magnetic reconnection events.

- Many similar sawtooth events averaged to reduce statistical noise.
- NPA calibrations used to approximate underlying fast ion distribution.
- Averaged measured energy (v_∥) used to characterize energy gain.

Large parallel electric field generated at sawtooth crash

Changing magnetic flux inductively generates a large electric field (often 50-100 V/m).

- Electric field strength will vary in different plasma conditions (v_∥, reversal parameter, density).

E = E_(0) (1 - \(\frac{v_{\perp}}{v_{\parallel}}\)) \(\frac{\alpha}{\beta}\)

ions experience reduced electric field due to nonclassical relativistic effects.

- T_e can remain constant as effective electric field overcomes friction.

Electric field profile at time of sawtooth crash.

Energization vs. initial energy

Good agreement between data and the expected acceleration due to electric fields and frictions in two different plasma conditions. Change in energy also scales with initial ion energy.

Energization in varying electric fields

Scanning the plasma current and reversal parameter (F - q/a) results in varying electric field strength. Ion energization scales with increase in electric field.

Energization vs. change in magnetic energy

Examining individual sawteeth shows proportionality between change in equilibrium magnetic energy and the increase in ion energy.

Deceleration observed during counter-I_p beam injection

By switching the direction of the plasma current, the electric field can be oriented to decelerate ions.

Future work

CQL3D is being used to study the effect of the sawtooth electric field on the bulk ion population. Initial results are promising, but will likely not explain all ion heating phenomenon (e.g., how can a parallel electric field produce T_e > T_i for impurities?).

The ANPA will soon be moved to a radial view to measure perpendicular acceleration (which is expected to be small).

Summary

- A large inductive electric field is observed to accelerate NBI-born fast ions during MST sawtooth crashes.
- The amount of acceleration scales with calculated electric field (varying with plasma conditions) and initial ion energy.
- Deceleration is observed when the direction of the electric field is flipped.
- This mechanism likely does not explain all ion heating in the RFP; multiple mechanisms should be considered.

References