Magnetic Reconnection during Fast Ion Driven Alfvénic Activity

Presented by Andreas Bierwage

JT-60U experiments: Abrupt Large-amplitude Events (ALE)

- Magnetic fluct. amplitude
- $\delta B_\theta$ [a.u.]

- Mirnov coil signal at wall

- Shot E048424

- Time [ms]


ALE simulation (MEGA):


- Found magnetic islands after large event.

Why?
Collaborators:
Kouji Shinohara (QST),
Yasushi Todo (NIFS),
Nobuyuki Aiba (QST),
Masatoshi Yagi (QST)

HPC:
● Helios, JFRS-1 at IFERC-CSC in Rokkasho, JP
● ICE X of JAEA in Tokai, JP
● K Computer of the RIKEN AICS in Kobe, JP

Funding:
● JSPS Grant-in-Aid for Scientific Research (16K18341)
● MEXT “Priority Issue on Post-K computer” (Accel. Development of Innovative Clean Energy Systems)
1. Code & model
   Hybrid MHD-PIC

2. Sensitivity study for ALEs
   Numerical resolution, dissipation

3. EP-induced magnetic islands
   Magnetic chaos, resistive decay
Hybrid model

**Bulk plasma: Single-fluid MHD**

Long-wavelength Alfvén modes. Dissipation of small-scale struct.

**Energetic particles: Gyrokinetic PIC**

\[ \parallel \text{streaming, } \perp \text{ drifts, gyroaverage, collisions, sources, wall losses.} \]

**MEGA code**

\[ [\text{Y. Todo, NIFS}] \]


\[ \frac{\partial \rho_b}{\partial t} = -\nabla \cdot (\rho_b \delta u_b), \quad \mu_0 J = \nabla \times B \]

\[ \rho_b \frac{\partial u_b}{\partial t} = -\rho_b u_b \cdot \nabla u_b - \nabla p_b + (J - J_{\text{h,eff}}) \times B \]

\[ - \left[ \nabla \times \nabla \rho_b \nabla \times u_b \right] + \frac{4}{3} \nabla \left( \nabla \rho_b \nabla \cdot u_b \right) \]

\[ \frac{\partial B}{\partial t} = -\nabla \times E, \quad E = -u_b \times B + \eta \delta J \]

\[ \frac{\partial p_b}{\partial t} = -\nabla \cdot \left( \rho_b u_b - (\Gamma - 1) \left[ p_b \nabla \cdot u_b + \eta (J - J_{\text{h,eff}}) \delta J \right] \right) \]

\[ + \nu \rho_b (\Gamma - 1) \left[ |\nabla \times u_b|^2 + \frac{4}{3} |\nabla \cdot u_b|^2 \right] + \chi |\nabla^2 p_b|^2 \]

**Gyro-avg.**

\[ J_{\text{h,eff}} \]

**B, E**

\[ \frac{d R_{\text{gc}}}{dt} = \frac{v_B}{qB^*} \nabla B \times \dot{b} + \frac{v_{\parallel}}{B^*} (B + \rho_{\parallel} B \nabla \times \dot{b}) + \frac{v_{E^*}}{B^*} = U_{\text{gc}} \]

\[ m v_{\parallel} \frac{dv_{\parallel}}{dt} = v_{\parallel}^* (qE - \mu \nabla B) \]

\[ \frac{d\mu}{dt} = 0 + O(\beta \epsilon_\delta) \quad \text{with} \quad \epsilon_\delta \sim \frac{\rho_{\perp}}{L_B} \sim \frac{\omega}{\Omega_L} \ll 1 \]

\[ \mu \equiv \frac{m v_{\perp}^2}{2 B^*}, \quad \rho_{\parallel} \equiv \frac{v_{\parallel}}{\omega_{\perp}}, \quad B^* \equiv B \left[ 1 + \rho_{\parallel} \hat{b} \cdot \left( \nabla \times \hat{b} \right) \right], \quad \hat{b} \equiv \frac{B}{B} \]

\[ v_{\parallel} = \frac{v_l}{\sqrt{v + \Delta v_l}} + \frac{v_l}{\sqrt{\Delta v_T \sin \Omega}}, \quad v_{\parallel} = \sqrt{v l + \Delta v_l^2 + \Delta v_T^2 - v_{\parallel}^2} \]
Hybrid model

**Bulk plasma: Single-fluid MHD**

Long-wavelength Alfvén modes. Dissipation of small-scale structures.

**Energetic particles: Gyrokinetic PIC**

∥ streaming, ⊥ drifts, gyroaverage, collisions, sources, wall losses.

MEGA code [Y. Todo, NIFS]

(t): 4th-order Runge-Kutta, \( \Delta t_{\text{mhd}} \approx 1 \text{ ns} \)

(R, \( \phi \), Z): finite differences, non-slip b.c.

**MEGACode**

\[
\frac{\partial \rho_b}{\partial t} = - \nabla \cdot (\rho_b \delta u_b), \quad \mu_0 J = \nabla \times B
\]

\[
\frac{\partial u_b}{\partial t} = - \rho_b \nabla \cdot u_b - \nabla p_b + (J - J_{h,\text{eff}}) \times B
\]

\[
- \left[ \nabla \times (\nu \rho_b \nabla \times u_b) + \frac{4}{3} \nabla (\nu \rho_b \nabla \cdot u_b) \right]
\]

\[
\frac{\partial B}{\partial t} = - \nabla \times E, \quad E = - u_b \times B + \eta \delta J
\]

\[
\frac{\partial p_b}{\partial t} = - \nabla \cdot (p_b u_b) - (\Gamma - 1) \left[ \rho_b \nabla \cdot u_b + \eta (J - J_{h,\text{eff}}) \cdot \delta J \right]
\]

\[
+ \nu \rho_b (\Gamma - 1) \left[ |\nabla \times u_b|^2 + \frac{4}{3} |\nabla \cdot u_b|^2 \right] + \chi \nabla^2 p_b
\]
Long-time simulation (100 ms scale)

▶ Multi-phase method: Speeds up the simulation by a factor 2-3.

EP motion + src.+coll.

ON continuously

OFF 4 ms

ON 1 ms

OFF 4 ms

ON 1 ms

MHD


Beam injection starts at time \( t = 0 \)

Fast ion tail forms
Long-time simulation (100 ms scale)

- **Multi-phase method:** *Speeds up the simulation by a factor 2-3.*
  - EP motion + src.+coll.:
    - ON continuously
    - OFF 4 ms, ON 1 ms, OFF 4 ms, ON 1 ms
  - MHD

- **Major milestone reached:** *Simulated sequences of 3 ALEs.*

Sensitivity study for ALEs

- Numerical resolution
- Dissipation
Procedure

► Selected ALE #2 at $t = 129\sim 130$ ms.

→ Use snapshot at $t = 129$ ms as new initial condition.

MEGA mult-phase simulation

Short-time initial-value simulations. Without sources and collisions.
Procedure

- **Selected ALE #2 at $t = 129$~$130$ ms.**
  → Use snapshot at $t = 129$ ms as new initial condition.

- **Simulate few millisecs. with different parameter settings:**

  **(1) Check numerical sensitivity**

  Resolution, noise

<table>
<thead>
<tr>
<th>$N_R \times N_Z \times N_{\phi}$</th>
<th>$N_P$</th>
<th>$\Delta t / \text{ns}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>384×352×96</td>
<td>6.9 M</td>
<td>1.0</td>
</tr>
<tr>
<td>800×720×96</td>
<td>27.8 M</td>
<td>0.5</td>
</tr>
</tbody>
</table>

  **(2) Reduce dissipation coeff.**

  $\mu_0^{-1} \eta = v = \chi = 1.0 \times 10^{-6} \nu A_0 R_0$

  $0.5 \times 10^{-6}$

  $0.3 \times 10^{-6}$
Sensitivity study: **1. PIC noise effects**

Noise floor

- **7M particles**
  - More particles per cell give lower noise level

- **28M particles**

**Suspicion:**

PIC noise aids ALE trigger (a little).
Sensitivity study: 2. Spatial resolution

Well reproduced.
Sensitivity study: 3. Dissipation effect ($\eta = \nu = \chi$)

Weaker dissipation ...
(a) reduces ALE threshold
(b) causes similar EP transport
Sensitivity study: 3. Dissipation effect ($\eta = \nu = \chi$)

Weaker dissipation ...
(a) reduces ALE threshold
(b) causes similar EP transport

Before ALE

Fast ion transport $\beta_{EP}(r)$ [%]

After ALE

Anticipate similar ALE period
EP-induced magnetic islands
- Magnetic chaos
- Resistive decay
Before large event

- **Mode amplitude evolution**
  - Magnetic fluct amplitude (a.u.) vs. Time (% ms)
  - n = 1, 2, 3
  - m = 2 EPM
  - m = 4, 5 TAE

**Before ALE**

- **Frequency (kHz)**
  - n = 1, m = 2 EPM
  - t = 386.689 (0.304 ms)
  - n = 2, m = 4,5 TAE
  - n = 3, m = 5,6 TAE

- **Magnetic field Poincaré plot**
  - No islands.
  - Only waves (40-50 kHz).

- Wiggly flux surfaces = shear Alfvén waves.
After large event

Mode amplitude evolution

Safety factor profile

Magnetic field Poincare plot

Questions:
(1) How did they form?
(2) How do they evolve?

Moderately large magnetic islands.
Islands appear within < 0.2 ms, during $B$ chaos & avalanche.

Poincaré plots of $B = B_{\text{eq}} + \delta B$. Ignored $\delta E \times B$.

Apparent left-shift due to plotting left to right.
**ALE ramp**

**Mode amplitude evolution**

- Magnetic fluct. amplitude (a.u.)
- Time \( t \) [ms]

- **Note:** @ \( t \approx 129.5 \) ms system already returned to state of only weak linear instability.
  - Most part of ALE is nonlin. overshoot.

- Islands appear within < 0.2 ms, during \( B \) chaos & avalanche.

**Reset fields. Randomize ptcls. along \( \phi \).**

**Islands appear within < 0.2 ms, during \( B \) chaos & avalanche.**
ALE peak

Mode amplitude evolution

B chaos in entire core plasma. Island width w / a ~ 20%.
Local perturbation in plasma current density reaches 100%.

Toroidal current density.
After ALE: Multi-time-scale decay

Time scales ($\Delta r / a \sim 0.1$):

- $1 \sim 10 \mu s$
- $100 \mu s$
- $1 \sim$ few ms

Tearing-stable system returns to unperturbed state.

Alfvén continuum phase mixing
EP avalanche
Current diffusion

$\partial B / \partial t = - \nabla \times E$,

$E = - u_b \times B + \eta \delta J$

$\eta / \mu_0 = 10^{-6} v_{A0} R_0 \sim w^2 / \tau_\eta$

$v_{A0} / R_0 \sim 10^8 \text{s}^{-1}$, $R_0 / a \sim 3$

$w / a = 0.1 \rightarrow \tau_\eta \sim 1 \text{ ms}$

Major part of pert. decays faster ($\sim 0.2 \text{ ms}$) than resistive time ($\sim 1 \text{ ms}$).
Presumably: NL structs. vanish with avalanche.
ALE-induced islands: Resitivity dependence

$\eta = 10^{-6}$

$0.5 \times 10^{-6}$

Smaller resistivity yields similar or larger islands!

Because: similar/larger ALE, slower decay

Snapshot 0.5 ms after ALE: n=1 similar, n=2,3 larger
Somewhat irregular decay on millisec scale

\[ \eta = 10^{-6} \]

\[ 0.5 \times 10^{-6} \]

Besides resistive decay:
- nonlin. coupling
- EPs
- waves may still play a role.
Summary: Simulations show reconnection during ALEs

Results:
- Confirmed sim. results with higher resolution & lower noise.
- Lower dissipation reduces threshold for ALE onset but amplitude remains large.
- Island decay time: $\tau_{\text{resistive}} \sim 1 \text{ ms}$
- Island formation to be clarified: $\tau_{\text{island}} \sim 0.2 \text{ ms} < \tau_{\text{resistive}}$
- Reducing dissipation by 1/2 gives similar (or larger) islands.

Tentative conclusion:
- Phenomenon seems to be physical within realm of resistive MHD (not a numerical artifact).
Discussion: **Open questions & relevance**

To be examined:
- How can 50 kHz Alfvén waves reconnect $B$ field?
- Analyze combined effect of chaotic $B$ & $\delta E\times B$ on EPs, bulk (… & vice versa).
- Experimental check?

Relevance:
- May explain enhanced electron transport observed during ALEs in JT-60U exp.
- May also be relevant for space plasmas; e.g. “flux transfer events (FTE)” in magnetopause.
Question: **How can 50 kHz Alfvén waves reconnect B field?**

_Educated guesses for parity mixing mechanisms:_

**(a) Chaotic B field effect:**
Interference of large-amp. MHD waves with multiple helicities \( m / n \).
- Mixed-parity low-frequency beats?
- Drive 3D reconnection at many locations?
- Merging micro-islands?

**(b) Collective NL interaction with EPs:**
Interactions with both oscillating \( \delta E \times B \) and quasi-steady \( \delta B \) causes phase space to be “reconnected” around resonances.
- EP phase space islands are imprinted onto \( B \) field via EP current?

**See also:** Thursday, P2-22 Shinohara et al.