IAEA-PPPL
Alpha particle dynamics and Alfvénic instabilities in ITER post-disruption plasmas

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Physical Concept

1. Resonant with Alfvénic modes
damping
α-drive
Landau
delayed thermalization
Collisional, resistive...
E-Field
RE-avalanche

2. Instabilities strong enough to interact with RE seed?

Burning ITER plasma

α-particles
Resonant with Alfvénic modes
Drive from radial gradients

Long enough to drive Alfvénic modes unstable?
Present day tokamaks already observe post-disruption modes

Current quench spectogram AUG#35618 [P. Heinrich]

Spectograms of DIII-D [Lvovskiy, PPCF, 2018]
Current quench spectogram of JET #89141. [S. Newton, P. Pölöskei]

Present day tokamaks already observe post-disruption modes

Current quench spectogram of JET DT shot #42976. [S. Sharapov]
Alpha particles – velocity distribution

Fusion born alpha population is energetic by nature:

\[ v_\alpha \approx 13 \times 10^6 \text{ m/s} \]

\[ v_{\text{alfven}} = \frac{B}{\sqrt{\mu_0 m_i n_i}} \]

Simulations\(^3\) show weakly unstable modes in ITER quiescent phase

Hypothesis

Post-disruption damping* drops faster then post-disruption alpha drive

* damping dominated by Landau damping \( \sim \exp(-T) \)

Fig. 1
CODION\(^1\) simulation: Isotropic alpha particle velocity distribution for ITER 15MA scenario\(^2\) #2

\(^1\)Embreus, PoP, 2015 \hspace{1cm} \(^2\)Polevoi, IDM, 2002 \hspace{1cm} \(^3\)Pinches, PoP, 2015
Consider ‘worst case’, unmitigated disruption:

\[ T(r, t) = T_f + \left[ T(r, 0) - T_f \right] \exp\left(-\frac{t}{t_0}\right) \]

with Fokker-Planck solver CODION\(^{1}\)

Collisional cooling ineffective for energetic particles

Resonances possible far into the thermal quench

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\(^{1}\)Embreus, PoP, 2015
Workchain towards post-disruption Eigenmodes

1. Lauber, JCP, 2007
2. Hirshman, CPC, 1986
3. Papp, NF, 2013
4. Vallhagen, JPP, 2020

CODION
- Pressure profile

LIGKA¹
- MHD spectrum & damping

VMEC²
- Plasma equilibrium

GO³
- Current density profile
Workchain towards post-disruption Eigenmodes

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CODION

Pressure profile

LIGKA¹

MHD spectrum & damping

VMEC²

Plasma equilibrium

Current density profile

GO³
Current density profile $j(r,t)$

GO code solves the induction equation in 1D
→ Electric field diffusion
→ RE generation
\[
\{ j(r,t) \}
\]

**Fig.2**
Currents of an unmitigated disruption identified by $T_f=3\text{eV}$ and $t_0=0.7\text{ms}$ and its background temperature

6. $T \sim 100\text{ eV}$: Alphas thermalize

8. $T < 100\text{ eV}$: Avalanching

**Fig.3**
Resulting profiles of safety factor $q$, current density $j$ and integrated current $I$. 

$t_N = 3$
Workchain towards post-disruption Eigenmodes

- Eigenmodes
  - MHD spectrum & damping
    - Plasma equilibrium
      - Pressure profile
      - Current density profile

LIGKA: CODION 
VMEC: GO
Eigenmodes in the ideal MHD spectrum

LIGKA tool employed:

- found frequency gaps for TAEs (and BAEs) in the ideal MHD spectrum
- scan over absolute scaling of q-profile (fig. 6a) shows vast availability irrespective of $q_0$

$q_0=1.07$ chosen

$n=[7-15, 22-26]$

$m=[[(n-2)-(n+4)], [(n-2)-(n+6)]]$

**Fig.4**
Radial location of the frequency gaps of toroidal mode number $n$=m TAEs as a function of $q_0$. 
HAGIS¹

Wave-particle interaction

Eigenmodes

MHD spectrum & damping

Plasma equilibrium

α-population

Pressure profile

Current density profile

¹Pinches, CPC, 1998
**Active mode evolution**

HAGIS calculates non-linear wave-particle interaction evolves mode through EPs and redistributes EPs through modes

![Graph](image)

**Fig. 5**

Evolution of mode amplitude $\delta B/B$ as caused by resonant interaction with $f_{SD}$ in multi-mode simulation.

$max(\delta B/B) \approx 0.1\%$ before RE avalanching
Mode effects on RE dynamics

max(\(\delta B/B\)) \(\sim 0.1\%\) before RE avalanching

→ effects on RE dynamics?

- HAGIS simulation indicating RE radial transport\(^1\)
- Study\(^2\) found (stochastic) mag. Perturb (~0.05%) sufficient for RE avalanche suppression
- Further study: use ASCOT\(^3\) to determine transport coefficients as a function of (E,\(\lambda\),r) for REs

\(^1\)Lier, NF, 2021
\(^2\)Svensson, JPP, 2021
\(^3\)Schneider, NF, 2019
Outlook – Limiting assumptions

Proof of principle stage¹:

- Unmitigated disruptions
- Perfect alpha particle confinement

Ongoing work:

- (simple) mitigated scenarios
- Alpha particle transport

¹[Lier et al, NF 2021]
Ongoing work – Addressing limiting assumptions

1. **Mitigated disruptions**

To assess the increased parameter space:

Alpha distribution now calculated by analytical model (O. Embreus)

\[ f_\alpha(r, t, v) \]

\[ T(r, t), \ n_e(r, t) \]

Ion composition secondary to collision dynamics

→ use ions to tune \( v_A \)?

Fig
Analytical (dashed) vs CODION (dashed) results for alpha population in mitigated disruption

\[ n_{\text{inj}} = 7n_e \]
\[ t_0 = 1 \text{ ms} \]
Ongoing work – Addressing limiting assumptions

2. Alpha particle transport

Avoid MHD simulations for the entire parameter space:

Solve diffusion equation

\[
\frac{\partial u(r,t)}{\partial t} = D(t) \frac{\partial^2 u(r,t)}{\partial r^2}
\]

with

\[D(t) = D_0 \exp(-t/t_0)^1\]

and scan \(D_0\) for stochasticity

\(^1\text{[Linder, 2020, NF]}\)
Scanning over $t_0$, $n_e$, $D_0$ and evaluate pressure gradients (strength, location)

→ Is there an optimal mitigation scenario? A strongest mode we can drive?
Summary & Outlook

- Showed survivability of the energetic tail of a fusion-born alpha population far into the thermal quench

- The post-disruption MHD spectrum shows availability of a wide range of Toroidal Alfvén Eigenmodes which experience low damping

- Wave-particle interaction showed those TAEs to be driven unstable by the alpha population up to amplitudes of $\delta B/B = 0.1\%$

- The modes driven indicate a capability to enhance RE transport $\rightarrow$ effect on RE dynamics (suppression?)

- **Ongoing work**: Analytical model to scan big parameter space (mitigated disruptions) and search for optimum for this mechanic
Backup – Ongoing work

Scanning over $t_0$, $n_e$, $D_0$ and evaluate pressure gradients (strength, location)

→ Is there an optimal mitigation scenario? A strongest mode we can drive?
Backup – Ongoing work

Spatio-temporal pressure evolution

\[ n_e \left[ 10^{20} \text{m}^{-3} \right] = 20; \quad t_0 \left[ \text{ms} \right] = 1 \]

only slowing-down losses

\[ D \left[ \text{m}^2/\text{s} \right] = 100 \]

only diffusive process

\[ D \left[ \text{m}^2/\text{s} \right] = 100 \]

\[ D \left[ \text{m}^2/\text{s} \right] = 10 \]
Backup - Mode effects on a RE seed

Which mode amplitudes to choose?
We are already $3t_N$ into the disruption and at $6t_N$ damping and avalanching becomes significant.

Fig. 9
Currents of an unmitigated disruption identified by $T_f=3eV$ and $t_0=0.7ms$ and its background temperature
Backup - Mode effects on a RE seed

**RE seed initialized:**

\[
\begin{align*}
E_{\text{kin}} & = [10 \text{ keV} - 30 \text{ MeV}] \\
\lambda & = \frac{v_\parallel}{v} = [0 - 1] \\
r/a & = [0.05 - 0.45]
\end{align*}
\]

Each triple combination represented by 25 REs, uniformly distributed along torus. \(\Sigma \#\text{REs} = 10000\)

Throughout interaction measure changes to the *toroidal angular momentum*

\[
P_\phi(p_\parallel, \Psi_p)
\]

as indication to changes of radial position.

**Fig.10**

Ensemble-averaged change to \(P_\phi\) of the RE seed as caused by the TAEs.

X and y-axis show initial RE attributes, color indicates change after \(t_N=2\). The Radii of the circles are the initial radial position of the particle in \(r/a=[0.05-0.45]\) in steps of 0.1.
Mode structures for $q_0 = 1.07$

→ total structure is **core localized** along flat shear

- α-pressure core-peaked
- RE-generation core-localized

**Damping strengths $\gamma/\omega$ [s$^{-1}$/s$^{-1}$]:**

- Landau+radiative (LIGKA) $\sim 0.1\%$ ($t_N = 3$)
- Fluid damping (CASTOR$^1$) $\sim 1\%$ ($t_N = 8$)
- Collisional damping$^2$ $\sim 1\%$ ($t_N = 6$)

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[Fig.6](#)

Selected TAE mode structures for $q_0=1.07$. Normalized amplitude of the real part with respective frequencies $\omega_{TAE}$ [kHz].

b) shows $m=n,n+1$ coupling and c) shows $m=n+1,n+2$ coupling.

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$^1$Pinches, CPC, 1998

$^2$Gorelenkov, PS, 1992
Backup – JET supershot

Spectrogram of JET 42976-DI/C1F-CHAN8/131

Color scale

0.0
0.2
0.4
0.6
0.8
Magnitude

JET Data Display

- 42976 PROC/IP1
- 42976 PROC/BT
- 42976 KG1V/LID3 Seq=131 (2)
- 42976 KG1V/LID4 Seq=131 (3)
- 42976 NBI/PTOT Seq=7 (2)
- 42976 ICRH/PTOT Seq=12 (2)
Case of lower $B_T$ shows strong coherent magnetic oscillations:

- Toroidal Alfvén Eigenmode (TAE) identified as the cause of runaway electron suppression
- Studies [1] estimated turbulence threshold level $dB/B \sim 0.1\%$ for suppression

ITER: could alpha particles provide drive for RE-suppressing modes?

Fig.1: Plasma current evolution and Mirnov coil signals from TEXTOR shots #115207-8 (2013)

Backup – pressure profile

\[ p(r,t) = n_e T_e(r,t) + n_{D,T} T_i(r,t) + p_\alpha(r,t) \]

with \( n_e = n_{D,T} = 10^{20} [m^{-3}] \)

and

\[ T(r,t) = T_f + [T(r,0) - T_f] \exp(-t/t_0) \]

\[ p_\alpha(r,t) = \frac{m_\alpha}{3} \int v^4 f_\alpha(v, r, t) dv \]

CODION is 0D in space: Each of the 100 radial points is populated by velocity distributions \( f_\alpha(v, r, t) \) advancing independently in time

Assumes case of good post-disruption confinement, as is also necessary for RE beam

**Fig.2**
CODION simulation: Initial fusion born alpha particle population on axis \( f_\alpha(v,0,0) \)

Exponential thermal quench, \( T_f = 3eV, t_0 = 0.7 \text{ms}, r/a = 0 \)
Energetic part of CODION obtained data is fitted with the analytic slowing down formula¹ $f_{SD}$

$$f_{SD}(r, v, t_N = 3) = \frac{C(r)}{v_c^3(r) + v^3} Erfc\left(\frac{v - v_\alpha}{\Delta v |r|}\right)$$

¹Gaffey, JPP, 76

Fig. 7
Pressure and temperature profiles for $t_N = 3$. Note that $p_{\alpha,EP}$ is used for mode drive, not $p_\alpha$, since the latter is misleading (due to CODION particle conservation)