Magnetic Reconnection in Magnetized Hot Plasmas

Magali MURAGLIA¹

Thanks to : O. Agullo¹, S. Benkadda¹, Y. Camenen¹, N. Dubuit¹, X. Garbet², J. Frank¹, G. Fuhr¹, M. Hamed³, A. Poyé¹, A. Sen⁴, A. Smolyakov⁵, M. Yagi⁶

¹. Aix-Marseille Université, CNRS, UMR 7345, Marseille, France
². CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
³. DIFFER, Eindhoven, Holland
⁴. IPR, Bhat, Gandhinagar, India
⁵. University of Saskatchewan, Saskatoon, Canada
⁶. JAEA, Rokkasho Mura, Japan
Magnetic reconnexion is ubiquitous in nature and it consists in a modification of magnetic field line topology between two moments. In magnetized hot plasmas, current driven instability leads to magnetis island formation at various scales.

Basic Mechanism leading to Large Magnetic Island:

- Equilibrium
- Tearing instability
- Tearing and reconnection of magnetic field lines
- Disruption
- Origin and Control of large magnetic islands
Magnetic Islands at various scales in tokamak

Magnetic reconnexion is ubiquitous in nature and it consists in a modification of magnetic field line topology between two moments. In magnetized hot plasmas, current driven instability leads to magnetis island formation at various scales.

Basic Mechanism leading to Micro Magnetic Island:

- Equilibrium
- Micro-Tearing instability
- Tearing and reconnection of magnetic field lines
- Micro (mm) magnetic islands
- Stochaztisation
- Impact on the electron heat transport
Open questions in tokamaks context relative to magnetic reconnexion at small and large scales:

1. Non ideal phenomenom to violate the frozen flux condition locally?
   => modification of the magnetic field line topology is allowed
      resistivity and collisions, electron mass inertia, other mechanisms?

2. Free energy to let the island grows?
   large island: magnetic equilibrium, resistivity, pressure gradient, turbulent modes, ...
   micro island: electronic temperature gradient, collisions, curvature, electric potential fluctuations, ...

3. Saturation mechanisms?
   Size of large island at saturation.
   Electron heat transport due to micro-reconnexion at plasma edge?
Outline

I. Classical theory of the tearing instability
   1. Resistivity at the origin of the reconnection
   2. Equilibrium current for the growth and the saturation
   3. Saturation ?

II. Turbulence Driven Magnetic island
   1. Resistivity at the origin of the reconnection
   2. Turbulent modes drive the island growth
   3. Saturation ?

III. Stability of Micro-Tearing Modes
   1. Collisions at the origin of the reconnection
   2. Instability growth : electron temperature gradient, curbature, electric potential fluctuations
   3. Saturation ?

Conclusions
I. Classical Theory of the Tearing instability

2D Reduced MagnetoHydroDynamic Model

Large island => Minimal model RMHD
Fluctuations dynamics evolution of the electrostatic Potential $\Phi$ and of the magnetic flux $\Psi$

2D model => near a resonant surface in a $(x, y)$
poloidal cross section

Fourier decomposition of $\Phi$ and $\Psi$ in poloidal direction :

$$\psi(x, y, t) = \sum_{m \in \mathbb{Z}} \psi_m(x, t) \exp \left( i \frac{2\pi m}{L_y} y \right)$$

\[
\begin{align*}
\partial_t \nabla^2_\perp \phi + [\phi, \nabla^2_\perp \phi] &= [\psi + \psi_{eq}, j + j_{eq}] + \mathbf{v} \nabla^4_\perp \phi \\
\partial_t \psi + [\phi, \psi + \psi_{eq}] &= \eta j
\end{align*}
\]

\[
\begin{align*}
  j &= \nabla^2_\perp \psi \\
  B_{eq} &= \psi_{eq}'(x) y
\end{align*}
\]

The model is solved numerically using the semi-spectral code AMON in a 2D $[L_x, L_y]$ box.
I. Classical Theory of the Tearing instability

◆ **Tearing instability of the mode m=1**
- Resistivity allows magnetic reconnection (step 1)
- Magnetic equilibrium $B_0$ induces an equilibrium current $j_0$ allowing the growth of a magnetic island (step 2)

=> An important parameter $\Delta'$

$\Delta'$ is a measure of the magnetic energy available in the equilibrium for the magnetic island growth

◆ **Linear prediction of instability**
$\Delta'$ is an good index stability parameter
$\Delta' < 0$ No island growth
$\Delta' > 0$ Tearing instability
Island growth

◆ **Island size at saturation? An open question**
Rutherford model [R.J. La Haye, POP 13 (2006)]

$$\partial_t w_{m=1} = \partial_t w_1 = \eta \Delta' + NL$$
I. Classical Theory of the Tearing instability

◆ Tearing instability of the mode m=1
- Resistivity allows magnetic reconnection
- Magnetic equilibrium $B_0$ induces an equilibrium current $j_0$ allowing the growth and the saturation of a magnetic island

$\Delta' = \text{equilibrium current integral over the radial profile}$
$\Delta'$ is a measure of the magnetic energy available in the equilibrium for the magnetic island growth

$\approx \text{An important parameter } \Delta'$

◆ Linear prediction of instability
$\Delta'$ is an good index stability parameter
$\Delta' < 0$ No island growth
$\Delta' > 0$ Tearing instability Island growth

◆ Island size at saturation ? An open question
Rutherford model [R.J. La Haye, POP 13 (2006)]

$\frac{\partial w_m}{\partial t} = \frac{\partial w_1}{\partial t} = \eta \Delta' + NL$

Does not work for large island. $\Delta'$ is not the good parameter.
I. Current sheets attract/repulse islands

- $w_1$ in the Rutherford model measures the $m=1$ mode width and not the full island size is given by taking into account all the mode => a good measure of the island width $w_s$ can be done directly using the simulations.

- Different saturation widths $w_s$ if current sheets are crossed

$=>$ External current sheets do modify island size at saturation

$=>$ Physics far from the resonance can not be casted into $\Delta'$ parameter

What is the missing ingredient to predict the saturated island size?
I. Island size prediction using Neural Network

- Neural Network training using MDH simulation of magnetic island $w_s$ with different equilibrium current profiles composed of various external current sheets

[Diagrams of Neural Network architecture and performance metrics]
I. Island size prediction: Importance of $J_{eq}$

◆ Which radial points are important for $w_s$ predictions? [O. Agullo et al, ICDDPS 2019]

◆ The forest of decision tree has scored points where current sheets are located (in the dataset they were at $x/\pi = 0.5, 1, 1.5$)

◆ No scoring at the resonance! (lack of profile diversity at the resonance $x=0$?)

◆ Scoring is concentrated on $J_{eq}$ dataset

=> $\Delta'$ is insufficient to predict saturated island size

=> Indeed, the radial structure and the amplitude of the equilibrium current profile affect also the saturated island size $w_s$ [O. Agullo et al., ICDDPS, Marseille (2019)]
I. Classical Tearing Mode – Conclusion

◆ In the classical theory, magnetic reconnection is allowed thanks to resistivity (step 1)

◆ The growth of the island is due to free energy available in the equilibrium magnetic field (and in the equilibrium current profile) (step 2)

◆ **Open question**: prediction of the saturated island size (step 3) ?

However:

Tearing instability is stable in tokamaks although a seed magnetic island (?) can be amplified by neoclassical effects and lead to a nonlinear growth of a Neoclassical Tearing Mode (NTM) which can damage the device.

=> Since tearing is stable, what is the origin of a such seed island in tokamak?  
=> Can there be other physical mechanisms to explain seed magnetic island growth in tokamaks?
II. MHD-Turbulence Interaction, a Multi-Scales Problem

◆ Interchange like instabilities coexist with macro MHD instabilities and lead to micro-turbulence in fusion devices.

◆ The interaction of magnetic island with interchange is a multi-scales problem.

[F. Militello et al, POP 15 (2008)]
[F.L. Waelbroeck et al, PPCF 51 (2009)]
[M. Muraglia et al, PRL 103 (2009)]
[A. Ishizawa et al, POP 17 (2010)]
[F. Hariri et al, PPCF 57 (2015)]
[L. Bardoczi et al, POP 24 (2017)]

◆ Turbulence Driven Magnetic Island (TDMI)

[M. Muraglia et al, PRL 107 (2011)]
[A. Poyé et al, POP 22 (2015)]
[W. Hornsby et al, PPCF 58 (2015)]
[O. Agullo et al, POP 24 (2017)]
[A. Ishizawa et al, PPCF 61 (2019)]

◆ TDMI amplified and at the origin of a NTM

[M. Muraglia et al, NF (2017)]
J. Frank, PhD thesis, CEA and PIIM Lab
II. Model: 2D Reduced MHD

- Model includes both resistive Interchange and Tearing Mode:
  \[ [M. Muraglia et al, NF 49, 055016 (2009)] \]

\[
\begin{align*}
\partial_t \nabla^2 \phi + [\phi, \nabla^2 \phi] &= [\psi + \psi_0, \nabla^2 \psi] - \kappa_1 \partial_y P + \nu \nabla^4 \phi \\
\partial_t P + [\phi, P] &= -\partial_x P_0((1 - \kappa_2)\partial_y \phi + \kappa_2 \partial_y P) + \rho^2_\star [\psi + \psi_0, \nabla^2 \psi] + \chi \nabla^2 \phi \\
\partial_t \psi &= [\psi + \psi_0, \phi - P] - \partial_x P_0 \partial_y \psi + \eta \nabla^2 \phi
\end{align*}
\]

- Instability characterization: THE PARITY of the eigenfunctions \( \psi_m, \phi_m, P_m \)

\[
\psi(x, y, t) = \sum_{m \in \mathbb{Z}} \psi_m(x, t) \exp(i \frac{2\pi m}{L_y} y)
\]

![Tearing mode](image1.png)

![Interchange mode](image2.png)
II. Linear Turbulent spectrum

- $\Delta' < 0$ Linear spectrum is stable with respect to tearing instability
  - $\Rightarrow$ No island
- Stable large scales modes
- Small scales turbulence driven by interchange instability
  - $\Rightarrow$ What's about non-linear dynamics?
II. NL generation of TDMI

◆ NL generation of TDMI by a beating of interchange modes

[W. Hornsby et al, PPCF 58 (2015)]
II. NTM growth from a TDMI

◆ Self-consistent generation of NTM from TDMI

1. TDMI formation => **Seeding regime**

2. NL growth of NTM => **Amplification (by neoclassical effects) regime**

[M. Muraglia et al, NF (2017)]
II. TDMI - Conclusions

◆ The tearing instability is stable in tokamaks ($\Delta'<0$).

◆ However, it has been shown that, in presence of resistivity (even weak), turbulent modes at small scales can drive at large scales a seed magnetic island (step 2).

◆ Such seed island can be amplified by neoclassical effects and a large magnetic island can damage the device.

◆ Open questions:

1. Prediction of the saturated island size in presence of turbulence (step 3)?

2. Experimental signature of such mechanisms

At small scales, $\Delta'<0$ and resistivity in tokamak is considered too weak for Micro-reconnection. However...
III. Contexte for micro-reconnection

◆ Challenge:
control of the confinement

◆ Open questions:
- Mechanisms leading to H-mode? Pedestal Physics?
- Origin of electronic turbulence? Origin of heat electron transport?

◆ Possible candidate:

=> Micro-TearingMode (MTM) instability?
III. Origin of Micro-Tearing Mode (MTM) ?

- Disagreement between **analytical theory** and **gyrokinetic simulations**

**Stable** MTM in weak collisional regime

- No MTM in tokamaks

- [Hazeltine et al (1975)]
- [Drake and Lee (1977)]
- [Garbet (1990)]
- [Smolyakov (1990)]

**Unstable** MTM in weak collisional regime

- [Applegate et al (2007)]
- [Doerk et al, Guttenfelder et al (2012)]
- [Dickinson et al, Predebon et al (2013)]
- [Swamy et al (2014)]
- [Hatch (2017)]

**Possible physical mechanisms at the origin of MTM destabilization**

- Collisions ?
- Magnetic curvature?
- Electric potential fluctuations?
III. Reconciliation between theory and simulations

- After a lot of theory...
- Reduced Kinetic Model equivalent to the RMHD model in fluide theory

\[
d^2_e \nabla^2 \mathbf{A}_\parallel = \sigma(\omega, \omega_d) \left( \mathbf{A}_\parallel - \frac{k_\parallel v_T e}{\omega} \mathbf{\phi} \right) \quad \text{Ampère's law}
\]

\[
\frac{\omega + \omega^*}{\omega} \rho_i^2 \nabla^2 \mathbf{\phi} = \frac{k_\parallel v_T e}{\omega} \sigma(\omega, \omega_d) \left( \mathbf{A}_\parallel - \frac{k_\parallel v_T}{\omega} \mathbf{\phi} \right) \quad \text{Poisson's equation}
\]

- Successful comparision between theory and gyrokinetic simulations
  In particular, MTM is stable in weak collisions regime

![Graphs showing comparison between theory and simulations](https://example.com/graphs.png)

[M. Hamed et al. CPP (2018)]
III. Destabilization of a MTM

- No instability without collisions => Magnetic reconnection is not allowed
- Unstable MTM in the pedestal region even if collisions are weak (step 1)
- Magnetic curvature and electric potential fluctuations can not destabilize MTM without collisions. However, in presence of collisions, they enhance the MTM growth rate (step 2) [M. Hamed et al. POP 26 (2019)]
III. MTM - Conclusions

- Derivation of a reduced kinetic model for the MTM stability
- Reconciliation between theory and gyrokinetic simulations
- In particular, without collisions, MTM is stable
- However, collisions are sufficient in tokamaks to let MTM unstable in the pedestal (step 1)
- Electron temperature gradient drive MTM. Magnetic curvature and electric potential fluctuations enhance the growth of unstable modes. (step 2)
- Open question on saturation mechanisms: impact of MTMs on heat electron transport (step 3)
General conclusion

◆ In hot magnetized plasmas of tokamaks, magnetic equilibrium is such as the tearing instability is stable ($\Delta'<0$).

◆ However, magnetic reconnection can occur:
  - at large scales: nonlinear growth of Neoclassical Tearing Mode can lead to disruption and can damage the device
  - at small scales: micro-tearing instability can lead to magnetic field stochasticisation and enhance the heat electron transport in the pedestal region

◆ Although resistivity and collisions are weak in such device, they are sufficient to allow magnetic reconnection

◆ It exist various mechanisms leading to an island growth:
  - Small-scales turbulent modes can drive nonlinearly a large magnetic island
  - Electron temperature gradient can drive micro-tearing mode in the pedestal

◆ Open question: Saturation mechanisms?
  - Saturated size of large island?
  - Electron heat transport due to MTM?