EXTRAP T2R active coils as a tool for the study of 3D magnetic field effects on plasma dynamics

L. Frassinetti, K.E.J. Olofsson, P. Brunsell and J.R. Drake

Association EURATOM-VR, School of Electrical Engineering, Royal Institute of Technology KTH

Y. Sun, Association EURATOM-FZJ, Julich, Germany
(present address: Chinese Academy of Sciences, Hefei, China)
OUTLINE

- **Experimental tools:**
  1. EXTRAP T2R
  2. The active coils and (some of) their capabilities, **a tool for the study of 3D magnetic field effects:**

- **Non-Resonant Magnetic Perturbations braking**
  1. Plasma viscosity estimation (experimental)
  2. Torque estimation (experimental)
  3. Torque estimation (via NTV theory, by Y. Sun)
  4. Comparison experimental results - theory

- **RMP screening**
  1. Goal: to study the effect of the plasma flow on the RMP screening
  2. The technique: how to modify the flow without affecting other plasma parameters?
  3. Experimental results
  4. Comparison with theoretical models (Fitzp.-Guo-Weal. and Rozhansky)

- **Error field assessment using external perturbations**
  see F. Volpe on Monday, 3.05pm

- **Conclusions**
EXTRAP T2R is a RFP with:

- $R = 1.24\text{m}$
- $a = 0.18\text{m}$
- $I_p \approx 80-150\text{kA}$
- $n_e \approx 10^{19}\text{m}^{-3}$
- $T_e \approx 200-400\text{eV}$
- $t_{\text{pulse}} \approx 90\text{ms}$

THE DEVICE

$(m=1 \, n<-12)$ are resonant

$\frac{d}{d\theta} b_\theta^{\text{TM}} (\text{mT})$
THE FEEDBACK SYSTEM

- **Sensor coils**
  4 poloidal x 32 toroidal located inside the shell

- **Digital controller**

- **Active coils**
  4 poloidal x 32 toroidal located outside the shell

\[ \tau_{\text{shell}} \approx 13.8 \text{ms} \] (nominal)

- **No feedback**

- **LCFS**
THE FEEDBACK SYSTEM

- **Sensor coils**
  4 poloidal x 32 toroidal located inside the shell

- **Digital controller**

- **Active coils**
  4 poloidal x 32 toroidal located outside the shell

\[ \tau_{\text{shell}} \approx 13.8 \text{ms} \text{ (nominal)} \]
The RIS algorithm can be used to generate external perturbation
[Olofsson PPCF 104005, 52 (2010)]

- A single resonant perturbation
- Two or more perturbations
Plasma flow braking via non-Resonant Magnetic Perturbations

1. Experimental viscosity estimation via RMP
   Then, the viscosity will be used along with the torque balance equation to obtain:

2. Torque estimation from experimental data

3. Torque estimation (via NTV theory, by Y. Sun)

4. Comparison experimental results – theory

5. Conclusion on Non-RMP braking
- RMPs produce plasma braking

- The maximum velocity reduction is localized at the resonance of the externally applied RMP
The viscosity $\nu_{\text{kin}}$ can be estimated via the torque balance:

$$\frac{R^2}{r} \frac{\partial}{\partial r} \left( r \nu_{\text{kin}} \frac{\partial \rho \Delta \omega}{\partial r} \right) = T_{EM}$$

For a RMP, the torque might be obtained by:

$$T_{EM} = k^{m,n} b_{TM}^{m,n} b_{RMP}^{m,n} \sin \phi^{m,n} \delta (r - r_s)$$

[Fitzpatrick and Yu, PoP 3610, 7 (2000)]

Is it a reasonable expression?

1. Absolute value: reasonable from comparison theory-experiments, [Frassinetti et al., NF 035005, 50 (2010)]

2. Radial shape (delta-function): reasonable from the experimental profile of the velocity variation.
The viscosity $\nu_{\text{kin}}$ can be estimated via the torque balance:

$$\frac{R^2}{r} \frac{\partial}{\partial r} \left( r \nu_{\text{kin}} \frac{\partial \rho \Delta \omega}{\partial r} \right) = T_{\text{EM}}$$

$T_{\text{EM}}$ is calculated from Fitzpatrick expression

The velocity profile variation $\Delta \omega$ is from experimental measurements

Uncertainty is estimated with a Monte Carlo approach

The large uncertainty in the core is due to the almost flat $\Delta v$ in the core

The viscosity is larger than the classic value, but in agreement with earlier estimations.

[Vianello et al., PRL 135001, 94 (2005)]
[Almagri et al., PoP 3982, 5 (1998)]
- Non-RMPs produce plasma braking
- The velocity braking is not localized in any radial position
- The torque is estimated from $\frac{R^2}{r} \frac{\partial}{\partial r} \left( r v_{\text{kin}} \frac{\partial \rho \Delta \omega}{\partial r} \right) = T$
- The torque is not localized in any specific position but affects globally the entire core
The Non-RMP braking depends on the harmonic.

- The more far from the resonant, the lower the braking.
- The torque has a similar trend.
ASSUMPTION: the NTV theory is valid in the RFP configuration

The code for NTV torque calculation [Sun et al., NF 053015, 51 (2011)] has been adapted to EXTRAP T2R

Ions and electrons are mainly in the collisionless regime

Since $\nu_{*di0} < 1$, ions are mainly in the $\sqrt{\nu}$ or super-banana regime.

Since $\nu_{*de0} > 1$, electrons are mainly in the $1/\nu$ regime.
TORQUE COMPARISON

- Reasonable qualitative agreement in the profile.
- From a quantitative point of view, NTV torque is \( \approx3 \text{ times lower} \).
- Reasonable qualitative trend versus the perturbation harmonic.
CONCLUSIONS and FUTURE WORK

- **Non RMP braking**

  (1) The torque is estimated from experimental velocity braking
      - the Non-RMP torque is not localized in any specific position but affects the entire core
      - the Non-RMP torque decreases as the perturbation harmonic is more far from the resonance

  (2) NTV theory has a reasonable qualitative agreement with the experimental results

  (3) NTV theory predicts a torque 3-4 times lower than the one necessary to obtain the experimental braking

  (4) Future work/open questions:
      - Study the dependence on the non-RMP amplitude.
      - The viscosity is estimated considering only the EM torque.
        - Underestimation of the viscosity?
        - Underestimation of experimental $T_{NTV}$?
      - The NTV calculation for EXTRAP T2R needs to be extended to the resonant harmonics:
        - How to consider the plasma response?
        - How to consider the perturbation screening?

  This leads us to the next topic…
RMP screening

(1) **Motivation of the work:**
   does the plasma rotation affect the penetration of a RMP?

(2) **The technique:**
   how to modify the plasma rotation without affecting other plasma parameters?
   Using a non-RMP.

(3) **Experimental results:**
   What to look? How to quantify the RMP effect?
   By studying the interaction of a rotating TM with a stationary RMP field for varying plasma rotation velocity.

(4) **Comparison with some theoretical models (preliminary):**
   - Fitzpatrick Guo Wealbroek models
   - Rozhansky model
• Using a non-RMP, the plasma rotation can be modified

• Then, the RMP will be applied during the stationary phase
The technique:

(1) Apply a non-RMP to obtain the “desired” velocity

(2) Apply a RMP to study the TM response

The TM response will depend on:
(a) the RMP (amplitude and harmonic)
(b) the plasma rotation (if the screening occurs)
By modifying the non-RMP amplitude, the plasma rotation is changed.

NO significant variation in: (1) $I_p$
(2) Impurities
(3) Equilibrium
(4) TM amplitude (see later)

(as long as the perturbation is not too large)
**EFFECT ON THE TEARING MODE**

- **Reference plasmas:**
  - (a) RMP is NOT applied
  - (b) Non-RMP is used to change the plasma velocity

  **No effect on the TM amplitude**

- **Plasmas with RMP:**
  - (a) always the same RMP harmonic and RMP amplitude is used: $b_{r1,-12} = 0.6$ mT
  - (b) Non-RMP is used to change the plasma velocity

  **At high plasma rotation the RMP effect on the TM seems negligible.**

  **RMP Screening?**
Comparison with theoretical models

- Fitzpatrick, Guo, Wealbroek models:
  
  for example [Phys. Plasmas 8 4489 (2001)]

  $$\Lambda \frac{\tau_R}{4r_s} c |\dot{\Psi}_s| = f(|\Psi_s|) + \frac{E^r_s E^\nu_w}{|E^\nu_v|} \frac{|\Psi_w|}{\sqrt{|\Psi_s|}} \cos \omega t$$

  assuming constant velocity and large RMP amplitude, the solution is:

  $$b_{TM} \approx \left( \frac{k}{\omega} b_r^{RMP} \right)^{2/3}$$

- Rozhansky model:
  
  (it considers radial current of electrons in a stochastic field)
  [Nucl. Fusion 51 083009 (2011)]

  $$\frac{b}{B} = \frac{1}{\sqrt{1 + f(B, T_e, n_e) \omega^2}} \frac{b_0^{RMP}}{B}$$

  Both models can give a reasonable agreement with experimental data. More detailed comparisons are in progress.
- **Reference plasma:**
  - TM amplitude approximately constant

- **RMP 0.6mT and fast plasma rotation**
  - the RMP amplifies and suppresses the TM depending on the phase

- **RMP 0.6mT and slow plasma rotation**
  - the TM is amplified and suppressed. But due to the lower rotation, the TM is in a positive phase relation with RMP for a longer time ⇒ stronger amplification
CONCLUSIONS and FUTURE WORK

- **Non-RMP braking**

  (1) The torque is estimated from experimental velocity braking
      - the Non-RMP torque is not localized in any specific position but affects the entire core
      - the Non-RMP torque decreases as the perturbation harmonic is more far from the resonance

  (2) NTV theory has a reasonable qualitative agreement with the experimental results

  (3) NTV theory predicts a torque 3-4 times lower than the one necessary to obtain the experimental braking

- **RMP screening**

  (1) Plasma rotation is modified by applying a non-RMP producing:
      - velocity reduction
      - no significant effect on equilibrium and TM amplitude

  (2) The same technique is used applying a RMP with constant amplitude

  (3) The analysis of the TM amplitude shows a smaller effect of the RMP at high rotation: the plasma rotation clearly affects the dynamics of the TM

  (4) Existing models seem to give a reasonable explanation

  (5) Future work: - increase of the statistic (more plasma shots) and of the velocity scan steps.
      - study of different RMP harmonics
      - more detailed comparison theory-experiment.