Finite Larmor radius effects in the linear plasma response to resonant magnetic perturbations in Tokamaks

Markus Markl[1]

[1] Fusion@ÖAW, Institut für Theoretische Physik - Computational Physics, Technische Universität Graz, Petersgasse 16, 8010 Graz, Austria

markl@tugraz.at

Introduction

- The tokamak experiment ITER, which is currently being built in Cadarache in France, aims at demonstrating feasibility of **fusion energy** production

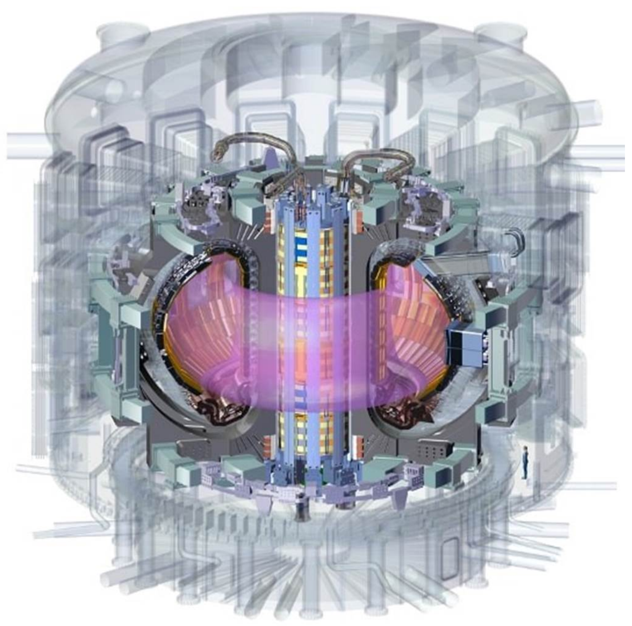

Fig. 1: Schematic of the ITER tokamak [1]. A tokamak magnetically confines a plasma in the shape of a torus.

- Operation of ITER is threatened by instabilities called **edge localized modes** (ELMs) [2], which are characterized by unacceptably large transient heat loads to the vessel wall

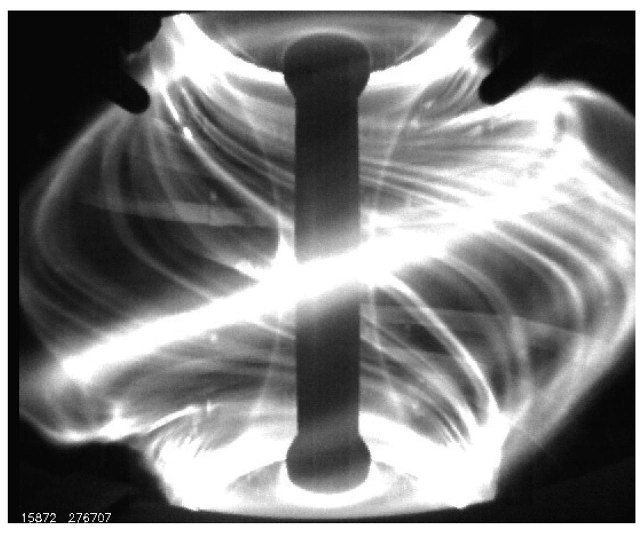

Fig. 2: Bright ELM filament observed in MAST experiment due to D_α radiation [2].

- Deforming the equilibrium magnetic field with externally generated perturbations ($\delta B/B_0 \approx 10^{-4}$), so-called **resonant magnetic perturbations** (RMPs), changes the transport properties of the plasma and leads to ELM suppression

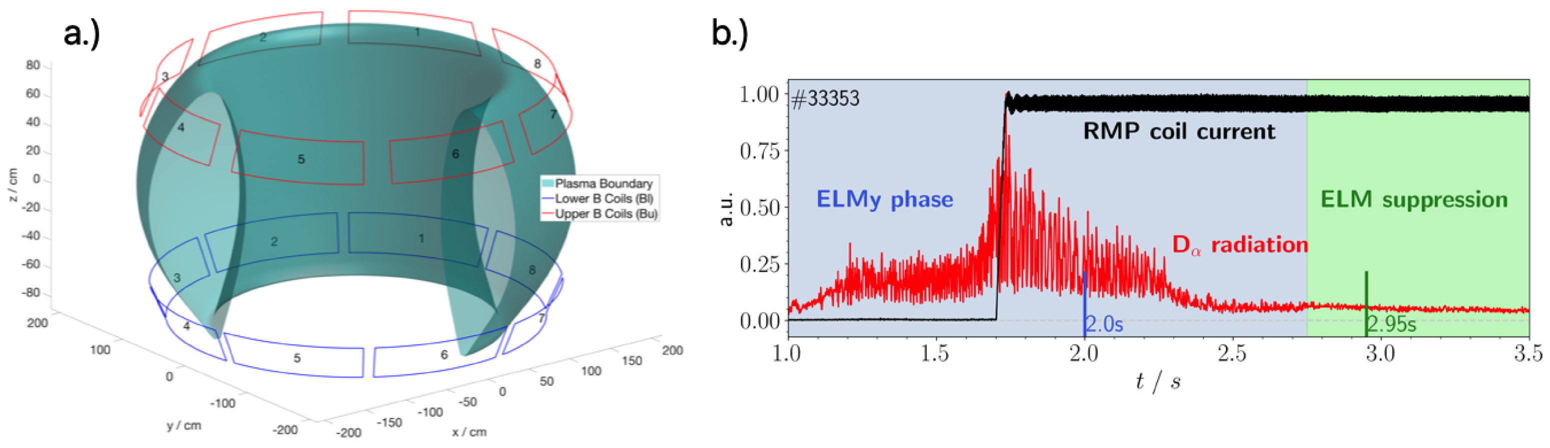

Fig. 3: a.): Illustration of the magnetic perturbation coils in the ASDEX-Upgrade experiment (taken from [3]).
b.): Data from ASDEX-Upgrade showing ELM suppression due to RMPs during the time evolution of the experiment.

- However, the conducting plasma responds to RMPs with a **shielding current**, whose relation to the magnetic field perturbation depends on plasma parameters, in particular on the density and temperature of the electrons
- Under certain conditions, the perturbation can outgrow the shielding current and a **bifurcation** to an unshielded state happens

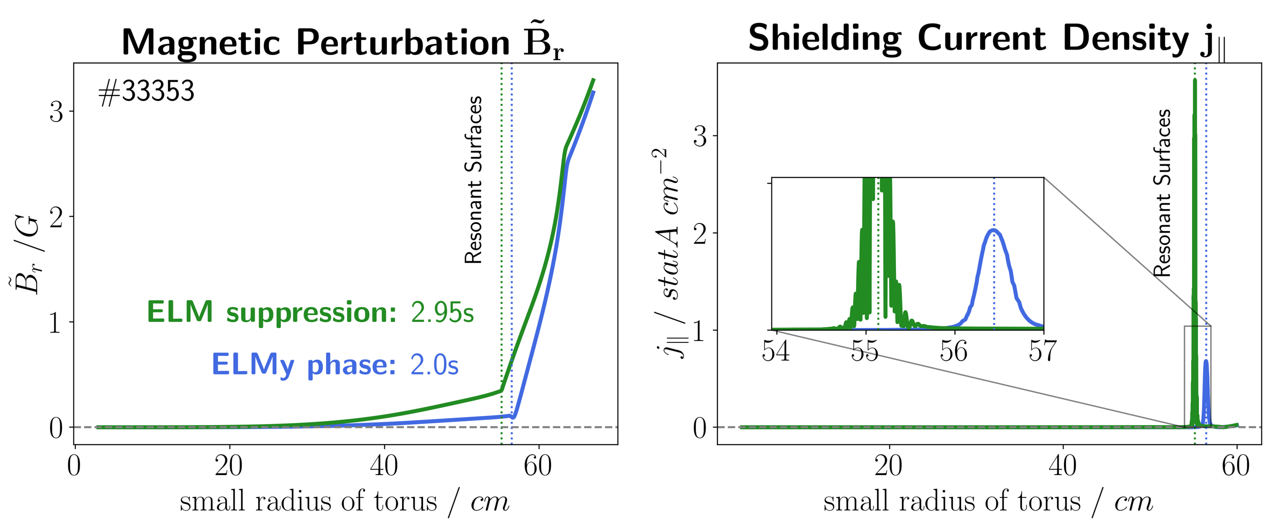

Fig. 4: P lots from simulations done with code KiLCA using ASDEX-Upgrade data from shot #33353 (c.f. figure 3b). At 2.95s the magnetic perturbation is penetrating the plasma and ELMs are suppressed. The resonant surface is the location for which the Fourier modes of the background magnetic field and the perturbation coincide.

- The **physical mechanisms** involved need to be thoroughly understood to effectively suppress ELMs that will occur in ITER

Acknowledgements

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Kinetic Modelling

- **Existing codes** are used and upgraded
- Code **KiLCA** [4] - Kinetic Linear Cylindrical Approximation: Maxwell solver that approximates the torus shape of a tokamak as a cylinder and uses a kinetic model for the plasma conductivity
- KiLCA in combination with the quasilinear transport model of [5] is presently applied to experimental data to **analyse ELM suppression** in experiments
- However, an **upgrade is necessary** to resolve important physics
- KiLCA, which is based on a finite Larmor radius (FLR) expansion resulting in a differential scheme, will be upgraded to an integral model that fully resolves **FLR effects**
- Additionally, the upgrade will include **multiple ion species** to model impurity effects

Finite Larmor Radius Effects

- When the width of the resonant current becomes comparable to the ion Larmor radius, an integral description is necessary to **accurately** resolve FLR effects
- Higher order FLR effects introduce additional **electrostatic modes** that can couple to the magnetic field perturbation in the resonant layer
- This coupling could explain **increased transport** in the plasma due to RMPs, which essentially leads to ELM suppression
- Impact of **different isotopes**, e.g. hydrogen instead of deuterium, can in KiLCA only be seen when considering FLR effects

Integral Model

- Solve **time harmonic Maxwell equations** for the field perturbations $\boldsymbol{E}$ and $\boldsymbol{B}$

$$\nabla \times \boldsymbol{E} = \frac{i\omega}{c}\boldsymbol{B} \tag{1}$$

$$\nabla \times \boldsymbol{B} = -\frac{i\omega}{c}\boldsymbol{E} + \frac{4\pi}{c}(\boldsymbol{j}_{\mathrm{RMP}} + \boldsymbol{j}), \tag{2}$$

where the total current density is given by a sum of the RMP coil current density $\boldsymbol{j}_{\mathrm{RMP}}$ and the plasma response $\boldsymbol{j}$

- In kinetic theory, the plasma current density is given by the **first velocity moment**

$$\boldsymbol{j}(\boldsymbol{x}) = q\int d\boldsymbol{v}\boldsymbol{v}\tilde{f}(\boldsymbol{x},\boldsymbol{v}), \tag{3}$$

where the perturbation of the particle distribution function $\tilde{f}$ is the solution to the linearized plasma kinetic equation, which depends on the electric field perturbation $\boldsymbol{E}$

- From this, the current density can be considered the action of a **conductivity operator** on the electric field

$$\boldsymbol{j} = \hat{\sigma}\boldsymbol{E} \tag{4}$$

- Due to axisymmetry, a **Fourier mode expansion** in toroidal (big torus circle) and poloidal (small torus circle) direction is possible, resulting in a one dimensional problem in the radial variable
- The derivation of the integral form of the conductivity operator assumes an **integral transform** ansatz of the plasma current [6]

$$\boldsymbol{j}(r) = \int dr' K(r,r')\boldsymbol{E}(r') \tag{5}$$

where the integral kernel is defined by the conductivity operator in k-space as

$$K(r,r') = \frac{1}{2\pi}\int dk_r dk_r' e^{-i(k_r r + k_r' r')}\tilde{\sigma}(k_r,k_r') \tag{6}$$

- Equation (5) can be used to numerically solve Maxwell's equations, which are then given as a **set of one-dimensional integro-differential equations**

References

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