INTERPRETATION AND CONTROL OF HELICAL PERTURBATIONS IN TOKAMAKS

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During the period January-December 2003, the common research between the **Mathematical Modelling for Fusion Plasmas Group** of **the National Institute for Lasers, Plasma and Radiation Physics (NILPRP),** Magurele - Bucharest, Romania with the **Max-Planck - Institut für Plasmaphysik (IPP)**, Garching, Germany has been focalized, according to the Work Programme 2003 approved at the 4th Steering Committee meeting, on the following objectives:

1. Improvement of equilibrium calculations for stability analysis of modes in the separatrix vicinity in order to determine the influence of the plasma triangularity on the tearing mode stability parameter Δ' for the ASDEX-Upgrade tokamak.

The continuation of this objective has been decided together with our German partners as strongly necessary in order to have an estimation of the remaining stability energy when the unconditionally unstable neoclassical tearing modes occur.

The knowledge of Δ' for realistic tokamak plasmas is especially important for an understanding of the plasma stability against neoclassical tearing modes (NTM's). NTM's are considered the most severe limitation to the maximum achievable normalized plasma pressure. These modes are driven unstable by the loss of the bootstrap current inside magnetic islands as a result of the flattening of pressure across these islands. A simple theoretical description of the growth of NTM's can be given in terms of a generalization of Rutherford 's equation describing the growth of classical tearing modes. To model the growth of NTM's as observed in experiments, for the tearing stability parameter Δ' often a simple approximation $\Delta' = -2\ m/r_s$ is used which is correct only in the limit of circular cylindrical plasmas. The modeling can be improved if for Δ' the correct value in realistic geometry is used. That way it might be possible to understand the observed influence of plasma shaping on NTM stability. The results shown in this work are at least in qualitative agreement with experimental observations on ASDEX Upgrade of a stabilizing influence of triangularity.

The following **milestone** has been achieved:

1.a Interpretation of different experimental discharges of the ASDEX-Upgrade tokamak from the Δ' (the tearing mode stability parameter) point of view.

We have interpreted different experimental discharges (advanced scenario) of the ASDEX Upgrade tokamak from the stability parameter (Δ') point of view for tearing instabilities with different wave numbers m/n. Taking the shot no. 13476 at 5.2 seconds as reference, we have investigated the influence of the triangularity, the ellipticity and the aspect ratio on Δ'. The results obtained show an increase of the stability with triangularity and ellipticity as well as a decrease of the stability with aspect ratio.

These works have been carried out in close collaboration with our German colleagues from the Tokamak Physics Department of the Max-Planck-Institut für Plasmaphysik, during the mobility 19.05.03-16.08.03 at IPP Garching and work at our home institute NILPRP.

2. Plasma Models for feedback control of helical perturbations

[4.2-2: from EUR(02) CCE-FU/SWG 5/4.2]

The goal of our common research is to advance the physics understanding of Resistive Wall Modes (RWM) stability, including the dependence on plasma rotation, wall/plasma distance, and active feedback control, with the ultimate goal of achieving sustained operation at beta values close to the ideal-wall beta limit through passive or/and active stabilization of the RWM. With this in view, the aim of the present work was to find an optimal feedback system needed to stabilize resistive wall mode instabilities in a large-aspect, low-beta tokamak plasma.

To perform an advanced analytical calculation we chose to find the behaviour of resistive wall modes as instabilities from a plasma equilibrium whose unperturbed magnetic flux surfaces map out concentric circles in the poloidal plane. Such an equilibrium is well approximated as a periodic cylinder; therefore we used cylindrical polar coordinates.

A rotation frequency in the perturbed field at the unperturbed plasma boundary has been introduced, the induced surface currents at a non-uniform wall have been investigated and the response of these currents has been evaluated.

The passive feedback system consists of a non-uniform resistive wall (“partial” resistive shell) possessing poloidally and toroidally non-uniform electrical resistance or gaps disposed anywhere on the wall surface. The wall is assumed to lie in the “thin-shell” approximation where the magnetic flux is assumed constant across the wall.

The active feedback system consists of a number of identical, radially thin, rectangular coils with various poloidal and toroidal extents accompanied by the same kind of detector loops centered on the same angular coordinates, whose dimensions do not necessarily match those of the coils. The inductive voltage generated in a detector loop is integrated, amplified and fed back into the feedback coil. The poloidal and toroidal disposal of the coils and detectors are not necessarily symmetrical. Because instabilities are considered as having no angular symmetry, the poloidal and toroidal couplings of the coils and detectors current harmonics are taken into account.

Starting from plasma instabilities equations integrated across the passive and the active shell, circuit equations in coils and detectors containing also mutual inductances between current distributions in various loops, we obtained an $(m_2-m_1+1)(n_2-n_1+1)$ linear algebraical system of equations in Fourier terms of the poloidal flux function at the resistive wall, where (m2-m1+1) and (n2-n1+1) represent the number of poloidal and toroidal harmonics taken into account as adjacent harmonics for an (m, n) resistive wall mode, intrinsically unstable for a physically plausible tokamak current profile; we used the so-called Wesson current profile [Wesson, Nucl. Fus. 18 (1978), 87] in calculus (m and n are the poloidal and toroidal mode number respectively). We have obtained a system of linear algebraic equations derived analytically in conditions of wall non-uniformity, feedback loops and detectors disposed anywhere, and whose current harmonics develop couplings of any kind.

By setting to zero the determinant of this linear algebraical system we obtained the dispersion relation consisting of a $2(m_2\text{-}m_1)$-degree algebraical equation in the growth of the (m,n) resistive wall mode, the physical issue who gives complete information about the mode stability.

In Figure 1, different dependencies of the growth rate are presented for m=1,…, 4; n=1; a=1; R_0=8;q_a=2.9; q_0=1.3; τ_{wSS}=400μs; τ_{wAl}=65ms; $\Delta\theta_f=\pi/8$; G_d=5; Ω_θ=50; $\Delta\theta_d=\pi/9$; G_p=5.5; Ω_θ=0; Ω_Φ=-30000; B_z=2.1T; r_f=1.25m; r_d=1.35m; μ_{visc}=9*10-14 kg/m/s; θcoils=[0, π/6, π/3, π/2, 3π/2, 5π/3, 11π/6]., where: m is the poloidal wave number; n is the toroidal wave number; a is the small plasma radius; R_0 is the big equivalent radius; q_a is the safety factor at the plasma boundary; q_0 is the safety factor at the magnetic axis; τ_{wSS} is the time constant for stainless steal; τ_{wAl} is the time constant for Al; $\Delta_{\theta f}$ is the poloidal angular distance between feedback coils; $\Delta\theta_d$ is the poloidal angular distance between detectors; G_d is the differential gain of the amplifier; G_p is the proportional gain of the amplifier; Ω_θ is the poloidal plasma rotation velocity; Ω_Φ is the toroidal plasma rotation velocity; B_z is the toroidal magnetic field; r_f is the radius of the feedback coils; r_d is the radius of the detectors; μ_{visc} is the plasma viscosity; θcoils is the poloidal angular location of the feedback coils.

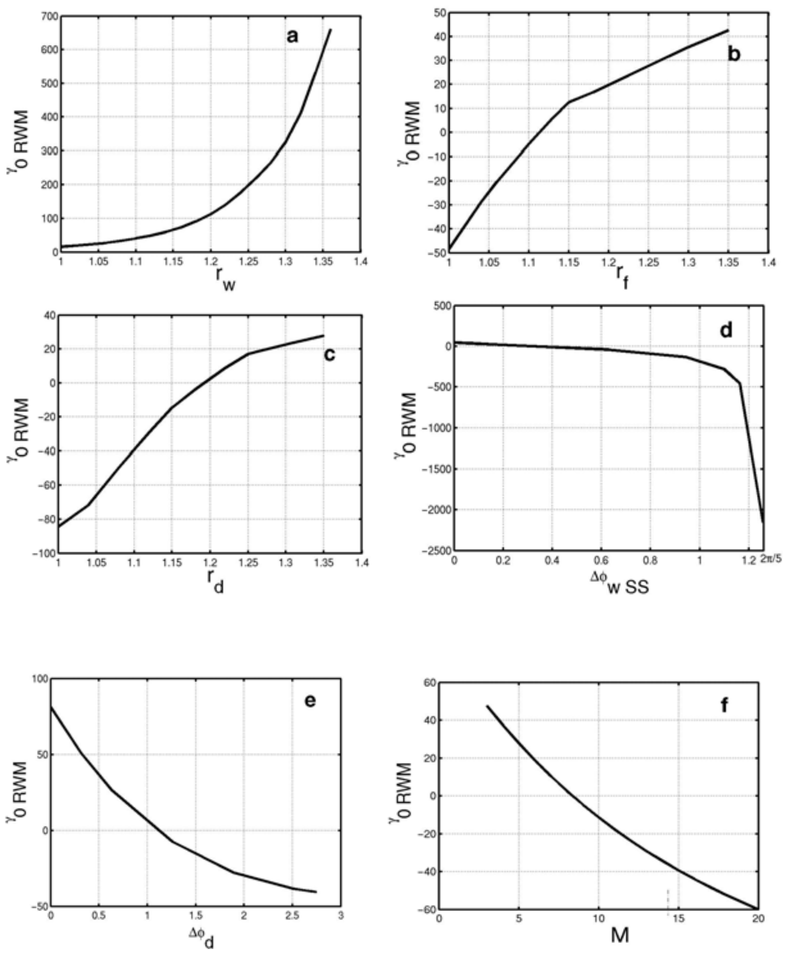

Figure 1. Growth rate dependencies γ_0 in the resistive wall mode m/n=3/1
a) $\gamma_0(r_w)$ (wall radius); b) $\gamma_0(r_f)$ (feedback coil radius); c) $\gamma_0(r_d)$ (detector radius);d) $\gamma_0(\Delta\theta_{wSS})$ (poloidal extent of the stainless steel wall); e) $\gamma_0(\Delta\theta_d)$ (poloidal extent of the detector); f) $\gamma_0(N)$ (toroidal number of feedback coils). The notation of symbols are the same as in the text above.

In a **next step:**

- we intend to investigate the influence of the sideband harmonics (i.e. other than the intrinsically unstable principal harmonic), as the principal failure mechanism for feedback systems.
- we have to take into account the coupling of different poloidal harmonics due to the non-sinusoidal nature of the feedback currents.
- development of a numerical code to deal with RWM's in 2D geometry. Of special importance is to find a suitable complex eigenvalue solver;
- implementation of the new eigenvalue solver into the CASTOR code, which recently has been generalized to deal with a resistive wall.
- as the results from the very recent measurements made by Garofalo *et al.*, Phys. Plasmas **10**, 4776 (2003) on DIII-D, claiming that the rotation of the RWM with respect to the wall, considered as an essential feature of the mechanism by which plasma rotation stabilizes RWM, appear inconsistent with the measurements, we intend to investigate theoretically this very important experimental result.

These works have been carried out in close collaboration with our German colleagues from the Tokamak Physics Department of the Max-Planck-Institut für Plasmaphysik, during the mobility 22.10.03-19.01.04 at IPP Garching and work at our home institute NILPRP.

3. Participation in the exploitation of the JET facilities

During our first participation at JET, campaign C10 (17 Aug. - 17 Sep. 2003), Task Force D, with the objective:

"**Numerical Data Analysis for Current and Pressure Profiles Reconstruction on JET**"

the following milestones have been accomplished:

- development of a numerical algorithm and code for 3D field error calculation in Helmholtz coils to be developed at JET, and to be used to furnish magnetic data for profile reconstruction. The imposed field error was less then 0.01%. All possible error positioning in a 3D space have been investigated and practical project data to build such coils has been given;
- the ESC equilibrium code has been implemented on the JACK cluster computer system (under LINUX);
- the ESC input format has been adapted to the output data files given by the diagnostic system of JET (of JPF and PPF type) (Raw data for each shot is stored in the JPF (JET Pulse File). This is processed as PPFs (Processed Pulse Files). Off line analysis of the PPFs and JPFSs creates more PPFs.

This work has been performed in cooperation with our JET, Princeton Plasma Physics Laboratory and IPP colleagues during the campaign C10 (17 Aug. - 17 Sep. 2003).

In a **next step**:

After our participation in the JET Campaign C10 HP1 (17 Aug-2003 - 17-Sep-2003) we will continue our work on "Numerical Data Analysis for Current and Pressure Profiles Reconstruction on JET" in the frame of the Campaign C13-C14 (2-Feb-04 – 4-Mar-04). We will use magnetic data and data resulting from the Motional Stark Effect measurements as constraints in the identification of the non-linear r.h.s. of the Grad-Shafranov equation.

Publications:

[1] **Zohm H., Angioni C., Arslanbekov R., Atanasiu C.V., et al**., "*Overview of ASDEX Upgrade resuls*", Nucl. Fusion **43** (2003) 1570.

[2] **Atanasiu C.V, Günter S., Lackner K., Miron I.G**., "*Analytical solutions to the Grad-Shafranov equation for diverted plasmas"*, 30th Conference on Controlled Fusion and Plasma Physics, St. Petersburg, Russia, July. 2003.

[3] **Atanasiu C.V, Günter S., Lackner K., Miron I.G**., *"Exact solutions to the Grad-Shafranov equation for toroidal plasmas"*, 12th Conference on Plasma Physics and Applications, Iassy, Romania, September, 2003.

[4] **Atanasiu C.V, Günter S., Lackner K., Miron I.G**., "*Analytical solutions to the Grad-Shafranov equation"* (submitted to Phys. Plasmas, 2003, PoP #27721)

[5] **Atanasiu C.V, Günter S., Lackner K., Moraru A., Subbotin A.A**., "*Boundary conditions for equilibrium and tearing modes calculation in diverted tokamak configurations"* (submitted to Phys. Plasmas, 2004)