ANALYSIS AND MODELLING OF NTMs DYNAMICS IN JET DISCHARGES USING THE EUROPEAN TRANSPORT SIMULATOR (ETS) AND INTEGRATED MODELLING TOOLS

S. Nowak¹, O. Sauter², D. Yadykin³, E. Alessi¹, D. Brunetti¹, A. Czarnecka³, V. Fusco³, G. Miron⁴, G. Puccella³, I. Ivanova-Stanik⁴, G Vlad³, M. Baruzzo³, P. Buratti¹, R. Coelho⁷, G. Falchetto⁷, E. Giovannozzi⁷, J. P. Graves³, P. Huynh¹⁰, M. Imrisek¹¹, J. Ferreira⁹, E. Joffrin⁷, D. Kalupin¹², F. Koechli³, N. Krawczyk³, E. Lazzaro¹, J. Mailloux⁸, C. Marchetto¹, A. Merle², F. Poli¹³, M. Romanelli⁸, P. Strand³, R. Zagorski¹⁴, JET contributors* and the EUROfusion-IM Team**

¹ Istituto di Fisica del Plasma ‘P. Caldirola’, CNR, Milano, Italy
² Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland
³ Department of Earth and Space Sciences, Chalmers University of Technology, SE-41296 Gothenburg, Sweden
⁴ Institute of Plasma Physics and Laser Microfusion, Herăstrău 23, 01-497 Warsaw, Poland
⁵ Centro Ricerche di Frascati, C.P. 65 00044 Frascati, Rome, Italy
⁶ National Institute for Lasers, Plasma and Radiation Physics, Magurele-Bucharest, Romania
⁷ Consorzio RFX, Padova, Italy
⁸ Culham Centre for Fusion Energy, Culham Science Centre, Abingdon, OX14 3DB, UK
⁹ Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Portugal
¹⁰ CEA, IRFM, F-13108 Saint Paul Lez Durance, France
¹¹ IPP AS CR, Za Slovankou 3, CZ-18200 Prague, Czechia
¹² EUROfusion Programme Management Unit, Boltzmannstr. 2, 85748 Garching, Germany
¹³ Princeton Plasma Physics Laboratory, Princeton, NJ, United States of America
* See the author list of X. Litaudon et al 2017 Nucl. Fusion 57 102001
** http://euro-fusionscibpub.org/eu-im

Max Planck Institute for Plasma Physics, D-85748 Garching, Germany

e-mail: nowak@ifp.cnr.it

Abstract

Stability of JET experimental scenarios is investigated in the framework of the JET1 task on MHD analysis and modeling in support of scenario development. Analysis and modeling of Neoclassical Tearing Modes (NTMs) onset and their effect on heavy impurity transport is performed using the European Transport Simulator (ETS), encompassing an NTM module and MHD stability calculation. Notably, the ETS simulator can compute the evolution of impurities in all their ionization states. The present study is aimed to predict plasma stability conditions investigating JET hybrid discharges in which NTMs limit the plasma performance. The NTM module implemented in the ETS describes the NTM dynamics by a set of equations for the mode width, through a generalised Rutherford equation and frequency. Effects of NTM on electron, ion and heavy impurity transport are modeled modifying the diffusion coefficients, perpendicular to the magnetic field, around the mode location by adding a Gaussian perturbation. The enhancement of tungsten diffusion coefficient initially observed around the mode location and then towards the plasma centre can be simulated with this description. The full MHD code MARS is also used for the study of the mode linear growth rate taking plasma data from outputs by ETS or other codes at some time snapshots. The results obtained from such an integrated analysis provide a new modelling investigation of the plasma stability for JET discharges. A detailed discussion of the calculations is reported.

1. INTRODUCTION

The stability of JET hybrid scenarios is investigated in the framework of the JET1 task on MHD analysis and modeling in support of scenario development. In particular, modeling of the onset of Neoclassical Tearing Modes (NTMs) and their effect on heavy impurity transport is performed via the modern and modular European Transport Simulator (ETS) [1], encompassing an NTM module and MHD stability calculation. The ETS simulator is particularly appropriate since it can compute the evolution of multiple impurities in all their ionization states. The aim of the present study is to predict plasma stability conditions in order to identify the tokamak operational space characterized by NTMs which contribute to limit the plasma performance and duration (~ 5s) in DT scenarios, where high performances, approaching high beta and current, are required. In addition, the high energy confinement in hybrid discharges, characterized by low central magnetic shear and on-axis safety factor q₀ ~1, can be deteriorated if impurities accumulate towards the plasma center. In JET an
accumulation of the tungsten from the divertor from off-axis to the plasma core has been observed with corresponding degradation of confinement [2] in presence of the 3/2 mode.

The NTM module [3-4] implemented in the ETS describes the NTM dynamics by a set of equations for the mode width, through a generalized Rutherford equation (GRE), and frequency. Investigation and validation of the mode trigger models, as the checking by the NTM module in ETS of the mode onset occurring at a sawtooth crash time after a long sawteeth period, can be performed with this module as well as the analysis of the effects of NTM on electron, ion and impurity transport. Specifically, the change of transport coefficients due to the presence of NTM is modeled by enhancing the perpendicular diffusion coefficients around the mode location, by adding a Gaussian perturbation [5]. In JET discharges, this kind of modification has been considered for the electron transport coefficient allowing the simulation of the experimental temperature profile flattening [6]; similarly, it is used here to model the enhancement of tungsten diffusion coefficient initially observed around the mode location, as considered also in JETTO-SANCO transport codes [7].

A first validation of the MHD stability models has been performed by comparing the evaluation of the mode stability parameter $\Delta'_0$ provided by different codes for the JET hybrid discharges #84812 and #90279 (Fig. 1). The data labeled as (a) are provided by the NTM module in ETS, where the assumption $\Delta'_0 = -m/r_s$ is made, with $m$ is the mode poloidal number and $r_s$ the mode radial location [6]. Data labeled as (b) are the results of the Delta Prime Calculation Code (DPCC), integrated as well in the NTM module in ETS, which is able to derive $\Delta'_0$ for any axisymmetric toroidal geometry, considering the temporal evolution of the current density profile as provided by the reconstructed equilibrium [8]. The data labelled as (c) are obtained with a 3D quasi-analytic code in which the $\Delta'_0$ values depend on the ratio between the local perturbed fluxes calculated outside and inside the magnetic island, also considering external coils and resistive wall [9]. Finally, in (d) $\Delta'_0$ is calculated from the current density and the safety factor profiles in cylindrical geometry as reported [10]. The results are in agreement showing slight differences due to the models used.

![Graph](image)

**FIG. 1.** $\Delta'_0$ provided by different codes for #84812 (left) and for #90279 (right). The vertical dashed lines indicate the 3/2 mode onset time.

2. LINEAR AND NON LINEAR STABILITY ANALYSIS OF JET HYBRID SCENARIO

The analysis of the plasma stability is carried out for 2 JET hybrid scenario discharges #90279 and #90339 ($I_p=1.4$ MA, $B_t=1.9$T, $P_{NBI}=16$ MW, $\beta_N=2.1$) part of the Ne seeding experiments (M18-02 JET task) in which the radiation increases with the Ne seeding rate. These selected pulses are interesting for our purpose because the NTM onset produces some localized changes on the W density profile and this effect can be isolated and better investigated for interpretative and predictive analysis.

The interplay between NTM and W heavy impurity is thus analyzed using the NTM module in ETS as well as a linear stability calculation with the resistive, global, full MHD MARS code [11] (see Section 3.2). The NTM 3/2 and 4/3 are present in both these discharges, as shown in the spectrograms (Fig. 2). In #90339 the 3/2 mode onset at 45.75s is due to a sawtooth crash whereas it is spontaneous at 47.3s in #90279, while spontaneous 4/3 NTMs are present from ~46.15s in #90279 and from 47.51 in #90339 as well. The NTM 3/2 and 4/3 seem associated to an additional localized small W accumulation, even if the central W peaking at 46.5s is not sensitive to the modes (Fig. 3), which appear later.
FIG. 2. #90279 and #90339 spectrograms. The 4/3 and 3/2 onset times are marked.

The sizes of these NTMs are estimated at about 0.03m – 0.04m, as shown later, and their impact on W dynamics is observed in some changes of W profiles at the radial position ~ 30 - 45% off-axis (Fig.3). Where tearing modes are present the impurity concentration can locally increase.

In Fig.3 the time evolution of the tungsten concentration (ratio of impurity density to electron density) at 3 radial positions r/a =0., 0.3 and 0.45 is shown with some W concentration profiles, as calculated using SXR data by SXR cameras [13], just before and after the 3/2 onset time between 46.5 and 47.3s for the pulse #90279. Strong W accumulation towards the plasma centre starts at 46.s, slightly before the appearance of the 4/3 mode and, as said before, is not sensitive to MHD activities. In this case the W peaking on-axis is due to the Ne seeding. However, a moderate W concentration is seen also at the off-axis locations. In the range between 46.15s and 47.3s only a 4/3 mode is present with a small size (see Fig. 5). The tungsten concentration time trace at r/a=0.3 (Fig. 3, left) presents a slight increase from about 46.5s to 47.s. This effect can be associated to the 4/3 mode presence, located more off-axis at r/a ≈ 0.42. Similarly, the 3/2 mode, triggered later at 47.3s and located at r/a=0.49, can affect at its onset the W profile slightly growing up at the inner radius r/a=0.45 (Fig.3). The effect of the 4/3 mode on W profile tends to decrease in time at r/a = 0.3, while the presence of 3/2 increases this impurity concentration at r/a = 0.45. It should be noted that the W concentration increase at ~ 0.45 from 46.8s is not due to any NTMs, but to Ne seeding, because the 3/2 mode, capable to produce an effect at the radial location 0.45, is absent at this stage.

FIG. 3. W concentration traces (left) at 3 radial locations (r/a = 0., 0.3, 0.45) and W concentration profiles (right) measured by SXR at 46.5s and 47.3s for #90279. The concentration is given as ratio of impurity density to electron density.

The label r/a here denominates the normalized toroidal radius.

The experimental data of the W density profile at the onset times for #90279 at 47.3s (Fig.3) and for #90339 at 45.75s are given in Fig.4. From the previous discussion the effects of the tearing modes on this profile can be localized between 0.3 and 0.45 and it can be simulated using the NTM model in ETS.
3. NTM ANALYSIS AND MODELING IN ETS AND INTEGRATED NUMERICAL TOOLS

Our aim is to isolate and quantify the impact on the local W enhancement of the NTM presence by using a transport model allowing modifications of the W transport coefficients only from the mode onset. The focus in the following will be on the simulations of the #90279 discharge. The linear and non linear stability of JET hybrid scenarios is investigated in the framework of the JETI task on MHD. The non linear study focuses on the analysis of the effect of NTMs on the tungsten dynamics, while the linear analysis is used to determine the classical or neoclassical character of the modes.

3.1. Non linear analysis

The NTM evolution has been modeled via the NTM module within ETS, validated against other codes, as detailed in the following. In Fig.5 the non linear growth of the 3/2 mode in #90279 is shown. The 3/2 mode widths, estimated using the measured poloidal magnetic fluctuations normalized to toroidal magnetic field [14], is compared with the NTM widths calculated using the NTM module in ETS and the 3D q.a. code [9]. The agreement between the estimated and calculated mode width evolutions is within the respective error bars. A systematic error of about 50% is applied on the estimated mode amplitude from measurements mainly due to the variations of the magnetic shear, while 30% of systematic error through free coefficients used in GRE and equilibrium reconstruction is considered for the calculated widths. The evolutions provided by the numerical codes are in good agreement with each other. The 4/3 evolution calculated in ETS is shown as well.

FIG. 4. Experimental W density profile data for #90279 at 47.3s and #90339 at 45.75s.

FIG. 5. Estimated from measurements (left) and calculated (right) evolutions of NTM 4/3 and 3/2 modes for the JET #90279.
The ETS simulation is performed using transport coefficients for the main ion species calculated by the Bohm-Gyro-Bohm model, and imposing constant transport coefficients for the tungsten. Coronal model [1] (Fig. 6, right) is used to calculate density profiles for the charge states of W (Fig. 6, left), that then summed up giving the initial W density profile. A modification of transport coefficients is then introduced by the NTM modules, so that the impact of their appearance on W dynamics can be isolated and analysed.

![Graph showing initial W density profiles](image)

**FIG. 6.** Initial W density profiles of some normalized ionization states with total constant value (left) for #90279 and coronal distribution (right).

The W diffusion and convective profiles for every ionization state $i$, $D_W(\rho,i)$ and $V_W(\rho,i)$, are calculated only considering an external contribution due NTMs. The NTM module in ETS allows to modify the W transport coefficients [6] adding to both the diffusive and convective parts a Gaussian perturbation with width proportional to the mode sizes and $D_W$ and $V_W$ amplitudes depending on W density and velocity, respectively. In the simulations for the pulse #90279 the initial W constant density value of the $10^{15}$ m$^{-3}$ is considered (Fig. 6) and the unperturbed W transport coefficients, before the mode onset, are set to $10^{-5}$ m$^2$/s and m/s. Taking into account both the sizes $w \sim 0.03$ m for 4/3 and $w \sim 0.04$ m for 3/2, the Gaussian width at 1/e is set at 2w.

At the 3/2 mode onset the numerical coefficients multiplying $D_W(\rho,i)$ and $V_W(\rho,i)$ are taken $5 \times 10^6$ and $5 \times 10^7$, respectively, in order to simulate the experimental W density profiles at the selected time range. The corresponding modification of the tungsten transport coefficients are shown in Fig. 7 for perturbations applied at the 3/2 mode location $\rho_{\text{norm}}=0.49$ at 47.4s just after the onset time. The convective term is taken negative in order to describe the inward tungsten accumulation.

![Graph showing W transport coefficients](image)

**FIG. 7.** W transport diffusion in m$^2$/s (left) and convective in m/s coefficients (right) at 49.4s at 3/2 mode location.

In Fig. 8 the single contribution of the 4/3 mode to the W density profiles is shown at times between 46.4s and 47s when a change in the W density is seen (as previously discussed). In this case the Gaussian shape of the perturbation, having a width proportional to the mode size, changes in time producing different peaks at the same radial location. In this figure the Y-axis has the same limits as in Fig. 4 for comparison.
FIG. 8. Contribution to the W density profile of the 4/3 mode from 46.4s until 47.s. Traces with different colors indicate the changes of the NTM effect depending on the Gaussian perturbation modifications proportional to the mode width.

In Fig. 9 we show the contribution to W density from both the 4/3 and 3/2 mode at the 3/2 mode onset. These effects on the W density profile are similar to the ones provided from the experimental measurements (Fig. 4).

The results show that for a transport diffusion modification with a Gaussian perturbation shaped with a width = 2 w_sat the extrapolated experimental data can be described without effect on plasma core. Both the effects from the 2 modes are present at the 3/2 onset time.

3.2. Linear analysis

A stability analysis of the previously shown discharges has been carried out with the MARS [11] code as well. MARS is a full, toroidal code, which solves the resistive, linear MHD equations. The equations are written as a complex eigenvalue problem in the flux coordinate (s, \( \chi \), \( \phi \)) system, where the perturbed variables are expanded using the Fourier series in the generalized poloidal (\( \chi \)) and toroidal (\( \phi \)) angles; s is the flux like coordinate, proportional to the square root of the poloidal magnetic flux.

The equations are discretized in the flux like coordinate using a generalized finite element method (FEM). The equilibrium fields and metrics quantities are supplied to MARS by a high-resolution equilibrium code (e.g., CHEASE [15]).

As an output MARS provides the complex eigenvalue \( \lambda = \gamma - i \omega \), where \( \gamma \) is the growth rate of the mode and \( \omega \) is
the real frequency, and the eigenvector, i.e., the perturbed magnetic field, current, pressure and plasma velocity.

The MARS code, as well as CHEASE, is fully compliant with the EUROfusion Integrated Modelling (EU-IM) environment [16] and, recently, it has been adapted to the IMAS framework as well [17]. The stability analysis using MARS has been carried out using the Equilibrium & MHD Stability Workflow, EQSTABIL workflow [12] developed within the Code Development for Integrated Modelling EUROfusion Work Package (WPCD) and available either using EU-IM or IMAS environments data objects. This workflow reads the CPOs [16] database and if required, refines the input equilibrium with a higher spatial resolution mesh, eventually packed where desired (e.g., around the magnetic rational surfaces).

The stability of three different discharges (#84812, #90279, #90339) has been analysed by selecting few time snapshots for each of them in order to cover the experimental onset of the (m,n)=(3,2) mode. The #84812 exhibits, experimentally, a (3,2) mode clearly triggered by a previous sawtooth, and, as shown in figure 1, the linear stability criterion \( r_\Delta \Delta_0' < 0 \) is always satisfied; in fact, MARS analysis (which includes pressure, toroidal shape and field line curvature as stabilizing effects on the tearing mode) confirms that the (3,2) mode is linearly stable. Both shots #90279 and #90339 are neon-seeded discharges; the first one is showing the spontaneous occurrence of the (3,2) mode while the latter being sawtooth triggered. Also for these two shots MARS does not observe any unstable (3,2) mode, meaning that the tearing is neoclassical with \( r_\Delta \Delta_0 < 0 \).

In order to illustrate the use of the stability code MARS, in Fig. 10 we present the stability analysis for a specific time snapshot of the discharge #90279, namely \( t = 46.15s \). The dependence of the growth-rate \( \gamma \) on the resistivity \( \eta \) is shown in the left frame, whereas the Fourier components of the perturbed magnetic field, for \( \eta = 5 \times 10^{-6} \), are depicted in the right frame. Above a certain value of the resistivity \( \eta \), two purely growing modes exist, whereas decreasing the resistivity, the solutions in the \( \gamma \) plane first merge in a single curve, becoming two complex conjugate solutions \( \lambda_1 = \gamma - i\omega \) and \( \lambda_2 = \gamma + i\omega \), and then eventually become stable [18]. This behavior was predicted analytically by Glasser, Greene and Johnson [19], who demonstrated that the tearing mode is stabilized by favourable average curvature, when \( \beta \) is large and \( \eta \) is sufficiently small. Note that the resistivity, as calculated for this particular time snapshot of the considered discharge, is \( \eta = 10^{-8} \), thus, well below the numerically observed stability threshold. Note that the main components of the perturbed radial magnetic fields are the 3/2 and 4/2 ones (see Fig. 10b).
4. CONCLUSIONS

The stability of JET hybrid scenarios has been investigated in the framework of the JET1 task on MHD analysis. A linear analysis has been carried out with the aim to classify the tearing modes in the selected JET discharges as classical or neoclassical in terms of positive or negative stability parameter $\Delta_0'$, using the full MHD, toroidal code MARS. The results classifying the modes as neoclassical were in agreement with the ones obtained from other codes.

The non linear analysis was focused on the role of the NTMs on the tungsten accumulation towards the plasma center. For this study the NTM module in ETS code has been used for the modification of the W transport coefficients. The interplay between NTM and W dynamics has been investigated considering in ETS a Bohm-gyro-Bohm model allowing to change the diffusion coefficients only at the NTM onset time. In this way the discrete effect coming from the NTM has been quantified and compared with experimental data. The analysis has shown that the on-axis W concentration is not sensitive to the presence of tearing modes with small sizes, even if they can provide changes of the W density profile at given off-axis positions. This conclusion is in agreement with the results shown in [2], because in this reference the amplitudes of the modes were larger and capable to produce a larger perturbation of the W transport coefficients with effects on the plasma core.

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