NTM threshold island width measurements on Globus-M based on the Fitzpatrick heat transport model

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Abstract. We estimate the neoclassical tearing mode (NTM) threshold island width, $W_c$, associated with the bootstrap current contribution to the time evolution of the magnetic island. Following the original work by Fitzpatrick, we solve the heat transport equation for the electron temperature distribution with $W_c$ being the input parameter. The obtained model temperature profile is then fitted to the Globus-M Thomson scattering (TS) data to deduce the actual $W_c$ value. Due to the relatively low resolution of the Globus-M TS in the island region, we have also adopted ASTRA to provide the benchmarking.

1. Introduction

The neoclassical tearing mode is one of the most dangerous tokamak MHD instabilities associated with plasma resistivity and accompanied by the formation of magnetic islands. It is observed when two limits are exceeded simultaneously: $\beta_p > \beta_{p,c}$ and $W > W_c$, where $\beta_p$ is poloidal beta, $\beta_{p,c}$ is its critical value and $W$ is the magnetic island width (see Figure 1). Thus, NTMs usually require a seed island of finite width [1] that can be provided by sawteeth [2, 3, 4], fishbones [5] or edge localised modes [2]. However, modes at $q = 2/1, 3/2$ rational surfaces, commonly observed on Globus-M, are excited without any preceding MHD activity. The sawtooth oscillations even suppressed NTMs in a number of the Globus-M discharges, e.g. shots 5922, 5926, 5946. $\beta_{p,c}$ and $W_c$ can be estimated from the modified Rutherford equation (MRE) [6] used to describe the island width as a function of time. However, this theory is well defined only in a limit of large island widths and is still under development for $W$ comparable to the width of the ion banana orbit, $\rho_{bi}$. On Globus-M, $\beta_{p,c} \approx (0.25 - 0.30)$ based on

![Figure 1. Magnetic island structure in the (r,ξ) plane. r is the tokamak minor radius, ξ is the helical angle, rs denotes a position of the rational surface. W is the magnetic island width. White dashed line corresponds to the island separatrix, i.e. the last closed magnetic flux surface.](image-url)
previous experimental observations. In Figure 2, NTM MHD activity (2/1 NTM) starts from $\sim 146$ msec, when $\beta_p = 0.25$. At $\sim 175$ msec, the NTM island stops rotating, leading to the discharge termination that can be seen as a current spike at $\sim 188$ msec.

NTMs set a soft beta limit in a tokamak reducing the fusion power output. In some cases, they can lead to plasma disruptions creating thermal quench energy losses and generating in-vessel halo currents and eddy currents in the vicinity of the plasma facing components during the current quench phase. In the ITER high-gain regime 70% of the initial plasma current is expected to be converted into the disruption-generated runaway current [6]. Two main NTM stabilisation technique are considered: LHCD (lower hybrid current drive) and ECCD (electron cyclotron current drive). The idea of LHCD is in reducing the classical tearing mode stability index, $\Delta'$, by modifying the plasma current density profile. While ECCD being more localised in the radial direction is to be applied directly to the island O-point to restore the bootstrap current, provided $\Delta'$ is already negative. The NTM theory for $W \lesssim W_c$ is required to improve the predictions for ITER and future tokamak machines.

2. Fitzpatrick’s heat transport model

The NTM enhances the parallel particle and heat transport from one side of the island to the other one. This results in flattening of the temperature profile across the magnetic island and hence leads to the bootstrap current reduction around the O-point. Following [7], we write the heat transport equation as

$$\chi_{\parallel} \nabla_{\parallel}^2 T + \chi_{\perp} \nabla_{\perp}^2 T = 0$$  \hspace{1cm} (1)

in the absence of heat sources and sinks (similar transport models have been considered by [8]-[11]). $T$ is the plasma temperature in the single fluid model. $\chi_{\parallel}$ and $\chi_{\perp}$ are the parallel and perpendicular components of the thermal conductivity tensor. The $\nabla$ components across and along the magnetic field lines are taken as in [7, 12]: $\nabla_{\perp} = (2/W) \partial / \partial x$ and $\nabla_{\parallel} = (B \cdot \nabla) / B$ is given by Equation (13) of [12], respectively, with $x$ being the poloidal flux centered around the rational surface and normalised to the island half-width, $W/2$. Then Equation (1) can be rewritten as

$$\left[ \frac{x}{x} \frac{\partial}{\partial x} + \frac{\sin \xi}{4} \frac{\partial}{\partial \xi} \right]^2 T + \frac{W_c^4}{W^4} \frac{\partial^2 T}{\partial x^2} = 0$$  \hspace{1cm} (2)

in accordance with Equation (24) of [7]. $W_c$ estimated from Equation (1) is proportional to $(\chi_{\perp} / \chi_{\parallel})^{1/4}$ and hence depends on a choice of the $\chi_{\perp}$ model. In a set of discharges we consider, plasma temperature is around $\sim (400 - 600)$ eV, while electron density reaches $\sim 10^{20}$ m$^{-3}$ and thus the choice of the heat transport model is justified. In a low collisionality plasma though, Equation (1) should be replaced by the kinetic equation solved simultaneously for the electron/ion plasma component. In the earlier work on ASDEX-Upgrade [8], a correction factor for the parallel thermal conductivity has been introduced to allow the electron mean free path, $\lambda_{mfp,e}$, being larger than the connection length, $L_c$. Equation (1) is valid provided $\lambda_{mfp,e} \lesssim L_T$, where $L_T = |\nabla T / T|^{-1}$. Across the magnetic field, $\lambda_{mfp,e} \sim \rho_{e,c}$ and $L_T \sim a$, and hence the
condition is still valid ($\rho_{c,e}$ is the electron Larmor radius and $a$ is the tokamak minor radius at the plasma edge). Along the field lines, $L_T \sim L_c \ll \lambda_{mfp,e}$ in a low collisionality plasma. Thus, the results for $W_c$ we obtain in this work are limited by the hydrodynamic regime requirements. $W_c$ is the input parameter in the simulation and hence does not require any certain approximations for thermal conductivity.

Equation (2) to be solved for $T = T(x, \xi)$ is a linear homogeneous second order differential equation in $\{x, \xi\}$ space. Hence, it allows the solution to be found by the integral transform. We multiply both sides of Equation (2) by $K = K(p, \xi)$, where $K$ is its kernel and integrate over $\xi$: $-\pi \leq \xi \leq \pi$. This reduces the dimension of the problem from 2D to 1D. Implying periodicity in $\xi$, we infer that $K$ is to be chosen in a class of trigonometric sine/cosine functions. Therefore, we solve

$$\alpha(p) \frac{\partial^2 U}{\partial x^2} + \beta(p) \frac{\partial U}{\partial x} + \gamma(p) U = 0$$

for each $p$ in $p$ space. Here $U$ is defined as $U(x, p) = \int_{-\pi}^{\pi} T(x, \xi) K(p, \xi) d\xi$. Following [7, 10], the boundary conditions are obtained by considering analytic limits of this equation (the limit of small/large islands, $W \ll W_c / W \gg W_c$, $T$ can be found in [7]). To go back to real space, we apply $T(x, \xi) = \int_{\mathbb{R}} U(x, p) K^+(p, \xi) dp$ with $\int_{\mathbb{R}} K(p, \xi) K^+(p', \xi) = ||K||^2 \delta_{pp'}$, $\delta_{pp'}$ is the Kronecker delta. We solve Equation (2) for arbitrary $W_c$. Then we compare the corresponding solution for $T = T(x)$ with the TS data/ASTRA [13] results. $W_c$ is to be varied until the matching is achieved. For the Globus-M parameters, $W_c$ has been found to be around 1cm. However, we have to stress the uncertainty of this approach for the magnetic island threshold width calculations is large due to a low resolution of TS on Globus-M. So the vicinity of the magnetic island cannot be fully captured.

The calculated $W_c$ is then has been used as the input to solve the modified Rutherford equation for $W$ vs. $t$. $W = W(t)$ has been compared with the time dependence of the island

![Figure 3](image3.png)  
**Figure 3.** Shot 5926. $W = W(t)$. Dashed purple line represents the MRE solution. Blue line represents time evolution reconstructed from the magnetic coil signal.

![Figure 4](image4.png)  
**Figure 4.** Shot 26148. $W = W(t)$. Purple solid line represents the MRE solution. Blue line represents time evolution reconstructed from the magnetic coil signal.

width reconstructed from the magnetic field perturbation at the plasma edge measured by the Mirnov coil system [14]. They have been found to be in relatively good agreement (see Figure 3 and Figure 4). The technique described above is also to be applied to Globus-M2 with upgraded TS diagnostic.
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