THE ITER ECRH UPPER LAUNCHER – PHYSICS GOALS AND DESIGN REQUIREMENTS

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The Upper Launcher of the ITER ECRH system is analyzed with respect to its capability of stabilizing (3,2) and (2,1) NTMs. A range of equilibria is considered to cope with the expected experimental variation. Interaction between physics analysis and design has led to an optimized design for the presently foreseen system option (24 MW launched through three upper ports in 24 waveguides). It is found that this system is marginal with respect to the task of full stabilization, but several ways to improve the performance exist.

Introduction

Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD) is one of the auxiliary heating systems foreseen for ITER. The present design foresees 20 MW at 170 GHz, to be launched from two different positions. One of these positions is the so-called ‘upper launcher’, i.e. a series of ports located in the upper part of the vessel. The launch from this location has been mainly dedicated to the control of Neoclassical Tearing Modes (NTMs), which can be avoided or suppressed (or at least appreciably reduced in size) by local ECCD. The present reference design of the upper launcher uses 3 ports at the same poloidal location, separated by 20^o and 40^o toroidally, thus covering a toroidal range of 60^o. An option exists to use another port, 20^o away. Through each port, 8 beams of 170 GHz radiation are injected in an arrangement of two horizontal rows with 4 beams each. Fig. 1 shows the present reference design [1]. It is the aim of this paper to analyze the performance of this configuration and point out ways to improve it.

Design Requirements arising from the Physics Objectives

The task of stabilizing NTMs leads to a number of requirements on the design. One of them is good localization of the deposition: Two physics effects contribute to NTM stabilization, namely the change in equilibrium current density and the generation of a helical current within the island. The stabilizing effect of the equilibrium current modification can be expressed as a modification of the stability index Δ’, which is related to the gradient in the equilibrium current density. The figure of merit is therefore the number I_{ECCD}/d^2, where d is the width of the driven current and I_{ECCD} the total amount of driven current. For the generation of helical current, only the current driven within the island counts. This is independent of d for d < W, where W is the island width, but scales as I_{ECCD}/d for d > W. Thus, although no unique criterion can be given, good localization is clearly needed for complete suppression. The need for accurate deposition at resonance surfaces means that feedback control must be used to ensure correct deposition. Here, the time scale of interest is the resistive growth time of magnetic islands. In ITER, this is expected to be of the order of 10-20 seconds. On this time scale, the launching mirrors will have to be moved.

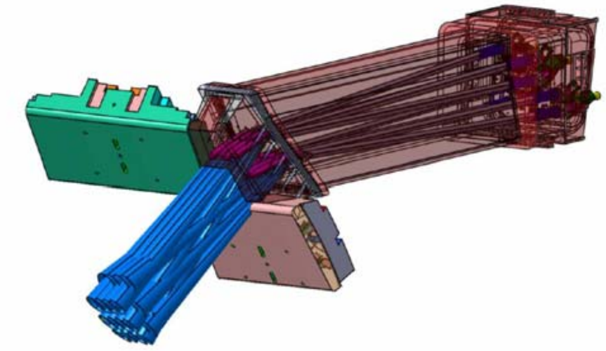

Fig. 1: Overview of the present reference design of the upper launcher.

NTM stabilization down to island widths smaller than the width of the ECCD driven current is difficult with continuous injection, and modulation of the ECCD in phase with the island O-point will be required to generate a helical current within the island. There is, however, an element of uncertainty concerning the locking of NTMs with respect to the vacuum vessel, which is expected to happen frequently in ITER. In this case, ECCD can be on all the time and the efficiency of generating a helical current is greatly enhanced (factor of 2.3 with respect to the modulated scheme at 50% duty cycle and a rotating mode), but a method to position the island with respect to the launcher, e.g. by using the ITER error field correction coils, is needed. For a toroidal spread of the deposition of 80^o (as would be the case if all 4 ports of the upper launcher were to be used to inject into an n=1 mode), the efficiency of generating helical current would roughly be a factor of 2 higher than with modulated ECCD at 50% duty cycle and a rotating mode. Even for 160^o spread (i.e. 4 launchers and n=2), a gain of 1.8 is found, so that from that point of view, locked modes would even be a favorable target.

Concerning the magnitude of the driven current, considerable uncertainty exists, depending on the model assumptions in NTM theory. A simple estimate compares the driven current density with that of the equilibrium bootstrap current density. Then, according to [2], about 1.2-1.6 times the bootstrap current density has to be driven by ECCD to completely stabilize the NTM. We note that schemes with partial stabilization (reduction to small but finite island width) can result in greatly reduced power requirements, but will require the ECCD to be on all the time, so that this becomes an issue of reduced Q (it is thought after complete suppression, ECCD at the resonant surface is not needed continuously). Also, the ECRH power is then not available for other applications, such as central heating.

Methodology for Performance Evaluation

The performance has been evaluated by calculating the profile of driven current at the q=1.5 and q=2 surfaces with a set of benchmarked codes, namely ECWGB [3] and TORBEAM [4], both beam tracing codes with an analytical absorption and current drive model and BANDIT-3D [5], a ray tracing code with a Fokker-Planck description of absorption and current drive. The results generally agree very well between ECWGB and TORBEAM, with BANDIT-3D usually giving somewhat (10-20 %) higher values for the driven current.

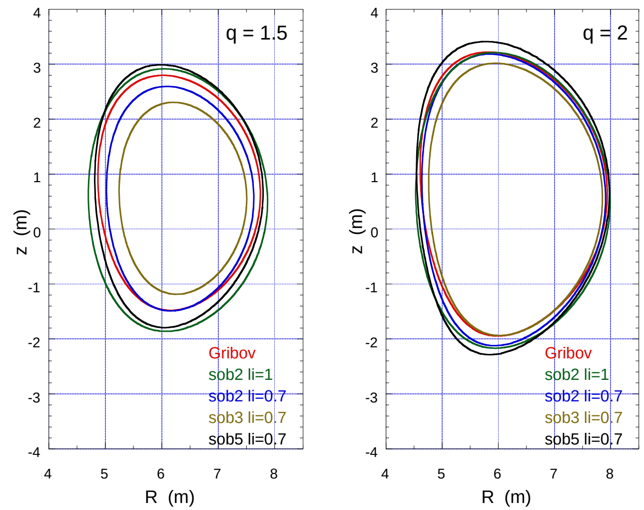

Fig. 2: Overview of positions of rational surfaces obtained in the equilibrium variation.

In order to cope with the possible variation of the location of the resonant surfaces in ITER, a series of equilibria was generated around scenario 2 (15 MA, 5.3 T, Q=10 with 400 MW of fusion power). The current profile was varied (variation of the internal inductance l_i between 0.7 and 1.0, where the reference case had l_i=0.76) leading to a variation of the location of resonant surfaces between ρ_p = 0.7 (q=1.5 at lowest l_i) and ρ_p=0.93 (q=2 at highest l_i). In addition, scenario 3 (hybrid operation at reduced I_p = 13.8 MA) and scenario 5 (low q operation at increased I_p = 17 MA) were also studied.

Fig. 2 gives an overview of the variation of the resonant surface locations (from [6]). For all cases, we determine the driven current density profile on the two rational surfaces for a range of toroidal injection angles (typically 15^o < β < 25^o). The optimum launch angle is then the one which maximizes I_{ECCD}/d or I_{ECCD}/d^2 (typically, both numbers peak at approximately the same β). This maximum occurs because both I_{ECCD} and d increase with β, but d increases stronger than linear and I_{ECCD} weaker than linear. The analysis then also determines the required steering range in poloidal launch angle α for this optimum β.

Performance of the Reference Design

A reference design with steering range ±8^o at the front mirror has been established by the design team [1]. The performance analysis is described in detail in a companion paper [6]. Here, we only summarize the main outcome of the study. It is found that for all cases considered, the optimum β for the lower row is around 18^o–20^o for q=1.5 and around β = 20^o-22^o for q=2 for both figures of merit I_{ECCD}/d and I_{ECCD}/d^2. Thus, launch at a fixed β of 20^o is possible, reducing the steering requirement to only one (poloidal) direction. For the upper rows, the same is true, but the optimum β is 18^o. The steering range requirements for reaching both surfaces with all beams in all scenarii are ±8^o for the upper and ±10.5^o for the lower row [6]. This is marginally beyond the capability of the present reference design, which allows for ±8^o at the front mirror. In principle, the steering range can still be increased, but at the expense of a less focused beam, since the possible focusing is determined by the size of the last mirror, which in turn is limited by the port size.

Fig. 3 shows a comparison of the driven current density using the present reference design (i.e. ±8^o at the front mirror) assuming 10 MW launched from the lower row and 10 MW from the upper row (the linear addition has been justified by Fokker-Planck calculations, showing no nonlinearities at these power densities [7]). This distinction is important because although the upper row drives nearly the same amount of current than the lower one, the profile of the driven current is wider, leading to a reduction of the current density. It can be seen that the bootstrap current density is only marginally exceeded for q=1.5, in some cases it is actually not reached. For q=2, the situation is somewhat better (note that the present design has put more emphasis on q=2 because the (2,1) NTM is believed to be the most detrimental NTM in ITER). However, given the uncertainties connected with NTM theory, the situation is still not satisfactory. Given the fact that Fig. 3 describes the situation with ±8° steering angle at the front mirror, it can clearly be seen that the present solution with ±10.5° steering range and therefore reduced current density is hardly an acceptable option.

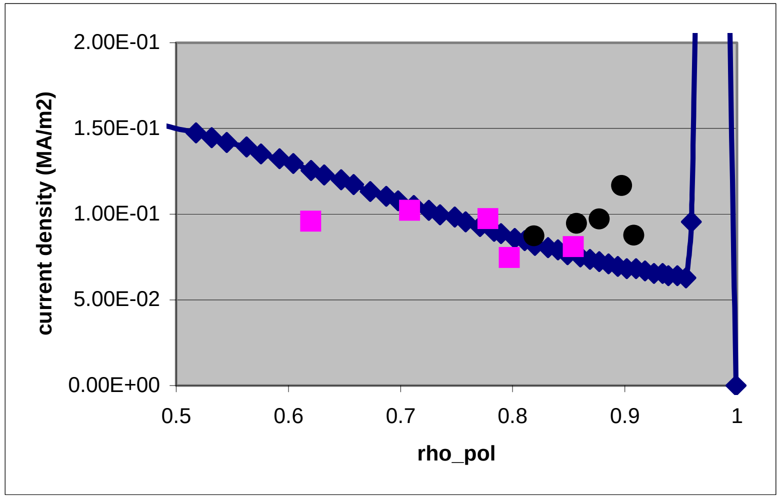

Fig. 3: Driven current (10MW injected through the upper row, 10 MW through the lower row) for several equilibria under consideration (boxes: q = 1.5, bullets: q = 2). Also, the bootstrap current density for scenario 2 (standard case, l_i = 0.76, diamonds) is shown.

Discussion and Outlook

In this paper, the performance of the upper launcher of the ITER ECRH system has been analyzed with respect to NTM stabilization. A poloidal steering range of 21° is found to be necessary to cope with the expected variation of the q=1.5 and q=2 surfaces in scenario 2, 3 and 5. In the present approach with remote steering and 2 x 4 beams per port, this large steering range leads to an insufficient beam focusing to guarantee complete stabilization of (3,2) and (2,1) NTMs. An increase in ECCD power to compensate this lack is not desirable since it has a negative impact on Q. Several other ways to improve the performance of this system have been suggested:

- By use of the fourth available upper port and assuming 1.5 MW per line (which is not at the limit of the transmission components, but asks for 1.5 MW sources), dedicated launchers (2 aiming at q=2 and 2 aiming at q=1.5) or dedicated rows (e.g. upper rows aiming at q=2 and lower rows aiming at q=1.5) can be realized. The advantage is a reduction in steering requirement, which in turn can lead to increased focusing and thus higher driven current density. This is an attractive solution, because it does not require any change in the ITER machine design. It will be analyzed in the near future by the EU design team.
- The use of front steering in the upper launcher may also provide a reduced spot size and thus increased current density, without changing the ITER machine design. Studies are under way to evaluate this option.
- Higher frequency would enhance the current drive efficiency with still good access to the resonant surfaces [8]. However, this is in conflict with the physics objectives for the midplane system, where higher frequency will reduce the radial range accessible with this system. A way out could be the use of multi-frequency gyrotrons, with 170 GHz used in the midplane system and a higher frequency used in the upper launcher (note that with remote steering, the upper launcher can only be used at one frequency which fulfills the Talbot condition). However, the corresponding gyrotron does not yet exist.
- Relocation of the upper launcher to a somewhat lower location would also be beneficial [8], because absorption is most localized when the beam reaches the resonant surface tangentially. Thus, a position of the launcher at a height somewhere in between the upper tip of q=1.5 and q=2 would be best suited. However, this represents a major change in the ITER machine design and therefore has to be carefully evaluated.

Thus, several promising options exist to improve the present design of the upper launcher. Future detailed analysis in close collaboration between design and physics groups is needed to point out the benefits and drawbacks of these options to arrive at a final design for the upper launcher.

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