THE CONCEPT OF ECRH/ECCD FOR ITER

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The Electron Cyclotron Heating and Current Drive system for ITER is described. Its physics objectives are central heating and current drive as well as localized off-axis current drive for MHD stability control. The performance of the present system design, consisting of 20 MW of ECRH power at 170 GHz launched into the plasma, is evaluated with respect to these objectives. While central plasma heating and current drive are well feasible with the present system with some minor changes, instability control through the upper launcher seems marginal, but room for improvement exists.

Introduction

Electron Cyclotron Resonance Heating and Current Drive (ECRH/ECCD) is one of the auxiliary heating systems foreseen for ITER. Due to its very localized deposition and its flexible steering, ECRH/ECCD is especially suited for control applications where localized heating or current drive with precise positioning is required, such as control of the q-profile or local current drive to suppress or control MHD instabilities. In this paper, first the present design, consisting of 20 MW at 170 GHz that can be launched from two different positions, is reviewed. Then, the physics objectives for the system are discussed and its performance is analyzed with respect to these objectives. Finally, the results are summarized and possible options for improvement are discussed.

Layout of the Present System Design

The present design incorporates an installed source power of 24 MW (1 MW gyrotrons) resulting in 20 MW delivered to the plasma. The frequency is 170 GHz, which has previously been found as an acceptable compromise between higher frequency resulting at higher current drive efficiency and lower frequency widening the operational space at lower toroidal field [1]. It is presently planned to inject the power from either a midplane position or from the so-called top launcher. A sketch of these two positions is given in Fig. 1.

The midplane system combines three mirrors that collect 9 individual beams in one equatorial port, so that a maximum of 27 beams can be transferred to the plasma [2]. The centers of the three mirrors are separated by 59 cm each and the lowest injects in the vessel midplane. All three inject with fixed zero poloidal injection angle. Thus, the present working design is not optimized to achieve the smallest spot size in the plasma, but this optimization is straightforward and will lead to small poloidal tilts of two of the three mirrors. The toroidal injection angle can be varied between 20^o and 45^o, by steering the launch mirror (‘front steering’), to allow for a variation in deposition radius.

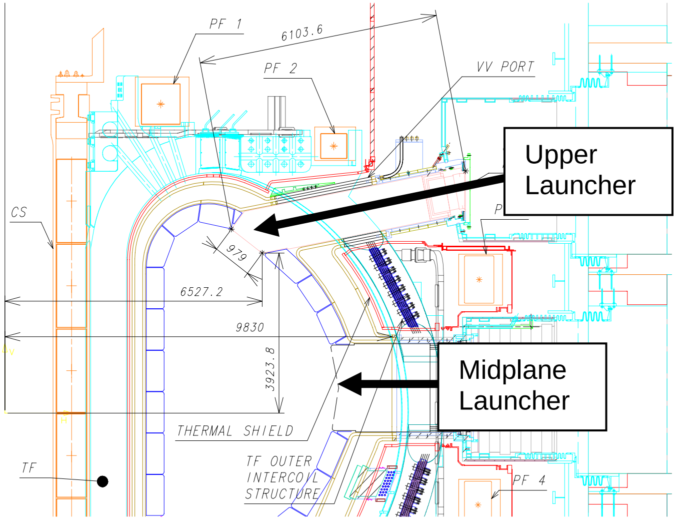

Fig. 1: Sketch of the two ECRH launch positions foreseen for ITER. The upper launcher consists of three (optionally four ports), the midplane system uses one port.

The present reference design for the upper launcher consists of three ports (sector 12, 13 and 15) through which 8 beams per port are launched in two horizontal rows of 4 beams each, allowing for 24 beams to be launched in total [3]. These ports are at same poloidal location, but separated toroidally by 20^o and 40^o (so that they span a total of 60^o toroidally). A fourth port (sector 16) another 20^o away has been reserved for ECRH as well. The upper launcher has a fixed toroidal steering angle of 20^o and, in the reference design, allows for a variation in poloidal angle of ±8^o at the front mirror. Here, steering is at present realized through ‘remote steering’, i.e. a moveable mirror at the final waveguide entrance. This waveguide then has an imaging property that produces a mirror image at its end if the condition for the Talbot-effect is fulfilled. Thus, both systems need only one steering axis, a fact that makes the mechanical design much simpler. Details of both launchers are shown in Fig. 2.

For both systems, the designers have to face trade-offs between reaching the physics objectives, which usually means largest steering range, and the harsh boundary conditions of the environment, which require minimum openings in the front shield to minimize heat and neutron fluxes. In addition, narrow focusing in the plasma to achieve localized deposition translates into relatively large beam radius at the launching structures, which in turn lead to problems concerning port space and openings. Therefore, a close interaction between physics and engineering is needed to optimize these launchers.

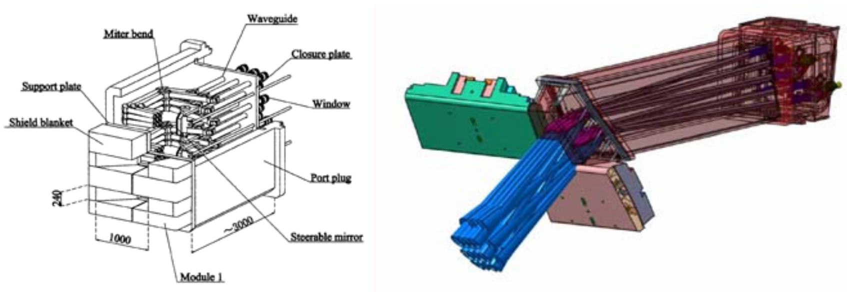

Fig. 2: Details of the present design of the midplane launcher (left) and the upper launcher (right).

Physics Objectives of ECRH/ECCD in ITER

The main tasks of any auxiliary heating system foreseen for ITER are central heating to ignition and a certain current drive capability to assist the development of long pulse/steady state scenarii [4]. For the ECRH/ECCD system, an additional task is the generation of localized current for MHD stability control. This can either be the sawtooth / fishbone instability located at q=1 or the Neoclassical Tearing Mode (NTM), which is expected to be especially harmful at q=1.5 and q=2 [5]. In addition, classical, current gradient driven tearing modes at the q=2 surface which are usually associated with disruptions are also a target for the ECRH/ECCD system.

From these requirements, it immediately follows that all minor radii should be accessible for a wide range of scenarii. If one takes into account the full variation of magnetic field possible, this is a very demanding task for an ECRH/ECCD system. However, since the primary objective of ITER is to achieve Q=10, this scenario (so-called scenario 2, with 15 MA, 5.3 T and a large plasma volume of 831 m^3) has been chosen as reference for the design. In the work described here, we have to some extent also varied the current profiles in scenario 2 in order to cover a variation of the position of the resonant surfaces. Also, scenario 3 (hybrid operation at reduced current 13.8 MA) and scenario 5 (low q operation at higher current 17 MA) were considered.

The requirements on the driven current for central ECRH/ECCD in the standard scenario or for off-axis ECRH/ECCD for advanced tokamak operation have not been clearly defined so far. We note that present scenarii for Q=5 steady state do call for off-axis CD at r~0.75, but mainly assume that this job is done by NBCD and LHCD, whereas only a small amount of central ECCD is used here. Thus, a possible contribution of ECCD at r~0.75 could be of importance for these scenarii.

For MHD instability control, narrow deposition is usually needed because for linear stability, the current gradient rather than the total current counts and for nonlinear stability, e.g. in the presence of a magnetic island, only helical current, i.e. current driven within the island counts. For NTMs, that are due to a helical hole in the bootstrap current distribution, it is a convenient zeroth order argument to postulate that the ECCD current density exceeds the equilibrium bootstrap current density.

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.

Finally, 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. Present predictions of the (3,2) NTM frequency range from 2-5 kHz, suggesting that this modulation frequency may be required. For the q=2 surface, this is typically much lower due to the location further outward and the lower toroidal mode number. 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 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 is needed. It is thought that this can be done by using the ITER error field correction coils. 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), the efficiency of generating a 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 favorable.

Midplane Launcher Performance

An analysis of the midplane launcher has been done using the TORBEAM code. The combination of 8 beams on one mirror has, for simplicity, been modeled by one beam with a similar spot size to the combination in the plasma region. Further analysis should consider the individual beams in detail. For each of the 3 mirrors, the toroidal injection angle was then varied to determine the deposition range. The result is shown in Fig. 3.

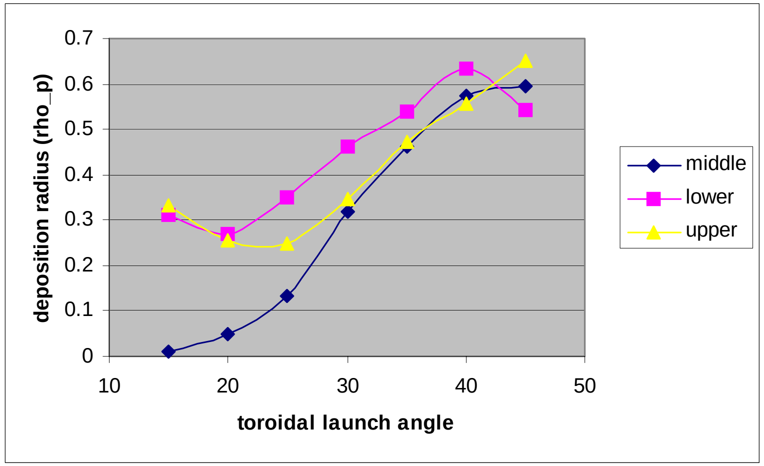

Fig. 3: Deposition radius versus toroidal launch angle for the three mirrors of the midplane launcher.

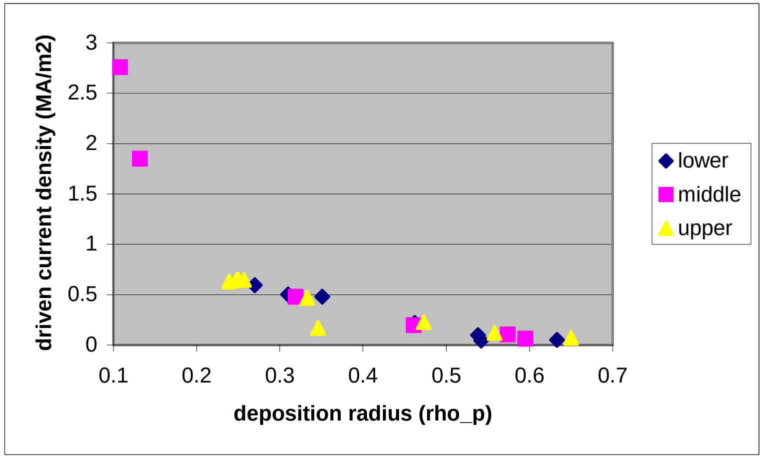

Fig. 4: Maximum of the driven current density as function of deposition radius for the three mirrors of the midplane launcher.

It can be seen that within the chosen range of 20^o to 45^o, the deposition ranges from the center out to approximately ρ_p = 0.6 for the middle mirror. For the upper and lower mirrors, the center is not quite reached, due to the fact that injection is strictly horizontal and the beams do not go through the plasma center, but this could easily be changed by a slight poloidal tilt of these mirrors. Although the upper and lower mirrors allow deposition slightly above ρ_p=0.6, this value represents the practical limitation, because the beams touch the resonance more or less tangentially and propagate outward from there on. In fact, absorption is no longer 100% for the outermost point of the upper and lower launcher. Thus, an increase in radial region can not simply be cured by increasing the toroidal steering range to larger angles. Here, an alternative may be to change to poloidal steering, which may provide a larger radial range.

Fig. 4 shows the maximum of the driven current density as function of the deposition radius. Significant central current drive is obtained with this system. The total driven current is around 25 kA per MW launched, i.e. may amount to roughly 500 kA for 20 MW. Thus, the driven current represents a significant fraction of the central total current and may have an important influence on the central q-profile and also the sawtooth instability. In addition, around ρ_p=0.5, the ECCD current density can be 0.1-0.2 MA/m^2 for 20 MW, compared to 1 MA/m^2 equilibrium current density. Such a current can still influence the sawtooth instability, but the local current density could still be increased by an increase in beam focusing.

Upper Launcher Performance

Performance of the upper launcher has been studied in detail by an EU initiative under the EFDA technology program [6] [7]. Close interaction between design team and physics analysis has led to an iterative process in which, through several steps, the upper launcher solution with 3 ports and 2x4 horizontal rows per launcher was optimized to give sufficient steering range and maximum localized current density. For the steering requirements, a set of equilibria was used to cover a range of situations. For scenario 2 (Q=10), the current profile was varied ($0.7 < l_i < 1.0$) to give a considerable variation of the position of q=1.5 ($0.7 < \rho_p < 0.87$) and q=2 ($0.87 < \rho_p < 0.93$). In addition, scenario 3 (hybrid) and scenario 5 (low q) were also analyzed.

For each case, the toroidal injection angle β was varied in the range 15^o-25^o and for each β, the poloidal steering angle α was then adjusted to obtain deposition on the q=1.5 or the q=2 surface. Both driven current and deposition width increase with β. However, for both surfaces and all scenarii, the driven current obtains a maximum within this range. This can be seen in Fig. 5 for the q=2 surface in different variants of scenario 2 using the lower row of the upper launcher. From similar plots for the q=1.5 surface, one can conclude that a fixed toroidal launch angle of β = 20^o provides deposition close to the optimum, requiring only poloidal steering. The requirements for the steering range can then be determined from the need to cover both surfaces for all scenarii mentioned above. This leads to a necessary steering range of 21^o (±10.5^o), i.e. partly in excess of the steering range of the present reference design (±8° 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 [3].

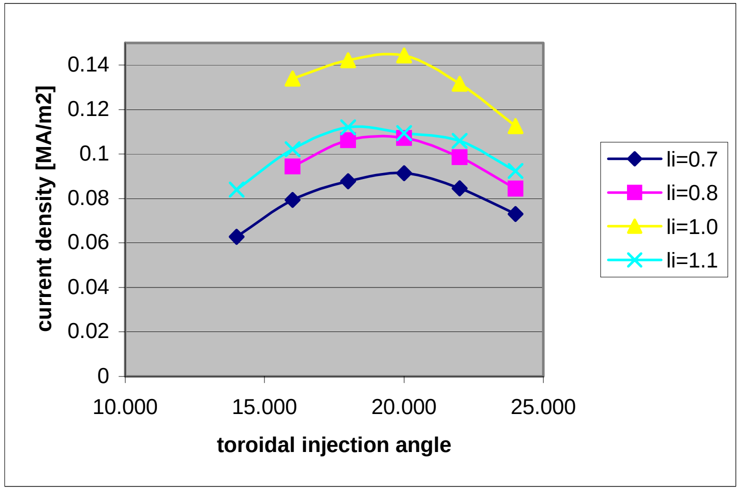

Fig. 5: Driven current density at the q = 2 surface for variations of the ITER scenario 2 (Q=10). This figure of merit for NTM stabilization obtains a maximum around β = 20 for all cases considered.

For the reference design with steering range ±8° at the front mirror, the driven current is shown in Fig. 6 together with the bootstrap current distribution of scenario 2. It can clearly be seen that the performance of this system is (sub)marginal for the q=1.5 surface, with somewhat better results for q=2. This reflects a design philosophy which puts more weight on optimizing CD at the q=2 surface, because the (2,1) NTM is expected to be the most detrimental NTM in ITER. However, Fig. 4 has been obtained by assuming that all beams are launched from the lower row of the upper launcher. Taking into account the split between lower and upper row leads to a decrease in driven current of the order of 10-15% in total [7] due to the steeper injection angle. Also, one has to keep in mind that the necessary increase in steering range will also decrease the driven current density. This, together with the present uncertainty about the NTM physics (stabilization criteria reach from 1.0 to 1.6 times the bootstrap current for full stabilization), leads to the conclusion that this system must still be improved in order to ensure that the physics goals can reliably be met.

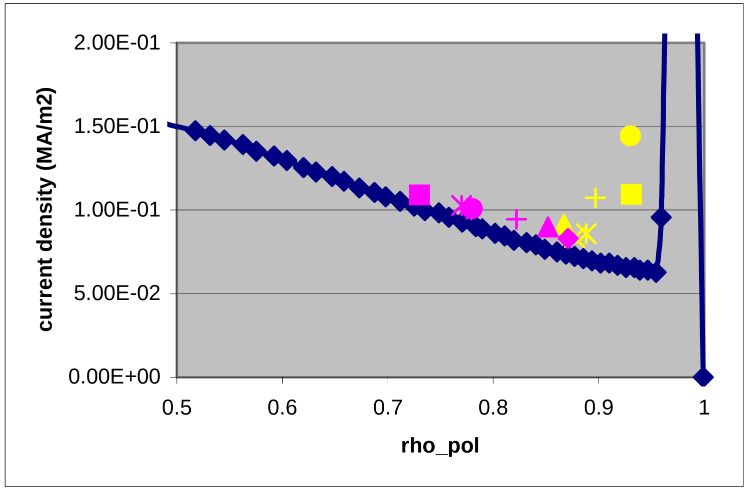

Fig. 6: Driven current density in ITER scenario 2 (Q=10) using the lower row of the upper launcher. Also shown is the bootstrap current density, which is exceeded only marginally for q=1.5 (points at ρ_p < 0.85). The situation is somewhat better for q=2 (points at ρ_p > 0.85).

Further analysis should also take into account the possibility of only partially stabilizing the NTM, which reduces the power requirements and leads to an optimization problem for Q. We note that modeling NTM stabilization with the use of the generalized Rutherford equation is more detailed than the criterion discussed above, but does at present not lead to significantly different answers [8]. A multi-machine scaling effort is presently under way, coordinated through the International Tokamak Physics Activity ITPA.

Discussion and Outlook

From the preceding analysis, it is clear significant heating and current drive can be obtained by the present ECRH/ECCD system foreseen for ITER. Central heating and current drive is provided by the midplane launcher for radii 0 < ρ_p < 0.6. This system is at present not optimized with respect to the small spot size in the plasma, since the three mirrors inject parallel beams, but a slight poloidal tilt is sufficient to obtain overlapping beams in the plasma center. While this is not crucial for central heating and current drive, it will offer significant advantage for sawtooth stabilization, so that the beams should actually be optimized to overlap there (i.e. around ρ_p = 0.5). From the modeling presented above, it is clear that sufficient current could be driven with such a system to influence sawteeth.

We also note that due to the relatively high frequency of the system (which is needed for good current drive efficiency), central deposition is only possible under oblique conditions, which inevitably drives some central co-current. This may be in conflict with several requirements for ITER operation, because it has recently been found that flat central q-profiles have significant advantages in optimizing the H-mode (e.g. all present hybrid scenarii are based on flat or elevated central shear) [9]. Here, a way out would be to foresee another, mirror imaged, toroidal steering range of –(20°-45°). With these two ranges, both co- and ctr-ECCD as well as pure ECRH (by injecting equal power in both directions) would be possible. We note that with the present front steering option, this should be feasible within the presently allocated port, but would require a significant design change (the range of –45° to 45° is impossible to cover with one single remote steering system). With these modifications, the midplane system is expected to meet all requirements for central heating and CD.

For the upper launcher, 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 [10]. 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 [10], 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 is needed to point out the benefits and drawbacks of these options to arrive at a final design for the upper launcher.

Finally, it is important to note that a final design of the system must also ensure that sufficient overlap in deposition exists between the midplane and the upper launcher systems. At present this is not the case, since the midplane launcher covers the range $0 < \rho_p < 0.6$ and the upper launcher the range $0.7 < \rho_p < 0.93$, so that a gap exists for $0.6 < \rho_p < 0.7$, which should be filled in. It is important to note that the region in which off-axis CD is needed for advanced scenario control is exactly in this range, so that further integrated design in this area should consider in detail the abilities to contribute to q-profile control in reversed shear scenarii. Further work should also analyze the capability of the system at reduced field, where a restriction of the accessible ρ-range is expected, but for fields around half the design value, second harmonic X-mode will become an attractive scheme as well.

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