The Front Steering Launcher Design for the ITER ECRH Upper Port

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Abstract. The ECRH ITER upper port antenna’s role is to stabilize the neoclassical tearing mode (NTM) on either the q=2 or 3/2 rational flux surfaces, which requires a narrow current deposition profile \(j_{\text{CD}}\) over a wide range along the resonance surfaces. The width of \(j_{\text{CD}}\) should be equivalent to the marginal island width to fully stabilise the NTM. Two antenna concepts are under consideration for the upper port launcher: front steering (FS) and remote steering (RS). The FS launcher decouples the steering and focusing aspects using a two mirror system (one focusing and one steering), achieving a wider steering range and higher current density for NTM stabilisation than required by ITER, offering a threefold increase in NTM stabilization efficiency over the RS launcher. The improved physics performance has motivated the further design study of the FS launcher aiming toward a build to print launcher. The present design is compatible with \(\geq 2.0\text{MW}\) CW operation and 8 beams per port plug. A frictionless backlash-free system is envisioned for the steering mechanism. An overview of the launcher design, the calculated physics performance and the possibility of using the upper port launcher for extended physics applications (beyond NTM stabilisation) are discussed.

1. Introduction

The purpose of the ITER electron cyclotron resonance heating (ECRH) upper port antenna (or launcher) will be to drive current (ECCD) locally inside the island which forms on the q=3/2 or 2 rational magnetic flux surfaces after the onset of the neoclassical tearing mode (NTM) \([1-4]\). In order to fully stabilize the NTMs, the launcher should be capable of steering the ECCD current deposition profile \(j_{\text{CD}}\) across the resonance surface over the range in which the q=3/2 and 2 surfaces are found, for the various plasma equilibrium susceptible to the onset of NTMs \([5]\), as shown in figure 1. Also, \(j_{\text{CD}}\) must be narrow relative to the marginal island width and its amplitude greater than that of the bootstrap current \(j_{\text{BS}}\) found outside the island in order to effectively stabilize the NTM \([6]\), as illustrated in figure 2. The ratio of these two currents, \(\max(j_{\text{CD}})/j_{\text{BS}}\), provides an NTM stabilisation

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figure of merit ($\eta_{NTM}$). The physics objective for the launcher is to achieve $\eta_{NTM}\geq 1.2$ for the various relevant plasma equilibria that are susceptible to NTMs (equilibria 2, 3a and 5) [5].

The European Fusion Development Agreement (EFDA) is currently in the process of developing two launcher designs in parallel: remote steering (RS) and front steering (FS) launchers. The RS concept [6] offers the advantage of not requiring moving parts within the vessel vacuum boundary (far from the thermal and nuclear radiation of the plasma). However, it has a limited angular range ($\leq \pm 12^\circ$) and projects a relatively broad beam spot size (>55mm) at the resonance surface [8]. By contrast, the FS launcher offers an extended angular range (up to $\pm 24^\circ$) and projects a much narrower spot size on the resonance surface [9,10], but requires a rotatable mirror near the plasma. EFDA’s strategy is to investigate the two launcher systems, comparing their physics performance, engineering reliability and costs, with the ultimate aim of providing the optimum launching system for the ITER upper port.

This paper will concentrate on the FS launcher design and its expected performance for NTM stabilization. First the overall launcher design is described in section 2. In section 3 the estimated NTM stabilization efficiency is given based on the beam tracing code ECWGB [11]. In section 4 the potential for extended physics applications using the FS launcher will be discussed followed by a conclusion in section 5.

2. FS launcher design
A simplified poloidal view of the FS launcher design is shown in figure 3. Eight circular waveguides enter at the port entrance on the right, with the waveguides arranged in two rows of four. Before the closure plate there is an in-line carbon vapor deposition (CVD) diamond window [12], which provides a tritium barrier preventing any tritium from penetrating into the evacuated waveguide transmission line and traveling up to the gyrotron. An in-line all-metal gate valve is placed on the plasma side of the CVD window (see figure 3). The gatevalve offers a secondary level of protection, which closes in case the CVD window leaks or is broken [13]. The gatevalve can be purchased with an auxiliary port installed on the gatevalve body, which provides pumping access to the inner vacuum region between
the valve and window. In addition, this auxiliary port on the gatevalve can be used to test the vacuum integrity of the CVD window by leaking helium into the auxiliary port and monitoring for helium in the transmission line’s in-line pumping station on the gyrotron side of the window. Both the window and gatevalve will be held rigidly to the port plug. The aluminum waveguide on the gyrotron side of the CVD window (not shown in figure 3) will bend (elastically) compensating for the displacement of the torus during thermal cycles or disruption events [13].

FIGURE 3. The FS launcher installed in the upper port plug.

The ITER transmission line (transmitting the RF power from the gyrotron to the launcher) uses evacuated HE_{11} corrugated waveguide with a nominal inner diameter of 63.5mm [14]. This is a standard size waveguide in use on existing ECH systems [15,16] and is compatible with 2.0MW transmitted power. However, this waveguide size requires a DN100 in-line gatevalve, which has a large actuator severely restricting the available space at the entrance to the port plug. A downtaper to 60mm HE_{11} waveguide (not shown in figure 2 or 3) is inserted just before the launcher, which offers the possibility to use a DN63 in-line gatevalve as planned for the ITER equatorial port FS launcher [17].

The waveguides proceed into the port plug for ~3.0m up to a mitre bend ‘dog-leg’ assembly. In addition to decreasing the neutron streaming rate in the waveguide, the mitre bend assembly is used to redirect and compress the 8 beams (both in the toroidal and poloidal directions) on to one single focusing mirror, with the incident beams partially overlapping in both directions. The reflected beams are then sent downward to two separate flat steering mirrors, which redirect the beams into the plasma with a toroidal injection angle of $\beta$~20°. The free volume in the port plug will be filled with shielding material, which absorbs the neutrons emitted from the burning plasma. The shielding block design (not shown in figure 3) is presented in reference [18].

The steering mechanism [10,19] is the critical component of the FS design and a failure of one steering mechanism would render 4 RF beams unusable. The FS launchers on existing tokamaks have been crippled when the steering mechanism grips, which typically occurs between two moving surfaces. The steering mechanism proposed for the ITER upper port FS launcher avoids all frictional surfaces. Traditional bearings are replaced with flexure pivots and the movement is controlled using a GHe pneumatic system consisting of bellows pushing against springs, see figure 4. The mirror rotation
is controlled by increasing (decreasing) the pressure in the bellows, which will compress (expand) the springs and rotate the mirror downward (upward) for the configuration shown in figure 4. A coiled cooling tube with either a single or double wall is envisioned to provide a flexible coolant feed to the mirror, following a similar design to that proposed for the equatorial launcher [17]. The angular rotation of the steering mirror provides access along the resonance layer from a height of 1.8 to 3.4m (corresponding to a mirror angular rotation of $<\pm 6.3^\circ$ or $\pm 12.6^\circ$ for the beam), providing access to all relevant $q=2$ and 3/2 rational flux surfaces as illustrated in figure 1. A more detailed description of the steering mechanism is provided in reference [19].

**FIGURE 4.** Side view of the entrance to the port plug showing the two rows of waveguides along with the gatevalves and CVD diamond window.

**FIGURE 5.** Illustration of the proposed frictionless and backlash-free steering mechanism to be used in the FS launcher.

The distance between the waveguide aperture and the focusing mirror is $>2.1m$, with the beam expanding from $\sim 20mm$ to $66mm$ (radius at $e^{-1}$ in E-field) as illustrated in figure 6. The large spot size on the focusing mirror enables to project a very narrow beam waist (19mm) far into the plasma ($>1.5m$ from steering mirror). The beam spot size in free space varies from 19mm to 45mm along the resonance surface. The launcher design is to be optimized to provide the narrowest profile averaged over the range between $Z_{\min}$ and $Z_{\max}$ (of figure 1). For example, choosing a slightly larger beam waist ($\sim 20.5mm$) will decrease the average spot size along the resonance surface improving the average NTM stabilization efficiency.

The large spot size on the focusing mirror decreases the power density so that with the 8 overlapping 2.0MW beams, the calculated peak power density is $<1.6MW/m^2$ (assuming circular polarization and OFHC copper reflective surface at 250°C). The highest peak power density in the launcher occurs on the mitre bend mirrors, where the spot size is relatively small ($\sim 20mm$). The peak power densities and temperatures occurring on the launcher mirrors are summarized in table 1 (input coolant temperature of 100°C). Note: a surface roughness factor of 1.3 was used for the mitre bend and focusing mirror, while 2.0 was used for the steering mirror (charge exchange neutrals coming from the plasma may degrade the surface quality of the plasma facing mirror). The cooling channels used for calculating the temperature rise were not optimised, with channels dimensions ranging from 5mm by 5mm to 15mm by 5mm at 15 to 30mm intervals and flow rates of 2 to 5m/s. Optimisation of the cooling channels will be performed in the next design phase. The mitre bend mirror design assumed the coolant could be in direct contact with copper for the miter bend, whereas for the focusing and steering mirror the coolant is in contact with stainless steel to avoid corrosion of copper into the blanket cooling water circuit.
FIGURE 6. The free-space mm-wave beam propagation planned for the FS launcher in the region of the port plug and plasma.

| Mitre bend | Focusing mirror | Steering mirror |
|------------|-----------------|-----------------|
| Spot size on mirror [mm] | ~19 | 66 | ~50 |
| Maximum power density [MW/m²] | <4.7 | <1.6 | <2.8 |
| Maximum temperature [˚C] | 228 | 186 | 211 |

3. NTM stabilisation efficiency
Using the beam characteristics of figure 6, the EC driven current profile has been calculated using the beam tracing code ECWGB [11] for the three ITER equilibria \( (I/\beta_p) \): EoB2 (0.7/0.65), 3a(0.7,1.0) and 5(1.0,0.8). The narrow beam projected into the plasma by the FS launcher results in a more peaked current density profile achieving \( 1.55 \leq j_{CD}/j_{BS} \leq 3.47 \) for all \( q=2 \) and \( 3/2 \) surfaces of the calculated equilibria (see figure 7 and table 1) [20]. The FS launcher provides a threefold enhancement over an equivalent 8 port/plug RS launcher and with a total injected power of 20MW was used for these calculations (from 24 1.0MW beams with a transmission efficiency of 83% from gyrotron to plasma).

FIGURE 7. The peak driven current density at each the \( q=2 \) and \( 3/2 \) flux surface compared to the bootstrap current profiles for the three scenarios susceptible to NTMs (2, 3a and 5).
TABLE 2. Comparison of the NTM stabilization efficiency ($j_{\text{CD}}/j_{\text{BS}}$) for the relevant rational surfaces and equilibria [5, 20]

| Scenario       | $q = 3/2$ | $q = 2$ | $q = 3/2$ | $q = 2$ | $q = 3/2$ | $q = 2$ |
|----------------|-----------|---------|-----------|---------|-----------|---------|
| FS Launcher    | 2.17      | 3.47    | 1.55      | 2.43    | 1.75      | 2.15    |
| RS Launcher    | 0.81      | 1.07    | 0.60      | 0.81    | 0.59      | 0.62    |

4. Extended physics

The ECH system is the only current/heating source on ITER that is both localized and steerable using external actuators. This unique current profile tool offers control of many plasma instabilities beyond NTMs, for example control the sawteeth, FIR and ELMs in addition to current profile tailoring. The front steering launcher design provides the flexibility to expand the role of the upper port launcher, increasing the deposition range beyond the region required for NTM stabilization. The steering mirror is rotated through ±6.3° (equivalent to a beam steering of ±12.6°), to access the region between $Z_{\text{min}}$ and $Z_{\text{max}}$ (figure 1). However, this range is only a fraction of the steering range feasible of the steering mechanism, ±12° (or ±24° for the beam). The scanning range can be arranged to so that the mirror rotates further downward to achieve more central deposition and access inside of the $q=1$ surface as shown in figure 8 for scenario 2, where the beam trajectory has been calculated using the ray-tracing code TORAY-GA [21,22]. Note the steering mirror size would have to be increased (or beam spot size on mirrors decreased) to achieve the steering range of figure 8. Since the flux surfaces are nearly tangential to the resonance surface, there may be a larger current density for central deposition obtained from the upper port FS launcher relative to that offered by the equatorial FS launcher [23], even though the upper port is extremely high and the beam is nearly tangential angle with the resonance.

Accessing inside of the $q=1$ surface indicates that the launcher may be useful in controlling the sawtooth crash frequency. ECCD deposition inside (outside) the $q=1$ surface has been shown to shorten (lengthen) the sawtooth period [24]. Shortening the sawtooth period may prevent the onset of the NTM by removing long sawtooth periods, which have been shown to trigger the NTM [25].

The extended range of the FS launcher can also be used to investigate the Frequently Interrupted Regime (FIR) [26] by applying $j_{\text{CD}}$ at the edge of the $q=4/3$ flux surface to modify the shear profile triggering the 4/3 mode NTM [5]. In such a scenario the degradation associated with the $q=2$ NTM is diminished by triggering an NTM on the $q=4/3$ flux surface.

Alternatively, the steering range of the launcher can be increased toward the plasma edge with the potential to trigger the Edge Localized Mode (ELM). The ELM frequency has been increased by driving current locally in the plasma edge [27] which could be obtained by applying $j_{\text{CD}}$ at $\rho_{\text{cut}} > 0.95$.

Dedicated design and ray tracing calculations are in progress for investigating such potential extended applications of the FS launcher. The upper port launcher may have a higher local current density on some inner flux surfaces than that provided by the equatorial port ECH launcher. Comparison of the current drive efficiency and localization between the two launchers is also under consideration similar to the study performed in reference [23].

5. Conclusions

An FS launcher is being designed for the ITER upper port ECRH launcher and compatible with 2.0MW CW operation. The launcher uses a set of focusing and steering mirrors to decouple the steering and focusing functions of the launcher and achieve a wide steering range and a narrow focused beam along the resonance surface. The steering mechanism (the critical component of the FS launcher) uses a frictionless and backlash-free design in order to have an increased reliability and avoid sticking of the actuator system.

The FS launcher is being designed to optimize the ECH power injected into the ITER plasma, obtaining the maximum performance for each injected megawatt. In the case of NTM stabilisation the mm-wave optics projects a very small beam waist as far as possible into the plasma. The narrow spot
size on the resonance results in a high current density relative to the local bootstrap current for the $q=2$ and $3/2$ surfaces of the three scenarios investigated, with NTM stabilization efficiencies in the range of $1.55 \leq \max(j_{\text{CD}})/j_{\text{BS}} \leq 3.47$. These values exceeds the physics demands for the upper port launcher of $\max(j_{\text{CD}})/j_{\text{BS}} = 1.2$ and offers a three-fold increase compared to the RS launcher results.

**FIGURE 8.** The FS launcher can be designed such that access over the range of $0.27 \leq r_{\psi} \leq 0.95$ from the upper port plug.

The only current source on ITER that is both localized and steerable using external actuators is provided by the ECH launcher systems. This unique current profile tool can also be used to control the sawteeth, FIR and ELMs instabilities, but requires a larger steering range in the plasma. Further design and dedicated beam tracing calculations are to be performed to investigate the practicality of each of these applications.

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**References**

[1] Aymer A, Chuyanov V A, Hugnet Y, and Shimomura Y 2001 Nucl. Fusion **41** 1301.

[2] Gantenbein G, Zohm H, Giruzzi G, Günter S, Leuterer F, Maraschek M, Meskat J and Yu Q 2000 Phys. Rev. Lett. **85** 1242.

[3] La Haye R J, Günter S, Humphreys D A, Lohr J, Luce T C, Maraschek M, Petty C C, Prater R, Scoville J T and Strait E J 2002 Phys. Plasmas **9** 2051.

[4] Isayama A, Kamada Y, Ide S, Hamamatsu K, Oikawa T, Suzuki T, Neyatani Y, Ozeki T, Ikeda Y and Kajiwara K 2000 Plasma Phys. Contr. Fusion **42** L37.

[5] Zohm H, Heidinger R, Henderson M, Poli E, Ramponi G, Saibene G, Verhoeven A G A 2005 *Comparison of the performance of different options for the ITER ECRH Upper Launcher* submitted JCPS IAEA-TM on ITER/ECRH.

[6] Sauter O 2004 Phys. Plasmas **11** 4808.

[7] Moeller C P 1998 *A method of remotely steering a microwave beam launched from a highly overmoded corrugated waveguide* Proc. 23rd Int. Conf. on IRMMW.

[8] Verhoeven A G A 2004 *Design of the mm-wave system of the ITER upper port launcher* Proc. 13th ECE & ECH, Nizhny Novograd.

[9] Henderson M A, Chavan R and Sanchez F 2-004 FS Launcher Study, Lausanne Research
[10] Chavan R, Henderson M A and Sanchez F 2005 An Alternative ECRH Front Steering Launcher for the ITER Upper Port, accepted for publication in Fusion Engineering and Design.

[11] Farina, D. et al., “ECWGB: a beam tracing code for EC heating and current drive”, Report FP 03/06 (October 2003), http://www.ifp.cnr.it/

[12] Danilov I, Heidinger R, Meier A and Spaeh P 2005 Torus window development for the ITER ECRH Upper Launcher submitted JCPS IAEA-TM on ITER/ECRH.

[13] Henderson M A, Alberti S, Bird J et al., 2003 Nucl. Fusion 43 1487.

[14] ITER detailed Description Document – 5.2 Electron Cyclotron Heating and Current Drive System, G 52 DDD 5 01-05-29 W 0.1.

[15] Goodman T P, Alberti S, Henderson M A, Pochelon A and Tran M Q 1996 Design and installation of the electron cyclotron wave system for the TCV tokamak Proc. 19th Symp. Fus. Tech. Lisbon Portugal ed C Varandas and F Serra (North Holland: Elsevier) pp 565-568.

[16] Lennholm M, Agarici G, Berger-By G et al., 2003 Nucl. Fusion 43 1458.

[17] Takahashi K, Imai T, Kobayashi N, Sakamoto K, Kasugai A, Hayakawa A, Mori S and Mohri K 2005 Fusion Science and Technology 47 1.

[18] Serikov A, Fischer U, Lang K, Heidinger R, Luo Y and Tsige-Tamirat H 2005 Radiation shielding analyses for the ECRH launcher in the ITER upper port submitted JCPS IAEA-TM on ITER/ECRH.

[19] Chavan R, Henderson M A, and Sanchez F 2005 A Frictionless Steering Mechanism for the Front Steering ECCD ITER Upper Port Launcher submitted JCPS IAEA-TM on ITER/ECRH.

[20] Ramponi G, Farina D and Nowak S 2005 Capabilities of the ITER ECRH Upper Launcher at low magnetic fields submitted JCPS IAEA-TM on ITER/ECRH.

[21] Matsuda K 1989 IEEE Trans. Plasma Sci. PS-17 6.

[22] Cohen R H 2002 Phys. Fluids 44, 139.

[23] Volpe F 2005 Resiliency of ITER ECRH Upper Launcher to Steering Errors and Changes of Profiles and Integration with Equatorial Launcher submitted JCPS IAEA-TM on ITER/ECRH.

[24] Angioni C, Goodman T P, Henderson M A and Sauter O 2003 Nucl. Fusion 43 455.

[25] Westerhof E, Sauter O, Mayoral M L et al 2002 Nucl. Fusion 42 1324.

[26] Gunter S, Maraschek M, de Baar et al 2004 Nucl. Fusion 44 524.

[27] Nave M F, Lomas P J, Huysmans G T A, et al, 1999 Nucl. Fusion 39 1567.