The ITER ECH FS Upper Launcher Design For An Optimized Physics Performance

M.A. Henderson[1], R. Chavan[1], R. Bertizzolo[1], D. Campbell[2], I. Danilov[4],
F. Dolizy[1], D. Farina[3], K. Kleefeldt[4], R. Heidinger[4], J.-D. Landis[1],
E. Poli[5], G. Ramponi[3], G. Saibene[2], F. Sanchez[1], O. Sauter[1], A. Serikov[4],
H. Shidara[1], P. Spaeh[4], H. Zohm[5], C. Zucca

[1] CRPP, EURATOM – Confédération Suisse, EPFL, CH-1015 Lausanne Switzerland
[2] EFDA Close Support Unit, Boltzmannstrasse 2, D-85748 Garching, Germany
[3] Istituto di Fisica del Plasma, EURATOM- ENEA- CNR Association, 20125 Milano, Italy
[4] Forschungszentrum Karlsruhe, EURATOM-FZK, D-76021 Karlsruhe, Germany
[5] Max Planck-Institut für Plasmaphysik, EURATOM-IPP, D-85748 Garching, Germany

Abstract. The purpose of the ITER electron cyclotron resonance heating (ECRH) upper port launcher is to stabilize the neoclassical tearing mode (NTM) by driving currents (co-ECCD) locally inside either the q=3/2 or 2 island[1]. A narrow current deposition profile along with a wide steering range is required to deposit current inside all islands forming at relevant flux surfaces over the wide spectra of possible ITER plasma equilibria. The ITER launcher reference design uses a front steering (FS) mirror that provides optimum focusing for NTM stabilisation and the possibility for a wide steering range. A two-mirror system (focusing and steering) decouples the steering and focusing functions of the launcher for enhanced performance[2] over that of a remote steering concept. The steering mechanism uses a frictionless system[3], flexure pivots replace traditional bearings and a gas pneumatic actuator replaces mechanical feeds. Two FS launcher designs are under consideration: an NTM launcher providing access over the region in which the NTMs are expected to occur ($0.64 \leq \rho_\psi \leq 0.93$), and an Extended Physics (EP) launcher increasing the access range ($0.40 \leq \rho_\psi \leq 0.94$) seeking a synergy with the equatorial launcher for an enhanced ECH system for ITER[4]. In either design, the launcher is capable of injecting up to 16MW per port (eight beams of up to 2.0MW). The best allocation of the four ports with respect to engineering and physics aspects is discussed.

Email of M.A. Henderson: Mark.Henderson@epfl.ch

INTRODUCTION

The principle role of the ITER electron cyclotron resonance heating (ECRH) upper port antenna (or launcher) will be to stabilize the neoclassical tearing mode (NTM)[5-6]. This is achieved by driving current (ECCD) locally inside the island which forms on the q=3/2 or 2 rational magnetic flux surfaces[7-8] after the NTM onset. The launcher is required to steer the ECCD deposition over the range in which the NTMs are expected to be found for the various plasma equilibria (scenarios 2, 3a and 5)[1] as shown in figure 1a. Also, the current deposition profile (j_{CD}) must be narrow relative to the marginal island width and its amplitude greater than that of the bootstrap current (j_{BS})

found outside the island in order to effectively stabilize the NTM[9], as illustrated in figure 1b. The ratio of these two currents, max(j_{CD})/j_{BS}, provides an NTM stabilization figure of merit (η_{NTM}) with the design aim of $\eta_{NTM} \geq 1.2$ assuming 20MW of injected RF power.

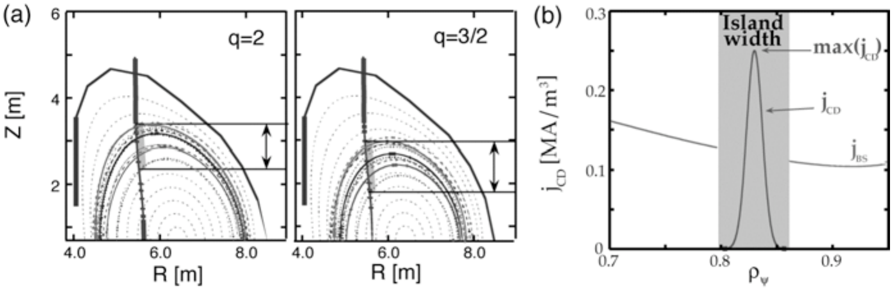

FIGURE 1. (a) The expected range in which the q=2 and 3/2 flux surfaces are expected to be found for ITER scenarios 2, 3a and 5. (b) The preferred j_{CD} would be narrow enough to be contained within the island and having max(j_{CD})/$j_{BS} \geq 1.2$.

The Close Support Unit (CSU) of the European Fusion Development Agreement (EFDA) has supported the development of two launcher designs (remote and front steering) with the aim of providing the optimum system based on the physics, engineering, costs, reliability, etc. The remote steering (RS) concept[10], see figure 2a, has the advantage of having the steering mechanism placed outside of the torus vacuum for easier repair access. However, the system has a limited steering range and limited focusing capabilities. Focusing the beam to a small size in the plasma requires a large beam spot size on the focusing mirror, which would have to be very large to 'catch' the beam at all steering angles coming from the square waveguide (note that a large distance is required between the waveguide and mirror to allow for the beam to expand). The front steering (FS) system, see figure 2b, uses two mirrors to decouple the focusing and steering functions of the launcher, achieving very narrow deposition width over a wide range in the plasma. The FS system has the disadvantage of having the steering mirror near the plasma complicating access if repair is required.

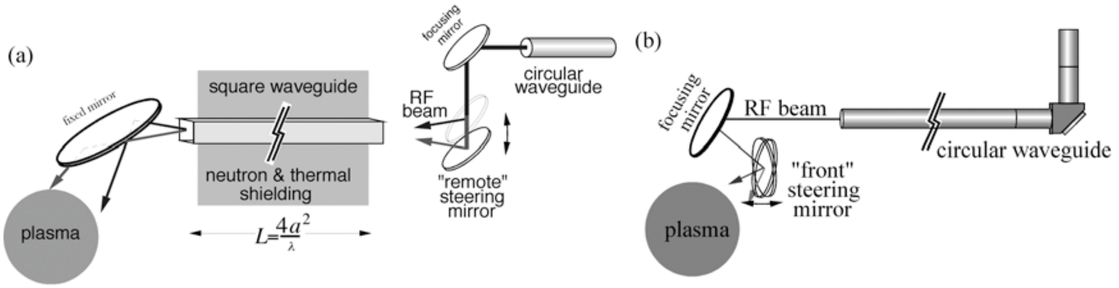

FIGURE 2. (a) The RS concept with the steering mirror placed prior to the long (~4m) square waveguide and (b) the FS concept with the steering mirror near the plasma for optimal beam focusing and steering.

The two launchers were compared based on engineering constraints, reliability, costs, physics performance, etc., again with the goal of providing an optimum launcher for ITER. The RS launcher design[11] offered the simpler access to the steering mechanism for repair, but requires a larger volume limiting 6 beams per port plug. The FS launcher design[2] demonstrated a significant increase in η_{NTM} over that of the RS launcher (on average a factor of 3.7) as shown in table 1. In addition, the cost of the FS launcher was estimated at <60% that of the RS launcher, the mm-wave components for the FS launcher are less expensive and only three ports are required (8 beams per port) compared to the four port RS launcher.

TABLE 1. Comparison of the RS and FS launchers capabilities in stabilizing the NTMs, η_{NTM} values are given for the three scenarios based on the calculated j_{CD}[1,12] using GRAY[13].

	Scenario 2		Scenario 3a		Scenario 5	
	q=3/2	q=2	q=3/2	q=2	q=3/2	q=2
RS Launcher[11]	0.56	1.27	0.36	0.69	0.53	0.91
FS Launcher[2]	2.52	3.54	1.82	2.69	1.93	2.07
Relative difference	4.5	2.8	5.1	3.9	3.6	2.3

OPTICAL DESIGN

The principle layout of the FS launcher is shown in figure 3. Eight HE_{11} waveguides (ϕ_{WG}=63.5mm, equivalent to the transmission line) enter the port plug with a CVD diamond window[14] and an in-line gate (or isolation) valve placed prior to the closure plate. The isolation valve is on the plasma side of the CVD window, such that the window can be isolated for leak testing or repair as was proposed for the JET-EP ECH system[15]. Inside the port, mitre bends are used to redirect the eight beams so that they are all aimed at a single focusing mirror and then separate to two steering mirrors each with four incident beams. The beams are allowed to expand to a relatively large size (w_{FM}~64mm) on the focusing mirror so that they can be focused far into the plasma with a small beam waist (w_0~21mm), optimized for the highest η_{NTM} value over access region[16]. Overlapping the beams permits a larger beam for a finite mirror size within the launcher's blanket shield module (BSM). The focusing mirror curvature, waveguide tilt angle and orientation of the steering mechanism has been optimized to insure that the 4 beams deposition coincide in the plasma[17-18].

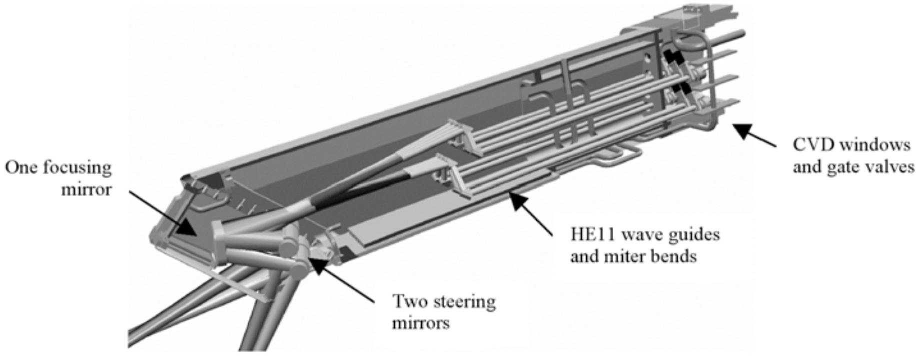

FIGURE 3. General design of the FS upper port launcher with 8 entries (~2MW) capable of accessing all relevant q surfaces susceptible to NTMs.

The steering mechanism will use a frictionless backlash-free system that replaces the traditional ball-bearings with flexure pivots and push pull rods with a pneumatic system. This eliminates the components that typically grip in present day FS launchers offering an improved reliability and precision in controlling the steering mirror angle. A full description of the steering mechanism design is provided in reference 3, based on the design status of June 2005.

OPTIMUM PORT USAGE

The number of ports allocated to the upper launcher had been increased from three to four to accommodate the additional requirements of the RS launcher (6 beams per port for the planned 24 beam lines of the ECH system). At the end of 2005 ITER-IT reviewed both launcher designs and switched the reference design back to the FS launcher, which had been the reference design up to 2000[19]. ITER-IT recommended that the FS launcher design team maintain the use of four ports (even though only three were required for the 24 beam lines), with the objective of using the fourth port to relax the engineering constraint and/or enhance the physics performance. Several options were considered for the additional port, these are listed in table 2.

TABLE 2. Possible options for the optimum usage of the additional forth port.

Launcher options	Description
Combination of FS and RS	Install 3 FS launchers and 1 RS launcher
4 NTM launchers	Install 4 FS launchers with steering range limited to accessing NTMs of figure 1. One port acts as a spare launcher.
4 EP launchers	Install 4 extended physics (EP) FS launchers with access of the upper and lower steering mirrors shifted to increase total coverage in the plasma and reduce steering mirror rotation requirements
Combination of NTM and EP	Use 1 to 2 NTM launchers and 3 to 2 EP launchers
Dedicated launchers	Use 2 launchers accessing further inward and two launchers the outer plasma region, but with steering range reduced.

The preferred fourth port usage would be for 4 EP launchers, which increases the overall access range in the plasma by shifting the steering range of the upper steering mirror further toward the plasma center, as shown in figure 4b. This relaxes the engineering constraints by reducing the rotation requirements of the steering mirror from 7° to 5.5°, limits the opening in the front panel reducing radiation exposure of the steering mirrors, uses a two focusing mirror system for optimum focusing for the two steering mirrors and makes feasible the enhanced physics proposals outlined in reference 4. Spreading out the range of the two steering mirrors limits only 13.3MW to be directed over the range of $0.38<\rho_\psi<0.75$ and $0.87<\rho_\psi<0.94$, and 20MW in the overlap region where a majority of the reference NTM surfaces are expected to be found. The focusing mirrors can be optimized for the two steering ranges providing a narrow deposition profile adequate for NTM stabilization (see Table 3) and sawteeth control[4,16]. In addition all four ports are identical minimizing the design and manufacturing costs.

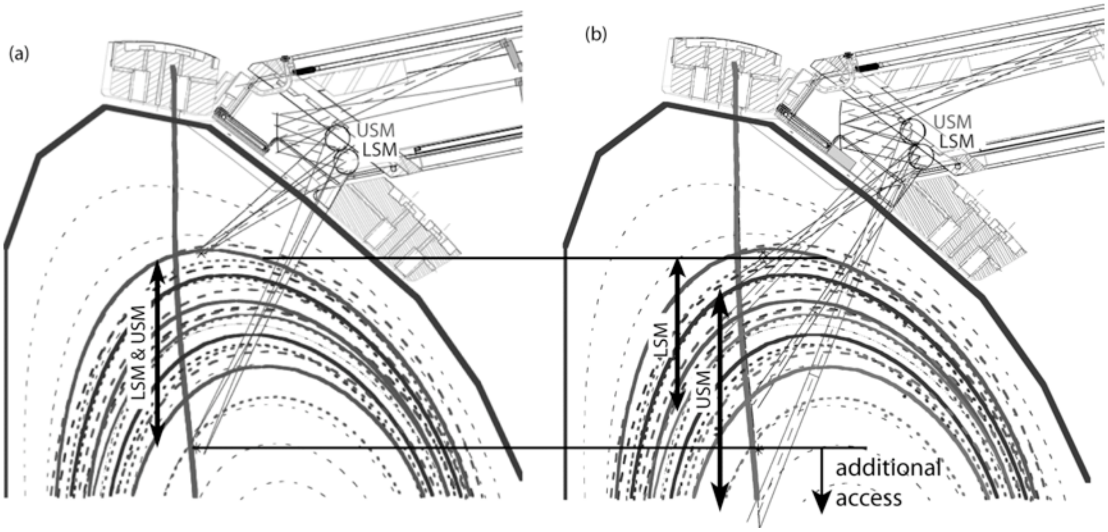

FIGURE 4. (a) The NTM launcher limits both lower (LSM) and upper (USM) steering mirrors to provide access over the region in which NTMs are expected to occur. (b) The extended physics (EP) launcher shifts the deposition of the USM to access further inward such that an enhanced physics programme can be realized.

TABLE 3. Comparison of the EP and NTM FS launcher capabilities in stabilizing the NTMs, η_{NTM} values are given for the three scenarios based on the calculated j_{CD}[12,16] using GRAY[13].

	Scenario 2		Scenario 3a		Scenario 5	
	q=3/2	q=2	q=3/2	q=2	q=3/2	q=2
EP FS Launcher	2.58	3.38	1.32[a]	2.63	1.85	1.32[a]
NTM FS Launcher[2]	2.52	3.54	1.82	2.69	1.93	2.07

a: Assumes only 16 beams (or 13.3MW) can access the flux surface.

The next preferred option would be four NTM launchers, with the scanning range accessing the NTMs, as shown in figure 4a. This option has one spare port that can be used in the event of a failed steering mechanism and provides the greatest safety margin at a reduced cost for NTM stabilization. The dedicated launcher option has all the beams of two launchers accessing a similar region as the lower steering mirror (LSM) of figure 4b and the beams of the other 2 ports similar to the upper steering mirrors (USM). This would have equivalent performance as the EP option but would require different launcher designs and BSM cutouts increasing the launcher costs. The option of combined NTM and EP launchers is not optimal in that it offers only limited performance inside of $\rho_\psi<0.64$ ($P_{RF}\leq 10$MW) while increasing the costs requiring the manufacturing of two different launcher types. The option of installing an RS launcher in the fourth port offers the least benefits to ITER. The RS launcher is more expensive than the FS, offers negligible physics performance relative to the FS, and would require developing two entirely different launching systems (nearly doubling the human and financial resources required for the ECH upper launcher).

CONCLUSIONS AND ACKNOWLEDGEMENTS

The FS launcher has been designed with the aim to improve the operating reliability and increase the physics capabilities of the upper port ECH launcher. Particular attention has been given to the design of a frictionless and backlash-free steering mechanism[3], which offers improved reliability and steering precision than that offered in present day FS launchers. The optical design offers significant focusing of the beam in the region of the resonance surface such that the NTM stabilization efficiency exceeds the physics requirements (η_{NTM}=1.2) by a factor of 1.5 to 3 depending on the ITER scenario and q surface. The additional fourth port available for the ECH upper launcher offers the possibility to extend the physics applications beyond just NTM stabilization and include control of the sawteeth, which is achieved by spreading out the deposition range of the two steering mirrors of each port. Using the upper launcher to control the sawteeth relaxes the steering range required of the equatorial launcher, which can then be optimized for a reduced number of physics applications based on the enhanced ITER ECH physics capabilities outlined in the synergy study[4]. In addition to the enhanced physics capabilities, the overall engineering constraints of the FS upper launcher are relaxed, a smaller steering range and narrower opening in the first wall are required. All ports would have identical launchers simplifying the design and reducing the procurement costs. Note that the FS launcher was estimated to cost <60% that of the cost for RS launcher option.

This work, supported by the Swiss National Science Foundation and the European Communities, was carried out within the framework of the European Fusion Development Agreement (ECHULB subtask (b) /contract EFDA 05-1228). The views and opinions expressed herein do not necessarily reflect those of the European Commission.

REFERENCES

---

[1] H. Zohm *et al*, Journal of Physics: Conference Series 25 (2005) 234-242.

[2] M. Henderson *et al*, Journal of Physics: Conference Series 25 (2005) 143-150.

[3] R. Chavan *et al*, Journal of Physics: Conference Series 25 (2005) 151-157.

[4] M. Henderson et al, *Synergy study of the Equatorial and Upper port ITER ECH Launchers for an enhanced Physics Performance*, this conference.

[5] J. How et al, ITER Project Integration Document, version 1.0 (2004) G A0 GDRD 6 04-09-09 R0.2.

[6] A. Aymer, V.A. Chuynov,Y. Hugnet and Y. Shimomura Nuclear Fusion 41 (2001) 1301.

[7] G. Gantenbein, H. Zohm et al, Phys. Rev. Lett. 85 (2000) 1242.

[8] A. Isayama et al, Plasma Phys. Contr. Fusion 42 (2000) L37.

[9] O. Sauter, Phys. Plasmas 11 (2004) 4808.

[10] C. Moeller, *A method of remotely steering a microwave beam launcher from a highly overmoded corrugated waveguide*, Proc. 23rd Int. Conf. IRMMW (1998) 116.

[11] A.G.A. Verhoeven *et al*, Journal of Physics: Conference Series 25 (2005) 84-91.

[12] G. Ramponi et al, Journal of Physics: Conference Series 25 (2005) 243-251.

[13] D. Farina, *Gray: A quasi-optical beam tracing code for EC absorption and current drive*, this conference.

[14] I. Danilov et al, Journal of Physics: Conference Series 25 (2005) 173–180.

[15] M.A. Henderson et al, Nucl. Fusion 43 (2003) 1487.

[16] G. Ramponi et al, *Capabilities of the ITER ECRH/ECCD Systems for Extended Physics*, this conference.

[17] H. Shidara et al, *ECRH beam optics optimization for ITER upper port launcher*, this conference.

[18] E. Poli et al, *Performance studies for the ITER ECRH Launcher*, this conference.

[19] N. Kobayashi et al, Fusion Eng. Design 53 (2991) 475-484.