The ITER EC Upper Launcher with Internal Optics: Beam Characteristics, Tracing and Planned Tests

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Abstract

The EC Upper Launcher for ITER aims to the stabilization of NTMs at the q=3/2 and q=2 rational surfaces and to sawteeth control. New flexibility is obtained with the substitution of the mitre bends in the port plug with suitable internal optics, contributing also to the cost reduction efforts. The new optics was developed minimizing the impact on the mechanical design. The analytical model describes individual beams from the HE11-TEM00 converter up to the steering mirrors using the local properties of the mirrors. The model was verified independently with the physical optics GRASP code, describing the effects of beam truncation on the mirrors and the presence of surrounding elements. Beam tracing calculations were performed for all the astigmatic beams, looking at the j_{CD} deposition profiles at q=2 and q=1.5 flux surfaces for three H-mode scenarios. They showed that the quasi-optical version of the launcher is applicable without disadvantages on the performances. Tests are scheduled to check the beam transmission through the whole system. High power tests are envisaged in a dedicated mechanical setup at the EU 170 GHz gyrotron test facility in Lausanne, Switzerland. The test jig will allow burn patterns, feedback-controlled steering and polarization, IR imaging, and phase reconstruction of the beam. Tests will be simplified by using one beam line, atmospheric pressure and limited pulse length.

1. Introduction

The main aims of the ITER ECRH Upper Launcher is to drive current locally in order to stabilize neo-classical tearing modes (NTM) which are expected to form on either rational surfaces q=3/2 and q=2 and to deposit EC power near the q=1 rational surface to control sawtooth instability. The Extended Physics Launcher (EPL) is based on a front steering (FS) concept (Fig.1, left) and it represents an upgrade of the FS design of 2006 [1]. This design is in advanced stage: latest refinements are being studied on the optics side, with lower impact on the mechanical design that is progressing in parallel. Refinements have the goal to lower RF losses, stray radiation and heat load on critical components, together with complexity and the cost of the launcher itself. At this stage any change in the optics that affects the beam shape have to be studied and the consequences must be evaluated precisely. In view of this, a model describing correctly the shape of individual beams is needed, interfaced with beam tracing codes that describe the propagation into the plasma. A tool for the evaluation of the degree of aberration that arises from the far-from-ideal propagation in the constrained volume of the launcher gives an increased confidence on the design. Finally, to ensure that the upper launcher will behave as expected in ITER the system analysis should then be confirmed with measurements on prototypes. Moreover it will be necessary to test the components during various phases of the design and production. A one-to-one scale mock-up millimeter wave test jig (MMWTJ) is proposed for these measurement tasks. The ensemble of these tools, together with the status of their analysis are briefly described in this paper.
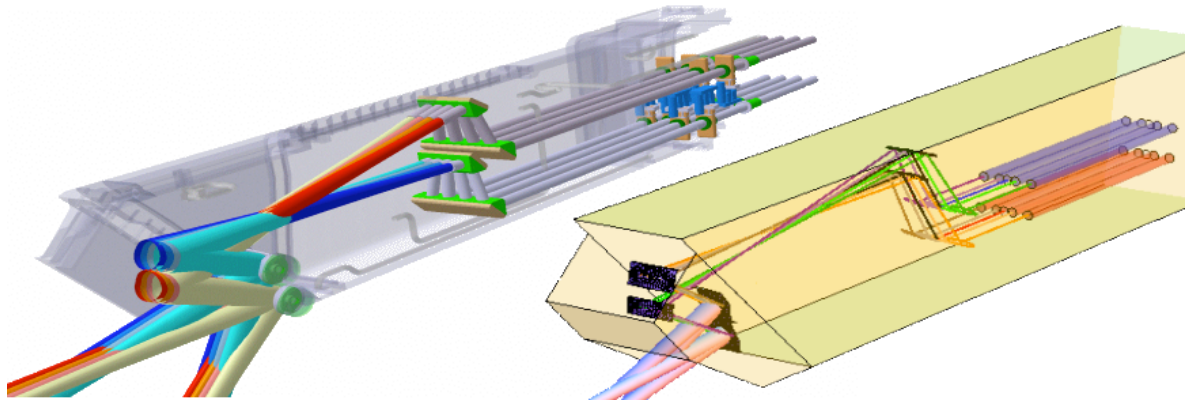
Fig.1: Left: the Extended Physics ITER Upper Launcher. Right: Sketch of the optical components and the beam trajectories in the full quasi-optical Upper Launcher.

2. Quasi-Optical Version of the Extended Physics Upper Launcher

In the EPL launcher two dedicated steering mirrors are used to launch up to 20 MW of EC power coming from 24 Gyrotron sources (f=170 GHz, 1-2 MW). Power is divided in four ports, with 8 beams per port in two rows (an upper row and a lower one), and using a single steering mirror for each row. A schematic view of the EPL Launcher is shown in Fig. 1 (left). The optimized poloidal and toroidal injection angles and beam parameters [2] ensure well-collimated beams with focus in the plasma of ITER and optimal injection angles.

One possibility to refine the optical design of the EPL have been explored: the replacement of the two internal mitre bends with mirrors, without great changes in the blanket shield module region (BSM), where the final focusing mirrors and the steering mechanism are placed. Besides the lower cost and complication of the mirror setup, other advantages include:
- lower losses in the quasi-optical propagation, provided the mirror is large enough,
- lower heat load on the mirrors due to increased beam width and higher incidence angle

First, a 2-D reference model have been used, with virtual beams helping to define distances, mirrors positions and preliminary geometry. Particular attention was paid to place the mirrors (those replacing mitre bends) where the beams were well separated and the spot radius not too small. An optimization of the position taking into account the space available in the top area of the internal port plug was done. Successively, quasi-optical (QO) elements were detailed and single beam-lines added. Special attention was paid on the beam launching angles and relative toroidal divergence $\Delta\beta$ with respect the optimal toroidal injection angle β_{OPT}. Beam tracing calculations [2] were necessary to determine the optimal divergence for perfect superposition of the different beams launched from different points of the last mirror. Other parameters were chosen to be kept unchanged with respect to the MB version: the beam spot size on the focusing mirror ($w_{FM} \approx 60$ mm) and the relative spacing between adjacent beam axes on the focusing mirror. The reduction of the power density on the M2 mirror was estimated for circularly polarized beams from 4.2 MW/m^2 down to 2.8 MW/m^2.

The optical properties of the FM and the orientation of both FMs and next SMs are fixed once the optimum values for beam waists are w_0=29 mm for the USM beam and w_0=21 mm for the LSM of the former design are reproduced. These constraints give simple astigmatic beams as a result, and the effective focal lengths (f_{pol}, f_{tor}) in the poloidal and toroidal directions are different. As the rotation of the steering mirror is introduced in terms of the steering angle γ around mirror rotation axis properly oriented (steering angle γ= -5.5°, +5.5°), the resulting beam parameters as a function of γ can be determined and tabulated for input in beam tracing codes. Beams are simply astigmatic [3] in the case of upper row (Fig.2), nearly

circular for the lower: the orientations of the spot ellipses are not purely toroidal/poloidal (maximum deviation from the poloidal/toroidal direction is about $|\varphi_W| \approx 14.4°$).

The present QO reference design (Fig.1, right) successfully reproduces the good beams of the EPL launcher, in particular in terms of resulting launching angles (with optimal divergence, as shown in Fig. 2), beam dimensions in the absorption region. The impact of the new optics on the former design is being checked with the implementation in the CATIA model.
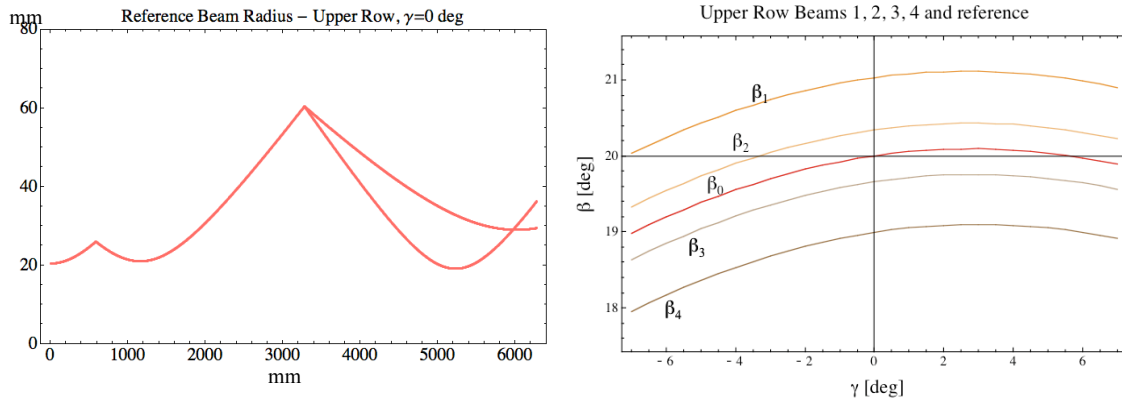

Fig. 2: Left: width (in vacuum) for the reference beams vs. distance from waveguides in two directions of astigmatism (upper row). Right: output β angle vs. steering angle γ for the upper row beams.

3. Physical Optics Code Evaluations

Given the constrained size of the space available for propagation, the beam undergoes diffractive effects and aberrations that can give rise to beam asymmetries and significant sidelobes. In order to accurately describe the beam non-gaussian features, numerical simulations with the electromagnetic code GRASP® have been performed.

The role of various effects on the beam propagation through the system has been analyzed separately, by mean of implementation of simplified launcher models with parts of the setup only. This approach allows the separation of the various contributions to the beam and the evaluation of possible design constraints. In particular, a detailed beam truncation study on the focusing mirror, an evaluation of the effect of limited passage through the shielding block structure on the beam propagation and the analysis of the effect of thermal deformation on the steering mirror were performed. The main results follows:

1) The aperture analysis shows that the focusing mirror size with $\phi_{mirror}/w=3$ is a good balance between providing optimal focusing while limiting the stray power.

2) The evaluation of the effect of limited passage through the shielding blocks suggests the choice of a 1.75w clearance between the shield wall and the beam center.

3) The effect of thermal deformation of the steering mirror on the reflected beam has shown no significant change in the reflection angle and no sidelobes down to 30 dB; the shape of the beam deviates from circular due to the distortion of the mirror in the major axis direction.

4) A preliminary simulation of the overall quasi-optical system, results in a good agreement between the beams numerically and analytically calculated.

4. Beam Tracing Analysis of Deposition Profiles

The performances of the FS Upper Launcher have been analyzed with the Beam tracing code GRAY [4] by taking into account four astigmatic beams launched by the upper steering mirror (USM) and four astigmatic beams launched by the lower steering mirror (LSM). Depending on launching location, to each of the 4 beams in a row is associated a toroidal

angle calculated in order to have the current driven at the same radial location when the four beams are launched with the same poloidal angle α [5]. The values are close to the 'optimal' toroidal angle already established for each row, i.e. β=20° for the USM and β=18° for the LSM [6]. Fig.3 shows the results obtained for Scenario 2, for the case of the USM and the LSM, respectively. It may be noticed that, in both cases, the values of the main quantities are close each other and not very different from the circular beam cases.

Aiming to evaluate the performances for NTM stabilization, the analysis has been extended to three reference scenarios, i.e., beside Scenario 2, also the hybrid Scenario 3 and the low q Scenario 5 have been taken into account. Calculations show that the quasi-optical version of the Upper ECRH launcher is applicable without disadvantages on the performances.
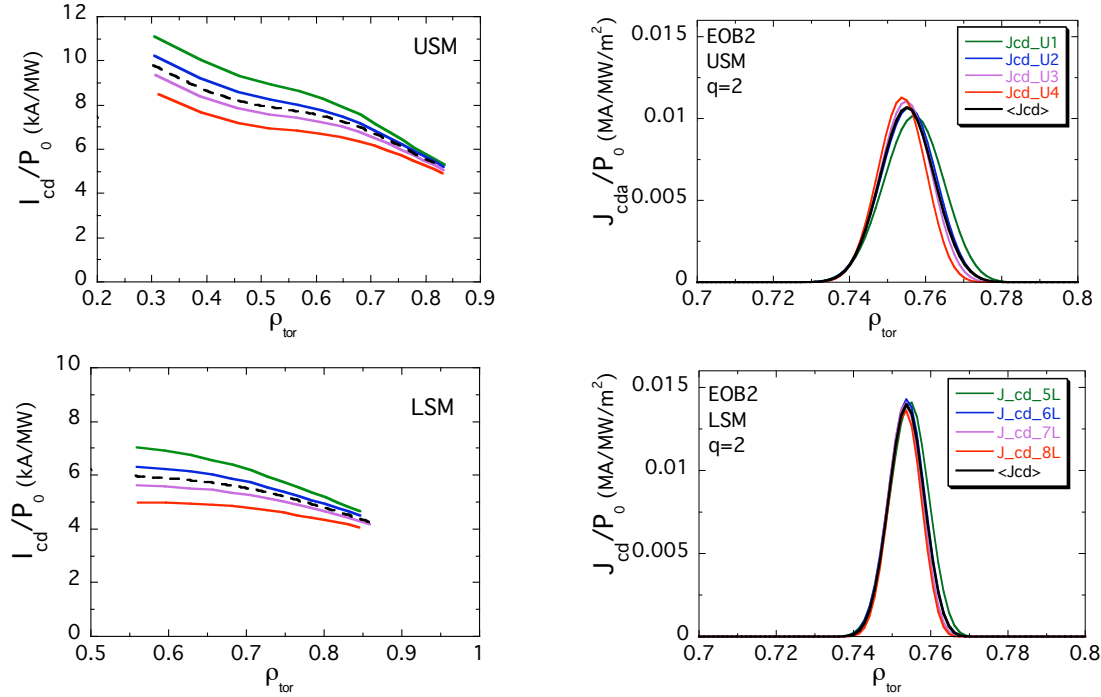

Fig.3. Total driven current (left) and current density profiles (right) at q=2 flux surfaces of Scenario 2. Continuous lines refer to the beams in Table I, dashed curves to a circular beam with waist 2.9 cm.

5. Test of Millimeter-Wave Components

To ensure that the upper launcher will behave as expected in ITER, testing of the components during various phases of the design and production has been included in the planning since the design activities were initiated. While testing of individual portions of the optical system has been carried out [7], the full optical system has not yet been assembled and tested. Full testing is centered upon low and high power measurements in a one-to-one scale mock-up millimeter wave test jig (MMWTJ). Mechanical-dimensional measurements, thermo-hydraulic measurements, cyclic fatigue issues etc., are addressed in other ways [8]. Here, we discuss only the tests related to the microwave characteristics of the system, prior to assembly in the port plug structure. We are interested in the beam profiles at the output, the transmission efficiency (and power loss in the system), and stray radiation effects. The latter is of particular concern as it could lead to overheating of the launcher structure if stray radiation is absorbed in poorly cooled (from the microwave standpoint) unpredictable regions of the port plug. As the stray radiation distribution is difficult to calculate, it is prudent to perform measurements. This should be done at high power for three main reasons. Firstly designers try to minimize stray radiation so power levels are expected to be small and thus

difficult to detect. Secondly the stray radiation is potentially spread over a large region. And thirdly the location of potential hot spots is of most interest; thus the measurement of infrared (IR) radiation is called for.

As IR measurements are used with phase-reconstruction techniques to analyze the RF output patterns of gyrotrons [9], they will be applied to the launcher output beams as well (typically using millisecond pulse lengths with targets in an RF box) as part of the QA documentation. By simulating the shielding blocks of the UL with partially absorbing target material, while still allowing viewing, and extending the pulse length by three orders of magnitude (using the), hot spots (if any) associated with stray radiation should be able to be located using the same camera. To facilitate these tests a MMWTJ is being designed at CRPP to provide: personnel protection, transportability, full-scale, full-power, short (~1s) pulse, atmospheric, testing of any, one, optical path – though all 8 paths can be mounted together – at the existing EU 2MW 170GHz Gyrotron Test Stand, hosted at the CRPP [see, for example, 10]. The MMWTJ will be interfaced, at the input, with the EU gyrotron via the RFCU (with polarizers) and transmission line and, at the output, with the RF box or 2MW CW load, as this equipment is available and used for the gyrotron testing. Figure 1 shows a schematic of the MMWTJ within the safety enclosure of the Test Stand, in relation to the gyrotron and RF box (the 2MW load will be interfaced at the same location for long pulses).
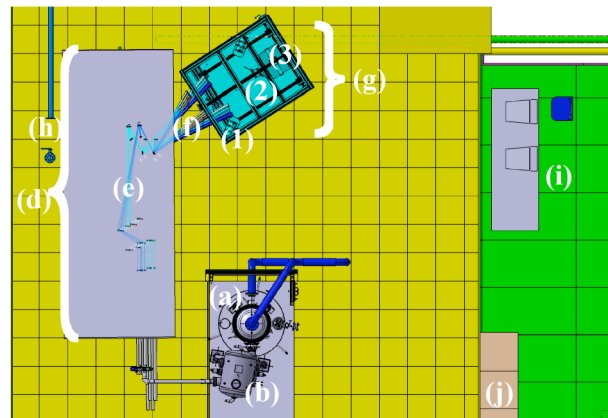

Figure 1 (a) EU gyrotron in its magnet, (b) RFCU with polarizers, (c) transmission line, (d) 20 foot aluminium maritime transport container, (e) beam trajectories, (f) ranges of the 8 possible output beams (with indicative beam size), (g) RF box containing: (1) movable shielded IR camera, (2) movable target, (3) beam deflector and dump, (h) 2MW CW load cooling circuit, (i) control room and (j) data aquisition. The entry to the shipping container is at the present UL closure plate.

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