Advanced Optics for the Remote Steering ITER ECRH Upper Launcher

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Abstract. The optics of the ECRH Upper Launcher in ITER based on the Remote Steering concept needs special attention, since any focusing element in front of the waveguide has combined effects on the range of steering angles achievable and the beam width in the plasma region. The effects are studied in detail for a setup composed by 8 beams per port (three ports), for a spherical and a hyperbolic mirror surface. Gaussian beam analysis is compared to beam pattern calculations with the optical physics code GRASP, in order to verify the validity of gaussian optics approximation. The standard description with simply astigmatic beams, not adequate in more complex systems as the proposed two-mirror set-up, requires approximations, which are compared with the generalized astigmatic beam description. The ohmic losses at the end mirrors and the related localized heating due to the very large power density cause deformations that depends on the design of the cooling circuit. The distortion of the beam shape has been evaluated in a realistic case of mirror cooling with a small-channel system. The quantification of the effect depends on the precise evaluation ohmic losses and their enhancement in the long term due to the surface deterioration.

1. Introduction
Within the applications of the ECRH Upper Launcher in ITER, Neoclassical Tearing Modes (NTM) stabilization is the most demanding. It requires off-axis injection, strong focusing and precise control of the deposition radius by beam steering. In order to locate moving parts far from the burning plasma, the launcher is based on the Remote Steering (RS) concept [1] for providing adjustable beam alignment.

However, the design of the optics in front of the RS wave-guide is not conventional, because the beam is swept onto the surface, with some uncommon features that require a careful design optimization process. The optimization work includes the consideration of the many requirements on the launcher optics mostly coming from mechanical design boundary conditions, but also from the need to withstand the electromagnetic forces acting on mirrors and to limit the thermomechanical stresses in the mirror with proper cooling.

From the optics side, the mirror has to provide a sufficient steering capability, in terms of scanning angle, while converging the beams at their lowest dimensions near the resonance. Moreover has to keep a low level of beam aberrations, for maximum control of the power deposition. Finally thermal losses have to be minimized and the heat adequately removed, for preventing problems of beam distortions due to thermal deformations.
2. Combined effect of focal length on beam size and range

Considering a single mirror set-up, the front mirror inclined in toroidal and poloidal direction is exploited to converge the beam (or to limit its divergence) to the minimum size required for NTM stabilization. The main requirement affecting the choice of the mirror focal length is the angular range required (dependent also on the mirror position).

Even in a first approximation (thin lens approximation) the mirror focal length defines both the beam axes directions (when the beam is swept onto the surface) and the beam convergence properties (described with gaussian beam optics). It is found that lowest beam size and widest steering range are not compatible. Thus, a trade-off between the range of steering angles and the beam width in the relevant plasma region is necessary.

Figure 1 shows the quantitative effect of the variation of the mirror focal length (or, more correctly, of the mirror curvature in the steering plane) on the beam size in the plasma region (computed with the formulas of the quasi-optical gaussian beam propagation [2]), on the range of angles of the beams coming out from the mirrors and on the extent of the region covered by the beam axes (at equal steering range at the waveguide output).

Note that the range of angles of the outgoing beams is not simply proportional to the real radial extent of the region spanned by the beams. If a suitable steering range has to be preserved (for example at least 5 degrees), not all the focal lengths are allowed. The same happens if a minimum beam size in the plasma region is required. Since the focal length minimizing the beam size produces a too small output steering range, an “optimized” focal length is chosen at the lower margin of the “insufficient steering range” region, as the one that keeps the minimum required steering range.

![Figure 1: The parameters, as a function of the inverse focal length (in m⁻¹), are shown for input distance d₁=0.4 m:
- output steering range (in degrees, for 10° steering angle at the waveguide output)
- beam radius in the plasma region (in cm, measured at 2 m from the mirror)
- size of the region spanned by the beam at 2 m from the mirror (in tens of cm, for 10° steering angle at the waveguide output)](image)

3. Effective focal length variation on the mirror surface

Another effect coming into play in the real geometrical configuration (with respect to the thin-lens approximation) is that during the steering of the beams both the local mirror curvature and the incident angle (so its focal length) vary. Moreover also the distance d₁ of the input beam waist from the surface varies appreciably, resulting in a variable beam size at every point on the mirror.

If on one side this fact causes very high power density in the smallest spot on the mirror, as discussed in section 7, on the other side the combination of these effects produces different output beams, whose parameters (output waist radii and positions) depend on the beam output direction. In figure 2 examples of beam contours for the two extreme launching positions and a realistic single-mirror setup, including effective local focal length variation, are shown.
Figure 2: Typical beam characteristics variation when the scanning angle is varied between two extremes of the range, due to the simultaneous variation of input beam distance, incidence angle and mirror local curvature.

4. Simple astigmatic beam
As effect of the variable incidence angle, even for fixed mirror curvature, the focal length is different in two directions (coincident with sagittal and tangential, for a spherical mirror), giving rise to an astigmatic beam (figure 3), which is characterized by an elliptical section. Output waist radii and positions are different for the two directions; the orientation of the astigmatism ellipse has to be added for the complete beam description.

If the beam incident on the mirror surface is spherically symmetric, the output beam astigmatism axes are do not change along the beam axis, and the “simple astigmatic” beam propagation can be computed with the standard formulas [2] applied independently in the two directions.

Figure 3: Sketch of a simple astigmatic beam: the axes of the astigmatism ellipse do not change.

5. Evaluation of real mirror surfaces
Two mirrors (spherical, hyperbolic) have been evaluated for the single-mirror RS set-up. The comparison is performed by looking at the beam width (for propagation in vacuum) at a distance where the interaction with plasma occurs. This distance was inferred (as a variable function of the steering angle) by the evaluations previously done with beam tracing codes [3] from the same mirror position for different ITER equilibria.

The spherical mirror gives rise to astigmatic beams, whether the particular hyperbole chosen (foci coincident with input and output optical focal points) have circularly symmetric output beams. Beam size evaluation is done for two different mirror locations, representative of the upper and lower rows of waveguides and mirrors composing each full launcher. The size in the interaction region has a non-negligible variation along the scanning range (figure 4).
Note that the beam size cannot be lower than a minimum, limited by diffraction, which depends on the spot size on the mirrors. A smaller spot on the mirror means a larger beam width in the resonance region. Note that the difference in angular scan even if alpha angle for zero steering has been kept equal for the two mirrors. The different steering range for positive and negative steering angles at the waveguide exit is the effect of the different curvature of the two mirrors in these two regions.

Figure 4. Beam size near the absorption location (mm) as a function of the poloidal launching angle (deg.) for two launching positions and for hyperbolic and spherical mirrors. The diffraction limit is given for reference.

6. Comparison with beam pattern calculations

Due to the scanning on the mirror surface, some aberrations of the output beams are expected to be more relevant, in particular for larger scanning angles, than those found for a mirror designed for a single beam with fixed position.

The physical optics code GRASP8 [4] was used in order to evaluate the beam patterns at 0 and ±12 degrees on a plane placed at around 2 m from the mirror, i.e. near the resonance in the plasma. Initial conditions for the patterns correspond to fundamental gaussian beams emerging with different directions from the waveguide aperture; the experimental or the computed distribution of the field at the rectangular waveguide will be required for more accurate patterns. The “large mirror” approximation used for the patterns in figure 5 shows only the effects of the mirror curvature (an increase of beam width of less than 5%) The effect of the mirror truncation, with the inclusion of real mirror shape and the possible presence of surrounding objects will be the object of future refinements.

Figure 5. Contour plots of beam patterns for the spherical (left) and hyperbolic (right) mirrors at 0 and ±12 degrees of steering angles. Levels are shown by 5 dB steps.
7. Test model for mirror cooling circuit

Given the very large power density at the end mirrors due to reflection losses, a careful design of the cooling setup is required with a strong heat transfer capability. In addition, the thermomechanical stability of the mirror requires that the mirror temperature has to be maintained within safe values. Also deformations must be small enough to avoid significant distortion of the beam shape. In these conditions the precise evaluation of the ohmic losses, together with their possible enhancement in the long term due to the surface deterioration, must be performed.

A model for the cooling circuit with narrow channels ensuring strong turbulence and high heat transfer coefficients has been studied. The main goal was to evaluate the mirror deformation in the most critical case that occurs when the beam hits the mirror at the minimum distance from the waveguide. The mirror is assumed with a copper layer (10 mm thick) at the surface and a thick steel bulk. Copper layer thickness has to be limited in order to contain the electromagnetically induced torques in case of plasma disruptions or VDE. For cooling purposes 8 semi-circular channels (6x3 mm) and a wider central channel (12x3 mm) placed in the copper layer in longitudinal directions are considered.

High pressure hot water (inlet pressure 18 bar, outlet pressure 3 bar, 120°C temperature), flowing at an average speed of 26.5 m/s, is considered at a total mass flow rate of 3.3 kg/s. Flow speed distribution and heat exchange coefficient is computed locally, neglecting the possible enhancement due to boiling at the channel surface. The maximum temperature reached on the mirror was 324°C, considering 10 kW of absorbed power (0.5% of MW).

Half of the mirror section is visible in figure 6, where the effect of deformation at the beam spot location is shown (enhanced). The temperature could be further limited (to around 300°C) maximizing the wetted surface of the central channel by building longitudinal fins on the hot side.

The high density of the power absorbed at the mirror surface causes a deformation whose extent depends on the absorbed power, on the structural properties of the materials involved, on the cooling setup and flow conditions. We studied the effects on the beam propagation in the above conditions, modeling the deformation with a spherical change of the local mirror curvature. It was done independently in the two (transversal and longitudinal) directions (figure 7), finding a degradation of the beam size in the plasma of the order of 10% in the worst case.
8. Multiple-mirrors case

Launching schemes for ITER with more than one mirror [5] have a beam propagation more complicated to describe, due to the fact that mirrors with different curvatures in different directions generate beams for which the standard description with simply astigmatic beams is no more adequate. In this case general astigmatic beam description is needed, with unusual features.

An example of this situation is found in the case of the Dogleg option [5], where the beam after the first mirror is simply astigmatic (figure 8) and is described by independent gaussian beam propagation in the two directions perpendicular to the beam axis direction. Being those axes neither perpendicular nor parallel to the plane of incidence associated to the second mirror, the output beam after the second reflection is generally described by general astigmatism laws. Furthermore the principal directions of curvature of the second mirror’s surface do not lay in the plane of incidence, unless for nominal (zero steering) position. The simplest example of this type of astigmatism is found when a simply astigmatic beam passes through a cylindrical lens with axes not coincident with the axes of the astigmatism ellipse [6]. The astigmatism axes are no more fixed in space in this case, rotating along the path of propagation (figure 8b).

9. Beam description at first order

For a first evaluation of beam size in the plasma position, the beams can be approximated (at first order) with simply astigmatic beams, introducing some simplifications in the analytical description of the setup, for the simpler evaluation beam characteristics.

The procedure for obtaining the output beams is:
- fully describe the simple astigmatic beams after first mirror, given first mirror curvatures and incidence angles; compute directions of the axes of the astigmatism ellipse for that beam.
- assume curvatures of the second mirror surfaces as constant.
- compute the local focal lengths as functions of the true incidence angle on the second mirror.
- assume independent propagation of the reflected beam in two directions chosen as the tangential and sagittal directions (may be different from poloidal and toroidal)
10. Simplest double curvature mirrors
The toroidal and the football-shaped surfaces have been chosen as mirrors (figure 9), because of the simplifying properties of these double-curvature surfaces: the curvature radii in two particular planes are constant. Choosing one of those planes as the incidence plane of the incoming beam at zero steering, the curvature radii are nearly constant when the beam is scanned on the mirror. In any case the surfaces are different out of the principal planes, requiring a precise description of the surface for an accurate computation of the beam output direction.

![Figure 9. Shape of the toroidal (left) and football-shaped (right) surfaces. The intersections with the planes on which the curvature is constant are shown.](image)

11. Beam width at a constant major radius
First-order beam width has been evaluated preliminarily with the method described above, at a fixed ITER major radius, corresponding nearly to the absorption layer. First and second mirrors are a torus and a football-ball respectively.

The final beams have a pronounced astigmatism (figure 10), with a more diverging beam in the quasi-poloidal direction, the one most limited by requirements on the steering range.

Further refinements to the beam description could be done:
- assuming the true geometry of reflection on the first and second mirror (compute principal curvatures at every reflection point)
- using formulas of general astigmatism in order to find the beam parameters after the second reflection,
- propagating the generally astigmatic beams after second mirror (no more independent propagation in the two planes).

A further step should include the description of generally astigmatic beams in beam tracing codes.

![Figure 10. Beam propagation with distance from the last mirror (left, measures in mm) for different steering angles and beam width (mm) near resonance (at R=5650) in quasi-toroidal and quasi-poloidal directions](image)
12. Conclusions
The choice of the optics for the Remote Steering is a result of trade-off of beam size with steering range. Only the curvature on the steering plane direction is constrained, leaving some margin for improvements in the perpendicular direction. The beam characteristics vary with steering angle, depending on focal length, but with different behavior for different mirror shapes, even at equal nominal focal length. Beam description, apart from the simplest case, involves astigmatic (if not generalized astigmatic) beams whose ellipse directions do not coincide with poloidal or toroidal directions. Typical beam sizes obtainable with the remote steering single mirror and dogleg configurations are around 80 and 100 millimeters respectively, with steering ranges required at the plasma of ±10° and ±18°, whose variability depends mainly on the launching position.

Sources of distortions are the use of a single mirror for many different beams (as emerging from the RS waveguide) and thermal distortions arising from heat losses on the surface. They can be quantified only when the thermal energy release is known and the cooling setup described. An accurate description of real beams coming out of real mirrors (in case including generally astigmatic beams, even in beam tracing codes) is a necessary step in the launching system evaluation and optimization. The beam characteristics in the plasma are, of course, only one of the many factors concurring to final choice on the configuration, which is still pending.

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