# ECRH Beam Optics Optimization for ITER Upper Port Launcher

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**Abstract.** The electron cyclotron resonance heating (ECRH) launchers are going to be installed in four ITER upper ports for stabilizing the neoclassical tearing mode (NTM) by driving currents (co-ECCD) locally inside either the $q$ = 3/2 or 2 island. The efficiency in stabilizing the NTM depends on the peak current density ($j_{CD}$), relative to the local bootstrap current. The mm-wave optical design has been optimized to provide the largest $j_{CD}$ over the region, where NTMs are expected to occur in the plasma cross section. The optimization has been carried out for two designs: one applied only to NTM stabilization and another for Extended Physics launcher for an enhanced ITER ECRH physics programme. The main limitation to the optical system is the spatial restrictions of the port plug and blanket shield module. The ECRH launcher has 8 beams (4 beams × 2 vertical rows) per port, with each beam incident on a focusing and steering mirror. The beam optics has been optimized by overlapping 4 beams on each mirror, this overlap maximizes the beam spot size (~64mm) on the focusing mirror within the available space, which can focus a narrow beam waist (~21 mm) far into the plasma (~2 m). The output beam characters can be controlled by modifying the focusing mirror curvature.

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## INTRODUCTION

The ITER ECRH system is designed to heat and drive current locally for the various plasma equilibria envisioned for ITER. Two ECRH launchers will be installed on ITER in order to access accessible nearly the entire plasma cross section for the corresponding the physics experiments. One launcher is located in the equatorial port and is used for steady state operation, L- to H-mode transition assist, Q>10 achievement and Sawteeth control [1]. The second launcher is located in four upper ports with the sole role to stabilize NTM instability occurring at the $q$ = 3/2 or 2 [2].

NTM stabilization is achieved by driving current (ECCD/CD) locally inside the magnetic island. The efficiency is evaluated by the ratio of the peak driven current density divided by the local bootstrap (BS) current density ($\eta_{NTM}$=Max($j_{CD}$)/$j_{BS}$) [2], thus favoring a narrow-peaked $j_{CD}$ deposition profile. The mm-wave optical design has been optimized to provide a maximum $\eta_{NTM}$ over the entire range in which the NTMs are expected to occur in the three ITER scenarios 2, 3a and 5, with the beam optic limited to the spatial restrictions of the upper port and the mm-wave mechanical/engineering limitations. Note that the physics objective was to provide sufficiently high $\eta_{NTM}$ ($\eta_{NTM}$>1.2) for completely stabilizing the NTM. This optimization was performed on two variants of the upper launcher: the NTM and the Extended Physics (EP) launchers. The NTM launcher has a limited steering range accessing only the region where the NTMs are expected to occur ($0.64 \leq \rho_\psi \leq 0.93$). The second (EP-launcher) has an extended steering range ($0.49 \leq \rho_\psi \leq 0.95$) with the physics applications more equally partitioned between the equatorial launcher (EL) and the upper launcher (UL) for an overall extended physics capabilities of the ITER ECRH system [3]. The EP launcher can be optimized for control of the Sawteeth or ELM in addition to its primary function of as NTM stabilization.

The steering range of the EP launcher is achieved by spreading out the steering range of the two steering mirrors of each port with the upper steering mirror aimed more toward the plasma center ($0.39 \leq \rho_\psi \leq \sim 0.89$) and the lower steering mirror toward the plasma edge ($\sim 0.75 \leq \rho_\psi \leq 0.93$). The rotation of each steering mirror is reduced, which relaxes the engineering constraints on the steering mechanism. The disadvantage of the EP launcher is that the full-20 MW injected power can only be applied in the overlap region of the two steering mechanisms as $\sim 0.75 \leq \rho_\psi \leq \sim 0.89$.

The optimization for obtaining the optimal output beam has been carried out for both designs, the parameters of optimization included: waveguide size and orientation, incident angle on the focusing mirror (see figure 1), focusing mirror curvature and output beam characteristics. This procedure was performed in collaboration with the beam tracing analysis presented in references [4,5].

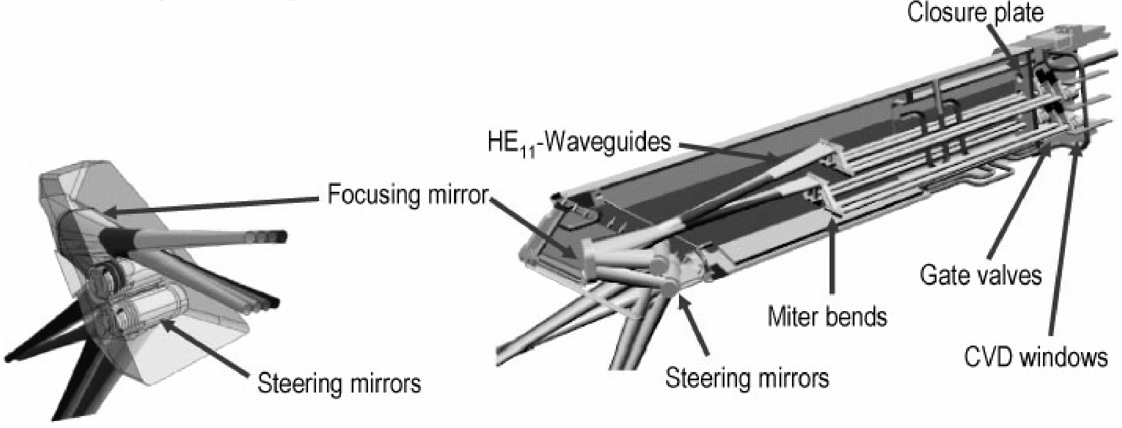

**FIGURE 1.** Upper port launcher's composition.

## LAUNCHER'S LIMITATIONS AND IDEAL BEAM PARAMETERS

The main limitation on the UL mm-wave optical design is the available space in the blanket shield module (BSM). The steering mirror ensemble (composed of a mirror and steering mechanism [6]) must fit into the narrow BSM (see figure 1). There is only enough space for two steering mechanisms, which implies that four beams must be incident on each steering mirror. Note that the UL was initially required to have 8 beams per port plug for the 24 beam ECRH system. The optimum arrangement is shown in figure 1 with a single focusing mirror (FM) placed above the two steering mirrors (SMs) [7].

The two mirrors are used for decouple the focusing and steering aspects of the launcher. Here we employed the combinations of; one FM and two SM for NTM launcher, or two FM and two SM for EP launcher. The size of FM and SM are limited to (H)×(W)=~300×370, 150×280 [mm], respectively. The dimension of FM is smaller for the NTM because the two beam rows partially overlap, while for the EP launcher two mirrors are used for optimizing the beam focusing based on the differing distances between the FM and deposition location in the plasma for the two SMs.

Superimposing 4 beams on each mirror maximizes the beam spot size on the FM (~64 mm), the large spot size makes it possible to focus a smaller beam waist (~21 mm) far into the plasma (~2 m). The four beams launched from a given SM have slightly different (R,Z) launch points, for fixed toroidal ($\beta$) and poloidal ($\alpha$) launching angles, the beams will be deposited in different locations, resulting in a broadening of the $j_{CD}$ profile and a degradation of $\eta_{NTM}$. The spread in deposition location of the four beams can be minimized over the entire scanning range by introducing a small divergence angle in the toroidal direction. The divergence angles can be controlled by modifying the focusing mirror curvature in the toroidal direction, which is also used to compress the beam assembly onto the steering mechanism. The optimizing parameters are listed in table 1.

**TABLE 1. Optimizing parameters**

| | |
|---|---|
| $w_{0,\mathrm{WG}}$ | Spot size at waveguide (WG) exit |
| $w_{0,\mathrm{p}}$ | Output beam's waist size |
| $z_1$ | Incident beam's focal length |
| $z_2$ | Output beam's focal length |
| $\theta_{\mathrm{i}}$ | FM incident angle of parallel direction along with the propagation |
| $\theta_{\mathrm{h\text{-}off}}$ | FM incident angle of perpendicular direction to the propagation |
| A | Ellipsoid's major axis length |
| B | Ellipsoid's minor axis length |
| $\Delta\beta$ | Divergent/convergent angle of endmost beam |

The ideal injected beam is assumed to have a circular Gaussian beam with the characteristics given in table 2 for the two UL variants. The optimum beams were determined by scanning the beam waist size, toroidal injection angle and steering mirror tilt angle as described in references [4,5,8].

**TABLE 2. Ideal Incident Beam Characters.**

| Launcher Type | $w_{0,p}$ / Focal Length [mm] | $\Delta\beta$ [deg.] |
|---|---|---|
| NTM Launcher (Upper row) | 21 / ~2100 | -0.35 |
| NTM Launcher (Lower row) | 21 / ~2100 | 0.00 |
| EP Launcher (Upper row) | 21 / ~1600 | +1.30 |
| EP Launcher (Lower row) | 29 / ~2700 | +1.00 |

# OPTIMIZATION RESULTS

The optimization was performed by varying the focusing mirror shape such that the output beam approached the optimum (Table 2), while maintaining the four beams on the steering mirror with the optimal divergence angle for the closest super positioning of the beams in the plasma. Note that the divergence angle optimization was performed only for the EP launcher. FM shape is set as an ellipsoidal and its initial shape has been calculated on the Gaussian beam reflection [9,10,11].

## Incident Angle Dependence

Although the incident angle, $\theta_1$ is mainly determined by the mm-wave component layout and port plug spatial restrictions, there is some flexibility in the design to take advantage of the optimum $\theta_1$. $\theta_1$ is scanned while keeping ellipse and input beam parameters ($w_{0,WG}$ and $z_1$) fixed. As $\theta_1$ varies from the optimum (16° for output circular beams) the beam becomes astigmatic as shown in figure 2, either which can be used to correct for opposite astigmatism that may occur in forcing the beam divergence (to be described in the following sections).

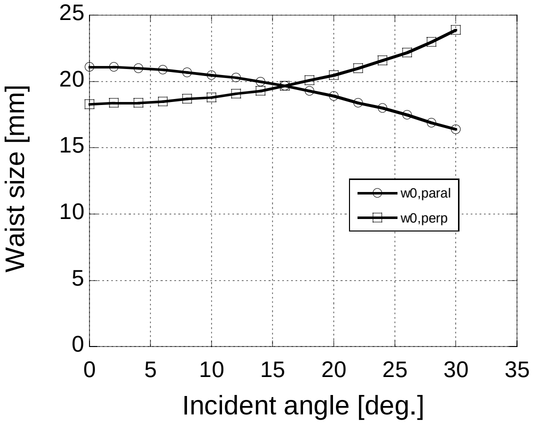

**FIGURE 2.** Incident angle dependence for center reference beam. ($w_{0,WG}$=19.3mm)

## Major and Minor Axis Lengths Modification

The optimum divergence angle and compressing the beams within the available space on the mirrors can be achieved by varying the FM curvature. The mirror curvature is taken as an ellipsoid of evolution with a major axis of A and minor axis of B, defined by a single beam launched from the ellipse focal point with the desired input and output beam characteristics described above. The major and the minor axis were varied from the optimum by ΔA and ΔB until the beams had the desired divergence angle, fit within the SM size and had the poloidal beam waist corresponding to the optimum. By varying the ΔA or ΔB respectively, it is found that ΔA modification gives the variation of $w_{0,\mathrm{paral}}$ with keeping $w_{0,\mathrm{perp}}$, while ΔB modification gives Δβ variation but distorting $w_{0,\mathrm{paral}}$ and $w_{0,\mathrm{perp}}$.as shown in figure 3. Under the actual conditions, ΔB variation requires ~ -450 mm for obtaining Δβ =+1.0°.

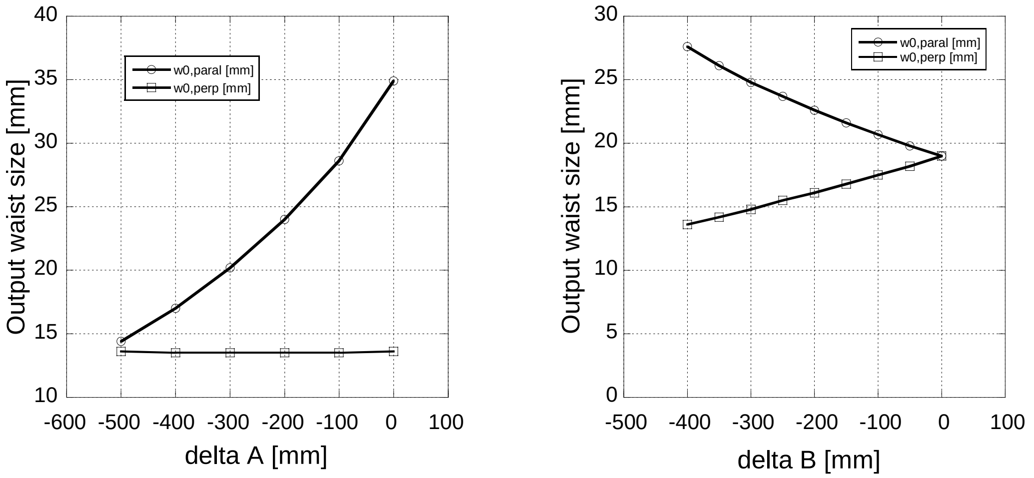

**FIGURE 3.** ΔA/B dependence. ($w_{0,\mathrm{WG}}$=19.3mm)

# CONCLUSION AND CURRENT OPTIMIZED CONDITION

ΔA/B modifications can make the output adjustment keeping the incident beam geometry, which is quite important for severely limited upper port launcher spacing condition. As can be expected the variations in ΔA strongly determine the output beam waist size, $w_{0,\mathrm{paral}}$, and ΔB is for Δβ (divergence angle). Note that the requirement on the divergence angle and fitting the four beams onto the available space affects the beam astigmatism severely. For the fixed SM size, a 1 degree divergence gives 30 % difference for the perpendicular (poloidal direction) waist size. Hence, the reasonable procedure for the optimization becomes; (1): set the minimum waveguide exit horizontal offset position in accordance with the waveguide size, (2): choose the incident focal length, spot size at FM and incident angle, (3): set the endmost beam's FM hitting point by the spatial limitations, (4): arrange and shape the outputs by ΔA/B modifications.

The optimized parameters at present (of 2006 May) are obtained taking into the limitations for NTM and EP launchers as shown in table 3 and 4. Note that the optimum divergence angle for the NTM launcher has not been determined. Note that the astigmatism provides only a moderate degradation (sometimes a small enhancement depending on the deposition location) to the NTM stabilization efficiency as described in reference [4].

**TABLE 3. Optimized Condition for NTM launcher for Upper and Lower Rows.**

| | **Δβ [deg.]** | **Spot Size at FM [mm]** | **$w_{0,\mathrm{WG,parallel}}$ [mm]** | **$w_{0,\mathrm{WG,parallel}}$ [mm]** | **$z_{2,\mathrm{parallel}}$ [mm]** | **$z_{2,\mathrm{perp}}$ [mm]** |
|---|---|---|---|---|---|---|
| Up | -0.35 | 62.0 | 21.0 | 13.8 | 2182.5 | 1483.2 |
| Lo | 0.00 | 64.0 | 18.4 | 14.2 | 2004.4 | 1577.5 |

**TABLE 4. Optimized Condition for EP launcher for Upper and Lower Rows.**

| | **Δβ [deg.]** | **Spot Size at FM [mm]** | $w_{0,\mathrm{WG,parallel}}$ **[mm]** | $w_{0,\mathrm{WG,parallel}}$ **[mm]** | $z_{2,\mathrm{parallel}}$ **[mm]** | $z_{2,\mathrm{perp}}$ **[mm]** |
|---|---|---|---|---|---|---|
| Up | +1.30 | 62.0 | 21.0 | 19.1 | 2183.1 | 2001.6 |
| Lo | +1.00 | 60.0 | 29.0 | 17.4 | 2714.7 | 1779.6 |

* The difference of $z_{2,\mathrm{parallel}}$ between NTM and EP is caused by waveguide exit position setting.

## ACKNOWLEDGMENTS

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