Sensitivity of ITER ECRH Upper Launcher to Steering Errors and Changes of Profiles and Integration with Equatorial Launcher

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Abstract. The influence of steering errors on Neoclassical Tearing Mode Control by means of the ITER ECRH Upper Launcher is numerically and statistically studied and recommendations are given for the alignment. Changes of density and temperature profiles are shown to have a negligible effect on the launch angles and to affect the driven current according to a well known scaling of current drive efficiency. Finally, a study of the radial positions accessible by the Upper and Equatorial Launchers is presented.

1. Introduction

The ITER Tokamak will be equipped with an electron cyclotron resonance heating (ECRH) facility. Depending on the application, the system will utilize an upper or a horizontal launcher to inject gyrotron beams into the plasma. While some 120GHz gyrotrons are envisaged for plasma start-up, most of the sources will operate at 170GHz and may serve a number of tasks:

- Core heating to burning conditions
- Current drive in the plasma core and off-axis
- Control of MHD instabilities such as sawteeth, Neo-classical Tearing Modes (NTMs) and possibly edge localised modes (ELMs).

In particular, the main use of the Upper launcher will be the control of the pressure-limiting \( m/n=3/2 \) and 2/1 NTMs. This will be achieved by compensating, by means of electron cyclotron current drive (ECCD), the missing bootstrap current inside the magnetic islands. In the case of continuous ECCD, the efficiency of NTM stabilization is proportional to \( I/d^2 \), where \( I \) is the driven current and \( d \) the width of the driven current profile \[1\]. We define \( d \) as the full width of the profile at \( 1/e \) of its peak value. In the case of time-modulated ECCD, the current driven within the island is relevant. Therefore, if the mode is suppressed in its early phase, when the island width \( w \) is small compared to \( d \), the figure of merit for modulated ECCD will be proportional to \( I/d \) \[1\].

The upper launcher is being optimized, within the geometrical constraints of the ports used, with an aim of maximizing \( I/d \) and \( I/d^2 \) \[2,3\]. One of the goals of the present paper is to study to what extent these figures of merit and the optimum launch angles are robust against variations of plasma parameters and of the launch geometry. In particular, the effect of density and temperature profile variations is investigated in Sec.2 and the effect of misalignment is considered in Sec.3. First we numerically predict the changes of \( I/d \) and \( I/d^2 \) and the displacement from the target absorption locations for a single misaligned mirror, then we statistically generalize the results to the full set of 24
“final mirrors” of the upper launcher, under the assumption that they are randomly and independently misaligned. These estimates translate to prescriptions for the precision of alignment required. Another goal of this study is to check the flexibility of the entire ECRH system to fulfill several tasks at different radial locations, ranging from the plasma core to close to the edge. As the current drive requirements significantly change with the application, the results are summarized in the form of a plot of the maximum density of current that can be driven at various radii (Sec.4).

![Fig.1](image1.png) **Fig.1** Temperature profile multiplied by $1 + a [1 - \cos(2 \pi \rho)]$, where the parameter $a$ is such that $T_e$ at mid-radius is perturbed by 0%, ±15% and ±30%

![Fig.2](image2.png) **Fig.2** Density profiles with various pedestal widths

![Fig.3](image3.png) **Fig.3** Current driven by 1MW deposited in the vicinity of the $q=3/2$ (left) or $q=2$ surface (right), as a function of $\Delta T_e / T_e$ at mid-radius (see fig.1) for optimum choice of $\alpha$ and $\beta$. Nearly overlapping curves correspond to different $n_e$ profiles in fig.2.

2. Effect of change of plasma parameters and profiles on CD efficiency

The propagation and absorption of gyrotron beams launched from the ITER ECRH upper launcher was modeled by means of the ray tracing and Fokker-Planck code BANDIT-3D [4]. The 3 port, spherical mirror “reference scheme” [3] was used for the shape of the mirrors. This implied the beams to be astigmatic and characterized by a non-negligible focal spread of 171 and 284mm for the lower and upper row of mirrors, respectively. To take this into account, different geometrical optics approximations (namely, different foci and angular widths) were adopted in different axial sections of the beams [5]. The equilibrium for ITER “scenario 2” (Q=10, 15MA, inductive, $B_0=5.3T$, $T_{e0}=24.8keV$, $n_{e0}=1.02x10^{20}m^{-3}$) [5] was imported from the equilibrium code EFIT. The density, temperature and effective charge profiles were tabulated by the transport code ASTRA against the square root of the normalised toroidal flux, $\rho$. 

![image3.png]
Pairs of poloidal and toroidal launch angles $\alpha$ and $\beta$ for which current is driven at the rational surfaces of interest $q=2$ and $q=3/2$ were identified. Among them, optimal pairs of $\alpha$ and $\beta$ yielding maximum $I/d$ and $I/d^2$ were obtained. The optimization was repeated for various $T_e$ and $n_e$ profiles.

Variations of the core temperature and density of up to 30%, while keeping the shape of the profiles constant, were found to modify the optimal launch angles for NTM stabilization by less than $0.5^\circ$, and to affect $I/d$ and $I/d^2$ according to the expected scaling of $I$ as $T_e/n_e$.

The shapes of the profiles were also varied. The $T_e$ profile was multiplied by a sinusoidal function keeping its core and edge values fixed while varying the value at mid-radius by up to $\pm 30\%$ (fig.1). This is equivalent to changing the peaking factor of the profile. The $n_e$ profile, instead, is expected to have a flat-top shape, therefore the only free parameter—besides the height—is the width of the pedestal. Density profiles with pedestals twice wider and twice narrower were considered (fig.2).

Ray tracing and Fokker-Planck simulations were repeated for each combination of $T_e$ and $n_e$ profile. The optimal launch angles $\alpha$ and $\beta$ varied by less than 0.15$^\circ$ and the width of the ECCD profile by less than 3%. Significant variations were registered only for the total driven current $I_{\text{cd}}$ when changing the $T_e$ profile, in agreement with the $T_e$ scaling of ECCD efficiency (figs.3). By contrast, variations of $n_e$ pedestal width were found to have a negligible effect, probably because they influence a narrow and dilute region at the edge, far from the deposition volume, resulting only in a modest effect on the refraction of the rays. This is hardly detectable in figs.3, where curves for different pedestal width nearly overlay.

Finally, note that figs.3 not only illustrate ECCD changes with $n_e$ and $T_e$, but also suggest how $n_e$ and $T_e$ errors propagate in ECCD estimates based, for example, on Thomson Scattering or other $n_e$ and $T_e$ diagnostics.

3. Sensitivity to steering errors

3.1. Single misaligned mirror

The angular sensitivity of NTM stabilisation from a single beam was studied via a simple 2D scan of $\alpha$ and $\beta$ with steps of 1$^\circ$ in both directions.

The contours in fig.4 summarize how sensitive $I/d$ and $I/d^2$ are to variations of $\alpha$ and $\beta$. However, note that steering errors are not completely arbitrary in the $\alpha$, $\beta$ plane, but are more likely along the steering direction $\gamma$. In turn, this is nearly poloidal, tilted by 2$^\circ$ counterclockwise with respect to $\alpha$. In that direction, fig.4 shows variations of 5-10% in $I/d$ and less than 10% in $I/d^2$ for each degree of misalignment. Hence, the misalignment of one mirror only slightly affects $I$ and $d$. The main effect is the displacement of the driven current. The displacement of the peak from the “targets” (i.e. the $q=2$ and $q=3/2$ surfaces) is plotted in fig.5 in units of $\rho$. Steering errors of the order of 1$^\circ$ lead to displacements of the order of 0.01. These values have to be compared with the island width.

Fig.5 also confirms what is intuitive, that the alignment is more critical for $q=3/2$, as it requires bigger poloidal angles and is farther from the launch position. A small change of angle may therefore result in a significant radial shift.

It is interesting to normalise the displacement to the CD profile width $d$. In this regard, fig.6 shows that each degree of misalignment causes a shift of about $d/4$. The condition of complete misalignment (depicted in black), in which almost no current is driven at the surface of interest, is reached for steering errors of 4-5$^\circ$.

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1 Note that the $n_e$ and $T_e$ changes under consideration are not correlated, the pressure profile is not conserved and could be inconsistent with the current profile and therefore with the magnetic configuration imported from EFIT. Note also that changes of pressure profiles imply changes of bootstrap current and therefore of the ECCD requirements for NTM stabilisation.
Fig. 4 Contours of $l/d$ (left) and $l/d^2$ (right) for the upper (top) and lower row (bottom) as a function of the poloidal and toroidal launch angle $\alpha$ and $\beta$. Here $l$ is expressed in kA and $d$ in units of $\rho$. Note the different colour scales for the lower and upper rows.
**Fig. 5** Displacement of the ECCD peak from the \(q=2\) and \(q=3/2\) targets, in units of \(\rho\), for the lower (left) and upper mirror (right). The upper white stripe indicates perfect alignment to \(q=3/2\), the lower one indicates perfect alignment to \(q=2\). Darker shades of gray indicate worse and worse misalignment. The amount of misalignment—in units of \(\rho\)—has to be compared with the island width.

**Fig. 6** Like fig. 5, but with the displacement normalised to the full width of the CD profile at \(1/e\) of the peak.
Fig. 7 Perturbed launching conditions for 5 sets of 12 randomly, independently misaligned mirrors of the lower row following a normal distribution of standard deviation $\sigma = 0.2^\circ$ (left) or an anisotropic distribution such that misalignment is more probable along $\gamma$ ($\sigma = 2^\circ$) than in the perpendicular direction ($\sigma = 1^\circ$) (right). The steering direction $\gamma$ is tilted by $\sim 2^\circ$ vs. $\alpha$. $\sigma$, $2\sigma$ and $3\sigma$ contours also shown. The pictures refer to NTM 3/2 stabilisation from the lower row. The same approach was used for NTM 2/1 and for the upper row.

To conclude, the effect of misalignment of a single mirror on the performance is a combination of two effects: a change, not necessarily a decrease, of ECCD efficiency (fig. 4) and the loss of some current which is driven outside the island (fig. 5-6) and therefore does not contribute to NTM stabilisation.

3.2. Array of misaligned mirrors

The considerations about the misalignment of a single mirror contained in the previous subsection can be generalised to an array of mirrors such as the upper launcher, by addressing how steering errors of individual mirrors correlate. First of all, one has to distinguish between systematic and statistical steering errors.

The first might originate from construction errors and thermal or electromagnetic stresses. Construction errors can be minimised to much less than $1^\circ$ by appropriate techniques. Systematic misalignments associated with the thermal deformation of the machine and of the mirrors can also be compensated by designing and numerically optimising the system, e.g. via ray-tracing and Fokker-Planck calculations, not at room temperature but at operating temperature. For the same reason, on the experimental side, the system should be aligned at operating temperature or in any other manner that accounts for thermal deformation. Electromagnetic stresses can also be incorporated in the design and the numerical optimisation be performed for the stressed mirror in a stressed machine. This seems possible for steady state, but could be challenging for transients.

Hence, systematic errors are likely to be small compared to statistical errors. In turn, on the basis of the experience with present tokamaks, statistical errors for ITER are speculated to amount to less than $2^\circ$. Within this limit, we make four choices: that the “average misalignment” will amount to $0.2^\circ$, $0.5^\circ$, $1^\circ$ or $2^\circ$, covering a wide range of experimental situations from good to poor alignment. The effects for other values can easily be obtained by interpolating between the results for these four values. As misalignments of distinct mirrors are statistically independent, they are expected to follow a Gaussian distribution of standard deviation $\sigma = 0.2^\circ$, $0.5^\circ$, $1^\circ$ or $2^\circ$. Here we are supposing a certain amount of misalignment to be equally probable in $\alpha$ as in $\beta$. In other words, we are assuming the distribution of steering errors to be isotropic in $\alpha$ and $\beta$. Nevertheless, there might well be a preferential direction more prone to misalignment (see previous Section). For this reason, an anisotropic distribution with $\sigma = 2^\circ$ along the steering direction $\gamma$ and $\sigma = 1^\circ$ perpendicularly, is also considered here. The optimal angles $\alpha$ and $\beta$ were perturbed according to these 5 distributions, as follows. First, 100 sets of 12
Fig. 8 Effect on the 24 mirror system of the mirrors being misaligned by, on average $\sigma=0.2^\circ, 0.5^\circ, 1^\circ, 2^\circ$. Deposition in the vicinity of the $q=3/2$ surface is considered here. Left: Histograms of displacements of the CD peak from $\rho=0.656$ (red) and probability distribution (blue). Right: Histograms of CD profile width for $\sigma=0.2^\circ, 0.5^\circ, 1^\circ, 2^\circ$. Dashed vertical line: width for perfect alignment. Solid vertical lines: widths for well-aligned beams broadened by $0.2^\circ, 0.5^\circ, 1^\circ, 2^\circ$.
Fig. 9 Schematic explanation of why the misalignments of several beams compensate each other, resulting in a “total beam” less misaligned (a) but broader (b). Consequently, the ECCD profile for n beams (d) is shifted by an amount √n times smaller than for 1 beam (c) but is a lot broader. In fact, if every beam is misaligned by, say, 1°, the total beam is defocused by ~1° and the ECCD profile is proportionally broader.

perturbed launching directions (one for each mirror of the lower row) were generated by using a random number generator (fig. 7). The procedure was repeated for the upper row, for 2/1 and 3/2 stabilisation. The random number generator was set to σ = 1°, then the same sequence of random numbers was adapted to wider (σ = 2°, anisotropic 1°/2°) or narrower (σ = 0.2°, 0.5°) Gaussian distributions.

The simultaneous injection of 1MW beams from 24 independently misaligned mirrors (12 from the lower row and 12 from the upper one) was modeled by BANDIT-3D. The simulation was repeated for 100 sets for each of the 10 cases (2 target deposition locations, 5 distributions of steering errors). The result is that the total CD profile is shifted and broadened compared to an ideal profile obtained in the absence of misalignment. The amount of displacement and broadening changes with the initial conditions. As the angular initial conditions are normally distributed, the final radial shift is also expected to follow a Gaussian distribution. This is confirmed by fig. 8, where the expected distribution is compared with histograms displaying the number of times that the displacement in ρ took certain values in the simulations. The standard deviation σρ of such a radial distribution is easily related, by dρ/dσ, to the standard deviation σα for the steering error of the “total beam”. By this, we mean a single beam yielding approximately the same ECCD profile as the real set of 24 beams. Due to partial compensation between the errors of the individual beams, the equivalent beam is misaligned by a smaller amount (fig. 9a). More precisely, it follows a distribution of standard deviation σe = σ / √24. Fig. 8 suggests that, even in the worst case, the overall steering error will amount to a fraction of a degree. For such a small misalignment there is no risk of missing the flux surface of interest, as illustrated by fig. 6.

The main consequence for the 24 mirror system of the mirrors being misaligned is rather the decrease of CD localisation. This is documented by the histograms for the width of the CD profile in fig. 8. The width for a single beam is also plotted for comparison. The plots refer to NTM 3/2 stabilization. Similar results were obtained for NTM 2/1. The plots show that steering errors of the order of the beam angular divergence, θ ≈ 2°, are equivalent to an increase in the angular width of the beams by the same amount. For smaller and smaller misalignments the approximation progressively loses its validity and the overall width tends to θ until, for σ = 0.2°, broadening becomes smaller than 2%. Simulations show that aligning all the beams with 0.5° precision results in a broadening of about

2 the radial shift ∆ρ is proportional to the steering errors ∆α and ∆β only in the limit in which they are small. For large angular variations the curvature of the magnetic surface and other effects must be taken into account, making the relation non-linear.

3 evaluated at ρ = 0.778 or 0.656, i.e. the q = 3/2 and q = 2/1 locations for ITER scenario 2
Fig. 10 For steering errors anisotropically distributed as in fig. 7 right, i.e. evaluating \(\sigma = 2^\circ\) along \(\gamma \approx \alpha\) and \(1^\circ\) in the perpendicular direction (\(\approx \beta\)), the total \(J_{\text{CD}}\) profile in the vicinity of the \(q=2\) surface behaves more like the \(2^\circ\) case than the \(1^\circ\) case of fig. 8, confirming that the system is more sensitive to misalignments in \(\gamma\).

The effect, in terms of \(I/d\) and \(I/d^2\), is comparable with that caused by changes of \(T_e\) and \(n_e\) and is therefore still acceptable. Average misalignments of \(1^\circ\) or \(2^\circ\), however, are clearly unacceptable, as they broaden the CD profile by 33% and 103%, respectively. The results for the anisotropic \(1^\circ/2^\circ\) case (fig. 10) resemble more those for \(\sigma = 2^\circ\) than for \(\sigma = 1^\circ\) in fig. 8, thus confirming that CD localisation is more sensitive to (de)focusing in the poloidal direction than in the toroidal one.

The effect on the current peak displacement illustrated in figs. 8 and 10 takes place for any antenna design because the observed distribution only depends on the steering errors, not on the individual beam width, in either direction. Therefore, it is also independent of the amount of astigmatism. The beam geometry, on the other hand, can affect the FWHM of the total CD profile, also shown in figs. 8 and 10. However the main conclusion, that its more likely value will be bounded between the FWHM in absence of misalignment and the FWHM for well-aligned but broadened beams- will still be valid.

Finally it should be noted that when single beams are misaligned by more than their width, they can form side-peaks or tails in the radial profile of total driven current. As an example, for \(\sigma = 2^\circ\), tails and multiple peaks were observed respectively in 14% and 8% of simulations for NTM stabilisation at \(\rho = 0.656\) (q=3/2), which may result in driving current in an undesired position.

4. Integrated Analysis of Upper and Equatorial Launcher

In addition to the upper launcher, the ITER ECRH system also features a front steering equatorial launcher sharing the same gyrotrons and injecting the 24 beams from 3 mirrors located at \(z = 0.03, 1.21\) and \(0.062\)m, i.e. at the plasma midplane, \(59\)cm above and \(59\)cm below. The launch will be horizontal, with toroidal steering capability in the range \(20\text{-}45^\circ\). Note that this angle is measured at the mirror and is relative to the vertical midplane of the port [6], but corresponds to \(\phi = 17.4\text{-}42.4^\circ\) relative to the poloidal section at the mirror and to \(\phi = 19.6\text{-}49.1^\circ\) when entering the plasma\(^4\), relative to the local poloidal section.

As mentioned in the introduction, the integrated system at 170GHz may serve a number of tasks. These include heating and current drive in the core and off-axis, and control of MHD instabilities such as sawteeth at \(\rho \approx 0.5\), NTMs at \(\rho \approx 0.6\text{-}0.8\) and ELMs at \(\rho \approx 0.9\). Hence, it will be desirable for the upper and equatorial launcher to access, together, any radial position from the plasma core to the edge.

\(^4\) for a major radius \(R = 8.2\)m where the beam enters the plasma
**Fig. 11** Contours of normalised current density vs. radial positions \( \rho \) and toroidal steering angle \( \phi \) for the equatorial launcher. Normalisation is such that red corresponds to the peak of current density for a given \( \phi \). Some negative current is also driven, due to \( \sim 10\% \) of power being absorbed by the relativistically down-shifted 2\textsuperscript{nd} harmonic, as already found in [7]. However, note from the colour scale that the negative current in question is 10 times smaller than the positive peak.

**Fig. 12** Contours of current density vs. radial positions \( \rho \) and toroidal steering angle \( \phi \) for 1MW injected from the lower, middle or upper mirror of the equatorial launcher.
Fig.13 Contours of $j_{CD}$ for 1MW injected from the lower (left) or upper (right) row of mirrors of the upper launcher, as a function of the steering angle $\gamma$ and radial location $\rho$, showing that, by scanning $\gamma$ between $-12^\circ$ and $+12^\circ$, the upper launcher covers the range $\rho \approx 0.46-0.82$. A wider steering range would not extend the range to outer radii and would result in too broad a ECCD profile at inner radii.

To check that this is possible, the geometry of the ITER ECRH equatorial launcher was implemented in BANDIT-3D using bundles of 160 rays with correct focus and divergence and a scan of the toroidal launch angle $\phi$ was performed. The radial locations accessible from the lower, middle and upper mirror (LM, MM, UM) are plotted against $\phi$ in fig.11. The trajectory of the current peak is shown in red. The asymmetry between LM and UM is due to the fact that, when entering the plasma, the upper and lower beams “see” the same toroidal field but opposite poloidal fields, one pointing toward the beam, the other away. As a result, the initial $N_{||}$ is different and the beams evolve in a different manner. The MM and UM plots may give the impression that the plasma edge can be reached, at least marginally, with the edge of the CD profile. However, they do so with very low efficiency (fig.12), partly because of the low $T_e$ at the edge and partly because of poor localisation. In this respect, note that the so-called “design 2” of the equatorial launcher has been implemented in this report. To date this is the favourite design because it offers better neutron shielding, but at the cost of a broader beam spot in the plasma, about 2 times broader than in “design 1” adopted in other studies [7,8]. Moreover, the fact that not all the beams are horizontal, but some of them are tilted vertically by $\pm 2.5^\circ$ has also been taken into account, and further broadens the CD profile.

The radial interval covered by the equatorial launcher with current density $J_{CD}>5kA/m^2$ per MW injected is $\rho<0.50-0.64$, depending on the mirror, with only the mid-plane mirror accessing $\rho<0.14$, in agreement with previous studies [7,8]. On the other hand, the upper and lower beam drive current more efficiently at $\rho=0.20-0.56$, thanks to narrower deposition as they impinge on the $\rho=0.20-0.56$ flux surfaces with nearly grazing incidence [7]. Outer radii, $\rho=0.46-0.82$, are accessible from the upper launcher (fig.13).

The information on the CD location contained in figs.12-13 is combined in fig.14. In that figure, the maximum $J_{CD}$ per MW injected is plotted -for the lower, middle and upper mirror of the equatorial launcher and for the lower and upper row of the upper launcher- as a function of $\rho$, irrespective of the launching angle $\phi$ or $\gamma$ at which that maximum is obtained. Note that the maximum $J_{CD}$ at a certain $\rho$ is not necessarily the peak of the CD profile for that case: sometimes the shoulder of a profile peaked elsewhere is higher than the local peak.
Fig. 14 Maximum driven current density –for proper setting of launch angles- by injecting 1MW from the lower, middle and upper mirror (LM, MM, UM) of the equatorial launcher and from the lower and upper row (LR, UR) of the upper launcher, as a function of $\rho$. Distinct radial ranges are accessible from different mirrors. The maximum current density for 20MW distributed among the mirrors according to their efficiency is also plotted, in a different scale (grey curve). The number in front of LM, MM, UM, LR, UR indicates how many beams are launched from each mirror or row of mirrors to generate the grey curve.

Six ranges with different characteristics of accessibility can be recognised in fig.14:

1. The plasma core $\rho < 0.14$ is accessible only from the middle mirror.
2. The interval $\rho = 0.14-0.47$ is accessible from all the equatorial launcher mirrors.
3. In the range $\rho = 0.47-0.63$ the equatorial and upper launcher domains overlap, even though some mirrors have very low efficiency. MM, UM and LR are more efficient in the subinterval $\rho = 0.47-0.57$.
4. UM, LR and UR are more efficient in the sub-interval $\rho = 0.57-0.63$.
5. The $\rho = 0.63-0.82$ range is practically accessible only from the upper launcher, if we exclude UM, which has a much lower efficiency.
6. There is no access to $\rho > 0.82$ with remote steering, for which the steering range is restricted to $\pm 12^\circ$. Outer positions, relevant for ELM control, could possibly be reached by front steering.

The total current density that can be driven by the equatorial launcher at $\rho < 0.47$, by the upper one at $\rho > 0.63$ or by a combination of the two in the overlap region is overlaid in fig.14. It ranges from 6.4MA/m$^2$ at the plasma centre to 100kA/m$^2$ at $\rho \geq 0.82$.

It should be remembered that fig.14 refers to ITER reference scenario 2 and will obviously change for other equilibria and profiles. A steering range $\gamma = -12^\circ/+12^\circ$ was considered for the upper launcher.
Fig. 13 suggests that increasing it to -15°/+15° would not give access to outer radii, e.g. the edge pedestal, to affect ELMs. It would only give access to inner radii, $\rho < 0.47$, where the upper launcher cannot compete with the equatorial one (see fig. 14).

Deeper penetration from the lower and upper mirror of the equatorial launcher could be achieved by tilting them upwards and downwards by $\sim 10°$. However, this would result in reduced efficiency at $\rho = 0.2-0.5$, because the benefits of grazing incidence would be lost.

5. Conclusions
Ray tracing and Fokker-Planck simulations have shown that the optimal launch angles for NTM stabilisation in ITER by means of ECCD are robust both against variations of density $n_e$ and temperature $T_e$ and against changes of the shape of the respective profiles. The effect on ECCD localization is also negligible, while the driven current changes according to the well known scaling of its efficiency as $T_e / n_e$.

The sensitivity of the upper launcher to steering errors has been investigated. The main effect for a single beam is the displacement of the deposition from the flux surface of interest. Such a displacement becomes comparable with the width of the current profile when the steering errors exceed 2°. In a set of 24 randomly, independently misaligned beams, these displacements compensate each other and the total CD profile is shifted by a negligible amount. The main effect, in the case of 24 beams, is the broadening of the total current profile. Simulations show that aligning all the beams with 0.2-0.5° precision results in a broadening of only 2-10%. In terms of efficiency of NTM stabilization this is comparable with the effect of $T_e$ and $n_e$ variations. Bigger misalignments however, of 1-2°, are clearly unacceptable, as they broaden the CD profile by 33-103%.

Finally, angular scans of the toroidally-steering equatorial launcher and of the poloidally-steering upper launcher show that the integrated ITER ECRH system covers all the radial positions from the core to $\rho = 0.82$. However, the CD efficiency might be marginal or not sufficient to fulfil some tasks, even at full power. Hence, as the upper and equatorial launcher share the same gyrotrons, it will be important to identify scenarios with a simultaneous need for upper and equatorial launch.

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References
[1] G.Giruzzi et al., Nucl.Fusion 39, 107 (1999)
[2] H.Zohm et al., this conference
[3] G.Ramponi et al., this conference
[4] A.G.A.Verhoeven et al., this conference
[5] R.Heidinger et al., this conference
[6] M.R. O'Brien et al., Proc. IAEA Technical Meeting on Advances in Simulation and Modelling of Thermonuclear Plasmas, Montreal (1992) p.527
[7] F.Volpe, Proc. 13th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Nizhny Novgorod, Russia, May 17-20, 2004
[8] K.Takahashi et al., Fus.Eng.Design 56-57 (2001) 587-592
[9] B.Lloyd et al., Proc. 12th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Aix-en-Provence, France, May 13-16, 2002
[10] H.Zohm, Proc. 13th Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating, Nizhny Novgorod, Russia, May 17-20, 2004