Crucial issues of multi-beam feed-back control with ECH/ECCD in fusion plasmas

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Abstract. Proof of principle of feed-back controlled Electron Cyclotron Heating and Current Drive (ECH/ECCD), aiming at automatic limitation (or suppression) of Neoclassical Tearing Modes amplitude, has been achieved in a number of present machines. In addition to Neoclassical Tearing Mode stabilization, more applications of well-localized ECH/ECCD can be envisaged (saw-tooth crash control, current profile control, thermal barrier control, disruption mitigation). However, in order to be able to take a step forward towards the application of these techniques to burning plasmas, some crucial issues should be more deeply analyzed: multi-beam simultaneous action, control of deposition radii $r_{dep}$, diagnostic of plasma reaction. So far the Electron Cyclotron Emission has been the most important tool to get localized information on plasma response, essential for both $r_{dep}$ and $r_{island}$ recognition, but its use in very hot burning plasmas within automatic control loops should be carefully verified. Assuming that plasma response is appropriately diagnosed, the next matter to be discussed concerns how to control $r_{dep}$, since all techniques so far used, or proposed (plasma position, toroidal field, mechanical beam steering, gyrotron frequency tuning) have limitations or drawbacks. Finally, simultaneous multiple actions on many actuators (EC beams), concurring to automatic control of one single parameter (e.g. NTM amplitude) might be a challenging task for the controller, particularly in view of the fact that any effect of each beam becomes visible only when it is positioned very close to the right radius. All these interlinked aspects are discussed in the paper.

1. Introduction
The non-inductive current driven by absorption of resonant Electron Cyclotron (EC) waves in high temperature and magnetically confined plasmas is successfully and routinely used to affect a number of key features of a tokamak discharge dependent on the current density profile, from heat confinement to plasma stability.

In major machines involved in the fusion programme (JT-60U, JET, AUG, DIII-D) the total current for best performances, with the electron density in the range $n_e \approx 10^{20} m^{-3}$, is in the 1÷10 MA range at
minimum, while the EC Current Drive (ECCD, where existent) in those conditions is in the range of 10÷100 kA at maximum. Although ECCD depends on many parameters, and special discharges with a much higher ECCD current percentage can be performed to address specific physics issues, likely those discharges will not be the best with respect to the fusion goal. For a successful control applications it is important that $I_{\text{ECCD}} / I_{\text{p,local}} \approx 1$, where $I_{\text{p,local}}$ is the non-ECCD current flowing in the layer in which $I_{\text{ECCD}}$ is driven. In high-$\beta$ plasmas, where ECCD efficiency is possibly limited by the high density and the total current is high for best confinement, localized EC absorption is important in order to have a local ECCD current density $J_{\text{ECCD}}$ comparable, if not larger, than the ohmic counterpart in the absorption region. Calculations of the EC driven current have been done on ITER reference scenarios, confirming this $I_{\text{ECCD}} / I_{\text{p}} \approx 1/100$ ratio also in this machine (with 25 MA of total non-ECCD current, and 24x1 MW Electron Cyclotron Heating power).

Since the ratio between ECCD and total current in most fusion-relevant conditions is in the order of 1/100, the capability to achieve any control with ECCD in this case is strictly dependent to the fact that the ratio $\delta_{\text{dep}} / a$ must be in the same range of values, $\delta_{\text{dep}}$ being the radial width of the driven current layer.

If ECCD is to be used for Neoclassical Tearing Mode stabilization [1,2], the non-inductive current should be driven inside the island, $\delta_{\text{dep}} \approx \delta_{\text{island}}$ with a ratio $J_{\text{ECCD}} / J_{\text{BS}} \approx 1$, $J_{\text{ECCD}}$ and $J_{\text{BS}}$ being respectively the ECCD peak current density and the local bootstrap current in the stable plasma. Since current NTM modeling [3] predicts a marginal island size $w_{\text{marg}}=2\div7$ cm (i.e. the size below which the island will collapse on itself) and a saturated size $w_{\text{sat}}=20\div30$ cm, while $\delta_{\text{dep}} = 5\div10$ cm, the combination of foreseen EC power availability (24 MW), absorption layer width and island width should be adequate for stabilization [1]. A similar picture can be given in case saw-tooth control with ECCD is the goal. In fact, it is a common experience [4,5,6] that sawteeth are strongly sensitive to an EC deposition close to the inversion radius, because of the role of magnetic shear at the $q=1$ resonant surface [7].

In order to get the required ECCD localization a good precision and stability in the deposition radius $r_{\text{dep}}$ and EC beam launching angle are necessary. Although this specific issue will be discussed in more detail in a following section, a simple argument is that the total jittering $\varepsilon_{\text{dep}}$ in $r_{\text{dep}}$ due to equilibrium fluctuations ($R_{\text{axis}}$, $z_{\text{axis}}$, q-profile), density gradient perturbations and mirror positioning should be such that $\varepsilon_{\text{dep}} \leq \delta_{\text{dep}}$. As shown later on, it follows that control application of ECCD must rely on an automatic system for the deposition radius control, which should be considered as an integral part of the launcher itself.

Symmetric to the need for precise localization of EC power deposition to get an effect on the island size, the experiments show that the effect on the NTM amplitude is negligible when the EC current layer is far from the island itself. Little or no information is provided by the plasma on the direction in which $r_{\text{dep}}$ should be moved in order to approach the island. Even worse the TM has a chance to react differently depending on the relative position of the absorption layer and of the island, if the absorption is close to the island. Because of the effect of the EC driven current on the current density gradient and on the general stability term $\Delta'$, it can be shown theoretically and experimentally that if $r_{\text{dep}} < r_{\text{island}}$ the mode can be further destabilized, while on the contrary the deposition outside the island tends to stabilize the mode [8,9]. This means that if $r_{\text{dep}}$ is moved according to the effect of the displacement on the NTM amplitude, the island might even repel it if the approach is from smaller radii, unless more sophisticated algorithms including the expected reaction are used [10]. A very similar behavior is observed with saw-teeth under the influence of ECH, which can be effective in preventing the sawtooth crash if deposited slightly outside the inversion radius [4], but both an increase and a decrease of the sawtooth period can be obtained when $r_{\text{dep}} < r_{\text{inv}}$, depending on the total ECH power [11].

Finally, the total EC power foreseen for ITER applications, where at least 120 MW of nuclear power are consumed for plasma heating, is far in excess to the capability of a single millimeter wave source. Gyrotrons under development [12,13,14,15] for ITER applications are designed to deliver a power in the range 1÷2 MW, so that many tubes are likely to be used in the ECH system (24 in the present design).
The multiplicity of the absorbing layers is an important feature to be taken into proper account in the development of the reliable and fast automatic control system necessary for efficient MHD control in ITER-like devices.

2. Methods for experimental recognition of the absorption and of the MHD island positions

It is a very positive case that the main applications of automatic control by ECH/ECCD, namely NTM stabilization and saw-tooth crash triggering, can be fully developed and tested in present day machines, since all ingredients crucial for ITER are already there.

In fact, automatic reaction to NTM onset has been successfully attempted in DIII-D [10] and JT-60 [16,17], after first experiments on NTM stabilization performed in AUG [18]. As a matter of fact, valid experiments can be performed even when ordinary TMs are present [9,19], the difference being the power required to get stabilization, and not the automatic reaction process itself. This is the main motivation of the experimental programme on this issue performed on FTU tokamak, described in this paper. Two basic architectures of the feed-back loop are considered: the first, developed in DIII-D and JT-60, uses the amplitude of the signal from the Mirnov coils produced by poloidal field oscillations \( \varepsilon_B = \dot{B}_\theta \), which is considered as the error to be minimized. The second, adopted in FTU, aims at the zeroing of the more elaborated information given by \( \varepsilon_r = r_{\text{island}} - r_{\text{dep}} \). We may name the two procedures as “search and suppress” (SS) and “just align” (JA) respectively.

The great advantage of SS procedure is the simplicity of the characterization of the reaction (mode amplitude=Mirnov signal) to a given action (\( r_{\text{dep}} \) modification), and of the decision to be taken accordingly: if \( \dot{B}_\theta \) decreases then keep going the same direction otherwise reverse \( r_{\text{dep}} \) modification.

As mentioned before, the main problem comes from the fact that the effect on the mode amplitude, and therefore on the Mirnov signal, is evident only when \( r_{\text{dep}} \) is close to \( r_{\text{island}} \), which means that the search is blind in principle unless absorption is almost on target. An elegant way to avoid the difficulty is to set \( r_{\text{dep}} \) at the radius correspondent to the resonant surface where the mode develops before closing the loop on \( \varepsilon_B \), which asks for a real-time equilibrium reconstruction, and in the approximation of a straight beam axis (no refraction). Although this additional computation, to be done in real time, frustrates the simplicity of the method and introduces a risk of misalignment, experiments in DIII-D and JT-60 have shown that the method works satisfactorily. A second serious problem could arise in case several beams are needed to get a result, the origin of the problem being twofold: on one hand, the effect of a single beam on the mode amplitude might be imperceptible, on the other, each single \( r_{\text{dep}} \) should be moved one after the other since the right motion of one could be masked by the wrong motion of another.

Contrarily to SS, JA method appears much more complicated since it requires the active and reliable measure of both \( r_{\text{dep}} \) and \( r_{\text{island}} \) in real time. The experimental recognition of \( r_{\text{dep}} \) is being performed by power modulation since the early use of ECH in toroidal devices, and the main question now is how to implement an automatic procedure, and if it is applicable in ITER (to be discussed in a following section). As regards \( r_{\text{island}} \) recognition, an algorithm has been developed and implemented in a processing unit based on Digital Signal Processors [20] and connected to the multichannel ECE diagnostic of FTU tokamak. The basis of the recognition process is that the electron temperature profile is flattened across the island by fast parallel transport along the helicoidal flux tubes inside the island. Since the island usually rotates, unless of locking on correspondent periodic perturbations of external fields, the local electron temperature, as measured e.g. by multichannel ECE radiometer, oscillates correspondingly. As shown in Fig.1, where a \( T_e \) profile of a reference ITER scenario (2 EOB2_076_062, 5.3 T, 15 MA) is considered, \( T_e \) oscillations extend over a large fraction of the plasma column, but change phase across the island O-point. This feature provides the rationale of the recognition process which calculates the cross correlation between nearby \( T_e \) measuring channels. On both sides of the island cross correlation is high (close to one), but for channels across the island O-
point cross correlation is low or negative. A dip in the cross-correlation pattern will clearly mark the island position.

The recognition process might be jeopardized by the presence of stabilizing ECCD, when \( r_{\text{dep}} \approx r_{\text{island}} \) [19]. Since EC current drive is always associated to EC heating, each time the island passes across the EC absorption volume some heating occurs, followed by some cooling before the next transit. A synchronous modulation of the electron temperature inside the island therefore has to be expected, which overlaps natural fluctuations due to the rotating profile flattening. The relative contributions to total \( T_e \) oscillations can be estimated, and it can be shown that also in the presence of strong EC heating the center island is characterized by a local minimum of the cross correlation function. Fig.2 shows an example of the “natural” and “forced” oscillation amplitude profile.

Fig.1 – Radial distribution of \( T_e \) coherent oscillations originated by the helicoidal rotating island. The green line shows the oscillations amplitude (difference between the continuous-blue and the dashed-red curves), which is zero at the O-point of the island.

Fig.2 – The figure shows the effect on \( T_e \) oscillations of an unperturbed island due to ECH associated to ECCD driven at the O-point. Antisymmetry is broken, but the resulting amplitude has still a minimum close to the O-point.

The essential processing steps are briefly summarized in the following (more details in [21]). First, a simple high-pass digital filtering on the \( i \)-th channel rejects low frequency fluctuations:

\[
o_i = T_{e,i} - \langle T_{e,j} \rangle_{T_i}
\]

where \( T_i \) is an appropriate averaging time. In FTU the Tearing Mode to be identified rotates at a frequency in the range 4÷10 KHz, so that integration is set at \( T_j = 2 \text{ ms} \). Second, amplitude averaging over a time constant \( T_2 \) (4 ms in FTU application) for amplitude normalization is performed:

\[
A_i = \sqrt{\left\langle o_i^2 \right\rangle_{T_2}} \quad o_i^{\text{norm}} = \frac{o_i}{A_i}
\]

Third, an operation substantially similar to cross correlation between \( i \)-th and \( j \)-th channels (usually \( j = i + 1 \)) is performed:

\[
P_{ij} = \left\langle o_i^{\text{norm}} o_j^{\text{norm}} \right\rangle_{T_3}
\]
where $T_3$ is a third integration time, set for maximum noise rejection (20 ms in FTU application). Finally, a dip or a local minimum in the correlation function $P_{ij}$ is identified, and $r_{\text{island}}$ is assigned between $r_i$ and $r_j$, these last being the radial positions of the $i$-th and $j$-th $T_e$ measuring channels. It should be noted that only simple calculations are performed by the DSP so that all variables $o_i$, $o_{i \text{ norm}}$, $P_{ij}$ can be updated at a very fast DSP rate (cycle completed every $\approx 0.02$ ms), although the effective time response of the recognition process is fixed by the longest integration time ($T_3$). The whole process can be tested and optimized off-line on data acquired and stored in the database, before linking the processing unit to a live shot. The DSP processing unit for $r_{\text{island}}$ recognition is being tested real-time in a forthcoming experimental campaign on FTU tokamak.

3. High temperature effects on measurements and EC deposition

The main impact of a burning plasma on an automatic control loop of $r_{\text{dep}}$ using ECE as the main diagnostic tool is expected to come from the very high electron plasma temperature [22]. This affects on one hand the position of the absorbing layer along the beam trajectory, since the very high optical thickness causes full absorption much before the ray reaches the cold resonance position. This adds a difficulty to the achievement of correct pre-alignment in the SS stabilizing scheme, even under the assumption of straight and refraction-free beam tracing. On the other hand a high $T_e$ degrades the spatial resolution of a multichannel ECE diagnostic because of the line broadening of each receiver in the radiometer.

Fig. 3 shows the width of the layer radiating at the nominal frequency of an ideal radiometer channel in ITER, Ordinary mode at the fundamental resonance, vs. the radial position in the range between resonant surfaces $q=3/2$ and $q=2$. In this case harmonic overlapping is absent. It happens that the spatial resolution of a likely ECE channel is of the same order of the absorption layer width, and larger than the marginal island width.

![Fig. 3](image-url) Fig. 3 – The figure shows the width of ECE emitting layer (O-mode, $\omega_{ce}$) vs. the position of a hypothetical ECE radiometer channel in ITER. The only effect considered here is the broadening of the spatial resolution due to the high electron temperature.

![Fig. 4](image-url) Fig. 4 – Radial distribution of $T_e$ oscillations possibly measured by ECE radiometer channels having the spatial resolution shown in Fig. 3, and the cross correlation $P_{ij}$ between nearby channels. The broadening does not prevent the O-point recognition.

In spite of the relatively poor spatial resolution, the phase jump across the O-point makes a reliable $r_{\text{island}}$ identification still possible. Fig. 4 shows a profile of $T_e$ oscillations (continuous line) averaged (dots) by the finite spatial resolution of an ideal radiometer, and the relative $P_{ij}$ plot. The dip in nearby channels cross correlation is evident.
The most critical aspect of using ECE measurement to detect the island rotation is the sensitivity required, because oscillations in the order of 50 eV must be recognized against a 25 keV, turbulent background ($\approx 2$ \%). An important contribution to the achievement of sufficient signal to noise ratio is the coherency of MHD-induced oscillations, exploitable with the use of FFT techniques, which could be further improved by synchronous detection of Mirnov oscillations.

4. Multiple beam impact on control strategies

The control strategy in ITER, where the total EC power required for MHD control is delivered by many beams, depends on how large is the expected effect of each beam on the parameter under control.

As regards the recognition of the deposition layer $r_{dep}$, the observable is the amplitude of the $T_e$ oscillations caused by EC power modulation, to be distinguished against a background temperature of 25 keV, possibly in the presence of quasi-periodic phenomena like saw-teeth and ELMs. The oscillation amplitude depends on the modulation frequency (i.e. the amount of absorbed energy in each cycle), on the absorption position (i.e. the volume over which the absorbed energy is diluted), on the electron density (i.e. heat capacity) and on energy confinement. As well described in the extensive work so far performed in transient transport analysis [e.g. 23], the amplitude can be estimated by solving the periodic heat diffusion equation. The result is that for a typical modulation frequency of 1 Hz, and an absorption position around $q=2$, the peak in electron temperature modulation with 100\% modulation of 1 MW beam power is in the order of 1 eV. This is close to the limit of detectability, although in this case synchronous detection techniques can be fully exploited to enhance the signal to noise ratio.

![Figure 5](image)

It might be useful therefore to consider all beams together as a cluster, and to split the control of the deposition radius in two parts: the feedback-loop involving plasma effects is applied to the $r_{dep}$ of the “center of gravity” of the beam cluster, while a different logic controls clustering. In SS feedback scheme, beam clustering seems to be the only option, since the effect of a single beam on the island is likely negligible, and because otherwise the single $r_{dep}$s should be adjusted one after the other with an unacceptable increase in the response time constant.

It should be noted that this issue of packing the beam absorption as densely as possible is relevant not only to the control process, but also to the MHD stabilization efficiency. A spreading of the absorption layer will decrease the peak in ECCD current density and the ratio $J_{ECCD}/J_{BS}$, and strongly affect stabilization capability [24,25].

In all present designs of ECH launchers, many end-mirrors (24 in total) are distributed in rows at different toroidal locations (12) and different heights (2). Toroidal displacement is not important as far as clustering in $r_{dep}$ is concerned (in principle if all beams are oriented in the same way with respect to the local major radius, they are absorbed on the same magnetic surface), and clustering optimization is
reduced to adjust the poloidal injection angle (or the frequency of each gyrotron). However, if ECCD modulation synchronous to the island has to be done, i.e. clustering in the poloidal angle $\theta_{dep}$ of the deposition volume is needed, this complicates the control strategy, since a different phasing of the modulation of the beam powers in a row could be needed.

As mentioned earlier, a precious opportunity is that fully relevant experiments are possible in present machines, allowing extensive tests and debugging of the different schemes foreseen.

5. FTU experiments on recognition of the absorption radii and of the island positions

The recognition of the radial position of the EC absorbing layer is a matter considered since the first application of ECH in toroidal configurations, and it is usually approached and solved by modulating the EC power and looking for the position of strongest $T_e$ oscillations. All present day ECH systems have more than one single beam, and this recognition is made so far for one beam each time in dedicated experiments.

Experiments have been performed in the FTU tokamak aiming at simultaneous $r_{dep}$ recognition, possibly applicable during any ECH assisted experiment. The ECH system in FTU is composed by four beams, three used in the experiments described in this paper, which are steerable independently in order to have an independent positioning of the absorption layer along the minor radius. However, the gyrotrons are fed in pairs by two RHVPSs (URS-A and URS-B), so that the timing of each couple of gyrotrons is the same. This means that the four gyrotrons cannot be separately modulated, but only in pairs.

The method used is similar to the one developed for $r_{island}$ detection, with the difference that a peak (not a “valley”) is searched in the correlation between the ECE channels and the reference signal controlling the gyrotron’s power supply. The algorithm is implemented in a second DSP module. The goal of the real-time data processing is the simultaneous detection of each $r_{dep}$ with all EC beams ON. In order to better distinguish the contribution to the oscillating temperature of each gyrotron pair, the two URS are modulated at different frequencies. The two $r_{dep}$ of the gyrotrons modulated by a single power supply are identified by different peaks in the cross correlation pattern, and in this case the relative positioning of the two has to be known a-priori (e.g. by the steering angle).

Fig.5 and 6 show the results of the real time processing of data taken in experiments in which two and three gyrotrons were used, and the relative power supplies were modulated during partially overlapping time windows. This timing arrangement allows the validation in a single of the method of modulation at different frequencies for discriminating the contributions from different sources.

FFT (amplitude) of two ECE channels are shown in Fig.5, while in Fig.6 the radial distribution of the cross-correlation peak is shown. During a first 0.1 s period only one gyrotron was modulated (gy.1,
URS-A, 1 kHz), during a last 0.1 s period the other was modulated (gy.3, URS-B, 1.1 kHz), and during the intermediate period all gyrotrons were ON. In the bottom-left picture of Fig.6 the dashed line shows the cross correlation between ECE signal and URS-A reference signal when URS-B is OFF, which is identical to the one with all beams ON.

In a second experiment, also shown in Fig.6 (top right), both gyrotron gy.3 and gy.4 were modulated by the same power supply (URS-B) at the same frequency. Nevertheless, the respective $r_{dep}$ are clearly identified by the two peaks in the cross-correlation distribution between different ECE channels.

It should be noted that exactly the same results could be obtained by off-line, fully featured fft analysis of the ECE electron temperature diagnostic, in spite of the low-amplitude $T_e$ oscillations ($\approx 3$ eV peak amplitude). This confirms that real-time $r_{dep}$ recognition also in the presence of multiple beams is feasible.

6. Strategies for $r_{dep}$ control

Assuming that the island amplitude $A_{island}$, its position $r_{island}$ and the deposition radius $r_{dep}$ of each one of the many beams can be measured in real time, the next goal is a strategy for changing all $r_{dep}$ in order to minimize $A_{island}$, or $|r_{island} - r_{dep}|$. Two options are in principle possible for $r_{dep}$ control (beam-to-beam independent): frequency tuning at fixed launching angle, and beam steering at fixed frequency. The first option is better discussed elsewhere in this conference [25], while the second one is the reference option for all ongoing work on ITER ECRH launchers [26,27,28]. From the point of view of the control strategy the two systems are very similar, since one free parameter (frequency or steering angle) controls each one of the deposition radii. We concentrate therefore on the strategy, which could be applied to any specific actuator.

The most mandatory task of the control system is to bring the peak of the current density driven by each beam at the same location, to the extent of not producing an unacceptable reduction of the $J_{ECCD}/J_{BS}$ ratio because of a too large beam scattering. A statistical estimate of ECCD density profile broadening following a scattering of the starting angles of the 24 beams of the ITER ECRH system is made in [22], showing that in order to keep line broadening within 2% the scattering in the angles must be less than 0.2 deg. Second essential requirement is that the peak of the total driven current must stay within the island. As a reference rule, a reduction in the current density peak larger than 20% is unacceptable, and a positioning error of the peak with respect to the island O-point larger than the island width is unacceptable.

In order to generalize the relationship between the total ECCD peak reduction and the mean deviation of the beam steering angle from ideal alignment, we assume that all $N$ beams are identical, with equal peak current density $J_0$ and ECCD layer width $w$. We assume that the error $\chi$ in the deposition radius due to alignment has a gaussian distribution with standard deviation $\sigma$, so that the actual shape of the total current density distribution can be written as:

$$\frac{J_{eff}(x)}{J_{max}} = \frac{1}{\sqrt{\pi}\sigma} \int_{-\infty}^{+\infty} e^{-\frac{(x-y)^2}{w^2}} e^{-\frac{\chi^2}{\sigma^2}} d\chi = e^{-x^2/(\sigma^2+w^2)}$$

$x$ being the normalized radial displacement relative to the normalized deposition radius $\rho_{dep}$. The beam resulting from the overlapping of $N$ scattered identical beams has therefore a lower peak current density $J_{peak}=J_{eff}(0)$ than the ideal maximum $J_{max}=N J_0$, and a larger ECCD layer width $w_{eff}$, to the extent respectively given by:
\[ \eta = \frac{J_{\text{peak}}}{J_{\text{max}}} = \frac{1}{\sqrt{1 + \left(\frac{\sigma}{w}\right)^2}}; \quad \zeta = \frac{w_{\text{eff}}}{w} = \sqrt{1 + \left(\frac{\sigma}{w}\right)^2} \]

Fig. 7 shows both \( \eta \) and \( \zeta \) versus \( s = \sigma/w \), and it can be used to get the maximum allowed error in the deposition radius \( s_\eta \) (e.g. \( s_\eta = 0.75 \) for \( J_{\text{peak}}/J_{\text{max}} = 0.8 \)), and the associated current layer increase (\( \zeta = 1.25 \)). In order to translate from the error in radius to the error in steering angle \( \alpha \) we use the \( \rho_{\text{dep}}(\alpha) \) and \( w(\alpha) \) functions, which are respectively the deposition layer radius and width, point-to-point built by beam tracing calculation with an ITER reference scenario (scenario EOB2_076_062, 15 MA inductive, 5.3 T) [29] and a specific ECRH launcher configuration (Front Steering, lower row since the beams are narrower and alignment precision is more demanding). The error \( \sigma_\alpha \) in the steering angle \( \alpha \) for which the peak current density decreases by a factor \( \eta \) is given by:

\[ \sigma_{\alpha,\eta} = \frac{d\alpha}{d\rho_{\text{dep}}} \times s_\eta \times w(\alpha) \]

Fig. 8 shows the graphics of the result. In order to prevent a drop in the \( J_{\text{peak}}/J_{\text{max}} \) ratio by more than 20%, the alignment error must stay within 1 deg. In order to have the drop negligible (less than 2%) the alignment shall be better that 0.2 deg, in agreement with [24].

Fig. 7 – Peak reduction coefficient \( \eta \) and total ECCD layer enlargement \( \zeta \) due to scattered beams overlapping vs. the error in the deposition radius \( \sigma \), normalized to the width \( w \) of each single beam.

Fig. 8 – Error in launching angle for maximum acceptable reduction in the peak current density (20%, red curve), and negligible reduction (2%, violet curve). Single beam width \( w(\alpha) \) is shown for reference.

It is certainly possible to achieve a relative positioning of each beam with respect to a reference direction with a precision better than 1 deg, but very unlikely the reference directions of all beams will stay within 1 deg, given mounting tolerances, different end-mirror positions (poloidally and toroidally), differential stresses, different slacks, different thermal expansions. It is therefore mandatory that some sort of “beam convergence calibration” has to be worked out.

As mentioned earlier, there are two strategies aiming at tight beam clustering around \( r_{\text{island}} \):

a) each beam is moved in feedback in a way to set at zero the difference \( r_{\text{island}} - r_{\text{dep}} \);

b) all beams are set feed forward in a way to tightly cluster around a reference direction, or radius \( r_{\text{ref}} \), and the reference direction is moved in feedback aiming at \( r_{\text{ref}} - r_{\text{dep}} = 0 \).

Option a) is certainly the safest in terms of getting \( J_{\text{peak}}/J_{\text{max}} \) as high as possible, since the NTM island itself would be the target for “beam convergence calibration”, nothing else being strictly necessary. Although FTU experiments have shown that simultaneous \( r_{\text{dep}} \) detection of several beams is
possible, it might turn out that this option is impractical for several reasons: it could be that the effect of single beam modulation is invisible against the background of a burning plasma, or it could take a too long integration time to be reliable and useful. In addition, the largest the number of feedback controlled beams, the highest the probability of missing beams because of a non-convergent decisional loop.

Option b) appears to be more robust, since feed forward might lead to a looser cluster, but it always converges to the target. In addition, since all beams would be modulated with the same timing, a stronger signal would be available for $r_{dep}$ detection, providing a more reliable feedback for $r_{island}$ tracking. It definitely requires “beam convergence calibration”, and an appropriate alignment procedure.

Both approaches can be tested in real experiments, the main differences with respect to ITER being the number of beams, which is not essential, and turbulence of the background plasma which is indeed more difficult to reproduce. However, since what matters in this case is the background noise versus coherent temperature oscillations induced by modulation, a way to scale from ITER to present devices could be the operation at reduced EC power.

7. Conclusions
The key issue in the realization of a reliable system for automatic MHD control by ECH/ECCD in ITER-like devices is the detectability of coherent $T_e$ oscillations to the level of 10 eV, against the background burning plasma in the 20 keV range. ECE is the best candidate for this measurement, in spite of the relative de-localization of the measure because of the high temperature. This very high sensitivity is required for the localization of both the island and the EC deposition radii.

Immediately after, the issue of multibeam control (24 beams in ITER) follows. Depending on single beam detectability, the strategies could consider either the independent control of each beam (most effective), or tight beam clustering in feed-forward and island tracking of the cluster in feedback.

All key issues can be fully approached in present day machines having an ECH system (multiple), and the preparation of a full package, adaptable to ITER requirements with minor adjustments, is possible.

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