On the use of step-tuneable gyrotrons in ITER

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Abstract. We discuss the use of step-tuneable gyrotrons in present day and future tokamak devices. It is shown that with a two-frequency system, the performance of the planned ITER ECCD system, using the present launcher designs, could be greatly enhanced. With step-tuneable gyrotrons, it should be possible to use fixed launchers without any steering at all.

1. Introduction
Electron Cyclotron Resonance Heating (ECRH) by millimetre waves is a well-established method for heating of magnetically confined fusion plasmas. It can also be used to generate non-inductive currents in the plasma (Electron Cyclotron Current Drive, ECCD), which opens up the possibility to locally control the current distribution. Such control can lead to enhanced confinement and stability of the magnetically confined plasma [1,2], thus making ECRH and ECCD a powerful tool for optimising plasma performance. It is thus foreseen to install such a system also in the next step experiment ITER.

In order to take full advantage of the favorable properties of ECRH and ECCD, a launcher system allowing flexible variation of the injection angles of the microwave beams is required. In present day devices such as ASDEX Upgrade, this is achieved by using movable mirror structures that allow variation of poloidal and toroidal launch angle. In future reactor grade devices, the movable mechanical structures in a harsh environment give rise to some concern on the engineering side and the steering range will be less flexible. In this paper, we discuss the use of frequency step-tuneable microwave sources to increase the flexibility. Although not discussed in this paper, such a system would also be very beneficial in extending the operational space, e.g. for reduced toroidal field. In Section 2, we discuss the requirements on the launching system arising from the physics applications and quantify these for ASDEX Upgrade and ITER. In Section 3, we review the status of step-tuneable gyrotron development. Based on this, we outline possible system designs for ASDEX Upgrade and ITER in Section 4, and examine the performance of these designs using beam tracing calculations at different frequencies for typical launcher geometries. A discussion of results and concluding remarks are given in Section 5.

2. Physics requirements on the launcher
Two main requirements arise for an ECRH/ECCD steering scheme. One is the requirement of quasi-continuous steering over the whole steering range. This demands that for a system with discrete steps in deposition, the variation of deposition centres should be smaller than e.g. the half width of the
driven beam profile. The steering range requirement is set by the physics application under consideration. In a flexible present-day experiment like ASDEX Upgrade, this usually means that the whole radial range should be accessible. In ITER with its limited flexibility, the present philosophy is to use two different launchers for different tasks, namely a midplane system for central H&CD up to, say, $\rho_p=0.5-0.6$ and a system located in an upper port which should drive current roughly in the outer half of the plasma. The main purpose of this latter system (the ‘Upper Launcher’) is to provide localised CD for NTM stabilisation.

Another requirement is that of the steering speed. For NTM stabilisation or current profile control in advanced scenarios, it is foreseen to follow by feedback control variations of the surface on which ECCD should be centered by changing the launching angle. This is a main concern for NTM stabilization: first of all, the correct deposition has to be found within the growth time of the mode, preferably within a fraction of it. In ASDEX Upgrade, it is of order 50-100 ms for a (3,2) mode and it will scale like $T_3^{1/2}a^2$, so a factor $(7.5/1.5)^{1/2} (2/0.5)^2 = 180$, resulting in 10-20 seconds can be expected in ITER (Numerical data for ITER are taken from the standard case, scenario 2). For the $q=2$ mode in ITER, the temperature is lower, but the radius larger, and roughly the same timescale can be expected. Changes of the location of the resonant surface will also occur due to the change of the equilibrium current profile. This is much slower (several seconds in ASDEX Upgrade and more than 100 s in ITER) than the mode growth time so that it is less restrictive. Finally, changes in the location can also come from changes of plasma position and Shafranov shift. This can in principle occur much faster, since position and equilibrium can change on the Alfvén time scale (in absence of eddy currents induced in the vessel). However, if we neglect off-normal events like failure of the control system etc., the only fastest cases are the drop or increase in beta due to a step-like change of the heating power. This will appear on the time scale of $\tau_a$, i.e. around 100 ms in ASDEX Upgrade and 3 s in ITER. Thus, a steering time of 100 ms is needed in ASDEX Upgrade, while a time scale of several seconds will be fully adequate for ITER.

![Fig. 1: Power achieved in short pulse with a slow step-tuneable gyrotron at FZK using a Brewster output window. Here, the typical frequency spacing is 3.7 GHz.](image)
3. Status of step-tuneable gyrotron development

Concerning short-pulse demonstration experiments, experiments at FZK Karlsruhe employing a conventional hollow cylindrical waveguide 140 GHz, TE\textsubscript{22,6}-mode cavity, a QO mode converter with dimple-type launcher, a broadband silicon nitride composite Brewster angle window and a single-stage depressed collector (SDC) gave up to 1.6 MW output power (pulse duration: 1-5 ms) at efficiencies between 48 and 60\% for the entire operating mode series in the frequency range from 114 to 166 GHz (TE\textsubscript{m,5} with m = 18 to 22, TE\textsubscript{m,6} with m = 20 to 26 and TE\textsubscript{m,7} with m = 22 to 26). Frequency tuning in steps of approximately 3.7 GHz was achieved by slow variation (in minutes) of the magnetic field in the cavity [3] (see Fig. 1). Recently, similar results have been achieved at IAP Nizhny Novgorod employing a 140 GHz, TE\textsubscript{22,8}-mode cavity in 50 µs-pulse operation [4]. The stepwise tuneable 140 GHz, TE\textsubscript{22,6}-mode gyrotron at FZK has also been investigated with respect to fast frequency tunability (in seconds) [5]. For that purpose, the tube has been operated in a special hybrid magnet system consisting of the superconducting (SC)-magnet in the cryostat and additional normal conducting (NC) cavity and gun magnets with a fast switching time constant. Problems due to the magnetic coupling between the different magnets were solved by using a current control system for the NC-magnets. Finally, step-tuning operation between five modes from the TE\textsubscript{24,6} mode at 132.6 GHz to the TE\textsubscript{24,8} mode at 147.4 GHz at MW power levels in time steps of 1 s was achieved [5]. However, the future of fast frequency tuneable gyrotrons will lie in the use of special fully SC-magnet systems which seem to be feasible.

The Russian and Japanese 1 MW, 170 GHz ITER gyrotrons operate in the cavity modes TE\textsubscript{25,10} and TE\textsubscript{31,8}, respectively. The corresponding lower and upper neighbor modes of the same mode families (TE\textsubscript{24,10}/TE\textsubscript{26,10} and TE\textsubscript{30,8}/TE\textsubscript{32,8}) have a frequency gap of 3.3 and 3.2 GHz, respectively. Coaxial-cavity gyrotrons operate at even higher volume modes, so that the frequency distances of mode families for a frequency-step-tuneable source are even smaller [6]. The 2 MW, 170 GHz coaxial cavity gyrotron under development in the EU employ the TE\textsubscript{34,10} cavity mode which has a gap of only 2.1 GHz to its neighbors TE\textsubscript{33,19} at 167.9 GHz and TE\textsubscript{35,19} at 172.1 GHz. Slow frequency step tuning between 19 different modes with approximately 2.2 GHz frequency spacing in the range between 134 and 109.5 GHz has been performed at power levels ≥1 MW with the FZK TE\textsubscript{31,17} coaxial cavity gyrotron, also equipped with a QO mode converter, a SDC and the silicon nitride composite Brewster angle window [2,8]. We thus conclude that for ITER, we may assume step-tuneable gyrotrons with 2-3 GHz frequency spacing and a tuning time constant of about 1 s.

Concerning long-pulse operation of frequency-tuneable gyrotrons in actual fusion experiments, a new EC H&CD system is under development for the ASDEX-Upgrade tokamak at IPP Garching [9]. Four 1 MW gyrotrons with SDC will generate 4 MW power with a pulse duration of 10 s. The first gyrotron has been built at GYCOM and can work at 140 GHz (TE\textsubscript{22,10}) and 104 GHz (TE\textsubscript{18,7}), making use of the resonances of the conventional CVD-diamond vacuum window at these frequencies (see Fig. 2). It has already shown MW-class performance at both frequencies with pulse duration of several seconds. A second step-tuneable gyrotron is designed to work at several frequencies within the same frequency interval (TE\textsubscript{28,8} at 140 GHz). This tube will have a double-disc window to allow multi-frequency operation.

Challenges for the development of step-tuneable gyrotrons lie in the fact that the different operating modes should have approximately the same radius of the electric field maximum and must have the same sense of rotation so that the coupling to the electron beam is comparably good and the pattern and direction of the mm-wave output beam are very similar [3]. Other challenges are the proper electron gun and SDC.
operating in varying magnetic field [6]. Moreover, the gyrotron launcher has to be designed such that a low stray radiation level inside the tube is achieved. This will be crucial when going to cw-operation with such a tube. A diamond output window mounted at the Brewster angle could allow broadband transmission. We note here also that the use of a Brewster window implies a constant polarization at the window so that the polarisers have to operate in vacuo. An alternative is a resonant double-disk window. Finally, we also note that for each mode, the beam will leave the gyrotron under a slightly different angle so that it may be needed to use different beam matching optics for each frequency.

4. Possible system designs using step-tuneable sources

In this section, we discuss the possible system designs based on step-tuneable sources. Two basic set-ups will be discussed:

- Use of step-tuneable gyrotrons and moveable launchers: this limits the number of frequencies (and thus the technical complexity) required because quasi-continuous steering is done by the launcher itself. However, the use of more than one frequency usually rules out the use of remote steering.

- Use of step-tuneable gyrotrons in combination with a fixed launcher: this asks for many frequencies with fine spacing, but has the big advantage of no need for any steering of mirrors.

4.1. ASDEX Upgrade

As mentioned above, an ECRH system based on step-tuneable sources is under construction for the ASDEX Upgrade tokamak. According to the discussion in section 3, the minimum frequency spacing is 3.7 GHz which, at 140 GHz, is a relative spacing of 2.6%, i.e. at a major radius of 1.65 m a radial distance of slightly above 4 cm for injection in the midplane. On the other hand, for perpendicular injection, the deposition width can be well below 2 cm so that it is clear that a continuous steering needs moveable mirrors as well. This can be seen in Fig. 3, where the driven current for 3 adjacent frequencies from the FZK experiments is shown for a toroidal injection angle of 15° and 5°. Here, and for all other plots of driven current profiles, the power is 1 MW and \( r/a \) is the poloidal flux radius. The latter corresponds to a typical NTM stabilisation experiment (HFS deposition at 2.1 T) with optimised deposition width of less than 2 cm. While for 15°, the situation is marginal, for 5°, there is clearly not enough overlap of the individual profiles to guarantee continuous radial coverage.

![Fig. 3: Calculated profiles of driven current for a typical ASDEX Upgrade NTM stabilisation experiment at 3 adjacent frequencies from the FZK experiments (Fig. 1). With a toroidal injection angle of 15°, spacing is marginal, but at 5°, it is not sufficiently dense for continuous radial coverage.](image_url)

On ASDEX Upgrade it was therefore decided to combine the step-tuneable sources with a launcher that allows for both poloidal and toroidal steering. This is also in line with the requirement for fast steering, which is about 100 ms in ASDEX Upgrade according to the criteria discussed in section 2, while the time constant for step-tuning is of the order of 1 s. Based on this decision, it was also decided to use only 4 different frequencies in ASDEX Upgrade. This, in combination with steering, opens the possibility of very flexible radial coverage over a wide range of toroidal fields with
reasonable technical effort for the construction of the individual matching optics which are based on sets of rotatable wheels carrying 4 individual sets of mirrors.

Fig. 4 Accessible radial range using a step-tuneable gyrotron with 4 frequencies (105 GHz, 115 GHz, 127 GHz and 140 GHz) in ASDEX Upgrade as function of the toroidal field. For a typical plasma current of 1 MA, this offers access to $\rho_p > 0.25$ in the range $2.9 < q_{95} < 4.2$.

Fig. 4 shows the radial range accessible with this choice. It can be seen that the four frequencies lead to a large range of applications with almost central ($\rho_p < 0.25$) deposition. Thus, on ASDEX Upgrade, steerable launchers cannot be replaced by step tuning, but the range of application of ECRH is greatly enhanced.

4.2. ITER

In ITER, three main differences with respect to the situation discussed for ASDEX Upgrade exist. First, two systems with dedicated physics tasks exist, so that the required steering range is larger. Second, the time scale required for changing the frequency (3-5 s) is compatible with the capabilities demonstrated in experiments [5]. Third, the relative magnitude of an individual gyrotron frequency step is smaller due to the use of higher order cavity modes. This is especially pronounced in the coaxial gyrotron, where 2.1 GHz at 170 GHz correspond to a relative change of 1.2 % (to be compared to 2.6 % in ASDEX Upgrade-type gyrotrons). We therefore analyse in the following the situation for an ITER system based on step-tuneable gyrotrons with a frequency spacing of 2.1 GHz, i.e. assuming the use of a coaxial cavity gyrotron. As launch points, we will assume that the presently foreseen upper and the midplane ports can be used. We discuss two variants: a system which is based on two frequencies (and thus has relatively modest technical requirements concerning window and matching optics) combined with the present steerable launchers and a system based on the full set of frequencies but without any steering. In all following calculations, we use the reference case of scenario 2 (Q=10).

4.2.1. Two frequency systems using the present launchers

Here, we discuss the benefits of using a two-frequency gyrotron in ITER as a compromise between the technically sophisticated multi-frequency tube and the standard single-frequency tube. In this case, steering of the launchers would remain as in the present design, i.e. toroidal steering from 20 to 45 degrees for the midplane launcher (fixed at a poloidal angle of 0 degrees) and poloidal steering.
(roughly) from 40 to 60 degrees from for the upper launcher (lower row, fixed at a toroidal angle of 20 degrees). For a two-frequency gyrotron, we can make use of the fact that a single window disc has the transparency minima at $(n\lambda)/(2\varepsilon^{1/2})$. Since previous analysis had shown that the choice of 170 GHz is a compromise between a higher frequency beneficial for CD efficiency in the upper launcher and a lower frequency beneficial for access in the midplane system, we chose the window such that it is resonant at 185 GHz and 154 GHz, i.e. $6\lambda/2$ and $5\lambda/2$ for a disk of 2.05 mm thickness ($\varepsilon_{\text{diam}} = 5.66$).

![Figure 5](image)

Fig. 5: Figure of merit for NTM stabilisation through the upper port for different frequencies (from [10]). A frequency of 185 GHz would clearly be very beneficial for this purpose.

The improvement for the upper launcher in using a higher frequency can be seen in Fig. 5, where the figure of merit $I/\Delta \rho$ for NTM stabilisation is plotted for launching a beam through the upper port (taken from [10]). It is clearly seen that increasing the frequency has a beneficial effect, the gain being as high as a factor of 2 as compared to 170 GHz, however at the expense of a decreased operational flexibility.

![Figure 6](image)

Fig. 6: Driven current using the midplane system at 170 GHz and at 154 GHz with 1 MW.

As mentioned above, one of the main problems of the present system at 170 GHz is that the overlap between the radial regions accessible by the individual systems may not be sufficient. We have thus assessed the performance of the midplane launcher at 154 GHz. Fig 6. shows a comparison between the driven current profiles at 170 GHz and at 154 GHz.
It can be seen that with a steering range of –15 to –45 degrees (as opposed to the presently foreseen -20 to -45 degrees), indeed the deposition can be significantly further outside. For 170 GHz, -45 degrees is already close to tangential injection so that increasing the toroidal angle does not really lead to deposition further outside. Thus, 154 GHz will increase the radial coverage of the midplane system. In addition, the possibility to create localised off-axis current (r/a > 0.3) is enhanced, but at the expense of the central current drive efficiency, which is roughly halved at the lower frequency. Thus, this system would be more favorable for sawtooth control or off-axis CD in advanced scenarios. The reduced CD-efficiency in the centre can be recovered (and actually improved) by using 185 GHz there, but this means that the launcher can not be based on remote steering, while use of 185 GHz in the upper launcher and 154 GHz in the midplane would still allow both systems to employ remote steering.

4.2.2. Multi-frequency system using fixed launcher structures

The final design assessed here is a system based on a fixed launcher and step-tuneable gyrotrons with 2.1 GHz steps. Fig. 7 shows profiles of the driven current using the midplane launcher using a fixed injection angle of 30 degrees.

For comparison, the corresponding 170 GHz cases with toroidal steering are shown in magenta.

Fig. 7: profiles of driven current for midplane launch at fixed toroidal angle of 30 degrees for 1 MW. For comparison, the corresponding 170 GHz cases with toroidal steering are shown in magenta.

It can be seen that the frequency spacing is dense enough to guarantee quasi-continuous radial coverage. Due to the frequency variation, the driven current density is higher than for 170 GHz at practically all radial locations: Inside ρ = 0.2, the frequency exceeds 170 GHz, which is beneficial for the total CD efficiency; outside ρ = 0.2, there is better localisation due to the smaller toroidal angle. Thus, this option would provide more current in the centre (beneficial for e.g. the hybrid application) and a better localisation off-axis (beneficial for AT scenarios and sawtooth control). In addition, it allows a wide steering range.

For the upper launcher, we plot in Fig. 8 the driven current by the upper launcher using step-tuning in steps of 2.1 GHz at fixed toroidal angle of -20 degrees. The left hand figure shows profiles along a
ray launched at poloidal angle 46.6 degrees, hitting the q=2 surface. It shows that the frequency spacing is again sufficient to guarantee quasi-continuous steering. Here, the radial steps corresponding to 2.1 GHz frequency steps are even smaller than in the midplane due to the oblique injection with respect to the resonance. In fact, we have used here the 2.1 GHz spacing of the coaxial cavity gyrotron, but as Figs. 6 and 7 show, a conventional gyrotron with 3 GHz spacing would do the job as well.

Fig. 8: current density profiles driven by the upper launcher using step-tuneable sources for 1 MW.

We conclude that for this angle, step-tuning has no disadvantage with respect to a system employing fixed frequency and steerable antenna. However, under this poloidal injection angle, it is not possible to reach the q=1.5 surface, where the (3,2) NTM is expected in ITER. Thus, we show in the right hand side of Fig. 8 the scan at a poloidal angle of 55.7 degrees, which hits the q=1.5 surface at 170 GHz. The frequency spacing is sufficiently dense to replace steering at the q=1.5 surface, too, but at the q=2 surface, the current density is under these circumstances almost a factor of 2 smaller than for 170 GHz and 46.6 degrees. On the other hand, the beam parameters correspond to the multi-purpose remote steering launcher, and a substantially narrower beam can be expected for a design at fixed launch angle, possibly making up for the apparent deficit. This will be subject to further studies.

5. Discussion and conclusions

We have shown that the use of step-tuneable gyrotrons in ITER could enhance greatly the flexibility and, to some extent, also the performance of the ITER ECRH system. We have analysed two design options:

A system based on a limited number of steps in combination with steerable launchers. Already a 2-frequency gyrotron, which is technically the simplest variant of a multi-frequency gyrotron, could greatly enhance performance and flexibility. In particular, the generation of localised current for NTM stabilisation (through the upper launcher at the higher frequency) and CD at mid-radius (through the midplane launcher at the lower frequency) are significantly improved. Thus, future source development for ITER should keep this option in mind.

A system based on multi-frequency step-tuneable sources with frequency steps of 2.1 GHz, as are possible with coaxial insert gyrotrons, could be used together with fixed launcher structures without loss in performance. This makes the design of the launcher much easier, but represents a big challenge to the gyrotron development. It will have to be seen in future if such a system could be possible.

In summary, we conclude that the development of step-tuneable gyrotrons should be pursued with high emphasis since it will certainly benefit the application of ECRH in ITER, also for the use at different magnetic fields, which we have not even assessed in the present study.

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