Theoretical Study of 174 GHz Operation of the W7-X 1 MW, 140 GHz Gyrotron

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***Abstract*—The existing 1 MW 140 GHz $TE_{28,8}$ gyrotron for W7-X is investigated as a two frequency source, to be operated in the $TE_{34,10}$ mode at 173.9 GHz. It turns out that this gyrotron, installed in a suitable magnet, may deliver 1 MW at 173.9 GHz in a reasonably focused rf beam without any modifications. First simulations of cavity interaction, quasi-optical mode converter and the electron gun are presented, and an experiment is proposed.**

I. Introduction And Background

Megawatt level gyrotrons for fusion plasma heating, operating at one frequency only, are state of the art today[1]. However, there is increasing demand for multi-frequency sources, on the one hand to increase the versatility in fusion experiments, and on the other hand to allow for lower magnetic field experiments on reactors such as ITER[2]. Apart from more advanced concepts, conventional gyrotron oscillators may be operated at frequencies determined by the need for low reflection at the output window. The 1 MW 140 GHz gyrotron for W7-X[1] has already been tested around 105 GHz[3], the next lower reflection minimum of the installed CVD-diamond window. In this paper possible operation at the next higher reflection minimum close to 174 GHz is investigated. Even though optimized results could be achieved by modifying the existing tube, the investigations concentrate on using the gyrotron without any modifications, but in a different magnet, in order to reach the required magnetic field strength. This concept would allow for relatively quick experiments and a high design safety, since the MW operation at 140 GHz and possible operation around 105 GHz has already been proven.

II. Parameter Choice for 173.9 GHz Operation

Four factors are crucial when an existing gyrotron tube should be operated at a different frequency, apart from the required change in magnetic field. First of all, the rf output window must have a reflection factor minimum, which for a 140 GHz window with thickness 1.8 mm, corresponding to $4\lambda/2$, is again the case at 175 GHz, corresponding to $5\lambda/2$. Second, the chosen mode should have a caustic radius $(m/\chi) * r_{cavity}$ similar to the original operating mode, in order to obtain reasonable focusing of the rf output beam. This is advantageous because the quasi-optical mode converter system usually shows at least tolerable performance for modes with similar Brillouin angles and wave numbers. Modes with similar caustic radius, oscillating in the same cavity, satisfy these conditions reasonably well. To use the same launcher, the chosen mode must of course also be excited with the same rotation direction as the design mode. Figure 1 shows the wall field intensity inside the launcher of the W7-X gyrotron, operated at 173.9 GHz in the $TE_{34,10}$ mode. It is found that the rf field is reasonably bunched and centered with respect to the launcher cut. This results in a quite good rf output beam with 90 % Gaussian mode content (Fig. 2), which is well centered, too. The produced stray radiation and reflection should also not be prohibitively high.

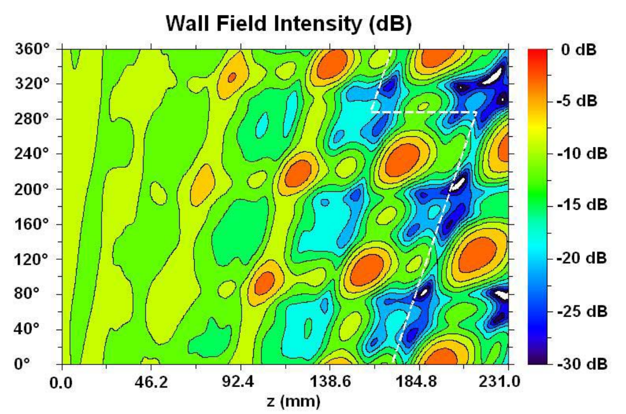

Figure 1: Wall field intensity for $TE_{34,10}$ at 173.9 GHz, calculated for the existing launcher (originally designed for $TE_{28,8}$ at 140 GHz). The dotted white line indicates the launcher cut.

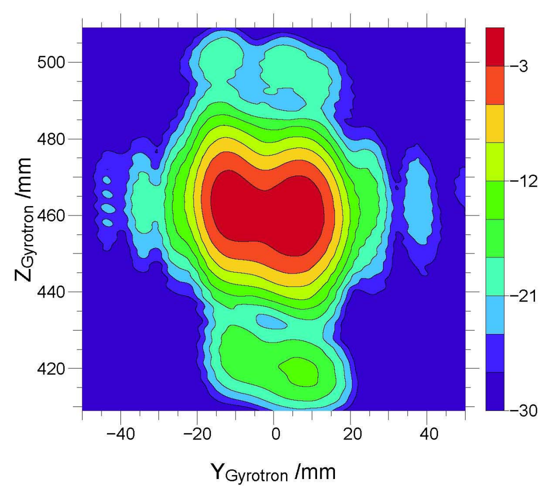

Figure 2: rf output beam in the window plane for $TE_{34,10}$ at 173.9 GHz, calculated for the existing launcher (originally designed for $TE_{28,8}$ at 140 GHz).

The second factor described above also defines the optimum electron beam radius. The third issue, to find a

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suitable mode that can provide effective interaction in the cavity at that beam radius, is less critical, at least for high power gyrotrons within reasonable frequency ranges. Since the mode spectra in current high power gyrotrons are very dense, it is almost always possible to find a mode close to the desired frequency with a suitable caustic radius – in our case the best choice is the $TE_{34,10}$ mode. The interaction efficiency can usually remain high as long as the normalized cavity length μ falls into an interval of $10 < \mu < 25$, which sets a limit to the usable frequency range[4]. For the W7-X gyrotron at 173.9 GHz, the normalized length $\mu = 17$ is well inside the region of high efficiency, while in the experiment at 105 GHz $\mu = 10$ is at the limit. And finally, the electron gun parameters must be adjusted to deliver a reasonable velocity ratio α. Using a diode gun at higher magnetic field and identical compression ratio, this can be done by increasing the voltage. At 140 GHz the operating voltage was 80 kV, but the electron gun can safely be operated up to 95 kV. The resulting α at the operating point can be as high as 1.3, at a slightly reduced beam radius of 9.6 mm. These values are suitable for high power and high efficiency operation.

III. Results

Having done these selections and parameter adjustments, the results for the single-mode calculation of the $TE_{34,10}$ mode are an rf output power of 1 MW at the window, at 40 A beam current and 95 kV cathode voltage (remaining parameters as in Fig. 3). The corresponding efficiency of 26 % without a depressed collector can be increased above 40% when the depressed collector of the existing gyrotron is used. At even higher voltages, power and efficiency would increase further, but the cavity wall losses above 2.3 kW/cm^2 would be prohibitively high.

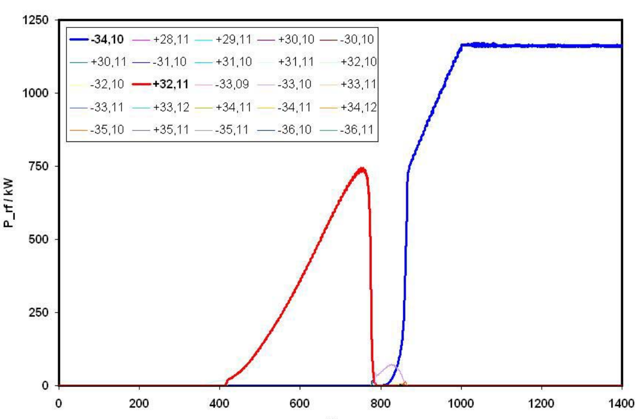

Figure 3: Generated rf powers in a multi-mode startup calculation for $TE_{34,10}$ in the existing cavity of the W7-X gyrotron (originally designed for the $TE_{28,8}$ mode at 140 GHz). The mode appearing before the final $TE_{-34,10}$ (blue) is $TE_{+32,11}$(red). Parameters at the operating point, in this simulation reached after 1000 ns, are $B_{resonator} = 7.1$ T, $U_{cathode} = 95$ kV, $I_{beam} = 40$ A, $r_{beam} = 9.7$ mm and $\alpha = 1.2$

To support these single-mode results, a self-consistent, time-dependent multi-mode calculation was done using the FZK code SELFT[5]. The simulation proves stable operation of the $TE_{34,10}$ mode at the chosen working point (Fig. 3) .

In conclusion, the existing W7-X gyrotron may be suitable for two- or even three-frequency operation, reaching high power and efficiency at least at both 140 GHz and 173.9 GHz. We propose to prove this in an experiment as soon as a suitable magnet will be available. At FZK this will probably be the case in 2009.

IV. Conclusions

The presented study on 173.9 GHz operation of the existing 140 GHz W7-X gyrotron in a suitable magnet promises output powers of 1 MW at efficiencies of 26 % (without depressed collector). Even though the employed gyrotron is not optimized for this operating point and the corresponding $TE_{34,10}$ mode, it is found that the electron gun can deliver a suitable electron beam within reasonable operating parameters, and that the quasi-optical system is at least good enough to allow rf power measurements. It is proposed to accomplish the corresponding experiment as a proof of principle, in order to demonstrate a 1 MW CW two-frequency source, or even three-frequency, if operation at 105 GHz is taken into account, too. After a successful experiment, it can be expected that a corresponding gyrotron, suitable for series production and with optimized performance, can be constructed with high design safety by modifying the existing W7-X design only slightly. With operating frequencies adjusted to 170 GHz and 135 GHz, respectively, this could be a favorable solution for the ITER ECRH heating system.

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