Towards a 4 MW 170 GHz Coaxial Gyrotron Resonator Design

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***Abstract*—In this work the feasibility of a 4 MW 170 GHz gyrotron resonator design is investigated. The realization of high power gyrotrons will reduce the number of gyrotrons and superconducting magnets required for future fusion reactors. Proper care has been taken in examination of mode competition in the case of very high order modes. A possible outer wall corrugation is discussed and possible improvements are shown. The design considers realistic technical constrains and nominal parameters.**

I. Introduction and Background

GYROTRONS are high power microwave sources widely employed for electron cyclotron resonance heating (ECRH) of plasmas and in other industrial or scientific applications. Recent experiments suggest that output powers of 2 MW at frequencies from 140 GHz to 170 GHz are feasible. For future fusion reactors gyrotrons with higher output power are desirable to reduce their number and the complexity of the whole heating system, including the number of superconducting magnets and the transmission lines towards the tokamak or stellarator installation. In this paper a mode selection and proper resonator design as a step towards a big leap to the 4 MW power level is presented. All calculations are self-consistent and time dependent using the slow-variable code package *Cavity* available at FZK [1]. The investigations consider technical parameters and a high number of competitive modes, due to the dense spectrum at the utilized eigenvalue range. At such high power several parameters reach the technical practicable limits. Ahead of all, the chosen competitive modes for the self-consistent regions have to be chosen carefully. As designs are scaled to high power and high frequency, the mode density in the cavity increases and it is not possible to find modes which are sufficiently isolated from their nearest neighbors [2]. During the gyrotron start-up the acceleration voltage reaches values where the cyclotron frequencies of the coupled modes pass through a wide range. These two effects raise the number of competitive modes to a high level. At a working point beyond 4 MW wall losses are additional ubiquity and have to be considered accurately.

II. Results

In the selection procedure, one well-qualified mode, namely $TE_{44,26}$, is chosen [3]. The $TE_{44,26}$ has a Bessel root of $\chi_{44,26} = 141.54$. A suitable coaxial cavity geometry for this mode is designed and optimized, output power and efficiencies are computed. The working point of the chosen mode is $120\,\mathrm{kV}$ at $100\,\mathrm{A}$ and velocity ratio $\alpha = 1.3$. Proper care has been taken in examination of the influence of numerical parameters to the simulation. The most critical are the time step and azimuthal discretisation. The number of macro particles used and the discretisation along the z-axis are not hypercritical but should kept in mind as not irrelevant. To obtain realistic theoretical results these values need a proper choice, particularly in gyrotron cavities operating with high order modes [5]. The competitive modes considered in the self-consistent calculation diversify the physical reliability and have to be chosen carefully. In a frequency band of ± 10 GHz around the nominal working point of 170 GHz, 71 competitive modes have a coupling to the electron beam better than 50% relating to the desired working mode. The passed relativistic cyclotron frequency over voltage for different magnetic fields is plotted in Fig. 1. According to the change of the cyclotron frequency during the start-up of the gyrotron, due to the voltage rise to above $110\,\mathrm{kV}$ and the consequentaly following change in the relativistic factor γ, a frequency range -10 GHz and $+20$ GHz around the desired frequency has to be considered. Within this range 97 competitive mode couple more than 50% to the electron beam, normalized to the main mode.

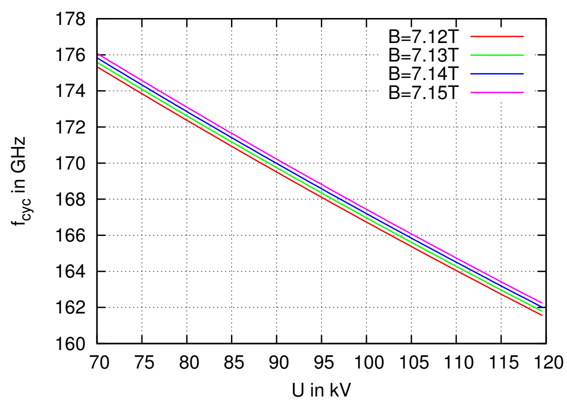

Fig. 1. Relativistic cyclotron frequency over beam voltage at several magnetic field strengths

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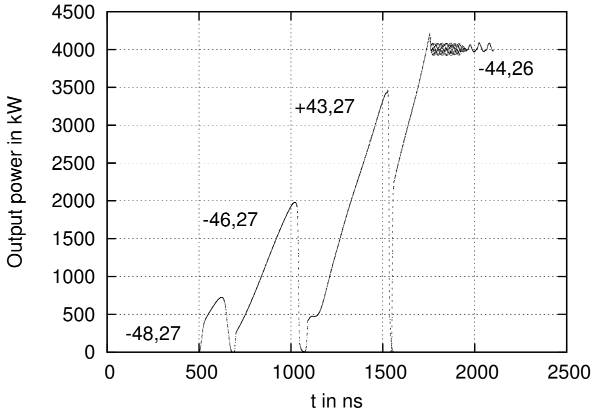

Fig. 2. Start-up simulation: Power and voltage vs. time; 76 competitive modes including all azimuthal neighbors are considered

Simulations indicate that it is necessary to include this broad frequency range. Corresponding simulations neglecting modes with lower coupling show that it is sufficient to consider modes with a coupling better than 70% to the electron beam relating to the working mode. For the given geometry 39 modes, including the main mode, have a couping better than 70% in the frequency range -10 GHz and $+20$ GHz. After optimization of the cavity geometry and beam parameters, single mode efficiency better than 40% is accessible and output power at the cavity of more than $4.5\,\mathrm{MW}$ is obtainable. This drops to a value around 35% in multi-mode calculations. In recent simulations a stable output power of $4.0\,\mathrm{MW}$ was achievable, as shown in Fig. II. Consequently, single mode operation is possible even when the density of modes in the cavity becomes very high. In the shown simulation 76 competitive modes including the azimuthal neighbors are considered. The mode has an optimized coupling to the electrons at a beam radius of $r_{beam} = 12.88\,\mathrm{mm}$. It is satisfactory insensitive in variation of the beam radius up to values around $\Delta r = 0.2\,\mathrm{mm}$.

The main mode has a stable operating area for magnetic field fluxes B from $7.10\,\mathrm{T}$ to $7.13\,\mathrm{T}$. This area can be broaden significantly using an outer wall corrugation in the cavity [6]. This corrugation couples both azimuthal neighbors $\mathrm{TE}_{m\pm1,p}$ to propagating modes so that they vanish. The Q values of the coupled azimuthal neighbors decrease strongly due to the negative slope of their eigenvalue curves in a resonator with negative tapered inner conductor. Their influence on the operating main mode at the upper end of the stability region can be neglected and higher output power is possible. The next residual azimuthal modes are the $\mathrm{TE}_{m\pm2,p}$, which have approximately twice the frequency displacement to the working mode $\mathrm{TE}_{m,p}$, compared to the azimuthal neighbors $\mathrm{TE}_{m\pm1,p}$. The corrugation depth dictates the strengths of coupling, which will be chosen as deep as possible to assure undisturbed operation of the desired mode [1]. Without the influence of the first azimuthal neighbors a broader stability region and higher output power are possible.

Realistic wall losses at these designs are within the given technical range of $< 0.25\,\mathrm{kW/cm^2}$ at the inner rod and $< 2.0\,\mathrm{kW/cm^2}$ at the cavity wall. The necessary beam current leads to a current density around $5\,\mathrm{A/cm^2}$ at the emitting gun, which is feasible with respect to cathode lifetime. For modern emitter materials a maximum emission current density between $6\,\mathrm{A/cm^2}$ and $10\,\mathrm{A/cm^2}$ is quoted as reliable for lifetimes of the order of several thousand hours [4]. Therefore, in these high eigenvalue regions mode competition turns out to be the major challenge for the feasibility of gyrotron output powers beyond $4\,\mathrm{MW}$. Next works are the final design of the coaxial cavity and parameter studies over nominal parameters. After mode selection and cavity design a proper layout for the electron gun and the quasi-optical output launcher with suitable mirror system has to be carried out. This work is in progress.

III. Summary

In this work the feasibility of a $4.0\,\mathrm{MW}$ gyrotron resonator design operating at $170\,\mathrm{GHz}$ is shown. One well qualified mode $\mathrm{TE}_{44,26}$ is chosen to introduce an optimized geometrical design, where technical constrains are examined. The focus in the simulations is on the related competitive modes. A region regarding of an electron beam coupling higher than 70% and a frequency area of -10 GHz and $+20$ GHz around the desired frequency can be named to be sufficient for realistic simulations. It was possible to find stable operation conditions in an sufficiently broad region. This area can be broadened with an outer corrugation of the cavity wall. The operating mode is insufficiently unstable against variation of the magnetic flux and the electron beam radius. The $\mathrm{TE}_{44,26}$ with its eigenvalue of $\chi_{44,26} = 141.54$, has a satisfactory high order to initialize acceptable wall losses on either the inner conductor and the cavity wall.

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