Design of Gyrotron FU CW VI for 600 MHz DNP-NMR experiment

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Abstract— **For the application of gyrotron to accurate measurement of DNP-NMR, frequency continuous tunability is desired in 2 GHz range at least. The demountable Gyrotron FU CW VI tube based on 15T helium free superconducting magnet are under development. The gyrotron operation is in CW mode at the fundamental cyclotron harmonic. The output power is 100 W in the whole frequency tunable range and the center frequency is 394.6 GHz. The gyrotron will be applied to 600 MHz DNP-NMR experiments.**

I. Introduction

FOR a number of applications including plasma diagnostics and different spectroscopy, microwave sources continuously tunable in a broad frequency range are required. One such newly emerging field is the Nuclear magnetic resonance (NMR) spectroscopy with signal enhancement through Dynamic Nuclear Polarization (DNP), which is promising to research in protein studies, structural biology, solid-state physics and other scientific areas. Several specialized tubes for DNP experiments are under developed at FIR FU. The main goal is to achieve a CW operation with stable (within 1% variation) output power about 100 W and broadband continuous frequency tuning in an interval of ±1 GHz around the frequency of 394.6 GHz, which corresponds to 600 MHz NMR resonance for a proton.

Several alternatives have been considered as possible candidates for frequency tunable FIR FU gyrotron[1,2]. The main focus of this paper is the coaxial cavity gyrotron with smooth and continuous mechanical frequency tuning. The tuning is based on displacement of an internal cone-shaped rod of coaxial cavity along device axis[3,4].

II. Concept and Results of the Simulations

The continuous-wave wideband frequency tuning was realized by varying the magnetic field in a gyrotron with a cone-shaped cavity[5], in which the mode was excited in a different regions of long cavity. In such regions, the resonance conditions are satisfied for different values of the homogenous magnetic field. Another way to realize the said frequency tuning was using a double-mirror cavity, i.e., an elliptical cavity with two narrow slits and small eccentricity[6,7] or a quasi-optical cavity, which two mirrors are set at a big distance from each other[8,9]. Unfortunately, such gyrotrons are not very useful due to the low selectivity (in the first case), a limited number of the operating mode (for the slit cavity, only non-symmetrical modes with a fixed polarisation and the zero RF electric field at the slots may be excited), and low efficiency.

The situation looks more optimistic for coaxial-cavity gyrotrons. It is possible to realize the frequency tuning by varying the mode eigenvalue v smoothly. To do this, one changes the ratio of the radiuses of the external and internal conductors by moving the tapered inner conductor longitudinally[10,11]. This is a mechanical method of frequency tuning (perhaps, with a variation in the magnetic field). It means that the tuning process is slow compared with the electronic tuning. In this paper, we analyze the wideband operation regime with a strong influence of the internal rod on the mode structure. Similarly to Reference[10,11] we do not analyze the design of the quasi-optical mode converter, the influence of the reflected power, the design of the wide-frequency-band output window, and the technical aspects of manufacturing the cavity.

In current coaxial gyrotrons, an impedance structure is used for mode selection. It is a system of rectangular grooves with depth d along the longitudinal axis. The impedance W is equal to $W = (l/s) * tg(2\pi d/\lambda)$ where λ is the wavelength, l is the groove width, and s is the corrugation period.. If the radius of the internal conductor approaches the radius of the caustic (i.e., the parameter C decreases), the eigenfrequency of the cavity decreases ($dv/dc > 0$). Then, when the radius of the internal conductor becomes greater than the caustic radius, the eigenfrequency increases rapidly ($dv/dc < 0$). It is also interesting to consider the region where $dv/dc \sim 0$. This area corresponds to the strongest influence of the wall impedance W on the mode eigenvalue $v(c)$. This effect can also be used for the frequency tuning.

For a smooth internal conductor (W = 0), the reduction of the mode eigenvalue in the region $dv/dc > 0$ is about 0.5 for volume modes and up to 1 for the whispering gallery modes. The linear region of the $v(c)$ curve is preferable for efficient frequency variation. Thus, for the 1% frequency tuning, the diameter of the cavity must be about 15λ and for 3% tuning, about 5λ. Such a situation obliterates the main advantage of the coaxial gyrotron, namely the possibility to use an oversized cavity with higher-order modes for high-power generation.

If a corrugated surface is used, it is possible to strongly increase the variation of the mode eigenvalue in the region $dv/dc > 0$. This phenomenon is best pronounced for relatively small values of the impedance, $W < 1$, which correspond to the groove depth $d \leq \lambda/10$. Unfortunately, in this situation the ohmic loss increases by an order of magnitude. Another negative factor is the strong dependence of the mode eigenfrequency on the impedance value for fixed C.

The requirement for the accuracy of manufacturing can be reduced if we use the strong influence of the impedance value on the eigenfrequency. The corrugation with a variable depth

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produces a variable impedance. The optimal value C_{opt} (maximum sensitivity to impedance variation) corresponds to $d\nu/dc \sim 0$. If $C > C_{opt}$, the ohmic loss increases (the maximum density ohmic losses is at the middle point of the $d\nu/dc < 0$ region. If $C < C_{opt}$, the ohmic loss reduces, but the rod influence on the mode structure increases and a great tube adjustment is needed. As the groove depth is varied from $d = 0$ (W=0) to $d \sim \lambda/4$ (W >>1), the required frequency band can be obtained for some initial position of the rod.

We selected $TE_{10.5.1}$ as operating mode at fundamental cyclotron harmonic. The central frequency 394.6 GHz correspond to the magnetic field about 14.5T. The diameter of external cavity wall is about 8 mm and the diameter of internal road is about 5 mm. A manufacturing accuracy of about 5 micrometers is needed to retain the output characteristics. One of the possible cavity profiles is shown in Fig.1. For this geometry, the relation $d\nu/dc$ is high enough for reasonable rod displacement. On the other hand, the mismatch with the closest parasitic mode is sufficient. This cavity profile looks unusual for coaxial gyrotrons. The operation in the considered region of the $\nu(c)$ curve needs a radical change in the cavity profile. The internal down taper reduces the cavity Q-factor sharply. The Q-factor increases if one uses an external down-taper conductor at the same time, but the Q-factors of the parasitic modes also increase. For parasitic modes with a relatively high excitation factor, the value of $d\nu/dc$ is lower than this value for the operating mode $((d\nu/dc)_{\text{parasitic modes}}<(d\nu/dc)_{\text{operating mode}})$, and the diffractive Q-factor of the parasitic modes increases more rapidly than the diffractive Q-factor of the operating mode. So, the up-taper profile of the internal rod looks much more preferable. This profile increases the diffractive Q-factor of the operating mode as compared with the parasitic one, and for the normal density of the ohmic loss, the profile of the external conductor also has the form of an up-taper.

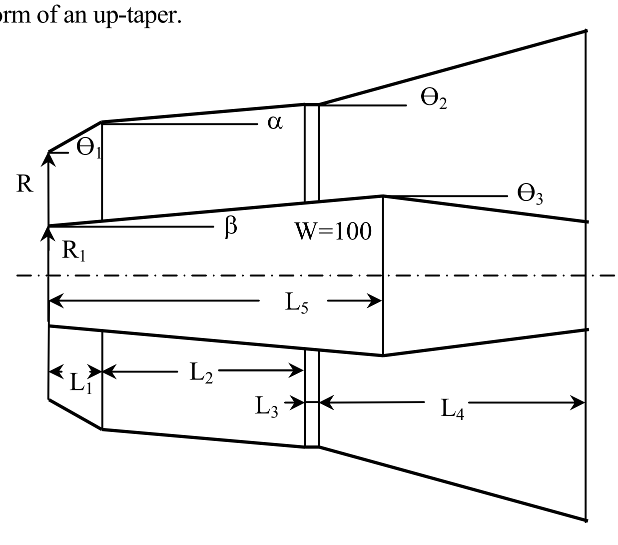

Fig. 2. Cavity profile for the $TE_{10.5}$ operating mode (f_{average} = 394.6 GHz). Main cavity parameters are: L_1 = 5 mm; L_2 = 19 mm; L_3 = 1 mm; L_4 = 25 mm; L_5 = 30 mm; $\Theta_1 = 3$; $\Theta_2 = 3^0$; $\Theta_3 = 1.5$; $\alpha = \beta = 0.25^0$, R_1 = 2.4 mm; R_2 = 4 mm

The electron beam is formed by the invert magnetron injection gun (typical for coaxial gyrotrons) with operating voltage U = 15 kV. The electron beam radius is equal 3.25 mm. The dependences of output power P, gyrotron efficiency and density of ohmic losses J versus beam current are shown in Fig.2. The maximal frequency tuning is about 8 GHz, i.e. $\Delta f/f \approx 2\%$ for ± 5 mm displacement.

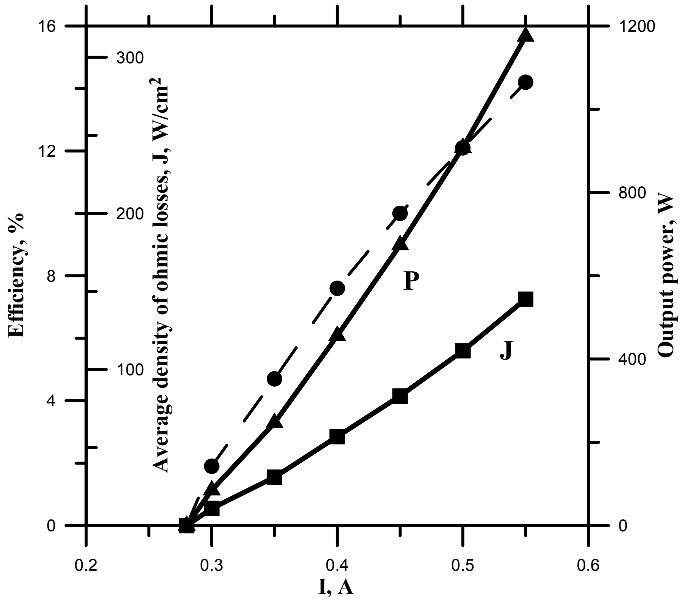

Fig.2. The gyrotron output characteristics

The output power at several hundreds watts is predicted by numerical simulations at CW regime with maximal density of the ohmic losses at the cavity wall less than 200 W/cm^2. For required for DNP experiments frequency band about ± 0.5 GHz the internal road displacement is ± 1.5 mm. Such shift looks optimistic with relation to manufacturing and adjustment with needed accuracy at construction based, for example, on corrugated pipe element.

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