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Frequency Tunable Gyrotron FU CW VA for Measuring Hyperfine Split of Positronium

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Abstract New uptapered cavity is designed for the gyrotron FU CW VA enhancing its tunability and enabling its use for measurements of the hyperfine split of positronium.

Keywords Gyrotron · Uptapered resonant cavity · Hyperfine split of positronium

1 Introduction

There are many kinds of exotic atoms (see e.g. [1]). Positronium, the bound state of an electron and a positron, is the lightest exotic atom. Since it is a purely leptonic system and is free from the uncertainties of strong (hadronic) interaction (as, for example in protonium [2]), it is very suitable for studying various corrections in quantum electrodynamics. Positronium has two states, the singlet and the triplet. The energy splitting between these states known as the hyperfine split of positronium atom is ~203.4 GHz. It has been proposed [3] recently to detect the hyperfine transition of positronium by means of the gyrotron FU CW VA operating in the $TE_{0,3}$ mode at fundamental. This gyrotron generates several hundreds of watt power in the required frequency range. However its frequency cannot be adequately tuned, therefore it can hardly be used for accurate hyperfine split measurements. In this paper we propose an uptapered cavity for the gyrotron. With the designed cavity it should be possible to tune the frequency of the gyrotron within the range >3 GHz by means of variation of the magnetic field. Such a tuning range is sufficient for accurate measurements of hyperfine split of positronium.

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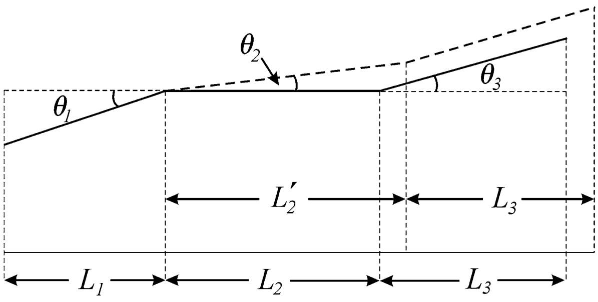

Fig. 1 Profiles of a standard resonator with the constant radius of its central part (*solid lines*) and that of an uptapered resonator (*dashed lines*).

2 Existing cavity

The geometry of the existing cavity is sketched in Fig. 1. The angles are: $\theta_1=2.55^0$, $\theta_2=0^0$, and $\theta_3=6^0$. The lengths of the sections are: $L_1=4$ mm, $L_2=15$ mm, and $L_3=5$ mm. The radius of the cavity (at the straight section) is $R_0=2.389$ mm.

The frequencies and quality factors obtained in the cold cavity approximation are summarized in Table 1. The field profile corresponding to the lowest value of the axial index $q=1$ is shown in Fig. 2.

This gyrotron is driven by an electron beam with the nominal current $I_{opt}=0.2$ A and the accelerating voltage Uopt=20 kV at which the pitch factor is $\alpha=1.5$. The operating mode is $TE_{0,3}$. The optimal electron beam radius providing the strongest coupling to this mode is $R_{el}=0.43$ mm. The gyrotron has produced 240 W output power at the magnetic field $B=$ 7.43 T. The measured frequency was $F=203.03$ GHz which corresponds to $q=1$.

In Fig. 3 starting currents are shown as a function of the magnetic field.

It can be seen that already for $q=3$ the minimum starting current lies above the operating current. Consequently with this cavity the frequency of the gyrotron cannot be tuned in a wide enough range by means of changing the magnetic field in such a way that the electron beam interacts with the backward-wave component of the corresponding high-order axial mode [4–6].

3 Uptapered cavity

We propose to use an uptapered cavity which is known to have several benefits [7, 8]. The middle section of this cavity is twice as long ($L_2' = 30mm$) as of the existing cavity ($L_2=$ 15 mm). The angle of the middle section was chosen such ($\theta_2=0.014^0$) that the resulting quality factor for $q=1$ is approximately the same as in the existing cavity. The frequencies and quality factors obtained in the cold cavity approximation are summarized in Table 2. The field profile corresponding to the lowest value of the axial index $q=1$ is shown in Fig. 4.

Table 1 Frequencies and diffractive quality factors for the $TE_{0,3,q}$ mode with different axial indices q.

q	F (GHz)	Q_D
1	203.37	4467
2	203.93	1124
3	204.85	506

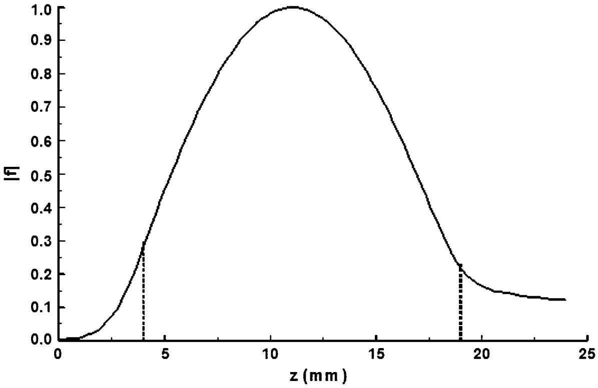

Fig. 2 Absolute value of the field profile of the $TE_{0,3,1}$ mode. The middle section of the cavity is between the two vertical dashed lines.

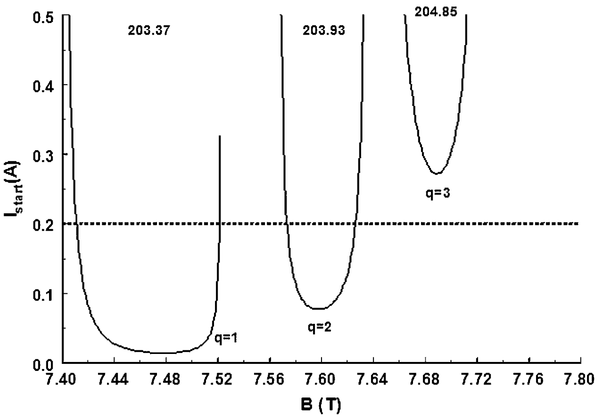

Fig. 3 Starting currents as a function of the magnetic field. The operating current I_b=0.2 A is marked by the horizontal dashed line. The numbers inside the starting current curves correspond to oscillation frequencies in *GHz* as listed in Table 1.

Table 2 Frequencies and diffractive quality factors for the $TE_{0,3,q}$ mode with different axial indices *q*.

q	*F* (*GHz*)	Q_D
1	202.87	4,659
2	203.11	4,026
3	203.38	2,507
4	203.75	1,560
5	204.22	1,055
6	204.80	762
7	205.49	578
8	206.27	457

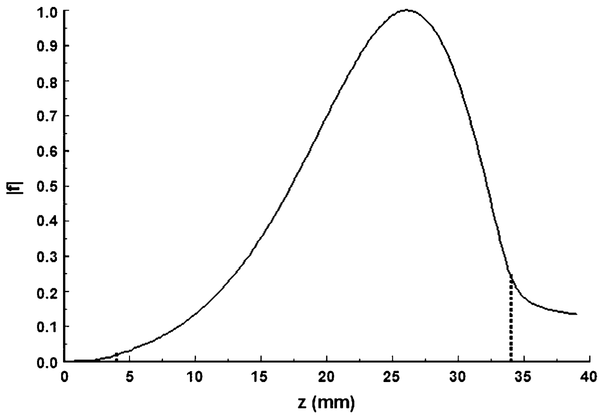

Fig. 4 Absolute value of the field profile of the $TE_{0,3,1}$ mode. The middle section of the cavity is between the two vertical dashed lines.

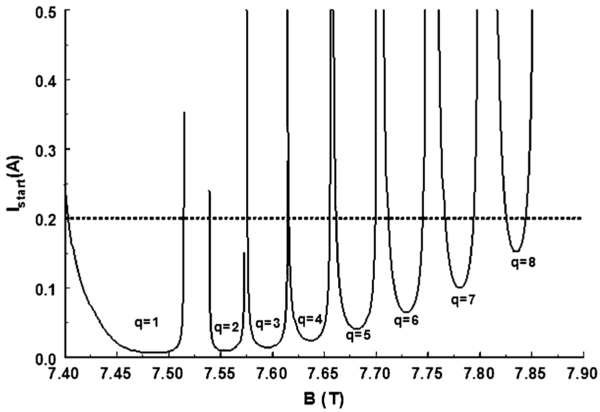

Fig. 5 Starting currents as a function of the magnetic field. The operating current I_b=0.2 A is marked by the horizontal dashed line.

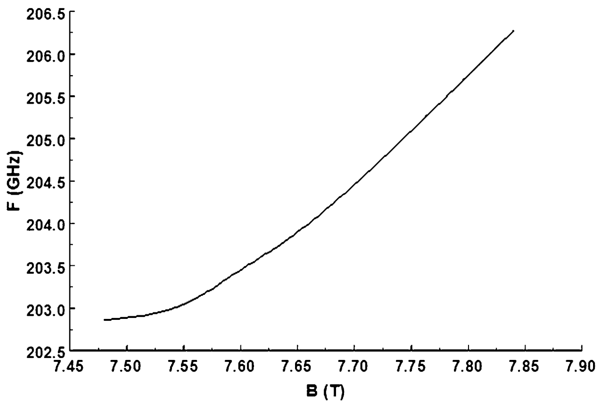

Fig. 6 Oscillation frequency as a function of the magnetic field.

It is interesting to compare the values of diffractive quality factors in the two cavities. It is evident that in the uptapered cavity the diffractive quality factors are significantly larger than in the existing cylindrical cavity, simply because of the fact that the middle section of this cavity is twice as long as the middle section of the cylindrical cavity. More interesting is the dependence of the diffractive quality factor on the axial index of the mode. In the cylindrical cavity the diffractive quality factor decreases according to the well known law $Q_D \sim 1/q^2$ (Table 1), while in the uptapered cavity this decrease is much slower (Table 2). To our knowledge no general analytic expressions have been derived for $Q_D(q)$ in uptapered cavities aside from the early attempt [9].

It is interesting to compare the field profiles in the two cavities. It can be seen that tapering the mid-section shifts the maximum of the field profile toward the output end. This shift can help to improve the efficiency because gradual increase of the wave amplitude near the entrance leads to a gentle modulation of electron energies and formation of a compact bunch, while then this electron bunch will be decelerated by the field of a large amplitude.

In Fig. 5 we show starting currents for different axial indices q.

It is remarkable that in the uptapered cavity the minimal values of the starting currents for $q \leq 8$ are smaller than the operating current I_b=0.2 A. This is a direct consequence of the large values of diffractive quality factors in this cavity and their slow decrease with increasing q. One can conclude that with the uptapered cavity the frequency of the gyrotron can be tuned within >3 GHz range by varying the magnetic field as shown in Fig. 6.

4 Fabrication error of the uptapered cavity

The tapering (θ_2=0.014^0) corresponds to 7 μm ($R_0 = 2.389mm \rightarrow 2,396mm$) increase of the cavity radius along the distance L_2=30 mm. It should not be difficult to manufacture such a cavity, because in the case of cylindrical cavities the fabrication error as small as 1 μm [10] and 0.2 μm [11, 12] have been reported.

5 Conclusions

A new cavity has been proposed for the gyrotron FU CW VA. The diffractive quality factors in this uptaperd cavity are significantly higher and starting currents significantly lower for large axial indices q of the operating $TE_{0,3,q}$ mode than in the existing cylindrical cavity. As a consequence, this gyrotron becomes tunable within the >3 GHz range and it can be involved in accurate positronium hyperfine split measurements.

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