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DESIGN OF A HIGH POWER, 2.75 GHZ RELATIVISTIC PENIOTRON OSCILLATOR

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In the peniotron oscillator, the kinetic energy of relativistic electrons can be efficiently converted to an electromagnetic wave. This feature makes the peniotron a very attractive source of high power microwaves, which is required in heating of fusion plasma in tokamaks and high gradient particle accelerators. In this report we present the design of a 2.75 GHz relativistic peniotron oscillator which is capable of generating a microwave radiation of 30 megawatt with an efficiency of about 60%. The experimental test results of the designed cavity are also pesented.

Keywords: Relativistic Peniotron Oscillator, Cyclotron, Magnetic Cusp

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2.75GHz相対論的ペニオトロン発振器の設計

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（1992年9月21日受理）

ペニオトロン発振器では，相対論的電子ビームの運動エネルギーを高効率で電磁波に変換することができる。このためペニオトロンは核融合におけるプラズマ加熱や高エネルギー加速器に利用される大出力電磁波源として期待されている。本稿では出力周波数2.75GHz，出力30MW，変換効率60％の相対論的ペニオトロンの設計，ペニオトロンキャビティの特性実験の結果について報告する。

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1. Introduction

There are now several applications in scientific research where high power microwaves and millimeter waves of the order of several hundred megawatts to several gigawatts is required. The RF linac in a TeV collider should have very high energy gradient of about 1 GeV per meter, for an accelerator of relatively short length and to realize this goal a gigawatt class RF sources are necessary. Space exploratory radar need equally high power RF in the millimeter wave region for probing distant planets and and near stars like the sun. In plasma fusion research, equally high power millimeter to submillimeter RF power is required for electron resonance heating (ECRH) of magnetically confined plasma.This high power requirement has restricted the source devices to electron tubes. In high power operation, the efficiency of converting electron kinetic energy to RF power is a major consideration in order to conserve energy and reduce investment in cooling equipment.

The peniotron, invented by Professor S. Ono and his co-workers in 1963, is an electron cyclotron resonance device in which cycloiding electrons are injected into an interaction circuit, where an electromagnetic wave has been excited[1]. The electrons interact with the wave and transfer some of their transverse kinetic energy to the latter. The peniotron falls into a class of electron tube devices now commonly known as electron cyclotron resonance masers (ECM).The gyrotron also belongs to this category. Unlike conventional microwave source devices such as klystrons, magnetron and traveling wave tubes, ECM devices do not need structures in their interaction circuits, and so are very attractive as sources of high power and high frequency RF radiation. The peniotron is unique among all electron tube devices in that electron bunching is not essential in its operation mechanism. This unique feature ensures that all electrons have the same experience in the interaction circuit and so no energy spread occurs as they lose their kinetic energy to the electromagnetic wave(EM). Because of this feature, the peniotron has a potential of higher efficiency operation when compared to other electron tube devices.

Substantial progress has been made in the experimental development of the peniotron with a view of improving its high frequency generation and its electron energy conversion efficiency capabilities[2,3], but no high power peniotron, suitable for the cited applications, has been built so far. In this report we present the design of a relativistic peniotron capable of generating a RF power of 30 megawatt (MW) at a frequency of 2.75 GHz with an efficiency of about 60%. The designed cavity and the electron gun have been fabricated and in this report we shall present the cold test results. After completion of all the necessary preliminary experimental tests, we intend to do experimental studies of the device in the JAERI LAX-1 laboratory, where an induction linac DC power supply of 1 megavolt (MV) is installed.

2. Structure of the peniotron oscillator

Figure 1 shows the schematic diagram of the peniotron oscillator. As is common for all electron tube RF source devices, the major sections are an electron gun, a drift tube, cavity, a collector and a RF output window. In the peniotron, the electron gun has a cathode with a ring emitting area, so when an accelerating voltage is applied at the anode, a hollow electron beam is emitted. At the anode, the electrons will have acquired a total velocity **v** determined by the accelerating voltage applied at the anode. In the peniotron, we need a cycloiding electron beam, so a DC magnetic cusp field, of the shape shown in figure 2a, is applied. At the cusp, a DC the magnetic field, B_1, is applied abruptly, so on crossing the cusp field, the electrons begin cycloiding, as in figure 2b, with the center of the orbits coincident with the axis of the gun and at a cyclotron frequency which is determined by the guiding DC magnetic field.

The drift tube connects the electron gun and the cavity. Its dimensions should be such that the RF power generated in the cavity cannot flow back to the gun region. Therefore its cut-off frequency should be well above that of the RF being generated. The cavity is immersed in a DC magnetic field, B_o, which not only causes the cycloid motion of the electrons, but also guides the electrons along the axis of cavity. The electrons will interact with the propagating whispering gallery mode RF electric field (TEp1) in the circular waveguide cavity and lose their kinetic energy if the electron and the propagating electromagnetic wave remain in resonance [4]. Figure 3 shows the RF electric field distribution at the cross-section of the $TE_{2\,1\,1}$ cavity, which we will use in the peniotron oscillator.

The electrons which have still residual axial kinetic energy at the end of the interaction leave the interaction space through a hole at the end of the cavity and are diverted to the collector with aid of a kicker magnet. The residual kinetic energy of the electrons is dissipated as heat at the collector, which should be cooled in high power devices.

3. Simulation method and results

To evaluate the amount of electron kinetic energy transferred to the electromagnetic wave, we should solve the following equation of motion of the electrons in the excited electromagnetic field.

$$\frac{d\mathbf{v}}{dt} = -\frac{e}{m}(\mathbf{E} + \mathbf{B} \times \mathbf{v} - \frac{1}{\mathbf{c}^2}(\mathbf{E}.\mathbf{v})\mathbf{v}) \qquad (1)$$

where e and m are the electron charge and relativistic mass respectively, **v** is the electron velocity, **B** is the magnetic field, **E** is the electric field and c the velocity of light in free space.

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In equation (1) the relativistic mass m is known only at the entrance of the cavity, where it is determined by the applied accelerating voltage, however it is unknown at all other points inside the cavity because it depends on the residual electron kinetic energy. The energy transfer is proportional to the difference in relativistic mass of the electrons at the entrance and exit of the cavity. At the entrance of the interaction waveguide circuit, the electrons have their maximum kinetic energy equivalent to the accelerating voltage. Their relativistic mass, m , is given by $m = m_0\gamma$ where m_0 is the rest mass of an electron and γ the relativistic constant. If we designate the relativistic constants at the entrance and exit of the interaction circuit as γ_0 and γ_f respectively, then we can calculate the electron electron energy conversion efficiency, η , as

$$\eta = \frac{\gamma_0 - \gamma_f}{\gamma_0 - 1} \tag{2}$$

Equation (1) can be solved numerically by a digital computer using the Runge-Kutta algorithm and in this way we can evaluate the final mass of the electrons at the exit of the interaction circuit and then use equation (2) to calculate the efficiency of electron energy transfer to the electromagnetic wave.

In order to solve equation (1), we should also know the equations that describe the electromagnetic waves inside the cavity. For a circular waveguide cavity with a standing TE_{mnk} electromagnetic wave pattern, they are given by

$$E_r = -A\frac{\mu\omega m}{r}J_m\left(\frac{U^*_{mn}}{a}r\right)\sin\left(\frac{k\pi}{L}z\right)\cos(m\theta - \omega t) \tag{3.1}$$

$$E_\theta = -A\frac{\mu\omega U^*_{mn}}{a}J^*_m\left(\frac{U^*_{mn}}{a}r\right)\sin\left(\frac{k\pi}{L}z\right)\sin(m\theta - \omega t) \tag{3.2}$$

$$E_z = 0 \tag{3.3}$$

$$B_r = A\frac{\mu k\pi U^*_{mn}}{La}J^*_m\left(\frac{U^*_{mn}}{a}r\right)\cos\left(\frac{k\pi}{L}z\right)\cos(m\theta - \omega t) \tag{3.4}$$

$$B_\theta = -A\frac{\mu k\pi m}{Lr}J_m\left(\frac{U^*_{mn}}{a}r\right)\cos\left(\frac{k\pi}{L}z\right)\sin(m\theta - \omega t) \tag{3.5}$$

$$B_z = -A\,\mu\left(\frac{U^*_{mn}}{a}\right)^2 J_m\left(\frac{U^*_{mn}}{a}r\right)\sin\left(\frac{k\pi}{L}z\right)\cos(m\theta - \omega t) \tag{3.6}$$

where U^*_{mn} is the nth non-vanishing root of $J^*_m = 0$, J_m is the Bessel's function, A the wave amplitude and the superscript stars indicate derivatives.

The RF power that can be stored in the cavity W is depends on the quality factor, Q, the frequency of the excited wave, ω, and the power that is radiated and leaves the cavity, P_{out}.

This relationship can be expressed as

$$W = P_{out}Q/\omega \tag{4}$$

If we use the wave dispersion equation

$$\frac{\omega^2}{c^2} = \frac{U^{*2}_{mn}}{a^2} + \frac{\pi^2 k^2}{L^2}$$

then the amplitude of the electromagnetic wave in the cavity is given by

$$A = \sqrt{\frac{4Wc^2}{\pi\mu\omega^2 L(U^{*2}_{mn} - m^2)J^2_n(U^*_{mn})}} \tag{5}$$

Using equations (4) and (5) we can calculate the amplitude of the waves in equation (3) for any assumed radiated output power and then solve equation (1) numerically to obtain the value of the relativistic mass of the electrons at any known position inside the cavity and then use equation (2) to calculate the efficiency of electron energy transfer to the electromagnetic wave.

Table 1 shows the simulation parameters, which were chosen for the convenience of our laboratory. At the cavity entrance, the electrons are assumed to have the kinetic energy of 1 MeV, equivalent to the accelerating voltage applied at the anode of the electron gun. The electron energy transfer to the EM wave is calculated at discrete points along the waveguide. Figure 4 shows RF power of about 30 MW can be generated at an optimum efficiency of 60% using a circular $TE_{2\,1\,1}$ cavity with a diameter of 55 millimeters and 20 centimeters long. At the optimum efficiency, the required current is about 50 amperes.

4. Cavity test results

The designed cavity has been fabricated and we have performed frequency response tests on it. Figure 5 shows the photograph of the cavity under cold test and figures 6a and 6b show the obtained reflection and transmission characteristics respectively .From the figures, we were able to identify the oscillation modes by comparing the measured and the calculated values. Table 2 shows that the measured and calculated oscillation frequencies for the various modes differ by less than 10%, which could be attributed to either fabrication or measurement errors. The peniotron interaction can only occur at the TE_{211} mode , which corresponds to the measured frequency of 2.7455 GHz. We measured the Q values at this frequency, using the response on figure 7, and obtained values of 372, 415 and 3575 for loaded Q, unloaded Q and external Q respectively. We will use the measured Q values in evaluating the experimental electron energy conversion efficiency.

5. Electron gun design

Figure 8 shows the electron trajectories in the designed hollow electron gun when an accelerating voltage of 1 MV is applied at the anode. As can be seen in the figure, the electron beam is well focused, so the electron trajectories are almost parallel to the gun axis. The anode has a 5 millimeter thick iron plate pole piece for forming the cusp DC magnetic field. On crossing the cusp field, the electrons begin cycloiding with their orbit center coincident with the axis of the electron gun. The hollow cylcoiding electron beam is then injected into the cavity, where it excites a strong RF radiation. In the peniotron oscillator experiment, we will use a velvet cathode, so the cathode assembly should have a structure for holding the velvet cloth firmly. Figure 9 shows the drawing of the designed cathode and figure 10 its photograph.

6. Conclusion

We have explained the design procedure for a TE_{211} mode relativistic peniotron oscillator. The designed oscillation frequency is 2.755 GHz and the expected output power is 30 MW at an operation efficiency of 60%.The designed cavity was fabricated and cold tests performed. The cold test results agreed well with the design parameters, which shows that the cavity was fabricated with great precision. We will soon start experiments on the designed relativistic peniotron oscillator.

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References

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Table 1 Simulation parameters

Operation mode	circularly polarized TE_{21}
waveguide radius	55 mm
waveguide length	200 mm
Operation frequency	2.75 GHz
Loaded quality factor (Q_L)	2000
Beam energy	1 MeV
velocity ratio v_t/v_z	2
DC magnetic field	0.246T

Table 2 Cavity cold test results

cavity mode	analytical frequency (GHz)	measured frequency (GHz)	deviation (%)
TE_{111}	1.764	1.740	1.361
TE_{112}	2.190	2.057	6.073
TM_{011}	2.210	2.213	0.136
TM_{012}	2.570	2.530	1.556
TE_{211}	2.755	2.745	0.363

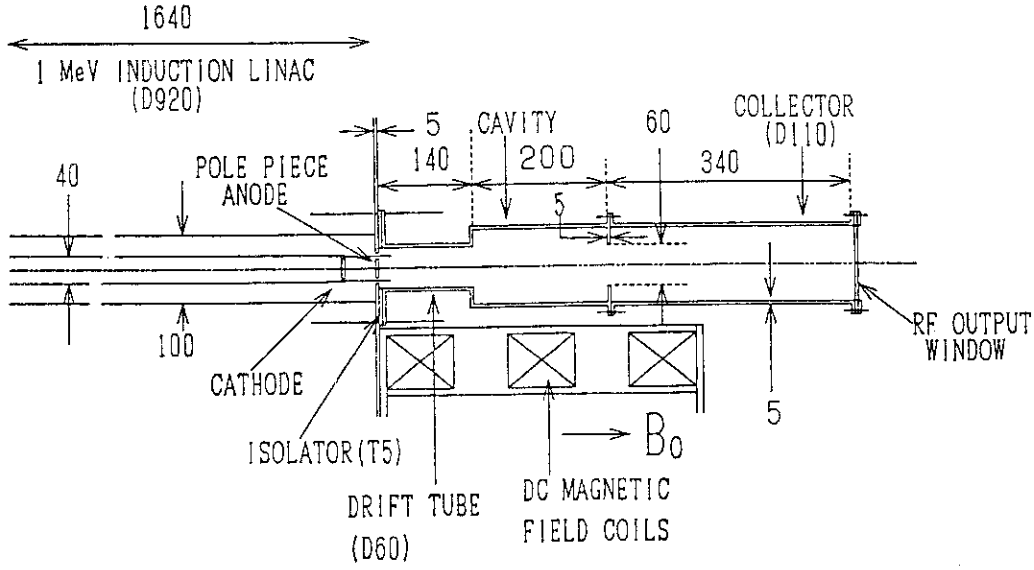


Fig. 1 Schematic diagram of a peniotron oscillator.

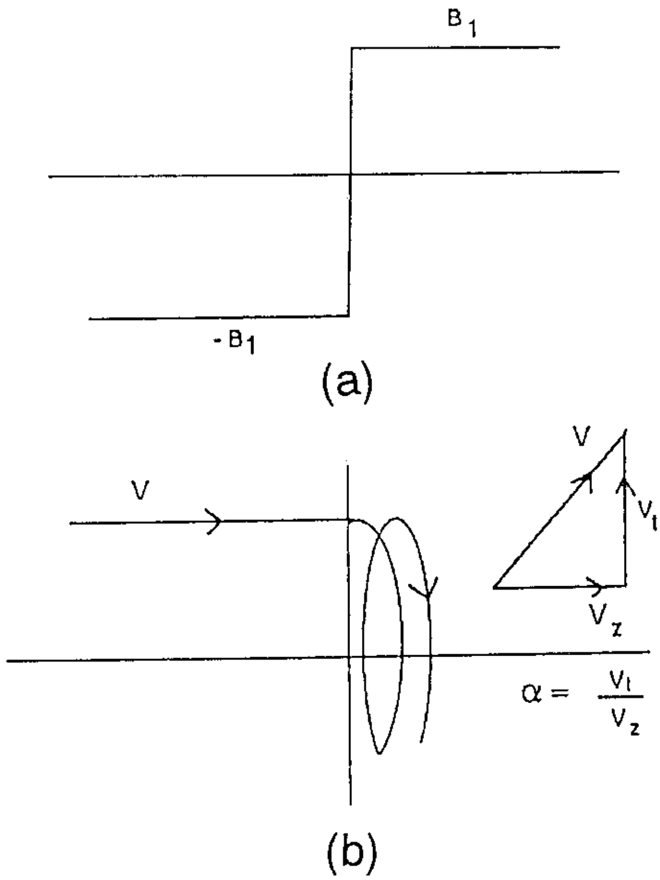


Fig. 2 (a) An ideal DC magnetic cusp, (b) Electron trajectory in an ideal cusp. Electrons cycloid after crossing the cusp.

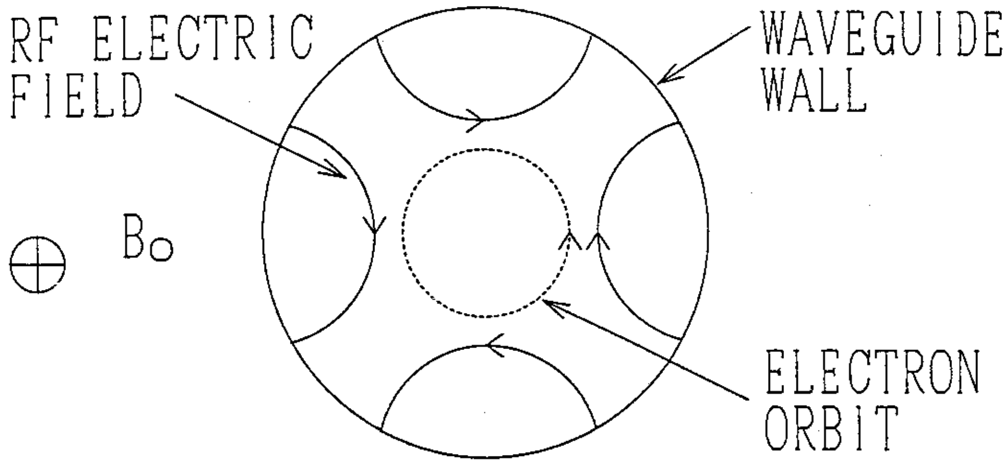


Fig. 3 Electric field distribution in the TE_{21} mode waveguide

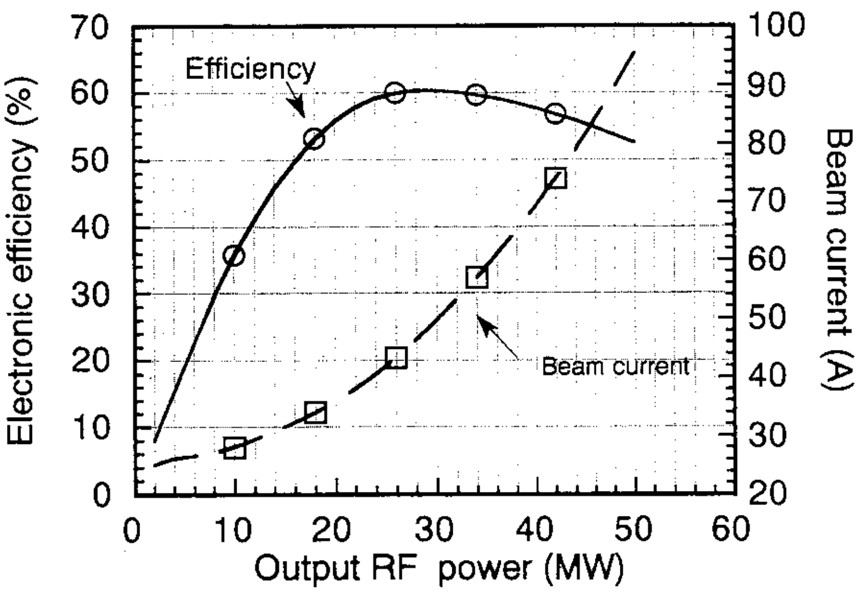


Fig. 4 Simulation results of a 2.75 GHz peniotron oscillator. An optimum power of 30 megawatts is obtained at an electronic efficiency of 60%.

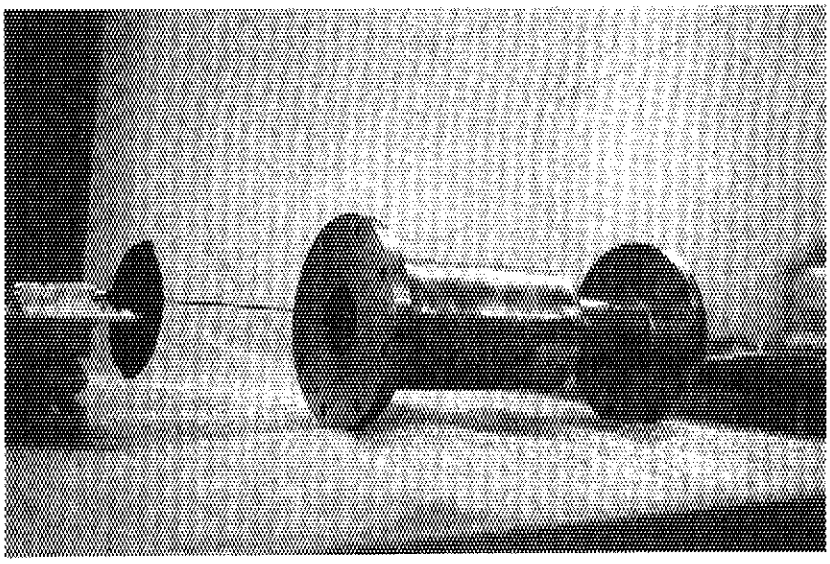
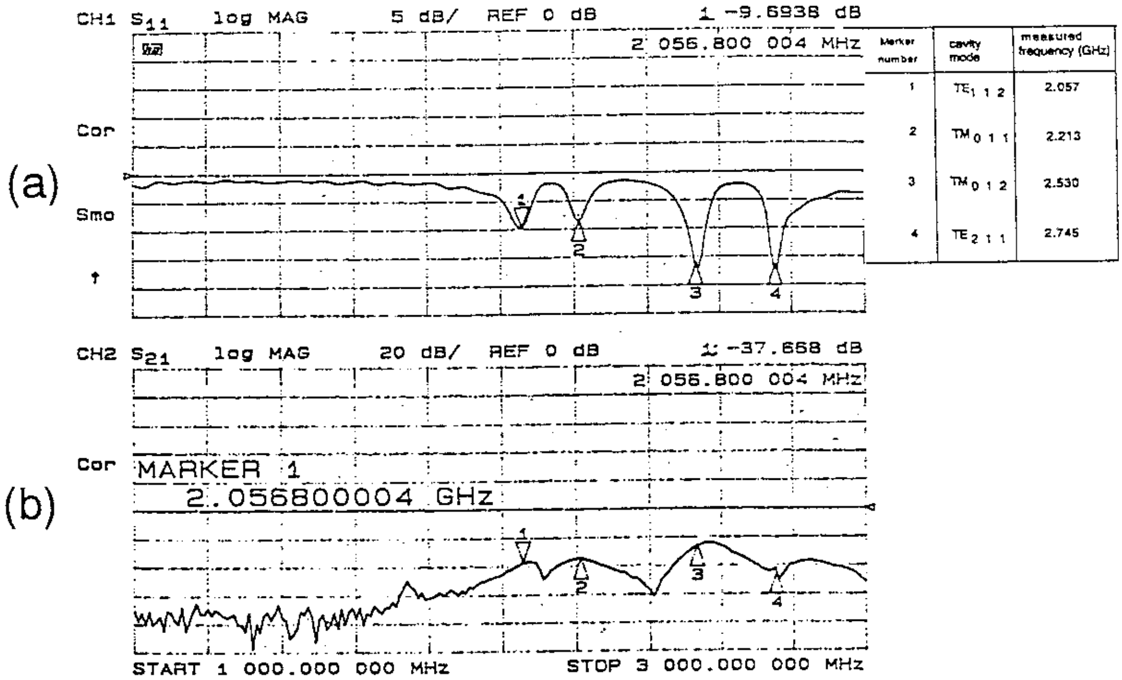


Fig. 5 Photograph of the designed cavity under cold test. A sweep generator injects a frequency swept RF power of 1 milliwatt into the cavity and a network analyzer displays its reflection and transmission frequency responses



Marker number	cavity mode	measured frequency (GHz)
1	$TE_{1\,1\,2}$	2.057
2	$TM_{0\,1\,1}$	2.213
3	$TM_{0\,1\,2}$	2.530
4	$TE_{2\,1\,1}$	2.745

Fig. 6 (a) Reflected wave frequency response
(b) Transmitted wave frequency response

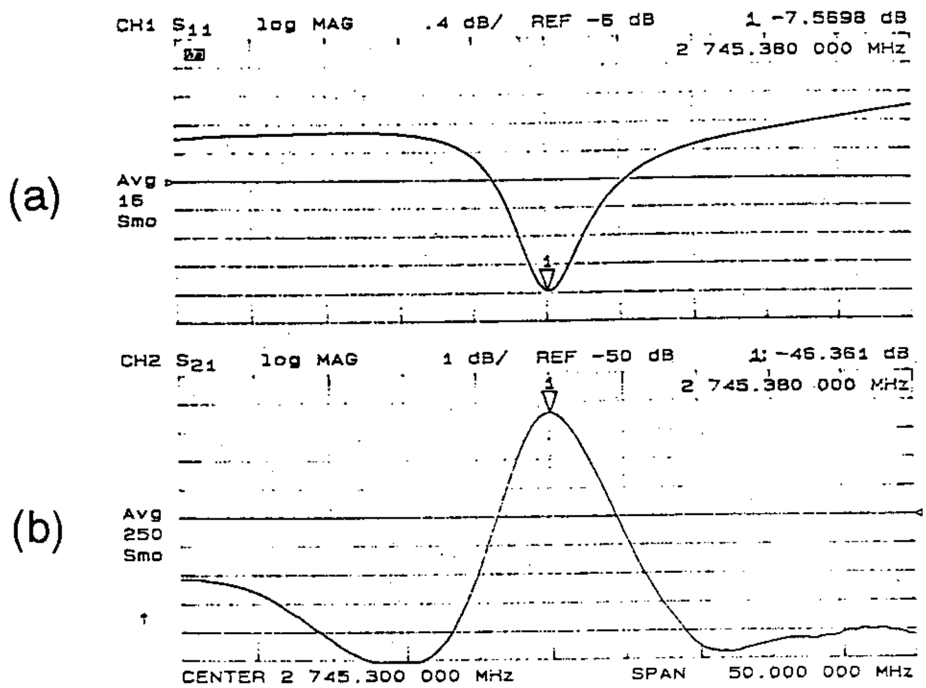


Fig. 7 Reflection and transmission frequency response at 2.745 Ghz. A strong peniotron oscillation is expected at this frequency.

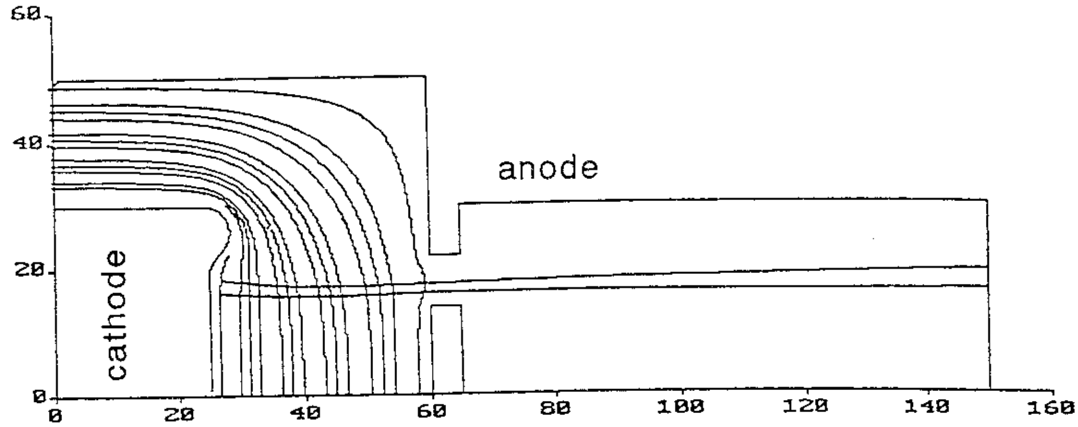


Fig. 8 Trajectory of a focused hollow electron beam in the designed electron gun.

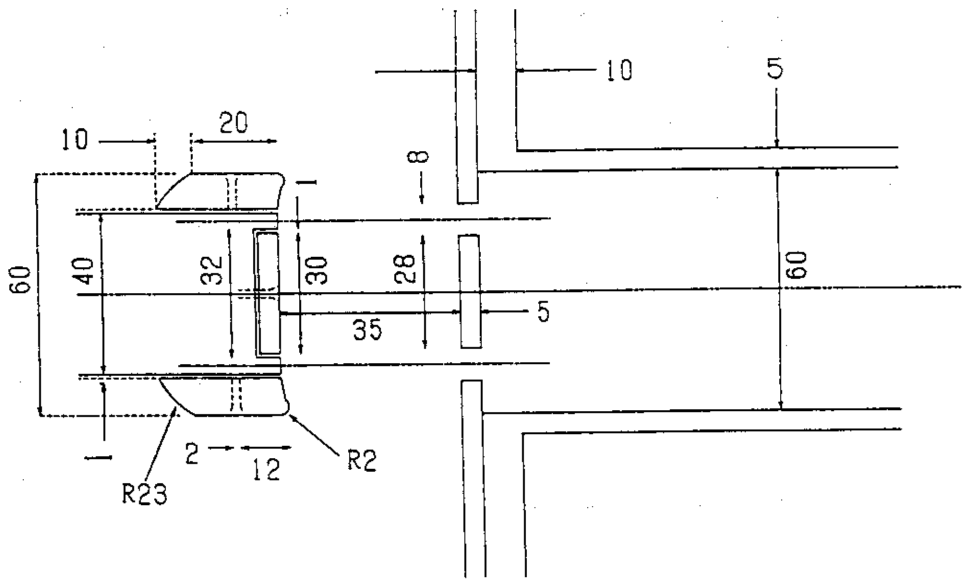


Fig. 9 Drawing of the designed cathode. It has a curved focusing surface and a steel washer for supporting a ring velvet electron emission area.

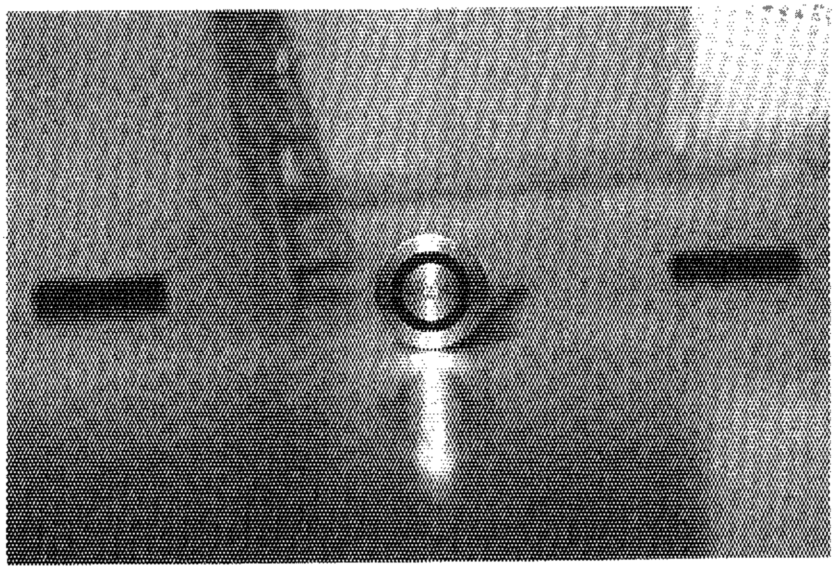


Fig. 10 Photograph of the cathode. A velvet ring can emit a hollow electron beam