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DESIGN OF A HIGH POWER, 10 GHz AUTO-RESONANT PENIOTRON AMPLIFIER

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The autoresonant peniotron amplifier is a suitable source of high power RF radiation because of its high gain, high power, high frequency and high efficiency operation features. In this report we present our simulation results of a 10 GHz, 2.2 GW auto-resonant-peniotron amplifier with an electron energy conversion efficiency of 72.5% and a gain of about 58 dB.

Keywords: Auto-resonant Peniotron Amplifier, Microwave, Submillimeter Wave, Electromagnetic Wave

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10 GHz帯自己共鳴型ペニオトロン増幅器の設計

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ミリ波及びマイクロ波領域の大電力電磁波発振の増幅器の1つに，自己共鳴型ペニオトロンがある。これは回転電子ビームを発生させ，その運動エネルギーを電磁波に変換するものであるが，発生する電磁波の位相速度（導波管内）を光速と一致させることにより，電子の回転エネルギーのみならず進行方向の運動エネルギーをも電磁波のエネルギーに変換できるため，極めて高効率の電磁波組成が可能となる。

本論文では，原研における大電流インダクションライナック LAX－1（電子ビームパラメーター：1 MeV，3 kA）を電子ビーム源とした時の，10 GHz，2.2 GW の出力を目標とした自己共鳴型ペニオトロンの設計結果を報告する。

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1. Introduction

Recent developments in fusion and elementary particle research have stimulated a need for high power microwave to submillimeter waves sources. 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 cyclotron resonance masers (CRM).The gyrotron also belongs to this category. Unlike conventional microwave source devices such as klystrons, magnetron and traveling wave tubes, CRM 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). When operated in the autoresonant mode, the electrons can lose both their longitudinal and transverse kinetic energy to the EM wave, resulting in a conversion efficiency of nearly 100% [2]. This feature makes the Auto resonant peniotron amplifier (ARPA) ideal for high power operation, where low efficiency would result in intolerable energy waste and high investment in cooling equipment. However for the auto-resonance interaction to occur, the phase velocity, v_p, of the electromagnetic wave must be equal to the velocity,c, of light in free space. This requirement cannot be satisfied in ordinary waveguides, where v_p is always greater than c, but it can be approached if a sufficiently oversize waveguide is used as the interaction circuit and a tapered guiding DC magnetic field applied [3]. The oversize feature is desirable for high power operation, because higher power dissipation can be tolerated in the device. In an oversize waveguide, the operation frequency is well above the electron cyclotron frequency because of the Doppler upshift effect. Therefore the required DC magnetic field for sustaining electron cyclotron oscillations in the interaction waveguide is reduced. This DC magnetic field requirement can be further reduced by operating at high cyclotron harmonics.

In this report we discuss the design considerations of a high power, 10 GHz ARPA, which we intend to use for experimental studies of high power microwave generation at the JAERI LAX-1 laboratory, where a 1 MV, 3 kA induction linac DC power supply source is installed.

2. The Auto-resonance mechanism

The peniotron amplifier has a waveguide interaction circuit which is immersed in a DC magnetic field, B_o .Into this waveguide both RF and a cycloiding electron beam are injected. The total velocity of the electrons is determined by the accelerating voltage applied at the anode. The electrons cycloid along the axis of the waveguide at a cyclotron frequency ω_c, which is determined by the guiding DC magnetic field according to the following equation:

$$\omega_c = eB_o/m \qquad (1)$$

where m is the relativistic mass of an electron. The electrons will interact with the propagating electromagnetic wave in the waveguide and lose their kinetic energy if the following interaction beam equation is maintained:

$$\omega = p\omega_c + \beta v_z \qquad (2)$$

where ω and β are the angular frequency and phase constant of the EM wave, respectively, and p is a positive integer. The term βv_z represents the value by which the EM wave frequency must be Doppler upshifted if the electron beam is to remain in phase with the propagating EM wave in the waveguide, where the wave mode is given by the following dispersion equation:

$$(\omega/c)^2 = (\omega_o/c)^2 + \beta^2 \qquad (3)$$

where c is the velocity of light in free space and ω_o the cut-off angular frequency of the waveguide. Fig 1 shows the graphical representation of the beam and wave modes. The electrons and the EM wave will interact if both the beam and the EM wave modes are coincident as indicated by point A in the figure.

The resonant condition described by equation (2) is valid if the mass of the electrons does not change. However if a high energy electron beam is used, the initial relativistic mass of the electrons is higher than the rest mass value and the electron mass decreases gradually as the electrons lose their kinetic energy to the EM wave. Therefore the resonant condition is no longer maintained if a high energy beam is used and in such a situation the electrons cannot transfer all their kinetic energy to the EM wave. In the auto-resonant condition, the cycloiding electrons can satisfy automatically the resonant condition all the time with the propagating EM wave, even when their relativistic mass is changing as they lose their kinetic energy to the EM wave. The essential auto-resonant condition is that the phase velocity of the EM must be equal to the velocity of light in free space. When this condition is satisfied, the longitudinal momentum of the electrons is favorably transformed into the transverse momentum, where the resonant condition is sustained all the time during the interaction. Therefore in the auto-resonant operation, the electrons can lose both their longitudinal and transverse kinetic energy to the EM wave, resulting in a very high conversion efficiency of nearly 100%.

The autoresonant condition can be derived by considering the electron-EM wave energy transfer mechanism. We know there must be conservation of momentum of the electrons as they transfer their kinetic energy to the EM wave. Therefore the electron-EM wave interaction must satisfy the following conservation of momentum equation:

$$m_o\frac{d(\gamma \mathbf{v})}{dt} = -e[\mathbf{E} + \mathbf{v} \times (\mathbf{B}+\mathbf{B}_o)] \qquad (4)$$

where $\mathbf{B} = 1/\omega.\beta\times\mathbf{E}$

Therefore

$$m_o\frac{d(\gamma \mathbf{v})}{dt} = -e[\mathbf{E}+(\mathbf{v}.\mathbf{E})\beta/\omega - (\frac{\mathbf{v}.\mathbf{E}}{\omega})\mathbf{E}+\mathbf{v}\times\mathbf{B}_o] \qquad (5)$$

In the above equations **E** is the RF electric field, **B** the RF magnetic field, $\mathbf{B}_o$ the DC magnetic field, m_o the rest mass of an electron, v the total electron velocity and γ the relativistic constant, given by

$$\gamma = \frac{1}{\sqrt{1 - (\frac{v}{c})^2}}$$

In the TE modes, that is $E_z = 0$ and $B_o = B_{oz}$, equation (5) is satisfied by the following equation:

$$m_o\frac{d(\gamma \mathbf{v}_z)}{dt} = e(v_t.\mathbf{E})\beta/\omega = -e/v_p(\mathbf{v}_t.\mathbf{E}_t) \qquad (6)$$

where E_t and v_t are the transverse electric field and electron velocity respectively. Considering the conservation of of electron kinetic energy, we can also write the following equation:

$$c^2 m_o\frac{d\gamma}{dt} = -e(\mathrm{E}_t.\mathbf{v}_t) \qquad (7)$$

From equation (6) and (7) we can write the following equation:

$$\frac{d\gamma}{dt} = v_p/c^2[d(\gamma v_z)/dt] \qquad (8)$$

After integration we obtain

$$\gamma(1 - v_p v_z/c^2) = K \qquad \text{where K is a constant} \qquad (9)$$

For a relativistic electron beam, $\omega_c = eB_o/m_o\gamma = \omega_{co}/\gamma$

Therefore the resonant condition of equation (2) can be re-written as

$$\gamma(1 - v_z/v_p) = p\omega_{co}/\omega \qquad (10)$$

If we let $v_p = c$, then equations (9) and (10) are identical and equation (10) can be re-written as

$$\gamma(1 - v_z/c) = p\omega_{co}/\omega = K \qquad (11)$$

Equation (11) represents the auto-resonance condition. When this condition is maintained, the right hand side of the equation can remain constant if any decrement in the relativistic constant γ is accompanied by a corresponding decrement of the longitudinal velocity v_z of the electrons.Therefore, as the electrons lose their kinetic energy to the EM wave and their relativistic constant decreases, their longitudinal momentum, and hence v_z, must decrease to keep the right hand side of equation (11) constant. We know this requirement can be satisfied because the $e(\mathbf{v}_t\times\mathbf{B}_t)$ RF force term has the effect of reducing the longitudinal velocity of the electrons by the right value to compensate for the changing cyclotron frequency, which must change with the changing relativistic term, and transform the longitudinal momentum of the electrons to the transverse momentum. In this way, the cycloiding electrons can lose both their transverse and longitudinal kinetic energy to the EM wave resulting in a conversion efficiency of nearly 100%.

3. Simulation of the ARPA

We have done simulation studies of an auto-resonant amplifier, which has a circular waveguide in which a circularly polarized TE_{21} mode EM wave. is excited. A cycloiding hollow electron beam is injected into the waveguide, as shown in fig 2, where it interacts with the propagating EM wave.The cyclotron frequency of the electrons is determined by the guiding DC magnetic field, B_{oz}, as described by equation (1) The TE_{21} mode was selected because it supports the fundamental cyclotron frequency peniotron operation

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In the ideal ARPA, the phase velocity, v_p, of the propagating EM wave must be equal to the velocity,c, of light in free space, a condition which cannot be satisfied in ordinary waveguides, where v_p is always greater than c. However if a sufficiently oversize waveguide is used and a tapered DC magnetic field applied, this condition can be adequately approached for a practical device.

We have developed a computer simulation code which we have used to calculate the electron-EM wave energy transfer at assumed arbitrary operation parameters.In the simulation 12 sample electrons which are evenly distributed along the their orbit center are injected into the interaction waveguide. At the waveguide entrance, the electrons are assumed to have the kinetic energy 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, in which a fixed TE_{21} RF field is assumed. Table 1 shows the simulation parameters, which were chosen for the convenience of implementation in our laboratory.

Figures 3 shows the dependence of electronic efficiency and electron beam velocity ratio on the v_p/c ratio. As the ratio approaches unity, the efficiency increases rapidly. because the auto-resonance mechanism becomes more effective. The required beam velocity ratio decreases as the ratio approaches unity because in the auto-resonant interaction we can convert the longitudinal energy of the electrons to an EM wave, so a beam with a high longitudinal energy can be used. Figure 4 shows that the required DC magnetic field can also be reduced as the auto-resonant condition is approached because of the Doppler upshift effect. A weaker magnetic field is also desirable because the increased beam radius increases the electron EM wave coupling, so a weaker input RF power can be used.

The auto-resonant condition can be approached in an oversize waveguide interaction circuit. However, as the v_p/c ratio approaches unity, the waveguide radius increases rapidly as shown in figure 5. Therefore the electron-EM wave coupling becomes weak and the necessary interaction length increases as shown in the figure. In a realistic device, the dimensions of the waveguide must be fixed to suit the laboratory parameters. For the convenience of our laboratory, we have decided to use a waveguide with a radius of 18.7 mm. In this waveguide $v_p/c = 1.6$ and the electron energy conversion efficiency is 72.5%. Figure 6 shows the calculated optimum output power and the necessary interaction length in this waveguide as the beam current increased and the other operation parameters fixed. From this figure, we observe that it is necessary to increase the beam current if high power is to be generated using a reasonably short waveguide interaction circuit, which is favorable from the point of view of reducing the investment on the guiding DC magnetic field and also ease of electron beam control.

4. Proposed Experimental set-up

Figure 7 shows the schematic layout of the proposed prototype ARPA device, with design parameters given in table 2..A Pierce type field emission equal to the velocity,c, of light in free space, a condition which cannot be satisfied in ordinary waveguides, where v_p is always greater than c. However if a sufficiently oversize waveguide is used and a tapered DC magnetic field applied, this condition can be adequately approached for a practical device.

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5. Conclusions

We have presented the operation mechanism of the auto-resonant peniotron amplifier and showed analytically that in the device cycloiding electrons lose both their longitudinal and transverse kinetic energy to the electromagnetic RF field, resulting in a energy conversion efficiency of nearly 100%. The device has the potential of high efficiency amplification of high frequency microwaves using relatively low DC magnetic field because of its Doppler upshift characteristic.The device has also an oversize waveguide interaction circuit, which makes it ideal for high power amplification. Its ability to convert longitudinal energy of the electrons to RF power opens the possibility of using an electron beam with high longitudinal energy, which is a very attractive feature for designing high power electron guns.

We have presented the computer simulation results of a 2.2 GW, 10 GHz auto-resonant peniotron amplifier. The simulated device has a electron conversion efficiency of 72.5% and a gain of about 58 dB.The device has operation parameters implementable in our laboratory.We intend to construct the device and use it for experimental study of high power auto-resonant peniotron amplifiers, which in the future may be used as sources of high power microwave RF radiation in applications such as ECRH heating of fusion plasma and particle accelerators.

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Table 1 Simulation parameters of the ARPA

Operation mode	circularly polarized TE_{21}
Operation frequency	10 GHz
Beam voltage	1 MV
Beam current	1 kA
Input power	1 kW

Table 2 Design parameters of the prototype ARPA

Beam parameters	
beam voltage	1 MV
beam current	3 kA
pulse width	100 ns
velocity ratio α	2
Magnetic field parameters	
main field	0.78T
cusp field	0.2T
Operation parameters	
operation frequency	10 GHz
operation mode	circularly polarized TE_{21}
waveguide radius	18.7 mm
waveguide length	50.23 cm
phase velocity	$V_p = 1.6c$
conversion efficiency	72.5%
input power	1 kW
output power	2.2 GW

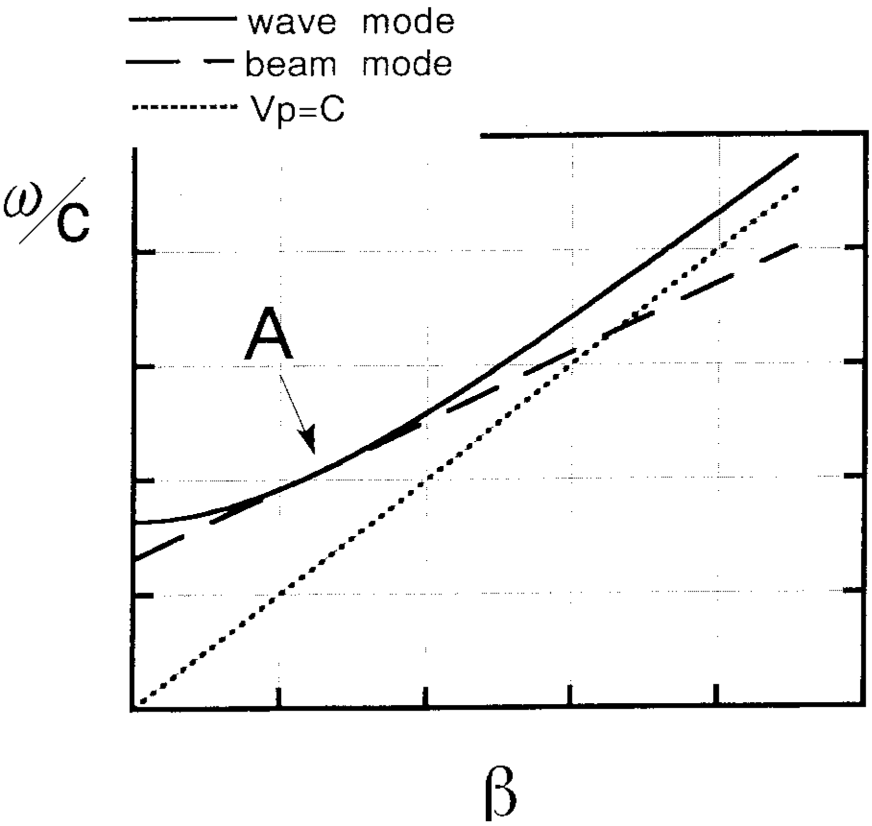

Fig. 1 Dispersion diagram, showing the beam and wave modes in a Doppler upshifted ARPA

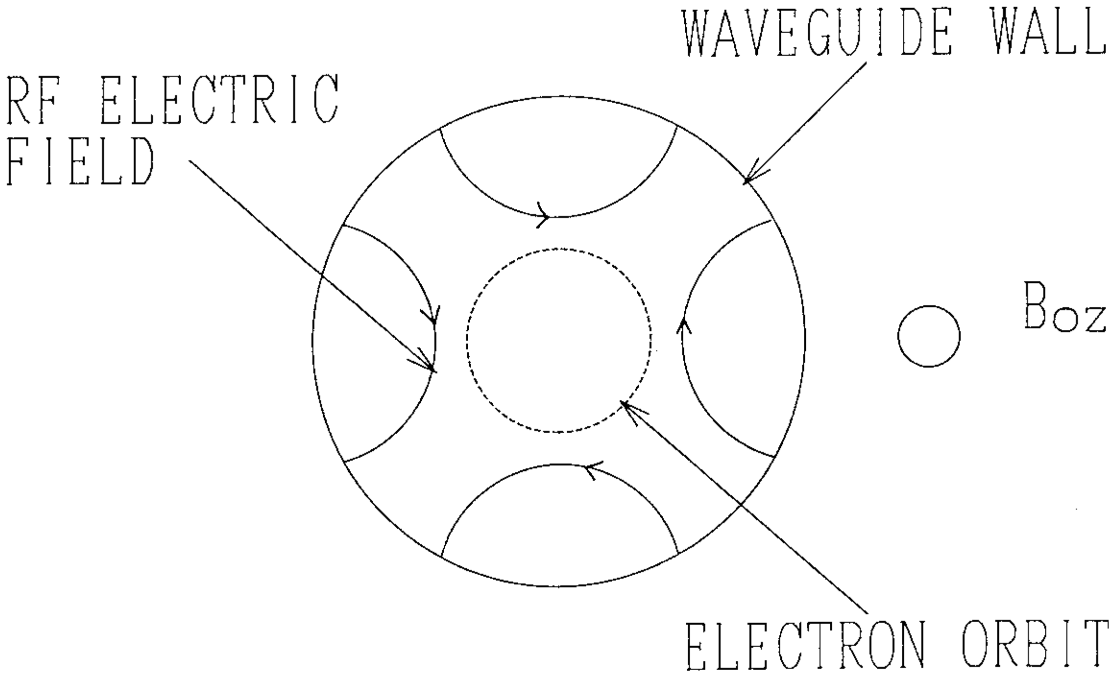

Fig. 2 Cross section of the interaction circuit waveguide in which a circularly polarized TE_{21} electric field is excited. The electrons cycloid along the waveguide axis at a cyclotron frequency determined by B_{oz}.

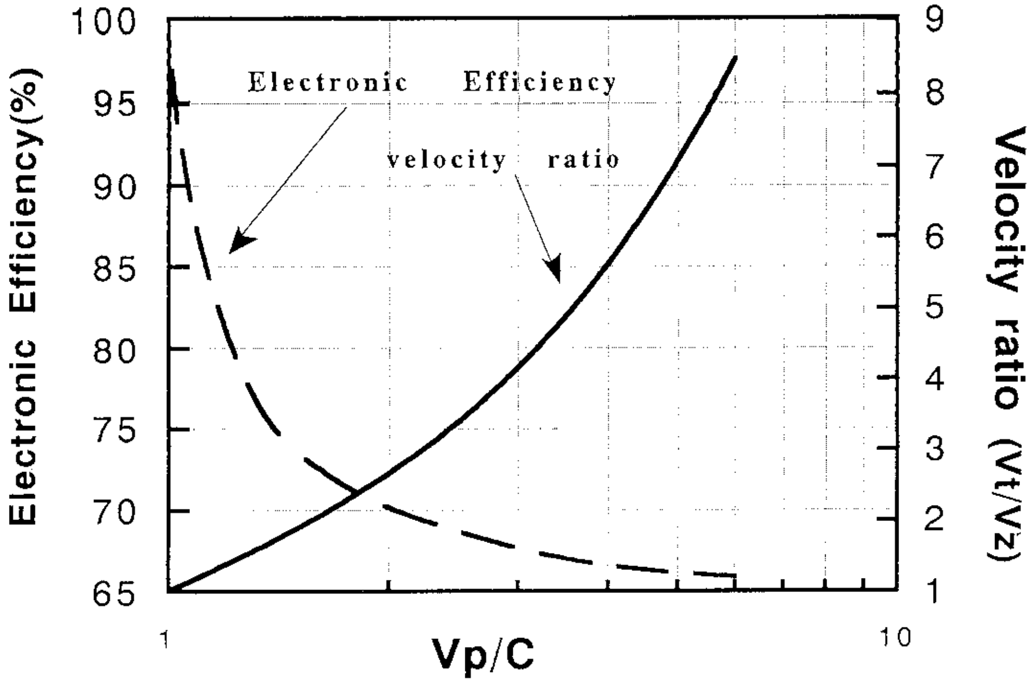

Fig. 3 Dependence of electronic efficiency and electron beam velocity ratio on the v_p/c ratio

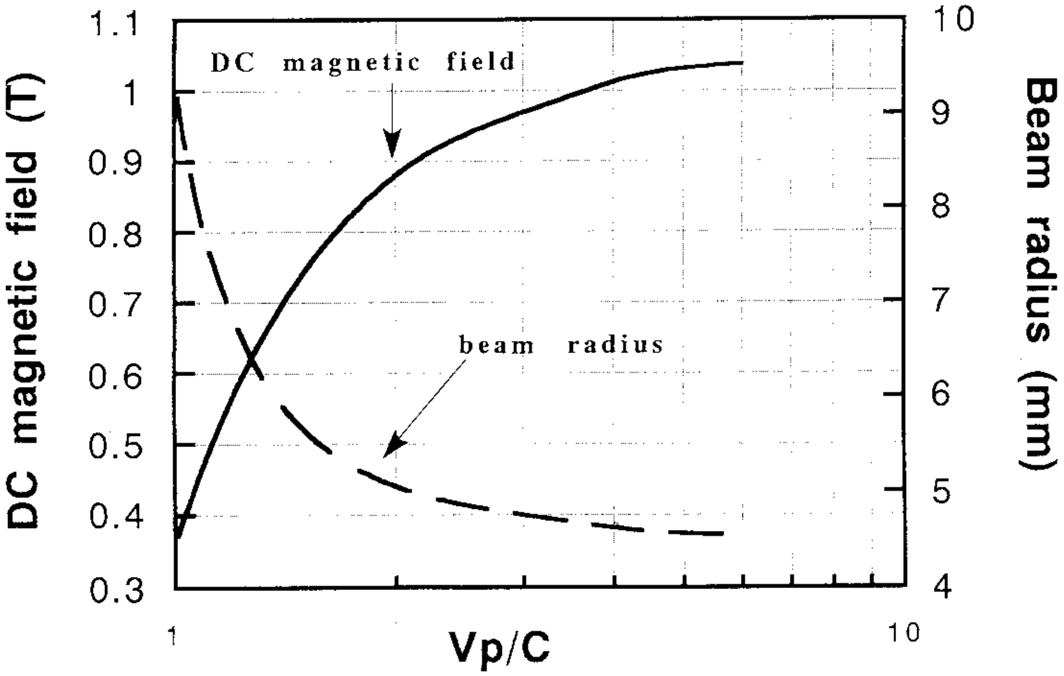

Fig. 4 Dependence of required Dc magnetic field and the electron beam radius on the v_p/c ratio

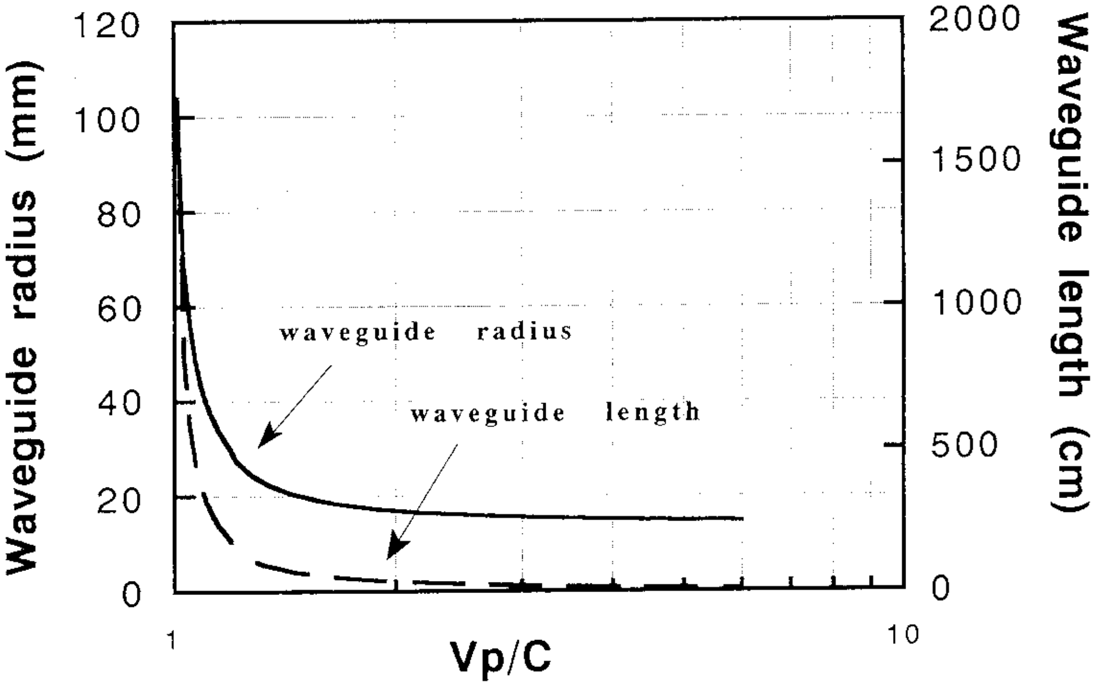

Fig. 5 Dependence of the waveguide length and radius on the v_p/c ratio

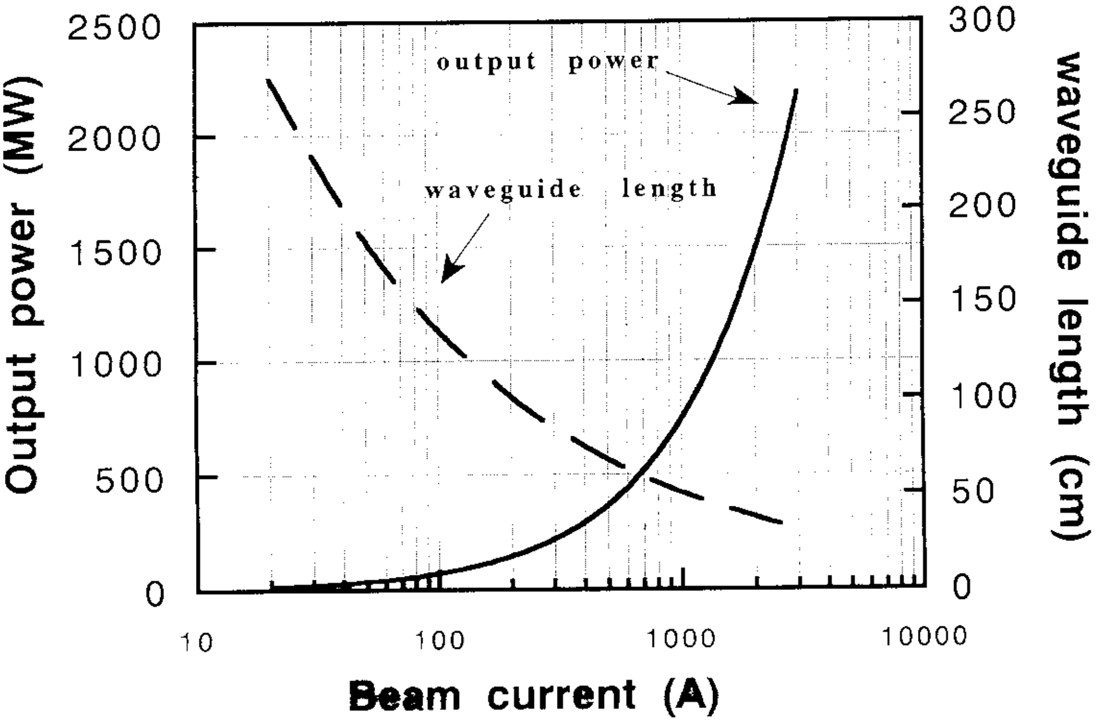

Fig. 6 Dependence of optimum output power and interaction length on the input beam current.
($V_p/c=1.6$, electronic efficiency=72.5%)

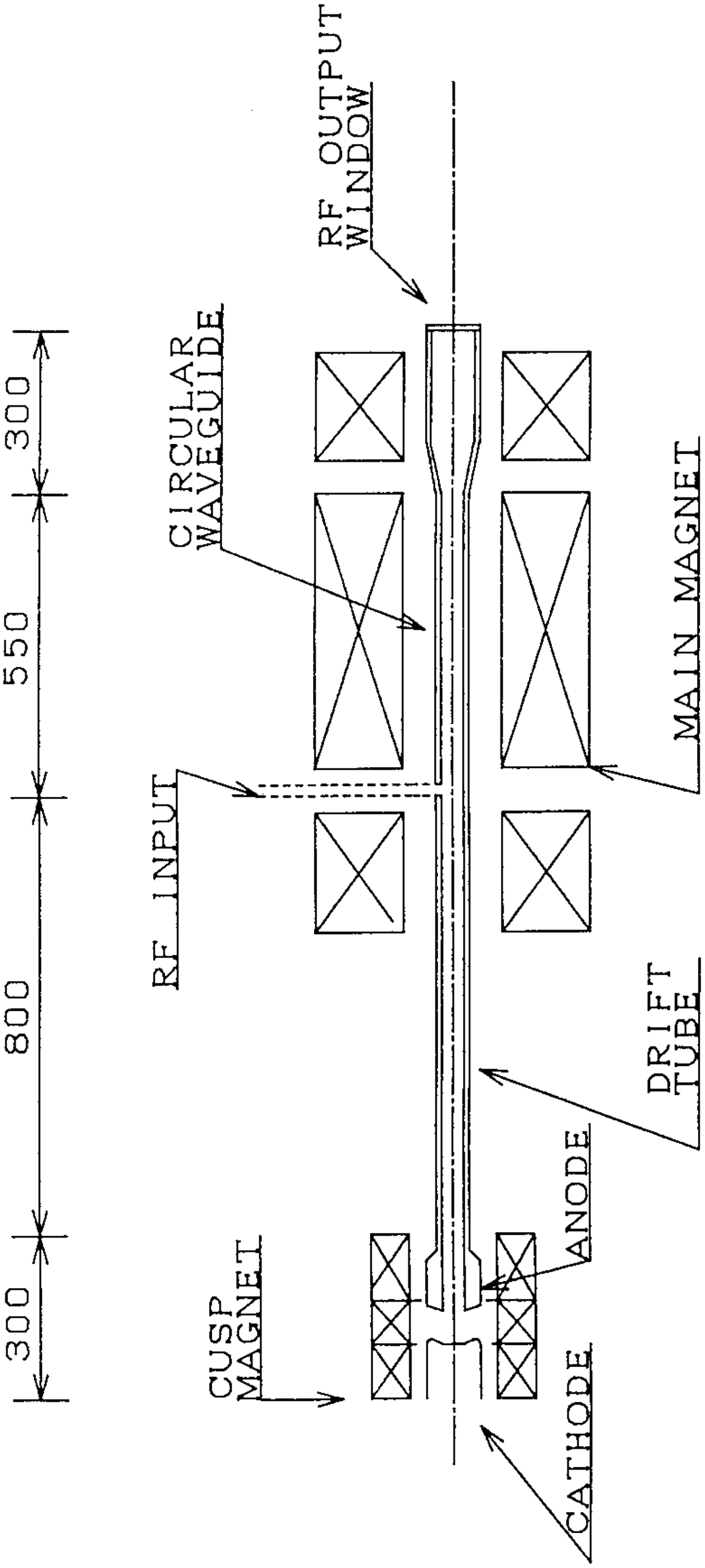

Fig. 7 Schematic diagram of the proposed ARPA. All dimensions are in millimeters