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# Design Features and Operating Characteristics of the MM-22 Microtron for Radiotherapy

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# 방사선 치료용 MM-22 마이크로트론의 설계 특징과 동작 특성

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## Abstract

The MM-22 medical microtron at Korea Cancer Center Hospital is now operational for high energy electron and photon therapy. This microtron is designed to produce 5.3-22.5 MeV electron beams and deliver these to the treatment head through beam transport system with an intensity and stability suitable for cancer treatment. The availability of high quality radiation modalities from the MM-22 shows new possibilities in the treatment of deep seated tumours. Principle of operation, system structures and operating characteristics of the MM-22 are described in this paper.

## 요 약

원자력병원에 설치되어 있는 MM-22 의학용 마이크로트론은 고에너지의 전자선 치료와 photon 치료를 위해 가동중에 있다. 이 마이크로트론은 5.3-22.5MeV의 전자선을 발생하도록 설계되었으며, 발생된 전자선은 암치료에 적합한 강도와 안정도를 유지하면서 빔 수송장치를 통해 치료기로 공급된다. MM-22에서의 양질의 방사선 이용은 심부 종양 치료에 새로운 가능성을 보여주고 있다. 본 논문에서는 MM-22의 동작원리, 장치의 구조 및 동작특성에 대해서 기술하고 있다.

## I. Introduction

During recent years, the 45 years old concept of the microtron accelerator has been attracting increasingly more interest as a machine suitable for clinical, industrial and research applications. Since the microtron principle was formulated by V. I. Veksler in the USSR in 1944[1], microtron development has been and is going on in Sweden, Canada, the US and the USSR. The first machine was put into operation in Canada in 1949[2]. Many circular microtrons for research were built during the fifties and sixties. The first clinical microtrons for radiotherapy have been in hospital use since the middle of the seventies in

Italy[3] and Sweden[4]. However, the microtron principle is still familiar to only very few people in Korea. Authors will therefore describe in some detail the theory of operation of the microtron as well as the operating characteristics of the MM–22.

The MM–22 installed Korea Cancer Center Hospital is a S–band microtron designed by Scanditronix in Sweden, is hospital based microtron connected with the rotational isocentric gantry for radiotherapy. The first beam was extracted in May 1985 after extensive work to overcome mechanical and electrical problems inherent in the machine for about one year. Since treatment was started from November 1986, the machine is at present running on a 6 day/week schedule ; five treatment days and one maintenance and beam measurement day.

## II. Principle of Operation

The microtron, or electron cyclotron, is an orbital electron accelerator in which the circular co–planar orbits have a common tangent.(Fig. 1). Electrons emitted from a pulsed gun are

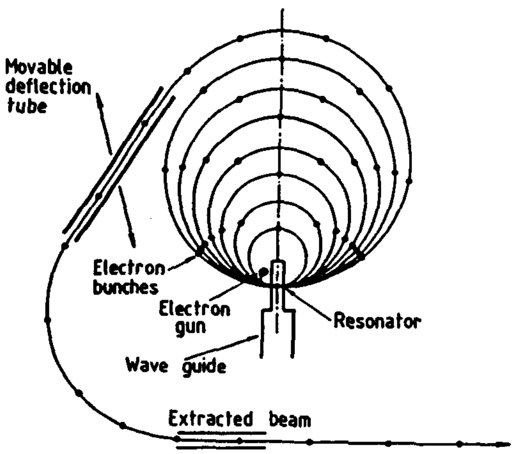



**Fig. 1. The MM–22 Medical Microtron.**

moving in circular orbits in a uniform magnetic field, perpendicular to the plane of the Fig. 1, obtaining for each revolution an energy increment from the RF field in a resonator cavity. The major operating parameters of a microtron, determining the resonance condition, are the energy per turn, the guide field strength and the frequency of the RF field. The fundamental equations may be easily deduced from first principles.

An electron with charge e and mass m, moving with velocity v in a homogeneous magnetic field B perpendicular to the direction of v describes a circle of radius r given by

$$Ber=mv=P \tag{1}$$

and the time to complete one orbit is

$$T=\frac{2\pi r}{v} \tag{2}$$

Thus, for an electron in orbit n, with the energy $E_n$, we have

$$T_n=\frac{2\pi}{eBc^2}\cdot E_n \tag{3}$$

The energy $E_n$ is given by

$$E_n=E_o+E_i+n\cdot E_r \tag{4}$$

where

$E_o$ : rest mass energy of electron

$E_i$ : injection energy given by electron gun

$E_r$ : gain energy per turn

The two conditions for resonance are (a) the revolution time $T_1$ for the first orbit must be an integer multiple of the microwave period and (b) the differences in revolution time for two consecutive orbits must be an integer multiple of the microwave period. This conditions can be represented as follows ;

$$T_1=\frac{2\pi E_1}{eBc^2}=\frac{a}{f} \tag{5}$$

$$T_{n+1}-T_n=\frac{2\pi E_r}{eBc^2}=\frac{b}{f} \tag{6}$$

where

a,b : integer

f : microwave frequency

n : number of orbit

After some arranging, we then have from the above

$$E_r=\frac{a}{b-a}\cdot(E_o+E_i) \tag{7}$$

$$B=\frac{2\pi f}{ec^2}\cdot\frac{1}{b-a}\cdot(E_o+E_i) \tag{8}$$

From these expressions, it follows that $b>a$, that the maximum value of B, and hence the minimum machine diameter, is obtained with $b-a=1$. And finally that for a given value of $b-a$, the value $a=1$ gives the minimum accelerating voltage at the cavity. Moreover, it can be shown that the choice of the mode numbers $a=1$, $b=a+1=2$ also results in the largest phase acceptance for electrons with respect to the accelerating microwave field.

From the above equations, we find the total energy in orbit n

$$E_n=(n+1)\cdot(E_o+E_i) \tag{9}$$

In the MM-22 microtron, the voltage of the electron gun is 63 kV. The rest mass energy of the electron corresponds to 511 keV. Thus, Eq.(9) gives $E_n=(n+1)\cdot 574$ keV. These calculations would exactly represent the conditions in MM-22 microtron if the accelerating gap in the resonator has zero width. However, in order to withstand the high voltage without break-down, the resonator gap must have a certain width. This means that the orbits in the microtron are not pure circles, and that the calculations above are not exactly valid. The energy gain per turn which is obtained in practice, is 535 keV. Thus, the total energy of the electrons of the MM-22 which has 42 orbits, is $E_{42}=(42+1)\cdot 535$ keV$=23.005$ MeV. Since the rest energy of the electron is 511 keV, the kinetic energy of the electrons in orbit 42 is 22.494 MeV.

## III. Features of the System

The operation principle of the microtron has been described previously. It is sufficient to recall that the microtron is a cyclic electron accelerator, where the electrons are repeatedly accelerated by the oscillating electric field of a microwave resonator. A homogeneous magnetic field forces the electrons to return to the cavity. The acceleration in the microtron will therefore depend on a resonance condition between the microwave frequency and magnetic field which implies a low energy spread and high reproducibility in energy of the accelerated electrons. Some of the main parameters of the MM-22 are listed in Table 1.

**Table 1. Characteristics of the MM-22 Microtron**

| Characteristics | Values |
|---|---|
| Extractable energy | 5.3−22.5 MeV |
| Energy gain per turn | 535 keV |
| Energy spread (FWHM) | 35 keV |
| Magnetic field | 0.112 Tesla |
| Magnet diameter | 2.22 m |
| Pole piece diameter | 1.80 m |
| Gap height | 0.11 m |
| Magnet width | 0.45 m |
| Microwave frequency | 3.0 GHz |
| Microwave peak power | 2 MW |
| Pulse duration | 4 $\mu$sec |
| Pulse repetition freq. | 60−240 Hz |
| Injection current | 1.0−1.5 A |
| Working vacuum | $10^{-4}$ Pa |

The magnet consists of two almost circular pole pieces with their electric windings at the periphery, completely enclosed in the return yoke. By this design, the stray radiation from the accelerator is kept low. The pole pieces are made 1.80 m diameter overall with a shimmed edge to maintain the uniform field over as large an area as possible. The gap between pole pieces has to accommodate the resonator cavity system. A clearance of 11 cm minimum has been allowed for this which permits room for any cooling pipes or ion pump. The MM-22 operates at a frequency of 3000 MHz in the mode a=1 and b=2, so that the magnetic flux density required in the air gap is 1122 Gausses. The magnet requires approximately 35 A at 100 V for full excitation. This power is obtained from 3-phase full wave rectifier bridge. The stability of the magnet current is held constantly to $2\times10^{-5}$ for 8 hours. The MM-22 magnet contains three correction windings which are used to correct local deviations in the magnetic field. One of these coils is located at the pole faces and is used to correct the magnetic field distribution. Another coil is located close to the resonator, and gives local correction of the magnetic field in the proximity of the resonator, which effects the direction of the common diameter of the electron orbits. The third trim coil is placed alongside the extraction tube, and is used for fine adjustment of the vertical direction of the beam extracted from the microtron. The relative radial variation of the field was determined with a pair of flip coils at Scanditronix factory, using a null method for comparing the field at any desired radius with the field at the center of the magnet.

The microwave resonator contains a strong electric field, which exerts an accelerating force on the electrons. This electric field oscillates at a 3 GHz microwave frequency which is generated by a magnetron (EEV, Model No.. ; M5125), capable of delivering 2 MW of peak power and 3 kW of average power. The electron injection system and the microwave resonator are similiar to the corresponding parts in the 11-orbit microtron built by the group at the Royal Institute of Technology in Stockholm[5]. The electrical energy is fed from the magnetron to the resonator via a waveguide system which is filled with Freon 12 gas at a pressure of 2.0-2.5 atm.. This gas is intended to prevent electrical discharging. The circulator which is placed at the waveguide prevents reflected power from the resonator to come back to magnetron. The circulator (Raytheon, Model No. : CSH132) and its associated dummy load (Raytheon, Model No. ; LSH106) are water cooled.

The electrons are supplied by an electron gun which is located beside the resonator and fires beam of electrons into it. The electron gun consists of a tubular anode and $LaB_6$ cathode as shown in Fig. 2.

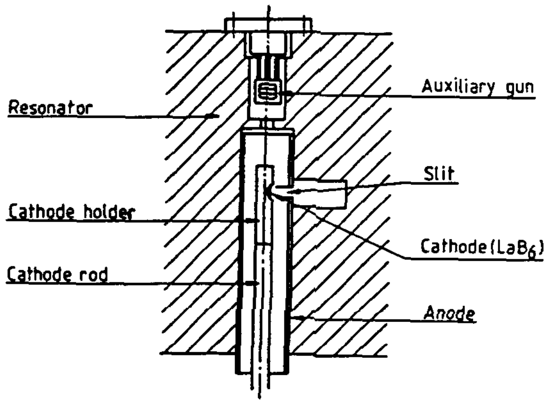



**Fig. 2. Structure of the Electron Gun.**

The $LaB_6$ cathode is heated to a temperature of approximately 1500℃ by bombardment with electrons from an auxiliary electron gun. The electrons are emitted from $LaB_6$ cathode through a slit in the anode tube. The magnetron and electron gun are powered by high voltage pulses of 4 $\mu$ sec duration. They are generated by the modulator, which consists of a high voltage d.c. supply which via a voltage doubler charges up a pulse forming network consisting of a number of capacitors and inductors. The pulse forming network is discharged by a hydrogen thyratron(EEV, Model No. ; CX1140) thus producing high voltage pulses. The pulses are transformed to their final voltage by pulse transformers located on the outside wall of the magnet.

The extraction of the electron beam from the magnet follows the suggestion of H. Reich[6] according to which the beam from any orbit can be extracted at the same place always with the same direction. Due to the large energy gain per turn, orbit spacing remote from resonator is about 3 cm, which enables a magnetic shielding tube to be introduced intercepting an orbit without unduly perturbing the magnetic field in the neighboring orbits. In practice, this is accomplished by a narrow deflection tube of steel which moves along a straight line, when electrons enter the iron tube, they cease to be effected by the magnetic field, and travel in a straight line along the tube. Therefore, the energy of the extracted beam is dependent upon the position of the deflection tube.

In order for the electrons to circulate uninhibited and to be able to maintain the strong electric field, the inside of the microtron chamber is evacuated through a single port. The vacuum system consists of turbo-molecular pump(Balzers, Model No. ; TPH510) backed by a mechanical pump. In addition, there is an ion pump built into the chamber. This pump works by ionizing any gas present and then accelerating the ions towards a titanium plate, where they are collected. The ion pump may only be operated if the vacuum is better than $10^{-3}$ Pa. The ion pump can only function if the magnetic field to the microtron is operating. The lowest pressure yet obtained is $5\times 10^{-5}$ Pa, in practice it has been found that the pressure of $10^{-4}$ Pa is sufficiently good for reliable operation.

## IV. Operating Characteristics

### IV. 1. Pulse Structures

From the principle of phase stability[7,8], electrons make their first entrance into the resonator within a certain interval of microwave phase, will be accepted for resonant acceleration. In the MM-22, this interval is about $\pm 16°$. Therefore, electrons consist of short bursts of duration corresponding to 32/360 parts of the microwave period. The microwave frequency is 3 GHz, so the duration of these bursts is about 30 pico-seconds. These bursts we call the "micro-pulses" or the "bunches". The microtron cannot go on delivering 3000 such bunches per micro-second for a very long period of time without rest, because the resonator would be over-heated. Therefore, the high voltage on the electron gun, and the microwave power in the resonator is applied in pulses ("macro-pulses") of 4 micro-seconds duration. The pulse repetition frequency of these macro-pulses is continuously variable in step of 60 Hz, from 60 to 240 Hz.

A few numerical values relating to the structure of the electron beam may be given as Table 2.

**Table 2. Characteristics of the Electron Beam**

| Characteristics | Values |
|---|---|
| Typical injection current | 1A |
| Average macro-pulse current | 89 mA |
| Typical macro-pulse length | 4 $\mu$sec |
| Number of electrons per macro-pulse | $2.23\times 10^{12}$ |
| Number of micro-pulses per macro-pulse | $1.2\times 10^{4}$ |
| Number of electrons per micro-pulse | $1.86\times 10^{8}$ |

Fig 3. shows the fine structure of the electron beam at 60 Hz pulse repetition frequency.

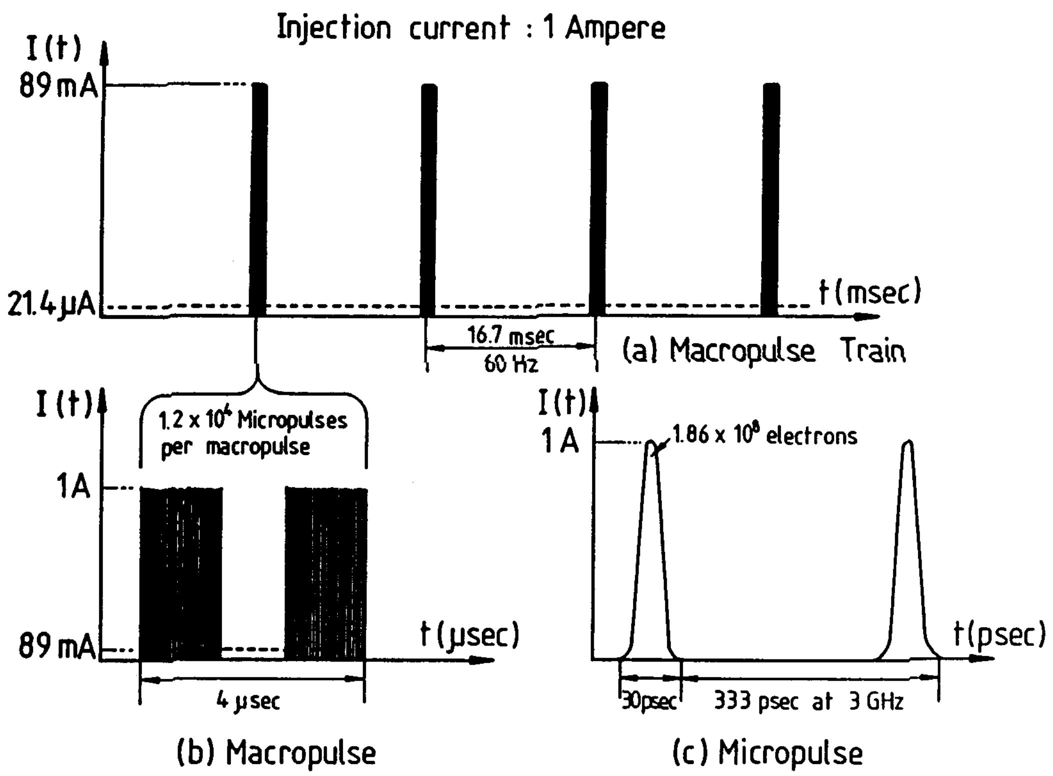



**Fig. 3. Fine Structure of the Electron Beam.**

## IV. 2 Electron Orbits

For an electron in orbit n, we have

$$\pi \cdot D_n = nv/f \tag{10}$$

where $D_n$ is a diameter of the $(n)^{th}$ orbit. After some rearranging, we have from the above

$$D_n = \frac{c}{f} \cdot \frac{n+1}{\pi} \sqrt{1-[\frac{E_o}{(n+1)E_r}]^2} \tag{11}$$

where c is a speed of light

Thus, the distance between the $(n-1)^{th}$ and $(n)^{th}$ orbit is

$$X_n = \frac{c}{f} \cdot \frac{1}{\pi} \cdot \left\{ (n+1)\sqrt{1-[\frac{E_o}{(n+1)E_r}]^2} - n\sqrt{1-(\frac{E_o}{nE_r})^2} \right\} \tag{12}$$

From above Eq.(12), it is found that the distances between the consecutive electron orbits in the MM-22 are between 3.45 cm to 3.18 cm. These large orbit spacing is sufficient to extract the beam from each orbit without perturbance of the neighbouring orbits.

## VI. 3 Gun Current

The electrons are emitted from a Lanthanum hexaboride cathode and pulled with a voltage of 63 kV through an anode slit as shown in Fig. 2. The cathode is heated to approximately 1500℃ by bombardment of electrons from an auxiliary gun, which delivers up to 40 mA d.c. beam of 2.1 keV electrons. The auxiliary gun consists of tungsten filament and two heat shields. The current through the filament is about 5–6A. The emission current is controlled by the temperature of the $LaB_6$ cathode. Also, this is controlled by the auxiliary gun current, which in turn, depends on the filament current of the auxiliary gun. Therefore, the relation between gun current and auxiliary gun current can be represent as follows;

$$I_G = K_1 \cdot \exp[\alpha \cdot I_{AG}] \quad (13)$$

$$I_{AG} = K_2 \cdot \exp[\beta \cdot I_F] \quad (14)$$

$$I_F = K_3 \cdot V_F \quad (15)$$

where $I_G$ : gun current
$I_{AG}$ : auxiliary gun current
$I_F$ : filament current of aux. gun
$V_F$ : filament voltage
$K_1$, $K_2$, $K_3$, $\alpha$, $\beta$ : constant

The gun current and auxiliary gun current as a function of the filament current are measured as shown in Fig. 4.

### IV. 4. Pulse Observations

To check the machine status, four different pulses are observed at several different system. Here, the characteristics and function of each pulse are described briefly.

The tank containing the pulse transformer for the magnetron also houses a current transformer which produces a voltage proportional to the current drawn by the magnetron. The magnetron current pulse is available at the oscilloscope panel. During normal operation, the magnetron current is approximately 90 A corresponding to 9 V on the oscilloscope as shown in Fig. 5(a). When some arc may occur inside the magnetron, this exhibits itself as much larger and more irregular current pulses than normal. If arc occurs with more than one occasional pulse, there is some fault in the magnetron. The most likely cause is lack of filament current of the magnetron. Also, if the plateau of the pulse has some variations more than 1%, or a too high peak appears in the current pulse, it cause to modulate the frequency of the RF power.

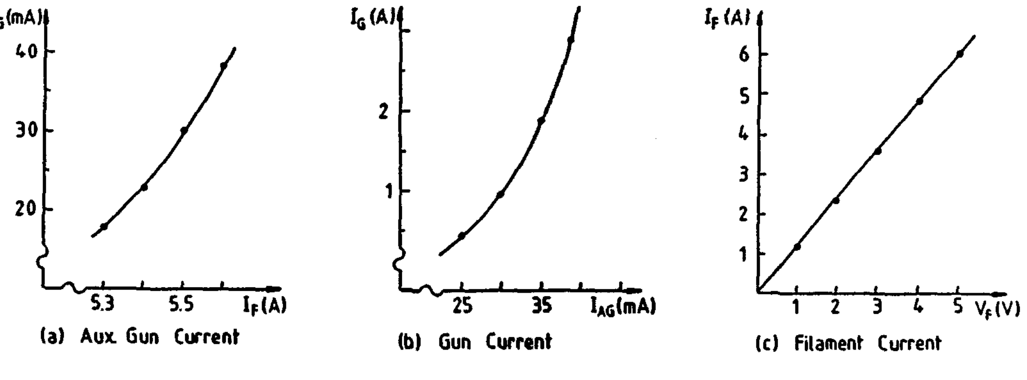



**Fig. 4. Characteristics of the Electron Gun.**

From these measured results, the constant values for Eq.(13), (14), (15) are to be deduced as follows;

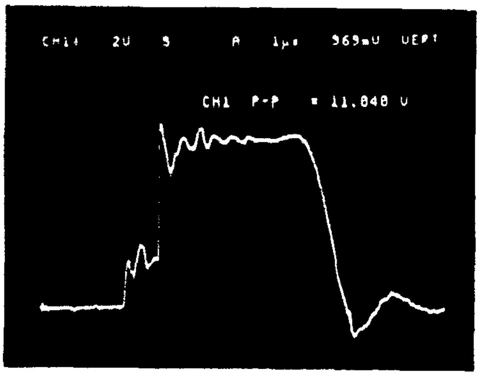
$K_1 = 0.015$, $K_2 = 2.76 \times 10^{-8}$, $K_3 = 1.190$, $\alpha = 138.6$, $\beta = 2.526$.

Optimum operating conditions have been maintained with the gun current of about 1–1.2 A and the auxiliary gun current of about 28–32 mA.

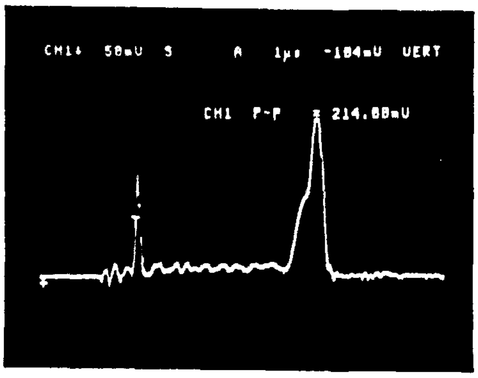
The waveguide system contains a directional coupler with two aerials. One of the aerials measures the microwave power from the magnetron to the resonator, while the other aerial measures the power reflected back from the resonator to the magnetron, that is, reflected power. The signal corresponding to the reflected power is detected by a microwave diode. The typical appearance of this signal is shown in Fig. 5(b). By examining the reflected power signal, the status of the microwave system has been recognized. During normal operation, the reflected power is nearly zero except at the start and finish of pulse.

The typical appearance of the gun current pulse is shown in Fig. 5(c). Occasionally, arc occurs in the electron gun. When such a discharge happens, the gun current pulse become much larger than normal, that is, greater than 10 A.

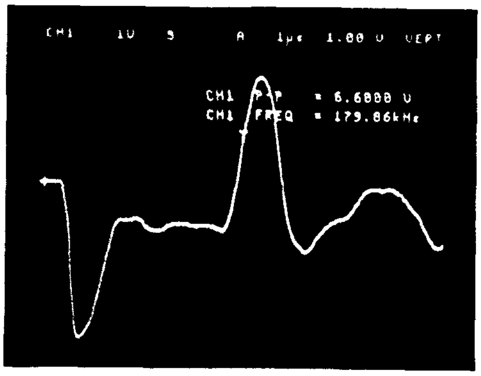
During photon therapy[9], the electron beam hits a target inside the treatment head which is electrically isolated. A current proportional to the accelerated electron current is forced to flow from the target through 50 Ω resistor. The voltage across this resistor is fed to one channel of the oscilloscope where it produces a signal of 50 mV for every mA of electron current. A typical electron current for 10MV photon therapy is 58 mA as shown in Fig. 5(d).



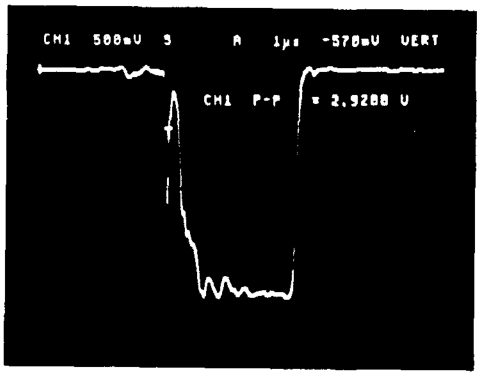
(a) Magnetron Current Pulse.



(b) Reflected Power Pulse.



(c) Gun Current Pulse.



(d) Target Current Pulse.

**Fig. 5. Pulse Signals**

## V. Conclusions

This paper has outlined the characteristics for the overall systems of the MM–22 and some measured results. From these results, the output of the MM–22 is more than enough for radiotherapy, and has been found to be unexpectedly stable. In the energy range below 22 MeV, three photon beams and nine electron beams are very useful and cover some 75 percent of the needed treatment modalities of the therapeutic department.

In view of the simplicity of the machine and the small amount of precision engineering involved compared with a linear accelerator, the authors feel that the microtron offers a competitive alternative in the energy region below 50 MeV.

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