COMPACT, MICROTRON-BASED GAMMA SOURCE*

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Abstract

The conceptual design of a prototype S-band pulsed, 9.5 MeV compact microtron with type-II injection is described. Estimates of parameters such as beam current and cathode lifetime, and comparisons with X-band and C-band parameters are presented. The electron beam can be extracted at various energies up to 9.5MeV. Estimated yields of gammas produced at 6.5 MeV operation and estimated yields of gammas and neutrons produced at 9.5 MeV are presented.

INTRODUCTION

The microtron is a cyclic electron accelerator that operates on the Principle of Resonant Acceleration first proposed and developed by V. Veksler [1]. The "classic" microtron features a magnetic field that is constant and uniform over a circular region in which the electron trajectories are executed. Acceleration is provided by an RF cavity located at the point at which the electron trajectories pass as illustrated in Fig. 1.

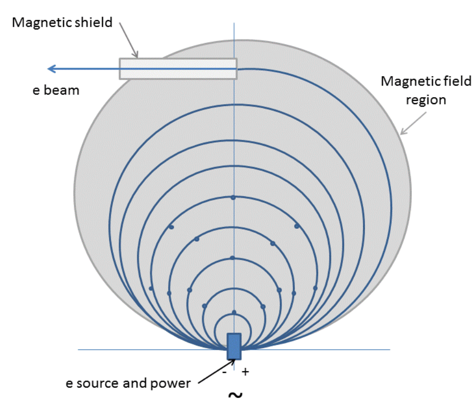

Figure 1: Simplified representation of a classic microtron. The source of electrons is a heated cathode within an injector. The acceleration is provided by a single RF cavity co-located with the source. Dots represent the RF periods in the first few orbits, e.g. the first orbit has 2 periods, the second has 3 periods, etc. Electrons can be extracted tangentially to the final orbit by means of a magnetically shielded tube, as shown. Alternatively, internal targets can be placed in the beam.

Electrons in the energy range from a few MeV up to ~ 10 MeV are used to produce gamma rays for a variety of applications, such as scanning for nuclear materials or explosives hidden in cargo containers or vehicles. By using appropriate targets photo-neutron reactions by the gammas produce useful fluxes of neutrons for active interrogation applications, particularly for electron energies near 10 MeV.

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MICROTRON PARAMETERS

A comprehensive exposition of the history and concepts of the microtron can be found in Ref. [2].

Basic Microtron Parameters

To satisfy the conditions of the principle of resonant acceleration, there are integer parameters, *n* and *m*, which are the number of orbits in the microtron and the number of periods that the accelerating field needs for the electron circulation along the first orbit. The parameter Ω, defined as H/H_C, where *H* is the magnetic field in the microtron, and H_C is the cyclotron magnetic field, in which period of revolution of electron with the total energy of m_0c^2 (its energy of rest) is equal to period of the accelerating field, $T_a=2\pi/\omega_a$.

For synchronicity, the fractional increase in electron total energy is

$$\Delta U/U = H/H_C = \Omega. \quad (1)$$

The integer parameter *m*, determines the length and dimension of the first orbit that completely encircles the cavity. The minimum value of m is 2, and two important relations involving *n*, and *m*, are the following.

The total energy of the n^{th} orbit electrons is:

$$U_n = (n+m-1)\ \Omega{\cdot}m_0c^2 \quad (2)$$

The diameter of the n^{th} orbit is:

$$D_n = (n+m-1)\ \lambda/\pi \quad (3)$$

λ is the wavelength of the accelerating field. These relations will be used in the following sections.

Design Alternatives

In addition to the basic microtron parameters above, there are design alternatives that are important for the performance of a microtron. One is the choice of the frequency band of the RF accelerating field.

Frequency band Eq. 3 shows that the frequency (and the corresponding wavelength) determines the diameter of the final orbit and that of the magnet. In addition the wavelength sets the scale of the Rf cavity and that of the injection source. Three wavelength bands are commonly used for compact microtrons: X-band (λ=3.2 cm), C-band (λ=5.1 cm), and S –band (λ=10.7 cm).

Injection type A second important design parameter is the injection type. Consider two injection types, type-I and type-II, as depicted in Figure 2 and Figure 3. Note that electrons emitted from the cathode which to not enter the proper trajectory to pass through the slit near the cathode are not shown; they are quickly removed by hitting a wall at low energy. In Type I injection, electrons emitted

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from the cathode pass through one of the two larger slits before assuming the paths taken by the successive full orbits through the cavity. The value of Ω is $0.65 < \Omega < 1.7$.

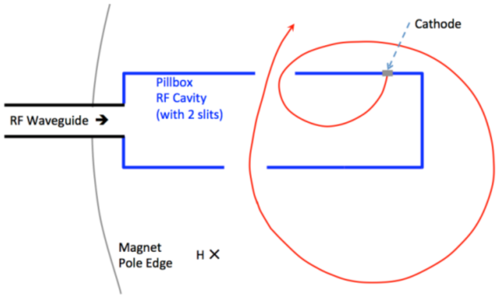

Figure 2: Initial trajectories of resonant electrons in a microtron using Type-I internal injection, based on [2].

In Type II injection, electrons emitted from the cathode, located near the symmetry axis of the flat-walled cylindrical cavity, pass through a small slit in the cavity wall, and make one revolution through the two larger slits before assuming the paths taken by the successive orbits through the cavity. The value of Ω is $1.7 < \Omega < 2.1$.

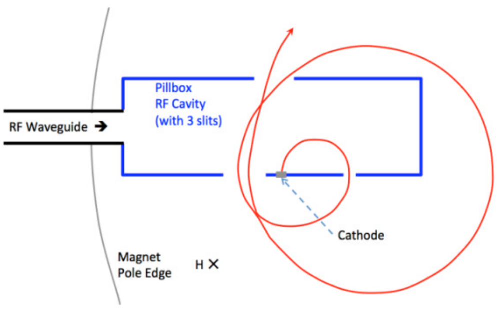

Figure 3: Initial trajectories of resonant electrons in a microtron using Type-II internal injection, based on [2].

The type-II injection scheme utilizes an additional radial slit in the median plane in the cavity cover for passage of the electrons along the first orbit. In type-II injection, Ω is greater, which allows a larger magnetic field, thus decreasing the diameter of the magnet and resulting in a more compact microtron. We have chosen type-II internal injection for the prototype.

Cathode heaters Compact microtrons have used various cathode designs with both direct and indirect heaters. Direct heaters have direct contact between the heating element, usually Ta, and the LaB_6 crystal, which causes diffusion of Ta into the LaB_6 and decreases the lifetime. Indirect heaters have a separation between the heating element and the LaB_6 crystal, such as shown in Figure 4, or heating by an electron beam, as shown in Figure 5. The final design may include a combination of the two types.

The injection parameters for S-band Type-II injection and C-band type-I injection are shown in Table 1, in which I_n/c_n is the ratio of current in the n^{th} orbit to the capture coefficient, D_C is the cathode diameter, E_0 is the electric field on the cavity axis, E_C is the electric field at the center of the cathode, i_C , is the current density at the cathode, and I_C is the cathode current. Note that $I_n/c_n < I_C$ for the S-band type-II case, which means that that the cathode temperature can be decreased, which further increases the cathode lifetime.

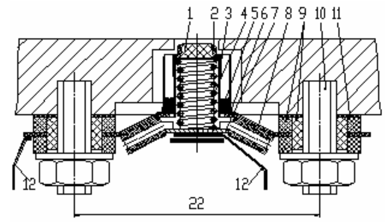

Figure 4: Layout of the microtron cathode assembly developed in Ref [**3**]: (1) emitter, (2) graphite holder, (3) cathode sleeve, (4) cylindrical filament, (5) heat shields, (6) carrying base, (7) tantalum plate, (8) ceramic insulators, (9) ceramic insulators, (10) titanium studs, (12) wire lead, reprinted from [3].

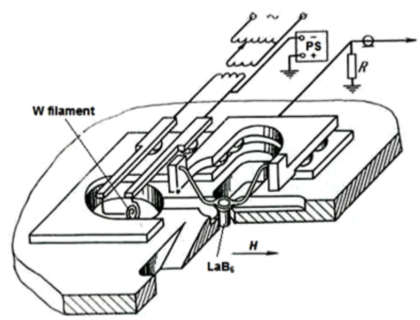

Figure 5: LaB6 cathode heated by an electron beam produced by a separate filament (reprinted from Ref. [2]).

Power system The RF system as depicted in Figure 6 is powered by a pulsed magnetron coupled to the accelerating cavity via a waveguide system that includes a ferrite insulator or a circulator with a matched load, a directional coupler and the waveguide vacuum window. The circulator and the matched load provide stable operation of the magnetron preventing discharges caused by a strong reflected wave. The magnitude of the reflected wave passing to the magnetron is reduced by 17-20 dB, which is enough for the reflected wave to stabilize the magnetron frequency. See [4], [5] for full discussion.

MAGNET AND BEAM EXTRACTION

The design of the magnet and the beam extraction system are presented in separate IPAC 16 contributions, references [6] and [7].

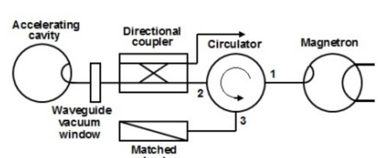

Figure 6: Schematic of the microtron RF system.

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Table 1: Injection Parameters for C-band Type-I, 12-Orbit (n=12) and S-band Type-II, 10-Orbit (n=10) Microtrons

Microtron, injection	I_n/c_n (A)	Ω	D_C (mm)	E_0 (MV/m)	E_C (MV/m)	i_C (A/cm^2)	I_C (A)
C-band, type-I	1.057	1.0	1.5	64.5	21.7	43.5	0.69
S-band, type-II	1.778	1.8	2.5	40.7	32.4	55.6	2.23

Table 2: Comparison of 6.5 MeV X-, C-, and S-band Versions and 9.5 MeV S-band Compact Microtrons (Note that X-band and C-band Versions Use Type-I Injection and S-band Versions Use Type-II Injection)

U_n, MeV -Band	Λ (cm)	n	D_n (m)	D_{Pole} (m)	I_n (mA)	Ω	c_n (%)	P_{RF} (MW)	i_C (A/cm^2)	Cathode	t_{Cath} (h)	Gamma Dose (R/min·m)
6.5-X	3.2	15	0.164	0.196	8.8	0.8	3–4	0.375	44.9-51.3	Ta	<10	133
6.5-C	5.1	12	0.212	0.263	37	1.0	3–4	1.0	43.5	LaB_6	500	643
6.5-S	10.7	7	0.273	0.38	90	1.8	4–5	2.0	55.6	LaB_6	1000	860
9.5-S	10.7	10	0.375	0.482	65	1.8	4–5	2.0	28.4	LaB_6	>1000	1660

PERFORMANCE CALCULATIONS

Table 2 shows a comparison of the calculated characteristics for several versions of microtrons, including number of orbits (n), n^{th} orbit diameter (D_n), magnet pole diameter (D_{Pole}), currents, energy gain per turn, capture efficiency, RF power, cathode current density, cathode type and lifetime, and gamma dose. In addition to the values in the table, the estimated neutron yield at 9.5 meV is $7{\cdot}10^{10}$ n/s. An analysis of a higher intensity microtron-based neutron source is presented in another IPAC 16 paper [8].

SUMMARY

We have studied various microtron parameters for a high intensity gamma source and we summarize our findings.

Table 2 shows that although the 6.5 MeV X-band microtron is the most compact, it provides the lowest gamma dose, and an unacceptably short cathode lifetime. In addition, the small size of the accelerating structure precludes the use of a LaB_6 cathode, and requires high-precision machining and high costs. Further, S-band 6.5 MeV version produces 34% higher gamma done and has a 44% larger magnet diameter, offering a potential trade-off. The S-band 9.5 MeV S-band version produces more than 2-3 times greater gamma dose, with a magnet that is 30-40% larger than the S-band or C-brand versions. The 9.5 MeV also version can be operated at 6.5 MeV, or at other energies, and is our optimum design choice.

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