MICROTRON-BASED INTENSE NEUTRON SOURCE

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Abstract

An L-Band, 7.7-9.8 MeV, CW, relatively inexpensive microtron with a warm accelerating cavity for multi-purpose applications in nuclear medicine and radiation industry is proposed. The microtron, with a photo-neutron converter, is intended to serve as an intense source of photo-neutrons with yield up to $4{\cdot}10^{12}$ n/s for nuclear medicine or/and production of short-lived isotopes, as a source of gamma-radiation with dose rates up to 130 kR/min·m with a heavy bremsstrahlung target, and as a source of electron beam with total energy of 9.8 MeV at an average current up to 4.4 mA for various radiation treatments.

INTRODUCTION

Relatively inexpensive and compact intense sources of electrons with energy up to 9-10 MeV at a beam power of a few tens of kW are interesting for application in medicine (as sources of intense photo-neutrons for boron-capture cancer therapy, production of short-lived isotopes, sterilization of medical waste, etc.) and industry (radiation treatment, sterilization, etc.). The classical warm-cavity microtron operated in CW mode may well solve the listed problems. In the literature, [1, 2], were proposed and considered such L-band projects, however they were not realized yet generally, we assume, because of absence of inexpensive, CW high power RF sources. Now industry produces L-Band magnetron RF sources with a power cost of $1.00 per Watt, thus the microtron projects represent an interest for customers. We propose and consider a design-project of such an L-Band, CW, laboratory-size classical microtron with total energy of 9.8 MeV as an intense source of γ-rays and photo-neutrons for various applications in medicine and industry. The total energy of the extracted beam can be varied in the range of 7.7-9.8 MeV. The microtron can operate in CW or pulsed mode with repetition rates up to 100 kHz and high duty-factor. It does not require the cryogenic equipment. The microtron is assumed to be easily controlled, reliable and stable in operation. Parameters of the CW microtron and its subsystems are presented and discussed here.

DESIGN PARAMETERS OF THE CW MICROTRON

One considers the type-I injection scheme microtron with the resonant frequency, f, of 1.5 GHz. The cyclotron magnetic field at this frequency, H_C, is ≈ 535 Oe. The magnetron RF source power, P_{RF}, is assumed to be 200 kW. This power presently is available with commercial generators. The total energy of the accelerated beam at the number of orbits, n = 23 is $U_n \approx 9.8$ MeV. This avoids photo-neutron activation of the microtron components. Using the type-I injection scheme with the microtron magnetic field, $H = \Omega{\cdot}H_C$, where $\Omega = 0.8$, one can provide laboratory-scale sizes of the microtron magnet with diameter of the n-th orbit of $D_n \approx 1.73$ m, at the accelerated beam power, P_e, of 30-40 kW, Table 1.

Table 1: Design Parameters of the 1.5 GHz CW Microtron

n	U_n, MeV	P_{RF}, kW	D_n, m	m_{Mag}, kg	P_e, kW
23	9.81	200	1.727	$\approx 2.8{\cdot}10^3$	40.9

Note that the required inhomogeneity of the magnetic field for n = 23, $\Delta H/H \leq n^{-2} \approx 1.9{\cdot}10^{-3}$, is technically feasible.

RF SYSTEM OF THE CW MICROTRON

The RF system of the CW microtron represents a respective magnetron generator coupled with a pillbox-type accelerating cavity, Fig. 1, via a ferrite circulator and directional couplers for measurements of the generator and the acceleration parameters. Vacuum in the accelerating cavity is separated from dry nitrogen at atmospheric pressure in the waveguide system by a vacuum waveguide window.

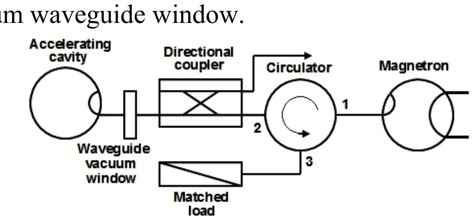

Figure 1: Conceptual scheme of the microtron RF system

The scheme provides stable operation of the microtron. At a circulator inverse loss of 17-20 dB the magnitude of the reflected wave passing towards the magnetron is enough to stabilize the magnetron frequency, making the generation frequency-locked by the reflected wave, [3, 4].

Assuming RF losses of the RF system, P_S, ≈1 dB on can estimate RF power, P_{Acc}, allowable for acceleration:

$$P_{Acc} = P_{RF} - P_S - P_{wl}\,.$$

Here P_{wl} is power lost in the walls of the RF cavity, [2]:

$$P_{wl} \approx \frac{1.02\sigma}{\lambda}\left(1.2 + \arcsin\frac{1}{1.88\varepsilon}\right)\varepsilon^2\Omega^2 P_0\,,$$ where σ is conductivity of the cavity walls, $\lambda = c/f$, $\varepsilon = E_0/H$, E_0 is strength of the RF electric field on the cavity axis, and P_0=8700 MW is the characteristic electron power. In microtrons about half of RF power is lost for acceleration of non-resonant electrons. Thus the coupling coefficient of the RF cavity with a waveguide, β, is: $\beta = P_{Acc}/(0.5\cdot P_{wl}) + 1$. This allows a determination of

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the loaded cavity Q-factor: $Q_L=Q_0/(\beta+1)$; Q_0 is determined by the cavity geometry. Parameters of the RF system for the injection scheme with ε=0.94, [2], are shown in Table 2. The parameters correspond to a beam power of ≈40 kW.

Table 2: RF Parameters of the CW Microtron

λ, m	P_S, kW	P_{wl}, kW	P_{Acc}, kW	β	Q_L
0.2	41	77.1	81.8	2.06	$4.88\cdot10^3$

In accordance with data Tab. II the RF and beam power lost in the cavity is 118 kW with a cavity surface of 550.5 cm2. This corresponds to a power density of ≈214.4 W/cm2. Such a heat sink with good cooling looks feasible.

Since 100 kW CW magnetron generators with a cost per unit power of ≤$1 are consistent with current manufacturer capabilities, one can consider a widely tunable (in power) CW, two-channel magnetron generator, Fig. 2, based on magnetrons with power combining, [5]. The power control is provided by the controlled phase shift of signals driving both channels. Such a generator allows operation of the microtron in CW and pulsed modes. In the latter case the minimum pulse duration can be a few μs at a repetition rate of hundreds kHz. One can expect that the cost of power in such a generator also should be ~$1 per Watt.

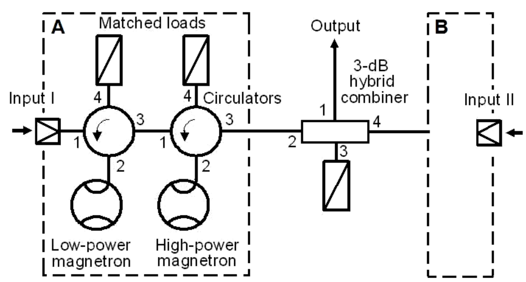

Figure 2: Conceptual scheme of the two-channel power-controlled magnetron RF source with power combining.

INJECTION IN THE CW MICROTRON

In accordance with the type-I injection scheme, [2], simulations of the injection were performed, Fig. 3.

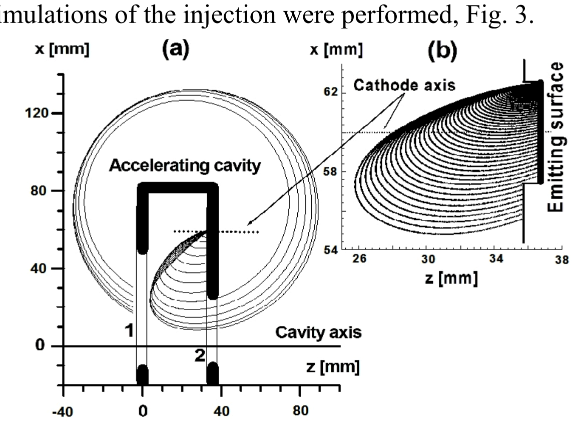

Figure 3: (a) 2-D tracking of the first orbit. With numbers 1 and 2 are marked the narrow slits directed along the x axis and used for input-output of the electrons. (b) 2-D tracking of the back-streaming electrons hitting the emitter.

In the simulation, the LaB_6 cathode emitting surface was recessed in a hole below the internal surface of the pillbox. The hole for the recessed emitter acts like a lens and provides some focusing of the injected electrons. For a hole of radius r_H and a recession depth d_C the RF field in the cathode surface center is, [6]:

$$E_{CS} \cong E_0 \cdot J_0(k_0 \cdot R_C)\cdot \cos(\varphi_S)\cdot \frac{J_0(k_r, r)}{\cosh(k_z \cdot d_C)} \approx 7.2 \text{ MV/m}.$$

Here J_0 is the Bessel function of the first kind,

$$E_0 = \frac{\Omega m_0 c^2 \cdot (\theta/2)}{e\cdot l\cdot \sin(\theta/2)\cdot \cos\varphi_S}$$ is the maximum field on the cavity axis, l is the cavity length, $k_r = \chi_{01}/r_H$, where $\chi_{01}=2.405$ is the first zero of the Bessel function and $k_Z=\sqrt{k_r^2-k_0^2}$, φ_S is the equilibrium phase for the microtron.

Considering the Schottky effect one can express the current density of a LaB_6 single crystal emitter as a function of (r,φ) as:

$$i_C(T,r,\varphi)=AT^2\cdot\exp\left[\frac{-e\phi_C+3.79\cdot10^{-4}\cdot\sqrt{E_{CS}(r,\varphi)\cdot10^6}}{k\cdot T}\right].$$

Here: A=73 A/K²cm² and $e\phi_C$ = 2.66 eV are the Richardson constant and the work function for LaB_6, respectively, k is the Boltzmann constant and T is the emitter temperature in Kelvin. The initial value of the emission current at the emitter radius r_C is equal to, [6]:

$$I_C(T)=\int_0^{2\pi}\int_0^{r_C} i_C(T,r,\varphi)\cdot r\,dr\,d\varphi\,.$$

From the simulations, it follows that at the cathode temperature of 1650 K the current emitted by 5 mm-diameter single-crystal LaB_6 emitter will exceed 200 mA. It is enough to provide a beam power of 40 kW. The quite low temperature of the cathode will increase the cathode life time to a few thousands hours. Design of the indirectly heated cathode with the LAB_6 emitter is shown in Fig. 4, [6].

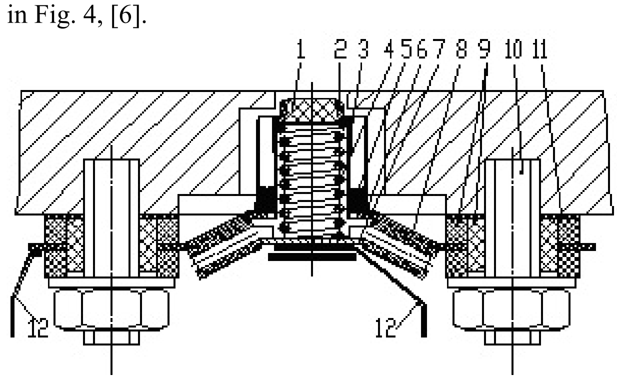

Figure 4: Layout of the microtron cathode assembly. 1- emitter, 2- graphite holder, 3- cathode sleeve, 4- cylindrical filament , 5- heat shields, 6- carrying base, 7-

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tantalum plate, 8, 9- ceramic insulators, 10- titanium studs, 11- spacer, 12- heater contact.

The 5 mm-diameter [100]-face LaB_6 single crystal tablet-shape emitter is fixed in the graphite holder. The emitter thickness is 1.1 mm. The graphite holder prevents the diffusion of boron inside tantalum components of the assembly; that significantly increases the cathode life time. The cathode is mounted on two titanium studs screwed into the cavity cover, so that the cathode assembly is recessed in the cavity cover. The depth to which the emitting surface is recessed into the cover can be adjusted with the spacers.

MAGNETIC-VACUUM SYSTEM OF THE CW MICROTRON

The combined magnetic-vacuum system of the CW microtron is assumed to be sealed by an indium wire between the upper and lower poles of the magnet, [7]. A schematic of the generic microtron magnet is shown in Fig. 5.

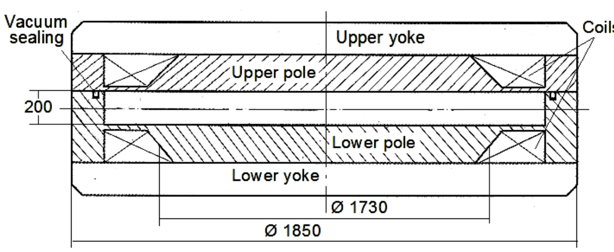

Figure 5: Sketch of the 9.5 MeV tubeless generic microtron magnetic-vacuum system. All sizes are in mm.

Since main parts of the magnet yoke are far from saturation, performed simulations show achievable inhomogeneity of the magnetic field of ~ $3\cdot10^{-5}$ for all orbits. This value is much less than the n^{-2} requirement. It allows optimization of the yoke sizes reducing the microtron weight.

The electron beam will be extracted by installing a magnetic channel of soft steel inside the microtron magnet at a tangent to the circular trajectory at the final orbit such the beam exits along the tangent. The extraction system allows compensation of perturbation of the magnetic field in the neighborhoods of the previous orbits resulting from the magnetic channel, by choosing the geometry of the magnetic rods, Fig. 6. The system was tested in a pulsed S-band microtron, [8], demonstrating 90-95% efficiency in extraction of the beam from the 4 last orbits. The extraction system will be simulated to reach highest extraction efficiency by compensation of perturbations of the magnetic field.

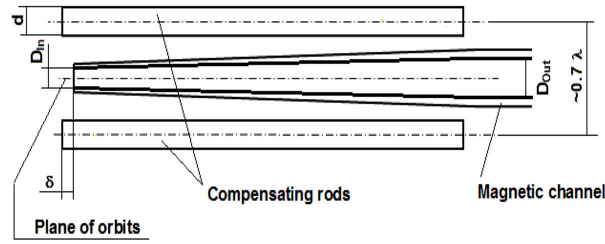

Figure 6: The extracting system of the L-band microtron.

GAMMA AND NEUTRON YIELDS OF THE CW MICROTRON

The bremsstrahlung dose power of the microtron at a distance of 1 m from a tungsten 0.3 radiation length-thick target, estimated in accordance with [2] is ≈130 kR/min.

The photo-neutron yield from U-Be target at a microtron beam power of 40 kW is estimated as $4.1\cdot10^{12}$ n/s, [2], at the optimal thickness of the target. Note that the beam power requires a dual-circuit cooling of the photo-neutron target. The expected bremsstrahlung dose powers and the photo-neutrons yields vs. the beam total energy at the accelerated beam power of $W_{Acc}/2 \approx 41$ kW are shown in Table 3.

Table 3: Radiation Parameters of the CW Microtron

n	U_n, MeV	Dose, R/min·m	Neutrons yield, n/s
19	7.7	$80\cdot10^3$	$2.3\cdot10^{12}$
21	8.5	$115\cdot10^3$	$2.9\cdot10^{12}$
23	9.8	$128\cdot10^3$	$4.1\cdot10^{12}$

Note that U_n<8 MeV allows avoiding of photo-neutrons from the tungsten target.

REFERENCES

[1] S.P. Kapitza, The CW Microtron, in Coll. Pap. “High Power Electronics”, V 4, 1965, pp. 165, (In Russian).

[2] S.P. Kapitza and V.N. Melekhin, in “The Microtron”, Harwood Academic Publishers, London, Chur, 1978.

[3] G.M. Kazakevich, V.M. Pavlov, Y.U. Jeong, B.C. Lee, PRST-AB 12, 040701 (2009).

[4] G.M. Kazakevich, V.M. Pavlov, Y.U. Jeong, and B.C. Lee, NIM A 647 (2011) 10-16.

[5] G. Kazakevich, R. Johnson, B. Chase, R. Pasquinelli, V. Yakovlev, “Regime of a wideband phase-amplitude modulation in a CW magnetron transmitter with a phase control”, http://arxiv.org/abs/1407.0304

[6] G. M. Kazakevich, V. M. Pavlov, G. I. Kuznetsov, Y. U. Jeong, S. H. Park, and B. C. Lee, J. Appl. Phys. 102, 034507 (2007).

[7] G. M. Kazakevitch, Y. U. Jeong, B. C. Lee, S. O. Cho, J. Lee, V. P. Belov, N. G. Gavrilov, “Magnetron Driven Classical Microtron as an Injector for a Wide Band Far Infrared Free Electron Laser” in Proc. PAC01, Chicago, USA, 2001, paper WPPH115, pp. 2739-2741.

[8] G. M. Kazakevitch, Y. U. Jeong, B. C. Lee, N. G. Gavrilov, M. N. Kondaurov, NIM, A 507 (2003) 146-149.