Design of a Compact 70 MeV Multi-Purpose Pulsed Race-Track Microtron

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Abstract

We discuss here a race-track microtron designed to produce 40 mA electron pulses with energy up to 70 MeV and which will be lorry transportable.

1. INTRODUCTION

Building on our experience with the theory and practice of classical microtrons [1], pulsed [2] and CW race-track microtrons [3] and standing wave accelerator structures [4] we have undertaken a design study of a pulsed industrial race-track microtron whose size and weight have been minimized so as to be portable and inexpensive and whose reliability and operation ease have been maximized so as to be operated by non-experts. The machine characteristics – beams of energy up to 70 MeV and pulsed current up to 40 mA – were set by the requirements of the Carbon and Nitrogen Cameras which are used to screen for concealed bulk narcotics and terrorists explosives [5]. Other applications for such a machine include, but are not limited to, nuclear physics research, infrared free electron laser driver, synchrotron light source injector, and short-lived medical radioisotope generator.

2. MICROTRON SETUP AND PARAMETERS

We have chosen to operate in the S-band radiofrequency and use the pulsed KIU-111 5 MW klystron [6] which operates at 2450 MHz and has average power of 5 kW which will provide the required maximum delivered beam power of 2.8 MW with losses in acceleration beam of 0.4-0.9 MW and linac walls of 1-1.5 MW. The magnetic field, B_0 = 1T, was chosen to avoid saturation effects. The energy gain per turn is thus $\triangle E_s = e\nu B_0\lambda/2\pi = 5.85$ MeV in the first few orbits. A total of 13 electron passages are required through the linac because of the decrease of magnetic field and the value of $\triangle E_s$ with radius of orbits.

The injection energy is chosen to be close to that of klystron high voltage so that modulator power supply could also be used for injection. The principal microtron parameters are listed in Table I.

Table I. The Main Microtron Parameter.

Injection energy	55 keV
Energy gain per turn	5.85 MeV
Operating frequency	2450 MHz
Orbit length increase per turn	1λ
Synchronous phase	16 deg..
Magnetic field induction	1 T
Number of electron orbits	12
Output energy	24-70 MeV
Beam current	30-40 mA/mkA
RF klystron power	5 MW/kW
Dimensions	$2,092 * 600 * 500$ mm^3
Weight	2,500 kg

Of the many possible designs which could provide a beam clearance of the linac on the first orbit – a narrow linac without axial symmetry, a linac with wide horizontal slots, adding magnets on the first orbit, etc. – we choose the simplest solution: An additional acceleration in the linac in the opposite direction provided by beam reflection. This reflection is accomplished after the beam first passage through linac by the same reversed end magnet fringe fields which ensures the vertical focusing on the first few orbits. On later orbits we focus vertically using the end magnets field gradients.

We horizontal focus using a quadrapole singlet on the linac axis whose horizontal focusing power decreases linearly with energy while its vertical power is almost energy independent. End magnets field gradients cause drift in the synchronous phase, so special attention must be paid to the longitudinal acceptance when choosing the field gradient value. Optics similar to

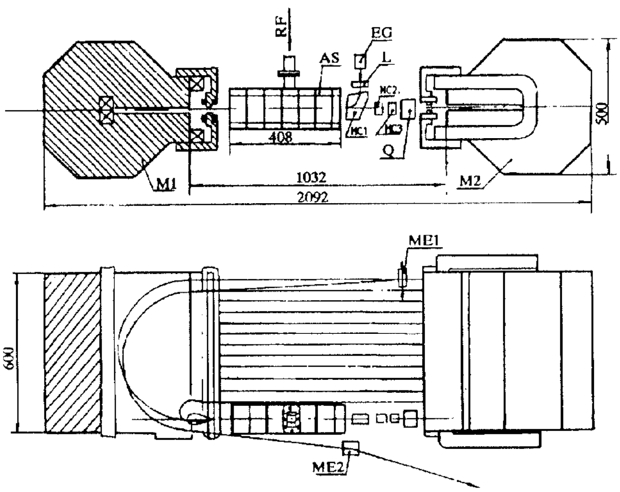

Figure 1. Race-track microtron setup
M1, M2 - 180° end magnets; AS - accelerator structure; EG - electron gun; Q - quadrupole singlet; MC1, MC2, MC3 - injection chicane magnets; L - solenoidal lens; ME1, ME2 -extraction magnets.

ours have been used elsewhere [7,8].

Fig. 1 is a schematic of the major microtron elements.

3. LINAC OPTIMIZATION

Since the linac must capture slow electrons and accelerate relativistic electrons we will use one full cell of β = 0.67 and six cells of β =1. The effective shunt impedance for cells without coupling slots will be Z_{eff} = 54 MOhm/m at β =0.67 and Z_{eff} = 78 MOhm/m at β =1. The coefficient K_{str} is the ratio of the largest electric field on the inner cell surfaces to that on the linac axis K_{str} = 1.9 and 2.9 at β = 0.67 and 1 respectively. With these values of Z_{eff} an energy gain of about 15 MeV/m can be achieved. The optimal axial voltage ratio on the first cell to those on subsequent cells is 0.96. With the decrease of Z_{eff}, caused by coupling slots, down to 64 MOhm/m at β = 1 the RF power losses in linac walls is about 1.4 MW for a 5.85 MeV energy gain at a 16 degree synchronous phase.

Linac beam dynamics showed the energy gain and output phase dependence on input phase produced phase bunching for 55 keV injected electrons: For an input phase range of about 100 degrees the energy gain is nearly constant while the output phases are confined to a 25 degrees interval. The linac will capture about 40% of the continuous 55 keV electron beam with initial space ±2 mm and angular ±50 mrad spreads. Space charge effects are small for injection currents below about 400 mA.

4. BEAM DYNAMICS AND POWER

To determine the microtron parameters we varied the M1 end magnet position relative to that of the linac so that the energy gain in the second beam passage through linac was maximized. This accomplished we positioned the M2 magnet so that phase oscillations on subsequence orbits would be small for the optimal 55 keV electron injection phase.

We found an end magnet fringe field configuration which ensured electron trajectory closure after first linac passage (beam reflection into the linac) consistent with sufficiently strong focusing on the first few orbits. Two-dimensional pole configuration for the magnet with reverse poles were obtained using computer simulations [9]. In beam dynamic calculations the fringe field was represented as a superposition of weighted fields from the main and reverse coils. We also optimized the pole gap height. We varied the fringe field optical properties independent of trajectory closure by simultaneously varying the reverse coil current and pole positions relative to the main poles.

We found stable transverse motion even with the quadrapole singlet, Q, switched off and uniform end magnet fields. However, to amplify the horizontal focusing we choose the Q gradient to be about 100 G/cm for an effective quadrapole length of 5 cm. For better vertical focusing we introduced a slight one-direction magnetic field gradient in the end magnets, a 4% decrease to the pole edge. This field decrease shifts the synchronous phase, reduces the energy gain per turn, and changes the distance between orbits. Thus, we had to increase the number of orbits from 11 to 12 so that a 70 MeV exit beam could be obtained. The synchronous phase shift at the last orbit can be as much as 10-15 degrees.

We investigated beam dynamics for two sets of initial conditions: (1) horizontal and vertical space spreads of ±2 mm and angular spreads of ±50 mrad in and (2) space spreads of ±1 mm and angular spreads of ±20 mrad. We calculated the horizontal, vertical, and longitudinal phase space emittances and acceptances for case 1 to determine the initial phases over the entire acceleration interval. The current transmission through the microtron is shown in Fig. 2 for injected currents of 370 and 240 mA for case 1 and 2, respectively.

A decrease in the injected beam transverse emittance results in an increase in the transmission of the continuous electron gun beam from 9% up to 18% , a very good value for a race-track microtron with 13 linac passages. For case 2, the beam power reaches 2.8 MW at exit with parasitic losses of about 0.6 MW and pulsed beam current of about 40 mA.

5. BEAM INJECTION AND EXTRACTION, END MAGNETS

A Pierce-type electron gun designed to reduce the output beam emittance will operate with a 55 kV

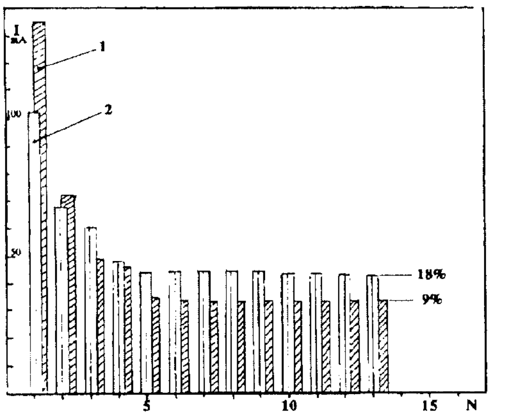

Figure 2. The dependence of beam current on number of passage through linac

anode voltage supplied by the klystron modulator. The 5 mm diameter cathode will produces a ~ 370 mA current. The transversal beam emittance, 5.5π mm $\cdot$ mrad, is matched to the microtron acceptance using a solenoidal lens, L, placed just behind the anode (see Fig.1). A standard LaB_6 cathode will require electric heater power of about 30 w.

Because the 55 keV injection energy and the 12 MeV first orbit beam energy are so different the injection through three magnet chicane is easily accomplished. A 55 keV beam in the first magnet, MC1, has a radius of about 5 cm, bending angle of 90°, and the pole face-to-beam axis inclination on entrance and exit of 30°. So a nearly parallel injected beam will be focused both vertically and horizontally at the first linac cell entrance. An accelerated 12 MeV beam will be deflected in MC1 by about 1 degree, which will be compensated by two smaller magnets, MC2 and MC3. Focal length of the chicane system, greater than 10 m at 12 MeV, increases quadratically with energy.

To make our microtron more compact we vertically displace the electron gun. Beam extraction will be accomplished after the 3rd linac passage using a movable M1 magnet placed on the desired orbit or an array of fixed magnets. The trajectories of the 70 MeV beam in the end magnet for displaced and non-displaced beams are seen in Fig.1.

For magnet calculations ARMCO steel permeability was used and the induction in steel was limited to less than 1.4 T for 1 T gap fields so that saturation is kept small. To increase the bending field region with a desired linear field slope the main magnet internal coils were shifted to the median plane. The magnet weight was reduced by trimming steel from the magnet corners. The reverse field poles can be shifted with respect to main poles. To allow extraction of the accelerated beam the M1 main and reverse field poles have been increased in area in the beam exit region.

An end magnet steel weighs about 1,030 kg, the main coil current is about 8.3 kA·w, and the reverse coil current is about 1.5 kA·w. Taking into account isolation and cooling channels, the current density will be about 5 A/mm^2 in both the main and reverse coils.

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