PRELIMINARY DESIGN STUDY OF A 60 MeV CW ELECTRON ACCELERATOR USING A CONVENTIONAL STANDING WAVE LINAC

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Summary

A preliminary design of an accelerating system which could produce up to 1 mA of 60 MeV electrons with 100% duty cycle has been studied. The preferred arrangement is a racetrack microtron configuration with an electron energy gain of approximately 10 MeV per pass. The accelerating structure consists of a conventional 2.4 GHz room temperature electron linac operating in the π/2 standing wave mode driven by a single 400 kW cw klystron.

Characteristics of the system including the accelerating structure, associated components and calculated performance are described and cost estimates given.

Introduction

100% duty cycle electron accelerators with currents up to 100 μA, with energy variability from 10 MeV to 100 MeV and with energy resolutions of 10^{-3} at 100 μA and 10^{-4} at 1 μA are ideally suited for photonuclear physics experiments. Currents up to 1 mA with 10^{-3} energy resolution would be useful for some experiments[1].

This paper describes a preliminary design of a racetrack microtron using a room temperature S-band standing wave linac that would meet these requirements. A racetrack microtron with 10 MeV energy gain per pass was preferred for this application because it was found to be more economical in space and costs than a single pass or double pass[2] linac.

Electron accelerators with 100% duty cycle beams have been proposed[3-7] for photonuclear research. One of these accelerators, a racetrack microtron[3] employing a superconducting accelerating structure, has been in operation at the University of Illinois[8,9] for several years. The microtron described in this paper is attractive in comparison because

a) larger average beam currents can be accelerated with a racetrack microtron using a room temperature linac than with one using a superconducting linac[10].

b) liquid helium cooling systems are not required.

The 60 MeV racetrack microtron could be upgraded at a later stage to 120 MeV by doubling the number of orbits and increasing the size of the magnets.

Design Concept

Figure 1 shows the 60 MeV racetrack microtron conceptual layout. Electrons from the 0.3 MeV electron gun are chopped, bunched and injected into the 4.4 m accelerating structure which operates in the π/2 mode at 2.388 GHz. The bunch phase length is less than 6° to satisfy microtron stable phase conditions, to reduce beam spill and activation and to achieve energy resolutions of 10^{-3}. To achieve energy resolutions of 10^{-4} the bunch phase is reduced to 3°. The energy gain per orbit is 10 MeV and the cw rf power required to establish a 2.3 MeV/m average accelerating gradient is 400 kW supplied by a tuneable 5 KM1000SG (X-3070) Varian klystron. Pole tip dimensions for each 180° bending magnet are 0.5 m by 0.25 m. Approximately 40,000 ampere turns are required to establish maximum 0.84 T pole gap magnetic fields. Beam paths for the ν = 2, 4 and 6 modes[11] are shown in Fig. 1 for the maximum gap field. Energy is varied from 60 to 5 MeV by changing rf power, magnet separation, magnetic field and mode number in such a manner that the parameters always satisfy microtron resonance conditions. In the ν = 2 mode the energy range is 60-30 MeV, ν = 4 is 30-15 MeV and ν = 6 is 20-10 MeV. Lower energies (10-5 MeV) are obtained using a single pass through the linac.

The design is based on a first orbit separation of 80 mm (ν = 2 mode) so that the electron beam clears the accelerating structure (58.4 mm radius) on its return path without complex deflection schemes. Such schemes would be required for the ν = 1 mode, in addition to 1.68 T magnetic fields which are expensive to attain with room temperature magnets. Axial and radial beam focussing are provided by sectored magnets suggested by Roberts[12], and verified experimentally by Froelich and Brannen[13] or by magnetic elements for each orbit.

The beam diameter from the injector is less than 3 mm to simplify beam handling. An injection energy of 0.3 MeV was chosen based on a compromise between the size of the gun with its high voltage supply and injection beam transport problems. A small injection angle is used to minimize deflections of the orbiting beams which pass through the injection magnet.

The standing wave π/2 mode on-axis coupled structure[14] consists of 71 accelerating cavities and 70 coupling cavities (Fig. 2). Assembly and brazing of the structure is not difficult since all components are coaxial. Two mechanical joints[15] may be required because of brazing furnace length limitations. Pulsed S-band rf measurements[14,16] with on-axis coupled accelerating structures have shown that multipactoring and arcing do not occur at the proposed 2.3 MeV/m average accelerating gradient. With a 5% intercavity coupling and the rf drive in the central cavity, rf fields from adjacent modes contribute less than 2% of the $\pi/2$ mode fields for this 4.4 m structure.

Beam break-up effects associated with propagation of TM_{110}-like modes are negligible because coupling slots between accelerating and coupling cavities are oriented 90° with respect to each other to minimize coupling of non-axially symmetric modes.

The accelerating structure absorbs 340 kW of rf power at maximum accelerating gradient, i.e. 4.8 kW in each cavity. Cooling is provided at the circumference of the structure and by two cooling channels near the drift tube region (see Fig. 2). Numerical mesh temperature calculations (which agree with experimental measurements on 0.8 GHz structures[15]) give a 115°C temperature rise from the drift tube nose to the outer surface with cooling ($20\ W/cm^2$) only on the outer surface. The two additional channels will reduce the temperature difference to 70°C. For this temperature difference the $\pi/2$ mode resonant frequency is lowered by $\sim$ 10 MHz, hence a tuneable klystron is needed. A 1.6 m on-axis coupled accelerating structure has been operated at CRNL at 100°C ambient temperature with pulsed S-band rf fields corresponding to an average accelerating gradient of 8 MeV/m. All cw parameters for the proposed structure were exceeded in these tests except for the $20\ W/cm^2$ cooling and the 70°C temperature differential.

Since 1.6 mm separates the vacuum from the high velocity water channel, an experimental check of copper erosion in a test cavity is being carried out. Water has been flowing through two 3.2 mm diameter 100 mm long bore holes continuously for 20 months with a 100 kPa pressure drop. No serious erosion problems have been noted to date.

The 400 kW cw klystron has a gain of 55 dB and requires a 1.3 W drive from a stable tuneable oscillator. Waveguide components such as a circulator to isolate the accelerating structure from the klystron may require some development beyond current practice. Waveguide between the accelerator and klystron requires cooling. Maximum beam loading is small so there should be no control problems associated with changes in match of the accelerating structure or with beam induced phase shifts as beam power changes.

Beam Dynamics

Calculations show that no energy degradation, beam blow-up or reduced current transmission should be encountered with the six orbit 1 mA current.

The time required for a 60 MeV $\nu = 2$ mode beam to complete six orbits is 0.2 μs, approximately 500 rf cycles. Therefore a large number of beam bunches are in the microtron at any instant of time, making the stored beam energy appreciable. Kosarev[17] has demonstrated that a microtron becomes unstable when the stored beam energy equals two thirds of the accelerating structure stored energy. The current limit is 45 mA for the proposed 60 MeV racetrack microtron, well above maximum design current.

Kapitza and Vainshtein[18] estimated the current limit related to retardation forces on an electron bunch in a magnetic field. The retarding force can shift the bunch phase by an amount sufficient that microtron resonance conditions are no longer satisfied when the charge in the bunch exceeds some value; in this case several amperes.

Beam blow-up associated with the interaction of a charged beam with transverse modes of a standing wave linac has been discussed by Gluckstern[19,20]. This type of blow-up is minimized by arranging intercavity coupling to prevent propagation of the TM_{110}-like mode. The estimated blow-up current for this structure is several amperes. For a standard side-coupled structure, the threshold for beam blow-up would be 2.5 mA, close to design current.

Detailed beam dynamics calculations have not been performed for this design. However, calculations[21] for a 0.1% duty cycle eight-orbit 25 MeV racetrack microtron using a room temperature linac indicate that no problems should be encountered.

Costs

Costs in 1975 dollars for this room temperature microtron system and one[7] using a superconducting accelerator are given in Table 1. The capital costs are similar but the room-temperature system would have higher electrical operating costs associated with the 400 kW rf system (estimated at \$80,000/year[a]). Other operating costs associated with cooling, machine operation, maintenance and electrical power for components other than the rf system should be similar for the two types of systems. The main components of the rf system for the room temperature linac are the cw klystron - \$125,000, electromagnet - \$12,000, oil reservoir - \$20,000, power supply - \$150,000 and miscellaneous rf components - \$13,000. The main components of the superconducting accelerating structure are niobium - \$35,000, cryostat - \$60,000, and an accelerating structure with rf accessories, cryogenic valves and associated electronic assembly - \$225,000. The helium system consists of a liquefier and purifier - \$85,000, a heat exchanger with pumps and controls - \$102,000 and recovery, storage and transfer lines - \$43,000.

Conclusions

A conceptual design of a racetrack microtron using a room temperature linac has shown that its costs are similar to those of a microtron using a superconducting linac. The room temperature linac can be made with only one accelerating structure which simplifies rf control. Energy variability from 5 MeV to 60 MeV with output currents up to 1 mA should be achieved without beam instabilities or accelerating structure breakdowns. There seems no reason why the 60 MeV system described could not

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[a] At 16 hours/day, 250 days/year for electricity at \$0.02/kWh.

be extended to 120 MeV for the small extra cost associated with a larger magnet and more beam paths.

Operating costs for the two systems should be similar except for higher electrical power costs of the rf system for the room temperature linac. The microtron based on a room temperature linac has two advantages from an operational point of view. When the system is not operated it can be completely shutdown without the need for maintaining the helium system and any beam spill in the accelerating structure will not lead to a reduction in operating duty cycle.

References

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Table 1

Component Costs of a Racetrack Microtron

	Room Temperature Accelerating Structure	Superconducting Accelerating Structure
Injector	$55,000	$55,000
Bunching, chopping	$10,000	$10,000
Accelerating structure	$100,000	$320,000
Focus, steering	$10,000	$10,000
Rf system	$320,000	$115,000
Helium system	-	$230,000
Pair of 180° magnets	$100,000	$100,000
Shielding	$150,000	$150,000
Building to house accelerator and subsystems	$220,000	$220,000
	$965,000	$1,210,000

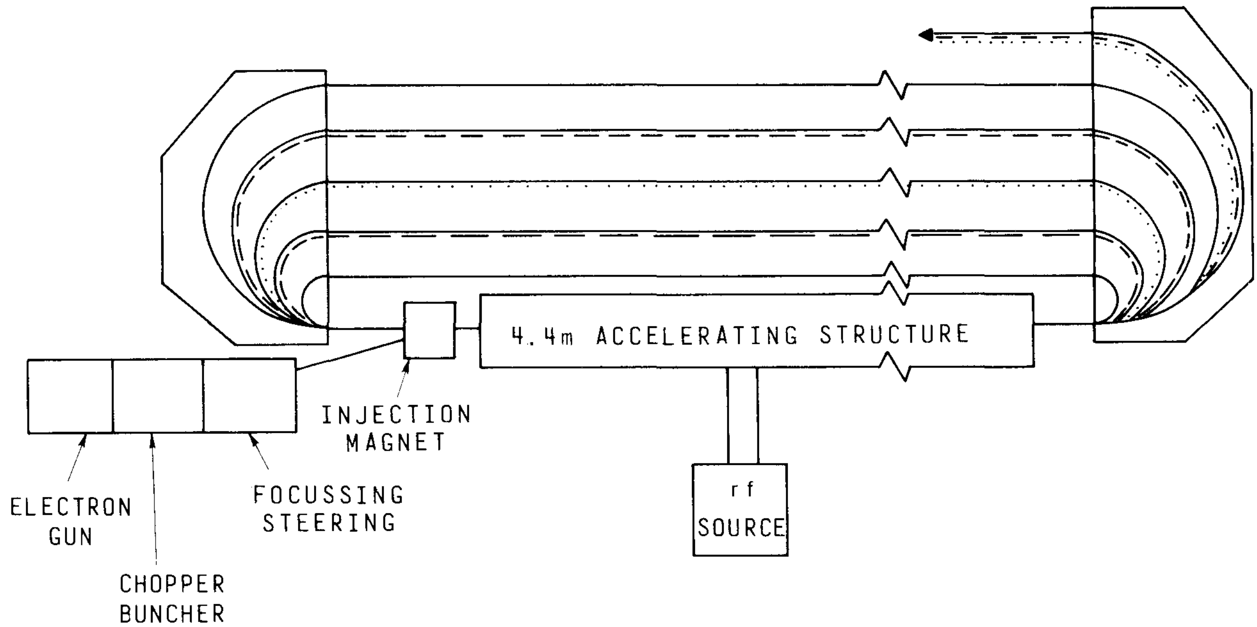

Fig. 1 Schematic arrangement of 60 MeV racetrack microtron showing the orbits of the different modes; $\nu = 2$ ——, $\nu = 4$ - - -, $\nu = 6$ ····.

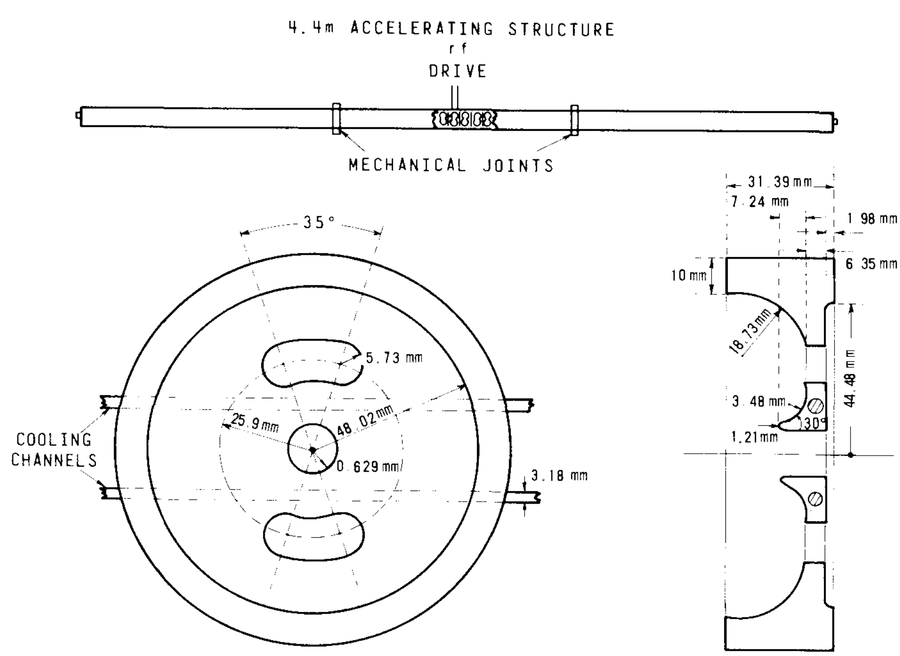

Fig. 2 On-axis coupled accelerating structure showing cavity profile.