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GEM, ANL 4-GEV CW ELECTRON MICROTRON DESIGN*

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Introduction

A six-sided hexagonal microtron has been chosen as the accelerator to generate the beams required to pursue a national research program at a CW 4 GeV electron laboratory.[1] This option has the advantage of superior beam quality, low capital and operating cost, and promise of furnishing beams of several electron energies simultaneously. Only moderate rf power is required because of the basic feature of all microtron designs, recirculation of the electron beam through the same rf accelerating section many times. The "hexatron" design has the additional feature of compatibility with an existing accelerator complex at Argonne which is currently unoccupied and available.

The basic components of the accelerator include an electron gun, chopper-buncher, a 23 MeV linac injector, a 23 - 185 MeV Racetrack Microtron (RTM), an interstage phase space matching section, a subharmonic cavity, a 185 - 4000 MeV Six-Sided Microtron (hexatron), extraction systems, and various transport lines. A plan view of the accelerator is shown in Figure 1. The electron energy at the output of the gun will be 100 keV. The beam will be chopped and prebunched at 100 keV. Independent current control for every third bunch will be provided by transversely directing every third bunch through independent

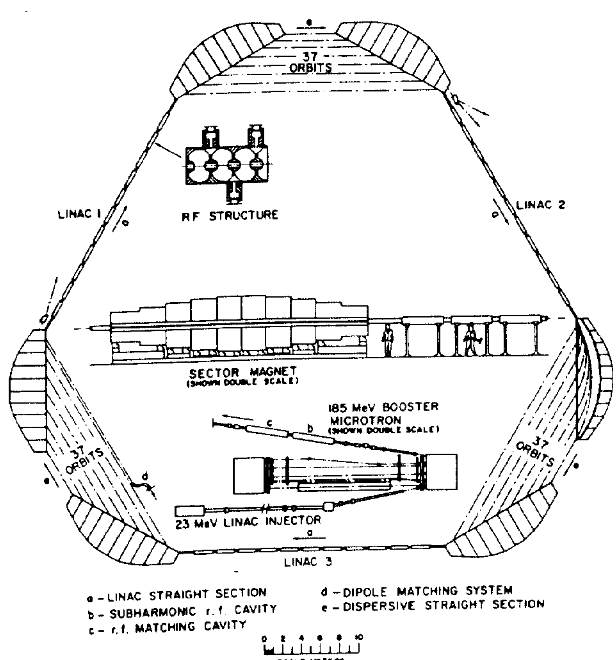

Fig. 1. Schematic of the Argonne National Laboratory 4 GeV Electron Microtron-GEM

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slits with a one-third subharmonic deflecting system. The 100 keV beam will be injected into a 2 MeV linac capture section which will be followed by a 3 MeV preaccelerator section. Acceleration to 23 MeV will be accomplished by 8 sections of linac consisting of on-axis-coupled structure. The 23 MeV beam will be injected into the RTM and accelerated to 185 MeV in 27 revolutions with a 6 MeV gain per turn.

The hexatron will be built with three 35 MeV linacs and six 60° sector bending magnets. Each linac will use eleven 2.06 meter biperiodic rf structures operated at 2.4 GHz. The beam optics in the hexatron will use a quadrupole system in the dispersive straight sections.

A longitudinal phase space matching section using bending magnets and an rf cavity will be located between the exit of the RTM and the injection point in the short straight section of the hexatron. A one-third subharmonic rf cavity will be located in the transport section between the RTM and the hexatron to permit multiple energy extraction from the hexatron. The one-third subharmonic cavity will displace the energy of the first and third bunches relative to the second so that extraction of individual bunches will be possible because of the physical displacement during passage through the dispersive straight sections of the hexatron due to the energy differences. Final extraction will be accomplished by an electrostatic septum followed by a magnetic septum. The extraction septa will be moved between the orbits to select the different energies for extraction.

Accelerator Design

Injector

The injector components will consist of an electron gun, chopper, independent intensity control system, 2 MeV $\beta = 0.548$ to 0.979 rf tapered capture section, 3 MeV preaccelerator, 18 MeV linac section, and the injector beam transport system to the RTM.

The electron gun design is based on the one selected by the NBS-Los Alamos project. The gun voltage will be applied between a grounded final anode and the cathode so that control variations on the modulating anode will not affect the beam energy. The pulsing capability will be achieved in this design by locating the pulser in the high voltage terminal. The gun optics will be arranged to bring the output beam to a waist of approximately 4 mm diameter at an accessible location where the first lens will be located. A transverse emittance limiting aperture, will also be located at the waist. A gun current of 2.1 ma will be required after the aperture in order that the beam can be chopped into ±30° segments of rf phase.

The independent current control system will use one-third subharmonic frequency cavities to separate individual bunches into separate beam

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lines with independently controlled slits. The parallel beams are recombined into a single beam by a similar cavity system.

A tapered capture section will be located at the end of the prebuncher drift length. The capture section will consist of two meters of in-line rf structure[2,3] in which the lengths of the rf cavities will increase smoothly to match the increasing velocity from $\beta = 0.55$ to $\beta = 0.98$, corresponding to an increase in energy from 100 keV to 2.0 MeV. The operating frequency will be 2.4 GHz. A final preaccelerator section will be located after the capture section. There will be two one meter long rf accelerator structures operating at 2.4 GHz. The first structure will be designed for $\beta = 0.985$ and the second structure will be designed for $\beta = 0.995$. The final linac section which accelerates the beam to 23 MeV will be eight 2.27 meter sections of $\beta = 1.0$ on-axis-coupled structure. The accelerating field will be 1.13 MeV/m and the power dissipation from cavity losses will be 17 kW/m.

Booster Microtron

Conventional racetrack configuration will be used to increase the energy from 23 MeV to 185 MeV. The change in harmonic number per turn in the Racetrack Microtron (RTM) will be equal to one. This choice will provide the largest range of stable phase angles and minimum requirements in phase stability. The RTM resonance condition will be met with an energy gain per turn, $\Delta W = 6.0$ MeV and the magnetic field of the end magnets, $B = 1.0$ Tesla. The extraction energy of 185 MeV will require 27 turns of acceleration. The orbit radius of the injected beam will be 7.6 cm and the radius of the final orbit, 61.6 cm. The corresponding orbit separation in the return path drift space will be 3.98 cm. These parameters are summarized in Table 1. A transverse beam emittance of 0.2 πmm-mr and a longitudinal emittance of 30 keV-deg has been assumed at the injection point of the RTM.

A plan view of the booster RTM is presented in Figure 2. The separation of the end magnets will be 8.0 meters, sufficient to accommodate a 4.6 meter linac structure similar to those in the hexatron, and return paths containing the necessary focusing and steering elements to give good beam transmission. The parameters of this design will be chosen to correspond to the end magnet design planned for the NBS-LANL-185 MeV microtron[4]. The width of the end magnets will be larger than

Table 1. Racetrack Microtron Parameters

Injection energy	23 MeV
Extraction energy	185 MeV
Energy gain/turn	6 MeV
Number of recirculations	27
Magnetic field	1.005 T
Minimum orbit radius	7.6 cm
Maximum orbit radius	61.6 cm
Orbit separation	3.98 cm
Rf wave length	12.5 cm
Mode number	1
Accelerating field	1.4 MV/m
Synchronous phase	20°
End magnet separation	8.0 m

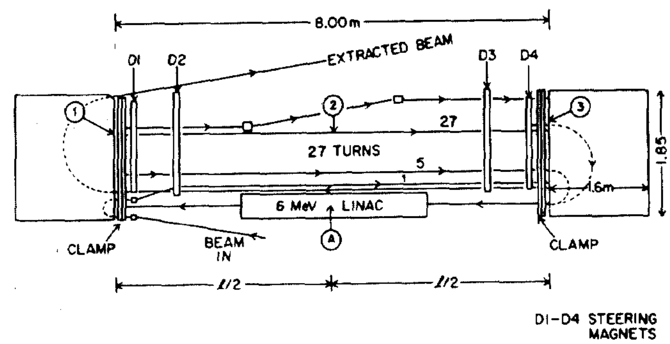

Fig. 2. Racetrack Microtron (RTM) Layout

required for simple acceleration in order to accommodate the lateral translation of the last return orbit so that the beam will make a complete turn without rf acceleration. This "drift orbit" will provide the longitudinal phase sheer required for matching of the extracted beam to the hexatron.

The containment system is designed to achieve matched $\beta^* = 5.0$ m in the linac center where β^* is a measure of the beam envelope at the waist. The 180° end magnets are assumed as hard-edge devices with central field of 1.0T. This is effected by using a reverse field stripe. Without the stripe the edge focussing gives rise to severe vertical defocussing -- at 23 MeV the dipole appears as a defocussing lens with 12.5 cm focal length.

The transverse focussing in the RTM will be obtained using five quadrupoles on each return path and two weak vertical focussing singlets on the linac axis. The optical system will be mirror symmetric about point 2 in Fig. 2. At points A and 2 the transverse phase-space ellipses are upright. The beam is matched in the linac center with $\beta_x^* = \beta_y^* = 5.0$ m. In addition, the beam is dispersion free in the linac.

Hexatron

The hexatron is designed with the rf wavelength equal to 0.125 m, the magnetic field in the sector magnets equal to 1.015T, the energy gain per turn equal to 105 MeV, and the number of rf wavelength increments per turn equal to 1. A more complete list of parameters is given in Table 2.

The sector magnets are designed with a gap of 6.0 cm to allow for the beam envelope, beam tuning, and possible orbit errors.[5] A cross section of the magnet is shown in Fig. 3. The main pole pieces will be 19 cm thick SAE 1010, Lectrefine, annealled steel with parallelism and flatness tolerances to be within 0.05 mm. Tolerances within this limit have been shown to be feasible by the actual construction of a 19 cm thick pole piece that was 6.2 m long and 1.4 m wide. The main excitation coils are 10.7 × 13.6 cm cross section. The required power per magnet is 91 kW.

A 0.3 cm Purcell gap will be located between pole pieces and the main yoke. The Purcell gap will reduce field variations across the pole piece to within 1×10^{-3}. A small coil will be located near the Purcell gap. The coil will prevent saturation of the end guards shown in Figure 3.

Table 2. ANL Hexatron Design Parameters

Maximum Energy	4000 MeV
Injection Energy	185 MeV
Current	300 μA
Energy Spread, $\Delta E/E$	$\approx 10^{-4}$
Beam emittance	<0.2 πmm-mr
Magnetic Field	1.015T
Maximum Orbit Radius	13.145 m
Minimum Orbit Radius	0.608 m
Energy Gain Per Turn	105 MeV
Rf Wavelength	0.125 m
Mode Number, ν	1
Synchronous Phase	18°(ν_s = 0.4)
Longitudinal Stability Limit	62.4°
Avg. Accelerating Field	1.46 MV/m
Energy Gain Per Linac	35 MeV
Number of Linacs	3
Length of Linacs	25 m
Shunt Impedance, ZT^2	75 MΩ/m
Rf Power Losses	2.30 MW
Length of LSS	28 m
Length of DSS for Low Energy Orbit	28 m
Minimum Length of DSS	5.26 m
Orbit Separation in DSS	0.1725 m
Orbit Length Increase Per Turn	3λ = 0.375 m
Maximum Number of Recirculations	109/3

LSS = Linac Straight Section
DSS = Dispersive Straight Section

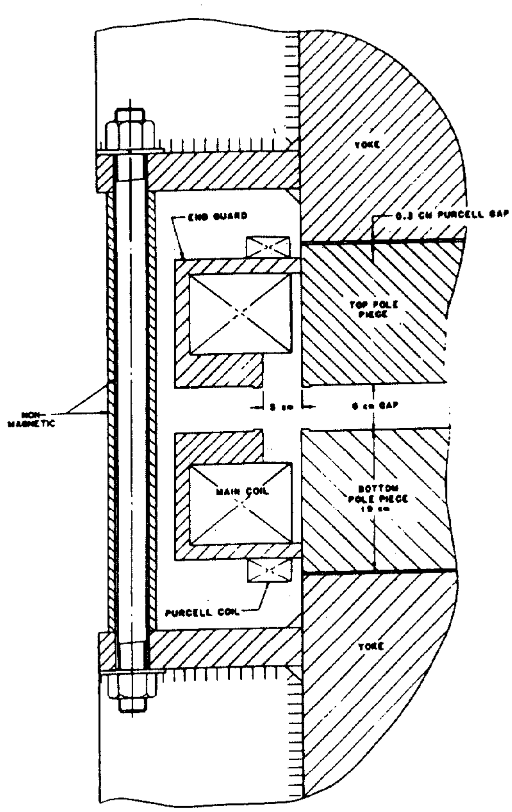

Fig. 3. Section Through Chord Edge of a Sector Magnet.

The end guards will be needed to achieve an extremely shoft edge field profile. In addition, steps will be machined into the magnet in the early orbits to make the pole face perpendicular to the equilibrium orbit and, thereby, avoid the strong vertical focussing effect of a 60° edge. Computer calculations and model magnet measurements indicate the required field profiles are achievable.

Three linac sections using side coupled structures operated at 2.4 GHz will be used in the hexatron design. Each section will consist of 11 accelerating structure sections, each 2.06 m long. Power will be fed into the center of the structure through an rf coupler from 2 CW, 50kW klystrons. The effective shunt impedance of the structure is assumed to be 75 MΩ/m and power loss per unit length is 35 kW/m.[7]

A total of 78 klystron tubes of the Thompson-CSF TV 2075 type will be needed for this design. The total rf power required will be 3950 kW including 400 kW for the injector and 200 kW for the RTM. A total of 6.3 MW of dc power will be required at 25 kV.

Multiple beam extraction will be accomplished by using 1/3 subharmonic energy modulation of the micropulses. A subharmonic cavity operating at 800 MHz will be located in the beam line between the RTM and the hexatron. The rf phase of the cavity will be adjusted to give three sets of bunches A, B, and C with energies $W + \delta W$, W, and $W-\delta W$, respectively. The technique is graphically shown in Fig. 4. These micropulses will be injected into the hexatron and rotate in longitudinal phase space. Periodically, in the dispersive straight sections, the three bunches will be physically separated due to the energy modulation. This physical displacement will be used to extract part of the beam at different energies by locating a thin (0.2 mm) electrostatic septum between the orbit of the highest energy bunches and the other bunches. The electrostatic septum will deflect the beam by 4 mm at the position of a magnetic septum. The magnetic septum will be located downstream from the electrostatic septum and before the sector bending magnet. The deflected beam will pass through the sector bending

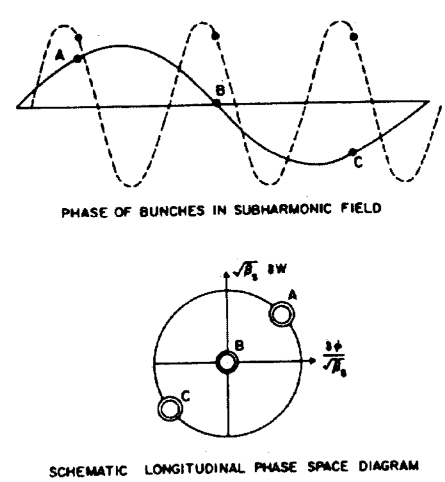

Fig. 4. Generation of bunch-to-bunch energy differences for multiple energy extraction with a one-third frequency subharmonic cavity.

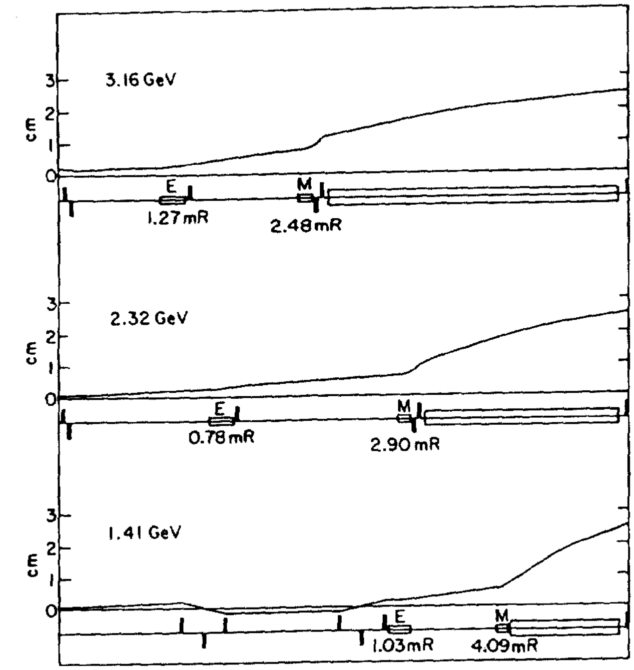

Fig. 5. Extraction orbits at 3 different energy ~(E) electrostatic septum, (M) maganetic septum, bars above and below line indicate quadrupoles and bars on both sides of center line indicate bending magnets.

magnet and will be displaced at the beginning of the linac straight section where the final extraction septum magnet is located. Figure 5 shows the position the extracted beams will have at three different energies.

Extraction at three different energies with independent current control is possible since every third micropulse is extracted by this technique and the charge in each corresponding micropulse will be controlled at the injector. The maximum extraction energy will be arbitrary. The simultaneous lower energies will be possible between 220 MeV and 3.1 GeV. The 3.1 GeV limit is due to the large energy difference that will have to be injected into the micropulses to get sufficient displacement for extraction and the resulting demand that the energy difference will place on the focussing element apertures near the injection energy.

The hexatron will use quadrupole focussing in the dispersive sections for transverse beam containment.[8] The location of the focussing system is shown in Figure 6. The system will be mirror symmetric about midpoint C. The optical transformation from points A to E will be achromatic in the bend plane and waist to waist in both transverse planes. The dispersion will be zero and constant ($\eta' = 0$) in the linac straight sections.

Three quadrupole focussing systems have been developed. The edge angle will be stepped on the sector bending magnets so that the exit angle is 0° between 185 and 1620 MeV. It will be 60° above 1620 MeV. The three optical systems are shown in Fig. 7.

Sensitivity of the equilibrium orbit to field and alignment errors indicate that the beam can be steered into the linacs and controlled.[9] The displacement of the equilibrium orbit will be very

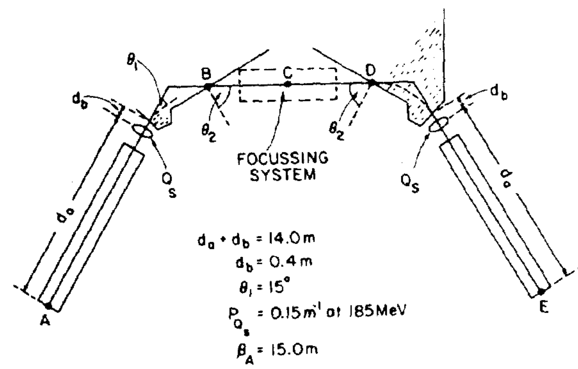

Fig. 6. Layout of hexatron for one superperiod showing location of focussing system.

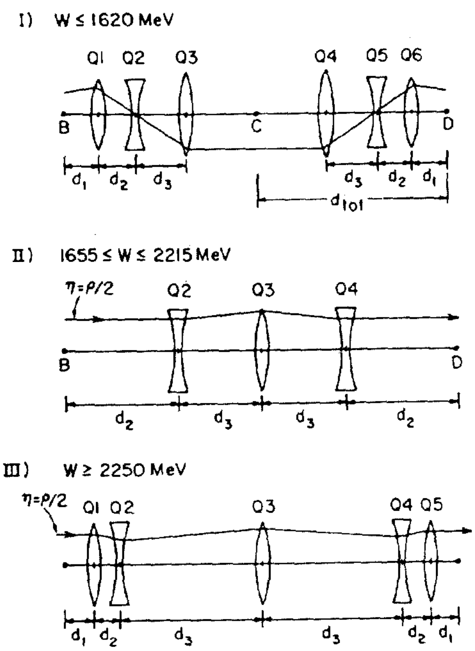

Fig. 7. Three focussing systems used in the hexatron for orbit containment.

sensitive to ∫Bdl errors in the sector bending magnets. However, a single small dipole located before the sector bending magnet leading to the linac can bring the beam on center in the middle of the linac and measurements on each end of the linac can be used to straighten the beam through the linac by adjusting pole face windings for each orbit in the sector bending magnets.

Figure 8 shows the longitudinal phase plane ellipses at various points in the RTM and hexatron. The points which correspond to these ellipses are shown in Fig. 9. The technique for meatching of the emittance of the RTM to that of the hexatron is graphically illustrated in Fig. 10 Two extra 180° bends in the RTM will cause phase elipse A in Figure 13 to shear in the direction of ellipse B. The rf cavity will act on the particles in phase ellipse B to move the ellipse in the direction of the arrows because of the large shear in phase angle. The dipole system in the transport line is designed to cause negative shear to restore the ellipse to upright ellipse D.

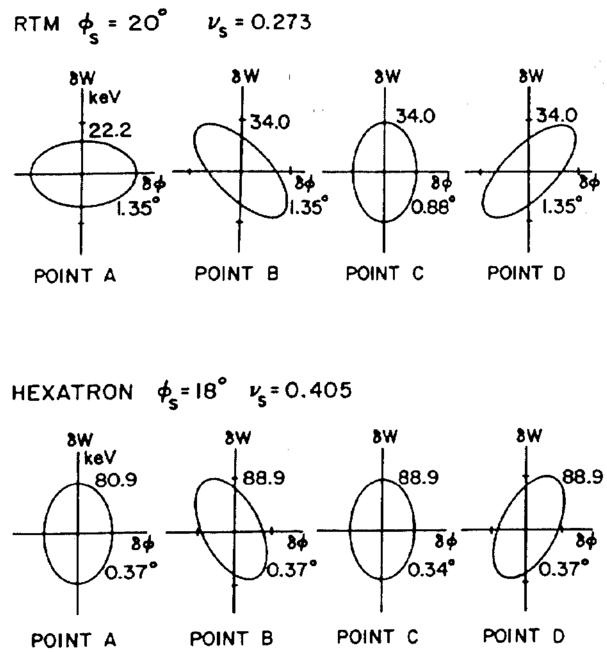

Fig. 8. Longitudinal phase ellipses at locations indicated in Fig. 9.

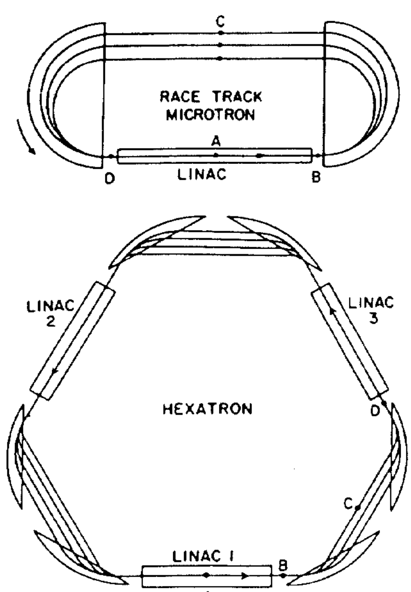

Fig. 9. Points along trajectory of the RTM and Hexatron for which longitudinal elipses are shown in Fig. 8.

The design goals for transverse emittance and longitudinal energy for the GEM facility are 0.2π mm-mr and $\pm 1 \times 10^{-4}$, respectively with three simultaneous beams with continuously variable current from 0 to 100 μa per beam. These goals are met by the proposed design. This includes the effect of synchrotron radiation in both the transverse and longitudinal planes.[10]

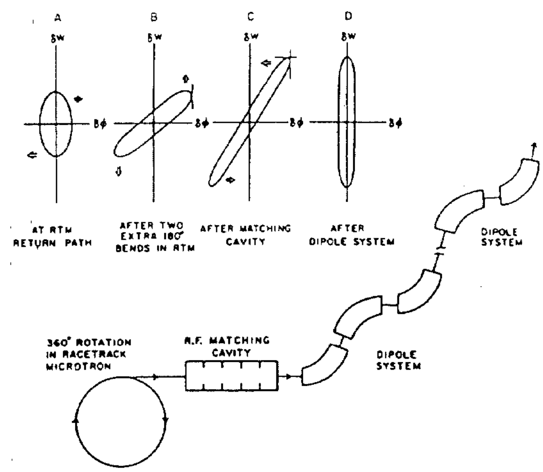

Fig. 10. Schematic of beam matching system between the RTM and hexatron.

Acknowledgments

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