DESIGN OF A 600 MeV SUPERCONDUCTING MICROTRON

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Summary

The design of a 600 MeV racetrack microtron proposed for the University of Illinois consists of a 30 MeV superconducting linac operating at 1.3 GHz between two uniform field bending magnets about 6.4 meters apart. There will be 19 parallel return paths separated by 14.7 cm. Vertical focusing is provided on each return orbit by a quadrupole pair close to each magnet. For quadrupoles 20 cm long and separated by 10 cm, the gradients required to advance the vertical oscillation phase by 90° per revolution increase monotonically from 150 to 350 gauss per centimeter. Only very weak horizontal focusing powers are needed to keep the return beams within 2 mm of linac axis. The linac itself provides some focusing but two weak quadrupole singlets on the linac axis, one near each magnet, provide additional focusing. Electron trajectories for all traversals through the linac and the magnets have been calculated in detail, by a step by step procedure where required, and are presented here. These results confirm earlier, less complete, calculations indicating that the microtron design parameters are not critical and that an output energy resolution of one part in 10^4 is easily obtainable.

Introduction

The racetrack microtron is an electron accelerator which could have the following properties which are desirable for nuclear research: An energy of several hundred MeV, high duty cycle, and low energy spread. Compared to an electron linac of the same energy, a microtron is smaller and costs less to build and to operate, being more efficient in its use of rf power (or refrigeration power, for the case in which a superconducting rf structure is used). The design of a microtron having a conventional linac was discussed by Wilk and Wilson(1). The design of the 600 MeV microtron using a CW superconducting 30 MeV linac, proposed for the University of Illinois, is discussed here.

Separate studies of the phase stability(1,2) and the spatial stability(1,3) have been made. We present the results of beam dynamic calculation made by generating single electron trajectories in which these two aspects were combined.

The basic elements of the design are displayed in Figure 1 and Table 1. An electron beam is made to circulate 20 times through the linac by two large bending magnets which have uniform field, B_o. The magnets are about 6.4 meters apart. There are quadrupole doublets on each orbit in this design, and two quadrupole singlets on the linac axis. The injector is a 300 kV gun with a chopper and a weak inflection magnet. Extraction is provided by a deflection magnet placed on the 20th orbit or other return path.

Our microtron design differs from that discussed by Wilk and Wilson in that we use low energy injection of 0.250 MeV as compared to 20 MeV in their design. The low injection energy allows one to place the entire superconducting linac in one arm of the microtron rather than use a part of it or a separate linac section, as an injector. The low initial injection energy, however, limits the lower energy range to which the microtron can be varied by simply changing the linac energy gain and the related magmetic fields. To obtain a usable injection condition for 20 orbit operation at 15 MeV per turn it is necessary to make small changes in the magnet separation or other equivalent changes.

Microtron designs can be discussed in terms of two resonance parameters μ and ν, which represent the number of rf periods (or wavelengths) in the first orbit and the number between successive orbits. Our design is characterized by $\mu = 58$, $\nu = 2$ as compared to $\mu = 39$, $\nu = 1$ for the WW design. The characteristics for $\nu = 1$ are discussed in reference 1. Although $\nu = 2$ constricts the maximum phase stable region by a factor of two, the region is more than ample to contain the well defined phase bunches required in our design. The choice of $\nu = 2$ is largely determined by the fact that, for $\nu = 1$ with low energy injection, the return beam does not clear the accelerator structure. Although it is possible to shift the first return orbit, in a special way so as to miss the linac, it seemed simple to choose $\nu = 2$. This choice gives twice the spacing between successive orbits and allows for the convenient installation of quadrupoles on all return paths.

The choice of the frequency of 1300 MHz was determined by considerations of ample orbit separation for focusing devices, tolerable microstructure in the beam, and convenient size of accelerating cavities.

Injection and Acceleration

The linac, as treated here, consists of two sections, the first one of 3 cells and the second (main) one of 36 cells. A small aperture one half wavelength long separates the two sections so that there may be a variable rf phase difference between them. The first section (which represents an injector and buncher) is run at 2 MV per foot and the amplitude of the main section is changed according to the desired final electron energy.

For these calculations the linac is taken to be the biperiodic structure of the Stanford design[4] which produces a standing wave field with a low space harmonic content except for the end cavities. We did not take these end effects into account in these calculations but it was found that these mainly delay the output phase by a few degrees.

The injection conditions are determined by requiring the beam to have optimum spatial characteristics at the output of the linac rather than to have optimum bunching.

For an injection energy of 0.250 MeV, the required nominal energy gain of about 30 MeV at a resonant phase of 9° is obtained for an injection phase of -70°. The electrons, thus, arrive at the entrance to the first cavity 70° before the zero of the rf field.

Although a phase spread of $\pm 7^{\circ}$ can be accepted we expect to chop the beam to $\pm 3^{\circ}$ or better to improve the energy resolution. The injected bunch is compressed by a factor of 3 to about 1° in phase in passing through the linac.

Space charge effects are small for the designed peak current (0.6 milliamperes) corresponding to the average current of 10 microamperes in a 6° phase interval. The space charge repulsion is calculated to produce a divergence of 0.15 milliradians in a 3 meter drift length.

Regenerative beam break-up due to the excitation of transverse modes will limit the current well below 10 microamperes unless the Q of the break-up modes are spoiled. These beam break-up interactions have been ignored in the present calculations.

Beam Transport

The fringe field at the edge of each bending magnet is the predominant source of vertical defocusing effects along the beam path in the racetrack microtron. For the present calculations of beam dynamics we have used an approximation to the fringe field measured in the presence of an iron window (field clamp)[1,5]. The field in the median plane used in these calculations represented by the relation

$$B(Z) = B_0\left[1 - 1/\left(1 + \exp(1.5\ (Z/g + 1)\right)\right]$$

where g is one half the gap width and Z is the distance into the magnet, perpendicular to the edge. For the first few orbits the trajectories through the magnet were calculated in detail by a step by step procedure but from the fifth orbit on it was found to be sufficient to use an approximation based on treating each fringe field as a thin vertically diverging lens. On the first orbit the fringe field at entrance or exit has a defocusing power similar to a lens of about -50 cm focal length. Nonlinear effects on the trajectories are not large and come mostly from the fact that with a radius of 7 cm and gap width of 3 cm a large part of the trajectory of the first bend lies in the fringe field. Detailed calculations were made for trajectories starting 2 mm and 4 mm off the linac axis but nonlinear effects were barely noticeable even for the first bend.

Edge focusing has been avoided in order to preserve the simple situation of a two dimensional field which leaves the horizontal motions very simple. Quadrupoles offer a great deal of flexibility and can be treated with sufficient accuracy as linear elements having chromatic aberration. There are symmetry considerations which simplify the matrix transform for any orbit. Symmetry about the plane midway between magnets permits one to make the beam in the linac be achromatic on every orbit (both position and angle can be independent of initial momentum in first order). Such an achromatic beam in the linac is accomplished by having no horizontal focusing on any return path but having all horizontal focusing done on the linac axis. The focusing controls of the horizontal and vertical motion are then almost independent. The quadrupole singlets on the linac axis provide adjustable horizontal focusing and contribute only little to vertical defocusing while the doublets on the return paths control the vertical motion of the electron trajectories.

For the purposes of these calculations the gradients of the quadrupole doublets were determined from the requirements that (1), the horizontal focal lengths of each doublet on the return paths are infinite at the nominal energy and (2), that the vertical focusing be sufficient to advance the vertical betatron oscillation phase by about 90 degrees per complete turn. The first condition is very simply included in program and will specify the gradient in the second quadrupole if the first is specified. Since the doublets at either end of each return path are completely symmetrical, only a single quadrupole gradient remains to be determined. This gradient is completely uncritical and is selected so as to approximate the second condition. The quadrupole singlets have been adjusted so as to advance the horizontal betatron phase by 90° for the first orbit but again this value is not critical. The gradients of the vertical doublets in the return orbits increase monotonically; the values used for the first doublet are -149 gauss/cm and +88 gauss/cm while those for the last are -343 gauss/cm and +318 gauss/cm. The gradient used for each of the two horizontal singlets is +6 gauss/cm.

As the emittance of the beam decreases with energy, the beam gets smaller and more parallel in the vertical plane but only more parallel in the horizontal plane due to the energy dependence of the focusing power of the singlets. The effect of small misadjustments of the quadrupole gradients for which the quadrupole doublet gradients are changed together and also for which the singlet gradients are changed together by 0.5% is displayed in Figure 2. It can be seen that such variations do not change the trajectories in any important way.

We have also calculated the trajectories for several other changes from the nominal operating conditions. In Figure 3 we show the trajectories for three injection phases. It can be seen that the trajectories vary only slightly and that the output phases vary about the resonant phase by about $\pm 1°$.

In Figure 4 we show the trajectories when the magnetic field B is changed by 0.3% and when the linac gradient is changed by 1%. It can be seen that this change in B leads to only moderate variations in the phase and in the horizontal amplitudes. The 1% change in the linac gradient, however, leads to extreme variations in the phase and the horizontal amplitudes although the trajectories are still retained through all 20 orbits. The energy changes for all the variations are small except for those in B as can be seen in Table 2. It is interesting to note that the output energy followed the variation in the magnetic field to within 0.002 percent.

We have not yet investigated the effect of small misadjustments of the angles and positions of the different elements but these are expected to be small.

We conclude that the requirements for space stability and for phase stability in the microtron are easy to satisfy and that it offers an accelerator with exceptional energy resolution.

References

1. B. H. Wiik and P. B. Wilson, Nucl. Instr. and Meth. 56, 197 (1967).

2. C. S. Robinson, D. Jamnik and A. O. Hanson, IEEE Trans. Nucl. Sci. NS-14, 624 (June 1967).

3. D. C. Sutton and A. O. Hanson, presentation to the 1968 Summer Study on Superconducting Devices and Accelerators at the Brookhaven National Laboratory.

4. J. N. Weaver, F. I. Smith and P. B. Wilson, IEEE Trans. on Nucl. Sci. NS-14, 345 (June 1967)

5. B. H. Wiik, private communication.

Table 1. Microtron Design Parameters

General	
Maximum energy	600 MeV
Injection energy	0.250 MeV
Injection phase spread	± 3 degrees
Energy gain per traversal	~30 MeV
Number of traversals	20
Orbit spacing	14.7 cm
Magnetic field	13.67 kilogauss
Duty factor	100 percent
Output current	10 microamperes
Output energy spread	± 60 keV
Superconducting Linac	
Nominal energy gain per traversal	30 MeV
Length of accelerating linac	15 feet
Current (20 traversals)	200 microamperes
Beam power	6 kilowatts
Operating frequency	1.3 gigahertz
Required radiofrequency power	10 kilowatts
Input power for radiofrequency	30 kilowatts
Refrigerator	
Cooling capacity (at 1.8 degrees Kelvin)	100 watts
Input power	200 kilowatts
End Magnets (for each of two)	
Weight - iron	234 tons
copper	1.33 tons
Power	5.4 kilowatts
Orbiting Time	
First orbit	42.3 nanoseconds
Last orbit	71.5 nanoseconds
Total	1138 nanoseconds

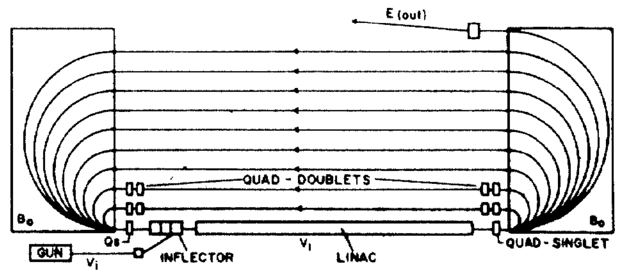

Fig. 1. Schematic Microtron Arrangement.

Table 2

Properties of the electron beam from the microtron in the 20th return path for different injection phases, accelerating voltages and magnetic fields. The nominal specifications of the beam injected into the linac for the trajectories considered here are: $V_1 = 0.250$ MeV, $\phi_1 = -70^\circ$, $X_1 = Y_1 = +2$ mm, $(dX/dZ)_1 = (dY/dZ)_1 = 0$. Those from the linac after the first traversal are: $V \approx 29.33$ MeV $X = Y = 0.4$ mm; $dX/dZ = dY/dZ = -0.04$ mr. The resonant energy gain for these conditions are 29.17 MeV at a resonant final phase of 9° with a magnetic field of $B = 13{,}237$ gauss.

Operating Conditions	Outgoing Beam					
	X mm	dX/dZ 10^{-6} rad.	Y mm	dY/dZ 10^{-6} rad.	E_{out} MeV	ΔE_{out} Percent
Nominal Phase	-0.77	-4.5	-0.28	-17.0	583.29	0.000%
$\phi - \phi_1 = +3^\circ$	-0.94	+6.7	-0.36	-10.0	583.35	-0.010%
$\phi - \phi_1 = -3^\circ$	-0.66	+2.4	-0.23	-21.0	583.25	+0.007%
$\Delta V/V = +1.0\%$	-1.10	+0.03	-0.13	-10.0	583.42	+0.022%
$\Delta B/B = +0.3\%$	-0.68	+2.0	-0.01	-10.0	585.03	+0.298%

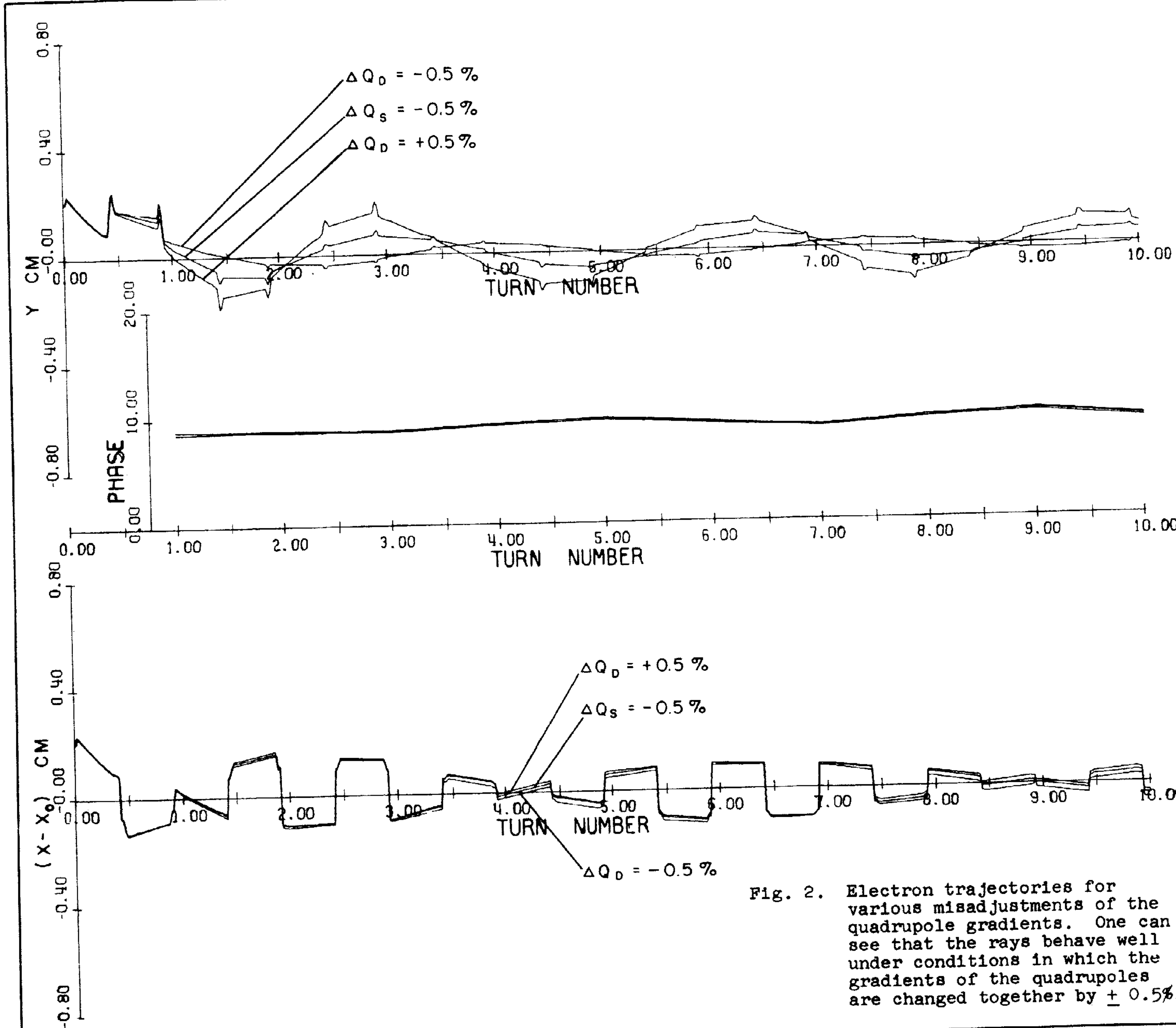

Fig. 2. Electron trajectories for various misadjustments of the quadrupole gradients. One can see that the rays behave well under conditions in which the gradients of the quadrupoles are changed together by $\pm$ 0.5%.

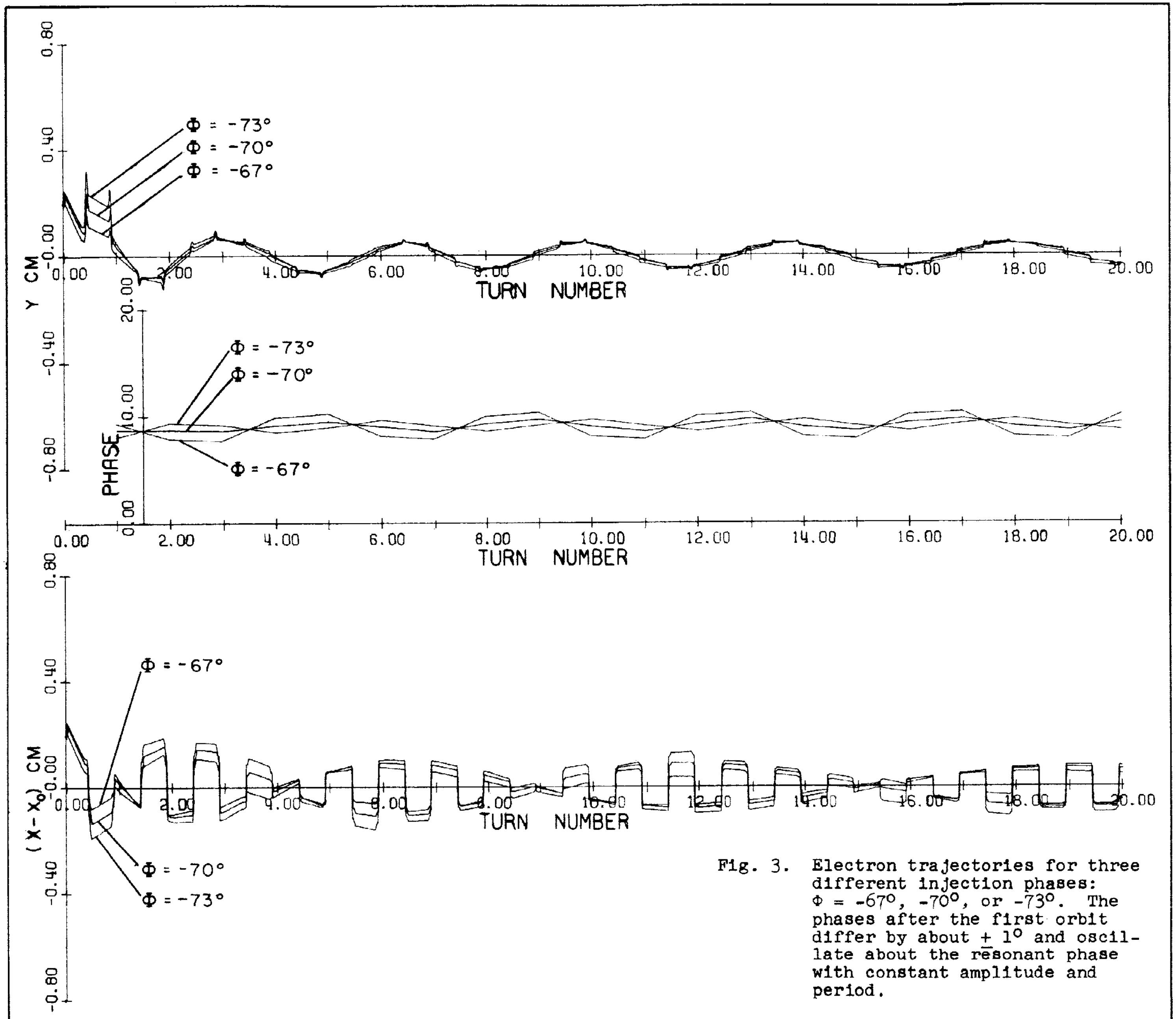

Fig. 3. Electron trajectories for three different injection phases: $\Phi = -67^o$, -70^o, or -73^o. The phases after the first orbit differ by about $\pm 1^o$ and oscillate about the resonant phase with constant amplitude and period.

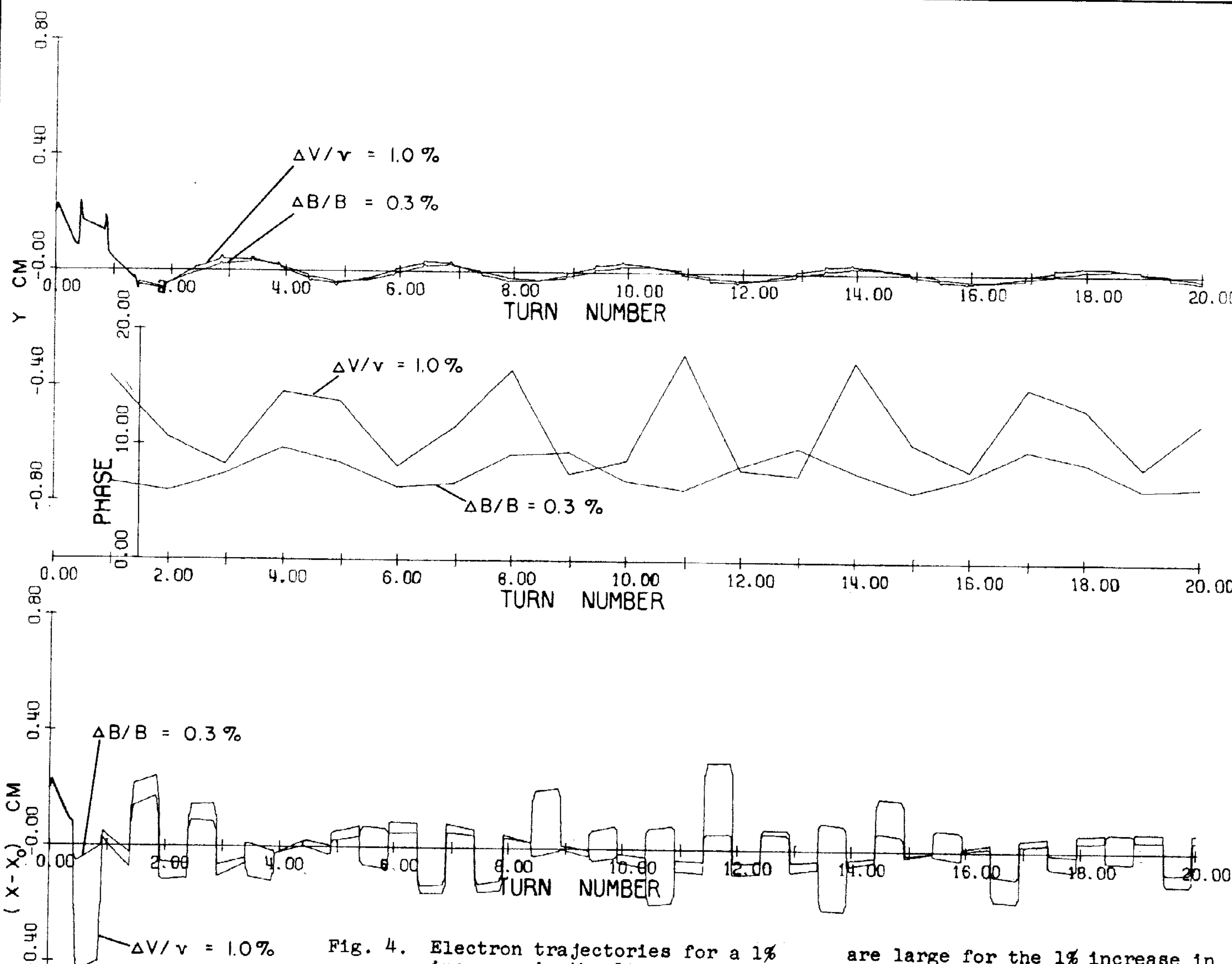

Fig. 4. Electron trajectories for a 1% increase in the linac energy gradient with B fixed and for a 0.3% increase in B at constant energy gradient. Phase oscillations are seen to occur about a different resonant phase in each case. The phase oscillations are large for the 1% increase in energy gradient. The large horizontal excursions in the return paths of various orbits imply that deviations from the nominal energy follow the oscillations in phase.