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A MULTI-ORBIT RECIRCULATION SYSTEM FOR A SUPERCONDUCTING

LINEAR ACCELERATOR - THE RECYCLOTRON

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Summary

The energy available from a superconducting linear electron accelerator (SCA) may be increased many times by means of an economical multi-orbit recirculation system, which preserves the most desirable characteristics of the SCA: good energy resolution (~ 10 ٠). high current and unity duty cycle. Furthermore, these properties of the SCA and its excellent emittance considerably simplify the design of the transport system and minimize aperture requirements. In order to maintain energy resolution each orbit of the recirculation system must be isochronous with respect to all phase space variables and beams must be reinjected into the linac precisely at the correct phase. These conditions have been achieved in a compact separated orbit design which uses multi-channel uniform field bending magnets. It is suggested that such a device be called a recyclotron. At HEPL a prototype 4 orbit recirculation system is being planned as part of the SCA program. Cost estimates for machines of this type have been made and show considerable advantage over other types of accelerator, especially at very high energies. The configuration also shows promise as an intermediate energy, high current accelerator, which could provide a source for a medical pion therapy facility.

Introduction

The superconducting linac is the ideal accelerating element for a multi-orbit recirculating accelerator, having unit duty factor, small beam phase space and high current capability. To take full advantage of this, a new type of recirculation system has been devised¹ utilizing a novel multichannel bending magnet. At low energies, the system has features in common with the race-track microtron, but the main magnets are an order of magnitude cheaper³ and the final energy resolution is significantly better. At high energies it is similar to the "mesotron"⁴ but is more flexible and capable of having a greater number of orbits.

The principle of the multichannel bending magnet is illustrated schematically in fig. 1. In this example the windings of the coil are split into four groups in such a way that flux passing through the first channel of the magnet links only one quarter (approximately) of the ampere-turns. The flux in the second channel links half the ampere-turns and so on. Thus the field in each channel is independent and may be separately varied. In comparison with a simple race-track microtron magnet, at final energies greater than 400 MeV, this arrangement saves at least an order of magnitude in weight³ (at 600 MeV, 230 tons compared to 6 tons). and has a field uniformity at least 100 times better. Furthermore the optics of each orbit are independent. In a very high energy recirculating machine, many independent channels may be built using the same amount of copper and the same power as would be required for the highest energy channel alone.

Ideally beam optics may be arranged in such a way that the overall transport matrix for each orbit is identically unity in first order. Second order effects are normally negligible. This condition may easily be achieved with eleven or less quadrupoles per orbit. Hence the complete recirculating machine is equivalent to a continuous superconducting linac, whose fine energy resolution, duty cycle and emittance may be preserved. The chief uncertainty at present is the possibility of beam-beam and beam-structure-beam interactions although these are not expected to be serious.

Prototype Recirculation Scheme at HEPL

It is intended to study the feasibility of recirculation at the HEPL superconducting accelerator⁵ (SCA) by building a prototype system inside the SCA tunnel as shown in fig. 2. This system will use a single multi-channel magnet at each end, the dimensions of the tunnel being such that a final orbit energy of 550 MeV would require a magnetic field of 18 kgauss.

The prototype system will not be isochronous with respect to momentum but it is possible to compensate this effect by a suitable choice of the r.f. accelerating phase for each orbit.

Details of Proposed System

The design is based on the expectation of 9 MeV from the pre-accelerator, giving initially a first orbit energy of 76 MeV with an energy increment of 67 MeV per orbit. 76 MeV is sufficient energy to provide an emittance of \leq 0.1 mm mr as required by the available apertures.

The complete system is shown schematically in fig. 2 with details of the orbit separation in fig. 3. Constant orbit separation is achieved by allowing the nth orbit beam to pass through n equally spaced, equal strength bending magnets. This arrangement gives equal orbit separation with the minimum number of magnets. The total deflection of each orbit is 15° . The beams then enter the multichannel magnet where they are bent through a further 165° .

The orbit separation must be approximately equal to $n\lambda_{rf}/2\pi$ where n is an integer and $\lambda_{rf} = 23$ cm is the Wavelength of the rf system. The value n = 2 is chosen to give an orbit separation of ~ 7.6 cm. For convenience the multichannel magnet is therefore designed with a channel separation of exactly 3.000". This separation is the minimum which will allow separate quadrupoles and steering coils to be placed on each orbit. The orbit splitting arrangement automatically allows one to extract the beam at any orbit as shown.

The beams are brought together again and reinjected into the linac by a system which is a mirror image of fig. 3, at the SCA filter, as shown in fig. 2. This filter which is used to analyze the beam from the injector and to modify the longitudinal and transverse phase space as required contains four bending magnets. The last of these magnets bends the 9 MeV beam 300 onto the SCA axis, and forms a convenient point at which to reinject the recirculated beams. This last magnet will bend the 76 MeV orbit 3.55°. In order to make the reinjection system achromatic to all orders, this magnet will be the last of a set of four which will form a vertical chicane. To compensate for the horizontal focussing of this section, it is proposed to build a horizontal, but otherwise identical chicane in front of the first beam separation magnet. Now if the overell transport matrix of each orbit is arranged to be that of a negative drift such that the two chicanes are optically superimposed, the beams will experience equal horizontal and vertical focussing between accelerations at all energies. Another important advantage of this negative drift condition is that the orbits may be tilted at an arbitrary angle with respect to the horizontal.

The necessary optical properties of each orbit are achieved as follows. The first quadrupole is adjusted so that at the exit of the multichannel magnet, the path is independent of initial horizontal displacement and the cosine-like trajectory and off-momentum-trajectory are parallel. (In the language of TRANSPORT: $R_{51} = 0$, $R_{11}/R_{21} = R_{16}/R_{26}$.) The next pair of quadrupoles focuses the beam in both dimensions at the center of the orbit ($R_{12} = R_{31} = 0$), while the quadrupoles at that point diagonalize the matrix. ($R_{21} = R_{13} = 0$.) At the center of the form:

	Mat	rix			_	(Coordinates)		
M	0,	-	-	-	С	х		
0	M_{x}^{-1}	· -	-	-	0	x '		
-	-	My	0	-	-	У		
-	-	0	м	1_	-	у'		
0	A	-	-	1	в	δØ (or δz)		
[-	-	-	-	-	ı	$\Delta p/p$		

where the constants are arbitrary.

The second half of the orbit is a mirror image of the first half. Hence it can be shown that the overall orbit matrix is unity with the exception of the term R_{56} -- the dependence of path length (or rf phase) on momentum. From the entrance of the first separation magnet to the exit of the last recombination magnet, the transport matrix corresponds to the required negative drift:

1	-L	-	-	-	0
0	l	-	-	-	0
-	-	1	-L	-	-
-	-	0	1	-	-
0	0	-	-	l	2В
-	-	-	-	-	1

Multiple scattering of the beams due to residual air in the system must be taken into account. At 76 MeV, in an orbit of length 72 m, calculations with TRANSPORT show that a vacuum pressure of 2×10^{-5} torr is adequate. This pressure will be achieved with diffusion pumps. Welded vacuum chambers are needed at the separation magnets, while the multichannel magnets form their own vacuum chambers.

Path length variation is provided for each orbit to allow fine adjustment of accelerating phase and compensation for thermal expansion. This is achieved by means of the horizontal steering coils placed at the entrance and exit of each multichannel magnet. Each pair of coils is located at conjugate points of unit magnification so that the deviation introduced by the first coil may be exactly cancelled at the second. Path length variation of at least $\pm 1 \text{ cm} (\pm 16^{\circ})$ is possible.

Phase Stability

For the ideal unit matrix recirculation system, the problem of phase stability is identical to that of a continuous linsc. However in the prototype system, the accelerating phase at reinjection depends on momentum. This is not difficult to correct. Figure 4 illustrates how this might be achieved for two orbits and three accelerations. The initial erect phase space ellipse as shown is about a factor of two larger in area than the best measured at 9 MeV. The energy gain of 80 MeV per pass is chosen purely for convenience in calculation. The phase for the first acceleration Al , is chosen to shear the ellipse counter clockwise as shown. The effect of the first recirculation, Rl, is then to tilt the ellipse further until it is reflected about the ordinate ($\delta \phi = -0.8 \delta E/E$ for each orbit). The second acceleration A2, takes place at a phase such that the maximum energy excursion becomes $\delta E = 40$ keV. Thus $\delta E/E$ for each orbit is the same. The second recirculation R2 again reverses the ellipse and the third acceleration A3 reforms the original erect ellipse. For continual acceleration, the period of phase stable oscillations is thus two orbits. Typical accelerating phases are in the region $\phi_{\rm o}$ = - 2 $^{\rm o}$ to - 4 $^{\rm o}$.

With this mode of operation and to first order the final absolute energy spread from the machine is no larger than the original spread. The process is modified and limited however, by the curvature of the cosine accelerating wave. At a phase spread of $\pm 0.5^{\circ}$, this effect is not large and it is expected that a final energy spread of $\triangle E/E \approx 10^{-4}$ should be attainable.

Multichannel Magnets

The multichannel magnets are an essential part of the recirculation system. Each magnet as planned consists of four 165° circular channels of uniform field, each of which is independently adjustable. A plen of the magnet is shown in fig. 3 and its cross section and dimensions in fig. 5. Each gap is 15.24 mm (0.600"). Ideally one would like to design the magnet as a "window frame," but it was thought advisable to remove the coils from the plane of the beam. The currents in the coils 1,2,3,4 (Fig. 5) are independent so that the field strengths are to good approximation independently adjustable provided they are set up in order of decreasing field as they would be in practice. This description would be exactly true for infinitely permeable iron. In practice, varying the current in coil 4, for instance, not only changes the field in the fourth channel but also changes the flux density in the iron which adversely affects the fields in the other channels. Typically a 1% change in the current of coil 4, at 18 kgauss, causes a decrease in field of ~ 0.02% in the other channels. Figure 6 shows the flux distribution as calculated by the program TRIM⁴ for an early design (3 channel) of the prototype magnet. The uniformity of the field in each channel is more than adequate being better than 1 part in 10⁴ over at least \pm 5 mm.

It should be pointed out that there are other possible configurations for a multichannel magnet. For instance, one could use a simple coil with a staggered gap. Such a magnet would however have a very poor field uniformity and be very inflexible. For a fixed energy machine, it would be advantageous to modify the present design, which requires significantly different ampere turns for each coil, by adjusting the gap and number of turns for each channel so that the coils could be connected directly in series.

Cost Comparison With Competitive Accelerators

Detailed cost estimates for recyclotrons have been made in the intermediate and high energy regions. In the range from 500 MeV to 1 GeV the machine is considerably cheaper than other accelerators, in particular the race-track microtron, and is capable of better beam quality, while at energies greater than 30 GeV it is cheaper than all other competitors. In the range 1 - 30 GeV the synchrotron may be cheaper but one should remember that the recyclotron has a current capacity ~ 100 times greater.

Figure 7 shows cost estimates up to 900 MeV for the superconducting linac, conventional linac, racetrack microtron (RTM) and recyclotron. The latter two machines are assumed to be based on a superconducting accelerating section but in principle this element could be a conventional linac, provided pulse lengths are sufficient, as in that suggested by Numan and Wilson.^O This variation would reduce the cost of the recyclotron more than that of the RIM. Cost of the SCA is based on an energy gradient of 2 ${\rm MeV}/{\rm ft}$ and cost of \$ 10,000/ft. (All costs include every necessary part of the machine except the building and real estate). Estimates for the RTM, are based on an energy gain of 27 MeV/orbit. Its cost is dominated by that of the magnet whose volume increases as the third power of the energy. Cost of the recyclotron is calculated for various numbers or orbits. Above 500 MeV, where a high current electron accelerator might be useful as a source for a pion therapy unit, the recyclotron becomes considerably cheaper than the RIM.

For energies above 10 GeV (Fig. 8), cost estimates for other machines are taken from Crowley-Milling.¹⁰ In this range, the optimum number of orbits for the recyclotron is between 8 and 10 for all energies. Eight orbits are chosen for the calculation since an 8 channel magnet is probably near the practical limit. Synchrotron radiation is allowed for by limiting the magnetic fields so that the energy spread due to this effect does not exceed one part in 1000. Actual radiation energy loss per orbit can be quite large in this type of machine which is the basic reason that it is so much cheaper than the synchrotron. In principle there is no reason why a high energy recyclotron with suitable injector, should not be used to accelerate protons. It might also find application as a self-injecting storage ring.

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Fig. 1. Principle of multichannel bending magnet.





Fig. 6. Cross section of early 3-channel magnet with computer (TRIM) calculation of field distribution.



Fig. 7. Electron accelerators: Cost comparison.



Fig. 8. High energy electron accelerators: Cost comparison.