IEEE Transactions on Nuclear Science, Vol. NS-26, No. 3, June 1979

THE STANFORD SUPERCONDUCTING RECYCLOTRON*

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Summary

With four orbits of recirculation, the HEPL superconducting recyclotron is expected to provide a high duty factor (> 70%) electron beam at 300 MeV by 1982. At present the beam has been recirculated twice and extracted. To date, maximum energy has been 156 MeV with best energy resolution (FWHM) 0.018%. The dependence of beam breakup starting currents on orbit optics has been investigated. Installation of the components for the third and fourth orbits will be completed this year.

Introduction

The recyclotron at the High Energy Physics Laboratory of Stanford University consists of a high duty cycle, high current superconducting linac and a four orbit recirculation system shown schematically in Fig. 1. Since the main components of this accelerator have been described previously,[1] only a brief physical description will be given here. Emphasis will be placed on the operation and performance of the machine.

Superconducting Linear Accelerator

The accelerating structures are made of niobium and operate at a frequency of 1.3 GHz and a temperature of 1.9 K. The injector consists of a 100 kV gun and room temperature buncher, a 1 m superconducting capture section and a 3 m pre-accelerator. At present the main linac consists of three or four 6 m structures and a modified 3 m "half" structure described elsewhere in this conference.[2]

Table I lists the characteristics of some typical beams which have been supplied by the linac to experimenters during the last year or so. In almost all cases, the peak current was limited by the experiment. The accelerator itself is capable of delivering 500 μA, a limit imposed by the maximum RF power available and the electron gun design. The regenerative beam breakup limit is estimated to be ~ 1 mA.

The high quality of the beam may be illustrated by the small phase volume it occupies. The longitudinal phase space is characterized by an energy independent energy spread of 15 keV FWHM and a phase length of 1.5°. The transverse phase space has been observed to be 0.02 π mm mr at 44 MeV at low currents. At 500 μA it is no greater than 1.5 times this value.

In principle duty factors up to 100% can be obtained at sufficiently low accelerating gradients. The structures may be operated at higher gradients (up to 3 MeV/m) but only at a reduced duty factor. This limitation is due to the presence of multipacting electrons in the structures. This phenomenon affects the accelerator in several ways. It can drive the structures out of the superconducting state, it can couple energy into undesirable cavity modes which modulate the beam energy and increase the energy spread and finally it can shift the resonant frequency of the structures. It is hoped that this problem will eventually be solved by new cavity designs such as that described by Lyneis et al.[2] Meanwhile it is observed that multipacting electrons, disappear more rapidly than they build up. This build-up occurs typically in a time of order 20-100 ms and has given rise to the "pulsed-off method of operation in which for instance the RF may be on for say 20 ms out of each 30 ms permitting beam duty factors in the range 50% to 70%.

* Work supported by the National Science Foundation under Grant No. NSF PHY76-80168.

Recirculation

The layout of the recirculation system is illustrated by Fig. 1 with details of beam separation and the multichannel magnets in Fig. 2. The beams are re-injected into the linac by a system which is a mirror image of Fig. 2, final recombination of the beams with the primary beam being achieved with a chicane of bending magnets.

Each multichannel magnet produces a stepped radial field profile with a uniform field at least 2 cm wide in each channel. The stepped field is achieved with a uniform gap and a staggered coil winding.[3]

In order to provide fine adjustment of the accelerating phase on subsequent passes, the length of each orbit is adjustable. This is achieved by pairs of horizontal steering magnets placed at conjugate points at the entrance and exit of each channel of each magnet. A path length variation of at least ± 1 cm (± 16°) is possible.

At present the first two orbits are installed and operating. The characteristics of some typical beams produced to date are shown in Table II. Of these the 90 MeV beam has been used extensively for nuclear physics experiments (e.g. $^{12}C(e,e'p)^{11}B$), and has proved to be stable in operation for days at a time. There is no reason why the recirculation should not be operated at high duty factors, but at present with only $3\frac{1}{2}$ structures available, it is necessary to operate at high energy gradients.

The average beam current available is at present limited by regenerative beam breakup (BBU). This is primarily due to the fact that one of the structures still lacks loading probes necessary to load down its transverse modes. This situation is soon to be corrected, but meanwhile it has given us the opportunity to investigate the control of BBU with orbit optics. Ideally the beam optics would provide point-to-point focussing from any point in the linac back to itself in each orbit. Then any deflection produced by a transverse field in a structure would produce no displacement of the beam on subsequent passes so that regenerative feedback would not occur. This ideal situation is not realizable in practice but may be approximated very closely. The focussing elements on each orbit consist of three pairs of quadrupoles located as shown in Fig.s 1 and 2, and a solenoid at the center of the linac which only has a significant effect on the primary beam. These lenses permit point-to-point focussing at the center of the linac, in a number of discrete optical modes. An example of a measured transport matrix and beam envelope is shown in Fig. 4 for the first orbit. (Notation used is that of TRANSPORT.[5]) At arbitrary points in the linac where the point-to-point condition is not exact, the optical mode may be selected to minimze the coupling to the BBU structure mode. Without elaborate beam rotation schemes,[4] the best optical arrangement available appears to be the "reflection" mode with a positive magnification in one plane and negative in the other. This mode has produced the highest BBU starting current (12 μA average) to date for one recirculation. The best average current obtained with the three pass beam is 3.6 μA.

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When loading probes are installed in all structures, it is expected that these BBU starting currents will be increased by two orders of magnitude. A fuller discussion of the general BBU problem is given by Vetter *et al*[6] in this conference.

The quality of the recirculated beams is shown in Table II. The emittance becomes so small as to be difficult to measure above 90 MeV but is consistent with being inversely proportional to the energy, confirming that second order effects of the beam optics are negligible. "Cleanliness" of the beam with regard to spot size and halo are such that solid state counters have been operated at only 7 cm from a target at 90 MeV and 25 μA peak current.

Plans for the Future

The third and fourth orbit of recirculation are expected to become operational in the near future. In addition, the number of accelerating structures will be increased to six so that by 1982, a 300 MeV beam with 70% duty factor should be available. This implies an energy gradient of 1.75 MeV/m. At a lower duty factor, 10% a gradient of 2.33 MeV/m should be possible giving a final maximum energy of 400 MeV.

Table I.

Typical Beams Delivered by the Superconducting Linac for Experimental Physics

Energy (MeV)	49	28	23	25	34
No. of 6 m structures	3	2	1	$3\frac{1}{2}$	$3\frac{1}{2}$
Duty factor	10%	100%	8%	60%	70%
Peak current (μA)	120	7	450	240	50
Average current (μA)	12	7	36	140	35
Resolution, $\Delta E/E$ (FWHM)	.03%	.05%	.10%	.06%	.05%
Emittance (π mm mr)	.02	.06	.08	.08	.04
Beam spot size* (mm)	< 1	---	---	< 2	< 2
Duration of runs	1 day	6 hours	few days	few days	few days

* FWHM at experimental target 200 m from accelerator.

Table II

Beams Delivered by Superconducting Recyclotron

Energy (MeV)	78	90	116	156
Passes through linac	2	2	3	3
No. of 6 m structures	3	$3\frac{1}{2}$	3	$3\frac{1}{2}$
Duty factor	10%	14%	10%	3%
Peak Current (μA)	120	14**	36	10
Average Current (μA)	12	2	3.6	0.3
Transmission, orbit A	100%	100%	100%	100%
Transmission, orbit B	---	---	100%	80%
Resolution, $\Delta E/E$ (FWHM)	.025%	<.03%	.018%	.027%
Emittance (π mm mr)	<.01	<.01	---	---
Beam spot size* (mm)	0.7	0.7	~0.5	---
Beam halo*, r > 1.5 mm	---	2×10^{-3}	---	---
Beam halo*, r > 3 mm	---	3×10^{-4}	---	---
Duration of runs	few hours	many days	few hours	few hours

* At experimental target 200 m from accelerator.
** Limited by experiment.

References

1. J. R. Calarco, M. S. McAshan, H. A. Schwettman, T. I. Smith, J. P. Turneaure and M. R. Yearian, IEEE Trans. on Nuclear Science, NS-24, No. 3, p. 1091, June 1977.

   C. M. Lyneis, M. S. McAshan, R. E. Rand, H. A. Schwettman, T. I. Smith, J. P. Turneaure and A. M. Vetter, Proc. Conf. on Future Possibilities for Electron Accelerators, Charlottesville, VA, January 1979.

   R. E. Rand, and T. I. Smith, Ibid.

2. C. M. Lyneis, J. Sayag, H. A. Schwettman and J. P. Turneaure, Particle Accelerator Conference, San Francisco, CA 1979.

3. R. E. Rand, IEEE Trans. on Nuclear Science, NS-20 No. 3, p. 938, June 1973.

4. R. E. Rand and T. I. Smith, in preparation.

5. K. L. Brown, D. C. Carey, Ch. Iselin and F. Rothacker, SLAC-91, 1974.

6. A. M. Vetter, C. M. Lyneis and H. A. Schwettman, Particle Accelerator Conference, San Francisco, CA 1979.

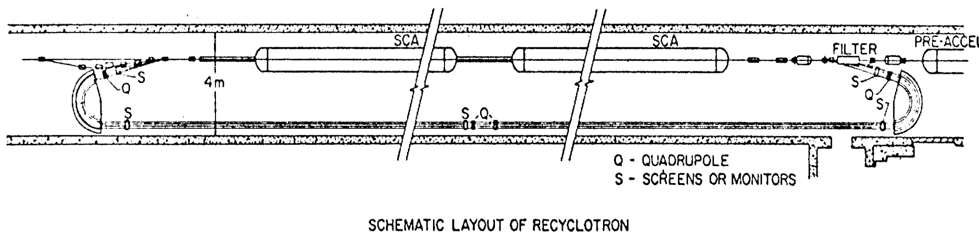

Figure 1. Schematic layout of Superconducting Recyclotron.

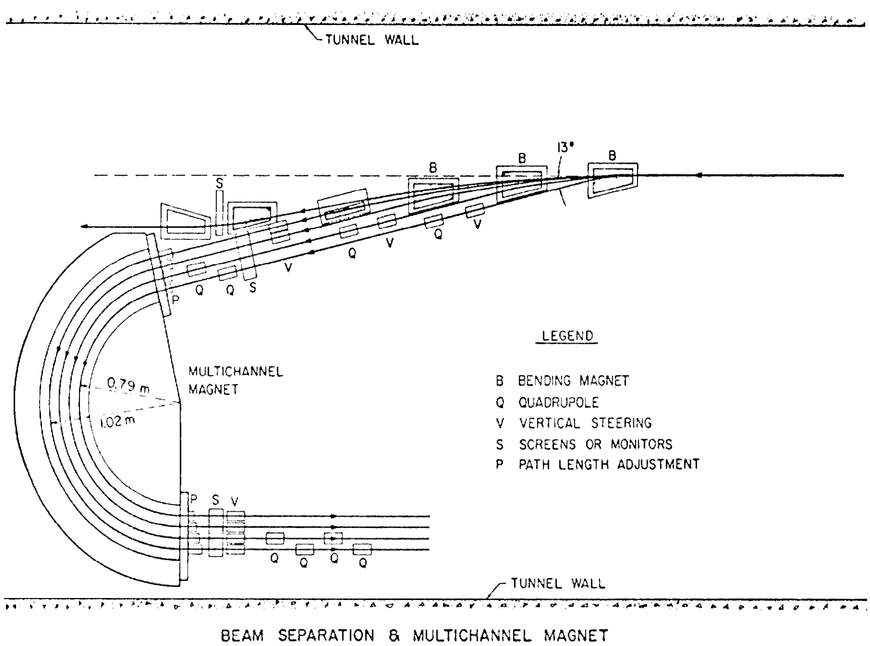

Figure 2. Beam Separation and Multichannel Magnet.

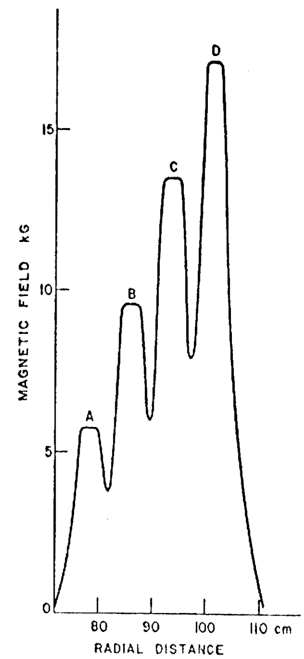

Figure 3. Radial Magnetic Field Profile in Multichannel Magnet.

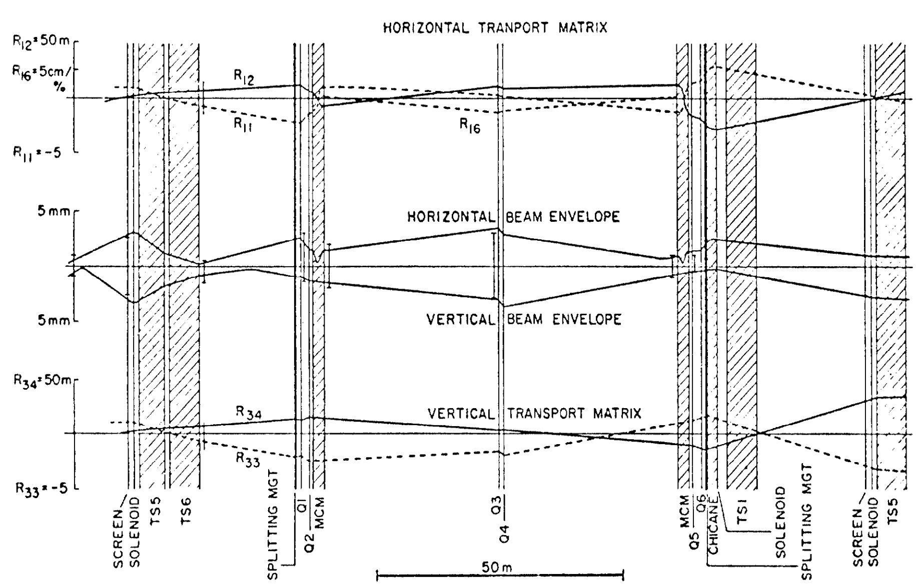

Figure 4. Typical Transport Matrix Elements and Beam Envelopes for First Orbit.