PROGRESS REPORT ON THE STANFORD SUPERCONDUCTING RECYCLOTRON*

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Summary

A prototype superconducting recyclotron is being constructed at Stanford High Energy Physics Laboratory (HEPL). It is designed to accelerate electrons to an energy of 700 MeV with a beam current of 100 μA at a duty factor of unity and with an energy resolution of one part in 10^4. In recent tests the superconducting linac has achieved the following beam parameters: maximum energy 37 MeV; maximum peak current 500 μA at a duty factor of 0.33 and at an energy of 25 MeV; energy resolution (FWHM) < 5×10^{-4} at 25 μA and 28 MeV; emittance < 1.2×10^{-4} π mc-cm at 25 μA and < 4×10^{-4}π mc-cm at 500 μA . Three 6-meter accelerator structures have achieved average energy gradients of ~ 3.0 MeV/m and Q-values of ~ 3×10^9 with CW operation. Two of these structures have been operated with beam currents 25-200 μA for about 1000 hours without significant deterioration. The four-orbit recirculation system is under construction.

I. Introduction

The primary objective of the HEPL superconducting accelerator program is to produce an intense high-quality beam of electrons in the energy range 500 MeV to 2 GeV, where some interesting and unique applications to nuclear and particle physics are possible. Specific objectives are shown in Table I. We are aiming at a beam current of 100 μA with a duty factor of unity and an energy resolution of one part in 10^4.

Such beam qualities are only feasible in a superconducting accelerator. Conventional high current linear accelerators are limited by power requirements to duty factors of a few percent, while the improvement of energy resolution (usually ~ 0.2%) by stabilization of the field levels is difficult with the short time constants involved. Beam break-up problems are more severe in a high Q superconducting linac, but by selective external loading of the break-up modes, it has been shown that the starting currents for regenerative beam break-up can be raised above 500 μA.[(1,2)] The most critical portion of a superconducting linac with regard to maximum beam current and ultimate energy resolution is the injector, which consists of a superconducting capture section and a superconducting pre-accelerator. Successful operation of this part of our machine has already been reported.[(3)] Energy spectra from the injector are shown in Fig. 1.

Recirculation of the beam was considered early on in the superconducting accelerator program as an economical method of increasing the beam energy. The superior beam quality and unit duty factor make this a particularly attractive possibility. In the last two years it has been shown that a multi-orbit recirculation system is indeed feasible and that beam quality can be conserved in such a system. Moreover the complete accelerator is then considerably more economical than a superconducting linac, as shown in Fig. 2. Construction of a prototype recirculation system (or recyclotron) capable of a final energy of 700 MeV has begun at HEPL.[(4)]

Table I

Objectives of HEPL SCA Program

Energy	500 - 2000 MeV
Current	100 μA
Duty Factor	~ 1.0
ΔE/E	~ 10^{-4}
Long term stability	~ 10^{-5}
Long term reliability.	

II. Results of Recent Tests

Recently two 6-meter sections of the superconducting accelerator have been operated together with the superconducting injector.

Figure 3 shows the injector and accelerator dewars set up in the tunnel. One of the niobium L-band structures complete with beam break-up probes, etc. installed inside its dewar, is shown in Fig. 4.

Table II summarizes the beam parameters which have been achieved during the last two runs.

Table II

SCA Achievements for Runs 12 and 13

No. of 6m Sections	1	1	1	1	2
Energy (MeV)	25	22	28	28	37
Duty Factor	0.33	CW	0.15	0.15	0.10
Pulse Length (msec)	30	-	15	15	10
Peak Current (μA)	500	25	25	100-200	25
ΔE/E (FWHM)	-	-	<5×10^{-4}	-	-
Emittance (π mc-cm)	<4×10^{-4}	-	<1.2×10^{-4}	-	-
Duration	~ hour	~hour	~week	~week	~hour

Using one 6-meter section, peak currents up to 500 μA with a duty factor of 0.33 and pulse length 30 msec at 25 MeV have been successfully achieved demonstrating that the regenerative beam break-up problem has been adequately controlled. This section has also been used in the CW mode to accelerate a beam to 22 MeV .

An energy resolution (FWHM) of better than 5×10^{-4} has been attained at an energy of 28 MeV with a peak current of 25μA . However, some difficulty - now understood - has been found in maintaining this resolution at higher currents. The beam emittance has exceeded all expectations and in fact has been impossible to measure accurately due to monitor saturation. The magnitude of the emittance (< 0.024 π mm mr) means, for instance, that a 25 MeV beam with a 1 mm waist only doubles in size after a drift of 72 meters. It has proved relatively simple to transport this beam a distance of 240 m to a dump in the HEPL end station. Beam currents up to 200 μA at 28 MeV have been run routinely for periods up to 3 weeks.

Using the second 6-meter section a total energy of 37 MeV has been obtained. Unfortunately this section could not be used extensively due to a problem with a mechanical tuner.

The properties and endurance of the accelerator structures themselves have been carefully monitored over the last few runs. Some results are shown in Table III. CW energy gradients average ~ 3 MeV/m with somewhat higher values in pulsed operation.

Two 6-meter sections have both been used in two runs of several weeks each. Between the runs they were kept under vacuum at room temperature and were not reprocessed. Energy gradients over this period have not deteriorated. Q-values degrade during a 3 week run (e.g. from ~ 7×10^9 to ~ 4×10^9) but recover between runs while the structure is at room temperature. This effect is almost certainly due to poor beam line vacuum, the structure itself being the best pump in the system, so that its surface gradually becomes contaminated with air, hydrocarbons, etc. Steps are being taken to improve this situation. These two sections have now run for about 1000 hours without significant deterioration. The pre-accelerator structure suffered a vacuum accident well over a year ago when a considerable amount of oil vapor was pumped through it. This immediately degraded its Q-value to 2×10^8 , but since then it has been used without reprocessing in 3 runs without any further degradation and is stable in operation.

The superfluid helium refrigerator has been operated continuously for many periods of 3 - 4 weeks and has now accumulated a total of 8000 hours of operation. This machine which is shown in Fig. 5 delivers 300 W at 1.9 K . We now have considerable confidence in both the reliability and stability of the whole accelerator and cryogenic system.

During the coming year we expect to complete and operate two more 6-meter structures and to obtain more data on the system's longevity.

III. Recirculation and Future Plans

It has already been shown that recirculation of the beam is an economically sensible way to increase the final energy of the superconducting accelerator. Such a recirculation system must satisfy the following conditions:

(a) multi-orbit capability
(b) possible extension to energies of a few GeV;
(c) final energy resolution better than 10^{-4} .

These conditions require that the main bending magnets themselves be multi-channel devices with very uniform fields in each channel and minimum field volume. A magnet configuration which satisfies these requirements by means of a split coil winding is shown in Fig. 6.

Table III

L-Band Niobium Accelerator Structure Performance

Run	6m Structure	Energy Gradient MeV/m	Duty Factor	Q Initial	Q Final
# 11	# 1	3.8	CW	2.5×10^9	
# 12	# 2	2.0	CW	3.0×10^9	
	# 4	3.0 – 4.2	CW – 0.15	9×10^9	3.3×10^9
# 13	# 2	2.0	CW	2.3×10^9	1.9×10^9
	# 4	3.0 – 4.2	CW – 0.15	6.9×10^9	4.1×10^9

A four-channel prototype recirculation system for a minimum final energy of 700 MeV has now been designed using this principle. The main magnets each bend the beam by 167° with orbits separated radially by 7.7 cm and with a gap of 15 mm . The rather stringent beam properties necessary to utilize such small apertures (as shown in Table IV) have already been exceeded in all respects. The beam current with a 4 orbit system will be restricted to ~ 100 μA by RF power limitations.

Table IV

Minimum Beam Specification for Prototype Recirculation

Minimum Energy	50 MeV
Maximum Emittance	0.05 π mm mr
	(5×10^{-4} π mc cm)
Maximum ΔE/E	$\pm 2 \times 10^{-4}$
Maximum Phase Spread	± 1°
(Beam Current	~ 100 μA)

A general layout of the complete prototype recyclotron in the accelerator tunnel is shown in Fig. 7. The way in which the beams of different energies are separated at the output end of the linac is shown in some detail in Fig. 8. The steering coils at the entrance and exit of each magnet channel are situated at optically conjugate points and provide a means for fine tuning of the path length of each orbit and hence the acceleration phase of each pass through the linac.

Ideally, each orbit of the system should be isochronous so that optically the complete recyclotron would be equivalent to a continous linac. However, such a system would require at least 11 quadrupoles per orbit with splits in the main bending magnets. Now, since the initial beam emittance has proved to be so small, a compromise design using only 5 quadrupoles per orbit is possible. This system operates on the longitudinal phase space of the beam as shown in Fig. 9, in such a way that provided the initial phase ellipse from the beam filter is suitably adjusted, a waist in longitudinal phase space can be maintained during each pass through the accelerator. Thus the final energy spread is better than 1 part in 10^4 and not significantly worse than that of a continuous linac as shown in Table V. The system does have an advantage over a continuous linac in that the initial phase spread of the beam can be somewhat larger.

The present status of the recirculation program is that all the small magnets for 2 orbits exist, while the multi-channel magnets are being manufactured. It will soon be possible to install two orbits with 4 sections of superconducting accelerator which should give a final energy in excess of 200 MeV.

References

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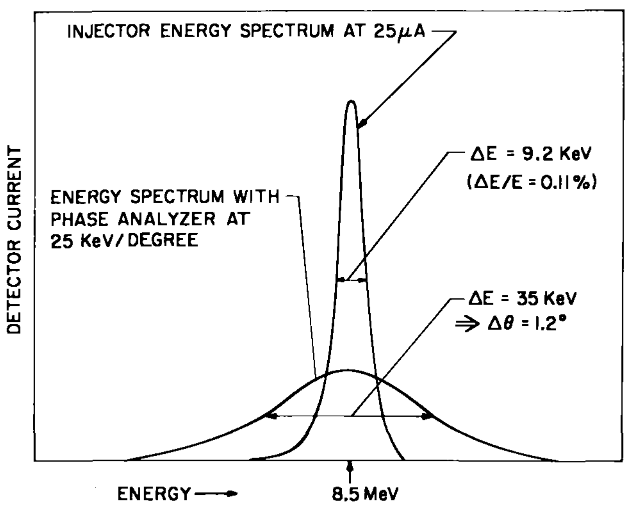


1. Energy Spectra obtained with the superconducting injector.

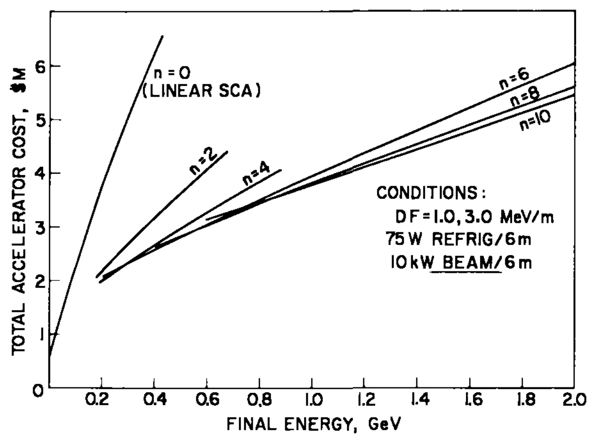
Table V

Calculated Energy Resolution From

Prototype Superconducting Recyclotron

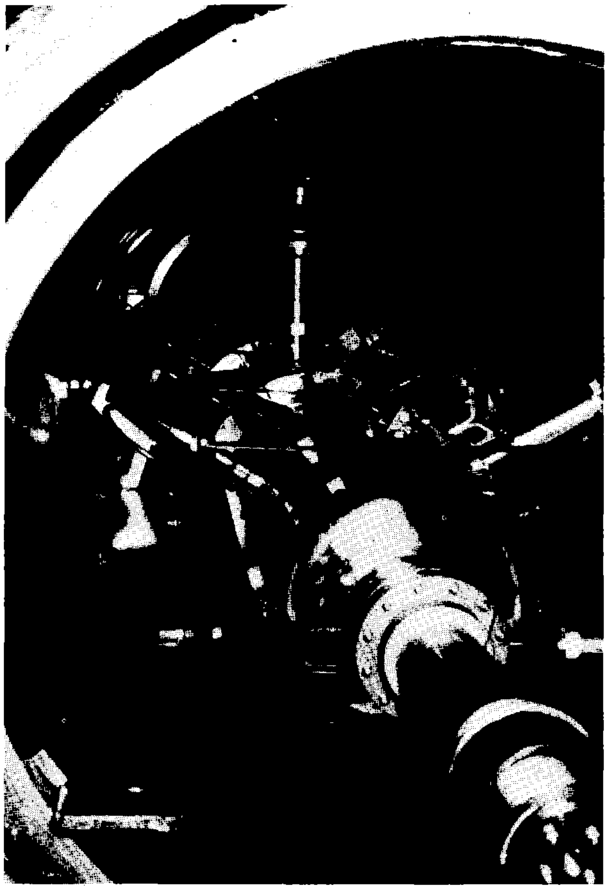
And Superconducting Linac

		at Beam Filter (9 MeV)	at 349 MeV
SCR	$\Delta\phi$	$\pm 0.70^{\circ}$	$\pm 0.64^{\circ}$
	$\Delta E/E$	$\pm 8.2 \times 10^{-4}$	$\pm 0.63 \times 10^{-4}$
SC Linac	$\Delta\phi$	$\pm 0.41^{\circ}$	$\pm 0.41^{\circ}$
	$\Delta E/E$	$\pm 14.0 \times 10^{-4}$	$\pm 0.44 \times 10^{-4}$

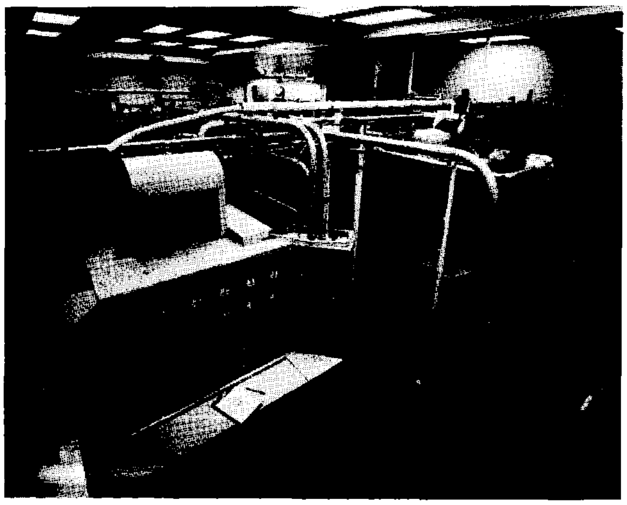


2. Estimated costs of superconducting recyclotron with various numbers of orbits (n) as a function of final energy.

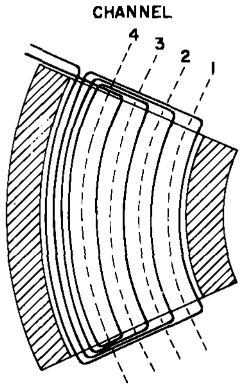
3. Photograph of superconducting accelerator installed in tunnel.



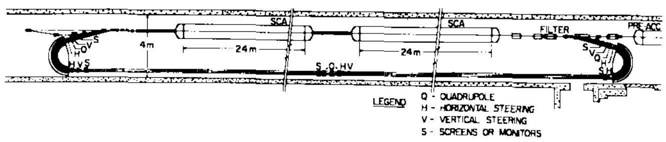
4. Photograph of Niobium accelerator structure complete with beam break-up probes installed in dewar.



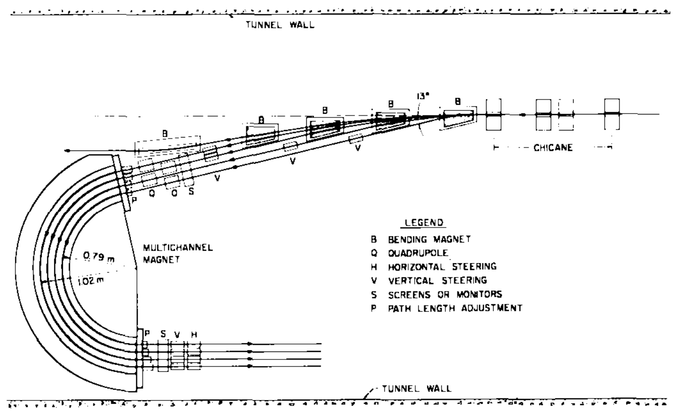
5. Photograph of superfluid helium refrigerator.



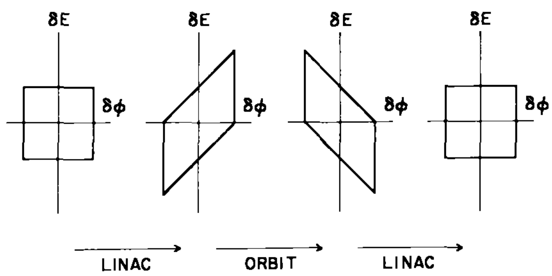
6. Principle of multi-channel bending magnet.



7. Schematic layout of prototype 700 MeV recyclotron.



8. Details of beam separation and multi-channel magnet.



9. Rotation of longitudinal phase space by re-circulation.

Discussion

W. Panofsky, Stanford Linear Accelerator Center: I have a question about the beam breakup situation. You said at 500 μa that you have been able to avoid the beam breakup problem by lowering the Q of the element at the various high modes. But the beam breakup threshold depends also on the length and you do recirculate. In your superconducting linac the radial regeneration is coherent turn-by-turn, producing an effective length of the beam length times the recirculation number. Have you investigated this ?

Rand: We are looking into these problems but we have come to the conclusion that probably the best way to investigate them is to build the first two orbits of the machine.

Panofsky: It's a very fundamental problem. If you write down the beam breakup equations, the threshold goes as Q/ℓ^2. One obtains coherence on a turn-by-turn basis producing a rather significant situation. Maybe there is a way with active feed-back to cure it.

A. Schwettman, Stanford University: We have taken a look at the relatively simple problem of cumulative beam breakup. We have not done any more complicated analysis for a recirculating system. The problem that you identify is analyzable in the sense that you describe, but we haven't really quantitatively analyzed what the current limitations will be in the recyclotron, yet.

H. Blosser, Michigan State University: One of your slides showed 28 MeV from one six meter section and I think 37 MeV from two. Why does the second section do so little ?

Rand: The 28 MeV includes the energy gain from the pre-accelerator which is 7 MeV and the second 6-meter section had a gradient of 2 MeV/meter. This is due to a poor cell in the second section, which is a statistical effect.

E. Michaelis, CERN: What is the effect of synchrotron radiation on your bending magnets ?

Rand: There is no serious problem until we get to 3 GeV.

Kuntze: I thought you had problems with your tuner.

Rand: We did have problems with the tuner. That's not the reason for the low gradient.

Kuntze: Do you get 3 MeV/meter reproducibly with your sections if you do not have trivial problems with tuners or leakage ?

Rand: Yes.

Kuntze: So it was statistical problems depending on the surface.