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UNIQUE BEAM PROPERTIES OF THE STANFORD 300 MeV SUPERCONDUCTING RECYCLOTRON*

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Introduction

Slightly more than a decade ago construction began on the Stanford University superconducting accelerator. The intention was to build a machine of great versatility with unique beam properties. Today the combination of beam emittance, energy resolution, beam current, duty factor, and beam stability that is achieved in the superconducting accelerator is unmatched in the world. The linac, together with its energy multiplying recirculation system (forming the superconducting recyclotron - SCR) now provides beams with energies from 20 MeV to 230 MeV, and in the near future the upper limit will exceed 300 MeV.

In this paper we shall describe the quality and versatility of the accelerator and its recirculation system. We will begin by describing three experiments that have been carried out using the superconducting accelerator. Each of these experiments exploited particular properties of the accelerator and none of these experiments would have been feasible at any other existing facility. We will then give a brief description of the linac and the recirculation system along with their capabilities. We will close with an outline of our studies of the beam breakup (BBU) problem which is so important to the new generation of medium energy accelerators.

Three Experiments

The first of the experiments we wish to describe is the recently published study of the fission modes of ^{24}Mg, by Sandorfi et al.[1] In this experiment an electron beam of 26 to 40 MeV is incident on a ^{24}Mg target and the back-to-back fission fragments are detected in coincidence. For the fission fragments to get out of the target with acceptable energy loss, the target must be extremely thin (33 $\mu g/cm^2$). Adequate counting rates can be achieved only if the fission detectors subtend a large solid angle (70 mΩ in our case) and the accelerator delivers high average beam current (150 - 250 μA in our case). Furthermore, since this is a coincidence experiment the beam current must be delivered at high duty factor (75 - 90% in our case) in order to minimize accidental coincidences. A subset of the data obtained is shown in Fig. 1. The beam time required to collect the data for this experiment was about 150 hours. No other accelerator has the combination of beam current and duty factor that would make this experiment feasible with less than 10,000 hours of beam time.

Beam currents and duty factor play an obvious role in making the fission experiment possible. The role of beam quality and beam stability is less obvious but equally important. The large solid angle fission detectors used in the experiment were solid state detectors placed within 10 cm of the target. Operation of solid state detectors in the immediate presence of a 150 - 250 μA electron beam places stringent conditions on beam emittance, beam halo, and beam stability. These conditions were met with the superconducting accelerator for long periods of time.

The second experiment we would like to describe is the free electron laser.[2] In this experiment a spatially periodic transverse magnetic field allows a relativistic electron beam to exchange energy with a photon beam. When properly adjusted there is a net transfer of energy from the electrons to the photons. We use this gain mechanism to power an optical oscillator[3] which we refer to as a free electron laser.

Since the gain at low power is directly proportional to the instantaneous current density, it is clear that this experiment belongs to the class in which instantaneous peak current is of major importance, as contrasted to the fission experiment where average current and duty factor were crucial. In addition, for fundamental reasons having to do with the electron-photon interaction, the beam emittance must be very small. For our experiment, with a 5 meter interaction length and a 3.2 cm magnet period, the beam emittance is limited to 0.05π mm mr. An additional practical constraint is imposed by the fact that the magnetic field is produced by a superconducting magnet whose windings are within 1 cm of the beam over the entire 5 meter interaction distance. In order that the magnet not quench, the fraction of the beam outside a 1 cm circle when the beam is focussed to a 1 mm waist must be very small, We typically keep this fraction to 10^{-4} or less.

The same reasoning which places limits on the emittance of the beam also places limits on its energy and positional stability. In our case the energy must remain fixed within a few parts in 10^4 and the position of the beam at a waist must remain fixed within about 10% of the waist size on a time scale of an hour or so.

Data taken in March 1981 are shown in Fig. 2. For all cases the SCA is delivering a 44 MeV beam with an average current over many rf cycles of 60 μA. However, since the injector is operating in a mode in which only every 110th rf bucket is filled, and since the beam pulse occupies less than 2° of one rf cycle, the instantaneous peak current is 1.2 A. The energy stability of the beam is indicated by Fig. 2a which shows the energy dispersed beam. The energy width is 0.05% (FWHM), and the figure is composed of four superimposed traces, taken over a period of forty minutes. Figure 2b again shows the energy dispersed beam but after it has passed through the laser. As the two traces are shifted by .25%, it's obvious that the energy exchange with the optical beam was substantial. The centroid of the distribution has shifted some .1% low, representing the increase in energy of the photon beam. It is interesting to note in passing that although the net energy shift of the beam was downward, a significant number of electrons gained energy. The upper limit of the energy gain was about 500 keV. This is probably the highest electron energy gain yet produced by a laser.

Again, no other accelerator is capable of delivering a beam with this combination of properties.

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The last experiment we wish to discuss is the study of the giant dipole resonance in ^{12}C through (e,e'p) and (e,e'α) coincidence experiments.[4] In these experiments the electron is detected in a spectrometer of 3.6 mΩ acceptance and the proton (or alpha) is detected in a solid state detector telescope of 40 mΩ (or 60 mΩ) acceptance. The solid state detectors, as in the fission experiment, are located within 10 cm of the target. Some results from the (e,e'p) experiment are shown in Fig. 3.

For the giant resonance experiments the recirculation system was used to provide beams of 80 to 120 MeV, at a duty factor of about 75%. The average beam current delivered at 80 MeV was typically 25 - 35 μA (limited by pile-up in the solid state detectors) and at 120 MeV was typically 15 - 20 μA (limited by regenerative beam breakup). As in the fission experiment beam quality and beam stability are important to the success of the giant resonance experiment. At 80 MeV the measured beam emittance was less than 0.01 π mm mr and the beam halo was less than 2×10^{-3} outside a radius of 1.5 mm with a beam spot on target of 0.7 mm FWHM. The energy width of the beam was 13 keV.

Using an array of proton (or alpha) detectors it is possible to reduce the data collection time for a typical giant resonance experiment to approximately 600 hours. This beam time is longer than desired and is fixed by the small acceptance of the electron spectrometer. However, at present no other facility is capable of mounting these experiments.

Superconducting Linac and the Recirculation System

The three experiments described above provide some indication of the uniqueness and versatility of the superconducting accelerator. In this section some technical details of the superconducting linac and the recirculation system will be discussed.

Since the details of the linac have been published elsewhere,[5] only a brief description will be presented here. With the exception of the injector, the linac consists of modular 6-meter structures made of niobium. They operate at 1.9 K and 1.3 GHz. The average field gradient which can be maintained at 75% duty cycle is about 1.75 MeV/meter. The amplitudes and phases of the fields in each structure are regulated by negative feedback electronics. The amplitudes are regulated to .01% and the phases are regulated to $.1^{o}$.

The injector[6] delivers a beam of approximately 5 MeV to the modular structures. It contains two superconducting structures: a 1 meter capture section and a 3 meter pre-accelerator section. The capture section accepts a 10^{o} by 2 keV bunch of electrons from a room temperature 100 keV system, and delivers a 1.5^{o} by 15 keV bunch at about 2.5 MeV to the pre-accelerator.

In the conventional mode of operation, each rf bucket of the linac is filled and the output consists of a train of electron bunches each 1.5^{o} wide separated by 769 ps. In this mode the injector can provide up to 500 μA averaged over each rf cycle. A second mode of operation exists, in which the gun is pulsed[7] to provide an intense burst of electrons each 110th rf cycle. In this mode the peak current during one rf cycle can be as much as 1.2 A . The current in the adjacent buckets is less than 5% that in the main pulse.

The recirculation system[8] of the SCR is shown schematically in Fig. 4. The beam splitter consists of an array of 4 identical magnets, and the beam funnel is a mirror image of this system. The field levels in the channels of the multichannel magnets are stepped by splitting the main windings as shown in Fig. 4. and controlled independently by means of current shunts. Beam focussing is provided on each orbit by 3 quadrupole doublets which are located in the beam splitter, at the center of the orbit, and in the beam funnel. This arrangement provides a wide range of possible beam optical conditions.

In normal operation the orbital beam transfer matrix is set to be a unit matrix (multiplied by a term to allow for the decrease in emittance with energy) at the center of the linac. It can then be shown that the orbit possesses betatron stability at all other points in the linac with R_{12} (TRANSPORT notation[9]) being proportional to the cube of the distance from the center of the linac.[10] The betatron phase advance is greater than 2 π with R_{12} positive at the injection end of the linac and less than 2 π with R_{12} negative at the exit. Near the center of the linac where the phase advance is close to or equal to 2 π, R_{12} from the first pass to the nth pass grows linearly with n. This configuration, chosen to minimize R_{12} and thus to reduce beam breakup,[10] is only suitable for small numbers of orbits.

The longitudinal optics exhibit phase stability with a phase stable region which is initially only 2^{o} wide but which grows linearly with orbit number.[11] This narrow acceptance is well matched to the high energy resolution of the SCA beam and maintains resolutions of order 10^{-4}.

Some of the measured beam properties of the SCR are given in Table I. The 2-pass beams and the 3-pass beams are reliable and have been used routinely for physics experiments. Some difficulties which have been experienced with the 4-pass beams due to restricted apertures in the 3rd orbit are being corrected. The installation of an additional structure which is nearly complete will increase the energies given in the table by approximately 25%. Increased loading of breakup modes in this new structure implies that after installation the average beam currents achieved in the SCR will also increase. It is expected that the beam current values given in the table will be increased by a factor of 2 to 3.

Table I

Properties of Recirculated Beams

Passes	2	2	3	3	4	4
Energy (MeV)	80	119	117	175	166	232
Duty Factor (%)	75	20	75	20	45	20
Average Current(μA)	50	20	20	13	9	5
Resolution ($\times 10^{-4}$)	1.6	1.1	1.1	1.2	1.6	<2

Regenerative Beam Breakup Studies

The variable beam optics and the relatively high Q-values of the transverse modes of the superconducting structures, make the SCR an ideal test bed for studies of regenerative beam breakup (BBU). Such studies in the past two years have resulted in a dramatic increase of the beam current achieved in the SCR and the knowledge that has been acquired should now be used to assess the performance of the numerous recirculating electron accelerators being proposed elsewhere. Before discussing

BBU in more detail is it worth noting that at the time of the last Accelerator Conference, the useful 2-pass average beam current was only a few µA.[12] Now, with successive improvements in cavity probes and beam optics it is 50 µA under "operator" conditions and a record of 92 µA has been reached.

A standing wave theory for regenerative BBU in a recirculating electron accelerator has been formulated[13] and experimentally verified.[14] The validity of the theory has been established by direct measurement of the interaction of the 2-pass beam with a particular transverse mode under known beam optical conditions in the SCR. Field profile measurements were used to characterize the mode in question. Multiple pass calculations[15] using only the dominant term in the BBU interaction have recently been used to calculate "worst case" starting current for normal operating conditions in the SCR. The "worst case" results are compared to the achieved beam currents in Table II.

Table II

Comparison of Beam Currents with BBU Calculations

Passes	2	3	4	5
Av. I_s(A) calculation,"worst case"	38	20	14	12
Av. I (A) "operator" conditions	50	20	--	--
Av. I (A) record	92	23	>9	--

The "useful" 2-pass and 3-pass beam currents are consistent with these calculations while the record currents for 2- and 3-pass exceed them. The 4-pass measurement was made with less than 100% transmission and is only a lower limit. The record 2-pass current was achieved with conditions different from those used in the calculation. In this case, the matrix element R_{12} was maintained very close to zero and in fact probably passed through zero at 3 points in the linac. This is a condition which is acceptable for an extracted 2-pass beam but it is not betatron stable and is unsuitable for further recirculation.

The success of the "worst case" calculations in reproducing the achieved SCR beam currents lends confidence to assessing the BBU properties of other recirculating electron accelerators.

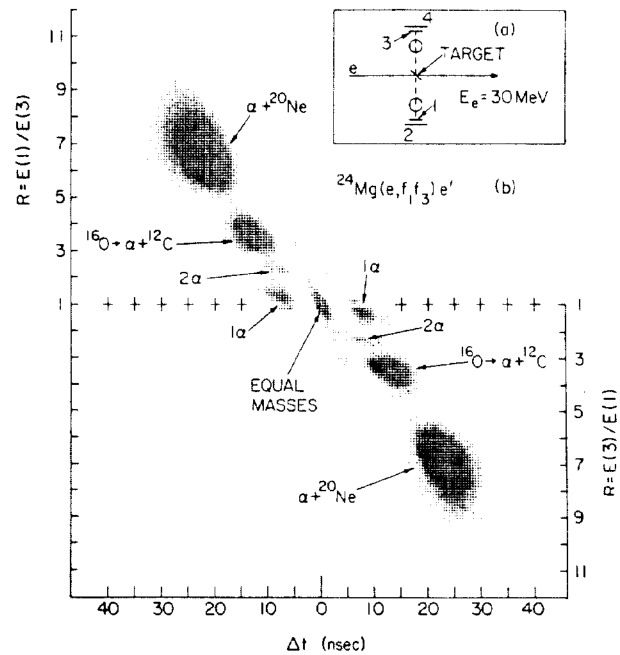

FIG. 1

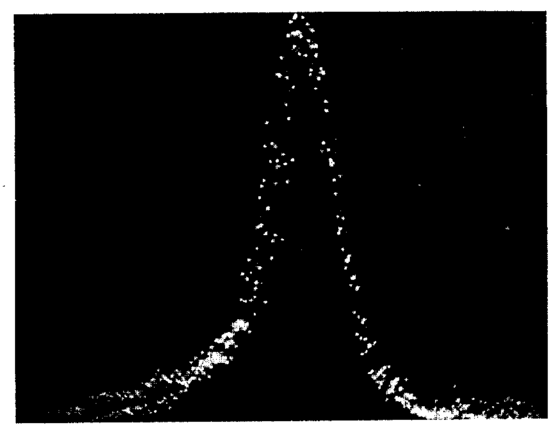

FIG. 2a

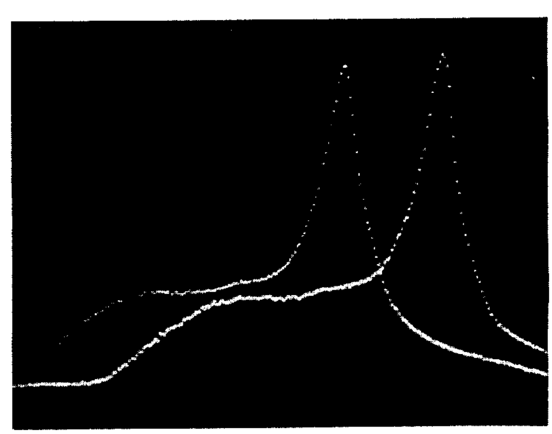

FIG. 2b

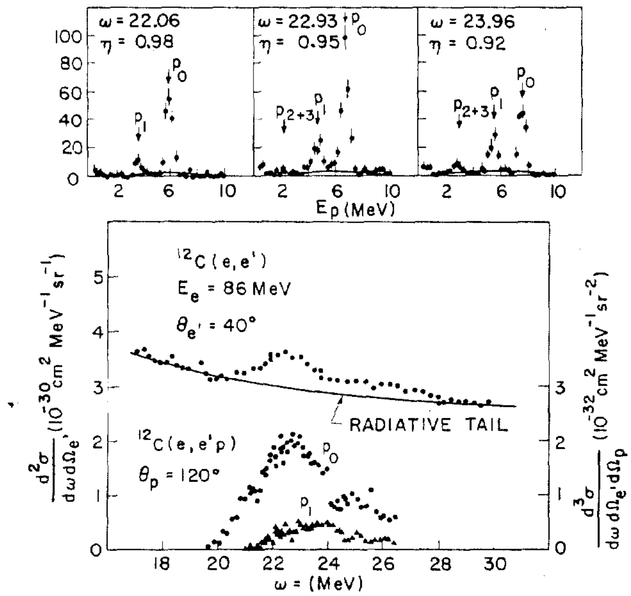

FIG. 3

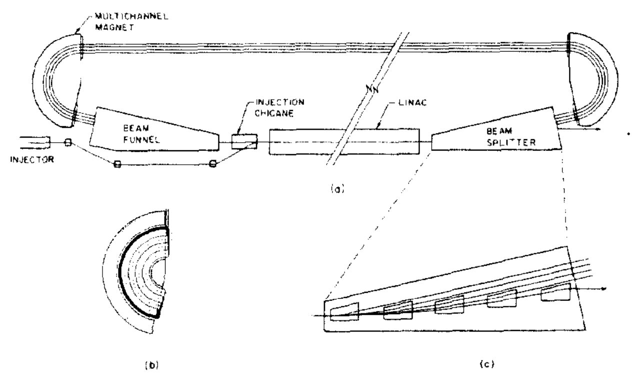

FIG. 4

Figure Captions

Fig. 1. The coincidence-detection geometry for the ^{24}Mg fission experiment is shown schematically in (a). A density plot of the fraction, formed from the energy of the light fragment over that of the heavy fragment, is shown in (b) as a function of the time difference between their arrival in opposite counters. The origin of the predominant peaks are indicated. Those labelled "2α" are from $^{24}Mg \to {}^{16}O + {}^{8}Be$ where both alphas from ^{8}Be are detected, while the "1α" peaks result from the detection of only one of these alphas.

Fig. 2 (a). Energy resolved beam of the SCA operating in the intense pulsed mode (see text) at 44 MeV and 1.2 A peak current. The energy width is 0.05% (FWHM). The energy stability of the beam is indicated by the fact that the figure is a superposition of four separate spectra, taken over an interval of 40 minutes.

(b). Energy spectrum of above beam after passing through Free Electron Laser. The two spectra have been displaced by 0.25% in energy. The centroid of the distribution has shifted about 0.1% low, representing the increase in energy of the photon beam.

Fig. 3. Bottom: The $^{12}C(e,e')$ and $^{12}C(e,e'p)$ cross sections measured in the experiment of reference 4.

Top: A sample of three coincidence proton spectra for various values of ω (energy transfer) with $\Delta\omega \simeq 150$ keV. The parameter η is the relative efficiency of the relevant electron channel. Accidental coincidence backgrounds are shown as solid lines.

Fig. 4. Schematic of the superconducting recyclotron.[8]

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