PROGRESS ON RF ELECTRON SUPERCONDUCTING ACCELERATORS*

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Summary

Superconducting rf electron accelerator prototypes have been operated at Stanford University and at the University of Illinois. Many of the beam performance goals for emittance, current, energy resolution and stability have been achieved. Lower-than-expected accelerating gradients have necessitated the re-evaluation of the energy objectives. Recirculation of the electron beam through the superconducting linacs will, however, increase the effective accelerating gradient.

Introduction

There have been two excellent summary papers in this last year concerning rf superconductivity and its application to particle accelerators. The most recent one which was presented by P. B. Wilson[1] at the 1972 Conference on Proton Linear Accelerators, discussed the status of superconducting accelerator technology throughout the world. Wilson discussed the long range goals and the immediate objectives of the various research groups and also summarized recent results and performance of their rf superconducting structures.

A second paper, presented by J. P. Turneaure[2] at the 1972 Applied Superconductivity Conference (Annapolis, Maryland) reviewed the somewhat broader scope of rf superconducting applications in general. In addition to discussing the various applications of rf superconducting structures, Turneaure summarized the fabrication and processing techniques being utilized for the production of superconducting structures for high-field applications such as for particle accelerators. The two above mentioned papers are complementary and each has an excellent bibliography.

In this paper I would like to discuss the currently operating superconducting electron accelerator prototypes; those at Stanford University and the University of Illinois. Most of the author's experience has been with the Stanford machines and consequently a major fraction of this paper will be concerned with the Stanford program.

Electron Superconducting Accelerator Prototypes at Stanford

In 1964 Fairbank, Schwettman, and Wilson[3,4] accelerated electrons with a superconducting rf structure for the first time. In this experiment 80 keV electrons were accelerated by a lead-plated (on copper) 3 cell, S-band structure to an energy of approximately 500 keV. This experiment demonstrated that a multicell, accelerating-mode structure could be operated at modestly high accelerating gradients (3 MeV/m) and Q's (10^8). It also demonstrated that there were no serious difficulties in interfacing with the cryogenics (electron beams in and out, rf power in, etc.).

In 1967 and 1968 the Stanford group performed accelerator tests with L-band structures operating at 952 MHz.[5,6,7] The cavities were lead-plated (on copper) bi-periodic, structures operating in the $\pi/2$ mode. Two structures, a 19-cell, $10\lambda/2$ and a 9-cell, $5\lambda/2$, were tested with an electron beam. The lower frequency L-band accelerating structures did not yield significantly higher field gradients or Q's when compared with the lead-plated S-band structures. Usually it was necessary to operate with the rf pulsed (100 ms pulse lengths) in order to achieve the 3 MeV/m accelerating gradients necessary for good capture of the injected electrons. The significant improvements for superconducting accelerator technology were in the control and operational aspects of the systems. The 80 keV electrons from the gun, for example, were chopped and prebunched before injection into the accelerating structure. Also the rf field levels were stabilized by feedback control systems. As a result, 1-2MeV electron beams having excellent energy stability, were produced.

Based on the performance of the prototype accelerators, the Stanford group began in 1968 to design and construct a full-length superconducting accelerator (SCA).[8,9,10] The objectives set for the SCA development were extremely ambitious. In summary, the principal objectives were: (1) an energy of 2 GeV produced by 24, 6-meter long accelerating structures operating at 1300 MHz (this would mean an equivalent accelerating gradient of 14 MeV/m would be required);(2) refrigeration design capability of 300 W at 1.85 K; (3) energy homogeneity and stability $\Delta E/E$ of 10^{-4}; (4) beam current of 100 μA at 2 GeV; and (5) duty factor of unity at 1 GeV (Q of 10^{10} with 300 watt refrigeration).

The very high gradient set as an objective for the SCA development was based on the expectation that, with careful metallurgical preparation of the cavity surfaces, peak magnetic fields of nearly one-half the theoretical limit could be achieved and that the required cavity preparation techniques would also be sufficient to control electron loading problems. At the time, the attention was directed toward niobium cavities which had been shown by Turneaure and Weissman[11] to produce both high rf fields and high Q's at X-band (8.5 GHz). Subsequently, Turneaure[12] reached peak rf fields of 1080 gauss and 70 MV/m with a Q of 10^{10} at X-band.

By 1971 extensive measurements had shown that the magnetic breakdown problems and particularly the electron loading problems were more severe in lower frequency accelerator cavities at 1300 MHz. There appeared to be a practical limit of gradients of about 4 MeV/m. In the spring of 1971 the first tests of the Stanford injector for the SCA were begun. Although the accelerating gradients of 1300 MHz accelerating structures were limited to 3 MeV/m, by the end of 1972 all of the objectives for energy resolution, intensity, and duty factor had been achieved or exceeded for the superconducting injector.

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The Stanford Superconducting Injector System

The basic components of the Stanford injector system[13] tested during the past year are diagrammed in Fig. 1. Electrons from the gun (which was operated at 100 kV in the most recent tests) are chopped, bunched, and injected into the capture section, where they are further bunched and accelerated to 1.8 MeV energy. In the pre-accelerator section the electron beam is accelerated by another 6.2 MeV to a total energy of 8 MeV.

Before being injected into the next accelerating section, the beam passes through the beam filter which is a beam transport system consisting of four bending magnets, and several solenoidal lenses and adjustable slits. In addition to removing any low-energy electrons, such as those generated by field emission from either the capture of pre-accelerator sections, the beam filter permits additional phase bunching of the beam to be realized through the path-length-versus-energy adjustment. The beam filter also provides adequate displacements and deflection of the injector beam so that a high-energy recirculated beam can be reinserted for another pass through the main portion of the accelerator.

The beam analyzing apparatus shown in Fig. 1 consists of a superconducting accelerator structure and a magnetic spectrometer. The superconducting structure is used to measure the spread in phase of the beam from the injector.

Most of the acceleration dynamics such as bunching and radial focussing of the electron beam occurs in the injector sections of the accelerator. The beam quality of a long linear electron accelerator depends, therefore, principally on the phase space area of the beam as it emerges from the injector. Also, space-charge effects are most severe at the low energies of the injector.

The properties of the electron beam from the Stanford injector were measured under a variety of conditions. In earlier tests, two main factors prevented Stanford from attaining all of the performance objectives; accelerating gradients were low, and beam breakup instabilities prevented definite measurements of beam quality at high currents. With an increased gun voltage to compensate for the deficiency in the accelerating gradient of the capture section, and with the addition of appropriate rf probes for loading the beam breakup modes, however, the performance objectives were achieved at high as well as at low currents.[14] A longitudinal phase space area $\Delta E \cdot \Delta\theta$ of better than 12 keV · deg (FWHM) at 8 MeV was measured at currents up to 250 μA. Also a phase spread $\Delta\theta$ of less than one degree could be achieved by adjusting the beam filter to provide a suitable amount of anisochronism with respect to energy. With a ΔE and $\Delta\theta$ of 10 keV and 1.2 degree respectively from the injector, the 10^{-4} resolution objective will be possible at energies as low as 200 MeV. The transverse phase space area of the injector beam at 8 MeV was less than $\pi \times 1$ mm mrad.

The quality and stability of the electron beam from the injector demonstrated well the performance of the rf control systems which regulated the rf fields in the accelerating structures. At 8 MeV the energy was observed to fluctuate less than ± 3 parts in 10^5 over a 30 minute period. When the current was increased from 10 to 250 μA by changing the gun emission only, a shift in energy of only 6 parts in 10^5 was observed.

The beam current capability of the SCA is severely tested in the injector system where regenerative beam breakup is most easily initiated. The question of beam breakup in the SCA is extremely important because the starting current is inversely proportional to the loaded Q of the relevant mode which, in a SCA, is inherently very high. During the past year at Stanford, extensive measurements[15] relating to beam breakup have been made for all relevant longitudinal and transverse modes in the 7-cell capture section, the 23-cell pre-accelerator, and the 55-cell 6-meter structure. There are 7, 23, and 55 longitudinal modes, respectively, in these structures, and there are 28, 92 and 220 transverse modes, including both branches of the HEM_{11} deflection band and both polarizations. Experiments with an electron beam provided measurements of the product $I_S Q_L$, where I_S is the starting current and Q_L is the loaded Q-value for each of the breakup modes, and thus, given a desired starting current, one can calculate the required Q_L for each mode. In addition, field profiles for the modes were measured which provided the information required for determining the location and character of the loading probes.

Future Plans at Stanford

In late spring 1973 the Stanford group will test and operate a system comprising their injector plus two of the 55 cell, 6-meter accelerating structures. The objectives of tests will be to achieve a beam current exceeding 100 μA at an energy of 42 MeV. The addition of two more 6-meter structures in the late fall of 1973 will extend the energy to 76 MeV. At this time the first orbit of a multi-orbit beam recirculation system will be tested.

The recirculation system, described by R. Rand at this conference, combines the advantages of the small phase space of the superconducting linac with novel multichannel bending magnets to achieve recirculation of the electron beam. Shown in Fig. 2 is a diagram of the planned four-orbit (five passes through the linac) system. With the presently achievable accelerating gradients of 3 MeV/m, the final energy of 350 MeV would be realized. The system has features in common with the racetrack microtron discussed in the next part of this paper, but the main magnets are much cheaper.[16]

University of Illinois Superconducting Microtron

In 1967 Robinson, Jamnik and Hanson[17] reported on the design and feasibility of a racetrack microtron for 600 MeV electrons. The configuration they considered which was similar to that suggested by Wiik, Schwettman, and Wilson,[18] consisted of a split microtron in which two uniform-field d.c. magnets with parallel edges are separated by a distance large compared to the magnet dimensions, and a superconducting linac is placed in the common straight section. At a 30-MeV energy gain per pass through the linac, a 600 MeV electron beam of superb quality would be produced after 20 passes. In addition to being a compact medium energy device, the microtron has an easily extracted beam.

In 1971 Hanson[19] reported that the injection section of the linac for the racetrack microtron had been tested. Electrons of 270 keV were chopped to a selected phase spread of 6 degrees and injected into a 3 λ/2 niobium structure operating at 1300 MHz. The niobium structure had not been outgassed at high temperature and had a Q of 1.4×10^8. The energy gain appeared to be limited by field emission to about 2.6 MeV/m. A one MeV electron beam of excellent quality was produced.

The low accelerating gradients presently attainable in the superconducting accelerating structures, as in the case of the Stanford group, has caused Hanson and his colleagues to re-evaluate the near term goals for their microtron. Hanson[20] says that their present objectives are to produce an energy of 30 MeV with six passes through the superconducting linac. Since L. M. Young of the Illinois group will report on the design and performance of the system at this conference, I will present only a very brief description in this paper.

Shown in Fig. 3 is a diagram of the six-traversed microtron under construction in the Physics Research Laboratory of the University of Illinois:

The electron gun at the lower right produces a 270 keV d.c. beam which is then chopped and deflected onto the linac axis. The beam travels through the linac from right to left. It is then bent by 180° by the large magnet on the left and emerges after following the path shown by the semicircle of smallest radius. The phase adjustment needed for the first return path is provided by deflecting the beam by 30° so that it passes from left to right along the lower side of cryostat. This first return beam is then deflected back to the position at which it emerges from the left magnet. It then enters the right magnet which has a magnetic field equal to that in the left magnet. Therefore, this beam emerges on the linac axis moving toward the linac. It moves through a magnet which compensates for the deflection caused by the inflector magnet which captured the low energy injector beam. The beam then proceeds through the linac, gains energy for a second time and emerges on the next larger semicircle. After emerging from the left magnet it proceeds through the cryostat and into the right magnet which again deflects the beam through 180° so that it emerges moving along the linac axis. The next three return paths are just like the second one. After the beam has been through the linac 6 times, it emerges from the left magnet. Note that the figure omits some magnetic steering and focussing devices. The beam can be diverted to the experimental area from any return path starting from the second. It is bent first by 17° and later by 73° to go into the experimental areas.

Shown in Fig. 4 is the linac cryostat. The superconducting linac consists of two separately powered accelerating sections; the phase of the $3\lambda/2$ capture section and the phase of the $13\lambda/2$ main section are set independently for efficient capture and acceleration. There is a mechanically adjustable coaxial E-field tuner mounted at the exit of the capture section; the resonant frequency of the capture section can be tuned to 1 Hz over a range of 0.3 MHz. As the linac is operating at present, the capture section increases the injected electron beam energy from 270 to 750 keV; the main section then increases this energy to about 3.5 MeV. The phase of the capture section makes it incapable of adding much energy to the recirculated beam; as seen by the recirculating beam, the phase difference between the capture section and the main section is about 90°. The 3.5 MeV recirculated beam gains about 2.9 MeV in the main section during the second traversal and emerges with an energy of about 6.4 MeV. A one kilowatt klystron is used to power the main linac section.

Hanson[20] reports that they have recently recirculated the electron beam two times (three passes through the linac) successfully. Although the low energy gain provided by the present niobium accelerating structures has aggravated the design and operational complexity of the recirculation, a very good quality beam ($\Delta P/P \simeq 0.1\%$) has been produced. The experimental program is well underway with some resonance fluorescence experiments already performed at six MeV (two passes through the linac). The six-pass system is expected to be operational by late spring or early summer 1973. With the present condition of the superconducting structures, approximately 18 MeV would be realized. A reprocessing of the structures should then increase the capability closer to the 30 MeV goal. It should be noted that the magnets have the capability of going to 60 MeV.

Some Other Efforts

In addition to the Stanford and Illinois efforts, there are other groups working on the application of rf superconductivity to the acceleration of electrons. V. K. Rasmussen[21] at the Bartol Research Foundation has designed and begun construction of a 10 MeV linac with properties similar to the injector of the Stanford group. A group[22] at Cornell University has been developing an S-band superconducting rf system for application to the Cornell synchrotron (see B-13 of this conference). There has also been some interest in developing high-resolution superconducting electron linacs in the few MeV range for application to electron microscopes.[23,24]

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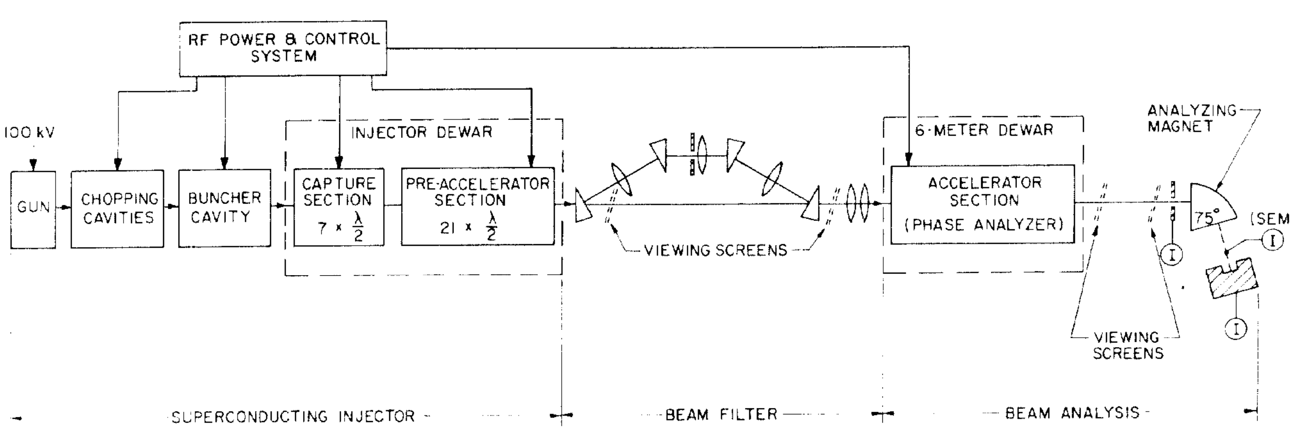

Figure 1. Schematic diagram of superconducting injector and beam analysis system for the Stanford Superconducting Electron Linac.

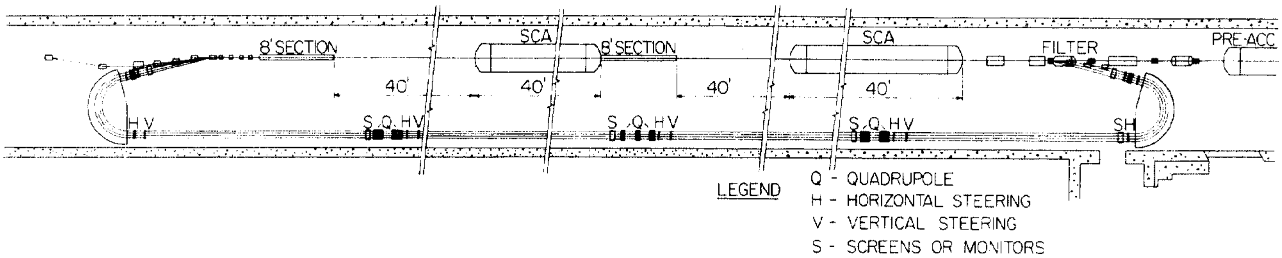

Figure 2. Schematic layout of prototype recirculation system for the Stanford Superconducting Electron Linac.

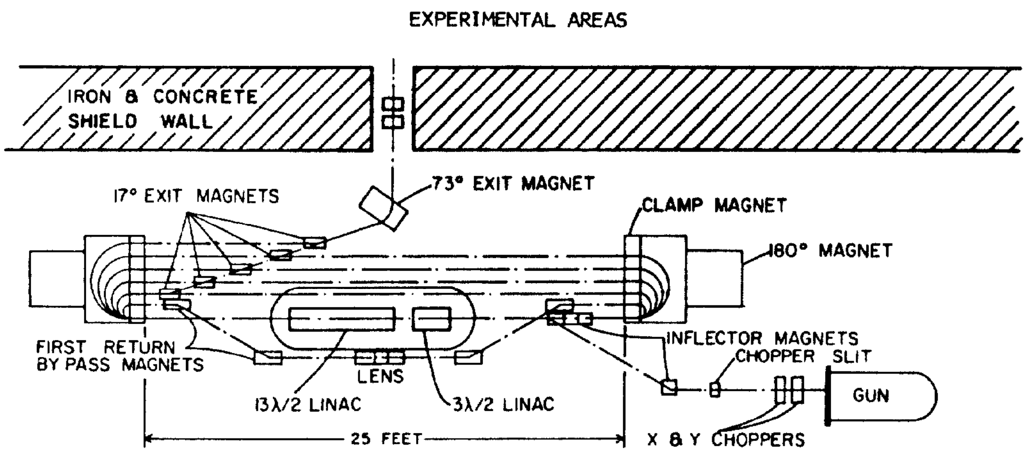

Figure 3. Diagram of the University of Illinois Superconducting Electron Microtron.

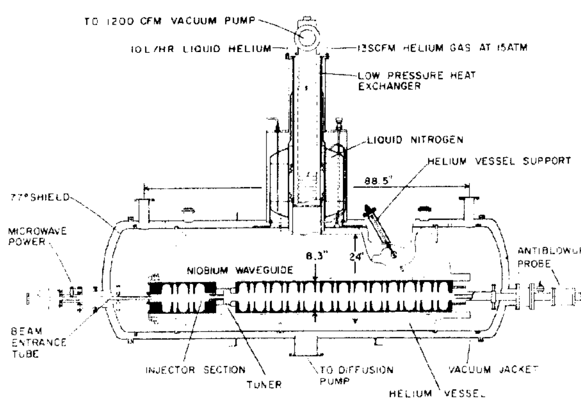

Figure 4. Linac Cryostat for the University of Illinois Superconducting Electron Microtron.