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

OPERATING EXPERIENCE WITH MUSL-2*

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Summary

The second 6 pass microtron using a superconducting linac has been completed and has operated on 24 hour schedules for nuclear physics for about 5000 hours during the past year. The Q of the linac has remained at $3x10^9$ and the C.W. energy gain has remained at 2.3 MeV/m as in its initial tests in 1975. Single pass C.W. currents up to 20 μA with energies up to 14.6 MeV have been available for resonance fluorescence experiments. Six pass beams with energies up to 67 MeV have been available to other experimental areas but useful currents have been limited to 0.3 μA by the excitation of transverse beam blowup modes around 2.3 GHz. The multiple pass currents, however, have been more than sufficient for all tagged photon experiments. Work is proceeding to replace our MUSL-2 linac with another Stanford linac in which the loading of the 2.3 GHz modes is increased by a factor of 100 or more by hybrid electric-magnetic loading probes. Plans to reach higher energies by using MUSL-2 as an injector into a second microtron continue to be attractive.

Introduction

The MUSL-2 6 pass system, described in a previous report(1) was completed during 1977 while mostly single pass beams were used for experiments. A 6 pass 66 MeV beam was first obtained in January 1978. Since that time MUSL-2 has operated for about 5000 hours providing to four experimental areas beams of various energies from 5 to 66 MeV with an energy spread of no more than 0.1%. The general arrangement is shown in Fig. 1.

A CTI 1400 helium liquefier is installed in a small building just outside of the accelerator barn. It keeps the linac at about 2 K with only routine attention. It has operated continuously except for modifications and occasional maintenance for 18000 of the 20000 hours since it was installed in 1976.

The performance of the linac has continued to be reliable. The Q of the linac has remained about the same at $3x10^9$ as in the initial tests in 1975. The maximum C.W. energy gain has remained at about 13 MeV which corresponds to an energy gradient of 2.3 MeV/meter.

The small size of the yokes in the end magnets limits the useful magnetic field to 5000 gauss which (at $\nu=2$) limits the useful gain for the 6 pass system to about 11 MeV per pass and a maximum energy of 67 MeV. MUSL-2 has also been operated at $\nu=4$ with the beam going through the 2nd, 4th and 6th return pipes. In this mode the full 13 MeV gain of the linac can be used. Maximum energies of 28 MeV and 41 MeV have been obtained for 2 pass and 3 pass beams. With new coils and a small amount of iron the end magnets would not be a limitation and the maximum 6 pass energy would be about 80 MeV.

As we began to recirculate the beam we encountered our first difficulties with beam blowup. A preliminary test for beam blowup was made in May 1977 with a 1.5 MeV D.C. beam passing through the unexcited linac. Blowup was found at 20 μA. This starting current was somewhat greater than that expected for such a low energy and we did not investigate it further at that time. In our work with single pass beams we encountered no blowup difficulties in delivering beams of 5 to 14.6 MeV with currents of 15 to 20 μA. In September 1977 when we attempted to deliver a two pass 20 MeV beam, the current was limited by blowup to 0.5 μA. In other runs typical maximum stable currents were 1.5 to 2 μA. For the 6 pass beam, blowup limits to about 0.3 μA the current which can be kept on target for long runs. More details about blowup will be given below after several recent improvements are described. The final summarizes our plans for MUSL-3.

Van de Graaff Regulation

The operation of the KN3000 Van de Graaff as a 2 MeV injector has been reasonably reliable. The positive corona current voltage regulator, however, has not been satisfactory. The points of the one mil wire screen was not a very effective source of positive ions in the N_2-CO_2 insulating gas mixture at 16 atmospheres. The screen was easily damaged and had to be replaced too frequently to be useful.

We recently installed a conventional negative corona head with 12 robust needles mounted from the inside of the high voltage terminal. The corona current is controlled by means of the usual 6BK4B high voltage regulator tube; the error signal is transmitted from ground potential by means of a glass fiber light link. This system has greatly improved the speed of response resulting in a fourfold reduction of the voltage variations associated with belt ripple.

Reduced Angle Injection Chicane

In our initial system the injected beam was inflected onto the linac axis by means of a 24° deflecting magnet which was the final magnet of the injection transport system. It was also the final magnet of the 3 magnet chicane required to remove the horizontal deflection of the returning beams. This chicane had a strong vertical focusing effect with an effective focal length of 3 meters. Although the focusing effect could be compensated for by adjusting the optics of the returning beam these adjustments were critical and difficult to maintain accurately.

A modification of the injection transport system provides an initial bend of 16° before the beam approaches the linac axis so that the final deflection is reduced by a factor of 3 to 8°. The focal length is increased by roughly a factor of 9 to 27 meters. This has greatly improved the ease of handling the first return beam. This modification is also useful in providing more stable conditions for multiple pass beam currents close to the blowup level.

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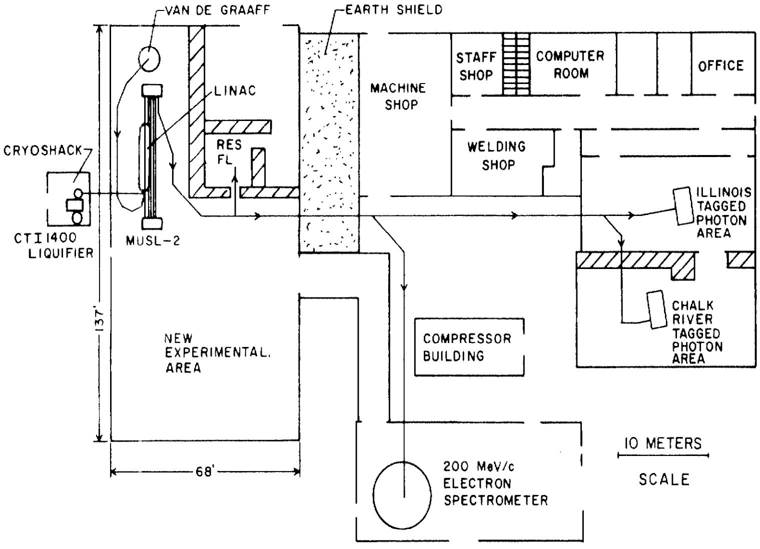

Fig. 1. MUSL-2 and the associated experimental areas.

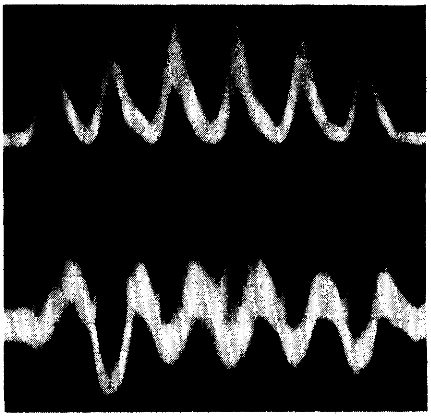

Fig. 2. Oscilloscope display of monitor signals from a pulsed 6 pass, 0.3 μA beam. The time between pulses is about 95 nsec. The upper trace indicates relative currents on successive passes. The minima of the lower trace represent phase differences of 16° and 8° with respect to the base line and the first pass.

Sequential Amplitude and Phase Monitor

A simple microwave cavity of the type suggested for the Mainz microtron(2) has been installed to monitor the magnitude and phase of the recirculating beam. This cavity is placed on the linac axis near the linac exit in order to obtain separate signals for each successive pass, a short pulse of about 50 nsec is used for these measurements. The time between the signals from successive recirculations is about 95 nsec. The decay time of the monitor cavity is reduced to about 8 nsec by externally loading the cavity to obtain a Q of about 65.

A measurement of the relative phases of the beam during each successive passage through the linac is particularly useful in adjusting the lengths of the return trajectories. The relative phases of electrons during successive traversals can be measured conveniently by adding to the cavity a reference signal whose magnitude and phase can be varied. It is then possible to obtain a null signal as the sum of a larger reference signal and the signal produced by the beam when these are about 90° out of phase.

An oscilloscope display of the sequential amplitudes and phases associated with a 6 pass, 0.3 μA beam is shown as Fig. 2. The upper trace is the signal due only to the successive passes of the beam and is a measure of the relative currents. The lower trace is the combined signal in which the injected reference signal is adjusted in amplitude and phase to produce a null signal for the first pass beam. The pattern corresponds to the usual operating condition for the 6 pass beam in which the first pass beam arrives at the monitor cavity 16° late with respect to the phase of the linac; the second beam arrives with no phase lag (i.e., 0°) and the other 4 passes have an 8° phase lag for phase stability. The minima under the second current peak, therefore, represents a 16° phase lead and the subsequent minima represent 8° phase leads with respect to the first beam. The reference signal for the lower trace is switched off regularly for a small fraction of the time resulting in a faint superposed current trace. This is convenient for simultaneously monitoring the returning beam currents.

Computer Control

The initial operation of MUSL-2 has been by a digital control system which interfaced the operator to more than 100 digitally controlled devices and provided simultaneous control of 4 of these devices. During the past year we have taken delivery of a DEC PDP 11/34 computer dedicated to the operation of the accelerator and the associated beam lines.

The computer system consists of the 11/34 with 64K of MOS memory, a 14 Megabyte removable cartridge disk drive, a 9 track tape drive and a LSI-11 microcomputer with a 512 x 512 dot plasma panel. The 11/34 has access to all digital control systems in MUSL-2, with limited access to various analog systems. Automatic recording of the digital and analog systems is performed on a selectable time basis. Logging can also be performed on a selectable time basis on request by the operator through a teletype.

The accelerator operator has access to this information storage and retrieval system. He can request differences of the data taken at different times, energies, etc. He can also request the computer to use the stored data of former experiments to write in the MUSL-2 parameters for a particular experiment. Under limited conditions the computer has also been used to control the accelerator in real time to maximize the beam current through the exit beam energy analyzer by an algorithm optimizing a number of parameters.

Beam Blowup

Soon after we recognized that the intensity of our recirculated beam was limited by beam blowup we identified some frequencies near 2.3 GHz that were excited regeneratively by a recirculated beam. Table 1 lists the frequencies of seven blowup modes that were excited with an injected 3 μamp beam and a second traversal. Changes in the focusing of the second traversal beam could shift from one regenerative blowup mode to another. In contrast, changes in beam steering did not affect the blowup modes noticeably.

Some of the characteristics of these blowup modes were measured by using a frequency synthesizer to excite them. The decay time and the inferred Q values are listed in columns 2 and 3 of Table 1. The plane of deflection of the blowup beam is listed in column 4; 0° corresponds to a horizontal deflection.

Additional information about these modes was obtained by making tests on very similar linac structures at the High Energy Physics Laboratory (HEPL) at Stanford(4). The 6 meter linac which is now in MUSL-2 (linac A) was fabricated for us at HEPL, and except for some differences in loading probes it is very similar to the superconducting linacs that are used at HEPL. The six meter linac consists of seven subsections, each of which contains seven accelerating cavities. After we had discovered these blowup modes, tests on a room temperature subsection at HEPL indicated that there were four modes near 2.3 GHz which had strong electric fields across the four irises nearest the center of the subsection. The four frequencies are listed in column 1 of Table 2. The Q values that we observed in linac A near these frequencies are listed in column 2. The HEPL tests also showed that the Q values of these modes were not reduced by magnetic loading probes such as those in linac A. Column 3 lists the high Q values corresponding to the very weak coupling between the 2.3 GHz modes and the magnetic probes. However, the HEPL tests showed that the 2.3 GHz modes were coupled to electric loading probes, and that electric probes would reduce the Q values by a factor of 200 or more as shown in column 4. These measurements on a room temperature subsection were confirmed by determining the Q values for these modes in a superconducting linac that had both electric and magnetic loading probes as listed in column 5 of Table 2.

TABLE 1

Frequencies and characteristics of blowup modes excited by a 2 pass 3 μA electron beam accelerated to a final energy of 22 MeV.

Frequency (MHz)	T(1/e) msec	Q_L $\text{x}10^{9}$	Polarization
2304.449	691	10	90°
2304.763	835	12	0°
2307.759	547	8	0°
2308.474	864	13	90°
2311.778	360	5	45° Ellipse
2312.262	115	2	
2312.656	Not seen in the coupling cell		

TABLE 2

Coupling to the 2.3 GHz modes as observed in Illinois and Stanford linacs and in a single room temperature subsection at Stanford.(4)

Frequency GHz	Q_L Illinois Linac A	Q_{EXT} Magnetic Probe	Q_{EXT} Electric Probe	Q_L Stanford Linac
2304	$10\text{x}10^{9}$	$14\text{x}10^{9}$	$7\text{x}10^{7}$	$5\text{x}10^{7}$
2312	$3\text{x}10^{9}$	$7\text{x}10^{9}$	$2\text{x}10^{7}$	$2\text{x}10^{7}$
2322	$2\text{x}10^{9}$	$4\text{x}10^{9}$	$1\text{x}10^{7}$	$5\text{x}10^{7}$
2338	$4\text{x}10^{9}$	$5\text{x}10^{9}$	$2\text{x}10^{7}$	$2\text{x}10^{7}$

Because the maximum current that can be obtained before beam blowup starts is inversely proportional to the Q of the blowup mode, the data in Table 2 makes it clear that we will be able to recirculate much higher currents in MUSL-2 without being limited by the 2.3 GHz modes when we obtain a linac with both electric and magnetic probes. There is a 6 meter linac that was reprocessed at HEPL for use at Illinois, linac B (which has been called 6m-2 at HEPL), which had only magnetic loading probes. In order to provide the loading of electric probes in linac B it was necessary to design a hybrid probe because, unlike most of the linac sections in use at HEPL, linac B lacks the ports into which electric loading probes can be placed.

A satisfactory hybrid probe was designed and tested largely through the efforts of Heinz Schwarz. The length of grounded side of the magnetic loop was changed to be $\lambda/4$ at 2.3 GHz so that an electric field at this frequency which capacitatively couples to the end of the loop does not get shorted out. This change increased the coupling to 2.3 GHz electric fields by a factor of 40. An additional factor of 5 in coupling was obtained by adding 4 mm electric atenna as an extension to the center of the loop. This hybrid probe will limit the maximum Q values for the 2.3 GHz modes to $5\text{x}10^{7}$ while maintaining the magnetic coupling needed to avoid the well known(3) lower frequency blowup modes. These hybrid probes are being installed in linac B. We intend to replace linac A with linac B when it is completed and performs satisfactorily.

Plans for Higher Energy

We hope to increase the electron energy available at Illinois considerably by building a cascade microtron, MUSL-3, such as we described previously.(1) We have been encouraged to believe that we may be able to obtain the required funds to do this after we have demonstrated that the blowup problems encountered with MUSL-2 have been solved.

MUSL-3 will inject the beam from MUSL-2 into the higher energy portion of a cascade microtron which would have an additional superconducting linac and new larger end magnets. It seems attractive to reduce the spacing between return paths from the 14.7 cm used with MUSL-2 to 7.35 cm so that more beam traversals can be accommodated for a given size of the end magnet.

Acknowledgements

We wish to express our appreciation to Heinz Schwarz and to the Stanford accelerator staff for their cooperation in the attempt to solve our beam blowup problem.

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