 IEEE Transactions on Nuclear Science, Vol. NS-32, No. 5, October 1985

STATUS OF THE STONY BROOK SUPERCONDUCTING HEAVY-ION LINAC*

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Summary

We describe the initial two years of operation of the first lead-based heavy-ion superconducting LINAC. The lead-plated copper technology has proven very successful in terms of achievable field levels, power consumption and reliability. The set-up and operation of the LINAC system are now largely automated, and, with the completion later this year of improvements to the cryogenics system and the upgrading of the low-β section of the machine to quarter wave resonators in 1986, the overall energy performance will exceed the original design goal. Recent advances of the electroplating research and development program hold promise for further improvements in the near future.

Introduction

The LINAC was first brought into operation in May 1983. Since that time, it has been in essentially continuous use (except for one extended down-time for repair of the tandem Van de Graaff injector), providing heavy ions in an energy range from ~150 to 350 MeV for an active research program in basic nuclear physics. The bulk of the experiments have been carried out by in-house users, although some outside users have been accommodated. Start-up and tuning of a beam through the LINAC have evolved from a rather labor-intensive manual task to a semi-automatic, computer-assisted procedure that is usually straightforward.

The machine consists of 40 lead-plated, copper, 150-MHz resonators of the split-loop type which were developed and fabricated by the Low Temperature Group at Cal-Tech. Sixteen are optimized for $\beta = 0.055$ and 24 for $\beta = 0.10$. The resonators were electroplated, balanced and tuned electrically, and installed into 12 modular cryostats at Stony Brook[1]. Cooling is provided by pool-boiling of helium at 4.5 K, which is gravity-fed to the resonators from reservoirs within each cryostat. The reservoirs are filled in parallel from a 1,000 L storage dewar, which is in turn filled by a 400 W turbine-expander type refrigerator.

This paper will report on the performance of the LINAC as it now stands, examine the factors that limit that performance, and describe work now under way that will increase the output energy of the machine.

Performance

Figure 1 summarizes the performance of the LINAC in its first two years of operation. The overall E/A versus A curve corresponds roughly to that of a 20 MV tandem accelerator. These beams typically receive approximately 10 MeV/charge in the LINAC. While the achievable field levels in individual resonators would imply a total energy gain some 50% higher than this, two factors impose limits in practical operation. In the high mass region (roughly Ni and above) the velocity boost in the low-β section is inadequate to enable optimum utilization of the high-β resonators. The low-β resonators suffer from excessive mechanical vibrations in the accelerator environment and cannot be kept properly phase-locked at field levels above ~1.5 MV/m. Phase locking is not a problem for the high-β resonators. For light ions, the presently available cooling power of 4W per resonator sets the limit by restricting the average operating fields of the high-β resonators to ~2.2 MV/m. For those experiments that demand a higher beam energy than what can be produced within this limit, the machine is run in a macropulsing mode. For example, a 10 MeV/A ^{16}O beam is produced by pulsing the high-β resonators to 2.8 MV/m at 0.1 Hz repetition rate with a 50% duty cycle and a peak power of 8W. The turn-on transient for amplitude and phase stabilization of the high-β resonators is less than 20 mS. The cryogenic system averages over the load fluctuation with no loss of stability.

Achievable beam intensities range from ~20 pnA for ^{16}O to a few pnA for the heaviest ions, limited by either beam loading or stripper lifetime in the tandem injector. The gas stripping capability of the tandem is not yet fully utilized due to the low-β resonator limitation. A second stripper foil of 5 $\mu g/cm^2$ is used before the LINAC. It has been found that such foils do not yield the equilibrium charge state distributions but thicker foils lead to excessive energy straggling. Both longitudinal and transverse beam emittances have been measured to ascertain the extent of emittance growth within the LINAC[2]. In the transverse dimensions no emittance growth has been observed. This is not the case, however, in the longitudinal dimensions where a factor of 4 increase has been measured. A computer simulation shows that the phase and amplitude fluctuations of 0.2° and 0.1% could account for half of this factor. The remaining portion is not understood, but it seems likely that resonator and quadrupole misalignments are likely causes.

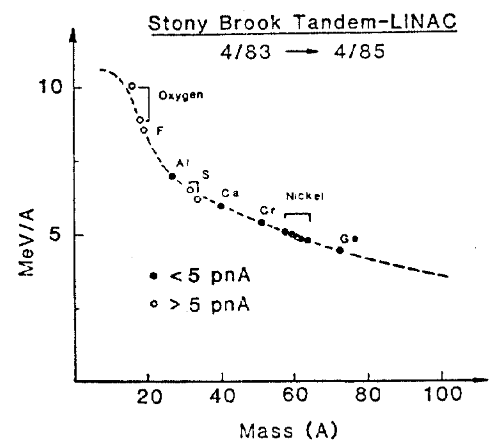

Fig. 1

The bunching system has been described in detail in a previous report[3]. It provides 60% capture efficiency of the DC beam with a pulse repetition period of 106nS. The 150-MHz superconducting post-tandem double drift buncher and feedback phase stabilization system are now in use. The fundamental frequency double drift buncher allows filling every RF bucket in the LINAC to produce an essentially continuous beam. The phase pick-up device used in the stabilization system is a coaxial resonator with a helical inner conductor. This low frequency resonator (18.8 MHz) gives ±13nS of phase tracking and, being located before the clean-up chopper, can accommodate even the largest phase jumps in the tandem.

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Tune-up of the LINAC and beam transport magnets continues to evolve, based on accumulating experience, toward a hands-off computerized procedure. Resonator phases are deduced directly from the beam in a sequential fashion by an accurate and convenient automated system. Direct calculation of resonator phases is not yet practical in view of present uncertainties in the absolute readout of resonator amplitudes. The automated phasing system works by momentum analyzing the beam from the LINAC at a 45° port of the target room switching magnet. A feedback loop derives an error signal from fast logarithmic slit amplifiers at the magnet's image point and locks the magnet to the beam. The magnetic field is modulated by a bipolar bouncer supply connected in parallel to the main high-current supply. Interference between these supplies, which could severly impare the dynamics of the feedback loop, is avoided by employing a minor loop derivative feedback system to stabilize the total current in the magnet. With the magnet locked to the beam, resonators are turned on one at a time and stepped by the computer through 360° of phase in 16 steps. At each step the computer reads the magnetic field, via an NMR probe, and deduces the beam energy. The resonator amplitude and phase are calculated from a fit to the energies, the resonator phases are set to a synchronous phase angle of -20°, and downstream quadrupoles are adjusted for the new energy. At present, the process requires about 30 s per resonator, limited mostly by the settling time of the NMR. The system gives good quality data which will be used in the next phase of development to calculate phases for an arbitrary beam. Misalignment problems make operator intervention necessary from time to time, as errors accumulate and steering in the quadrupoles becomes excessive. Gross beam energy adjustments are made by turning off the last resonators and fine adjustments are made by changing the amplitude of the final resonator.

Cryogenics

The BOC Turbocool 100 liquid helium refrigerator reliably delivers its rated cooling capacity of 400W (with LN_2 precool). A turbine failure (non-catastrophic) earlier this year has been the only serious maintenance problem encountered thus far. The standing losses of the modular cryostats satisfy the design specifications of <2W per cryostat. The cryogenic distribution system, on the other hand, has been a major disappointment. Of the 400W generated by the refrigerator, only approximately 140W are actually available for resonator cooling. Excessive losses have been identified in several areas. Losses in the 13 U tubes connecting the cryostats to the main trunk line have been measured to be on the order of 8W, compared to their specified value of 1W. The measurements were performed by balancing the refrigerator against an electrical heater load with no U tubes connected, then adding U tubes and noting the decrease in the heater load needed to maintain balance. Part of these losses have been localized at the cryostat bayonets. Direct calorimetry shows at least 4W are dissipated in this area alone. The main trunk line constitutes a significant load on the system. Use of the balancing technique has shown that on the order of 100W are added when the trunk line is connected to the system. Part of this loss may be due to thermal oscillations. Another loss mechanism is associated with the pressure difference that must be maintained between the storage dewar and the gas return side of the refrigerator. This is the pressure difference that drives the flow to fill the cryostat reservoirs. A fraction of the cold gas that returns from the dewar will liquify during the expansion in the pressure drop. This liquid is unavailable for resonator cooling, but still is included in the total output of the refrigerator. This effect has been estimated to be equivalent to ~30W.

Resonators

Forty resonators have been in service for over two years. On the whole, their durability has been excellent, surviving the test of time and sundry vacuum mishaps. The Qs at operating field levels are stable with time. This is illustrated in figure 2, which shows Q versus field level for a typical high-β resonator measured in 1982 and 1984. Isopower contours indicated in the figure show that within the 4W limitation dictated by the present state of the cryogenic cooling system a field level of 2.2 MV/m is possible, whereas the anticipated cooling power of 8W will allow 3 MV/m.

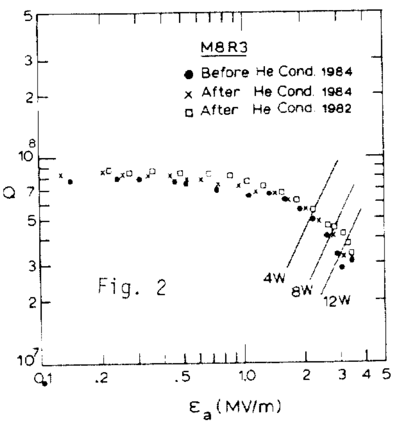

Fig. 2

Every resonator requires two types of conditioning when it is first put on line: helium conditioning and multipactor conditioning. Helium conditioning pushes up the onset of field emission to above operating field level. Multipactor conditioning is done without helium gas in the resonator and utilizes high-power pulsed RF to clean up low-lying multipactor levels which invariably occur in a new resonator. Helium conditioning need not be repeated until the resonator is exposed to atmosphere. Multipactoring, however, depends strongly on quality of the vacuum environment. If the cryostat vacuum deteriorates to $>10^{-5}$T due to air leaks or release of cryo-pumped gases during a warm-up, then multipactor conditioning usually will have to be repeated. In extreme cases involving vacuum accidents, the standard multipactoring conditioning may fail and the resonators are warmed up and baked at 80°C, in situ, for ~48 hours. After baking, the standard multipactor conditioning has always been successful.

The frequency stability of the high-β resonators is very good. Long-term frequency drifts on the order of 30K Hz do occur over the first several months after assembly, but eventually the drifting is complete and the frequency stabilizes. Short-term stability (resonator shaking), while good in the high-β resonators is unacceptably bad in the low-β resonators. In fact, with the 200W of RF tuning power available, it is not possible to keep the low-β resonators phase-locked for a useful fraction of time at field levels above ~1.5 MV/m. Figure 3 is Fourier transform spectra of the instantaneous frequency excursions of a high and low-β resonator on-line in the LINAC. On the left, the spectrum for a low-β resonator has a full scale range of 100 rms Hz and for the high-β on the right, full scale is 1.0 rms Hz. The spectra were both averaged over a 32 S interval. It is clear that shaking in the low-β resonators is very much worse than in the high-β. A bench top study of the two resonator structures revealed that the underlying cause of the very different behavior is that in the high-β resonators, the loop structure is sufficiently rigid that when it moves the two loops move as a unit, whereas in the low-β resonators, the loops move independently and, hence, the coupling between displacement and frequency shift is much larger for the low-β resonators.

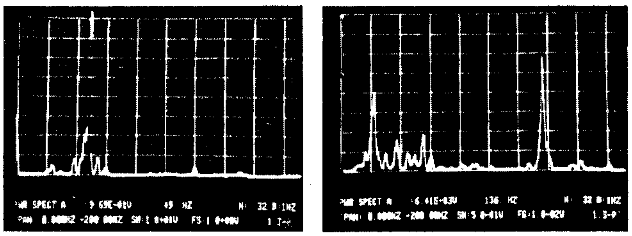

Fig. 3

The Improvements Program

Two major improvements to the cryogenics system will be implemented within the next few months: 1) the capacity of the refrigerator itself will be increased by about 100W by the installation of a wet expander piston engine manufactured by Koch Processing Co. to be used in lieu of the current J-T system. The liquid fraction of the flow from such a wet engine is much higher than from a J-T system: 90% vs. 20%. The "wet engine" will be connected outside to the existing cold box and will be equipped with bypass valves so that the J-T system can be used during periods of light load or maintenance; 2) new U tubes are under construction in the Stony Brook machine shop. They have been engineered without stand-off spacers between 4 and 300K and incorporate a maximum of superinsulation. Small bleed holes have been built into the bayonet assembly to allow a small flow (<1 CFM) of helium from the standing helium column to be bled back directly to the system compressor. This small flow serves to damp thermal acoustic oscillations and intercepts heat flow from room temperature to the helium temperature end of the bayonet. These two improvements will add ∿160W of cooling capacity, enough to permit operation of all resonators at 3 MV/m.

Utilization of this added capacity in the low-β section will require a solution to the excessive shaking problem. The stability of the quarter wave resonator developed at Stony Brook, has been shown to be excellent[4]. Work is under way to replace the low-β split loop resonators with quarter wave resonators. The expense of this program is rather modest because: 1) all the fabrication work will be done in-house, 2) the quarter wave resonators can be retrofitted into the existing cryostats, leaving all external cryogenic and RF components unchanged. Model studies are nearly complete and copper forgings for the first 4-resonator set are on hand. Optimum drift tube geometry is being explored in electrolytic tank studies. The welding scheme developed by Steck[5] will be used. This should eliminate difficulties that have occurred in the past with micro-fissures in cosmetic welds. Table 1 lists the parameters of the new resonator.

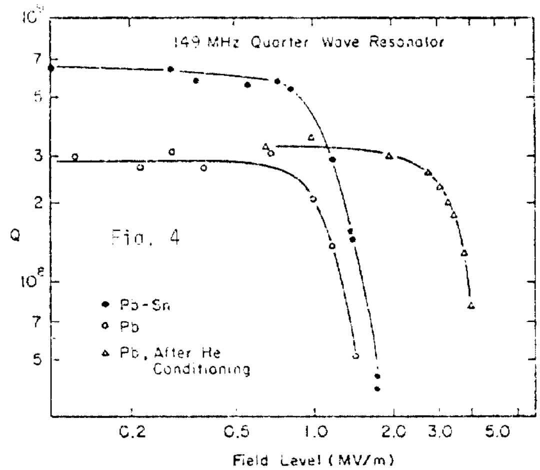

Fig. 4

The power consumption of these resonators is expected to be quite low, based on performance of other quarter wave resonators and on some encouraging new developments in the electroplating technology. Recently, a much higher conductivity superconducting surface has been prepared by plating an alloy of Pb/Sn instead of pure Pb. An average surface resistance of 40nΩ has been obtained in a 149 MHz quarter wave resonator. Figure 4 shows Q versus field level data for this resonator with pure Pb and Pb/Sn alloy surfaces. The Pb/Sn Q exceeds by more than a factor of 2 the best Q yet reported for Pb at this frequency. Field emission behavior with Pb/Sn was typical for this resonator before helium conditioning. This causes the precipitous drop in Q. The range of the variable coupler in these tests was too weak to permit a proper conditioning of the resonator and, thus, prohibiting a full high-field test. The most likely explanations for the superiority of the Pb/Sn surface are: 1) the throwing power of the Pb/Sn plating bath is greater than that of pure Pb. This allows a much thinner layer (∿1 μm) to be plated with full coverage, 2) the Pb/Sn surface is much more stable and resistant to oxidation and, consequently, the post-plating chemical polish procedure is unnecessary. An attempt to force the conditioning of the resonator, even with the weak coupling, by initiating gas discharge in the resonator caused the Q to drop irreversibly to about the pure Pb value. The same lower value of Q was measured at 2.3K, below the transition temperature of Sn, in a test of the integrity of the alloy.

Table 1

Frequency	150.405 MHz
Effective length	17 cm
Optimum ion velocity, v/c	0.065
Acceleration gaps	3.0 cm
Inner conductor length	50.5 cm
Energy content	63 mJ/(MV/m)^2

References

*Supported in part by the National Science Foundation.

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