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THE STONY BROOK SUPERCONDUCTING HEAVY-ION BOOSTER PROJECT*

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Summary

A superconducting LINAC to be injected with heavy-ion beams from the Stony Brook FN tandem is described. The basic LINAC elements are lead-plated copper split-loop resonators operated at a frequency of 150 MHz and a temperature of 4.2 K. With the anticipated effective accelerating gradient of 3.0 MV/m, the booster will provide an energy gain of 20 MeV per charge for (Q=19) ^{58}Ni ions, and have a useful mass range of A=16 to about A=100.

The linac structure consists of compact independent cryostat modules separated by room temperature quadrupole doublets, each module containing four (β=0.055) or three (β=0.10) independently phased resonators. The tandem beam is bunched at the 16th subharmonic (pulse spacing 107 nsec) to facilitate lifetime and flight time measurements. A post-tandem rebuncher system compresses these bunches into less than ±6° around the -20° mean phase of the LINAC. Existing room geometry dictates charge selection after the first as well as the second stripping.

A β=0.055 prototype cavity has already been operated with beam and successfully stabilized to ±0.1° in phase with a computer-controlled RF feedback system. A prototype module of 4 such cavities in a common cryostat is presently under construction.

I. Introduction

The heavy-ion capability of the Stony Brook Nuclear Structure Laboratory will be extended at moderate cost by a superconducting LINAC injected by the existing 9 MV FN tandem. The design goal is an additional effective potential of about 20 MV for Ni ions and a useful mass range from A=16 to A=100. The inexpensive lead-plated copper split-loop resonators developed at Cal-Tech and tested at Stony Brook[1,2] are sufficiently reliable at a level of 2.5-3.0 MV/m to proceed with the design of the LINAC. The design allows for future improvements in the cavity performance up to 4.0 MV/m. Our facility will be similar in overall conception to that proposed for the Argonne FN tandem[3], but it differs in some of the design choices, as discussed below.

II. The LINAC Module

The two basic design decisions were those of a LINAC operating frequency of 150 MHz and that the cryostats be relatively small modular units. The comparatively high frequency was chosen to give a manageable diameter cavity without the complexity of a re-entrant loop geometry.[3] It also reduces the cavity energy content for a given field strength, and hence the RF power required for stabilization. The choice of modular cryostats offers the advantages of fast cryogenic turnaround and easy access. Consecutive modules are separated by room temperature spaces containing quadrupole focussing elements and beam diagnostic and steering devices.

Figure 1 shows the geometry of the prototype 150 MHz cavity. At an average accelerating gradient of 3.0 MV/m this cavity has peak surface fields of E_s=18 MV/m and

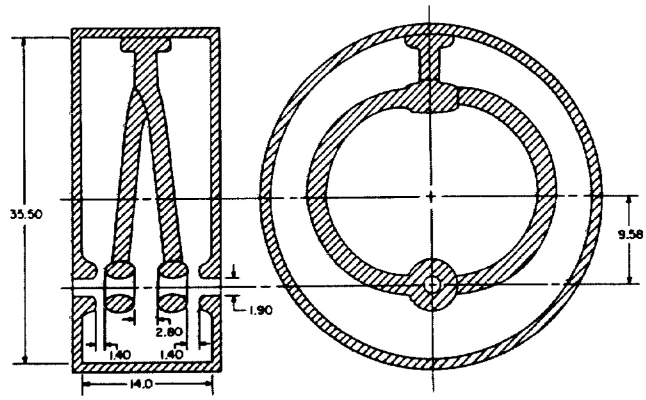

Fig. 1 The β=0.055 150 MHz prototype split-loop cavity. Dimensions are in cm.

B_c=300 gauss, and an energy content of 125 mJ. Most important for a heavy-ion accelerator is the broad beta acceptance curve which results from the fact that the center gap is twice as large as the two side gaps. Figure 2 shows the transit-time curve obtained for this resonator with ^{16}O beams in the manner described previously.[1] The empirical curve fitted to the measured points, which represents the total transit time dependence, is given by $T(R)=[\cos(2R/3)-\cos(\pi R)]/1.794$, where $R= 0.052/\beta$.

Most ions are injected from the tandem with E=72.5 MeV, which for Ni beams corresponds to β=0.052 at the LINAC input and β=0.136 at the output. The broad β acceptance curve allows this range to be covered efficiently with only two sets of resonators, optimized for β_o=0.055 and 0.10. The longitudinal dimensions scale as β_o, leading to inside cavity lengths of 14.0 and 26.0 cm, and axial energy gains of 430 and 780 keV/charge, respectively, at the design field strength of 3 MV/m.

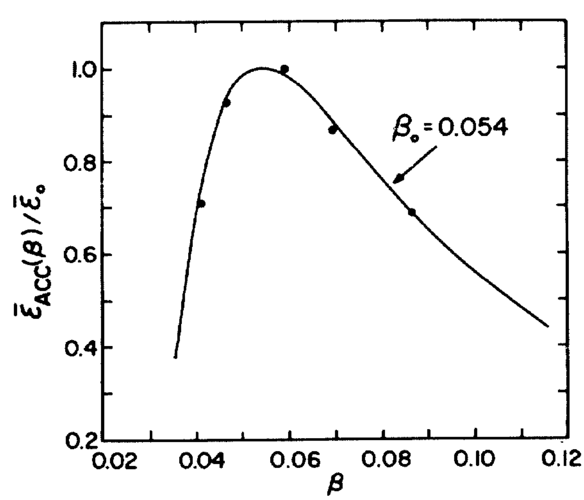

Fig. 2 The measured T.T.F. curve for the low-β cavity.

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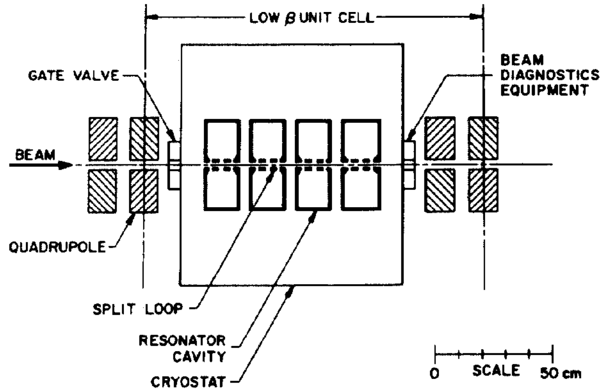

Fig. 3 Schematic (top view) of the low-β unit cell.

The transverse focussing requirements lead to a maximal modular length of 4 low-β or 3 high-β cavities. The unit cell of the LINAC as shown in Fig. 3 then consists of the low-β (high-β) cryostat module and a room temperature quadrupole doublet. Overall length of the unit cell is 145 cm (160 cm) with a packing fraction of 0.40 (0.49).

Each cryostat contains a common He reservoir which cools the resonators by conduction to 4.2 K. All resonators share a common vacuum. Coarse tuning of the resonators is accomplished by a mechanical lever device through step-motors operated at 77 K. The required squeezing force of 0.5 N/kHz is easily realized. Fine tuning and phase stabilization is achieved through RF feedback circuits[4] outside the module to an accuracy of 0.1° of phase. Necessary tuning power is proportional to the frequency range and energy content, $P=\Delta\omega \cdot U$. At 3 MV/m, $P \lesssim 400$ W.

III. The LINAC Structure

The available laboratory space allows a LINAC of 10 modules (Fig. 4). The optimal division into 4 low-β and 6 high-β modules gives a total length for 34 cavities of 15.5 m. At the design field level this LINAC produces 20 MV per charge for Z=19 Ni ions. Final energies achieved for other ions are shown in Fig. 5. Injection conditions are: 9.0 MV tandem potential, gas stripping in the terminal, and foil stripping after the tandem. The highest charge state with an overall stripping efficiency $\gtrsim 2\%$ was selected. With this efficiency beams of $\gtrsim 20$ particle-nA should be obtainable for many elements.

An indication of how efficiently a broad mass range is accelerated by this structure is given by the dashed curve at the top of Fig. 5. This shows the final energy at 4.0 MV/m for an "ideal accelerator" of the same total length in which the transit-time factor is unity in each cavity. The sharp cutoff at about A=100 in the actual LINAC results from the rapid drop of the β acceptance curve at low β's and the increasingly inefficient stripping. This cutoff also corresponds to the natural limit where the final energy per nucleon ($E/A \gtrsim 5$ MeV) equals the Coulomb barrier for Pb.

Although more realistic beam dynamics calculations have been performed, the focussing requirements along the LINAC structure are most easily presented in the (semi)periodic approximation. Figure 6 shows the quadrupole field strengths required for stable acceleration of a Mo beam at 3.5 MV/m cavity field using 30 cm long quadrupole doublets (Fig. 3). Stable operation over a phase range of ±10° around $\phi_s=-20°$ requires a field strength of 2.5 kG/cm quite uniformly along the entire accelerator. Also shown is the quadrupole field distribution corresponding to a radial phase advance of $\mu=45°$ per unit cell. The input transverse acceptance associated with this curve is very large, $A=37\pi$ mm·mrad, for a quadrupole gap radius R=1.5 cm. Thus standard quadrupole elements capable of pole-tip fields up to 4 kG are quite adequate. Maintaining a constant acceptance A along the accelerator (solid curve in Fig. 6) leads to field levels slightly lower at the end of the LINAC than at the beginning.

Under the above focussing conditions the longitudinal acceptance $\Delta W\,\Delta\phi$ of the accelerator is also large. Heavy-ion beams have been routinely bunched into time intervals $\Delta t=\pm 100$ psec[1], corresponding to a phase interval $\Delta\phi=\pm 5.5°$ at 150 MHz. The energy spread ΔW for a matched condition is related to the phase spread by $\Delta W=(\beta\lambda W Z E_0 \sin\phi_s/\pi)^{1/2}\Delta\phi$ where β, W and Z are the input ion velocity, energy and charge, $\lambda=2.0$ m is the RF wavelength, E_0 is the effective accelerating field gradient, and $\phi_s=-20°$ is the synchronous phase. The accelerator is easily matched to a wide range of ions, e.g., $\Delta\phi=\pm 6°$ corresponds for Ni to $\Delta W=713$ keV, for Mo to $\Delta W=730$ keV. However, since ΔW scales as $(\beta W E_0)^{1/4}$, this energy spread

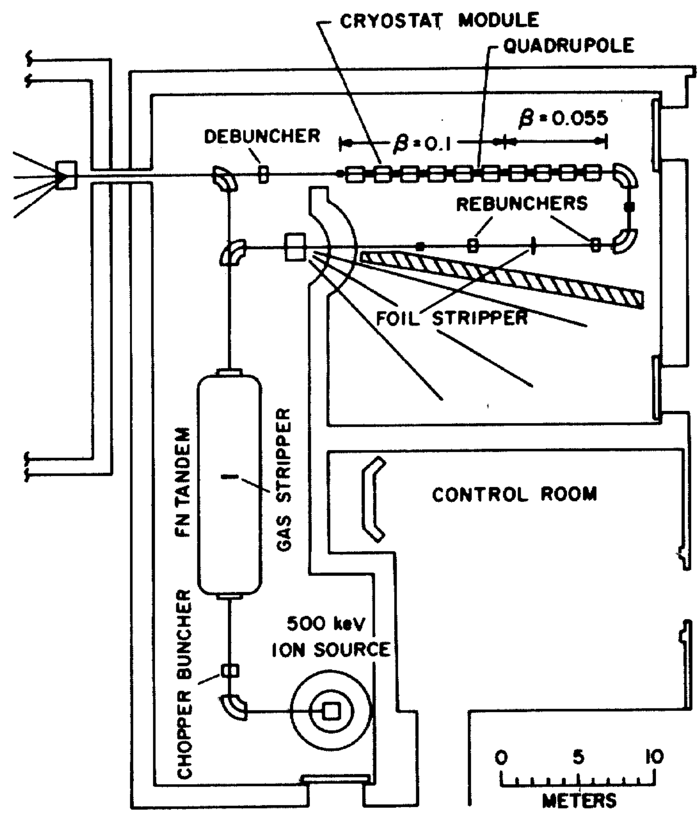

Fig. 4 Overall layout of the Stony Brook Laboratory.

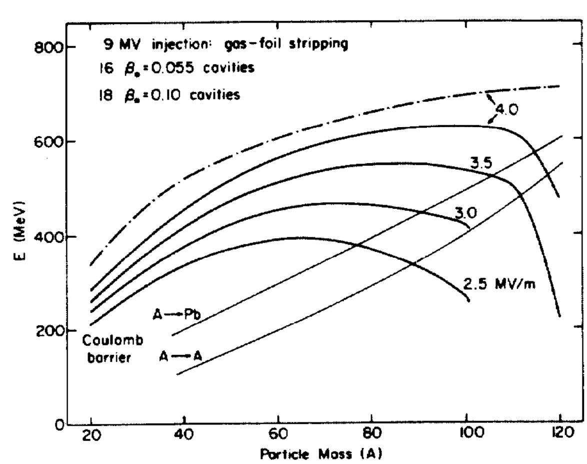

Fig. 5 Final ion energies as a function of A.

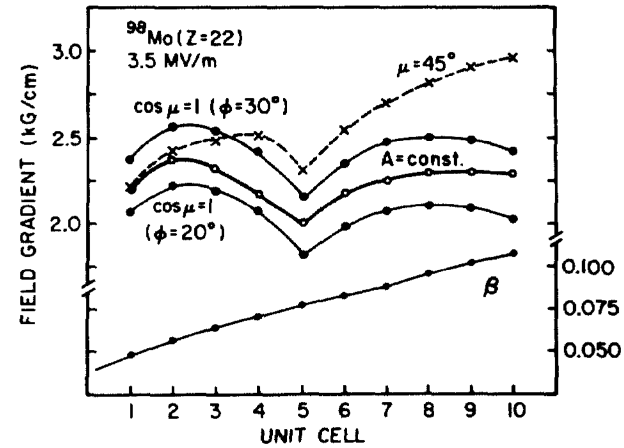

Fig. 6 Quadrupole fields required for radial stability.

becomes twice as large at the LINAC output, leading to an overall energy resolution of $\Delta W(out)/W(out) \cong 2.5 \cdot 10^{-3}$ Improvements are possible by injecting into ±35 psec, as demonstrated at Heidelberg[5], or by debunching the beam at the output. We note that the present detector capability, $\sim 5 \times 10^{-3}$ in energy resolution, is worse than the direct output resolution.

The cavities will operate at $Q \cong 10^8$. The cooling power needed at 4.2 K is estimated as 7W/MV or about 140 W. Quiescent losses are $\sim$2 W/module. The total refrigeration power of 160 W corresponds to a plug power of $\sim$130 kW if the refrigerator is operated in a closed-loop configuration. The RF stabilization of 34 cavities will require less than 20 kW and another 20 kW is estimated for maximum quadrupole operation.

IV. Injection into the Booster

Figure 4 shows the room geometry which applies to transferring the beam from the tandem to the booster. It has the advantage that the beam may be alternatively switched into the booster or directly deflected into the target area through a bypass line.

In parallel with the LINAC design, work is proceeding on upgrading the tandem and ion source for use with heavy ion beams. The main considerations are high transmission and good timing characteristics. Both will be improved by installation of a variable energy 500 keV open air ion source with a specified short time stability of ±25 eV. Beams will be chopped and bunched at the 16th subharmonic of the booster frequency, 9.38 MHz. The resulting bunch spacing of 107 nsec is considered optimal for heavy ion time-of-flight and lifetime measurements. Improvements to the tandem itself will allow stable operation ($\Delta V_T < 1$ keV) at terminal voltages V_T up to 9.5 MV. Realistic calculations indicate that beams up to A=100 can be bunched into Δt=1 nsec after the 90° analyzing magnet.

The 180° turn required before injection into the LINAC provides the opportunity for charge state selection after the second (foil) stripping. Compact K=30 90° double-focussing magnets can be employed after stripping, and the symmetric system shown in Fig. 4 is isochronous and achromatic. The energy spread introduced by the foil stripper is universally $\sim$80 keV; for heavy ions because of the large energy straggling, and for light ions because of the rather thick foils required for high equilibrium charge states.

To minimize the effect of the stripper on the transverse and longitudinal phase spaces the stripper must be placed at a sharp space and time focus. To do this in the present geometry requires two (split-loop cavity) rebunchers. The first rebuncher compresses the 1 nsec beam bunch to a time waist at the stripper with $\Delta W \cong \pm 300$ keV. The second rebuncher then forms a second time waist at the entrance to the LINAC with $\Delta W \cong \pm 200$ keV and $\Delta t \cong \pm 30$ psec; the axis ratio $\Delta W/\Delta t$ thus fulfills the matching condition $\Delta W/\Delta t \cong 7$ keV/psec.

Under these conditions the beam enters the booster with transverse and longitudinal emittances no larger than twice the values ($\sim 1\pi$ mm$\cdot$mrad, $\sim 5\pi$ keV$\cdot$nsec) expected from the tandem. Both emittances are much smaller than the respective acceptances of the LINAC. Having a time focus at the foil stripper also allows a precise determination of the arrival time of the bunch (needed for precise phasing to the LINAC) by detecting the copious electrons emitted from the stripper foil.

V. Present Status and Timetable

The prototype β_0=0.055 cavity has now been operated extensively with heavy-ion beams from the Stony Brook tandem at field levels of 2.5 MV/m. The resonators can be fabricated reliably using the established lead plating and chemical polishing procedures, and they retain their properties under beam line vacuum conditions. Phase stabilization has been demonstrated to ±0.1° with the RF feedback circuit operated under computer control.[4]

As the next step, the first full module with independent phase control for all 4 resonators is presently under construction. The cryostat design, coarse tuning devices and control electronics are prototypes for the full accelerator. This module will be tested in-beam in the fall of 1977. Following successful operation, the beginning of full scale construction is anticipated early in 1978.

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