PARTIAL ENERGY BEAMS FROM AN ION LINAC*

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Introduction

Under normal operating conditions, the HILAC at Berkeley accelerates ions in the mass region below argon to an energy of 10 MeV/nucleon.[1] This energy was chosen so that ions bombarding the heaviest target nuclei would be well above the coulomb barrier, and a good reaction rate would be obtained.

To date the elements which can be readily obtained in gaseous form and lithium ions, derived from the pure metal, have been accelerated. These particles represent two-thirds of the elements from hydrogen to argon on the Periodic Table.

An important part of the experimental program with heavy ions has been the study of nuclei excited by the coulomb forces between projectile and target nuclei. In these experiments it is important to eliminate the possibility of nuclear reactions by keeping the projectile energy below the coulomb barrier. Initially beams of various ions in the range from 2.5 to 5 MeV/nucleon were produced for these experiments by putting absorbers in the 10 MeV/nucleon beam. However, the increase in energy spread, multiple scattering, the sensitivity of many of the experiments to neutron and X-ray background, and destruction of the absorber foils by the beam limited the effectiveness of this method. These difficulties have been eliminated by tuning the HILAC so that partial energy beams are produced without absorber foils.

In a multi-cavity linac, of course, the beam energy can be lowered by turning off the rf fields in the later cavities and drifting the beam through them. Partial energy beams with energies that normally would be obtained within a cavity have been observed in many linacs when they have not been tuned correctly. Normally the energy spread has been large, and it has usually been desired to eliminate the effect rather than to exploit it.

At Berkeley and Minnesota, usable partial energy proton beams have been produced by changing the tuning conditions.[2, 3] However, higher intensity and better energy resolution could be obtained at Minnesota by installing a diaphragm in the cavity to keep the rf fields out of the high energy end.[4] Operation with the diaphragm was enough better that it was worth opening up the cavity before and after the partial energy experiments to install and remove the diaphragm.

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At the HILAC and, more recently, at the heavy ion linear accelerator at Manchester, partial energy beams of intensity more than half the normal intensity for full energy beams have been obtained by changing only the tuning conditions. The energy spread is comparable to that of the full energy beam. While tuning for the partial energy beams is more critical than for full energy beams, stability of operation has been satisfactory.

HILAC Cavities

The 70 mHz linac is divided into two Alvarez cavities (Fig. 1). The beam is injected into the first cavity (pre-stripper tank) by a Cockcroft-Walton injector at an energy of 70 keV/nucleon ($\beta = 0.012$). The pre-stripper is a 15 ft (4.6 m) long grid-focussed machine that accelerates the ions to 1 MeV/nucleon ($\beta = 0.045$). Between cavities electrons are stripped from the ions by passing the beam through a thin beryllium-oxide foil. The second cavity (post-stripper tank) accelerates the particles to their final energy of 10.3 MeV/nucleon ($\beta = 0.15$). Focussing is provided by quadrupole magnets in each of 67 cylindrical drift tubes. The quadrupoles are connected in groups of two, except for the first one and the last six which are connected to individual power supplies. Each group can be tuned independently of the other groups.

The post-stripper cavity is 90 ft long (27.4 m) with an electrical length of 6.4 λ. To reduce sparking at the input end and still maintain a high average rate of energy gain, the design value of the average rf electric field along the axis was tapered linearly from 1.45 MV/meter at the input end to 1.92 MV/meter at the exit end. The linear tip in the gradient is provided by adjusting the position of half drift tubes in the two end walls. These end tuners can be adjusted remotely from the control room so the tip can be tuned for optimum beam. Prior to the recent conversion to increase the duty factor from 3% to 30%[5], it was possible to trim the "flatness" of the fields with 11 L-C tuners mounted on the side wall of the cavity. The side tuners had not proved to be important to the full energy operation of the machine.

The post-stripper was designed to accelerate ions with charge-to-mass ratios between 0.3 and 0.5. In order for a beam of a particular e/m ratio to be successfully accelerated through the cavity the voltage level must be adjusted to its proper value corresponding to that e/m. The same rf gradient tip is used for all full energy beams.

RF Monitoring

Fifteen small pick-up loops mounted along the side wall of the tank are used to measure the rf field distribution by monitoring the azimuthal component of the rf magnetic field, H_φ. These probes were constructed and positioned in the cavity with considerable precision. Before mounting in the accelerator cavity, their calibration was checked against a standard probe in a test cavity, and their response was found to be identical to within a few tenths percent. The rf signals are detected with diodes mounted permanently on each probe and cathode followers are used to drive the cables to the control room where the signals are presented on a CRT. It is believed that this system gives relative readings of the H_φ at different points along the length of the cavity to within 5 to 7%. Unfortunately the relation between H_φ and E_z is not known; however the mesh programs for cylindrical drift tubes are being improved at low β and it may now be possible to calculate H_φ/E_z for this tank.[6]

Partial-Energy Beam Tuning

To tune for a partial-energy beam, the tip of the rf field is reduced from its initial value of $H_\varphi(15)/H_\varphi(1) \simeq 1.4$. Figure 2A shows the values of H_φ measured by the 15 probes displayed simultaneously on a CRT as they appear during normal acceleration of a full-energy beam. The tip is reduced by adjusting the two end tuners in such a way that the resonant frequency of the cavity stays fixed.

As the tip in the H_φ distribution is reduced, groups of ions with energies in the region of 5 MeV/nucleon begin to appear and the intensity of full-energy beam decreases. Finally as the tip is further reduced to $H_\varphi(15)/H_\varphi(1) \simeq 1.1$, all of the beam is located in the partial-energy peaks. The rf field distribution in this situation is shown in Fig. 2B.

Figure 3 shows a typical full-energy spectrum for the total beam at the exit end of the post-stripper. The spectrum was obtained by scattering a small fraction of the beam into a solid-state energy-measuring detector coupled to a multi-channel pulse height analyzer. The width of the full energy peak at half maximum is about 0.7%.

The partial-energy spectrum as a result of simply flattening the gradient tip is shown in Fig. 4. It can be seen that the energy peaks are not of the same intensity.

To find groups of energies lower than those of Fig. 4, the rf tip is further reduced, as shown in Fig. 5, until the very lowest peaks are obtained when the tip is actually slightly less than 1:1.

Normally a particular energy peak is selected by magnetically analyzing the beam in the target cave. Once the desired peak is on the target, the beam intensity and focus can be optimized by additional tuning of the machine, in the same manner as a full-energy beam.

The effect of this optimization is quite striking in that most of the beam can be made to come through at the selected energy, rather than merely eliminating the particles in the unwanted peaks. To achieve this result, it is necessary to adjust all the tuning parameters of the accelerator including the quadrupole magnets in the drift tubes, the difference in phase between the rf fields in the two cavities, and the rf power levels in the two cavities. Sometimes adjusting the side tuners in the post-stripper cavity has seemed to help, but it is not clear that this is necessary.

While tuning partial-energy beams, the most significant difference noted in the machine behavior is an increased sensitivity to changes in the tuning parameters. In particular the rf level must be controlled to ± 0.2% for stable operation, compared to ± 1% for full-energy operation. Just as for full-energy operation, all parameters are optimized during tune-up, and their increased sensitivity combined with the normal complexities of operation can lead to many hours of tune-up time when searching for a beam energy previously not attempted.

Once beam of a given ion at a given energy has been found and tuned-up to any degree, regardless of the difficulty in initially finding it, the machine can be quickly re-tuned to that energy for any subsequent run simply by reproducing the values recorded for the different parameters. If the change involves only a small change in output energy (as opposed to switching to a different ion) re-tuning can usually be accomplished within an hour. This experience with the HILAC is as good or better than that with variable-energy cyclotrons such as the 88-inch machine at Berkeley.

Characteristics of Partial Energy Beams

Tuning for optimization of beam at a selected energy typically results in a spectrum like the one shown in Fig. 6. The very low energy beam that shows in this photograph is from beam scattered off the walls of a narrow vacuum chamber. The beam in this case has an energy of 5.8 MeV/nucleon and its full width at half maximum is 0.14 MeV/nucleon or 2.5%. Other partial energy peaks which have been analyzed have energy spreads of the same order. At times resolutions as good as 1.5% have been observed.

The experiments a few years ago required spending long periods maximizing the beam through collimators as small as 2 x 2 mm. After such tune-up partial-energy beams with currents above 60% of the full-energy beam could be focussed through the collimator. At times the full-energy beam current can even be equalled at partial-energy through small collimators. Since the conversion to higher duty factor and the development of sensitive germanium counters such careful tuning has not been necessary. The partial energy beams that have been used at the HILAC during the past six months are listed in Table I. Beams corresponding to most of the blanks in the table were not attempted during this period. However in the case of He, some of these energies were attempted. Small amounts of beam could be found, but attempts to tune them up and obtain large currents were unsuccessful. It is significant that the same partial energy can be obtained with different charge states of a given atom. For comparison, the table also shows the design energy at the various drift tubes for normal full-energy operation. It is seen that, in some cases, the differences in the energies that have been obtained for a given ion are comparable to the energy gained in a single gap.

The 70 mHz rf structure of the HILAC beams has been observed with a sampling oscilloscope. The oscilloscope was connected to two signal lines of equal electrical length. One line monitored the rf signal from a tank probe, and the other was attached to a beam interceptor at the exit end of the post-stripper. Figure 7 shows the beam in relation to the rf when tuned for partial and for full energies. Figure 7A shows the normal full-energy beam in its bunched packet of approximately 75 degrees. Figure 7B shows the 5.8 MeV/nucleon beam of Fig. 6. Although having a small energy spread, it has debunched completely and emerges with uniform intensity during all parts of the rf cycle.

Discussion

It is tempting to explain this type of operation by assuming that the beam moves outside the stable phase bucket at some point in the machine. The energy of an unstable beam drifting through the rest of the cavity should fluctuate, but the average net gain should be zero. This picture is qualitatively consistent with what is observed, but it is difficult to explain in this way the small energy spreads than can be obtained. Further experiments and orbit studies using the Parmila program are planned to improve our understanding of the process.

Two unusual features common to the HILAC and the Manchester linac, two machines which operate successfully with a partial-energy beam, are of interest:

1. Both machines use large bores in their post-stripper cavities (at Berkeley the bore varies from 2.0 inch to 3.5 inch), and both use quadrupole focussing. The large bore allows freedom to maneuver the low emittance beam from the pre-stripper in the transverse space without losing it. The important part tuning the individual groups of quadrupoles plays in producing the partial-energy beams suggest that this feature might be significant.

2. Each machine injects beam into these cavities with a grid-focussed tank having a very narrow (~ 35°) band of stable phases. In the tune-up procedure, phasing of the pre-stripper rf relative to the post-stripper and the rf levels in both cavities are important parameters for optimization. It is possible that these adjustments set up a coherent oscillation in longitudinal phase space that is important in producing a partial energy beam.

The importance of these two features has not been established, but good variable energy operation with a linac that does not have them has not been reported.

Although the mechanism of partial-energy beam production is not fully understood, the fact that new energy peaks can be systematically found and beam energies previously run can be re-tuned from recorded data, makes this mode of operation an extremely valuable tool in the HILAC experimental program. A new drift-tube magnet control system is presently being installed that will make it possible to exploit these characteristics with even greater speed and flexibility.

We wish to acknowledge the important contribution that R. M. Diamond and F. S. Stephens have made to this work. Their interest and cooperation played an important role in developing the partial energy beams. We are also indebted to the HILAC operating crew for many hours of patient and careful tuning of the accelerator, and to E. C. Hartwig and T. Sikkeland for their work in connection with these studies.

References

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DISCUSSION

E. HUBBARD, LRL

CAMERON, Yale: Did you make some comment that you also change phase relationships between the pre-stripper and the post-stripper?

HUBBARD, LRL: Yes, we're doing this as a part of the tuning procedure.

CAMERON: How about the buncher, any changes there?

HUBBARD: In that procedure, no.

VOGEL, ANL: What are you using your beams for?

HUBBARD: These partial energy beams in the region of 3- to 5-MeV nucleon are used primarily for coulomb excitation experiments. Hence, you want to make sure that the beam is below the coulomb barrier, and you don't get a lot of contaminating nuclear reactions. The heavy ions are particularly useful for coulomb excitation experiments.

VOELKER, LRL: In reference to Cameron's question, you might point out that this seems to be a function of the large bore.

HUBBARD: Yes, I should mention that similar partial energy beams have been found at Manchester at the heavy-ion linear accelerator there, and one property that our HILAC and the Manchester machine have in common is that we have 2-in. diameter bores in the post-stripper tank. We're injecting into them with a quite small diameter beam so this gives you quite a bit of freedom to maneuver the beam in the transverse space without losing it. Being able to do this might possibly be important.

BOUSSARD, Orsay: I would like to say that I have found such partial energy beams in a little Sloan-Lawrence linac without any focusing device (quadrupoles or grids). Intermediate peaks may easily have higher currents than the full energy beam, and their energy spread is quite small. I would be very interested in any theory about this phenomenon.

HUBBARD: I think that most everybody that has had a linac has had it mistuned at some time so they have seen some of these partial energy beams. But normally the energy spread is quite large, and the intensity is not as high as the full energy beam. Most people have not been as interested as we have in tuning them up and trying to make use out of them.

PANOFSKY, SLAC: I might mention that in the 32-MeV Alvarez linac, the proton-proton scattering experiments of Cork and Johnston were done with the beam tuned up at low-energy peaks.

Table I

The energies of the various ions that have been accelerated during the past six months are given in MeV/nucleon. The next to last column is a list of energies in MeV/nucleon that the ions have during normal full-energy operation in the drift tube specified in the last column. Accurate comparison of energies listed in different columns should not be made.

He^4	B^{11}	C^{12}	N^{14}	O^{16}	F^{19}	Ne^{20}	A^{40}		Design Energy	Drift Tube No.
				3.75					3.73	32
3.80									3.85	33
									3.96	34
									4.11	35
4.22									4.24	36
				4.37					4.38	37
4.45									4.52	38
4.70							4.69		4.66	39
				4.88					4.80	40
4.95	4.91	5.00		4.96					4.95	41
				5.19	5.07				5.10	42
		5.34		5.31					5.25	43
5.37				5.47	5.47				5.41	44
		5.51		5.56		5.53			5.57	45
5.65				5.69		5.60			5.73	46
		5.81			5.95	5.90			5.89	47
		6.05	6.00	6.04					6.06	48
6.15			6.18	6.16						
6.235									6.23	49
		6.44			6.48				6.41	50
		6.64		6.59		6.59			6.58	51
6.82				6.80					6.76	52
					7.05				6.95	53
									7.14	54
									7.33	55
7.60				7.60		7.57			7.52	56
									7.72	57
									7.92	58
									8.13	59
				8.28					8.34	60
8.45									8.55	61
									8.77	62
									8.99	63
									9.21	64
9.30										
									9.44	65
9.62									9.67	66
									9.90	67
10.37									10.14	68

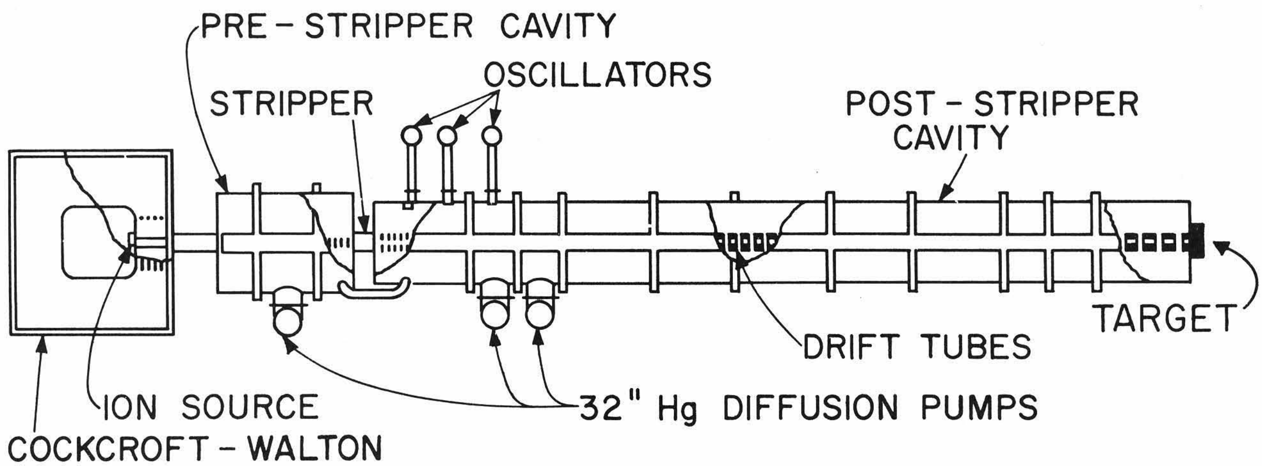
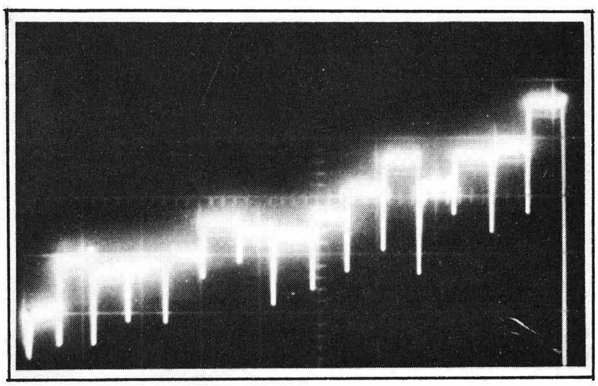


Fig. 1. Schematic plan-view of the Heavy Ion Linear Accelerator (HILAC).



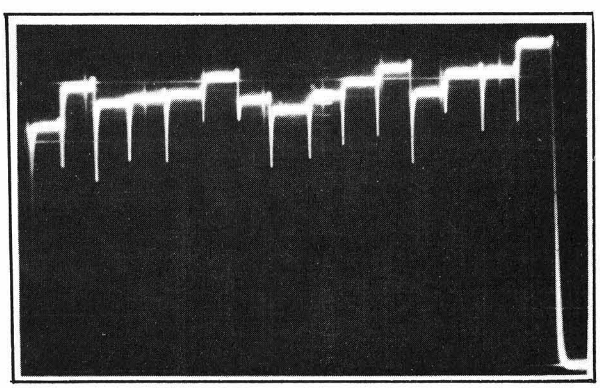


Fig. 2a. A CRT display of the 15 rf field monitoring probes with the baseline suppressed. The output-to-input end gradient ratio is 1.5:1.0.

Fig. 2b. After reducing the rf field tip, the probes show a ratio of 1.1:1.0.

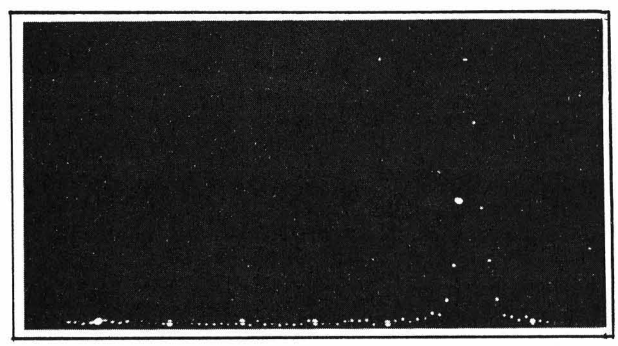


Fig. 3. The total beam energy spectrum for 10.3 MeV/nucleon $^{+4}C^{12}$ ions at the end of the post-stripper. The beam was scattered 10° from a thin foil and measured with a crystal detector. A pulse generator was used as a gain check on the multi-channel analyzer.

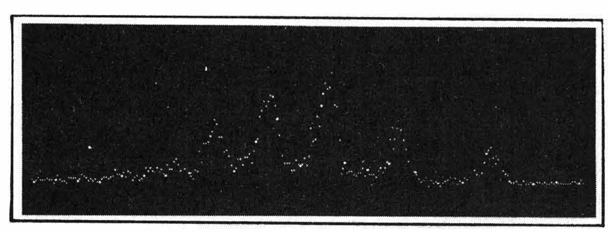


Fig. 4. Simply reducing the tip of the rf gradient causes a group of energies in the region of 5 MeV/nucleon to appear with no full-energy beam remaining. Note that the beam currents of the different $^{+6}O^{16}$ energy peaks are not equal.

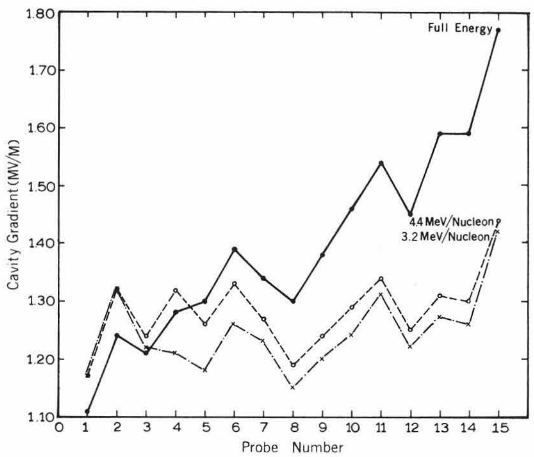


Fig. 5. The rf gradient tip is shown for three typical beam energies of $^{+6}O^{16}$ ions.

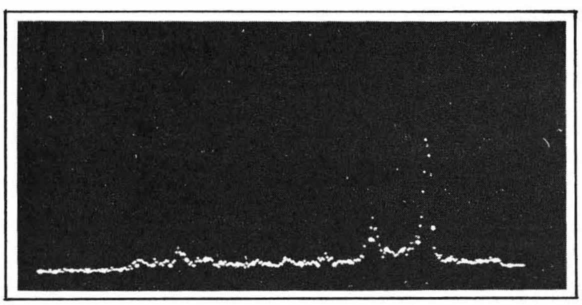
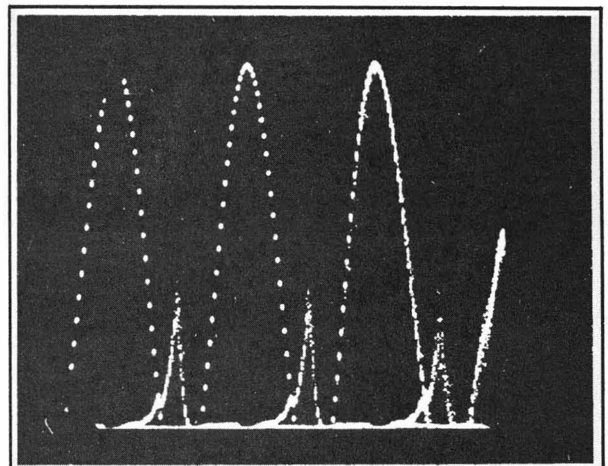


Fig. 6. After careful optimization of the HILAC tuning parameters almost all of the $^{+4}C^{12}$ beam is in the 5.8 MeV/nucleon energy with only one other peak remaining of the initial group. The very low energy peaks are due to beam scatter from the vacuum chamber walls.



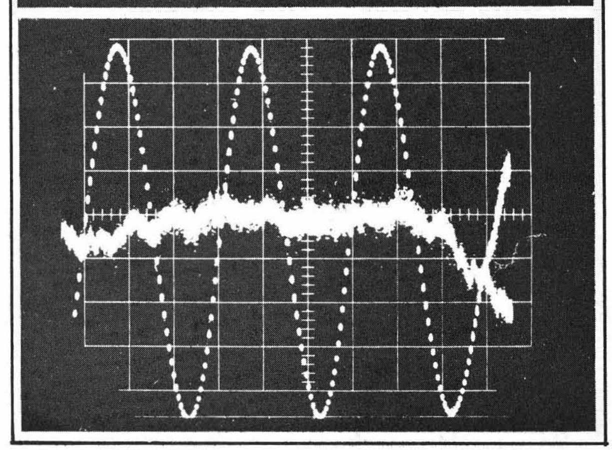


Fig. 7a. The full energy beam pulse is shown simultaneously with the 70 mHz rf. No corrections have been made for phase change due to the drift length from the post-stripper exit to the target electrode.

Fig. 7b. Complete debunching of the 5.8 MeV/nucleon beam is shown. There is a noticeable decrease in beam level during the phase angle corresponding to normal acceleration of full-energy beam; however, the total beam current at partial energies can exceed 60% of the full energy, even through small collimators.