PROGRESS WITH THE SUPERHILAC*

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Within the last six weeks we have made great strides toward making the SuperHILAC a viable super-heavy ion accelerator. As you may know we have encountered some unforeseen difficulties so the purpose of my talk will be to discuss some of these troubles and give a progress report on the machine.

Fig. 1 is a photograph of the SuperHILAC taken about a year ago before the shielding was put in place. The accelerator consists of two sections of Alvarez-type 70 MHz linac provided with ions from either of two dc injectors. The injector at the bottom of the photograph, designed to accelerate positive ions with q/A as small as 0.045 through a potential of 2.5 MV, was built with R&D funds from the ill-fated Omnitron project which was the predecessor of the SuperHILAC. The other injector, not visible but located through a door to the right, is our old 500 kV unit updated by means of a new power supply and column to 800 kV for use with positive ions with $q/A \geq 0.14$.

The SuperHILAC was built at the "bare bones" level at a cost of about 3 million dollars. The old HILAC was simply removed from the building and replaced with the new accelerator. The old power supplies were used to a large extent with some new modulators and control circuits and the 70 MHz high power amplifier circuitry was completely revamped. The accelerator design and construction was directed by Robert Main and revolves around his unique tape-wound magnetic quadrupole. This quadrupole which he has discussed in previous accelerator conferences achieves an extremely high magnetic gradient in a very small space and makes it possible to use strong focussing in each of the short drift tubes that become necessary at our low injection velocity (112 keV/A). The highly precise magnetic field shapes were achieved by a clever computer program developed by Klaus Halbach. Fig. 2 shows a quadrupole under test to check the flow of the freon-113 coolant.

The linacs were built and installed in a remarkably short time. On February 9, 1971 the old HILAC was turned off and a little over a year later on April 20, 1972 a new full energy beam of $^{+3}N^{14}$ ions was obtained. The mechanical staff under Ken Mirk and the electrical staff under Bert Kortegaard had performed heroic deeds and richly deserved the congratulations on their accomplishment. We were elated of course but this was beam from the 800 Kv injector so that we were limited to beams of argon or lower in atomic number.

Our funds were so limited that we were forced to devote all of our efforts to the really new parts of the SuperHILAC project, the linacs and their components. We were very successful in this regard as it was soon evident that Bob Main's design was adequate in every way. We have never had a failure of a drift tube quadrupole, we have achieved our design RF gradient, and our cryogenic pumping system is superb. Incidentally, our accelerator was the first to utilize this method and we routinely operate in the 10^{-7} torr region. We find it to be inexpensive, clean, and very forgiving of errors in contrast to the old diffusion pump methods and we plan to extend the method to the experimental areas. Fig. 3 shows the interior of the pre-stripper tank with the 20°K cryopumping line near the bottom of the tank.

The 3 MV injector had been constructed with R&D funds but had not yet been thoroughly debugged. In retrospect we might have realized that this was the weakest link in our machine. At first it didn't seem that this would be the case since the new uncharted areas were in the basic linac design and the 3 MV injector was a modification of existing designs with relatively few innovations. We really had no choice because the limitation of funds became evermore depressing and we felt that we were doing well if we could overcome the reduction caused by inflation alone. The Nuclear Chemistry Division of the AEC was the source of our funds and it worked very had to increase our support. Eventually an extra 0.3 million dollars was added to the $2.7 million that was appropriated by Congress for the SuperHILAC conversion project.

With the machine working well with light ions we next turned our attention to the 3 MV injector since it soon became evident that we had problems with it and much more electrical and mechanical effort would be required before it could supply very heavy ions. The injector high voltage power supply is a shunt-fed rather than series-fed voltage multiplier operating at 100 KHz with solid state diodes. Fig. 4 shows a schematic layout of both injectors relative to the pre-stripper. Initially we had had a high voltage breakdown problem with the 800 KV injector since we had substituted a new series-fed power supply with a higher voltage capability than the old one, and we had been able to fix that problem in a few weeks with a concentrated effort. The high voltage problem that we now had to tackle with the 3 MV machine was something else.

The entire system is enclosed in a pressure vessel operating at about 200 PSI nitrogen plus 10% CO_2 pressure. The terminal is very small-about four feet in diameter and five feet long - making access difficult and control problems severe. The terminal vacuum system uses a small cryopump operating at 20°K. Our first big problem was that we couldn't get up to a reasonable high voltage without initiating violent crowbar action, often blowing up rectifier and control circuitry. For some weeks we chased the will-o-the-wisp problem. We weren't certain whether the basic difficulty was inside or outside of the beam column, whether the voltage multiplier was at fault or its control equipment. The symptoms were not consistent; it took some time to isolate faults since we had to be careful to protect the equipment itself. This involved redesigning and rebuilding much electronics hardware. It seemed often as if we introduced as many problems as we solved! The terminal voltage was not the only recalcitrant factor for we soon found that there was erratic and marginal operation of the ion source magnet, arc, and extractor power supplies. To make matters even worse there were difficulties with the high speed light beam telemetry system used for control because of transients caused by the spark discharge problems. And of course all of the problems could only be attacked in series as usual!

As you can imagine it took considerable time to discover and correct the faults. If we had been able to put enough man-hours into the 3 MV part of the project in parallel with the building of the linacs we would not have been delayed at all. Since we had many experimental groups waiting to use the accelerator we have made the lighter ions available to them so that they could debug their own equipment. Principally we have concentrated on ^{40}Ar and have been able to furnish stable beams with variable energy for a variety of experiments. Intensities have been modest, usually in the range between 1 and 100 nanoamperes average meter current and in the last few months we have tried to run the accelerator about half of the time for experimenters with the other half devoted to construction and beam studies.

Before the machine was built we knew that its operation could be very complex. This comes about because a magnetically-focussed linac will allow injected ions to pass through its drift tube apertures under a wide variety of conditions of velocity, phase, and gradient. The old HILAC with its grid-focussed pre-stripper would only work over a particular range of these parameters - the pre-stripper acted as a velocity filter - so that tuning was relatively straightforward to attain full energy acceleration. And this is what we observed of course - almost anything that we injected into the new pre-stripper would come out, though not necessarily at the proper energy and phase! Since at first we had no simple way of measuring these quantities acceleration of the stripped beam through the post-stripper was somewhat hit or miss and often very tedious and difficult.

Fig. 5 is an energy-gain diagram and shows why this must be so. The input velocity corresponds to an energy of 112 keV per nucleon with a tolerance of a percent or two. For a light ion such as argon this presents no great problem since the proper charge state and injector voltage can be readily obtained but when ions of krypton or heavier are to be accelerated the difficulties quickly multiply since there are many more charge states and other isotopes whose masses are nearby on a percentage basis. After the ions are accelerated to 1.20 MeV per nucleon they pass through a 5-10 μgm/cm^2 carbon stripper foil with the attendant production of the equilibrium charge state distribution. This complicates the situation considerably for they can all be accelerated to some extent by the succeeding post-stripper sections and thus give rise to ions with various energies. Eventually we will have a magnetic analyzer section through which the stripped beam will pass in traversing the distance between the two linacs so that we will be able to select a particular charge state for acceleration through the post-stripper but we do not have this now. As a consequence we have had great difficulty in developing new beams. The old-fashioned diagnostic technique which simply bends the beam magnetically into a faraday cup depends on the equation

$$B\rho = \frac{mv}{q} \qquad (1)$$

and both the momentum and charge state may be unknown after passage of a beam through the post-stripper tank. What is obviously needed is a simple direct measure of the energies of the particles.

The conventional method of measuring heavy ion energies has been to scatter the particles through an angle of 10°-30° into a semiconductor detector. This is an adequate technique for an experiment designed to use a limited range of particles and energies. In our case where we wish to measure energies from 0.1 to 8.5 MeV/A for ions from ^{12}C to ^{238}U and intensities from single events to hundreds of microamperes this method is simply not good enough. Placing the semiconductor detectors directly in the beam eliminates most of the problems of measurement if the intensity of the beam can be reduced to a level that can be handled by the crystal.

The methods of attenuation that have been used in the past have not been very satisfactory or reproducible; we have used fine-meshed metal screens in tandem, for example. It occurred to me that an ideal attenuator would be thin sheets of mica with tiny holes penetrating through them with the desired area and spacing. We exposed 2 mg/cm^2 mica normal to spontaneous fission fragments from a ^{252}Cf source and then etched the sheets with HF acid in the usual manner. Typically we use attenuators with ~ 10^4 holes/cm^2, each hole ~2 microns in diameter, so that we can readily achieve enormous attenuation factors as desired. In practice we use the metal screens to reduce beams to the microampere level so that the mica attenuators will not be damaged. These attenuators are placed in the beam lines leading to the pre-stripper so that any scattered particle is immediately lost. As a result, the energy spectra measured by the crystals do not have the typical low energy tails that one observes when using the scatter-foil technique. Neither are there any corrections to be made in the spectra corresponding to increased scattering yield for lower energy and smaller angle. Since there is no scattering foil there is no additional correction for energy or atomic number. The only corrections that need to be made are for energy losses caused by the crystal window and the so-called "ionization defect"; these have to be determined by calibration.

This diagnostic technique was put into service with immediate success. Calibration of the crystals was made with 5.476 MeV alpha particles from ^{241}Am. Two ions with the same q/A were used simultaneously, $^4He^{1+}$ and $^{12}C^{3+}$, and measured after they had been accelerated through the pre-stripper tank. Within an accuracy of a few tenths of a percent we observed 4.80 MeV ^{4}He and 14.40 MeV ^{12}C with a full-width at half-maximum of 0.6%. These energies correspond exactly with the 1.20 MeV/A design value. Since this method worked so well we went one step further and added the electronic hardware that enabled us to measure the time between the arrival of each beam particle and the next RF cycle thus giving us an accurate measure of the phase distribution of the beam within 50 picoseconds.

We have not used this technique long enough to be able to give a lot of quantitative information about the behavior of the machine. It does seem to behave very much as expected by Bob Main and Frank Selph (who is giving a later paper at the conference on its measured performance). By tuning the pre-stripper and injector in a particular way I have observed that the phase distribution can be narrowed down to less than 10° with a consequent energy distribution of less than 0.5%. This method will become increasingly valuable to both the accelerator diagnostician and the experimenter and I heartily recommend that it be tried in other heavy ion accelerators such as cyclotrons and tandems.

We have tried using the method as a primary means of tuning the whole accelerator and it appears that it may solve our problem of having such "permissive" linacs. A crystal is placed at the exit of the post-stripper on the drift tube axis. With only the pre-stripper operating we readily observe a strong beam from that tank drifting through the post-stripper if the post-stripper magnetic quadrupoles are reduced in current. In fact there are a series of current peaks observed with the intensity dropping to a low value when the currents are at maximum. The first cavity in the post-stripper (Tank 3) is then turned on and tuned in amplitude and phase until the energy at the crystal achieves its proper value. The quadrupoles are increased in current, correspondingly. Tank 4 is then turned on, the process repeated, and the preceding tanks also slightly retuned in gradient and phase. In this way it has been possible to achieve full or partial energy in a very short time all the way through Tank 7 and we expect to be able to use the procedure routinely.

In this way a couple of nights ago we were able to accelerate a modest beam of ^{84}Kr to full energy. Although we had put krypton through the machine before, it was a thousand-fold lower in intensity due to our methods of tuning. This time we had some 200 meter nanoamperes dc in the stripper area (mean charge state of 23) and we would have been capable of delivering ca 10^{10} particles per second to an experiment if there had been time. Since we were using Kr^{6+} ions from the source and only 10% duty cycle we could easily increase this intensity by one or two orders of magnitude.

There are still many things that have to be done before we can claim that the SuperHILAC has reached a stable operating condition. In particular we would like to start using the sputter-ion source developed by Basil Gavin because this will make many non-gaseous atoms available to us for acceleration. At the moment the element germanium is thought to have the best prospects for creating superheavy elements by bombardment of thorium. Much remains to be learned about the idiosyncrasies of our new accelerator and it will take some time with our limited funds for us to pursue this task but I feel confident that now we have the means to do it.

I would like to take this opportunity to invite scientists from outside our laboratory to come and use the SuperHILAC. We have a formal organization of outside users (mostly nuclear chemists) which considers proposals on their merit, much as is done with other accelerators. There is no charge for beam time and we will do our utmost to help you with your experiments. At the moment about a third of the available research time is devoted to outsiders but this is intended to be a very flexible fraction depending on the need and importance of the various programs.

A very important advance will have been made to facilitate the multi-user capability of the accelerator when we have completed the electronic changes which will allow us to use the two injectors on alternate pulses. Time-sharing will enable us to accelerate a light ion up through ^{48}Ca to one experimenter and on the next pulse (which can be of a different length) a heavy ion to a different energy to another experimenter. For many purposes we will have two separate accelerators. The time-sharing funds are being supplied by the BevaLac project which has now been funded and which is discussed in detail in a following paper at the Conference. When we abandoned the Omnitron project we had to give up the high energy heavy ions temporarily; however, we promised our biomedical friends that we would find some way of achieving this objective later. After the last accelerator conference I was discouraged from using a superconducting linac for this purpose and we turned our attention to the possible use of the Main-type linacs running at a higher frequency. After a few days study Frank Selph reported that this did not look economically feasible. On a large map of the Radiation Laboratory grounds he had laid out long tunnels into the hillside for the linacs. Looking at the map I was struck by the fact that the Bevatron was not very far away though on a different level and I suggested that maybe we should inject our beam into that machine. At first the suggestion was made almost in jest. I decided though that we should look into the question as to its feasibility just in case someone else should suggest it. A little thought immediately showed that it was not only a practical idea but an excellent one and by the next day I had written a memo[1] to McMillan on the subject.

I would especially like to express my appreciation to J. M. Nitschke for his untiring role in our diagnostic debugging program and to all of our hardworking staff for their continuing efforts to make the SuperHILAC a viable accelerator.

[1]A. Ghiorso, "The 'Bevalac' - A Versatile Accelerator Concept", Lawrence Berkeley Laboratory Annual Report LBL-666, p. 315.

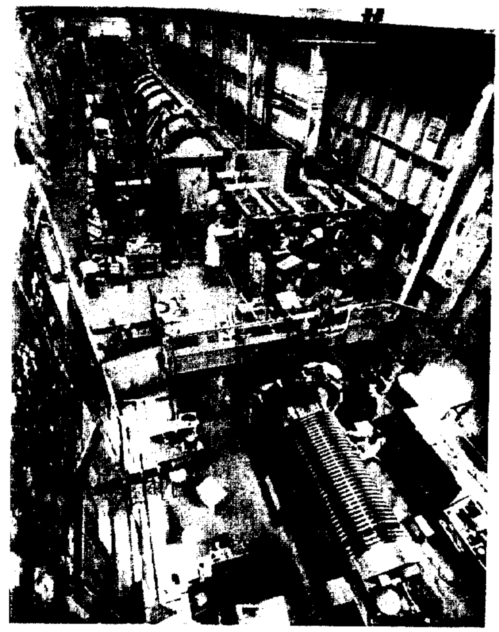


Fig. 1. Photo of SuperHILAC.

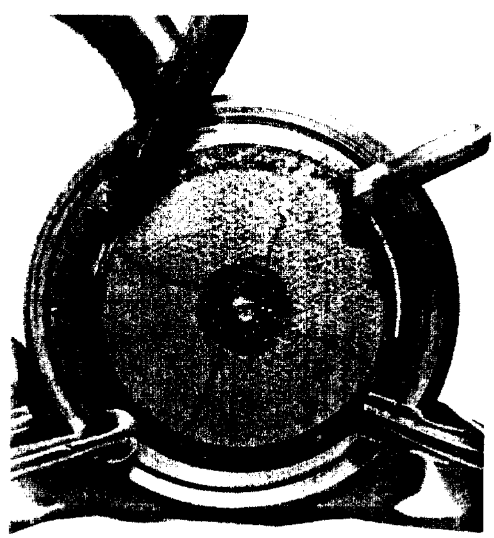
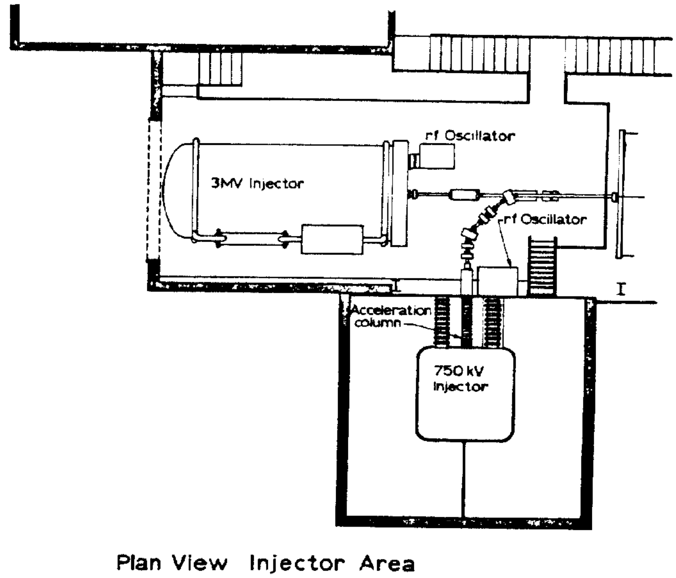


Fig. 2. Drift tube magnet under test.

Fig. 3. Completed pre-stripper tank inside.



Plan View Injector Area

Fig. 4. Schematic layout of both injectors.

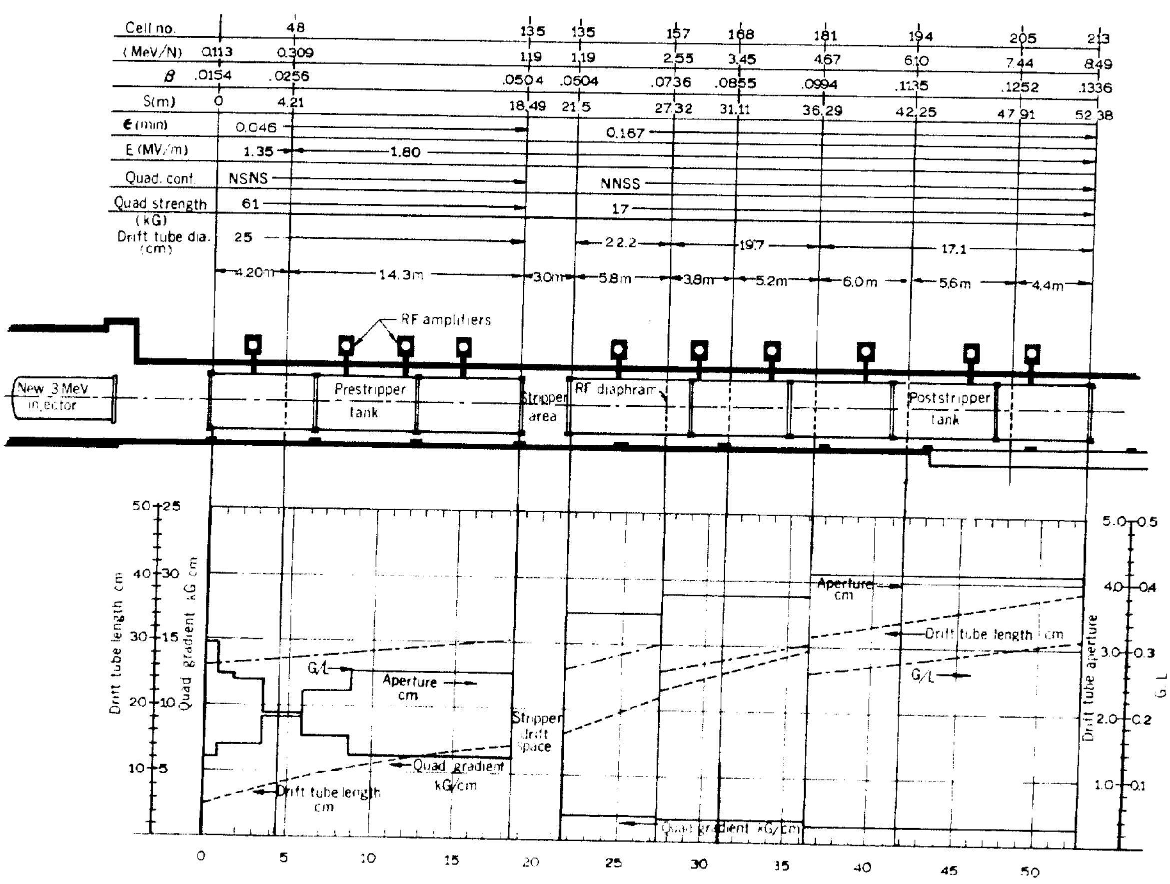


Fig. 5. Energy-gain diagram.