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ABSTRACT

The in-house constructed computer codes at the SuperHILAC can be divided into three main categories: accelerator and component design; control and operation; performance and diagnostics. The first category includes design programs of rf cavities, magnets, and beam optics. The second group contains programs for administration and logbook entries, machine parameter specifications, and openloop parameter control. Programs in the third category are those which directly or indirectly test the mechanical design and geometry of the machine, such as magnet testing, drift-tube-alignment, beam behavior an diagnostics. The present coversion of the SuperHILAC to computer control and a dual-ion time-sharing mode of operation is outlined in context with the complexities of operating this multi-ion, variable energy accelerator. Routines are discussed from the user's standpoint, covering such topics as on-line/off-line implementation, expected gain, actual results, and differences in characteristics which determine the method of computation.

INTRODUCTION

The Heavy Ion Accelerator at Berkeley was initially put into operation in April of 1958 and had an impressive record of accomplishments in the nuclear chemistry and biophysics fields. Ion beams in useful quantities were limited to mass number 40 (Argon) and below. During the late sixties, increased interest in the acceleration of ultraheavy ions (M = 240), made it mandatory that the HILAC be upgraded by major modifications. These modificiations were implemented in the period from February 1971 to April 1972, and the improved accelerator is now known as the SuperHILAC.

The HILAC will accelerate any ion with the proper charge-to-mass ratio (e/m) to a final energy of 8.5 MeV/nucleon. Particles from either of the two Cockcroft-Walton injectors must have an $e/m \geqslant 0.046$ for acceptance by the prestripper linac tank, and the poststripper will accelerate those with the range $e/m \geqslant 0.17$. Due to the wide range of e/m which can be accomodated, almost 200 components are adjusted during tuning optimization to achieve a precise configuration. Computers are ideally suited to the problem of monitoring numerous components without confusion, and a computerized control system is now being implemented at the SuperHILAC. Initially the system will provide open-loop parameter setting on a recallable basis. Most of the tuning and adjustments which are changed routinely will be included in the network, and it will also monitor the status of major devices.

In this paper, computer codes written or adapted for use at the HILAC and for use in subsequent operations are discussed with the intention of revealing not only their specific role in the design and operation of the machine, but also the user aspects associated with their execution.

Computer routines can be thought of as successful if they accomplish the goals of the programmer. However, operation of an accelerator is successful only if beams of ions of adequate intensity are delivered to an experimenter's target for a prescribed time period. Codes for design and measurement, just like the individual accelerator components with which they are concerned, must be evaluated on that same basis. They must also reflect the heavy reliance of the operations staff upon readily usable and easily comprehended information. The following discussion is presented with this theme in mind. All routines should be assumed to be written in Fortran IV unless otherwise noted.

ION SOURCE CODES

The two electrostatic injectors at the HILAC use the same type of ion source to create charged particles, but they differ somewhat in mechanical detail. This type is known as a cold cathode PIG with radial extraction.[1] Ions are created in an arc discharge inside the anode electrode and are pulled through a small window at the side of the discharge by an extractor operating at a voltage of about 15 kV. The emerging ions have an inherently small energy spread, and they form a beam whose angular divergence is ±11 degrees in the horizontal (radial) plane, and ±1 degree in the

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vertical (axial) plane. The source is pulsed at the repetition rate of the linac but with a slightly wider width to provide stable beam output during the acceleration period of the rf envelope. Most ions yield pulsed beams in the milliampere range, and due to the mass of the particles there is little space charge effect in the extracted beams.

The ion source operates within the field of a dipole magnet whose role is twofold. First of all the magnet provides the confining field necessary for the arc plasma, and secondly it acts as a mass analyzer to select and guide the proper charge-state particles into the accelerating tube of the injector.

Ray tracing codes have been developed to aid in the design of the ion source magnets using the known optics of the source and the desired optics to be achieved at the accelerating tube entrance. One of the codes uses hypothetical magnetic fields, and two use actual measured fields. These codes rely on cal-comp plot output for information transfer. They produce full scale plots which show the source location, beam envelope size, focal length and exit angle of the magnet, and mass discrimination of the system.

The program BLUSER was designed to pinpoint the source location in the 750 kV injector magnet necessary to match the necessary exit conditions. It has been used at both the HILAC and the Bevatron with gratifying results. The code uses a rectangular mesh of points from magnetic measurements, and starts its iterations with an initial source location and angle selected by the user. The resulting exit conditions are tested against those desired, and the location is shifted until the final desired location is converged upon which satisfies the specified optics.

The most powerful use of this code is realized when the characteristics of experimentally observed beams are fed back into the code. The foregoing iterative process really results in only a best guess for the proper source location since the inaccuracies in the model, though consistent, are cumulative. However, as is shown schematically in Fig. 1, exit rays which have been experimentally measured can be reverse-traced by BLUSER, and having done so, their point of crossover inside the magnet reveals the apparent source position. The Δx and Δy distances between this latter apparent position (point B in the figure) and the former desired location (point A in the figure) gives the required displacement of the source to achieve the specified exit optics. This is possible because the same modeling inaccuracies are present in both the forward and the reverse traces. Results at the HILAC gave a position error of less than 0.5 inch, and after relocating the source a single time the desired exit optics were observed by experimental analysis.

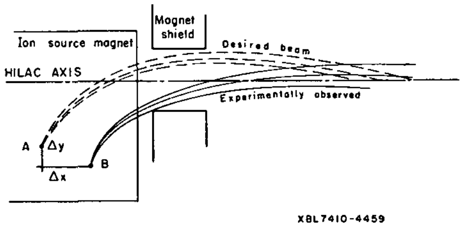


FIG. 1. Schematic of procedure used to position source using ray tracing code.

Two ray-tracing codes called MEGAN and MAGOO are used for the 3 MV injector. MEGAN uses an algorithm to generate a magnetic field, and MAGOO uses the true field as measured. MEGAN was written to establish some of the parameters for the prototype magnet such as exit edge angle for a given focal length, and polewidth taper from source to exit. It describes the longitudinal fringe field falloff as a cosine function whose order n and width are input options.

Following construction of the source magnet, MAGOO was used to model transverse field effects on the beam, and it proved that edge shimming was unnecessary. It also determined mass analysis discrimination, delineated the equivalent sharp cut off field edge, and helped analyze the results of ray-tracing beam experiments.

Ray-tracing codes are extremely useful for beam optics experimentalists. Great detail is revealed and, when valid modeling techniques are employed, accurate particle behavior is predicted. In some cases, as encountered at the HILAC, extremely confusing experimental results can be easily deciphered by the use of a computer model in parallel with beam measurements. The validity of the model is proportional to the amount of factual information upon which it is based. The model can never stand alone but must be used in conjunction with actual measurements of physical phenomena to reveal the true credibility gap. However, even in rudimentary form it can suggest valuable insights into the behavior of real particles.

BEAM TRANSPORT CALCULATIONS

It is frequently useful to describe particle orbits relative to the orbit of some reference particle. Let the vector $\mathbf{x}_2(x_2,x_2')$ represent the position of a particle, where relationship of the harmonic amplitudes determines the symmetry with which the magnet has been assembled, and the precision with which the Danby-type pole faces were machined. To make effective use of these measurements it is important to be able to relate multipole components to the configuration of the magnet iron and conductor. This has been achieved, notably by Halbach.[11]

Approximately two hundred fifty quadrupoles were constructed for the HILAC modification program. Statistics gathered for the prestripper magnets showed that a relative value of 0.25% was achieved on the average for the $n=3$ harmonic, when compared to the $n=2$. The $n=6$ had an average value of 0.3%, and the $n=10$ was 0.15%.

DRIFT TUBE ALIGNMENT

The physical alignment of each quadrupole contained within the drift tube shells of the linac cavities has to be less than an rms deviation of 0.005 inches from the straight line axis. The alignment technique, utilizing a pulsed wire, and the computer program, DTPLOT, are described elsewhere in these proceedings.[12] DTPLOT uses the least-squares-fit method to match the measured positions to the best first or second order polynomials. The minimum number of drift tubes which must be moved to attain a given fit is computed, and their identities are tabulated in the printout. Conventional methods of fit estimation predicted sixty-seven drift tubes should have been moved, whereas DTPLOT moved only thirty-seven, resulting in a saving of many hours of alignment time. Additional output from DTPLOT graphs the drift tube positions as measured along with the fitted axes. The horizontal and vertical planes of the quadrupoles are measured independently.

BEAM EMITTANCE

At any point along the accelerator each particle of the beam can be defined as a point in a 2n-dimensional phase space completely describing position and momentum. A two-dimensional sub-space may be adopted to represent the horizontal and vertical planes of the the machine with the axes representing transverse position and momentum. This sub-space is called the transverse phase space. The area of the closed figure projected on the transverse phase space from the 2n-dimensional volume of beam particles is called the emittance of the beam. For simplicity, the transverse momentum component of the ion is usually normalized by the longitudinal momentum. Therefore, we describe the particle in each plane of interest with the phase space position coordinate, x, and the angle coordinate, x'.

The entire accelerator may be thought of as a series of limiting apertures whose admittance, the counterpart of the beam's emittance, is the phase area that the beam may fill without being collimated by the aperture. Measurement of the transmission of the emittance through the collective admittance of the accelerator reveals important evidence of the quality of the alignment of the machine, and gives a direct indication of the precision to which the shape of the emittance has been matched to the admittance shape of the individual components. Results of such a measurement are shown in Fig. 3.

To date, 80% of the emittance at the prestripper entrance compared to the surviving area at a target has been recorded, and transmission better than 90% through the linac tanks is regularly achieved.

The program EMITT, which computes the emittance and its shape is also reported elsewhere in these proceedings.[10] Included is a description of the method by which the two scanning slits provide the data to the code.

Unfortunately, the data system is too slow to be used as an on-line diagnostic tool, since each series of scans comprising a transmission analysis requires approximately fifteen to twenty minutes. Modifications to the mechanical and electronic hardware are presently underway to permit transmission scans to be completed in only a few minutes. The PDP-8/I which controls the hardware, and manipulates the data flow to the tape deck, will graph the emittance figure on a Tektronix 4023 CRT terminal, which in turn will simultaneously send the figure to a Conrac monitor TV at the operator's control console. As the plotting is complete, the area of the figure will be computed and written below the plot. Appropriate tuning adjustments will then be made and the emittance remeasured as necessary.

SETUP SCRATCH LOG PROGRAM

This program is used to prepare a list of accelerator elements which are to be used in a run, together with recommended settings of magnet currents, etc., where appropriate. During a run, readings are taken by the operator and written on the list. This "scratch log" is saved and becomes an important record in the accelerator operations log. A portion of a log is shown in Fig. 6. To obtain such a log from the computer, an operator, using a teletype terminal, remotely submits the program to the CDD 6600, gives information as to the injector to be used, the experimental line, the particle mass, energy, and charge state before and after stripping. Information from results of a calculation in which misalignments of quadrupole position have been introduced. The effect is to excite a quasi-periodic oscillation in the beam position, which grows in amplitude as the beam proceeds through the linac. The problem is solved for two values of quadrupole focusing strength. The upper curves show beam profile and beam centroid for low quadrupole gradients, the lower curves show the corresponding profile and centroid for high quadrupole gradients. Used in this way, the computer program becomes a model of the linear accelerator. Operation of the computer program while varying the properties of the particle array and the accelerator parameters becomes an exacting task in itself because of the number of parameters that can be varied. In some ways the computer program model is more difficult to operate than the actual accelerator. For example, the pattern of quadrupole focusing magnets can easily be changed in the model. In the actual accelerator only limited changes would be made.

Major design problems which were studied with this program in planning the SuperHILAC were 1) the linac admittance resulting from a chosen set of drift tube apertures, 2) required precision of quadrupole alignment required to keep wandering of the beam centroid within reasonable limits, 3) investigation of transverse focusing stability limits, 4) choice of focusing pattern for quadrupole magnets, 5) effects of breaks in the quadrupole pattern, i.e., of "missing" quadrupoles, 6) the variation of energy of the beam emerging from the linac, as electric gradient is varied, 7) calculation of the energy spread under various operating conditions.

Finally, a very important use of the linac model is in checking theoretical predictions of linac behavior. These theories are invaluable to the linac designer because they allow him to generalize about certain aspects of linac performance which taken simply as a collection of disjointed facts, would be very difficult to deal with. Predictions of transverse focusing stability limits, for example, was vital to the operation of the SuperHILAC. A theory of these limits has been worked out.[6] However, this theory is based upon a model of the accelerator which ignores longitudinal oscillation amplitudes, i.e., changes of the ion's phase relative to the RF. Using the program it was possible to show that the predictions of the theory held true even in the presence of longitudinal particle oscillations, if the phase relative to the RF was assumed to be the synchronous phase, which is a constant. Consequently, a method of dual-ion time-sharing has been proposed to take advantage of the fact that the stability region for the dc-excited quadrupoles is wide enough to accomodate two ions of disparate charge-to-mass ratios.[7] A limited number of pulsed quadrupoles and dipole magnets has been constructed to allow fine tuning and appropriate beam switching on a pulse-to-pulse basis.

MAGNET DESIGN

Two codes of notable achievement are used to design the steel and conductor geometry of all types of magnets. The first of these, TRIM, is a program for solving magnetostatic problems, in the presence of iron and current-carring conductors.[8] The second, PISA,[9] uses matrix inversion techniques to invert the problem so that given a desired magnetic field and conductor geometry, the steel poletip configuration is derived, consistent with constraints specified by the user.

Virtually all of the HILAC magnets have been designed using these codes, and the magnetic measurements on each one has proven the codes to be remarkably accurate in predicting the field strength, uniformity as a function of excitation, the behavior of the steel including saturation effects, and eddy current power losses caused by time varying fields.[10]

A certain amount of user ability is involved with their operation, because a large part of the input requires that he construct a 2-dimensional mesh with now uniform data point distribution densities. As the user becomes more adept at mesh construction the input process becomes more routine. However, even for a beginner, the result of using these programs is faster and more accurate than any other method known.

Quadrupoles that are fabricated at the HILAC are designed by POISSION and measured using FOURIER. As its name implies, FOURIER is a harmonic analysis code which has as input a magnetic tape containing magnetic measurement data points. The data points are collected from a search coil of precisely known radius and sufficient length to extend beyond the fringe field. It is rotated about the axis of the quadrupole. Two revolutions of the search coil, each divided into 200 steps, comprise a complete measurement of the magnet. The first rotation digitally records the fourfold signal comprising the quadrupole field including all harmonics. During the second rotation a bucking coil is incorporated in the measuring system which reduces the n=2 (quadrupole) component to less than 3% of the primary signal, enhancing the analysis of the higher harmonics.

Output is in the form of line printer produced tables organized according to the amplitude of each harmonic computed at various radii from 75% to 95% of full aperture. The

x_2 is the displacement and x_2' the angle relative to the reference orbit at a position s_2, and a vector $\bar{x}_1(x_1,x_1')$ the corresponding coordinates at an earlier position s_1. Then we can express $\bar{x}_2$ as a power series in $\bar{x}_1$:

$$\bar{x}_2 = T(s_2,s_1)\ \bar{x}_1 + [\text{higher terms in } x_1]. \quad (1)$$

If the higher terms in $\bar{x}_1$ can be neglected, the problem is linear, greatly simplifying the calculation. In order for this to be true, two conditions must be satisfied: 1) $\bar{x}_1,\bar{x}_2$ must represent small displacements and 2) the magnetic and electric fields which give rise to the matrix T and to the coefficients of the higher terms must be "linear"; i.e., the fields or their derivatives are constant relative to x. In the case of most magnetic transport systems the beams are small, so that the first condition is satisfied, and care is taken to carefully shape the magnetic fields so that the second condition is satisfied. This is done not only to simplify calculation, but primarily because the higher-order terms introduce aberrations which irreversibly degrade beam quality.

Let $E(s_1)$ be a symmetric matrix with coefficients chosen such that

$$1 = \tilde{\bar{x}}_1\ E(s_1)\bar{x}_1 \quad (\tilde{\bar{x}}_1 \text{ is the transpose of } \bar{x}_1) \qquad (2)$$

defines an ellipse, which can be supposed to enclose a distribution of particles in x,x' space. Substituting (1) into (2) and neglecting higher terms it can be shown that the result is another ellipse, and

$$B(s_2) = T\ (s_2,s_1)\ B(s_1)\ \tilde{T}\ (s_2,s_1) \qquad (3)$$

where the matrix B is the inverse of E.

Equation (3) was first derived by K. L. Brown, and was used by him and his collaborators at SLAC to construct a powerful computer program for first order beam optics calculations.[2] The version in use at the HILAC is called BELIN. In such a program both the transport line elements and the beam are represented by matrices. The history of a particle or of a beam traversing such a system can be followed by multiplying successively the corresponding vector using Eq. (1), and the beam matrix using Eq. (3), step by step through the system. In practice, instead of a two dimensional vector $\bar{x}(x,x')$ a six dimensional vector $\bar{x}(x,x',y,y'z,\Delta p/p)$ is used. x,y are displacements orthogonal to each other, z a relative displacement along the axis, $\Delta p/p$ the momentum difference. The same equations 1-3 still apply. E is now a six dimensional ellipsoid. Figure 2 shows results of a beam calculation through the transport elements between one of the ion sources and the linac, in which x and y beam envelopes are plotted.

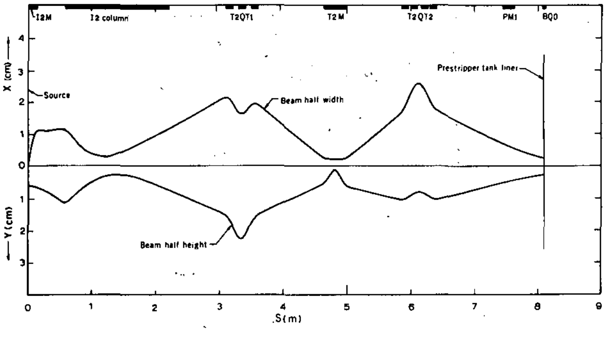


FIG. 2. Plot of BELIN calculation of beam envelope in transport line from injector to prestripper entrance.

These calculations are very useful in the conceptual design of a beam line, and also in investigating the performance of existing lines.[3,4] In the first case, the program can be used to explore many different conceptual designs. The usual method of working with the program as a design code is as follows: The initial beam matrix E_i is taken as known, as are certain other desired beam conditions downstream. The program is allowed to vary one or more chosen parameters until a transfer matrix T is found which gives a solution matching the desired result as closely as possible. In the design phase, however, definite information on the beam is not usually available so that the initial ellipsoid E_i used for the calculations must be guessed. If the performance of the system, as explored using the computer program, is critically dependent upon the choice of initial conditions, this can be taken as a warning that the planned beam line may be difficult to operate. As a general rule those transport line designs are best which will allow the widest variation in the choice of E_i. Sometimes the desired final beam properties are well known — when the transport system leads to a target, for example. In this case the problem can be run backwards, using inverse transfer matrices, to deduce E_i from the final beam matrix E_f.

For investigation of operating beam lines, BELIN can also be very useful. If an emittance measurement can be made at a point s_1, so that a beam ellipsoid E_1 is known, then the program can be used to calculate beam envelopes back to E_i and forward to E_f. Figure 3 reproduced from Ref. 3, shows a typical emittance measurement.

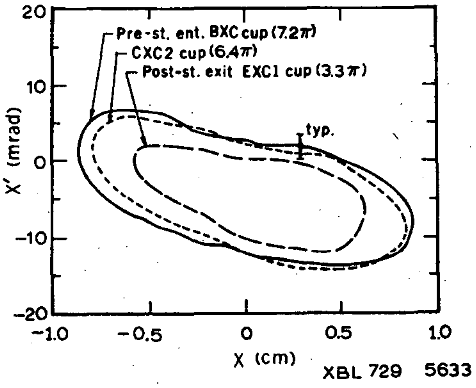


FIG. 3. Measurement of injector emittance for a carbon beam (horizontal plane) and of transmitted emittance to stripper area and to poststripper exit.

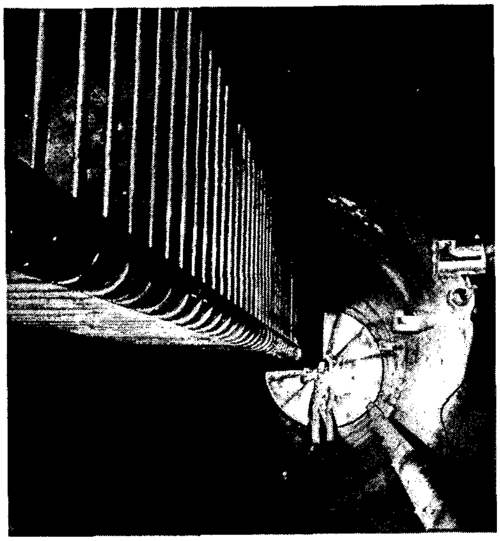


FIG. 4. Linear accelerator cavity. Drift tubes, at left, are supported by hangers from the top side of cavity.

LINAC CALCULATIONS

A Linac consists of a succession of high-voltage accelerating gaps for the acceleration of a beam of particles. The SuperHILAC consists of several Alvarez cavities resonant at 70 MHz, which are excited to produce an axial electric field. Along the central axis is placed a succession of drift tubes, arranged so that particles advance from one gap to the next during one RF cycle (Fig. 4). They experience an accelerating force in the gaps, but when the electric gradient has the wrong sign for acceleration the particles are inside the drift tubes and shielded from the field. Most drift tubes contain quadrupoles which provide transverse focusing of the beams.

As an ion passes through a gap, the energy gained is a nonlinear function of radius. This has the consequence that programs used for linear beam transport calculations cannot be used for a linac. Instead, particles are followed through the structure step-by-step in a modified ray-tracing approach. A program called PARMILA, using this approach, was originated in 1965 by the MURA group.[5] This same program, with various additions and modifications, is in use at most linear accelerator centers. The version in use at the HILAC we call LINAC.

As a collection of several hundred particles is traced through a structure the properties of the distribution-beam position, maximum and rms beam envelope, energy, energy spread, etc. can be calculated at each step to give a reliable indication of the behavior of a real beam in the linac. Figure 5 shows the

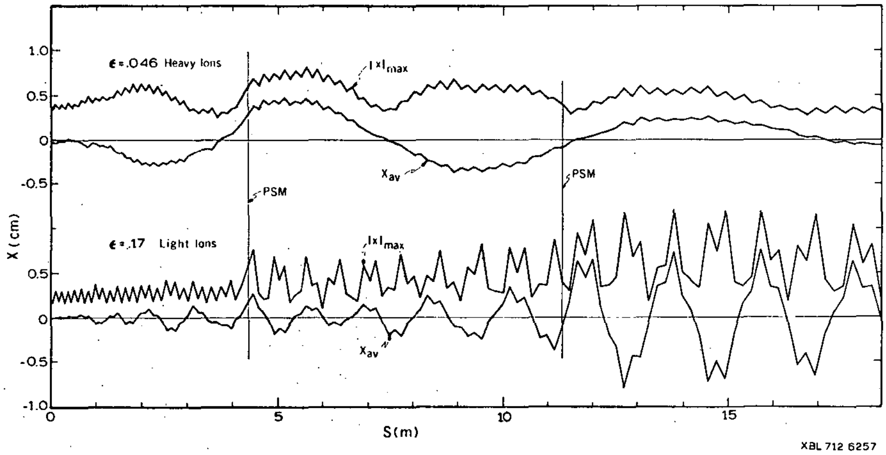
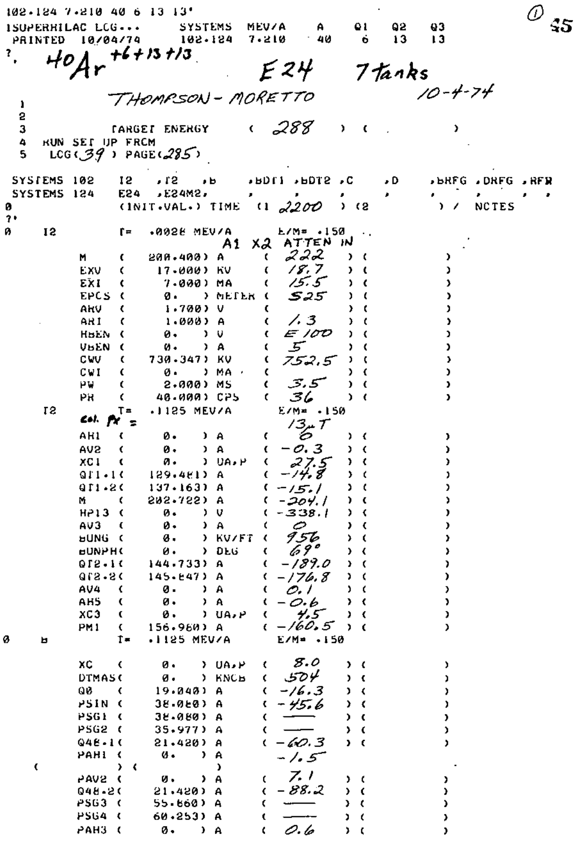


FIG. 5. Plot of LINAC output. Prestripper beam envelopes and beam centers with quadrupoles randomly misaligned by 5 mils rms.



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0     I2        T=   .0028 MEV/A       E/M= .150
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          EXI   (      7.000) MA      (  15.5    ) (              )
          EPCS  (      0.   ) METER   (  525     ) (              )
          AHV   (      1.700) V       (          ) (              )
          AHI   (      1.000) A       (  1.3     ) (              )
          HBEN  (      0.   ) V       (  E 100   ) (              )
          VBEN  (      0.   ) A       (  5       ) (              )
          CWV   (    730.347) KV      (  752.5   ) (              )
          CWI   (      0.   ) MA      (          ) (              )
          PW    (      2.000) MS      (  3.5     ) (              )
          PR    (     40.000) CPS     (  36      ) (              )
      I2        T=   .1125 MEV/A       E/M= .150
          Col. Px =                     13μT
          AH1   (      0.   ) A       (  0       ) (              )
          AV2   (      0.   ) A       ( -0.3     ) (              )
          XC1   (      0.   ) UA,P    (  27.5    ) (              )
          QT1.1 (    129.481) A       ( -14.8    ) (              )
          QT1.2 (    137.163) A       ( -15.1    ) (              )
          M     (    202.722) A       ( -204.1   ) (              )
          HP13  (      0.   ) V       ( -338.1   ) (              )
          AV3   (      0.   ) A       (  0       ) (              )
          BUNG  (      0.   ) KV/FT   (  956     ) (              )
          BUNPH (      0.   ) DEG     (  69°     ) (              )
          QT2.1 (    144.733) A       ( -189.0   ) (              )
          QT2.2 (    145.847) A       ( -176.8   ) (              )
          AV4   (      0.   ) A       (  0.1     ) (              )
          AH5   (      0.   ) A       ( -0.6     ) (              )
          XC3   (      0.   ) UA,P    (  4.5     ) (              )
          PM1   (    156.960) A       ( -160.5   ) (              )
0     B         T=   .1125 MEV/A       E/M= .150

          XC    (      0.   ) UA,P    (  8.0     ) (              )
          DTMAS (      0.   ) KNOB    (  504     ) (              )
          Q0    (     19.040) A       ( -16.3    ) (              )
          PSIN  (     38.060) A       ( -45.6    ) (              )
          PSG1  (     38.080) A       (  ——      ) (              )
          PSG2  (     35.977) A       (  ——      ) (              )
          Q4B.1 (     21.420) A       ( -60.3    ) (              )
          PAH1  (      0.   ) A         -1.5
     (          ) (            )
          PAV2  (      0.   ) A       (  7.1     ) (              )
          Q4B.2 (     21.420) A       ( -88.2    ) (              )
          PSG3  (     55.660) A       (  ——      ) (              )
          PSG4  (     60.253) A       (  ——      ) (              )
          PAH3  (      0.   ) A       (  0.6     ) (              )
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XBL 7410-1938

FIG. 6. Portion of scratch log prepared by program SETUP.

which the list of accelerator elements is prepared is on a permanently stored file. The lists are grouped for convenience into major systems whose components are generally listed in the order in which the beam encounters them in the accelerator. Names for elements are chosen which are as brief as possible but which remind the operator of the function of the device to which they belong.

Precalculated settings for a given energy and charge state are also stored on the file. The program scales these values according to information that is given by the operator, and prints the results alongside the element name. When the run is made, it is found that the predicted value is frequently departed from in tuning the SuperHILAC. This is because settings of many of the components will depend upon operating conditions in a way that is unanticipated when tuning discrepancies occur, comparison of actual with predicted values is evidence which can be used in diagnosing machine behavior. Calculated values of bending magnet currents however, are especially valuable to the operator, because a departure from a predicted current can indicate that the wrong charge state or even the wrong ion was chosen for tuning, which would mean a loss of achievable intensity, or negate the entire run.

CONCLUSION

All of the programs described here are designed to answer specific questions in the design and operation of an accelerator. Our interest is not, and has never been, in finding an application for an interesting computer program. We have problems, and we attempt to solve those problems using the resources at our disposal. Increasingly, we have found that the computer facility is an economical and useful resource. Many of the programs referred to here can be described as models. They attempt to represent, as closely as possible, the operation of a process so that the process can be better understood by the manipulation of the model. It is our belief that this modeling with computer programs can best be carried out by one person who understands both the physical process and the computer program. Only in this way can the fidelity of the model be preserved.

There is another property which all of the programs described share — that is while they all are useful and contribute to our understanding, none are vital to accelerator operation. The machine will run without them. This situation will be changed in the future at the SuperHILAC. We will begin to make use of computers not only as an aid to operation, but as control components of the machine as well. This project cannot be described here for lack of space, but will consist of the installation of a ModComp IV central processor with a 96K 16-bit word memory, and four ModComp II acting as peripheral cluster units for real time processing. In addition, some of the programs which now run on the CDC 6600 will be transferred to the mini-computer where they will be more readily accessible to the operator and perhaps will become more useful in day-to-day operations.

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