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COMPUTER PROGRAMS FOR AGS INJECTION*

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Abstract

Since the injection system of the AGS requires very tight control over many parameters, computer programs were written to achieve this. One program initiates an emittance measurement device and reduces its output data to provide the characteristics of the linac beam. The second program utilizes these results to set six quadrupoles and four bending magnets so that requested beam parameters are obtained at the inflector exit. A third program measures the circulating beam and attempts to maximize it by adjustment of quadrupoles and bending magnets. These programs and our experience in using them on-line are described.

Introduction

Multiturn injection into a synchrotron requires accurate knowledge and control of the transverse parameters of the beam offered for injection. In the injection system of the Alternating Gradient Synchrotron at Brookhaven National Laboratory, that knowledge is obtained by measuring the density distributions in the horizontal and vertical phase planes. The results are used to compute the coordinates of the beam axis (x,x', y,y') and the characteristic parameters of the emittance ellipses ($\alpha_x,\beta_x,\gamma_x,\epsilon_x,\alpha_y,\beta_y,\gamma_y,\epsilon_y$). The measurement takes place in the transport line from the injection linac to the AGS at a point somewhat upstream of the inflector and is performed on request by automated equipment under control of the PDP10 control computer of the AGS. One part of this paper is devoted to a description of this system and its practical use.

Six quadrupoles and two pairs of dipoles, one for horizontal steering and one for vertical steering between the point of measurement and the point of injection (inflector exit) may be adjusted to obtain desired values for the beam characteristics at the point of injection. This requires finding the necessary change for each of ten magnet excitations from eight desired changes in beam characteristics. The emittance areas cannot be changed of course. We describe program "ORTHO" similar in function to the SLAC Transport Program[1], but specialized for the injection system of the AGS and for on-line operation on the AGS's control computer, that we use to trace the beam and to calculate magnet settings for desired conditions. Program "MATCH" that would maximize the beam that circulates in the AGS shortly after injection by adjustment of the magnet excitations without knowledge of the beam parameters functions well in a model on BNL's CDC 6600. Since it has not yet been used on the AGS, we do not describe it.

Program LINEM

This program, written in Fortran IV for the PDP10 computer, collects data on the phase-space density distribution of protons from the 200 MeV injector for the AGS and then extracts pertinent parameters from the data which can be used by the program ORTHO. LINEM is liberally divided into subroutines which the operator calls into use when prompted for a mode selection by the Teletype. The program prompts the operator for all input data or control information, which is given in free format.

Subroutine SCAN, after being given the phase space region to be covered, initiates scanning devices in the 200 MeV proton beam via the PDP-10 AGS operating program OPER and a PDP-8 which acts as the interface between the AGS and PDP-10. A subsection of the PDP-8 monitor program receives starting point and range data and then carries the scan through to completion. Simply put, a moveable slit samples a 1.0 mm section of beam in the given plane (horizontal or vertical) while an array of 30 secondary emission detectors (10 mil wires) farther downstream simultaneously samples the angular distribution of the transmitted protons. These 30 proton density measurements are stored in the PDP-8 for each slit position. Up to 29 positions may be covered, spaced 1.0 mm apart. In addition, the slit and wire array positions are read from linear potentiometers and the total linac current, for normalization, is read from a current transformer. The scanning system chosen is slow compared to magnetic systems which could be constructed, but it is inexpensive and employs the same bellows coupled motor drive units used for a number of other applications in the vacuum system of the machine. The time required for an emittance scan in one plane is 2 to 3 minutes. One slit position is measured on each AGS pulse, and about half of the time is required to move the devices to their starting positions. When the PDP-8 signals completion, SCAN retrieves and unpacks these 957 pieces of data using two of the OPER system subroutines.

Subroutine PEAK begins reduction of the data. It first subtracts the amplifier offset for each wire (taken to be the minimum current observed on that wire) from the data, then normalizes the data according to the linac current measured for each slit position. After this is done, PEAK further prepares the density distribution array $\rho(x,x')$ for use by normalizing it to unit integral over the transverse phase space area scanned and providing the operator with the maximum density value, the coordinates (x_m, x'_m) of that value, and the coordinates ($\bar{x}$, $\bar{x}'$) of the centroid of the distribution. These coordinates usually agree to within 0.1 cm and 0.15 mrad respectively when the linac is well tuned and the beam well-framed by the selected scan region.

Subsequent data reduction consists of analyzing the contours traced by the intersection of the density function $\rho(x, x')$ with a plane parallel to but above the $x - x'$ plane. Subroutine CONTUR finds the set of coordinate pairs (x_i, x'_i) defining this (irregular) contour from the measured data. Up to 80 pairs are found and stored by scanning the rows and columns of the array $\rho(x,x')$. Linear interpolations between adjacent points give the coordinate values whenever $\rho(x,x')$ is seen to pass through the plane selected. The percentage of total beam contained within this contour and its area are also given. A subsequent call to ELLFIT then attempts to fit an ellipse to the set of contour coordinates. This fitting procedure evaluates 3 parameters which define the ellipse size and shape plus the 2 coordinates of its center. The prescription for fitting is to minimize the residual

$$R = \sum_i \left(A - A_i\right)^2$$

where A is the area of the fitted ellipse and A_i is the area of an ellipse of the <u>same</u> shape passed through the contour point (x_i, x'_i). A failure of this procedure is evidenced by too few points on the contour or by a hyperbolic fit to badly jumbled points on contour planes down near the "noise" under the measured density distri-

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bution. This subroutine also integrates $\rho(x,x')$ over the ellipse to obtain the enclosed fraction of beam.

Subroutine ELPLOT permits the operator to produce line printer and CRT teletype plots of the contour points and/or fitted ellipses for human inspection of the results. At times, bad ellipse fits are found when the beam is not framed well by the scanned region, producing poorly closed contours.

In place of selecting these last three routines individually, REPEAT will find a series of contours, fit ellipses, and plot the results. A summary table of those results is also printed and displayed. Figures 1, 2, and 3 contain examples of typical contours at 50% of ρ_{max} in the horizontal and vertical planes, and a summary of results for a series of contours in the horizontal plane.

A certain constancy of α and β is exhibited in the mid-range of the summary of Figure 3, but clearly some operator judgment, based on the injection aims in mind, must be made on those values of area, α, and β to be passed on to ORTHO for matching to the AGS admittance. So far, these programs have only been utilized for accelerator research periods. When more experience is acquired, it is hoped that some criteria can be adduced for selecting linac emittance values to be used so that streamlined versions of these programs may be employed for routine AGS tune-up.

Program LINEM has a few other modes of interest. It is possible to insert a known artificial density distribution into the appropriate array in order to test the data reduction. The operator may also elect to have an index of modes displayed on the console, to make changes in the various constants defining the scanning system, and to cause the line printer to copy data from a Dectape unit when the operator has chosen to store it there to avoid tying up the printer during scanning operations. LINEM occupies 12k words in lower core and 2k words in the shared upper core.

Program ORTHO

This program is a code in Fortran IV for on line operation on the AGS's control PDP10, where it requires about 17 kW in core memory. Its prime purpose is to enable the operators of the AGS to vary up to eight of the transverse parameters of the beam to be injected independently of each other. The program's name stems from this orthogonalisation feature. It may be divided in three parts. The first part performs input, output, and provides for services and conveniences. The second part represents an accurate model of the physical situation in the injection system; it calculates the beam parameters at the inflector exit from knowledge of their values at the system input and the excitations of the ten magnets mentioned in the introduction. The third part generates proposed values for those magnet excitations that would produce requested values for beam parameters at the exit.

Part two traces the motion of rays on and near the beam axis through the system by standard matrix multiplication, taking surveying data, dimensions and calibrations into account. Part three assumes that the r.m.s. error of the actual beam parameter values with respect to their requested values is a smooth function of the magnet excitations and reduces that error to below a chosen limit by variation of the proposed values of those excitations in an iterative loop or until the variations in all excitations are reduced to below the resolution of adjustment. The actual function is approximated by a quadratic one. The coefficients of the quadratic are found by sequentially changing and reseting the proposed excitations, first individually, then in pairs, to produce changes of about 10% in the computed error. The eigen values and vectors of the coefficient matrix are used to generate a set of better excitations. The next cycle begins with this new set and the process continues until a minimum is found. This minimum represents a true solution if it is very small, i.e. ≈ 0, else it is just a local minimum. The chance of finding local minima increases with the number of variables and the initial r.m.s. error. The problem may be avoided by moving from the actual point to the desired one in a series of small steps such that at each step the initial r.m.s. error is small. The method works more reliably, in the sense of avoiding local minima, and less efficiently, in terms of time, with decreasing step size. It is used in ORTHO only after it becomes evident that a local minimum has been found. The step size is reduced by halving it until the iteration finds true solutions after which the search for the final solution is restarted. This procedure takes care of most local minima but occasionally the step size is reduced to zero or the program falls back to the local minimum it just climbed out of. In practice this happens so seldom that no correction has yet been introduced as should be done to make the program truly trustworthy. In our experience, the program converged nearly always; waiting for a solution may require patience however. The operator may specify a maximum number of iterations cycles after which the process is interrupted and a status report is typed out. Thereafter, execution may be resumed, perhaps with changed data, or discontinued as the operator decides.

The program is loaded from tape or disc with a complete set of data. The operator has to decide on the mode of operation; he may ask for and/or change the value of any variable or parameter at will and he may have the magnet excitations in the program replaced by the ones in actual use for the accelerator. After the program has run, it prints out a status report (Fig. 4) and draws emittance diagrams at the inflector exit on a CRT (Figure 5). If it proposes any new magnet currents, the operator may or may not choose to have them transferred to the magnets after which he may try a new set of conditions or terminate. Before terminating, he may replace the old data file by the new one. The program is reasonably fool proof. To most operator errors, it responds with a diagnostic and waits until the error has been corrected.

Acknowledgment

The generous assistance of a number of people has made this work possible. The electronic control circuits were designed by Robert Larson, and the installation and maintenance of the scanning system has been carried out, under his direction, by Edward Elliott and Ronald Clipperton. The interaction of the programs described here with the AGS depends heavily upon the PDP-10 program OPER and the PDP-8 monitor program which have been written by Robert Warkentien and John Smith, both of whom have given valuable advice in the construction of the programs. Program ORTHO is especially indebted to John Dabrowski, who wrote several of the subroutines for the input of data and control information and for the modification of beam line parameters.

References

1. K. L. Brown, et al, "Transport/360", SLAC Report SLAC-91.

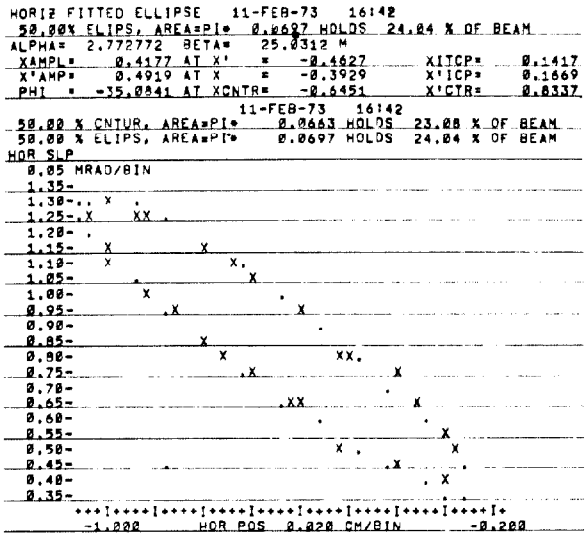


Fig. 1 Contour at Half-maximum for horizontal distribution.

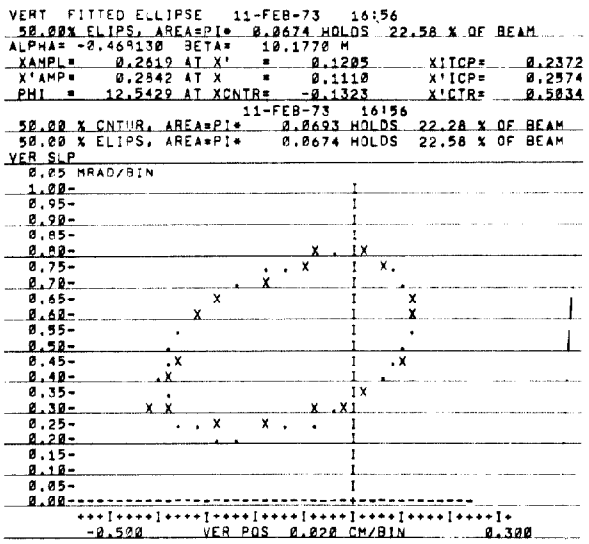


Fig. 2 Contour at Half-maximum for vertical distribution.

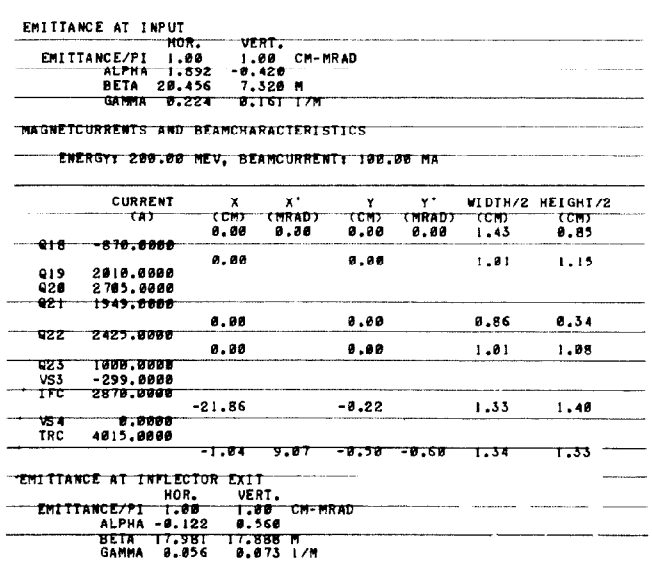


Fig. 4 Status Report for "On-Line" Matching.

Beam emittance at the exit of the AGS inflector

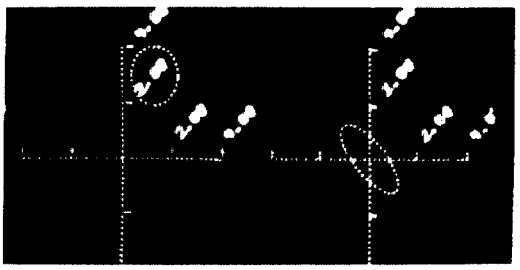


Fig. 5 "On Line" Matching for AGS Multi-turn Injection.

SUMMARY

L	CONTOUR %	CONTOUR AREA/PI	CONTOUR %BEAM	ELLIPSE AREA/PI	ELLIPSE %BEAM	ALPHA	BETA
1	88.890	0.002	1.323	*******	*******	*******	*******
2	66.668	0.025	10.430	0.037	13.345	3.512	30.895
3	50.001	0.066	23.076	0.070	24.842	2.773	25.031
4	37.500	0.107	32.642	0.113	34.196	2.639	23.442
5	28.125	0.149	40.228	0.157	42.170	2.607	22.370
6	21.094	0.216	49.243	0.222	50.300	2.887	23.976
7	15.821	0.309	58.627	0.314	58.172	3.275	25.793
8	11.865	0.461	69.988	0.472	69.596	4.029	29.734
9	8.899	0.589	77.158	0.689	76.265	4.480	31.569
10	6.674	0.690	81.320	0.942	81.293	4.419	30.016

Fig. 3 Contour and ellipse summary for horizontal distribution.