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AUTOMATIC CONTROL PROGRAM FOR SPEAR*

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Introduction

In the operation of SPEAR, it is necessary to change the configuration (defined by the betatron numbers ν_x, ν_y, the beam energy E, and the beta functions β_x^*, β_y^* and eta function η^* in the interaction regions) from one operating point to another without losing the stored beams. For example, filling the ring is done at one configuration, while experiments may require another which has different energy, η^*, β^* and ν in order to obtain the desired luminosity.[1] This is accomplished by controlling the set points of the magnet power supply regulators by means of a control computer. This paper describes salient features of the hardware, the controlling computer, and its software to make such changes possible. SPEAR has been operated successfully under computer control using the code RING. Some results of its operation will be presented.

I. Computer

The computer is an XDS Sigma-5 (32-bit word length, 48 K words of memory) operated in a time-shared manner, using a modified version of the XDS Batch-Time Sharing Monitor. The SPEAR control program RING is a job which is swapped with other time-shared jobs, such as those for experimental analysis. Time-critical, interrupt-driven tasks are not swapped, however, and remain resident in core. The time-shared program is written in Fortran IV, while interrup-driven programs are written in symbolic machine language. Interrupt-driven programs (such as the power supply driver described later, or a 10-pps-driven routing for determining when changes are made in switch settings on an operator control and display panel) can awaken a specified time-shared job from a "sleeping" state. This time-shared job would then perform its task, and when finished put itself to sleep again. In this way, jobs can be swapped into core only when needed, thus providing more computer time for other jobs that can use it.

II. Hardware

The computer controls thirteen power supplies driving the main magnetic elements as well as eleven trim supplies for orbit corrections. The power supplies can be ramped in unison by means of a controller having a digital-to-analog converter (DAC) and a binary rate-multiplier (BRM) for each supply, all driven by a common master pulser. (A BRM circuit is capable of gating an incoming pulse train of frequency f_0 such that output pulses are generated at a time-averaged frequency $f = R \times f_0/(2^I - 1)$ where R is a number stored in a binary register having I bits, $0 \leq R \leq 2^I - 1$.) The BRM for each power supply has a register with 13 bits, so that $f_i = R_i \times f_0/8191$ is the pulse rate sent to the DAC for the i^{th} power supply, and f_0 is a common pulse rate to all BRM's. The value of f_0 is in turn variable through a separate BRM, such that $f_0 = (R_0/2047) \times 50$ pps. Since the outputs of the DAC's control the output currents of the power supplies, the values of the R_i's provide control of relative ramping rates between supplies, while the value of R_0 scales the ramping speed of all supplies together. In the software, the R_i's are referred to as RATE's, while R_0 is named INTRATE, since this is also the interrupt rate to the computer. The computer sets up these BRM registers, and then turns the master pulser on to drive all the BRM's together. As the DAC's ramp up or down, according to their specified rates, an interrup-driven program in the computer constantly examines all DAC's, and stops those that reach their set points (DACSP). When all DAC's reach their set points, the master pulser is turned off. In this way, all power supplies can be ramped in unison from one configuration to another.

While ramping, the magnet currents monitored by transductors (VMON's) are also read continually by the computer by means of a digital voltmeter/scanner system capable of sampling up to 15 channels per second. The values of DAC, DACSP, VMON and the desired VMON set point (VMONSP), as well as on/off and reversing status for each power supply can be displayed on a scope while the supplies change as shown in Fig. 1. This is one of several displays that may be made by selecting switches on a display panel.

Activating the control program RING to perform certain tasks is done by pushing one of 16 push buttons. Each pushed button results in a call being made to a corresponding subroutine in the control program which may ask for new parameters from a teletype, or perform a computation, etc.

III. Software

A. Control of Individual Power Supply

There are several levels of control, depending upon the complexity required, provided by the computer program RING. An individual supply may be changed by pushing a button and then typing in its DACSP or its VMONSP, and the program will ramp that supply to the DACSP. (When a VMONSP is specified, the program calculates the required DACSP by means of built-in linear transfer functions between DAC and VMON values for that supply, i.e., $DACSP_i = VSLOPE_i \times (VMONSP_i - VO_i)$, where $VSLOPE_i$ and VO_i are constants for supply i.) Alternately, the DACSP or VMONSP may be "tweaked" by turning a knob which is constantly read by the computer. By means of thumbwheels and switches on the display panel, the operator selects the index i of the power supply to be tweaked and the DACSP or VMONSP option. Then any increments resulting from turning the knob (64 counts per turn) are added to the variable being tweaked. Changing the DACSP does not change VMONSP, which then allows one to see on the scope display the percent change that occurs in the value of VMON (or strength) from its set point as shown under %DS/S in Fig. 1.

All VMON's may be brought back to their VMONSP values by pushing a TOUCHUP button, which calculates the required DACSP's and, if necessary, may iterate new DACSP's until all VMON's agree within tolerance with their VMONSP's. Frequently used configurations can be saved on disk files and recalled quickly into memory when needed, by pushing a button and typing in the name of the configuration, followed by a touchup operation to carry the power supplies to the VMONSP's of that configuration.

B. Control of all Power Supplies

At a higher control level, another push button allows the operator to type in new configuration parameters (or obtain them from a disk file) to calculate all the corresponding VMONSP's and then take the power supplies there without losing the beams.

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We define a configuration segment as a straight line in the configuration space which joins one configuration to another. Because of the very nonlinear nature of the VMONSP's as functions of the configuration parameters, the program actually takes many small steps, and recalculates new VMONSP's for each mini-step along a configuration segment until the end configuration is reached. Calculation of the VMONSP's for each mini-step along a segment will be described in Section V.

Since it is sometimes impossible to use a single segment to reach a configuration (because of inoperative regions or power-supply limitations), several segments in series are used. We call such a set of linked segments a path in configuration space. Another feature of the control program is the ability to save all the mini-steps along a path made up of any number of given segments onto a single file having a specified path number. Later, the operator may take this path again by simply pushing a button and typing in the path number. Up to 20 such paths can be saved. For example, the storage ring is filled at one configuration, and then the beams are taken to a running configuration along one of these previously saved paths. An example of this operation is described in Section D.

C. Other Useful Features

The program RING performs other useful functions besides controlling the ring magnets. The beam position monitors positioned at 20 locations around the ring can be scanned by the computer. The computed horizontal- and vertical-orbit distortions can be viewed graphically or listed numerically on the scope. Orbit distortions can then be corrected by tweaking the trim supplies, and these corrected VMONSP's can be saved with the configuration on the disk. It is then possible when traversing a configuration segment, to have the trim supplies follow linearly with the size of the mini-step from their values at the beginning configuration to those at the end configuration, thus correcting the orbit distortions along the configuration change.

Another very useful feature of RING is the display of the fifty most recent readings of the e^+ and e^- beam currents as shown in Fig. 2. These currents, obtained from photodiodes which monitor the synchrotron light of each beam, are normally read once every second; however, the reading interval is a changeable parameter. The program calculates the best straight-line fit to a selected number of points and displays the rate of fill and/or decay of the beam currents over this interval of time. During injection, the rate of fill is useful for maximizing injection with the steering magnets, etc., while during running periods, the calculation of decay time is useful. Also, as shown in Fig. 2, the integrated luminosity, specific luminosity, as well as average currents, can be displayed.

D. An Example of Magnet Control

The above features are illustrated in the following steps that an operator might use in bringing up the SPEAR magnets, filling the ring, getting a new configuration, saving a configuration, saving a path, and going from an injection to an operating configuration.

Push Button Command	Function of the Command
GETV INJ	Fetch the VMONSP's from disk for the configuration having name "INJ"
STDZ	Run all magnets through a standardizing cycle (up to maximum, down to zero, then to VMONSP's of "INJ"). Now the ring is ready to be filled.
GET XX	Go to configuration "XX" (and also interpolate trim supplies along the way).
NUX = .2, β_x = .10*	Change from "XX" configuration to one having $\nu_x = 0.2$ and $\beta_y^* = 0.1$ m. (The * terminates the input string.) Trim supplies might be tweaked at this point.
SAVE YY	Save present configuration with the name "YY". Other configurations might be saved in this manner.
GETV INJ	Go back to configuration "INJ".
SAVP N; XX, YY, ZZ	Save all mini-step into path number "N" while going from "INJ" to "XX," "XX" to "YY" and "YY" to "ZZ".
GETV INJ STDZ GETP N	Start again, from "INJ", then take path number "N" to "ZZ", the operating configuration.

IV. Calculation of VMONSP

There are eight types of quadrupole magnets in the SPEAR lattice. The gradients in these magnets are determined by the values of ν_x, ν_y, β_x^*, β_y^* and η^* corresponding to any desired mode of operation, the condition that the beta and eta functions are repetitive from cell to cell, and the desired beam energy. The value of the bending field in kG is given by 2.62308 E with E in MeV.

Due to the symmetry of the SPEAR lattice the values of ν_x, β_x^*, and η^* can be expressed in terms of the elements of the transport matrix[2] for a quarter of the lattice between points 0 and 2 as shown in Fig. 3. Denoting the x-matrix elements as M_{xij} we have:

$$\nu_x = \frac{1}{\pi}\cos^{-1}\left[\,\mathrm{sgn}(M_{x12}M_{x22})(2M_{x12}M_{21}+1)\right]$$

$$\beta_x^* = \frac{2|M_{x12}M_{x22}|}{\sqrt{1-(2M_{x12}M_{x21}+1)^2}}$$

$$\eta^* = -\left(\frac{M_{x23}}{M_{x21}}\right) \qquad (1)$$

The tune is just the excess over the next lower integer. Similar expressions can be written for ν_y and β_y^* by interchanging the subscript x for y and $\eta^* = 0$ for the y motion. In addition, since the magnetic elements in a SPEAR cell are symmetric about the center of the cell, the periodic requirement for the beta and eta functions from cell to cell can be expressed in terms of R_{xij}, the elements of the transport matrix for a section of the lattice between points 0 and 1, as shown in Fig. 1:

$$\alpha_{x1} = -\left(\beta_x^* R_{x11}R_{x21} + \frac{R_{x12}R_{x22}}{\beta_x^*}\right)$$

$$\eta_1' = R_{x23} + R_{x21}\eta^* = 0 \qquad (2)$$

and a similar expression for $\alpha_{y1} = 0$. The matrix elements M_{xij}, M_{yij}, R_{xij} and M_{yij} are functions of the gradient strength of the eight quadrupole magnets divided by the particle regidity, k_i for $i = 1, 2, \ldots, 8$.

The method used to compute the strengths on the quadrupole magnets is as follows. Consider a typical case in which we start from Conf. A as specified by ν_{xa}, ν_{ya}, β_{xa}^*, β_{ya}^*, η_a^*, α_{xla}, α_{yla}, and η_{1a}' and we wish to go to Conf. B as specified by ν_{xb}, ν_{yb}, ... Imagine that a line segment is drawn in the 8-dimensional space connecting these two points, Conf. A and Conf. B. Divide this line segment into N equal-length subsegments and label the configuration at the end of the ith subsegment S_i. Assume the magnet strength vector $\vec{k}_0$ is known at S_0 (Conf. A). First, using the value of the derivatives of ν_x, ν_y, ... at $\vec{k}_0$, we compute $\vec{k}_1$, the approximate value of the magnet strength vector for S_1. Then from Eqs. (1) and (2) we

compute the value of ν_x, ν_y, ... at $\tilde{k}_1$ and compare these values with those for S_1. If their differences are smaller than some acceptable values, we continue to calculate the magnet-strength vector for S_2 using $\tilde{k}_1$ as a starting point. In order to speed up the computation, after P successful steps we double the length of the subsegments and then proceed. Whenever the test of acceptability fails, the length of the subsegments is halved and the same procedure is carried out using the last acceptable solution as a new starting point. This procedure will continue until Conf. B is reached.

The strengths of the sextupole magnets are chosen so that the rates of change of betatron tunes with particle momentum, i.e., the chromaticities, are made to be zero. For a system with two types of sextupoles λ_D and λ_F, the required corrections are given by:

$$\left(\sum_D \eta\beta_x\right)\lambda_D + \left(\sum_F \eta\beta_x\right)\lambda_F \approx \frac{2\pi}{\ell}\left(\sum_i \frac{\partial\nu_x}{\partial k_i} k_i\right) \qquad (3)$$

and

$$\left(\sum_D \eta\beta_y\right)\lambda_D + \left(\sum_F \eta\beta_y\right)\lambda_F \approx -\frac{2\pi}{\ell}\left(\sum_i \frac{\partial\nu_y}{\partial k_i} k_i\right) \qquad (4)$$

In these expressions the summation over D denotes summing the values of $\eta\beta$ over all the D magnets and summation over F denotes summing over the F magnets; ℓ is the length of a magnet and λ's are the sextupole strengths divided by the particle rigidity.

To find the VMONSP's first we calculate the magnet excitation current corresponding to the field-strength values required for each type of magnet from the measured magnetization characteristics. The output of each supply VMONSP is found from the transfer characteristics of the current monitoring transductors.

The strengths for orbit correction may be determined either experimentally or theoretically by using a program MOVQ.[3] The VMONSP for the trim supplies can be found likewise.

V. Performance

The computer program RING has been in operation for almost a year and has gone through considerable modification during this time, to the form described here. The time-shared nature of the computer allowed developments and changes to be made to RING even during the operation of SPEAR, with very little interference. As more time-sharing users began using the computer, it became necessary to move some functions (such as reading the beam currents) into interrupt-driven programs, and to provide means of locking RING into memory during critical times (such as tweaking supplies or reading beam-position monitors). The model of the ring has been refined by adjusting the values of the magnet strengths to fit the experimentally measured betatron wave numbers at various configurations. The predicted values of ν_x and ν_y from the modified model agree to within ±0.006 of the measured values over normal operating regions. Deviations as large as 0.02 have been observed at previously unfitted configurations. However, this large difference may be due to the magnets not being standardized, i.e., hysteresis effects.

The sextupole field strength as calculated from Eqs. (3) and (4) have been found empirically to be about 10 to 15% too low. It was necessary to increase these values by this amount in the program. Linear scaling of the orbit correction strengths, according to the step size along a path, has been found to be working satisfactorily. The time regularly required to change configurations can be as short as a few seconds when the change is small, to a few minutes for a large change. Ramping in energy from 1.5 GeV to 2.5 GeV takes about 1 minute, while changing from a $\eta^* = 0$ to a $\eta^* = 5$ meters can take 10 minutes or more because of the many steps required.

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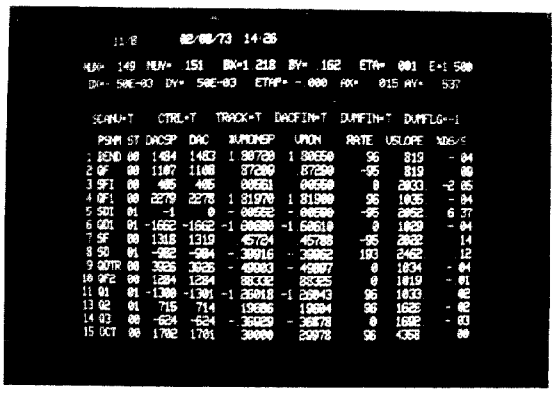


FIG. 1--Power Supply Display

The top portion of the display shows the values of the nine configuration parameters ν_x(NUX), ν_y(NUY), β_x^*(BX), β_y^*(BY), η^*(ETA), energy (E), η_1'(ETAP), α_{x1}(AX), and α_{y1}(AY) of the storage ring. For each power supply, there is one column which gives the power supply name (PSNM), its status (ST), the desired DAC set point (DACSP), the actual reading of the DAC, the desired transductor set point (VMONSP), the actual transductor reading (VMON), the ramping rate (RATE), the calibration constant (VSLOPE) between DAC and VMON, and the % difference between desired and actual magnet strength (%DS/S).

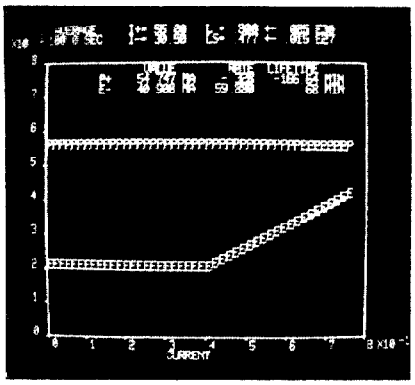


FIG. 2--Beam Current Display

This display shows the last fifty readings made on the e^+ and e^- beam currents. The horizontal axis is time in minutes (seconds or hours also possible) while the verticle scale is in milliamperes. The labels P or E on the curves designate the positron or electron currents. The break in the electron curve shows the beginning of injection of electrons. The slope of the line fit to the last few points (8 in this example, but more or less could be chosen) provides the rate of fill or decay for each beam. The values of the beam currents, fill/decay rates and lifetimes are displayed above the curves. The time averaged values of the beam currents, luminosity, and specific luminosity are shown at the top. The time interval in the averaging was 100 seconds for this example.

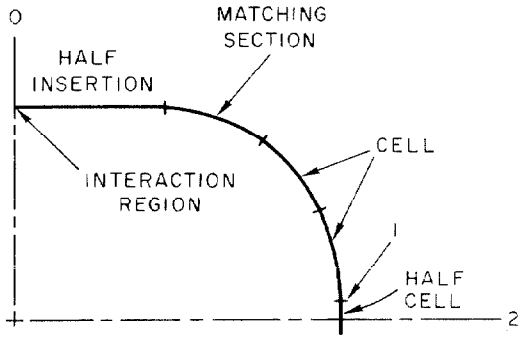


FIG. 3--The magnetic lattice is symmetric about the axes as shown by a quadrant of SPEAR.