

## BEAM MATCHING, STEERING, AND DESIGN USING A CDC-924, AN OSCILLOSCOPE, AND PROGRAMS DEVELOPED AT ARGONNE NATIONAL LABORATORY\*

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### Summary

Computer programs have been developed at Argonne National Laboratory (ANL) to match given input beam phase-space conditions to desired output conditions in a system with up to six quadrupoles. An oscilloscope will produce beam envelopes, trace rays, or produce phase-space diagrams at given locations in a much larger simulated beam system. Provisions are available for treating off-axis and off-momentum beams. Elements include slits, drift space, quadrupoles, and bending magnets. The phase-space configuration accepted by a system with displaced elements, off-momentum beams, asymmetrically placed slits, and element apertures can be displayed on the oscilloscope. These features have been used to design experimental beams, tune the Zero Gradient Synchrotron (ZGS) external proton beam, and steer the ZGS external proton beam. Excellent agreement has been found between the program predictions and actual beam parameters. Measurements of beam spot sizes at one or more locations have been used to compute beam phase-space conditions which are subsequently used in the other programs. The programs used have been entitled WIEMNY, MATCH, and QUISP.

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Computer matching of the first ANL-ZGS external proton beam from the exit of the ZGS to several experimental target positions was found necessary because of difficulties in empirical beam tuning. There are three consecutive targets in the beam with quadrupole magnets between. There is also a septum magnet which allows the beam to be divided and transported along two channels. We started by using existing beam optics programs on a CDC-3600, but limitations in these programs and the slow job turnover time on large computers soon forced us to go to the smaller CDC-924. This CDC-924 is the control computer for the ANL-ZGS and is used on-line with the machine for other jobs. Therefore, beam calculations are background jobs and time-share the computer with the

operational programs which are foreground jobs. A large display scope with memory had been built for use with the computer. The computer has paper tape, magnetic tape, and typewriter inputs with magnetic tape, printer, typewriter, and scope outputs.

An outmoded existing program, MATCHLESS, which had been used on a different computer for matching the linear accelerator to the ring of the ZGS, using four quadrupoles, became the heart of our new program. After considerable revision of the program, to meet our needs, and evolution as we applied the program to real problems, we arrived at the present (not yet final) version which we call MATCH.

MATCH uses as input, beam phase-space conditions (assumed to be ellipses), drift lengths, quadrupole lengths and gradients, and desired output beam phase-space conditions. The matching process can be done either manually by changing parameters on the typewriter, using an internal search routine, or combinations of these. The beam envelope is displayed at each change on the scope. Aperture and gradient limitations are the responsibility of the man operating the program.

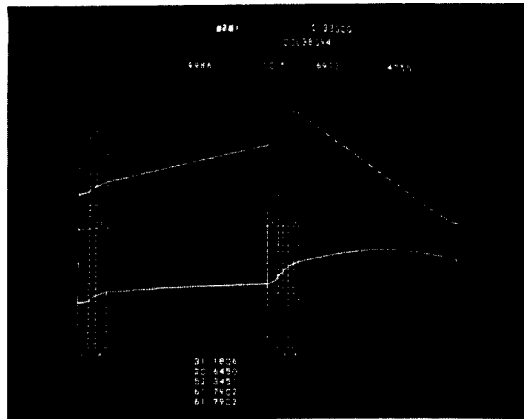


Fig. 1

Figure 1 is a photograph of a scope display for a case involving five quadrupole magnets. The center horizontal line is the axis. The horizontal beam envelope, measured from the axis, is the upper curve. The vertical envelope,

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measured from the axis, is the lower curve. The spacing between horizontal lines is one-tenth inch in this display. The momentum is given at the top. The second number is a chi-squared fit to the desired conditions. The four numbers on the next line are the final beam phase-space conditions. The first and third numbers are related to the horizontal and vertical ellipse tilt ( $\pm 1.0$  for waists or upright ellipses). The second and fourth numbers are beam spot half-sizes in the horizontal and vertical planes. Input parameters are not repeated on the display because of limited space. The phase-space area is not repeated since it is constant. The vertical lines are the effective edges of the quadrupoles with their centers marked. The polarities are given by the signs below. The gradients are the numbers below the graph in appropriate units (millivolts on our shunts!).

The internal search routine varies only gradients. If there are two quadrupoles, only two phase-space conditions can be met; these are the spot sizes in the vertical and horizontal planes. For three quadrupoles the horizontal ellipse will be completely determined. With four quadrupoles both ellipses conditions are determined. With five, a position of a horizontal waist at some interior position must be specified and with six, a position of a vertical waist must be added. The program will not search with more than six quadrupoles. However, up to twenty quadrupoles can be displayed and adjusted manually. Figure 2 is a scope display of a beam with eleven quadrupoles which has actually been used. Problems involving consecutive targets can be broken into sections with output of one as input for the next to keep the number of quadrupoles in the range of the search routine.

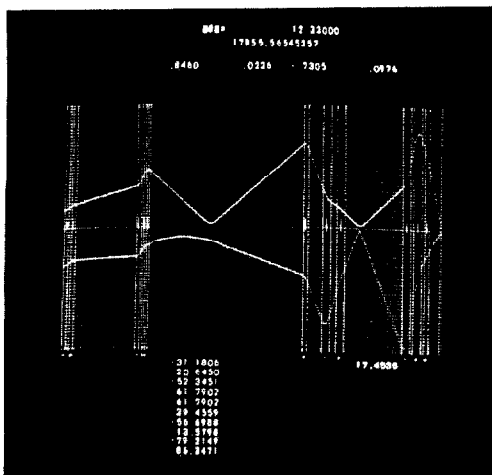


Fig. 2

QUISP is a program which was taken from a large general beam transport program, TOTAL, developed at ANL. Because of the core limitations of the CDC-924 (32K of 24 bit words total, but considerably less memory for background jobs), QUISP has no search routine. QUISP has provisions for bending magnets, drift lengths, quadrupole magnets, and aperture limits. QUISP will track rays (trajectories), phase-space ellipses, and the residues of phase-space ellipses through more than a hundred elements. Figures 3 and 4 are photographs of scope displays of phase-space ellipses at several positions along the same beam.

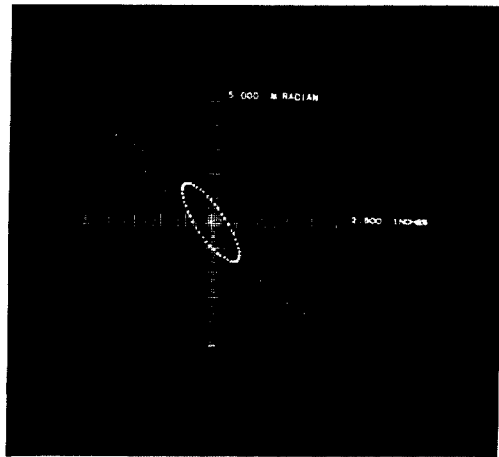


Fig. 3

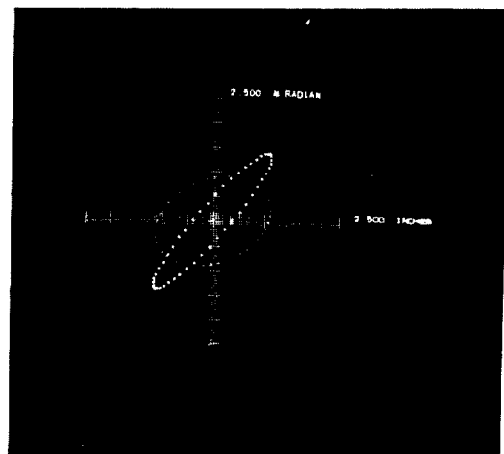


Fig. 4

Figure 5 is a scope display of the residue of a phase-space ellipse after passing a septum magnet (essentially an asymmetric slit).

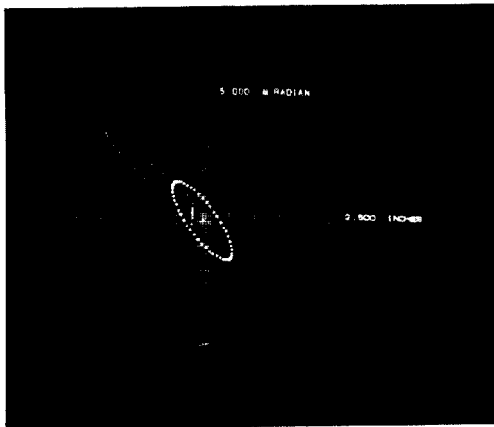


Fig. 5

By using an infinite ( $10^{22}$  GeV/c) design momentum, a rigid axis is established, and by tracking the central trajectory of a finite momentum (12.33 GeV/c), one can study beam steering in bending magnets and quadrupoles. Figure 6 is a ray trace of the central ray through bending magnets. The external proton beam is restored after a magnet in a zero angle production beam, for a lower momentum experiment, drives the external proton beam off axis.

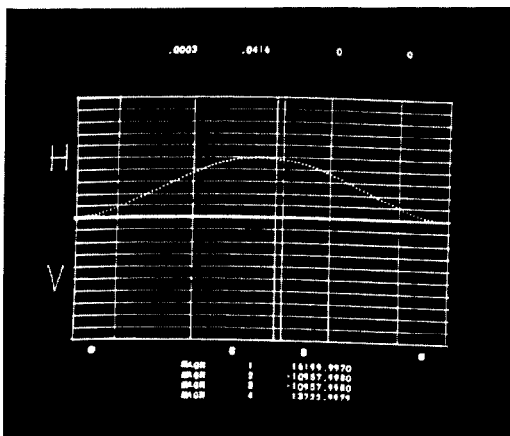


Fig. 6

Displacements<sup>1</sup> of an element laterally from the axis can be simulated by shifting the beam ellipse axis before the element, tracking the off-axis ellipse through the element, and then shifting the beam ellipse axis back an equal distance after the element. Figure 7 is a photograph of an ellipse shifted off axis. This procedure has been used to study the effects of quadrupole steering.

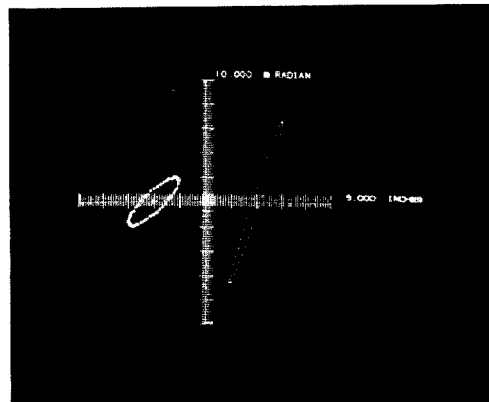


Fig. 7

By setting aperture limits before and after the elements of a beam, the phase-space acceptance at various momenta (and solid angle accepted) can be studied. This is done by tracking a very large phase-space area through the system and observing the phase-space residue at the end. This can be tracked through a time-reversed system to study the target requirements at the beginning of the beam. These features have been used in the design of experimental beams.

WIEMNY is a program which uses three measured beam spot sizes to calculate the phase-space properties of a beam.<sup>2</sup> The measurements can be made at the same position consecutively with different magnet settings, at three different locations along the beam line, or combinations of these. The input required is the drift lengths, quadrupole lengths, and quadrupole gradients. Beam spot sizes have been measured with optical densitometer profiles of radiation-damaged glass exposed in the proton beam. X-ray films exposed to induced radiation on copper foils placed in the beam have also been used. The latest modification is the use of segmented wire ionization chambers (SWIC), the subject of another report by Fred Hornstra, Jr., in this journal. Because of the density distribution in the beam (and phase-space), beam spot size is

not a trivial thing to determine. A study is now under way to get more reliable and consistent spot sizes from available data.

These programs have been used successfully in tuning and steering the ANL-ZGS external proton beam. They are, however, still being refined and changed as more is learned and new applications are seen. They will soon be applied to the control of the 50-MeV beam as it leaves the ZGS linac and is injected into the ring. They will also be applied to the more complicated second proton beam of the ZGS and, hopefully, will be used in the design of many general experimental beams.

#### References

1. S. M. Marcowitz, "A Note on a Mathematical Treatment of Displaced Beam Elements," SM-10, Internal Report (1968).
2. G. A. Concaildi, F. Hornstra, Jr., H. Lucks, and S. Marcowitz, "A Procedure Used to Determine the ZGS External Proton Beam Phase-Space Properties," GAC/FH/HL/SMM-1, Internal Report (1968).