MATCHING AND ALIGNMENT FROM THE LINAC TO THE ZERO GRADIENT SYNCHROTRON

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The injection and matching system from the Linac to the Argonne Zero Gradient Synchrotron is described in detail. Some theoretical matched solutions are shown. Practical methods for achieving a good beam into the ZGS are discussed.

Introduction

The 50.8 MeV proton beam from the Argonne Linac has a measured emittance of about one π mr. in. It travels a distance of approximately 1000 in. before being injected into the ZGS, 5/8 in. below the median plane and 13.5 in. outside the central equilibrium orbit. Along its path the beam is acted upon by correcting steering magnets, two sets of quadrupole matching doublets, an achromatic bending system and an inflector. It is monitored by segmented quadrant detectors and slit systems (to give position and emittance measurements) and TV screens (to give coarse size and position measurements). While the radial acceptance of the ZGS is not particularly stringent, the vertical aperture of $\pm$ 2.5 in. limits the total vertical divergence of the injected beam to $\pm$ 2 mr., requiring a waist for the injected beam of greater than $\pm$ 0.42 in. In practice, we attempt to inject a circular 1-in. diameter beam with waists in both planes.

Detection Equipment

Figure 1 shows the position of the beam monitoring and handling equipment between the Linac and the injection straight section of the ZGS.

Beam Receivers and Slits

The Beam Receivers (BR 500, 501, 502 and 701) are special boxes which contain, at least, beam monitoring toroids and remotely controlled pairs of horizontal and vertical slits. The slit widths and positions are adjustable.

Work performed under the auspices of the U. S. Atomic Energy Commission

Position 602 contains a vertical slit of 10 mils width. Position 702 contains two fixed width vertical slits, one 20 mils wide and the other 60 mils wide.

Beam Stoppers

The Faraday Cups, FC 501, 502, 601 and 702 are beam stoppers used to measure total current. FC 702 is really two beam stoppers, one being 1 in. in diameter (the design beam size at this position), the other large enough to intercept all the beam through the inflector. Signals from the beam stoppers can be used in conjunction with the appropriate pairs of slits for measuring beam emittance. The position of the slits and the intensity of the passed beam are automatically recorded on an x - y plotter.[1]

Matching Quadrupoles

The matching system is composed of two sets of doublet quadrupoles (QM 501, 502, 503, 504) made from 10-in. long, 3-in. diameter bore magnets with hyperbolic poles. The field is supplied by water cooled coils having 8 turns per pole. The coils are designed for a maximum current of 800 amperes at 22 volts which yields a gradient of 2.81 kG/in. Each doublet is excited in series from one current regulated power supply. The strength of each quadrupole is independently controllable by means of parallel transistor shunts which can bypass up to 200 amperes.

Steering Magnets

The steering magnets, SM 501 and 502, are used to line up the beam from the Linac with the principal axis of the matching quadrupoles. Each position has a vertical and a horizontal steering Helmholtz coil capable of producing 40 gauss-in. per ampere. The power supplies provide up to 25 amperes. SM 600 B provides vertical steering only.

Segmented Detectors

The segmented detectors (located at ST 501 A, ST 501 B, BR 502, BR 601 and behind FC 702) are groups of 4 beam stopping plates arranged to intercept the beam in quadrants. They are positioned symmetrically about the principal axis of the quadrupoles. A simple resistive adding circuit sums the signals from each pair of plates. The differences between the sum signals of adjacent pairs of plates can be displayed on an oscilloscope to determine whether the center of charge of the beam is positioned correctly.

Since the segmented detector at ST 501 A is positioned at the same location as the steering magnet SM 502, correct steering is easily accomplished by adjusting SM 501 to give a centered beam at ST 501 A, after which SM 502 is adjusted for a centered beam at ST 501 B.

Achromatic Bending Magnets

The Achromatic Bending Magnet System[2] is composed of three magnets, the first and third (ACBM1 and ACBM3) being identical and designed to bend the beam 78.8° each. The center magnet (ACBM2) bends the beam in the reverse direction by 50.6° so that the total bend is 107°. Three degrees additional bend is provided by the inflector. The ACBM's are designed to operate at 12.340 kG with a radius of curvature of 33.3 in. for 50.8 MeV protons. Each achromatic bending magnet has a 42-turn coil and the inflector has a single-turn coil. The four coils are connected in series from a 1900-ampere dc, current regulated power supply. Provisions are made for individual variations by transistor shunts across each coil capable of bypassing up to 100 amperes.

Protons with energies greater than or less than 50.8 MeV have their maximum displacement from the central orbit at the center of ACBM2. The system is designed so that all particles, to the first order in the momentum error, emerge from the system with equal bends and positions.

A unique feature of this system is the use of an edge angle of 25.56° at the entrance to ACBM1 and the exit of ACBM3 to focus the beam vertically. The focusing properties of the system are such that incident particles having displacement X, Y and zero slope with respect to the principal axis pass through the centerline at the middle of ACBM2 and emerge from ACBM3 with displacement -X, -Y and zero slope.

Television Screens

Remotely operated television screens are located at ST 501 B, BR 502, BR 601 and BR 701 for rapid determination of beam size. Some representative TV pictures are shown in Figs. 2, 3 and 4. The screen at ST 501 B (Fig. 2) is currently a quartz plate coated with alumina. The screens at BR 502 and BR 601 (Figs. 3 and 4) are made of 0.05-in. grid of tungsten wires coated with fluorescent paint. The screens are set at 45° to the direction of the beam and are viewed by the TV cameras at 90° to the beam direction. A triggered image-storage system permits storage of the image either for the entire interval between pulses or for any time duration desired.

Matching the Linac Beam to the ZGS

Theory

When the radial phase space emittance of the beam from the Linac is specified, the desired orientation and radial size of the phase space ellipses in two planes at the exit of the inflector completely determines the strengths of the four quadrupoles. In arriving at a theoretical solution, we assume the focal properties of the ACBM's to be known. A computer program is used to solve the four transcendental equations by an iterative method to give the required quadrupole strengths.[3] Figures 5, 6, 7 and 8 show the existence of four separate solutions for matching a typical Linac beam emittance to produce a 1-in. size upright ellipse in both planes at the exit of the inflector. (The configuration of the quadrupoles is the same for all solutions, namely FDFD in the horizontal plane.) The four solutions are characterized by the existence or absence of waists in either or both planes in the space between the two sets of doublets. The double waist solution requires, of course, higher quadrupole strength than the no waist solution. All, however, are well within the capabilities of the quadrupole power supplies. When other output emittance figures from the Linac are used, there is no guarantee that all of these solutions will exist.

The abrupt discontinuities in the profiles at the entrance and exit of the ACBM system are caused by a sharp edge approximation to the effect of the vertically focusing and horizontally defocusing edge angles. In the horizontal plane, the achromatic system behaves like a short drift length of 18.0 in. Thus, the X plane profile proceeds from the exit of the ACBM system very nearly as a continuation of the input. In the vertical plane, the ACBM system behaves like a negative drift length of 139.3 in. Since the distance from the exit of ACBM3 to the exit of the inflector is 158.6 in., the Y plane profile at the entrance to ACBM1 is very nearly the same as that at the exit of the inflector.

As is shown, a matched beam produces very sharp horizontal and fairly sharp vertical waists just upstream from the center of ACBM2. The exact location and size of these waists depends on the radial phase space area. In any case, the beam is very small horizontally at the center of ACBM2, the location of maximum positional change due to energy spread. Thus, a measurement of the size of a well-matched beam at the center of ACBM2 gives a good measure of the energy spread of the beam.

Matching in Practice

The measurement of the Linac emittance and the subsequent calculation to determine the matching conditions is a fairly lengthy process. There are many variables between the proton source and the exit of the Linac, most of which can change the emittance. We are slowly approaching but have not yet arrived at a condition where we can be sure of obtaining, each time the system is turned on, the same kind of beam from the Linac. A further complication has been the recent discovery of an, as yet, unexplained steering variation of the beam during the length of the 120 μsec pulse. This effect has been observed to be as much as 1 mr. Since the usual emittance measuring technique depends on the total amount of charge passing through slits at known positions, the apparent emittance area may be too large by as much as 30 to 40 per cent. To determine the emittance as a function of the time during the pulse is a lengthy process indeed.

Thus, we are seldom in a position of being able to set the matching quadrupoles at calculated values. If the focal properties of the ACBM system are known, however, the sizes of the beam at locations following the matching doublets depend only on the quality of the beam and the desired matching conditions. An iterative process, such as adjusting QM 503 and 504 to give the desired size at TV 601, followed by an adjustment of QM 501 and 502 to give the desired size at TV 502, readjustment of QM 503 and 504 looking at TV 601, etc., has been found to converge. We are also aided in this adjustment by observation of the screen at 701 and by making use of the partial (1-in. diameter) and total beam stopper currents at 702. With this method we may arrive at any one of the solutions mentioned above, depending on the starting currents for the iterative procedure. The screen at ST 501 B can be used to determine just what kind of solution has been obtained.

In the final analysis, the best adjustment of the matching quadrupoles is determined by maximizing the total amount of beam accelerated by the ZGS. However, there are many tuning variables within the ZGS itself.[4] Therefore, we are always faced with the possibility of attempting to adjust the input beam to an improperly tuned ZGS. Subsequent readjustment of the ZGS parameters under these conditions would lead, most probably, only to a local maximum for the total amount of accelerated beam. Therefore, it is worthwhile to concentrate on trying to produce an input beam that theory tells us should lead to a maximum amount of accelerated beam when the synchrotron is correctly tuned.

References

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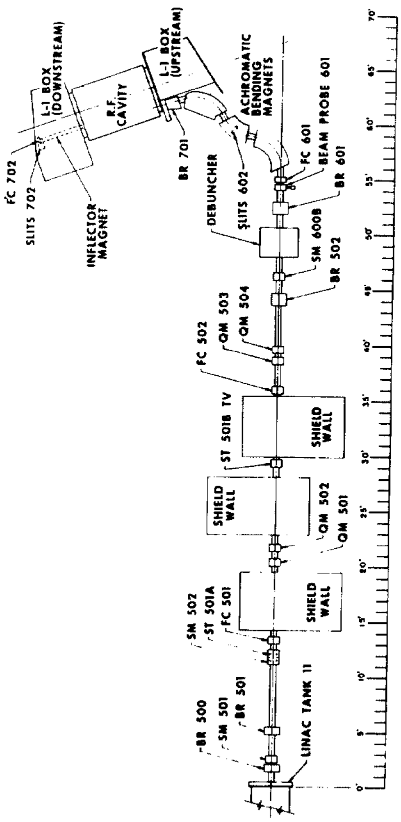

Fig. 1. Position of components in the 500 and 600 areas.

Fig. 2. Typical beam pattern on TV screen 501 B.

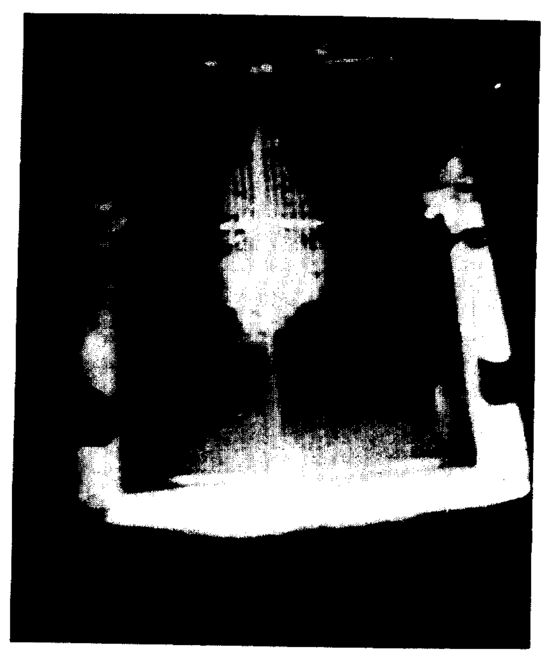

Fig. 3. Typical beam pattern on TV screen 502.

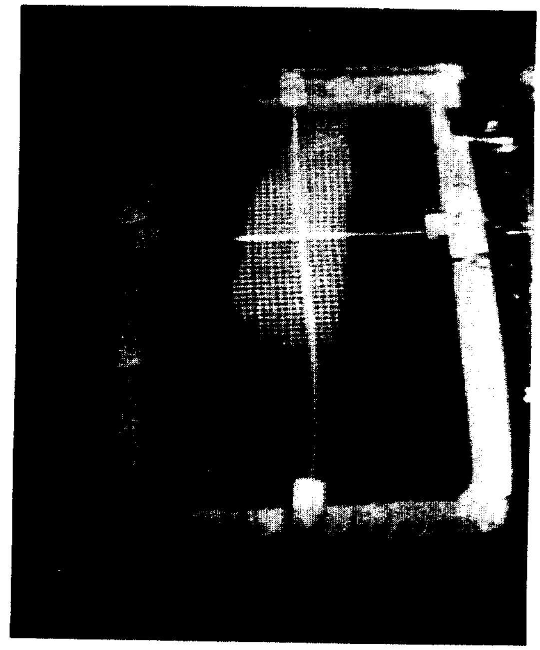

Fig. 4. Typical beam pattern on TV screen 601.

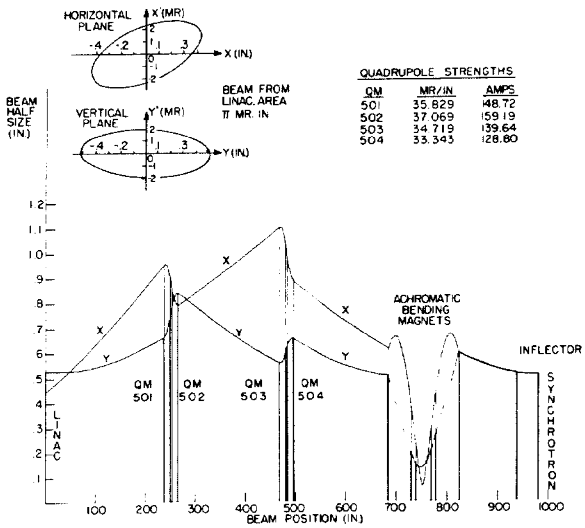

Fig. 5. Matched beam profile (No waist solution).

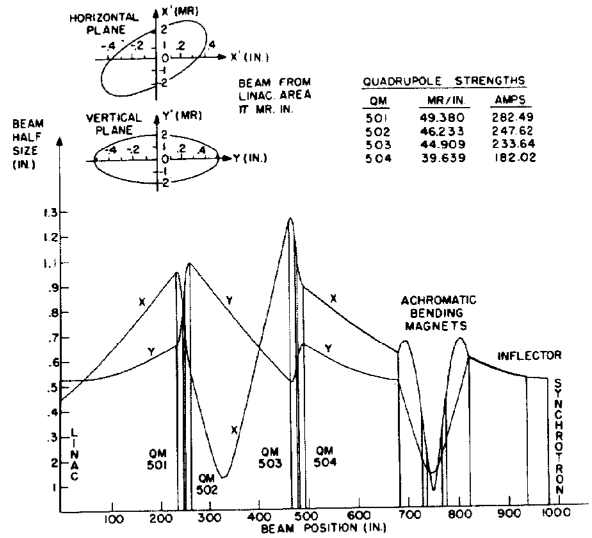

Fig. 6. Matched beam profile (X waist solution).

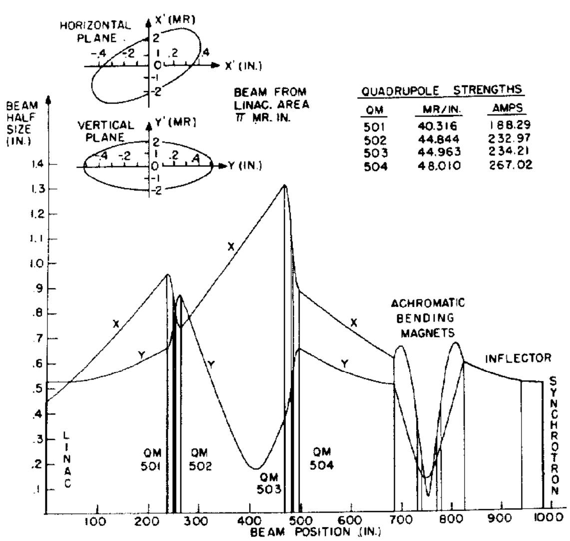

Fig. 7. Matched beam profile (Y waist solution)

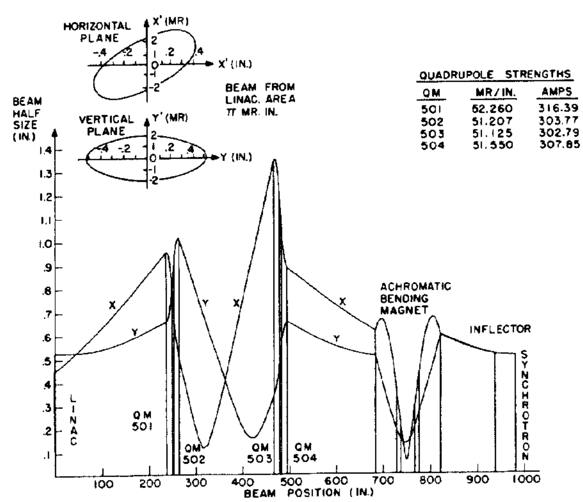

Fig. 8. Matched beam profile (Double waist solution).