DESIGN CONSIDERATIONS FOR A 200-MEV PROTON BEAM TRANSPORT SYSTEM*

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ABSTRACT

The design of the beam transport system (HEBT) between the new 200-MeV injection linac and the AGS at Brookhaven National Laboratory involved consideration of the following points: physical situation, requirements of the AGS in terms of beam emittance and energy spread, characteristics of the linac beam and space-charge effects. The design adopted was strongly affected by space-charge effects. It consists of a nearly periodic focusing structure with gradually increasing betatron wavelength, a momentum recombining (achromatic) bend, a matching section for emittance adjustment and a double bend of which the magnetic AGS inflector is the last part. A debuncher system will be available and it is proposed to tune it in combination with the linac to yield bunches with a phase spread of about π radians and an energy spread of a few hundred keV or less. Space-charge effects are expected to become noticeable in the form of emittance blow-up in the proposed system for 100 mA beams with emittances of less than 0.2π cm-mrad.

1. Introduction

One of the more interesting results to be expected from the AGS Conversion Program is that it will be possible to charge the AGS to far beyond its conventional space-charge limit of 1.3×10^{13} protons with the new 200-MeV injection linac. This implies that the space-charge densities in the circulating beam may be very high even with intensities below that limit. Therefore space-charge effects and reduction of current densities were major considerations in the design of the HEBT, the high energy beam transport system between the two accelerators.

Another aspect is that 200-MeV protons represent enough of a radiation hazard at the intensities expected to make it important to minimize beam losses.

A study of possible injection and bunching methods showed the desirability of a small bunching factor and a small energy spread in the beam to be injected. Consideration of the effects of space charge in bunched beams indicates that effective emittance blow-up may be minimized by matching the beam to the local focusing structure.[1] Consequently the linac beam should be about matched to the focusing system of the AGS when entering this accelerator. Because the linac beam current is too small to deliver the design charge of 1.3×10^{13} protons (500 mA) during a single revolution in the AGS a multiturn injection scheme must be used. In order to minimize the current density in the circulating beam as much as possible of the available AGS aperture should be used. Hence an injection scheme was chosen that permits vertical stacking in addition to the

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

conventional horizontal stacking. A magnetic inflector is to be used instead of an electrostatic one. This is convenient for vertical stacking, and permits larger beam deflection angles so that stray fields of the AGS in the injection line are avoided while focusing and steering elements may be moved to close in front of the inflector.

Summing the requirements we find that we want at the inflector exit a beam with a small bunching factor and a small momentum spread. We also want tight control of the beam axis and emittance.

The raw linac beam is highly bunched. Its emittance is far from matched to the AGS because the transverse focusing is much stronger in the linac than it is in the AGS.

The conversion of the linac beam into one suitable for injection into the AGS takes place in the HEBT. As may appear from Fig. 1 this transport system consists of three parts. In the first part, 77 m long, the bunching factor is reduced to about 2.5, the energy spread to about $\pm 10^{-3}$ and the transverse focusing strength is gradually reduced by a factor of 4.5. The second part is a dispersion-free bending system of 27 m length in which the beam direction is changed by $36^{\circ}43'$. In the last part, with a length of 39 m, the final transverse matching operation to the AGS is performed. The emittance may be adjusted in a group of six quadrupoles. This group is followed by horizontal and vertical steering elements. In this fashion coupling between emittance adjustments and beam axis control is minimized.

A constraint for the design of the HEBT was that the relative positions of linac and AGS as well as the layout of the transport tunnel had already been chosen. This imposed severe limitations on the geometry of the beam path. Another complication was the presence of the BLIP facility (BLIP for Brookhaven Linac Isotope Producer) which required a beam switch and its own transport system.

We shall consider consecutively:

The longitudinal motion.
The transverse motion.
The transport to the BLIP facility.
The effect of the earth's magnetic field.
Beam monitoring.
Accuracy requirements.
Apertures.

2. Longitudinal Motion

Let us consider the longitudinal motion first. As Lloyd Smith pointed out,[2] the energy spread in a bunched beam will increase with drift length due to longitudinal space-charge forces. The effect increases with beam current and bunching factor. This means that such a beam will show dispersion after passing through a nominally dispersion-free bending system because such systems rely on the constancy of the energies of the individual particles. This makes it necessary to debunch intense bunched beams upstream of such bends.

Computer runs by A. Benton indicated that the available drift space of 77 m is too short to reduce the bunching factor sufficiently if the beam was matched to the rf buckets in the linac. As expected they also showed that in intense beams the energy errors increase drastically with increasing distance to the linac due to space charge, the increase in energy error coming too late to affect the bunch length appreciably, however. Therefore we propose to increase the energy spread at the linac exit to $\pm 10^{-2}$ by adjustment of the linac. With this large spread the beam debunches to bunching factors of 2.5 or less after a drift space of 50 m. At this point the coherent part of the energy spread may be removed by a debuncher arrangement, leaving the incoherent part at rather less than $\pm 10^{-3}$. As Lloyd Smith pointed out,[2] the energy spread increases again beyond the debuncher but the effect is inconsequentially small with the small bunching factors obtained. Because the bunches have become so long ($\approx \pi$ rad), a single debuncher cavity operating on the fundamental may not reduce the energy spread sufficiently. It may be necessary to use several cavities running at harmonic frequencies.[3] It is this increasing debuncher complexity which limits the bunching factor achievable with practical means.

3. Transverse Motion

3.1. Bending System

The dispersion-free bending system occupies a central position in our considerations because it establishes independently an input axis and an output axis in space. For optimum results the beam has to enter along the input axis; if it does it will emerge along the output axis. The bending system proper is conventional and consists of two identical bending magnets of wedge shape and with uniform fields, each deflecting the beam by $18^{\circ}21'$. Their field strength is 12 kG and the effective bending centers are separated by 27.35 m. This limits the local betatron wavelength to $\lambda = 54.70/(2n + 1)$ m with $n = 0,1,2,3,\ldots$. Consideration of transverse space-charge effects to be expected in anticipated beams (i.e., 100 mA, $E \geq 0.3$ cm-mrad, $B \lesssim 2.5$) showed that $n = 0$ would provide sufficient focusing strength so that the quadrupole system between the two bending magnets could consist of three symmetrically placed quadrupoles. The system is arranged to yield a betatron wavelength of 54.70 m in both transverse directions. The beam displacement due to momentum change is 7 cm/% $\Delta p/p$ in the midplane of the central quadrupole.

As shown in Fig. 2, quadrupoles have been added to each side of the system proper such that the midplanes of the bending magnets and the midplane of the central quadrupole are planes of mirror symmetry. In the absence of space-charge effects this arrangement yields unitary transformations for the two transverse directions from input plane to output plane and -1 transformations from planes upstream of the first bending magnet to corresponding planes upstream of the second. Hence the emerging beam is nominally identical with the entering beam. We make use of the -1 transformations for beam-monitoring purposes. The possibility of this bend was shown analytically; the actual values for the components were calculated with the SLAC beam transport program.[4]

3.2. Transport Between Linac and Bend

The transport system between the linac and the bend consists of a string of 13 quadrupoles (the last one of which has been combined with the first one of the bending system to a single physical unit) which is centered on the elongated input axis of the bend. This elongated axis should coincide with the linac axis; adjustable dipole moments in the last several linac quadrupoles provide steering for the correction of errors in this respect. The system is an extension of the linac focusing structure; it forms a nearly periodic system with betatron phase changes per cell of $\pi/2$ rad for both the horizontal and the vertical motion. The departure from exact periodicity is caused by the gradual increase in cell length necessary to match to the linac focusing structure at the input end and to the bending system at the exit. The individual cells are formed of mirror symmetric half-cells; each half-cell is composed of two quadrupoles of equal strength and opposite polarity, separated by a drift space. In the thin lens approximation the quadrupole strength is related to the drift length ℓ via

$$Q\ell = \frac{1}{E_o \beta\gamma}\, c\, \frac{\partial B}{\partial r} \cdot \ell_{quad} \cdot \ell = \pm 1/\sqrt{2} \quad ,$$

where	E_o	rest energy of protons in eV,
	c	velocity of light in m/sec,
	$\partial B/\partial r$	quadrupole gradient in tesla/m,
	ℓ_{quad}	effective length of quadrupole.

The whole structure is obtained by butting the quadrupoles of successive half-cells together, combining each pair into a single physical unit. Depending on the strength of the first quadrupole the system may begin with either a quarter-cell or a half-cell. This leaves some choice for the quadrupole law inside the linac. In choosing the individual cell lengths we repeatedly made use of the property that in this structure one may pass from one length ℓ_1 to another length ℓ_2 without loss of match if the two structures are joined by a matching cell of length $\ell = \sqrt{\ell_1 \ell_2}$. Only at the two ends of the matching cell the beam is mismatched. This is a consequence of the fact that one cell corresponds with half an envelope oscillation (and a quarter betatron oscillation). The final list of quadrupole spacings was obtained by trial and error, satisfying the matching requirements at the two ends and fitting the system to the predetermined available length. The mismatch is small everywhere except possibly in the linac because the fractional increase in cell length per cell is only of the order of 0.1. Another mismatch occurs at the joint to the bending system. Although the betatron wavelengths are accurately matched at that point the focusing structures are not, so that the matched emittances are different in shape. Since the mismatch is not very large we did not pursue this matter.

3.3. The AGS Matching Section

In the AGS matching section the beam which emerges from the bend, where the betatron wavelength is 54.70 m, is matched to the AGS where the betatron wavelength is about 92 m. This would require a wavelength matching cell with a length of about 17.7 m ($= \frac{1}{4} \sqrt{\lambda_1 \lambda_2}$) and one-eighth of a structure with wavelength equal to the AGS wavelength for emittance shape matching, or a similar configuration. Each of these choices would require six quadrupoles downstream of the last bending magnet, would be weighted in favor of matched beams inside the AGS and therefore prejudiced against other modes of operation and impose severe but different restrictions on the quadrupole locations. This led us to prefer a more general approach, accepting the consequences of resulting local mismatches. We put the two quadrupoles belonging to the bending system in their calculated locations and distributed four additional quadrupoles uniformly over the available drift space. Then we used the SLAC transport program to calculate the quadrupole strengths necessary to obtain a matched beam inside the AGS and to check whether the resulting beam was "reasonable." For this calculation we set the first quadrupole, which still belongs to the bending system, to its calculated strength. In addition to this, we used this program to satisfy ourselves that this arrangement permits a wide range of operating conditions if all six quadrupole strengths are regarded as variables. Comparison with four quadrupole matching schemes showed the proposed one to be far more flexible. Our calculations suggest that it will convert nearly any linac beam into practically any AGS beam one might ask for.

4. Transport to the BLIP Facility

In order to be able to operate the linac independently of the AGS a beam dump close to the linac was planned from the early stages of the project. The beam reaches this dump via a switching magnet in the main line, as indicated in Fig. 3, so that all linac pulses except the ones to be used for AGS injection may be used for linac tuning, diagnostics and studies.

The large time average intensity of 200-MeV protons (> 180 μA or > 36 kW) available in this area makes it into an attractive facility for the production of neutron deficient isotopes, the BLIP facility.

As shown in Fig. 3, the part common to the transport system to the AGS and the BLIP contains the first two quadrupoles and the switching magnet. The switching magnet is off while the AGS is being injected; for BLIP operation it forms the first element of a nominally dispersion-free bending system in which the beam is deflected through 30°. Of this the switching magnet and the second bending magnet each supply 7.5° and the third one supplies 15°. Between the last two magnets are three quadrupoles. Because the beam is still highly bunched in this area the effects discussed in Sec. 3.1 are very much in evidence. As an example consider a normal, matched linac beam of 100 mA and π cm-mrad emittance. In the drift space between the last two bending magnets the beam may have an effective diameter of the order of 2 cm while the bunches might be about that long. In that case the electric field strength on the bunch surface would be some 45 kV/m and the energy spread would be increased by about ± 300 kV by the time the bunch reaches the last bending magnet. This increase leads to an increased angular spread beyond that magnet of ± 400 μrad, increasing the effective horizontal emittance by a factor of 1.5.*

The same dispersion occurs about one-sixth as strong at the exit of the second magnet; it is reduced because the angle of bend is smaller and the drift space from the first magnet shorter.

Beyond the bend the beam drifts through a vacuum pipe towards a thin window which it penetrates. At this point it becomes available to the users of the BLIP facility. Throughout the vacuum pipe it is focused by a conventional quadrupole arrangement.

5. The Effect of the Earth's Magnetic Field

The earth field causes displacement and distortion of the beam axis; the resulting shape is determined by the balance between the earth field and the local correction by the quadrupole fields. Without further action the maximum displacement is 0.6 mm immediately after the linac. Due to the decrease in focusing strength with increasing distance to the linac the maximum displacement increases to 3.6 mm at the entrance to the main bend. The dispersion caused by this bending field is $< 0.003\ \Delta p/p$ mm, negligibly small. Although the displacements are relatively small the beam pipe will be wrapped with a double magnetic screen so that they will be reduced by about an order of magnitude.

6. Beam Monitoring

In view of the problems with heat dissipation, radiation and activation of devices which intercept the beam partly or wholly, it is important that the beam monitors be as transparent as possible. Even better are nondestructive devices. We shall monitor our beams as much as possible with nondestructive or nearly nondestructive devices and limit the use of destructive equipment to special, nonroutine applications.

Most measurements will be done using beam current transformers, beam position monitors, and beam profile monitors. We also intend to install a nondestructive device that measures the longitudinal charge distribution in the bunches.[5]

Our position monitors are truly nondestructive, highly linear, and show rise times of the order of 1 μsec. Operated as passive devices (without electronics), they produce an output voltage of the order of 10 μV/mA·mm across 100 Ω.

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[*] The effect can be compensated for at least partly by a beam-sweeping device which is driven in synchronism and in phase with the bunches, the modulation strength being related to the charge distribution within the bunches. We are not at present proposing to install such a device.

Possible profile monitors are briefly discussed in another paper at this Conference.[6] No firm decisions have been made and alternatives are under consideration.

6.1. Energy Measurement

The energy of the beam may be measured employing the dispersive properties of bending magnets already present for other reasons. The maximum usable displacement in the bend to the BLIP facility is about 1.3 cm/% $\Delta p/p$; in the bend in the main line it is about 6 cm/% $\Delta p/p$. Using pairs of position monitors upstream of the dispersive magnets to determine the position and direction of the incident beam one measures energy errors as transverse displacements with a third position monitor. In the first bend the position monitors limit the accuracy achievable to about 10^{-3} and in the main bend to about 10^{-4}, assuming that their effective resolution is ± 0.1 mm.

6.2. Energy Spread

According to a suggestion by Dr. Th.J.M. Sluyters the energy spread may be measured by comparing the width of the dispersed beam with the width of the incident beam as measured in transverse planes that are couplee by a transformation of the form

$$\begin{pmatrix} a & 0 \\ b & -1/a \end{pmatrix}$$

The dispersed beam is wider by an amount determined by the energy spread.

In the main bend we measure the energy spread primarily to ensure proper adjustment of the debuncher. As locations for the width measurements we chose the homologous transverse planes mentioned in Sec. 3.1 because of the -1 transformation between such planes. Immediately beyond the linac the energy spread may be measured in the bend to the BLIP facility in similar fashion. The measurement is not as convenient because this bend lacks a number of the ion optical conveniences of the main bend. A disturbing factor is the dispersion associated with longitudinal space-charge effects mentioned in Sec. 3.1.

6.3. Transverse Motion

6.3.1. Beam axis. If our beam position monitors will resolve 0.1 mm, they will permit us everywhere to locate the beam axis in phase space to within less than 10% of the dimensions of the box which contains the local emittance ellipsoid, provided that the two-dimensional emittance is given by $E_2 \geq 0.3\ \pi$ cm-mrad. They have to be used in pairs in order to do this. We will measure the axis coordinates close to the exit of the linac in order to establish its short-term and long-term stability and to have a reference for energy measurement in the BLIP line. In the main line we will do it again after the switching magnet to make sure that it does not deflect the beam while it is off; we measure on both sides of the main bend, to make sure that it is operating properly, to have a reference for energy measurements, and to provide known coordinates for the AGS matching section. We measure position only in the bends for energy measurement and in the injection area. In total we will install about 22 individual units.

6.3.2. Emittance. Elsewhere[6] we have discussed emittance measurements. Using the measurement principle described there we will measure the emittances close to the linac exit and again close to the AGS. The BLIP line will contain a destructive device.

7. Accuracy Requirements

The uncertainty in the coordinates of the beam axis in the inflector due to misalignments of elements in the transport system is less than 15 times the standard deviation of the alignment errors. Since these errors should be within ± 0.2 mm we are practically certain that the beam axis will be somewhere inside a circle with 1 cm radius around the design axis. Moving upstream towards the linac the radius of the circle decreases, of course. This limit on these errors may be compared with the available aperture which is 3 in. or more. Because the focusing system is not only nearly periodic but also resonant, the beam is rather sensitive to the quality of the quadrupoles used. Calculations by Dr. M. Month show that we have to require a constancy of the effective field gradient to within 10^{-3} over the useful aperture.

The deflection angles in the two bending magnets of the main bend should be equal to within a few parts in 10^5. This poses a severe problem. It is relieved somewhat by making the two magnets nominally identical, and by providing each one of them with a main excitation coil and a trimming coil. The main coils may be run in series and the trimming coils in series opposition. In this way the stability requirement for the main excitation current may be relaxed to 10^{-3} to 10^{-4}, provided that the temperature differences between the two magnet structures are kept small.

The switching magnet is another potential source of trouble. It should cause no beam deflection in the nominally "off" position with a tolerance of ± 10 μrad.

8. Apertures

The aperture requirements were based on the consideration that the transport system should be able to pass at least the worst beam still acceptable to the AGS. This led to the use of vacuum pipe with a diameter of 3 in. nearly everywhere. Exceptions are the BLIP line, the central part of the main bending system and a part of the AGS matching section. There the pipe diameter is 4 in., either because the space is needed (main bend) or to provide space for beam gymnastics.

References

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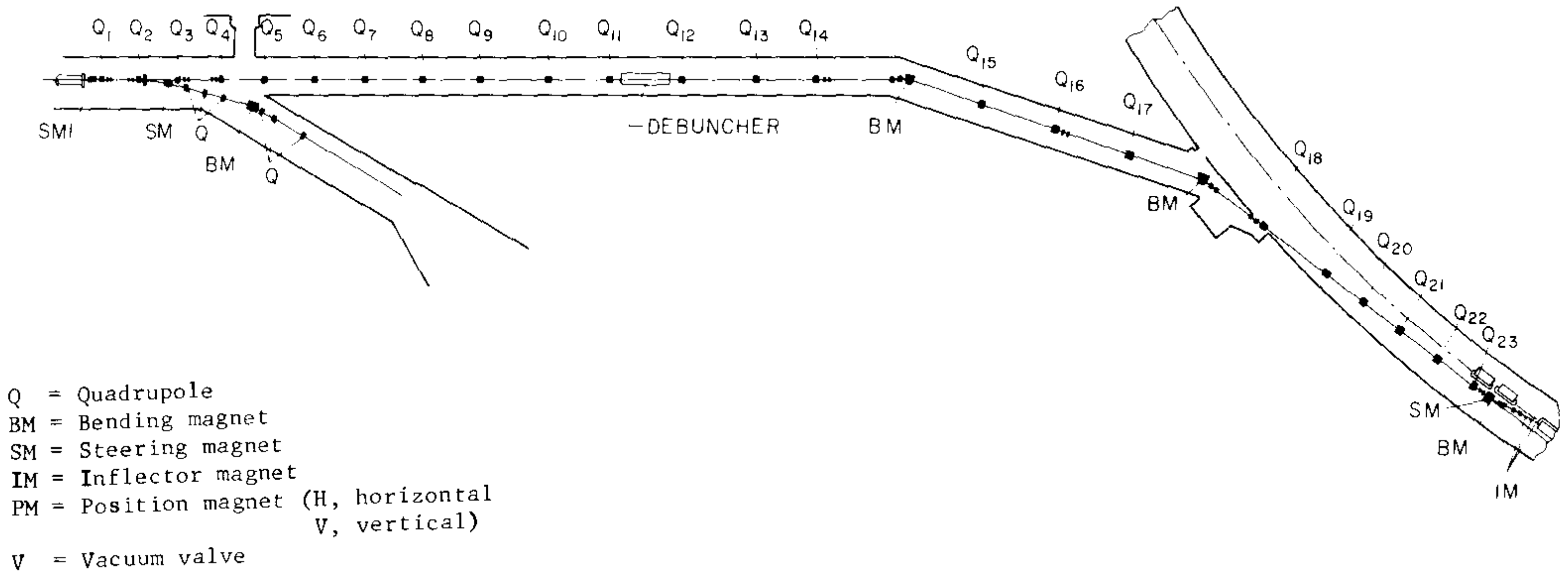

Q = Quadrupole
BM = Bending magnet
SM = Steering magnet
IM = Inflector magnet
PM = Position magnet (H, horizontal
V, vertical)

V = Vacuum valve

Fig. 1. The High Energy Beam Transport system.

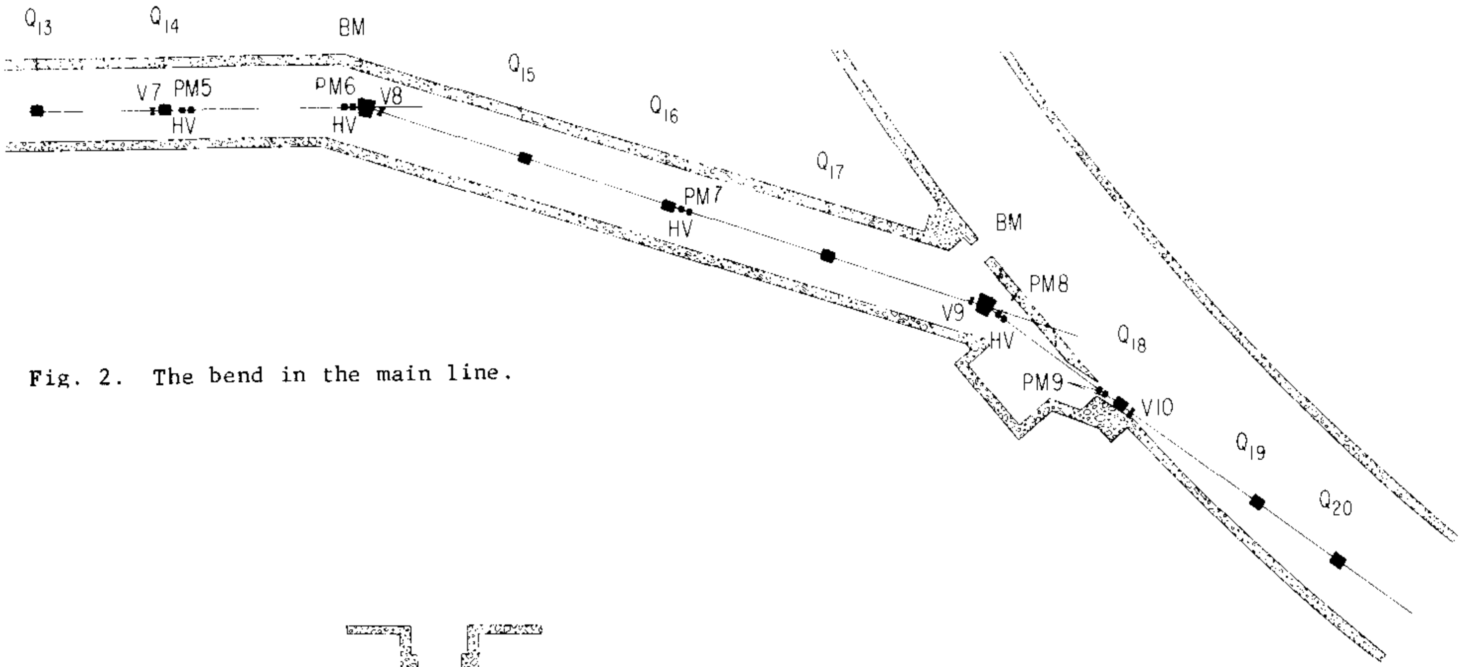

Fig. 2. The bend in the main line.

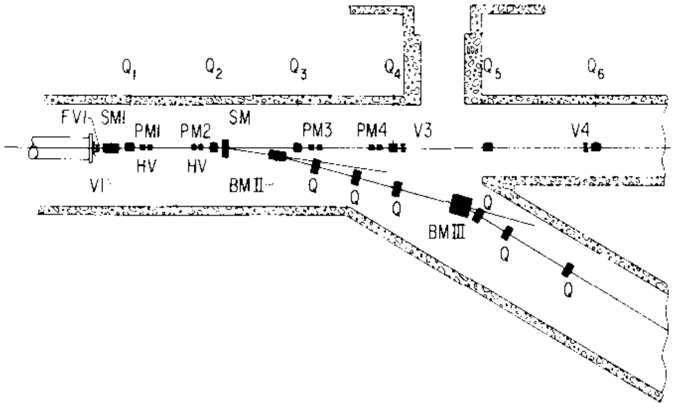

Fig. 3. Transport to the BLIP.

DISCUSSION

J. M. Lefebvre (Saclay): Could you say a few words about the septum-magnet inflector?

J. Claus (BNL): The first thing that should be taken into account is that we plan to stack in both the horizontal and vertical directions. That is to say, we stack with a fixed betatron amplitude in the vertical direction. The reason for doing this is to minimize the number of turns that we have to stack horizontally, which, if you inject in a lossless fashion, as we plan to do, would dilute the available admittance of the AGS in a dramatic way. The inflector itself consists of three magnetic units. A magnetic inflector has been chosen because it can be built rather easily in such a fashion that it has both a horizontal and vertical septum, one being a copper septum, the other being an iron septum. This makes the vertical stacking process possible, and that is much more difficult to achieve with an electrostatic arrangement, with its sparking problems. Our three units are all two feet in length, and they are graded in strength so that the final septum is very thin. The upstream septa are thicker. There are arrangements to prevent leakage fields that would be felt by particles in the AGS.

E. Regenstreif (Rennes): Am I right in saying that you use four quadrupoles for achieving a minus unity transformation or a phase shift of π and eight quadrupoles for achieving a transformation of +1?

J. Claus: That is true for the beard, but it is not just for quadrupoles. The bending magnets form an essential part of the focusing system.

A. Citron (Karlsruhe): You mentioned that your last quadrupoles could be controlled from the control room, which implies that the first cannot. Is the optimum setting of these quadrupoles dependent on the beam current?

J. Claus: No. The scheme I described uses a focusing strength that will prevent space-charge effects from detuning the betatron tunes in any serious way. The change in betatron tunes due to space charge is very small compared to the betatron tune that is there already. That means that you don't have to change the quadrupoles if you increase the beam-current intensity.