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Correction to AD/RHIC-47, Beam Transfer From AGS to RHIC

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Beam Transfer from AGS to RHIC

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Introduction

RHIC, an acronym for Relativistic Heavy Ion Collider, is a facility for colliding heavy ions with each other, proposed for construction at Brookhaven National Laboratory. This facility, and the motivation for building it, have been described in [1]. It consists of two intersecting storage rings and the purpose of this note is to describe how these two rings are to be filled with beam.

The AGS will serve as the injector for RHIC. It will accelerate a number of bunches per pulse that may vary with the mode of operation. These bunches will be parked on an extraction orbit when they reach the extraction energy. There they circulate until they are transferred, one at a time, to one of the two RHIC rings, where they will be received in designated buckets. The option of transferring them all at once may also be available. The AGS extraction system exists already [2, 3], injection into RHIC occurs in its 6 o'clock insertion. The AGS extraction system works in the horizontal plane, RHIC's injection systems in the vertical one. The rings are filled one after the other. Filling RHIC will take initially about two minutes and later on up to, conceivably, fifteen minutes, per RHIC cycle of ten hours or more. Below we describe the system, sketch a mode of operation and consider tolerances.

Relevant characteristics and parameters

The reference orbit of the AGS has a circumference of about 807.125m and its harmonic number is 12, the circumference of each RHIC ring is 3833.845m, (i.e., 19/4 AGS circumferences) and its harmonic number during injection is 342 (=6×12×19/4). All of RHIC's six insertions are set for β^*=6m during the filling operation in order to provide sufficient aperture. The energy at which the bunches are transferred is $\gamma \approx 31.4 \cdot Z/A$, with Z and A the charge and mass numbers, so that the magnetic rigidity at transfer is always the same, regardless of the particle species: $B\rho \approx 98.224$Tm. Nominally the bunches will be about 17nsec long, i.e., less than 0.075 of the distance between bucket centers (224.3nsec) in the AGS, but 0.45 of that in RHIC (37.4nsec); proton bunches may be somewhat shorter. Their nominal longitudinal emittance is 0.3eVsec, their nominal radial and axial emittances are 20πmm-mrad each for protons and 10πmm-mrad each for all other particles. When the bunches are transferred one at a time, it is always the last bunch of the train circulating in the AGS that is extracted and it is always injected to form, or, occasionally, to replace, the last bunch of the train being built up in RHIC, so that the fall times for the extraction and injection kickers can be relatively long. The rise time of the injection kicker determines the best obtainable filling factor of RHIC; we propose to make it 95nsec, so that every third bucket may be filled (filling every bucket would require it to be $\leq$20nsec). This may be contrasted with the rise time required for AGS extraction kicker, which must be $\leq$207nsec (always assuming bunch lengths $\leq$17nsec).

Equipment

The bunches pass through a transfer line in moving from the AGS to RHIC. A layout of this line is shown in Fig. 1. It begins as the existing AGS's Fast Extracted Beam (FEB) line, which has been in operation for many years for the neutrino physics program. A switching magnet, placed in this line, will define the beginning of a spur which will lead, via an also already existing tunnel, to RHIC. This arrangement allows normal operation of the AGS program as long as the switching magnet is off, and interrupts it only when RHIC is being filled. The spur contains a second switching magnet, the ring selector, where it splits in two branches, one leading to the RHIC ring in which the particles rotate clockwise, the other to the counter-clockwise ring. The design is very similar to the one made for the CBA project, and nearly all of the components already available or designed for that project are used (see Figure 2 and ref [4]). The deviations from that design were dictated by the differences in geometry and lattice functions between RHIC and CBA, and consist of a change in beam level and minor adjustments at the downstream end.

The first switching magnet drives the beam into the first section of the spur which deflects the beam both horizontally and vertically, such that, at the entrance to the ring selector, its axis runs along the intersection of a horizontal plane, 40cm above RHIC's median plane and the vertical plane through the machine center and the crossing point at 6 o'clock. This plane is a plane of reflection symmetry: reflecting one ring in it yields the other; the same is true for the two branches of the transfer line.

The horizontal deflection in this first section is 20° in an arc with an average radius of 405.82m, the change in vertical level is 1.4m. The horizontal deflection and the change in level are mixed: the former is performed by a string of 8 gradient magnets in an AG focusing arrangement, the latter by a pair of pitching dipoles, the first one of which is located between the second and third horizontal deflectors. The first horizontal deflector functions as switching magnet. The gradient magnets are each about 3.66m long, produce a radius of orbit curvature of 83.83m and carry therefore a field of 1.17T, they are separated from each other by drift spaces that are 14.05m long. The second pitching dipole is placed between the second and third quadrupoles of a string of six between the last horizontal deflector and the ring selector. These, together with the quadrupoles in the fast beam line upstream of the switching magnet, provide for flexibility in the choice of focusing parameters at the entrance of the ring selector. At that point the beam is nominally free of horizontal and vertical dispersion ($x_p=x'_p=y_p=y'_p=0$); however, the system may be reset to compensate for the vertical dispersion generated by the final drop in beam level of 40cm in the injection region.As it stands, the design of this section does not preserve the vertical polarization of polarized beams. A different configuration separating the horizontal and vertical bends would have to be adopted to preserve polarization in this section.

The next section consists of the two branches which begin at the entrance to the ring selector and end in the injection halls. Since they are mirror-symmetric we shall describe only one. The ring selector guides the beam via a dispersion match into one of these two 'big bends', strings of gradient magnets which guide the beam along arcs with average radii of 96.333m and deflection angles of 1.04 rad each. The 24 gradient magnets in each big bend are arranged in six cells in a OFoFOODoDO pattern with horizontal and vertical betatron phase advances of about $\pi/2$ rad per cell, and maximum values for the amplitude and dispersion functions of $\hat{\beta}$ = 26.5m, $\hat{x}_p$= 2.2m. The O's stand for drift spaces of 0.715m each, the o's for drift spaces of 0.45m each while the F's and D's represent focusing and defocusing bending magnets with lengths of about 3.66m, fields of about 1.27T and gradients $|B'/B|$ of 2.9381m^{-1}. The 1.43m long OO spaces are available for collimators, beam monitors and correction magnets.

Each big bend ends in its associated injection hall. There it is followed by a string of five horizontally deflecting dipoles which are located and excited to make the projection of the transfer line axis onto RHIC's median plane coincide with the reference orbit of the appropriate ring down stream of the last dipole. These magnets will be about 2.95m long, deflect the beam through about 0.049rad each and must therefore have fields of about 1.61T. Six quadrupoles for adjustment of the match between big bend and RHIC are imbedded in this string, one at each end and one in each of the four drift spaces between the dipoles.

Injection occurs at end of the last part of the transfer system. This section contains four special magnets, the last one being the injection kicker, which guide the approaching beam from its initial level, 40cm above RHIC's median plane down onto the injection closed orbit. Their arrangement is shown in Fig. 3 in elevation and in plan. The first magnet, SI0, is located directly above ring magnets BS2 and Q70; it must have a bending strength of 5.46Tm, thus with a length of 4.77m a field of 1.14T. It sends the beam downward, via the last quadrupole of the transfer line, QMI7, to septum magnet SI1. This magnet has a bending strength of 4.74Tm, a length of 4.15m and a field strength of 1.14T. Its current septum lies between the incident beam and the circulating one. Leaving SI1 the beam passes off axis through the aperture of vertically defocusing ring quadrupole Q80, then through septum magnet SI2, and is finally bent into the median plane by injection kicker KI. SI2 must have a bending strength of 0.275TM. It is 1.4m long and has therefore a field strength of 0.196T. The kicker will have to provide a bending strength of 0.132Tm. Its length is 3.25m, its aperture at least 40mm vertical $\times$ 20mm horizontal, its field 0.04T.

The behavior of the beam downstream of SI2 is may be judged from Fig.4. The elevation and plan admittance envelope traces in this figure are drawn for an admittance of 3.2πmm-mrad for the incident beam and 3.2πmm-mrad and 6πmm-mrad for the circulating one. The septa of SI1 and SI2 must fit between the admittance envelopes for the incident and the circulating beams. We determine the available space, assuming that the apertures in the transfer line should provide everywhere for at least twice the local beam dimensions, and that the ring admittance must be 6πmm-mrad. The transfer line admittance must then be at least 3.2πmm-mrad, since the largest real (2.5σ) incident beam emittance expected is 0.8πmm-mrad; the quoted ring admittance provides ample space for the increases in emittance from intra beam scattering. Using this, one finds that the spaces available for the septa in question are 15mm for SI1 and 1mm for SI2 at their downstream ends. This severe constraint may be relaxed to a much more reasonable 20mm for SI1 and 4.5mm for SI2 if one allows vertical displacement of these magnets over a distance of 5mm immediately after the ring has been filled. They are placed to leave a ring admittance at least equal to that of the transfer line, namely 3.2πmm-mrad, during the filling interval and they are moved to increase it to at least 6πmm-mrad after the ring is filled. In doing so one takes advantage of the fact that a smaller ring admittance is quite acceptable during the filling period, since the emittance increase of the circulating beam occurs only on a time scale that is long compared to that period. The dimensions given for magnets SI0, SI1 and SI2 are only rough estimates. Detailed design work, in particular for the latter two, may produce configurations that offer the nominal admittance of 6πmm-mrad also during the filling operation. Their physical withdrawal after that operation is complete would then not be necessary.

Operation

The mode of operation proposed here is based on the assumption that the conditions in RHIC represent the standard of reference for all activities. In a setup procedure[1] RHIC is made ready for filling and then kept stationary in that state until it is filled. Similarly, nearly all magnets in the beam transfer system are excited and also kept stationary. Exceptions are the extraction and injection kickers and the pulsed septum magnets. The case considered in the following is the most general one: the transfer of individual bunches, one by one, from whatever bunch train has been accelerated in the AGS, into the waiting rf buckets of RHIC.

When used for filling RHIC the AGS may accelerate trains of from 1 to 12 bunches. Just prior to the events leading to extraction the closed orbit control system is set to hold the circumference of the closed orbit at $4/19-\delta$ of the circumference of the injection orbit in RHIC ($19/4 = 4.75$ is the ratio between the circumferences of the reference orbits, δ is a small number, yet to be determined). The acceleration continues and the rf frequency keeps increasing until its sixth harmonic approaches the rf frequency in RHIC. When the difference has become small enough a phase locking loop between the two rf systems takes over from the radial position loop as controller of the AGS rf frequency and fixes it at exactly the 1/6 sub-harmonic of the frequency in RHIC with predetermined relative phases of the charge distributions in the two rings. The bunch that is to be extracted from the AGS must arrive in the bucket in RHIC that trails the last one filled by a predetermined number of buckets, in order to accommodate the injection kicker rise time, while maximizing the filling factor.

Acceleration continues because the AGS guiding field is still increasing. It will be stopped, by blocking further changes in the guiding field, when the synchronous particles reach the extraction energy. The strength of the guiding field is taken as a measure for the synchronous energy and its change is stopped at the instant that it reaches a reference value. Use of

RHIC's guiding field as reference makes the beam transfer process relatively insensitive to small variations in that field. The closed orbit, which had been too short until the phase lock took over, expands with the continuing increase of the AGS field. The conditions are chosen such that it will coincide with the extraction orbit at the instant that the field increase is terminated. At that moment the phase of the AGS rf relative to that of RHIC isjumped so as to place stationary buckets around the bunches and the rf voltage is adjusted to preserve the match between bucket and bunch. These measures help to prevent dilution of the bunches in synchrotron phase space. It may be useful to reduce the rate of acceleration and the stable phase angle during the preceding operations in order to gain time for them, to reduce the changes in the guiding field that are associated with changes in the ($\dot{B}$-driven) eddy current distribution, and to lend them a measure of adiabaticity.

The AGS functions as a storage ring from this point onwards. The bunches in it have the proper synchronous energy and circulate on the proper extraction orbit, the last bunch in approximately proper phase relationship to the charge distribution in the ring to be filled. Any remaining small phase error is now corrected by adiabatic adjustment. The rate at which such an adjustment can be made depends upon the synchrotron period in the AGS and on the amount of dilution in synchrotron phase space considered acceptable; it is rather low: 2rad/sec for protons, 0.15rad/sec for gold for a 1% blow up in bunch area. The rate must be so low because the bunches are so short, relative to the rf period; their dilution per synchrotron period increases with the square of their fractional displacement.

With its phase now as correct as it can be made to be the bunch keeps circulating until its transfer to RHIC is initiated by excitation of the extraction and injection kickers. Each is triggered by the rf of the ring it serves after some form of coincidence circuit has flagged the fact that the charge distributions have reached appropriate azimuthal positions in both rings. This waiting period may last up to 19 revolution periods in the AGS and up to 4 in RHIC, thus up to about 50μsec, which time represents a 'superperiod' in the AGS/RHIC cycle. The bunch moves out of the AGS, through the transfer line and arrives in the bucket in RHIC which it finds waiting upon passing through the injection kicker. The kickers are reset to zero excitation immediately thereafter, and preparation for the next transfer begins.

If the AGS is now empty it is returned to injection energy and a new cycle begins. Matters are more complex if it contains more bunches. Unless one can shift these bunches in the AGS with respect to the raster defined by the buckets in RHIC one would now face the following situation: The choice of harmonic numbers, 12 in the AGS and 342 in RHIC implies that a particular bunch in the AGS could only be placed in one of 19 equally spaced buckets in RHIC after the two rf systems are synchronized. Calling the bucket which houses this bunch bucket 1, one finds easily that bunches in buckets 4, 7 and 10 could only reach these same 19 buckets in RHIC. Another set of 19 is available to bunches 2, 5, 8 and 11 and still another to bunches 3, 6, 9, and 12. It follows that this method makes only 57 (=3x19) buckets in RHIC available for filling. One finds also that one cannot invert the order of the bunches, as is necessary for proper injection. If the counting above goes upstream it gives the proper sequence of extraction: first the bunch from bucket 1, then the one from bucket 2, etc. But the bucket in RHIC that is available to bunch 2 and closest to the one occupied by bunch 1 lies upstream, rather than downstream of that bucket; using it would damage bunch 1 due to the fall time of the injection kicker. In contrast, one of the buckets available to bunch 3 lies one AGS bunch spacing downstream from the bucket for bunch 1. One must therefore move the bunches that stay in the AGS one bunch spacing upstream after each extraction. We shall discuss a few methods for doing this.[1]

We showed earlier that, if the AGS yields a single bunch per cycle, the number of buckets that can be filled is only restricted by the rise time of the injection kicker because that single bunch can be phased arbitrarily relative to the bucket pattern in RHIC. There is therefore no problem in filling every n^{th} of the 342 available buckets, with n any integer, provided that the rise time of the injection kicker is less than 37.4n-17 nsec, with 37.4 and 17 the distance between successive bucket centers and maximum bunch length in nsec, and that a few 'fillable' buckets are left unoccupied near the end of the filling cycle to accommodate the injection kicker's fall time. (This is no real loss since a hole of the order of 1μsec, the length of some 27 buckets, must be left in any case to accommodate the rise time of the beam disposal kicker.) The only objection to this procedure, apart from its slight economic cost, is that it takes time, about 320 AGS pulses, or about 450 sec. This is time is no longer short in terms of the time constants for longitudinal intra beam scattering in heavy ion beams of the proposed brightness at this energy and one fears that, in the absence of a stochastic cooling system, considerable degradation might result.

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[1] An alternative is to fill only odd numbered buckets in the AGS. However, this is of little help if more than 57 buckets are to be filled in RHIC.

The parking time and the beam degradation can be reduced by accelerating more than one bunch per AGS pulse, because filling RHIC then requires fewer AGS pulses. Such a procedure requires separate phasing of the AGS bunches relative to the bucket pattern in RHIC if more than 57 buckets are to be filled per ring.

There are at least two methods for manipulating bunch phases in the AGS, besides the adiabatic phase adjustment mentioned before. Both leave its guide field undisturbed and use rf gymnastics. According to one method, suitable for shifts of several bucket lengths or more, one decelerates the beam in the AGS somewhat, in order to move it to an orbit of smaller circumference. Its angular velocity increases accordingly, since its energy is above the AGS transition energy, and it begins to advance relative to the bucket pattern in RHIC. This means that the rf frequency must be increased slightly while the phase and the voltage must be adjusted to keep the bunches centered on the synchronous fixed points and their shapes matched to the bucket shape. The change in frequency can be obtained by modulating the reference signal of the phase-locked loop mentioned above, or by returning the frequency control temporarily to the radial position loop. Coming close to the desired configuration one returns the beam to the extraction closed orbit by reduction of the rf frequency. The process is relatively fast: shifting a bunch by a bucket length takes about $n=1/(h\eta\Delta E/E)$ revolutions. Here is $\Delta E/E$ the energy reduction relative to the extraction energy, η the phase slip factor and h the harmonic number. For protons with $\gamma=31.4$, $\Delta E/E=10^{-2}$ and h=12: $\eta\approx0.013$ and $n\approx641$ revolutions or 1.7msec; for the heaviest ions: $\gamma\approx12.59$, $\eta\approx0.0077$ thus $n\approx1080$ revolutions or 2.9msec. The $\Delta E/E$ chosen displaces the orbit by about $\alpha_p\Delta E/E\approx2.5$cm in the points where α_p has its maximum value of 2.5m. How large $\Delta E/E$ may be chosen depends on the dynamic acceptance of the AGS at this energy. The process will cause dilution in synchrotron phase space, and the phase and the amplitude of the rf voltage must be tightly controlled to minimize this effect. It may be difficult to realize the desired bunch phase relative to RHIC's bucket pattern exactly and adiabatic trimming of that phase may be unavoidable. The displacements of the closed orbit must appear adiabatic to the betatron motion in order to avoid dilution in horizontal betatron phases pace. In particular one cannot jump instantaneously from one orbit to another or back by jumping the rf frequency from one value to another without doing serious damage.

The other method seems more suitable for smaller shifts, although it may be applied repeatedly to obtain large ones. It is only superficially different from the first one since it exploits the same physical mechanism. It is slower, but logistically simpler and therefore, perhaps, less likely to cause dilution. Making use of the fact that the bunches are so small in comparison with the bucket, one induces a coherent synchrotron oscillation by jumping the phase of the rf voltage by half the amount one wants to displace the bunch. At the instant the bunch has completed half an oscillation the rf phase is jumped again, by the same amount and in the same direction. This stops the coherent synchrotron motion because the stable fixed points are centered once more on the bunches. The second phase jump is applied at the instant that the bunch(es) cross the extraction closed orbit, as detected by a precision BPM. This scheme is slower than the previous one: small shifts take half a synchrotron period (2.7msec for protons, decreasing with the root of the mass number for ions, down to 1.7msec for the heaviest ions, and increasing with the amplitude of the forced oscillation in the familiar nonlinear manner). The shift per half oscillation is restricted to perhaps 1/2 the distance between bucket centers by the dilution caused by the spread in synchrotron frequencies over the particles in the bunch. Beyond this there is little chance of error: the needed phase references can be obtained, essentially error less, from RHIC's rf system, the rf frequency and voltage remain untouched, there is no consideration of adiabaticity, either in synchrotron or in betatron phase space. The non-linearity of the synchrotron half period as function of amplitude will cause an increase in energy spread. The effect is small since the phase spread over the bunch is small: in the time that the central particle requires for the half oscillation the one with the smallest phase offset performs slightly more, the one with the largest slightly less than a half oscillation, this shows up as energy errors of those boundary particles at the instant that the oscillation is terminated.

The effect, a skewing of the bunch shape, increases with the size of the bunch, the amplitude of the coherent oscillation and the number of half oscillations performed. The bunch dilution caused by the various ways for moving bunches azimuthally will have to be studied in more depth than has been done so far.

Tolerances

Transfer of a beam from the AGS to a RHIC ring will in general affect its quality adversely. The deterioration may be the result of the mislocation of a bunch's center of charge relative to its intended synchronous fixed point in 6D phase space, and/or of a mismatch between the 6D emittance of a bunch and the lattice functions of the ring in which it is to circulate. Tolerances must be established to ensure that such deterioration can be kept within accepted bounds. Some of these tolerances can be relaxed if means are provided for error correction after injection. Dipole errors, i.e., errors in position or energy and direction or phase, can be corrected to some extent by transverse or longitudinal dampers, which have to be present anyway for the control of beam instabilities. Normally such dampers are not particularly powerful, since they are intended for damping of coherent motion with infinitesimal small amplitude. That power has to increase in proportion to the error if the errors to be corrected are not very small, because the correction must be completed in a time that is small compared to the decoherence time of the error motion. The betatron decoherence, controlled by the spread in betatron frequencies due to nonlinearities, and chromaticity and momentum spread, may be estimated at a few hundred revolutions; the synchrotron decoherence, controlled by the nonlinearity in the synchrotron motion, takes a time of the order of a synchrotron period, thus several thousand revolutions, depending on the rf voltage. Betatron errors must therefore be corrected within several tens of revolutions, while synchrotron corrections can be allowed to take several hundreds. Assuming that the correction per turn is proportional with the instantaneous error, one finds that the betatron correctors must provide each turn a kick that is a non-negligible fraction of the absolute error. E.g., correction of a 1% error in the injection kicker, corresponding to a $\Delta B\ell$ of $13.2\cdot 10^{-4}$Tm ≈ 13.4μrad, would require a corrector capability of about

$$2[(-\ell n 0.01)/20]\cdot 13.4\cdot 10^{-6}\cdot B\rho \approx 6\cdot 10^{-4}\text{Tm per turn,}$$

in order to have it reduced to 1% of the original error in 20 turns; the factor two accounts for the fact that the average correction per revolution is only one half of the nominal one in betatron phase space. The correction system would require a bandwidth that goes well beyond the bunch frequency of about (27/k)MHz, with k the number that specifies the number of buckets per bunch in RHIC. Similarly, reduction of energy errors of the order of 10^{-4}, or 3.1MeV/u, to 10^{-5} or 0.31MeV/u in 200 revolutions would require a wide band accelerating capacity of the order of 36keV/turn/u.

An exact discussion of the consequences of errors is rather complex, principally because most errors tend to modify the distribution functions in phase space qualitatively, e.g., Gaussian beams do not remain Gaussian. For the order of magnitude type of estimates necessary for setting tolerances, we limit ourselves to the simplest approximations. In order to judge closed orbit errors, in either one of the two transverse phase spaces or in the longitudinal one, we estimate the increase in emittance of an elliptical beam, injected into a ring with a closed orbit error, though properly matched to its focusing characteristics. The emittance that ultimately develops is the area of an properly centered matched ellipse that circumscribes the injected one. One finds then for the relative increase in emittance

$$\Delta\varepsilon/\varepsilon = (\bar{\varepsilon}-\varepsilon)/\varepsilon \approx 2[\{x_c^{\,2}+(\alpha x_c+\beta x_c')^2\}/(\varepsilon\beta)]^{1/2}$$

where the various symbols are generic ones. α and β stand for the linear focusing parameters, x_c and x_c' for the orbit errors, ε and $\bar{\varepsilon}$ for the old and new emittance.

We distinguish between systematic and random errors. Systematic errors are errors that are constant, or, at most, drift slowly during a filling cycle. Among them are errors in the transfer line magnet excitations, and in the coordinates of the nominal extraction and injection closed orbits. Their consequences can be made unobservably small. Random are the errors that change randomly on successive beam transfer operations. Principal among them are the excitations of the extraction and injection kickers, the pulsed septum magnets, and errors in rf voltage amplitudes and phases. We consider only random errors in what follows.

It is easily seen that an absolute deflection error x_c' causes $\Delta\varepsilon/\varepsilon \approx 2x_c'\sqrt{\beta/\varepsilon}$, if the location where the error is introduced has an amplitude function value β. The principal sources of such errors in the filling system under discussion are the kickers for AGS extraction and RHIC injection. Other important sources are the pulsed septum magnets. The magnets associated with AGS extraction affect the horizontal emittance because extraction occurs horizontally, those associated with RHIC injection affect the vertical emittance because injection occurs vertically.

Random mislocation of the extraction closed orbit represent another source of emittance blowup. We make use of the design, or reference, orbit of the transfer line, defined for surveying purposes. This reference orbit intersects with the nominal extraction closed orbit in the AGS and with the nominal injection closed orbit in RHIC. The extraction and injection kickers are located at these intersection points. One verifies during the set up procedure that this situation is realized by checking that beams that are free of coherent motion in 6D phase space before extraction from the AGS are, on average, free of such motion after injection into RHIC. Random closed orbit misalignments, relative to the nominal configuration, will still occur in consequence of variation of the AGS guiding field while the beam is circulating on the extraction closed orbit, misexcitation of or changes in the closed orbit bump for extraction and of noise in the BPM that is used to announce the arrival of the beam on the extraction closed orbit. Using the expression above we obtain for the contribution to $\Delta\varepsilon/\varepsilon$ by closed orbit errors:

$$\Delta\varepsilon/\varepsilon \approx 2x_c[(1+\alpha^2)/(\varepsilon\beta)]^{1/2}$$

where α and β represent lattice parameters for the horizontal plane at the kicker locations. We may now determine tolerances for the various contributors by permitting each of them an equal fractional increase of the emittance, determining the fraction from the total fractional increase considered acceptable for the coordinate under consideration (horizontal, vertical or longitudinal) and the number of contributors, assuming statistical independence.

The longitudinal motion can be treated in similar fashion if we let x_C stand for synchronous energy error δE, x_c' for the (longitudinal) displacement from the synchronous fixed point $\delta t = \delta\varphi/(h\omega_2)$, $\alpha = 0$ and $\beta = \beta_s$ for:

$$\beta_s = h\omega_s[-\beta^2\gamma E_0 e\cos\varphi_s/(2\pi h\eta)]^{1/2}[1+\pi h\eta eV\cos\varphi_s/(2\beta^2\gamma E_0]^{1/2} \text{ [eVsec]}$$

$$\approx h\omega_s[\gamma E_0 eV/(2\pi h|\eta|)]^{1/2}$$

where the approximation is valid for our purpose. The symbols are the familiar synchrotron ones: e electrical charge, eV peak energy gain per turn, E_0 rest energy, γ Lorentz factor, h harmonic number, ω_s angular velocity and η phase slip factor. The emittance ε stands now for the bunch area (in eVsec).

It must be noted that an error in synchronous energy causes not only an increase in bunch area, but also one in horizontal emittance, because the dispersion parameter, $x_p \neq 0$ at the location of the extraction kicker in the AGS. It is therefore accompanied by a misalignment and a misdirection of the closed orbit. Since any horizontal deviation from the extraction closed orbit represents an energy error, and vice versa, the coherent horizontal betatron amplitude at the extraction kicker is given by $\hat{x}_\delta = x_p \Delta E/E$. This motion is not correlated to any other horizontal betatron motion; it contributes a term $\Delta\varepsilon/\varepsilon = 2x_p\Delta E/E/(\varepsilon\beta)^{1/2}$ rms. There are no further effects, provided that the transfer line is properly matched on both sides.

Working out a particular case we choose protons, transferred at γ=31.4, with a bunch area of 0.3eVsec and invariant transverse emittances of $20\text{x}10^{-6}\pi$ m-rad. A peak energy gain per turn of 300kV and γ_{tr}=8.447 yield $\beta_s = 2.66 \cdot 10^{15}$ [eV/sec], thus the half height and half length of the bunch are ΔE=16MeV and 6nsec, respectively. In order to calculate the relationship between errors in the coordinates of a bunch's center and the volume enclosed in its ultimate envelope we scale the coordinates such that the bunch appears spherical with radius r. The errors cause its center to be located at a distance dr from the origin. The sphere that is centered on the origin and that contains the bunch has than a radius r+dr. Calling the volume of the bunch its emittance ε one finds for the increase in emittance as a consequence of the displacement of the bunch center: $d\varepsilon/\varepsilon = n\ dr/r$, where n represents the dimensionality of the problem. The displacement depends upon the individual coordinate errors dc_n as $(dr)^2 = \sum n(dc_n)^2$, thus the expectation for the relative increase in emittance due to relative coordinate errors dc/r with equal expectations is then $(d\varepsilon/\varepsilon)_{rms} = n^{3/2}(dc/r)$. It follows that a rms blowup with a factor ≤1.1 of the individual transverse and longitudinal emittances (n=2) requires $(dc/r)_{rms} \leq 0.07$ for all coordinates, preservation of the transverse brightness to within 10% requires $(dc/r)_{rms} \leq 0.0125$ for the transverse coordinates while preservation of the luminosity to within 10% requires $(dc/r)_{rms} \leq 0.025$, because it is proportional to the root of the transverse 4D emittance. Preservation of the 6D brightness to within 10% would require $(dc/r)_{rms} \leq 0.0068$. Tolerances for the critical magnets, calculated under the assumption that the luminosity should be preserved to within 10%, are shown in Table I. The first few rows give values for the focusing parameters at the locations of the kickers and septum magnets, the next one the deflection angles ϑ in these magnets and the last one the calculated relative rms accuracies $\Delta\vartheta/\vartheta$ for these angles.

Table I

	AGS H5	AGS H10	Transfer line			RHIC
	Ext Kckr	Spt Mgn	SI0	SI1	SI2	IKI
β[m]	15	23	33	39	23	45
α_p[m]	1.5	2.2				
ϑ[mrad]	1.1	22	55.5	48.2	2.8	1.3
$\Delta\vartheta/\vartheta$	$1.9\cdot10^{-3}$ $2.1\cdot10^{-3}$	$7.7\cdot10^{-5}$ $8.5\cdot10^{-5}$	$2.6\cdot10^{-5}$ $2.0\cdot10^{-4}$	$2.7\cdot10^{-5}$	$6.0\cdot10^{-4}$ $6.6\cdot10^{-4}$	$9.3\cdot10^{-4}$ $1.0\cdot10^{-3}$

Two tolerances are shown for each magnet, those in the first row are based on the assumption that they have mutually independent power supplies, those in the second row assume that SI0 and SI1 are electrically in series on a common power supply, or coupled in some other manner that guarantees a 1 to 1 relation between their fields to within 10^{-5}. The relaxation of the tolerances in that case results from the fact that these magnets deflect the beam by about the same amount but in opposite directions, so that they more or less cancel each other as far as their net deflection angle is concerned.

Accepting also a longitudinal blowup with a factor 1.1 we will tolerate rms uncertainties in synchronous energy and location of the bunch center of 1.12MeV, thus $\delta E/E = 3.8\cdot10^{-5}$, and $\delta T = 0.42$nsec, corresponding with an rms rf phase error in the AGS of $\delta\varphi$=11.8mrad=0.7°. The energy error causes a radial bunch displacement in the $\hat{\beta}$ points of $\alpha_p \Delta E/E$ = 0.0836mm, and contributes a $(\Delta\varepsilon/\varepsilon)_x$=0.03 which we neglect at this point.

It is evident that the tolerances on the fields in the magnets are rather small. They can be relaxed by introducing a transverse damping system, as mentioned earlier. The field tolerances and the strengths of the error correctors in a ring can be traded: stronger correctors allow larger tolerances; finding the best arrangement requires detailed engineering.

The synchronous energy may be obtained from the strength of the guiding field if the rf frequency, thus the synchronous revolution period, is fixed. The relation between synchronous energy and magnetic field for fixed rf frequency may be described by:

$$\Delta\gamma/\gamma = (\gamma^2-1)/(\gamma^2-\gamma_{tr}^2)\ (\Delta B/B)$$

Since γ_{tr}=8.447 in the AGS one finds for protons at γ=31.4: $\Delta\gamma/\gamma=1.077\cdot\Delta B/B$ and for ions with A/Z=2.5: $\Delta\gamma/\gamma=1.828\cdot\Delta B/B$. It follows, that the tolerance on a guiding field measurement as a measure for the synchronous energy is $2.0\cdot10^{-5}$ if the energy must be determined to within $3.8\cdot10^{-5}$.

It was mentioned earlier that the bunches in the AGS may be shifted relative to the raster imposed by RHIC by inducing a (sequence of) coherent half synchrotron oscillation(s). The completion of each half oscillation was to be detected by a precision BPM. An error by that monitor leaves a coherent energy error given by $\Delta\gamma/\gamma=(1-1/\gamma^2)(\Delta x/x_p)\approx\Delta x/x_p$. Placing the BPM at a point of maximum dispersion ($x_p\approx$2.2m), one finds that detecting $|\Delta\gamma/\gamma|=3.8\cdot10^{-5}$ requires a resolution $\Delta x\approx80\cdot10^{-6}$m of the BPM. It seems likely that the BPM will be used as a null-detector (comparing the orbit locations at the beginning and the and of the half oscillation), this would require a resolution of 59μm since the two measurements are statistically independent. In RHIC the rf frequency is not imposed but controlled by a radial loop. There a BPM resolution $\le\alpha_p\Delta\gamma/\gamma = 5.7\cdot10^{-5}$=57μm would be acceptable.

We noted before that the guiding field in the AGS must be established to within about $4\cdot10^{-5}$ and assumed that it would remain constant at that level with that tolerance for as long as the AGS functions as a storage ring. It may be difficult to satisfy this tolerance requirement, and the longitudinal damper necessary for correcting such errors may have to be rather large. It is convenient, but not strictly necessary, to demand constancy. The fundamental requirement is not that the synchronous energy be fixed, but that the angular velocities of particles and the synchronous energies remain matched in the AGS and in RHIC. A field error at fixed rf frequency changes both the energy and the closed orbit such that the revolution period remains unchanged. On the other hand, a change in frequency in a fixed field causes the energy and the closed orbit to change. It appears possible to change the 'common' rf frequency (i.e., the frequency in the AGS and its sixth harmonic in RHIC) in response to a known field error in the AGS in such a manner that the two rings remain matched: the two closed orbit circumferences change in the same proportion.

The variation in revolution period in any synchrotron may be described by

$$\Delta T/T = (\gamma_{tr}^{-2}-\gamma^{-2})\Delta p/p - \gamma_{tr}^{-2}\Delta B/B.$$

Keeping the angular velocity and the synchronous energy in the two rings matched implies equal values for $\Delta T/T$ and $\Delta p/p$ in them. This is achieved, regardless of deviations of the guiding fields, if one imposes:

$$[\gamma_{tr}^{-2}\Delta p/p - \gamma_{tr}^{-2}\Delta B/B]_{AGS} = [\gamma_{tr}^{-2}\Delta p/p - \gamma_{tr}^{-2}\Delta B/B]_{RHIC}$$

or

$$\Delta p/p = \frac{\gamma_{tr_{AGS}}^{-2}\ \Delta B/B_{AGS} - \gamma_{tr_{RHIC}}^{-2}\ \Delta B/B_{RHIC}}{\gamma_{tr_{AGS}}^{-2} - \gamma_{tr_{RHIC}}^{-2}} = \frac{\gamma_{tr_{RHIC}}^{2}}{\gamma_{tr_{RHIC}}^{2} - \gamma_{tr_{AGS}}^{2}}\ \Delta B/B_{AGS}$$

since $\Delta B/B_{rhic} = 0$ if B_{rhic} is the field reference. It is not difficult to enforce this relation fairly accurately. One measures $\dot{B}_{AGS}$, e.g., as a voltage across a pickup coil and integrates it from the instant that B_{AGS} crosses the reference field onward. The $\dot{B}$ voltage is proportional to the rates with which the particles must be accelerated in each ring in order that the synchronism condition above be met, its integral is proportional with the deviation of the synchronous frequencies from their reference values.The $\dot{B}$ signal can be used to control the stable phases of the rf systems relative to the bunches to establish the necessary rates of acceleration or deceleration, itsintegrated value is supplied as a correction signal to the frequency control loop of RHIC. The rf voltage amplitudes should in principle be adjusted to match the phase shifts, but since the changes in stable phase angle will be small, such adjustment may well fall within the noise.

Though this approach reduces the consequences of AGS field errors in longitudinal phase space it tends to cause dilution in transverse phase space because it displaces the actual closed orbit from the reference closed orbit in each ring[2]: the field error at transfer is now expressed as a coherent

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[2]and because the deflection angles in the magnets of the transfer line change.

betatron motion. The deviation is given by

$$\delta x = \alpha_p \, \Delta p/p = \alpha_p \frac{\gamma^2_{tr_{RHIC}}}{\gamma^2_{tr_{RHIC}} - \gamma^2_{tr_{AGS}}} \Delta B/B_{AGS}$$

$$\delta x' = \alpha'_p \, \Delta p/p = \alpha'_p \frac{\gamma^2_{tr_{RHIC}}}{\gamma^2_{tr_{RHIC}} - \gamma^2_{tr_{AGS}}} \Delta B/B_{AGS}$$

Numerically one finds for $\Delta B/B = 10^{-4}$ in the AGS ($\alpha_p \approx 2.5$m) $\delta x \approx 0.28$mm and in RHIC ($\alpha_p \approx 1.5$m) $\delta x \approx 0.17$mm, no longer negligible compared to the local betatron half widths of 3.78mm and 5.64mm, respectively. The relative effect is smaller in betatron phase space than in synchrotron phase space primarily because the longitudinal emittance is rather smaller than the betatron emittance. This coherent betatron motion can be dampened by active dampers in RHIC; one could also prevent it from occurring by forcing the reference orbit in the transfer line to track the extraction orbit in the AGS. This, however, would require modification of existing equipment at the upstream end of the transfer line to an extend that seems unwarranted in view of the expected benefit.

Remarks

A number of important issues have still to be considered in the future. First among them is the conception and design of the injection septum magnets, particularly SI1 and SI2. Detailed study and prototype work on these magnets is essential and may make it possible to re-optimize the configuration of the injection section to yield a ring admittance of 6πmm-mrad even during the filling period. This would obviate the need for their physical withdrawal after the rings have been filled. The overriding consideration is the magnitude and shape of their stray fields in the space reserved for the circulating beam. These fields present high order, off-axis multipoles to the circulating beam and vary adiabatically with time as far as the betatron motion is concerned . The stray dipole field, for example, causes a closed orbit distortion which may be compared with the distortions caused by ring quadrupole misalignments. A quadrupole displaced by 0.25mm presents (at injection) a dipole with $\Delta y \int B' d\ell = 0.002$Tm. Quadrupole misalignments of that order require significant dipole correction; this suggests that the stray field dipole have $\int B d\ell < 2 \cdot 10^{-3}$Tm, implying that the stray field of SI1 should be less than $4 \cdot 10^{-4}$ of its main field. The next multipole is a quadrupole, it causes a (time-dependent) tune shift. We will not discuss its implications here, nor those of the multipoles of higher order. Clearly the design of SI1 and SI2 is a critical task.

Means for adjusting the coordinates of the axis of the incident beam at the exit of the injection kickers must be provided. Four properly located steering magnets can satisfy this requirement and locations and strengths have to be specified. These functions could also be provided by vernier controls on the extraction and injection kickers and septum magnets.

Tolerances on the strengths and the locations of the components in the transfer line must be determined in order to judge the need for and the size of a dipole corrector scheme. The transverse locations of the bending magnets are important, since they are gradient magnets, not dipoles.

Diagnostic equipment with adequate resolution and accuracy which responds to the passage of a single bunch is required in the transfer line.

The dispersion matches between the entrance of the beam selector and the entrances of the big bends are fairly critical, but no trimming quadrupoles for adjustment of those matches have been proposed. Mismatches are inconvenient, but, within limits, not lethal because they can, presumably, be compensated with the 7 quadrupoles at the exit end of the big bends. This approach may cause some loss of horizontal acceptance of the transfer line, its acceptability must be checked.

The transfer system is designed and its component values have been chosen to provide a match between the linear focusing parameters of the AGS and RHIC. It contains enough quadrupoles which can be adjusted to obtain such a match experimentally. They can also be used to obtain deliberate mismatches which constitute one way for controlling the distribution in the emittances of the beams circulating in RHIC. Means and methods for measuring the quality of the match have not yet been considered.

The possible need for sextupoles for the correction of chromatic effects has been mentioned. That need depends upon the desired accuracy of the match. The betatron phase advance along the transfer line is about 11πrad in both reference directions. It varies with momentum, in first estimate proportional to the inverse square root of the relative momentum deviation, causing, in the first place an equal rotation of the emittance ellipses at the exit of the injection magnet. The eccentricities will also change. These two effects represent mismatches relative to the nominal situation and cause dilution. They must be estimated.

Finally the exact balance of tolerance and damper requirements must be resolved in the context of other dampers in RHIC. It seems clear that both strict equipment tolerances and dampers will be required if serious growth of the 6D emittance is to be avoided.

Acknowledgment

The beam transfer system we described is in large measure a development of the system designed for the CBA Project, closed some years ago. A large group of people contributed to that design, among them W.T. Weng, who was involved in the general layout and beam dynamics, and R.E. Thern, who was concerned with magnet design and testing. Thern worked also on matters of geometry and survey. He produced the spread sheet, mentioned in the appendix, that is used for determining the surveying coordinates of the components of the previous and present designs.

References

1 Conceptual Design of the Relativistic Heavy Ion Collider RHIC, May 1989, BNL 52195

2 W.T. Weng: The New AGS Fast Extraction System, BNL 51310, September 15, 1980

3 W.T. Weng: The AGS New Fast Extraction System and the Single Bunch Extraction Test, Trans. Nucl. Sci., Vol. NS-30, No.4, p. 2956, August 1983

4 R.E. Thern: Bending Magnets for the CBA Beam Transport Line, Trans. Nucl. Sci., Vol. NS-30, No.4, p. 2950, August 1983

Appendix

The tables that follow describe the principal parameters of the transfer line between AGS and RHIC for a particular choice of settings. They are extracted from a Synch output file which can be found in the RHIC data base on the BNLDAG VAX under the name: [rhic.main.lat]rhinj.out. The Synch input file that generated that file is called: [rhic.main.lat]rhinj.dat. It must be noted that the program was run on BNL's IBM 3090, not on any VAX. A further three files: [rhic.main.lat]rhinj.geo1, [rhic.main.lat]rhinj.geo2 and [rhic.main.lat]rhinj.geo3 describe the geometry of the system in an absolute way as well as relative to BNL's established surveying coordinate systems. These last three files were generated by a PC spread sheet program that takes its input from the Synch output file. They were used as input for the CAD program that produced the component layout drawings Figs. 1 and 2. The geometry program should be rerun whenever the input file for Synch is changed and it will be necessary to check the consistency of the various files whenever decisions are to be made.

The tables show the betatron phase advance Q (in units of 2πrad or 360°), the Twiss and Frank parameters α and β for each of the two transverse reference directions x and y, and the dispersions α_p and ψ_p, all as functions of the distance from the extraction septum magnet at H in the AGS along the nominal trajectory. The initial values for the α's, β's and the dispersions are experimental values derived from beam size measurements in the U-line [1], since a believable calculation of the transfer function between the extraction kicker's entrance plane to the exit of the extraction septum magnet's exit plane is not yet available. That calculation requires a path integration through the stray fields of the AGS main magnets. It will be performed and the gradients of the quadrupoles in the transfer line will be adjusted to match the results. The tables show also the lengths, deflection angles, radii of orbit curvature and gradients of the various components.

[1] R.E. Thern: Measurement of Twiss Parameters and Emittance in the U Line. AGS Studies Report 193, October 12, 1985

Pos	Name	S [m]	Q_x	β_x [m]	α_x	α_p [m]	Q_y	β_y [m]	α_y	ψ_p [m]
0		0.000	0.000	37.59	-4.778	-2.960	0.000	8.05	1.053	0.000
1	ks	5.000	0.012	101.21	-7.947	-4.435	0.169	4.06	-0.256	0.000
2	u01	5.374	0.013	107.25	-8.184	-4.545	0.183	4.30	-0.354	0.000
3	uq1	6.326	0.014	91.50	23.042	-4.151	0.213	6.79	-2.520	0.000
4	u12	6.821	0.015	70.10	20.162	-3.605	0.223	9.56	-3.057	0.000
5	uq2	7.774	0.018	51.95	0.693	-3.038	0.236	12.70	0.077	0.000
6	u231	8.252	0.020	51.30	0.680	-2.983	0.242	12.64	0.039	0.000
7	ud1	10.332	0.027	48.59	0.621	-2.714	0.268	12.82	-0.122	0.000
8	u232	10.792	0.028	48.03	0.608	-2.648	0.274	12.95	-0.158	0.000
9	ud2	12.872	0.035	45.62	0.548	-2.328	0.298	13.94	-0.319	0.000
10	u233	13.332	0.037	45.12	0.535	-2.251	0.304	14.25	-0.355	0.000
11	ud3	15.412	0.044	43.02	0.476	-1.879	0.326	16.06	-0.515	0.000
12	u234	15.667	0.045	42.78	0.469	-1.831	0.328	16.32	-0.534	0.000
13	uq3	16.124	0.047	42.30	0.577	-1.742	0.332	16.85	-0.619	0.000
14	u34	31.264	0.114	32.05	0.100	1.230	0.415	54.42	-1.862	0.000
15	uq4	31.990	0.118	33.90	-2.686	1.411	0.417	53.83	2.648	0.000
16	u45	38.914	0.138	82.72	-4.365	3.527	0.449	24.30	1.617	0.000
17	uq5	39.641	0.140	85.52	0.567	3.672	0.453	23.02	0.174	0.000
18	u56	46.574	0.154	78.40	0.460	4.316	0.502	22.76	-0.137	0.000
19	uq6	47.300	0.155	74.45	4.898	4.291	-0.507	23.98	-1.561	0.000
20	u67	61.893	0.373	2.98	-0.000	1.932	-0.556	100.07	-3.653	0.000
21	uq7	62.620	0.411	3.34	-0.512	1.872	-0.557	99.32	4.672	0.000
22	u78	75.219	0.555	76.16	-5.267	1.820	-0.605	18.07	1.776	0.000
23	uq8	75.946	0.557	80.61	-0.774	1.778	-0.612	16.32	0.672	0.000
24	u891	79.481	0.564	86.33	-0.844	1.391	-0.651	12.68	0.358	0.000
25	u4f	83.138	0.571	71.79	4.482	0.898	-0.697	14.35	-0.851	0.000
26	u892	83.748	0.572	66.43	4.303	0.804	-0.703	15.43	-0.924	0.000
27	u5d	87.406	0.582	51.86	0.012	0.384	-0.736	19.00	0.032	0.000
28	u193	88.015	0.584	51.85	-0.000	0.335	-0.741	18.98	0.000	0.000
29	u293	88.625	0.586	51.86	-0.012	0.286	-0.746	19.00	-0.032	0.000
30	u6d	92.283	0.597	66.43	-4.303	0.083	-0.779	15.43	0.924	0.000
31	u894	92.892	0.598	71.79	-4.482	0.063	-0.786	14.35	0.851	0.000
32	u7f	96.550	0.605	86.33	0.844	0.000	0.831	12.68	-0.358	0.000
33	u895	113.641	0.642	63.28	0.505	0.000	0.949	50.90	-1.878	0.000
34	uq9	114.367	0.644	64.56	-2.294	0.000	0.951	52.02	0.348	0.000
35	u910	125.063	0.663	124.73	-3.331	0.000	0.986	47.04	0.117	0.000
36	uq10	125.790	0.664	106.49	26.803	0.000	0.988	56.52	-13.995	0.000
37	u011	126.896	0.666	55.43	19.326	0.000	0.990	91.77	-17.850	0.000
38	uq11	127.623	0.669	37.96	6.106	0.000	0.992	101.52	5.222	0.000
39	u112	141.851	1.124	68.36	-8.243	0.000	1.068	9.29	1.260	0.000
40	uq12	142.577	1.125	72.47	2.800	0.000	1.081	8.57	-0.229	0.000
41	w01	160.101	1.228	11.80	0.663	0.000	1.232	54.29	-2.381	0.000
42	w1d	163.759	1.281	11.80	-0.663	0.082	1.243	54.29	2.381	0.000
43	w12	177.811	1.374	54.50	-2.376	0.728	1.337	11.64	0.655	0.000
44	w2f	181.469	1.384	54.50	2.377	0.853	1.391	11.64	-0.655	0.000

Pos	Name	S [m]	Q_x	β_x [m]	α_x	α_p [m]	Q_y	β_y [m]	α_y	ψ_p [m]
45	w231	187.580	1.408	30.00	1.631	0.981	1.450	24.23	-1.406	0.000
46	wp1	189.409	1.419	24.44	1.409	1.019	1.461	29.79	-1.631	-0.009
47	w232	195.520	1.478	11.78	0.663	1.146	1.485	54.30	-2.381	-0.070
48	w3d	199.178	1.531	11.77	-0.661	1.494	1.495	54.30	2.381	-0.094
49	w34	213.230	1.624	54.46	-2.377	3.940	1.590	11.64	0.655	-0.132
50	w4f	216.888	1.635	54.48	2.373	4.017	1.643	11.63	-0.655	-0.164
51	w45	230.940	1.728	11.82	0.663	2.153	1.738	54.28	-2.380	-0.374
52	w5d	234.597	1.781	11.83	-0.664	2.071	1.748	54.28	2.380	-0.369
53	w56	248.649	1.874	54.54	-2.376	3.292	1.842	11.63	0.655	-0.116
54	w6f	252.307	1.884	54.52	2.380	3.167	1.896	11.64	-0.655	-0.065
55	w67	266.359	1.978	11.77	0.662	1.007	1.991	54.31	-2.382	0.083
56	w7d	270.017	2.030	11.76	-0.661	0.659	2.001	54.31	2.382	0.107
57	w78	284.068	2.125	54.46	-2.378	0.078	2.095	11.64	0.655	0.136
58	w8f	287.726	2.135	54.48	2.373	0.000	2.149	11.63	-0.655	0.166
59	v01	301.698	2.227	11.93	0.672	0.000	2.243	53.91	-2.371	0.370
60	vq1d	302.438	2.237	11.76	-0.442	0.000	2.245	53.85	2.444	0.369
61	v12	316.896	2.344	45.77	-1.911	0.000	2.351	10.25	0.572	0.102
62	vq2f	317.636	2.347	45.60	2.132	0.000	2.362	10.12	-0.397	0.091
63	v231	325.850	2.392	18.78	1.133	0.000	2.450	24.37	-1.337	0.009
64	wp2	327.679	2.409	15.04	0.911	0.000	2.461	29.64	-1.546	0.000
65	v232	333.671	2.498	8.49	0.182	0.000	2.485	52.27	-2.231	0.000
66	vq3d	334.411	2.512	8.90	-0.745	0.000	2.487	51.83	2.810	0.000
67	v34	348.484	2.612	64.48	-3.204	0.000	2.623	6.73	0.395	0.000
68	vq4f	349.224	2.618	64.72	2.883	0.000	2.641	6.70	-0.344	0.000
69	v45	368.805	2.800	6.98	0.066	0.000	2.795	84.18	-3.613	0.000
70	vq5d	369.545	2.817	7.40	-0.649	0.000	2.797	84.27	3.499	0.000
71	v56	387.683	2.937	94.06	-4.129	0.000	2.911	9.04	0.649	0.000
72	vq6f	388.423	2.939	93.14	5.343	0.000	2.924	8.81	-0.330	0.000
73	v60	388.955	2.940	87.55	5.174	0.000	2.934	9.20	-0.398	0.000
74	swm	392.612	2.948	53.80	4.045	0.086	2.986	13.79	-0.858	0.000
75	l12	402.568	3.049	5.24	0.832	0.555	3.053	43.35	-2.111	0.000
76	g1d	406.225	3.188	5.13	-0.795	0.981	3.066	36.81	3.583	0.000
77	l13	410.850	3.265	19.29	-2.268	1.884	3.102	11.71	1.845	0.000
78	g2f	413.796	3.284	26.66	0.048	2.180	3.161	6.23	0.216	0.000
79	l14	415.081	3.292	26.60	-0.	2.180	3.195	5.95	-0.000	0.000
80	hol	415.796	3.297	26.62	-0.027	2.180	3.214	6.03	-0.120	0.000
81	g3f	419.454	3.323	15.77	2.473	1.731	3.287	13.52	-2.259	0.000
82	os	419.904	3.328	13.63	2.269	1.625	3.292	15.64	-2.463	0.000
83	g4d	423.561	3.399	6.13	0.119	1.213	3.318	26.47	0.027	0.000
84	hol	424.276	3.418	6.05	0.000	1.213	3.322	26.45	-0.000	0.000
85	hol	424.991	3.437	6.13	-0.118	1.213	3.327	26.47	-0.027	0.000
86	g5d	428.649	3.508	13.62	-2.268	1.626	3.353	15.64	2.463	0.000
87	os	429.099	3.513	15.75	-2.470	1.732	3.358	13.52	2.259	0.000
88	g6f	432.756	3.539	26.60	0.027	2.182	3.431	6.04	0.120	0.000
89	hol	433.471	3.544	26.58	0.000	2.182	3.450	5.95	0.000	0.000

Pos	Name	S [m]	Q_x	β_x [m]	α_x	α_p [m]	Q_y	β_y [m]	α_y	ψ_p [m]
90	hol	434.186	3.548	26.60	-0.027	2.182	3.469	6.04	-0.120	0.000
91	g7f	437.844	3.574	15.75	2.470	1.733	3.541	13.52	-2.259	0.000
92	os	438.294	3.579	13.62	2.268	1.627	3.546	15.64	-2.462	0.000
93	g8d	441.952	3.651	6.13	0.118	1.214	3.572	26.47	0.027	0.000
94	hol	442.667	3.669	6.05	-0.000	1.214	3.577	26.45	0.000	0.000
95	hol	443.382	3.688	6.13	-0.119	1.214	3.581	26.47	-0.027	0.000
96	g9d	447.039	3.760	13.63	-2.269	1.627	3.607	15.64	2.462	0.000
97	os	447.489	3.765	15.77	-2.473	1.733	3.612	13.52	2.259	0.000
98	g10f	451.147	3.791	26.62	0.027	2.183	3.685	6.04	0.120	0.000
99	hol	451.862	3.795	26.60	-0.000	2.183	3.704	5.95	-0.000	0.000
100	hol	452.577	3.799	26.62	-0.027	2.183	3.723	6.04	-0.120	0.000
101	g11f	456.234	3.825	15.77	2.473	1.733	3.796	13.52	-2.259	0.000
102	os	456.684	3.830	13.63	2.269	1.627	3.800	15.64	-2.463	0.000
103	g12d	460.342	3.902	6.13	0.119	1.213	3.827	26.47	0.027	0.000
104	hol	461.057	3.921	6.05	0.000	1.213	3.831	26.45	-0.000	0.000
105	hol	461.772	3.939	6.13	-0.118	1.213	3.835	26.47	-0.027	0.000
106	g13d	465.430	4.011	13.62	-2.268	1.626	3.862	15.64	2.463	0.000
107	os	465.880	4.016	15.75	-2.470	1.732	3.867	13.52	2.259	0.000
108	g14f	469.537	4.042	26.60	0.027	2.181	3.939	6.04	0.120	0.000
109	hol	470.252	4.046	26.58	0.000	2.181	3.958	5.95	0.000	0.000
110	hol	470.967	4.051	26.60	-0.027	2.181	3.977	6.04	-0.120	0.000
111	g15f	474.625	4.077	15.75	2.470	1.731	4.050	13.52	-2.259	0.000
112	os	475.075	4.082	13.62	2.268	1.625	4.055	15.64	-2.462	0.000
113	g16d	478.732	4.153	6.13	0.118	1.213	4.081	26.47	0.027	0.000
114	hol	479.447	4.172	6.05	-0.000	1.213	4.085	26.45	0.000	0.000
115	hol	480.162	4.191	6.13	-0.119	1.212	4.090	26.47	-0.027	0.000
116	g17d	483.820	4.262	13.63	-2.269	1.625	4.116	15.64	2.462	0.000
117	os	484.270	4.267	15.77	-2.473	1.731	4.121	13.52	2.259	0.000
118	g18f	487.928	4.293	26.62	0.027	2.180	4.194	6.04	0.120	0.000
119	hol	488.643	4.298	26.60	-0.000	2.180	4.213	5.95	-0.000	0.000
120	hol	489.358	4.302	26.62	-0.027	2.180	4.232	6.04	-0.120	0.000
121	g19f	493.015	4.328	15.77	2.473	1.731	4.304	13.52	-2.259	0.000
122	os	493.465	4.333	13.63	2.269	1.625	4.309	15.64	-2.463	0.000
123	g20d	497.123	4.405	6.13	0.119	1.213	4.336	26.47	0.026	0.000
124	hol	497.838	4.423	6.05	0.000	1.213	4.340	26.45	-0.000	0.000
125	hol	498.553	4.442	6.13	-0.118	1.213	4.344	26.47	-0.027	0.000
126	g21d	502.210	4.514	13.62	-2.268	1.626	4.370	15.64	2.463	0.000
127	os	502.660	4.519	15.75	-2.470	1.732	4.375	13.52	2.259	0.000
128	g22f	506.318	4.545	26.60	0.027	2.182	4.448	6.04	0.120	0.000
129	hol	507.033	4.549	26.58	0.000	2.182	4.467	5.95	0.000	0.000
130	hol	507.748	4.553	26.60	-0.027	2.182	4.486	6.04	-0.120	0.000
131	g23f	511.406	4.580	15.75	2.470	1.733	4.559	13.52	-2.259	0.000
132	os	511.856	4.584	13.62	2.268	1.627	4.563	15.64	-2.462	0.000
133	g24d	515.513	4.656	6.13	0.118	1.214	4.590	26.47	0.027	0.000
134	hol	516.228	4.675	6.05	-0.000	1.214	4.594	26.45	0.000	0.000

Pos	Name	S [m]	Q_x	β_x [m]	α_x	α_p [m]	Q_y	β_y [m]	α_y	ψ_p [m]
135	hol	516.943	4.693	6.13	-0.119	1.214	4.598	26.46	-0.027	0.000
136	g25d	520.601	4.765	13.63	-2.269	1.627	4.625	15.64	2.462	0.000
137	os	521.051	4.770	15.77	-2.473	1.733	4.630	13.52	2.259	0.000
138	g26f	524.708	4.796	26.62	0.027	2.183	4.702	6.04	0.120	0.000
139	hall	525.226	4.799	26.60	0.007	2.183	4.716	5.96	0.033	0.000
140	qmi1	525.906	4.803	26.38	0.306	2.174	4.734	6.04	-0.155	0.000
141	m121	527.494	4.813	25.52	0.240	2.131	4.774	6.96	-0.424	0.000
142	bmi	530.441	4.832	24.46	0.118	2.124	4.828	10.91	-0.915	0.000
143	m122	531.755	4.840	24.22	0.064	2.152	4.846	13.61	-1.137	0.000
144	qmi2	532.435	4.845	22.45	2.482	2.090	4.853	16.32	-2.944	0.000
145	m231	533.593	4.854	17.13	2.113	1.852	4.862	23.93	-3.630	0.000
146	bmi	536.540	4.896	7.45	1.173	1.319	4.876	50.38	-5.338	0.000
147	m232	537.179	4.912	6.08	0.969	1.219	4.878	57.45	-5.712	0.000
148	qmi3	537.859	4.931	5.63	-0.282	1.191	4.880	57.59	5.524	0.000
149	m341	539.392	4.970	6.95	-0.576	1.304	4.885	41.94	4.685	0.000
150	bmi	542.339	5.022	12.00	-1.141	1.592	4.901	19.01	3.086	0.000
151	m342	542.921	5.030	13.40	-1.253	1.664	4.907	15.61	2.764	0.000
152	qmi4	543.601	5.037	13.41	1.240	1.640	4.914	13.87	-0.094	0.000
153	m451	544.492	5.049	11.35	1.071	1.470	4.924	14.09	-0.159	0.000
154	bmi	547.438	5.104	6.68	0.514	0.979	4.956	15.63	-0.361	0.000
155	m452	550.499	5.190	5.31	-0.065	0.542	4.985	18.51	-0.583	0.000
156	qmi5	551.179	5.210	5.72	-0.546	0.456	4.991	18.54	0.549	0.000
157	m561	552.579	5.243	7.69	-0.864	0.300	5.003	17.14	0.451	0.000
158	bmi	555.525	5.288	14.75	-1.533	0.044	5.033	15.05	0.256	0.000
159	m562	563.088	5.333	50.93	-3.251	-0.431	5.116	15.23	-0.280	0.000
160	qmi6	563.768	5.335	51.80	2.003	-0.460	5.123	16.75	-1.997	0.000
161	m671	564.811	5.338	47.73	1.902	-0.476	5.131	21.24	-2.308	0.000
162	si0	568.899	5.354	33.69	1.527	-0.545	5.153	45.07	-3.525	-0.103
163	m781	570.237	5.361	29.78	1.395	-0.568	5.157	55.04	-3.924	-0.171
164	qmi7	570.917	5.365	30.59	-2.608	-0.605	5.159	55.38	3.439	-0.197
165	m782	571.917	5.369	36.06	-2.864	-0.700	5.162	48.73	3.208	-0.223
166	si1	575.417	5.381	59.14	-3.726	-1.028	5.177	29.12	2.397	-0.238
167	o782	576.417	5.384	66.85	-3.978	-1.122	5.183	24.56	2.165	-0.221
168	q8o	577.034	5.385	69.77	-0.713	-1.162	5.187	22.67	0.934	-0.213
169	q8o	577.651	5.387	68.57	2.637	-1.168	5.191	22.21	-0.184	-0.212
170	o891	578.651	5.389	63.41	2.521	-1.150	5.198	22.62	-0.230	-0.216
171	si2	580.051	5.393	56.58	2.359	-1.124	5.208	23.36	-0.296	-0.219
172	o892	594.414	5.483	12.75	0.693	-0.855	5.284	41.45	-0.964	-0.229
173	ki	597.664	5.531	9.48	0.316	-0.794	5.296	48.21	-1.115	-0.229
174	o893	598.164	5.539	9.19	0.258	-0.785	5.298	49.34	-1.139	-0.229
175	q9o	598.576	5.546	9.09	0.000	-0.781	5.299	49.81	-0.000	-0.228

Pos	Name	length [m]	bend [mrad]	ρ [m]	$B'/(B\rho)$ $[m]^{-2}$
2		5.374005			
3	uq1	0.952500			0.32885802
4		0.495300			
5	uq2	0.952500			-0.31874932
6		0.477256			
7	ud1	2.080006	24.725	84.127764	
8		0.459994			
9	ud2	2.080006	24.725	84.127764	
10		0.459994			
11	ud3	2.080006	24.725	84.127764	
12		0.255397			
13	uq3	0.457200			0.0062707454
14		15.139416			
15	uq4	0.726440			-0.11450203
16		6.924040			
17	uq5	0.726440			0.081090116
18		6.933184			
19	uq6	0.726440			0.081090116
20		14.593062			
21	uq7	0.726440			-0.11450203
22		12.599619			
23	uq8	0.726440			0.080325355
24		3.534764			
25	u4f	3.657600	34.906	104.789606	0.018823143
26		0.609600			
27	u5d	3.657600	34.906	104.789606	-0.018823143
28		0.609600			
29		0.609600			
30	u6d	3.657600	34.906	104.789606	-0.018823143
31		0.609600			
32	u7f	3.657600	34.906	104.789606	0.018823143
33		17.090476			
34	uq9	0.726440			-0.060001498
35		10.695975			
36	uq10	0.726440			0.36507553
37		1.106874			
38	uq11	0.726440			-0.32883725
39		14.227735			
40	uq12	0.726440			0.21564016
41		17.524174			
42	w1d	3.657600	43.633	83.833108	-0.023528529
43		14.051700			
44	w2f	3.657600	43.633	83.833108	0.023528529

Pos	Name	length [m]	bend [mrad]	ρ [m]	$B'/(B\rho)$ $[m]^{-2}$
45		6.111450			
46	wp1	1.828800	10.	182.78	
47		6.111450			
48	w3d	3.657600	43.633	83.833108	-0.023528529
49		14.051700			
50	w4f	3.657600	43.633	83.833108	0.023528529
51		14.051700			
52	w5d	3.657600	43.633	83.833108	-0.023528529
53		14.051700			
54	w7f	3.6576	43.633	83.833108	0.023528529
55		14.051700			
56	w7d	3.657600	43.633	83.833108	-0.023528529
57		14.051700			
58	w8f	3.657600	43.633	83.833108	0.023528529
59		13.972064			
60	vq1d	0.740000			-0.1204328
61		14.457299			
62	vq2f	0.740000			0.11939398
63		8.214856			
64	wp2A	1.828800	-10.	182.87	
65		5.991919			
66	vq3d	0.740000			-0.13049325
67		14.072442			
68	vq4f	0.740000			0.12684975
69		19.581019			
70	vq5d	0.740000			-0.11365668
71		18.138067			
72	vq6f	0.740000			0.13605879
73		0.532168			
74	swm	3.657600	47.165	77.5775756	0.
75		9.955836			
76	g1d	3.657600	47.419	77.1392391	-0.0380886
77		4.624169			
78	g2f	2.946400	38.199	77.1367914	0.0380886
79		1.284570			
80		0.715			
81	g3f	3.657600	47.419	77.1392391	0.0380886
82		0.450000			
83	g4d	3.657600	47.419	77.1392391	-0.0380886
84		0.715000			
85		0.715000			
86	g5d	3.657600	47.419	77.1392391	-0.0380886
87		0.450000			
88	g6f	3.657600	47.419	77.1392391	0.0380886
89		0.715000			

Pos	Name	length [m]	bend [mrad]	ρ [m]	$B'/(B\rho)$ $[m]^{-2}$
90		0.715000			
91	g7f	3.657600	47.419	77.1392391	0.0380886
92		0.450000			
93	g8d	3.657600	47.419	77.1392391	-0.0380886
94		0.715000			
95		0.715			
96	g9d	3.657600	47.419	77.1392391	-0.0380886
97		0.450000			
98	g10f	3.657600	47.419	77.1392391	0.0380886
99		0.715000			
100		0.715000			
101	g11f	3.657600	47.419	77.1392391	0.0380886
102		0.450000			
103	g12d	3.657600	47.419	77.1392391	-0.0380886
104		0.715000			
105		0.715000			
106	g13d	3.657600	47.419	77.1392391	-0.0380886
107		0.450000			
108	g14f	3.657600	47.419	77.1392391	0.0380886
109		0.715000			
110		0.715000			
111	g15f	3.657600	47.419	77.1392391	0.0380886
112		0.450000			
113	g16d	3.657600	47.419	77.1392391	-0.0380886
114		0.715000			
115		0.715000			
116	g17d	3.657600	47.419	77.1392391	-0.0380886
117		0.450000			
118	g18f	3.657600	47.419	77.1392391	0.0380886
119		0.715000			
120		0.715000			
121	g19f	3.657600	47.419	77.1392391	0.0380886
122		0.450000			
123	g20d	3.657600	47.419	77.1392391	-0.0380886
124		0.715000			
125		0.715000			
126	g21d	3.657600	47.419	77.1392391	-0.0380886
127		0.450000			
128	g22f	3.657600	47.419	77.1392391	0.0380886
129		0.715000			
130		0.715000			
131	g23f	3.657600	47.419	77.1392391	0.0380886
132		0.450000			
133	g24d	3.657600	47.419	77.1392391	-0.0380886
134		0.715000			

Pos	Name	length	bend	ρ	$B'/(B\rho)$
		[m]	[mrad]	[m]	$[m]^{-2}$
135		0.715000			
136	g25d	3.657600	47.419	77.1392391	-0.0380886
137		0.450000			
138	g26f	3.657600	47.419	77.1392391	0.0380886
139		0.517663			
140	qmi1	0.680000			0.018017221
141		1.588065			
142	bmi	2.946400	48.507	60.7471175	
143		1.314723			
144	qmi2	0.680000			0.15645349
145		1.158010			
146	bmi	2.946400	48.507	60.7471175	
147		0.639683			
148	qmi3	0.680000			-0.28441136
149		1.533050			
150	bmi	2.946400	48.507	60.7471175	
151		0.582034			
152	qmi4	0.680000			0.27595845
153		0.890697			
154	bmi	2.946400	48.507	60.7471175	
155		3.061489			
156	qmi5	0.680000			-0.092385216
157		1.399065			
158	bmi	2.946400	48.507	60.7471175	
159		7.563012			
160	qmi6	0.680000			0.15006942
161		1.043211			
162	si0	4.088028	50.407	81.0309163	
163		1.337782			
164	qmi7	0.680000			-0.19498627
165		1.000000			
166	si1	3.500000	43.193	81.0309163	
167		1.000000			
168	q8o	0.617102	-1.545		0.07867868
169	q8o	0.617102	-1.545		0.07867868
170		1.000000			
171	si2	1.400000	-2.800	500.	
172		14.362796			
173	ki	3.250000	-1.324	2454.5	
174		0.500000			
175	q9o	0.411734			-0.056282546

6 O'CLOCK INSERTION

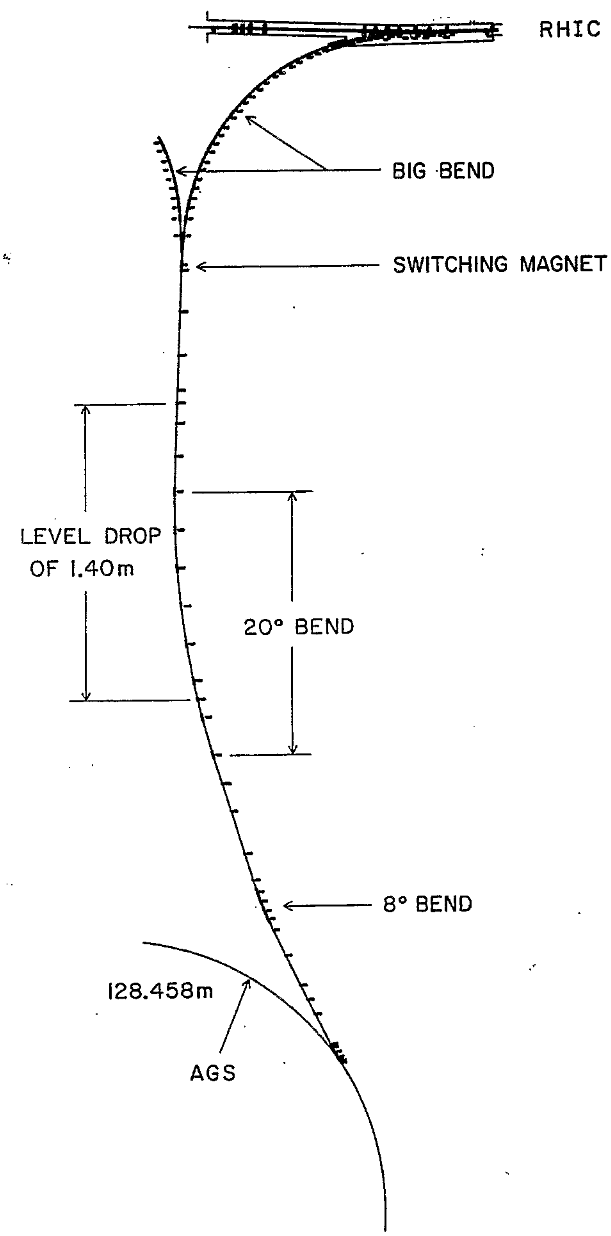


Figure 1

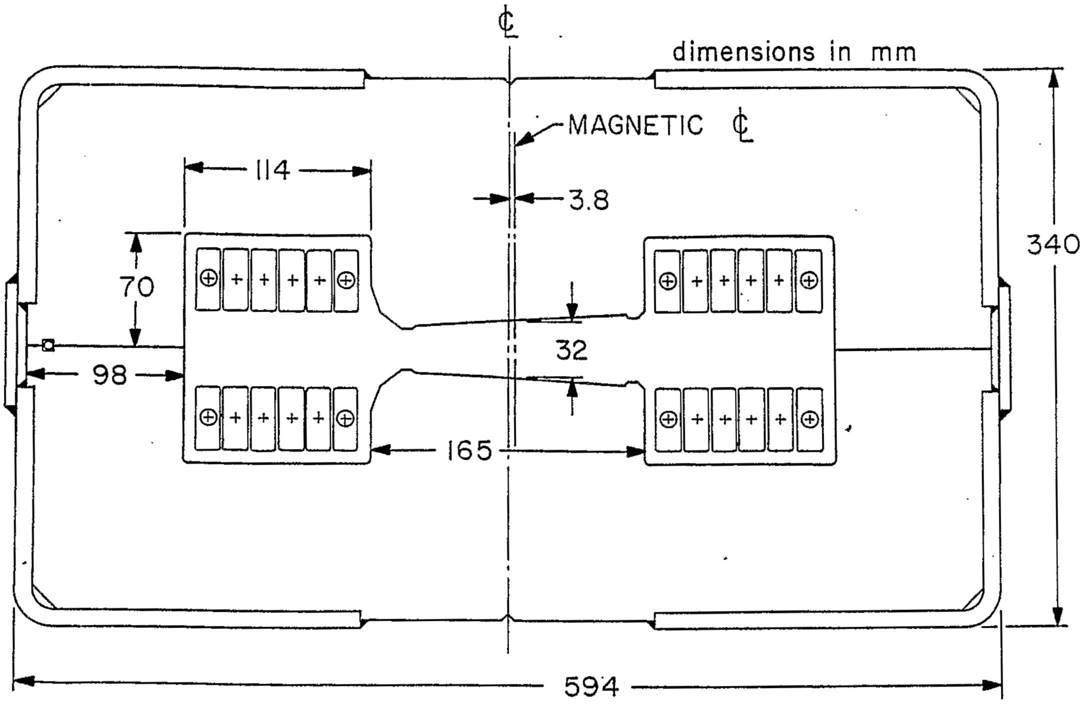


Fig. 2a Cross-section of gradient magnet for BIG BENDS.

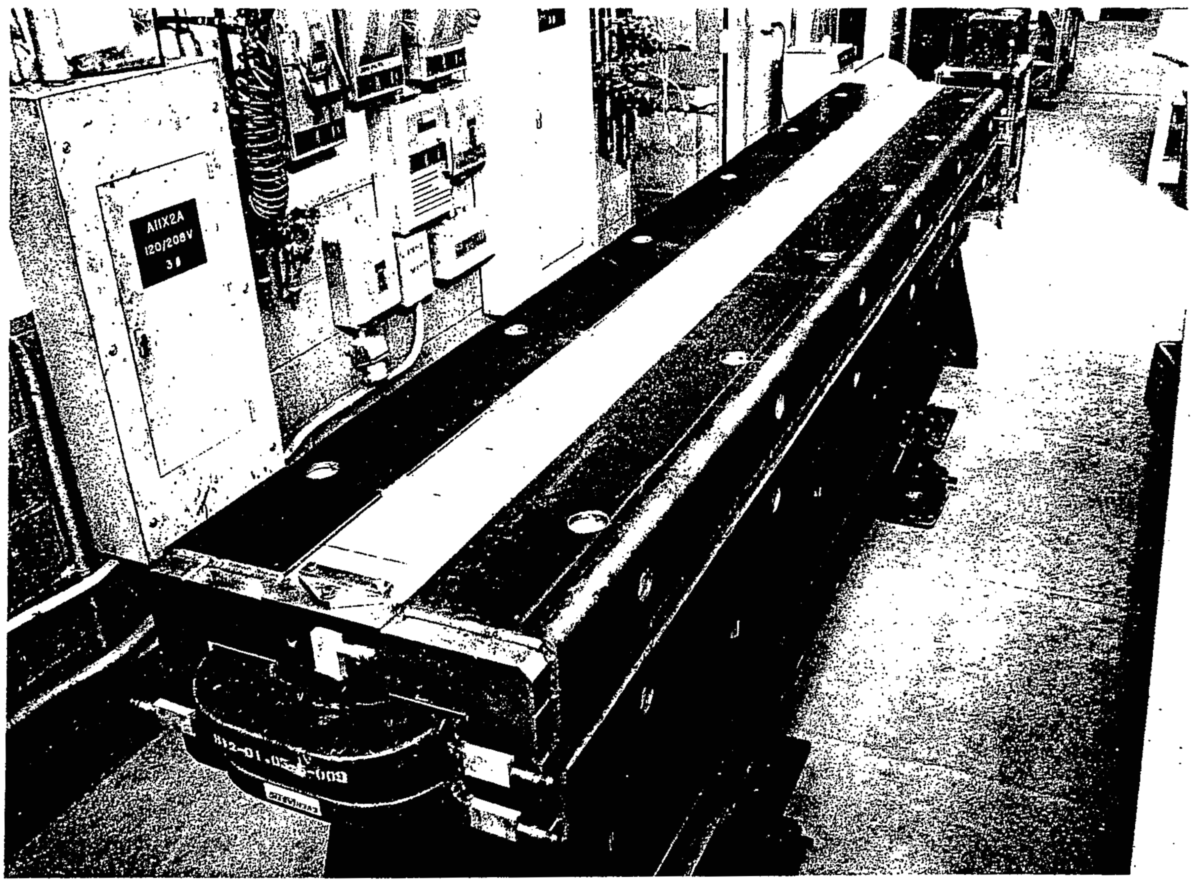
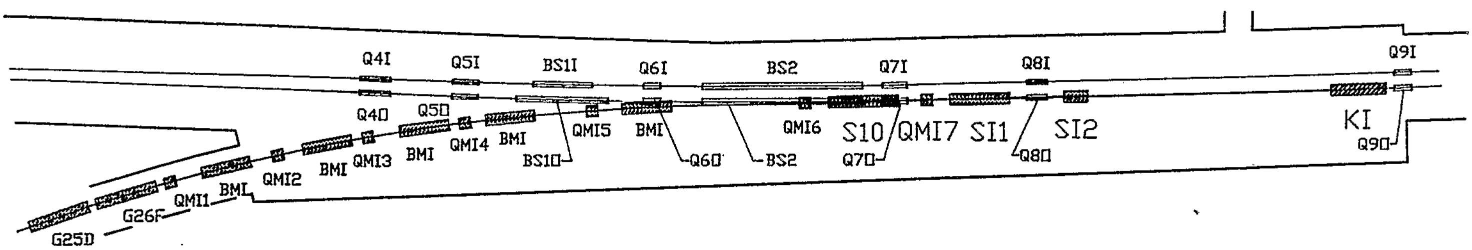


Fig. 2b Photograph of gradient magnet for BIG BENDS.



RHIC INJECTION

Fig. 3a.

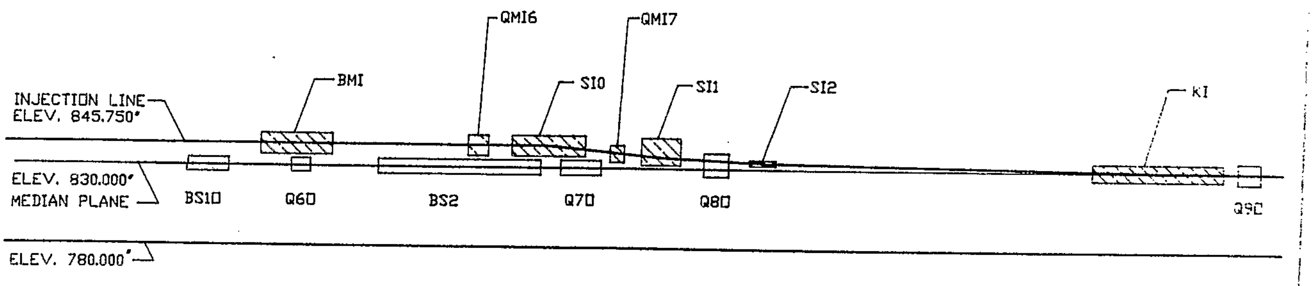


Fig. 3b

Fig. 3a,b Layout of east injection area, plan view and elevation.

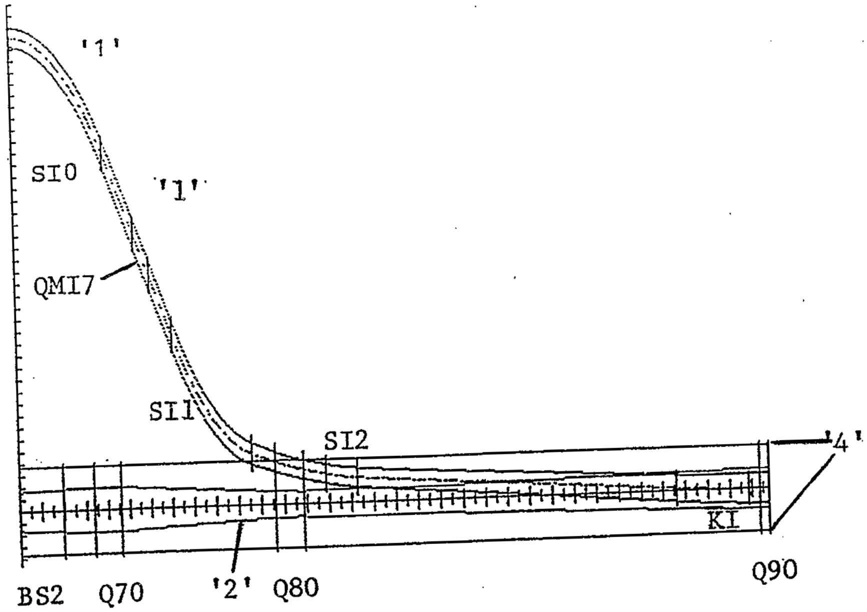


FIG 4a

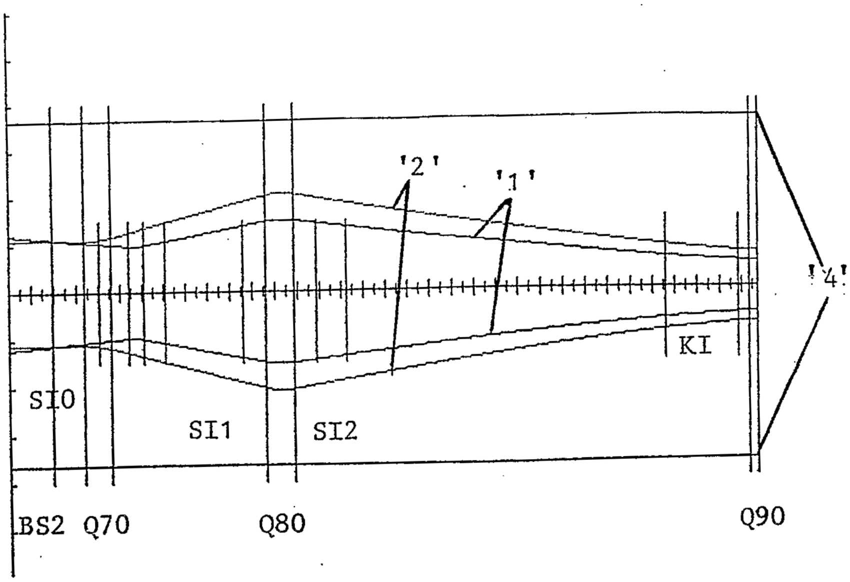


FIG 4b

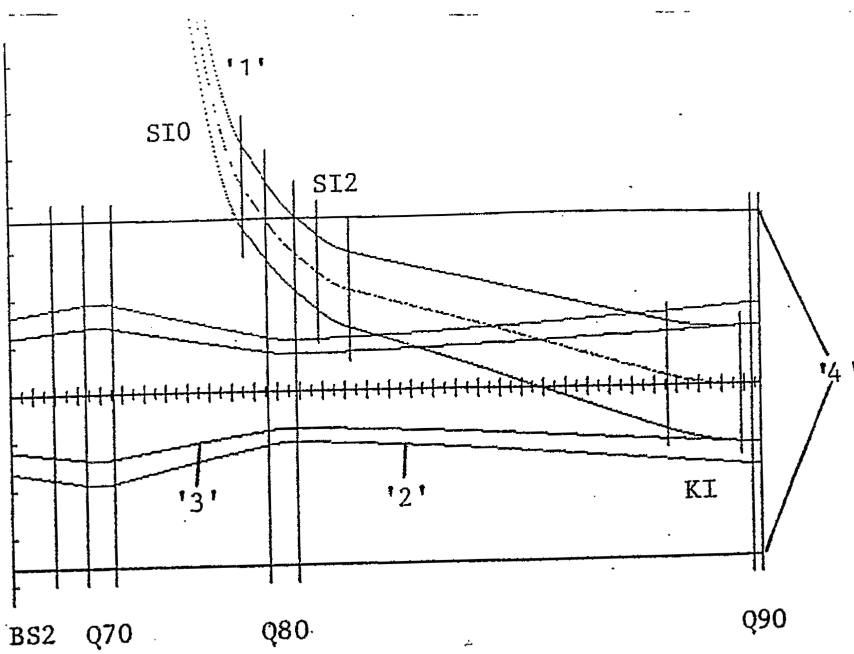


FIG 4c

Fig. 4a,b,c Details of admittance profiles for incident and circulating beams in east injection area. Horizontal scale: 1m between large divisions, vertical scale: 1cm between divisions. Each diagram shows the exit face of ringmagnet BS2, the entrance and exit faces of ringmagnets Q70 and Q80 and the entrance face of ringmagnet Q90. Also shown are the entrance and exit faces of the injection line magnets SI0, QMI7, SI1, SI2 and injection kicker KI. The curves labeled '1' represent the boundaries of the 3.2π mm-mrad for the incident beam, '2' represents the 6π mm-mrad admittance for the circulating beam, '3' represents the admittance for the circulating beam temporarily reduced to 3.2π mm-mrad during the filling period. '4' represents the inner surface of the nominal beam pipe. Fig. 4a shows an elevation, 4b a plan view and 4c an elevation at a larger vertical scale.