MULTITURN INJECTION INTO THE CONVERTED AGS*

J. Claus, H.N. Brown, M. Month, A. van Steenbergen
Brookhaven National Laboratory
Upton, New York

Abstract

A description is given of the status and performance of the AGS multiturn injection system. Experimental results are presented and compared with analytical predictions. Details are given concerning on-line computer emittance-acceptance matching and multiturn stacking in either the "horizontal only" mode or "horizontal-vertical" mode. In addition, a description is given of specific components such as the "horizontal-vertical" inflector and the emittance measurement device.

Introduction

High circulating beam intensities in synchrotrons require some form of multiturn injection if the intensity of the beam offered for injection (called the linac beam hereafter) is limited. Such is the case for the Alternating Gradient Synchrotron at Brookhaven National Laboratory where at present the linac beam is limited to ≤ 40 mA, i.e. to $\leq 1.2 \times 10^{12}$ protons per revolution. Since in practice our net efficiency is of the order of 30% we are effectively injecting about 3.5×10^{11} protons/turn. Thus reaching our target of 10^{13} accelerated protons/pulse would require injection during some 30 turns.

One has the choice of stacking in betatron phase space or in synchrotron phase space. Although the second method is useful for injection into proton storage rings from a synchrotron it shows serious disadvantages for synchrotron injection. It puts a large momentum spread in the beam and tends to be a time consuming process that requires extensive gymnastics with the rf system and/or very fast kicker magnets. For the converted AGS we chose to stack in betatron phase space, using a method with which we had already considerable experience.[1]

We inject the linac beam via a thin septum magnet (called inflector) while moving the closed orbit away from it. This motion occurs only near the inflector; the instantaneous closed orbit consists of the unperturbed stationary orbit with a bump of half a betatron wavelength of variable magnitude superimposed. The bump is controlled by two bump coils. The range through which the bump may be moved is restricted by the location of the inflector and the other aperture restrictions of the accelerator. The length of the injection interval is determined by the range and the rate of the bump motion. This last variable we shall call bump collapse rate (Bcr).

Theoretical Considerations

Area and density being conserved in phase space, the ultimate beam intensity in the accelerator is determined by its acceptance and by the brightness of the linac beam. The ultimate may not be achievable because of intensity dependent effects or because the current in the linac beam is so low that it requires an injection interval of many turns. In that case the finite width of the inflector septum will restrict the net acceptance available. Although the ultimate beam intensity should not be affected by the details of the injection method the efficiency of the process is. If the linac beam pulse is restricted both in intensity and in length, considerations of efficiency may become important. Since the part of the injected beam that is lost is lost inside the accelerator it contributes to the radiation dose. Especially at high intensities and at high injection energy this radiation problem may set a limit to the acceptable rate of beam loss.

One defines as partial acceptance the region in transverse phase space that contains the phase points of all protons that could be injected successfully at a particular instant. The area within and the shape and location of the boundary of the partial acceptance change during the injection interval; the area in particular increases from zero to a maximum and reduces to zero again. The details of this behavior are determined by the closed orbit motion and the betatron frequencies. If the linac beam is stationary in its characteristics during injection the only way of populating all of the accelerator acceptance is to have the linac beam emittance cover the envelope of all partial acceptances.

Figures 1, 2, 3 and 4 represent the subdivision of an acceptance in partial acceptances. We made use of a normalized system of coordinates in which transformations around the accelerator appear as pure rotations over an angle equal to the betatron phase advance per turn.[2] Therefore, the acceptances seen by the linac beam are identical to the ones in the figures but for a rotation and a translation. The bump collapse rate was constant in all four cases and equal to a/n per turn, with a representing the half aperture (= radius of acceptance circle) and n = 10, 20, 40 and 20 respectively. The betatron frequency was $\nu = I + 3/4$ in the first three figures and $\nu = I + 0.707$ in the last one with I an arbitrary integer. The area of the partial acceptance appears to be non-zero during 11, 21, 40 and 21 turns in these four cases. For $\nu = I + 3/4$ the shape is rectangular during most of the injection interval; the width is given by $\Delta x = 4\ a/n$ and the angular spread increases linearly towards its maximum value at a rate $2a/(n\beta)$ per turn. β represents here Courant's and Snyder's amplitude function at the inflector exit. Figure 5 shows the development with time of the area for the first three examples, expressed as a fraction of the accelerator acceptance.

For a linac beam that is independent of time during the pulse we define as area efficiency η_A the ratio of the area of the accelerator acceptance and the total injected area. This efficiency is highest if the linac emittance just covers the envelope of all partial acceptances and the pulse length just covers the injection interval. For $\nu = I + 3/4$ the envelope is identical with the largest partial acceptance and the ellipse that covers it has $\pi/2$ its area, thus $\eta_A \approx n/(4m)$ where m indicates after how many turns the acceptable angular spread has become maximum. We find in actuality η_A = 0.30, 0.33, 0.35 for the first three examples and η_A = 0.2 for the last one where $\nu = I + 0.707$.

For a particular frequency the efficiency appears to improve slightly with increasing length of the injection interval. In practice this improvement is offset by the increasing influence of the septum thickness. For equal intervals, "simple" frequencies give better efficiencies than arbitrary ones, mainly because the emittance cannot be matched very well to the odd shaped envelope in the latter case.

To optimize, one first measures the current as a

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function of emittance inside the linac beam. Then one adjusts the betatron frequency to a simple fraction and the bump collapse rate so that the area of the maximum partial acceptance equals $2/\pi$ of that of the chosen emittance. Finally one adjusts the orientation and the eccentricity of the ellipse so that it may cover the partial acceptance.

Application to AGS

Applying this reasoning to the AGS one finds that circulating beams of 1.9×10^{13} protons should be achievable under the present conditions if the linac pulse could be increased to 300 µsec from the nominal 200 µsec. This estimate was obtained in the following manner. With the inflector at 50 mm from the unperturbed closed orbit the acceptance of the AGS is 15 π mrad-cm. The linac beam contains at present about 30 mA inside the 0.5 π mrad-cm emittance contour for a total current of 40 mA. Populating the acceptance with this density, the circulating beam would be 900 mA. With $\nu_H = 8.75$ and $\eta_A = 0.35$ the injection interval would have to be $900/(0.35 \times 40) = 65$ turns. With this many turns the shadow of the 0.75 mm thick inflector septum would occupy $\sim 4\ \pi$ mrad-cm so that only 11 π mrad-cm may be populated. This corresponds to 660 mA or 1.9×10^{13} protons. This estimate neglects the fact that the emittance is not uniformly populated but more or less gaussian. Assuming it to be valid still the net efficiency (the best one possible for a fully populated acceptance with the assumed linac beam!) is only 26%. This intensity is well beyond the level beyond which one expects intensity dependent effects to become noticeable (1.4×10^{13}). The design pulse length of the linac is 42 turns. Reducing the linac pulse length from 65 to 42 turns while preserving the injection interval at 65 turns should not reduce the circulating beam proportionally because the efficiency early and late in the interval is poor compared to that of the middle part.

At present the AGS is operated with an injection interval of 25 turns. With the 40 mA linac beam mentioned before we achieve circulating beams of 1.4×10^{13} protons, i.e. an efficiency of 0.46. Comparing this with the previous theoretical values one sees at what price more intensity comes: a 35% increase requires a 2.7-fold increase in injected charge. Because the linac beam is not uniformly populated but more or less gaussian, area efficiency curves, as those in Fig. 5, cannot be measured directly. Instead we measure so-called short sample survival curves (s.s.s.'s) which yield an intensity efficiency curve — in effect an area efficiency curve weighted with the density profile of the linac emittance. The s.s.s.'s are measured by reducing the pulse length of the linac beam to shorter than a revolution period and measuring its intensity, as a function of time, by means of a beam transformer, while it circulates inside the AGS. By changing the instant of injection relative to the injection interval one obtains a record of the injection process from which an intensity efficiency curve may be derived. Figure 6 shows a typical s.s.s., Fig. 7 intensity efficiency as a function of injection time. It may be noted that in this particular case the curve is not triangular as one might expect but trapezoidal. This may be due to too small an angular spread in the linac beam which would cause the large partial acceptances to be filled incompletely.

The s.s.s.'s form an important diagnostic device by themselves. The loss pattern they exhibit, in particular if they are taken with zero bump collapse rate, is primarily determined by the betatron frequency, the emittance of the linac beam at the inflector exit and geometrical factors. The loss pattern for simple betatron frequencies is easily recognized, e.g. 2 pulses for $\nu_H = I + \frac{1}{2}$, 3 for $\nu_H = I \pm 1/3$, 4 for $\nu_H = I \pm \frac{1}{4}$, 5 for $\nu_H = I \pm 1/5$ and $\nu_H = I \pm 2/5$. By changing the betatron tune of the accelerator one may calibrate the tuning means at injection time. At a fixed betatron tune, the pattern is set by the emittance, the bump excursion, the relative locations in the accelerator aperture of the inflector and the unperturbed closed orbit. The changes in the pattern as function of the bump excursion make it possible to derive the essential characteristics of the emittance and also to determine whether the limiting aperture is formed by the inflector or something else. If the latter appears to be the case, one may change the condition by changing the unperturbed closed orbit.

Inflector

Figure 8 shows our inflector assembly. Its copper current septum, together with its conetic magnetic shield is effectively 0.75 mm thick and its iron magnetic septum 4.5 mm. It consists of three rectangular magnet units that bend the linac beam through 130, 65 and 10 mrad by means of pulsed uniform fields of 0.427 T, 0.213 T and 0.025 T. The pulses are half sinusoids with base lengths of about 8 msec. The peak current through the first two units is about 7000 A, while that through the (electrically independent) last one is 1200 A. The first two units are electrically in series with a uniform field magnet upstream that bends through -230 mrad. The net effect on the beam is a displacement of -80 cm and a rotation of -25 mrad with respect to the nominal axis of the incoming linac beam at the inflector exit with negligible dispersion. The three units are built up of ¼" mu-metal laminations cut away to form C-shaped apertures. The assembled system presents a free aperture of 4×4 cm^2 to the beam. Where necessary, the upper left-hand corner (looking in the direction of beam travel) of the laminations is also cut away to provide space for the circulating beam when stacking vertically. The horizontal iron septum left between this space and the aperture is 4.5 mm thick. In all units the open end of the aperture that faces the circulating beam is closed by a mu-metal or conetic shield to reduce the stray fields inside the AGS aperture. Some units carry an experimentally adjusted backleg winding to assist in this and a tight fitting heavy copper shield envelopes the AGS aperture for the same purpose. In this way we succeeded in keeping the stray field below 1G in all important areas. There is no doubt we could improve on this by further (lengthy) development. The 0.5 mm thick electroformed copper septum in the third unit is cooled by water flowing in triangular inconel channels in the corners of the aperture, all other copper by water flow in longitudinal channels in the solid. Nearly all joints in the cooling channels are brazed in order to prevent leakage when hit by the beam. A 5 cm thick water-cooled copper shadow target immediately upstream of the first inflector unit protects most of the inflector assembly from direct hits by either the linac or the circulating beam, the third unit being the most critical one in this and all other respects. The target consists of four electrically insulated sections with connections to the control room so that it may be used for beam diagnostics. We have used it for locating the beam and for determining both horizontal and vertical beam profiles. More diagnostics are provided by a movable fluorescent screen and scanning wire assembly at the inflector exit. The base plate on which all this equipment is mounted may be moved from the control room in the horizontal plane to adjust its distance and direction with respect to the AGS structure; vertical position and tilt can be set with locally controlled electric motors, an exercise of 45 minutes from beam off to beam on.

Vertical Stacking

At less than π mrad-cm, the vertical emittance of the linac beam is sufficiently smaller than the 4.9 π mrad-cm vertical acceptance of the AGS[3] to consider injection with a coherent vertical betatron oscillation. The motion may be induced by injecting off the medium plane. If the inflector has a "thin" horizontal septum placed suitably with respect to the medium plane the beam will miss the inflector structure vertically for a number of turns by the same mechanism that works horizontally.[2] The net result is that the horizontal partial acceptances have their areas increased at the expense of the vertical ones. One may use this for increasing the beam intensity or for increasing the injection efficiency, or both.

Figure 9 shows to the left the development of the partial acceptances in the horizontal plane, to the right that for the vertical plane, using a bump collapse rate of a/40, $\nu_H = I + 3/4$ and $\nu_V = I + 2/3$. The large size of the horizontal partial acceptances and the reduced size of the vertical ones is evident. Since particles injected three revolutions apart move on the same vertical level all the time the horizontal diagram is the composite of three, each drawn for a bump collapse rate of 3a/40 but with different starting times. This is shown in the diagram by solid, dashed and dash-dot lines. For want of a better word we call this vertical stacking and the first experiments have been started recently.

With the mid-plane of the iron septum 4.3 mm below the medium plane we induce a vertical betatron motion of 17.2 mm amplitude. This leaves a vertical partial acceptance of about 1.40 π mrad-cm. Under these conditions we noticed a drop in intensity of about 10% in comparison with medium plane injection. Since optimum results require specific betatron frequencies we began a program of measuring short sample survivals as a function of the frequencies. We do this in a static condition, with the bump collapse rate equal to zero in order to eliminate that variable.

We have seen 25% of the beam survive for up to 15 revolutions in this state without doing any emittance matching. Figure 10 shows a typical short sample survival. There the sample survived for 8 turns, the first three of them practically unharmed, then a slight loss occurred,followed by a large loss after which there were another three undisturbed revolutions followed by a large loss. This pattern may be explained in several ways and more information is needed to decide on the correct one. As was expected, the experimental curves are very sensitive to the betatron frequencies. During actual injection the intensity of the circulating beam builds up gradually and the changing space-charge forces will depress the phase advances experienced by each sample of the linac beam in a way that depends upon the sample's injection time and the beam intensity. If this effect is serious it may be necessary to introduce dynamic control of the nominal betatron frequencies.

Programmed Bump Collapse Rate

Since a large part of the inefficiency of the injection process is due to the change in area of the partial acceptance with time, which change is inherent in a constant bump collapse rate, one may expect improvement with a factor of 2 if the collapse rate is varied to keep the area constant. This would imply large rates near the ends of the injection interval and a low one in its middle part. An immediate consequence would be that the shape and position of the partial acceptance change more drastically than they do with a constant collapse rate. Such changes can possibly be met by dynamic control of the linac beam emittance. This matter is under consideration.

Injection Controls

Injection is a process controlled by 20 parameters, 10 of these describe the linac beam, the other 10 the accelerator. Because of this large number it is practically essential to have independent control of each of them if one is to find an optimum experimentally. The beam delivered by the linac passes through a transport line and the inflector.[4] The last part of the transport line forms the matching section, consisting of first six quadrupoles and then of two pairs of steering magnets, one horizontal pair, which incorporates the inflector and one vertical pair. The linac is asked to deliver beam of specified and fixed characteristics at a point immediately upstream of the matching section, where we have equipment to measure those characteristics.

It consists of a drift space of 8 m length that contains two pairs of nondestructive magnetic position monitors[5] for determining the position and direction of the beam and of movable slits and movable arrays of secondary emission wires, a slit and an array for each of the two transverse directions with which density distributions in the transverse phase planes may be measured.[6]

The linac group succeeds pretty well in meeting the specifications most of the time. The quads are used to adjust the emittance parameters to desired values at the inflector exit. Since the quads are nominally centered on the nominal beam axis the axis is hardly effected by quadrupole adjustments. The steering magnets are used to bring the centers of the emittances to the desired locations in phase space. Since the relative variations are small the changes in dipole focusing are also small. Still it appears to be extremely difficult and time consuming to find the proper settings of these ten magnets by individual experimental adjustment. Therefore we make use of an online computer program[6] that can calculate the magnet excitations necessary to transform the beam characteristics measured at the input of the matching section to desired values at the inflector exit. We do not have at present a method for direct measurement of the betatron frequencies during injection; this is a serious inconvenience, partly because they depend fairly strongly on the location of the unperturbed closed orbit via the as yet uncompensated sextupole component of the main field. (That due to eddy currents in the vacuum chamber should be small because $\dot{B} \sim 1$ kG/sec during injection.) It is easy to introduce known changes in the betatron frequencies via a series of tuning quadrupoles. This may effect the shape and location of the closed orbit to an extent we can estimate only by extrapolating from measurements taken later in the machine cycle.

Acknowledgment

Building the injection system and making it behave was and is a large effort to which too many people contributed that they can all be named. We make an exception for H.C. Hsieh and A.A. Bertsche who were responsible for the design and construction of the inflector magnets. The AGS operators are to be thanked for their support during the many hours of experimental study.

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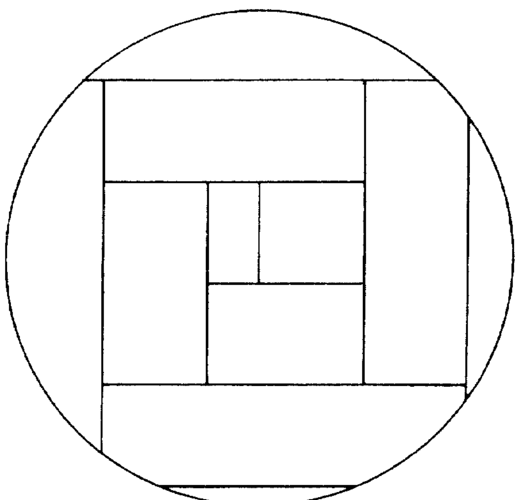
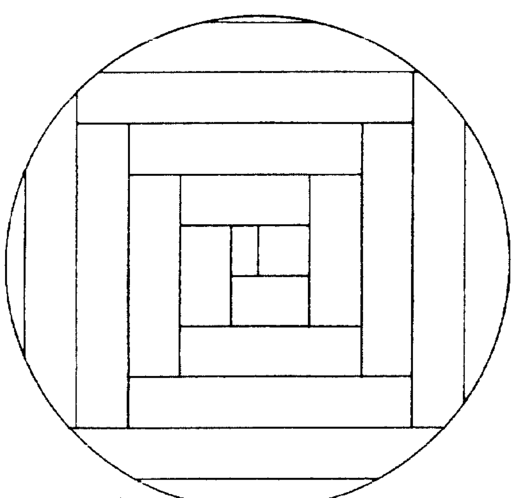


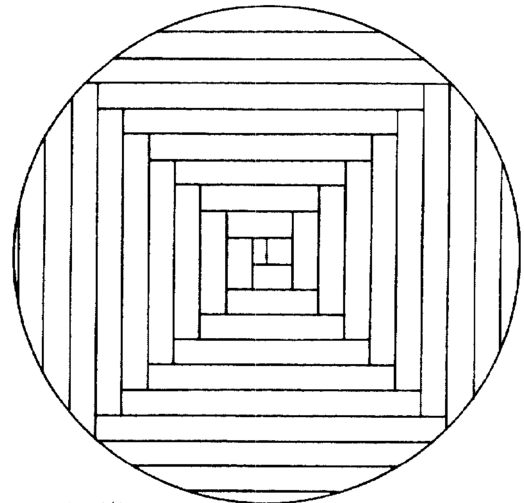
$\nu_H = I + 3/4$
$Bcr = a/10$

Fig. 1



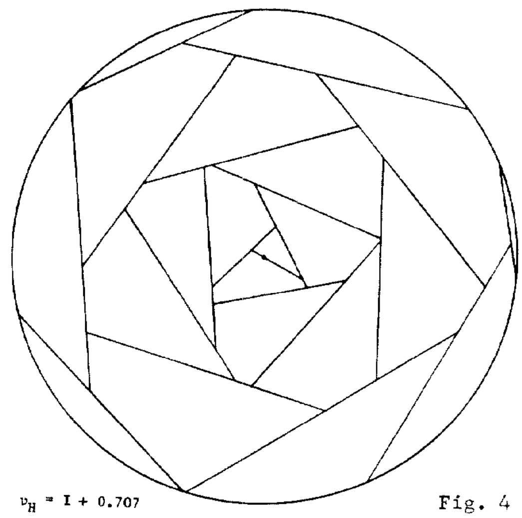
$\nu_H = I + 3/4$
$Bcr = a/20$

Fig. 2



$\nu_H = I + 3/4$
$Bcr = a/40$

Fig. 3



$\nu_H = I + 0.707$
$Bcr = a/20$

Fig. 4

Figs. 1, 2, 3, 4. Acceptance and partial acceptance.

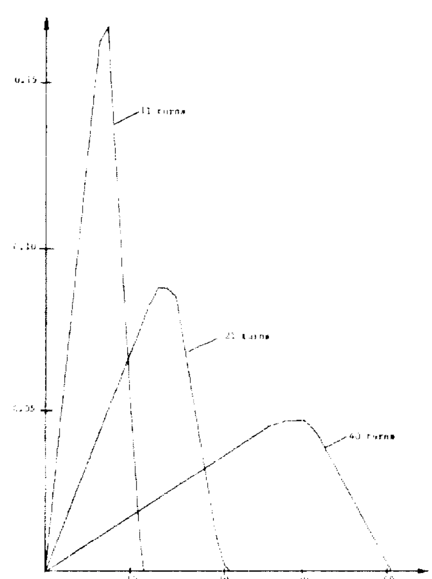


Fig. 5

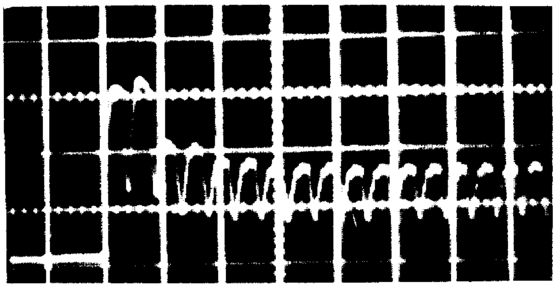


Fig. 6

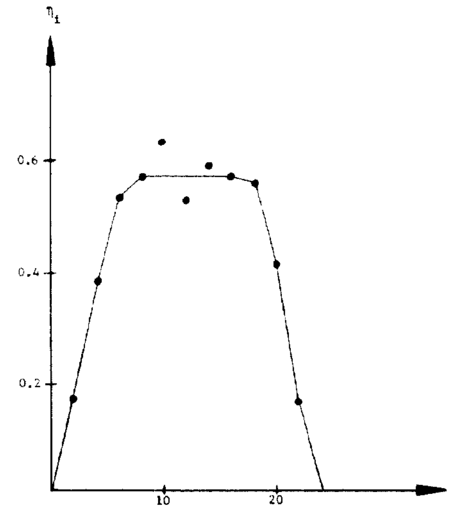


Fig. 7

Fig. 8. Inflector Assembly.

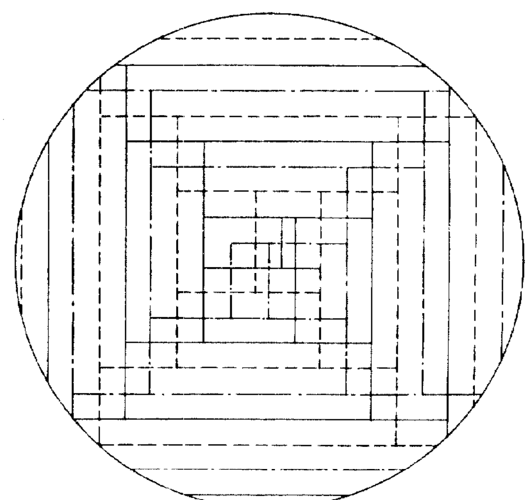


Fig. 9a

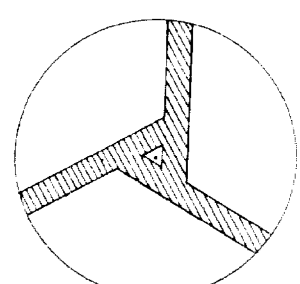


Fig. 9b

Fig. 9. Acceptances and partial acceptances for vertical stacking.

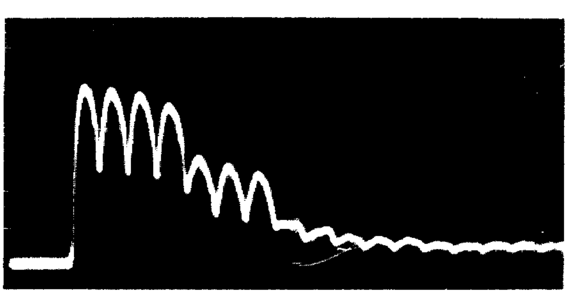


Fig. 10