FAST EXTRACTION OF DEBUNCHED AGS BEAM

L.N. Blumberg, J.G. Cottingham, J.W. Glenn, J.J. Grisoli,
M. Month and A. van Steenbergen
Brookhaven National Laboratory
Upton, New York

II. Location and Required Deflection

For Thin Septum

The deflection required for the El0 septum can be obtained from linear theory if we assume that the horizontal phase shift $Y$ from El0 to H10 is independent of momentum. The matrix transport is then

$$ M = \begin{pmatrix} \cos Y + a \sin Y & b \sin Y \\ -a \sin Y & \cos Y - a \sin Y \end{pmatrix} \tag{1} $$

with $a = 1.264$ and $b = 603$ in. from AGS orbit calculations,$^4$ $\gamma = (1 + a^2)/b$, and $Y \approx 61^\circ$. For the El0 septum at distance $d$ from the center of an ellipse containing particles of momentum $p_{\text{max}}$, the position at $H_{10}$ of points on the El0 septum, designated 1 and 2 in Fig. 2, after deflection is

$$ x_{1(2)} = d \cos Y + b \sin Y \mp \sin Y \sqrt{x_{1(2)}^2 - (d+D)^2} \tag{2} $$

where $\pm$ refers to point 1, $x_{1(2)} = \sqrt{E}$ is the ellipse half-width, and the emittance $E = \mu_c = .1$ in-mrad is approximately twice the present AGS horizontal value. The "shaved" portion of the ellipse between $x = d$ and $x = x_{10}$ in Fig. 2 also contains protons of lower momentum with equilibrium orbits on the line $x_{10} = (b/a) x_{10}$. If we designate by $1'$ and $2'$ the intersections with the septum of an ellipse centered at $x = \pm D$ and of momentum $p < p_{\text{max}}$ then the position of these points at $H_{10}$ is given using Eq. (1) as

$$ x_{1,2} = (d+D) \cos Y + b \sin Y \pm D \pm \sin Y \sqrt{x_{1,2}^2 - (d+D)^2} \tag{3} $$

If we form the difference $(d,d) = x_{1,2} - x_{1,2}$ and set $(df/dD)_{\text{max}} = 0$ we obtain the critical septum position $D_C = x_{10} \sin Y/2$ such that, for $d > D_C$, we have $x_{1,2} > x_{10}$ and the separation $S$ between the deflected and undeflected beam at $H_{10}$ is just $x_{10} - x_{10}$. For $d < D_C$ we can show that if $(3,d)$ has a minimum at $D_D = c - d$ such that $x_{1,2} < x_{10}$ and the separation is then decreased by momentum spread.

For the two cases

Work supported by the U.S. Atomic Energy Commission.

\*\*
We have considered two configurations of backleg windings and separated by larger phase shifts than required to restore the beam to the unperturbed orbit. We therefore made computer calculations of the separation function at H10 using the AGS ray-trace program BEAM7 which contains the appreciable machine non-linearity at the design momentum of 29 GeV/c. The results are given in Fig. 3 for 4 momentum groups. The clearance is in good agreement with the estimates of linear theory for this case; however, in other cases where the septum and ejector are separated by larger phase shifts than for E10 to H10, we see appreciable discrepancies with linear theory.

III. Orbit Deformations

The function of the fast orbit deformation is to move the beam adjacent to the septa at E10, H10 and I10, which are positioned at the injection aperture of the machine (about 2 in. from the central orbit). Since the SEB is assumed to be on prior to fast extraction, the orbits are contained between ψF = ±π/2 and ψF which imposes several constraints on the fast bumps: ψF must decrease if the SEB-exciting sextupoles are on, and the deformation of the orbits near 28 = 9 (low momentum, inside orbit) must not be further increased by perturbations introduced by the bumps. We have considered two configurations of backleg winding bumps (BLWB).

Method A

We center a λ/2 BLWB at each of the three FEB septa and energize three additional inward λ/2 bumps to compensate for the ψF = ±π/2 shift caused by the primary bumps. The compensating bumps are superimposed on the existing three λ/2 outward SEB bumps centered at F1, G10 and H10 and thus "cancel" the SEB bumps without causing an objectionable inward excursion and thus beam loss of low momentum protons. The cancelling bumps also aid in suppressing the slow beam by moving the beam away from the SEB septa.

The orbits resulting from the 6 FEB and 3 SEB bumps are shown in Fig. 4 for a momentum near the 8-2/3 resonance and 6% lower momentum. The low momentum orbit at ψ0 = 8.90 is seen to be highly deformed, with peak-to-peak oscillations of 5.2 in. which exceed the available aperture in the AGS. This orbit can be corrected with the aid of additional dipoles. In Fig. 5 the strength of the "cancelling" bumps has been increased to assure that the ϕ shift is positive near 0-2/3. We note that, because of the small width of the 8-2/3 resonance, we can effectively move the entire beam out of its influence by a small (ϕ < .02) ϕ increase. We also point out that the oscillations from low momentum orbits can be mitigated by pulses the AGS superperiod sextupoles and thus decreasing dϕ/dp.

The large oscillations in the orbits of Fig. 4 result from the dipole and quadrupole perturbations introduced by the bumps, and the proximity of the tune to the integral and half-integral resonances at 28 = 9. The dipole errors arise from two effects: the deviation of the BLWB from a perfect λ/2 separation, and the non-linearity of the AGS field. Consider first the combination of the orbit oscillation from dipole errors due to one λ/2 bump (4 magnets):
deformations, we would still have a large gradient stop-
band at \( \nu_h = 9 \) from the second term in Eq. (9).

**Method B**

Only fast \( 1/2 \) bumps centered at \( \nu_1, \nu_2 \) and \( 10^5 \) are used. We require that the SEB sextupoles be turned off during fast extraction. The horizontal tune of the high momentum orbit shifts from 0.67 to 0.55 while the low momentum orbit shifts to \( \nu_h = 8.80 \). The orbits are shown in Fig. (6). Since we are no longer near \( \nu_h = 9 \) the horizontal orbits are reasonably well behaved. However, \( \nu_h \) for the high momentum particles shifts up to \( \nu_h = 8.59 \); thus we require that the super-
period quadrupoles be pulsed to shift \( \nu \) away from the \( \nu_h = 8+1/2 \) and \( \nu_h = 9 \) resonances. The method requires

- the horizontal tune of the ring be small
- that the 26 sextupole component in the ring be small
- the principal source of sextupole error will be 10 \( \nu_h = s-1/2 \) and 1, \( \nu = 9 \) resonances. The method requires

off during fast extraction. The horizontal tune of

- the high momentum orbit shifts from 8.67 to 8.55 while
- the low momentum orbit shifts to \( \nu_h = 8.80 \).

The orbits are shown in Fig. (6). Since we are no longer near

- \( \nu_h = 9 \)
- \( \nu_h = 8+1/2 \)
- \( \nu_h = 9 \)

We estimate that the strength of the 26 \( \nu_h \) sextupole error will be 10

\[
g = \frac{24}{\nu_h} \left( \frac{\Delta B}{\nu} \right) \tau_0 \left( \frac{\nu - \nu_h}{\nu} \right) \left( \frac{E}{126\nu} \right) = 2 \times 10^{-4} \text{ in.}^{-2}
\]  

which is small compared to the \( g = 5 \times 10^{-4} \text{ in.}^{-2} \) introduced by the SEB sextupoles. By pulsing two inde-

- dependent sets of extraction sextupoles we can ensure a
- sufficiently small 26th harmonic as the beam moves
- through the resonance. We favor Method B since fewer
- orbit bumps are required and dipole orbit corrections
- do not appear necessary.

**IV. Expected Beam Losses on Hyper Thin Septum**

We have calculated\(^{11} \) beam losses using a Monte

- Carlo technique by selecting proton coordinates at
- random from the phase space distribution of Fig. 2
- and following the particles through either a solid
- foil electrostatic septum or an array of wires\(^{12} \) parallel to
- a high voltage electrode. For a wire septum with
- wire radius \( r_w \), wire spacing \( a \), gap \( b \) relative to a plane at voltage \( V \), the potential is know\(^{13} \) and can be shown to give a nearly uniform field within the

- septum of strength \( E = (V/b)f \) where

\[
f = f(1 + \frac{a}{2mb}) = \frac{1}{2}\nu_h \]

with \( f \) near unity. Protons strike the septum either at

- its upstream end or along its length. Within the array, proton scattering angles are selected randomly\(^{14} \) from a Molière\(^{15} \) multiple-coulomb scattering distribution. In addition, elastic proton-nucleus scattering angles are selected from a distribution constructed from the differential cross section given by an optical model calculation.\(^{16} \)

- Finally, protons are absorbed with a probability derived from the approximate interaction cross section\(^{17} \) \( \sigma_B = 43 \times 0.67 \text{ mb} \), where \( A \) is the atomic weight. The numerical results give a loss from

- a Molière\'s multiple-coulomb scattering distribution.

\[
\text{Septum}
\]

\[
\text{Voltage (kV)}
\]

\[
\text{V. Description of Components}
\]

The beam kickers will be single turn, full aperture ferrite dipoles, 33 in. long and with a 6 in. \( \times 2/3 \) in. aperture. A capacitor bank will be discharged into the magnet through a deuteron thyratron to attain a peak

- current of 5000 A from a 1.75 \( \mu \)sec half-sinusoid wave-

- form. The resulting 870 G field will produce a .75

- mrad deflection, giving .4 in. displacement at the HTS. With a third, correction kicker in straight

- section D15, we can attain an ideal local bump. With a 3, correction kicker in straight

- section D15, we can attain an ideal local bump.

The H10 EM septum will be built in two sections of

- length \( l_1 = 25.5 \text{ in.} \) and \( l_2 = 56.5 \text{ in.} \). To obtain the

- inward, -3 mrad, deflectio-

- for ejection at 110, the

- septum units will be powered with opposite polarity.

- For ejection at H10, the septum will deflect by +22 mrad. The septum is \( 0.90 \text{ in.} \) Cu, edge-cooled and with a 1 in. vertical gap. The peak current of 21,000 A will be obtained from a capacitor-discharge power

- supply with \( x 1 \text{ msec} \) half-sinusoid waveform. The unit

- will be capable of pulsing \( 4 \) times at 100 msec intervals. The \( 0.10 \text{ in.} \) Cu septum required for the E10 hybrid straight section will be of similar design and

- capable of 1.2 mrad deflection. The electrostatic

- rms upstream of the \( 0.10 \text{ in.} \) Cu septum in E10 will be

**samples of \( 10^9 \) protons, the results are (NABS = number

- absorbed, NSCAT = number diffraction scattered, NTARG = number lost in downstream septum, and \( L = \) loss):

**Wire**

<table>
<thead>
<tr>
<th>Material</th>
<th>Z</th>
<th>NABS</th>
<th>NSCAT</th>
<th>NTARG</th>
<th>L (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>4</td>
<td>38</td>
<td>24</td>
<td>1305</td>
<td>1.37</td>
</tr>
<tr>
<td>Al</td>
<td>13</td>
<td>41</td>
<td>26</td>
<td>1264</td>
<td>1.33</td>
</tr>
<tr>
<td>Fe</td>
<td>26</td>
<td>59</td>
<td>73</td>
<td>1048</td>
<td>1.19</td>
</tr>
<tr>
<td>Cu</td>
<td>29</td>
<td>78</td>
<td>64</td>
<td>1054</td>
<td>1.20</td>
</tr>
<tr>
<td>Mo</td>
<td>42</td>
<td>74</td>
<td>76</td>
<td>935</td>
<td>1.10</td>
</tr>
<tr>
<td>W</td>
<td>74</td>
<td>104</td>
<td>101</td>
<td>794</td>
<td>1.00</td>
</tr>
<tr>
<td><strong>W Wire Dia.</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2p (inch)</td>
<td>NABS</td>
<td>NSCAT</td>
<td>NTARG</td>
<td>L (%)</td>
<td></td>
</tr>
<tr>
<td>.002</td>
<td>104</td>
<td>101</td>
<td>794</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>.004</td>
<td>373</td>
<td>393</td>
<td>543</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>.006</td>
<td>828</td>
<td>807</td>
<td>397</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>.008</td>
<td>1118</td>
<td>1063</td>
<td>202</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>.010</td>
<td>1116</td>
<td>1163</td>
<td>119</td>
<td>2.4</td>
<td></td>
</tr>
</tbody>
</table>

**Spacing (mm) | NABS | NSCAT | NTARG | L (%) | W Wire**

| Voltage (kV) | NABS | NSCAT | NTARG | L (%) |
| 10          | 516  | 165   | 84    | .84   |
| 20          | 794  | 101   | 1.00  |
| 30          | 363  | 101   | 1.01  |
| 40          | 1159 | 124   | 1.24  |
| 50          | 1363 | 1.42  |
| 2p = .002 in. V = 100 kV | | | | |

The losses show a significant increase between \( .004 \) and \( .006 \text{ in.} \) Cu, an gradual decrease with increasing \( Z \); an increase with larger wire spacing due to a de-

- crease in deflecting field (decrease in \( f \) of Eq. (11)), and significant decreases with higher voltage.

**V. Description of Components**

The kickers will be single turn, full aperture ferrite dipoles, 33 in. long and with a 6 in. \( \times 2/3 \) in. aperture. A capacitor bank will be discharged into the magnet through a deuteron thyratron to attain a peak current of 5000 A from a 1.75 \( \mu \)sec half-sinusoid wave-

- form. The resulting 870 G field will produce a .75

- mrad deflection, giving .4 in. displacement at the HTS. For full extraction of the AGS beam in three turns, we will add additional capacitor-switch systems to attain \( \sim 15,000 \text{ A in 8 } \) \( \mu \)sec. The kickers are separated by \( 2/3 \) in. to obtain a nearly local bump in the vicinity of the HTS. With a third, correction kicker in straight

- section D15, we can attain an ideal local bump.

The H10 EM septum will be built in two sections of

- length \( l_1 = 25.5 \text{ in.} \) and \( l_2 = 56.5 \text{ in.} \). To obtain the

- inward, -3 mrad, deflectio-

- for ejection at 110, the

- septum units will be powered with opposite polarity.

- For ejection at H10, the septum will deflect by +22 mrad. The septum is \( 0.90 \text{ in.} \) Cu, edge-cooled and with a 1 in. vertical gap. The peak current of 21,000 A will be obtained from a capacitor-discharge power

- supply with \( x 1 \text{ msec} \) half-sinusoid waveform. The unit

- will be capable of pulsing \( 4 \) times at 100 msec intervals. The \( 0.10 \text{ in.} \) Cu septum required for the E10 hybrid straight section will be of similar design and

- capable of 1.2 mrad deflection. The electrostatic

-rms upstream of the \( 0.10 \text{ in.} \) Cu septum in E10 will be

1011
1.5 m long with a 1 cm gap. At $E = 100 \text{ kV/cm}$ we should attain .5 mrad deflection.

Some operational experience has been gained from a prototype, 2.25 m long tungsten wire electrostatic septum recently installed in the AGS. The wires are .004 in. diam. at 2 mm spacing and the septum has held over 100 kV across a 1 cm gap in bench tests. The electrode is polished titanium and the straight section pressure is not higher than $1 \times 10^{-7}$ torr. In the AGS we find that circulating beam losses occur for $V \gtrsim 10^{11}$ when the machine tune crosses $k' \approx 1$ near injection. We believe that the gradient error causing these losses is due to an excessive ion density in the straight section, resulting from ion bombardment of the cathode with subsequent emission of secondary electrons which can penetrate the grid. Efforts are in progress to diminish the ion density and correct the gradient error. At reduced AGS intensity ($8 \times 10^{11} \text{ ppp}$) we have observed beam separation of the expected magnitude on scintillating screens.

Acknowledgments

We thank A. Maschke, C. Germain, S. Senator, M. Fruitman, M.Q. Barton, Th. Sluyters, and J. Herrera for numerous suggestions regarding the hyper thin septum, and E. Forsyth and M. Fruitman for design studies of fast kickers. We are grateful to G. Bennett, A. Tranis, L. Repeta and J. Lancaster for design and planning of beam components. We acknowledge the efforts of H. Heiss and A. Soukas in design studies for septum magnets and power supplies, of G. Bagley and F. Pallas for backleg winding development, of J. Schuchman and A. Bertsche for design of vacuum and positioning components, and J. Curtiss for instrumentation. We thank G. Parzen and K. Jellet for field calculations for the electrostatic septum and kicker magnets.

### References


![Fig. 1](image-url)  
Fig. 1. Configuration of fast beam components in the AGS ring. The deformed equilibrium orbit resulting from $\lambda/2$ backleg winding bumps is indicated by the solid curve. The trajectory of the central ray deflected by the beam kickers and E10 and H10 septum magnets is given by the dashed curve. The AGS magnets used for producing the PEB orbit deformations are darkened. BK1 and BK2 refer to the beam kickers at C15 and F15.)
Fig. 2. Beam ellipse at E10 and "shaved" beam at H10 ejector magnet as described by Eqs. (1) to (4) in text. The shaved beam has been displaced downward for illustration purposes.

Fig. 3. Fast extraction at H10 and J10. Orbit corrections, extraction sextupoles, and superperiod quadrupoles are on. The SEB orbit deformations are overcompensated by 25% with fast orbit deformations.
(a) Beam "shaving" by the hyper thin septum at E10.
(b) Separation at the H10 septum.
(c) Separation at the J10 septum.
Fig. 5. Fast external beam orbit deformations at E10, H10, and I10. The SEB orbit deformations are overcompensated by 25% with fast orbit deformations to obtain a slight upward $\nu$ shift. The extraction sextupoles and superperiod quadrupoles are on. Additional backleg windings are used for both SEB and FEB orbits to correct the low momentum (inside) orbit.

Fig. 6. Fast external beam orbit deformations at E10, H10, and I10. The SEB orbit deformations are present and not compensated. No correction windings are used and the extraction sextupoles are off. The superperiod quadrupoles are on and keep the horizontal $\nu$ value above $\tilde{\eta}$. 

1014