INITIAL PERFORMANCE OF THE AGS SLOW EXTERNAL BEAM*

L.N. Blumberg, M.Q. Barton, G.W. Bennett, J.D. Fox, J.W. Glenn, H.C.H. Hsieh, R.J. Nawrocky, and A.V. Soukas
Brookhaven National Laboratory
Upton, New York

Summary

The internal beam of the Brookhaven AGS has been extracted by exciting the third-integral non-linear resonance, a horizontal tune of \( \nu_H = 8.2/3 \). The extraction efficiency is approximately 80% and the spill duration \( \sim 300 \) to 400 ms. The beam has been extracted over the energy range \( 20 \) to \( 29 \) GeV. Preliminary measurements of horizontal and vertical emittance give \( \epsilon_H \approx 0.036 \pi \text{ in.-mrad} \) and \( \epsilon_V \approx 0.09 \pi \text{ in.-mrad} \). Intensity modulation of the spill is presently about 40%.

I. Introduction

The need for an external beam of long duration (hundreds of milliseconds), high extraction efficiency, small emittance and large duty factor to improve capabilities for counter experiments at high-energy synchrotrons has long been recognized. Initial calculations of Hereward\(^4\) on extraction from synchrotrons by exciting resonant growth of betatron oscillation amplitude led to the development of the CERN PS slow external beam\(^5\) (SEB) at the integral resonance \( \nu_H = 6 \). For the Brookhaven AGS Barton\(^3\) proposed nonlinear third-integral resonance extraction at the horizontal tune \( \nu_H = 8.2/3 \) which corresponds to the \( \nu_H \) value of the unperturbed AGS near the center of the AGS aperture. The resonance is stimulated by a configuration of four sextupoles separated azimuthally by \( 90^\circ \) and of alternating polarity to provide a nonlinear perturbation containing a 26th harmonic force term in the radial equation of motion

\[
x'' + \nu^2 x = Ax^2 \cos \theta, \quad \nu = \nu/3.
\]

Detailed numerical calculations\(^4\) using the AGS ray-trace code BEAM\(^2\) established the required sextupole strength, position and strength of ejection magnets, orbit deformation to displace the beam toward the ejection magnets, and the trajectory and emittance of the external beam. Resonance extraction based on this design was first accomplished in March 1968 and the beam has since been successfully utilized in the AGS experimental physics program. The purpose of this paper is to describe some features of the beam performance such as spill modulation, emittance and extraction efficiency.

II. Description of SEB Components and Method of Extraction

The configuration of extraction components in the AGS ring is indicated in Fig. 1. A two-stage ejection system is used consisting of a thin-septum \( (0.030\text{-in.}) \) magnet located in a short \( (5\text{-ft}) \) straight section at a lattice position for which the horizontal \( \beta \)-function is maximum, and an ejection magnet \( (0.25\text{-in. septum}) \) in an adjacent long \( (10\text{-ft}) \) straight section about \( 1/2 \) of a betatron wavelength \( (\lambda_B) \) from the septum. The septum magnet is capable of maximum dipole strength of \( 0.9 \text{ kG-m} \) with a 13% duty factor and the ejector magnet of \( \approx 20.3 \text{ kG-m} \) with 25% duty factor. The magnets and associated power supplies are described in detail elsewhere.\(^b\)

The orbit deformation required to displace the beam by approximately \( 1.5 \text{ in.} \) at the septum position is obtained by powering backleg winding coils on four pairs of AGS magnets, each pair separated by \( \frac{\lambda_B}{2} \) to produce a \( 3/2 \lambda_B \) bump configuration. The septum and ejector magnets. All parameters of the beam are controlled from a specially designed console in the AGS main control room shown in Fig. 2. Power supplies are triggered on and off at adjustable times relative to a master clock which in turn is gated by externally controlled relays. The SEB can thus be selected on predetermined AGS cycles. This feature is utilized operationally to provide alternate pulse sharing between the external beam and internal targeting.

The sextupole, backleg winding, septum and ejector magnets are energized shortly after the start of the "flattop" phase of the AGS current cycle. The equilibrium orbit of the beam at this time is located approximately \( 0.3 \text{ in.} \) inside of the resonance radius. The flattop slope is adjusted so that the beam drifts radially outward toward the resonance. As the beam tune approaches \( \nu = 8.2/3 \), the stable region (separatrix) in the horizontal phase plane shrinks. Particles outside the separatrix execute oscillations of rapidly increasing amplitude and move outward along the three asymptotes associated with the separatrices. The flattop slope is adjusted so that the beam drifts radially outward toward the resonance. As the beam tune approaches \( \nu = 8.2/3 \), the stable region (separatrix) in the horizontal phase plane shrinks. Particles outside the separatrix execute oscillations of rapidly increasing amplitude and move outward along the three asymptotes associated with the separatrices. The calculated coordinates of a typical particle are shown for successive turns around the machine. It is seen that the separatrices are favorably located at this azimuth for efficient extraction through a septum located radially outside the resonance radius, and the change in position of the particle along the asymptote for every third turn (the "solenoidal phase") is seen to increase rapidly to \( \sim 0.3 \text{ in.} \) at the septum position. Thus, the extraction efficiency is expected to be \( \sim 90\% \).

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†Present address: Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany.
The duration of the spill is influenced by the flattop slope as well as the momentum spread of the circulating beam. In practice, it is found necessary to increase the momentum spread from the intrinsic \( \Delta p / p \approx 0.1 \% \) to approximately 0.5\% to enhance de-bunching of the beam and suppress rebunching which results from beam-cavity interactions and negative-mass instability. The momentum spread is introduced by a phase change of approximately 170° in the RF accelerating voltage at 2.3 ms (\( \pm \frac{1}{3} \) of a synchrotron oscillation period) prior to RF turn-off. The momentum spread results in a radial spread in equilibrium orbits of about 0.3 in. and a \( \Delta p / p \approx 0.08 \) spread of about 0.1 \( \ell \). Consequently, only a small fraction of the AGS beam is affected by the resonance at any given time since, as indicated in Fig. 3, the instantaneous momentum "bite" in the extracted beam is only \( \approx 0.01 \% \) (corresponding to a resonance width of \( \Delta p / p \approx 0.001 \)). The rate of spill is thus more readily controlled than would be the case for a monoenergetic beam.

The large spread in \( \psi \) values, however, introduces complications in locating the beam at an optimum initial horizontal and vertical tune. Measurements of the AGS tune for various energies (typically the beam operates at flattop start time \( \psi \approx 940 \) ms with \( p \approx 29 \) GeV/c), the \( \psi \) operating point is outside of the \( \psi = \psi \) coupling. Further, the measurements indicate that with the \( \Delta \psi \) spread cited above, part of the beam could be affected by the coupling resonance \( \Delta \psi + \psi = 26 \) which is avoided by the SEB sextupole configuration. Indeed, we were initially unable to extract the beam with good efficiency for momenta \( \geq 28 \) GeV/c and observed on scintillating screens tilted beam spots of irregular shape and with anomalously large vertical size at these energies. It was therefore necessary to energize the 12 horizontal and vertical AGS high-field correction quadrupoles to shift the initial tune to a point between the \( \psi = \psi \) line and the \( \psi \) = 8-2/3 resonance line. For typical operating conditions we obtain \( \psi \) shifts of \( \Delta \psi \approx 0.10 \) and \( \Delta \psi \approx 0.04 \).

III. Comparison of Calculated and Measured Parameters

Considerable effort was devoted to optimizing magnet positions and currents to obtain maximum extraction efficiency. We first adjusted the initial radius of the beam, the magnitude and time of the RF phase shift, the RF turn-off time, and the slope of the AGS flattop to obtain a qualitatively good spill. Then, our procedure was to fix the radial position of the thin septum magnet at the calculated value of Fig. 3, vary the septum angle and current for maximum transmission, adjust the radial position, angle and current of the ejection magnet, and then vary the current in the sextupole magnets and back-leg winding coils for maximum external beam. The instrumentation used to detect the beam are fluorescent screens, secondary emission chambers, ion chambers, counter telescopes, lucite Cerenkov counters, and insulated plate signals. The SEB instrumentation is described in detail elsewhere. Results of the angle variation of the septum magnet are given in Fig. 5. Maximum transmission is obtained for a septum angle of 1.5 mrad relative to the straight section axis rather than the \( \approx 1 \) mrad indicated by Fig. 3 calculations. Moreover, the variation of extraction efficiency with angle is greater than would be expected for an 0.03-in. septum and a calculated particle "jump" of \( \approx 0.3 \) in. A resurvey of the coordinates and flatness of the septum have not indicated the cause of these discrepancies. Also in Fig. 5 are results of the position variation of the extraction magnet. Here the results are in good agreement with calculations. The beam loss on the ejection does not vanish for the optimum magnet position due to scattered interaction in the septum magnet as discussed in Sect. V. In Fig. 6 the variation of sextupole current indicates good agreement with the calculated 185 A. Also in Fig. 6 we show the measured orbit deformation at the septum azimuth and note that the current required to produce this deformation is greater than estimated from the ratio of back-leg winding to AGS coil ampere-turns. In Fig. 7 the beam loss on the septum magnet is given as a function of position of a 1-cm-long tungsten shadow target located one straight section upstream of the septum. The shadow target position and radial extent of the beam are in good agreement with calculations. Note that the shadow target increases the extracted beam by \( \approx 3 \% \) and decreases the septum losses by a factor of 2.

IV. Emittance

The external beam emittance has been measured by comparing the width of the beam profile at an external target for three different settings of a quadrupole lens located upstream of the target position. Assuming that the phase plane contours are ellipses of the form

\[
\gamma x^2 + 2n xy + n y^2 = \varepsilon,
\]

the emittance \( \varepsilon = \pi \varepsilon \) and the ellipse parameters \( \alpha \) and \( \beta \) can be related to measured half-widths \( w_1 \), \( w_2 \) and \( w_3 \) by the expressions

\[
\sigma = \frac{a}{2} \left| \frac{A}{S_{23}} \frac{B}{S_{13}} \frac{C}{S_{12}} \right| \\
\gamma = \frac{\frac{A}{S_{23}} \left| S_{23} \right|^2 - \frac{B}{S_{13}} \left| S_{13} \right|^2 + \frac{C}{S_{12}} \left| S_{12} \right|^2}{2 \lambda^2 S_{13}^2 S_{23}} \\
\text{where } A = (W_1 S_{23})^2, B = (W_2 S_{13})^2, C = (W_3 S_{12})^2
\]
and the quantities $S_{ij} - S_i$ are differences in the quadrupole strength parameter $s$ at 1/GeV. At beam momentum $p = 25.9$ GeV/c we obtain $S_i = 0.036 \, \text{in.-mrad}$ and $S_i = 0.090 \, \text{in.-mrad}$. The vertical emittance is about 2.5 times larger than the vertical AGS acceptance $S_i = 0.036 \, \text{in.-mrad}$ at injection to 25.9 GeV/c. The calculated acceptance contains what tilted, even when $v$-shifting is employed to secure the beam spot for momenta $29$ GeV/c. We have also calculated 11 the AGS acceptance $S_i = 0.036 \, \text{in.-mrad}$ at injection to 25.9 GeV/c. The measured horizontal emittance is again about 2.5 times larger than indicated by the calculations of Fig. 3, which in turn assume a horizontal emittance for the AGS internal beam approximately 1.3 times larger than the adiabatic $S_i$ scaled from the calculated AGS horizontal acceptance at injection of $\approx 9 \, \text{in.-mrad}$. The calculated acceptance contains corrections for closed orbit deformation, sagitta and synchrotron oscillation amplitude. Emittance measurements at $p = 29$ GeV/c based on Eqs. (3) were unsuccessful, presumably due to distortion of the emittance contour by coupling of vertical and horizontal motion in the AGS as discussed in Sect. II. The beam spot for momenta $\geq 29$ GeV/c is still somewhat tilted, even when $v$-shifting is employed to avoid the $\psi = \psi_0$ coupling.

The unexpectedly large emittance resulted in beam scraping at apertures in the external optics and this caused objectionable background for experiments. Subsequent modifications in the optics to increase the acceptance of the external channel reduced the background to an acceptable level for counter experiments. 13 We have also attempted to understand the source of the emittance discrepancy by study of beam profiles at various locations in the optics system. A horizontal profile obtained at a position three AGS magnets downstream of the septum magnet is given in Fig. 8 and illustrates that the beam width is $\approx 1.5$ times larger than predicted by calculations based on the emittance in Fig. 3. This measurement suggests that scattering from the 0.030-in. septum contributes to dilution of the external emittance. However, Monte Carlo calculations 14 of the beam distribution, which consider both multiple-coulomb and diffraction scattering in the septum and take account of the nonuniform vertical and horizontal phase space density distribution at the septum, indicate that scattering contributes a negligible amount to beam width. We are presently installing an array of segmented-plate detectors 15 and computer-assisted readout for rapid acquisition of profile data to study the effect of various SEB parameters on emittance and obtain nearly instantaneous pro-
files rather than the time-averaged data of our present measurements.

V. Extraction Efficiency

Polyethylene, Al and Au foil activations 16 have been used to measure the integrated proton beam at an external target position. Intercomparison of results from these irradiations indicate satisfactory agreement between the three foils and we have subsequently relied on polyethylene for the efficiency determination. Annihilation gammas from $^6$Li produced in the $^6$Li$(p,pn)^6$Li reaction are counted in a calibrated wall-counter and compared to the integrated circulating beam measured by the AGS current monitor. 17 The full irradiation techniques are discussed in detail elsewhere 18 and only results are quoted here. The highest extraction efficiency measured by this method was 71% at 21 and 29 GeV/c. We do not observe a significant change in efficiency over the momenta range 21-30 GeV/c. A secondary emission chamber was also calibrated against the polyethylene data and is used as the operational efficiency monitor. We have also measured the SEB extraction efficiency relative to the AGS fast external beam by extracting the circulating beam in a single-turn mode into the SEB channel. After small corrections for observed losses the fast beam extraction efficiency measured by the polyethylene activation method is 86%. Thus, the slow external beam efficiency relative to the fast beam is 83%. The disagreement between the relative and absolute SEB efficiencies are outside the error limits expected from the $\pm 5\%$ uncertainty in the $^6$Li$(p,pn)$ cross section and the $\pm 2\%$ calibration 19 of the beam monitor.

We have also calculated the expected efficiency of beam transport from the septum magnet to the foil irradiation position using a Monte Carlo method as discussed in Sect. IV and known external beam apertures. The results are summarized in Table I. The calculated efficiency is in reasonable agreement with the relative SEB efficiency measurement.

### TABLE I

<table>
<thead>
<tr>
<th>Location</th>
<th>Efficiency</th>
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<tbody>
<tr>
<td>On thin septum magnet</td>
<td>8.5%</td>
</tr>
<tr>
<td>On ejection magnet</td>
<td>7.1%</td>
</tr>
<tr>
<td>Inside AGS</td>
<td>2.9%</td>
</tr>
<tr>
<td>On external beam apertures</td>
<td>0.2%</td>
</tr>
<tr>
<td>On target</td>
<td>85.3%</td>
</tr>
</tbody>
</table>

Beam loss on ejection components presents a serious radiation hazard to maintenance personnel and results in objectionable radiation damage to components. We are therefore designing a more efficient ejection system based on a thin ($\approx 0.003$ in.) electrostatic septum located upstream of the present septum magnet.

VI. Spill Modulation and Control

The usefulness of the beam for counter experiments is largely determined by the quality of the spill. Modulation of the beam affects experiments both in decreased duty factor and increased chance coincidence rate. The principal source of modulation in the AGS slow beam has been current ripple in the main magnets which causes fluctuations in the beam position relative to the resonance radius and thus undulation of the separatrix of Fig. 3. The fundamental ripple frequency of 720 Hz from the 12-phase rectifier of the main magnet power supply is attenuated by an electronic filter. 19 Subharmonics which result from mistiming of the rectifier firing angles are monitored and minimized by a specially designed orthogonal correction network. 20 Beam modulation from residual ripple is further reduced by a spill servo in which a beam-derived signal is fed back to the main power supply voltage regulator. This circuit and other beam-control devices are discussed in detail.
The bandpass of the spill servo is intentionally small (~50 Hz) to avoid interaction with the electronic filter. A computer-generated program which utilizes spill data from the preceding pulse has also been used and found effective in controlling pulse-to-pulse uniformity. For higher frequency corrections a signal derived from an AGS magnet backleg winding is used to program the current in an AGS quadrupole and thereby modulate the machine tune. Other sources of current ripples can also affect the spill through external sources and current power supplies. We have observed that ripples in the horizontal quadrupole current results in the highly modulated spill of Fig. 9. Also in Fig. 9 is an example of the ~40% modulation which can be attained for an ~350 ms spill when the control devices cited above are used.

Modulation at RF frequency has been studied by an experimental group using the slow beam. They compare the prompt chance coincidence rate from secondaries produced at the SEB target to chance coincidences with one counter delayed by 120 ns (~3 period of the 4.455 MHz final AGS RF frequency). They find that the structure diminishes during the first 50 ms after RF turn-off to about 1%. Structure at other frequencies is not reproducible from pulse to pulse.

We have also observed a component of the spill which appears after the main spill. This "satellite" coincides in time with the loss signal observed when the sextupoles are not energized. We thus associate the satellite with particles that drift through the resonance radius without a sufficient growth in betatron amplitude for extraction. Maschke and Symon find that the satellite loss is proportional to $\frac{v}{f}$, where $v$ is the average rate of change of $v_\perp$ as the beam drifts through the resonance and $f$ is the ripple frequency. Our observations confirm that the satellite diminishes as the flattop slope is decreased. We also find, by gating external beam monitors, that the extraction efficiency is smaller for the satellite than for the main spill. Further, the satellite is ejected on a different trajectory and is lost preferentially on external beam apertures; it is not visible at the SEB target.

VII. Acknowledgements

The slow external beam has been a major effort of the entire Brookhaven Accelerator Dept. and as such has involved more people than could be properly acknowledged here. We would, however, like to express our gratitude to several individuals who contributed importantly to the success of this project. We are grateful to Dr. A. Maschke for the design of the external beam optics and numerous important suggestions on the construction program; to Mr. E.B. Forsyth for design of power supplies and flattop controls; to Mr. R.L. Cassel for design of power supplies and flattop controls; to Dr. G. Levine for contributions to the beam instrumentation; to Dr. T. Toohig for important suggestions on the beam optics and to Mr. J. Gabusi for design of the operational under-switching system and work on the flattop controls. Mr. F. Pallas designed the backleg winding coils and special straight sections, Mr. J. Schuchman designed the vacuum system and Mr. R. Dryden directed the vacuum system installation. The SEB control console was designed by Mr. J. Curtiss and the computer interface equipment was designed by Mr. R. Frankel. We thank Mr. R. Warkentien for numerous optics calculations and Mr. F. Schneider for construction of the many devices in the external beam instrumentation. The efforts of Mr. G. Cottingham in design and improvement of the flattop controls have resulted in the good quality of the present spill. Mr. W. Gaters has ably directed the maintenance effort on SEB equipment. We gratefully acknowledge the efforts of Mr. J. Grisoli who directed the mechanical design of all of the slow beam components.

References

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Fig. 1. Configuration of AGS ring components for slow external beam.

Fig. 2. Slow beam control console.
Fig. 3. Calculated separatrix and trajectory of unstable particle in the radial phase plane at straight section F5.

Fig. 4. Measured horizontal and vertical AGS tunes for various radial beam positions and times in acceleration cycle. E.C. Raka, ANS-DIV 67-5.
Fig. 5. Top: Transmitted beam through the F5 septum magnet as a function of septum angle. Bottom: Transmitted beam through the F10 ejection magnet as a function of magnet radial position.

Fig. 6. Top: Extracted beam as a function of current in the SE5 sextupoles. Bottom: Measured orbit deformation as a function of current in the backleg winding coils.
Fig. 7. Top: Extracted beam as a function of radial position of a 1 cm x 0.03 in. hemispherical target in straight section F4. Bottom: Beam loss on F5 septum as a function of shadow target position.

Fig. 8. Measured radial profile of slow beam at straight section F8.

Fig. 9. Spill signals, 50 ns/div. Top: Insulated plate sum signal at end of experimental channel and, below, C5 correction quadrupole current. Bottom: Modulated spill detected by R20 Cerenkov counter when ripple is present in horizontal quadrupole current.