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# 1.5 GeV/c MULTITURN SHAVING EXTRACTION AND ITS TRANSPORT LINE FOR THE BROOKHAVEN AGS*

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## Summary

A system for fast shaving extraction at 1.5 GeV/c is implemented to extract the circulating beam in five turns. A numerical simulation is first carried out to determine the emittance and the rf structure of the extracted beam. This is followed by several machine study sessions which establish the optimal extraction configuration, confirm the emittance, and modify the transport line for low energy beam. Finally, a one-week run for the "Neutrino Oscillation" experiment demonstrates that the system is very stable and capable of delivering 7.5 x $10^{12}$ p/sec with 70% extraction efficiency and 95% transport efficiency.

## Introduction

Experiment 704/706--A Study of Time Evolution of a Long Lived $\nu_\mu$ Beam--requires extraction of 1.5 GeV/c protons into the Fast External Beam (FEB) channel at an intensity of 5 x $10^{12}$ ppp with rep. rate of 1.7 per sec and preferably with all the particles arriving within 10 to 15 μsec. A fundamental problem confronting us in this attempt is the large beam size at such low energy. A simple scaling from the adiabatic relation, $\varepsilon p$ = constant, shows that the beam size is even larger than the physical aperture of the E10 septum magnet (SM) and H10 ejector magnet (EM). Therefore, a multiturn shaving scheme is proposed to slice the beam for extraction and reduce the horizontal emittance of the external beam. Vertically, the scheme selected is to scrape the beam by a vertical internal target (J19) to reduce the beam size within the 1 in. vertical aperture of extraction magnets. Although this is a completely new mode of operation at the AGS, the decision is to achieve the goal by using the existing high energy extraction configuration, components, and transport system making minimal necessary modifications and/or additions.

## The FEB Arrangement

The set-up of the AGS high energy fast extraction system is shown schematically in Fig. 1.[1]

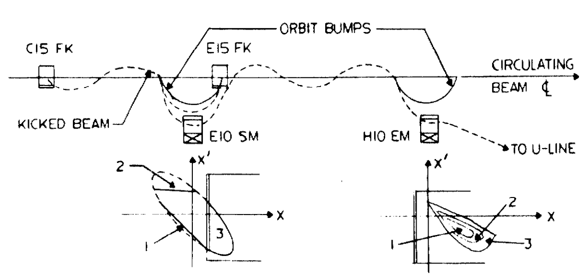


Fig. 1. Schematic layout of the fast extraction configuration and multiturn shaving at E10 SM.

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Two ½λ local orbit deformation bumps are created about 5 msec before extraction to move the beam as close to E10 SM and H10 EM as possible. At extraction, the C15 kicker magnet (KM) is turned on to move the beam into the E10 aperture to receive an additional kick to reach H10 aperture and finally to get deflected out of the ring by H10 ejector. Those parts of the beam which do not reach into E10 SM aperture will receive a correction kick at E15 to park them back on the unperturbed equilibrium orbit to be kicked again when they reach C15 the second time around.

For one-turn extraction, an ideal kicker should be able to rise to its full strength between bunches in order not to generate any losses on the septum magnet. For the AGS, the bunch separation is about 200 nsec. But for multiturn shaving extraction, we do not want to kick the whole beam out in one turn. Here the goal is to shave the beam from the circulating flux to give as a uniform distribution as possible and to reduce the external beam emittance as much as possible. Therefore, an ideal kicker for multiturn shaving extraction is one in which the strength can be controlled at an interval of the revolution time $T_R$ (3.17 μsec) of the protons in the AGS. With existing kickers at the AGS, the best we can do is to lengthen the risetime of the kicker and use the first quarter of a sinusoidal waveform to kick the beam out. Since the length of the spill is limited by the focusing horn to be within 10 to 15 μsec, the half period the sinusoidal supply should be larger than 40 μsec. It is better to use the linear part of the waveform; therefore, the actual half period tried is 60 μsec which is shown in Fig. 2. At the straight section (s.s.) of H13 the separation of the extracted beam with that of the circulating beam is about 17 in. and the fringe field from the main magnet is negligible; hence, it is considered as the end of extraction and the beginning of the external beam transport line (the U-line).

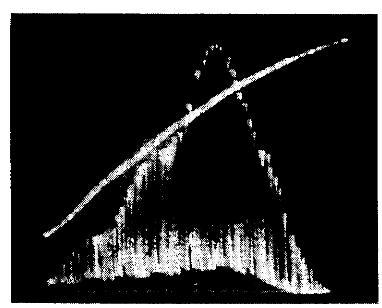


Fig. 2. Spill structure superimposed on the waveform of C15 kicker.

## Numerical Analysis

Since there is no theory capable of predicting the emittance of a multiturn-extracted beam, a numerical simulation program is set up to trace the particles one by one from inside the ring all the way to the entrance of the U-line.[2] It is assumed that the particle distribution in the horizontal phase plane can be reasonably represented by a two-dimensional Gaussian distribution and the equal density contours are concentric ellipses in the phase plane. A test particle is defined by three coordinates (x, x', t) where x and x'



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are obtained by calling a random number generating routine Gauss ($\sigma$). The ensemble of all the random numbers generated by this routine forms a Gaussian distribution about the origin with a standard deviation $\sigma$. Then each particle starting at C15 with coordinates x and x' receives a kick proportional to K sin ($2\pi/T_R$ t) and its trajectory is traced through the lattice, E10 SM, and H10 EM respectively to reach H13. The particles arrive at H13 with new coordinates ($x_1$, $x_1'$, $t_1$). The ensemble of all the particles extends over 15 μsec in time. Spatially they are 40 to 50 pieces shaved 5 to 6 times from 12 bunches inside the ring. The shape of each piece is very much irregular, however, the time projection of them falls into a finite region in horizontal phase space. A least square fitting routine is then used to determine the emittance which best represents the extracted beam.

The analysis is performed for four different types of kick at C15. The first three are sinusoidal waves with half period 40, 60, and 80 μsec respectively and the last one is a ladder type kick whose strength is kept constant in one revolution $T_R$. (The strength of the ladder kick from turn to turn can be adjusted to give a best choice on the spill distribution and final emittance.) The ladder kick gives the best emittance. For the case of sinusoidal kicks, the longer the half period the better.[2] The parameters of the AGS extraction components used in the simulation study is listed in Table I. For the calculation we also assume

Table I. Specifications of Extraction Components

| | C15,E15 KM | E10 SM | H10 EM |
|---|---|---|---|
| Aperture | 3"Vx6"H | 1"x1.37" | 1"x2.47" |
| Deflection | 3.0 mrad | 3.2 mrad | 1.8 mrad |
| Half Period | 60 μsec | 200 μsec | 1.4 msec |
| Septum Thickness | | 0.01 in. | 0.09 in. |

that at the extraction the machine has horizontal tune $\nu_x = 8.67$ and vertical tune $\nu_y = 8.77$. During actual operation we measured the tunes to be $\nu_x = 8.65$ and $\nu_y = 8.79$. The results of the calculated extracted beam characteristics for the 60 μsec half period kicker is given in Table II. The calculated emittance of 7.26 π μm-rad is about five times smaller than that of the circulating beam at 1.5 GeV/c (36 π μm-rad).

As mentioned before, the vertical beam size is larger than the vertical aperture of the E10 SM of 1 in. After the scraping of the beam by the J19 target, we expect the resultant vertical emittance to be 10.63 π μm-rad with 70% of the particles left for extraction. Another source of loss comes from the finite thickness of E10 SM. In Ref. 1, Blumberg et al., calculated

Table II. Beam Characteristics of Low Energy FEB At the Entrance to the U-Line

| | Horizontal | | Vertical | |
|---|---|---|---|---|
| | Calcu- tion | Measure- ment | Calcu- tion | Measure- ment |
| $\varepsilon$ π μm-rad | 7.26 | 11.30 | 10.63 | 8.89 |
| $\beta$ m | 32.5 | 15.0 | 7.47 | 6.62 |
| $\alpha$ | -2.55 | -2.99 | 1.14 | 1.08 |
| $X_p$ | 4.8 m | | | |
| Loss | 25% | | 30% | |
| Spill | 15 μsec (5 turns) | | | |

that the extraction loss on the 0.01 in. septum magnet is about 6% for one turn. Now we have to extract the beam in five turns, the expected loss is 20%. Furthermore, since now the beam is larger than that at high energy, the kick required for the E10 SM to reach the H10 EM aperture gives too large a deflection at E13 where the betatron function is maximum. In order to get rid of the possible losses, we not only enlarge the vacuum pipe here from 6" to 8", but also introduce a local bump to move the beam away from the outside edge of the wall. The overall extraction efficiency is expected to be ≈ 50%.

Another important factor to consider is the rf structure of the extracted beam. According to the simulation calculation, the particle distribution will peak at the third, fourth and fifth turn. It is mainly due to the fact that we are running at horizontal tune close to 8-2/3 and the fact that the waveform of the kicker is linear. With a ladder type excitation of the kicker, we can manage to obtain a more uniform distribution. The final rf distribution is shown in Fig. 2 which is identical with the result of the numerical simulation.

## Emittance Measurement

The values obtained from the numerical analysis are used for initial extraction studies and transport line design. However, to gain confidence in these numbers, experimental verification of the emittance parameters is of the outmost importance. Therefore, we proceed to do emittance measurements after we manage to deliver a reasonable external beam.

Since there are three unknowns, $\varepsilon$, $\beta$, and $\alpha$ in the emittance parameters, in principle, any three independent measurements can give a unique solution. But from our previous experiences, we find it is more reliable to measure a large amount of beam sizes at one location

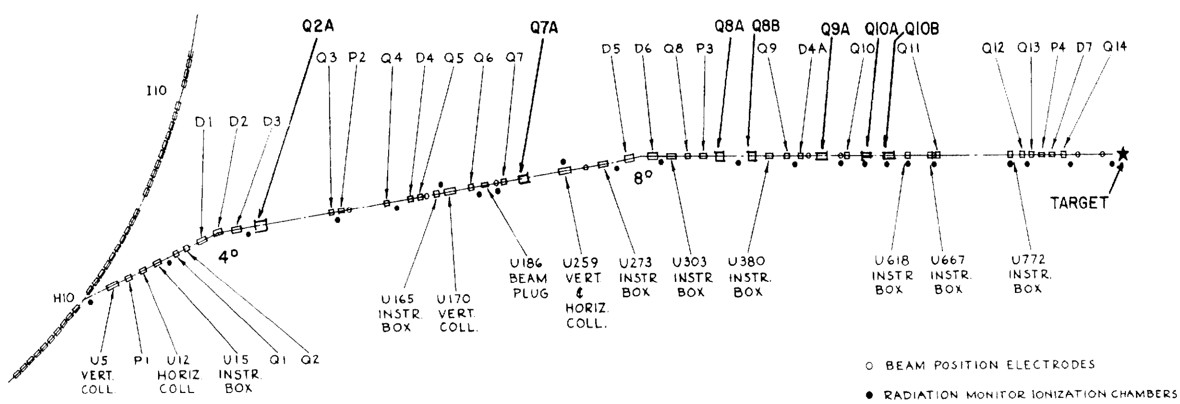


Fig. 3. Plane view of the U-line from the ejector magnet to neutrino production target.

by tuning one upstream quadrupole. For our case, the detector is located at U168 as shown in Fig. 3. The detector used in the measurement is a single-wire secondary emission monitor (SEM) scanner. By changing the strength of UQ3, we can generate different beam sizes at U168. We can only generate a horizontal waist when UQ3 is horizontally focusing. In order to produce a vertical waist, we have to change the polarity of UQ3. For example, a scan taken near the vertical waist condition is shown in Fig. 4. Totally, there are eight points taken in each plane and they are uniformly distributed around the waist as shown in Fig. 5. Assuming that the density distribution is Gaussian, the radius 90% down from the peak is obtained for each scan and used in a FORTRAN program which performs a least square fit to find the emittance parameters at the entrance of UQ3 to best fit the measured radii.

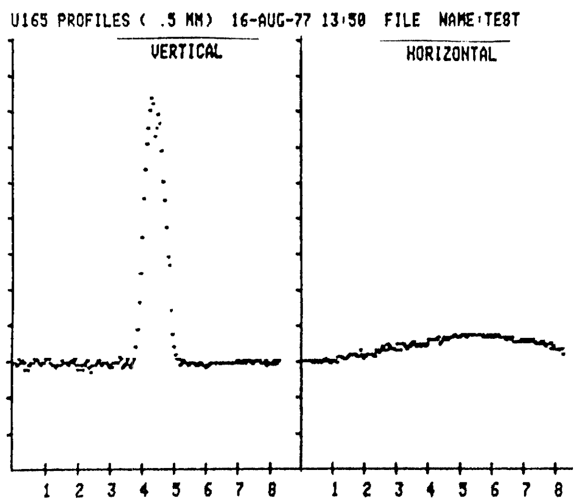


Fig. 4. Beam profile at vertical waist condition.

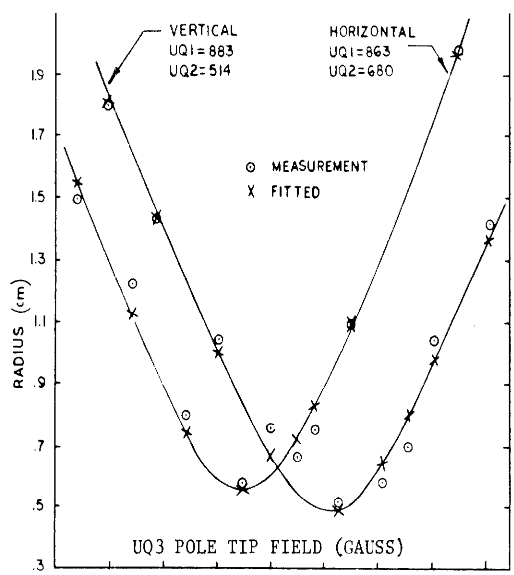


Fig. 5. Beam sizes at U165 as a function of the strength of a upstream quadrupole UQ3.

The fitted results are then transferred back to the s.s. of H13 to be compared with the parameters obtained from calculation. From Table II it is clear that the simulation calculation is reasonable compared to the measured results. Some of the discrepancies can be attributed to the mismatch of the beam introduced by the E15 kicker and the uncertainties of the remnant field of UQ3, UQ4, and UQ5. The measured parameters are used as input to design the final beam transport system.

Undoubtedly, the confidence of the fit increases with the number of points, but it is more important to distribute the measurements evenly around the contour of the phase ellipse. It is also essential that points on either side of the major axis be included, otherwise, the fit is subject to large deviation for small errors in the measurements.

## Transport Line

The size of the existing transport pipe from UQ3 to UQ11 is 4" and from UQ11 to UQ14 it is 8". Using the measured emittance parameters as shown in Table II, the beam envelopes obtained from the TRANSPORT[3] program almost fill up the pipe (see Fig. 6). This is no surprise, since now the emittance of the external beam at 1.5 GeV/c is still four times larger than that at high energy. In other words, the beam size is twice that of high energy beam even after multiturn shaving. It is clear that we are going to suffer beam losses in the transport line if nothing is done to modify the optics.

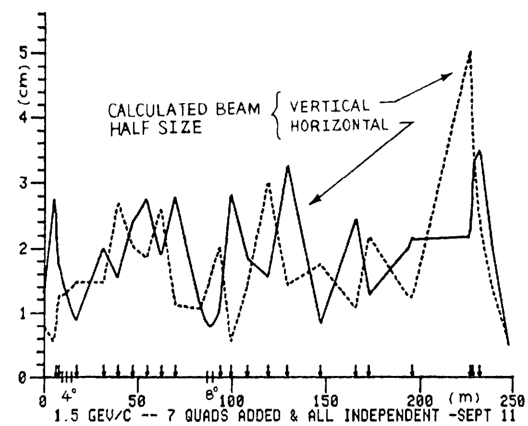


Fig. 6. Calculated beam half size in the U-line.

In addition to the general consideration of a large beam size, of particular concern is the window frame superconducting bending magnet $8^{\circ}$ (see Fig. 3). It has an aperture of 2.25"--the smallest in the whole transport line. In order to avoid risking excessive particle losses in the $8^{\circ}$ bend, a horizontal waist is generated in this region as shown in Fig. 6. The final configuration of the beam transport system for the low energy beam is shown in Fig. 3. Seven additional quadrupoles--UQ2A, UQ7A, UQ8A, UQ8B, UQ9A, UQ10A, and UQ10B--are introducted at the strategic locations to eliminate transport losses. The resultant average filling factor is about 55%.

In attempting to transport the extracted 1.5 GeV/c beam, we are confronted with several constraints. We have to use as much of the existing U-line equipment as possible and we should make it easy to convert from low to high energy operation. Two serious problems becomes evident in an attempt to transport the beam. The first is that the power supplies utilized in the beam line are designed for high energy operation with typical currents of several thousand amperes. A stability of 1 part in $10^3$ is readily achieved, and the resolution (or current stability) is more than adequate. At low energy, all the currents scale down by a factor of 20, implying operation at 30-100 amperes region. Now the sensitivity and stability become unacceptable. For example, the new operating current of the 4° bending magnets is approximately 150 A instead of 3000 A. It is found that the 1 A minimum increment available to us would swing the beam downstream from one edge of the aperture to the other. Therefore, most of the power supplies in the U-line are replaced by smaller units which give required stability and resolution. In addition, to get better control of the beam it is decided to independently power the quadrupoles UQ3-UQ7 and UQ8-UQ9 which are normally powered in series for high energy transport.

The second major problem we encountered is the remnant fields. The remnant fields of most of the quadrupoles are about 20 Gauss. At high energy, this is not a problem at all. But at 1.5 GeV/c, some of the quadrupoles have to run at a low current of 10-20 A which is equivalent to pole tip field of 170-340 Gauss. Therefore, the remnant field is 6-12% of the excitation, apparently, it is not negligible. We first measure the remnant fields of those sensitive quadrupoles, then perform de-gauss treatment to reduce the remnant field to less than 5 Gauss.

Another modification in the U-line is the preventive abort program FMON. Normally, during high energy FEB operation a computer program FMON is utilized to protect the 8° magnet from beam quenches in case any steering or focusing magnet upstream drifts or changes from its set value. This program is modified to include a larger number of units to be monitored.

## Major Modifications in the AGS

Even though it is possible to use the original Siemens motor/generator set as the power supply of the main magnet and achieve energy stability of ¼%-½%, it is certainly very inefficient due to its high losses. An alternate scheme for pulsing the AGS main ring magnets, which had previously been used for injection studies during a Siemens downtime, is to use multiphase, thyristor controlled solid state power supplies. This latter scheme is adopted for operation; therefore, some modifications of connections are made to accommodate a dual power supply arrangement. For higher reliability reason, the units should run at 70% tap which gives us the required energy at a time of ≈ 225 msec. The total pulse time is ≈ 500 msec with short term stability of ≈ ¼% and long term stability of ≈ 1%.

As mentioned before, for multiturn shaving extraction, the pulse width of the C15 and E15 fast kickers has to be extended to ≈ 60 μsec with required peak current at 1200 A. It is achieved by adding capacitance to the energy storage system (12 μF in C15 and 18 μF in E15) and in the case of the E15 power supply, some series air-core inductance is added also. In order to match these supplies, we adjust the capacitance and inductance and trigger the E15 KM ≈ 500 nsec later than C15.

For 1.5 GeV/c extraction, the ejector excitation is about 900 A where the power supply stability is only marginal as evidenced by the extracted beam motion at the U15 flag. To overcome this problem, we have introduced two changes to improve the signal to noise ratio of the voltage feedback divider of the capacitor bank and hence the stability by a factor of ten. These changes are first, the DCN reference range is modified to go lower to 600 A min., and also filtered better and secondly, the divider at the capacitor bank voltage is made 10 to 1 instead of 100 to 1 and also filtered better via a low-pass network at the input of the voltage comparator chassis.

The last item we want to mention is the vertical resistive wall instability. Although the damper was already used as in the high energy extraction mode,[4] after switching to different power supply, we found that the beam was unstable and started to blow up before extraction as shown in Fig. 7a. This was quickly identified and attributed to the fact that now we were running at lower $\dot{B}$, hence faster blow-up rate. This was cured by turning up the gain in the damper and the result was exactly as expected as shown in Fig. 7b.

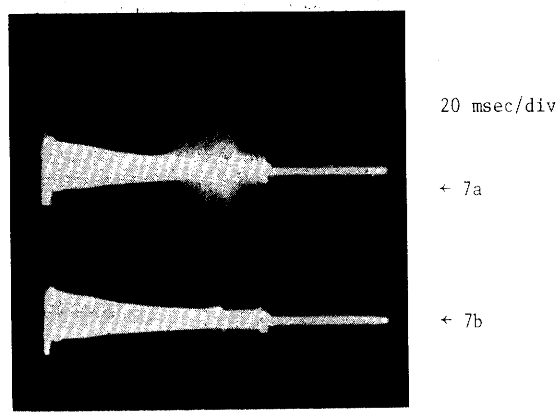


Fig. 7. Radial difference signal at I-7. The gain of vertical resistive wall instability damper is set to be 2.5 and 3.2 respectively.

In conclusion, a multiturn shaving extraction system has been successfully implemented at Brookhaven. It reduces the horizontal emittance by a factor of four to be able to use the existing beam transport line without appreciable losses as shown in Fig. 8.

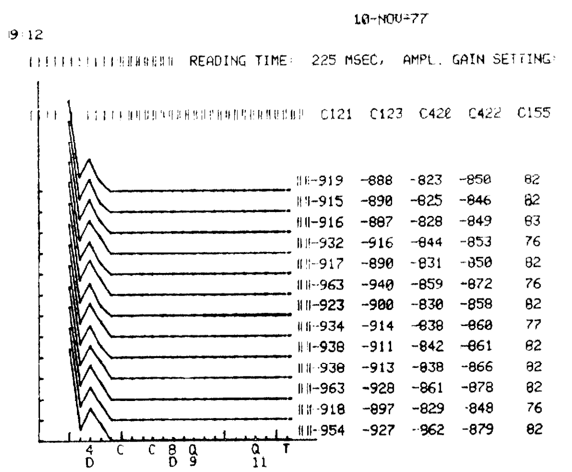


Fig. 8. Radiation loss pattern in the U-line.

## Acknowledgment

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## References

1. L.N. Blumberg, et al., IEEE Trans. Nucl. Sci. NS-18, 1009 (1971).
2. W.T. Weng and L.N. Blumberg, AGS DIV 77-10 (1977).
3. K.L. Brown et al., TRANSPORT, NAL-91 (1974).
4. E.C. Raka, BNL AGS Tech. Note No. 118 (1976).