PERFORMANCE REPORT ON THE POST CONVERSION AGS*

M. Barton, K. Batchelor, L. Blumberg, J. Cottingham, J. Glenn,
J. Grisoli, J. Herrera, A. Maschke, E. Raka, A. van Steenbergen

Brookhaven National Laboratory
Upton, New York

(Presented by A. van Steenbergen)

Summary

The present AGS status and recent performance results are described and details are given regarding the 200-MeV linac injector, multiturn injection, orbit improvements, intensity limitations and longitudinal effects, the bunched fast extraction, the "shaving" mode of fast extraction and the slow external beam switchyard development.

Introduction

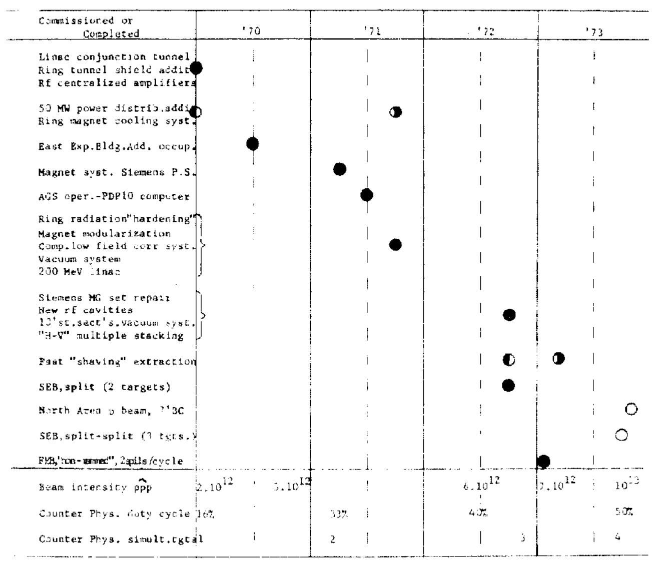
In recent years extensive modifications were made to the Alternating Gradient Synchrotron in order to gradually transform the accelerator into a higher intensity 30 GeV proton facility capable of handling simultaneously a larger number of high energy physics experiments. The per pulse intensity capability has been increased with the commissioning of a 200-MeV linear accelerator injector, the average intensity has been upgraded by means of a new magnet system power supply and rf acceleration system. The AGS ring proper has been modified to tolerate the higher proton fluxes by means of "radiation hardening" of many components and modularization of the ring structure. The use of on-line computers is rapidly being implemented for more efficient and reliable operation, and the external beam systems are being expanded by use of beam "splitters" in order to provide for simultaneous illumination during one machine cycle of 3 of more target stations.

AGS Performance

A summary of the more significant "recent AGS modifications and improvements" is given in Table I. As indicated a peak accelerated beam intensity of 7×10^{12} ppp has been achieved. This was obtained with an injected beam intensity of 40 mA. It is anticipated that the Conversion project intensity goal of 10^{13} ppp will be reached soon with the restoration of the linac injector to somewhat higher intensity operation (while maintaining its present beam quality), commissioning of the 200 MeV debuncher unit and the completion of "vertical-horizontal" stacking studies. Paired with the gradual improvement in AGS peak beam intensity since the commissioning of the new 200-MeV linac in the fall of 1971 has been the increase in weekly average beam intensity, i.e., weekly operational values of $> 5 \times 10^{12}$ ppp average are now readily obtained. In order to improve reliability of operation, the new 200-MeV linear accelerator injector, even though capable of higher intensity operation, is now routinely kept at an operating intensity of 50 mA nominal. This, in addition to recent improvements in AGS ring subsystems, has improved the overall reliability of operations, so that presently the weekly average downtime approaches 10 to 15%. Further improvements are in progress to achieve a better than 90% reliability level. The Conversion project objective of a counter physics duty cycle of 50% is inherently available now for internal target operation, as is shown in Fig. 1a, presently it is limited operationally only because of simultaneous operation with the SEB system, as shown in Fig. 1b, which is limited to a 40% duty cycle associated with the tolerable temperature rise of the slow beam ejector septum. The very significant improvement in simultaneous operation of a number of counter physics targets and the increase in duty cycle is shown in Fig. 2 which indicates past, present, and projected AGS operational modes.

TABLE I

Recent AGS Modifications and Improvements



200-MeV Linac Injector

Even though the linac has reached a peak accelerated beam of 100 mA with a pulse length of 150 μsec, routinely for the past 8 months its level of accelerated beam intensity is kept at ~ 50 mA for reasons of reliability of operation and degradation of beam quality (momentum vs time, ($\Delta p/p$) magnitude and beam transverse emittance) when running significantly in excess of 50 mA. Nevertheless, at this intensity level the AGS has operated consistently at a level of $5\text{-}6 \times 10^{12}$ ppp. The degradation of longitudinal parameters at the higher beam intensity are due to present limitations in the cavity rf drive system, mainly associated with reliable voltage holding of the 8618 modulator tubes. Work is in progress to improve this situation.

Presently, linac performance data are regularly recorded by means of the linac PDP-8 computer system, which is a part of the linac control and monitoring system.[1] An example of this is the computation of transverse phase space values versus beam intensity, calculated from recorded data for, typically, a 750 keV, 150 mA beam. A summary of normalized beam emittances recorded at various energies along the linac is given in Table II. This indicates a transverse phase space growth of a factor of 2 to 3 through the linear accelerator, which agrees satisfactorily with the computed value.[2]

*-Work performed under the auspices of the U.S. AEC.

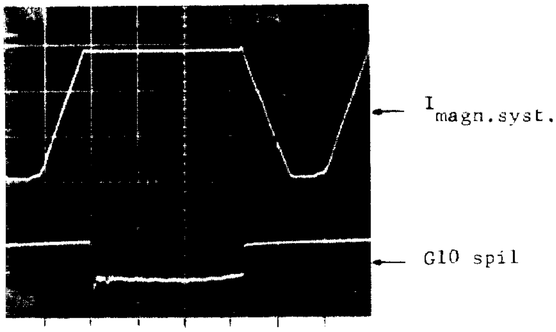
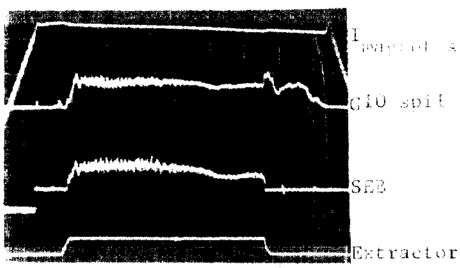


Fig. 1a ⟶ t (0.5 sec/cm)
AGS Internal Target Spil (G10), Duty Cycle 54%



⟶ t (130 msec/cm)

Fig. 1b
Simultaneous Operation Internal Target (G10) and Slow External Beam. Duty Cycle ≈ 40%.

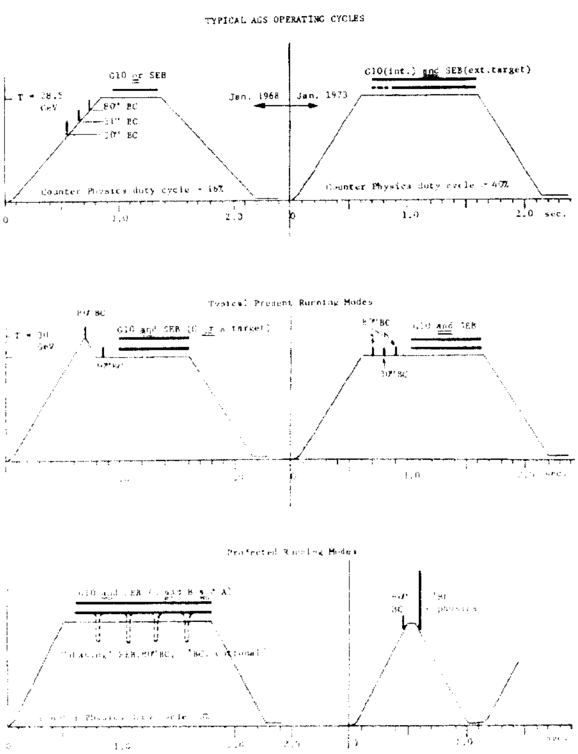


Fig. 2. Typical AGS Operating Cycles.

TABLE II

Beam Parameters Between "Cockcroft-Walton" and AGS Inflector

Location	Energy	Intensity	Normalized Emittance (H/V)
C-W	750 keV	225 mA	($\beta\gamma A_2$, cm-mrad, 80% I_{tot})
LEBT	" -	150 -	$0.14\pi/0.16\pi$
Linac in	" -	100 -	-
Tank 1	10 MeV	60 -	$0.29\pi/0.29\pi$
Tank 9	200 -	50 -	$0.44\pi/0.42\pi$
"Match"Sect.	" -	40 -	$0.37\pi/0.42\pi$

Early results of beam energy spread, measured at the 200 MeV level, indicated values of approximately 2 MeV, full width, at a current level of 50 mA. In order to reduce this and also the mean energy variation with time the possibility of use of a modified "field law" along the linac was investigated.[3] The linac was designed and set up with a field distribution which resulted in a constant stable phase angle of -32° along the length of the accelerator. The result of the recent computations indicated that a modified field law, which retained the -32° stable phase angle at injection, but allowed for a linear reduction of this to -8° at the output of tank 9, would provide for a phase acceptance which would conform more closely to the longitudinal emittance at any location along the length of the linac, up to beam intensities of 100 mA.

Calculation showed a factor of 2 to 3 improvement in both output momentum spread and also change in momentum due to rf phase or field level changes provided those changes did not exceed ± 1% or ± 1° values, which are attainable with the present field amplitude and phase servos in use on the machine. Subsequently, the cavity fields were set to an approximation to the calculated values and the expected reduction in energy spread was attained so that the current operational energy spread is ~ 1 MeV full width. In addition, the lowered field values, associated with the "linear synchronous phase reduction" field law, resulted in a further improvement of linac reliability.

Further improvement work is in progress. Remote operation, by means of an AGS PDP-10—Linac PDP-8 link, is being implemented. Modulator improvements are being made, which, together with the completion of the debuncher should permit higher intensity operation, while preserving good beam quality. Alternatively, the possibility of long pulse, low intensity H^- acceleration with the goal of injection into the AGS by means of electron stripping is being pursued[4] and extensive development work is being done toward an operational, high intensity (≥ 5 mA) H^- source.

Multiturn Injection

Performance of the multiturn stacking process has been significantly improved during the recent period. In addition, by means of a specially designed magnetic inflector unit, the combined mode of "horizontal-vertical" multiturn stacking is now possible also and has already been explored to a certain extent. The details of the multiturn injection into the converted AGS[5] and associated computer programs[5] are presented elsewhere in the Conference Proceedings. The performance of the stacking process is best described by the ratio of circulating beam current, I_c, to linac current, I_L, (taking I_c immediately after multiturn injection completion). Actually, (I_c/I_L) equals the effective number of lossless stacked turns in the AGS. This is given in Table III which illustrates recent performance results. For comparison, equivalent quantities obtained with the earlier 50-MeV linac injector are given.

TABLE III

AGS Multiturn Stacking Performance

	50 MeV Injection	200 MeV Injection	200 MeV Injection
	Jan. '71	Jan. '72	Jan. '73
I_L (mA)	40	40	40
t_L (μsec)	86	48	100
turns	10	10	21
pr/mA turn	$5\ 10^{10}$	$3\ 10^{10}$	$3\ 10^{10}$
N_L (equiv)	$20\ 10^{12}$	$12\ 10^{12}$	$25\ 10^{12}$
N_{st} (AGS)	$10\ 10^{12}$	$7.2\ 10^{12}$	$14\ 10^{12}$
$N_{accel.}$	$3\ 10^{12}$	$2.6\ 10^{12}$	$7\ 10^{12}$
I_c (mA)	336	242	470
(I_c/I_L)	5.0*	6.0	11.7

*Corrected for (β_{50}/β_{200}) ratio.

Orbit Corrections

Correction, by means of the present low field correction system, of the low field orbits has increased the available AGS aperture at injection and thereby increased the AGS intensity capability.[7] An on-line computer program has been developed which calculates the point dipole fields required to correct an observed vertical or horizontal orbit at injection field. With this the vertical closed orbit deviation has been reduced from approximately 2 cm to 2 mm, peak-to-peak values. Similar impressive corrections have been achieved for the horizontal closed orbit deviations.

In contrast to the low field orbit which can be corrected with the "point" dipoles distributed around the ring, the mid-field orbit in the AGS can only be corrected by placement correction of the main ring magnets. In addition, the position of the magnets is determined by optical survey. By using a modification of the orbit correction program, it has been possible to improve the mid-field orbits by only moving those magnets which had the largest placement errors. In this manner, by placement correction of 153 out of 240 ring magnets the peak-to-peak mid-field horizontal orbit distortion has been reduced by a factor of 2 to a 1 cm peak-to-peak value.

Longitudinal Effects

With the commissioning of the Siemens magnet power supply, it became possible to obtain precise programmed $\dot{B}$ variations at injection energy. This has made it possible to approach adiabatic[8] capture conditions. With a $\dot{B}$ .25 T/sec the initial rf gap voltages are increased from a few hundred volts to 3 kV in .6-.8 ms. The relevant injection parameters and the rf capture and early bunching, with these conditions, are shown in Fig. 3. If only a few turns are injected, capture efficiences of $\sim$ 80% have been achieved. At higher intensities (5-7 $\times$ 10^{12}) the efficiency goes down to about 50%. Some of this decrease is due to

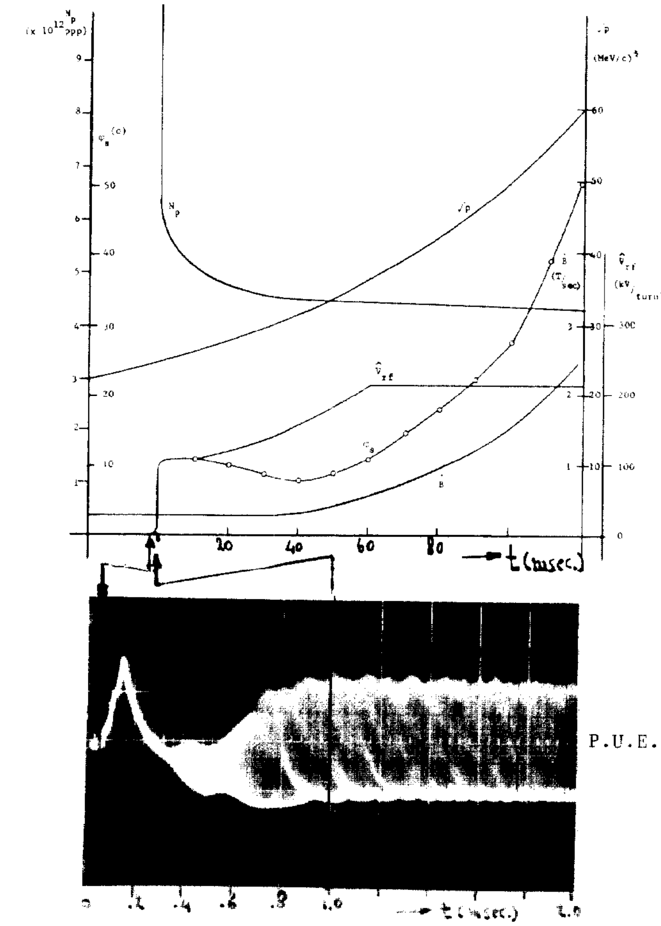


Fig. 3. Injection Parameters and Bunch Formation During "Quasi" Adiabatic Capture.

the aperture being filled by the multiturn process while the rest is most likely due to beam loading effects. A study of these effects and how they may be related to the higher impedance of the new accelerator cavities will be undertaken in the near future.

So far no transverse instabilities have been observed at the highest intensity achieved (7 $\times$ 10^{12} ppp). One contributing factor to this is the improved vacuum in the converted AGS, i.e., $\approx$ 2 $\times$ 10^{-7} torr average.

With the installation and commissioning of the 10 new rf cavities the last major component of the AGS Conversion program was completed. The new cavity configuration presents a somewhat higher impedance to the beam with some noticeable undesirable consequences. The first problem is that of coherent beam loading instabilities such as those reported before.[5] In the old cavities, these were caused by parasitic resonances in the structure. In the new cavities, considerable attention has been given to such parasitic modes to keep the impedance and Q values low. It is possible, however, for this type of instability to develop because of coupling into the main resonance of the cavities. By carefully programming the tuning servos to assure good tuning, the problem does not appear serious.

Further, as the higher accelerated beam intensities are reached, space charge effects at transition become noticeable. This problem has received considerable attention at CERN.[10] Notwithstanding that with the AGS basic parameters, it is less sensitive to this problem than the CERN PS, at the present highest intensities ($> 6 \times 10^{12}$ ppp) considerable debunching and phase space dilution occurs at transition. This problem is further aggravated by the rf waveform distortion due to the high capacitive reactance of the cavities. With the present parameters, the waveform distortion effect is probably comparable to the space charge effect. So far no measures have been taken to correct the bunch mismatch during transition, but it is planned shortly to use the "triple switch" method to provide some degree of correction.

The self bunching phenomena during flat top occurred recently again in a more pronounced fashion. To alleviate this problem the beam is maintained on the "unstable fixed point" for approximately a millisecond just before rf turn-off. The large energy spread which results, stabilizes the beam against instabilities. With the higher cavity impedance present now, the energy spread required for such stabilization is very near the practical upper limits set by spacing of resonance lines when the AGS is run at higher intensities than 5×10^{12} ppp.

Methods of lowering the effective impedance of the rf system are being studied to improve the situation on all of these problems.

Fast Extraction, Single Bunch

During the period of construction and commissioning of the new "shaving" extraction system, continued reliance is placed on the existing single bunch extraction technique to serve the 80-in. bubble chamber program. This system employs a full aperture ferrite fast kicker (L10), a 1.5 mm septum magnet (A10) and a 4-turn ejector magnet (I10). Several modifications have been made to improve reliability and performance capability of these components and reduce beam losses: (1) The fast kicker aperture has been increased to 2-3/4 in. x 6 in. and deuterium thyratrons (EEV CS1168) have replaced the earlier hydrogen-filled tubes, making possible an increase in pulse voltage by approximately 15%. (2) The thickness of the I10 septum was reduced from 27 mm to 19 mm. (3) A second capacitor-discharge power supply was added to I10 to make possible double pulsing operation of the bubble chamber. An example of this operating mode is whereby two bunches are extracted per AGS cycle with a time separation of 200 ms on a 30.8 GeV/c "front porch". When utilized in a mode whereby the AGS was devoted entirely to bubble chamber operation, the double-pulsing method made possible a picture taking rate of $\sim$ 100,000 pictures per day. (4) "Ramming" of the A10 and I10 magnets into the machine aperture prior to extraction, was eliminated in favor of local "fast" orbit deformations centered at the septum and ejector azimuths, thereby improving significantly the inherent reliability of fast external beam operation.

Fast Extraction, "Shaving Mode"

Components for this new mode of fast beam extraction[11], first developed at BNL, have now been commissioned. Presently, extraction studies are in progress for the new North (H10) Experimental Area, where the primary beam transport, the neutrino "horn" and the 7-ft bubble chamber are nearing completion. Design parameters for the extraction components are summarized in Table IV. Briefly, the system consists of two full aperture ferrite core beam kickers, which produce a fast (3 μsec half sinusoid) $3/2\ \lambda$ orbit deformation, with a peak amplitude of 1.2 cm at a long AGS straight section (E10), where a hyper thin (HTS) septum beam deflector unit is located. That part of the beam intercepted by the HTS unit is channeled to a septum extractor magnet (H10). A $\lambda/2$ backleg winding slower orbit deformation, centered at E10 and H10, positions the circulating beam near these septa, prior to ejection. It is expected that up to 4% of the AGS beam will enter the E10 septum aperture in a 2 μsec time interval corresponding to the "window" of the present rf separators. The deflected beam at E10 will enter the aperture of the H10 magnet where it will experience either, a net 3 mrad inward deflection and be subsequently extracted at I10 (see above) for the 80-in. bubble chamber, or, an outward 22 mrad deflection for extraction to the 7-ft chamber. The system is designed for a capability of four such extractions per AGS cycle at 100 ms intervals. Additional capacitor banks are being assembled for the beam kicker power supplies, which then will have the capability of a 10 μsec half sinusoid deformation at E10 of 4 cm amplitude, sufficient to extract the entire AGS beam at H10 in about 5 μsec for the planned neutrino experiments. A likely operating mode will be two fast fractional extractions at I10 followed by extraction of the remainder of the beam at H10.

The external beam transport consists of 16 quadrupoles arranged to produce an achromatic system to first order. The expected beam spot at the production target is 1.5 mm diameter. A novel feature of the transport system is inclusion of two superconducting dipoles, each with 7.5 cm aperture, 1.9 meter effective length, giving a 4° bend at B = 37.9 kG. A prototype has been successfully tested and fabrication of the operational magnets is nearing completion.

TABLE IV

"Shaving" FEB, Component Parameters

Component	Aperture (cm)	Current Time(ms)	Current Peak(A)	$\hat{B\rho}$ (kG-m) or $\hat{\alpha}$	Yoke
C15 + E15 Beam Kickers	7.6 x 15.2	.003 .010	6,000 20,000	.88 2.93	Ferrite
E, H and I Backleg Winding Deformation	AGS Vacuum Chamber	15	1,100	2.13	AGS Magnets 2,3,16,17
E10 Septum Magnet .25 mm Cu	2.54 x 3.49	.4	3,600	1.22	.75 mm M36 Steel Lamin.
E10 Electr. Septum .05 mm SS Foil	1 x 2	DC	120 kV/cm	.4 mrad at 31GeV/c	SS Cathode
H10 Ejector Magnet 2.29 mm Cu	2.54 x 6.27	1 1	21,500 8,000	22.70	.36 mm M36 Steel Lamin.

Slow External Beam

A continuing program of improvement of operational capability of the slow extraction system has been pursued. Extraction efficiencies of 80% and ripple frequency amplitude of 10% peak-to-peak is routinely achieved, with a spill duration of $\sim$ 750 ms. Since the addition of a hyper thin electrostatic septum unit, upstream of the sequence of thin extractor magnet (F5) and thicker septum extractor magnet (F10), did not result in significant increased extraction efficiency, alternative methods are being investigated to improve this, i.e., reduction of high field horizontal-vertical coupling and, possibly, the use of a "Piccioni target". Also, since the present duty cycle is limited to $\sim$ 40% associated with the F10 unit duty cycle limit, a new dc extractor septum magnet is being constructed, with sufficient magnetic shielding to permit excitation during the early part of the acceleration cycle. With the operational commissioning of the shaving mode of fast extraction, simultaneously with slow beam and G10 operation, it will be necessary to interrupt intermittently the resonant blow-up. In addition, the "slow" orbit perturbations (SBLW) have to be countered with "fast" orbit perturbations (FBLW) in order to avoid beam interception during the fast extraction interval. The interrelation of these orbit perturbations is indicated in Fig. 4, illustrating the complexity of simultaneous operation.

With anticipated beam intensities of 10^{13} ppp, rapid progress in the further development of the external beam switchyard is essential. By means of a thin septum, bidirectional field, splitter magnet and, in sequence, two simple 0.5 in. thick, septum magnets, the first stage in simultaneous operation of two external targets has been commissioned. A second beam splitter system is being completed, to be incorporated in the upstream end of the switchyard, so that three external targets can be illuminated simultaneously. This second system makes use of a superconducting beam splitter unit, first of its kind, of which construction has been completed. The basic parameters of this unit are given in Table V. Early tests, in a temporary dewar, have been satisfactorily concluded.[12] Operational tests of the final assembly is in progress.

TABLE V

Parameters Superconducting Beam Splitter

Magnetic Length	1.25 m
Operational Field	15.7 kG
Current	236 A*
Aperture	twice 0.87" x 2.5"
Superconductor	Nb_3Sn
Septum Thickness	0.35 in.
Power Supply	"Flux Pump"

$^{*}(I_c)$ 20 kG, $4.5^{o}K$ = 450 A, $T_c(Nb_3Sn) = 18^{o}K$

For completeness sake, the present arrangement of the AGS internal targets, fast external beams and slow external beam switchyard, with associated experimental facilities and secondary beams is given in Fig. 5, indicating the utilization capability of the post Conversion AGS.

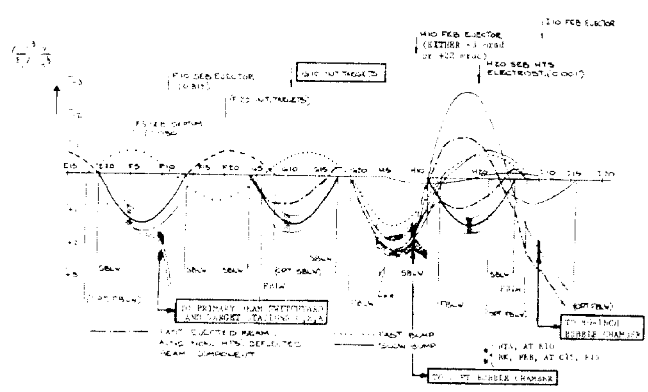


Fig. 4. AGS Orbit Manipulation for Simultaneous Operation of the Internal Target, SEB and FEB Systems.

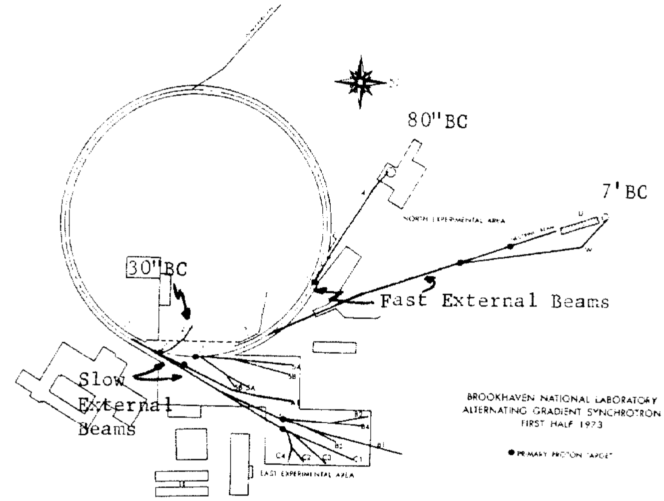


Fig. 5. Present Arrangement of AGS Primary and Secondary Beams.

Acknowledgments

This paper summarizes the work of many of the AGS staff, who assisted in the very pronounced improvements which have been made. The authors wish to acknowledge their contributions categorically.

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