MACHINE OPERATION AT THE BROOKHAVEN ALTERNATING GRADIENT SYNCHROTRON*

R.R. Adams, W.F. Gefers, and J. Spiro
Brookhaven National Laboratory
Upton, L.I., N.Y.

Summary. A description is given of the experimental facilities available at the 33 billion electron volt Alternating Gradient Synchrotron (AGS). Using complex beam gymnastics to spill beam on several targets, it is possible to run simultaneous experiments at a number of energy levels. The logistics in planning and setting up experiments are discussed and a summary of machine operations for the year 1964 is presented. Improvements to increase the beam intensity, reliability, and flexibility of the machine are outlined.

Experimental Operations

Facilities.

Fig. 1 shows the plan of the AGS complex. There are four general areas in which the experimental program has been carried out: the East Area, the West Area, the North Area, and the Southwest Area. Present target locations are at F10, F20, G10, G20, and I10.

The East and West Areas, with 83,000 sq ft of enclosed floor space, house most of the experimental beams. A secondary beam generated on the F10 target has provided an intermediate ($P_{max} \sim 2.7$ BeV/c) momentum separated beam for the 20-in. bubble chamber. A low ($P_{max} \sim 950$ MeV/c) momentum separated beam generated from the F20 target has been used by the 30-in. bubble chamber. The G10 target is the source for many counter experiments located in both East and West Areas. As many as five prime experiments, several test beams, and secondary experiments have run simultaneously from this source. The G20 target is used for radiochemistry experiments.

A high momentum ($P_{max} \sim 8.5$ BeV/c) separated beam, located in the North Area, is used by the 80-in. bubble chamber. This beam is, thus far, the most complex ever erected at the AGS and it consists of two "triplets" (i.e. groups of three) dc beam separators, collimators, steering and focusing magnets, and counters along its length of 460 feet.

The Southwest Area was established as a neutrino physics facility. The circulating beam is extracted in one revolution from the machine by means of three successive kicks generated in turn by a fast kicker located at L10, a septum magnet located at A10, and an ejector magnet located at B10.[1] At this point, the beam must be raised some 10 ft because of the difference in elevation between the tunnel and the experimental area. Standard optics are used to accomplish this and deliver the proton beam on target.

Targeting.

The techniques developed for the system of multiple operation have required some rather sophisticated beam manipulation involving close control and adjustment of the beam radius, rapid beam deflection, magnet flat-top control, and rf turn-off by a hall probe field marker, all in conjunction with precise target flipping.

Targets. Many types of targets differing in material, shape, and size have been in use, with new ones constantly being produced, to accommodate the experiments depending on wanted particle yield and length of spill. The principle materials used have been aluminum, beryllium, and tungsten. For special requirements, however, more exotic materials have been used.

The shape and size of targets vary from large blocks one in. sq cross section and four in. long, to small targets made of 30 to 40 mil wire. Airlocks exist at all target locations to permit rapid changes to be made with minimum machine downtime. A programmed control erects the target in 50 milliseconds, holds it in position as required, and drives it down in 50 milliseconds. The entire target assembly can be remotely positioned, radially, to an accuracy of five mils.

Radius Control. A radius shift control, with multiple channels, is used to position the accelerated beam for targeting at different radial positions as required by beam transport optics. It operates on the bootstrap radio-frequency system by capacitive imbalance of the radial pickup electrode. By imbalancing either one or the other half of the electrode, the beam is moved as much as 1" inside or outside of the normal beam orbit. A time constant of fifty milliseconds is built into the radius shift control to prevent excitation of phase oscillations in the beam.

Rapid Beam Deflectors. Bubble chambers require beam spill lengths ranging from 20 to 200 microseconds. Small and rapid deflections of the beam, already positioned by the radius control, is accomplished by the rapid beam deflectors (RBD), which cause the beam orbit to be warped into a target with a switched high current discharge from a capacitor bank into a coil of a few turns.

Flat-top Control. Counter experiments require beam spills of several hundred milliseconds duration with no rf structure. This can be

*Work carried out under contract with U.S. Atomic Energy Commission

produced by holding the magnetic field constant and, at the same time, turning the accelerating fields off. In practice, the magnetic field is sloped slightly in either direction so that, with the rf system off, the constant energy beam can be moved radially to an inside or outside target as desired.

Simultaneous Experiments.

In the past, the AGS has had as many as four targets in use during a given acceleration cycle. Furthermore, several experiments simultaneously have used beams scattered from the G10 target. A good example of one of the typical setups is shown in Table I. The Table shows rather clearly the gymnastics through which the beam must be programmed to service all targets.

Operations Time Allotments

Logistics.

The complexity of experiments in high energy physics has grown tremendously in the last decade. This has required that design and procurement of equipment be anticipated literally years in advance. In addition, the demand for machine time is such that approval, planning, designing, and erecting of an experimental beam at the AGS can take from six to eight months from proposal submittal to data taking.

Proposals for research at the AGS are submitted to the High Energy Advisory Committee by the experimenter. When this group has approved the experiment, it is placed on the AGS long-range planning schedule. At the time, an Experimental Planning Work Sheet is completed by the experimenter and, together with the proposal, is used by the AGS planning and experimental operations groups in making preliminary designs. A liaison physicist and liaison engineer from the AGS is assigned to the experiment. In the preliminary stages, the realities of equipment availability in the months ahead has its impact, and compromises in design or schedule delays must be considered. When it has been established, that the equipment will be available, special apparatus design is started and, if required, new operating techniques developed, the final detailed information and parameters for the experiment are confirmed. It is desirable that this be accomplished about three months in advance of the setup date. The experiment now is carried on a short-range schedule and an estimated shutdown date is given. Detailed working drawings of the entire beam are made. Finally, work orders are prepared for technicians, electricians, riggers, and other skills required to erect an experiment.

In general, a beam that is set up in conjunction with a bubble chamber has been more permanent than those set up with other types of detection apparatus. As a consequence, the scheduling of bubble chamber experiments for a given period is somewhat more straightforward compared to the counter efforts. The bubble chamber experiments, as approved by the High Energy Advisory Committee, are run in series and scheduled on the basis of compatibility with other machine users. To provide more flexibility within the schedule, the experiments may be run in uninterrupted periods, as well as a number of short periods, to afford the experimenter time to review the acquired data for possible beam changes before completion of the program.

Schedule Cycle.

The AGS operates twenty four hours a day, seven days a week. A two-week repetitive cycle is used and is set up as follows: let us consider high energy physics experiments starting at 0001 Monday morning; on Wednesday a 24-hour period is scheduled for maintenance immediately followed by a 16-hour accelerator research session; the high energy physics program is resumed and runs without interruption to the following Wednesday when a second 16-hour period is devoted to accelerator research. This two-week cycle also has a so-called "floating" eight-hour maintenance shift which may be used if necessary. In summary, a normal cycle has a potential 336 hours. Of this, 280 hours are assigned to the experimental program, 32 hours to accelerator research, and 24 hours to scheduled maintenance.

Each week, the AGS planning group together with those experimenters using the synchrotron and those who are scheduled to come on shortly, meet and discuss details of the following week's program and resolve existing problems.

Day-by-Day Schedule.

Despite all this scheduling, it is extremely important to follow the program as it evolves day by day. Within the framework of the weekly schedule, the operations engineer is responsible for machine performance, meeting exigencies as they occur. At his discretion, and whenever possible at times convenient to the experimenter, the machine may be shut down so that work may be performed on any apparatus to prevent longer term failures or to improve the performance of the synchrotron. The weekly schedule is based on an assumed performance level of the synchrotron. If this level is not achieved and sufficient beam is not available to satisfy all users or, if because of experimental equipment failure another experiment should be scheduled, a conflict on beam assignment may occur. The responsible member of the AGS planning group acts as the arbiter and together with the duty operations engineer adjusts the program accordingly.

AGS Performance

Analysis of Running Time.

During the calendar year, 1964, 6610 hours of operating time were available and were utilized as follows: high energy physics, 62%; accelerator research, 9%; machine startup, shutdown, readjustment, 5%; accelerator failure, 16%; experimental equipment failure, 1%; downtime requested by experimenters, 1%; and routine maintenance, 6%. Also, 1514 hours of shutdown, primarily for new experimental setup, were made available.

During this year, the machine averaged 4×10^{11} protons per pulse.

Number and Type of Experiments.

The AGS was available to, and operating for, high energy physics experiments about 4100 hours during the calendar year 1964. The total number of experimental hours logged for all experiments performed during this time amounted to approximately 14,400 hours. Five counter type experiments were completed and four more were started during this time. In general, data was acquired on the total cross section of $K^{\pm}$ and $P^{\pm}$ on deuterium, the total cross section of π^{+} on protons, and the elastic scattering of $P^{\pm}$, $\pi^{\pm}$, and $K^{\pm}$ on protons, covering momenta of 2.5 to 20 BeV/c. Other data have been gathered on K^{o} regeneration and specific reactions of pions on protons.

During 1964, the three bubble chambers took over 4,000,000 photographs of $P^{\pm}$, $\pi^{\pm}$, and $K^{\pm}$ particles on deuterium, hydrogen, and propane for twelve groups of experimenters.

Over 500 hours of experimental time were devoted to the neutrino experiment using the 30 BeV ejected beam.

Several short periods were used for radiochemistry experiments, using foils on internal targets, in both the low momentum separated beam and the external beam. A few short periods were also used for exposures of seeds in the separated beams and the external beam for biology.

Analysis of Troubles.

Of the total downtime due to accelerator failure, 32% is attributable to the linear accelerator, 17.5% to the vacuum system for the entire machine, 15% to the AGS rf accelerating system, 17.5% to external beam equipment, and 8.5% to the main magnet and its power supply.

In the linear accelerator, blocks of downtime were caused by two breakdowns of the Cockcroft-Walton high-voltage transformer, breakdowns of high-voltage power supplies for the ion source, and breakdowns of the power triodes in the rf system. All these systems have been or are being redesigned for more reliable operation.

In February, a coil of one of the ring magnets shorted to ground due to a water leak and seepage under the insulation. This has been the only instance of a ring magnet failure in the AGS. Arc-throughs and overcurrents caused by misfiring of the rectifiers in the main magnet power supply accounted for short periods of downtime.

Radiation damage to the rf cavity saturating power supply transistor banks and short life of replacement class power tubes in the AGS rf power amplifier stations have required frequent access to the magnet enclosure to repair, tune, and adjust the stations locally. Placing the transistor banks under concrete shielding has greatly reduced failures due to radiation damage. Improved servo systems, which provide automatic adjustment of the cavity tuning circuits, are being installed in the power amplifiers.

With the increase of beam intensity, vacuum leaks in the rf cavities and other places in the ring have developed due to radiation damage to insulation and vacuum seals. Some vacuum leaks in the ion source and the linear accelerator were very difficult to locate. The rf cavities are being rebuilt using radiation resistant insulation and vacuum seals. As leaks occur "O" ring seals in the vacuum system are replaced with seals more resistant to radiation damage.

A major cause of machine failure, while the external beam was operated, has been the ejector magnet power supply. Diametric operation of thyratrons with attendant cross-coupling had made it difficult and required a great deal of time to ascertain the nature of the real failures. The septum magnet, with a water leak, a broken vacuum seal, and open coil added its bit to the total downtime. A new ejector magnet power supply has been installed recently. Redesign of the septum magnet system has greatly reduced the number of failures.

Power dips due to storms and line transients required local resetting of vacuum pumps and ion gauge chassis both in the ring and at the linear accelerator. The vacuum pumps now reset automatically after power failure and an independent power source has been designed for the ion gauge chassis.

Shutdowns.

Three periods, of several weeks each, have been used for dismantling completed experiments and to erect the new ones for the ensuing program. This time was also used for major machine modifications. Because the shielding which continues the tunnel through the East Area has to be opened up to rearrange the experimental equipment inside the magnet enclosure, the accelerator has to be shut down. To prevent the decompression of the underlying sand and the subsequent misalignment of the ring magnets through the area of work, the shielding is removed and replaced sequentially.

During March and April, 1964, a period of three weeks was used to change over to a new set of counter experiments. A 40-hour period on August 16-18 was needed to complete the installation of equipment for multiturn injection. From the latter part of September to the middle of November, major modifications of the linear accelerator were made to increase the beam intensity, and a number of counter experiments were added in the East Area. During the two-week period spanning the year end holidays, separated beam #1 was dismantled, and the erection of a diffracted proton beam was started.

Improvements

Improvements have been made to increase beam intensity. The output of the ion source has been increased and the admittance of the linear accelerator has been enlarged to accommodate an increased beam. A circuit to compensate for beam loading controls the rf drive. A pulsed momentum analyzer permits unused pulses of the linear accelerator to be analyzed during AGS operations. Multiturn injection extends the time during which the AGS accepts beam from the linac. A new ion source[2] and a higher-power rf system are being designed for the linear accelerator. Improvements, to date, have resulted in peak beam intensities of 1.4×10^{12} protons per pulse.

To increase reliability, many pieces of equipment from the original design, have been replaced with second generation equipment. This program includes the changing of electronic systems to solid state design with plug-in printed circuits, removal of electronic gear from the magnet enclosure, the installation of more spare equipment in a state of readiness, improvements in water cooling systems to combat corrosion and plug-ups, expanded air cooling facilities for the main magnet motor-generator set, and electronic adjustment of its motor-control. "Viton" "O" rings will be used to systematically replace the "Convaseal" type. New AGS rf power amplifiers with higher-power tubes and cavities[3] with better vacuum structure have been designed, and construction has gotten under way.

Eventually, the new power amplifiers and cavities will make two or three 10 ft straight sections available for new uses, out of the 12 presently required for acceleration. Other efforts to increase machine flexibility include the installation of a new magnet cycle timer[4] to provide additional cycling modes as needed for the increasingly complex experimental program, the connection of a shunt regulator ripple filter to smooth out beam spills during flat-top, and the installation of additional power facilities bringing total capacity to 35 MVA to satisfy demands in the experimental areas. New rapid beam deflector systems are being designed to set up beam orbit perturbations in the associated target location only, and to fit in five-foot straight sections.

New separated beams[5] are being designed and installed to meet the demands of new experiments.

Conclusions

The operation of the AGS, since its beginning, has been quite successful. Its flexibility, in large part, has contributed to the very active high energy program. There is always room for improvement, however, in any accelerator. A long range program to increase the beam intensity and to reduce the concommitant problems of radiation[6] is being studied.

Acknowledgements

The authors wish to thank the AGS staff members who contributed to the writing of this paper, and the patient secretarial staff who typed the several revisions.

References

1. E.B. Forsyth and C. Lasky, "Engineering Design of the AGS Fast Beam Extraction System". Paper presented at this conference.
2. A. van Steenbergen, "Recent Developments in High Intensity Ion Beam Production and Preacceleration". Paper presented at this conference.
3. M. Plotkin, "A Proposed AGS Accelerating Cavity". Paper presented at this conference.
4. R. Frankel, "Variable Mode Solid State Magnet Cycle Timer". Paper presented at this conference.
5. H. Foelsche, J. Lach, and J. Sandweiss, "Design Studies for the RF Separated Beam at the AGS". Paper presented at this conference.
6. C.R. Flatau, "Proposed Remote-Handling Methods for a Modified AGS". Paper presented at this conference.

TABLE I - MULTIPLE TARGETING OPERATIONS - December, 1964

Time After "to" (ms)	Target (Radial Position in inches)	Radius Shift	Rapid Beam Deflector, RF and Flat-top	Beam Spill Beam Intensity Energy Level, Spill Period	Experiment No. Particles & Momentum Detectors
350	F10 (1.2" outside) start up				
400		start outside			
500	F10 start down	start inside	RBD at F20 pulsed	2.5×10^{10} p/pulse 17 BeV, 30 μsec long	197 3.5 BeV/c π^- 20" hydrogen bubble chamber
600	F20 (0.5" inside) start up				
630	I10 (0.32" inside) start up				
700	F20 start down	start outside	RBD at G20 pulsed	1.25×10^{11} p/pulse 24 BeV, 25 μsec long	179 Stopped K^+ 30" hydrogen bubble chamber
800	G10 (0.76" outside) start up	start further outside	RBD at F20 pulsed again	2.4×10^{11} p/pulse 27 BeV, 1 msec long	121 3.5 - 4.0 BeV/c $K^\pm$ 80" hydrogen bubble chamber
801	I10 start down				
814			rf turned off		184 3.0 - 6.0 BeV/c $\pi^\pm$ Spark chambers & counters
815			flat-top start		205 K^0 particles Spark chambers & counters
900				3.4×10^{10} p/pulse 28 BeV, 100 msec long	206 π^- at 0^0 hydrogen target & counters
1070			flat-top ended		213 1.3 - 2.8 BeV/c π^- Spark chambers, hydrogen target and counters
1400	G10 start down				

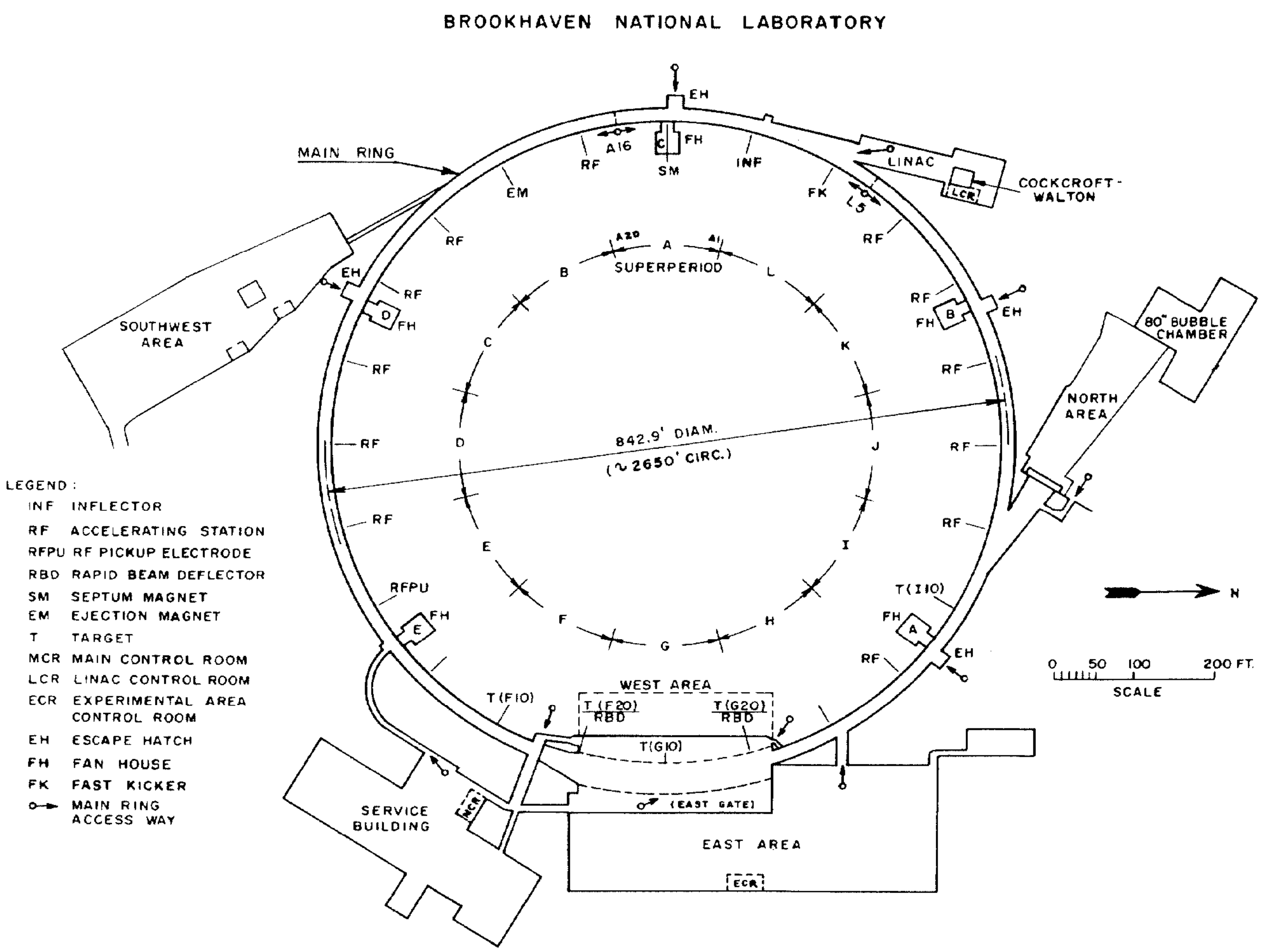

Fig. 1. Alternating Gradient Synchrotron (AGS) complex.