SLOW EXTERNAL BEAM EJECTION MAGNETS AND POWER SUPPLIES

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Introduction

The slow or resonant extracted beam (hereinafter referred to as SEB) at the AGS has been described in the literature. Several other papers presented at this conference will describe in some detail the results, difficulties and operational status of this beam.

Briefly, the scheme is based on the third-integral resonance which is created in the AGS by four symmetrically spaced sextupoles of alternating polarities. This produces a resonance at \( y = 5\frac{2}{3} \) and when particles drift to a radius corresponding to this \( y \) value, they become unstable and undergo large betatron oscillations. After three revolutions in the AGS, they spiral radially outward and are ready to be intercepted by a thin septum type magnet and hence extracted. The extracted beam or "spill" is controlled by a careful adjustment of the main magnet "flat top" current or by closed loop feedback regulation. In order to prevent mechanical rammings of the extraction magnets, the equilibrium orbit of the AGS is locally distorted in the \( F \) superperiod by use of backleg windings on main ring magnets selected to give a half wavelength outward bump centered at \( F7 \).

Since the efficiency of extraction is directly related to the thickness of the extractor magnet, it is desirable to make this as thin as possible. However, in order to deflect the high energy beams, a high magnetic field strength is required which results in a high current in the magnet. A compromise scheme developed for the extraction step at the AGS consists of a two magnet system. These are a 30 mil kicker septum located at the \( F5 \) straight section and a final 1/4 in. thick ejector magnet located at the \( F10 \) straight section. The \( F5 \) kicker magnet is used to deflect the particles initially \( y \) so that they just clear the septum of the \( F10 \) ejector magnet and then this second magnet gives the full kick to extract the beam from the AGS.

General Considerations

The above introductory paragraphs give a brief description of the AGS SEB. This paper deals basically with a description of the magnets and power supplies which were designed for the final step of extraction. These two special magnets, the thin septum kicker magnet and the thin septum ejector magnet, are required to produce a uniform constant dipole field inside their aperture gap and a near zero field outside of the aperture gap where the normal AGS circulating beam orbit is situated. Since these magnets are quite close to the undisturbed equilibrium orbit of the AGS at all times, problems such as fringing fields and remanent fields must be taken into account in order that the 50 MeV injected beam is not affected. Thus, for this consideration one must pulse these magnets near flat top when they are called upon to deflect the resonant particles out of the machine.

In order to provide an external beam which is relatively free of position modulation, the power supplies used must have a high degree of regulation and must also be relatively ripple free. It was decided that a figure of \(< 0.1\% \) should be attained for both regulation and ripple. The power supplies in addition should be pulsed, with peak currents adjustable over a wide range to permit operation of the SEB at various energies. They must also contain elaborate systems of interlocks and protective features to safeguard both the supply and the delicate magnet load.

The Thin Septum Kicker Magnet System

Magnet

The thin septum magnet is a "C" magnet with an iron core laminated with 0.25 in. low carbon intermediate silicon steel. The overall length is 2b-1/4 in. The magnet coil consists of a single turn with \( 1.5 \times 10\) ohm resistance. The total inductance is \( \approx 5\) mH. The magnet has a peak design field of 1500 gauss which produces a total kick of approximately one milliradian at a machine energy of 30 GeV. A typical cross section of the septum magnet construction is shown in Fig. 1.

The thin septum is electrically shorted to the iron core, a high resistance of the type iron core is required to avoid an excessive amount of current flowing through the iron core and bypassing the septum.
The laminations thus were insulated with a layer of thermally induced oxide film. Stacking was accomplished by introducing an extra layer of alumina filled epoxy system. The packing factor of this core exceeds 90%, the total resistance from end plate to end plate exceeds $10^6$ ohms.

The thin septum was machined out of a solid copper block. It has 1/4 in. slots spaced every 1/2 in. apart. Cooling coils made of Inconel "X" tubing which has an order of magnitude higher resistivity than that of copper are soldered to the edges of the tabs. This geometry provides cooling means and also minimizes the amount of current flowing outside the aperture gap. An undesirable high stray field outside of the septum was expected in view of the rather peculiar geometric shape of the septum, hence a set of compensating coils was built into the design. Figure 2 shows the fringe field in percent of the internal field versus the distance from the face of the thin septum, at currents of 1680 amp and 1000 amp. Figure 7 also shows a plot of the compensated fringe field which was made equal to zero at a distance of ~ 1/4 in. from the septum. The compensating current is 10% of the peak current. The magnitude of the fringe field is time variable during the flat top.

Computation shows that the thickness of the septum for a particle with 3/8 in. spiral pitch should be .030 in. in order to yield an extraction efficiency of approximately 85%. With a peak current of 1500 amperes, the current density in the thin septum is approximately 2300 amp/in². The thermal capacity of the thin septum is only $12 \times 10^{-5}$ Btu per °F. It is obvious that the thermal problem is the thin septum limitation for this magnet. The edge cooling method was chosen due to lack of space for any other method. There is a long heat conduction path between the heat source and the cooling tubes. In addition, the cross section is very thin near where the heat source is. Therefore, an efficient heat transfer is difficult to achieve. The magnet has been operated at 1500 amperes for a flat top of 650 milliseconds. The machine repetition rate is 2.4 seconds. Temperature rise at the center of the septum is approximately 100 °F, but the cooling water temperature rise is only a few °F.

The electrical insulation of this magnet is a layer of aluminum oxide mechanically bonded to the copper substrate. Good adhesion is difficult to achieve due to the geometric shape and size of the substrate, but the mechanical shock acting on the magnet is negligible, hence, there has not been any problem experienced with this coating since the beginning of SEB operation.

Power Supply

The stringent requirements of regulation and ripple together with the fact that it be pulsed, pose a severe restriction on the type of power supply that can be used to power a one turn magnet similar to the P5 thin septum kicker magnet. The low magnet inductance does not permit use of phase controlled thyristor type power supplies. The long pulse lengths of up to one second, exclude capacitor discharge ringing type power supplies. These facts and also the relatively good experiences on previous applications led us to the decision of utilizing a transistor bank in a simple series regulator configuration to control the power flow to this magnet. The transistor bank consists of 200 germanium power transistors. The transistors are parallel mounted on a common copper plate heat sink. Cooling is provided by chilled water (5°C) flowing through copper tubes soldered to the collector heat sink. The transistors have base and emitter fuses and also emitter resistor degeneration is utilized. The driver consists of 20 transistors in parallel. See Fig. 3 for typical schematic.

The d.c. power is supplied by a six phase capacitively filtered source. The maximum ratings are 12 volts d.c. and 2000 amperes. Taps are provided on the rectifier transformer to provide different output voltage and current ranges, and hence, optimize the dissipation on the transistor bank.

Regulation is accomplished by sensing the output current through a stable shunt and comparing this to a low temperature co-efficient zener reference voltage. The voltage reference is applied to the system by a mercury relay which is normally de-energized. Logic circuits accept on and off input pulses and create the drive to pulse the reference relay for the pre-determined pulse width. Because of the nature of the thin septum load, a "long pulse" can be disastrous. Therefore, several features to protect against this happening are designed into the power supply. In the logic circuits, we incorporate a unijunction-SCR circuit which creates turn-off pulses to the system which are derived from the on pulse and these assure the system will turn off after a pre-determined time has elapsed. A second feature measures the instantaneous power across the transistor bank, and the instantaneous power and energy across the magnet. This system is based on the Hall Effect. A Hall multiplier is fed voltage and current signals and their product or power is fed to a Schmidt trigger circuit and on overpower interrupts main contactors to the system. Besides the above, routine water-flow interlocks and thermocouple over-temperature indicators and trips are provided for both the magnet and power supply. In addition, overcurrent devices, a.c. and d.c., and both slow and quick acting are incorporated in the system.

The Ejector Magnet System

The ejector magnet assembly is located five magnets downstream of the thin septum kicker magnet. It intercepts the particles deflected by the thin septum magnets and gives them a larger bend which causes the particles to exit from the AGS ring and to be guided by the beam transport system to the target. The thickness of the septum of this magnet assembly at the beam entrance end determines the kick requirement of the thin septum upstream. The total kick requirement of ejector magnet assembly is 850 kG-inches equivalent to a total bend of 20 milli-radians at a machine energy
The ejector magnet assembly consists of three segment magnets which are connected electrically in series. The required angular deflection is realized at a current of ~ 6400 amperes. The magnet assembly has a total cold resistance of $3.5 \times 10^5$ ohms and total inductance of $47 \times 10^6$ henry. It occupies a total space of 93-1/2 in. in length. The first segment is a two-turn "C" magnet, 32 in. long, 8 kG field strength. The total thickness of the septum is 1/4 in. The total displacement of the beam is large enough to allow a three-turn second segment. The second segment is placed in the shadow of first segment and oriented at an angle equal to the bend produced by the first segment. Both the second and third segments are three-turn "C" magnets, 24 in. long, 12 kG field strength. The total thickness of the septum is 3/8 in. Two typical cross sections of the segments are shown in Fig. 4.

The current sheets of the septum for all the segments are electroformed copper. This process is well known, so it will not be described here. The current sheet contains three rectangular coolant passages. They are .050 in. x .160 in. The number of passages and their dimensions chosen are the best compromise between effective heat transfer and required coolant pressure drop. The first current sheet has a cross section of .120 in. x .796 in. It has a thin layer of protective hard chrome plating to prevent excessive wear of the soft copper due to the thermal expansion of the current sheet. The first current sheet is electrically shorted to the iron core so that the leakage flux due to the gap created by the insulation between the current sheet and iron core is greatly reduced. This leakage flux usually contributes the major portion of the stray field in front of the septum. The total displacement of the beam is large enough to allow a three-turn segment magnets which are connected electrically in series.

Due to an anticipated high temperature rise and high radiation dose on this magnet, the insulation of the coil is very critical. A great effort was devoted to develop an industrial source for an inorganic type insulation material. An inorganic type insulation not only will prolong the usable life of the coils under a high radiation environment but also will make the outgassing rate independent of temperature variation. The latter will enable us to maintain a good vacuum in the box. An alumina compound known as NOROC #214 produced by Norton Co. of Worcester, Massachusetts has 98.6% aluminum oxide and a dielectric strength of 40 to 50 volts per mil. The maximum porosity of the coating is 7%, mechanical bond is excellent, it will take normal handling, and it is also capable of taking thermal and mechanical shock. The dimensional variation over an area of 0.8 in. x 34 in. was controlled to within .002 T.I.R.

The coils are mechanically fixed to the core at one end and free to expand at the other end. This flexibility is provided to minimize the fatigue stress on coils due to the repetitive thermal expansion. The flexibility of the connectors are provided by the combination of metal bellow for coolant passage and braided copper strips for the electric current. Metal seals are used for all non-soldered coolant joints.

The current density in the thin current sheet is in the order of 2300 amperes/in². The heat dissipation of the 34 in. long current sheet is approximately 16 kW, but the heat capacity of the copper is only .073 Btu per °F. Each turn of coil is individually cooled in order to have a reasonable coolant pressure drop requirement. The water speed is approximately 30 ft/sec. This relatively high speed improves the heat transfer rate across the stagnant film between the wall and bulk of coolant. This is important because the temperature gradient across this thin film usually contributes a major part of the copper temperature rise. On the other hand, the erosion problem created by the high speed coolant presents a threat to the longevity of the thin-walled conductor. A clean water system, de-mineralized and de-ionized, is used for this magnet, and aids in minimizing the erosion problem, and also reduces the electrolysis problems which are encountered in conventional water systems.

The coolant has a temperature rise of 20°F. The coolant pressure drop requirement. The cold end of coil is in the order of 2300 amperes/in². The heat dissipation of the 34 in. long current sheet is approximately 16 kW, but the heat capacity of the copper is only .073 Btu per °F. Each turn of coil is individually cooled in order to have a reasonable coolant pressure drop requirement. The water speed is approximately 30 ft/sec. This relatively high speed improves the heat transfer rate across the stagnant film between the wall and bulk of coolant. This is important because the temperature gradient across this thin film usually contributes a major part of the copper temperature rise. On the other hand, the erosion problem created by the high speed coolant presents a threat to the longevity of the thin-walled conductor. A clean water system, de-mineralized and de-ionized, is used for this magnet, and aids in minimizing the erosion problem, and also reduces the electrolysis problems which are encountered in conventional water systems.

The ejector magnet has been powered to 6400 amp for a 600 millisecond flat top. The peak temperature rise of the thin current sheet, sensed by a thermistor is 40°F. The coolant has a temperature rise of 20°F.

The stray field was measured by using a 33 in. long search coil which is long enough to pick up the end effect of the magnet. The stray field was measured at three azimuthal positions and the results were summed at each horizontal position to give the total integrated fringe field at that horizontal position. The fringe field measurements were made at two values of current, and the results are shown in Fig. 5.

The requirements imposed above for the power supply of the thin septum kicker magnet, also can be applied to the design of a power supply for the P10 ejector magnet. However, one must keep in mind also that we are talking of a system of at least ten times more power capability (approximately 300 kW), therefore, the problems associated with this unit become extremely more difficult and dangerous.

A multi-phase thyristor power supply was considered. However, because of the amount of

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phase back to take care of a magnet load resistance variation of ~ 15 percent, and also difficulties encountered in generating multiple phase voltages, i.e., transformer manufacture with a high degree of phase balance, led to the elimination of such a scheme. One other problem associated with the above is the inflexibility of the system. For example, if output ripple is large due to phase unbalance, to correct this would take a major modification or addition.

Therefore, it was decided to construct the ejector power supply similar to that of the thin septum kicker magnet, i.e., a large source of d.c. power with the switch and dynamic regulator portion comprised by a large transistor bank. The configuration is again a simple series regulator with current sensing feedback. Refer to Fig. 3 for typical connections. There are several major differences between the thin septum and ejector magnet supplies. The d.c. power is supplied from a commercial 45 V d.c., 7000 ampere source purchased as per our specifications. The 440 V, three phase input to the supply is varied from 30% to 110% by an induction voltage regulator (IVR) which provides continuous "stepless" control. Since the transistor bank is designed to continuously dissipate 50 kilowatts, but to control the flow of approximately 150 kilowatts to the magnet, the IVR is a crucial part of the system. In operation, one varies the d.c. voltage on the system in conjunction with the output current. In this way the power on the transistor bank is controlled and limits of design are not exceeded.

In addition, the high power rating of the transistor bank can be attributed to the unique cooling system developed for it. It consists of a direct expansion freon 502 system which keeps the unit operating at approximately -20°C. In this way, peak power ratings of power transistors can be approached. In addition, one can then utilize germanium power transistors and take advantage of their lower cost as opposed to silicon units. In construction, 480 transistors are mounted on a large copper plate which is kept tightly sealed and insulated. Square copper cooling tubes are soldered to the plate and these are each fed by their own expansion valve whose superheat range is adjusted and then maintained by a sensing bulb attached to the exhaust or drier loop. The other side of the plate is also insulated except for small holes through which the leads attached to the base and emitter of the transistors come out and attach to fuse blocks and balancing resistors.

Regulation of current in the magnet is accomplished by sensing the current in a homemade, water-cooled shunt and feeding this signal back through a high gain amplifier loop. The reference is a very low temperature co-efficient zener source. The open loop gain characteristic of the system is adjusted so that enough gain is provided at 360 Hz to bring the current ripple within specifications. Dynamically, to prevent transients during turn-on and turn-off, the gain is reduced during these conditions. In addition, the rise time of the reference pulse is adjusted by an RC network to closely match the natural time constant of the magnet load.

The protection problems in this power supply and magnet system are very critical. Whereas one could conceive of the possibility of operating the AGS SEB without the F5 thin septum kicker magnet, at lower extraction efficiency, one could not operate without the ejector magnet. Therefore, the same protective features as described above for the F5 magnet are incorporated into this unit, however, with higher redundancy. For example, instead of two thermocouple indications and trips, a total of eight are employed in the ejector system. In addition, many thermostats are used to monitor the transistor collector plate temperature. A different protective feature of this transistor bank makes use of a feed relay connected across the emitter resistor of each transistor, and hence, monitors the current in each unit. This information is simultaneously used to flash a lamp for visual indication, and also gets summed into a trip circuit. If a number greater than a pre-determined value of transistors become inoperative, the power supply is turned off.

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References

Fig. 3. Typical thin septum magnet power supply connections showing transistor bank and feedback regulator loop.

Fig. 4. Ejector magnet.

Fig. 5. Fringe field of ejector magnet.