INVESTIGATION OF A SUPERCONDUCTING BEAM SPLITTER FOR ATLAS

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Introduction

In the ATLAS[1] accelerator system, the heavy ion beam delivered to the linac from the tandem is sent through a stripping foil prior to acceleration by the linac. The stripping process produces several charge states in addition to the one for which the linac is tuned. The linac operates in a phase focussing mode in order to preserve the beam quality and timing of the bunches. This mode of operation also allows the linac to accelerate other charge states which differ by only one or two charge units from the tuned charged state. The energy of these charge states at the end of the first stage of the linac vary by less than 1% from the energy of the tuned ion. This allows the tuned charge state, Q, and an adjacent charge state, Q-1, to be separated in a 40 degree bend region which connects the first and second stage of the linac. Charge state Q can then be further accelerated in the second stage of the linac while charge state Q-1 is split from the main beam and provided to a secondary target area for parasitic performance of other experiments.

The device which is being investigated for use as a beam splitter consists of a dipole bending magnet in which a superconducting flux shield (supertube) is placed. The supertube produces a field free region for one of the charge states while the second charge state enters the magnetic field produced by the dipole magnet and is directed toward the remainder of the ATLAS accelerator. This type of device is appealing because of its simplicity and because the two beam regions are decoupled. The superconducting flux shield is a passive device requiring only that it be cooled below the superconducting transition point for proper operation.

The beam splitting region is shown in fig. 1. The two charge states of interest are dispersed in the horizontal plane by the action of the first bend of 22 degrees. The dispersion induced causes a separation at the entrance to the second 17 degree bend which varies from 2 cm to 6 cm depending upon the ion species and charge state combinations considered. The typical beam diameter at this point is 3 mm.

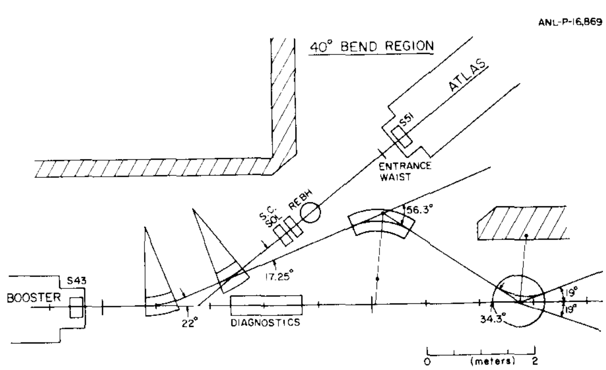

Fig. 1 40° Bend Region of ATLAS showing the location of the beam splitting device.

The splitting of two beams with a superconducting flux shield-magnet device presents two major problems which must be addressed in order for the device to perform successfully. First, and most obvious, the device must work in a highly reliable way. The magnetic field which must be excluded by the flux shield is as high as 6.8 kilogauss during actual operation of the shield. Other situations require an external field as high as 9.5 kilogauss.

Second, the act of excluding a field from a region which contained an initially homogeneous field produces a field which is no longer homogeneous. The effect of such an inhomogeneous field on the beam optics for the beam traversing this region is unacceptable. The external field must be made homogeneous by shaping the external dipole field and arranging the magnet-supertube geometry in such a way so as to produce a field of acceptable quality in the beam region.

Superconducting flux shields have been studied and used in a number of laboratories[2-4] and have been used in at least one experiment.[2] The results of such studies have indicated that flux shields can be developed which will provide complete shielding to values as high as three tesla.[2] The body of experience indicates that a great deal of "art" goes into the making of such a shield and the guarantee of achieving a design shielding goal on an individual device is uncertain. On the other hand once a particular device has been constructed, tested, and shown to provide a certain degree of flux shielding, that value of shielding is highly reproducable and does not appear to deteriorate with time or exposure to unusual conditions.

The Supertube

The literature and private conversations[3,5] indicated a likely cause for an unpredictable result could be due to the lack of mechanical rigidity of the tubes which were often constructed by layering sheets of superconducting material and then soldering these layers together or otherwise clamping the layers. Therefore we undertook the investigation of a flux shield design which would be inherently structurally rigid.

A tube was purchased from Teledyne Wah Chang[6] which consisted of an inner core of copper surrounded by a spiral sandwich of layers of niobium and bronze encased in an outer sheath of copper. The tube was made by assembling a billet of the materials as described above and then extruding the material to the final overall dimensions. After the initial heat treatment was completed the inner copper core was removed. The cross section of the tube is shown in fig. 2. The total length of the tube is approximately 0.75 m. The total number of layers of niobium-bronze is approximately 250. Upon receipt, the cylinder was placed in an inert argon atmosphere oven and reacted at 700°C for 100 hours in order to produce Nb_3Sn in the interface region. Subsequent photomicrographs of etched samples indicated that a layer of Nb_3Sn approximately 2.5 microns had been formed at each niobium-bronze interface. Therefore the total thickness of super-conductor produced was approximately 500 microns. The thickness of superconductor required to shield an external field is given by:[2]

$$t = 2(2B_e^2 + B_eB_o)/\mu\alpha. \quad (1)$$

The external field is B_e; B_o and α are constants of the superconductor which relate the critical current to the local magnetic field. For Nb_3Sn, B_o and α are approximately -3200 gauss and 4.15×10^{14} gauss $-A/m^2$, respectively. Therefore the tube tested should have been able to shield external fields to nearly thirty kilogauss.

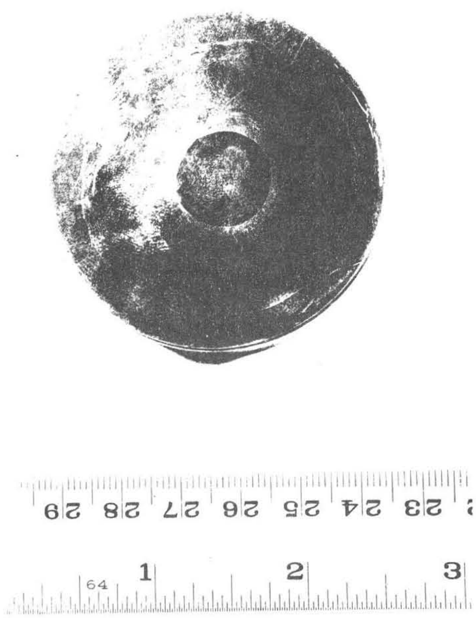

Fig. 2 Cross section of the superconducting flux shield. The shielded inner diameter is 1.5 cm, the thickness of the superconducting region is 1.6 cm, and the outer copper jacket is 0.5 cm thick.

The tube was tested by placing it in a transverse field produced by a large bore (21 cm. diameter) superconducting dipole wound in a "cos Θ" pattern. The ends of the tube were in a region which was very non-uniform. Both the superconductor and the magnet were completly immersed in liquid helium. The magnetic field, both interior to the tube and exterior to the tube, could be sampled with a Hall probe inserted from outside the cryostat. The probe could be moved along the tube in order to sample the field at essentially any point within the volume of interest although the transverse position could not be determined with high precision. The field of the superconducting magnet was ramped up and down at rates of approximately 30 gauss/second.

The flux shield exhibited complete shielding of the external field (less than one gauss penetration) in a repeatable way up to external fields of 8.8 kilogauss. When a external field of 8.8 kilogauss was reached a flux penetration was observed for that section of the tube which was exposed to the 8.8 kilogauss field. Portions of the tube which were immersed in lower fields continued to shield the external field completely until those regions also were exposed to this limiting field of 8.8 kilogauss. The condition of flux penetration along the tube after the external field has been raised to a maximum value of 15 kilogauss is shown in fig. 3. The figure shows that the field penetrating the tube varies wildly and has local variation of as much as 5 kilogauss. These local variations occurred on a scale of nominally 2-4 cm whereas on the larger scale of approximately 10 cm the entire tube behaved in a similar way. That is, all parts on the tube would allow penetration at the level of approximately 8.8 kilogauss.

After these initial results, the flux shield was subjected to an additional heat treatment of 750°C for 50 hours. Photomicrographs showed that the thickness of Nb_3Sn at each niobium-bronze interface had increased to approximately 5 microns. The shielding tests were repeated. Flux penetration again occurred at 8.8 kilogauss. Since doubling the thickness of the superconducting layer showed no increase in flux shielding, it would appear that the flux limitation stems from some other source.

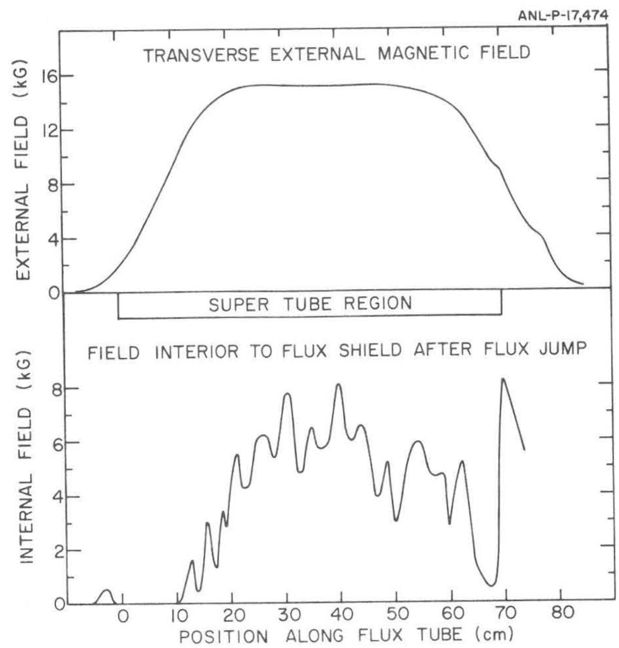

Fig. 3 Interior and exterior field of supertube after many flux jumps.

The spiral construction of this tube poses a limitation on the field configuration which can be excluded from the interior. Longitudinal fields require effective current sheets which are concentric with the cylinder. There are no available superconducting paths of this type in a spiral construction available on the macroscopic level. Therefore, the flux shielding capability of a spiral conductor tube placed in a fringing magnetic field which has a longitudinal field component such as that used in these tests will be adversely affected. Such an explanation would result in the expectation that the spiral supertube should perform better in fields with little or no longitudinal component. Additional tests are planned to investigate this possibility.

The External Field

The magnetic field produced by a cylindrical flux shield in an initially homogeneous field is:

$$B_r = B_e\,(R^2/r^2)\cos\Theta \qquad (2)$$

$$B_\Theta = B_e\,(R^2/r^2)\sin\Theta$$

in cylindrical coordinates, where B_e is the initial value of the field prior to the introduction of the tube into the region and R is the tube radius. A field of this shape will adversely affect the focussing of the beam injected into the remainder of the accelerator. The important consideration is to minimize the path integrated higher order terms of the magnetic field due to the field inhomogeniety.

The problem of producing a uniform field in the region of the primary beam can be completely discussed, at least through second order, by focussing on the values of the field derivatives with respect to the horizontal axis evaluated in the median plane at the point of the central trajectory:

$$A_{1N} = \frac{\partial^N By}{\partial x^N} \quad @\ x = 0; y = 0 \qquad (3)$$

This approach has been discussed by Brown[7] who shows, for example, that the magnetic field in the median plane with symmetry about the plane is given by:

$$B_y\,(x,y,t) = A_{10} + A_{11}\ x\ 0.5A_{12}X^2 \qquad (4)$$

These considerations show that near the central trajectory a uniform field is realized if the coefficients A_{11} and A_{12} vanish. It is possible to get a qualitative understanding of the higher order terms in the external field by applying these results. An approach which has been given preliminary study for the solution to this problem is to place the supertube in the fringing field of a "C" dipole magnet. The fringe field of a "standard" dipole magnet with gap, g, can be characterized by the relation:

$$B_y\,(x) = B_o/(1+e^s) \qquad (5)$$

where $s = (x-x_{eff})/g$.

The field in the region of the particle trajectory can be made uniform to within 4% by adjusting the position of the tube with respect to the magnet. The remainder of the field shaping can then be accomplished by tilting the pole tips to remove the first derivative term and shaping the fringing field from that described by equation (5). Compensation of the second order terms can be performed by edge shaping of the dipole or the use of separate sextupole in the system. These preliminary studies on the fringing field case look encouraging but detailed magnetic computations remain to be performed.

Conclusion

The results of this study indicates that a beam splitting device using a superconducting flux exclusion tube in conjunction with a normal C-magnet can be produced. Additional tests are planned in an effort to increase the flux shielding capability of the supertube and to test the tube in a more homogeneous external field. Preliminary studies indicate the external field of such a device can be made with sufficient homogeniety in a simple manner so that no significant deterioration in beam quality will occur.

Acknowledgements

I would like to thank W. K. McDonald (Teledyne Wah Chang) for his suggestions concerning heat treatment cycles and metallurgical analysis of the treated samples. Fruitful discussions with R. P. Smith (FNL), K. W. Shepard (ANL) and L. M. Bollinger (ANL) are also gratefully acknowledged.

This work is supported by the U.S. Department of Energy under contract W-31-109-Eng-38.

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