*Magnet Design for SLIA Proof-of-Concept Experiment**

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ABSTRACT

The beam transport system for the Spiral Line Induction Accelerator (SLIA) proof-of-concept experiment (POCE - 9.5 MeV, 10 kA, 35 nsec) contains seven basic magnetic field coil configurations. The magnets are for the transition from the field-free diode into the nominal 5 kG longitudinal guide field; the transition into/out of the accelerating section; the axial field within the 1.5 MV accelerating units; the matching elements for transition on/ off stellarator fields in the bend; the toroidal, $\ell = 2$ stellarator, dipole, and quadrupole field in the 80 cm bends; the extraction of the beam from the longitudinal guide field; and the beam steering/field correction. Prototype magnet coils have been fabricated. The measured magnetic fields compared well with the predicted amplitudes, gradients, and multipole field components. Because of the large number of pulsed magnetic field coils in POCE, the shot-to-shot and day-to-day reproducibility of the magnet coil current from a PSI designed electrolytic capacitor bank was measured and found to be better than ± 0.15% for currents up to a factor of two (several kiloamperes) larger than the design values.

INTRODUCTION

An experiment to evaluate the feasibility of the spiral line induction accelerator (SLIA)[1] as a high current electron accelerator is currently underway at Pulse Sciences, Inc. The experiment involves injecting a 3.5 MeV, 10 kA electron beam into a strong focussing, two-turn, racetrack type spiral magnet transport line with two passes through each of two 1.5 MV induction accelerating units, giving a nominal 9.5 MeV output. The magnet coils which make up the magnetic transport system for the SLIA proof-of-concept experiment (POCE) are shown schematically in Figure 1. The magnet coils are grouped into the seven basic systems for the functions shown.

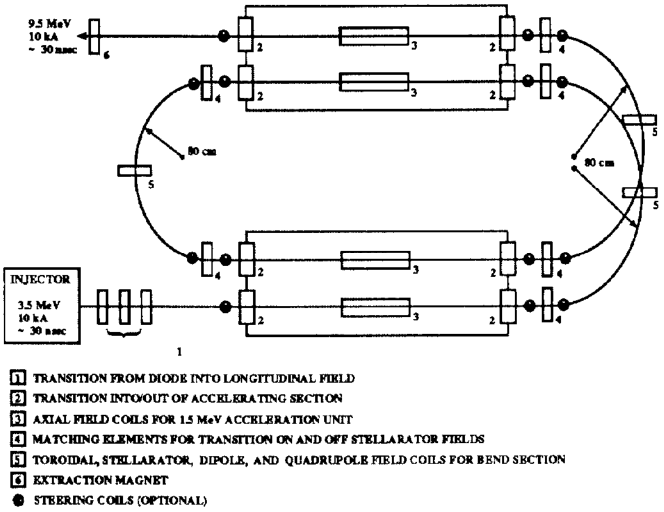

Figure 1. Magnet coils for SLIA-POCE.

UNCONVENTIONAL ASPECTS OF THE SLIA/POCE MAGNETS

Because of size and cost constraints all the SLIA-POCE magnets are pulsed. This minimizes size in that smaller conductors, without iron pole pieces, can be used to provide the desired dipole, quadrupole, stellarator, and steering fields. The electrolytic capacitor bank designed to power the SLIA-POCE magnets costs approximately 1.5 cents per watt of power delivered to the magnetic field coil as compared to the 0.5 to 1.0 dollar per watt for conventional steady-state power supplies.

The diode focussing system does not include a bucking coil to obtain a field-free cathode. Instead the focussing coil is surrounded, both radially and axially, by a magnetically thick piece of aluminum. This reduces the peak magnetic field over the emitting area of the cathode to 2.4 G which is approximately a factor of two less than could be obtained with a steady-state focussing and bucking coil which satisfy the geometrical constraints of the experiment. This removes the alignment problems and stray error fields associated with the large

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*Work sponsored by DARPA under Order No. 4395, Amendment 90 and by the Navy under Document N00039991 WXDZ002; monitored by the Naval Surface Warfare Center.

0-7803-0135-8/91$01.00 ©IEEE

radius bucking coil and allows a simpler geometric and magnetic alignment procedure.

MAGNETIC SHIELD

All magnetic field coils, except at the entrance and exit, are enclosed in a magnetic shield to avoid "cross-talk" between the turns of the spiral which are separated by ~ 30 cm over most of the transport distance. Both conducting and ferromagnetic shields were evaluated. Experiments were done with aluminum (6061-T6) and low carbon steel (AISI-1024) shields to compare the bank energy efficiency, required alignment tolerances, and flux confinement times.

For the same capacitor bank energy and dimensions of interest to POCE, the solenoidal field with a low carbon steel shield was 40% larger than with an aluminum shield. For practical material thicknesses (~ 1/2-inch) and for times greater than 1 ms after excitation, the return flux was better confined with a low carbon shield. The parallelism required between the solenoid and the shield for the same percentage of transverse field error was a factor of five more stringent for the aluminum shield. Uncompensated holes in the low carbon steel of diameter up to 5 cm (in a shield of diameter 16.5 cm) caused a field perturbation of 0.1% of the solenoidal field. The field of a discrete air core quadrupole was enhanced by $\approx$ 21% by the addition of a low carbon steel shield. The non-quadrupole components of the field out to a 1 cm radius, where the measurements were done, were within the experimental error bars for the Hall probe and positioning technique (a few percent).

The saturation wave velocity and rate of diffused flux were measured and used, with numerical modeling, to construct a transient ($\approx$ a few ms) magnetization curve (B vs. H). The magnetization curve was used extensively in the finite element code ANSYS to carry out transient, nonlinear calculations of the predicted magnetic fields during the design of the magnet coils.

END TERMINATIONS FOR MULTIPOLE MAGNETS

The end terminations for the dipole, quadrupole, $\ell = 2$ stellarator (twisted quadrupole), and steering (two dipole magnets at 90° angles) magnets are those suggested by Laslett, Caspi, and Helm[2] (LCH). The LCH prescription for the end terminations was applied directly for the matching quadrupole magnets and steering magnets which are used on straight sections. In the case of the dipole and quadrupole magnets for the bends the LCH prescription was applied in a coordinate system which rotated with the bend. For the $\ell = 2$ stellarator winding on the bend the end terminations also included the stellarator rotation.

The purpose of the LCH end terminations is to preserve the quality of the field integrated through the entire magnet. As a test of this, the predicted focussing field for the matching quadrupole coil design, which is composed almost entirely of end terminations, was integrated from -50 cm to 50 cm along the axis of the quadrupole coil at several positions inside the 5.3 cm winding radius. The integrated focussing field followed the ideal value, linearly proportional to the radius, to within 0.26% for radii less than 3 cm.

BEND MAGNETS

The design selected for the bends of the POCE is a stellarator achromat[3] which gives an identity transformation for the beam centroid to first-order in $\Delta E/E_0$, the fractional energy variation from the mean or matched energy. With an achromat, off-energy or momentum particles all exit the bend with coordinates and velocities the same as those at the entrance. Achromat designs have been developed for all POCE bends which give (predicted) submillimeter centroid displacements for $\Delta E/E_0 \approx \pm$ 8-10%.

The 80 cm major radius POCE bends contain four (toroidal, stellarator, dipole, and quadrupole) magnetic field coils built up radially on top of each other. The inner most magnet coil is the toroidal field coil which is composed of two helical windings of opposite pitch.

The next magnet coil in terms of radial position is the $\ell = 2$ stellarator coil which is wound on a minor radius of 5.23 cm. The toroidal M numbers ($M = 4\pi R_0/L$, where R_0 is the major radius and L is the pitch length of the winding) for the three

POCE bends are M = -16, -12, and -8, where the minus sign indicates that the Larmor rotation of the electrons is in the same sense as the rotation of the stellarator windings. Each bend has a separate M number in order to minimize the second order ($\Delta E/E_0$) effects while maintaining stable propagation for both the centroid and particle motion. The stellarator field gradient is approximately constant within the 6 cm diameter beam pipe and varies from 0.1346 G/cm/A for the first bend (M = -16) to 0.1397 G/cm/A for the third bend (M = -8). The predicted field purity is excellent at the center of the bends but has a small phase angle shift from the ideal value at the entrance and exit from the bend.

The combination of the dipole and quadrupole magnet coils on the bends provide a betatron vertical field. By controlling the current in each of the coils separately, the amplitude and field index of the betatron field can be adjusted independently. For example, in the third POCE bend the kinetic energy of the electrons, including space charge depression, will be ≈ 7 MeV. For a matched bending field of 312 G and a betatron field index of 1/2 the currents in the dipole and quadrupole field coils would be 647 A and 31 A respectively.

CURRENT AND MAGNETIC FIELD REPRODUCIBILITY

Because of the large number of pulsed magnetic field coils in POCE, a series of experiments were done to determine the shot-to-shot and day-to-day reproducibility of the field and magnet coil current from a PSI designed electrolytic capacitor bank[4]. The discharge current of the capacitor bank was measured into prototype stellarator and solenoidal coils. The current density in the experiments was larger by 50% for the stellarator coil and 100% for the solenoidal coil than the design values for POCE.

The power supply set voltage was held constant during the stellarator field experiments. In a series of 23 shots taken at two-minute intervals the bank voltage varied from 397.50 to 397.89 volts, or approximately one digitization step. The current in the stellarator coil varied from 6158 A to 6148 A (± 0.08%). Two random data points were taken at 5 and 10 minute intervals following the first 23 pulses, and showed no deviation outside the range of the previous data. The following day the procedure was repeated. After five conditioning shots, the current was measured and found to be 6152 A. The power supply was then turned off for two minutes then powered up. After a five-minute warmup interval the discharge current from the bank was 6148 A which was within the ± 0.08% variation measured the previous day.

In similar experiments (17 data points at two-minute intervals) with the solenoidal coil the current varied from 4439 A to 4427 A (0.135%). Concurrent magnetic field measurements showed a ± 0.129% field variation which appeared to be random with relation to the current. The nominal 13 kG solenoidal field in these experiments was significantly above the 5.5 kG POCE design value.

SUMMARY

The conceptual design of the magnets for the beam transport system for SLIA-POCE is complete. Fabrication of the bend magnets to tolerances of ≤ 15 mils will be completed by mid-June 1991. The remaining magnets are either in the final engineering design phase or are being fabricated. Thirty-three independently controlled capacitor bank power supplies for the magnets have been built and tested.

REFERENCES

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