The Mechanical and Shielding Design of a Portable Spectrometer and Beam Dump Assembly at BNL's Accelerator Test Facility

J.-P. Hu, W. R. Casey, D. A. Harder, S. Pjerov, G. Rakowsky, J. R. Skaritka

National Synchrotron Light Source, Brookhaven National Laboratory, Upton, NY 11973, U.S.A.
Phone: (631) 344-7113; Fax: (631) 344-3029
E-mail: hu1@bnl.gov

Abstract

A portable assembly containing a vertical-bend dipole magnet has been designed and installed immediately down-beam of the Compton electron-laser interaction chamber on beamline 1 of the Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL). The water-cooled magnet designed with field strength of up to 0.7 Tesla will be used as a spectrometer in the Thompson scattering and vacuum acceleration experiments, where field-dependent electron scattering, beam focusing and energy spread will be analyzed. This magnet will deflect the ATF's 60 MeV electron-beam 90° downward, as a vertical beam dump for the Compton scattering experiment. The dipole magnet assembly is portable, and can be relocated to other beamlines at the ATF or other accelerator facilities to be used as a spectrometer or a beam dump.

The mechanical and shielding calculations are presented in this paper. The structural rigidity and stability of the assembly were studied. A square lead shield surrounding the assembly's Faraday Cup was designed to attenuate the radiation emerging from the 1"-copper beam stop. All photons produced were assumed to be sufficiently energetic to generate photoneutrons. A safety evaluation of groundwater tritium contamination due to the thermal neutron capturing by the deuterium in water was performed, using updated Monte Carlo neutron-photon coupled transport code (MCNP). High-energy neutron spallation, which is a potential source to directly generate radioactive tritium and sodium-22 in soil, was conservatively assessed in verifying personal and environmental safety.

Keywords: dipole magnet, spectrometer, beam dump, portable magnet, accelerator

1. Introduction

The Accelerator Test Facility operated by the National Synchrotron Light Source of the Brookhaven National Laboratory has long been a facility dedicated to leading edge accelerator physics research. ATF Beamline 1 currently supports a Compton scattering experiment, using a polarized subterawatt CO_2-laser beam to interact with the ATF's high-brightness electron beam. Instrumentation necessary to record the x-ray emission was placed down-beam of the interaction chamber. A spectrometer previously used for another experiment had been disassembled and an additional beam tube and beam stop added to facilitate scattered electron-beam and x-ray studies. At the same time the experimenter wished to relocate the x-ray instrumentation closer to the interaction point. A new, compact, vertical-bend dipole magnet and beamstop assembly was needed

between the Compton chamber and the x-ray instrumentation [1]. The assembly also had to be easily transportable for quick beamline reconfiguration or use on other experiments.

This paper describes the design, analysis, and processes to produce and install this novel vertical-bend, portable assembly. It discusses possible advantages of this type of design to be used elsewhere at the ATF and other accelerator facilities.

2. Design of Dipole Magnet Assembly

The design objective was to incorporate (1) a 90° dipole magnet to deflect the electron beam vertically downward, (2) a vacuum chamber to transport the electron beam along the 90° arc between the magnet poles, (3) beam diagnostics to analyze the deflected electrons, (4) a beamstop to absorb the deflected electron beam, and (5) lead shielding to attenuate x-ray and neutron radiation emitting from the beamstop. All hardware was to be contained in a compact, "portable" assembly to allow quick reconfiguration of the beamline as needed for different experiments. The vacuum chamber also required a 0° port for additional diagnostics downstream of the magnet. Finally, the support structure had to be rigid, stable, and had to locate the magnet and beamline precisely.

The magnet was designed to deflect an electron beam with energy up to 60 MeV through 90°, with a nominal bend radius of $15^3/_4$". This requires a magnetic field of up to 0.7 Tesla. The gap between the magnet poles is 1.1" to accommodate the 1"-ID vacuum chamber. The poles are $2^3/_8$" wide and have 1 mm high shoulders along the inner and outer edges to enhance field uniformity. The pole edges at the entrance and exit are chamfered to reduce saturation effect. The yoke is fabricated from low-carbon 1006 steel.

By Ampere's law, nominally 17,000 ampere-turns of excitation are needed to produce the required field. Instead of fabricating special coils to fit the curved poles, the magnet was designed using simple, racetrack-shaped, water-cooled coils salvaged from decommissioned quadrupole magnets. Since the return leg of the C-shaped iron yoke had to be split into two to allow passage of the straight-ahead beam tube, the two return legs were made to fit three stacked racetrack coils each, as shown in Figure 1. A current of 50 amps in the 6 coils in series produces the desired 0.7-Tesla field. A 3-dimensional analysis using the code RADIA confirmed that the design of the poles and yokes was conservative with no excessive saturation [2].

In order of importance, the initial design requirements that had to be met were the magnetic field requirements, followed by the size and weight limits set by the ATF facility. An optimized design of the assembly capable of performing all the key functions from the hardware aforementioned was proposed. It includes a 400-lb magnet and coils, 180-lb aluminum stand and plate, 60-lb non-magnetic vacuum chamber (Nitronic-40), 1,600-lb lead shield, and 40-lbs of beam diagnostic devices. Additional hardware included optics, monitors, flanges, and vacuum accessories. Calculations showed that because of the lead shield, the 57"-tall 2,300-lb assembly will have a low gravity center ($7^1/_2$" aboveground) and large inertia moment (15" arm), assuring good static and dynamic stability for rolling safely on its casters without danger of tipping.
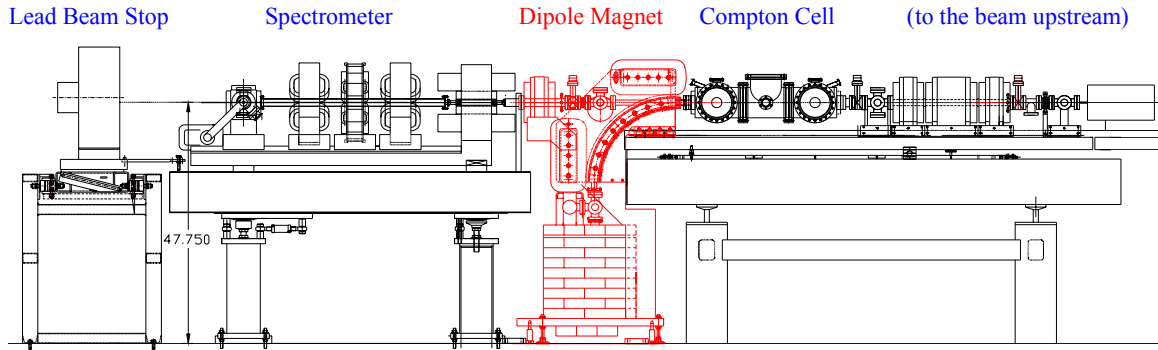
Fig. 1: The 90$^{\text{o}}$ vertical-bend dipole magnet assembly along the ATF beamline 1.

3. Assembly Fabrication

The 1006-steel components of the magnet were precision machined, inspected, assembled and shimmed to establish alignment of the poles and parallelism of the gap. The yoke pieces were pinned and bolted to allow disassembly and reassembly, if needed, without loss of alignment. The entire magnet-coil set as shown in Figure 2a forms a stable boxlike structure that can be oriented without affecting its functionality and dimensionality.
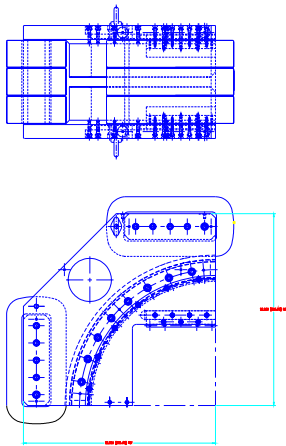

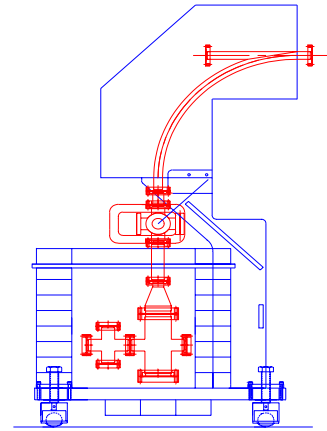Fig. 2a: 2-D drawings of the dipole magnet showing the yokes, poles, coils, and backlegs.

Fig. 2b: The central vacuum tube and diagnostics above beamstop.

The assembly's Nitronic-40 tube system, as shown in Figure 2b, has a second beam profile monitor after the bending dipole just prior to the Faraday Cup termination, permitting both the determination of beam's energy and charge. At position below the

magnet, the pipe's vertical section was enclosed by an array of stacked lead bricks to attenuate photons and photoneutrons emerging from the bottom beam stop. The use of easily handled 2"x4"x8" lead bricks allow a quick apparatus changeover by off-loading the shield to a height for part's access. The 1"-ID tube system located at the exact center of the two parallel poles was independently supported by the assembly's base plate. Two 1"-diameter bellows adapted by the horizontal pipe of the dichotomous system were flanged onto the vacuum tube of the beamline 1, which also has a 1" inner diameter. The dipole assembly was made portable by the use of heavy-duty ball-casters bolted under the base plate (Figure 2b).

A locating hole coupled with an on-axis alignment slot was drilled on the assembly's base plate to assure reproducible installation. Two locating pins as shown in Figure 1, made to match the size and location of the locating hole and the slot on the base plate, were surveyed to align with the beamline axis and secured to the floor. The magnet assembly can then be repeatedly installed onto a beamline with minimal effort from the surveyor. Once the assembly is in place, jackscrews are used to off load the casters and provide 4-point leveling and height adjustment.

The magnet assembly was designed to have the capability to either "key" into an aligned railing system at ATF-1 or be independently "surveyed" into the position lined up with the beam axis. Fiducial holes as shown in Figure 2a are located on either side of the magnet, symmetric to the beamline axis. Survey targets can be inserted into these holes to be used for precision elevation and leveling. A single line scribed onto a plate, placed over the top coils and pinned to the top edge of the steel yoke using fiducial holes, was set to locate the magnet center. This fiducial line can also be used for precision on horizontal adjustment.

4. Magnetic Field and Thermal Measurements

4.1   Magnetic Field Measurements

Magnetic measurements were conducted at the BNL's Magnetic Laboratory, using a calibrated Hall probe in location along the pole's centerline. The Hall probe that connected to a digital Teslameter in series for the field measurements has accuracy up to 0.2%, checked by a precision NMR Teslameter. Before the measurement, the dipole magnet was placed on a jack-table with leveling feet. As shown in Figure 3a, the probe was mounted onto an aluminum boom, which was attached to an 8" precision rotary-table with stepper motor drive. This table was secured to the surface of a second jack-table at position close to the one supporting the magnet. The boom assembly had a micrometer used for length adjustment. A calibration block with horizontal and vertical centerline marks was fabricated. It fit between the pole faces and served as a visual means to position the active element of the Hall probe at the center of the magnet gap.

A precision level was placed on the upper surface of the magnet, which was leveled using the adjustments on the jack-table supporting it. The level was then placed on the surface of the rotary-table and the calibration block was inserted between the pole

faces. Using the adjustments on the jack-table supporting the rotary-table, the probe was set to the marked height on the calibration block with the rotary-table leveled.

The probe was swung on an arc through the magnet as shown in Figure 3b. The calibration block was alternately inserted between the poles at either end of the magnet and the vertical position of the probe was checked. By making small adjustments to the leveling feet, the probe trajectory was aligned vertically. The misalignment was less than ±0.01". The probe was on axis in the vertical for all field data collected.

Fig. 3a: The Hall probe setup at center of poles' gap, water channels on 3 coils.

Fig. 3b: The field and thermal test setup includes magnet, probes, recorder on table.

The axis of the rotary-table was aligned to the axis of the magnet by attaching a dial indicator to the end of the boom and swinging it along the outer surface of the pole face. Screw-type adjusters were used to position the table laterally. After successive adjustments, the axis of the rotary-table was aligned to the axis of the dipole magnet within ±0.003" range.

The 6 magnet coils were connected in-series, with a total resistance at ~0.8 ohm. The coil set was connected to a power supply. A calibrated shunt was placed in the circuit to monitor the current up to 0.3% accuracy. The current was set at 25-amp. The magnet was not water cooled during the field survey.

The Hall probe was zeroed at the start of the data collection using a zero-gauss chamber. LabVIEW software operating on a laptop PC was used to control the probe motion and data collection. The Hall probe was stepped through the magnet in angular increments of 3° and a field reading was logged to spreadsheet each time. The total angular sweep was 120°, as shown in Figure 4a. The data collection started and ended outside the fringe field region. Multiple sweeps were done with the probe incremented in radius by 0.2" for each successive sweep; the probe radius was varied off axis by ±1" to survey the transverse field versus the on-axis field along the pole gap, as shown in

126

Figures 4a and 4b. A final baseline scan of the remanent field was done with the probe on axis and the power to the magnet turned off.
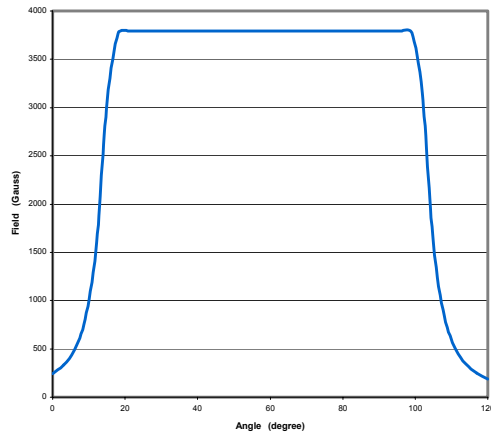

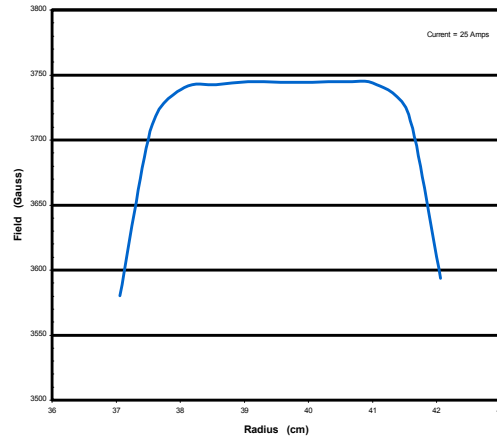Fig. 4a: Field strength in 120° along the nominal orbit radius at 25-amp.

Fig. 4b: Transverse field profile along the gap of magnet poles at 25-amp.

4.2   Thermal Measurements

The magnet's thermal tests were performed using four thermocouples placed in locations along the poles' centerline and in spots on the inner and outer surfaces of the magnet coils. An additional one was used to measure the ambient temperature. The accuracy of each thermocouple was individually checked at water's ice point and boiling point. At those calibration points the accuracy of all 5 thermocouples was ±0.5°C. Test results indicate that the coils can be run up to 25 amps under air cooled (Figures 4a and 4b), and up to 50 amps under 60°F chilled-water cooled. The maximum field strength obtained at 50-amp is 0.7 Tesla.

5. Beam Dump Shielding Design

A radiation shield consisting of piled lead bricks was installed to enclose the vertical portion of the beam dump [3]. Below the square shielding around the copper target, 3 side-by-side lead bricks have been bolted under the base plate. By so doing, a seamless shield has been formed around the beam stop except for openings left for the viewing window, fiducial posts, and beam tube (ingress). This 4" lead shield will be under Administrative Control for any necessary modification to restrict staff exposure to radiation during and after ATF operation. Strict environmental requirements at BNL also required evaluation of production of radioactivity in soil.

The amount of tritium produced from the thermal neutron capture of deuterium in ground water was calculated by the Monte Carlo neutron-photon coupled transport code MCNP [4]. According to the beam characteristics of 1.5 Hz repetition rate and 1 nC per pulse operated conservatively at 70-MeV, the maximum neutron yield per second from a copper target will be 10^8. Using this number as a fixed scaling factor for the MCNP

output tallies, the maximum tritium yield in the ground water will be $\leq 5.7 \times 10^{-6}$ pCi/liter, a statistical value that is below the detectable range.

The high-energy neutrons (≥ 25 MeV) generated from the photons' inelastic collisions have the potential to directly produce radionuclides through spallation in soil. These production rates were estimated through a series of calculations based on conservative assumptions [5], including beam's incident angle (0°), target medium (lead) and distance (20"), attenuation length (55 g/cm^2 in concrete), and neutron cross-sections of soil (SiO_2). The estimated tritium concentration in the underground water is about 0.17 pCi/liter.

In addition, ^{22}Na production from neutron's spallation was calculated using reported data from SLAC [6]. ^{22}Na in soil water leachate was calculated at 0.028 pCi/liter. This shield provides required personnel and environmental safety for the use of dipole magnet assembly in the ATF Experimental Hall.

6. Conclusion

We have presented the design of the vertical-bend dipole magnet assembly, which is a unique device that combines all the components of a wide-angle spectrometer and beam dump in a highly compact and self-contained form. It is portable and may have a variety of applications at BNL's Accelerator Test Facility. The design may have further use at other accelerator facilities as a flexible means of terminating a beam or inserting a branch point to temporarily add diagnostic devices along a beamline to efficiently serve multiple users. A radiation safety study has been performed, and the results of which show that the magnet assembly can be operated safely with shielding as described.

7. Acknowledgement

8. References

[1]   J.-P. Hu and J. R. Skaritka, "ATF Beam Line 1 Upgrade," BNL/NSLS/ME Engineering Design Proposal (2001).
[2]   G. Rakowsky, simulation of bending magnet for the design and tests (2001).
[3]   J.-P. Hu, "ATF-1 Dipole Magnet Beam Dump Shielding Analysis," BNL/NSLS Memorandum (2002).

[4] MCNP-4B2, "Monte Carlo N-Particle Transport Code System," developed by the Los Alamos National Laboratory and distributed by the RSICC of the Oak Ridge National Laboratory (1997).

[5] W. R. Casey, "Radionuclides Production in Soil from 60 MeV Electrons at the ATF," BNL/NSLS ES&H Review Report-000219 (2002).

[6] J. Liu and S. Rokni, "Analytical Method in Estimating the Induced Radioactivity in Soil around High Energy Accelerators," SLAC-RP Note (2000).