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A TABLE-TOP ALPHA-MAGNET*

A. V. Smirnov#, R. Agustsson, T. Campese, Y. Chen, J. Hartzell, F. O'Shea, and E. Spranza,

RadiaBeam Technologies LLC, Santa Monica, CA 90404, USA

Abstract

A compact electromagnetic alpha-magnet design, engineering, and operation are presented. The magnet was designed and engineered at RadiaBeam for a low-energy, laser-free, coherent Cherenkov THz-sub-THz source developed in collaboration with Argonne National Laboratory and integrated into the Injector Test Stand (ITS) of the Advanced Photon Source (APS). The magnet having 15 cm depth, 14" height, and up to 4 T/m gradient features a rectangular yoke, two on-axis coils, and substantially truncated, substantially non-hyperbolic poles. The profiled vacuum chamber for the magnet includes a motorized scraper and means of optical control.

INTRODUCTION

A growing number of low-energy electron beam applications impose serious limitations on the sizes of the beamline components that may include alpha-magnets. Among these applications are, e.g., compact ultra-short pulse X-ray radiation sources. In particular, an alpha-magnet can perform phase space rotation to enable a sub-ps microbunching of a few MeV electron beam injected from an RF electron gun (or small electron linac, "microlinac") having "natural" energy chirp. In that case a sub-ps laser photoinjector can be avoided allowing orders of magnitude higher average beam current. A substantial portion of the long RF bunch from the injector cannot contribute effectively into the microbunching in that case. That portion is usually filtered out (typically at low momentums) with a beam scraper placed inside the alpha-magnet chamber. RadiaBeam Technologies has developed such a compact alpha-magnet for 0.5 THz radiation source recently commissioned [1]. The experiment was jointly developed by RadiaBeam Technologies, LLC, and Accelerator Systems Division of Advanced Photon Source (APS) at Argonne National Laboratory (ANL) and performed in the Injector Test Stand (ITS) of the APS.

MAGNETIC DESIGN

Since the magnet to be deployable on the optical table of the existing ITS beamline, the main specification requirements to the magnet design are rather stringent: 360 mm magnet height (determined by beamline height ~180 mm), 4 T/m maximum gradient, ~15 cm maximum trajectory depth, and ~1% field quality.

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#asmirnov@radiabeam.com

A novel design was introduced to satisfy the challenging requirements. It features co-axis coils and a rectangular frame yoke. Such an approach implies a pole profile that essentially deviates from the conventional hyperbolic shape, because the magnetic flux distribution within the core of the pole in such a C-shaped, dipole-like configuration acquires naturally some intrinsic gradient and also higher order multipole components. Corresponding distortions must be compensated all the way along the trajectory depth with a non-canonical pole shape.

A special algorithm has been developed to provide the compensation. It is integrated with the model and makes correction of the pole shape on each iteration step. It uses prediction-correction technique to minimize field deviation from the linear curve of an ideal magnet. The correction function balanced with "weights" is based on a magnetic circuit approach in which the gap is considered as an array of magnetic resistors. As an initial example the approach was applied to design a larger magnet with 34 cm trajectory depth, and 1.25" minimum gap. The iterative optimization enabled ~0.3% field inaccuracy. The second model of the magnet was designed using this approach specifically for the RadiaBeam-APS experiment. The Radia [2] code used for the simulations demonstrated exceptional efficiency and required only several iterations to converge (or achieve satisfactory field quality). The model is shown in Fig. 1.

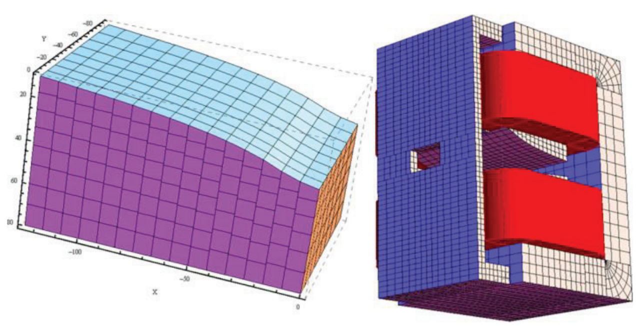

Figure 1: Radia model for the pole (left) and for the entire magnet (right).

The magnetization in the yoke is shown in Fig. 2. One can see that in spite of compactness the saturation effects in the yoke do not present the major limiting factor for the magnet performance. That enables gradients higher than 4 T/m for short periods of time.

In Fig. 3 and Fig. 4 the simulated magnetic field is plotted along the axis of symmetry and in the transverse direction respectively. The iterative simulation procedure

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resulted in 1.29% and 0.51% maximum and rms field deviations (related to the maximum field) from the ideal magnet piece-wise linear fit.

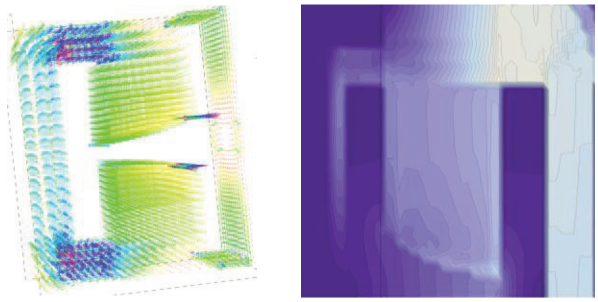

Figure 2: Vector plot for the yoke magnetization (with shims, left) and contour plot of the magnetic field in the vertical plain of symmetry (right).

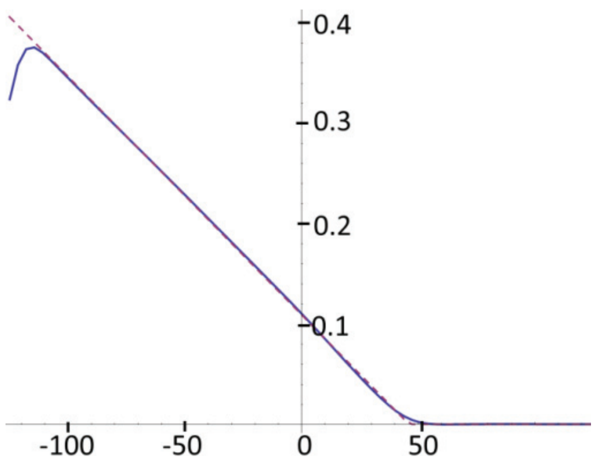

Figure 3: Vertical magnetic field along the axis of magnet symmetry [mm] (solid) and ideal alpha-magnet field fit (dashed) at 2.37 T/m gradient. X=0 corresponds to the pole edge.

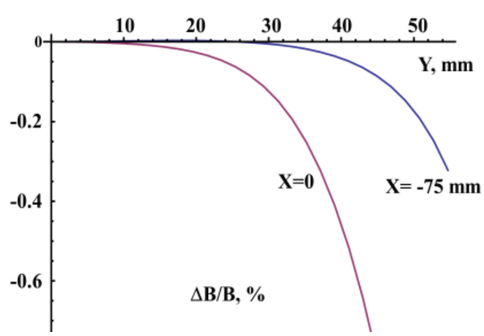

Figure 4: Relative deviation of the vertical field component [%] in transverse to axis of symmetry direction in median plane at 5/6th (x=-75 mm) and 1/3rd (x=0) depth of the magnet.

As it can be seen from Fig. 5 the maximum gradient error occurs in the low field region: in the region of the entrance and exit, the field is no longer dominated by the poles, but by the fringe fields. A number of shimming variants applied in that region provide only insignificant improvement of the field quality. The final result simulated with Radia has been confirmed with the Maxwell code simulations.

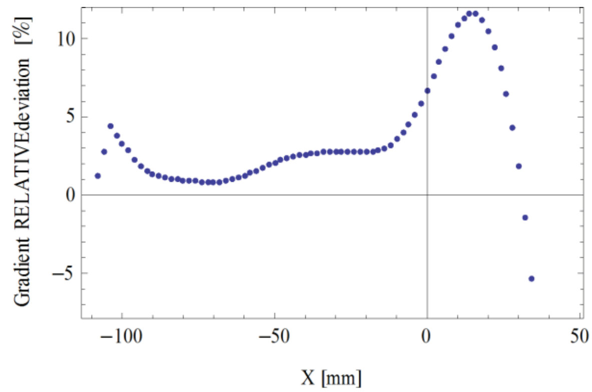

Figure 5: Field gradient relative deviation [%] from ideal magnet with respect to the maximum field plotted along the axis of symmetry.

The stray fields calculated outside the field clamp with the window are sufficiently low (not exceeding 5 Gauss for 4 T/m gradient).

THE MAGNET AND CHAMBER ENGINEERING

Compactness of the magnetic design enabled construction and assembling of the magnet yoke as a set of several blocks (see Fig. 3). The magnet has a minimum magnetic gap of 2.2 cm and a maximum gradient of the magnetic field of 4 T/m at an excitation current of 16.4 A limited by air cooling. The magnet height, width and length are 34.9 cm, 24.6 cm and 28 cm correspondingly. The pole dimensions (projected on the median plane) are: 125 mm × 178 mm enabling up to ~16 cm trajectory depth. The magnet weight is ~322 lbs.

The magnet winding consists of 392 turns. The maximum electrical power consumption does not exceed 400W. The magnet inductance is 0.67 H.

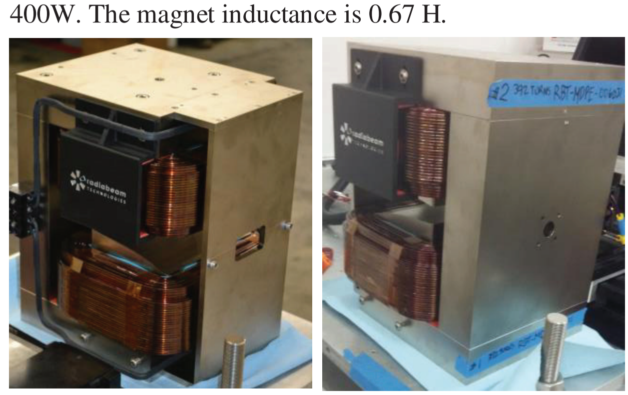

Figure 6: Front (left) and back (right) views of the table-top alpha-magnet fabricated, assembled and tested at RadiaBeam.

The alpha-magnet vacuum chamber has a vertically profiled shape resembling the magnetic gap. The vacuum

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chamber is supplied with a separate vacuum port and two beam ports of 2.18 cm aperture. It enables trajectory depths up to 16 cm, with vertical beam aperture ranging from 1.79 cm to 2.18 cm. The chamber assembly includes a scraper system to collimate the low energy portion of the beam. The actuator driven scraper position is remotely controlled in the range of (8.3-17.3) cm with respect to the magnet entrance. The scraper can operate at up to 50 W beam power deposited by the collimation with cooling provided by external water jacket.

The chamber system also enables optical observation of the beam scraping the collimator tip. It is accomplished with a phosphorous coating of the collimator tip, an optical port in the chamber, and through hole made in the center of the yoke back leg (see Fig. 6, right).

MEASUREMENTS

The magnetic field measured along the axis of the magnet symmetry is presented in Fig. 7.

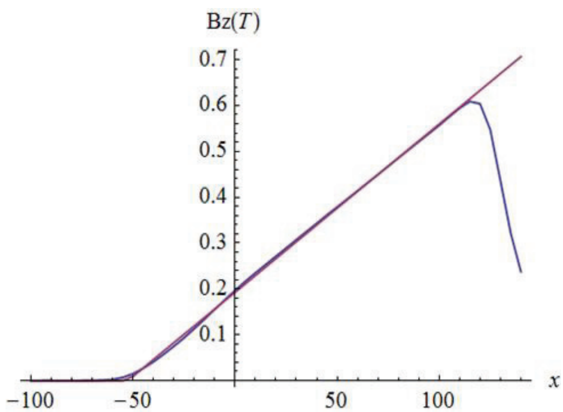

Figure 7: Magnetic field [T] measured along the magnet axis [mm] at 14.95 A current. X=0 corresponds to the pole edge.

The measurements indicate 1.3% and 0.63% maximum and rms field deviations from the ideal piece-wise linear fit respectively (normalized to the maximum field). Shimming to improve the field quality did not give a noticeable effect. Nevertheless the field quality turned out satisfactory for the THz source experiment.

The magnet efficiency we measured is 3.13-3.16 Gauss/(Ampere-turn-meter). It is close to the simulated value of 3 Gauss/(Ampere-turn-meter). Negligible saturation effects are observed up to 16 A current and the hysteresis effect demonstrated in Fig. 8 is also insignificant.

We have run a number of tests of temperature-limited performance of the magnet at room ambient temperature and convection air cooling. The winding temperature achieved 80°C after 4 hours of operation at 11.5 A, 17.83 V and 117°C after 3.5 hours at 14.95 A current and 25.79 V power supply voltage. The infrared images of the magnet under normal operation are shown in Fig. 9. These coils are much hotter than desired and next magnets change to water-cooled coils will improve the thermal stability and operating range of the system.

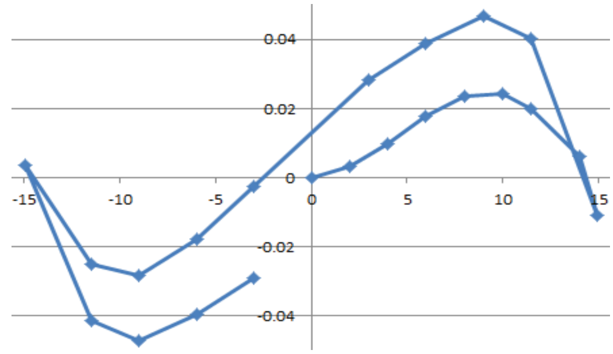

Figure 8: Hysteresis effect for deviation of field gradient [T/m] from the main curve of Fig. 8 versus of current [A].

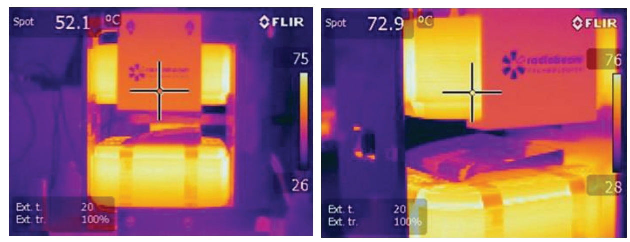

Figure 9: Infrared thermographs taken at 11.5 A, 17.83 V after 1 hour (left) and after 2.5 hours operation (right).

OUTLINE

A table-top electromagnetic alpha magnet with a remotely controlled scraper have been designed and commissioned. Successful alpha magnet system operation enabled adjustable production of intense, sub-THz coherent Cherenkov radiation [1].

The novel and inexpensive design can be applied in relatively small, low energy facilities, especially where weight and/or dimensions are limited including free electron lasers, far infrared sources, inverse Compton sources of ultra-bright hard X-rays, as well as beam instrumentation for microbunching and phase-space manipulation (e.g., magnetic compression combined with round-to-flat beam transformation [3]).

ACKNOWLEDGEMENTS

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