Characterization of the Magnetic-Field Parameters of an Electron Cyclotron Resonance Plasma System

M. T. Nichols, H. Sinha and J. L. Shohet, *Fellow IEEE*

Department of Electrical and Computer Engineering and Plasma Processing and Technology Laboratory,
University of Wisconsin-Madison, Madison, WI 53706, USA

Abstract—The magnetic field in an electron cyclotron resonance plasma processing system was characterized using IEEE standard measurement practices. We discuss methods for a low-cost Hall-effect sensor array construction, calibration, and measurement collection to meet or exceed available standards. Utilizing standard measurement practices, we find measured magnetic field parameters to be in excellent agreement with theoretical calculations.

Index Terms— Hall-effect sensors, Magnetic Field Measurements, IEEE standard practices

I. INTRODUCTION

MAGNETICALLY confined plasmas are becoming increasing ubiquitous in commercial materials processing and semiconductor device fabrication. As a result, there is a growing need for accurate and robust magnetic field characterization methods. By utilizing IEEE standard measurement practices, we create a well-defined and repeatable procedure for magnetic field measurements using low-cost components.

This work characterizes the magnetic field used to contain microwave and radio frequency plasmas in an electron cyclotron resonance (ECR) machine. Following the procedures defined in IEEE standard 1460-1996, we construct and calibrate a suitable magnetic-field sensor using a 3-axis array of Hall-effect sensors. We use this sensor array to map spatial variations in magnetic flux density and to characterize any time variations.

Since theoretical calculations for the magnetic field generated by parallel coils are well known, we compare our measurements with those calculated using a numerical model. These magnetic flux density calculations will be shown to be in excellent agreement with our measured results.

II. THEORY

Electron cyclotron resonance is exploited as an efficient means for generating ionized plasma. In an ECR system, a large current is driven into a pair of parallel magnet coils to create a magnetic mirror field. This field is superimposed onto a high-frequency electromagnetic field, typically created by a microwave or radio frequency (RF) source [1]. A schematic diagram of the ECR machine used for this work is shown in Figure 1.
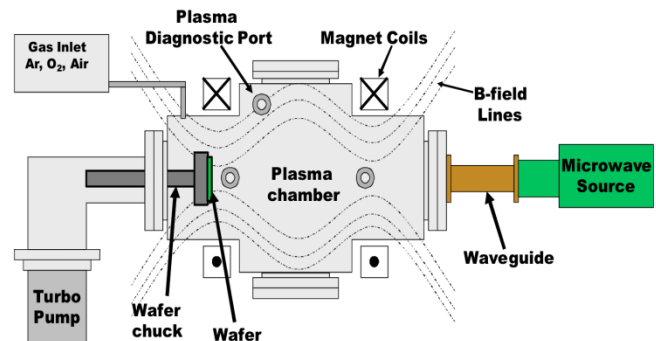

Figure 1: Profile view of a typical ECR machine

The magnet-coil currents can be varied to produce a suitable field so that the cyclotron frequency of electrons in the magnetic field matches that of the microwave signal, allowing for efficient transfer of energy to the electrons. Since the magnetic field strength varies with position, the cyclotron-resonant region can be placed where desired. However, undesired variations in the applied current or resultant magnetic field due to coil heating or power-supply fluctuations can cause drifts of the resonant surface to other locations in the plasma chamber. This has deleterious effects during plasma processing, such as reduced etching rates and decreased uniformity [2]. Generally, an optimum location for the resonant layer is found which tends to maximize the plasma temperature and density [3].

Other magnetically confined plasmas, such as those used during plasma enhanced chemical vapor deposition (PECVD), also suffer from magnetic field variations. Magnetron sputtering systems, which are actively pursued as a method to deposit high-k dielectrics during advanced device fabrication, can also produce non-uniform deposition due to magnetic field non-uniformities [4].

III. MEASUREMENT DESCRIPTION AND SENSOR CALIBRATION

A magnetic sensor array was constructed using inexpensive and widely available ratiometric Hall-effect sensors (OHS3150U). Typical cyclotron resonant magnetic fields in an ECR machine are on the order of 875 gauss, equivalent to .0875 Tesla, which is resonant at a frequency of 2.45 GHz. Our sensors were chosen for their excellent sensitivity at these fields.

Each sensor is capable of measuring the magnetic flux density normal to its axis. By aligning three mutually orthogonal sensors, it was possible to create an array capable of simultaneously measuring the flux density in each of the three coordinate axes.

Calibration of the sensor array was performed following IEEE standard 1308-1994 [5]. A magnetic field of known magnitude was created by winding 80 turns of 12-gauge magnet wire around a toroidal ferrite core. A one-mm slit was cut radially into the ferrite using a carbide blade. Current was driven through the magnet wire using a calibrated current source, creating a known magnetic field inside the torus. Each of the three sensors making up the Hall-effect sensor array was separately placed inside the one-mm slit, and measurements were read using a digital voltmeter. By plotting the output voltage versus calculated toroidal field, a calibration curve was created from which the flux density from the sensor voltage output could be obtained. This calibration was performed with the sensor array placed inside the ECR vacuum chamber to eliminate possible environmental sources of error.

IV. MEASUREMENT PROCEDURE

Multiple three-dimensional discrete sensor arrays were constructed and aligned horizontally, each measuring the flux contributions from the coordinate axes with a spatial resolution of one cm. Measurements were taken over the entire 42 x 42 cm cylindrical chamber to fully characterize the magnetic-field profile. Because of the symmetry of the chamber, the sensors were aligned such that the contributions from the z-direction were zero. This allowed construction of a profile of the flux density that is radially symmetric about the axis of the chamber, with the z-direction orthogonal to the radial-axial plane [6]. Figure 2 illustrates the spatial orientation of the sensor array.

Each individual sensor was interfaced with a 12-bit high-resolution analog-to-digital (A/D) converter (Labjack, U3). Each sensor was electrically connected to the A/D converter
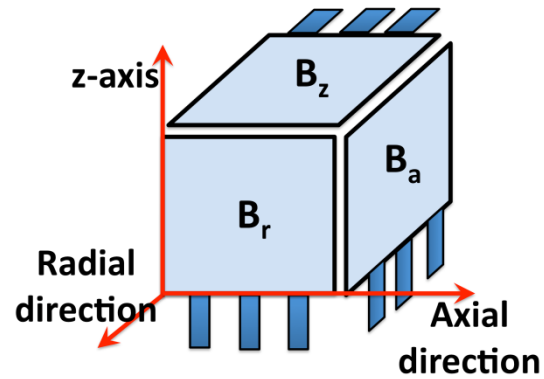

Figure 2: Orientation of Hall-effect Sensor Array

using 50ohm coaxial cable with grounded outer conductors. The sensor arrays were powered using a 12V battery source to provide an added layer of electrical isolation, and each sensor was bypassed using 0.1µf ceramic capacitors placed as close to the sensor power leads as possible.

Data acquisition was accomplished by interfacing the A/D converter over USB to a computer running LABVIEW virtual-instrumentation software. This software was written to sample each sensor channel at a rate of 120 samples per second. Each channel was sampled in parallel, and the results were averaged over five seconds to minimize any environmental noise that might still be present. Each sensor was also interfaced with a 60 Hz notch filter, implemented in software, to eliminate electrical interference from the mains.

In order to properly understand any observed variations in the magnetic field, it was important to characterize the power supply used to provide current to the magnet coils accurately. Coil currents were measured using a calibrated 50mV, 1500A current shunt connected in series with the magnet coils. Contacts were cleaned using an abrasive pad to eliminate potential stray resistances, and the voltage was measured using a calibrated digital voltmeter.

V. RESULTS

Measurements of the magnetic flux density were taken over the extent of the chamber with 1000A current driven through the magnet coils. However, at this current it was not possible to achieve the desired sensitivity from the Hall-effect sensor output. As a result, the current output was decreased by a constant factor resulting in a measured current using the current of 370A.

Results of the magnetic-field measurements are shown in Figure 3. Each curve represents a line of constant magnetic flux density. As can be observed, a coil current of 370A creates a resonant layer equal to 326 gauss, which is equivalent to 872G at a current of 1000A. Further, the curves
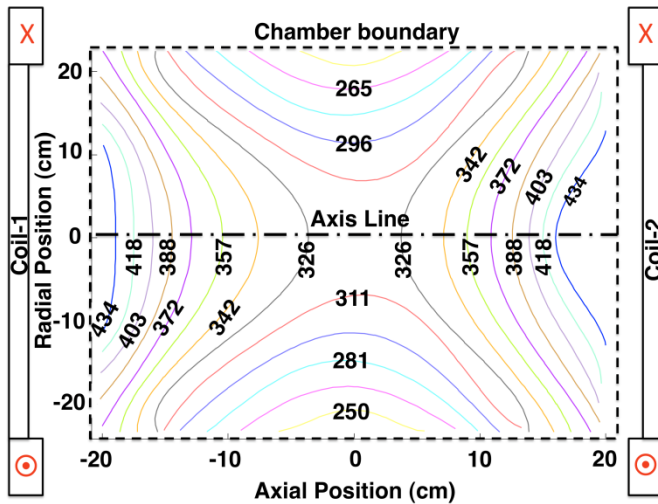
Figure 3: Measured surfaces of constant magnetic field in Gauss

Figure 4: Measured and Calculated Magnetic Field Lines

of constant magnetic field are demonstrated to have excellent axial symmetry. Axial symmetry can be used to locate problematic spatially varying magnetic fields caused by improper matching between the two magnet coils or incorrect alignment. Our results indicate an absence of these spatial non-uniformities.

It is possible to generate the magnetic field line trajectories from the magnitude and direction of the measured magnetic field vectors. These are shown as dashed lines in Figure 4. Magnetic field lines were generated by numerically placing a mesh over the radial-axial plane, with each mesh grid containing one point of measured data [7]. By iteratively plotting along the magnetic field vector in each subsequent mesh until the opposite chamber boundary, we were able to recover the field line trajectories from our measured magnetic field components.

For comparison with theory, the field line trajectories were also computed using well-established theoretical formulae magnetic fields from a set of circular loops representing the magnet coils [8]. The results of this theoretical model are shown as solid lines in Figure 4.

Comparison of measurement results to numerical calculations shows excellent agreement. A high degree of symmetry about the indicated axis line illustrates good spatial uniformity in the magnetic field and by extension improved spatial uniformity in ECR plasmas. The small deviation between calculation and measurement near the chamber boundaries is the result of idealization necessarily introduced in modeling the physical geometry of the copper coils.

Characterization of temporal variations in the magnetic field was performed using a modified version of the LABVIEW virtual instrument software. Using the same experimental apparatus, we configured the software to take three hours worth of data at a rate of 60 samples per minute. The aim of
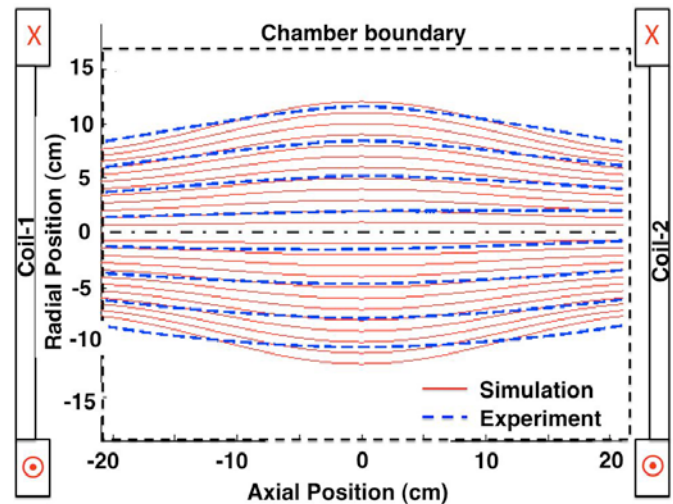
this measurement was to characterize any significant temporal variations in the magnetic field. Possible sources of such variation include power supply fluctuations, coil heating due to inadequate cooling, and inductive coupling between the coils and surrounding equipment.

Magnetic flux density measurements were sampled in the chamber for three hours, and the results averaged over this time period. By comparing the average and standard deviation of long-timescale measurements to our earlier data, we were able to determine that our results demonstrated no appreciable decline in magnetic field uniformity over this measurement period.

VI. CONCLUSIONS

We show that IEEE standard measurement practices can be utilized to experimentally characterize the magnetic field used in magnetically confined plasma experiments. Using low-cost Hall-effect sensors and IEEE calibration standards, we created a reproducible method that can be implemented in academic or industrial settings with little investment and high reliability. Measured magnetic flux densities are shown to be in excellent agreement with numerical calculations. Similarly, temporal variations in the magnetic field can be characterized by collecting sensor data over an extended time period. Analysis of this empirical data can be used to improve existing processes and to ensure reproducible results in applications of magnetically confined plasmas.

REFERENCES

[1] S.M. Rossnagel, J.J. Cuomo, and W.D. Westwood, "Electron Cyclotron Resonance Microwave Discharges for Etching and Thin Film Deposition," *Handbook of Plasma Processing Technology,* 1990 Noyes Publishing, N.J. pp. 285-307

[2] A.Wendt, N. Hershkowitz, R. C. Woods. "RF discharge with multidipole surface magnetic confinement for low pressure plasma etching," *Plasma Science, 1990. IEEE*

Conference Record - Abstracts., 1990 IEEE International Conference on , vol. 212, pp. 21-23 (1990)

[3] Matsuoka, M., and Ono, K. "Magnetic field gradient effects on ion energy for electron cyclotron resonance microwave plasma stream." J. Vac. Sci. Technol. A Volume 6, Issue 1, pp. 25-29 (January 1988)

[4] L. Khomenkova, C. Dufour, P.-E. Coulon, C. Bonafos and F. Gourbilleau. "HfO2-based thin films deposited by RF magnetron sputtering." *Materials Research Society. Mater. Res. Soc. Symp. Proc. Vol. 1160* (2009)

[5] "IEEE Recommended Practice for Instrumentation: Specifications for Magnetic Flux Density and Electric Field Strength Meters:10 Hz to 3 kHz." *IEEE Standard 1308 (1994)*

[6] "IEEE guide for the measurement of quasi-static magnetic and electric fields." *IEEE Standard 1460 (1996)*

[7] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes: The Art of Scientific Computing* Cambridge University Press, Cambridge, 1986☐.

[8] Landau, L. D.; and Lifschitz, E. M. (1971). *Classical Theory of Fields*. Course of Theoretical Physics. Vol. 2 (3rd ed.). London: Pergamon
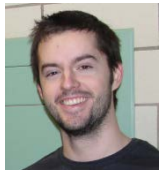
Mike Nichols is currently pursuing the B.S. degree in Electrical Engineering at the University of Wisconsin-Madison. He is enrolled in the Electrical Engineering Master's program at UW-Madison for the Fall of 2010, with a planned focus in Applied Physics. He presently works as an undergraduate research assistant at the Plasma Processing and Technology Laboratory at UW-Madison.

Harsh Sinha received the Bachelor's degree in Electrical Engineering from the University of Wisconsin-Madison in 2009. He worked at the Center of Nanotechnology as an undergraduate research assistant during his Bachelor's studies. Currently he is enrolled in Master's degree program, with Procknow Graduate Fellowship, in the department of Electrical Engineering at the UW-Madison. He is also a research assistant at the Plasma Processing and Technology Laboratory at UW-Madison. His work on the effects of VUV and UV irradiation on low-k porous organosilicate dielectrics has resulted in journal articles and conference papers.

J. Leon Shohet (S'56-M'62-SM'72-F'78) received his Ph.D. degree from Carnegie Mellon University in Electrical Engineering in 1961. He served on the faculty of The Johns Hopkins University before joining the University of Wisconsin faculty in 1966 and was appointed Professor of Electrical & Computer Engineering in 1971. He is the Director of the Plasma Processing and Technology Laboratory and is the Founding Director of the University's NSF Engineering Research Center for Plasma-Aided Manufacturing as well as the past chairman of the Department of Electrical & Computer Engineering.

He is the author of two textbooks on plasma science, over 170 journal articles and more than 460 conference papers. Dr. Shohet holds eight patents. His research interests are: plasma-aided manufacturing; fusion, especially waves, instabilities, heating, confinement and diagnostics; communications; magnetohydrodynamics; electromagnetic field theory; biophysics; and nonlinear science

Dr. Shohet is a Fellow of the American Physical Society and the Institute of Electrical and Electronics Engineers (IEEE). He received the Frederick Emmons Terman award of the American Society for Engineering Education, the Merit Award of the IEEE's Nuclear and Plasma Sciences Society, the IEEE Richard F. Shea Award, the IEEE Plasma Science Prize, the IEEE Centennial Medal and the John Yarwood Memorial Medal from the British Vacuum Council. Dr. Shohet founded the IEEE *Transactions on Plasma Science* in 1973.