Understanding The Calibration Methodology For The Axcelis GSD/HE Final Energy Magnet And A Means For Manipulating The Calibration Curve

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Abstract. In the course of monitoring and maintaining an accurate calibration of the Final Energy Magnet (FEM) located at the output end of the RF Linac structure in an Axcelis GSD/HE ion implanter, it would be useful to know exactly how the control system generates FEM setpoints for a given ion species. This paper presents the physical equations and mathematical model used by the HE control system to control the FEM magnetic field as measured by an internal gauss probe. Details of the mathematical model used by the control system to correlate actual gauss probe readings to calculated (theoretical) field strengths is presented. Included is a discussion of the relationship between ion electromagnetic rigidity and magentic field. Finally, a method for directly manipulating the calibration curve of the FEM is discussed as it relates to the specific methodology employed by the HE FEM.

Keywords: Axcelis, GSD/HE, FEM, final energy magnet, calibration
PACS: 61.72.Tt, 85.40.Ry, 29.17.+w,

INTRODUCTION

The ion energy delivered by the Axcelis GSD/HE ion implanter is determined by the setting of the Final Energy Magnet (FEM). A gauss probe situated between the FEM poles is used to measure magnetic field; this probe has high precision and repeatability, but does not measure absolute magnetic field. The location of the probe outside of the central field region leads to measurement non-linearity and to errors in actual field value. In order to translate readings from the gauss probe to values useful for controlling the FEM, a calibration curve is used which correlates the gauss probe response of a particular field to the actual field required for a given ion. The FEM is set to a value of magnetic field corresponding to the ion's rigidity and via the calibration curve, the FEM is controlled by a servo loop that matches actual gauss probe readbacks to what is required by the ion's rigidity.

The gauss probe response is linear to a measured field up to around 2500-3000 gauss, but the response becomes less sensitive at higher magnetic fields. Axcelis chose a quadratic fitting function for higher rigidity ions (up to 9000 gauss). The fitting function factors, along with the original FEM Calibration point data are stored in a file called, *cal_config.dat* on the system hard drive. The determination of the correction factors and a method to calculate the whole calibration curve is the subject of this paper.

PHYSICAL RELATIONS

Electromagnetic rigidity, ρ, is related to an ion's mass, energy and charge. For a given magnetic field, B, an ion's rigidity determines the radius of curvature, r, along which the ion will travel while subject to the field:

$$\rho = Br = \sqrt{[2mE/(eq)^2]},\ \text{Tesla-meters} \qquad (1)$$

In the HE system, mass is customarily measured by amu and energy by keV; therefore some conversion constants will be required to enable accurate calculations:

$$\rho = Br = \sqrt{[2*(mk)*(e'E*1000)/(eq)^2]} \qquad (2)$$

k = 1.6605E-27 kg/amu
e' = 1.602E-19 Joules/eV
e = elementary charge = 1.602E-19 Coulomb

For example, 31P+ at 1000 keV and at 500 keV, the respective quantities are:

m = 31, E = 500 and 1000, q = 1, which gives
ρ(500 keV) = 0.5666 T-m or 5666 gauss-meters, and
ρ(1000 keV) = 0.8013 T-m or 8013 gauss-meters.

An important factor in relating measured gauss to required gauss for the calibration curve calculations is the radius of curvature for the FEM. A number of measurements on the HE systems indicates this value is around 0.84 meter. Using this value with the rigidities above gives:

B(500 keV) = 0.6745 T or 6745 gauss, and B(1000 keV) = 0.9539 T or 9539 gauss.

Both of these ions have adequate rigidity(field) to require quadratic correction in the FEM calibration curve; for such processes, it is essential to have a repeatable method for matching the energy calibration among multiple HE systems.

CALIBRATION OVERVIEW

The HE system software provides four calibration points that are set by tuning specific ion beams at specific energies (with all rf cavities off). The software records ion mass, extraction voltage and gauss probe reading for each of the four points. The gauss measured by the FEM probe always reads lower than the actual gauss required for a given rigidity. All of the relevant data collected during the calibration is stored in the *cal_config.dat* file. Once the calibration data have been recorded, the software generates a linear fitting function for low to moderate rigidity ions and a quadratic fitting function for the moderate to high rigidity ions.

The field where these two functions intersect is labeled 'FEM cal quadratic cutoff B'. The linear fit results are stored in the configuration file as a slope/intercept format ($y = mx + b$) with the quantity 'FEM magnet scale correction' serving as the slope and the 'FEM magnet offset correction' as the intercept. For the quadratic fit, three constants are listed that correspond to a general quadratic equation of the form, $y = Ax^2 + Bx + C$. The one oddity of the organization of the constants is that 'y' corresponds to the real gauss while 'x' corresponds to the gauss probe response so that to find the internal gauss probe reading required for an ion of rigidity, y, requires one to invert the appropriate equation and solve for 'x'. This is trivial to do for the linear fit, but more involved for the quadratic portion of the FEM calibration curve. Possibly, the software may use an iterative method to calculate the uncorrected readback. Figures 1 and 2 illustrate the departure of the gauss probe readback from linearity at higher field strengths.

DISCUSSION

The calibration mechanism provided by Axcelis corrects the gauss probe reading to improve energy linearity over a wide range of electromagnetic rigidities. For the highest rigidity ions that the system is designed to accelerate, the departure from linearity of the gauss probe response can lead to errors in the measurement of B of 5%, or higher. Since a linear fit to the HE gauss probe response over-estimates B, use of such a fitting function could lead to energy errors of +10% or higher.

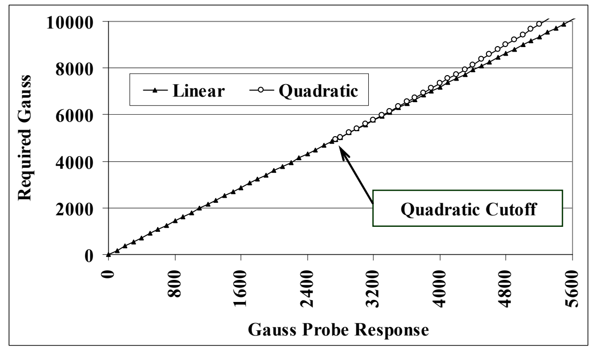

FIGURE 1. Example plots of the linear and quadratic curve fits for HE FEM Calibration

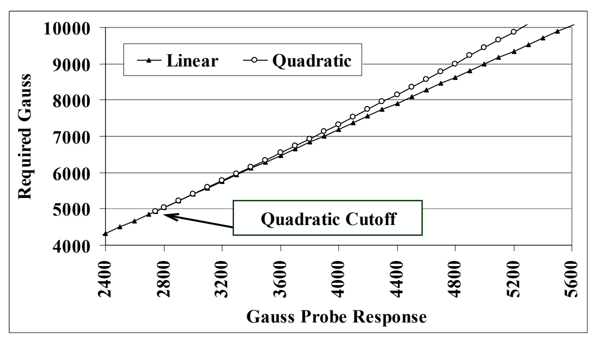

FIGURE 2. Example plots of the linear and quadratic curve fits for HE FEM Calibration - Detail

In principle, the calibration procedure offered by Axcelis is straightforward. The FEM high and low points are obtained from simple to tune boron and argon ion beams. However, the two so-called FEM ULTRA calibration beam set-ups require triply-charged Xe to be introduced into the HE linac. The FEM is then adjusted to analyze the singly charged fraction that results from collisions with the background gas over the 2 meters of the linac's length. Due to limitations in mass analysis prior to the linac, correct identification of the desired Xe isotope is not always clear. Again, energy errors may result.

The time involved in tuning the four ion beams, optimizing their transport through the linac and in gas bottle changes for the Xe source gas can be significant. Also, depending on the level of pre/post FEM Calibration verification one chooses to require, additional non-productive tool time can be consumed. A regular calibration or calibration verification program can be costly in a production environment.

MANIPULATION OF THE CALIBRATION CURVE

One can imagine a scenario where a site with multiple HE installations establishes an energy monitoring program with the intent of maintaining good agreement across all machines. If, however, one determines that the energy delivered by a particular machine has deviated from the norm (and the deviation were small), it would be useful to be able to adjust the machine's energy output with as little interruption to production as possible. Knowing the form of the FEM calibration curve fit and how to interpret the constants stored in the software system allows for direct manipulation of the FEM calibration curve without running the complete FEM calibration procedure.

There are two potential solutions to this endeavor. One is to realize that when executing the FEM Calibration procedure (or even the Analyzing Magnet Calibration procedure), that the system software doesn't actually check the quality of the beam set-up or even whether any beam current exists. The software verifies only that the extraction energy, amu setpoint and ion charge are correct for a given step – no actual ion beam need be set-up. The final, crucial information the system needs to set a calibration point is for the FEM to be set at the desired value. An approximation of the required magnetic field can be made from an estimate of the energy error:

$$\Delta B/B \approx \tfrac{1}{2}\Delta E/E \qquad (3)$$

Using the calibration constants, one can then estimate how to set the FEM to give the desired change in calibration. This method does not involve detailed calculations on the part of the user – the system software will automatically udpate the configuration constants.

The second method involves direct editing of the configuration constants using only calculated values. This method requires more detailed calculations and an understanding on the part of the user of how to apply curve-fitting routines to data sets. In order to effect this, one would need to know how to fit a parabola to an existing line given two additional points (FEM ULTRA1 and FEM UTLRA2). When mating two curves, e.g., a line and a quadratic, it is customary for the two functions to have continuous first derivatives which also have the same value at the point of intersection. In the case of the FEM Calibration curve, this requirement is what partially defines the 'Quadratic cutoff B' value. This requirement also ensures that the quadratic portion of the curve fit always lies above the linear fit for a given ordinate value. Once having calculated the desired values for ULTRA1 and ULTRA2, then one could also calculate the quadratic fitting constants and directly edit the configuration file. A system reboot would be recommended to ensure that the values are activated. While it has been verified that user chosen values can be directly entered into the configuration file and the system will use those values in setting the FEM, this approach has not been deployed in production.

CONCLUSIONS

The FEM calibration curve relies on a two part curve fit comprised of a linear portion for lower rigidity ions and a quadratic portion for higher rigidity ions. The constants used to define these curves as well as the data used to calculate them are contained in a file called *config_cal.dat*. It is possible to directly manipulate the constants to produce a calibration curve without executing the FEM Calibration procedure. This would be desirable for maintaining an energy match between mupltiple machines and also for reducing tool down time for the purpose of checking or resetting the FEM calibration curve.

ACKNOWLEDGMENTS

The work presented in this paper was developed on HE/VHE Software Revision 3.1

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