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Semi-Empirical Calibration Technique for the MSE Diagnostic on the JET and DIII-D Tokamaks

M.A. Makowski[1], M. Brix[2], N.C. Hawkes[2], and the EFDA-JET Contributors[3]

[1]*Lawrence Livermore National Laboratory, Livermore, California 94550, USA*
[2]*EURATOM/UKAEA* Fusion Association, Culham Science Centre, Oxon OX14 3DB, UK
[3]*See the Appendix of M. L. Watkins et al., Fusion Energy 2006 (Proc. 21st Int. Conf. Chengdu, 2006) IAEA.*

Abstract. Calibration of the motional Stark effect diagnostic is technically straightforward but complicated by a number of practical considerations that potentially introduce systematic errors. We have developed a semi-empirical method to optimize calibrations that is based on constraining the calibration to agree with equilibria derived from simple current-ramp discharges. The optimized calibrations quantitatively improve the equilibrium reconstructions and yield good agreement between the onset of a variety of MHD phenomena and the predicted appearance of corresponding mode rational surfaces.

I. Introduction

Calibration of the motional Stark effect (MSE) diagnostic has traditionally been carried out using either *in-situ* measurements, as on DIII-D, or with bench measurements of major sub-assemblies of the optical train, as on JET. Efforts to characterize the system under laboratory conditions constitute a “first principles” calibration. In addition, beam-into-gas measurements are used to further refine the zero pitch-angle value under conditions analogous to those in a plasma discharge. The “first principles” approach, while generally providing a very good 0^{th}-order calibration, has proven inadequate to reliably analyze the wide variety of conditions and plasma configurations which are now routine (L-mode, H-mode, high-β_N, reverse-shear, current-hole, …). Adjustment of some channels has always proven necessary to obtain agreement with known plasma physics, such as the spatial extent of the $B_Z = 0$ region in a current hole or matching the time of onset of MHD phenomena such as sawteeth and neoclassical tearing mode with the appearance of a corresponding mode rational surface. These adjustments are generally restricted to a single coefficient. To improve the calibration, a semi-empirical method has been developed [1]. The method is based on constraining the calibration to agree with equilibria derived from current ramp discharges. Current ramps are used as they slowly scan the measured pitch-angle of each channel through a range of values. Because the shots are essentially ohmic, accurate EFIT reconstructions can be obtained. Such EFITs, *unconstrained by MSE data*, are then generated to form a dataset to which the MSE data is matched using a minimization algorithm. The simplex algorithm is used for this purpose, together with a least-squares measure of the goodness-of-fit of the MSE data to the EFITs. This technique has proven to be straightforward to implement and applicable to JET and DIII-D data. The results presented show that the χ^2_{mse} is reduced and improved EFIT reconstructions are obtained that are in better agreement with other physical phenomena without further adjustment of the calibration coefficients.

II. DIII-D MSE Calibration Results

The upgraded MSE system on DIII-D now has 64 active channels viewing 2 beams from 5 different vantage points [2]. Achieving consistency from one MSE array to the next and between arrays viewing different beams is extremely challenging. Over the past several years the *in situ* calibration techniques have been refined to the point that it is now possible to derive equilibrium reconstructions directly from the raw calibration data, albeit with a relatively high value of χ^2_{mse}. Despite the improvements, this first-principles calibration still lacks the level of accuracy that is theoretically possible and needed to simultaneously resolve the edge E_R and B_z. Further improvements upon the in-vessel measurements will be difficult to achieve.

To refine the calibration we have developed a semi-empirical method using I_p–ramp shots as described above. The results have greatly improved the equilibrium reconstructions in many quantitative ways. These include a reduction in χ^2_{mag} and significant decrease (factor of 5-10) in χ^2_{mse}, improved convergence, and E_R profiles in better agreement with profiles derived from charge exchange measurements. The q and current density profiles inferred from either of the two beams alone or both beams together, are statistically the same. The optimized calibration predicts the time of appearance of integer and half-integer q-surfaces in agreement with measurements of RSAE modes [3] as well as the onset of tearing mode activity with the appearance of a particular mode rational surface. Figure 1 shows an example of a transition from a single MSE co-beam to a co- and counter-MSE beam.

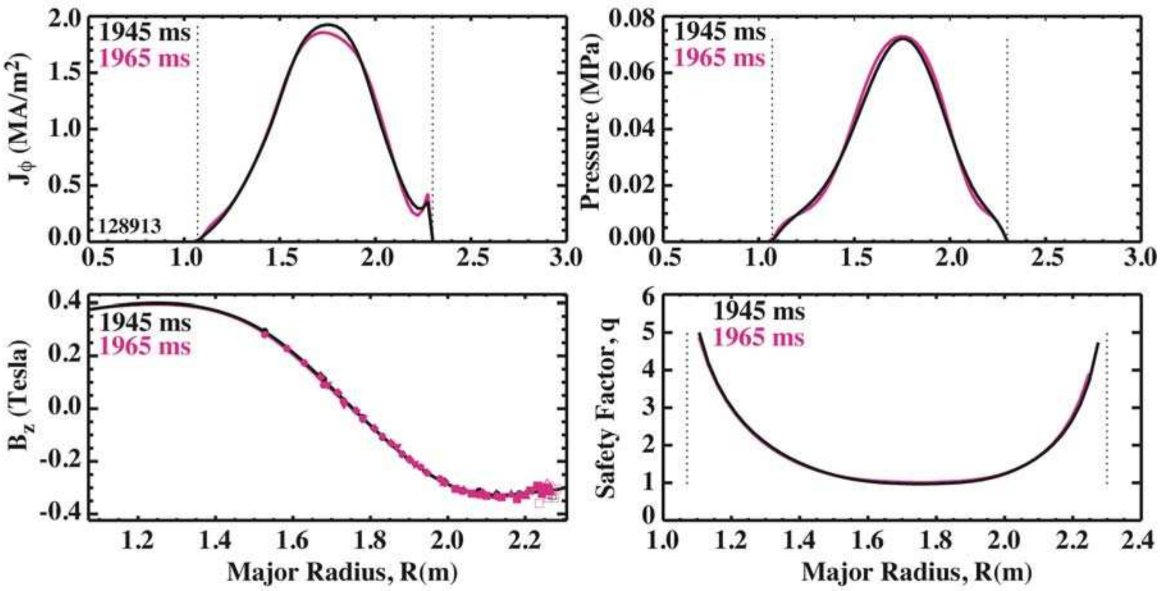

Fig 1. Profiles before and after a transition from a single MSE co-beam (black curves) to both a co- and counter MSE beam (magenta curves) based on a simplex optimized calibration. Symbols indicate loacations of individual MSE channels.

III. JET Calibration Results

A code was developed to apply the optimization technique to the JET MSE system [4]. An analysis of the calibration data was undertaken with emphasis on the parameters that characterize the optical system: α = the tilt angle of the viewing optic, δ = retardance of the optical train about a fast axis at angle α, and r_m = relative reflectance of the s- and p-polarized light. In addition, an electronic gain factor, a_{23}, was included. The goal of the analysis was to determine if there were any systematic errors that could be uncovered.

As with the DIII-D analysis, I_p-ramp discharges were produced and several data sets were created that included equilibria with varying data constraints. EFITs constrained only with magnetics data were used to form the data set. Due to the significantly longer resistive time scale on JET, it was not possible to obtain a data set with a wide range of pitch angles for each channel, but there was sufficient data for the purpose of this analysis.

Optimizations were carried out on single calibration coefficients and selected pairs of coefficients. The results for an α-δ optimization with a constant value of the a_{23} coefficient are shown in Fig. 2. A relatively large difference is obtained in δ between the laboratory and optimized calibrations. There is a smaller corresponding change in α. The change relative to the laboratory values is largest for the core channels and is within the experimental error of the laboratory measurements for α and large enough in δ to strongly suggest that it is a source systematic error. Additional results show that it is possible to optimize the calibration with different coefficients or combination of coefficients. However, the goodness-of-fit measure for the minimization of Fig. 2 was among the lowest found. Improving the data set by increasing the range of magnetic field values and range of pitch angles used in the minimization would allow better discrimination between different coefficient optimizations and help to positively identify sources of systematic error.

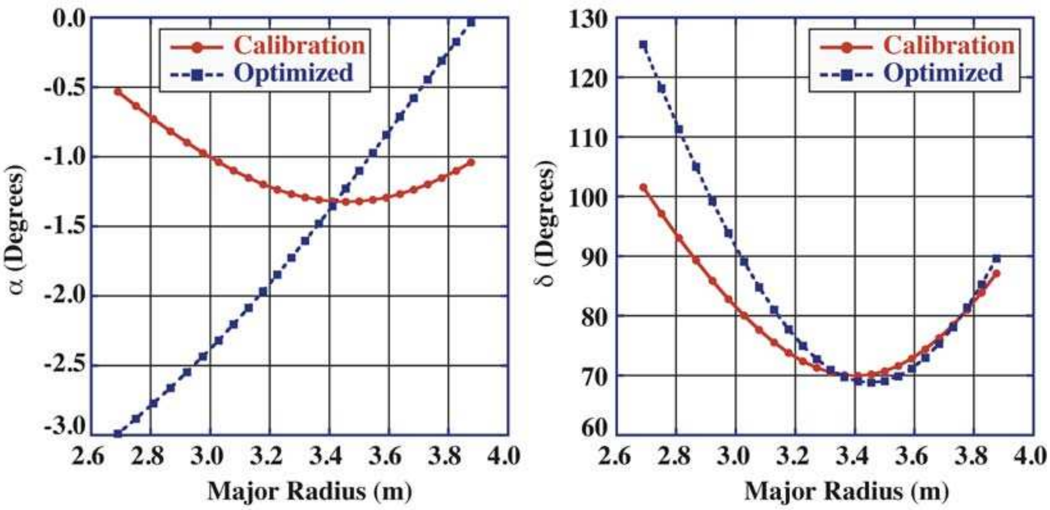

Fig 2. Comparison of laboratory measured calibration coefficients with those from a combined optimization of α and δ and a fixed value of a_{23}. The difference is within the experimental error in the measurement of the calibration coefficients.

Figure 3 shows a comparison of q-profiles derived from equilibrium reconstructions based on a variety of MSE calibrations. Curves labeled 91, 100, and 104 are based on laboratory measurements, while those labeled 616 are from the α-δ optimization with constant a_{23} as described above, both with and without an additive offset. The points with error bars on the $q = 1$ horizontal line correspond to the sawtooth inversion radius and the black bar indicates the radial location of the MSE channels. The optimized calibration falls between the previous and most recent laboratory calibrations, results in a broader q-profile, lower $q_{\min}$, and modestly improved agreement with the inversion radius, all of which improve the agreement with other measurements.

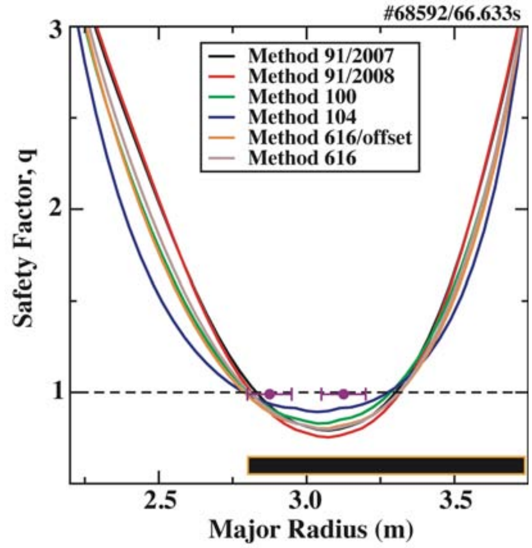

Fig. 3. q-profiles from equilibrium reconstructions based on a variety of calibrations. The horizontal black bar indicates the radial extent of the MSE system.

IV. Conclusions

Optimization of calibration coefficients based on the simplex method and simple plasma discharges is a powerful means of quantitatively improving equilibrium reconstructions based on MSE data. When applied to DIII-D data, equilibrium reconstructions are substantially improved for a wide range of plasma configurations. Results for JET indicate that systematic errors in the calibration are present. However, the correction is found to be small and as yet cannot be uniquely ascribed to single calibration constant.

Acknowledgement

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