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M.A. Makowski, M. Brix, and N. Hawkes and JET EFDA contributors

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M.A. Makowski[1], M. Brix[2], and N. Hawkes[2] and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

[1]Lawrence Livermore National Laboratory, Livermore, California 94550, USA
[2]EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK
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ABSTRACT.

Calibration of the MSE diagnostic is technically straightforward but complicated by a number of practical considerations that potentially introduce systematic errors. These include the fact that in many instances only a portion of the diagnostic can calibration under laboratory conditions and the uncertainties resulting from inexact knowledge of the location of the beam centerline, to name just two. Uncovering systematic errors is difficult as they can be masked by overestimating the statistical errors in the calibrated quantities. Thus alternative means of validating the calibration and correcting it are of interest. Below we present a semi-empirical means of achieving this goal through the use of current ramp shots.

1. INTRODUCTION

Calibration of the 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 magnetic axis in a current hole or MHD phenomena such as sawteeth and neo-classical tearing mode onset. These adjustments are restricted to a single coefficient and generally based on matching physics constraints such as those just mentioned. To improve the calibration, a technique based on simple I_p-ramp shots has been developed [1]. These shots are ohmic and heated with only the minimum NBI power needed to make the MSE measurements. The current ramp slowly scans the measured pitch-angle of each channel through a range of values. Because the shots are essentially ohmic, accurate EFITs reconstructions can be obtained. Such EFITs, *unconstrained by MSE data*, are then generated to form a data set 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 both 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 physics constraints. The technique can also be applied to aid in the calibration of the MSE diagnostic for ITER.

2. 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 system to the next and between one beam and the other 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 CER derived profiles. Further, the q and current density profiles inferred from either of the two beams alone or both beams together, are statistically the same. In addition, the semi-empirical calibration predicts the time of appearance of integer and half-integer q-surfaces in agreement with measurements of RSAE modes [4] as well as the onset of tearing mode activity with the appear-ance of a particular mode-rational surface. Figure 1 shows an example of a transition from a single MSE co-beam so a co- and counter-MSE beam.

3. JET CALIBRATION RESULTS

A code was developed to apply the semi-empirical calibration technique to the JET MSE system [3]. 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, 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 from the inter-shot analysis were used to form the data set. A second EFIT data set using both magnetic and Faraday rotation measurements was also generated, but the EFITs differed insignificantly from the inter-shot only analysis indicating that the inter-shot analysis was sufficient for our calculations. 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. Significantly, this case yields a value of α that is linearly varying with channel. Experimentally, this trend would be expected as the viewing angle should be a monotone function of channel and is counter to the experimentally measured parabolic profile. There is a corresponding change in the retardance, δ. The change relative to the measured values is largest for the edge channels. The differences between the laboratory and derived calibration coefficients are within the experimental error of the laboratory measurements. Other optimizations results show that it possible to absorb the difference between the pitch angles inferred from the laboratory calibration and those derived from this analysis with different combinations of coefficients. Thus it is difficult to precisely determine the source of systematic error. However, it is clear that systematic errors are present.

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 slightly broader q-profile, and modestly improved agreement with the inversion radius.

CONCLUSIONS

Adjustment 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. The correction is small and cannot be uniquely ascribed to single calibration constant.

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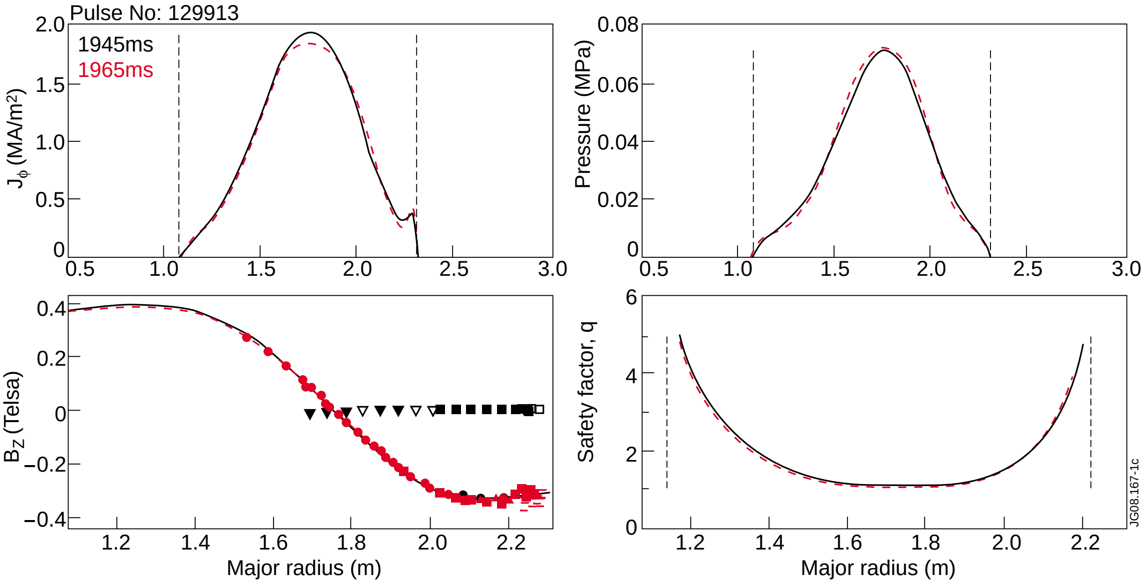

Figure 1: Profiles before and after a transition form a single MSE co-beam (black curves) to both a co- and counter MSE beam (red curves) based on a simplex optimized calibration

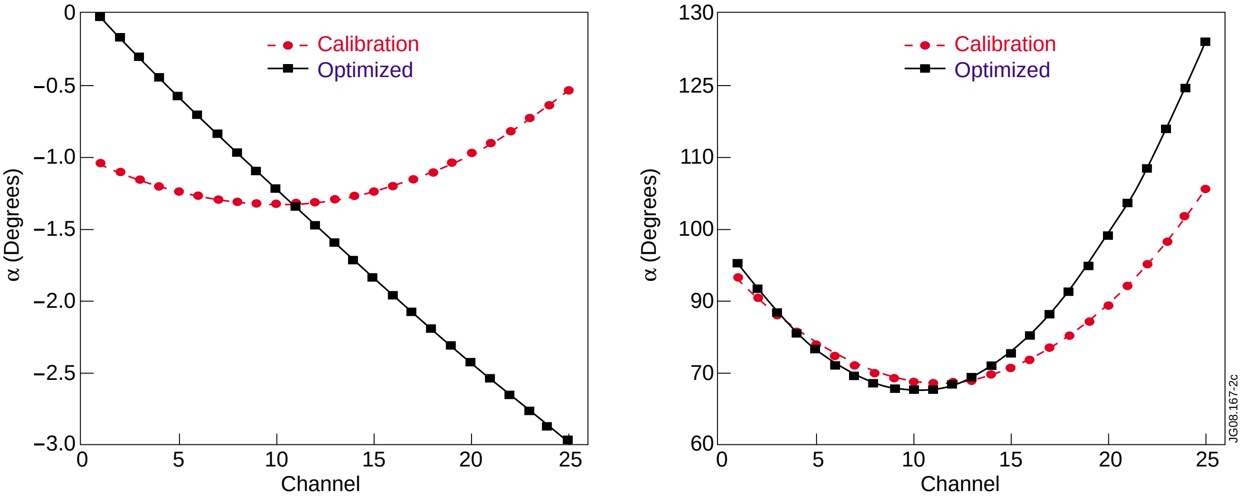

Figure 2: Comparison of measured calibration coefficients with those from a combined optimization of and and a fixed value of a_{23}.

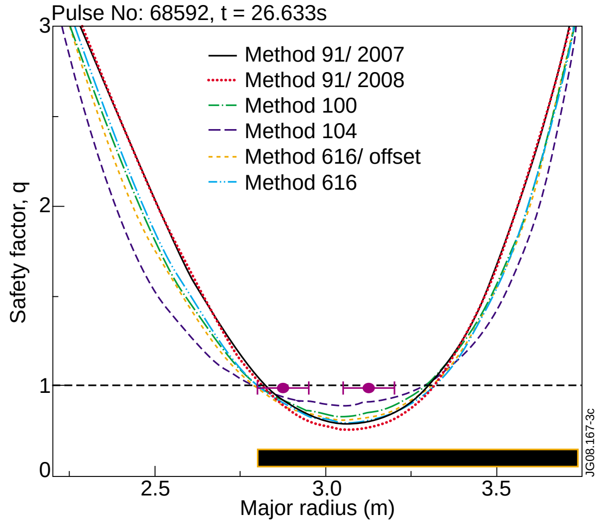

Figure 3: Q-profiles from equilibrium reconstructions based on a variety of calibrations.