Calibration and uncertainty analysis of magnetic measurement for plasma shape reconstruction on EAST

(The paper will be submited to Fusion Engineering and Design)

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Abstract: Magnetic diagnostics is one of basic measurement systems for Tokamak plasma current and shape control. The accuracy of magnetic data will influence the plasma shape reconstruction. In this paper, the calibration of magnetic diagnostics is carried out on the EAST Tokamak. The overall uncertainties of magnetic sensors are analyzed from the calibration and vacuum shots. The uncertainty results are used as fitting weight in plasma shape reconstruction code (EFIT). Based on EFIT simulation and experiment data fitting results, the sensitivity of the magnetic data uncertainty in the plasma shape reconstruction is analyzed.

1. Introduction:

Magnetic diagnostics is the basic and essential parts in Tokamak device. On EAST superconducting Tokamak, the magnetic diagnostics includes plasma current rogowski coils, magnetic pickup coils, mirnov probes, poloidal flux/saddle loops, diamagnetic loops, Halo current monitors, and poloidal field coil current sensors. The configuration of EAST magnetic diagnostics is showed in figure 1[4].

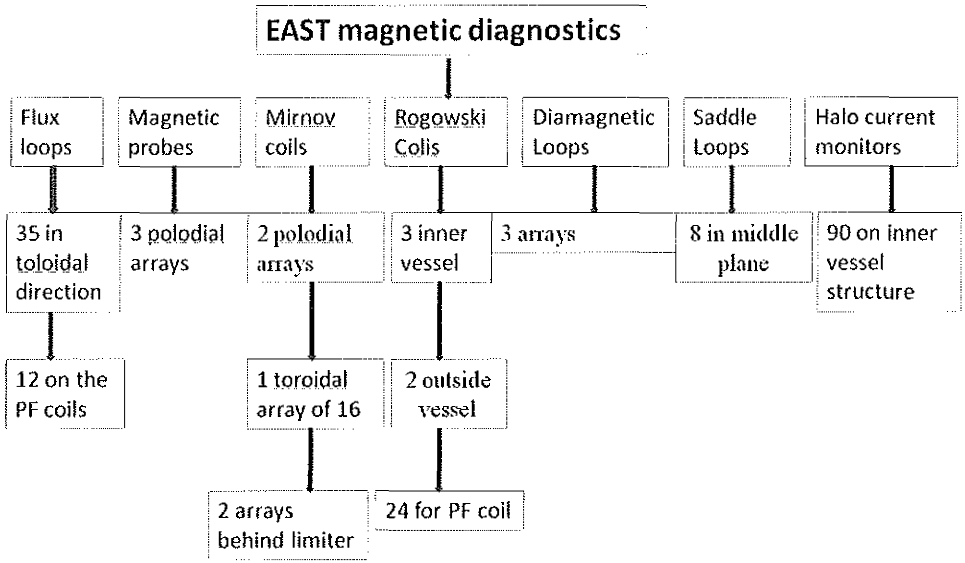

Figure 1. EAST magnetic diagnostic configration

In magnetic diagnostics, sensors which are used for equilibrium reconstruction contain: plasma current rogowski coil, 38 poloidal magnetic probes, 35 poloidal flux loops and 12 poloidal field coil currents.

The basic principle to reconstruct the plasma shape is to solve the Grad-Shafranov equation[1], the parameters are determined from magnetic data by minimizing the fitting error:

$$\chi^2 = \frac{1}{k}\sum_{i=1}^{k}\frac{\left(X_i^c - X_i^e\right)^2}{\sigma_i^2} \quad (1)$$

$$X^c = G\left(\vec{r}_d, \vec{r}_{PF}, \vec{r}_{plasma}, \vec{r}_{eddy}\right)\times I \quad (2)$$

Where X_i^c and X_i^e are the computational and experimental values of magnetic measurement. Fitting weight σ_i should stand for the offset $\Delta_i = X_i^c - X_i^e$. G is matrix of green functions, I and $\vec{r}$ are the matrix of currents and positions.

The total offset comes from green functions and measurement:

$$\Delta = \Delta^c + \Delta^e \approx G\left(\vec{r}_d, \vec{r}_{PF}\right)\times I_{PF}^{\Delta} + G^{\Delta}\times I_{PF} + \sigma_d \quad (3)$$

The offset contains the effects of all uncertainty sources. They can be divided into two parts, the system uncertainties and the random uncertainties. The system uncertainties include PF current, and uncertainty of magnetic diagnostics σ_d. The uncertainty of magnetic diagnostics contains the error of diagnostics active areas, the error of integrator-acquisition system, the signal attenuation of the 70m twisted pair, and the imperfection of the diagnostics. The mainly random uncertainties are base on the positions of poloidal field(PF) coils and magnetic sensors[2].

In EAST magnetic diagnostics system, the system uncertainty parameters which are needed to be calibrated are listed in following: sensors effective area, integrator and amplifier, signal transfer line. Different methods for calibration are introduced in detail in this paper.

For flux loop, $\phi = \int V_s dt = \frac{G}{RC}\int V_s dt \cdot T_{das\_fl}$

For magnetic pickup coil and rogowski coil, $\begin{cases} B = \frac{1}{NS}\int V_s dt = \frac{G}{RC}\int V_s dt \cdot T_{das\_probe} \\ I = \frac{1}{2\pi r_0}\cdot\frac{1}{NS}\int V_s dt = \frac{G}{RC}\int V_s dt \cdot T_{das\_PF} \end{cases}$

Where: ϕ is the measurement result of the flux loop, and G is additional gain of the amplifier, and RC is the time constant of the integrator, NS is the magnetic probe's effective areas, and T_{das} is the translation coefficient of the data acquisition system.

The random uncertainties are base on the PF coils and sensors positions, and cannot be obtained by measured directly. For example, when the superconducting coils are cooled down from room temperature to 4.5K, the coils positions will be changed because of contraction. Also, the sensors positions will be changed when the vacuum vessel baked or pumped. These changes will influence the green functions. A lot of vacuum shots will used to analyze and estimated the error of plasma shape reconstruction.

2. Calibration of EAST magnetic diagnostics

In the whole magnetic measurements circuit, there are several system uncertainties sources from the sensor to signal processing unit. It includes following side: the effective area of pickup coil or flux loop, the integrator parameter (RC) and amplifier factor (G), the influence of 70m twist signal transfer line, the current of poloidal field (PF) and plasma current rogowski coils. The details of all these calibrations are list as following:

(1) Calibration of 12 poloidal field rogowski coils

These rogowski coils are calibrated by a same HALL current sensor. The error of the absolute coefficient is determined by the accuracy of the Hall sensor. The error of the absolute coefficient is about 0.5%. All PF coils current were tested with 9KA/turn close to full scale of Hall sensor(10KA).

(2) Calibration of pickup coils

The effective areas(NS) of pickup coils are calibrated by a solenoid coil[5]. Figure 2 shows the parameters of the solenoid. A standard pickup coil and measured pickup coil are put in the centre of a solenoid coil with 200Hz AC power supply. The figure 2 shows the parameters of solenoid coil, the positions of standard and measured pickup coil, the field uniformity at the center of solenoid. The NS value of measured pickup coil is obtained by compare the induced voltages of two pickup coils. The uncertainty of NS value is about 0.5%. The calibration system is showed in Figure.3.

Conductor size	Coil turns	Coil inner diameter	Coil Length	Coil resistance
2.8×4mm	200×2=400	200mm	1000mm	0.562Ω

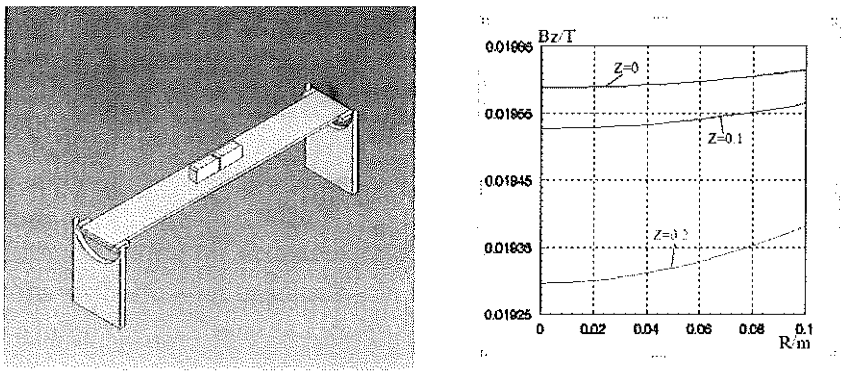

Figure 2. the parameters of solenoid

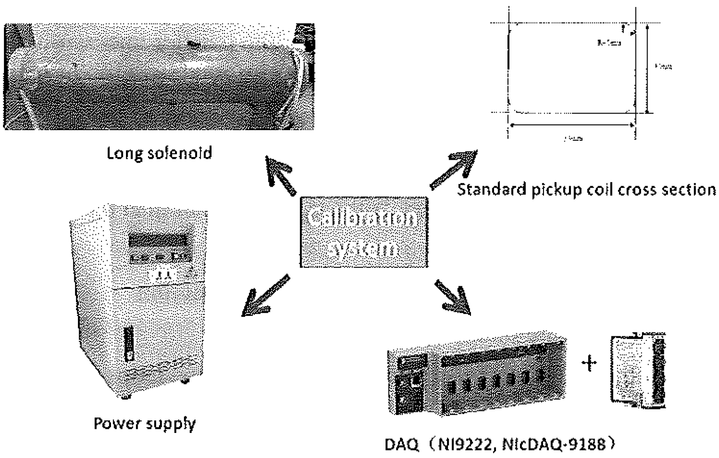

Figure 3. The calibration system of picket coils

(3) Calibration of integrator and amplifier

The integrator–amplifier-digitizer were calibrated before the experiment operation. Different RC values are designed base on the different effective area of pickup coil and flux loop. RC=20ms is set for pickup coils and RC=200ms is set for flux loop. In the calibration, the reference input signal is a 3V (100 Hz form pickup coils and 10Hz for flux loops) square-wave, which is checked by a high precision voltmeter. The value of RC/G is obtained from the output triangle wave (calculate the slop, shown in

Fig. 4). The uncertainty of the RC/G calibration can be ignored (less than 0.00001).

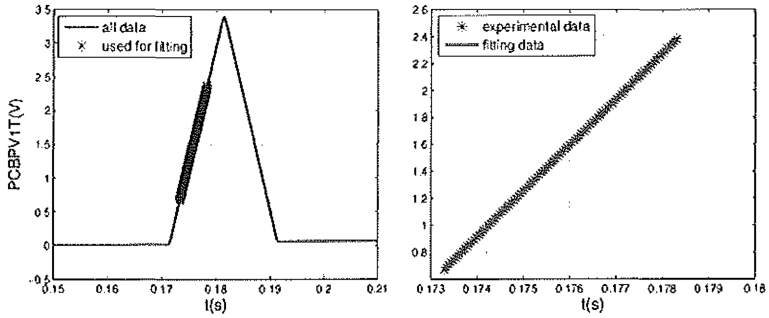

Figure 4. Calibration of integrator

(4) The influences of 70m twist signal transfer line

From the magnetic measurement system which installed inside the vacuum vessel to the integrator and DAQ system, there are about 70m length. To improve the anti-interference ability of the signal, the twisted-pair line with shield is used for signal transfer. An electric model is built to analyze the influences of signal transfer, and the experiment result is given too[3]. It is showed in Figure 5.

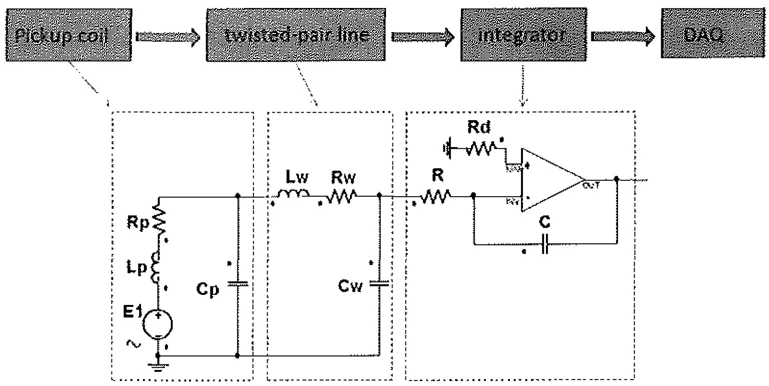

Figure 5. the circle model of 70m transfer line

In the circuit model, the parameters of twisted-pair line are measured as following:

$$R_w = 5.825\Omega, L_w = 0.1713mH, C_w = 0.2nF$$

For 10KHz magnetic signals for plasma shape reconstruction, the impedance of twisted-pair line compare integrator is very small. The influence to the signal is small than 0.03%, it can be ignored.

3. Random uncertainties analysis for plasma shape reconstruction

(1) The uncertainties analysis base on the vacuum shot

To estimate the positions influence of pickup coils and flux loops to green function (see the equation 2), many vacuum shots were carefully designed and performed before each machine operation. 37 different vacuum shots were used in the analysis which including: individual PF coil powered shots; un-down symmetric PF coils co/counter powered shots; other special designed vacuum shots. They are designed to obtain high signal-to-noise ratio of the signal to do the analysis. All the PF currents used are 8-9KA/turn. The vacuum shots are shown in Fig. 6. To avoid eddy current on the vessel and some other structure, the yellow area signals data which in the current flat are used.

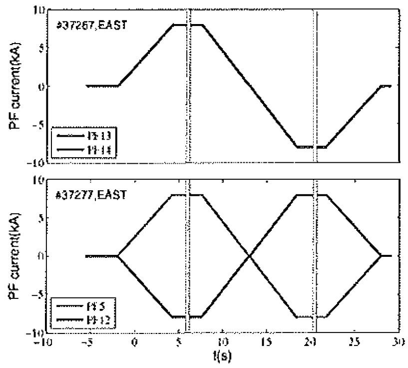

Figure 6. PF coil current for vacuum shot

By statistics from poloidal field vacuum shot-database, random uncertainty of flux loops and pickup coils on EAST are shown in Fig.7. The random uncertainties of most of pickup-coils are less than 10G, while random uncertainties of most of flux loops are less than 10mWb. The 6 sensors (pb19, pb38, fl 12,33-35) will not be used in equilibrium reconstruction.

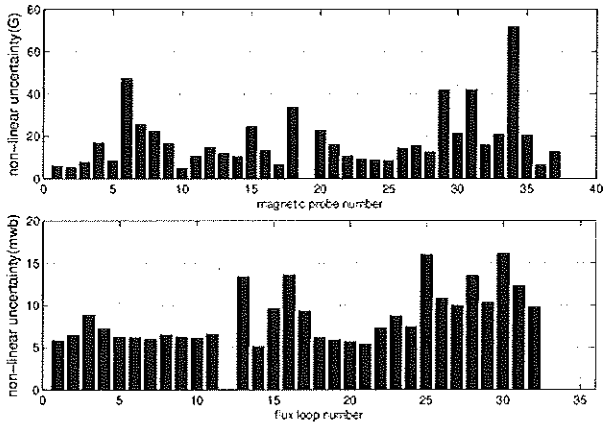

Figure 7. The random uncertainty of the magnetic probe and flux loops

(2) Equilibrium reconstruction based on uncertainty analysis

The equilibrium reconstruction on EAST is accomplished by EFIT, using 2- and 3-knot spline representation for P' and FF'. The uncertainty values of sensors are used as fitting weight in EFIT. In the simulation, plasma equilibrium shot is set as the reference, and the magnetic data from the reference will be used as accurate calculated data. The calculate data add the uncertainty value is set as the measurement data to do the reconstruction simulation. At last, the uncertainty is obtained by statistics of the difference between the reconstruction results and the reference equilibrium. The uncertainty parameters of two X-points, 4 strike points and 6 control gaps in Plasma Control System (PCS) will be presented.

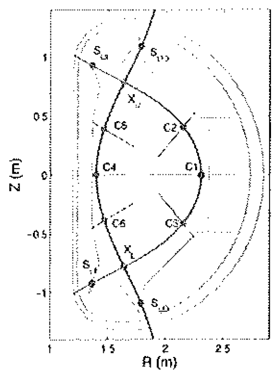

Fig.8 The cross-section of EAST. The green lines, pink lines, the orange lines and the black lines are the vacuum vessel, the limiter, the last close magnetic surface and the SOL control lines separately, and C1-C6, X_U, X_L, S_{UI}, S_{UO}, S_{UI}, S_{LI}, S_{LO}, are 6 control gaps, 2 X-points, and 4 strike point separately.

There were 3 equilibriums used as reference. The key parameters are shown in table 1. Shot 42059 is one of the normal discharges on EAST in last campaign, and shot 3000 and 1000 are 2 simulation results for comparison. These three equilibriums have similar plasma shapes and pressure and current profiles, and different plasma total currents and B_T.

Table 1. Key parameters of the reference equilibriums

Shot	type	R	B_T	I_p	l_i	β_T	κ	q^*
3000	simulation	1.9m	3.5T	1MA	1.4	0.66	1.7	4.9
1000	simulation	1.86m	1.9T	500kA	1.15	0.039	1.7	5.3
42059	experiment	1.86m	1.8T	400kA	1.23	0.19	1.75	6.6

The results of the uncertainty of equilibrium reconstruction are summarized in Fig.7. The uncertainties of the gaps on low field side and the strike points are larger than others uncertainties. The uncertainty of the gap on low field side (C1) is larger because the sensors are farther away from this gap. In the discharges with plasma current of about 400-500kA, the uncertainties uncertainty is 0.5~1.4cm for 6 control gaps, less than 0.8cm for X-points, and 1.0~1.6cm for strike points (95% confidence). However, as the plasma current increasing, the signal to noise ratio of the diagnostics system is larger, which will lead to the reducing of the uncertainty of equilibrium reconstruction. It's clarified that in the discharges with plasma current of 1MA, the uncertainties are less than 0.7cm for 6 control gaps, less than 0.4cm for 2 X-points, and less than 1.0cm for 6 strike points, for 1MA discharge (95% confidence).

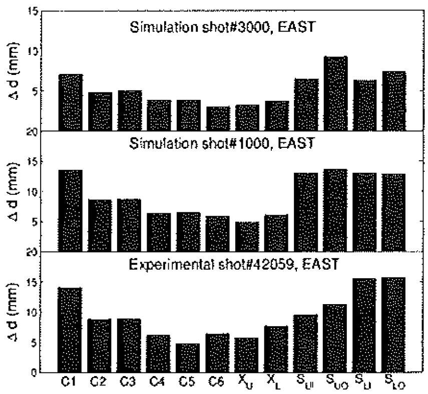

Fig.9 position uncertainties of these 12 points from the equilibrium scan (95% confidence).

4. Conclusion

The calibration of magnetic measurements is carried out on the EAST Tokamak. The uncertainties of magnetic measurements are analyzed on EAST by comparison between experimental and green-function calculations based on vacuum shots. The overall uncertainty and its origins are analyzed from the calibration. The sensitivity of the magnetic data uncertainty in the plasma shape reconstruction is analyzed based on EFIT fixed boundary and fitting mode by applying overall uncertainty as fitting weight in EFIT.

This work is supported by National Natural Science Foundation of China (Grant No.

11475002) .

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