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Numerical Determination of the Last Closed Magnetic Surface for the Reconstructed Magnetic Field Profile in the LHD

LHDの逆解析された磁場分布に対する最外殻磁気面の数値的決定法

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The three-dimensional (3-D) Cauchy condition surface method has been developed to reconstruct the magnetic field profile in the Large Helical Device. The reconstructed field shows acceptable accuracy, however, the Poincaré plot does not form the last closed magnetic surface (LCMS) clearly. One here proposes a technique to determine the LCMS numerically. The Poincaré plot is converted to contours of a 'quasi' magnetic surface function using the expansion of radial basis functions. Introducing the 'inside/outside' ratio related to the scatters in the Poincaré plot, the most probable contour is extracted as the LCMS, which agrees well with the reference LCMS.

1. Introduction

The three-dimensional (3-D) Cauchy condition surface method [1,2] was recently developed to reconstruct the 3-D magnetic field profile outside the non-axisymmetric plasma from the sensor signals in the Large Helical Device (LHD). A test calculation was made for the plasma with a volume-averaged beta being $\langle\beta\rangle = 2.7\%$ in the LHD. The reference field for this condition had been calculated beforehand using the HINT2 code [3].

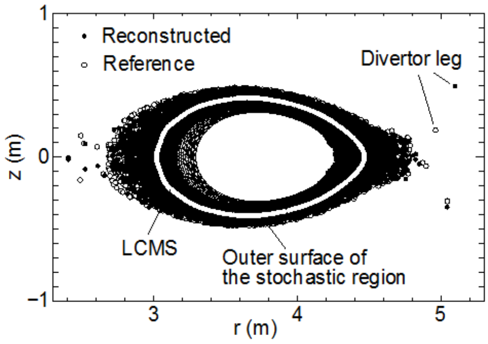

Fig.1. Poincaré plot: Peripheral region

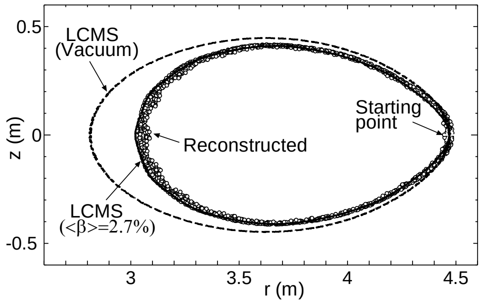

Fig.2. Poincaré plot: LCMS

Magnetic field line tracing was carried out using the reconstructed field. Figure 1 shows the Poincaré plots on the *r-z* plane at $\varphi = 18°$. The outer surface of the stochastic region was identified precisely. However, the Poincaré plot does not form the last closed magnetic surface (LCMS) clearly. The plot points in Fig. 2 are distributed along the reference LCMS. One here proposes a method to identify the LCMS numerically for the distributed plot points.

2. Numerical Scheme to Identify the LCMS

2.1 *Quasi magnetic surface function*

In the field line tracing, the starting points of the traces were set as

$$r_{start}^{k} = 4.30 + 0.01k\ (k = 0, 1, \cdots, 40)\,m,\quad z_{start}^{k} = 0.0m,$$

and $\varphi_{start}^{k} = 18°$. For convenience, one recognizes the r-coordinate of the starting points as 'quasi' magnetic surface functions, say, $\psi_k = r_{start}^{k}$. One here introduces the radial basis function (RBF) expansion

$$\psi^k(r,z) = \sum_{i=1}^{N} w_i f_i(r,z;r_i,z_i) = r_{start}^{k}\quad (k = 1, 2, \cdots, K) \quad (1)$$

with the Gaussian type RBF

$$f_i(r,z;r_i,z_i) = \exp\left\{-\left((r-r_i)^2 + (z-z_i)^2\right)\big/\sigma^2\right\}, \quad (2)$$

where (r_i, z_i) means the center of each RBF. The weights w_i are determined in a least-square manner.

With the use of the RBFs, the Poincaré plot shown in Fig. 2 can be converted into a contour map of 'quasi' surface function as shown in Fig. 3. Contours are found even outside the LCMS in Fig. 3, however, they are not the true magnetic surface. One needs to exclude them to determine the true LCMS.

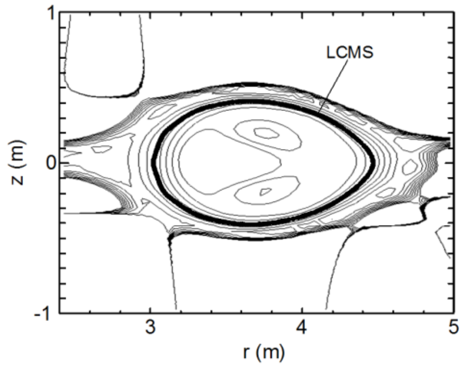

Fig.3. Contours of quasi magnetic surface.

2.2 *Definitions of four regions*

In addition to the vacuum region and the stochastic region, one here defines the following two regions as shown in Fig. 4 and Table I. The 'dirty' region is the domain sandwiched between the LCMS and the CCS. The 'black' region is the region inside the CCS, which is out of the analysis under consideration

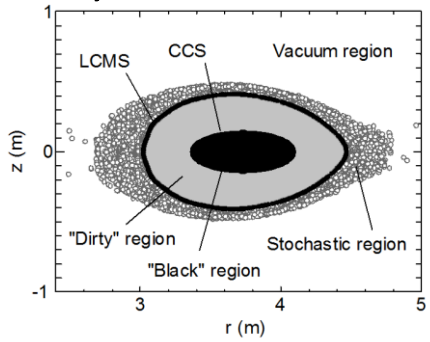

Fig.4. Definitions of the four regions

In the CCS analysis, the reconstructed field in the dirty region has a large error which causes the large scatter in the Poincaré plot. Note here that in the vicinity of the LCMS the scatter inside the LCMS is much larger than that outside the LCMS (see Fig. 2). This is because the plots inside the LCMS pass through the dirty region.

Table I. Features of the four regions

Region	Current density	Accuracy of the reconstructed field
Vacuum	No	Acceptable
Stochastic	Weak	Fair
"Dirty"	Strong	Large error
"Black"	Strong	Out of the analysis

2.3 *Method of 'inside/outside' ratio*

One here introduces the 'scatter' given by

$$s^2 = \frac{1}{m}\sum_{j=1}^{m}(\psi_j - \psi_0)^2 \ . \qquad (3)$$

Here ψ_0 denotes r_{start}^k in Eq. (1), while ψ_j means the value at the point (r_j, z_j) of quasi magnetic surface function that is taken by the RBF approximation for m points originating at r_{start}^k. Next, one defines the 'inside/outside' ratio as

$$R = s_{inside}^2 \big/ s_{outside}^2 \qquad (4)$$

with s_{inside}^2 and $s_{outside}^2$ being the scatters calculated using Eq. (3) respectively for the points inside and outside the contour under consideration.

3. Results

Figure 5 shows the variation in 'inside/outside' ratio as a function of r_{start}. The ratio jumps where r_{start} is reduced to a value smaller than 4.47m. Because of this, one can judge $r_{start} = 4.47m$ to be the most probable value that corresponds to the LCMS.

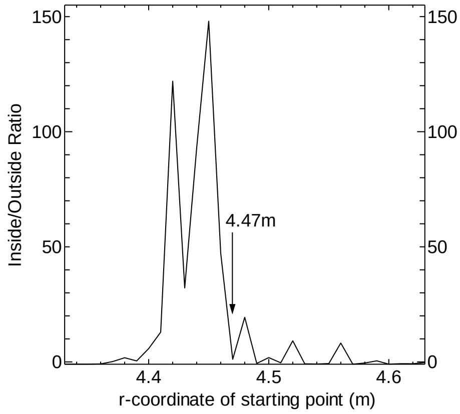

Fig.5. Variation in 'inside/outside' ratio

Among the contours drawn by the RBF expansion scheme, the contour corresponding to $r_{start} = 4.47m$ was extracted. This estimated LCMS agrees well with the reference LCMS as shown in Fig. 6.

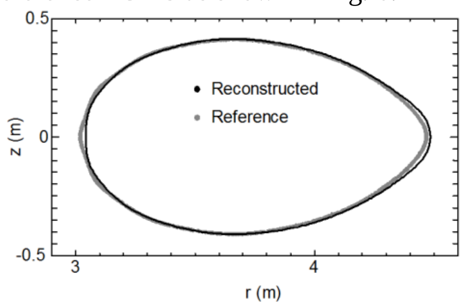

Fig.6. Reconstructed LCMS

4. Conclusion

The Poincaré plot based on the reconstructed magnetic field was converted into contours of a smooth magnetic surface function using the expansion of the radial basis functions. Introduction of the 'inside/outside' ratio enables one to extract the LCMS from the contour map. The LCMS thus determined agrees well with the reference LCMS.

References

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