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Plasma boundary identification in HL-2A by means of the finite current element method*

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In this paper, the finite current element (FCE) method used in HL-2A is described. The calculation and test results show that the error of the reconstructed boundary given by the FCE method (<3mm) is smaller than that obtained by the current filament method used before (<6mm). Even if some current elements are located out of the plasma boundary, the FCE method can also identify the plasma boundary successfully. If the location of the finite current elements is changed in a certain area, the error of the reconstructed boundary is always very small. By employing a conventional PC (Pentium 4 2.4GHz), the calculation time of one set of plasma discharge parameters does not exceed 1ms. Thus, the FCE method can identify the diverted plasma configuration quickly and accurately. This is essential and important for real-time shape control in HL-2A.

Keywords: finite current element method, boundary identification
PACC: 5255

1. Introduction

The fixed current filament (FCF) method has been successfully used for plasma boundary identification in HL-2A,[1] however, when the position of some filaments is near or out of the boundary, this method cannot reconstruct the plasma boundary exactly. In this paper, we use another method, the finite current element (FCE) method, to reconstruct the boundary. This method can give more accurate results even when some of the current elements are near or outside the plasma boundary,[2] but at the cost of longer calculation time than that with the FCF method.

In Section 2, the algorithm of the FCE method is introduced. The test results of the FCE method are given in Section 3. In Section 4, the FCE method is compared with the FCF method.

2. The FCE method

The FCE method was described in detail in Ref.[2], and was used in TCV and KSTAR.[3] In this approach, plasma current is modelled by a set of rectangular grids inside the plasma. The pyramid-shaped current with bilinear basis function at each current element is

$$I_j = \int_{Z_j-\Delta Z}^{Z_j+\Delta Z}\int_{R_j-\Delta R}^{R_j+\Delta R} J_j F_j \mathrm{d}R\mathrm{d}Z. \tag{1}$$

where

$$F_j = \left\{1-\frac{|R-R_j|}{\Delta R}\right\}\left\{1-\frac{|Z-Z_j|}{\Delta Z}\right\}. \tag{2}$$

R_j and Z_j are the horizontal and vertical coordinates of the jth node respectively. ΔR and ΔZ are the horizontal and vertical widths of the current element.

The summation of current of all current elements is equal to the measured plasma current I_p. Therefore, we have

$$g(J_j) = \sum_{j=1}^{nf}\int_{Z_j-\Delta Z}^{Z_j+\Delta Z}\int_{R_j-\Delta R}^{R_j+\Delta R} J_j F_j \mathrm{d}R\mathrm{d}Z - I_\mathrm{p} = 0. \tag{3}$$

The sum of squares of the residual function is

$$f = \frac{1}{2}\sum_{i=1}^{m} w_i(\hat{b}_i - \sum_{k=1}^{nc} q_{ik}(R_i, Z_i; R_k, Z_k)I_k - \sum_{j=1}^{nf} q_{ij}(R_i, Z_i; R_j, Z_j)I_j)^2, \tag{4}$$

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where m is the total number of the magnetic probes, $\hat{b}_i$ the measured value of the ith probe, q_{ik} the computed value of the magnetic field coefficient for the kth poloidal coil, and q_{ij} the computed value of the magnetic field coefficient for the jth current element.

In order to obtain the minimum of the functional f in formula (4), the improved Lagrange method[4] is used. Thus, the merit function is

$$S(J_j, \lambda) = \sum_{k=1}^{nf} \left(\frac{\partial f}{\partial J_k} \right)^2 + g^2(J_j) + \alpha \sum_{j=1}^{nf} J_j^2, \quad (5)$$

where $\frac{\alpha}{2} \sum_{j=1}^{nf} J_j^2$ is the regularization term. From function (5), a set of linear equations, $AX + \lambda C = B$, are obtained and they can be calculated by the singular value decomposition method, so the current density of every node is obtained, and then the plasma boundary of the limiter or diverted configuration can be identified by a method described in Refs.[1].

3. Results and analyses

In the FCE method, the error of the reconstructed plasma boundary in HL-2A is related to the distribution of current elements, other than the measurement errors of the current and magnetic field or flux. Because the 18 probes are distributed on half circumference of the outside plasma, the number of current elements is not larger than 18. The 12 elements located in the vacuum vessel is the best distribution in HL-2A, where current elements are symmetrical about r=1.65m and z=0, as shown in Fig.1.

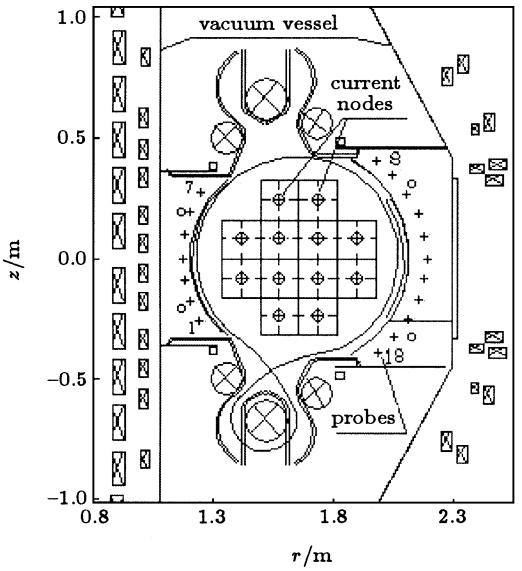


Fig.1. Distribution of current elements in HL-2A.

Based on the algorithm discussed in Section 2, the random errors are introduced in order to simulate the magnetic field and current measurement of the evolving plasma in HL-2A. We have compared the reconstructed boundary with the equilibrium calculated boundary for a number of diverted plasma configurations. The positions of x points in all the reconstructed and calculated cases are always the same.

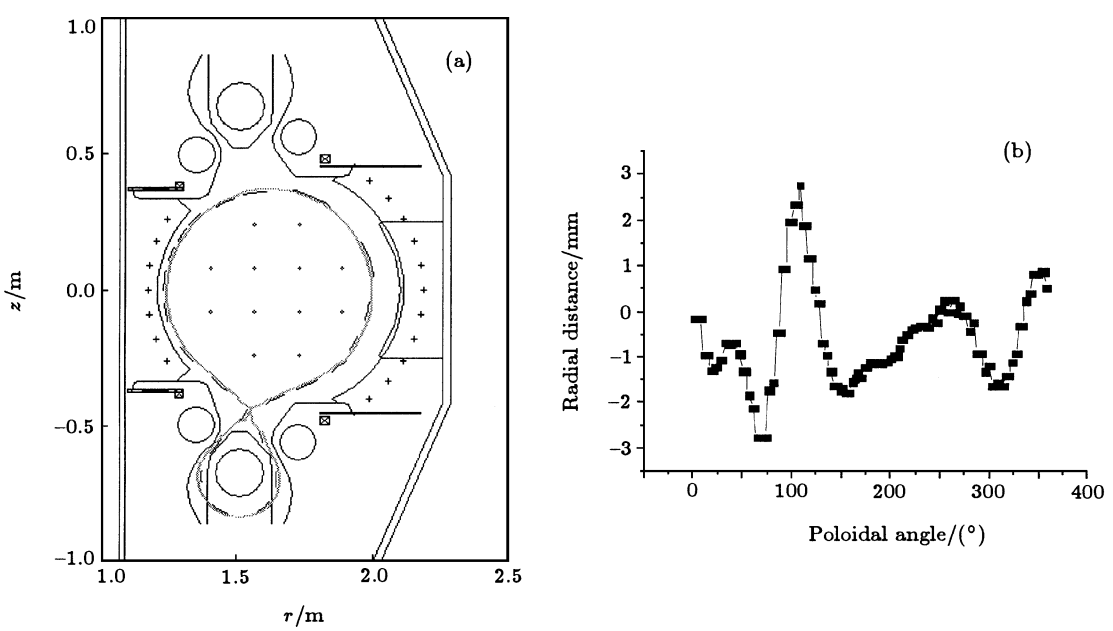


Fig.2. Single null (SN) configuration (The solid line is the reconstructed boundary, and the dashed line denotes the calculated equilibrium one in Fig.2(a)).

The error of radial distance between the reconstructed plasma boundary and the equilibrium one calculated is shown in Figs.2 and 3 for the normal diverted configuration. There, (a) shows the boundaries, in which the dashed line denotes the equilibrium calculation and the solid line denotes the reconstruction using the FCE method, and (b) shows the changes of the radial distance error with the poloidal angle.

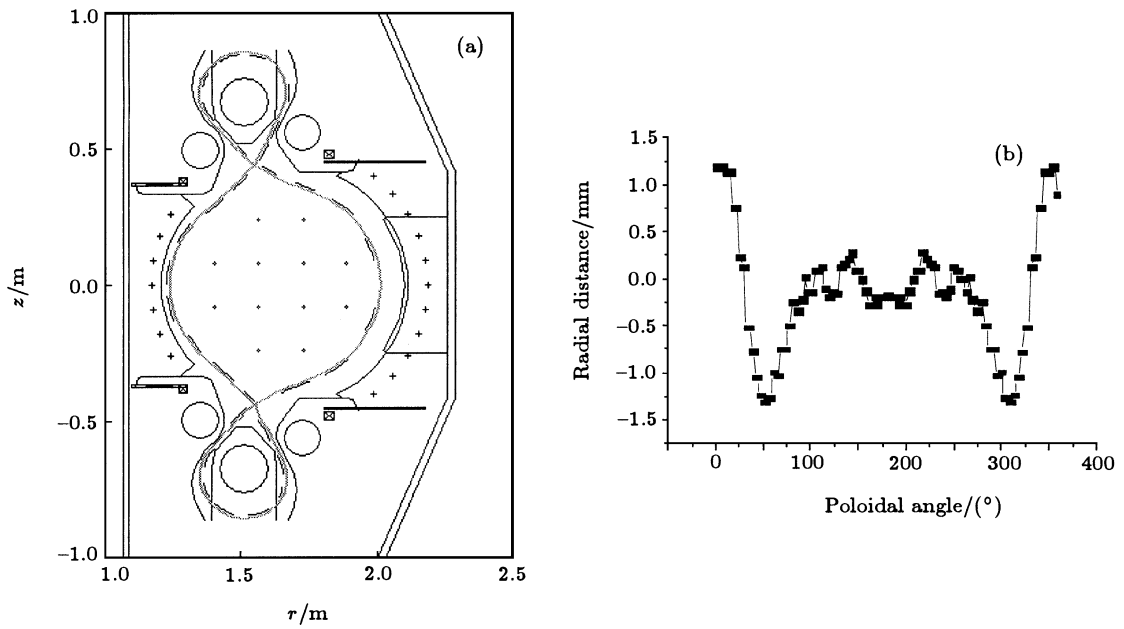


Fig.3. Double null (DN) configuration (The solid line is the reconstructed boundary, and the dashed line denotes the calculated equilibrium one in Fig.3(a)).

From Figs.2 and 3, we can arrive at the conclusion that the radial errors are usually smaller than 3mm for SN configuration, and smaller than 1.5mm for DN configuration.

The relationship between the average error and ΔR (ΔZ) for some configurations is shown in Fig.4. The changes of the average error caused by all current elements moving up or down, left or right at the same time are shown in Fig.5. Figure 5(a) shows the changes caused by all current elements moving left or right, and Fig.5(b) shows the changes caused by all current elements moving up or down.

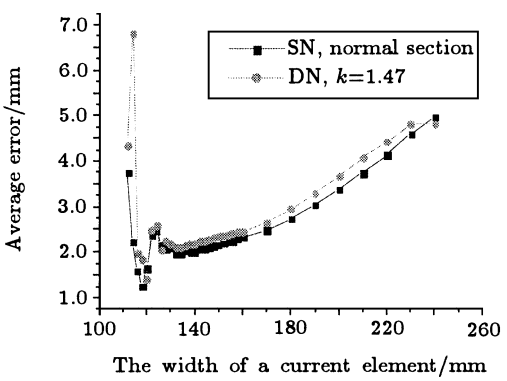


Fig.4. The relation between the average error and ΔR (ΔZ).

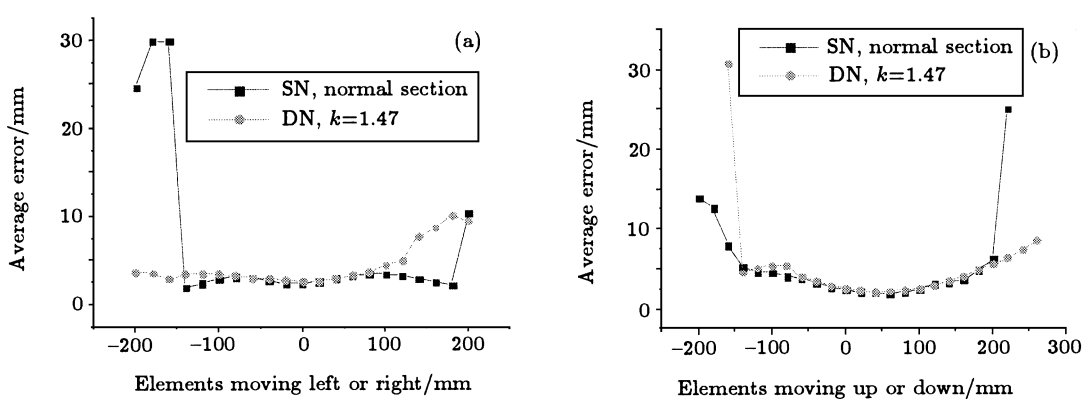


Fig.5. The relation between the average error and all current elements' movements.

Figures 4 and 5 show that if the distribution of the current elements is like that in Fig.1 and ΔR=ΔZ=116mm–180mm, the average error of the diverted configuration is smaller than 3mm. In fact, when ΔR=ΔZ < 110mm, for some configurations, the average error may be small, but the radial errors at some angles become very large. From Fig.5, we can also conclude that if the left-right symmetric axis is changed from –60mm to 40mm, or up-down symmetric axis changed from –20mm to 100mm, the average errors are smaller than 3mm.

In Fig.6, 16 elements are located in the vacuum vessel. The content in Figs.6(a) and 6(b) is the same as that in Figs.2 and 3.

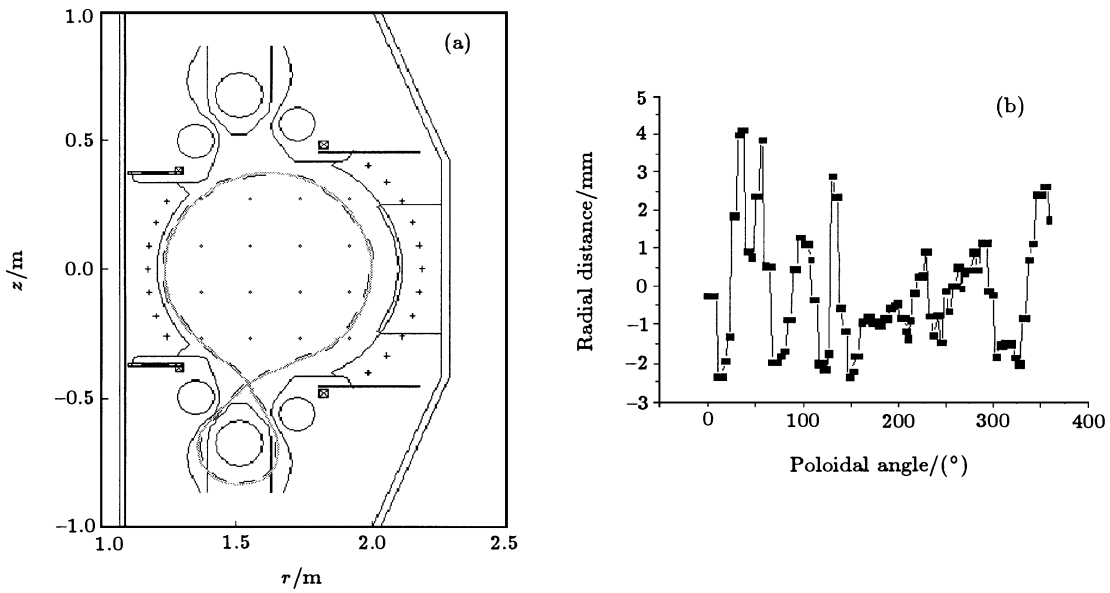


Fig.6. Some currents located outside the plasma boundary (The solid line is the reconstructed boundary, and the dashed line denotes the equilibrium one in Fig.6(a)).

It can be concluded from Fig.6 that when some elements lie outside the plasma boundary, the FCE method can also give the accurate plasma boundary. So the number and locations of current elements do not have to be changed during an entire discharge, as discussed in Ref.[2]. From Fig.2 through Fig.6, we can also conclude that node positions are not critical for reconstructing the boundary by the FCE method.

We have demonstrated many discharges in HL-2A in the year 2003 using the FCE method. The results are almost the same as those obtained by the FCF method. The reconstruction of the 1766 shot discharge by the FCF method has been described and analysed. The reconstructed boundary at 192ms for 1766 shot is shown in Figs.7, 8 and 9, which illustrate the changes of the curve of x point position and the strike point position at target plate for the impurity flow during the plasma discharge for 1766 shot. From calculation, we infer the x point position (R_x=1.572m, Z_x=–0.444m), the position of hit points on the target plate z=–0.791m (inner), z = –0.820m (outer), plasma geometric centre (R_g=1.694m, Z_g=-0.027m), plasma current centroid (R_c=1.754m, Z_c=0.004m), plasma minor radius a_p=0.384m, and elongation k=1.06. These agree with some diagnostic measurements related with plasma boundary.

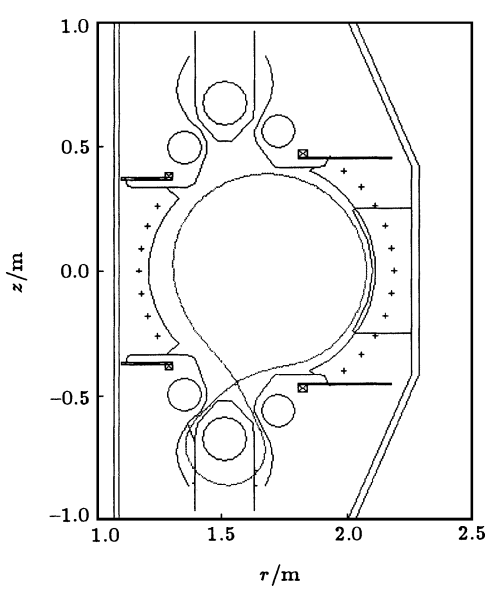


Fig.7. The reconstructed boundary at 192ms for 1766 shot.

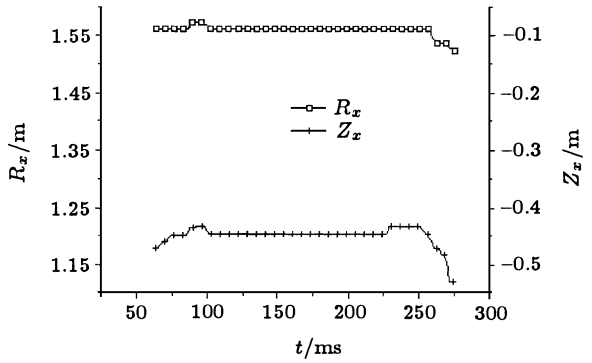


Fig.8. Variation of the position of x point during discharge for 1766 shot.

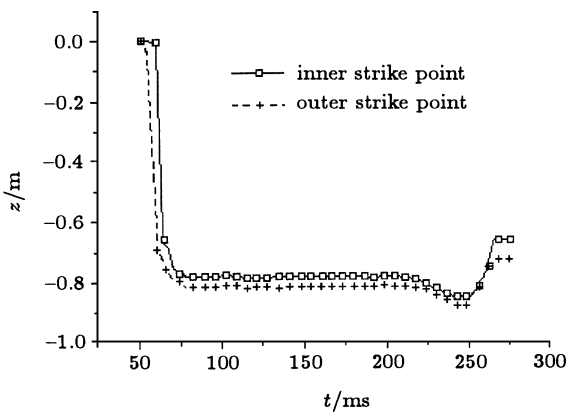


Fig.9. Variation of the strike point of impurity flow at the diverter target during discharge for 1766 shot.

4. A comparison with the FCF method

We have successfully reconstructed the plasma boundary quickly and accurately by the FCF and the FCE methods in HL-2A. From the data of the magnetic field measurement of probes, the plasma boundary can be reconstructed. Comparing the reconstruction of the 1766 shot discharge by the FCE method with that of the FCF method, we can gain the results that, during all the time of this discharge, the plasma boundaries reconstructed by these two methods are almost the same, the positions of x point are the same, and the deviation of the positions of hit points or plasma current centroid is not more than several millimetres.

During discharge in lower SN configuration, if the plasma contact with the inner limiter or the stainless steel cover of the MP1 and MP3 coils, the reconstruction errors in these two methods become a little larger because there are no probes distributed at the top.

The reconstruction errors caused in the FCE method (<3mm) are usually smaller than those by the FCF method (<6mm). When some current filaments are near or outside the plasma boundary, the FCF method cannot identify the plasma boundary accurately, but the FCE method can do. The calculation time of one set of plasma discharge parameters by the FCE method is longer than that of the FCF method, but still less than 1ms by employing a conventional PC (Pentium 4 2.4GHz). The 18 probes and the FCE method or the FCF method can satisfy the requirement of the plasma shape identification for SN and DN configurations in HL-2A experiment. Thus, these two methods appear to be sufficiently accurate and fast for real-time shape control. The FCF method is faster, and the FCE method is more accurate.

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