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A Method of Equilibrium Reconstruction in an RFP on the basis of Gradient-Based Optimization

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Reversed Field Pinch (RFP) is one of the magnetic confinement systems for high-beta fusion plasmas where beta is the ratio of plasma pressure to magnetic pressure. One of the advantages of the RFP is that it requires weak external magnetic field, which may lead to possible design of an Ohmic-ignition fusion reactor using normal conductors. One of the issues yet to be solved for the RFP reactor concept is to develop a means for steady-state operation. An equilibrium analysis for the RFP has shown that the neoclassical effect in the RFP configuration can become important as the aspect ratio A (=R/a, where R is the major radius, and a, the minor) is lowered. Specifically, a high bootstrap current fraction (>90%) could be achieved in A=2 RFP equilibrium with reactor-relevant plasma parameters, if a high beta value around 60% could be achieved[1].

Reversed field pinch of Low Aspect ratio eXperiment[2]-[3](RELAX) is an RFP experiment with R/a=0.51m/0.25 m, thus A=2. The major research subjects of RELAX experiment are concentrated on exploring low-A regime RFP configuration, including experimental studies of bootstrap current. The experimental evaluation of the bootstrap current strongly depends on equilibrium reconstruction, i.e., how accurately we can reconstruct the equilibrium configuration whose parameters are compatible with experimental measurements. Thus development of an efficient equilibrium reconstruction technique is an urgent issue particularly for the experimental evaluation of bootstrap current in RELAX.

We are developing a new method of equilibrium reconstruction on the basis of gradient-based optimization. The equilibrium reconstruction is a process to find a solution of the Grad-Shafranov (G-S) equation which is compatible with experimental measurements. Figure 1 shows a flowchart of the reconstruction procedure in the present new method. In the G-S solver[4] the axisymmetric G-S equation for the poloidal flux function $\psi(R, Z)$(R and Z are the major radial and vertical coordinates respectively) is solved, where the toroidal plasma current is approximated by a set of filament currents and the pressure function $P(\psi)$ and poloidal current function $F(\psi)$ (=$RB\varphi$) are specified by a set of parameters $\vec{x}$ characterizing the equilibrium. In the present new method, the set of parameters for pressure and poloidal current functions are optimized such that the differences between the experimental measurements ex_i and those values cal_i calculated from the G-S solution are minimized; the reconstruction is replaced by the optimization problem. The use of gradient-based optimization guarantees local convergence of the set of parameters for minimization of the errors E between experiments and computation results. Since computation results depend on the parameter, we derived the parameter sensitivity equation of the G-S and solved it. Using the steepest decent method(SDM), parameters are updated iteratively by a given gradient to minimize E.

In order to evaluate the new method, we have applied this method by use of the so-called α-Θ_0 model[5] for the RFP equilibrium. The equilibrium is characterized by the following three parameters: $\vec{x}$=(x_1, x_2, x_3)=($P(0)$, α, $B\varphi(0)$), where $P(0)$ and $B\varphi(0)$ are the on-axis values of pressure and toroidal field respectively, and α is an indication of the degree of peakedness of the pressure profile. Then we set an objective parameter $\vec{x}_{ob}$ and virtual measurement data obtained by the solution of G-S, when $\vec{x} = \vec{x}_{ob}$. In this test, the experimental measurements are assumed to be the total toroidal current, average toroidal field and local current. The advantage of this verification test is that the object, which is unknown in the actual, is known. It becomes easy to evaluate. In Fig.2, a trajectory of the parameter set is plotted, from the initial to the final locations, in a (x_1, x_2) plane where E contours are indicated by color code. We set initial parameter to be (0.5,5.0,1000), and $\vec{x}_{ob}$(black point) to be (0.3,3.0,1000). The trajectory advances to the final location according to the gradient of E surface, which shows that the gradient-based optimization works well.

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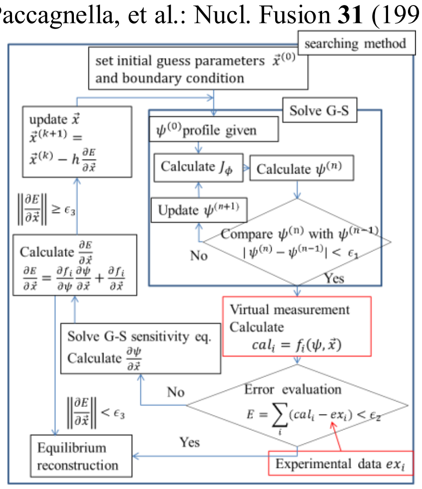

Fig.1. Flowchart of the method

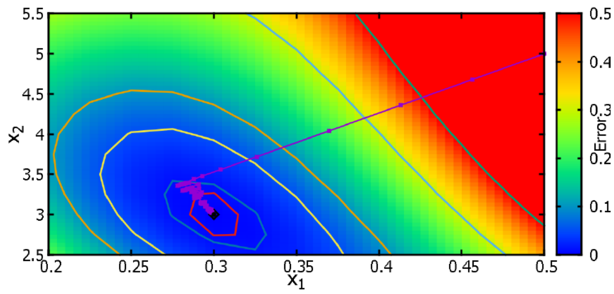

Fig.2. Trajectory of searching $\vec{x}_{ob}$ using the SDM