Analysis of the Eddy Current Loss in KSTAR Joints

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1. Introduction

The cable-in-conduit conductor (CICC) concept is widely accepted for huge magnet and high magnetic field machine such as ITER and KSTAR. One of the sensitive issues of high current carrying system is the joule heating and mechanical instability of joint which has normal conductor. Joints for high current conductor should be designed to have low resistance down to nano ohm for reducing the DC joule heating. The thermo-hydraulic instability is affected by not only intrinsic resistance but also the magnetic field around joint. Time variation of magnetic field is also a cause of the induced current inside conductor. To find efficient joint, we compared eddy current loss at three kinds of joint, lap joint, butt joint and mini-lap joint in the circumstance of the reference magnetic field scenario of the KSTAR.

2. Calculation Procedure

We have considered three kind of joint for KSTAR. The lap joint and butt joint that we considered is conventional one. Due to the bulky size of lap joint, high eddy loss is expected. On the other hand butt joint is not confirmed its electrical and mechanical stability. The mini-lap joint which we developing now is originally same as the concept of butt joint except mechanical binding part. It is designed to have good electrical conductance and mechanical stability. The most beneficial thing of it is its small size compared with conventional lap joint. This makes us expect lower eddy loss in mini lap joint than that of convectional lap joint.

Fig. 1. shows the designed position of the joint at in-cryostat of the KSTAR. The magnetic field corresponding to the solid circle was calculated using well-confirmed historical code, MAFLO [1]. For eddy current calculation, we modeled finite element for copper region of joint with commercial FE code, ANSYS. Instead of using vector potential around joint, we simply generate parallel and perpendicular magnetic field against joint surface with one directional vector potential.

$$A_y(x,t) = B_{z0}x \pm |dB_z / dt| xt \qquad (1)$$

$$A_z(y,t) = B_{x0}y \pm |dB_x / dt| yt \qquad (2)$$

Here, x and y are the positions on the surface of the model and t is the time during magnet operation.

After calculating the eddy current density, we summed eddy current loss of every element from the initial magnetization (IM) to the shut-off of the magnet operation.

$$\sum_i^N \int_0^{t_0} j_0^2(t) \rho V_i dt = Joule\ loss \qquad (3)$$

Here, J_i is the i-th eddy current density, ρ electrical

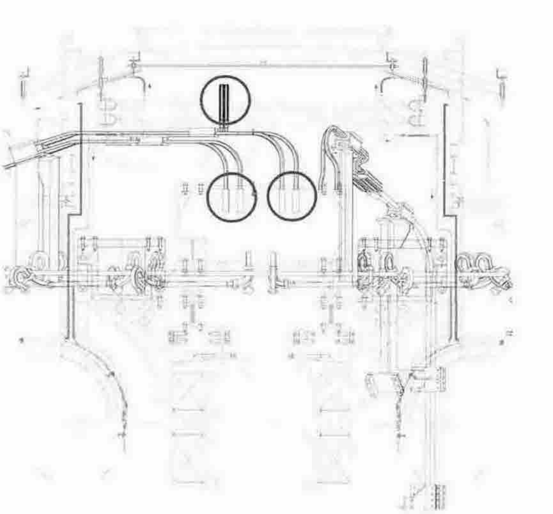

Figure 1. Rectangular bar shape inside solid circle are the joints.

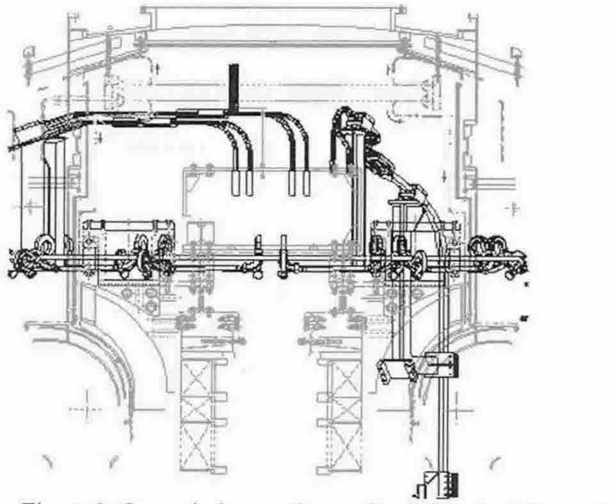

Figure 2. Open circles are the result of FE calculation and solid line is the fitting curve using Eq. 4. This curve was evaluated using the field condition, 1.76 T/sec, from IM to Blip.

resistivity, V_i i-th element volume and N total number of element. The resistivity of the copper were extracted through the commercial code named ‘cryocomp’ with RRR = 250, T = 4.5 K and various magnetic field situation.

3. Results

Fig. 2. shows the comparison between the result of FE calculation and the fitting line. Linear time dependence of the magnetic field during plasma operation leads us to estimate eddy current easily. It can be described with the solution of the first order ordinary differential equation.

$$i(t) = -(\alpha / R)\left(1 - e^{-\frac{R}{L}t}\right) \qquad (4)$$

Here, α is the time derivative of magnetic flux and R electric resistance. The current behavior is well fitted with Eq. 4. Small variation is due to the mutual inductance between many current paths inside model. In spite of the rapid magnetic field drop from initial magnetization (IM) to Blip, 1.76 T/sec, the eddy current reach to relatively small value, ~ 6×10^7 A/m^2 due to the shortest operation period, 60 msec. Because of the inducting behavior, eddy current cannot reach to the maximum value at the short operation time, <L/R.

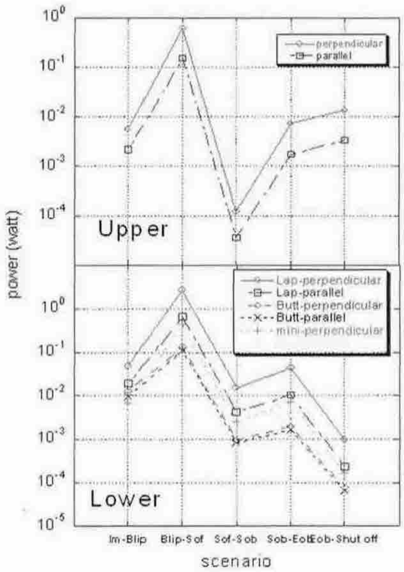

Figure 3. Eddy current loss of each joint during plasma operation. Maximum loss was 2.672 watt between Blip and SOF.

As can be seen Fig. 3., the joint located in high magnetic field and rapid field changing region, ‘Lower’, has higher eddy loss than that of ‘Upper’. As a matter of course, the eddy current depends on the size of the surface against applied magnetic field and loss of it is proportional to the volume of itself. As we expected the lap joint which has largest copper shows maximum loss and butt joint shows minimum value. The mini-lap joint shows smaller power loss than that of lap joint.

Maximum loss was occurred between Blip and SOF. This is due to the relatively high dB/dt ratio than others, 0.37 T/sec. Although the period from SOF to Shut-off has long operation time, the field changing rates, dB/dt, are small enough, 0.068, 0.02 and 0.005, respectively. Thus the low induced eddy current and loss was occurred.

4. Conclusion

Through the numeric calculation of the eddy current on three types of joint for CICC connection, we can clarify the shape dependence of eddy current loss. The lap joint positioned at ‘Lower’ shows the maximum eddy loss, 11.38 joule during magnet operation. And the butt joint has the minimum value, 0.55 joule. The characteristics of the mini-lap joint shows promising result for KSTAR. It shows almost 7 times lower than that of lap joint.

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