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Nicolai N. Martovetsky

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Analysis of Losses in ITER Joints in varying parallel Field

Nicolai N. Martovetsky

Lawrence Livermore National Laboratory, Livermore, CA, 94550

Abstract— One of the options for a design of a Central Solenoid in ITER and other tokamak machines is pancake wound modules. In this configuration joints have to be placed in maximum magnetic field with high changing rate. In this condition joints should be designed to have at least the same or larger temperature margin as that for the conductor in the same field. It is argued that joints in parallel field can be designed to meet this requirements along with reasonably low DC resistance. Losses in parallel field are calculated and design features which can suppress AC losses without increasing DC resistance are discussed. Recommendations for low loss, low DC resistance joints are made.

I. INTRODUCTION

Joints between the conductors and terminals have always been a very sensitive issue in superconducting magnets. In joints, transport current crosses the interface between two superconductors that almost always have elevated heat generation and/or deteriorated properties in the area of the joint. In many cases in the past, superconducting magnets underperformed due to joint problems. Therefore in most applications joints are located in a low field, low field change rate region, so some deficiency in the joint properties are balanced by a much less severe environment than that for the conductor.

In the segmented ITER Central Solenoid (CS) the most convenient location for the joints from the point of view of assembly and support is the bore of the solenoid.

An isometric schematic view of the joint is shown in Fig. 1 which shows two mating cables compacted in the sleeves joined through the transition copper block. Chrome, plated on strands, is removed from the strand surfaces facing the sleeve only, but not from the strands inside the cable. This measure is supposed to keep losses acceptable and DC resistance low.

Several possible joint orientations were looked at and generally it is almost obvious, that longitudinal orientation promises lower losses and higher temperature margin than in the perpendicular field of the same amplitude.

In different options of the CS the perpendicular component of the field in joints varies in the range of 0.2-0.4 T/s with a background field up to 6 T, but in the segmented solenoid option, joint is located in a 13 T field with a maximum dB/dt of 1.2 T/s.

Generally, that the losses in longitudinal field will be lower than that in the transverse field, because electro motive force in the parallel field is equal

Fig. 1. Joint - praying hands configuration with the resistive barriers

to:

$$E = B \sum_{i=1}^5 \frac{\pi r_i^2}{l_p} \quad (1)$$

where r_i and l_p are radius of the center of the stage $i-1$ from the center of the i -th stage subcable and twist pitch of the subcable of the i -th stage, and the summation is performed over all stages (5 for both TF and CS ITER conductors). In transverse field e.m.f. of the twisted cable is the order of:

$$E = B \frac{l_p}{2\pi} \quad (2)$$

Usually, $l_p \gg r_i$, therefore losses in perpendicular field expected to be higher than in the parallel one.

Typically coupling losses in the cable represent significant fraction of all losses. Using relationship for losses per unit of cable space volume:

$$P = \frac{n\tau B^2}{\mu} \quad (3)$$

one can compare coupling losses by comparing corresponding parameter $n\tau$.

Measurements of the losses in the subcable and full scale Prototype ITER joints and conductors show that characteristic time of coupling losses $n\tau$ dramatically increases when cable is compacted to a void fraction less than 35% [1-3]. That shows that losses in the joint in perpendicular field will be much higher than that in the cable in the perpendicular

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field, therefore stability and temperature margin in the joint will be always much worse than that in the conductor, which is unacceptable for a high field joint.

Fig.2 . Characteristic coupling time in the cables and subcables versus void fraction [1-3]

Point at 27% in Fig. 2, is measured on the full scale cable [2], all other points correspond to the 1/6th subcable [1]. Since these test points roughly in line with the tendency, it shows, that Inconel tape, used in the full scale cables to wrap last stage subcables is effective to suppress last stage cabling losses. For comparison, parallel field losses on the subcable joint had coupling time constant of 60 ms with copper block without any resistive barrier [1].

High compaction of the cable is believed to be necessary to maintain DC resistance low which causes dramatic loss increase.

Fig.3 shows distribution of losses in the joint shown in Fig. 1 in varying perpendicular field of 0.4 T/s when no resistive barriers are employed [4].

Fig.3 Distribution of the Losses in the joint components

It is seen from Fig. 3, that using resistive barriers, one can significantly limit losses in the sleeve and the transition block, but total losses will remain high since losses in the cable, which give 80 W in 0.5 m long joint will not be affected. It was assumed in calculating the losses in Fig. 3,

that direction of the varying field is perpendicular to the cable axis and field is directed parallel to the plane created by cable center lines. When field is directed perpendicular to the plane of the cables, losses become much higher, since shielding currents can flow along low resistivity path. For example, 0.4 T/s field acting in this unfavorable direction will cause up to 350 W losses assuming joint resistance of 2 nOhm, this loss is unacceptable [4]. So, the only hope to have reasonably low losses in high field region is to orient the joint with cable axis to be parallel to the field vector.

III. LOSSES IN THE JOINTS IN PARALLEL FIELD

The shielding current pattern is shown schematically in Fig. 4.

Fig. 4 Shielding currents in the joint in parallel field

Each strand in the cable represents a complex spiral, which traps the magnetic flux and change of the flux induces an e.m.f. according to the relationship (1). This shielding current returns through the copper block thus closing the loop. In steady state conditions, the equivalent scheme could be represented as shown in Fig.5:

Fig.5. Equivalent circuit for joint in parallel field

The current distribution in the joint is obtained from the equation:

$$R_s \frac{d^2 I}{dx^2} = E + IR_{Cu} \quad (4)$$

where: R_s - is a transverse resistance [Ohm*m] between the SC cable strands and the copper block per unit length;

$I = I_{Cu} = I_{sc}$ - shielding current;

E - e.m.f. generated by parallel dB/dt [V/m];

R_{Cu} - resistance of the Cu block per unit length [Ohm/m].

Natural boundary conditions are:

$$\frac{dI}{dx} = 0 \quad \text{at} \quad x = 0$$

$$I = 0 \quad \text{at} \quad x = L$$

where $x=0$ corresponds to the joint middle point and $2L$ is a joint length. We assume here, that current flowing through the conductor on the top of the transport current does not cause current anywhere in the cable to reach critical value.

Equation (4) in dimensionless form reduces to:

$$\frac{d^2 i}{dx^2} = (1 + i\gamma)$$

where

$$x \equiv \frac{x}{L}; \quad i = \frac{IR_s}{EL^2}; \quad \gamma = \frac{R_{Cu}L^2}{R_s} \quad (5)$$

L is a half length of the joint

Boundary conditions:

$$x=0 \Rightarrow i=0$$

$$x=1 \Rightarrow di/dx=0$$

Solution of (5) is:

$$i = \frac{1 - \cosh(\sqrt{\gamma}x) + \tanh(\sqrt{\gamma})\sinh(\sqrt{\gamma}x)}{\gamma} \quad (6)$$

Let us make some numerical estimates of this result. For ITER CS cable in a parallel field with dB/dt=1 T/s, e.m.f. will be about $2.3 \cdot 10^{-3}$ V/m [4]. At $2L=0.55$ m, $R_s=1.21 \cdot 10^{-9}$ Ohm*m (corresponding to DC joint resistance of 2.5 nOhm; $R_{Cu}=2.63 \cdot 10^{-7}$ Ohm/m [5]), characteristic length of the current transfer between the cable and the copper block is:

$$L_t = \sqrt{\frac{R_s}{R_{Cu}}} \quad (7)$$

for ITER joint: $L_t = 0.068$ m = 6.8 cm. Maximum Current through the Cu block, when joint resistance is small (or $L_t \ll L$) will be:

$$I_{\max} = \frac{E}{R_{Cu}} \quad (8)$$

for ITER joint $I_{\max}=10\,260$ A at dB/dt=1 T/s.

Loss due to longitudinal current in copper and transverse current through the joint interface are:

$$W_{\text{parallel}} = I^2 R_{Cu}; \quad W_{\text{transv}} = \left(\frac{dI}{dx}\right)^2 R_s \quad [\text{W/m}]$$

Heat generation in the joint (in addition to hysteresis, coupling loss in the cable and eddy current losses) will be about 10.6 W in steady state, which is significantly less than in transverse field, but still quite high.

To cut down losses one needs to restrict or to break return current through the copper block. Resistive barrier (or insulating breaks) should have a distance comparable or less than characteristic length given by relationship (7) to be effective.

In transient process, as it is the case with initiation of plasma, one needs to take into consideration inductance of the loop which restricts growth rate of the shielding current.

If time constant τ of the shielding current decay is comparable or larger than the duration of pulse, losses will be somewhat lower. For ITER joint, 0.5 m long, the decay time is about 0.5 s [4] and losses in field pulse:

$$Q_{\text{transient}} = P_{\text{steady state}} T \left[\left(1 - \frac{\tau}{T}\right) (1 - \exp(-T/\tau)) \right]$$

$$\text{where } T = \frac{\Delta B}{dB/dt}$$

In the above we assumed that two mating cables have the same direction of the twist on all stages. If mating cables will have opposing directions of the twist, shielding current will flow in opposite directions and across the joint interface. In this case, any measures to restrict these currents will negatively affect DC resistance, since the path of the shielding currents coincide with the transport current path.

Table I. Losses and shielding currents versus joint resistance in the joint in parallel field with opposite twist directions in the mating cables [9, 10].

Rj	P, W	I shield cable, kA
1	50	122
2.5	20.7	54
5	10	24.4

Table I shows heat generation in the joint in parallel field of 0.5 m ITER joint when CS1 grade conductors have opposite twist (scaled for 0.36 T/s field change rate). The table shows very high losses and currents, which might cause also mechanical problems, so mixture of opposing cable twist directions is in general undesirable.

IV. OPTIMIZATION OF THE BREAKS LOCATION FOR JOINTS IN COMBINED TRANSVERSE AND PARALLEL VARYING FIELD

As shown above, to reduce losses the transition copper block should have resistive or insulating breaks for longitudinal currents with a spacing shorter than characteristic transfer length. If there is a transverse component of the magnetic field, resistive breaks should be introduced to cut eddy current losses and coupling losses in the transition block as well. A view of the transition block with the resistive breaks is shown in Fig. 6.

Fig. 6 Transition block with breaks

Minimum effective amount of the resistive breaks in the circumferential direction is two, since if there is only one break, no coupling currents are restricted, because from the symmetry considerations no coupling currents crosses the center of the symmetry anyway. Therefore, break in the center is useless. This is illustrated in Fig. 7.

Fig. 7. On the circumferential resistive barriers optimum locations.

Resistive barriers in the sleeve are necessary to make resistive barriers in the transition block effective. As numerical analysis shows [6], if they are aligned, two circumferential barriers can reduce coupling and eddy current losses by factor of 10 in comparison with no barriers or misaligned barriers cases.

V. TEMPERATURE MARGIN OF THE CABLE IN THE JOINT

As shown above, parallel location of the joint can give acceptably small losses. What temperature margin can we get for the cable in the joint if it is oriented parallel to the magnetic field?

When the cable is oriented parallel to the field, strand axis is not strictly parallel to the axis of the cable. At a cabling factor of 1.1 (ratio of the strand length in the cable to the cable length), average angle of the strand axis to the cable axis is 25.8° .

Preliminary measurements [7] show that critical current in the field oriented 40° to the strand axis is about 30% higher

than its value at 90° , and in a parallel field it is higher than in perpendicular roughly by a factor of 2.

Let us estimate, what current sharing temperature T_{cs} will be for a joint in parallel field of 13 T and compare it to the T_{cs} of the conductor in 13 T perpendicular field with the transport current of 42 kA. Using the formula, recommended for ITER conductor design [8] and assuming 40% jc enhancement for the strand in the cable, parallel to the field, one can obtain that current sharing temperature in the joint will be 8.67 K, while in the conductor in the perpendicular field it will be 8.15 K. This show that a properly designed joint can have bigger or the same temperature margin, low losses and low DC resistance.

One of the concerns for high field joint is to provide favorable stress and strain on the strands. If choice of the materials or design is not optimal, additional compression on the strands of the cable in the joint may deteriorate properties and make a joint the weakest point in the magnet. We can estimate a strain in the cable which will wipe out 40 % jc enhancement. Using the same approach, we obtain that if strand in the regular cable experiences 0.25% compression, joint could be compressed down to 0.55% before its properties would become inferior to the cable properties in perpendicular field. This should give enough margin for a designer to design a joint with sufficient temperature margin.

VI. CONCLUSION

Analysis of the joint losses shows, that a low loss, low resistance lap joint is possible if oriented parallel to the field and a system of insulating breaks is used in the transition block and in the sleeves. It is shown that transverse field orientation is not promising for high field joints.

Available data indicate that the joint in parallel field can have the same or better temperature margin than the conductor in the same strength perpendicular field.

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