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Analysis of the AC Losses in the US Preprototype ITER Joint

Nicolai N. Martovetsky
Philip C. Michael

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Lawrence Livermore National Laboratory

Analysis of the AC Losses in the US Preprototype ITER Joint

Nicolai N. Martovetsky
Lawrence Livermore National Laboratory, 7000 East Ave, Livermore 94550, CA

Philip C. Michael
Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, 185 Albany St., 02139, MA

Abstract **- The first low resistance, low loss US joint for ITER was tested at the MIT facility. Test results and analysis on the AC losses in the US Preprototype ITER joint with different field orientation, with and without transport current are presented. Losses in the joint components are evaluated; measures to improve the joint performance are discussed.**

I. INTRODUCTION

The US Pre prototype ITER joint was built and tested at the Pulsed Test Facility (PTF) at MIT in the second half of 1996. This was the first full scale joint designed to have low losses and low resistance for operation in pulsed ITER fields. For the first time such a joint was tested in pulsed fields with large amplitudes, high dB/dt rates and with a transport current. The detailed design and manufacture of the joint sample are described in [1]. Cross section of the ITER Pre prototype joint is given in Fig. 1.

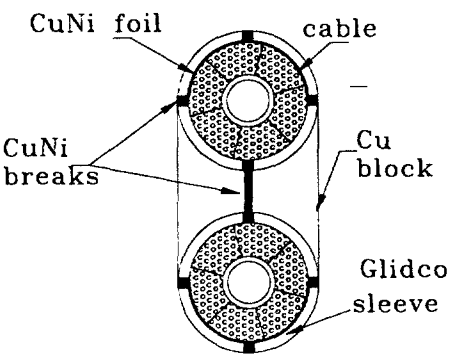

Fig.1. Cross section of the US PP joint

The main features of the joint include:

- Twisted compacted cables in the Glidcop sleeve
- Chrome plated strands in the cable; chrome removed only from the strands on the cable surface
- Insulating Inconel tape between last stage subcable was left intact
- Glidcop sleeve and copper saddle piece with resistive breaks
- One twist pitch long

Preliminary analysis of the ITER type joint is given in [2]. It predicted that about 50 % of the losses would come from the cable coupling and hysterisis losses and the rest of it would come from the other components. The cable coupling losses are very much dependent on the cable compacting, and void fraction was chosen to be 20% to ensure good sintering of the strands to the Glidcop sleeve and low DC resistance [1].

Losses in the joint were measured in three field orientations:

Parallel field

Transverse field, when field is parallel to the plane containing both cable axes (we refer to this orientation as "ITER" transverse field)

Transverse field, when field is perpendicular to the plane containing both cable axes (we refer to this orientation as "non-ITER" transverse field)

The reason for the "non-ITER", highest loss orientation is to obtain information regarding the joint DC resistance and to see if this type of measurements could give better understanding of the joint behavior.

Losses were measured by the calorimetric technique with temperature sensors installed at the inlet, outlet of the joint sample and on the conductor, so integral of the inlet and outlet enthalpy:

$$Q = \int mh_{out} - \int mh_{in}$$

which constitutes losses, could be calculated. Calibration showed that 75% to 90% of the heat deposited in helium is detected. The experimental error of the loss measurements is estimated to be within 20%.

In the loss measurements, we used triangular and trapezoidal pulses with a ramp up rate in most cases equal to ramp down rate. The flat top duration in trapezoidal pulses was usually 30 s. The purpose of the trapezoidal pulse was to see a magnetic flux penetration in the joint. Comparing losses in a trapezoidal cycle with triangular pulse losses one can deduce the magnetic moment decay (or field penetration) in the joint.

The ITER "praying hands" layer to layer joints will experience up to 7 T parallel field in the Central Solenoid (CS) baseline design. In some design options 13 T field, mostly parallel, is considered. Transverse field can be as high as up to 4 T in the Central Solenoid and up to 7 T in the Toroidal Field coils. In ITER scenario the field drops 2 T at plasma initiation with maximum dB/dt of 1.2 T/s in the bore of the CS which is considered the largest nominal disturbance for the joints. In the PTF testing program we were trying not only to characterize joint losses but also simulate close conditions to ITER and CS Model Coil scenarios and measure the joint operating margins.

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N.N. Martovetsky (510) 422 4269, FAX (510) 422 2477, martovetsky@llnl.gov.
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II. JOINT LOSSES IN PARALLEL FIELD

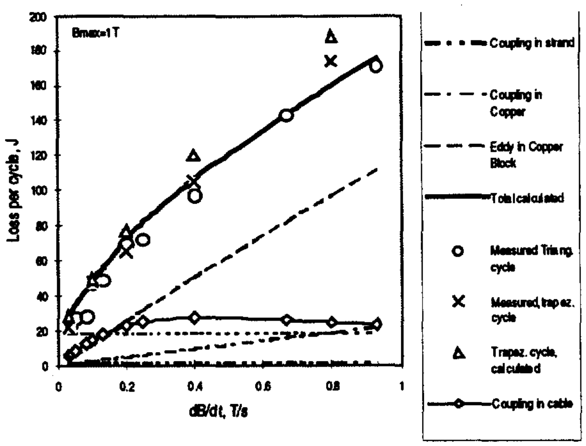

Fig.2 Losses in parallel field, 1 T cycle

Fig. 2 shows losses in the joint in the parallel field in 1 T triangular cycle versus dB/dt. Fig. 3 shows results of the loss measurements and calculations for dB/dt=0.1 T/s for different amplitudes. Fig. 4 represents losses versus amplitude for dB/dt =0.4 T/s.

Eddy current losses in the copper block were calculated by integrating Maxwell equations. Hysterisis losses in the strands were deduced from the strand loss measurements with an appropriate geometry factor, assuming current density to be the same in both parallel and transverse field. Coupling losses in the copper block were calculated as described in [2]. Coupling losses in strands were calculated as described in [3]. As it can be seen from Fig.2-4, this last component is small for small amplitude changes and therefore is typically ignored in loss evaluation, but for large amplitudes, it is not negligible and should be taken into account.

Cable coupling losses were calculated as a difference between the total measured losses and all calculated components of the losses mentioned above. In a parallel field this loss component should be small if a cable is fully transposed. Tests show that this component is not negligible and represents clear saturation effect in 1 T pulses. We assumed that there is a certain cable volume, which has effective loops. These loops trap some magnetic flux and dissipate the energy in the resistive contacts. These loops can be within one cable or between two cables, shorted through the copper block. Using two fitting parameters – coupling time constant for the cable in parallel field and fraction of the cable volume, dissipating the energy, we were able to fit the data in wide range of the amplitudes and dB/dt both for triangular and trapezoidal pulses, shown in fig. 2-4. The best fit corresponds to the coupling time τ and "dissipating fraction of the cable volume" of 0.6 s and 9%, respectively. This part of the loss can not be predicted in advance, as there is no theory developed yet for this loss component.

The loss analysis in parallel field suggest the following:

An approach to describe the total loss as a summation of hysterisis and coupling loss did not work for ITER joint, at least in the range of dB/dt, where time constants of the joint were comparable or longer than the ramp up – ramp down times. Shielding effects should be taken into account.

Strand magnetization in a parallel field gives significant contribution into total loses at more than 3-4 T field change, therefore it should be included in loss calculations in pulses with large amplitudes.

Losses in the copper block and in the Glidcop sleeve are significant and, depending on the field pulse, represent up to 60% of total losses. These elements can be optimized to improve AC performance of the joint by introducing resistive barriers in the copper block as discussed in [2]. Resistive barriers in the Glidcop appear to be very effective to suppress large loop currents and associated losses in a parallel field.

Losses at 1 T amplitude and 1T/s field changing rate suggest that it is possible to design a joint operating in the 13 T parallel field with an acceptable performance, capable to withstand initiation field drop.

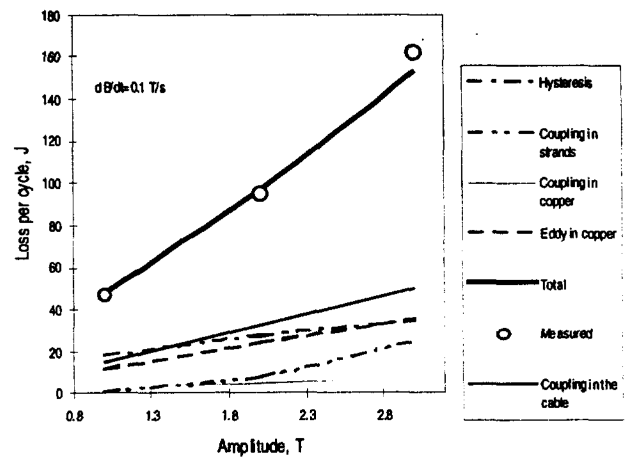

Fig.3 Losses in parallel field, dB/dt=0.1 s

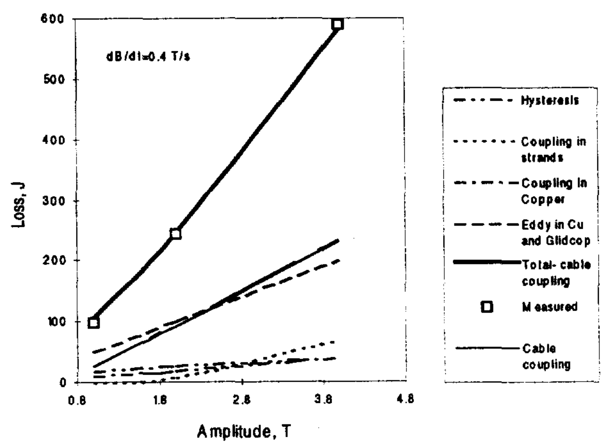

Fig.4 Losses in parallel field, dB/dt =0.4 T/s

III. JOINT LOSSES IN ITER TRANSVERSE FIELD

It was expected that the joint losses in a perpendicular field would have higher losses than in a parallel field [2]. Fig. 5 shows that they are several times higher in similar pulses. It is seen that in the 1 T triangular cycle the loss saturation occurs at 0.2 T/s which suggests that there are some loss contributors which have much longer time constants – 5 s or more.

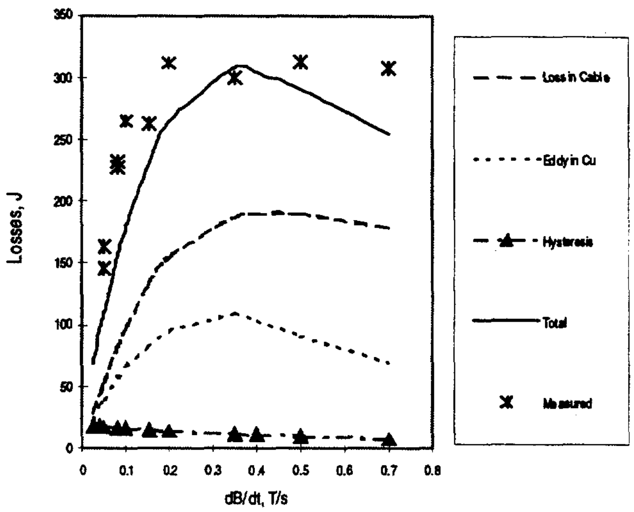

Fig. 5 Loss in ITER transverse field, the 1 T triangular cycle, calculated versus measured

Analyses of the joint losses in the transverse field shows, that if cables in the joint would be removed, and only the copper block left, losses in copper would have been higher than measured in the entire joint assembly at dB/dt>0.5 T/s. The cable coupling time constant τ, measured by observation of the magnetic moment decay was found to be about 0.6 s. The cable shields the copper block effectively in 1 T fast (dB/dt>0.3 T/s) pulses, so magnetic field penetrates copper much slower than it would have been without the cable; that reduces total losses in relatively small amplitude fast pulses. This effect is similar to the multifilament wire loss decrease when frequency exceeds some certain level and the field does not penetrate a wire interior [4].

Fig. 6 presents a comparison between losses in a trapezoidal and in a triangular cycle with an amplitude of 1 T. It is seen that shielding effect is very strong, much stronger than in a parallel field and when field can penetrate the joint in a trapezoidal cycle, losses increase almost two fold. That means that fast pulses associated with plasma control or plasma initiation should not produce high losses in the joint. On the other hand, large amplitude swings, when field penetrates deep into the joint elements, will cause noticeable integrated losses, with loss power in the joint up to several tens of watts at ITER relevant dB/dt of 0.1-0.25 T/s (see Fig. 7).

It is seen from Fig. 5 and 6, that loss in copper represents significant part of the total losses, which suggests that losses can be noticeably reduced by laminating the copper block as discussed in [2]. To reduce losses further it is necessary to increase the void fraction in the cable (providing that does not dramatically increase DC resistance).

Analysis [2] indicate that existent barriers in the Glidcop sleeve were not efficient to reduce cable induced losses in the sleeve in a transverse field, but optimized barriers should reduce cable induced losses by 10-30%. In the Pre prototype joint tests we could not separate the losses in the Glidcop and in copper induced by the cable from the losses in imaginary stand alone cable. Comparison with the loss measurements on subcables suggests that the subcables are effectively decoupled, since coupling time τ in the 20% void fraction subcable (0.8 s), [5] is close to the measured coupling time of the full scale cable (0.6 s) per cable volume.

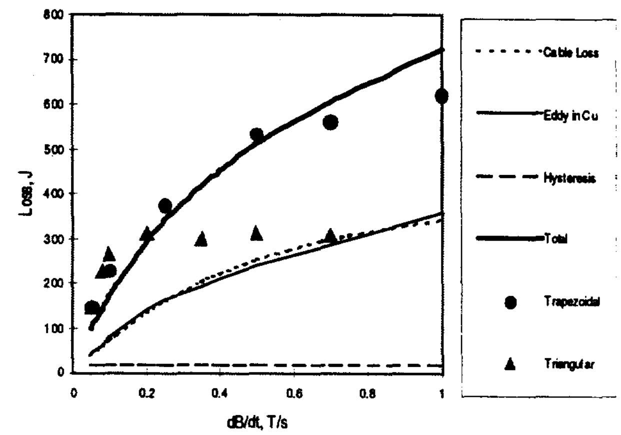

Fig.6 Losses in ITER transverse field, 1 T trapezoidal cycle, long flat top (triangular cycle measured losses are shown for comparison)

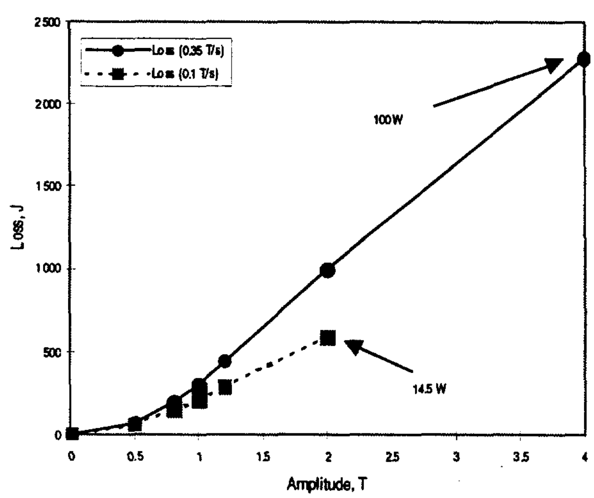

Fig.7 Losses in transverse field, triangular cycle

IV. JOINT LOSSES IN "NON ITER" TRANSVERSE FIELD

In a non-ITER field, the current path in the joint coincides with the current path of the DC transport current. The difference is in the Electro motive force distribution in the joint: ideally constant at the DC tests and monotonous from positive to negative profile in a non-ITER varying field. That makes it possible to deduce the effective resistance of the joint, assuming that the resistivity of the joint is constant along the length. Fig. 7 represents comparison of the loss measurements and calculation of the losses in the joint, assuming total resistance of the joint 6 and 10 nOhm, respectively. It is seen that the calculated losses about 50 % higher than measured. This difference can be explained by evidently more "resistive" ends of the joint, which was observed in DC measurements by miniature Hall probes, installed on the joint [6]. That reduces the current density at the joint ends that would have given the highest contribution into the joint losses, which explains why measured losses are lower than expected assuming uniform resistivity of the joint along the length.

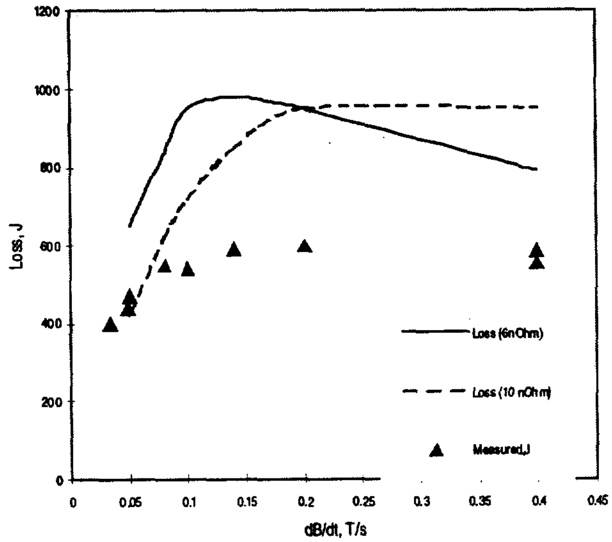

Fig. 8 Non-ITER field losses, calculated versus measured, 1 T triangular cycle

V. Joint Losses and Stability in a Varying Field with a Transport Current

Influence of the transport current on the losses in varying magnetic field is difficult to predict analytically, as this requires knowledge of the detailed current density and electrical field distribution in the joint. From general consideration, one may expect that because transport current in the joint is much lower than the critical current, effect of transport current should be small. Comparison of the losses in a combined current and field pulse against the sum of the losses in separate identical field and current pulses showed that the effect of the transport current is not negligible at high currents. In both parallel and transverse field, effect of 20 kA transport current was below 15% in all tests. The transport current of 46 kA increases the losses of separate field and current pulses losses combined by up to 70% in transverse ITER field and up to 40% in a parallel field. This phenomenon deserves more systematic study in the future joint tests.

Stability tests with 45 kA pulses and synchronized filed raise to 4 T showed that the joint can withstand up to 0.5 T/s change rate without going normal. This result gives enough margin for stable CS ITER joint operation, but the margin is lower than expected from analysis. It is thought that the heat transfer in the cable space is not as efficient as expected and heat very slowly drifts from the cable space to helium which flows mostly through the central hole. This speculation is supported by the observed long time (tens of seconds) of the joint re-cooling after the pulse which is more than 10 times helium replacement time. In addition, increasing the flow rate from 5 to 30 g/s changed maximum stable dB/dt by only about 10%. Blocking a central passage in the joint and forcing helium through the cable space should significantly increase stability of the joint.

VI Summary

Loss measurement showed a stable behavior of the Pre prototype US ITER joint in all ITER relevant pulses. Losses in the cable in a parallel field were higher than expected. Losses in a transverse field, in line with expectations, can be as high as several tens of Watts in some moments of ITER operating scenario. However, it is believed that it is possible to meet average heat generation requirement of 15 W over the ITER 2000 s cycle per joint. Measures to improve joint AC losses and stability are discussed.

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Technical Information Department • **Lawrence Livermore National Laboratory**
University of California • Livermore, California 94551