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Busbar arcs at large Fusion Magnets: Model Experiments on Busbar arcing in a Double Walled Feeder Tube with the LONGARC device

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Electric arcs moving along the power cables (the so-called busbars) of the toroidal field (TF) coils of large fusion devices like DEMO and ITER may reach and penetrate the cryostat wall. The present work concludes a series of model experiments studying the propagation and destruction mechanisms of such busbar arcs in small scale. While it went clear from previous findings that the inner feeder tube of a busbar won't withstand a powerful arc, the present work investigated the impact of the arc on the second, coaxial outer feeder tube. The key finding is that the outer feeder tube will stay intact in any case, proving the robustness of the ITER TF busbar confinement concept. As the basic DEMO magnet concept will be "ITER-like", the knowledge of weaknesses and strengths of the ITER TF busbar feeder design may be helpful in the preparation phase of a detailed DEMO magnet feeder design.

Keywords: magnet safety, electric arc, busbar arc.

1. Introduction

The inductive energy stored inside the toroidal field (TF) coils of large tokamak devices like DEMO (~185GJ) [1] and ITER (~40GJ) provides a considerable potential of hazard in case of an accident. Calculations with the code system MAGS (MAGnet System) in the frame of ITER already proved that for most accidents the damage is limited to the coils themselves. However electric arcs moving along the power cables of the coils, the so-called busbars, may threaten the cryostat wall. Knowledge of the arc velocity and destruction mechanisms is crucial for an assessment of possible hazards and relevant timescales. Because of the lack of accurate numerical modeling and missing suitable experimental data, small scale model experiments were initiated to investigate the basic propagation and destruction mechanisms of busbar arcs.

The whole campaign orientates very close to expected ITER busbar arc scenarios and due to the intended similarity of the DEMO magnet design to the ITER magnet design [2], results are also expected to be helpful in answering questions on the DEMO magnet design concept.

This work is a continuation earlier experimental work on this topic [2, 3] to get closer to realistic conditions. In [2] it had been shown that the inner feeder tube of the double walled feeder tube concept as foreseen in the ITER will not be able to withstand an arc.

2. Important previous results

As this work concludes the campaign of busbar arc related experiments at KIT, a preceding section that briefly and very qualitatively summarizes the very basic results seems appropriate. We found that the busbar is always destroyed at its complete cross section, a fast propagation mode cutting only the insulation does not exist for a typical ITER-like cable design. In half tube experiments, only up to 20-30% of the arc energy would have been consumed for destruction if pure melting was assumed [2]. This rather low value together with the visible metal fallout on the vessel wall may be taken as an indication to additional vaporization. Vaporization enthalpies are about an order of magnitude higher than for melting. We conclude that melting is dominant, although vaporization may not be neglected with regard to the consumed energies.

Tubes or other parallel metal structures have no significant impact on the burning down velocity of the conductors, i.e. the arc propagation speed. Particularly, arcs show a distinct tendency to split to series arcs in the presence of conducting structures. With regard to the safety aspect, this allows for the important conclusion that no arc lengths in the order of meters with corresponding huge powers are to be expected. Nevertheless arc powers up to the order of a hundred megawatts seem possible in large fusion devices like ITER or DEMO.

All simulated full and half tubes did show severe damage indicating that the ITER inner TF feeder tube will not withstand a busbar arc. The still outstanding key question is whether the outer feeder tube may withstand arcing or not. Consequently, the focus of this work is to investigate the impact of a moving busbar arc on the outer wall with the inner wall being present, too.

2. The LONGARC experimental device

The LONGARC device, see fig. 1, was set in service in 2012 as a successor of the previous VACARC device. The main components are a 20m^3 vacuum vessel (a former cryostat) and a power converter capable of 175 kW (peak) at 1.5 kA DC. LONGARC has three windows spaced 45° at the vessel perimeter and one window in the top cover. Four video cameras, one with a frame rate

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of up to 500 s^{-1}, are installed at different positions. The arc behavior inside the tube is made partly visible by one in-plane camera placed to allow a view inside the open tube end.

Fig. 1: LONGARC vessel.

3. In-vessel experimental setup

Fig. 2 shows a schematic of the cross section of an ITER TF coil double walled feeder tube. It carries two busbars separated by a vertical, 20mm thick steel wall that divides the inner tube into two half tubes.

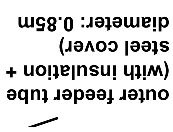

Fig. 2: Schematic cut view of an ITER TF double feeder.

The present setup models both the inner and the outer feeder tube. The division of the inner feeder tube into two halves was investigated in previous work [2] and is not taken into account in this simplified setup.

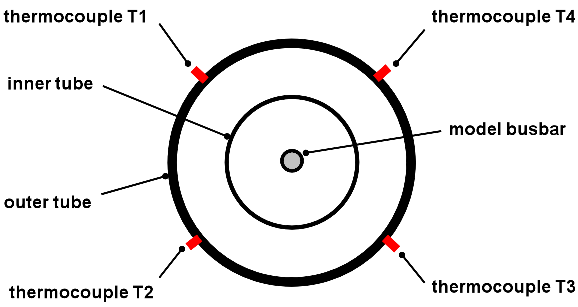

Fig. 3: Schematic cut view of the simplified setup.

According to the schematic in fig. 3, instead a simple, circular inner tube in scaled wall thickness carrying a single model busbar in its center was installed. Several experiments were equipped with thermocouples at four radial positions inside bores in the outer tube. Figs. 4 and 5 show the setup which was used for all experiments described below.

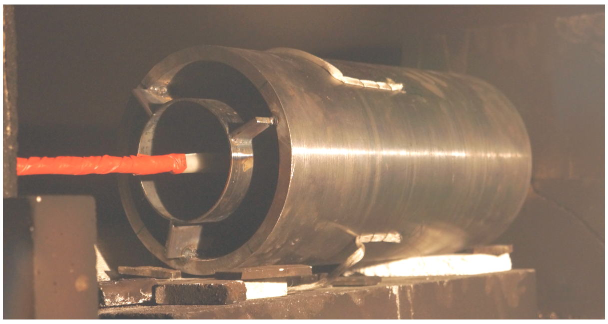

Fig. 4: Setup of a double walled feeder line carrying a single model busbar. The setup is symmetric, i.e. a picture of the other tube end would look the same. The visible instrumentation are thermocouples placed on the outer tube.

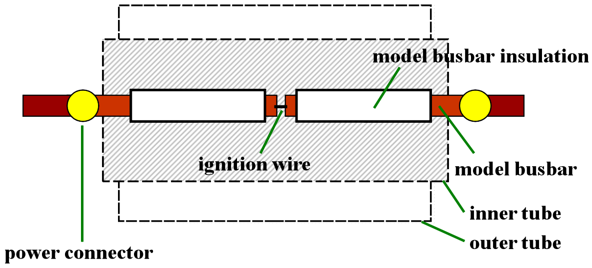

Fig. 5: Schematic view of the setup in fig. 4.

Experiments were performed at a geometric scaling vs. an ITER TF busbar of 1:7 and 1:4. Arc currents were selected to reproduce the assumed arc power per unit volume of a real ITER busbar cable at operating conditions.

In the assumed accident sequence, after quench of the superconducting cable with subsequent overheating up to melting, an arc is ignited in the molten conductor gap. The tokamak TF coils in series mean a huge inductive power source, so the current won't just stop because of a gap. This busbar arc may grow and destroy the walls of the surrounding tubes as well as it will move together with the melting end of the busbar.

The model experiment to this scenario starts at the point when an arc is ignited in the molten gap. The power converter is set to the target current which ignites the arc by blowing up the weak ignition wire between the two conductors. The gap between both electrodes grows until in a later phase, the arc splits into two arcs in series. Then the remaining structure parts carry a part of the current between the two new structure arc spots. From previous experiments a complete destruction of the inner tube is expected. Three steel fins spaced at 120° fix the inner tube at both ends so it cannot move or fall down. The real strength of the supports for the inner tube in a full scale feeder is not clear and also the impact of possible compensator pipe elements is beyond the scope of this study.

4. Results

4.1 Tube damage results

The first experiments with double walled tubes had been performed with 1:7 (6mm copper core) conductors. As expected, the damage to the inner tubes was similar to the previous single inner tube experiments. Figure 6 shows pictures taken from a 45° angle to the tubes setup. On the left picture, light from the arc is visible only inside the circle of the still intact inner tube. On the right picture an annular illumination between the inner and the outer tube indicates the penetration or destruction of the inner tube wall.

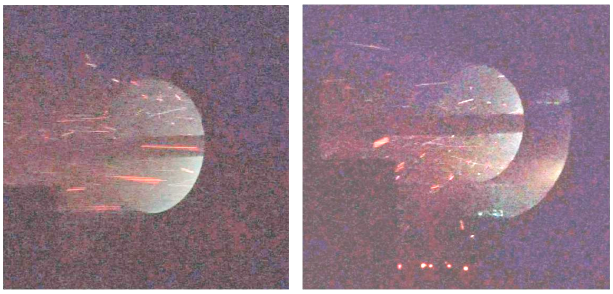

Fig. 6: LK1101 Left: arc burns in inner tube only. Right: light between inner and outer tube indicates failure of the inner tube after about 11s.

Fig. 7 illustrates the damage during LK0801 (1:4, 1256A, 148kW, 31s) which represents a quite typical result for all experiments of this campaign. The outer tube is still intact. No glowing on the outside of the outer tube could be observed, only slight tempering colors are visible. In obvious contrast, the inner tube is destroyed completely by melting over a considerable length.

Fig. 7: LK0801 Left: the outer tube shows no structural damage, just slight tempering colours. Right: the destroyed inner feeder tube after removal from the outer tube.

In order to check out the limits of outer tubes, now in the two experiments LK0402 and LK0702 1:4 conductors were installed in double tubes originally foreseen for a 1:7 setup. This way arc currents in the order of 1000A inside a 1:7 model feeder tube were possible too. Even in this setup with considerably overscaled arc powers additionally combined with reduced arc propagation speed, the outer feeder tube was not harmed beyond heating it up to temperatures that caused slight tempering colors after the experiment. Similarly for LK1201, a 1:3 conductor had been placed in a 1:4 double tube.

Following the previous representation in [2,3], the melting energy consumed for the destruction of the inner tubes was related to the total electric energy consumed during an experiment. The melting energy is estimated from the hole size using the melt enthalpy of steel starting from room temperature. Figure 8 shows the ratio of melt energy for holes in the inner tube as a fraction of the total arc electric energy consumption during an experiment. The double wall results had been added as the crossed symbols to the similar figure from [2]. For both scales 1:7 and 1:4 the energy fraction consumed for hole melting is in the order of 20-35%. This is somewhat larger than in previous experiments. Especially for 1:7, a strong dependence on the arc current is visible indicating that additional arc power is preferentially used for melting destruction.

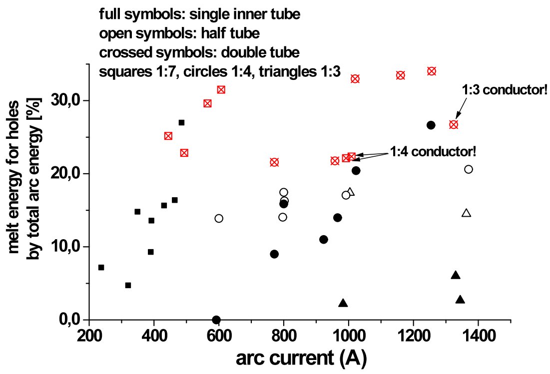

Fig. 8: ratio of melting energy for holes (in inner tube) vs. total arc energy.

4.2 Velocity results

Due to the poor observability inside the tubes, there is no option for an accurate, transient speed analysis for each side of the conductor like in free inline experiments. Instead, the burning down speed of the conductors may only be estimated from the gap width at the end of the experiment divided by the arc burning time. Fig. 9 shows the gap growth speed.

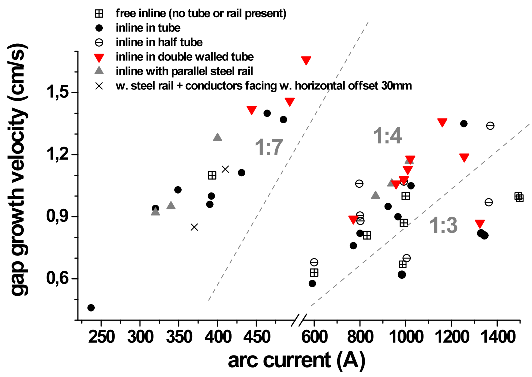

Fig. 9: gap growth velocity vs. arc current.

Again the double wall results have just been added as the down triangle symbols to a figure known from [2]. The double walled containment shows no significant impact on the burning down of the model busbars although it looks like there may be some weak tendency to slightly higher speeds. The “mixed scale” experiments LK0402, LK0702 and LK1201 appear inconspicuously in the region related to their conductor scale. This confirms the low impact of surrounding structures on the arc propagation speed.

4.3 Temperature results

After it was clear from the first experiments that the outer tube won’t melt, the outer tubes were equipped with four NiCr-Ni thermocouples as indicated in fig. 3. The sensor tips were placed in bores at the center of the outer tube to estimate the achieved temperatures. The bores 90 degrees off from each other at the circumference would allow detecting a possible preferential burning direction of an arc. The remaining wall thickness of these blind bores was about 2mm to the inside. It turned out that during the typical arc burning time of 20-30s the temperatures did rise at strong rates and in all cases only the extinction of the arc limited the temperature rise beyond a maximum value of about 430°C. Several experiments showed temperatures far below this value.

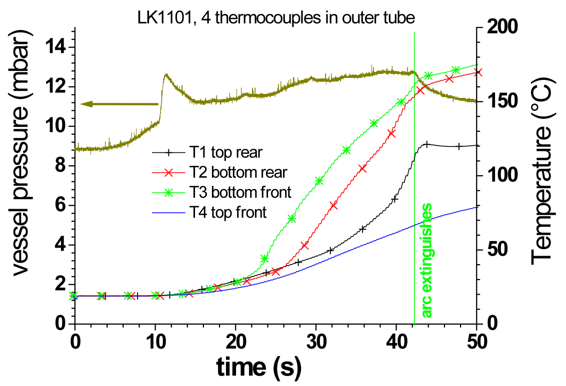

Fig. 10: LK1101 (771A, 84.4kW), short term temperature data.

Figure 10 shows the short term temperature results of LK1101. The vessel pressure data is shown in this graph, too, because there are hints from previous experiments that the pressure peak at 10.5s is probably correlated to the failure of the inner tube. Such pressure peaks together with a luminous effect (which simultaneously occur in the pressure data and the videos of LK1101, too) already had been observed in earlier experiments with single tubes. The observation had been addressed to the release and ignition of hydrocarbon residuals that originate from the conductor insulation. The failure of the inner tube will create an opening for release which is suspected to initiate the above process in this case. The temperature data nicely confirm this hypothesis as the pressure peak also perfectly marks the starting point of the temperature rise at all four thermocouples on the outer tube. Except for the signal of T4, all temperatures show a significant increase of slope after some time. After the experiment the inner tube was found still partly intact in the direction towards T4. This finding may allow for the plausible conclusion that the steeper heating up observed for T2 and T3 and weaker also for T1 is due to direct contact of the arc plasma jet with the tube wall. At arc extinction, all temperatures are below 200°C but they are still rising as at a vessel pressure in the order of ten millibars convection cooling plays no significant role compared to heat redistribution by conduction in the metal parts.

The presence of a sudden change of slope in the data of a specific thermocouple may be regarded as an indication for a failure of the inner tube wall towards this thermocouple. Beyond this abrupt behavior, smooth, correlated shifts in the ramp rates between thermometers may indicate that the orientation of the arc was not constant. Analyzing fig. 10 in this sense, the curvature of T3 data becomes negative after about 24s while the curvature of T1 starts to increase from a more or less constant slope after about 32s. T2 seems to have several regions of more or less constant slope, however slope changes abruptly at 10.5s and 26s. In summary this may be interpreted as an arc turning from T3 (bottom front) to T2 (bottom rear) including the failure of the inner tube towards T2 after about 26s. The arc seems basically burning to the bottom between T2 and T3 where the steepest temperature increase is observed, however the T1 and T3 data indicate a slight change of orientation from front to rear with time (T4 + T3 flatten while T1 + T2 steepen).

This (indirectly derived) turning behavior of the arc column seems not predictable. In some cases the burning direction does not change significantly after failure of the inner tube. Then maximum temperatures of 400°C at one side and only 100°C at the opposite side of the outer tube diameter could be observed. In other cases the differences between the four thermometers were lower (but never less than 100°C), indicating a turning of the arc burning direction during the experiment.

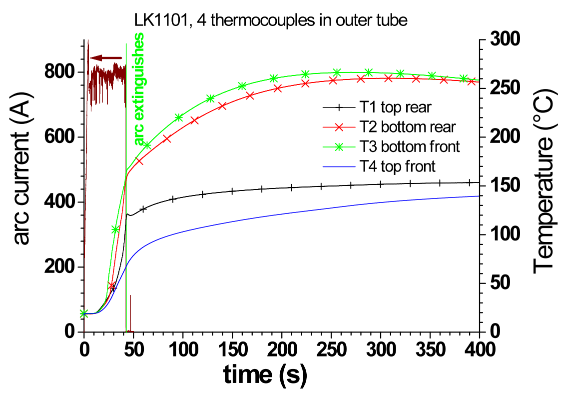

Fig. 11: LK1101 (771A, 84.4kW), long term temperature data.

Fig. 11 expands the temperature data of fig. 10 up to several minutes after the arc extinguished. The first temperature maximum in the order of 270°C is reached at T3 not before 200s after arc extinction. T2 shows a similar maximum value at a similar time while T1 and T4 show significantly lower signals that are still rising when the temperature measurement was stopped. As the highest temperatures are observed at the bottom thermocouples T2 + T3, one can assume a heating up from melt of the destroyed inner tube which was partly collected at the bottom inner side of the outer tube during the experiment. The slower temperature rise of T1 + T4 is due to thermal conduction from the bottom melt carrying region upwards along the tube walls.

4.4 Temperature results at mixed scale conditions

Fig. 12 shows the temperature data for an experiment in a 1:7 double tube, however a 1:4 conductor was installed so an arc current of about 1000A was possible in this experiment. For the uppermost curve the temperature stops rising at about 780°C as soon as the arc extinguishes. The curve suggests a further rise if the arc had not extinguished, however on the other hand the arc is already quite far away from the thermometer spot so further considerable heating up to melting could be excluded. An intuitive extrapolation of T2 data from the curvature may suggest a maximum temperature in the order of 900°C if the arc would not have extinguished. This result should be taken with care, as changes in curvature may also be related to changes of the arc column burning direction. But in this case arc column turning seems not probable because obviously all other three temperatures show no hints to such behavior.

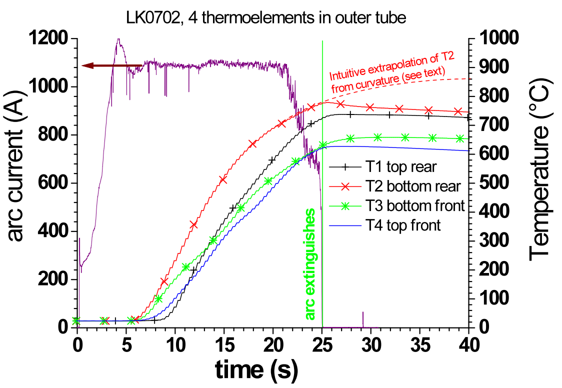

Fig. 12: LK0702: short term temperature data during an experiment with a 1:4 conductor in a 1:7 double tube.

As a conclusion even under these extreme conditions the outer tube maximum temperature is still far below melting conditions. Fig. 13 shows the tempering colors after this experiment. They represent the maximum observed “damage” to an outer feeder tube in the whole experimental campaign.

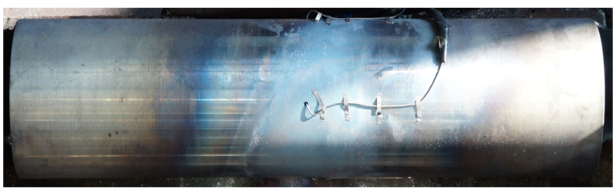

Fig. 13: LK0702: tempering colours on the outer tube after an experiment with a 1:4 conductor in a 1:7 double tube.

5. Summary and Conclusions

The double tube experiments did show slightly more severe damage to the inner tube than comparable single inner tube experiments. This finding is most probably related to the confinement of the plasma jet between the tube walls after failure of the inner wall.

The fraction of arc energy consumed for tube melting turned out to depend considerably on the arc current. This finding suggests that additional arc power is preferentially consumed by structure (tube) destruction and not, as might be suspected alternatively, to increase the vaporized fraction against the melted fraction. This observed behavior will make a reliable predictive damage modeling difficult.

The most important result of the present campaign is the fact that the outer tube as designed for ITER TF busbars is expected to withstand high current arcing in any case.

The conclusion for DEMO is that the double walled TF feeder tube concept of ITER seems a very promising approach to avoid holes in the cryostat vacuum caused by a moving busbar arc along the feeder region. Here other safety relevant components may still heat up from the heated tubes but they won’t be hit by an arc directly.

Nevertheless the issue of a busbar arc passing the interface between cryostat and reactor building (i.e. the coil terminal box) still remains unsolved.

Acknowledgments

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