A superconducting magnet feeder system that avoids the risk of Paschen discharge

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Abstract. Current is traditionally fed to magnets in fusion devices via a system of superconducting busbars in a thermally insulating vacuum enclosure. Some of the magnets are pulsed, taking the busbars to a potential of several kilovolts, so these must be well insulated electrically. There is a risk of helium leaking into the insulation vacuum, so the electrical insulation of the busbars must be permanently hermetic in order to avoid the risk of Paschen discharge, subsequent arcing and concomitant heavy damage. Such so-called Paschen-tight insulation is difficult to achieve, especially considering that the system is pulsed and the required lifetime may be of the order of 20 years. This report describes a conceptual study of such a feeder system that avoids the risk of Paschen discharge by routing the superconducting busbars via a pressurized helium environment, thus eliminating the necessity of thorough hermetic sealing of the insulating envelope. In the concept that is presented several other features address design issues that have occurred in recent feeder systems for fusion magnets.

1. Introduction
The conductors related to the large pulsed magnets used for confining the plasma in experimental fusion reactors must be electrically insulated. It is customary to enclose the busbars and current leads in the associated feeders in a vacuum enclosure to provide thermal insulation. At each pulse or rapid discharge of a magnet large voltages are present on these busbars. A great deal of effort is put into providing good quality insulation [1]. If there is a crack it is imperative that the vacuum be good; should there be a leak of helium into the vacuum an electric discharge with destructive arc may occur. For this reason great care is devoted to making the insulation hermetic and to proving that it is so, which is both expensive and time-consuming. There have been instances of spectacular failures in the past, leading some experts to propose enclosing the whole system in earthed cans and filling the spaces with vacuum/pressure impregnated resin. It has also been suggested that by carefully monitoring the vacuum pressure and interlocking the power converters disaster could be avoided, but this is considered to be a risky alternative because leaks of helium are most likely to occur from the coolant in the bus and if there is a crack in the insulation then the local vacuum will be degraded before the degradation is detected by the monitoring system. This problem does not appear in superconducting magnet systems for accelerators: such magnets are based on the use of Rutherford cable purposely insulated electrically with permeable material that allows good thermal exchange with the liquid helium coolant. In this paper it is suggested that a viable alternative for fusion magnets using cable-in-conduit conductors (CICC) may be to avoid the risk of Paschen discharge by enclosing the entire bus system in a pressurized helium environment. It is further argued that CICC may not be the most appropriate topology for the feeder busbars.
2. Feeder insulation
In this section we discuss alternative approaches to insulating the feeder busbars.

2.1. Traditional layout
The traditional layout of a tokamak busbar system is shown in figure 1. The superconducting coils are wound using cable in conduit conductor, the large Lorentz forces being withstood by the stainless steel conductor casing and/or by additional thick structural casing. At the exit the conductors are connected electrically to the busbars supplying the excitation current; coolant helium gas for each busbar is connected via an insulation break. A different cryogenic circuit supplies the coolant via another break for the coil. The busbars and cryogenic pipework are surrounded by a vacuum enclosure that provide heat insulation and leads through the shielding wall to the valve and connection cryostat (feedbox), where the busbars connect to the current leads [2]. As the feedbox is fixed, the busbars incorporate an S-bend to allow for thermal contraction. The magnets are large and produce high fields: the stored energy is large (some GJ), and the excitation current is of the order of 60 kA. The power source must provide high voltage (of the order of 10 kV) to enable fast ramping of the magnets, as well as fast de-excitation to extract the energy in case of problems. This means that the whole busbar and current lead system must be well insulated between conductors and to ground. This insulation must be hermetic in order to avoid Paschen discharge in case of helium leakage into the technical vacuum. This is achieved by wrapping the components in a combination of polyimide film and glass-fibre tape followed by epoxy impregnation. Experience has shown that this insulation must be strictly controlled for cracks, and subjected to extensive “Paschen testing” to verify its integrity before commissioning of the system. The insulation is required to remain hermetic for many years.

![Figure 1. Schematic view of a feeder for which the insulation should be Paschen-tight.](image1)

![Figure 2. Modified general feeder layout that avoids the risk of Paschen discharge and arcing.](image2)

2.2. Alternative proposal
The required long-term hermetic nature of the feeder insulation is a concern. The epoxy resin impregnation must be executed with extreme care to avoid the formation of resin-rich pockets that are subjected to internal stresses and possible cracking. Ivanov [3] has proposed encapsulating the whole busbar system, wrapped in fibre-glass tape, in a stainless steel jacket and vacuum impregnating the system with epoxy resin. This should improve the long term viability of the insulation of the feeder system, but the risk of resin-rich pockets still exists, and while the system would be protected in such a case against degraded vacuum conditions outside the jacket it would not be protected against helium leaks occurring within (where they may be more likely due to the connections of the CICC busbars). Eventual maintenance would also be hampered by the presence of the impregnation.

Superconducting windings of magnets and busbars for accelerators are usually bath-cooled using liquid or supercritical helium; current leads operate in chimneys filled with stratified gaseous helium. High voltage never appears in the technical (insulating) vacuum: should this become degraded by a helium leak there will be no voltage breakdown. Large magnets for experiments are usually indirectly cooled: the busbars are in vacuum, but the magnets are not pulsed and the maximum voltage seen in the vacuum is of the order of 50 V. In the event of degraded vacuum there will not be a discharge.

In the light of these observations it is proposed to enclose the insulated busbar system in a pressurized helium environment as depicted in figure 2, such that should a helium leak occur in the
busbar (and cryogenic) pipework this would not affect the environment of the insulation: components at high voltage would not be surrounded by low pressure helium associated with Paschen discharge. And should a leak occur in the technical vacuum ensuring thermal insulation, there would not be electrical repercussions as there would not be any component at high voltage within that enclosure.

The current leads are shown to be vertical in this arrangement: this is preferable because the helium in the annular chimney must be stratified by use of close-fitting baffles to avoid convective heat leak into the helium enclosure. The temperature of the enclosure could be maintained close to that of liquid helium by controlling the liquid feed via a level gauge in a local pot. The gas recovered from evaporating helium could be used to cool the heat shield (not shown in the figures) placed between the vacuum and helium enclosures.

2.2.1 Insulation breaks
The cryogenic pipes for cooling the coils should also be routed through the helium enclosure. If these are insulated the ensemble of insulation breaks associated with these pipes, and the current leads, could be grouped in a cryostat close to the feedbox, thus addressing another concern, i.e. the long-term reliability of these components, by providing easy access to eventually defective insulation breaks without having to enter the vacuum vessel of the tokamak. Other specific concerns related to the high current busbars feeding fusion magnets.

3. Other features

3.1. Torque
There is a considerable stray magnetic field surrounding a tokamak. This can be locally up to 1 T, and in conjunction with a pair of busbars carrying up to 60 kA the $J \times B$ forces on the conductors give rise to a large torque requiring a sophisticated mechanical support structure. For currents up to 10 kA this is less of a problem (and could in any case be solved by using concentric cables). For large currents it is suggested that an interesting solution would be to divide the cables as illustrated in figures 3 and 4. The four insulated cables are connected mechanically and there is no net torque on the assembly. For a 60 kA system the cable dimension would reduce from a diameter of about 40 mm to about 30 mm for 30 kA [4] and the required transverse space would be unchanged. An insulation thickness of < 2 mm (combined polyimide film layers and GFRP) should suffice. The additional complexity of having 4 conductors instead of 2 is offset by the advantages of increased flexibility (making joints easier), and less massive current leads. And eliminating gimbals from the support structure reduces complexity. Equalization of the current in the parallel conductors would be ensured by the resistance of the warm section of the busbars (connecting warm ends of current leads to the power converter) being far greater than that of the joints in the superconducting section.

**Figure 3.** Left: standard arrangement. Right: arrangement eliminating torque. **Figure 4.** Schematic cross-section of the horizontal long straight section of a 60 kA feeder bus.
3.2. Cable variants
Because a magnet for a fusion device may be based on the use of cable-in-conduit conductor (CICC) does not imply that the feeder busbar should also be made of CICC. In particular if the insulation is allowed to be permeable (as can be the case in this proposal) other types of cable may be preferred, e.g. as shown in figure 5. Studies have been made [5] of using HTS material in such feeders, but not (yet) found to be economically viable. However, cables based on the use of MgB$_2$ could be interesting [6], if a conductor is developed that does not contain ferromagnetic material, and hybrid LTS/HTS conductors could also be considered [7].

3.3. Thermal contraction
An alternative to the classical S-bend is shown in figure 6, where the radius of curvature is about 1.5 m – typically that with which it is wrapped on the drum for transport. It should also be noted that for some types of cabled conductor the longitudinal modulus is low (for small extensions) and that the thermal contraction can be absorbed (at least partially) by allowing it to go into tension. The helium vessel can be of the corrugated (Nexans) type as used for the LHD feeder system [8], or made from Invar, so thermal contraction is not an issue. If the straight section is made long, to bring the feedboxes close to the power converters, thermal contraction can be conveniently taken into account by “snaking” the conductor, e.g. by supporting it periodically and allowing (encouraging) it to sag between supports using springs. One could consider housing these links out of the way in trenches as proposed in the original report [9] on superconducting power transmission.

Figure 5. Example of alternative feeder cable.  
Figure 6. Compensation of contraction.

4. Conclusion
It should be possible to improve on the feeder systems being deployed for the present generation of fusion magnet systems. Integration of the design of the feeders should be given the same level of attention as that devoted to the magnets. Use of cables other than CICC should be considered.

5. References
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