Paschentests during coil manufacture – experience of Babcock Noell on W7-X coils

Agenda

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2. Paschen's Law
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4. How to test against Paschen condition
5. Impressions from the W7-X test facility
6. How to handle a Paschen problem
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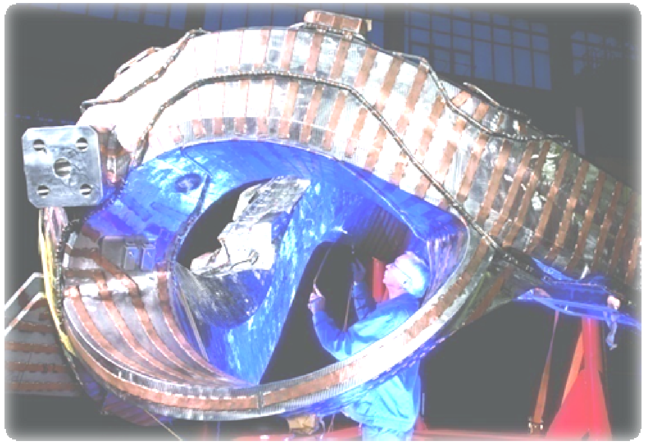
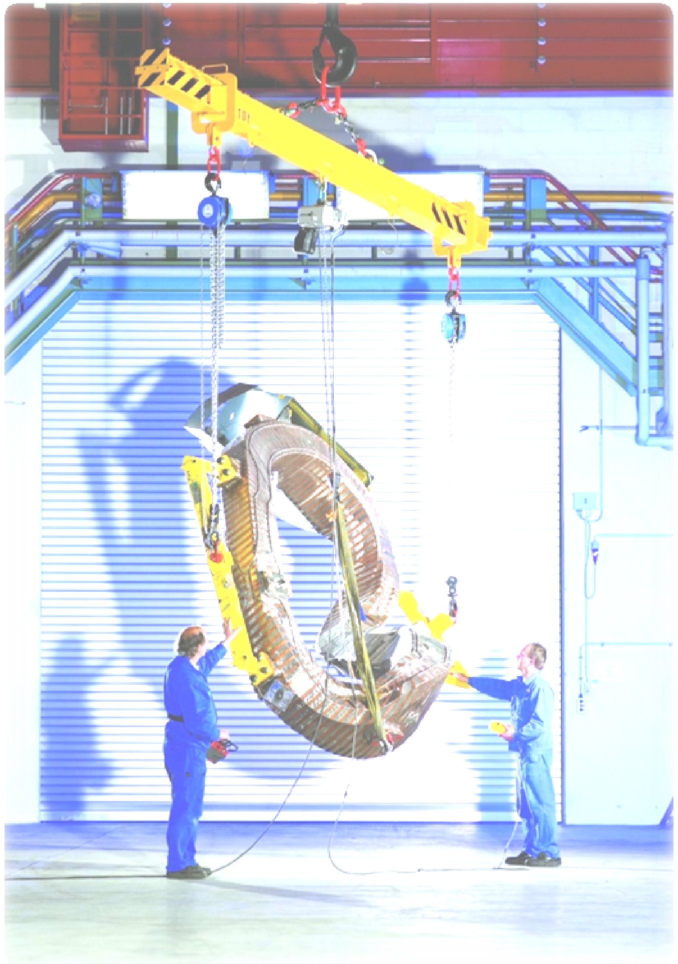
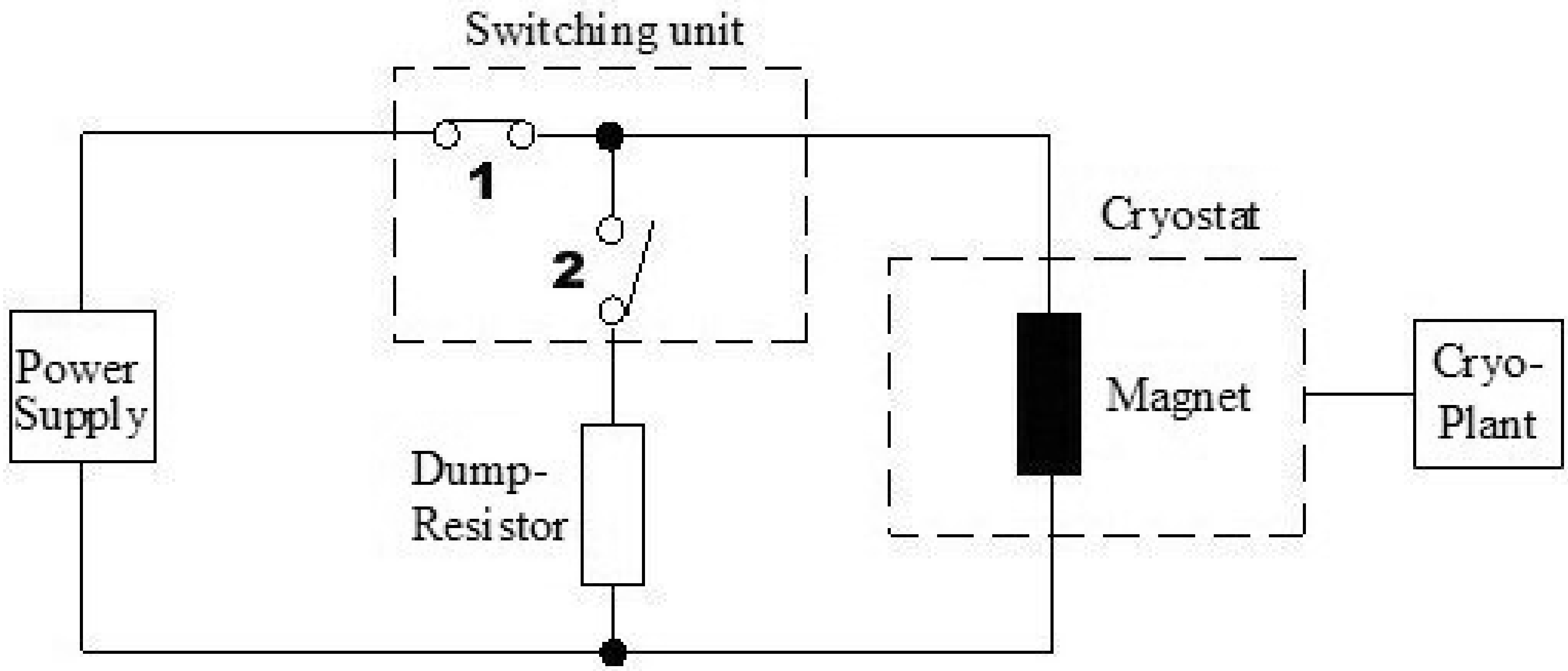




1. Operating of superconducting magnets

To reach the low temperature needed for operation of a superconducting magnet, special technology (so called cryo-technology) is required.

The magnet has to be installed inside a cryostat – a large vacuum tank where the low temperatures can be maintained. The plant for magnet operation looks like this (more details can be found in [1]):



1. Operating of superconducting magnets

In the case of malfunction or other disturbances, the magnet coil has to be de-energized immediately. Such cases could be:

- Quench of the superconductor (loss of superconductivity)
- Failure of the cryo-plant
- Failure of the electrical power supply
- Vacuum breakdown

The energy stored in the magnet can only be dumped by application of a negative voltage

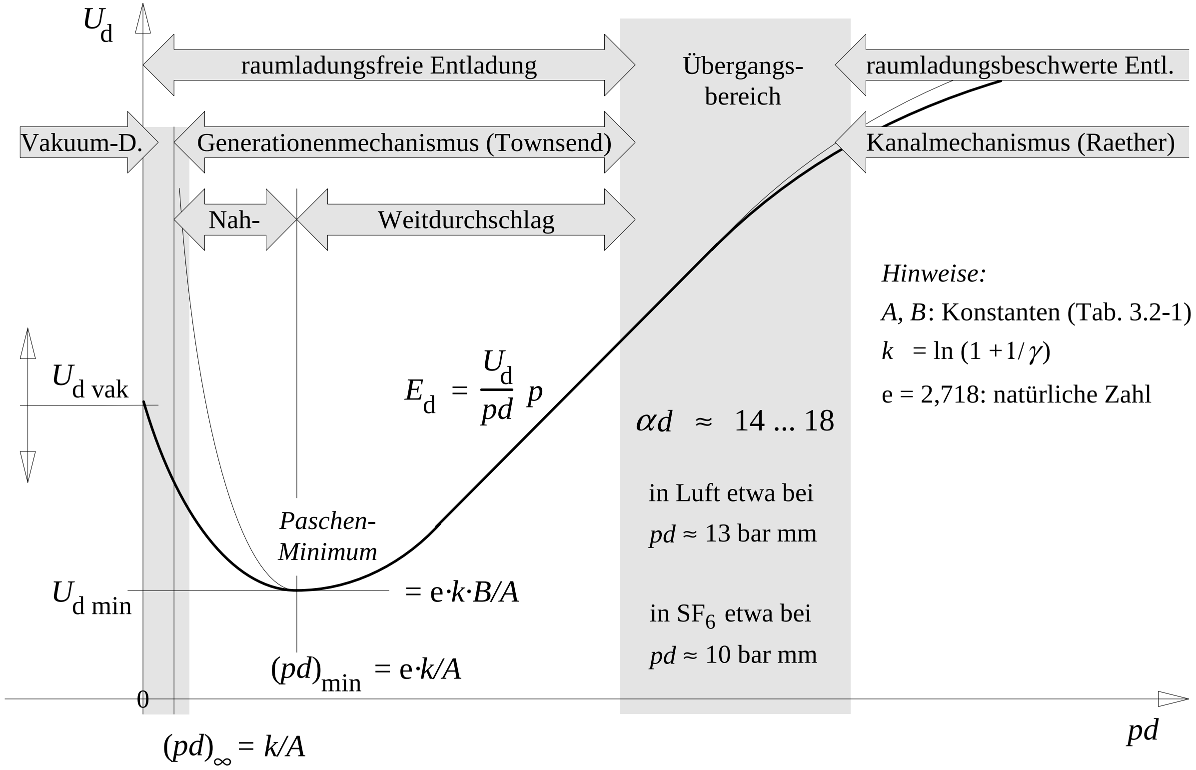
$$U = L \cdot dI/dt < 0.$$

In magnets for fusion technology a huge amount of energy is stored (for W7X about 900MJ). This has to be released in a safe way by deposing it in dump resistors. The voltage arising during such a fast discharge can be several kV over the magnet busbars.

A gaseous insulation withstands high voltage (high electrical fields) best in two cases:

- Either there is high pressure of gas in between the electrodes
- Or there is a very low pressure in between the electrodes (high vacuum)

In between there is the so called Paschen minimum (picture courtesy of A. Küchler [2]):



3. Why to test against Paschen condition?

That means, if the high voltage arises at the same time as a breakdown of the insulating vacuum, Paschen conditions might be fulfilled and if the electrical insulation of the magnet or the busbars is not sufficient or damaged, it could come to arcing and severe failures.

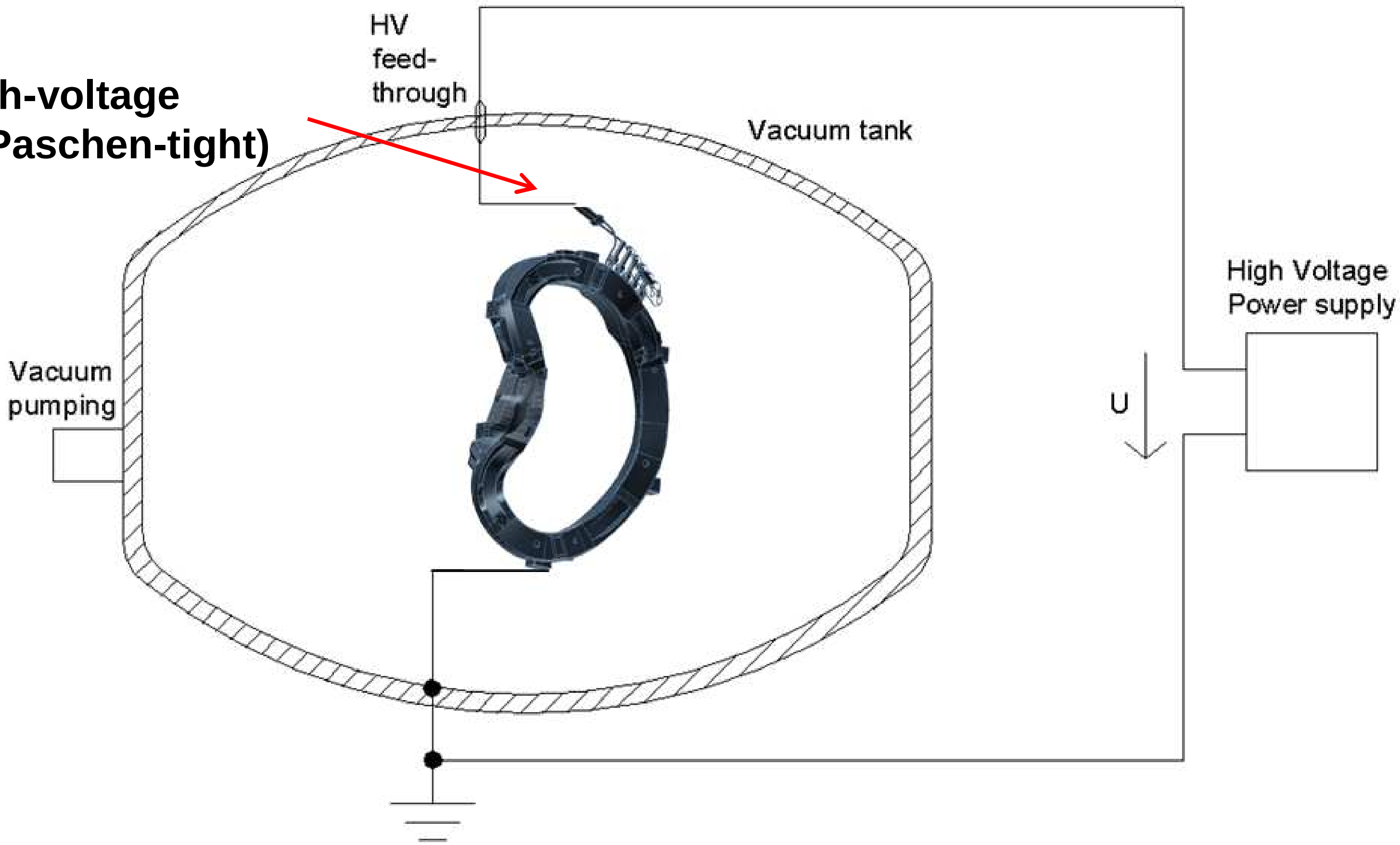
$\Rightarrow$ Danger for the machine!

$\Rightarrow$But: Paschen problems could occur, even if high-voltage tests at normal ambient conditions do not show any problems! I.e. under normal testing, the insulation seems to be well, but when testing with Paschen conditions around, it comes to discharges.

$\Rightarrow$ So, in advance of installing W7-X magnets, they were tested for their Paschen-tightness.

These Paschen-tests can be performed inside a large vacuum tank, where different levels of pressure as well as the high voltage can be applied. A typical set up for such a test looks like this:

Connection of the high-voltage to the winding pack (Paschen-tight)



4. How to test against Paschen condition

The Paschen-tests done at W7-X coils were done according to the following procedure:

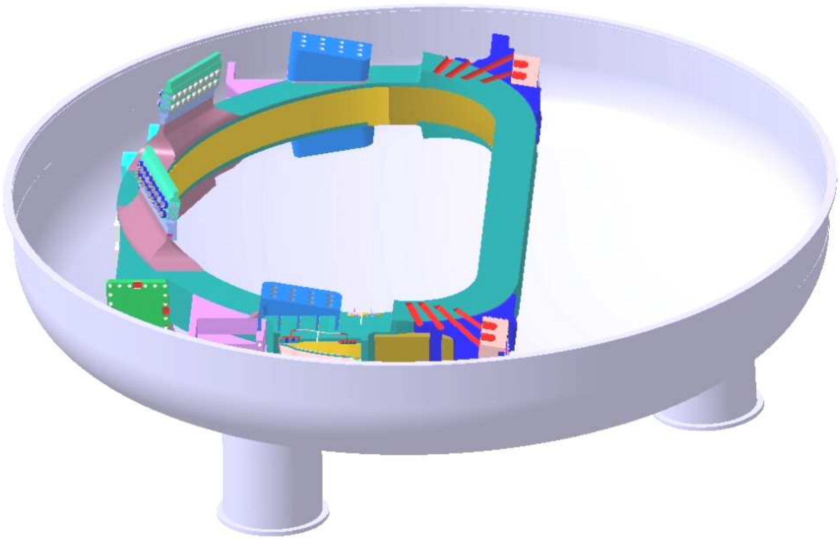
- Placing the coil in the vacuum tank
- Insulation of all free high-voltage-parts and connection of the feed-through
- Pumping down to a vacuum of about 10^{-4} mbar (as low as achievable, but lower than the Paschen minimum at about 10^{-2}…1 mbar)
- Application of the first voltage test at constant pressure (9 kV, 1 min)
- Increasing the pressure to about 10^{-3} mbar and repeat the HV-test
- Same for the pressure levels at 10^{-2}, 10^{-1}, 1, 10, 100 and 1000 mbar

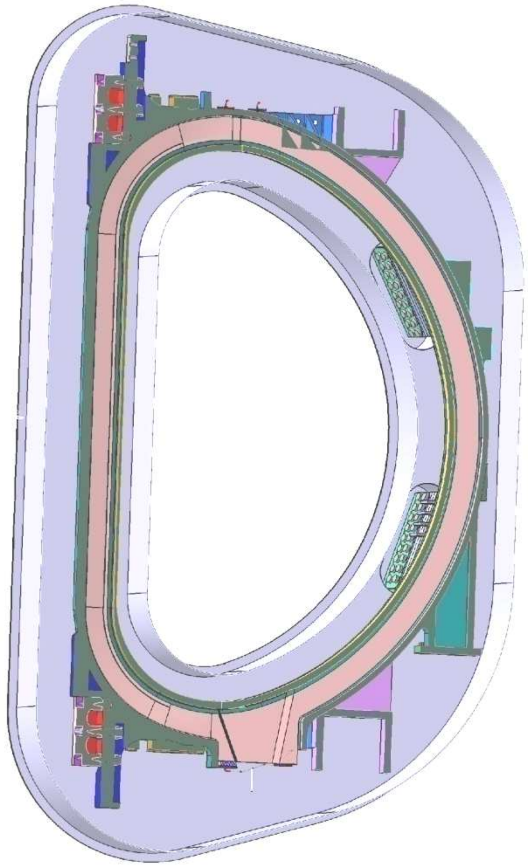
Criterion for a successful test is a pressure independent leakage current of less than 20 µA at all tests.

4. How to test against Paschen condition

For the ITER TF coils, the following test equipment would be necessary (Pictures courtesy of FZK):

- Vacuum tank to place the coil inside with according
- High Voltage equipment
- High Voltage feed-throughs and Paschen-tight connections
- Paschen tight cables inside the test facility





Could such vacuum tank also be used for cold test as a cryostat?!

5. Impressions from the W7-X test facility

Vacuum tank for W7-X-Paschen-tests (diameter approx. 4.50 m), existing at Babcock Noell.

5. Impressions from the W7-X test facility

Test facility with (old) equipment

5. Impressions from the W7-X test facility

Connectors at a W7-X-coil

5. Impressions from the W7-X test facility

Connectors at a W7-X-coil mounted inside the vacuum tank

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Paschen discharge at the coil terminations, seen by video camera

⇒ **A Paschen discharge shows up as a lightning.**

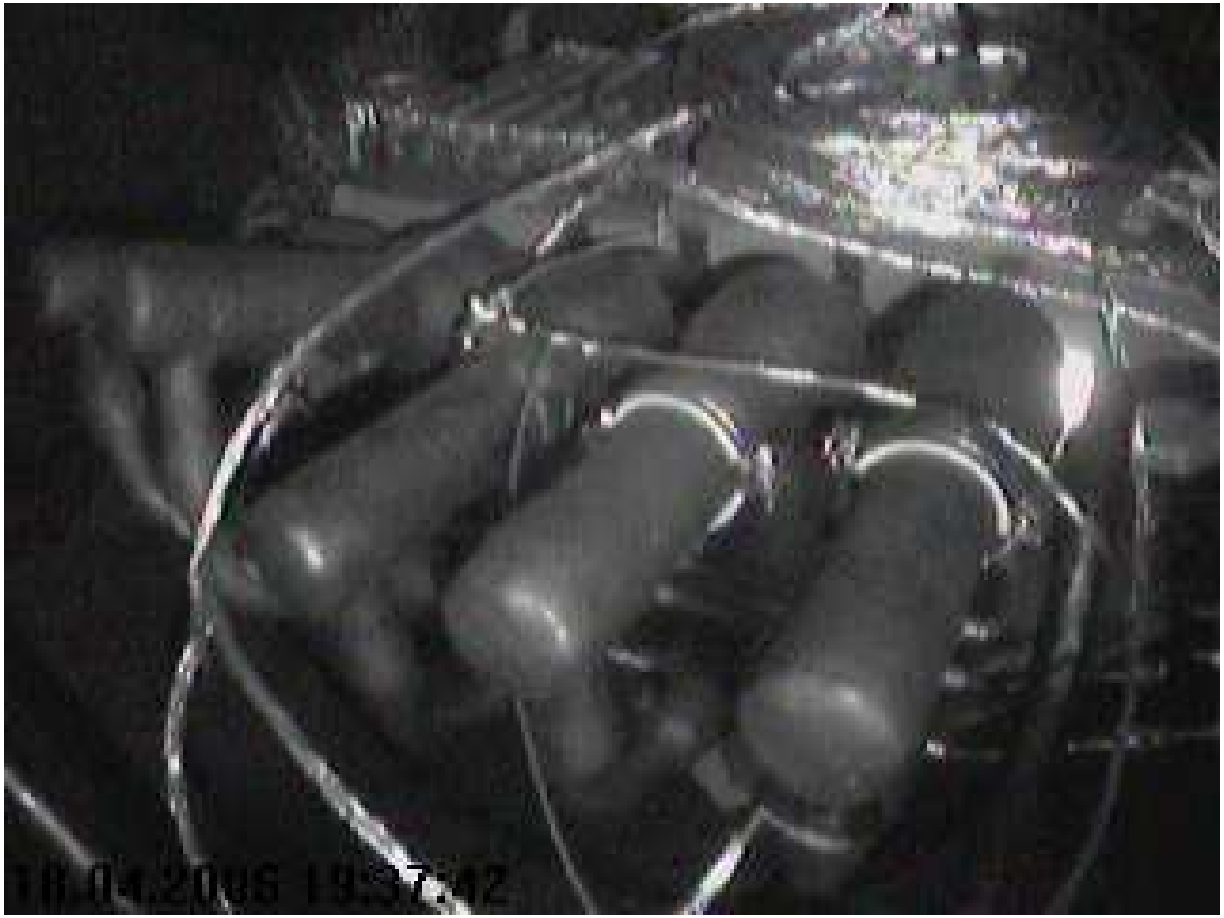
Depending on the vacuum level, atmospheric composition and the type, the lightning is more or less strong and visible.

5. Impressions from the W7-X test facility

Paschen discharge at the coil head

5. Impressions from the W7-X test facility

Paschen discharge at the outlet of a connector



6. How to handle a Paschen problem

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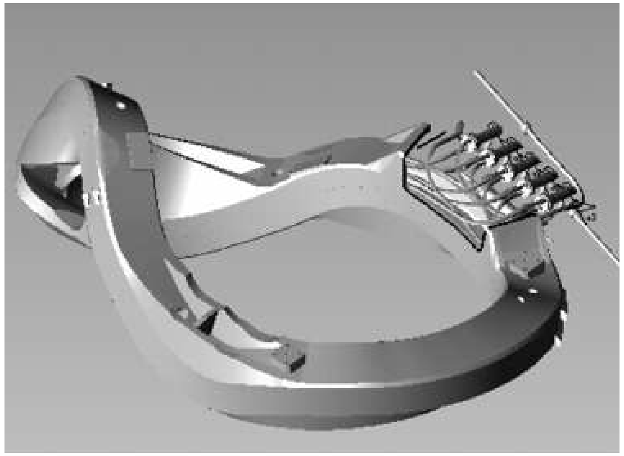
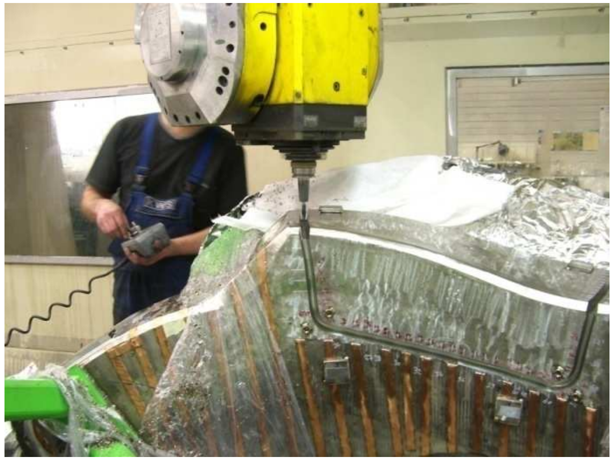
1. Failure detected by „Paschentest“



2. Repair concept



3. Machining of opening

4. Access to affected region

5. Repair of Winding Pack

6. Repair finished

7. Lessons learned

In general it can be said there are some principle difficulties in electrical insulation of superconducting devices.

For cryo-applications we cannot use every insulation technology that may be applied for room-temperature because of:

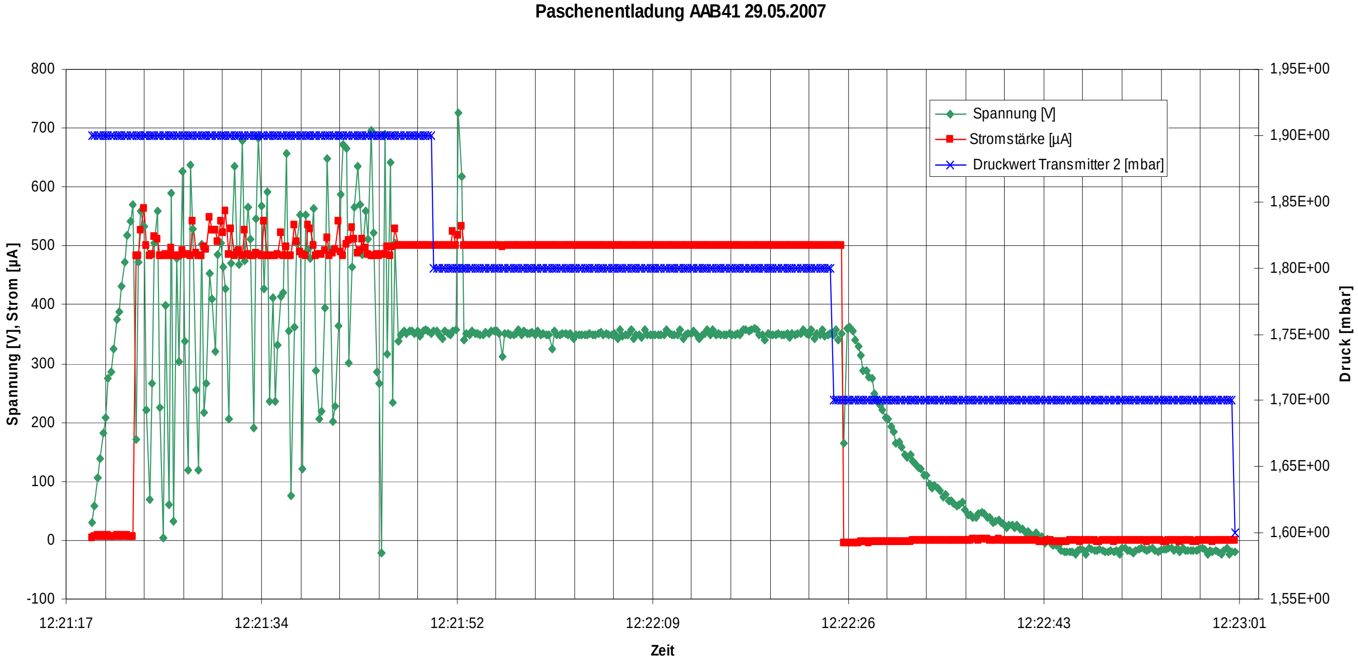
- Thermal contraction (different materials; cracking)
- Mechanical and electrical degradation due to cryo temperature (not so critical)
- For fusion devices even radiation degradation has to be considered

At some points (e.g. in the region of the coil heads) the insulation has to be finished by hand in wet-winding technology. These points need to be treated carefully as the insulation is not that uniform as in other regions. If it is not done well, there can be air entrapments enclosures or pure resin pots which cause Paschen failures or which show bad performance only after the first cool down (cracking etc.).

To sum up the results of the Paschen tests at W7-X it can be said, that:

1. Paschen tests show weak parts of the insulation, which can not be seen at normal ambient condition tests!

Discharges can only be found at a certain pressure level respectively within a certain pressure range. Below as well as above this range, there are no discharges detectable.



2. Paschen tests are difficult to interpret and to find the weak part of the insulation, if there are problems

At some W7-X coils there were discharges visible at the so called Pins (reference-plates upon the ground potential of the winding pack).

It was able to find weak points in the region of the head of the coils. The discharges in this area, triggered at Paschen-condition, charged the conductive paint around the ground insulation. This charge did lead to discharges at the Pins around 1m away from the coil head.

⇒ It can easily come to misinterpretation of discharges under Paschen condition and much experience from the practical side is necessary to predict possible failures.

This photo shows a lightning under Paschen condition which starts underneath the insulation (3 layers of hand-wrapped Glass-Epoxy).

If there would be a ground layer e.g. made out of conductive paint, you would only see the lightning at the point, where it comes out.

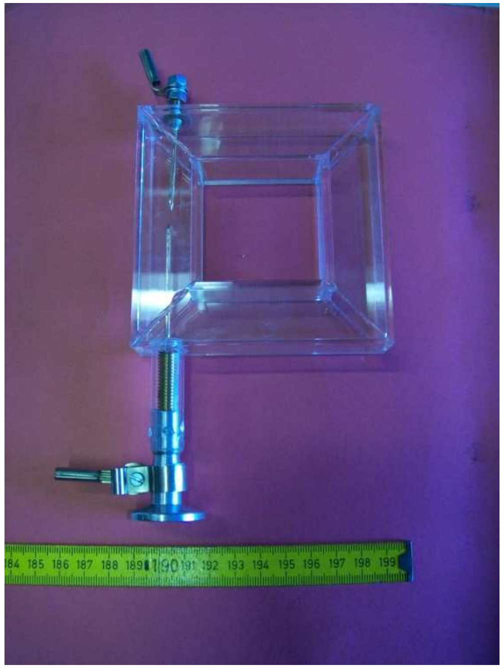
To reach such a discharge, the insulation must be defective

(i.e. a channel to the outer vacuum must exist) and you have

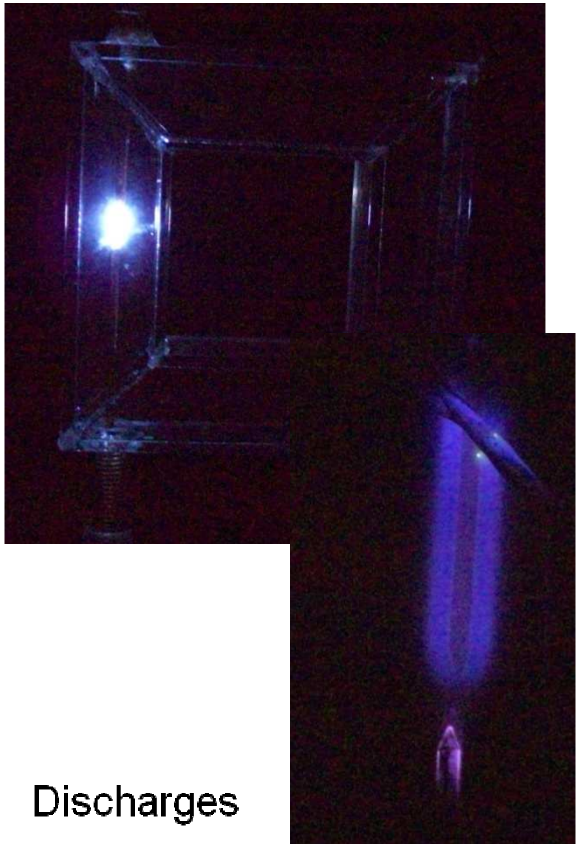
to apply Paschen conditions.

7. Lessons learned

Also to consider: Paschen discharges can behave completely different to normal high-voltage experience. The following experiment is called “Hittorf’sches Umwegrohr”:

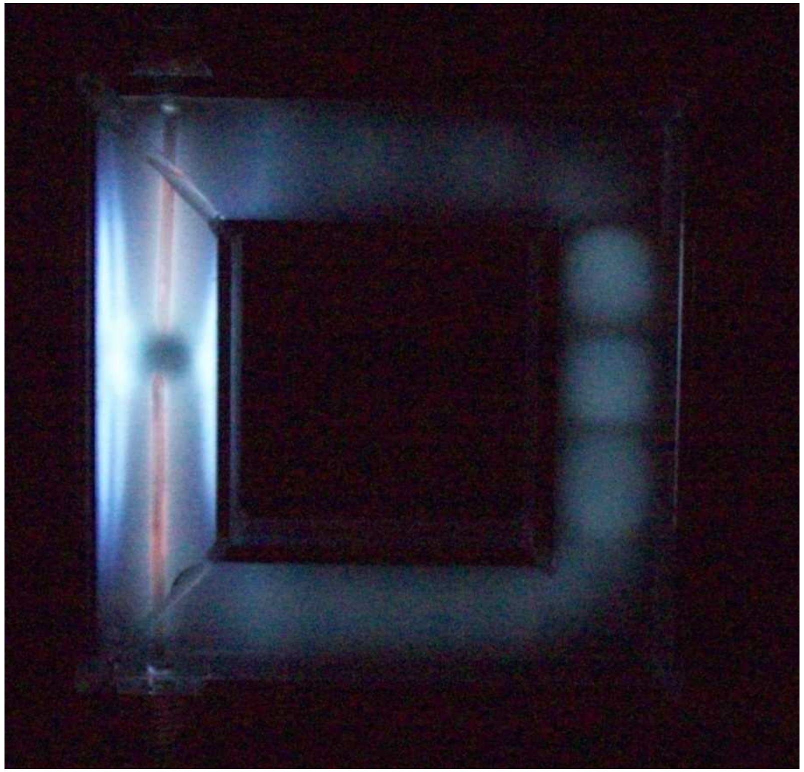


Setup



Discharges

at normal & reduced pressure



Discharge within the Paschen Minimum

7. Lessons learned

Further difficulties to take care:

- To follow the technical design principles, Paschen tests should be performed during fabrication at different manufacturing steps in order to be able to compare and locate errors – whether this is possible depends at the geometry of the coil and the manufacturing sequence

- The behavior of the coil under a Paschen tests does also depend on the coil design (like ground potential geometry etc.)

- Costly difficulties:
    - Large vacuum tank and sensitive test equipment required
    - Long process times (pump down and measuring at different pressure levels) even more when test is applied after different manufacturing steps
    - All parts of the test equipment has to be “Paschen free” – according know-how is available at Babcock Noell due to the experience gained in W7-X

Conclusion

Besides the exciting physics behind Nuclear Fusion, it is today also an ambitious engineering task to realize fusion experiments.

The magnet system is sometimes considered as the heart of a fusion machine – of course there are many other essential parts like the heating and the vacuum system etc.

Working together hand-in-hand with research institutes for many years now in several projects, manufacturing of superconducting magnets became mostly the know-how of specialized industry. Babcock Noell did collect large experience in performing high voltage tests for magnet coils especially during testing of the W7-X coils.

For future projects, BNG would like to continue to work on the engineering challenges such as Paschen tests in collaboration with the research institutes.

The aim of this lecture was to give an impression of Paschen tests at superconducting magnets. More information can be found in literature and by contacting Babcock Noell.

Literature, References

[1] M. Borlein „Optimization of a Quenchdetection System of Superconducting Magnets“, FZK-Report, 2004

[2] A. Küchler „Hochspannungstechnik“, Springer Verlag, 2005

[3] H. Scheller et al. „Paschen testing on W7–X coils and components in the BNN test facility”, Magnet Technology Conference 2005