Some of the lesson learned during the construction and use of superconducting magnets in the last decades

Roberto Penco
Superconducting Magnet Design

Not an easy job.
All disciplines are interconnected
  Magnetic field, Superconductivity, Cryogenic, Pressure vessel, Insulation, Stress analysis, etc
For example the dimension of the safety valve of the cryostat could be related to the degree of insulation of the magnet!

Good insulation $\rightarrow$ higher voltage during quench $\rightarrow$ more energy extracted $\rightarrow$ less energy in the bath $\rightarrow$ less evaporation of helium

https://youtu.be/1R7KsfosV-o
Superconducting Magnet Design

There are two Kind of s.c. magnets

**Series magnet**
- it is convenient to make prototypes

**Single or few unit**
- Full scale prototype not convenient

To design series magnet lower safety margin can be used. Reliability and feasibility can be checked with prototype.

The design of single magnet should be more conservative. Mistakes are not permitted.

And the design error were very few indeed compare to the accident occurred during the construction

*PS clearly I am speaking of LTCS superconductor. For HTCS we are still in the development phase*
An example how the risk reduction on one side generates risk in other direction. To permit substitution in case of failure of one, the double pancakes were not glued each to the others but kept in place only by friction due to the compression force. The stainless steel large flange should act as a Belleville spring.

During its first cool down its tie rods lose strength until they were no longer able to provide adequate pressure on the winding. Fortunately they had been equipped with strain gauges to keep residual force under control, but it was necessary to heat a magnet delivered back to the workshop to increase the elasticity of the tie rods and their cooling replacing them with beryllium-copper ones.
Magnet Design...SULTAN

In the design large attention was put to the cool down circuit of the flanges avoiding induced electric current but, instead, for inexperience and delivery problems they were built by simple 304 and we found after cool down dimension change and some martensitic transition.

Anyway the fact the pancakes are not glued permitted the split of the magnet to reach the present configuration that is still working today after almost 40
Superconducting Magnet Design

As you can see in the past some distraction or error of inexperience were occurred also in design ...As example, to day is clear to everybody that simple AISI 304 could not be used for cold mechanical element to avoid martensitic transition (with dimensional change, magnetic and fragile)

On the contrary sometime somebody still forgot to calculate the forces acting on the thermal shield due to electrical current induced by the fast field variation during a quench: a light thermal shield can completely crumpled up if any electric break are insert in the shield cylinder
S.C: magnet construction, test and use

As already said most of accident can occur due to mistake made during construction, test or use more than due to the design errors. Nevertheless a good design with good safety margin can mitigate the risks.
S.C cable ... dummy cables

When a new magnet is designed, winding tests are often required to test the technology and the ability to maintain tolerances. Usually a dummy cable free of superconductor is usually used to perform these tests without considering that when the superconductor copper ratio is very high in the real cable, *the mechanical characteristics of the dummy cable can be very different from those of the superconductor cable*. 
S.C cable ... the dummy cable

TORE SUPRA (Tokamak 1984)

9T
Circular double pancake 2.3-2.8 m
1400 A on NbTi
Winding of dummy copper cable (2.8 x 5.6 mm) on the short side without any problem. Then the real DP winding with s.c. cable (Cu:CuNi:NbTi 2.2:0.33:1) started BUT when the roll were released all the turn rotate 45° and the DP has to be scrapped. A small calander was introduced in the winding line to overcome the problems.
S.C cable ... dummy cables

Similar problem occurred for the ZEUS magnet:
No problems for bending the dummy (0.6 m dis), problems came for bending the real cable over 2 m diameter because different annealing of the aluminum matrix.
S.C cable performance: FINUDA

FINUDA was an experiment magnet built in 1996 for LNF,
S.C. cable performance: FINUDA

- It was built using a co-extruded Al conductor with inside a Rutherford cable made by 8 s.c strands Cu-NiTi.
- During the construction of this conductors large attention was requested during the co-extrusion phase when very high temperature is developed.
- If, for any reason, the extrusion process stops, the piece of conductor that remains at 450°C for more of 30-40 sec will have a critical current degraded for more than 50%.
- No test could be performed to check in the middle of the unit length.
S.C. cable performance: FINUDA

- For this reason the process must be strictly monitored.
- We require to report conductor temperature during extrusion every 30 seconds: distant of the marks gave evidence of time spent in the high temperature region.
- ALL the other controls can be made by usual quality control procedure for s.c. conductor.

- **BUT ACCIDENTS APPEARS WHERE YOU DID NOT EXPECT!**
## S.C. cable performance: FINUDA

### Technical specifications:

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<th>TIPO DI CONTROLLO</th>
<th>APPLICABILI</th>
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<tr>
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<td>TYPE OF CONTROL</td>
<td>Controlled</td>
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<tr>
<td>1</td>
<td>Certification of conformity (raw material)</td>
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<tr>
<td>2</td>
<td>Chemical analysys of Cu ETP</td>
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<td>3</td>
<td>Exagons preparation E.C.T.</td>
<td>QSP+DE.E.E.T.RSC</td>
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<td>4</td>
<td>Ingots assembly including welding leak test</td>
<td>QSP-T.5 / TRSC</td>
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<td>5</td>
<td>Extrusion E.C.T.</td>
<td>QSP-NDE.EE.TRSC</td>
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<td>Drawing E.C.T.</td>
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<td>Twist Pitch</td>
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<td>700RM05801 Rev.1</td>
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<td>Wire metallographic examination</td>
<td>QSP-T.12/ TRSC</td>
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<td>12</td>
<td>Cu / non Cu ratio</td>
<td>QSP-T.13/ TRSC</td>
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<td>RRR measurement</td>
<td>700RM05801 Rev.1</td>
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</table>
S.C. cable performance: FINUDA

Controllo visivo e dimensionale del cavo

CONDIZIONI SUPERFICIALI DEL CAVO
La superficie del cavo s.c. risulta essere uniforme ed esente ca difetti.

VERIFICA DIMENSIONI CAVO SUPERCONDUTTORE Nb/Ti
Cavo tipo Finuda 1 (7filix0.88): mm 2.95x1.60

ESITO DELLA VERIFICA : CONFORME
S.C. cable performance: FINUDA

- ALL the certifications of the last unit length over the six requested (delivered with a delay) were OK.
- The unit was wound as the end of the second layer inside the outer cylinder of the indirect cooled magnet.
- The magnet was Vacuum impregnated in epoxy resin.
- We started to prepare the electrical exits connection.
- To reduce the joule heating in the joints, it was designed to remove with sodium hydroxide the Al matrix for 20 cm and to perform a direct soldering between the Cu connection to the Rutherford cable.
S.C. cable performance: FINUDA
I remember well when the chief of workshop came in my office to tell me that at the end of the reaction he found a piece of one strand in the becker!

We tried to imagine any possible accident but not one so large as the real one came at our mind!

Immediately we analyzed the two lengths kept as usual from the tail and the head of the unit spool and we started to dissolve the Al on some pieces sample.

NOTE: -SAMPLES SHOULD BE KEPT IN STORE FOR THE WHOLE LIFE OF THE MAGNETS (as we did)
S.C. cable performance: FINUDA

- What we found was the worst nightmare a s.c. magnet designer could imagine.
- One unit length (the last delivered in nov/1995) had one of the 8 strands broken every 80 mm
- In some of the not broken strands we found up to 50% of filament broken in 250 mm sample
- The other 5 units were perfect
- After the first shock we analyzed the situation: coil, cryostat, iron joke, moving system, were all about ready. Experiment was waiting...
- Question was if going forward and testing the coil like it was or to start building a new one immediately
FINUDA: this the situation of the cable: random strand rupture

| ~80 mm | ~80 mm |
FINUDA: this the situation of the cable: random strand rupture
S.C. cable performance: FINUDA

Anyway we consider that by design the magnet presented a stability much larger of the most of the other similar ones.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>MPE (Joule, monodimensional theory) (RRR 1000)</th>
<th>MPE (Joule, FEM model) (RRR=500)</th>
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<tbody>
<tr>
<td>Aleph</td>
<td>29</td>
<td>6.1 (*)</td>
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<tr>
<td>Delphi</td>
<td>72</td>
<td>6.2</td>
</tr>
<tr>
<td>D0</td>
<td>-</td>
<td>1.2</td>
</tr>
<tr>
<td>LHCb</td>
<td>40</td>
<td></td>
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<tr>
<td>CDF</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Venus</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Cleo II</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Finuda</td>
<td>151 (36 with RRR 500)</td>
<td>5.5 (12 with RRR 1000)</td>
</tr>
</tbody>
</table>
S.C. cable performance: FINUDA

- Several attempts were made to calculate the joule effect due to the strand ruptures.
- It was difficult to found the current distribution in the different strands and the effect of the current sharing.
- Using different hypotheses for distribution of the needed 3000A (for example: 3 strand with 1000 A each or 8 strand with 375 A) we got a total joule effect from 1 to 50 W near the limit that the coil could withstand on the inner layer (maximum field and minimum cooling).
- We needed a Ic measurement on a significant length of conductor!
- INFN-LASA and INFN-Ge helped to make measurements on the last 20m meters of the damaged length kept in our store
S.C. cable performance: FINUDA

Measurement made by INFN (GE P.Fabbricatore) on 18.3 m of damage conductor. Extrapolation of the measurements to the total length of 940m gave a value between 0.2 and 3 W
S.C. cable performance: FINUDA

FINAL DECISION WAS TO GO FORWARD
S.C. cable performance: FINUDA

- Magnet was tested successfully and reach the nominal field without problem BUT a residual resistance was found in the 940m of damaged length

- The damaged cable had an $n$ value of 2.3 and gave a joule heating of 10W at nominal current
S.C. cable performance: FINUDA

Only 4% of the current flow in the Al matrix giving finally a temperature increasing less than 0.25 K. Due to a very good VPI bonding as well as due to the very good cryogenic design the total losses remain inside the spec. FINUDA Magnet remains in operation for 20 years and no further degradation of conductor was found.
Lesson learned: FINUDA

- Design decisions should always consider the higher safety margin possible in the coil design:
- ANYTIME (but especially for one single magnet construction) YOU SHOULD COMPARE THE COST WITH THE RISK MITIGATION.
- Increasing of Ic of this kind of conductor had a negligible cost compared with the safety margin increase, so we asked Ic = 3 In !
- Same for the RRR of Al...we asked >1000, we had 1700 !
- Copper RRR we request >100, we had 150
- Good contact resistance: measured 8.9 e-11 ohm m
S.C. cable performance: FINUDA

Lesson learned

- BETTER to ask to third parties to check the performance of the conductor especially for a single magnet construction (put the cost in the budget).

- Increase the safety margin as much as the cost is negligible. Total cost of the Finuda cable was 3% of the total for this reason we could ask for a so large critical current.
### S.C. cable performance: twist

- If the strand are twisted twice to get the right pitch... The second time you should go in the same direction.

### S.C. cable performance: length

- If you order kms of cable in a single length you and the supplier should consider a proportional safety margin.
- Only in a layer winding solenoid can be recovered a short cable length by insert some spacer between the last ten turns.
JOINT & TERMINATION

- Never use chloride acid for copper soldering of stainless steel jacket cable: also vapor or small quantity can reach the jacket and induce “stress corrosion” during impregnation or cool down.
- Always connect also the Al or Cu matrix not only the s.c. strands
Insulation: voltage taps

- Small wires directly connected to the conductor that go out of the magnet ground insulation sometime in vacuum atmosphere.
- It is easy to broken the wire (sometime 10-50 m long) at the level of exit from the insulation if not well reinforced.
- Most of the sparks during the coil Paschen test come from these exits.
- Wires insulation itself should withstand Paschen test.
- It is common use to insert a protection resistance in the voltage circuit.
Many years ago when they wanted to build superconducting magnets with a very high stability, to increase heat exchange with liquid helium bath sometimes a completely naked superconducting cables was used achieving isolation between the turn and layer with spacers or insulating tapes. This system though very effective from the point of view of stability it has proved to be unreliable from the point of view of insulation and mechanical effort.

Memorable was the accident at the one ToreSupra TF coils already in operation due to a turn to turn short circuit during a fast discharge.

From that time most of the s.c. magnets were vacuum impregnated with resin. Nevertheless, the process of impregnation itself has become perhaps the most at risk for the construction of magnets as it is an irreversible process (if you do not use wax that has other disadvantages).
Coil : impregnation

- Pay large attention to weight the acceleration agent in the resin or better do not use it at all
- Do not use the same port for pumping and resin input
- Test the vessel tightness at the curing temperature
- Put always more than one resin input in the vessel: second input was providential for a very large magnet impregnation
If aluminized maylar is used for your superinsulation remember that is highly flammable and a small arc of the welding made to repair a leak could ignite the whole superinsulation of a magnet already installed. It is preferable use of pure aluminum sheets interlaced with flame-proof glass tulle.
Cool down

- Cold ceramic feed through can be broken during cool down. They should be tested at a cooldown speed 2-3 time larger than the nominal one.
If you use a mechanical breaker for quench protection be sure that the fringe field of the magnet will not push the electric arc of the breaker on the wrong direction preventing the arc extinguish.

Please after use remove the hairdryer from the current lead
Warm up

- Warm up could be more dangerous than cool down: do not push it faster
- In a inner wound coil indirect cooled by the outer cylinder, a fast warm up of the cylinder could produce the detachment of the cylinder from the winding
- Never use current to warm up the winding if not forecast and well controlled. Magnet are usually well thermally insulated, also a low power can finally increase the temperature at very high and dangerous level
Conclusion

- SC magnet started to be built and used more than 40 year ago.
- Even if they can withstand a traumatic event like the quench, about the totality ended their service not for a rupture but yet in full operation. Others are still working.
- As happens in any other technologies occurred accidents ARE LESSONS LEARNED to improve our ability to design, built and maintain these system.
- To day a common practice is established also based on the past experiences.