



The NED Conductor Review: Experience gained and outlook for future development

CARE08, Dec 3 2008, G. de Rijk, The NED Conductor Review

Gijs de Rijk (CERN)

on behalf of the NED collaboration

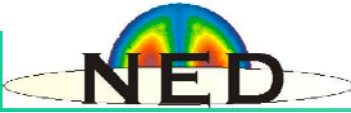
3rd December 2008

Outline



- **NED External Scientific Advisory Committee**
- **Review mandate**
- **Programme of the review**
- **Summary of the Contributions**
- **Recommendations from the NED-ESAC**

NED External Scientific Advisory Committee



EDMS 548039



From: A. Devred
To: J.L. Duchateau, P. Lebrun, L. Rossi, R. Scanlan, J.B. Strait, H.H.J. ten Kate,
cc: R. Aleksan, E. Baynham, P. Fabricatore, D. Leroy, G. Volpini, J.M. Rifflet
Subject: External Scientific Advisory Committee
Date: 28 January 2004

During the NED Steering Committee meeting of 8 January 2004, we confirmed the creation of the External Scientific Advisory Committee (ESAC), to be chaired by J.B. Strait (Fermilab).

The membership to the External Scientific Advisory Committee is

- Jean-Luc Duchateau (CEA/DSM/DRFC)
- P. Lebrun (CERN/AT)
- L. Rossi (CERN/AT)
- R.M. Scanlan (formerly LBNL),
- J.B. Strait (Fermilab),
- H.H.J. ten Kate (CERN & Twente University)

The main charge of the ESAC is to advise the NED Coordinator on

- the scientific objectives,
- the technical program to achieve these objectives,
- the work organization,
- the resources allocation,
- the planning.

The ESAC will meet at least once a year, and will write a detail report within one month of each meeting.

The ESAC members are also expected to provide informal advices in their specific area of expertise and, whenever possible, to help setting up bridges between NED and the programs with which they are themselves involved. This may go as far as exchange of services between their home institution and the NED collaborators.

The ESAC members will have an extended access to all documents pertinent to NED, but will have to respect the confidentiality of the relationship with NED industrial sub-contractors.

NED

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The NED-ESAC was consulted in the beginning of the project (2004) and is now asked to review what was achieved.

Members:

A. Devred,
D. Dietrich (LBNL)
J-L. Duchateau (CEA)
P. Lebrun (CERN)
L. Rossi (CERN)
J. Strait (FNAL) Chairperson
H. Ten Kate (CERN & Twente Univ.)

Review mandate



The aim of the review is twofold.

1. The NED Nb₃Sn conductor development program should be reviewed such that the achievements, the main difficulties and the limitations are brought out.
2. Using the experience of this conductor program, the requirements for new dipoles and quadrupoles and the existing open issues, recommendations for the next steps in Nb₃Sn conductor development for accelerator magnets at CERN should be formulated.

Programme of the review



Tuesday November 4th

13h30	History of the NED conductor program	<u>Luc Oberli</u>	15'+5'
13h50	Results of the PIT conductor development	<u>Thierry Boutboul</u>	20'+5'
14h15	Results of the IT conductor development	<u>Luc Oberli</u>	20'+5'
14h40	Results of the cable development	<u>Thierry Boutboul</u>	15'+5'
15h00	Guidelines on Magneto-Thermal stability	<u>Bernardo Bordini</u>	20'+5'
16h10	Review on stress sensitivity	<u>Rene Flukiger & Bernd Seeber</u>	30'+5'
16h45	Dipole conductor needs: examples for Fresca2	<u>Glyn Kirby</u>	20'+5'
17h10	Quadrupole conductor needs: examples for HQ	<u>Shlomo Caspi</u>	20'+5'

Wednesday November 5th

- **9h00-12h00** **Discussion session and report writing**

1: History of the NED conductor program

Luc Oberli



The aims, the developments over the 4 years, the benchmark numbers, how we got to the NED specification

- In the 2 types of design for a NED dipole and for all the apertures, a ~ 14 T bore field (peak field on the conductor > 15 T) can be reached with a Nb₃Sn strand of the following specification,

“the NED strand specification”:

<input type="checkbox"/> Diameter	1.250 mm
<input type="checkbox"/> Effective filament ϕ	$< 50 \mu\text{m}$
<input type="checkbox"/> Cu to non-Cu ratio	1.25 ± 0.10
<input type="checkbox"/> Minimum critical current	818 A at 15 T & 4.2 K
<input type="checkbox"/> non-Cu Jc at 4.2 K	1500 A/mm ² at 15 T
<input type="checkbox"/>	3000 A/mm ² at 12 T
<input type="checkbox"/> $2 \mu_0 M$	$< 300 \text{ mT}$ at 2 T & 4.2 K
<input type="checkbox"/> RRR (after heat treatment)	> 200

1: History of the NED conductor program (2)



“the NED cable specification”:

- Trapezoidal Rutherford cable with a width of 26 mm
- Number of strands : 40
- Minimum critical current : 29440 A at 15 T & 4.2 K
- Residual resistance ratio after reaction ≥ 120
 - Av. Mid-thickness : 2.275 mm
 - Av. Width : 26 mm
 - Av. Keystone angle : 0.44 degree
 - Cable transposition pitch : ~180 mm



2: Results of the PIT conductor development

Thierry Boutboul



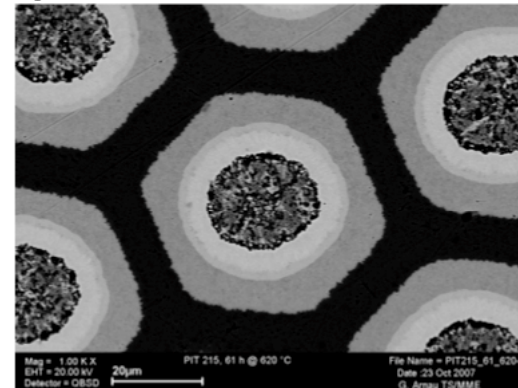
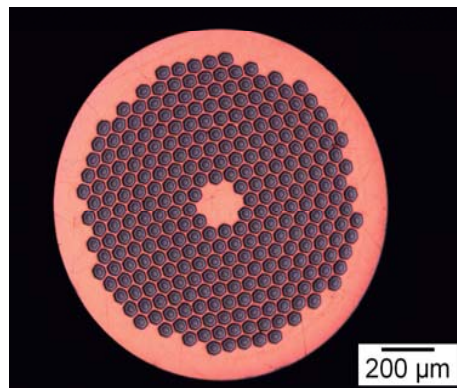
In the frame of the NED project, EAS/SMI successfully developed a Powder-In-Tube Nb₃Sn conductor design and is currently manufacturing the final strand. The strand development, fabrication and delivery will be reviewed, together with characterization results for the achieved strands.

- Following [call for tender](#) in [Summer 2004](#), ShapeMetal Innovation (SMI, Enschede, The Netherlands) awarded a [NED](#) contract ([300 k€](#)) for [Powder-In-Tube](#) (PIT) conductor.
- [PIT](#) technique developed by [ECN](#) (since 1975) and purchased by [SMI](#) in [1992](#).
- [PIT](#) technology acquired by [EAS](#) (Germany, now Bruker EAS) in December [2006](#)
- [PIT](#): [NbSn₂ powder](#) (possibly enriched with pure Sn) compacted and inserted into a Nb-X/Cu tube. After tube drawing to smaller diameter, stacked into Cu tube with a Cu core for final cold drawing

2: Results of the PIT conductor development (2)



- During R&D phase for NED, SMI developed a strand with $\sim 50 \mu\text{m}$ filament size and $J_c \sim 2500 \text{ A/mm}^2$ at 12 T and 4.2 K with HT schedule recommended by firm (84 h @ 675 °C).
- For 320 h @ 625 °C, **increase of 10 %** as compared to **standard HT** observed in critical current ($I_c \sim 1500 \text{ A}$ @ 12 T and 4.2 K, $J_c \sim 2700 \text{ A/mm}^2$, $I_c \sim 840$ @ 15 T and 4.2 K, $J_c \sim 1500 \text{ A/mm}^2$), **new record!!** RRR high (~ 220) as well for this treatment.
- This strand fully within NED specifications, due to **optimized HT**.
- EAS/SMI currently producing **final strand** according to R&D strand design. **6.4 km** already delivered and part of it found with current abilities almost similar to R&D. Remaining **6.3 km** to be delivered by **end of 2008**.



3: Results of the IT conductor development

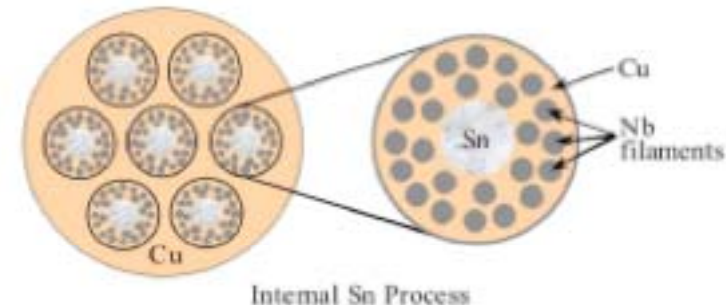
Luc Oberli



The strand development performed by Alstom through an innovative fabrication process and through a more conventional process will be reviewed together with the results achieved during the first two steps of development preceding the final fabrication on the NED strand. Alstom is currently launching in fabrication the final strand for the NED project. The delivery schedule of the final strand will be presented.

- The Nb_3Sn strand manufacturing process Alstom is based on the Internal Tin process.

Two **roads** (Ways) have been studied.



Road 1 : “innovative” manufacturing process Fabrication by cold drawing, both for the sub-element and for the final billet.

Road 2 : “classical” manufacturing process Fabrication based on extrusion of the sub-element and on cold drawing for the final billet.

3: Results of the IT conductor development (2)



- The workability problems were solved by Alstom. Alstom has developed a strand with 246 sub-elements with $\sim 50 \mu\text{m}$ diameter

Best Performances:

Road 1: $J_{c\text{non-Cu}}(12 \text{ T}) \sim 1880 \text{ A/mm}^2$

Problems: workability, J_c

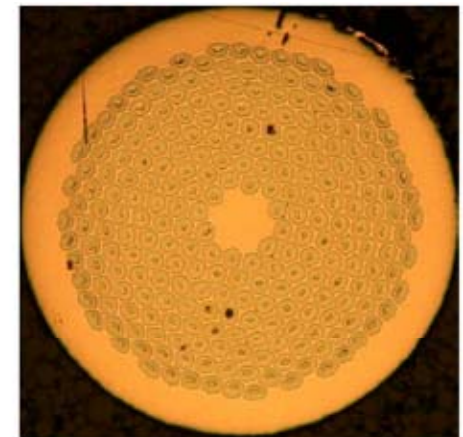
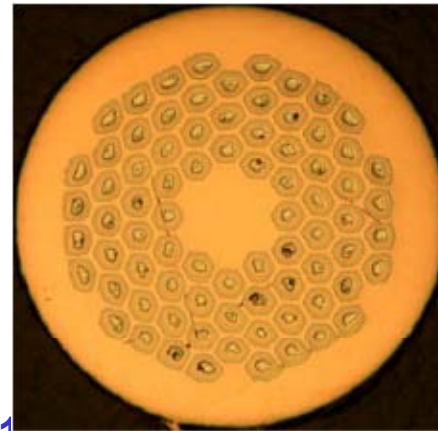
Next billets with NbTa +

many optimized processes

Road 2: $J_{c\text{non-Cu}}(12 \text{ T}, 4.2 \text{ K}) \sim 1880 \text{ A/mm}^2$

Problems: J_c

Next billets with NbTa



- Final strand production (24 km) will be achieved with both roads.
- **Road 1:** 3 billets in production for 6 km of strands
 - A first billet should be completed in December 2008 and I_c results are expected for January 2009.
- **Road 2:** 2 sub-elements in production to get 20-30 km of strands
 - Completion of the fabrication foreseen in April 2009.

4: Results of the cable development

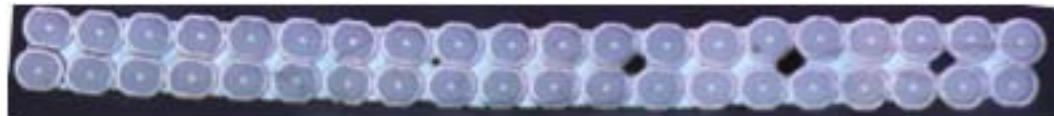
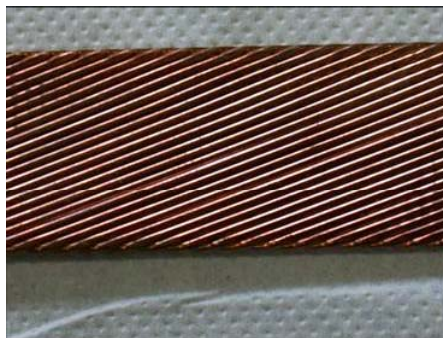
Thierry Boutboul



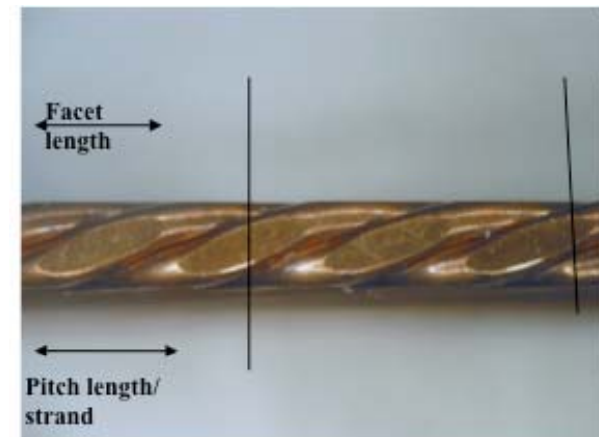
For the NED program, two Rutherford-type cables were already made on the basis of PIT strands: a 40-strand ~ 27 mm wide cable by LBNL and a 14-strand ~ 10 mm wide cable for the Short Model Coil program at CERN. The characterization results for strands extracted from both cables are summarized and the cabling critical current degradation is discussed as function of the heat treatment schedule.

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NED 40 strands
(LBNL)



SMC 14 strands
(CERN)



4: Results of the cable development (2)



- Cabling trials were performed at LBNL (40-strand cable) and CERN (14-strand SMC cable).
- For the same heat treatment schedule, critical current degradation measurements showed much more significant degradation for SMC cable (**10-17 %**) as compared to LBNL one (**4-8 %**) despite no sheared filaments observed in both cases and cabling parameters similar.
- Mainly due to shorter transposition pitch (**80 mm vs 150 mm**), the ratio of deformed strand is **3 times larger** for SMC cable. This could be the reason for degradation discrepancy.
- A SMC-type cable with a longer transposition pitch will be soon made at CERN to check the pitch effect on degradation. **Work underway...**

5: Guidelines on Magneto-Thermal stability

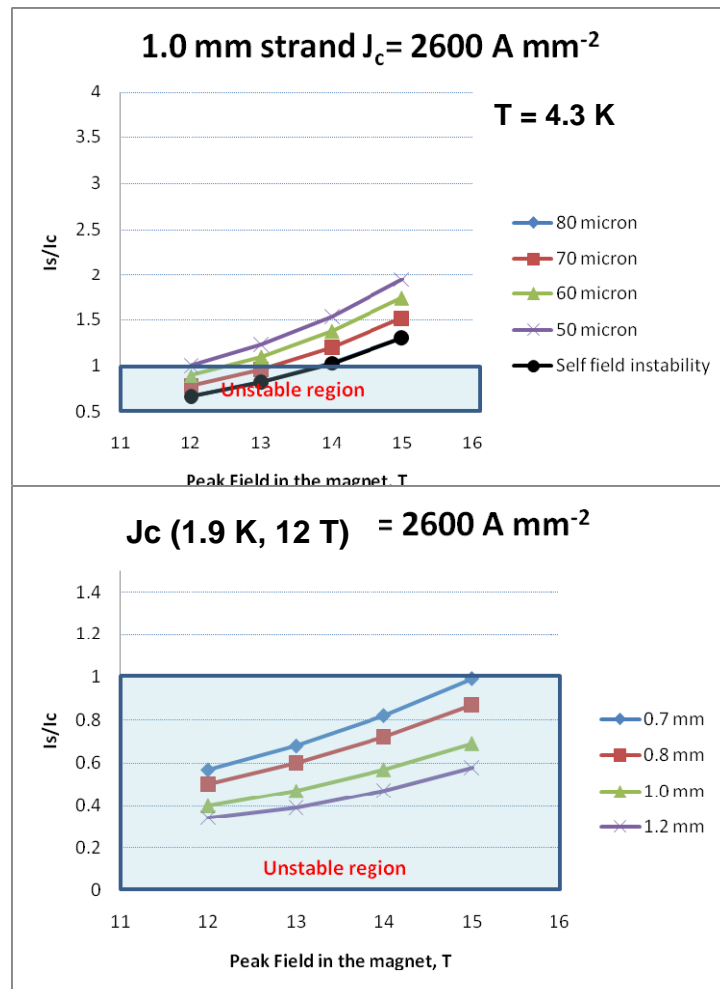
Bernardo Bordini



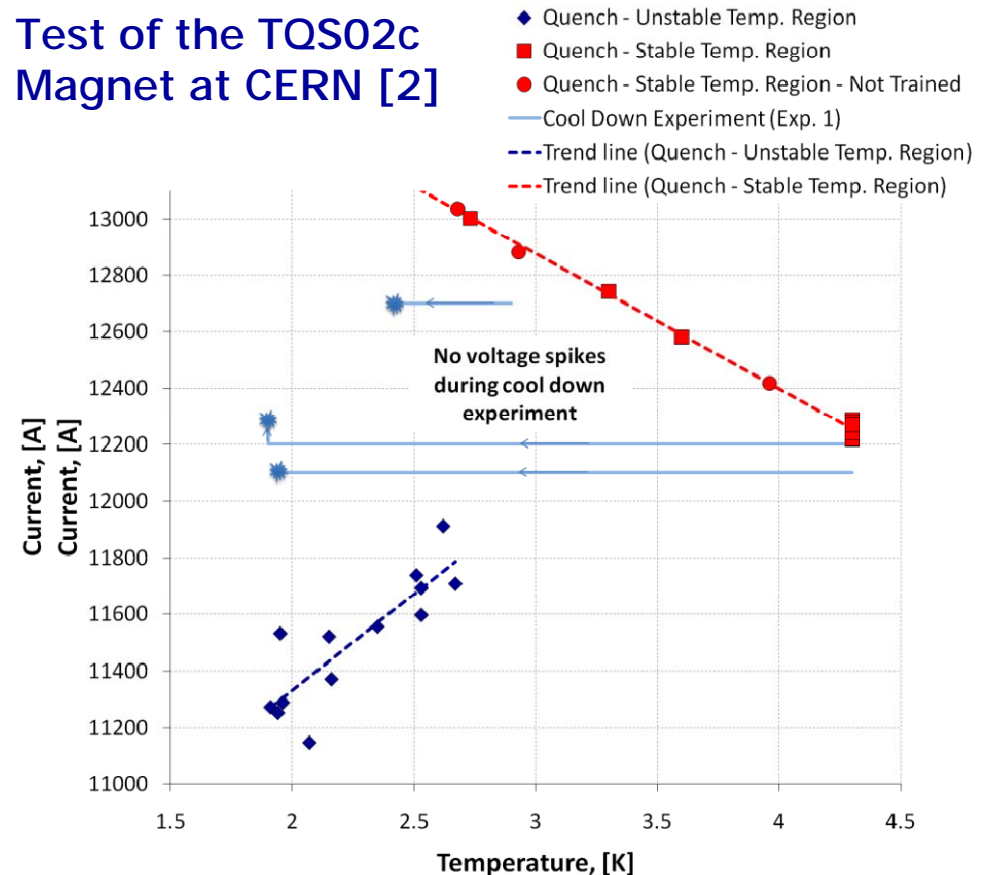
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What are the outstanding stability issues and what does this mean for the parameter space of Fresca2 and HQ. Requirements on strand diameter, filament diameter and RRR in relation to J_c and B .



Test of the TQS02c Magnet at CERN [2]



5: Guidelines on Magneto-Thermal stability (2)



- Increasing the **RRR** above **150** does not improve the conductor magneto-thermal stability
- A local damage of the copper stabilizer can completely Jeopardized the dynamic stabilization of the conductor → we can not rely on the dynamic stabilization is better to **design a magnet assuming a low RRR**
- High- J_c Nb₃Sn conductor ($J_c > 2600$ A/mm² at 4.2 K and 12 T) is not perfectly suitable for 12 T magnets because of magneto-thermal instabilities; this problem disappears if we **move towards higher field magnets**
- Magneto-thermal instability is not a problem for 15 T magnets that have to operate at 4.3 K (as Fresca2) if the strand diameter (\emptyset) and the effective filament size (D_{eff}) are sufficiently small ($\emptyset \leq 1$ mm, $D_{eff} \leq 70\mu\text{m}$)
- A 15 T magnet designed to work **at 1.9 K** could still have **problems** if the strand diameter and the J_c are not sufficiently small (for an RRP strand $J_c = 2600$ A/mm² at 4.2 K and 12 T → $\emptyset \leq 0.7$ mm); for larger strands and J_c we have to improve the **strand layout**.

6: Review on stress sensitivity

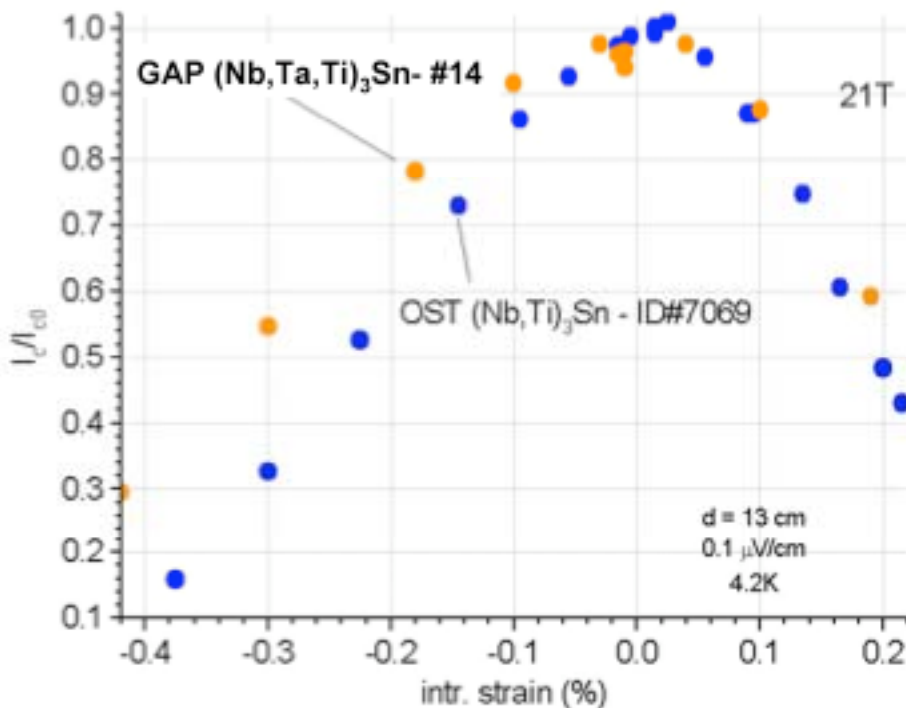
Rene Flukiger & Bernd Seeber



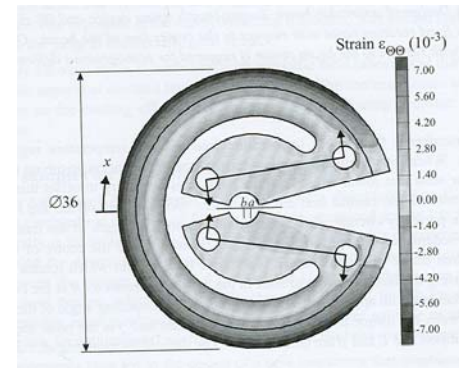
What do we know about stress sensitivity and where do we need more data. What do we need for Fresca2 and HQ on stress robustness.

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Uniaxial strain behavior of Nb₃Sn wires



The Pacman strain device (University of Twente)



The Walters Spiral (Univ. Geneva)



6: Review on stress sensitivity (2)



- $J_c(B, \epsilon)$ have been measured at very high fields (21 T) for Nb₃Sn Bronze Route, Internal Sn and PIT wires.
- The results show a dominant effect of the axial components 1 D approximation: $J_c(B, \epsilon)$ curves usually analysed with the Ekin and ten Haken models
- 3D distribution revealed by crystallography. Calculations still needed for larger filament sizes (subelements)
- Transverse compressive stresses: still no theoretical understanding. The very low reversibility of J_c suggests that nano- and microcracks are the major responsible for the much observed effects, which are much stronger than for uniaxial tensile stresses.

7: Dipole conductor needs: examples for Fresca2 Glyn Kirby

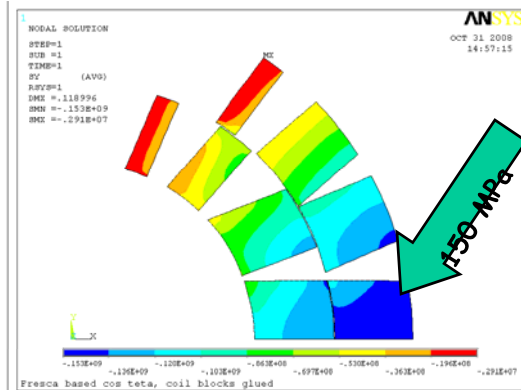


Using several existing cables (e.g. HD2-OST and NED) a comparison will be presented between the existing HD2 and a set of conceptual Fresca2 designs. The conceptual designs are cosQ, block coil and hybrid Nb₃Sn - Nb-Ti block coil. From this directions and its consequences for conductors needed for high fields will be indicated.

- Fresca2: 15 T bore field, 100mm aperture

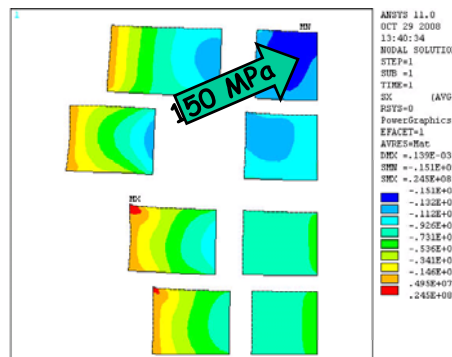
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Cos Θ design

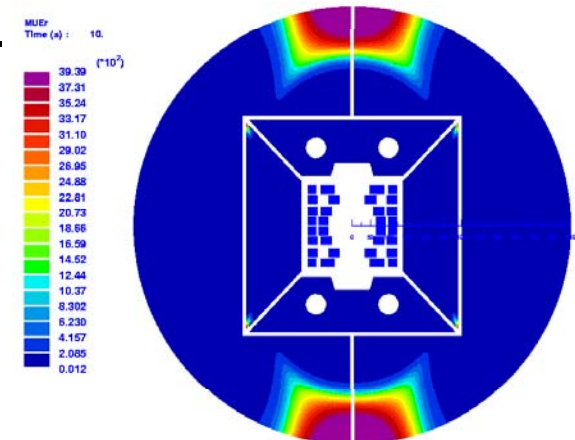


150 MPa @ 13 T

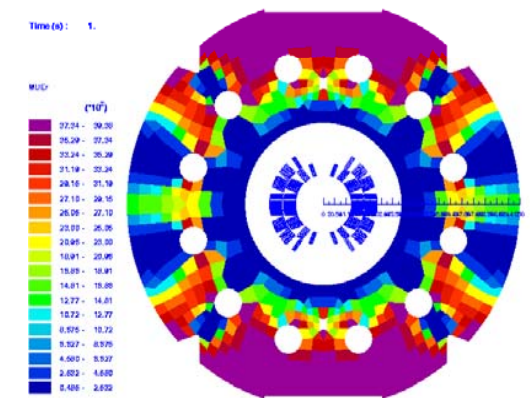
Block design



Bonded coil @ 15.5T
93%ss @ 1.9K



16T_BASE 08/03/20 08:49



7: Dipole conductor needs: examples for Fresca2 (2)

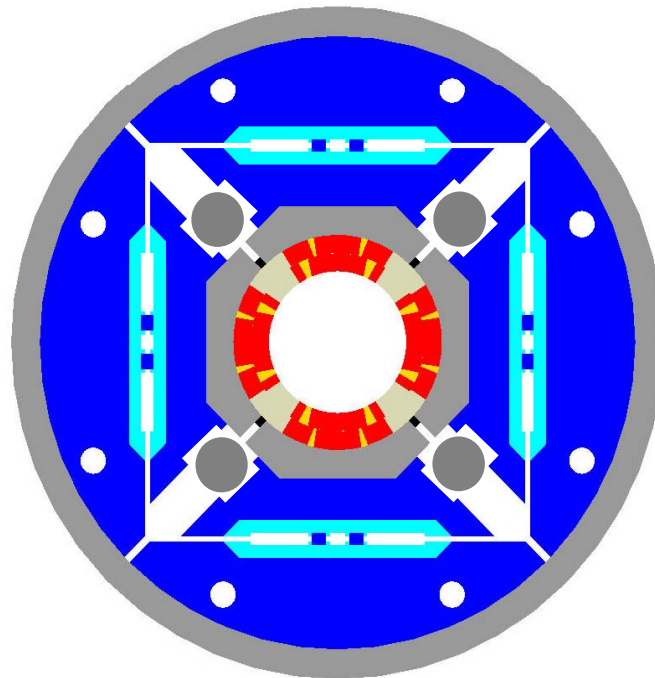


- Lots of development work is needed!
- Quench heaters that work in Nb₃Sn at 1.9K low field volumes!
- Some problems can be avoided by design!
 - Use Nb-Ti in low fields, then we have a quench heater that work.
 - Use Nb-Ti in low fields, high stress not a problem for Nb-Ti.
 - Change the strand design so that it can withstand the high stress. Internal protection for the filaments,
- What temperature to use 4.5K or 1.9K?(at 1.9K many magnets show damage!)
- Small Strands in Wide Cables using block design hybrid magnets.
 - Smaller strands are more stable!
- For the “Fresca” replacement high field, large aperture magnet planned at CERN an operating current of under 17KA.
- Stress sensitivity (> 150 MPa) is an issue above 13T
 - Get stress-strain resistive conductor
 - Design ‘around the problem’: block bonded coil or Nb₃Sn Nb-Ti hybrid design
- There are always low field areas in a high field coil → stability can be an issue
 - Nb₃Sn Nb-Ti hybrid
 - Thin strands (≤ 1 mm) and 4.2 K

8: Quadrupole conductor needs: examples for HQ *Shlomo Caspi*



Using the HQ as an example, the possible field and stress values for a fixed number of conductor cases and coil layouts are to be evaluated. From this a recommendation which type of conductor would be best is to be deduced.



Coil aperture	mm	120	
Yoke OR	mm	260	
Cable reference name	-	HQ-KC2	
Bare cable width	mm	15.150	
Bare cable mid-thickness	mm	1.437	
Cable keystoneing angle	deg	0.750	
Cable insulation thickness	mm	0.100	
Turns per quadrant IL/OL	-	20/26	
Minimum pole width	mm	23.82	
Midplane shim per octant	mm	0.140	
Quench* gradient @ 1.9K	T/m	219.78	
Quench* peak field @ 1.9K	T	15.29	
Quench* current @ 1.9K	kA	19.57	
Inductance @ quench*	mH/m	7.71	
Stored energy @ quench*	MJ/m	1.48	
Octant forces @ quench	F _x total	MN/m	3.38
	F _y total	MN/m	-5.03
	F _θ IL/OL	MN/m	2.63/3.15

* $J_c(12T, 4.2K) = 3000A/mm^2$, $K_{cu/nonCu} = 0.87$

8: Quadrupole conductor needs: examples for HQ (2)



	HQ @ 1.9 K	
	Design point	Operating point*
Jsc @ 4.2K, 12T (A/mm ²)	3000	2000
I strand (A)	556	500
B (T)	15.2	13.7
Stress (MPa)	177	143
Gradient (T/m)	219	197
Cu-nonCu and RRR	0.89, ~100	

HQS conductor needs

HQ cable parameters

- Strand diameter: 0.80 mm
- No. strands: 35
- Thickness: 1.437 mm
- Width: 15.15 mm
- Keystone angle: 0.75 degrees

Summary

- ☺ No instabilities in TQS01 models at 4.5 K & 1.9K (MJR)
- ☺ No stability limitations in TQS02 models at 4.5 K (RRP)
- ☺ Instability should play a lesser role in high field magnets (HQS)
- ☹ Signs of instability in TQS02 models at 1.9K (RRP)
- ☹ Self field instability in strand measurements cannot completely explain < 2.5K performance of TQS02
- What role does the fabrication process and conductor damage play in instabilities ?

Recommendations from the NED-ESAC – global-1



- 1) **Successful;** Overall, the NED program has been quite successful. It has been executed by and strongly supported by important contributions from all of the collaborating institutions
- 2) **Correct targets:** It is clear that the goals and high-level conductor performance targets set at the beginning of the program five years ago were the correct ones
- 3) **Two vendors:** The program has been successful in developing two European vendors for advanced Nb₃Sn conductor suitable for high-energy accelerator magnets.
- 4) **SMI-EAS:** One vendor has delivered a substantial quantity of wire which meets the targets, roughly doubling the J_c relative to the performance before this program.
- 5) **Alstom:** A second vendor, who had no previous experience with Nb₃Sn technology, has made good progress, but has not yet delivered conductor that meets the targets. (Note: meanwhile Alstom has announced to stop this activity !)

Recommendations from the NED-ESAC – global-2



- 6) **HFM:** In the judgment of the Committee, A-15 superconductors and specifically Nb_3Sn continue to represent the best path towards higher field magnets for high-energy accelerators, and they will remain so for the foreseeable future.
- 7) **Continue:** Vigorous development of Nb_3Sn technology needs to continue (SC wire and cable, design and construction of accelerator-type magnets)
- 8) **15T:** Given the world-record performance of the PIT Nb_3Sn conductor especially developed for this NED program, the committee concludes that the NED program was successful and rightly targeted. It has given the Eu collaborators a feasible conductor technology suitable for 15T class high-field accelerator magnets, provided the research is continued and the conductor is used in demonstration magnets.
- 9) **EuCARD:** The FP7-EuCARD-HFM program will be an important part of the world-wide effort and will position Europe as one of the leaders in advanced superconductor development.

Recommendations from the NED-ESAC – PIT conductor



- 1) **Strand Diameter:** Consider having some or all of the remaining PIT strand drawn to a smaller diameter of, for example, 0.8-1.0 mm. Hold the remaining PIT wire one step before the final drawing to 1.25 mm diameter and before twisting to allow for a decision on the final size. Such a decision should be made promptly.
- 2) **Cable:** Make additional cable from the production strand, as required for the completion of the NED program, and perform the proper characterization.
- 3) **Characterization:** Make a full and prompt characterization of the production wire recently delivered at 1.25 mm diameter, and of the final production once it is drawn to its final size. This characterization should be made with “virgin” strand and with strands extracted after cabling.

Recommendations from the NED-ESAC – IT conductor



- 1) Road1:** Drop “road 1” (cold drawn sub-elements) unless the wire being manufactured now shows a substantial improvement in piece length, J_c and RRR, and concentrate on “road 2” (hot extruded sub-elements).
- 2) Keep developing:** If possible, include 2-3 iterations in the wire design using the remaining road 2 material. These iterations might include, for example: doping with Ti rather than Ta; variation in the relative concentrations of Cu, Nb and Sn in the elements; or different starting diameters of the filaments and spacing between them. The NED program leader, working with Alstom, should identify a practical and effective subset of these to pursue.
- 3) Cable:** For the strands produced by each method and each iteration, which yield good results, produce cable to determine strand characteristics after cabling as well as cable characteristics. Cabling the wire is also necessary for the completion of the NED program.
- 4) Characterization:** Make a full and prompt characterization of the wire made from each process.

Recommended goals for future conductor development



- 1) **Filament size:** Further reduction in effective filament size towards 20 μm .
- 2) **Strand diameter:** Work with smaller diameter wires, which are favored by stability arguments. Smaller wires, however, imply either narrower cable, or more wires per cable.
- 3) **Stability:** Further exploration and understanding of stability issues and how they affect wire, cable and magnet design.
- 4) **Strain sensitivity:** Reduction in strain sensitivity. In this regard, studies need to be undertaken that are more easily connected to conditions in real cables and coils.
- 5) **Cabling:** Continued tests of cabling of Nb3Sn wires, both to understand the influence of cabling parameters on wire and cable performance, and to understand if there are wire design characteristics that affect the success of cabling.
- 6) **Production size:** Production of wire and cable needs to be scaled up to provide sufficient quantities, with sufficiently reproducible and understood characteristics, to make real accelerator-type magnets, e.g. the FRESCA2 magnet.

Recommendations, future conductor development



- 1) **Specification:** Specification of J_c for future wire and cable should concentrate on the performance at 15 T, () This implies the use of ternary alloys.
- 2) **Two technologies:** Continue the development of both PIT and IT technologies. To be effective, there needs to be reasonable continuity of support for the industrial partners.
- 3) **Large scale:** Develop the technology necessary for large-scale production of PIT conductor.
- 4) **Road 2:** Concentrate on the hot-extrusion method for producing IT sub-elements
- 5) **Keep developing:** Continue to iterate the design and the production process for the IT conductor to increase J_c , by redesign of the sub-elements and inclusion of Ti or Ta.

Recommendations, future conductor development



- 6) **Design magnet:** Develop a complete and serious design for a 15 T, large bore magnet (e.g. for FRESCA), to allow the specification of wire and cable.
- 7) **Build magnet:** Build a 15 T, large bore magnet in order to fully qualify the conductor performance.
- 8) **Scale modeling:** Continue the Small Model Coil (SMC) program, which is an important component of the conductor development program. Attention needs to be paid to the differences between the cables used for the SMC program and for the full-scale 15 T magnet, which are (at least) very different widths and lack of keystoneing in the SMC conductor, and to the consequent performance differences.
- 9) **Collaborate:** Continue to coordinate and collaborate with other Nb₃Sn R&D programs, specifically those in the US, including LARP.

Final



A warm thank-you to the ESAC members for their solid advice