Next European Dipole (NED) Overview & Status

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on behalf of the NED Collaboration

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NED Program

- At present, the NED JRA is articulated around four Work Packages and one Working Group

    1 Management & Communication (M&C),

    2 Thermal Studies and Quench Protection (TSQP),

    3 Conductor Development (CD),

    4 Insulation Development and Implementation (IDI),

    5 Magnet Design and Optimization (MDO) Working Group.

- NED web site

http://lt.tnw.utwente.nl/project.php?projectid=9

CANDIA

- Since the launching of NED, INFN has approved on 30 November 2004 a complementary program, called CANDIA (Italian acronym standing for CAvi in Niobio-stagno per DIpoli ad Alto campo or niobium-tin cables for high field dipoles), supported by INFN/Frascati, INFN/Genova and INFN/Milan.
- The main goal of CANDIA is the development of a Nb_3Sn conductor according to NED-like specifications, and a call for tender was issued in the Fall of 2005.
- Of course, close ties are maintained between CANDIA and NED.

US LARP

- Ties are also maintained between NED and the US-LHC Accelerator Research Program (LARP).
- LARP is aimed at supporting US efforts in LHC commissioning and at designing and developing equipment for LHC upgrade (such as advanced beam instrumentation and Nb_3Sn magnets).
- It is carried out by a collaboration made up of BNL, Fermilab, LBNL and SLAC.
- Serious things have started in FY06, with a budget of 11 M$ (5.7 for magnets, 4.0 for accelerator-related R&D and 1.3 for management); this budget is expected to be maintained at a constant level for a few years.
- The magnet part of LARP is aimed at building by 2009 one or two 4-m-long, 90-mm-aperture, 200 T/m quadrupole magnet prototypes, so as to demonstrate the feasibility of "long," accelerator-class Nb_3Sn magnets.

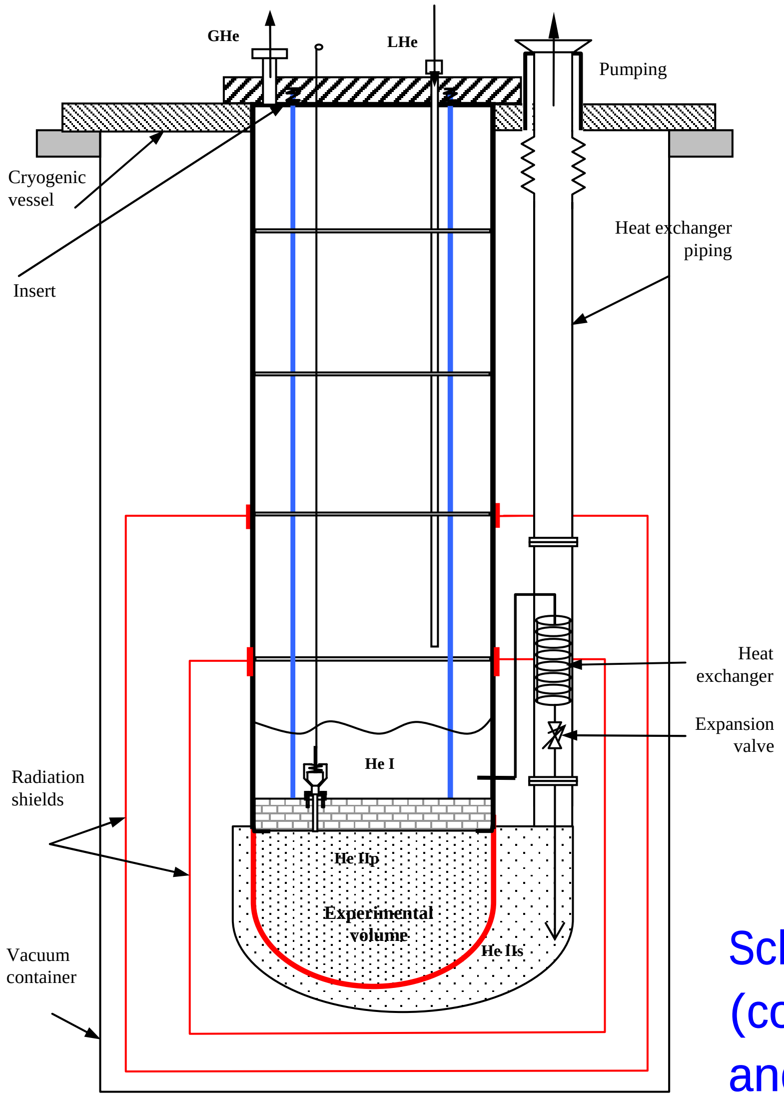
Contents

- **Status**

TSQP Work Package

- The TSQ Work Package includes two main Tasks
  - development and operation of a test facility to measure heat transfer to helium through Nb_3Sn conductor insulation (CEA and WUT; Task Leader: B. Baudouy, CEA),
  - quench protection computation (INFN-Mi; Task Leader: G. Volpini).

Heat-Transfer Measurement Task (2/3)



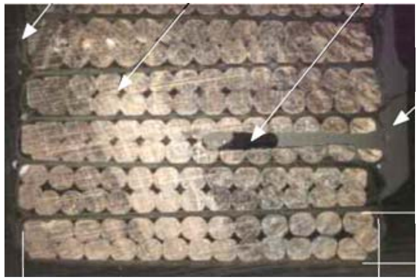
- The first part of the Task was to design and build a new He-II, double-bath cryostat.
- CEA wrote detailed specifications that were handed out to Wroclaw University in June 2004.
- Wroclaw University performed a call for tender in the Summer of 2004 and selected Kriosystem in Poland to manufacture the cryostat.

Schematic of NED cryostat (courtesy F. Michel, B. Baudouy and B. Hervieu, CEA)

Heat Transfer Measurement (2/3)

- A successful reception test was performed at Kriosystem early July 2005 (which included thermal and leak tests in liquid helium at 4.2 K).
- The cryostat was delivered to CEA/Saclay on 20 September 2005, where it is being readied for commissioning.
- Measurements will be carried out on various insulation systems and two sample configurations: 1-D drum samples, to study basic phenomenon, and stack samples, representative of actual magnet coils.

Drum Sample
(Courtesy B. Baudouy, CEA)



Stack Sample
(Courtesy N. Kimura, KEK)

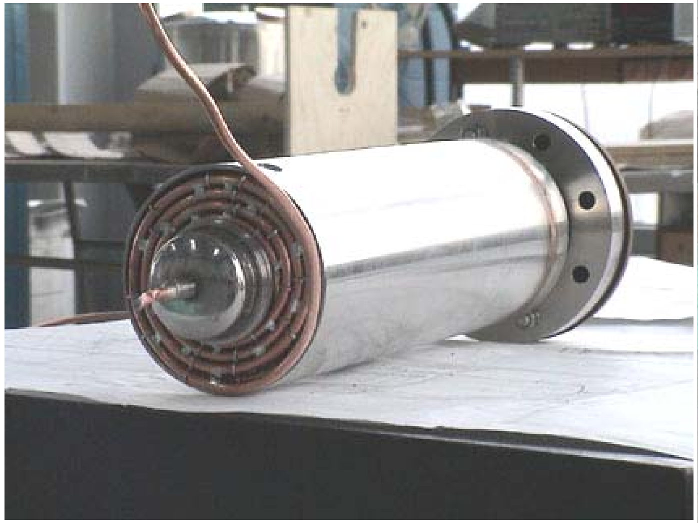
Heat Transfer Measurement (3/3)

Lambda plate

Cryostat with thermal shields

Inner view of cryostat with Instrumentation

(Courtesy M. Chorowski, WUT)



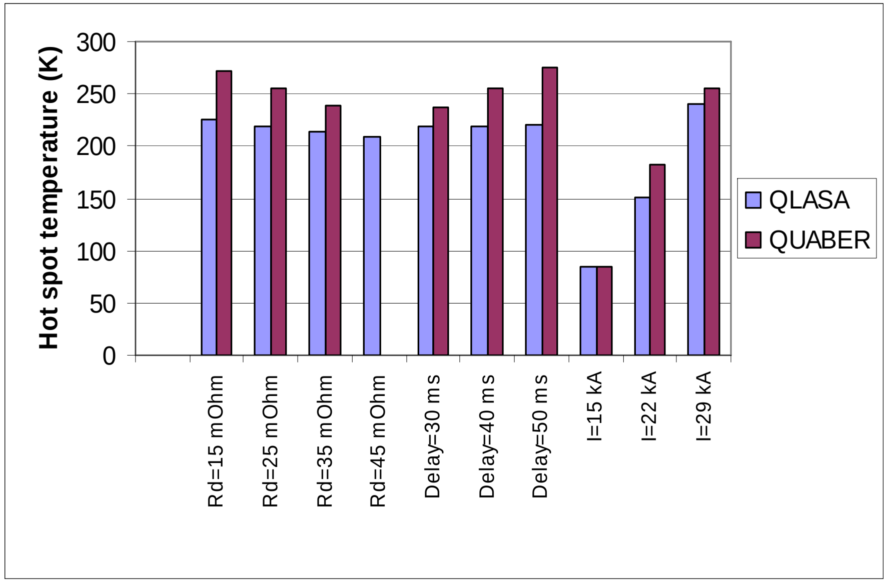
He II heat exchanger

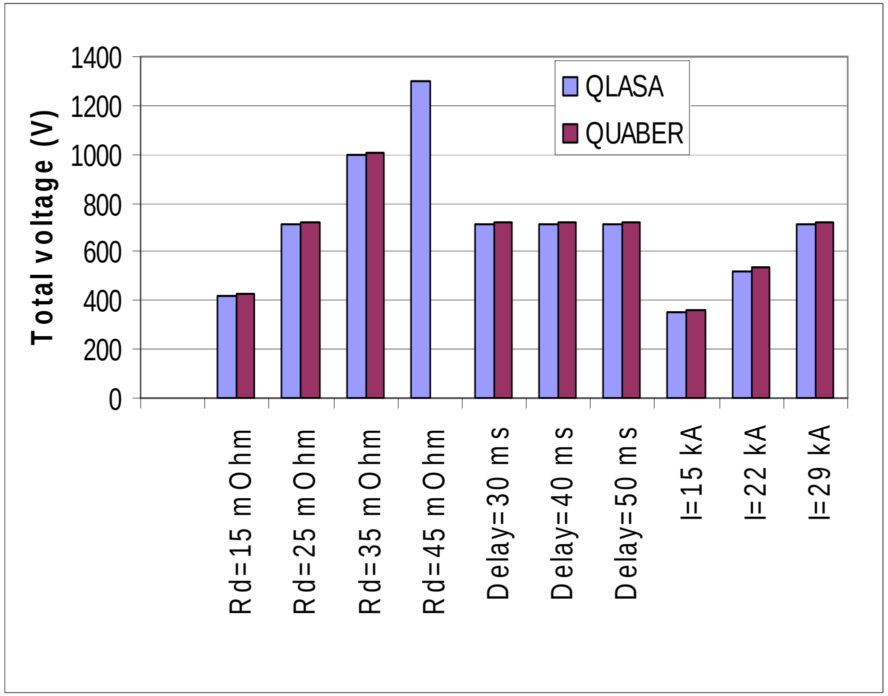
Quench Computation (1/3)

- INFN-Mi has undertaken a detailed analysis of the thermal and electrical behaviors of NED-like magnets during a quench.
- The computation was started considering the "conservative," 88-mm-aperture, cosθ, layer design developed by D. Leroy at CERN (and chosen as Reference Design V1).
- It studies the influence of
  - magnet length (1, 5 and 10 m),
  - operating current (15, 22 and 29 kA),
  - external dump resistance (15, 25 and 35 mΩ),
  - quench detection delay (30, 40 and 50 ms),
  - quench protection heater length.
- It also compares the results obtained by two different codes: QLASA at INFN-Mi and QUABER at CERN.

Quench Computation (2/3)

- The simulations show that, with a proper choice of quench protection heaters and external dump resistor, the magnet can be operated safely, thereby justifying the choice of conductor parameters made early on.

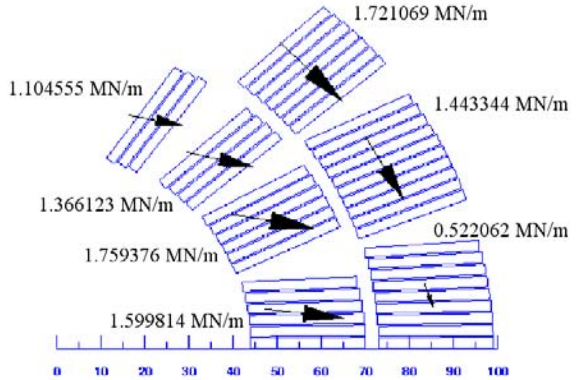




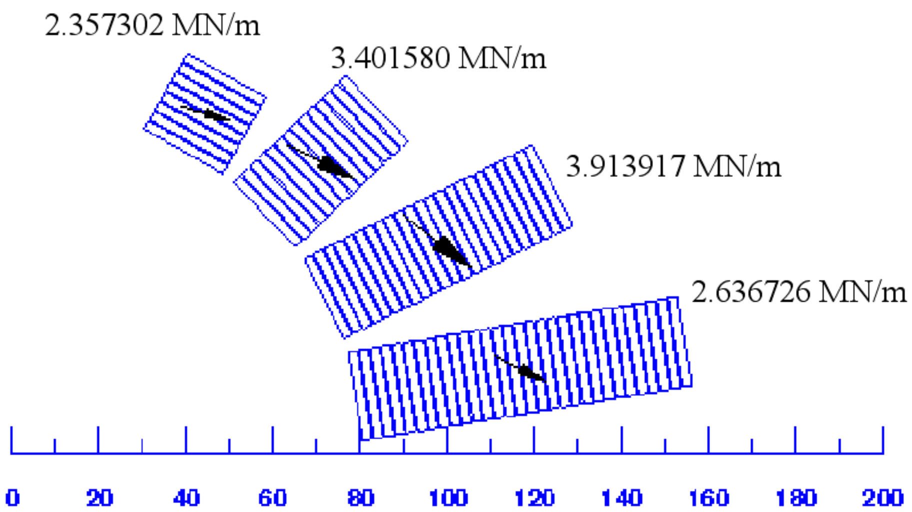
Quench simulation results on 10-m-long,
88-mm-aperture, cosθ, layer design
(Courtesy M. Sorbi, INFN-Mi)

Quench Computation (3/3)

- Computations have now been started on a more "innovative," 160-mm-aperture, cosθ, slot design also proposed by D. Leroy.



88-mm-aperture, layer design
(Courtesy D. Leroy, CERN)



160-mm-aperture, slot design
(Courtesy D. Leroy, CERN)

TSQP Scope Extensions

- Since the start of NED two extensions of scope have been agreed upon
  - D. Richter (CERN) is presently analyzing available LHC magnet test data at high ramp rate to determine how well the Saclay measurements correlate with what is observed in actual magnets,
  - R. van Weelderen (CERN) has undertaken a review of magnet cooling modes to estimate, on the cryogenics system point of view, what are the limitations on power extraction and to provide guidance on how to improve cooling of magnet coils; preliminary conclusions indicates that NED-like magnets may have to be operated in superfluid helium.

Contents

- **Status**

CD Work Package

- The CD Work Package includes three main Tasks
  - – conductor development

    (under CERN supervision; Task Leader: L. Oberli),
  - – conductor characterization

    (CEA, INFN-Ge, INFN-Mi, and TEU; Task Leader: A. den Ouden, TEU),
  - – FE wire model (to simulate cabling effects)

    (CERN and INFN-Mi; Task Leader: S. Farinon, INFN-Mi).
- It is the core of the Program and absorbs about 70% of the EU-allocated funding.

Conductor Development (1/3)

- As a conclusion of preliminary design studies carried out in 2003 and 2004 under the supervision of D. Leroy, the following specifications have been derived for NED Nb_3Sn strands

– **diameter**	**1.250 mm,**
– **eff. filament diameter**	**< 50 μm,**
– Cu-to-non-Cu ratio	1.25 ± 0.10,
– filament twist pitch	30 mm,
– **non-Cu J_C**	**1500 A/mm^2 @4.2 K & 15 T,**
– **minimum critical current**	**1636 A at 12 T,**
	818 A at 15 T,
– *N*-value	> 30 at 4.2 K and 15 T,
– RRR (after heat treatment)	> 200.

(It is also requested that the billet weight be higher than 50 kg.)

Conductor Development (2/3)

- Although the final cable parameters will be decided later on, the preliminary studies (of 88-mm-aperture, cosθ layer design chosen a Reference Design V1) call for

– **width**	**26 mm,**
– mid-thickness	2.275 mm at 50 MPa,
– keystone angle	0.22 degrees,
– **number of strands**	**40,**
– **minimum critical current**	**58880 A at 4.2 K and 12 T,**
(field normal to broad face)	**29440 A at 4.2 K and 15 T,**
– RRR (after heat treatment)	> 120,
– **minimum unit length**	**> 145 m.**

(Cable critical currents assume a cabling degradation of 10%.)

Conductor Development (3/3)

- Based on these specifications, a call for tender was issued by CERN in June 2004 and two contracts were awarded in November to 2004 to
  - Alstom/MSA in France ("Enhanced Internal Tin" process),
  - SMI in The Netherlands ("Powder in Tube" Process).
- After discussion with CERN, the two companies have agreed to work out their development program into two successive RD Steps (referred to as STEP 1 and STEP 2) followed by final cable production.
- A tentative schedule is
  - STEP 1: Fall 2005,
  - STEP 2: Summer 2006,
  - Final production: December 2006.

Alstom/MSA Status (1/2)

- For Alstom/MSA ("Enhanced Internal Tin" process), STEP 1 is devoted to a Taguchi-type plan to study the influence of salient parameters on workability and performances, while STEP 2 will be devoted to a critical current density tuning.
- As part of STEP 1, Alstom/MSA has launched the production of five different types of strands, which can be classified into two main families
  - sub-elements with central tin sources,
  - sub-elements with distributed tin sources.
- The designs of these strands (which has been been discussed extensively with CERN) are radically new compared to the strand for the CEA quadrupole magnet.

Alstom/MSA Status (2/2)

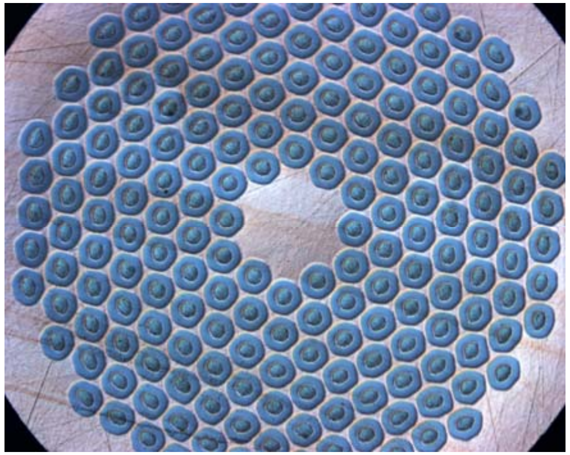
- Alstom/MSA has encountered a few problems in the preparation of the Sn rods used in billet assembly; solutions have been found and CERN has performed quality assurance tests on the Sn rods to verify their suitability.
- All sub-element billets have been assembled and drawn down, but only those of the central-tin family have achieved a diameter suitable for restacking.
- One final billet has been restacked and is presently being drawn down; wire should be available before the end of the month for heat treatment optimization.
- In parallel, Alstom/MSA and CERN have agreed on the production of two additional sub-element billets with a modified process.

SMI Status (1/2)

- SMI ("Powder In Tube" Process) has already produced a 1-mm-Ø wire that achieved a non-copper critical current density of ~2500 A/mm^2 at 4.2 K and 12 T (only 17% below the target of 3000 A/mm^2 at 4.2 K and 12 T).
- Based on these promising results, STEP 1 calls for iterations on the existing layout to achieve the desired critical current density while STEP 2 will be devoted to a scale up to larger billet sizes.
- As part of STEP 1, SMI has produced four 3-Kg billets
  - 2 with Ta tubes,
  - 2 with improved powder content.

SMI Status (2/2)

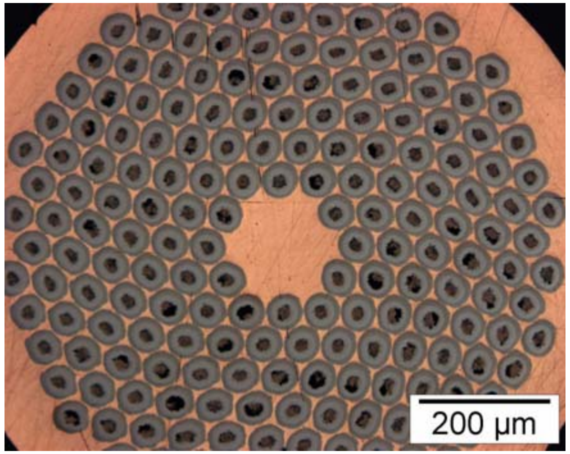
- The drawing down of the two Ta-lined billets was accompanied by a high breakage rate, attributed to a poor quality of the Ta tubes.
- The billets with improved powder mixture were drawn down to a 1-mm-diameter without breakage and yielded unit lengths of ~320 m.
- However, the measured non-Cu J_C were below expectation (2350 A/mm^2 at 4.2 K and 12 T), presumably due to ruptures of the Nb tubes and Sn leakage occurring at the melting point of Sn.



Before HT

Example of NED/STEP 1 PIT wire with improved powder content produced by SMI (courtesy L. Oberli, CERN)

After HT

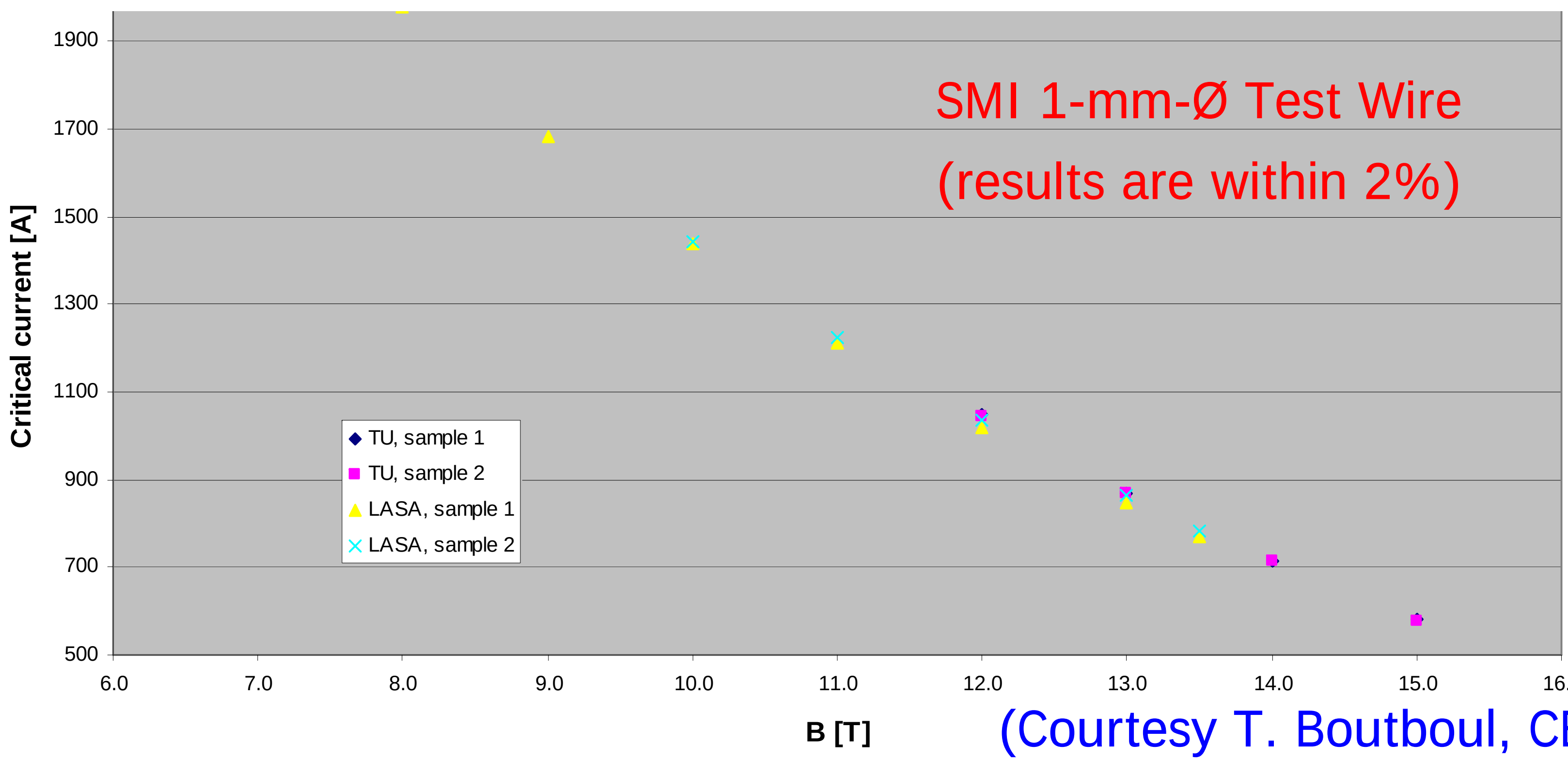


Conductor Characterization (1/4)

- NED conductors will be characterized by performing critical current and magnetization measurements.
- The critical current measurements represent a real challenge, given the unprecedented performances that are expected (*e.g.*, a critical current of ~1600 A at 4.2 K and 12 T on a 1.25-mm-Ø wire, to be compared to the ~200 A presently achieved on 0.8-mm-Ø ITER wires).
- To validate sample preparation and measurement processes, the laboratories involved (CEA, INFN and Twente University) have launched a cross-calibration program reminiscent of the ITER/EDA cross-calibration program carried out in the mid-1990's.
- Since the Summer of 2004, three rounds of calibration wires have been prepared and circulated among the various partners.

Conductor Characterization (2/4)

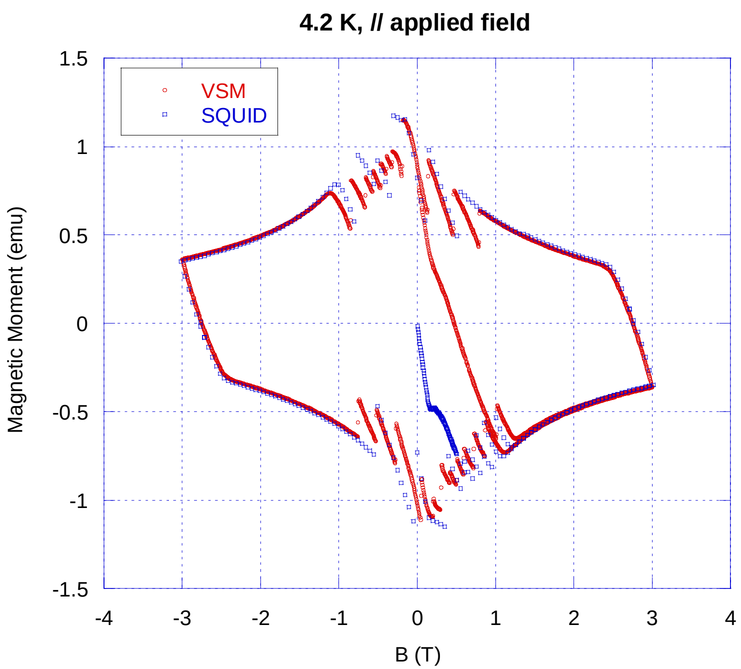
- Twente University and INFN-Mi have achieved a good convergence on I_C measurements, while CEA is still upgrading its test set up.
- All 3 partners should be ready when the first wires become available.



(Courtesy T. Boutboul, CERN)

Conductor Characterization Task (3/4)

- Magnetization measurements are performed under the supervision of INFN-Ge using a SQUID magnetometer, a Vibrating Sample Magnetometer (VSM) and an AC susceptibility apparatus.



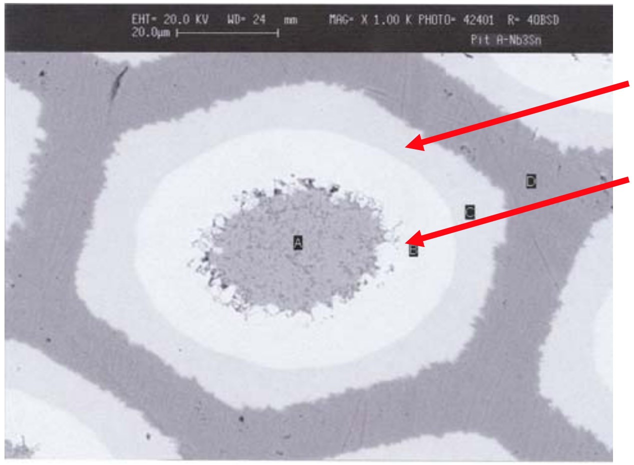
- The measurements are performed as a function of field to evaluate the effective filament diameter and the presence or not of flux jumps.

Exploratory measurements on a 5-mm-long Nb_3Sn wire sample (SQUID measurements are courtesy of C. Ferdeghini, INFM/Genova; VSM measurements are courtesy of U. Gambardella, INFN/Frascati)

Conductor Characterization Task (4/4)

- The magnetization measurements are also performed as a function of temperature to study various issues, such as the proportion of un-reacted Nb in PIT wires.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

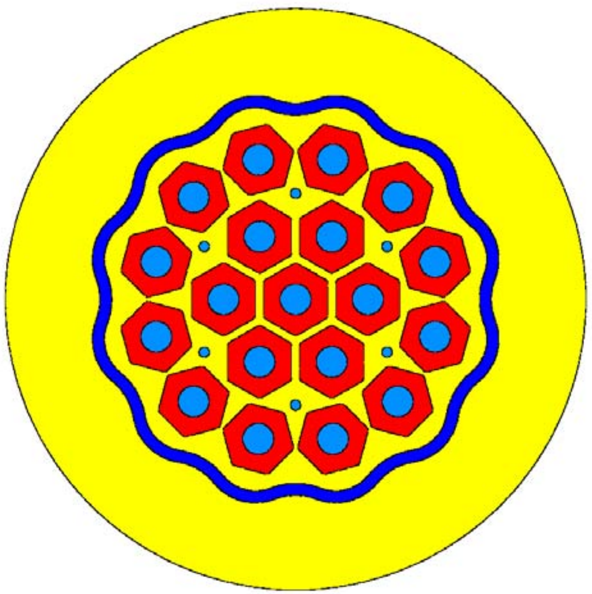


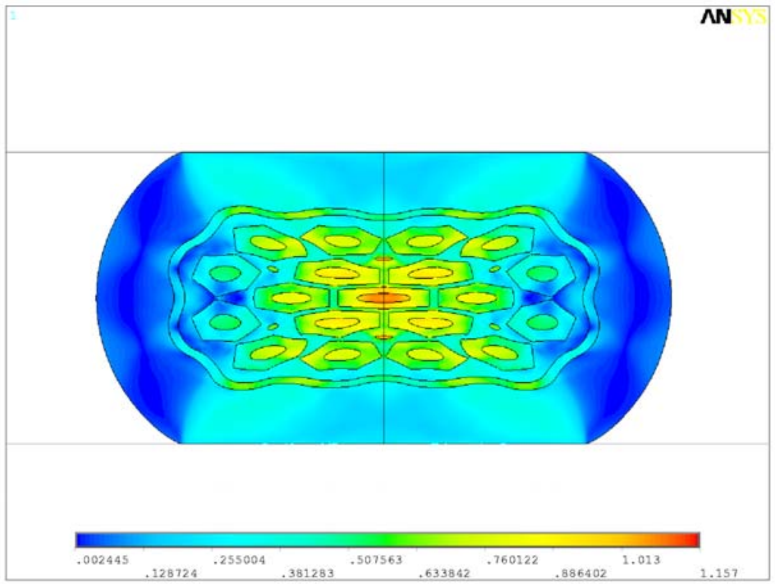
(SMI-type PIT wire)

(Courtesy M Greco, INFN/Genova and C. Ferdeghini, INFM/Genova)

FE Wire Model (1/2)

- INFN-Ge has started to develop a mechanical FE model (based on ANSYS®) to simulate the effects of cabling on un-reacted, Nb-Sn wires so as to optimize their design.

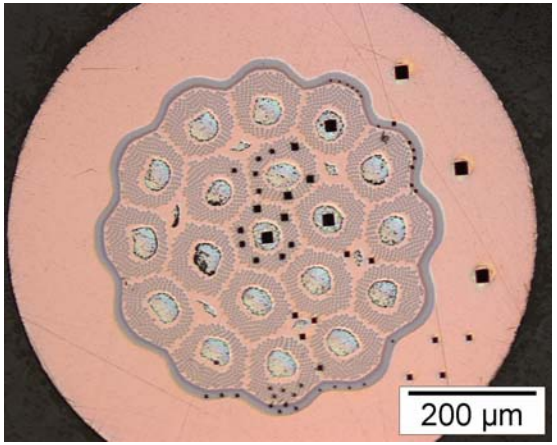




Examples of mechanical FE model for “old” Alstom/CEA internal tin wire and of Von Mises strain due to a diameter reduction of about 40% (courtesy S. Farinon, INFN-Ge)

FE Wire Model (2/2)

- Running such computation requires a detailed knowledge of the mechanical properties of the materials making up the wire (in the cold-worked state where they end up prior to the cabling operation).
- To determine these properties, CERN has supervised or carried out a series of nano-indentation and micro-hardness measurements on various wire samples, and compared the results with literature data.



Microhardness measurements on X-cut of Alstom/CEA wire (courtesy C. Scheuerlein, CERN)

Nanohardness measurements on longitudinal cut of Alstom/CEA wire (courtesy S. Sgobba, CERN)

Contents

- **Status**

IDI Work Package

- The IDI Work Package includes three main Tasks

  – redaction of an engineering specification and definition of characterization tests,

  (CCLRC and CEA ; Task Leader: E. Baynham),

  – studies on “conventional” insulation systems relying on ceramic or glass fiber tape and vacuum-impregnation by epoxy resin

  (CCLRC; Task Leader: S. Canfer),

  – studies on “innovative” insulation systems relying on pre-impregnated fiber tapes and eliminating the need for a vacuum impregnation

  (CEA; Task Leader: F. Rondeaux).

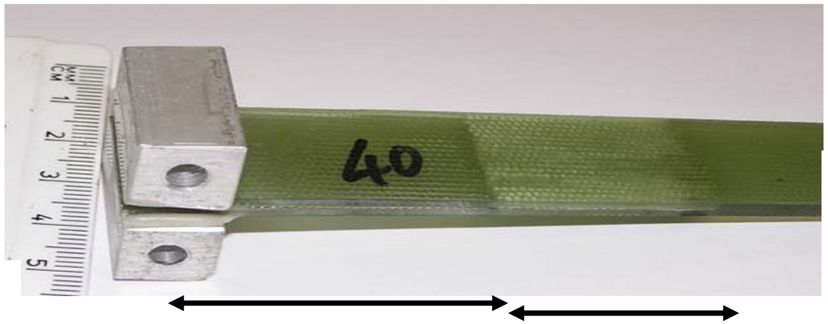
Insulation Specification

- CCLRC and CEA have jointly developed an Engineering Specification (issued in July 2004) and a Coordinated Test Program (issued in October 2004) for "wind & react", NED-type, accelerator magnet coils.
- The main conductor insulation parameters are

– thickness	**0.2 mm per conductor face,**
– dielectric strength	1 kV inter-turn in He at 300 K,
– compressive strength	**> 200 MPa at 300 K & 4 K,**
– short-beam shear strength	> 50 MPa at 4 K,
– transverse tensile strength	> 25 MPa at 4 K,
– thermal contraction	0.3-0.4% between 300 & 4 K,
– thermal conductivity	> 20 mW/K at 4 K,
– thermal cycle	> 10,
– running cycle	> 100.

Conventional Insulation (1/2)

- CCLRC/RAL is carrying out screening tests of candidate materials for fiber tapes and impregnation resin.
- The tests are applied to standardized laminates representative of inter-turn insulation and include
  - – electrical breakdown test,
  - – short beam shear test,
  - – inter-laminar fracture test.



Example of Double Cantilever Beam (DCB) fracture test (Courtesy S. Canfer, CCLRC)

Conventional Insulation (2/2)

- CCLRC has also investigated the issue of “sizing”.
- The sizing is a lubricant, usually organic, coated onto the fibers of tapes to facilitate their weaving, and, which, in the case of the “wind & react” coil manufacturing process, needs to be removed prior heat treatment.
- However, “de-sized” fiber tapes become fragile and easy to tear off, which complicates the manufacturing process.
- Very promising results have been obtained with an improved polyimide sizing, produced by Hydrosize, NC, and applied by JPS, SC, which seems to be able to sustain the required Nb_3Sn heat treatment without carbonization (thereby eliminating the need for “de-sizing”).
- More complete evaluation tests are underway.

Innovative Insulation

- The Innovative Insulation Task is meant to build upon the ongoing R&D program at DAPNIA/SACM.
- The feasibility of the innovative system has been demonstrated; the next step is to better characterize and improve the mechanical properties after heat treatment and to reduce the thickness of the pre-impregnated tape.
- However, the work has been put on hold at CEA/Salcay due to a lack of human resources; it is expected to restart in January 2006.

Contents

- **Phase I Status**

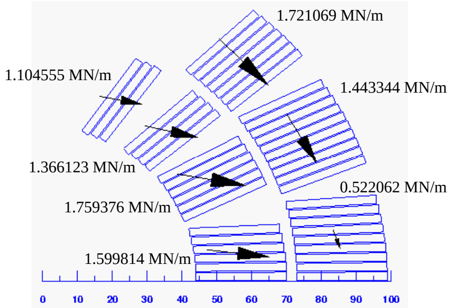
MDO Working Group (1/5)

- The MDO Working Group is made up of representatives from CCLRC, CEA, CERN and CIEMAT
(Chairman: F. Toral, CIEMAT).
- Its main charge is to address the following questions
  - How far can we push the conventional, cosθ, layer design in the aperture-central-field parameter space (especially when relying on strain-sensitive conductors)?
  - What are the most efficient alternatives, in terms of performance, manufacturability and cost?

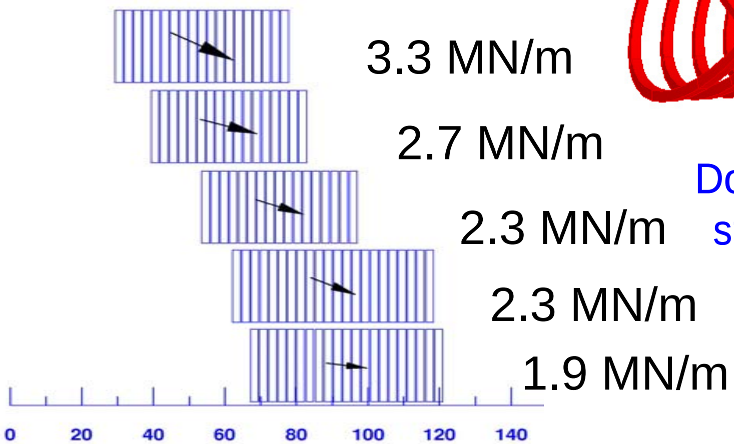
MDO Working Group (2/5)

- The MDO WG has selected
  - a number of magnetic configurations to be studied (see next slide),
  - ranges of design parameters,
  - terms of comparison between solutions.
- Each Institute participating to the WG has chosen one or two configurations and will carry out detailed 2D and 3D magnetic and mechanical modeling.
- Preliminary results have been shared with the Fusion community (“EFDA” Dipole).

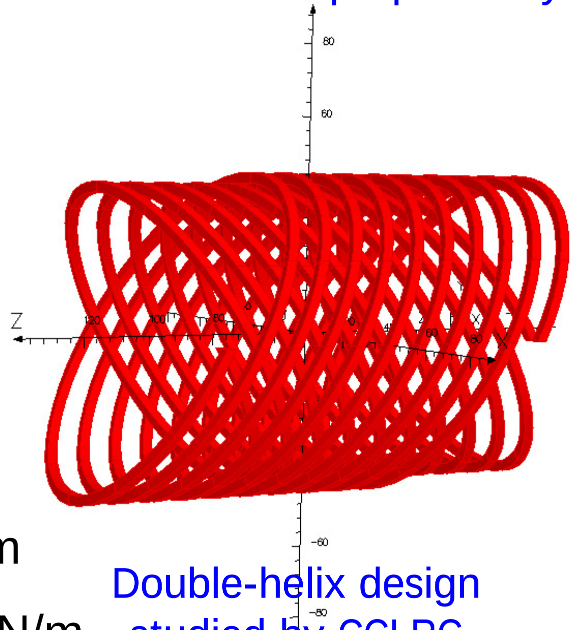
MDO Working Group (3/5)



88-mm-aperture, cosθ, layer design studied by CCLRC & CERN

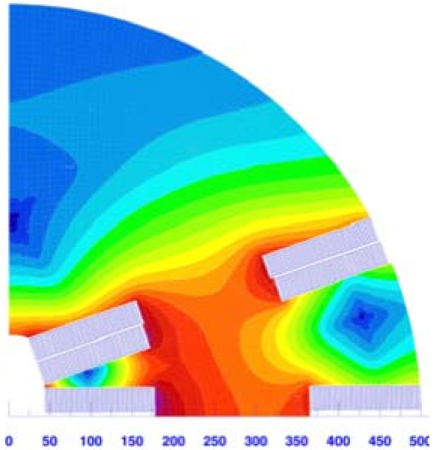


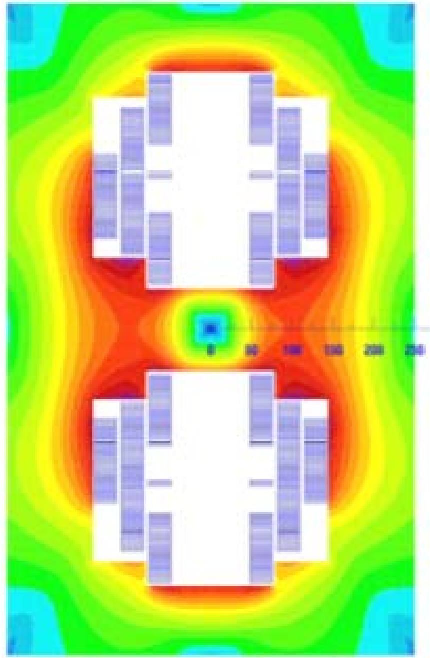
130-mm-aperture, intersecting-ellipse design proposed by CEA



Double-helix design studied by CCLRC

88-mm-aperture, motor-type design proposed by CIEMAT

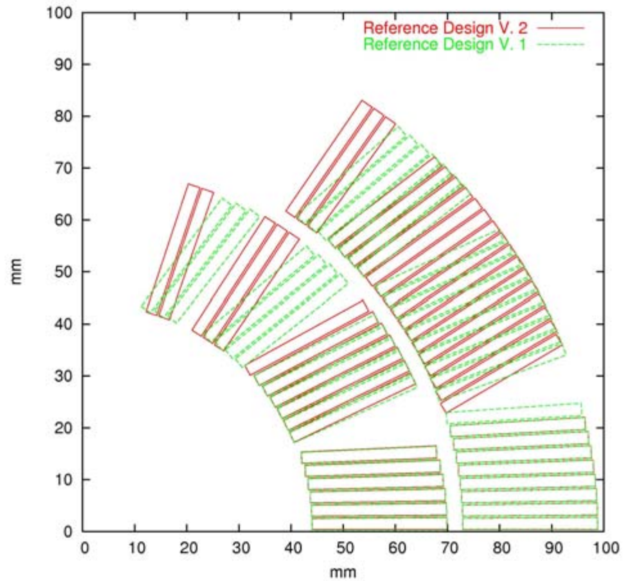


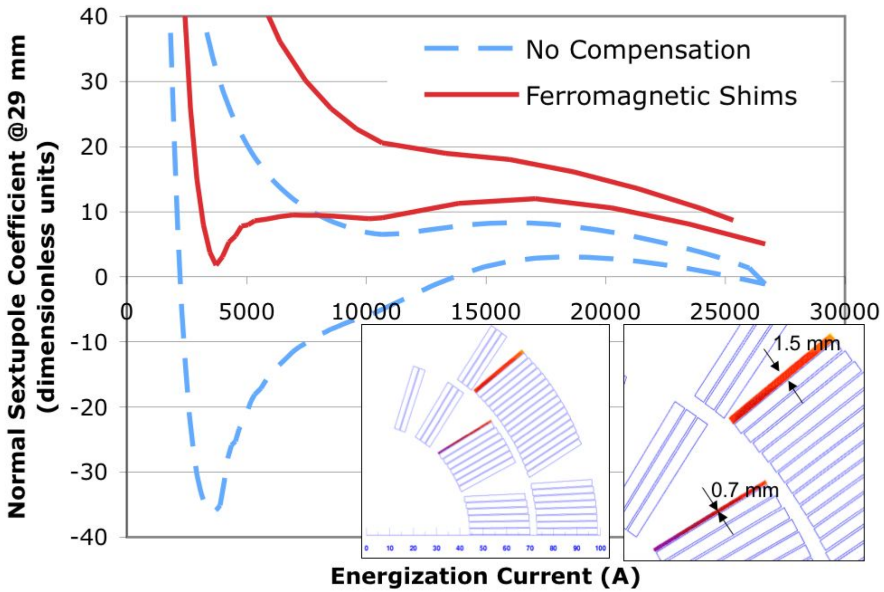


88-mm-aperture, common-coil design studied by CIEMAT

MDO Working Group (4/5)

- CERN has pursued the electromagnetic optimization of the baseline, 88-mm-aperture, cosθ layer design with respect to
  - conductor geometry,
  - iron shape (to reduce saturation effects),
  - ferromagnetic shims (to compensate magnetization effects).

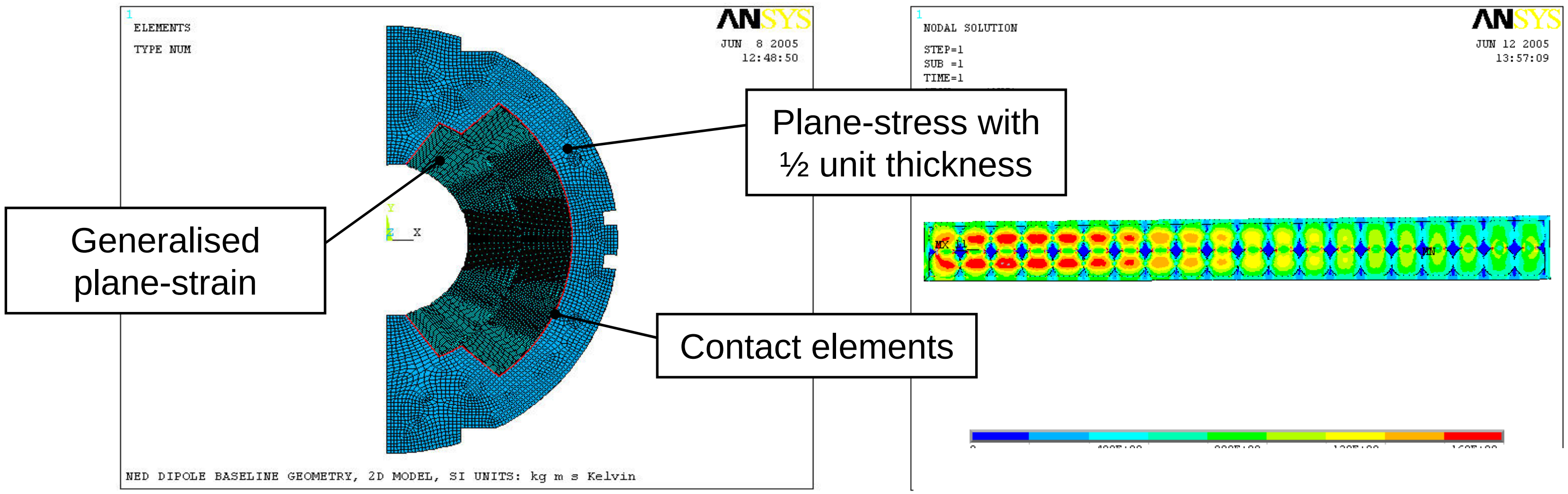




(Courtesy N. Schwerg, CERN)

MDO Working Group (5/5)

- CCLRC/RAL has started the development of a 2D, ANSYS,® mechanical model of the 88-mm-aperture, cosθ layer design (Lorentz forces are up to 5 times higher than in LHC dipole magnets!).
- This model includes “sub-models” of individual coil turns to compute peak stresses in cable strands and cable insulation.



(Courtesy P. Loveridge, CCLRC)

Conclusion

- Save for the innovative insulation, all the Tasks of the NED program have been launched and are well under way.
- The cryostat for heat transfer measurements is completed and has been delivered to CEA.
- The next few months will be critical for the Conductor Development Task with the results of STEP 1 wires.
- The NED collaboration is actively seeking additional funding to complete the detailed design, manufacturing and test of the model magnet left out from the present program.