Review of WP7 results: High Field magnets R&D

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10th June 2013
CERN

Contents

EuCARD WP7 HFM: Superconducting High Field Magnets for higher luminosities and energies

Aim: Development of high field magnets for accelerator applications

- Program start 1/4/09, 4 years; budget: total 6.4M€ , EU contrib. 2.2M€
- 1 management task, 1 studies task, 4 design/construction tasks
  - High field model: build a 13 T, 100 mm aperture Fresca2 magnet (15 T ultimate)
  - support studies for the 100 mm aperture magnet
  - Very high field dipole insert: build a HTS insert coil (into Fresca2) to approach 20 T (ΔB ~ 6 T)
  - HTS link design study
  - Build a Helical Undulator model
- 13 participant institutes: CERN, CEA-DSM-Irfu, CNRS-Grenoble, COLUMBUS, BHTS, KIT, INFN-Milano, Politechnika Wroclawska, SOTON, STFC-DL/RAL, Tampere University of Technology and Université de Genève

Collaborators

The HFM work-package was (and still is !) possible due to a large collaboration:

Task 1: F. Kircher, G. de Rijk

Task 2: H. Allain, B. Baudouy, P. Bielowka, P. Bogdan, S. Canfer, M. Chorowski, R. Flukiger, M. Grymajdo, F. Kircher, K. Kosinski, M. Matusiak, A. Milanese, S. Pietrowicz, J. Piglowski, J. Polinski, P. Pyrka, F. Rondeaux, E. Roszak, Strychalski, E. Todesco, R. van Weelderen, S. Wronka

Task 3: H. Bajas, M. Bajko, B. Baudouy, V. Benda, C. Berriaud, L. Bottura, S. Canfer, S. Caspi, S. Clément, M. Devaux, M. Durante, G. Ellwood, P. Fazilleau, P. Ferracin, P. Fessia, J. Feuvrier, M. Guinchard, J-E Muñoz Garcia, R. Gauthier, F. Kircher, C. Kokkinos, P. Manil, A. Milanese, J-F. Millot, L. Oberli, J-C Perez, S. Pietrowicz, J-M Rifflet, G. de Rijk, F. Rondeaux, B. Sailer, E. Todesco, A. Vande Craen

Task 4: X. Chaud, M. Devaux, F. Debray, M. Durante, J. Fleiter, P. Fazilleau, R. Flukiger, R. Heller, F. Hornung, T. Lécrevisse, E. Mossang C. Pes, J-M. Rey, J-M Rifflet, C. Senatore, M. Sorbi, A. Stenvall, P. Tixador, C. Trophime, B. Vincent, G. Volpini, G. Willering

Task 5: : A. Aubele, A. Ballarino, C. Beduz, B. Bordini, V. Cubeda, J. Fleiter, A. Gharib, G. Grasso, A. Hallbauer, G. Hurte, M. Sitko, M. Tropeano, Y. Yang,

Task 6: V. Bayliss, T. Bradshaw, G. Burton, A. Brummit, S. Canfer, J. Clarke, G. Ellwood, F. Hornung, B. Shepherd, O. Taylor, G. Volpini

ESAC: G. Ambrosio (Fermilab), S. Caspi (LBNL), P. Fabbricatore (INFN Genova),

A. Ghosh (BNL), Y. Iwasa (MIT), T. Nakamoto (KEK), L. Rossi (CERN)

Task 1: Coordination and communication

Over the 4 years of EuCARD:

- Organisation of:
  - 11 collaboration meetings
  - 4 reviews by the ESAC (External Scientific Review Committee)
  - Assisted some tasks to get started
  - Reviewing of the deliverables after 2 and 3 years
  - Budget follow-up and adjustments
- Reporting:
  - Status report presentation in EuCARD SCs and annual meetings (~3/yr)
  - Produce 18 months reports (with the task leaders)
  - Push for and finalise the delivery reports
- From 2011 onwards:
  - Closer following of the tasks:
    - visit to main labs of the tasks
    - monthly management (phone) meetings followed by 'lobbying'

Very good collaboration between CERN and CEA; merci François !

Task 2: Support studies (1)

Macej Chorowski & Jarek Polinski (PWR) PWR, CEA, CERN

7.2.1 Radiation studies for insulation and impregnation (PWR with CEA and CERN)

Aim: Certify radiation resistance of coil insulation and impregnation

Situation in 2009:

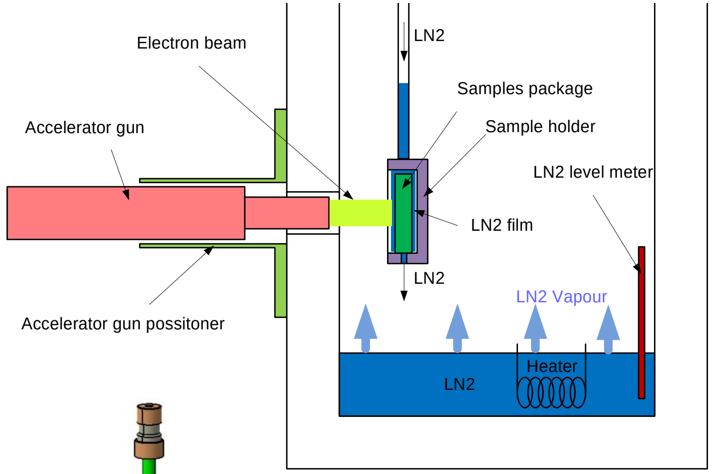
- Most work (outside ITER) on insulator rad resistance >15 years ago
- Scattered literature
- High dose expectations for HL-LHC low beta zones (≥50 MGy)

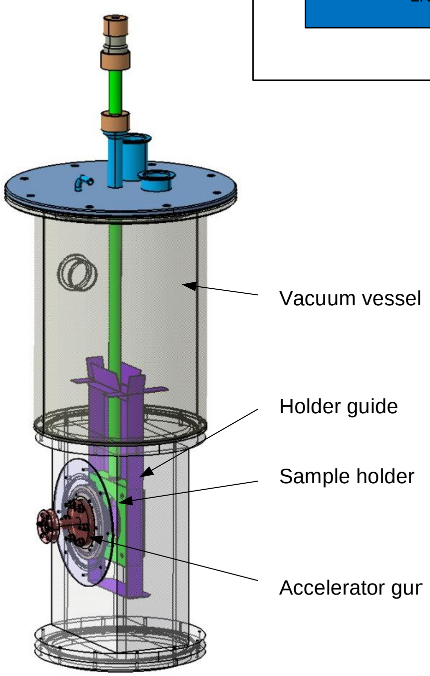
Work done in the 4 years:

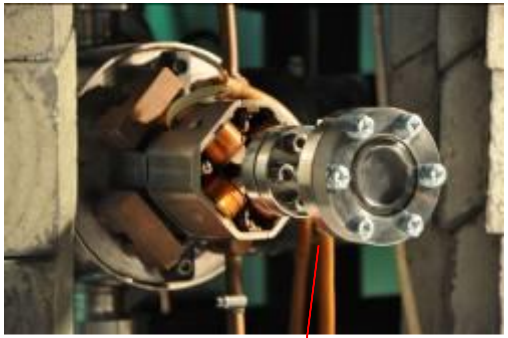
- Literature study
- Identification of HL-LHC radiation dose situation
- Inventory of insulator candidates for HL-LHC Nb_3Sn coils
- Selection of irradiation test beam and conditions
- Design and construction of irradiation cryostat
- Design and construction of material property measurement equipment (mechanical cold test, electrical insulation cold test, thermal conductivity cold test)
- Irradiations at Swierk (Pl) and material test (PWR & CEA)

Irradiation set-up

designed and commissioned at PWR and transferred to NCBJ, Swierk

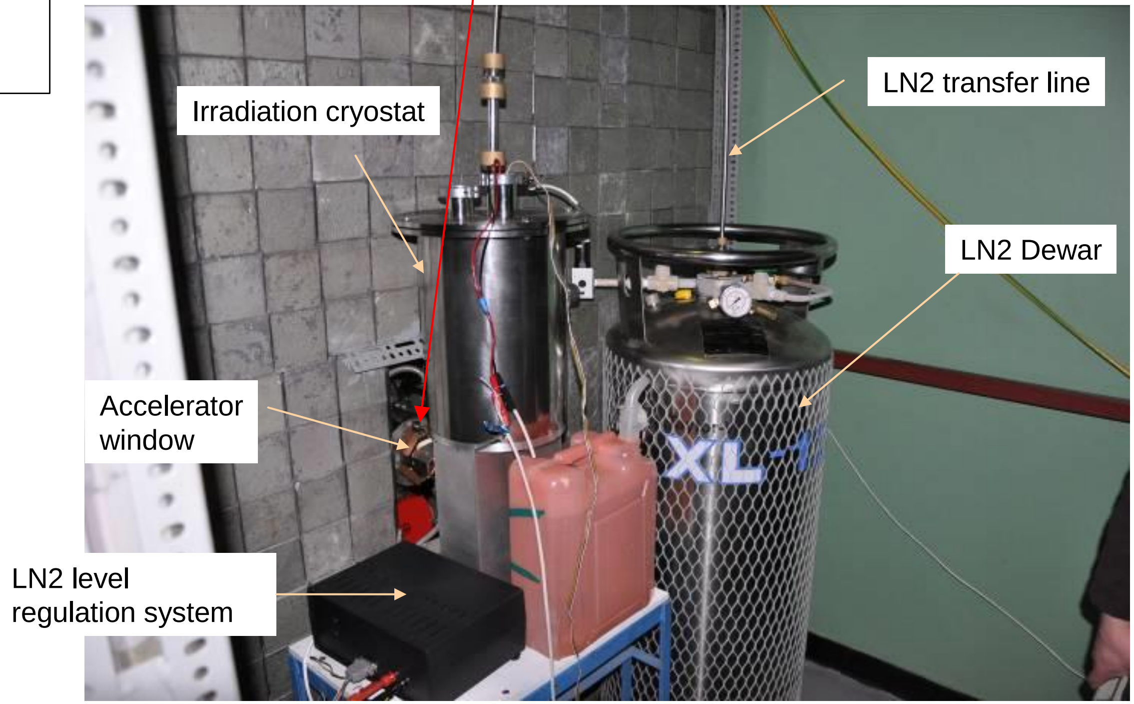






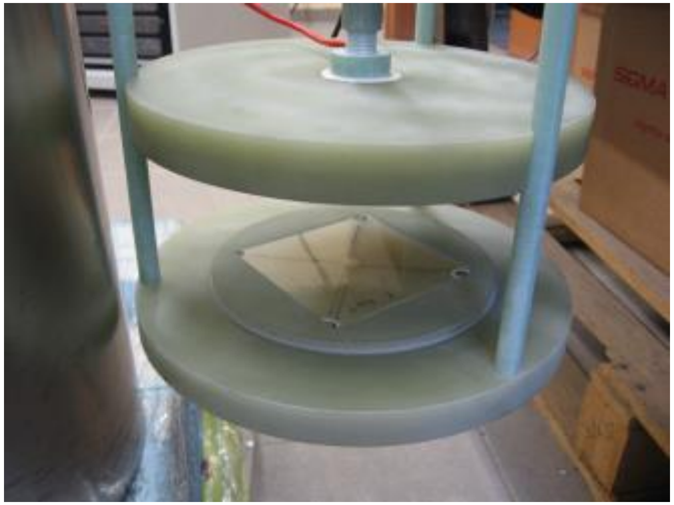
Accelerator 0.2 mm thick Ti window

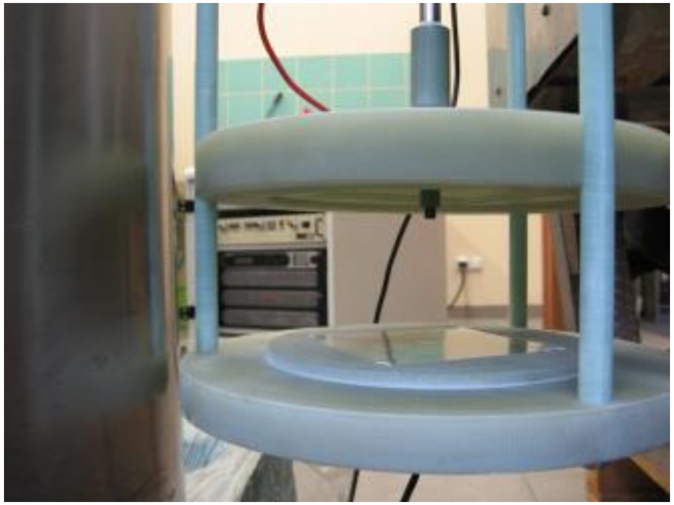
Irradiation set-up



Electrical certification test cryostat at PWR

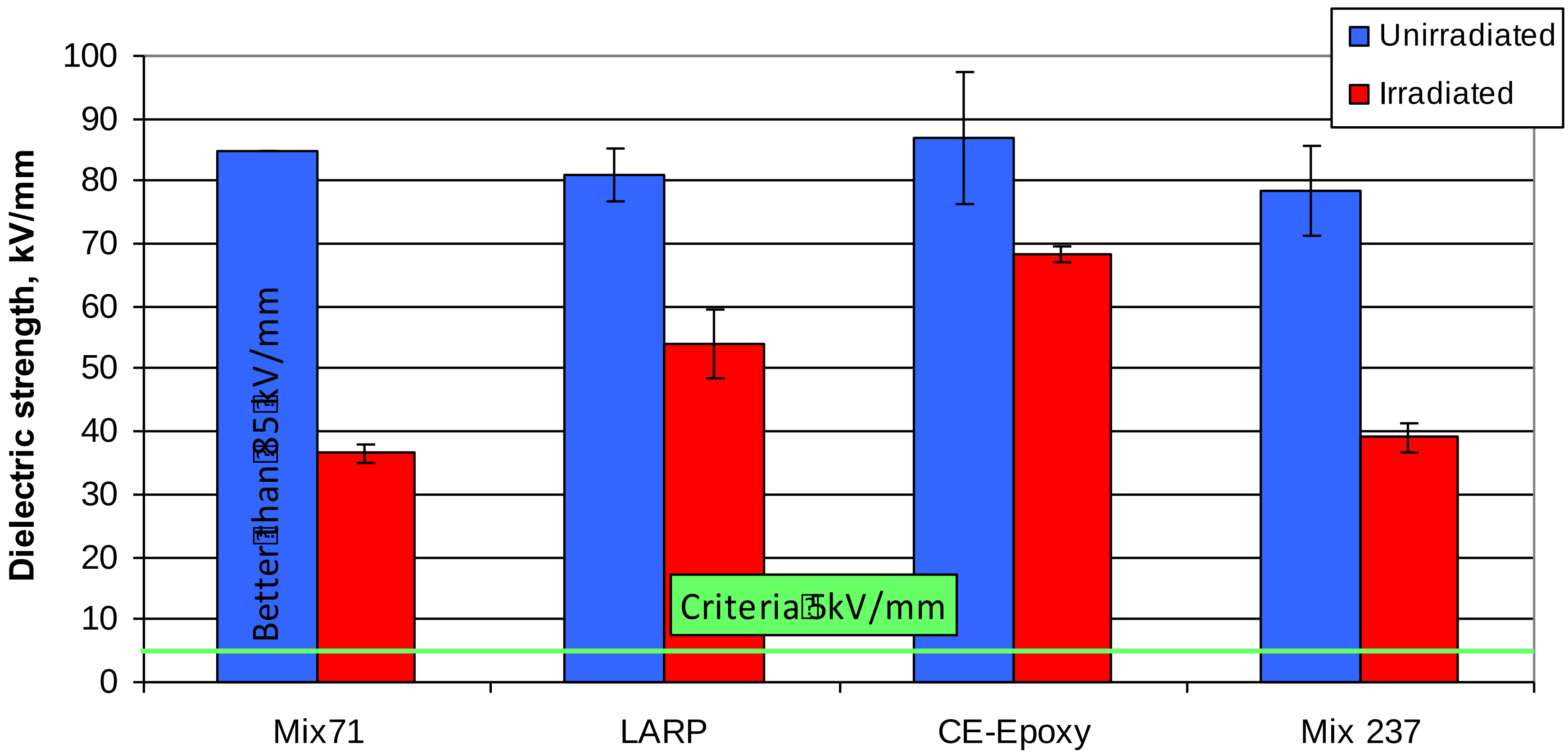
Electrical breakdown test in LN2 at 77K: equipment built at PWR.





Radiation certification electrical tests summary

4 material types irradiated with 6 MeV e- beam 50 MGy dose



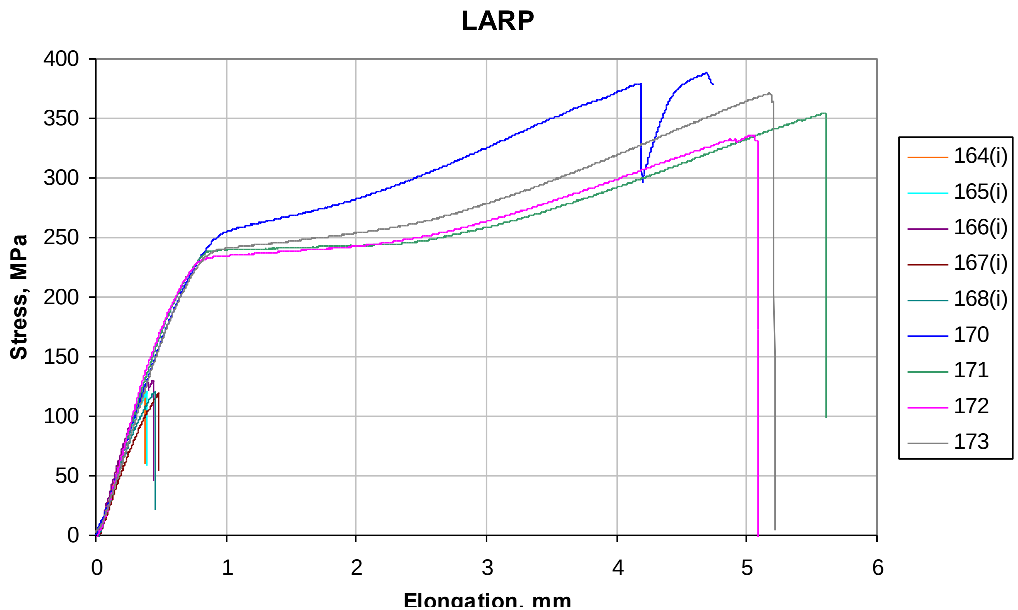
Radiation certification mechanical tests

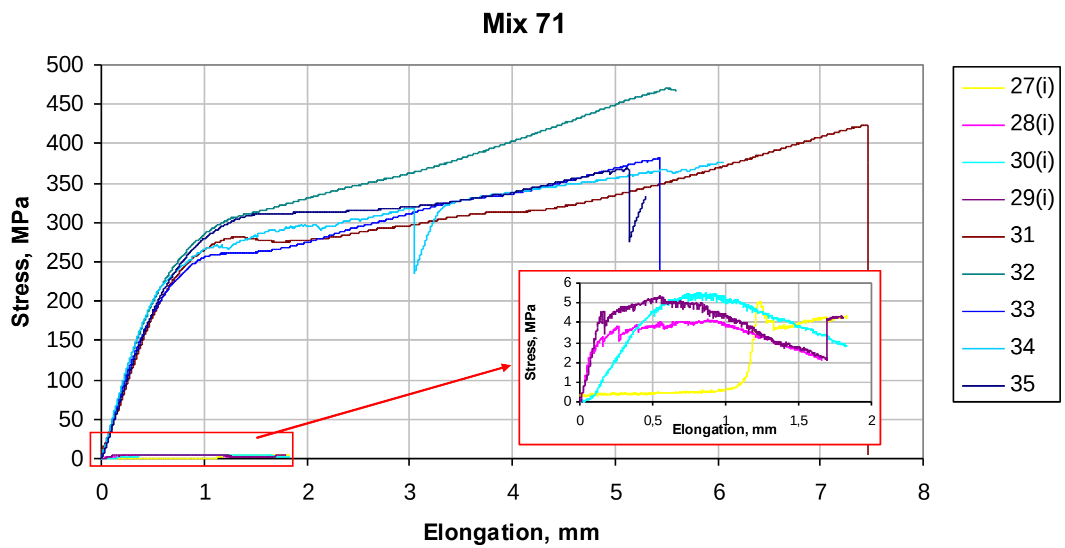
2 materials (Mix71 and LARP) irradiated (50 MGy)

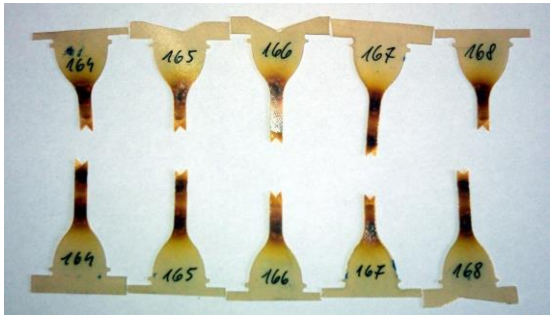
2 materials (Mix237 and CE-epoxy mix) following by autumn 2013

@50MGy LARP mix reduces 50 %

but Mix 71 is unusable







Task 2: Support studies (6)

2) 7.2.2 Thermal studies (CEA with PWR and CERN)

Aim: Make a heat deposition and heat removal model for the dipole Nb_3Sn model with experimental validation and determine the thermal coil design parameters for the dipole model magnet.

Work done:

- Complete the thermal conductivity measurements from CARE/NED for input to the models at CEA (existing NED cryostat) and PWR (new cryostat)
- 2D FE simplified heat transfer model of Fresca2 for cool-down scenarios studies and heat load studies as support to the task3 magnet design
- FE model with He 2-fluid model

Task 2: Support studies (7)

Results for the thermal task:

- Models (2D & 3D) for Fresca2 with He I and II for cool-down and static heat load.
- Heat transfer measurements for the various epoxies for coils
- New He 2-fluid 3D model in FE

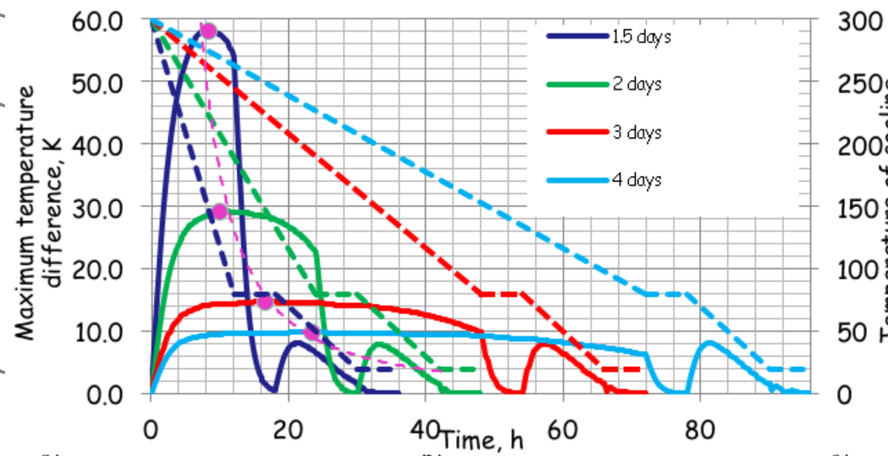
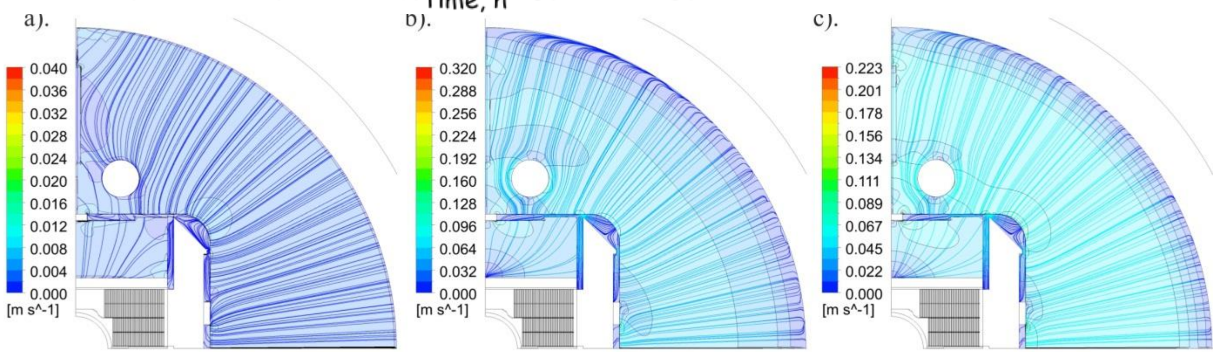


Table 5.2.a - VALUES OF MAXIMUM TEMPERATURE RISE AT 1.9 AND 4.2 K FOR ALL VARIANTS OF SIMULATIONS

		Unit	Maximum tempearture rise				Margin of temperature (K) (at B = 13.5 T and I = 10.5 kA)
			AC losses model	Homogenous model			
Heat load	Total	W	0.50	1	5	10	
	By length of conductor	W/m	0.11	0.53	2.64	5.29	
	By volume of conductor	W/m^3	4.34	21.78	108.88	217.75	
Bath temperature	@ 1.9	K	0.23	1.05	2.91	3.95	**5.84**
	@ 4.2	K	0.07	0.35	1.34	2.20	**3.54**



Streamlines and velocity fields for total, superfluid and normal components

Task 3: High field model (1)

Jean-Michel Rifflet (CEA) CEA, CERN, PWR

Aim: design, build and test a 1.5 m long, 100 mm aperture dipole with a design field of 13 T, using Nb_3Sn high current Rutherford cables.

To prepare the technology Short Model Coils are being build with 14, 18 and 40 strand cable at CERN

The lifecycle of the project was accompanied by 4 working groups:

- cable design WG: cable and strand specification made
- Specification WG: magnet functional specification made
- Magnet pre-design WG: layout selection and conceptual design
- Magnet design WG: detailed design of magnet and tooling

The construction is progressing accompanied by the MDWG.

Magnet ready with 2 coil packs: summer 2014, with 4 coil packs: Q1 2015

In parallel CERN designed a new test station which is now under construction: it will be operation in September 2014

Task 3: conductor development

2 conductor types developed for this project: EU PIT, US RRP

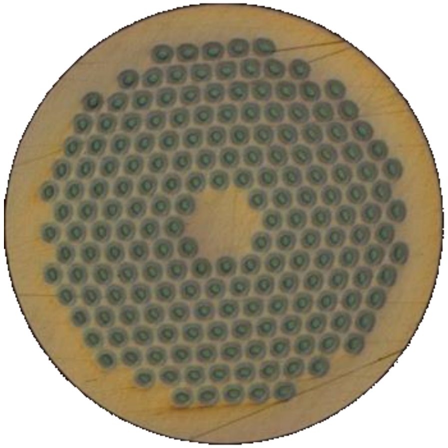
PIT : development based on 1.25 mmNED strand

RRP: based on LARP strands

- Strand diameter: 1 mm
- Cu/Sc: 1.3 → 56% Cu
- Strand #: 40
- Bare width after cabling: **20.90** mm
- Bare thickness after cabling: **1.82** mm
- Braided insulation: 0.2 mm
- Assumed growth during HT
  - 4% in thickness and 2% in width
- Bare width after HT: **21.32** mm
- Bare thickness after HT: **1.89** mm

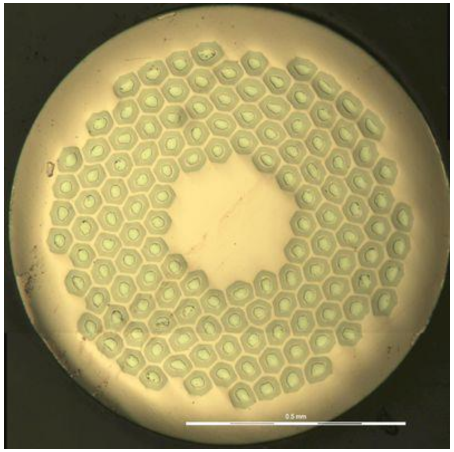
Cable amount for 1 coil set (5) delivered, for a second set on order

PIT strand

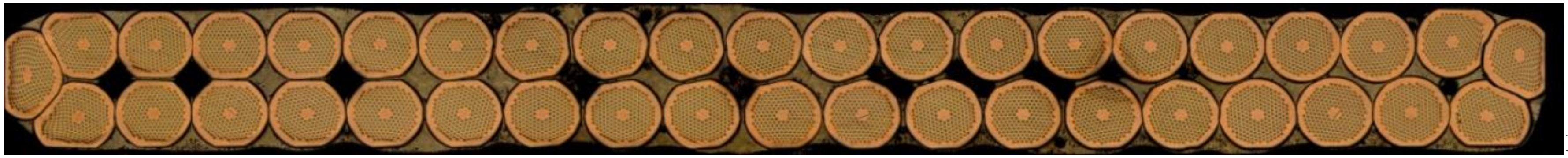


PIT (192)

RRP strand



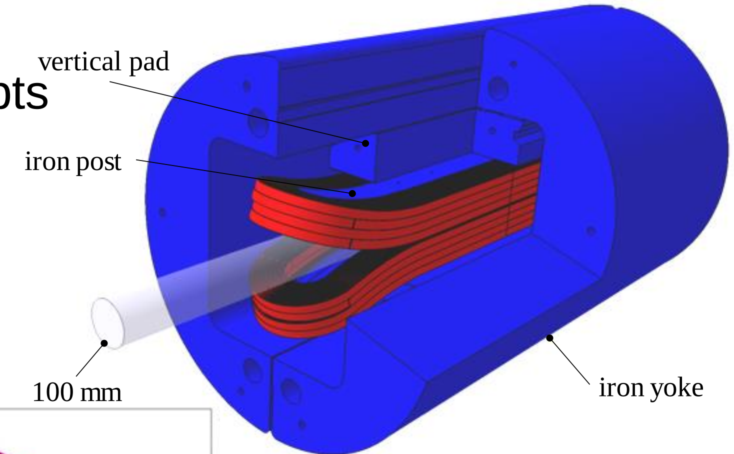
RRP(132/169)

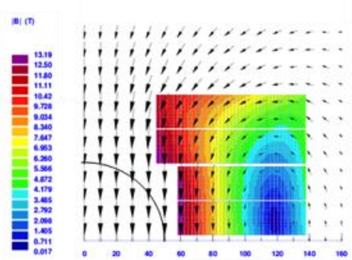


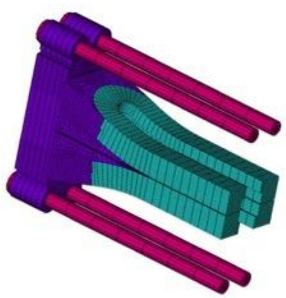
Task 3: magnet design

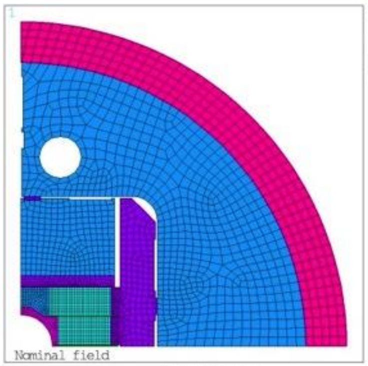
Done in 3 steps:

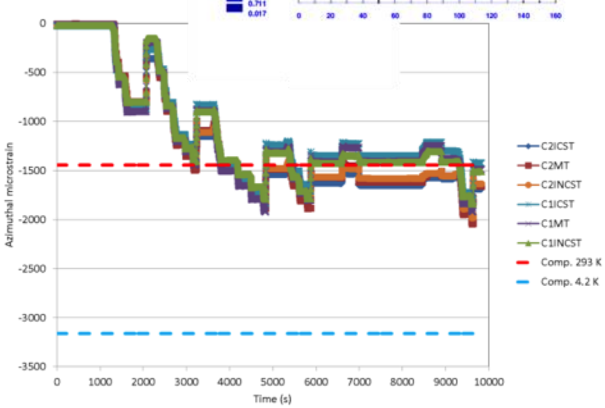
- Studies to choose the coil and structure concepts (very contested) ended June 2010
- Conceptual design of the block coil with flared ends in a shell, bladder and keys structure , ended January 2011)
- Detailed design , completed mid 2012



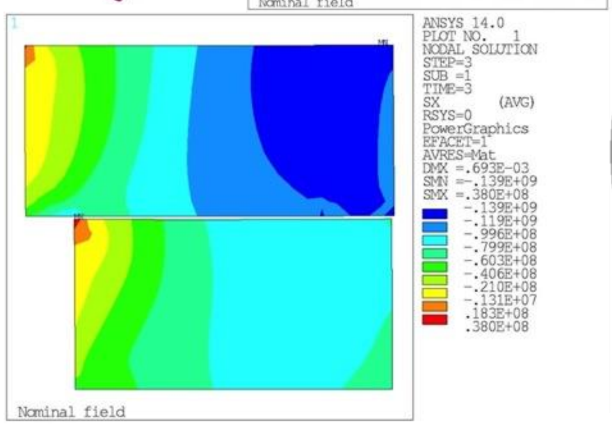


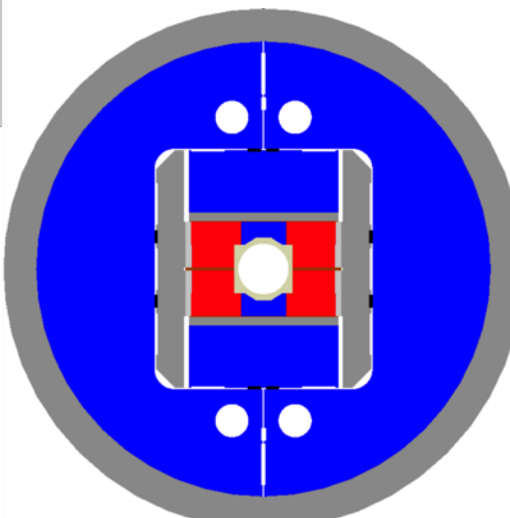






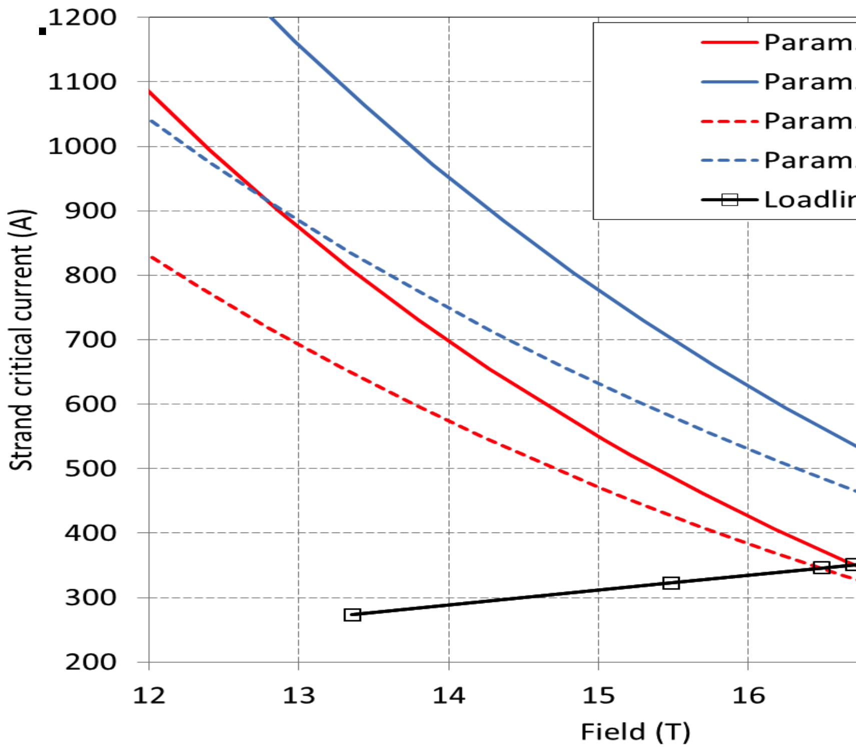
Dummy coil azimuthal strain vs. time
Straight section



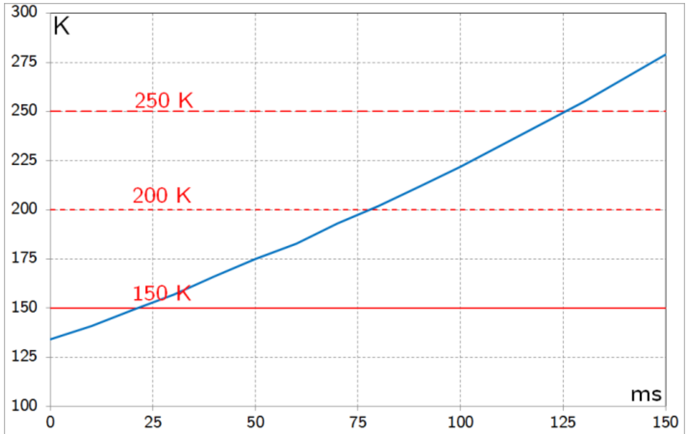


Task 3: magnet parameters

- OD: 1.030 m; length: 2.255 m
- Al shell, 65 mm thick, 1.6 m long
- Bladder and key pre-load
- Operational condition (13 T)
  - I_{op}: 10.9 kA
  - B_{peak_op}: 13.4 T, ~79% of I_{ss} at 4.2 K
  - B_{bore_ss}: 16.0 T, ~72% of I_{ss} at 1.9 K
  - B_{bore_ss}: 17.2 T;
- 15 T bore field ("ultimate")
  - 86% of 1.9 K I_{ss}



Critical surface and loadline

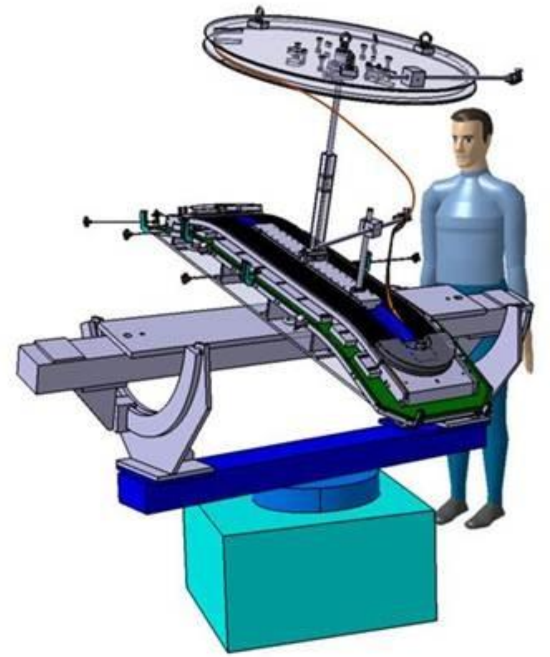


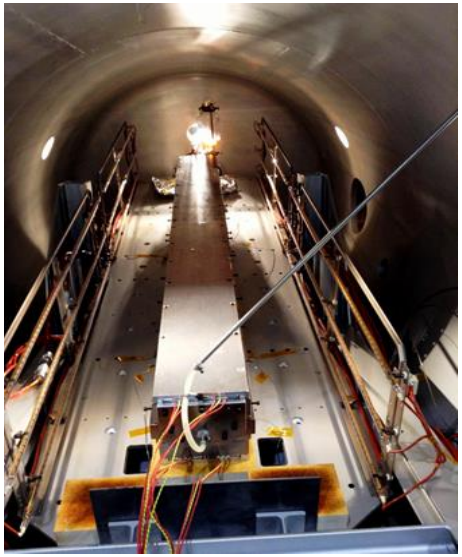
Quench hot spot temperature

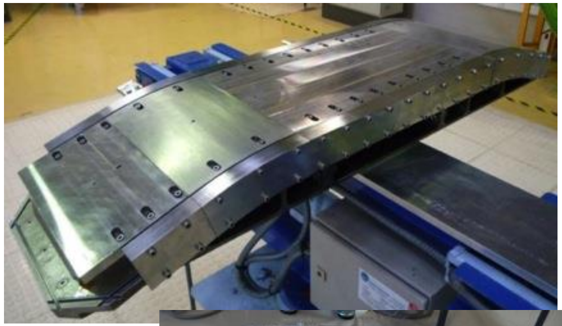
Task 3: coil manufacturing tooling

All tooling for coil manufacturing is designed Type 3-4 done, Type 1-2 on order

- Winding table : operational
- Reaction moulds: meanwhile we want a modification: will be implemented after the Cu coil: (split mould)
- Impregnation moulds : final version
- Reaction oven: operational
- Impregnation tank: operational



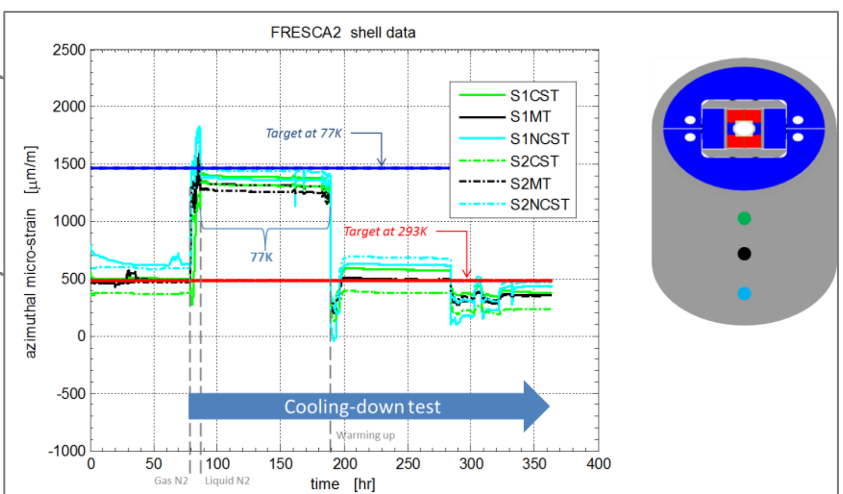




Task 3: magnet structure

Shell, Bladder and key structure

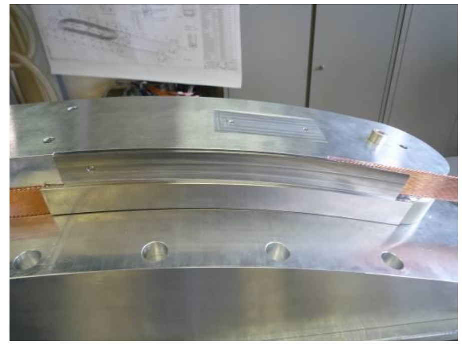
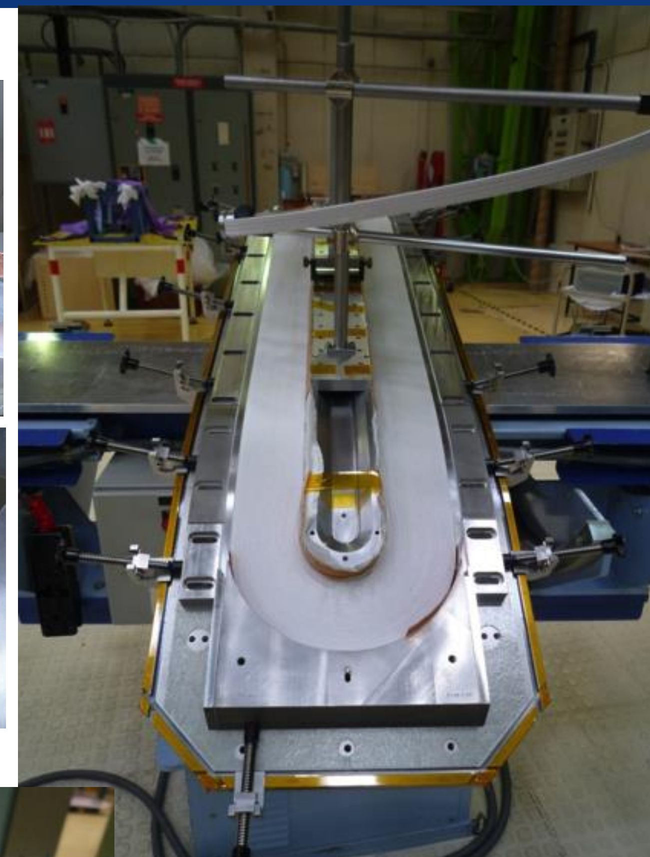
- Structure completed
- First test with Al coil dummy at 77K done



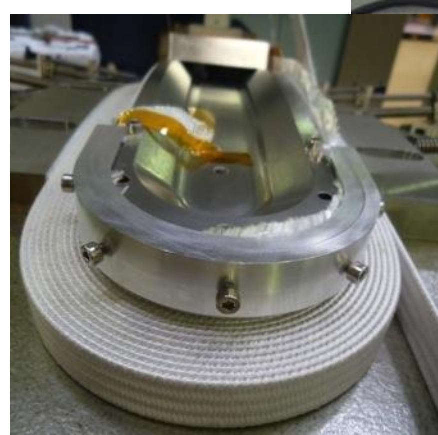
Task 3: coil manufacturing

Coil manufacturing development during the project:

- Winding flared end coils
- Layer jump winding test
- Cable dilatation tests
- Insulation braiding
- Moulded inter coil shims
- First Cu coil: 1 layer done
  2nd next week






Task 3: 13 T Fresca2 dipole: conclusions

The dipole manufacturing is well underway:

- Sufficient conductor in-house , more on order
- Winding, reaction and impregnation tooling in-house for coil type 3-4 (one modification still needed)
- Winding, reaction and impregnation tooling designed and partly ordered for coil type 1-2 (one modification still needed)
- Coil manufacturing infrastructure operational (winding bench, furnace, impregnation tank)
- Structure finished and mechanically tested at low temperature
- 1.9K tests station mostly designed, cryostat on order, outer vacuum tank exists

We need this magnet for : Cable tests for HL-LHC and HE-LHC, EuCARD1 insert test, EuCARD2 magnet test as insert, HE-LHC insert development:

full commitment of CERN and CEA to finish it and use it !

Task 4: Very high field dipole insert (1)

Pascal Tixador (CNRS Grenoble-INPG)

CNRS, CEA, KIT, INFN, TUT, UNIGE,PWR

- Objective:
  Design and realization of a high temperature superconductor (HTS) very high field dipole insert (6-7 T), which can be installed inside the 13 T Nb_3Sn dipole of task 3

NB: test of the two dipoles together is not part of the present EuCARD contract but will be done nevertheless...

Sub tasks:

7.4.1 Specification, characterization and quench modelling

7.4.2 Design, construction and test of solenoid insert coils

7.4.3 Design, construction and test of dipole insert coils

Task 4: Insert conductor

After 1 year new developments on I_{eng} YBCO

Thus conductor choice was adapted as the I_{eng} advantage of Bi-2212 was gone (I_{eng}>200A/mm^2 are needed)

- Bi-2212: fragile, precise coil heat treatment (850°) can be cabled into a Rutherford cable
- YBCO: tape, difficult cable concepts mechanically strong

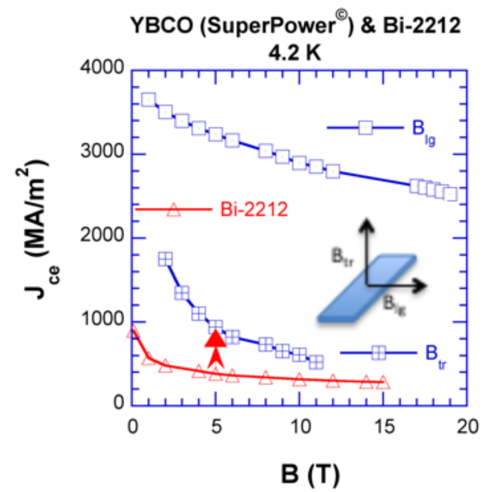
High current cable:

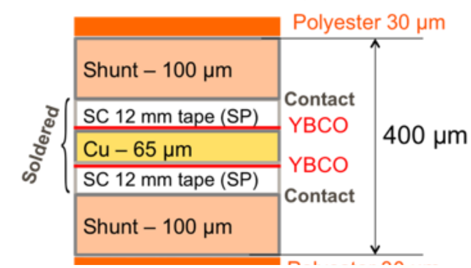
2 core conductors wound together “2800 A cable”

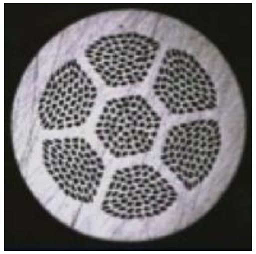
Core conductor: 2 tapes: soldered face-to-face on a Cu strip

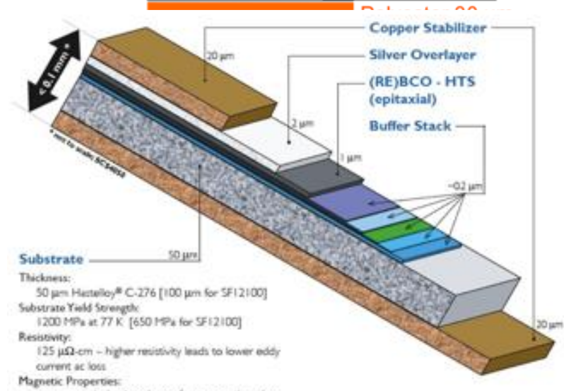
Two CuBe shunts added for extra mechanical strength

Conductor is on order delivery june 2013









YBCO, Superpower

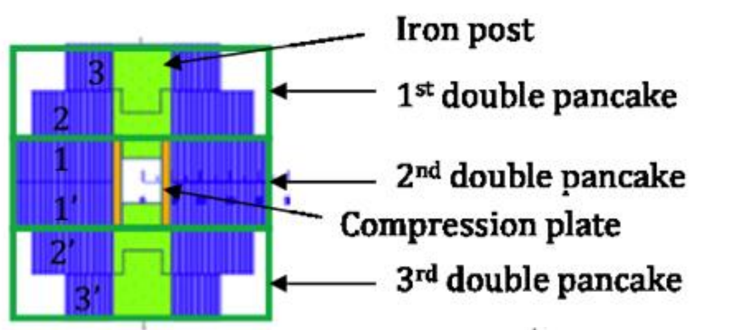
Task 4: magnet design

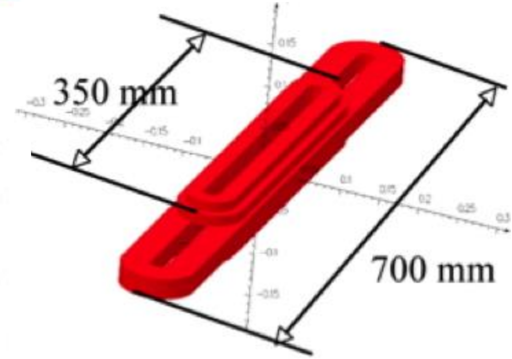
Completely new innovative design

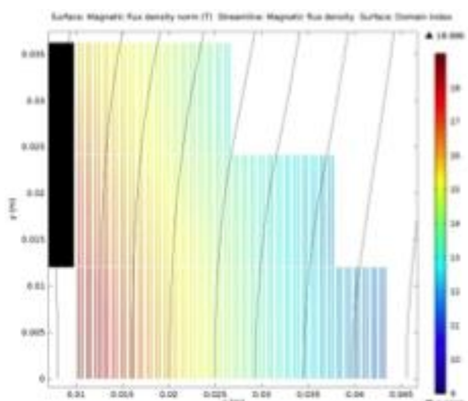
Coil: 3 double pancakes with 2x2 tape cables, transposed per pole

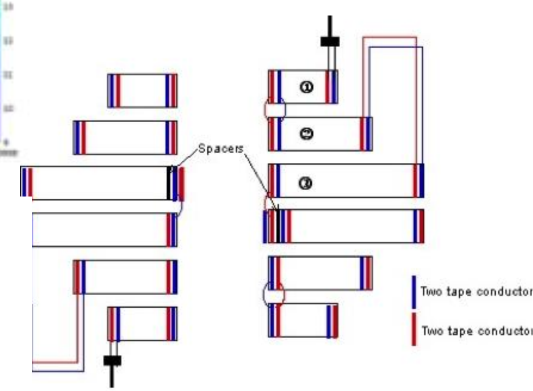
Insert has to be self supporting,

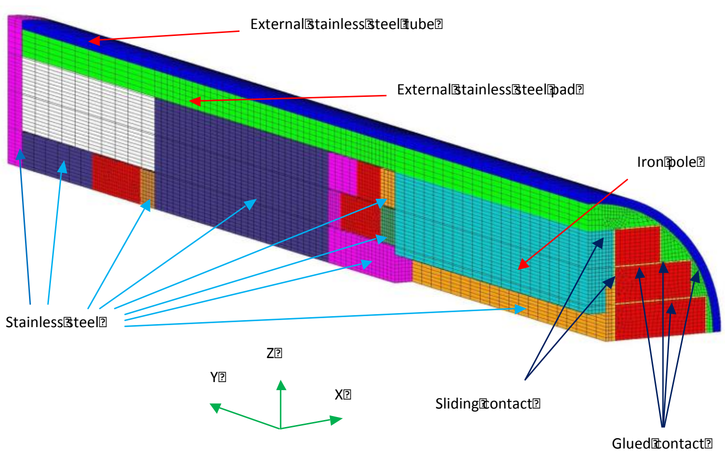
Structure: e- beam welded steel pad steel shrinking cylinder

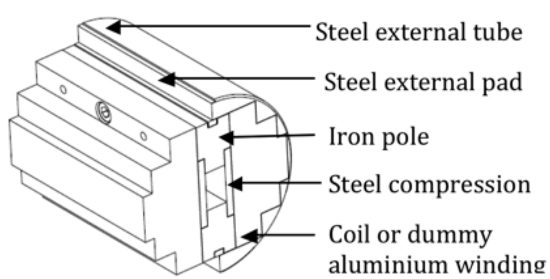










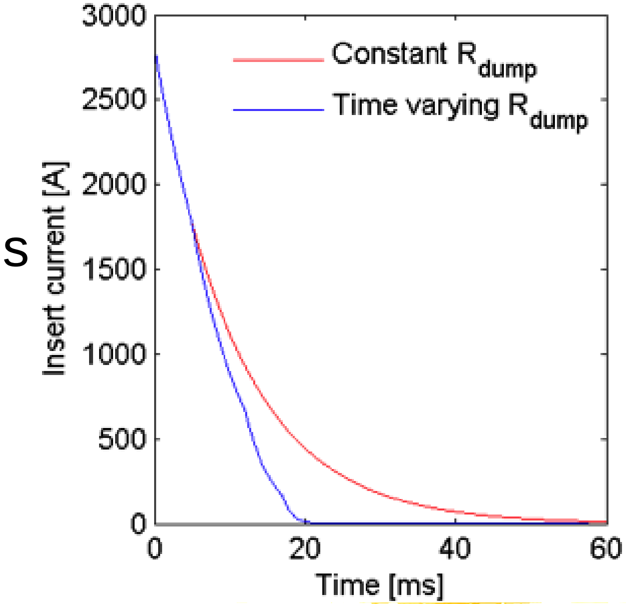


Task 4: quench studies

The quench of HTS coils is problematic due to slow quench propagation speeds and thus slow voltage development and thus high temperature spots with high mechanical stress

Studies done:

- quench propagation modelling
- Quench tests with small solenoid coils



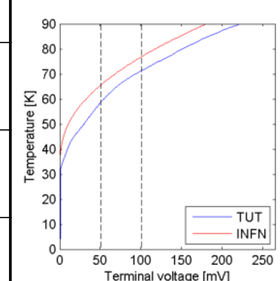
A solution was found to protect the insert , standalone and with the outsert

t_{decay} can be as low as 50 ms or even 20 ms with V≤800 V (low inductance)

$T_{hot\text{-}spot}$ ≈70 K with $V_{threshold}$=100 mV (CuBe shunt)

The fast insert discharge (<50 ms) with the long Fresca2 time margin (~50 ms) makes the combination workable

Scenario	T_{hot} (K) *100 mV*	Remark
Insert quench **No** Fresca disch.	77 K	$V_{fresca\ p.s.}$ = - 19 V **ΔI_{fresca} = + 255 A**
Insert quench Fresca discharge	77 K	ΔI_{fresca} = + 67 A
Quench Fresca No insert discharge	85 K	**$V_{insert\ p.s.}$ = - 78 V** **ΔI_{insert} = + 260 A**
Quench Fresca Insert discharge	< 70 K	ΔI_{fresca} = + 67 A



Shunt:
50% Cu, 50% CuBe

Task 4: test coils

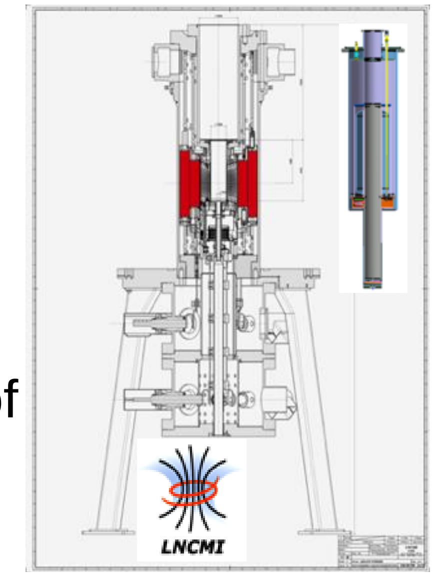
2 types were done or are being done

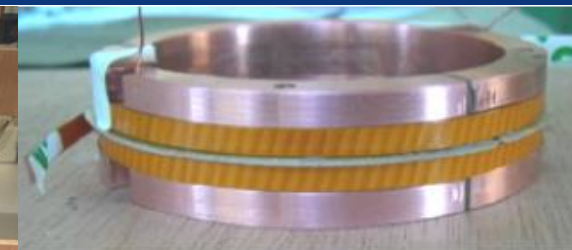
Solenoid test coils for quench tests and mechanical resistance tests:

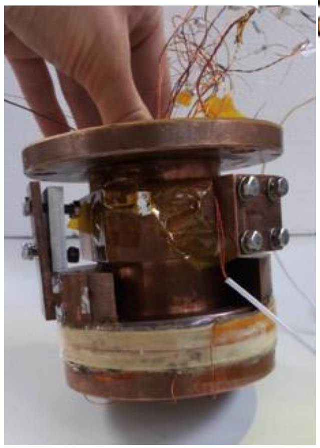
Tested at High field facilities of KIT and Grenoble

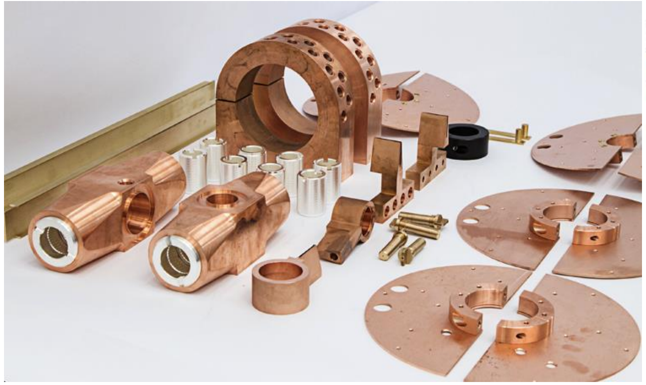
Single pancake test at Grenoble in a 10T magnet to test the pancake coil type and to measure the field angle dependence of I_{eng}

Background field









Task 4: conclusions

The insert manufacturing is well underway:

- Conductor is on-order: delivery this month
- Coil manufacturing is prepared, a test coil will be wound this month
- Test of the test-coil in July/August in Grenoble
- Structure designed and critical assembly steps were tested
- Insert should be ready by end of 2013
- Stand alone test
- Test inside Fresca2 in 2015

We need this insert for : EuCARD2 experience (despite the different cable) and HE-LHC magnet development:

full commitment of CNRS and CEA to finish the insert and test it

Task 5: High Tc superconducting link (1)

Amalia Ballarino (CERN) CERN, COLUMBUS, BHTS, SOTON

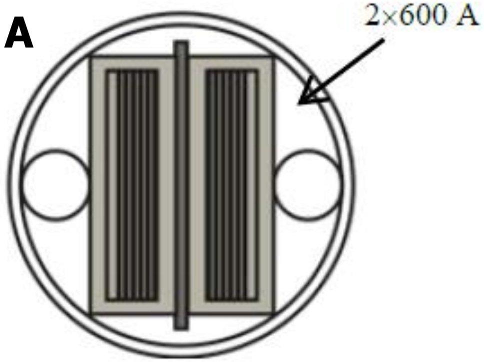
Aim: design and build a prototype 600A HTC link

Main achievements:

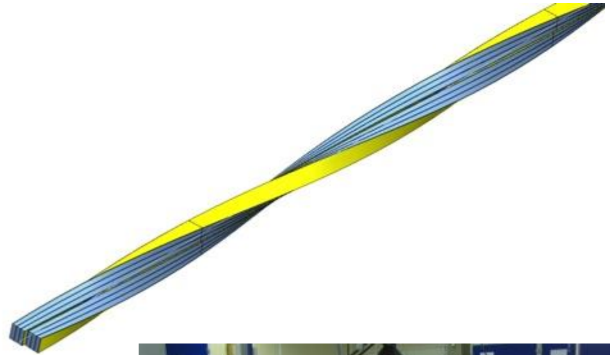
- Development of a novel type, twisted-pair, cable with tape conductor and optimized for DC currents. Iop ~1 kA Conductors: MgB_2, YBCO and BSCCO 2223. Cable geometry and cabling process accommodate for the three types of conductors
- Validation of 2 m long cables at 4.2 K (Fresca). Iop up 2×4.2 kA @ 4.2 K and in self-field
- Preparation of short (up-to 5m) multi-cable assembly (2×24 cables) as required for integration in the SC-Link for LHC P7
- Quench tests performed on a full-scale 5 m long SC-Link at SOTON
- Cabling of stacked, insulated and twisted conductor being at CERN, using the newly developed cabling machines
- Deliverable – 20 m long superconducting link assembly with MgB_2 tape conductor (Columbus) fulfilled

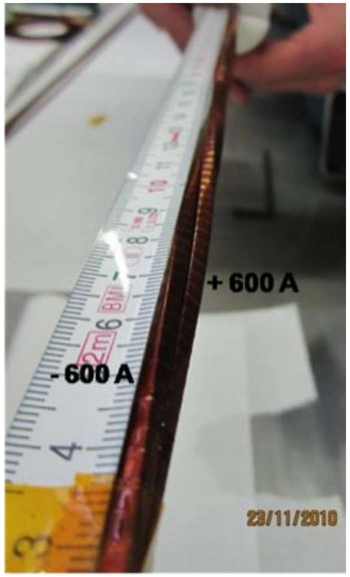
Twisted-pair cable (I_{op} □ 1000 A)

+ 600 A **- 600 A**

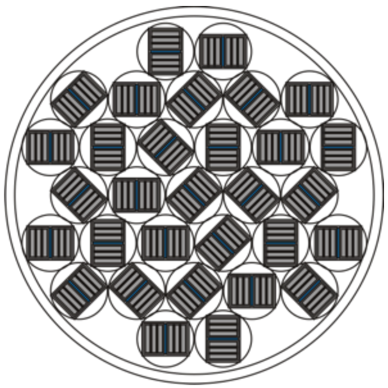


Φ~5.6 mm

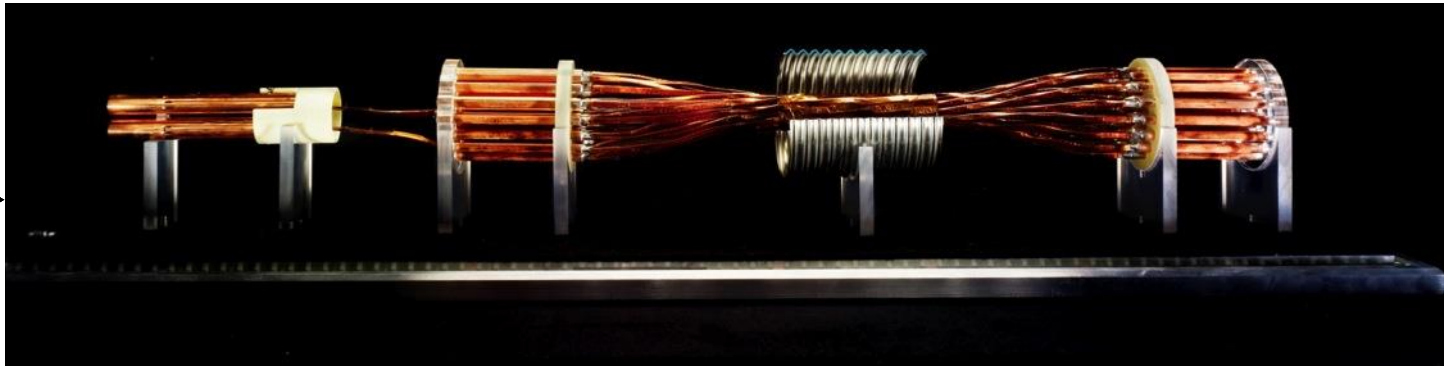




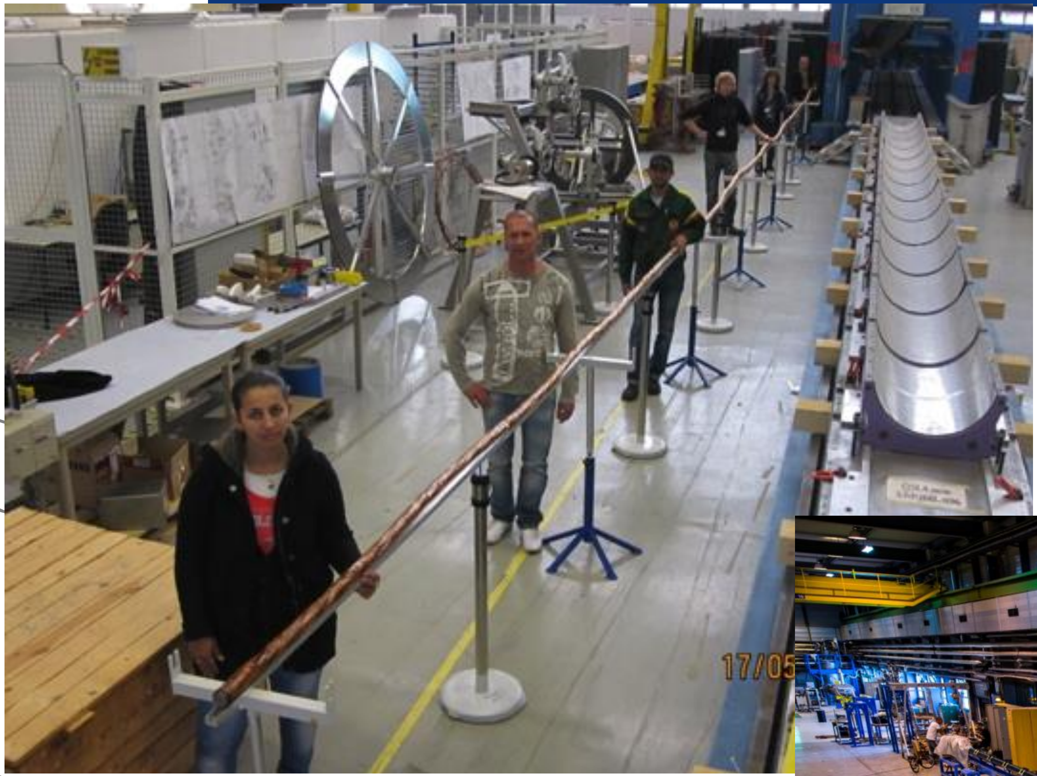
30 kA
~2 kg/m
~ 150 m_{HTS}/m_{cable}



Φ = 40



Task 5: High Tc superconducting link (3)



The 20m prototype link finished

SM18 link test station with NEXANS cryostat connected

Post Eucard-era and conclusions

Post EuCARD

- Test at CERN of the Eucard deliverable (20 m long link)
- Parallel development in collaboration with Columbus Superconductors of MgB_2 round wires for application to high-current cables (up to 20 kA)
- Design assembly and test of 60 m a long SC-link system as required for integration in the LHC machine at Point 7
- Development and test of high-current cables, multi-cable assemblies (Itot > 150 kA) and SC-links for application at LHC P1 and P5 (vertical transfer along ~ 80 m)
- SC-Links transferring the current from the surface to the LHC tunnel for the LHC Hi-Luminosity upgrade

Conclusions:

Very successful task, results will directly be applied to the LHC,

Important links with Industry and power transmission projects

Task 6: Short period helical undulator (1)

Short period undulator for the ILC positron source

Jim Clarke (STFC-DL) STFC (DL and RAL)

Period 11.5 mm , field >1 T

Aim :

- fabricate and test a short helical undulator prototype using Nb_3Sn wire.
- With: 11.5 mm period and winding bore of 6.35 mm, 300 mm long
- Nb_3Sn usage for high current density and large thermal margin to go higher than the 1.15 T achieved for Nb-Ti

Task 6: design

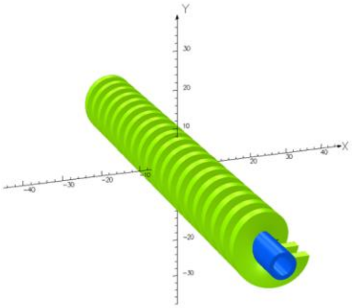
Parameters:

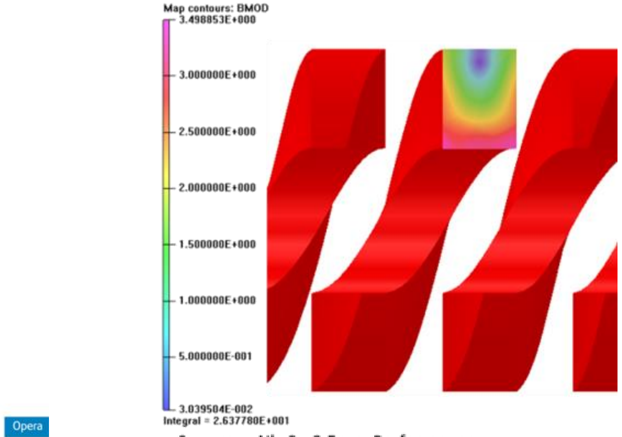
- 215A
- Beam tube ID: 4.7 mm
- Winding ID: 6.35 mm
- Field on axis: 0.86 T
- Margin with this conductor: 30%

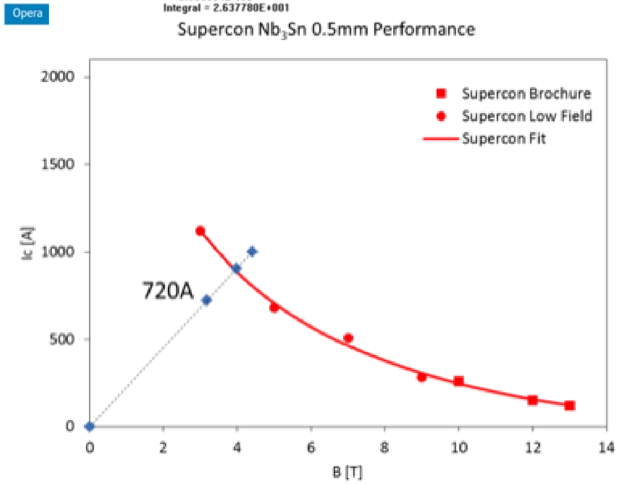
Iron former, (no separate beam-tube)

Insulation:

- Alumina coated former ,
- glass fibre braided around the strands
- Charged epoxy impregnation



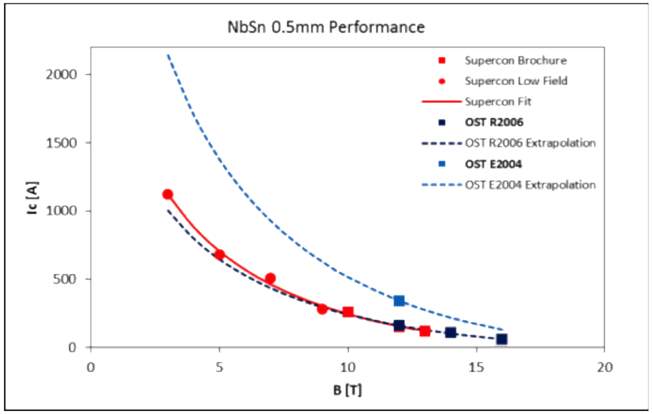




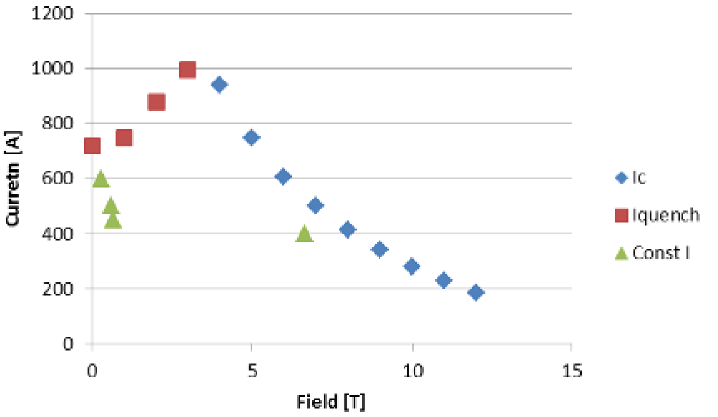
Task 6: conductor

The issue with the undulator is to find a strand with sufficient stability at low field

- Nb3Sn is industrially produced for high field applications so low field properties are poorly known
- Conductor characterization was done at KIT and CERN to find the best candidate
- Selected Supercon strand 0.5 mm diam.



Conductor measurements



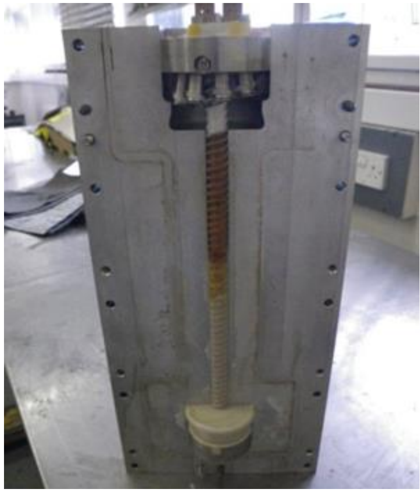
Stability measurement Supercon strand (CERN)

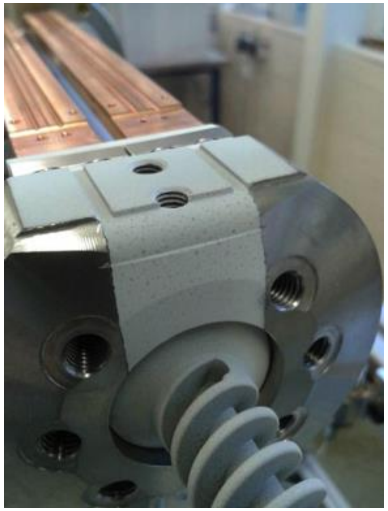
Task 6: construction

Construction was done at STFC/RAL

For all steps ,

Winding, reaction, impregnation, splicing, etc, tooling was developed in-house.

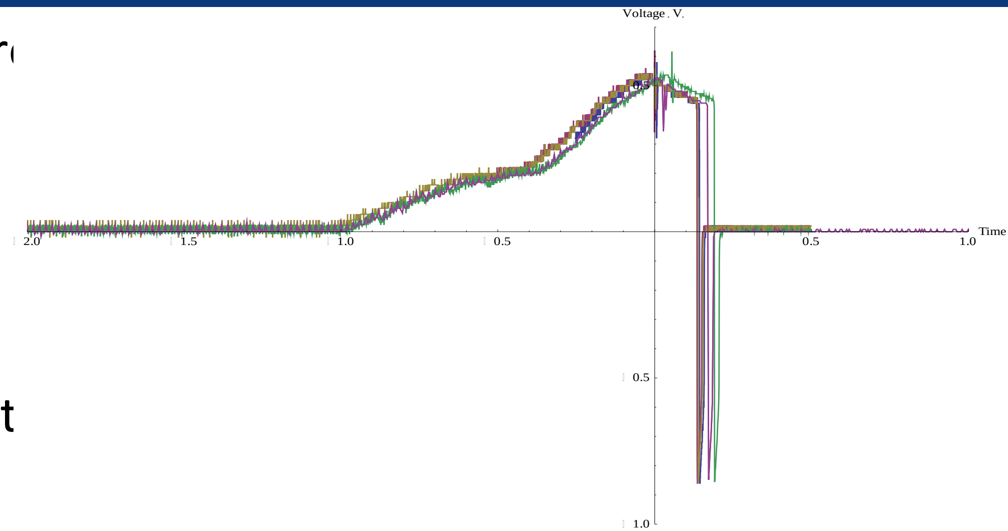


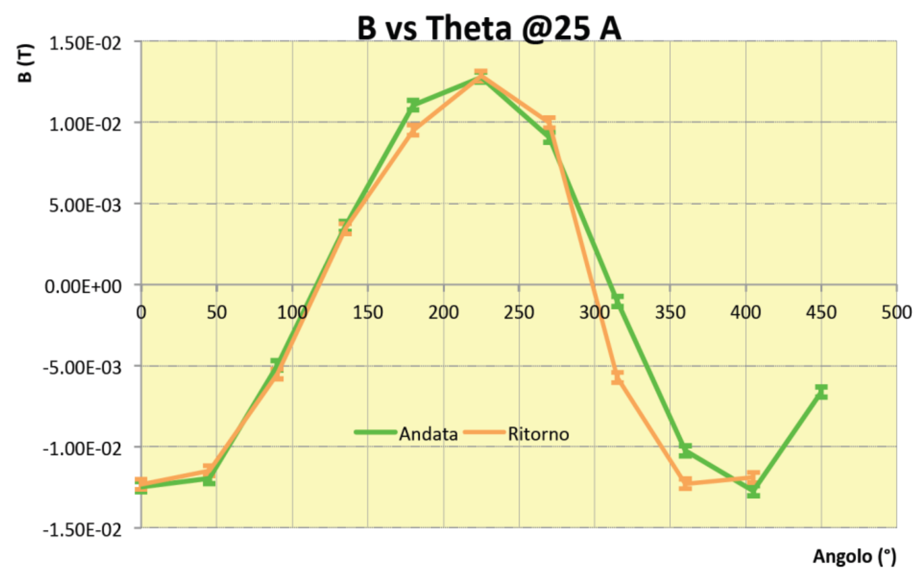


Results from undulator test (at LASA)

- Resistance at room temperatur
  Coil A - 15Ω
  Coil B - 1400 Ω – not tested
- Coil A quenched consistently at 28-30A
- Coil A 1.375µ Ω at small current
- RRR ~3
- Field measurements at 25A
- Inductance ~ 2.75mH

- Undulator B: wire found broken in ends after 'unpacking'





Task 6: conclusions

Two helical undulators were built.

Problems encountered:

- Conductor instability at low field and high current: need to find a conductor even better optimized for these conditions (industry)
- Wire breakage: new design needed for the ends
- Insulation fragility: more development needed
- Tolerances on grove dimensions and insulation thickness: need another iteration.

This task was crucial to do a step towards Nb_3Sn helical undulators and discover the issues. A continuation project should be started

Deliverable summary

Deliverables of tasks	Description/title	Nature	Delivery month
7.1.1	HFM web-site linked to the technical & administrative databases	O	30/06/13
7.2.1	Certification of the radiation resistance of coil insulation material	R	10/06/13
7.2.2	Thermal model for a dipole Nb_3Sn model magnet	R	M36
7.2.3	Superfluid helium transport model for the thermal design of the high field model magnet	R	15/05/13
7.3.1	Dipole model test with one superconducting coil; results analyzed	R	
7.3.1.a	Design report for the dipole magnet	R	07/06/13
7.3.1.b	Dipole magnet structure tested in LN2	R	10/06/13
7.3.1.c	Nb3Sn strand procured for one dipole magnet	D	22/05/13
7.3.1.d	One test double pancake copper coil made	D	31/08/13
7.4.1	A HTS dipole insert coil constructed	D	
7.4.1.a	Design report for the HTS dipole insert	R	22/05/13
7.4.1.b	One insert pancake prototype coil constructed with the setup for a high field test	D	15/07/13
7.4.1.c	All insert component ordered	D	10/06/13
7.5.1	HTS 20 m 600 A link assembled	P	03/06/13
7.6.1	Final prototype SC helical undulator measured	R	03/06/13

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Lessons we learned

- Task 1:
  Next to the regular collaboration and task meetings immediately start to follow all the tasks in some detail, we started to do this at the end of year 2
- Task 2:
  The description for the irradiation task was too vague as too little was known: we should better have limited ourselves to a study of the needs and making a plan for irradiations without actually doing them due to lack of time in 4 years. We were perhaps a bit too ambitious
- Task 3:
  The task suffered 9 months effective delay due to the LHC incident at CERN. It takes 1.5 years longer than foreseen (4). We remark that making a completely new design takes more time than one thinks.
- Task 4:
  We had to completely change the conductor choice: as a result it took a year more to do all the development steps, this includes the conductor development in the company and procurement.

Lessons we learned (2)

- Task 5:
  The ideal task, moreover, we profited from the pressure from the LHC needs
- Task 6:
  We learned (again) that we cannot simply adapt a Nb-Ti concept for Nb_3Sn, it is much more difficult. It also suffered from the turnover in personnel at STFC which is outside the influence of the project leaders but more linked to the general situation.

Conclusions

- 6 tasks
  - Task 1: completed by 30/6/13
  - Task 2: Deliverables completed
  - Task 3: 1.5 years delay, design complete, construction well underway, full commitment to finish
  - Task 4: 9 months delay, design complete, construction well underway, full commitment to finish
  - Task 5: Deliverable completed
  - Task 6: Deliverable completed
- The collaboration will continue as 'The HFM collaboration' , an MoC is in preparation
  - The HFM collaboration will accompany the completion of the magnet and the insert and take new initiatives

For HFMs EuCARD was a very successful venture, it made the required steps forward and forged a solid collaboration

All participating people can be proud of the work done !

www.cern.ch