Annual EuroCirCol Meeting 2017
Monday 9 -Tuesday 10 October 2017

WP5 Summary

Davide Tommasini

WP5 Agenda

Monday

10:30	→ 10:45	**Introduction to the review and road-map** Speaker: Davide Tommasini (CERN)
10:45	→ 11:00	**Conductor characterization** Speaker: Bernardo Bordini (CERN)
11:00	→ 11:15	**Update on ERMC/RMM** Speaker: Susana Izquierdo Bermudez (CERN)
11:15	→ 11:45	**Quench protection** Speaker: Tiina-Mari Salmi (Tampere University of Technology, Finland)
11:45	→ 12:00	**Circuit** Speaker: Marco Prioli (CERN)
12:00	→ 12:15	**Cost model** Speaker: Daniel Schoerling (CERN)
12:15	→ 12:30	**Update on CCT** Speaker: Bernhard Auchmann (CERN)
14:00	→ 14:30	**Cosinetheta electromagnetic design** Speaker: Vittorio Marinozzi (University of Milan / INFN)
14:30	→ 15:00	**Cosinetheta mechanical design** Speaker: Barbara Caiffi (INFN - National Institute for Nuclear Physics)
15:00	→ 15:30	**Block-coil electromagnetic design** Speaker: Clement Lorin (CEA)
15:30	→ 16:00	**Block-coil mechanical design** Speaker: Clement Lorin
16:00	→ 16:30	**Common-coil electromagnetic design** Speaker: Fernando Toral (Centro de Investigaciones Energéti cas Medioambientales y Tecno)
16:30	→ 17:00	**Common-coil mechanical design** Speaker: Javier Munilla Lopez (CIEMAT)
17:00	→ 18:00	**Closed Session** Convener: Stephen Gourlay (LBNL)

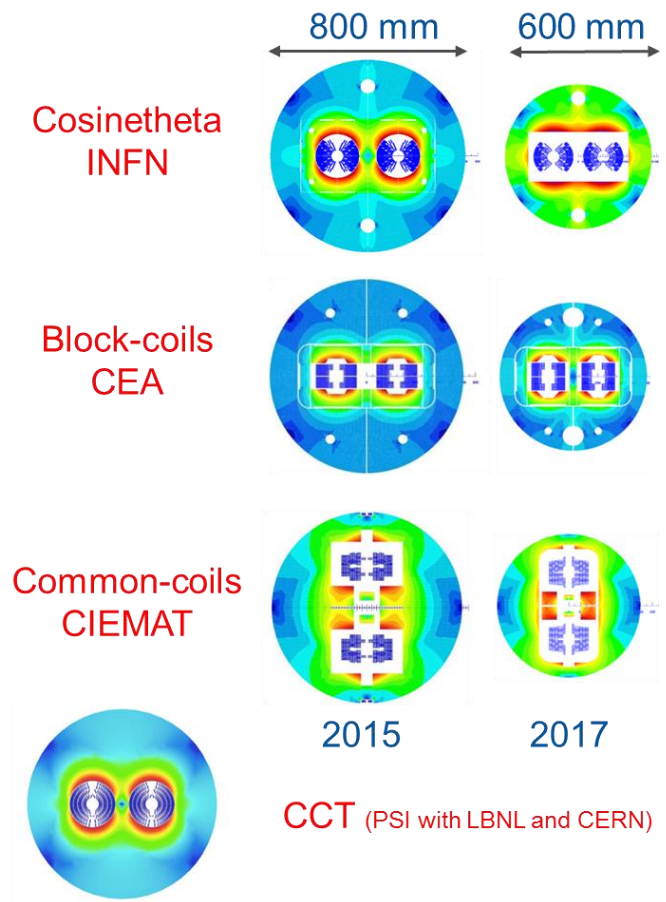
Tuesday

08:30	→ 09:30	**Tour of 927 for the reviewers** Speaker: Juan Carlos Perez (CERN)
09:30	→ 10:10	**Discussion with reviewers**
10:10	→ 10:30	**Coffee break**
10:30	→ 12:00	**Closed Session** Convener: Stephen Gourlay (LBNL)
12:00	→ 12:30	**Close-out** Speaker: Stephen Gourlay (LBNL)

Questions to the Reviewers

1) Are the baseline parameters considered in the study credible for a FCC CDR?
2) In the CDR we will describe a baseline design, with also a brief description of alternatives. The proposed baseline design is the cosinetheta: do you support this choice or would you suggest a different one?
3) Do you have any suggestions for improvements to the design options presented during the review?
4) Is there any specific additional study that you suggest to perform in view of the preparation of the FCC CDR?
5) Do you have any comments on the EuroCirCol WP5 Road-Map?

Evolution of the design options since the 1st review



The reference parameter space has been finalized considering recommendations from the 1st WP5 EuroCirCol Review (11-13 May 2016, http://indico.cern.ch/event/516049) and follow-up of the 2017 FCC Week (http://indico.cern.ch/event/556692)

The considerable decrease of the coil size comes from a reduction of the margin on the load-line from 18% to 14%, and of the cold mass size from allowing a stray field of up to 0.2 T at the cryostat surface

Magnet length	14.3 m	
Free physical aperture	50 mm	
Field amplitude	16 T	
Margin on the load-line @ 1.9K	14 %	
Total time margin	40 ms	
Critical current density @ 1.9 K, 16T	2300 A/mm^2	
Conductor fit (Jc/B)	EuroCirCol fit	
Degradation due to cabling	3%	
Minimum Cu/nonCu	0.8	also check 0.9-1.0
Maximum strand diameter	1.2 mm	also check 1.1 mm
Maximum stress on conductor at warm	150 MPa	
Maximum stress on conductor at cold	200 MPa	
Maximum hot spot temperature (@ 105% I_{nom})	350 K	
Maximum number of strands in a cable	40	check up to 60
Maximum voltage to ground (magnet contribution)	1.2 kV	set as tentative value
Maximum TOTAL voltage to ground	2.5 kV	
Conductor cost (performance based)	5 Euro/kAm	

Status of ERMC and RMM

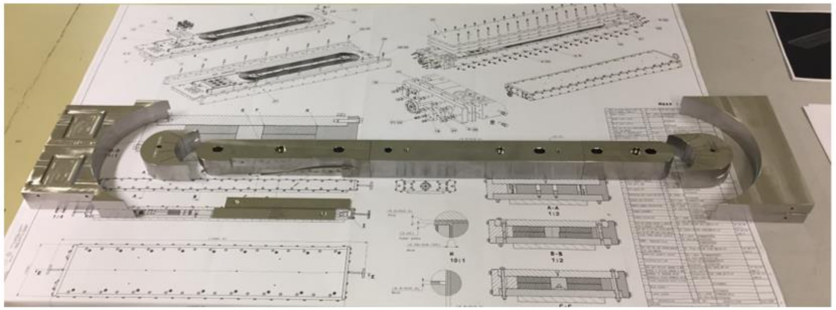
Susana Izquierdo Bermudez and Juan Carlos Perez

CERN-TE/MSC/MDT: N. Bourcey, P. Ferracin, J. Ferradas Troitino, L. Lambert, J. Massard, G. Maury, J. Mazet, R. Ortwein, J. Osieleniec, E. Rochepault, D. Tommasini
CERN-TE/MSC/SCD: A. Bonasia, J. Fleiter, B. Bordini
CERN-TE/MSC/MM: C. Petrone
CERN-TE/MSC/TF: H. Bajas
CERN-TE/MME: P. Moyret

EuroCirCol Review

Coil components

- Coil parts for 3 ERMC coils in house.



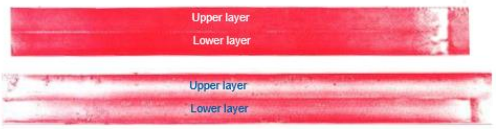
- Traces under procurement, expected to be delivered mid-November.

Cable insulation

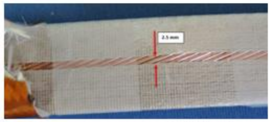
Remark: plots not on scale

- Some evidences on 11 T and SMC 11 T that the C-Shape mica can have a negative impact on the uniformity of the pressure distribution.

Contact pressure on outer coil turns, SMC11T under 50 MPa compression



- After some iterations, braiding with wider mica tapes (44 mm) feasible.
- One cable unit length insulated, ready to be wound.
- The other two cable unit lengths will be insulated end of October.



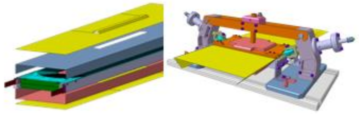
https://indico.cern.ch/event/641884/
https://indico.cern.ch/event/659541/contributions/2689641/attachments/1507432/2349396/Visite_CGP_ERMC.pdf

Magnet assembly

Under procurement. Expected delivery January 2017

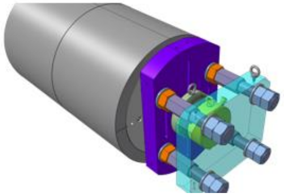
ERMC50
Coil Pack Assembly

ERMC60
Ground Insulation

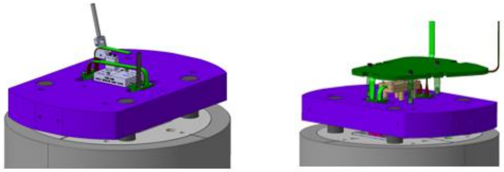


ERMC70
Insertion

ERMC80
Axial loading



ERMC90
Splicing and Connection box



CERN – 9th October 2017

Conductor Studies

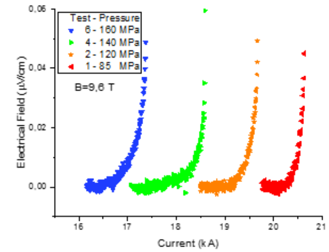
B. Bordini, J.E. Duvauchelle – CERN
M. Dhallé, P. Gao – Uni. Twente
C. Senatore, L. Gamperle, C. Barth – UniGe

2nd Review of the EuroCirCol WP 5

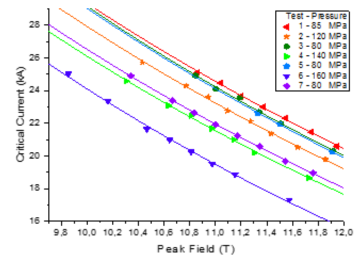
Experimental Studies

Test at CERN on a RRP cable* – Measurements

- The critical current of the cable was defined at an electric field equal to 0.03 μV/cm



- The first test was done at a relatively low transverse pressure (85 MPa)
  - at this pressure, as verified in the experiment, the I_c is not significantly affected by the transverse load



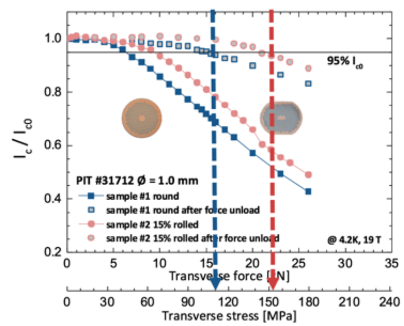
- The following tests consisted in measuring the I_c at higher and higher transverse loads;
  - in between these tests, I_c measurements at 80-85 MPa were carried out to verify whether or not the previous test produced a permanent degradation in the sample.

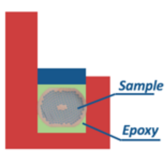
*J. E. Duvauchelle , B. Bordini, J. Fleiter, A. Ballarino presented at EUCAS 2017 and submitted for publication, *IEEE Trans. Appl. Supercond.*

Experimental Studies

1 mm PIT wire @ UniGe – Effect of Rolling 1/2

I_c vs. transverse stress on 15% rolled wires





F_{irr} = 22 kN

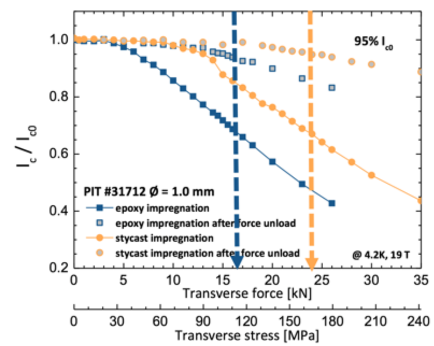
σ_{irr} = 150 MPa

Normalized I_c
Round vs. 15% rolled
Shift of σ_{irr} by ~ 40 MPa

Experimental Studies

1 mm PIT wire @ UniGe – Epoxy vs. Stycast 1

I_c vs. transverse stress: epoxy vs. stycast



The change of resin, from epoxy to stycast, leads to an increase of σ_{irr} by > 50 MPa
The result is comparable to the value found with epoxy + glass fiber sleeve

EuroCirCol 16 T Nb_3Sn dipoles: Quench protection

Tiina Salmi (TUT) and Marco Prioli (CERN)

With contributions from

E. Ravaioli (LBNL), A. Stenvall (TUT), A. Verweij (CERN),

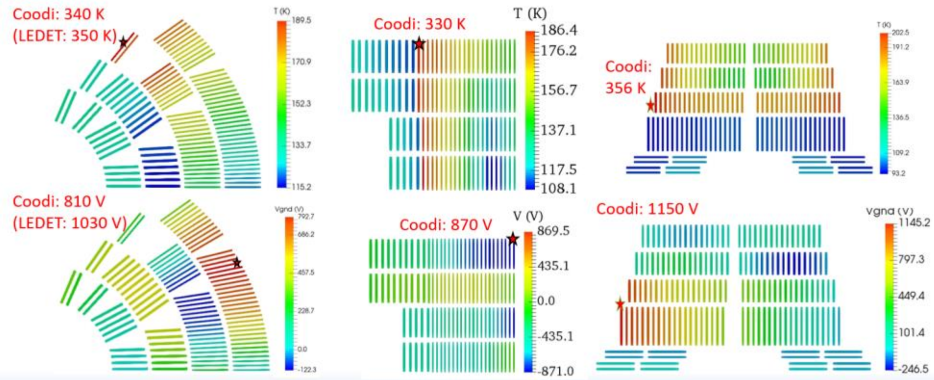
B. Auchmann (CERN, PSI), J. Ruuskanen (TUT),

and all the EuroCirCol WP5 members

2nd review of EuroCirCol WP5, 9 Oct 2017, CERN

1

Simulated temperature and voltage after the 20+20=40 ms delay



- With 20 ms delay the peak temperatures are ~250 – 270 K (Lower limit to temperatures after protection)

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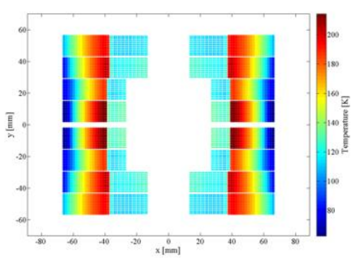
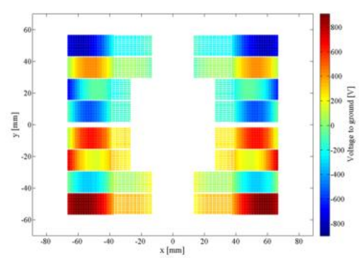
Protection with CLIQ: Block

Final temperature distribution



Voltage to ground distribution



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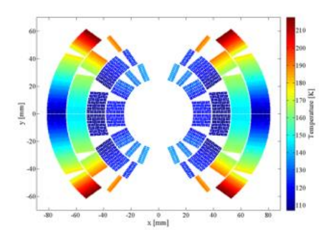
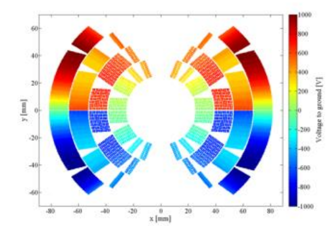
Protection with CLIQ: Cos-theta

Final temperature distribution



Voltage to ground distribution



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2nd review of the EuroCirCol WP5, 9-10 Oct. 2017

Dipole circuit layout and protection

M. Prioli and T. Salmi

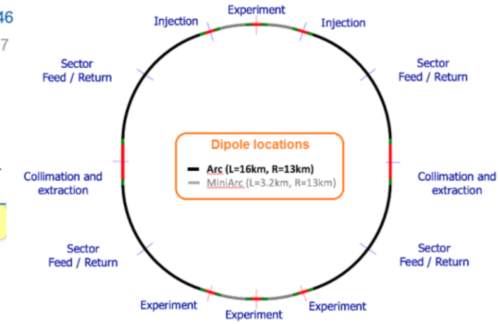
With contributions from: B. Auchmann, L. Bortot, M. Maciejewski, M. Mentink, E. Ravaioli, A. Verweij

STEAM FOR FCC hh ee he EuroCirCol

Motivation and input parameters

	Nominal current I_{nom} [kA]	Stored energy @ I_{nom} (2 ap.) [MJ]
Cos-theta	11.2	37
Block coil	10.0	38
Common coil	16.1	42
Canted cos-theta	18.0	46
LHC MB	11.9	7

	Number	Length [km]	Number of magnets
Arc	4	16	876
Mini-arc	4	3.2	180
LHC arc	8	3	154



Circuit design

Number of circuits per PS (N)	1	2	3	4	5	6	7	8	LHC
Total number of circuits	20	40	60	80	100	120	140	160	8
Number of magnets per circuit	219	110	73	55	44	37	32	28	154
Circuit energy [GJ]	8.1	4.1	2.7	2.0	1.6	1.4	1.2	1.0	1.1
PC max voltage [V]	1202	604	401	302	241	203	176	154	150
PC peak power [MW]	13.5	6.8	4.5	3.4	2.7	2.3	2.0	1.7	1.8
Time to 37% of nominal current [s]	555	279	185	139	111	94	81	71	100
MIITs [MA^2*s]	35E+3	18E+3	12E+3	9E+3	7E+3	6E+3	5E+3	5E+3	7E+3
Busbar cross-section (ΔT=300K) [mm^2]	490	350	280	240	220	200	180	170	200

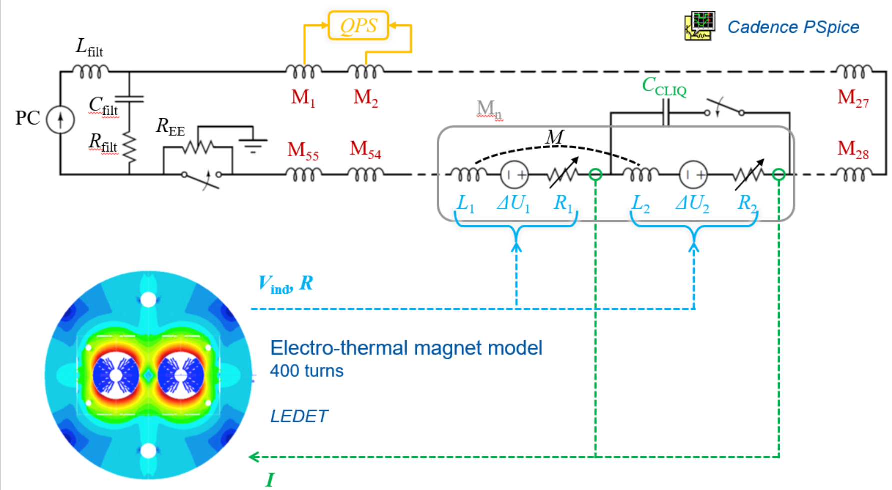
t_{ramp} = 20 min (PC max voltage, PC peak power)

V_{gnd} = 1.3 kV (Time to 37%, MIITs, Busbar cross-section); V_{gnd} = 450V (LHC)

Magnet + circuit co-simulation

Circuit model
2800 components

Cadence PSpice



STEAM

EuroCirCol CERN FCC hh ee he

Cost model status towards the CDR

Daniel Schoerling

On behalf of WP5.3
09th of October 2017

Phase 1: Cost of conductor

- **Baseline**: Ballarino, 2015 obtains the specified target cost 5 EUR/kA.m at 16 T and 4.2 K by scaling from the present cost (10 EUR/kA.m, 12 T, 4.2 K, 2300 A/mm^2, HL-LHC):
  1. If the volume production cost is the same for HL-LHC and FCC-hh wire (50% larger performance than HL-LHC wire): J_c(B = 12 T, T = 4.2 K, HL-LHC) / J_c(B = 16 T, T = 4.2 K, FCC-hh) = 1.5 ($\rightarrow$ 15 EUR/kA.m, 16 T, 4.2 K, 1500 A/mm^2)
  2. Scale-up: Production cost HL-LHC/FCC-hh = ~3, achievable according to the analysis of Cooley, 2005 by increasing the billet mass and yield by ~10 ($\rightarrow$ 5 EUR/kA.m, 16 T, 4.2 K, 1500 A/mm^2)
- Scanlan, 2001 proposes a cost of $1.5/kA.m (12 T, 4.2 K, J_c = 3000 A/mm^2), which scales for the FCC-hh target performance to 4 EUR/kA.m in 2016 with a PPI industry data factor of 1.4 (2001 to 2016; BLS, 2017)
- Zeitlin, 2001 proposes a price (including 40% gross margin!) of $0.67-0.82/kA.m (12T, 4.2 K, 3000 A/mm^2) according to his analysis of raw material and production cost

References:

A. Ballarino and L. Bottura, "Targets for R&D on Nb_3Sn Conductor for High Energy Physics", *IEEE Trans. Appl. Supercond.*, vol. 25, no. 3, Jun. 2015, Art no. 6000906.

L.D. Cooley, A.K. Ghosh and R.M. Scanlan, "Costs of high-field superconducting strands for particle accelerator magnets", *Supercond. Sci. Technol.* 18 (2005) R51-R65

R.M. Scanlan, "Conductor Development for High Energy Physics - Plans and Status of the U.S. Program", *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, Mar. 2001, pp. 2150-2155

BLS, U.S. Bureau of Labor Statistics, Producer Price Index (PPI) Industry Data 2001-2016, www.bls.gov/data/

B.A. Zeitlin, E. Gregory, and T. Pyon, "A High Current Density Low Cost $Niobium_3Tin$ Conductor Scalable to Modern Niobium Titanium Production Economics", *IEEE Trans. Appl. Supercond.*, vol. 11, no. 1, Mar. 2001, pp. 3683-3687

Phase 2: Cost of parts (CIEMAT & CERN)

- Manufacturing of main components (strict fabrication tolerances):
  - Cu-Alloy wedges: Contacts with three companies, different materials under investigation, samples are currently under investigation at CERN
  - Iron yoke laminations: Material characterisation of high-strength steel and invar currently under investigation
  - End spacers: Optimization for additive manufacturing and study of Metal Injection Moulding (sample production on-going, could be competitive despite small number of parts 20,000/type)
  - Iron pad laminations
  - Master keys
- Conductor and wedges insulation
- Impregnation
- Ground insulation
- Plasma coating insulation
- Aluminium shell
- Axial rods
- End plates
- Quench Heaters

F. Toral, Cost estimate collaboration meeting #11, Update on cost for parts,

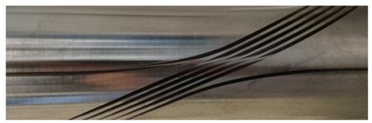
Phase 2: Assembly cost (CEA)

- Coil winding (38,672 coils, 150 coils/week, 2 week/coil)
- Coil heat-treatment (38,672 coils, 150 coils/week, 2 weeks/heat treatment)
- Transfer from reaction fixture to impregnation mould (38,672 transfers, 150 transfers/week)
- Main lead splice manufacturing (77,344 splices, 300 splices/week)
- Coil instrumentation
- Coil impregnation (38,672 coils, 150 coils/week, 1 week/impregnation)
- Coil pack assembly (9,668 coil packs, 40 coil packs/week)
- Coil quality control including magnetic measurement at RT
- Structure assembly and splicing
- Cold mass assembly (4834 cold mass, 20 cold mass/week)

M. Durante, Cost estimate collaboration meeting #12, Update on cost for assembly,

B. Auchmann (CERN/PSI), L. Brouwer (LBNL), S. Caspi (LBNL), R. Felder (PSI), J. Gao (PSI),
G. Montenero (PSI), M. Negrazus (PSI), G. Rolando (CERN), S. Sanfilippo (PSI), S. Sidorov (PSI)

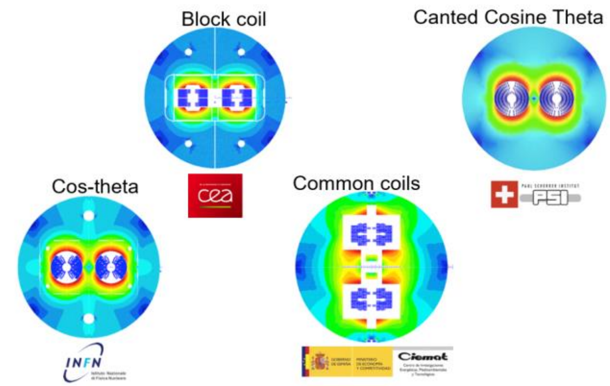
Update on CCT



09.10.2017, EuroCirCol WP5 Review, CERN.

Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

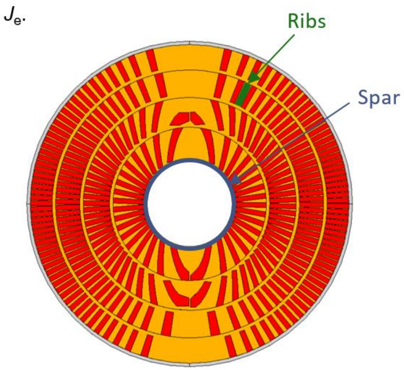
CCT joined the fold in Nov. 2016



CCT Design for FCC

- Keys to an efficient CCT design:
  1. Thin spars
  2. Wide cable, large strands
  3. Thin ribs.

  (1.–3.) Increase J_e.



Manufacturability and Cost

- Deep channels, aspect-ratio ~10.
- Inclined channels → 5-axis machining on long rotating cyl., **machining tests under way**.
- Selective Laser Melting (3-D printing) not successful.
- **Collaboration with IWS Fraunhofer** on fabrication of **thin-lamination formers**.
  - Laser cutting, spot welding + diffusion welding.
  - Goal: improve scalability and cost.

E uro C ir C ol

2nd Review of the EuroCircol WP5

Block coil: mechanics

CEA

CERN, 9 oct 2017

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E uro C ir C ol

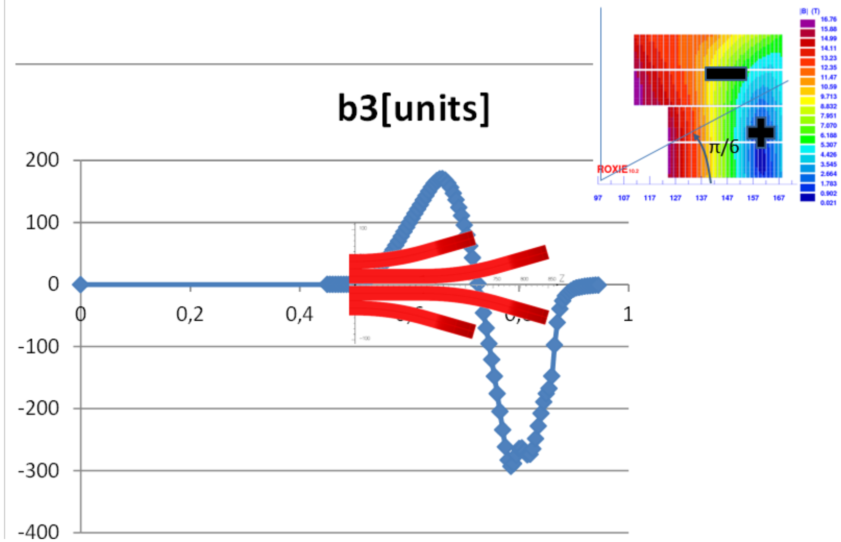
2nd Review of the EuroCircol WP5

Block coil: electromagnetic

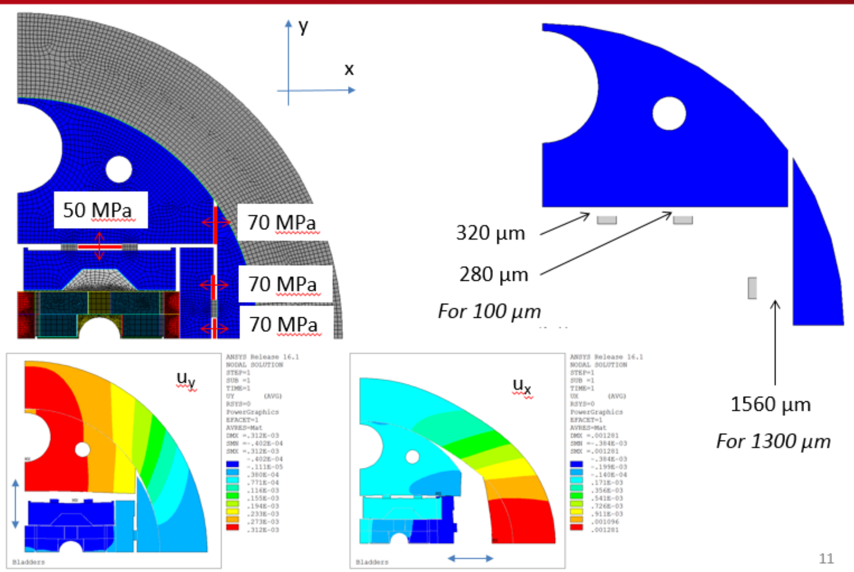
CEA

CERN, 9 oct 2017

Field b_3



Bladder inflation



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EXTRA: Block magnet comparison

Magnet	Bore field [T]	Pole tip thickness [mm]	displacement [µm] cold	displacement [µm] powering	Δdisp [µm] pow-cold	Strain [µm/m] cold	Strain [µm/m] powering	Δε [µm/m] pow-cold	Δε/Δdisp [µε/µm]	Material properties Nb3Sn	Material properties Ti-6Al-4V
ECC block v20ar	16.8	1.75	-198	-49	149	-5887	-1580	4307	29	ECC (E~25;30;27.5;33 GPa)	116 GPa / 126.5 GPa
ECC block v19ar	16.8	1.75	-169	-57	112	-5231	-1598	3633	32	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
ECC block v18ar	16.8	1.9	-162	-50	112	-4558	-1019	3539	32	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
ECC block v17ar	16.8	2	-167	-55	112	-4436	-955	3481	31	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
ECC block v16ar	16.8	6.3	-179	-72	107	-4878	-1272	3606	34	LARP (E~44 GPa,52 GPa)	130 GPa / 130 GPa
Fresca2	13	5	-304	-140	164	-5048	-2480	2568	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	13	6.5	-306	-142	164	-5051	-2481	2570	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	13	8	-307	-141	166	-5058	-2472	2586	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	15	8	-409	-190	219	-7187	-3778	3409	16	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
Fresca2	13	16	-232	-101	132	-3931	-1042	2889	22	LBNL (E~44 GPa,44 GPa)	100 GPa / 120 GPa
RMM_graded_v21_d	16	1	-174	-56	118	-4617	-1071	3546	30	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
RMM_graded_v21_c	16	2	-173	-55	118	-4666	-1056	3610	31	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
RMM_graded_v21_b	16	4	-171	-55	116	-4757	-1115	3643	32	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
RMM_graded_v21_a	16	6	-168	-58	111	-4832	-1245	3587	32	LBNL (E~44 GPa,44 GPa)	110 GPa / 120 GPa
HD3	14	1.65	-134	-51	83	-3690	-667	3023	36	LARP (E~44 GPa,52 GPa)	110 GPa / 120 GPa

ECC displacement and strain **impacted** by material properties not by bore tip thickness

RMM_graded and **ECC** similar behavior with similar properties

Fresca2 biggest displacement – **HD3** smallest displacement…

Thanks to:
HD3: Helene Felice (CEA)
RMM_graded: Susana Izquierdo-Bermudez (CERN)
Fresca2: Etienne Rochepault (CERN)

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EuroCirCol

16 T dipole in common coil configuration: mechanical design

J. Munilla, F. T…

Common coil configuration: electromagnetic design

J. Munilla, F. Toral - CIEMAT

Thanks to R. Gupta (BNL), Q. Xu (IHEP), S. Izquierdo-Bermúdez (CERN) and T. Salmi (TUT) for their sugges…

2nd Review of EuroCirCol WP5, Oct 9th, 2017

Summary of 2-D magnetic results

- Design #11 needs more superconductor, but fulfils all requests.
- Design #12 is even better, but cable fabrication is more challenging (Cu:Sc=0.8).
- Design #13 and #14 are valid for an upgrade of LHC (650 mm outer iron diameter). They need more superconductor, specially when reducing the intra-beam distance (which also reduces the fringe field). A large intra-beam distance would be very convenient for react-and-wind coils.

TABLE I
COMPARISON OF 2-D MAGNETIC DESIGNS

Design Id.	#10	#11	#12	#13	#14	Units
Nominal current I	9.17	16.1	16.1	16.1	16.1	kA
Minimum Cu:Sc ratio	1	1	0.8	1	1	
Intra-beam distance	320	320	320	320	280	mm
Iron outer diameter	750	750	750	650	650	mm
Stored magnetic energy	3.47	3.04	2.93	3.05	3.16	MJ/m
$L*I$	757	378	364	379	392	H·A/m
Vertical Lorentz force	0.73	0.57	0.43	0.34	0.92	MN/m
Horizontal Lorentz force	14.7	14.6	14.4	14.4	14.5	MN/m
Maximum stray field (600 mm radius)	0.19	0.15	0.17	0.19	0.15	T
FCC bare cable weight	8592	9353	8951	9446	9631	ton

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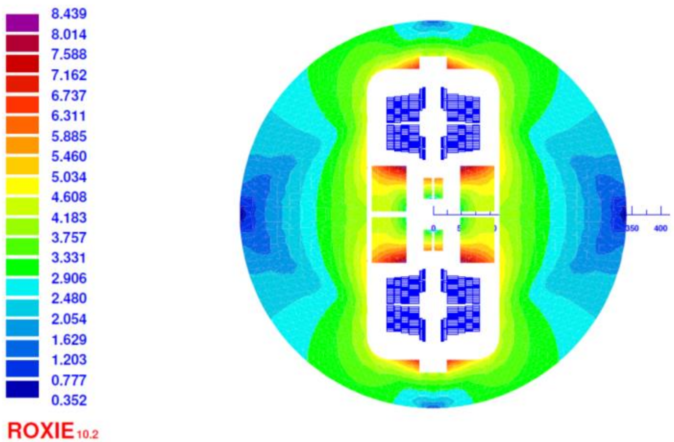
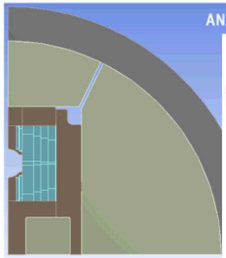
Electromagnetic design: Design #12



Concept design: open support

- 40 mm stainless steel shell, small clearance for easy assembly.
- No prestress at warm
- Main coils are impregnated together with, but NONE of them are bonded to supporting structure



- It results in quite big displacements
- Contact pressure is not preserved at all

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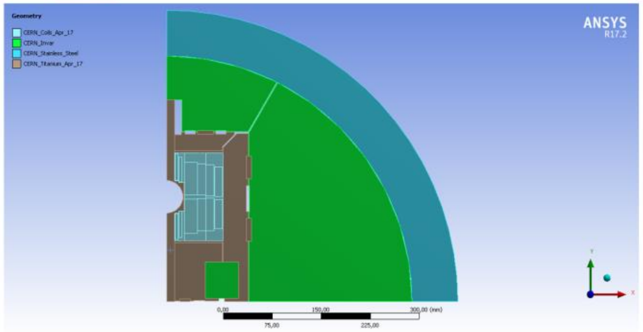
Concept design: CLOSED external support

- An outer shell of stainless steel (70 mm) holds the magnet against horizontal forces.
- Yoke is cut in 4 pieces. Invar to increase pre-stress. Magnetic simulation was made considering iron yoke, then changed to invar at structural analysis
- Main coils are impregnated together with, but NONE of them are bonded to supporting structure



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Cosine-theta: electromagnetic design

Vittorio Marinozzi,

Giovanni Bellomo, Barbara Caiffi, Pasquale Fabbricat

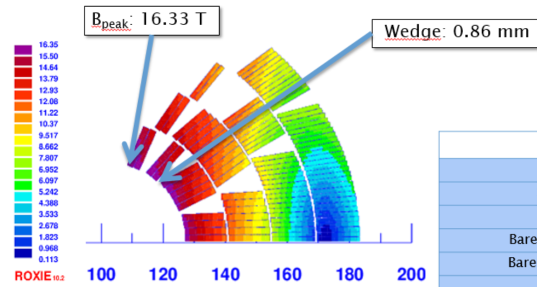
EuroCirCol Cosθ 16 T dipole

2nd EuroCirCol WP5 Review
Monday 9 -Tuesday 10 October 2017

B. CAIFFI

G. BELLOMO, P. FABBRICATORE, S. FARINON, V.MARINOZZI, A.M. RICCI, M. SORBI

2.1 Cross section layout



Number of turns:
Layer 1: 13
Layer 2: 19
Layer 3: 29
Layer 4: 39
Tot: 200/ap.

	HF Cable (inner)	LF Cable (outer)
Strand number	22	37
Strand diameter	1.1 mm	0.7 mm
Bare width	13.2 mm	13.65mm
Bare inner thickness	1.892 mm	1.204 mm
Bare outer thickness	2.007 mm	1.3231 mm
Insulation	0.15 mm	0.15 mm
Keystone angle	0.5°	0.5°
Cu/NCu	0.85	2.2
Operating current	11240 A	11240 A
Operating point on LL (1.9 K)	86 %	86 %

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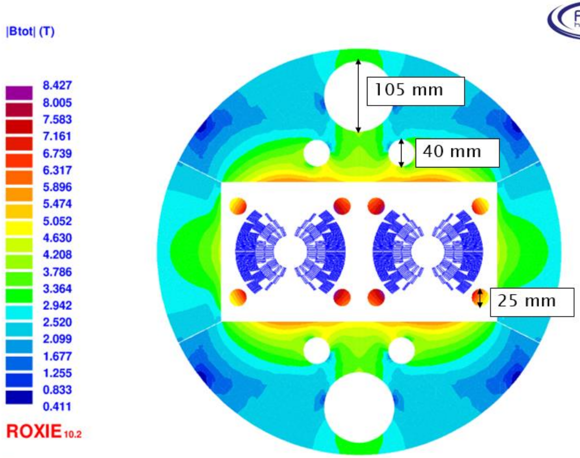
2.2 Iron yoke



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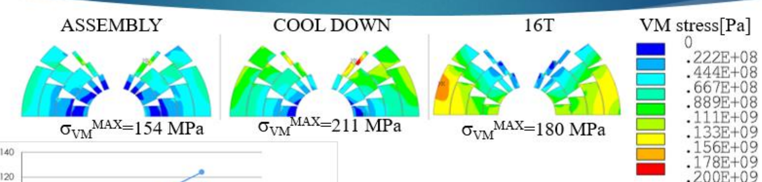
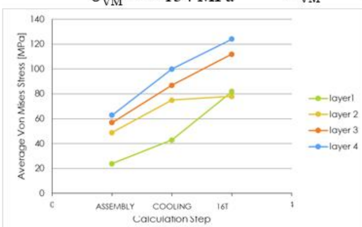
VM stress on conductors





- VM stress far below current degradation limit (150 MPa @ RT -200 MPa @ 1.9K)
- Localized hot spot after cooling down (edge effect, negligible)

2nd WP5 Review · Mechanics of Costheta 16T dipole · 10/10/2017

Conclusion

- Considerable progress made on all fronts since last annual meeting
- Great team-work, average of 2 meetings per month and genuine sharing of information & knowledge, spontaneous adhesion of “non EuroCirCol ” Colleagues
- A shared baseline for the FCC CDR has been set
- Opportunities for experimental work have been set for all design options
- Field quality requirements still to be finalized with WP2 (under way), in particular for management of b2 and for 3D management of b3
- We believe to be on time with respect to the FCC CDR schedule
- We are having a great support with good advises and constructive discussions with many Colleagues, and particularly the members of the WP5 Review Commitee

Steve Gourlay
Joe Minervini
Luisa Chiesa
Giorgio Ambrosio
Diego Arbelaez

Thank you for your attention