Hardware Challenges and Limitations for the IR Upgrades

Stephan Russenschuck

for the (EU) WP-5 and WP-6 teams

[LHC IR Phase-I Upgrade WP-4, WP-5]

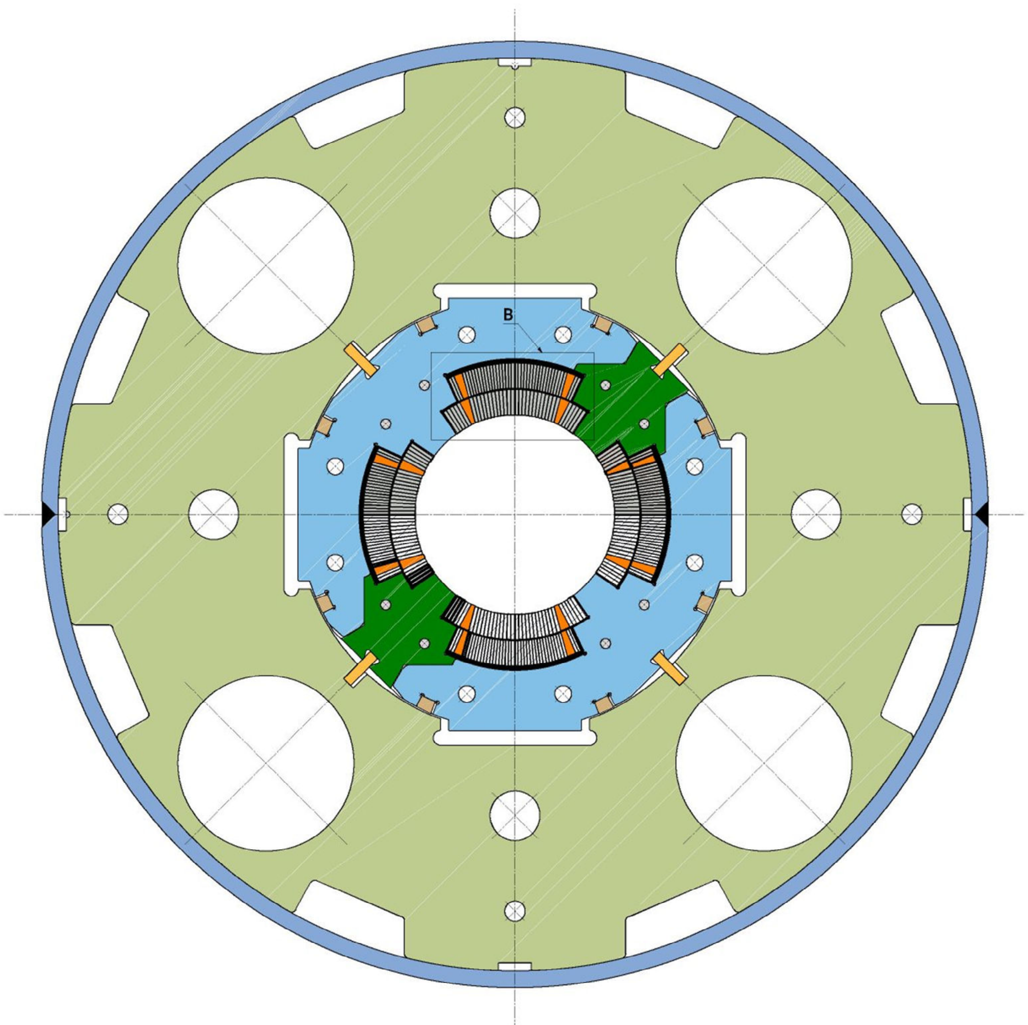
MQXC, Cryostats, and Corrector package

28.01.2010

Overview

- ➔ Framework: EU-WP6 and White-Paper
  - – Deliverables and Milestones
- ➔ Design and construction activities/challenges
  - – Challenges (Heat load, powering and protection, axial forces, collaring)
  - – New features (Porous cable and ground-plane insulation, tuning shims)
  - – Integrated design process (quench simulation, end-spacer design)
- ➔ Planning issues (How much R&D)

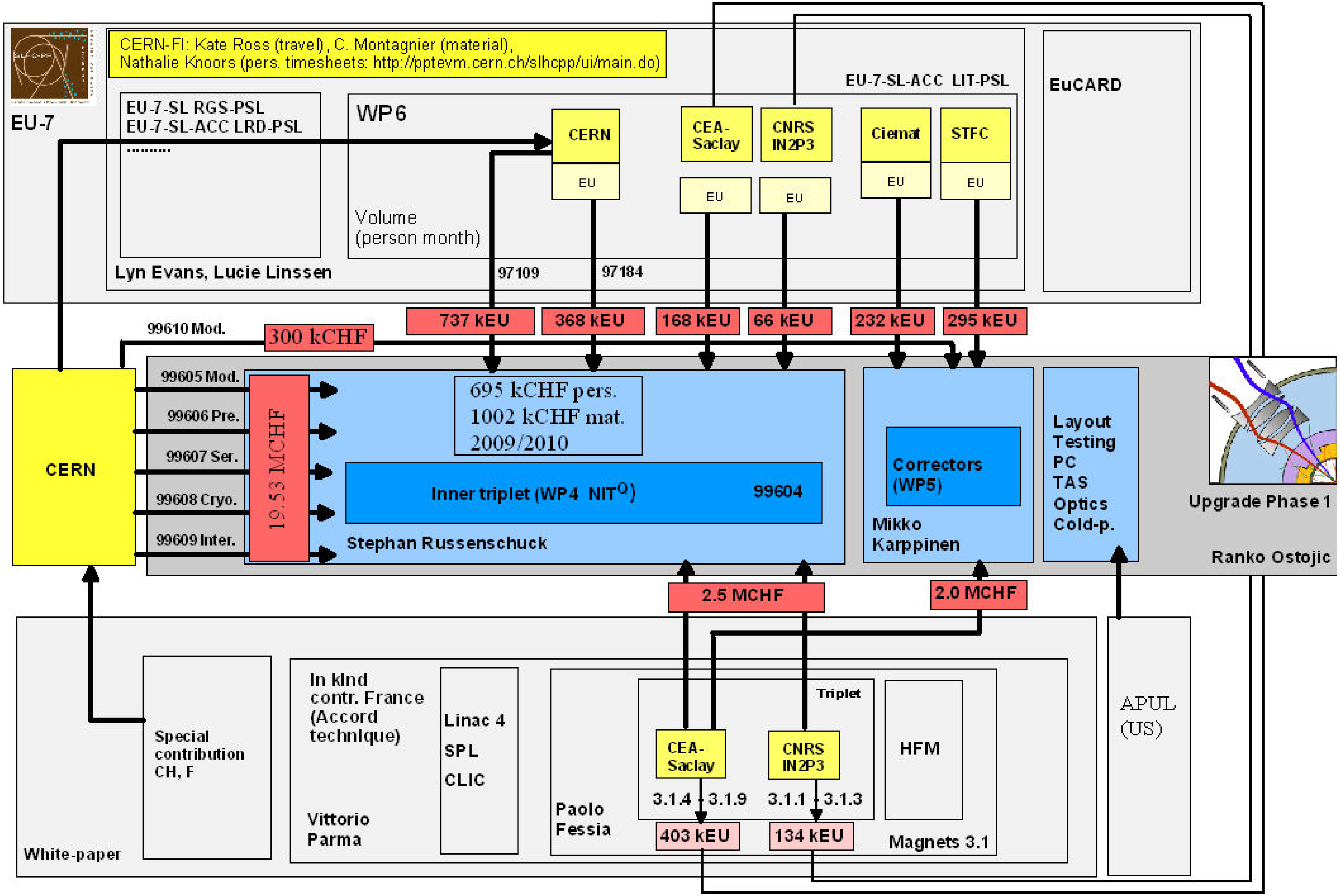
Low-β Quadrupole MQXC



➔	Coil aperture	120 mm
➔	Gradient	127 T/m
➔	Operating temp	1.9 K
➔	Current	13.8 kA
➔	WP on load-line	85%
➔	Inductance	5.2 mH/m
➔	Yoke ID	260 mm
➔	Yoke OD	550 mm
➔	Magnetic length	9160 mm (Q1,Q3)
		7760 mm (Q2)

- LHC cables 01 and 02
- Porous cable polyimide insulation
- Yoke OD identical to MB
- Self-supporting collars
- Single piece yoke
- Welded-shell cold mass

The EU and White-Paper Frameworks



EU-FP7 and Accord-Technique (F)

Year	Q	Deliverables	Milestones	Accord-Technique
2008	4		Component qualification (6.1)	
2009	1		Basic magnetic design (6.2)	
	2	Basic MQXC design (6.1.1)		Cryostat proto. design review
	3		Coldmass design (6.3)	
	4	Model construction (6.2.1)	Cryomagnet design (6.4)	Cryostat proto. production review Cryostat f. corrector package design review Corrector magnet design Cold-bore tube tech. spec.
2010	1			Cryostat f. corrector package production readiness review Quench heater tech. spec. Collars for MQXC tech spec.
	2	Model cold-test and design assesment (6.2.2)		
	3	Corrector package construction (6.3.1)		
	4	Prototype construction (6.3.2)	Corrector package cold-test (6.7) MQXC ELQA (6.6)	Cryostat prototype tooling installation Cryostat component delivery Corrector magnet series production start First quench-heater delivery Collar delivery for MQXC
2011	1	MQXC prototype cold-test (6.3.3)		Cryostat f. corrector package ready
	2	Complete IR design (6.3.4)		
	3			
	4			All corrector magnets delivered

EU-FP7 and Accord-Technique (F)

Year	Q	Deliverables	Milestones	Accord-Technique
2008	4		Component qualification (6.1)	
2009	1-4		Basic magnet design (6.2)	
2010	1	Basic MQXC design (6.1.1)		
	2			Cryostat proto. design review
	3		Coldmass design (6.3)	
	4	Model construction (6.2.1)	Cryomagnet design (6.4)	Cryostat proto. production review Cryostat f. corrector package design review Corrector magnet design Cold-bore tube tech. spec.
2011	1			Cryostat f. corrector package production readiness review Quench heater tech. spec. Collars for MQXC tech spec.
	2	Model cold-test and design assesment (6.2.2)		
	3	Corrector package construction (6.3.1)		
	4	Prototype construction (6.3.2)	Corrector package cold-test (6.7) MQXC ELQA (6.6)	Cryostat prototype tooling installation Cryostat component delivery Corrector magnet series production start First quench-heater delivery Collar delivery for MQXC
2012	1	MQXC prototype cold-test (6.3.3)		Cryostat f. corrector package ready
	2	Complete IR design (6.3.4)		
	3			
	4			All corrector magnets delivered

EU-FP7 and Accord-Technique (F)

Year	Q	Deliverables	Milestones	Accord-Technique
2010	1	Basic MQXC design (6.1.1)		Parameters fixed for all correctors (except for orbit correctors in Q2)
	2	All drawings (magnet, instrumentation and tooling)		
	3	All tooling (winding, curing, collaring, lifting, assembly, coil finishing, yoking) All components Coil measurements	Coldmass design (6.3)	
	4	Model construction (6.2.1)	Cryomagnet design (6.4)	Cryostat f. corrector package design review Corrector magnet design
2011	1	Test in vertical cryostat Integration in horizontal cryostat, test-bench preparation, cycling, field measurements		Cryostat f. corrector package production readiness review Quench heater tech. spec. Collars for MQXC tech spec.
	2	Model cold-test and design assesment (6.2.2)		
	3	Corrector package construction (6.3.1)		
	4	Prototype construction (6.3.2)	Corrector package cold-test (6.7) MQXC ELQA (6.6)	Corrector magnet series production start First quench-heater delivery Collar delivery for MQXC
2012	1	MQXC prototype cold-test (6.3.3)		Cryostat f. corrector package ready
	2	Complete IR design (6.3.4)		
	3			
	4			All corrector magnets delivered

List of Components, Tooling, Assembly Activities, and Tests (MQXC)

Components	Tooling	Assembly	Tests/Studies
Concept design Drawing Specifications Prototype (Series) manufacture	Concept design Drawing Manufacture Installation	Started Finished	
Coil (50%) End-spacers (80%) Ramp and splice box (50%) Copper wedges (100%) Quench heaters (80%) Wiring diagrams (0%) Capacitance gauges (100%) Strain gauges (100%) Spot heaters (0%) Head shims (0%) Collars (Instrumented) (100%) Collar (Non-instrumented) (0%) Collar (Punched) (0%) Collaring shoe (100%) Collaring keys (100%) Ground insulation (50%) Pole turn fishbones (60%) Outer layer fish-bone (60%) Yoke laminations (Wire, punched) (100%) Yoking tie rods and nut assembly (0%) Aperture end plate components (0%) Joint box components (0%) Yoke end plates (0%) Main assembly drawing (20%) Instrumentation feedthrough system Helium vessel End-domes	Coil winding mandrel (20%) Curing mold assembly (50%) Collar pack assembly tooling (0%) Assembly for collar packs on coil (100%) Multipurpose test press (Hydraulics) (100%) Collaring press horizontal (100%) Auxiliary tooling for collaring press (50%) Ground insulation former (0%) Layer jump and splice former (0%) E-mod size press (straight section) (80%) E-mod size press (end section) (0%) Steel dummy coils (straight section) Steel dummy coils (end section) Collapsible mandrel for apert. assemb. (short) Collar rectification table Longitudinal compaction press Lifting tooling Quench heater fabrication tooling Soldered joint tooling	Insulate and cut wedges Cure and measure coil packs Calculate best position of coils Assemble collar packs Assemble 150 mm model Insulate cable Insulate Cu wedges Coil winding Coil curing Coil size measurements Collaring Mechanical measurements Warm magnetic field measurements Mount end flanges Solder electrical joints Yoke assembly Warm magnetic field measurements	Arch curing tests Arch E-modulus test Cold test 150 mm model Quench heater discharge Quench heater high-pot Connection box ELQA 1 After collaring ELQA 2 After joking Warm magnetic field meas. 1 Warm magnetic field meas. 2 Cold test in vertical cryostat: Field quality Quench behavior Cold test in horizontal cryostat Dump Quench heater delay Propagation velocity RRR Field quality Dynamic effects

MQXA (KEK)

5 years

- 1996_asc_Design.pdf
- 1998_asc_Model_test.pdf
- 1998_epac_TUP20G.pdf
- 1999_mt16_00828194.pdf
- 1999_mt16_Mech_tolerance.pdf
- 2000_asc_5Model_comp..pdf
- 2000_asc_00920090.pdf
- 2000_asc_00920094.pdf
- 2001_mt17_01018377.pdf
- 2001_mt17_01018386.pdf
- 2001_mt17_01018733.pdf
- 2001_mt17_Prototype_testing.pdf
- 2002_asc_01211840.pdf

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 7, NO. 2, JUNE 1997

Design Study of a Superconducting Insertion Quadrupole Magnet for the Large Hadron Collider

A. Yamamoto, K. Tsuchiya, N. Higashi, T. Nakamoto T. Ogitsu, N. Ohuchi, T. Shintomi, and A. Terashima
National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki, 305, Japan

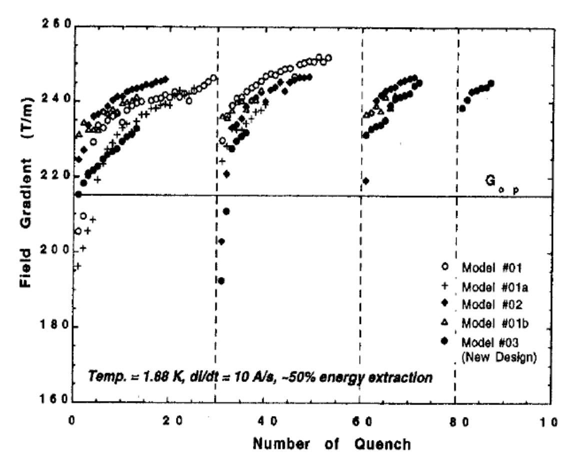
G. Kirby*, R. Ostojic, and T. M. Taylor
European Laboratory for Particle Physics (CERN), 23 Geneve, CH-1211, Switzerland

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 9, NO. 2, JUNE 1999

Quench and Mechanical Behavior of an LHC Low-β Quadrupole Model

T. Nakamoto, K. Tanaka, A. Yamamoto, K. Tsuchiya, E. Burkhardt, N. Higashi,
N. Kimura, T. Ogitsu, N. Ohuchi, K. Sasaki,† T. Shintomi, and A. Terashima,
High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

G. A. Kirby, R. Ostojic, and T. M. Taylor
European Laboratory for Particle Physics (CERN), 1211 Geneva 23, Switzerland



170 IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 12, NO. 1, MARCH 2002

Quench Protection Study of a Prototype for the LHC Low-Beta Quadrupole Magnets

Tatsushi Nakamoto, Earle E. Burkhardt, Toru Ogitsu, Akira Yamamoto, Takakazu Shintomi, and Kiyosumi Tsuchiya

5 Models built (revision of inner layer)

MQXB (Fermilab)

5 years

- 1996_asc_00614571.pdf
- 1996_epac_Design.pdf
- 1996_epac_MOP045G.pdf
- 1997_pac_6P001.pdf
- 1997_pac_6P004.pdf
- 1998_asc_00783334.pdf
- 1998_asc_Model_test.pdf
- 1999_mt16_00828186.pdf
- 1999_mt16_00828187.pdf
- 1999_mt16_00828189.pdf
- 1999_pac_THP96.pdf
- 1999_pac_THP103.pdf
- 2000_asc_9Model_performance.pdf
- 2001_mt17_01018352.pdf
- 2001_mt17_01018368.pdf
- 2001_mt17_Prototype_result.pdf
- 2002_asc_01211835.pdf
- 2003_pac_WPAE015.pdf
- 2004_asc_01439830.pdf
- 2004_asc_01439834.pdf
- 2005_mt19_01642881.pdf
- 2005_nim.pdf
- 2006_epac_WEPLS109.pdf

DESIGN OF A HIGH GRADIENT QUADRUPOLE FOR THE LHC INTERACTION REGIONS

R. Bossert, S.A. Gourlay, T. Heger, Y. Huang, J. Kerby, M.J. Lamm, P.J. Limon, P.O. Mazur, F. Nobrega, J.P. Ozelis, G. Sabbi, J. Strait, A.V. Zlobin
Fermilab, Batavia, Illinois, USA;

S. Caspi, D. Dell'orco, A.D. McInturff, R. M. Scanlan, J.M. Van Oort
Lawrence Berkeley National Laboratory, Berkeley, California, USA;

R.C. Gupta, Brookhaven National Laboratory, Upton, New York, USA

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 9, NO. 2, JUNE 1999

Design, Development and Test of 2m Quadrupole Model Magnets for the LHC Inner Triplet

J. Kerby, A.V. Zlobin, R. Bossert, J. Brandt, J. Carson, D. Chichili, J. Dimarco, S. Feher, M.J. Lamm, P.J. Limon, A. Makarov, F. Nobrega, I. Novitski, D. Orris, J.P. Ozelis, B. Robotham, G. Sabbi, P. Schlabach, J.B. Strait, M. Tartaglia, J.C. Tompkins,
Fermi National Accelerator Laboratory, Batavia, Illinois, USA

S. Caspi, A.D. McInturff, R. Scanlan,
Lawrence Berkeley National Laboratory, Berkeley, California, USA

Field Measurement of a Fermilab-Built Full Scale Prototype Quadrupole Magnet for the LHC Interaction Regions

R. Bossert, R. Carcagno, J. DiMarco, S. Feher, H. Glass, J. Kerby, M. J. Lamm, A. Nobrega, T. Nicol, T. Ogitsu, D. Orris, T. Page, R. Rabehl, G. Sabbi, P. Schlabach, J. Strait, C. Sylvester, M. Tartaglia, J. C. Tompkins, G. Velev, and A. V. Zlobin

TABLE V
Quench current and b_6 as a function of coil curing cycle

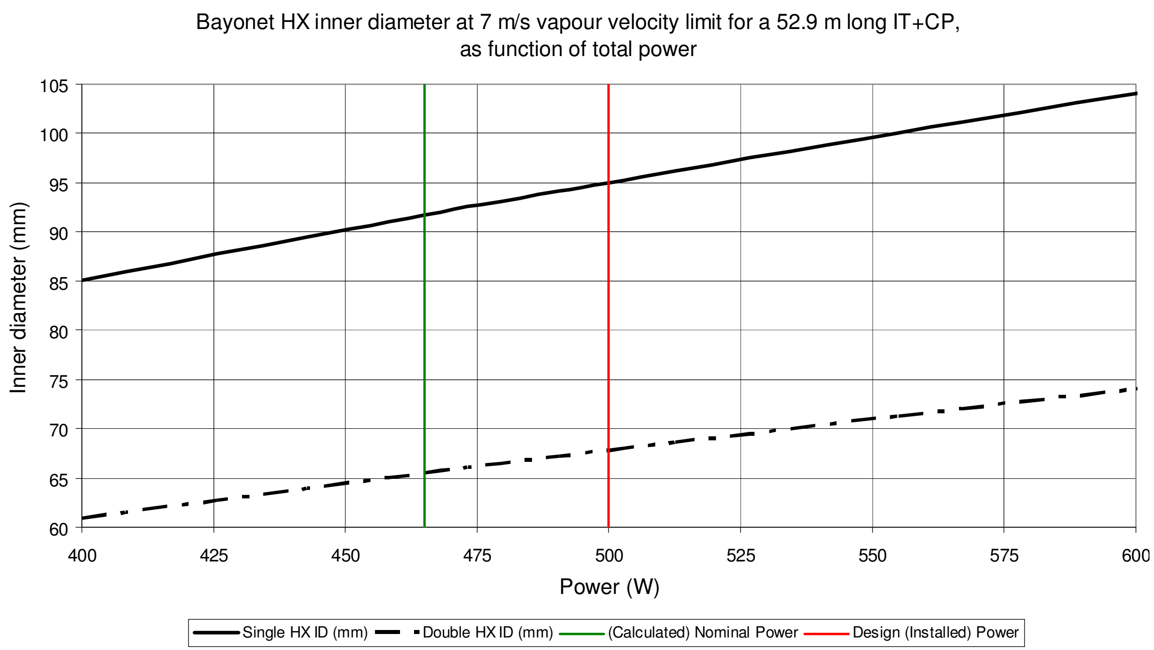
	coil curing cycle		I_c	$\Delta b_6, 6kA$
	temperature	pressure	300 A/s	40 A/s
HGQ01	135°	low	10965	0.02
HGQ02	190°	low	11335	0.21
HGQ03	195°	low	11298	0.16
HGQ05	130°	low	10519	0.12
HGQ06	190°	high	6433	-1.04
HGQ07	190°	high	4487	-0.55
HGQ08	190°	high	3941	-0.72
HGQ09	190/135°	low/high	12946	0.13

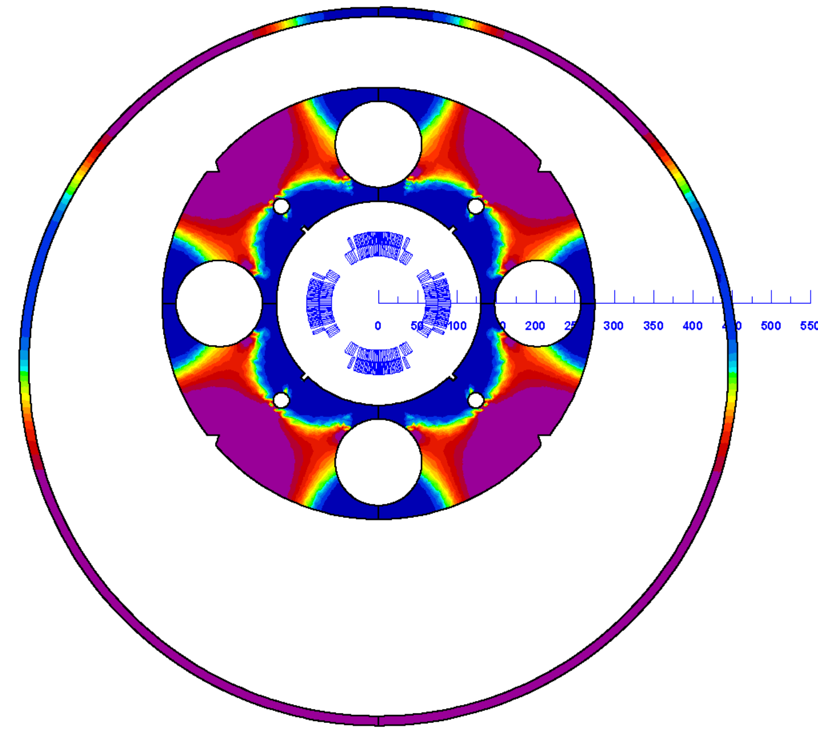
9 Models (change of cables)

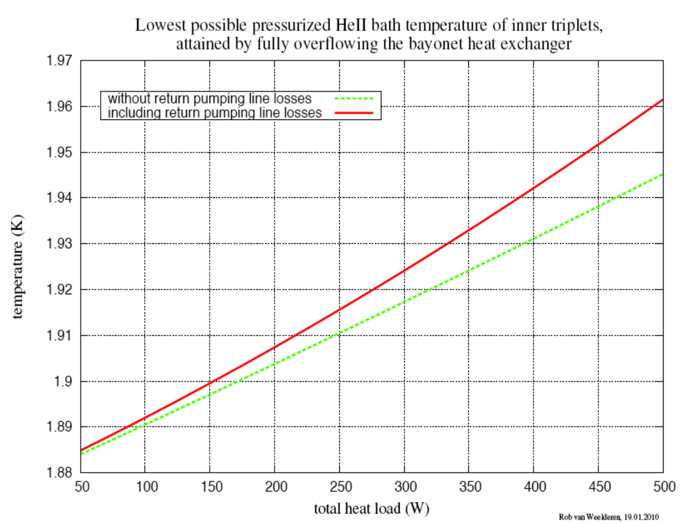
Can we do Better than 4-5 Years ?

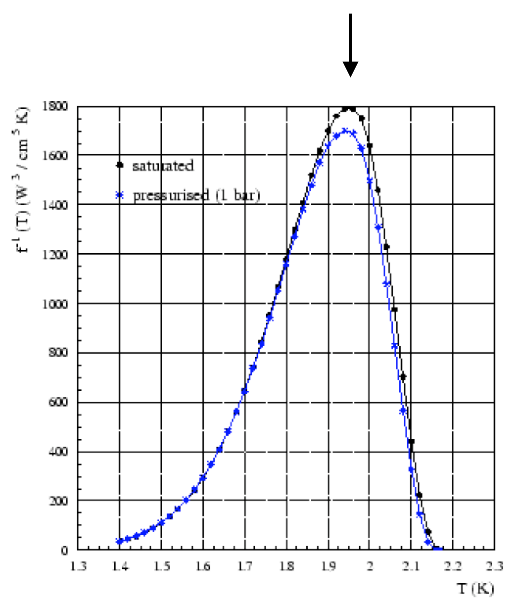
Pro		Contra
More advanced simulation tools	Cable available	Heat load (porous insulation; coil modulus)
Integrated design and manufacture for end-spacers	Large aperture	Busbar design and routing
Faster link between CAD and FE modeling	EU-Industrial suppliers	Horizontal collaring (new press to be procured)
More sophisticated CAD/CAM	EU/White paper	Magnet protection (nested PCs, heaters)
Existing specifications	Technical experience	Axial forces
Cryostat identical to MB	In-house production	EU-Certification of tooling

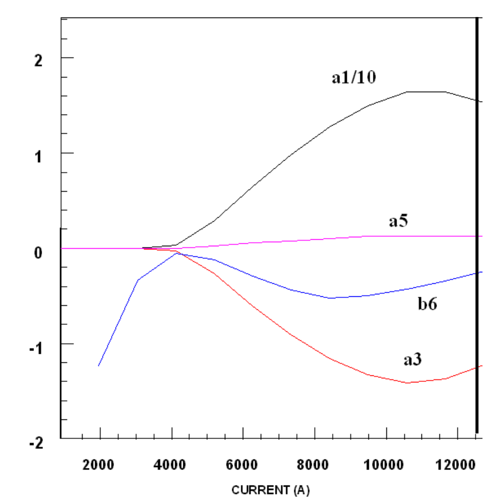
Heat-Load and Cooling Requirements



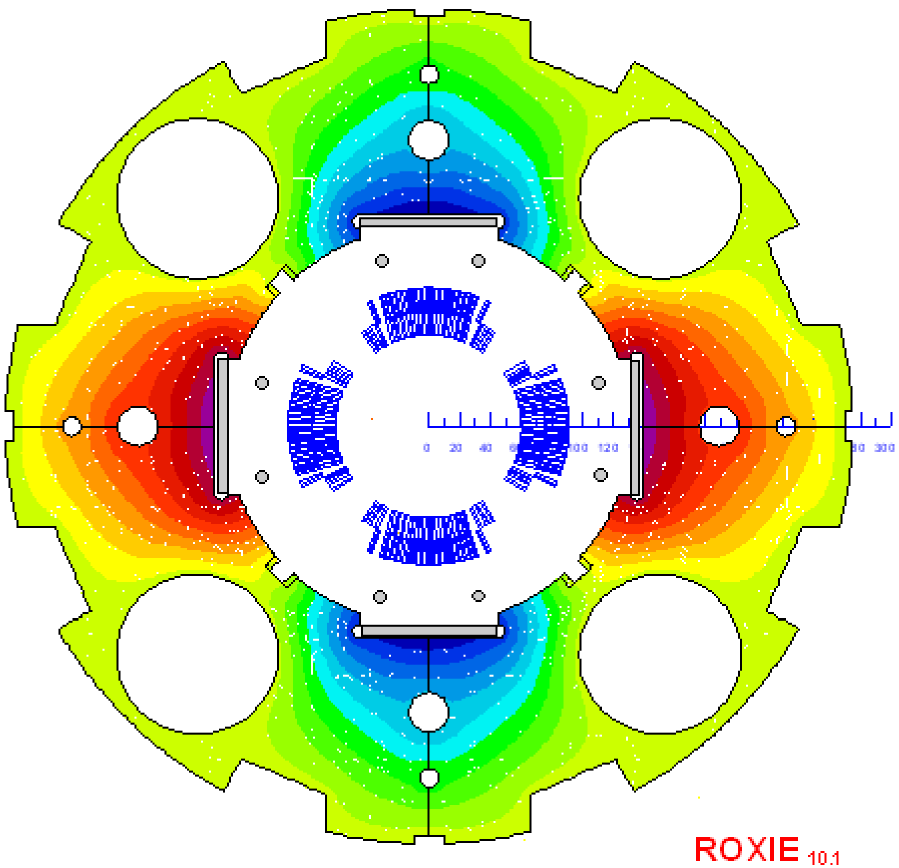


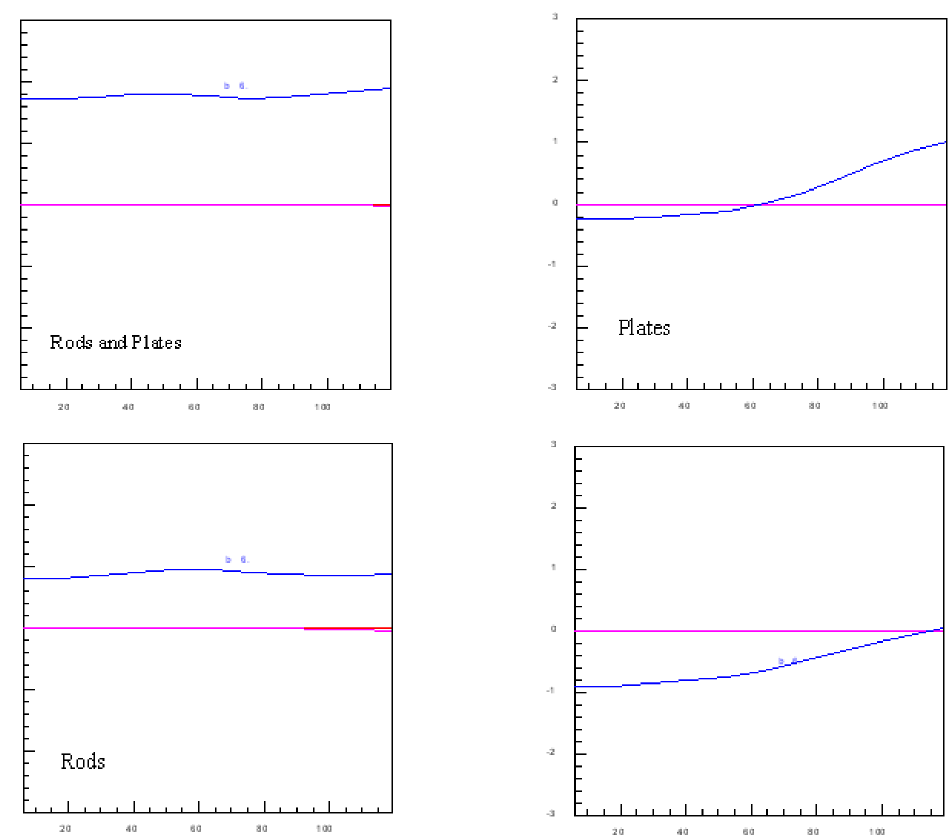




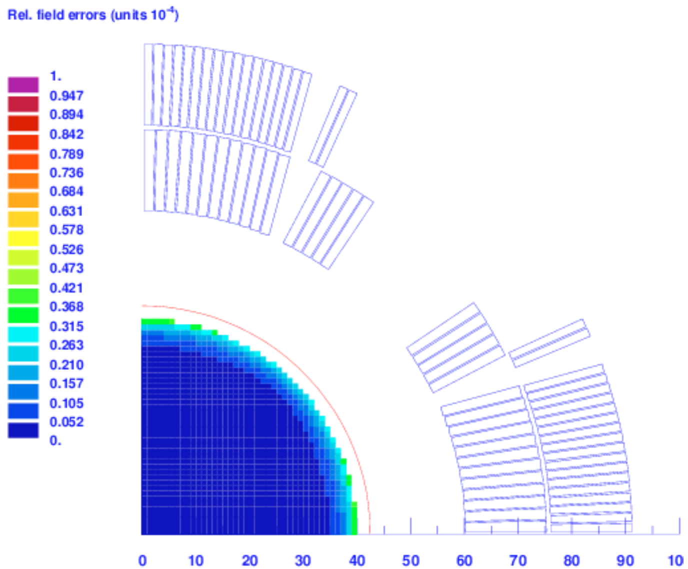


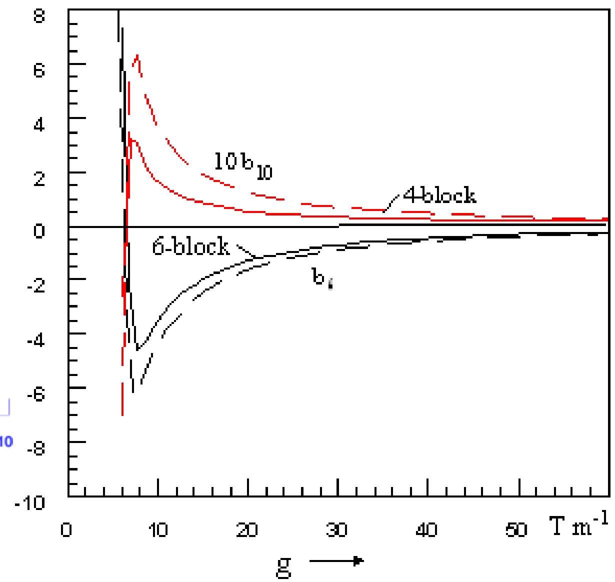
Ferromagnetic Tuning Shims (Rods and Plates)

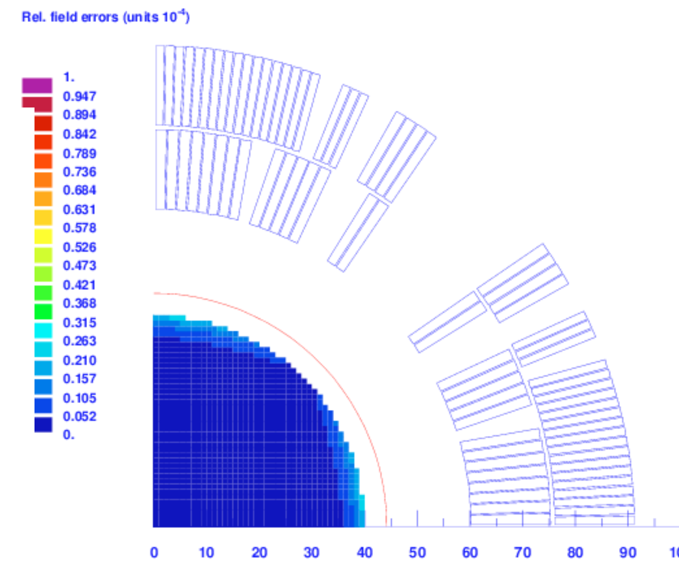




Coil Layouts (4-Block / 6-Block)





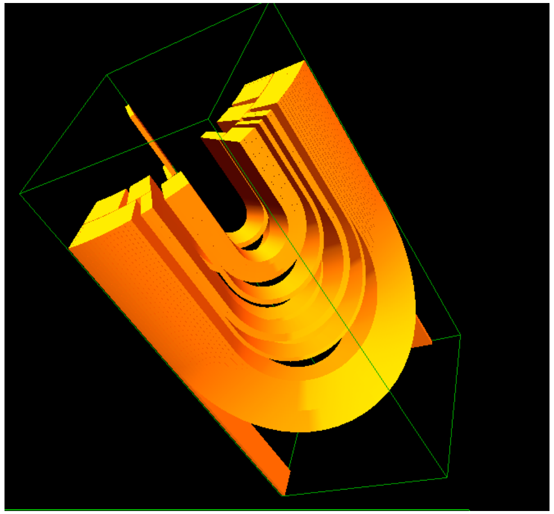


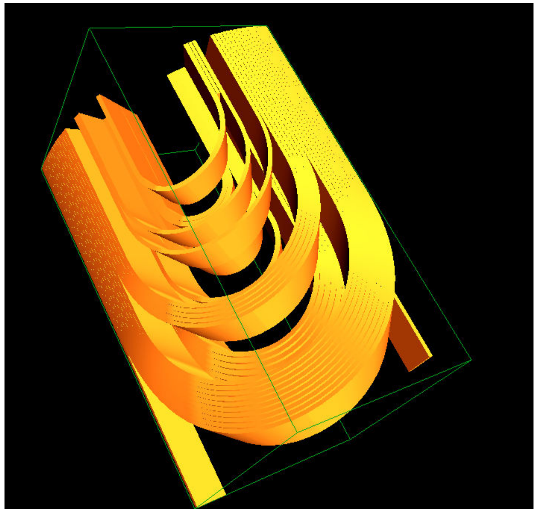
12804 A, 79.6% on load-line
(for 120 T/m)

BEMFEM ★ ROXIE10.1

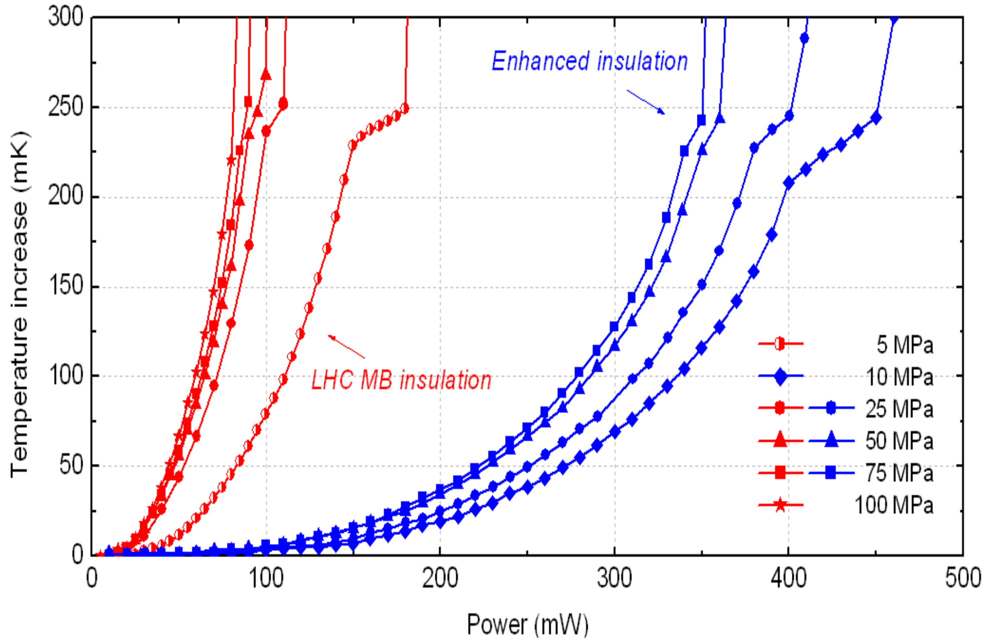
12683 A, 78.45% on load-line

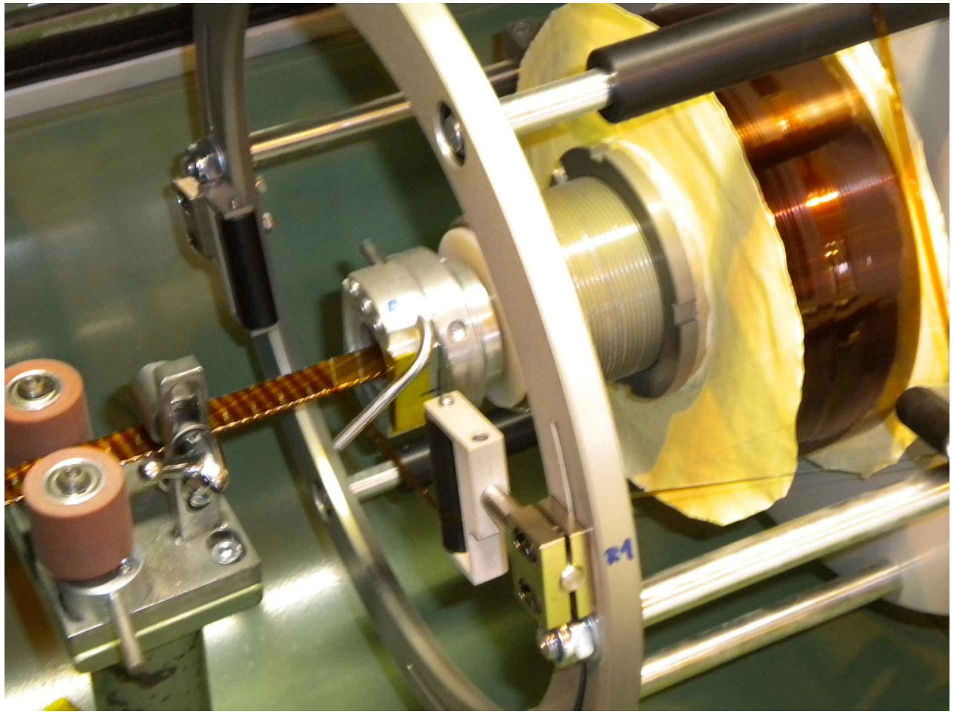
	4-block	6-block
Only outer layer: b_6	128.9	0.803
Only outer layer: b_{10}	-4.99	0.202
Only inner layer: b_6	-115.7	-0.905
Only inner layer: b_{10}	4.48	-0.227

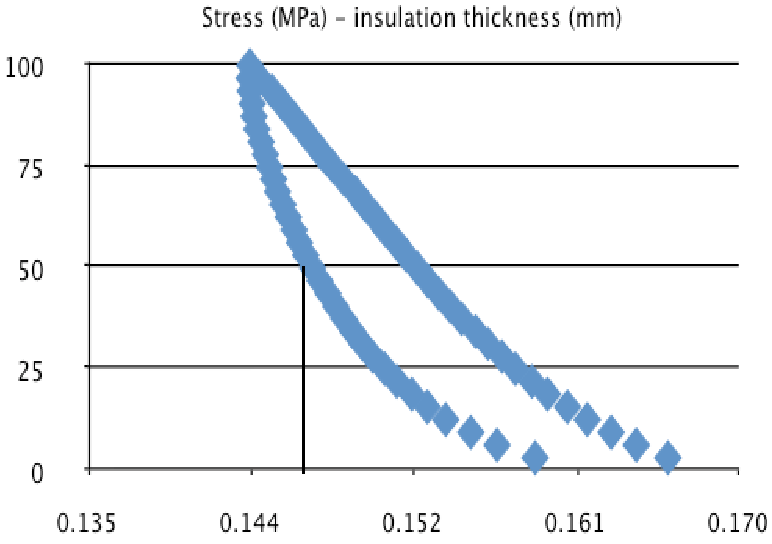


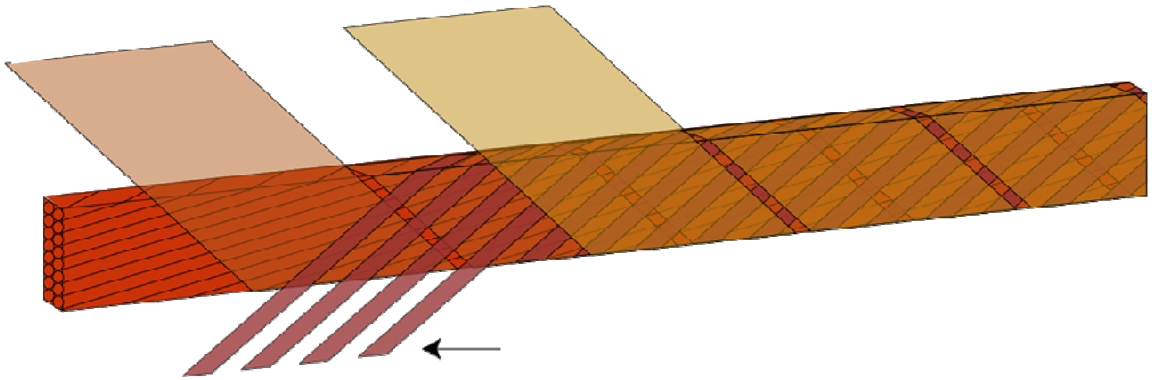


Improved Heat-Extraction (1: Porous Cable Insulation)

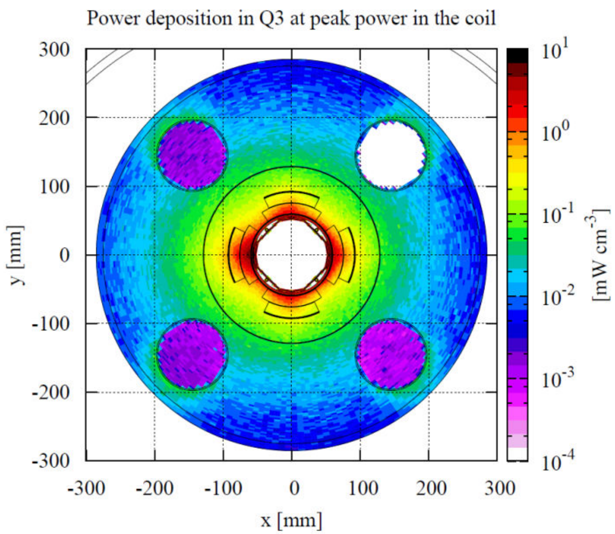


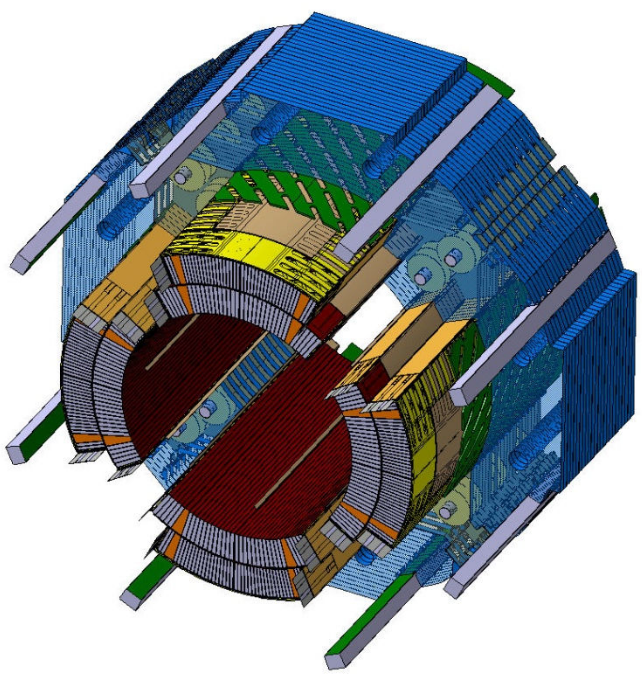


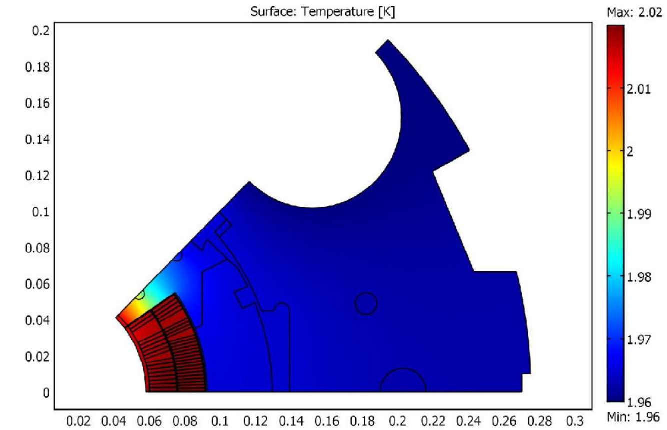


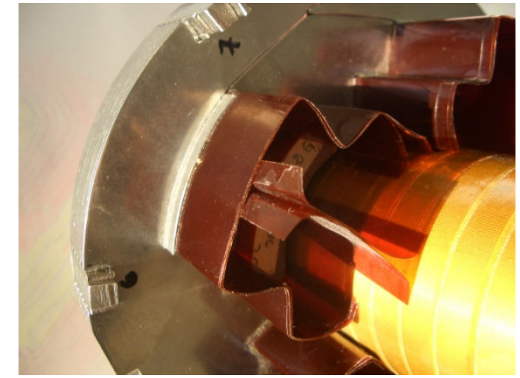


Improved Heat-Extraction (2: Porous Ground-Plane Insulation)

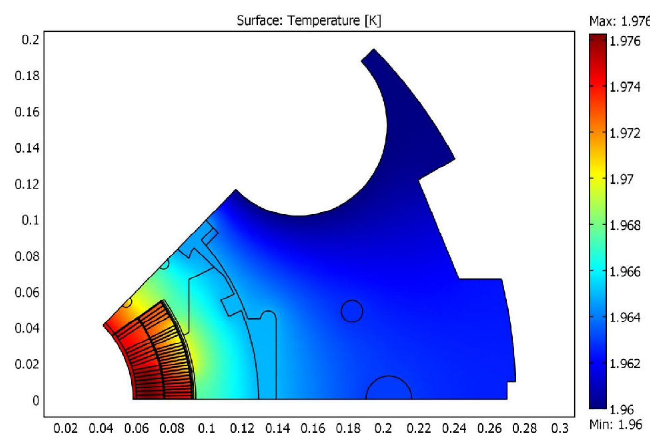


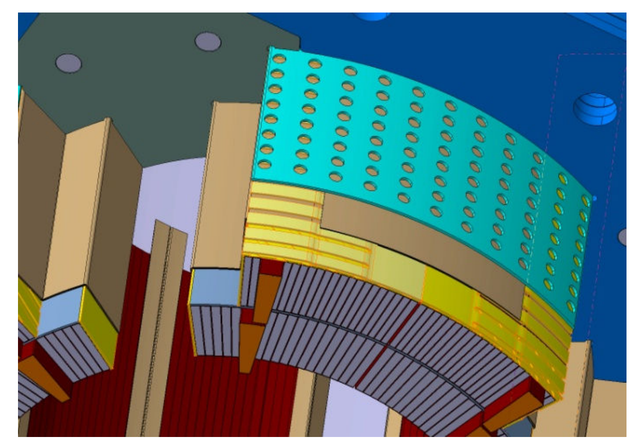






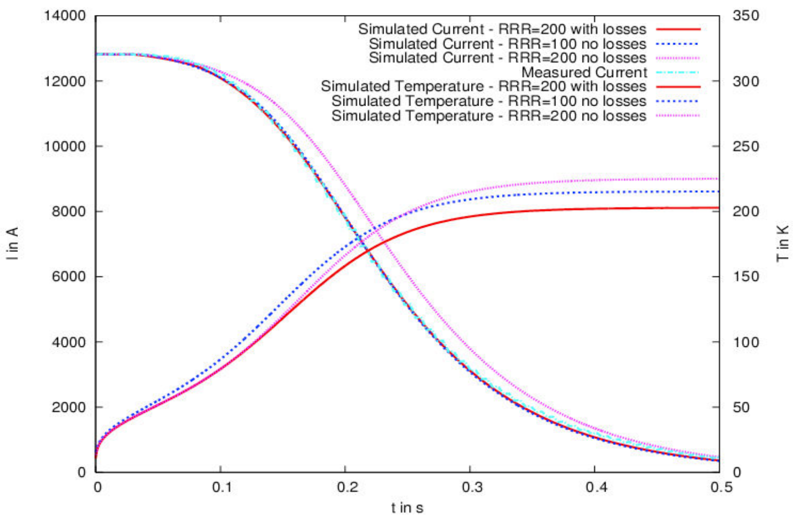
Conventional ground insulation

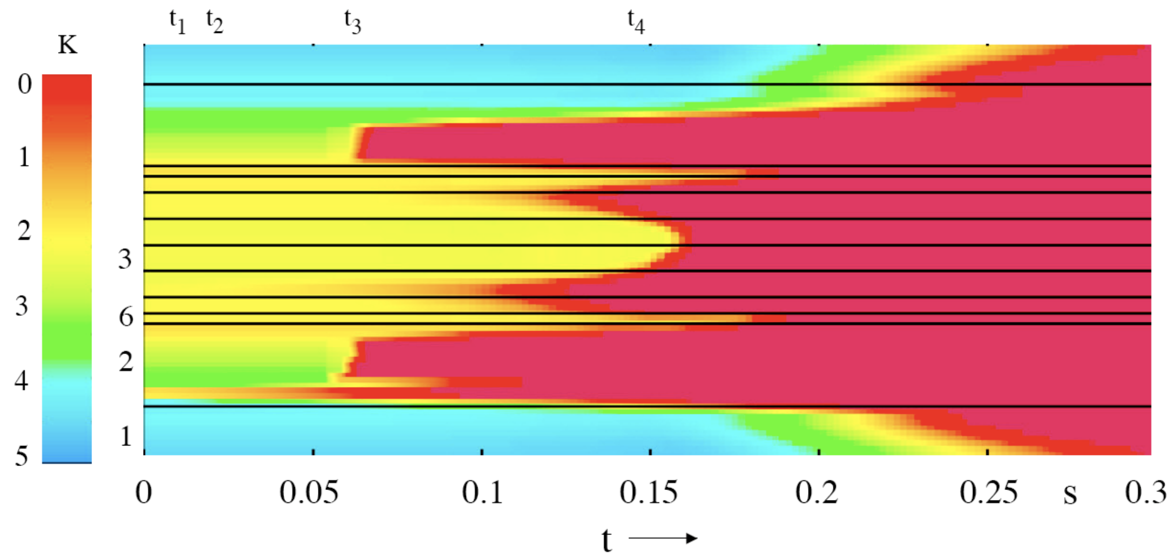


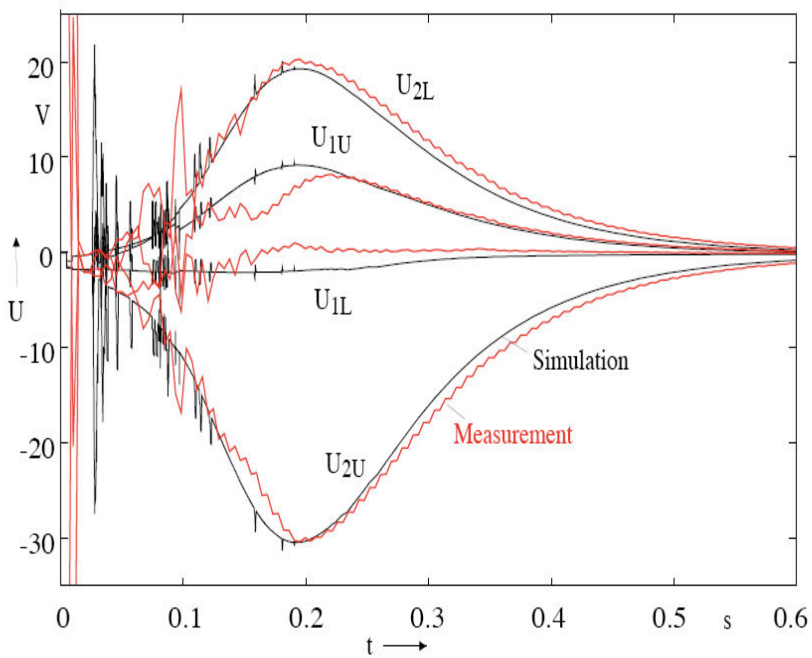


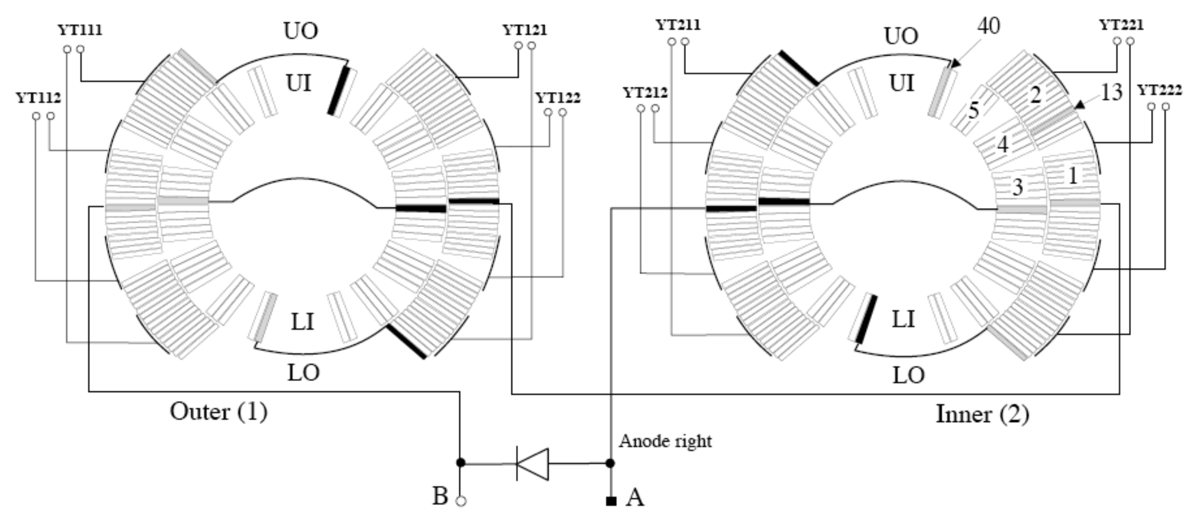
Open ground insulation

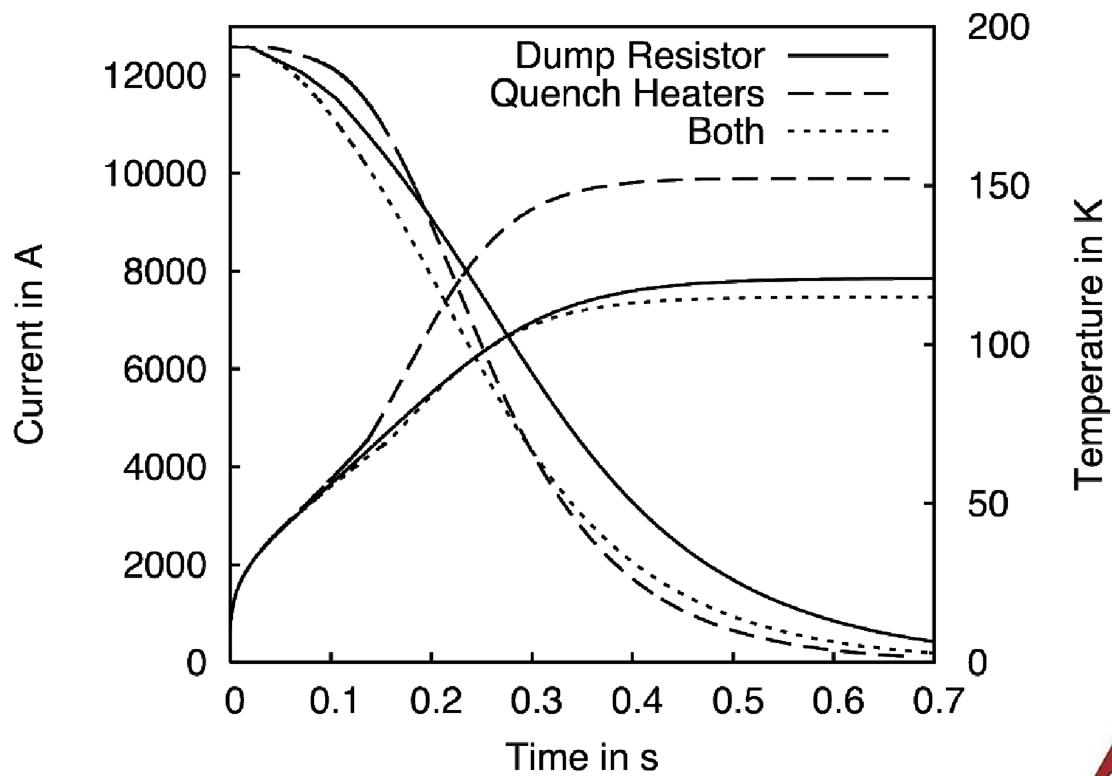
Quench Simulation (LHC MB)

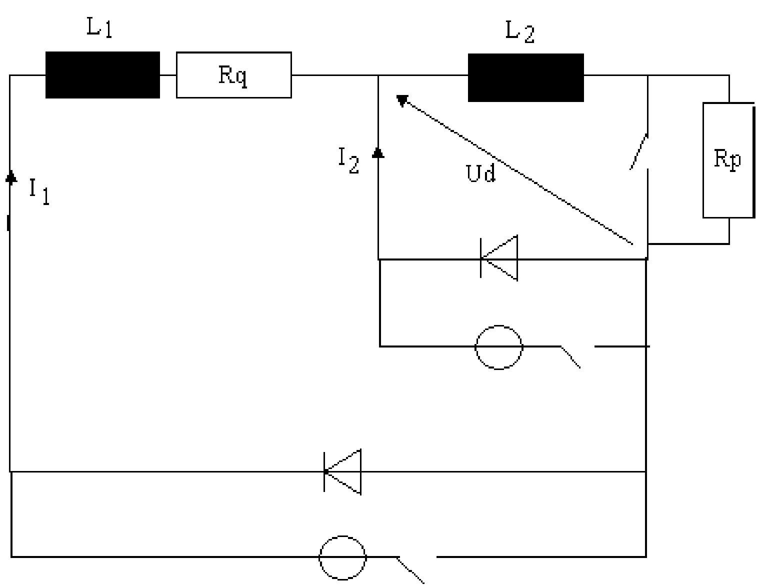


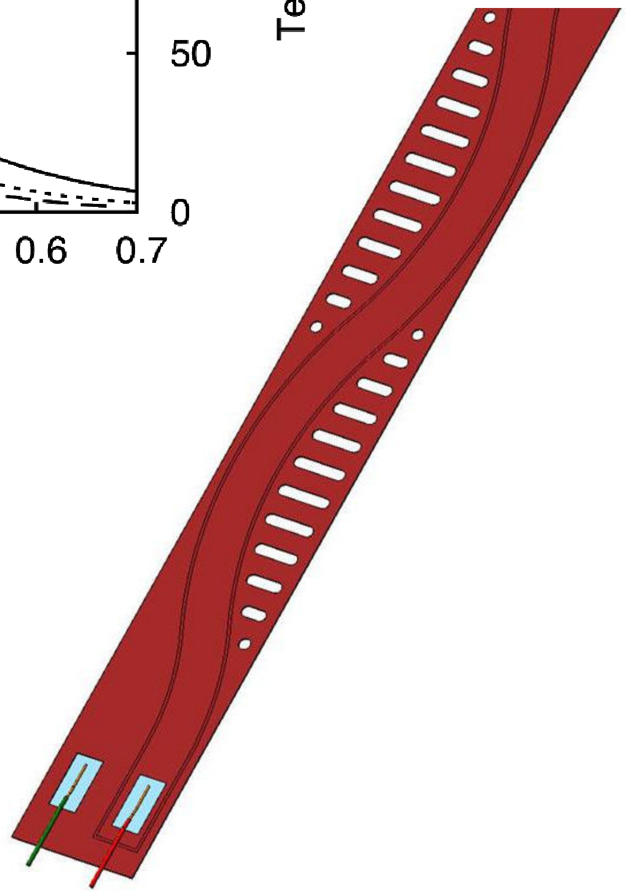






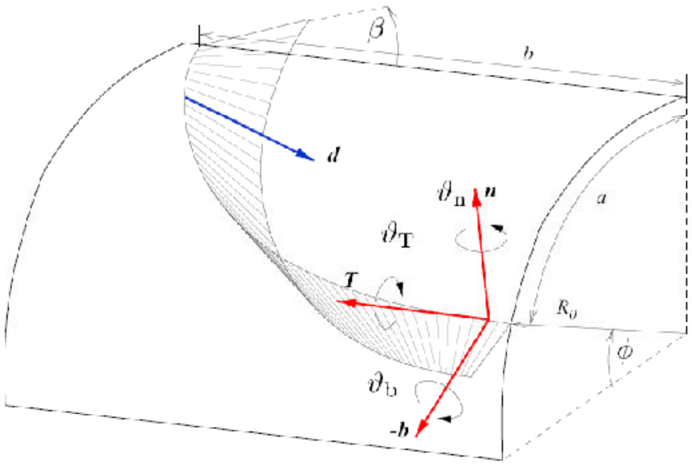

Dump Resistor
Quench Heaters
Both
Current in A
Temperature in K
Time in s
0
2000
4000
6000
8000
10000
12000
0
50
100
150
200
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7

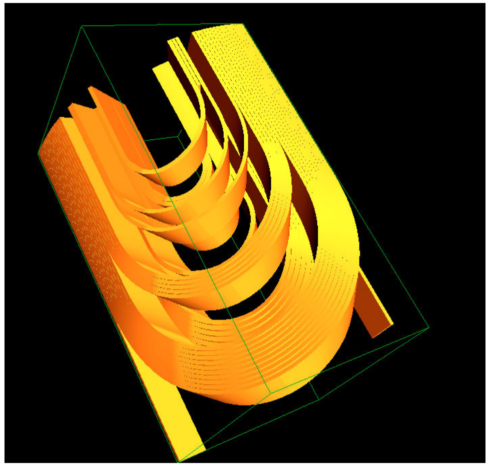

L1
Rq
L2
I2
Ud
Rp
I1



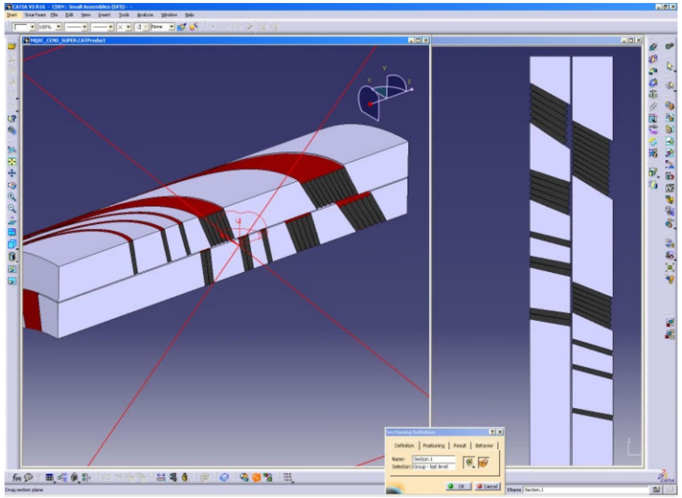
Endspacer Design and Manufacture

Differential Geometry Model

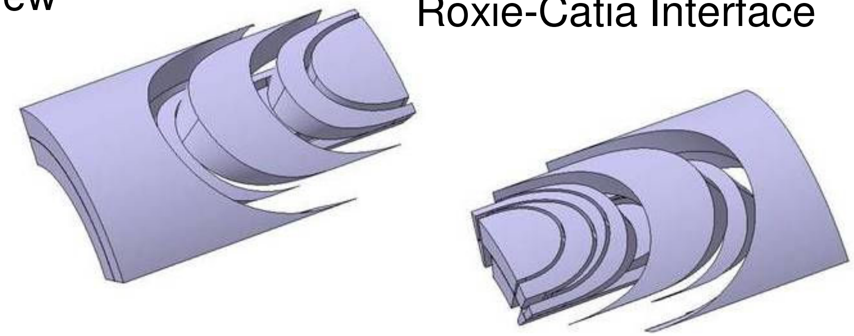




Virtual Reality Preview

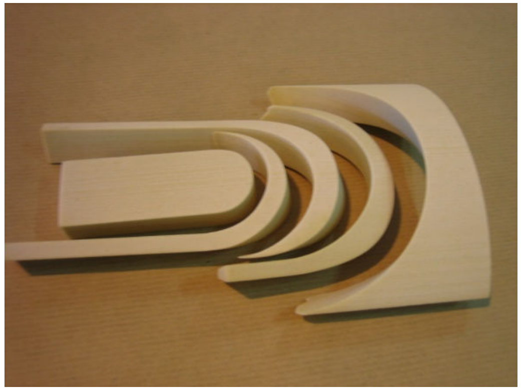


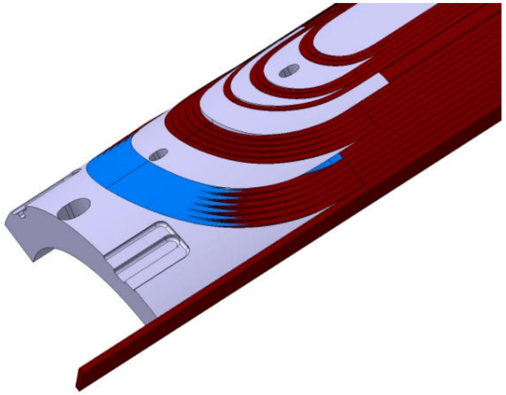
Roxie-Catia Interface



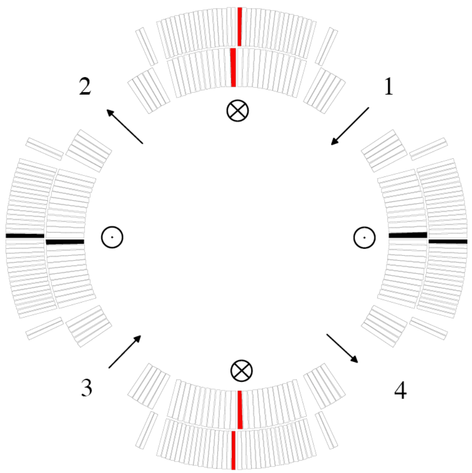
CNC-Machining

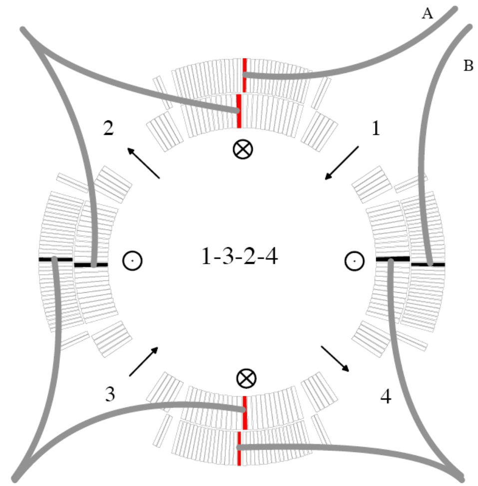
Rapid Prototyping

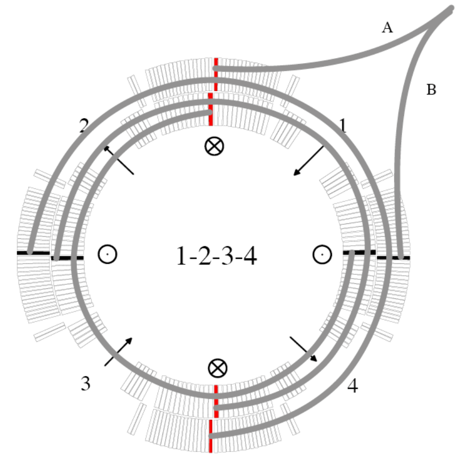


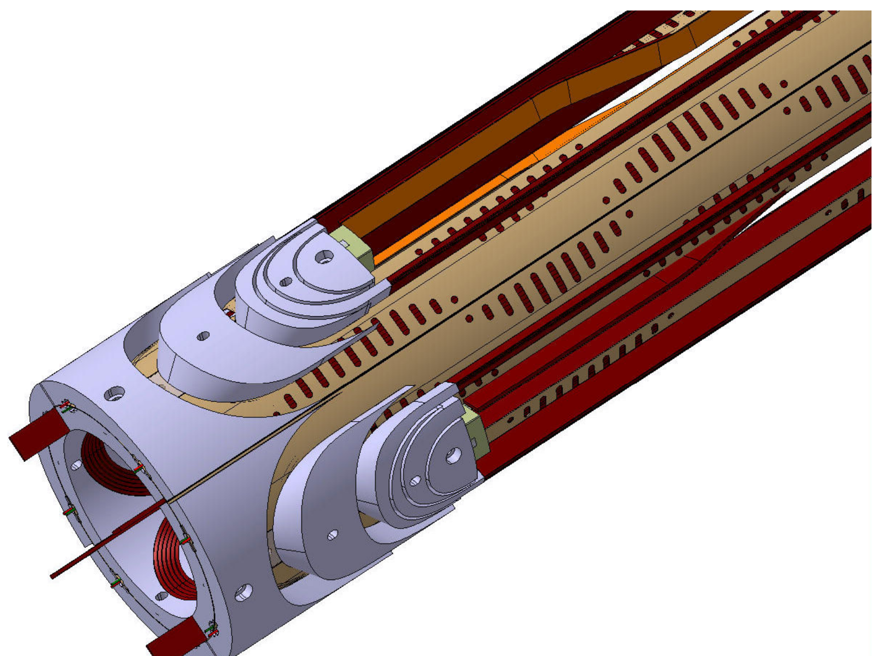


Electrical Connection Scheme

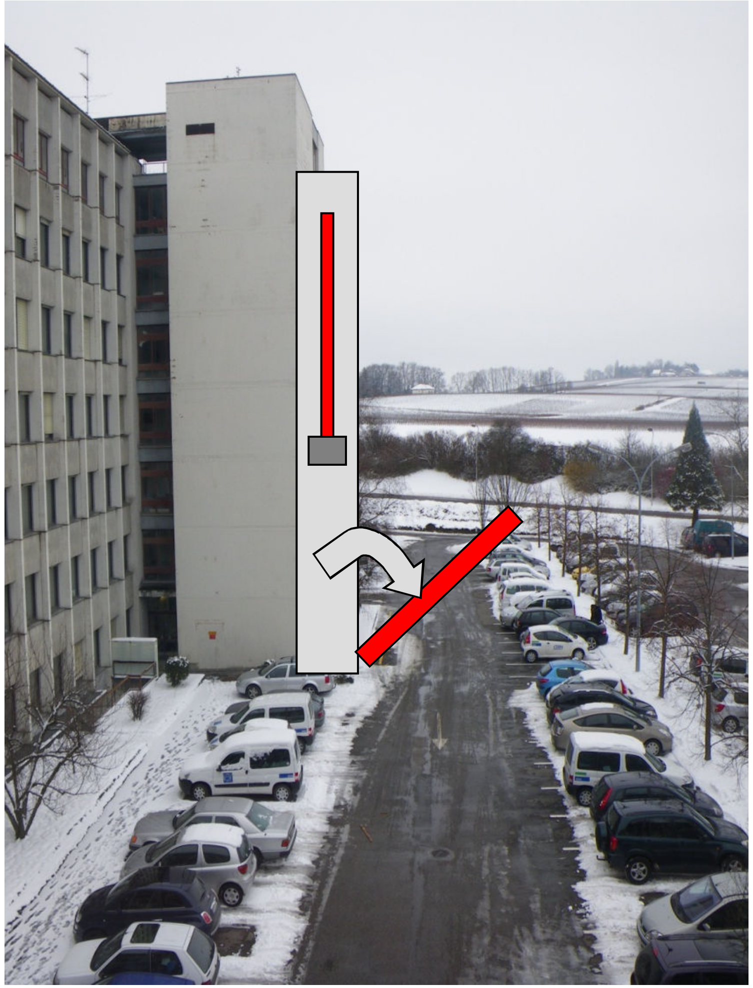






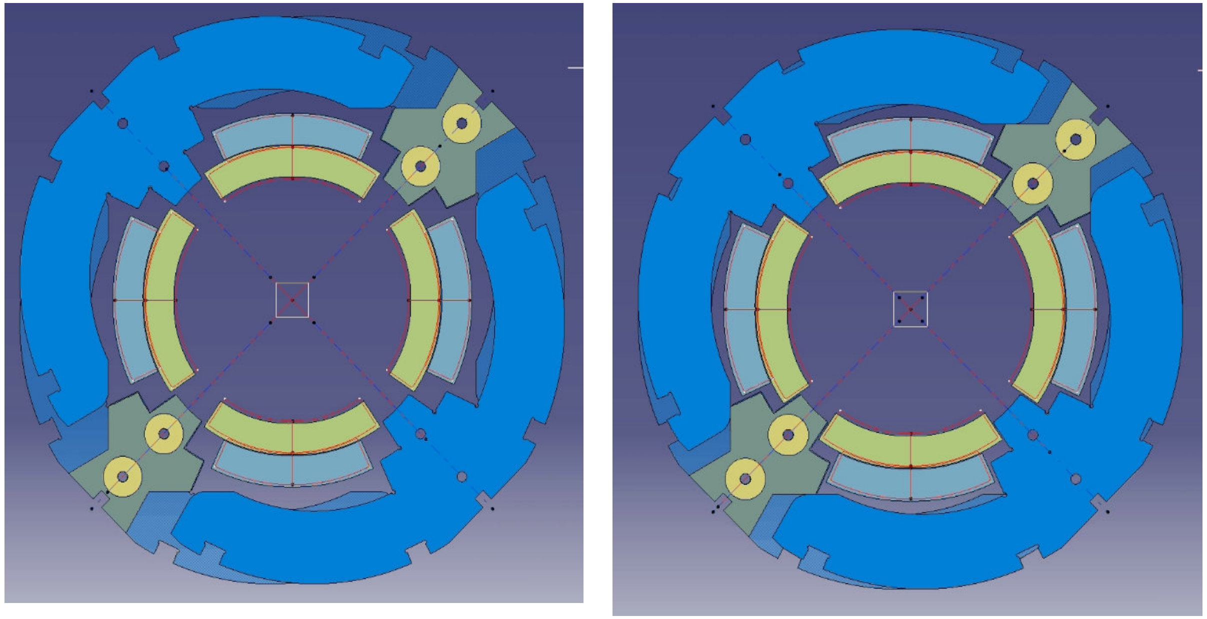


Vertical Collaring (Hardly Possible for 10-m-long Magnets)

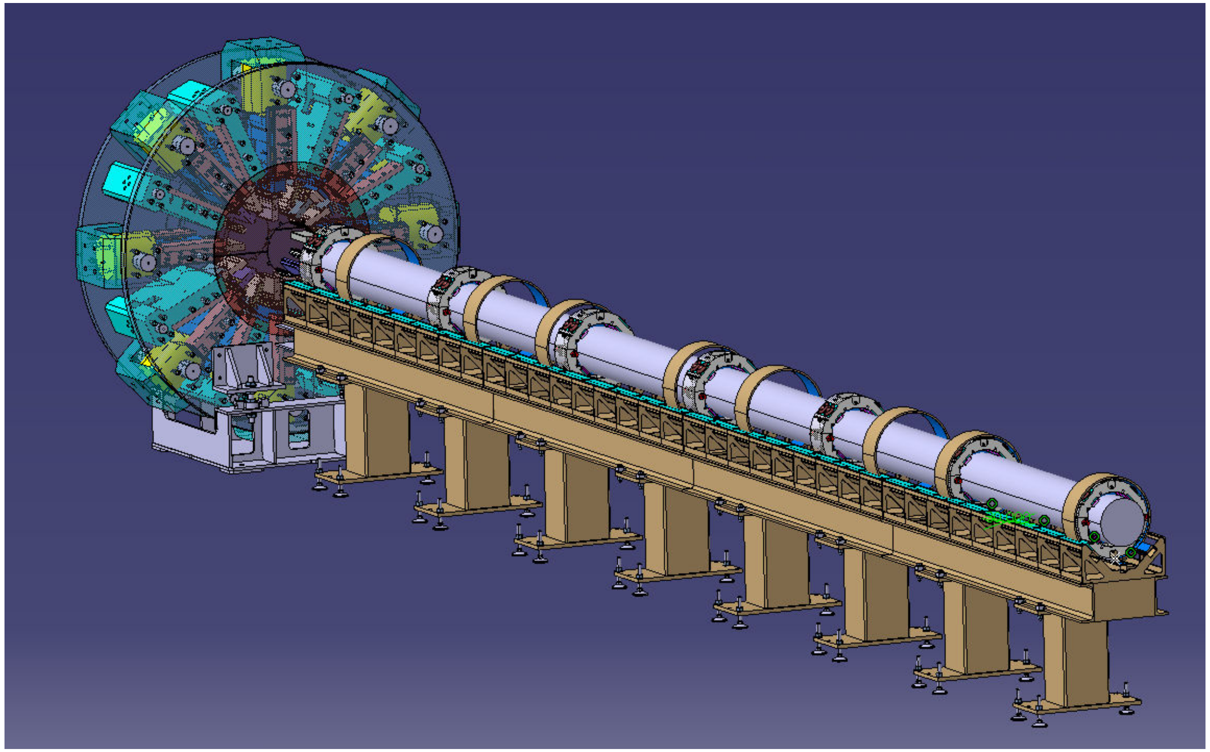


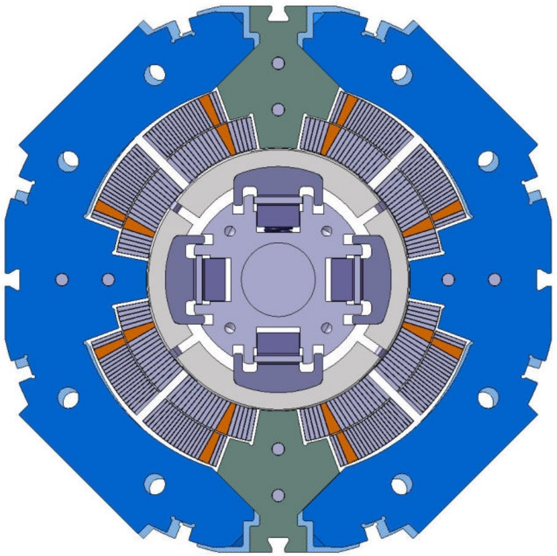
Horizontal Collaring

Self-locking collars



Collaring Press





Assembly mandrel

Large Magnet Facility (Building 180)

Cable insulation

Ex-Ansaldo winding machine

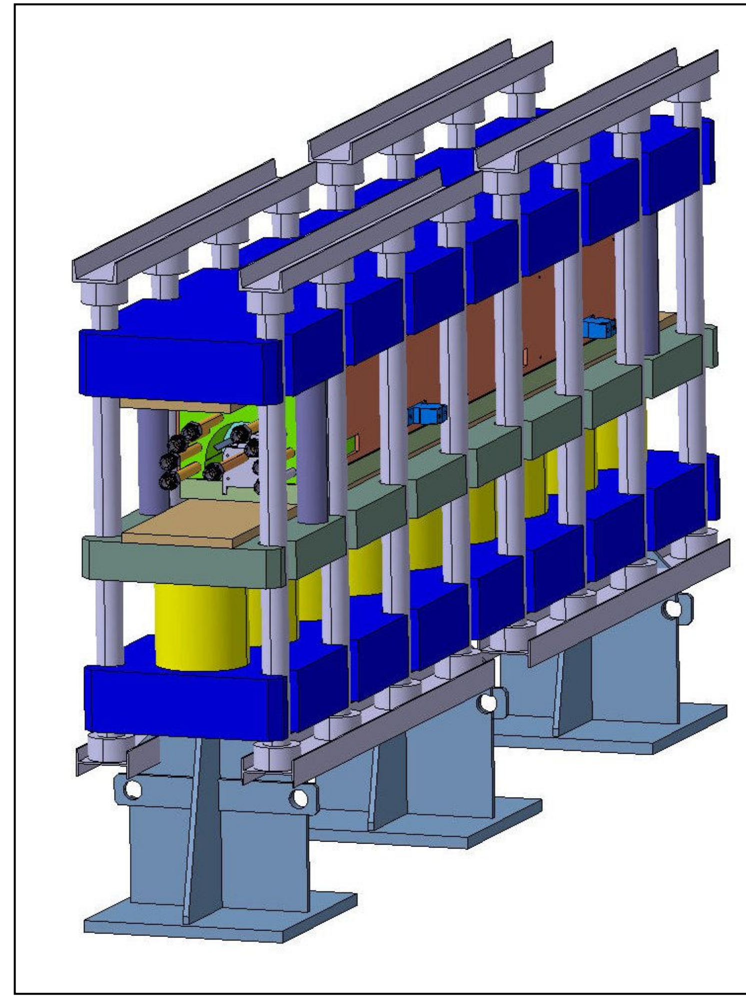
Alignment tables

Ex-Jeumont winding machine

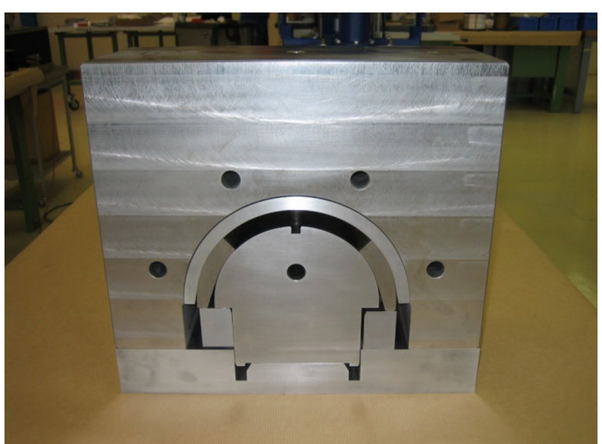
Welding press area

Re-Commissioning of Tooling in 927

Winding machine

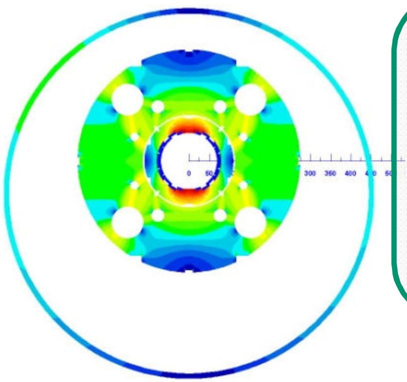


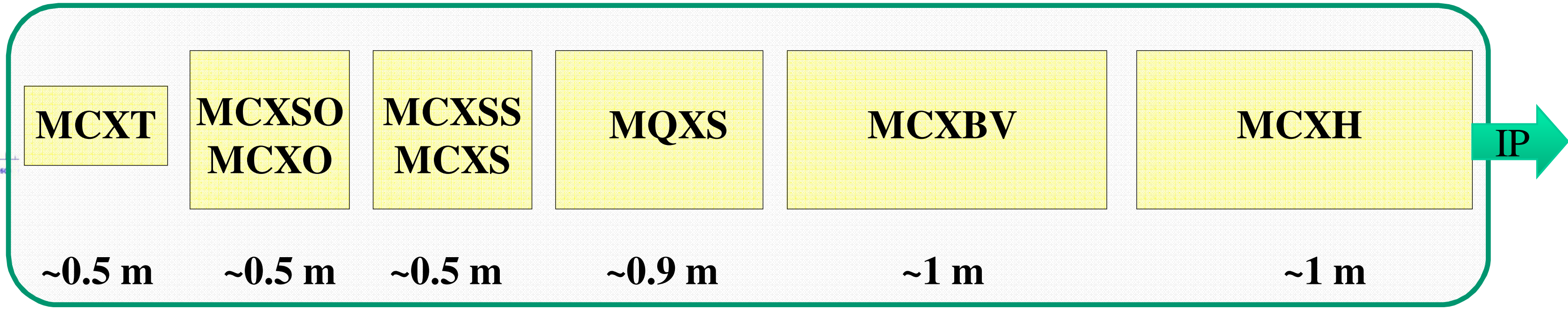
Curing press



Modulus tester

Corrector Package

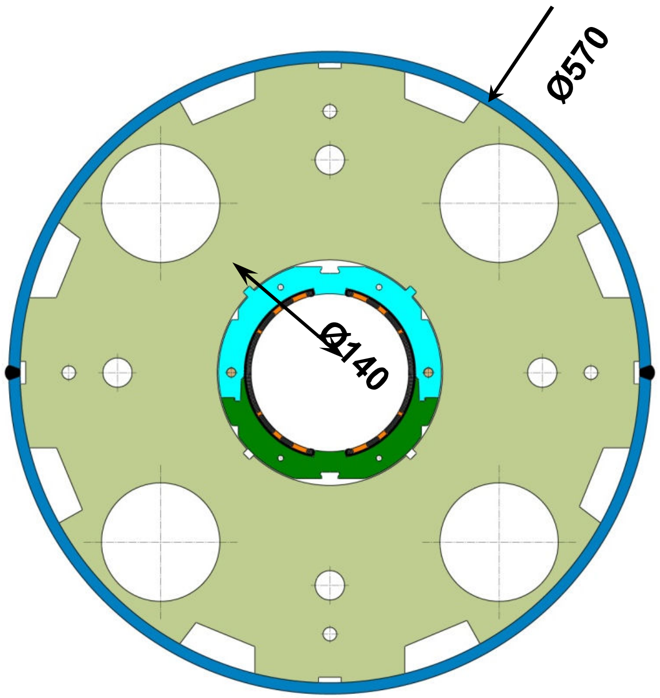


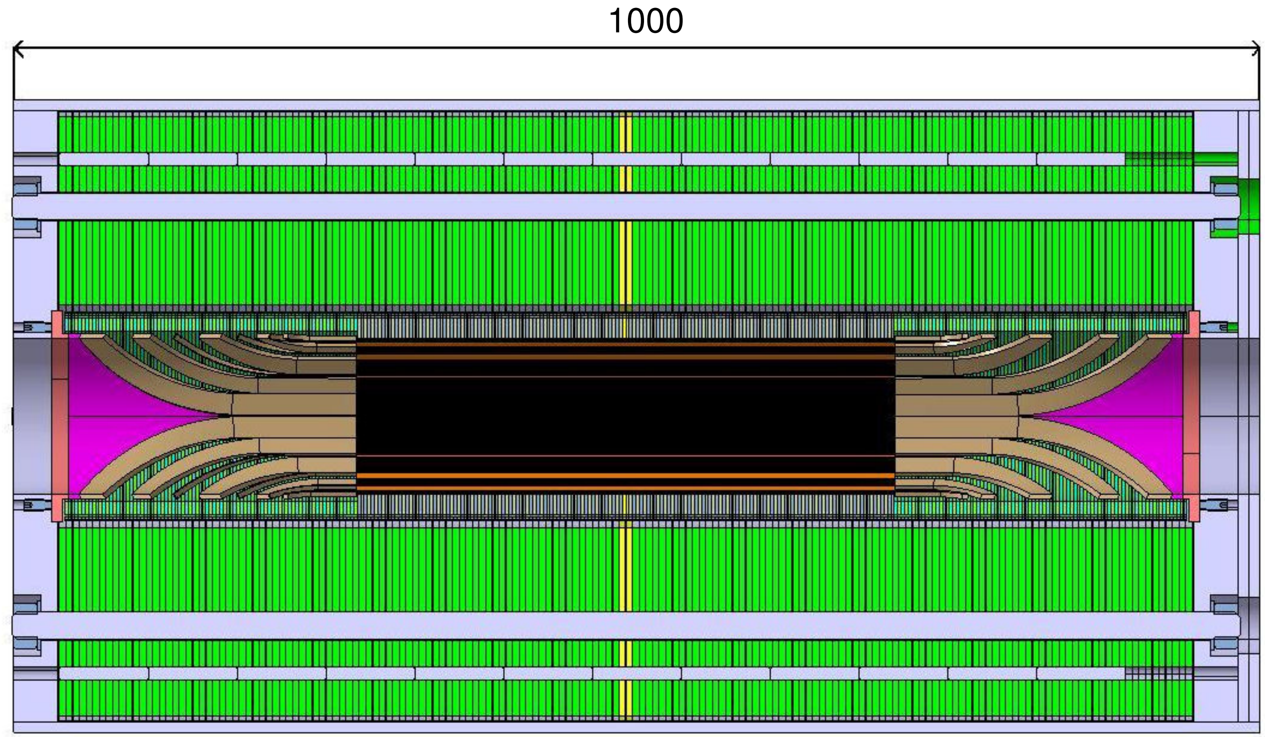


	Current	Integrated strength (field)	Aperture
MCXB (B_1/A_1)	**+/- 2.4 kA**	**1.5 Tm**	**140 mm**
MQXS (A_2)	**+/- 2.4 kA**	**0.65 Tm @40 mm**	**140 mm**

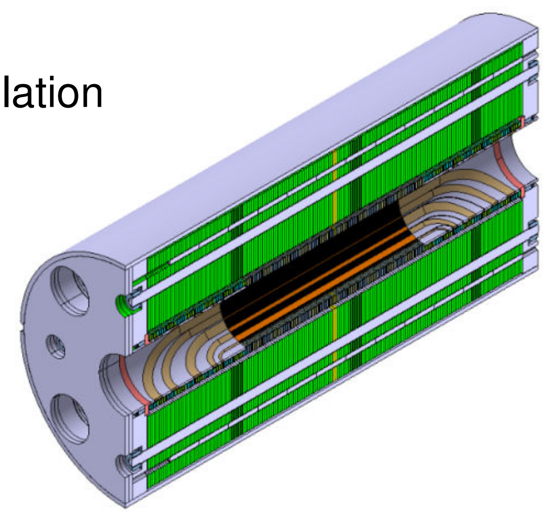
MCXT (B_6)	+/- 120A	*0.075 Tm @ 40 mm*	*140 mm*
MCXO (B_4)	+/- 120A	*0.035 Tm @ 40 mm*	*140 mm*
MCXSO (A_4)	+/- 120A	*0.035 Tm @ 40 mm*	*140 mm*
MCXSS (A_3)	+/- 120A	*0.055 Tm @ 40 mm*	*140 mm*
MCXS (B_3)	+/- 120A	*0.055 Tm @ 40 mm*	*140 mm*

MCXB 4-Block Design





New 4.37 mm cable & Polyimide insulation
Self-supporting collars
Single piece yoke

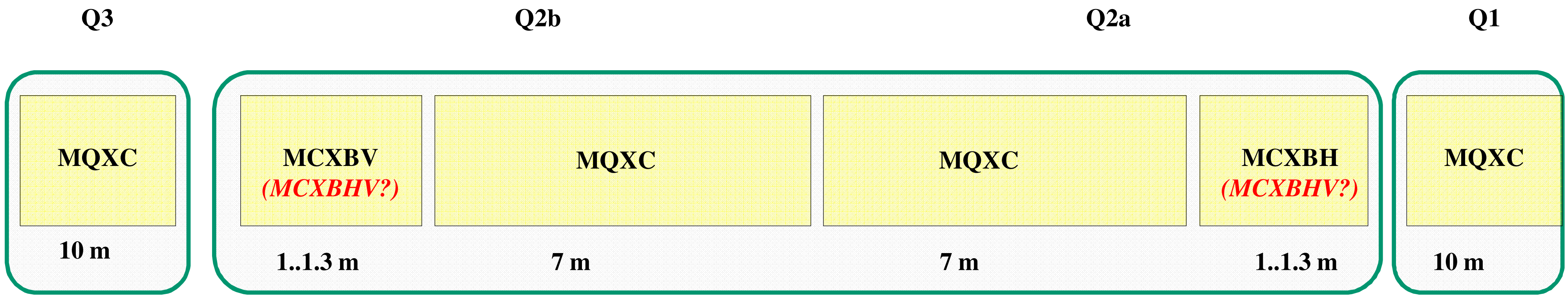


Field strength	**1.5 Tm**
Operating temp	**1.9 K**
Current	**2.4 kA**
Inductance	**10 mH**

Milestones… (MCXB & MQXS)

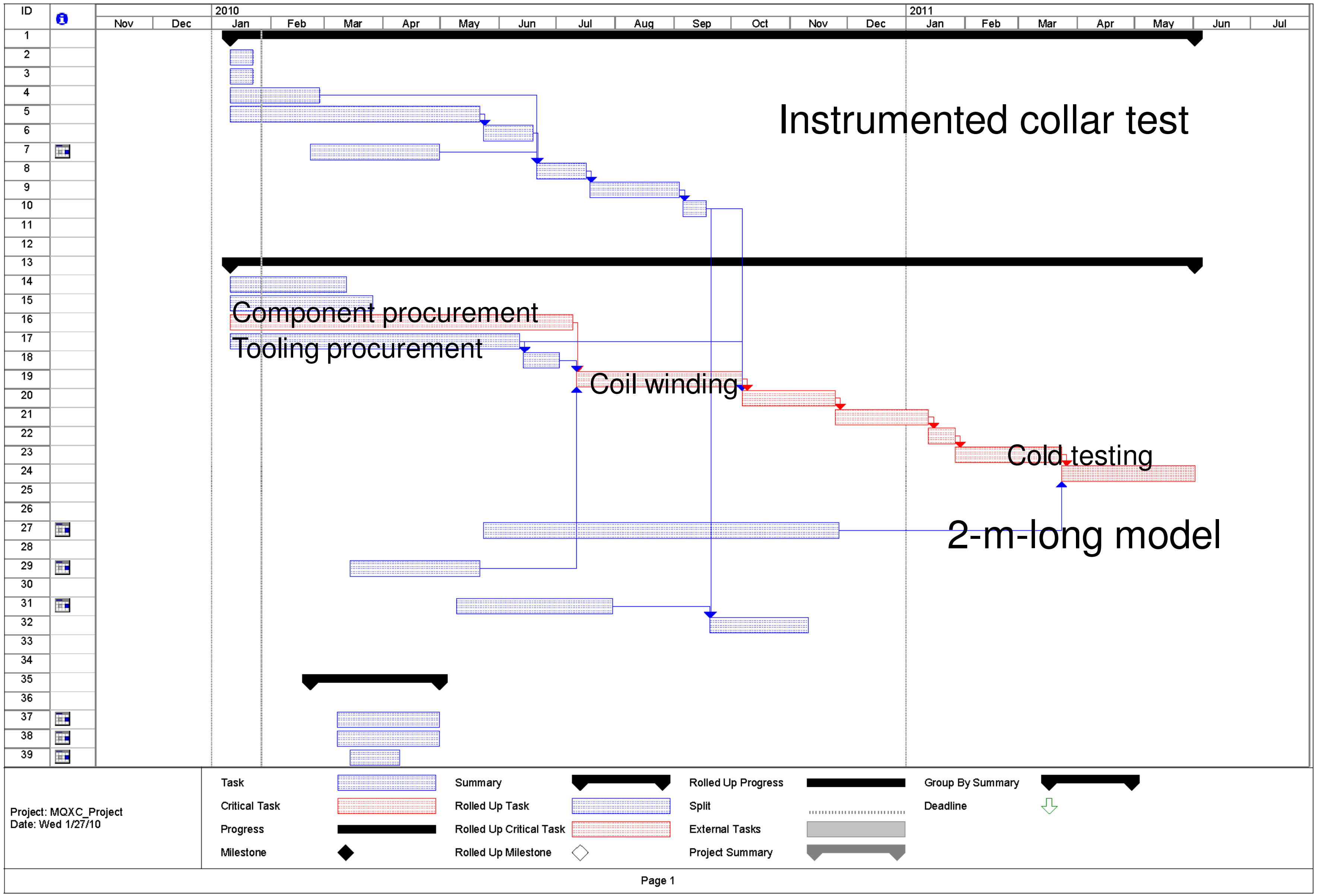
→ Parameter list	October 09 / January 10
→ Magnetic and mechanical design	November 09
→ Fabrication drawings	May 10
→ Trial coils	July 10
→ Mechanical model	May 10 / July 10
→ Model magnets completed	December 10
→ Technical specifications	March 11
→ Industrial contracts	July 11
→ Pre-series magnets	July 12
→ Series production	September 12 / December 13

Correctors in Q2



- ➔ To reach the same level as the effective BPM resolution:
  - Provide 1.5 Tm (1.8 Tm) in H&V-plane in BOTH locations.
  - Feasibility study underway on combined H/V-corrector that meets the reliability requirements (Report by Mid-2010 + Model work..)
- ➔ An extra H/V pair means:
  - Magnet R&D, material R&D, design, component & tooling procurement
  - Additional powering and protections circuits

Planning (Only MQXC)



Collaboration Website