FUSION FOR ENERGY

The European Dipole Project

A Portone, Fusion For Energy

OUTLINE

1. Design (Specs, design options, key features)
2. Manufacturing (DC Coils Winding, Reaction Heat Treatment, Impregnation)
3. Acceptance Tests (Electrical and Hydraulic tests, insulation repair work)
4. Conclusions

Special thanks to: Amend, Baker, Bauer, Bertinelli, Besi, Bruzzone, Cau, della Corte, Di Zenobio, Duglue, Fernandez, Fabbricatore, Gartner, Maccaferri, March, Molinari, Musenich, Salpietro, Sattler, Scheller, Stepanov, Testoni, Theisen, Vogel, Vostner, Weiss, Wesche

MAGNET DESIGN

SPECIFICATIONS

Specifications

- Magnet test facility for sc samples with current up to I~100 kA
- Background DC field B_{DC}=12.5 T in clear bore
- Rectangular (circular) clear bore of 15 x 10 cm^2(∅ =13 cm)
- AC field with B_{AC}~±0.3 T, f~1-5 Hz, B_{DC}~2-3 T ($B_{AC} \perp B_{DC}$)

To assess the design options, common reference were set for:

- Strand scaling (Summer)

  ➔ B_{c20m} =28 T, T_{c0m} =18 K, J_c(12T, 4.2K, -0.25%) = 2000 A/mm^2
- Thermal strain ε_{th} = –0.6% for CICC, otherwise ε_{th} = –0.3%
- Index n = 7 for CICC
- Delay for current dump t_0 = 0.25 s, dump voltage < 2 kV
- Turn Insulation 0.4 mm wrap, ground insulation 2 mm thick

SPECIFICATIONS

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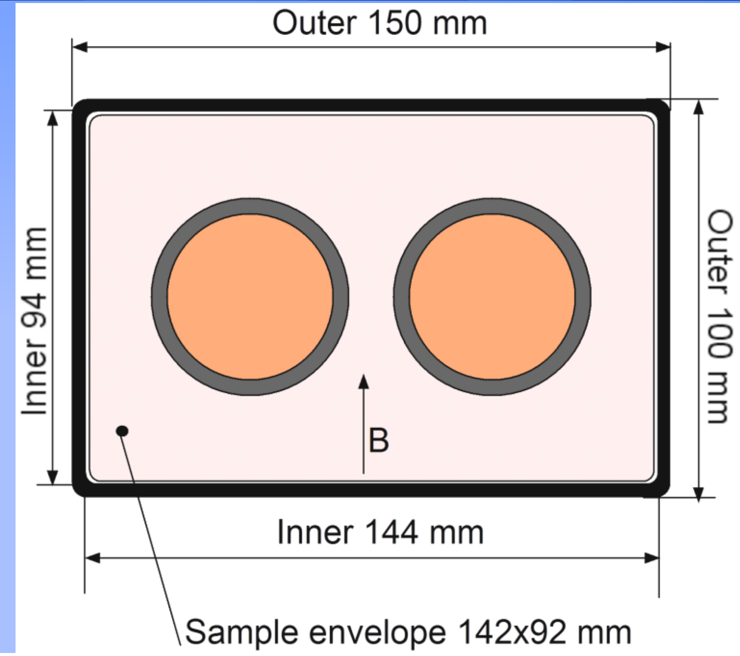
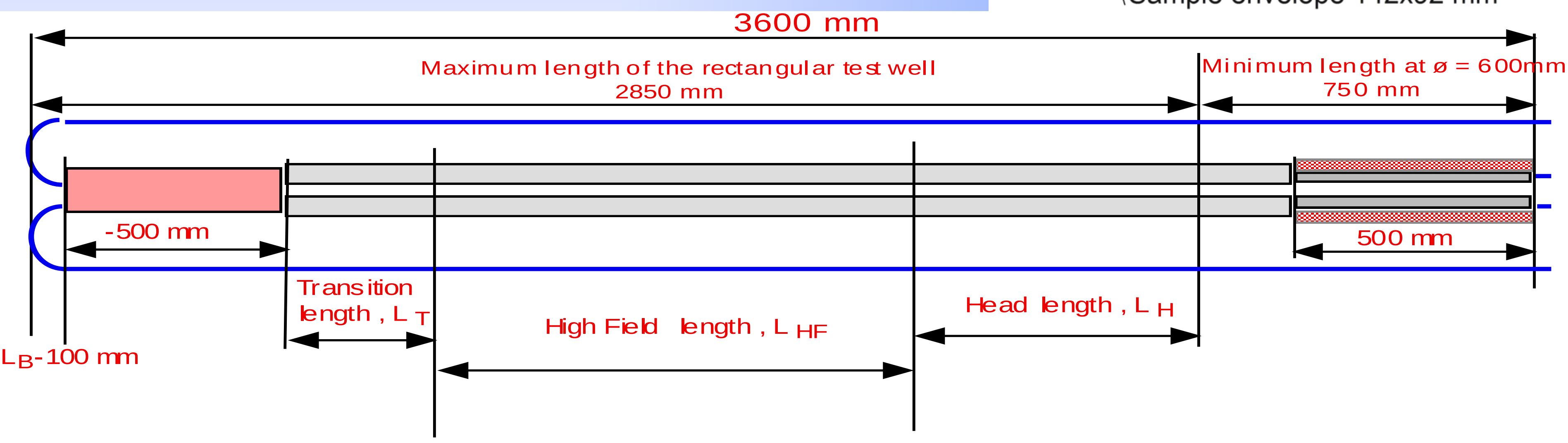
Facility constraints

- CRPP/PSI Villigen, next to SULTAN facility
- Cold mass weight <20 t (crane)
- Cold mass height <3.5 m (ceiling)
- (SULTAN sample holder exchangeability)





Cos(θ) design (JM Rifflet et al. CEA)

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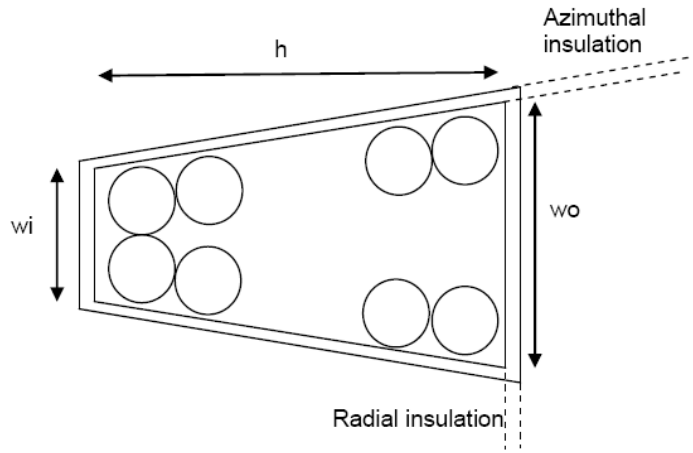
$$h = 1.04 * \frac{N}{2} * \phi$$

$$wi = 2 * 0.87 * \phi$$

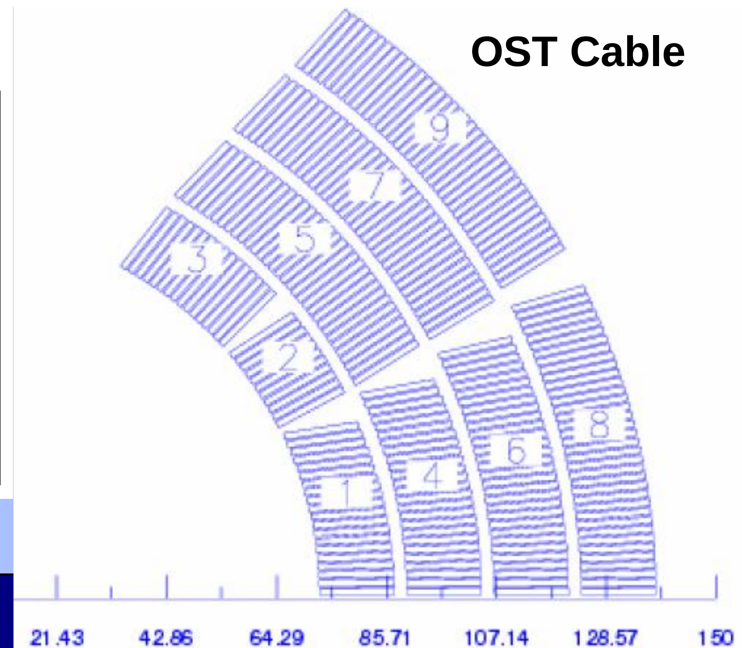
$$wo = 2 * 0.95 * \phi$$



Where ϕ is the strand diameter, h the cable height, wi the small side thickness, wo the large side thickness and N the number of strand in the cable.

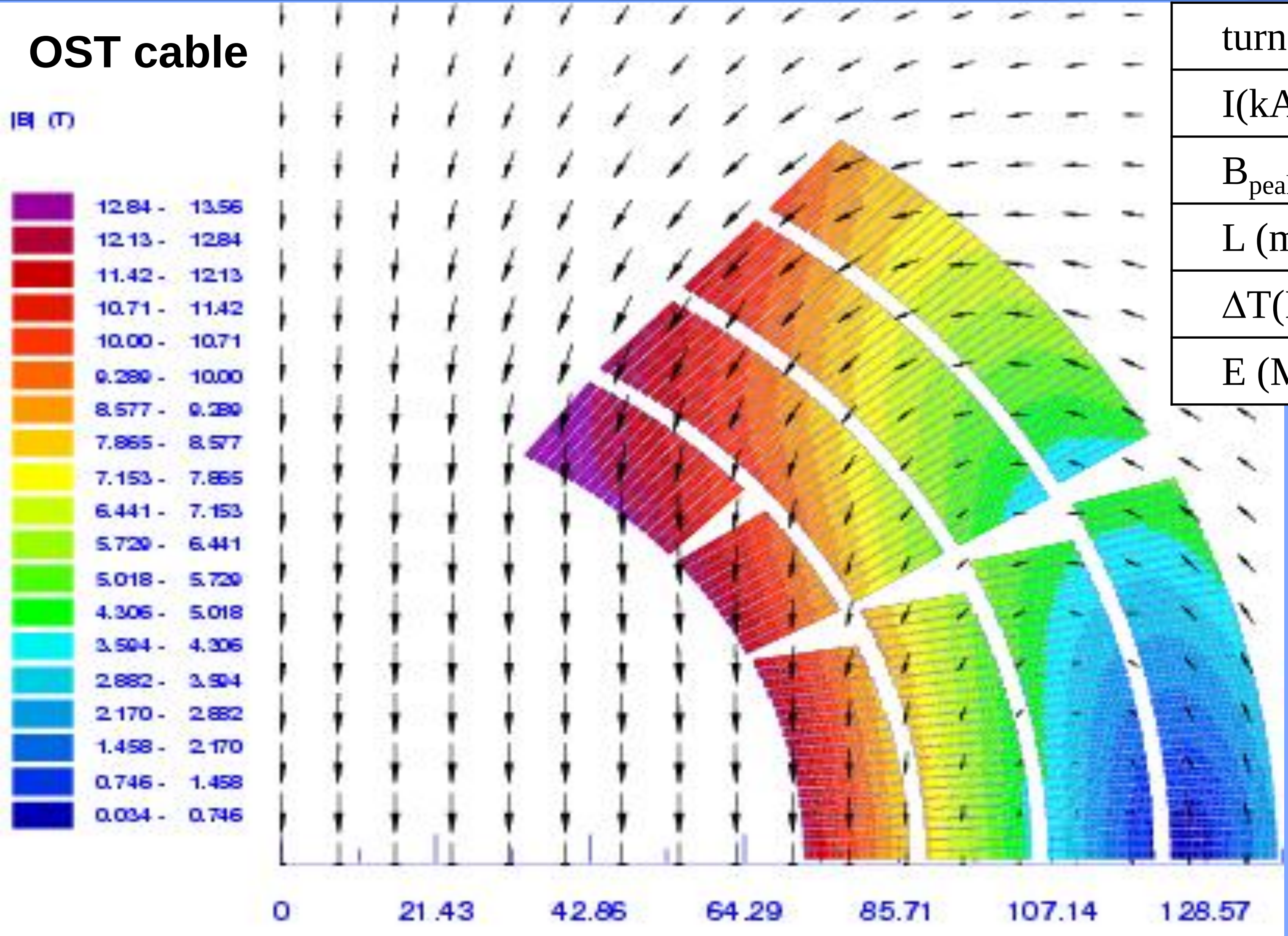
	OST cable	Alstom cable
h (mm)	14.56	17.16
wi (mm)	1.218	1.436
wo (mm)	1.330	1.568
Mid thickness (mm)	1.274	1.502
Radial insulation thickness (mm)	0.2	0.2
Azimuthal insulation thickness (mm)	0.2	0.2

Block	Layer	Number of conductors
1	1	20
2	1	11
3	1	16
4	2	25
5	2	32
6	3	30
7	3	35
8	4	36
9	4	37



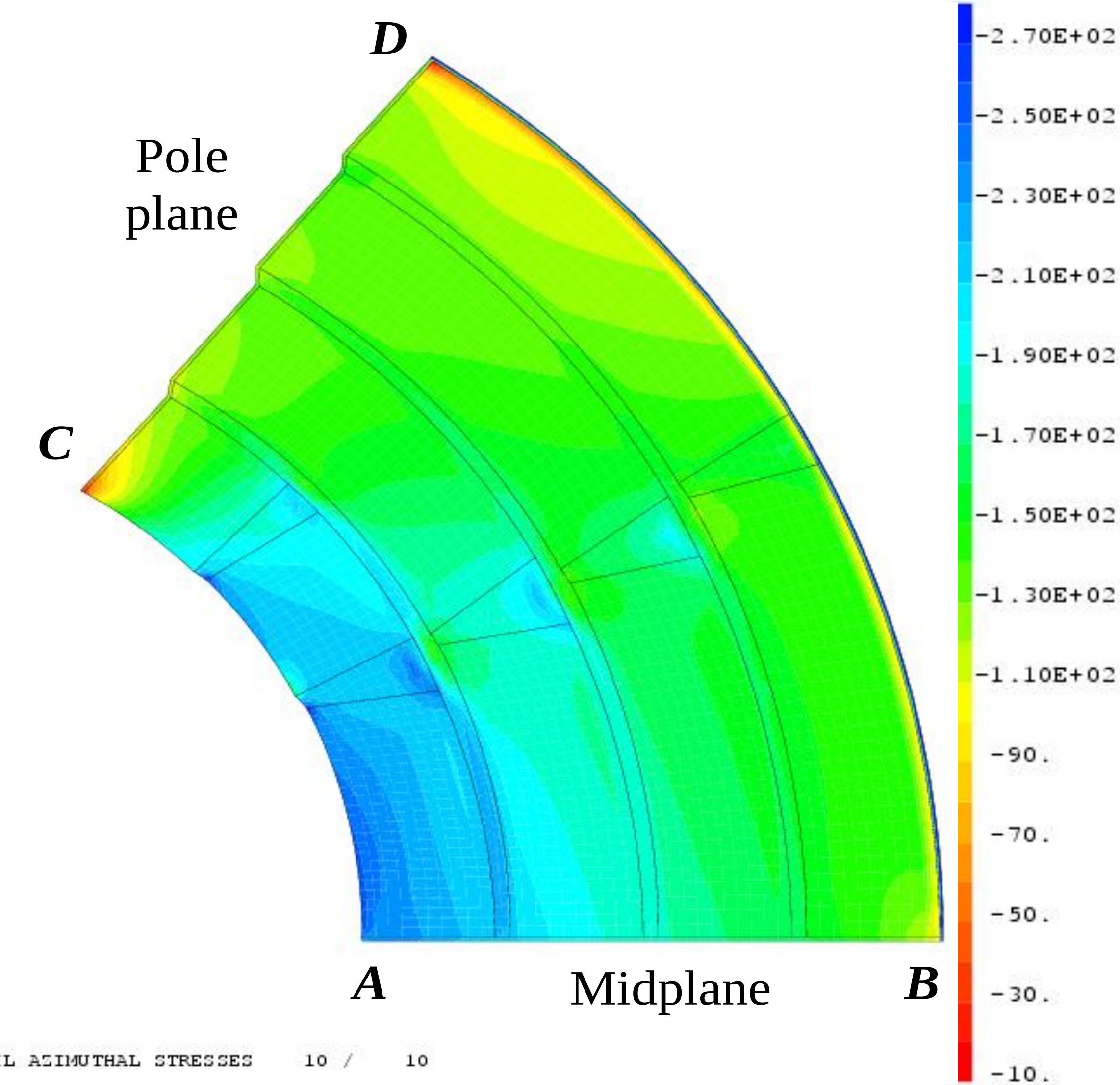
Cos(θ) design (JM Rifflet et al. CEA)

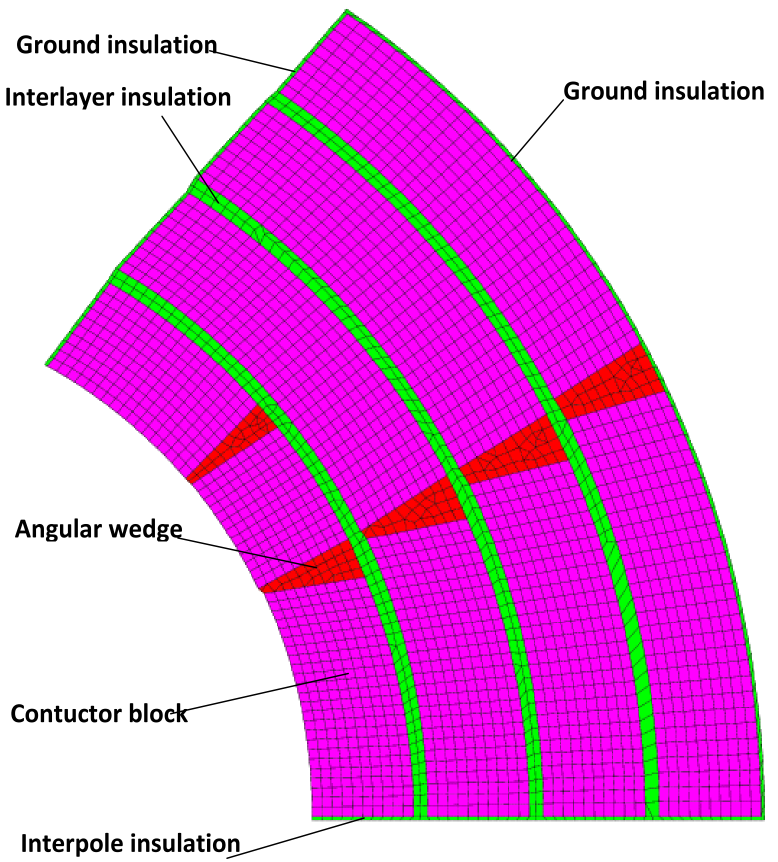
OST cable



turns	242
I(kA)	6.51
B_{peak} (T)	13.56
L (mH/m)	142
ΔT(K)	1.9
E (MJ/m)	3.00

Cos(θ) design (JM Rifflet et al. CEA)





Cos(θ) design (JM Rifflet et al. CEA)

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Coils	Cool down		Energization	
Stress (MPa)	σ_θ	σ_r	σ_θ	σ_r
Average over coil	**-157**	-52	**-160**	-78
Average over mid-plane	-142		-178	
Average over pole plane	-177		-112	
Minimum over pole plane	-23		-10	
Point A	-182		**-231**	
Point B	-75		-103	
Point C	-188		-35	
Point D	-23		**-10**	
Displacement (mm)	Δ_θ	Δ_r	Δ_θ	Δ_r
Average over midplane		-0.696		-0.582
Average over pole plane	-0.144	-0.775	-0.190	-0.779
Collars Peak von Mises stress	1292		1236	

Cos(θ) design (JM Rifflet et al. CEA)

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Conclusions (CEA)

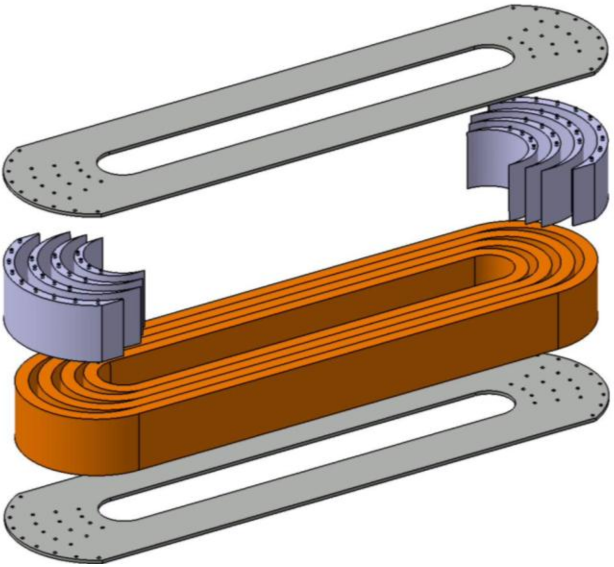
1. Safety margin on load line < 10 %
2. Protection OK, but quench heaters needed on each layer
3. Losses acceptables for 0.01 T/s
4. Mechanics : Stresses on coils are too high
5. → Alternative mechanical structure → time consuming development
6. → or decrease of B^2R by 35 % ??
    1. ∅ 130 mm → B ~ 10 T
    2. B = 12.5 T → ∅ coil ~ 94 mm → ∅ ~ 80 mm

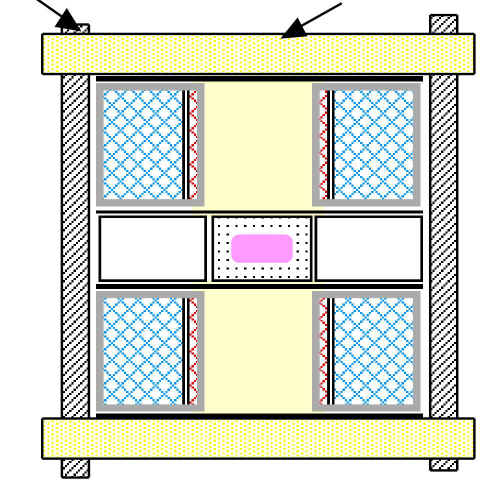
Final assessment: Cos(θ) design

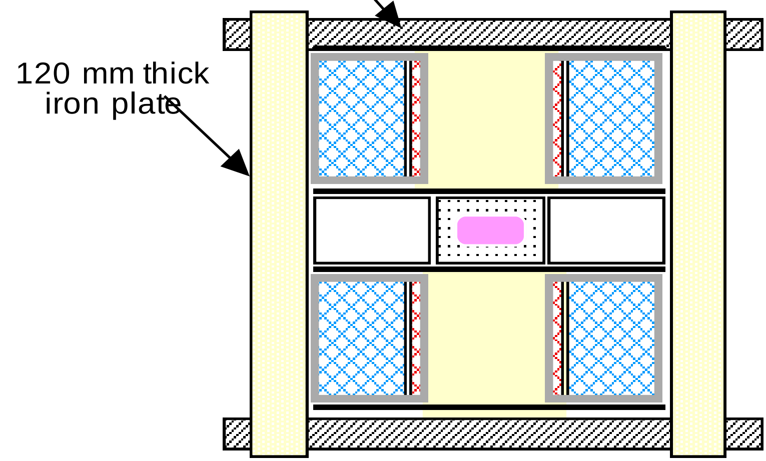
➔Excellent compactness, field quality and magnetic design features

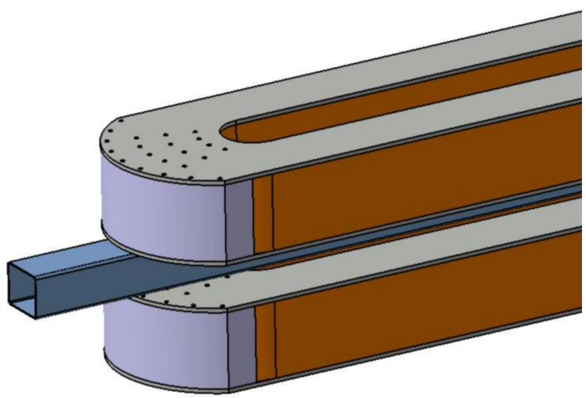
➔However, this design did not seem mature for its engineering phase since the results presented show the need of a substantial improvement from the mechanical design standpoint (Von Mises stresses in the collar structure exceed 1.2 GPa, peak stresses in strands ~ 230 MPa i.e. ~ 50% above maximum allowable)

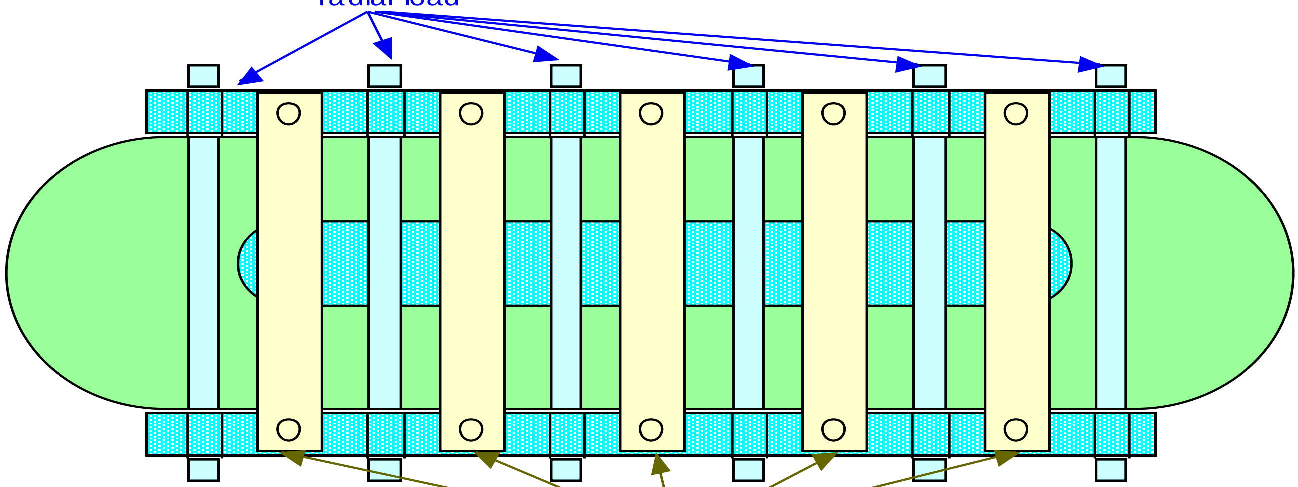
Racetrack design (P Bruzzone et al. CRPP)





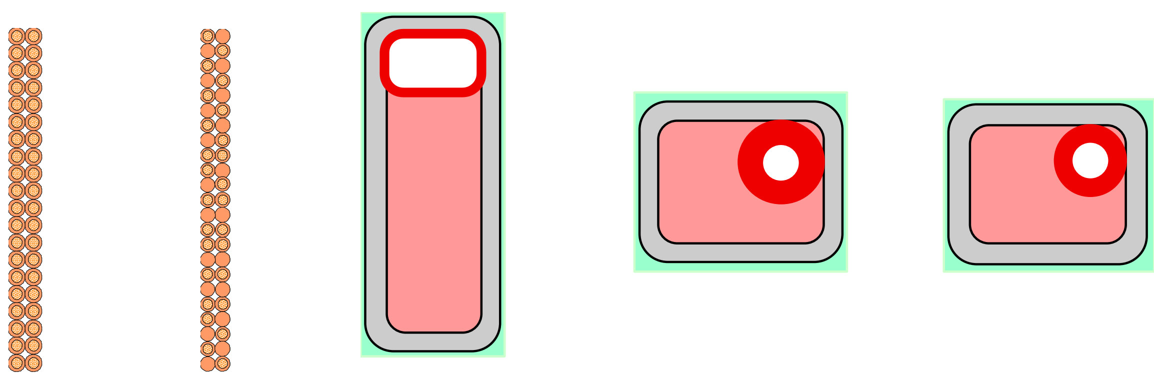






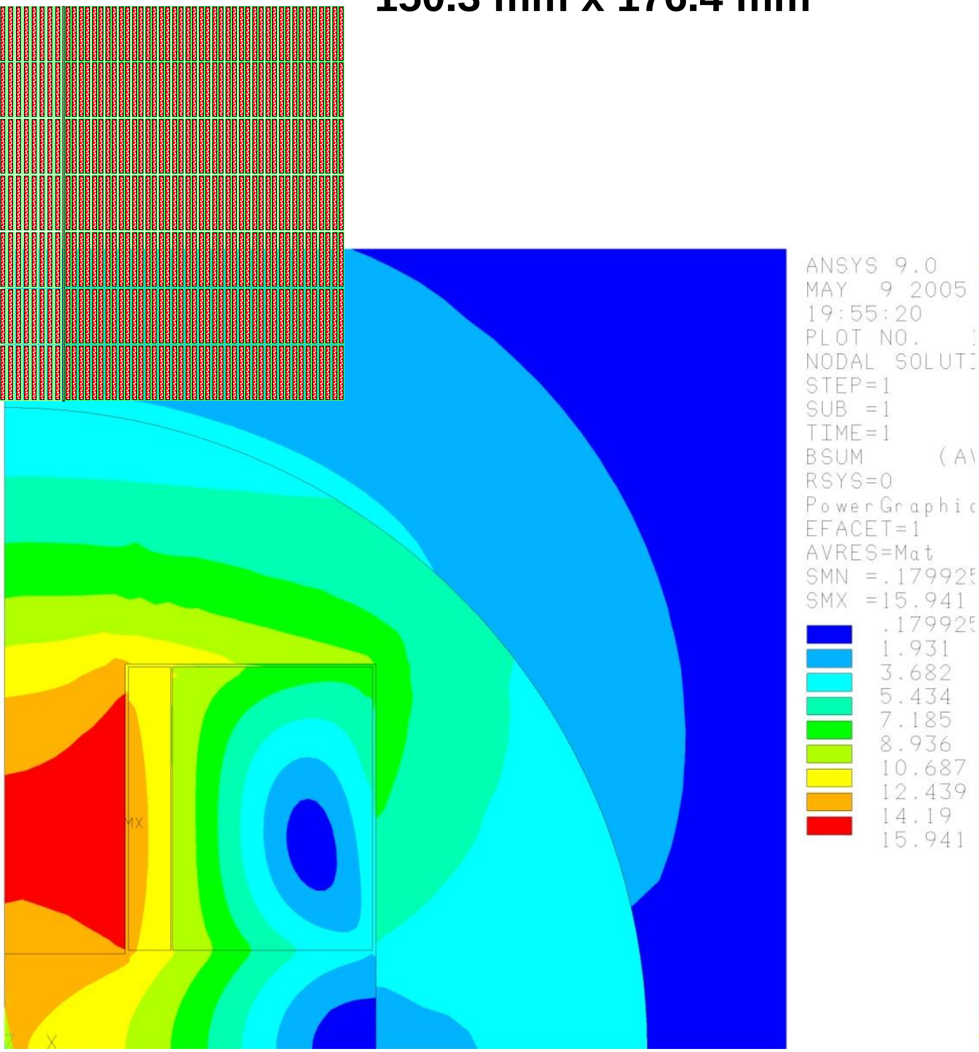
Racetrack design (P Bruzzone et al. CRPP)

	Flat cable		CICC		
	high grade	low grade	high grade	medium grade	low grade
Strand diameter, mm	1.31	1.13	0.85	0.90	
Cu:non-Cu	2.2		1		
Coating	None		Cr		
RRR	200		100		
# of sc/cu strands	40 / ø	25 / 21	144 / ø	54 / 27	27 / 54

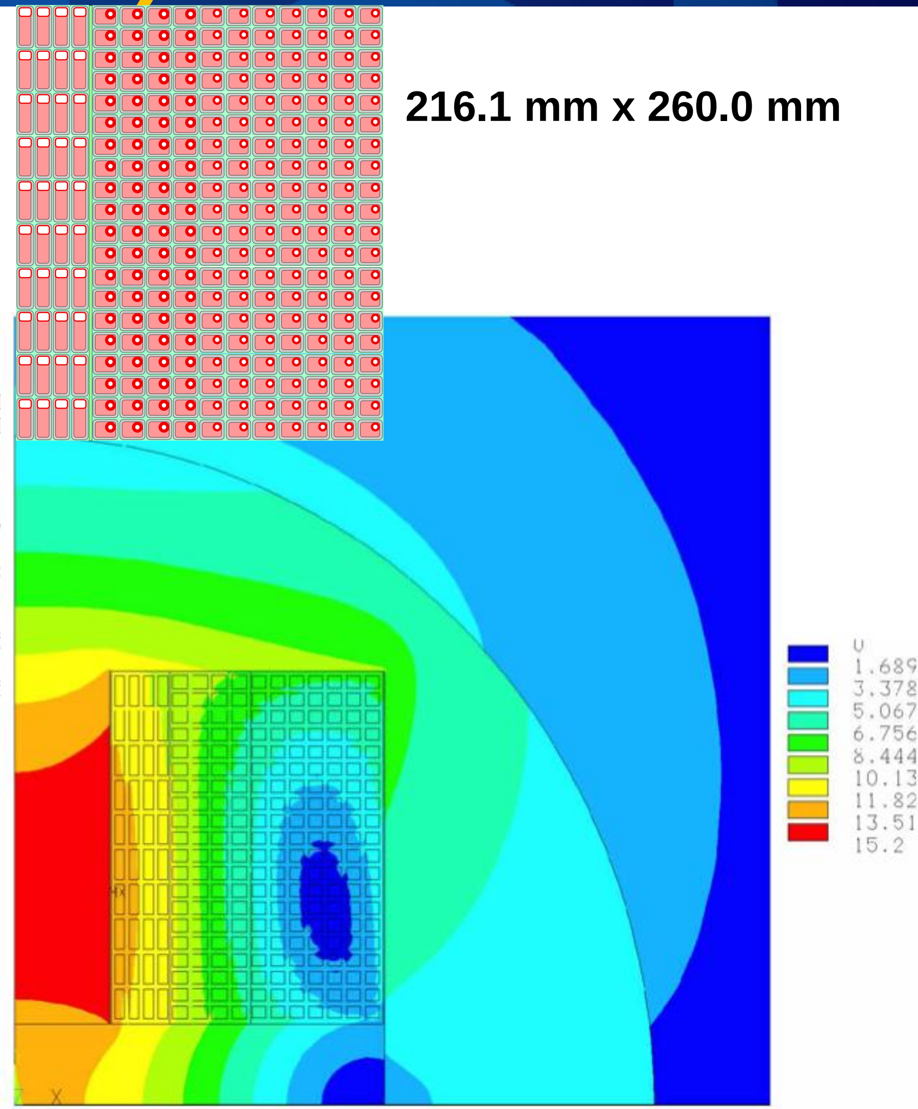


Racetrack design
(P Bruzzone et al. CRPP)

150.3 mm x 176.4 mm



216.1 mm x 260.0 mm



Racetrack design (P Bruzzone et al. CRPP)

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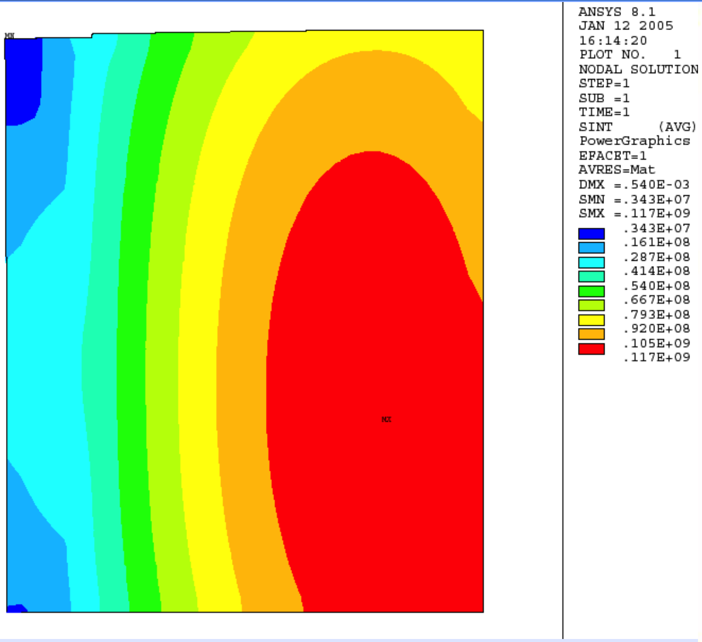
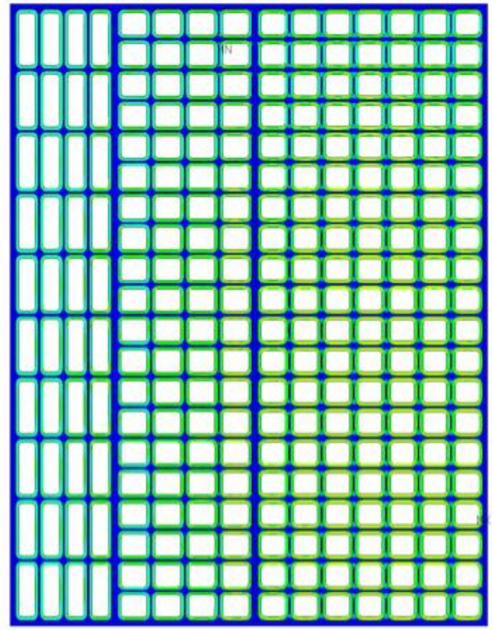
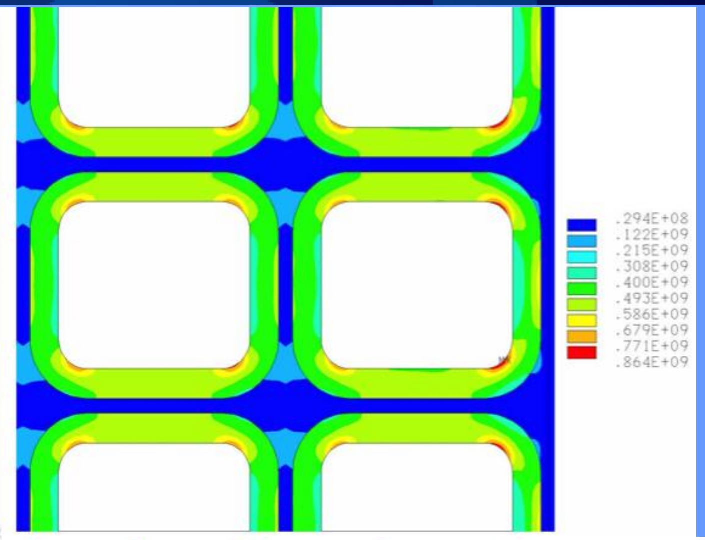
Electromagnetic, 2D results for planar race track coils 12.5 T at test well

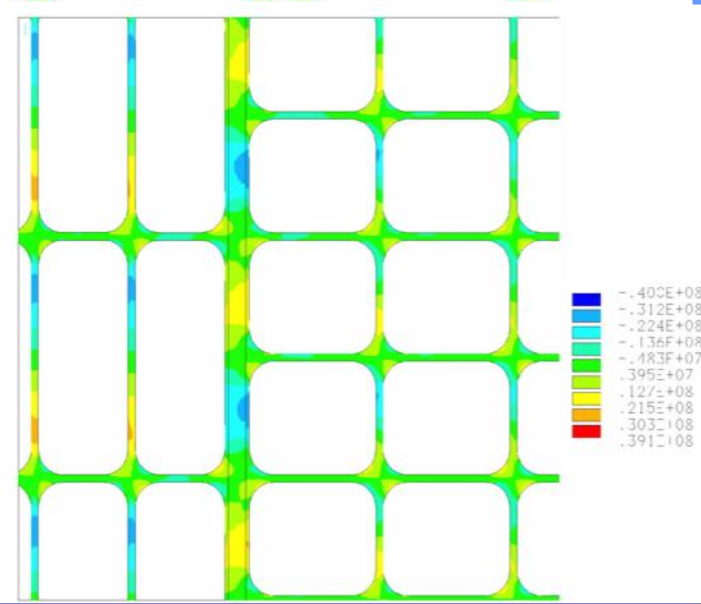
	Flat cable		CICC		
	high grade	low grade	high grade	medium grade	low grade
Peak field in WP	13.7 T	10.8 T	13.17 T	10.67 T	8.22 T
T_{cs}	6.45 K	6.67 K	6.20 K	6.31 K	6.34 K
Operating current	11.6 kA		19.35 kA		
Eng. current density	139	156	67.6	92.4	93.6
Non-cu current density	690	1487	473	1127	2252
Operating temperature	4.2 K		4.5 - 4.7 K		
Equiv. Iron Radius	400 mm		500 mm		
Temperature margin	*2.25 K*	*2.47 K*	*≈ 1.6 K*	*≈ 1.7 K*	*≈ 1.7 K*
Stored Energy/m	12.6 MJ/m		17.8 MJ/m		
Inductance /m	188 mH/m		95.1 mH/m		

Racetrack design
(P Bruzzone et al. CRPP)









Peak stress, ≈ 120 MPa, is located close to the 0 field. At B ≥ 6 T, the load is comfortably < 100 MPa

An inter-grade insulation layer, 2 mm thick reduces high stress in “misalignment” zone between high and middle field layers. The layer/turn transition is moved at the heads, protected by the staggering spacers

Racetrack design (P Bruzzone et al. CRPP)

Final assessment: Rutherford cable, racetrack winding

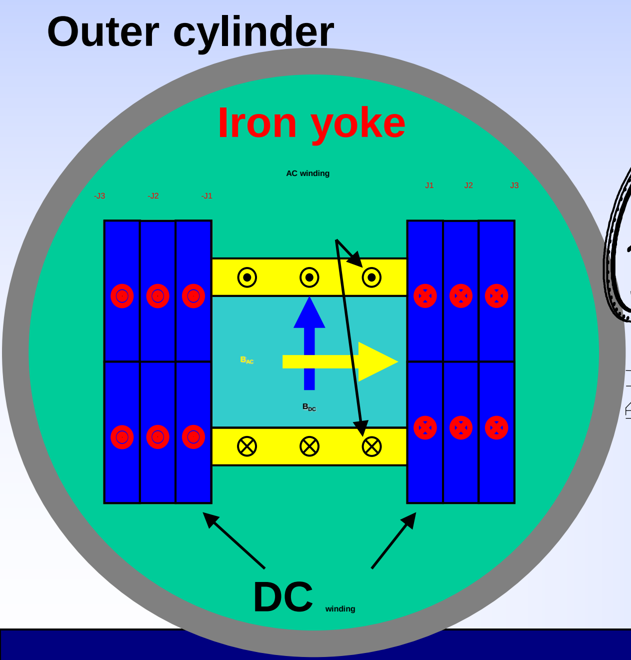
➔High peak field in the winding (~14 T?) still to be optimized in head regions (>14 T?)
➔Rutherford cable stability remains a major issue for such design
➔The advantages brought by the simplified winding of a planar, racetrack coil not sufficient to balance the uncertainties in cable performances

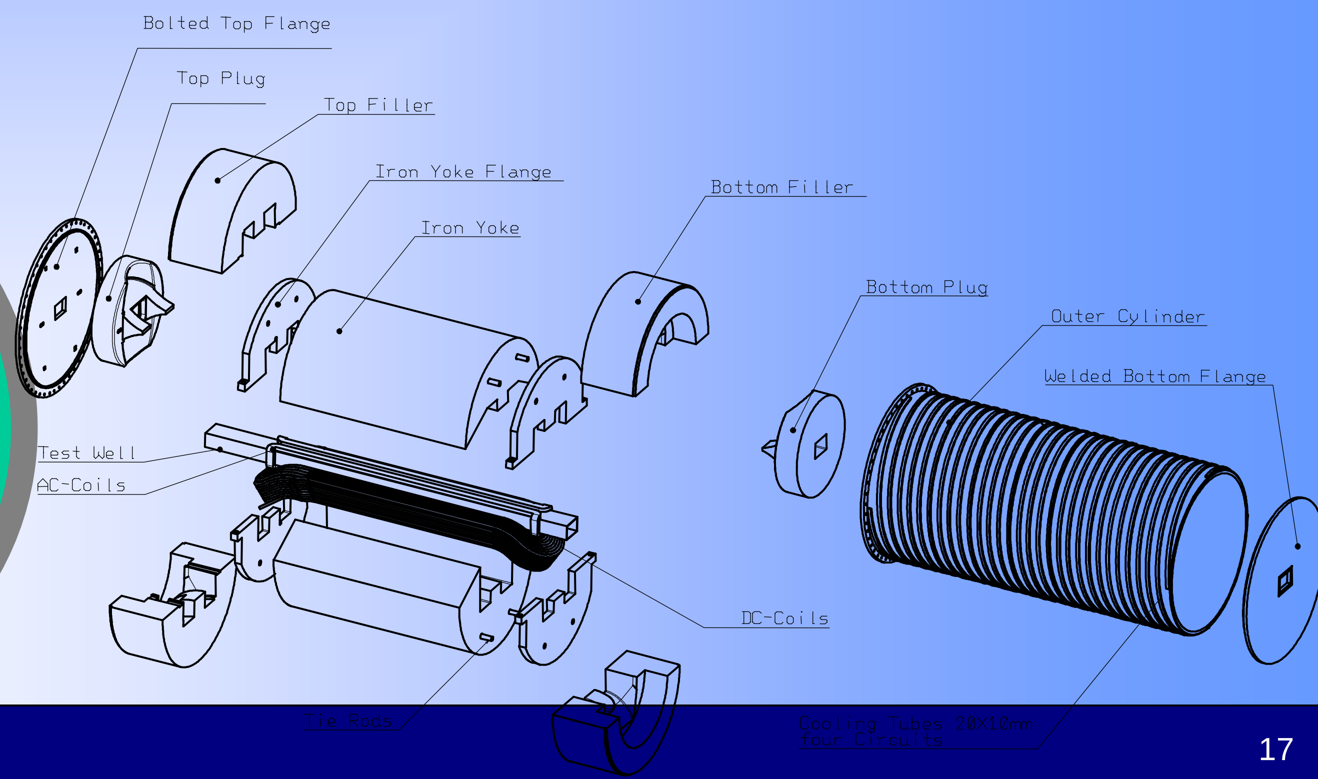
Final assessment: Cable In Conduit, racetrack winding

➔Massive and expensive (cabling lengths > 2 km, stored energy ~33 MJ) due to unfavourable use of space that is made by leaving a gap between the two main coils
➔Use of a central pressure release channel complicates cabling and jacketing while improves the heat removal capability and it decreases the peak quench pressure
➔Unbalance between advantages (and disadvantages) of this solution as opposed to the use of a thicker jacket, no pressure release channel and shorter cabling lengths;

Saddle coils design (EFDA, CIEMAT, ELYTT)

- Dipole configuration: E_{mag} ~ L (dipole), E_{mag} ~ L^2 (split-solenoid)
- DC field by LTS winding: Cu cable @ RT→P_J>50 kW/m →size/cooling!!
- AC field by Cu winding: RI^2 ~ 0.5 kW (~P_{AC}@nτ~100ms,f~5Hz)
- Fe-Yoke: lower A-turns & main structural element to react horizontal forces
- Outer cylinder: pre-loading and mould for final impregnation





Saddle coils design (EFDA, CIEMAT, ELYTT)

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DC WINDING

- Saddle-shaped coils (winding studies→MT-19)
- Double layer-winding → Good conductor/cable grading (length <150m)
- Inter-turn voltage <50 V → No kapton barrier, wind, react & impregnate
- CICC w/o central channel → Good stability, well-known tech in fusion community
- Jacket: circular steel pipe butt-welded & compacted → Cheap, simple orb. welding

AC WINDING

- Saddle coil rotated by 90 deg, Cu strand ~15mm^2 (~95 turns,350 A each)

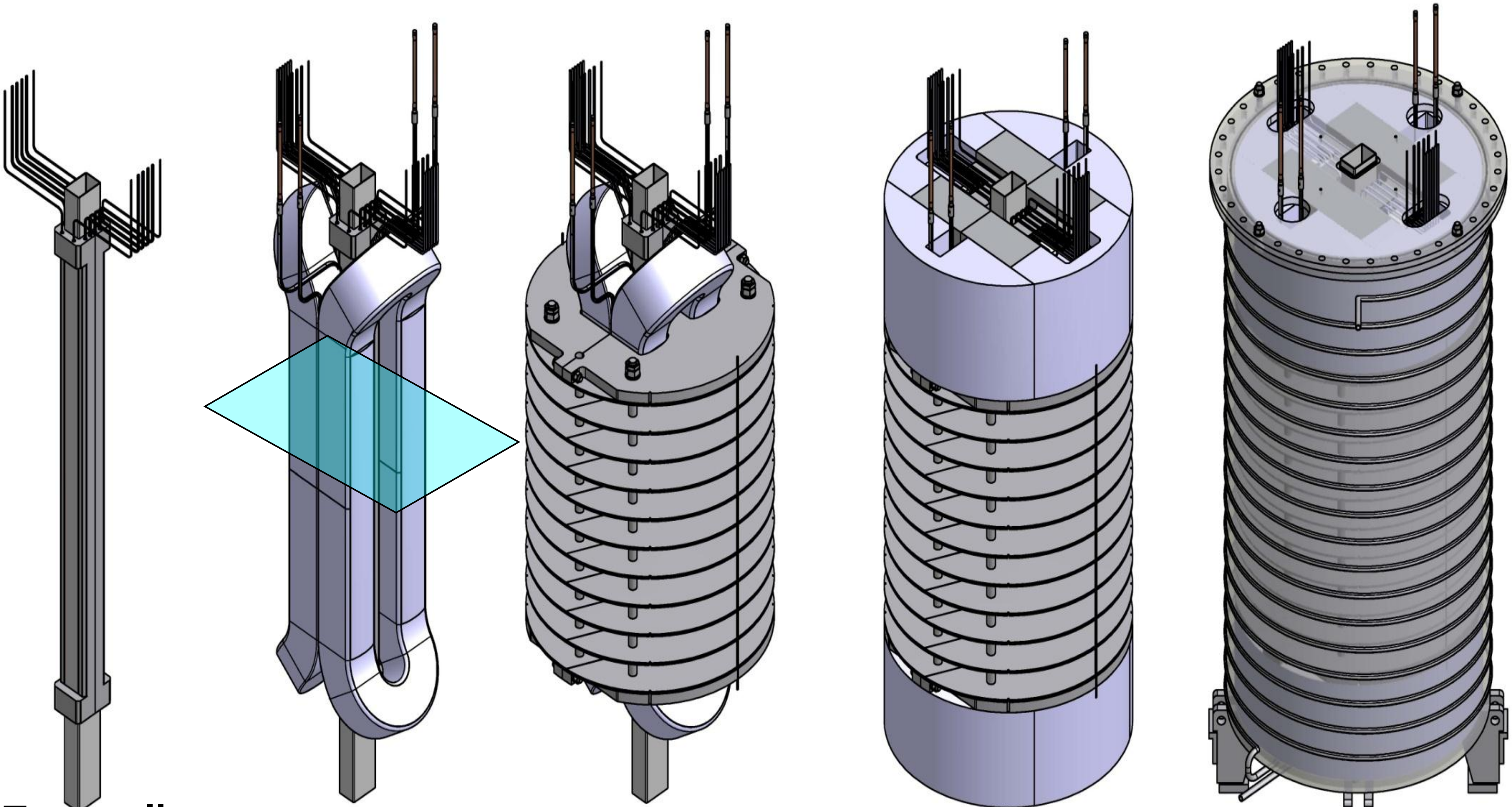
YOKE

- Low carbon steel (→LHC) laminated sheets in 2 halves kept at ground potential
  →Low reluctance flux return path reduces A-turns, stiff mechanical structure

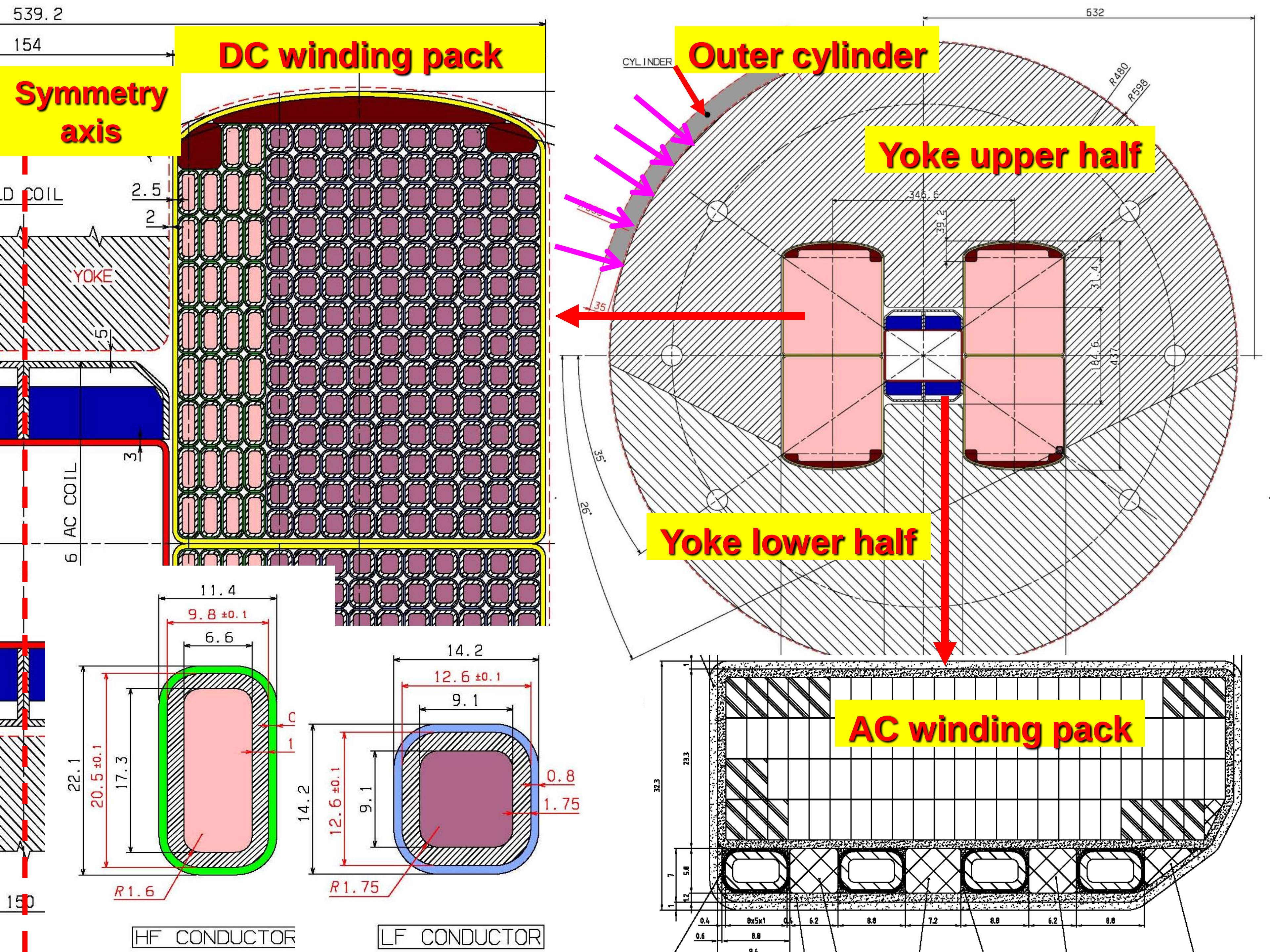
OUTER CYLINDER

- 316 LN steel sheet with longitudinal weld
  →Easy assembly, Yoke locking at cool-down due to different COEs
  →Good mechanical/thermal contact with yoke, cooling by supercritical He flow
  →Ground potential anchor, last impregnation mould (→TFMC)

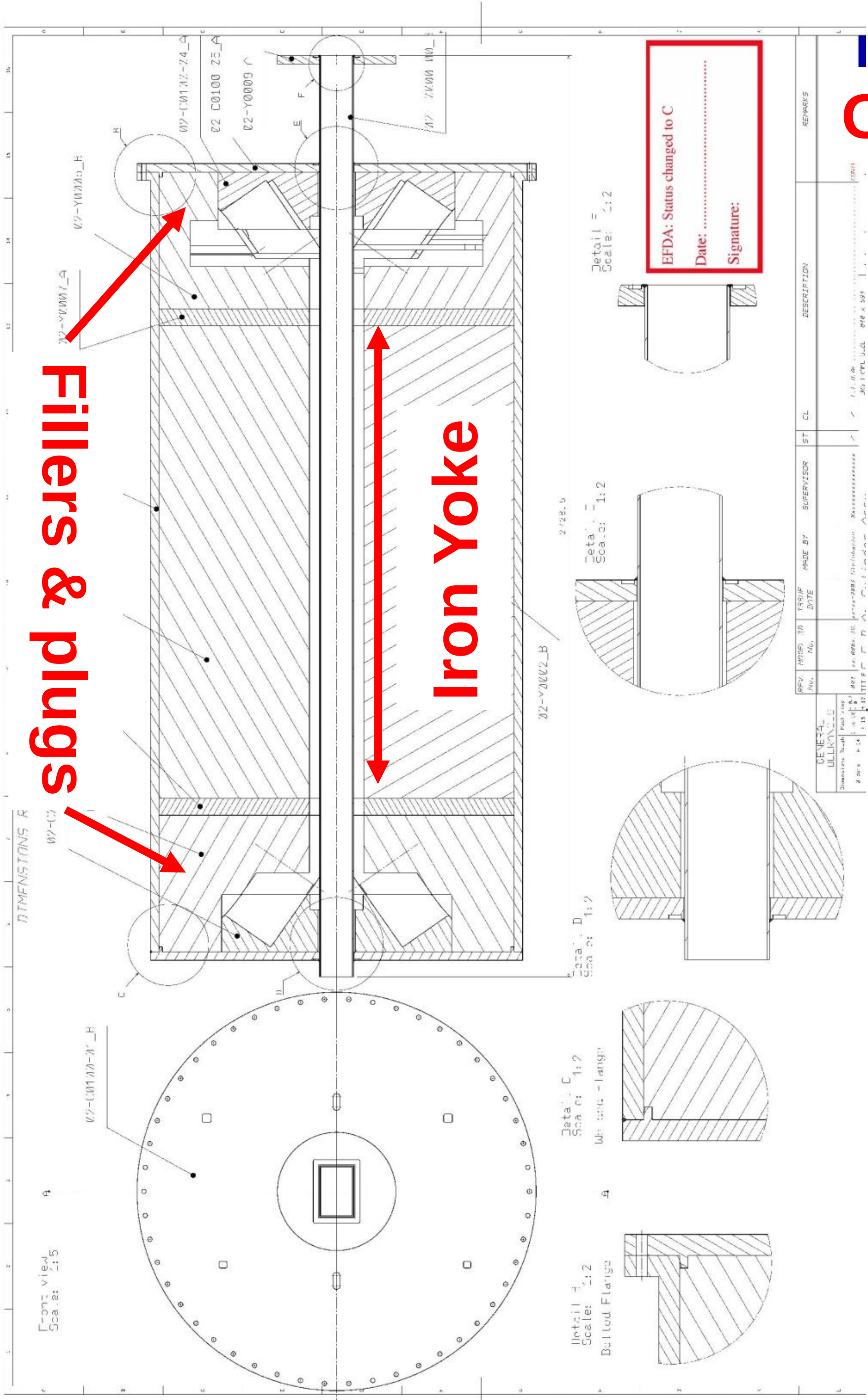
Saddle coils design (EFDA, CIEMAT, ELYTT)

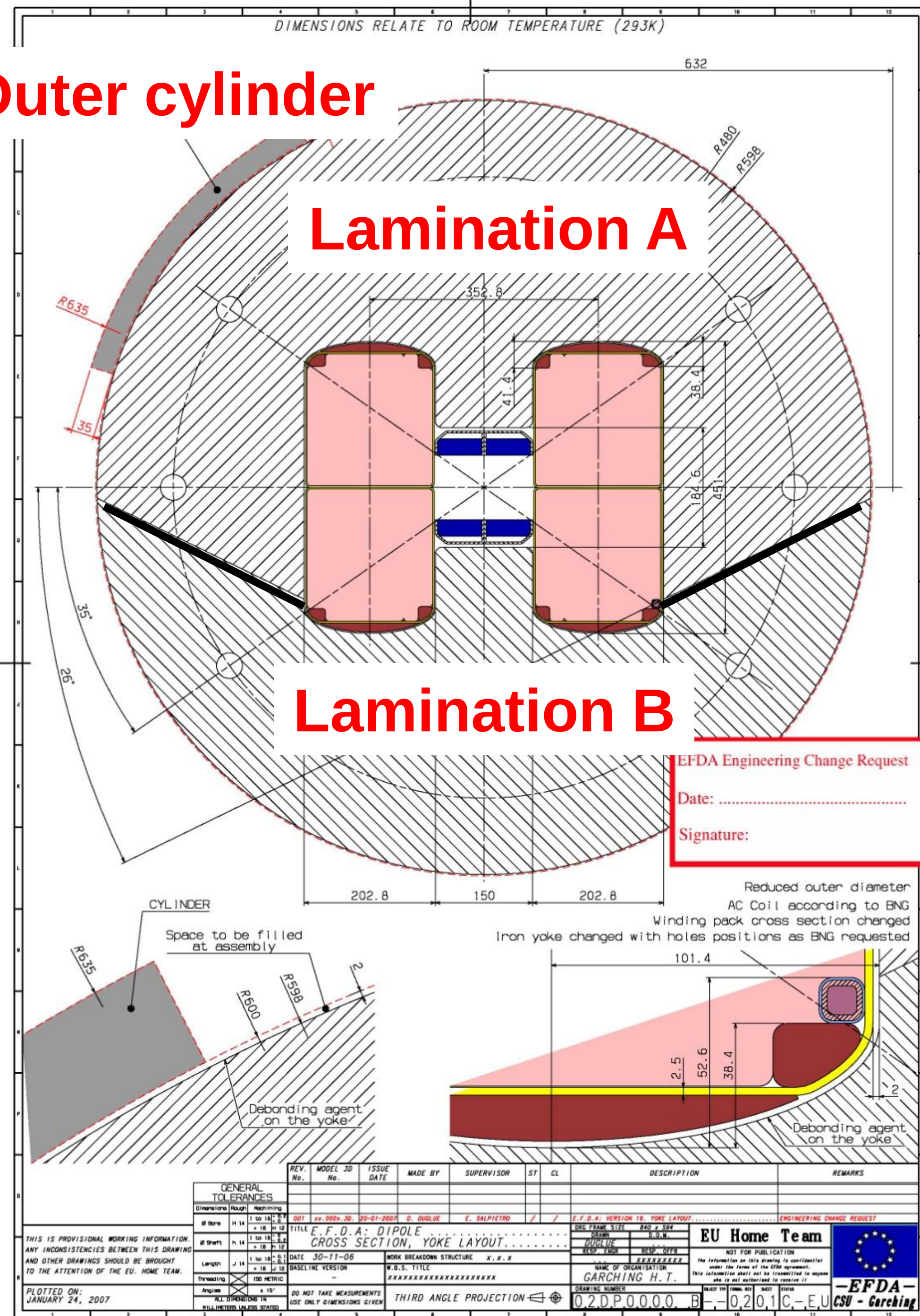


Test-well AC coils | DC coils | Yoke | End plugs Filler pieces | Outer cylinder Support structure

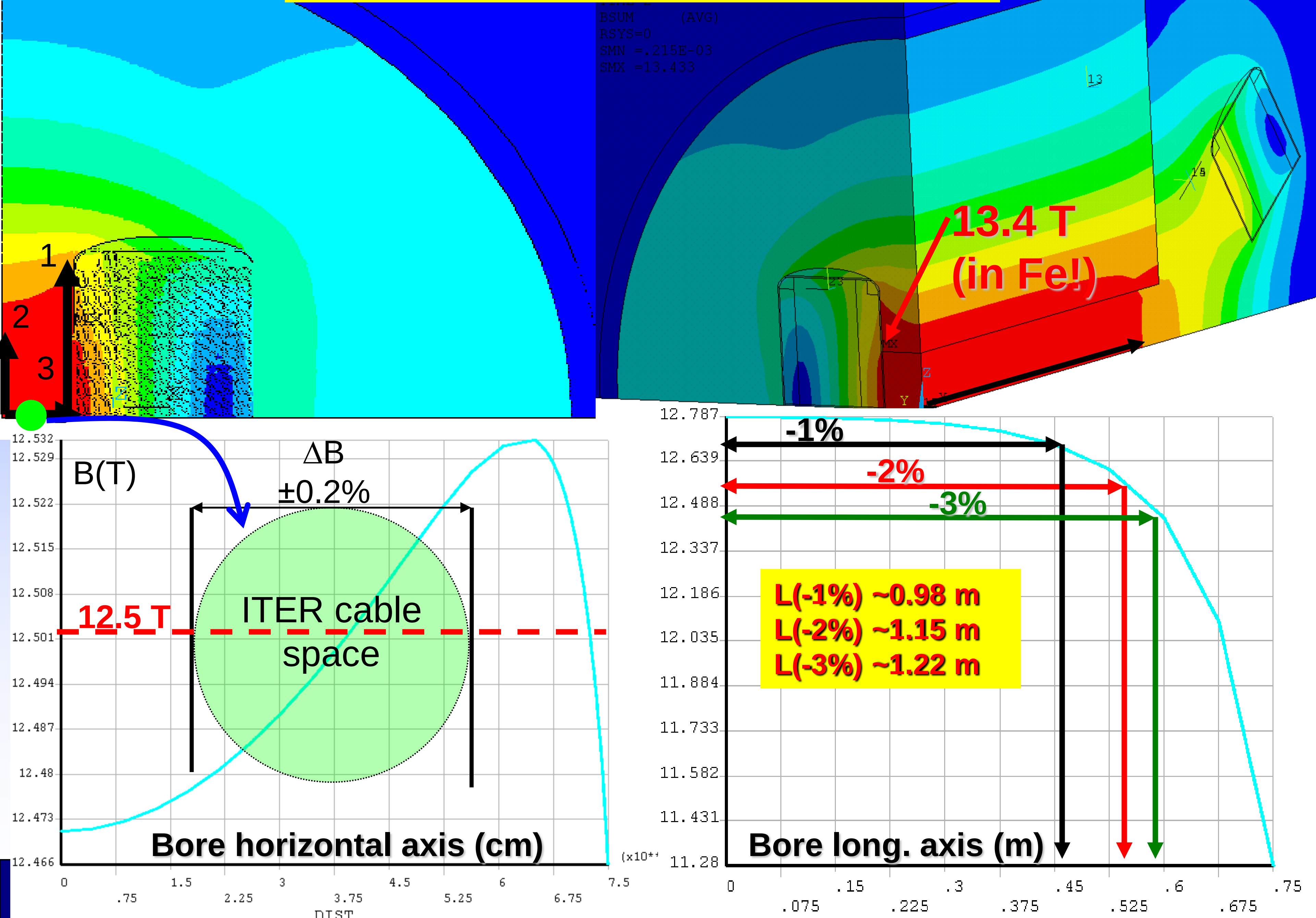


DC winding pack
Symmetry axis
Outer cylinder
Yoke upper half
Yoke lower half
AC winding pack
YOKE
AC COIL
CYLINDER
HF CONDUCTOR
LF CONDUCTOR
539.2
154
632
R480
R598
346.6
11.4
9.8 ±0.1
6.6
22.1
20.5 ±0.1
17.3
R1.6
14.2
12.6 ±0.1
9.1
0.8
1.75
R1.75


Fillers & plugs
Iron Yoke
EFDA: Status changed to C
Date:
Signature:

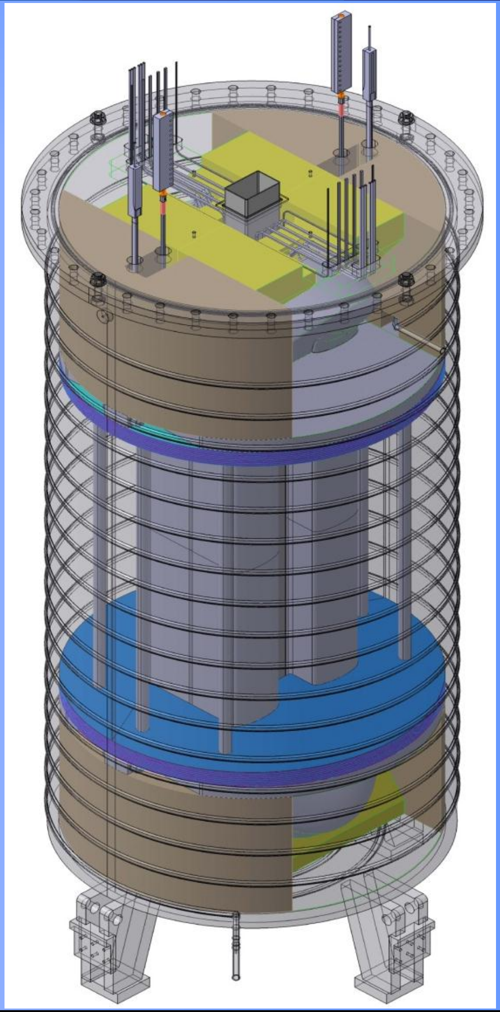

DIMENSIONS RELATE TO ROOM TEMPERATURE (293K)
Outer cylinder
Lamination A
Lamination B
EFDA Engineering Change Request
Date:
Signature:
632
R480
R598
R635
352.8
41.4
38.4
184.6
451
35
35°
26°
202.8
150
202.8
Reduced outer diameter
AC Coil according to BNG
Winding pack cross section changed
Iron yoke changed with holes positions as BNG requested
CYLINDER
Space to be filled at assembly
R600
Debonding agent on the yoke
101.4
EU Home Team
E.F.D.A.: DIPOLE
CROSS SECTION, YOKE LAYOUT
GARCHING H.T.
THIRD ANGLE PROJECTION
-EFDA-
CSU - Garching
PLOTTED ON: JANUARY 24, 2007

Electro-magnetic analysis



Saddle coils design (EFDA, CIEMAT, ELYTT)

Operating current	(kA)	17.2
Central magnetic field	(T)	12.5
Stored magnetic energy	(MJ)	16.1
Iron yoke outer diameter	(mm)	1200
Outer cylinder thickness	(mm)	35
Total CIC conductor length	(m)	1683
SC strand weigth	(kg)	486
CU strand weigth	(kg)	418
Total assembly weigth	(ton)	~22
Helium flow in DC winding	(g/s)	8.5
Inlet He temperature	(K)	4.5
Inlet He pressure	(bar)	10.0
Discharge peak voltage	(kV)	2.0
Discharge time	(s)	0.9



Cable types (cu strand #, sc strand #)	(3+0)x3x4x4=144+0=144 (HF1) (2+1)x3x4x4=96+48=144 (HF2)	{2x(2+1)+1x(1+2)}x3x4=60+48=108 (LF1) {1x(2+1)+2x(1+2)}x3x4=48+60=108 (LF2)

	Unit	HF1	HF2	LF1	LF2A	LF2B	LF2C	LF2D
Peak magnetic field	(T)	12.71	10.97	9.29	7.38	6.37	5.47	4.84
Current sharing temperature	(K)	6.24	6.87	7.22	8.27	9.07	9.77	10.25
Hot spot temperature	(K)	159	94	191	147	138	129	122
Void fraction	(%)	32	33	30	30	30	30	30
Insulation thickness	(mm)	0.80	0.80	0.80	0.80	0.80	0.80	0.80
Jacket thickness	(mm)	1.60	1.60	1.75	1.75	1.75	1.75	1.75
Insulated conductor width	(mm)	11.50	11.50	14.30	14.30	14.30	14.30	14.30
Insulated conductor height	(mm)	22.20	22.20	14.30	14.30	14.30	14.30	14.30
Insulation area	(mm2)	60	60	54	54	54	54	54
Jacket area	(mm2)	81	81	69	69	69	69	69
Cable space area	(mm2)	114	114	82	82	82	82	82
Helium flow area	(mm2)	37	37	24	24	24	24	24
Number of non-cu strands		144	96	60	48	48	48	48
Number of cu strands		0	48	48	60	60	60	60
Non-cu area	(mm2)	39	26	16	13	13	13	13
Copper area	(mm2)	39	51	42	45	45	45	45
Conductors unit length	(m)	70.8	80.7	130.0	135.0	140.0	145.0	140.5
SC strand weigth	(kg)	95	72	72	60	62	64	62
CU strand weigth	(kg)	0	37	60	77	80	83	81
Wetted perimeter	(m)	0.31	0.31	0.23	0.23	0.23	0.23	0.23
Hydraulic diameter	(mm)	0.48	0.49	0.42	0.42	0.42	0.42	0.42
Mass flow	(g/s)	2.35	2.16	0.93	0.87	0.83	0.80	0.80
Power/channel to reach Tcs@outlet	(W)	16.0	25.9	15.1	22.7	26.9	30.4	33.5
Outlet He temperature	(K)	6.1	6.8	7.2	8.3	9.1	9.8	10.3

Saddle coils design (EFDA, CIEMAT, ELYTT)

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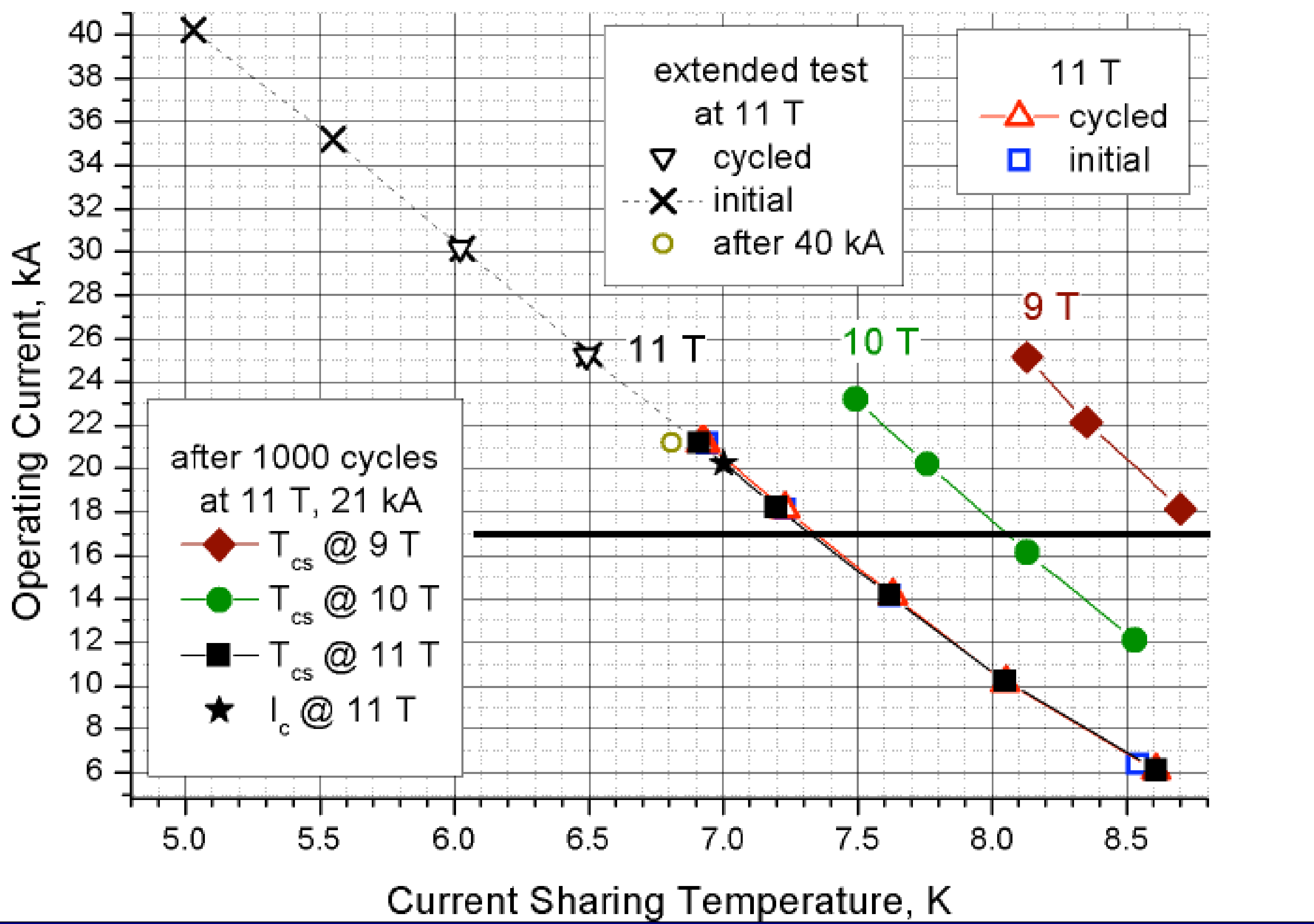
Final assessment: Cable in Conduit, saddle winding, cold bore

➔This design solution provides a balanced trade off of cost and performance, affordable manufacturing risks and need of limited R&D

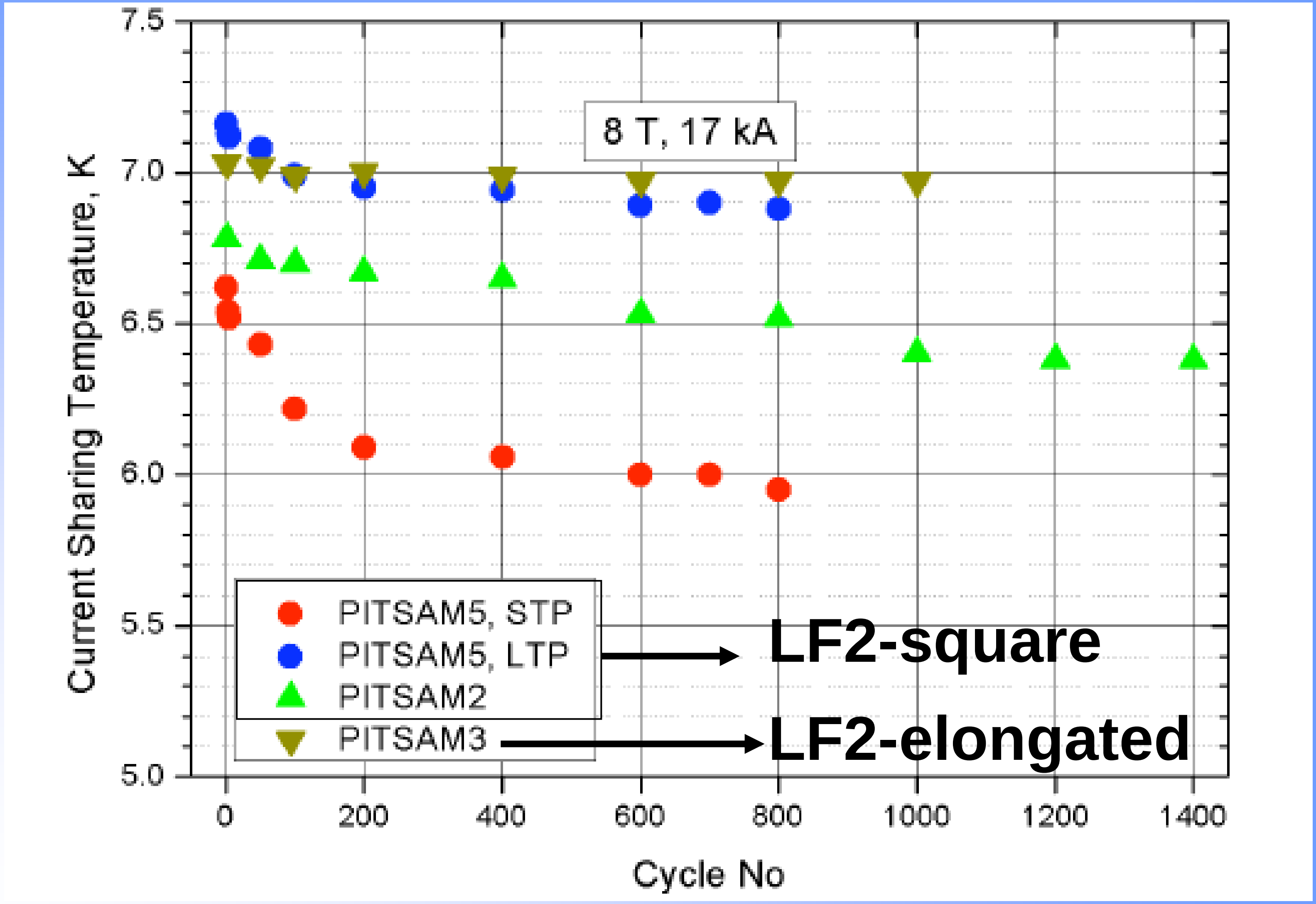
➔It has been selected for the engineering design phase and dipole call for tender

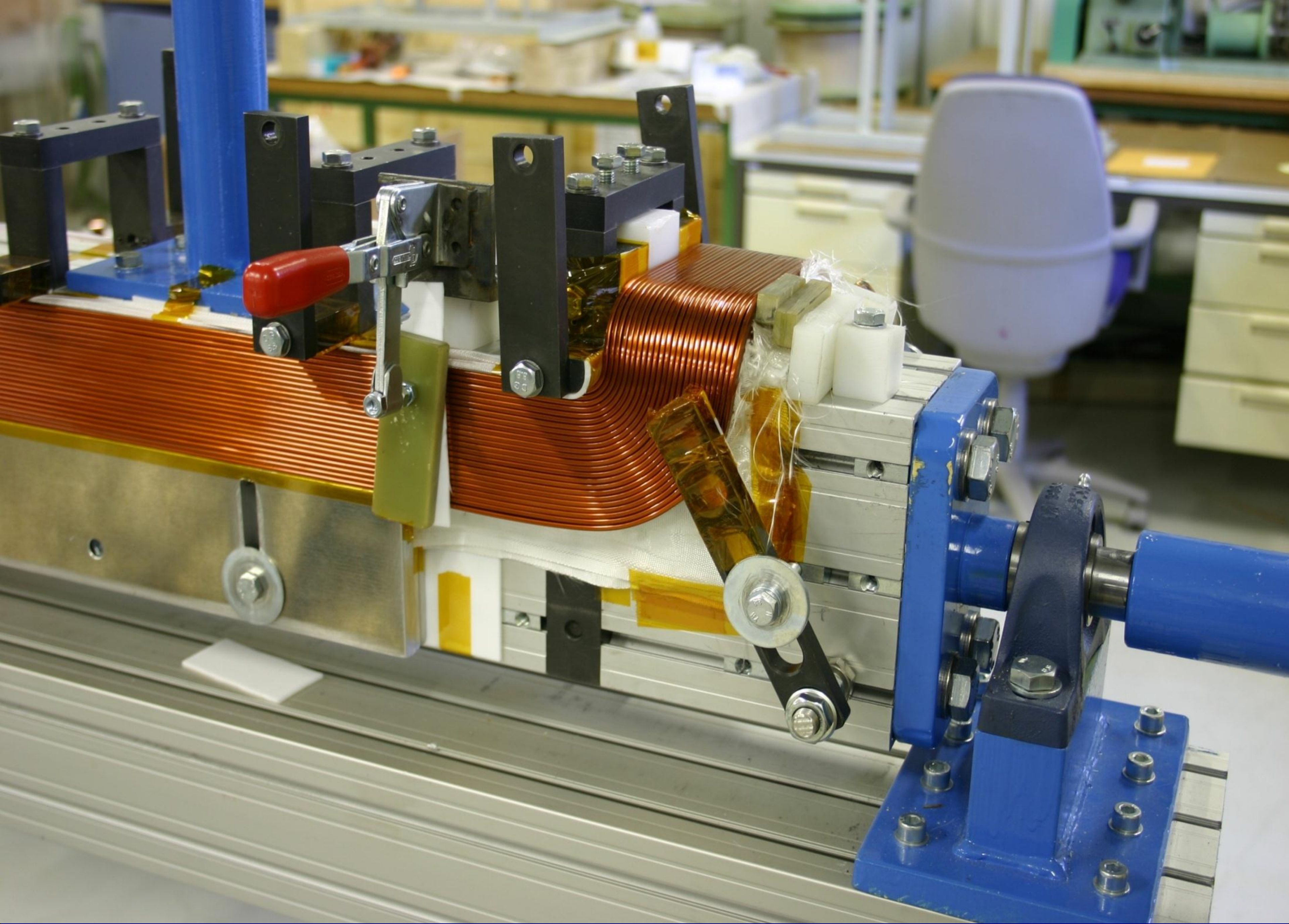
MAGNET R&D AND MANUFACTURING

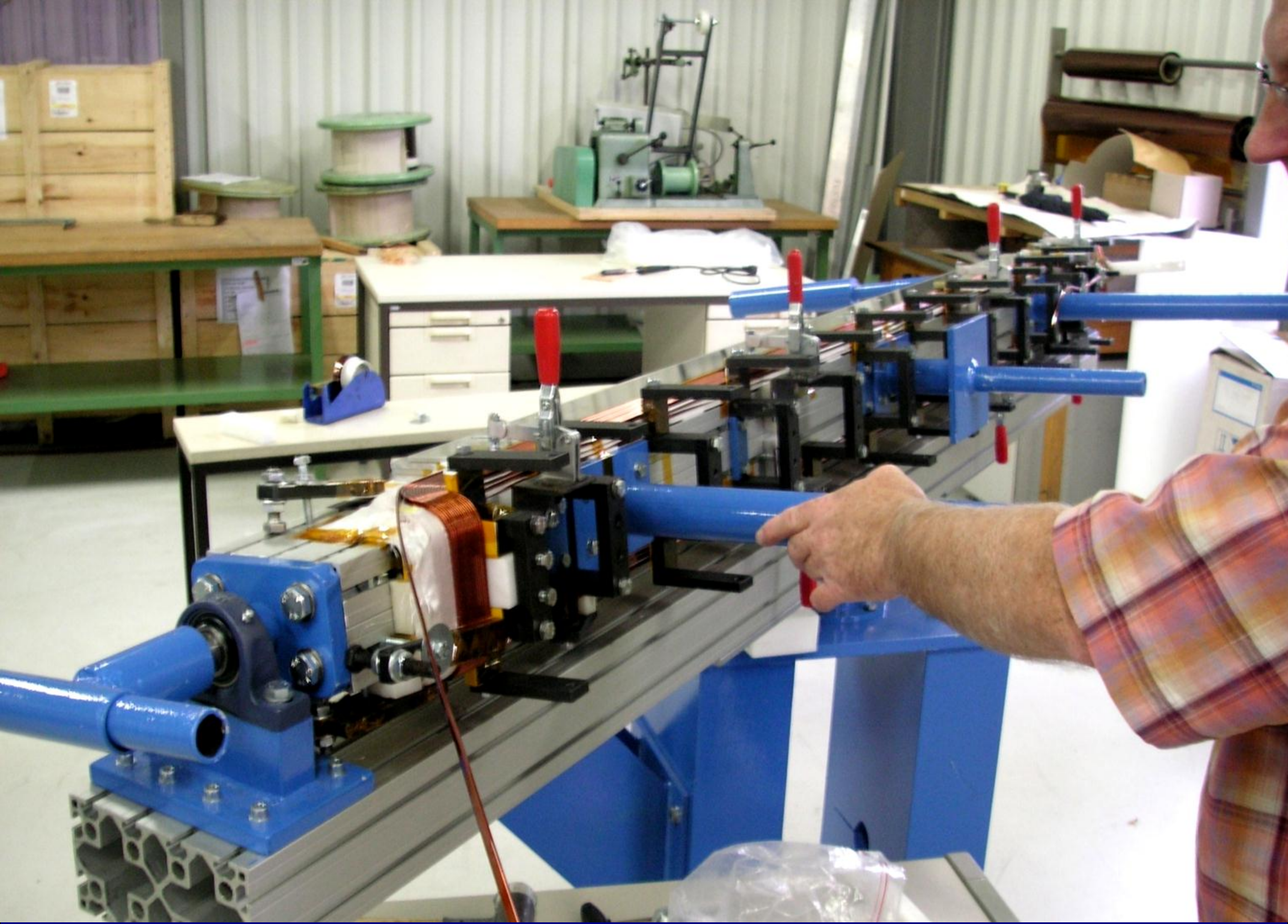
HF1 conductor tests



LF2 conductor tests







AC COILS & TEST WELL

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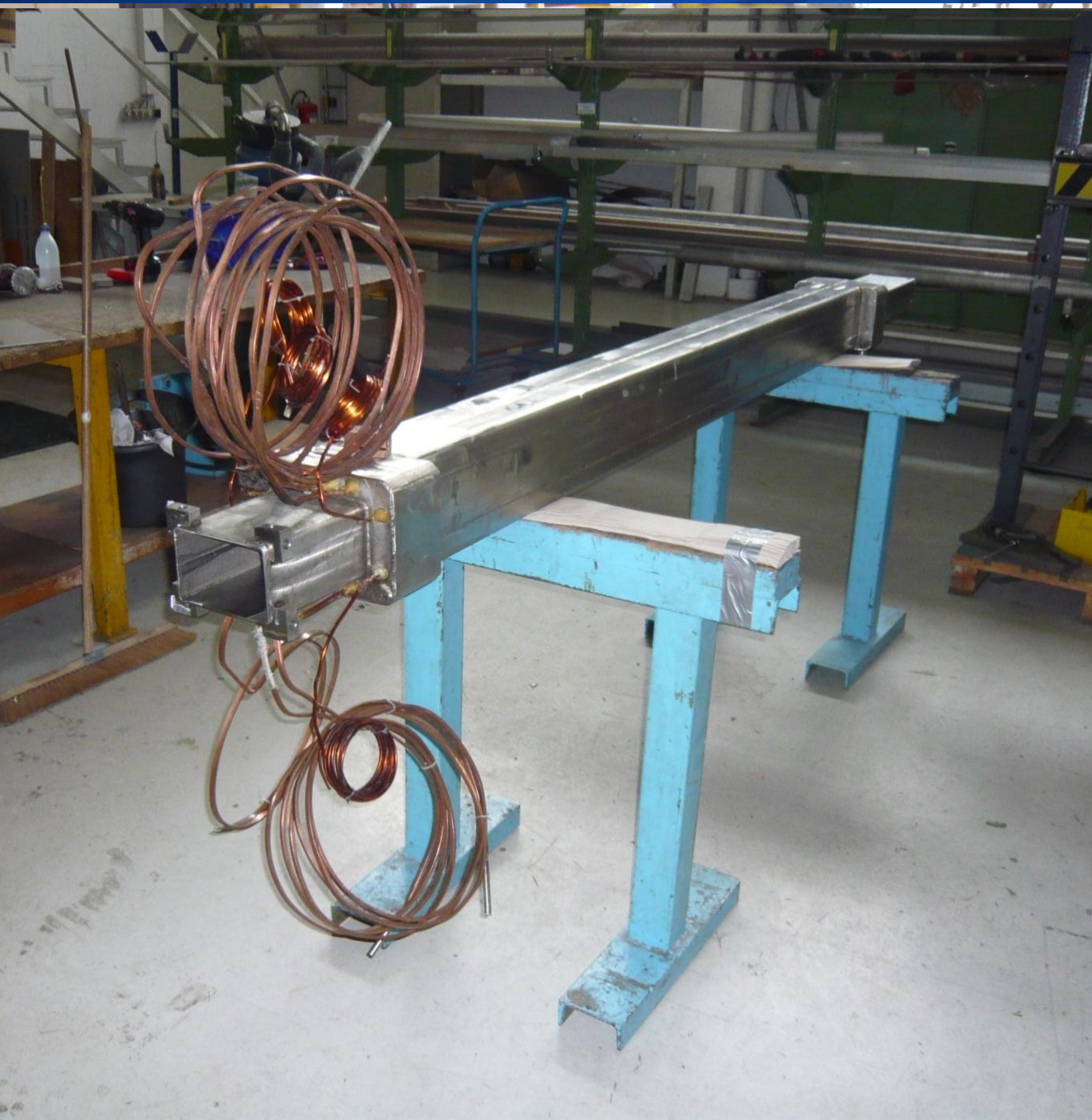

DC COILS MANUFACTURING

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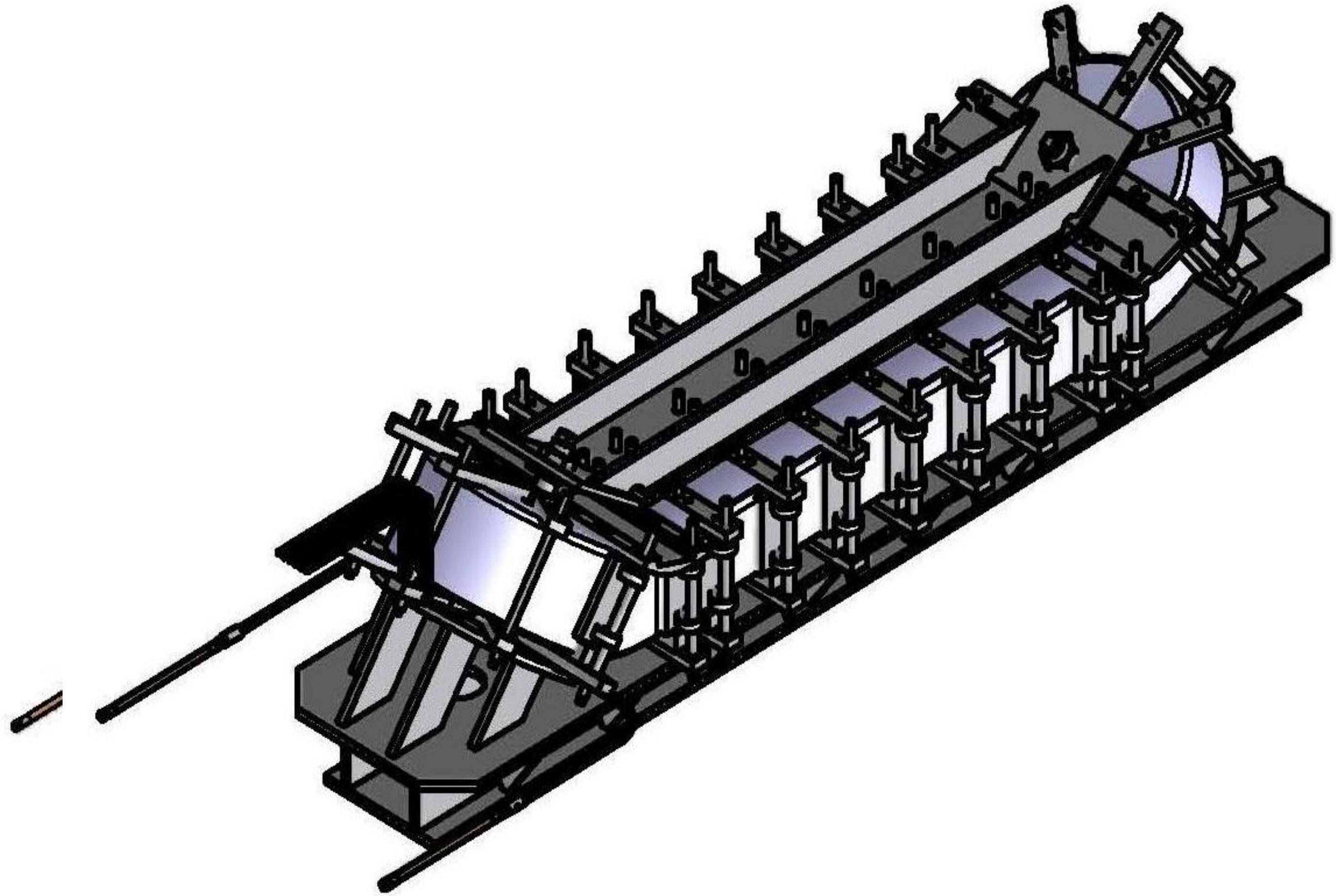

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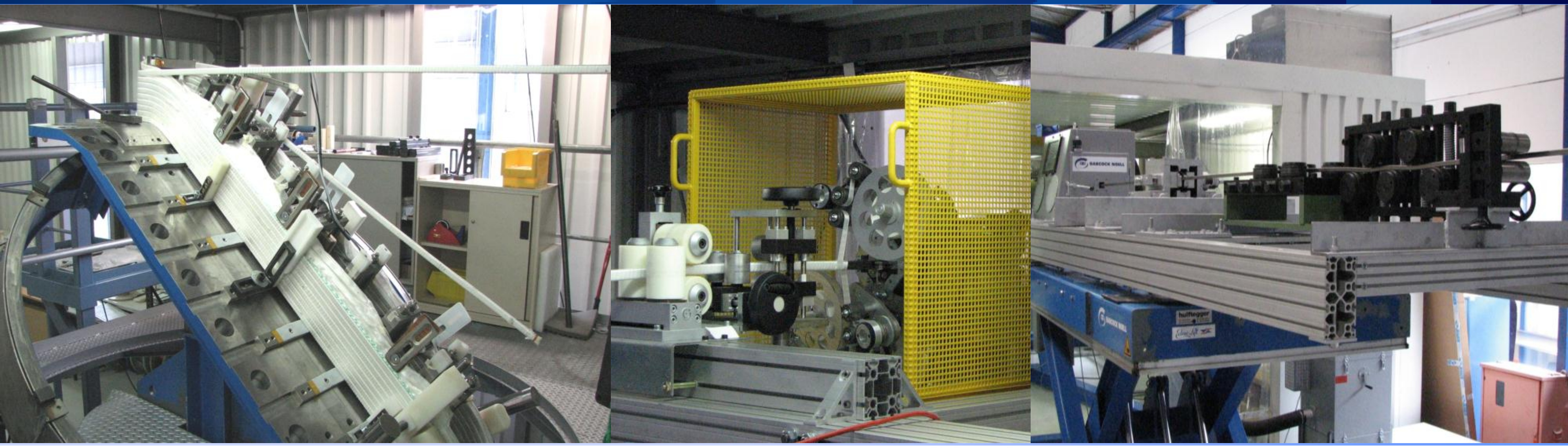
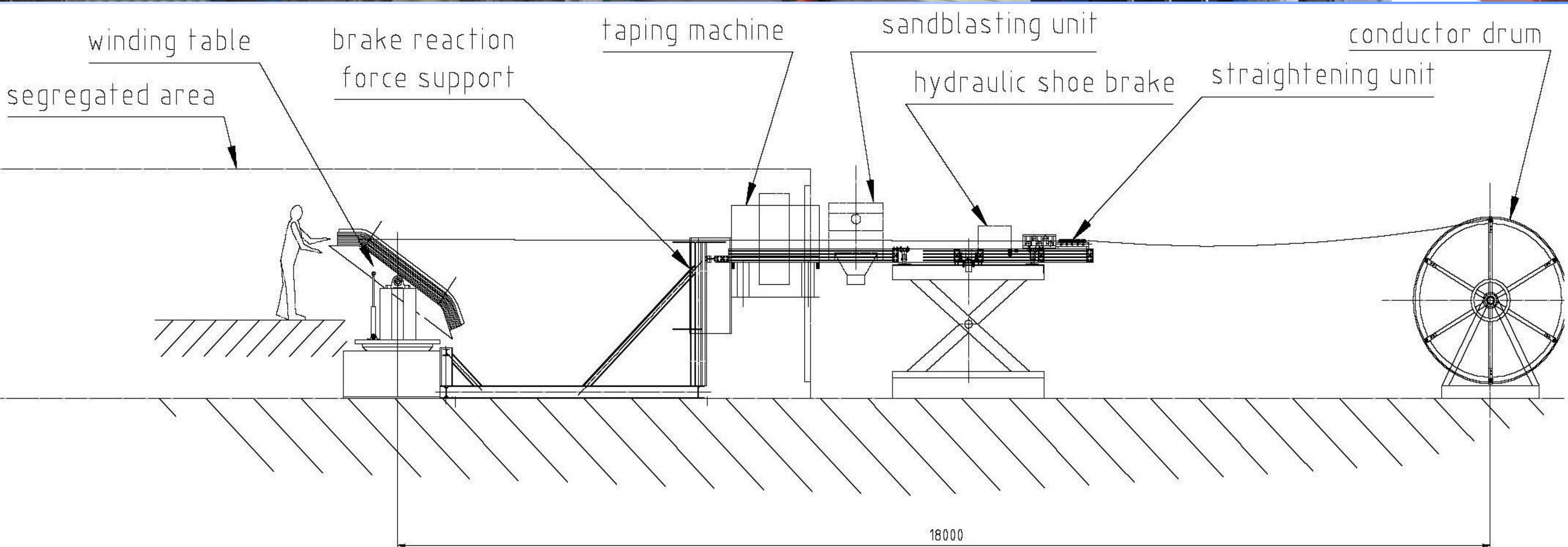
WINDING LINE

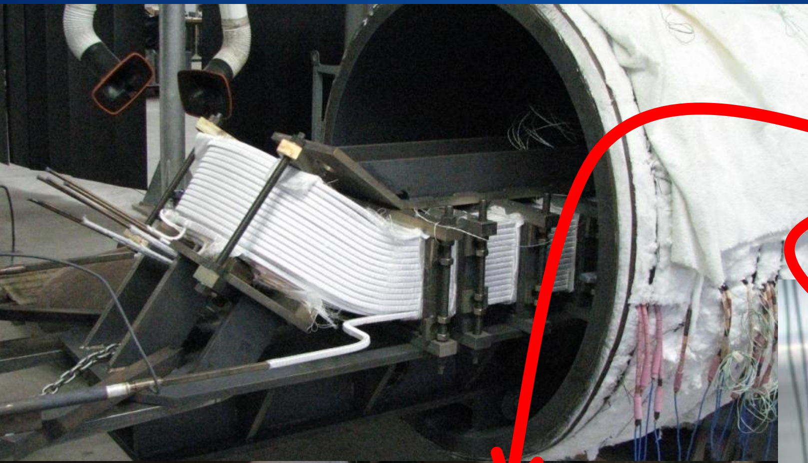




DUMMY DC COIL WINDING: SPRING BACK & CLAMPING

FUSION FOR ENERGY

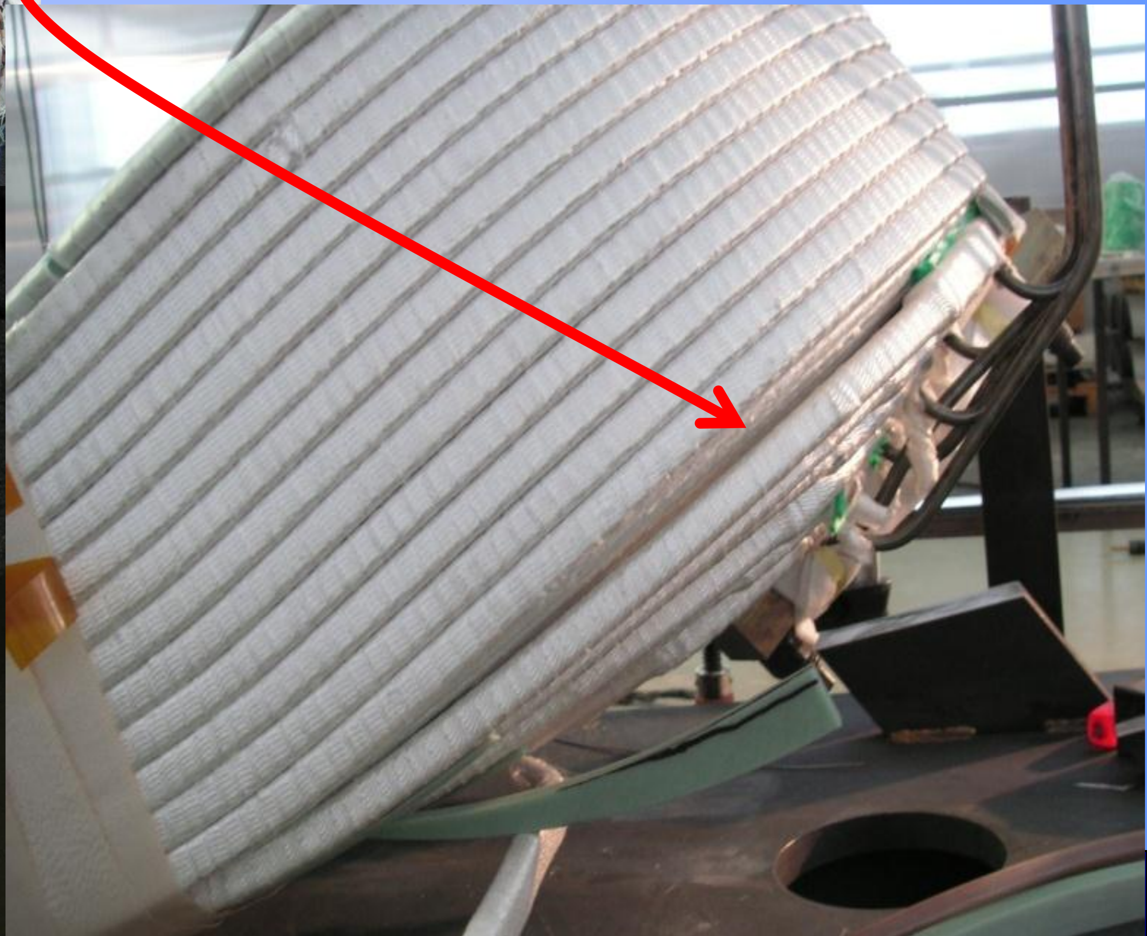
DUMMY DC COIL WINDING: SPRING BACK & CLAMPING



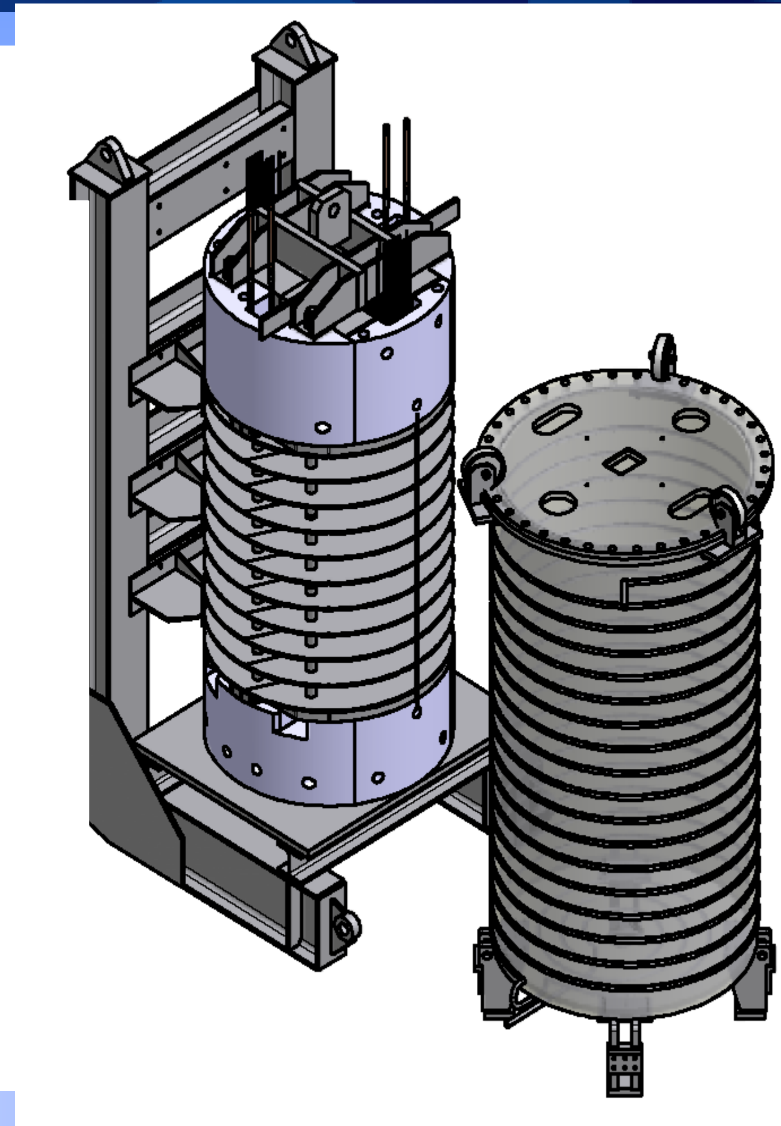
After RHT (Dec. 08) & clamped removed….

(1) Sever damages to the turn insulation

(2) Large misalignments in the joint region



ASSEMBLY SEQUENCE

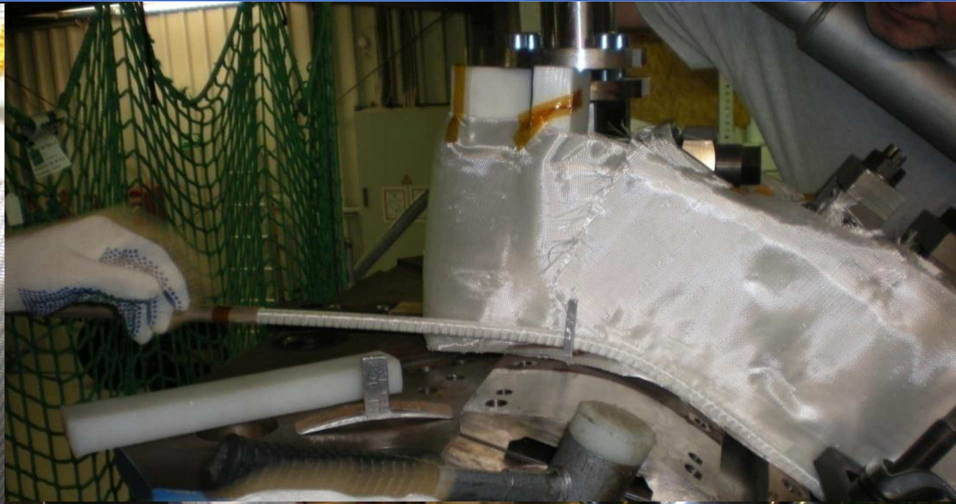


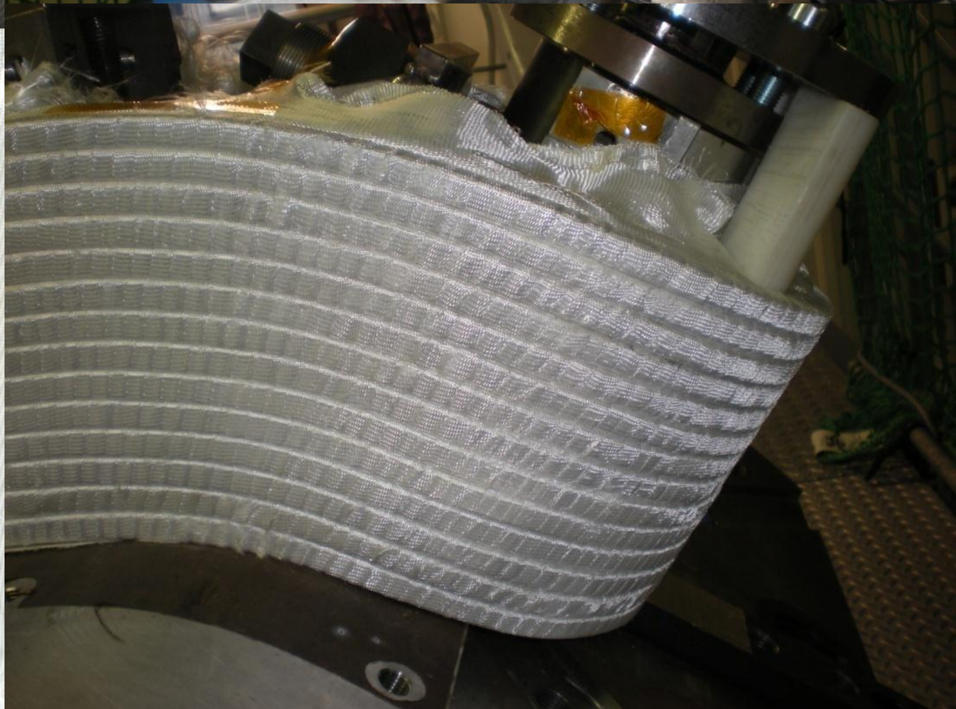
DUMMY ASSEMBLY FINAL IMPREGNATION

FUSION FOR ENERGY

EDIPO DC COILS WINDING: USE OF BENDING INSERTS

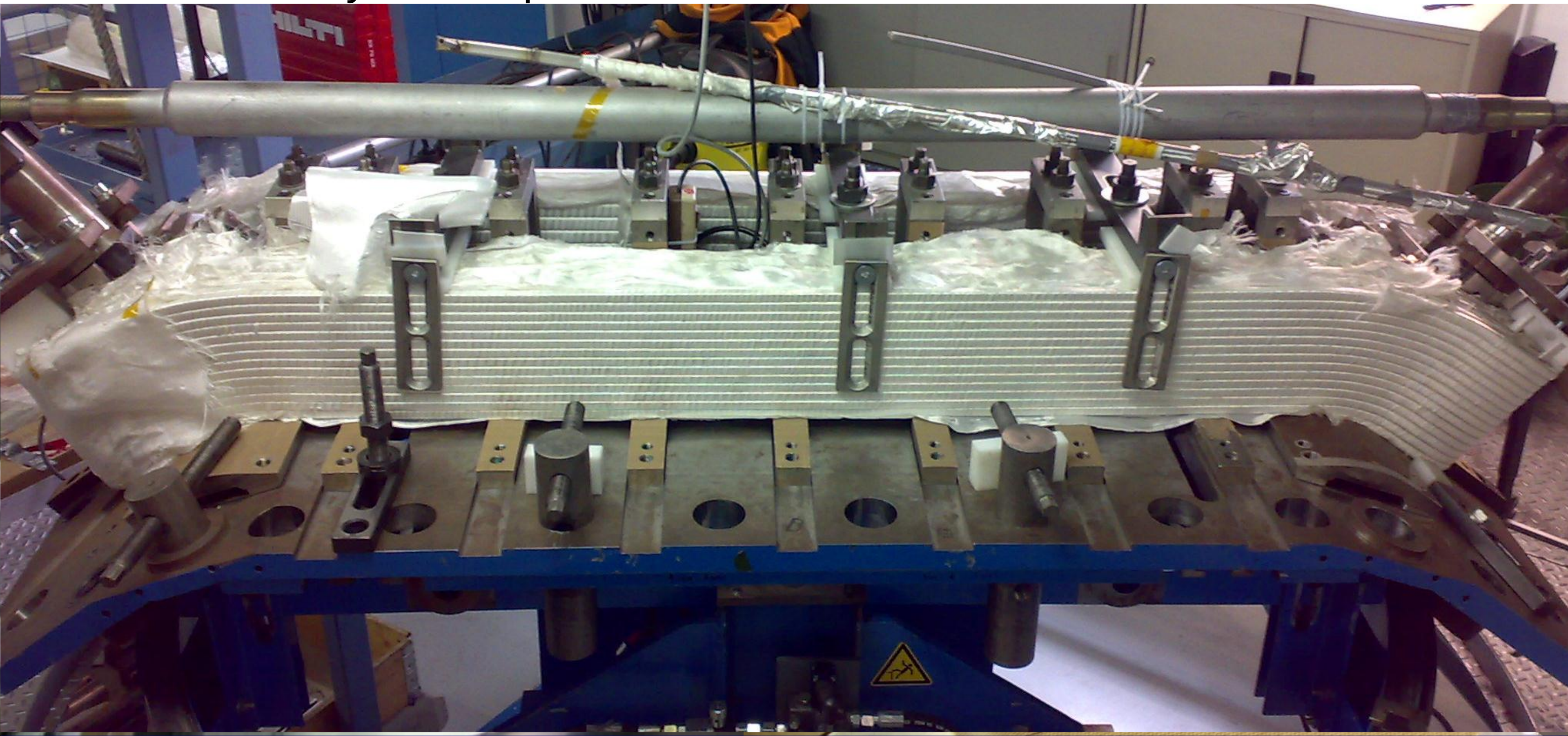
FUSION FOR ENERGY



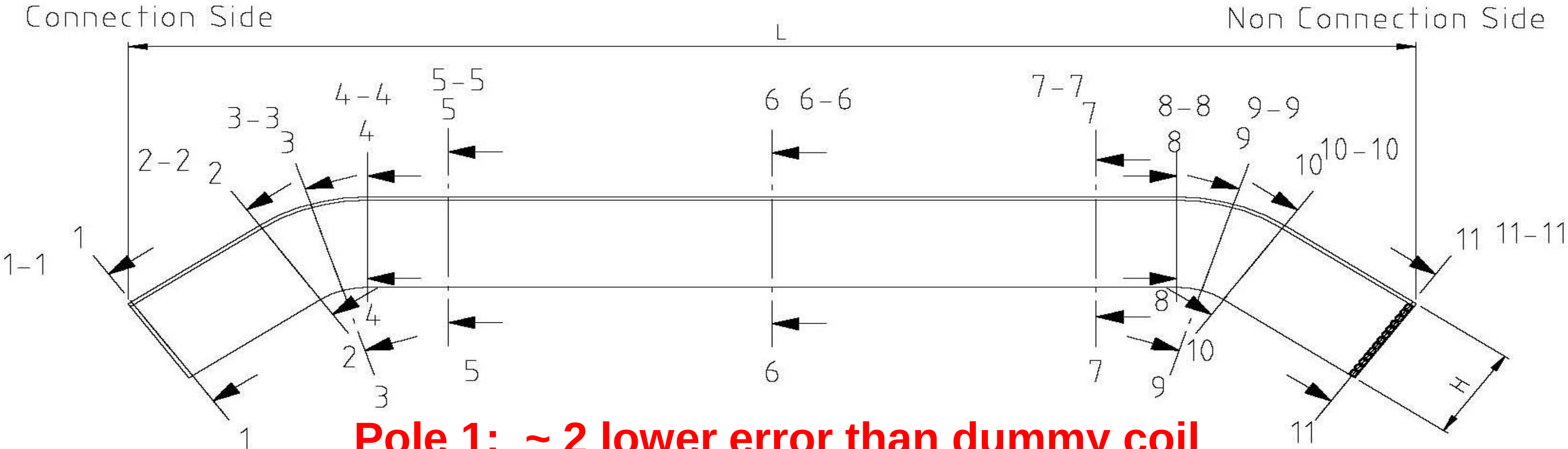


EDIPO pole#1 dc coil

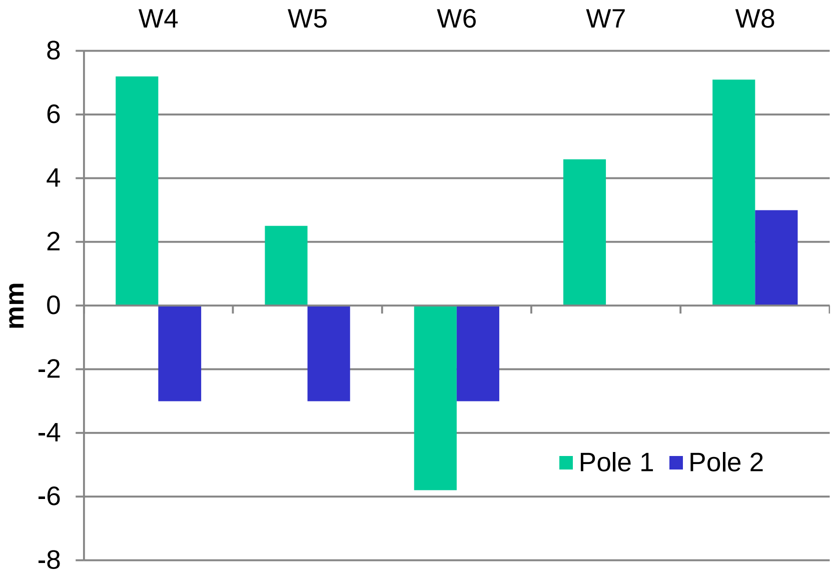
- Many tests carried out to find the best solution to over-bend the conductor
- Bending tools are qualified by a pre-test before staring winding a new layer
- 10 out of 14 layers completed, coil width deviations <10 mm



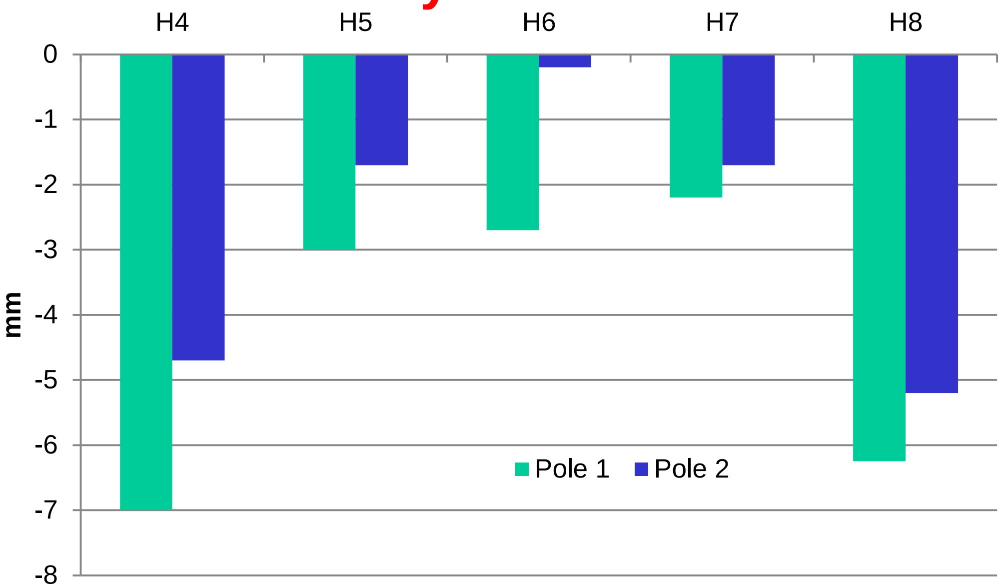
DC COILS WINDING: GEOMETRICAL SURVEY



Pole 1: ~ 2 lower error than dummy coil

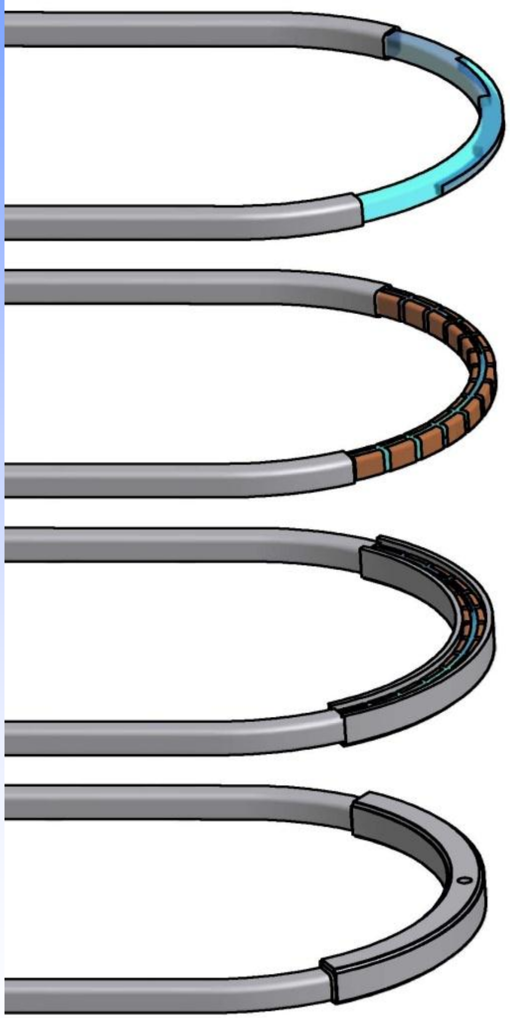


Winding pack width deviation from reference



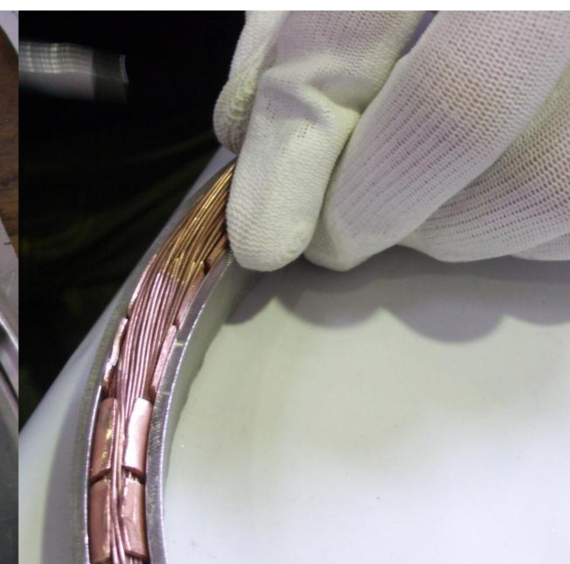
Winding pack height deviation from reference

INTER-LAYER JOINTS

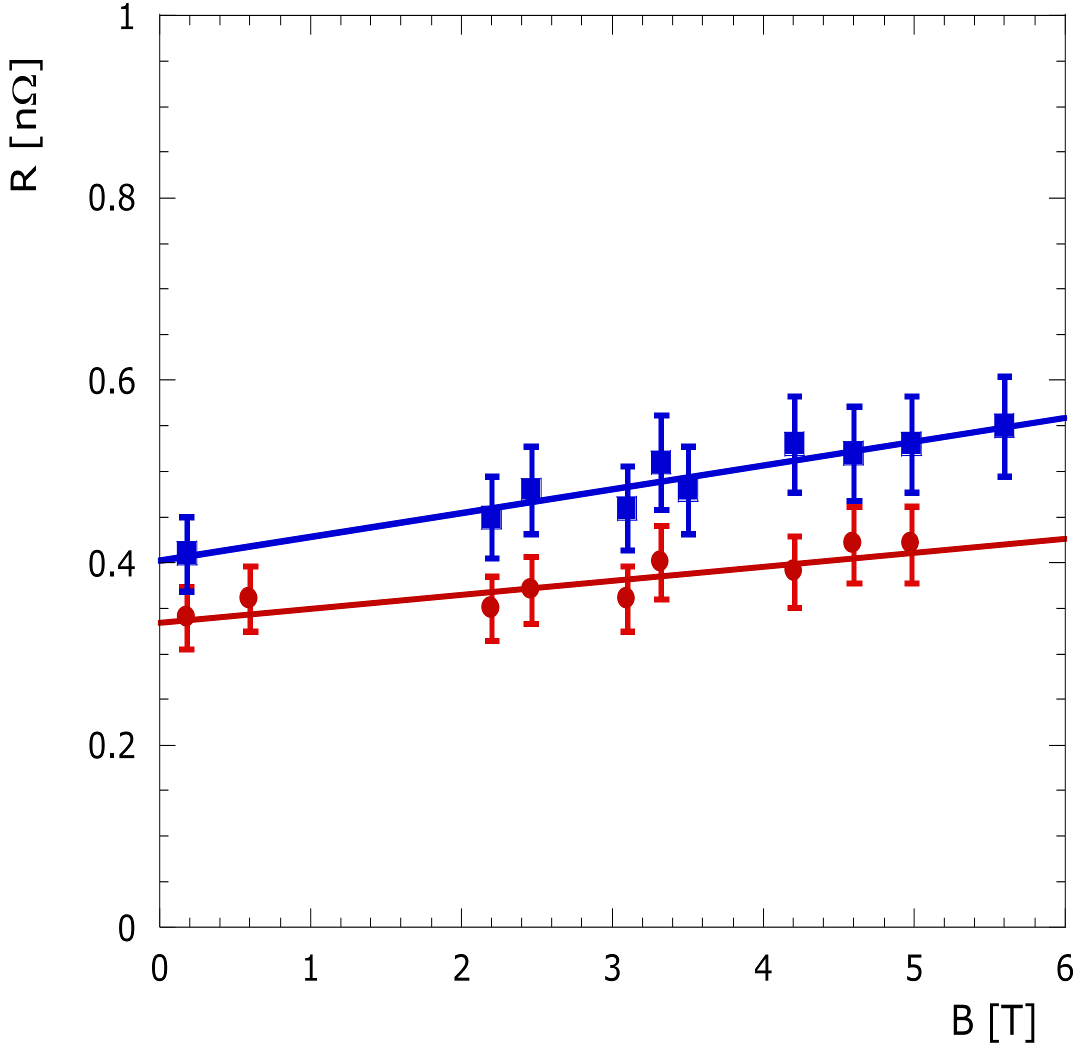


Manufacturing cycle

- Bend conductor ends
- Cut Jacket by oscillating grinder (limit stop)
- Etch Chromium coating
- Trim sub cables and adjust
- Place of U-bent copper stripes
- Place U-shaped joint box and weld to jacket
- Flip copper stripes over
- Place joint box lid
- Compress <20% void fraction and weld

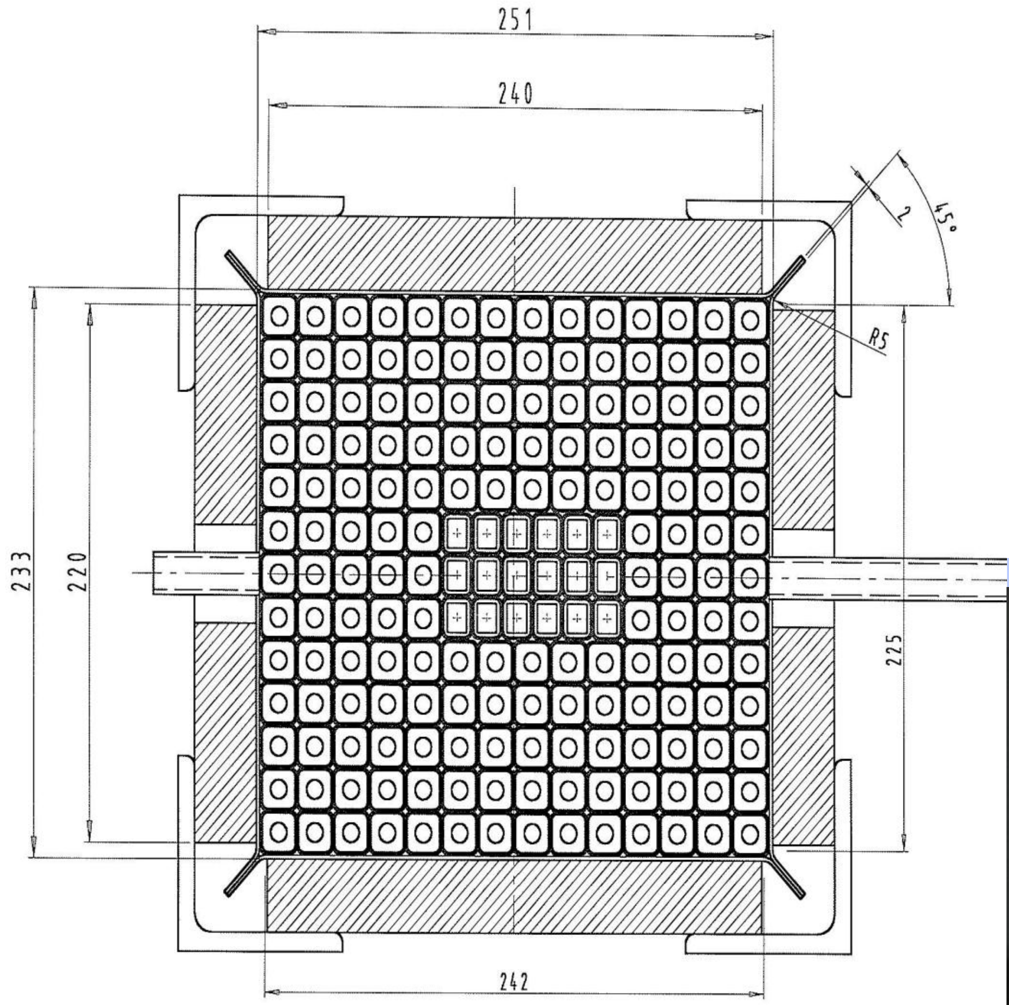


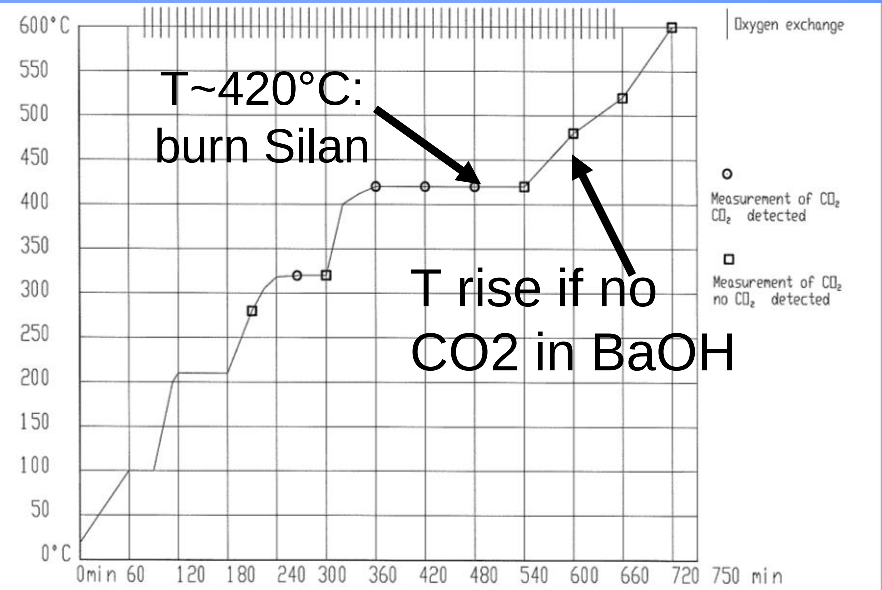
INTER-LAYER JOINTS

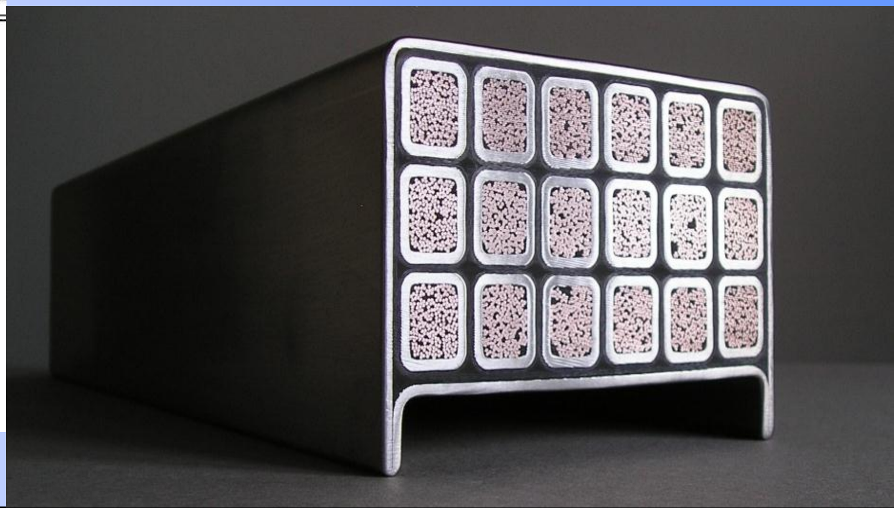


B [T]	R [nΩ] (V-I)	R [nΩ] (I-t)	I-range [kA]
0.18	0.34	0.41	0-27
0.6	0.36		0-34
2.2	0.35	0.45	0-27
2.5	0.37	0.48	0-23
3.1	0.36	0.46	0-21
3.3	0.40	0.51	0-23
3.5		0.48	0-6.5
4.2	0.39	0.53	0-21
4.6	0.42	0.52	0-21
5.0	0.42	0.53	0-19
5.6		0.55	0-7.5

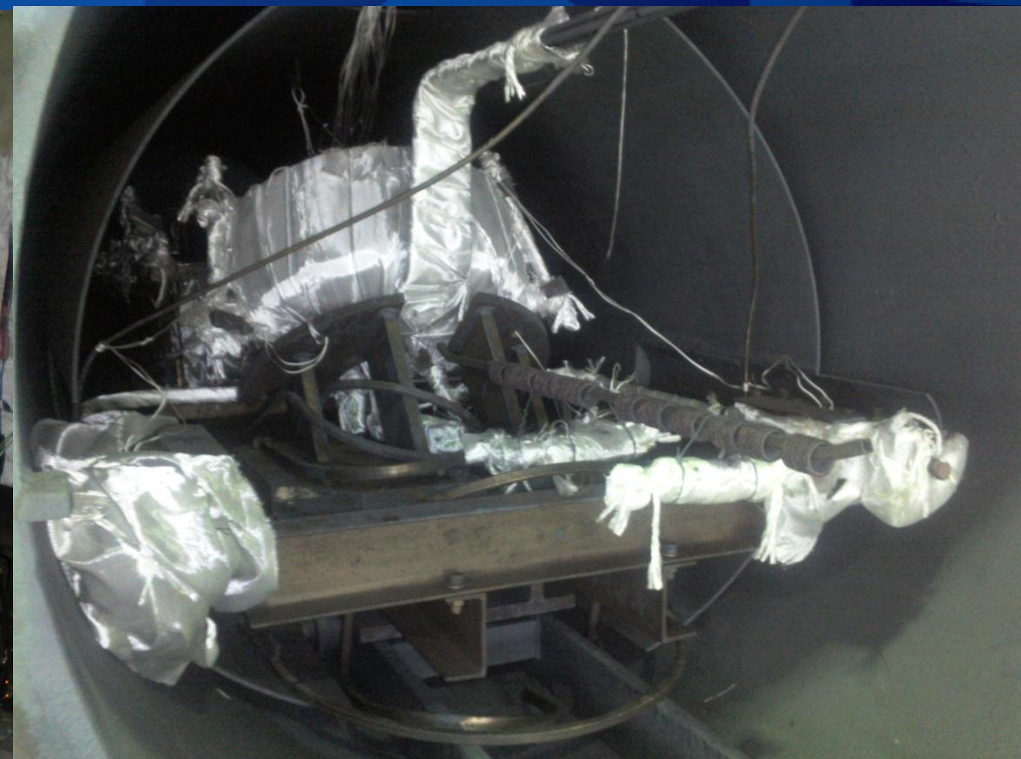
DE-SIZING AND RHT

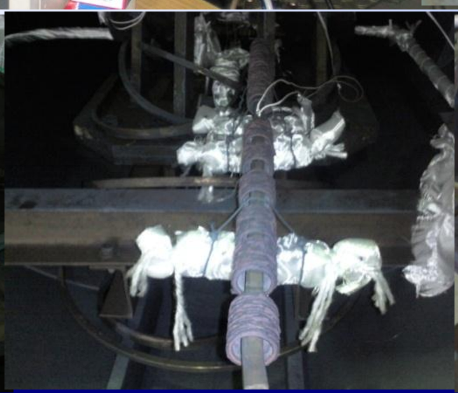




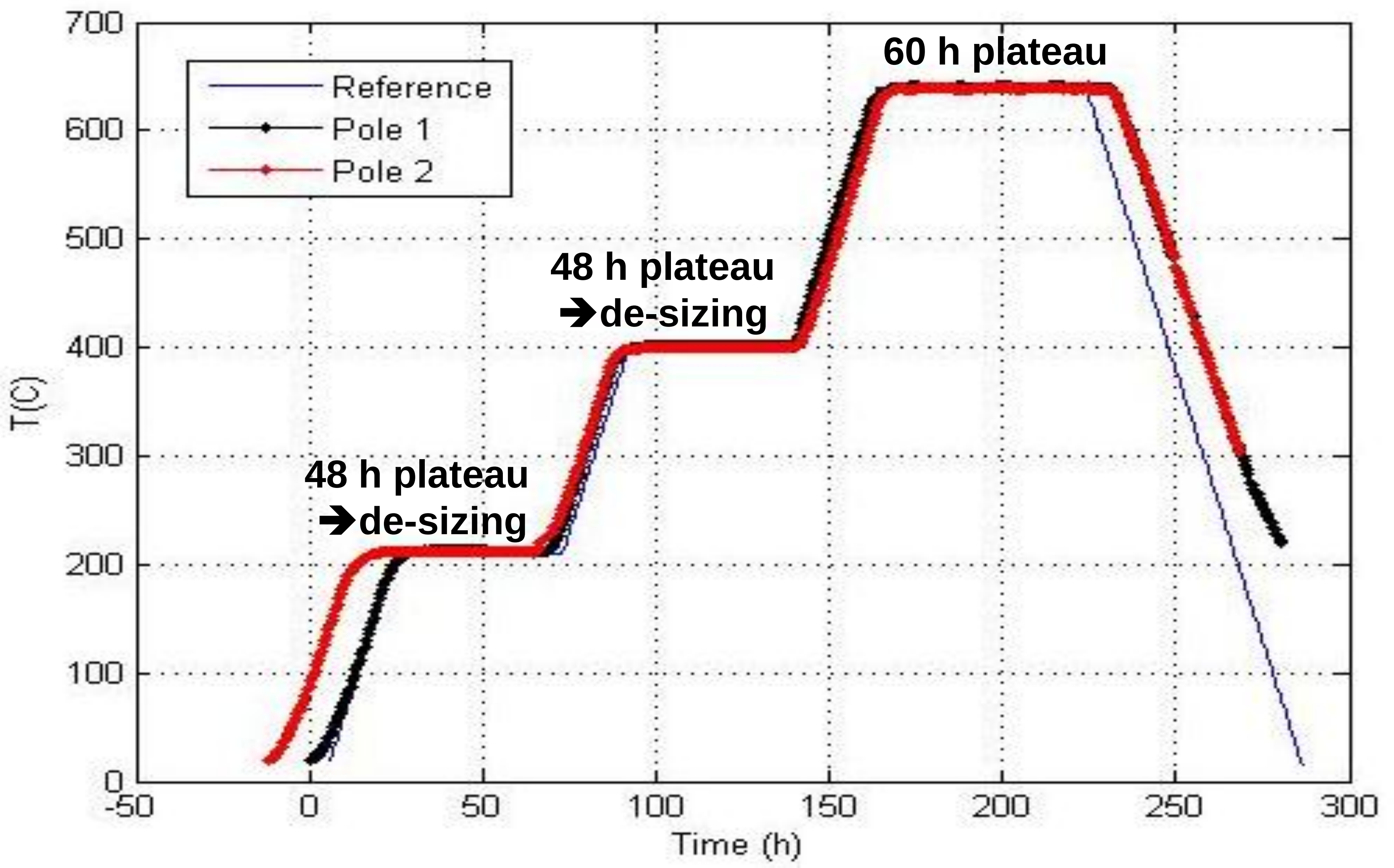


DC COILS REACTION HEAT TREATMENT

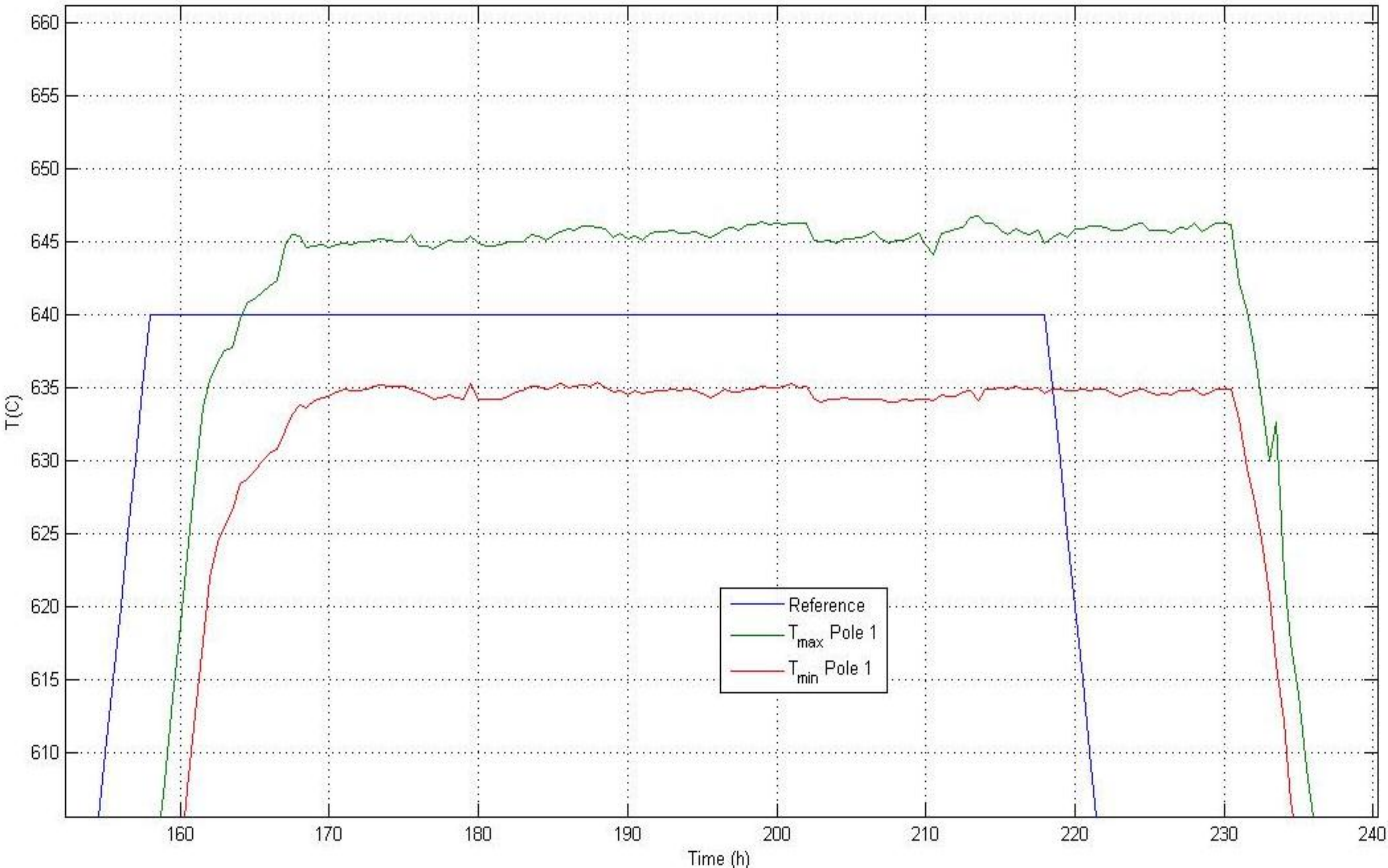




DC COILS REACTION HEAT TREATMENT

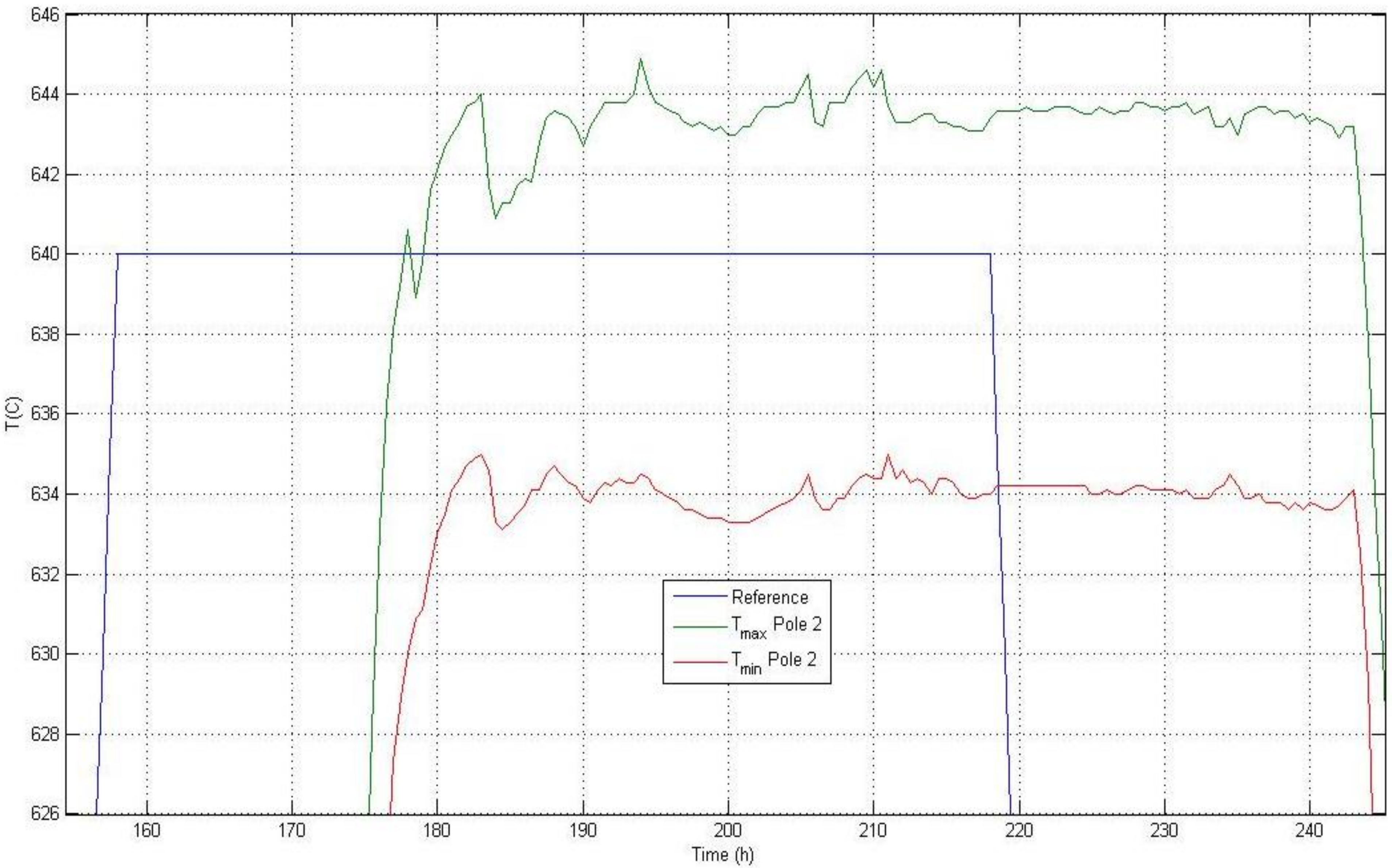


DC COILS RHT: POLE 1 640 C PLATEAU

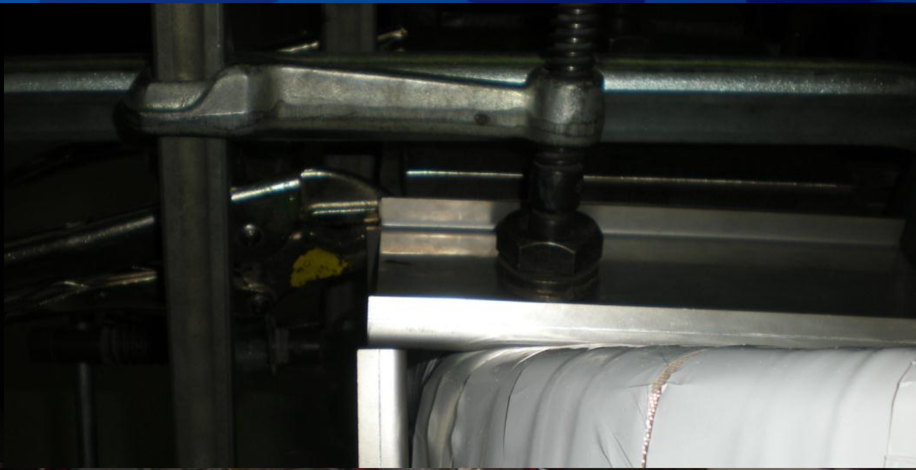


EDIPO DC COILS RHT: POLE 2 640 C PLATEAU

FUSION FOR ENERGY



DC COILS IMPREGNATION



DC COILS IMPREGNATION POLE 1

FUSION FOR ENERGY

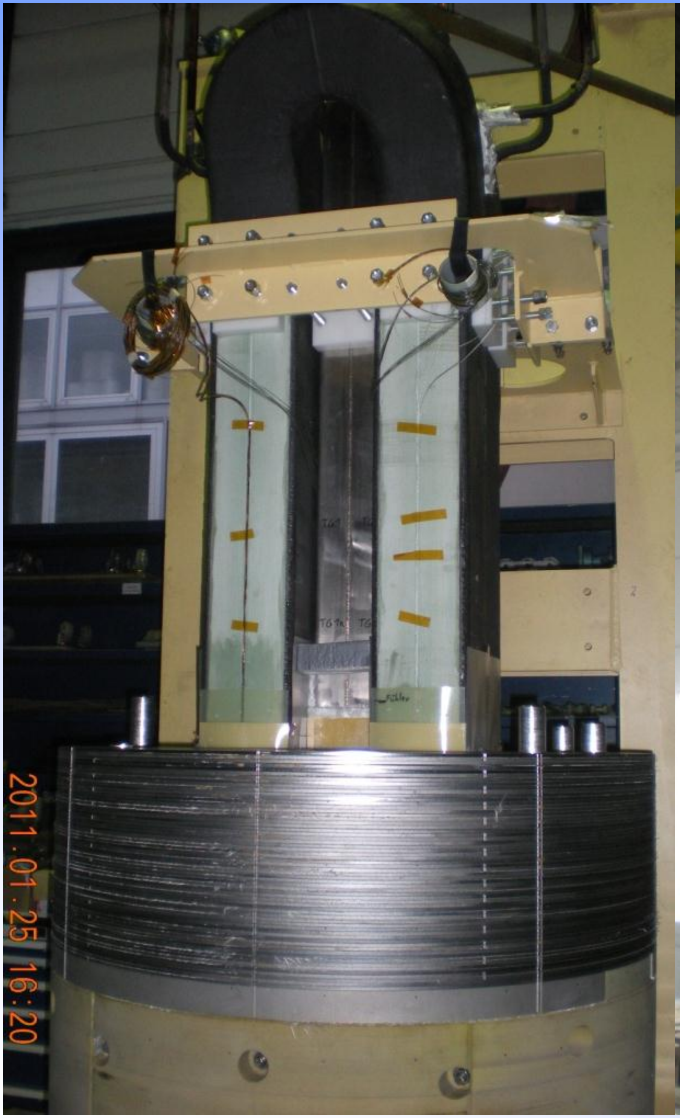
DC COILS IMPREGNATION POLE 2

DC COILS PRIOR TO POLE 1 FAULT DETECTION

27/07/2010

DC COILS-YOKE ASSEMBLY

FUSION FOR ENERGY



25/01/2010 09/02/2011 01/03/2011

DC COILS-YOKE TRANSPORT

FUSION FOR ENERGY

03/03/2011

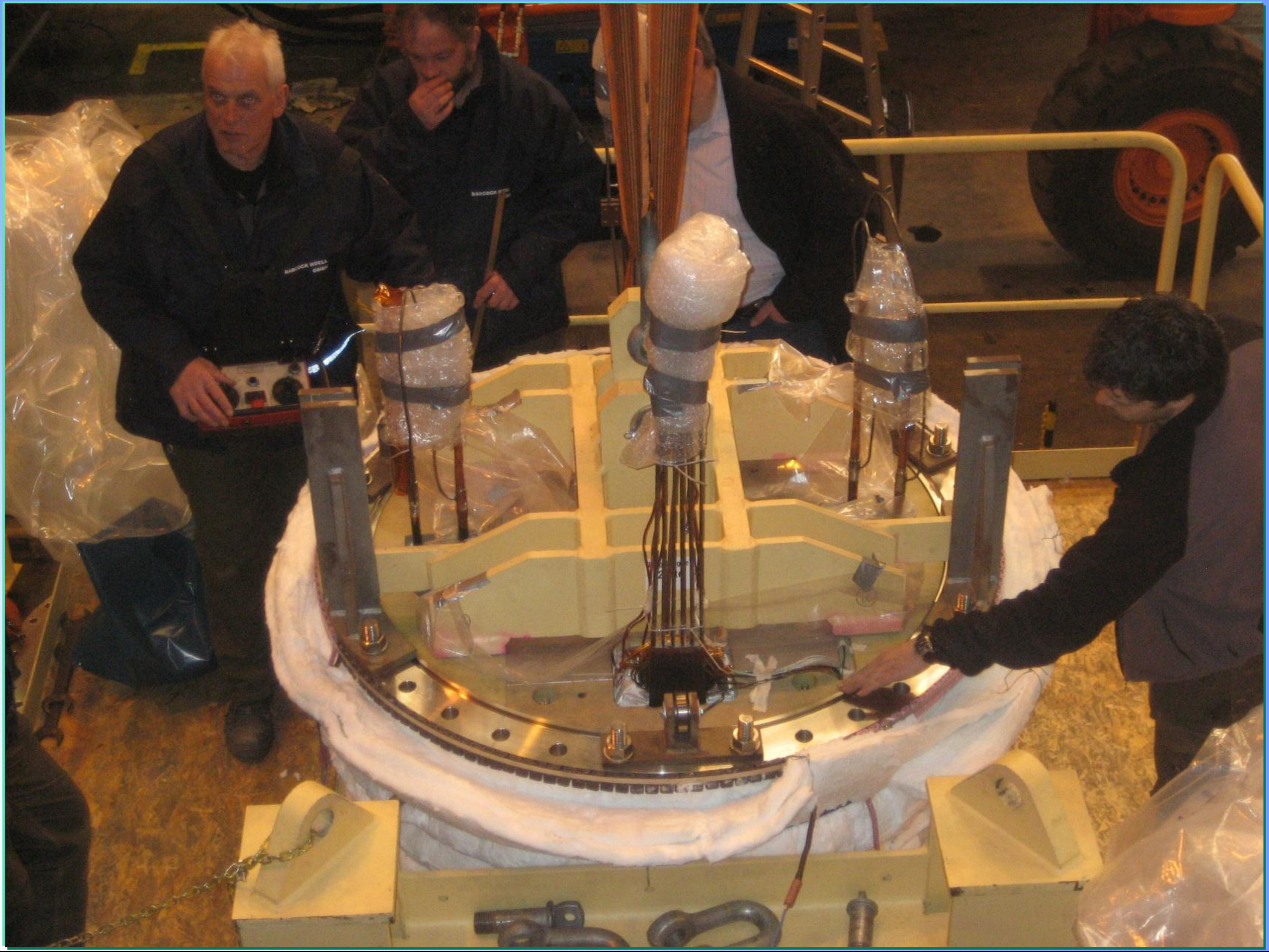
DC COILS-YOKE AND OUTER CYLINDER TRIAL ASSEMBLY

FUSION FOR ENERGY

04/03/2011

DC COILS-YOKE AND OUTER CYLINDER TRIAL ASSEMBLY

FUSION FOR ENERGY



04/03/2011


2011.04.06 07:42


DVA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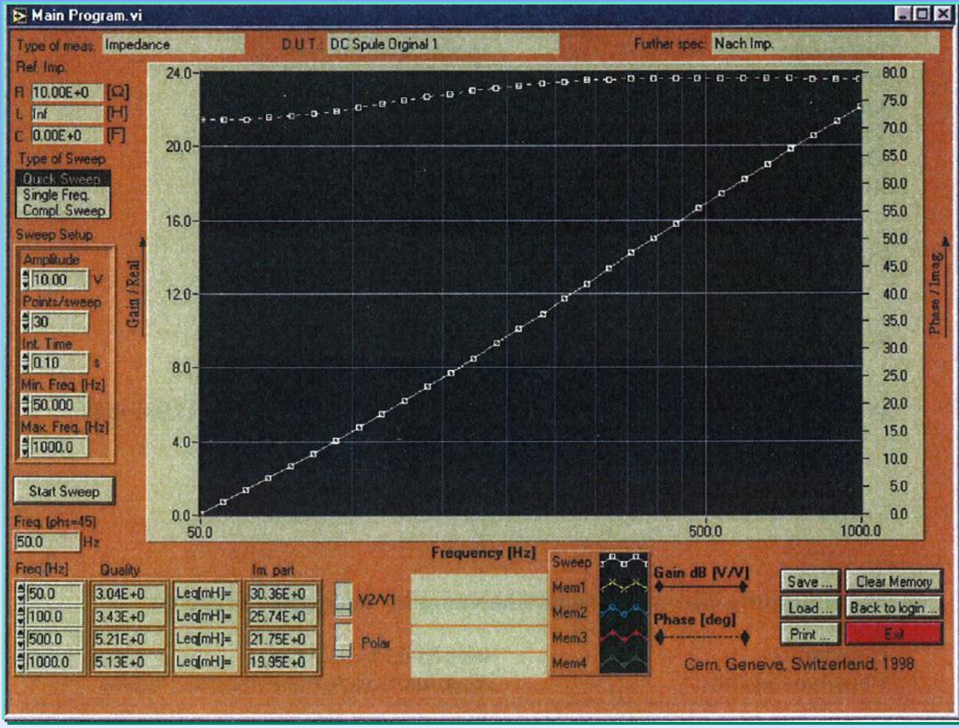
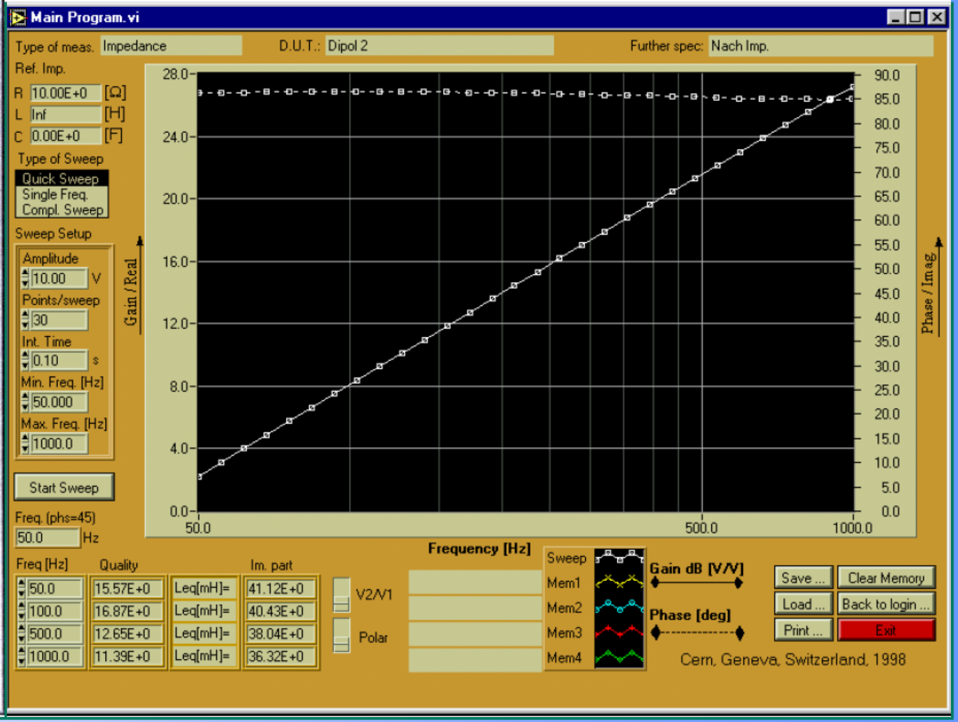
ACCEPTANCE TESTS AND REPAIR WORK

DC COILS PRIOR TO POLE 1 FAULT DETECTION

DC COILS ELECTRICAL TEST AFTER COILS IMPREGNATION





Pole 1 (28/04/2010) **Pole 2 (07/07/2010)**

DC COIL POLE 1 FAULT SEARCH (Aug.-Oct. 2010)

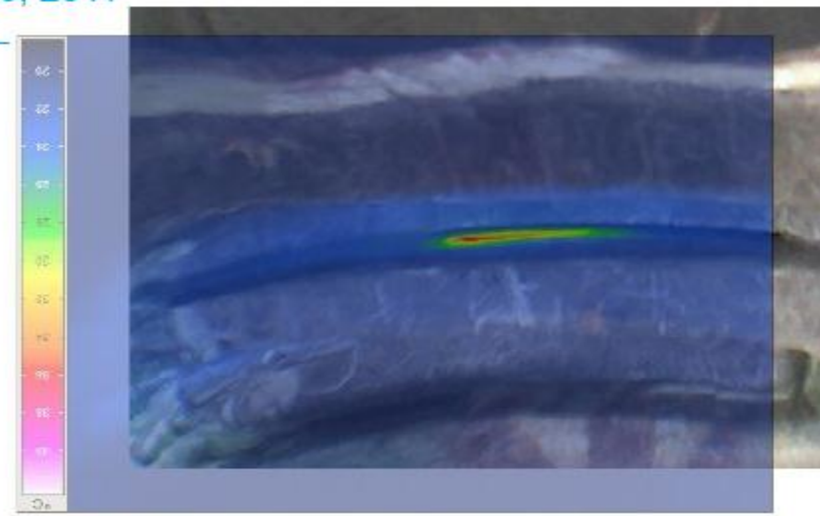
FUSION FOR ENERGY

EDIPO

Interface Meeting F4E/PSI-CRPP/BNG January 26, 2011

BABCOCK NOELL

- DC coil 1 fault search



DC COIL POLE 1 FAULT REPAIR (Oct.-Nov. 2010)

FUSION FOR ENERGY

EDIPO

Interface Meeting F4E/PSI-CRPP/BNG January 26, 2011

BABCOCK NOELL

- DC coil 1 repair impregnation in 4 steps
- Step 1: impregnation of slot using evacuated resin

DC COIL POLE 1 FAULT REPAIR (Oct.-Nov. 2010)

FUSION FOR ENERGY

EDIPO

BABCOCK NOELL

Interface Meeting F4E/PSI-CRPP/BNG January 26, 2011

- DC coil 1 repair impregnation in 4 steps
- Step 2: impregnation of grooves between joint tails using evacuated resin

DC COILS POST-REPAIR ELECTRICAL TESTS

FUSION FOR ENERGY

EDIPO

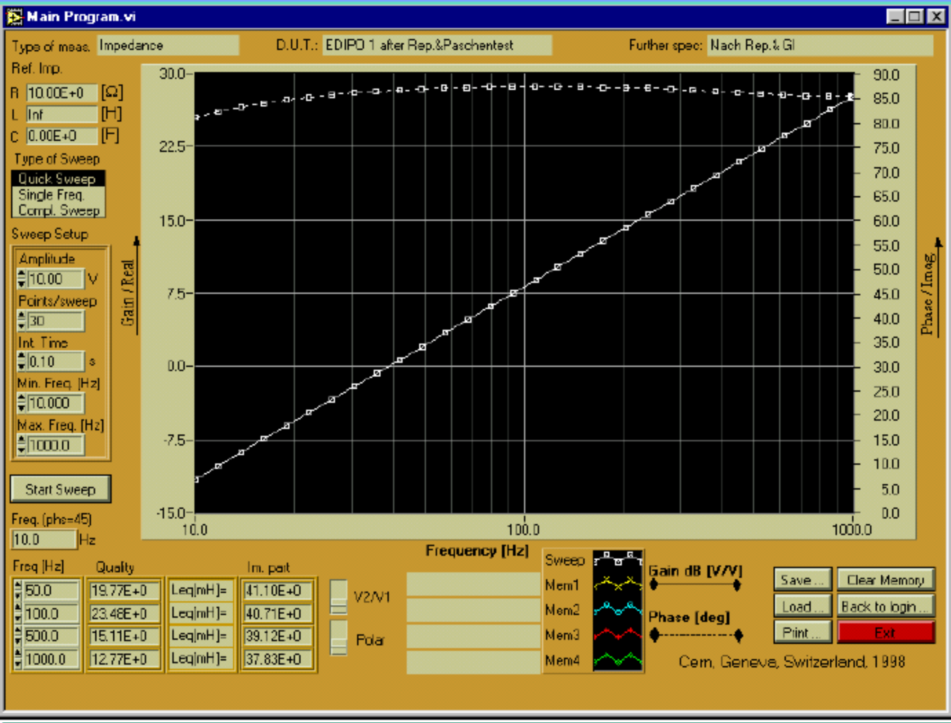
Interface Meeting F4E/PSI-CRPP/BNG January 26, 2011

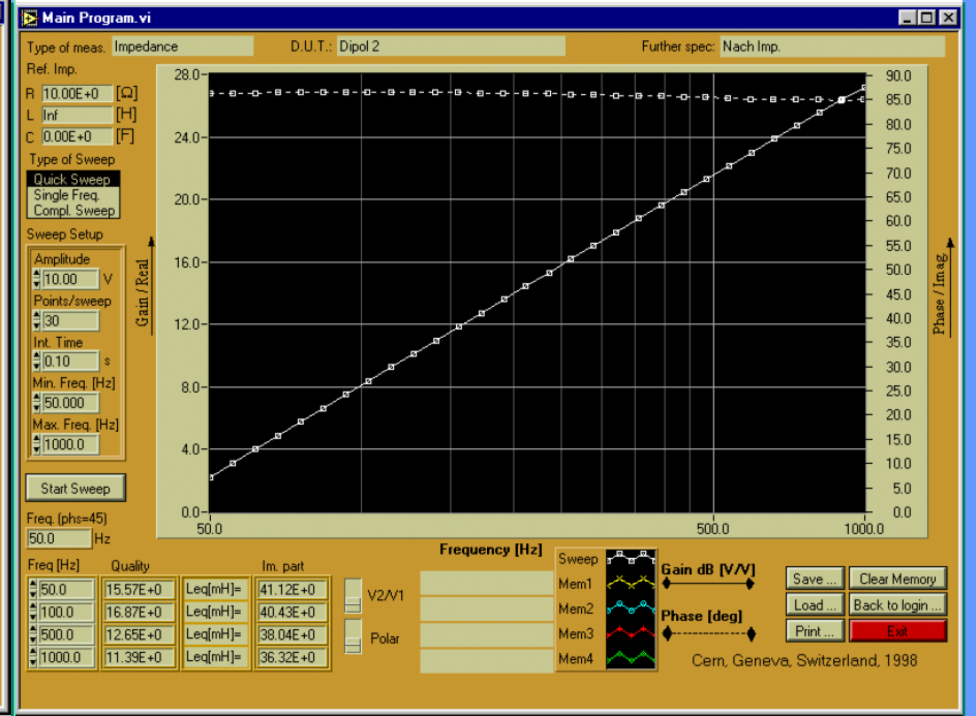
BABCOCK NOELL

	Pole 1	Pole 2
DC Resistance / mΩ	333	325
Inductance by frequency sweep		
L @ 50 Hz / mH	41.10	41.12
L @ 100 Hz / mH	40.71	40.43
L @ 500 Hz / mH	39.12	38.04
L @ 1000 Hz / mH	37.83	36.32
Inductance with RCL meter		
L @ 50 Hz / mH	40.43	40.02
L @ 100 Hz / mH	39.93	39.51
L @ 500 Hz / mH	38.47	37.30
L @ 1000 Hz / mH	37.38	35.77
Inductance and eigenfrequency in pulse discharge test		
	36.32 mH @ 591 Hz	37.12 mH @ 584 Hz

DC COILS ELECTRICAL TEST AFTER POLE 1 REPAIR

FUSION FOR ENERGY

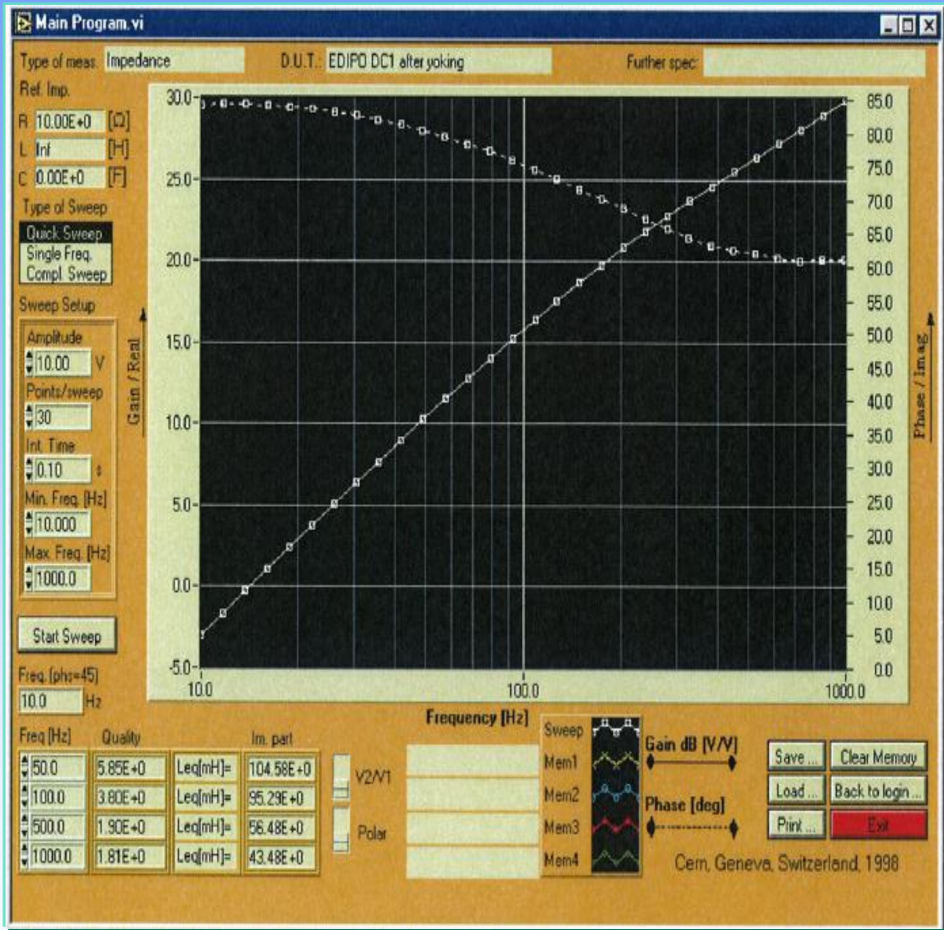


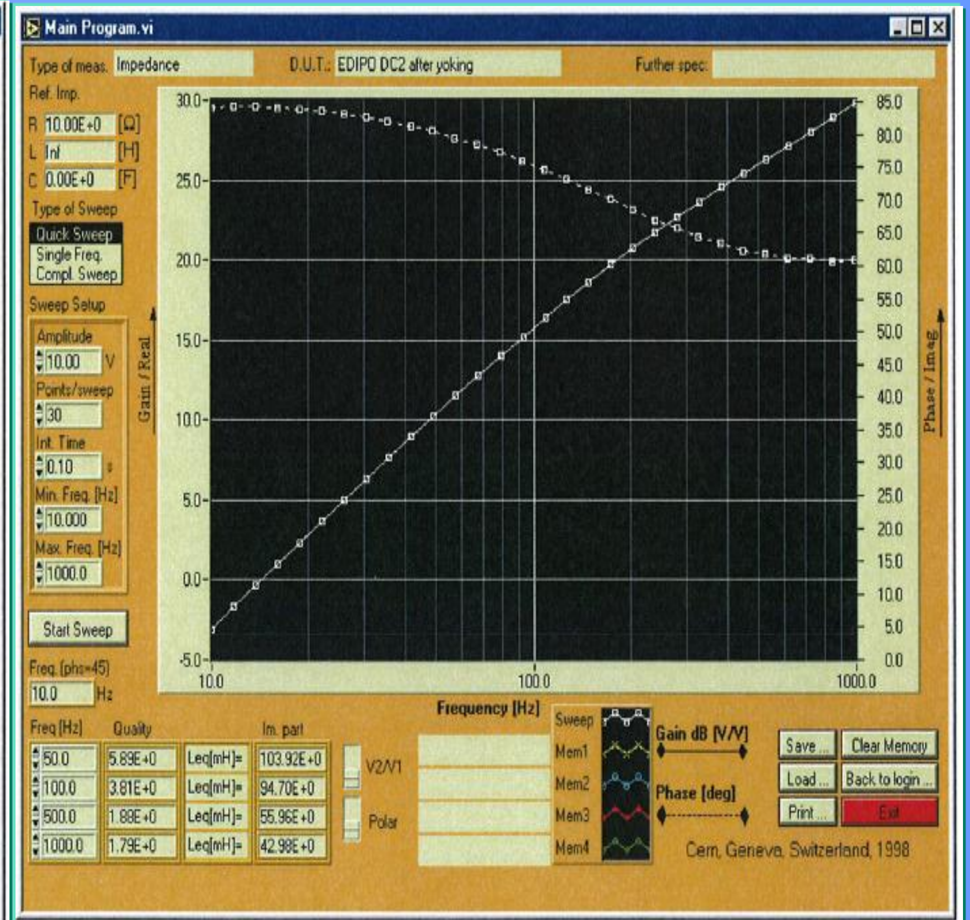


Pole 1 (17/12/2010) **Pole 2 (07/07/2010)**

DC COILS ELECTRICAL TEST AFTER YOKE ASSEMBLY

FUSION FOR ENERGY





Pole 1 **Pole 2**

FINAL ACCEPTANCE TESTS

FUSION FOR ENERGY

1. The last manufacturing step was completed on April 8th 2011 with the final assembly impregnation and curing
2. Over the next month the assembly has undergone successfully the final acceptance tests
   - ✓ Paschen high voltage tests (AC/DC coils)
   - ✓ Resistance/inductance/impulse electrical tests (AC/DC coils)
   - ✓ Leak tests (AC/DC coils + cylinder cooling circuit)
   - ✓ Flow tests (AC/DC coils + cylinder cooling circuit)
   - ✓ Sensors check (8 Strain Gauges, 12 T-sensors)
   - ✓ Final geometrical survey by laser scan
3. Dispatched to CRPP@PSI on 13/5/11
4. Flow tests and sensors checks repeated (ok)
5. Installation on going
6. Commissioning expected in 2012

HISTORY AND OUTLOOK

FUSION FOR ENERGY

Original schedule **Delivery date: March 2008**

Jan.05-Feb. 06 → design, C4Ts for strand/conductor/magnet/facility

Feb.06-Jul. 06 → conductors qualification (CRPP)

Feb.06-Sep.07 → magnet fabrication (BNG)

Oct.07-Mar. 08 → magnet installation & commissioning at CRPP

July 06 → HF+LF conductors qualification failure

1st Revised schedule **New delivery date: June 2010**

Aug.06-Jun.08 → re-design, conductors re-qualification, negotiations

December 09 → Magnet ready for dispatching

December 08 → Winding process qualification failure

2nd Revised schedule **New delivery date: June 2011**

Jan.09-Aug. 09 → new winding process qualification

Aug.09-Jul. 10 → both poles completed, electrical tests on-going (on track)

Aug.10-Nov.10 → magnet assembly, final impregnation, final acceptance tests

Dec.10-Jun. 11 → commissioning of EDIPO facility at CRPP

HISTORY AND OUTLOOK

August 10 ➔ Turn insulation failure

3rd Revised schedule **New delivery date: June 2013 (?)**

Aug.10-Dec.10 ➔ Fault localization and repair
Jan. 11-Apr. 11 ➔ Final cold mass assembly and impregnation
May 11 ➔ Final acceptance tests
13 May 2011 ➔ Dispatching to CRPP/PSI
April 2012 ➔ Complete installation in SULTAN hall
2012-2013(?) ➔ Final facility commissioning

CONCLUSIONS

FUSION FOR ENERGY

- EDIPO project aims to build a 12.5 T dipole with CIC Nb_3Sn conductors wound in a pair of saddle shaped coils to test sc samples with currents up to I~ 100 kA in a clear bore of ~10 x 15 cm^2

- Although the overall budget (EC contribution) is within its 2006 allocation, the original project schedule has been disrupted by 3 major problems:
  (1) delayed qualification of both Nb_3Sn CIC
  (2) delayed qualification of winding process
  (3) turn insulation repair

- All problems have been fixed and now the EDIPO magnet is completed

- Final commissioning is delayed by conflict to access SULTAN hall and manpower whose priority are set to test ITER samples in the existing SULTAN facility

LESSONS LEARNED

FUSION FOR ENERGY

1. CONDUCTORS

- Square shaped conductors maximize compactness (J_{ENG}) but have lead to poor (unexpected) NbSn cable performances; high aspect ratios show higher Tcs performances and robustness to cyclic loads. Longer twist pitches and lower void fraction improve performances and resistance to cyclic degradation;
- Pull-through and compaction jacketing time and cost effective. Beware of additional jacket cold-work

1. WINDING

- Pull-and-wind method for (steel jacketed, thick wall) CICC doesn't work with multiple radii of curvature, tight bents and many layers. Cold work during compaction leads to remarkably high yield strength. To grant geometrical compliance too large clamping pressure needs to be applied (insulation damages, impregnation hydraulic impedance, ...).
- Its apparent attractiveness (and some manufacturing experience by main contractor) has been deceiving leading to a rushed submission of a cheap technical offer that has lead to under-estimation of the difficulties and associated technical risks by the proposed winding process (➔long and painful resolution!)

LESSONS LEARNED

PROJECT MANAGEMENT

1. Insufficient critical challenging of contractor's choice by EC/EFDA has lead to a de-facto endorsement of pull-and-wind method. Eventually EFDA has imposed its view (pre-bend-and wind method) with substantial delays that have lead to costs overrun by the contractor (!)
2. Insufficient critical supervision of specific duties assigned to contractor such as electrical tests. More modelling of electrical system and verification of electrical tests findings were needed (lack of manpower for technical monitoring?)
3. Customers of high tech projects need to follow-up with proper manpower the tasks to be carried out by industry (➔simulate/test and check!)
4. All problems encountered have been of essential technical nature and their resolution was based on technical improvements of present processes. Delicate balance need to be stricken from both customer as well as contractor side to assign proper managerial responsibilities to technical people

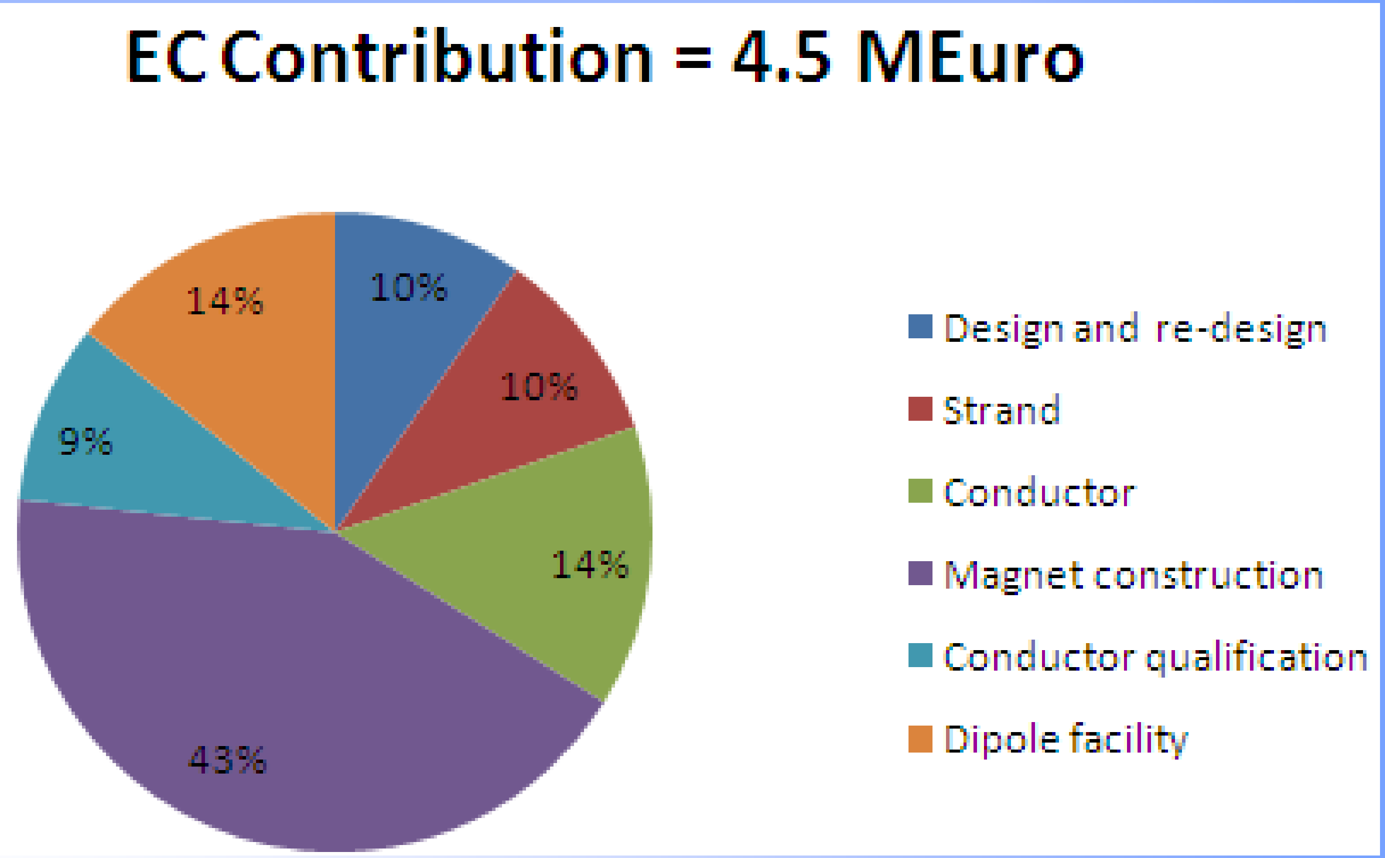
BACK-UP SLIDES

BUDGET

- **Budget**

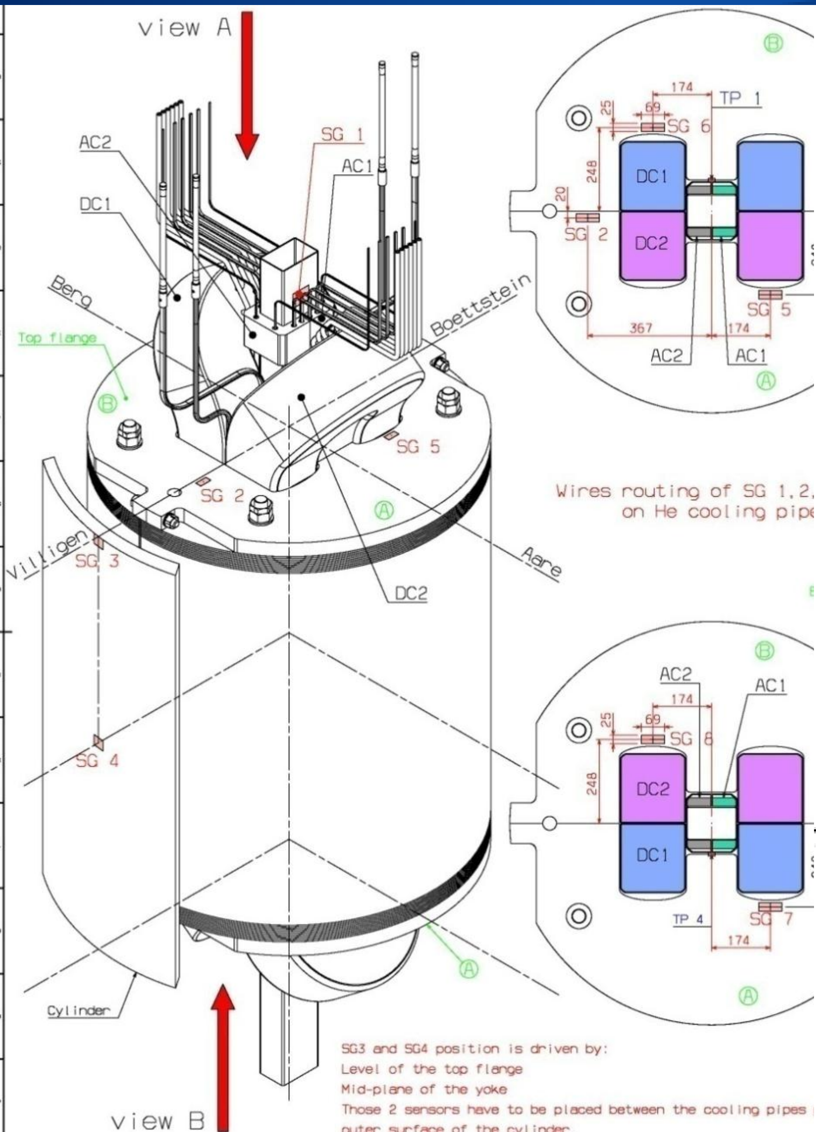
  Present (2010): EC contribution=4.52 M€

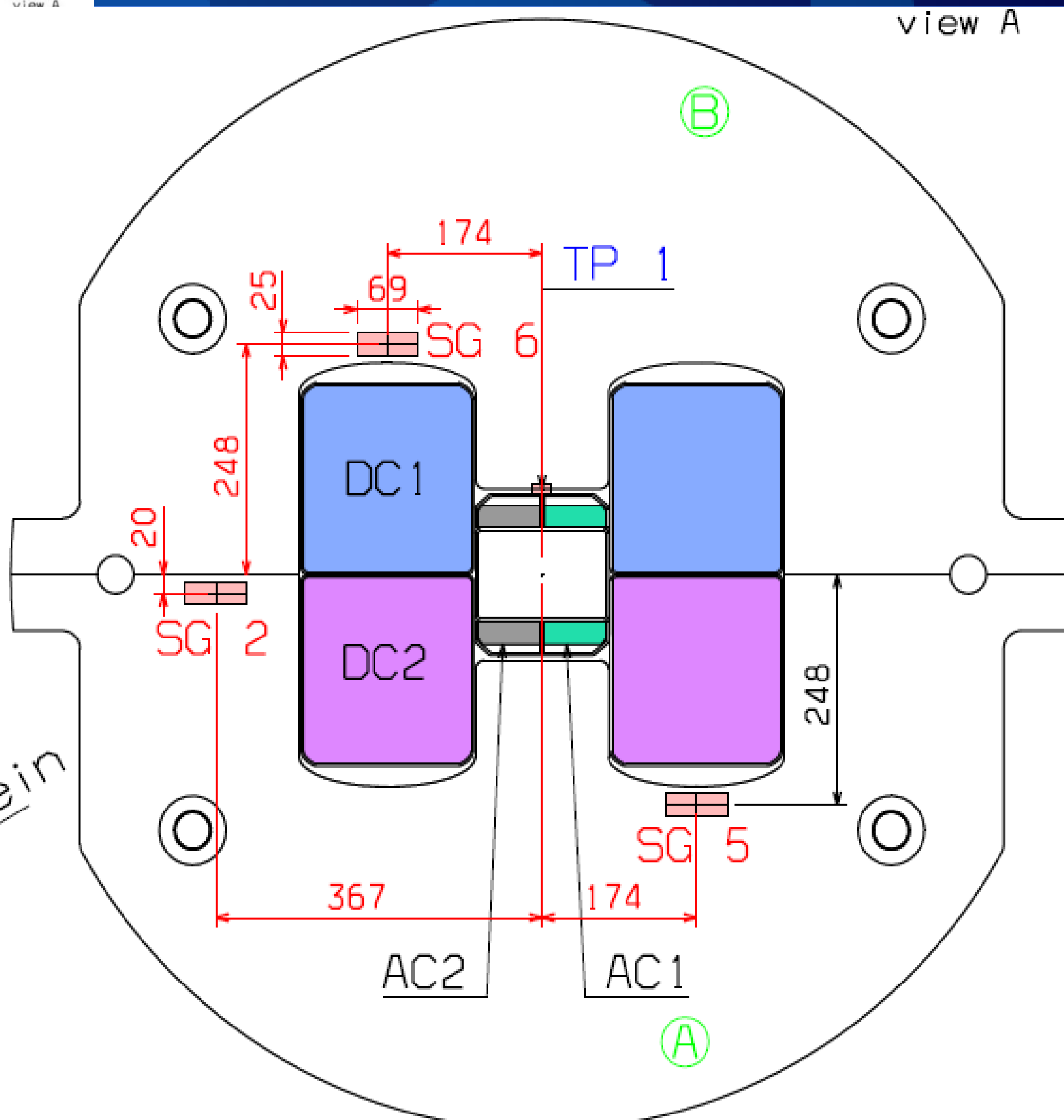
  Original (2006): EC contribution=4.56 M€



EDIPO sensors

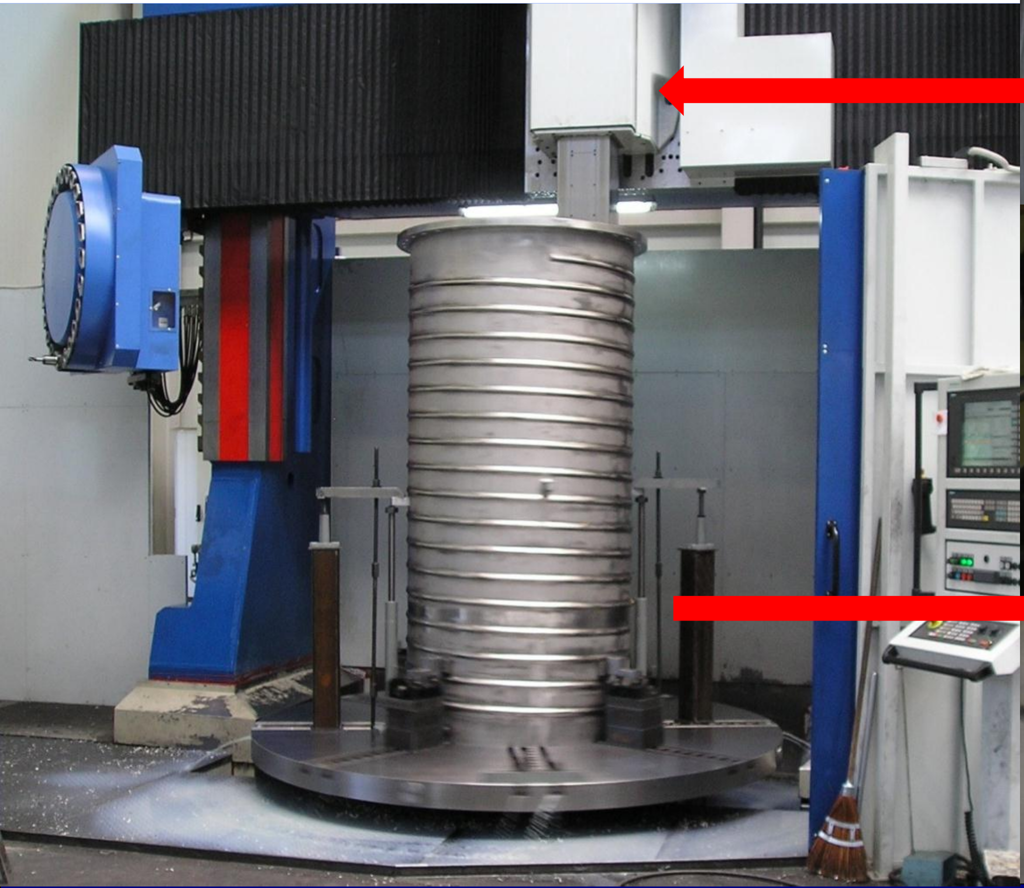
FUSION FOR ENERGY

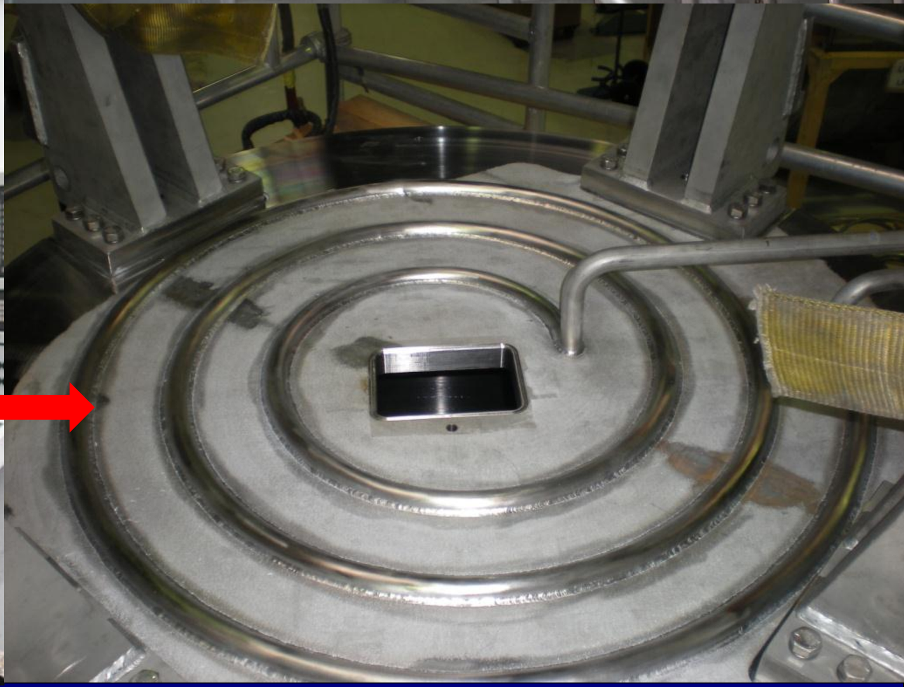


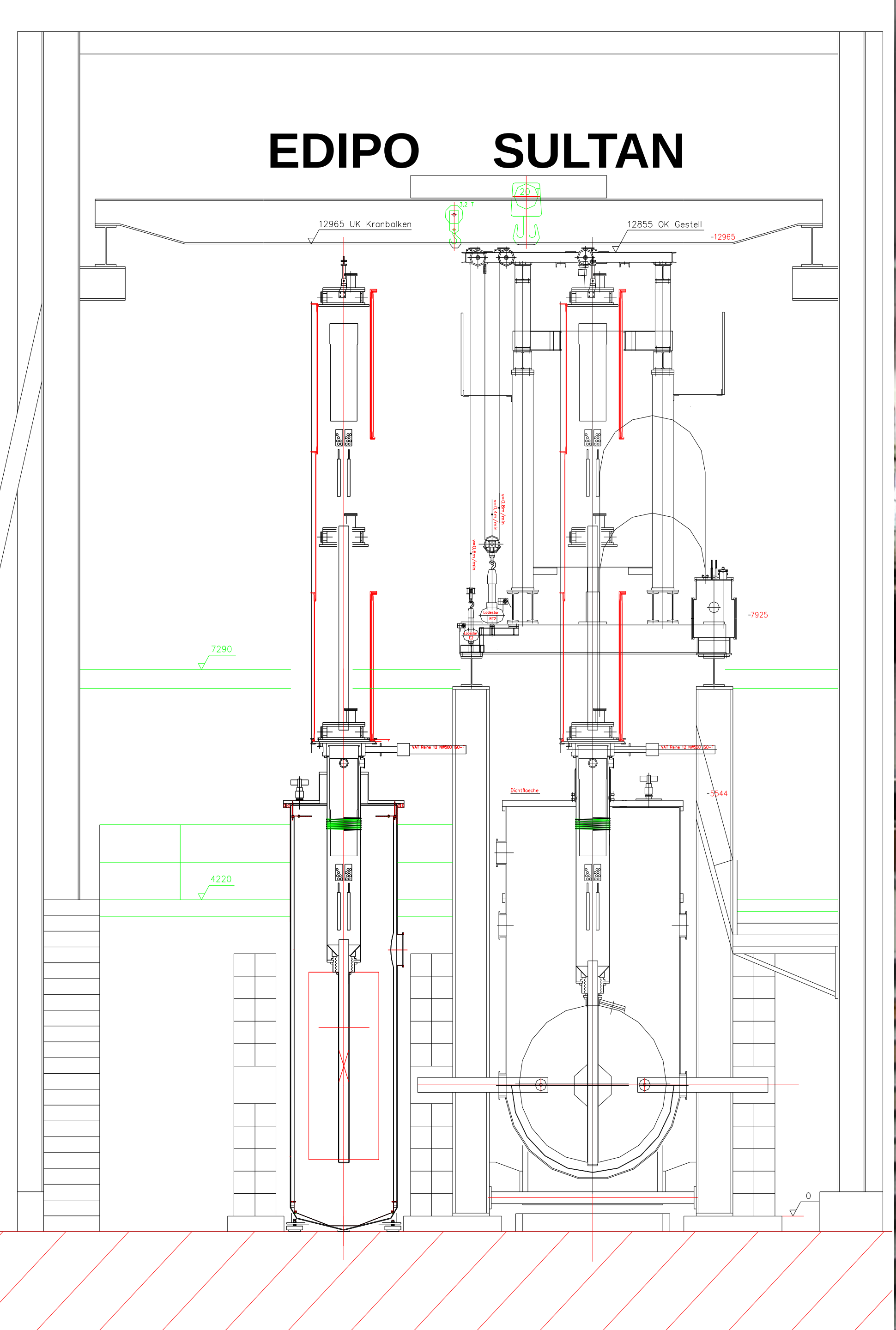


OUTER CYLINDER(S)

- Helical cooling tubes welded
- Final machining completed
- Spiralling tube welded on bottom flange



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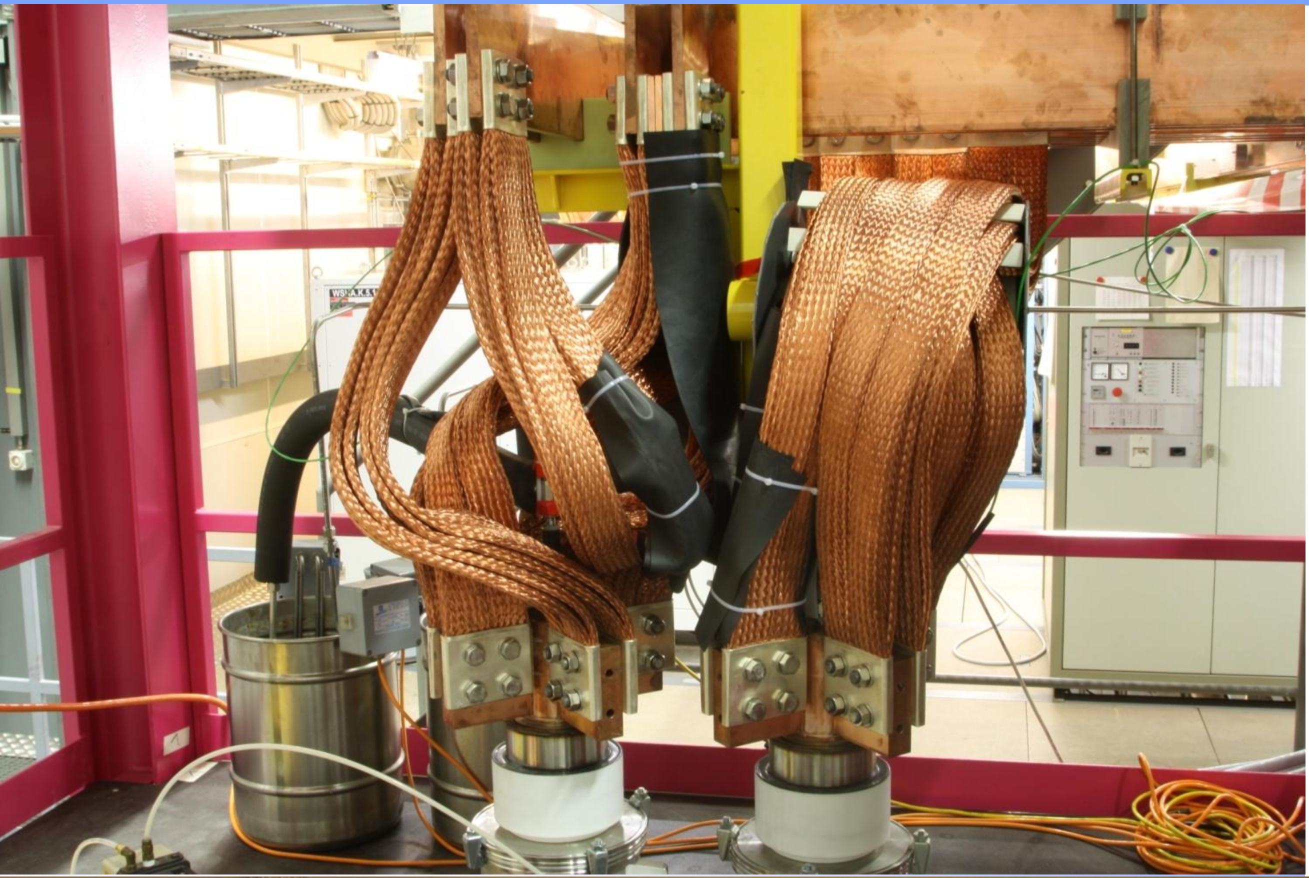
EDIPO
SULTAN
CRPP
SULTAN
Superconductor
Test Facility

HTS CURRENT LEADS (CRPP)

FUSION FOR ENERGY



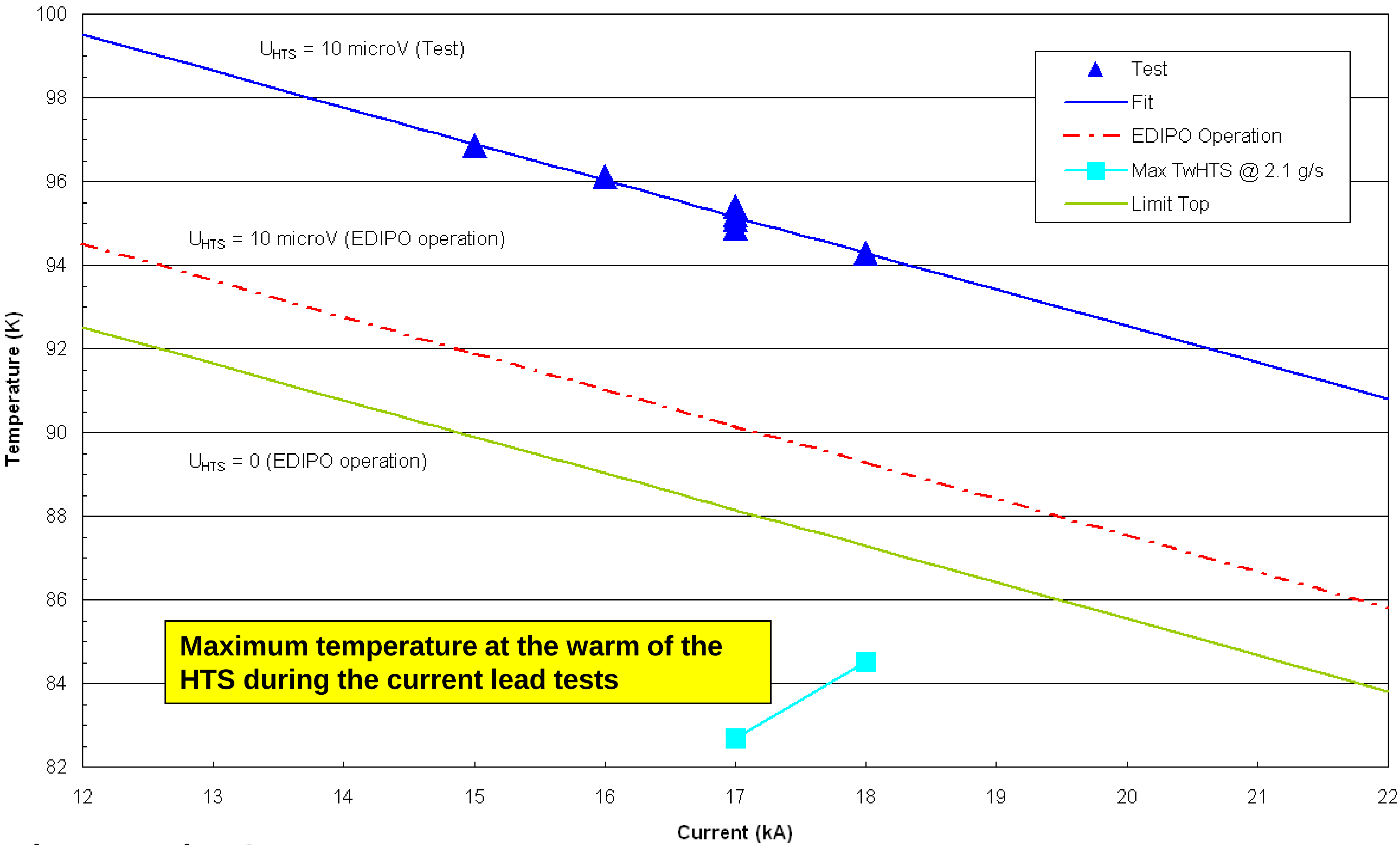
HTS CLs successfully tested up to I~18 kA

Heat leak (conduction):
≈5.5 W at T_{HTS}^{w} = 83 K
Nominal op. conditions:
I = 17 kA
dm/dt = 1.9 g/s
T_{HTS}^{w} = 83 K
T_{He}^{out} ≈ 263 K
U_{Hex} ≈ 97 mV
Contact resistances:
R_{wm} ≈ 10 nΩ (83 K)
R_{cm} ≈ 3.3 nΩ (17 kA)

Rainer Wesche, CRPP

HTS CL T_{CS} EXPERIMENTS

FUSION FOR ENERGY



Rainer Wesche, CRPP

HTCL T_{CS} EXPERIMENTS

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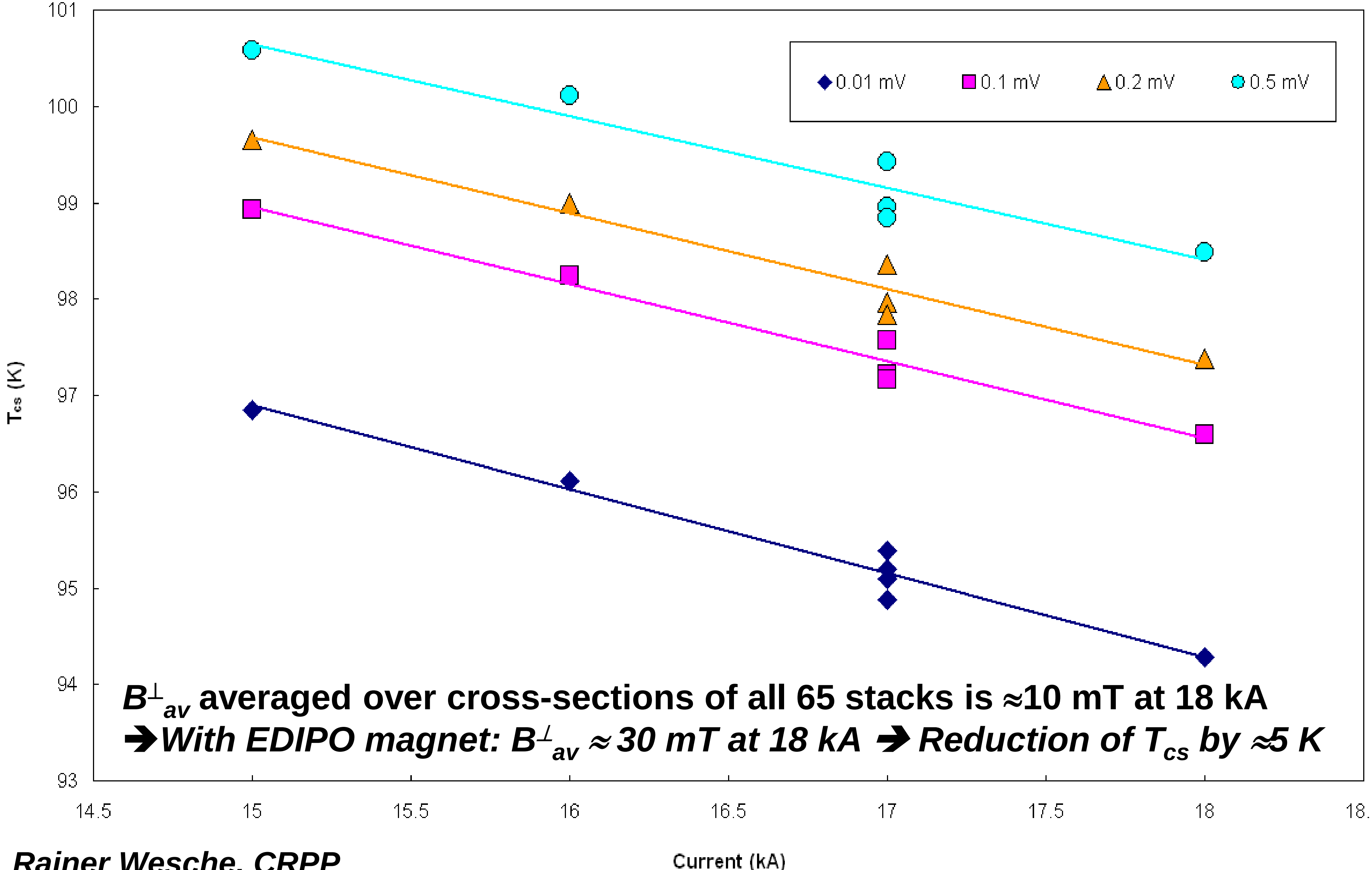


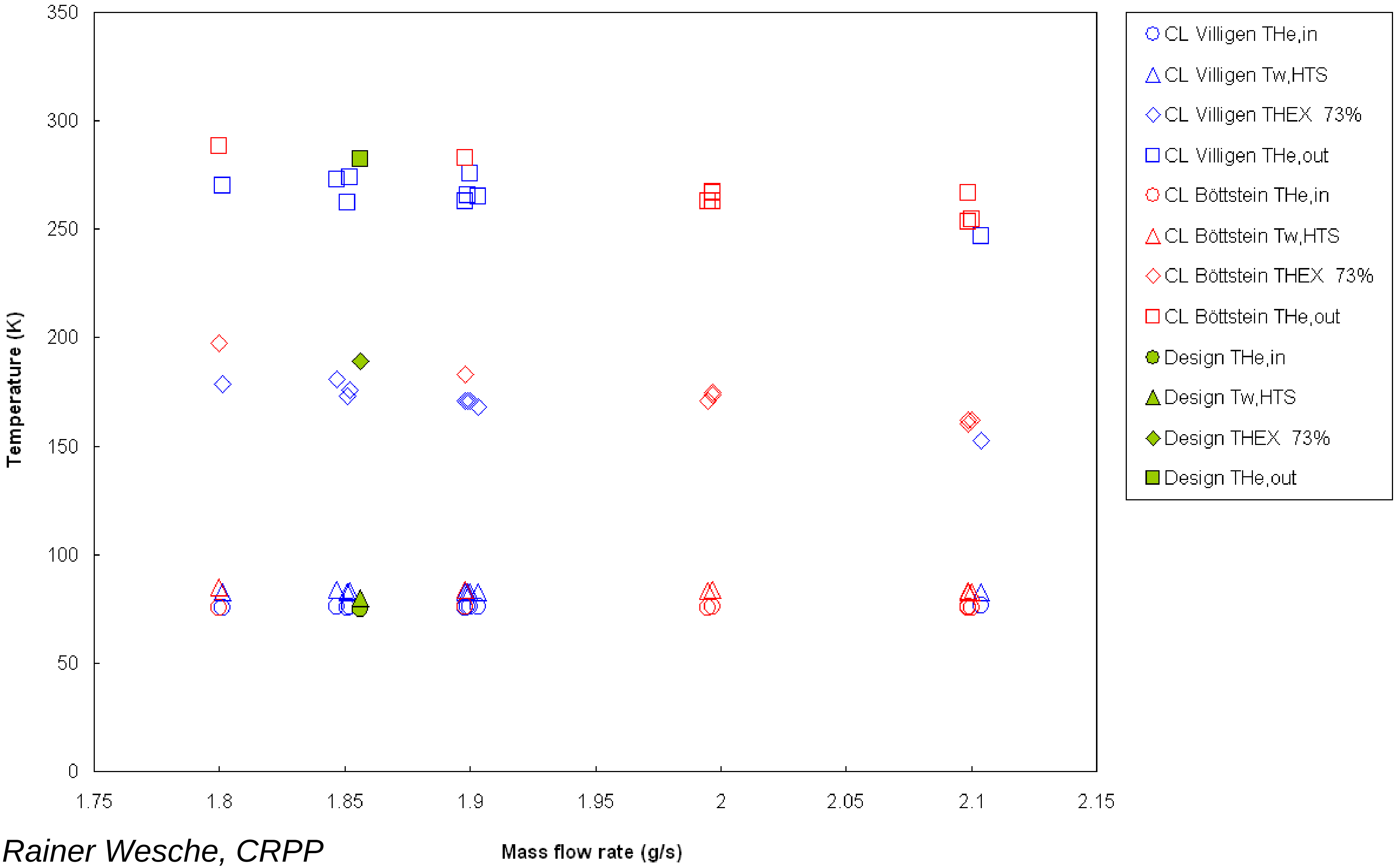
$B^{\perp}_{av}$ averaged over cross-sections of all 65 stacks is ≈10 mT at 18 kA

➔*With EDIPO magnet: $B^{\perp}_{av}$ ≈ 30 mT at 18 kA ➔ Reduction of T_{cs} by ≈5 K*

Rainer Wesche, CRPP

STEADY STATE MASS FLOW

FUSION FOR ENERGY

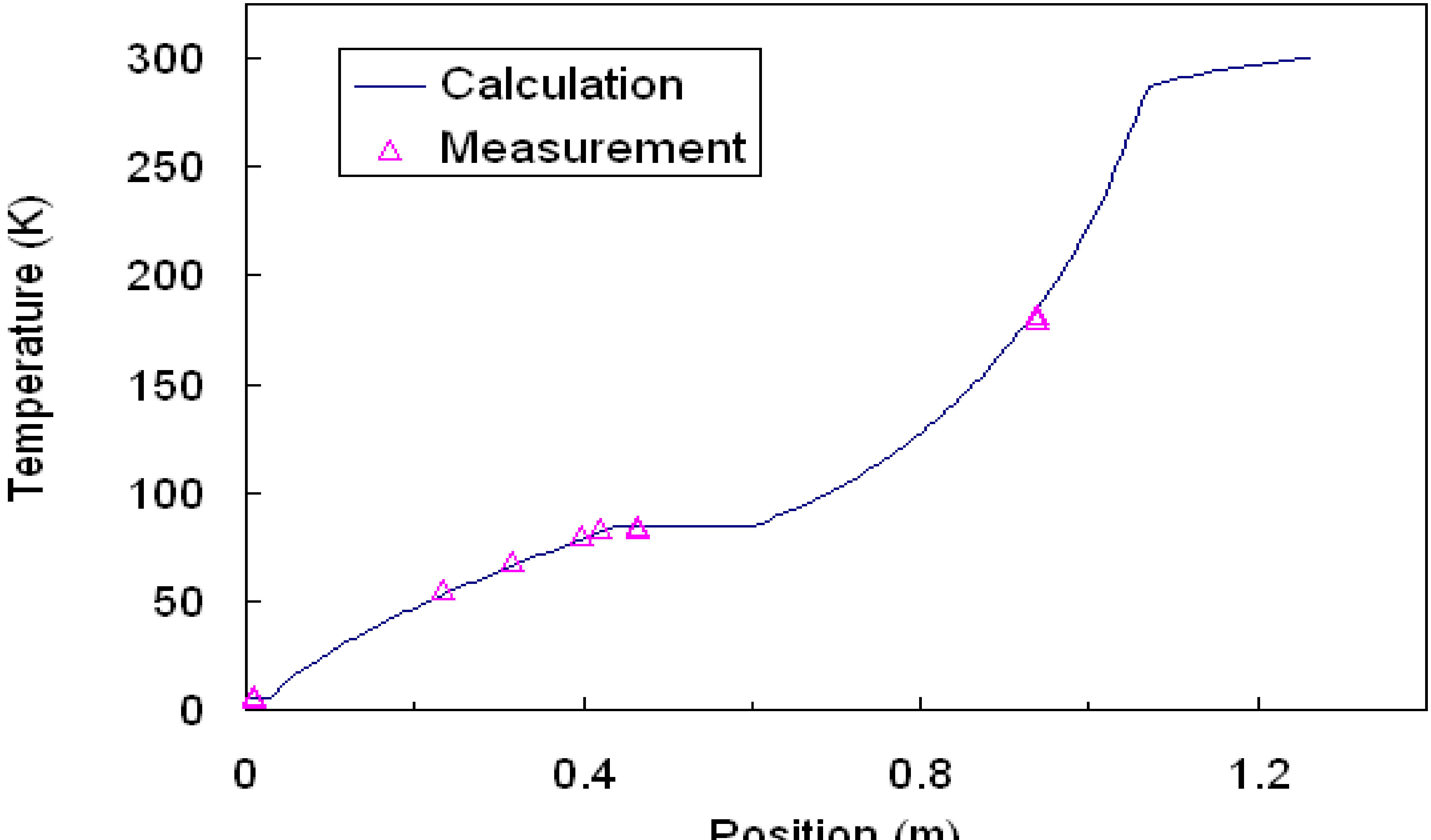


Rainer Wesche, CRPP

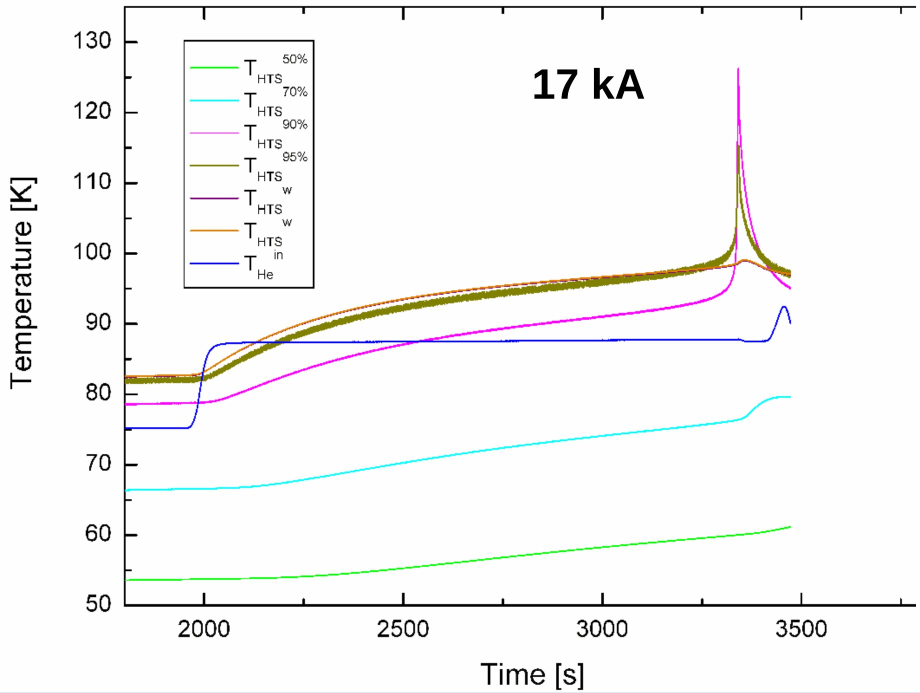
STEADY STATE TEMPERATURE PROFILE

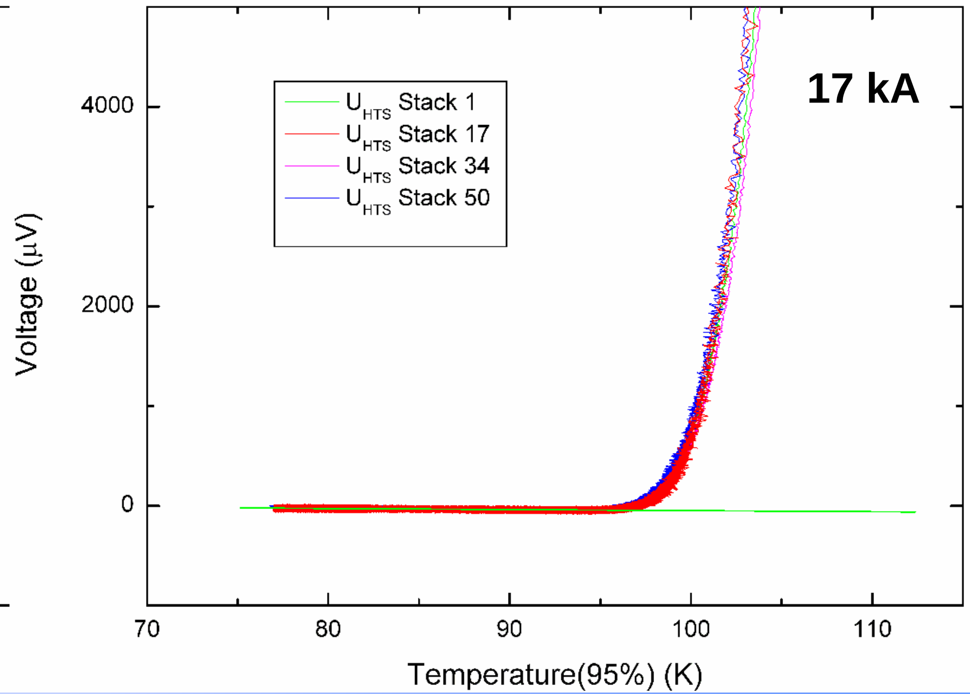
FUSION FOR ENERGY

Good agreement of measured and calculated temperature profile



Rainer Wesche, CRPP





By means of a heater the He inlet temperature is increased until the HTS module quenches.

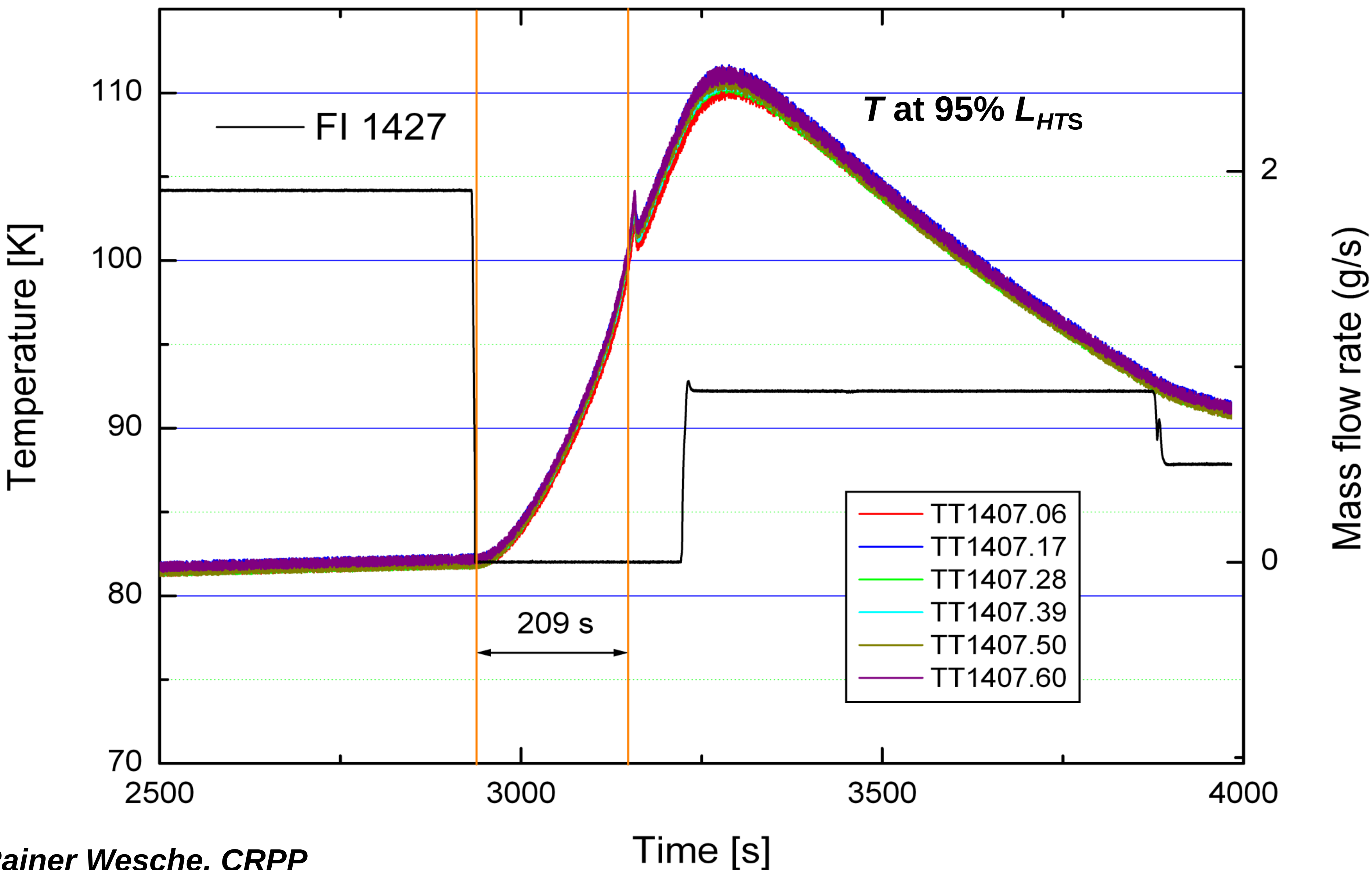
Voltage versus temperature curves for a 17 kA run.

For current leads, T_{cs} can not be defined in the usual way (E = 1 μV/cm) because of the existing temperature gradient.

Therefore, use of a voltage criterion to define T_{cs}.

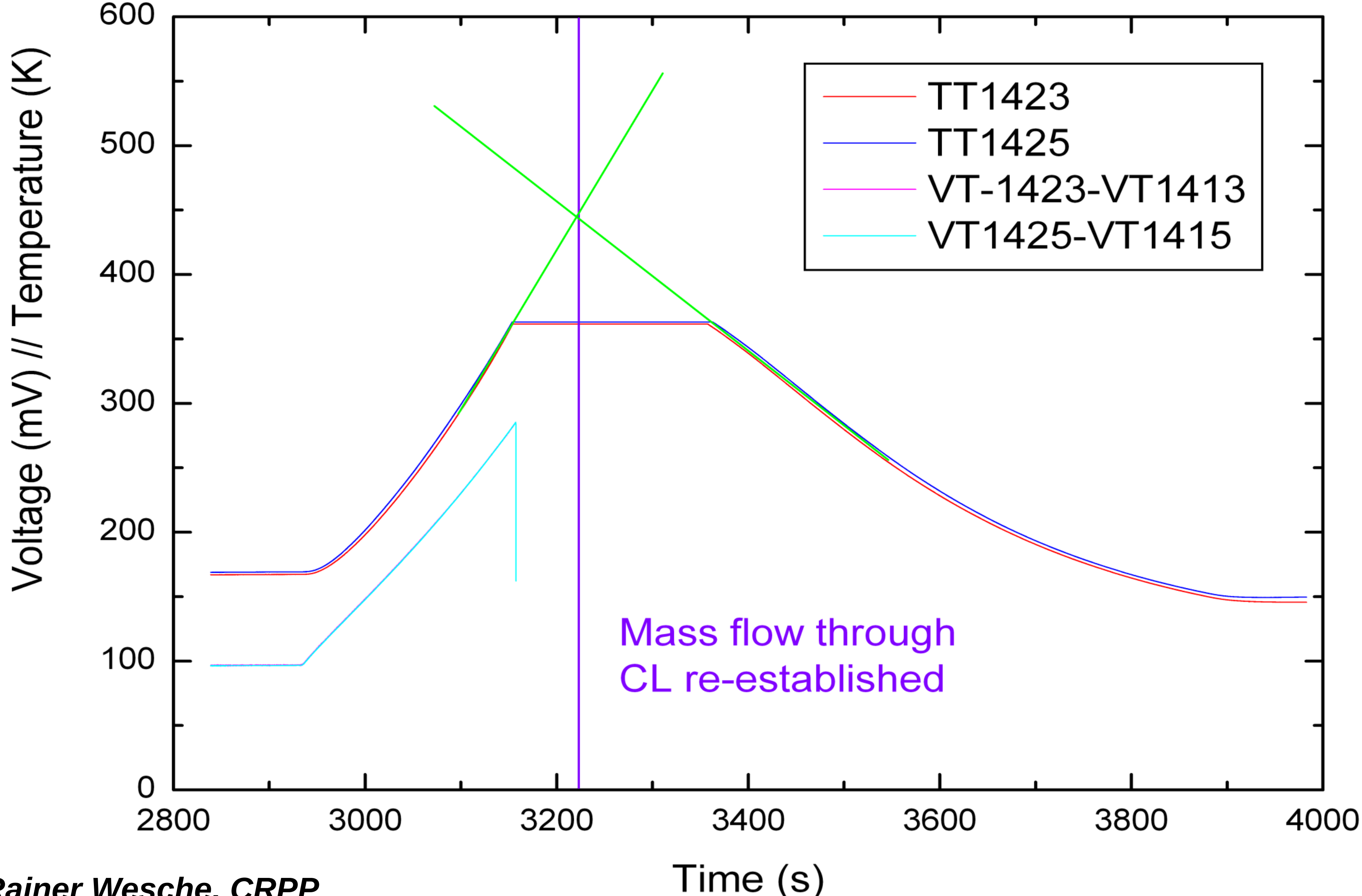
Rainer Wesche, CRPP

LOSS OF FLOW TEST EXPERIMENT (*I* = 17 KA)

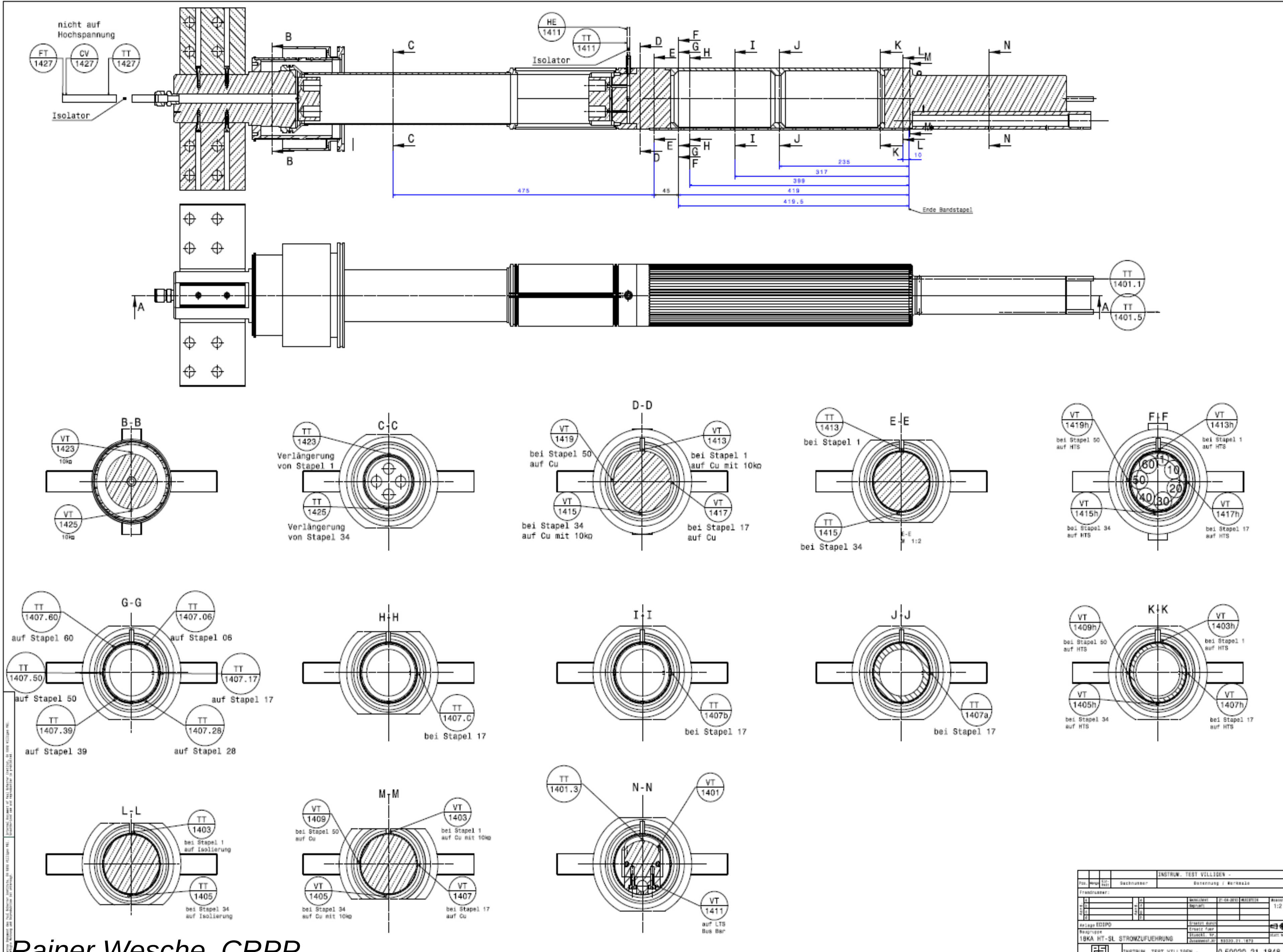


Rainer Wesche, CRPP

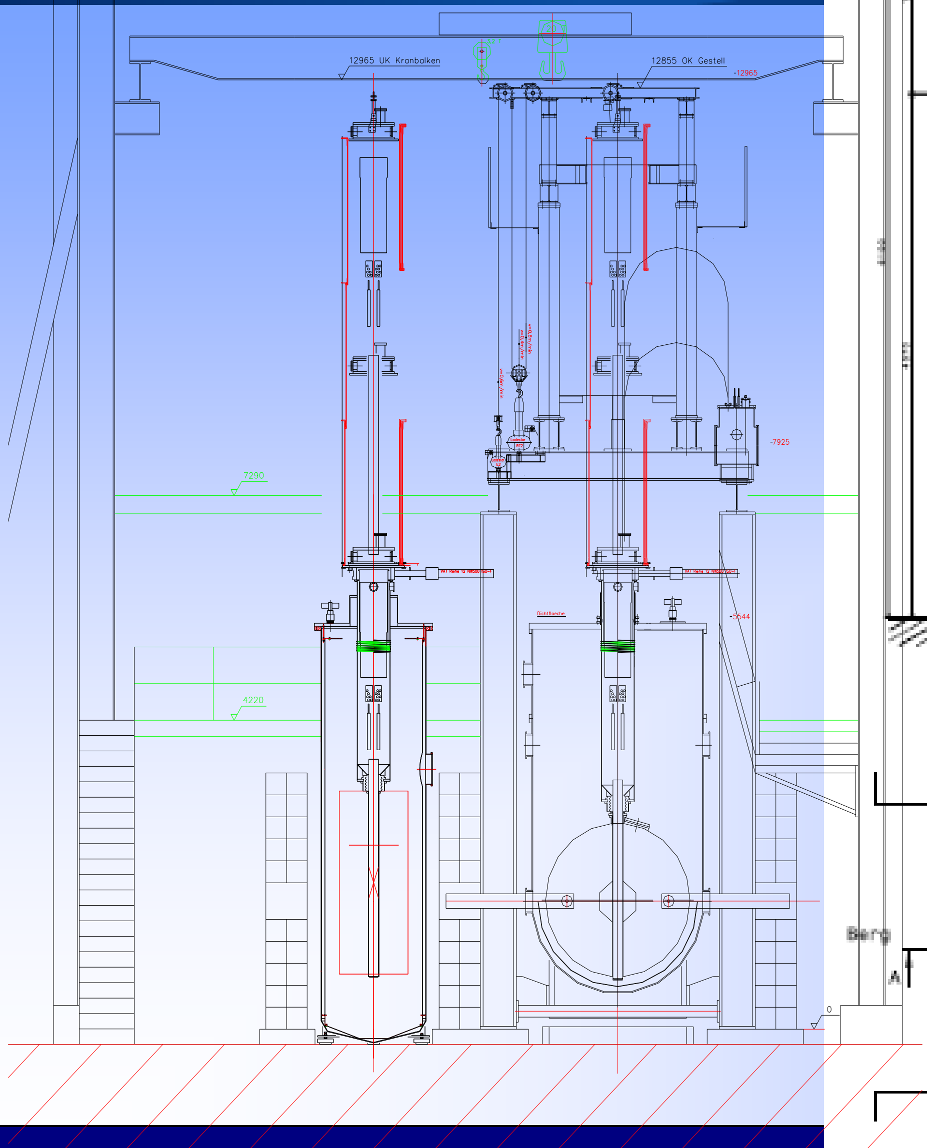
LOSS OF FLOW TEST EXPERIMENT (*I* = 17 KA)

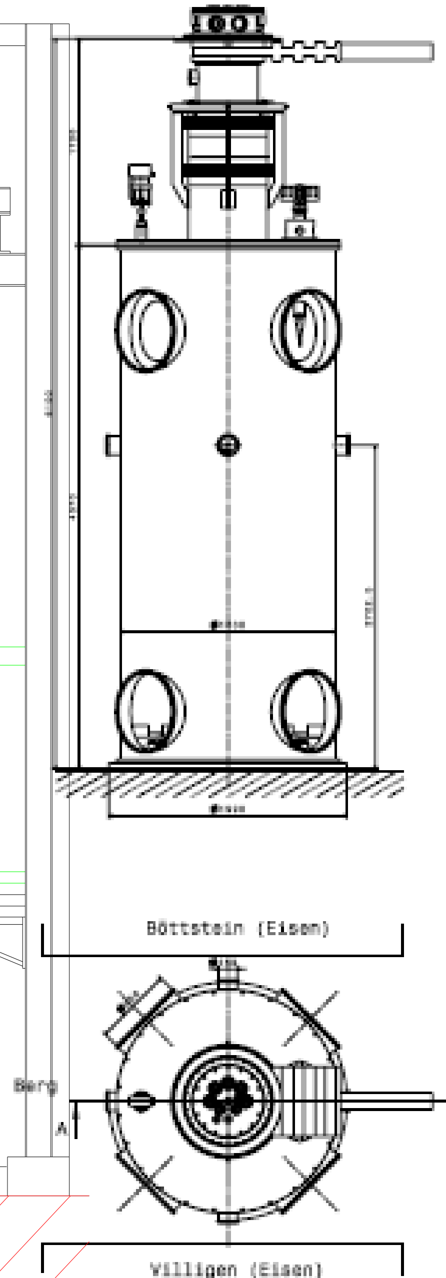


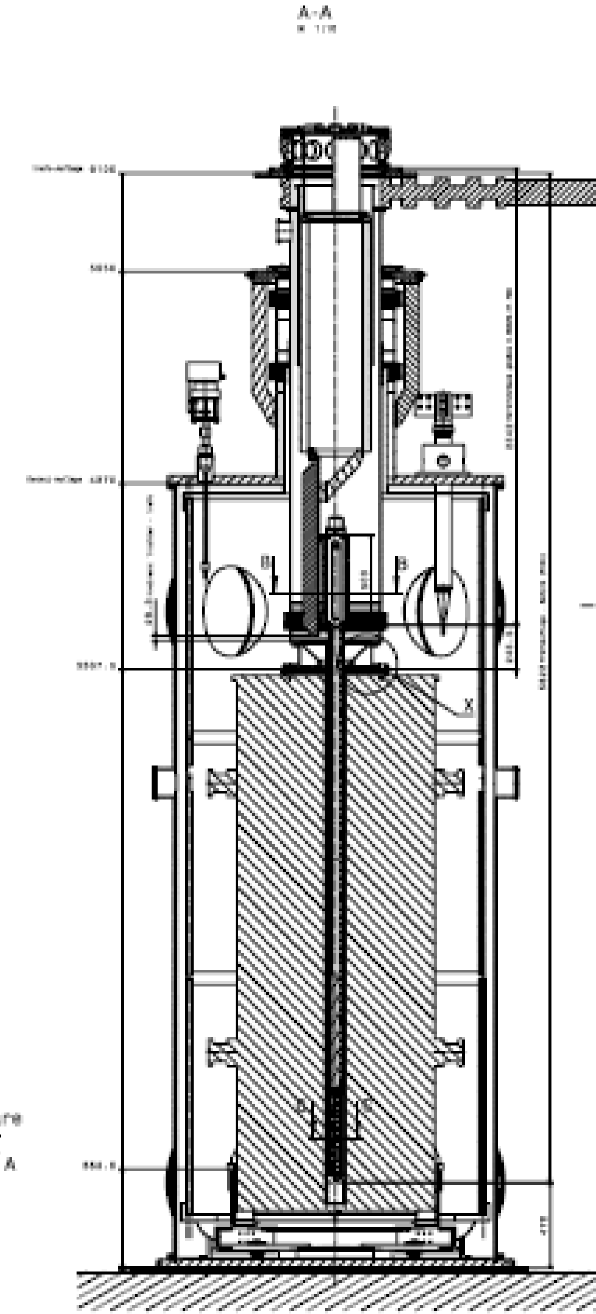
Rainer Wesche, CRPP

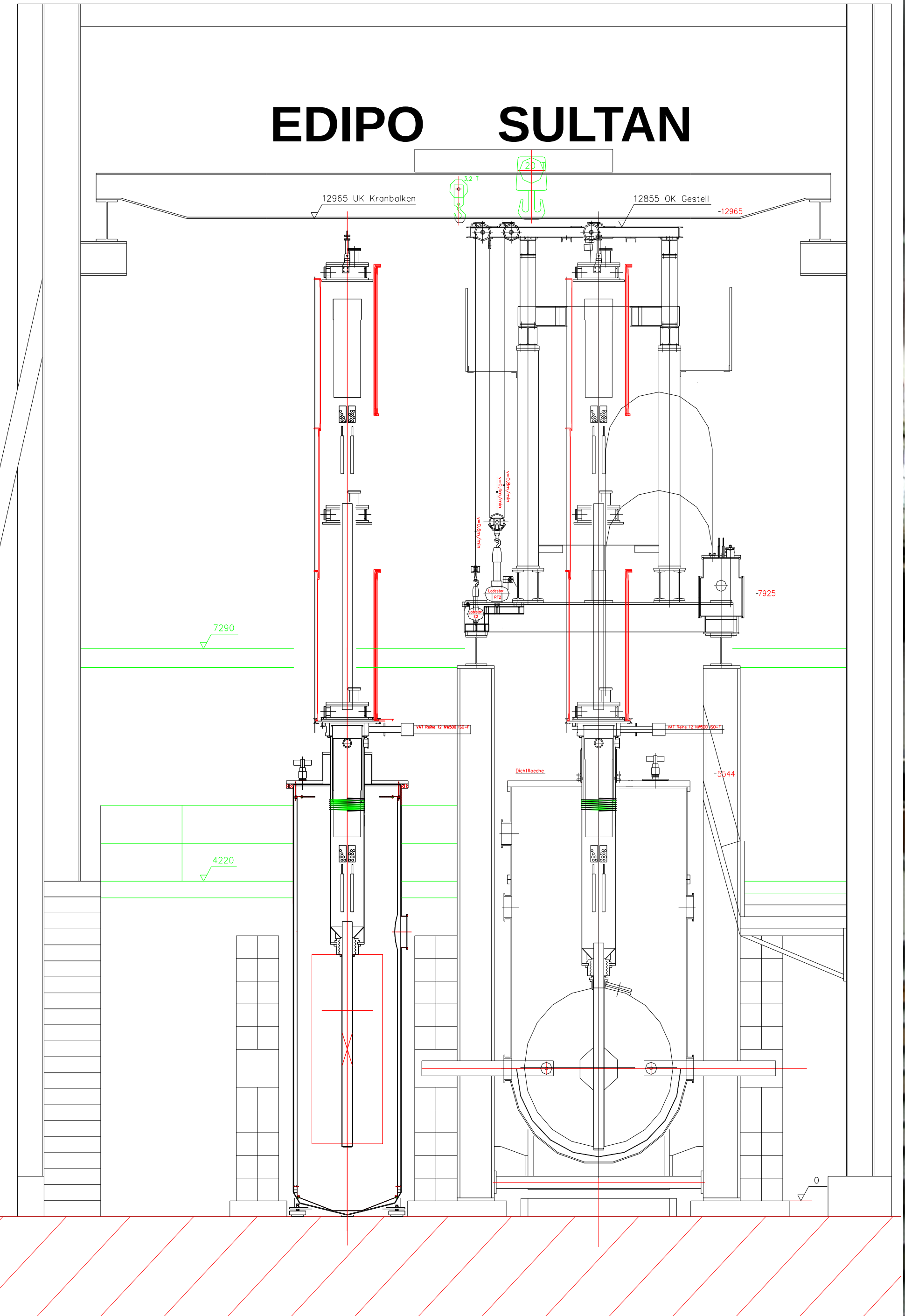


Rainer Wesche, CRPP

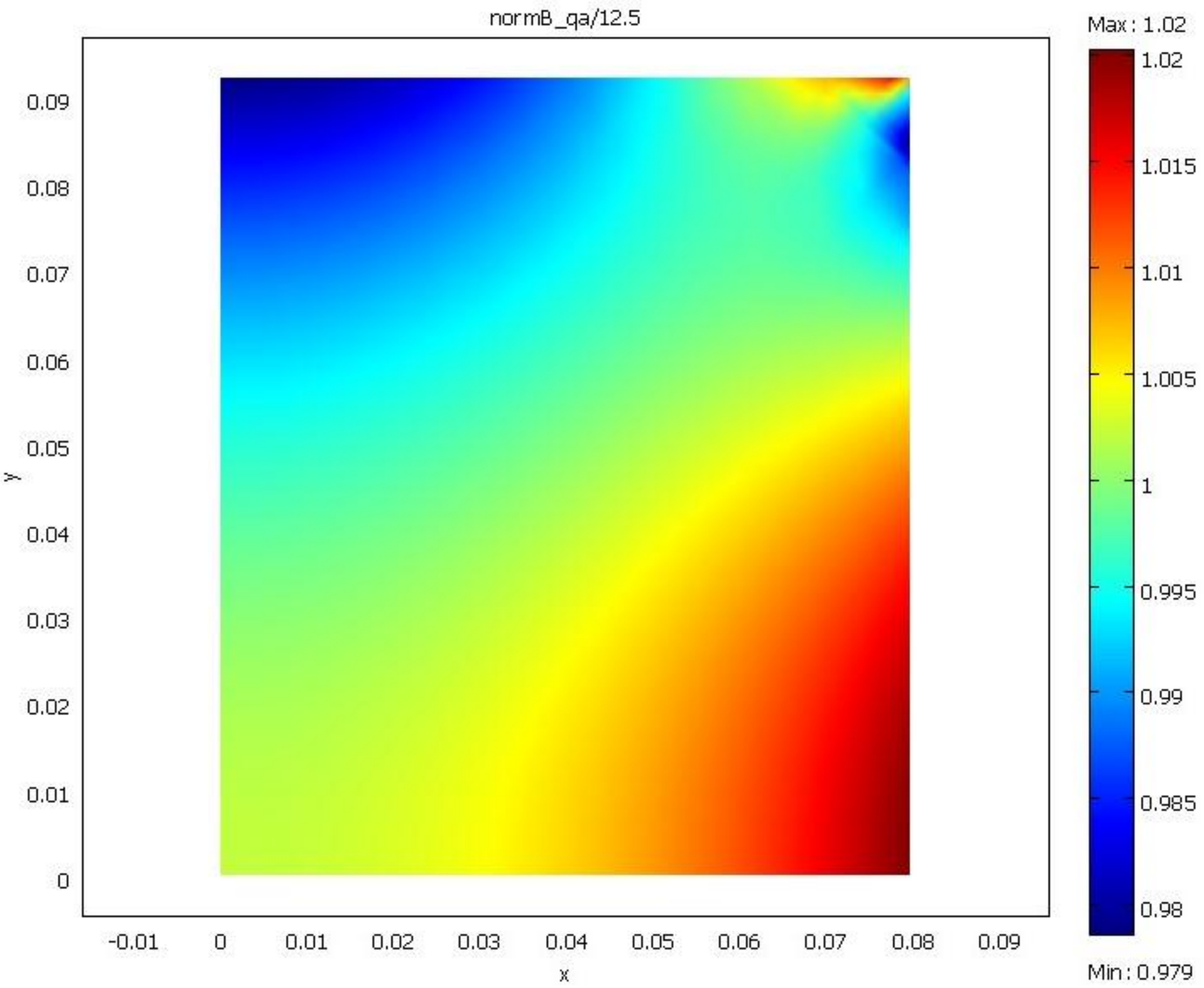

12965 UK Kranbalken
12855 OK Gestell
-12965
-7925
7290
Dichtfläche
-5644
4220
0

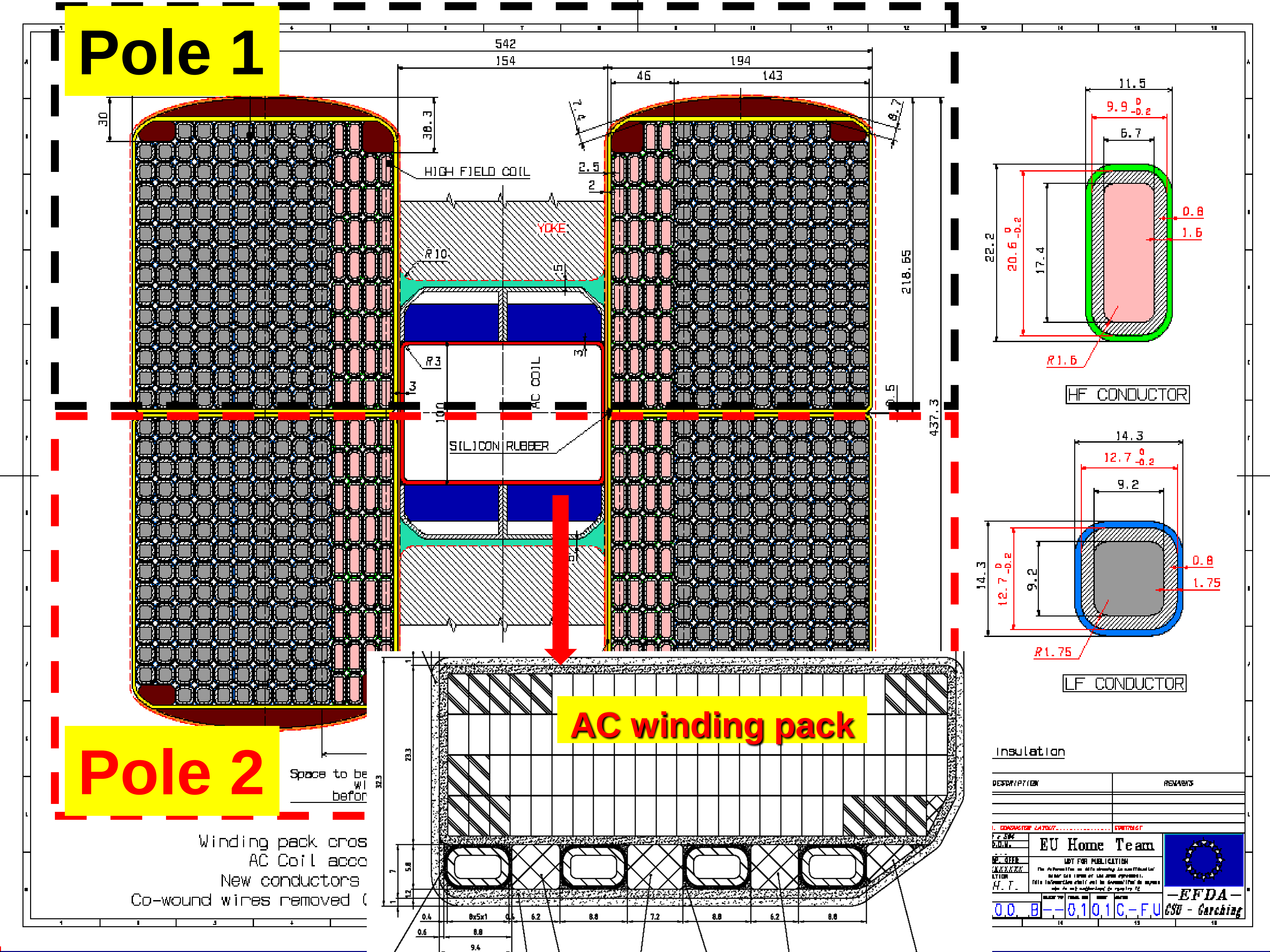

Böttstein (Eisen)
Berg
Aare
A
A
Villigen (Eisen)


A-A

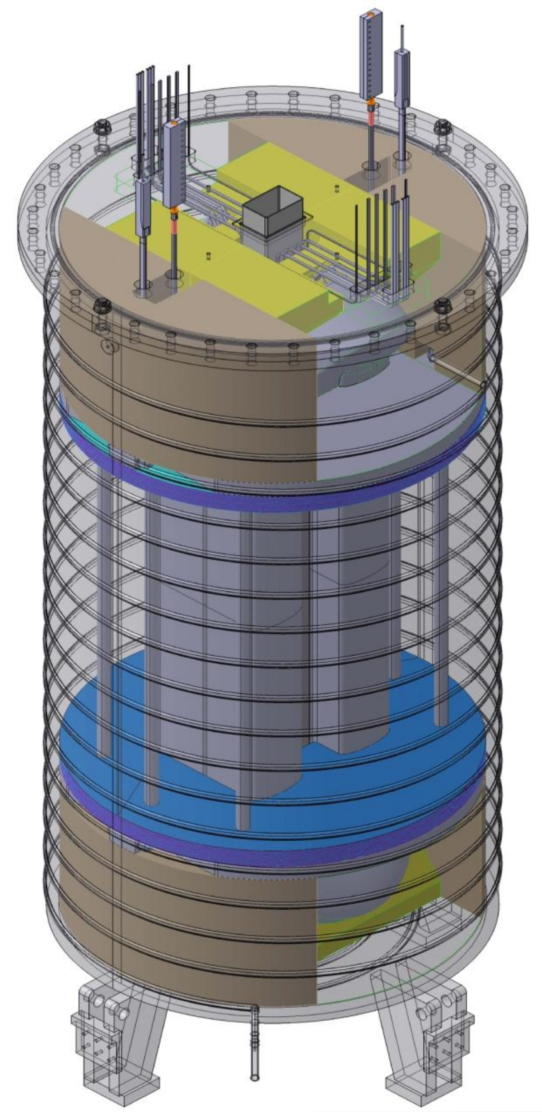

EDIPO
SULTAN
12965 UK Kranbalken
12855 OK Gestell
-12965
-7925
7290
-5544
4220
0


EDIPO
SULTAN
SULTAN
Superconductor
Test Facility


normB_qa/12.5
Max: 1.02
1.02
1.015
1.01
1.005
1
0.995
0.99
0.985
0.98
Min: 0.979
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
y
-0.01
0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
x

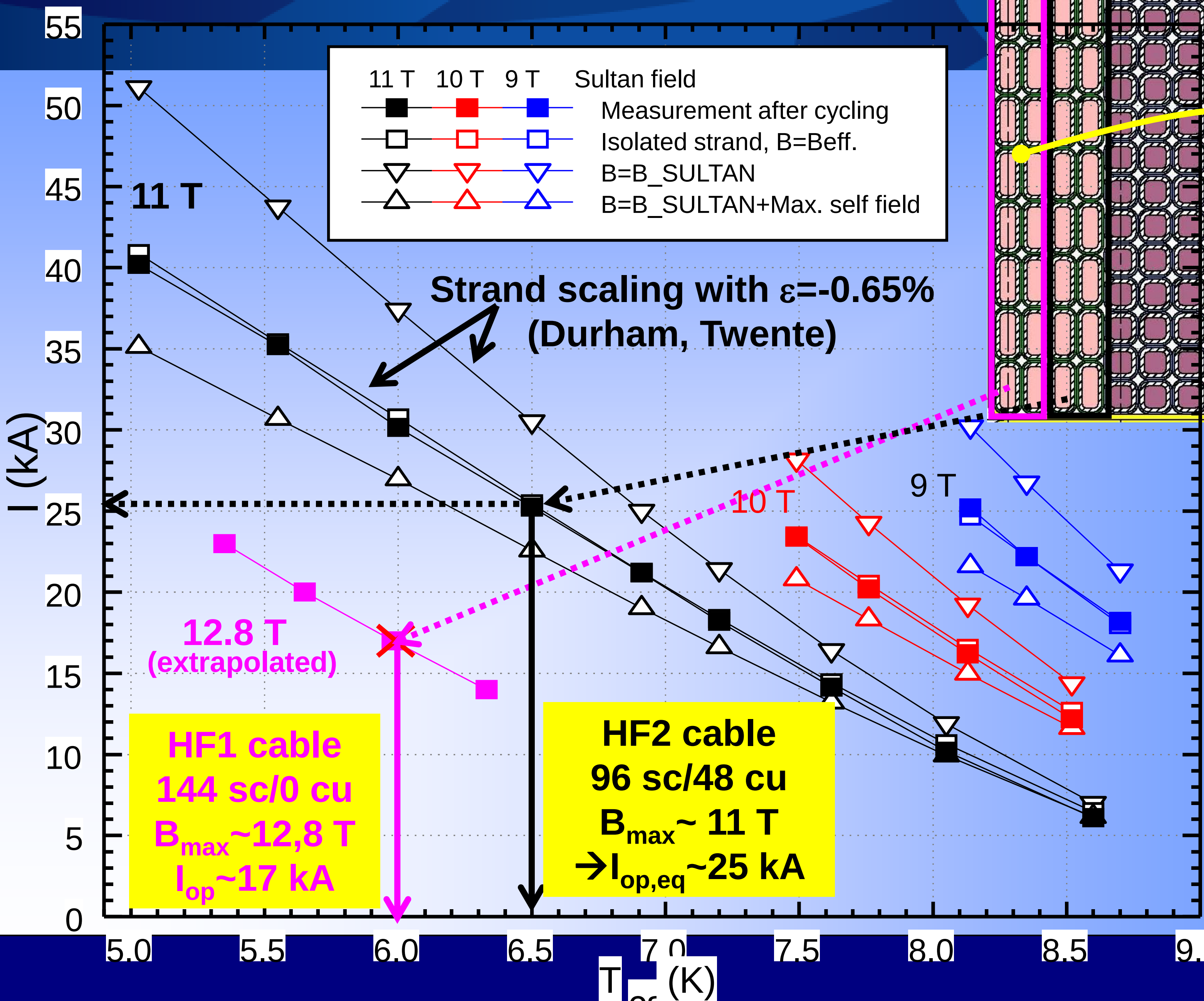

Pole 1
Pole 2
AC winding pack
HIGH FIELD COIL
YOKE
AC COIL
SILICON RUBBER
HF CONDUCTOR
LF CONDUCTOR
Insulation
EU Home Team
NOT FOR PUBLICATION
EFDA
CSU - Garching

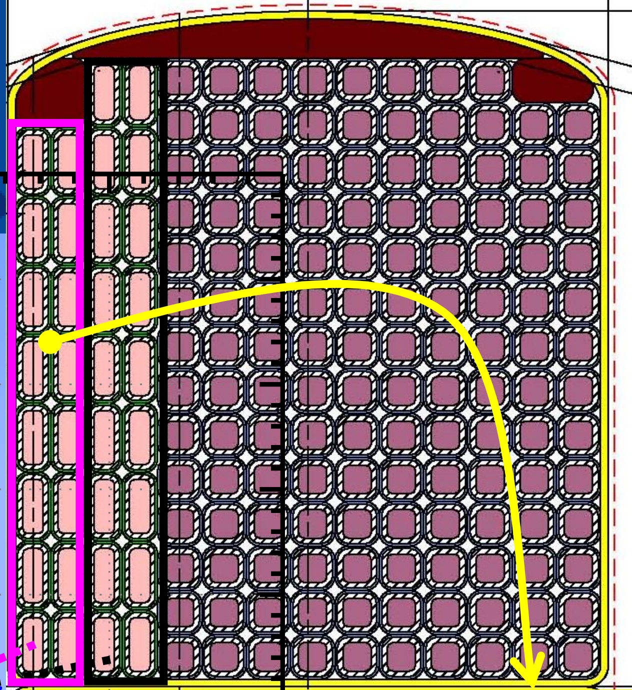
Saddle coils design (EFDA, CIEMAT, ELYTT)



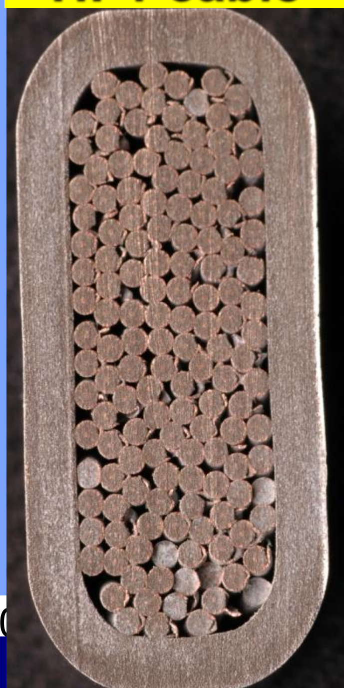
Operating current	17 kA
Central magnetic field	12.5 T
Stored magnetic energy	~16 MJ
Total height (feet →up. flange)	~3 m
Total assembly weight	~20 ton
Iron yoke/steel cylinder weight	11.3 t/3.5 t
Total conductor length	1.69 km
SC strand weight	490 kg
CU strand weight	420 kg
Helium flow in DC winding	~ 8 g/s
Inlet temperature	4.50 K
I/O pressure (int. re-cooling)	10/3.5 bar
Discharge voltage	2 kV
Discharge time	~1 s

HF1 conductor tests

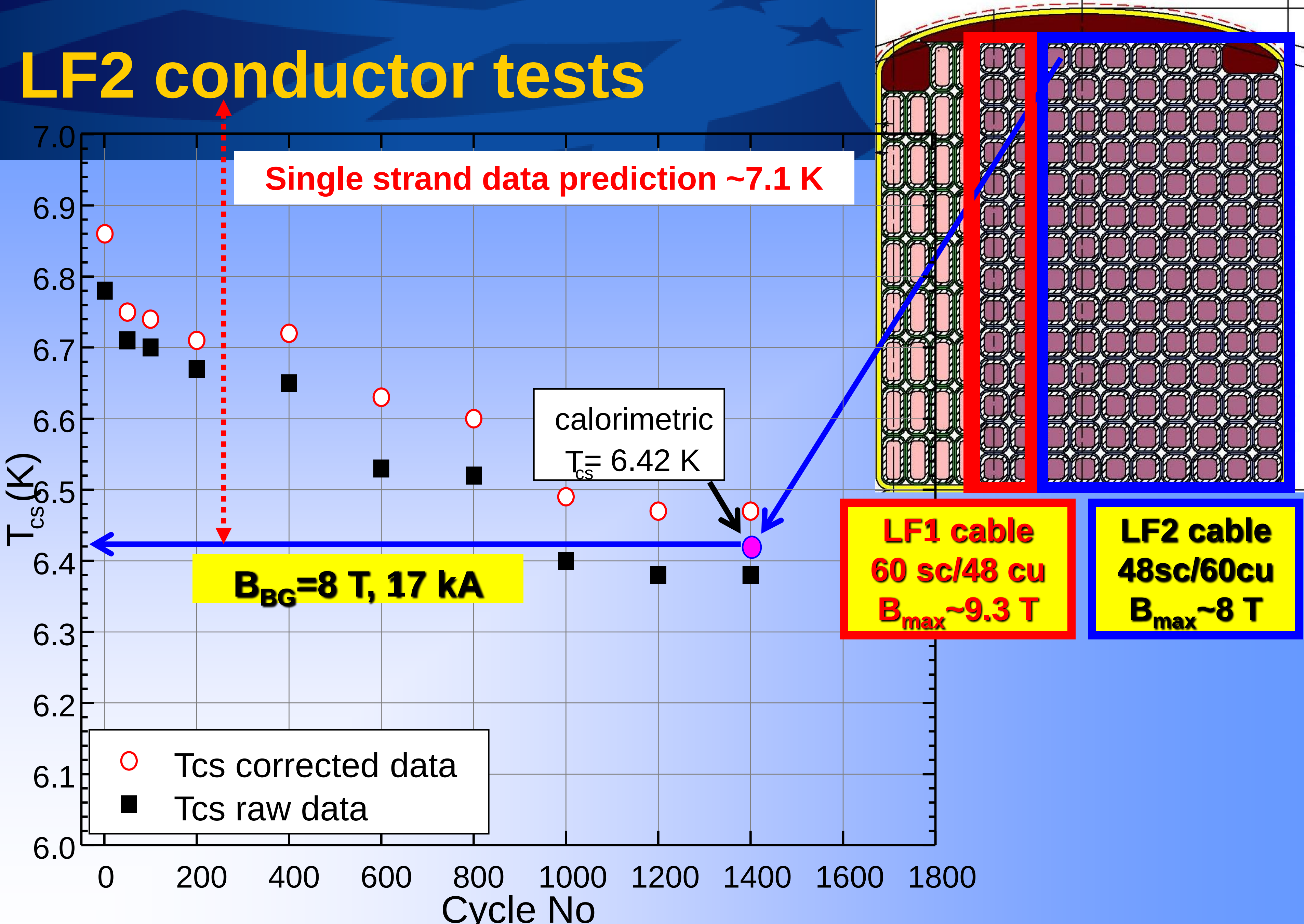




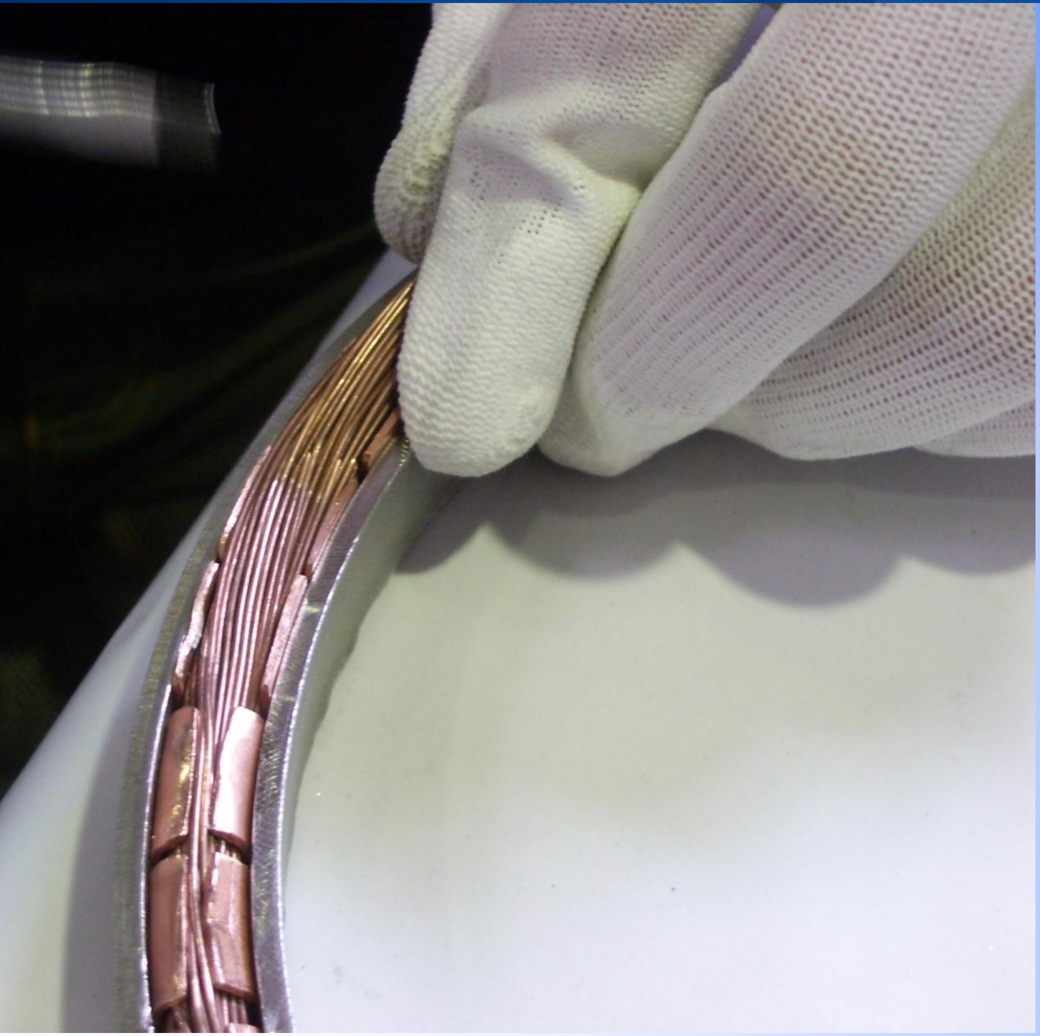
HF1 cable



LF2 conductor tests



INTER-LAYER JOINTS



- The first qualification sample achieved R~5 nΩ (expected ~1 nΩ)
- Reason was found in too weak joint box design + insufficient supporting during compression➔U-box opened and void fraction increased
- In second sample the supporting was improved and the joint box design was changed from welded sheets to a machined block.

Manufacture of qualification sample 1st attempt

INTER-LAYER JOINTS