EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT

# EFDA Dipole Status

Presented by

Ettore Salpietro

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  - Objectives, Schedule
  - System specifications
- **System description**
  - Design concept, guidelines, main features
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- **Conclusions**

# Project overview

- **Objective**
  - Build a test facility to perform full size conductor tests in high background DC field (~12.5 T) and small pulsed AC field for (~0.3 T, f~10 Hz)
- **Applications**
  - ITER conductor tests (short term)
  - Backup of SULTAN (>20 years old)

# Project overview

- **Milestones**
  - Project start: Oct 04
  - CFT for facility preparation: Oct 04
  - Conceptual design phase: Oct 04-June 05
  - CFT for strand procurement: May 05
  - CFT for cabling and jacketing: June 05
  - CFT for dipole construction: July 05
  - **Contracts signed by CEU: Dec. 05**
  - Dipole procurement: Jan 06-Dec 07
  - Dipole facility commissioning: Spring 08

# System Specifications

- Test well clear bore *(SULTAN samples)*

  Width x height = 144 mm x 94 mm

- Test well length *(SULTAN samples)*

  L=2850 mm

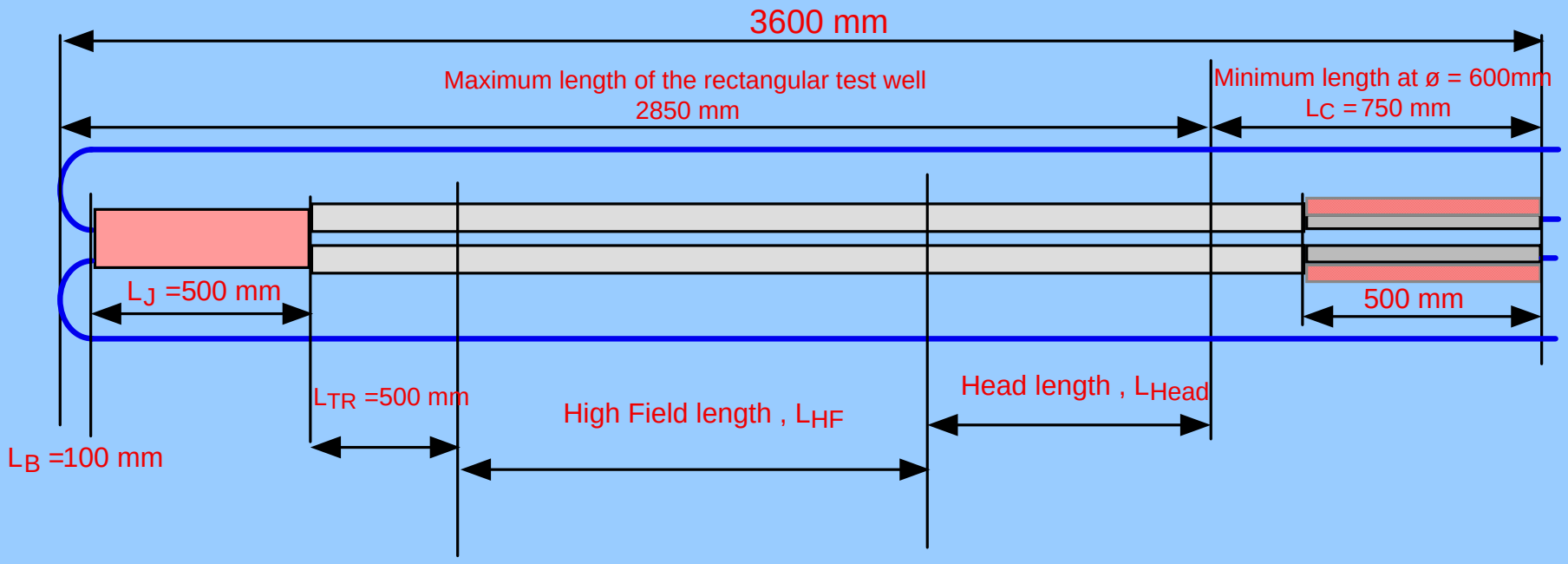
- DC Field

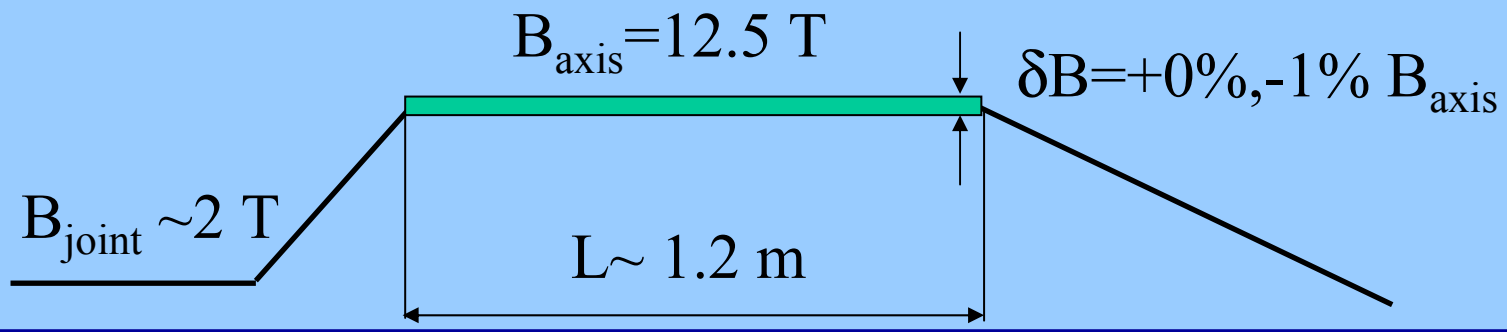
  $B_{DC}$=12.5 T (1% in-plane homogeneity)

- AC Field

  $B_{AC}$ = ±0.3 T (f~5 Hz, T~100 s)

# Test Sample

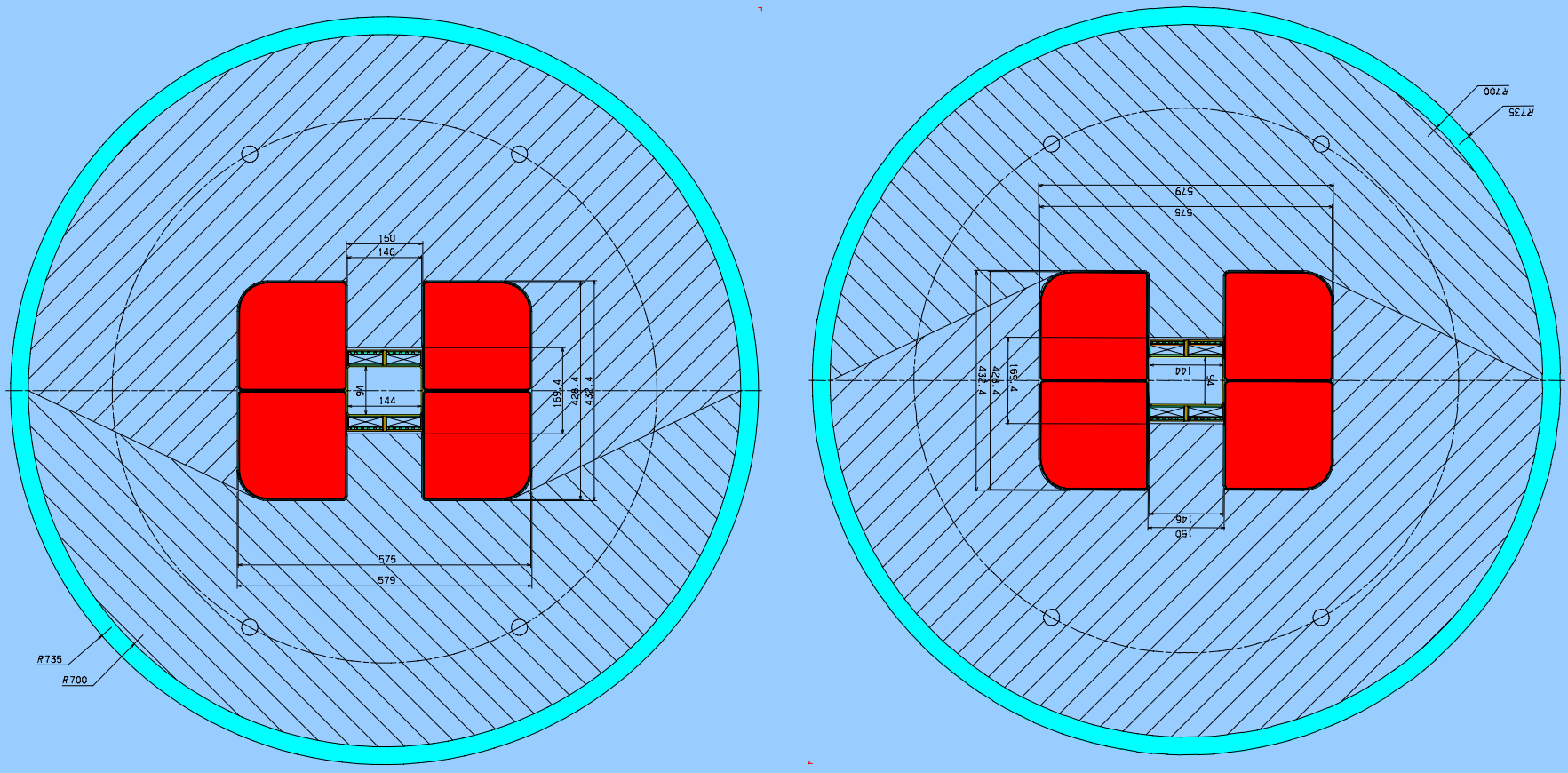

3600 mm
Maximum length of the rectangular test well
2850 mm
Minimum length at ø = 600mm
Lc = 750 mm
LJ =500 mm
500 mm
LTR =500 mm
High Field length , LHF
Head length , LHead
LB =100 mm


Baxis=12.5 T
δB=+0%,-1% Baxis
Bjoint ~2 T
L~ 1.2 m

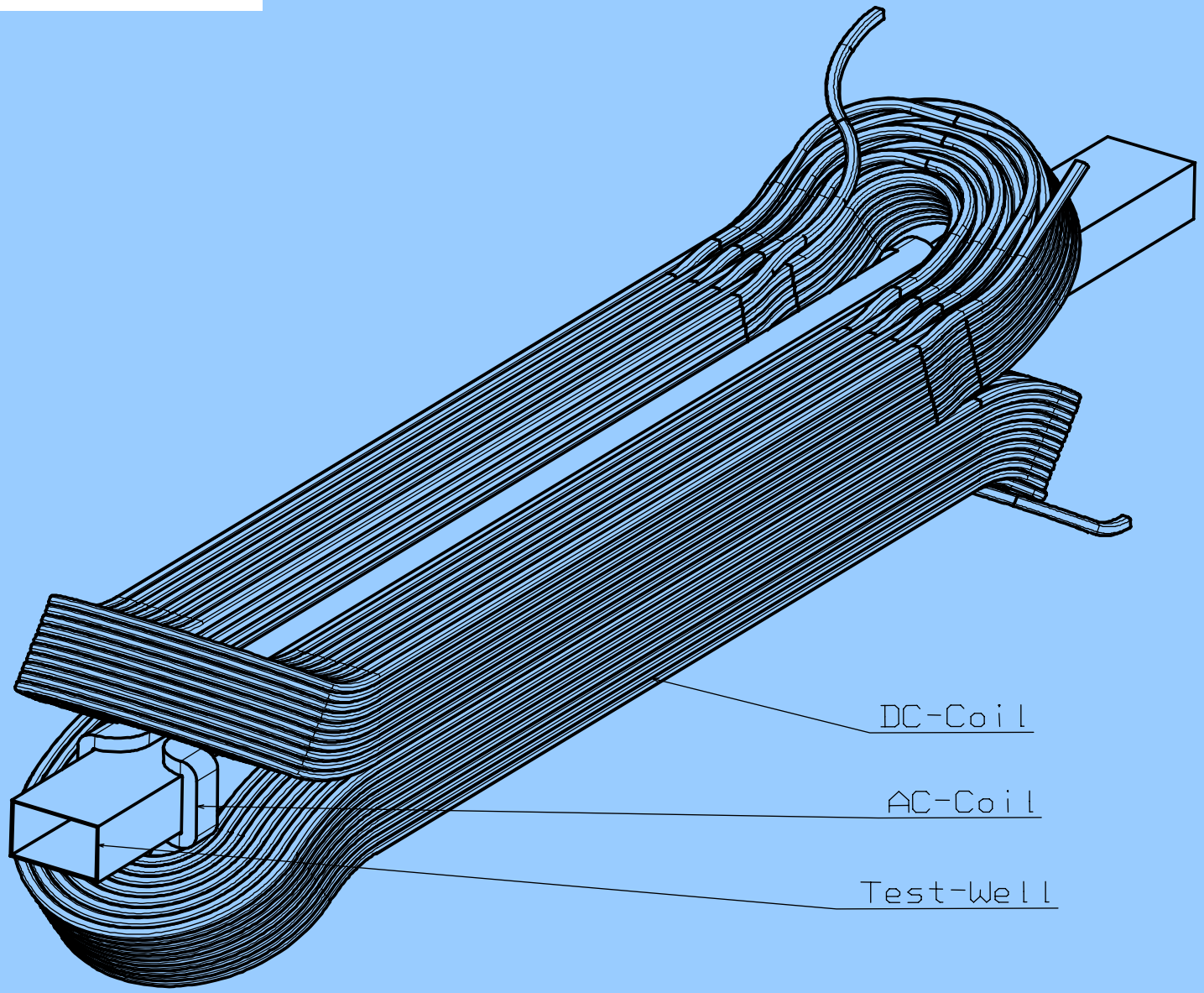
# Design concept

- **Test well**
  - Rectangular bore (SULTAN)
  - Cold bore (compactness)
- **DC coils (SC)**
  - Saddle shaped coils (compactness)
  - Layer wound (grading)
  - CIC conductor (stability)

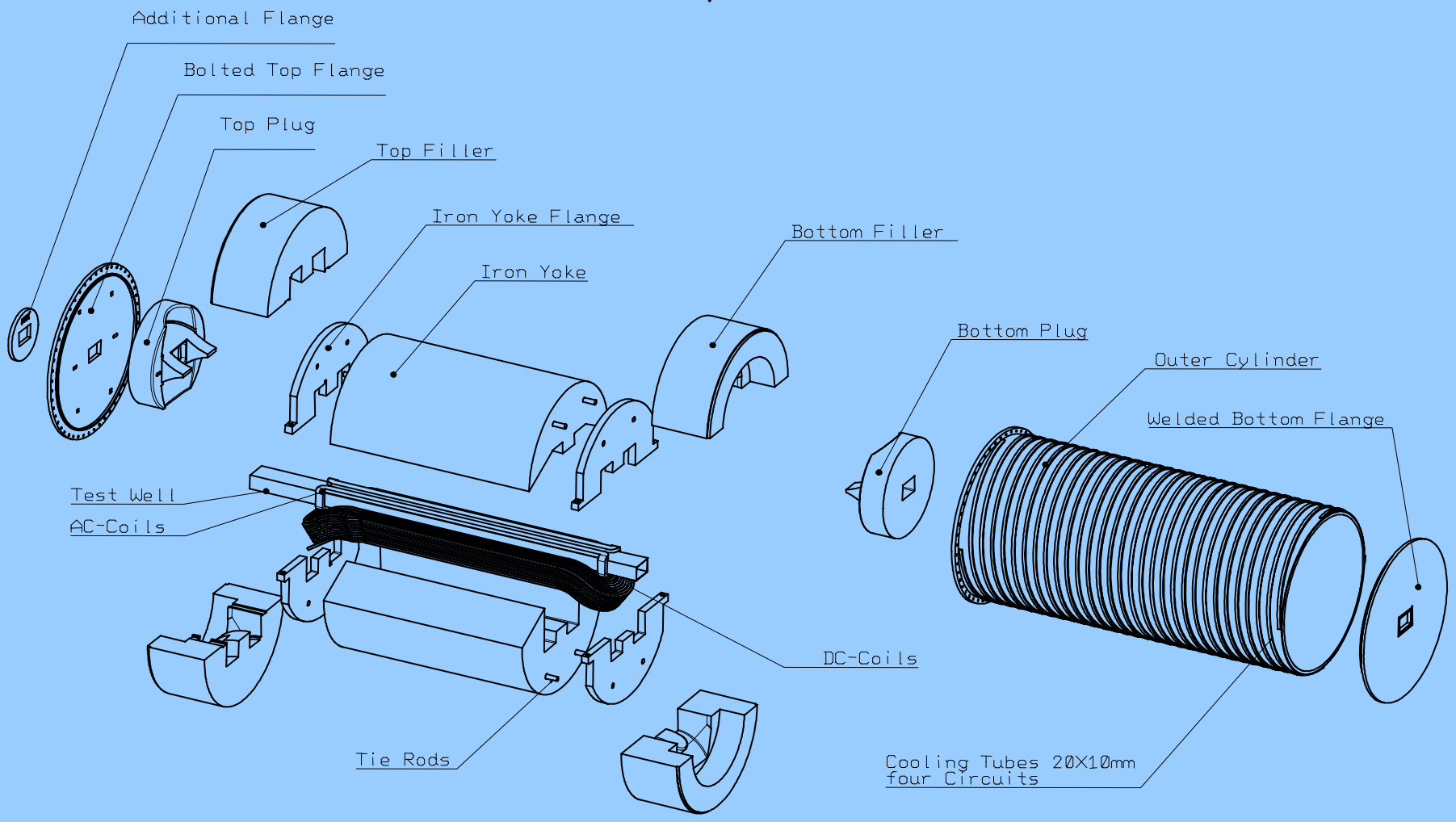
# Iron yoke & Outer cylinder



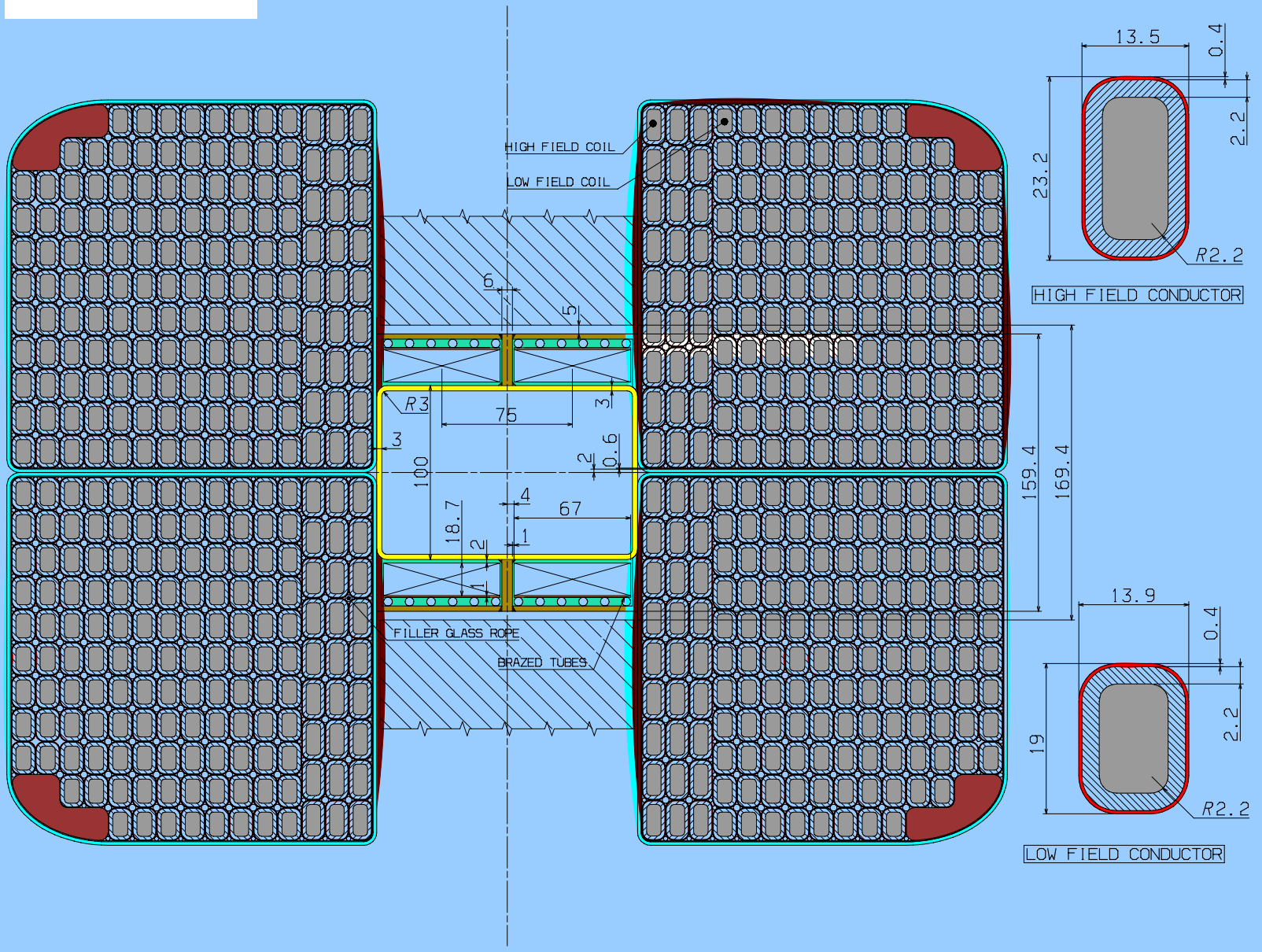

**Even laminations** **Odd laminations**

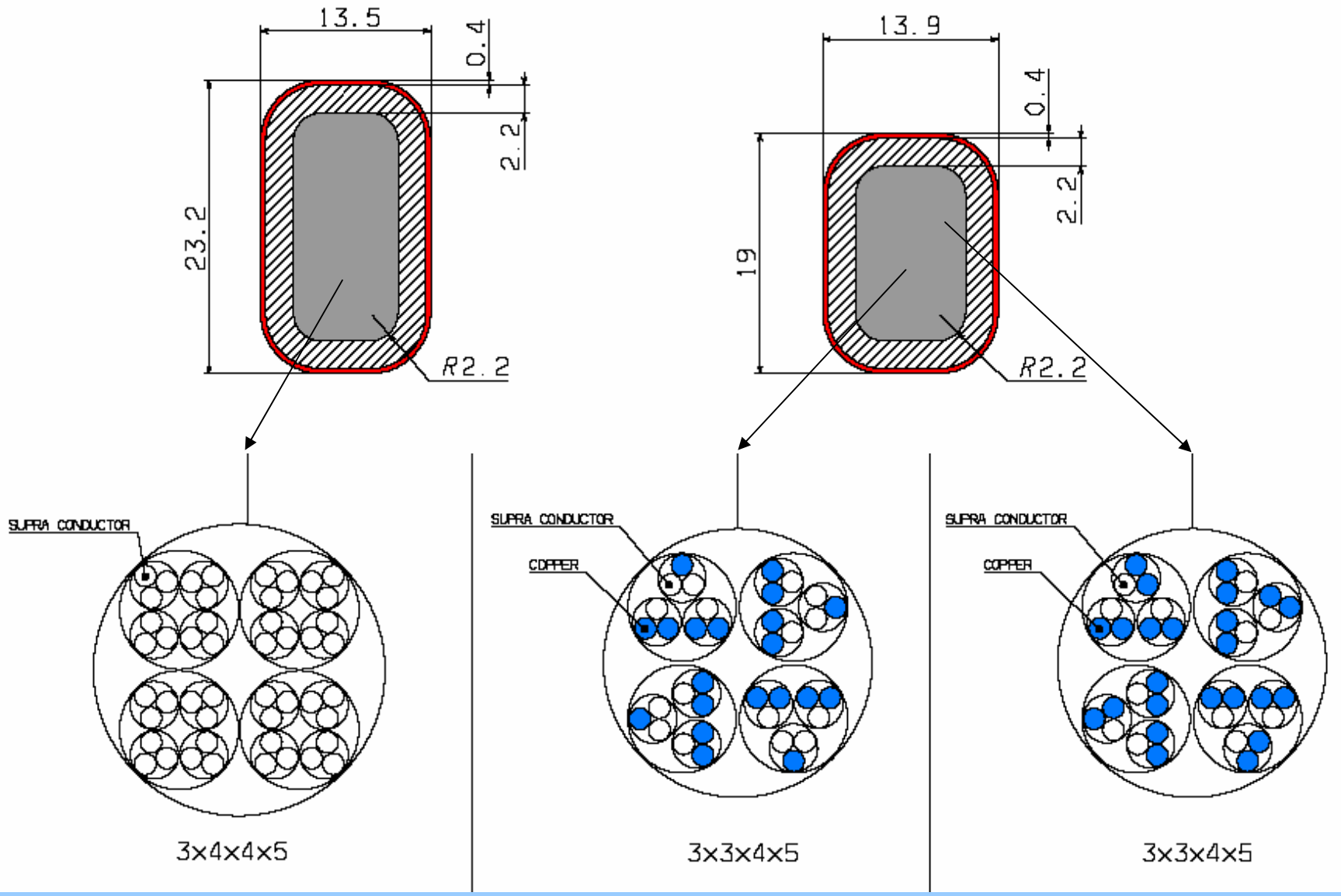

DC-Coil
AC-Coil
Test-Well

# Exploded View



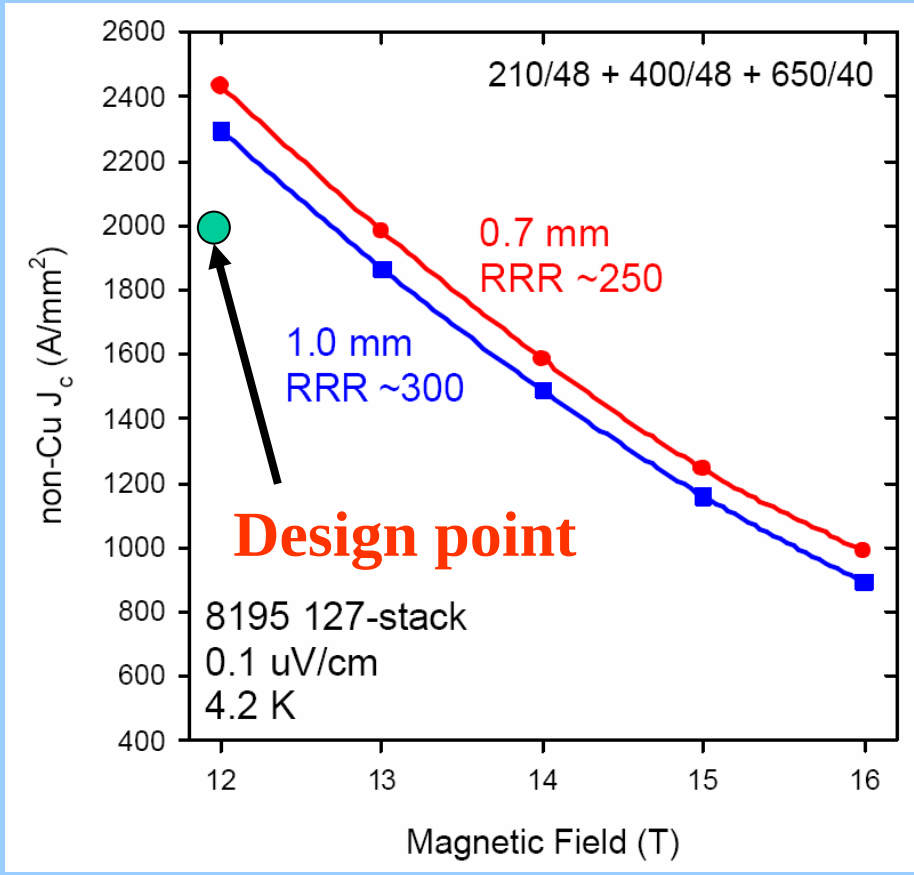

EFDA_DI-POLE
01.07.05


HIGH FIELD COIL
LOW FIELD COIL
FILLER GLASS ROPE
BRAZED TUBES
R3
75
100
67
18.7
6
5
3
2
0.6
4
1
159.4
169.4
13.5
0.4
2.2
23.2
R2.2
HIGH FIELD CONDUCTOR
13.9
0.4
2.2
19
R2.2
LOW FIELD CONDUCTOR


13.5
0.4
2.2
23.2
R2.2
13.9
0.4
2.2
19
R2.2
SUPRA CONDUCTOR
COPPER
3x4x4x5
3x3x4x5
3x3x4x5

| | | |
|---|---|---|
| Operating current | (kA) | 19.90 |
| Clear bore area | ($mm^2$) | 144 x 94 |
| Central magnetic field | (T) | 12.51 |
| Magnetic energy per meter (long. force) | (MN) | 9.82 |
| Stored magnetic energy | (MJ) | 16.21 |
| Total conductor length | (m) | 1539 |
| Cylinder height | (m) | 2.85 |
| Cylinder outer diameter | (m) | 1.27 |
| Iron yoke outer diameter | (m) | 1.20 |
| Helium inlet temperature | (K) | 4.50 |
| Helium inlet pressure | (bar) | 6.00 |
| Helium outlet pressure | (bar) | 3.00 |
| Helium flow in DC winding (indicative) | (g/s) | ~31 |
| Discharge voltage | (kV) | 1.60 |
| Discharge time | (s) | 1.02 |
| Quench detection and switching time | (s) | 0.35 |

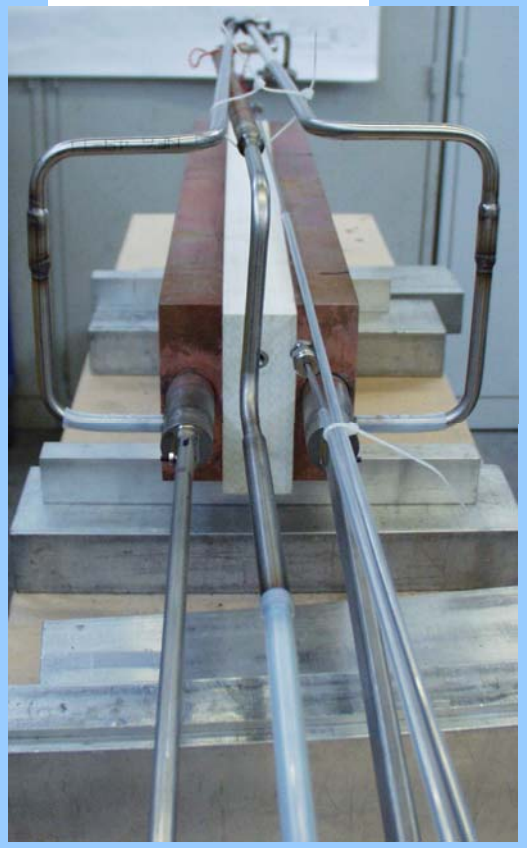
# HIGH Jc STRAND



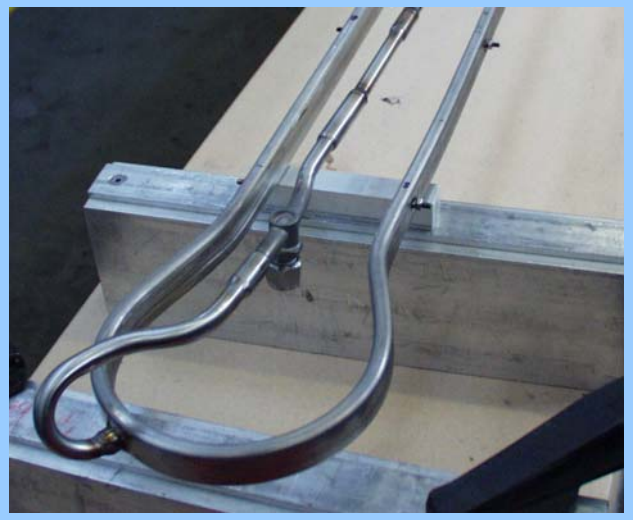

- $D_{eff}$ about 60 µm
- Short HT
- RRR > 200
- Max conductor unit length ~ 150 m

# Conductor Layout

- The bundle consists of 84 $Nb_3Sn$ strands and 24 Cu wires
- The cable pattern is 3 x 3 x 3 x 4 = 108
- The rolled steel jacket has 1 mm thickness
- Outer dimension 18.4 x 7.7 mm
- Void fraction ≈ 35%
- Non-Cu area = 21.64 $mm^2$

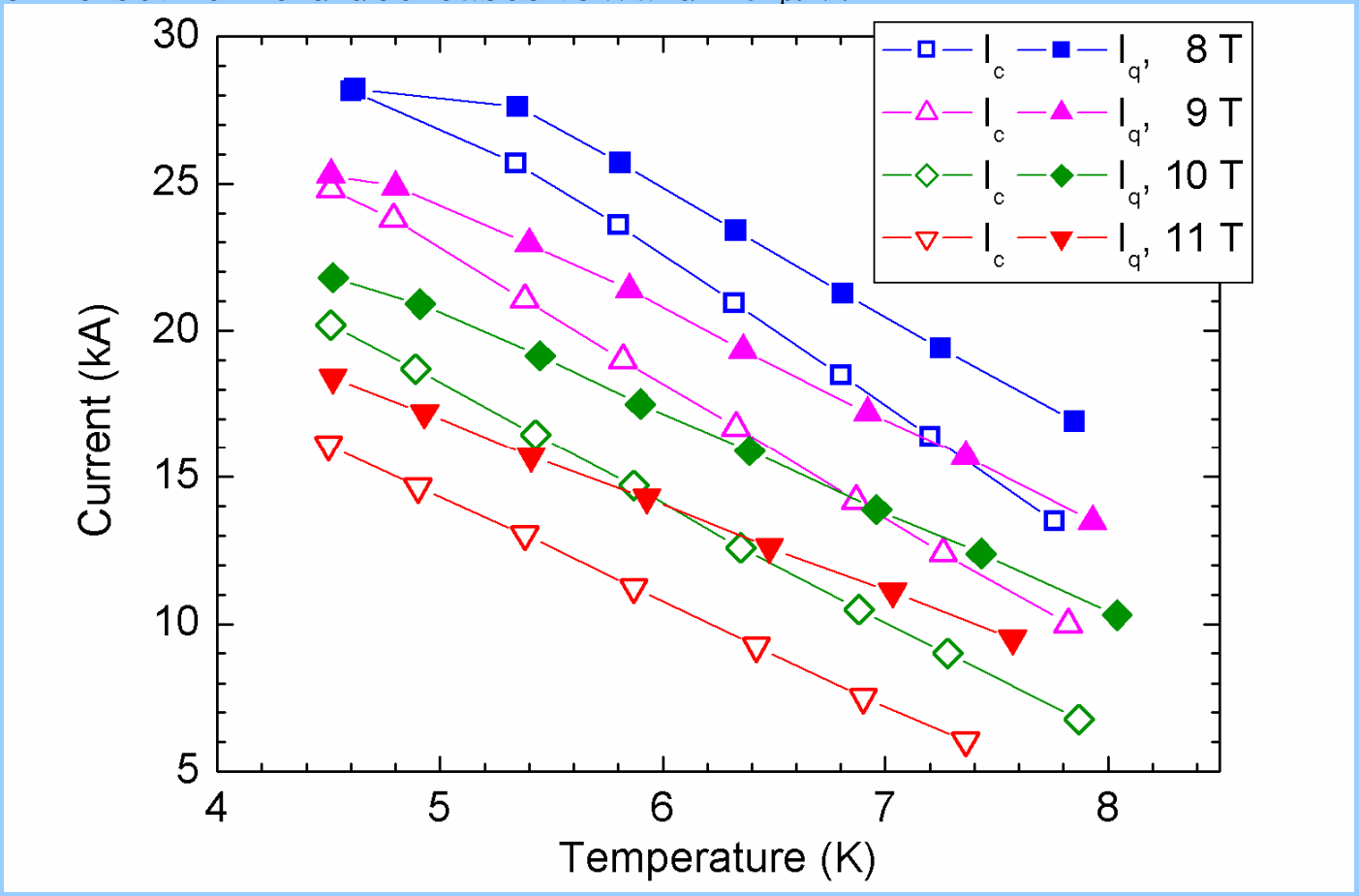


## SULTAN Sample

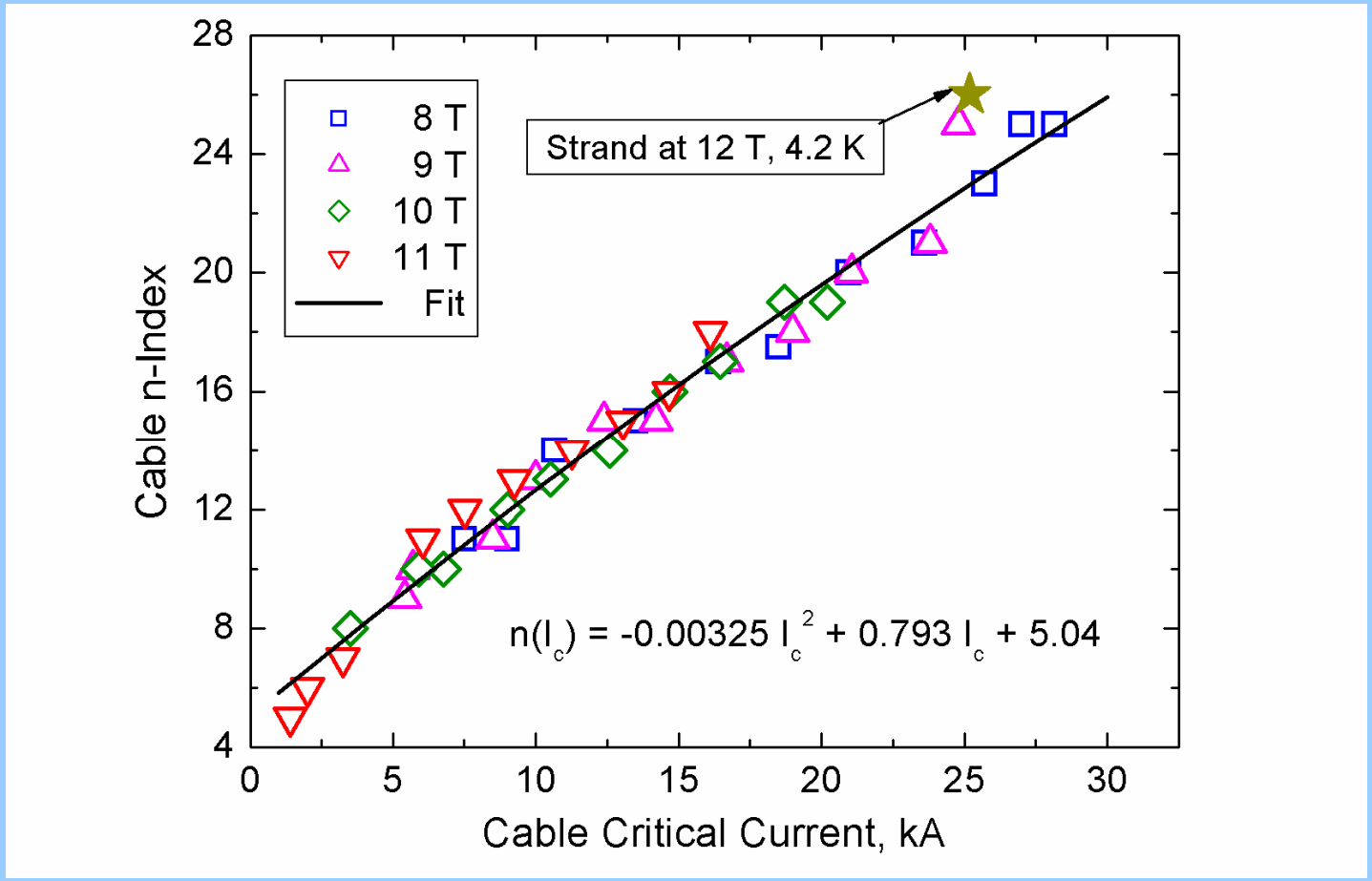


- Standard hairpin sample, with helium inlet at the U-bend
- Termination EB welded, swaged and finally solder filled
- Instrumentation for voltage taps, temperature sensors and pressure taps

- Critical current / Quench current: At increasing current (decreasing temperature, the quench and critical current "converge", i.e. the take-off electric field decreases toward 10 μV/m



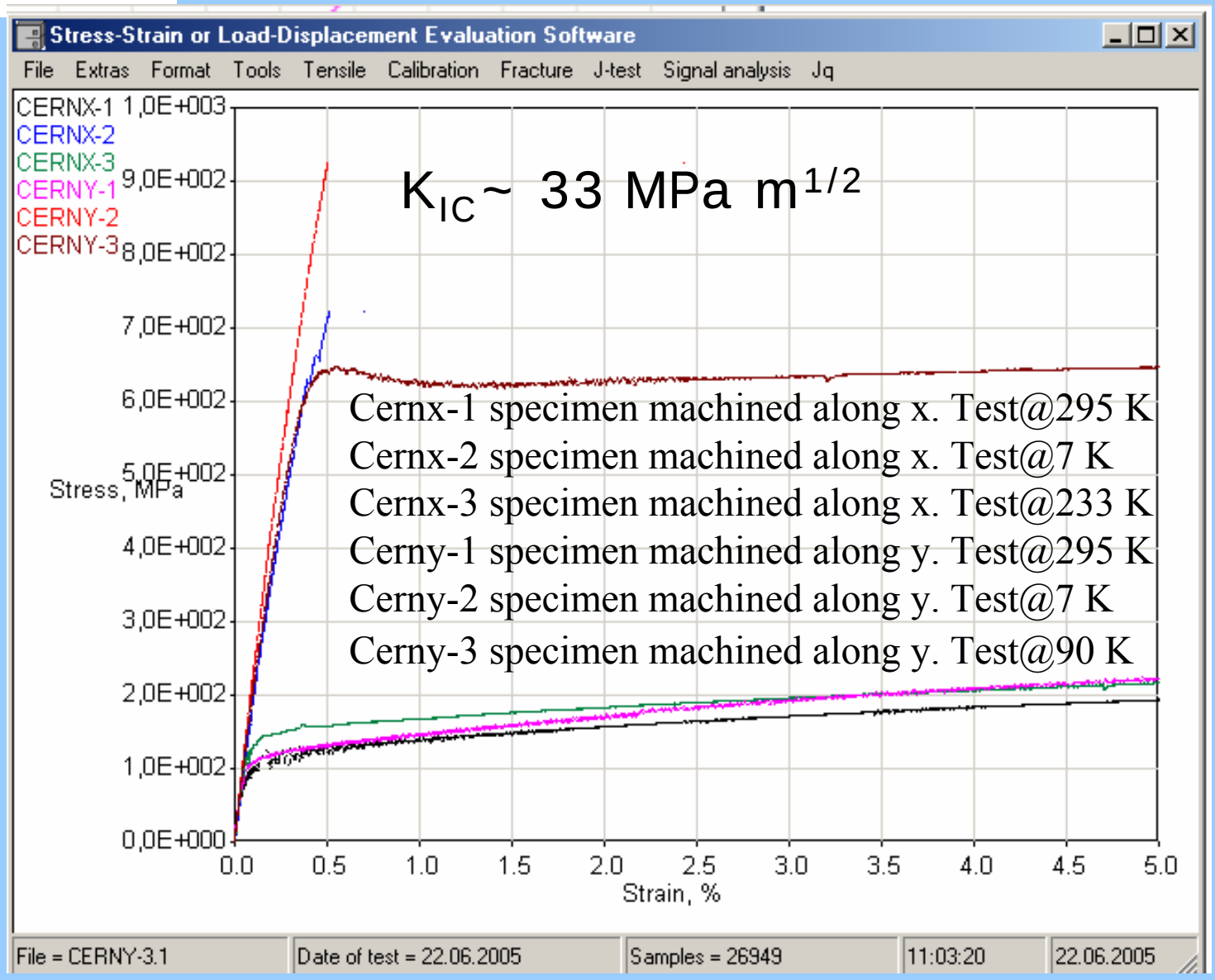
- N - Index: In the series of test before cyclic load, the n-index of the CICC is very close to the strand one



# Iron yoke & Outer cylinder

- **Yoke**
  - MAGNETIL BC 5.8™ (LHC dipole), high saturation field, $\mu_0 M_{sat}$ ~ 2 T;
  - Laminated iron plates insulated and impregnated

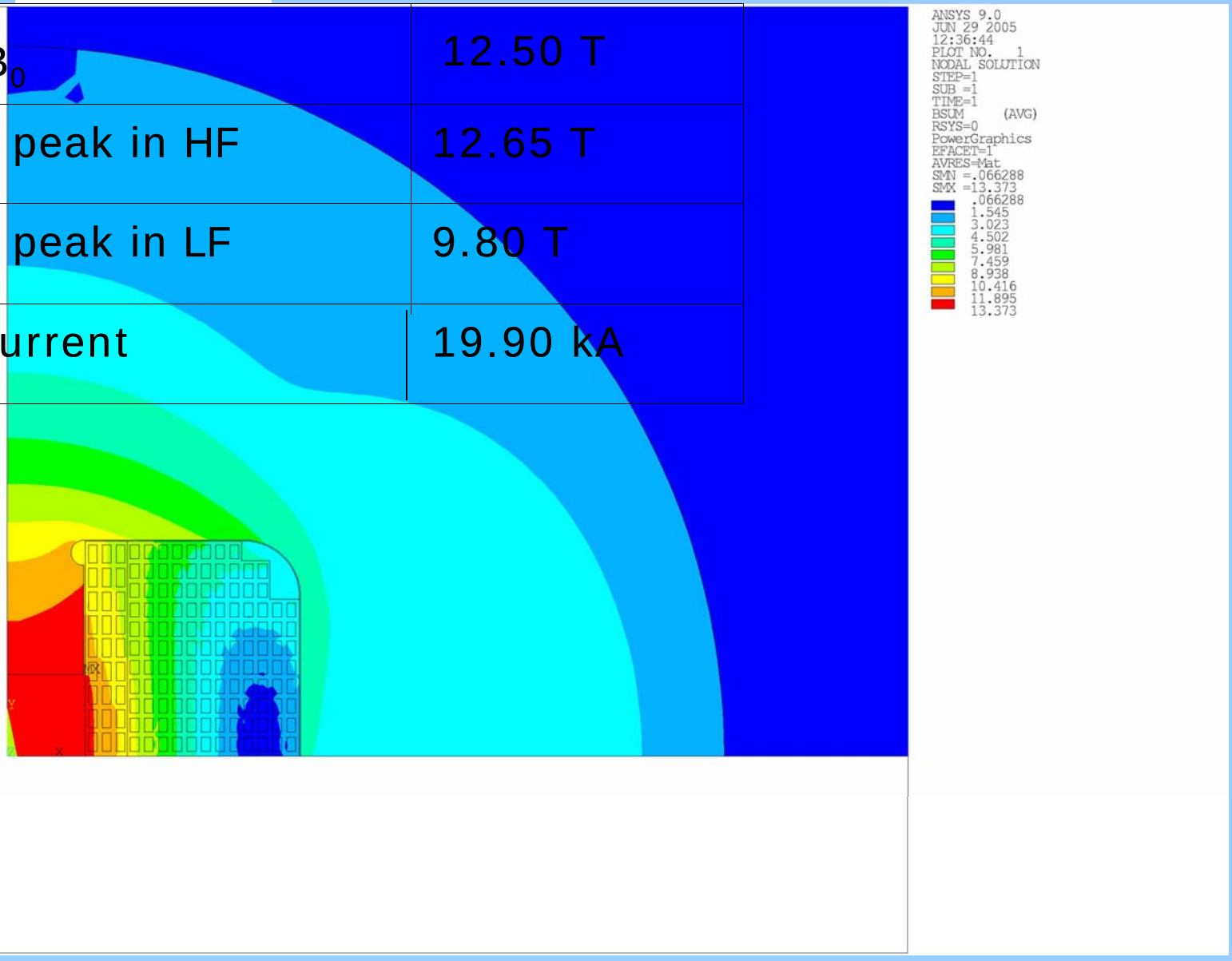
| *File & heat* | *Temperature K* | *Young's Modulus GPa* | *Yield Strength MPa* | *Ultimate Tensile strength MPa* | *Uniform elongation %* | *Total elongation %* |
|---|---|---|---|---|---|---|
| Cernx-1 | 295 | 205 | 115 | 249 | 32 | 52 |
| Cernx-2 | 7 | 200 | - | 723 | 0,5 | 0,5 |
| Cernx-3 | 233 | 196 | 151 | 260 | ~25 | ~50 |
| Cerny-1 | 295 | 200 | 123 | 282 | 26 | 44 |
| Cerny-2 | 7 | 211 | - | 926 | 0,5 | 0,5 |
| Cerny-3 | 90 | 210 | 642 | 653 | 5,9 | 20 |

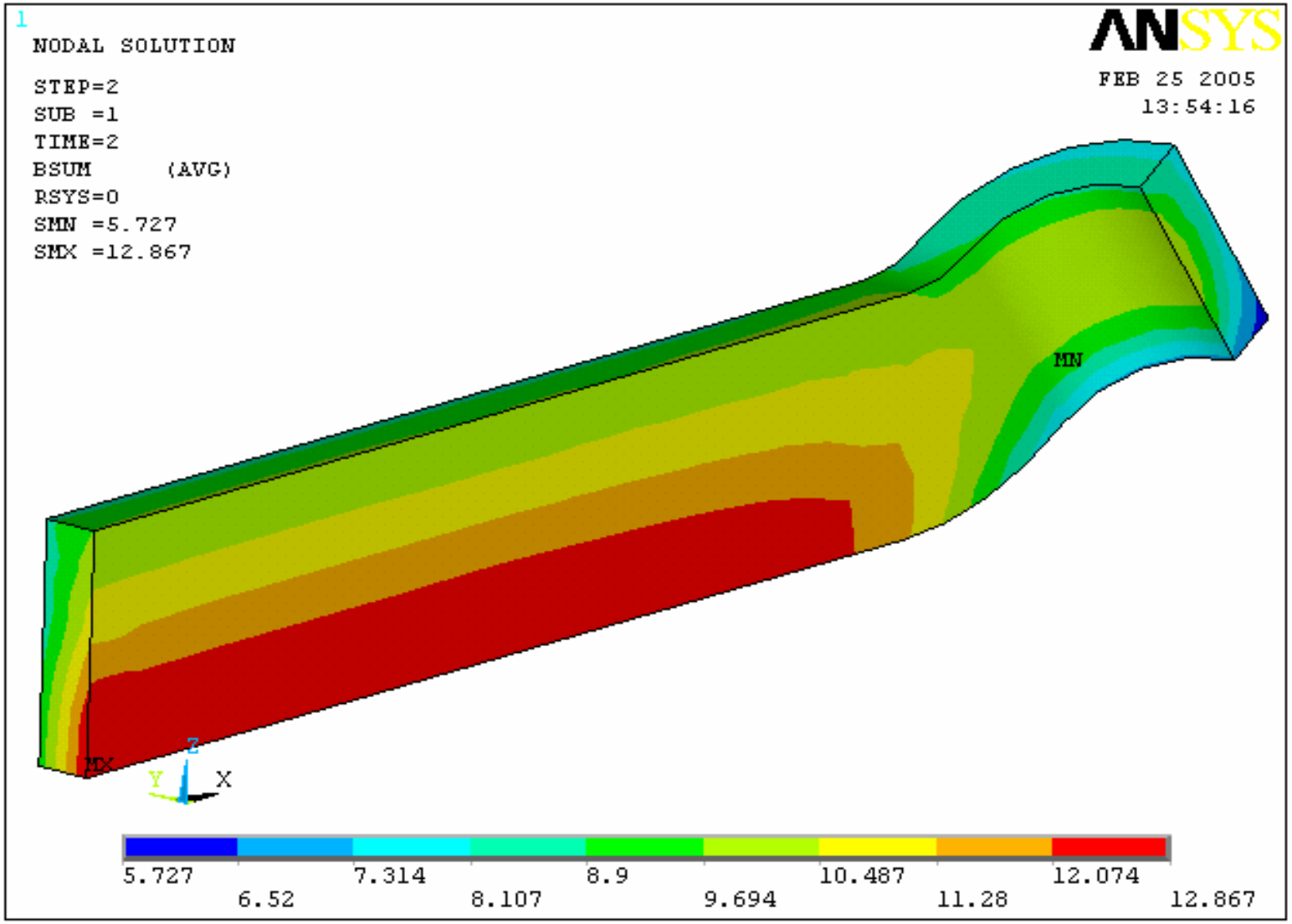

Stress-Strain or Load-Displacement Evaluation Software
File Extras Format Tools Tensile Calibration Fracture J-test Signal analysis Jq
CERNX-1
CERNX-2
CERNX-3
CERNY-1
CERNY-2
CERNY-3
1,0E+003
9,0E+002
8,0E+002
7,0E+002
6,0E+002
5,0E+002
4,0E+002
3,0E+002
2,0E+002
1,0E+002
0,0E+000
Stress, MPa
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
Strain, %
$K_{IC}$~ 33 MPa $m^{1/2}$
Cernx-1 specimen machined along x. Test@295 K
Cernx-2 specimen machined along x. Test@7 K
Cernx-3 specimen machined along x. Test@233 K
Cerny-1 specimen machined along y. Test@295 K
Cerny-2 specimen machined along y. Test@7 K
Cerny-3 specimen machined along y. Test@90 K
File = CERNY-3.1
Date of test = 22.06.2005
Samples = 26949
11:03:20
22.06.2005

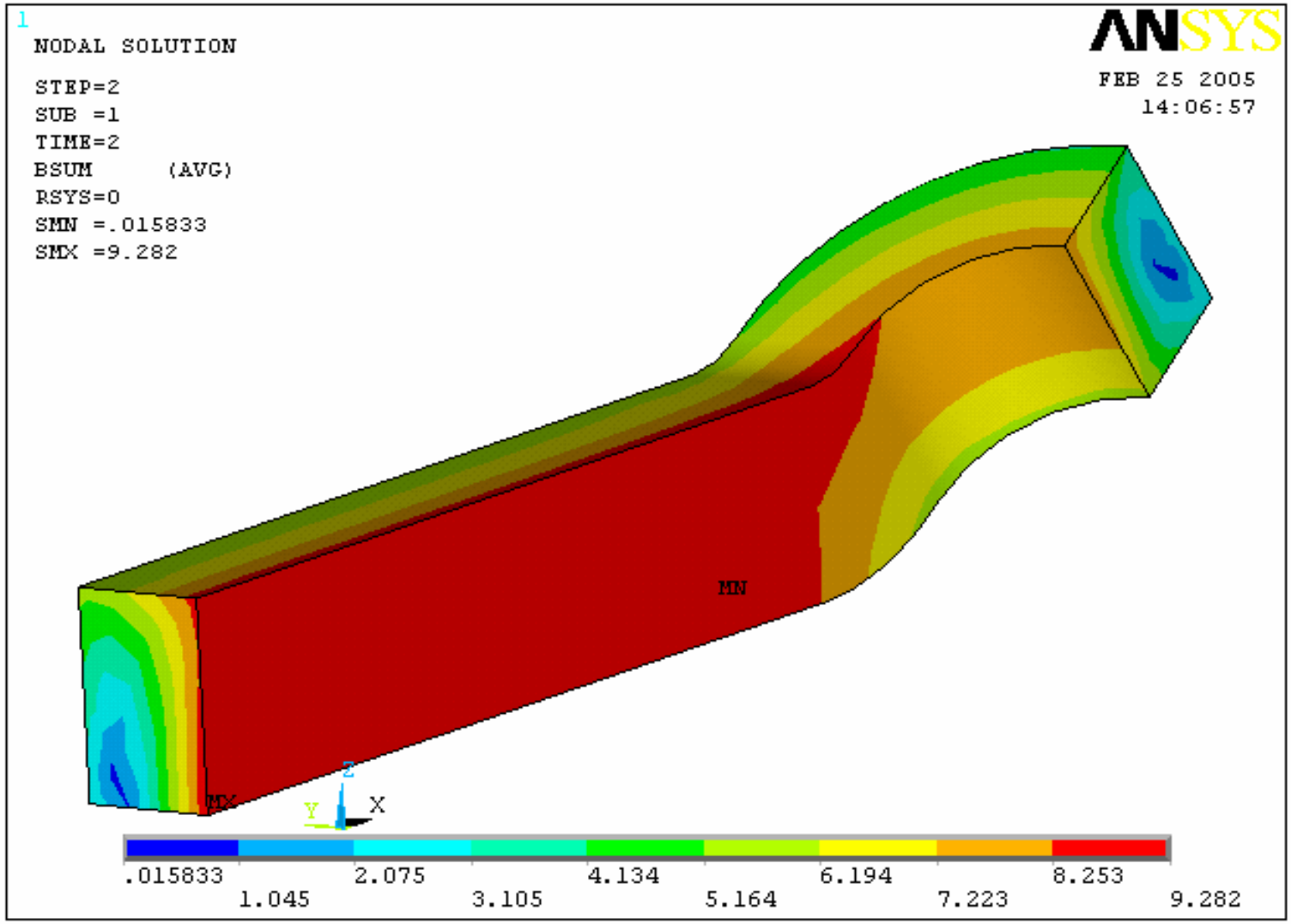
| | | |
|---|---|---|
| S | = safety factor | = 2 |
| Y | = geometric factor | = 1.8 (surface crack) |
| a | = diameter of crack | ~ 0.5 mm |
| $K_{IC}$ | = fracture toughness | ~ 33 MPa $m^{0.5}$ |

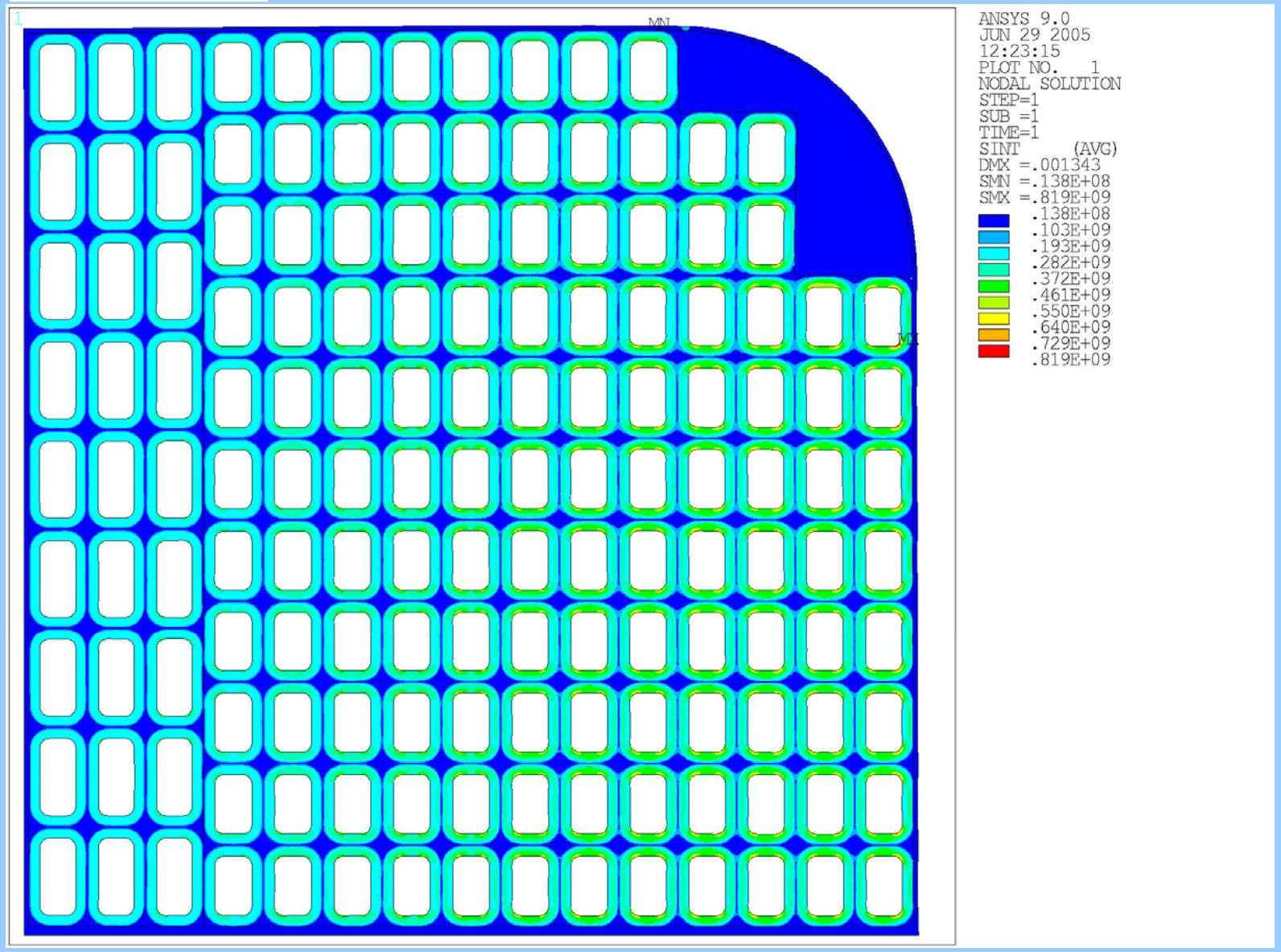
$$\sigma < \frac{K_{IC}}{S\,Y\,\sqrt{\pi\,a}} \sim 230\,\text{MPa}$$

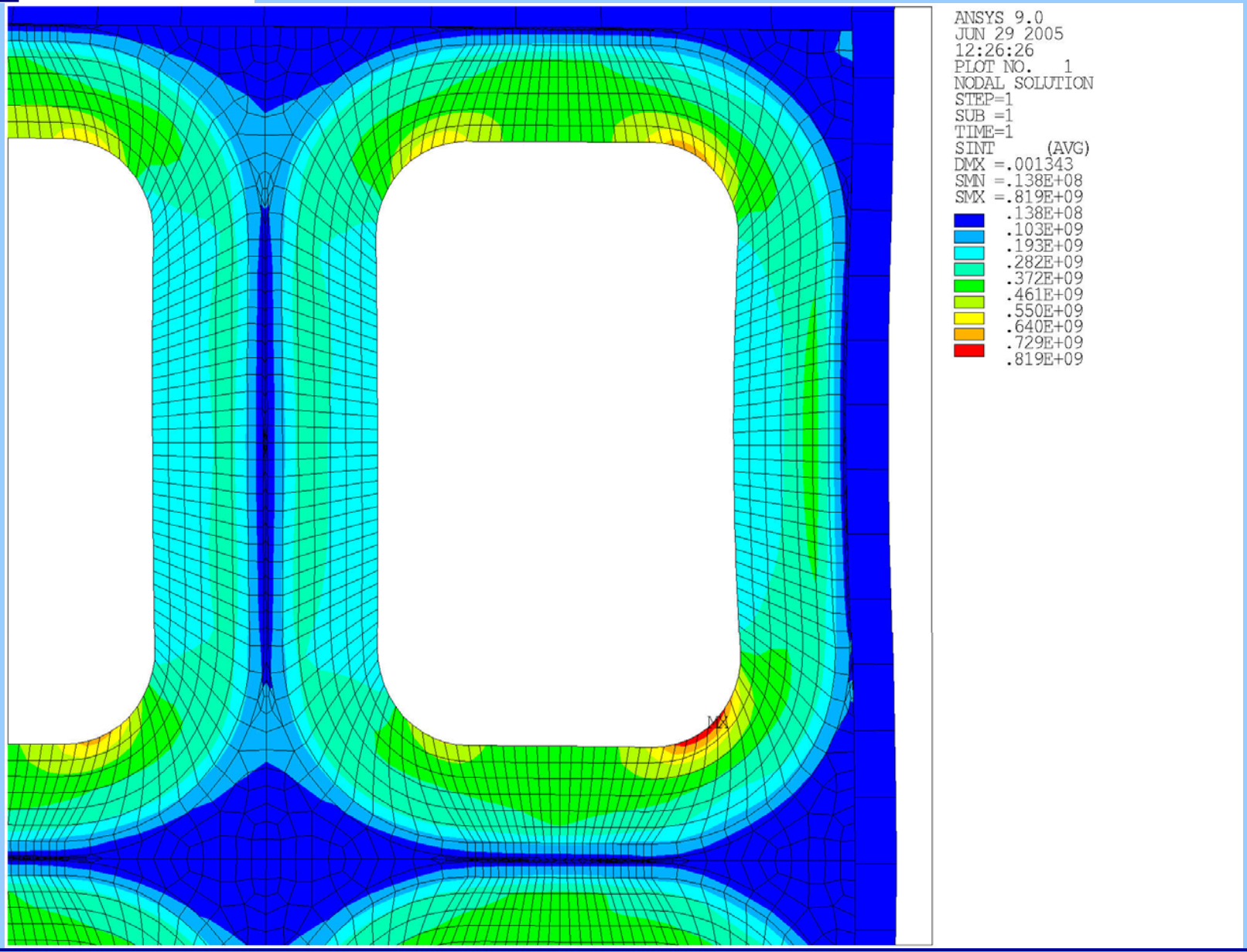
| | |
|---|---|
| $B_0$ | 12.50 T |
| B peak in HF | 12.65 T |
| B peak in LF | 9.80 T |
| Current | 19.90 kA |

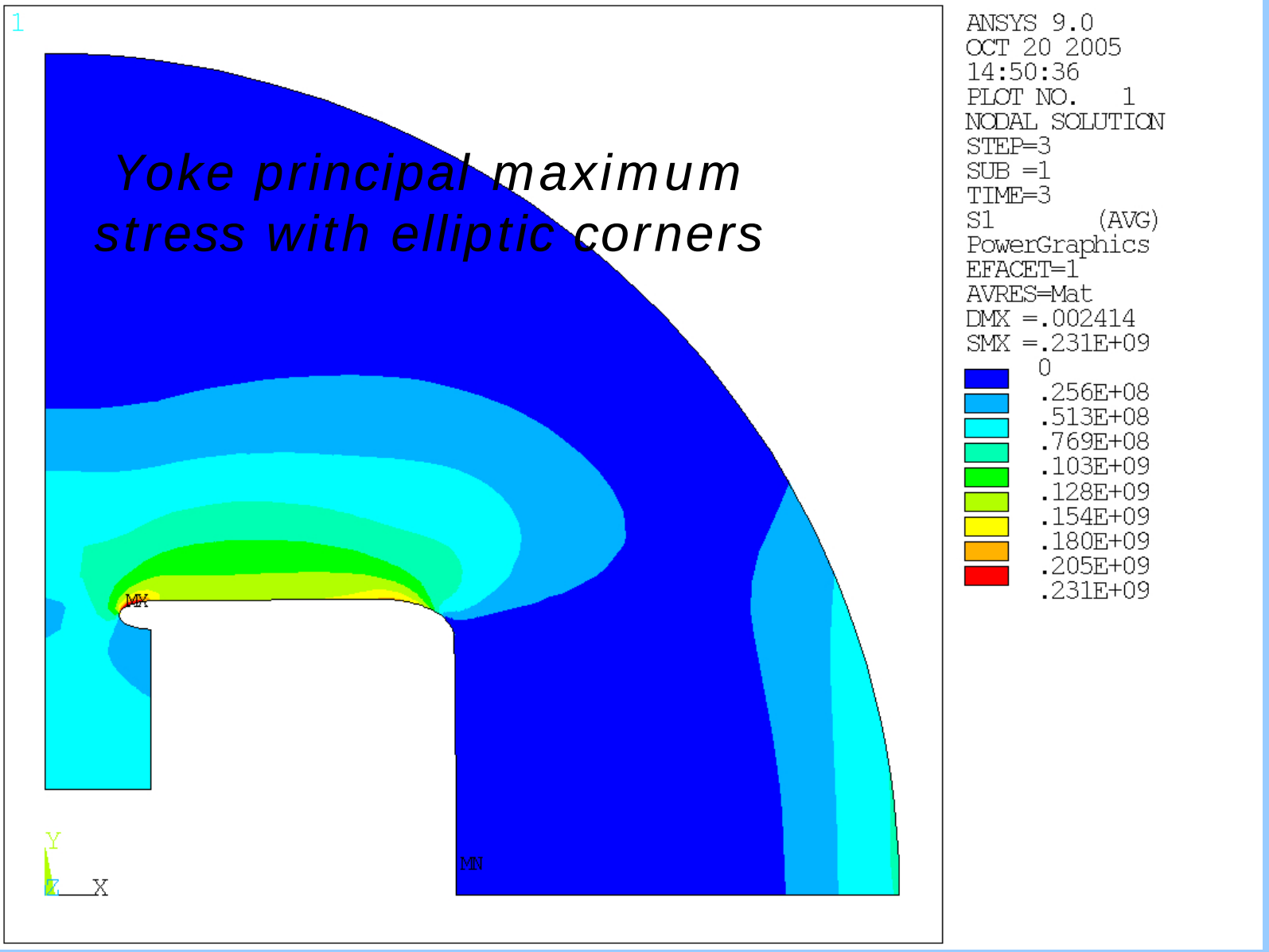


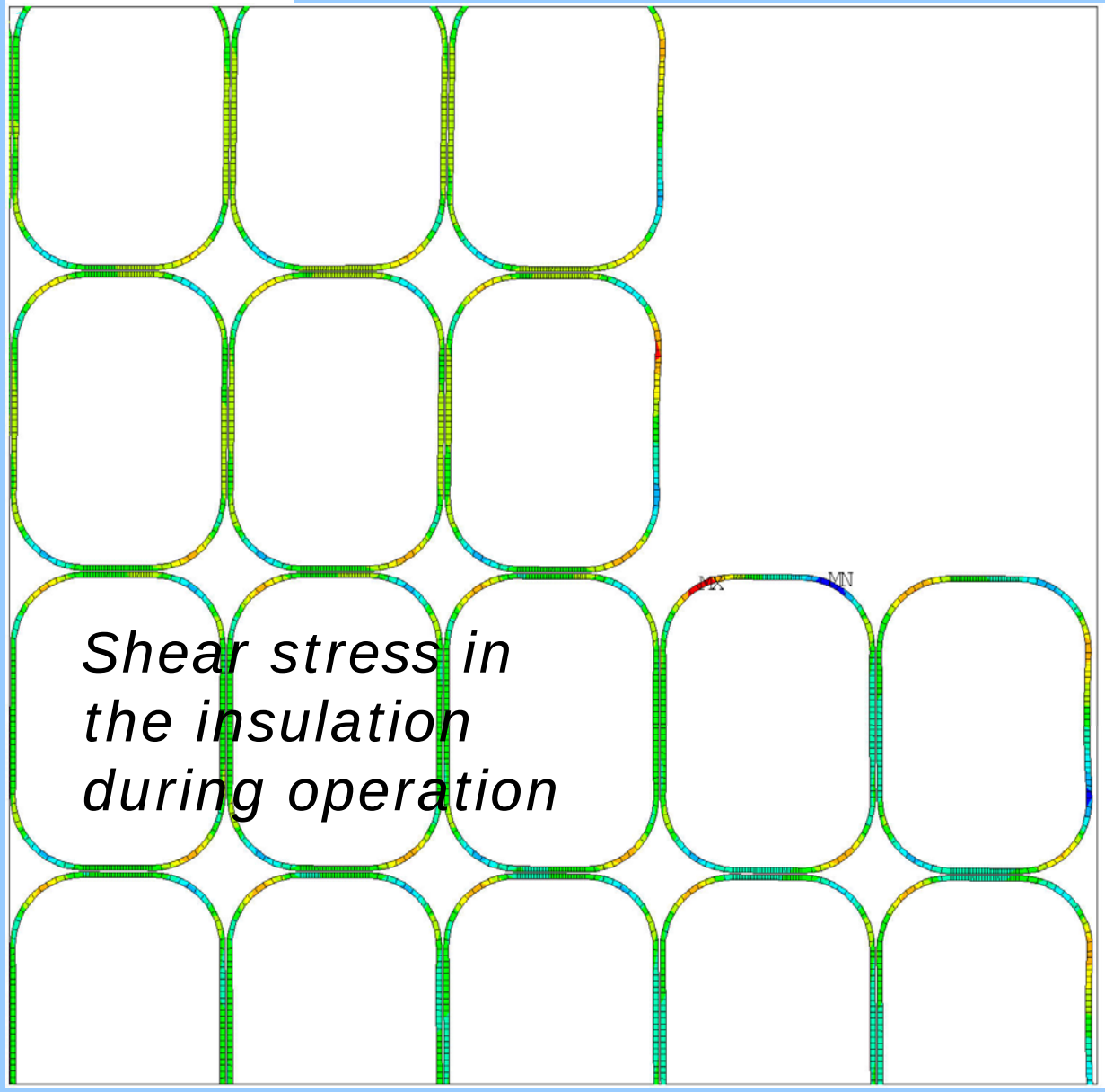

1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
BSUM (AVG)
RSYS=0
SMN =5.727
SMX =12.867
ANSYS
FEB 25 2005
13:54:16
MN
MX
Z
Y
X
5.727
6.52
7.314
8.107
8.9
9.694
10.487
11.28
12.074
12.867


1
NODAL SOLUTION
STEP=2
SUB =1
TIME=2
BSUM (AVG)
RSYS=0
SMN =.015833
SMX =9.282
ANSYS
FEB 25 2005
14:06:57
MN
MX
Z
Y
X
.015833
1.045
2.075
3.105
4.134
5.164
6.194
7.223
8.253
9.282


1
MN
MX
ANSYS 9.0
JUN 29 2005
12:23:15
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SINT (AVG)
DMX =.001343
SMN =.138E+08
SMX =.819E+09
.138E+08
.103E+09
.193E+09
.282E+09
.372E+09
.461E+09
.550E+09
.640E+09
.729E+09
.819E+09

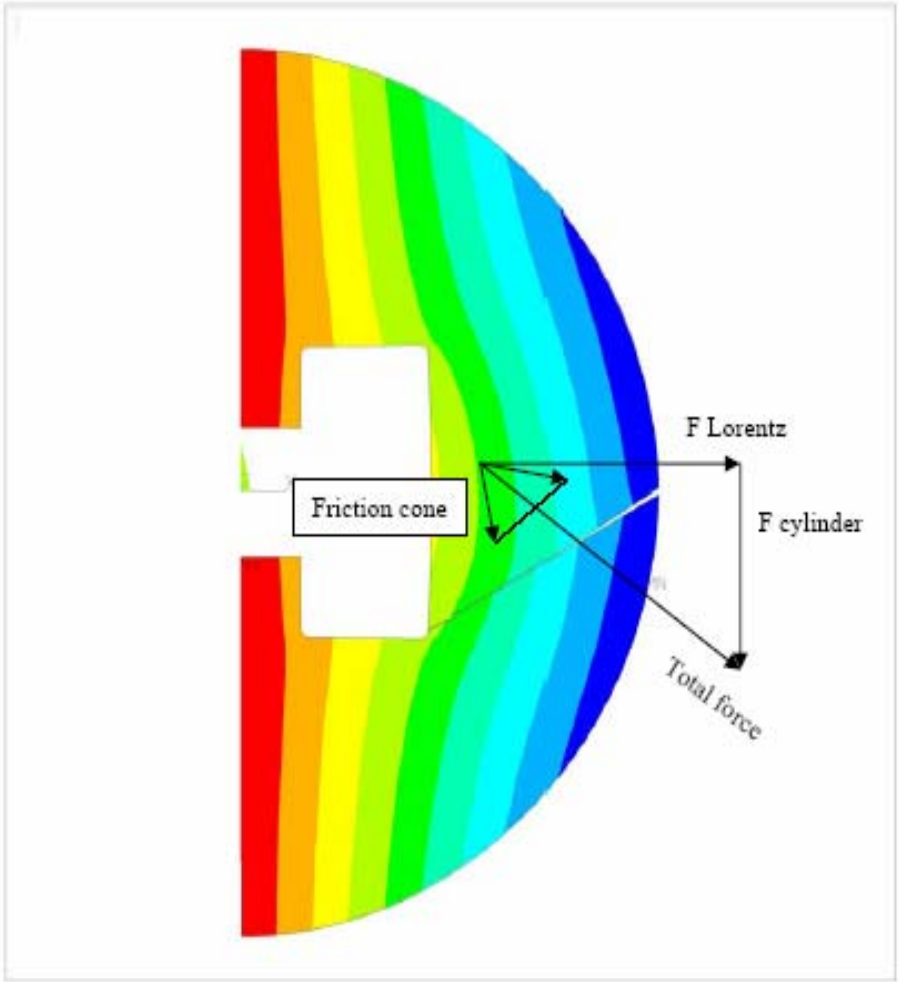

ANSYS 9.0
JUN 29 2005
12:26:26
PLOT NO. 1
NODAL SOLUTION
STEP=1
SUB =1
TIME=1
SINT (AVG)
DMX =.001343
SMN =.138E+08
SMX =.819E+09
.138E+08
.103E+09
.193E+09
.282E+09
.372E+09
.461E+09
.550E+09
.640E+09
.729E+09
.819E+09


1
Yoke principal maximum
stress with elliptic corners
MX
MN
Y
Z
X
ANSYS 9.0
OCT 20 2005
14:50:36
PLOT NO. 1
NODAL SOLUTION
STEP=3
SUB =1
TIME=3
S1 (AVG)
PowerGraphics
EFACET=1
AVRES=Mat
DMX =.002414
SMX =.231E+09
0
.256E+08
.513E+08
.769E+08
.103E+09
.128E+09
.154E+09
.180E+09
.205E+09
.231E+09




*Shear stress in the insulation during operation*

# Yoke locking

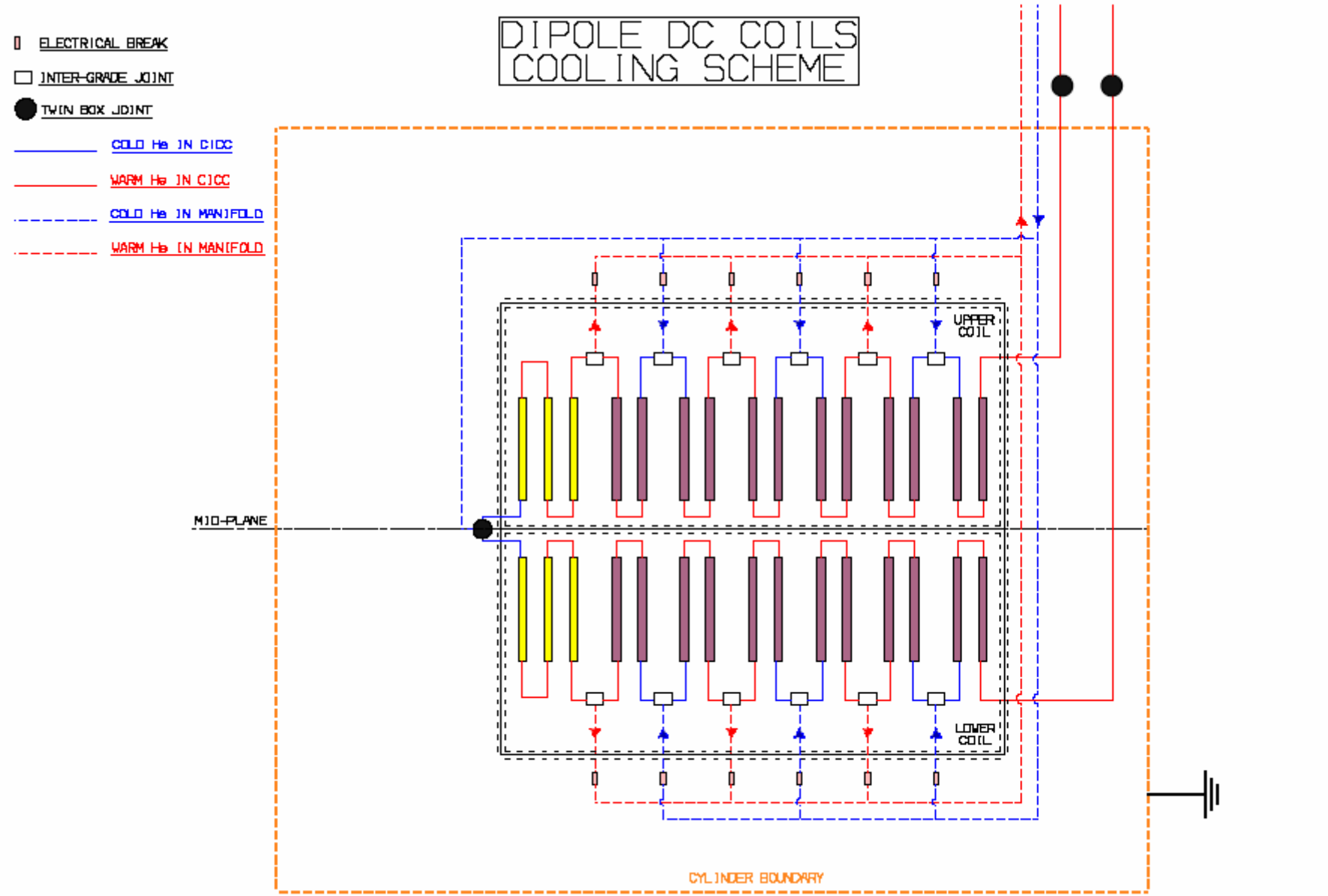


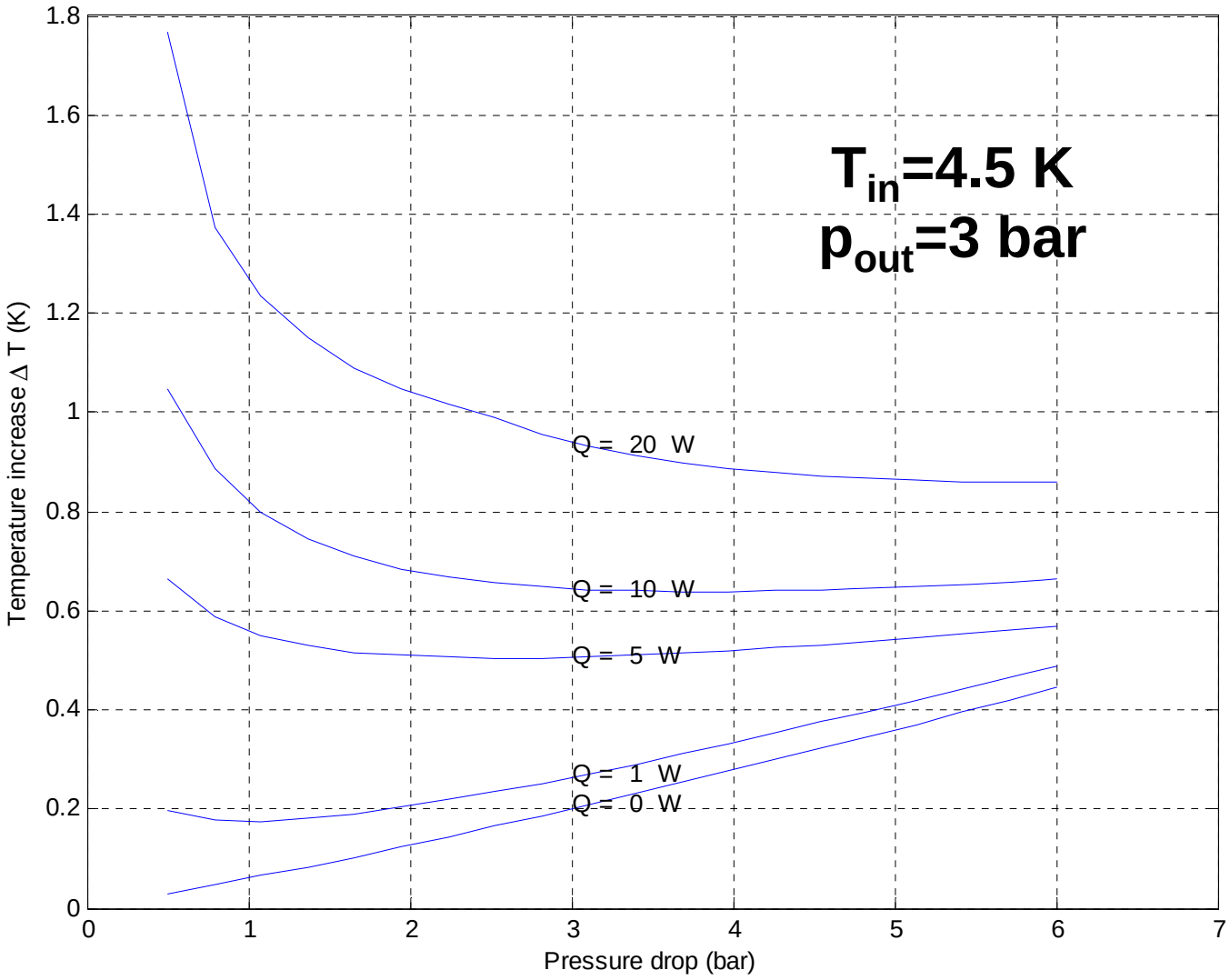


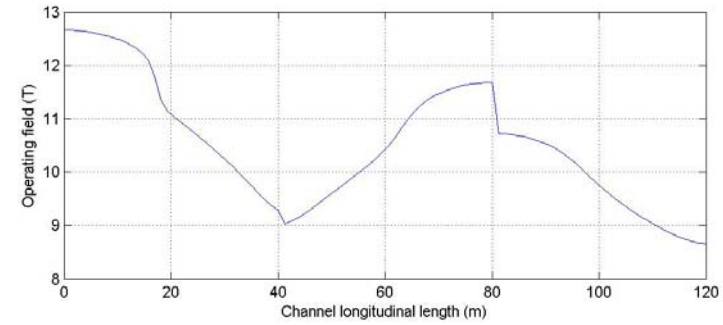
The gap is very efficiently blocked by friction.

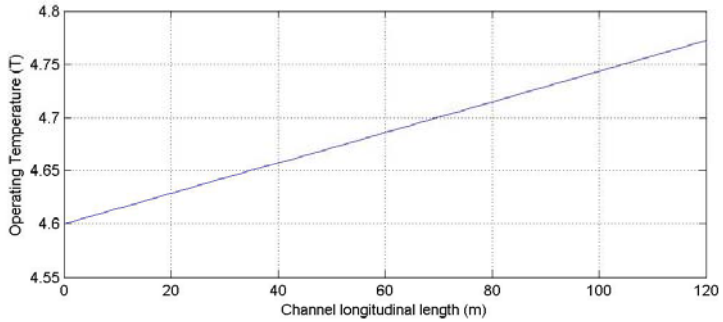
The vertical force due to the shrinking cylinder and the horizontal Lorentz forces give an almost normal force in the gap

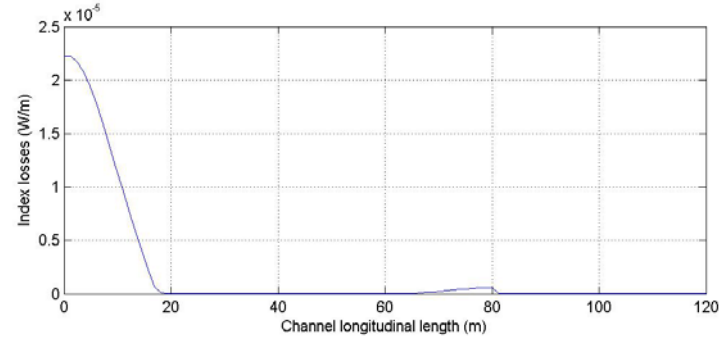
A friction factor of 0.2 is enough to block the sliding in the gap

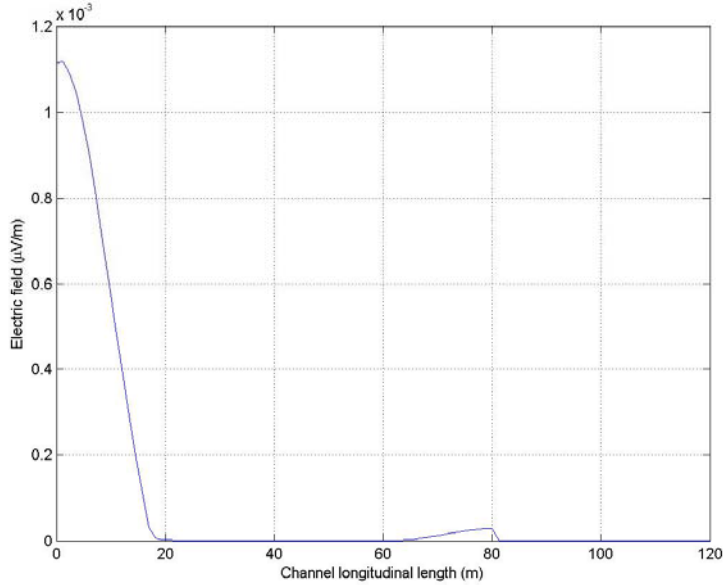

DIPOLE DC COILS
COOLING SCHEME
ELECTRICAL BREAK
INTER-GRADE JOINT
TWIN BOX JOINT
COLD He IN CICC
WARM He IN CICC
COLD He IN MANIFOLD
WARM He IN MANIFOLD
MID-PLANE
UPPER COIL
LOWER COIL
CYLINDER BOUNDARY

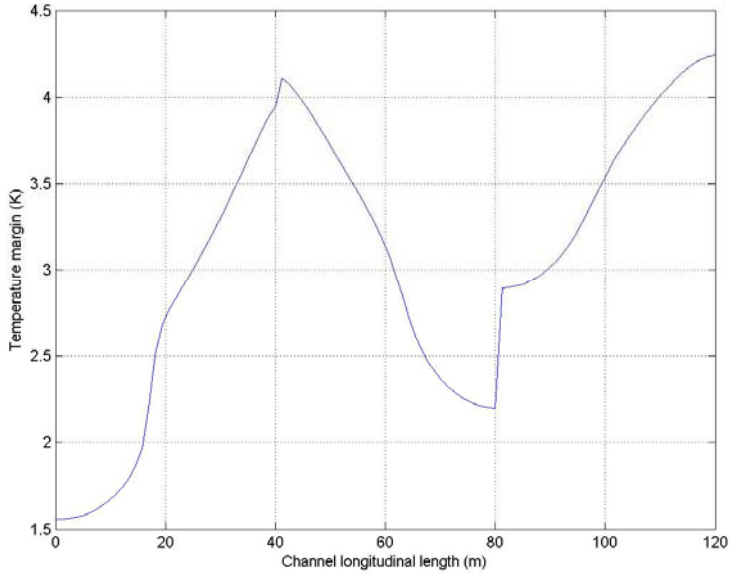

$T_{in}$=4.5 K
$p_{out}$=3 bar
Q = 20 W
Q = 10 W
Q = 5 W
Q = 1 W
Q = 0 W
Temperature increase Δ T (K)
Pressure drop (bar)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
1
2
3
4
5
6
7


Operating field (T)
Channel longitudinal length (m)

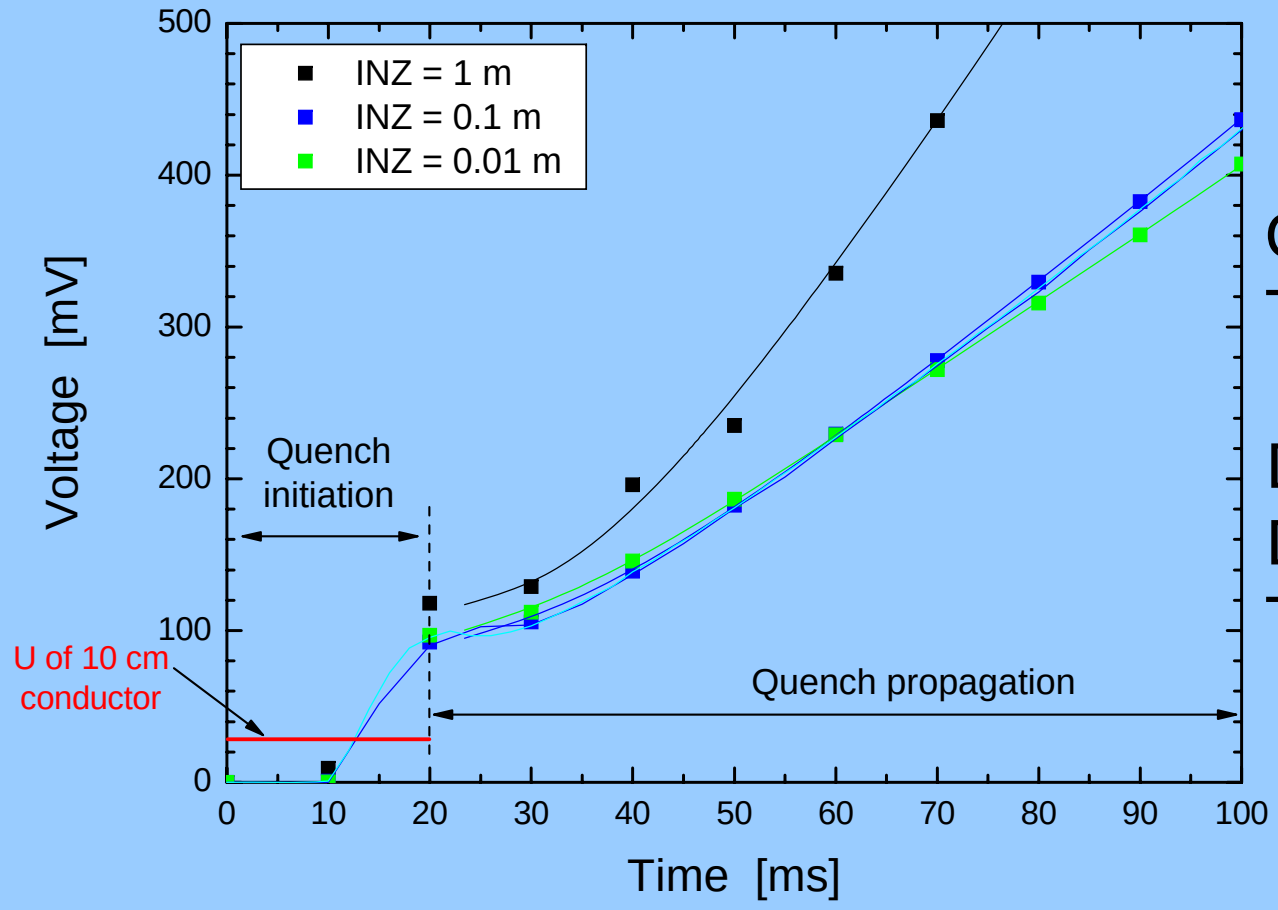

Operating Temperature (T)
Channel longitudinal length (m)


x 10^-5
Index losses (W/m)
Channel longitudinal length (m)


x 10^-3
Electric field (μV/m)
Channel longitudinal length (m)


Temperature margin (K)
Channel longitudinal length (m)

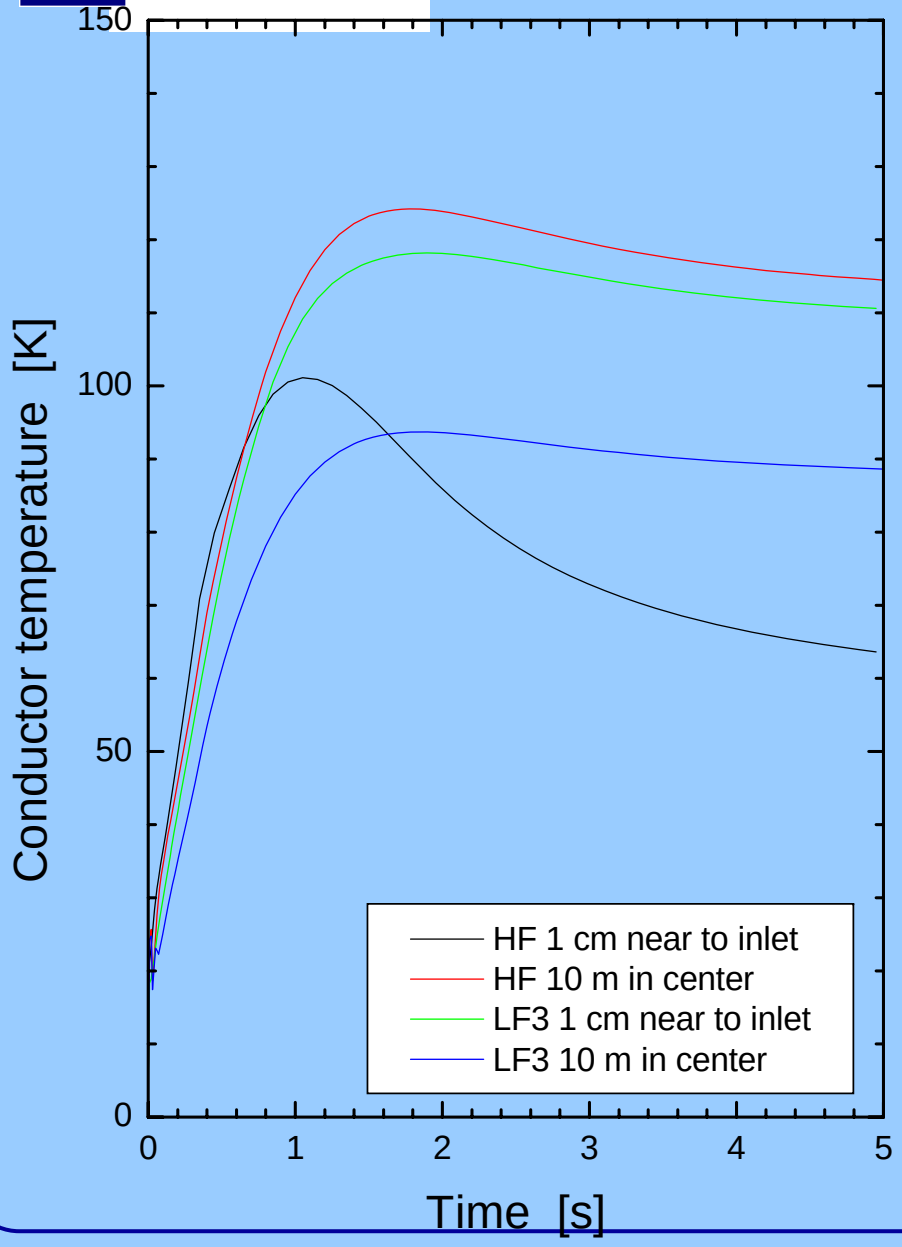
# Quench detection

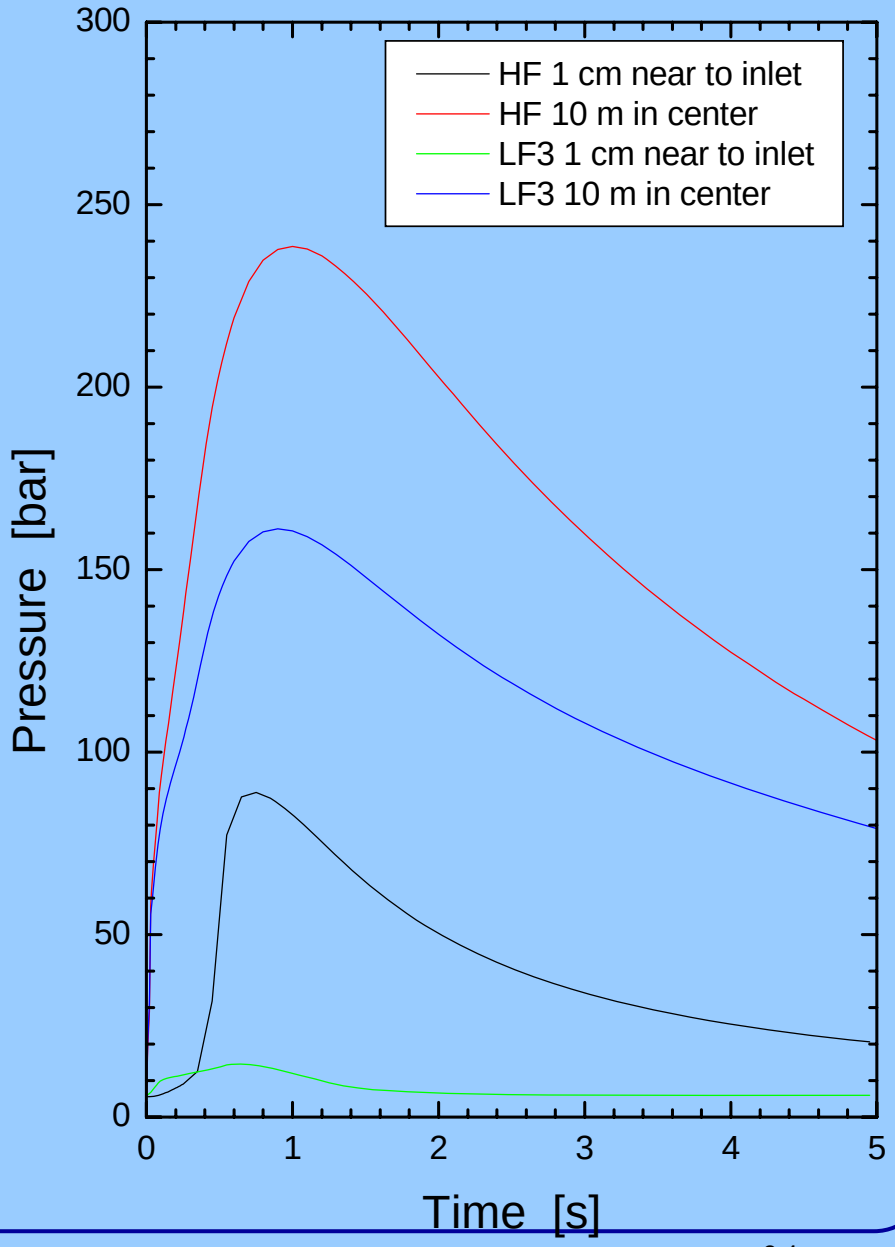


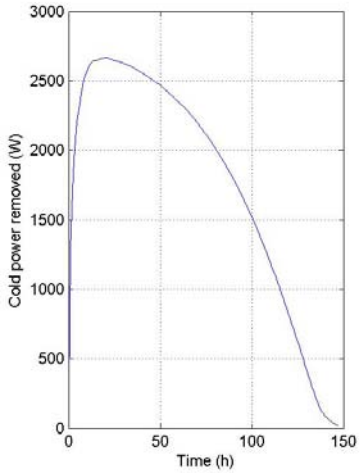

**DESIGN**

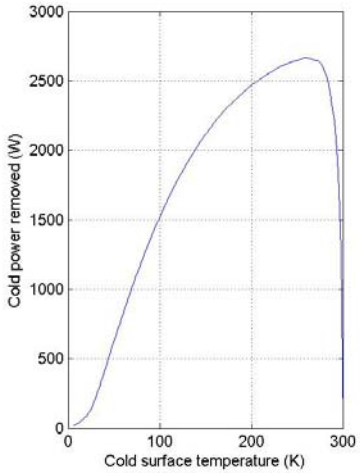
Quench detection
Time <200 ms

Discharge
Dump delay
Time <150 ms

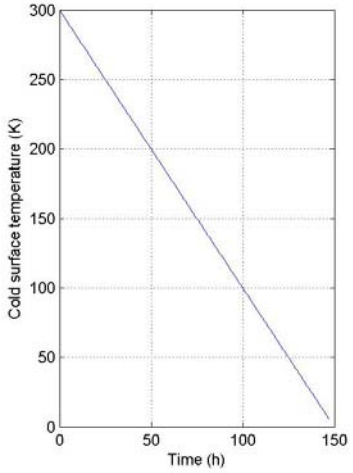

Conductor temperature [K]
Time [s]
HF 1 cm near to inlet
HF 10 m in center
LF3 1 cm near to inlet
LF3 10 m in center

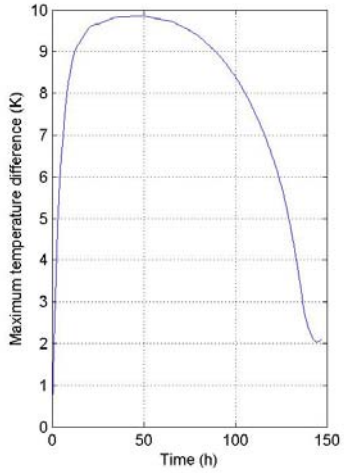

Pressure [bar]
Time [s]
HF 1 cm near to inlet
HF 10 m in center
LF3 1 cm near to inlet
LF3 10 m in center

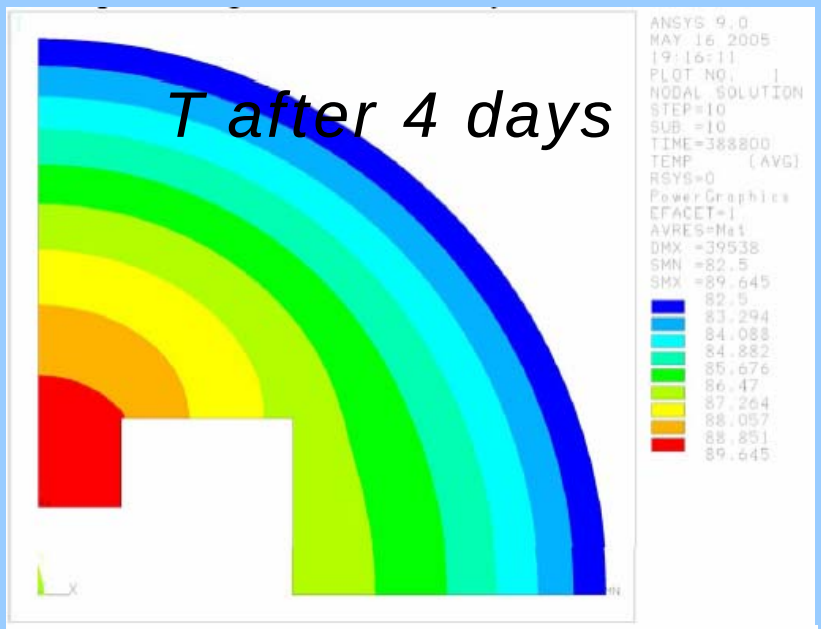


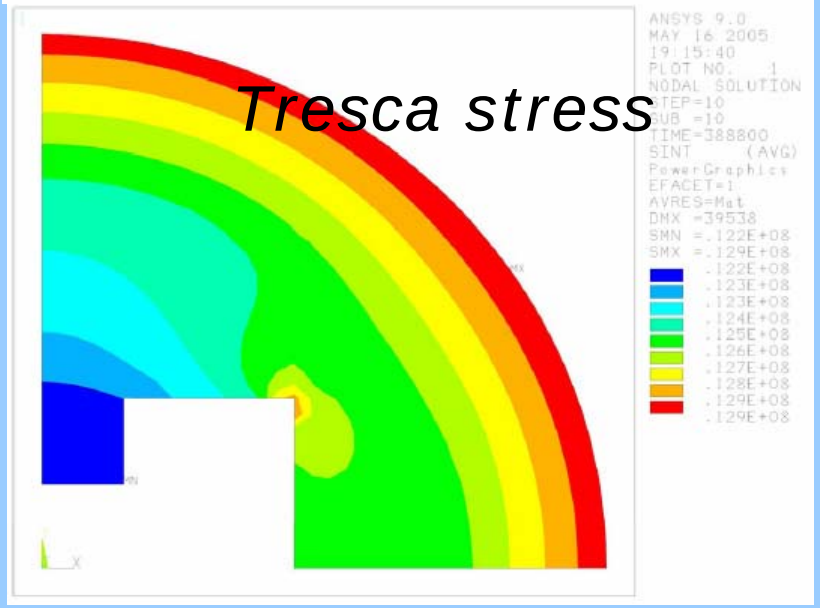




## COOL DOWN ANALYSIS



# Conclusions

- All manufacturing contracts completed
- The facility expected to operate by middle2008
- R&D results available for CARE
- What about a cos(teta) coil with CICC?