The SIS100 Dipole Magnet

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MAC-3

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The SIS100 Dipole Magnet: Contents

The references to the original papers are omitted in this presentation as there content is summarised as well as referenced in the distributed report:

E. Fischer, P. Schnizer:
Design and Test Status of the SIS100 Dipole Magnet

1. Introduction
2. Main magnet components
3. Mechanical stability of the coil windings
4. Magnetic steel
5. Magnetic field design
6. Losses and hydraulic limits
7. Vacuum chamber and temperature fields
8. Milestones towards a curved single layer dipole
9. Conclusion

Introduction: Design principles

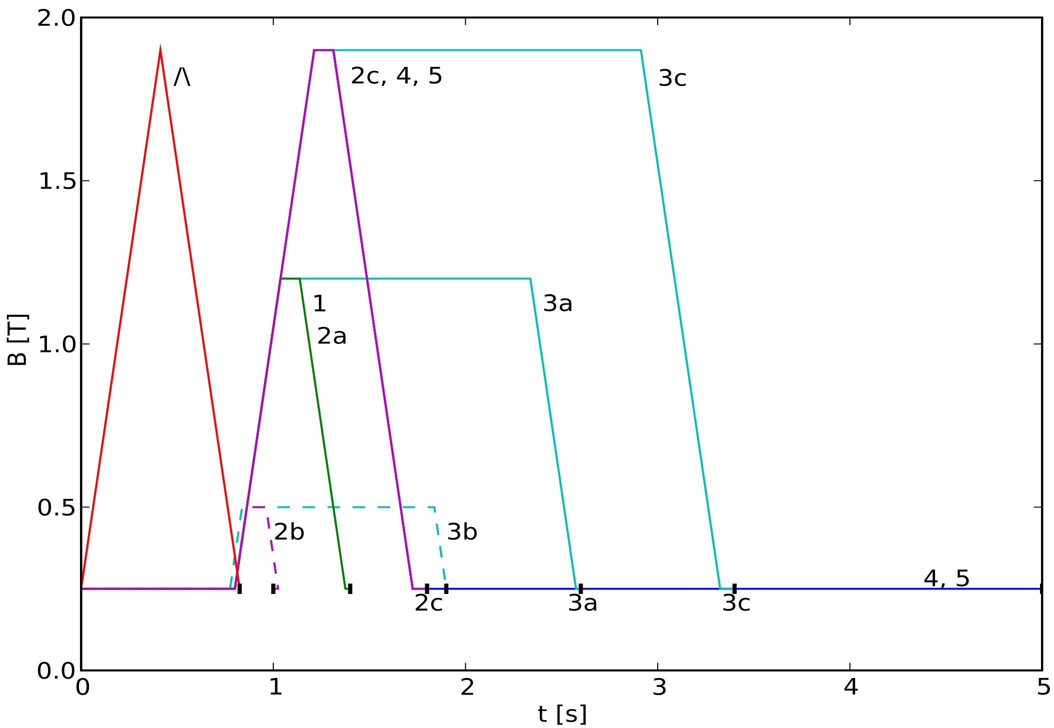
- simple magnet design
- coil cooled by two phase Helium flow
- straightforward robust magnet yoke
- start from Nuclotron design

	unit	Nuclotron	**S2LD** BNG	C2LD BINP	**Curved dipole**
B x $L_{effective}$	[Tm]	2.823	5.788	5.819	5.818
B_{max}	[T]	1.98	2.1	1.9	1.9
$L_{effective}$	[m]	1.426	2.756	3.062	3.062
Estimated L_{yoke}	[m]	1.370	2.731	3.002	3.002
Bending angle	[deg]	3.75	3.33	3.33	3.33
Radius of curvature	[m]	22.5	47.368	52.632	52.632
Usable aperture (h x v)	[mm]	110 x 55	130 x 60	113 x 58	120 x 60

Introduction: Requirements

- a field strength curvature of Bp = 100 [Tm]
- good field region: an ellipse a = 57.5 mm, b = 30 mm

Main operation cycles



Cycle	B_{max} [T]	t_f [s]	t_c [s]
1	1.2	0.1	1.4
2a	1.2	0.1	1.4
2b	0.5	0.1	1
2c	1.9	0.1	1.8
3a	1.2	1.3	2.6
3b	0.5	1.0	1.9
3c	1.9	1.7	3.4
4	1.9	0.1	5.0
5	1.9	0.1	5.0
/\	1.9	0	0.84

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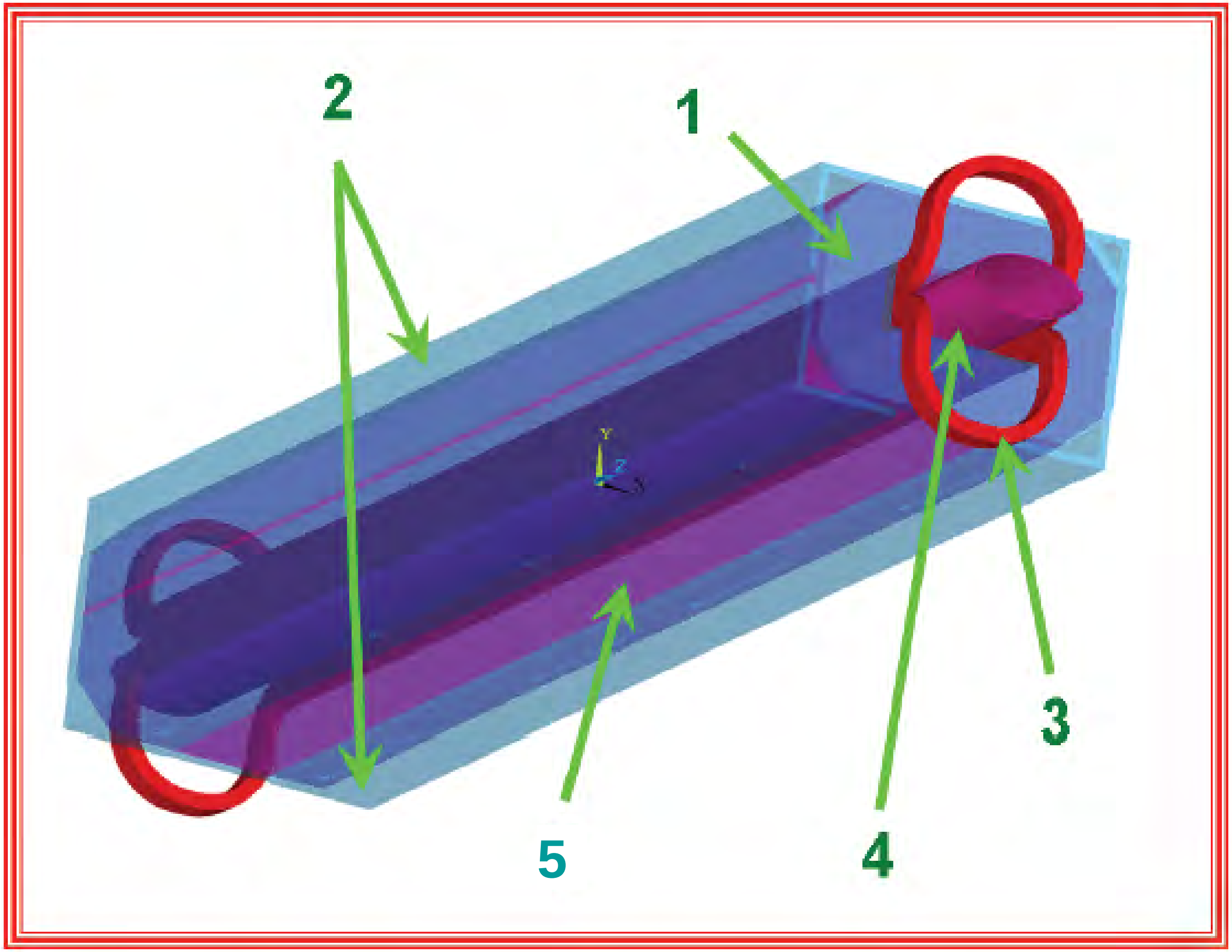
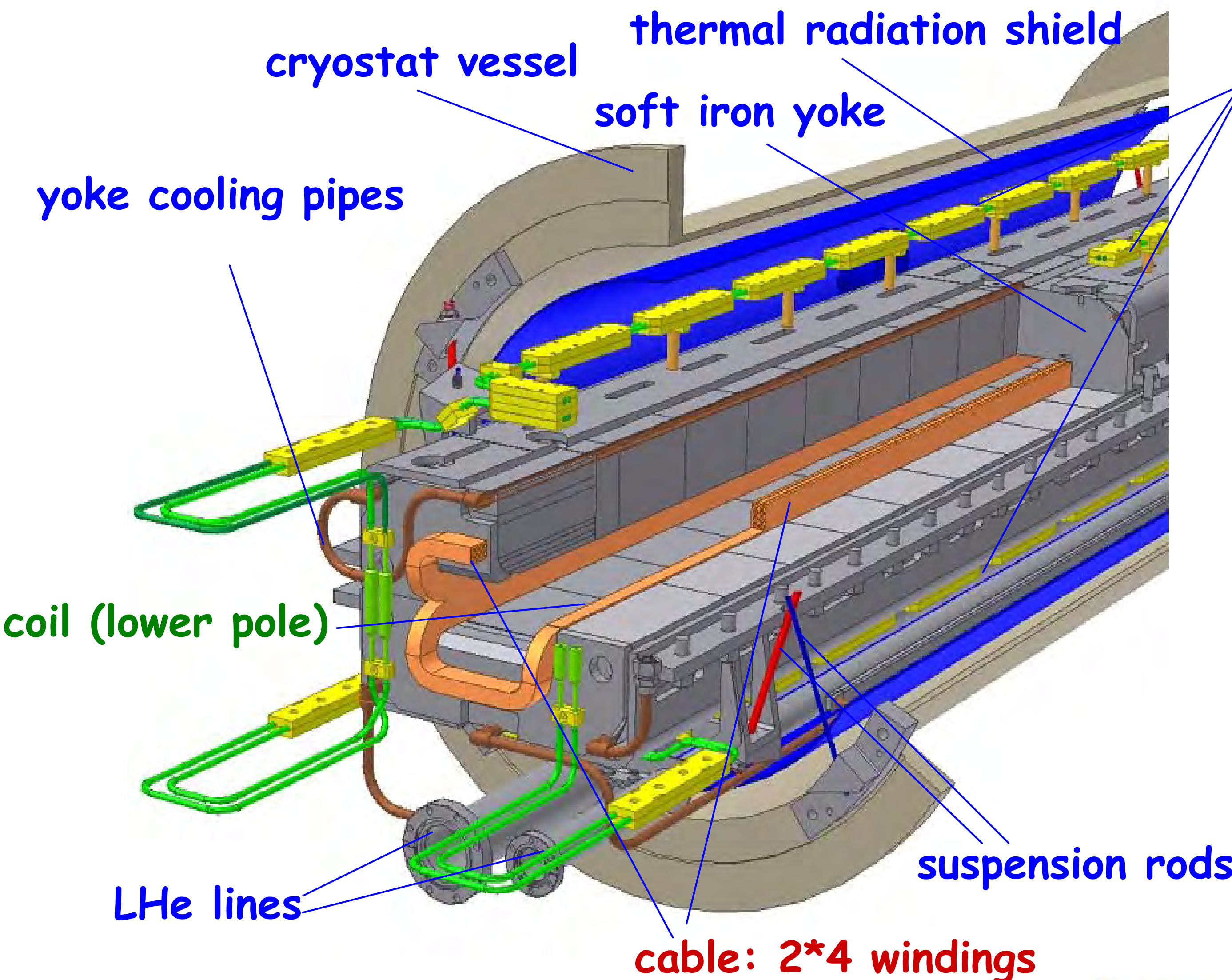
Main magnet components

ANSYS Model:

1 – yoke end plate
2 – brackets
3 – coil end loop
4 – beam pipe
5 – laminated yoke

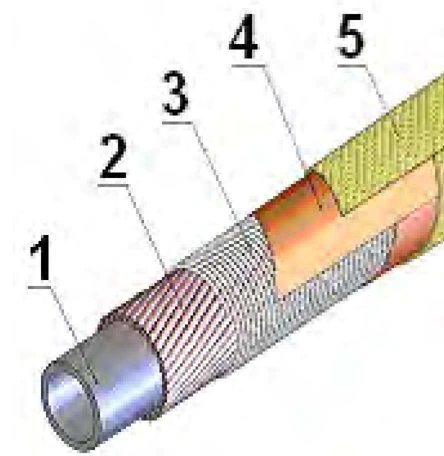


Main magnet components: Layout 1st dipole



Nuclotron cable:

1 - Cooling tube CuNi
2 - SC wire NbTi
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape

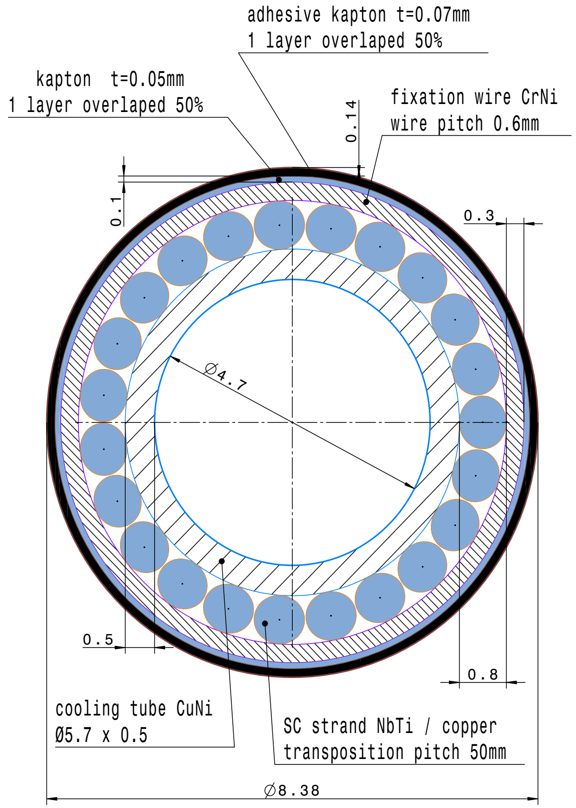


Main magnet components: Dipole parameters

Number of magnets		108 + 1 reference magnet
Design		Window-frame, laminated cold iron yoke, lamination thickness 1mm, **one layer coil with 8 turns**
Max. Field	T	1.9
Min. Field	T	0.23
Bending angle	Deg.	3.33
Edge angles (entrance / exit)	Deg.	1.665 / -1.665
Orbit curvature radius, R	m	52.632
Effective magnetic length, L	m	3.062
Coil aperture	mm	165 · 68
Useable aperture (good field region):	mm mm	120 · 60 115 · 60
Field quality (goal)		$\pm 6 \cdot 10^{-4}$
Current at max. field	A	12745
Inductance	mH	0.55
Ramp rate	T/s	4
Cycle 2c		
Cycle length	s	1.735
High field flat top duration	s	0.1
Low field flat top duration	s	0.8
AC loss @4.2K per magnet (cycle number 2c)	W	35.7
Overall width (cryostat)	m	1.0
Overall height (cryostat)	m	1.0
Overall weight	kg	1850

Main magnet components: High current cable

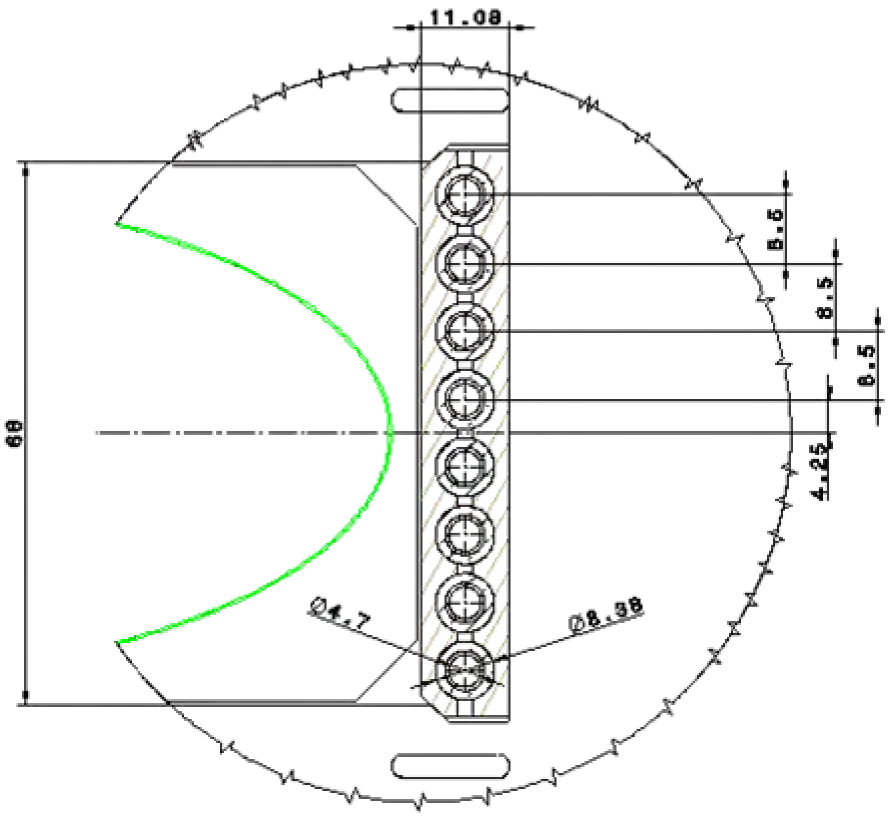
Number of strands				23	
Transposition pitch				50	mm
Cooling tube material				Cu-Ni	
Cooling tube outer diameter				5.7	mm
Cooling tube wall thickness				0.5	mm
Critical current @ 2.1 T, 4.2 K				19840	A
1st insulating layer		with epoxy impregnation			
	material	Kapton	tape	2	layers
	thickness/layer			50	µm
2nd insulating layer		with epoxy impregnation			
	material			2	layers
	thickness	Kapton	tape	70	µm
Wire					
Strand diameter				0.8	mm
Filament diameter				3.5	µm
Number of filaments				18144	
Filament twist pitch				5-8	mm
Superconducting material				NbTi	
Copper to superconductor ratio				1.5	
Copper RRR				196	
Fixation of the strands		CrNi-wire	D=0.3	transp. = 0.6	mm
Coating		epoxy compound			



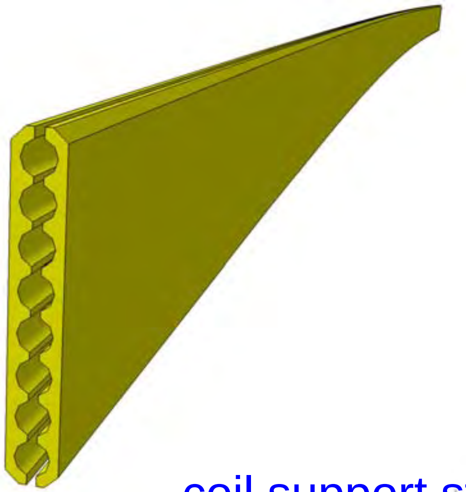
Cross section of the cable adopted for the SIS100 dipole coils (Nuclotron-type cable).

Main magnet components: Coil reinforcement

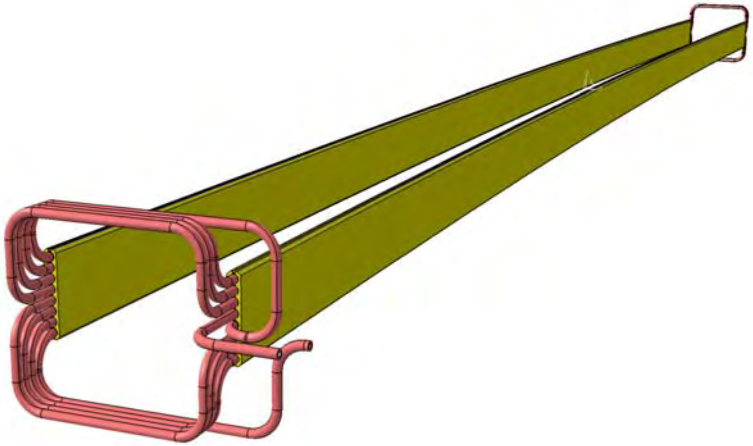
Geometric details of the dipole coil



coil support structur



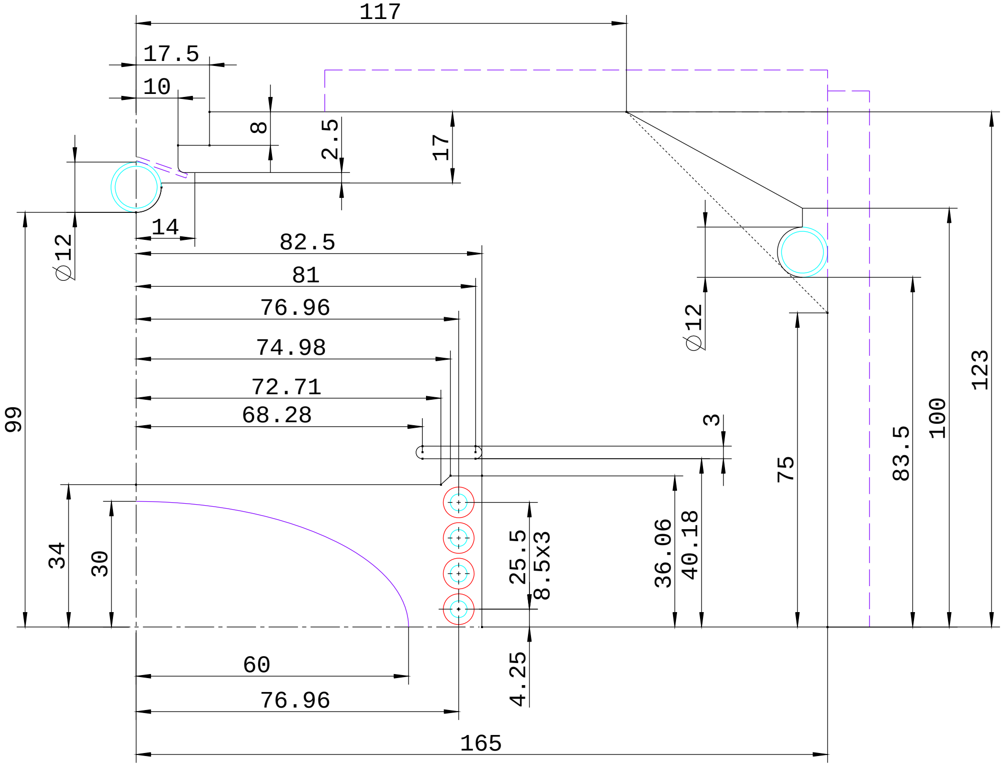
coil support structure
with the coil inside



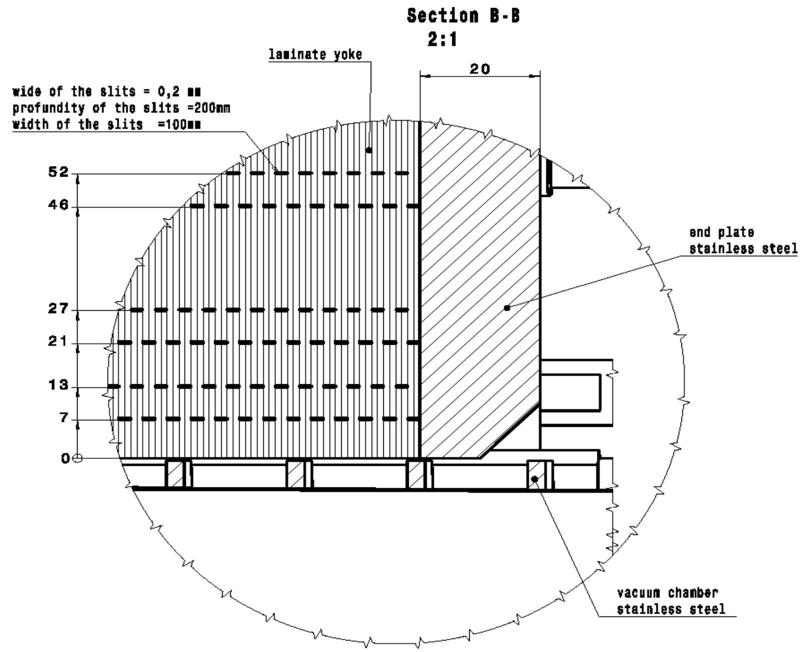
Main magnet components: Yoke lamination

Curved single layer dipole (CSLD)

lamination geometry ▼

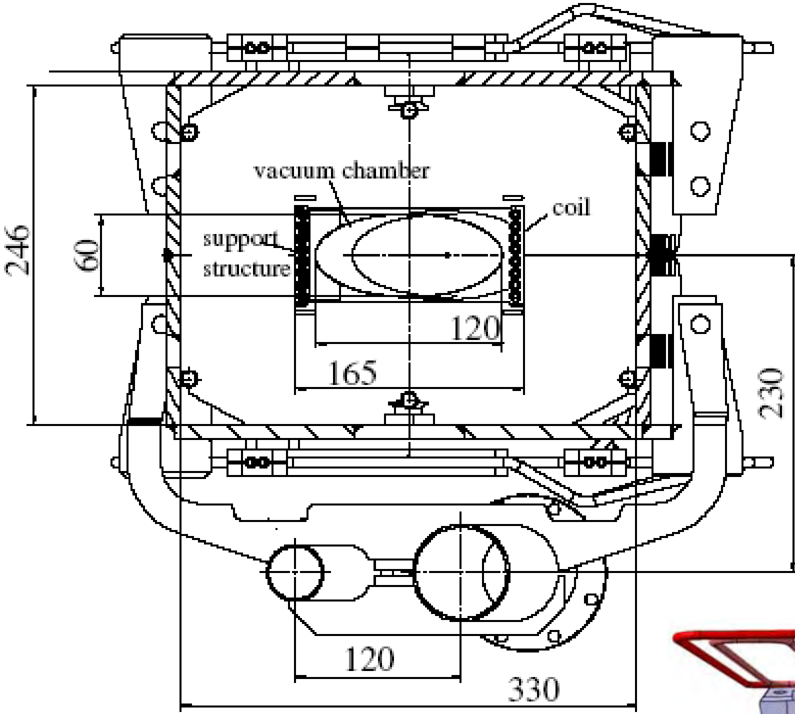


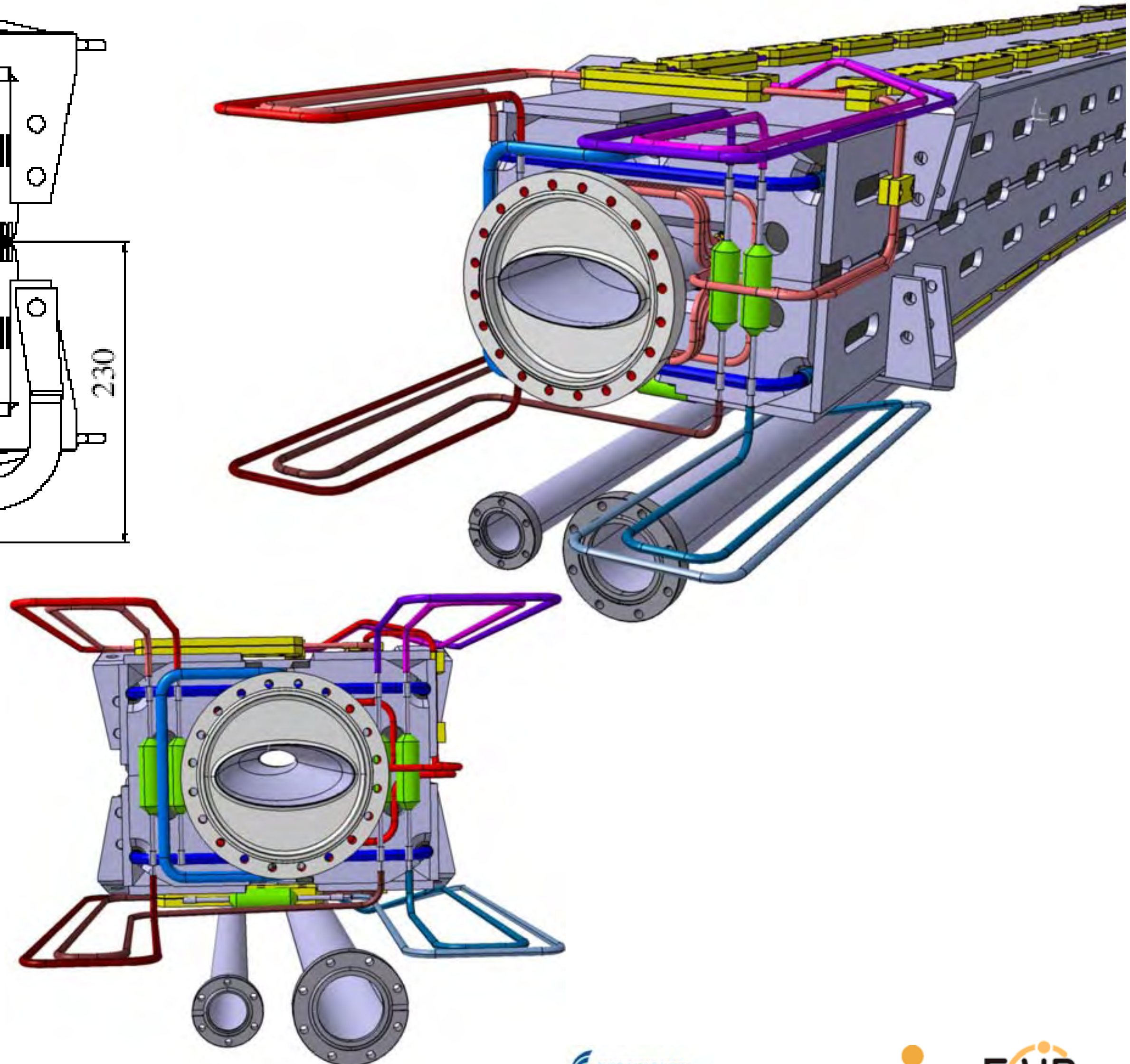
cross section



lamination slits near yoke end

Main magnet components: 3D View





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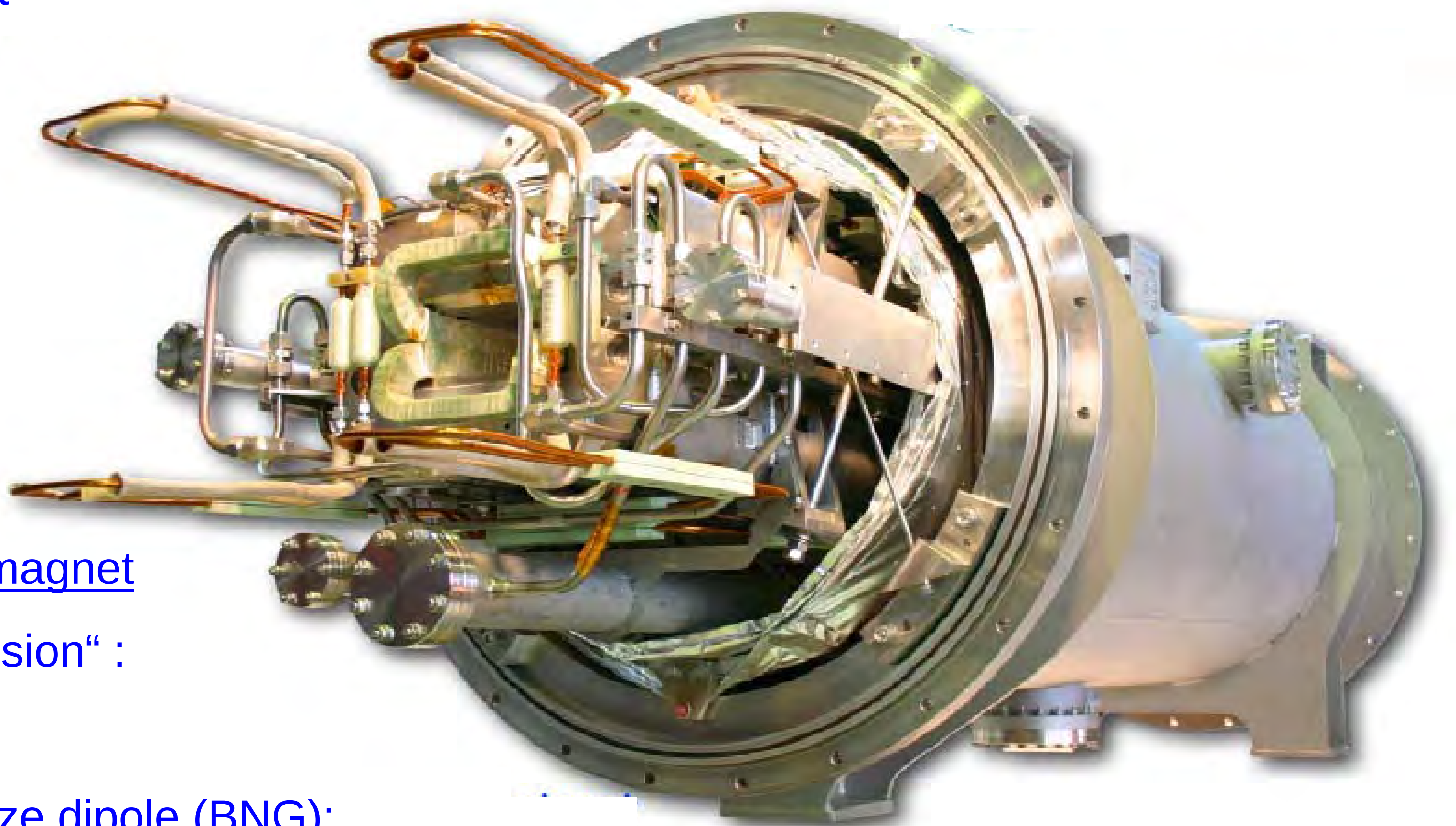
Main magnet components: First full size Dipole

- Curved single layer design made
- but not yet built



- production & magnet

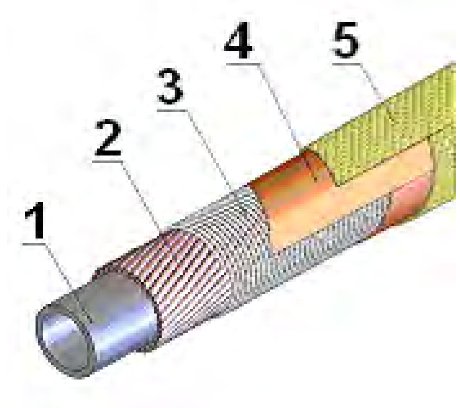
„ get an impression“ :

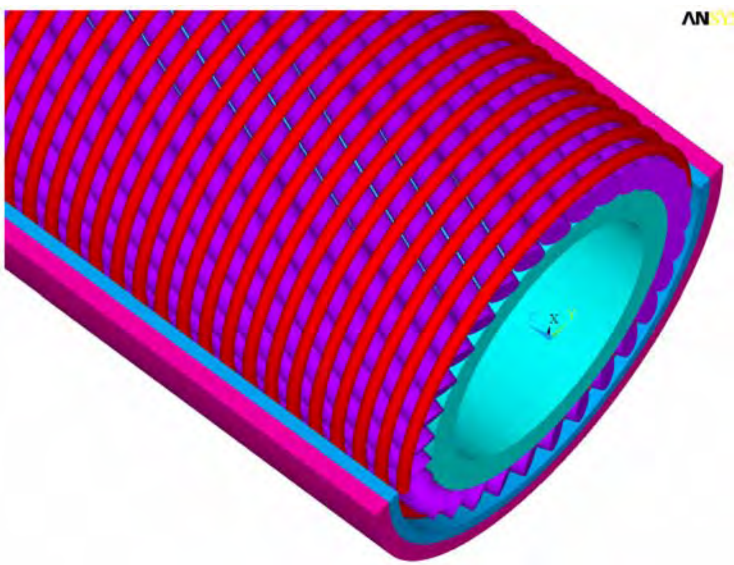
  - Nuclotron
  - First full size dipole (BNG):
    - Production steps illustrated →

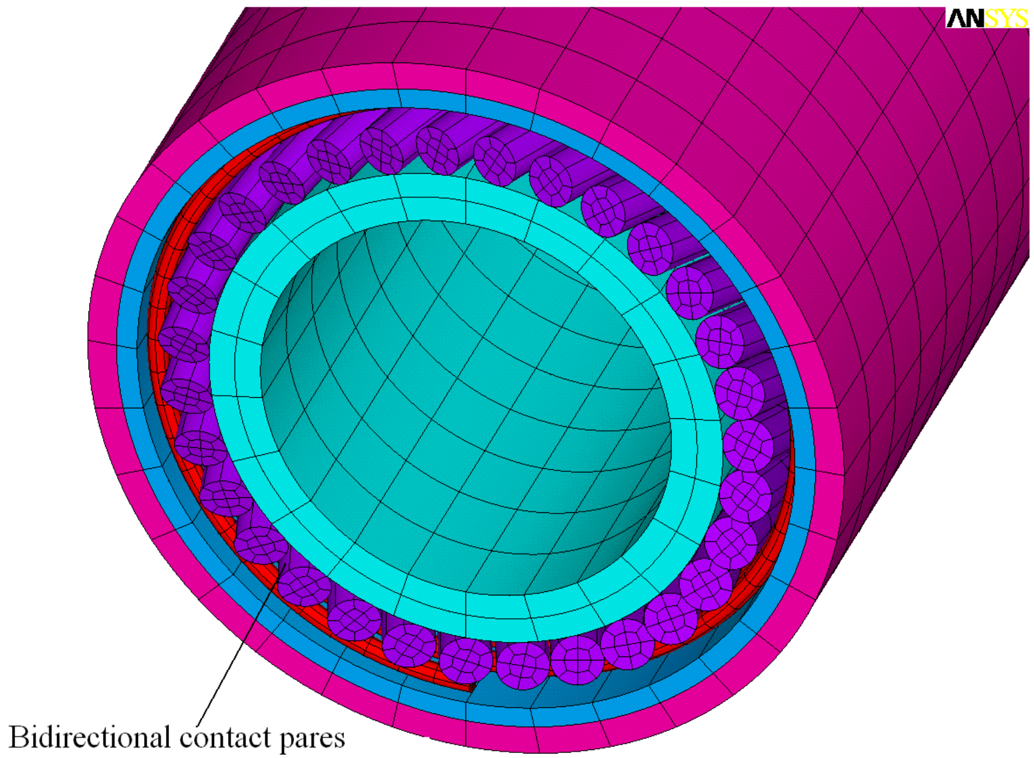
Main magnet components: Nuclotron type Cable

Nuclotron cable:

1 - Cooling tube CuNi
2 - SC wire NbTi
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape



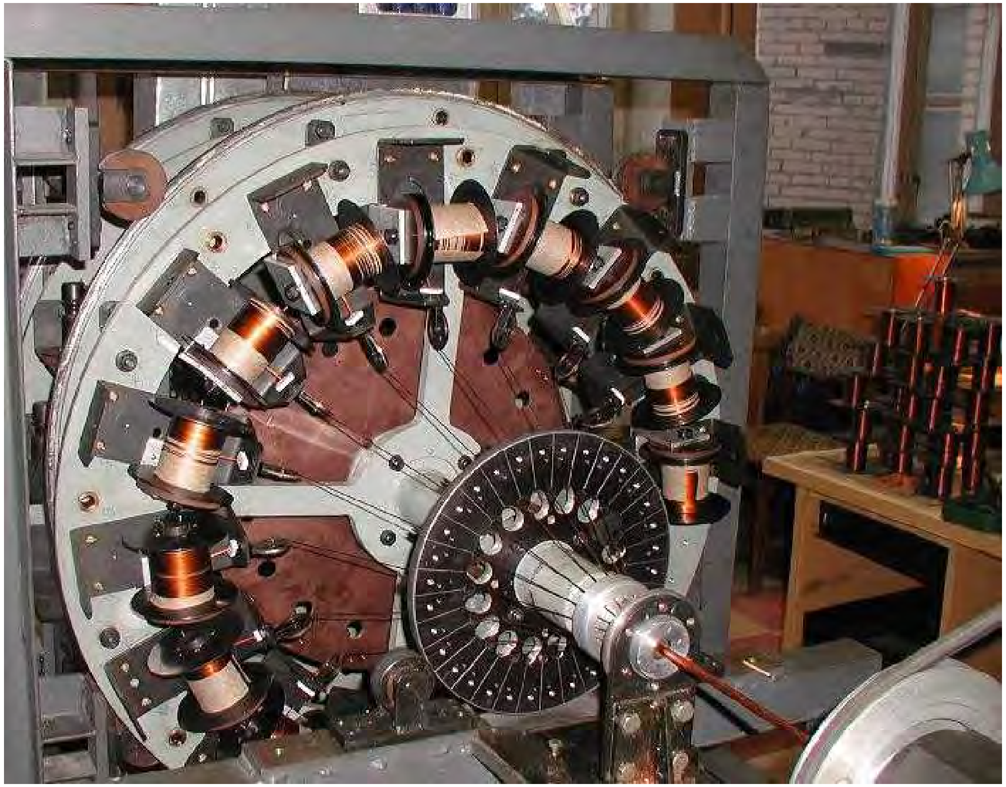




3D ANSYS modelling

SIS100 Magnets: Production of the cable

First cabling machine for the production of Nuclotron type cables



Cabling facility at JINR Dubna

Parameters

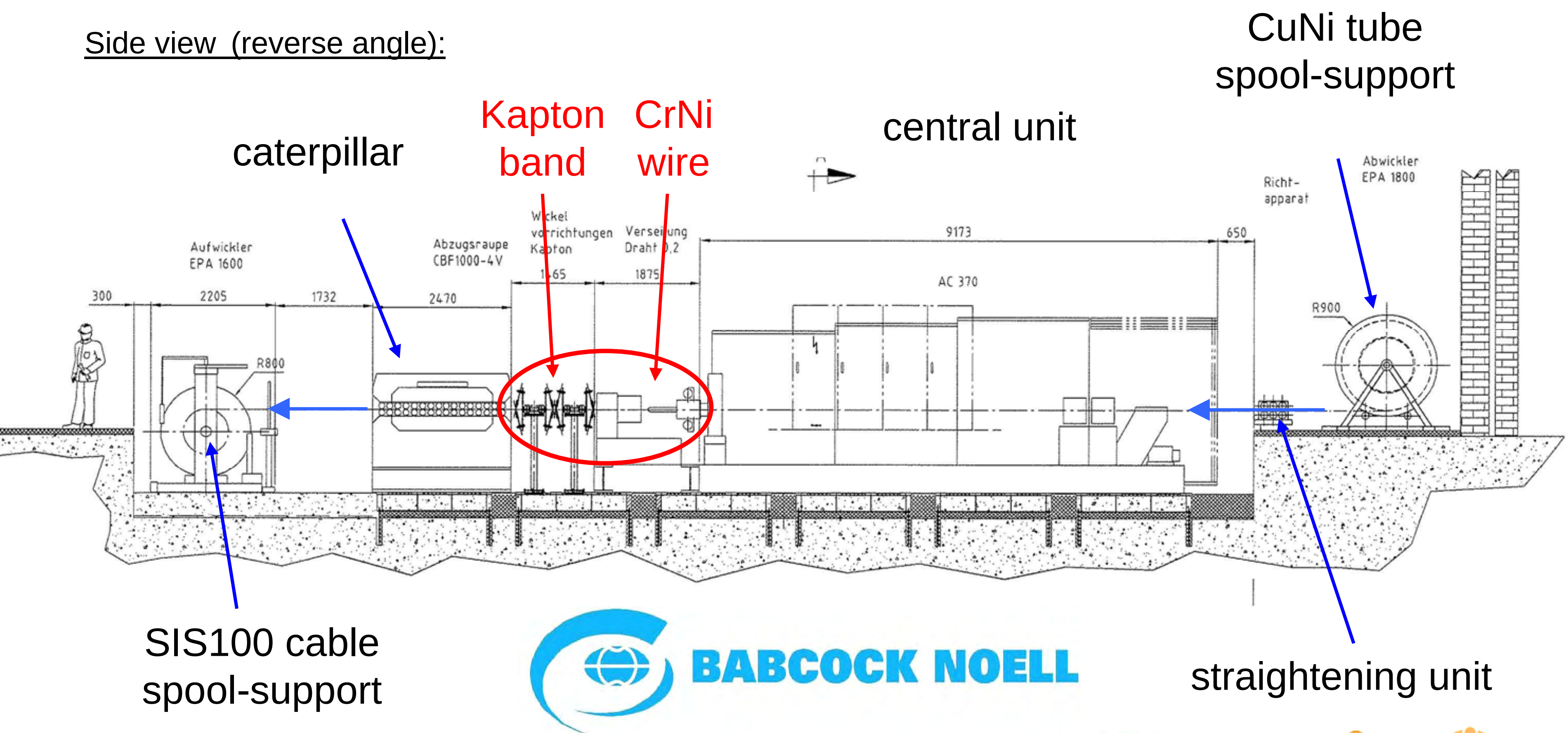
- *up to 32 wires*
- *"dry" and "wet" technology*
- *isolation with polyimide tape (2 layers)*
- *flexible adjustment to different cable designs (number and size of strands, size of cooling tubes, ...)*

Estimated production rate: ≥ 15 m/h

SIS100 Magnets: Cable machine

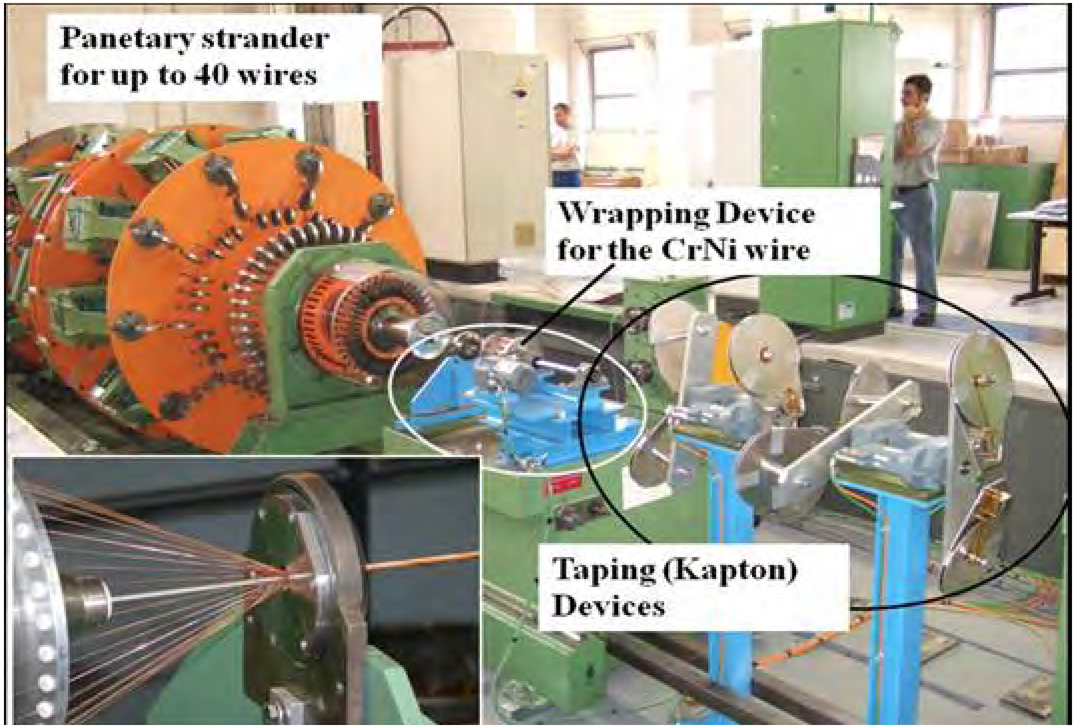
Second cabling machine for industrial production of Nuclotron type cables

Side view (reverse angle):



SIS100 Magnets: Cable production machine

Industrial cabling facility !



Cabling machine at the premises of BNG

Estimated production rate: ≥ 120 m per 8 h-shift.
≈ 2 complete dipole magnets

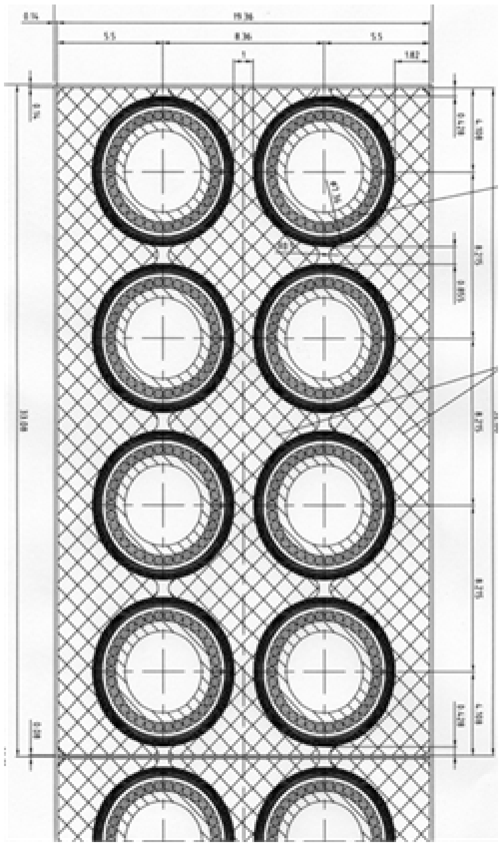
cabling facility of the BNG's :

- process safety
- reproducability
- stable quality
- "dry" technology

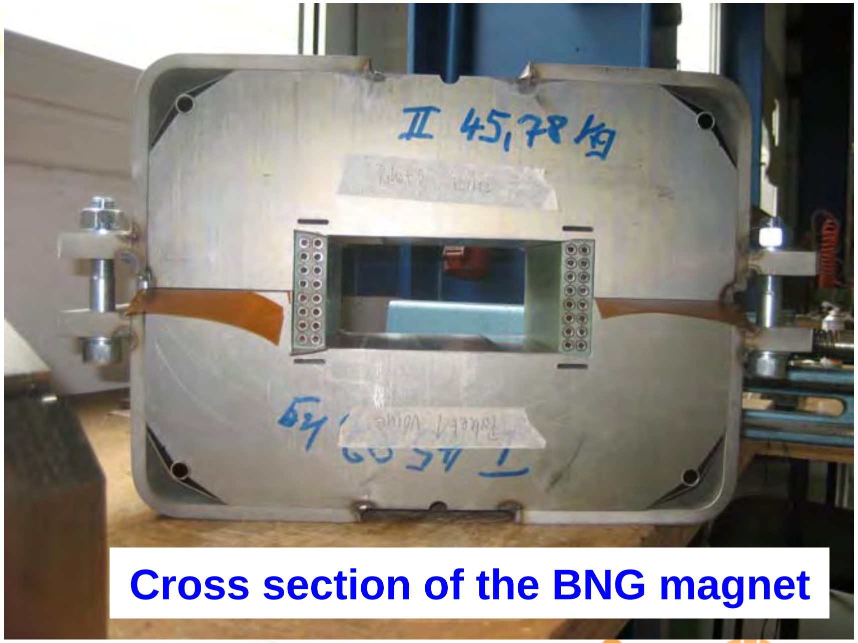
due to:

- **Active and adjustable back rotation of the SC wire supply coils for all strands, avoiding torsion for all individual wires and for the cable.**
- **Active control of the winding force (including emergency stop) for all strands to avoid wire break and to keep winding force constant.**
- **Constant and adjustable torque (during operation) of CrNi wire spinning device to keep winding force of CrNi wire constant.**
- **Isolation with polyimide tape (up to 8 layers, with two different pitches) on-line Flexible adjustment to different designs (number and size of strands, size of cooling tube, …)**
- **All actual machine-values for winding forces, torques, speeds, and pitches can be recorded for the quality documentation.**

Main magnet components: Coil package

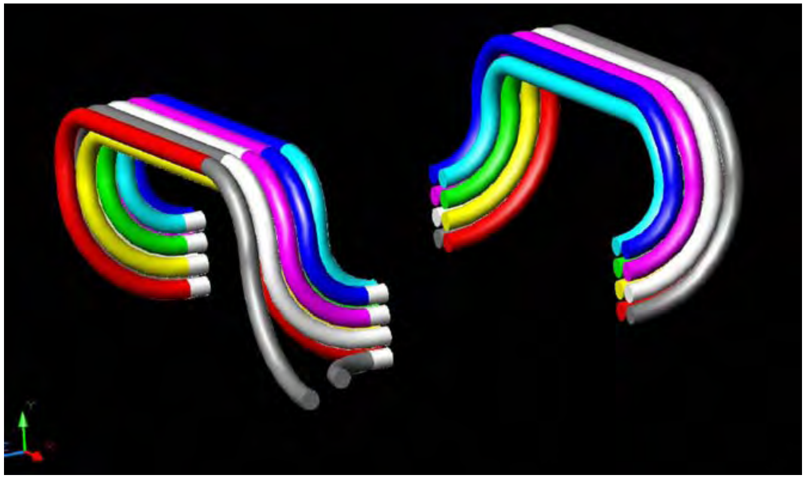


Support structure combs

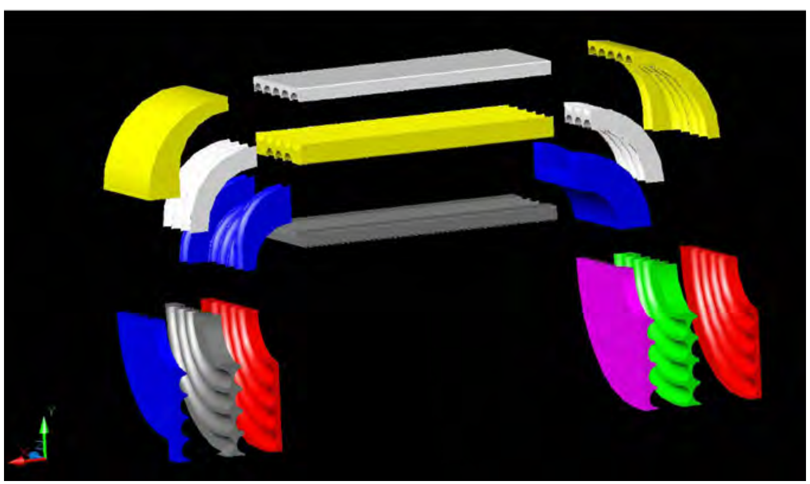


Cross section of the BNG magnet

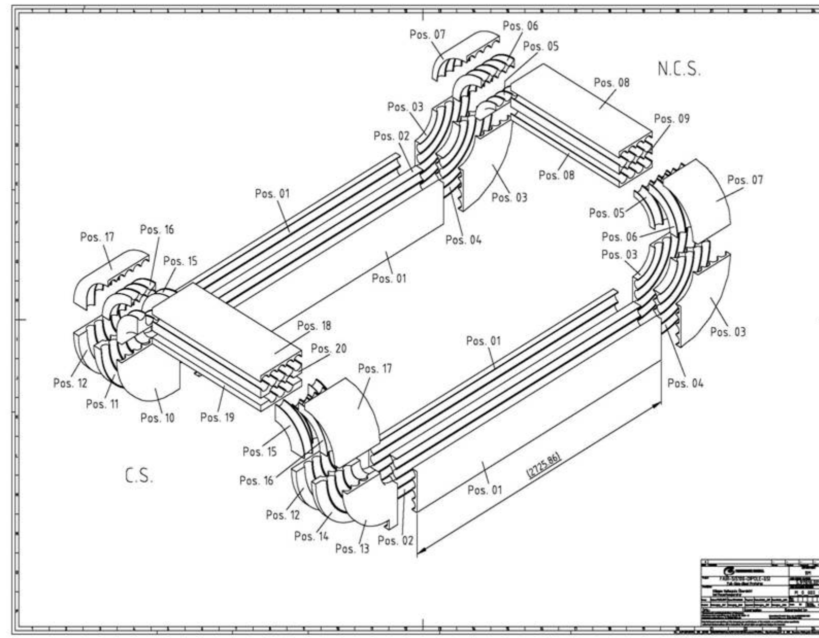
Main magnet components: Coil package



▲ layout of the coil end windings



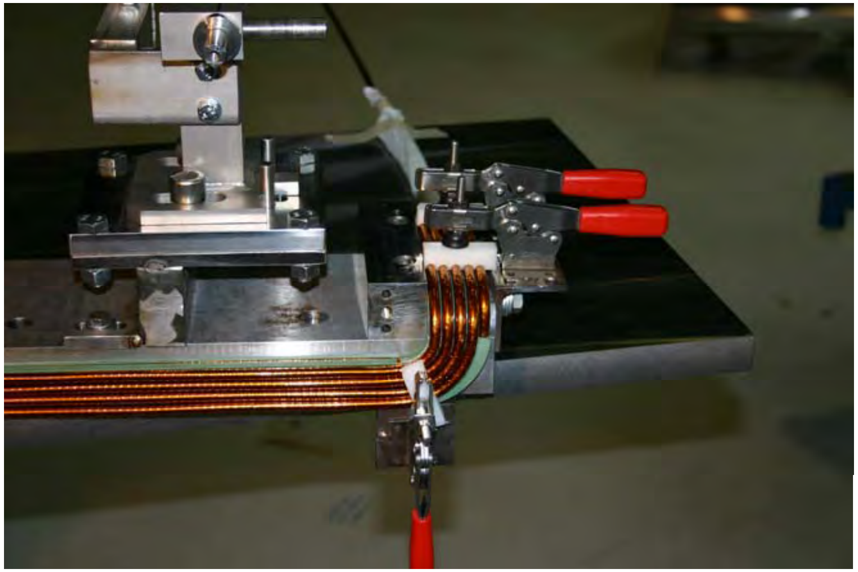
▲ reinforcement structure



▲coil end support drawing

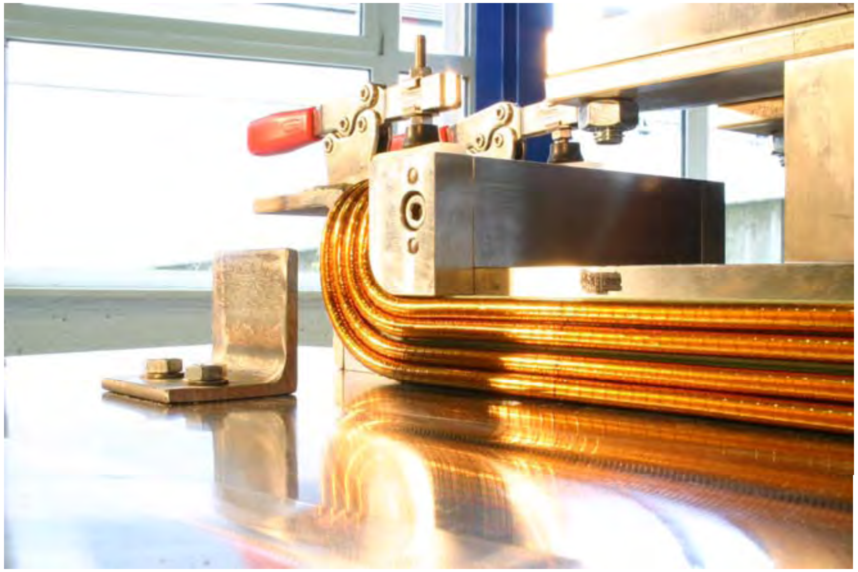
Main magnet components: First full size dipole

The coil ends during fabrication at the Babcock Noell GmbH

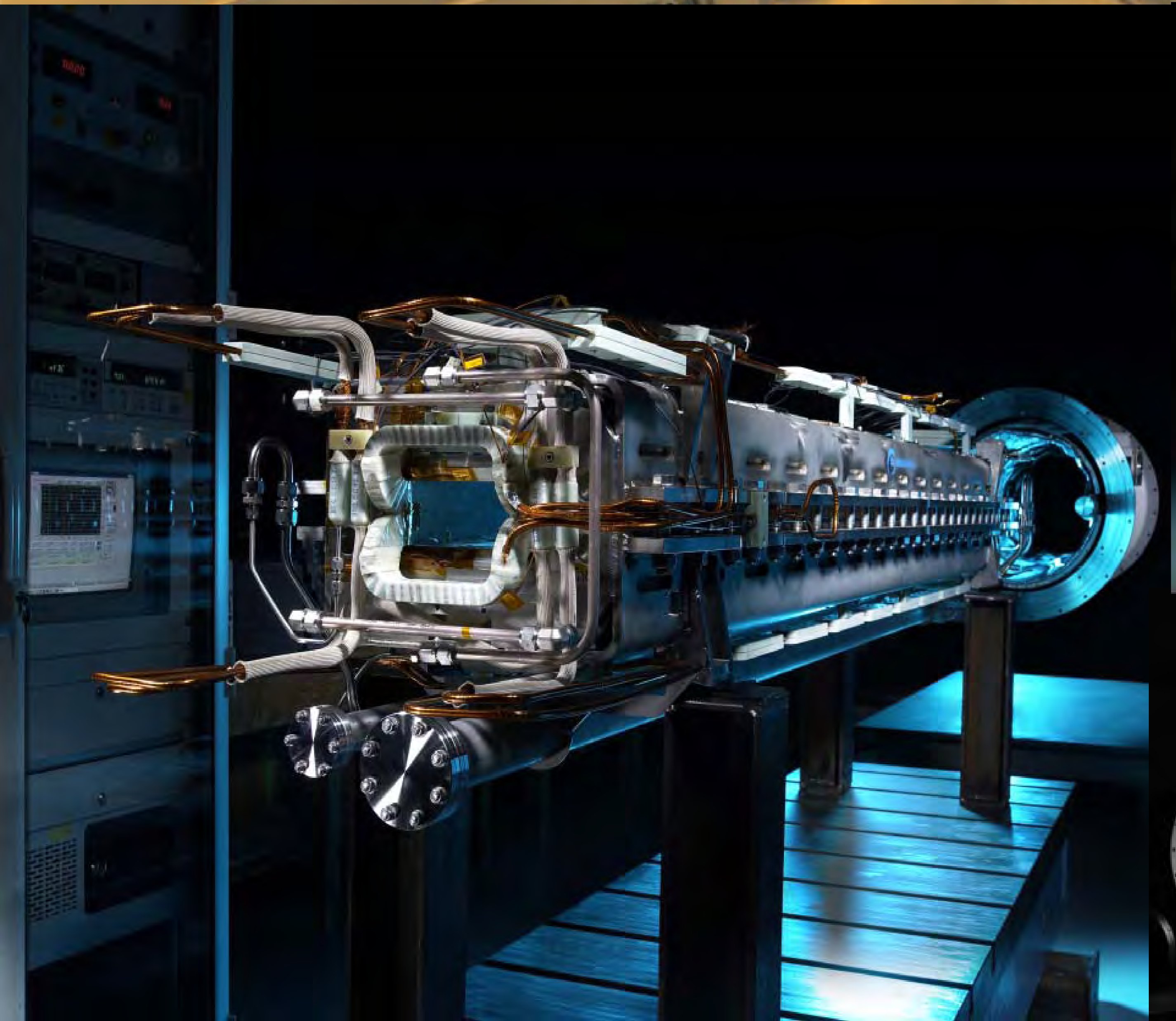


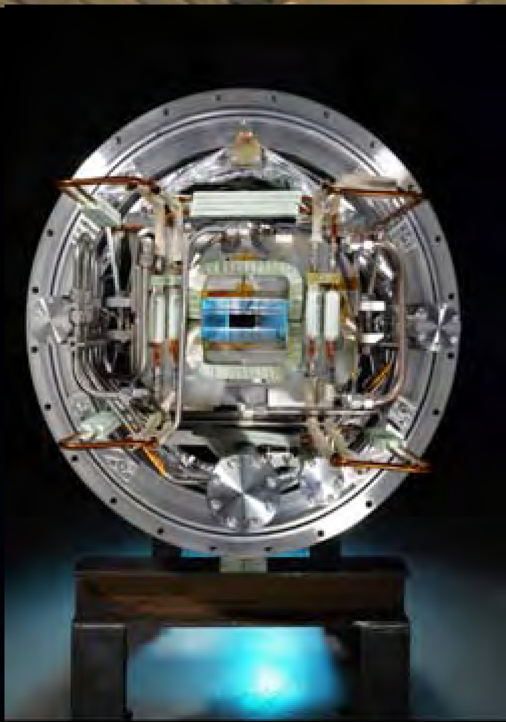
Winding process. The 4th turn of the inner layer is just being pre-bent to fit into the framework created by the innermost G11 pieces. Besides the coil in progress, the winding core the (pre-) bending tooling and various clamping elements are visible.

Precision of < 0.05 mm for Cable Position and Coil Shape
+
Enhancement of Winding Pack Rigidity



Main magnet components: First full size dipole





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Mechanical stability: Tests

Goal:

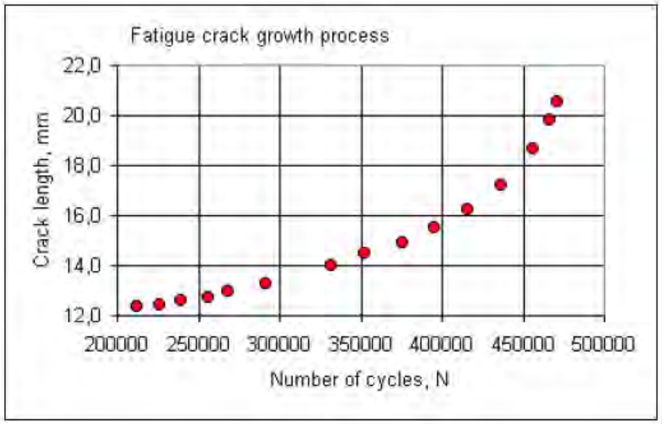
- Survival of the Cu-Ni- tube for at least 20 years of operation
- Stable coil package
- Technological optimization for production process of the cable

Tests of the mechanical properties of parts of cable and coil (at FZ Karlsruhe):

- fatigue crack growth rate of the CuNi material
- thermal expansion coefficients
- tensile strength at 4K and 300K
- leak test after mechanical load
- G11 material of the coil support structure modulus in different directions
- stress-strain curves before and after 2 million cycles
- leak test before and after 3 million cycles
- thermal expansion coefficients and leak test before and after thermal cycles
- stress-strain-curve after thermal cycling

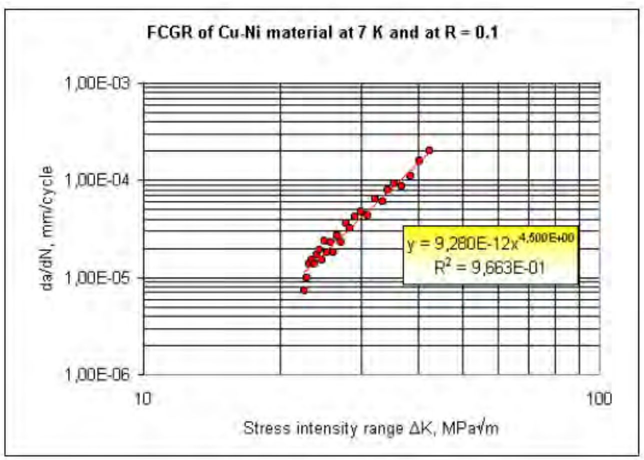
Mechanical stability: Crack growth in CuNi tube

Measurements of the fatigue crack growth rate on CuNi material at FZ Karlsruhe:



$$a_0 = d/2 = 0.1\,mm$$

$$a_f = \frac{1}{\pi}\left(\frac{KIC}{\Delta\sigma YS}\right)^2$$



Integration of Paris law:

$$N_f = \int_{a_0}^{a_f} \frac{1}{C\left(YS\Delta\sigma\sqrt{\pi a}\right)^m}\,da \approx 250 \cdot 10^6$$

➢ Under the given conditions the tube will sustain more than 250 million cycles.

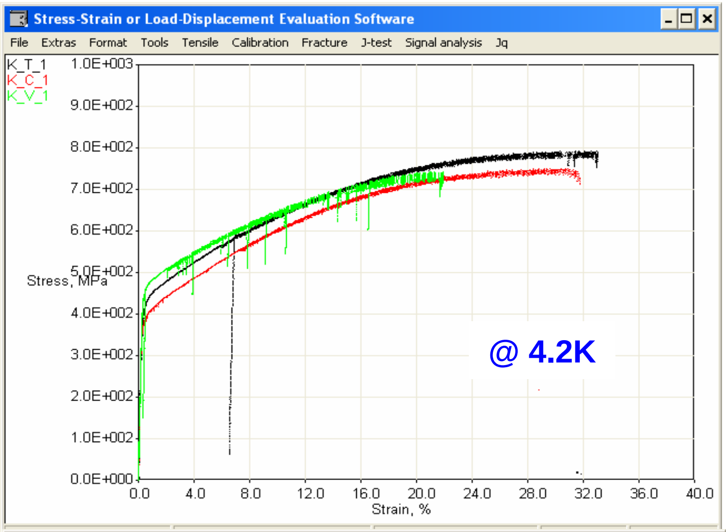
HELMHOLTZ GEMEINSCHAFT

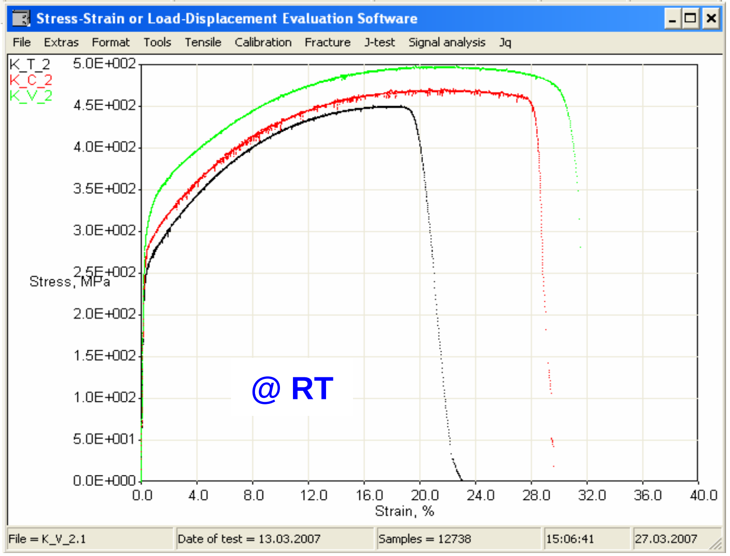
Mechanical Stability: CuNi tube – stress strain

stress-strain measurements on the CuNi tube for different treated samples:

K_t: annealed in Argon gas
K_c: after 100 rapidly thermal cycles (80 – 300K)
K_v: annealed + 100 thermal cycles

File	T K	E-Modulus GPa	Yield Strength MPa	Ultimate Tensile Strength MPa	Uniform Elongation %	Total Elongation %
K_t_1	4.2	163	414	792	32,1	33,1
K_t_2	RT	165	250	451	18,6	23,1
K_c_1	4.2	156	385	751	28,8	31,6
K_c_2	RT	154	274	471	21,8	29,9
K_v_1	4.2	161	379	743	21,0	21,9
K_v_2	RT	155	300	498	19,7	32,2

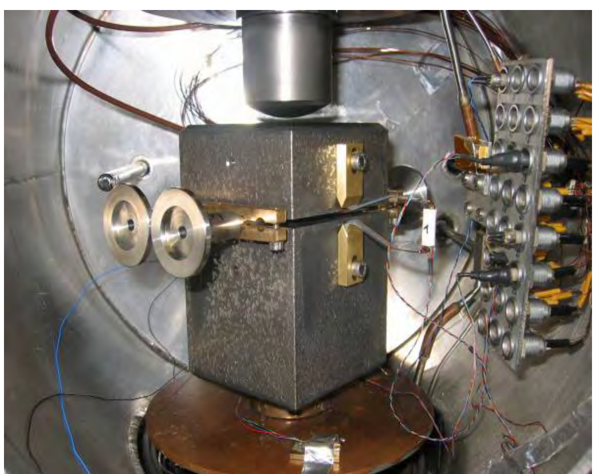




Mechanical Tests: CuNi tube – leak tests

Mechanical test of the CuNi tube

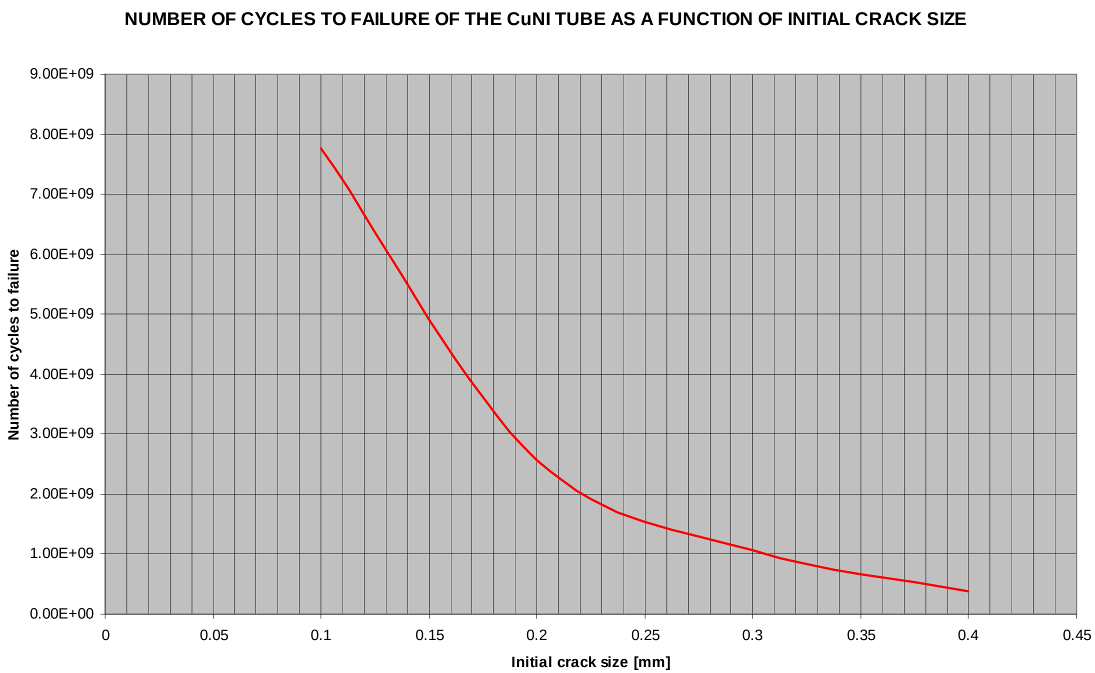
load	leak rate test for cycling with F_{max} = 800 N and T < 7 K	
	before cycling	after 2,6x10^{6} cycles
sample nr.	LR. mbarl/s	LR. mbarl/s
1	1,3x10^{-9}	1,2x10^{-9}
2	1,7x10^{-9}	2,1x10^{-9}
3	9,2x10^{-8}	2,8x10^{-9}
4	1,5x10^{-9}	1,5x10^{-9}
5	3,3x10^{-9}	6x10^{-9}
6	2,8x10^{-9}	3,2x10^{-9}

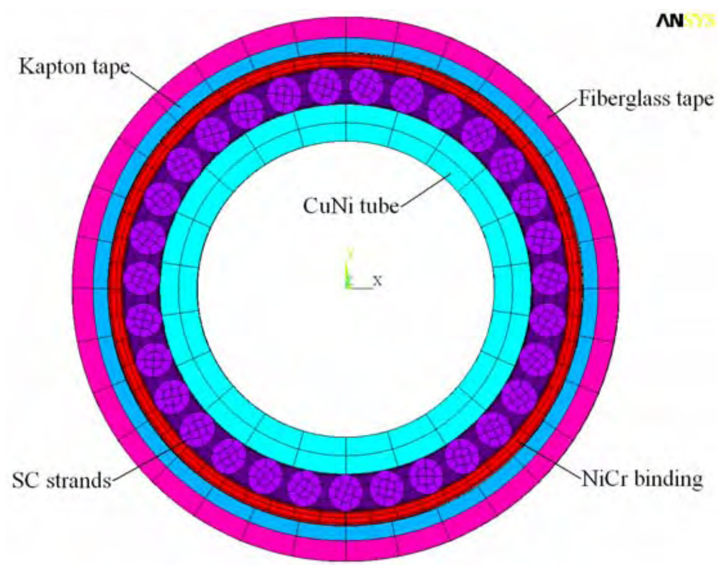


- **the mechanical cycling test had shown no impact on the leak rate for the CuNi tube of the SC-cable !**

Mechanics: Cable -- FEM Analysis

ANSYS calculations for fatigue behaviour and structural integrity:



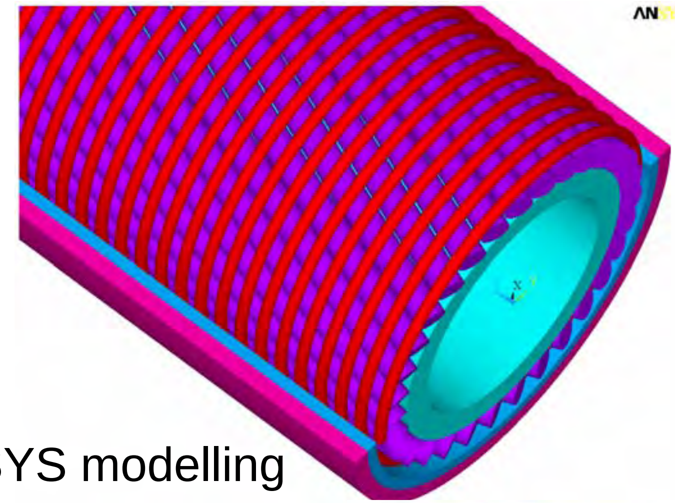


Detailed and physical accurate FEM modeling of the cable, also for further investigations

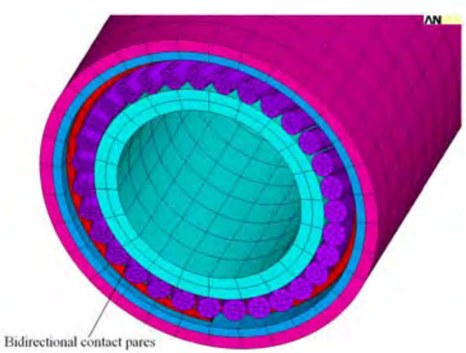
- no fatigue problems
- no crack propagation problem
- tube will survive 20 years of operation

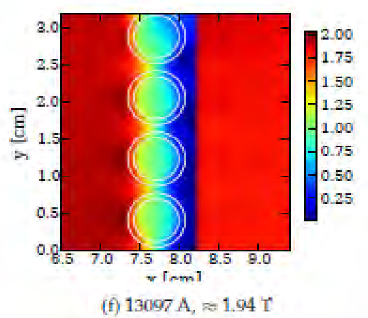
Mechanics: Cable - FEM Analysis

- study of structural integrety of the cable
- analysis of the thermo-mechanical properties
- impact of the load cycles on the coil pack > $2*10^8$ cycles

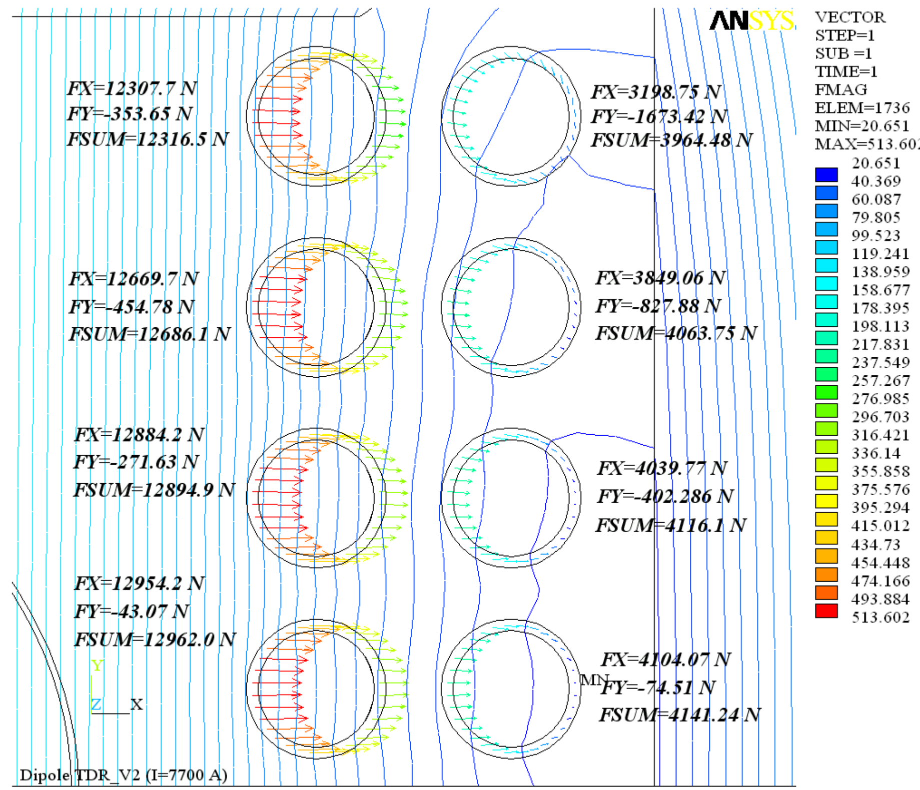


3D ANSYS modelling





field distribution **B**(x,y)



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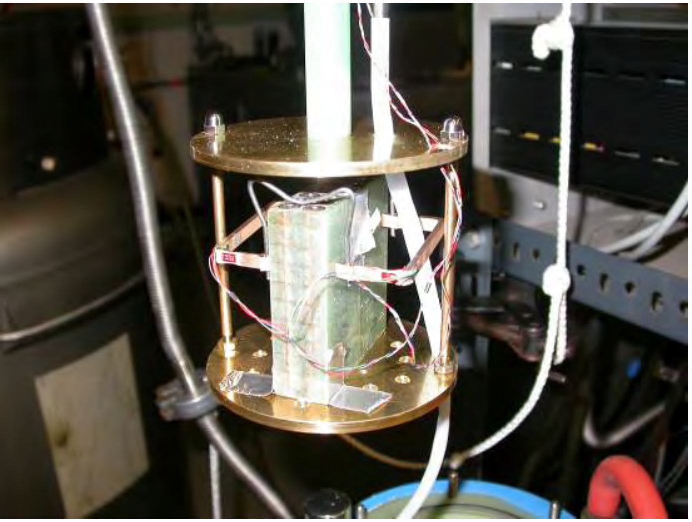
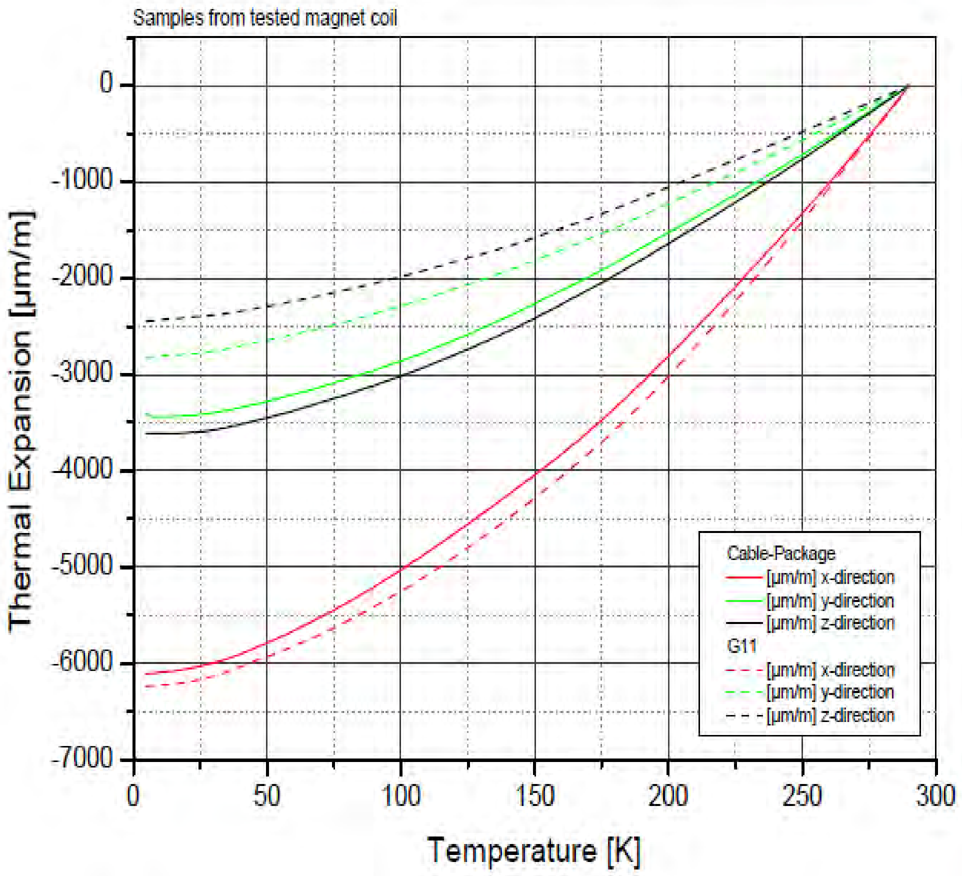
Coil package: thermal expansion

Test of the support structure material



▲ Thermal expansion measurements

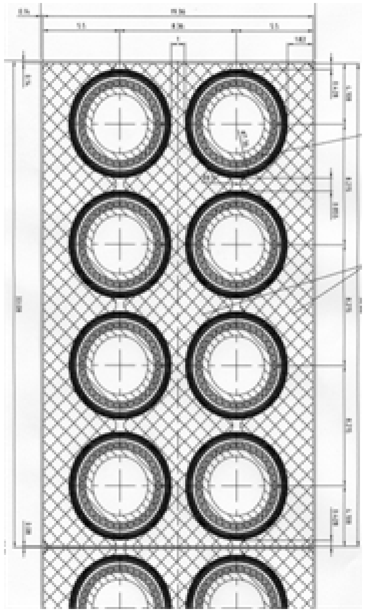


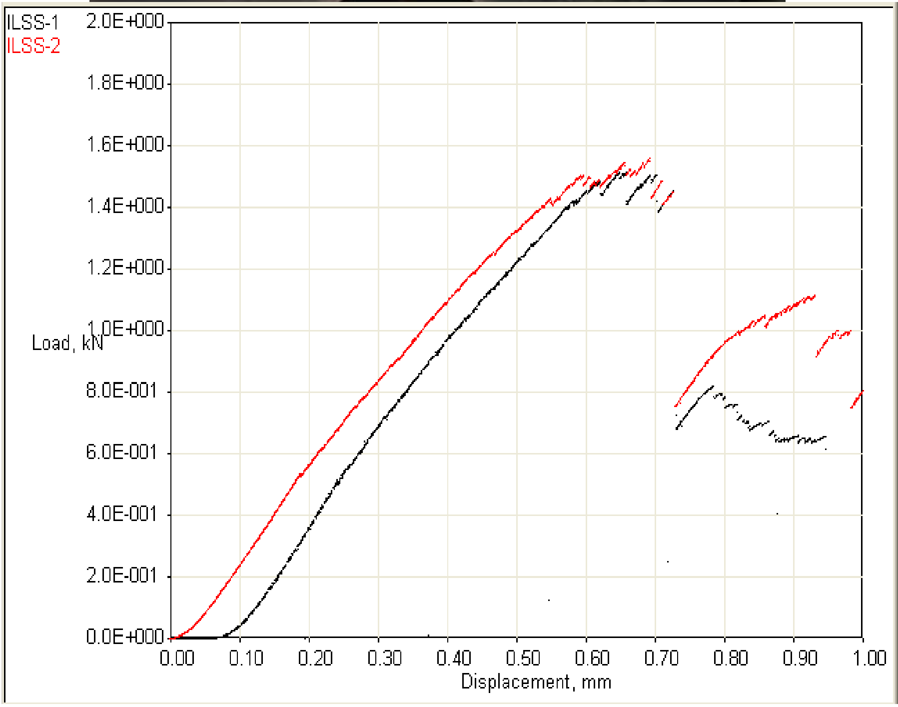
▲ Measurement result of the thermal contraction for the coil pack

Coil package tests: Interlamination shear

Coil support structure:

- reduction of point loads
- accurate positioning



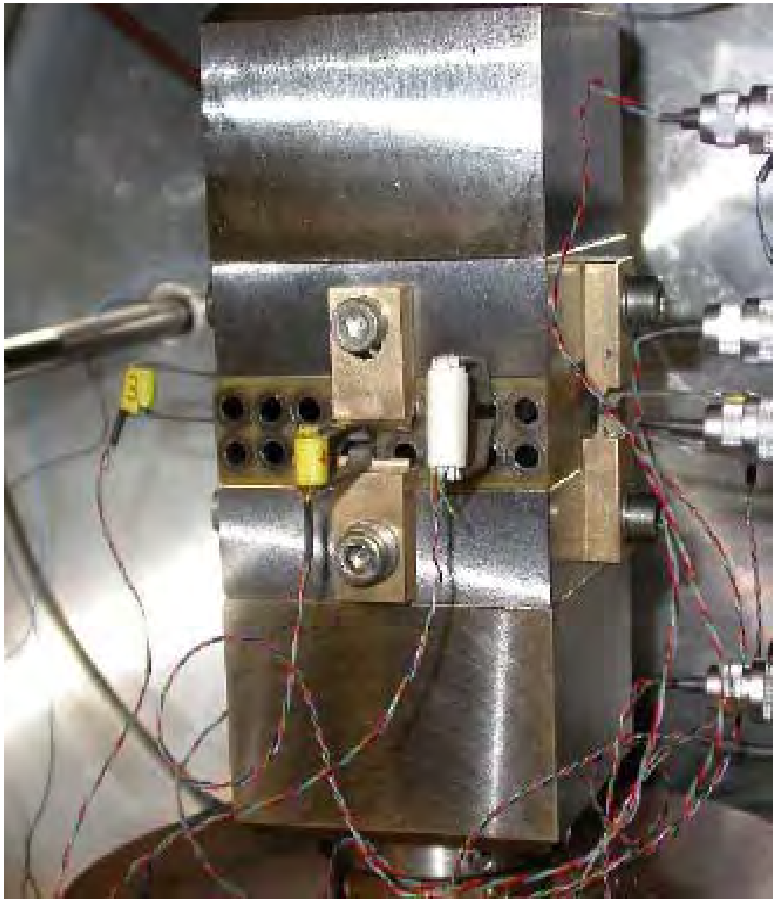


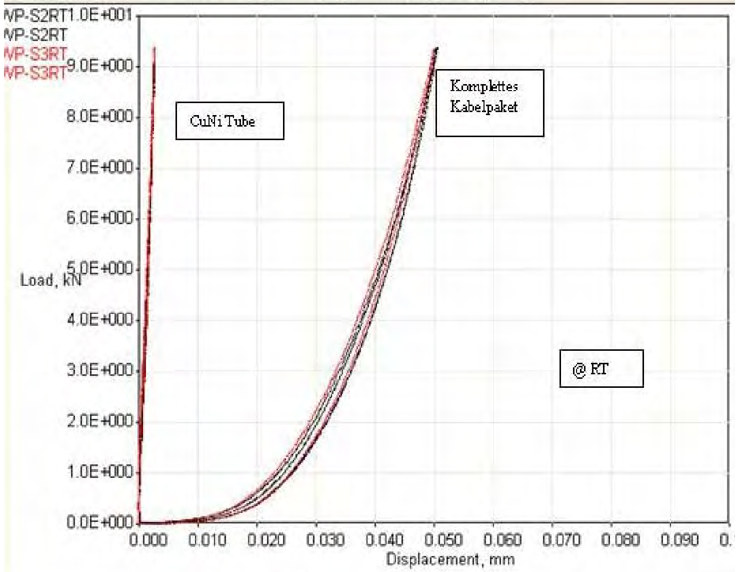
- **mechanical measurements of the coil support structures textured material G11**

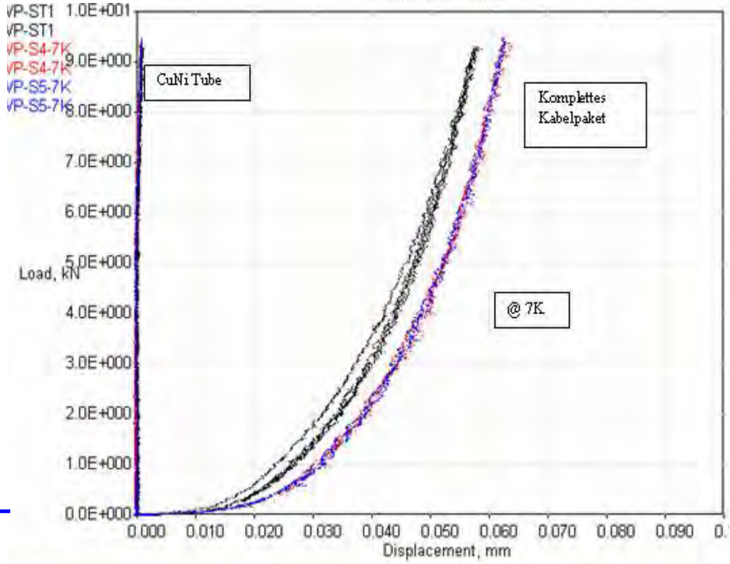
G11 Sample	T K	Stiffness N/mm	E Modul GPa	Fmax N	ILSS MPa
Sample 1	7	162,8	32,9	1,515	57,8
Sample 2	7	163,9	33,1	1,559	59,1

Coil package: stiffness @ RT, 7K

- **Measurement of the coil pack stiffness at room temperature and at 7 K.**

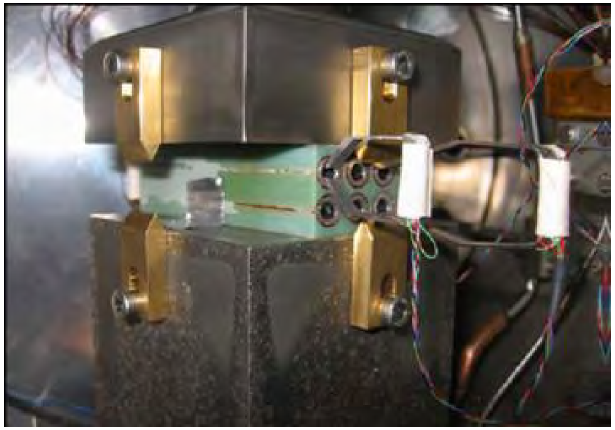


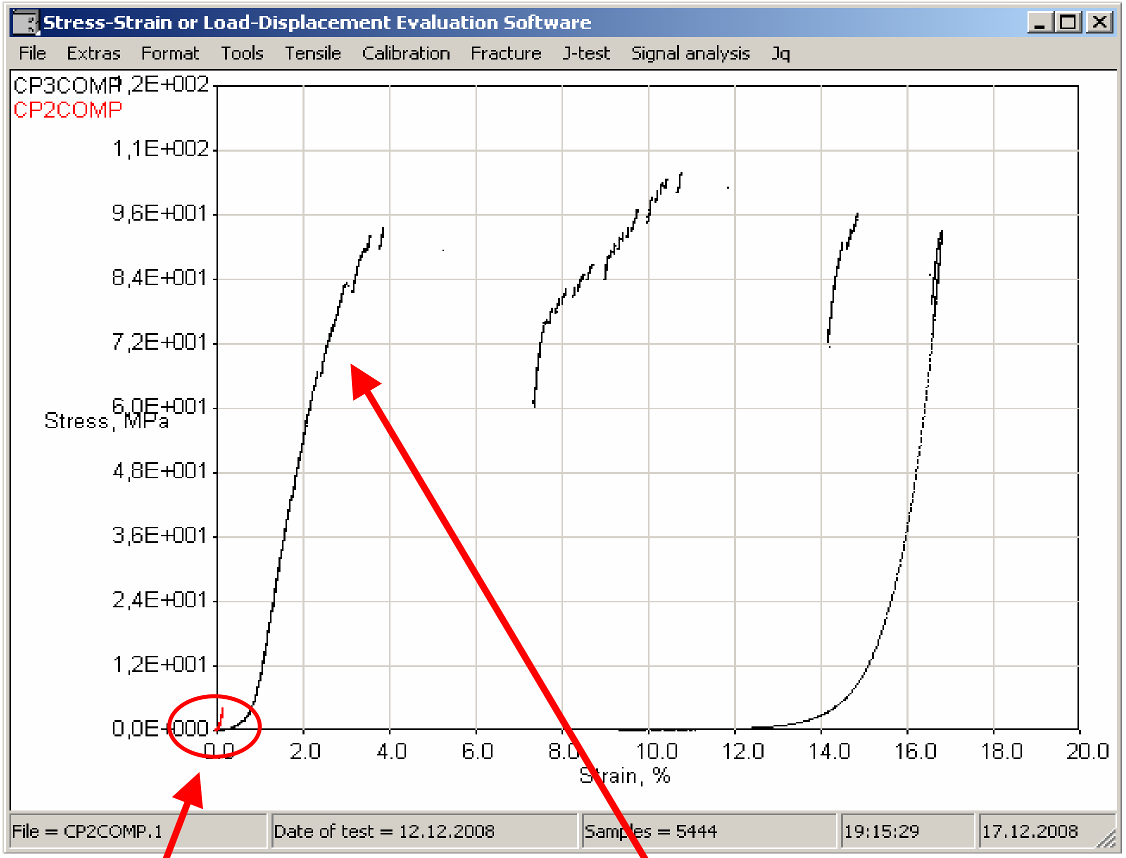




movement of the coil windings < 5 µm at B_{max} = 2 T

Coil package tests: cycling - destruction





destruction

load cycles

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    2. Test of the coil pack
    3. Integral test
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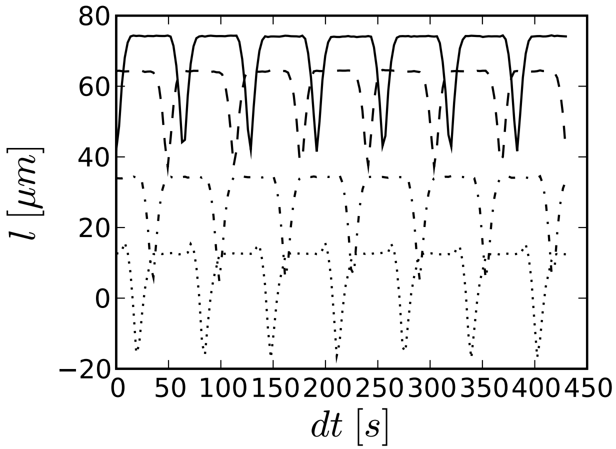
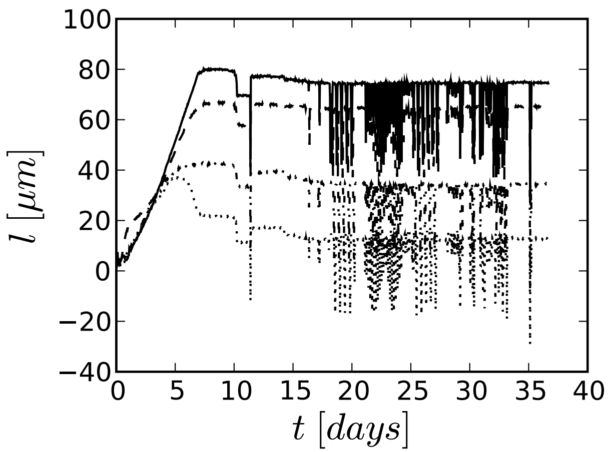
Mechanics: Integral test

The movement of the coil versus the yoke



▲ **while cycling the magnet**



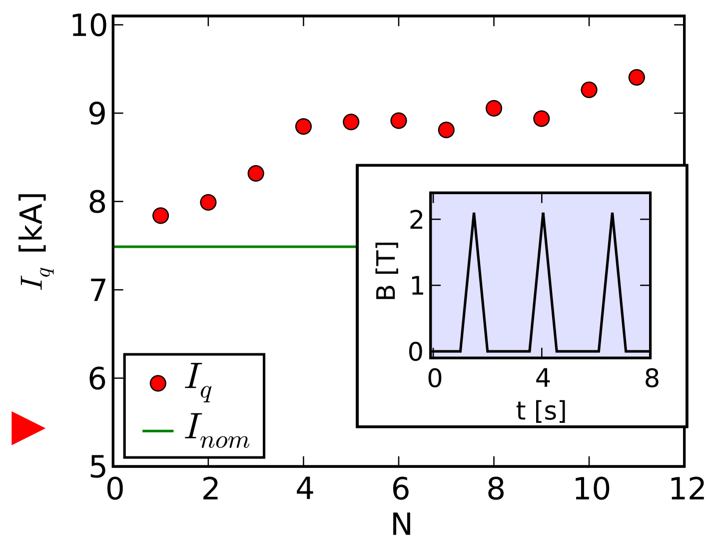
▲ **during cool down and cycling**

cycling tests

▼

inset on the right:
the strongest cycle mode of the magnet continuously tested during one week and up to now for $5*10^5$ cycles. ▼

DC Quench training ▶



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Magnetic steel

The choice of the electrical steel, best appropriate for the operation parameters of the main SIS100 magnets, is crucial for an optimal adjustment of the requirements to achieve high field quality, minimum AC losses in the yoke and a safe, reproducible production technology.

The search for this was made in both principle possible directions, i.e. analysing the intrinsic properties of the Si-donated Fe system as well as the available commercial steel. In the latter case also the impact of the technological and real application effects was discussed.

- **hysteresis losses:**

$$P_h = \frac{1}{2} k_h \, H_C \, B_{\max} \frac{\mathrm{d}B}{\mathrm{d}t}$$

- **eddy current losses**

$$W_h = c_h \, B_{\max}^2 = \underbrace{k_h \, H_C}_{c_h} \, B_{\max}^2$$

- **optimal B-H curve**
  (high permeability at low B, high M_s ~ 2.1 T)

characteristic parameters:

d thickness of steel sheet

H_c coercive force

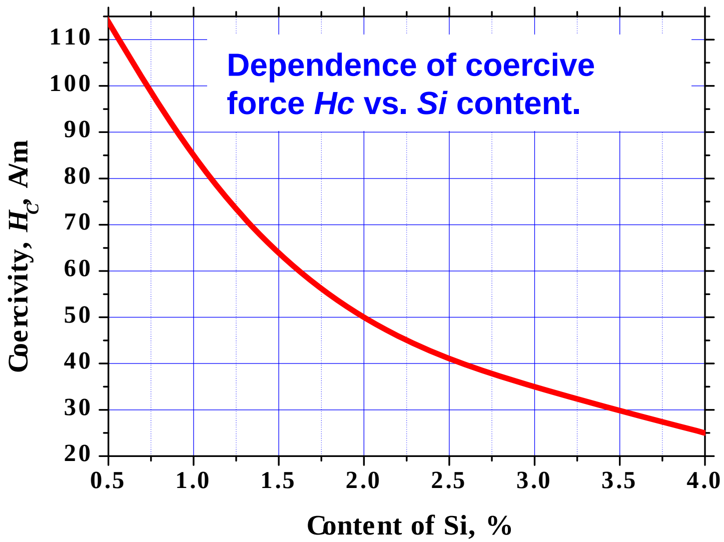
μ_{max} maximum permeability

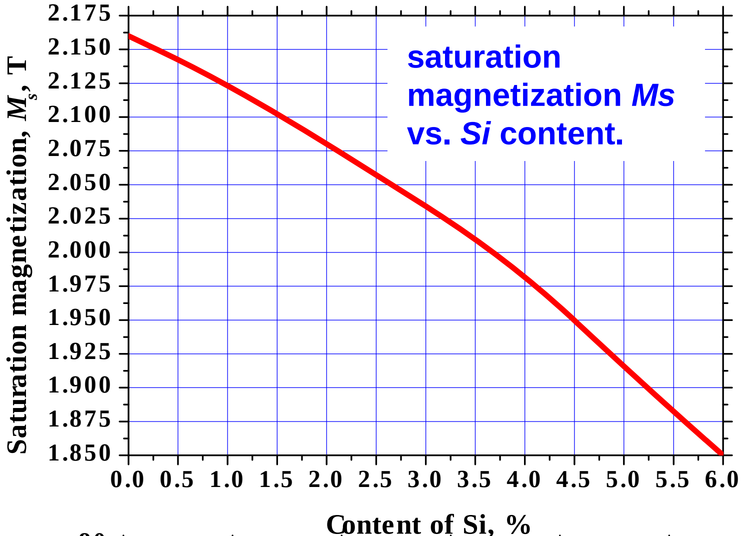
M_s magnetisation saturation

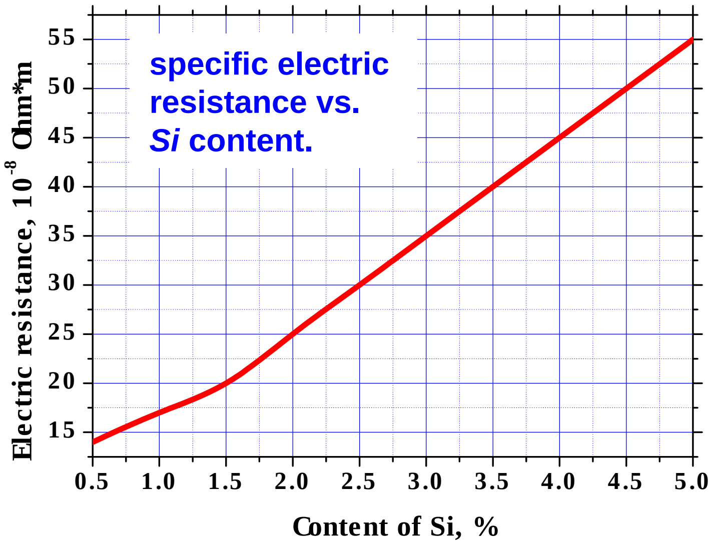
W_{hyst} specific hysteresis losses

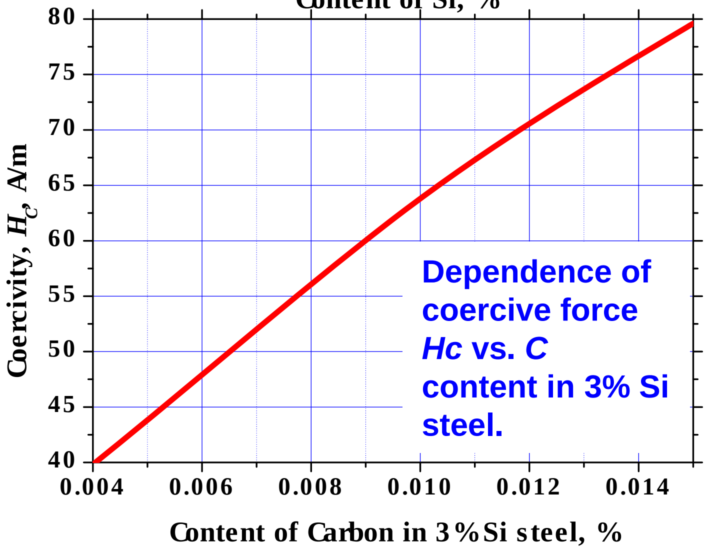
ρ electric resistivity

Magnetic steel: Si content

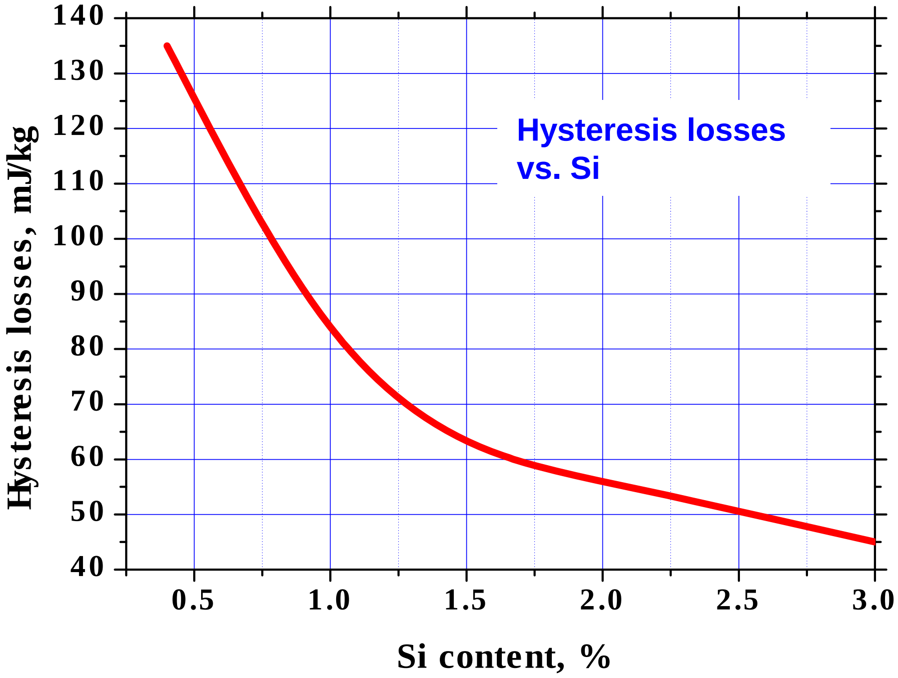


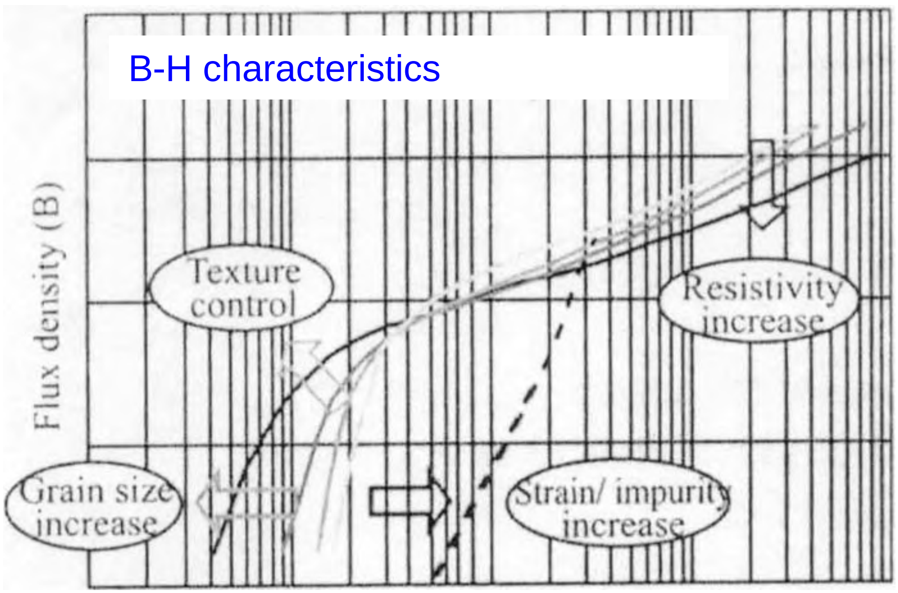






Magnetic steel: Influence of Si





Parameter	Approximation function	unit
Saturation magnetization	$M_s = 2.16\text{-}0.048 * Si$	T
Coercive force	$H_c = 120 – 30 * Si$	A/m
Resistivity	$\rho = 0.1 +0.12 * Si$	μΩm
Density	$d = 7.865 – 0.065 * Si$	kg/dm^3

◄ Dependence of the main parameters on Si content in %

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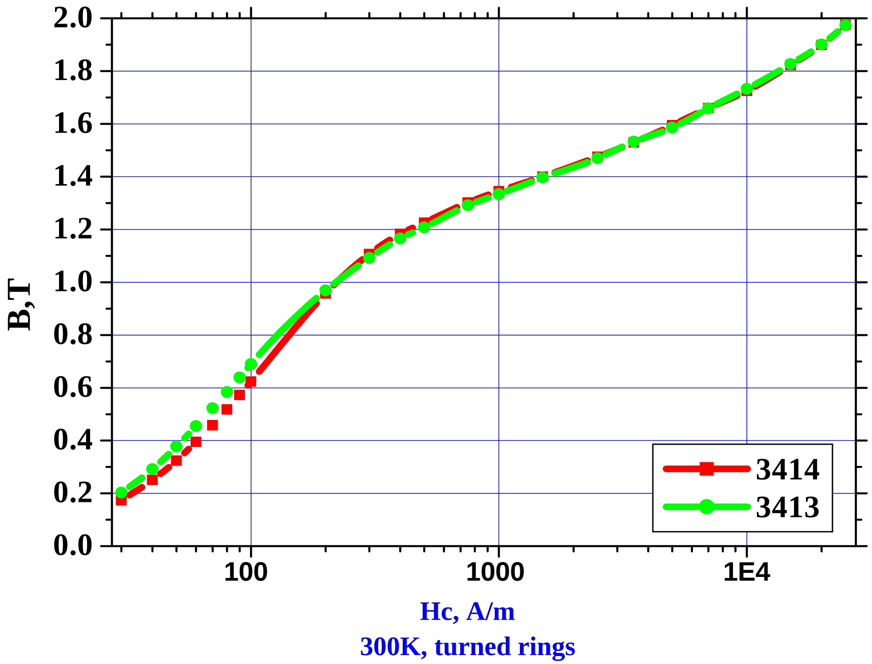
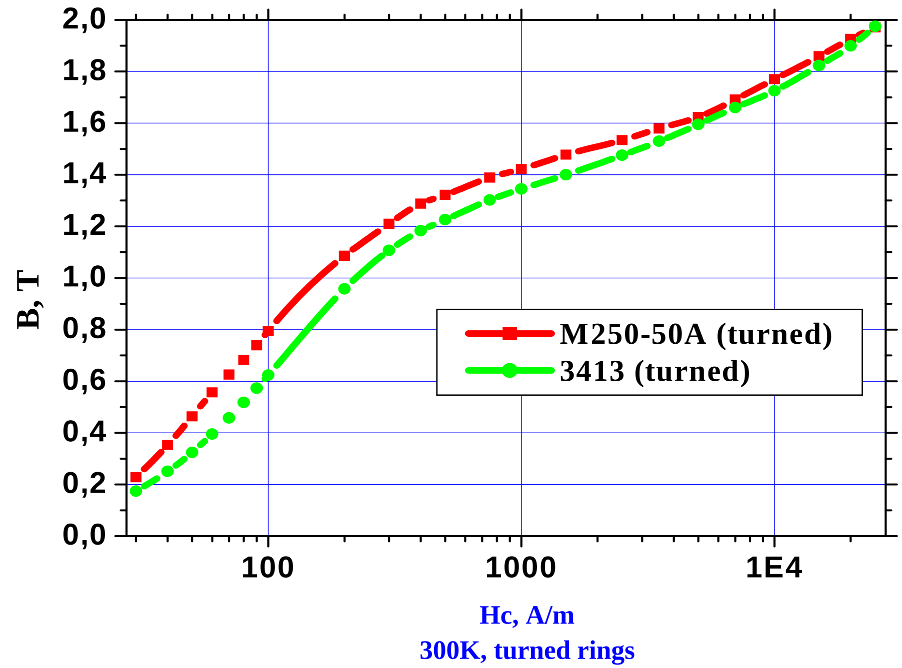
Magnetic steel: Comparison of Si steels

Measurements: Hc and B-H curves





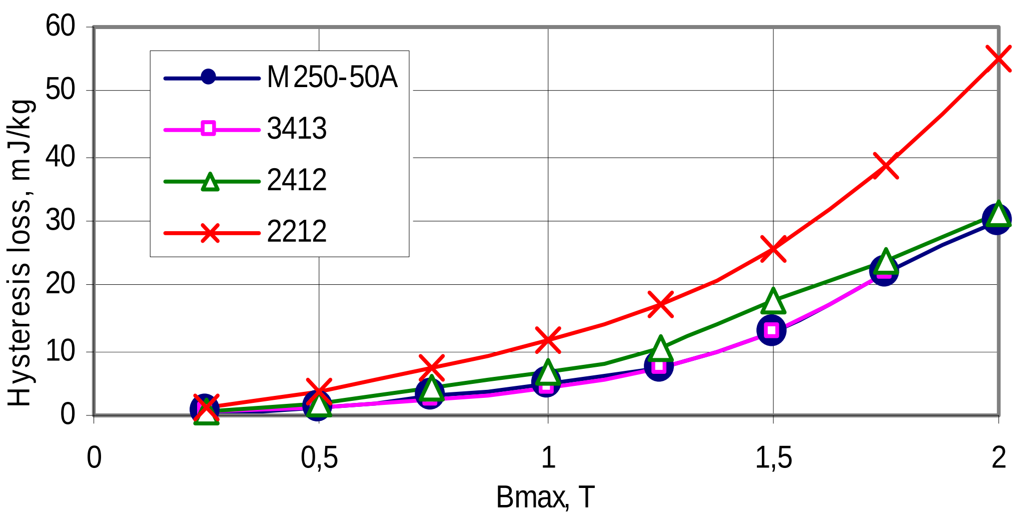
Hc [A / m]	300 K	77 K	4.2 K
ET3413	21.3	20.8	21
ET3414	20.3	19.5	19.5
Stabocor M250-50A	31.53	30.5	30.9

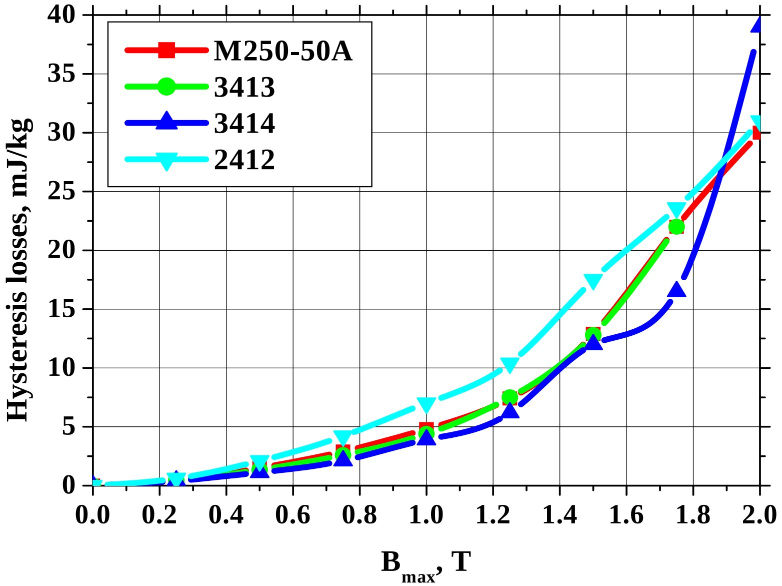
Hc [A / m]	Along rolling	Across rolling	Mixed
3413, B_{max} = 1.64 T	16	48	28
3414, B_{max} = 1.64 T	26	41	32
Stabocor M250-50A, B_{max} = 1.67 T	30	50	39

Magnetic steel: Comparison of Si steels

Measured hysteresis loss in unipolar cycles 0 - B_{max} at 4.2 K

Steel	ET3413	M250-50	M600-100	M700-100
Ms [T]	2.055	2.035	2.035	2.1
Hc [A/m]	20 – 30	30 – 33	30 – 33	35 - 40





250-50 3413 3414 2412

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Magnetic yoke: Selecting the steel

- There are large uncertainties in magnetic properties of steels and one should be very careful when optimising the 2D cross section:
  - measurement method (strip, rings, static (low frequencies) or 50 Hz);
  - anisotropy;
  - technology (production, stamping, turning);
  - operating temperature;
  - tension.

- An approved agreement about correct use is required by users of the B-H data and its recalculation for different cases.

- Accurate test measurements and detailed recalculations are required to obtain a high resolution magnetic field description.

Magnetic steel: Conclusion for steel selection

- Commerically available steels:
  - comparison: catalog and measurement data (GSI @ RT, IHEP @ RT, 4K)
- Hysteresis loss: isotropic and anisotropic comparable
  - thickness 0.5mm: M250-50 ↔ ET2414, ET3414
  - thickness 1 mm: M250-50 ↔ M600-100
- Steel development: costly, time consuming (not an option)
- Full size magnet: M700-100
- Natural choice : M250-50 or equivalent ET3414, ET2414
- Steel in series → requirements series production → e.g reliable material properties

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Magnetic Field Description: Circular multipoles

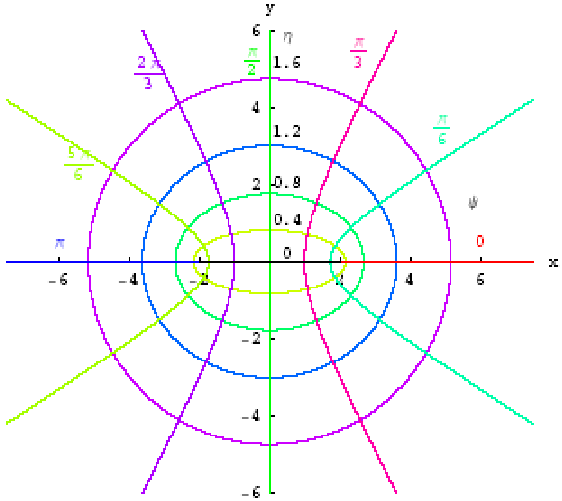
Standard field description:

$$\mathbf{B(z)} = B_y + iB_x = \sum_{m=0}^{\infty} \mathbf{C_m} \left(\frac{\mathbf{z}}{R_{ref}}\right)^m .$$

- convergent also outside R_{ref}
- satisfactory field description only for analytical data
- cofficients $\rightarrow$ FT on data on R_{ref} (FEM, measurement) $\rightarrow$ thus with artifacts

Magnetic Field Description: Elliptic multipoles

- allow to represent the field in the whole aperture of SIS 100 / NESR / CR
- allow to give a consise error propagation for rotating coil measurements in elliptic aperture
- allows to calculate circular multipoles within the ellipse



Plane elliptic coordinates η, ψ. Here the foci F, F' are at ± 2.

Field expansion:

$$\mathsf{w} = \eta + i\psi$$

$$\mathsf{B}(\mathsf{w}) = \frac{\mathsf{e}_0}{2} + \sum_{n=1}^{\infty} \mathsf{e}_n \frac{\cosh[n(\eta + i\psi)]}{\cosh(n\eta_0)}$$

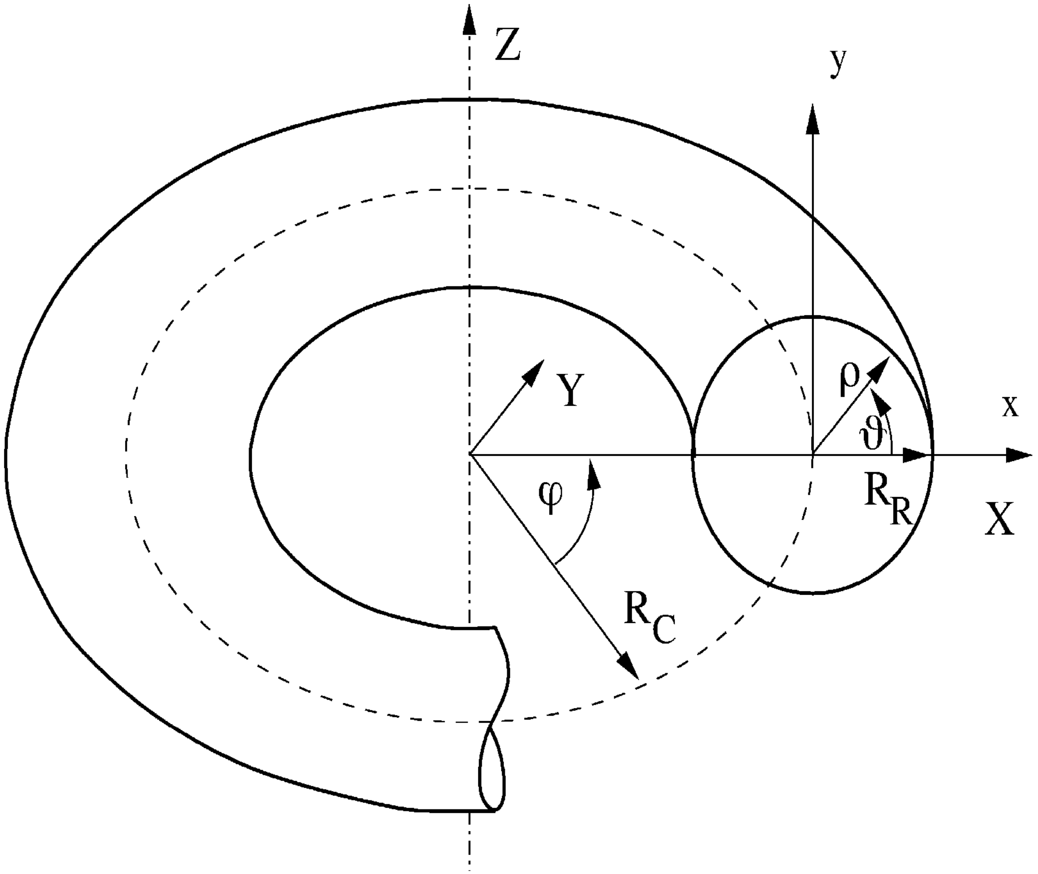
$\eta = const \ldots$ hyperbola $\qquad \psi = const \ldots$ ellipse

Expansion coefficients:

$$\mathsf{e}_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} \mathsf{B}\left(\mathsf{w} = e \cosh(\eta_0 + i\psi)\right) \times \cos(n\psi)\, d\psi.$$

Linear Analytic Transformation to Circular Ones

Magnetic Field Description: Toroidal multipoles



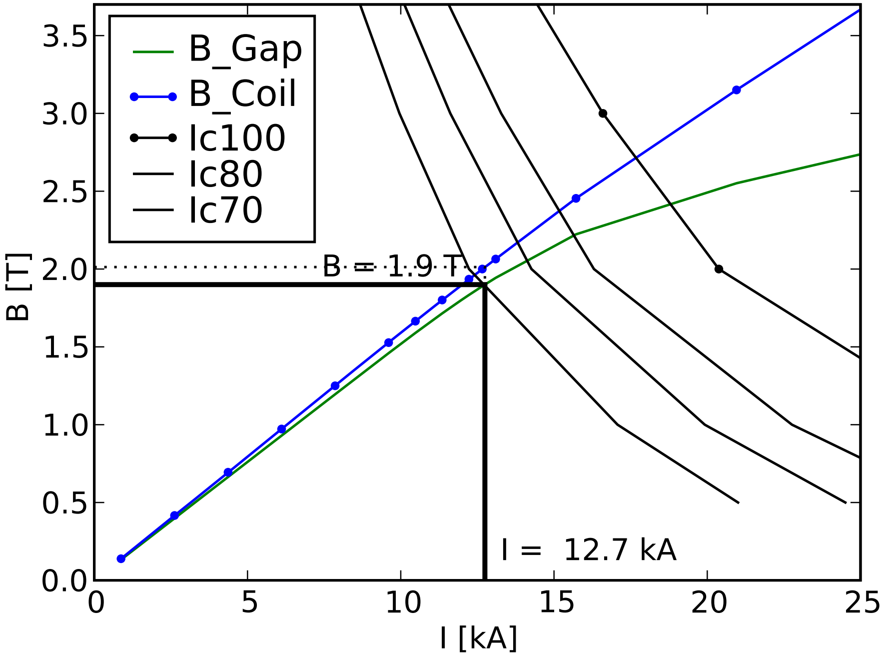
Local Toroidal Coordinates ρ, ϑ, ϕ

$X + iY = R_c\, h\, e^{i\,\phi}$

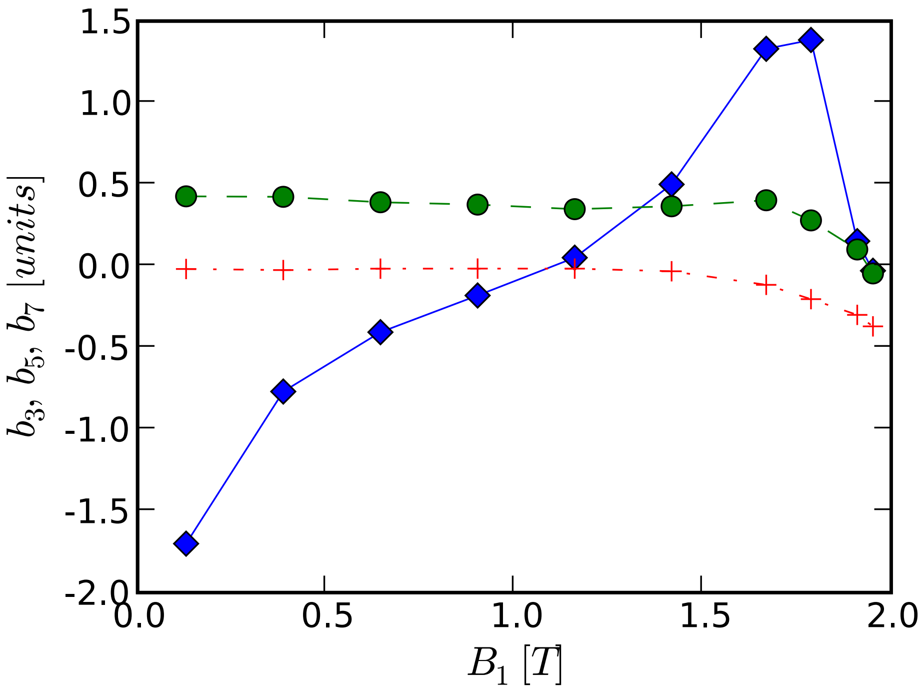
$h = 1 + \varepsilon\, \rho \sinh \vartheta$

$\boldsymbol{\varepsilon} = R_R / R_c << 1$

Magnetic Field: 2D calculations for the CSLD



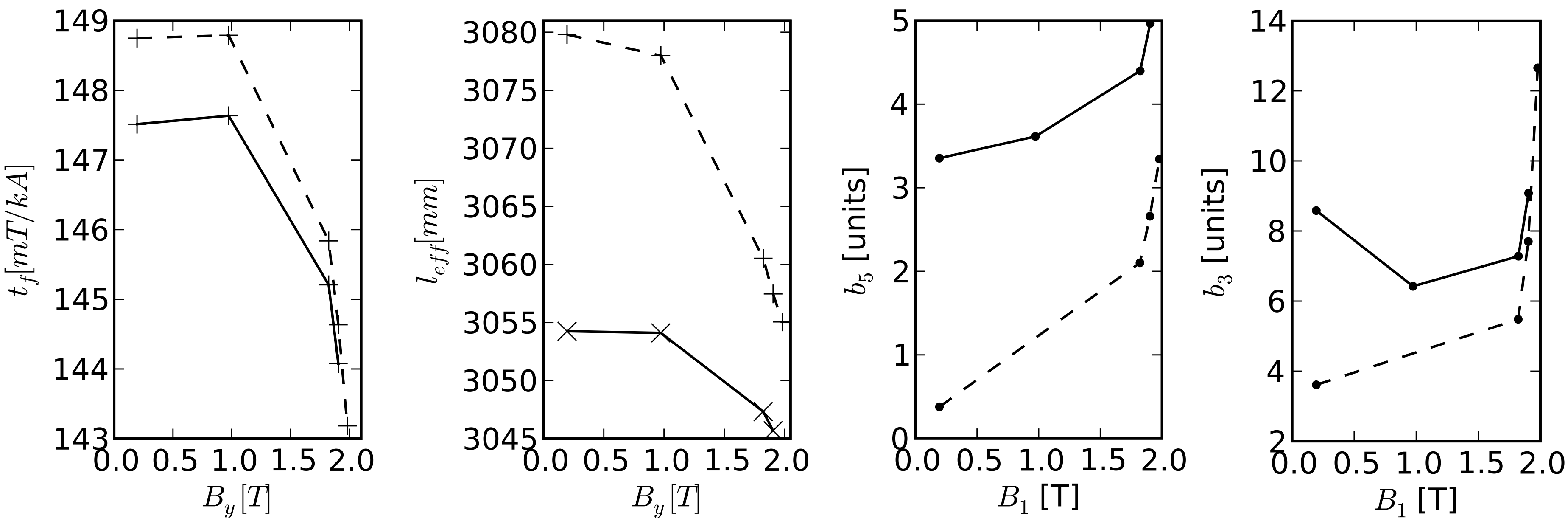
load line and margin



b3, b5, b7

Magnetic Field: 3D Field quality

Calculated characteristics of the CSLD



transfer function, centre

transfer function, length

b_3

b_5

Rogowsky profil

Rectangular ends

iron non linearity → 4 %

rectangular end → 1 %

Rogowsky end → 0.5 %

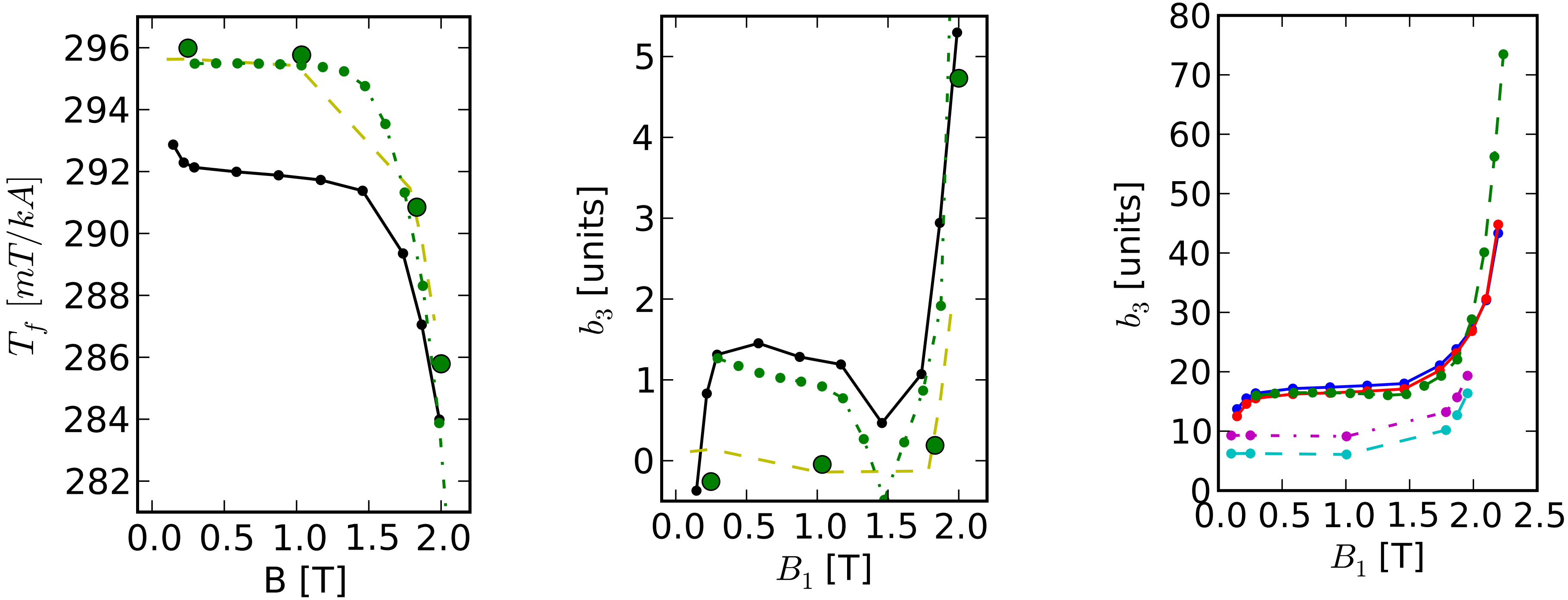
Calculation quality and measurement results

- Curved single layer dipole
  - not yet built
  - presented data → calculations

- First full size dipole
  - thoroughly measured → mole, mapper
  - multipoles calculated → distributed
    (e.g. beam dynamics calculations)

- Comparison: measurements ↔ calculations

Magnetic Field: S2LD-calculation & measurements

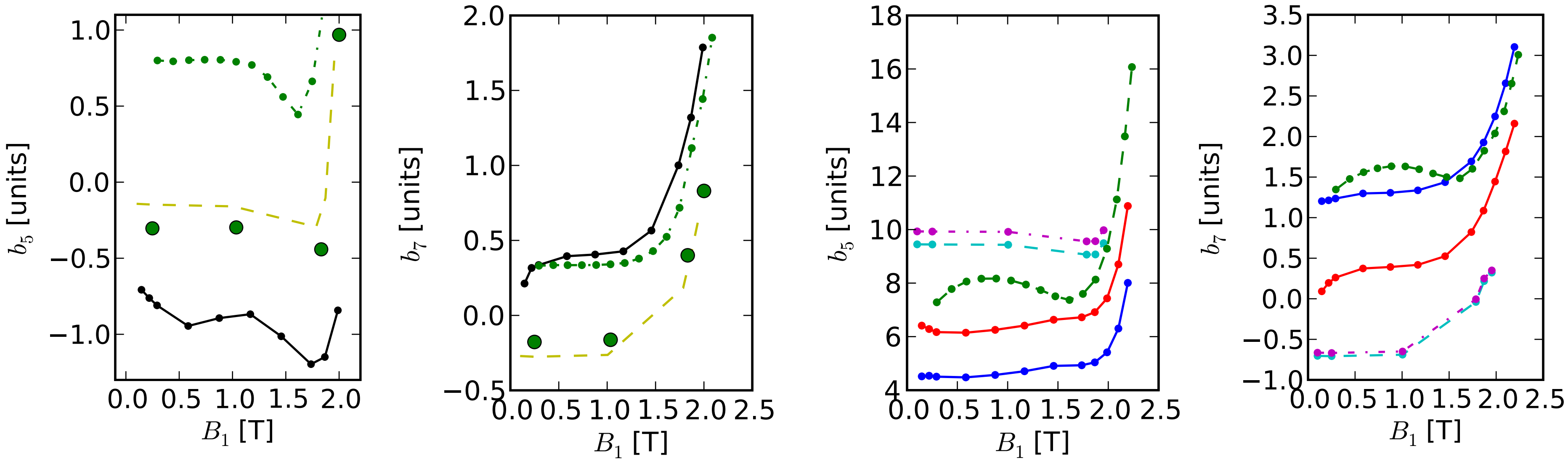


Centre: **black: measurement**
green: ANSYS (2 models)
yellow: TOSCA 3D

End CS: **blue : measurement**
cyan: TOSCA 3D
green: ANSYS

End NCS: **red : measurement**
magenta: TOSCA 3D
green: ANSYS

Magnetic Field: S2LD-calculation & measurements



Centre: **black: measurement**
green: ANSYS (2 models)
yellow: TOSCA 3D

End CS: **blue : measurement**
cyan: TOSCA 3D
green: ANSYS

End NCS: **red : measurement**
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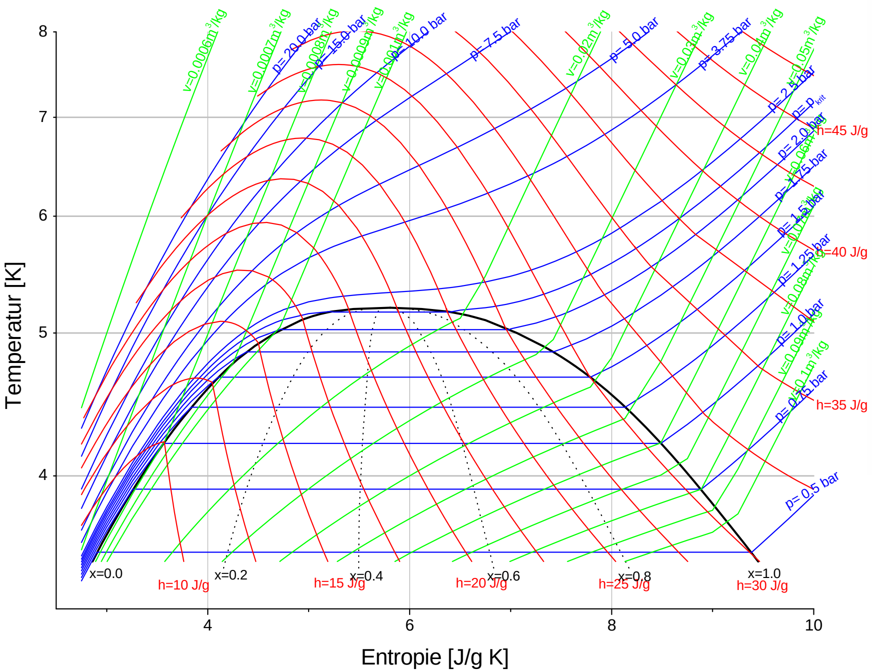
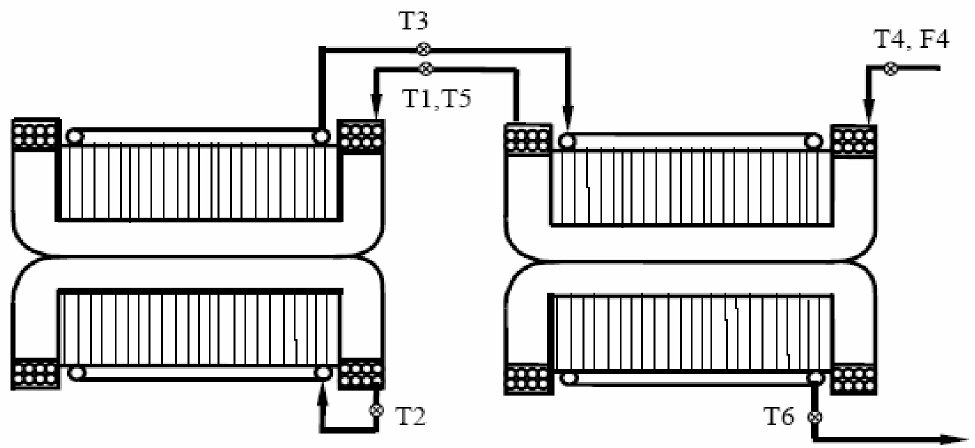
Losses & hydraulics: equivalent model

The hydraulic restistance of the coil limits the feasibility of the cycles!



T – S phase diagrams for He⁴

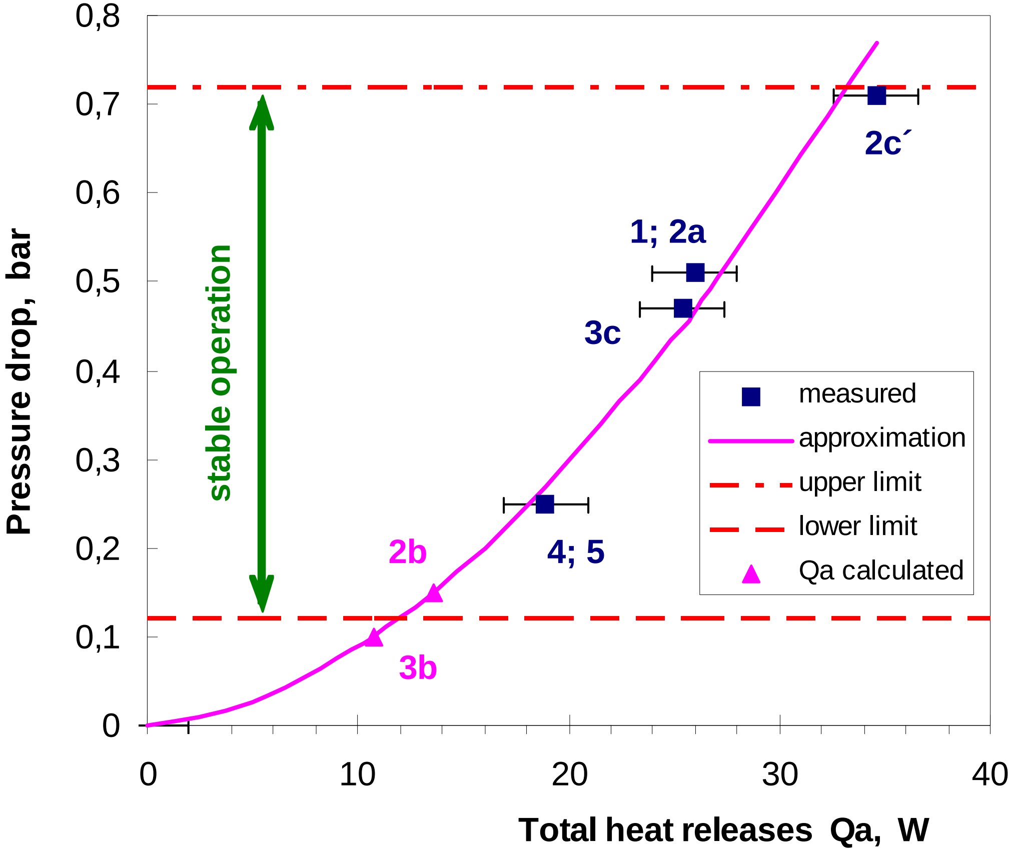


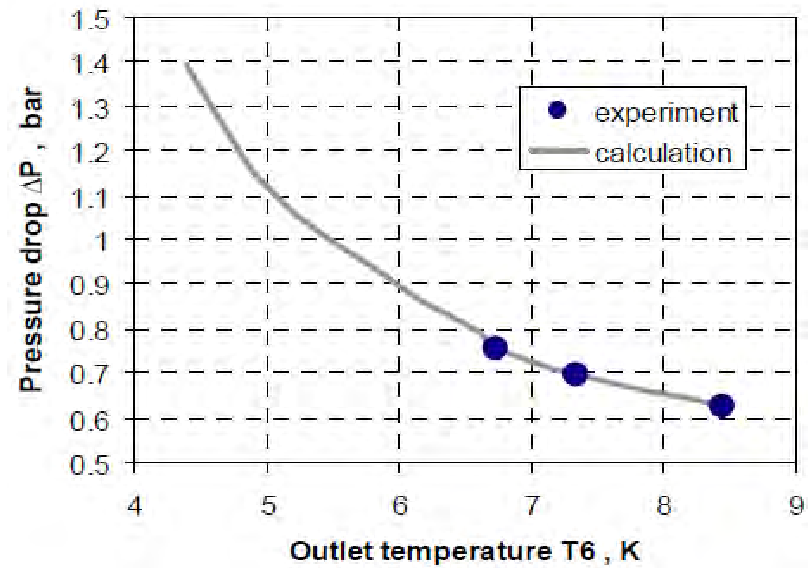
Cooling schema of <u>the equivalent dipole model</u>:

T1, T2,. . . T6 – temperature measurement points, F4 - measured helium flow. The two-phase helium flow enters the laminated yoke after cooling the two short coils all connected in series.

Losses & hydraulics: feasible cycles

The hydraulic restistance of the coil limits the feasible cycles!





Confirmed by the Measurements on the Full Size Straight Dipole (BNG)

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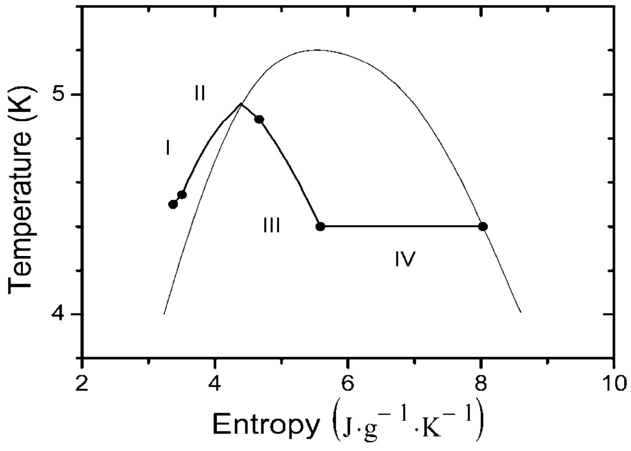
Losses & hydraulics: alternatives

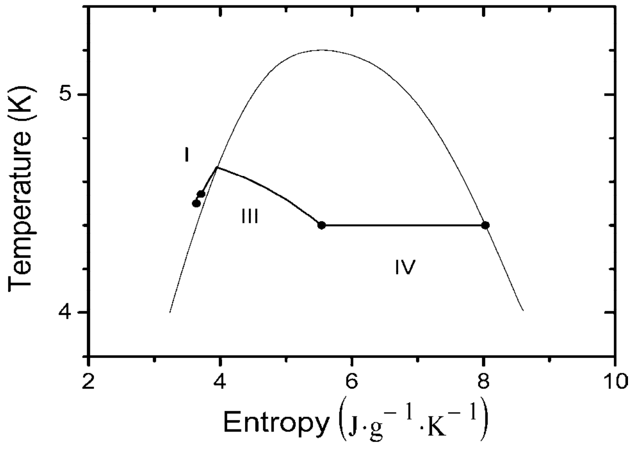
Parameter \ Version	straight	curved	C2LD-a	CSLD
Maximum field, T	2.11	1.9	1.9	1.9
Magnetic length, Tm	2.756	3.062	3.062	3.062
Turns per coil	**16**	**16**	**16**	**8**
Usable aperture, mm^2	130 · 60	115 · 60	115 · 60	140 · 60
Cables				
Number of strands	**31**	**31**	**38**	**23**
Outer diameter, mm	7.36	7.36	7.5	8.25
Cooling tube inner diameter, mm	**4**	**4**	**4.7**	**4.7**
Length of the cable in the coil, m	110	110	110	57
Bus bars length, m	37	39	39	39
Operating current	**7163**	**6500**	**6500**	**13000**
Critical current @ 2.1 T, 4.7 K	11900	11900	11900	19840
Wires				
Strand diameter, mm	**0.5**	**0.5**	**0,46**	**0.8**
Filament diameter, µm	2.5 - 4	2.5 - 4	2.5 - 4	3.5 - 4
Filament twist pitch, mm	4 – 5	4 – 5	4 - 5	5 - 8
loss and hydraulic				
Static heat flow, W	7	7	7	7
Heat load to bus bars, W	0.5	0.5	0.5	0.5
cycle 2c				
AC losses, W	36.3	35.4	35.4	35.7
Pressure drop, bar	1.10	1.15	0.604	0.389
T_{max} of *He* in the coil (for $x_6 \approx 1$) , K	4.94	4.95	4.78	4.64
triangular cycle [dB/dt = 4 T/s, $t_{cycle} = 2 \cdot B_{max} / (dB/dt)$]				
AC losses, W	75.1	74.0	74.0	74.6
Pressure drop, bar	**1.14**	**1.20**	**0.657**	**0.486**
T_{max} of *He* in the coil, K	5.08 at T_6=8K	5.10 at T_6=8K	4.86 at T_6=8K	4.72 at T_6=7K

- **The original Nuclotron cable had to be adapted for the main parameters of the SIS100 dipole.**
- **An optimisation of the sc wire characteristics is not sufficient.**
- **Even if the triangular cycle will not be requested, the design change was unavoidable due to the failure of cycle 2c !**
- **The optimal solution of the hydraulic boundary condition is the Curved Single Layer Dipole providing the continuously triangular cycle and a larger aperture for a stable and cryo cooled beam pipe with save margins.**

Losses & hydraulics: phase diagram



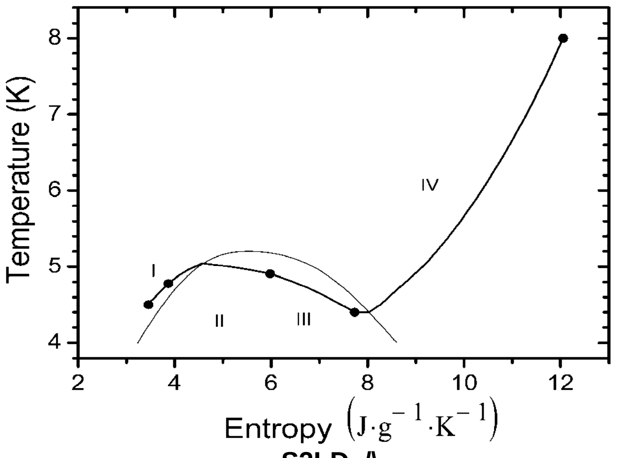
S2LD, 2c



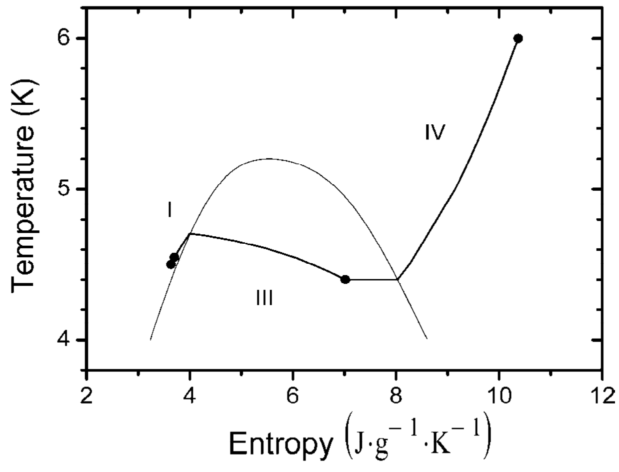
CSLD, 2c

The straight Two Layer Dipole (S2LD) and the Curved Single Layer Dipole (CSLD) at intensive ramping modes

new geometry of the cable ⇨ reducing hydraulic resistance ⇨ stable operating 2c and /\ cycle



S2LD, /



CSLD, /

T – S diagrams for the 2c and /\ operation

Helium flow trough the bus bars I, the coil II - III (inner - outher layer) and the iron yoke IV at cycles - 2c (left) and triangular (right)

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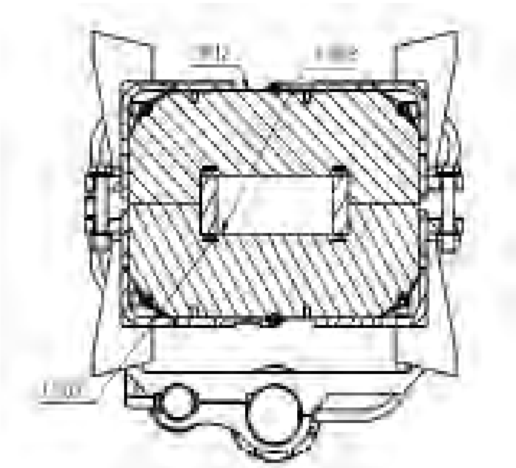
Losses & hydraulics: AC losses for BNG dipole

dB/dt $[T/s]$	B_{max} $[T]$	t_d $[s]$	f $[Hz]$	$\bar{P}$ $[W]$	T_{out} $[K]$	dP $[mbar]$	$TM08$ $[K]$	$TM09$ $[K]$	$TM11$ $[K]$	$TM12$ $[K]$
1	2.1	0	0.23	30	6	640	6.5	7.6	6.4	6.1
1.5	1.4	0	0.51	30	5.75	658	6.34	7.5	6.2	5.9
1.5	1.6	0	0.44	33	6.49	667	6.9	7.8	6.8	6.5
1.5	1.9	0	0.31	35	7.12	674	7.4	8.1	7.3	7.0
1.5	2.1	0	0.33	37	7.8	691	7.9	8.4	7.9	7.5
2	1.9	0	0.49	43	9.6	735	9.2	9.4	9.2	8.9
2.5	2.1	0.8	0.37	41	8.9	740	8.8	9.1	8.9	8.5
3	1.9	0.8	0.45	43	9.2	780	9.0	9.3	9.1	8.7
3.5	1.9	0.8	0.49	43	9	775	8.9	9.1	9.0	8.5
4	1.9	1.6	0.37	40	8.4	733	8.3	8.7	8.4	8.0
4	2.1	1.5	0.39	43	8.08	793	8.1	6.9	8.3	7.7

- **calorimetric method**
- **VI – method**



AC loss: estimates and measurements for the FAIR cycles

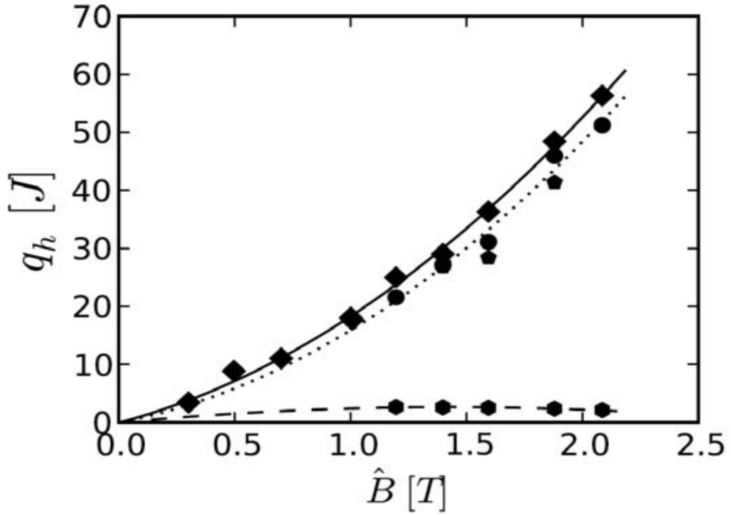
cycle	$B_{max}[T]$	$t_f[s]$	$f_c[Hz]$	$\bar{P}_t[W]$	$Q_t[J]$	$\bar{P}_v[W]$	$Q_v[J]$	$\bar{P}_m[W]$	$Q_m[J]$	$\bar{P}_{VI}[W]$	$\bar{P}_C[W]$
1	1.2	0.1	0.71	26.8	40.4	10.7	15.9	14.6	22.7		
2a	1.2	0.1	0.71	26.8	40.4	10.7	15.9	14.6	22.7	16.4	18.
2b	0.5	0.1	1.00	4.8	7.8	3.5	4.4	3.6	5.9		
2c	2.0	0.1	0.55	49.1	92.3	14.9	28.1	34.7	65.5		
3a	1.2	1.3	0.38	14.4	40.4	5.8	15.9	7.8	22.7	9	12.
3b	0.5	1.0	0.53	2.5	7.8	1.8	4.4	1.9	5.9		
3c	2.0	1.7	0.29	26.3	92.3	8.0	28.1	18.6	65.5	23	24.
4	2.0	0.1	0.20	17.9	92.3	5.4	28.1	12.6	65.5	15	17.
5	2.0	0.1	0.20	17.9	92.3	5.4	28.1	12.6	65.5		
Λ	2.1	0	1.05	96.7	101.7	29.4	30.9	69.6	73		

Losses & hydraulics: parametrisation

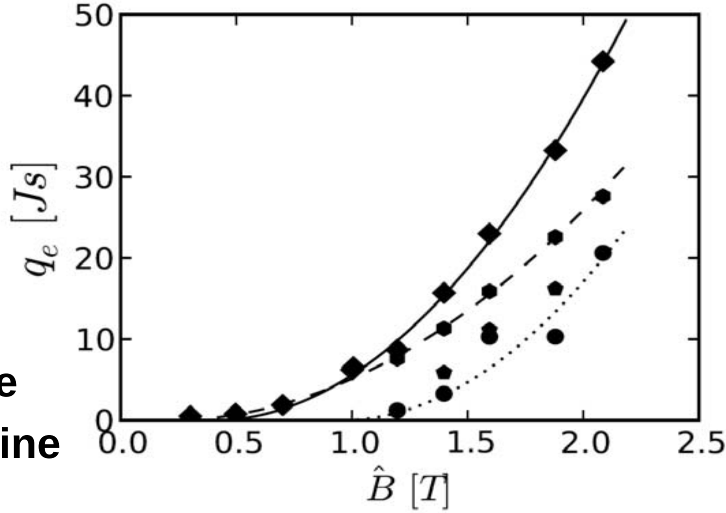
$$P_\wedge = q_h(B_{max})f + q_e(B_{max})f^2 \quad f = 1/\tau_\wedge$$

$$q_h = h_a B_{max} + h_b B_{max}^2 \qquad q_e = \begin{cases} 0 & B_{max} < B_{th} \\ e_a\,(B_{max} - B_{th})^2 & B_{max} \geq B_{th} \end{cases}$$

Component	h_a	h_b	e_a	B_{th}
Magnet	7.6	8.3	15.5	0.95
Vacuum Chamber	3.7	-1.3	8.0	0.2
Total	10.3	8.3	15.5	0.4



results agree well with calculations (ANSYS, extrapolation from short model magnet measurements)



magnet – doted line

VC – dashed line

magnet + VC – solid line

Losses & hydraulic: potential reduction

Extrapolation to the curved single layer dipole

for Λ cycle

- Cable → low loss wire ≈ 10 W↓
- Yoke steel → M700-100 (BNG) → M600-100 ≈ 12 W ↓
- Magnet ends → rectangular →

  eddy current reduction ≈ 7 W ↓
- Vacuum chamber cooling → conduction cooling ≈ 6 W ↓

- Total ≈ 35 W ↓

1. Introduction
2. Main magnet components
3. Mechanical stability of the coil windings
4. Magnetic steel
5. Magnetic field design
6. Losses and hydraulic limits
7. Vacuum chamber and temperature fields
8. Milestones towards a curved single layer dipole
9. Conclusion

Vacuum chamber: requirements

cryopump functionality for the operation with high intensity intermediate charge state heavy ions:

1. cold surface $\longrightarrow$ cryogenic adsoption pump 10^{-12} *mbar* for 20 years, infinitely refreshable
2. ramped field $\longrightarrow$ eddy currents in conducting materials $\longrightarrow$ AC losses $\longrightarrow$ field distortion
   minimise by geometry and material selection
3. mechanical stable $\longrightarrow$ cryostat vacuum break (1 bara)
4. beam image current
5. shield beam (skin depth)

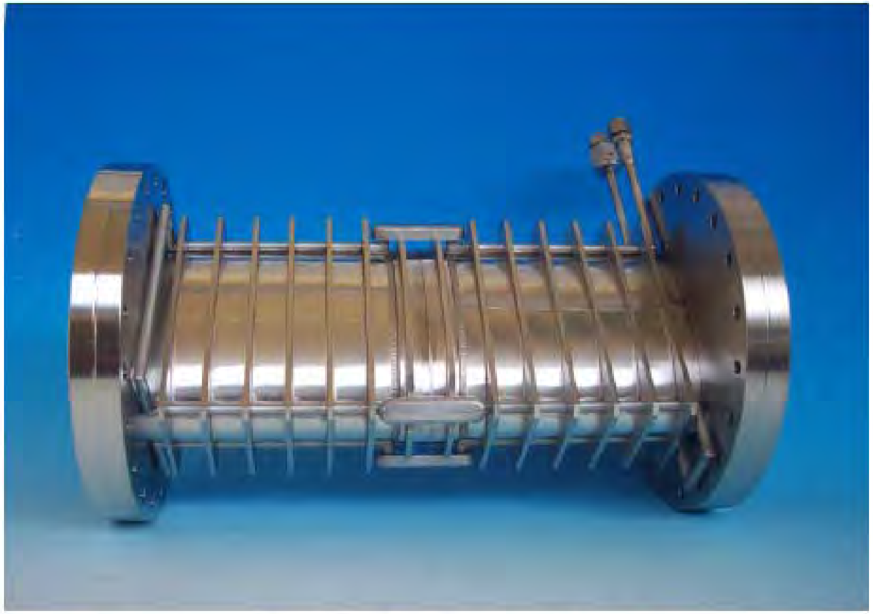
The vacuum chamber design was based on S. Wilfert, K. Keutel *SIS 100 Kryogene Vacuumkammern* Otto-von-Guericke-Universität, 2004.

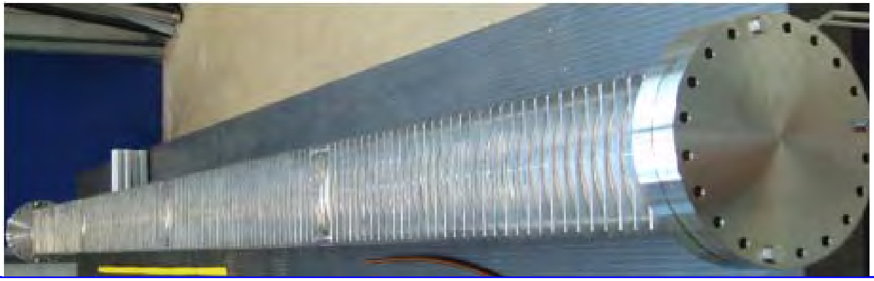
Vacuum chamber: current design

- cooling $\longrightarrow$ separate tubes
- mechanis $\longrightarrow$ ribs
- field distortion $\longrightarrow$ stainless steel (Böhler Uddenholm)

but

- eddy current loops (ribs + cooling tubes)?
- final temperature?
- contact to magnet / coil?





short model and full size test chamber of the BNG dipole with mechanical stabilizing rips and additional cooling tubes

Vacuum chamber: measured temperatures

The temperature of the vacuum chamber for the different FAIR cycles at He flow 0.17 g/s

	B_{min} [T]	B_{max} [T]	dB/dt [T/s]	t_f [s]	t_p [s]	t_c [s]	T_{in} [K]	T_{out} [K]
2a	0.24	1.2	4.0	0.1	0.70	1.408	5.12	15.46
3a	0.24	1.2	4.0	1.3	0.70	2.608	5.09	10.03
3c	0.24	2.0	4.0	1.7	0.68	3.408	5.14	12.66
4	0.24	2.0	4.0	0.1	3.88	5.008	5.09	9.84
2b	0.24	2.0	4.0	0.1	1.	1.4	magnet can not	
2c	0.24	2.0	4.0	0.1	0.7	1.82	be operated	
$\wedge$	0	2.0	4.0	0	0	1	in these cycles	

The existing design for the vacuum chamber was tested at the first full size dipol:

- fulfills the requirements for cryo cooling the inner surface of the beam pipe below 15 K and is mechanically stable,

but:

- significant losses and additional cooling circuit
- magnetic field distortions

Alternatives ?

Vacuum chamber: temperature fields

Calculation Procedure

- vacuum chamber in defined contact with yoke and coil
- transient analysis steady state after 60 cycles
- used steady state mode for thermal calculations
- Different options studied

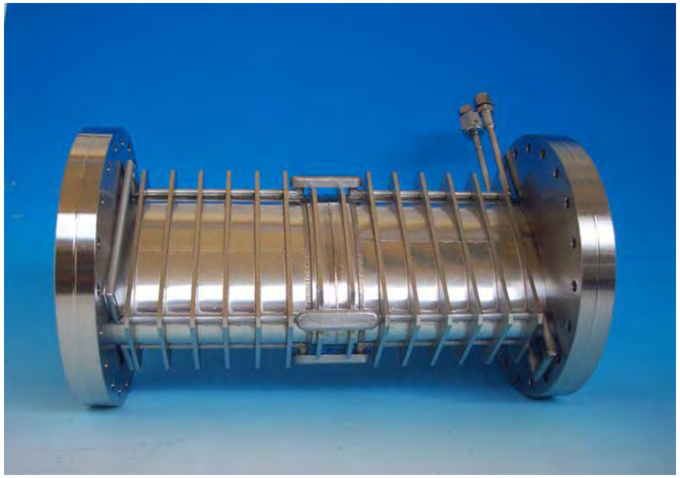
  a) design as built by BNG

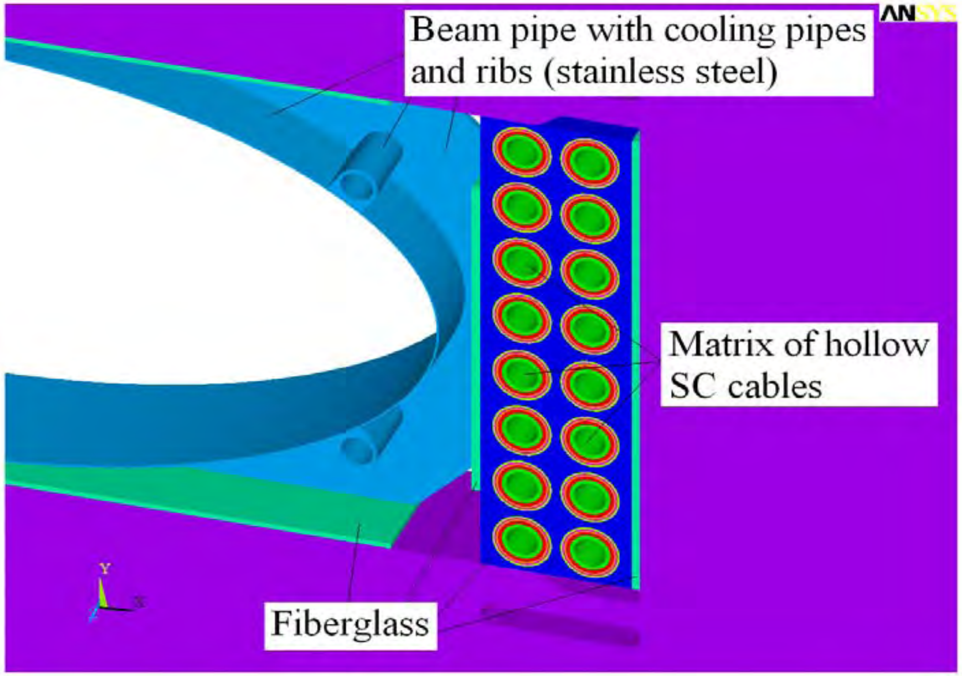
  b) without coolant in the tubes

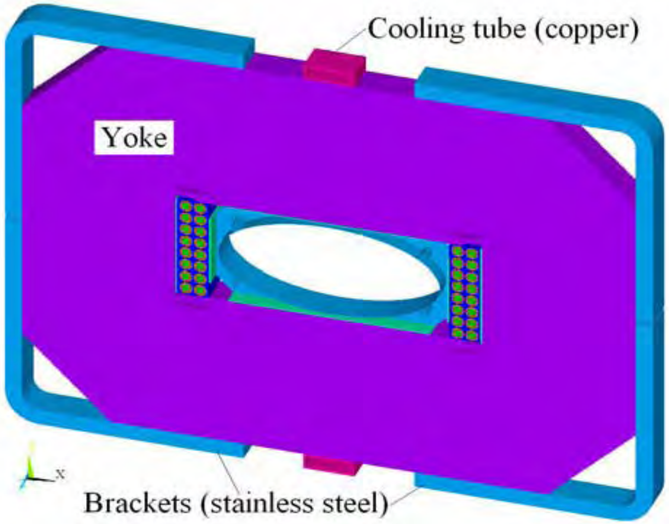
  c) without ribs
- calculating the magnetic field within the vacuum chamber

Vacuum chamber: temperature fields

- central part -- periodic "quasi 2D" model
- end part – 3D "short end model "
- transient analysis: steady state after 60 cycles
- Additional 25 W heat load (= 1/3 of the magnet)

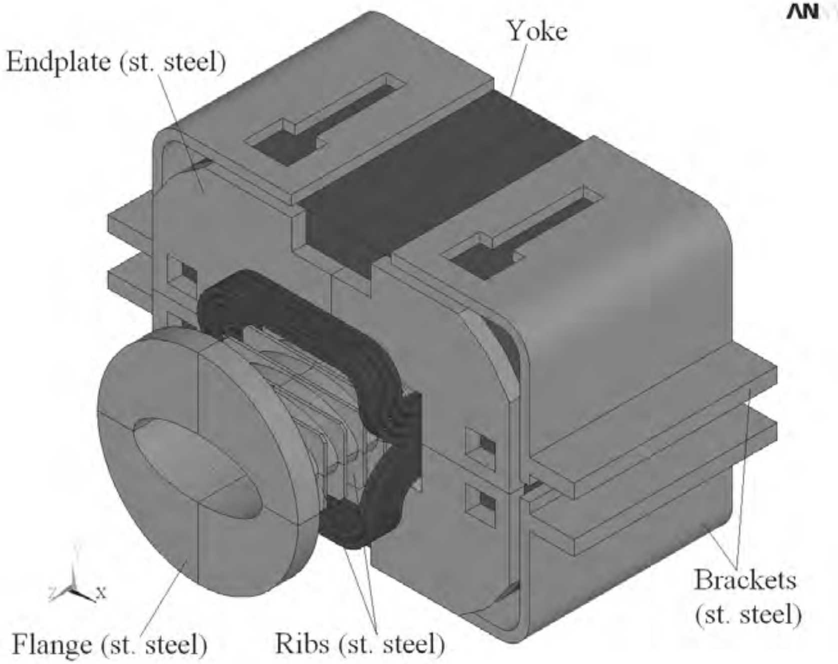




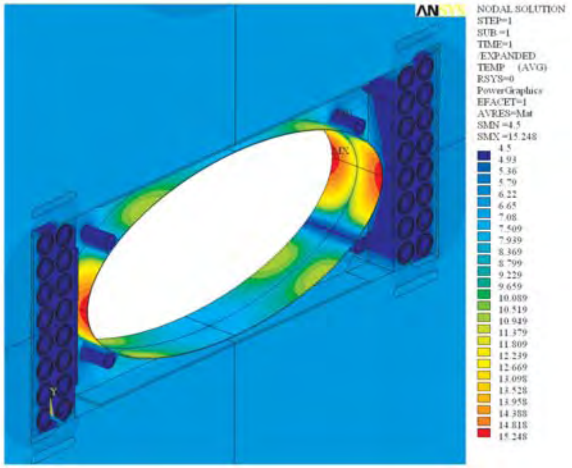


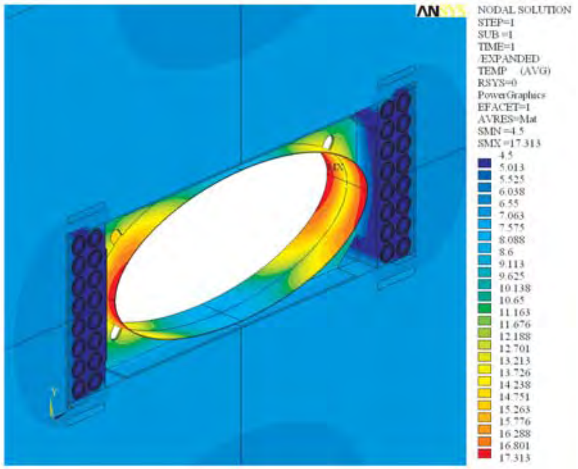
Vacuum chamber: Calculated average power

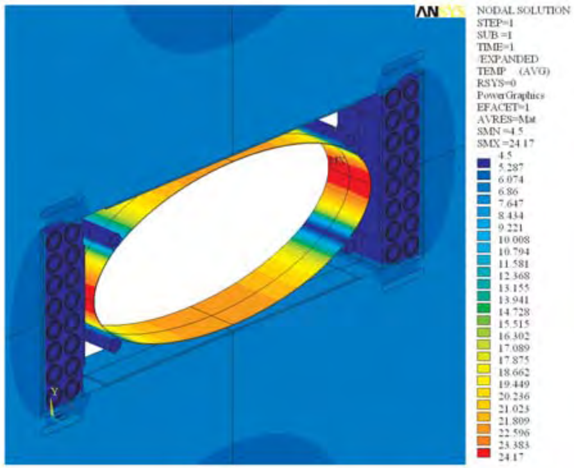
cycle	2a H	2a E	2b H	2b E	2c H	2c E	Λ H	Λ E
				magnet central part				
yoke	0.6	0.1	3.6		11.8	0.3	23.7	0.6
				magnet end part				
brackets				0.4		0.7		1.2
endplates		1.1		3.3		3.8		8.0
yoke		0.4	0.8	1.5	2.2	3.0	4.0	5.3
				beam pipe central part				
pipe		1.7		4.7		6.7		13.9
tubes		0.7		1.9		2.7		5.6
ribs		0.1		0.2		0.3		0.6
				beam pipe end part				
pipe		0.3		0.7		0.9		1.9
				Total				
magnet								
centre	0.7		3.9		12.2		24.5	
end	1.8		6.0		9.7		18.5	
coil	6		1		8		16	
total	8.5		10.8		29.5		57.0	
vacuum chamber								
	2.8		7.6		10.6		22.2	
total load								
	11.2		18.4		40.5		79.1	



Vacuum chamber: Calculated temperatures



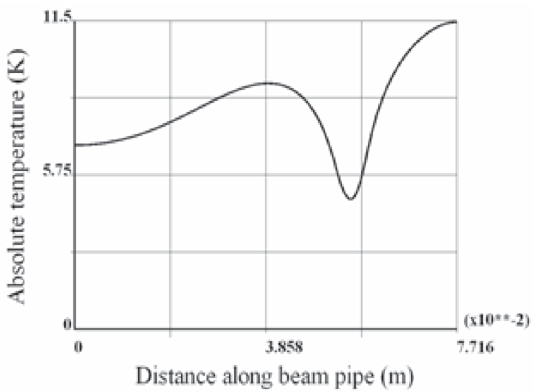


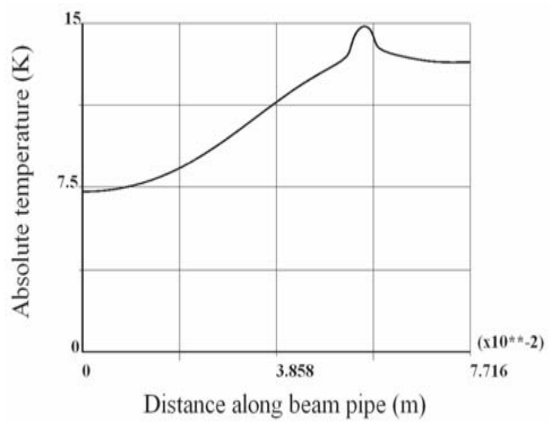


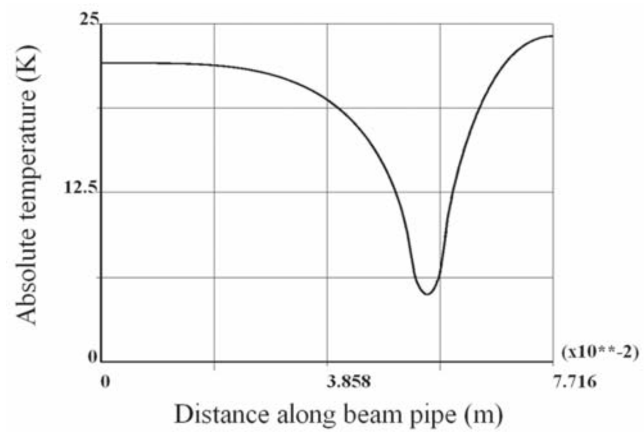
as a build

without coolant in the tube

without rib

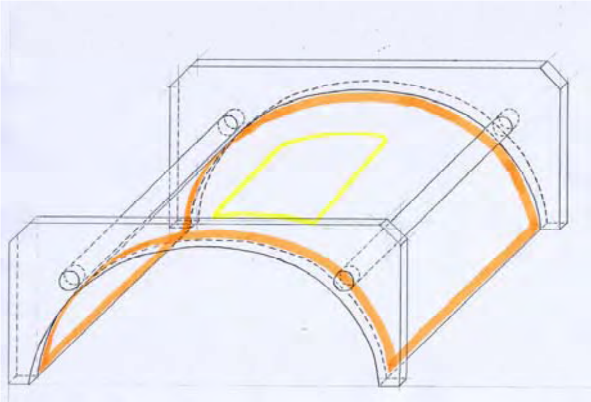




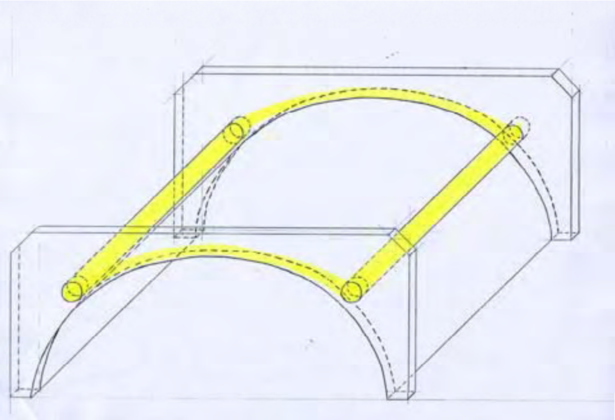


Vacuum chamber: Analytical model

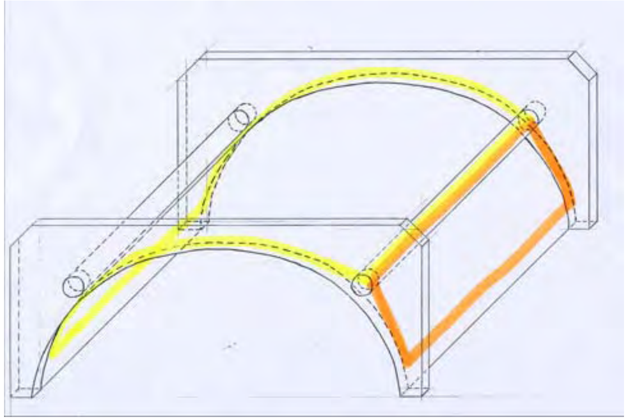
- Resistance of different components of VC and losses in the 4 cooling pipes



Loop1: vacuum chamber



Loop2: pipe – rib - pipe

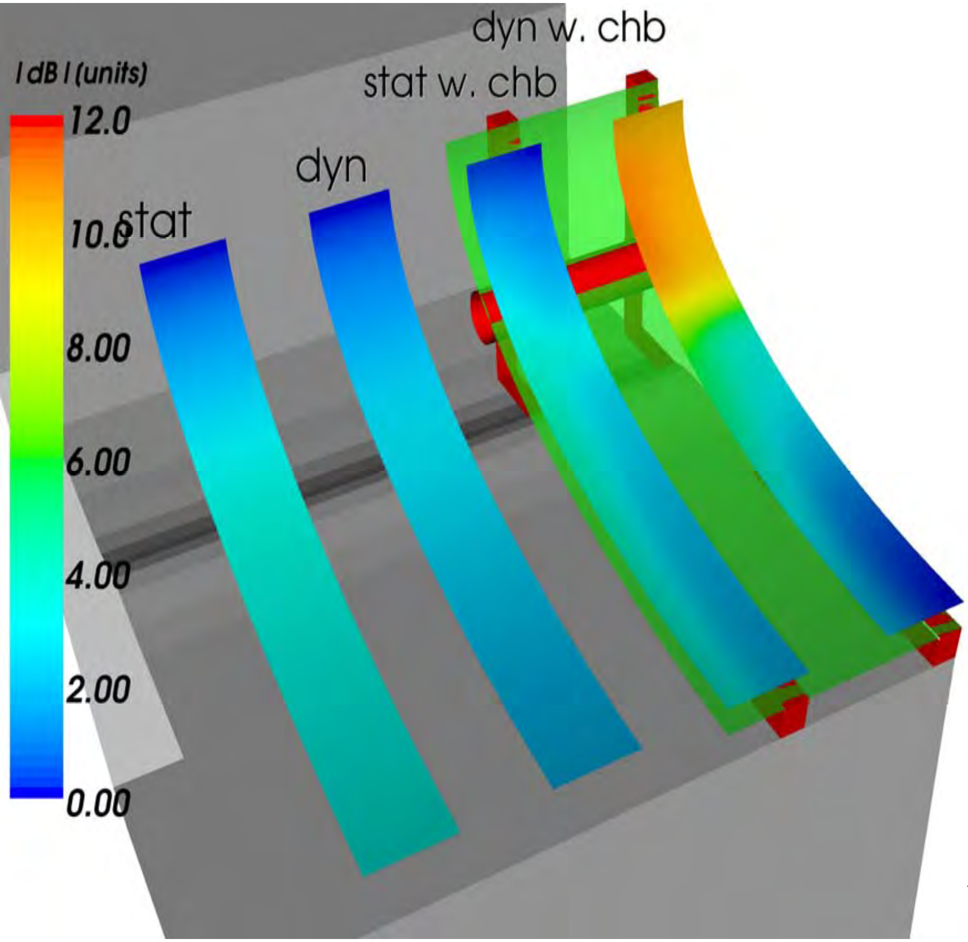


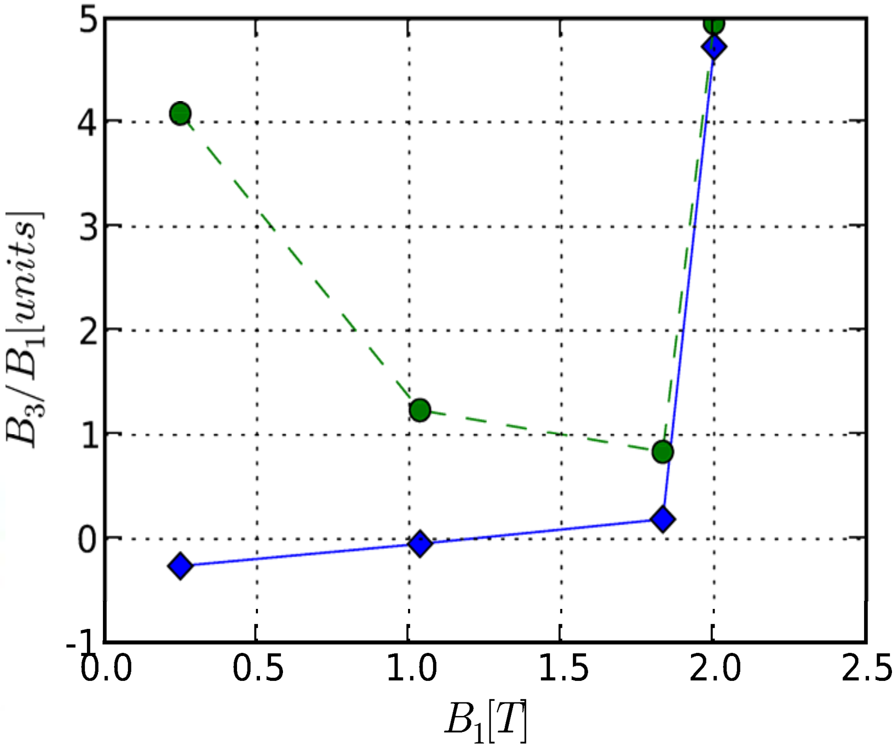
Loop3: chamber – rib - pipe

Part	decay constant τ µs	current A	resistance mΩ / m	$\text{loss}_{\text{pipes}}$ mW / m
chamber	22		5	
tubes	5		27	
Loop 1		0.1	30	2
Loop 2		2.7	variable	0.8
Loop 3		1.7	265	0.3

HELMHOLTZ | GEMEINSCHAFT GSI FAIR

Vacuum chamber: Field deterioration

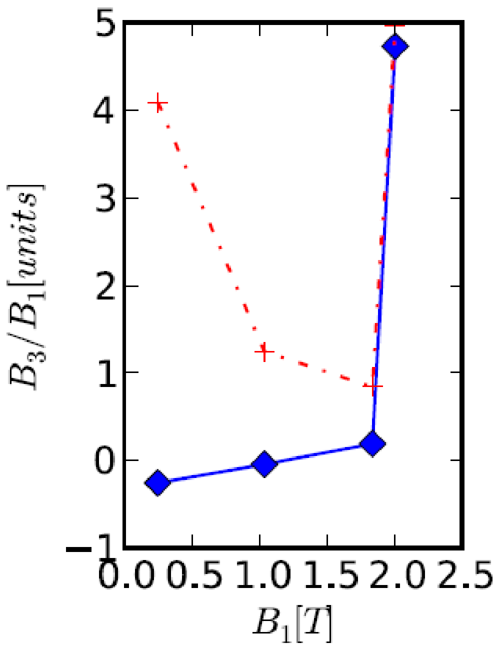




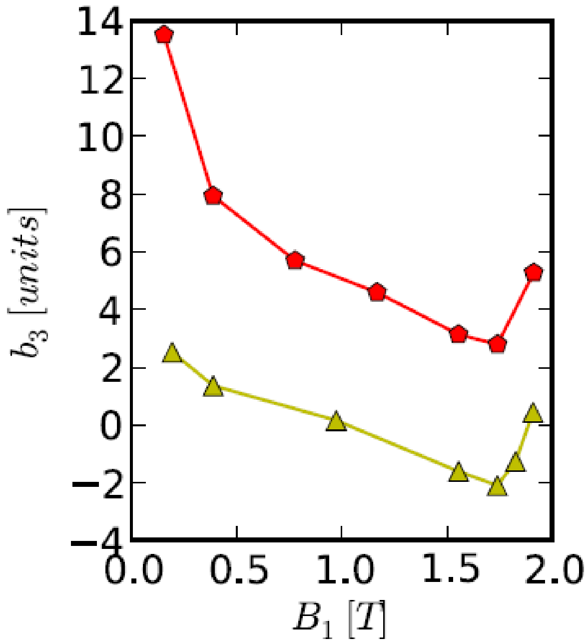
Vacuum chamber: ribs & cooling pipes
eddy currents large field deviation at injection

Vacuum chamber: Field deterioration I/II

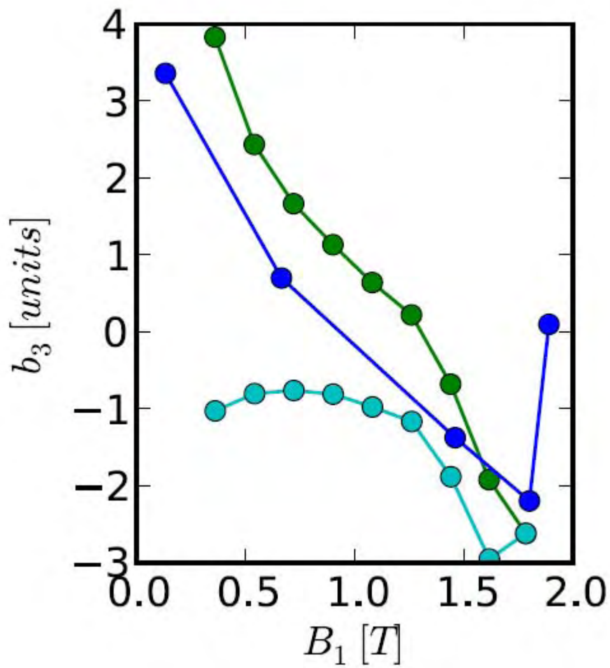
Sextupole



ANSYS, S2LD



OPERA 3D, CSLD



OPERA 2D, CSLD

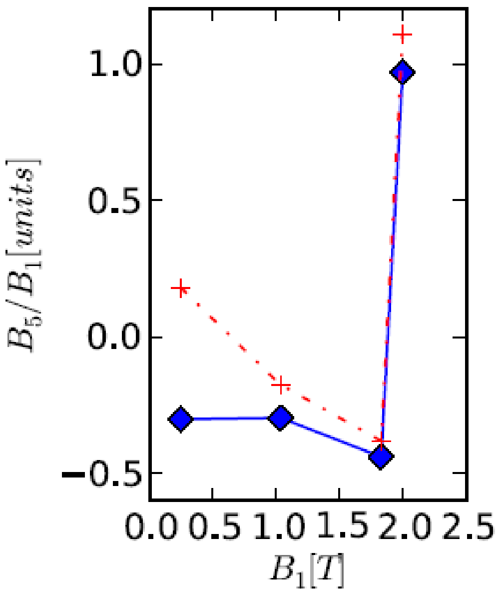
S2LD with ANSYS
static – **blue line**
transient rump up – **red line**

OPERA 3D:
static – **yellow line**
transient rump up – **red line**

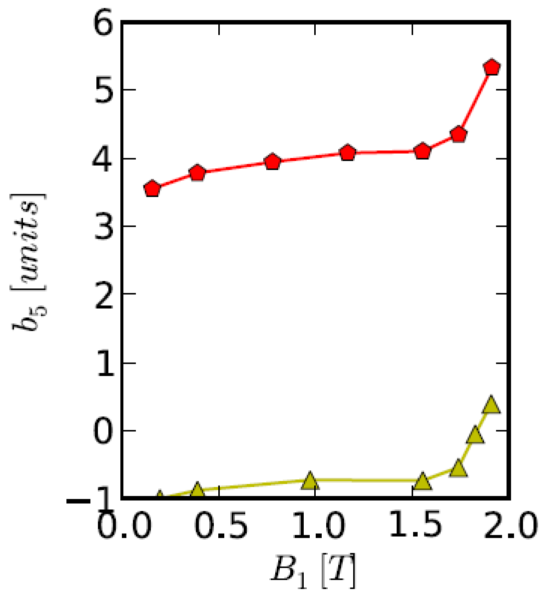
OPERA 2D:
static – **blue line**
transient rump up – **green line**
transient rump down – **cyan line**

Vacuum Chamber: Field deterioriation II/II

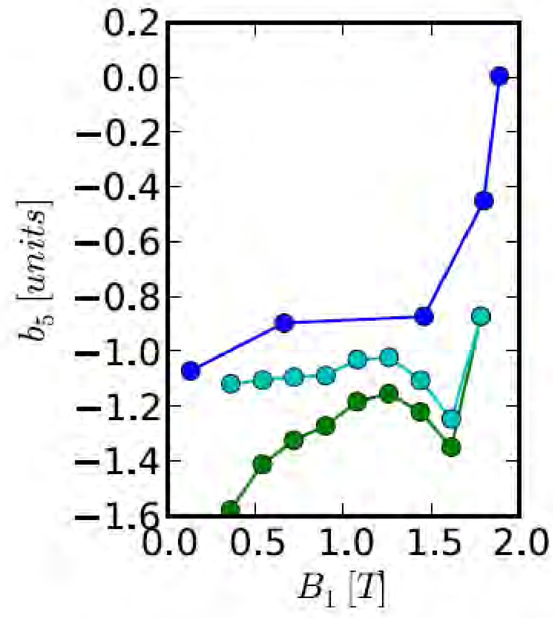
Dekapole



ANSYS, S2LD



OPERA 3D, CSLD



OPERA 2D, CSLD

S2LD with ANSYS
static – **blue line**
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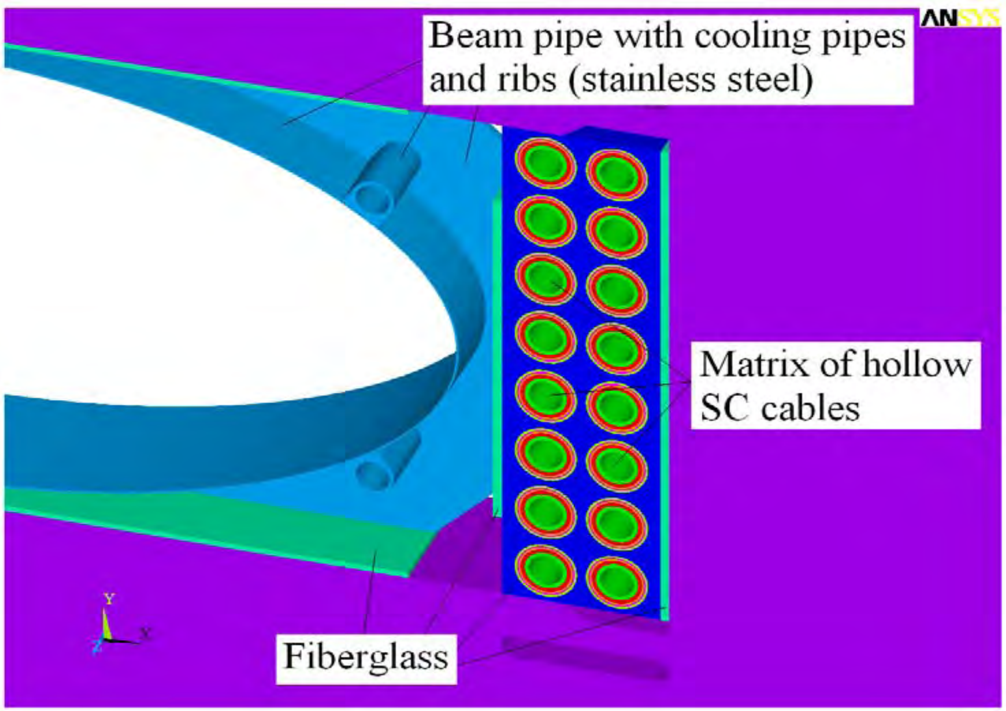
OPERA 3D:
static – **yellow line**
transient rump up – **red line**

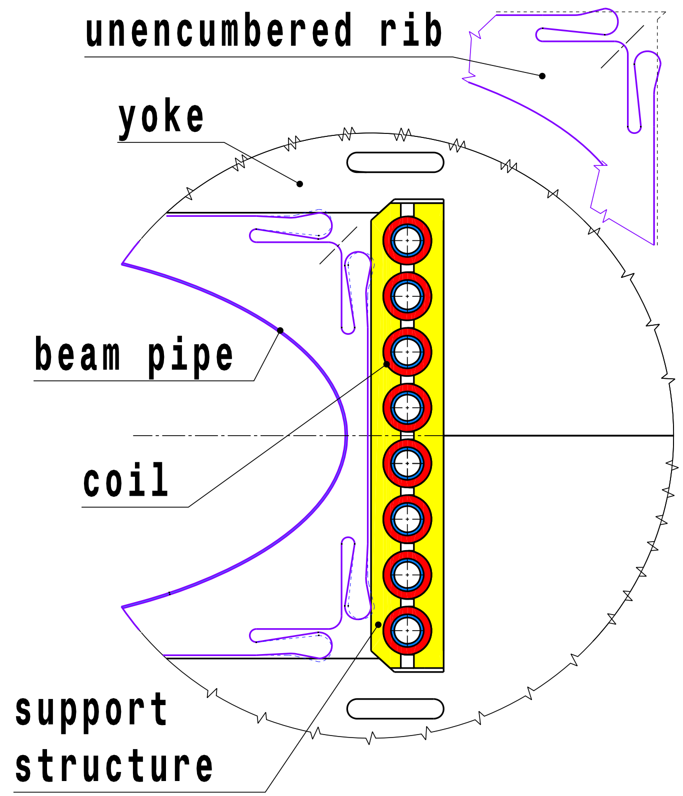
OPERA 2D:
static – **blue line**
transient rump up – **green line**
transient rump down – **cyan line**

Vacuum Chamber: Cooling options

additional cooling ▼



Conduction cooling ▼

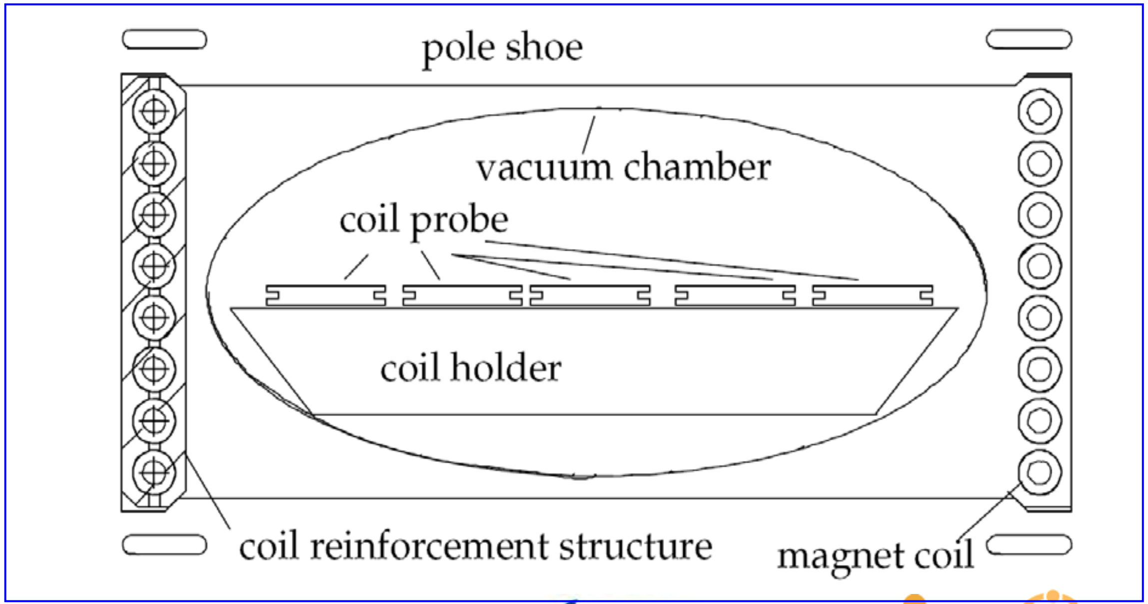


Stand: 09. Sept 2009

Elastic rib for
Dipole SIS100

Vacuum Chamber: Magnetic field measurement

1. Field → magnet measured without vacuum chamber
2. FEM model → adjust B-H curve → match field quality
3. Vacuum chamber → measured within nc magnet → material properties
4. VC installed in magnet → measured with “woodlouse”



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Milestones toward the curved single layer dipole

2002	March: Decision to start high current Nuclotron cable larger aperture, hydraulic limits, AC losses
2003	Cooling power calculation; comparison to other cables Strands tested, design for 4 T magnet
2004	Dipole magnet with single layer coil → design and tested Nuclotron cable → strands direct contact to helium
2005	Nuclotron cable cos θ magnet design → 4 T Review of SIS100 cooling concept
2006	Increase of magnet aperture for beam dynamics, triangular cycle hydraulic limits → necessitated single layer coil : presented at internal review Equivalent model test @ JINR / Dubna → confirming calculations Decision for 2 layer magnets (straight and curved)
2007	10 Hz Quadrupole, sc wire development for high current cable flexible cabling machine at BNG
2008	Status and limits of current SIS100 magnets presented at WAMSDO, ASC08
2009	Test of BNG magnet confirms predictions: no 2c High current cable: fabrication of wires

Conclusion

- The first SIS100 prototype dipole was intensively tested.
- The magnet training, the intensive long-term ramping stability, the measured current, the magnetic field characteristics as well as the AC-loss and cooling parameters have proven the preliminary design estimations and show that the applied production technologies are working well and ready for series production.
- These tests will be completed on a second straight dipole, a curved dipole utilising a two layer coil and on a prototype quadrupole with 6 coil per pole.
- The results obtained on the first prototype dipole confirm that our methodical design work is correct and the optimised curved single layer dipole is expected to fulfil all operation requirements for the SIS100 accelerator.
- This curved single layer dipole, while not yet built, is based on a sound R&D conducted since 2002.
- The next step toward final series production of the main magnets will be constructing and testing a curved dipole with a single layer coil made of high current superconducting cable.