Common design aspects for fast ramped superconducting accelerator magnets

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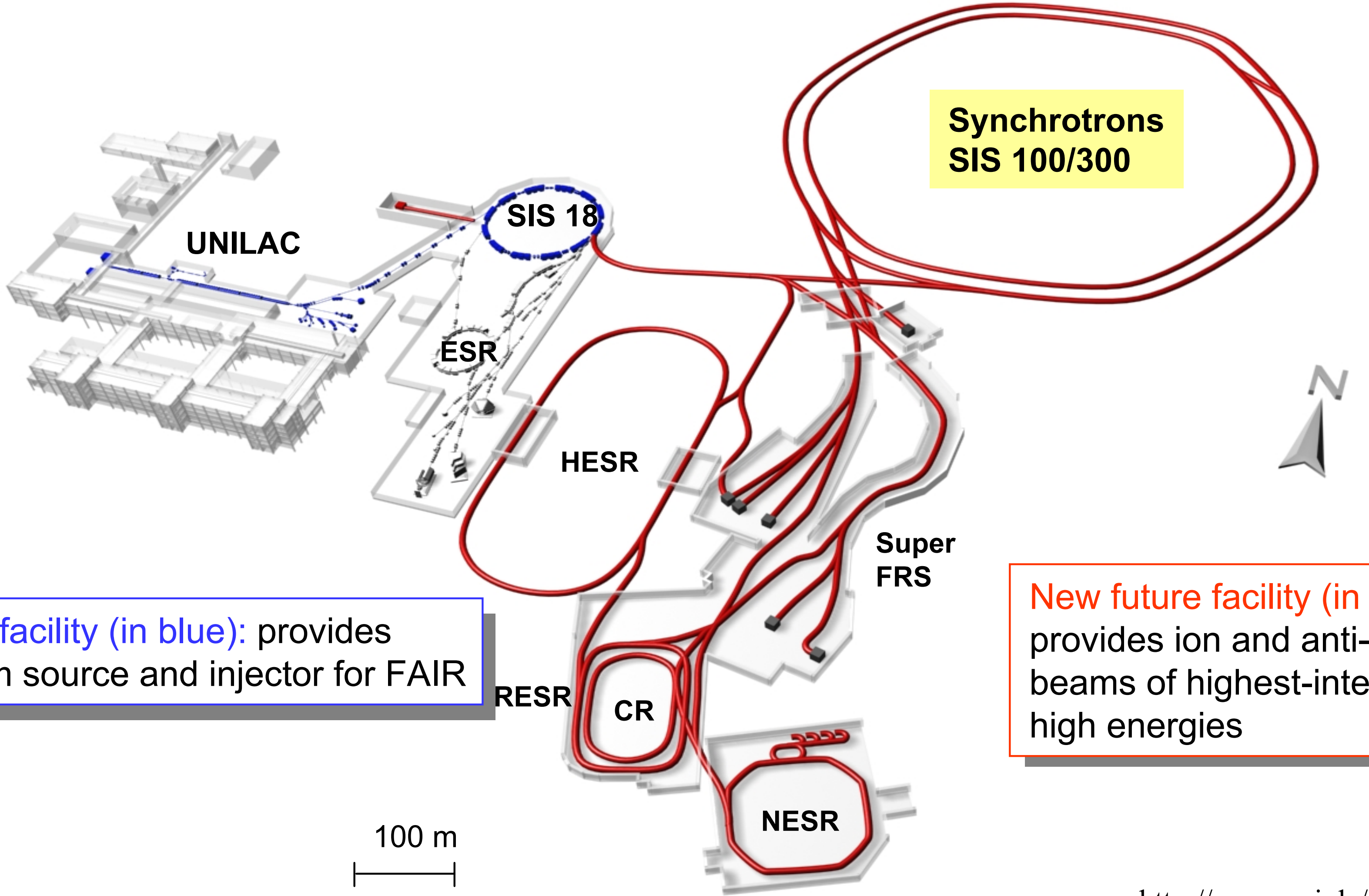
Fast Ramped SC Magnets: Contents

- SIS100 within FAIR
- Basic Design and FEM Topics for Nuclotron Type SC Magnets
- Corrector Magnets
- Magnetic field: Calculation - Measurement – Multipoles
- First Prototypes: Design – Manufacturing – Testing
- Additional Requirements and Critical Operation Parameters
- Design Update for the Main Dipole
  - Design of the Curved SIS100 Dipole based on a Single Layer Coil
  - Main Operation Parameters of the CSL-Dipole
- Update for cos Θ up to 4.5 T ?
- Summary

FAIR: Facility for Antiproton and Ion Research

fast cycled sc magnets



Existing facility (in blue): provides ion-beam source and injector for FAIR

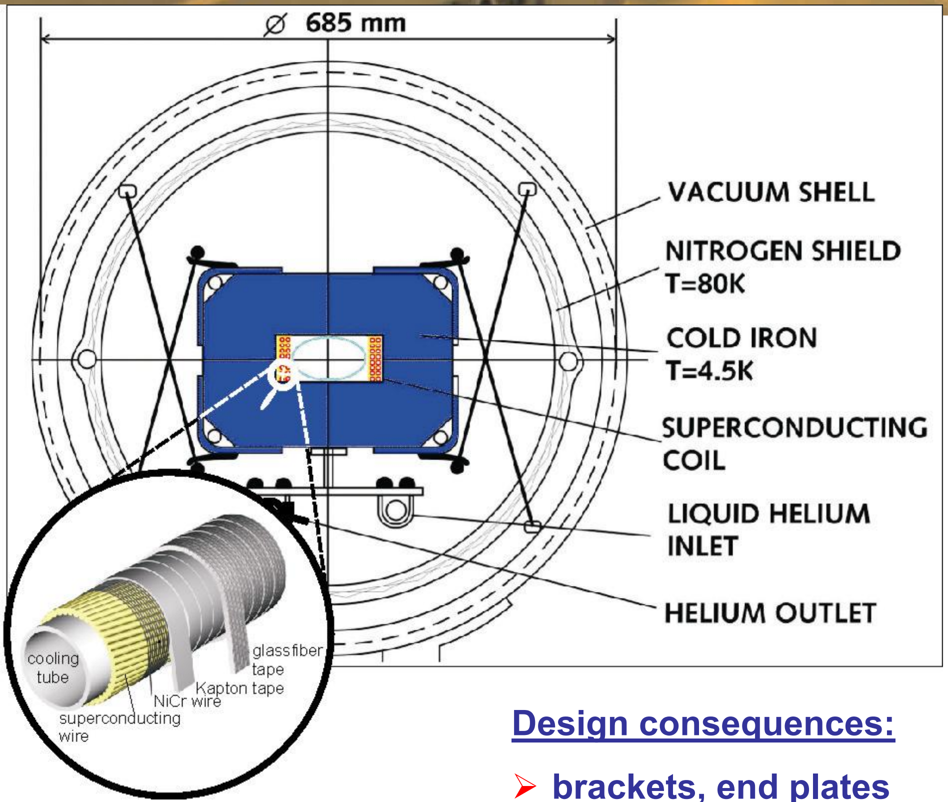
New future facility (in red): provides ion and anti-matter beams of highest-intensity and up to high energies

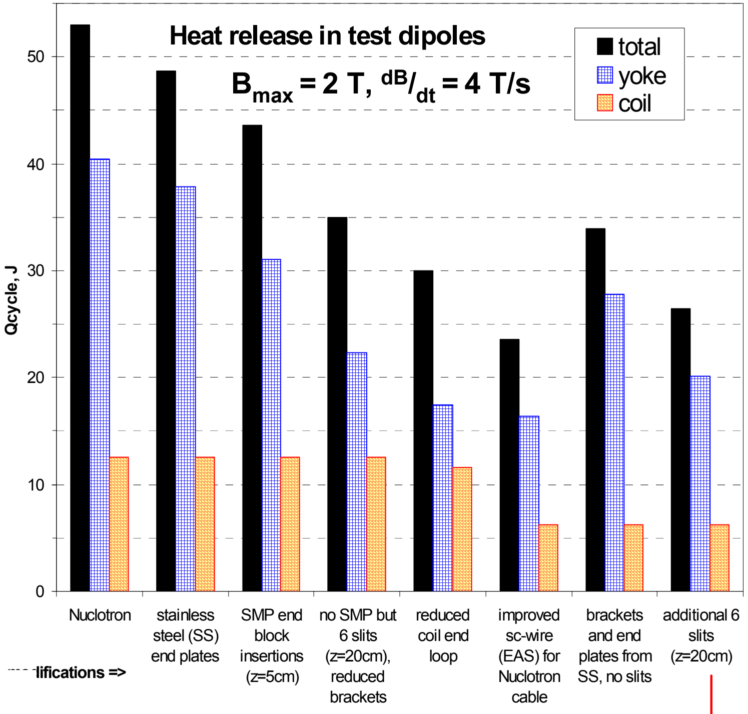
http://www.gsi.de/fair/

Main R&D Results: Short Test Models

Starting point Nuclotron dipole inside cryostat:

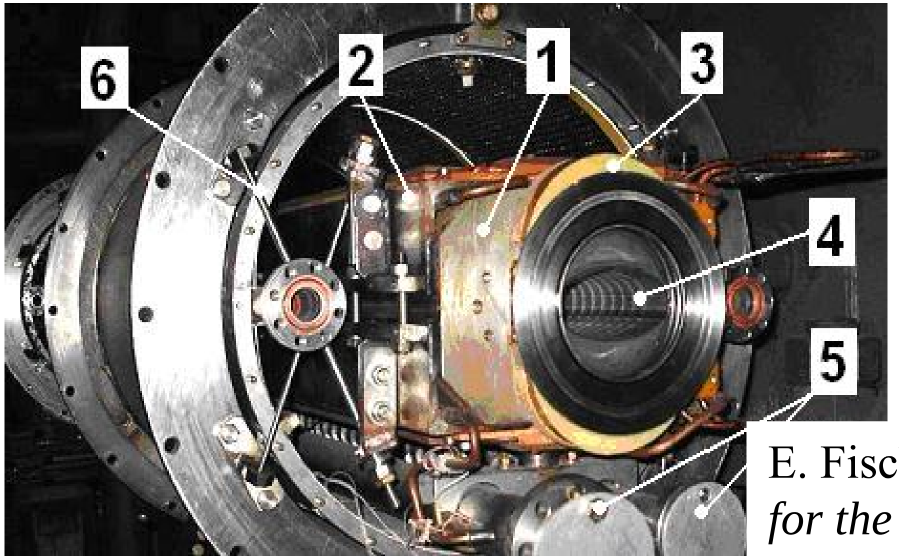
1 - yoke end plate
2 - brackets
3 - coil end loop
4 - beam pipe
5 - helium headers
6 - suspension
7 - laminated yoke





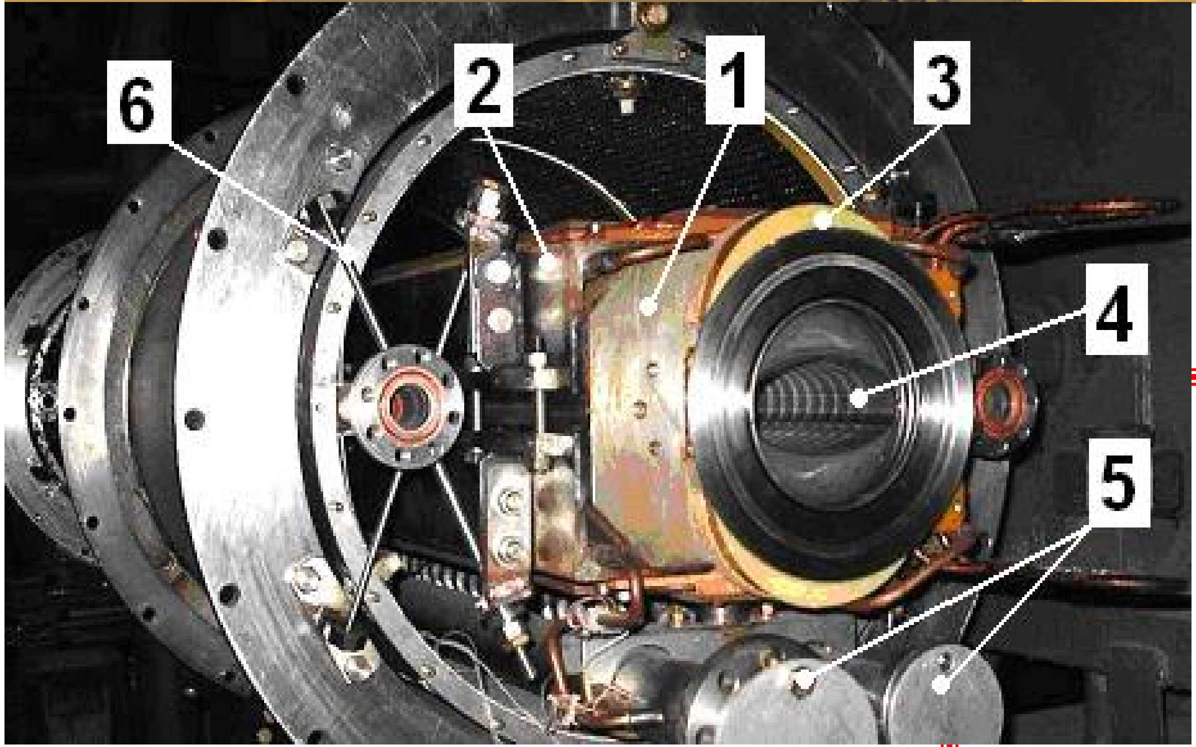
Design consequences:

- **brackets, end plates made from SS**
- **laser cut lamination slits**
- **minimized coil ends**
- **optimized lamination geometry**
- **new coil package structure**

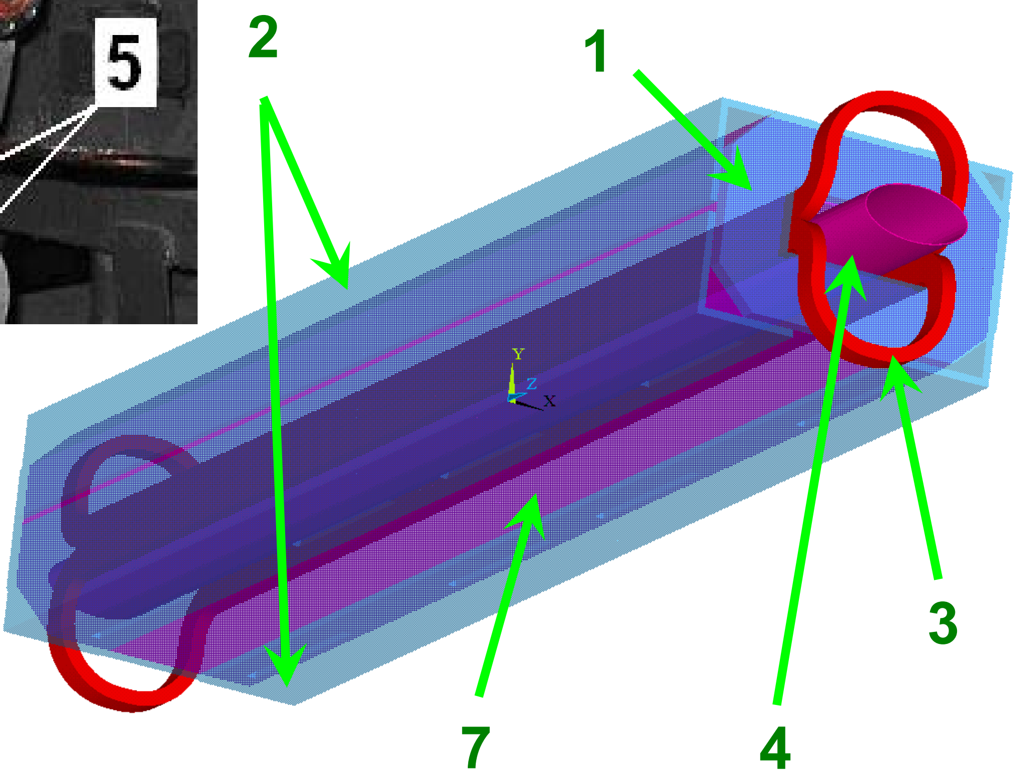


E. Fischer et al: *Fast Ramped Superferric Prototypes and Conclusions for the Final Design of the SIS 100 Main Magnets* ASC 2008

Common model structure



- Test measurements on magnet modifications
- FEM calculations on detailed 3D-models

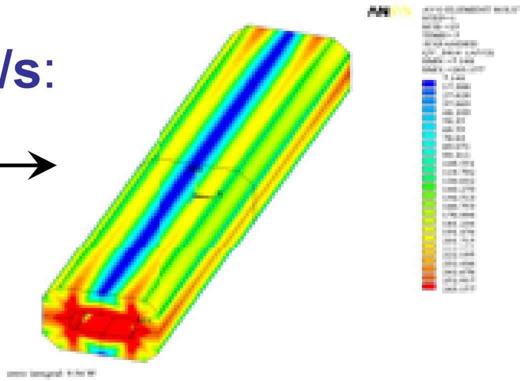


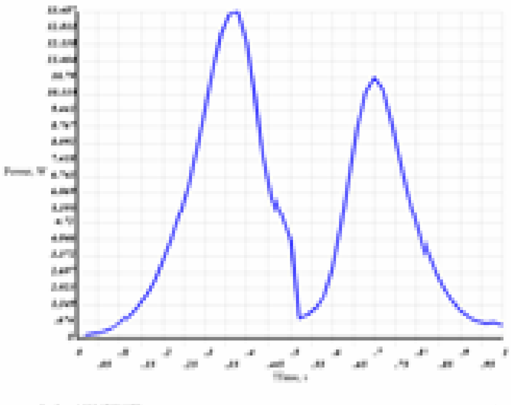
Nuclotron dipole inside cryostat:
1 - yoke end plate
2 - brackets
3 - coil end loop
4 - beam pipe
5 - helium headers
6 - suspension
7 - laminated yoke

Main R&D Results: FEM Calculation of the AC Loss

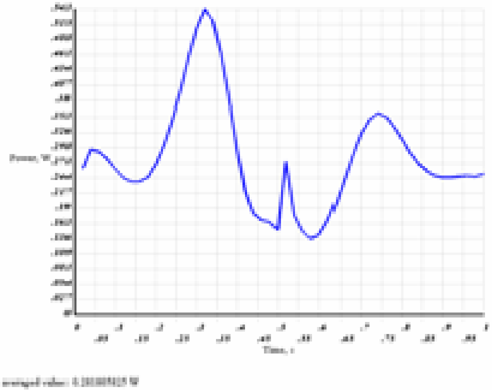
4KDP6a results for the triangular cycle with B_{max}= 2 T, $^{dB}/_{dt}$=4 T/s:

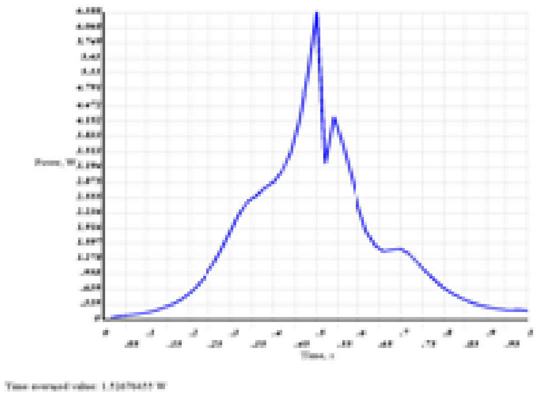
- Hysteresis loss in the laminated yoke
  = 9.56 J/cycle



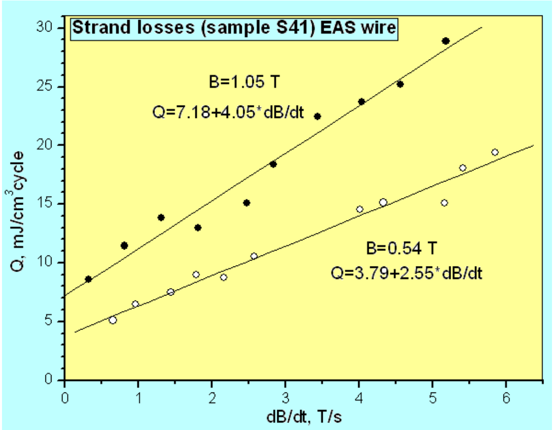


- Eddy current loss in the yoke ends
  = 4.81 J/cycle
- Eddy current loss in the ss end plates
  = 0.28 J/cycle





- Eddy current loss in the ss brackets
  = 1.53 J/cycle
- AC loss in the superconducting coil
  = 6.4 J/cycle (from short sample measurements at JINR)

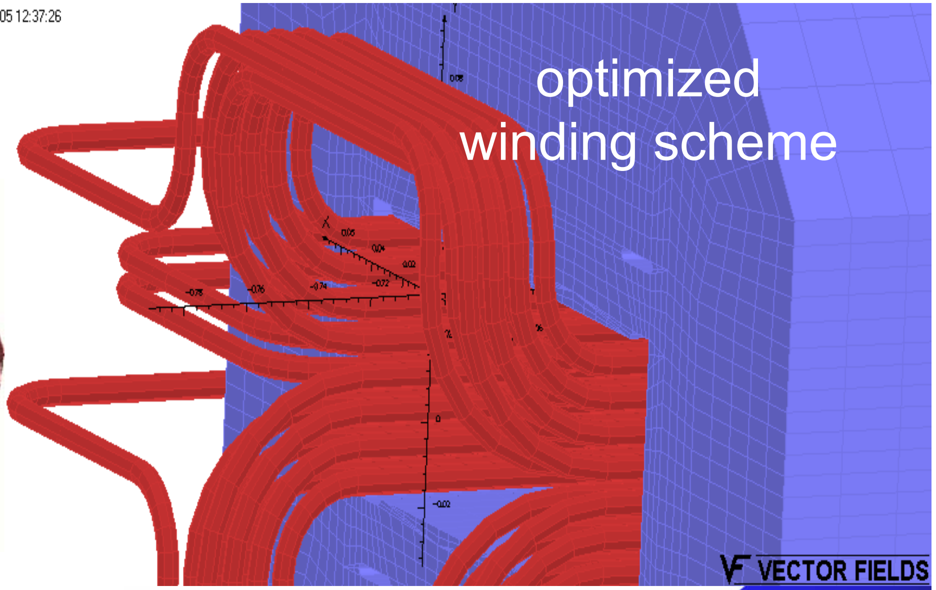


► **see also:** E. Fischer et al.“Analysis of coupled electromagnetic-thermal effects in superconducting accelerator magnets”, J. Phys.: Conf. Ser. 97 (2008) 012261

SC Magnets R&D Results: Field quality

(2D) 3D OPERA studies

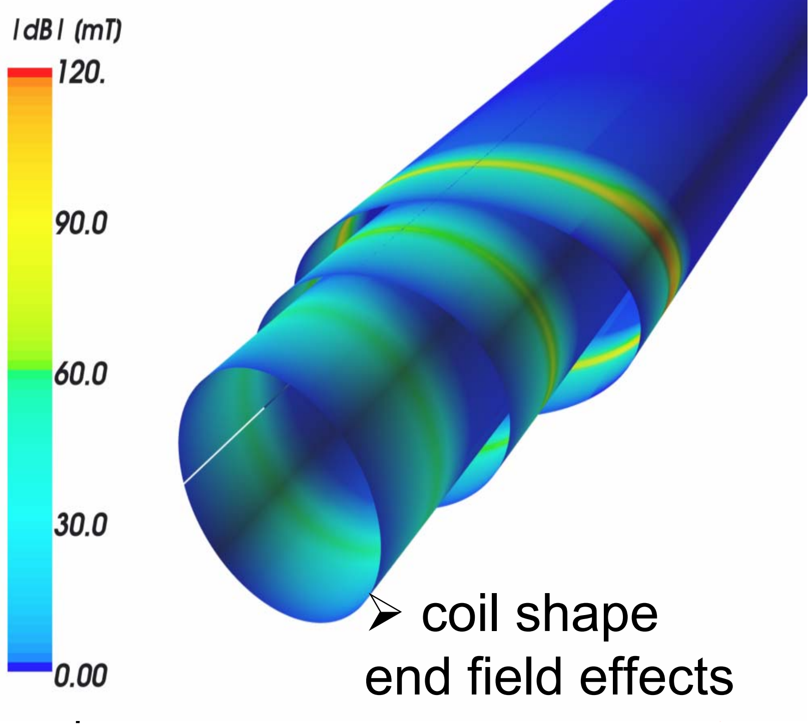
Nuclotron cable: round thus modelled by bricks



optimized winding scheme

Field quality and technology improvements:

- ➢ Negative shimming
- ➢ Homogenisation slits
- ➢ Rogowski end profile
- ➢ Coil winding simplification

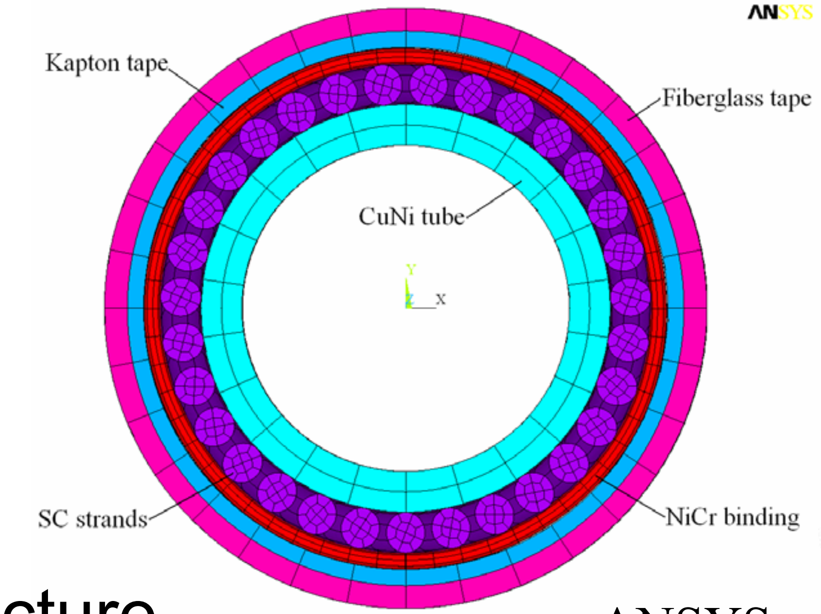


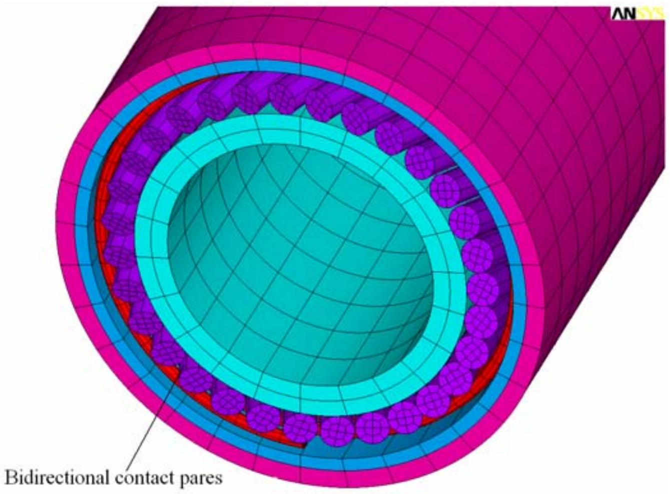
➢ coil shape end field effects

Coil mechanics R&D: SIS 100 dipole coil design

goal:

- ➢ reduction of point loads
- ➢ accurate positioning

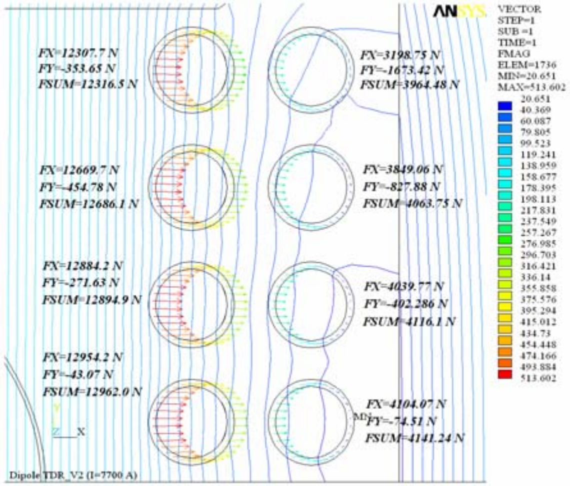




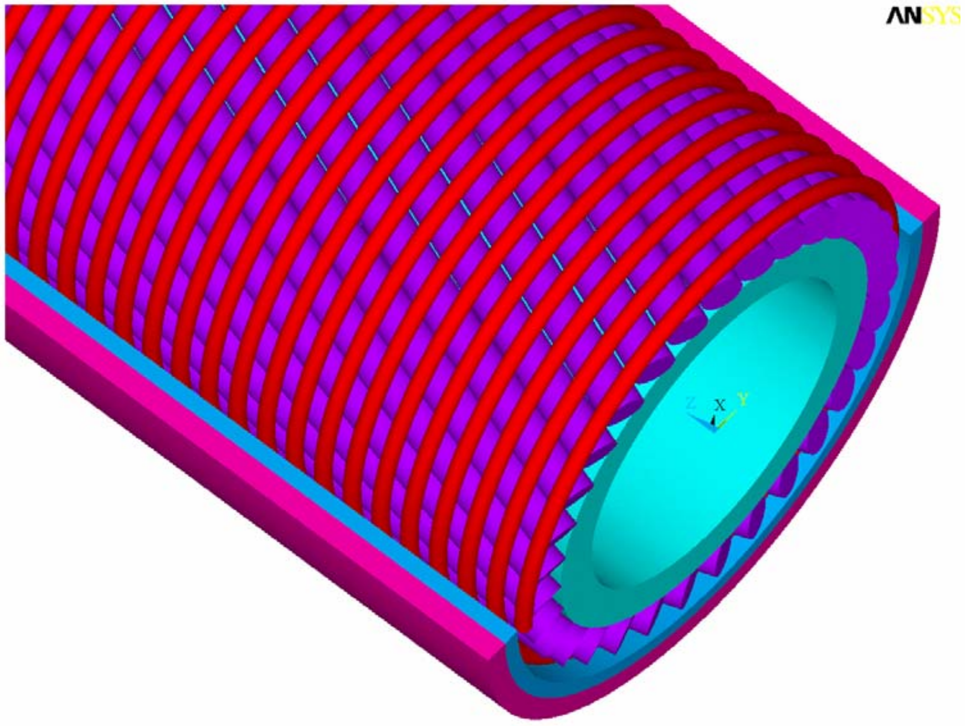
Coil support structure

ANSYS model of the coil / conductor

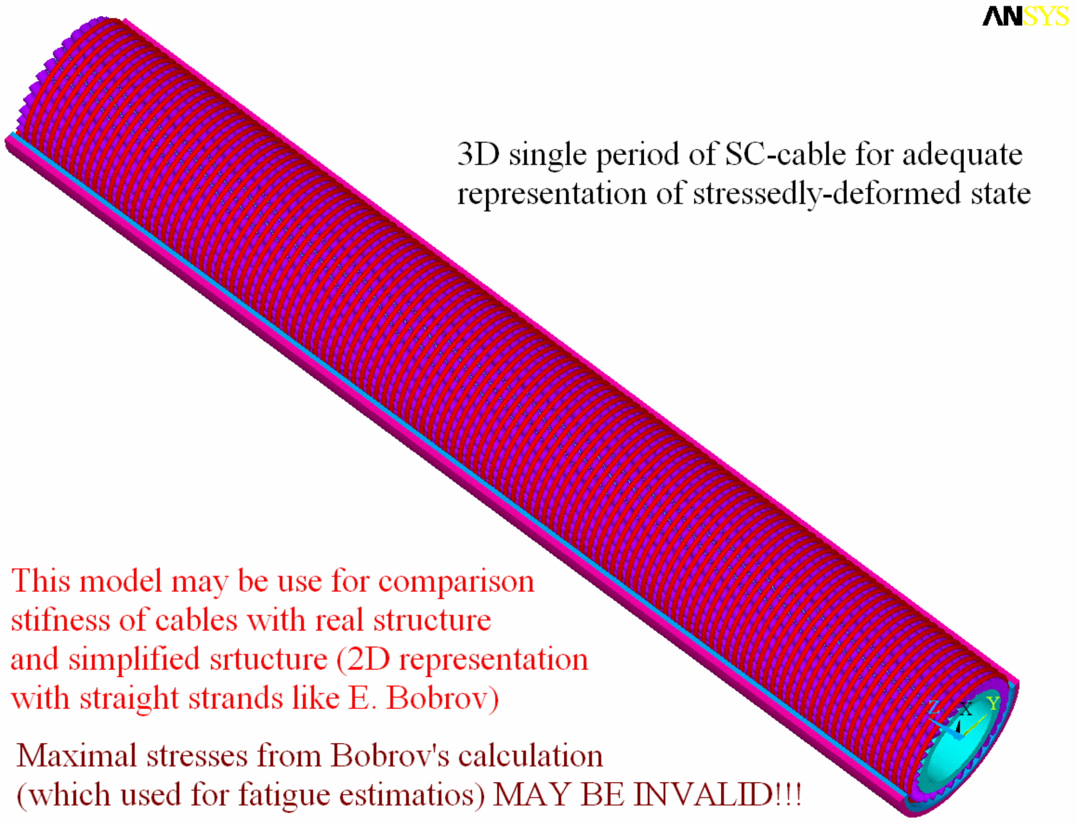
- mockups were produced at BNG
- mechanical properties tests at FZ Karlsruhe
- FEM Analysis



Main R&D Results: Coil Mechanics



3D single period of SC-cable for adequate
representation of stressedly-deformed state



3D single period of SC-cable for adequate
representation of stressedly-deformed state

This model may be use for comparison
stifness of cables with real structure
and simplified srtucture (2D representation
with straight strands like E. Bobrov)

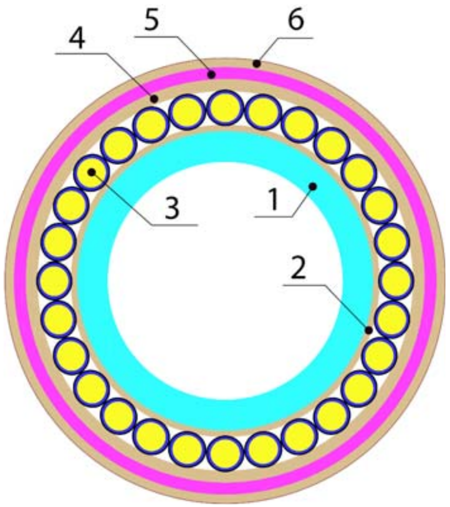
Maximal stresses from Bobrov's calculation
(which used for fatigue estimatios) MAY BE INVALID!!!

SIS100 Corrector Magnets: Cable Design

- **Nuclotron type cable with insulated wires**

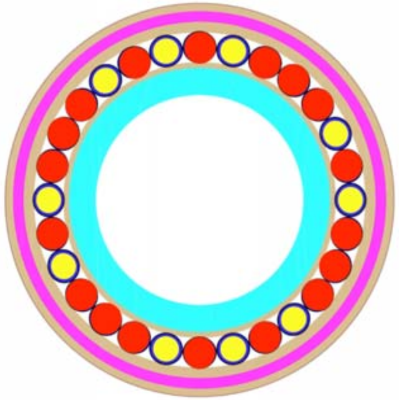
– Connect wires in series

– By replacing sc. wire, operation current is adjustable.



1. CuNi tube
2. Kapton, t=0.05mm, 1 layer, 50% overlapped
3. Superconduting wire, 0.5mm diameter, with enamel
4. Kapton, t=0.05mm, 2 layers, 50% overlapped
5. CrNi wire, 0.2mm diameter
6. Kapton, t=0.07mm, 1 layer, 50% overlapped

Maximum 28 sc. wires

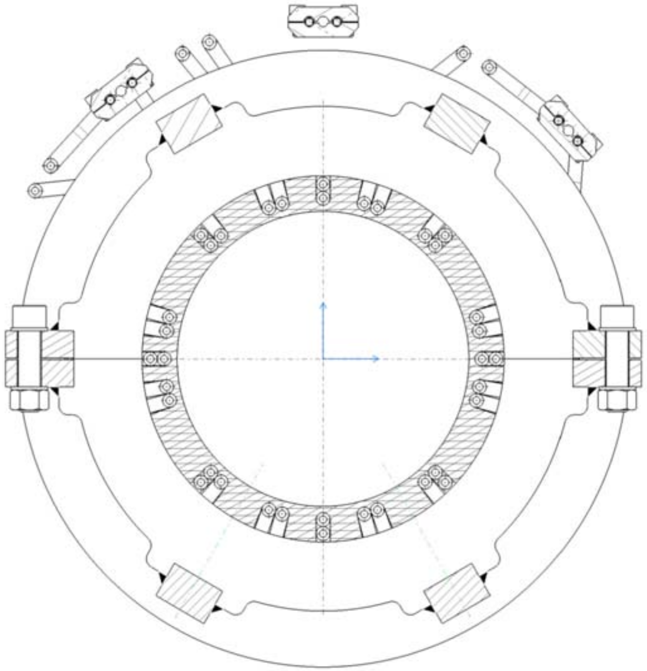


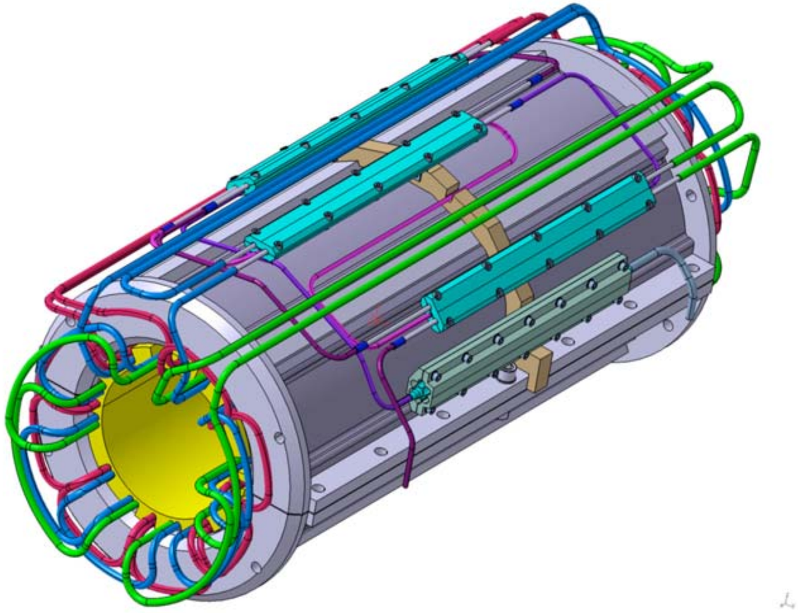
ex. 10 sc. wires cable for the quadrupole corrector

► **see also:** K. Sugita et al. "Design Study of Multipole Corrector Magnet for SIS 100", ASC 2008

SIS100 Corrector Magnets: Multipole

Error compensation multipole corrector
– Quadrupole, sextupole, and octupole are nested.





Quadrupole

Sextupole

Octupole

Magnetic Field Description: Circular Multipoles

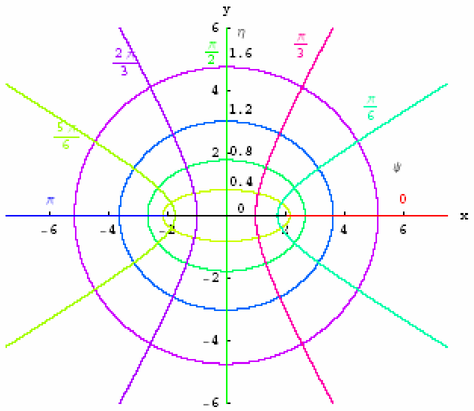
Standard field description: Circular Multipoles

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

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

SC Magnets R&D: 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:

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

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

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

Expansion coefficients:

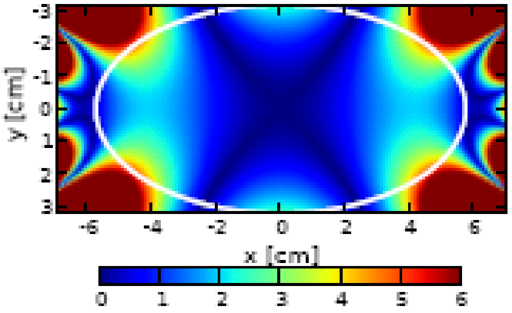
$$\mathrm{e}_n = \frac{1}{2\pi} \int_{-\pi}^{\pi} \mathrm{B}(\mathbf{w} = e\cosh(\eta_0 + i\psi)) \times \cos(n\psi)\, d\psi.$$

Linear Analytic Transformation to Circular Ones

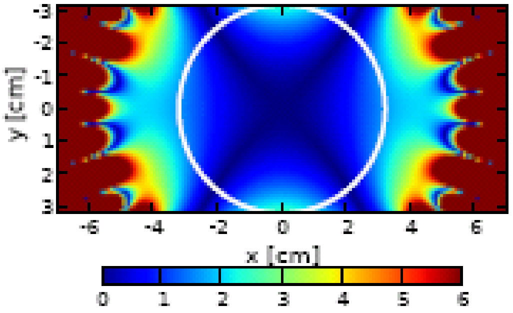
P. Schnizer, B. Schnizer, P. Akishin, E. Fischer: Magnetic field analysis for superferric magnets using elliptic multipoles. IEEE Trans. Appl. Supercon. 2008 vol 18 pp. 1605 - 1608

P. Schnizer, B. Schnizer, P. Akishin, E. Fischer: Plane Elliptic Multipoles for Static Magnetic Fields. Submitted to NIMA

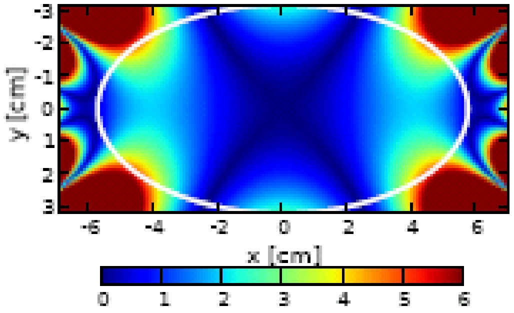
Magnetic Field Description: Elliptic Multipoles



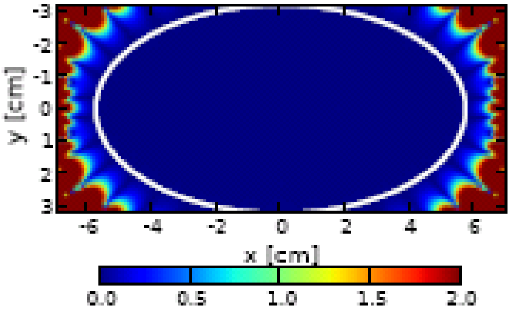
elliptic $\mathcal{C}_e$



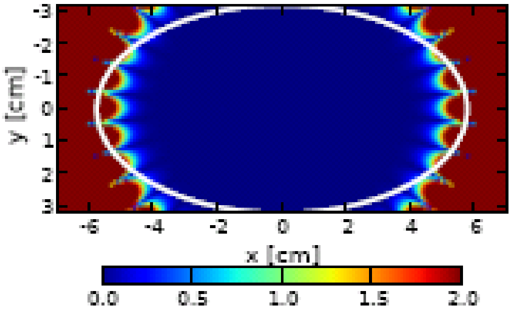
cyclic $\mathcal{C}$



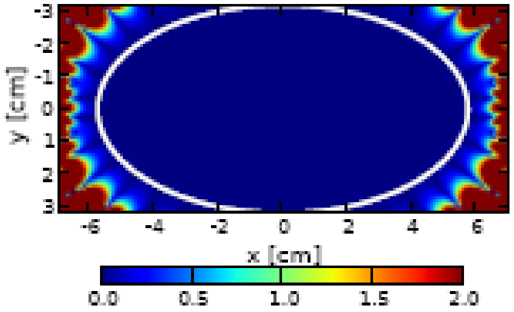
ell. $\rightarrow$ cyclic in $\mathcal{C}_e$



Δ elliptic $\mathcal{C}_e$



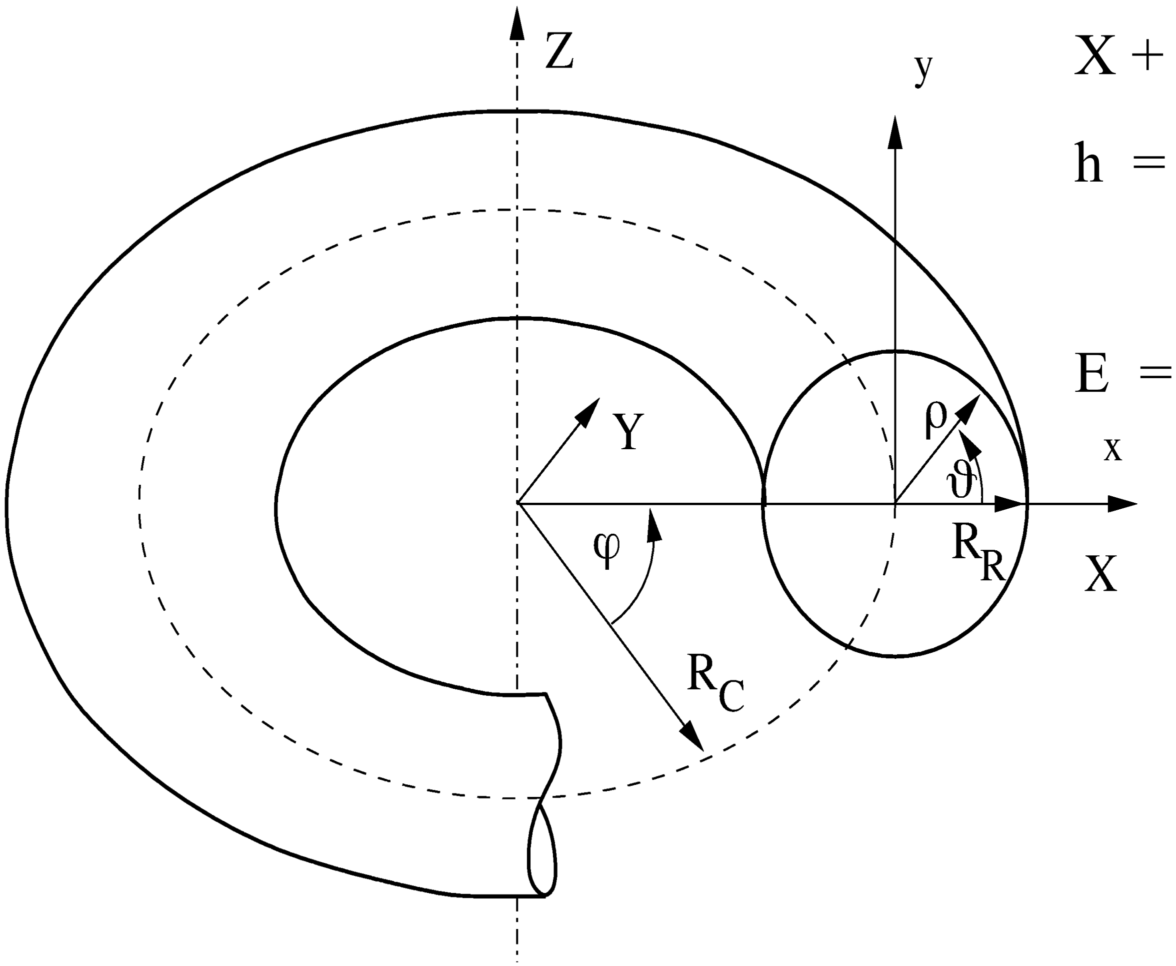
Δ cyclic $\mathcal{C}$



Δ ell. $\rightarrow$ cyclic in $\mathcal{C}_e$

Illustrated for CSLD at Injection Field ($\approx 0.25\ T$)

Magnetic Field Description: Toroidal Multipoles



Local Toroidal Coordinates ρ, ϑ, ϕ

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

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

$E = R_R / R_c << 1$

Main R&D Results on Nuclotron based SC Magnets

- **The sources of the loss generation are understood, numerical calculations match the respective measurements**
- **Stainless steel end plates and brackets**
- **Minimized coil end loops**
- **Laminated and horizontally cut endblocks**
- **New wire with higher current density and lower losses**
- **More rigid coil structure**

- **Decision: design and build full size models** (contracts Dec. 2006)
  - **Two straight dipoles:** BNG Wuerzburg (Industry), JINR Dubna(Institute) → different manufacturing technologies and materials
  - **Quadrupole: JINR Dubna**
  - **Curved dipole: BINP Novosibirsk → "no sagitta": significant benefits for lattice design and operation**

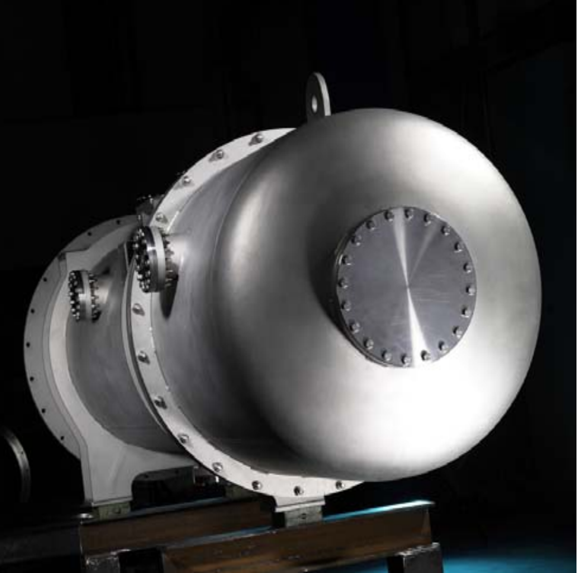
SIS 100 full Size Models: Design Parameters

		Straight dipole FBTR (March 2006)	**Curved dipole** (Oct. 2006)
B x $L_{effective}$	[Tm]	5.818	5.818
B	[T]	2.11	1.9
$L_{effective}$	[m]	2.756	3.062
Estimated L_{yoke}	[m]	2.696	3.002
Bending angle	[deg]	3 1/3	3 1/3
Radius of curvature	[m]	47.368	52.632
Aperture (h x v)	[mm]	130 x 60	115 x 60

		Quadrupole FBTR (March 2006)	**Quadrupole Elongated**(Oct.2006)
B' x $L_{effective}$	[T]	35	35
B'	[T/m]	32	27
$L_{effective}$	[m]	1.1	1.3
Estimated L_{yoke}	[m]	1	1.2
Aperture (h x v)	[mm]	135 x 65	135 x 65

SIS 100 Full Size Model: Dipole from Babcock Noell GmbH

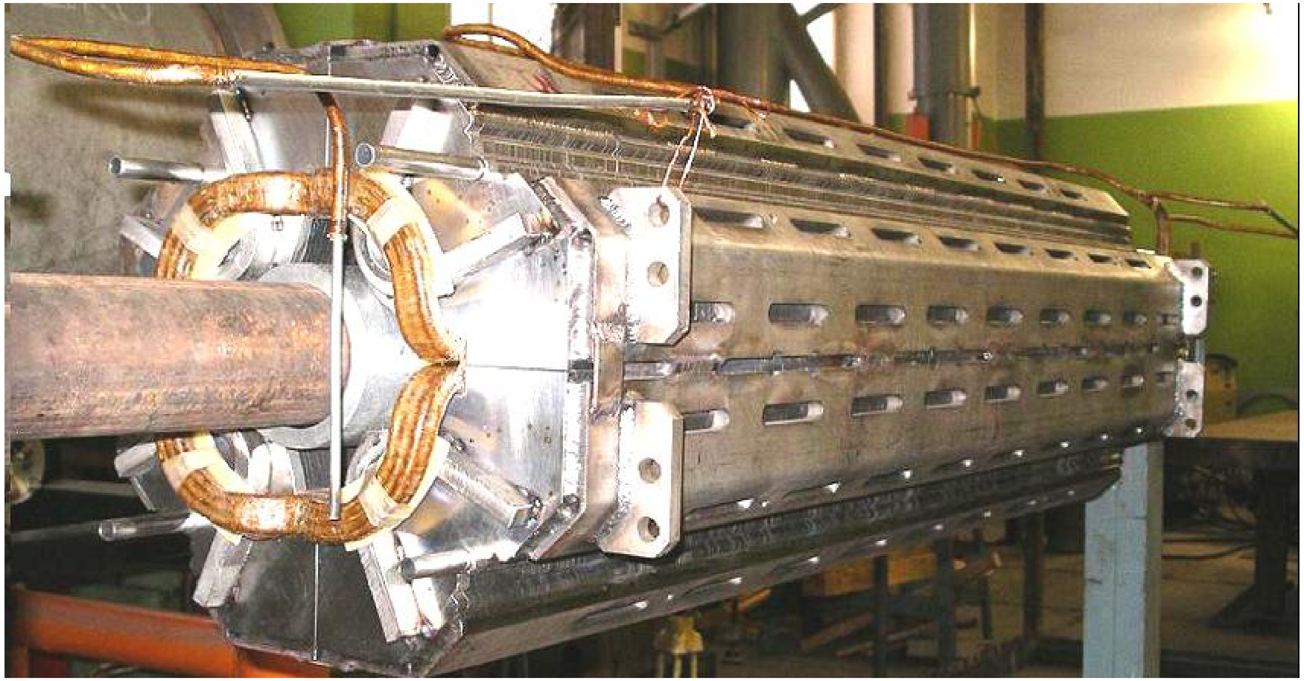
1st Full Size Dipole is ready for testing

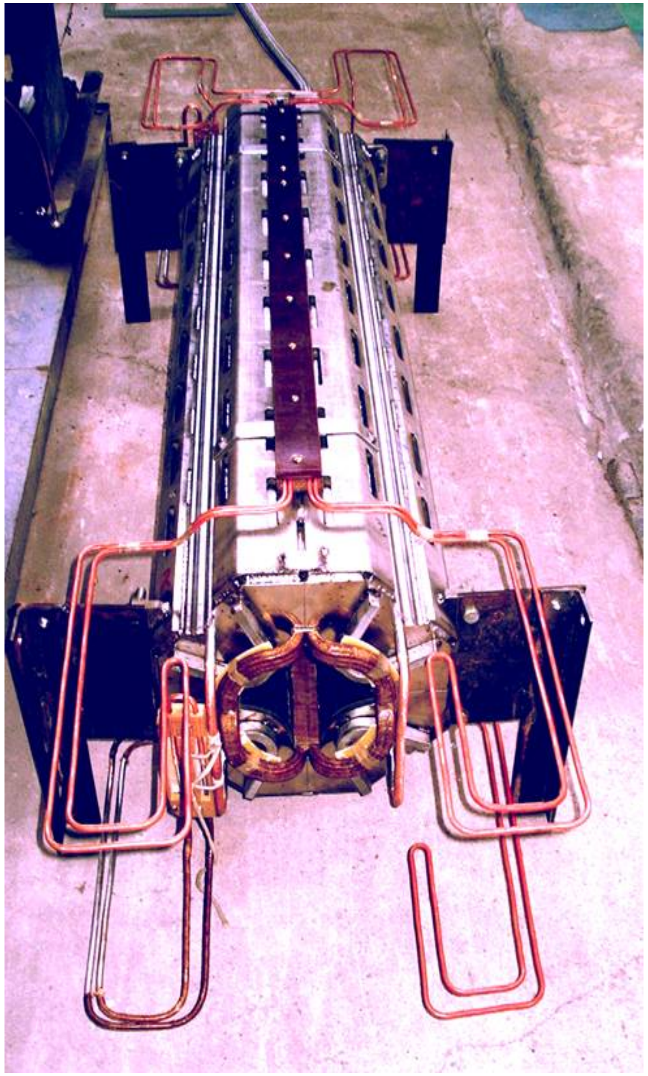


► see also: G. Sikler et al. "Manufacturing of the first Full Size Model of a SIS100 Dipole Magnet", WAMSDO 2008, 19-23 May, CERN, Geneva

PAC09: MO6PFP065, TH5PFP057

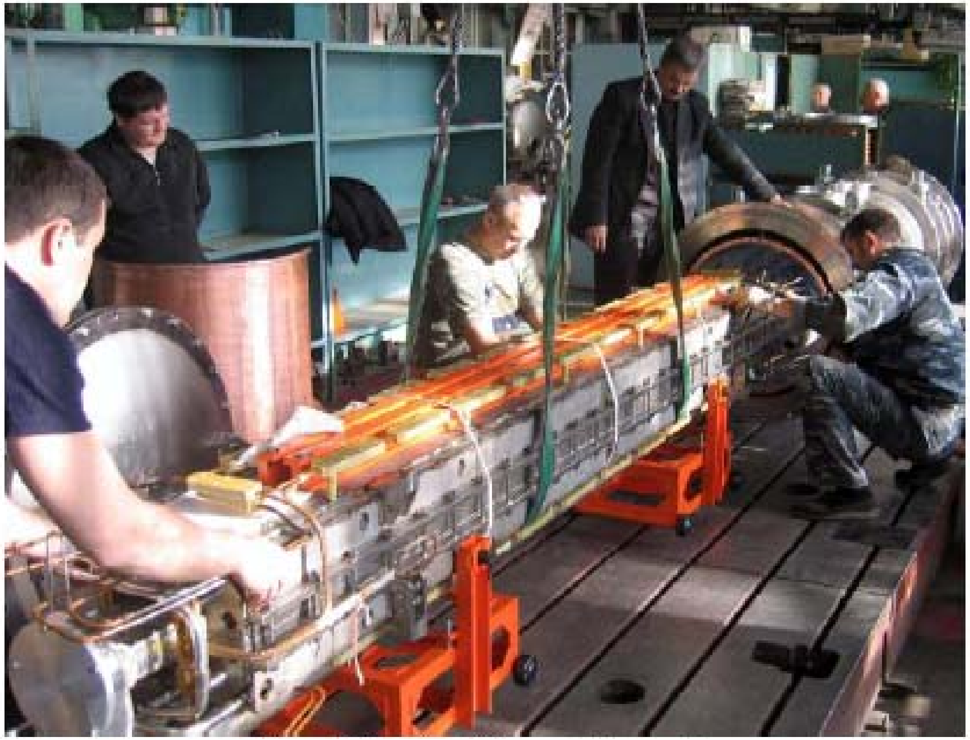
Full Size Model: Quadrupole Manufacturing at JINR



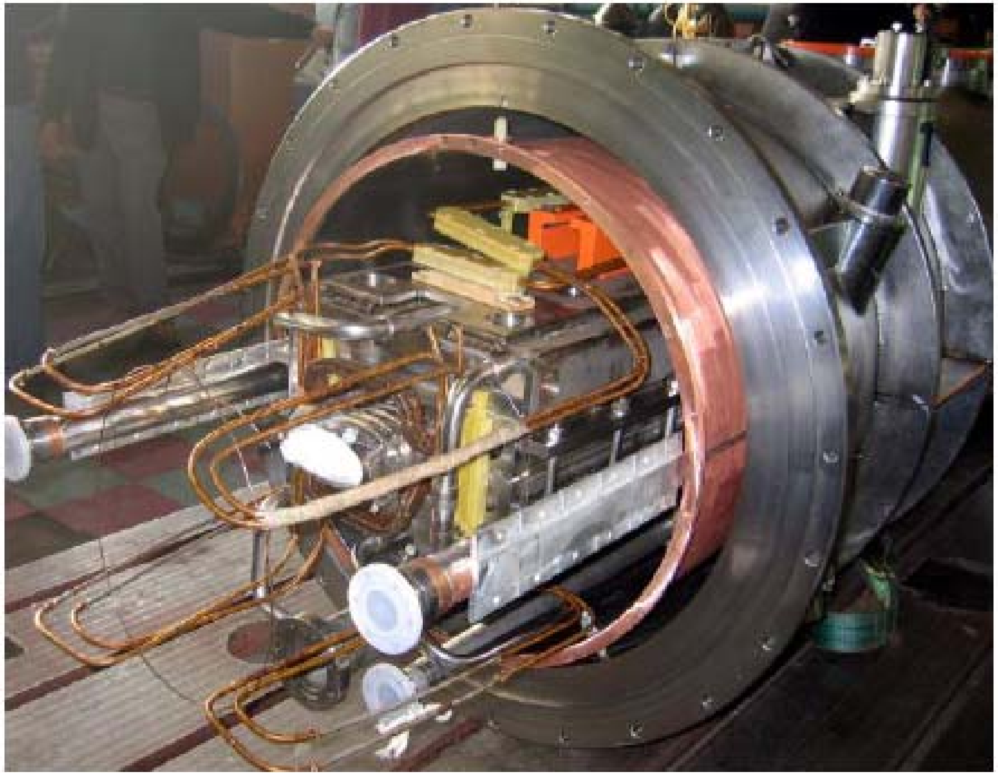


Photos of the manufactured quadrupole

Full Size Model: Curved Dipole from BINP



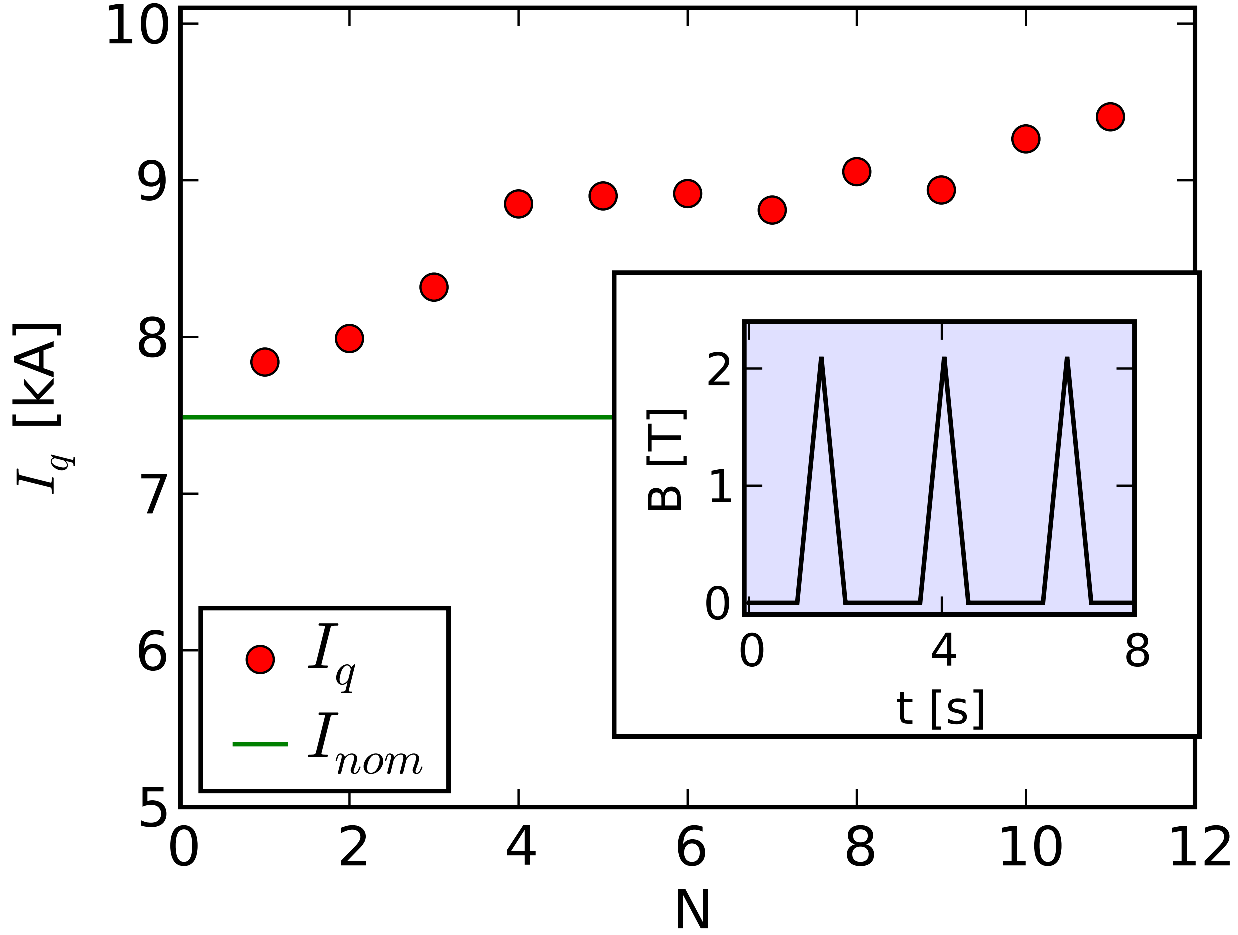
Inserting the dipole into the cryostat



Magnet in cryostat

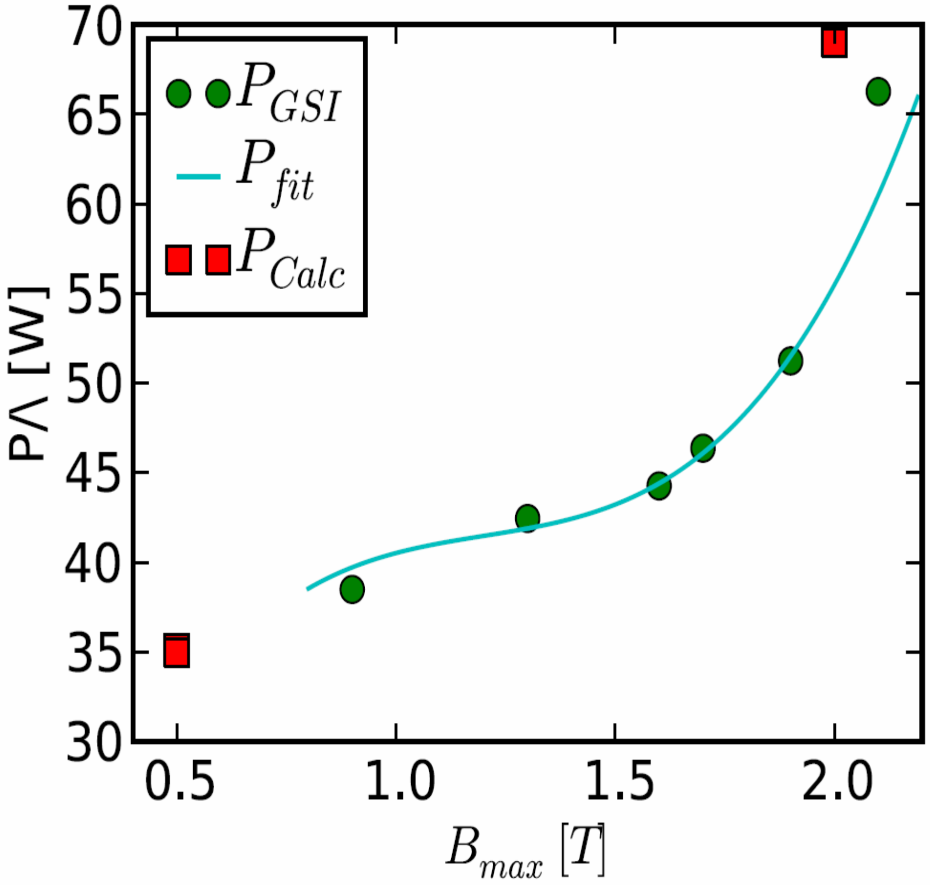
- ► **Yoke and cryostat from BINP Novosibirsk**
- ► **SC coil produced at JINR Dubna**
- ► **completion for testing at GSI**

Measurement Results : Magnet Training

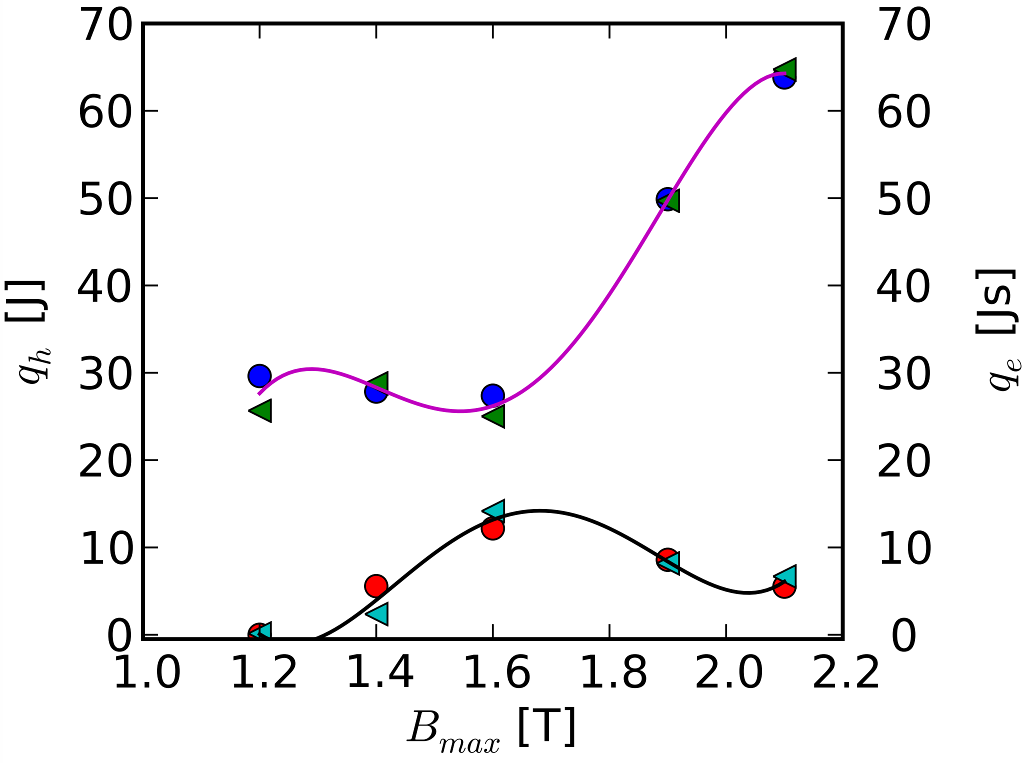


Quench training curve for the first prototype. The insert on the right shows the strongest cycle mode of the magnet continuously tested during one week.

Measurement Results: Magnet Losses



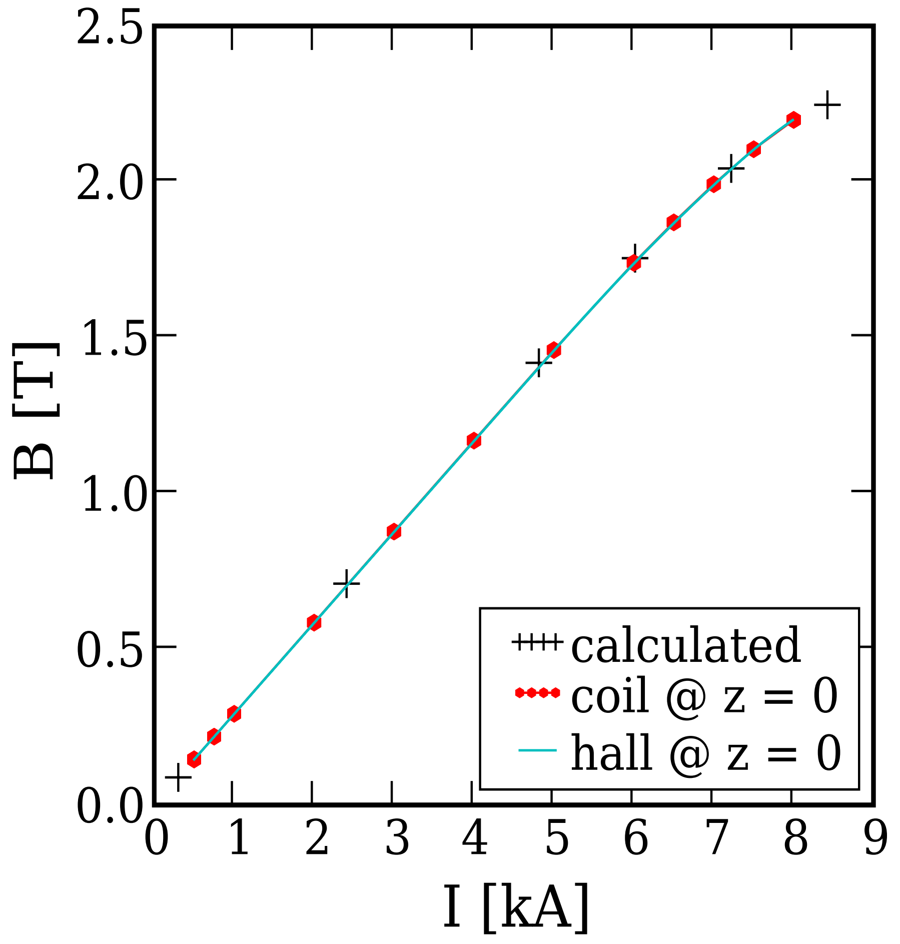
dB / dt = 4 T/s



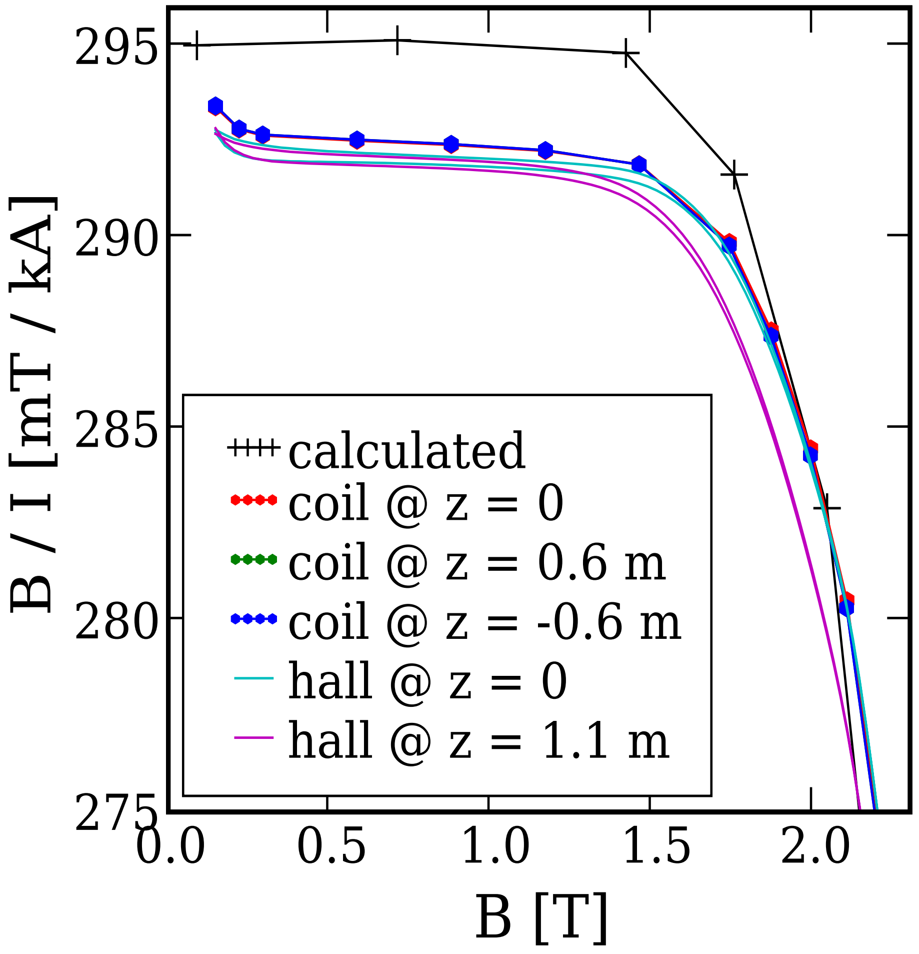
$P = q_h(B_{max})\, f + q_e(B_{max})\, f^2$

Preliminary results within good agreement with calculations (ANSYS, and extrapolation from short model magnet measurements)

Measurement Results: Loadline



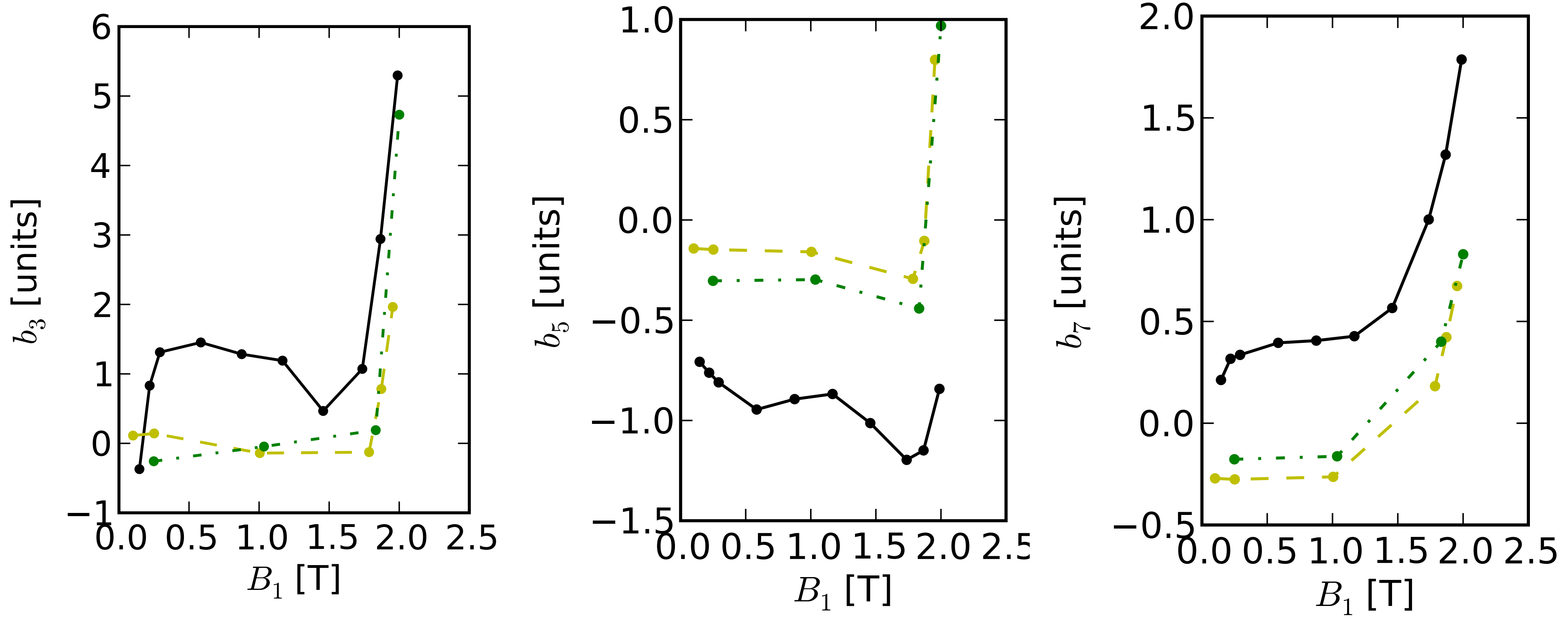
Load Line



Transfer function

Measurements in good agreement with calculation (only catalog data at 50 / 60 Hz)

Measurement Results: Allowed Multipoles



Measurements versus Calculation for the centre:

black: measurement
green: ANSYS
yellow: TOSCA 3D

See also: Poster TH5PF05

Additional Operation Requirements

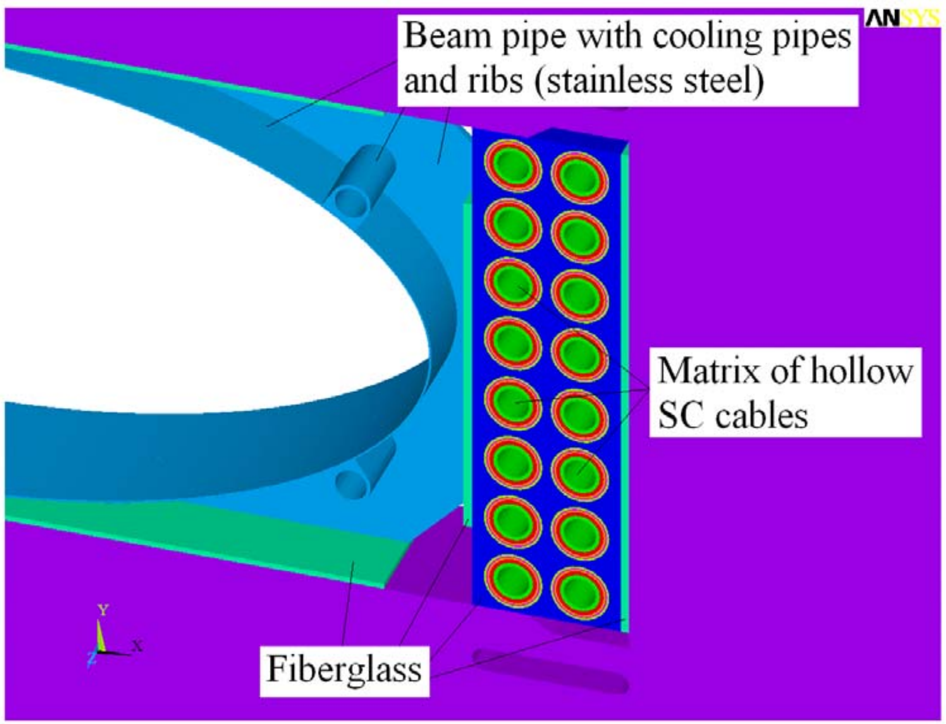
- current dipole delivers triangular cycle with a pause of 1.55 s → $\tau = 2.55$ s
- limited by the maximum cooling capacity
  - hydraulic resistance of the coil
  - maximum pressure due to two phase regime

  → new high current cable → half turns → Curved Single Layer Dipole

- but reduction to t = 1 (no pause required)

- vacuum chamber as cryopump → additional cooling of the vacuum chamber

Vacuum Chamber Issues



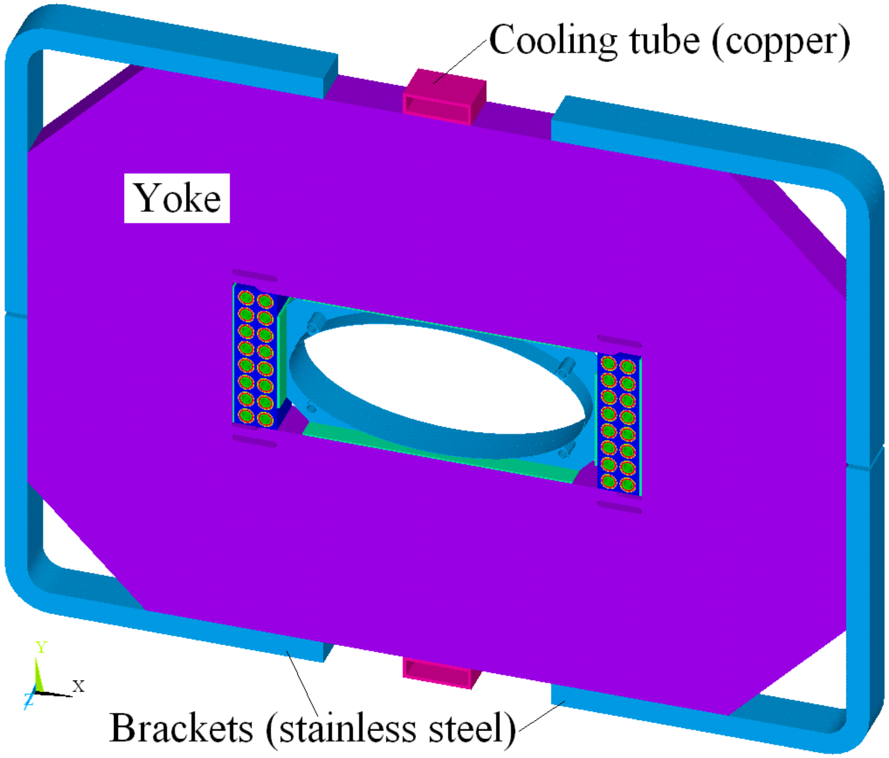
Vacuum chamber: ribs & cooling pipes

periodic "quasi 2D" model

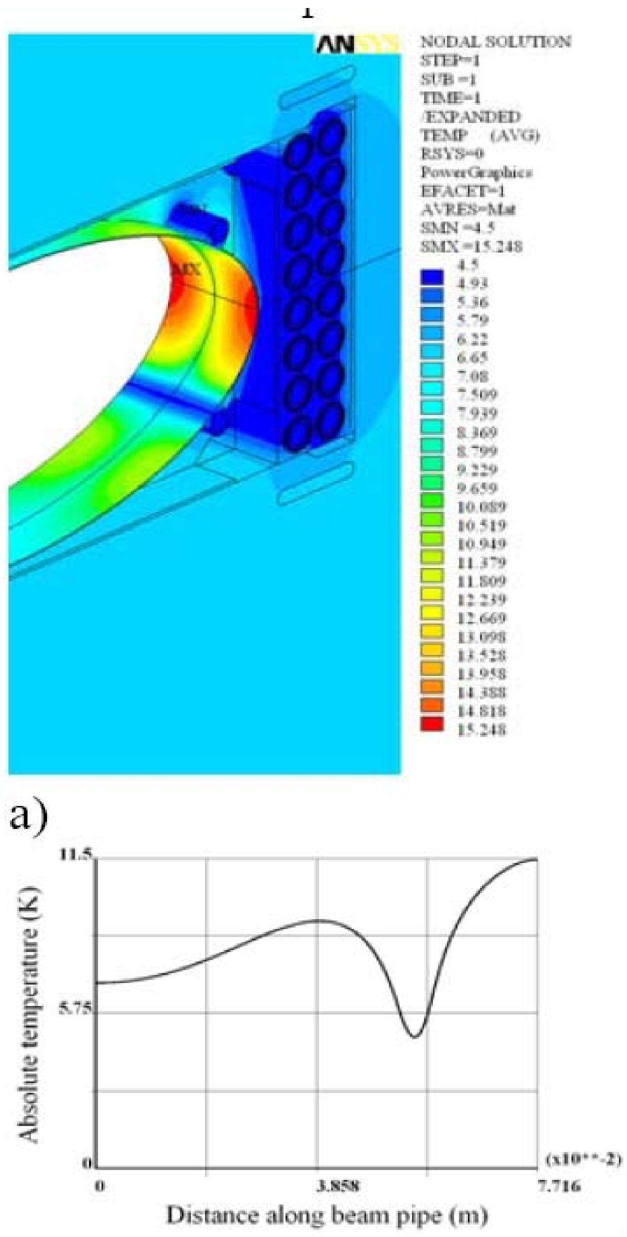
transient analysis: steady state after 60 cycles

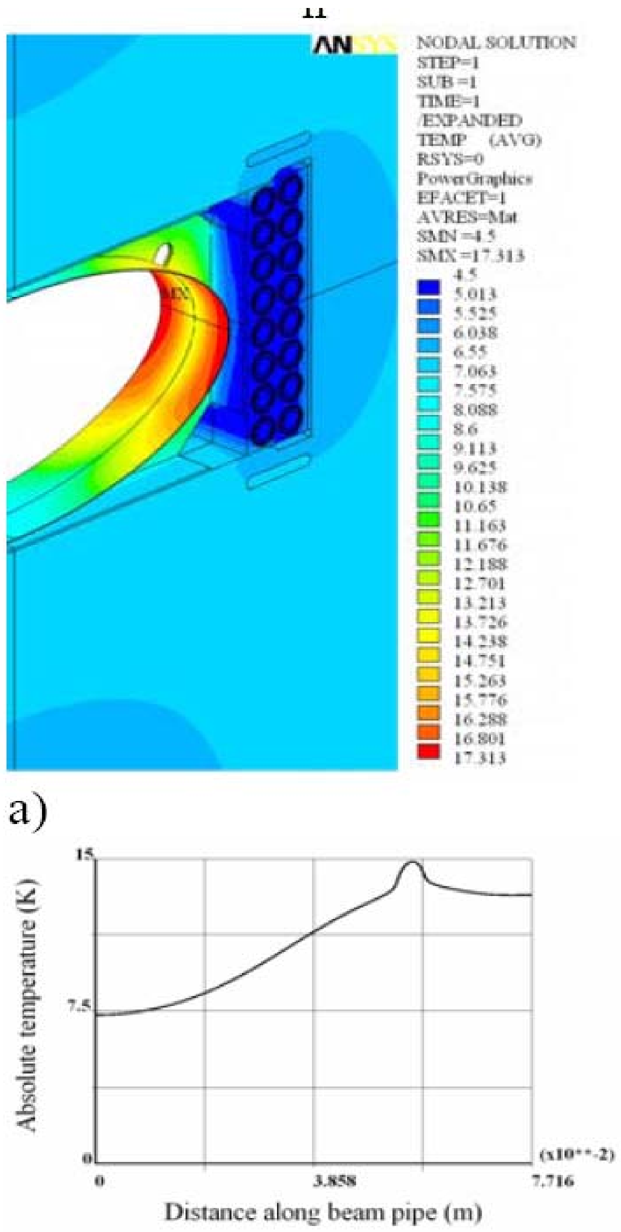
Additional 25 W heat load (= 1/3 of the magnet)

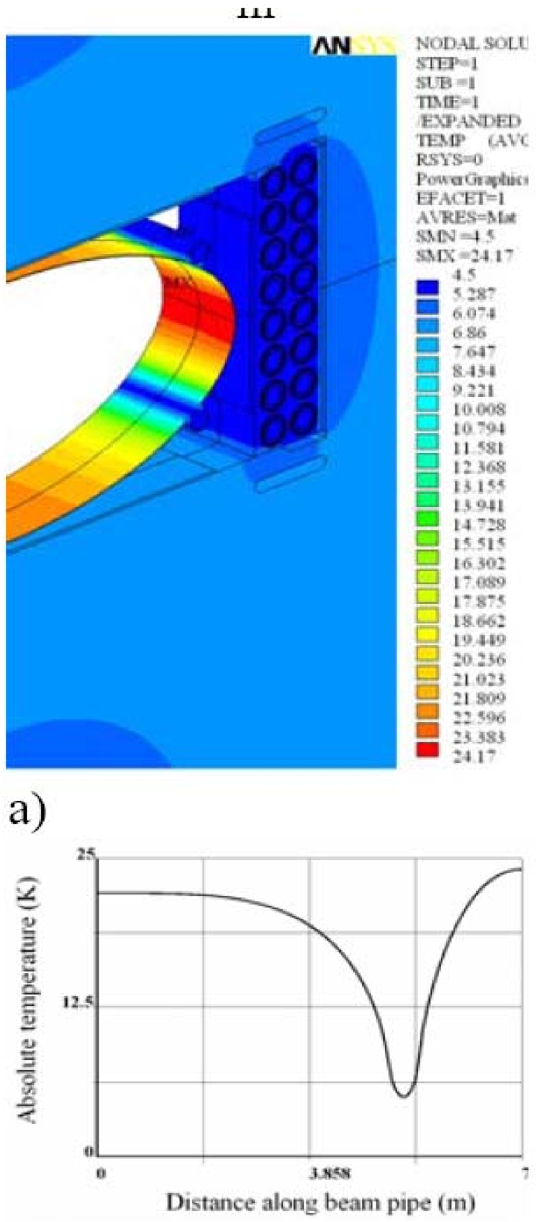
E. Fischer, R. Kurnyshov, and P. Shcherbakov, “*Analysis of coupled electromagnetic-thermal effects in superconducting accelerator magnets*”, EUCAS *2007*



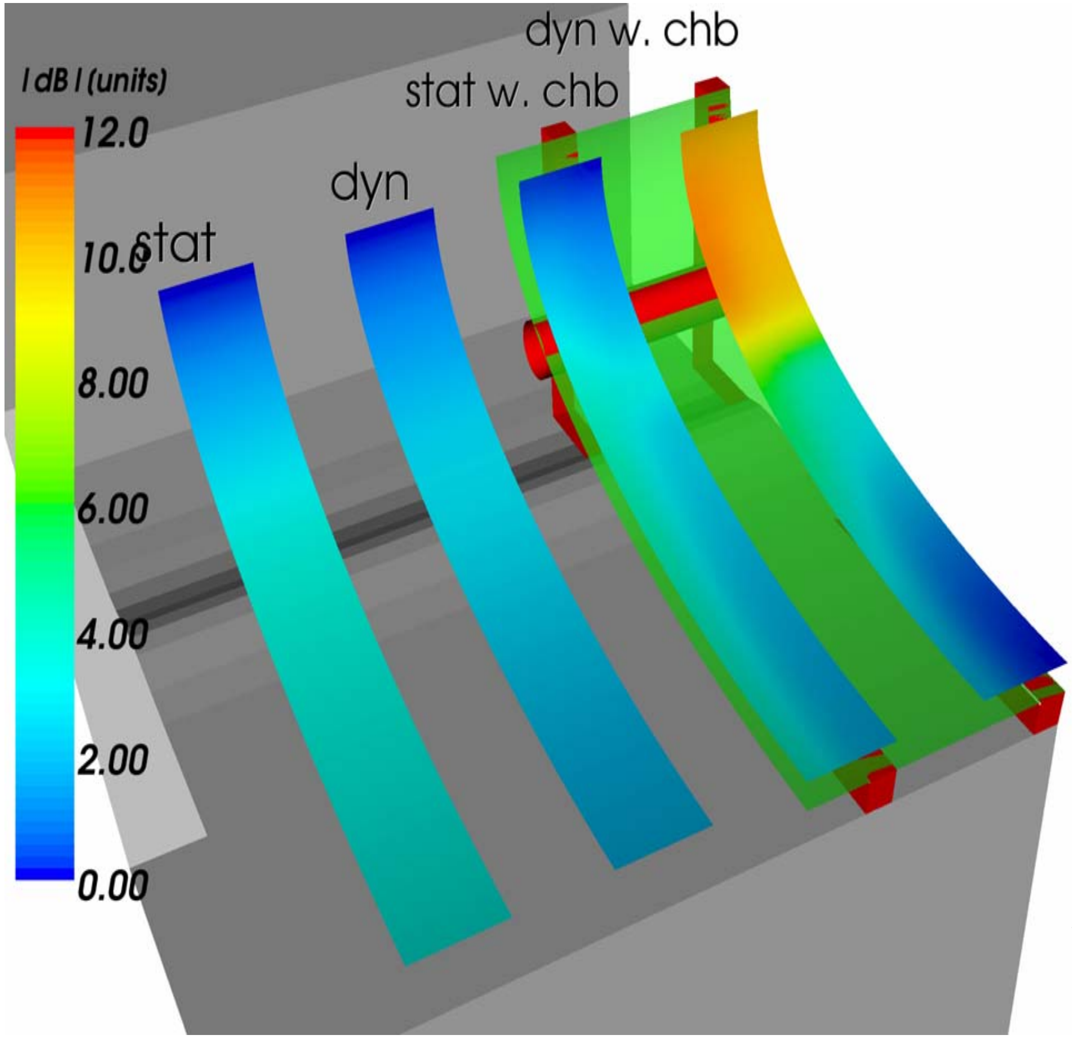
Vacuum Chamber: Temperature Profile

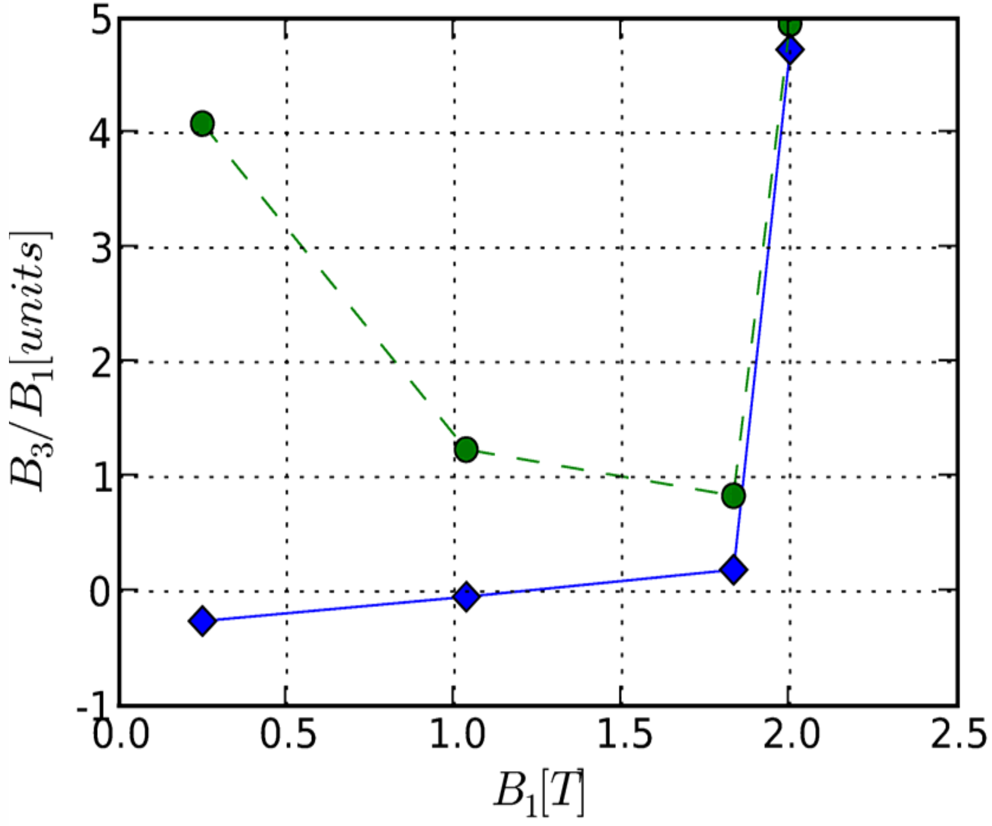






Vacuum Chamber Issues: Field Quality





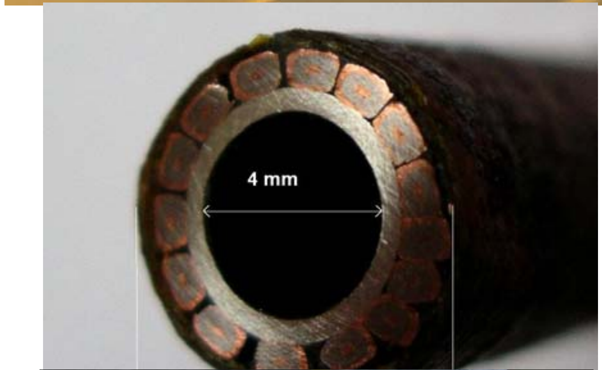
Vacuum chamber: ribs & cooling pipes eddy currents large field deviation at injection

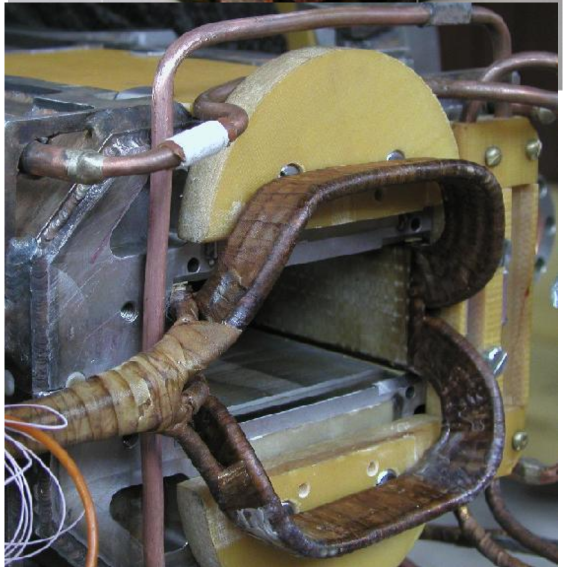
see also E. Fischer et al, *Numerical Analysis of the Operation Parameters of Fast Cycling Superconducting Magnets* ASC08

The Final Dipole Design

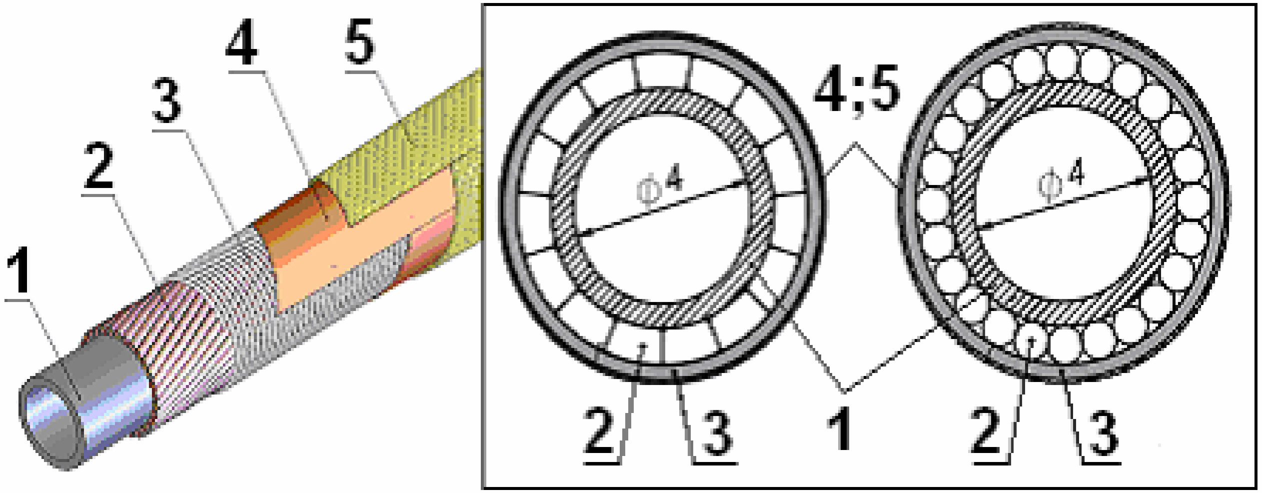
- **Current Design non sufficient period τ**
  - **vacuum chamber, safety margin**
- **Redesign:**
  - **new cable design (with lower hydraulic resistance)**
  - **shorter coil length**
  - **CSLD (curved single layer dipole)**
  - **based on already developed cable and tested model magnets**

Magnet Design Options: new cable and single layer coil





"DESIGN AND TEST OF A HOLLOW SUPERCONDUCTING CABLE BASED ON KEYSTONED NbTi COMPOSITE WIRES", ASC 2004, October 2004, Jacksonville, USA H. G. Khozhibagiyan et al., ASC2004, Jacksonville, Florida, USA, IEEE Trans. on Supercond., Vol. 15, No. 3, Part II, pp. 1529-1532, June 2005

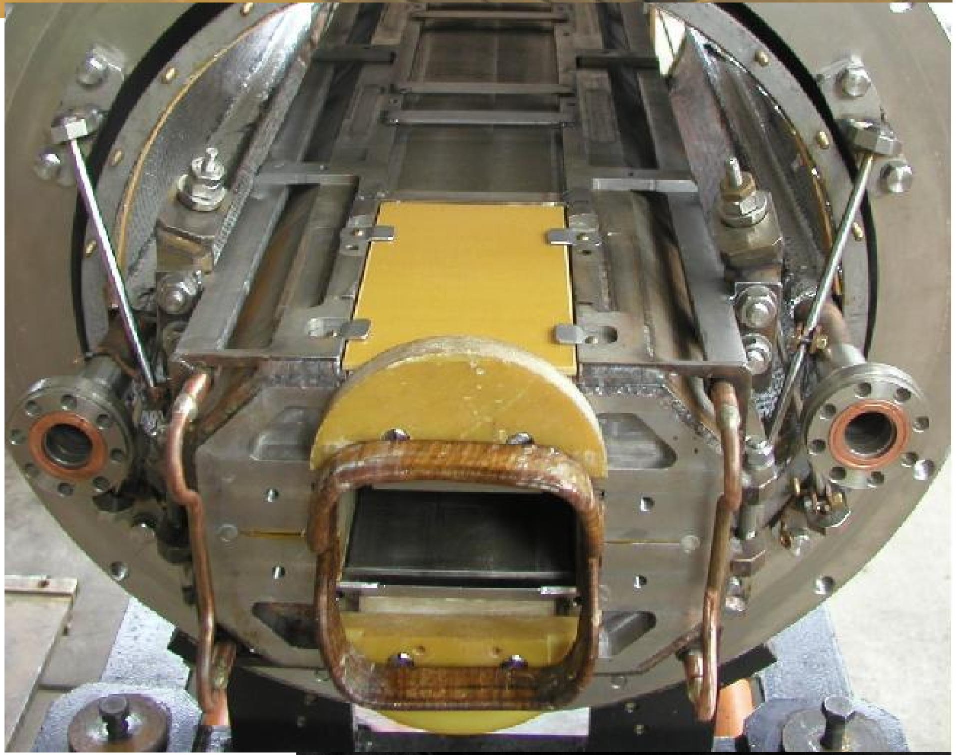


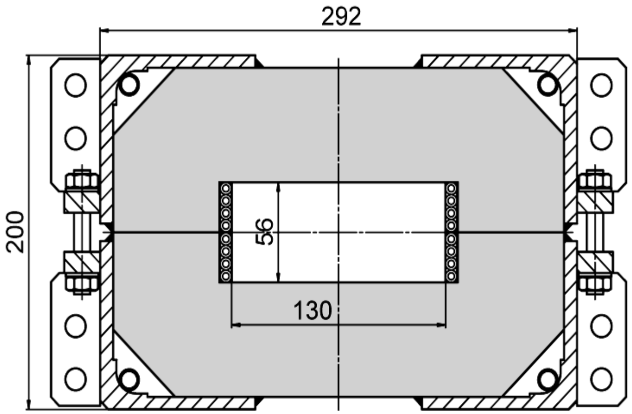
- **cycle limit estimations for a round wire cable CSLD with 8 turns (detailed specification in MT-INT-EF-2007-002, GSI):**

Dynamical heat release (cycle 2c)	W	**≈ 31**
Pressure drop for cycle 2c	bar	**≈ 0.42**
Maximal temperature of helium in the coil (2c)	K	**4.7**
Dynamical heat release (B_{max} = 1.9 T, f = 1 Hz)	W	**≈ 54**
Pressure drop (B_{max} = 1.9 T, f = 1 Hz)	bar	**≈ 0.7**
Maximal temperature of helium in the coil (triangular cycle with B_m = 1.9 T, f = 1 Hz)	K	**4.8**

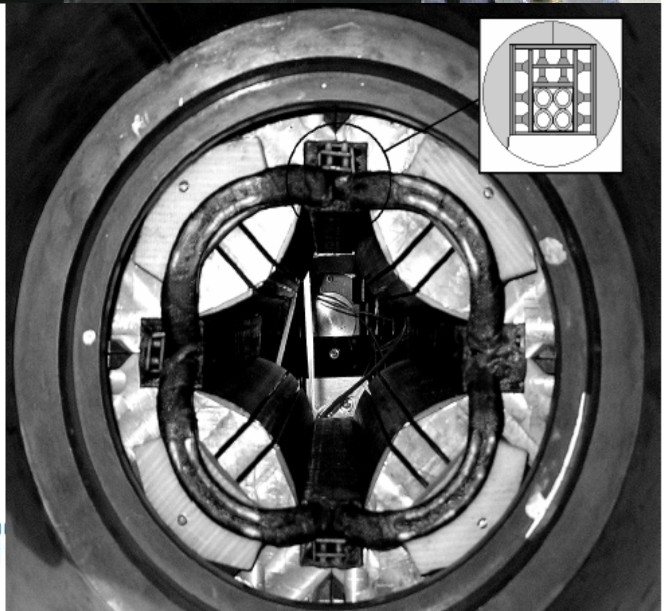
Design and Test of a Single Layer Coil Model

- advantages of a high current cable:
  - single layer coil
  - allows reducing the aperture and AC loss
  - simplifies cooling
  - simpler coil mechanics

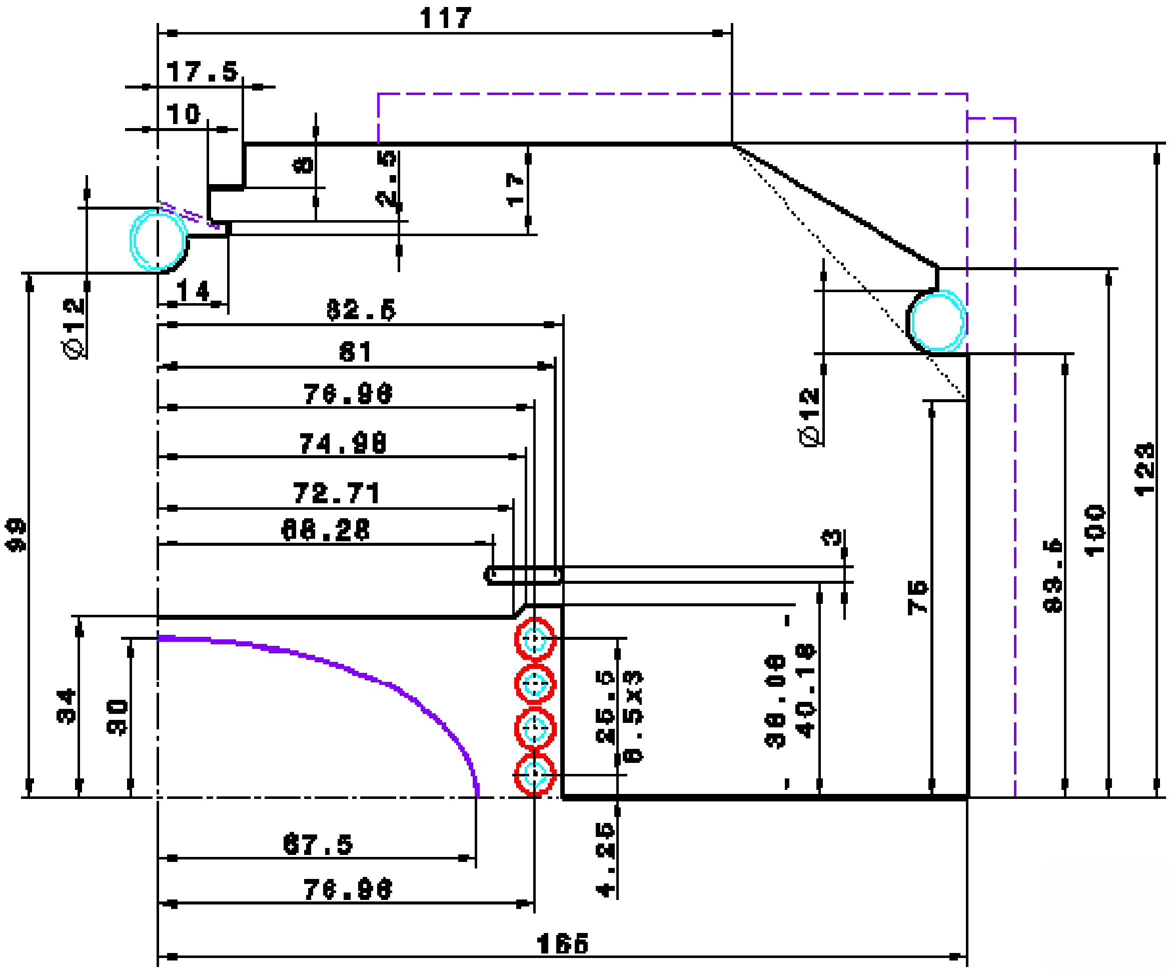




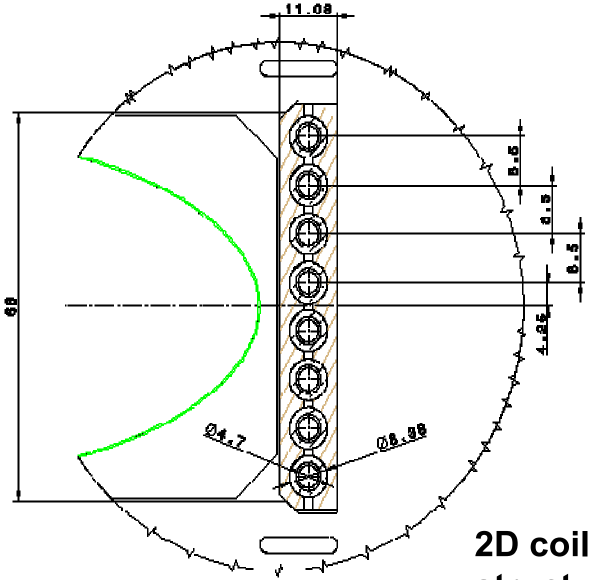
model dipole with a single layer coil, tested at JINR Dubna in 2004 and quadrupole in 2006



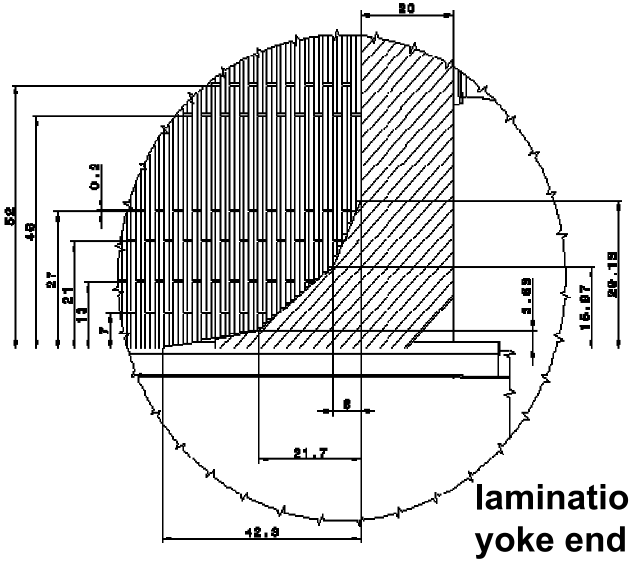
Dipole Redesign: Geometric Details (TDR)



lamination geometry



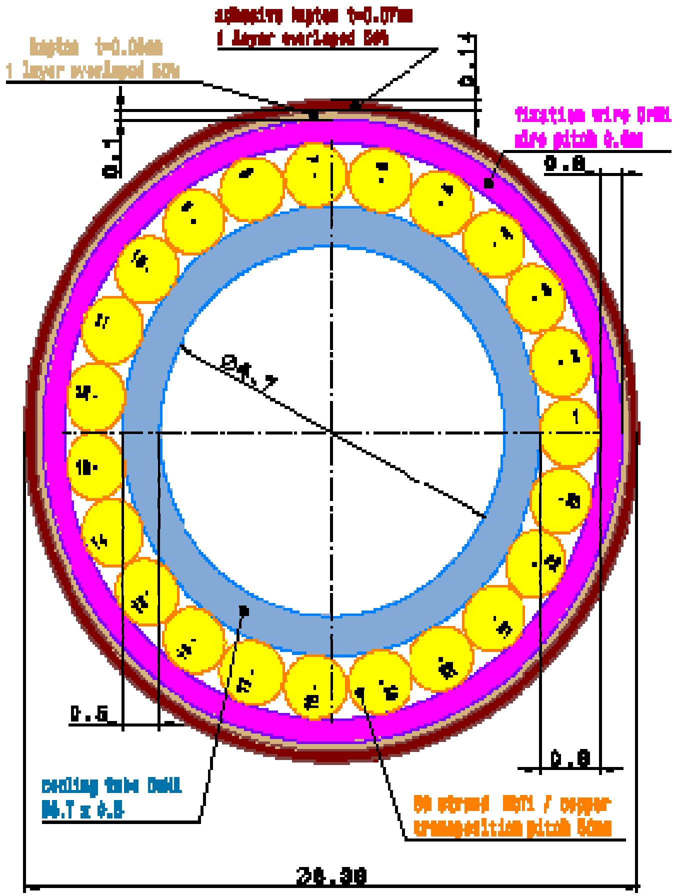
2D coil structure



lamination slits near yoke end

Dipole Redesign: Cable Parameters (TDR)

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	microns
2nd insulating layer		with epoxy impregnation			
	material			2	layers
	thickness	kapton	tape	70	microns
Wire					
Strand diameter				0.8	mm
Filament diameter				3.5	microns
Number of filaments				18144	
Filament twist pitch				5-8	mm
Superconducting material				NbTi	
Copper to superconductor ratio				1.5	
Copper RRR				196	
Transverse resistivity					Ωm
Fixation of the strands		CrNi-wire	D=0.2	transp. = 0.4	mm
Coating		epoxy compound			

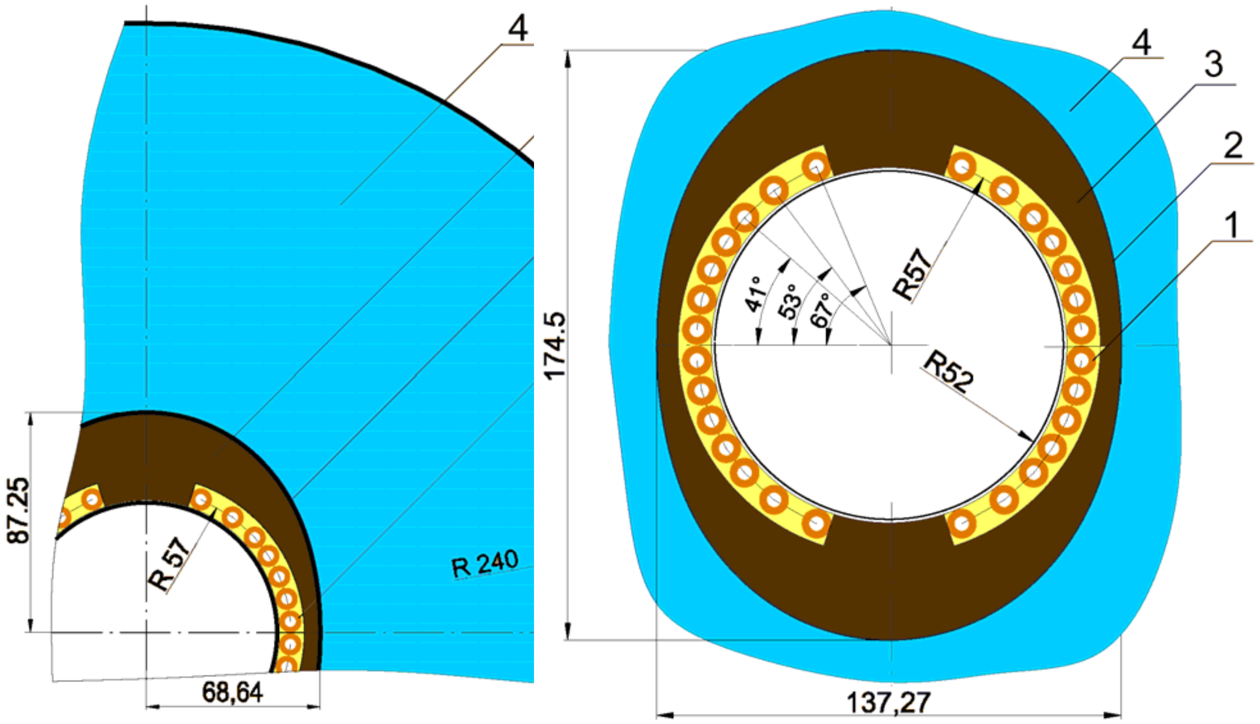


Cross section of the cable adopted for the SIS100 dipole coils (Nuclotron-type cable).

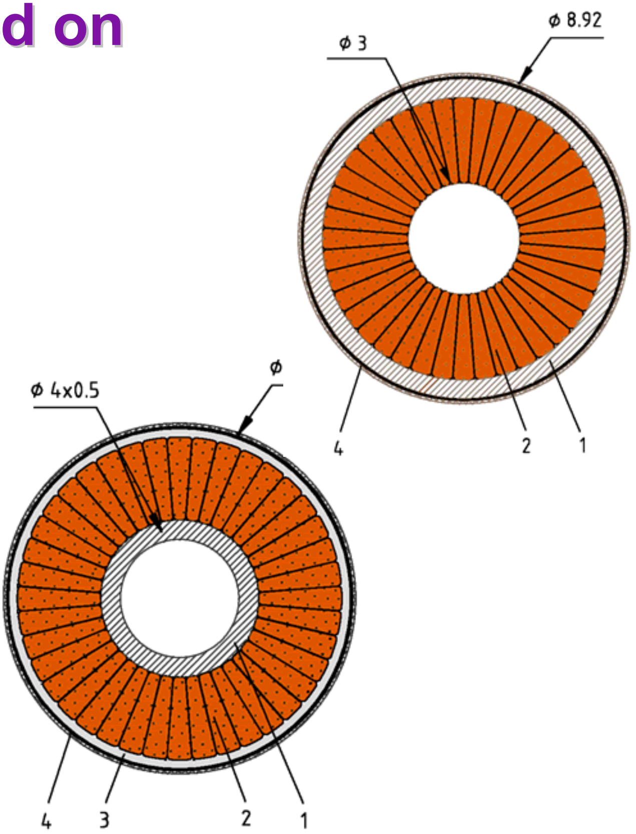
E. Fischer et al: *Fast Ramped Superferric Prototypes and Conclusions for the Final Design of the SIS 100 Main Magnets* ASC 2008

Common Design Aspects up to 4.5 T ?!

Design of a Fast- Cycling CosΘ-style Dipol Based on High Current Hollow Superconducting Cable



Optimized cross section of 4 T dipole: 1 – coil made from hollow super-conducting cable, 2 – ferromagnetic inner boundary, 3 – non magnetic collar, 4 – laminated ferromagnetic yoke.



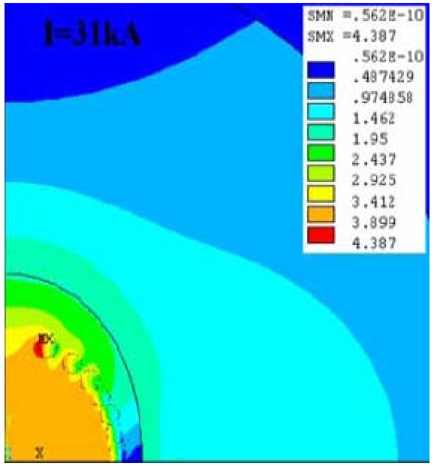
Cross sections of the high current cables: 1 - copper-nickel tube, 2 - composite NbTi strand of keystoned profile, 3 – strands binding by wire, 4 - electrical insulation.

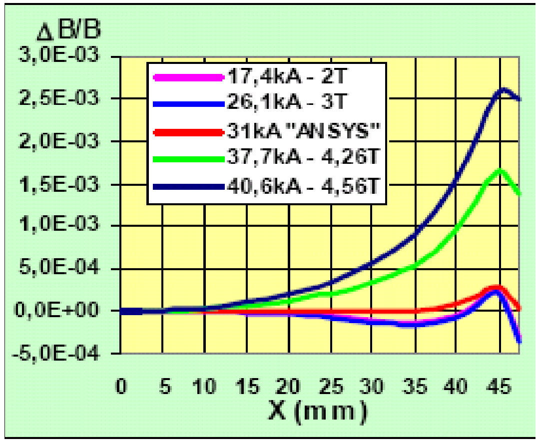
Ref.: H Khodzhibagiyan *et al.* 2006 *J. Phys.: Conf. Ser.* 43 731-734

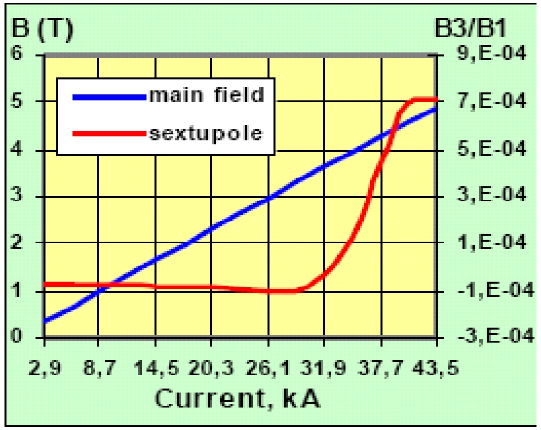
Common Design Aspects up to 4.5 T !

Parameter	Units	KWAT1	KWAT2	KWIT1
Cable diameter with insulation	mm	7.34	8.92	8.92
Cooling channel diameter	mm	4	3	3
Number of the strands		15	40	40
Strands cross-section area	mm^2	12.0	37.2	35.3
NbTi cross-section area	mm^2	4.29	16.8	15.9
Percentage of NbTi in cable cross-section	%	10.1	26.9	25.4
Critical current density @ 4.5T, 4.5K	A/mm^2	2070	2960	2960
Operating current at T=4.5 K	kA	12 @ 2T	40.1@ 4.5T	40.1@ 4.5T
Structural current density at T=4.5 K	A/mm^2	223@ 2T	504 @ 4.5T	504 @ 4.5T
Critical current at 4.5 K	kA	17.4@2T	49.6@ 4.5T	47.1@ 4.5T
Critical to operating current ratio		1.45	1.24	1.17

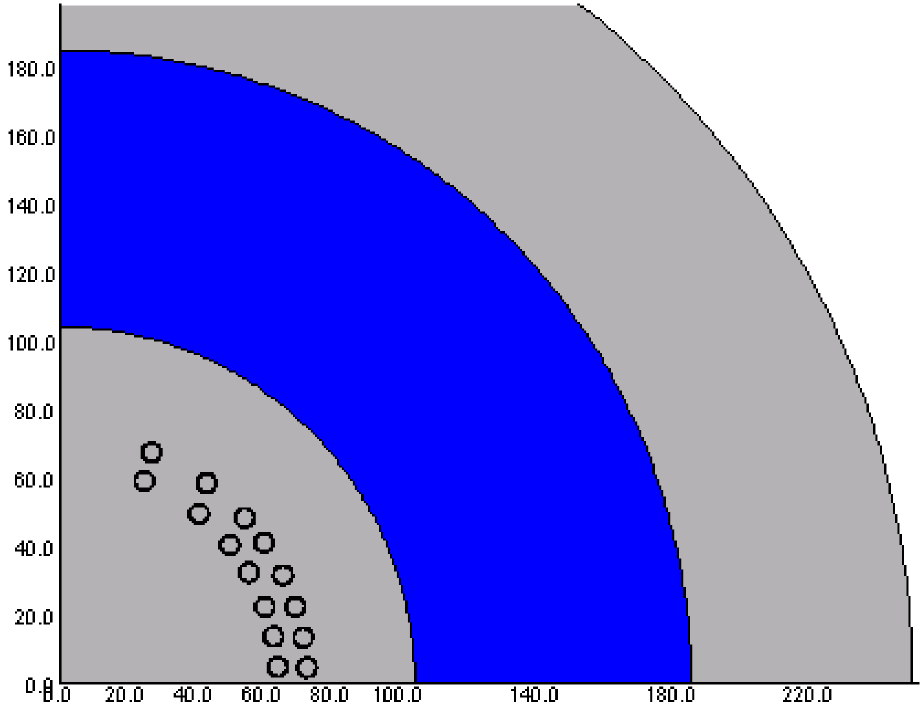
The results of 4 T dipole optimization: left – the field map, obtained with the ANSYS; middle plot – relative inhomogeneity of the field along horizontal axis; right – the dependencies of the gap magnetic field and the field sextupole component on supply current;

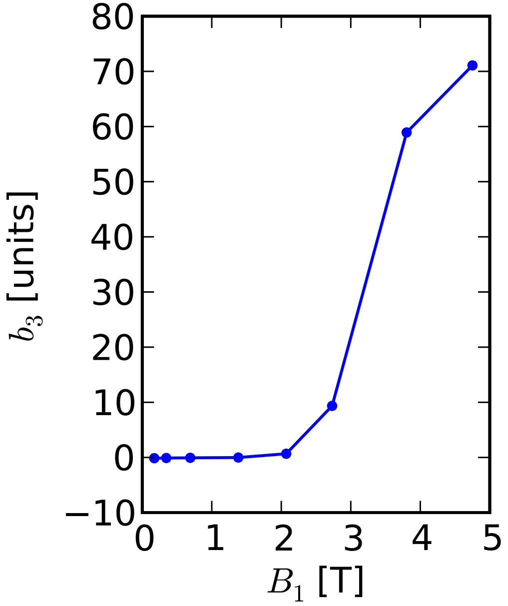


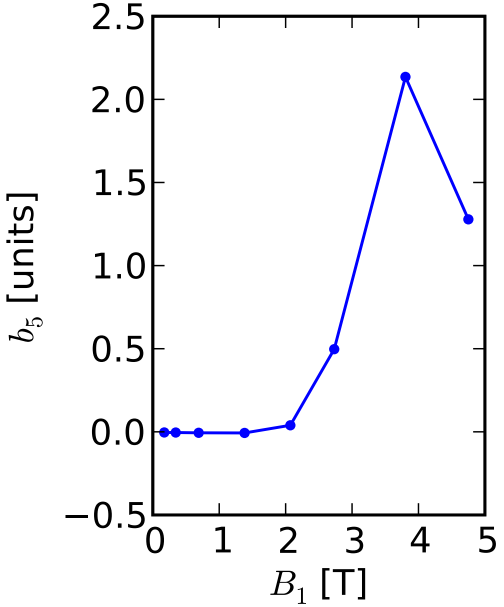


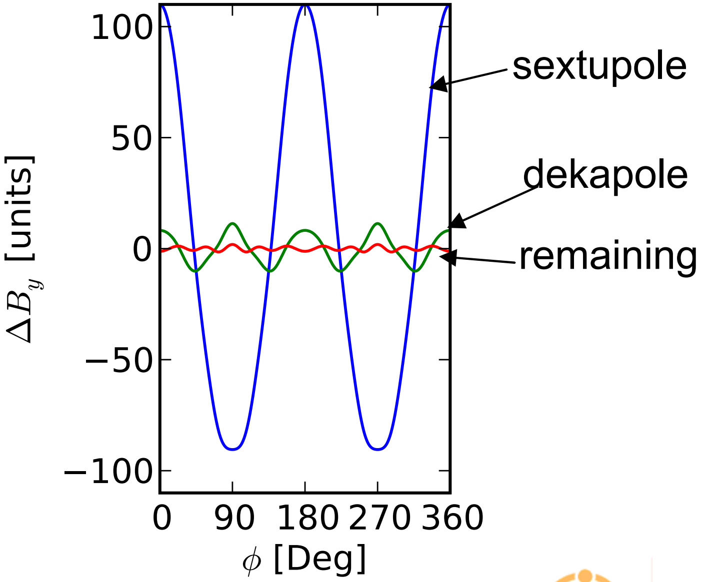


Common Design Aspects up to 4.5 T !









Field Quality study using TOSCA 3D:

large sextupole

but subtracting sextupole and dekapole gives field variation of one unit (red line)

thus Nuclotron cable does not limit achievable field quality

Summary

- The main R&D goals for the SIS100 magnets have been reached and were used to specify the design of the first full length model magnets for industrial production.
- The first full size dipole is being testing at GSI, a second dipole, a quadrupole and a curved dipole will be tested at GSI and JINR in 2009.
- The first test results (BNG dipole) confirm our R&D results and calculations of AC loss behaviour; magnetic field quality and stable coil mechanics.
- The comprehensive test of these models will give us important information required to optimize the final design and to specify the pre-series magnets.
- The redesign toward an optimized curved dipole with a single layer coil can fulfill the recently updated operation requirements of the FAIR SIS100 accelerator.
- We are sure that we are able to produce the superconducting magnets fulfilling the requirements and operation parameters of SIS 100.

Conclusion

The R&D results obtained for the SIS100 sc magnets, based on a superferric design utilizing Nuclotron type cables and cooled by two-phase Helium forced flow, provide effective alternatives for the construction of fast ramped accelerator magnets at least up to 4.5 T dipole field.