Full size model manufacturing and advanced design status of the SIS100 main magnets

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CARE-HHH-AMT Workshop
WAMSDO 19.-23. May 2008
CERN, Geneva

SIS100 main magnets: Contents

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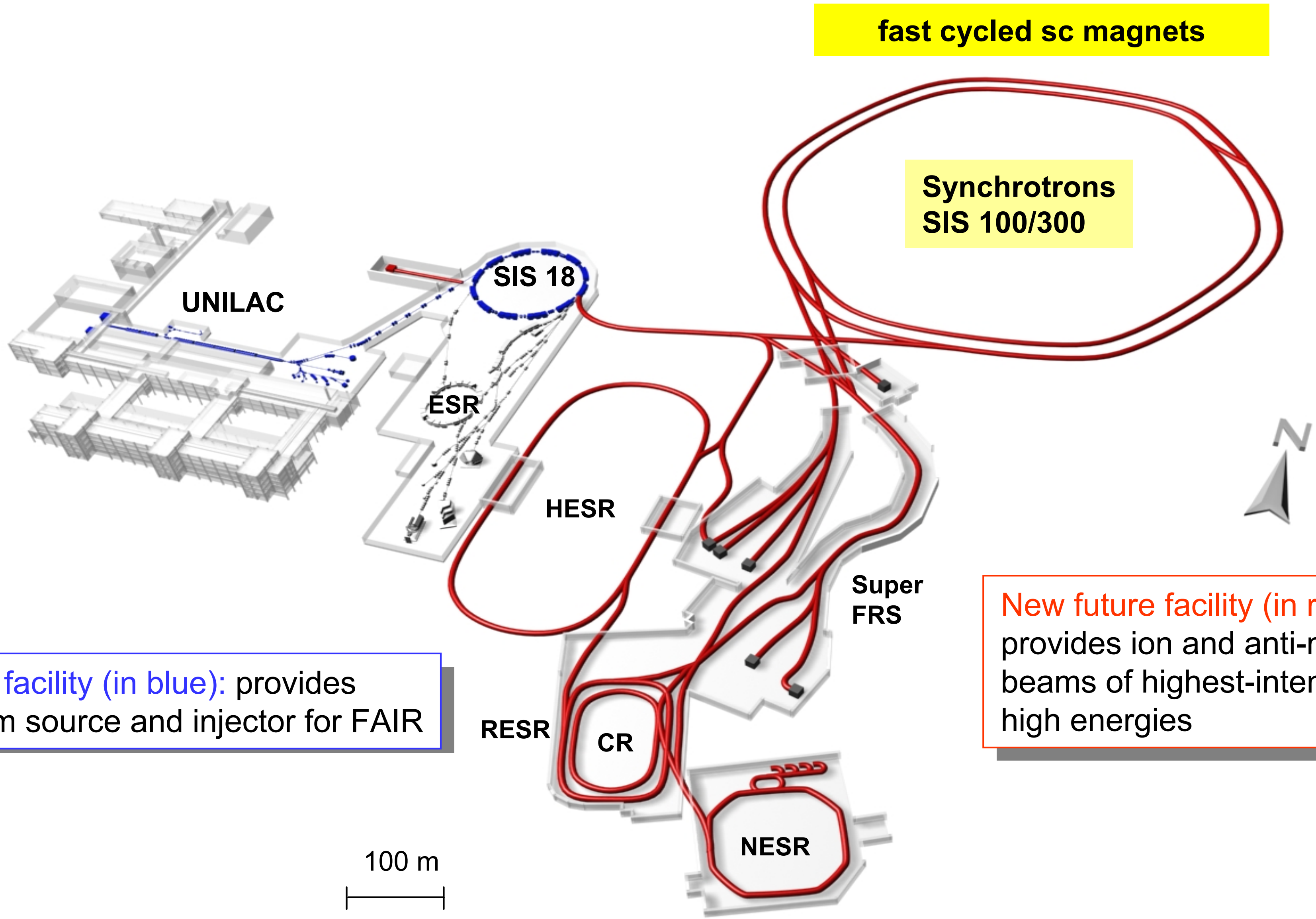
  - Design of the Curved SIS100 Dipole based on a Single Layer Coil
  - Main Operation Parameters of the CSL-Dipole
- Summary

FAIR: Facility for Antiproton and Ion Research



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

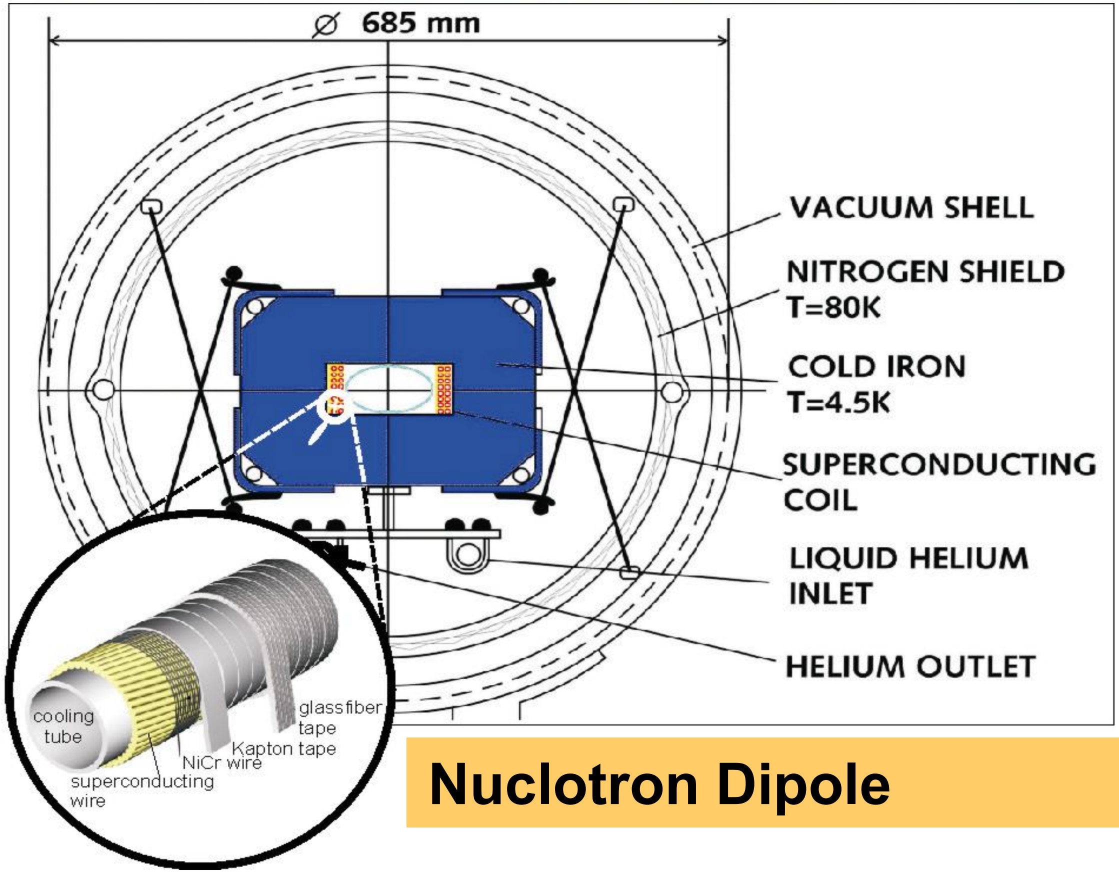
New future facility (in red): provides ion and anti-matter beams of highest-intensity and up to high energies

Basic magnet parameters of the SIS100

SIS100 Magnets	Number of magnets	nc/sc	Magnet design /type	Max. field (T), Gradient (T/m), etc.	Effective field length (m)	Bending angle(mrad) /radius (m)	*Useable horizontal / vertical aperture (mm)	Max. ramp rate (T/s,...)
Dipole	**108 + 1**	**sc**	**sf wf curved**	**1.9**	**3.062**	**58.18 / 52.632**	**115 / 60**	**4**
Quadrupole	**168 + 3**	**sc**	**superferric**	**27**	**1.3**		**135 / 65**	**57**
Quadrupole Inj./Extr.	**4**	**sc**	**superferric**	**27**	**1.3**		**135 / 65**	
Correction Magnets								
Error Comp. Quadrupoles**	12	sc	cos-theta	0.75 T/m	0.75		150	5 T/m*s
Chromat. Sextupoles	48	sc	superferric	350 T/m2	0.5		135 / 65	2000 T/m2*s
Error Comp. Sextupoles**	12	sc	cos-theta	50 T/m2	0.75		150	210 T/m2*s
Resonance Sextupoles	12	nc	6-fold	150 T/m2	0.74		150	2000 T/m2 *s
Error Comp. Octupoles**	12	sc	cos-theta	2000 T/m3	0.75		150	8500 T/m3*s
Fast quadrupole	1	nc	4-fold	12.5 T/m	0.54		125	125 T/m*s
Steering magnets								
Comb. h/v	84	sc	cos-theta	0.3	0.5	1.5	135 / 65	1.5
Extraction system steerer	1	sc	cos-theta	0.3	0.5	1.5	135 / 65	
Magnetic Septa								
Injection septum	1	nc	wf	0,82	1,5	h: 69	70 / 40	
Lambertson septum	1	nc	wf	0,6	1	v: 5.6/166.67	30 / 40	
Extraction septum 1	1	nc	wf	0,35	1,5	v: 5.1	60 / 30	
Extraction septum 2	1	nc	wf	1	1	v: 10	70 / 35	
Extraction septum 3***	1	nc	wf	v: 1.85 h: 0.25	2,2	V: 40.5 h: 5	80 / 45	
Transfer septum 1	1	nc	wf	0,8	0,5	v: 4	40 / 40	
Transfer septum 2	1	nc	wf	1,57	3	v: 47.2	40 / 40	

* (horizontal x vertical) or diameter if circular
** form one magnet unit
*** separate coils: vertical and horizontal

Main R&D Results on Nuclotron based SC Magnets



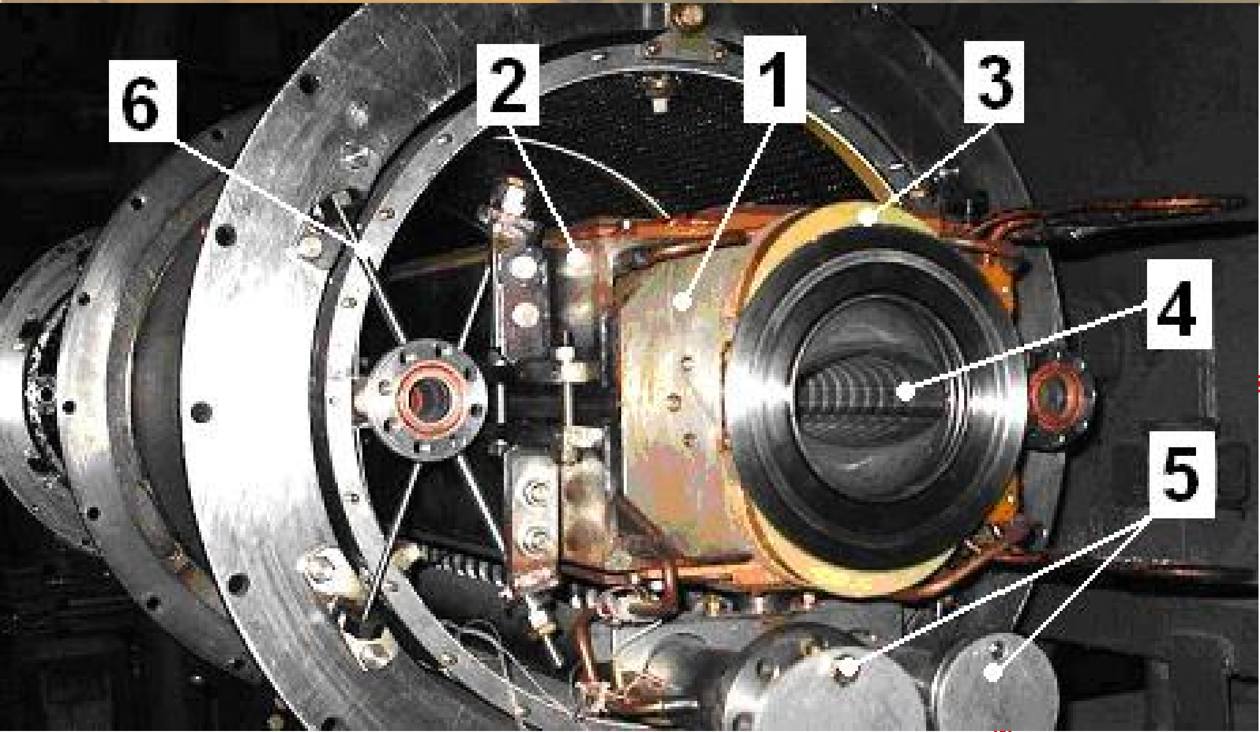
R&D goals

- **Reduction of eddy / persistent current effects at 4K (3D field quality, losses)**
- **Improvement of DC/AC - field quality**
  - 2D / 3D calculations
  - magnetic measurements
- **Guarantee of long term mechanical stability**
  (≥ $2 \cdot 10^8$ cycles) ► Main concern: fatigue of the conductor and precise positioning

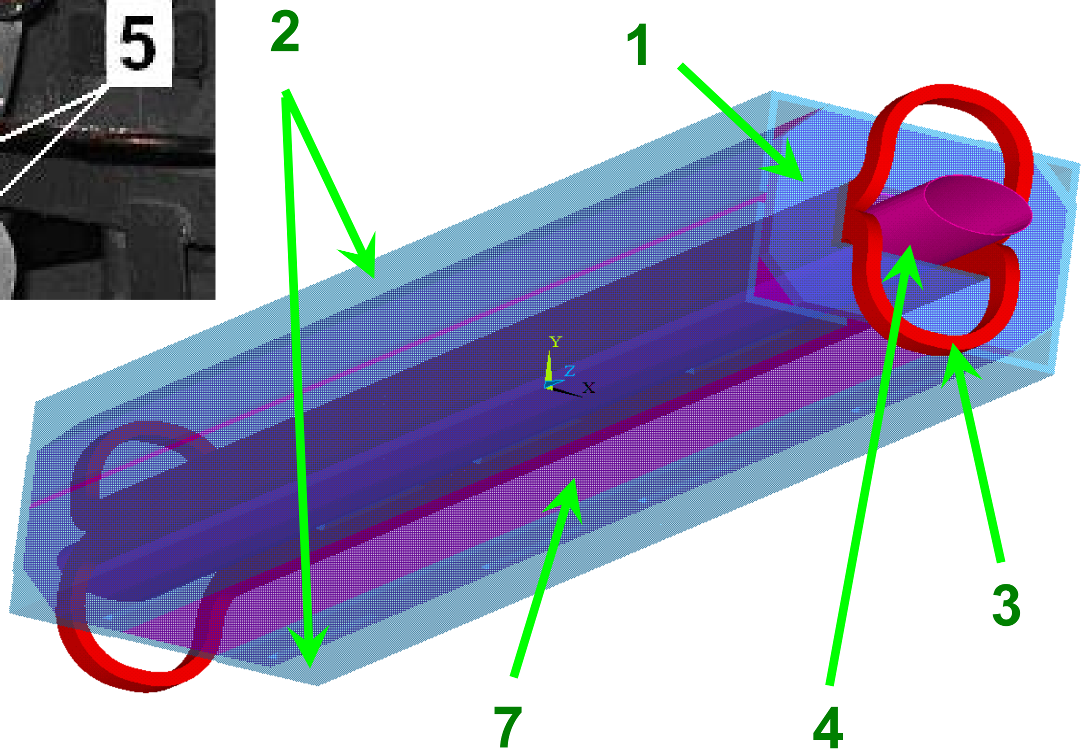
Nuclotron Dipole

- Iron Dominated (window frame type) superferric design
- cold iron
- Maximum magnetic field: 2 T, Ramp rate: 4 T/s
- Hollow superconducting cable, indirectly cooled
- Two-phase helium cooling

Main R&D Results: short test models & FEM

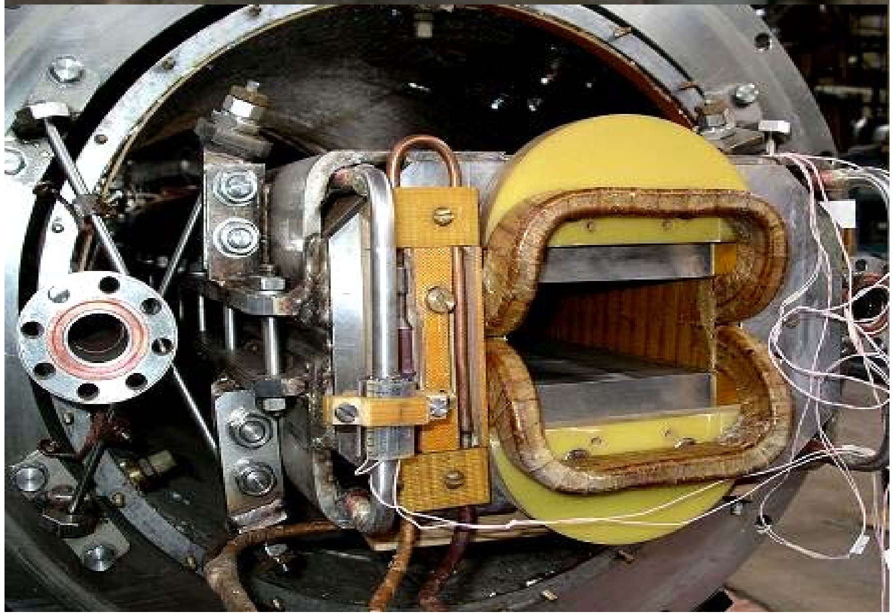


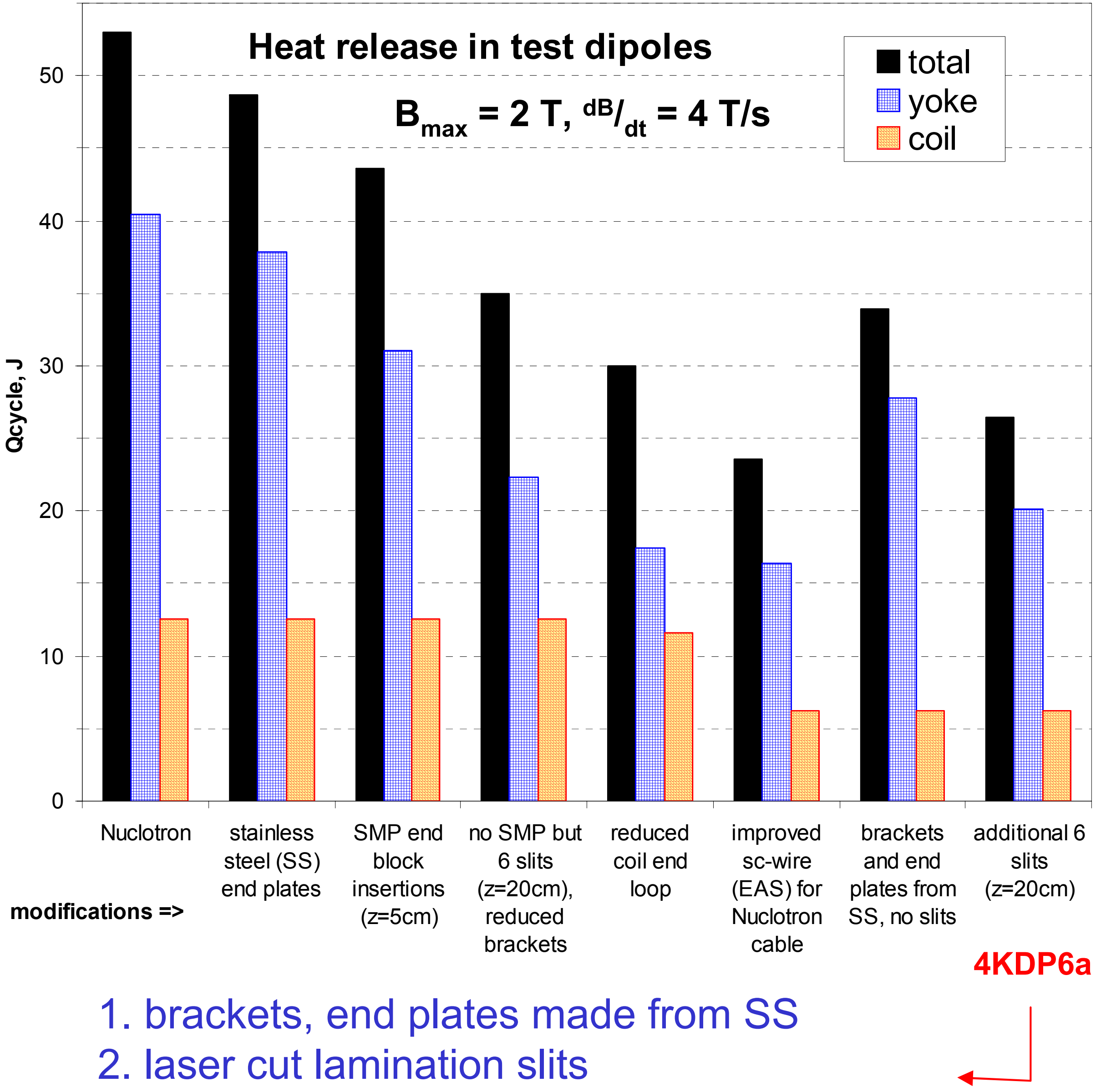
- Test measurements on magnet modifications
- FEM calculations on detailed 3D-models



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: status of loss reduction





1. brackets, end plates made from SS
2. laser cut lamination slits
3. minimized coil ends

Main R&D Results: FEM data vs. loss measurements

Original Nuclotron	P_{eddy}, W	P_{hyst} W	Sum, W	Calorimetric measurements, W @ JINR Dubna
Yoke (SI)	9.51	9.04	18.6	
Endplate (ST3)	8.37	2.21	10.6	
Brackets (ST3)	10.5	5.42	15.9	
Total	28.4	16.7	45.1	42 ± 2

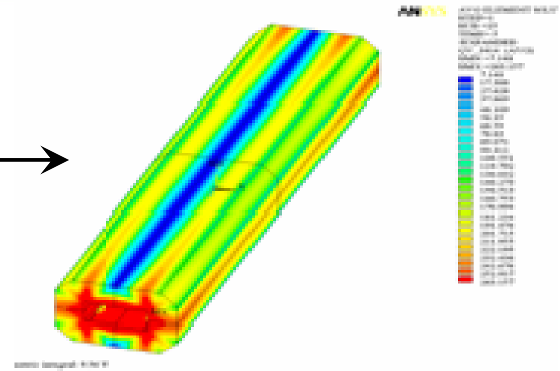
Calculated 45.1 W - measured 42 +/- 2 W

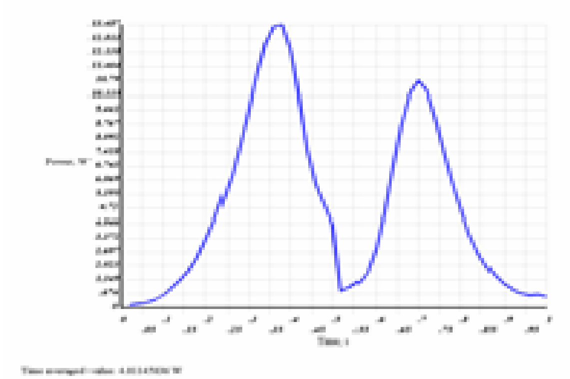
Good agreement with experimental results!

Main R&D Results: loss calculation and measurement

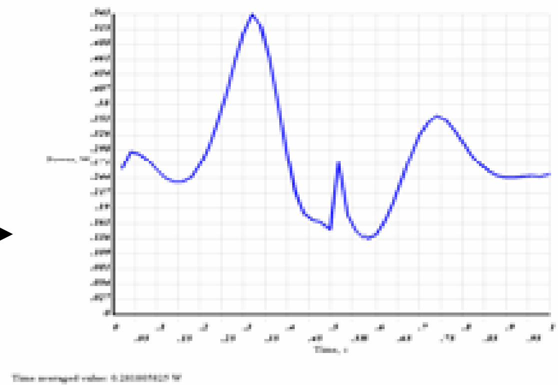
4KDP6a results for the triangular cycle with B_{max}= 2 T, $^{dB}/_{dt}$=4 T/s:

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

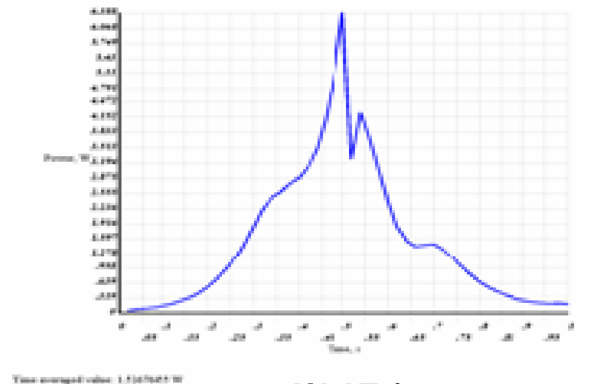




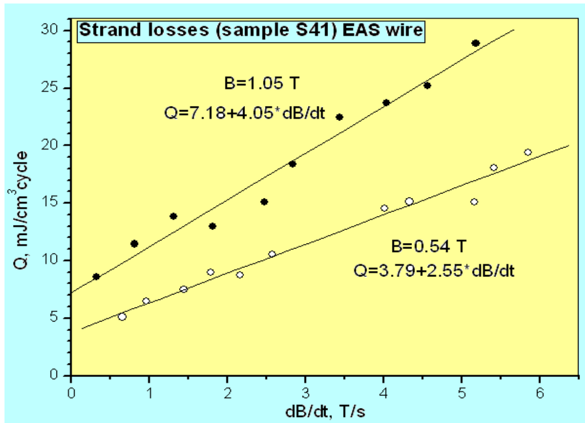
- Eddy current loss in the yoke ends = 4.81 J/cycle
- Eddy current loss in the ss end plates = 0.28 J/cycle



- Eddy current loss in the ss brackets = 1.53 J/cycle



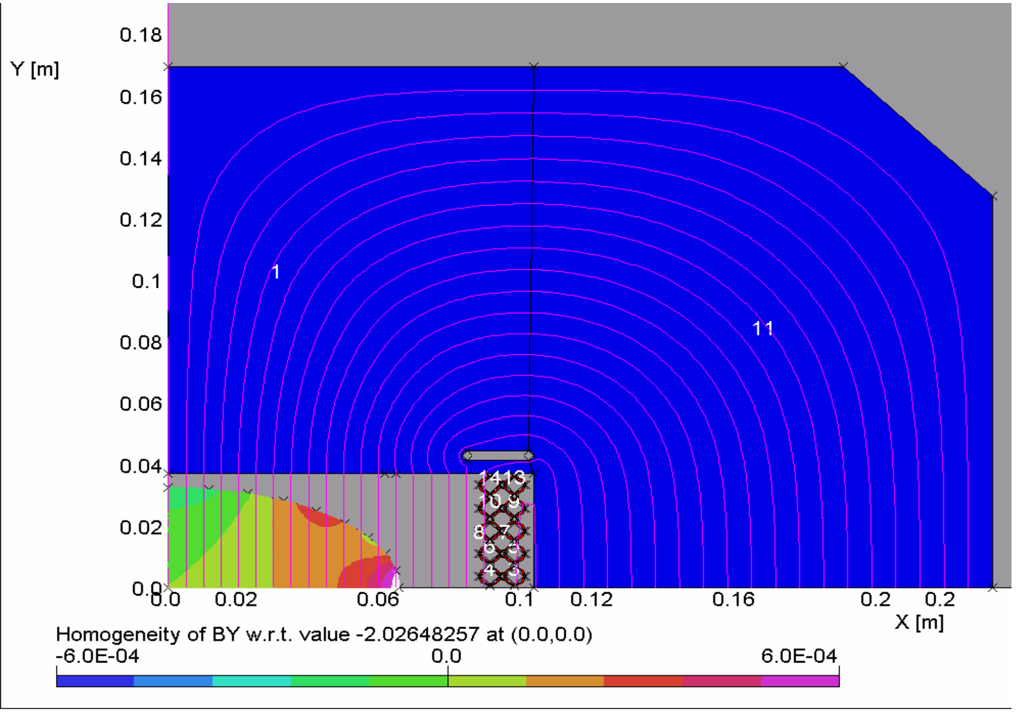
- AC loss in the superconducting coil = 6.4 J/cycle (from short sample measurements at JINR)

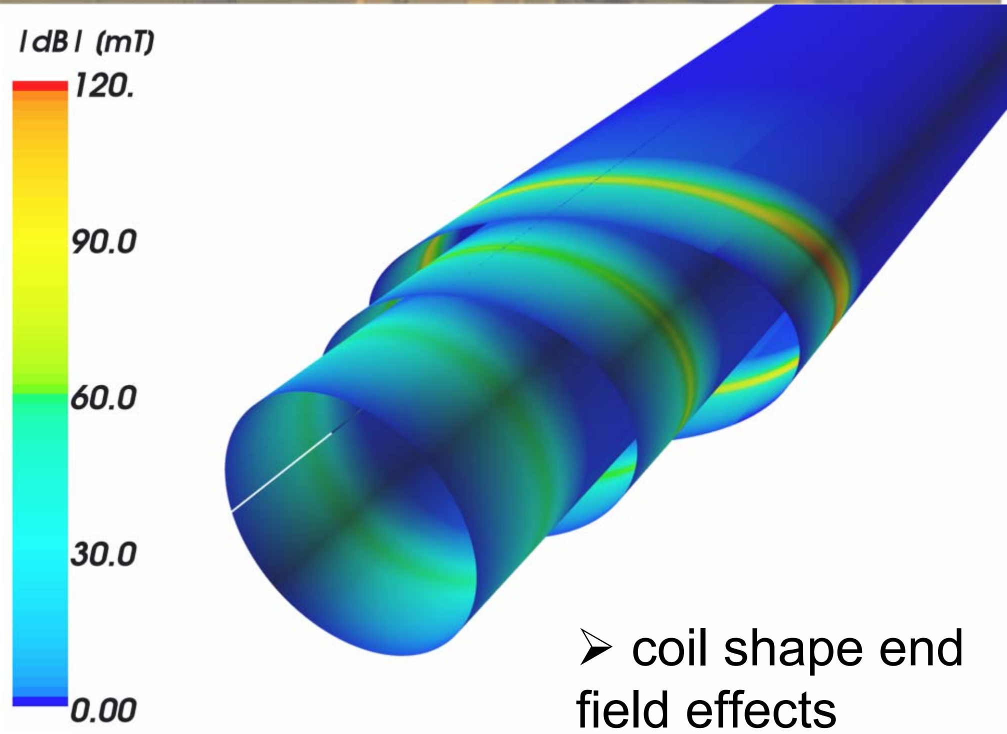


► **see also next session at WAMSDO:**
"Cold testing of rapidly cycling model magnets..."

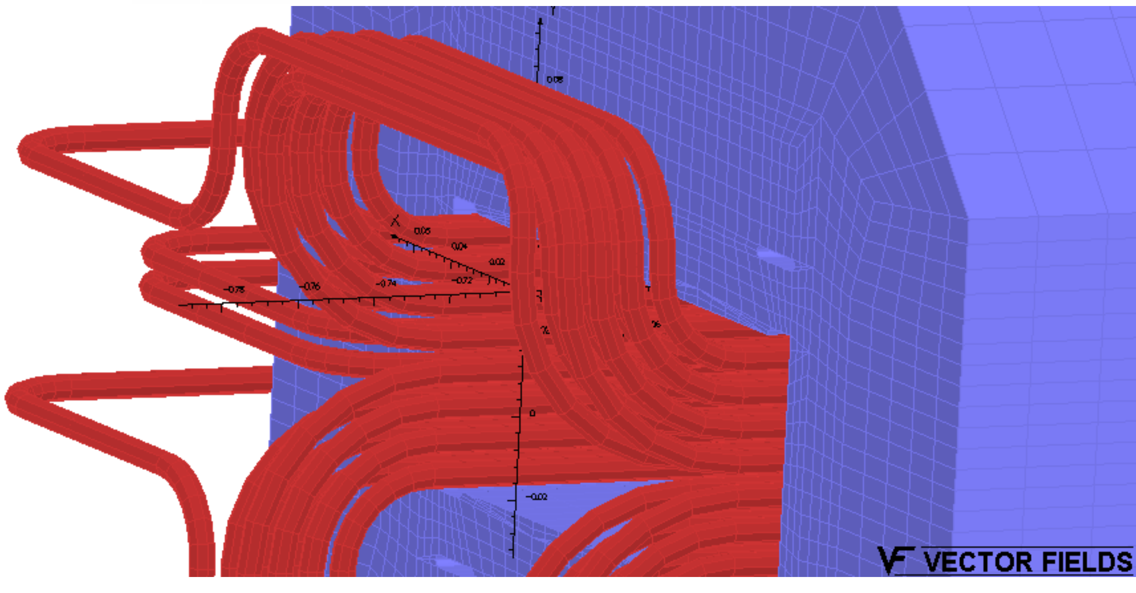
Main R&D Results: field quality analysis

- 2D and 3D FEM studies (using OPERA and ANSYS) for optimization of the field quality
- Theoretical R&D for effective magnetic field representation: Elliptical Multipoles



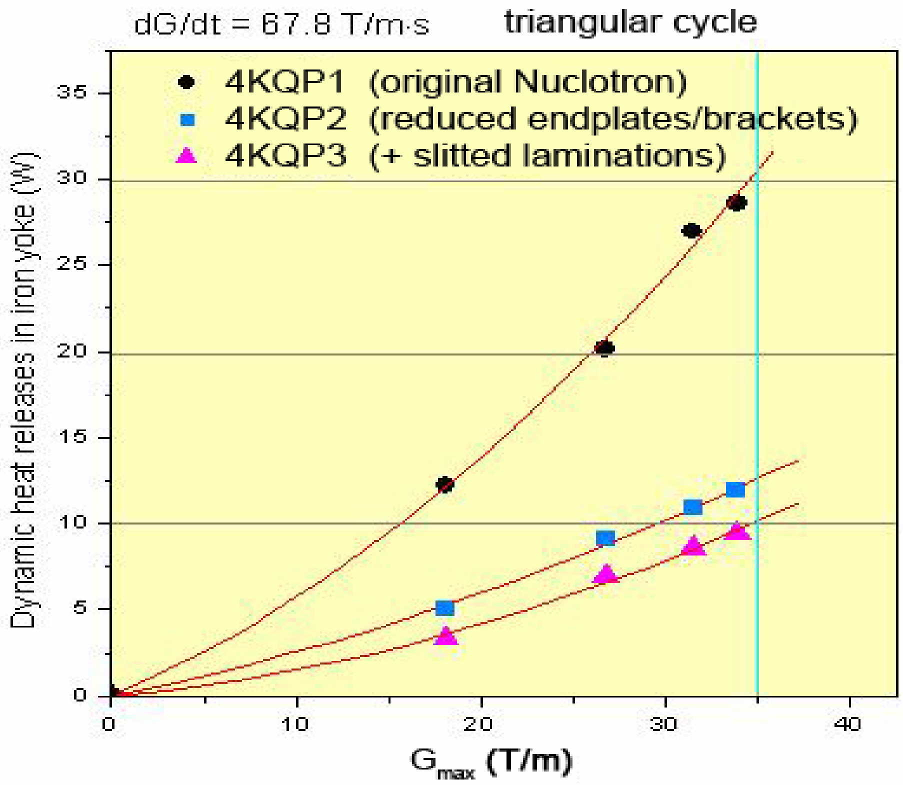


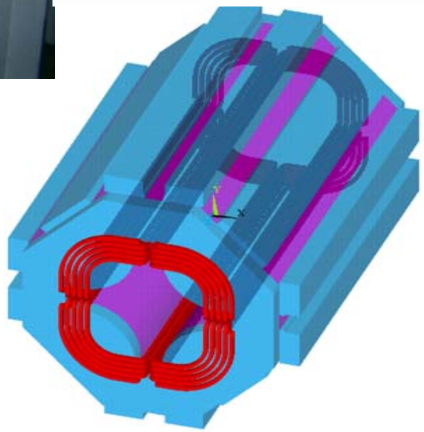
- coil shape end field effects



► see also next session at WAMSDO: "Optimized magnetic field design for superferric rapidly-cycling ..."

Main R&D Results: for Quadrupoles analogous to DP





▲Test measurements on quadrupol modifications

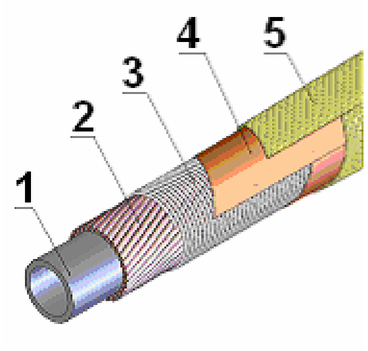
◄ FEM calculations on detailed 3D-models

Nuclotron Quadrupole :

- Nominal gradient: 34 T/m
- Ramp rate: 68 T/m·s

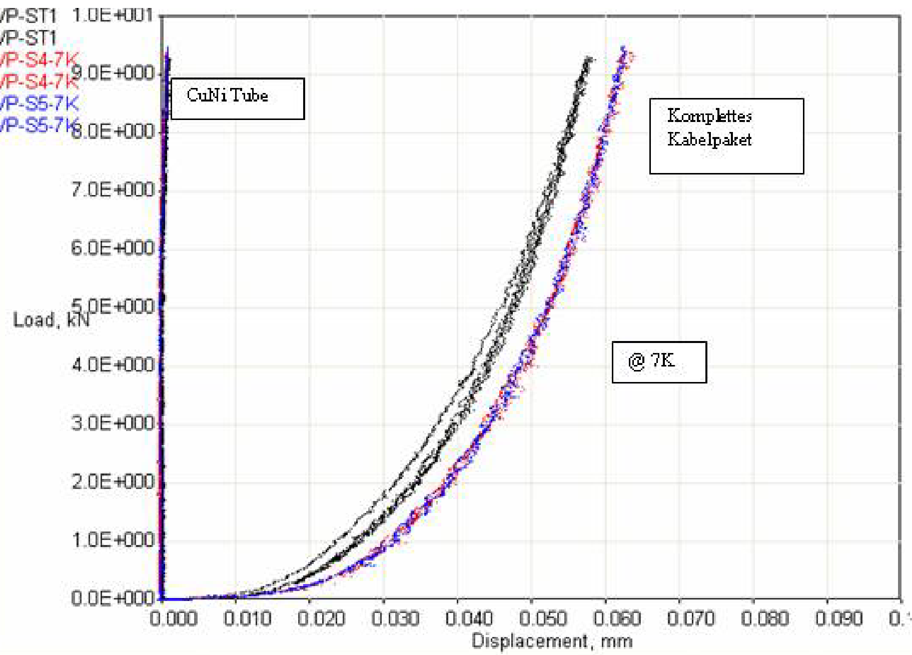
Main R&D Results: Coil mechanics

Nuclotron cable:



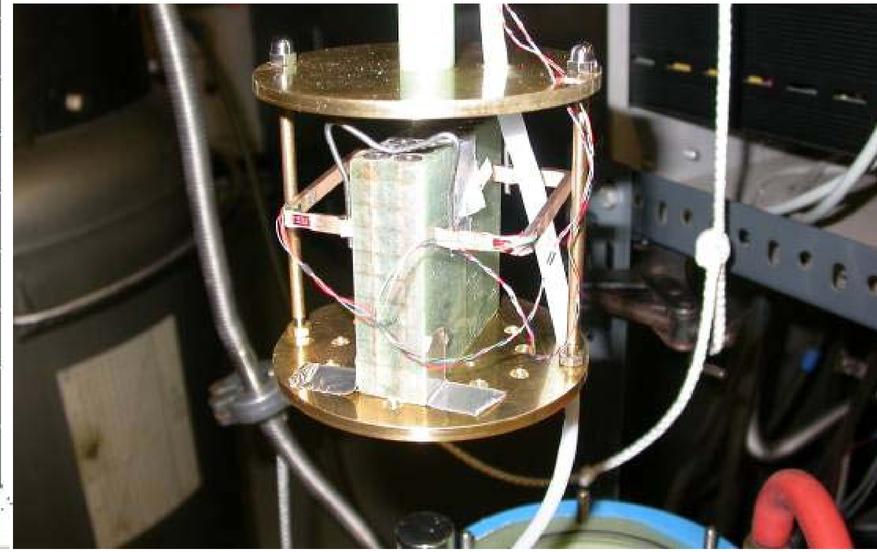
1 - Cooling tube
2 - SC wire
3 - CrNi wire
4 - Kapton tape
5 - Glasfiber tape

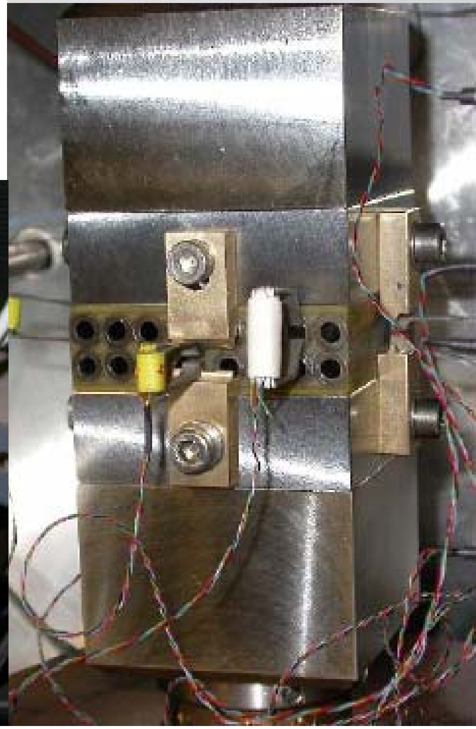
stress strain load tests on the complete coil winding pack:



Analysis of:

- wire and cable design
- Insulation concept
- Winding scheme
- Technological optimization
- ANSYS Models
- Substrate: comb or block
- Model coils production (BNN)
- Mechanical tests





Main R&D Results on Nuclotron based SC Magnets

FAIR

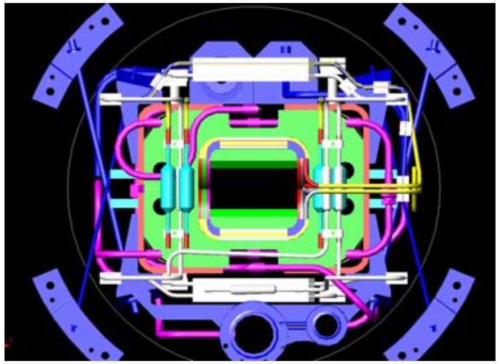
- The sources of the loss generation are understood, numerical calculations match the respective measurements
- Stainless steel end plates and brackets
- Minimized coil end loops
- Laminated and horizontally cut endblocks
- New wire with higher current density and lower losses
- More rigid coil structure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

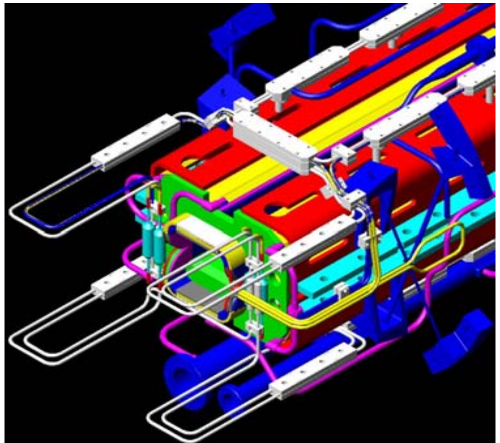
SIS 100 full size models: design parameters

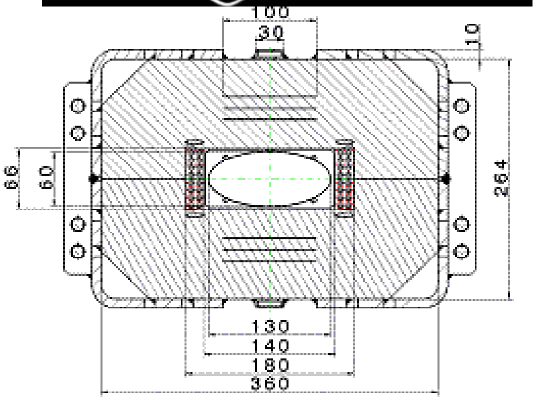
		Straight dipole FBTR (March 2006)	**Curved dipole** (Oct. 2006)
B x $L_{effective}$	[Tm]	5.818	5.818
B	[T]	2.11	1.9
$L_{effective}$	[m]	2.756	3.062
Estimated L_{yoke}	[m]	2.696	3.002
Bending angle	[deg]	3 1/3	3 1/3
Radius of curvature	[m]	47.368	52.632
Aperture (h x v)	[mm]	130 x 60	115 x 60

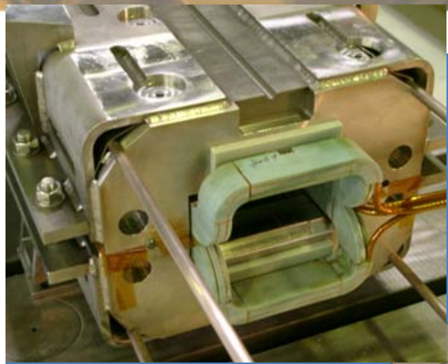
		Quadrupole FBTR (March 2006)	**Quadrupole elongated** (Oct. 2006)
B' x $L_{effective}$	[T]	35	35
B'	[T/m]	32	27
$L_{effective}$	[m]	1.1	1.3
Estimated L_{yoke}	[m]	1	1.2
Aperture (h x v)	[mm]	135 x 65	135 x 65

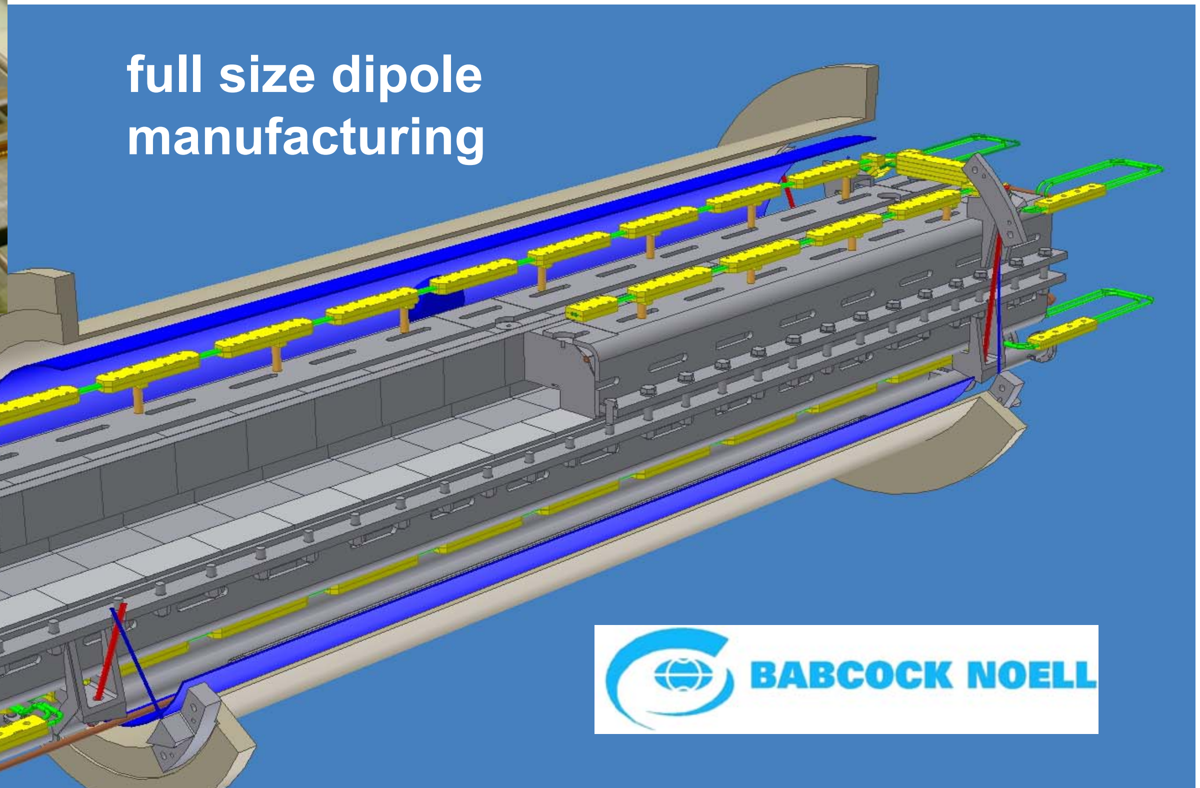
SIS 100 full size model: dipole from Babcock Noell GmbH

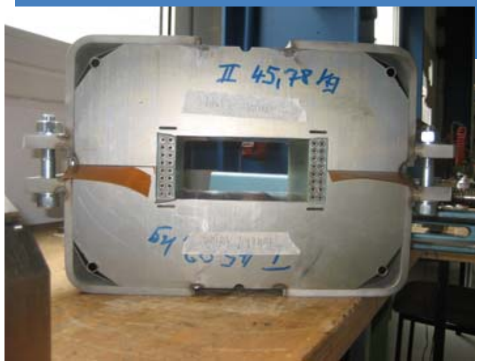








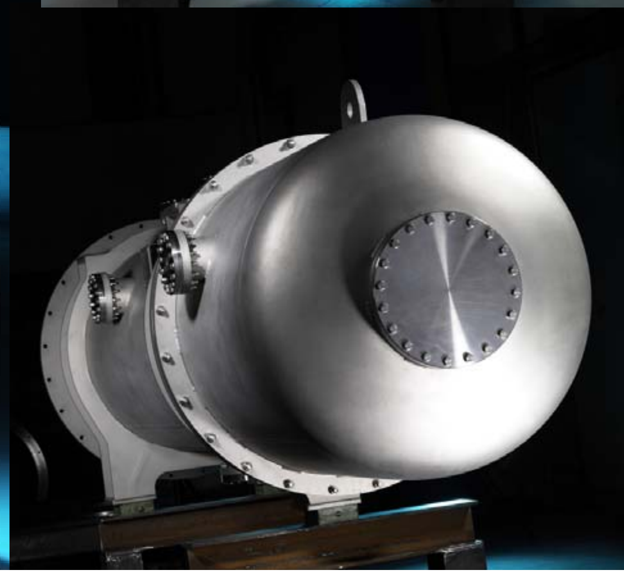




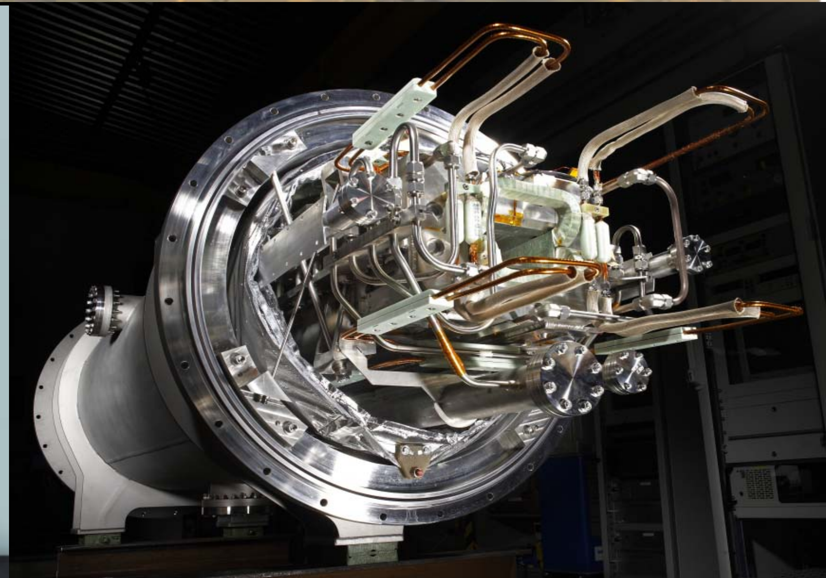
SIS 100 full size model: dipole from Babcock Noell GmbH

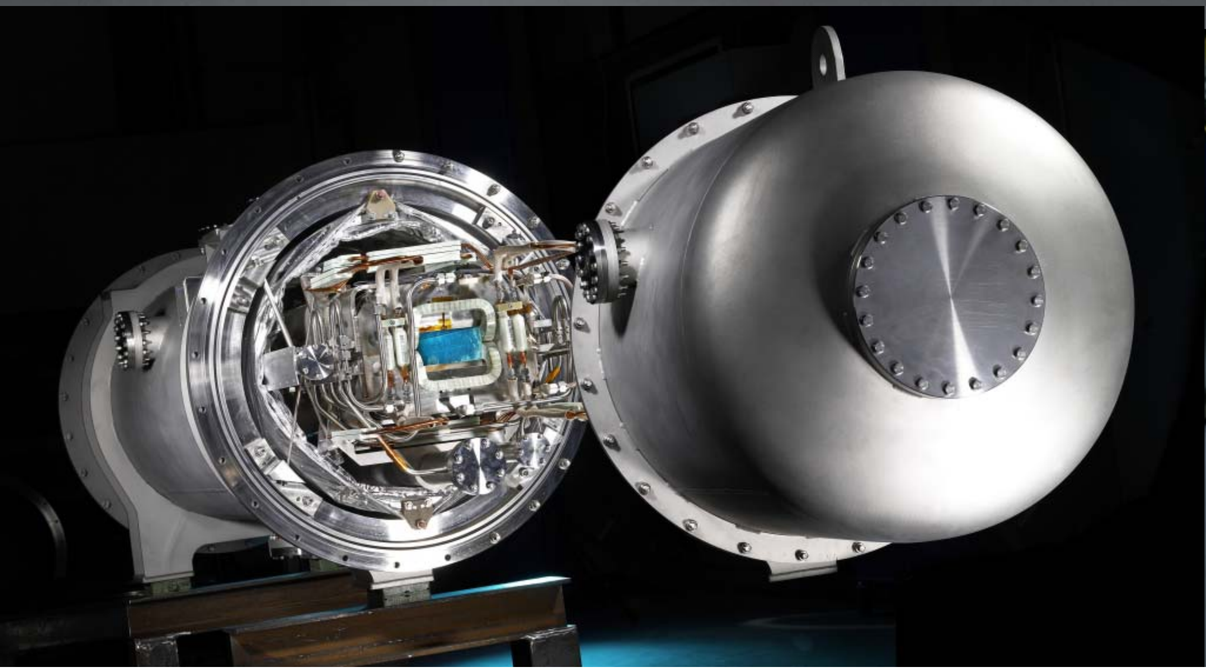
1st Full Size Dipole is ready for testing!

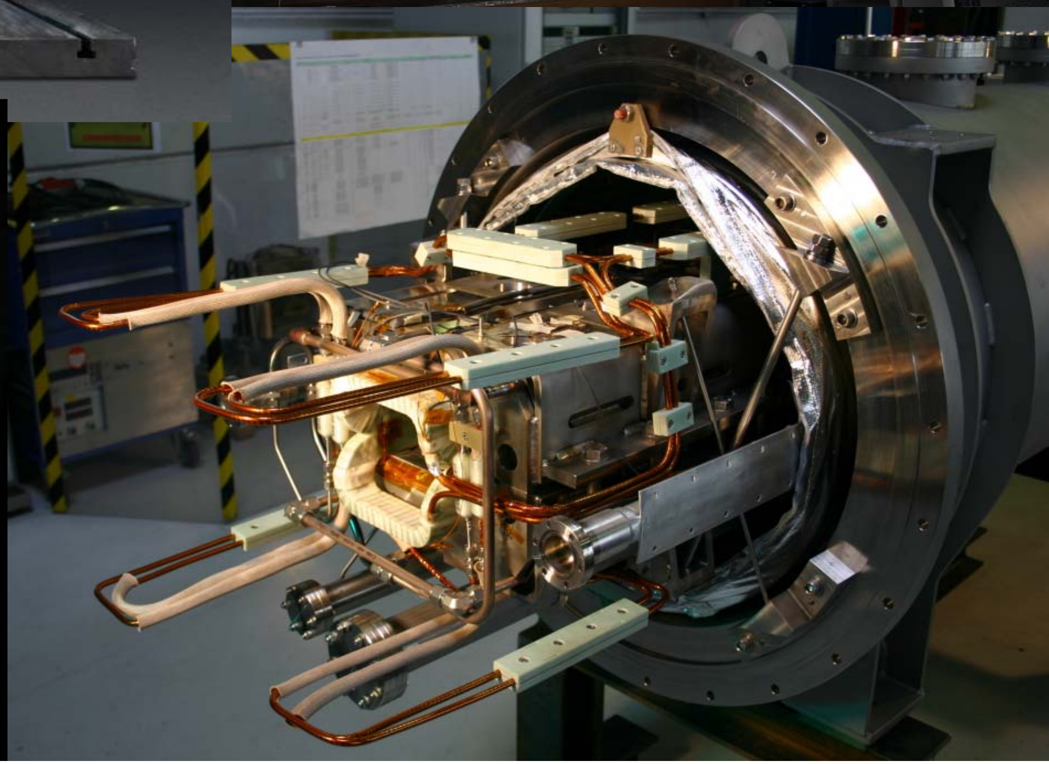
► see also Industry session at WAMSDO: BNG Company presentation and "Manufacturing of the first SIS100 full size model"



SIS 100 full size model: dipole from Babcock Noell GmbH







SIS 100 full size model: dipole manufacturing at JINR

TO CABLE BOBBINE

ROTATING TABLE

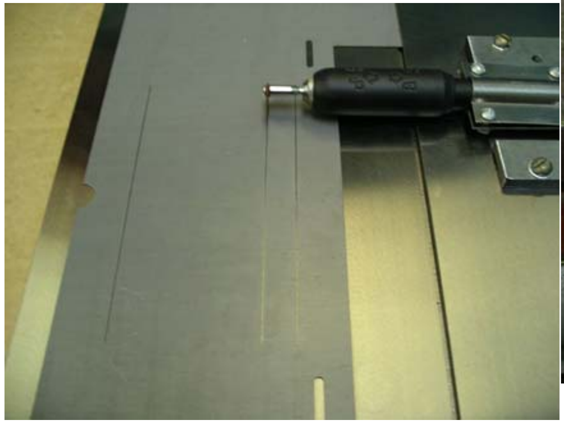
1. WINDING RACETRACK COIL

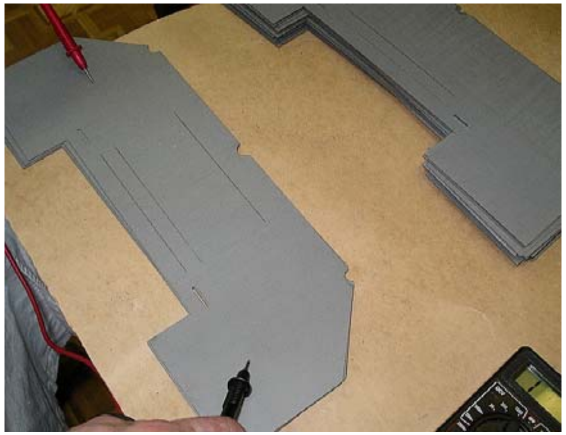
TWO-STAGED MANUFACTURING OF THE COIL ENDS:

2. BEND THE ENDS AS WHOLE

COIL MANUFACTURING TIME WAS REDUCED. WINDING PROCESS IS MUCH EASY

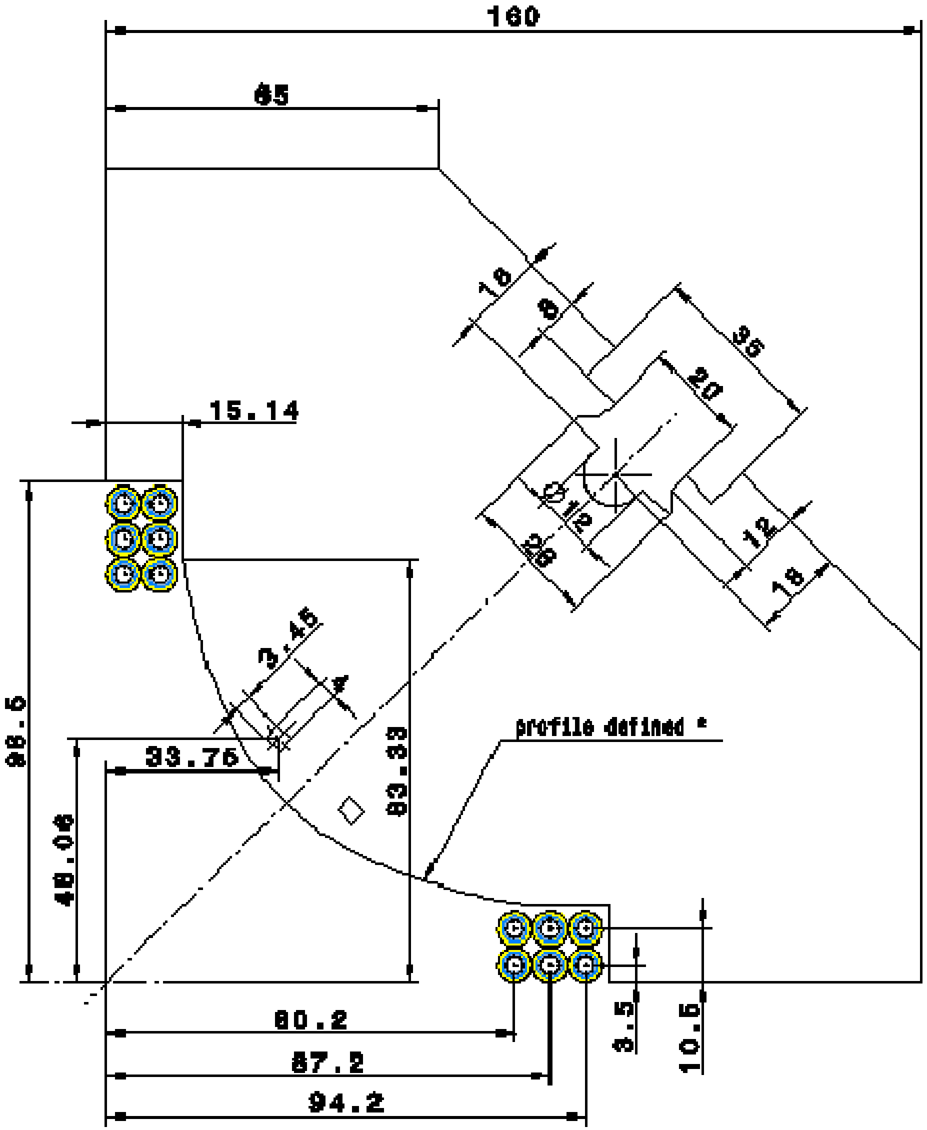
SIS 100 full size model: dipole manufacturing at JINR





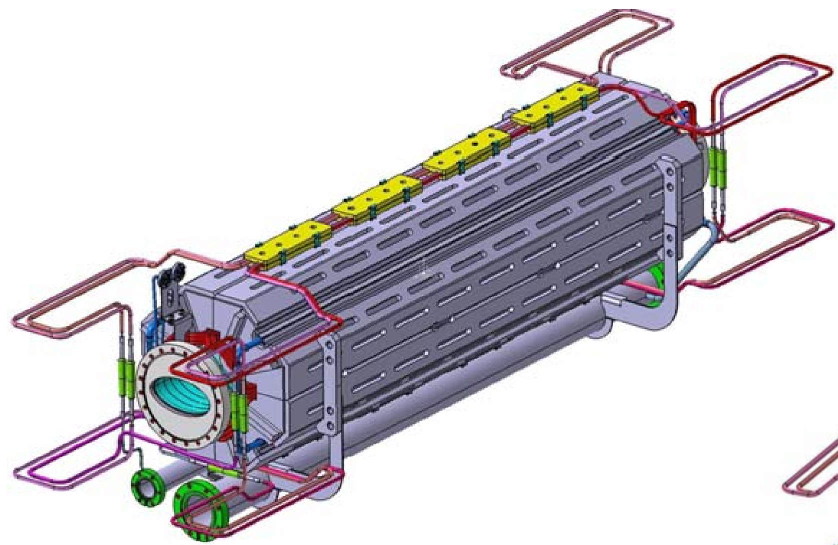
high quality and reproducible production of the lamination shape and the the iron yoke

Full size model: quadrupole manufacturing at JINR

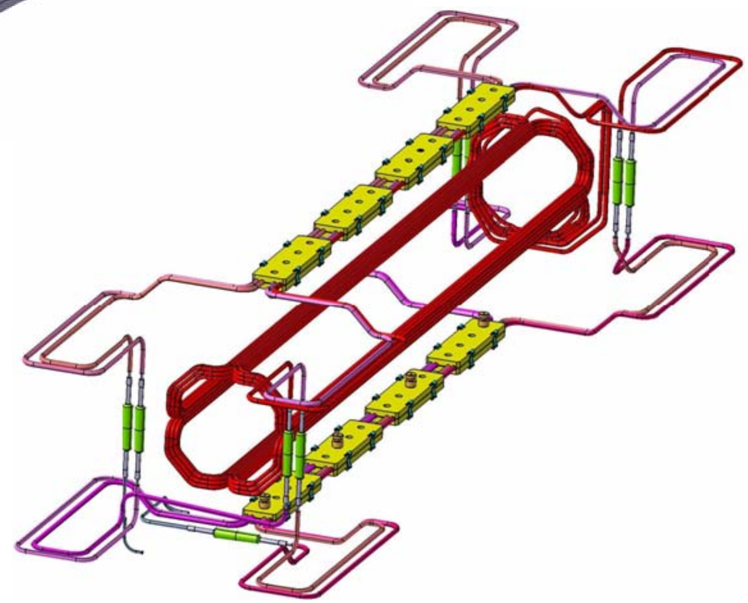


lamination geometry

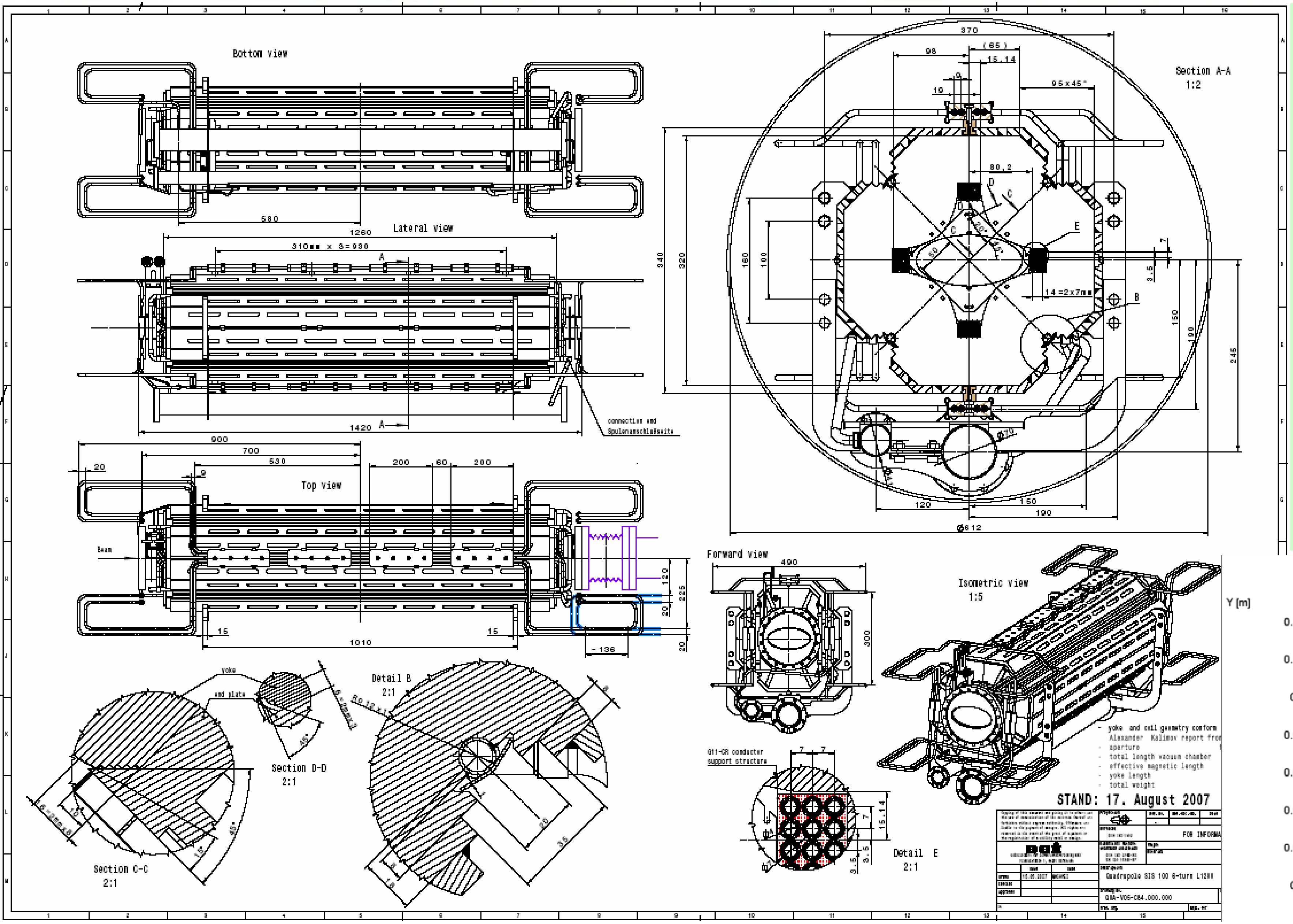
geometric details of the full length quadrupole design



3D drawings: complete QP and coil structure



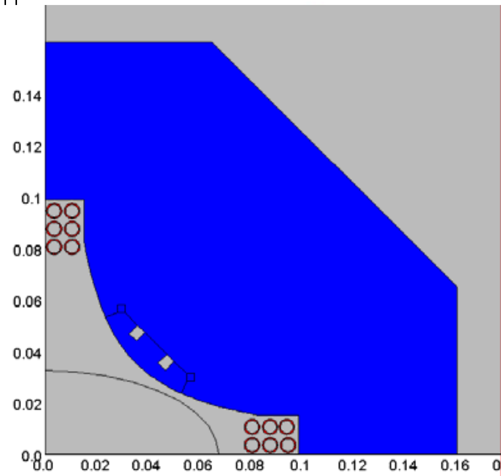
Full size model: quadrupole manufacturing at JINR



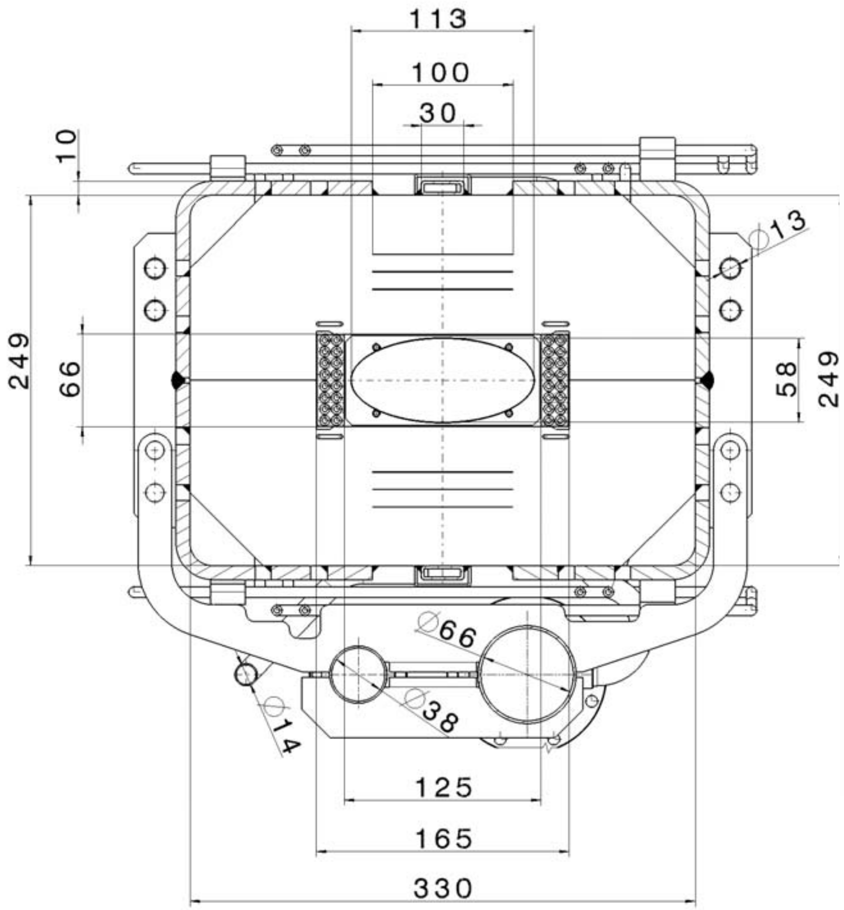
Completion of manufacturing and ready for tests
of full length main magnets produced at JINR Dubna:

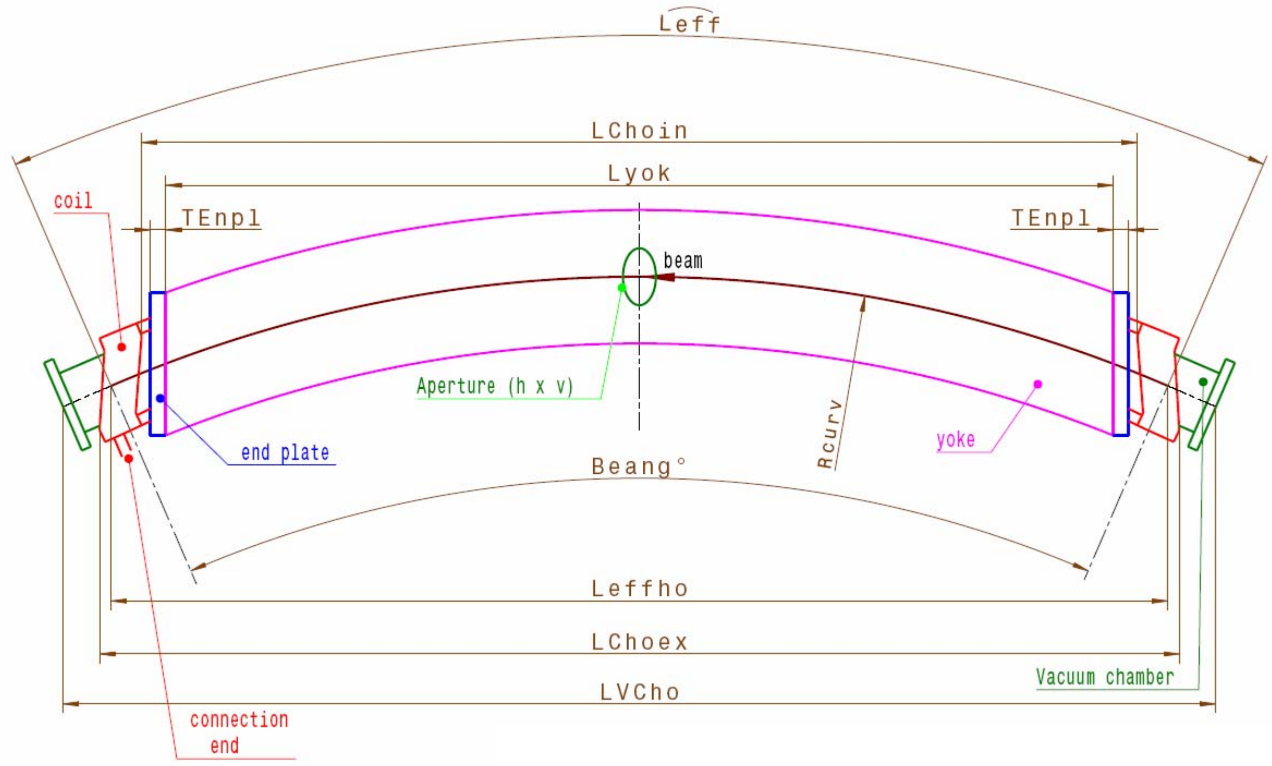
Dipole:
July 2008:

Quadrupole:
October 2008

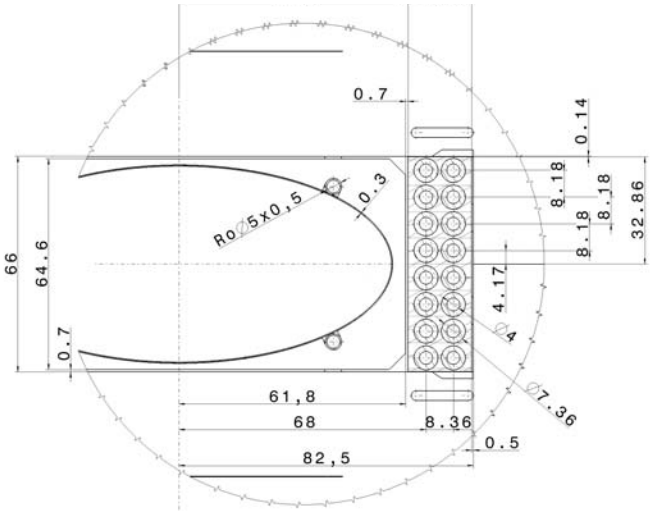


Full size model: curved dipole geometric parameters

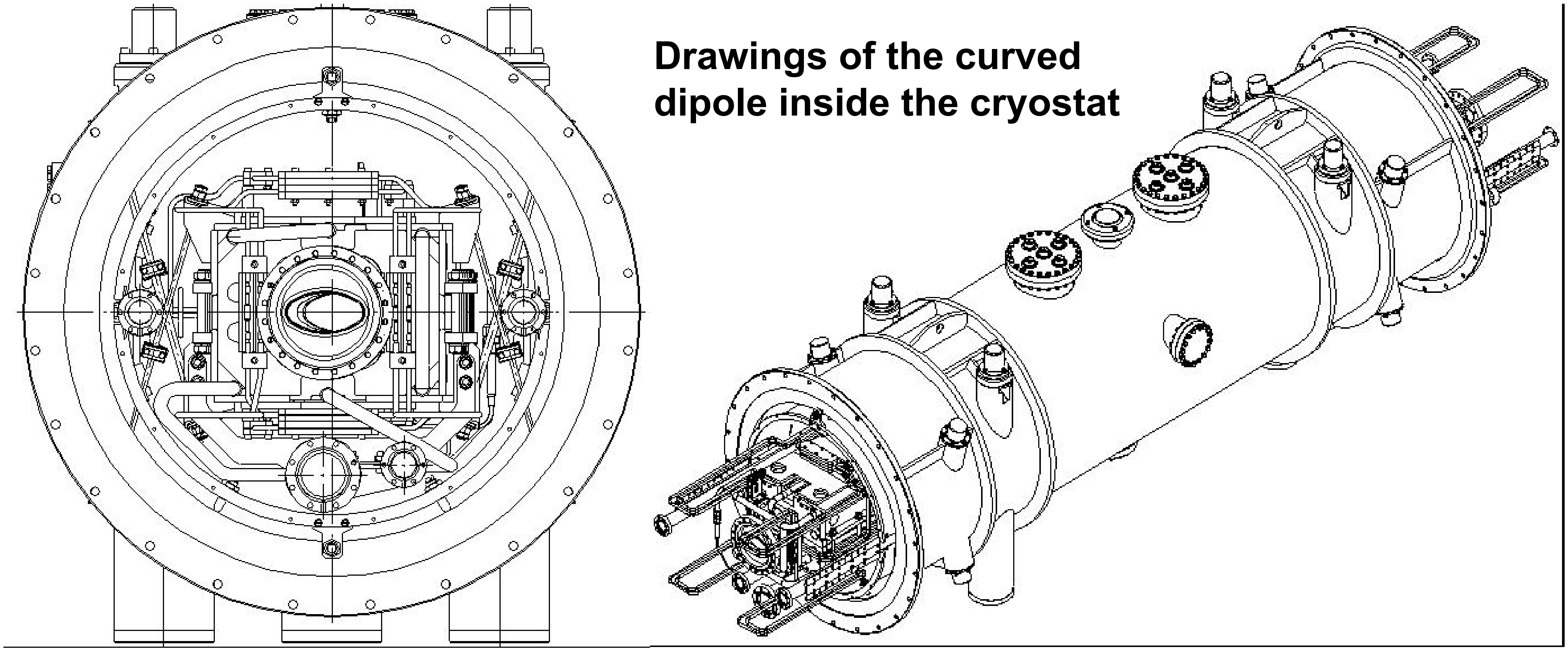




► Geometrical details and dimensions



Full size model: curved dipole assembly at BINP



Drawings of the curved dipole inside the cryostat

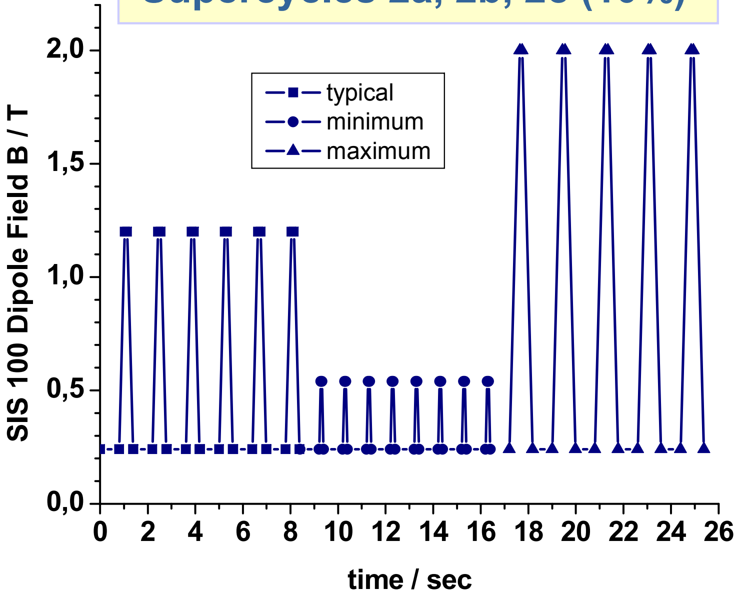
► Yoke and cryostat from BINP Novosibirsk

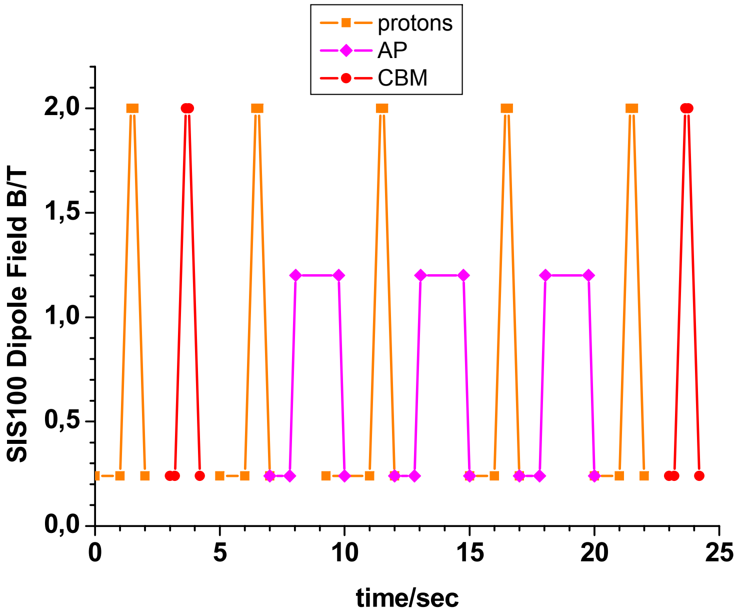
► SC coil will be produced at JINR Dubna

► completion scheduled for July 2008

Requirements and Operation Parameters: FAIR cycles

Supercycles 2a, 2b, 2c (10%)





Requested SIS100 operation cycles and expected losses

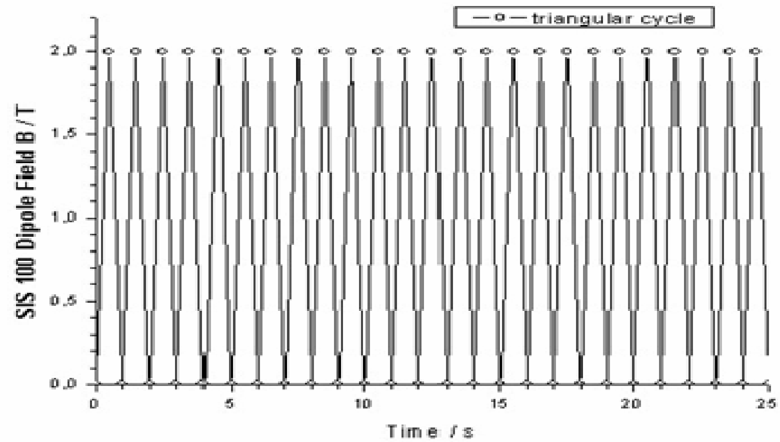
cycle	B_{max} (T)	t_f (s)	cycle period (s)	Q_d (J/cycle)	P_d(W)	Q_q (J/cycle)	P_q(W)
1	1.2	0.1	1.4	35.2	25.2	13.1	9.4
2a	1.2	0.1	1.4	35.2	25.2	13.1	9.4
2b	0.5	0.1	1.0	8.8	8.8	3.3	3.3
2c	2.0	0.1	1.82	89	48.9	24.4	18.9
3a	1.2	1.3	2.6	35.2	13.5	13.1	5.0
3b	0.5	1.0	1.9	8.8	4.6	3.3	1.8
3c	2.0	1.7	3.4	89	26.2	34.4	10.1
4	2.0	0.1	5.0	89	17.8	34.4	6.9
5	2.0	0.1	5.0	89	17.8	34.4	6.9

◄ Supercycle 5 (30% annual beam time)

Additional requirements: triangular cycle with 1Hz

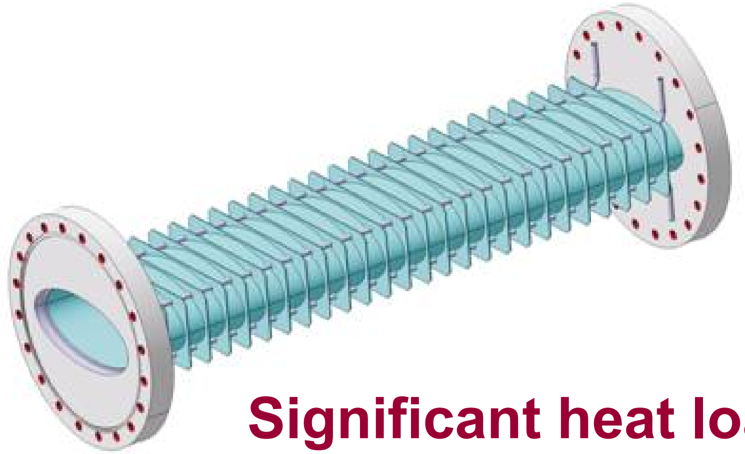
FAIR Supercycles for Parallel Operation

- Purpose: Standard scenario for layout of magnets, cryogenics, power supplies etc.
- Each cycle may run for several hours (... days)
- Different extraction energies may be used, but for the standard supercycles, for each experiment, a typical energy was chosen.
- For the calculation of a mean energy consumption of the accelerator complex, a percentage of the annual beam time is assigned to each cycle.
- During commissioning of experiments, many other operation modes may occur.
  - March 2007: Additional requirements from beam dynamics:
    continously triangular cycle must be provided,
    i.e. B_{max} = 2T, $^{dB}/_{dt}$ = 4 T/s, f = 1 Hz!

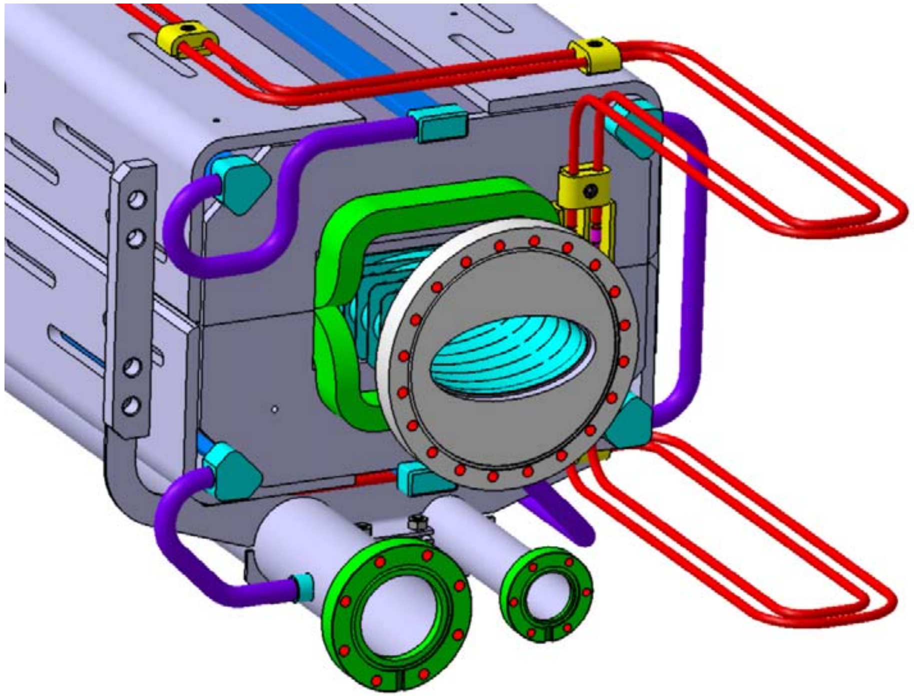


Additional requirements: Beam pipe as cryopump

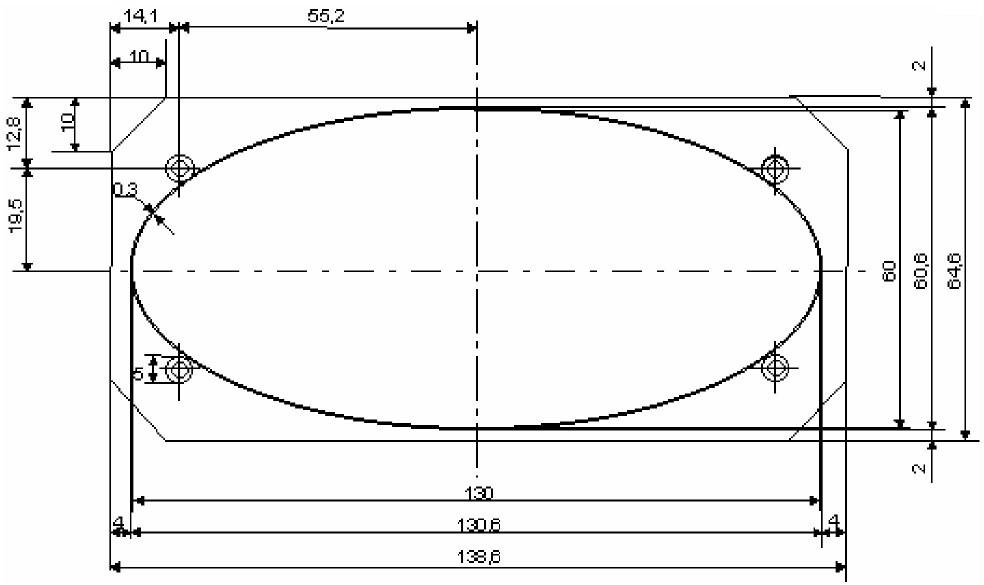
- elliptical cross section
- wall thickness: 0.3 mm (minimize AC-losses!)
- strengthening of chamber by ribs
- T_{max} < 15 K (to be cooled by forced flow or yoke)



Significant heat load !

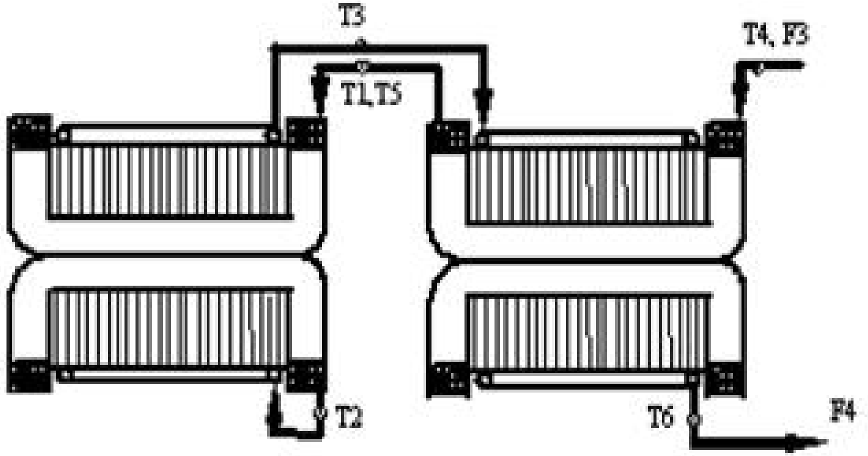


► see also next session at WAMSDO:
"Optimized magnetic field design...",
"Cold testing of rapidly cycling..."



Schematic drawing of cross section of the dipole vacuum chamber

Critical Operation Parameters: Test on composite DP



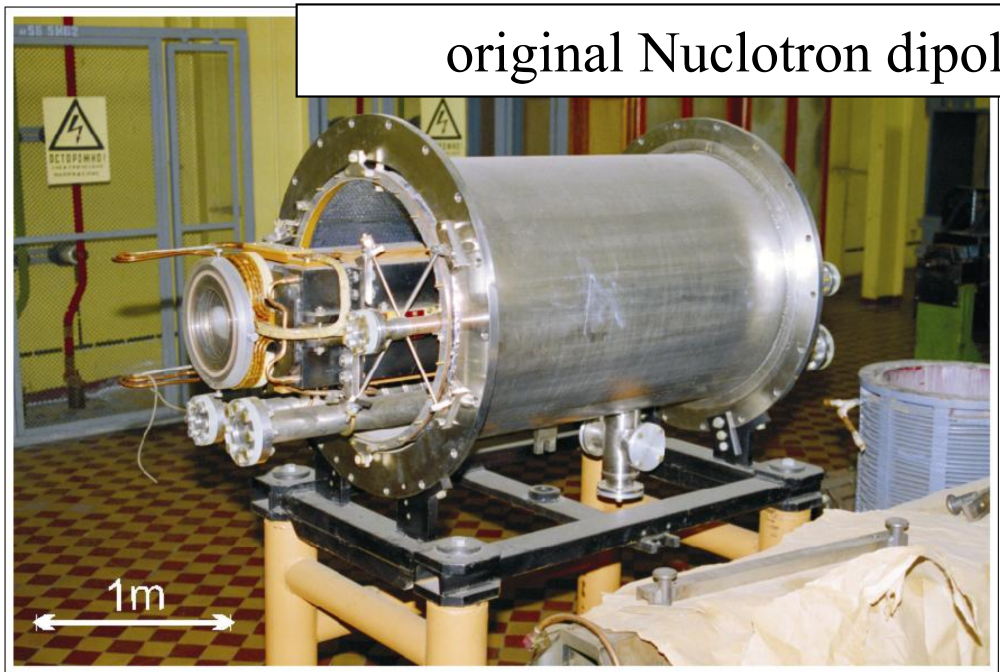
Equivalent model for cooling tests

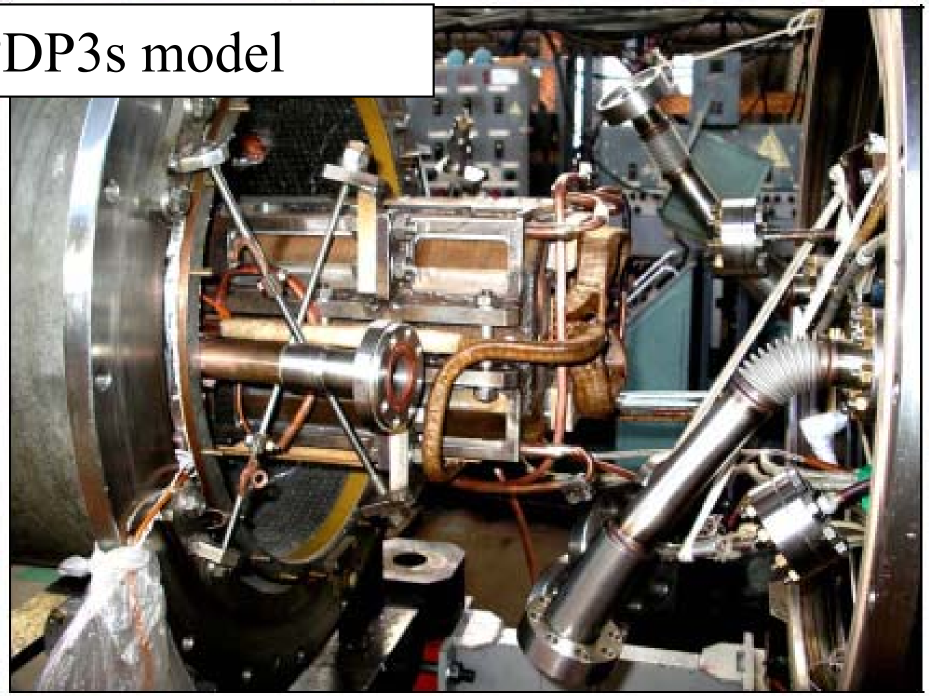
Fig. 1. Flow diagram of the new model magnet:

T1, ...T6 – temperature measurement points,

F4 – helium flow measurement point.

original Nuclotron dipole + PDP3s model

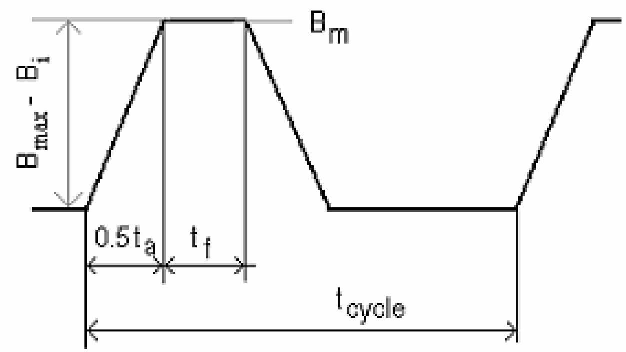




Operation Parameters: Full length composite dipole

JINR Dubna: experimental results at 4KDP7 for FAIR cycles

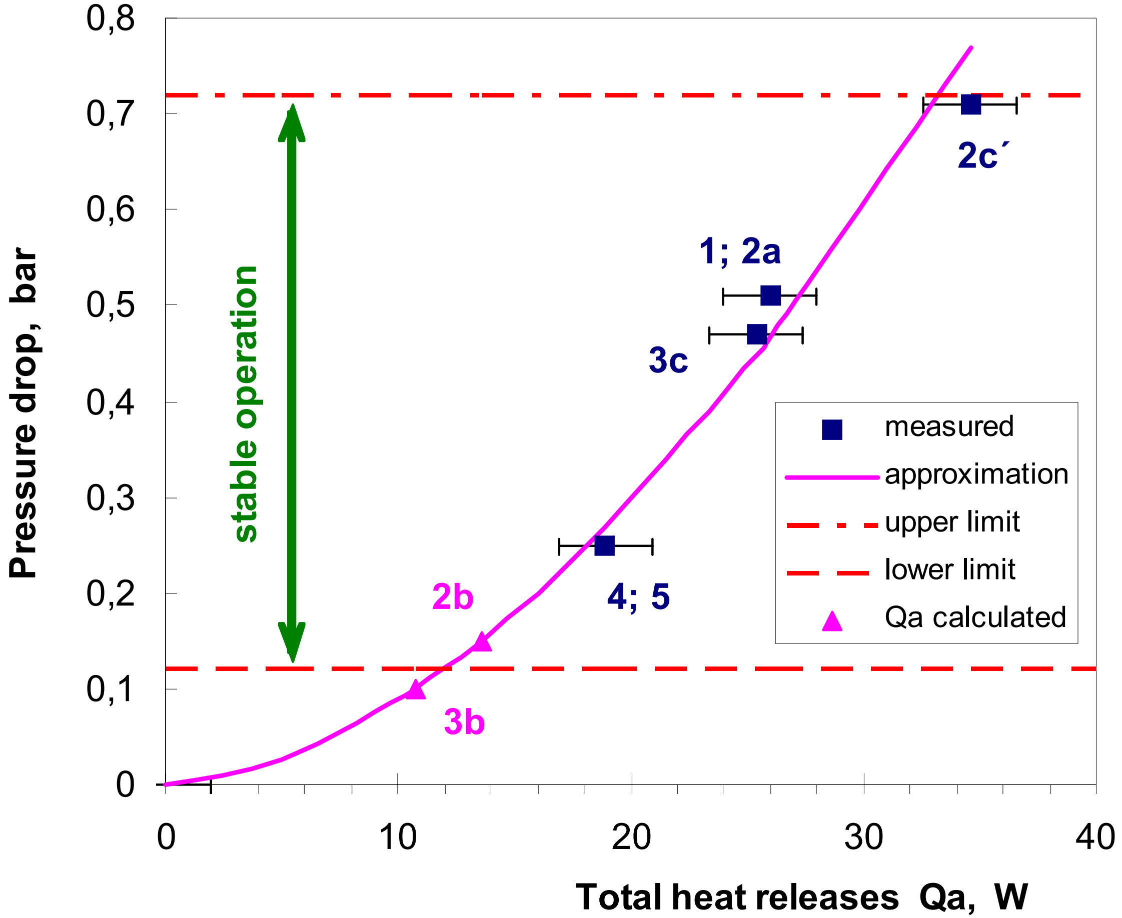
cycle	B_m (T)	I (A)	t_f (s)	t_c (s)	t_a (s)	P_{loss_sum} (W)	P_{loss_dyn} (W)	ΔP bar	Remarks
1*	1.2	3340	0.1	1.4	0.6	35.1*)	25.5*)	0.74	at $x_6 \approx 0.9$
1	0.96	2710	0.1	1.4	0.48	23.9	14.2	0.51	at $x_6 \approx 0.9$
2a	0.96	2710	0.1	1.4	0.48	23.9	14.2	0.51	0.51 bar ($x_6 \approx 0.9$)
2b	**0.26**	**720**	**0.1**	**1.0**	**0.13**	**P_{loss_dyn} below measurable level**		**0.15**	at $x_6 \approx 0.9$ **Stable operation yet**
2c´	**1.76**	**5000**	**0.7**	**2.2**	**1.0**	**30.0**	**20.3**	**0.72**	**Unstable operation**
3a	0.96	2710	1.3	2.6	0.48	not measured			
3b	**0.26**	**720**	**~ 0**	**1.9**	**0.13**	**P_{loss_dyn} below measurable level**		**0.1**	at $x_6 \approx 0.9$ **Unstable operation**
3c	1.76	5000	1.7	3.4	0.88	22.8	13.1	0.47	at $x_6 \approx 0.9$
4	1.76	5000	0.7	5.2	0.88	18.3	8.6	0.25	at $x_6 \approx 0.9$
5	1.76	5000	0.7	5.2	0.88	18.3	8.6	0.25	at $x_6 \approx 0.9$

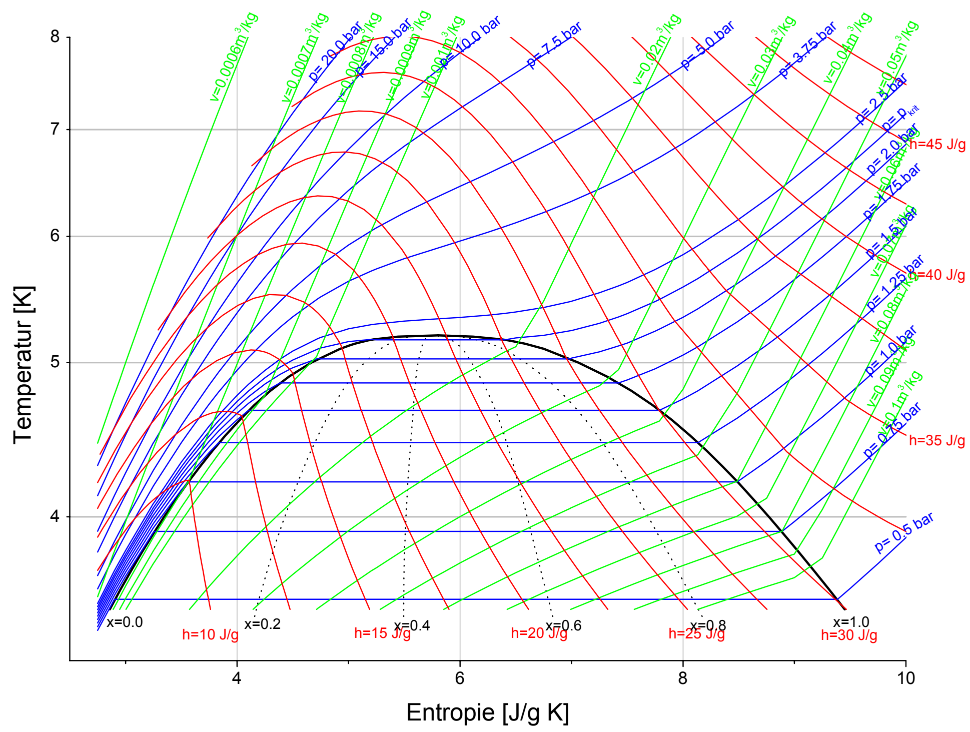


- **Experimental results for the full length model agree with the estimation based on the measurements of the short model within 15 %**

Operation Performance: Full length composite dipole

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

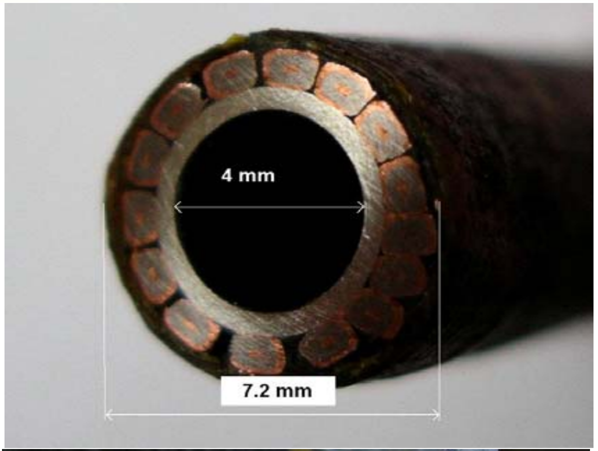


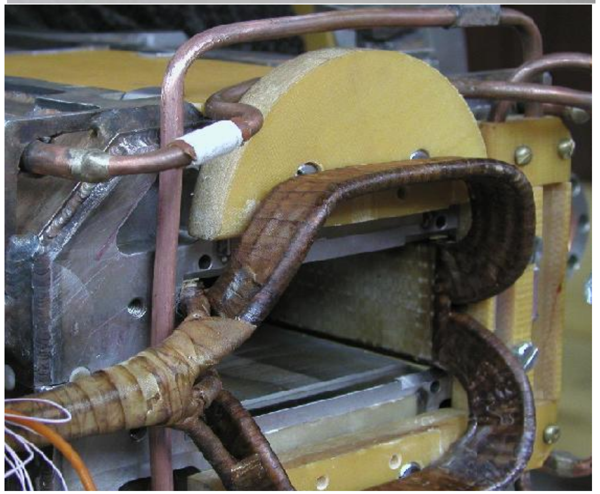


Conclusions toward the final dipole design

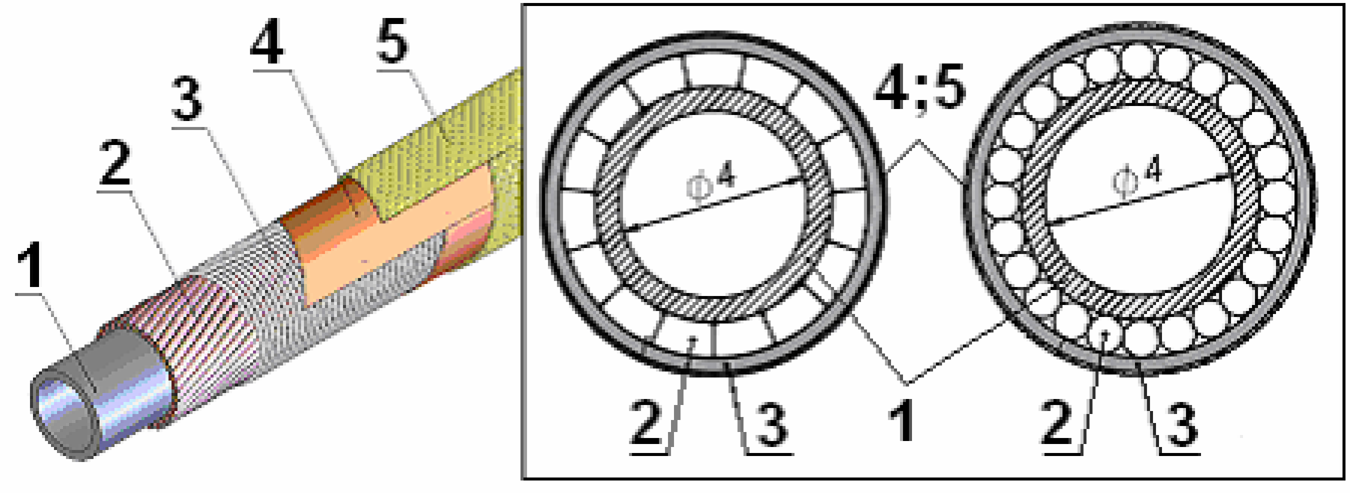
- The estimated limits of the actual full size models are not sufficient for the recently changed requirements of the SIS100 machine (also a significant operation margin has to be provided).
- Redesign options to satisfy the updated operation parameters:
  - new cable design (with lower hydraulic resistance)
  - shorter coil length
  - CSLD (curved single layer dipole)

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

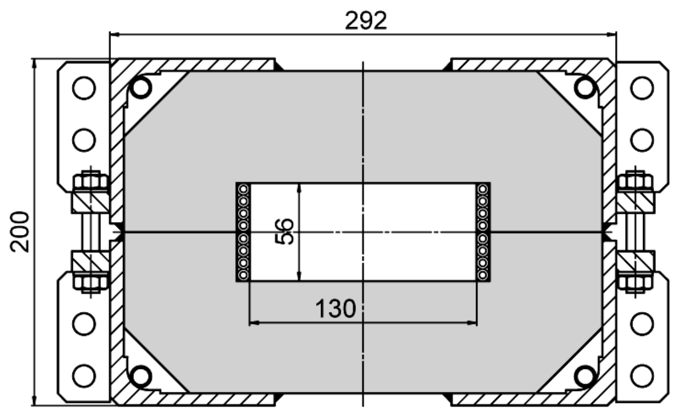


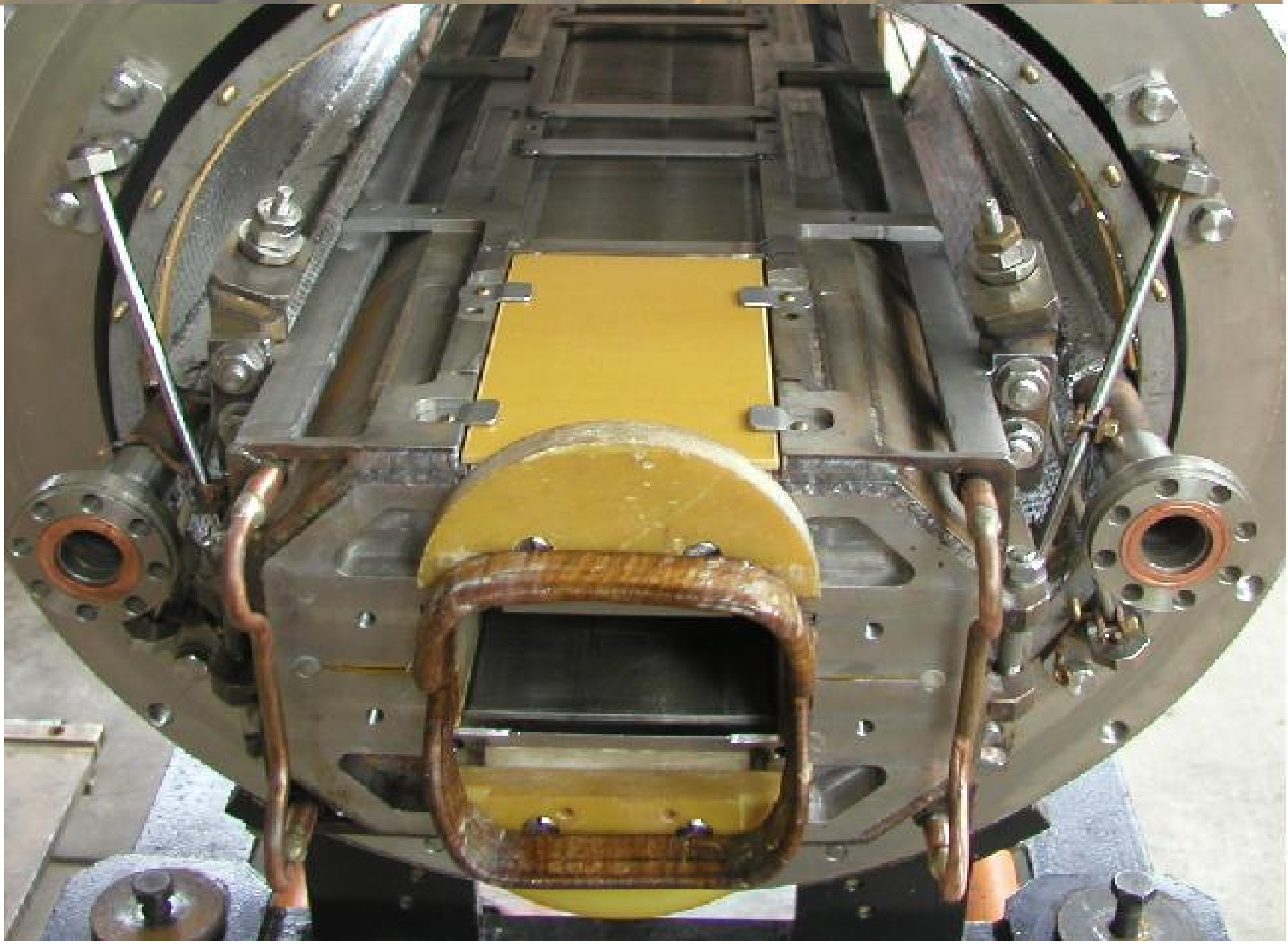
- **cycle limit estimations for a round wire cable CSLD with 8 turns (detailed specification in MT-INT-EF-2007-002, GSI):**

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





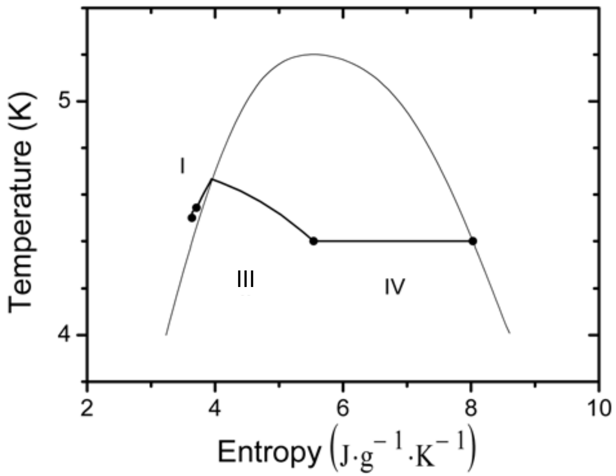
model dipole with a single layer coil, tested at JINR Dubna in 2004

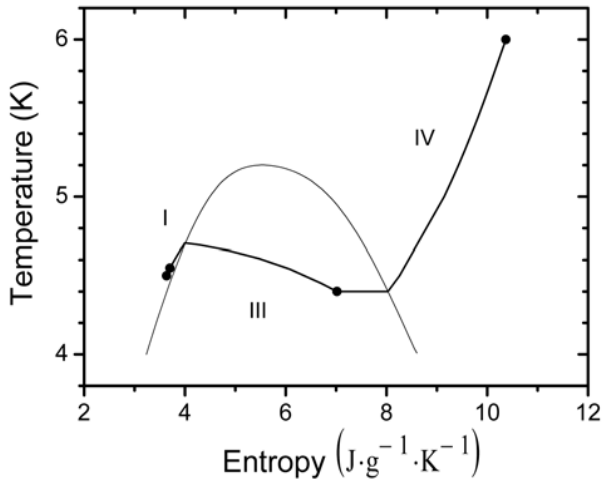
Main Operation Parameters of the CSL-Dipole

FAIR

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

Curved Single Layer Dipole at intensive ramping modes:





T – S diagrams for the CSLD operation

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

Single Layer Dipole:
"Minimization of AC Power Losses in Fast Cycling Window Frame 2T Superferric Magnets with the Yoke at T=4.5K",E.Fischer et al., ASC 2004, 3LR04; Internal Note GSI: MT-INT-EF-2004-09

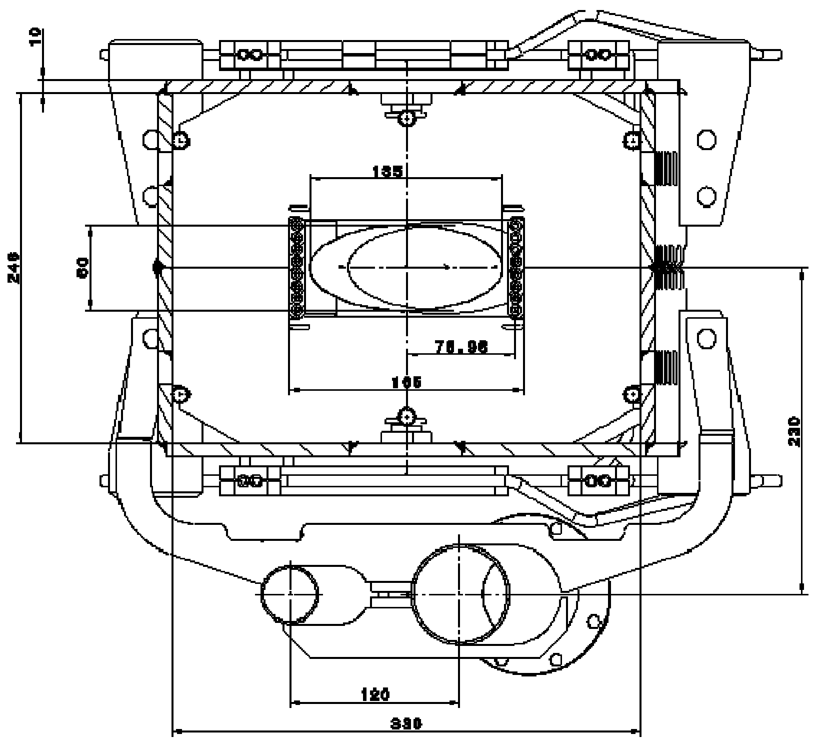
Curved Single Layer Dipole:
"Full Size Model Magnets for the FAIR SIS100 Synchrotron"; Egbert Fischer, Hamlet Khodzhibagiyan, Alexander Kovalenko; MT-20; 4V07; 2007; Internal Note GSI: MT-INT-EF-2007-03

for details see →

Dipole redesign: magnet parameters (TDR)

FAIR

Name of the magnet		SIS 100 Main Ring Dipole
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
Aperture (good field region):	mm	115 · 60
Field quality (goal)		$\pm 6 \cdot 10^{-4}$
Overall magnet length (slot length)	m	3.354
Overall width (cryostat)	m	1.0
Overall height (cryostat)	m	1.0
Overall weight	kg	1850
Current at max. field	A	12745
Inductance	mH	0.55
Ramp rate	T/s	4
High field flat top duration	s	0.1
Low field flat top duration	s	0.8
Cycle length	s	1.735
AC loss per cycle @4.2K per magnet (cycle number 2c, no beam pipe))	J	62

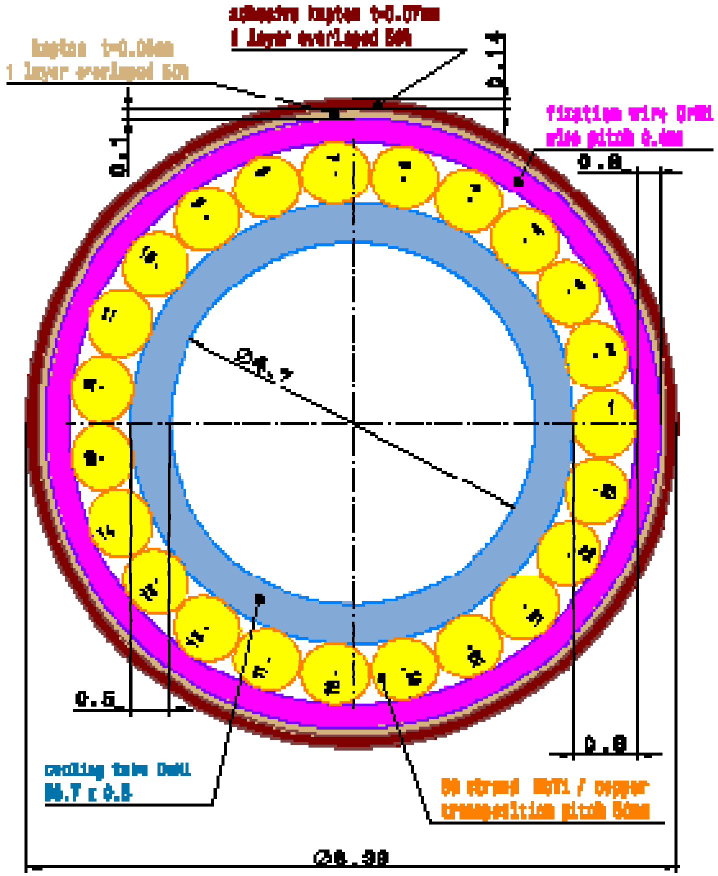


curved single layer dipole (CSLD)

(details: see Technical Design Report, GSI Darmstadt, 2008)

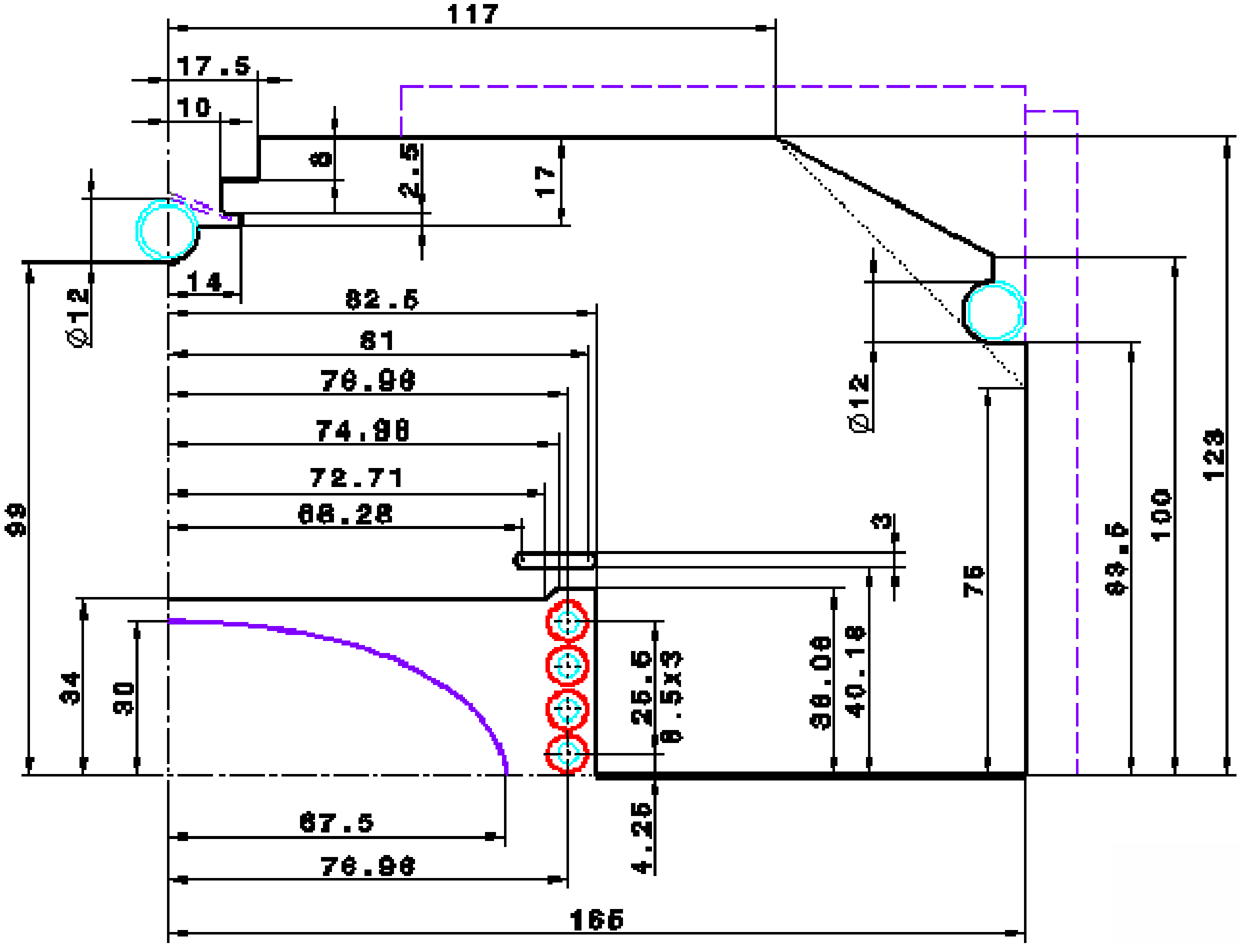
Dipole redesign: cable parameters (TDR)

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			

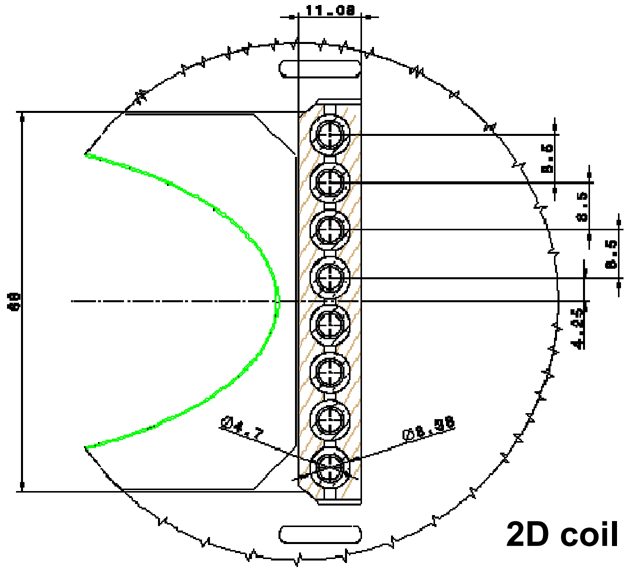


Cross section of the cable adopted for the SIS100 dipole coils (Nuclotron-type cable).

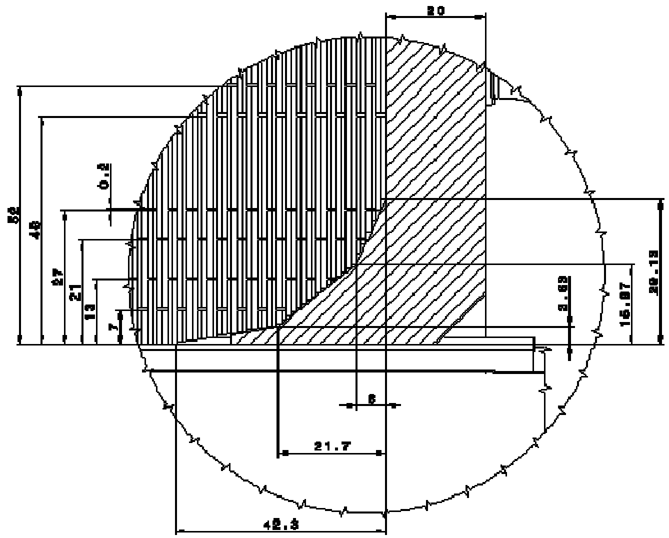
Dipole redesign: geometric details (TDR)



lamination geometry



2D coil structure



lamination slits near yoke end

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 ready for testing at GSI, a second dipole, a quadrupole and a curved dipole will be ready in III 2008.
- 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.

Thank you for your attention!

Acknowledgement

H. Kodhzibagijan, A. Kovalenko (JINR/LHE)
J. Macavei, P. Schnizer (GSI)
W. Gaertner, G. Sikler (BNG)
P. Akishine (JINR/LIT)
R. Kurnyshov (Electrostal)
P. Shcherbakov (IHEP)
A. Kalimov (SPTU)
and for all the professional contributions of our colleagues from GSI, JINR, BNG, BINP and FZK to this work