Cable in conduit and thermal budget at Nuclotron

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4, Place Jussieu – 75006 Paris

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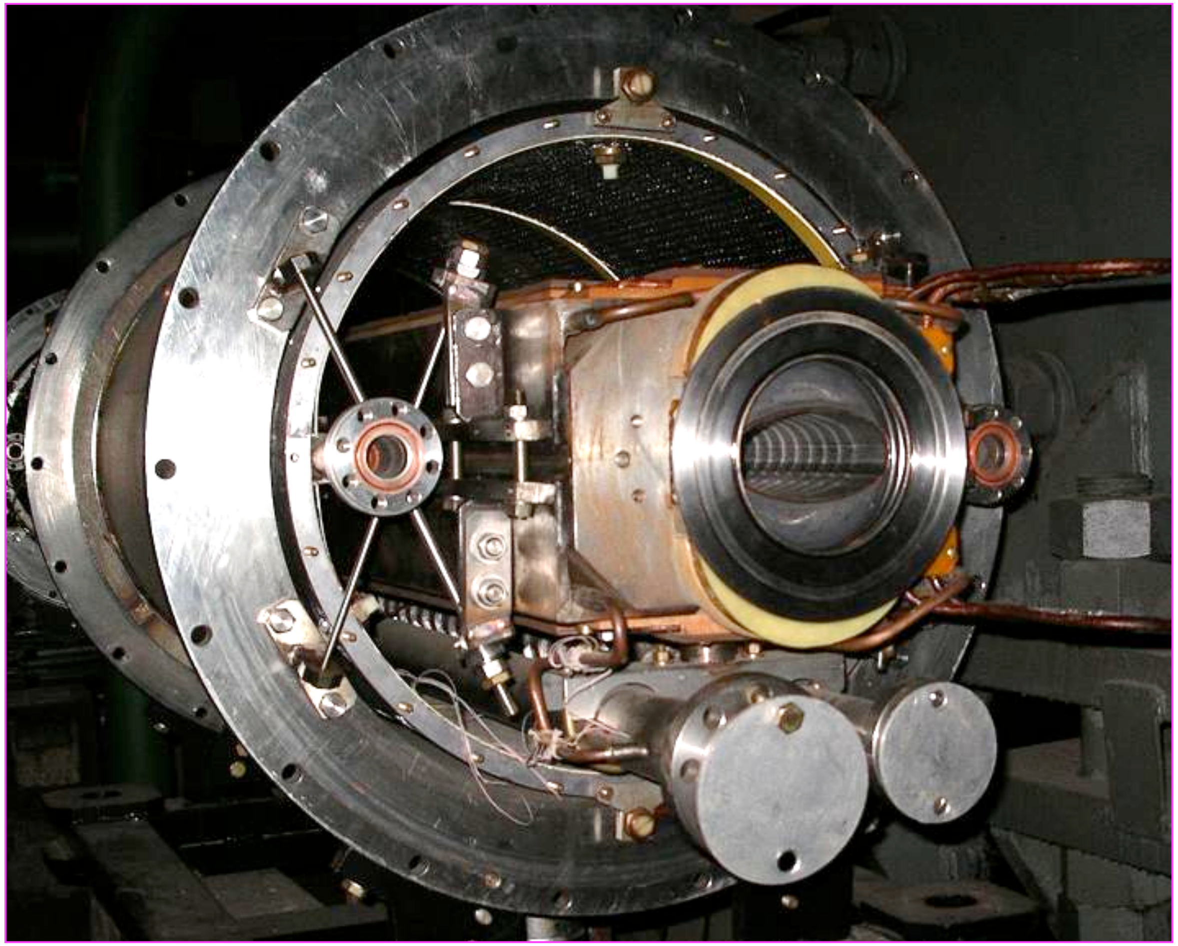
- New Motivation: Project NICA at JINR
- SC cable R&D for FAIR:
  - cable design for fast cycling superconducting synchrotron magnets
  - high current superconducting NbTi cable
  - Nuclotron type & CICC
- Cable options for the SIS 100 magnets
- Summary

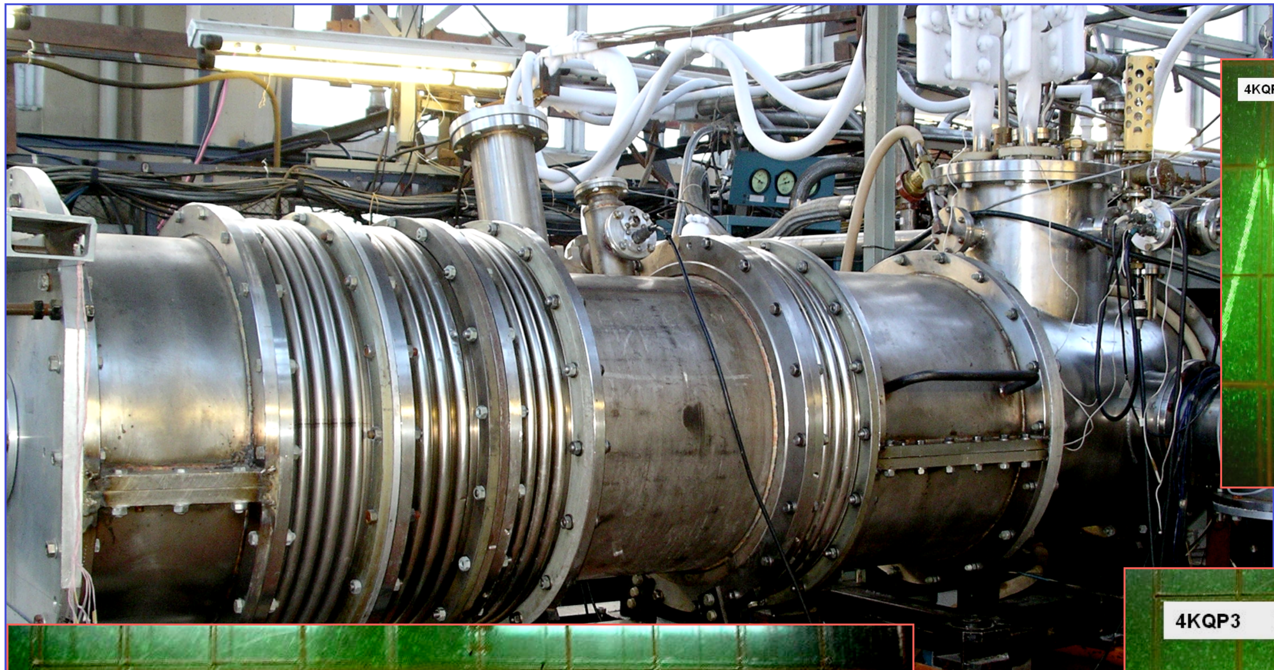
- 2 T, 4 T/s, 1 Hz superferric magnets were designed and first tested at LHE JINR(Dubna) in 1978-79

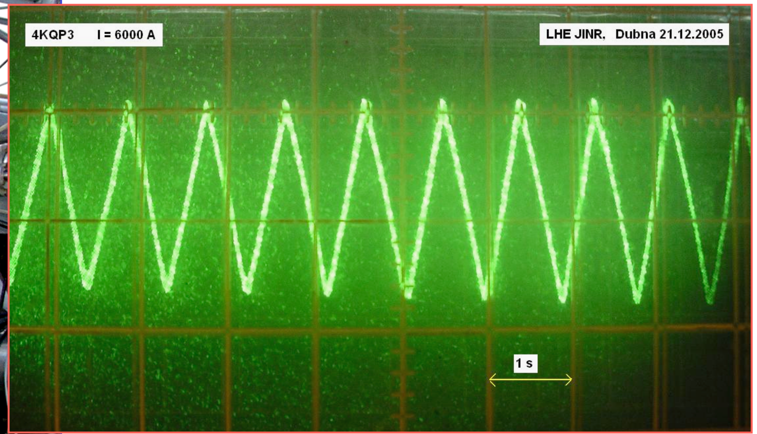
- JINR/GSI collaboration on improvements of the magnets parameters in accordance with the SIS100 specification - from 2000

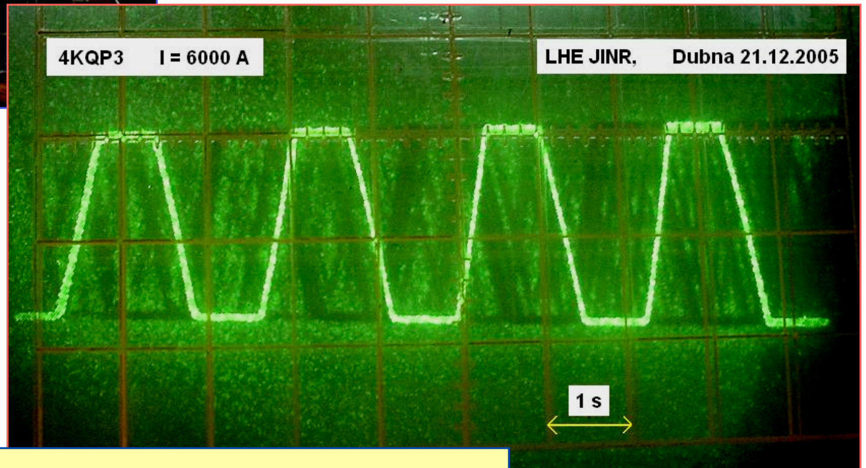
- 4 T, 4 T/s Cos(theta) – style dipole based on a hollow high current conductor – EUCAS 2001, 2003, 2005

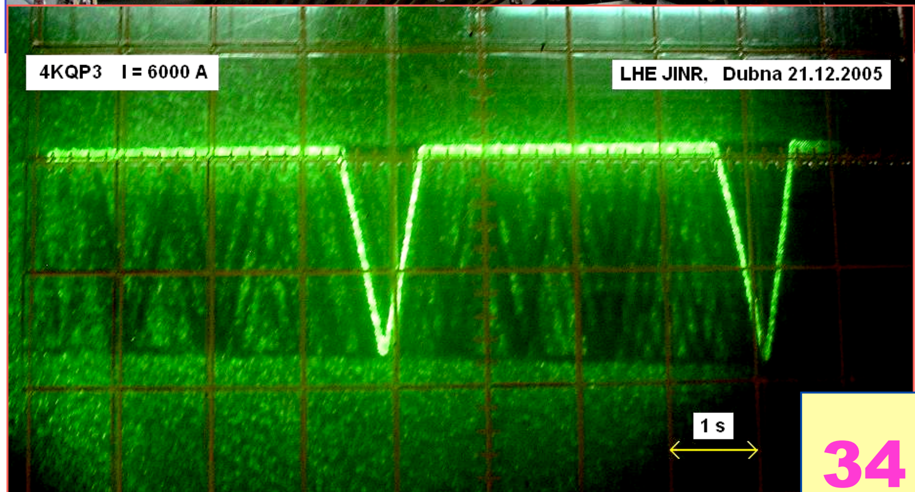
Original Nuclotron 2 T dipole







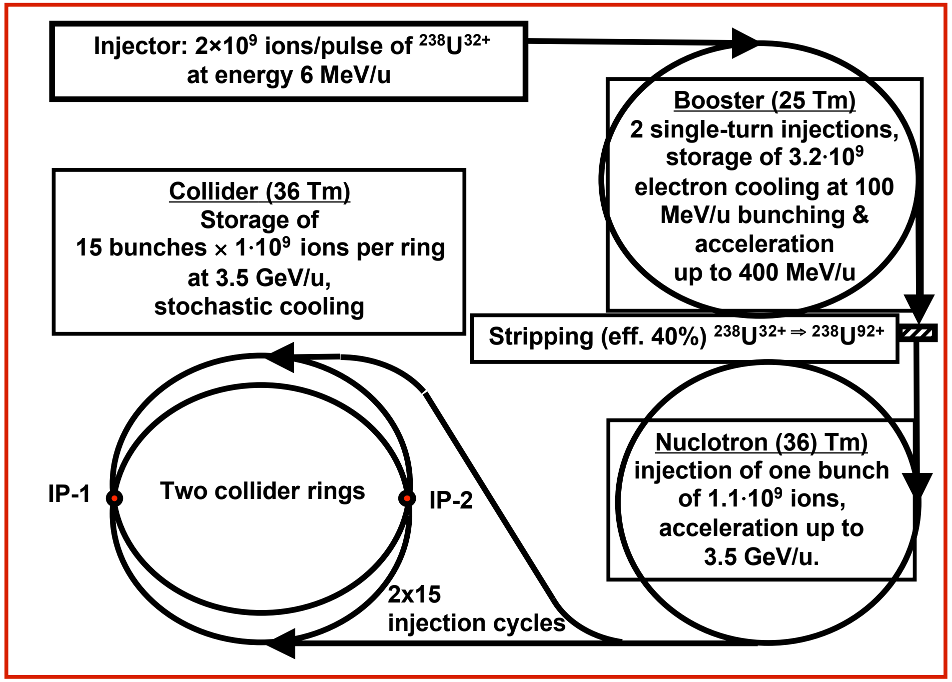


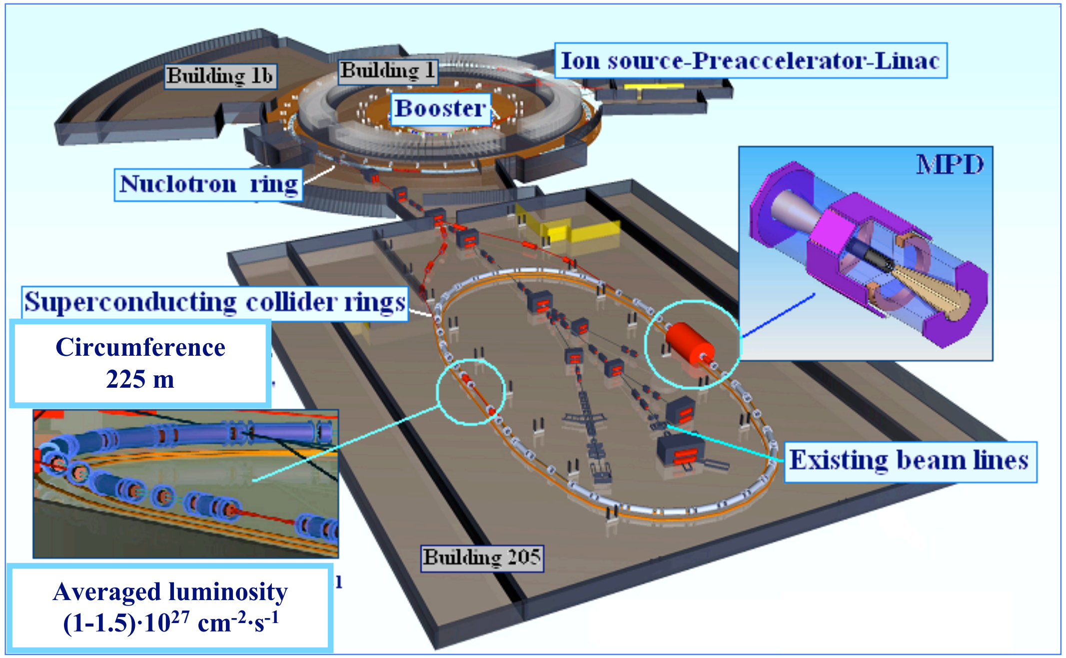


34 T/m QUADRUPOLE

New Motivation:

Project NICA at JINR Dubna:
Nuclotron-based Ion Collider fAcility





Ш The JINR has relevant experience in superconducting cables, magnets design and technology to manufacture the magnet-cryostat system of the collider rings

Table: General parameters of the NICA rings

	Booster	Nuclotron	Collider
Ring circumference, m	215	251.52	225
Initial kinetic energy, MeV/u	6	400	
Final kinetic energy, MeV/u	400	1000 - 3500	1000 -3500
Magnetic rigidity, Tm	2.4 - 25	8.2 - 36	14 - 36
Bending radius, m	14	22	9
Magnetic field, T	0.17 – 1.8	0.37 – 1.64	1.56 – 4
Number of dipole magnets	40	96	24
Maximum gradient of quadrupoles, T/m		33.4	30
Number of quadrupoles	48	64	32
Magnetic field ramp , s	2.65*	1.27	
dB/dt, T/s	1	1	0

- **Hydraulic calculations**
  - supercritical helium flow
  - two-phase helium flow
  - comparison
- **Thermal analysis**
  - supercritical helium flow
  - two-phase helium flow
  - NC without epoxy => theory
  - NC without epoxy => experiment
- **Stability comparison**
  - mechanical
  - AC losses
  - friction factor
  - thermal margins (adiabatic, contineous)
- **Summary**

Nuclotron Cable Stability

1- two-phase helium,

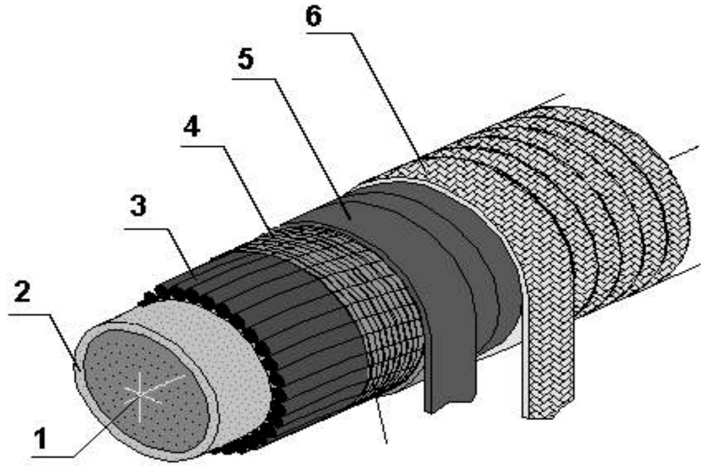
2- copper-nickel tube,

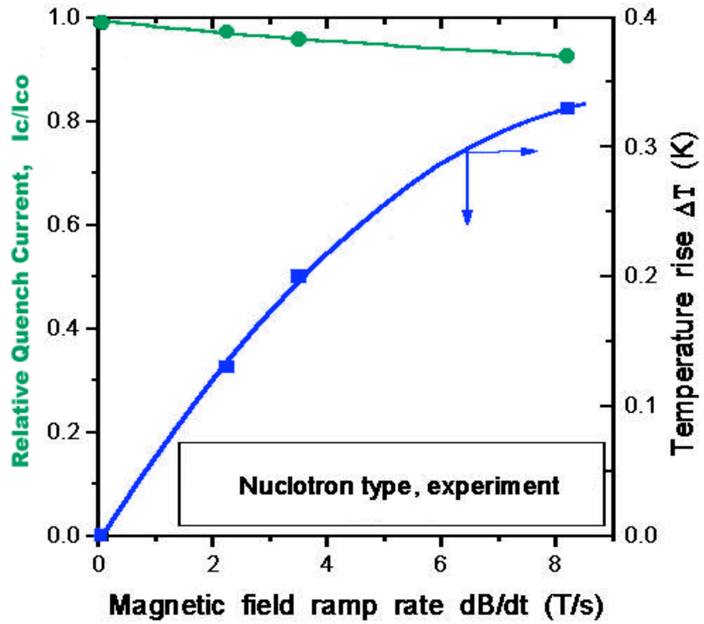
3- superconducting NbTi-wire (10μm filaments, 5 mm twist pitch)

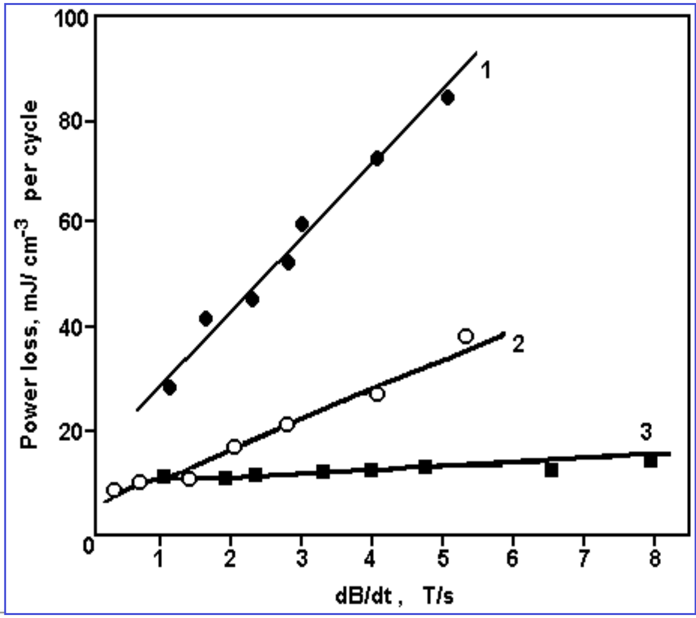
4- nichrome wire,

5- kapton tape,

6-glassfiber tape.







A.Kovalenko, E.Fischer, H.Khodzhibagiyan, Thermomag'07, *Paris 19-20 Nov 2007.*

Hydraulic calculations: parameters

Calculation parameters of the Nuclotron dipole:

Magnet length: 1.46 m
Cable length: 62 m
Diameter of the cooling channel: 0.004 m

Indices:
1- input
2- output coil
3- output iron

ΔP_{yoke} - pressure drop in yoke: negligible

$T_1 = 4.55K$ - He-temperature at input
(set by the pressure in the lHe bath P=1.24 bar
and temperature difference at subcooler outlet ΔT=0.1 K) .

supercritical He:	P_2 = 2.3 bar	[sc He]
two-phase He:	P_2 = 1.25 bar	[2ph He]

Hydraulic calculations: pressure

$\Delta P = \Delta P_f + \Delta P_l$,

with:

$\Delta P_f = 0.5 * f * \rho * w2 * L / d$ **(pressure drop due to friction)**

$\Delta P_l = 0.5 * \xi * \rho * w2$ **(pressure drop due to local resistance)**

with:
- ξ - local resistance coefficient (for Nuclotron coil: $\xi = 16.88$)
- ρ - density of He (kg/m^3)
- w - He-velocity (m/s)
- L - length of the cooling channel (m)
- d - diameter of the cooling channel (m)
- f - friction coefficient

➢ for tubes with round cross-section: with smooth inner walls and Reynolds numbers $4*10^3 < Re < 1*10^5$

the friction coefficient is:

$f = 0.3164*Re^{-1/4}$,

and

$Re = \rho * w * d / \eta$, (η - viscosity of He , $N*s/m^2$)

Hydraulic calculations: pressure and mass flow

He mass flow: $\dot{m} = dm/dt = \rho * w * d^2 * \pi / 4 \Rightarrow Re = 4 * \dot{m} / (\pi * d * \eta)$

$\Delta P_f = 0.2414 * \dot{m}^{1.75} * \eta^{0.25} * L / (\rho * d^{4.75})$, (Pa)

with η, ρ:

- for averaged pressure and temperature values of scHe in the cooling cannel
- and 2ph He (homogeneous theory of two phase flow):

$\rho = \rho_L * \rho_V / \{ (\rho_L - \rho_V) * X + \rho_V \}$, (ρ_l and ρ_v are taken from the saturation line; $\eta = \eta_L$;

X – mass vapour content, i.e. $X = (X_1 + X_2)/2$;

$X_1 = (i_1 - i_{1L})/(i_{1V} - i_{1L})$, $X_2 = (i_2 - i_{2L})/(i_{2V} - i_{2L})$,

(formulas are also well confirmed by the experimental results for pressure drop calculations and measurements in Nuclotron dipole magnets; i = enthalpy of the He in J/K)

- $\Delta P_{f,\,Nucl.} = 3.676 * 10^{12} * \dot{m}^{1.75} * \eta^{0.25} / \rho$

with d = 0.004 m and L = 62 m

Hydraulic calculations: analysis

Calculations for two cooling conditions

a) supercritical helium flow: $T_2 = 4.8$ K (Helium temperature at coil outlet)

$\dot{m} = Q_{coil} / (i_2 - i_1)$, (kg/s) ; Q_{coil} = heat release in the coil , (W)

b) two phase helium flow: $T_2 \leq 4.7$ K

$X_3 = 1$, mass vapour content at the outlet of the iron yoke

$\dot{m} = (Q_{coil} + Q_{yoke}) / (i_3 - i_1)$

$Q_{yoke} = 31$ W (actual heat release in the yoke)

$Q_{coil} = 12$ W

calculations for $3\ W \leq Q_{coil} \leq 12\ W$ and $Q_{yoke} = 31\ W$.

results:

- mass flow rate and pressure drop dependence on the heat load in the coil: Fig. 1 - 3
- **$Q_{coil} \approx$ 6.4 W** is the maximum possible heat load for supercritical cooling at equal temperature margins

supercritical helium flow

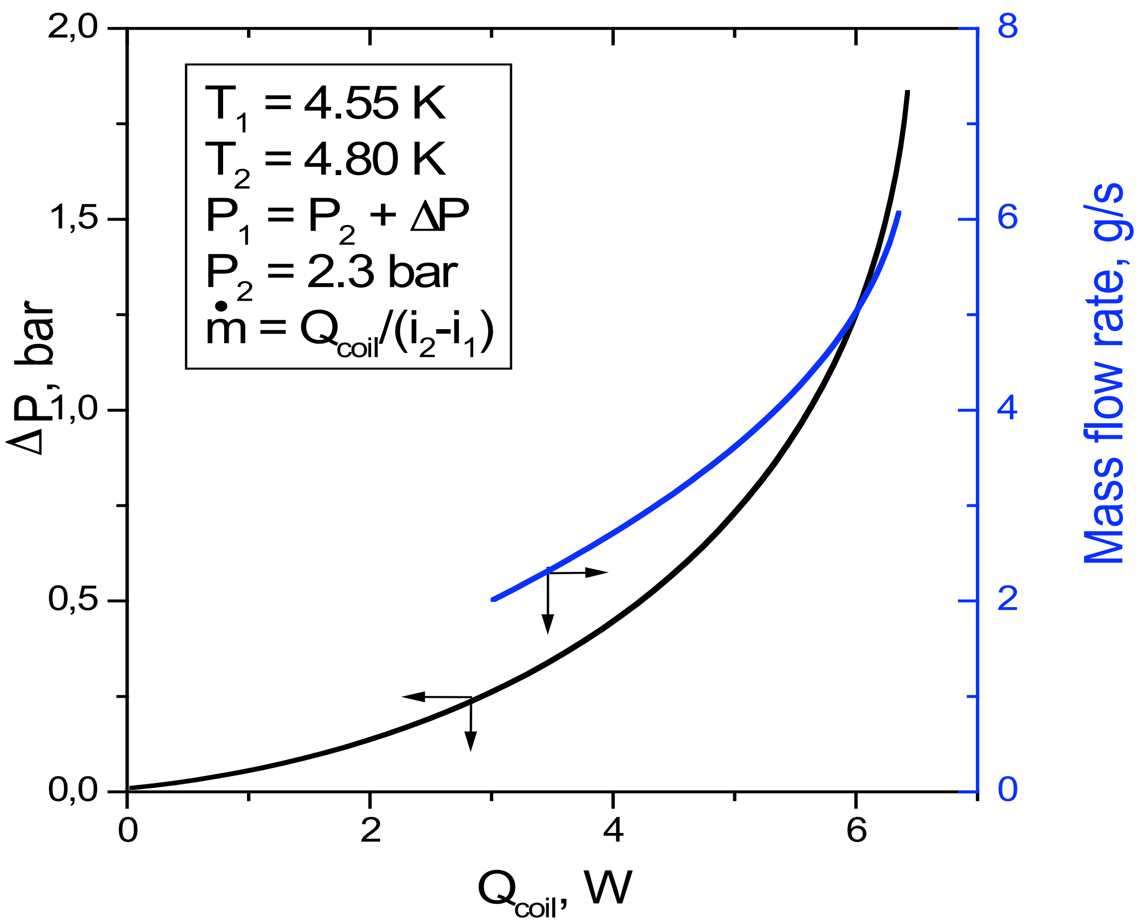


Fig.1 :

Mass flow rate and pressure drop in the coil, cooled with supercritical helium, as functions of the heat production

Hydraulic calculations: results for two phase He

two-phase helium flow

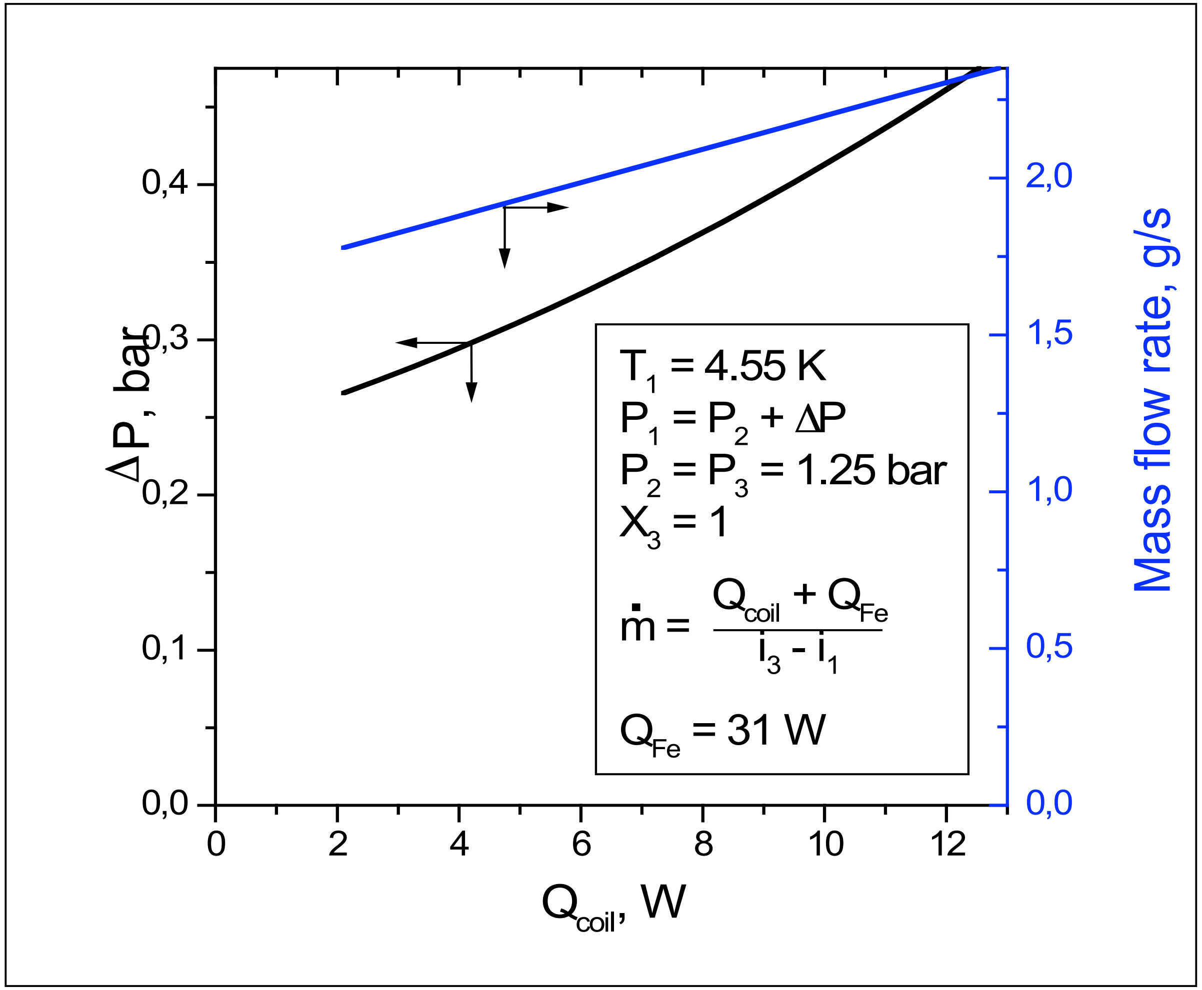


Fig. 2 :

Mass flow rate and pressure drop in the coil, cooled with a two phase helium flow, as functions of the heat production in the coil

Hydraulic calculations: comparison

comparison: supercritical & two-phase helium

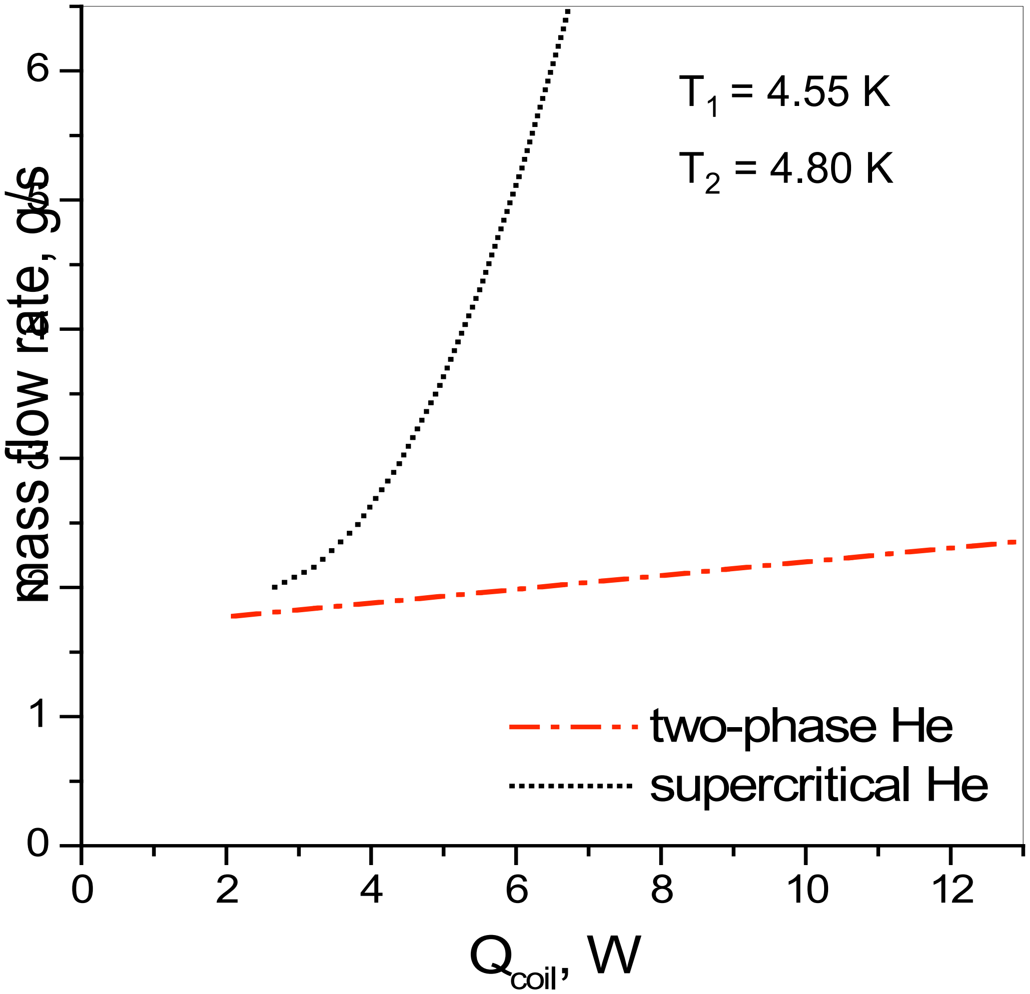


Fig. 3 :

Comparison of the helium mass flow rates in the Nuclotron coil as function of the heat production in the coil for supercritical and two-phase cooling.

Thermal analysis: overload situation

Thermal stability of the coil under overload situations

- possible reasons: ⇒ fault in the refrigerator system,
  ⇒ local defect in the insulation vacuum,
  ⇒ radiation input, ...

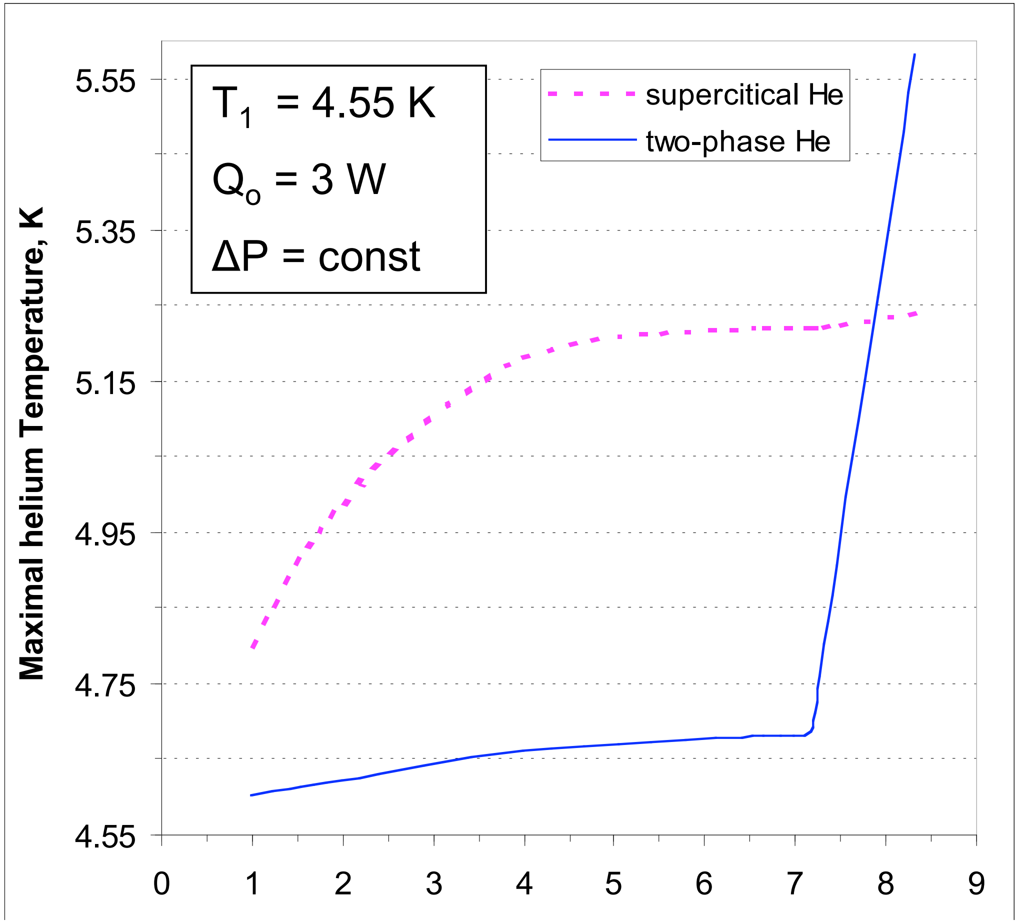
- Calculation parameters: Q_o = 3 W ; (operating heat load without overload)
  ΔP = const ; (inlet and output pressure for the dipoles are fixed)
  ΔP = 0.27 bar for supercritical cooling ; (see Fig. 1)
  ΔP = 0.28 bar for two phase cooling ; (see Fig. 2)

- **Clear gain for two phase cooling: Fig. 4**

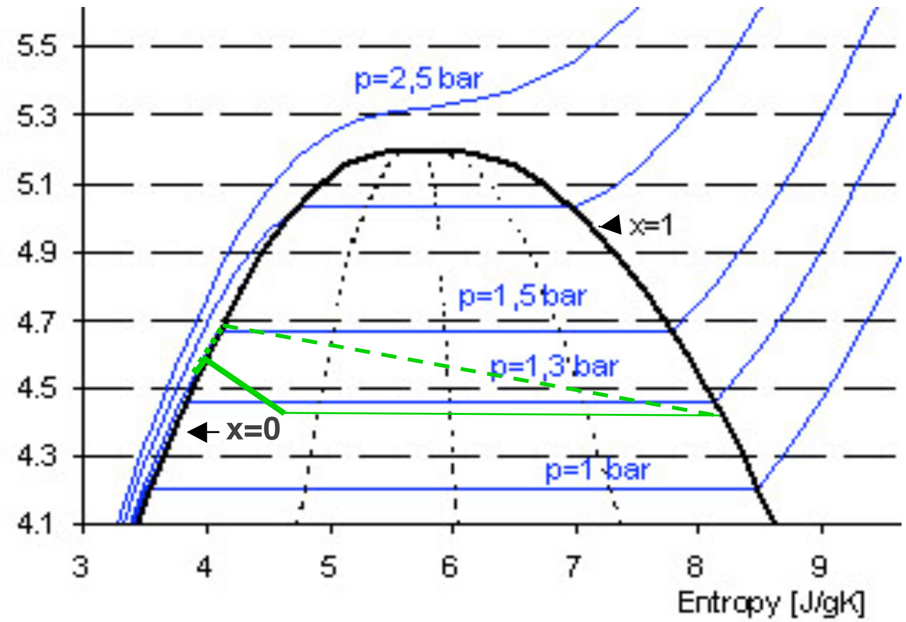
Thermal analysis: overload situation

NICA FAIR

comparison: for supercritical and two-phase cooling



⇐ Fig. 4 :
Overload situation in the coil for supercritical and two-phase cooling based on a nominal heat load Qo = 3 W



Thermal analysis: inner He-tube

NC without epoxy => theory

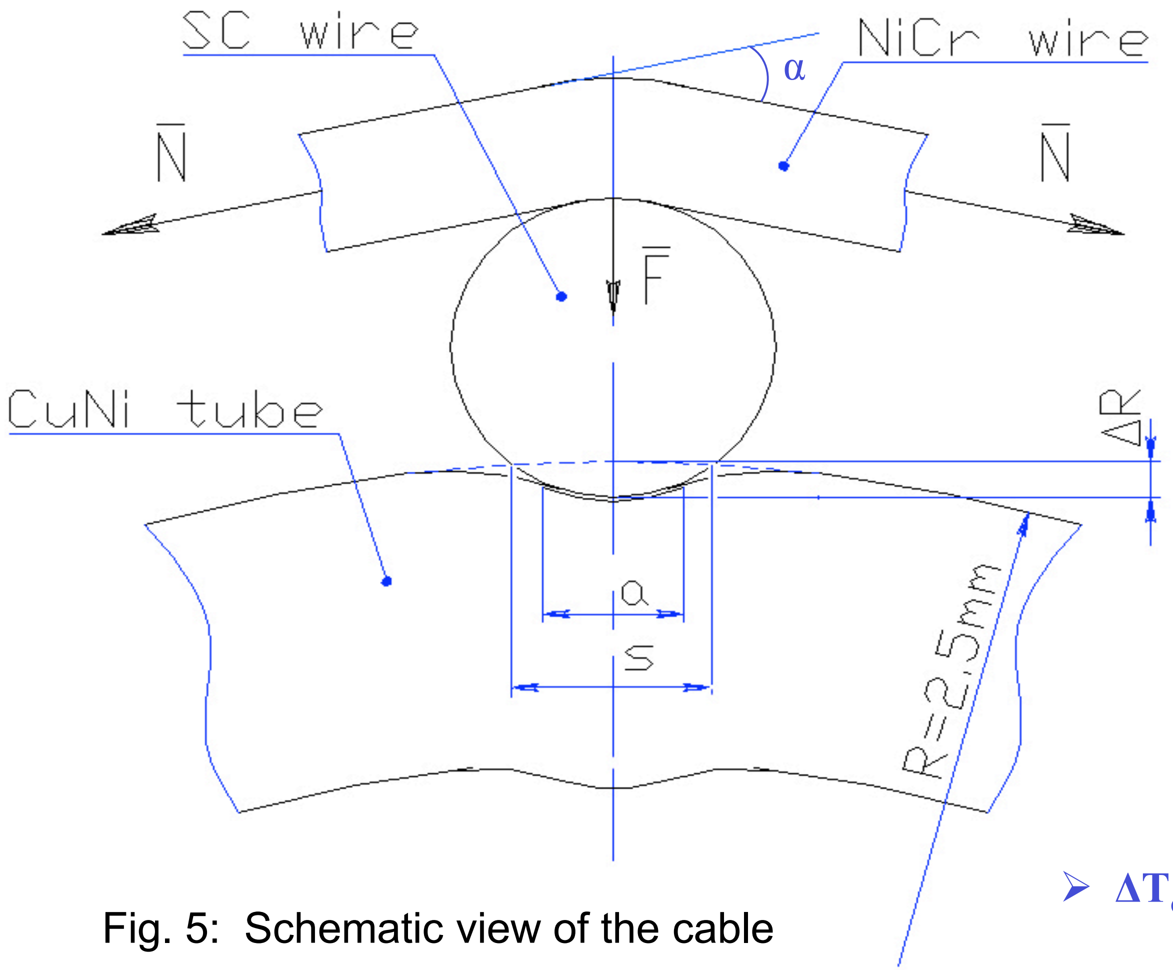


Fig. 5: Schematic view of the cable

stress: $\bar{N} = 9.8$ N

NiCr-wire pitch: $t = 4*10^{-4}$m

angle: $\alpha = 360°/31$

equivalent pressure:

$P = [31*N*\sin(\alpha/2)]/[\pi*R*t]$, Pa

-- -

$P = 9.78$ MPa

$\Delta R = 9.57*10^{-7}$ m

$a = 3.5*10^{-5}$ m

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- **$\Delta T_{contact}$ = 0.053 K @ B_m=2T and f=1Hz**

Thermal analysis: supercritical helium

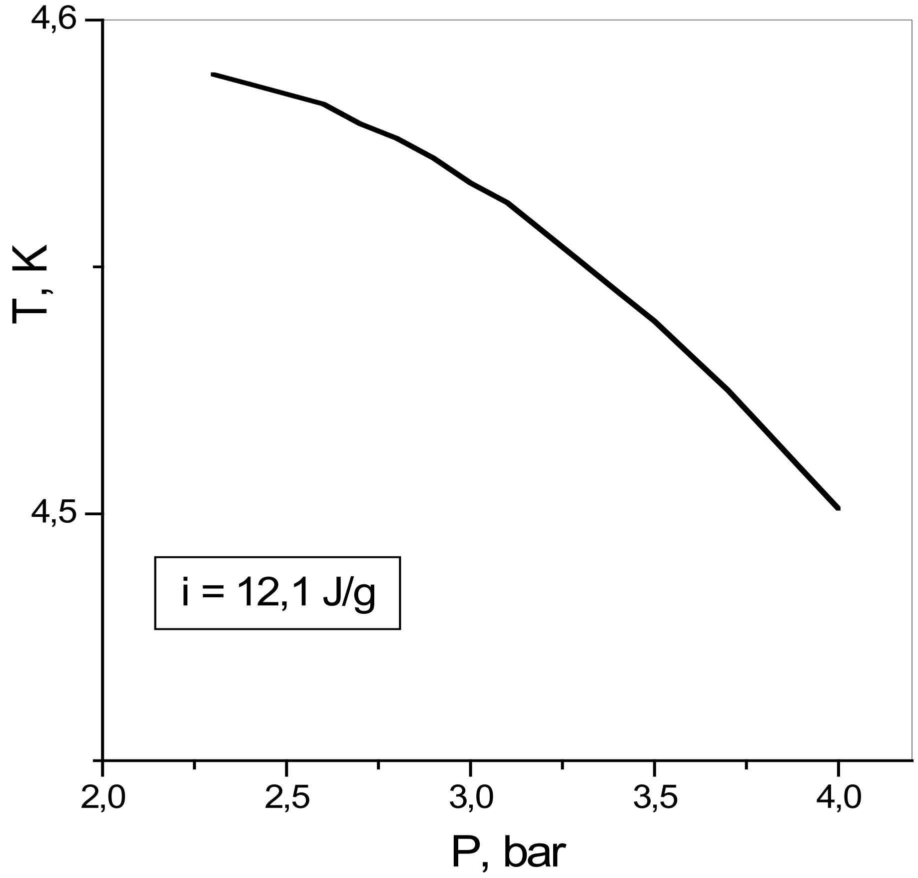


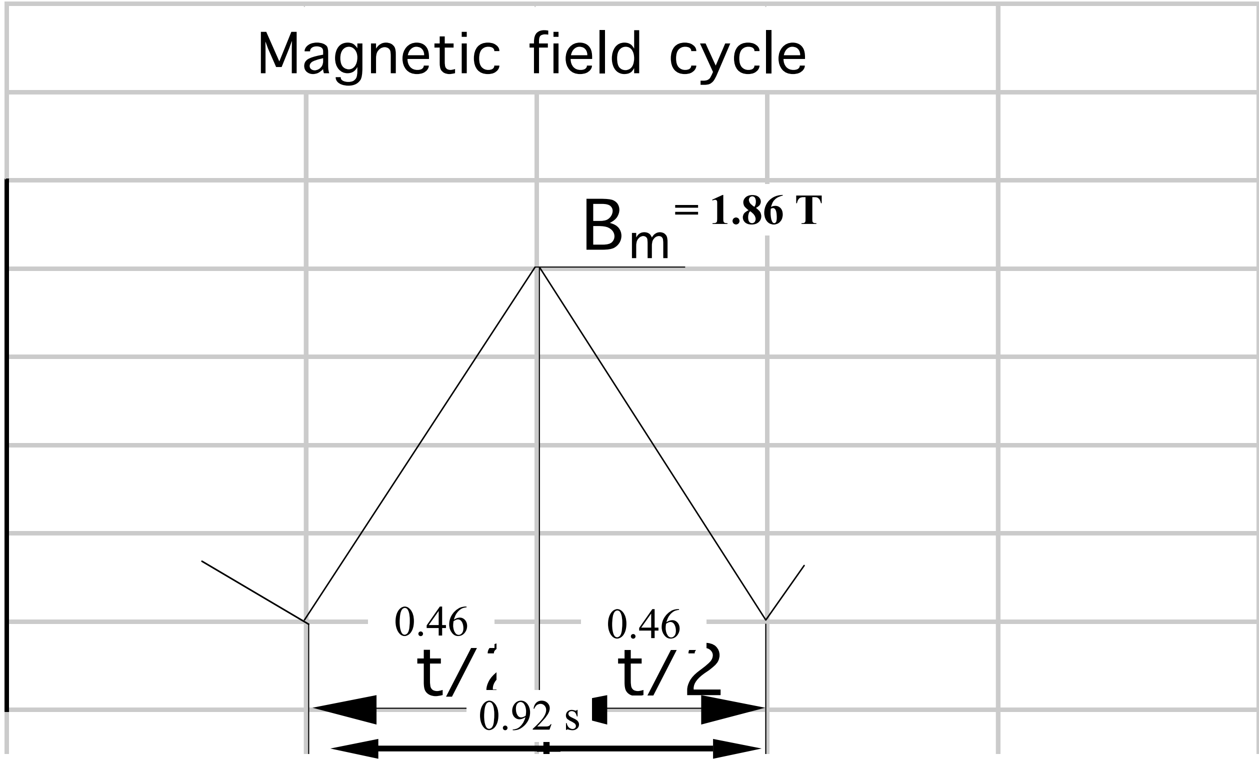
Fig. 6 :

Supercritical helium heating due to the negativ Joule-Thompson-Effect

⇒ larger than ΔT=0.05K, caused by the heat conduction across central CuNi tube

Thermal analysis

NC „without epoxy“ => practical results



dB/dt = 4 T/s, f=1.1 Hz

Fig. 7:

Operating cycle of a Nuclotron winding „without epoxy“

- stable operation ($2*10^4$ cycles)
- thus, epoxy is not necessary, but also not harm

Thermal margins for the cable

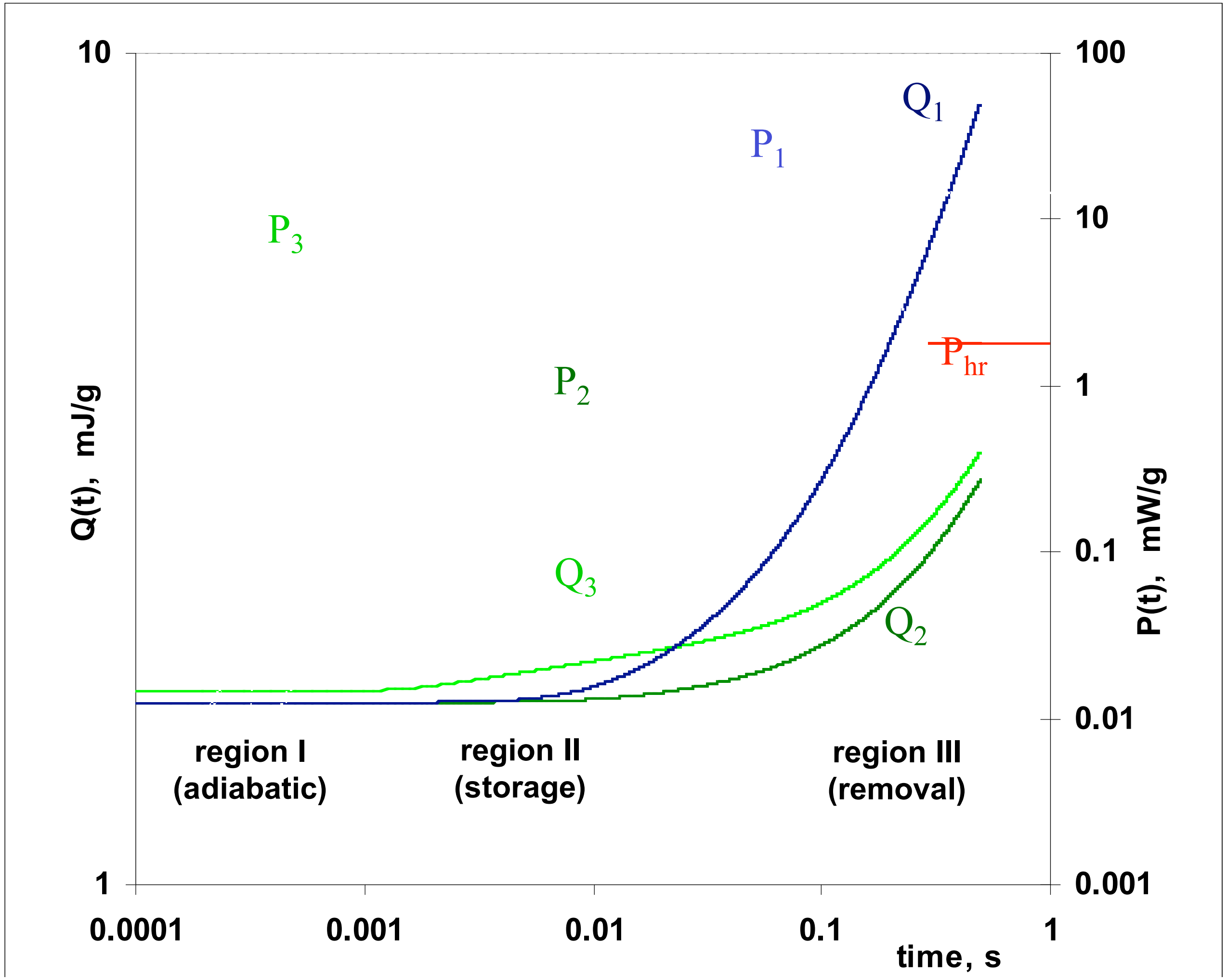


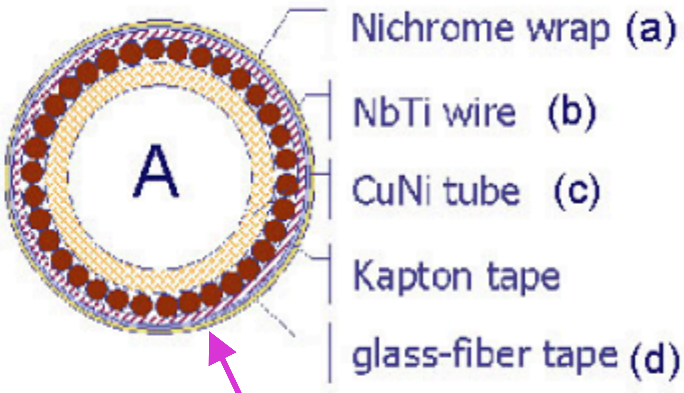
Figure:8

Sketch of margin spectra for a standard Nuclotron cable (Q_1 , P_1), a Nuclotron cable with smaller inner He-tube - or higher friction factor- (Q_2 , P_2) and a similar NCICC cable with additional heat capacity (helium) near the SC wires (Q_3 , P_3). P_{hr} is the minimum cooling power for heat removal from the coil at standard cycle (if $P_{hr} > P_3$ the alternative cable version fails). The adiabatic limits for Q(t→0) are reached at the left scale.

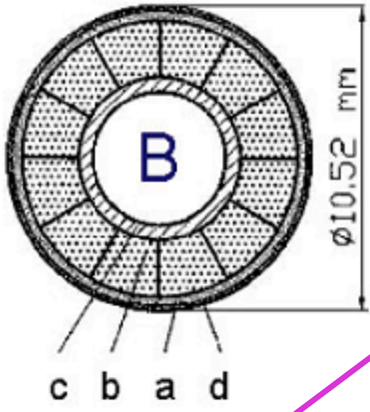
Main influence in the time scales (regions):

- **I. superconductor, current density, temperature level**
- **II. heat capacity and thermal conduction in the coil elements**
- **III. hydraulic parameters and heat transfer coefficient**

Keystone wire - new cable version (1)

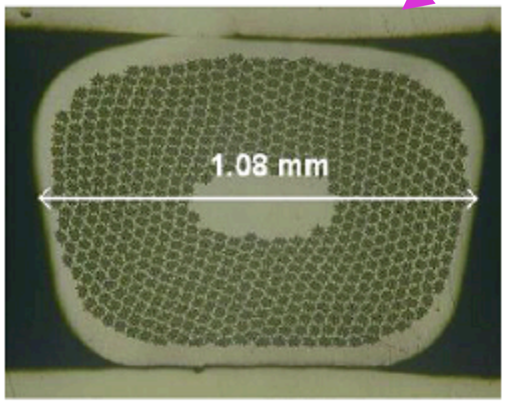


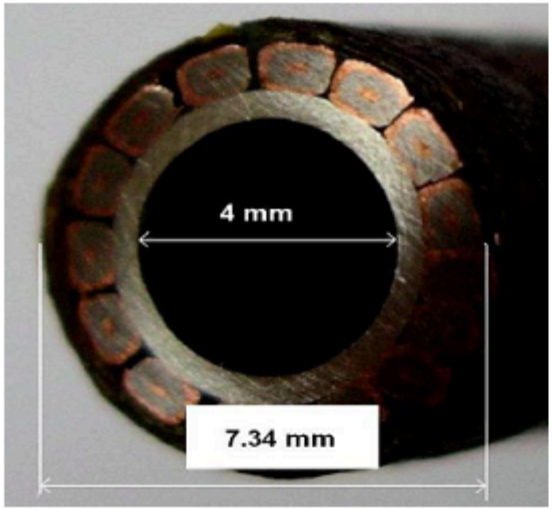
original Nuclotron cable - round superconducting wires



New hollow cable made of keystoned wires

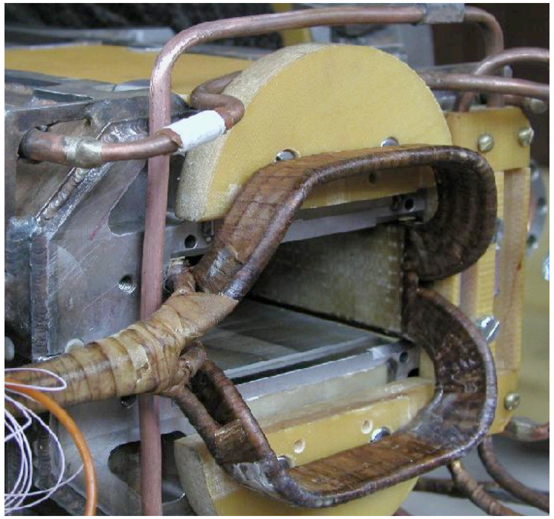
keystone wire

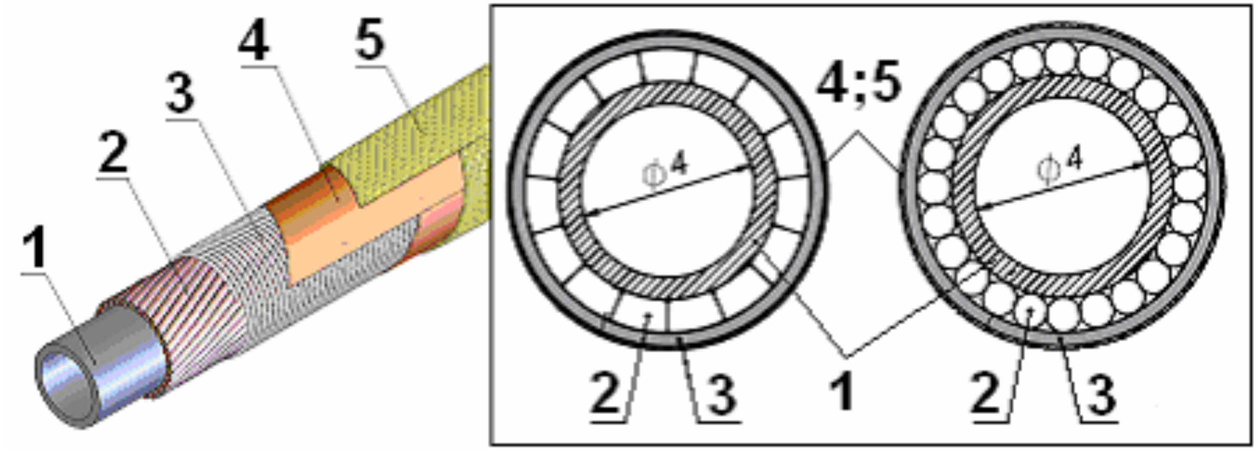


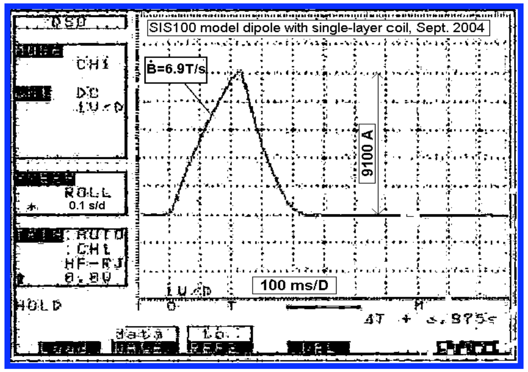


keystoning – increased engineering current density

Single-layer coil – new magnet options







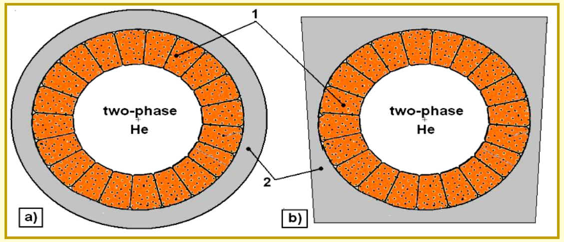
"DESIGN AND TEST OF A HOLLOW SUPERCONDUCTING CABLE BASED ON KEYSTONED NbTi COMPOSITE WIRE",

ASC 2004, October 2004, Jacksonville, USA

		10 turns	8 turns
Dynamical heat release (cycle 2c)	W	≈ 33	**≈ 31**
Pressure drop for cycle 2c	bar	≈ 0.6	**≈ 0.42**
Maximal temperature of helium in the coil (2c)	K	4.75	**4.7**
Dynamical heat release (B_{max} = 1.9 T, f = 1 Hz)	W	≈ 57	**≈ 54**
Pressure drop (B_{max} = 1.9 T, f = 1 Hz)	bar	≈ 1	**≈ 0.7**
Maximal temperature of helium in the coil (triangular cycle with B_m = 1.9 T, f = 1 Hz)	K	4.9	**4.8**

Keystone wire - new cable version (2)

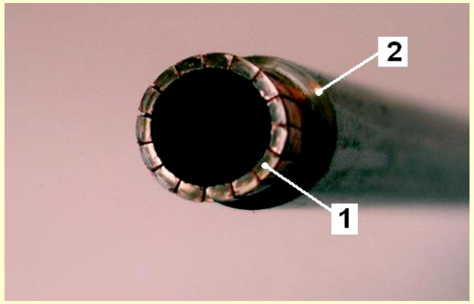
New design: (KWIT)
Keystoned Wires Inside a Tube

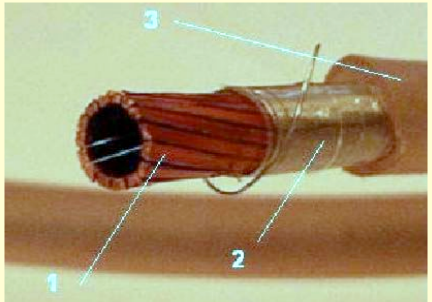


The wires fix themselves (arc principle) and form a cooling channel with small hydraulic resistance. The direct contact of two-phase helium flow with the wires provides the highest cryogenic stability any time interval.

E. Fischer, H. Khodzhibagiyan, A.Kovalenko, and G. Moritz.

EU-patent Nr. 04009730.5, 23.04.2004.

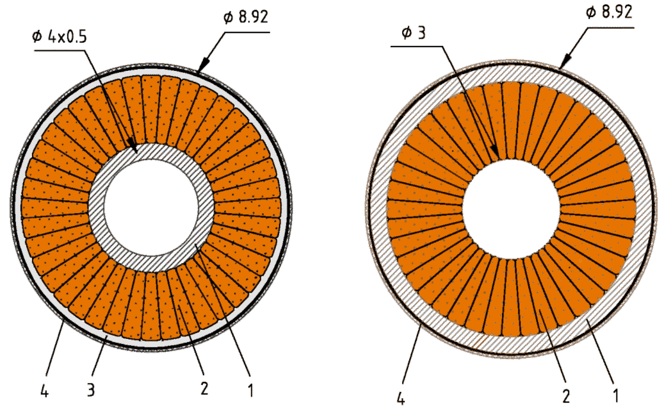




Keystone wire - new cable version (3)

Comparison of hollow cables

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



Cross section of the KWAT2 (a) and KWIT1 (b) cables: 1 - copper-nickel tube, 2 - composite NbTi strand of keystoned profile, 3 – strands binding by wire, 4 - electrical insulation.

MODEL CABLE TEST RESULTS

The KWAT1 version has been manufactured and tested as real dipole coil in the Nuclotron-type dipole. The R&D stages from keystoned wire fabrication at the Bochvar Research Institute (Moscow) to the first 50 m of the cable production LHE JINR as well as the first coil from KWAT1 and it's tests were described earlier. The maximum cycle operation current of 11.4 kA obtained in the July 2005 tests was limited not by the cable but by the test bench capabilities. The standard operation limits of the LHE test facility were: supply current of 6 kA, current ramp rate of 12 kA/s at inductance of 1 mH. The power supply upgrade performed in 2004-2005 made it possible to increase the current by a factor of two. The geometry of a single-layer 8 turn winding made from KWAT1 corresponds to the 1.4 m long Nuclotron window frame yoke. The sizes of a window are 126mm x 59 mm. The coil was separated from the yoke window by a gap of 2 mm. A stable operation of the magnet at dB/dt = 4 T/s, f = 0.5 Hz was observed up to the supply current of about 10700A. The first quench occurred at a current of 11400 A after more than ten cycles, initiated by the current leads. No normal zone was detected in the coil.

R&D: SC Dipole Cycling up to 20 Hz

NICA

FAIR

The works on the design of a superconducting synchrotron magnets with a pulse repetition rate up to 20 Hz are continued at the Laboratory of High Energies of JINR. Modification of the magnet from the 4K yoke option to the 50 K one was made. The new test was performed in July 2005.

A cold iron (T = 4.5 K) window-frame Nuclotron dipole with a single-layer coil made from the new high current hollow NbTi composite cable was constructed and tested first time about a year ago. The pulse repetition rates from 3 to 5 Hz was obtained. Operating current and the current ramp, limited by the power supply voltage, reached the level of 6 kA and 37.5 kA/s respectively. The magnetic field in the gap did not exceed of 1 T at that tests.[1] Partial upgrade of the power supply was realized and the new test of the modified dipole has been performed.

MODIFICATION OF THE DIPOLE

Cross section of the new dipole version is presented in Fig.1. Similar to that was made earlier for manufacturing the model dipoles 80KDP2 and 80KDP3 [2] the magnet coil at T = 4.5 K was separated from the yoke with a gap of 1 mm. Epoxy impregnated glass fiber multilayer wound around the coil was used to compensate Lorentz forces. The cold mass of the dipole is fixed inside the yoke window with special adjustable G10 pins and plates. General view of the magnet in the cryostat is shown in Fig.2.

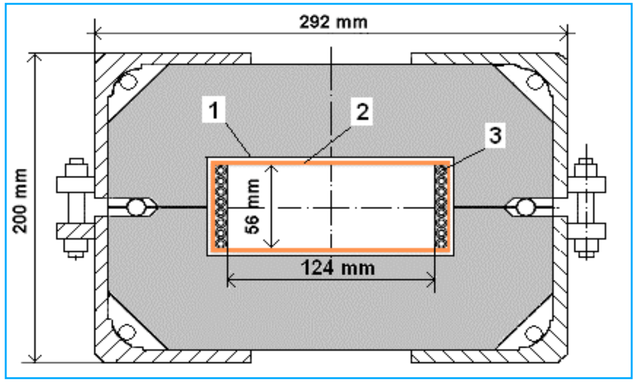


Fig. 1. Schematic cross section of the 50 K yoke dipole

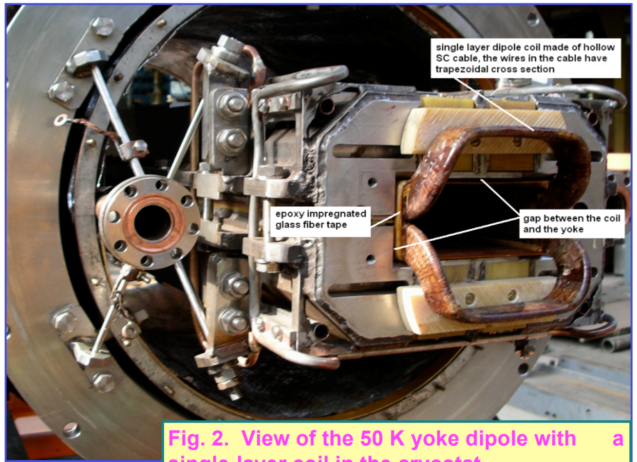
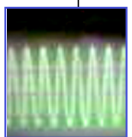


Fig. 2. View of the 50 K yoke dipole with a single-layer coil in the cryostat

TEST OF THE MAGNET

The magnet was tested at different conditions, nevertheless, limited by the power supply parameters. The measured AC losses (in W) are presented in the Table. The coil and the yoke are cooled with two-phase helium flow in series at that test. One can see from the data that the maximum field ramp in the magnet gap reaches of 6.7 T/s and maximum pulse repetition rate – of about 5.8 Hz. The operating current maximum ramp rate was about 42.6 kA/s.

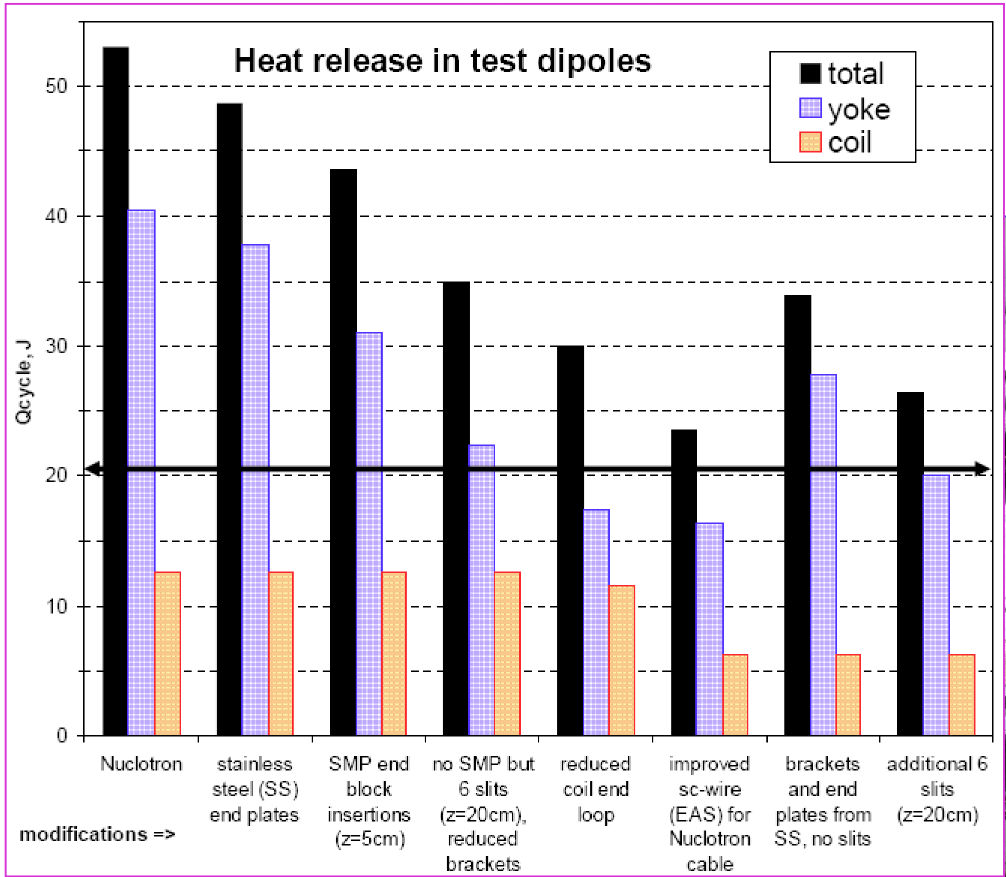
FIELD RAMP & GAP FIELD	CYCLE	Dynamic heat releases		
		coil	yoke	total
dB/dt=5.0 T/s Bm=1.0 T	Im=6800 A 0.43s	16.09	19.47	35.56
dB/dt=4.0 T/s Bm=1.0 T	Im=6810 A 0.54s	11.27	12.35	23.62
dB/dt=5.8 T/s Bm=0.5 T	Im=3400 A 0.173s			35.35
dB/dt=6.7 T/s Bm=1.07 T	Im=6810 A 0.32s			49.15
		25.71	25.22	50.93

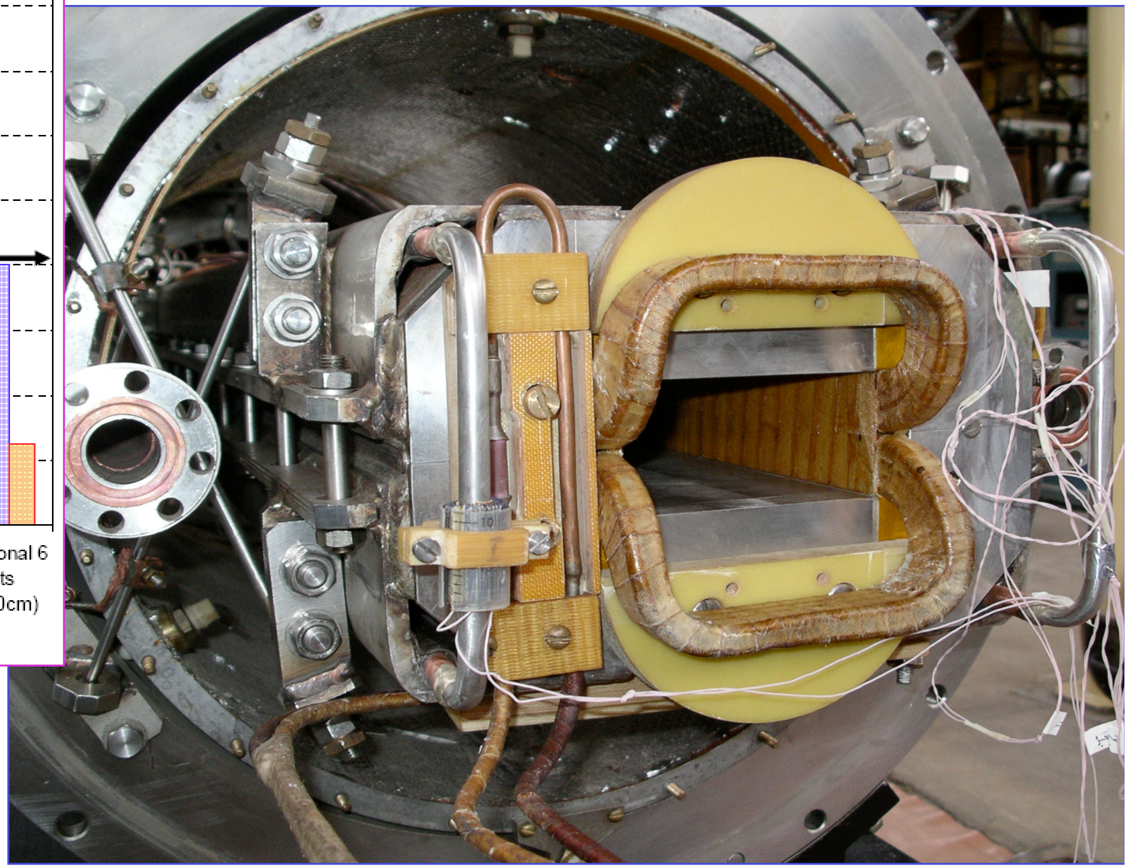
JINR

GSI

A.Kovalenko, E.Fischer, H.Khodzhibagiyan, Thermomag'07, *Paris 19-20 Nov 2007.*

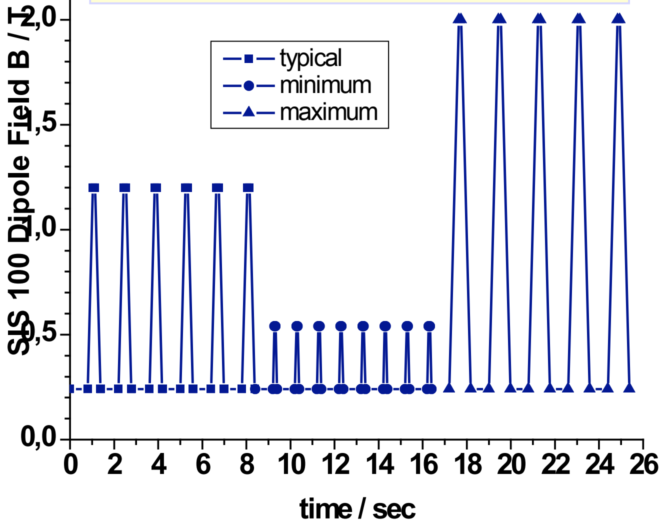
Dipole R&D: SIS100 at GSI (1)

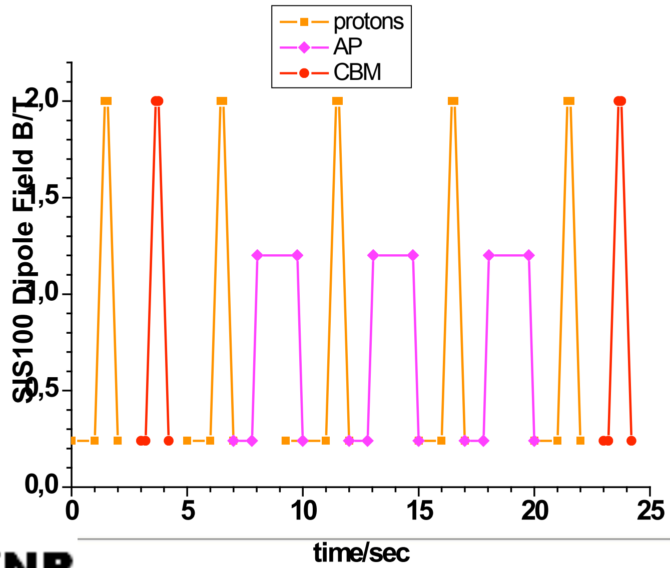




FAIR cycles requirements

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





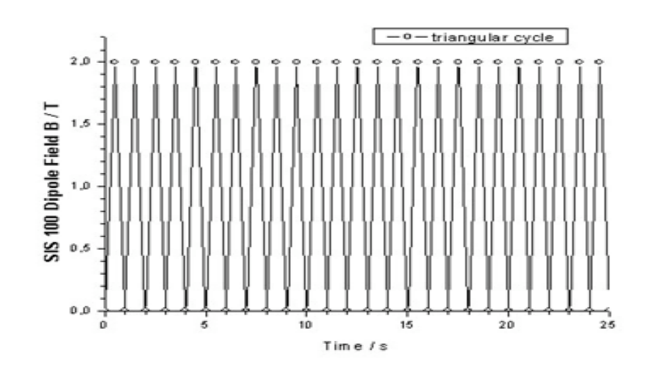
The SIS 100 operation cycles and the Expected Losses

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%)

FAIR cycles requirements

Supercycles for Parallel Operation



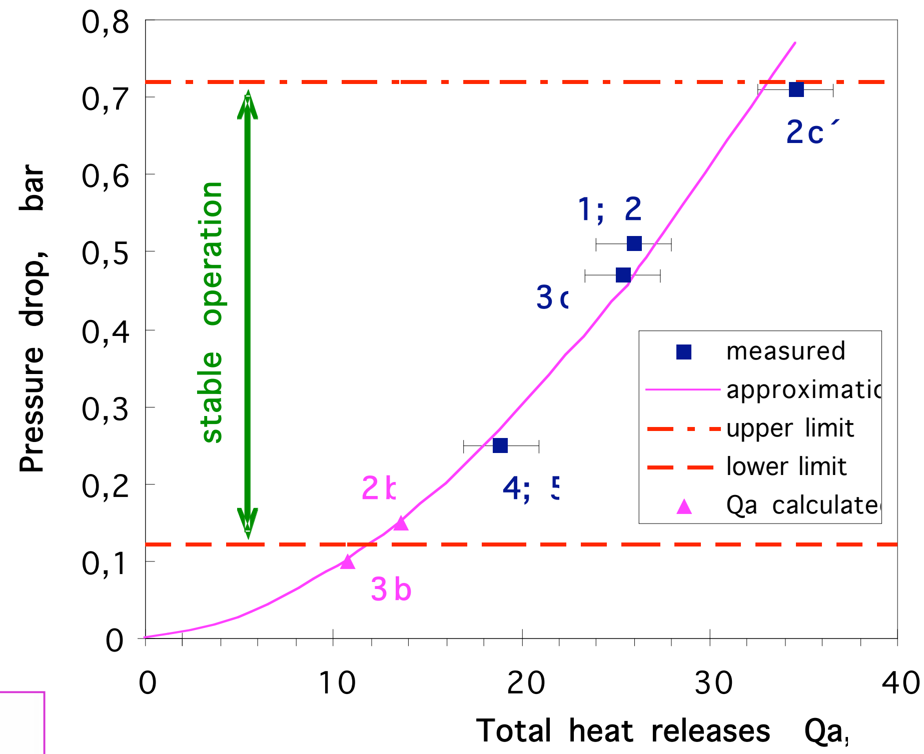
reference cycle:
2 T, 4 T/s, 1Hz

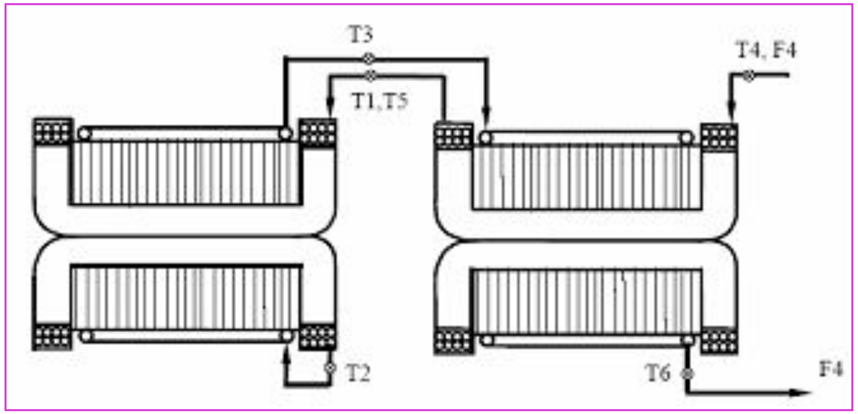
- Purpose: Standard scenario for layout of magnets, cryogenics, power supplies etc.
- Each cycle may run for several hours (... days)
- Different final energies may be used, but for the standard supercycles, for each experiment, a typical energy was chosen.
- For the calculation of a mean energy consumption 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.

Dipole R&D: SIS100 at GSI (2)

Table: Operation cycles and estimated 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





Straight dipole:

cryogenic stability range ↑

and the

← test scheme of the equivalent model dipole

NICA

SIS 100 magnets: Nuclotron cable redesign

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 ?1) , K	4.94	4.95	4.78	4.64
tria gular cycle [dB/dt = 4 T/s, t_{cycle} = 2?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	5.10	4.86	4.72
	T_6=8K	T_6=8K	T_6=8K	T_6=7K

My personal vision: **optimal version of the SIS100 dipole is a single-layer 10-turns coil curved magnet.**

See also: E. Fischer, H. Khodzhibagiyan and A.Kovalenko "Full size model magnets for the FAIR SIS100 synchrotron", The 20th international conference on magnet technology. IEEE, August 2007

JINR

GSI

Summary:

Ш Hollow cable cooled with two phase helium flow provide sufficient cryogenic stability in a wide range of heat load

Ш Several new HC modifications were designed and tested at LHE JINR during the last years

Ш Many of the new results were obtained in our collaboration with GSI magnet group