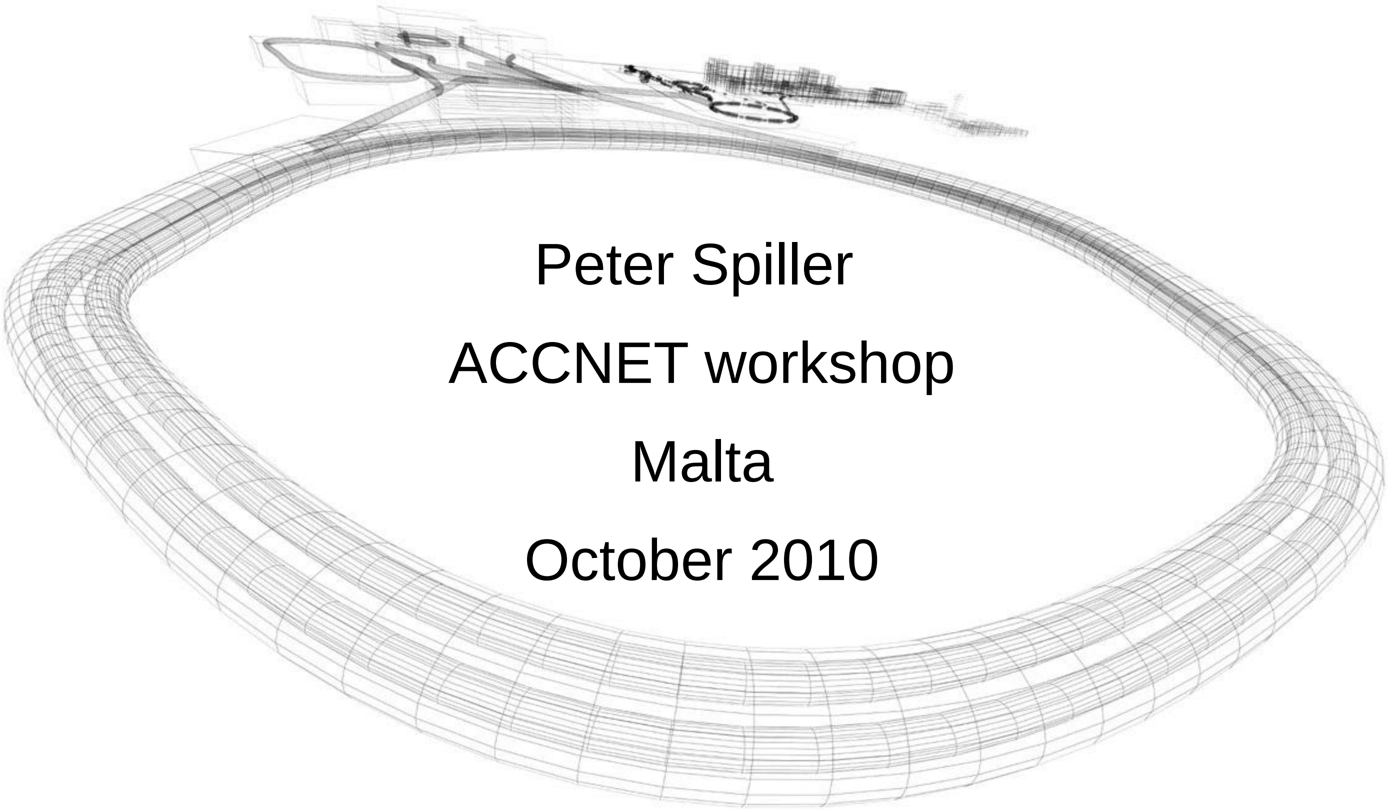
Development of Fast Ramped Superconducting Magnets for FAIR



Peter Spiller

ACCNET workshop

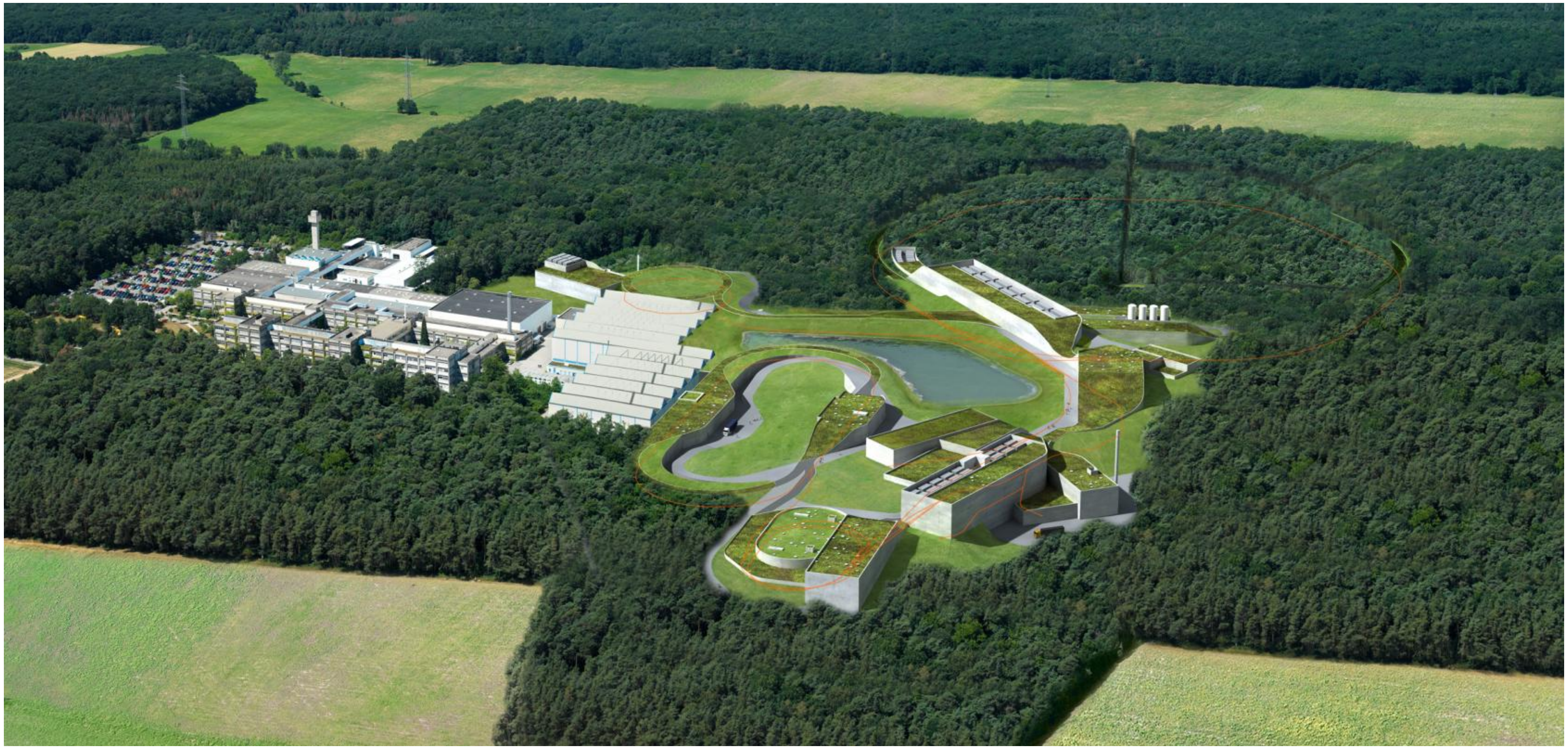
Malta

October 2010

FAIR Formation

On 4th of October the Formation of the FAIR GmbH took place.

Nine countries have signed the contract on the level of an international law.



FAIR

- FAIR experiments require high average intensity > Fast ramped magnets

(short cycle times)

- FAIR is supposed to be highly parallel and flexible
- At a circumference of about 1km, curved dipole magnets are needed. > Restriction in total pulse power (magnet aperture) and acceptance drop by large sagitta.

CERN/SLHC

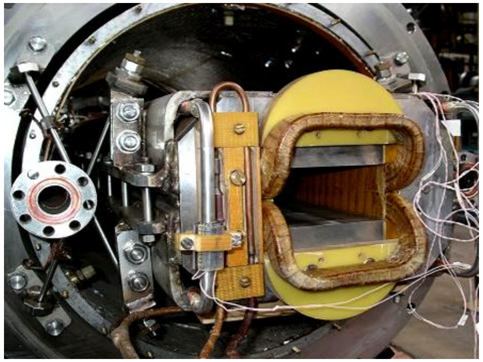
- SIS100 magnet technolgy, its design and R&D may be of interest for a s.c. PS.
- SIS300 magnets technology, its design and R&D may be of interest for a s.c. SPS (e.g. increase of final energy, energy consumption/pulse power)

SIS18 Operation

<table>
<tr><th colspan="6">Week 36</th><th colspan="7">Week 37</th><th colspan="7">Week 38</th><th colspan="7">Week 39</th><th colspan="3">Week 40</th></tr>
<tr><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>10</td><td>11</td><td>12</td><td>13</td><td>14</td><td>15</td><td>16</td><td>17</td><td>18</td><td>19</td><td>20</td><td>21</td><td>22</td><td>23</td><td>24</td><td>25</td><td>26</td><td>27</td><td>28</td><td>29</td><td>30</td></tr>
<tr><td colspan="29">U243, Yakushev/Düllmann, 48Ca (ECR), ~4.5-5.5 MeV/u, 4 particle-microAmp (pulse) in X8, >=5 ms / 50 Hz, X8 TASCA</td><td>a)</td></tr>
<tr><td colspan="6">U238, Block, 48Ca, 4-5 MeV/u, long pulses: 5ms, 5 Hz, Y7 SHIPTRAP</td><td colspan="4">B, U.Scheeler, U-PIG/MEVVA, UNILAC</td><td></td><td></td><td></td><td colspan="7">U225, Heßberger/Heßberger, 48Ca, 4.4- 5.1 MeV/u, 1000 pnA, 5 Hz, 5 ms, Y7</td><td colspan="5">U226, M. Roth/A. Blazeviv, Ca, mean charge state, Z6 stripper, 4.9, 1 pµA, 1 ms, Z6</td><td></td><td></td><td colspan="2">b)</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td colspan="8">S349, Fabbietti/Leifels, p, MUCIS, 3.5 GeV, ~5-10 10e7/spill, long extraction (max), HTB</td><td></td><td></td><td colspan="6">S351, Yamazaki/Bräuning, U89+, MEVVA, 190 MeV/u, 1e4/s, SIS cooler, long flat extraction, HTA</td><td colspan="4">S361, Bruce/Gorska, 238U73+, MEVVA, 750 MeV/u, 5e9 particles per spill, , 4 s extraction, FRS,</td><td colspan="4">S337, Gadea/Gorska, 238U, MEVVA, 750MeV/u, 5e9/spill, FRS, S4</td><td colspan="5">S350, Benzoni/Gorska, 238U, MEVVA, 1000 MeV/u, 5x10^9 /SPILL, FRS, S4</td><td>c)</td></tr>
<tr><td colspan="2">d)</td><td>e)</td><td colspan="5">S386, Schwarz/Schwarz, p, 2.5 GeV, 1e5, 10s extraction, HTD</td><td></td><td></td><td colspan="2">f)</td><td colspan="9">S331, Mintsev/Varentsov, U73+, 200-500 MeV/u, MAXIMUM (>2e9), preferably SIS cooler, HHT</td><td colspan="4">S394, Lemmon/Leifels, U, 400MeV/u, ~5e5/spill, long extraction (10s), HTD</td><td colspan="3">g)</td><td colspan="2">h)</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td colspan="2">B, U.Scheeler, U, ESR</td><td colspan="6">E080, Grisenti/Winters, 238U92+, 50-400MeV/u, 10e8 particles, ESR</td><td colspan="7">E093, Thorn/Thorn, 238U91+, 100,200,400 MeV/u, normal ESR intensity, ESR</td><td colspan="7">E065, Brandau/Kozhuharov, 238U, 200 MeV/u, 1e8/spill (SIS), SIS cooler, ESR</td></tr>
</table>

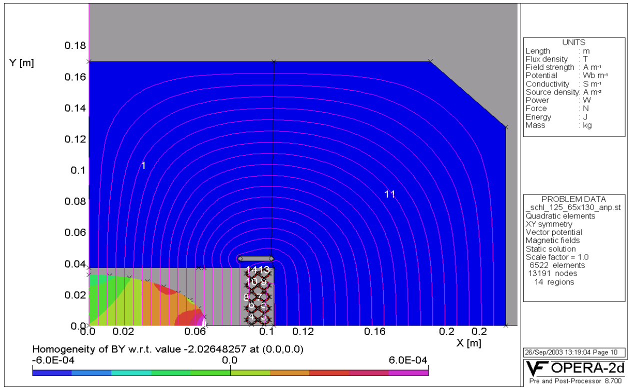
- Typically 6700 h operation per year
- Change of ion species and all beam parameters cycle by cycle
- Up to three experiments in parallel

SIS100 Fast Ramped S.C. Magnets



R&D Goals

- **Reduction of eddy / persistent current effects at 4K (3D field, AC loss)**
- **Improvement of DC/AC-field quality**
- **Guarantee of long term mechanical stability** ($\geq 2\cdot10^{8}$ cycles)



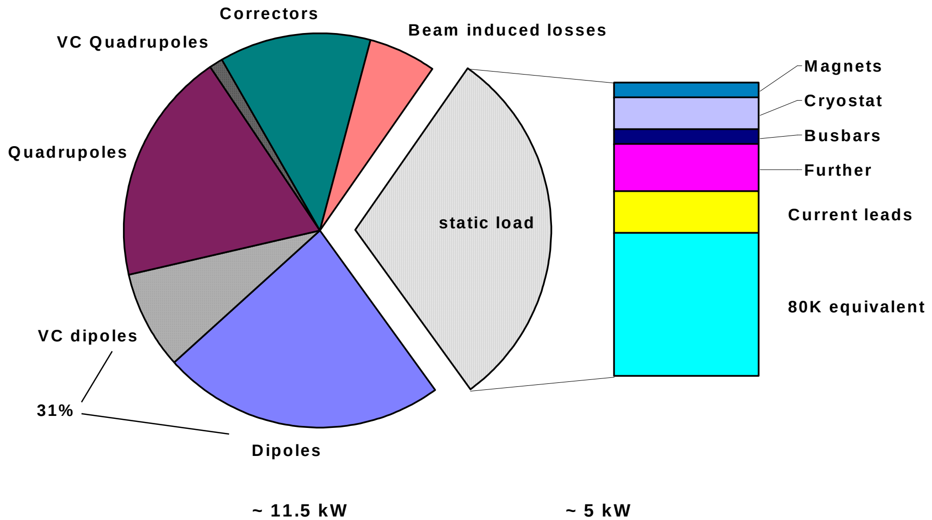
Activities

- AC Loss Reduction (exp. tests, FEM)
- 2D/3D Magnetic Field Calculations (OPERA, ANSYS, etc.)
- Mechanical Analysis and Coil Restraint (design, ANSYS) (>Fatigue of the conductor and precise positioning)

Experimental studies with modified Nuklotron magnets in JINR

SIS100 Heat Load

- Dynamic load is dominating
- During SIS100 stand by, large refrigerator capacity available for e.g. cooling down
- At high ramp rates (high AC loss) the advantage of s.c. magnets compared to n.c. magnets fads..
- S.c. magnet are typically operated close to the limit of cooliing power, therefore early definition of the extreme cycles needed.

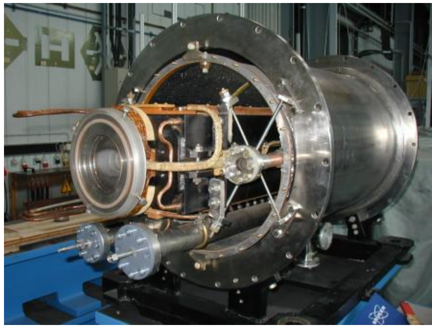


Values for Reference Cycle 2c

Two-Stage Synchrotron SIS100/300

- **1. High Intensity- and Compressor Stage**

SIS100 with fast-ramped superconducting magnets and a strong bunch compression system.

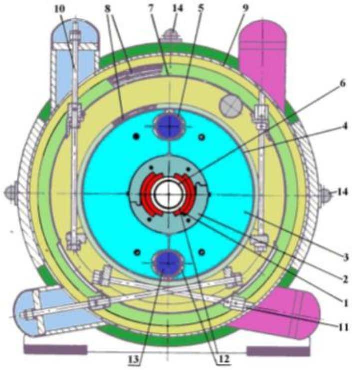


Intermediate charge state ions e.g. U^{28+}-ions up to 2.7 GeV/u
Protons up to 30 GeV

$B\rho$= 100 Tm - B_{max}= 1.9 T - dB/dt= 4 T/s (curved)

- **2. High Energy- and Stretcher Stage**

SIS300 with superconducting high-field magnets and stretcher function.



Highly charges ions e.g. U^{92+}-ions up to 34 GeV/u
Intermediate charge state ions U^{28+}- ions at 1.5 to 2.7 GeV/u with 100% duty cycle

$B\rho$= 300 Tm - B_{max}= 4.5 T - dB/dt= 1 T/s (curved)

SIS100 Fast Ramped S.C. Magnets

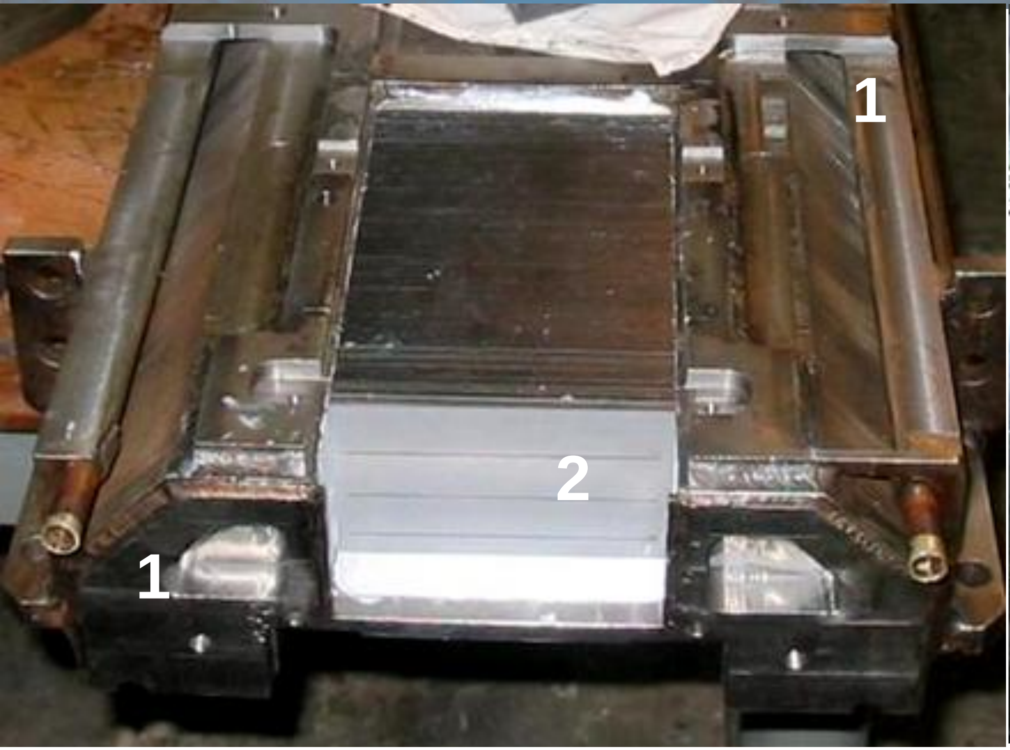
•SC Magnets R & D

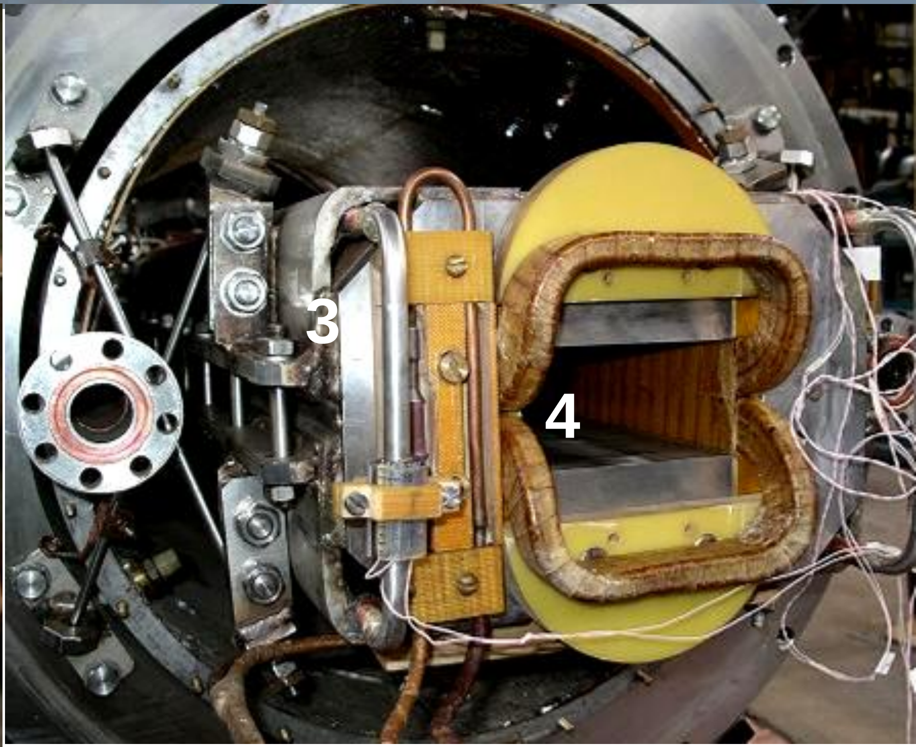
- –AC Loss Reduction (exp. tests, FEM)
- –Mechanical Analysis and Coil Restraint (design, exp. tests, ANSYS)
- –Magnetic Field Calculations (OPERA, ANSYS, elliptic multipoles)

•Full size models

- –Straight dipoles (JINR Dubna, BNG Wuerzburg)
- –Curved dipole (BINP Novosibirsk)
- –Quadrupole (JINR Dubna)
- –Operation Performance (composite model)

AC Loss Reduction





Modificated Nuclotron dipoles with:

1 partly removed brackets and end plates

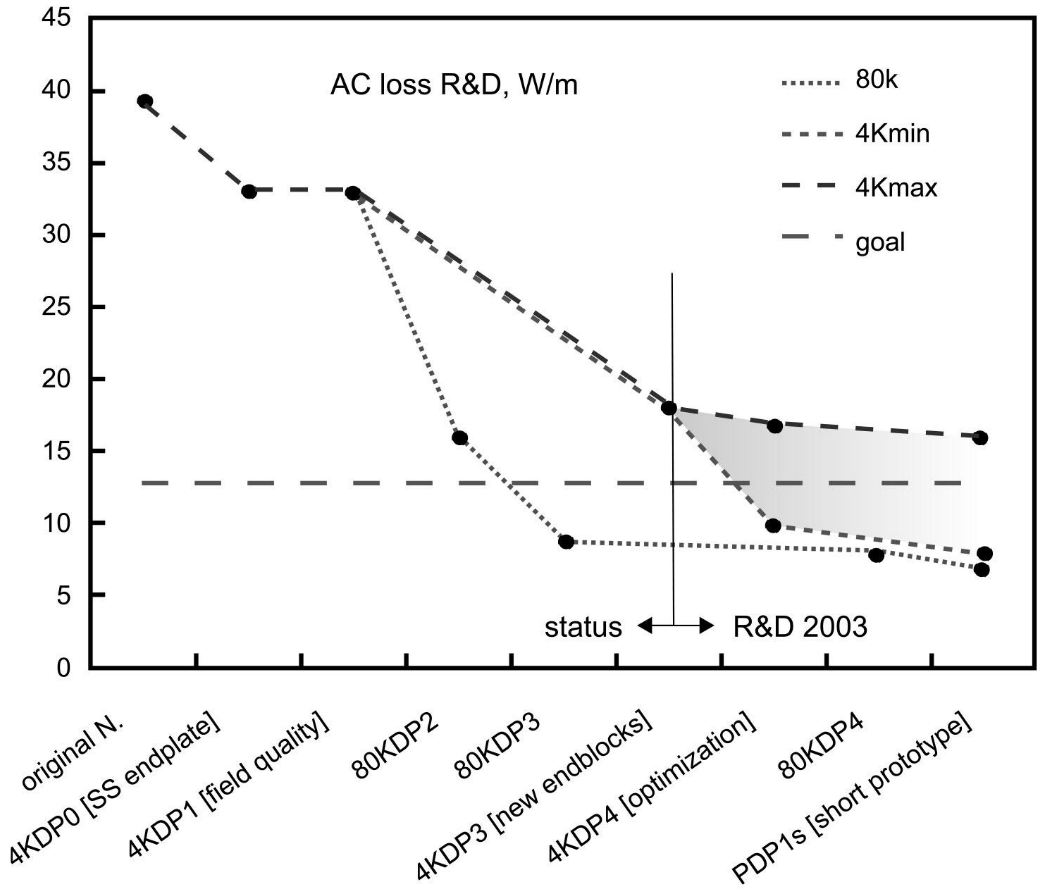
2 and laser cut lamination slits

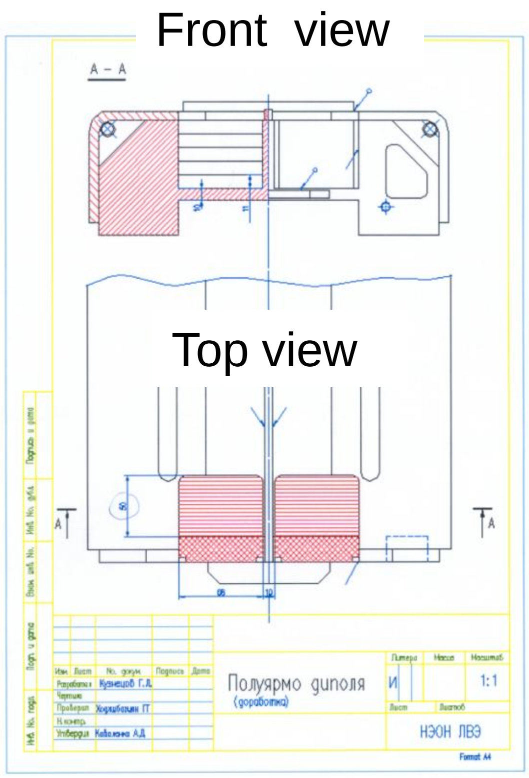
3 ▲ stainless steel brackets and end plates

4 ▲ reduced coil end shape

SIS 100 Fast Ramped S.C. Magnets

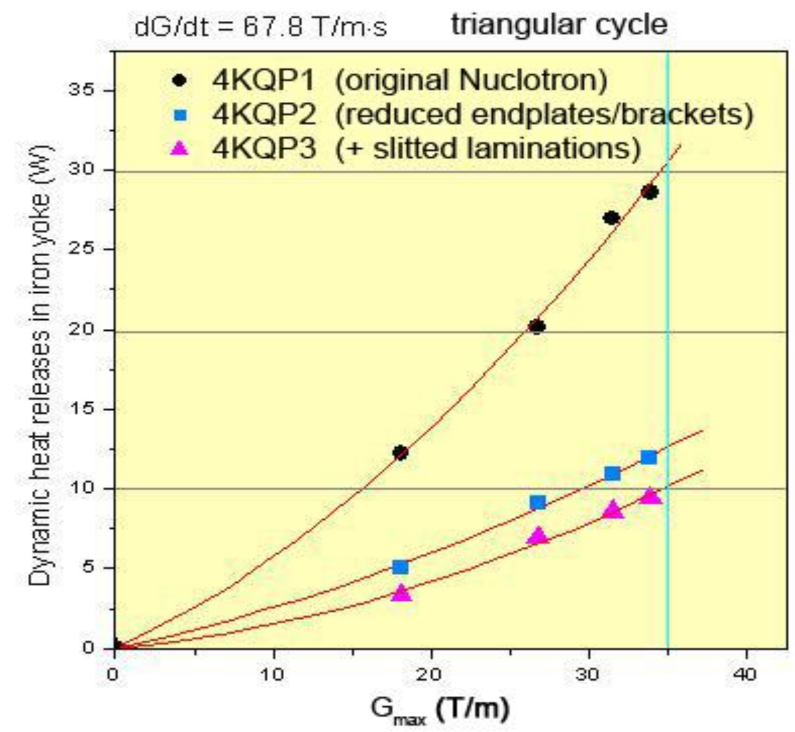
R&D goal: AC loss reduction to 13 W/m @ 2T, 4 T/s, 1 Hz

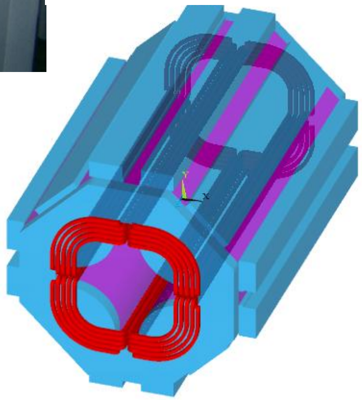




New endblock design

Analogous R & D Results for the Quadrupoles





Nuclotron Quadrupole :

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

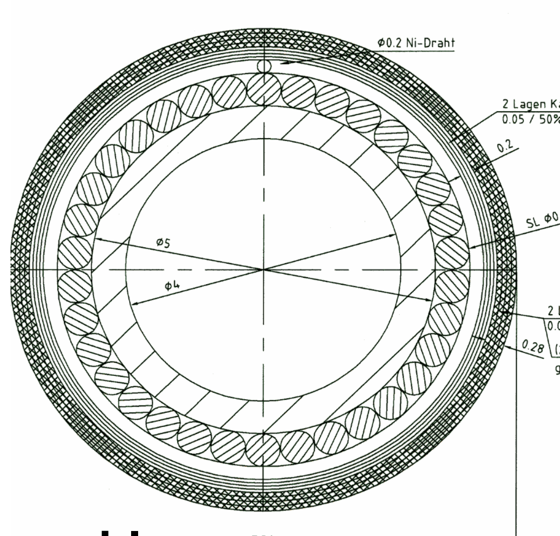
Test measurements on quadrupol modifications

FEM calculations on detailed 3D-models

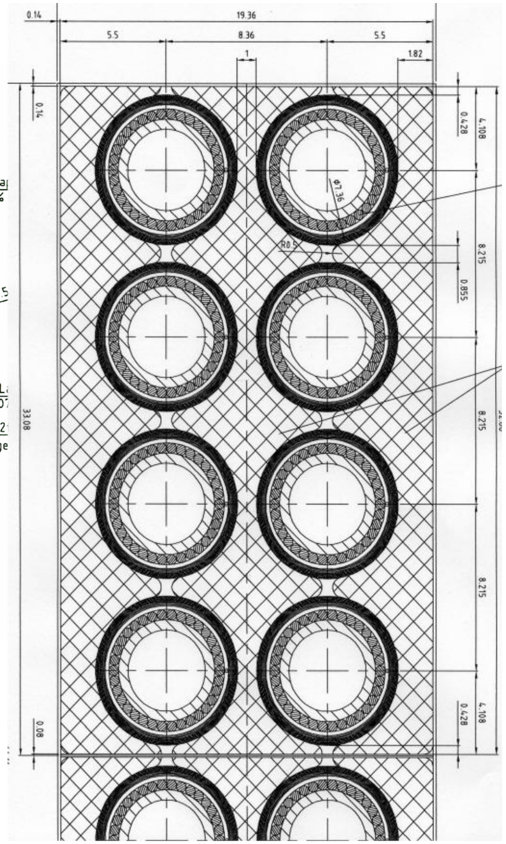
Coil R&D: Technological and FEM Investigations

Analysis of:

- Nuclotron cable design
- Insulation concept
- winding scheme
- technological optimization
- ANSYS Models
- Substrate: comb or block
- model coils production
- mechanical tests



cable



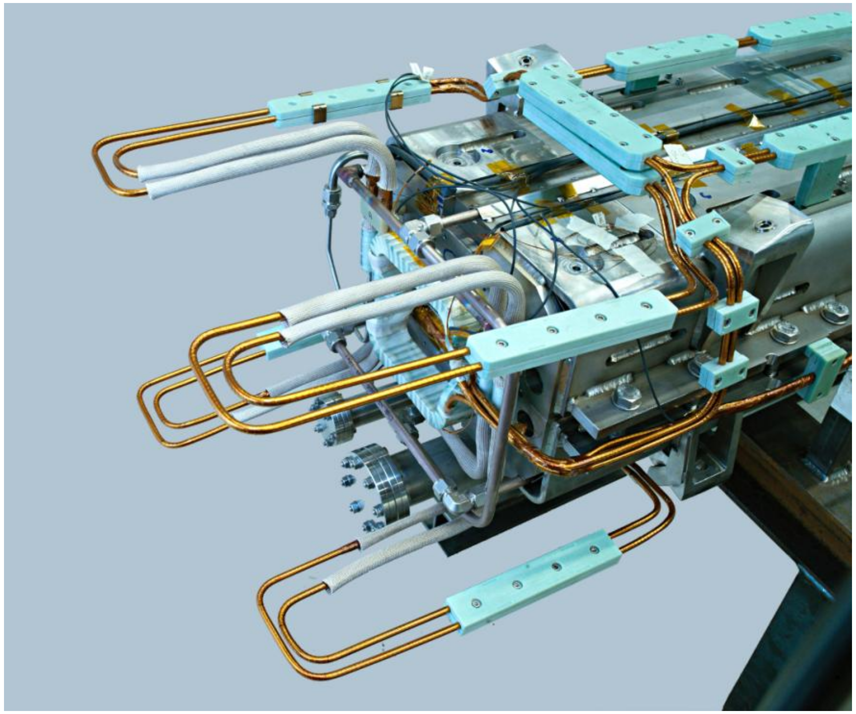
2D coil

3D coil end

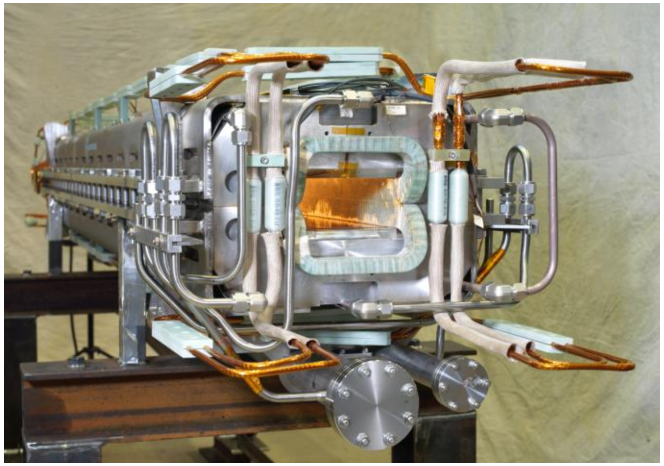
(a) 3D JINR (b) 3D BNN

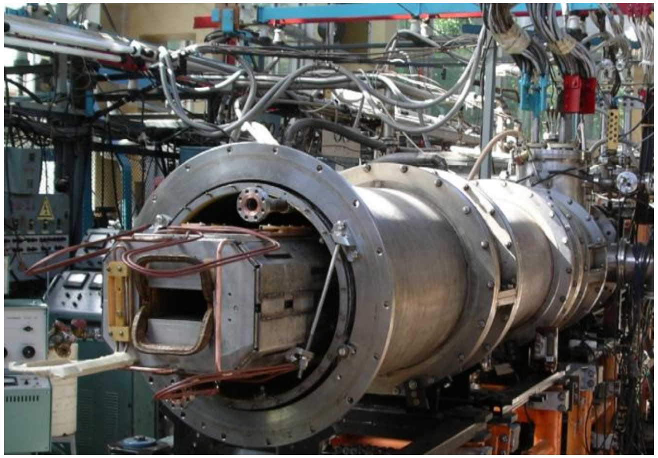
Straight SIS100 Prototype Dipole - BNG

Manufactured by BNG (Würzburg)



- Second straight dipole and quadrupole under manufacturing at JINR
- Curved dipole under manufacturing at BINP

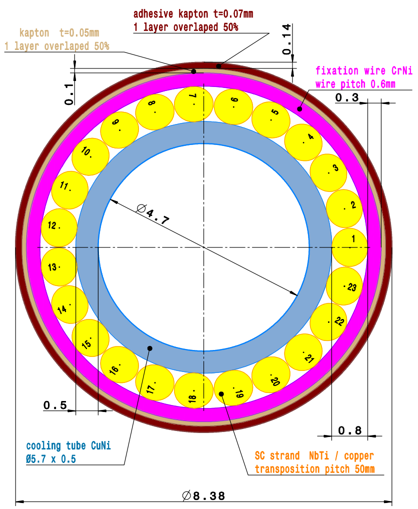


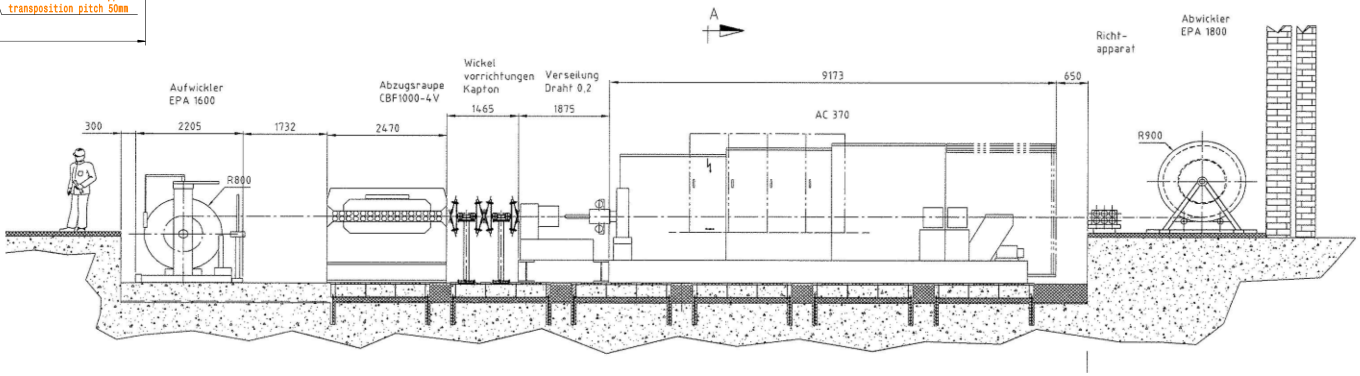


Prototype SIS100 dipole in JINR

Nuklotron Cable Production at BNG

Second Nuklotron type cable production capability set-up at BNG in Würzburg





Curved SIS100 Prototype Dipole - BINP


Figure 17 SIS100 curved magnet assembled without vacuum chamber.


Figure 16 Top view of SIS100 curved magnet coil inserted into lower part of iron yoke.

Curved two layer coil with Nuclotron cable

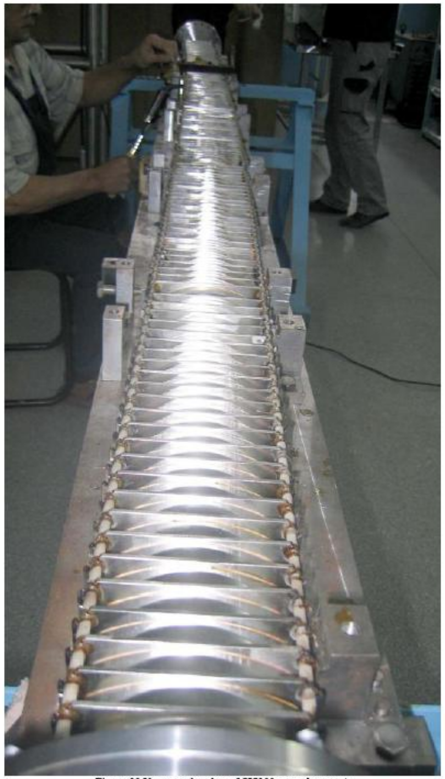
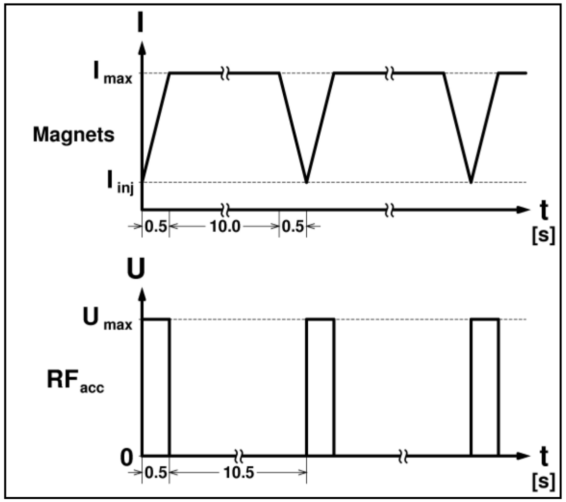
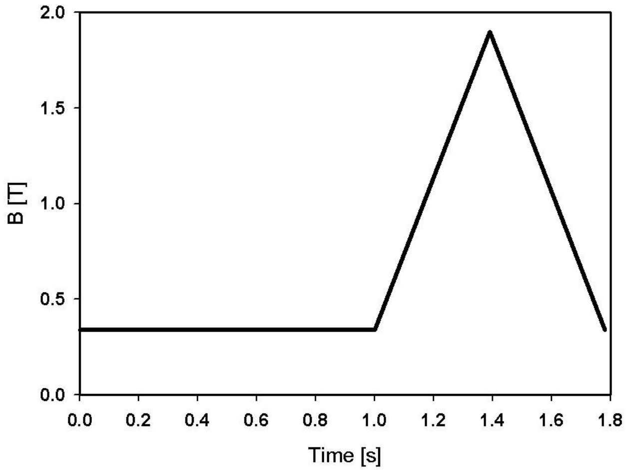


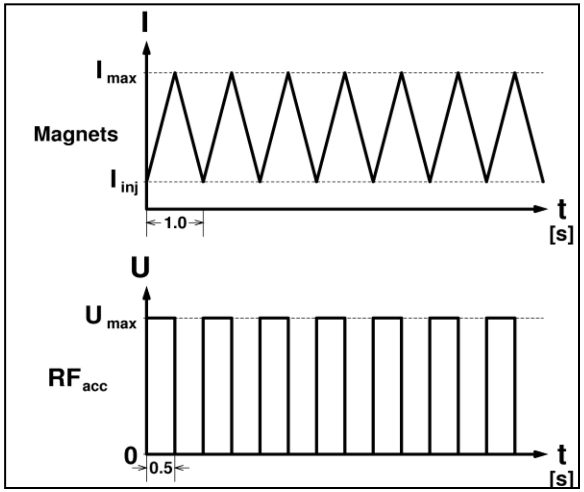
Figure 29 Vacuum chamber of SIS100 curved magnet.

Curved thin wall (0.3 mm) chamber

SIS100 - Extreme Cycles and Combinations







quasi static load (4 kW)
(requires local heater)

Reference cycle 2c

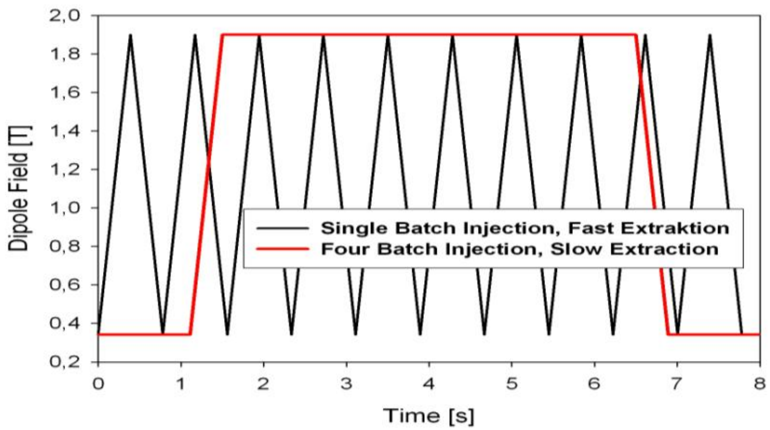
static and dynamic load (28 kW)
(not covered by initially installed cooling power)

Single layer dipole enables high loss (triangular) cycles

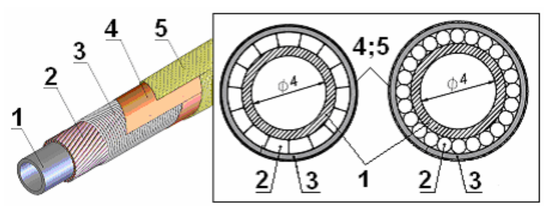
Operation Cycles and Magnet Cooling Limits

Triangular Cycles must be possible

Risk of beam loss on long injection plateau



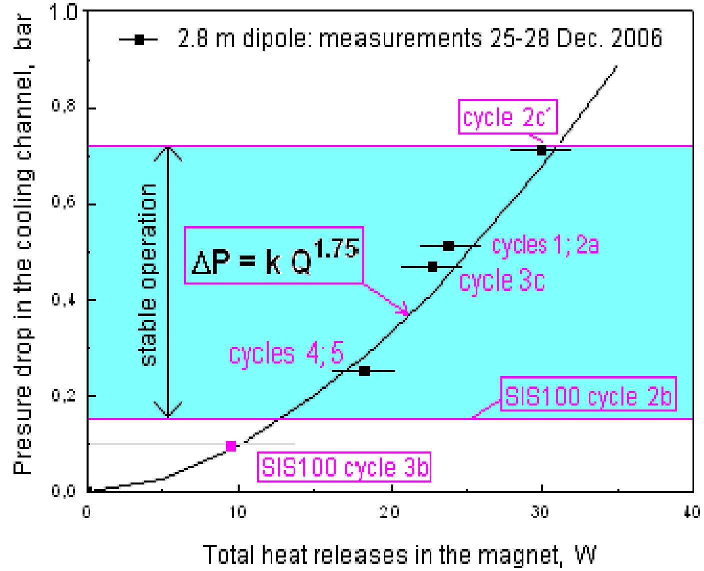
- Singel layer coil with low hydraulic resistance
- High current cable
- Active heaters to stabilize the crogenic load



Alternative coil design and high current cable

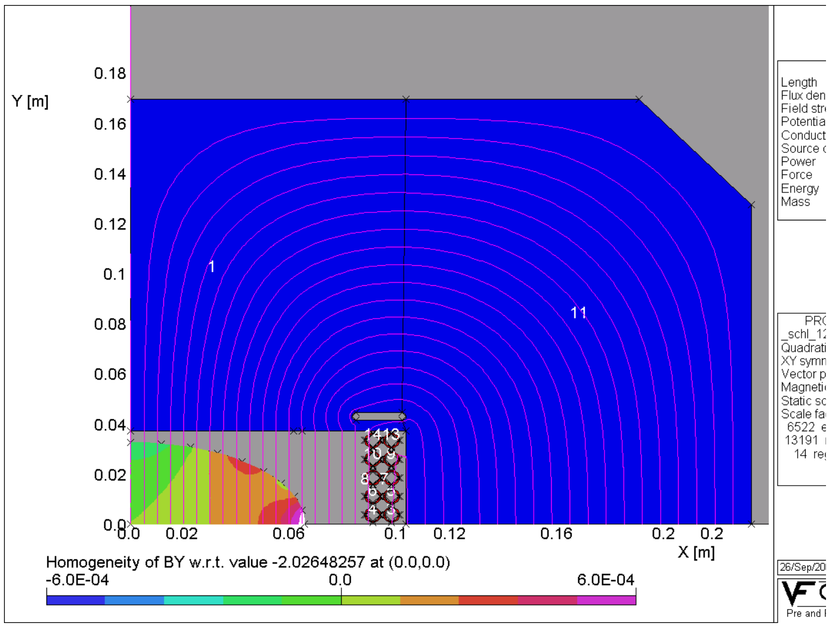
TABLE II OPERATION CYCLES AND EXPECTED LOSSES

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



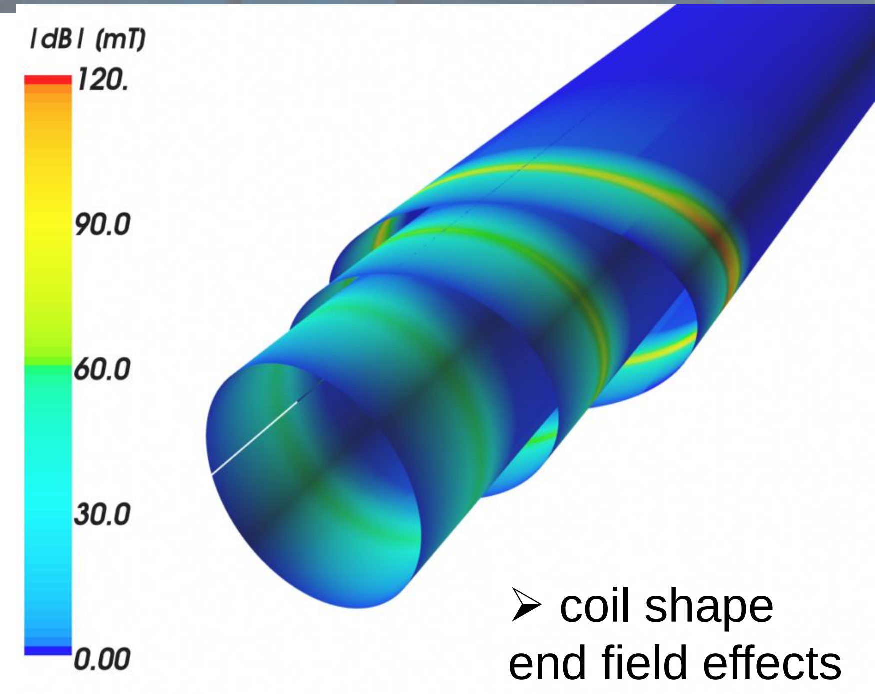
SC Magnets R&D Results: Field quality

2D and 3D OPERA studies

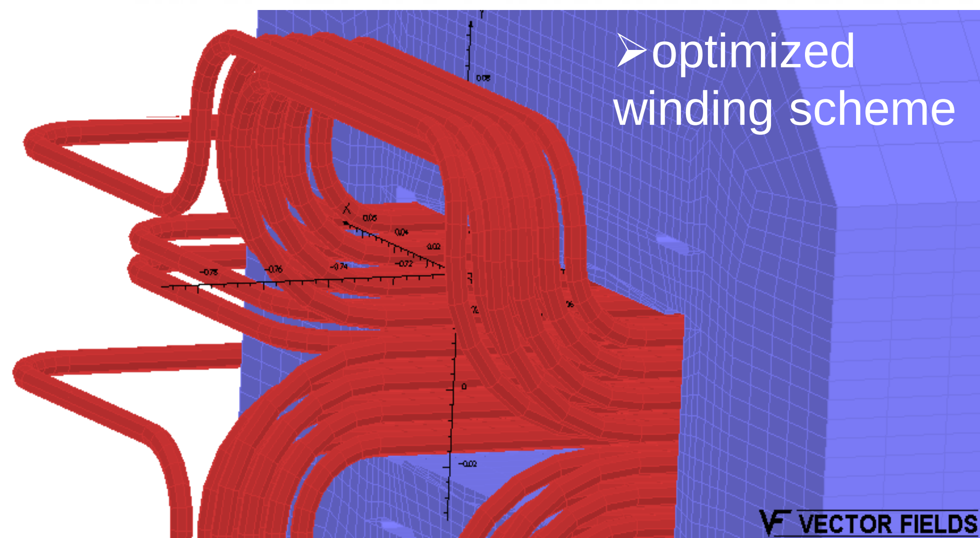


Improved 2D field quality:

- Negative shimming
- Homogenisation slits
- Rogowski end profile



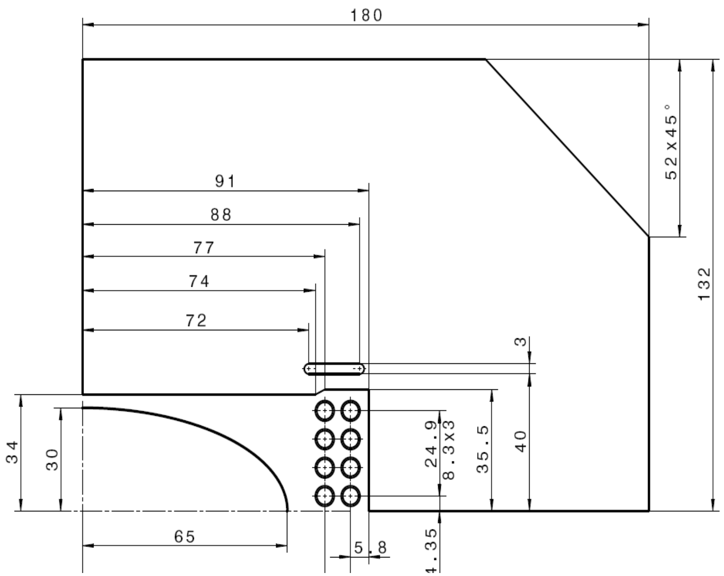
- coil shape end field effects

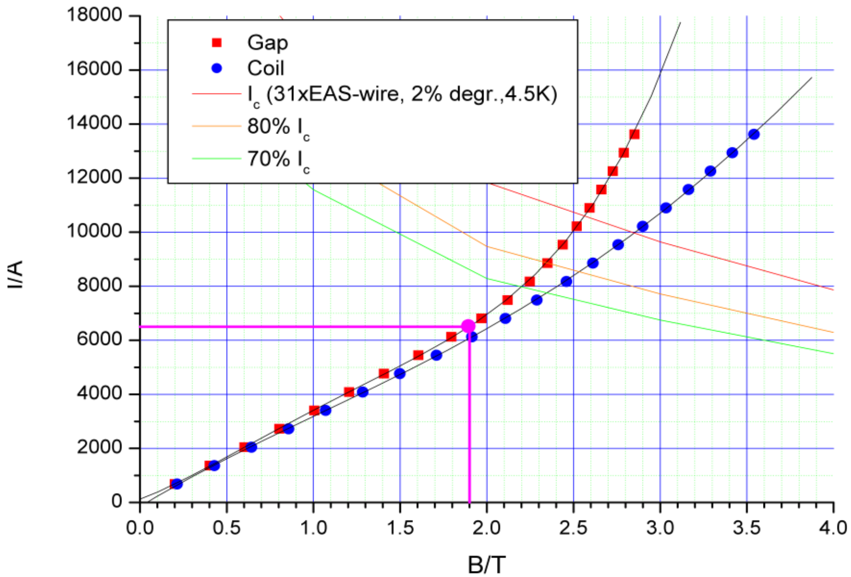


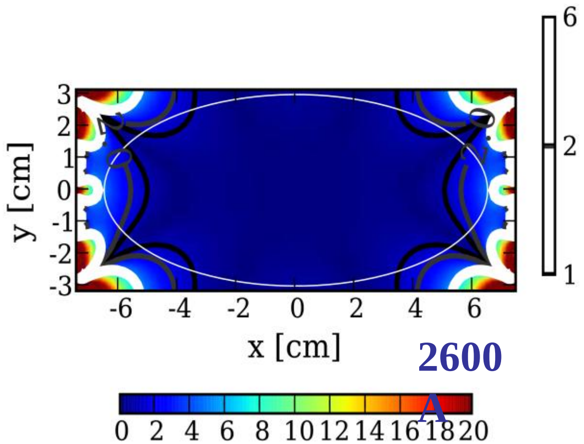
- optimized winding scheme

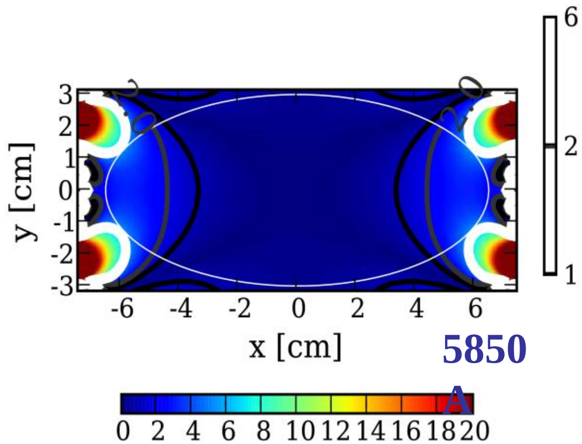
SIS 100 straight dipole: Field parameters

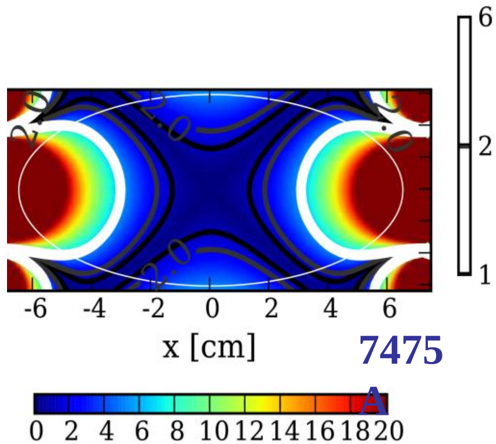
2D Geometry, Load line and Field quality











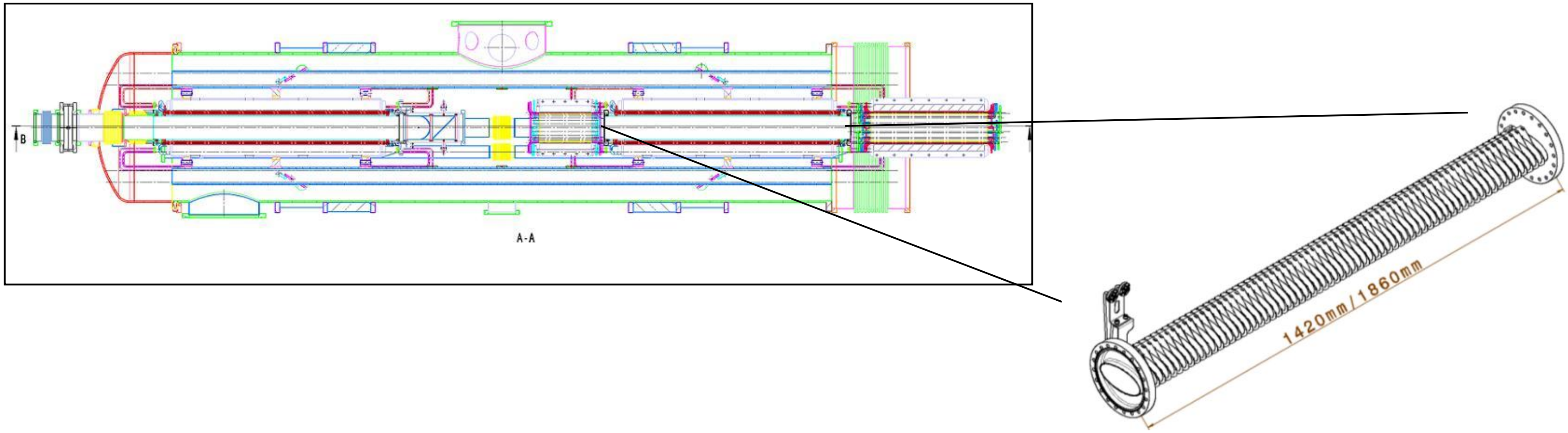
- For the maximum beam intensity simulations indicate high beam loss. Beam loss is driven by periodic cross of resonances (trapping) under the influence of space charge and synchrotron motion over the „long“ (1 sec) injection plateau. Particles with increases amplitude reach the dynamic aperture, which is relatively small compared to the beam size.

- Therefore, actually the influence of an increased horizontal aperture on the field quality is under investiagtion. Consequences, enhanced AC loss, refrigerator power, ramp rates, quench protection etc. are presently studied.

Thin Wall Magnet Chambers in Cryogenic Environment

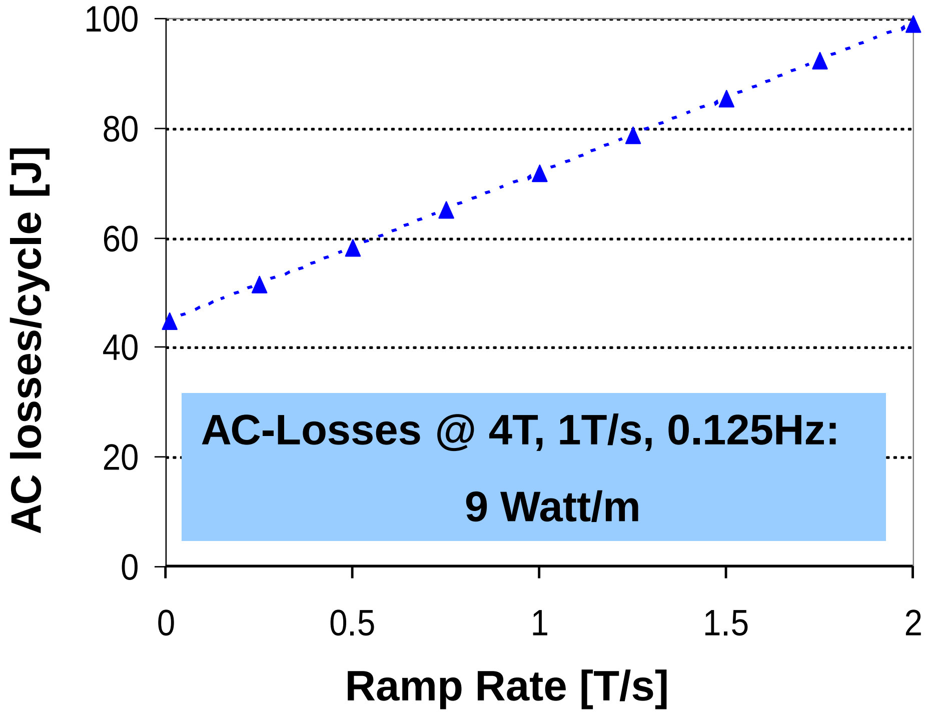
First superconducting, fast ramped synchrotron with thin wall vacuum chambers.

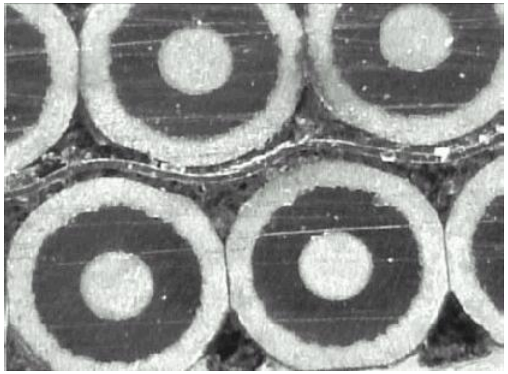
- Reinforced, ripped thin wall (0.3 mm) chambers are needed for fast ramping
- Chambers have high risk of failures (leagues) and fatigue, especially at thermal cycles.
- Only high quality manufacturers (approved)
- No experience in s.c. synchrotrons in cold environment
- In contrary to a warm machine, damage (or series of damages) of chambers requires a large service effort



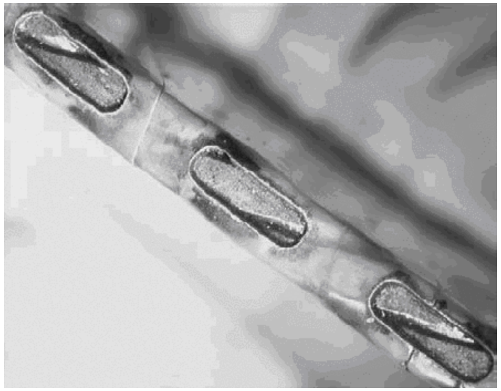
SIS 300 Magnet R&D - GSI/BNL

Results of the advanced coil tests: 4.38 T @ 2 T/s





Cored rutherford cable



Laser cutted cooling slots

Major Improvements :

Reduced filament twist pitch, strand coating (stabrite), stainless steel core

Design report based on GSI001 model and UNK dipole

SIS300 Dipole Prototype at INFN/ANSALDO

Nominal field (T) :	4.5
Ramp rate (T/s)	1
Radius of magnet geometrical curvature (m)	66 2/3
Magnetic length (m)	3.879
Bending angle (deg)	3 1/3
Coil aperture (mm)	100
Max temperature of supercritical He (K)	4.7

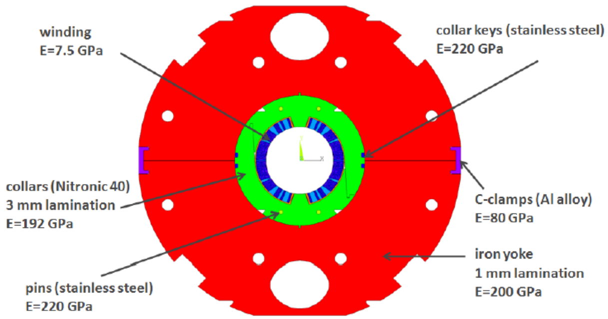
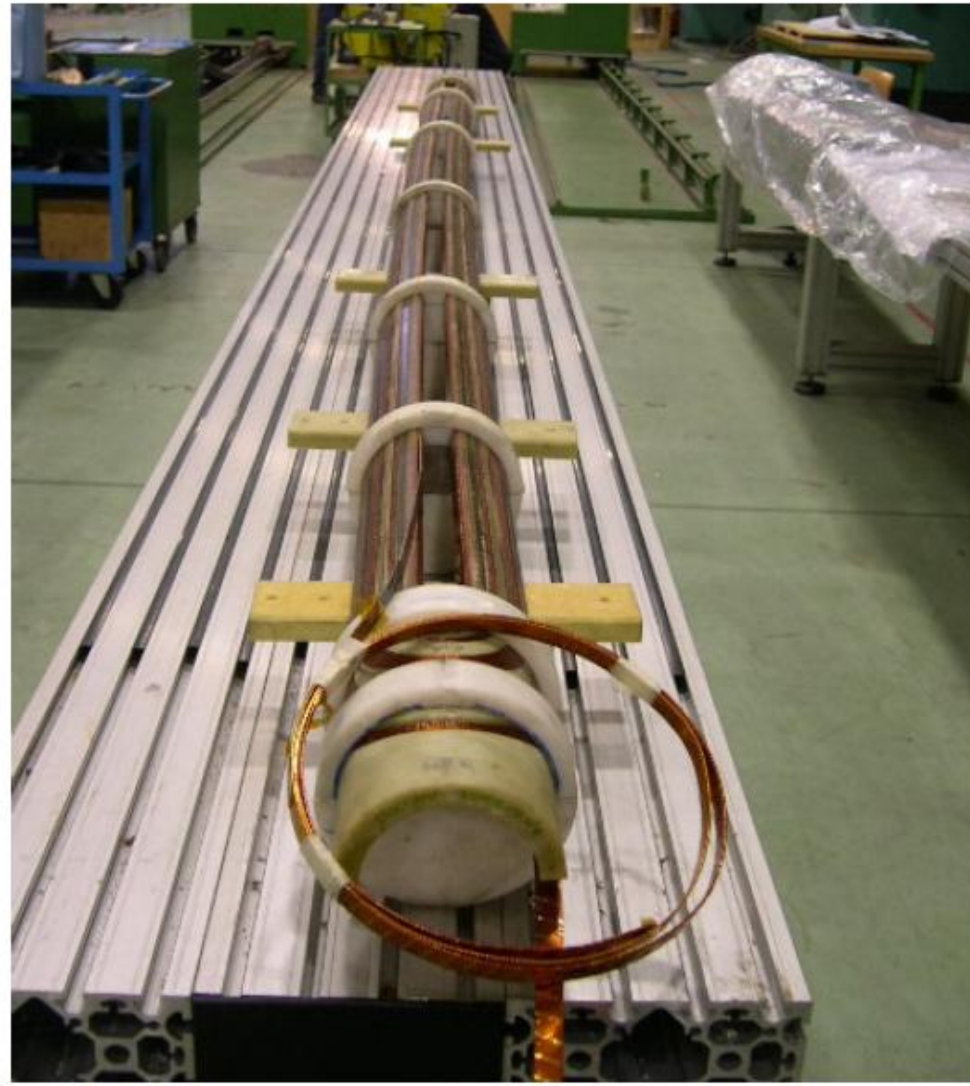


FIG.3: Cross section of the cold mass. The 5 blocks winding is in blue, the collars are in green and the iron yoke lamination in red. The two halves of the iron are clamped together using Al alloy clamps.

FIG.5: The 36 strand Rutherford cable. In between the strands one can see the thin stainless steel core used for depressing the inter-strand coupling currents.

> talk:

P. Fabbricatore



Next Activities

SIS100:

Preparation of the first pre-series dipole magnet tendering, with a single layer, high current coil and enhanced horizontal aperture.

SIS300:

Preparation of a common development of a second generation SIS300 dipole magnet in the frame of the FP7 cluster call with benefit for potential applications in a future s.c. SPS.

Collaboration partners: CERN, INFN, GSI

Work package proposal:

Production of a low loss (cored) cable and collar for the existing yoke of the first generation SIS300 dipole