Electro-Thermal 1D Model of the SIS100 Superconducting Dipole Magnet

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GSI Helmholtzzentrum für Schwerionenforschung GmbH
Departament: Superconducting Magnets and Testing
Outline

- FAIR Project
- SIS100 accelerator
- SIS100 Dipole Magnet
  - Selected Parameters
  - Magnet Design
  - Low AC Loss Nuclotron-Type Cable
- Quench Calculations (Standalone Magnet)
  - Instantaneous Quench, MIITs and Powering Limits
  - 1D Electro-Thermal Model and GSI Quench Calculation Software
- Verification of Calculation Results
- Summary and Outlook
Physics research program addresses broad variety of topics ranging from fundamental questions of the evolution of the universe to the structure of matter.

- Linear acc. UNILAC (GSI) upgrade↑
- NC synchrotron SIS18 (GSI) upgrade↑

Pre-acceleration

- Injection to → SC synchrotron SIS100
  - fast cycling machine (2 T, 4 T/s)
- Experiments
- Storage rings

Antiproton and collector rings – beam storage and modification for various experiments

- SC Fragment Separator Super-FRS
  - Magnetic spectrometer for study of exotic particles.

Courtesy of GSI
SIS100 = Schwerionensynchrotron 100 [Tm] = Heavy ion synchrotron (beam rigidity*) 100 [Tm]

- Hexagonal, circumference 1083.60 m
- Superconducting (magnet) accelerator
- Max. dipole field 1.9 T
- Ultra High Vacuum (10-11mbar)
- Adsorption by cold vacuum chamber (10 – 15 K)

Dipole Module
- dipole magnet
- BB system

Quad. Doublet Module
- 2 x quad
- BB system
- Corr. magnets
## Why SIS100 is Unique?

<table>
<thead>
<tr>
<th>Accelerator</th>
<th>Circumference (km)</th>
<th>$B_{\text{dipole}}$ (T)</th>
<th>$B_\rho$ (T·m)</th>
<th>$\frac{dB_{\text{dipole}}}{dt}$ (T/s)</th>
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<tr>
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### Parameters of superconducting dipole circuit of LHC and SIS100

<table>
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<tr>
<th>Machine</th>
<th>LHC</th>
<th>SIS100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of magnets</td>
<td>154/circuit</td>
<td>108</td>
</tr>
<tr>
<td>Number of power converters</td>
<td>1/circuit</td>
<td>2</td>
</tr>
<tr>
<td>Nominal current (kA)</td>
<td>11.85</td>
<td>13.1</td>
</tr>
<tr>
<td>Nominal ramp rate (A/s)</td>
<td>10</td>
<td>28000</td>
</tr>
<tr>
<td>Total inductance of the circuit (mH)</td>
<td>154 \times 2 \times 51 = 15.7 \times 10^3</td>
<td>108 \times 0.55 = 59.4</td>
</tr>
<tr>
<td>Inductive voltage at cycling (V) per twin dipole / overall in the circuit</td>
<td>1/ \approx 160</td>
<td>15.4/ \approx 1660</td>
</tr>
<tr>
<td>Energy extraction system</td>
<td>2 \times R_d per circuit</td>
<td>12 \times R_d</td>
</tr>
<tr>
<td>Cold by-pass</td>
<td>cold diode</td>
<td>none</td>
</tr>
<tr>
<td>Quench back heaters</td>
<td>on each coil</td>
<td>none</td>
</tr>
</tbody>
</table>

SIS100 is a fast cycling machine with extremely high ramp rate!

Protection system of SIS100 considers only extraction resistors.
SIS100 Dipole Magnet

Design
- super-ferric
- window frame
- sc coil - 4 turn per pole
- Nuclotron-type cable
- cooling with 2-phase He

Main Design Parameters

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Number of the magnets in SIS100</td>
<td>108</td>
</tr>
<tr>
<td>Effective length $L_{\text{eff}}$</td>
<td>m</td>
</tr>
<tr>
<td>Usable aperture</td>
<td>60 x 120</td>
</tr>
<tr>
<td>Bending angle</td>
<td>1 1/3 deg.</td>
</tr>
<tr>
<td>Bending radius</td>
<td>52.632 m</td>
</tr>
<tr>
<td>Nominal Field</td>
<td>1.9 T</td>
</tr>
<tr>
<td>Field homogeneity $\Delta B/B_{\text{main}} \times 10^4$</td>
<td>$&lt; \pm 6$</td>
</tr>
<tr>
<td>Ramp rate</td>
<td>4 @1Hz T/s</td>
</tr>
</tbody>
</table>

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

Magnet cross section

Cold mass with beam chamber

Nuclotron cable:
SIS100 Dipole Magnet: Low AC Loss SC Cable

**SIS100 dipole prototype**

**Low AC-loss cable (CuMn matrix)**

**histeresis loss in NbTi**

\[ P_h \propto d_f, \quad P_{ifc} \propto \frac{t_{pf}^2}{Q_{IF}} \]

inter-filament loss: eddy currents through the matrix

**SC strand**

**NbTi filament**

Inter-filament matrix (CuMn)

**Quench back effect is not expected!**

If a single magnet quenches, other magnets will not quench due to high \( \frac{di}{dt} \) at current extraction (very low probability).
Quench Calculations: Data Collection

1) SC strand/cable and coil details: size, cross-sections, etc.

2) Material database: NbTi, Cu, CuNi, CuMn, Polyimide, GRP (e.g. G11)...
3) Critical current of the selected NbTi-conductor

“The wire manufacturer specifies few measured $J_c$ values at 4.2 K and various external magnetic field.

Bottura's fit (empirical):

$$J_c(B, T) = J_{c\text{ref}}(T_{\text{ref}}, B_{\text{ref}}) \cdot \frac{C_0}{B} \cdot \left[ \frac{B}{B_{c2}(T)} \right]^\alpha \cdot \left[ 1 - \frac{B}{B_{c2}(T)} \right]^\beta \cdot \left[ 1 - \left( \frac{T}{T_{c0}} \right)^{1.7} \right]^\gamma$$

$$B_{c2}(T) = B_{c20} \cdot \left[ 1 - \left( \frac{T}{T_{c0}} \right)^n \right]$$
Bulk conductor: **NbTi + Cu + ... + insulation**. Averaged material properties are weighted by the volumetric proportion.

\[
\rho(RRR, B, T) = (A_{\text{NbTi}} + A_{\text{Cu}} + \ldots) \cdot \left( \frac{A_{\text{NbTi}}}{\rho_{\text{NbTi}}(T)} + \frac{A_{\text{Cu}}}{\rho_{\text{Cu}}(RRR, B, T)} + \ldots \right)^{-1}
\]

\[
C_V(B, T) = \frac{A_{\text{NbTi}} \cdot C_V^{\text{NbTi}}(B, T) + A_{\text{Cu}} \cdot C_V^{\text{Cu}}(T) + \ldots + A_{\text{ins}} \cdot C_V^{\text{ins}}(T)}{A_{\text{NbTi}} + A_{\text{Cu}} + \ldots + A_{\text{ins}}}
\]

\[
k(RRR, T) = \frac{A_{\text{NbTi}} \cdot k_{\text{NbTi}}(T) + A_{\text{Cu}} \cdot k_{\text{Cu}}(RRR, T) + \ldots + A_{\text{ins}} \cdot k_{\text{ins}}(T)}{A_{\text{NbTi}} + A_{\text{Cu}} + \ldots + A_{\text{ins}}}
\]

**MII/Ts:**

"M" - Mega (prefix), "II" - current x current, "Ts" - time in seconds

\[
IITs = \int_{t=0}^{t=\infty} i^2(t)dt
\]

Characteristics of fuses

**MII/Ts vs. I**
**Quench Calculation: 0-D Case / MII Ts**

**Joule heating**

\[
 i(t) \cdot g(T) \frac{\Delta z}{A} \cdot \Delta t = A \cdot \Delta z \cdot C_V(T) \cdot \Delta T
\]

**heating up**

\[
 \int_{t=0}^{t=\infty} i^2(t) dt = A^2 \int_{T=T_{cs}}^{T_{max}} \frac{C_V(T)}{\varepsilon(T)} dT
\]

**IITs**

\[
 IITs = A^2 \int_{T_{cs}}^{T_{max}} \frac{C_V(T)}{\varepsilon(T)} dT
\]

**Time**

\[
 t_{Rd} \quad \tau = \frac{L}{R_d}
\]

\[
 t_{Rd} \text{ – time until current extraction}
\]

\[
 i(t) = \begin{cases} 
 I_0, & t \in (-t_{Rd}, 0); \\
 I_0 \cdot e^{-\frac{t}{\tau}}, & t > 0; 
\end{cases}
\]

\[
 \int_{t=-t_{Rd}}^{t=\infty} i^2(t) dt = I_0^2 \left( t_{Rd} + \frac{\tau}{2} \right)
\]

\[
 \tau_{max} = 2 \left( \frac{IITs(T_{max})}{I_0^2} - t_{Rd} \right)
\]

---

P. Szwangruber et al., GSI -> SCM -> MES

2019-07-10
Thermal Model: 1-D Case

Thermal model: heat-balance equation:

\[ \varrho(RRR, B, T) \cdot J^2(t) + \frac{\partial}{\partial x} \left( k_x(T) \cdot \frac{\partial T(x, t)}{\partial x} \right) = C_V(B, T) \cdot \frac{\partial T(x, t)}{\partial t} \]

Joule heating \hspace{1cm} \text{heat conduction} \hspace{1cm} \text{heating up}

Numerical calculation: Finite Difference Method (FDM)

Stability condition:

\[ dt \leq \frac{C_V dx^2}{2k} \]

Explicit

Implicit

Unconditionally stable!
Thermal Model: 1-D Case

Implicit scheme:

\[ J^2(t) \cdot \rho(\text{RRR}, B, T) + k(\text{RRR}, T) \cdot \frac{T_{j-1}^{t_{i+1}} - T_j^{t_{i+1}}}{dz^2} - k(\text{RRR}, T) \cdot \frac{T_j^{t_{i+1}} - T_{j+1}^{t_{i+1}}}{dz^2} = C_V(B, T) \cdot \frac{T_j^{t_{i+1}} - T_j^t}{dt} \]

rewritten as:

\[ a(j, t_i) T_{j-1}^{t_{i+1}} + b(j, t_i) T_j^{t_{i+1}} + c(j, t_i) T_{j+1}^{t_{i+1}} = T_j^t + d(j, t_i), \]

where:

\[ a(j, t_i) = - \frac{dt}{dz^2 \cdot C_V(B, T)} \cdot k(\text{RRR}, T), \quad b(j, t_i) = 1 + \frac{dt}{dz^2 \cdot C_V(B, T)} \cdot 2k(\text{RRR}, T), \]

\[ c(j, t_i) = - \frac{dt}{dz^2 \cdot C_V(B, T)} \cdot k(\text{RRR}, T) \quad \text{and} \quad d(j, t_i) = \frac{\rho(\text{RRR}, B, T) \cdot J^2(t) \cdot dt}{C_V(B, T)}. \]

Current density: \[ J(t) = I(t)/A_{\text{cond}} = I(t)/(A_{\text{NbTi}} + A_{\text{Cu}} + \ldots) \]

Matrix equation:

\[ A_{jj} \cdot T_j^{t_{i+1}} = T_j^t + D_j \quad \Rightarrow \quad A \cdot X = B \]
The matrix equation is solved at each time step with updated material properties and updated current density.

\[ A_{jj} \cdot T_{j}^{t+1} = T_{j}^{t} + D_{j} \quad \Rightarrow \quad A \cdot X = B \]

\[ A = \begin{bmatrix} b(1) & c(1) & 0 & 0 & 0 & \cdots & 0 & 0 \\ a(2) & b(2) & c(2) & 0 & 0 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & a(j) & b(j) & c(j) & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & 0 & a(j_{\text{max}}) & b(j_{\text{max}}) \end{bmatrix} \]

Sparse matrix! There are dedicated algorithms for fast computation.

\[ X = \begin{bmatrix} T_{1}^{t+1} \\ T_{2}^{t+1} \\ \vdots \\ T_{j}^{t+1} \\ \vdots \\ T_{j_{\text{max}}}^{t+1} \end{bmatrix}, \quad B = \begin{bmatrix} T_{1}^{t} + d(1) \\ T_{2}^{t} + d(2) \\ \vdots \\ T_{j}^{t} + d(j) \\ \vdots \\ T_{j_{\text{max}}}^{t} + d(j_{\text{max}}) \end{bmatrix} \]
Electrical Model: 1-D Case

Electrical model (macroscopic - calculation done at a single component level, e.g. coil)

El. circuit description:

\[ L_d(I) \cdot \frac{dI(t)}{dt} + (R_q(t) + \delta(t) \cdot R_d) \cdot I(t) = V_{PS}(t) \]

- Magnet inductance
- Quench resistance
- Energy extraction resistor
- Power supply action

Optional: by-pass, inductive coupling, etc.

Update of the electrical current:

\[ I_{ti+1} = I_{ti} - \frac{(R_q^{ti} + R_d) \cdot I_{ti} \cdot dt}{L_d(I_{ti})} \]
Material prop. are strongly dependent on $T$.
$\Delta T$ has to be controlled and limited for all mesh elements (e.g. $< 0.5$ K)!

**Novel adaptive time stepping algorithm:**

$$E_{\text{Joule}} = E_{\text{heating}} \uparrow$$

(adiabatic approx.)

$$\varrho(\text{RRR}, B, T) \cdot J^2(t) \cdot \Delta t = C_V(B, T) \cdot \Delta T$$

$$\Delta T = \frac{\varrho(\text{RRR}, B, T) \cdot J^2(t)}{C_V(B, T)} \cdot \Delta t$$

vice versa:

$$\Delta t_{\text{max}} = \frac{\Delta T_{\text{max}}}{J^2(t)} \left[ \frac{\varrho(\text{RRR}, B, T)}{C_V(B, T)} \right]_{\text{max}}$$

1: trivial (quench recovery) $\rightarrow \Delta t_{\text{min}}$

2: $[\varrho(\text{RRR}, B, T)/C_V(B, T)]_{\text{max}} @ T_{cs}$

3: $[\varrho(\text{RRR}, B, T)/C_V(B, T)]_{\text{max}} @ T_{\text{min}}$ or $T_{\text{max}}$
Electro-thermal Model: Quench Propagation Velocities

1D simulation performed with 2 cable models:
- "conductor model" - 23 SC strands,
- "cable model" - 23 strands + CuNi tube + ground insulation.

Measurement principle

Conclusions:
- Computation with the “cable model” gives the correct $v_{fp}$;
- $v_{fp} < 30$ m/s; dipole coil $\approx 51$ m; typical discharge time in SIS100 ring $\approx 300$ ms;
- => max. 9 m of cable can quench
- => a quench in the dipole circuit will be confined within a single dipole!
  (no quench heaters, low AC-loss cable).
Electro-Thermal 1D Model: Results

Case of a standalone magnet. Calculations with “GSI quench software” vs. measurements on FoS DP.

\[ \tau \approx \frac{L}{R_d + R_q(t)} \approx 75 \text{ ms} \]

\[ I_n = 13.2 \text{ kA}, \quad L = 0.55 \text{ mH}, \quad R_d = 5.4 \text{ m}\Omega, \quad R_q = 0 \rightarrow 4 \text{ m}\Omega \]
SIS100 dipole prototype, $R_d = 5.4$ mΩ quench at 10 kA DC, $V_{th} = 400$ mV, $t_v = 10$ ms
Series Test Facility (STF)

- Cryo-plant 1.5 kW – commissioned Q2/2015
- Power converters 2 x 20 kA (66 V) – commissioned Q1 & Q3/2016
- 14 kA DC HTS Current Leads (CL) – commissioning Q3/2015 – Q1/2017
- QD / Magnet protection system
- 687m² total area
- 4 test benches for cold tests
- 4 preparation benches

Test benches for superconducting magnets: 1-end box, 2 - feed box, 3 - distribution box, 4 - power switch, 5 - preparation bench
SIS100 HTS Current Leads

- 14 kA DC
- Cu: vapour cooled
- HTS: conduction cooled

\[ P_{in} = \frac{A_{Cu}}{L_{Cu}} \int_{4 \text{ K}}^{300 \text{ K}} k_{Cu}(T) dT \]
SIS100 Splices

- approximately 2200 splices in SIS100
- Sn96Ag4 tin - melting point 221 °C
- stabilizing Cu clamp 120 mm x 38.5 mm x 0.5 mm
- specification R < 3 nOhm

☑ DC resistance obtained from the V-I method
☑ proved stable operation even for 10 nOhm splice so far only few bad joints were manufactured with 3 < R < 10 nOhm
☑ measurement error is estimated as +/- 0.5 nOhm due to fluctuation of the cooling system in the test facility
SIS100 Series Dipole Magnets: Training

- nominal current (nc) to be reached:
  - at 3rd quench in first cycle
  - at 1st quench in further
- de-training limited to 5% of nc (compared to previous quench)
- quench current has to stabilize at 110% of nc at least (14.5 kA)

Specified:

- Outstanding quench performance!
  - nom. current reached at 2nd quench at least
  - no significant de-training observed

Training close to the short sample limit of the cable (17.8 kA)
→ high stability of the coil structure in the yoke.
Electrical Model Improvement: Work is Ongoing...

GSI Quench Code: migration from Matlab to Python (OOP)
- freeware
- scalability, classes
- voltage nodes modelling in progress
- goal: SIS100 transient simulation
Summary and Outlook

- New FDM quench calculation software was developed (2010 - ...)
  - unconditionally stable implicit scheme
  - innovative adaptive time stepping algorithm
  - flexible topology of the coil supply and protection circuit (option: $R_d$, cold by-pass, etc.)
  - yoke’s magnetic characteristics taken into account in the inductance function
  - options: 3D for potted coils, cooling by He bath, heaters

- Simulation results are in good agreement with available measurements

- Outlook on the quench software:
  - commercial MATLAB → Python (OOP, classes, scalability)
  - upgrade of the electrical model (warm cables, line capacitance, de-centralised?, etc.)
  - SIS100 transient effects study
  - user friendly **Graphical User Interface (GUI)**
  - Nuclotron-type cable: development of a 3D thermal model (force-flow cooling), implementation of cylindrical coordinate system
Thank You for Your Attention!
Thank You for Your Attention!

Are there any questions?
Back-up Slides
Quench Calculation: Heat Transfer to He

Heat-balance equation:

\[
\rho(RRR, B, T) \cdot J^2(t) - \frac{1}{\text{vol}} \oint_{A_{\text{He}}} P_{\text{He}}(\Delta T) \cdot dA_q + \nabla [k(T) \cdot \nabla T(x, y, z, t)] = C_V(B, T) \cdot \frac{\partial T(x, y, z, t)}{\partial t}
\]

Joule heating
heat conduction
heating up
heat transfer to He \([\text{W/m}^3]\)


The measurement fit is proposed by Dr. E. Floch, my GSI supervisor 2010-2013.
SIS100 Quadrupole Units
SIS100 Main Quadrupole QD

courtesy V. Plyusnin
SIS100 Main Quadrupole F1/F2

courtesy V. Plyusnin
IGBT DC Circuit Breakers at GSI

700 V

1.1 kV
KIT QuD-System

- KIT QuD system was considered for the initial QuD concept.
- A detailed specification of the FAIR bridge design requirements was initiated and discussed with KIT.
- We have procured 4 full-size cabinets for STF (16 detectors each) and 1 small-size for PTF (8 detectors).
- Never observed malfunction so far (experience limited to sc solenoid and 1st pair of MCL @ STF).
- Limited remote control ability (remote desktop by Windows).
- GSI control software (development ongoing – H. Brand/LabVIEW).
- V-tap detection is not perfect (issues in ac operation, cable detection on -> QuD off).
- Max. input voltage is limited to 15 V (external voltage dividers are required for super-bridges).
- System seems to be expensive (125k€ per cabinet, 2750€ per detector, price 2014).