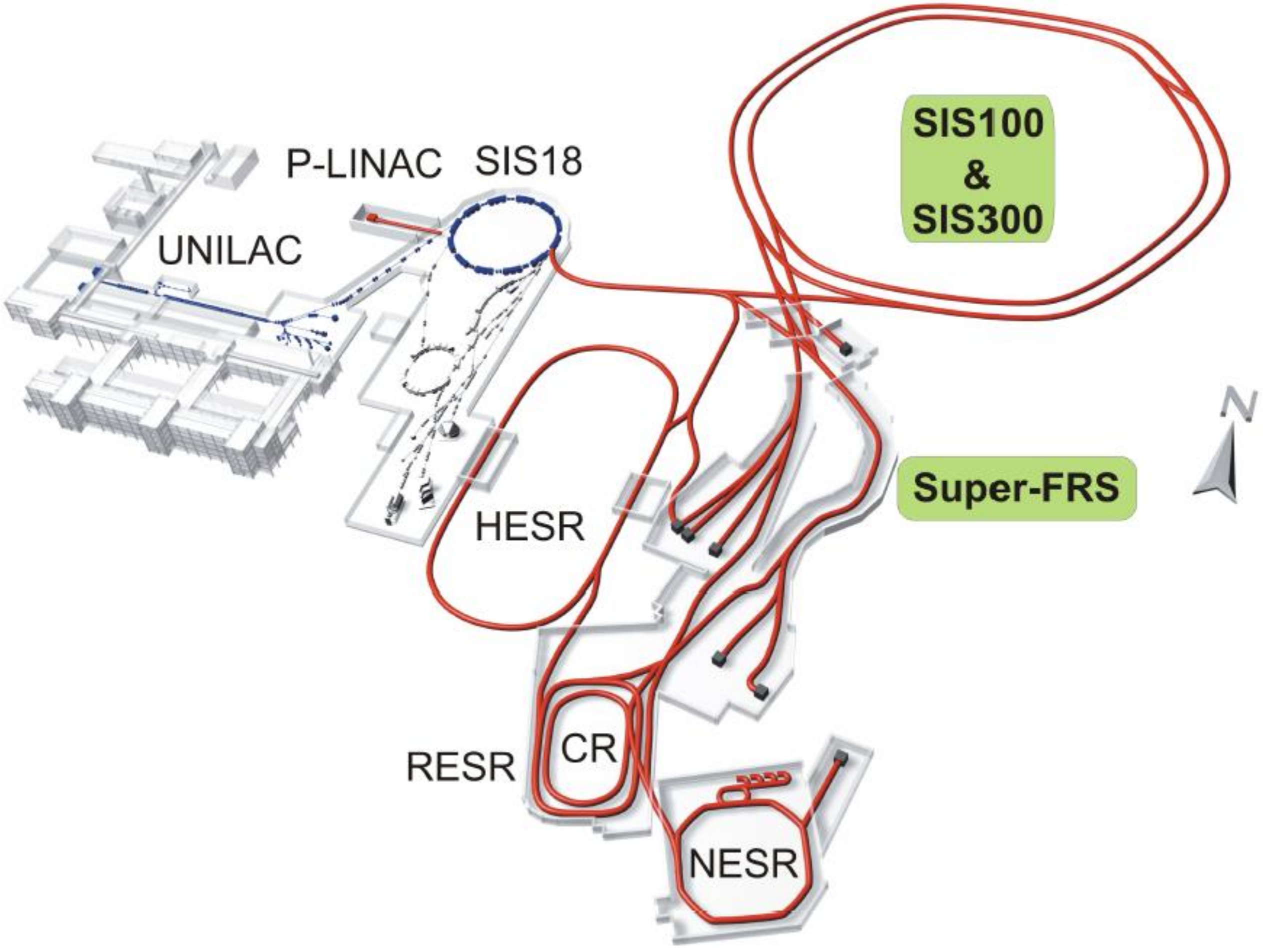
Quench Simulation at GSI

HGS-HIRe *for* FAIR
Helmholtz Graduate School for Hadron and Ion Research

FAIR Project

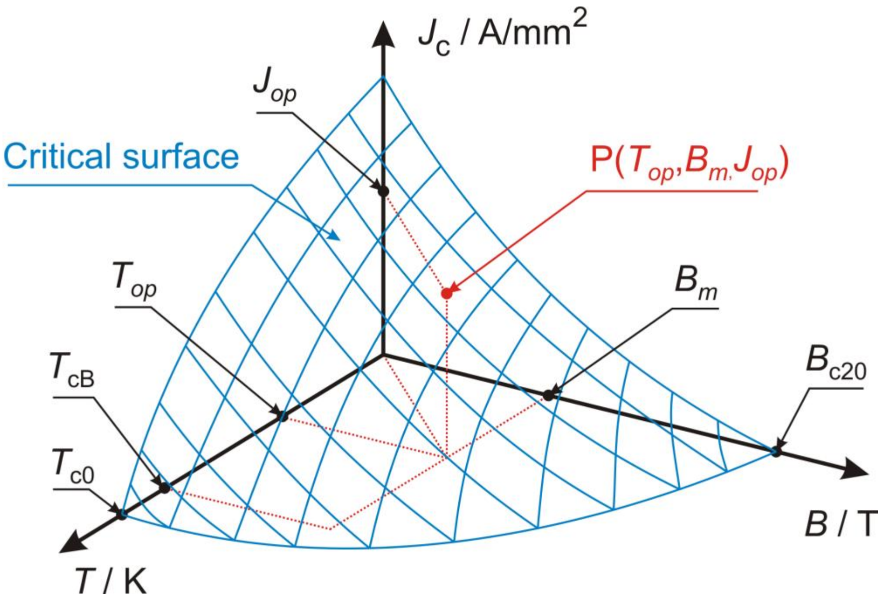


Quench

A sudden transition from the superconducting state to the normal-conducting state.

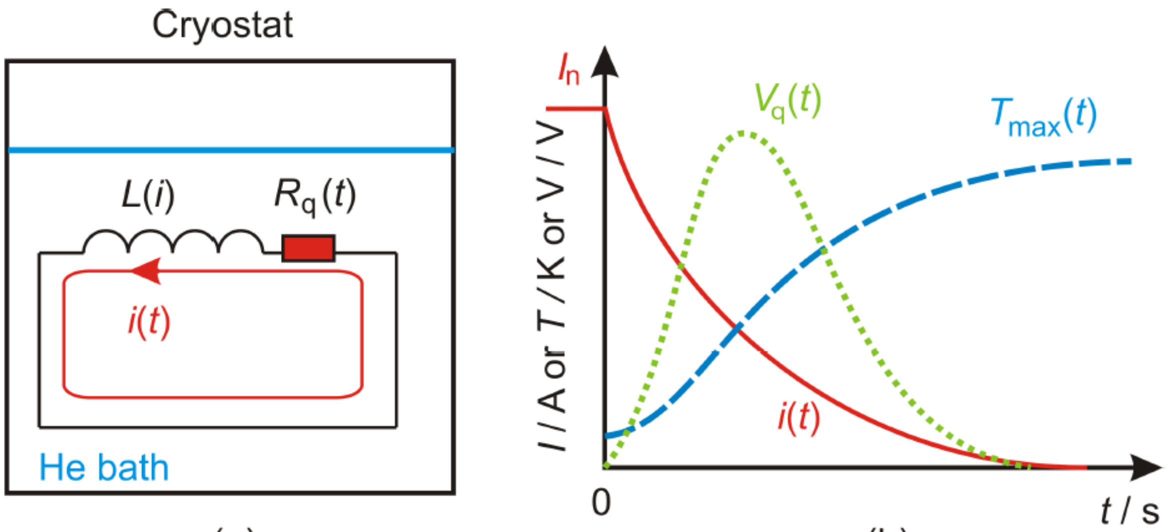
Quench causes:

- conductor movement
- eddy currents in the conductor
- beam losses
- poor cooling



Self-protecting and not self protecting magnets

$$L(i) \cdot \frac{di(t)}{dt} + R_q(t) \cdot i(t) = 0$$



(a) (b)

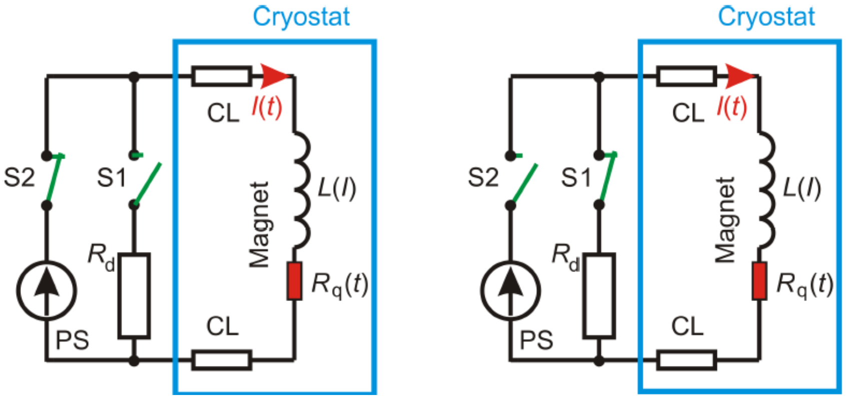
If max. temp. < 300 (350) K
and
max. voltages
(coil-to-ground, coil-to-coil)
do not damage the insulation

magnet / group of magnets
is self protecting

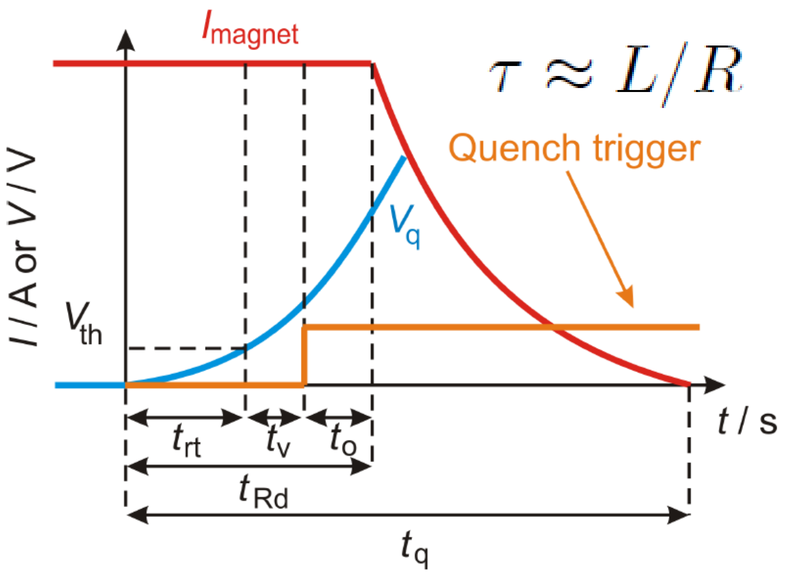
if not

Quench protection is required
dump resistors, cold diodes, quench heaters etc.

Self-protecting and not self protecting magnets: Tau and *MIITs*



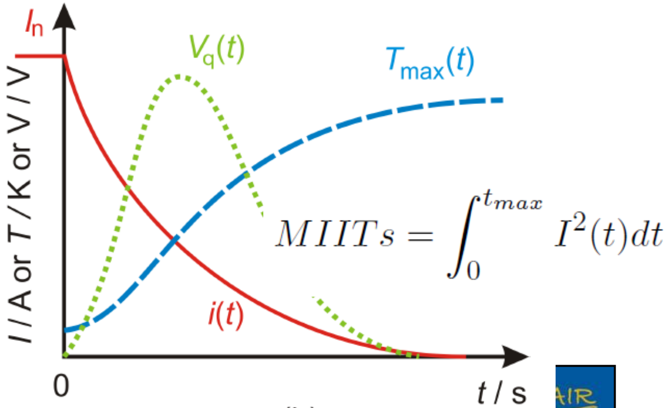
$$\boxed{L(i) \cdot \frac{di(t)}{dt} + (R_q(t) + R_d) \cdot i(t) = 0}$$



$$I^2(t) \cdot \frac{\rho(T) \cdot dx}{A} \cdot dt = C_v(T) \cdot A \cdot dx \cdot dT$$

$$I^2(t) \cdot dt = \frac{C_v(T) \cdot A^2}{\rho(T)} \cdot dT$$

$$\int_0^{t_{max}} I^2(t) \cdot dt = \int_{T_{cs}}^{T_{max}} \frac{C_v(T) \cdot A^2}{\rho(T)} \cdot dT$$



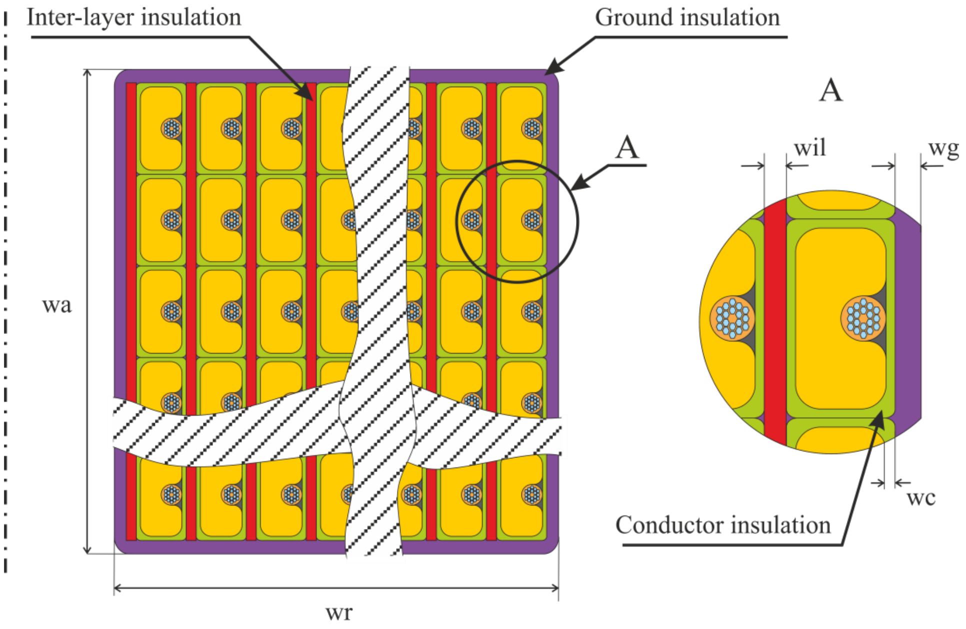
Self-protecting and not self protecting magnets @ FAIR

- All Super-FRS magnets - self protecting
- SIS100 rings (dipole ring, quadrupoles rings, chromaticity sextupoles
  - 6 magnets in series, other correctors) – not self-protecting
    - single SIS100 dipole almost self-protecting
- SIS300 magnets – not self-protecting

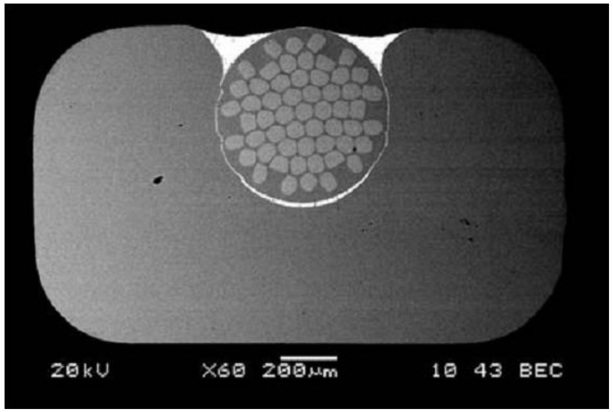
FAIR Project: Super-FRS

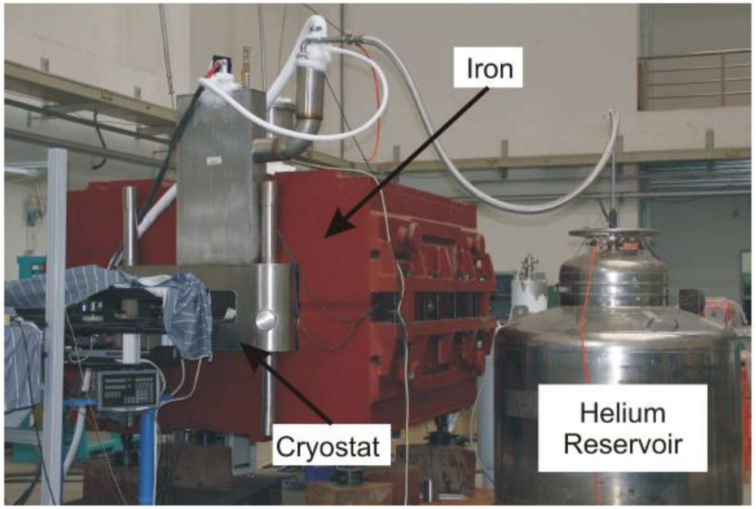
Super-FRS dipole (66 um)

Potted coil: 28 layers, 20 turns/layer
In= 232 A, Emag=414 kJ
DC machine



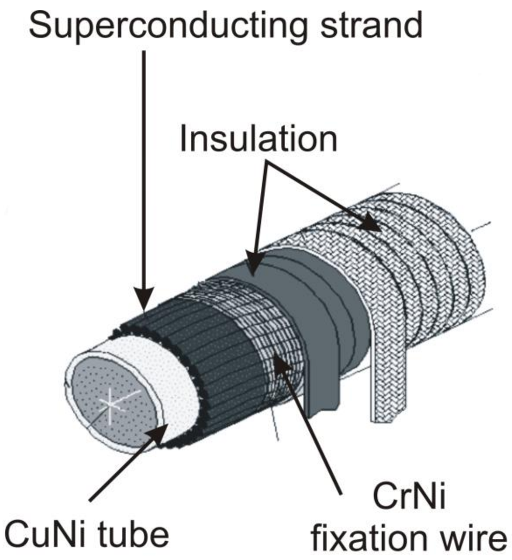
3D Simulation

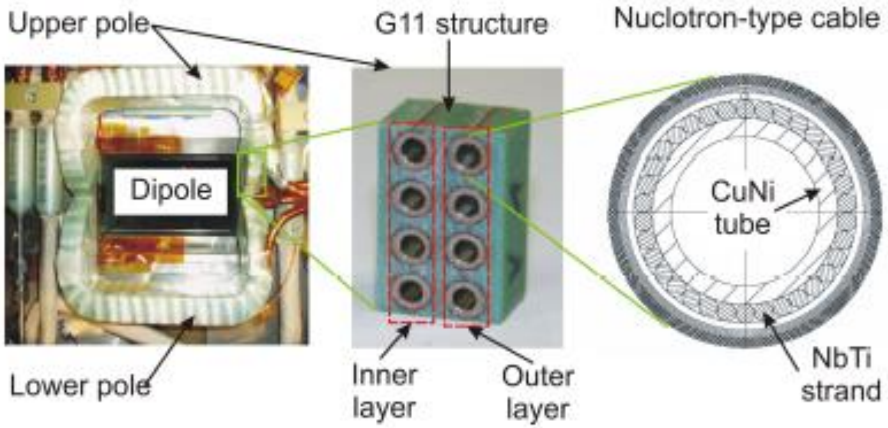


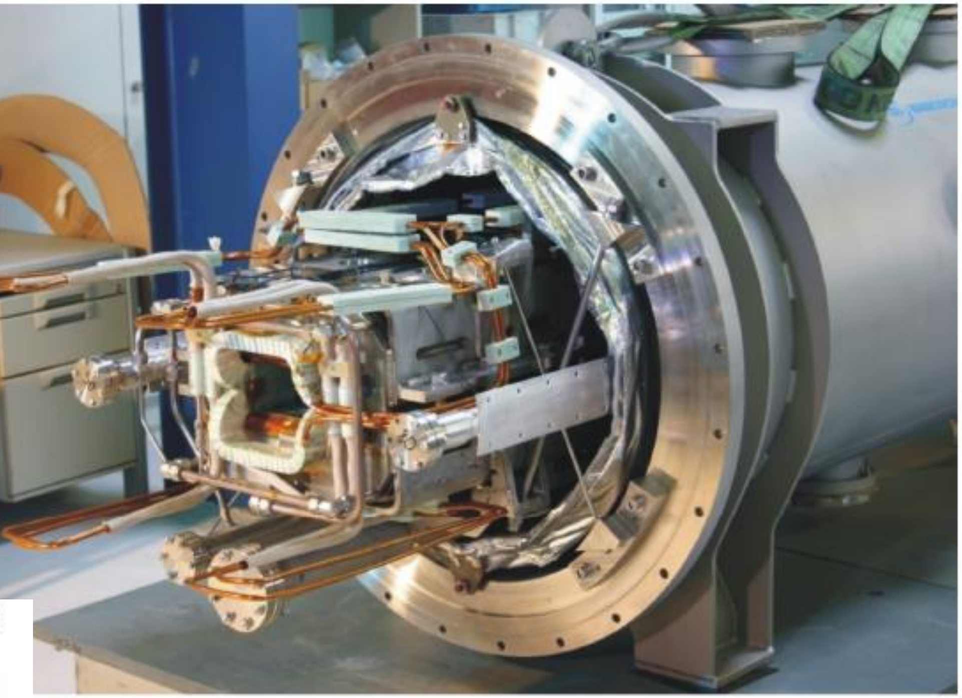


FAIR Project: SIS100

Nuclotron cable





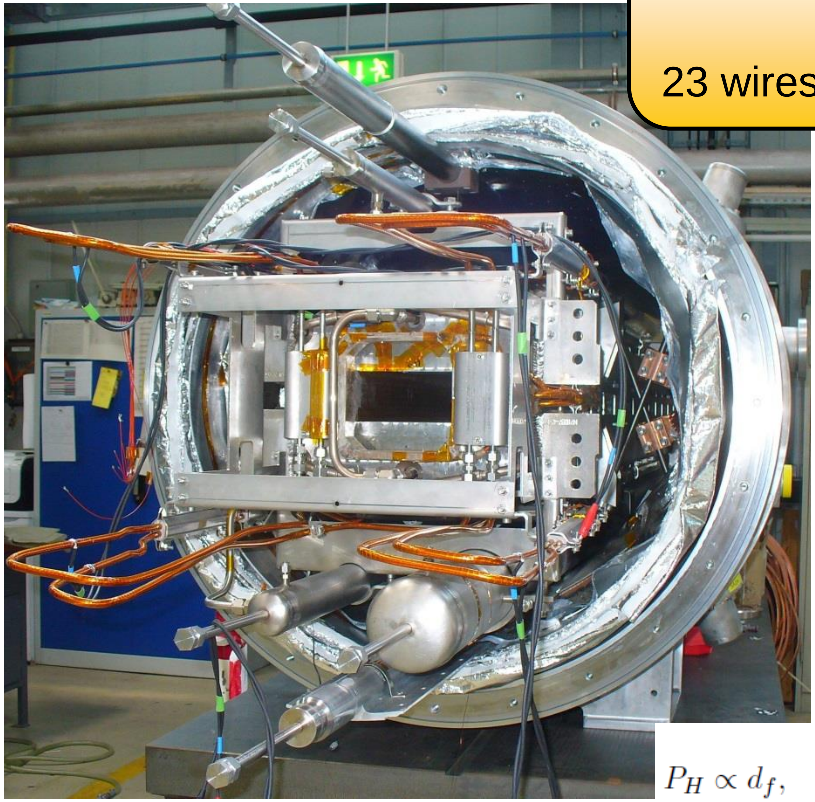


SIS100 dipole (2 layer prototype, 4.3 um)

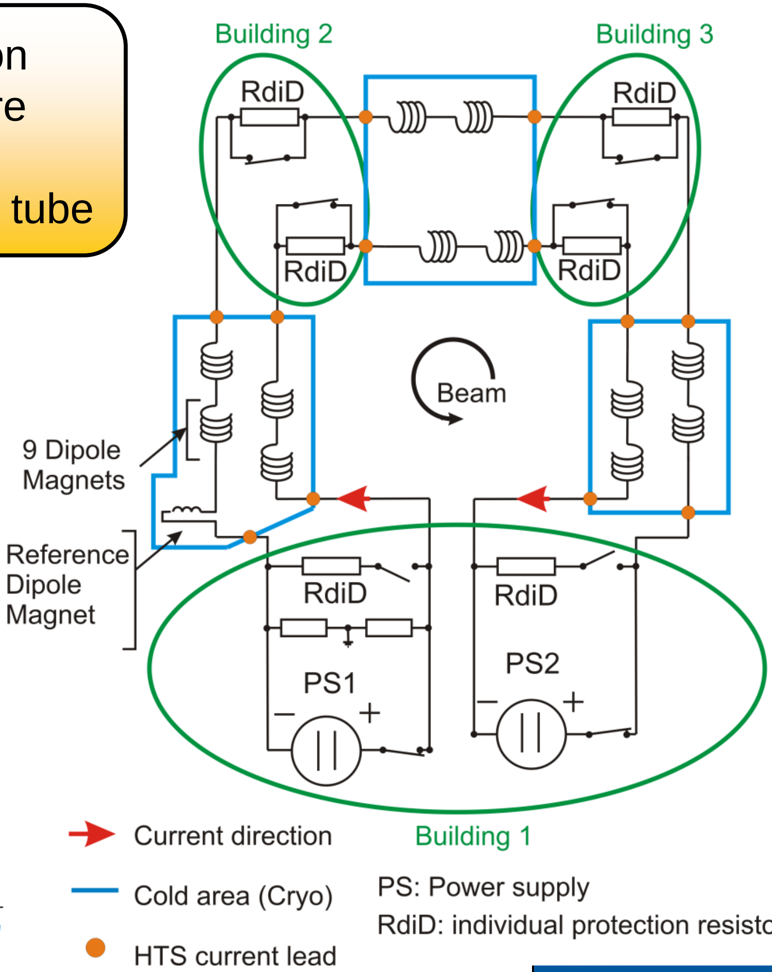
FAIR Project: SIS100 dipole magnets fast cycling 2 T/s -> 28 kA/s, one dipole = 47 kJ

FoS dipole magnet

1D Simulation
Insulated wire
and
23 wires + CuNi tube



$$P_H \propto d_f, \quad P_{ifc} \propto \frac{t_p^2}{\rho_{IF}}$$

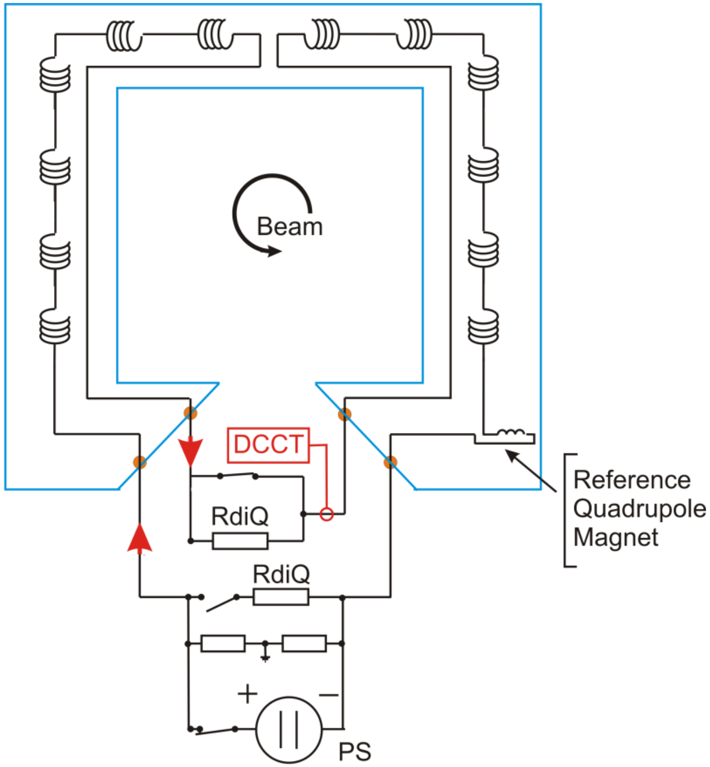


109 dipoles in series

13.1 kA, 1.9 T, CuMn matrix in order to reduce AC losses

FAIR Project: SIS100 quadrupole magnets

up to 84 quadrupoles in series



➔ Current direction

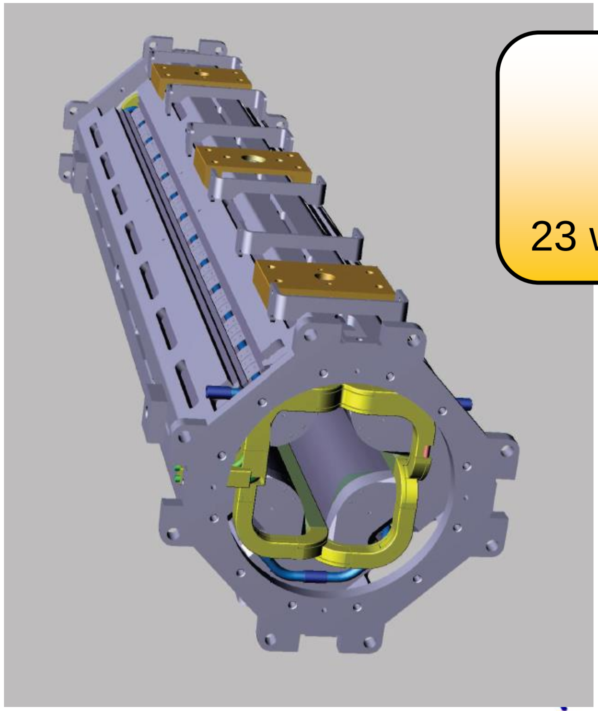
▬ Cold area (Cryo)

● HTS current lead

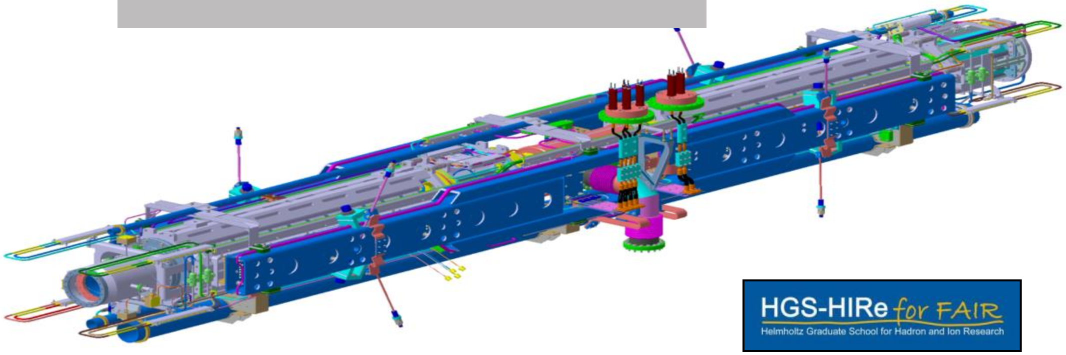
PS: Power supply

RdiQ: individual protection resistor

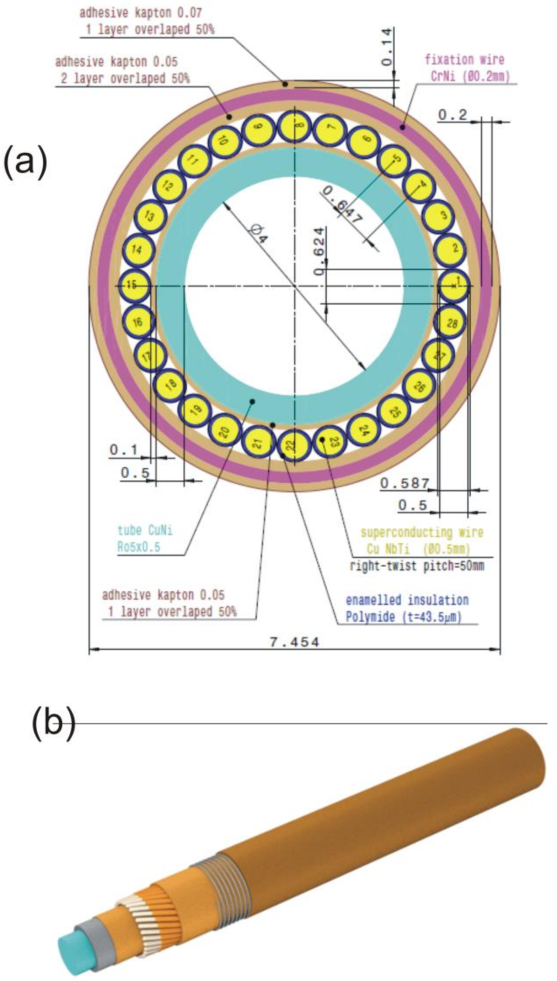
3 quadrupole circuits: QD, F1 and F2

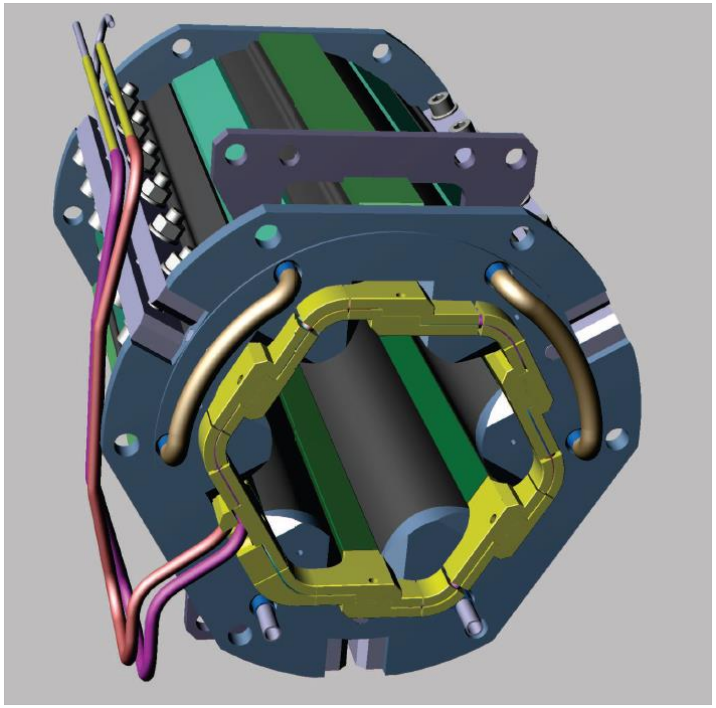


1D Simulation
Insulated wire
and
23 wires + CuNi tube



FAIR Project: SIS100 corrector magnets



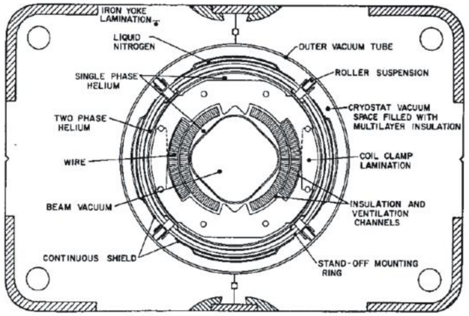


- Chromaticity sextupole magnets
- Steering magnets (2 dipoles)
- Multipole corrector magnets (Quadrupole + Sextupole + Octupole)

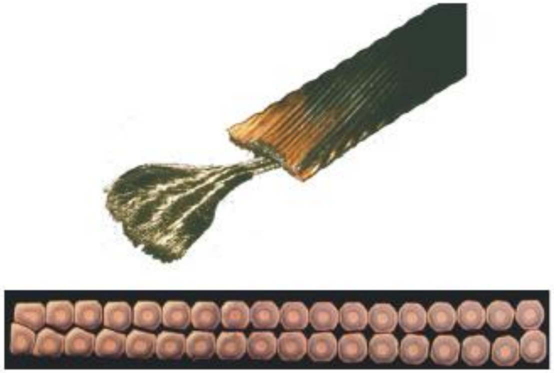
1D Simulation
Insulated wire

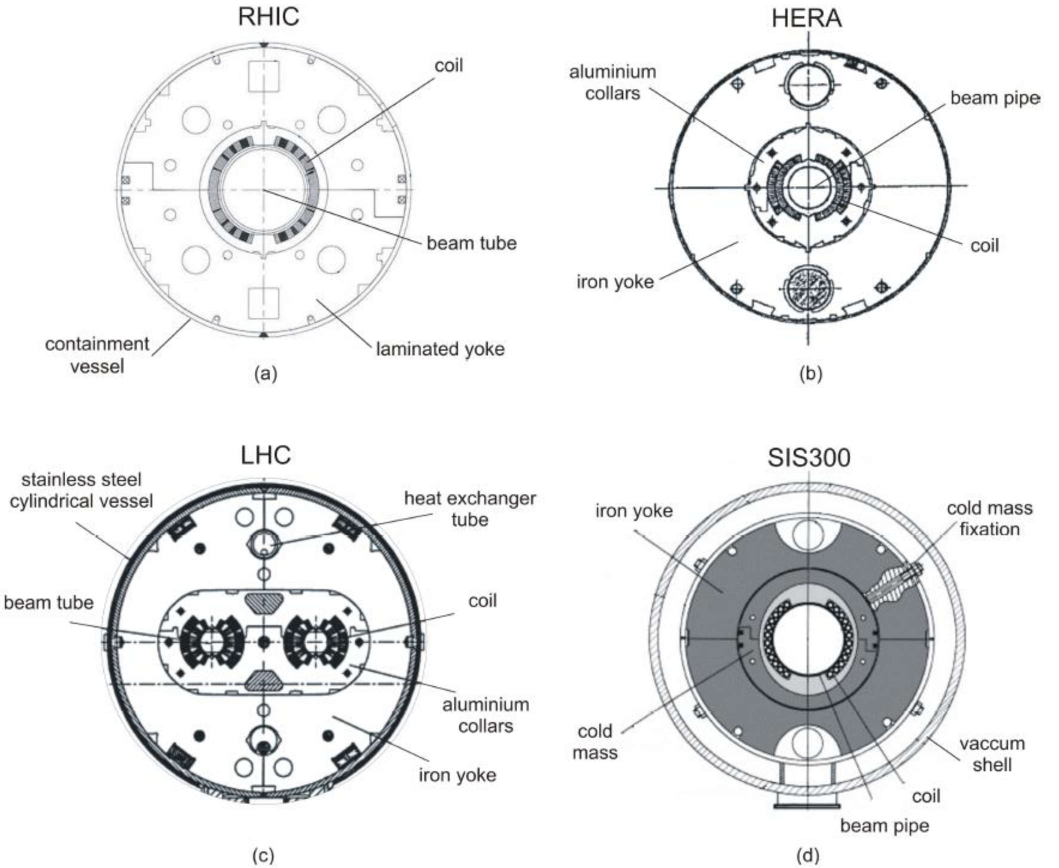
FAIR Project: SIS300

TEVATRON



Rutherford cable



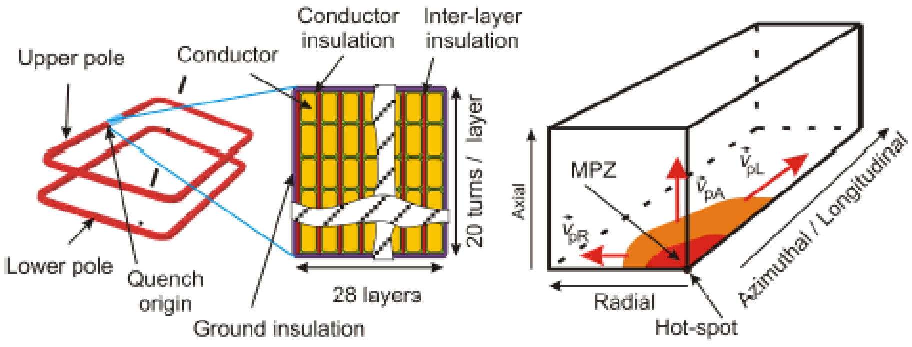


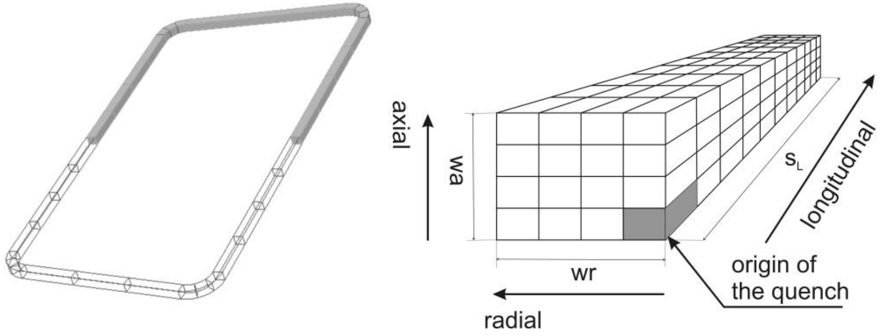
Arjan Verweij's talk

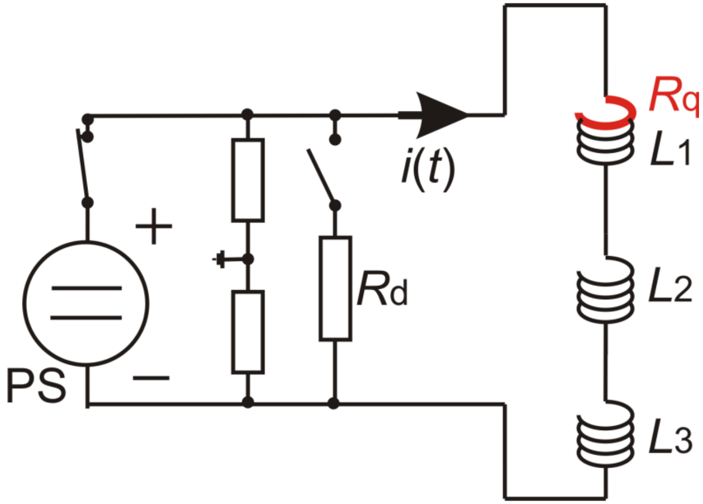
FAIR Project: other superconducting magnets

- High Energy Beam Transfer Line (HEBT)
  - SIS300 type magnets (Rutherford cable), line to CBM and beam dump
- CBM Dipole
  - potted coil, “wire in channel”, similar to Super-FRS, 5.15 MJ
- Quadrupoles of HEDgeHOB final focusing system (Rutherford cable)

GSI Quench Program







$$\rho(B,T)\cdot J^2(t)+\nabla\left(k(x,y,z,T)\cdot\nabla\cdot T(x,y,z,t)\right)=C_v(B,T)\cdot\frac{\partial T(x,y,z,t)}{\partial t}$$

@ microscopic scale

$$L_d(I)\cdot\frac{dI(t)}{dt}+\left(R_q(t)+\delta(t)\cdot R_d\right)\cdot i(t)=V_{PS}(t)$$

@ macroscopic scale

Heat-balance equation (implicit method)

$$J(t)^2 \cdot \rho(T_{x,t}) +$$

$$+k\left(\frac{T_{x-dx,t}+T_{x,t}}{2}\right)\cdot\frac{T_{x-dx,t+dt}-T_{x,t+dt}}{dx^2} - k\left(\frac{T_{x,t}+T_{x+dx,t}}{2}\right)\cdot\frac{T_{x,t+dt}-T_{x+dx,t+dt}}{dx^2} =$$

$$= C_v(T_{x,t})\cdot\frac{T_{x,t+dt}-T_{x,t}}{dt}$$

i – position
j – time

$$a(i)\cdot T_{i-1,j+1}\cdot b(i)\cdot T_{i,j+1}+c(i)\cdot T_{i+1,j+1}=T_{i,j}+d(i)$$

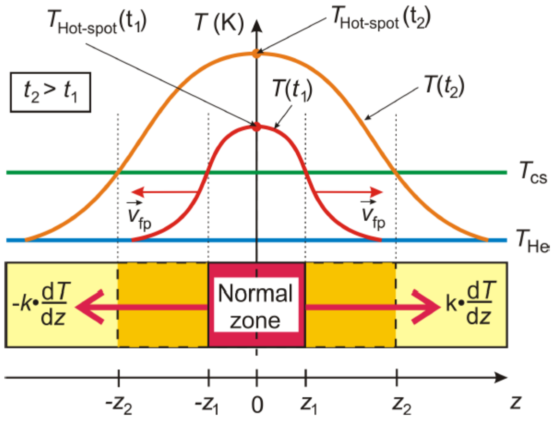
where the parameters:

$$a(i) = -\frac{dt}{dx^2\cdot C_v(T_{i,j})}\cdot k\left(\frac{T_{i,j}+T_{i-1,j}}{2}\right),$$

$$b(i) = 1+\frac{dt}{dx^2\cdot C_v(T_{i,j})}\cdot\left(k\left(\frac{T_{i,j}+T_{i-1,j}}{2}\right)+k\left(\frac{T_{i+1,j}+T_{i,j}}{2}\right)\right),$$

$$c(i) = -\frac{dt}{dx^2\cdot C_v(T_{i,j})}\cdot k\left(\frac{T_{i+1,j}+T_{i,j}}{2}\right),$$

$$d(i) = \frac{\rho(T_{i,j})\cdot J^2(j)\cdot dt}{C_v(T_{i,j})}.$$



GSI Quench Program

Equation matrix

$$\begin{pmatrix} b(1) & c(1) & 0 & 0 & 0 & \dots & 0 & 0 \\ a(2) & b(2) & c(2) & 0 & 0 & \dots & 0 & 0 \\ \ddots & \ddots & \ddots & \ddots & \ddots & \dots & \ddots & \ddots \\ 0 & 0 & a(i) & b(i) & c(i) & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & 0 & 0 & \dots & a(i_{max}) & b(i_{max}) \end{pmatrix} \cdot \begin{pmatrix} T_{1,j+1} \\ T_{2,j+1} \\ \vdots \\ T_{i,j+1} \\ \vdots \\ T_{i_{max},j+1} \end{pmatrix} = \begin{pmatrix} T_{1,j} + d(1) \\ T_{2,j} + d(2) \\ \vdots \\ T_{i,j} + d(i) \\ \vdots \\ T_{i_{max},j} + d(i_{max}) \end{pmatrix}$$

Initial temperature profile is known!

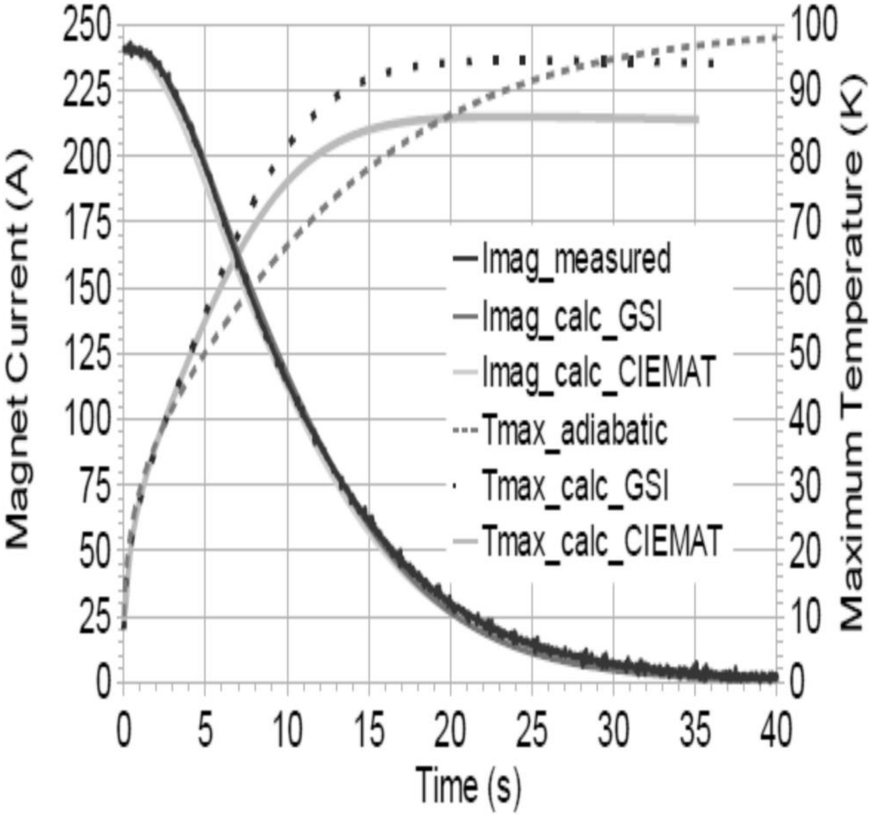
i – position
j – time

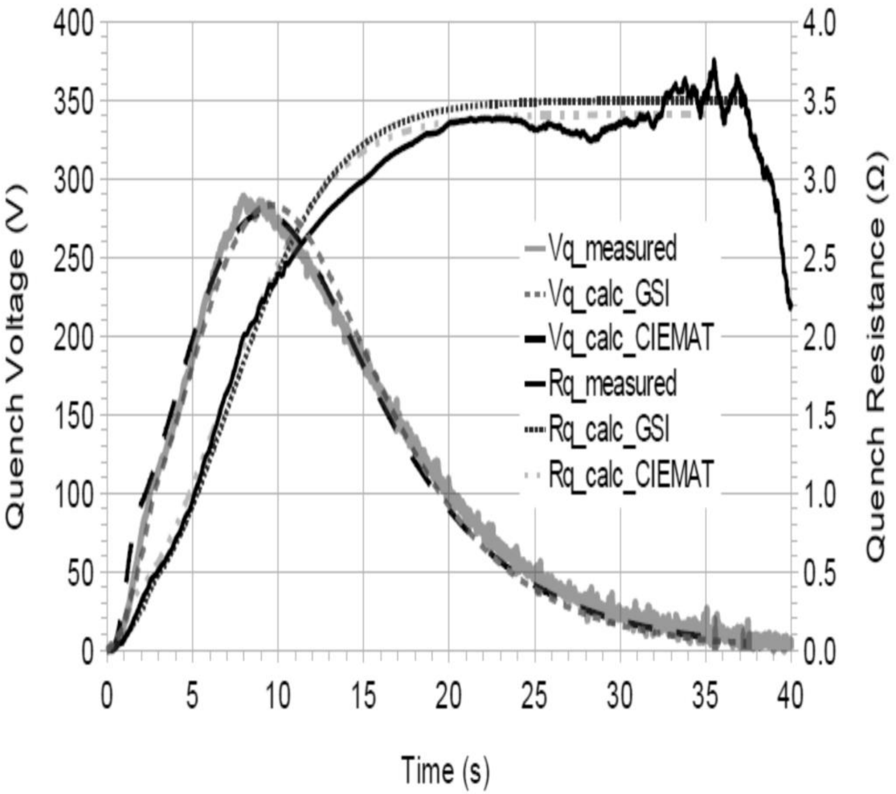
we compute: $\begin{pmatrix} T_{1,j+1} & T_{2,j+1} & \dots & T_{i,j+1} & \dots & T_{i_{max},j+1} \end{pmatrix}$

⇒ then electrical equation is updated

⇒ to avoid high jumps in temperature, an adaptive time stepping algorithm is applied (max dT is fixed)

3D Simulation vs. measurements

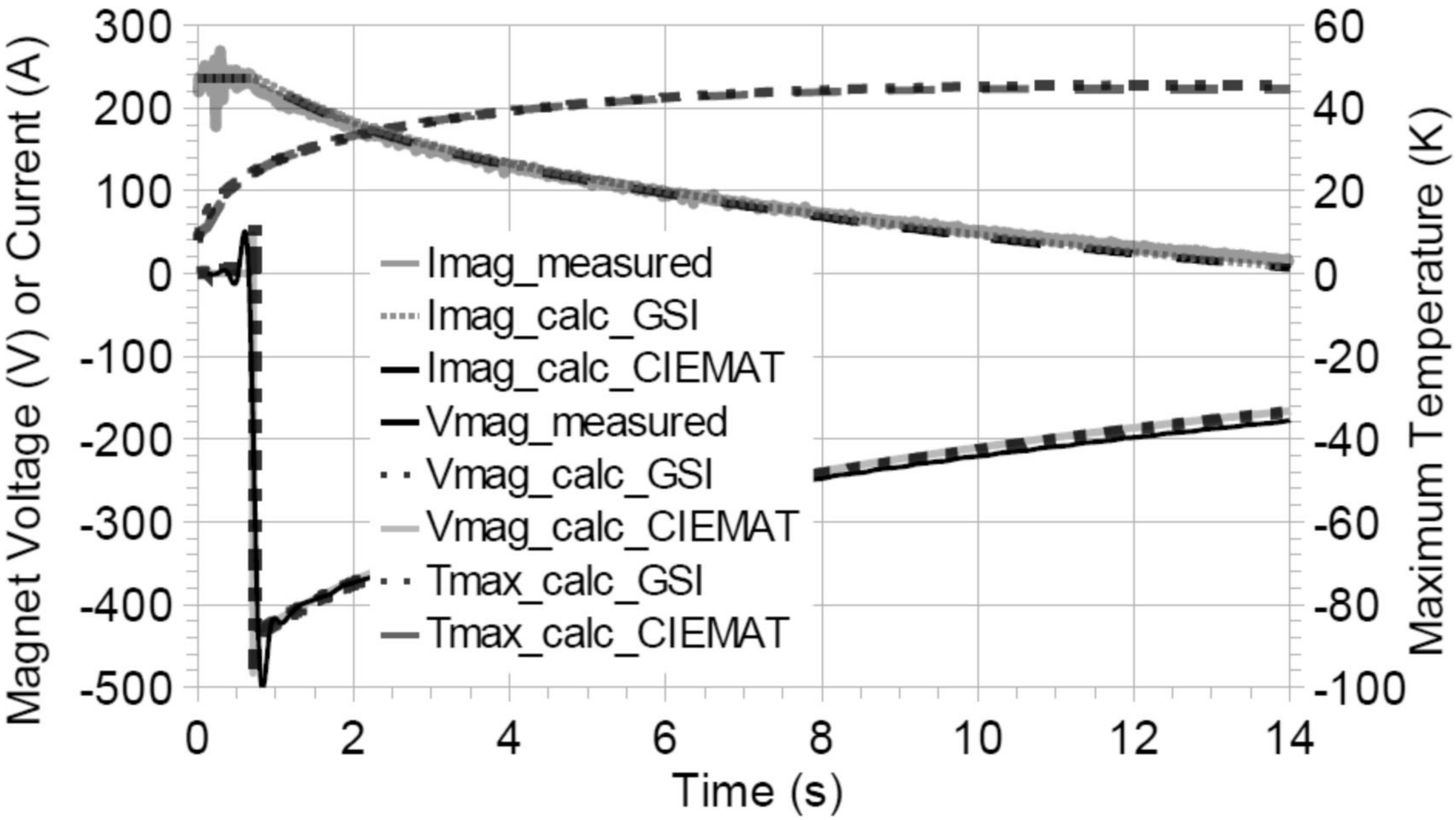




Super-FRS dipole (prototype)

$$0 = R_q \cdot I + L_d(I) \cdot \frac{dI}{dt}$$

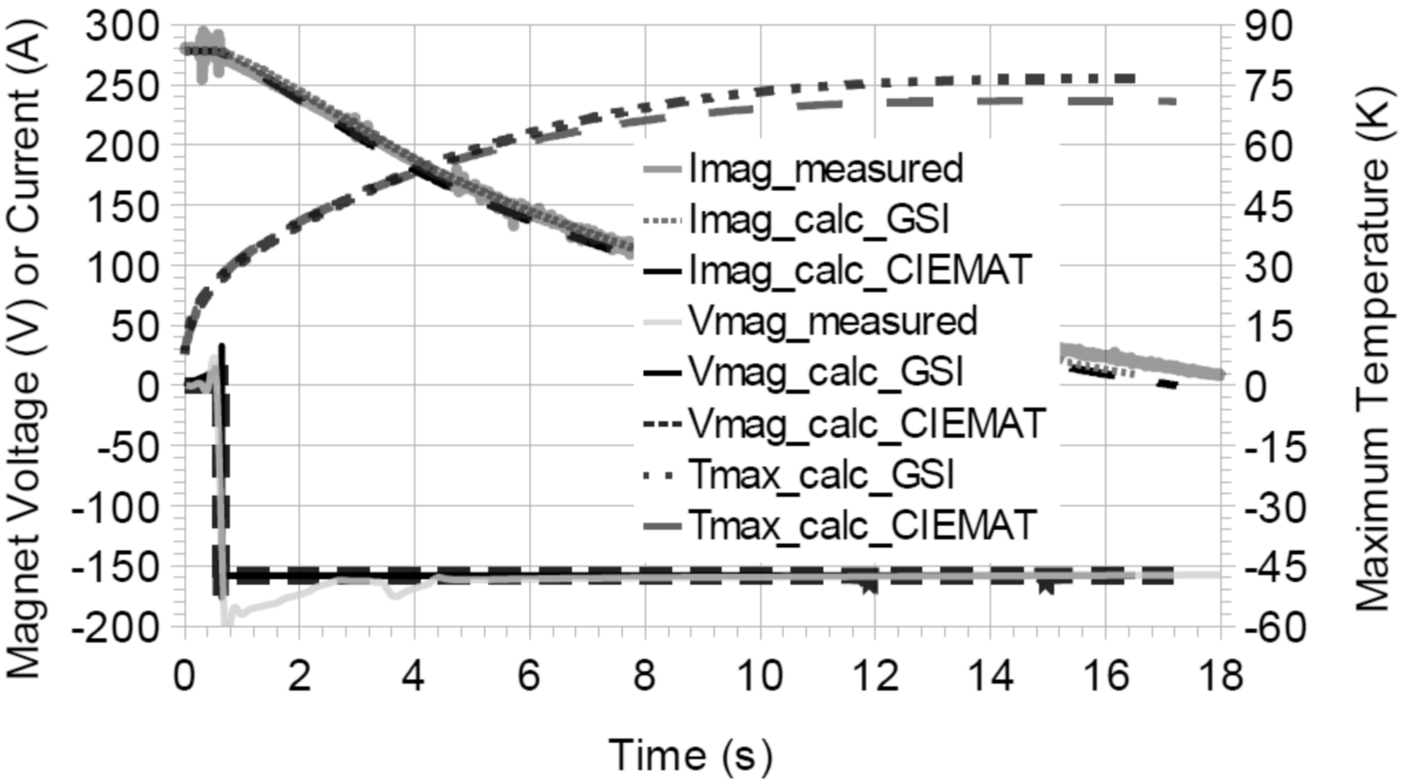
3D Simulation vs. measurements



Super-FRS dipole (prototype)

$$V_{PS} = (R_d + R_q) \cdot I + L_d(I) \cdot \frac{dI}{dt}$$

3D Simulation vs. measurements

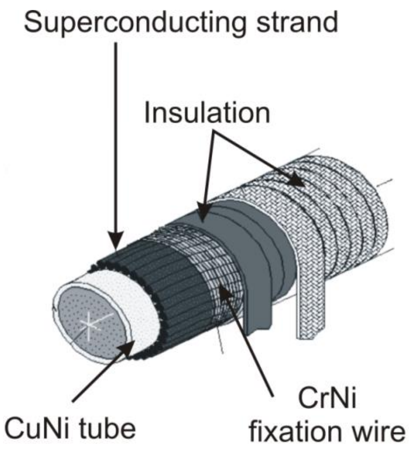


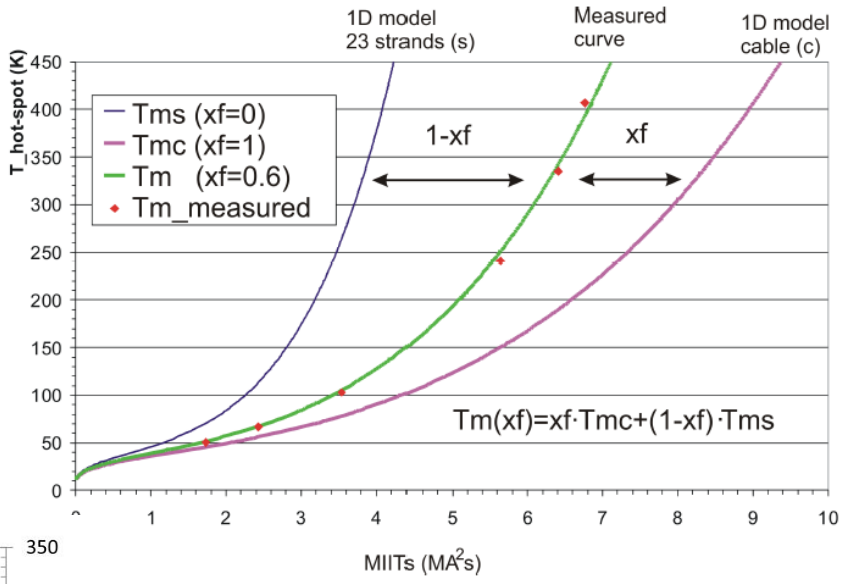
Super-FRS dipole (prototype)

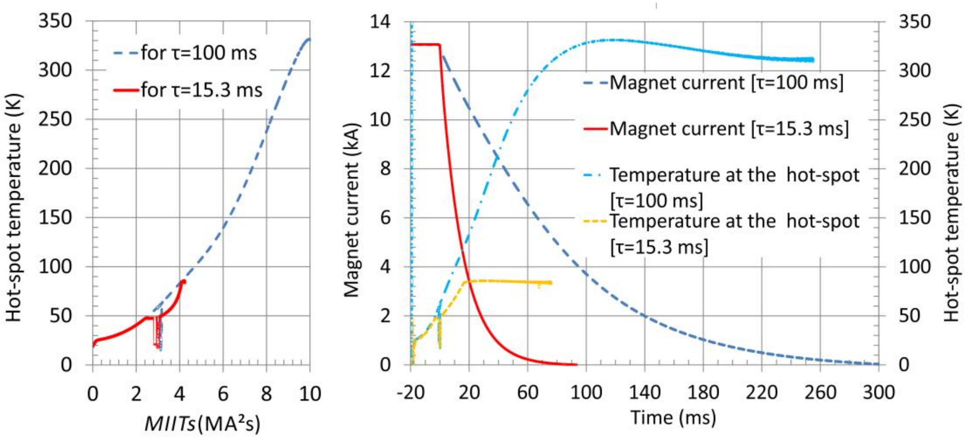
$$V_{PS} = R_q \cdot I + L_d(I) \cdot \frac{dI}{dt}$$

1D Simulation vs. measurements: SIS100 FoS dipole and 2 layer prototype

2 layer prototype







FoS dipole

Conclusion

- One need to perform at least simplified quench calculation before the experiment.
- Expected max. temp. and max voltages (coil-to-ground and coil-to-coil) need to be known in advance ⇒ safety of the machine and personnel!
- Tmax < 300 (350) K, sometimes lower < 100 K; High Voltage (HV)! Insulation? Electrical sockets?
- HV? He gas in the cryostat? ⇒ Paschen effect!

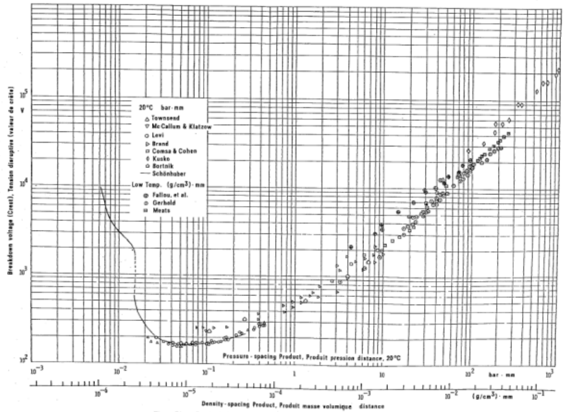
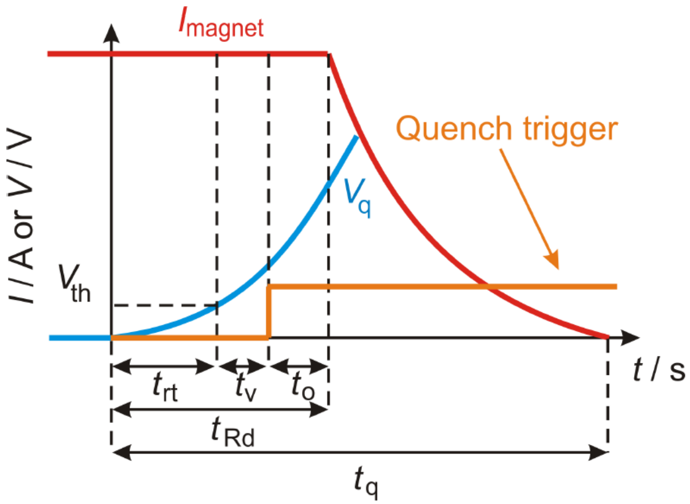


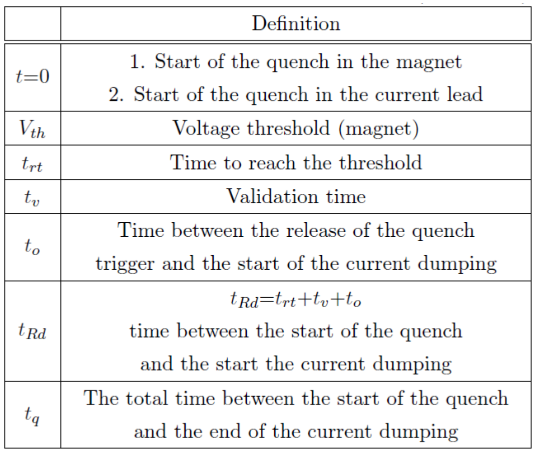
Figure G1 – Courbe de Paschen pour l'hellium en échelles logarithmiques. Température 20°C.
Paschen curve for helium in log log scale. Temperature 20°C.

- Small change in MIITs value corresponds in a big change in Tmax.
- Quench calculation is a part of the machine design!

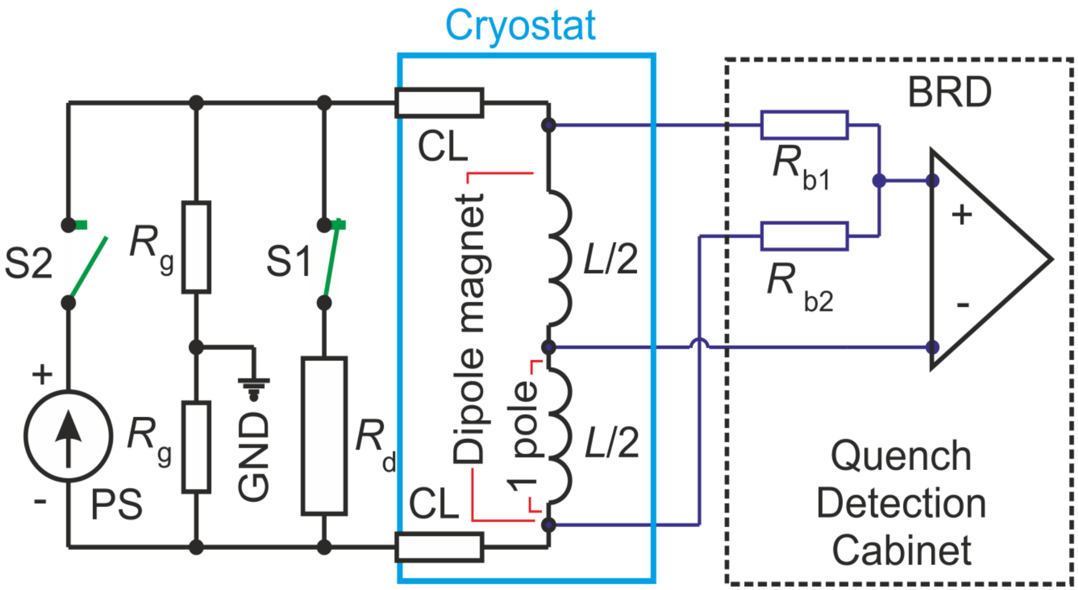
Thank you for attention!

Quench Detection





	Definition
t=0	1. Start of the quench in the magnet 2. Start of the quench in the current lead
V_{th}	Voltage threshold (magnet)
t_{rt}	Time to reach the threshold
t_v	Validation time
t_o	Time between the release of the quench trigger and the start of the current dumping
t_{Rd}	$t_{Rd}=t_{rt}+t_v+t_o$ time between the start of the quench and the start the current dumping
t_q	The total time between the start of the quench and the end of the current dumping



$$V_b = \pm\frac{1}{2}\cdot R_q\cdot I = \pm\frac{V_q}{2}$$