Cable stability in accelerator magnets

Case 1: LHC
Case 2: FAIR - SIS 300

Gerard Willering

PhD student at the University of Twente

Experimental research at CERN

In collaboration with GSI

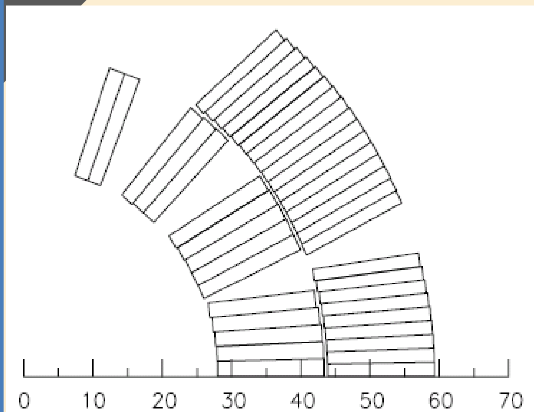
- Introduction cable stability

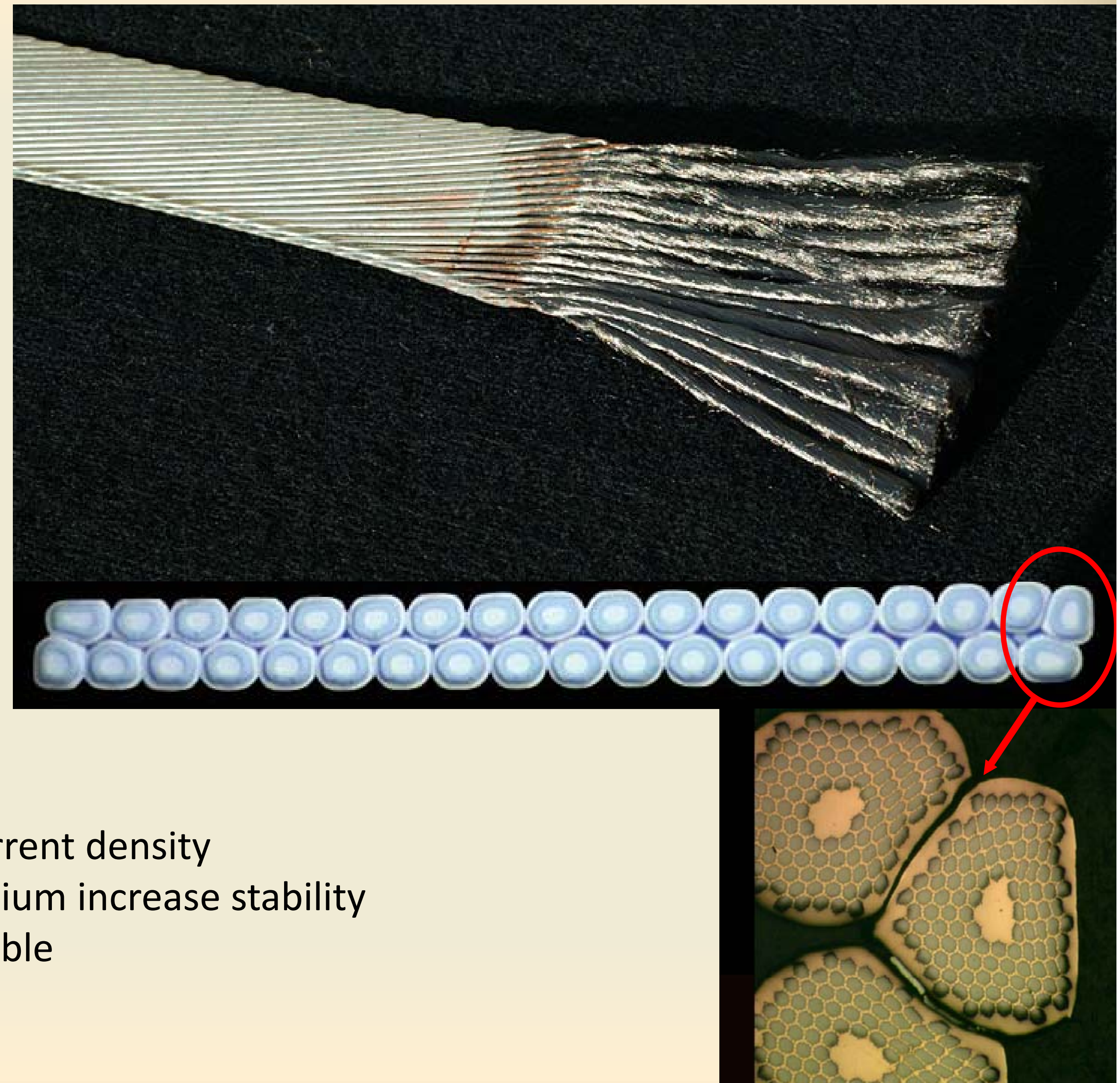
- LHC Superfluid helium

- SIS 300 Measurement in fluid helium
  Simulations with supercritical helium

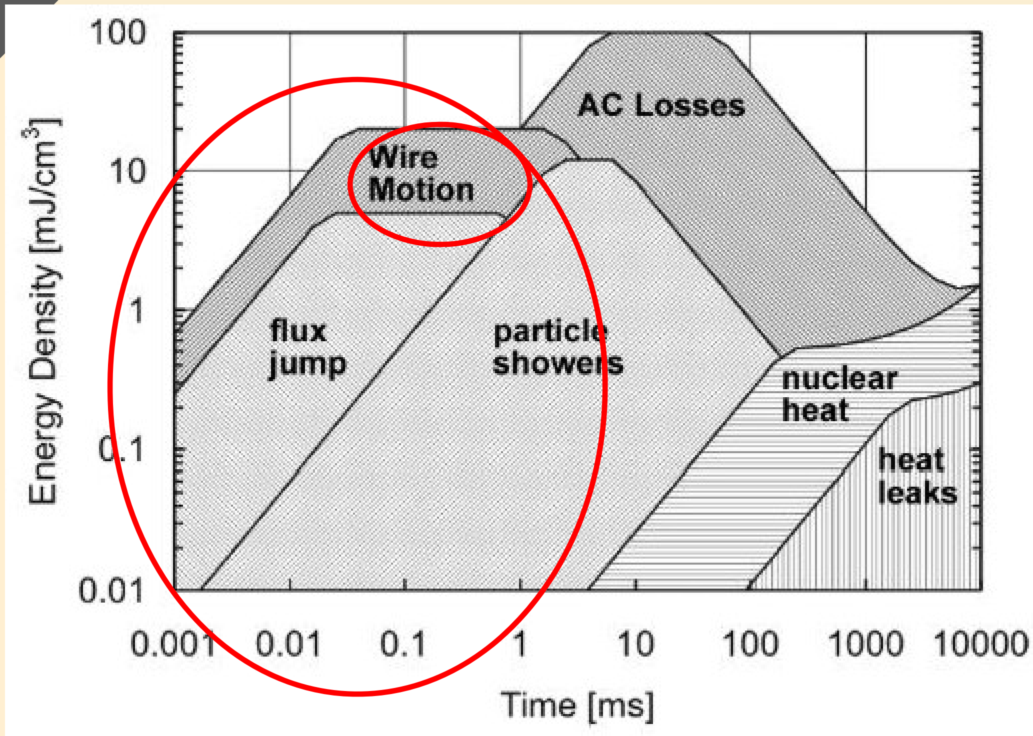
- Design considerations for SIS 300 magnets

- Conclusion





Rutherford Cable
20 – 40 strands
High compaction, high current density
Cable voids containing helium increase stability
Stacking of windings possible



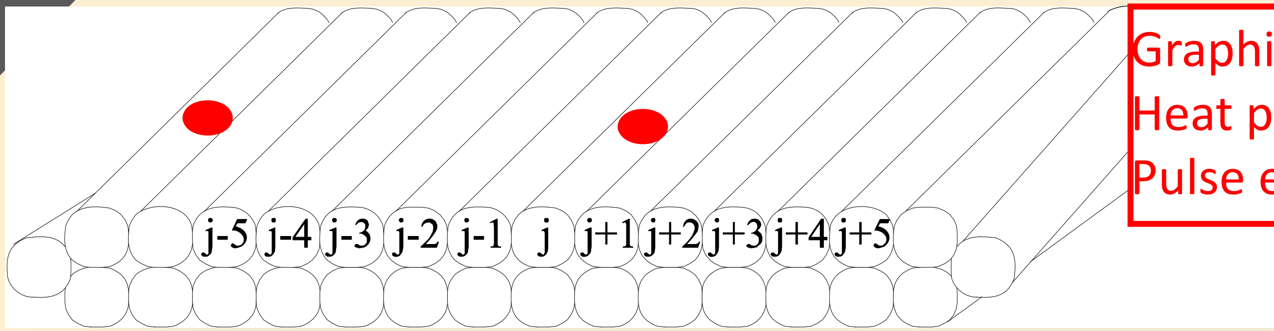
Luca Bottura in (Iwasa, Y, "Stability and protection of superconducting magnets – a discussion", IEEE. Trans. Appl. Supercond., Vol. 15, 2, pp 1615.)

Disturbance energy spectra for LTS magnets

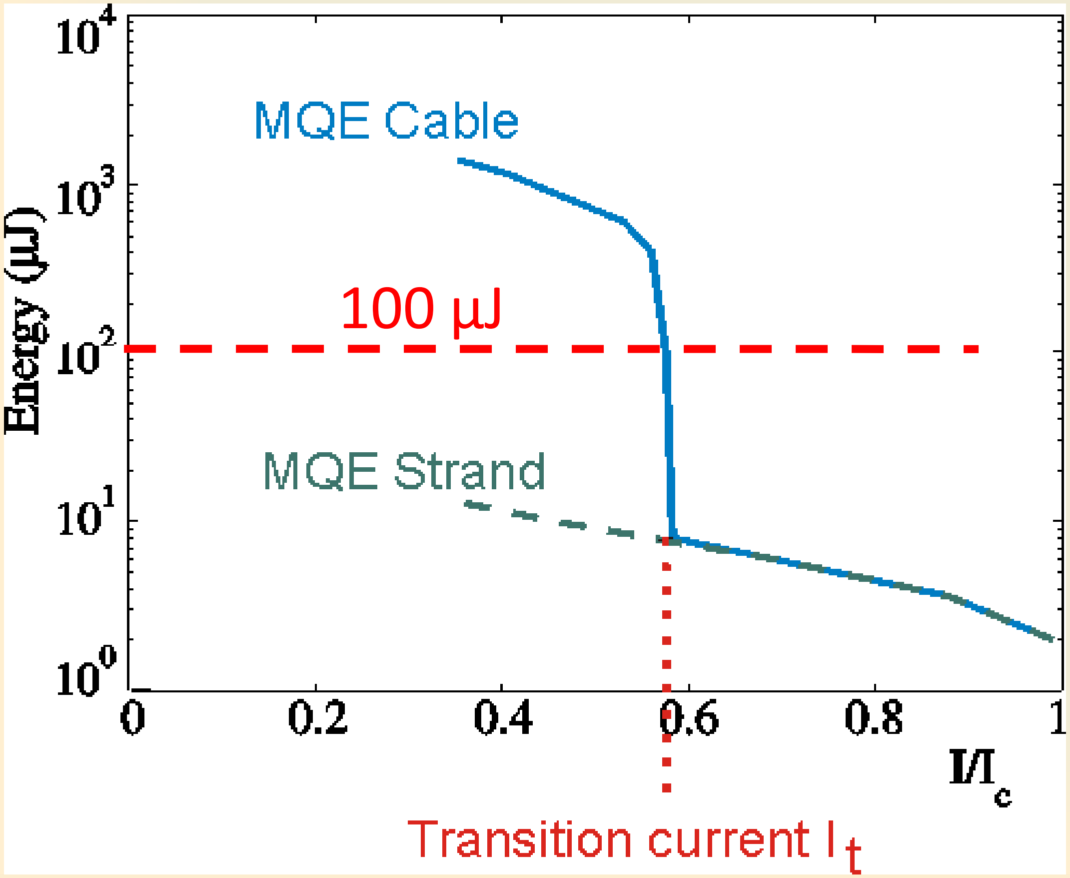
Typical disturbances of interest this research: Wire motion.
(Training quenches)

Disturbance duration < 1 ms.
Affected volume: 1 strand.

20 mJ/cm^3
Normally half a twist pitch can move
Total energy dissipated
LHC type I ≈ 100 μJ
LHC type II (SIS 300) ≈ 50 μJ



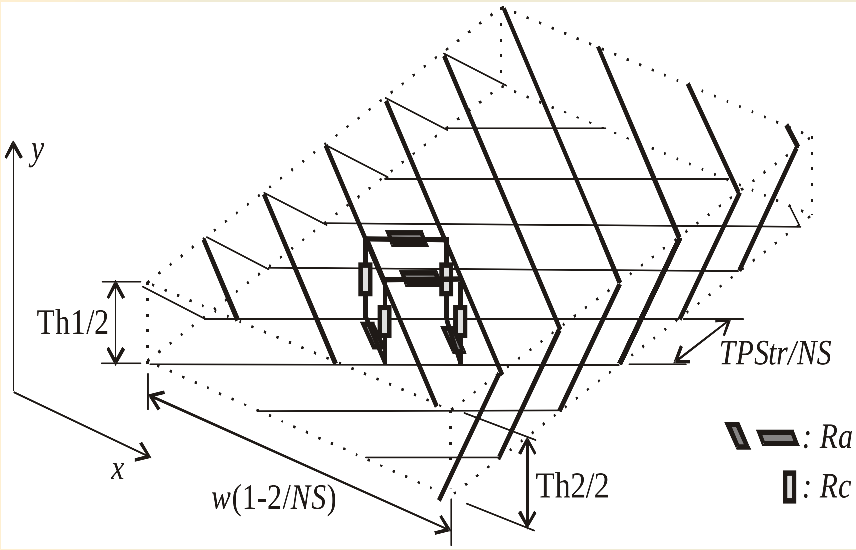
Graphite paste heater
Heat pulse duration 100 µs
Pulse energy 2 – 5000 µJ



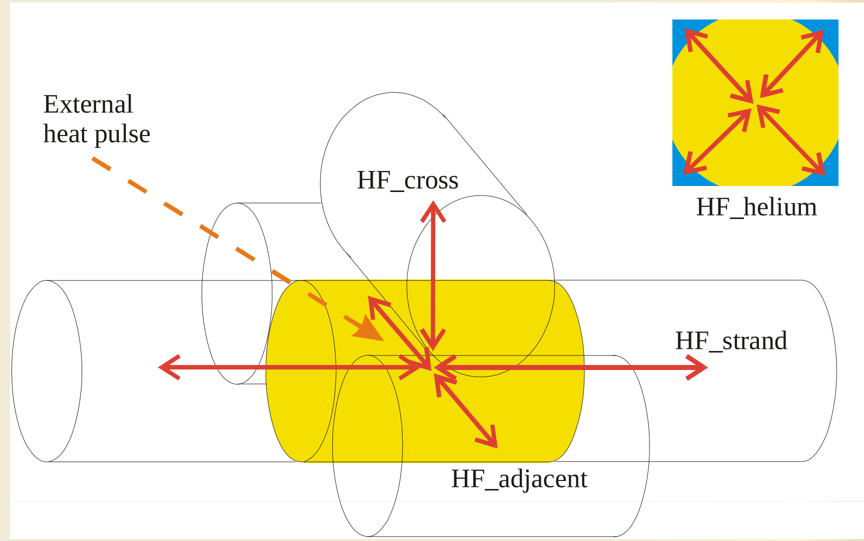
To increase the stability of a cable the value of transition current ***I_t*** should be as high as possible.

Simulation program CUDI

Electrical network



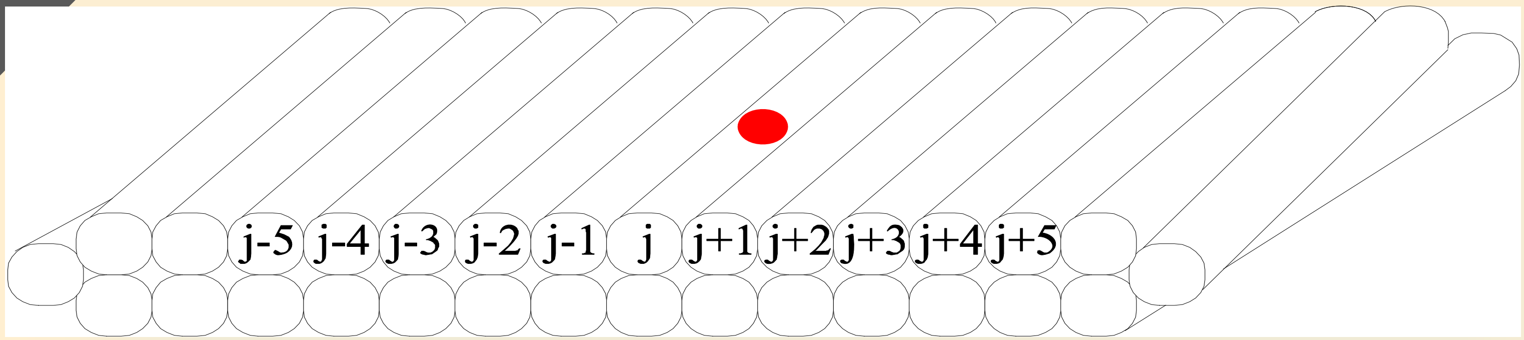
Thermal network

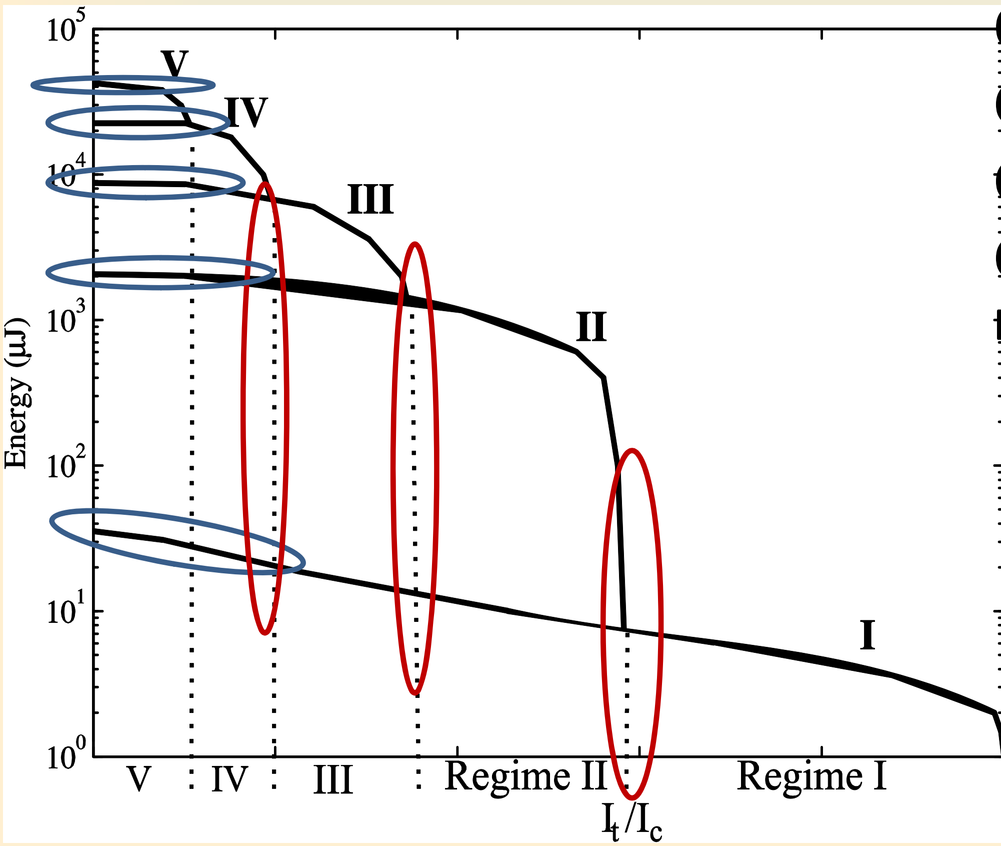


Main Equation:

$$c_p \frac{\Delta T_s}{dt} V_s = P_{inp} + I_s^2 R_s + I_a^2 R_a - k_{He}(T_s - T_{He})A_{He} - k_{is}(T_s - T_a)A_a - k_s \frac{dT_s}{dx} A_s$$

Heat capacity	Input Pulse	Joule Heating normal zone	Joule Heating interstrand currents	Cooling by Helium	Interstrand heat transport	Longitudinal heat transport





Quench Criteria:

Criterion I $T_{j,\,max} > T_{j,c}$

Criterion II $T_{j+1,\,max} > T_{j+1,c}$

Criterion III $T_{j+2,\,max} > T_{j+2,c}$

Etcetera.

At low current the criteria depend only on thermal behavior with absence of current.

The upper current limits of the criteria depend also on current redistribution.

Characteristics of the LHC dipole magnets

Aperture field	8.33 T
Slow ramp rate	7 mT/s
Temperature	1.9 K
Cooling	Superfluid helium

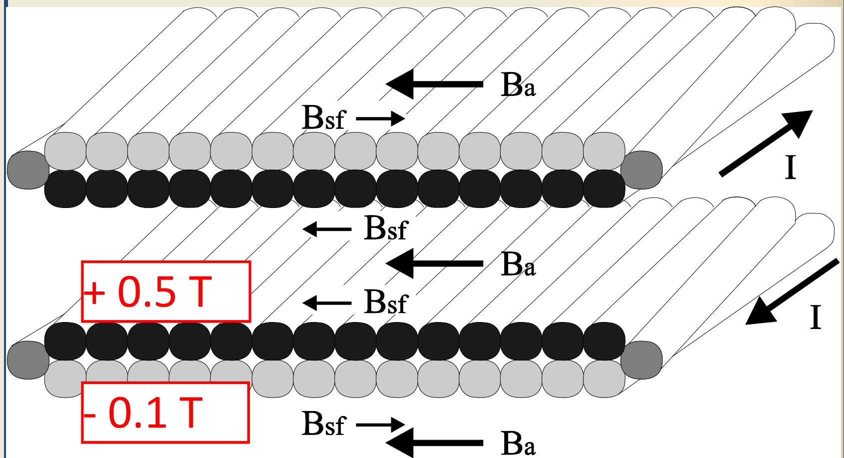
Cable characteristics LHC type I

R_c	> 20 μΩ
R_a	> 5 R_c
Coating	$Ag_{95\%wt}$ Sn
Core	None
Mid-thickness	1.9 mm
Width	15.1 mm
Number of strands	28
Strand diameter	1.065 mm
Twist-pitch	110 mm
Cu/Sc ratio	1.65

FRESCA measurement characteristics

Field	9 T
Temperature	1.9 K
Bath	He II
Sample length	2.3 m
Cable pressure	50 Mpa

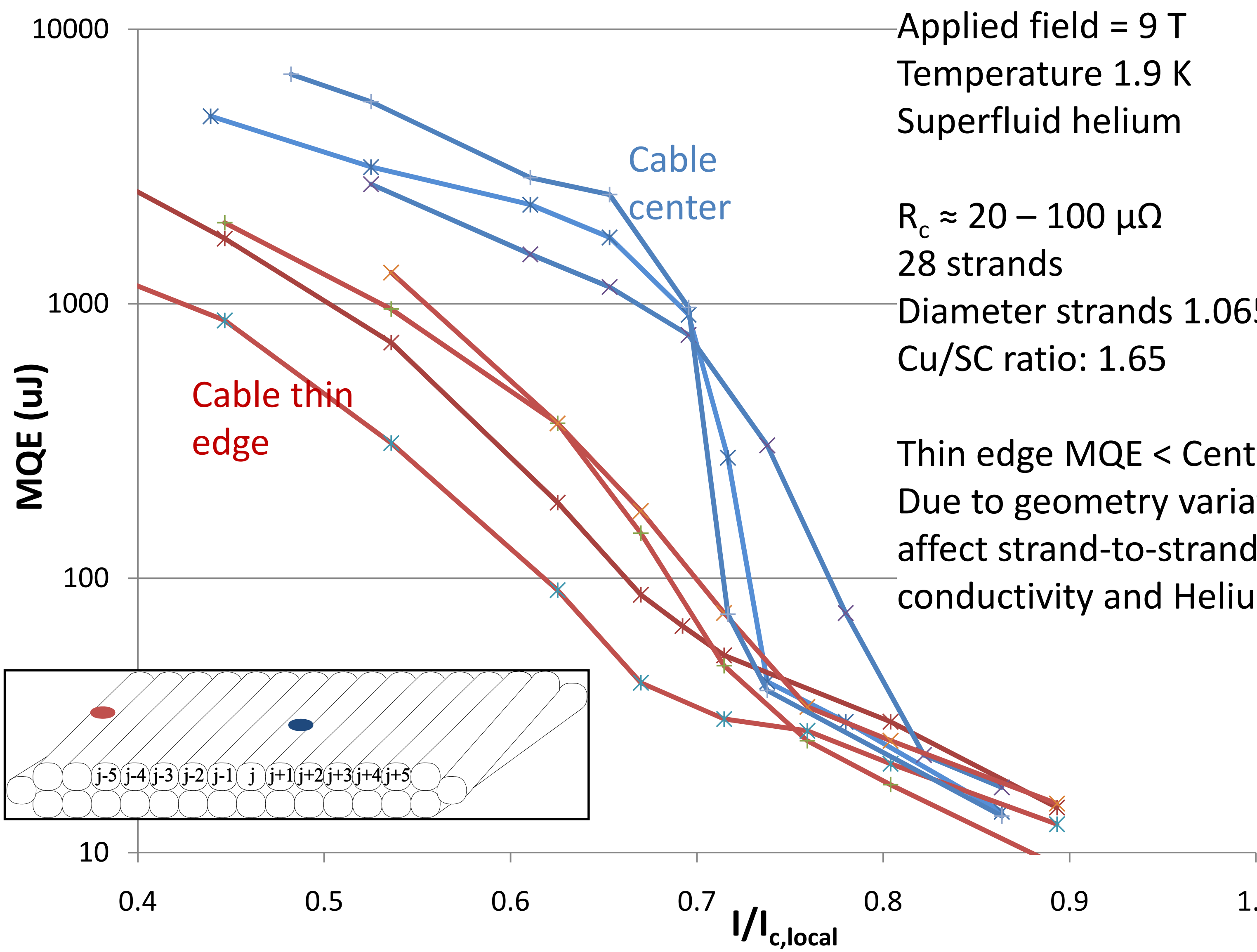
Double cable layout



Field and I_c are varying locally because of self field.

Light-gray strands - 0.1 T

Black strands + 0.5 T

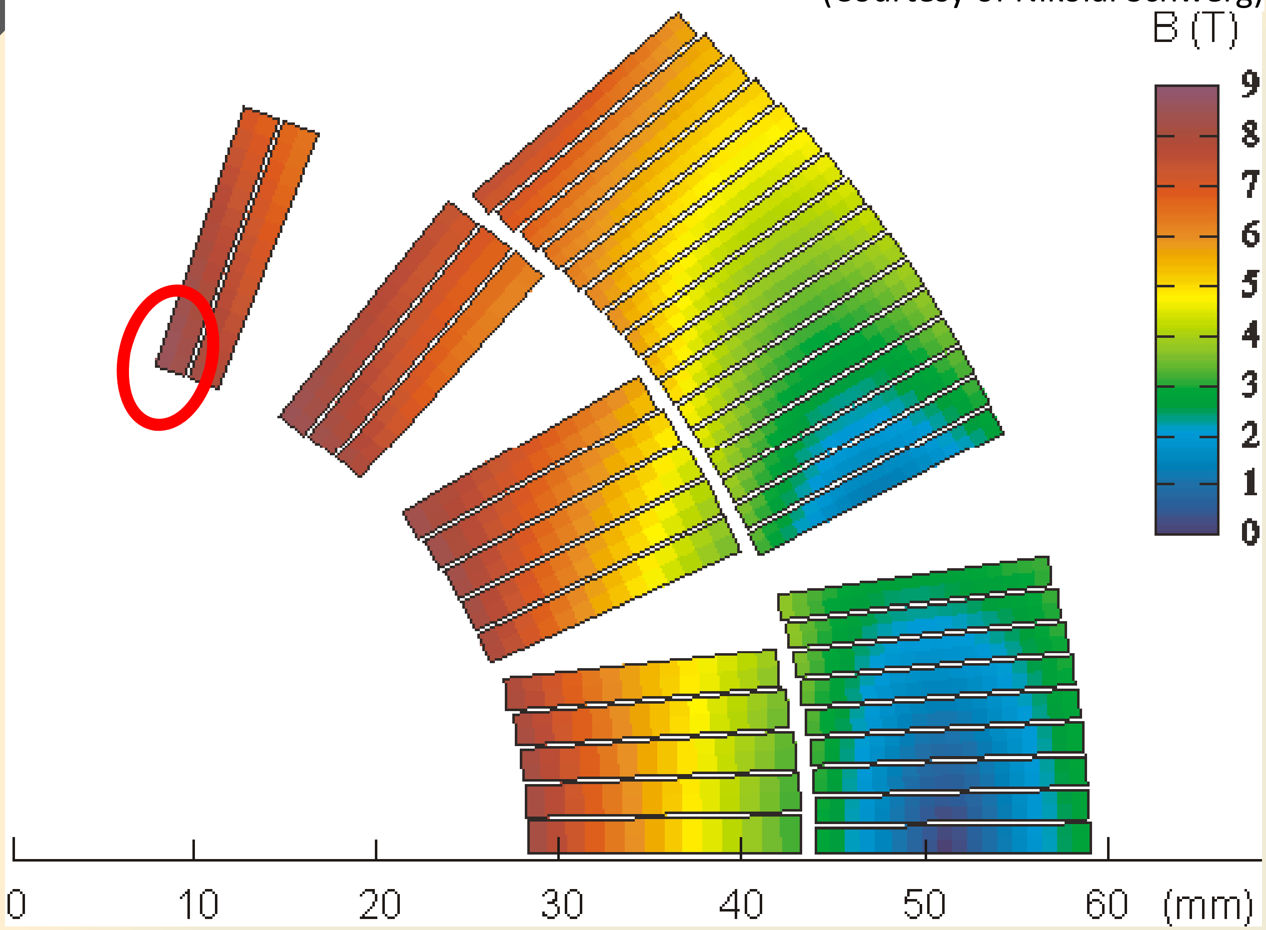


FRESCA test station
Applied field = 9 T
Temperature 1.9 K
Superfluid helium

$R_c \approx 20 - 100\ \mu\Omega$
28 strands
Diameter strands 1.065 mm.
Cu/SC ratio: 1.65

Thin edge MQE < Center MQE
Due to geometry variations that affect strand-to-strand thermal conductivity and Helium voids.

(Courtesy of Nikolai Schwerg)

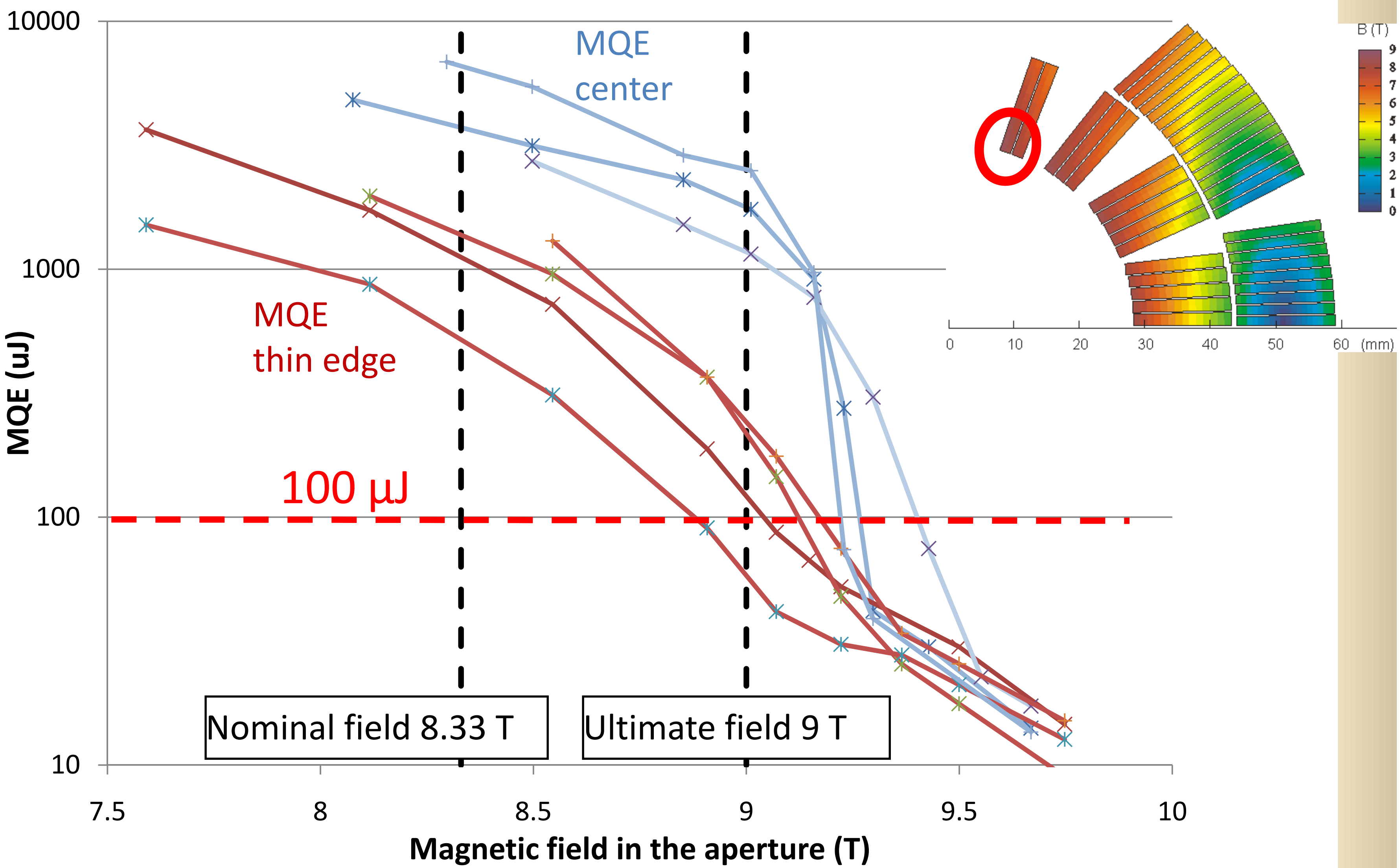


Quadrant of an LHC dipole magnet

Nominal aperture field 8.33 T

Maximum field in the conductor 8.6 T at the edge position

Temperature 1.9 K


10000
1000
100
10
MQE (μJ)
MQE
center
MQE
thin edge
100 μJ
Nominal field 8.33 T
Ultimate field 9 T
7.5
8
8.5
9
9.5
10
Magnetic field in the aperture (T)
B (T)
9
8
7
6
5
4
3
2
1
0
0
10
20
30
40
50
60 (mm)

Remarks on LHC stability

1. Training quenches did and do occur below 8.33 T.
Do we underestimate the energy of 100 μJ or did these training quenches originate from another source. **?**

2. If heat is deposited by wire movement in multiple wires, the transition current will be much lower.
In that case, the single strand stability applies. But still 100 μJ per strand would not be enough to quench the magnet.

Characteristics of the first design SIS 300 dipole magnets, also used for a prototype

Aperture field	6 T
High ramp rate	1 T/s
Temperature	4.4 to 4.78 K
Cooling	Supercritical helium
Helium pressure	4 Atm

Cable characteristics SIS 300

R_c	> 20 mΩ
R_a	≈ 200 -300 μΩ
Coating	$Ag_{95\%wt}$ Sn
Core	Stainless Steel 25 μm
Mid-thickness	1.48 mm
Width	15.1 mm
Number of strands	36
Strand diameter	0.825 mm
Twist-pitch	100 mm
Cu/Sc ratio	1.95

Fast cycling will give considerable loss !!!

Loss reduction by increase in R_a and R_c will affect stability.

TABLE II
LOSS PER CYCLE (Joules/m)

Transverse B, crossover R_c	3.2
Transverse B, adjacent R_a	10.7
Parallel B adjacent R_a	0.1
matrix coupling current	15.0
Filament hysteresis	47.9
Total magnet	**76.9**

(J. Kaugerts et al., "Cable design for FAIR SIS 300", IEEE trans. Appl. Supercond., Vol. 17, 2, 2007)

FRESCA measurement characteristics

Field	6 T
Temperature	4.32 K
Bath	Fluid helium

4 identical cables with different treatment

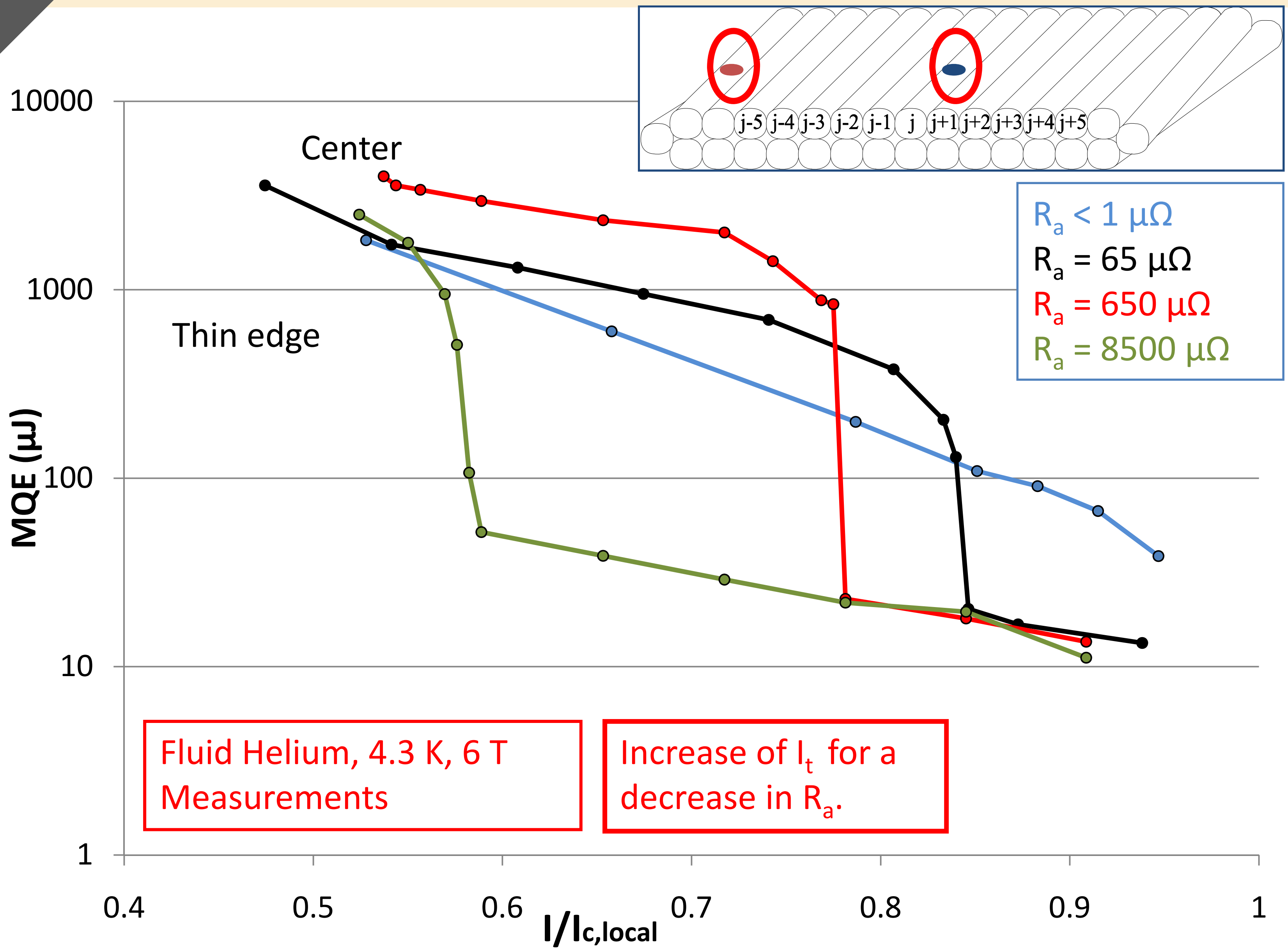
R_a < 1 μΩ

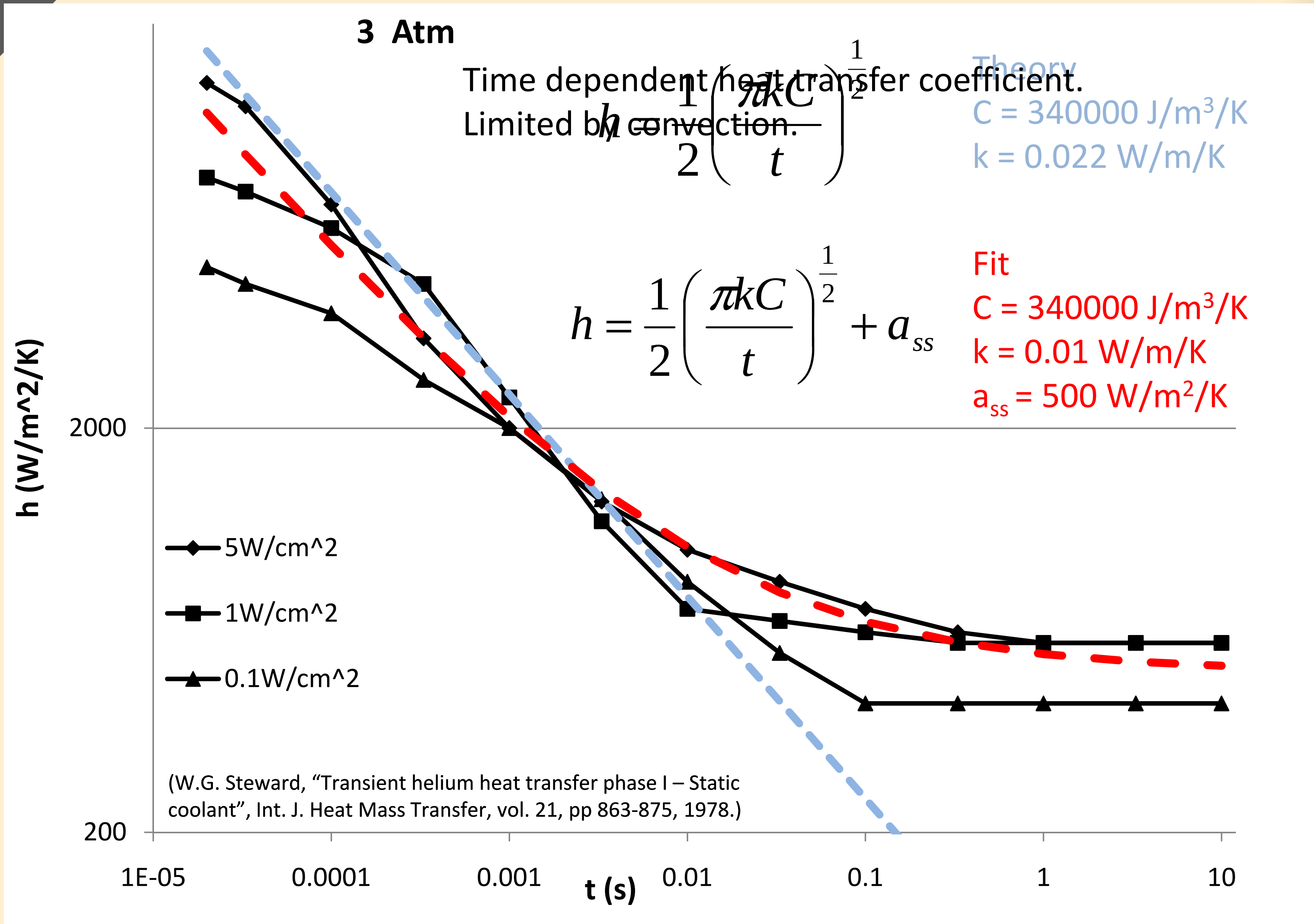
R_a ≈ 65 μΩ

R_a ≈ 650 μΩ

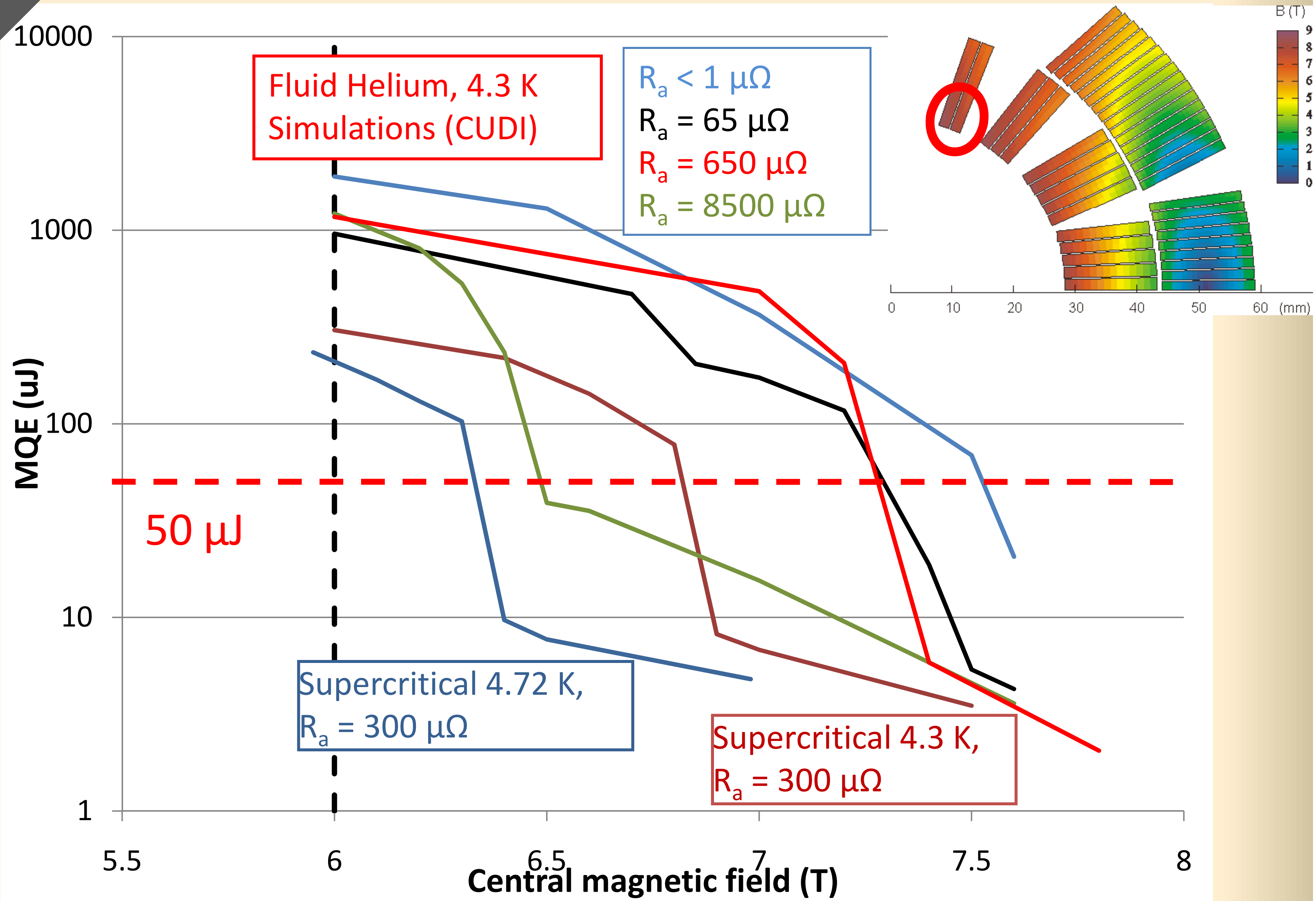
R_a ≈ 8500 μΩ

SIS 300 – MQE in measurements – Fluid Helium




3 Atm
Time dependent heat transfer coefficient.
Limited by convection.
$$h = \frac{1}{2}\left(\frac{\pi k C}{t}\right)^{\frac{1}{2}}$$
Theory
C = 340000 J/m³/K
k = 0.022 W/m/K
$$h = \frac{1}{2}\left(\frac{\pi k C}{t}\right)^{\frac{1}{2}} + a_{ss}$$
Fit
C = 340000 J/m³/K
k = 0.01 W/m/K
a_{ss} = 500 W/m²/K
h (W/m^2/K)
2000
200
5W/cm^2
1W/cm^2
0.1W/cm^2
(W.G. Steward, "Transient helium heat transfer phase I – Static coolant", Int. J. Heat Mass Transfer, vol. 21, pp 863-875, 1978.)
1E-05
0.0001
0.001
t (s)
0.01
0.1
1
10

SIS 300 – MQE on magnet load line



Conclusion

1. High R_a reduces the transition current I_t and the transition field.

2. I_t for the sample with R_a = 8.5 mΩ cooled with fluid helium at 4.3 K is even lower than I_t for R_a = 300 μΩ cooled with supercritical helium at 4.3 K, while cooling is worse. R_a is a critical design parameter.

3. The curves with MQE on the load lineSimulating the effect of short local energy pulses, MQE depending on B(I) may show a limit in the operation field of a magnet.

Design considerations for SIS 300 dipoles cooled by **supercritical helium**

1. Heat transfer is only depending on convection in the helium. Therefore surface conditions are not important for conductor cooling (contrary to cooling by fluid He I or superfluid He II).

2. AC-loss needs $R_c > 20\ \mathrm{m}\Omega$. Coupling of R_a and R_c with high resistance coating reduce current redistribution drastically, reducing cable stability.

3. Good solution for pulsed magnets:
   Decoupling of R_a and R_c by a resistive core.
   $R_\mathrm{c} > 20\ \mathrm{m}\Omega$
   $R_\mathrm{a} < 1\ \mathrm{m}\Omega$ (smaller is better)

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