CERN Accelerator School
Superconductivity for Accelerators

Current Leads, Links and Buses

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3 May 2013

SC Devices in SC Accelerators

- Magnets
- RF Cavities
- Current Leads
- SC Bus-Bar
- SC Links
- Beam Instrumentation (based on SQUIDS, Superconducting Quantum Interference Devices)

Auxiliaries

Quench Protection

Cold Diodes (semiconductors)

Energy Extraction

Post Mortem System

Interlocks……..

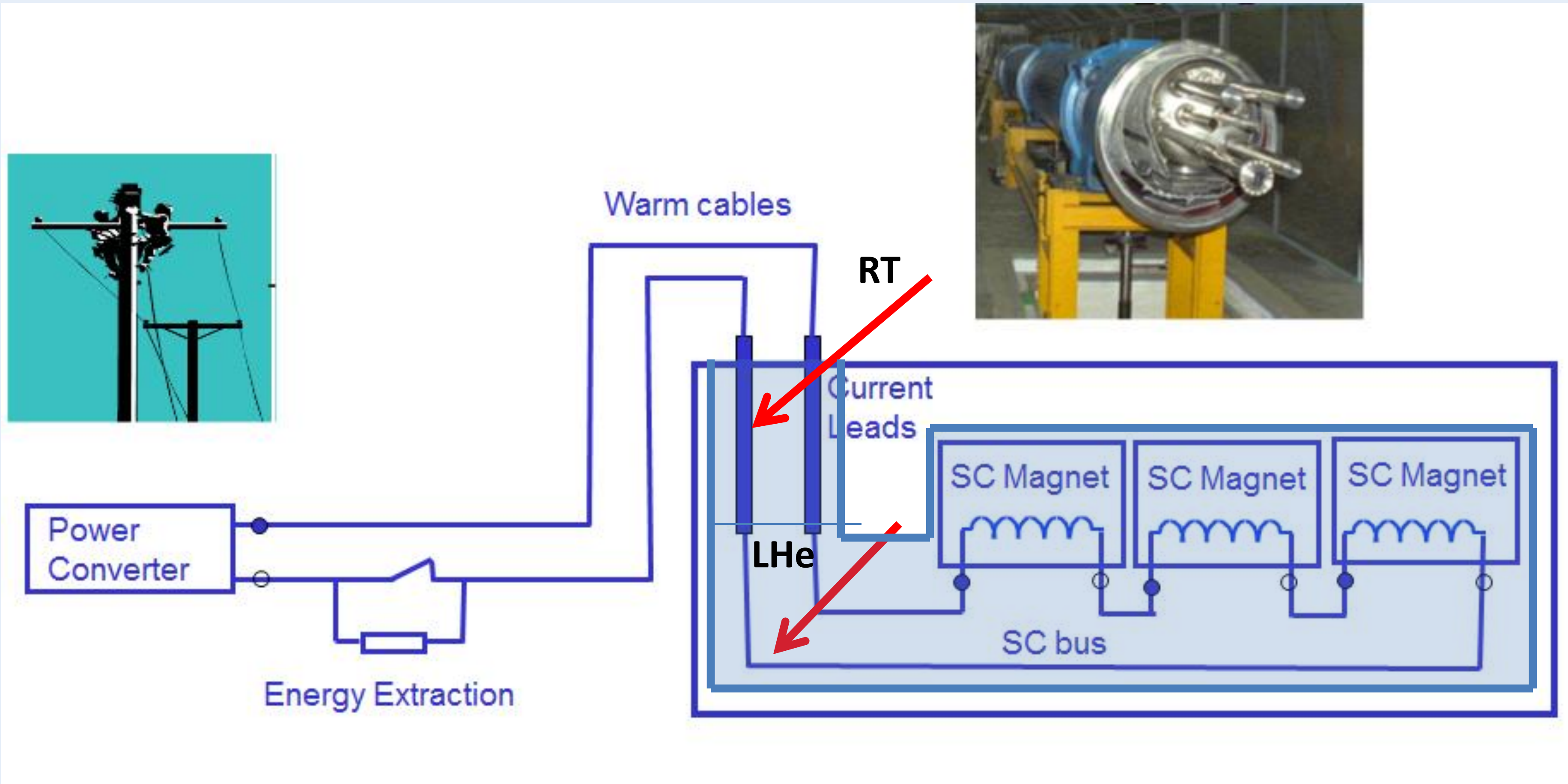
Outline

- Current Leads
  - Conventional leads
  - HTS Leads (Bi-2223, Y-123)
- Bus-Bar
  - Nb-Ti bus-bar
  - Superconducting Links (MgB_2)
- Protection

FROM
↓
TO

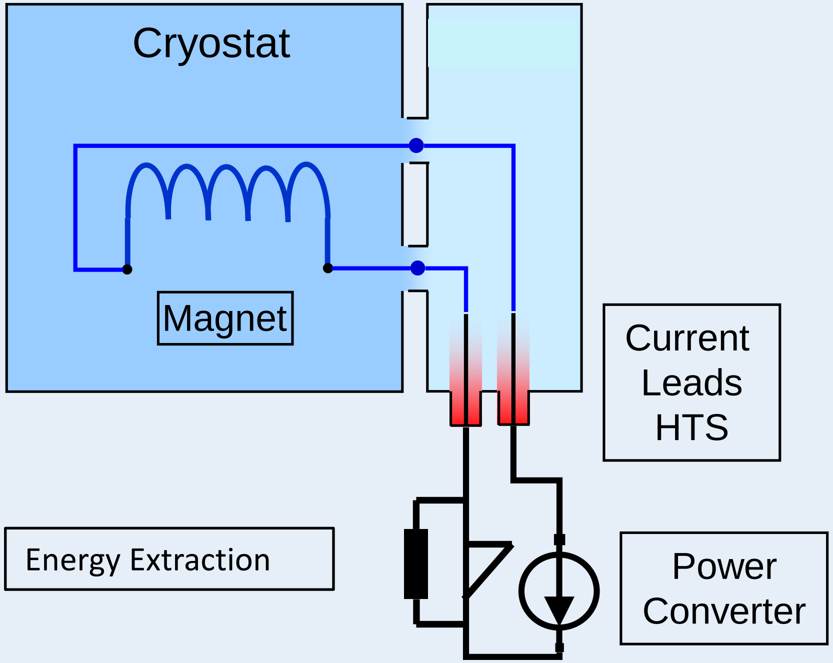
FROM
↓
TO

Leads and Bus-Bar in a Magnet Circuit



Single Magnet

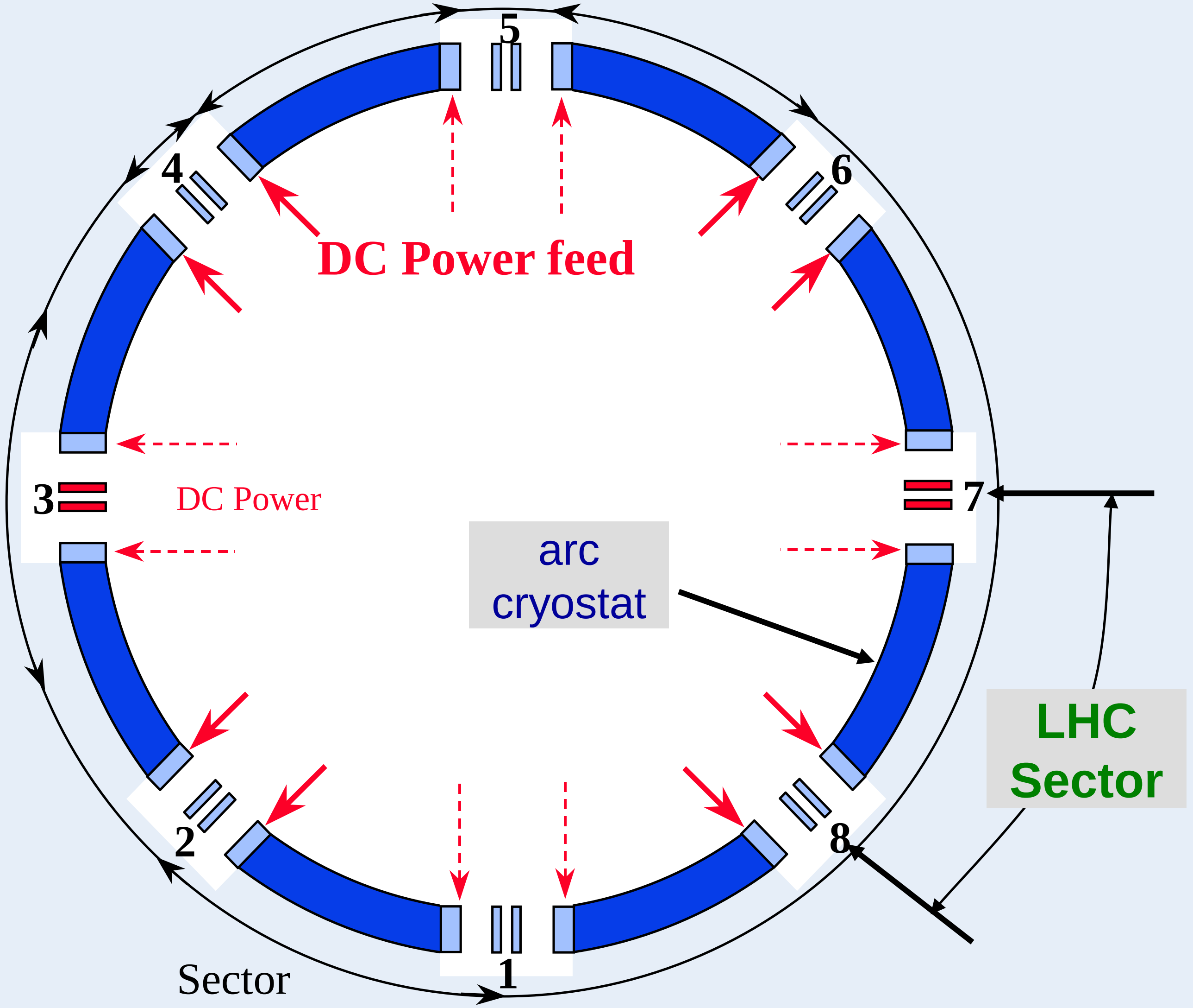
Individual magnet operated at LHe temperature



Powering the LHC Machine

- ~ 8000 Superconducting magnets
- ~ 1700 Electrical circuits
- More than 3 MA of current
- More than 3000 current leads (from 60 A to 13000 A)
- More than 2000 km of Nb-Ti bus-bar
- More than 50000 interconnections

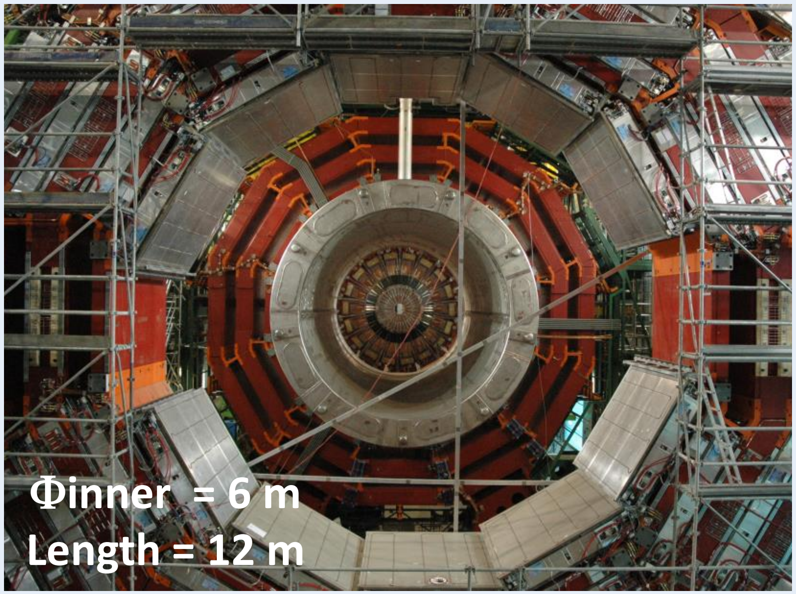
Powering of LHC machine



For superconducting magnets, no DC powering across LHC Interaction Points

Magnets Individually Powered

CMS Solenoid



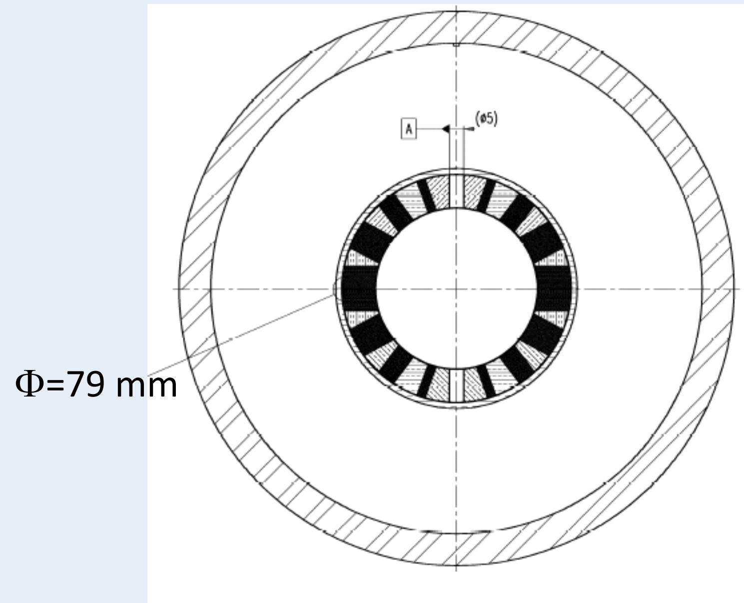
Imax = 19500 A

L = 14 H

E-stored = 2.7 GJ

Energy extraction (50 mΩ)

LHC Dipole Orbit Corrector



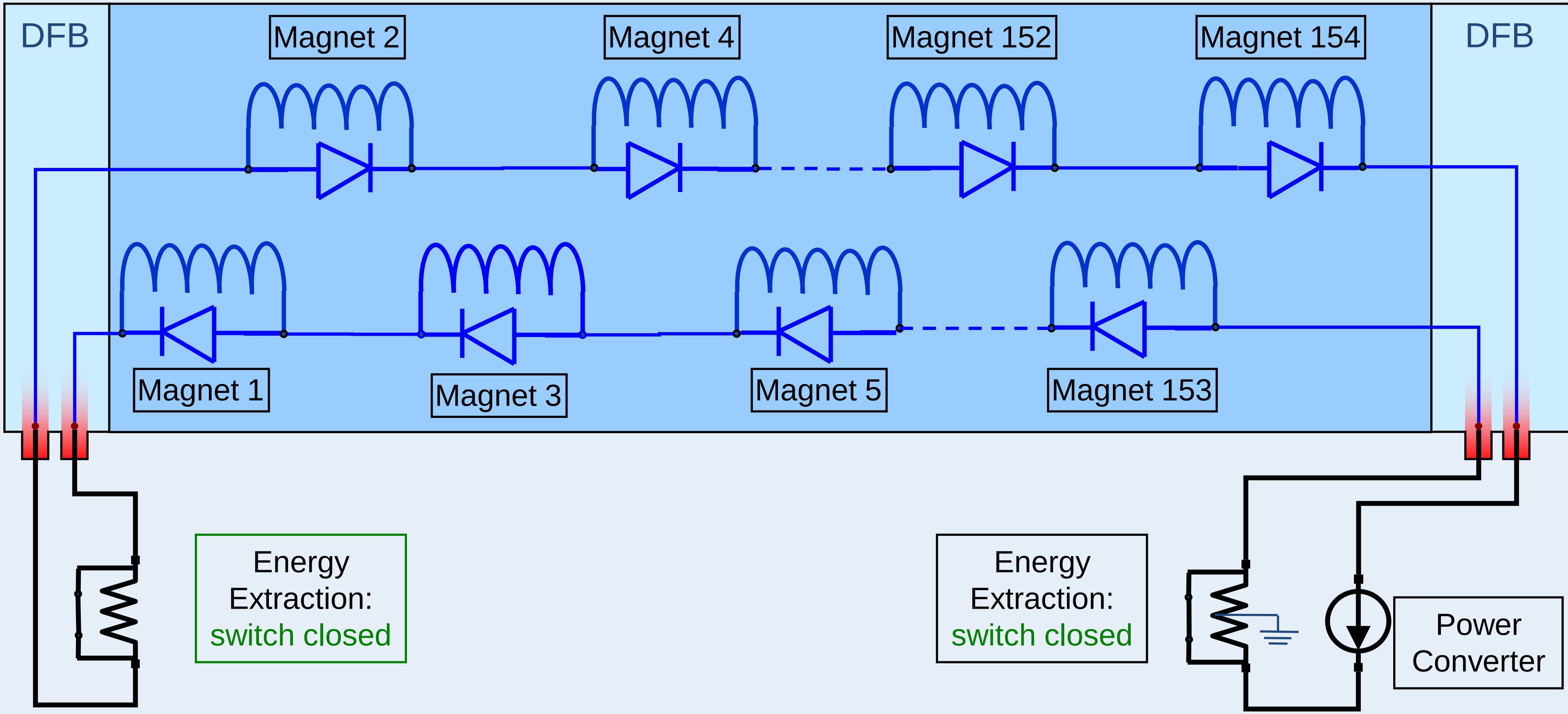
Imax = 55 A

L=7 H

E-stored=9.2 kJ

No energy extraction

LHC Main Dipole Circuit



- LHC **powered in eight sectors**, each with 154 dipole magnets (1232 dipoles)
- Time for the energy **ramp** is about **20 min** (Energy from the grid)
- Time for discharge is about **the same** (Energy back to the grid)

Current Leads

Current leads

- Current leads are usually the dominant source of heat leaking into the magnet cryostat

- Objective of a current lead design: minimisation of the heat leak introduced by the transmission of a given current

- Sources of heat: thermal conduction from room temperature to cryogenic environment and ohmic loss

Thermal Conductivity in Metals

- In metals, the principle thermal conduction mechanisms are electronic and lattice

$$K = K_l + K_e$$

Kl = lattice conductivity

Ke = electron conductivity

- In pure metals, electron contribution is dominant

$$K_e = (1/3)\ Cv\ \langle v \rangle\ l$$

Cv = eletronic specific heat per unit volume

l = mean free path of electrons

<v> = velocity of electrons

Thermal Conductivity in Metals

K_e = (1/3) Cv <v> l

<v> = 2 $(E_F/m)^{1/2}$

l = <v> τ

$$c_V = \frac{\pi^2 n k_B{}^2 T}{2E_F}$$

<v> = average speed

m = mass of electron

k_B = Boltzmann constant

n = number of electrons per specific volume

τ = mean free time

T = absolute temperature

E_F = Fermi Energy

$$k_e = \frac{\pi^2 n k_B^2 T \tau}{3m}$$

Wiedemann-Franz Law

- Free electrons also conduct electricity → in metals, high thermal conductivity gives low electrical resistivity

$$\frac{\kappa}{\sigma} = \frac{\pi^2 n k_B{}^2 T \tau / 3m}{n e^2 \tau / m} = \frac{\pi^2}{3} \left(\frac{k_B}{e}\right)^2 T.$$

$\sigma = 1/\rho$

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2}{3} \left(\frac{k_B}{e}\right)^2 = 2.45 \times 10^{-8}\, \mathrm{W}\, \Omega\, \mathrm{K}^{-2}.$$

$k\, \rho = L\, T$

L= Lorenz number

Wiedemann-Franz Law

- Wiedemann and Franz (1853): ratio of thermal to electrical conductivity has about the same value for different metals at the same temperature

$$k\,\rho = L\,T$$

- Lorentz (1872): the proportionality constant is $L = 2.45 \cdot 10^{-8}\ W \cdot \Omega \cdot K^{-2}$

NB We did not consider lattice thermal conduction

Optimization of a Current Lead

$k\,\rho = L\,T$ $L = 2.45 \cdot 10^{-8}\ W \cdot \Omega \cdot K^{-2}$

A good electrical conductor has high thermal conductivity

- There is a minimum heat leak associated with the transmission of a given current
- This minimum heat leak is independent on conductor's properties

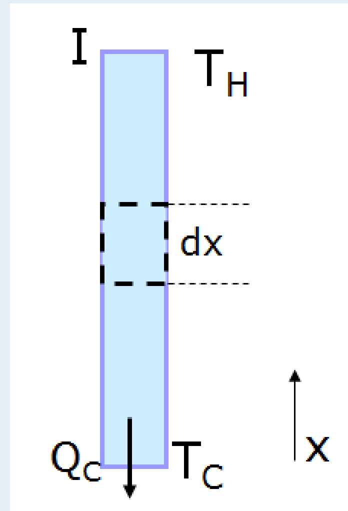
Conduction-Cooled Current Lead

$$\frac{d}{dx}\left(k(T)A\frac{dT}{dx}\right)+\rho(T)\frac{1}{A}I^2=0$$

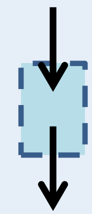
$$Q(T)=\left(k(T)A\frac{dT}{dx}\right)$$

$$\rho(T)=\frac{L_0 T}{k(T)}$$

$$Q_C=\sqrt{Q_H^2+L_0 I^2(T_H^2-T_C^2)}$$



$$Q(T)=\left(k(T)A\frac{dT}{dx}\right)$$



$$\rho(T)\frac{dx}{A}I^2$$

$$\left(k(T)A\frac{dT}{dx}\right)+\frac{d}{dx}\left(k(T)A\frac{dT}{dx}\right)dx$$

$Q_{C,min}$ ⇨ $Q_H=0$

$$Q_{C,min}=\sqrt{L_0 I^2(T_H^2-T_C^2)}$$

$$Q(T)=\sqrt{Q_C^2-L_0 I^2(T^2-T_C^2)}$$

$$\left(\frac{L}{A}\right)_{opt}=\int_{T_C}^{T_H}\frac{K(T)}{\sqrt{Q_{C,min}^2-L_0 I^2(T^2-T_C^2)}}$$

If $T_H=300\ K$ and $T_C=4.2\ K$

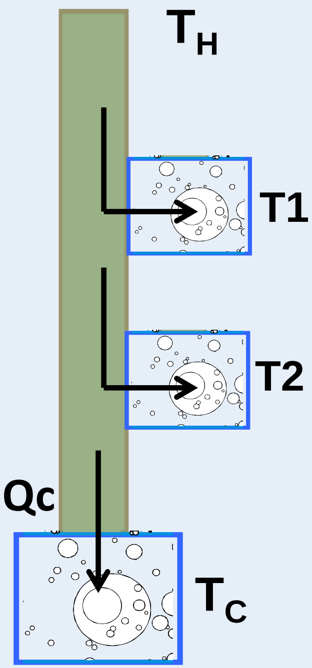
$$\frac{Q_{C,min}}{I}=47\frac{W}{kA}$$

1W @ 4.2 K → Wmin = 70 W

$\left(\frac{IL}{A}\right)_{opt}$ Shape Factor

Conduction-Cooled Current Lead

Multiple-stage cooling



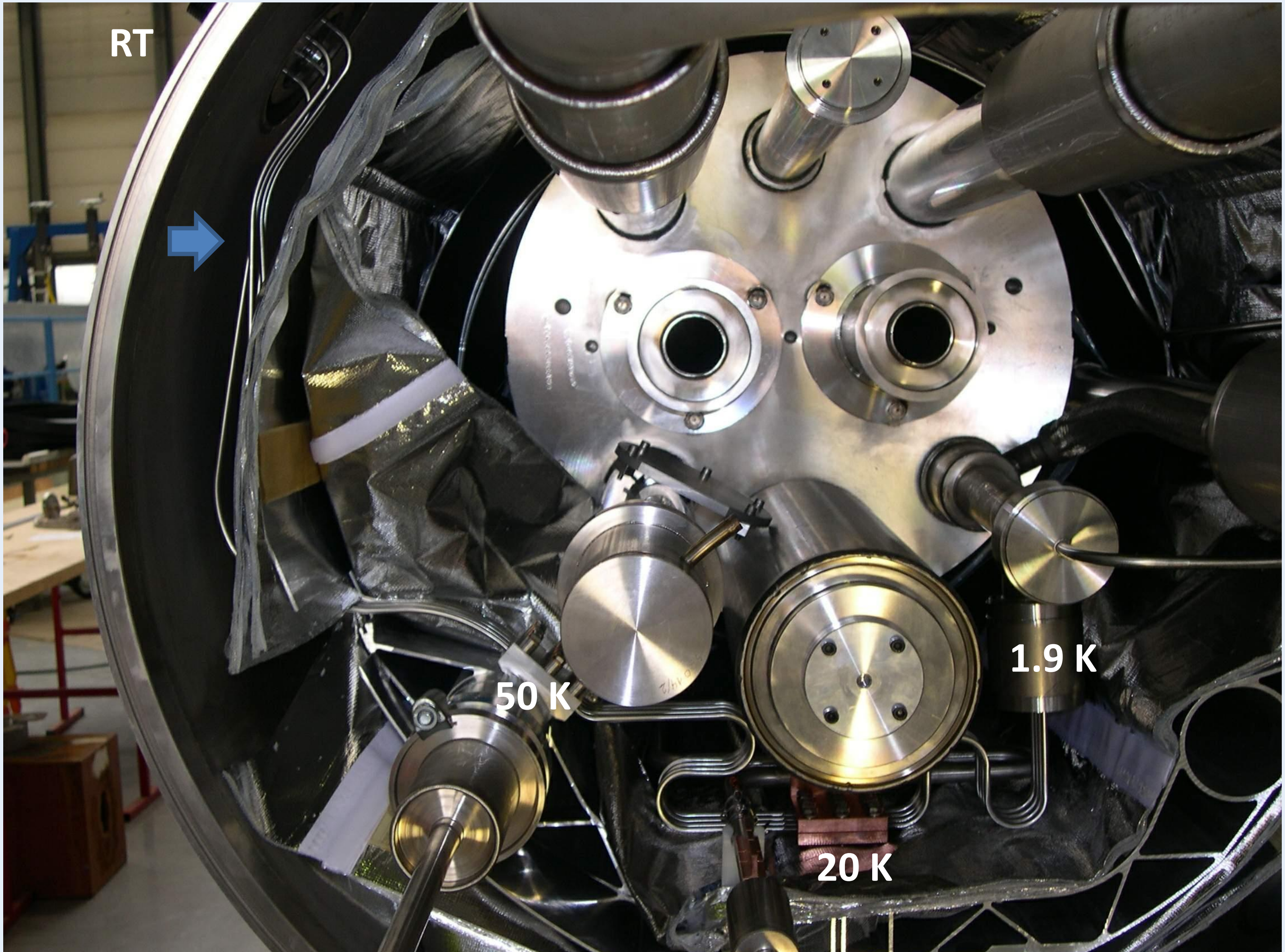
Cryo-cooler
A stand-alone cooler providing intermediate temperatures

or

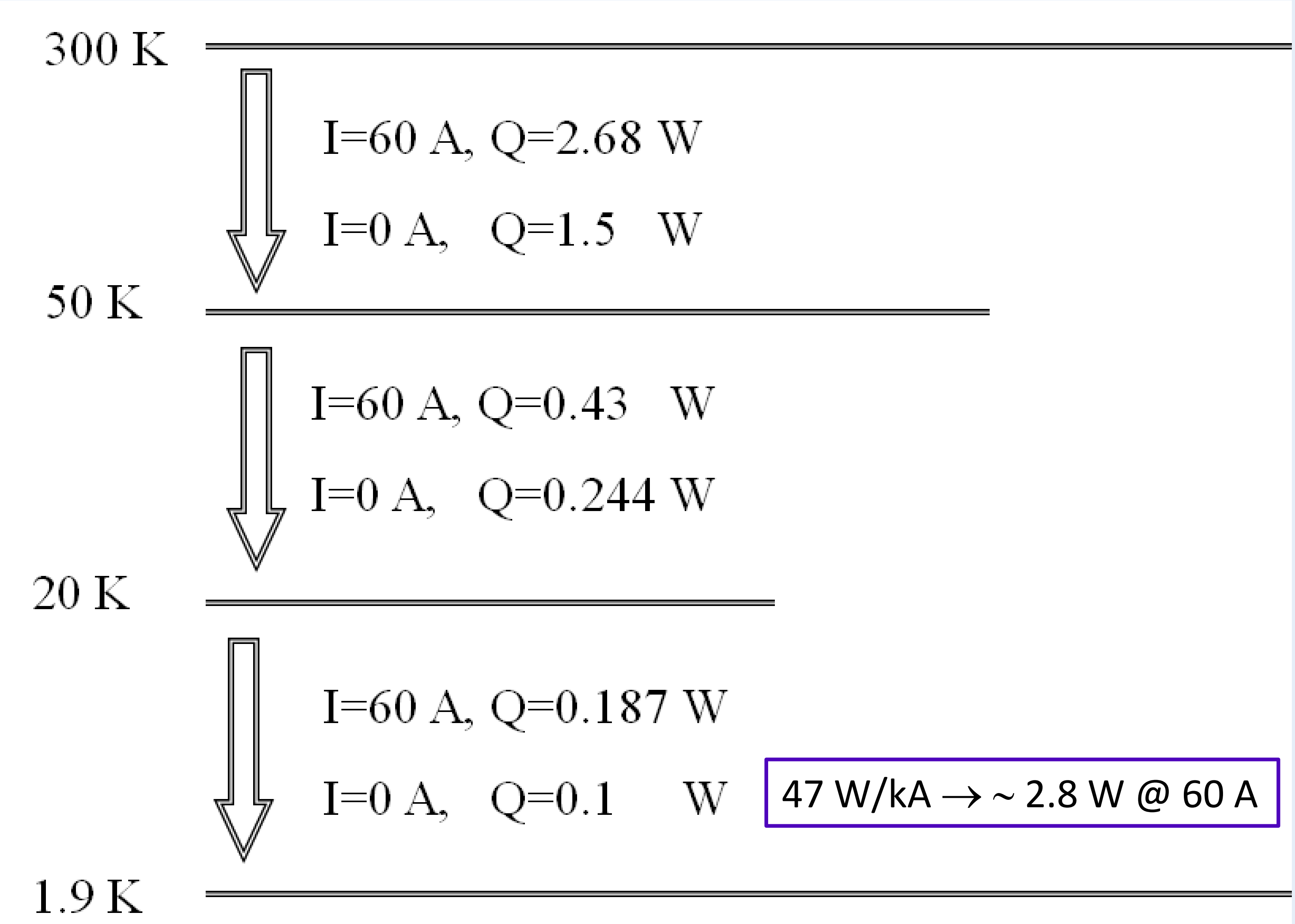
Heat exchangers using cryogen at the temperatures available in the cryogenic system

$$Q_{C,min} = \sqrt{L_0 I^2 (T_2^2 - T_C^2)}$$

LHC Dipole Corrector Current Leads



LHC Dipole Corrector Current Leads

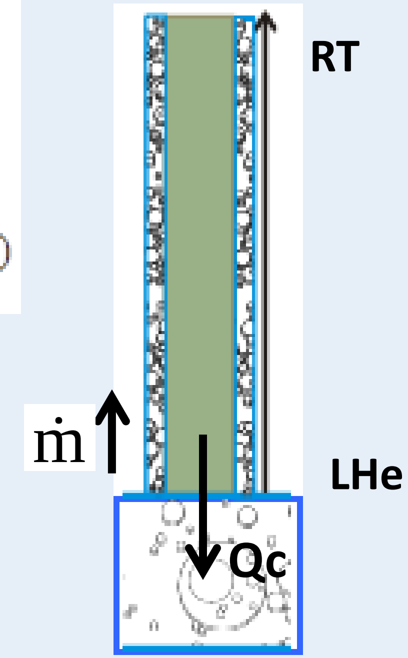


47 W/kA → ~ 2.8 W @ 60 A

Self-cooled Current Lead

$$c^{C}(T)\,\nu^{C}(T)A^{C}\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(k^{C}(T)A^{C}\frac{\partial T}{\partial x}\right)+\frac{\rho^{C}(T)I^{2}}{A^{C}}-Ph(T)(T-\theta)$$

$$c_{p}^{He}(\vartheta)\,\nu^{He}(T)A^{He}\frac{\partial \vartheta}{\partial t}=\frac{\partial}{\partial x}\left(k^{He}(T)A^{He}\frac{\partial q}{\partial x}\right)-\dot{m}c_{p}^{He}(\theta)\frac{\partial \theta}{\partial x}+Ph(T)(T-\theta)$$



In steady state conditions and neglecting k^{He}:

$$\frac{d}{dx}\left(k^{C}(T)A^{C}\frac{\partial T}{\partial x}\right)=-\frac{\rho^{C}(T)I^{2}}{A^{C}}+Ph(T)(T-\theta)$$

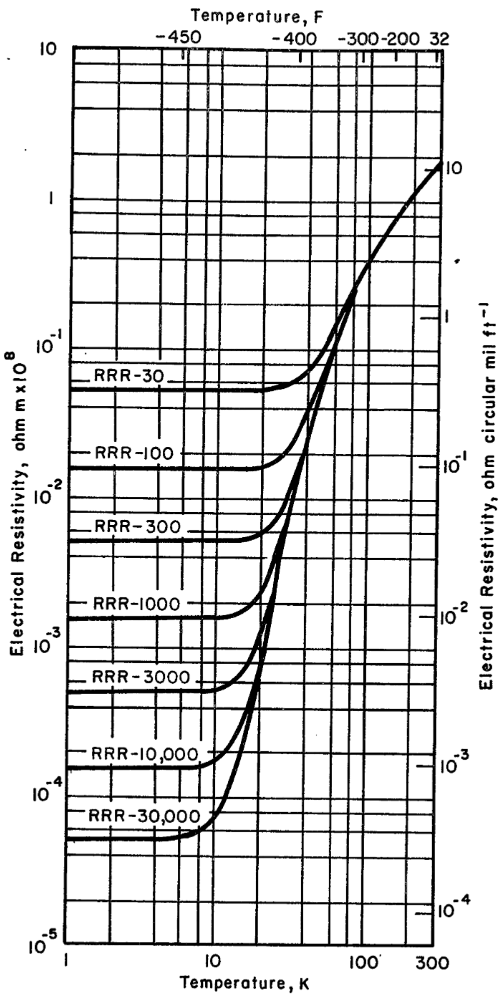
$$\dot{m}c_{p}^{He}(\theta)\frac{d\theta}{dx}=Ph(T)(T-\theta)$$

$$\dot{m}=\frac{kA^{C}}{c_{L}^{He}}\left.\frac{dT}{dx}\right|_{x=0}$$

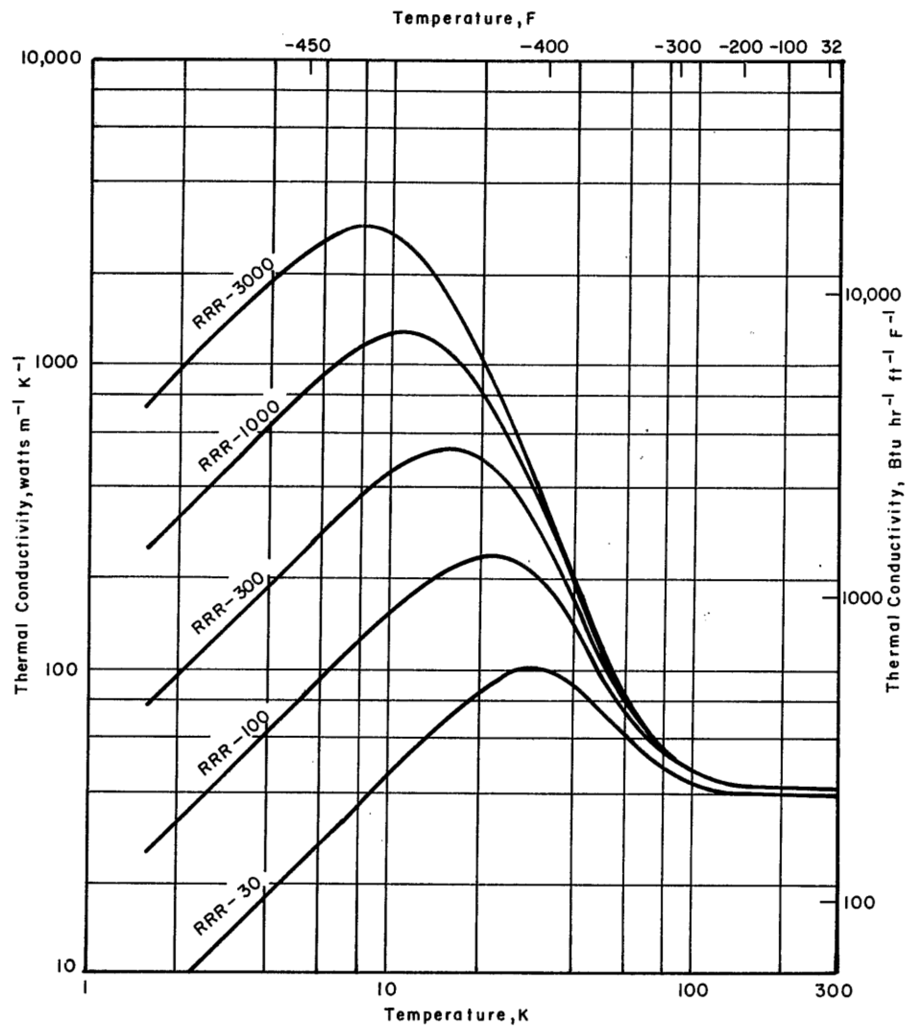
Self-cooling conditions

$$Qc=\dot{m}C_{L}$$

Material properties



ELECTRICAL RESISTIVITY VERSUS TEMPERATURE FOR COPPER



THERMAL CONDUCTIVITY VERSUS TEMPERATURE FOR COPPER

Temperature Dependence of Material Properties

Self-Cooled Current Lead

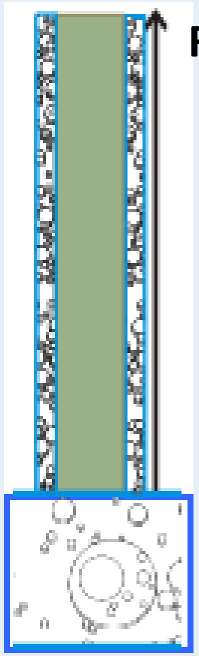
$h \to \infty, \; T = \theta$

$$\frac{d}{dx}\left(k^C(T)A^C\frac{dT}{dx}\right) = -\frac{\rho^C(T)I^2}{A^C} + \dot{m}c_p(T)\frac{dT}{dx}$$

$$Qc = \dot{m}C_L$$

See "Superconducting Magnets", M. Wilson, Chapter 11

$$\left(\frac{dT}{dx}\right)_{x=L} = 0$$



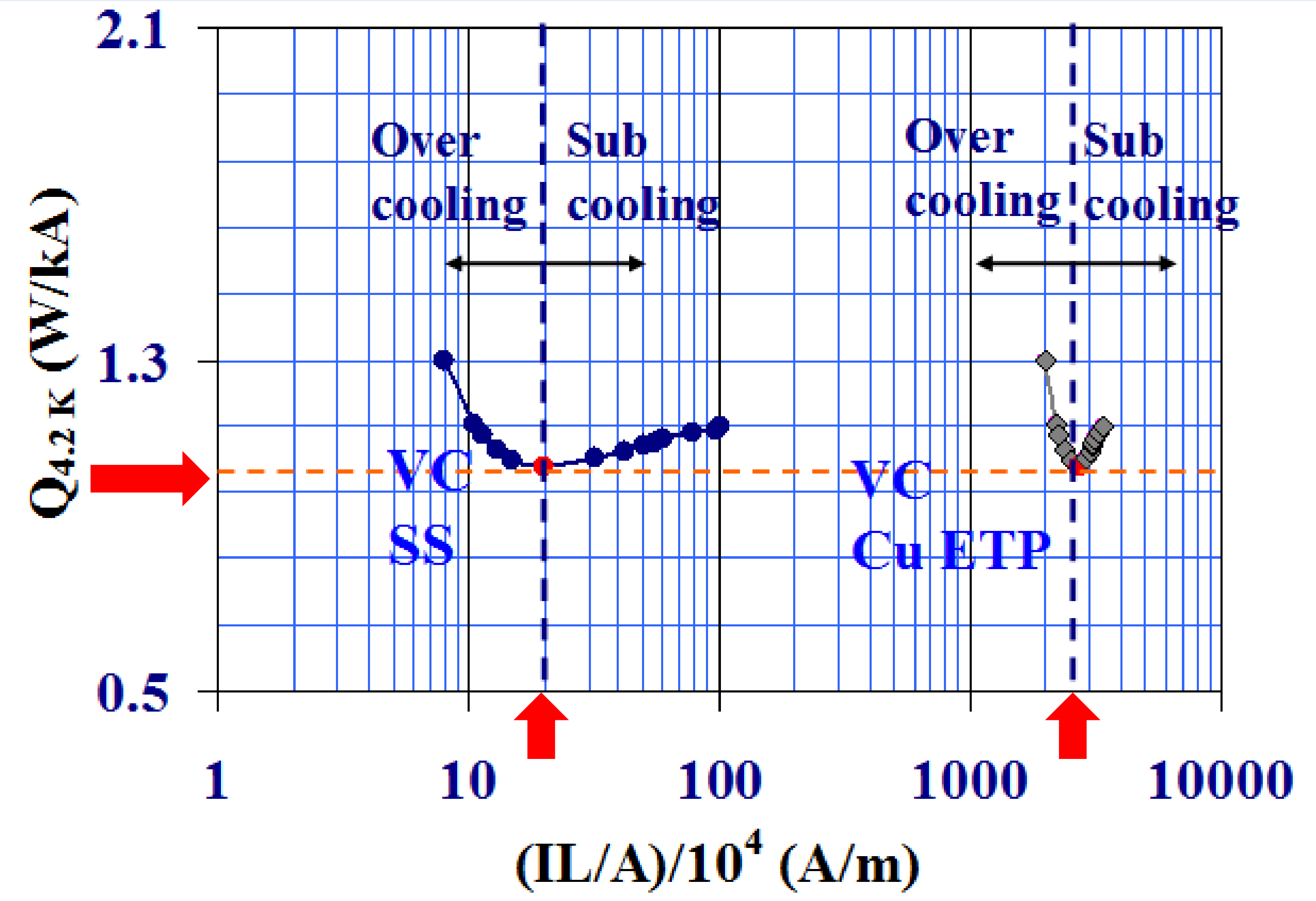
$Q_{C,min}$(LHe) = 1.04 W/kA → $I\frac{L}{A_C}$ **Optimum Shape Factor**

- **$Q_{C,min}$(4.2K) is independent on material properties**

BUT

- **The optimum geometry , i.e. the shape factor, depends on material properties**

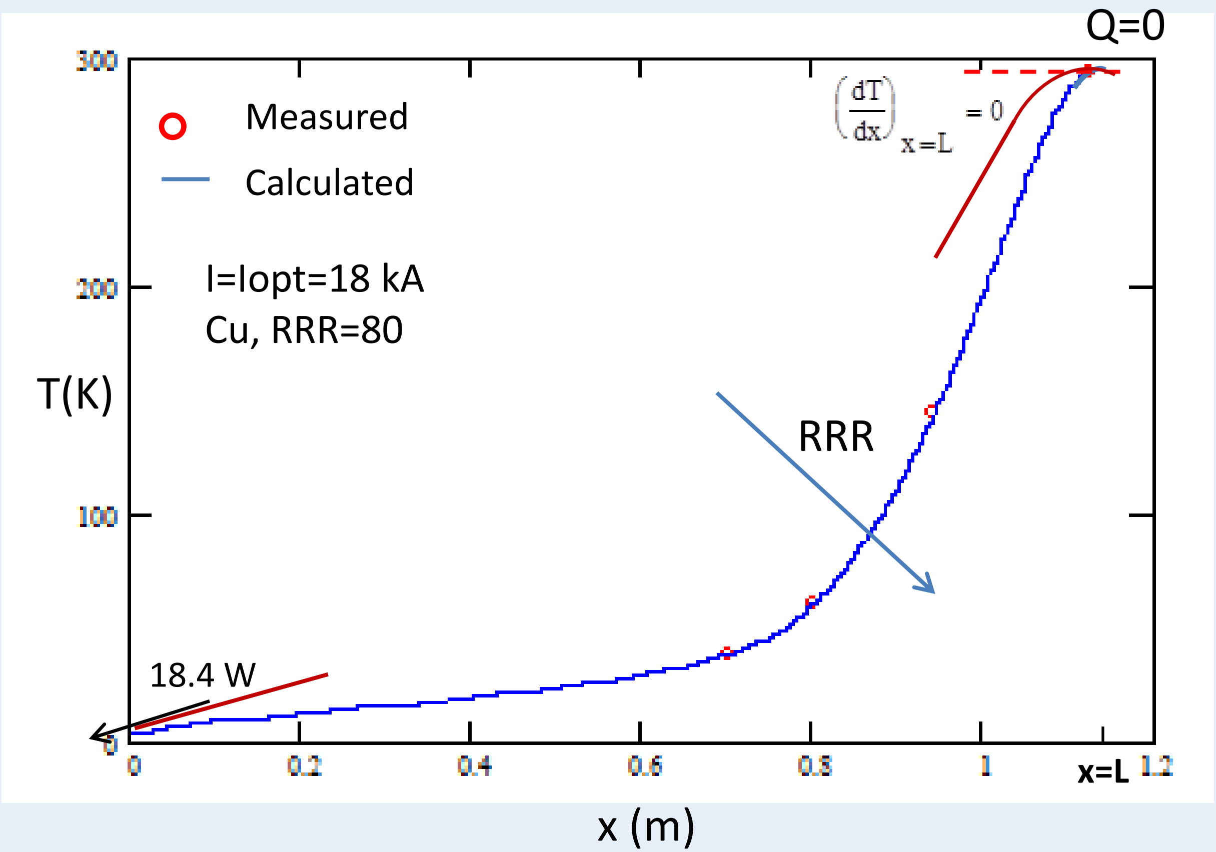
Conventional self-cooled leads



SS=Stainless Steel

Cu ETP=Electrolytic-Tough-Pitch Copper

Conventional self-cooled lead

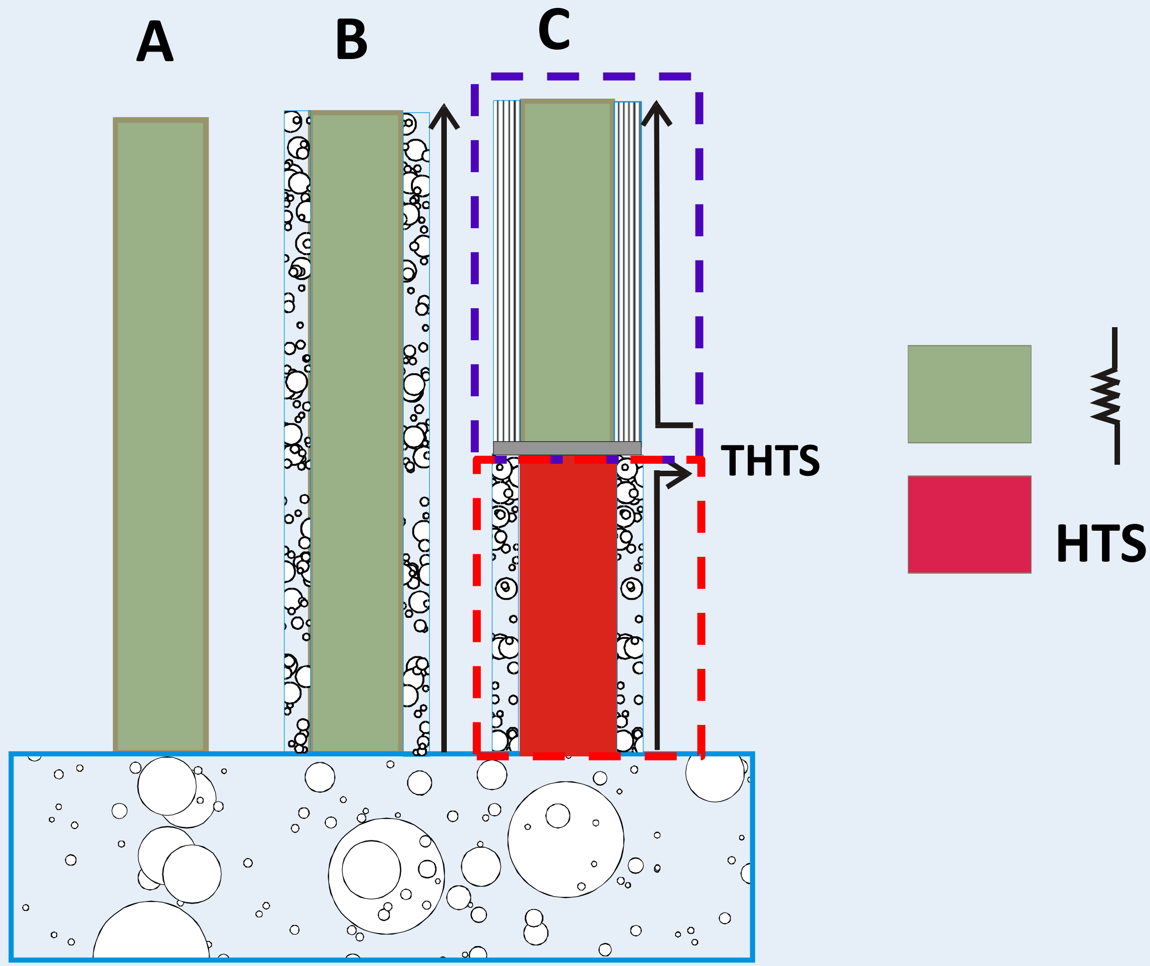


- **The temperature profile depends on material properties**
- **The thermal performance in stand-by conditions (0 A) depends on material properties ($k^C(T)$, with A and L defined)**

Conventional vs HTS leads

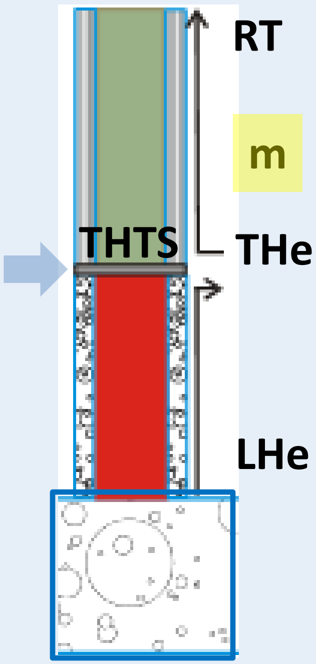
Room temperature

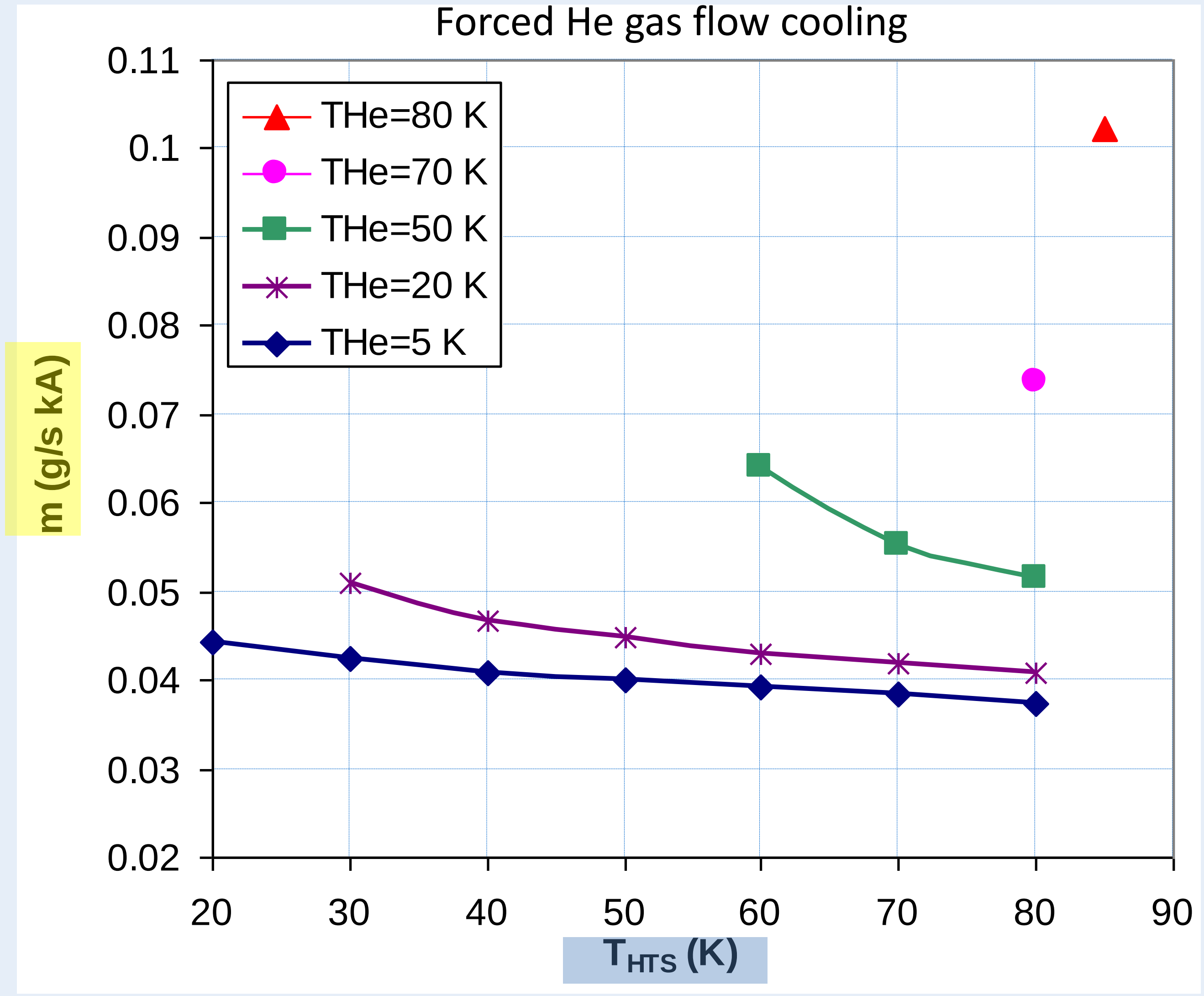
LHe temperature



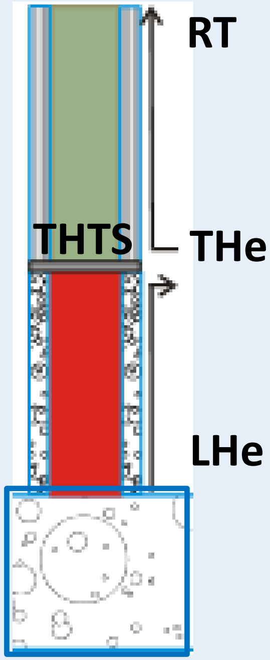
QA = 47 W/kA	QB = 1.04 W/kA	QC = ?

HTS Current Lead-Resistive Section

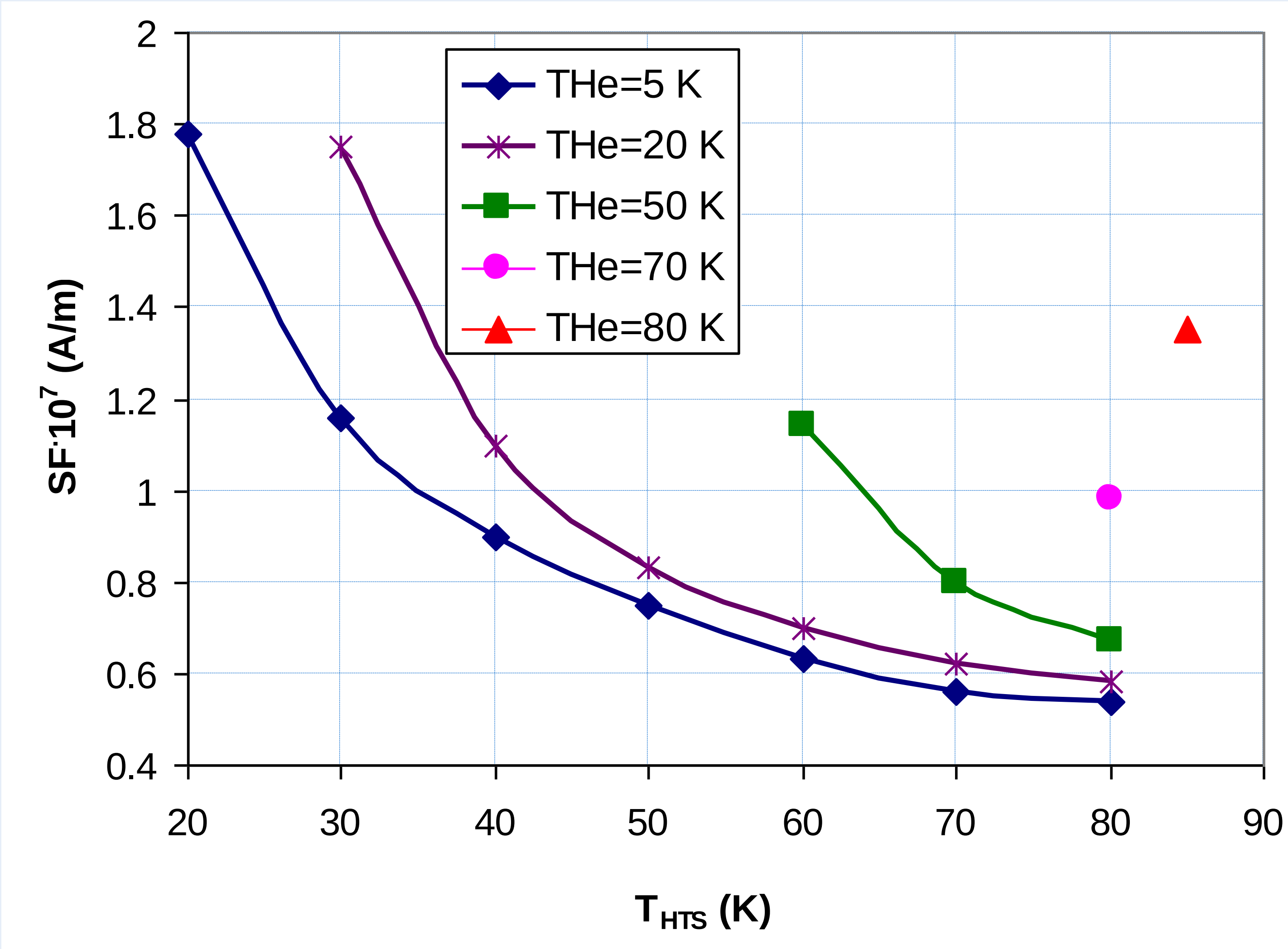




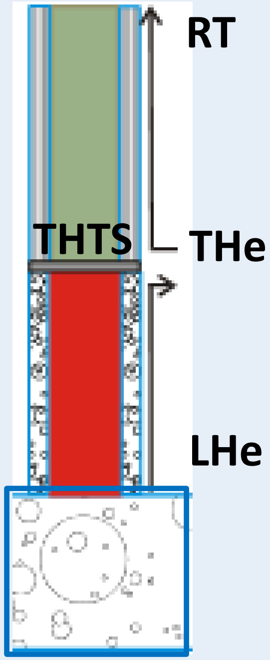
HTS Current Lead-Resistive Section



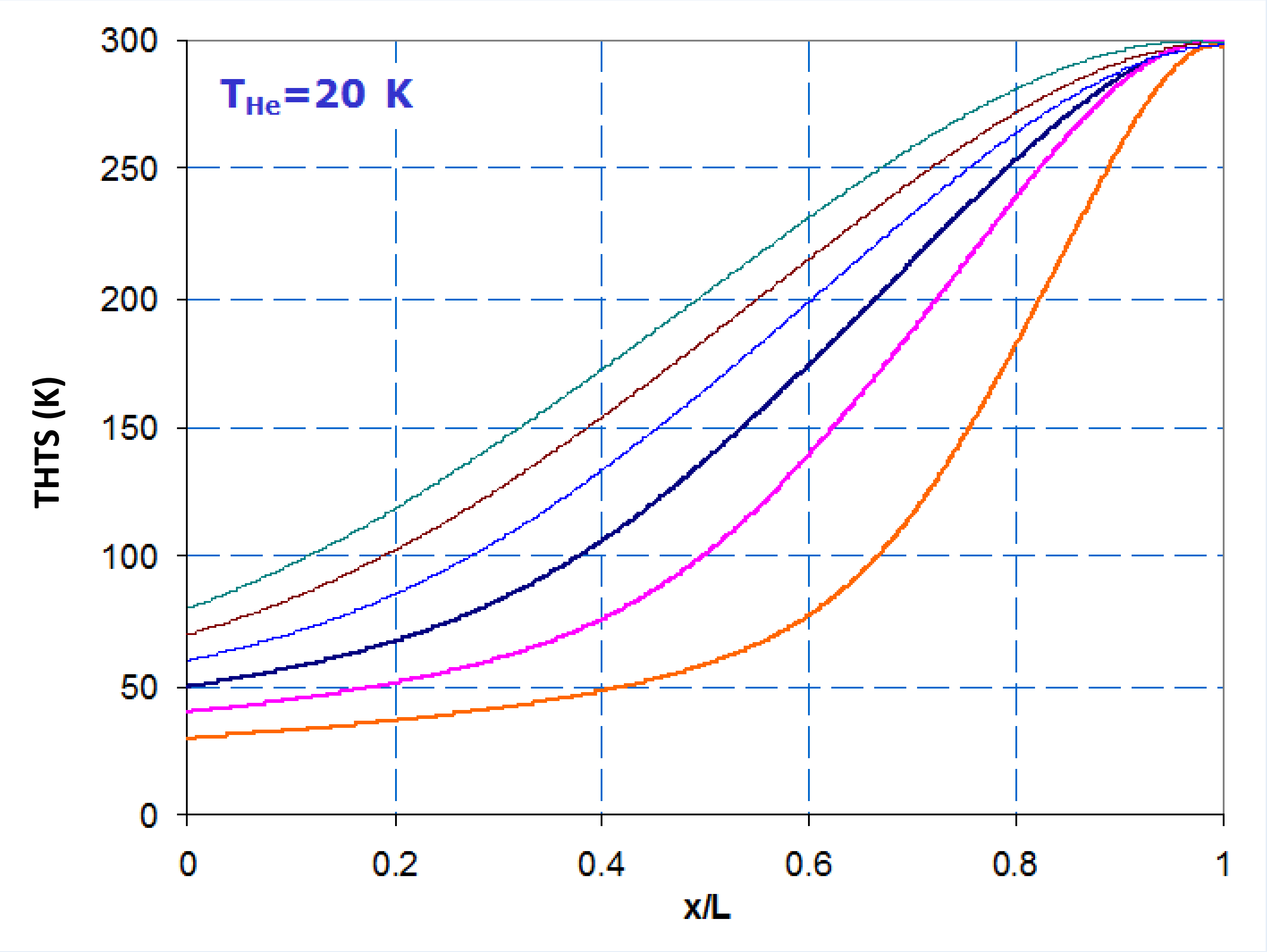
$$SF = I\frac{L}{A_C}$$



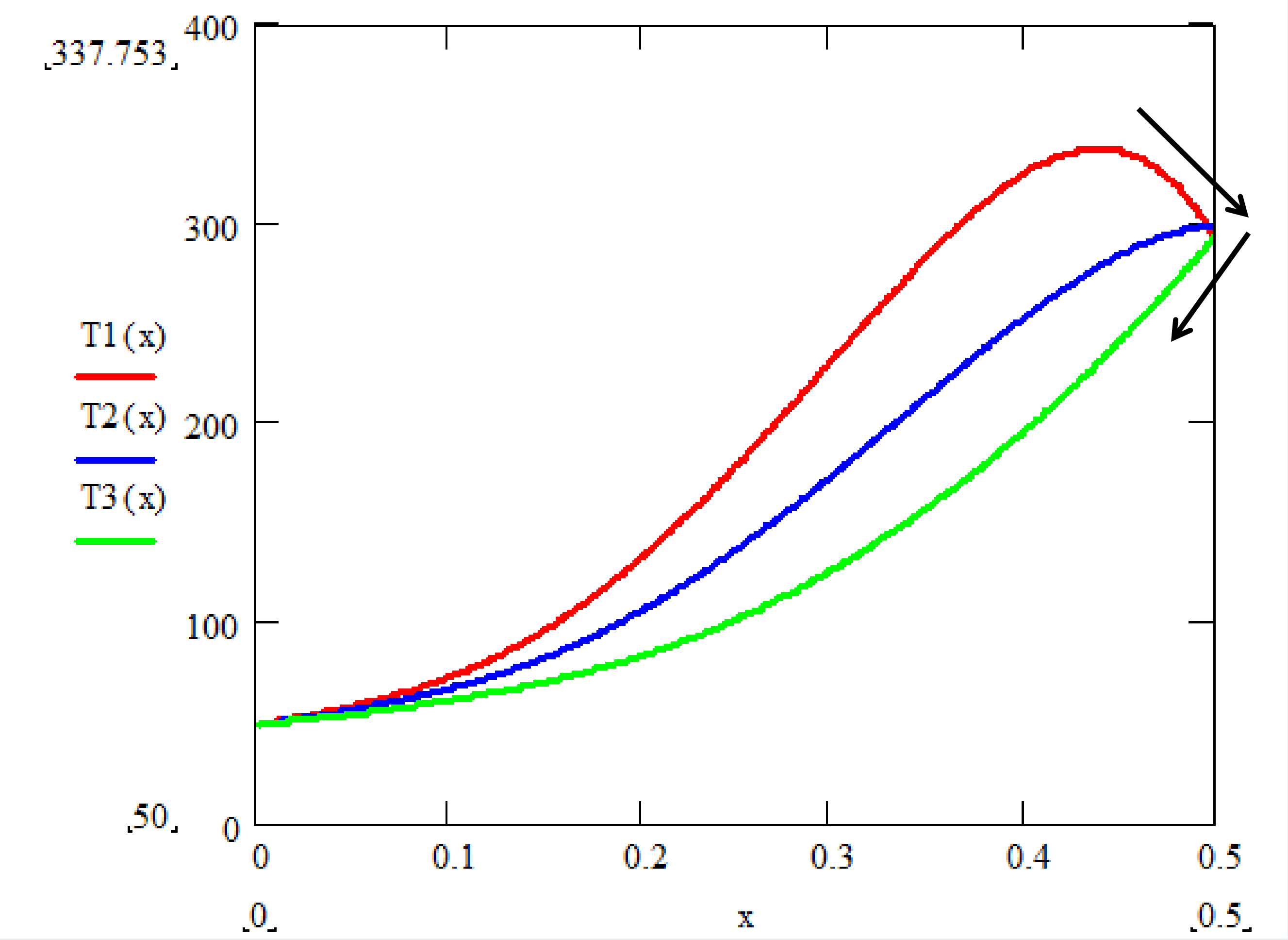
HTS Current Lead-Resistive Section



I → nominal
A → optimum



HTS Current Lead-Resistive Section

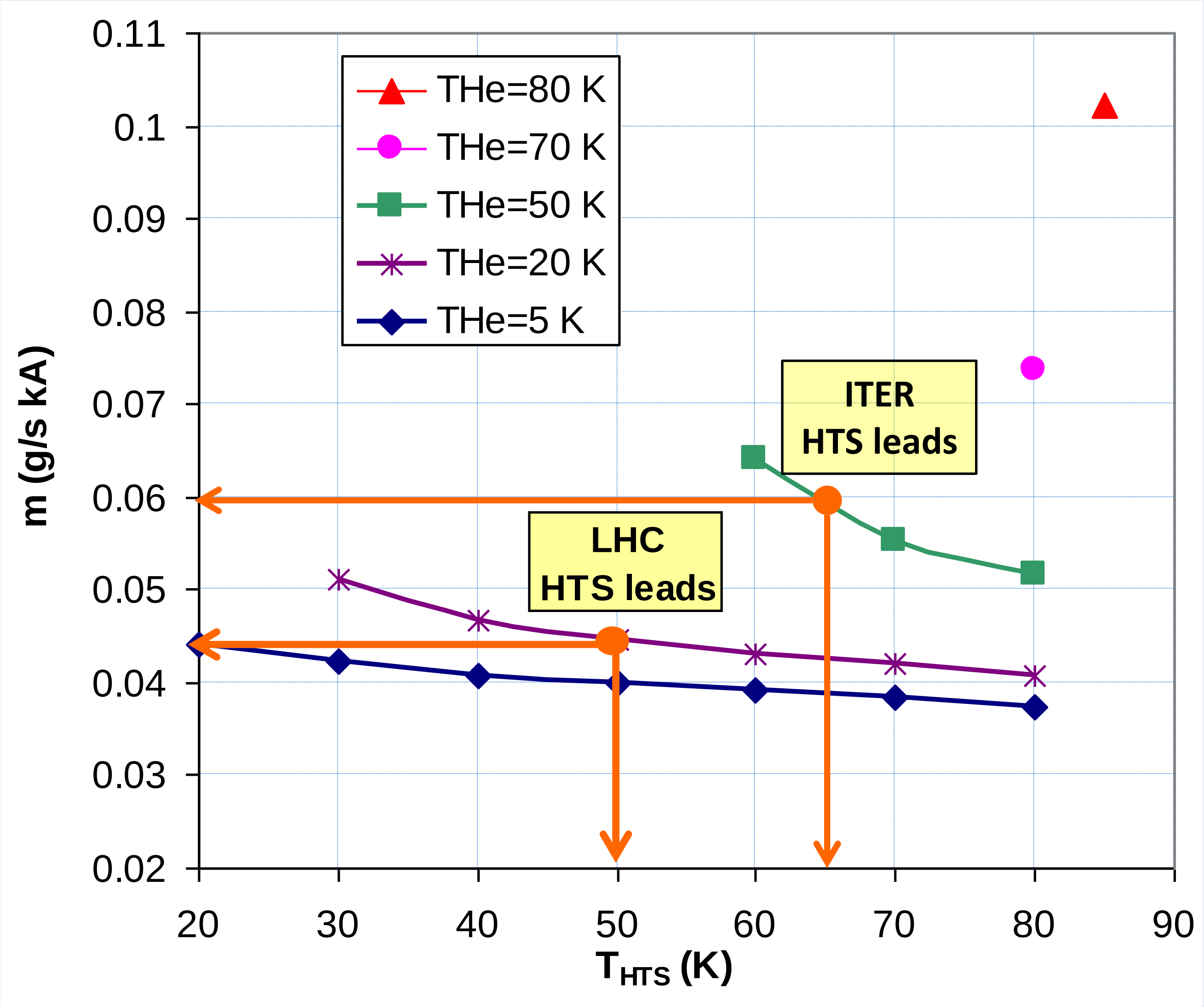


T1(x) : (IL/A) > $(IL/A)_{OPT}$ - m_{He} > $m_{He\ OPT}$

T2(x) : (IL/A) = $(IL/A)_{OPT}$ - m_{He} = $m_{He\ OPT}$

T3(x) : (IL/A) < $(IL/A)_{OPT}$ - m_{He} > $m_{He\ OPT}$

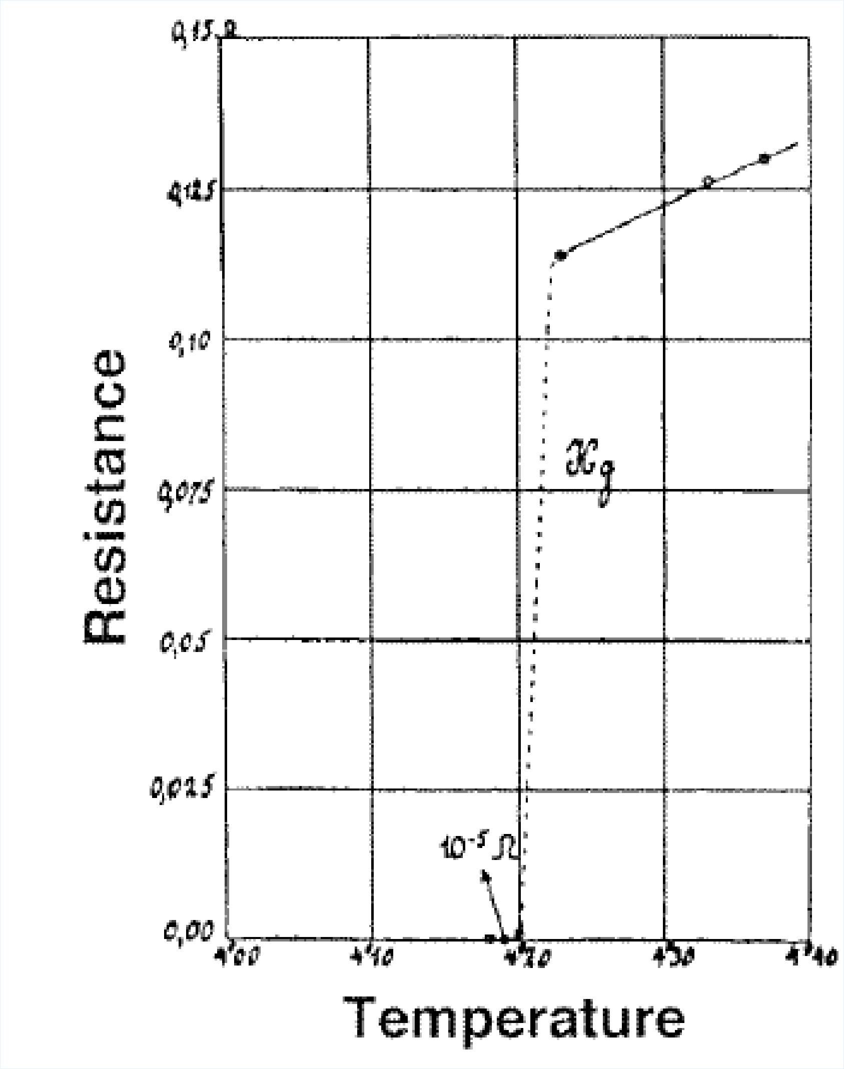
LHC and ITER HTS Current Leads



LHC: from 60 A to 13000 A

ITER: from 10000 A to 68000 A

HTS Current Lead-HTS Section



K. Onnes, 1911

$\rho \rightarrow 0$

Low K(T)

~~$K(T) \cdot \rho(T) = L \cdot T$~~

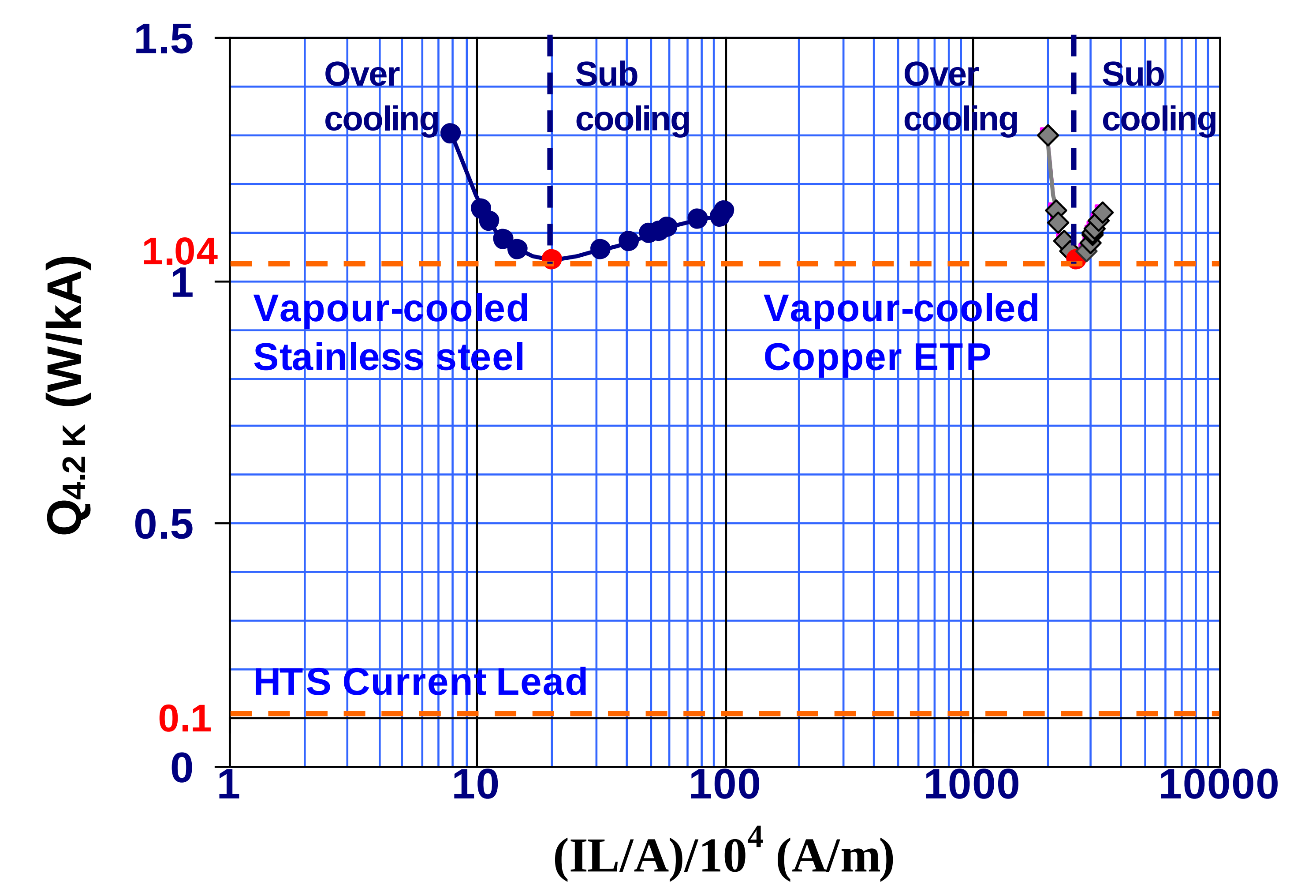
WFL abolished

High Temperature Superconductors

- BSCCO 2223, Bi-2223, Bi(2223), 1-G wire
- YBCO, Y-123, 2-G wire, REBCO (RE=Rare Earth Ba-Cu-O), Coated Conductor (thin layer of superconductor on a substrate), REBCO coated conductor

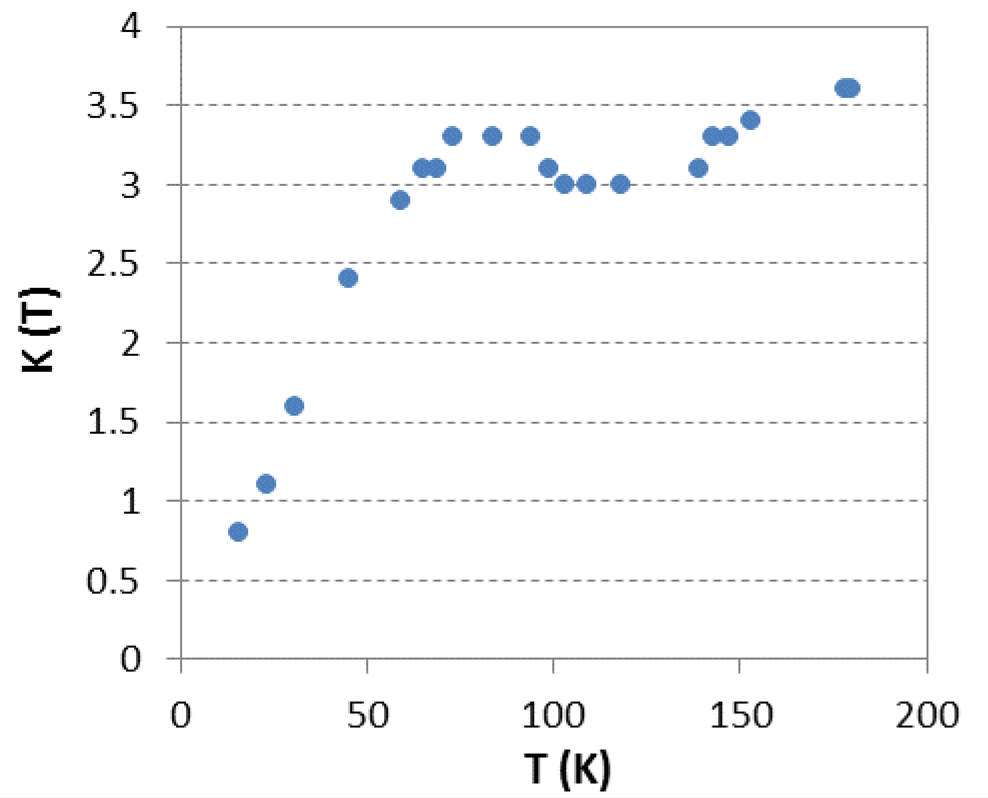
Not to get lost when you will found different acronyms in the literature

Conventional vs HTS Leads



Thermal Conductivity Bi-2223

BSCCO: Bi-Sr-Ca-Cu-O



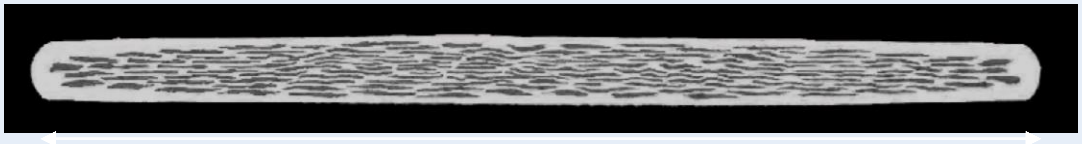
Bi-2223 sintered polycrystals

Anisotropy of K(T) because of anisotropy of crystal structure

High Temperature Superconductors

Bi-2223

~ 4 mm



~ 0.2 mm

Ag Matrix
Bi-2223 filaments

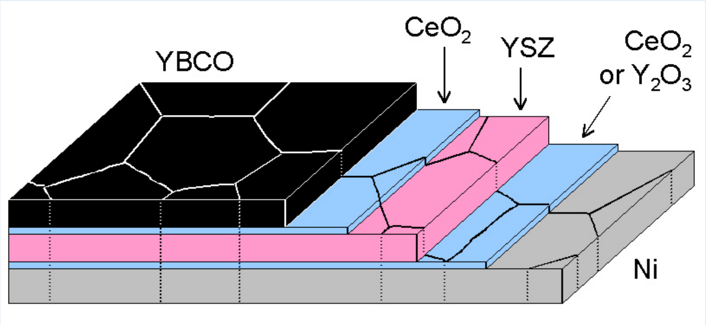
Fill factor ~ 30 %

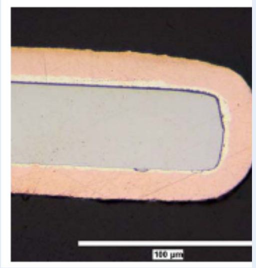
Y-123

~ 4 mm

~ 0.1 mm

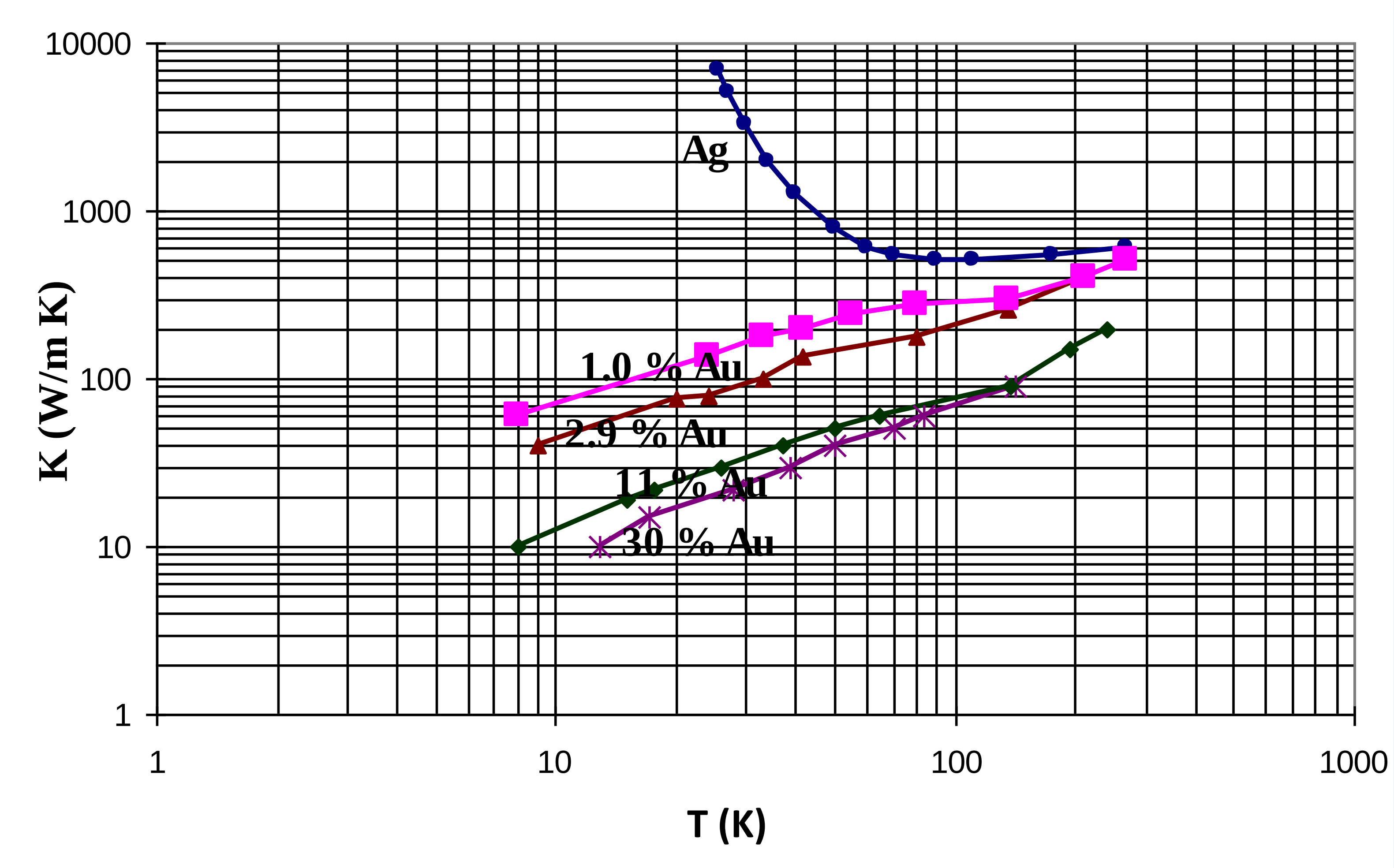
Metallic substrate
Buffer layer
Y-123 layer





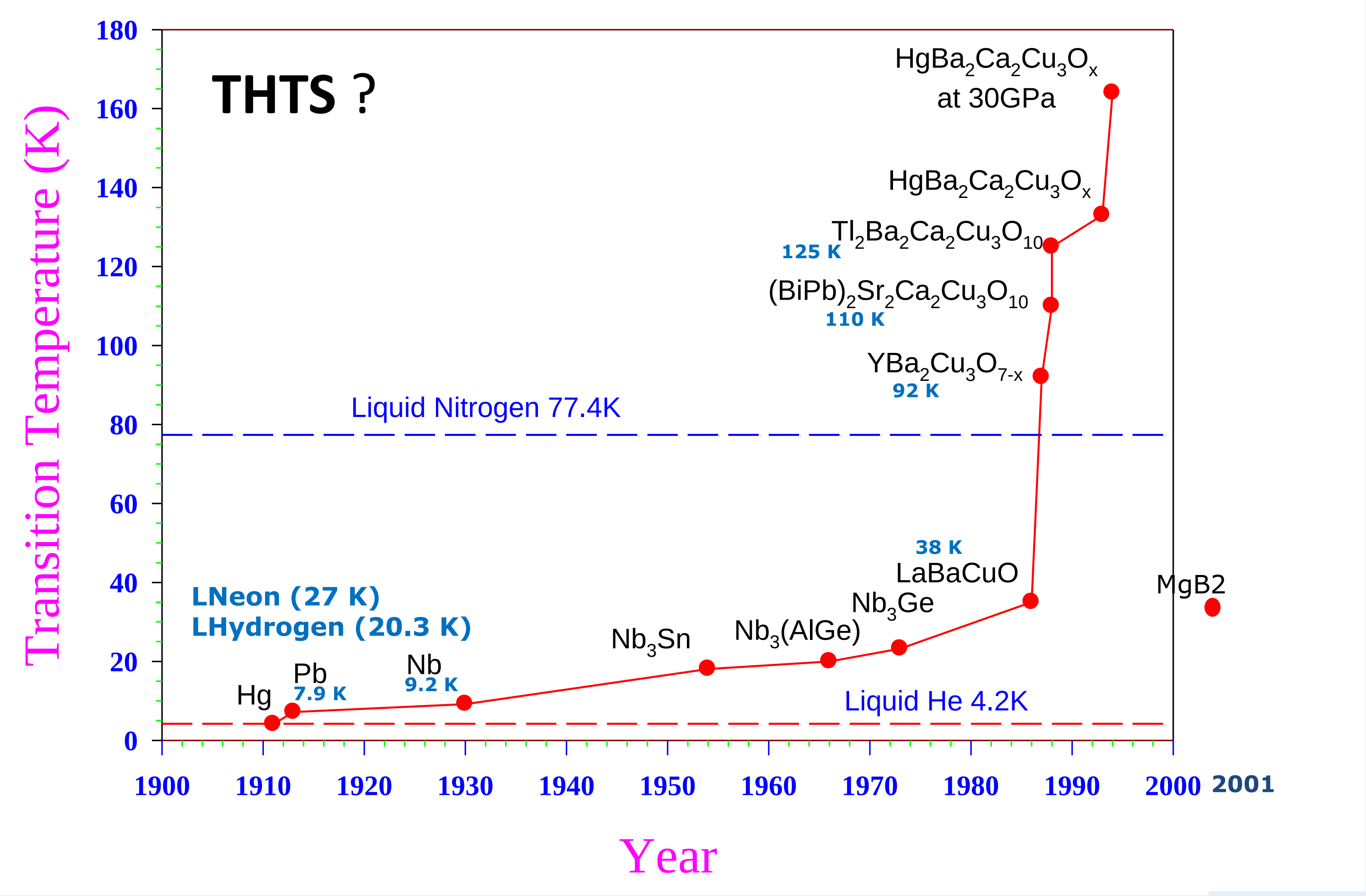
Fill factor ~ 1 % (1 to 3 μm of Y-123)

Thermal Conductivity Ag-Au Alloy

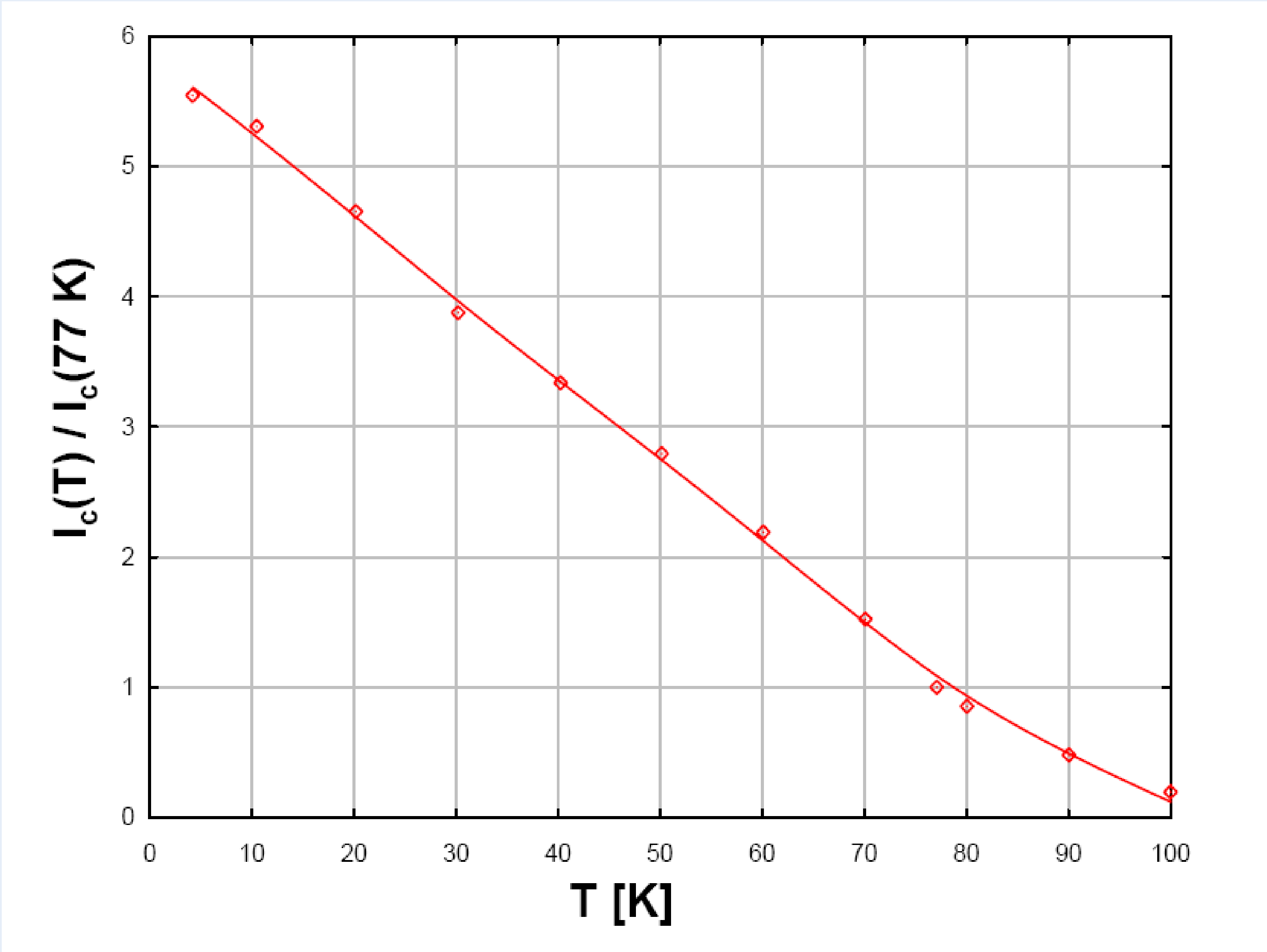


N.B. The thermal conductivity of an alloy is not a weighted average of its elemental constituents

High Temperature Superconductors

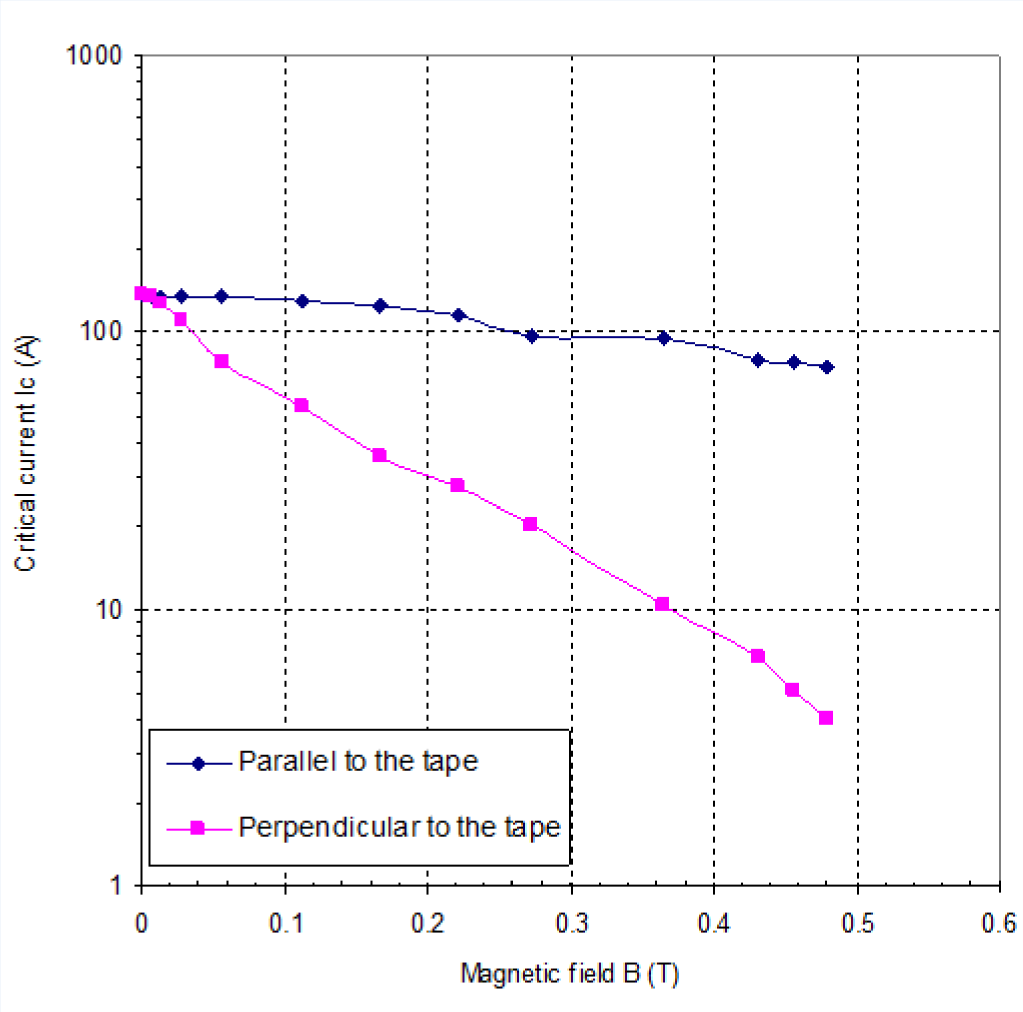


Ic(T) Dependence – Bi-2223



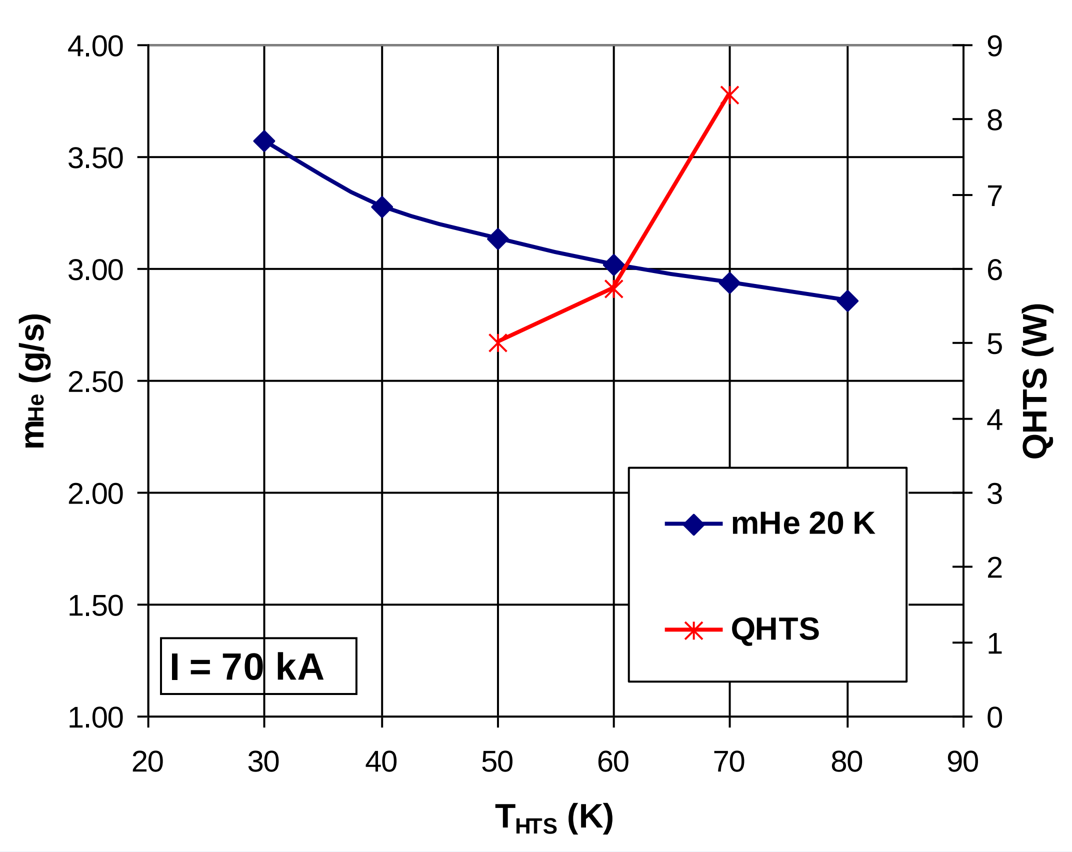
Self-field conditions

Ic(B) Dependence – Bi-2223



HTS: Highly Anisotropic Materials

Operating temperature THTS



Higher T_{HTS} → More HTS conductor → Higher heat load at 4.2 K

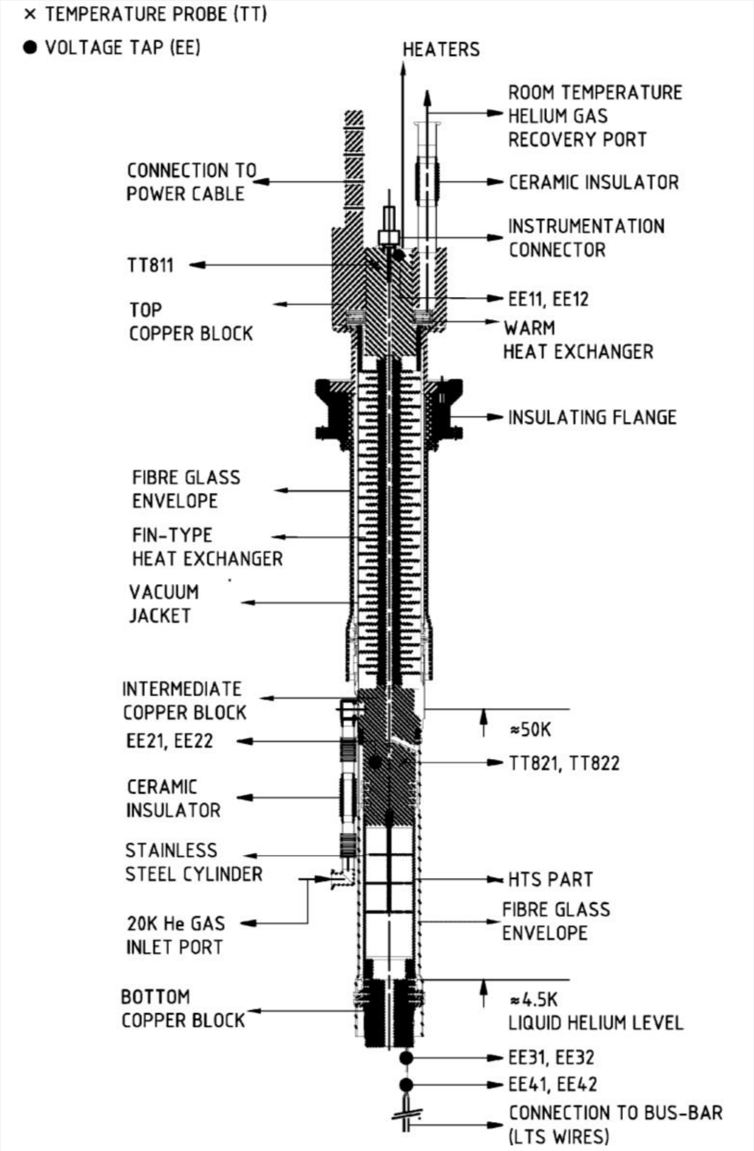
LHC Current Leads: Saving

Current = 3 MA

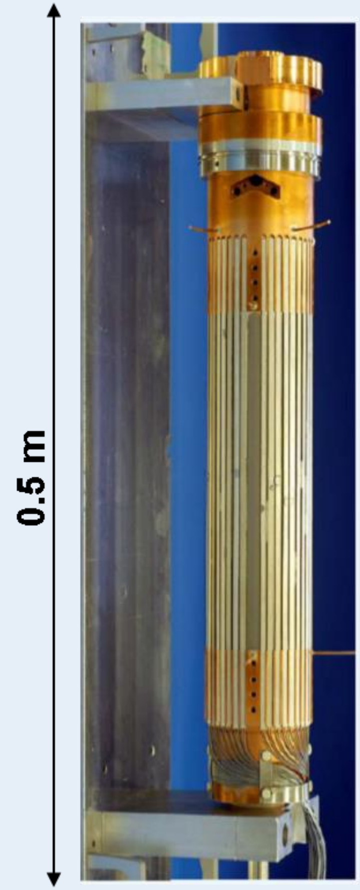
	Conventional leads	**HTS leads**
Heat load into LHe	1.1 W/kA	0.1 W/kA
Exergy consumption	430 W/kA	150 W/kA
Exergy consumption (% conv. lead)	100	35
Total exergetic power	1290 kW	450 kW

LHC HTS Current Leads

13000 A LHC Lead



HTS Part

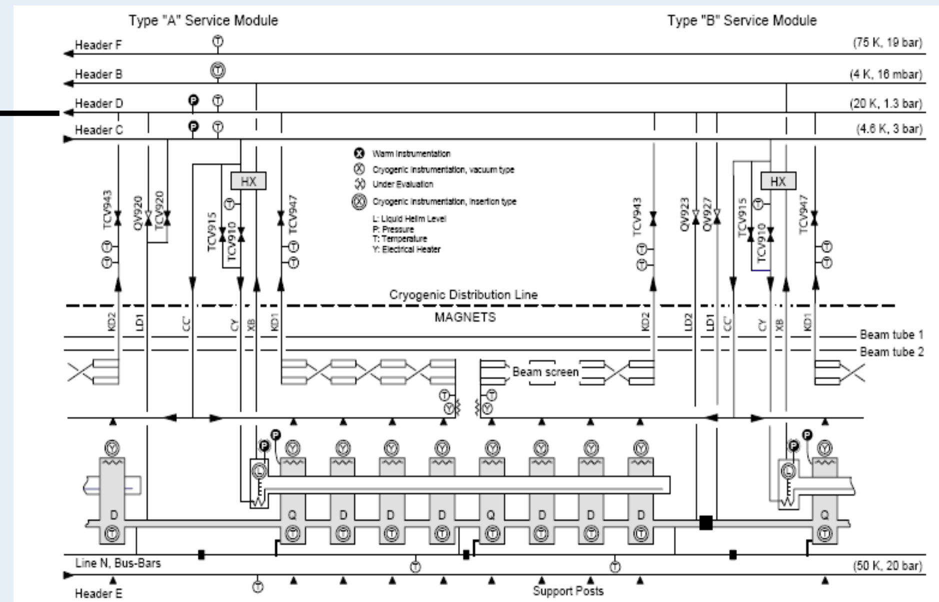


LHC HTS Current Leads

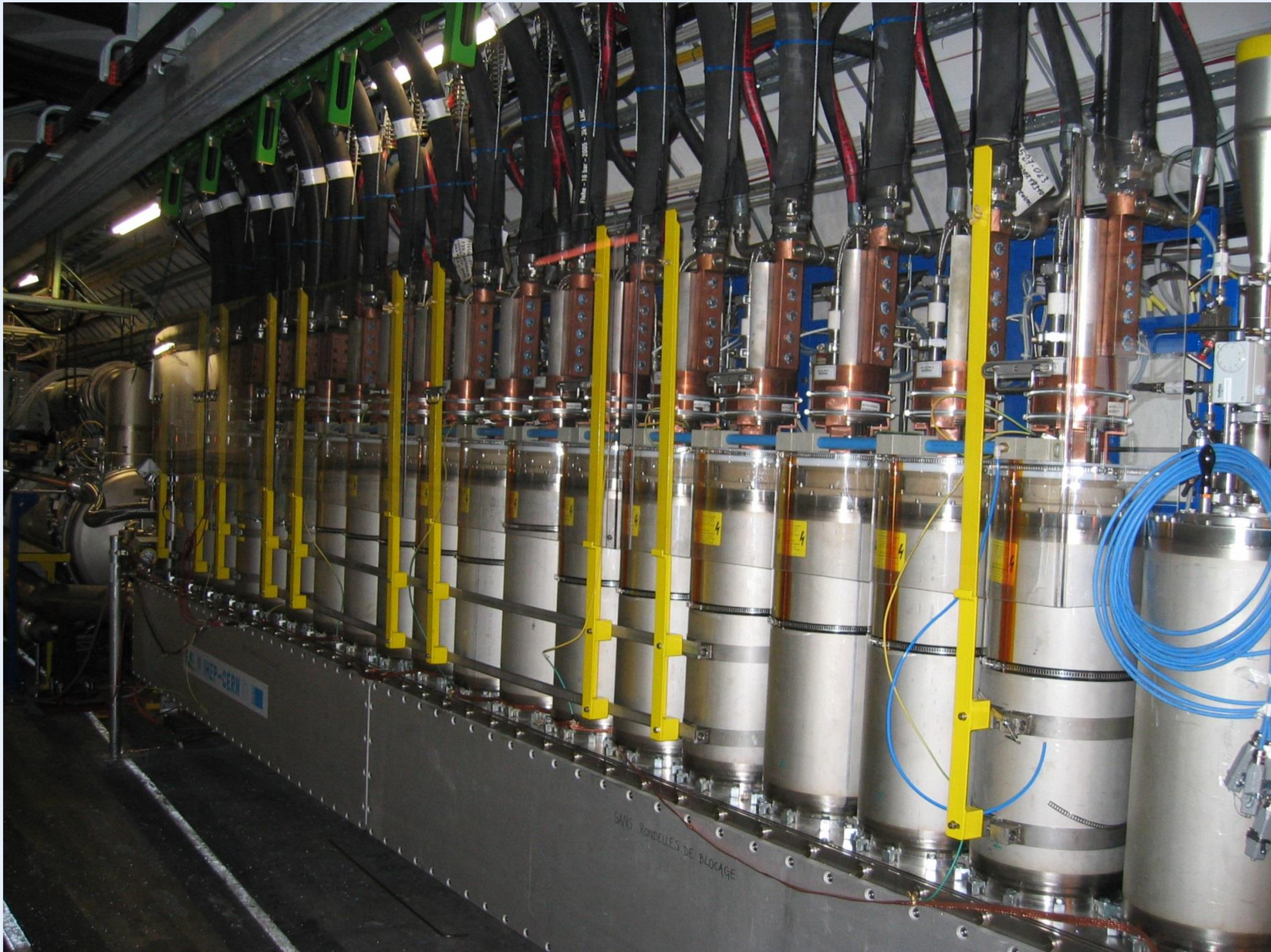
T_{HTS}=50 K

T_{He}=20 K

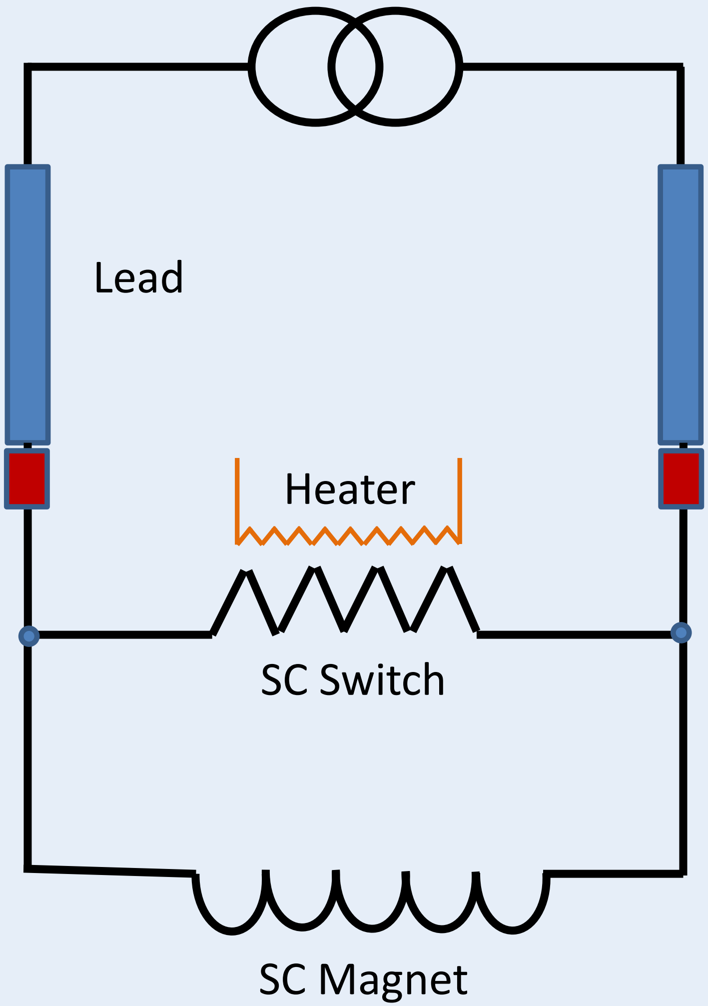
T_{He}=4.2 K



LHC HTS Current Leads in LHC Tunnel



Persistent-Current Mode Operation



- Long time operation of magnet at steady fields
- Demountable leads
- Superconducting switch
- Need of VERY low resistance joints in the superconducting circuit to guarantee uniformity of current in time – required current stability in LHC main dipole circuit ~ 1 ppm

Buses, Links and their Protection

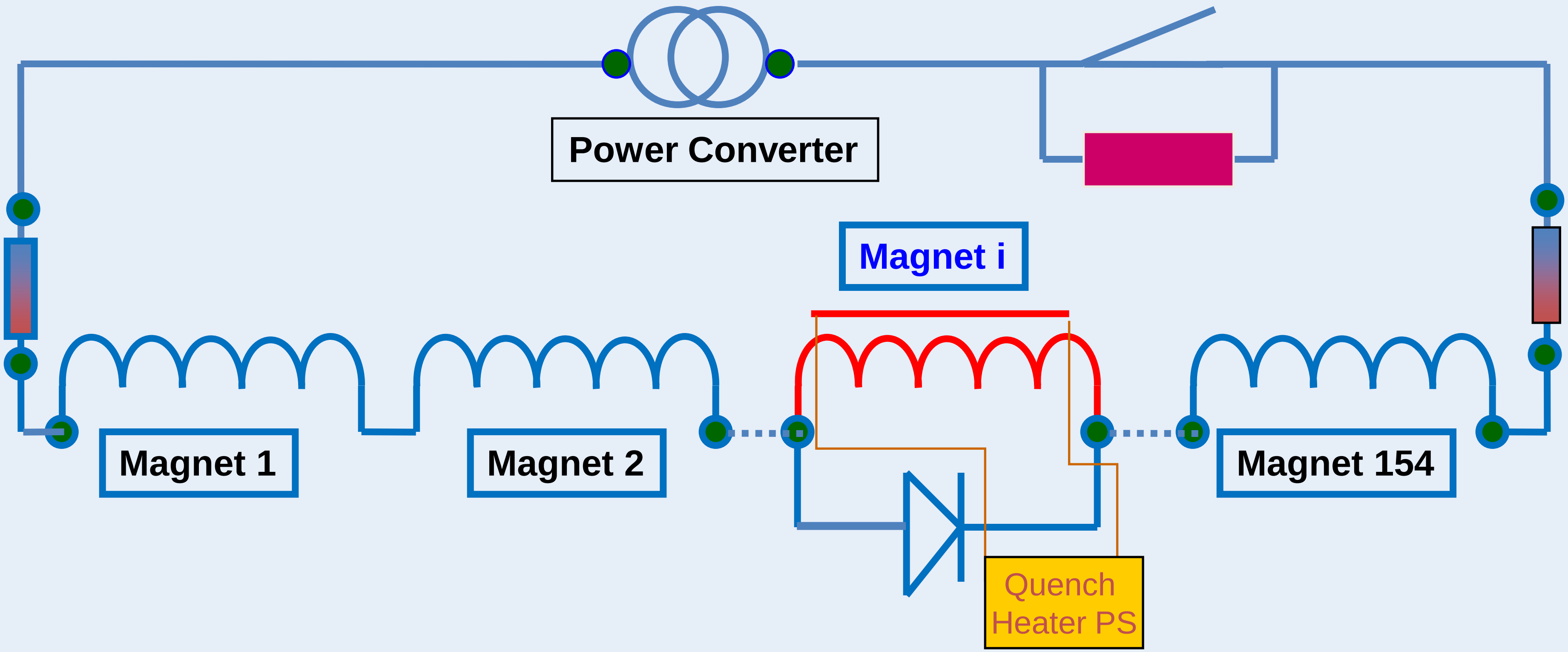
Protection of leads and bus-bar

- A conventional self-cooled current lead needs to be protected against thermal run-away

- The resistive and the HTS part of a HTS lead need to be protected against respectively thermal run-away and resistive transition

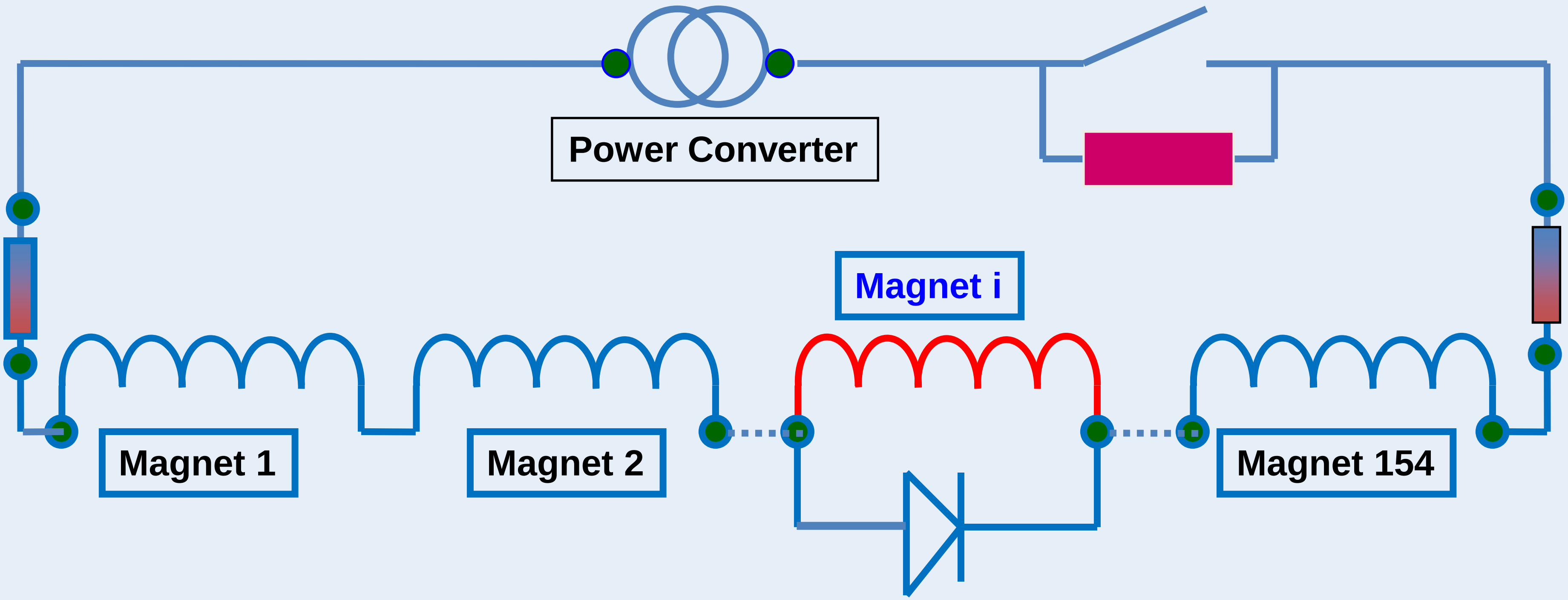
- In most cases, the superconducting bus needs to be protected against resistive transition

Protection of leads and bus-bar



- When **one magnet quenches**, quench heaters are fired for this magnet. Resistance is switched in the circuit
- The current in the quenched magnet decays in about **200 ms** – it flows through the bypass diode

Protection of leads and bus-bar

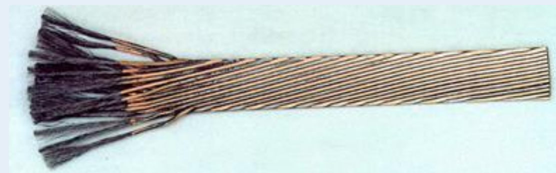


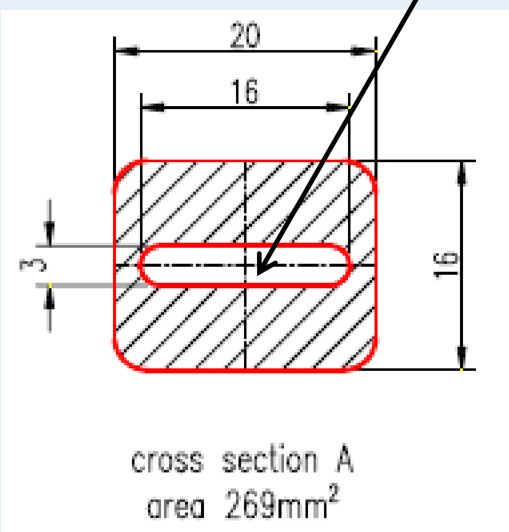
- The **time constant** of the LHC Main Dipole circuit is **107 s**. This “rapid” current decay is obtained by switching an external resistance into the circuit
- If the **leads or bus-bar quench**, the time constant for the discharge is given by the circuit (**107 s** for the LHC Main Dipole chain)

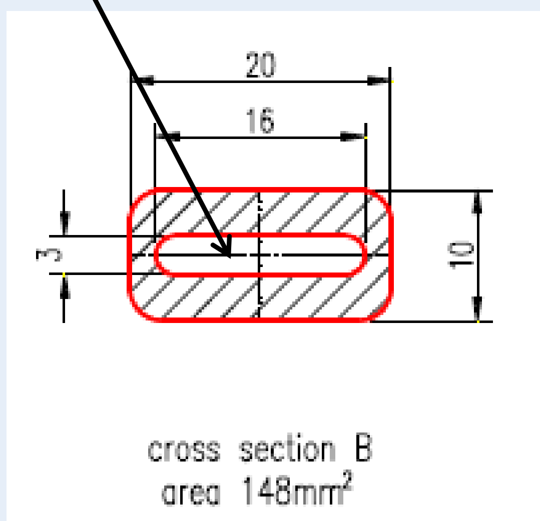
Protection-LHC Bus-Bar

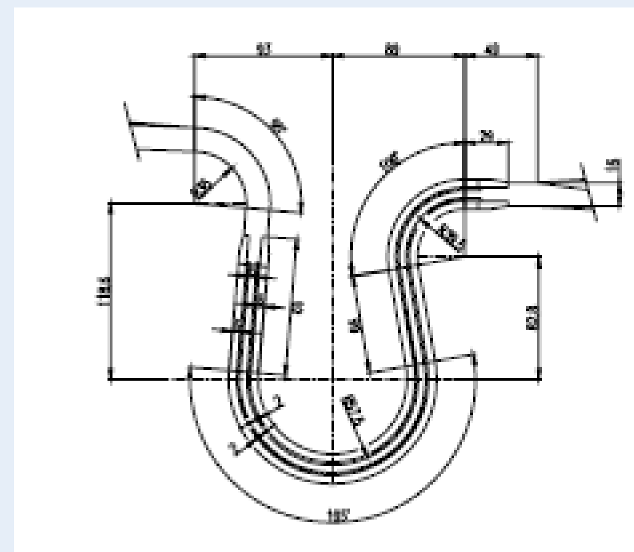
Bus-Bar: Nb-Ti Rutherford Cable/Strand with **copper stabilizer**

Rutherford Cable









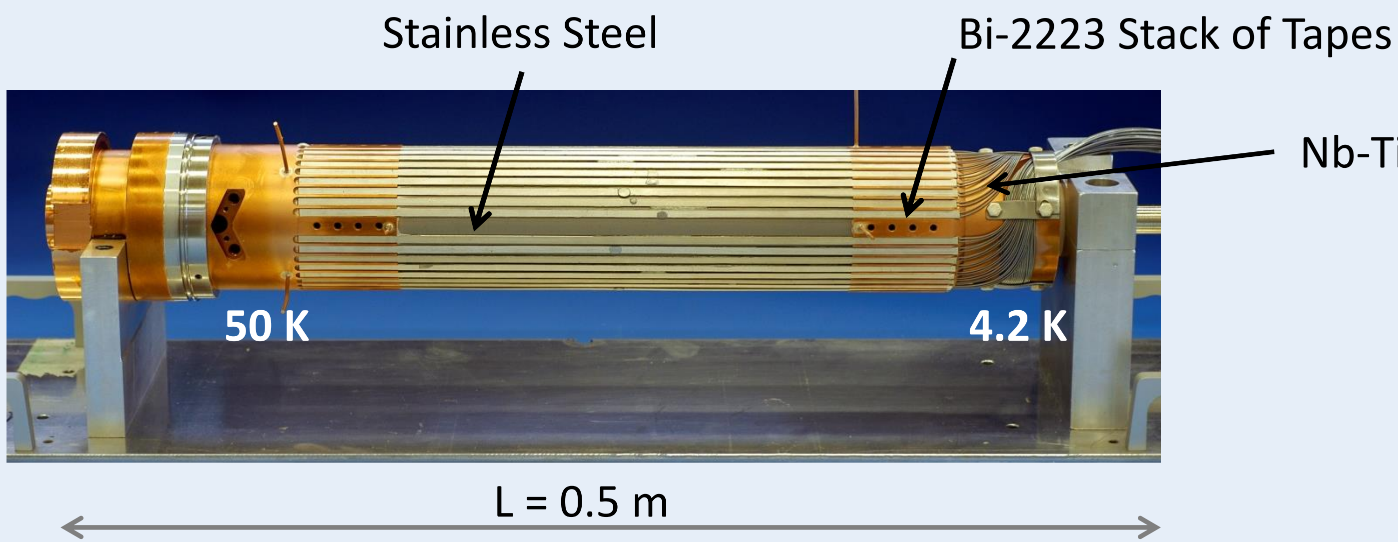
LHC Main Dipole Bus-Bar Stabilizer (τ=107 s)

LHC Main Quadrupole Bus-Bar Stabilizer (τ=40 s)

LHC Main Dipole Lyra

Protection-LHC HTS Current Leads

BSCCO 2223 Superconductor with stabilizer: Ag-Au matrix of tapes plus stainless steel supporting structure



Long circuit time constants may make the use of HTS leads not appropriate for that specific application.
Ex. ATLAS toroid leads (20.5 kA) are conventional (slow discharge of circuit: $\tau \sim 3$ hours).

Energy Stored in LHC Dipole Magnets

$$E_{dipole} = 0.5 \bullet L_{dipole} \bullet I^2_{dipole}$$

- Energy stored in **one dipole** operating at 7 TeV with 11850 A is **7.4 MJoule**

- For **154 dipoles** in one sector, E ~ **1.2 GJoule**

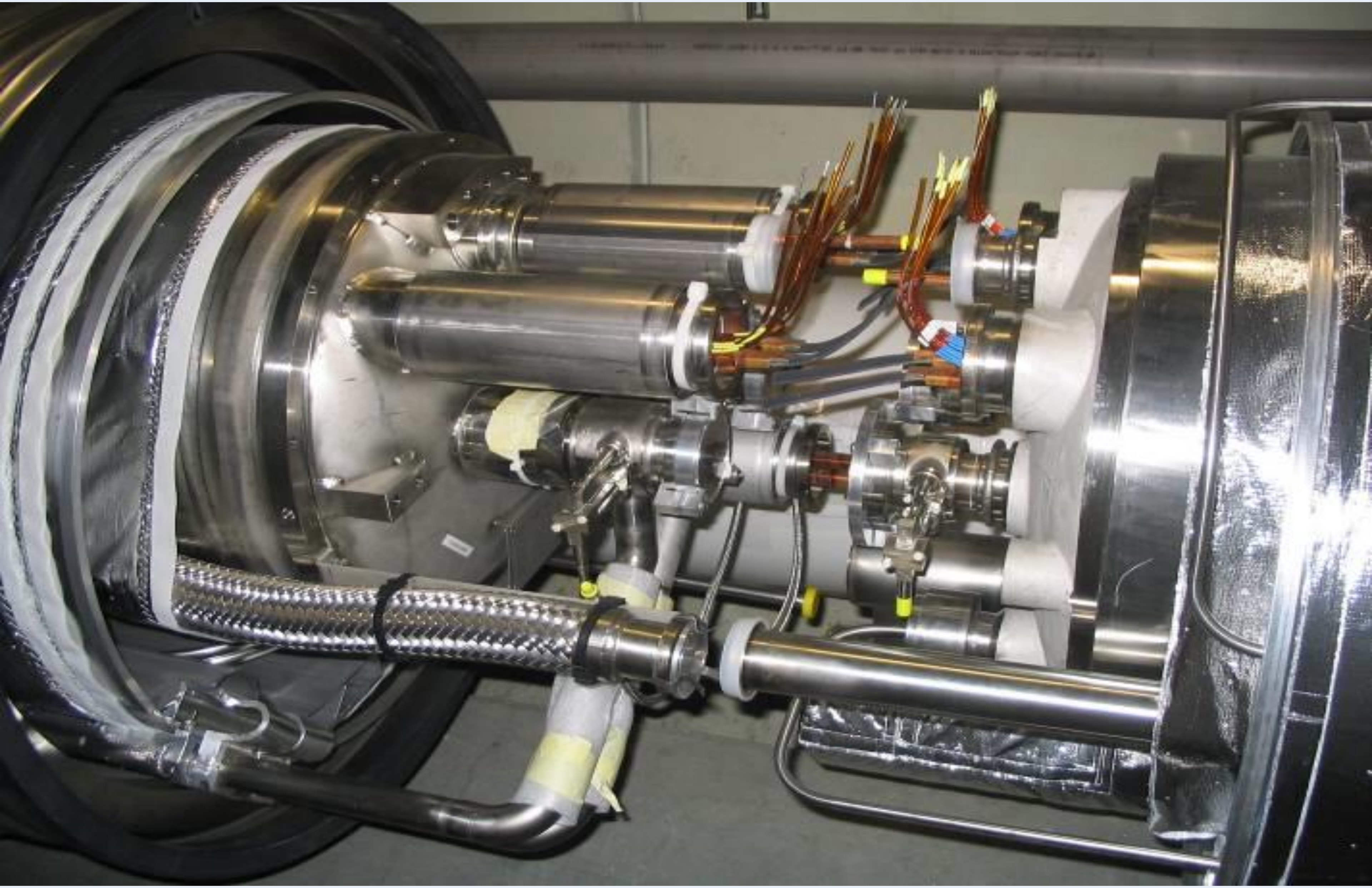
400 kg of TNT

- For all **1232 dipoles** in the LHC, E ~ **9 GJoule** (good reason for dividing the powering into 8 sectors)

Energy must be dissipated in the resistor and not in magnets, bus-bar or current leads

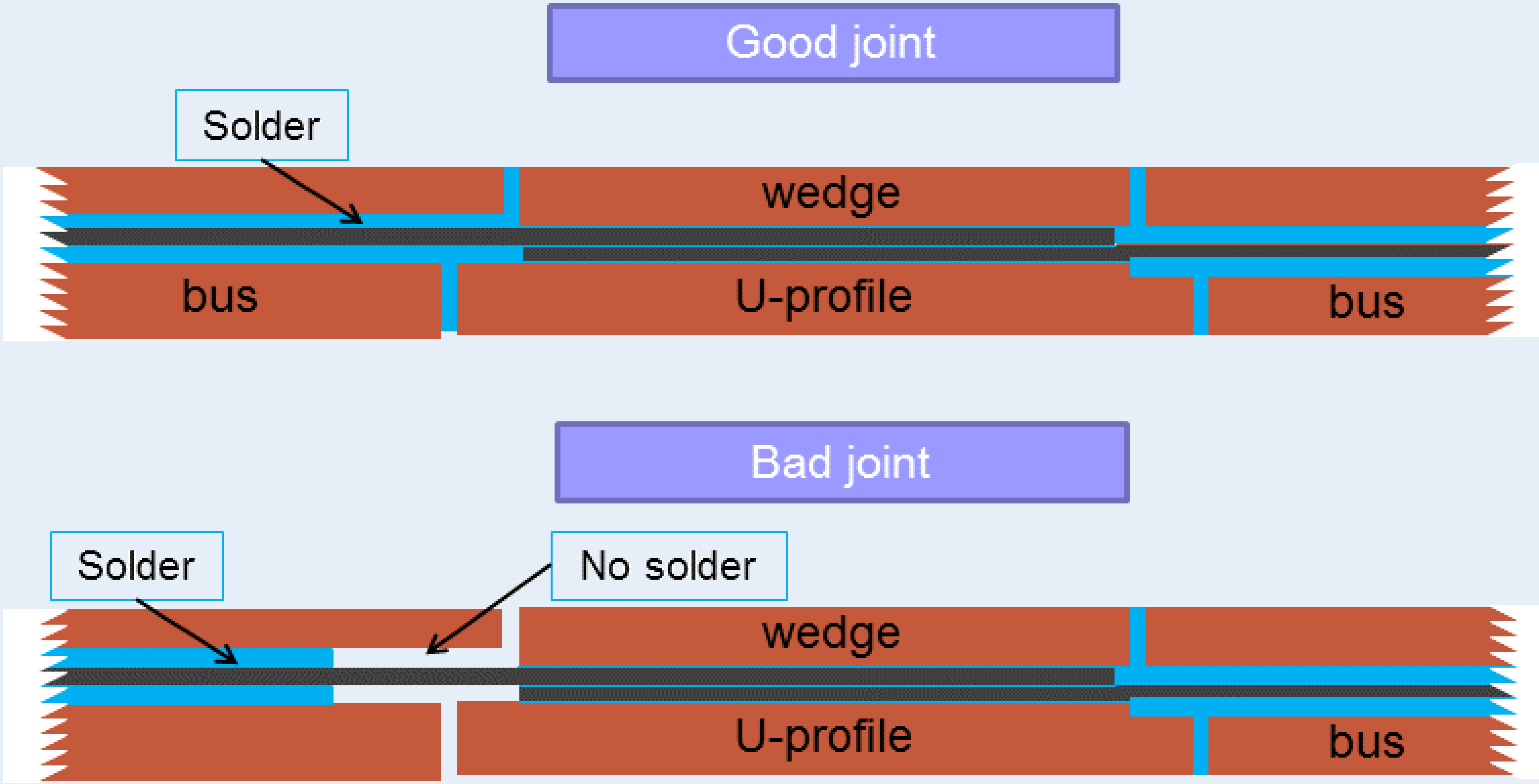
Effect of 7.4 MJ in a Dipole Coil

LHC Nb-Ti Bus-Bar and Interconnections



Protection-LHC Bus Bar

LHC Main Dipole Splice

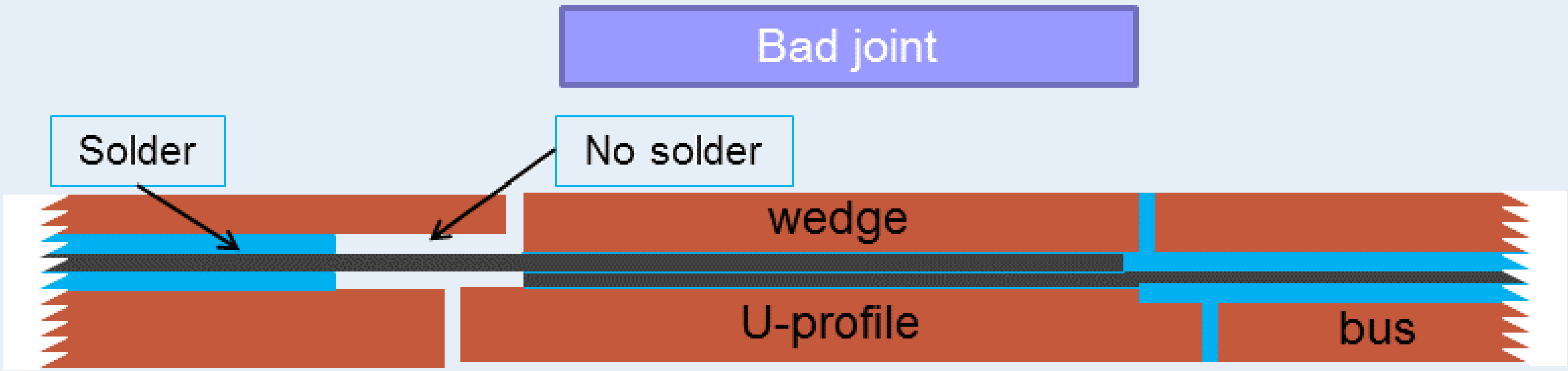


Highly resistive splice → Quench in bus-bar
→ Detection of voltage → Energy discharge in resistor

BUT

Protection-LHC Bus Bar

LHC Main Dipole Splice



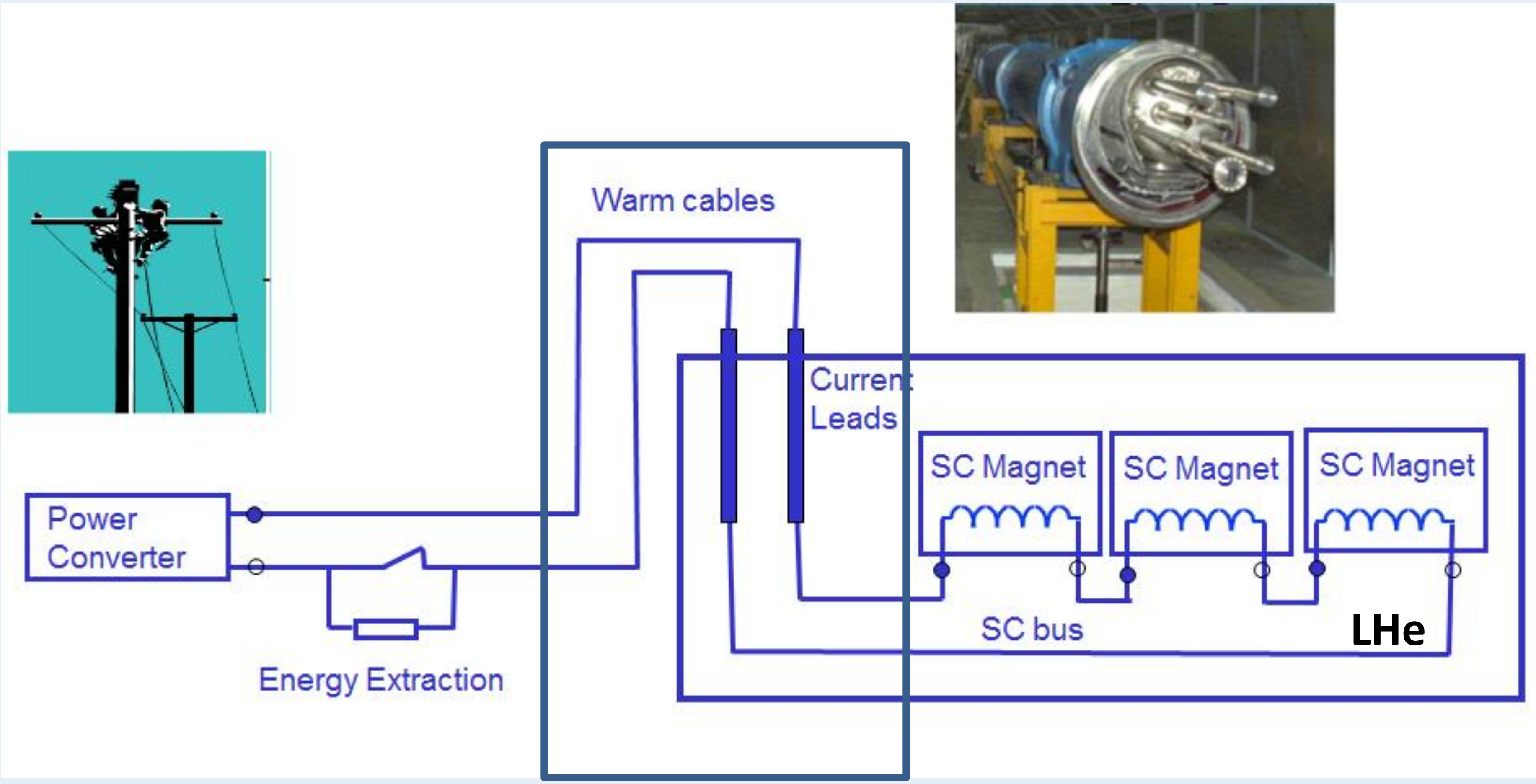
Highly resistive splice + non-continuity of stabilizer

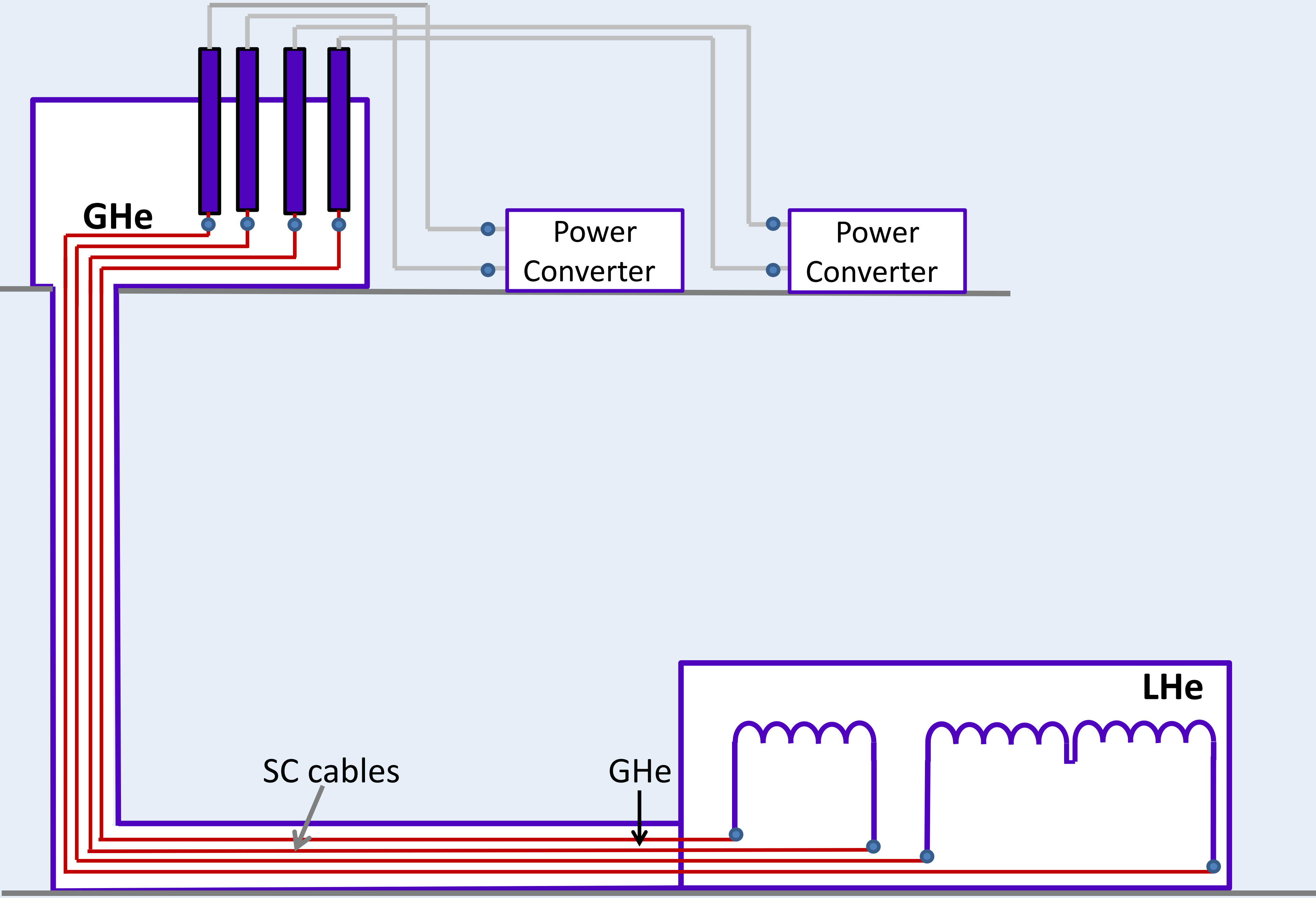
↓

Localized over-heating until melting of the cable and local discharge of the circuit energy

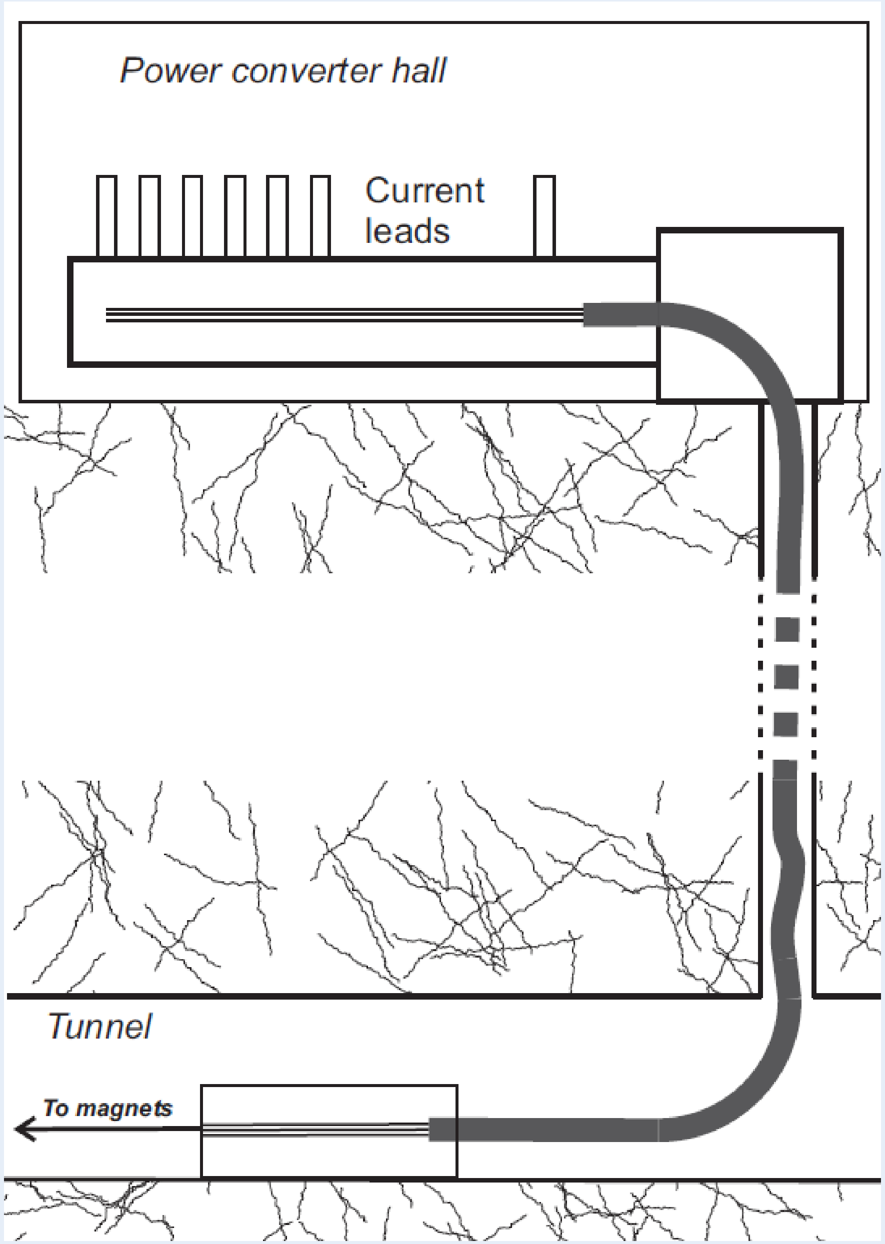
LHC Incident, 19th Sept 2008, Sector 3-4

Superconducting Links

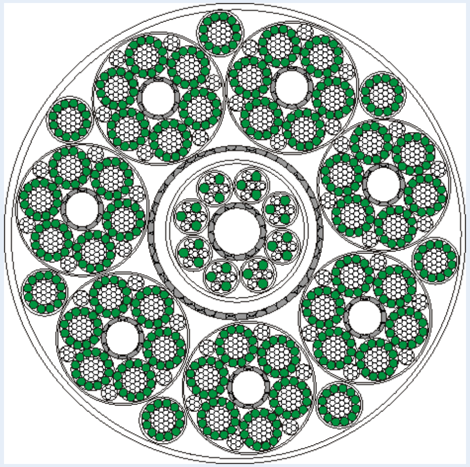


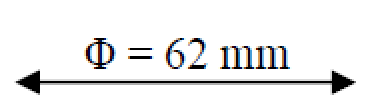

GHe
Power
Converter
Power
Converter
LHe
SC cables
GHe

Superconducting Links for LHC Upgrade



Ex. Development for LHC





Itot = 120 kA
N =22 cables
MgB_2 Round Wire

HTS Power Transmission Cables

HTS cables for integration in the grid

- **AC** cables for operation in the network
- **First** and **second** generation **HTS** conductors
- **LN_2** operation
- Cables operated at up to max **4000 A (I_{RMS})**
- **One** or **there cables** in the cryogenic envelope
- **Horizontal transfer**
- **High-voltage**

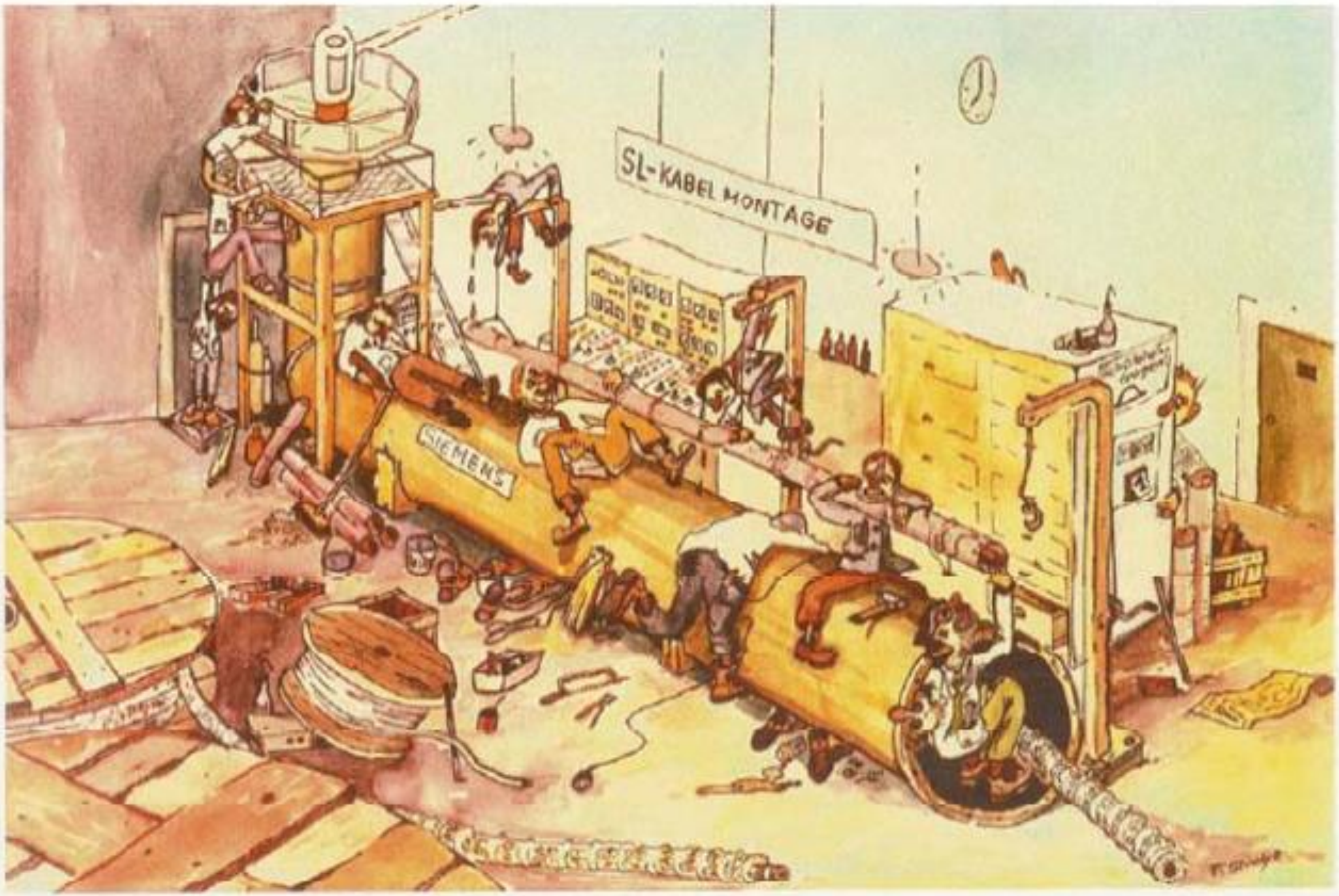
Superconducting Links for LHC Upgrade

SC links for the LHC machine

- **Quasi-DC** operation
- Also **MgB_2** conductor
- **GHe** operation
- Cables operated at **up to 20 kA**
- **Multi-cable** (~ 50 high-current cable) **assemblies**
- Horizontal + **Vertical (~ 80 m**) transfer
- **1.5 kV – 2 kV** electrical insulation

Cables for Superconducting Links

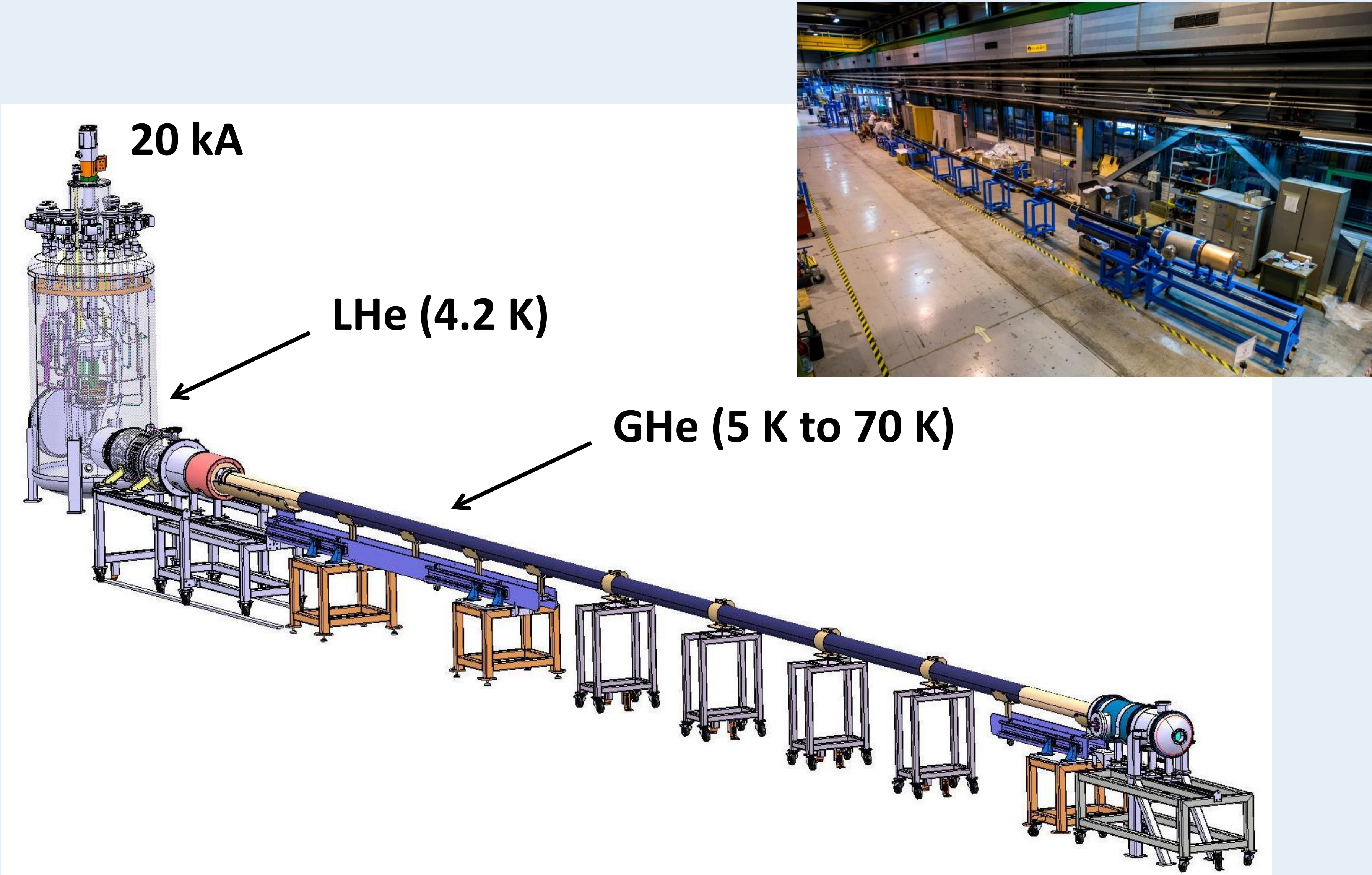
- High-current and low-field
- High temperature (5 K to 25 K)
- High temperature margin
- Compact cables and compact multi-cable assemblies
- Rutherford cables: why not, but they require **round** conductor with good **mechanical properties** (bending radius ~ wire diameter)
- The cost of the conductor should be a small fraction of the cost of the system



Courtesy: Dr. Heinz-Werner Neumüller, former Siemens Corporate Technology

M. Noes , CAS, Erice 2013

SC Link Test Station at CERN



Thanks for your attention !