Iseult-Neurospin 1500 A Currents Leads: Conceptual and Experimental Results

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Abstract. In the framework of the French-German project Iseult, we chose to design the 4.5 K vapor cooled current leads of the 11.75 T MRI magnet using a burn-proof approach, *i.e.* they are able to withstand a 3-hour current slow dump without any active cooling. This constraint led us to select brass instead of pure copper, resulting in higher mass and thus in higher thermal stability. The drawback is a slightly higher cryogenic consumption. We present here the design studies of those current leads and compare their theoretical characteristics with the experimental results obtained during the test campaigns at CEA-Saclay.

Slow Dump and Fault Scenario

- I_0 = 1 483 A
- L = 307.7 H ⇒ E = 338 MJoules
- **Slow dump** : the magnet energy is dissipated through a diodes bridge under a **40 V** voltage U_{sd}
  - → Linear current dump
  - → Dump duration τ_{sd} = $L \times I_0 / U_{sd}$ = 11 408 s ≈ 3h10'
- **Fault scenario :** No helium cooling during the slow dump, the current lead temperature must stay below **100 °C**
  - → **Brass current leads**

Current Lead Theory (cf. Wilson "Superconducting Magnet")

- Self-consumption regime : $\dot{m}L_v = \varphi_{4.5}$ (heat flux at cold end)
- Wiedemann-Franz Law : $\lambda \times \rho = L.T$
- Optimum : $\varphi_{4.5}$ minimal ⇔ $\varphi_{293} = 0$
- $Voltage = U_0 = \frac{I}{A}\int_{4.5}^{293} \rho(T)dz = \bar{\rho} \times \frac{I \times L}{A} = C^{st}\ \forall\ RRR \approx 80\ mV$
  - → Joule Power dissipated ($U_0 \times I$) independent of RRR
  - → $\dot{m} \times (L_v + \Delta H_{4.5}^{293}) = U_0 \times I + \varphi_{293} = U_0 \times I$ mass flow independent of RRR
  - → Normalized cryogenic load at 4.5 K = $\phi_{4.5}/I$ ≈ 1W/kA independent of RRR
  - → $Lead\ Vol. = A \times L = \bar{\rho} \times \frac{I \times L^2}{U_0}$ the lower the RRR the higher the mass
    (I, L are fixed, U_0 is constant)
  - → In case of lack of Helium cooling low RRR are better

Real life

- Wiedemann-Franz Law is not exact
  - → U_0 thus Normalized Cryogenic load depends on RRR :
  - @1.25 bar and 4.45 K RRR 100 : 0.95 W/kA Brass (RRR≈ 2) : 1.22 W/kA (≠ 30%)
- Nevertheless low RRR leads have lower volumic dissipated power by a factor 10

Low RRR leads are safer but use more Helium

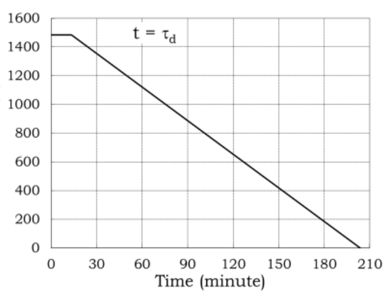
DESIGN CURRENT LEAD CHARACTERISTICS
SELF-CONSUMPTION REGIME

Symbol	Characteristics	Value
	Current lead type	**Braid in Tube**
	Braid material	**Brass CuZn90-10**
	Tube material	Stainless Steel 304
	Tube dimensions (Øext.×thick.)	43×1.5 mm×mm
	Braid wire diameter	0.5 mm
	Wires number	3 068
A	Braid cross-section	**602 mm²**
L_0	Length	**1.05 m**
D_h	Hydraulic diameter	0.54 mm
S	Heat exchange Area	5.06 m²
P	Wetted perimeter	4.82 m²/m
	Current design	1 800 A
I_0	Nominal current	**1 483 A**
T_c	Cold end temperature	**4.45 K**
T_f	Warm end temperature	293 K
	Helium gas pressure	**1.25 bar**
Q_c	Cryogenic load at 1 483 A	**1.82 W**
	Normalized Cryogenic Load	**1.23 W/kA**
Q_w	Heat input at warm end at 1 483 A	33.9 W
G	Helium mass flow at 1 483 A	**0.095 g/s** or 32.0 Nl/'
	Cryogenic load at 0 current	0.65 W
U_0	Voltage at 1 483 A	**75.1 mV**
	Voltage at 1 800 A	97.2 mV
ΔP	Pressure drop	≤ 6 hPa
W_{conv}	Convective exchanged heat	143.5 W
h	Mean heat transfer coefficient	684.7 W/m².K
ΔT_m	Mean temperature difference	41.4 mK

$$\dot{m} \times \Delta H_{4.5}^{293} + Q_c = U_0 \times I + Q_w$$

Fault Scenario : Helium mass flow = 0 Computations

- **Slow dump sequence :**
  - **→ Onset delay to permit an eventual intervention**

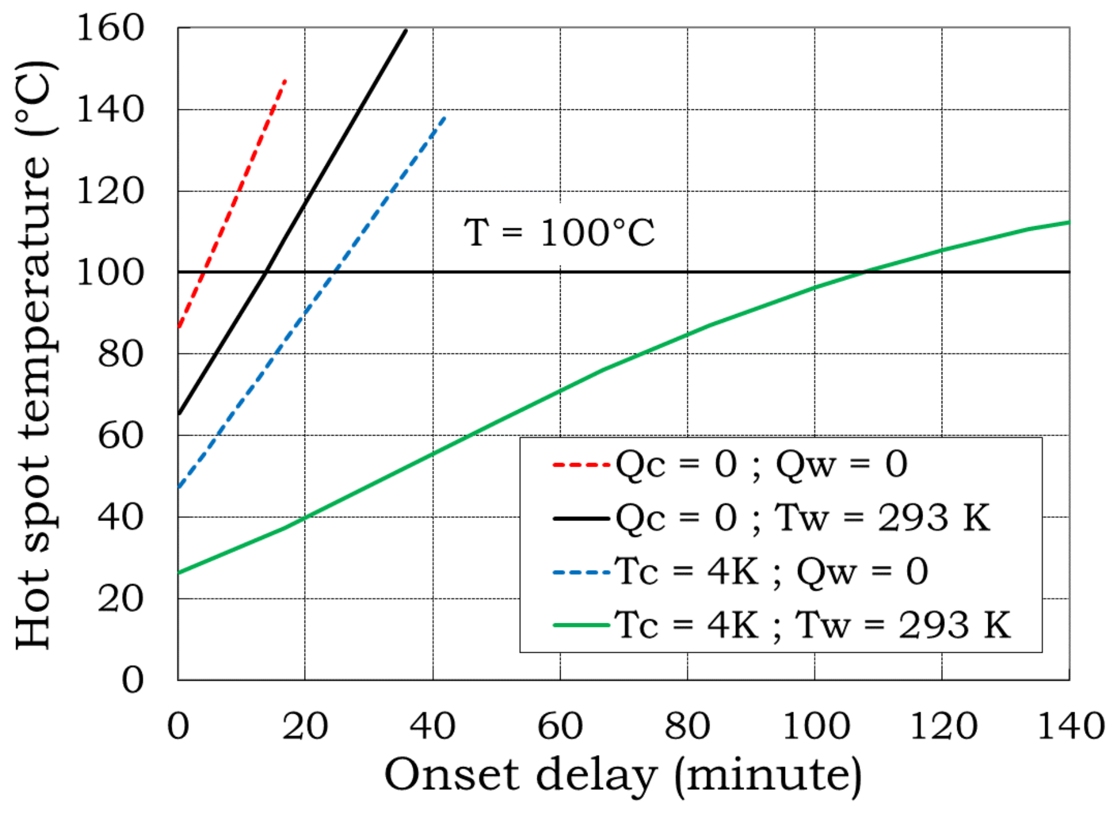


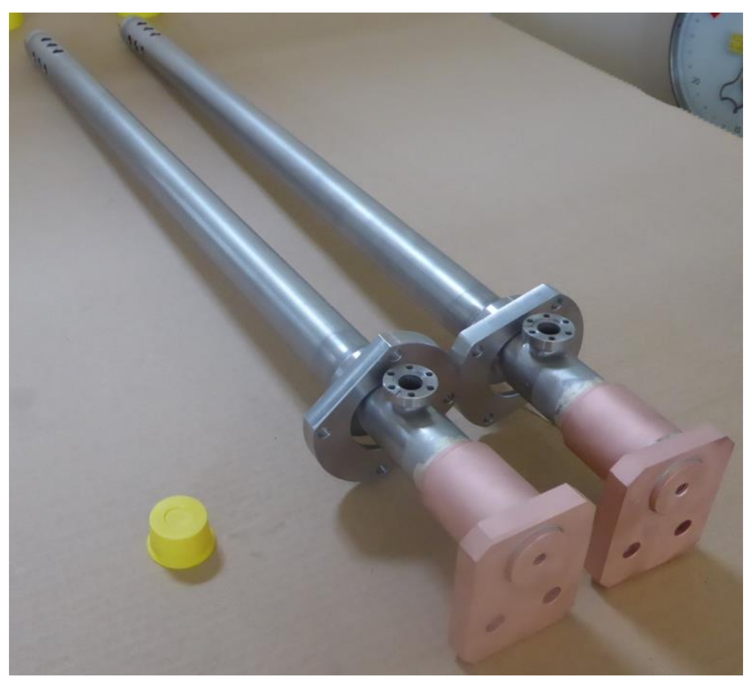
- $t \leq 0$: normal regime I = 1 483 A + cooling
- t = 0 : helium mass flow = 0
- $t \leq \tau_d$: I = 1 483 A
- $t = \tau_d$: beginning of the slow dump
- $t = \tau_d$+11 408 s : end of the slow dump; I = 0

- **Computations Hot spot = f(τ_d)**
  - finite-element method Cast3M
  - 4 sets of limit conditions : isothermal or adiabatic at each end
    - **→ Adiabatic at warm end Q_w = 0 : very unlikely**
    - **→ Isothermal at each end : the most likely**
    - **→ Adiabatic at cold end Q_c = 0 : unlikely**
- Permitted onset delay : **Temperature Hot Spot ≤ 100°C**

Whatever limit conditions Hot Spot ≤ 100°C is possible

- **→ T_c = 4.5 K and T_w = 293 K : $\tau_d \leq$ 110'**
- **→ Q_c = 0 and T_w = 293 K : $\tau_d \leq$ 13' 30"**





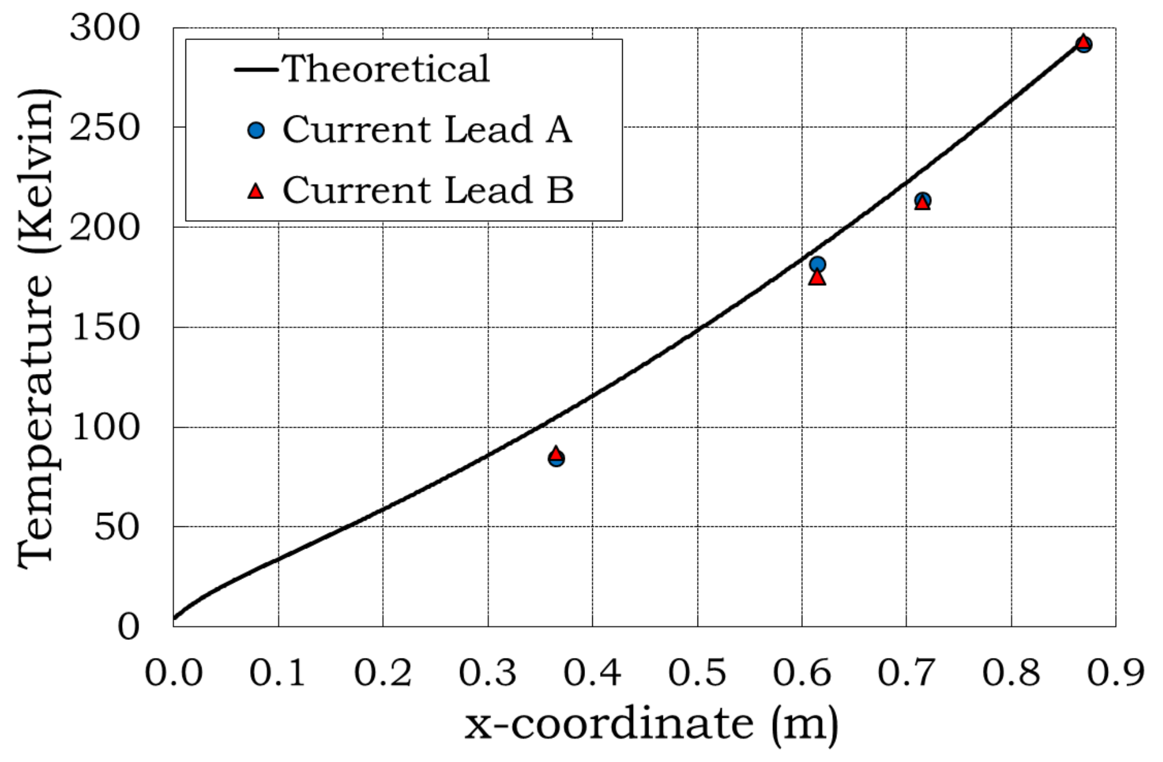
Measurements in Steady State Regime

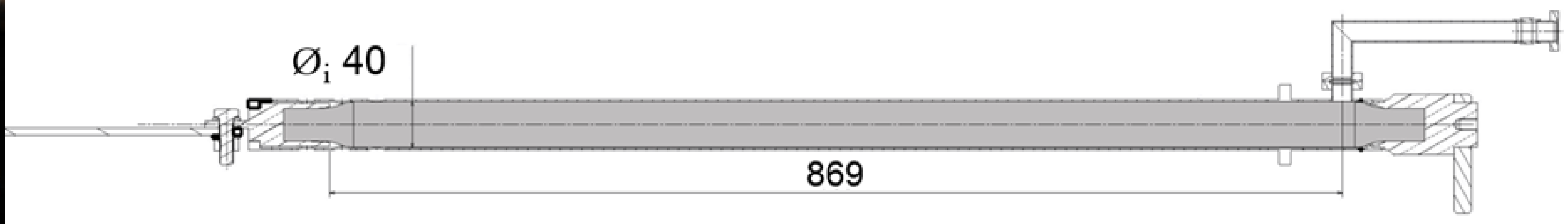
- CL length = 0.869 m between isothermal sections *i.e.* pure copper foot at cold end and He exhaust tube at warm end
- **Compactness = 1.12**
(deduced from resistivity measurements)
  - → Effective length = 0,869 m × 1.12 = 0.973 m

	C.L. A	C.L. B
Helium gas pressure	1.05 bar	
Bath temperature	4.25 K	
Helium Mass Flow	**32.6 Nl/'**	**32.2 Nl/'**
Self-Consumption Mass Flow	**32.2 Nl/'**	
Voltage	**69.9 mV**	**68.6 mV**
Theoretical Voltage	**69.6 mV**	**70.0 mV**
Cryogenic Load	1.99 W	1.96 W
Normalized Cryogenic Load	1.34 W/kA	1.32 W/kA
Self-consumption Cryo. Load	1.32 W/kA	1.32 W/kA

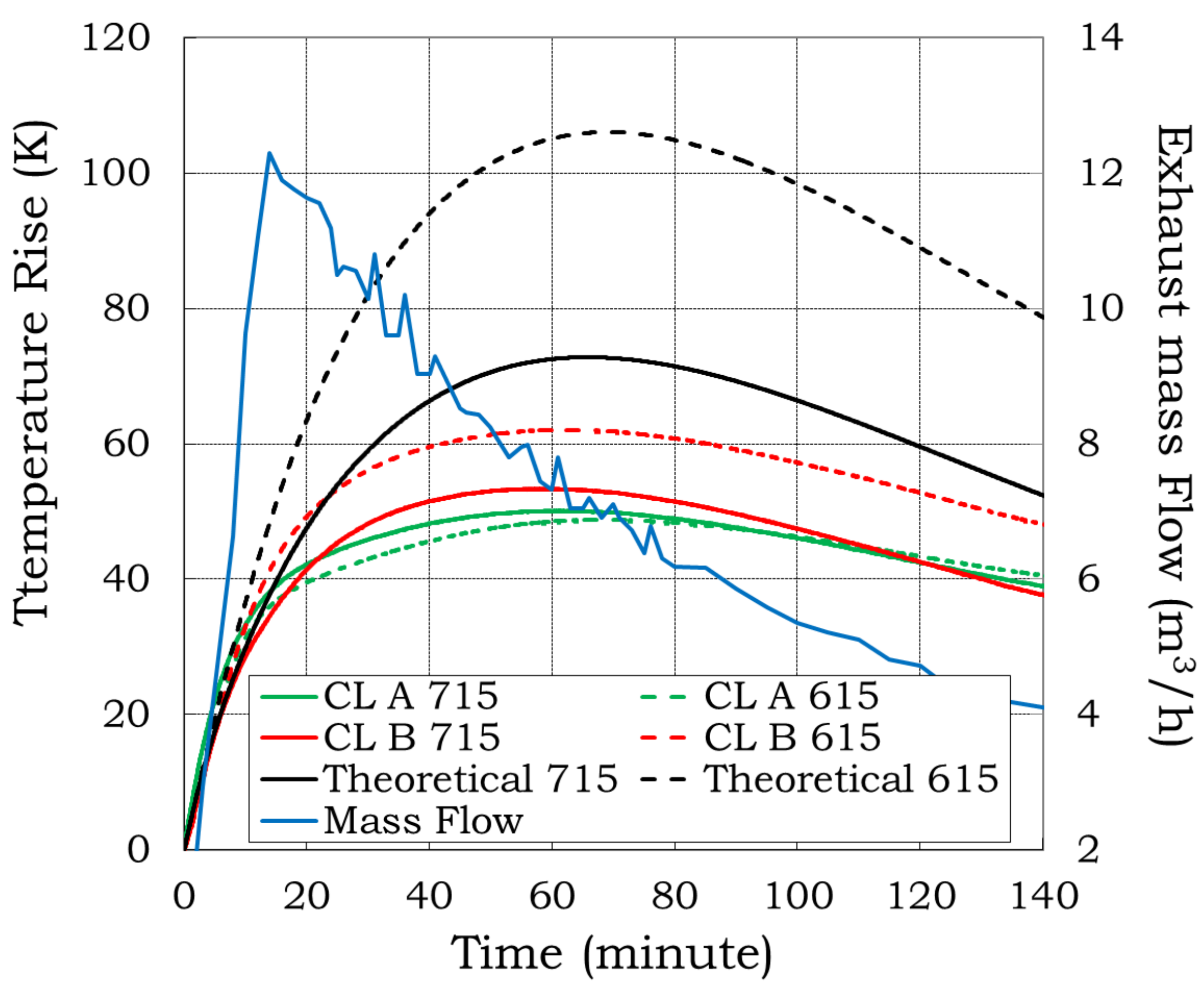
Theoretical voltages are calculated with L = 0.973 m and measured mass flows

- **Voltage :** Good agreement computations/measurements 4 ‰ for CL A and 2.0 % for CL B…but difference of 1.3 mV between leads, probably due to different compactness
- **Temperature** : Good agreement, measured temperatures are 5-10 °C lower that computed values





Manufactured by "TRESSE METALLIQUE J. FORISSIER INTERNATIONAL WIRE Group" St CHAMOND France



Measurements in Fault Scenario

- Helium mass flow inside leads = 0
- Slow dump onset value = 15'
- Closed to "isothermal at each end" conditions
- Temperature rise evolutions of sensors placed at x = 0.615 m and x = 0.715 m, closed to the expected hot spot location (T_{max} = 302 K at x ≈ 0.73 m)

→ Temperature rises are lower than expected, possibly due to the external convection with the exhaust helium mass flow

→ The measurements made after the fault scenario tests did not show any modification nor degradation of both current leads behavior.

Conclusion. A pair of brass current leads for the Iseult/NeuroSpin project have been designed and tested at Saclay The measurements have shown a good agreement with the calculations; the helium mass flow required is of 0.095 g/s at 1 483A corresponding to a 1.23 W/kA ratio. A small and inconsequential discrepancy has been measured between leads which nevertheless fulfill the specifications, notably in case of lack of helium cooling.