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Operation of Power Diodes at Cryogenic Temperature

Yasmine Baazizi, Lauro Ferreira, Simon Meunier, Tanguy Phulpin, Loïc Quéval

Université Paris-Saclay, CentraleSupélec, CNRS, GeePs, 91192, Gif-sur-Yvette, France.
Sorbonne Université, CNRS, GeePs, 75272, Paris, France.

Purposes

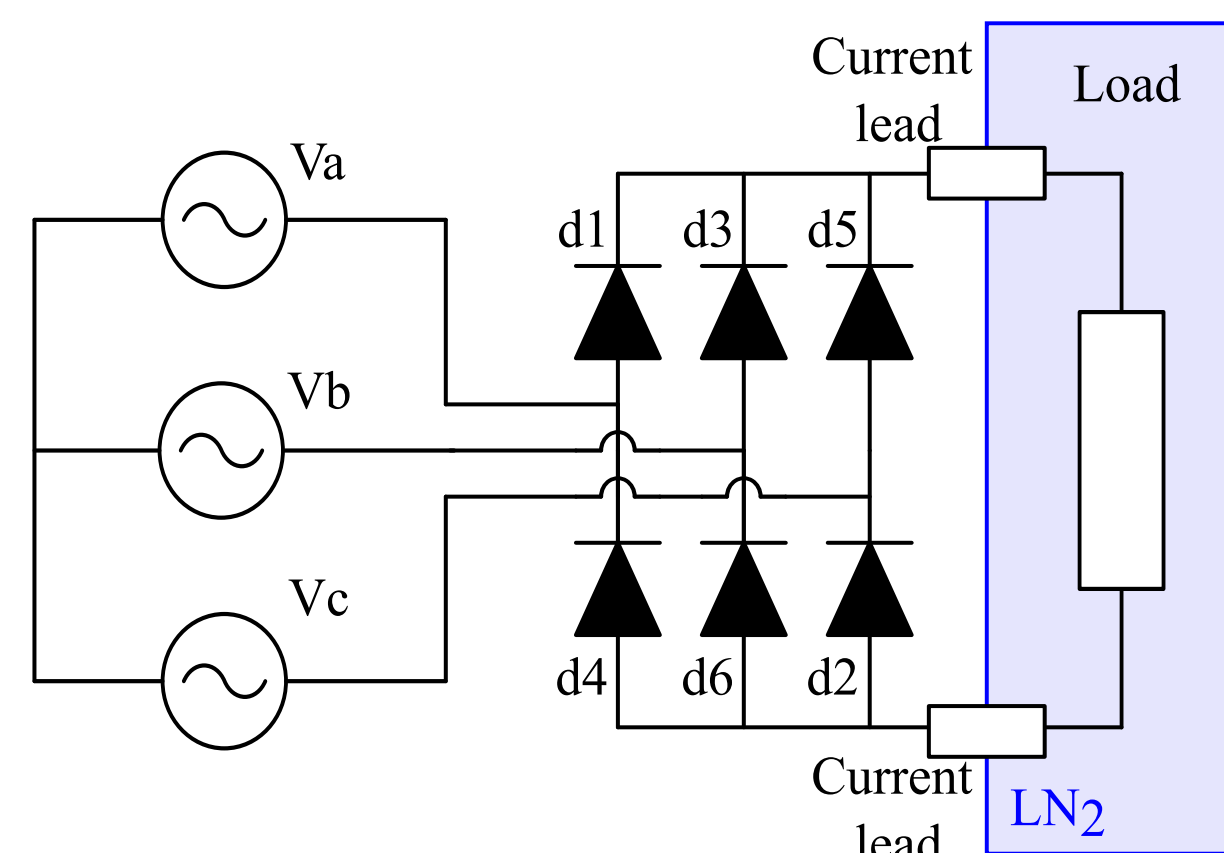
- Study the **feasibility** of a three-phase diode rectifier operating at **cryogenic temperature**.
- Electrical characterization of power diodes at cryogenic temperature.

Converter design

- ✓ 2 DC current leads
- ✗ High rectifier losses
- ✗ Bulky, heavy

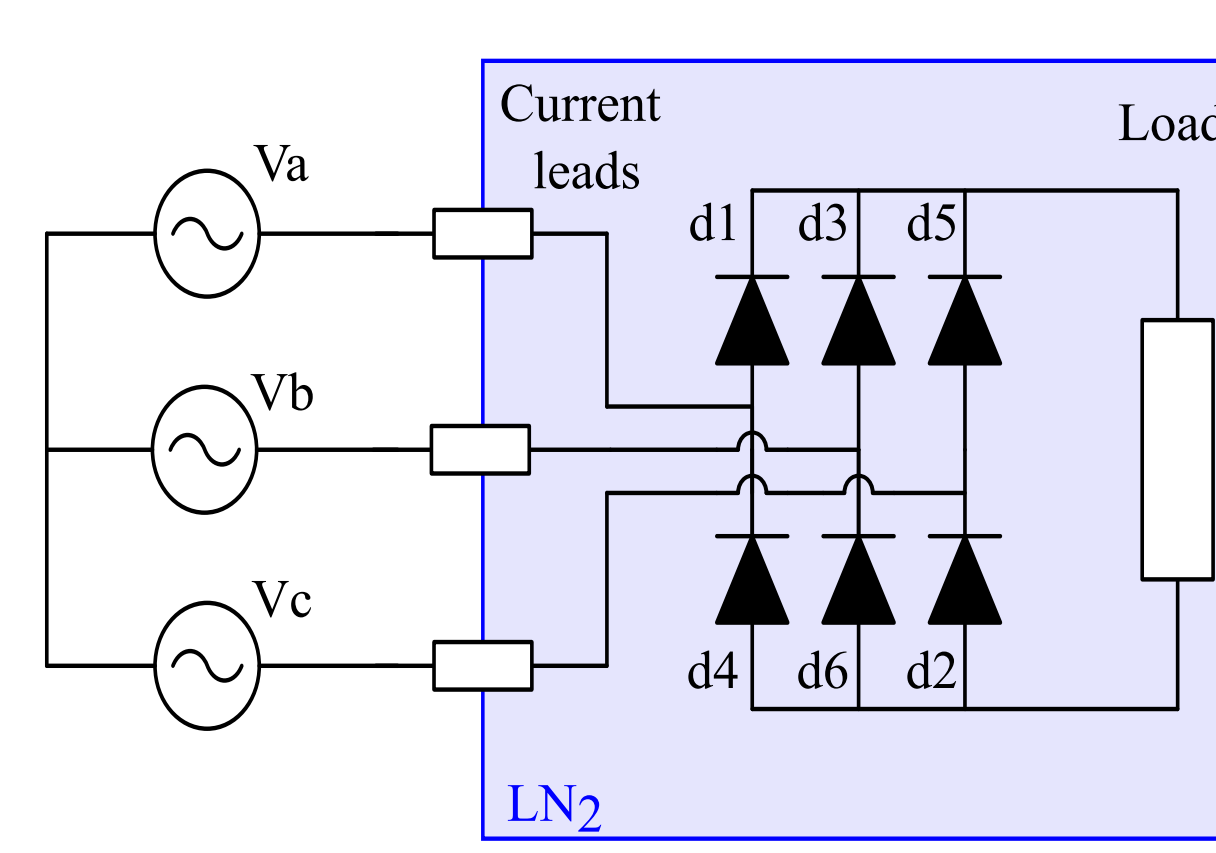
Requirements :

- AC voltage [L-L RMS] : 800 V
- Operating frequency : 50 Hz
- Nominal power : 100 kW



a) Topology #T1

VS



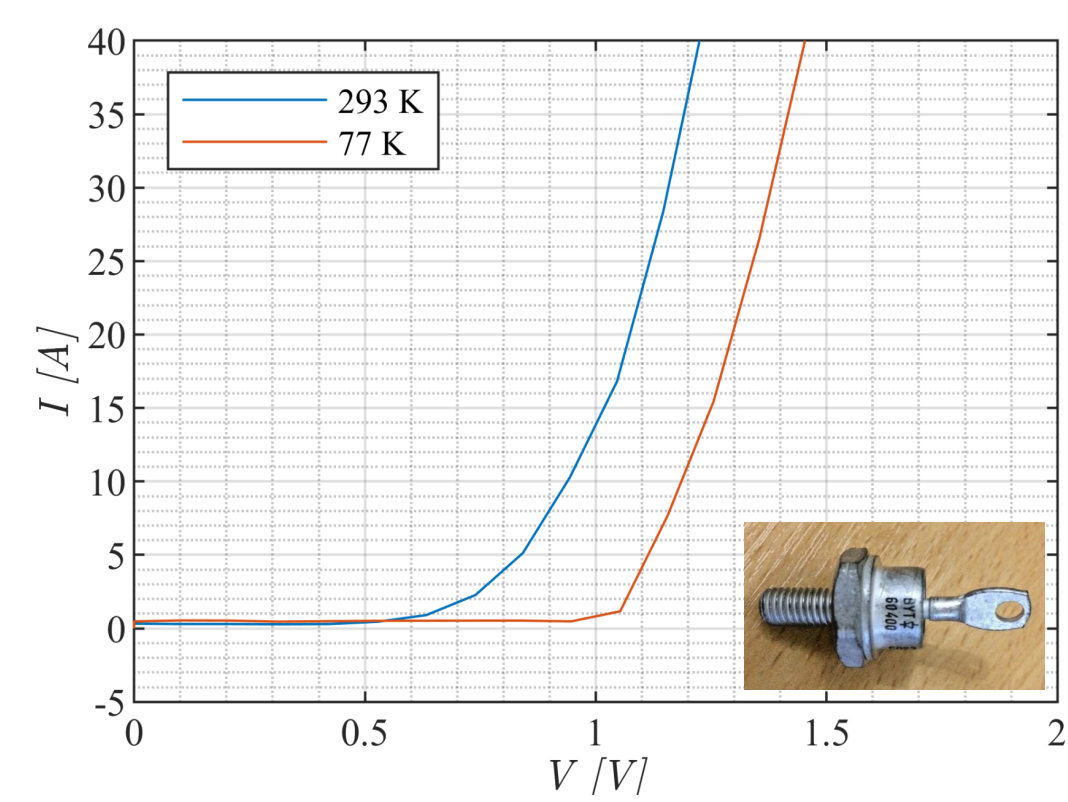
b) Topology #T2

- ? 3 AC current leads ?
- ? Diode characteristic
- ✓ Less rectifier losses ?
- ✓ Compact, light ?

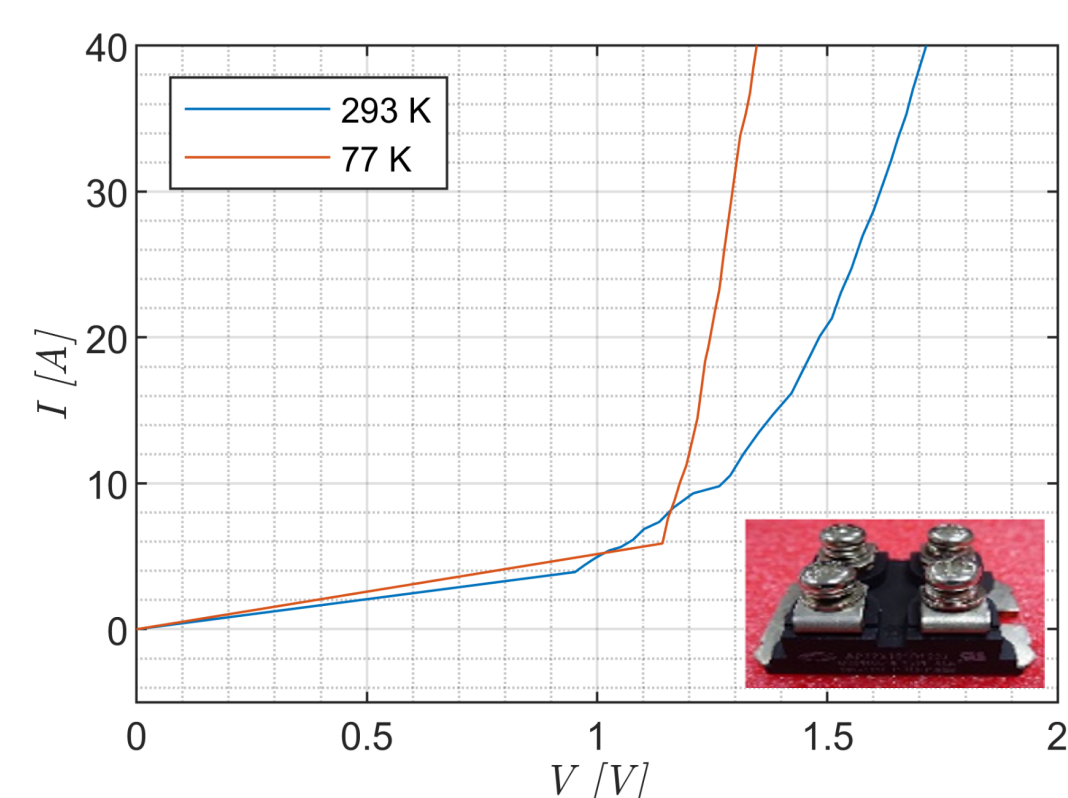
Figure 1: AC/DC power supply system topologies

Diode characterization

- Power diodes have different electrical properties at room and cryogenic temperatures.
- Some diode technologies are more suitable for operation at cryogenic temperature.



a) BYT60-400 ✗



b) APT2X101_100D120J_E [1] ✓

Fig.1. Measured diode current-voltage curve

Table 1. Measured diode parameters at room and cryogenic temperatures

| Symbol | Parameter | Temperature | BYT60-400 | APT2X101_100D120J_E |
|----------|---------------------|-------------|-----------|---------------------|
| R_{on} | On-state resistance | 77 K | 10.8 mΩ | 4.1 mΩ |
| | | ~293 K | 8.7 mΩ | 6.0 mΩ |
| V_{t0} | Threshold Voltage | 77 K | 1.11 V | 1.17 V |
| | | ~293 K | 0.82 V | 1.47 V |

Models

Thermal model

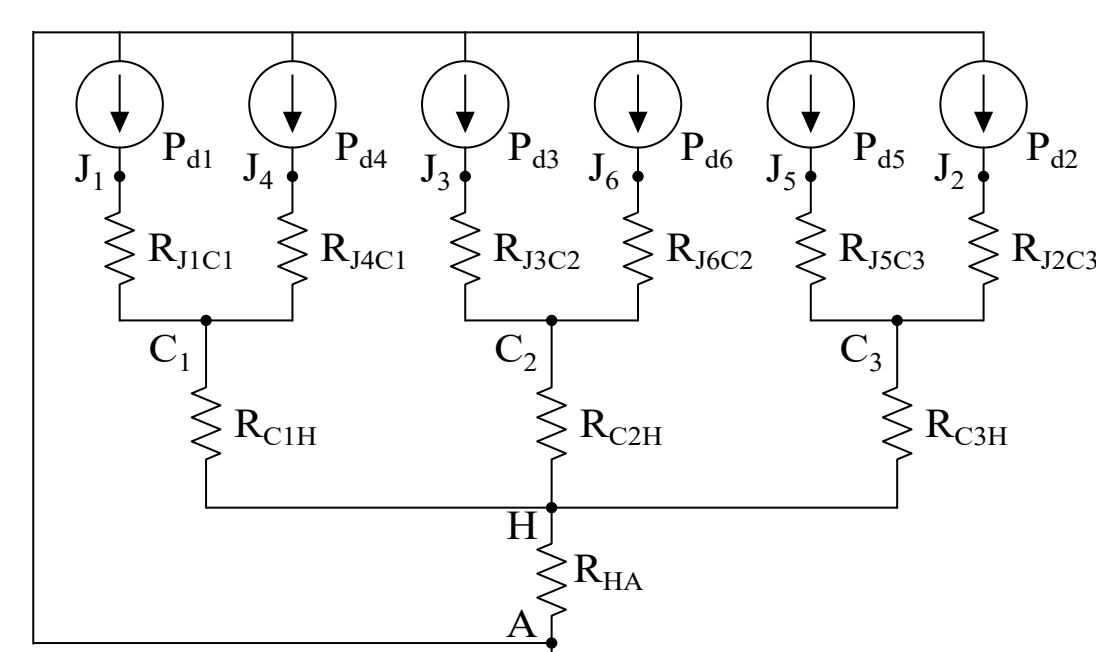


Fig.2. Thermal model

Current lead model

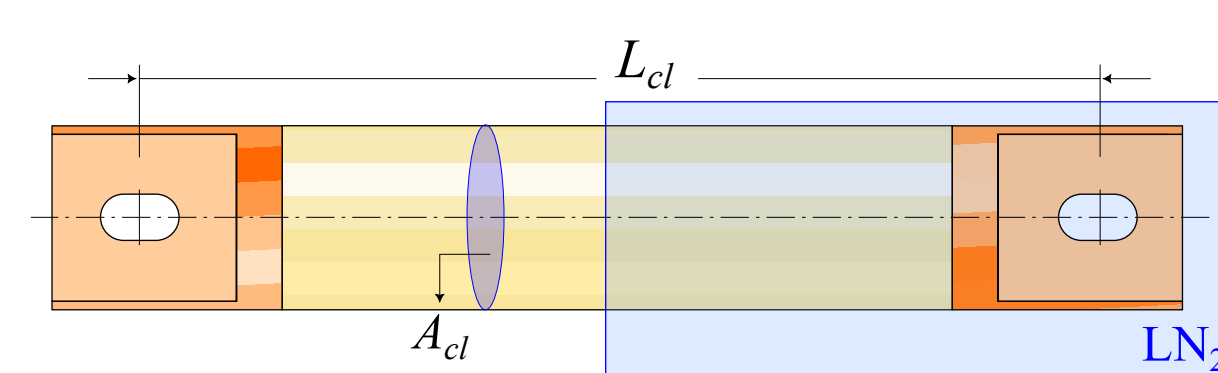


Fig.3. Current lead design

- The losses in one current lead consist of: the heat flow into the cryostat and the heat generated by Joule effect [2],

$$dT = -\frac{dL_{cl}}{\kappa A_{cl}} \dot{Q} \quad d\dot{Q} = I^2 \frac{dL_{cl}}{\sigma A_{cl}}$$

- The ratio between the length and the area of the current lead is defined by the minimum heat flow,

$$\frac{L_{cl}}{A_{cl}} = \frac{\sigma}{I^2} \dot{Q}_{c,min} = \frac{1}{I} \sqrt{2\sigma\kappa(T_h - T_c)}$$

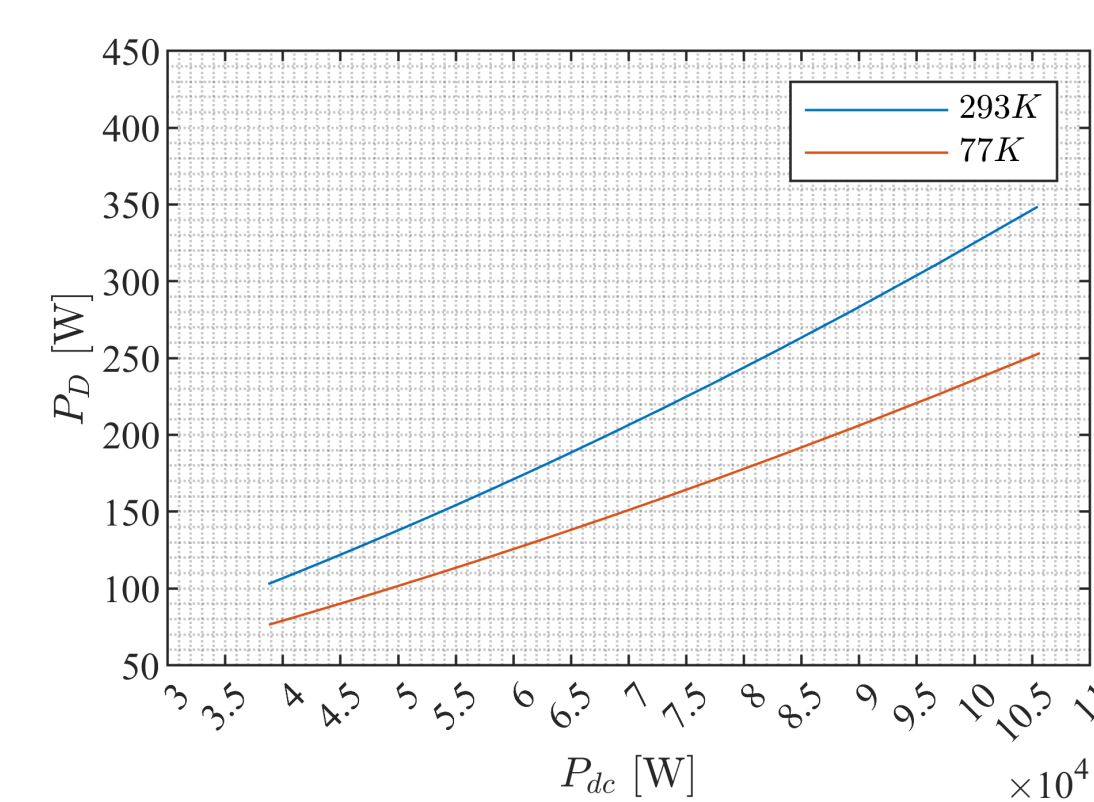
Table 2. Current leads parameters

| Symbol | Parameter | Topology #T1 | Topology #T2 |
|-------------|---------------------------|---------------------|---------------------|
| R_{on} | Number and Type | 2DC | 3AC |
| I_{RMS} | RMS current | 98 A | 80 A |
| $Q_{c,min}$ | Heat flow to the cryostat | 5.26 W | 4.29 W |
| L_{cl} | Length | 10 cm | 10 cm |
| A_{cl} | Cross sectional area | 3.1 mm ² | 2.5 mm ² |
| R_{cl} | Electrical Resistance | 0.55 mΩ | 0.67 mΩ |

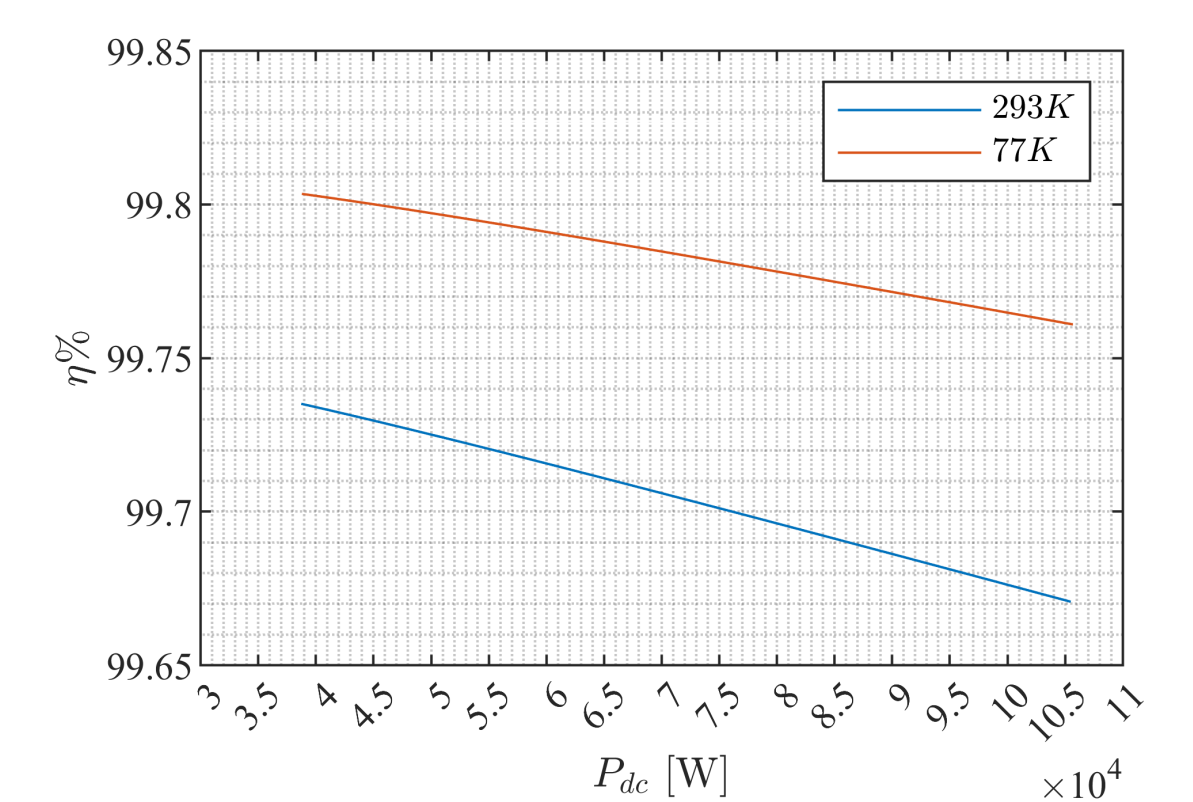
Results

Diode rectifier losses and efficiency

- The losses of the diode rectifier are reduced by 26% at cryogenic temperature.
- The efficiency of the diode rectifier is only improved by 0.07%.



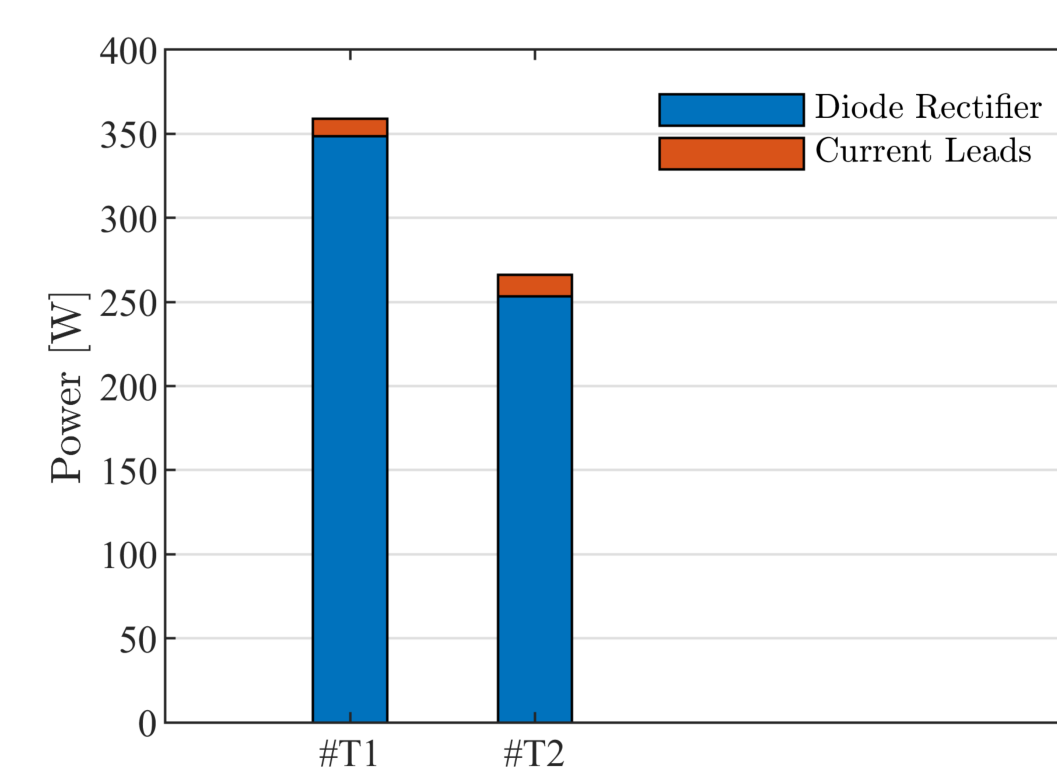
a) Diode rectifier losses



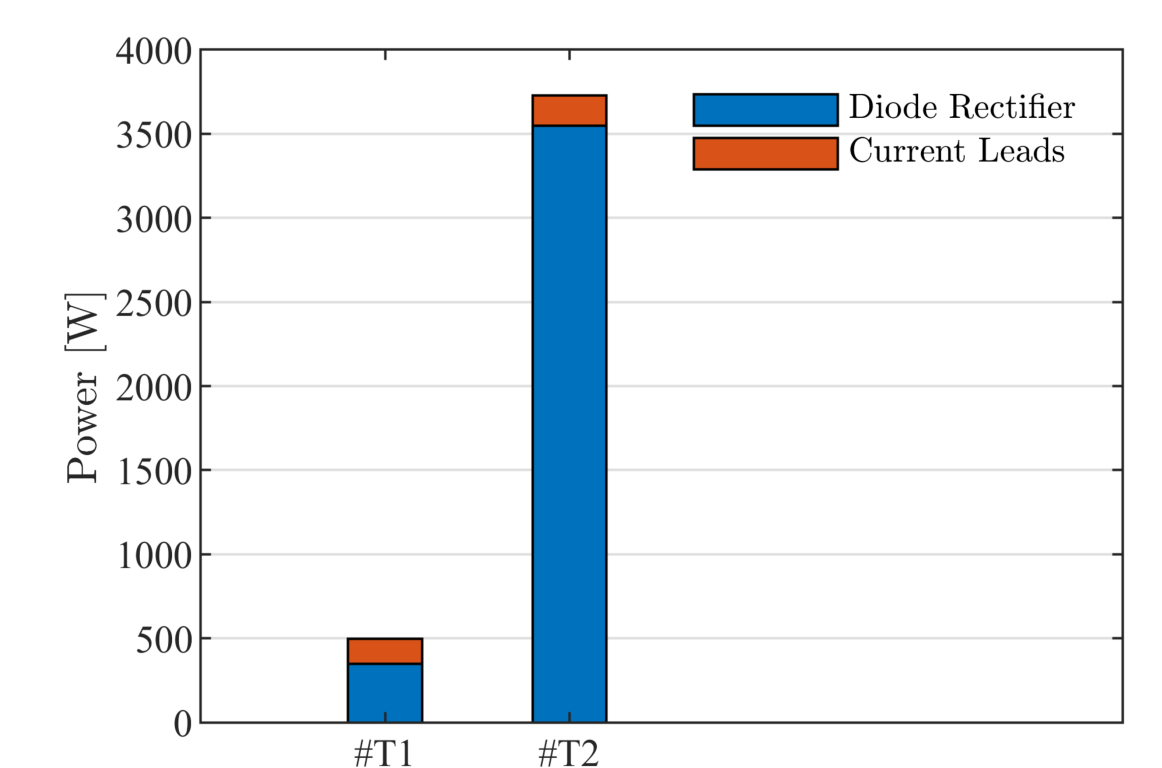
b) Diode rectifier efficiency

Fig.4. Simulated diode rectifier performances at room and cryogenic temperatures

System losses



a) The cooling is "free" (e.g. case of future hydrogen aircraft)



b) The cooling is produced by a machine

Fig.5. Comparison of the losses for each topology

Heat sink sizing

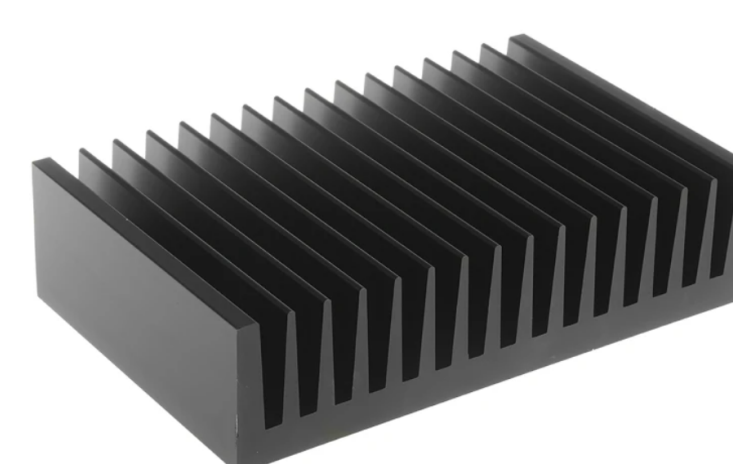


Table 3. Heatsink sizing

| Symbol | Parameter | Topology #T1 | Topology #T2 |
|--------------|--------------------|--------------|--------------|
| R_{jHA} | Thermal Resistance | 0.22 K/W | 1.20 K/W |
| H_{length} | Length | 0.18 m | 0.07 m |
| V_H | Volume | 4.50 L | 0.42 L |
| M_H | Mass | 0.120 kg | 0.001 kg |

Conclusion

Power diodes have different electrical characteristics at cryogenic temperatures, requiring a specific semiconductor study to select the best diode for the desired application. Operating a diode rectifier at 77 K slightly improves the system efficiency, but this efficiency is reduced if cooling power must be generated (i.e. is not "free"). The notable advantage is the potential reduction in the heatsink volume and weight by up to 90%, making it a promising solution for applications where weight is limited, such as wind power generation, aeronautical or naval transportation, especially when cooling power is freely available. The next steps are to build a prototype and test the models.

References

- [1] A. Elwakeel, Z. Feng, N. McNeill, M. Zhang, B. Williams, W. Yuan, "Study of power devices for use in phase-leg at cryogenic temperature," *IEEE Trans. Appl. Supercond.*, vol. 31, no. 5, pp. 1–5, Aug. 2021.
- [2] R. McFee, "Optimum input leads for cryogenic apparatus," *Rev. Sci. Instrum.*, vol. 30, no. 2, pp. 98–102, Feb. 1959.

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