Development of a cryogen-free test cryostat for a superconducting CCT short magnet

ICEC/ICMC
29th International Cryogenic Engineering Conference
International Cryogenic Material Conference 2024
July 22-26, 2024, Geneva, Switzerland

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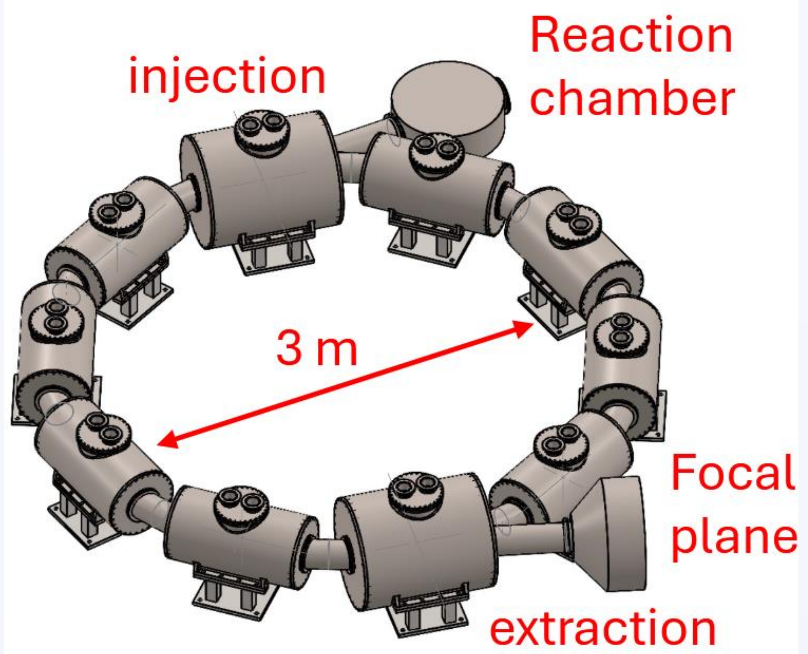
ABSTRACT

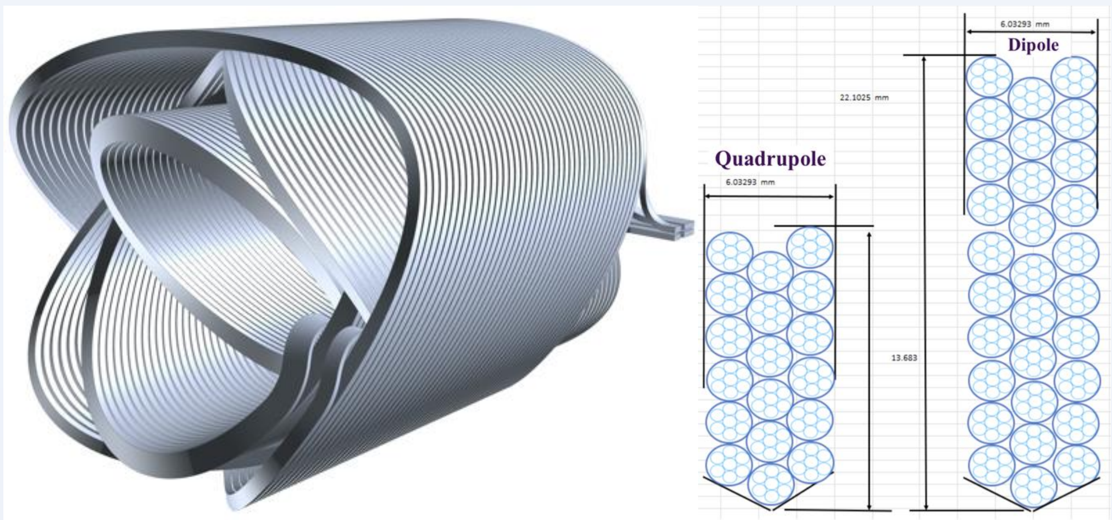
In the framework of the ISOLDE Superconducting Recoil Separator (ISRS) project (Martel, 2021), a short and straight CCT magnet demonstrator (MAGDEM) has been designed composed of a dipole and a quadrupole. The final ISRS spectrometer is intended to consist of 10 units of this CCT magnet arranged in a ring configuration. Additionally, this type of magnet could be used for proton therapy gantry systems. A cryogen-free test cryostat has been developed for the MAGDEM, considering the space constraints related to the installation of the spectrometer at ISOLDE. The magnet will be conduction cooled using cryocoolers to be independent of any liquid Helium supply. To speed up the cool-down time, a liquid nitrogen pre-cooling system has been included. This work mainly focuses on the design of the cryostat, encompassing descriptions of the different components, an optimization study of the current leads, and an analysis of the cool-down time. A prototype of the MAGDEM and its cryostat will be built and tested at Huelva University in the forthcoming years, funded by Spain's Recovery and Resilience Plan.



Conceptual design of the ISRS ring composed of 10 MAGDEM

SOLENOID DESIGN

- Bending angle of the beam : 36°.
- Dimensions of the MAGDEM : 580 mm length with a 200 mm beam aperture.
- Composed of 4 layers of wiring, with the 2 inner layers forming a dipole and the 2 outer layers forming a quadrupole.
- The wiring is made in aluminium formers. Additionally, an aluminium yoke surrounds the MAGDEM for dealing with Lorentz forces.



View of the MAGDEM wiring and assembly of the superconducting cables (Kirby, 2024)

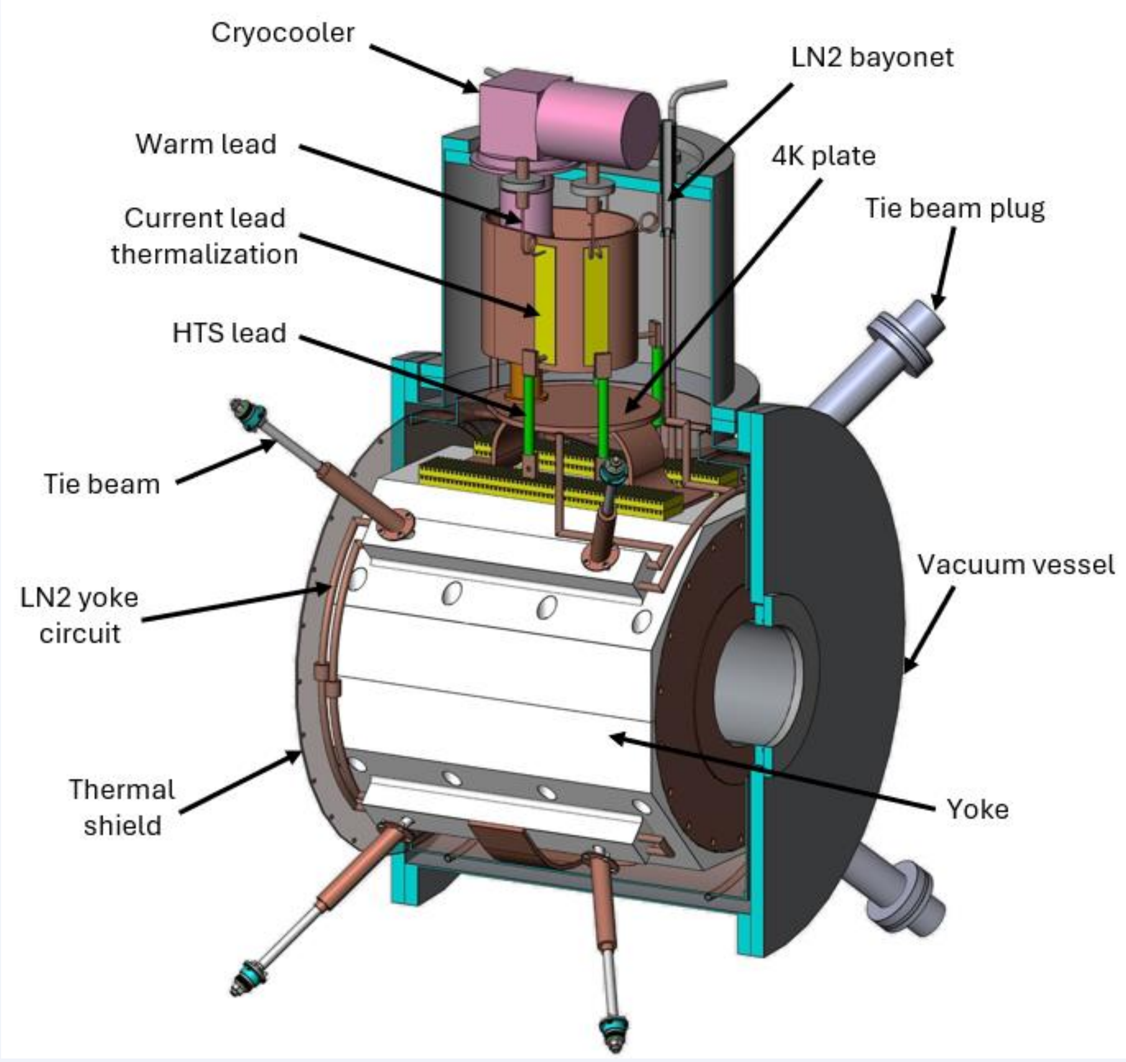
Specifications	Dipole	Quadrupole
Nominal current	91.6 A	112.8 A
Integrated field	0.751 T.m	0.246 T.m
Inductance	25.6 H	
Stored energy	112 kJ	
Inner radius (m)	115 mm	171 mm
Outer radius (m)	166 mm	203 mm
Number of layers	2	
Number of turns per layer	43	
Number of ropes per layer	30	18
Number of strands per rope	7	
Number of strands	210	126
Strand diameter	0.5 mm conductor + 0.125 mm insulation	
Strand conductor	Copper stabilized Nb Ti	
Copper / Nb Ti ratio	2 : 1	
Mass of conductor	27 kg	23 kg
Rope length	2.5 km	2.1 km
Strand length	17.5 km	14.7 km

Characteristics of the MAGDEM

CRYOSTAT DESIGN

Two versions of the cryostat were designed: one with a single cryocooler positioned at the top of the magnet, and another with two cryocoolers positioned at both the top and the bottom. In the end, the single cryocooler version detailed below was selected for the future construction.

- *Vacuum vessel* : made of Stainless Steel with 775 mm length, 1300 mm height and 900 mm width. The pressure inside must be maintained below than 1e-6 mbar to avoid convection heat transfer.
- *Thermal shield* : made of copper with a gold cover instead of using MLI for saving space.
- *Supports* : 8 tie beams thermalized made of Ti-6Al-4V, positioned with an angle relative to the radial component to accommodate the Lorentz forces and the weight. The thermal contractions are compensated with spring washers at the warm ends.
- *Cryocooler* : 2-stage G-M with the cooling capacity of 1.5W at 4.2K and 40W at 40K.
- *Current leads* : the two pairs of current leads were designed to operate at 120 A and are composed of two stages : the warm lead and the HTS lead.
- *LN2 circuit* : this was implemented to enable a LN2 pre-cooling of the cryostat.

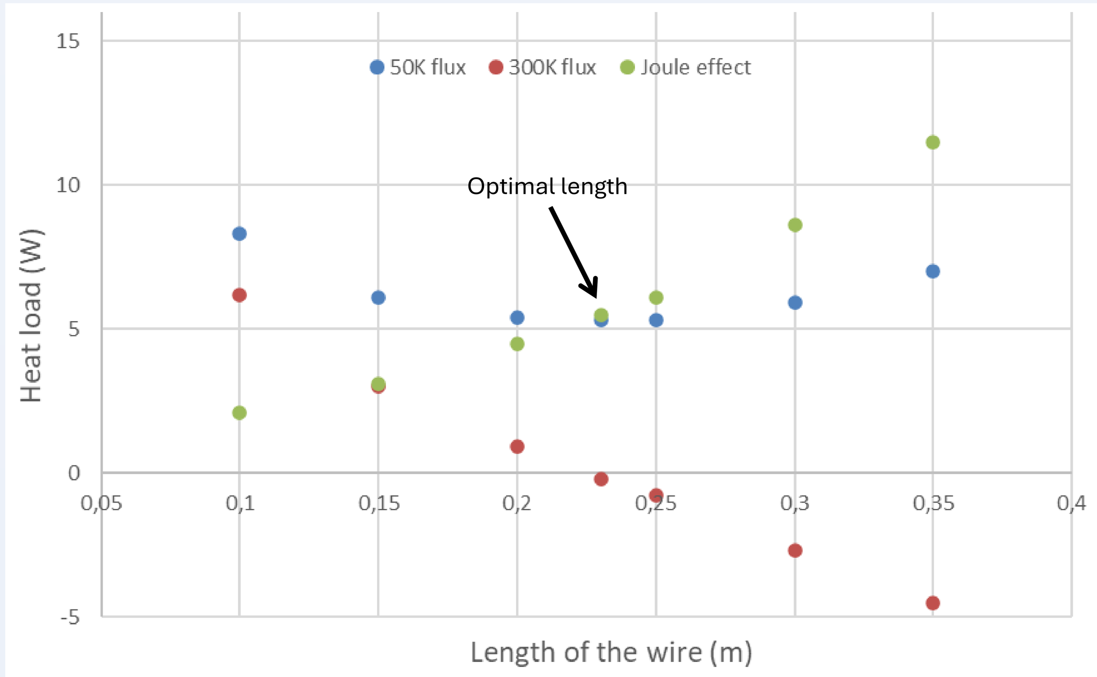


3D model of the MAGDEM cryostat

WARM LEAD OPTIMISATION

The warm leads are copper wires of diameter 3 mm and length 23 cm. These optimal dimensions were determined by solving a 1D model with conduction and the Joule effect for different lengths and diameters.

The result obtained with the 1D model are shown below. The minimum heat load of 5.3 W at 50K is achieved when the heat flux is equal to zero at the 300 K side.



Heat load of the 3 mm diameter copper warm lead

STATIC HEAT LOADS

- The heat loads at 50 K and 4 K are relatively low because the low currents in the dipole (92 A) and the quadrupole (113 A) reduce the heat loads associated with the current leads.

Component	On 50K (W)	On 4.2K (W)
Supports	12.1	0.36
Current leads	24.0	0.13
Radiation heat flux	12.1	0.01
Wire joints	-	0.02
Total heat loads	48.2	0.52

Result of the thermal study of the MAGDEM cryostat

COOL-DOWN STUDY

A python program was written based on the work of (Dhuley, 2021) to estimate the cryostat cool-down time. The idea is to compute the temperature variations of different components in the cryostat by solving the simplified heat equation :

$$\sum_k [m_k C_{p,k}(T_i)] \frac{dT_i}{dt} = Q_{\text{cond}} + Q_{\text{rad}} + Q_{\text{contact}} + Q_{\text{cryocooler}}$$

Where i are the components and k the component's materials. The conduction heat fluxes, the radiative heat fluxes and the thermal contact heat flux are given by :

$$Q_{\text{cond},i\to j} = \frac{S_k}{L_k} \int_{T_i}^{T_j} \lambda_k(T)\, dT$$

$$Q_{\text{rad},i\to j} = \sigma F_e S_j (T_j^4 - T_i^4)$$

$$Q_{\text{contact},i\to j} = \int_{T_i}^{T_j} C_{\text{contact}}(T)\, dT$$

As the materials properties vary significantly at low temperatures, interpolation functions based on the *Cryodata* libraries are used in the program for the thermal conductivity λ and the heat capacity C_p. Also, the solid-solid joint conductance $C_{contact}$ was taken in (Ekin, 2006).

The heat flux $Q_{cryocooler}$ is computed according to the capacity map of a PT415 from Cryomech which delivers 1.5W at 4.2K given in (Green, 2015). A python function was written to approximate this capacity map.

In the model, the different components whose temperature are resolved and the various thermal resistance considered are represented on the figure below, and the masses and materials of the components are given in the following table.

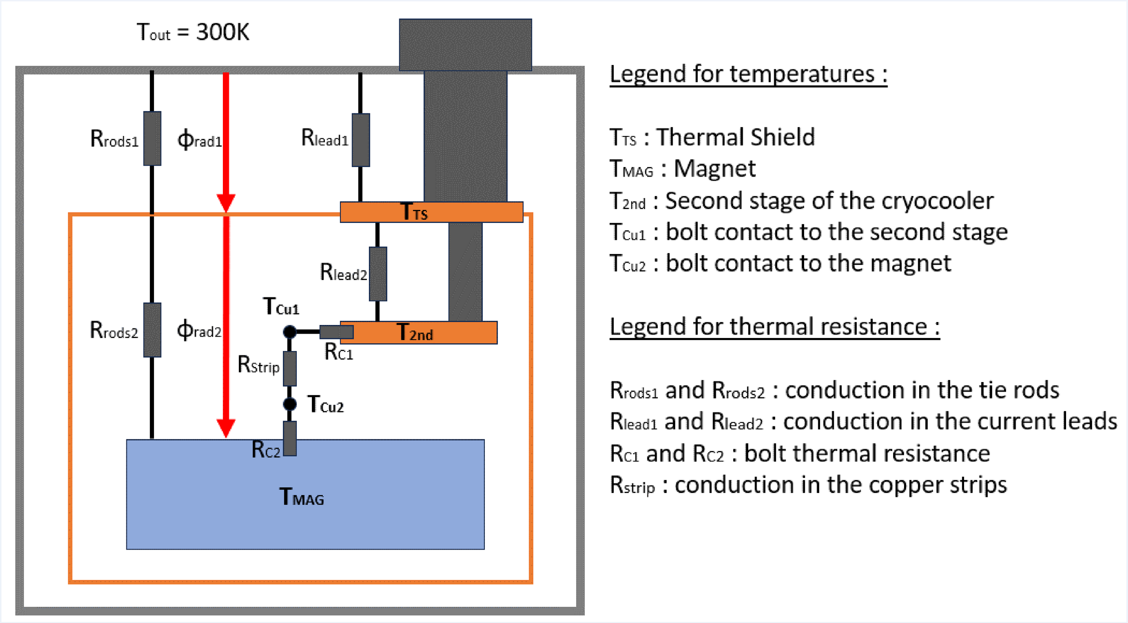


Diagram of the modelled cryostat

Component	Material	Mass
Thermal shield	Cu	50 kg
Magnet and yoke	Cu NbTi Al	40 13 kg 275
2nd stage copper plate	Cu	10 kg
Copper strips (4 units)	Cu	0.2×4 kg

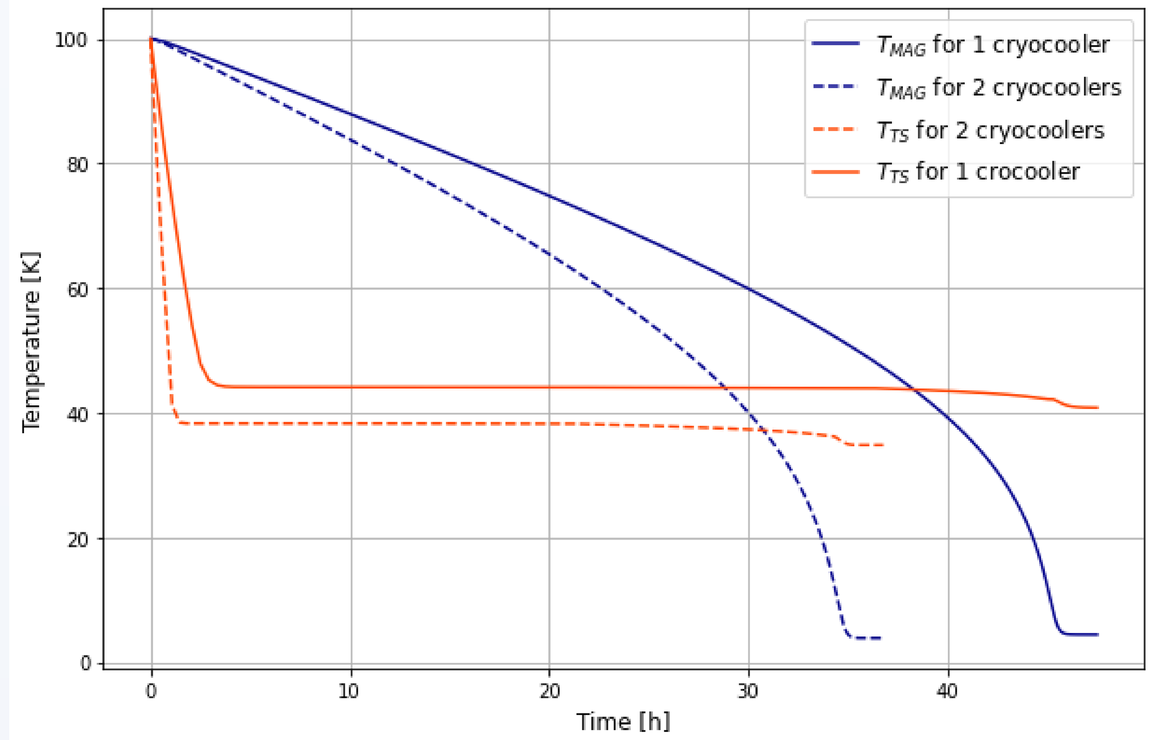
Component's masses and materials

Results of the cool down study starting at 100 K (assuming LN2 pre-cooling)

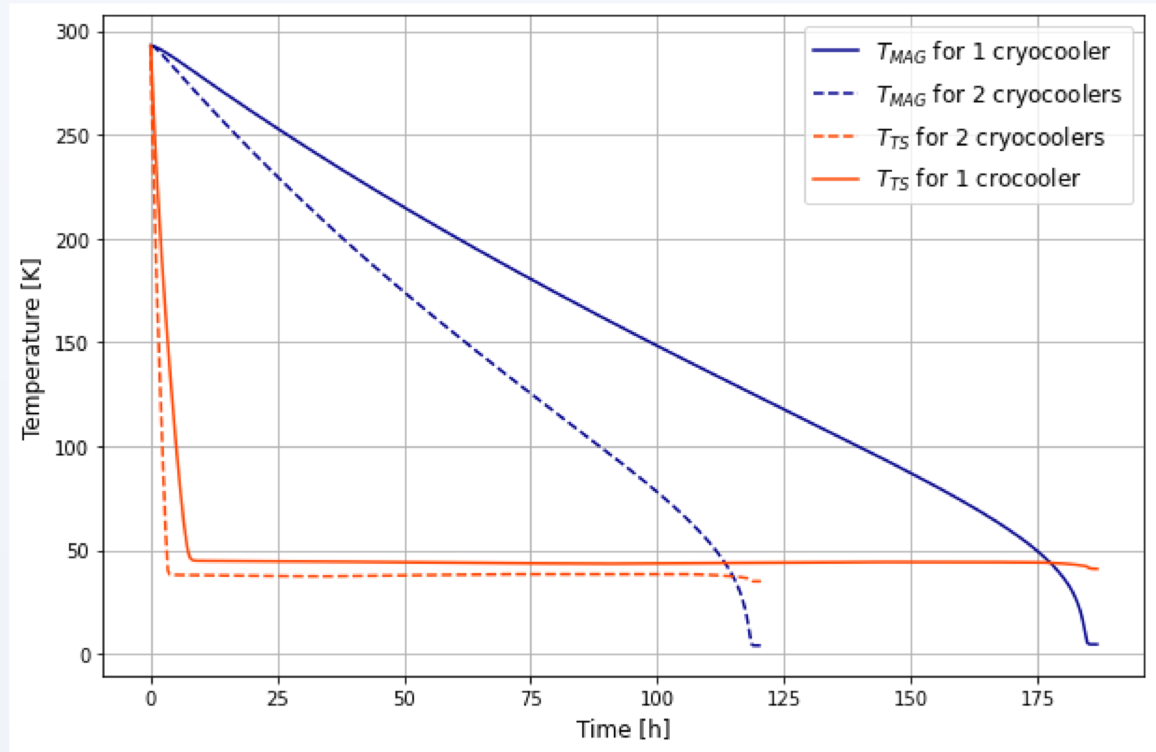
- 1 cryocooler : 46 hours
- 2 cryocoolers : 35 hours

Results of the cool down study starting at 293 K

- 1 cryocooler : 185 hours
- 2 cryocoolers : 119 hours



Cool-down simulation starting at 100 K



Cool-down simulation starting at 293 K

SUMMARY

A dry test cryostat was designed within the framework of the ISRS collaboration, for cooling down a CCT superconducting magnet called MAGDEM to approximately 4 K. The cryostat was design to be as short as possible, and it was optimized for having the lowest heat loads. The cool down study performed has shown that the cryostat with a single cryocooler should take about 46 h to cool down after LN2 pre-cooling. The MAGDEM prototype and its cryostat will be built and tested at Huelva University in the forthcoming years.

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Acknowledgement :

This work was supported by European Union NextGenerationEU/PRTR project C17.I02.P02 - SGI-GICS-Nuevas actuaciones en grandes infraestructuras de investigacion europeas e internacionales, subproject ISRS (Univ. Huelva) C17.I02.P02.S01.S05.

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