Justification of resources

Cost effectiveness: The programme benefits from substantial prior investment in people and laboratory infrastructure and from a network of project partners with world-class expertise in specialised measurement and sample characterisation methods as well as theory. We have recruited four fully funded students to work in this field of research, with two more likely to join in October 2022, and key equipment is already available. Funding for this 36-month programme is needed primarily to support postdoctoral research assistants totalling 1.4 FTE in crystal growth and low temperature/high pressure/high field measurements and to support collaborative research with project partners around the world.

1. Directly allocated costs

Principal investigator: Prof. Grosche will commit 15% of his time to experimental studies in Cambridge and at central facilities, coordination of collaborative work with project partners, data analysis and dissemination of results as well as supervision of PDRAs.

Pooled labour: To support the technical aspects of this programme, such as cryogenic probe modifications, high pressure cell design and manufacture, and maintenance of our cryogenic and crystal growth equipment, we require 27% of a pooled technician.

2. Directly incurred costs

2.1. Staff

Co-Investigator: Dr. Sutherland will commit 10% of his time to quantum oscillation and thermal transport experiments, coordination with project partners, instruction of PDRAs, data analysis and dissemination of results. He is already fully funded by a college position and requires no support from this project.

Assistants: The wide-ranging nature of this programme necessitates support from a postdoctoral research assistant for the full duration. We have identified a suitable PDRA, Dr. Jiasheng Chen, who has grown the materials mentioned in the scientific case using careful and systematic optimisation of growth protocols. Dr. Chen's extensive experience in crystal growth but also in low temperature measurement as well as neutron scattering and muSR studies will ensure that the challenging programme of research will be successfully completed and that postgraduate students are trained for crystal growth and high sensitivity measurements at low temperature and in high magnetic fields. High pressure measurements form an important part of this programme. We ask for 12 months' support for a suitable PDRA, Dr. Puthipong Worasaran, who has developed world-class skills in high pressure transport measurements during his PhD. We also ask for 10% support over 36 months to enable Dr. Patricia Alireza, a world-class expert in high pressure techniques and measurements, to oversee high pressure technique development and train PhD students. As an Emeritus Professor, Prof. Lonzarich requires no support from this project.

2.2. Travel and subsistence

To publicise the scientific results and train students and PDRAs, two researchers will attend an overseas conference every year ($2 \cdot 3 \cdot £1,400$), and two researchers will visit a national or European conference or workshop every year ($2 \cdot 3 \cdot £500$).

We will visit UK or European research facilities for some of our research, benefiting from existing arrangements which guarantee full funding of travel and accommodation and thereby avoiding direct costs. The only exception is PSI (Switzerland) (3·£1,000). We intend to run measurements at LNLS (Brazil) remotely.

Collaborations with project partners form an important component of this project. We anticipate three visits by Cambridge researchers to collaborating groups (3· £1,000) and budget £1,000 for 3 weeks accommodation for visitors to Cambridge.

2.3. Equipment

We need to replace our aging radio frequency generator, which has become so unreliable that it is holding back our crystal growth programme. We depend on it for induction heating on a water-cooled hearth in UHV-compatible conditions for stand-alone crystal growth and to produce precursors for other growth methods. Costs have come down recently, allowing us to acquire a modern transistor operated 40 kW/200 kHz Trumpf TruHeat MF 3000-40 G3 generator for £32,015.36. This reliable machine will be the new centrepiece of our crystal growth effort.

3. Other directly incurred

Crystal growth: We employ our established equipment (arc furnaces, a mirror furnace, numerous box and tube furnaces, dedicated glovebox, glass-working station) to implement a wide range of growth methods. For this, we budget

£6,000 for raw materials (20 growths per year at £100 per growth), £1,500 for vacuum spares, £3,000 for crucibles and glassware, and £2,000 for a diamond saw to complement our wire saw.

Research at extremes of field, temperature and pressure: We optimise cost effectiveness by using a hierarchy of low-consumption cryostats to reduce the load on the highest field systems.

The lowest temperatures and highest fields provided by our 20.4 T/single-mK system will be required to observe quantum oscillations in challenging materials with high quasiparticle masses, to investigate non Fermi liquid phenomena to the lowest temperatures and in high applied fields and to open up a wide parameter space for the search for novel forms of quantum order. We keep utilisation of this facility for this project to 90 days per year by spreading most measurements to other systems with lower helium consumption: our 15 T/300 mK system is well suited for electronic structure determination in clean materials with low effective carrier masses, and its wider magnet bore enables rotation studies with our larger pressure cells. A cryogen-free adiabatic demagnetisation refrigerator, which reaches 7 T/100 mK, offers convenient and low-cost access to low temperatures and moderate magnetic fields. It is well suited for electrical transport, heat capacity and thermal conductivity measurements over a wide temperature range. Our commercial measurement platforms (PPMS, SQUID magnetometer) are crucial for research measurements and sample characterisation and alleviate the pressure on more costly cryomagnets. Including maintenance and helium liquefaction, the cost of running these systems is about £35/day. Thanks to their low running costs and near 100% utilisation, they offer excellent value for money.

We have recently developed multi-stage demagnetisation refrigeration modules which offer superior cooling performance and longer hold time at base temperatures less than 80 mK. We will produce such modules to upgrade our 7T/100 mK system and to extend the capabilities of our PPMS measurement platform. These modules have significant commercialisation potential, because they can be retrofitted to wide-spread platforms such as PPMS or Heliox, which can create tangible economic impact from this project.

Research cryostats: The total cost of running the research cryostats will be £116,950, of which £25,600 are directly incurred (facility costs are given below). These divide up into £7,000 for the 20.4 T system (£6,000 for maintenance, £1,000 for low temperature consumables such as wiring or indium), £3,000 for maintenance of the 15 T/300 mK system, £6,600 for the cryogen-free 7 T/100 mK system (£3,600 for maintenance, £3,000 for machining and materials for the new demagnetisation module mentioned above), £6,000 for running the PPMS (£3,000 for maintenance, £3,000 to create the new demagnetisation module mentioned above), and £3,000 for maintenance of the SQUID magnetometer.

High pressure: New, miniaturised high pressure cells will be required for quantum oscillation studies using tank circuit oscillator techniques and for magnetic or transport measurements. With their reduced length and outer diameter of only 11 mm they fit the highest field systems at the Nijmegen HFML facility and they allow rotation studies in the Cambridge cryomagnets. We draw on our experience in pressure cell design and manufacture to undercut commercially available cells by a factor of ten. We budget for four new high pressure anvil cells at a materials and machining cost of £1,800 each (including anvils).

Signal detection equipment, general consumables: We budget £5,500 each to acquire two SR860 lock-in amplifiers, which can be moved between measurement systems for challenging measurement tasks, and £4,300 for tools and workshop materials (£300), a calibrated low temperature resistance thermometer (£2,000) and a batch of 20 piezoresistive cantilevers for magnetic torque measurements (£2000).

4. Directly allocated: facilities

The research cryostats will incur £91,350 for helium liquefaction. The unique capabilities of our 20.4 T system and the prohibitive cost of replacing other platforms by dry systems require the use of liquid helium. Economy of scale allows a competitive rate of £5.00/ℓ. We require £33,750 for running the 20.4 T system (25ℓ He/day for 90 days/year), £9,000 for the 15 T/300 mK system (10ℓ He/day for 60 days/year), £32,400 for the PPMS (6ℓ He/day for 360 days per year), and £16,200 for the SQUID magnetometer (6ℓ He/day for 180 days per year). X-ray and microprobe sample characterisation will incur a facilities charge of £6,000 (30 days at £200 each). The pressure work incurs facilities charges of £2,850 for clean room access to deposit tracks on anvil surfaces (£950 per year over three years), and £3,200 for using the Cavendish focused-ion-beam facility ($10 \cdot 4$h at £80/h) for sculpting and contacting samples on the microscale.