REPORT OF THE
ROADMAPPING WORKSHOP:

BULK SUPERCONDUCTIVITY

7 June 2016

This workshop was commissioned by the EPSRC Impact Acceleration Account (IAA) at the University of Cambridge.

EXECUTIVE SUMMARY

The Bulk Superconductivity Group is working to apply high-temperature superconductors to practical engineering problems. The group was originally part of the former IRC in Superconductivity and is now part of Division C (Materials and Mechanics) of the Department of Engineering.

The Group organised a Roadmapping Workshop in Cambridge on 7 June 2016 to identify where the bulk superconductivity field may develop over the medium and long terms and to align the research strategy of the academic community to the needs and requirements of its industrial partners.

The most pressing **industry needs** identified were:

- Developing manufacturing processes for large-scale bulk production;
- Developing reliable manufacturing processes for medium-scale bulk production;
- Demonstrating devices for small-scale system demonstrations;
- Developing better magnetisation techniques and higher trapped fields;
- Developing better and cheaper cryogenic modules and systems;
- Reducing the production cost of bulk superconductors without compromising performance;
- Better mechanical properties;
- Optimising geometries and reducing thickness.

Overall, 32 potential applications were identified across 5 different sectors. These were prioritised using pre-selected criteria and 20 were shortlisted as presenting both good market opportunity and being feasible. From this shortlist, the following **five applications** were selected for further exploration:

- Portable, high-field magnet systems (not NMR or MRI);
- Portable medical instruments, for example, NMR and MRI;
- Magnetic shielding applications for electric machines, equipment and other high-field devices;
- Rotational and linear magnetic bearings;
- Ultralight superconducting motors / generators.

These five applications were scoped and explored in more detail in five focus groups. The technology developments required for their commercialisation were explored, as well as the current or anticipated roadblocks and barriers. The main **technology priorities** were identified as:

- Building interdisciplinary groups for excel system integration;
- Cheap and reliable cryocoolers; cryosystems' development;
- Material performance;
- Reduced system cost / life-cycle cost;
- Cost breakdown of components and market analysis (aircraft, ships);
- Technology prototype; development of lab demonstrator;
- Furnace technology high stability;
- Magnetisation (pulsing); pulse charging development; development of magnetisation system / process;
- Scaling the manufacturing process; scale-up of materials processing;
- Large plates MgB_2;
- Large plates (RE) BCO; materials' development / larger samples;
- Mechanical properties (analysis / improvement); YBCO J_c and mechanical properties' optimisation;
- Demagnetisation and mitigation (AC loss, flux creep);
- FEM – modelling for bearing development.

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WORKSHOP DETAILS

DATE

7 June 2016, 9.30am–5.00pm

VENUE

The Institute for Manufacturing (IfM)
17 Charles Babbage Road
Cambridge
CB3 0FS

FACILITATORS

Dr Nicky Athanassopoulou
Senior Industrial Fellow
IfM Education and Consultancy Services

Ms Andi Jones
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IfM Education and Consultancy Services

A list of delegates is provided in the Appendix.

WORKSHOP GOALS

BACKGROUND

The Bulk Superconductivity Group was originally part of the former IRC in Superconductivity and is now part of Division C (Materials and Mechanics) of the Department of Engineering. The Group's research is aimed at both enhancing the fundamental performance of superconducting bulk materials and tailoring them to specific applications. Superconducting bulk samples have the potential to replace conventional permanent magnets in existing devices, such as motors and generators, with considerably superior performance.

The group has developed a new practical growth route using a "generic seed" that has allowed the production of bulk material in larger diameters, which can trap fields of up to 1 Tesla.

The group has longstanding collaborations with other academic institutions, industry and end-users around the world.

AIMS

The Bulk Superconductivity Group initiated a Roadmapping Workshop to understand the main industrial needs and potential future applications for the bulk superconductivity field. The workshop's specific aims were to:

- Identify where the bulk superconductivity field may develop over the medium and long terms;
- Frame a research strategy for the academic bulk superconductivity community; and
- Align the research strategy to those of its industrial partners.

The roadmap covers three time periods: the short term (+3 years, i.e. up to 2019); the medium term (+5 years, i.e. up to 2021); and the long term (+10 years, i.e. up to 2026). This includes three broad layers: (1) customer needs; (2) applications; and (3) technology.

The workshop was designed to capture and prioritise the current and anticipated industry needs and to enable the generation of multiple and diverse application ideas. These applications were then prioritised with five applications selected and explored further. Aspects such as the desired performance parameters of these applications, and the current or anticipated roadblocks and barriers, were addressed and summarised. Finally, specific research priorities were derived that could assist the further development of the four priority applications.

Overall, 16 participants contributed to the workshop. The participants were from both academia and industry, working on the bulk superconductivity area.

METHODOLOGY

The Roadmapping Workshop methodology consisted of three parts; planning and design; the workshop; and the client report.

PLANNING AND DESIGN

During the planning and design phase, the following activities took place:

- Confirming and detailing the aims and scope of the workshop;
- Discussing and designing the workshop methodology and process. The workshop used the **S-Plan** framework developed by the IfM over a period of several years [1, 2, 3]. The framework has been configured to support universities to align their research activities with industry needs, supporting decision-making and action;
- Designing the workshop templates necessary for any pre-work activities and the workshop;
- Agreeing on the selection criteria that are important for the Bulk Superconductivity Group in terms of assessing the different applications;
- Agreeing the detailed workshop agenda;
- Finalising any logistical arrangements required (venue, catering etc.).

WORKSHOP

The workshop process brought together 15 participants and had the following structure:

- Welcome and introductions;
- A presentation by Dr John Durrell on the workshop's main aims, a detailed presentation of the new technology, its potential benefits and its current limitations;
- A presentation by each participant of the main customer needs and potential applications for the technology;
- Prioritisation of customer needs;
- Prioritisation of the different applications using a list of pre-defined selection criteria;
- Selection of the most appropriate applications;
- Exploration of the selected applications in small groups, and clarification of the technology development required to enable commercialisation;
- Identification of key research priorities to enable faster commercialisation of the technology;
- Feedback and review.

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[1] http://www3.eng.cam.ac.uk/research_db/publications/rp108
[2] Phaal, R., Farrukh, C.J.P. and Probert, D.R. (2004), "Customizing Roadmapping", *Research Technology Management,* 47 (2), pp. 26–37.
[3] Phaal, R., Farrukh, C.J.P. and Probert, D.R. (2007), "Strategic Roadmapping: A workshop-based approach for identifying and exploring innovation issues and opportunities", *Engineering Management Journal,* 19 (1), pp. 16–24.

REPORTING

Finally, IfM ECS transcribed all the output from the workshop in electronic format, drafted the current report and distributed it to the Bulk Superconductivity Group for review and wider circulation.

CUSTOMER NEEDS

Each participant contributed his / her views on the most important customer needs. These were consolidated and reviewed at the beginning of the workshop, whereby a few additional needs were added to the list. Each participant was provided with four sticky dots and asked to select a maximum of four **needs** that they considered to be the most important. Academics were given blue-coloured dots and industrial participants black. This was to enable the identification of the **needs** considered most important by each of the different sectors, as well as the needs considered important for both academia and industry.

The customer needs and the votes received by participants are shown in Table 1 (below).

Customer needs	Timescale	Total votes	% of votes	
			Academia	Industry
A. Develop better magnetisation techniques and higher trapped fields	ST-MT	9	20%	5%
H. Develop better and cheaper cryogenic modules and systems	ST-LT	8	15%	10%
I. Develop reliable manufacturing processes for medium-scale bulk production	ST-MT	6	10%	10%
N. Better mechanical properties	LT	6	8%	15%
G. Develop demonstrator devices for small-scale system demonstration	ST-MT	5	10%	5%
B. Develop manufacturing processes for large-scale bulk production	ST-LT	4	5%	10%
C. Having bulks with high and uniform current densities, Jc	ST-MT	4	10%	0%
E. Develop bulk devices and components to integrate into larger systems	ST-LT	3	0%	15%
F. Reduce production cost of bulk superconductors without compromising their performance	MT-LT	3	3%	10%
O. Optimised geometries and reduced thickness	LT	3	3%	10%
S. Proper modelling techniques	ST	2	0%	10%
T. Demonstration of safety concept	ST-MT	2	5%	0%
U. Environmental impact	ST	2	5%	0%
D. Increase the size of hollow bulk samples and square plates with reproducible synthesis methods	ST-LT	1	3%	0%
K. Improve the long-term operational stability of bulk superconductors	LT	1	3%	0%
M. Synthesise large-scale seeded bulks, doping	MT	1	3%	0%
J. Develop higher Tc materials	MT	0	0%	0%
L. Synthesise perfect textured and doped bulk material – unseeded	LT	0	0%	0%
P. Reduce the amount of superconducting material required for applications	LT	0	0%	0%
Q. Develop better joining techniques for bulk superconductors	LT	0	0%	0%
R. Commercial suppliers	MT	0	0%	0%
V. Adequate customer information	ST	0	0%	0%
W. Understanding of mechanical properties under magnetisation	ST-MT	0	0%	0%
X. Safe supply choice	MT	0	0%	0%

Table 1: Prioritised customer needs

The customer needs voted ***important by both academia and industry*** were the following eight:

- Developing manufacturing processes for large-scale bulk production;
- Developing reliable manufacturing processes for medium-scale bulk production;
- Demonstrating devices for small-scale system demonstrations;
- Developing better magnetisation techniques and higher trapped fields;
- Developing better and cheaper cryogenic modules and systems;
- Reducing the production cost of bulk superconductors without compromising performance;
- Better mechanical properties;
- Optimising geometries and reducing thickness.

The customer needs deemed ***important for industry,*** but which didn't attract any academic votes were:

- Developing bulk devices and components to integrate into larger systems;
- Proper modelling techniques.

The customer needs deemed ***important by academia*** only were:

- Having bulks with high and uniform current densities, J_c;
- Demonstration of safety concept;
- Environmental impact.

The eight customer needs identified as being most important by both academia and industry were subsequently used to assess the different applications proposed for the bulk superconductivity field.

IDENTIFICATION AND PRIORITISATION OF APPLICATIONS

Overall 32 potential **applications** were identified for the bulk superconductivity field. These were subdivided into the following sector-based layers:

- Levitation
- Rotating machines
- Trapped fields
- Biomedical
- Other

Table 2 (below) shows the number of applications included within each sub-layer.

Sector	Number of applications proposed
Levitation	11
Rotating machines	8
Trapped fields	6
Biomedical	2
Other	5

Table 2: Number of bulk superconductivity applications identified for different sectors

The majority of applications identified were in the levitation sector. There is a good balance between short-, medium- and long-term applications. A list of all applications identified is shown in the Appendix.

Each of the 32 applications proposed during the workshop was assessed using two different and broadly separate considerations: opportunity and feasibility. Opportunity was defined as the magnitude of the opportunity plausibly available to an organisation. Feasibility was defined as how well prepared the organisation is to grasp the opportunity.

The opportunity and feasibility criteria had been selected prior to the workshop by circulating a list of possible factors to Dr Durrell at the Bulk Superconductivity Group at the Engineering Department and asking him to select the top three opportunity and feasibility criteria respectively. The ones selected and used during the workshop are shown in Figure 1 (below).

Industry/market readiness	How easy will it be for customers or adopters to take up the product; do they have to change their behaviour or processes?	**Market knowledge**	Do we understand the size and requirements of the market?
Business cost reduction or simplification	Facilitates cost reduction or simplification of business processes	**Technical challenge**	How confident are we that the proposed product is technically feasible?
Customer benefit	Identifiable benefit to customers (internal or external) or potential adopters	**Technical capability**	Do we have the required technical competence to design the product? Do we have ownership of required IP?

Figure 1: Opportunity and feasibility criteria used to assess the different bulk superconductivity applications

The assessment process took place in two parts. First, each participant was asked to review the 32 applications and independently select 6, based on the 3 opportunity factors. The participants placed their votes on the actual post-its using six green sticky dots. Participants were discouraged from voting for the applications they had contributed to unless they were part of a larger group or cluster. This created a shortlist of 20 applications.

In the second step, participants were asked to consider only applications that had already received opportunity (green) votes. Each participant was then asked to independently select three applications based on the three feasibility factors. Participants placed their votes on the actual post-its using four orange sticky dots. The second step narrowed the applications down to a shorter list of 11, which was considered further during the workshop. This shorter list still contained applications from all sub-layers of the roadmap and across all different timescales.

The first shortlist of 20 applications that were assessed as having a good market opportunity and / or feasibility are shown in Table 3 (below).

Rank	Applications	Opportunity votes	Feasibility votes
1	6. Electric machines utilising trapped flux magnets; 8. Motors and generators	15	9
2	2. Rotational and linear bearings	12	9
3	11. Portable, high-field magnet systems	9	10
4	1. Portable medical instruments, for example, NMR and MRI	7	1
5	31. Biomedical applications such as cell separation, magnetic drug targeting	7	7
6	3. Flywheels and rotating machines for energy storage systems	6	1
7	4. Magnetic shielding applications for electric machines, equipment and other high-field devices	4	1
8	30. Superconducting machines for electric aircraft; 34. Aircraft propulsion	4	3
9	35. Handling systems for industrial automation plug and play "non-contact"	4	2
10	21. Prototypes of positioning systems	2	1
11	33. Superconducting wind turbine generators	1	1

12	15. Rocket launchers for space or military applications	3	0
13	15. Rocket launchers for space or military applications	3	0
14	10. Magnetic levitation tube transport	2	0
15	14. Magnetic flux collecting and compression device	2	0
16	16. Shielding for space applications	2	0
17	5. Magnetic levitation trains	1	0
18	13. Current leads	1	0
19	17. Passive dampers	1	0
20	32. Diamagnetic applications FM / SM hybrid magnetic lenses	1	0

Table 3: The first shortlist of 20 applications, including the feasibility and opportunity votes received by each

Eleven applications from the shortlist above had both good market opportunity and feasibility. These were transferred onto a 2x2 matrix, with opportunity shown on the vertical axis and feasibility on the horizontal axis (see Figure 2 below). This was to facilitate both decision-making and selection of the most appropriate applications for exploration during the workshop.

Applications placed on the top-right quadrant (high feasibility and high opportunity) were of immediate interest. Applications on the top-left quadrant (low feasibility / high opportunity) may represent possible long-term opportunities. Applications placed on the bottom quadrants (low / high feasibility and low opportunity) were not automatically dismissed, as they might enable other applications or support longer-term prospects.

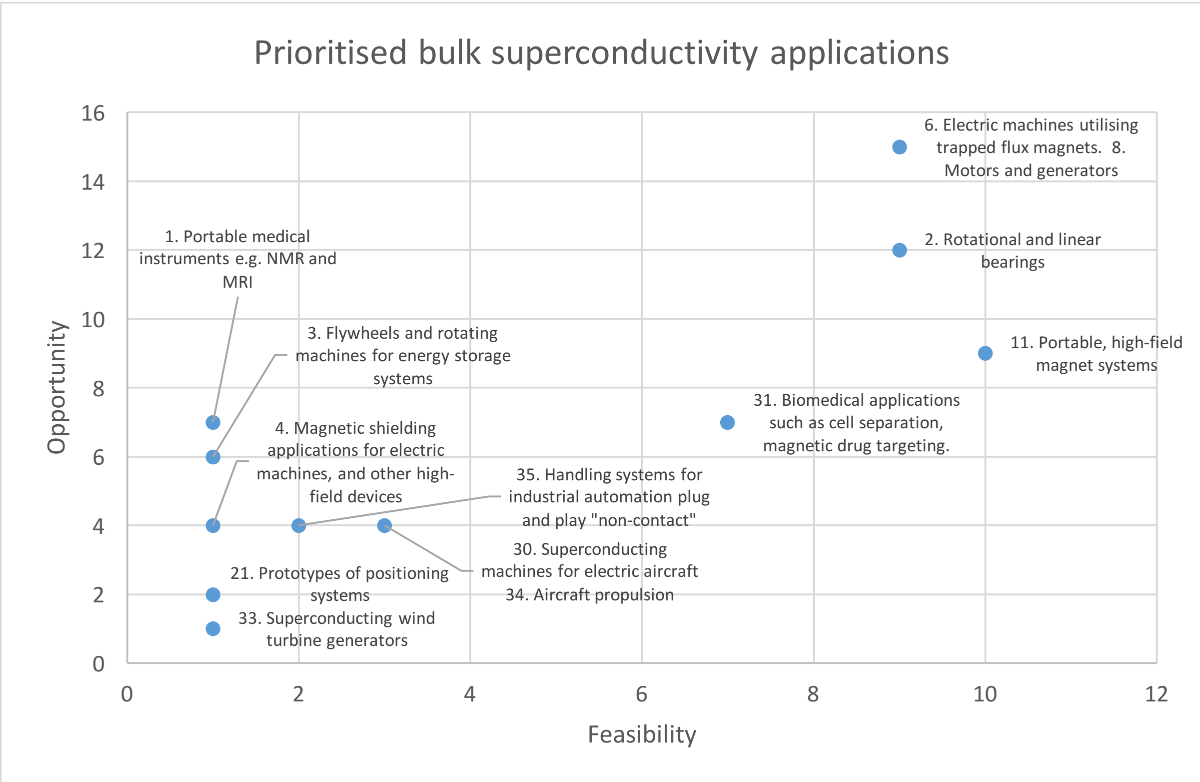


Figure 2: Application prioritisation chart using feasibility–opportunity axis

Some applications were further grouped, as they were quite similar. These were:

- 30. Superconducting machines for electric aircraft; 33. Superconducting wind turbines (generators) and 34. Aircraft propulsion.
- 2. Rotational and linear bearings; and 35. Handling systems for industrial automation plug and play “non-contact”.

Applications and groups were then reviewed regarding the following aspects to achieve a balanced selection: their relative scores and position in the 2x2 chart; the sectors or categories to which they belonged; and the timeline of the application (short, medium or long term).

Consequently, the following five applications were shortlisted for further exploration:

- Portable, high-field magnet systems (not NMR or MRI);
- Portable medical instruments, for example, NMR and MRI;
- Magnetic shielding applications for electric machines, equipment and other high-field devices;
- Rotational and linear magnetic bearings;
- Ultralight superconducting motors / generators.

A summary of the workshop output is shown in Figure 2, where the key customer needs, the final shortlist of 11 applications and the technology benefits and limitations are shown across the different timescales and sectors.

Figure 3: Summary of workshop output of priority customer needs, applications and technology benefits and limitations

SELECTED APPLICATION ROADMAPS

The summaries and high-level roadmaps for the five priority applications are described in the sections below. The high-level roadmaps include the following fields:

- Detailed description of the application and its performance requirements;
- Scope and boundaries of the application, indicating aspects that are included and excluded from further development;
- Desired milestones for a top-level development plan;
- Required technology, research and / or capabilities for each milestone;
- Links to the key customer needs and requirements;
- Any key success factors or important knowledge gaps that need to be addressed;
- Specific actions and commercialisation steps required to assist further development of the application.

The current and future performance requirements for each application are also summarised. These were assessed using a linear Likert scale from (1) to (5), where (1) indicates poor performance and (5) indicates excellent performance. Four performance requirements were required by more than one application. These were *cost* (especially system or production cost), *size / compactness of the system*, *fast magnetisation* and *scalability*. These requirements would therefore need to be addressed as a priority by putting in place specific research and technology development activities. Table 4 (below) shows the four common performance requirements, their applicability for each of the five applications, as well as the current performance gap (i.e. 0 = no performance gap, 4 = maximum performance gap).

	Portable, high-field magnet systems for biomedical applications (not NMR or MRI)	Portable medical instruments, for example, NMR or MRI	Magnetic shielding applications for electric machines, equipment and other high-field devices	Rotational and linear magnetic bearings	Ultralight motors / generators
Cost	3.0	2.5	4.0	1.5	2.0
Size / Compactness	1.0		0.0	1.0	
Scalability			4.0	2.0	
Fast magnetisation	2.0	1.5			

Table 2: The four common performance parameters across the five applications. The numbers indicate the current performance gap (i.e. 0 = no performance gap, 4 = maximum performance gap)

When the overall performance gap of each application is assessed (i.e. the difference between future and current for each performance requirement), the *portable, high-field magnet systems for biomedical applications* and *specific magnetic shielding applications* showed the smallest gap. These probably represent good, shorter-term commercial opportunities. *Portable medical instruments (NMR or MRI), magnetic bearings* and some *magnetic shielding applications* are medium-term opportunities and *ultralight motors / generators* show the largest performance gap and therefore represent a longer-term option.

PORTABLE, HIGH-FIELD MAGNET SYSTEMS FOR BIOMEDICAL APPLICATIONS (NOT NMR OR MRI)

This application uses the gradients of a static magnetic field to trap species that are tagged with bio-compatible magnetic nanoparticles. Three areas of interest were identified. The first is magnetic drug targeting, where a tagged drug is brought to the right place using a magnetic field (e.g. for cancer or other therapies). The second area uses hyperthermia to treat tumours; for example, bringing a magnetic field into close proximity with a tumour, targetting it and using RF or other methods to produce local heating to destroy the tumour. The third area of interest identified was cell separation, whereby tagged cells are separated using magnetic fields.

A success factor for such an application would be combining magnets with other techniques, namely ultrasonic, and designing a modular system that is plug and play. It is important to be able to design magnets with high-field gradients, for either *in vivo* or *in vitro* applications. For *in vivo* applications, the magnet diameter would need to be approximately 80 millimetres in order to achieve a useful magnetic field. For *in vitro* applications the magnet's diameter can be a lot smaller (e.g. 15 mm), as such a system would predominantly be used in small laboratories.

For a full-scale design model that would enable a production model, there are a few critical requirements, such as further material development to achieve better homogeneity during the magnesium diboride production process. The production capacity of the raw materials would also need to be increased and the system production costs reduced. In the non-technical areas, commercial engagements must be established and IP captured and protected.

The anticipated risks for this application are the thermal loads during charging, the availability of research funding, the potential market size of such an application, IP leakage and legislations that may restrict the use of magnetic gradients on humans.

Figures 4 and 5 (below) show the roadmap and the current and future performance requirements for this application.

Application description/scope	**Application summary description:** Static fields for trapping species tagged with biocompatible magnetic nano-particles	**Scope** **What's IN:** Magnetic drug targeting Hyperthermic Cell separation **What's OUT:** MRI/NMR Imaging	**Desired future** **What success would look like** • Combined u/s and magnet. Plug & Play • High field and gradient. In vivo, in vitro • High Jc. Large diameter. In vivo ~ 80mm In vitro ~ 15 mm
WHEN	***Short term (+3 years)***	***Medium term (+5 years)***	***Long term (+10 years)***
Stepping Stones / Milestones / Demo Chain	System requirements and definition Detailed design and prototyping Materials and property demonstrator	Cost reduction Production engineering. Sub-system costs analysis Pre-production model. Commercial engagement	
Required research/technology development	Cryo-systems development Pulse charging development MgB2 Material Jc. Flux pinning. Processing fully dense material YBCO. Nano-pinning centres homogeneity. Improvement of mech props	IP capture Scale-up of materials processing	
Link to Key Customer Needs	A. Develop better magnitisation techniques and higher trapped fields H. Develop better and cheaper cryogenic modules and systems G. Develop demonstrator devices for small scale system demonstration N. Better mechanical properties F. Reduce production cost of bulk superconductors without compromising their performance I. Develop reliable manufacturing processes for medium scale bulk production		
Risks	R1 Thermal loads during charging R5 Research funding availability	R2 Cost of RE Elements R3 Market size (reliant on success of medical therapies) R6 IP leakage	R4 Field gradient for humans legislation

Figure 4: Roadmap for portable, high-field magnet systems for biomedical applications, excluding NMR and MRI

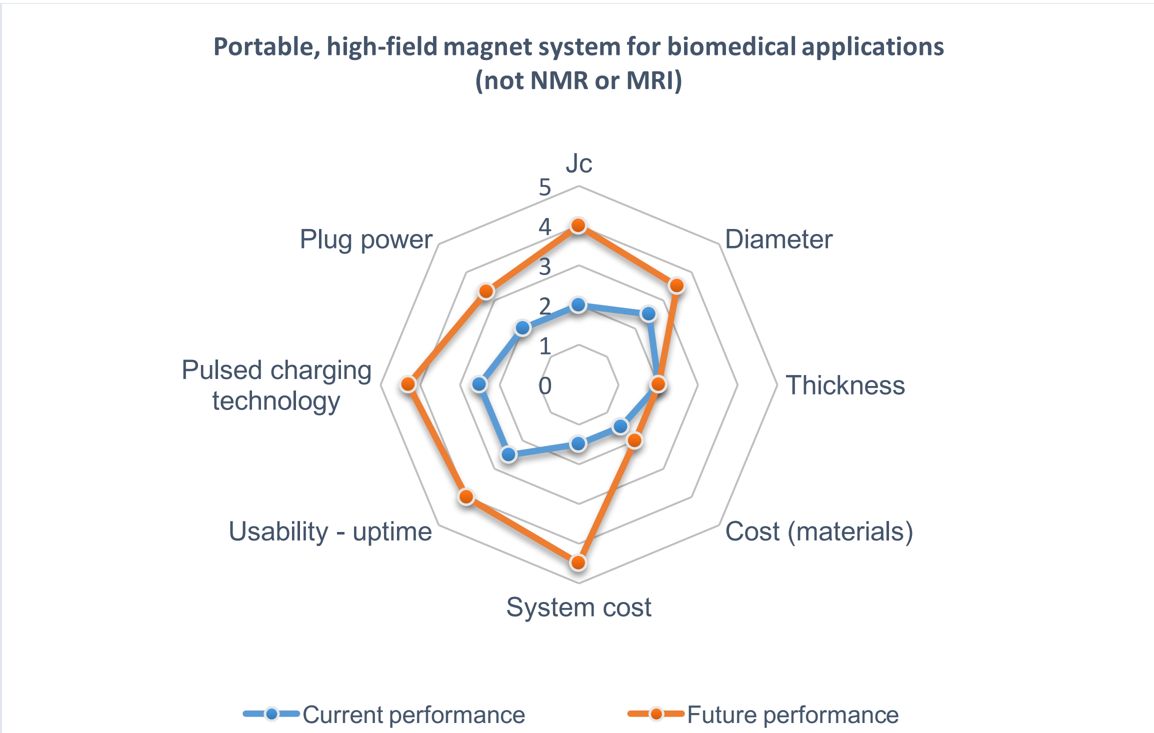


Figure 5: Current and future performance requirements for portable, high-field magnet systems for biomedical applications, excluding NMR and MRI (5 = excellent performance, 1 = poor performance)

PORTABLE MEDICAL INSTRUMENTS, FOR EXAMPLE, NMR OR MRI

In this application the development of portable medical instruments such as NMR or MRI was explored. This instrument would be used as an investigative tool for either imaging or monitoring in a doctors' surgery, for example, and would have relatively low resolution and a small magnetic field (below 5 Tesla). It would also be produced in low volumes and be small and compact.

The vision would be for one in every hundred doctors' surgeries to have such an instrument. Although this is a relatively modest aim, it still represents a multi-billion-dollar industry globally if such a system could be produced and sold for fewer than 100,000 euros.

An initial key milestone, in order to develop such an instrument, would be field stability and homogeneity. If this were not possible, then the application could not be developed further. Another key milestone is the development of an effective magnetisation process, probably coupled with larger diameter sample fabrication, using multi-seed or single-seed processes. In the short term there is a requirement for materials' development, specifically for MRI applications. There are already publications showing MRI images of various organisms, and mice, in particular, which are perfectly recognisable, so this milestone is likely to be achievable. Finally, a cost-performance analysis would be essential. This might mean that specific applications need to be targeted in order for the overall system to be optimised and produced at an acceptable cost.

The main technology advancements required in the short term are the development of the cooling systems to make them more compact, quieter and a lower weight. In the medium term, reliable production processes would need to be developed, as well as demonstrators and prototypes. In the longer term, it would be important to reduce cost and to produce larger volumes of components and systems, reliably.

Various risks were identified, but achieving the right field stability and homogeneity was probably the greatest. Solving this issue would be a major enabler for adoption of the technology. Being able to reduce system costs was also a risk, as well as being able to demonstrate the concept in the short term. In the long term, material availability in large quantities, for example, hundreds of tons, would be essential and more material suppliers would be needed.

Figures 6 and 7 (below) show the roadmap and the current and future performance requirements for this application.

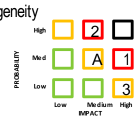
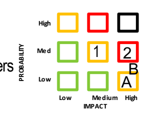
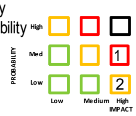
Application description/scope	**Application summary description** • Low res MRI for doctors surgeries • Low field NMR • Non invasive surgery • Magnetic clamping • Drug delivery • Stem cell separation	**Scope** **What's IN:** MRI, NMR, imaging based applications Prepolarized devices Small sample volume, low frequency Low resolution devices Food processing and verification (automated) Cryogenic cooling **What's OUT:** High field MRI/large volume	**Desired future** **What success would look like** • More than 100 surgery use low cost MRI • Development of oxygen free systems • First small series manufacturing of low field NMR • Less than 100£$ per system!
WHEN	***Short term (+3 years)***	***Medium term (+5 years)***	***Long term (+10 years)***
Stepping Stones / Milestones / Demo Chain	Optimise temperature of operation to minimise flux creep Demonstration of existing cooling systems to NMR/MRI Fabrication of larger diameter bulk samples Effective magnetization processes Cost performance analysis Target specific applications	Produce functional/lab demonstrator Practical deployment Concept demonstration Start to develop low cost systems Develop production processes System conformity (regulations) SGa(?) lime etc. Quality control of bulk materials	Functional prototype Large scale production Reduce cost On-going product development Higher field systems
Required research/technology development	Materials processing Cryocooler advances Flue creep stacks	Systems assembly Develop batch process(?) (large samples) Develop QA spec Improved thermal properties	Improved mechanical properties
Link to Key Customer Needs	B. Develop manufacturing processes for large scale bulk production G. Develop demonstrator devices for small scale system demonstration H. Develop better and cheaper cryogenic modules and systems	A. Develop better magnetisation techniques and higher trapped fields N. Better mechanical properties	A. Develop better magnetisation techniques and higher trapped fields
Risks	1. Field stability and homogeneity 2. Cost 3. Concept demonstration A. Reliable magnetization process 	1. Portability 2. Resilience A. More material suppliers B. Industry standards 	1. Material availability 2. Material reproducibility 

Figure 6: Roadmap for portable medical instruments, for example, NMR or MRI

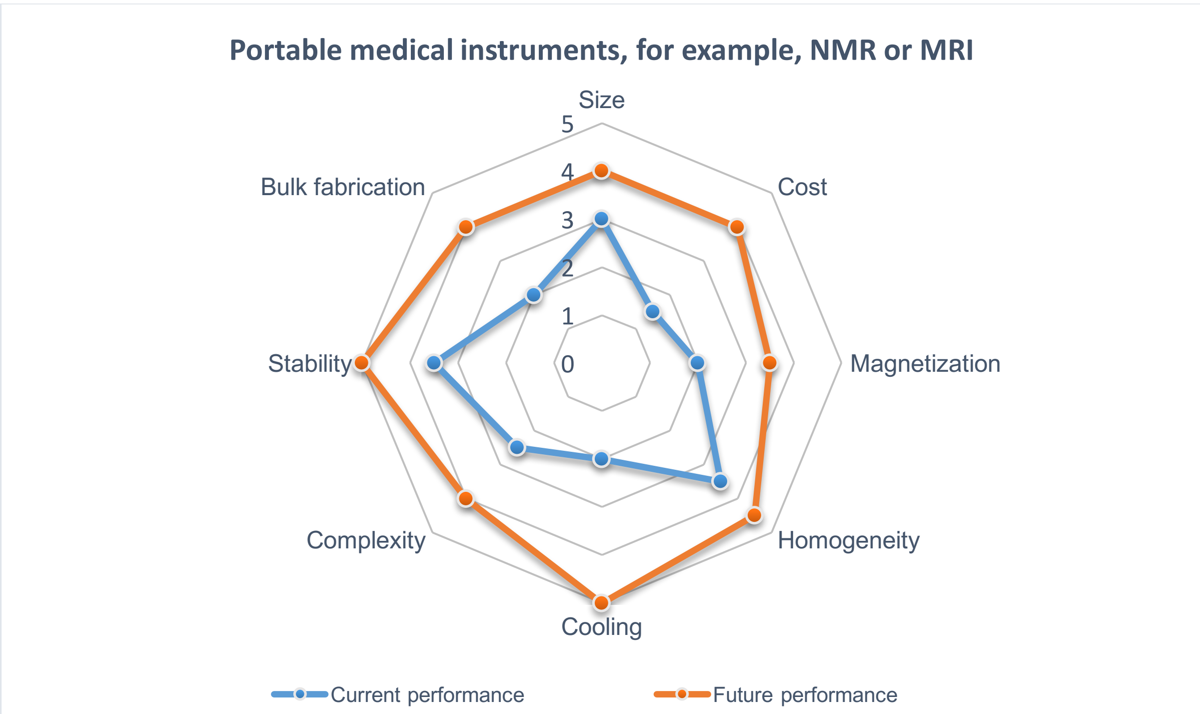


Figure 7: Current and future performance requirements for portable, medical instruments, for example, NMR and MRI (5 = excellent performance, 1 = poor performance)

MAGNETIC SHIELDING APPLICATIONS FOR ELECTRIC MACHINES, EQUIPMENT AND OTHER HIGH-FIELD DEVICES

This application could be summarised as creating magnetic field spaces for shielding. There are two possible alternatives. The first is shielding an interior space from a magnetic field outside that space. The second is the reverse, namely, shielding an exterior (ambient) space from a magnetic field. This application concentrates on DC and low-frequency magnetic fields, which are compatible with superconductivity.

The desired future could be realised through two slightly different application regimes. One is the classic shielded room, which could be converted into a superconductive shielded room. The second regime is to shield large magnetic fields that are located in smaller volumes. The latter is a concern for many people.

The main development steps are initially to develop a small “box” that can shield external fields and gradually move to larger-sized shields. The required research and development would be around the design and development of large plates of MgB_2, which are arranged into a magnetic shield. Developing better furnace technology for the production of larger quantities of MgB_2 may be required, as well as establishing a continuous production process rather than the currently used batch process. This would help reduce production costs and make this technology commercially competitive.

In terms of risks, the production of large plates of MgB_2, the furnace technology development, the overall system cost production and the joining are probably the most significant.

The latter (joining wires), if solved, would be a huge enabler for this technology. Currently, joining wires is extremely challenging; it would be transformative if the technology could be developed to allow large currents to be transferred across a join. A second enabler would be achieving high production rates for the superconducting plates to facilitate system cost reductions.

Figures 8 and 9 (below) show the roadmap for this overall application and the current and future performance requirements for the two different types, namely, shielding an interior or an exterior space.

Application description/scope	**Application summary description** • Creating magnetic field free spaces	Scope **What's IN:** Shielding both out from and in and vice versa DC low f <100Hz **What's OUT:** High f	**Desired future What success would look like** • Room sized shield (low fields) • Smaller shields for high fields – 5T
WHEN	***Short term (+3 years)***	***Medium term (+5 years)***	***Long term (+10 years)***
Stepping Stones / Milestones / Demo Chain	Head size shield Box for ?? B 20 cm x 20 cm YBCO shield 77k 1-2T	Medium size box High production rate demo MgB2/BSCCO	Room size earth B shielded Shield for box 10 x 10 x 10 cm 4-5T
Required research/technology development	Large plates of MgB2	Furnace tech/ T Control Large plates BSCCO 222 3 BSCCO non-batch Multiseeded YBCO	Large plates REBCO Continuous production of REBCO bulks
Link to Key Customer Needs	B. Develop manufacturing processes for large scale bulk production G. Develop demonstrator devices for small scale system demonstration O. Optimised geometries and reduced thickness Protecting people & equipment from high fields More sensitivity Shielding in motors		
Risks	1. Can't cool large plates 2. Unforeseen problems with costing large MgB2	1. Furnace tech 2. GB in multiseeded 3. Jointing	1. Impossible to make large plates of YBCO

Figure 8: Roadmap for magnetic shielding applications for electric machines, equipment and other high-field devices

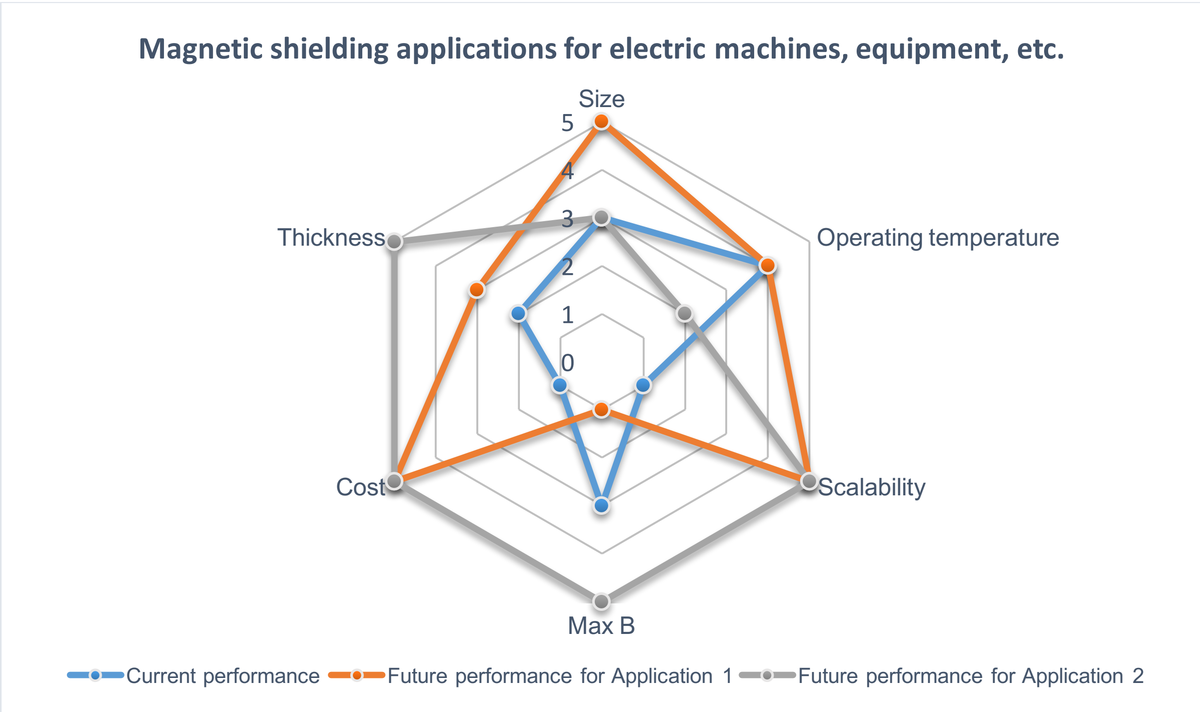


Figure 9: Current and future performance requirements for electric machines, equipment and other high-field devices (5 = excellent performance, 1 = poor performance)

ROTATIONAL AND LINEAR MAGNETIC BEARINGS

Magnetic bearings are already commercialised using superconductivity. These are typically small bearings (20 mm in diameter), which can have a load of several hundred newtons or larger bearings (200 mm in diameter) that have a load capacity of approximately 1 to 1.2 tons. These bearings are self-regulating, with no internal electronic parts. They are inherently stable, which is very important for safety.

In the current applications, between the rotor and stator, the magnetic field is 0.5 Tesla. If this could be increased to 5 Tesla, the force density would amplify 100 times, and on this basis very compact systems could be built. These bearings could operate at high speeds (100,000 rpm), and / or high loads (e.g. 100-ton load for a generator).

In the medium term, if liquid nitrogen cooling could be eliminated and a cryocooler operation used instead, this would enable a safer and cheaper system to be designed. In the long term plug and play system designs will be important. Furthermore, engineers need to be informed and educated about how the system works to alleviate concerns about their reliability and safety. Interdisciplinary teams need to be put together to develop magnetic bearings further.

Most of the risks are neither technical nor engineering-based, but rather societal (concerns about the technology, its safety and reliability). There is currently a lack of technology acceptance, so developing and exhibiting good demonstrators is very important in changing public perceptions. This can show the level of technology maturity that has been achieved and demonstrate the technological advantages.

Finally, as a sector, it may be preferable not to try and explain the technology details to potential customers and users but rather to focus on the system’s functionality and performance. For example, the ability of the system to achieve high speeds with no noise, the elimination of friction and component ware and a lack of pollution and operational stability at both low and high temperatures are some of the distinct advantages of magnetic bearings that cannot easily be achieved with other technologies.

Figures 10 and 11 (below) show the roadmap and the current and future performance requirements for this application.

Application description/scope	**Application summary description** • Handling through walls • Non-contact (frictionless) • Self-stabilized • Quite(?); Friction-less; High speed • Temperature independent • Clean	**Scope** **What's IN:** High tech B2B Civil and Military Interdisciplinary; Technology; Rotational and linear; Clean room operating Cold conductivity **What's OUT:** High forces app Limited stiffness; higher costs; capital intensive Low cost Household Hot conductivity	**Desired future What success would look like** • Plug and Play • Cost reduction • Standardization • Easy calculation
WHEN	***Short term (+3 years)***	***Medium term (+5 years)***	***Long term (+10 years)***
Stepping Stones / Milestones / Demo Chain	Force ≤1 to Stiffness ≤ 5kN/tom LN_2 operation Marketing key-demo prototype – increased number of customers	Compactness Forces 5-10 to Full HTS bearing coil-bulk Higher flux in 6AP	From project to product Industrialisation, standardisation, comm
Required research/technology development	Better assembling Fem modelling LN_2 => cryocooler Tailored cooling concepts	Joining bulk Higher averaged trapped flux Reliable coils Cryogenics	Reduced R&D Cost-quantity improvement Force density >100N/cm^2
Link to Key Customer Needs	In order of priority: F. Reduce production cost of bulk superconductors without compromising their performance H. Develop better and cheaper cryogenic modules and systems A. Develop better magnetisation techniques and higher trapped fields B. Develop manufacturing processes for large scale bulk production I. Develop reliable manufacturing processes for medium scale bulk production G. Develop demonstrator devices for small scale system demonstration Nice to have: O. Optimised geometries and reduced thickness N. Better mechanical properties		
Risks	Technological advances 1. Global economy, political situation 2. No Plug & Play	1. High costs 2. Reliability of Cryocooler & low cost Cryo-systems	1. No acceptance and no disruption

Figure 10: Roadmap for rotational and linear magnetic bearings

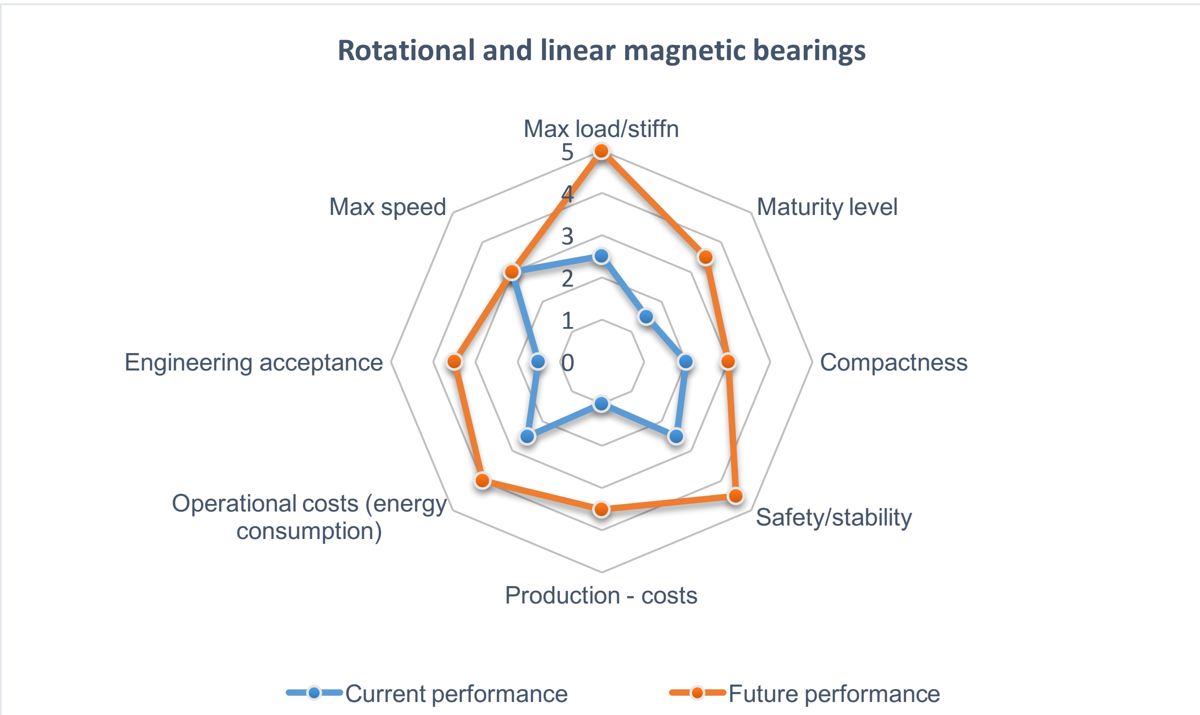


Figure 11: Current and future performance requirements for rotational and linear magnetic bearings (5 = excellent performance, 1 = poor performance)

ULTRALIGHT SUPERCONDUCTING MOTORS / GENERATORS

This application uses bulk superconductors as trap field magnets, to develop high-torque-density motors and generators. The aspiration is to create a 5 Tesla magnetic field and greater than a 100 newton x meter / kilogram torque density. Such a system could be used in aircrafts or ships as an AC synchronous machine. Offshore wind generators may be another area of application for such a system.

In the short term some fundamental research and development will need to take place to enable the development of a technology demonstrator in the medium term, and an application-specific prototype integrated into an aircraft or ship in the long term.

The main milestones in the short term are achieving a 5-Tesla trap magnetic field using bulk superconductors and completing a cost / benefit analysis of the components of a bulk-superconductivity-based motor or generator. The expectation is that bulk superconductors will be slightly cheaper than stacked tapes, but a market and cost analysis is required to assess this assumption in detail. This analysis will need to include parameters such as the cost and weight of components.

Reliability aspects would have to be addressed during this period. The first domain will be the magnets themselves, namely their electrical reliability, which includes possible demagnetisation properties. Other reliability areas would be their mechanical properties, analysing the properties in the bulk superconductor and whether it can withstand the electromagnetic forces in the machine. Finally, the temperature optimisation will need to be investigated, which will include the operating temperature, the type of cryocooler used and any supporting technologies required to make the whole system operational.

In the medium term, better magnetisation techniques and mechanical support of the motor itself to withstand the electromagnetic forces generated by a magnetic field of 5 Tesla will be required. Commercial activities such as marketing and sales, as well as commercial investment, will be essential to developing a technological prototype. Activities during this period will include integrated electrical and mechanical machine designs, and the whole cryocooler system. In the long term, an application-specific product needs to be developed that is fully integrated into an aircraft or ship.

In terms of the risks and enablers, magnetisation is the largest risk; even reaching 3 Tesla is challenging. If this issue cannot be resolved it will have a major negative impact on any further application developments.

The mechanical properties could pose a medium risk, as well as insufficient manpower and expertise that is both academic and industrial. For this, the technological prototype stage is extremely important. If conventional permanent magnet machines continue to improve, they would be a key competitor in this application space, although they cannot trap magnetic fields that are as large as the bulk superconductors. Finally, a lack of investment in prototype development can delay or stop further activity in this area.

Figures 12 and 13 (below) show the roadmap and the current and future performance requirements for this application.

Application description/scope	**Application summary description** • Using bulk superconductors as trapped field magnets • High torque density motors and generators >100nm/kg	**Scope** **What's IN:** Aircraft Ships (<1MW?) Med-large wind generators >1MW AC synchronous **What's OUT:** Electric vehicles, Machines <1MW, Hysteresis/reluctance	**Desired future** **What success would look like** • Ships with hybrid electric, superconducting, drive train • Airplanes with electric, super-conducting drive trains • Industry generators with superconducting components (offshore wind)
WHEN	***Short term (+3 years)*** Answer unanswered questions	***Medium term (+5 years)*** Prototype (working)	***Long term (+10 years)*** App-specific development
Stepping Stones / Milestones / Demo Chain	Reliability (magnets) Reliability (mechanical) Cost/benefit analysis 3-5T trapped field	7ST trapped field Demagnetisation creep, temp fluctuations Long-term testing (performance, reliability)	Application prototype
Required research/technology development	Demagnetization properties (AC fields) Mechanical properties analysis Market analysis (aircraft, ship) Weight/cost of components breakdown (bulks – how much?) Magnetization process Temperature optimisation	Magnetization techniques Mechanical support structure Market, selling, commercial investment Integrated machine design (electrical, mechanical)	Production/development Full system integration
Link to Key Customer Needs	A. Develop better magnetisation techniques and higher trapped fields H. Develop better and cheaper cryogenic modules and systems N. Better mechanical properties O. Optimised geometries and reduced thickness	A. Develop better magnetisation techniques and higher trapped fields F. Reduce production cost of bulk superconductors without compromising their performance G. Develop demonstrator devices for small scale system demonstration I. Develop reliable manufacturing processes for medium scale bulk production O. Optimised geometries and reduced thickness	B. Develop manufacturing processes for large scale bulk production
Risks	1. Magnetization 2. Mechanical properties	1. Increased performance of PM machines	1. No investment

Figure 9: Roadmap for ultralight superconducting motors and generators

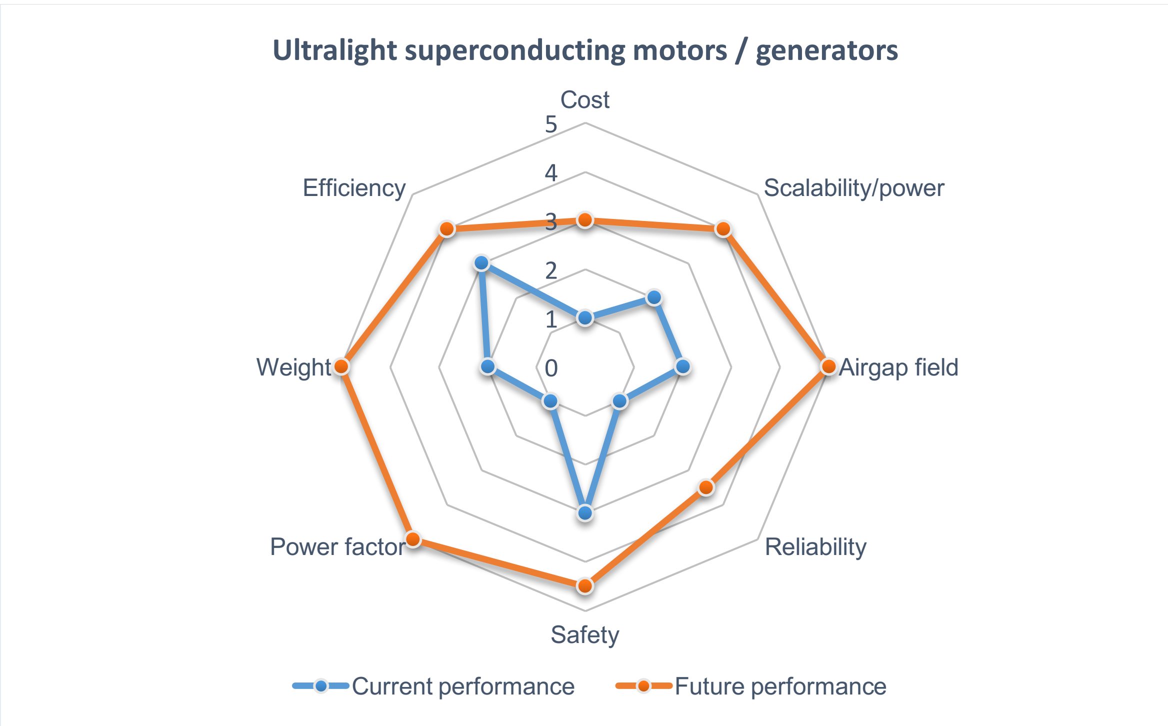


Figure 10: Current and future performance requirements for ultralight superconducting motors and generators (5 = excellent performance, 1 = poor performance)

LINKING APPLICATIONS TO CUSTOMER NEEDS AND RESEARCH PRIORITIES

The links between the selected applications and the key customer needs and research priorities were captured and assessed. Figure 14 (below) shows the links between the five applications and the customer needs.

Customer Needs		Portable, high field magnet systems (not NMR or MRI)	Portable medical instruments, e.g. NMR and MRI	Magnetic shielding applications for electric machines, equipment and other high field devices	Rotational and linear magnetic bearings	Ultralight superconducting motors/generators
A	Develop better magnitisation techniques and higher trapped fields	1	1		1	1
H	Develop better and cheaper cryogenic modules and systems	1	1		1	1
I	Develop reliable manufacturing processes for medium scale bulk production	1			1	1
N	Better mechanical properties	1	1			1
G	Develop demonstrator devices for small scale system demonstration	1	1	1	1	1
B	Develop manufacturing processes for large scale bulk production		1	1	1	1
F	Reduce production cost of bulk superconductors without compromising their performance	1			1	1
O	Optimised geometries and reduced thickness			1		1
	TOTAL	6	5	3	6	8

Figure 14: Links of the five selected applications to the most important customer needs

It is evident that all key customer needs are covered by the five applications. In particular, the applications *portable, high-field magnet systems (not NMR or MRI), rotational and linear magnetic bearings* and *ultralight superconducting motors / generators* are the most comprehensive. The *magnetic shielding applications* is the least comprehensive, covering only three of the eight key customer needs, although it is one of two applications that is important in fulfilling the customer need of *optimised geometries and reduced thickness*.

In order to derive key research priorities for the bulk superconductivity domain, participants were asked to summarise from the technology layer of each application roadmap the most important research activities. These were then individually ranked from (0) to (3) across all applications using the following scoring criteria:

(3) = Will contribute strongly
(2) = Will contribute moderately
(1) = Will contribute slightly
(0) = Will not contribute

In total, 18 research activities were put forward and assessed. From these, the following 14 scored the highest, indicating that their realisation and achievement would have a positive impact on several applications:

- Building interdisciplinary groups for excel system integration;
- Cheap and reliable cryocoolers; cryosystems' development;
- Material performance
- Reduced system cost / life-cycle cost;
- Cost breakdown of components and market analysis (aircraft, ships);
- Technology prototype; development of lab demonstrator;
- Furnace technology high stability;
- Magnetisation (pulsing); pulse charging development; development of magnetisation system / process;
- Scaling the manufacturing process; scale-up of materials processing;
- Large plates MgB_2;
- Large plates (RE)BCO; materials' development / larger samples;
- Mechanical properties (analysis / improvement); YBCO J_c and mechanical properties optimisation;
- Demagnetisation and mitigation (AC loss, flux creep);
- FEM – modelling for bearing development.

The two applications that require most of these research activities for their further development are the *portable, high-field magnet* and the *portable medical instruments, for example, NMR and MRI.* The former (***portable, high-field magnet***) also has the lowest performance gap between current and future performance requirements, and meets most of the key customer needs; therefore, active research activities in this domain would have a positive spillover effect on the overall bulk superconductivity technology development and its commercialisation.

Will contribute strongly = 3
Will contribute moderately = 2
Will contribute slightly = 1
Will not contribute = 0

Research Priorities	Portable, high field magnet systems (not NMR or MRI)	Portable medical instruments, e.g. NMR and MRI	Magnetic shielding applications for electric machines, equipment and	Rotational and linear magnetic bearings	Ultralight superconducting motors/generators	TOTAL
Large plates MGB2 B3:B20	3	3	3	1	1	**11**
MgB2 Jc optimisation	3	2	2	1	1	**9**
Furnace technology high stability SHLD	1	2	3	3	3	**12**
Continuous production (non-batch) REBCO	2	2	3	1	1	**9**
Multiseeded YBCO	0	0	3	2	2	**7**
Large plates REBCO; Materials development/larger samples	2	3	3	1	2	**11**
Magnetisation (pulsing); Pulse charging development; Development of magnetization system/process	3	3	0	3	3	**12**
Mechanical properties (analysis/improvement); YBCO Jc & mechanical properties optimisation	3	2	1	2	3	**11**
Material performance	3	2	3	3	3	**14**
Demagnetisation and mitigation (AC loss, flux creep)	3	3	1	1	3	**11**
Improved trapped held homogeneity and stability	1	3	1	1	2	**8**
Reduced system cost/life cycle cost	3	3	3	3	1	**13**
Cost breakdown of components and market analysis (aircraft, ships)	3	3	1	3	3	**13**
Technology prototype; Development of lab demonstrator	3	3	2	2	3	**13**
Cheap and reliable Cryocoolers; Cryosystems development	3	3	3	3	3	**15**
Scaling the manufacturing process; Scale up of materials processing	3	2	3	2	2	**12**
FEM – modelling for bearings development	1	1	2	3	3	**10**
Building interdisciplinary groups for excel system integration	3	3	3	3	3	**15**
TOTAL	**43**	**43**	**40**	**38**	**42**	

Figure 15: Links of the five selected applications and research activities

CONCLUSIONS

Sixteen participants from both academia and industry participated in a workshop to scope potential future developments of the bulk superconductivity field that may develop over the medium and long terms, and to align industrial requirements to research priorities, thus enabling the development of a research strategy for the domain.

The following five applications were judged to be the most important regarding their potential commercial opportunity and feasibility:

- Portable, high-field magnet systems (not NMR or MRI);
- Portable medical instruments, for example, NMR and MRI;
- Magnetic shielding applications for electric machines, equipment and other high-field devices;
- Rotational and linear magnetic bearings;
- Ultralight superconducting motors / generators.

One application in particular, *portable, high-field magnet* appears to be provide a good short-term opportunity, as it meets most of the key customer needs, requires development of several research priorities and has the lowest performance gap between current and future product requirements.

The main research priorities identified for the bulk superconductivity domain are as follows:

- Building interdisciplinary groups for excel system integration;
- Cheap and reliable cryocoolers; cryosystems' development;
- Material performance
- Reduced system cost / life-cycle cost;
- Cost breakdown of components and market analysis (aircraft, ships);
- Technology prototype; development of lab demonstrator;
- Furnace technology high stability;
- Magnetisation (pulsing); pulse charging development; development of magnetisation system / process;
- Scaling the manufacturing process; scale-up of materials processing;
- Large plates MgB_2;
- Large plates (RE) BCO; materials' development / larger samples;
- Mechanical properties (analysis / improvement); YBCO J_c and mechanical properties optimisation;
- Demagnetisation and mitigation (AC loss, flux creep);
- FEM – modelling for bearing development.

APPENDIX

LIST OF BULK SUPERCONDUCTIVITY APPLICATIONS PROPOSED

Applications	Sublayer	Timescale
1. Portable medical instruments, for example, NMR and MRI	Levitation	MT-LT
2. Rotational and linear bearings	Levitation	ST-MT
3. Flywheels and rotating machines for energy storage systems	Levitation	ST-MT
4. Magnetic shielding applications for electric machines, equipment and other high-field devices	Trapped fields	ST-LT
5. Magnetic levitation trains	Rotating machines	ST-LT
6. Electric machines utilising trapped flux magnets. 8. Motors and generators (grouped with application no 8)	Rotating machines	LT
7. Applications for the cryogenics industry utilising trapped flux magnets	Trapped fields	ST-MT
8. Motors and generators (grouped with application no 6)	Rotating machines	ST-LT
9. Actuators and sensors	Trapped fields	ST-MT
10. Magnetic levitation tube transport	Levitation	LT
11. Portable, high-field magnet systems	Biomedical	ST-MT
12. Applications for the semiconductor industry utilising trapped flux magnets	Rotating machines	ST
13. Current leads	Other	ST
14. Magnetic flux collecting and compression device	Trapped fields	ST
15. Rocket launchers for space or military applications	Levitation	MT
16. Shielding for space applications	Other	LT
17. Passive dampers	Levitation	LT
18. Hybrid bulk – wire devices up to 10 T	Rotating machines	LT
20. MHD & mini-nuke plant applications	Trapped fields	LT
21. Prototypes of positioning systems	Levitation	ST
22. Increase in process trials	Other	ST-MT
25. Target-specific devices	Other	MT
27. Bespoke manufacturing equipment	Levitation	LT
29. Commercial devices developed	Other	LT
30. Superconducting machines for electric aircraft 34. Aircraft propulsion (grouped with application no 34)	Rotating machines	MT
31. Biomedical applications such as cell separation, magnetic drug targeting.	Biomedical	ST
32. Diamagnetic applications FM/SM hybrids magnetic lenses	Levitation	MT
33. Superconducting wind turbine generators	Rotating machines	MT
34. Aircraft propulsion (grouped with application no 30)	Rotating machines	MT
35. Handling systems for industrial automation plug and play "non-contact"	Levitation	MT
36. Flux compression devices	Trapped fields	MT
37. Handling systems for industrial automation projects / prototypes "non-contact"	Levitation	ST

Table 5: List of all bulk superconductivity applications proposed during the workshop

WORKSHOP AGENDA

09.15	Arrival	
09.30	Welcome, introductions and agenda	BSG and IfM ECS
09.40	Overview of aims, objectives and research challenges	BSG
10.15	Individual presentations of customer needs and applications	All
11.15	Prioritisation of the most important customer needs	All
11.45	Prioritisation of the most important applications using pre-defined criteria	All
12.15	Select four to five applications for further exploration	BSG
12.30	Lunch	
13.30	Exploring the selected applications (one per group)	In groups
16.00	Link selected applications to research priorities	In groups
16.30	Review and feedback	All
17.00	Close	

Table 6: Workshop agenda

LISTS OF PARTICIPATING ORGANISATIONS AND DELEGATES

Name	Organisation
Mark Ainslie	UCAM
Hari Babu	Brunel University
Tom Bradshaw	RAL
David Cardwell	UCAM
Pavol Diko	Slovak Academy of Science in Kosice
John Durrell	UCAM
Mike Filipenko	Siemens
Tomas Hlasek	CAN Superconductors
John Hull	Boeing (Via video conferencing)
Lars Kuhn	eVico
Mathias Noe	KIT
Jan Plechacek	CAN Superconductors
Hua Shi	UCAM
Susannah Speller	Oxford
Philippe Vanderbemden	Liege
Frank Werfel	ATZ GmbH
Nicky Athanassopoulou	UCAM (Facilitator)
Andi Jones	UCAM (Facilitator)

Table 7: List of workshop participants

Group	Participants
Portable, high-field magnet systems (not NMR or MRI)	David Cardwell, Hua Shi, Mathias Noe
Portable medical instruments, for example, NMR and MRI	Susannah Speller, Pavol Diko, Tom Bradshaw
Superconducting machines for electric aircraft	Hari Babu, Mark Ainslie, Mike Filipenko
Magnetic shielding applications for electric machines, equipment and other high-field devices	John Durrell, Jan Plechacek, Philippe Vanderbemden
Lineal and rotational magnetic bearings	Frank Werfel, Tomas Hlasek, Lars Kuhn

Table 8: Groups of participants exploring each of the five selected applications

WORKSHOP FEEDBACK

Feedback was received at the end of the workshop from nine participants. Ninety-nine per cent considered the workshop to be excellent, very good or good, as well as being useful and stimulating. All participants considered their participation to be worthwhile. The detailed feedback is shown below.

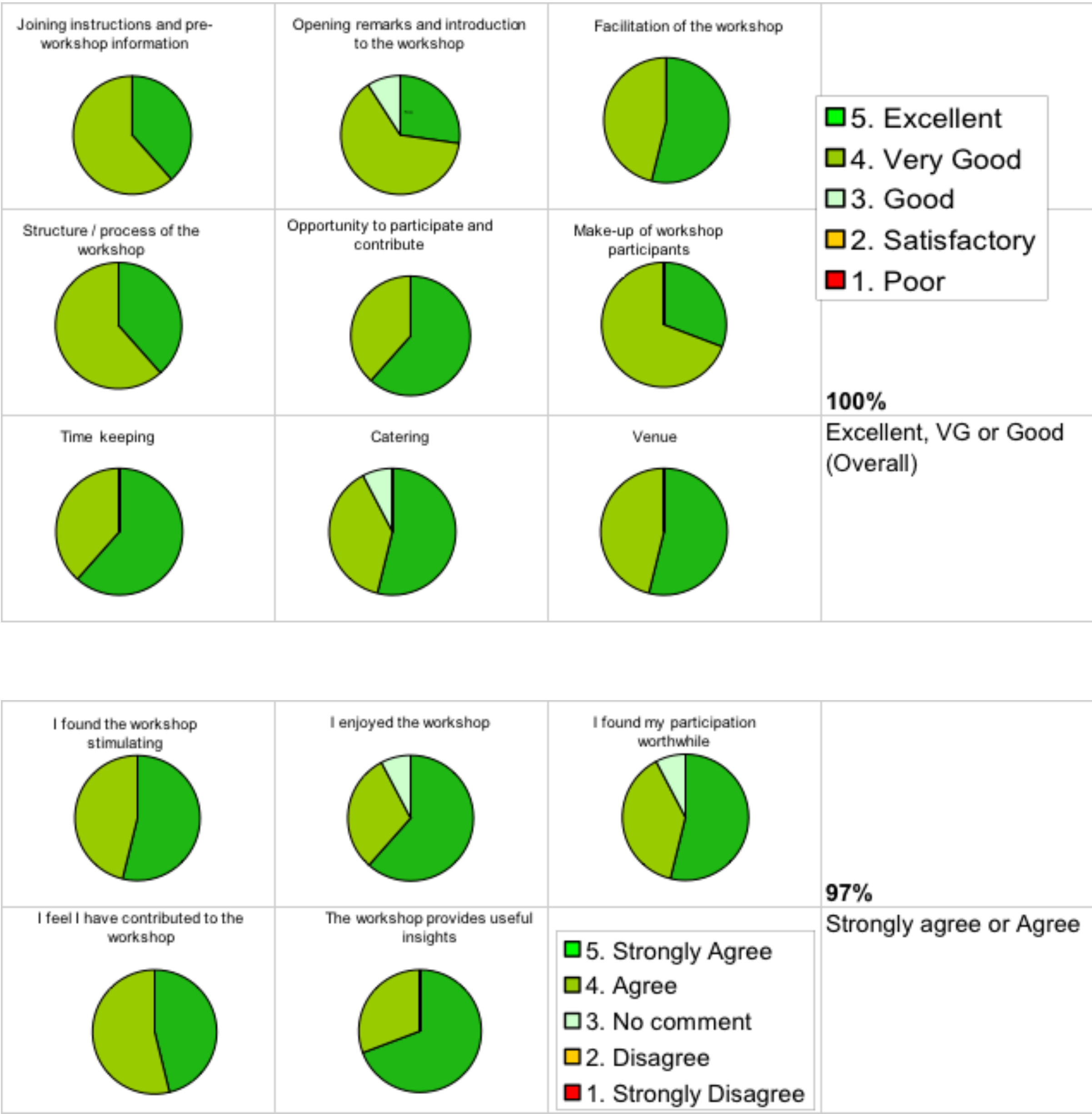


Table 9: Participants' feedback

PRE-WORKSHOP INPUT RECEIVED

Name: Adelwitz Technologiezentrum GmbH (ATZ), F. N. Werfel, “Master Plan of Research and Development 2026”

Timeline	**Short** **(3 years)** **2016** **2019**	**Medium** **(5 Years)** **2021**	**Long** **(10 Years)** **2026**
Customer Needs and Requirements	A. High Jc bulks, Dia 30 – 60 mm, plane & radial seeded; hollow cylinders, assembled, multi – seeded; surface stabilized, machined	B. Large –scale seeded bulks, doping; higher Tc materials; sc PM up 3 T@77 K; bulk devices & components; high -current GB’s, cost reduction, long-term operation	C. Perfect textured & doped bulk material – unseeded; optimized geometries and reduced thickness; material economy; hybrid bulk & cryogenics modules; Perfect joining of bulks;
Possible Applications to address customer needs	1. Trapped flux magnets (electric machines, medicine; semiconductor industry; rotational & linear magnetic bearings 3-4 tons; small flywheels < 5 kWh; bulk cryostat; motors, (wind) generators, current lead, m. shielding, actuators,	2. HTS bearings > 10 tons; Flywheel 10-25 kWh, improvement safety factors (cooling), bulk coil NMR & MRI; all – electric plane (bulk dev.); integrated sensing & actuator elements; magn. flux collecting and compression device; growing space & military application, demonstrator maglev train & rocket launchers	3. Hybrid bulk –wire devices up to 10 T; practical magnetic Technol.- standards; MRI systems 30 – 60 cm; large electric machines >10 MW; MHD & mini- nuke plant appl. Public Maglev train; high-speed tube transport; passive dampers; shielding- space appl.

Name: Dr Mark Ainslie

Timeline	**Short** **(3 years)** **2016** **2019**	**Medium** **(5 Years)** **2021**	**Long** **(10 Years)** **2026**
Customer Needs and Requirements	A. Uniform J_c, reproducible superconducting properties B. Practical, compact magnetization technique (> 5 T)	B. Cheap & powerful cryocooler technology C. Reliable & uniform batch processing on a large scale D. Large samples (> 50 mm diameter)	C. Complete, end-user-friendly products (able to be delivered on large scale/volume)
Possible Applications to address customer needs	1. Portable, high-field magnet system demonstrators (> 5 T)	2. Portable high-field magnet systems (> 5 T) for bespoke applications (e.g., magnetic separation, crystal growth) 3. Motors/generators	3. Motors/generators 4. Portable MRI / NMR systems

Name: David Cardwell

Timeline	Short (3 years) 2016 2019	Medium (5 Years) 2021	Long (10 Years) 2026
Customer Needs and Requirements	A. Reliable cooling systems B. Medium scale bulk process C. Routine bulk process using standard equipment	A. Bulk superconductors incorporated in systems B. Demonstrator devices C. Some cost reduction	A. Large scale bulk process B. Significant cost reduction C. Devices in service
Possible Applications to address customer needs	1. Increase in process trials 2. Closer collaboration with cryocooler industry 3. Demonstration of process reliabilty	2. Increase in process trials 3. Target specific devices 4. Optimise materials content	1. Bespoke manufacturing equipment 2. Cost-properties optimisation studies complete 3. Commercial devices developed

Name: Mathias Noe

Timeline	Short (3 years) 2019	Medium (5 Years) 2021	Long (10 Years) 2026
Customer Needs and Requirements	A. System demonstration B. System integration	B. Higher performance at 20-40 or 77K C. Commercial suppliers	C. ?
Possible Applications to address customer needs	1. Levitation 2. Bearing	2. Rotating machines	3. ?

Name: Philippe Vanderbemden

Timeline	Short (3 years) 2016 2019	Medium (5 Years) 2021	Long (10 Years) 2026
Customer Needs and Requirements	A. Reproducible synthesis of hollow bulk samples and square plates with shielding currents flowing on a macroscopic scale	B. Increasing the size of hollow bulk samples and square plates	C. Hollow bulk samples of large size or plates assembled together to act as large size magnetic shields
Possible Applications to address customer needs	1. DC or low frequency magnetic field reduction for large volumes / efficient magnetic shielding of small volumes	2. Magnetic shielding of a small piece of equipment (e.g. PCB)	3. Magnetic shielding of magnets, rotating machines and other high-field devices

Name: Jan Plechacek & Tomas Hlasek, CAN SUPERCONDUCTORS

Timeline	Short (3 years) 2016 2019	Medium (5 Years) 2021	Long (10 Years) 2026
Customer Needs and Requirements	A. Bulk in various shapes in small scale for various applications prototypes, higher levitation forces	B. Larger volumes of bulk pieces with unified properties, targets for tapes production	C. Large scale production of bulks with guaranteed properties
Possible Applications to address customer needs	1. Prototypes of bearings, flywheels, positioning systems, mixing systems using sc levitation	2. First really commercially used bearings in automation industry, clean operation etc., energy storage systems	3. Transport systems, energy storage systems, automation

Name: Pavel Diko

Timeline	**Short** (3 years) 2016 2019	**Medium** (5 Years) 2021	**Long** (10 Years) 2026
Customer Needs and Requirements	A. Lower cost, higher trapper field (Bt), higher Bt/G ratio (G-sample weight)	B. Lower cost, higher trapper field (Bt), higher Bt/G ratio (G-sample weight)	C. Lower cost, higher trapper field (Bt), higher Bt/G ratio (G-sample weight), better mechanical properties
Possible Applications to address customer needs	1.	2.	3.

Name: Susie Speller

Timeline	**Short** (3 years) 2016 2019	**Medium** (5 Years) 2021	**Long** (10 Years) 2026
Customer Needs and Requirements	A. Large diameter bulks. B. Portable, reliable and cheap magnetisation systems and cryogenics.	B. Complex geometries of bulk materials. C. Reliable, durable and cheap materials. D. Field stability	C. High temperature performance? D. Resistance to demagnetisation?
Possible Applications to address customer needs	1. Biomedical applications such as cell separation, magnetic drug targeting.	2. Compact MRI / NMR	3. Superconducting machines for electric aircraft

Name: Mykhaylo Filipenko

Timeline	**Short** **(3 years)** **2016 2019**	**Medium** **(5 Years)** **2021**	**Long** **(10 Years)** **2026**
Customer Needs and Requirements	A. Reliable Magnetization Techniques B. Proper Modelling Techniques C. Material Properties	B. Reliable Production of Bulks in Small Quantities C. Scalability of Magnitization D. Endurance Magnetization Experience	C. Full Availability of High Quality Bulks up to Specification
Possible Applications to address customer needs	1. Bulk Experiments	2. Medical Applications	1. Electric Machines 2. Medical Applications

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