Fusion Futures – Direct Industry Stimulus (DIS)

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Fusion Futures - Direct Industry Stimulus (DIS)

Purpose of this Document

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Helixos

Supply and demand of non-planar HTS magnets

February 2026

Industry Report

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Executive Summary: key insights across domains

Four domains are explored, with themes emerging that give insight into potential use cases of non-planar HTS magnets, how specific industries value and prioritise magnet characteristics, what supply chain capabilities exist today, and what technical challenges limit the development and deployment of NP-HTS magnet technologies.

Design priorities and magnet requirements

- Design priorities for non-planar HTS magnets centre around **system-level performance**, as well as **usability, safety, simplicity,** and **field performance**. Commercial applications of non-planar HTS magnet systems favour technologies that **easily integrate surrounding systems** or **improve the fundamental business cases** of an application.
- Requirements are closely coupled by design choices, demanding a systems approach to whole-magnet-system design.

Industry benchmarks

- Tape manufacturers state they are **capable of forming tapes in any fusion-relevant geometry**, whilst coil **designers and builders remain limited to racetracks and flat coils**.
- **Pulsed laser deposition dominates tape production (90% of production).**
- **High-quality industry metrics can measure performance across multiple elements** of the supply chain, for example achievable energy density requires not only large-scale testing facilities and cryoplants but also high-quality tape over long lengths.

Technical challenges

- **Variations in tape quality and qualification** capabilities introduce **uncertainty and lack of standardisation across the industry.**
- **Testing large-scale magnets at 20 T and 20 K** is a key bottleneck for fusion.
- **Design complexity** from tight coupling, **large scales, end-product quality,** and **information flow** are dominant challenge themes across technical domains.

Use cases

- Future use cases revolve around **increasing precision (**medical and sensors) and **system-level efficiency** e.g. cost or volume, not simply maximising one magnet quality.

Executive Summary: key insights from outputs

NP-HTS supply chains today are immature but show potential, with individual market segments and technology applications displaying fusion-grade performance in combination. The scale, complexity, and availability of information around these magnets act as sources of bottlenecks, however systems-level frameworks for magnet development have the potential to overcoming most technical challenges.

State of play	• A large degree of **variation and uncertainty** exists across the industry, with **little standardisation** yet **tight coordination required across the supply chain** to design high-performance magnet systems. • Whilst fusion does not have the most stringent requirements in every domain, fusion magnet environments that combine strong fields, large scales, and cryogenic temperatures in non-planar geometries represent domains not previously studied.
Key challenges and bottlenecks	• Technical challenges are dominated by **design complexity, large scales, end-product quality**, and **information flow and availability.** • Standout bottlenecks and challenge areas are **“2020 testing” of 20 T magnets at 20 K**, **tape standardisation and adaptation to fusion environments**, and **capital barriers to entry for full-scale magnet design and development.**
Impactful solutions and funding pathways	• **Three clear investment options emerge** that range in specificity from industry-wide funding to highly targeted investments: **Creating the conditions**, **Enhancing the market**, and **Directional pushing**. • Investment can **create the conditions** for firms to remove bottlenecks themselves by **budgeting for research** that addresses gaps in critical shared tools such as tape qualification equipment, and magnet modelling software. Similarly, barriers to entry for firms must be lowered by **reducing costs** of raw materials and materials design, as well as **reducing risks** that make capital-intensive magnet design less attractive – such as improving the safety of contracts for firms. • Investment that builds physical infrastructure can **enhance the market** by providing firms access to magnet testing facilities that are otherwise too costly. Similarly, targeted investments in tape production and specific trusted firms to increase survivability will boost industry longevity over fusion development timescales. • **Directional pushing** toward prototypes and demonstration coils can plug gaps as well as spurring industry by incentivising coordination and encouraging alignment with fusion priorities.

Context and background

Background

The Fusion Futures Industry Capability is a strategic initiative aimed at strengthening the UK's fusion supply chain by building both capability and capacity. It is scheduled to run from 2025 to March 2028; the goal is to establish a supply chain that can sustain and grow independently beyond the intervention period. The programme is designed to equip UK suppliers to successfully compete for domestic and international fusion-related contracts.

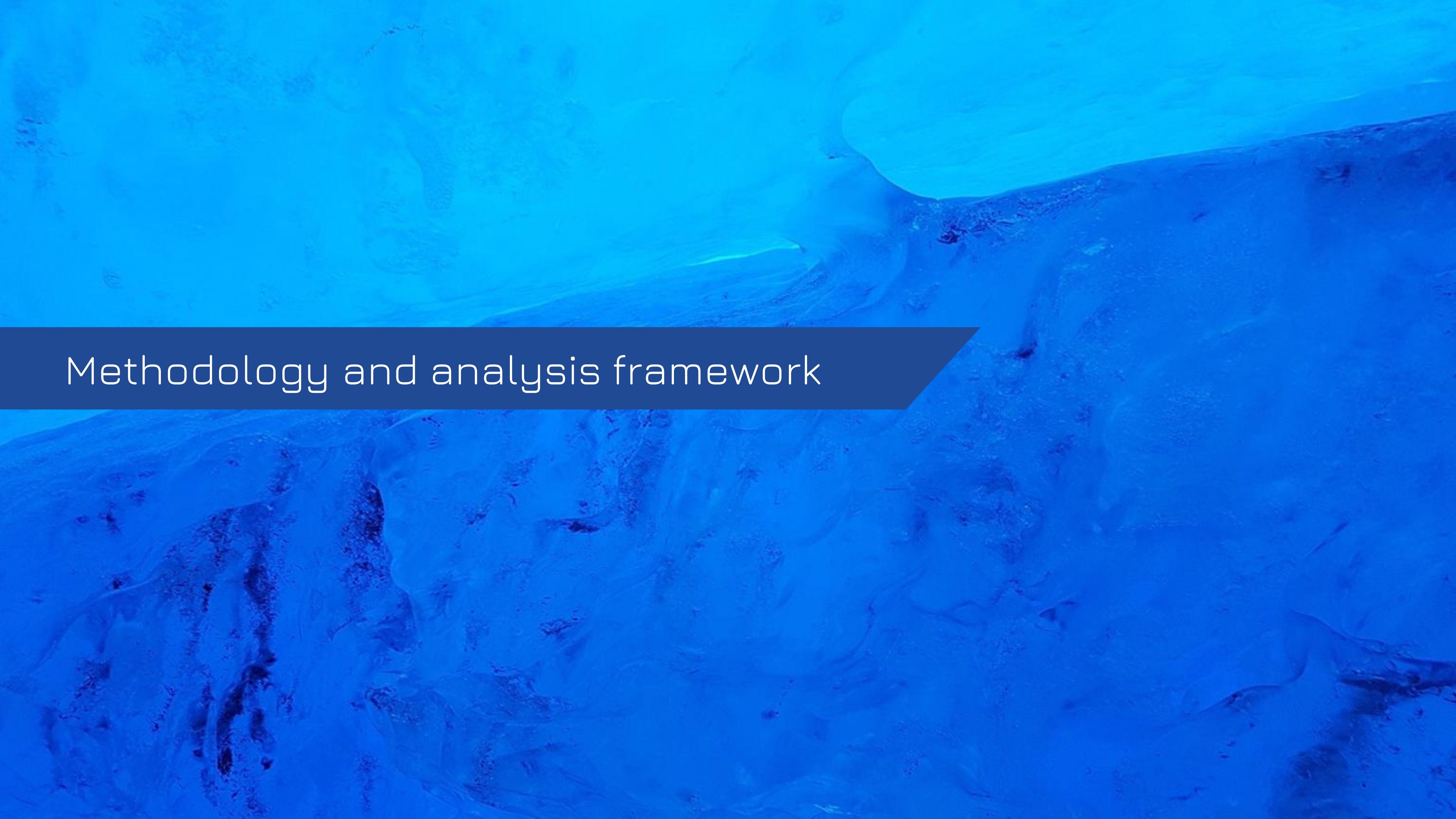
Superconducting magnets are a core enabling technology for fusion, with growing interest in high-temperature superconductors (HTS) due to their higher current density, larger thermal margins, and potential for more compact and efficient devices compared to low-temperature superconductors. Non-planar (3D) coil geometries are central to several fusion concepts, particularly stellarators, where complex magnetic field shaping is required. Strong potential lies in combining HTS with non-planar geometries, but new challenges are introduced: conductor forming, mechanical support, quench behaviour, cryogenic integration, and manufacturing yield. As fusion and adjacent sectors scale HTS adoption, supply-chain and capability bottlenecks are becoming increasingly visible.

The project

This project aims to inform UKAEA of the current global and UK capability in non-planar HTS magnet design and development.

The non-planar HTS (NP-HTS) landscape is assessed through a structured supply- and demand-side analysis. On the supply side, it examines the capabilities, constraints, and near-term development limits of HTS tape manufacturers and magnet builders. On the demand side, it captures magnet requirements, design priorities, and risk considerations across fusion and adjacent application sectors.

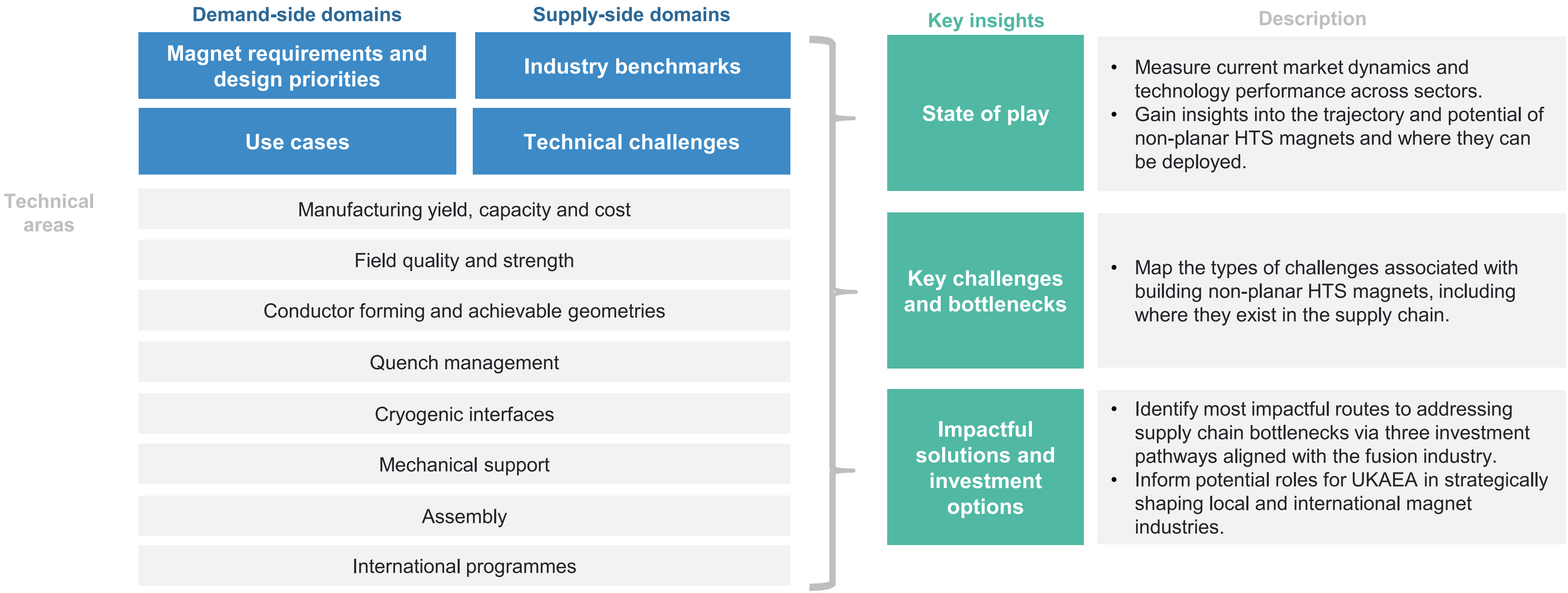
By engaging a targeted but diverse set of stakeholders, the analysis enables direct comparison between application needs and realistic supply-side capabilities, identifies key technical and manufacturing bottlenecks, and informs potential pathways for strategic intervention or investment.



Methodology and analysis framework

Methodology and analysis framework

This analysis gathers data in supply- and demand-specific domains and cross-cutting technical areas to generate insights across the non-planar HTS supply chain, covering current capabilities, future potential, and pathways to solving technical challenges and industry bottlenecks.



Demand-side domains	Supply-side domains
Magnet requirements and design priorities	**Industry benchmarks**
Use cases	**Technical challenges**

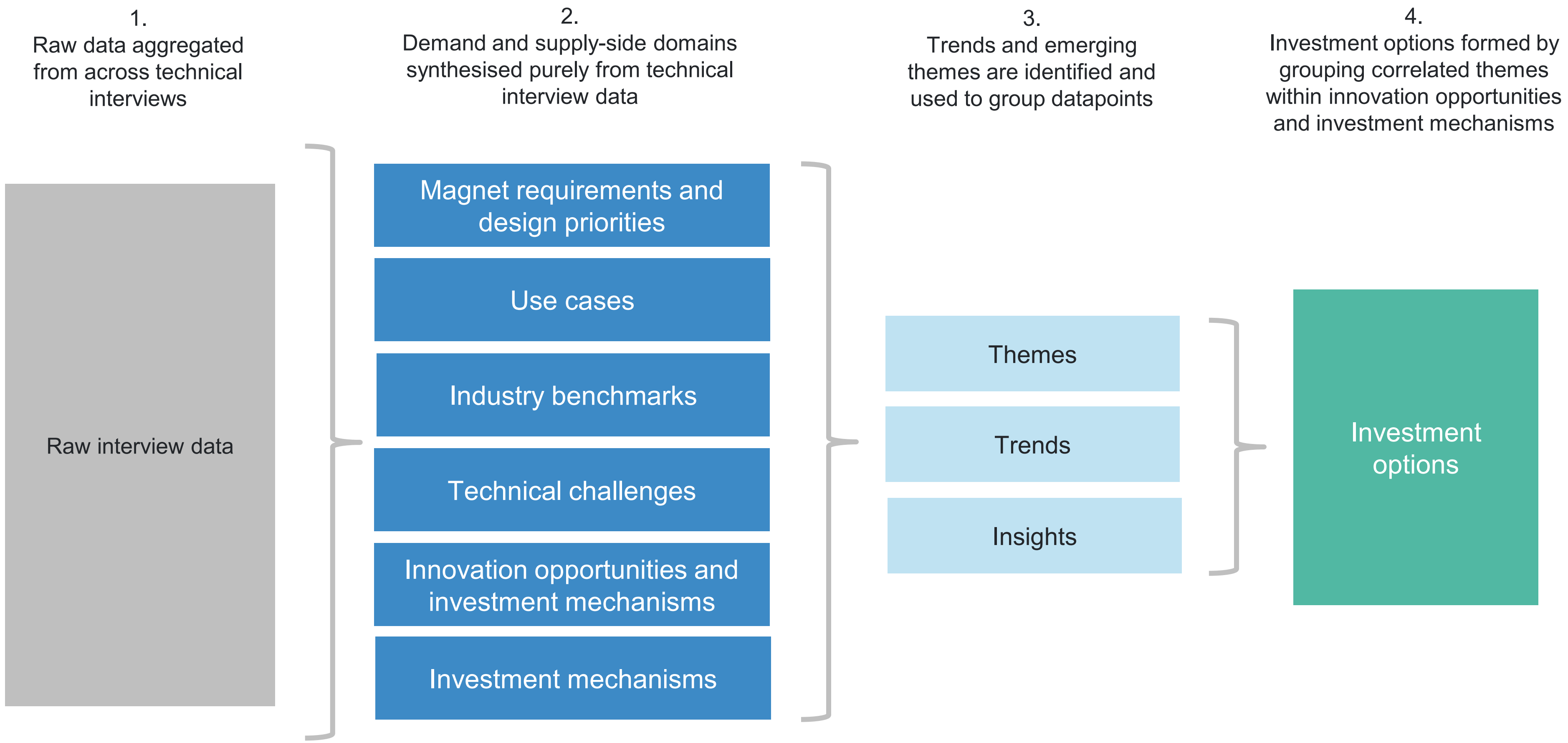
Technical areas

- Manufacturing yield, capacity and cost
- Field quality and strength
- Conductor forming and achievable geometries
- Quench management
- Cryogenic interfaces
- Mechanical support
- Assembly
- International programmes

Key insights	Description
State of play	• Measure current market dynamics and technology performance across sectors. • Gain insights into the trajectory and potential of non-planar HTS magnets and where they can be deployed.
Key challenges and bottlenecks	• Map the types of challenges associated with building non-planar HTS magnets, including where they exist in the supply chain.
Impactful solutions and investment options	• Identify most impactful routes to addressing supply chain bottlenecks via three investment pathways aligned with the fusion industry. • Inform potential roles for UKAEA in strategically shaping local and international magnet industries.

Methodology and analysis framework

Insights are developed purely from primary market research inputs to provide a “voice of the industry”, ensuring industry views are highlighted in derived themes and trends.



1.
Raw data aggregated from across technical interviews

2.
Demand and supply-side domains synthesised purely from technical interview data

3.
Trends and emerging themes are identified and used to group datapoints

4.
Investment options formed by grouping correlated themes within innovation opportunities and investment mechanisms

Raw interview data

- Magnet requirements and design priorities
- Use cases
- Industry benchmarks
- Technical challenges
- Innovation opportunities and investment mechanisms
- Investment mechanisms

- Themes
- Trends
- Insights

Investment options

Use cases

Use cases of non-planar HTS magnets [1/5]

Potential applications for non-planar HTS magnets cases span demand segments, focussing on increasing precision and performance efficiency at the system level, with some overlap with uses cases identified prior to interview target mapping.

Application	Description
Sub-Sea Cables	HTS sub-sea power cables benefit from non-planar cable layouts that manage mechanical strain, thermal contraction, and magnetic fields under dynamic marine conditions. Three-dimensional cable architectures improve reliability and efficiency for long-distance, high-capacity power transmission. However, underwater marine environments can present challenges, for example in cryogenic system integration and coolant transmission.
MRI and NMR	HTS NMR and MRI magnets can reduce size, operating cost, and helium dependence of LTS systems. Non-planar shim and insert coils provide improved field uniformity, supporting higher resolution imaging in smaller instruments. They can enable open or unconventional scanner geometries that improve patient access and comfort while maintaining adequate field strength. Today, high fixed costs block adoption, where a significant value-add is required to sway incumbents.
MR-LINAC	MR-LINAC systems combine MRI with linear accelerators for real-time image-guided radiotherapy. Non-planar HTS magnets can help integrate magnetic fields around radiation paths and shielding structures, enabling more compact systems and improved treatment precision. For HTS to be adopted, these improvements must meaningfully improve the business case around MR-LINAC systems, either through significant cost reductions of improved patient outcomes.

Use cases of non-planar HTS magnets [2/5]

Application	Description
Magnetometry	Non-planar HTS coils can generate highly tailored magnetic field geometries for magnetometry. Their ability to shape fields in three dimensions enables local field amplification or cancellation, improving sensitivity and spatial resolution for applications such as geophysics, materials characterisation, and biomagnetic experiments. HTS material characteristics make fabrication difficult, with only a handful of labs producing planar systems.
NMR Devices Using REBCO Inserts	Ultra-high-field NMR systems (>1 GHz) increasingly rely on REBCO HTS inserts inside conventional LTS background magnets. Non-planar HTS coil geometries help manage mechanical stress and field homogeneity at extreme fields, enabling compact insert designs that push spectral resolution beyond the limits of Nb_3Sn technology. Similar to other medical applications, HTS has yet to significantly improve the overall business case for NMR devices due to high costs.
Twisted Cables to Reduce Eddy Current Losses	Twisting HTS tapes or cable assemblies in non-planar geometries reduces eddy current losses under AC or transient magnetic fields. This is particularly important in power transmission and grid applications, where field orientation varies along the cable length and losses directly affect efficiency and cryogenic load.
REBCO Accelerator Magnets for Gyrotrons	Gyrotrons used for plasma heating require compact, high-field magnets that can integrate with existing cryogenic infrastructure, typically employing LTS magnets. Non-planar REBCO magnets allow tighter bending radii, complex field shaping, and integration around waveguides and cooling systems, enabling higher performance and improved reliability at moderate fields.

Use cases of non-planar HTS magnets [3/5]

Application	Description
Cyclotrons	Cyclotrons require strong, spatially varying magnetic fields to guide and accelerate charged particles. Non-planar HTS coils enable more compact cyclotron designs, higher achievable fields, and greater flexibility in pole shaping, which can reduce system size and improve beam control for medical isotope production and research accelerators.
Rotary Machines	In motors and generators, non-planar HTS coils allow field windings to conform to rotating geometries, improving power density and torque. HTS enables higher magnetic loading, while non-planar designs support compact rotors - key advantages for aerospace and high-performance industrial machinery. System-level innovation is required to reduce costs for low-value-density applications, such as wind turbines, and minimise cryogen and weight footprints in aerospace.
Detectors	Non-planar HTS magnets are used in particle and radiation detectors to generate complex field profiles for particle tracking or background suppression. Their low noise, high stability, and geometric flexibility are valuable for high-energy physics, neutron detection, and advanced sensing platforms.
Crystal Growers	Magnetic fields are used to control melt flow and impurity distribution during crystal growth. Non-planar HTS coils allow precise tailoring of magnetic field gradients around growth chambers, enabling improved crystal uniformity and quality in semiconductor and optical material production. HTS requires significant cost reduction or growth performance to replace conventional LTS in this commercial application.

Use cases of non-planar HTS magnets [4/5]

Application	Description
Synchrotrons	Synchrotron light sources rely on precisely shaped magnetic fields for beam bending and focusing. Non-planar HTS magnets enable compact dipoles, quadrupoles, and insertion devices with higher field strength and reduced power consumption, supporting next-generation, smaller-footprint synchrotron facilities.
Targeted Saddle Coils for Local Field Manipulation	Saddle-shaped, non-planar HTS coils are used to locally boost or manipulate magnetic fields without redesigning an entire magnet system. These coils are valuable for fine tuning, beam steering, plasma shaping, or correcting local field errors in complex systems.
Modular Coils Made of Blocks of Cables	Modular non-planar HTS coils assembled from cable blocks offer scalability, manufacturability, and fault tolerance. This approach reduces sensitivity to tape variability and enables large, complex magnet systems to be built from repeatable sub-units, particularly attractive for fusion and accelerator magnets.
Moderate Fields in Compact Settings	HTS enables moderate magnetic fields (e.g. 2–10 T) in very compact volumes without liquid helium. Non-planar geometries allow magnets to conform to constrained spaces, making them suitable for portable, mobile, or space-limited scientific and industrial systems.

Use cases of non-planar HTS magnets [5/5]

Application	Description
Magnets for Shielding Electronics	Non-planar HTS coils can generate tailored counter-fields to shield sensitive electronics from external magnetic interference. This approach is attractive in fusion devices, accelerators, and aerospace platforms where conventional passive shielding is too heavy or ineffective.
Shim Coils for Boosting Uniformity	Non-planar HTS shim coils are used to correct field inhomogeneities in MRI, NMR, and accelerator magnets. Their geometric flexibility allows precise local correction, improving ppm-level uniformity without redesigning the main magnet.
Flexible Imaging Chambers	Non-planar HTS magnets enable larger, more open imaging volumes by decoupling field generation from simple cylindrical geometries. This can allow patients to be scanned standing, sitting, or in non-standard positions, improving comfort and expanding diagnostic possibilities.
Magnetic Particle Imaging (MPI)	MPI relies on highly non-linear magnetic field gradients to image magnetic nanoparticles. Non-planar HTS magnets enable compact, high-gradient field sources with low power consumption, supporting higher resolution and faster imaging.
Electric Aircraft	Electric aircraft require ultra-high power-density motors and generators. Non-planar HTS coils allow magnetic fields to be optimised around complex airframe and propulsion geometries, enabling lighter, more efficient propulsion systems that are critical for aviation electrification.

Magnet requirements and design priorities

Magnet requirements & design priorities [1/2]

Seven overarching themes encompass the requirements for useful NP-HTS magnets and industry design priorities. Themes are highly interconnected via design choices – for example, magnet bore size or critical current density – demanding a systems-level approach when designing effective magnet technologies.

Theme	Description
System-level efficiency and optimisation	• Industry players value magnet technologies that increase overall efficiency, for example reducing cost per unit current per unit length, cost per unit field strength, or maximising field strength per unit volume. • New magnet systems must be designed using a systems-level approach, aiming to optimise design features not simply maximise them. For example, increasing critical current density increases cost through more stringent tape quality requirements, yielding diminishing returns.
Clear business cases	• Commercially-focussed applications, such as medical scanners and power transmission, require magnet technologies to add clear value to the underlying business case if they are to be adopted over tried-and-trusted solutions. • NP-HTS technologies should be designed with minimal cost footprints, including OPEX. Magnet systems should also be designed with insurance in mind, particularly where human safety is of importance.
Safety	• Safety encompasses both human safety and the protection of electronics and surrounding equipment under normal operation and fault conditions. It is particularly significant in medical and transport settings, which involves people and consumer-type electronics, such as simple control interfaces. In transport settings, safety encompasses predictability, where quenches may lead to sudden loss of flight. • Strong safety performance enables higher operational confidence, improves insurability and acceptance (business case), and often drives simpler, more conservative system-level design choices that improve usability.

Magnet requirements & design priorities [2/2]

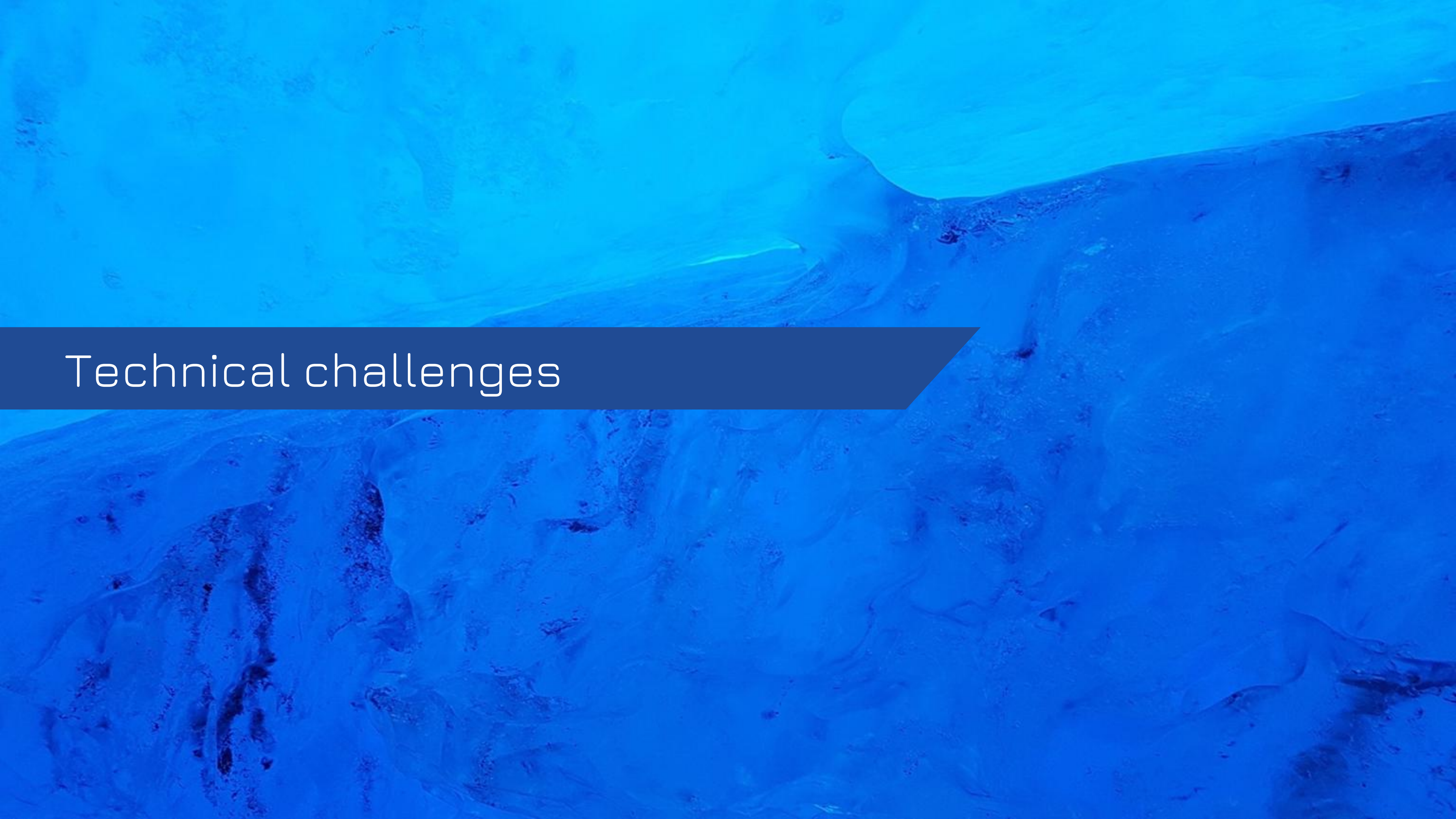
Theme	Description
Synergies with surrounding systems	• Synergies with supporting systems and other surrounding elements improves the system-level performance of magnets and surrounding components. For example, the ability for NP-HTS magnets to run at 20 K enables synergies between hydrogen fuel cell liquefaction and coil cryogenics in aerospace and transport applications. • Technologies should be developed in close collaboration with domain experts in application sectors, whilst ensuring synergies and surrounding systems remain aligned with other themes here. For example, magnet systems for aircraft must operate with a high degree of reliability to ensure safety.
Field performance	• Magnet homogeneity in both time and space is crucial for applications in medical imaging as well as accelerators and science, where field error truncation over many particle orbits leads to a loss of beam focussing. • High-uniformity applications typically use small-bore magnets, meaning that magnet systems can be designed with adjustable performance – for example compromising field uniformity at large sizes whilst remaining relevant for fusion and optimising overall cost.
Simplicity	• Simpler complete systems enable better integration and usability, for example NP-HTS magnets may eliminate the requirement for quench pipes, saving space and costs when designing medical imaging departments. Simpler systems also increase safety through lack of failure modes.
Usability	• Magnets that are usable and practical have wide-ranging impacts, from faster ramp rates enabling researchers to test samples quicker and fusion devices to provide dispatchable power, to longevity under many pulses and exposure to various types of radiation.

Benchmarks

Key benchmarks

Supply-side capabilities demonstrate significant potential for meeting fusion production and performance requirements, with fusion-grade relevant performance achieved at some scale or in some part of the supply chain or wider industry.

Area	Description
General	• **General:** Benchmarks and specifications vary across the industry, however intelligent metric design can be used to selectively gauge and monitor the health of specific segments of the supply chain. For example, monitoring achievable tape power densities – not total power – simultaneously measures tape quality, as well as access to test equipment. • **Programmes:** Efforts within the UK are starting to yield significant results, highlighted by recent technical achievements around demountable joints. However, the need for an industrial ecosystem is felt, requiring more system-level industrial coordination. Outside the UK, magnet programmes were identified in China and the US, whilst Japanese firms in particular are replicating UK efforts to drive innovation through public-private partnerships, with the National Institute for Fusion Science playing a central role.
Production	• **Manufacturing Capacity and Yields:** Pulsed laser deposition emerges as the dominant manufacturing method for HTS tape, due to its reproducibility and ease of adoption. On average, firm capacity stands at 3000 km/year, with near-term expansion plans being widespread. • **Achievable geometries:** Tape and cable producers are able to achieve any geometry, whereas limitations are introduced at the winding and assembly stage, with industry currently limited to planar forms due to a lack of strong demand signals.
Performance	• **Field quality:** Strength and uniformity surpassing fusion requirements have been achieved, however performance is closely geometry dependent. • **Quench:** A variety of approaches exist for quench monitoring and mitigation, however reliably achieving quench management in high-power-density magnets has not been achieved. Few facilities exist for testing quench at relevant 20K20T conditions.



Technical challenges

Technical challenges: area summaries [1/2]

Challenges are defined by seven technical areas relating to specific points along the non-planar HTS magnet value chain, with a further area for capturing general challenges. Most challenges arise due to mechanical support, conductor forming and winding, cryogenic integration, and quench management.

Technical area	Description
Mechanical support	Mechanical support challenges are raised by magnet designers as well as fusion users across the globe. Fragile tapes and coil casings undergo extreme, multidimensional stresses that compound due to thermal, magnetic, and physical interactions. These regimes go beyond the limits of knowledge of materials science and low-temperature superconductors, creating capability gaps in existing modelling and design tools.
Conductor forming and winding	Challenges with conductors are dominated by tape fragility, large-scale winding, and joint performance. Similarly, variation in the quality of tapes was acknowledged on both sides of supply and demand.
Field quality and accuracy	Impacts on field quality are highlighted mostly by tape manufacturers. Mechanical forces, such as tape strain and bending, alter the performance of tapes in unpredictable ways due to the complex geometries that may become non-linearly perturbed over multiple degrees of freedom.
Cryogenic interfaces	Coolant pipe geometry and shaping become challenging due to need to reduce thermal touches and localised heating within the pipes due to coolant compression and reduced flow. A lack of coolant availability and low diversity in the supply chain for high-power cryogenic systems introduces large OPEX and CAPEX entry costs for testing integrated magnet systems at relevant scales.

Technical challenges: area summaries [2/2]

Challenges are defined by seven technical areas relating to specific points along the non-planar HTS magnet value chain, with a further area for capturing general challenges. Most challenges arise due to mechanical support, conductor forming and winding, cryogenic integration, and quench management.

Technical area	Description
Quench detection and management	Complex cooling geometry and adjacent coil systems, make designing quench mitigation systems difficult. Likewise, testing quenches is operationally difficult due to long magnet energising times and the extremely high voltages and currents required. As a result, very little industry knowledge exists, leading to firms operationalising quenches as opposed to mitigating them, despite perceived reputational risks of failures of this strategic technology.
Manufacturing yield and cost	Ensuring tapes maintain their characteristics over extremely long lengths is challenging. For tape manufacturers, their small demand for non-standard upstream materials increases tape costs.
Assembly	Challenges in coil assembly are highlighted by fusion firms, where the size and geometry of non-planar coils make it hard to transport and design effective maintenance strategies, which cascades down to the design of supporting systems and buildings.
General	Coil shapes and topologies introduce many more degrees of freedom which combines with tight system coupling to create systems that are challenging to design. Testing these complex designs at scale is required to instil confidence however requires significant CAPEX, increased workforce capability, updated simulation codes, and must be repeated for each coil design. A patchwork of test facilities exist globally, for example at NIFS, however significant adaptations are required to accommodate fusion-scale non-planar magnets; no single test facility or national capability can support the complete magnet development cycle, from small-scale mock-up to full coils.

Technical challenges: emerging themes [1/2]

Eight cross-cutting themes emerged to characterise the specific technical challenges of developing non-planar HTS magnets. Most challenges are characterised by themes relating to specific magnet properties: complexity and design, scale, end-product quality and performance, and information flow.

Theme	Description
Complexity and design	Non-planar HTS magnets introduce extreme geometric, electromagnetic, thermal, and mechanical coupling, where curvature, field orientation, stress, quench behaviour, and cryogenic integration interact non-linearly, making design highly case-specific and difficult to generalise or standardise. This complexity pushes current modelling tools, material data, and design rules beyond their validated limits, increasing reliance on bespoke engineering judgement and iterative prototyping rather than predictive design alone.
Scale	Scaling non-planar HTS magnets from small demonstrators to full-scale systems exposes emergent behaviours - such as compounded mechanical strain, altered quench dynamics, and cryogenic inefficiencies - that cannot be reliably extrapolated from mock-ups, necessitating expensive, high-risk full-scale testing. Infrastructure limitations (power supplies, cryoplants, test volumes) and capital intensity make scale-up one of the most significant technical and commercial bottlenecks.
End-product quality and performance	Achieving consistent field quality, stability, and reliability in non-planar HTS magnets is challenging due to sensitivity to tape variability, joint resistance, winding precision, and mechanical support fidelity, all of which are amplified by 3D geometries. End users often prioritise robustness, quench tolerance, and system efficiency over maximum field strength, yet translating these priorities into manufacturable, repeatable specifications remains unresolved.
Information availability and flow	Critical data on HTS tape behaviour under combined bending, strain, field angle, radiation, and cryogenic conditions is fragmented, proprietary, or incomplete, limiting design confidence and cross-industry learning. Weak feedback loops between tape manufacturers, magnet builders, and end users slow optimisation, while IP concerns and competitive pressures further restrict transparent information sharing.

Technical challenges: emerging themes [2/2]

Fewer challenges sit within more generic themes relating to wider industry dynamics and adjacent technologies, however implications are wide-reaching, for example a lack of skilled workforce trained in magnet making or misaligned incentives in the wider market.

Theme	Description
Availability of production factors (tools, labour)	Non-planar HTS magnet manufacture depends on scarce specialised tooling (3D winding, impregnation, precision assembly), limited test infrastructure, and a small pool of experienced engineers and technicians with hands-on HTS knowledge. This skills and equipment scarcity constrains yield, repeatability, and throughput, particularly as designs move beyond one-off prototypes toward low-volume production.
Market dynamics and incentives	The high capital cost, technical risk, and fragmented demand for non-planar HTS magnets weaken private incentives to invest in enabling infrastructure, standards, or capability development. Many suppliers prefer incremental improvements to established planar or LTS products, leaving non-planar HTS caught in a coordination gap where system-level benefits may be recognised but are under-rewarded by current market structures that lack disruptive, incoming businesses.
Supporting technologies and materials	Non-planar HTS magnets depend upon suboptimal supporting technologies from immature adjacent industries, for example high-power cryoplants that may rely on scarce materials such as coolant. Costs increase due to a lack of standardisation and variety driving over-specification. Poor operational reliability of these systems due to technological immaturity may limit overall plant performance.
Other	Additional challenges relate to quench and the requirement for penetrations for monitoring as well as the implications for maintaining electrical insulation at high voltages. Developing one coil that serves both fusion and non-fusion markets is also challenging due to the difference in price points amongst sectors.

Investment pathways

Investment pathways

Three investment pathways form from nine investment themes that emerge from industry input. All themes incorporate investments of varying risk and cadence and cut across the technical challenges, whilst varying by specificity, from general cross-industry support to highly targeted action. To ensure alignment with the voice of the industry, investments are derived purely from investment mechanisms and opportunities raised in interviews, as well as technical challenges, meaning funding sources are not identified but should be coordinated across the industry.

1. Creating the Conditions
   Focus on **reducing costs, reducing risks** of developers,
   and **budgeting research** for generating public goods.

2. Enhancing the Market
   Focus on **building infrastructure,** production **capacity expansions**,
   and **improving resilience and diversity** of the supply chain.

3. Directional Pushing
   Focus on **building prototypes and demonstrators**,
   creating signals and incentives, and **pushing market alignment**

Investment themes [1/3]

Deploying industry-wide support to reduce costs, risks, and develop public goods through research-type budgets can culminate in **creating the conditions** for firms to solve challenges and plug gaps themselves.

Theme	Description	Investment pathway
Reducing costs	Investments can target the high costs that are faced by developers throughout the design and development chain, from tape development to magnet testing facilities. Subsidies can also be used to reduce differences in prices and purchasing power of competing technologies and industries, which may price fusion out, especially if scarce manufacturing locks into producing tapes for other uses.	Together, reducing costs, risks, and introducing research budgets offers blanket support across the industry that is agnostic to specific firms, projects, or facilities, **creating the conditions** to enable firms to freely engage in magnet development.
Reducing risks for developers	NP-HTS magnet development can bring significant risks for firms, from financial to reputational. Investments can reduce this risk via encouraging co-creation models or setting up financing facilities that underwrite risk. Similarly, establishing contracting and mediation services creates a safer environment for firms to engage.	
Research budget	Investing in public goods can tackle challenges that individual firms may not be capable or incentivised to tackle themselves or even together. For example, establishing and maintaining industry codes and standards, and building public knowledge, can improve standardisation across the industry. This theme is a vital compliment to but not replacement of direct industry action.	

Investment themes [2/3]

Directly building specific yet shared capability and improving longevity through investments in infrastructure, production capacity, and well-timed injections can **enhance the market** with strategically aligned capability.

Theme	Description	Investment pathway
Building infrastructure	Investments in magnet testing and updated In Silico design codes is required due to a lack of available testing infrastructure. Building a range of test apparatus covering a range of test regimes, as well as adapting pre-existing sites that may not be suitable for fusion-scale magnets, is vital for granting small firms access to high-power testing.	Investments in shared tools, facilities and production capacity can **enhance the market**, building industrial capability through improving access to large-scale infrastructure that would otherwise prove too risky for firms to finance alone. These and other investments can be timed to maintain this capability over fusion development timescales.
Production expansion	Tape firms are receptive to co-investments into production capacity expansion, enabling them to achieve their ambitious near-term growth targets, which may otherwise be CAPEX-limited.	
Improving supply chain health	Investment timing and distribution can maintain supply chains over periods of fluctuating demand, where market recession and consolidation may risk the loss of strategically significant firms and capabilities over fusion deployment timescales.	

Investment themes [3/3]

Publicly building and procuring multiple magnet prototypes and demonstrations, and crowding in firms through incentives and co-investments, can **directionally push** the industry toward a shared goal aligned with fusion programme aims.

Theme	Description	Investment pathway
Prototypes and demonstrations	Financing prototypes of multiple scales, maturities, varieties, over long timescales can build investor and industry confidence, demonstrate performance and integration at the system level, and even contribute toward FOAK construction.	Targeted orders and investments in fusion-specific projects, such as magnet prototypes, generates **directional pushing** toward a shared goal, forming a mission-oriented magnet development programme that attracts and aligns industry stakeholders.
Incentives and signalling	Industry players can be driven and aligned through investments and signals that incentivise and direct firms toward building specific technologies and capabilities. Strong, visible signals are also vital to maintain industry innovation and R&D activities when internal drivers are weak.	
Market alignment and co-investing	Specific investment structures, such as co-investments, joint ventures, and shared cost initiatives, are tools to encourage industry cohesion and alignment whilst maintaining diversity and IP arrangements.	

1. Creating the conditions

Pathway 1 aims to create the necessary conditions for firms to step in to fill gaps by accomplishing three things: reducing costs, reducing risk for developers, and creating a communal financing mechanism spanning the industry for research targeting fundamental science around magnet design, quality and performance, as well as improving the flow of information and the availability of shared design tools.

Reducing costs	Reducing risk for developers	Research budget
Subsidise high CAPEX requirements for tape R&D	Building patient relationships with firms through e.g. co-creation models	Fixed allocation earmarked for research purposes, with potential matches from private firms e.g. tape manufacturers
Sharing costs of tape manufacturing plants	Signal to firms who is underwriting investments	Creating and maintaining codes and standards covering HTS tapes
Subsidies for power supplies and cryogenics in test facilities	Improve ability for firms to contract safely	Building knowledge base of ”clever” design principles that eliminate magnet challenges
Reduce price gap with low-cost competing LTS technologies		
Level playing field with non-fusion sources of tape demand (power)		
Funding facilities		

Pros	Cons
Solves a wide range of technical challenges	Reducing costs felt by firms can be capital intensive
Targets challenges that industry is unlikely to solve by itself	Significant progress not guaranteed
Plays to UK national strengths of research and development	
Short time to impact	

2. Enhancing the market

Pathway 2 aims to empower firms directly by improving their access to shared infrastructure, expanding their production, and improving the overall health and resilience of the market. Specific infrastructure to target involves tape qualification and an ecosystem of magnet testing facilities at multiple scales but focussing on 20K20T testing, as well as access to in silico engineering services. Meanwhile, investments in a selection of potential technically qualified suppliers may reduce risks of firm exits whilst plugging gaps in relevant corners, for example the provision of large-scale cryogenics systems.

Building infrastructure

- Investment in multiple coil test facilities at varying scales
- Enabling smaller firms to perform large-scale testing
- High demand for engineering services e.g. In Silico quench modelling
- Funding to adapt pre-existing test sites
- Creation of industrial consortia to tackle communal challenges
- Facilities targeting 20K20T testing, high energy densities, and coil cycling
- Updating LTS computer models

Production expansion

- Significant CAPEX required to expand tape factory and machinery throughput

Improving supply chain health

- Adopting cross-sector learnings to smooth demand peakiness and preserve firms
- Investing in multiple technically qualified suppliers, as CERN did

Pros	Cons
Relevant throughout the magnet industry	Requires building physical assets
In Silico engineering plays to UK strengths and has large spillover potential	May require significant international cooperation

3. Directional pushing

Pathway 3 aims to actively steer market players through financing prototypes and demonstrations, creating incentives and signals, and encouraging market players to cooperate and co-invest to align on priorities. Financing full-scale prototypes, which can be used as FOAK, has been successful strategy for previous magnet technologies, and it is required to solve much of the many specific challenges that arise at large scales. Drafting future orders today may also spur preparations in the market by initiating R&D and align firm internal development with fusion requirements.

Prototypes and demonstrations

- Financing build of a specific magnet to increase stakeholder confidence at the system level
- Initiating early prototypes that may be used as the FOAK if to a sufficient standard
- Building short prototypes e.g. 1m
- Aiming for full-scale prototypes to demonstrate manufacturing and integration as much as coil design
- Replicate the CERN approach: steady, long-term financing for multiple model coils and prototypes

Incentives & signalling

- Deploying investment as "persuasive messaging" to create believable orders that triggers R&D in firms
- Drafting purchases of experimental tape or spare coils that use a variety of tapes
- Incentivising continual R&D when firms not driven by immediate orders
- Align industry players through strategic orders; firms look for orders that drive the company in desirable directions
- Spur market to increase the variety of cryoplants available
- Drive innovation through increasing competition amongst incumbents

Market alignment and co-investing

- Co-investments already exist across markets e.g. firms in fusion and the power sector
- Joint ventures for non-fusion applications of magnet technologies
- Shared cost initiatives for tape manufacturing plants
- IP-friendly arrangements e.g. cost sharing
- Patient, risk-optimised financing that enables firms to innovate without facing existential risks

Pros	Cons
Fusion-relevance baked in	Capital intensive
Encompasses elements of pathways 1 and 2	Requires expertise and knowledge of direction

Definitions and acronyms

NP-HTS – Non-planar High-Temperature Superconductor:
Superconducting materials arranged in 3D geometries that operate at higher temperatures than conventional superconductors, enabling higher current density and improved thermal margins.

NMR – Nuclear Magnetic Resonance:
A technique using strong, uniform magnetic fields to analyse the structure and properties of materials at the atomic level.

REBCO – Rare Earth Barium Copper Oxide:
A leading HTS material used in coated conductor tapes, valued for high current density and strong performance in high magnetic fields.

PLD – Pulsed Laser Deposition:
A thin-film fabrication method used to deposit high-quality REBCO layers onto substrates for HTS tape production.

MOCVD – Metal-Organic Chemical Vapour Deposition:
A scalable chemical deposition process used to manufacture REBCO HTS tapes with high throughput.

MPI – Magnetic Particle Imaging:
A medical imaging technique that uses magnetic fields to detect and image magnetic nanoparticles.

LTS – Low-Temperature Superconductor:
Conventional superconducting materials that require operation at liquid helium temperatures.

Definitions and acronyms

W7-X – Wendelstein 7-X:
A large, advanced stellarator fusion experiment in Germany featuring complex non-planar superconducting coils.

CERN – European Organization for Nuclear Research:
An international research laboratory operating the world's leading particle accelerators and advanced superconducting magnet systems.

OPEX – Operating Expenditure:
Costs and expenses associated with incremental production or day-to-day running of systems, for example consumption of fuel and power.

CAPEX– Capital Expenditure:
Costs and expenses associated with initial costs of production equipment, for example power plant reactors.

FOAK – First-of-a-kind:
Pilot plants that are the first demonstrated example of a technology reaching commercial relevance. STEP aims to act as a FOAK fusion power plant.

Quench:
Events where superconducting magnets experience a loss in superconductivity and increase in resistance. Increasing resistance increases conductor temperature, further increasing magnet resistance, producing a positive feedback loop that must be controlled to safely operate magnets.

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