Technology Development Programme

Technology Mapping
2025 Series

Magnets

FUSION FOR ENERGY
EUROfusion
CERN

Contents

Version history

VERSION	DATE	CHANGES
0.0	10/09/2025	First issue: input data for online workshop. Covers: 1. Introduction 2. The mapping process 3. Fuel cycle technology breakdown (draft) Other sections will be completed after the workshop.
1.0	17/11/2025	After the online workshop, incorporating the changes agreed to the technology map
2.0	27/02/2026	After the in-person workshop - Draft final report for comments by participants
2.1	02/04/2026	Final report for publication

Foreword

We are entering a new era for the fusion sector, marked by a significant acceleration in technology development. Academia, public research organisations and private actors now need to rise to the challenge and coordinate efforts to ensure that the community follows a common technology roadmap that clearly shows how to advance critical technologies for fusion from fundamental research to industrial application.

EUROfusion and F4E, as European fusion technology hubs, can play a significant role at the heart of the fusion ecosystem, identifying research and development opportunities for future fusion power plants, facilitating exchange of knowledge and fostering partnerships across the fusion community. It is with this ambitious objective in mind that F4E, with the support of EUROfusion experts, organized a series of fusion technology mapping workshops.

Exploiting obvious synergies with other sectors is also critical to accelerating technological development. When it came to organizing a workshop on superconducting magnet applications, it was natural for CERN to join as co-organiser. Holding the in-person session in the Globe of Science and Innovation, opposite the entrance to CERN, a world leader in the field, was a sign of the strong joint interest of the three organisations to push the boundaries of superconducting magnet technologies together for the benefit of fusion, high energy physics and many other research and industrial applications.

As a result of a participative process involving over 180 participants from more than 60 public and private actors, we are now proud to present this report which will serve as a valuable resource for all interested economic operators seeking national, international, and private funding.

CERN, F4E and EUROfusion will continue to commit resources to superconductng magnet technology development. Our efforts will not be enough. We hereby invite all stakeholders to act. Let’s accelerate fusion and high energy physics technology development together!

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Executive summary

The 2025 Superconducting Magnets Technology Mapping Workshop, co-organized by CERN, Fusion for Energy (F4E), and EUROfusion, brought together over 180 participants from 65+ public and private entities. It delivers an overview of the current European capabilities in the field and establishes a strategic roadmap for advancing superconducting magnet technologies in the territory. The output of the exercise is intended to be used by the public and private European superconducting magnets community as a reference document to guide current and future investment.

Technology mapping

The mapping exercise identified and characterized 42 technologies across 7 key domains critical to superconducting magnet development:

- Superconducting materials
- Cabling and conductors
- Modelling
- Joining and insulation
- Manufacturing
- Magnet protection
- Instrumentation and auxiliaries.

Each technology was evaluated for Technology Readiness Level (TRL), applicability to other sectors, criticality, development needs, and European capabilities. This data was presented conveniently in a visual dashboard for each technology for reference and regular update.

European Competitive Position:

Competitive strengths were identified:

- World class R&D ecosystem and knowledge from past large LTS projects
- Established industrial supply chains for LTS, MgB2 and magnet manufacturing
- Advanced test infrastructure
- Emerging start-up ecosystem

The assessment revealed the following weaknesses that may threaten Europe's competitive position:

- Fragile HTS supply chain and associated dependence on other territories for supply
- Testing bottlenecks for high field, high current applications
- Over-reliance on stacked tape for HTS conductor configurations
- Shortage of experience in HTS quench detection and protection
- Lack of public funding continuity for large projects threatening the established supply chain

The report points out four key opportunities to strengthen European capability in the delivery of superconducting magnets systems:

- Set up coordinated validation programmes for large scale HTS magnets using both established manufacturers and start-ups
- Improve the production capacity of HTS material and cables
- Expand test facility capacity
- Boost R&D in emerging iron-based HTS technology
- Exploit synergies between High Energy Physics, Fusion and other relevant sectors

Strategic Roadmap

The technology development roadmap prioritizes actions across multiple timelines:

Immediate Actions (2026-2027):

- Reinforce HTS validation programs: initiate further small-scale prototype development and testing and improve coordination between public and private partners.
- Strengthen supply chain: provide targeted funding to expand production capacity for LTS and REBCO and stimulate R&D on alternative conductor architectures.
- Upgrade test facilities: enhance existing infrastructure to limit downtime and accommodate higher fields and currents where possible.
- Foster collaboration: create communities for knowledge exchange between research institutions, industry, and start-ups on the topics of HTS model coils and superconducting materials supply chains.

Medium-term Objectives (2028-2030):

- Scale up LTS and HTS production: ensure European suppliers capture a significant share of upcoming public and private contracts.
- Expand test capacity: establish new facilities for high-field, high-current, and neutron irradiation testing.
- Standardize quench protection: develop and validate robust quench detection and protection systems for HTS magnets.
- Promote cross-sector projects: launch joint initiatives between fusion, high-energy physics, and medical imaging to maximize resource efficiency.

Long-term Vision (2031+):

- Diversify HTS production chain: commercialize new products based on helically wound conductors, innovative material deposition or manufacturing techniques or alternative HTS materials (e.g. iron/based).
- Validate full scale HTS or hybrid prototypes in relevant environments including neutron-irradiated conditions for fusion applications.

Call to Action

Europe’s leadership in superconducting magnets will be based on **coordinated investment, cross-sector partnerships, and sustained funding**. CERN, F4E, and EUROfusion commit to driving these efforts and urge all stakeholders—**academia**, **research institutions, industry, start-ups, and policymakers**—to do the same. By addressing critical gaps and leveraging collective strengths, Europe can secure its position at the forefront of superconducting magnet technology for fusion energy, high-energy physics, and many other applications.

1 Introduction

1.1 Context

In 2024, Fusion for Energy launched a Technology Development Programme (TDP) as part of the implementation actions of its Industrial Policy. This TDP is dedicated to building and reinforcing European Fusion Supply chain capabilities for those technologies that are deemed to be critical for the future of commercial fusion. The programme requires the identification of key technologies to direct R&D contracts to European contractors.

Since 2014, EUROfusion has been paving the way for fusion power reactors by funding research based on the "European Roadmap to the Realisation of Fusion Energy" as a joint programme within Euratom Horizon Europe. EUROfusion currently manages a research programme evolved from short-, mid- and long-term roadmaps.

Prioritizing and allocating funding opportunities across both organizations requires a comprehensive review of the technologies involved in each major fusion technical domain. Doing this exercise in a collaborative way will enable stakeholders to identify which technologies are fundamentally needed (technology mapping) and when they are needed (technology road mapping). A roadmap built through consensus of key stakeholders in the field can also serve as a powerful argument when seeking additional funding from national and international public and private investors.

CERN is a major actor in the field of superconductive magnet systems, boasting a long tradition of carrying out in-house R&D then transferring technology to industrial suppliers for manufacturing large-scale "one-of-a-kind" detector magnets and mass-producing accelerator magnets for particle accelerators and high energy physics experiments.

There are joint lessons learnt from the past decade and strong synergies in research and development activities linked to superconducting magnets for fusion and high energy physics applications, it was therefore natural for CERN, EUROfusion and F4E to coordinate their efforts, and launch a technology mapping initiative uniting academia, research laboratories, industry, start-ups and the ITER Organization to develop a comprehensive technology development roadmap for superconducting magnets technologies.

The outcome of this exercise will help all stakeholders to guide their action in their respective domains, allowing an effective investment of resources. Given the fast evolution of technology, a periodical follow-up of the workshop outcome shall be assured in subsequent technology mapping exercises.

1.2 Magnets technology mapping

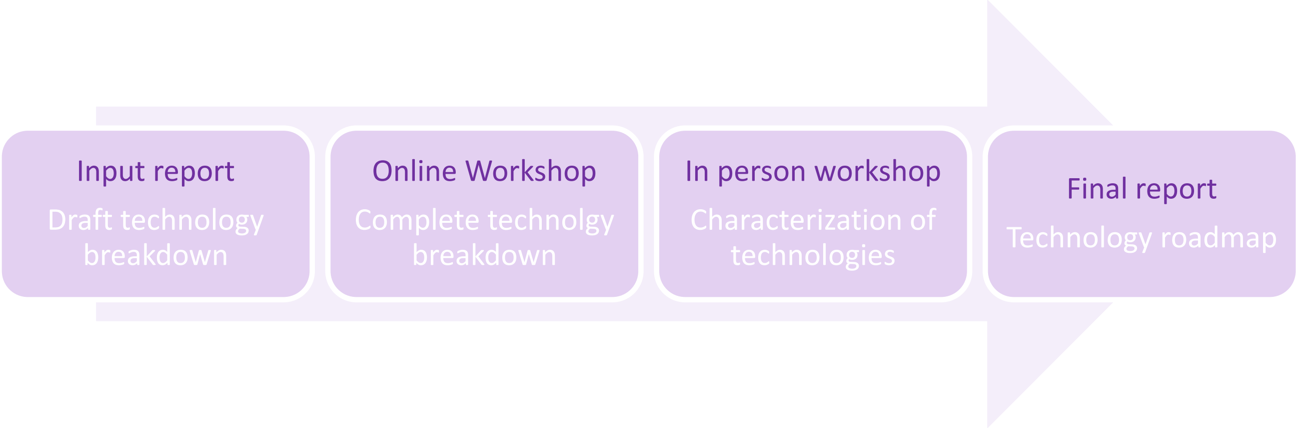
The scope of the of the Magnets Technology Mapping Workshop covers relevant technologies for superconducting magnets including materials, conductors, coil design and manufacturing, quench management as well as instrumentation and auxiliary systems required for coil integration and operation. The workshop will hold a specific focus on High temperature Superconductivity given the maturity of the Low Temperature Superconductivity technologies and the potential relevance of HTS for high energy physics and fusion applications.

The main associated event is a workshop held in September and November 2025 to generate most of the relevant data and provide an opportunity for participants to network and exchange knowledge.

This document provides a complete overview of the exercise, detailing the process and scope through a comprehensive technology breakdown, summarizing the meetings held and providing the resulting proposed technology development roadmap.

2 Technology mapping process

The technology mapping process consists of 4 stages.



2.1 Input report

In preparation of the exercise, staff from CERN, Fusion for Energy and EUROfusion prepared a draft technology breakdown, listing technologies of interest and grouping them functionally.
This breakdown, together with a brief description of each selected technology, was distributed to participants and discussed during the online workshop on September 17th 2025.

2.2 Online workshop

The online workshop is the opportunity for all participants to the technology mapping exercise to come together with the following agenda:

- Welcome and introductory remarks
- The technology mapping process
- Overview of the European landscape
- Networking opportunity between participants
- Brief overview of technology breakdown
- Joint review of the technology breakdown
- Explanation of the next step (in person workshop)
- Survey feedback and wrap-up

The main output of the online workshop is an exhaustive list of relevant technologies agreed between participants in the workshop. This breakdown forms the basis of the technology mapping to take place during the in-person workshop. An updated version of the input report (this report v 1.0) with an updated technology breakdown is made available to participants before the in-person workshop.

2.3 In-person workshop

The in-person workshop aims at providing a detailed characterization of the technologies part of the breakdown agreed during the online workshop including their prioritization (timeline).
The characterization of technologies takes place in three steps applicable to each technology:

- Quantification of the characteristics of the technology (see appendix 2 for a typical list of characteristics to be evaluated).
- Definition of several technology development actions to increase its maturity (eg analysis, prototype, testing, industrialization plan etc).
- Prioritization of the technology development actions leading to development roadmaps for the technologies considered in the technology mapping. Typical timelines can cover short-, medium- and long-term activities.

The workshop is highly collaborative, with sessions designed for participants to exchange, build consensus and provide feedback on specific interests and the mapping process itself.
The workshop also provides ample opportunities for participants to share knowledge and form partnerships over a typical duration of one and a half day which includes specific times for formal and informal networking.

2.4 Final report

After the in-person workshop, staff from CERN, Fusion for Energy and Eurofusion compile the outcome in a final report (an evolution of the input report). The report will include an overview of European capabilities in the field as well as the proposed technology roadmap detailing and prioritizing possible actions for the period until the next review (typically 2 to 3 years).
Participants and additional peer reviewers from the fusion or high energy physics communities are given an opportunity to comment before the final version of the report is published.

3 Magnet technology Breakdown

3.1 Technology overview

Superconducting magnets are fundamental to both magnetic confinement fusion and high-energy physics as they are the enabling technology to generate strong and stable magnetic fields with compact structures and minimal energy loss.
In magnetic confinement fusion devices like tokamaks and stellarators, superconducting magnets provide confinement and plasma shaping functions. Magnets for fusion applications are characterised by their large bore (multiple meters), high conductor peak field (10 to 20 Tesla), transient operation for some sub-systems (in the case of tokamaks) and high neutron radiation load.
In particle accelerators, superconducting magnets are used to bend and focus charged particle beams. The Large Hadron Collider, for example, uses over 1,200 superconducting dipole magnets generating a bore field of 8.3 Tesla to guide proton beams around its 27-kilometer circumference. The beam energy is directly proportional to the bending dipole field strength times the accelerator radius, hence, the higher the field, the higher the beam energy for a given tunnel size.
For particle detectors, large superconducting magnets systems curve charged particle trajectories, allowing precise momentum measurements. The magnetic field strength directly correlates with measurement precision—stronger fields produce greater curvature, enabling better discrimination between particles with similar properties.

Except for Nb-Ti, all superconducting materials are brittle and strain sensitive, which call for specific manufacturing processes and mechanical support during cooldown and operation to mitigate degradation risks.
Without superconducting magnets, neither controlled fusion energy nor modern high-energy physics experiments would be feasible at their current scale and precision.

3.2 Superconducting magnets technology map

Relevant technologies to superconducting magnets have been listed and broken down into 7 areas:

Superconducting materials

- REBCO
- BSCCO
- Iron-base superconductors
- MgB2
- LTS

Cables and conductors

- Rutherford cable
- Roebel cable
- Stacked tape cables
- Helically wound cable
- Internally cooled conductors
- Dry conductors

Modelling

- Digital twins
- Tape mechanical failure modes
- Multiphysics
- Electro-mechanical analysis
- Thermo-hydraulic analysis
- AC losses

Joining and insulation

- LTS joints
- HTS joints
- Demountable joints
- Terminations, feeders and current leads
- Radiation tolerant insulation
- Non insulated HTS coils

Manufacturing

- High precision coil winding
- Vacuum Pressure Impregnation
- Modular coil winding
- Laser engraving of wide HTS
- 3D printed formers

Magnet protection

- Quench propagation models
- Quench detection
- Integrated quench detection
- Quench propagation
- Energy extraction

Instrumentation and auxiliaries

- Fiber optic sensing
- Voltage taps extraction
- Cooling systems
- Persistent current switches
- Feedthroughs
- Field mapping
- Acoustic emission monitoring
- Power supplies
- Shimming coils

3.3 Description of individual technologies

3.3.1 Superconducting materials

REBCO

REBCO (Rare Earth Barium Copper Oxide) materials are high-temperature superconductors with chemical composition ReBa2Cu3O7-x, where Re is a rare earth element as yttrium or gadolinium. These are typically fabricated as coated conductors, using thin superconducting layers on flexible metal substrates. REBCO's superior performance in high magnetic fields, combined with its mechanical strength and thermal stability, makes it particularly suitable for high-field magnet applications providing issues with anisotropy, brittleness, AC losses and slow quench propagation can be controlled.

BSCCO

BSCCO (Bismuth Strontium Calcium Copper Oxide) is a family of high-temperature superconductors, notably Bi-2212 and Bi-2223, with critical temperatures above 77 K. BSCCO conductors are produced as tapes or wires, often incorporating silver matrices for mechanical stability and current transfer. Bi-2212 conductors are manufactured as multifilamentary composite wires using powder-in-tube techniques, making them compatible with existing LTS winding technologies and particularly suitable for high-field insert magnets. Bi-2223 tapes provide good current-carrying capability in moderate magnetic fields but exhibit significant performance degradation in high transverse fields. Bi2212 relies on wind-and-react technology, with the heat treatment carried out at high temperature (800 C), under overpressure and a partial pressure of oxygen. Both Bi-2212 and Bi-2223 are “niche” productions.

Iron-based superconductors

Iron-based superconductors (IBS) are a class of materials featuring iron-arsenide or iron-selenide compounds exhibiting superconductivity at intermediate temperatures (20–60 K). They feature high upper critical fields and low anisotropy as well as easier quench detection and protection than for copper-oxide magnets due to their lower critical temperatures. Their granular structure and sensitivity to strain pose challenges for conductor fabrication, but their potential for high-field performance and lower material costs offer potential for future magnet applications.

MgB2

MgB_2 is a metallic superconductor with a critical temperature of 39 K, bridging the gap between conventional LTS and high-temperature cuprate superconductors. The material shows particular promise for applications requiring modest magnetic fields (a few T) with reduced cooling complexity compared to LTS systems. Their intermediate critical temperature ensures that quench will propagate, enabling detection and, thereby, protection.

LTS

LTS (Low Temperature Superconductors) refers to materials such as Nb-Ti and Nb3Sn that exhibit superconductivity at low temperatures, typically below 5 K. These materials have been the working horses of superconducting magnet technology, operating primarily with helium cooling. LTS wires and tapes are widely used in accelerator magnets, MRI, and fusion devices due to excellent mechanical properties, good control of quenches and AC losses, manufacturing maturity, and cost-effectiveness.

3.3.2 Cabling and conductors

Rutherford cable

Rutherford cable is a flat, multi-strand cable design where round composite multifilamentary wires are transposed and slightly compacted. This form minimizes AC losses and optimizes current sharing among filaments. It is widely used for accelerator and detector magnets based on LTS materials, enabling efficient winding, good geometry control, high engineering current density, robust performance under high stress and easy quench detection/protection.

Roebel cable

Roebel cables, derived from electrical machines, are fabricated assembling single wires or tapes with a meander structure. This has been applied lately to copper-oxide HTS tapes, punching REBCO tapes to form the meander shape. The Roebel design is transposed with respect to external field change, thus reducing AC losses and improving the distribution of current and magnetic fields within the cable, making it advantageous for applications requiring low-loss, high-current, high engineering current density HTS conductors. However, the required punching requires discarding a large portion of the tape surface, making it very onerous

Stacked tapes

When using HTS REBCO tapes, one option to obtain a high current conductor is to assemble the tapes directly as stacks of two or more tapes. These tape stacks can reach high current, and high engineering current density, though winding may be an issue because the conductor is not transposed. A solution to this is to twist stacks together in helical configurations. This allows high current and flexibility for winding into coils, while maintaining mechanical integrity and minimizing coupling losses in high-field magnet designs.

Helically wound conductors

Helically wound HTS cables are made by winding HTS tapes helically around a round former. This geometry results in high current capacity, isotropic properties, mechanical flexibility, and compatibility with standard coil winding techniques, characteristics of interest for compact, high-field superconducting magnets. The former material can also be adapted (copper to increase stabilisation, stainless steel for mechanical reinforcement etc.). However, the engineering current density tends to be reduced due to the round filling factor.

Internally cooled conductors

Internally cooled conductors (ICC) are cables where the coolant (customarily helium) flows in the cable space or in pipes in intimate thermal contact with the cable. Several variants are possible for ICC's, one of which is a Cable-in-conduit conductor (CICC). A CICC consists of superconducting strands roped inside a metallic conduit, with forced-flow coolant circulating around the filaments. This design provides integrated mechanical support, cooling, and electrical insulation in a single component, making it ideal for large-scale applications like fusion magnets. Alternative ICC configurations are cables around a cooling tube, either LTS or HTS.

Dry conductors

Dry conductors are superconducting cables that operate without direct contact with liquid cryogens, using conduction cooling or cryocoolers to achieve and maintain low temperatures. Such designs require solid thermal links—typically copper or aluminium—that connect the conductor, coil or case to a cooling system. One common design is the Conduction-Cooled Conductor (CCC), where strands or tapes are embedded in or wrapped around a high-thermal-conductivity material, ensuring efficient heat transfer. This approach is more suited for compact magnets, medical devices, and high-field research where liquid cryogens are impractical.

3.3.3 Modelling

Digital twins

Digital twins integrate real-time sensor data with multiphysics models to simulate magnet performance, predict degradation, and optimize operation. They enable proactive maintenance and design validation by mirroring physical assets in a virtual environment.

Tape mechanical failure modes

Models predict delamination, cracking, or buckling in HTS tapes under Lorentz forces, thermal cycling, and bending. Finite element analysis (FEA) identifies stress concentrations and guides reinforcement strategies to ensure mechanical integrity.

Multiphysics

Multiphysics modelling involves simultaneous simulation of electromagnetic, thermal, mechanical, and fluid dynamic phenomena in superconducting magnets. This approach provides comprehensive understanding of coupled effects, guiding optimized design, quench protection, and operational strategies for complex magnet systems.

Electro-mechanical analysis

Electro-mechanical analysis simulates electromagnetic, thermal, and mechanical behaviour in magnets, resolving field distributions, stress, and temperature gradients. It is essential for validating designs, optimizing coil geometries, and predicting failure modes.

Thermo-hydraulic modelling

Thermo-hydraulic modelling simulates the combined behaviour of heat transfer and fluid flow in cryogenic systems associated with superconducting magnets. Computational techniques range from one-dimensional network models to three-dimensional CFD analysis depending on system complexity and required resolution. Thermo-hydraulic analysis enables cooling system optimization, and design verification, ensuring adequate cooling margin and thermal stability throughout magnet operation.

AC losses

AC loss modelling quantifies the energy dissipated as heat in superconducting conductors due to alternating current and changing magnetic fields. Accurate modeling of hysteresis, coupling, and eddy current losses is essential for cryogenic load estimation, stability analysis, and efficient magnet operation.

3.3.4 Joining and insulation

LTS joints

LTS joints are electrical connections between low temperature superconductor segments, typically Nb-Ti or Nb3Sn wires. These joints must minimize resistance and maintain superconductivity under high current and magnetic field conditions. Techniques include mechanical lap joints, soldered connections, or diffusion bonding.

HTS joints

High-temperature superconductor joints face unique challenges due to the tape geometry and material properties of REBCO and BSCCO conductors, requiring specialized techniques for achieving low-resistance connections. Methods include resistive soldering, diffusion welding, and mechanical compression joints using intermediate superconducting materials or optimized metal interfaces. Joint design considerations include minimizing current redistribution, preventing delamination, and ensuring long-term stability under electromagnetic and thermal stresses typical of HTS magnet operation.

Demountable coils

Demountable coils are magnet coils designed for mechanical separation, enabling replacement, maintenance, or upgrade without full system disassembly. Demountable designs are particularly important for large-scale applications like fusion magnets where the ability to carry out remote maintenance and component replacement are essential. The joint technology must maintain electrical, mechanical, and thermal performance equivalent to permanent connections while providing reliable operation through multiple assembly cycles and exposure to operating stresses.

Termination, feeders and current leads

Terminations, feeders and current leads form interfaces between superconducting magnets and room-temperature power supplies. They must conduct large currents while minimizing heat influx to the cryogenic environment. Hybrid designs, often combining copper , HTS and LTS segments are used to optimize thermal and electrical performance. Termination design includes stress relief, electrical insulation, and thermal anchoring to intermediate temperature stages. Current leads must handle fault conditions including quenches and overcurrent situations while maintaining structural integrity and preventing damage to the superconducting system.

Radiation tolerant insulation systems

Radiation-tolerant insulation materials and systems are designed to maintain electrical and mechanical properties under intense neutron and gamma radiation environments typical of fusion reactors and high-energy physics applications. These systems utilize inorganic materials such as ceramic-fiber tapes, mica-based compounds, and mineral-filled epoxies that resist radiation-induced degradation of dielectric strength and mechanical properties. Design considerations include radiation dose limits, outgassing characteristics, and long-term stability under combined radiation, thermal, and mechanical stresses.

Non Insulated HTS coils - transverse resistance control

Non-insulated HTS coils are wound without inter-turn insulation, allowing current sharing across turns and self-protecting against hot spots. Transverse resistance control introduces engineered resistive paths to manage current diffusion, protect the coil from quench, and optimize field penetration dynamics in HTS magnet applications.

3.3.5 Manufacturing

High precision coil winding

Precision winding ensures accurate placement of superconducting cables or tapes, minimizing field errors and mechanical stress. CNC-controlled winding machines, real-time tension monitoring, and laser metrology achieve tight tolerances for field quality and structural integrity.

Vacuum Pressure Impregnation

VPI (Vacuum Pressure Impregnation) is a coil insulation process where windings are impregnated with resin under vacuum and pressure. Resin fills voids, bonds conductors, and enhances mechanical strength, electrical insulation, and quench stability in superconducting magnet coils.

Modular coil winding

Modular coil winding divides large or complex superconducting magnets into multiple independently wound and assembled modules. This technique simplifies manufacturing, transport, and maintenance, and supports scalable, flexible magnet architectures for fusion devices and accelerators.

Laser engraving of wide HTS

Laser engraving of large HTS material relies of the production of wide sheets of HTS material where the different layers can be engraved with a laser to distribute the current in complex paths to fabricate complex, high-performance superconductors onto a support surface. This approach provides infinite possibilities for the shape of the HTS material and could provide major simplifications in the production of complex magnets.

3D printed formers

3D printed formers are coil supports or mandrels fabricated using additive manufacturing, allowing rapid prototyping and complex geometries matched to coil requirements. These formers facilitate precise coil placement, reduce waste, and can be customized for specialized magnet designs.

3.3.6 Magnet protection

Quench propagation models

Quench propagation models simulate the spread of normal (resistive) zones in superconducting magnets during resistive transitions. Advanced models include multi-dimensional effects, current redistribution, and coupling between electromagnetic and thermal phenomena. Quench propagation models predict temperature, current, and voltage evolution, supporting the design of protection systems and helping to prevent damage. Modelling should include conventional insulated coils with active detection/protection systems, as well as non-insulated (NI) coils involving both passive and active protection approaches and must be benchmarked and validated using experimental and operational data.

Quench detection techniques

Quench detection techniques for LTS coils are matured technologies implemented on many existing devices. Techniques for the detection of quench initiation range from standard electrical means (i.e., voltage taps) to novel approaches based on non-electrical detection of quench (e.g., fibre optics, thermocouple, etc.). In HTS coils, when coil pack heat capacity and critical temperature is much higher, energy dissipation remains localized and quench propagation is very slow. Extremely sensitive detection techniques will be needed to achieve the quench detection times needed to safely protect the magnet. They will require dedicated validations and qualifications to demonstrate their robustness and reliability.

Integrated quench detection systems

Integrated quench detection systems employ multiple sensor technologies including voltage measurements, temperature monitoring, acoustic emission detection, and magnetic field sensing to identify the onset and location of quench events in real-time (a machine-learning approach to fuse the input from sensors as described in the previous section). Rapid detection is essential for activating protection circuits and initiating energy extraction to limit thermal and mechanical stress. Predictive analytical or FEA models can be used to shorten the reaction time of active protection systems. Those systems will also require dedicated validations and qualifications to demonstrate their robustness and reliability.

Quench acceleration systems

To minimize concentrated heating in the quench initiation zone, quench acceleration systems are engineered features, such as resistive elements or heaters, that promote rapid and uniform distribution of a quench throughout the coil to dissipate the stored energy rapidly and efficiently within the cold mass. Such quench acceleration could be achieved by resistive or inductive means (and sometimes both).

Energy extraction systems

Energy extraction systems safely transfer stored magnetic energy from a superconducting magnet during a quench. These systems typically use fast switches and dump resistors to divert current away from the magnet, limiting voltage buildup and protecting magnet integrity. This technology is amture for LTS systems.

3.3.7 Instrumentation and auxiliaries

Fiber optic sensing

Fiber optic sensing employs optical fibers embedded within or around superconducting coils to measure strain, temperature, or magnetic field with a high spatial resolution. These sensors are radiation resistant and offer immunity to electromagnetic interference. They can integrate flexibly into complex magnet assemblies but can be costly and exhibit poor long-term reliability.

Voltage taps extraction

Voltage taps extraction involves attaching electrical contacts at defined points along the conductor to monitor voltage differences. This technique is critical for quench detection, diagnostic measurements, and ensuring the electrical integrity of superconducting coils. A key issue for successful execution is the compatibility between insulation and resin to avoid deterioration of the insulating material.

Magnetic field mapping

Magnetic field mapping uses arrays of sensors, such as Hall probes or fluxgate magnetometers, to characterize the spatial distribution of magnetic fields around a superconducting magnet. Accurate mapping ensures field uniformity, alignment, and compliance with design specifications. Magnetic field mapping is critical for detector magnets to accurately re-compute particle trajectories.

Acoustic emission monitoring

Acoustic emission testing monitors superconducting magnets by detecting stress waves from micro-defects or quenches. Using surface sensors, this non-invasive method works effectively in cryogenic environments, offering real-time insights into structural integrity. It complements other diagnostic techniques to help maintain magnet performance and reliability in applications like fusion and particle accelerators.

Cooling Systems

Cooling systems for superconducting magnets include cryostats, helium liquefiers, closed-loop coolers, and thermal links. They maintain required operating temperatures, remove heat from joints and current leads, and ensure stable superconducting operation across a range of magnet technologies.

Power supplies

Power supplies for superconducting magnets deliver stable, precisely controlled direct currents, often in the kiloampere range. These supplies are engineered for low ripple, high stability, and include features for ramping, protection, and remote operation in large-scale magnet installations.

Persistent current switches

Persistent current switches are superconducting or hybrid devices that enable the transition of a magnet between powered and persistent current operation. Once closed, they allow the magnet to carry current indefinitely with negligible loss, maintaining stable fields for extended periods.

Shimming coils

Shimming coils correct field errors using active or passive conductors. Superconducting or room-temperature coils, often with optimized geometries, compensate for harmonics and enhance field uniformity.

Feedthroughs

Feedthroughs provide critical interfaces that allow electrical, optical, or fluid connections to pass through cryogenic boundaries while maintaining vacuum integrity, thermal isolation, and electrical performance in superconducting magnet systems. These components must minimize heat conduction from room temperature to cryogenic regions while carrying electrical current, signals, or coolant flow without compromising system performance. They must operate reliably under thermal cycling and electromagnetic forces typical of magnet operation.

4 Summary of meetings

In total, 188 people registered for participation in the 2025 Magnets Technology Mapping workshop. The online workshop registered a peak of 115 participants whilst 82 people attended the in-person workshop. 65 public and private entities were represented. CERN, Fusion for Energy and EUROfusion wish to thank all participants for their input during and after the workshop.

Logos of participating entities (excluding CERN, EUROfusion and Fusion for Energy)

Geographical repartition of the participants to the in-person workshop

Details of the meetings can be found on the event web page[1]. The agenda and outputs including presentations, documents and recordings are also available there.

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[1] https://app.swapcard.com/event/magnets-mapping-workskop

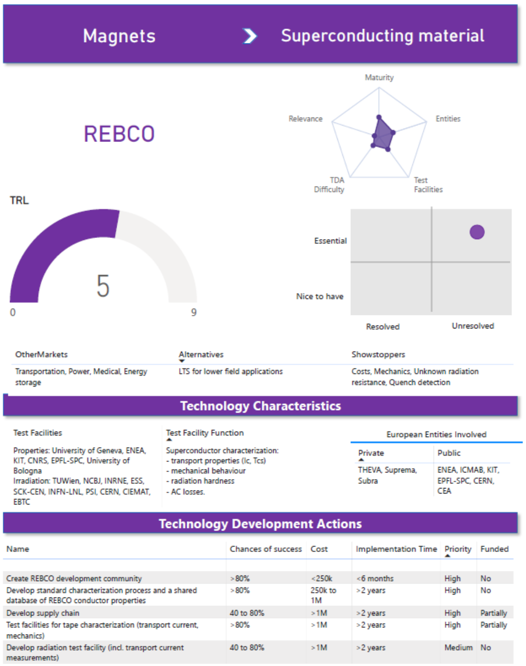
5 Outcome: technology road-mapping

5.1 Technology dashboards

During the in-person workshop and in the process of preparing this report, a lot of valuable data was collected into a database. For each technology, the following data is now available:

- TRL
- Criticality
- Other fields of application
- Alternative technologies
- Potential showstoppers
- Existing and needed test facilities
- European entities involved
- Technology development actions

This data has been arranged into a dashboard for each of the technologies:



Magnets › **Superconducting material**

REBCO

OtherMarkets	Alternatives	Showstoppers
Transportation, Power, Medical, Energy storage	LTS for lower field applications	Costs, Mechanics, Unknown radiation resistance, Quench detection

Technology Characteristics

Test Facilities	Test Facility Function	European Entities Involved: Private	European Entities Involved: Public
Properties: University of Geneva, ENEA, KIT, CNRS, EPFL-SPC, University of Bologna Irradiation: TUWien, NCBJ, INRNE, ESS, SCK-CEN, INFN-LNL, PSI, CERN, CIEMAT, EBTC	Superconductor characterization: - transport properties (Ic, Tcs) - mechanical behaviour - radiation hardness - AC losses.	THEVA, Suprema, Subra	ENEA, ICMAB, KIT, EPFL-SPC, CERN, CEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Create REBCO development community	>80%	<250k	<6 months	High	No
Develop standard characterization process and a shared database of REBCO conductor properties	>80%	250k to 1M	>2 years	High	No
Develop supply chain	40 to 80%	>1M	>2 years	High	Partially
Test facilities for tape characterization (transport current, mechanics)	>80%	>1M	>2 years	High	Partially
Develop radiation test facility (incl. transport current measurements)	40 to 80%	>1M	>2 years	Medium	No

Typical technology dashboard

Note that the spider diagram (scores out of 9) has been arranged in such a way that the more the colored area, the more development is needed.

All technology dashboards are available in Appendix 3: Technology dashboards.

The dashboards are a view of the database at the time of publishing this document. The database will be updated regularly, and Appendix 3 may be re-published as necessary. We encourage the community to communicate updates to their Fusion for Energy, EUROfusion or CERN contact. In the future, we may publish this data for interactive consultation on the CERN, EUROfusion or Fusion for Energy websites.

5.2 Overview of the EU landscape for superconducting magnets

5.2.1 SWOT analysis

Strengths	**Weaknesses**
• Strong basis to build upon: infrastructure and know-how in R&D, modelling and manufacturing • Solid LTS and MgB2 supply chain • Emerging start-up ecosystem (tape + HTS magnet technologies)	• Fragile and underdeveloped HTS supply chain for both materials and cables • Bottleneck in high field, high current cable test facilities • Limited expertise on HTS magnets operation (including quench detection and protection)
Opportunities	**Threats**
• Set up coordinated validation programmes for large-scale HTS magnets using both established manufacturers and start-ups • Improve the production capacity of HTS material and cables • Expand test facility capacity • Boost R&D in emerging iron-based HTS technology • Exploit synergies between High Energy Physics, Fusion and other relevant sectors	• Possible dependance for materials on other territories benefiting from more centralised and well-funded strategies. • Lack of continuity in public funding for large projects posing existential threat to established manufacturers

Strengths:

Europe has developed **a strong basis for further advancements in superconducting magnet technology**.

- At its core is a **network of leading public research institutions and centres**. Key organizations such as CERN, ENEA, CEA, the University of Geneva, SPC-EPFL, PSI, the University of Twente, The University of Tuscia, TU Wien, ICMAB-CSIC, ITER, KIT, INFN, or CIEMAT contribute extensive expertise in magnet research and development. This collective knowledge covers areas such as materials science, magnet design, and advanced manufacturing processes. It also benefits from lessons learnt in the design and operation of large superconducting magnets for multiple fusion machines as well as accelerators and detectors for high energy physics experiments.
- In addition, Europe hosts a **well-established community focused on magnet modelling**. This community has created advanced simulation tools that improve the accuracy of magnet design and performance predictions, facilitating efficient development and reducing technical risks. It is based both in the public and private sector both involved in designing some of the most advanced magnets in the world in the last 20 years.
- The EU's **magnet manufacturing supply chain** has indeed benefited from major projects like HERA, Tore-Supra, LHC, W7X and ITER, which have provided demand and helped maintain a skilled industrial base. Europe can also count on an experienced supply chain for superconducting magnets for applications outside the high energy physics and fusion fields such as MRI, NMR, power etc. Companies like **ASG, Bruker, Bilfinger Noel, General Electric, ELYTT, SigmaPhi or Tesla Engineering (UK)** are historic players in the European ecosystem.

- Europe also offers several **specialized test facilities**, including the Sultan test bench (SPC-EPFL), FRECA2 and the SM18 test benches at CERN, Josefa, Selfie and the Saclay magnet test facilities at CEA, FBI at KIT as well as many test benches in academia (notably at the University of Twente, Tuscia, Geneva and Barcelona - ICMAB-CSIC). They play a crucial role in supporting R&D activities. These facilities enable thorough testing and validation of cables and magnet prototypes under realistic operational conditions, supporting fast development cycles.

The presence of **established European manufacturers for LTS and MgB2 materials** represents a significant strength for the European superconducting magnet ecosystem. Companies like **Bruker Energy & Supercon Technology (BEST)**, **Luvata** and **ASG-Columbus Superconductors** provide a local supply chain for both Low Temperature Superconductors (LTS) such as NbTi and Nb3Sn, and MgB2, which is critical for advanced applications in fusion energy, medical imaging, and high-energy physics. Their long-standing collaborations with research institutions and industrial partners ensure reliable access to high-performance superconducting materials and reduce dependency on non-European suppliers.

Europe is rapidly developing a **start-up ecosystem** focused on superconducting tape and high-temperature superconducting (HTS) magnet technologies.

- In the **HTS materials sector**, start-ups such as **TE Magnetics** (UK), **Suprema** (Italy), and **Subra** (Denmark) are aiming at producing high performance and cost-effective tape and conductor solutions for magnet manufacturers. They add their capabilities to more established players in the tape or cable fields such as Theva, Bruker, ICAS, ASG Columbus Superconductors and Nexans.
- On the **magnet technology front**, fusion start-ups like **Tokamak Energy** (UK), **Gauss Fusion** (Germany), **Renaissance Fusion** (France), and **Proxima Fusion** (Germany) are entering this area directly or in partnership with other established private and public magnet manufacturers and growing rapidly.
- The total capitalization of these start-ups is increasing rapidly and is worth over **€600 million** as of the end of March 2026.

Weaknesses

Europe's HTS supply chain remains fragile and under-developed, a key weakness in the broader superconducting magnet ecosystem. The number of suppliers capable of producing advanced HTS materials (e.g.REBCO) and cables is limited, and most are either in **early-stage development** or **lack** the **capacity** to meet large-scale production demands. The scarcity of established suppliers creates bottlenecks in the procurement of high-quality European HTS tapes and cables. The established European HTS cable supply chain also still faces difficulties in pursuing long length production due to process maturity and quality issues. All this tends to generate a dependency to other more advanced territories and puts Europa at a competitive disadvantage.

Europe also faces a significant **bottleneck in high field, high current cable testing infrastructure**, which hampers the development and validation of superconducting magnet technologies. Only a handful of facilities can perform high-field, high-current evaluations. **Sultan (EPFL-SPC)**, the primary test station for superconducting cables in those conditions is a world class facility. Nevertheless, it can become oversubscribed and subject to downtimes for maintenance and upgrades. These constraints result in delays for critical qualification campaigns, slowing down innovation cycles and time-to-market for new magnet designs.

Europe's **manufacturing experience with HTS conductors is heavily concentrated on stacked tape configurations**, limiting its ability to explore and optimize alternative designs. Other conductor architectures—helically wound conductor, Roebel—attract very limited interest in Europe. This leads to a narrow focus and contrasts with other territories, where a broader range of HTS conductor technologies are being actively developed and commercialized. The lack of diversity in conductor experience restricts innovation in magnet design and poses a risk of possible technological lock-in, reducing the ability to adapt to new requirements.

Europe currently faces a **shortage of expertise for the operation of HTS magnets**, particularly in critical areas such as **quench detection and protection systems**. This limited experience slows the reliable deployment of HTS magnets in demanding applications, where robust performance are essential. The shortage of knowledge in these areas generates risks during scaling and commercialization, potentially delaying progress in critical projects for fusion and high energy physics.

Opportunities:

To address the gaps identified in Europe's HTS magnet ecosystem in the HTS field, it is crucial to **support private and public validation programmes for large HTS magnets.** Targeted investment coupled with adequate coordination in the development of relevant model coils would ensure that Europe can compete with regions that have already advanced their HTS technologies. There are several **existing initiatives** already ongoing in start-ups (Tokamak Energy, Renaissance Fusion, Proxima Fusion, Gauss Fusion), in the public sector (e.g. Suprafusion with CEA, EUROfusion, CIEMAT, UKAEA STEP, ENEA-DTT) or in Public-Private partnerships (20T@20K, UKFIS). They **need to be supported financially and accelerated.** Collaboration between research institutions, start-ups, and established manufacturers also needs to be fostered to create a cohesive ecosystem that drives innovation and commercialization. **Europe should actively pursue parallel and coordinated development paths by engaging both established manufacturers and emerging start-ups** in the validation effort for large HTS magnets. This dual approach leverages the strengths of each group: traditional manufacturers bring proven industrial capacity, quality assurance, and scalability, while start-ups contribute agility, novel ideas, and disruptive technologies. The Large Coil Task in the 80s enabled a step change in technological development for LTS magnets coordinating efforts and sharing knowledge widely. A similar effort in Europe for HTS coils could bring similar results.

Europe must urgently **improve the volume and performance of its domestic production lines for HTS tapes and cables,** capitalizing on the opportunity presented by the growing market for fusion magnets. It will also reduce dependence on external suppliers and secure its place in the superconducting technologies global market. This requires a triple strategy: strengthening existing manufacturers, enticing LTS manufacturer to step into the HTS market and fostering the growth of innovative start-ups.
Firstly, Europe must provide targeted funding and incentives for companies like **THEVA, BEST** and **ASG Superconductors** to expand production lines, modernize equipment, and diversify the range of LTS wire and high-performance HTS tapes and cables offered. Secondly, Europe must provide more direct investment for emerging players such as **TE Magnetics**, **Suprema**, and **Subra** to accelerate their transition from R&D to large-scale manufacturing. Public-private partnerships can help bridge the gap between prototype development and commercial production by exploiting valuable IP generated in academia such as the Transient Liquid Assisted Growth (TLAG) process developed at **ICMAB-CSIC** for high-throughput growth of REBCO.
In general Europe must **facilitate collaboration** between material suppliers, cable producers, and end-users to create a robust, end-to-end HTS ecosystem. It must launch **EU-wide initiatives to support breakthroughs in tape and cable development**, such as higher current density, improved mechanical strength, and cost-effective manufacturing processes.
By expanding production capacity, Europe can ensure a reliable supply of critical components for fusion, high energy physics, medical and power applications, while reducing vulnerabilities in the global supply chain. This will position the EU as a self-sufficient leader in LTS and HTS technologies, driving both economic growth and technological sovereignty.

To overcome Europe's testing bottlenecks and support the full development cycle of superconducting magnets, a **tiered expansion of test infrastructure is essential**. This requires investment in three distinct types of facilities, each addressing critical stages of R&D and industrial validation:

- **Full magnet test facilities (eg CERN, ITER, CEA Saclay, FCCTF at ENEA):** Large-scale infrastructure capable of testing complete magnet systems under operational conditions, including high-field and cryogenic environments.
- **Advanced conductor test facilities (e.g., Sultan at EPFL-SPC):** Specialized stations for evaluating high-temperature superconducting (HTS) cables and advanced conductor architectures under realistic operational conditions. These facilities enable validation of conductor performance, mechanical stability, and quench behaviour. No facility is currently available for high-field (15-20 T), high current (>100 kA) and high temperature (20-77K) testing.
- **Wire, tape or material characterization facilities:** Accessible, smaller-scale labs for routine testing of properties, such as critical current, thermal stability, thermos-hydraulic characteristics and mechanical integrity in relevant conditions of field and temperature that are beyond present capability, or available with limited access. These facilities support rapid iteration during early-stage development and quality control in manufacturing.

Existing facilities must be upgraded to adapt to emerging requirements (higher field and current for example) and opened to third parties access when this is not the case. Whenever required, new facilities must be built, possibly using public/private partnerships to ensure adequate capacity and long term sustainability.

Additionally, for some of the applications such as fusion, **access to neutron irradiation facility** should be facilitated to test the impact of neutron bombardment on the performance of tapes, conductors and coils as well as other materials used in magnet manufacture (eg insulation). Extension to other particles and high energy spectra would draw much interest from other applications in nuclear and high-energy physics.

Europe could also **invest in Iron-based HTS research and development**. These materials typically exhibit critical temperatures up to about 55 K, which is similar to that of MgB2 and much lower than other HTS compounds like cuprates (which can exceed 130 K). This reduces the enthalpy margin and facilitates quench propagation, making quench protection much easier. This intermediate range, combined with their high upper critical fields and expected lower anisotropy, makes iron-based superconductors suitable for high-field applications. Also, iron-based HTS usually rely on conventional powder in tube production techniques, and do not call for sophisticated deposition techniques, which could make their production cost-effective compared to REBCO.

As an emerging technology, iron-based HTS could offer **significant competitive advantages**. Europe must accelerate material characterization, optimization, manufacturing scalability, and system integration. Currently, research in the field is mostly fundamental research and university based. This knowledge could be leveraged into large R&D programmes led by national laboratories or universities with the experience of translating fundamental research into small scale production. Existing powder in tube manufacturers (eg BEST, ASG Columbus) could also help speed up the qualification of production methods. Investing in iron-based HTS could **reduce dependency on rare-earth materials, enhance supply chain resilience, and position Europe** alongside China **as a leader** in this evolving field.

Europe can maximize its impact in superconducting magnet technology by **fostering cross-sector collaboration** between high energy physics, fusion research, and industries such as medical imaging, energy production and transportation**.** These sectors share common technical challenges and needs: optimize and validate conductor configuration, develop knowledge in magnet protection and operation, secure a robust supply chain. They can be addressed through **knowledge transfer, joint and complementary R&D programs and shared infrastructure**. This workshop sets the tone and pursues the long-established tradition of exchanges between the fusion and high energy physics communities. More needs to be done to identify synergies and target funding at initiatives that bridge multiple sectors to maximize funding efficiency.

Threats

Europe’s superconducting magnet sector faces a significant threat due to its **reliance on external territories not only for raw materials but also for transformed products such as superconducting tapes.** Regions like Asia and North America benefit from well-funded programmes that dominate both material extraction and the production of advanced superconducting components. Those programmes required major advances in technology and therefore place those territories at the frontier of technological development in the field. This dual dependence—on raw materials and finished products—poses a critical risk, as the EU’s own production capacity remains limited and fragile. The lack of robust domestic manufacturing for superconducting tapes and other key components heightens vulnerability to supply chain disruptions, geopolitical tensions, or trade restrictions. Such dependencies could lead to delays, increased costs, and reduced competitiveness in the global market. Without strategic investments to strengthen domestic production and secure alternative supply chains, Europe’s ability to innovate and deploy next-generation superconducting magnets may be compromised.

Europe’s superconducting magnet sector faces an existential threat from **the lack of continuity in public funding for large-scale projects.** Institutions such as CERN, W7X, ITER and DTT have invested 100s of millions of Euros into the sector over the last 20 years. These initiatives have historically driven demand, sustained industrial supply chain expertise, and maintained a skilled workforce within the EU. These projects come and go, and do not provide a continuous support and funding to the industrial eco-system which is chronically struggling to survive. It destabilizes established manufacturers, who rely on such projects for long-term contracts and revenue stability.
Without reliable, sustained investment, manufacturers may struggle to retain their experienced workforce as well as critical manufacturing capabilities and may not be in a position to innovate, or compete globally. This uncertainty could lead to the erosion of Europe’s industrial base, loss of specialized jobs, and weakened leadership in superconducting technologies.

5.2.2 Main test facilities

Material and tape characterization

Name	Operator	Functionality and main characteristics
UNIGE Test Facility	University of Geneva	Superconducting material characterization Up to 21T, 4.2K to 50K, 2kA
TARSIS	University of Twente	Simultaneous mechanical and electrical characterization of superconductor wires and tapes (4.2K, 77K in liquid), up to 150N load
	University of Tuscia	Electrical and magnetic characterization at 77 K in self-field and external magnetic field (up to 0.3-0.4 T)
	University of Tuscia	Characterization from 77 K up to room temperature under bending, tensile, compressive, and torsional loads up to 50 kN
	University of Tuscia	Testing tapes under high variable current using supercapacitor IGBT power supplies (600 A and 1.2 kV).
	ICMAB-CSIC	Transport measurement 16 T, 50 mm, up to 400 A,
	ICMAB-CSIC	Mechanical properties for tapes - strain mapping with image correlation analysis and Ic determination 77K, up to 20 cm, up to 5000 N load and 400 A
Cryogen free test stand	PSI	Superconducting material characterization 1.5 W @ 4.2 K and 35 W @ 50 K, 2kA
17T station	TU Wien	Transport current measurements 4.2K to 150K, 1kA, 17 T, torque meter for angular dependence
6T station	TU Wien	Anisotropy of critical current density 4.2K, 150A, 6T
Scanning probe station	TU Wien	Local properties: critical current density, losses at overcurrents; 77 K, self-field only
E-WASP	ENEA	Walters spring measuring system to test critical current of LTS wires as function of axial strain, temperature, and magnetic field (B_{max}=18T, I_{max}=950A, temperature range 5-12K)
Cryo-free 6T facility	ENEA	Electrical measurements of HTS tapes as a function of the angle (B_{max}=6T, T range 65-77K)
Cryo-free Cryogenics 18T facility	ENEA	Magnetic and electrical measurements on superconducting samples (B_{max}=18T and temperature range 4-40K)
FIB-SEM with laser writing	ENEA	Microstructural characterisation of superconductors and laser writing of HTS tapes (currently being purchased)

Magnets, coils, cables and conductors testing

Name	Operator	Functionality and main characteristics
Cryogen free test stand	University of Twente	20K, conduction cooled, 1.5m diameter coil size, 1.5 kA
Gersemi	Uppsala University	Test of full coils Up to 90W at 1.8K, 4kA, 1.1m diameter
Jordi	EPFL-SPC	High current testing of cables and coils 4.5K, 10kA
Twente press	University of Twente	Superconducting cable characterization, (4.2K, 77K in liquid), cyclic loading up to 300 kN
LTS/HTS Cable test facilities	University of Twente	LTS 4.2K 50 kA superconducting transformer, up to 15T, transverse loads up to 240 kN, HTS stacked cables, HTS 30 - 80K, helium gas cooled cables, 2 kA
FRESCA 2	CERN	Cable tests, 60 cm long 13 T dipole field, 32 kA PC or 50 kA transformer, 1.9 K, 4.5 K, He gas up to 80 K.
B163 Conductor tests	CERN	Wire and conductor performance, 1.9 K, 4.5 K, up to 4 kA, up to 20 T.
CryoMak / FBI	KIT	Cable and conductor performance 4.2K-77K, 100kN, 12T
Sultan	EPFL-SPC	Cable and conductor performance 100 kA, 10.9T, 4.2 K
STAARQ	CEA	Test of full coils 1.9 K bath, 13 kA
MATTRICS	CEA	Test of full coils 5 K/16 bars forced flow, 25.7 kA, ~9x5x2 m^3
SM18 magnet tests	CERN	Magnet and coils tests, vertical cryostats and horizontal benches, up to 30 kA, 1.9 K, 4.5 K LHe, 4.5 K supercritical, He gas up to 80 K,
Magnet Cold Test Facility	ITER	Test of full coils 65 kA, 4.2K
Frascati Coil Cold Test Facility	ENEA / DTT	Test of full coils 42.5 kA, 4.5 K (Currently under construction)
SELFIE	CEA	High current joints characterization Self-field, 4.2K, 70kA

AC losses

Name	Operator	Functionality and main characteristics
AC loss facility	University of Twente	Cables and joints, 4.2K, up to 1.5T transverse field
	University of Bologna	AC Loss and quench characterization HTS and MgB2
JOSEFA	CEA	AC losses characterisation 4.2K, 2T, 1T/s

Radiation resistance

Name	Operator	Functionality and main characteristics
LIV-15	IPP-CR	Neutron radiation resistance testing
Frascati Neutron Generator	ENEA	Frascati Neutron Generator for irradiating superconducting samples
Calliope	ENEA	Gamma irradiation of superconducting samples
TRIGA MARK II	TU Wien	Neutron radiation resistance testing Fast neutrons up to 10MeV
	CIEMAT	Radiation resistance testing Van de Graaff accelerator for 2 MeV electrons and a Co-gamma source

5.2.3 Gaps in the ecosystem

This section describes the areas where new actors (R&D or Suppliers) would need to be mobilized to successfully develop the associated technology. This covers all actors based in the EU, UK and Switzerland.
More critical items are highlighted in **bold.**

Research and development		
Handful of actors	One actor	No identified actor
• **Helically wound conductor** • Dry conductors • HTS Roebel cables • HTS Rutherford cables • Feedthroughs • 3D Printed formers • High precision coil winding	• **Persistent current switches** • MgB2 • Laser engraving of wide HTS • Acoustic emission monitoring	• Resin Vacuum Pressure Impregnation • Digital twins • BSSCO

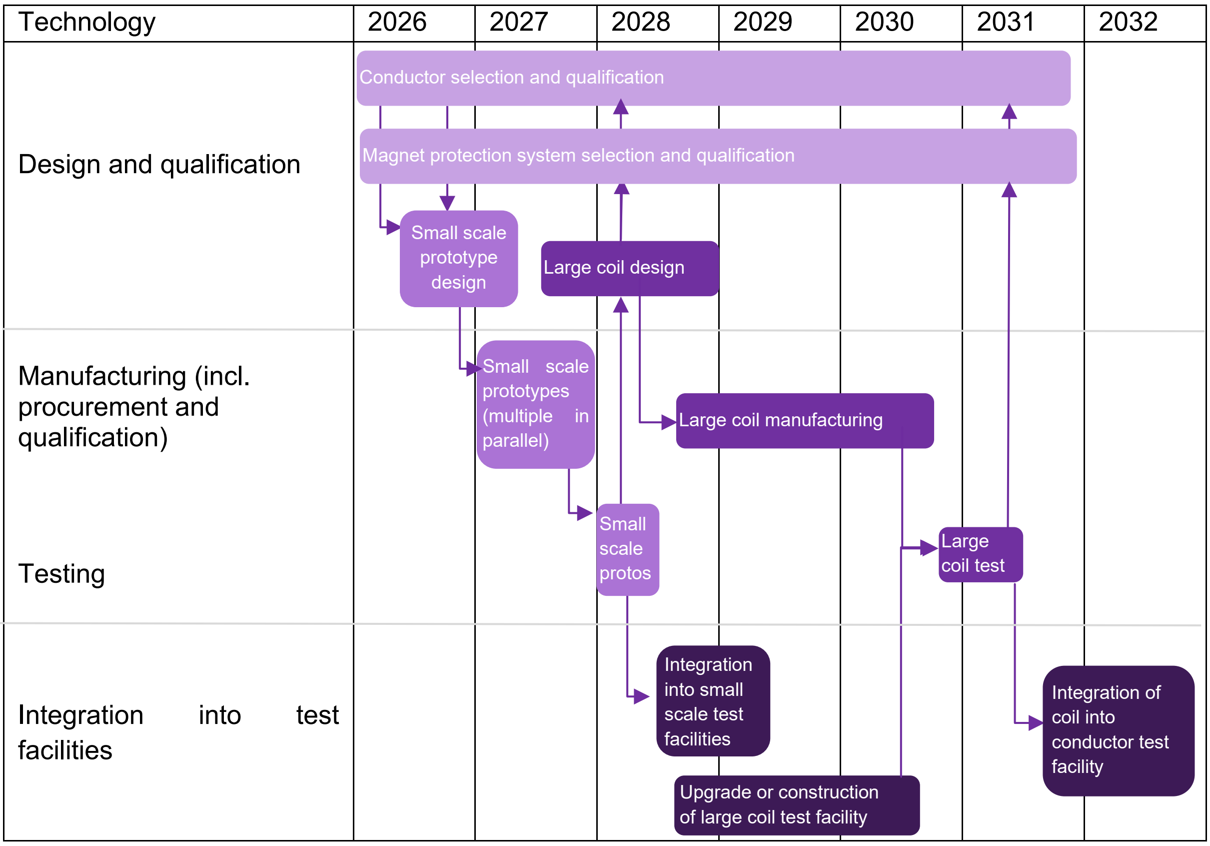
Supply chain		
Handful of actors	One actor	No active supplier
• Dry conductors • HTS Rutherford cables • Internally cooled conductors • **Stacked tape cables** • Cryogenic cooling systems • Feedthroughs • Power supplies • Demountable joints • **HTS joints** • **Non-insulated HTS coils** • **REBCO**	• MgB2 • Laser engraving of wide HTS • BSCCO	• **Helically wound conductor** • Roebel cables • Acoustic emission monitoring • Persistent current switches • Voltage taps extraction • Multiphysics modelling • Iron-based superconductors

5.3 Roadmaps

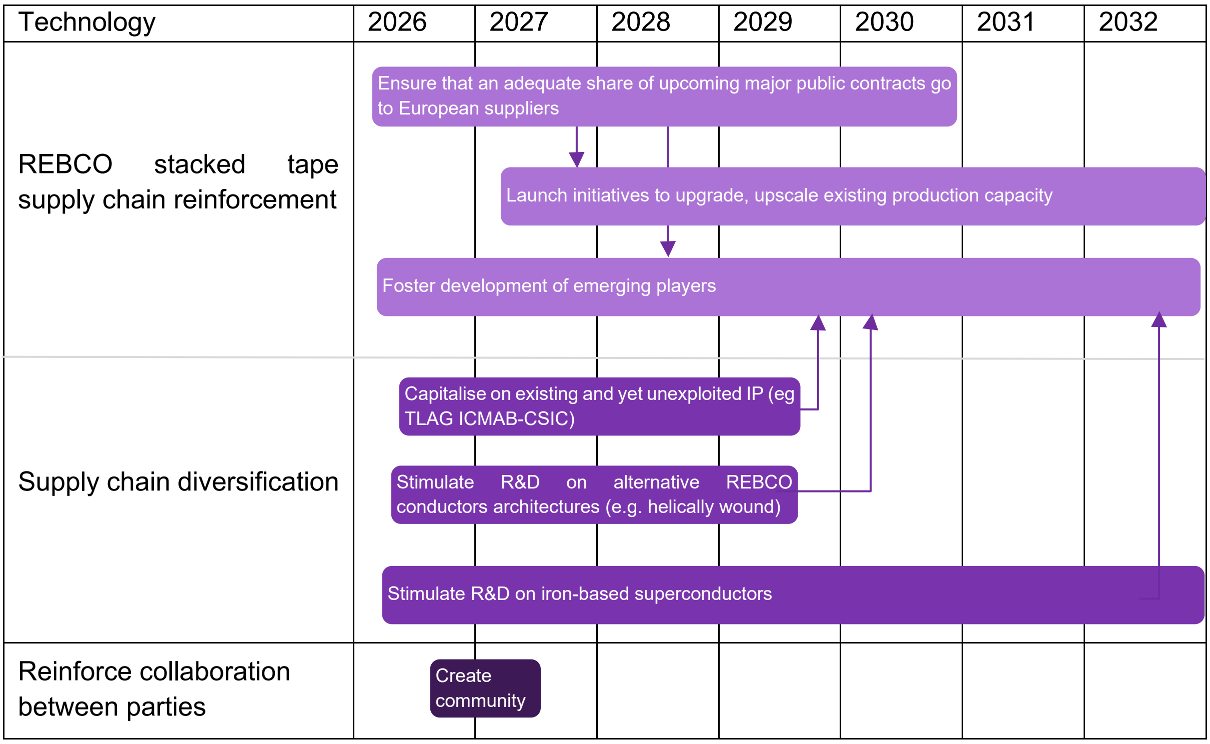
This section presents some of the Technology Development Actions (TDAs) in the form of roadmaps for relevant technologies. The timings are indicative and may evolve significantly depending on funding available from various sources and associated priorities.
TDAs which are not fundamentally linked to other activities and can be executed independently are not included on roadmaps. This is true, for example, for the pumping area.

5.3.1 HTS coils validation programme

This roadmap provides an example of HTS coil validation programme. It includes the option of integrating the coils manufactured into conductor test facilities. It is also suitable for implementation through a Public-Private Partnership if adequate.



5.3.2 HTS supply chain development



6 Conclusion

The 2025 Superconducting Magnets Technology Mapping Workshop has successfully **brought together a diverse community of over 180 participants from more than 65 public and private entities**, fostering collaboration and knowledge exchange across Europe's superconducting magnet ecosystem. Through a structured process of online and in-person discussions, this initiative has delivered a comprehensive technology breakdown, a detailed SWOT analysis, and actionable roadmaps to guide future R&D and industrialization efforts.

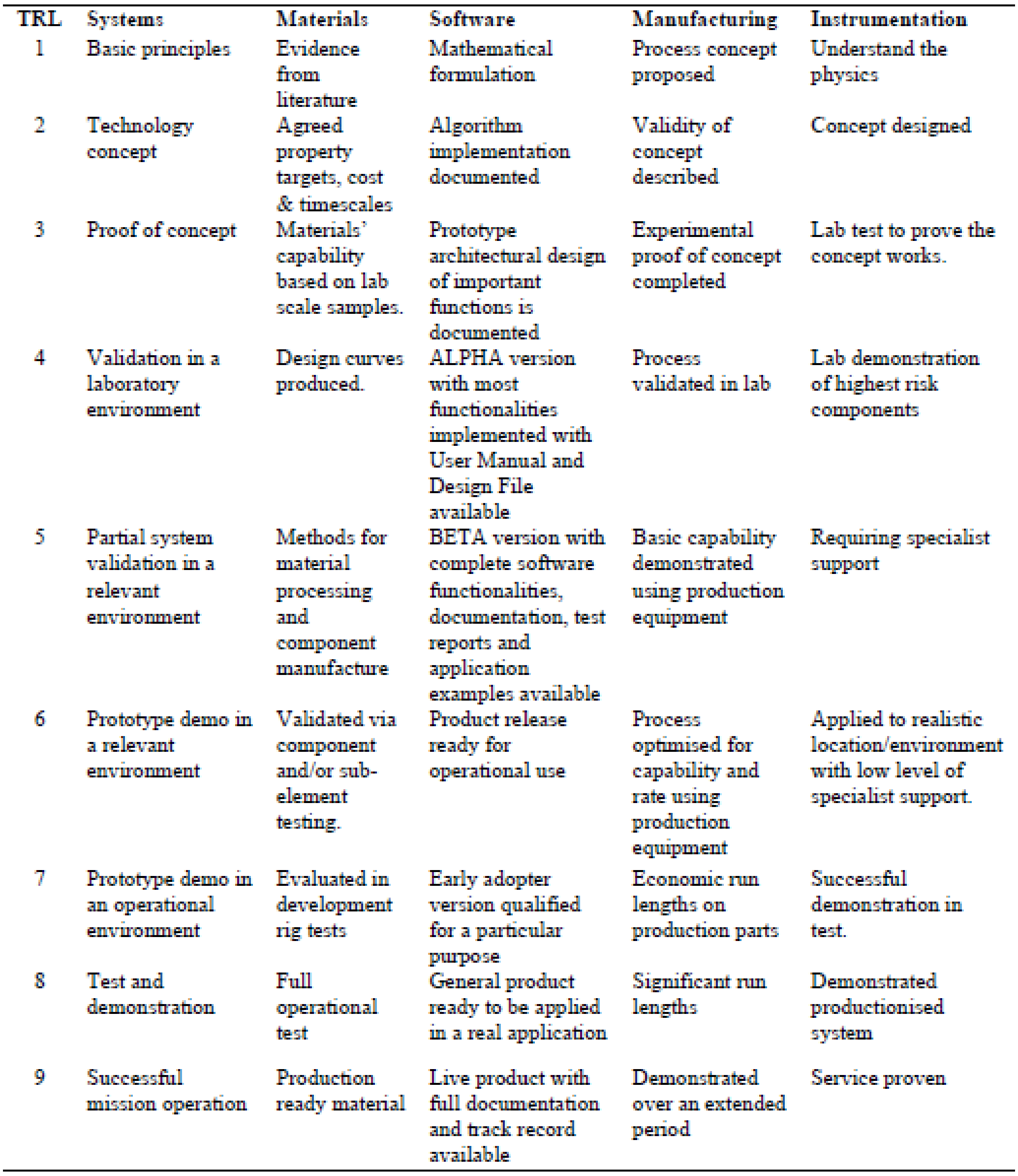
Europe's strengths in superconducting magnet technology—rooted in **world-class research infrastructure, a skilled industrial base, and emerging start-ups**—provide a solid foundation for advancing both high-temperature and low-temperature superconducting applications. However, the workshop also highlighted critical weaknesses and threats. They include a **fragile HTS supply chain, limited testing capacity**, gaps in operational expertise, particularly in **HTS quench detection and protection** as well as a lack of project funding continuity **threatening the existence of the established supply chain**. Addressing these challenges will require targeted investment in coordinated validation programs, supply chain diversification, and expanded test infrastructure, as well as stronger cross-sector collaboration between fusion, high-energy physics, and industry.

The proposed roadmaps, including the **HTS coils validation programme and tape, wire and conductor supply chain development initiatives**, offer clear pathways to close existing gaps and position Europe as a global leader in superconducting technologies. By **leveraging public-private partnerships**, fostering innovation in iron-based HTS for example, and **ensuring continuity in public funding to secure its established supply chain**, Europe can secure its technological sovereignty and drive progress toward commercial fusion energy and next-generation high energy physics applications.

This report serves as a strategic resource for stakeholders seeking to align their efforts with the identified priorities in Europe. CERN, Fusion for Energy, and EUROfusion remain committed to supporting these objectives and invite all actors in the ecosystem to contribute to their implementation. **Together, we can accelerate the development of superconducting magnets, ensuring Europe's leadership in fusion, high-energy physics, and beyond**.

Appendix 1: Technology Readiness Levels

For this workshop, a TRL scale from 1 to 9 will be used, in line with the IAEA definitions[2].
It considers the different criteria for different streams as illustrated in the table below extracted from the document in reference. By default, the “System” stream will be used. For more details, please refer to the TECDOC 2047 itself[1].



TRL	Systems	Materials	Software	Manufacturing	Instrumentation
1	Basic principles	Evidence from literature	Mathematical formulation	Process concept proposed	Understand the physics
2	Technology concept	Agreed property targets, cost & timescales	Algorithm implementation documented	Validity of concept described	Concept designed
3	Proof of concept	Materials' capability based on lab scale samples.	Prototype architectural design of important functions is documented	Experimental proof of concept completed	Lab test to prove the concept works.
4	Validation in a laboratory environment	Design curves produced.	ALPHA version with most functionalities implemented with User Manual and Design File available	Process validated in lab	Lab demonstration of highest risk components
5	Partial system validation in a relevant environment	Methods for material processing and component manufacture	BETA version with complete software functionalities, documentation, test reports and application examples available	Basic capability demonstrated using production equipment	Requiring specialist support
6	Prototype demo in a relevant environment	Validated via component and/or sub-element testing.	Product release ready for operational use	Process optimised for capability and rate using production equipment	Applied to realistic location/environment with low level of specialist support.
7	Prototype demo in an operational environment	Evaluated in development rig tests	Early adopter version qualified for a particular purpose	Economic run lengths on production parts	Successful demonstration in test.
8	Test and demonstration	Full operational test	General product ready to be applied in a real application	Significant run lengths	Demonstrated productionised system
9	Successful mission operation	Production ready material	Live product with full documentation and track record available	Demonstrated over an extended period	Service proven

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[2] IAEA TECDOC 2047 Considerations of TRL for Fusion Technology Components available from: https://www-pub.iaea.org/MTCD/Publications/PDF/TE-2047web.pdf

Appendix 2: Technology assessment

1. Added-Value Towards Nuclear Fusion		
Criterion	*Scale*	*Explanation*
Need for and potential benefit	Major / Medium / Minor	*Does this technology address a critical and unresolved challenge in nuclear fusion?*
Availability of alternative solutions	Yes/No (EU) Yes/No (Outside EU)	*Are there competing solutions in Europe or globally?*
Differentiation / Competitive Advantage	Yes / No	*Does this technology offer a unique advantage over existing solutions?*
2. Maturity & Feasibility		
Criterion	*Scale*	*Explanation*
Technology Readiness Level (TRL)	1 to 9	*Standard TRL scale (see Appendix).*
Expected time to TRL 9 (full maturity)	<5 years / 5–15 years / >15 years	*How long until the technology is commercially viable?*
Availability of test facilities	Yes / No	*Are there existing facilities in Europe to validate the technology?*
3. Interest from the Innovation Ecosystem		
Criterion	*Scale*	*Explanation*
Interest from start-ups	None / 1–3 interested parties / >3 interested parties	*Level of engagement from early-stage companies.*
Interest from industry	None / 1–3 interested parties / >3 interested parties	*Level of interest from established industry players.*
Interest from research institutions	None / 1–3 interested parties / >3 interested parties	*Interest from universities, national labs, and research centers.*
4. Other Investment Decision-Making Factors		
Criterion	*Scale*	*Explanation*
Market potential	Nuclear fusion-specific / Wider market potential	*Is the technology limited to fusion, or does it have broader applications?*
Competences & skills development	Yes / No	*Will this technology enhance European expertise in fusion?*
Regulatory impact	Yes / No	*Does the technology pose significant regulatory challenges?*
5. Risk, Cost, and Implementation Timeline of Next Step on Roadmap		
Criterion	*Scale*	*Explanation*
Outcome predictability & risks	Low risk / Medium risk / High risk	*How uncertain are the results of the next development?*
Estimated development cost	0–500k EUR / 501k–2M EUR / >2M EUR	*Rough cost estimate for next development step.*
Time to first output (once funded)	<1 year / 1–2 years / >2 years	*Timeframe for delivering tangible results.*

Appendix 3: Technology Dashboards

Superconducting materials

- REBCO
- BSCCO
- Iron-base superconductors
- MgB2
- LTS

Cables and conductors

- Rutherford cable
- Roebel cable
- Stacked tape cables
- Helically wound cable
- Internally cooled conductors
- Dry conductors

Modelling

- Digital twins
- Tape mechanical failure modes
- Multiphysics
- Electro-mechanical analysis
- Thermo-hydraulic analysis
- AC losses

Joining and insulation

- LTS joints
- HTS joints
- Demountable joints
- Terminations, feeders and current leads
- Radiation tolerant insulation
- Non insulated HTS coils

Manufacturing

- High precision coil winding
- Vacuum Pressure Impregnation
- Modular coil winding
- Laser engraving of wide HTS
- 3D printed formers

Magnet protection

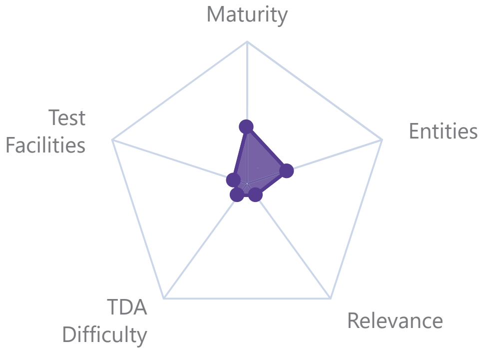
- Quench propagation models
- Quench detection
- Integrated quench detection
- Quench propagation
- Energy extraction

Instrumentation and auxiliaries

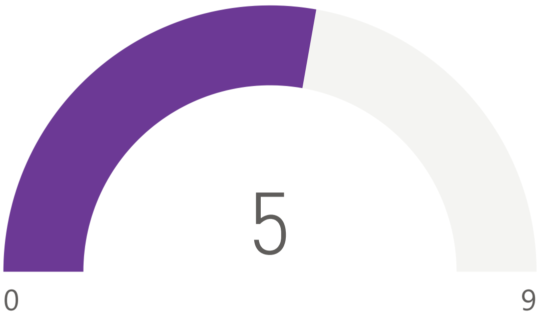
- Fiber optic sensing
- Voltage taps extraction
- Cooling systems
- Persistent current switches
- Feedthroughs
- Field mapping
- Acoustic emission monitoring
- Power supplies
- Shimming coils

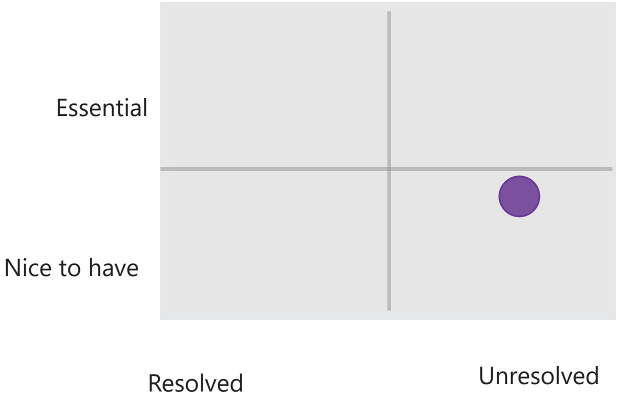
Magnets > Superconducting material

BSCCO



TRL





OtherMarkets	Alternatives	Showstoppers
Medical, Current leads, Energy storage, Mobility	REBCO LTS for other applications	Commercial availability, Cost, Complex heat treatment process for Bi2212

Technology Characteristics

Test Facilities	Test Facility Function
Properties: University of Geneva, ENEA, KIT, CNRS Irradiation: TUWien, NCBJ, INRNE, ESS, SCK-CEN, INFN-LNL, PSI, CERN, CIEMAT, EBTC	Superconductor characterization: - transport properties (Ic, Tcs) - mechanical behaviour - radiation hardness.

European Entities Involved

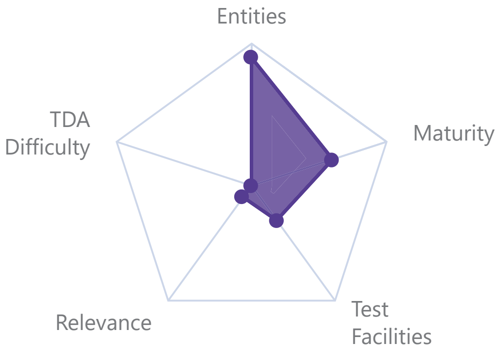
Private	Public
Bruker	

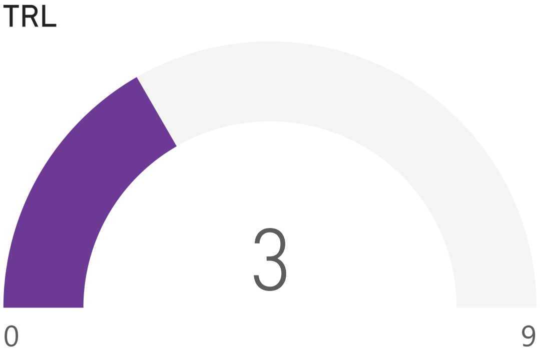
Technology Development Actions

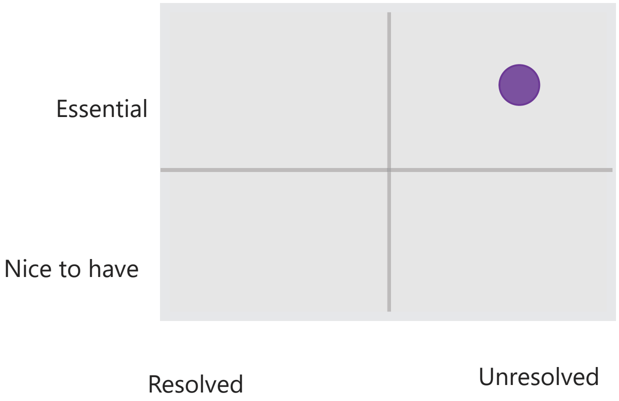
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Supply chain development	40 to 80%	>1M	>2 years	Low	No

Magnets ❯ Superconducting material

Iron-base superconductors







OtherMarkets	Alternatives	Showstoppers
Medical, Energy storage, Mobility, Power	REBCO LTS for some applications	Toxicity, Low critical current

Technology Characteristics

Test Facilities	Test Facility Function
CNR-SPIN, ENEA	Material characterization at lab scale Test synthesis process.

European Entities Involved

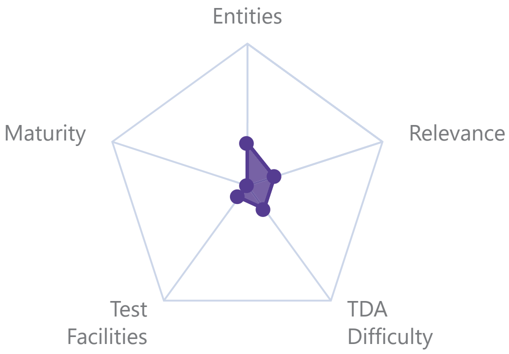
Private	Public
	CNR-SPIN, ENEA, , EPFL, Max Plank Institute, ICMM-CSIC, IFW Dresden, TU Wien, LMU

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Foster R&D on Iron Based Superconductors in Europe	>80%	>1M	>2 years	High	Partially

Magnets > Superconducting material

LTS



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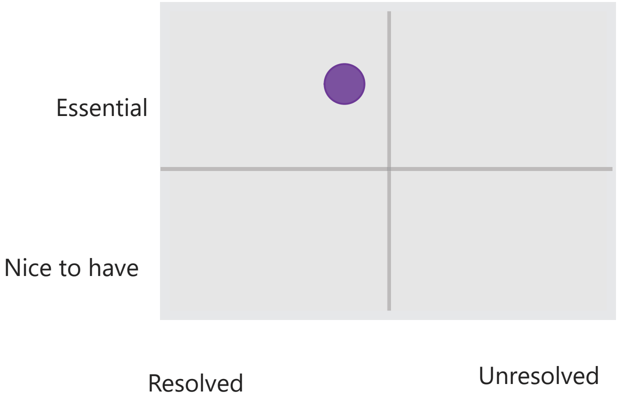


OtherMarkets	Alternatives	Showstoppers
Medical, Energy Mobility	REBCO	Use of Helium as cooling system, Medium field applications only

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

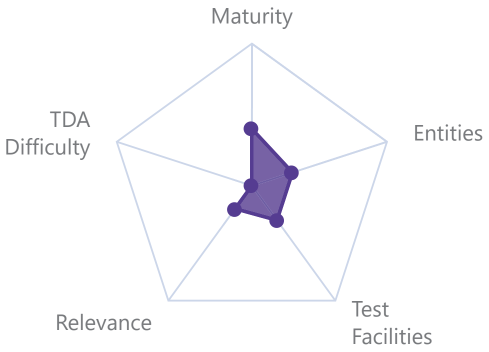
Private	Public
Bruker, Luvata	University of Geneva, ITER, F4E, CERN, ENEA, CEA, KIT

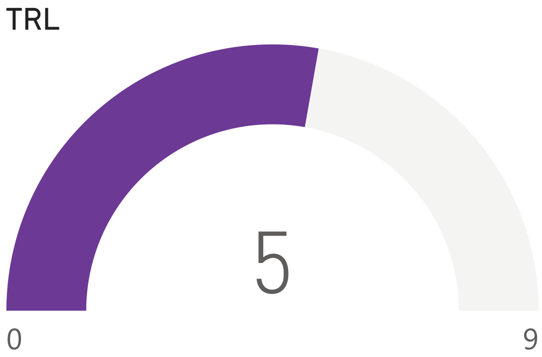
Technology Development Actions

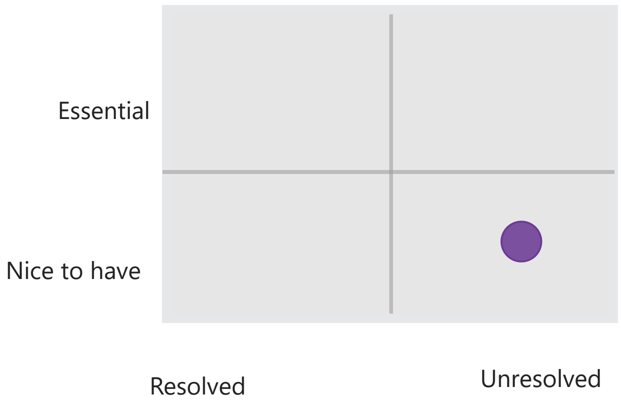
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop EU supply chain on LTS to anticipate large projects (FCC, EU-DEMO)	>80%	>1M	>2 years	High	No
Improve Europe sovereignty for raw materials (Nb)	40 to 80%	>1M	6 months to 2 years	Low	No
Share the knowledge and expertise on LTS radiation damage	>80%	<250k	<6 months	Medium	Yes

Magnets > Superconducting material

MgB2







OtherMarkets	Alternatives	Showstoppers
Current leads, busbars, Energy transport, Medical	REBCO LTS for some applications	Low field applications only

Technology Characteristics

Test Facilities	Test Facility Function
Properties: University of Geneva, ENEA, KIT, CNRS,, University of Bologna Irradiation: TUWien, NCBJ, INRNE, ESS, SCK-CEN, INFN-LNL, PSI, CERN, CIEMAT, EBTC	Superconductor characterization: - transport properties (Ic, Tcs) - mechanical behaviour - radiation hardness - AC losses.

European Entities Involved

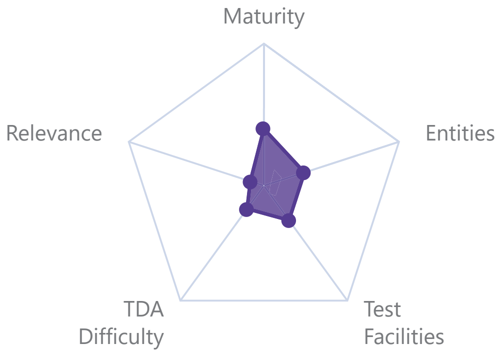
Private	Public
Columbus (ASG)	ENEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded

Magnets > Superconducting material

REBCO



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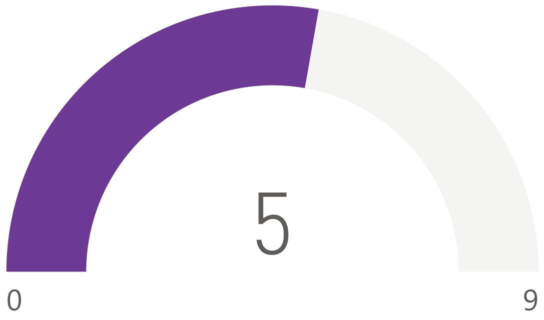
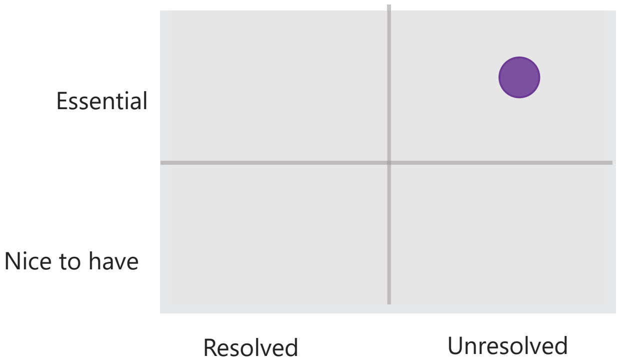




OtherMarkets	Alternatives	Showstoppers
Transportation, Power, Medical, Energy storage	LTS for lower field applications	Costs, Mechanics, Unknown radiation resistance, Quench detection

Technology Characteristics

Test Facilities	Test Facility Function
Properties: University of Geneva, ENEA, KIT, CNRS, EPFL-SPC, University of Bologna Irradiation: TUWien, NCBJ, INRNE, ESS, SCK-CEN, INFN-LNL, PSI, CERN, CIEMAT, EBTC	Superconductor characterization: - transport properties (Ic, Tcs) - mechanical behaviour - radiation hardness - AC losses.

European Entities Involved

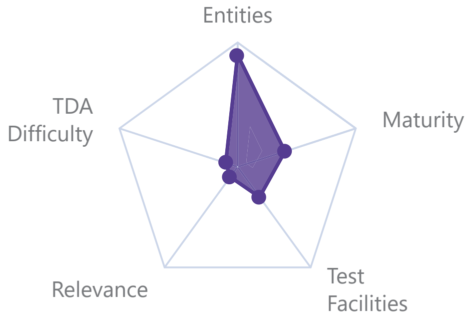
Private	Public
THEVA, Suprema, Subra	ENEA, ICMAB, KIT, EPFL-SPC, CERN, CEA

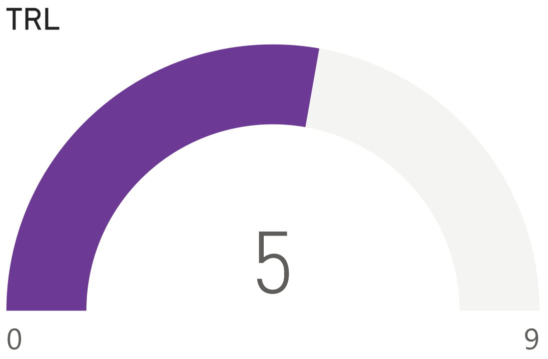
Technology Development Actions

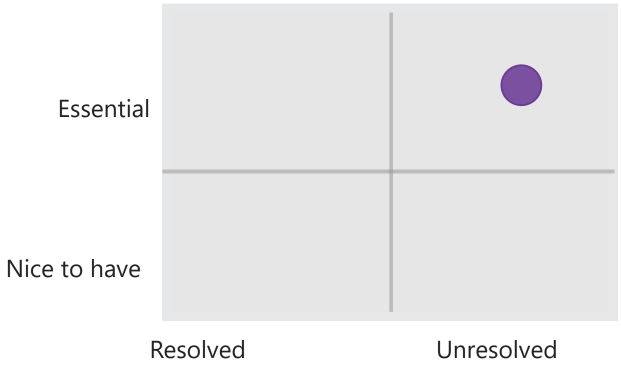
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Create REBCO development community	>80%	<250k	<6 months	High	No
Develop standard characterization process and a shared database of REBCO conductor properties	>80%	250k to 1M	>2 years	High	No
Develop supply chain	40 to 80%	>1M	>2 years	High	Partially
Test facilities for tape characterization (transport current, mechanics)	>80%	>1M	>2 years	High	Partially
Develop radiation test facility (incl. transport current measurements)	40 to 80%	>1M	>2 years	Medium	No

Magnets > Conductors and cables

Helically Wound cable







OtherMarkets	Alternatives	Showstoppers
AC cables, Power, Medical, Transport		Strain sensitivity, Cost, AC losses, Manufacturing, Low current density, Field quality.

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC), FBI (KIT), CryoMaK (KIT), Twente press (UniTwente), Magnet Test Stand (PSI), Saclay test facility (CEA) FCCTF (ENEA)	AC and DC characterization Mechanical assessment Thermal and electromagnetic cycling tests Quench behaviour Thermo-Hydraulic characterization Neutron irradiation High voltage tests

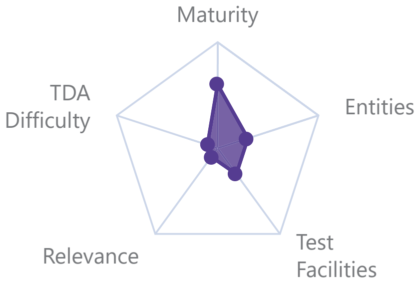
European Entities Involved

Private	Public
	University of Twente, CEA CERN

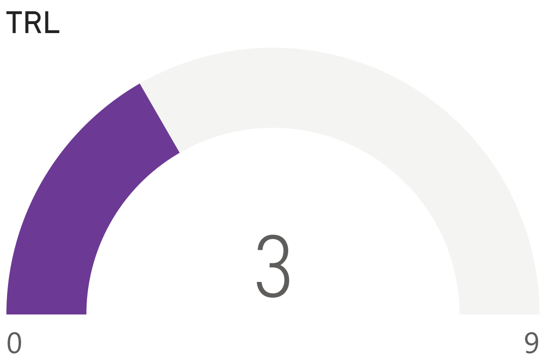
Technology Development Actions

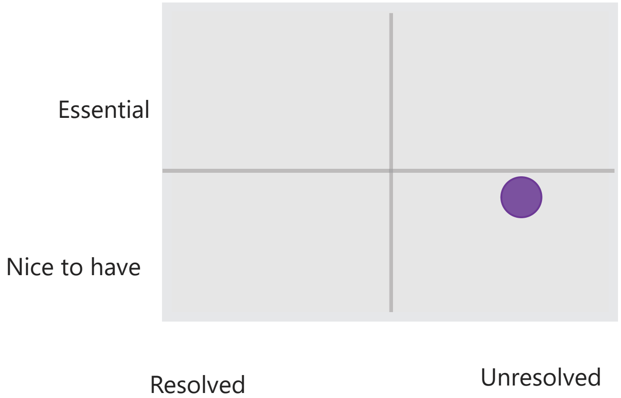
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Design, build and test model coil	40 to 80%	>1M	>2 years	High	No
Development of a new high field, high current facility for full scale, long length conductors	>80%	>1M	>2 years	High	No
Identification of optimal HTS cable layout depending on the application	>80%	>1M	6 months to 2 years	High	No
Industrial scale up of long length production	>80%	>1M	>2 years	High	No
Development of neutron source to test coils and conductors	<40%	>1M	>2 years	Low	No
Development of a Sultan-like facility with higher performances	>80%	>1M	>2 years	Medium	No

Magnets > Conductors and cables



Dry conductors





OtherMarkets	Alternatives	Showstoppers
Medical, Motors, Energy storage, Gyrotrons	CICC Stacked tapes	Heat load extraction, Quench protection

Technology Characteristics

Test Facilities	Test Facility Function
CryoMaK (KIT) Twente press (UniTwente) Magnet Test Stand (PSI) Saclay test facility (CEA) FRESCA 2 (CERN)	AC and DC characterization Mechanical assessment Thermal and electromagnetic cycling tests Quench behaviour Thermo-Hydraulic characterization Neutron irradiation High voltage tests

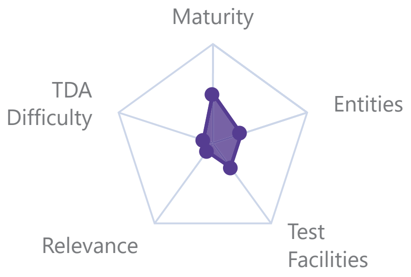
European Entities Involved

Private	Public
ICAS NEXANS NKT	SPC CERN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of dedicated test facility for dry conductors	>80%	>1M	>2 years	Low	Partially
Design, build and test model coil	40 to 80%	>1M	>2 years	High	No
Development of a new high field, high current test facility for full scale long length conductors	>80%	>1M	>2 years	High	No
Identification of optimal HTS dry cable layout depending on the application	>80%	>1M	6 months to 2 years	High	Partially
Industrial scale up of long length production	>80%	>1M	>2 years	High	No

HTS Rutherford cables



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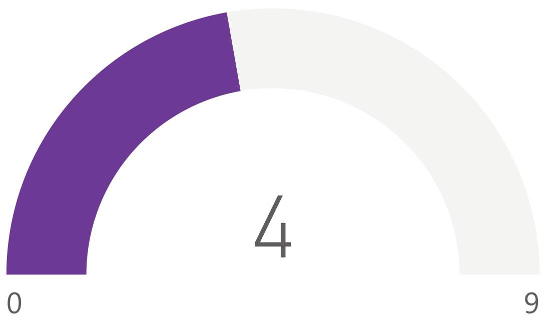
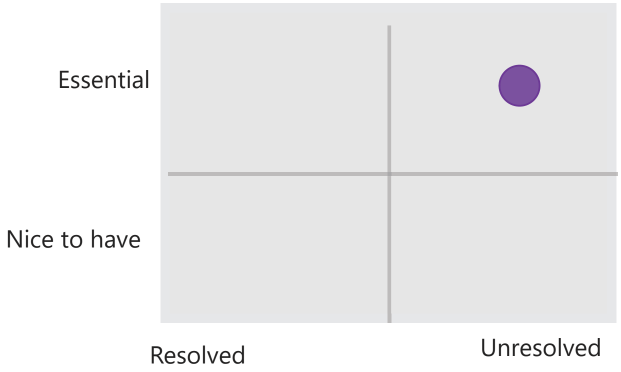




OtherMarkets	Alternatives	Showstoppers
Medical, NMR, MRI	Helically wound cable Stacked tapes	Maximum transverse stress, Heat load extraction, Complex manufacturing

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC)	AC and DC characterization
FBI-CryoMaK (KIT)	Mechanical assessment
Twente press (UniTwente)	Thermal and electromagnetic cycling tests
Magnet Test Stand (PSI)	Quench behaviour
Saclay test facility (CEA)	Thermo-Hydraulic characterization
FRESCA 2 (CERN)	Neutron irradiation
FCCTF (ENEA)	High voltage tests

European Entities Involved

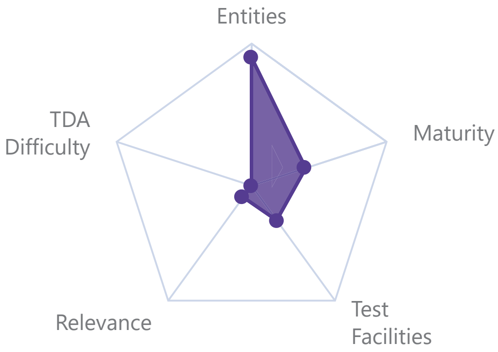
Private	Public
ICAS, Nexans, NKT	CERN, EPFL-SPC, INFN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Design, build and test model coil	40 to 80%	>1M	>2 years	High	Partially
Development of a new high field, high current test facility for full scale long length conductors	>80%	>1M	>2 years	High	No
Identification of optimal HTS cable layout depending on the application	>80%	>1M	6 months to 2 years	High	Partially
Industrial scale up of long length production	>80%	>1M	>2 years	High	No
Identification or development of neutron source to test coils and conductors	<40%	>1M	>2 years	Low	Partially
Development of a "Sultan like" facility with higher performances	>80%	>1M	>2 years	Medium	No

Magnets › Conductors and cables

HTS Roebel cables



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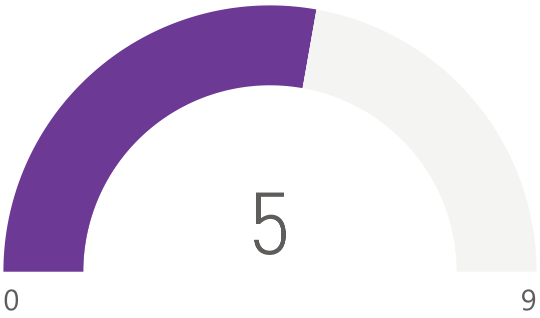
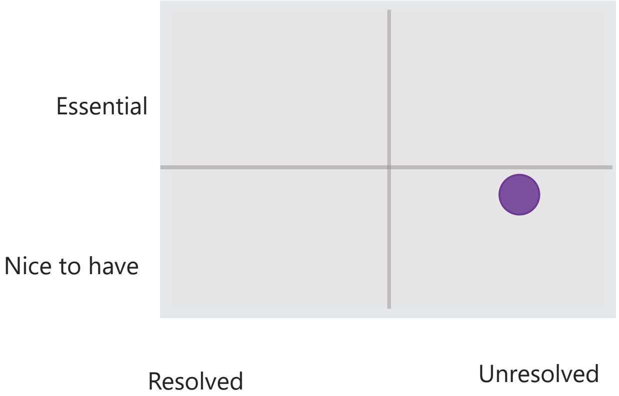




OtherMarkets	Alternatives	Showstoppers
Power (motors, generators, convertors)	All other types	Cost, Manufacturing, Mechanical strength, Material waste

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC) FBI-CryoMaK (KIT) FCCTF (ENEA) Twente press (UniTwente) Magnet Test Stand (PSI) Saclay test facility (CEA)	AC and DC characterization Mechanical assessment Thermal and electromagnetic cycling tests Quench behaviour Thermo-Hydraulic characterization Neutron irradiation High voltage tests

European Entities Involved

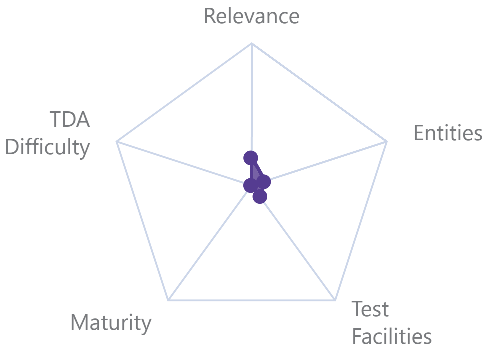
Private	Public
	CERN KIT

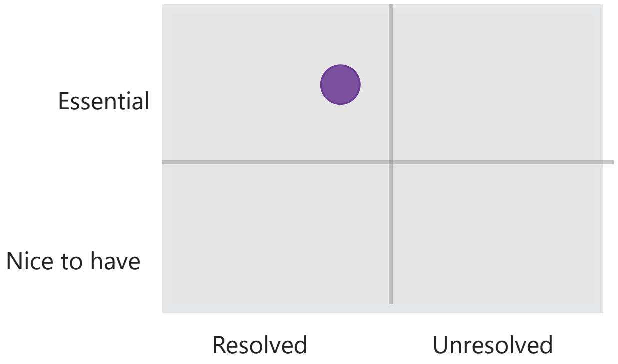
Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded

Internally cooled conductors

TRL





OtherMarkets	Alternatives	Showstoppers
Power, Busbar, current leads	Dry conductor	Low current density, Field quality

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC)	AC and DC characterization
FBI-CryoMaK (KIT)	Mechanical assessment
FCCTF (ENEA)	Thermal and electromagnetic cycling tests
Twente press (UniTwente)	Quench behaviour
Magnet Test Stand (PSI)	Thermo-Hydraulic characterization
Saclay test facility (CEA)	Neutron irradiation
	High voltage tests

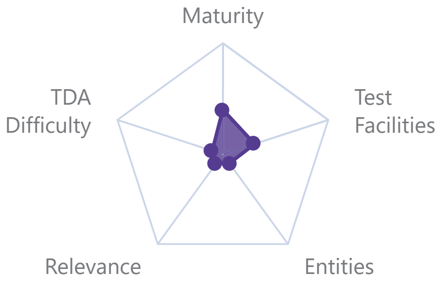
European Entities Involved

Private	Public
ICAS, Gauss, Proxima Fusion, TE Magnetics, ELYTT Energy	CERN EPFL-SPC CEA ITER ENEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded

Stacked tape cables



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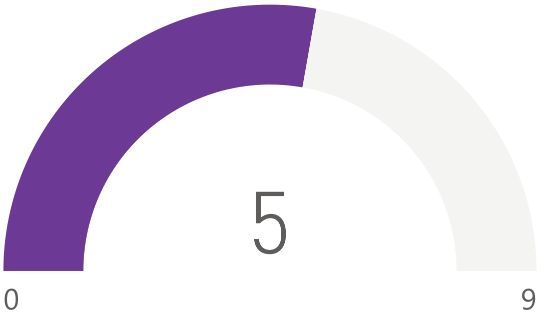


OtherMarkets	Alternatives	Showstoppers
Current leads and busbars, DC cables, Medical, Power	All other types	AC losses, Quench protection, Potential damage to tape, Field quality

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC) FBI-CryoMaK (KIT) FCCTF (ENEA) Twente press (UniTwente) Magnet Test Stand (PSI) Saclay test facility (CEA)	AC and DC characterization Mechanical assessment Thermal and electromagnetic cycling tests Quench behaviour Thermo-Hydraulic characterization Neutron irradiation High voltage tests

European Entities Involved

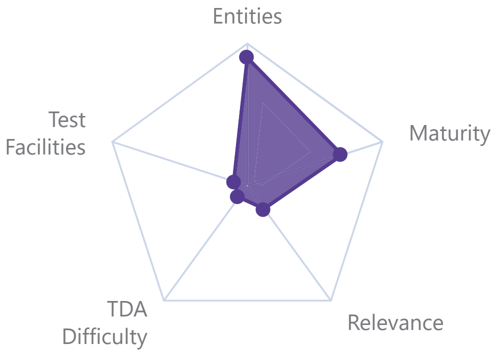
Private	Public
ICAS, TE magnetics, Proxima Fusion, Gauss, ELYTT Energy	CERN, SPC, ENEA, CEA, PSI

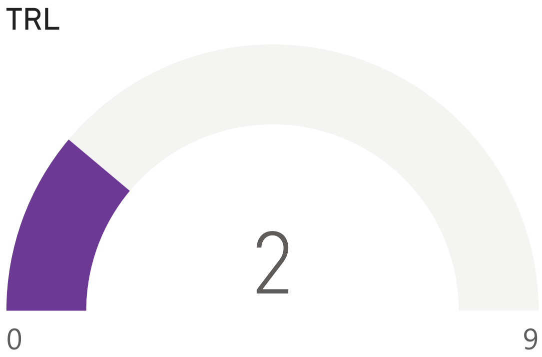
Technology Development Actions

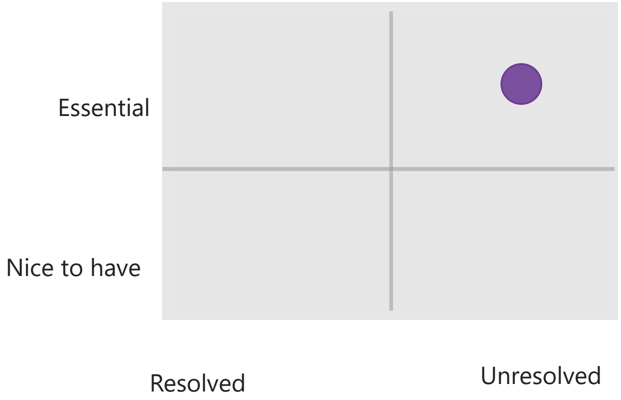
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of a "Sultan like" facility with higher performances	>80%	>1M	>2 years	Medium	No
Identification or development of neutron source to test coils and conductors	<40%	>1M	>2 years	Low	No
Design, build and test model coil	40 to 80%	>1M	>2 years	High	Partially
Development of a new high field, high current facility for full scale, long length cable performance validation	>80%	>1M	>2 years	High	No
Identification of optimal HTS cable layout depending on the application	>80%	>1M	6 months to 2 years	High	Partially
Industrial scale up of long length production	>80%	>1M	>2 years	High	Partially

Magnets > Modelling

AC losses







OtherMarkets	Alternatives	Showstoppers
MRI Energy management Mobility Electrical machines	Increased thermal margin Empirical models	Computational complexity (many length scales) Experimental validation

Technology Characteristics

Test Facilities	Test Facility Function
Josefa (CEA), SULTAN (EPFL-SPC), ITER MCTF, SM18, University of Bologna, Cryo-free 18T facility (ENEA)	With dedicated power supply

European Entities Involved

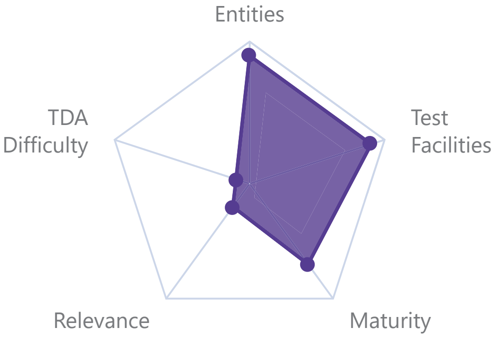
Private	Public
	CEA, PSI, ITER, CERN, ENEA

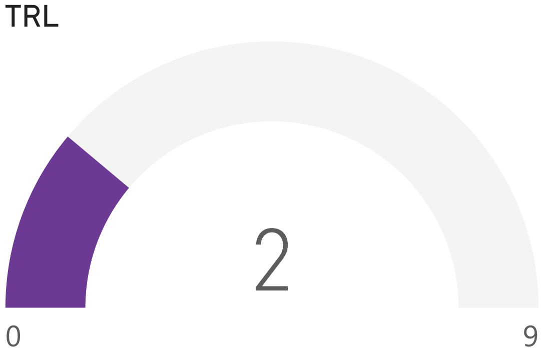
Technology Development Actions

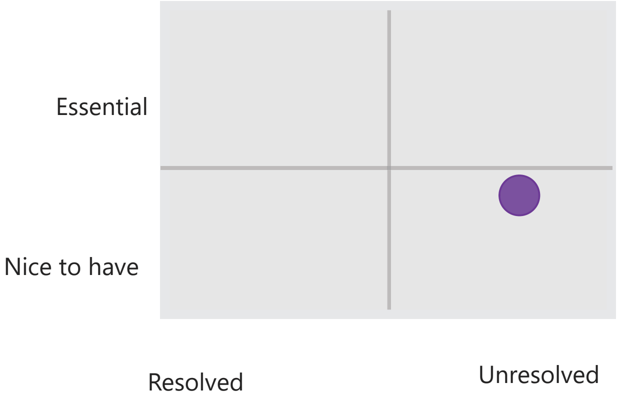
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of analytical formulae for real HTS cabling	40 to 80%	250k to 1M	>2 years	High	Partially
Eddy current calculations in large/detailed models	>80%	250k to 1M	>2 years	Medium	Partially

Magnets > Modelling

Digital twins







OtherMarkets	Alternatives	Showstoppers
Automation industry, robotics, mobility, civil engineering, power plants, aviation	Only for individual goals of digital twin - verification data, data-driven simulators, but not for all	Lack of test facilities Real-life application disturbances High system complexity

Technology Characteristics

Test Facilities	Test Facility Function
No Test facility oriented to digital twins	Validation, training and fine-tuning of the digital twin

European Entities Involved

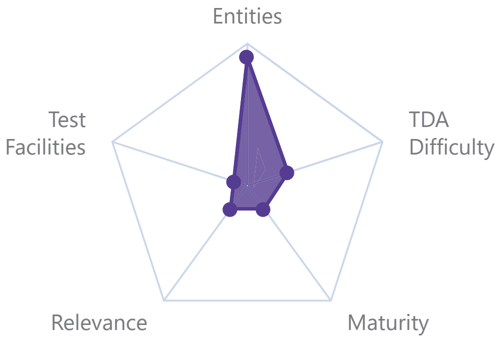
Private	Public
	University of Bologna

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Identification and development of capabilities to start building digital twins	>80%	250k to 1M	>2 years	Medium	No

Magnets › Modelling

Electro-mechanical analysis



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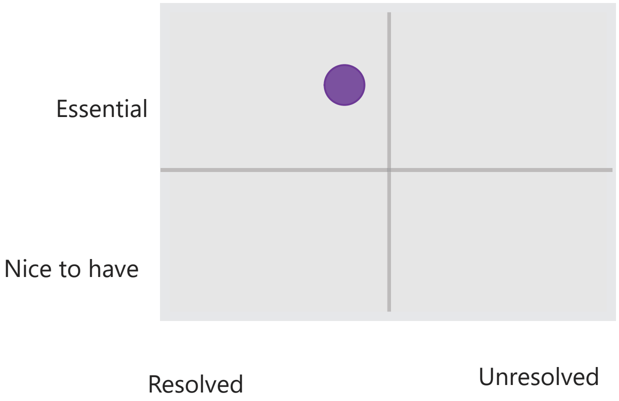


OtherMarkets	Alternatives	Showstoppers
Abundant examples		Input material properties, computational resources, knowledge of failure mechanisms

Technology Characteristics

Test Facilities	Test Facility Function
CERN	Material properties Validation of failure models

European Entities Involved

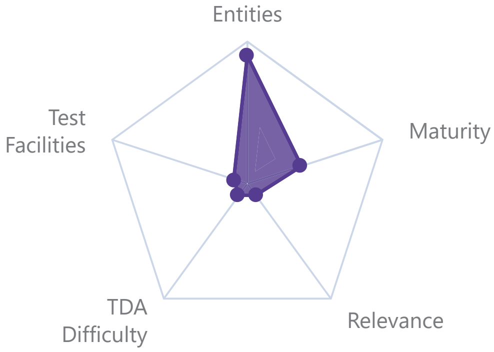
Private	Public
	F4E, CERN, ITER, ENEA

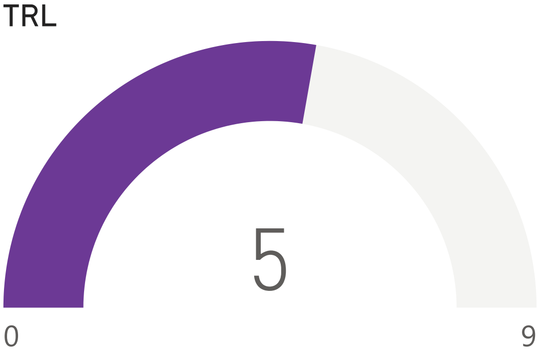
Technology Development Actions

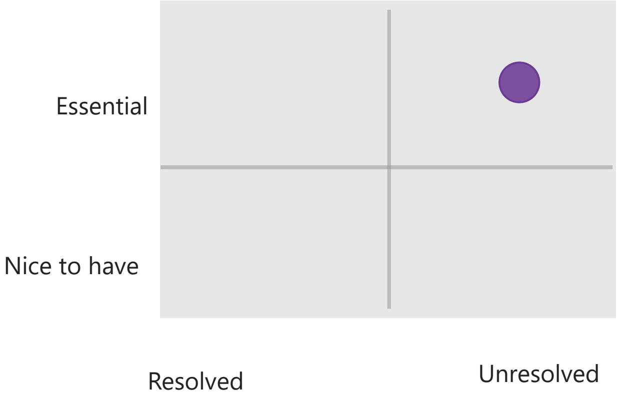
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Understanding of acceptable stress levels in copper former for HTS conductors	>80%	<250k	<6 months	Medium	No

Magnets › Modelling

Multiphysics







OtherMarkets	Alternatives	Showstoppers
Abundant examples	Safety factors accounting for other physical effects, experimental data	Computational resources, need of HPC Validation of models Deep knowledge-base needed to develop these models

Technology Characteristics

Test Facilities	Test Facility Function
ITER MCTF, ASDEX, WEST, W7-X, SM18 at CERN, FCCTF (ENEA), SULTAN (EPFL-SPC), TCV, Jordi	Validate models used to design fusion magnets and HTS devices Validation of assumptions, input parameters, interaction between sub-components

European Entities Involved

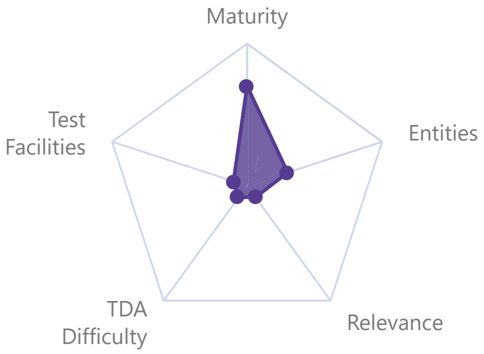
Private	Public
	ITER, CERN, ENEA, CEA, PSI, KIT, SPC

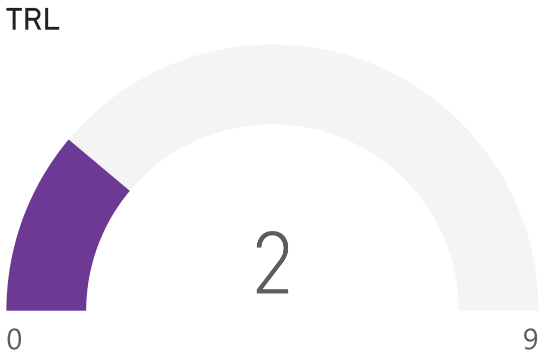
Technology Development Actions

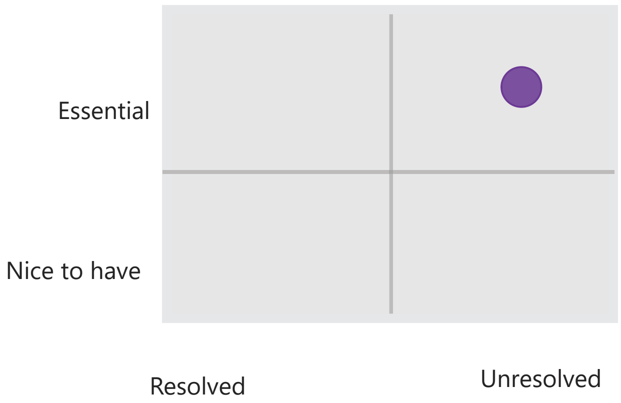
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Validation of numerical models for HTS/cables/magnets	>80%	>1M	>2 years	High	No
Development of techniques to speed up of models	40 to 80%	250k to 1M	>2 years	Medium	No

Magnets > Modelling

Tape mechanical failure modes







OtherMarkets	Alternatives	Showstoppers
HTS powerlines, composite materials, MRI		Connection between the strain (and degradation) and superconductivity state in HTS, Homogeneous characteristics in samples

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC), Twente Press University, KIT, ENEA, CERN	Characterization of failure modes for tapes/cables/conductors Qualification of failure modes for tapes/cables/conductors

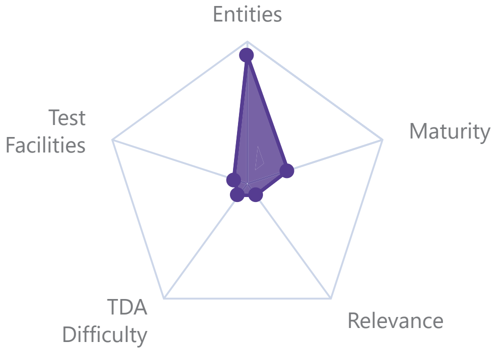
European Entities Involved

Private	Public
RINA, ASG	PSI, Twente University, KIT, ENEA, CERN, University of Bristol, ICMAB, CEA, University of Tuscia

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Experimental Campaigns to Characterize mechanical properties and strength	>80%	>1M	>2 years	High	Partially
Modelling of mechanical failure in tapes	>80%	>1M	>2 years	High	No
Understanding of irradiation damage mechanism	>80%	>1M	>2 years	High	No

Thermo-hydraulic analysis



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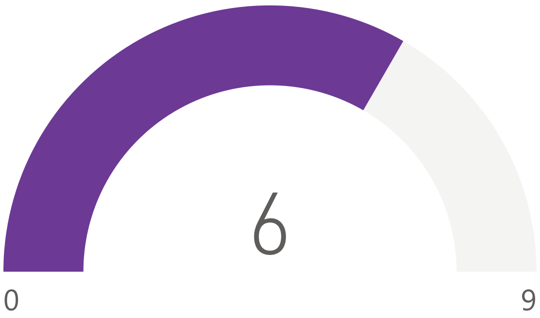
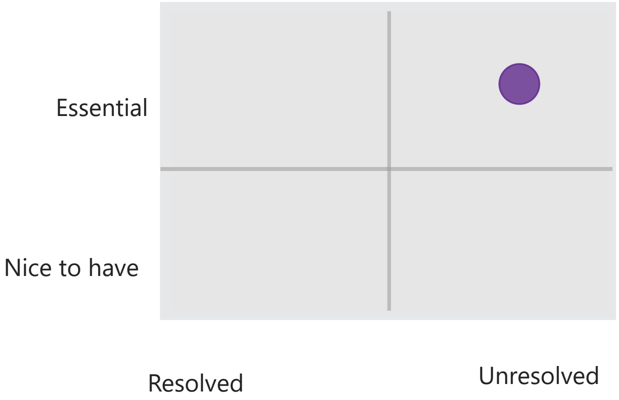




OtherMarkets	Alternatives	Showstoppers
Cryogenics, Heat exchangers	Experimental data	Understanding two-phase flow behavior in narrow environments, Complex models or difficult validation (liquid metal). Limited validation data.

Technology Characteristics

Test Facilities	Test Facility Function
	Model validation, measurement of material properties

European Entities Involved

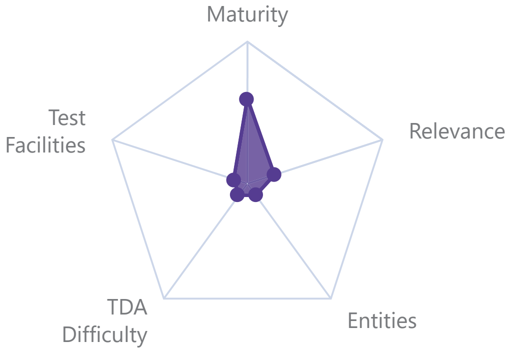
Private	Public
	CEA (Grenoble), ENEA

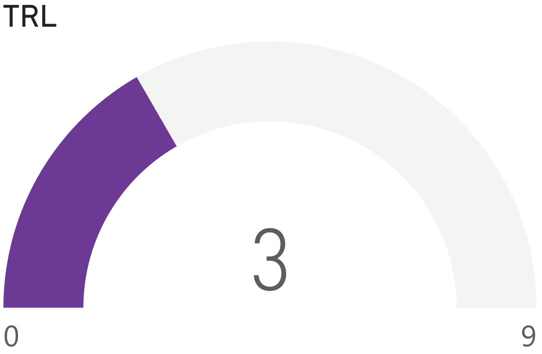
Technology Development Actions

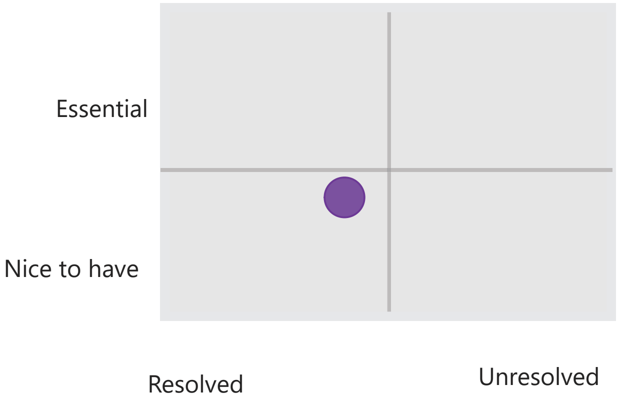
Name	Chances of success	Cost	Implementation Time	Priority	Funded
Tailoring existing tools for HTS tapes/cables and magnets	>80%	250k to 1M	6 months to 2 years	High	Yes
Different coolants: experimental campaigns to feed models, establish basic correlations	>80%	>1M	>2 years	Medium	No
Thermal management based on different cooling schemes	>80%	250k to 1M	>2 years	Medium	No

Magnets > Manufacturing

3D printed formers







OtherMarkets	Alternatives	Showstoppers
Anywhere where structural parts are used	Machined Cast	Mechanical and physical properties

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

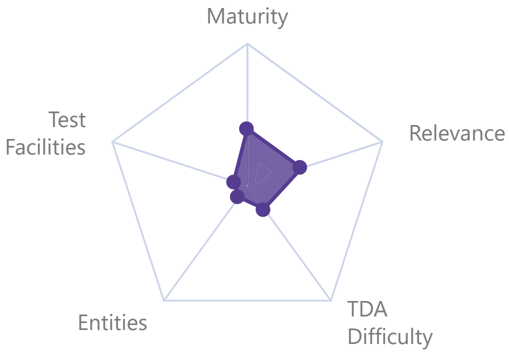
Private	Public
HP, Rosswag, Probeam, AMCM GmbH, ASG, Bruker, SeaAlp	CERN, PSI

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
3D Former Proof of Concept	>80%	>1M	6 months to 2 years	Medium	Partially

Magnets > Manufacturing

High precision coil winding



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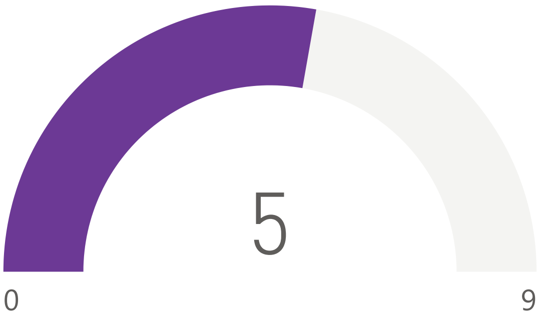
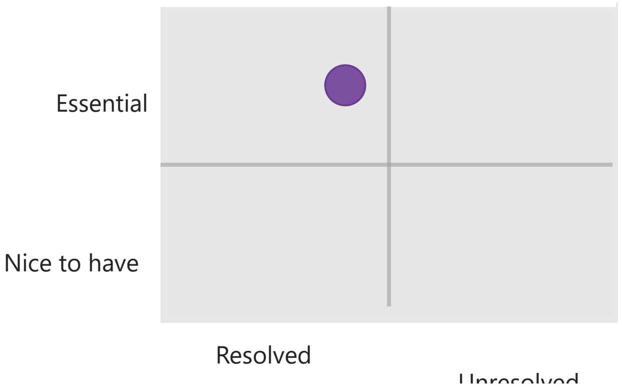




OtherMarkets	Alternatives	Showstoppers
NMR Medical Energy storage Mobility Power	3D printing/etching Modular coils	

Technology Characteristics

Test Facilities	Test Facility Function
CERN PSI (SW)	Test winding accuracy

European Entities Involved

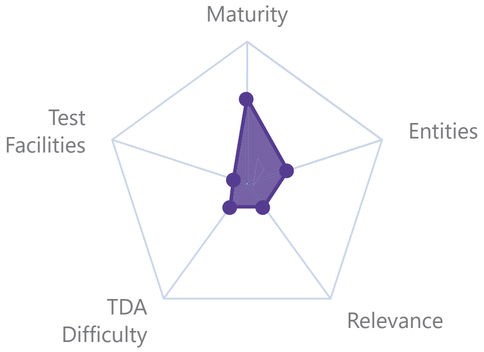
Private	Public
ASG, Ridgway (UK), Tesla Engineering (UK), ICE Oxford (UK), SigmaPhi, Elytt, Bilfinger, TE Magnetics, Antec Magnets	CERN, ITER, PSI

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Winding Automation	40 to 80%	>1M	6 months to 2 years	Medium	Partially
Winding of Large Section HTS Conductors	40 to 80%	>1M	6 months to 2 years	Medium	Partially

Magnets > Manufacturing

Laser engraving of wide HTS



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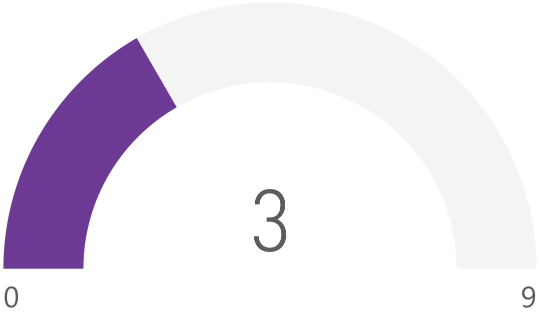
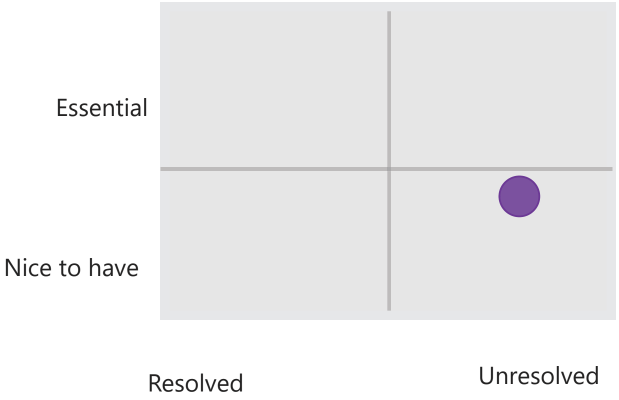




OtherMarkets	Alternatives	Showstoppers
Medical Energy storage Mobility	Narrow tapes Complex windings	Reliability of HTS production processes over large surfaces

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

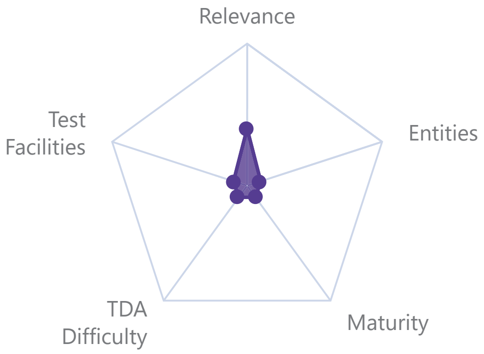
Private	Public
Renaissance Fusion	KIT

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Improve deposition process to guarantee quality over width and length of the wide sheets	40 to 80%	>1M	6 months to 2 years	High	Partially
Qualify laser engraving technique for HTS materials	40 to 80%	>1M	>2 years	Low	Partially
Proof of concept using Cu sheets	>80%	250k to 1M	6 months to 2 years	Low	Yes

Magnets > Manufacturing

Modular coil winding



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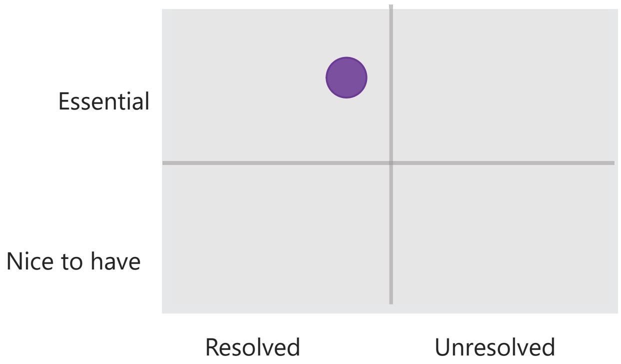


OtherMarkets	Alternatives	Showstoppers
Medical Energy storage Mobility Medical NMR	Layer wound coils	

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

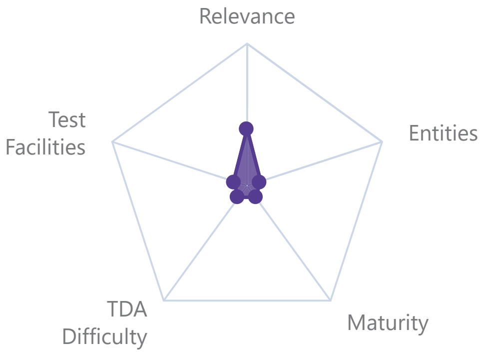
Private	Public
ASG, Bruker, Tokamak Energy, Ridgway, ELYTT Energy, Antec Magnets	ENEA, CEA, PSI, CERN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop Coil Architecture for High Performance HTS Coils	40 to 80%	>1M	>2 years	High	Partially
Inter-module Joints for HTS Coils	40 to 80%	>1M	>2 years	High	Yes

Magnets > Manufacturing

Resin Vacuum Pressure Impregnation



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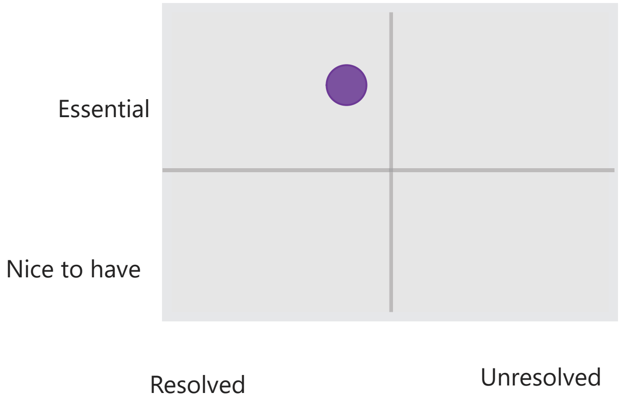


OtherMarkets	Alternatives	Showstoppers
Automotive	Wet and wind	
Electrical machines	Pre-impregnated	
NMR	Non insulated coils	
Medical	Dry insulation	
Composite structures		

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

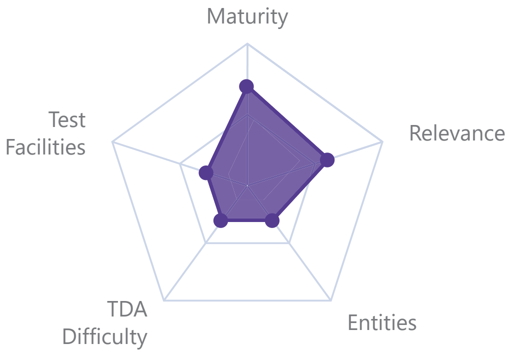
Private	Public
DEMAK, ASG, Bruker, Elytt Energy, Antec Magnets	ITER

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of Solder Impregnation Process	40 to 80%	>1M	6 months to 2 years	High	Partially

Magnets › Insulation and joining

Demountable joints



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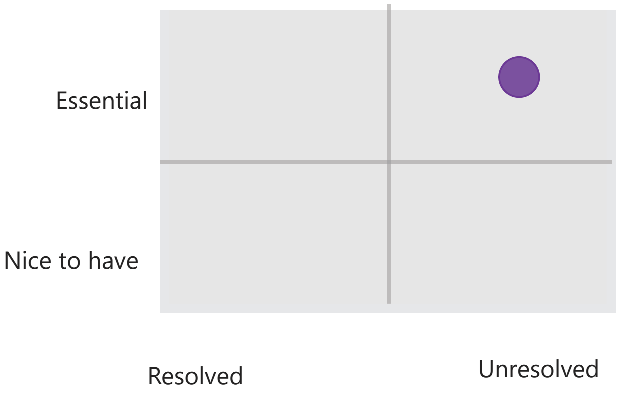


OtherMarkets	Alternatives	Showstoppers
	Complexity and low asset integrity	Repeatability Ability to use remote handling Reliable performance (resistance and leak tightness)

Technology Characteristics

Test Facilities	Test Facility Function
Sultan (EPFL-SPC)	Ability to test batches of demountable joints

European Entities Involved

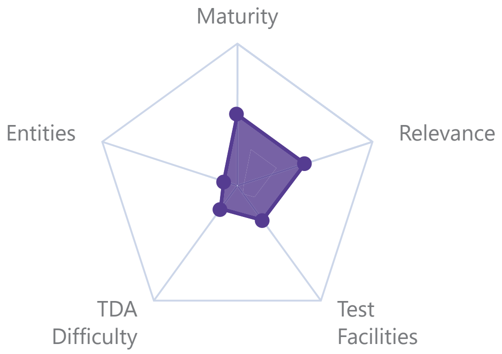
Private	Public
Gauss Fusion	ENEA
ENI	F4E
ASG	CEA
ELYTT Energy	KIT

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Define resistance requirements for demountable HTS joints	>80%	<250k	<6 months	High	Partially
Prototyping and Testing of HTS Joints against EM forces	40 to 80%	>1M	6 months to 2 years	High	Partially
Development of specialized tooling for mounting / dismounting Joints	40 to 80%	<250k	6 months to 2 years	Low	No
Improve reliability in a variety of conditions (mounting/demounting cycles, stresses, radiation, etc.)	40 to 80%	>1M	>2 years	Medium	Partially

Magnets > Insulation and joining

HTS joints



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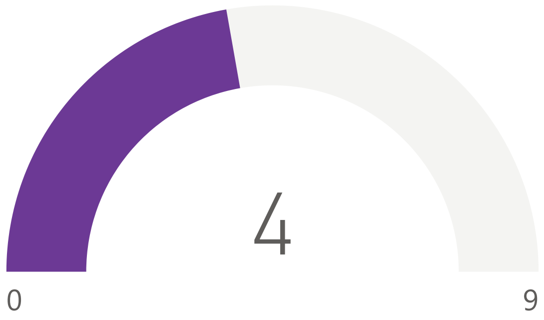
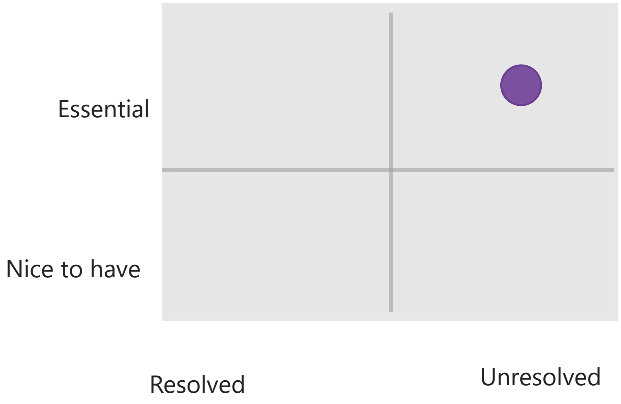




OtherMarkets	Alternatives	Showstoppers
MRI, Defense, Rotary Machines, Mobility, Medical	LTS	

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC) SELFIE (CEA)	Qualification of the junction, exposure to different environmental conditions, radiation exposure, reliability

European Entities Involved

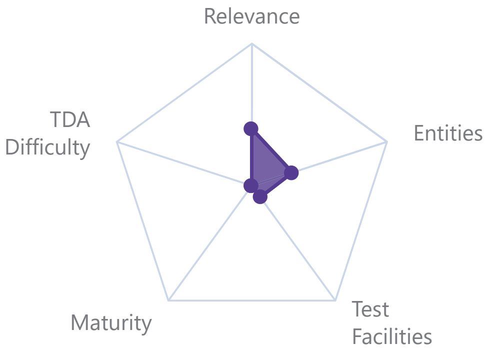
Private	Public
ASG, Renaissance Fusion, Gauss Fusion, Tokamak Energy, ELYTT Energy	KIT, ENEA, CEA, CIEMAT, EPFL-SPC

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop pressure-based concepts for HTS joints	<40%	250k to 1M	>2 years	High	Partially
Dedicated Testing Facilities for HTS Joints	>80%	>1M	>2 years	High	No
Standardization of joint design for most promising families of HTS tapes	>80%	>1M	>2 years	Medium	Partially
Develop repair strategy for existing concepts	40 to 80%	250k to 1M	>2 years	Medium	No

Magnets > Insulation and joining

LTS joints



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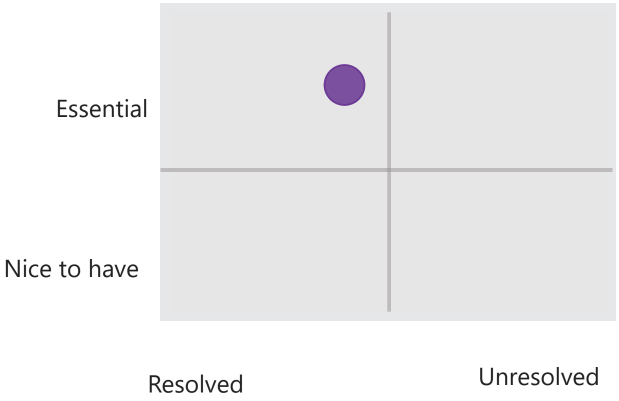


OtherMarkets	Alternatives	Showstoppers
MRI, Militar, HEP, NMR, Accelerators		

Technology Characteristics

Test Facilities	Test Facility Function
SULTAN (EPFL-SPC), SELFIE (CEA)	Additional capability for testing for a scalable market

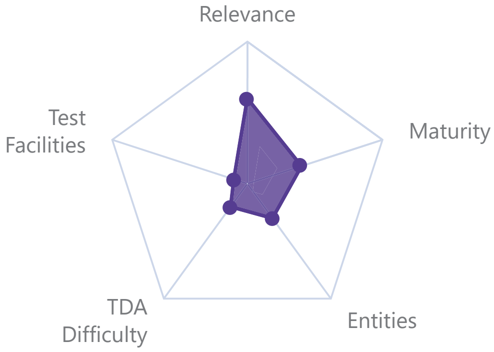
European Entities Involved

Private	Public
ASG, ELYTT, Bilfinger Noel, GE	ENEA, CIEMAT, CEA, CERN, PSI, KIT, VTT

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded

Non insulated HTS coils - resistance control



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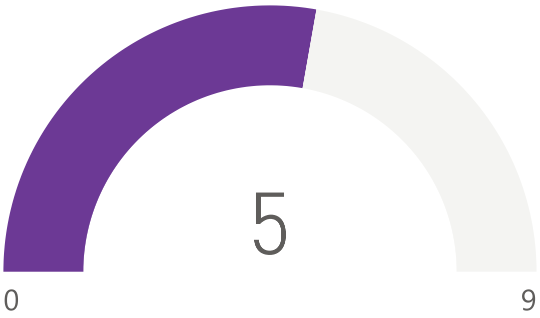
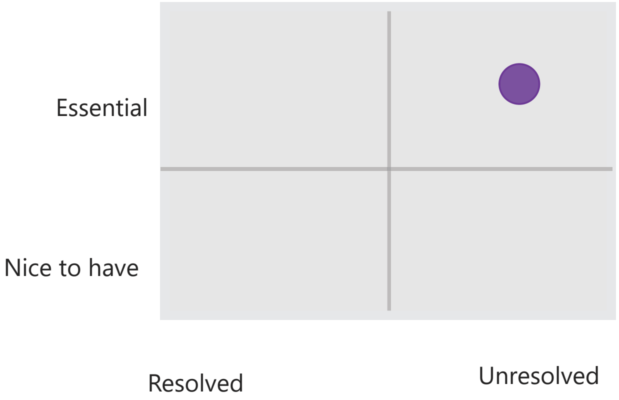




OtherMarkets	Alternatives	Showstoppers
	Insulated coils (high current)	Mechanical stability Detection of fast signals

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

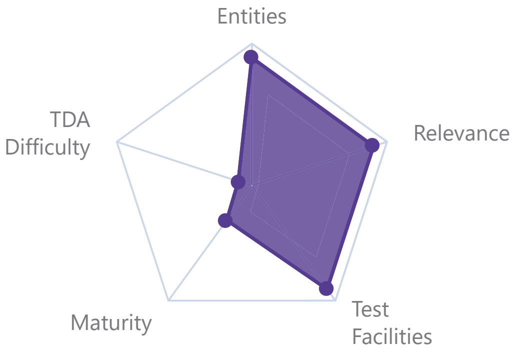
Private	Public
ASG, Tokamak Energy	ENEA, UKAEA, CERN, PSI, CEA, INFN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Build and test a small prototype coil to evaluate solutions	>80%	>1M	6 months to 2 years	High	Partially
Define QA standards for the winding of non-insulated HTS coils to enhance reproducibility and reliability	>80%	250k to 1M	6 months to 2 years	Medium	No
Build and test a large coil to validate findings	40 to 80%	>1M	>2 years	High	Partially
Material development and characterisation	40 to 80%	>1M	6 months to 2 years	High	Partially

Magnets › Insulation and joining

Radiation tolerant insulation systems



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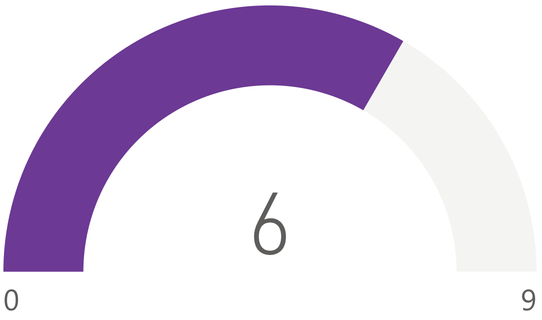
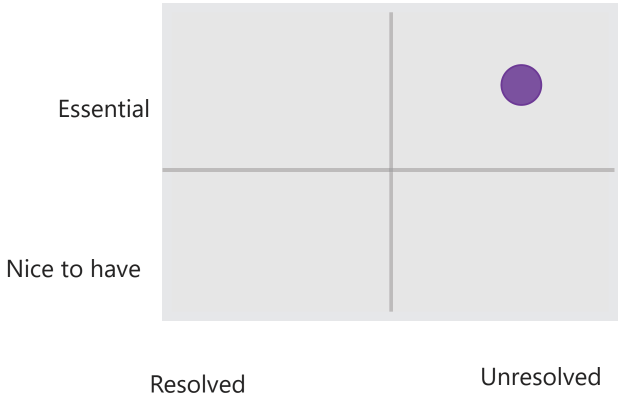




OtherMarkets	Alternatives	Showstoppers
	Uninsulated coils Cyanate Ester (up to 10MGy)	

Technology Characteristics

Test Facilities	Test Facility Function
CERN (mechanical, uncoupled), KIT, Vienna University, Experimental Fission reactors	Radiation test

European Entities Involved

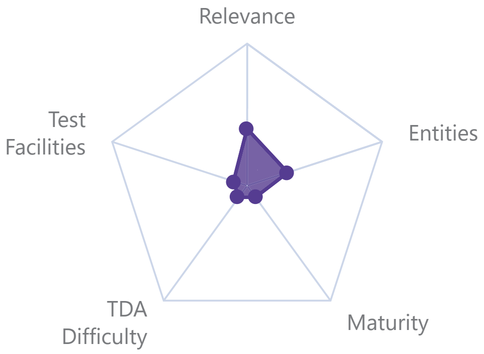
Private	Public
	ITER

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Dedicated facility for testing coils insulation	>80%	250k to 1M	>2 years	Medium	No
Further exploration and optmization of radiation tolerant insulation	>80%	250k to 1M	6 months to 2 years	Medium	No

Magnets > Insulation and joining

Terminations and current leads



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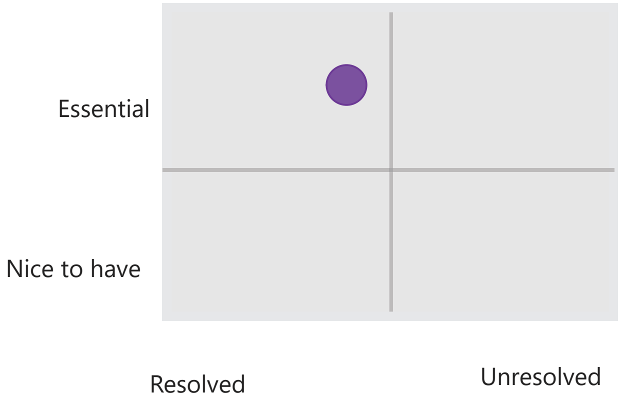


OtherMarkets	Alternatives	Showstoppers
Power transmission Data centers		

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

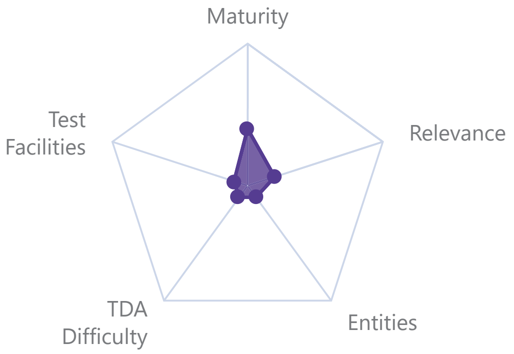
Private	Public
ASG, Bruker	CERN, KIT, CIEMAT, CEA, ENEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Assessing degradation and obtaining qualified HTS current leads	>80%	250k to 1M	6 months to 2 years	Low	No

Magnets > Magnet protection

Energy extraction systems



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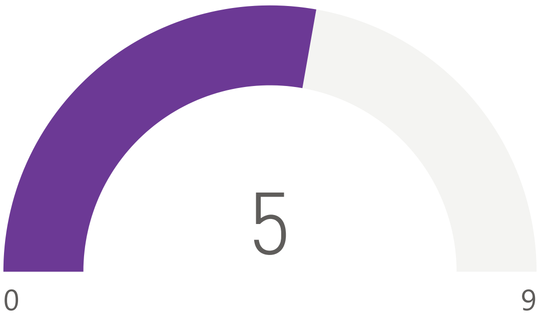
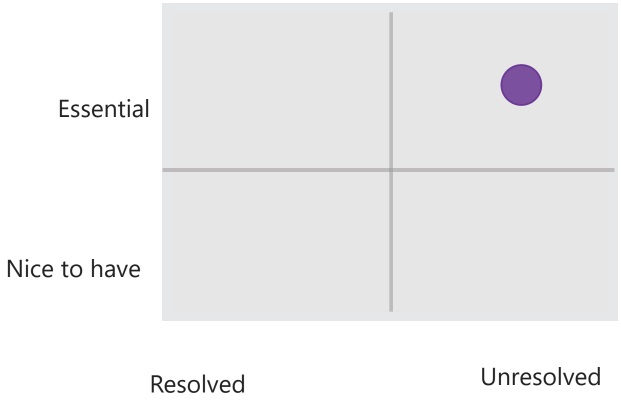




OtherMarkets	Alternatives	Showstoppers
NMR, MRI, SMES LTS magnets	internal energy dump	Voltage management

Technology Characteristics

Test Facilities	Test Facility Function
ITER, CEA, CERN, DTT, ENEA	no need for a specific facility, we could use any other existing facility with minor adaptation

European Entities Involved

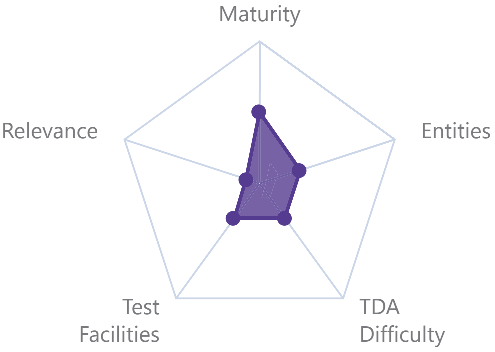
Private	Public
Varistors (Metrosil), Danfysik, Ocem, ABB, Secheron	ITER, CEA, CERN, DTT, ENEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop high current DC (~60kA) switches	40 to 80%	>1M	>2 years	Medium	Partially

Magnets > Magnet protection

Quench acceleration



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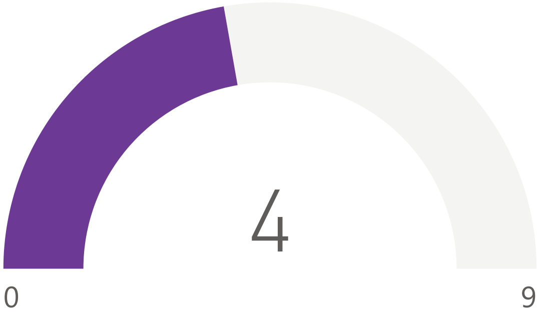
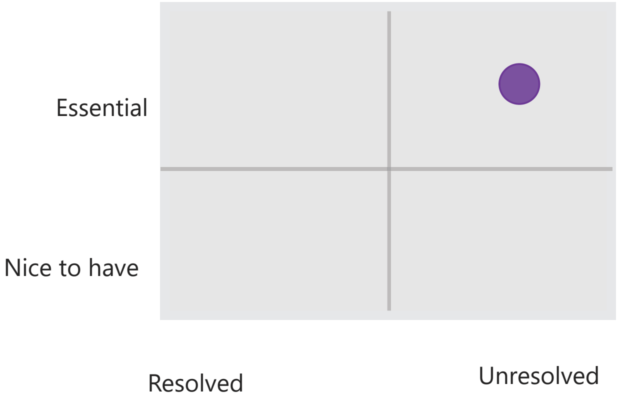




OtherMarkets	Alternatives	Showstoppers
MRI, LTS magnet systems, medicine, motor/generator, aerospace	external energy extraction (when applicable)	Suitable facility, Validation, Difficult to implement.

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

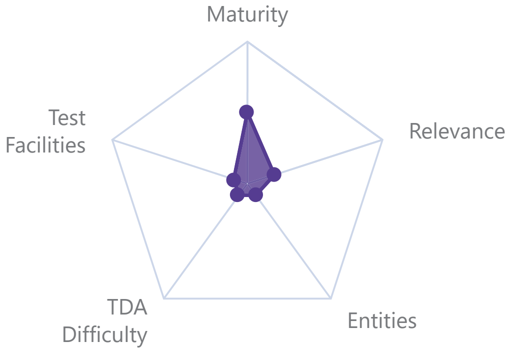
Private	Public
Proxima	INFN, EPFL-SPC

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Create benchmark models for HTS to investigate all quench propagation methods (distributed heaters - internal or external, EM, uniformous conductors or conductor with current flow divertor)	40 to 80%	250k to 1M	6 months to 2 years	High	Partially
Develop models for EM quench propagation models	40 to 80%	<250k	6 months to 2 years	Medium	No

Magnets › Magnet protection

Quench detection techniques



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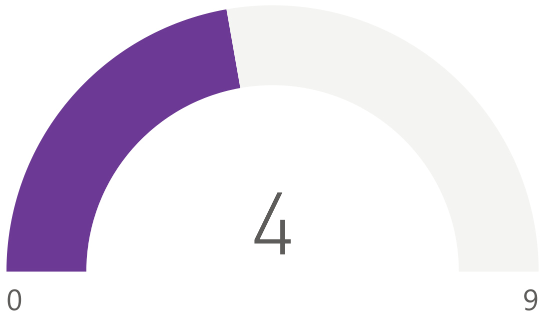
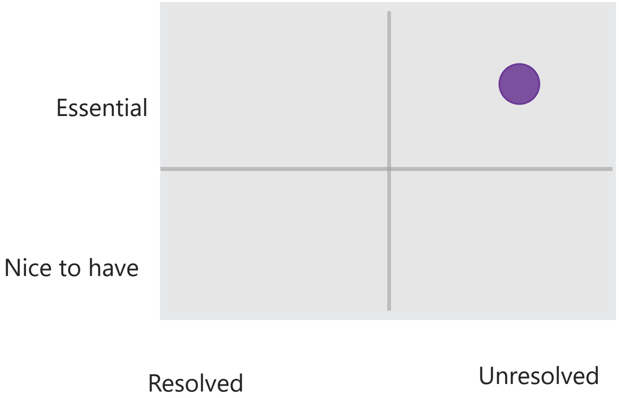




OtherMarkets	Alternatives	Showstoppers
MRI, LTS magnet systems, medicine, motor/generator, aerospace	Passive quench protection	Sensitivity of the instruments Lack of test facilities.

Technology Characteristics

Test Facilities	Test Facility Function
CEA, FBI (KIT), DTT, Sultan (EPFL-SPC)	Validate quench detection techniques for different magnet configurations

European Entities Involved

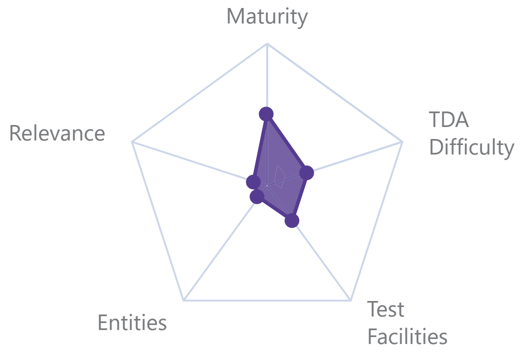
Private	Public
Renaissance, Proxima, Tokamak Energy, ASG superconductors, Bilfinger, SIGMAphi, Tesla	CEA, KIT, DTT , EPFL-SPC, ITER, CERN, ENEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
develop AI-assisted quench detection techniques	>80%	>1M	6 months to 2 years	Low	No
Develop facilities for quench detection validation	>80%	>1M	>2 years	Medium	No
Model coils to identify suitable quench detection techniques	40 to 80%	>1M	>2 years	High	No

Magnets > Magnet protection

Quench models



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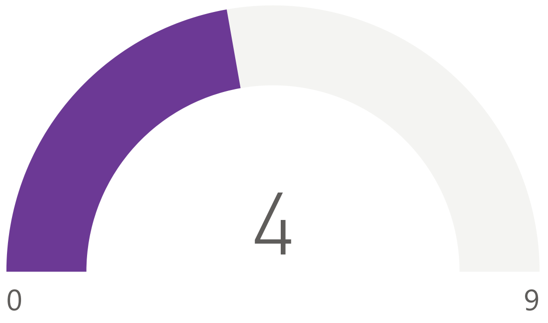
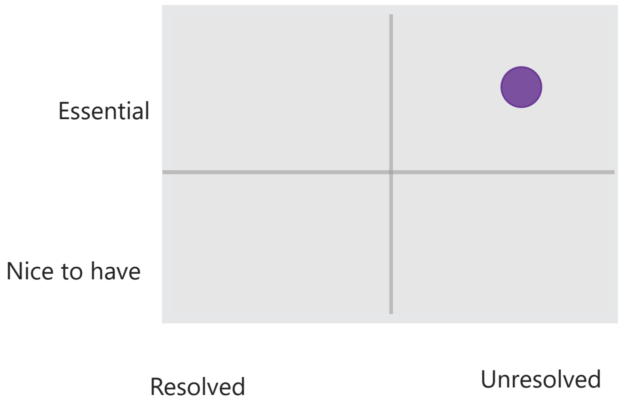




OtherMarkets	Alternatives	Showstoppers
MRI, NMR market, accelerator magnets, oncology, military, motor/generator, energy transmission, space application		Complexity, Validation of the models.

Technology Characteristics

Test Facilities	Test Facility Function
TEAM (Testing Electromagnetic Analysis Methods) TFMC	(benchmark pre-defined cases)

European Entities Involved

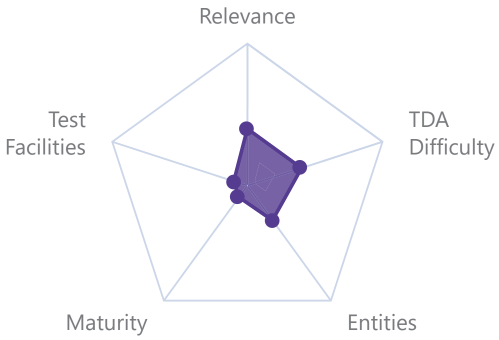
Private	Public
Proxima, ASG, Renaissance, Bruker Tokamak, LBE	University of Liège, KIT, Darmstadt, ENEA, University of Bologna, DTT

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Connect to the existing HTS quench propagation model community	>80%	<250k	<6 months		
Develop quench design criteria specific for HTS	40 to 80%	250k to 1M	>2 years	Medium	No
Develop/extend database for cryogenic properties	>80%	<250k	6 months to 2 years	Medium	No

Magnets > Instrumentation and auxiliary systems

Cryogenic cooling systems



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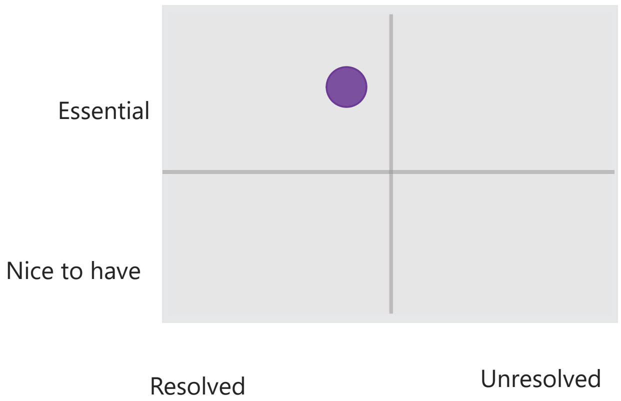


OtherMarkets	Alternatives	Showstoppers
Hydrogen Mobility Medical Electronics Energy Quantum computing		

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

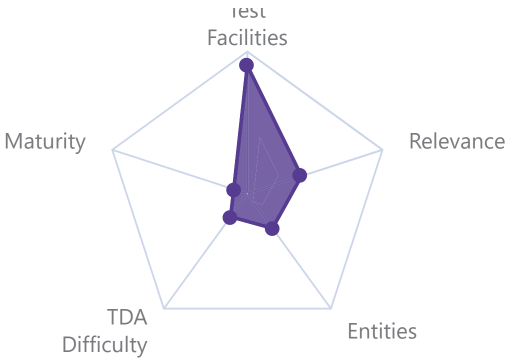
Private	Public
Air Liquide Linde Absolut Systems	ESET, F4E, CERN, ITER, ENEA, CEA (Grenoble)

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Development of Turbo Brayton for HTS magnets	40 to 80%	<250k	<6 months	Medium	Partially

Magnets › Instrumentation and auxiliary systems

Feedthroughs



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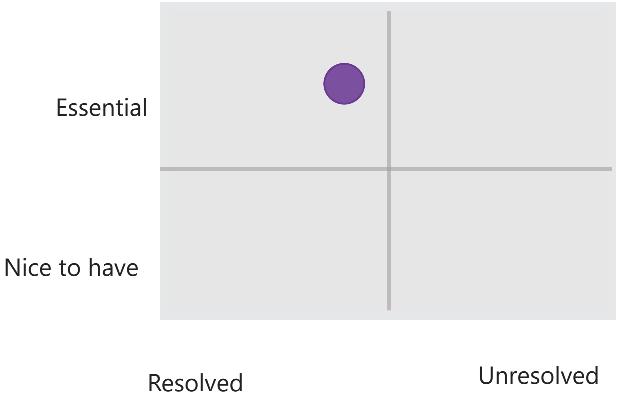


OtherMarkets	Alternatives	Showstoppers
Medical Mobility Energy		

Technology Characteristics

Test Facilities	Test Facility Function
	High current test facility for commercializing feedthroughs

European Entities Involved

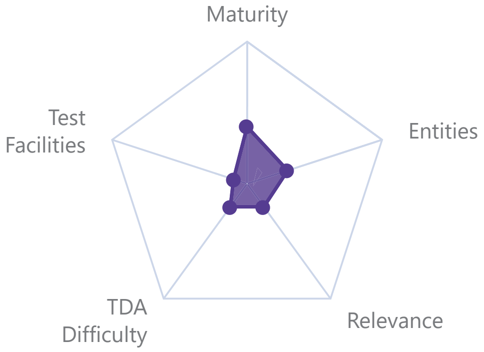
Private	Public
Allectra	ITER, CERN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop a program for qualification of commercially available connectors for required environment conditions	40 to 80%	250k to 1M	6 months to 2 years	Low	Partially

Magnets > Instrumentation and auxiliary systems

Fiber optic sensing



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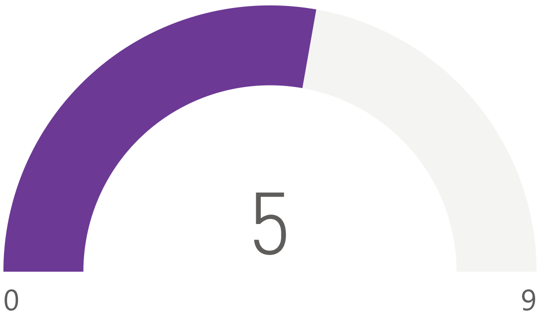
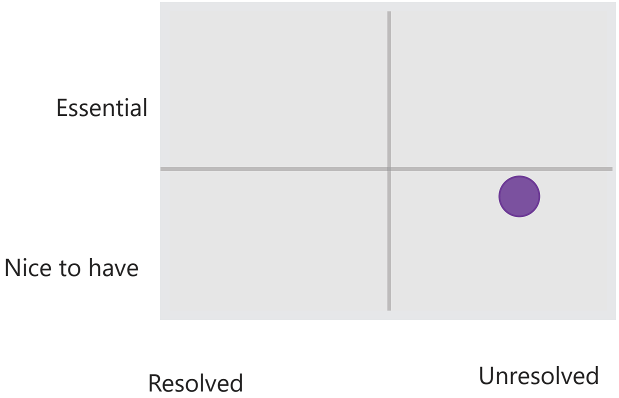




OtherMarkets	Alternatives	Showstoppers
Power plants Infrastructure Aerospace	Voltage taps	Fragility

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

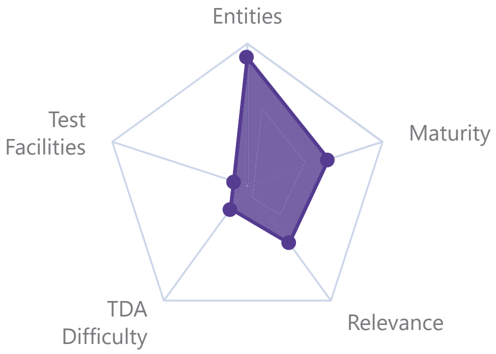
Private	Public
Exail	Hubert Curien Laboratory

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop a robust way for fiber optics integration into a magnet for a reliable operation	40 to 80%	250k to 1M	6 months to 2 years	Medium	No

Magnets > Instrumentation and auxiliary systems

Acoustic emission monitoring



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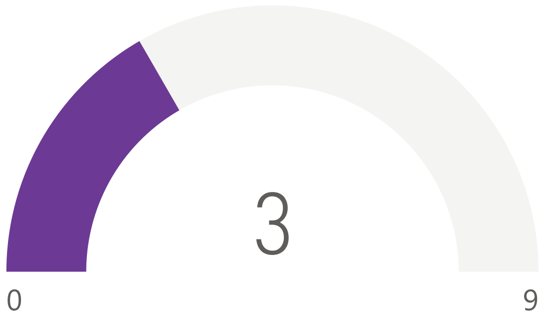
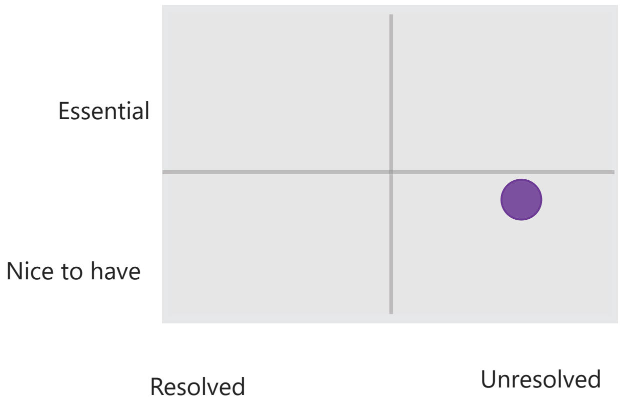




OtherMarkets	Alternatives	Showstoppers
Pressure vessels		

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

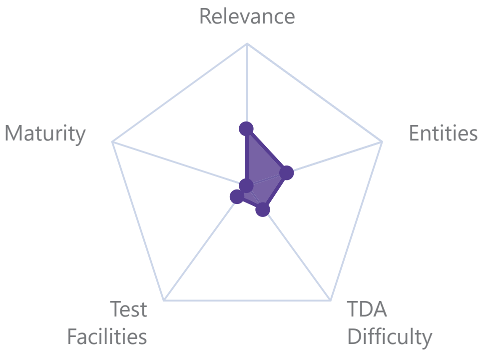
Private	Public
	CERN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop associated cryogenic amplification electronics	40 to 80%	250k to 1M	6 months to 2 years	Low	Partially

Magnets ❯ Instrumentation and auxiliary systems

Magnetic field mapping



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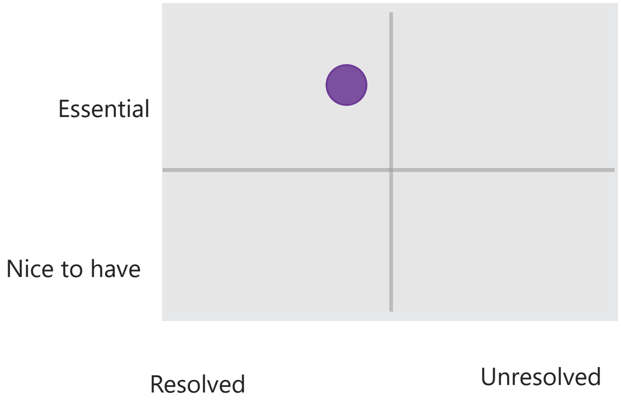


OtherMarkets	Alternatives	Showstoppers
Mass detection Medical Space Spectrometers		

Technology Characteristics

Test Facilities	Test Facility Function
	Calibration of Hall probes in high fields

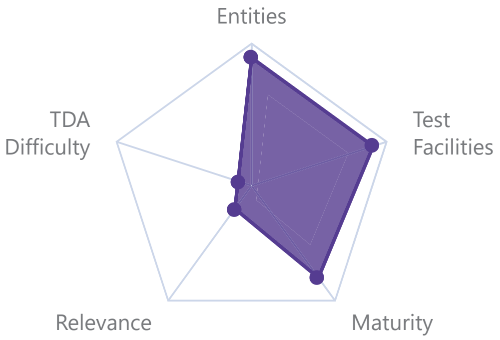
European Entities Involved

Private	Public
Sensis Innovent	PSI, CEA, CNRS

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop practical method for measuring magnetic field in large volume coils	40 to 80%	250k to 1M	6 months to 2 years	Low	No
Develop supply chain for high field cryo calibrated Hall probes	40 to 80%	250k to 1M	6 months to 2 years	Low	No

Persistent current switches



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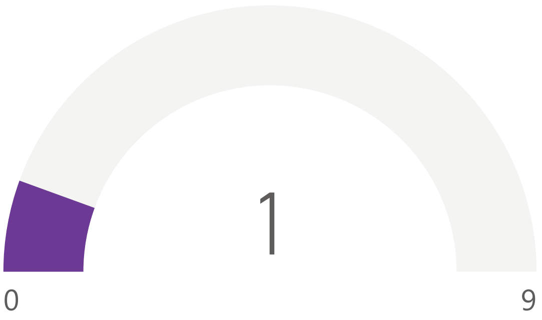
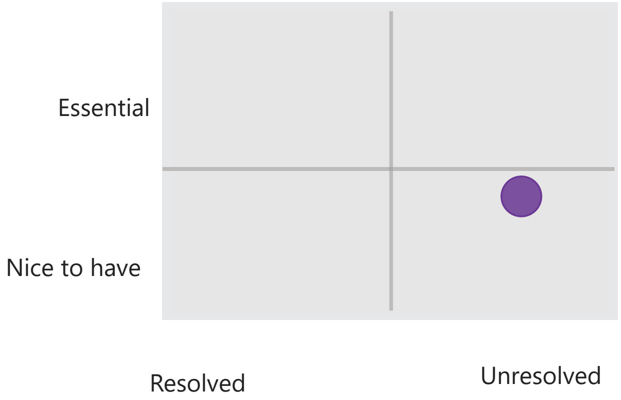




OtherMarkets	Alternatives	Showstoppers
Energy storage Mobility Medical NMR	Protection as per current state-of-the-art by room temperature circuit breakers	High demands to residual resistivity of the switch Strict demands for heat dissipation

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

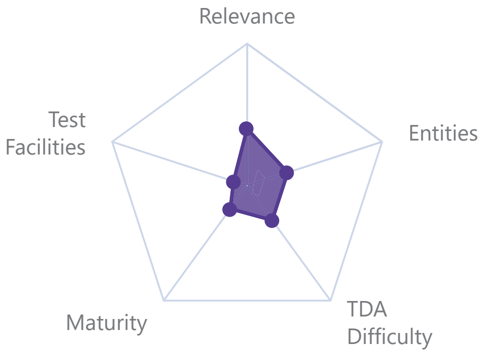
Private	Public
	EPFL-SPC

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop high current superconducting switches for magnets protection	40 to 80%	>1M	6 months to 2 years	Low	No

Magnets > Instrumentation and auxiliary systems

Power supplies



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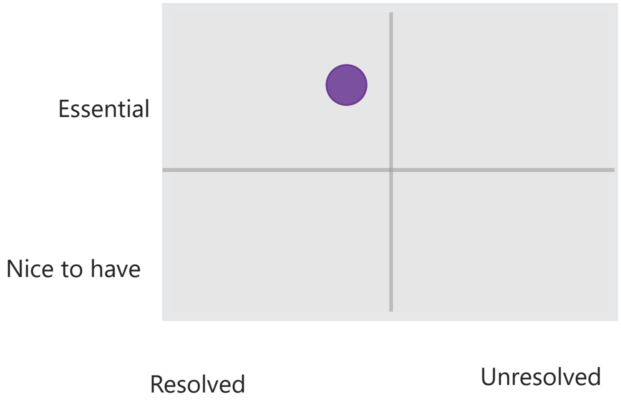


OtherMarkets	Alternatives	Showstoppers
Mobility		
Medical		
Space		
Data centres		
Metal production		
Defense		

Technology Characteristics

Test Facilities	Test Facility Function

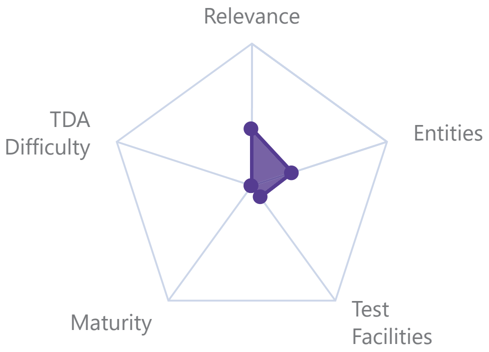
European Entities Involved

Private	Public
Ampegon, ABB, Tektronix	ITER, ENEA, CEA

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Formulate requirements which are applicable for future magnets	>80%	<250k	<6 months	Medium	No

Shimming coils



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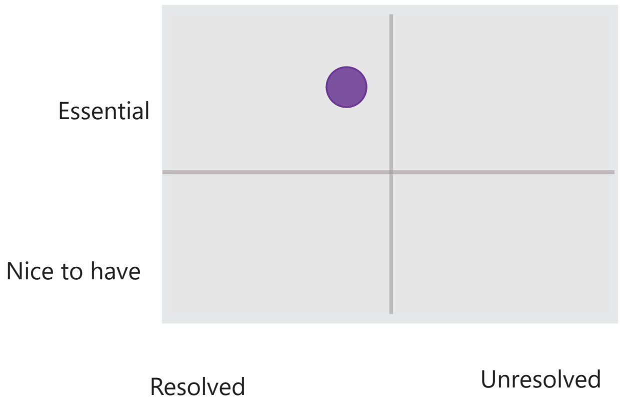


OtherMarkets	Alternatives	Showstoppers
Medical NMR		

Technology Characteristics

Test Facility Function

European Entities Involved

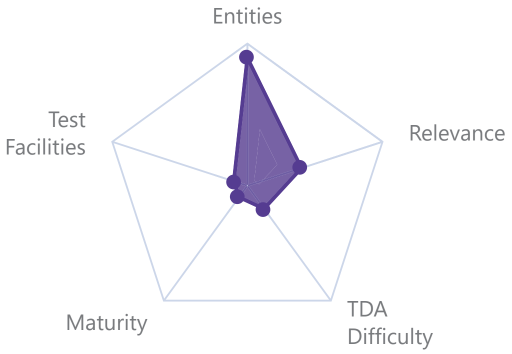
Private	Public
ASG, Many for MRI and NMR magnets	ITER, CERN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded

Magnets › Instrumentation and auxiliary systems

Voltage taps extraction



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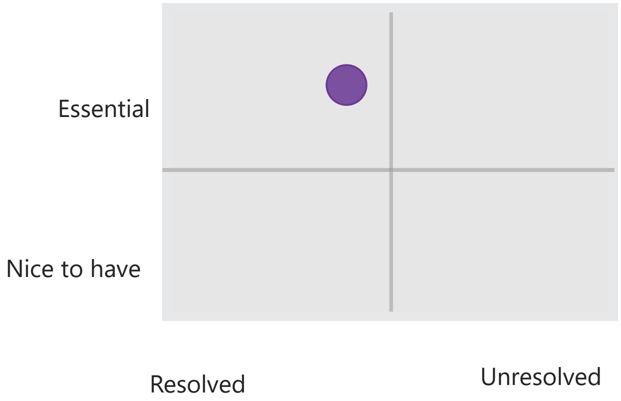

OtherMarkets	Alternatives	Showstoppers
Electrical systems	Optical fibres Thermocouple arrays	

Technology Characteristics

Test Facilities	Test Facility Function

European Entities Involved

Private	Public
	ITER, ENEA, DTT, CERN

Technology Development Actions

Name	Chances of success	Cost	Implementation Time	Priority	Funded
Develop reliable insulation methods for magnet penetrations	>80%	250k to 1M	6 months to 2 years	Medium	No
Develop industrial standard for HV extraction	>80%	<250k	6 months to 2 years	Low	No
Developing cold electronics for remote sensing	40 to 80%	250k to 1M	6 months to 2 years	Low	No

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