Superconductivity Global Alliance (ScGA)

for

Greener, Healthier, Prosperous and Sustainable Future

Special Session

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WG 6: Smart Discovery Science

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What is SMART Discovery Science?

We focus on two groups of applications that require **large-scale superconducting magnets and radio-frequency cavities**:

(1)“High field research” (condensed-matter physics, chemistry, and biology).

(2)“Particle Physics” (high energy, nuclear, and astro-physics).

Impact of Discovery Science - Examples

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Field	Device/Technology	Later Impact
High Energy Physics	The Internet was developed to allow scientists to share data.	A revolution in communications with major impact on reducing inequalities and all other UN Sustainable Development Goals.
High Energy Physics	NbTi wire was developed to the point to allow all colliders from the Tevatron to the LHC.	NbTi wire is now used in MRI magnets which have been a revolution in medicine.
Physics at High Field	Nb_3Sn wire was developed to allow for higher fields.	Nb_3Sn wire is now used mainly in NMR magnets that have been central to the pharmaceutical industry's development of dozens of drugs in recent decades. It is also used for fusion reactors such as KSTAR, ITER, DEMO, etc.
Nuclear Physics	Cyclotrons were developed to study exotic nuclei.	Cyclotrons have generated beams of particles to treat millions of cancer patients directly. Proton and ion therapy machines are now equipped with compact SC gantries. Cyclotrons enabled radiochemistry that is used to make some forms of chemotherapy for cancer.
Low Temperature Physics	REBCO tape was discovered.	REBCO tape is now seen as enabling tokamaks to provide sustainable electric power.
Nuclear Physics	Accelerator-Driven Nuclear Reactors	These could be used both to control nuclear fission, an energy source that can be implemented on a large scale that does not require fossil fuels, as well as to burn the long-lived nuclear ashes, reducing them to shorter-term decaying waste.

Impact of Discovery Science - MRI

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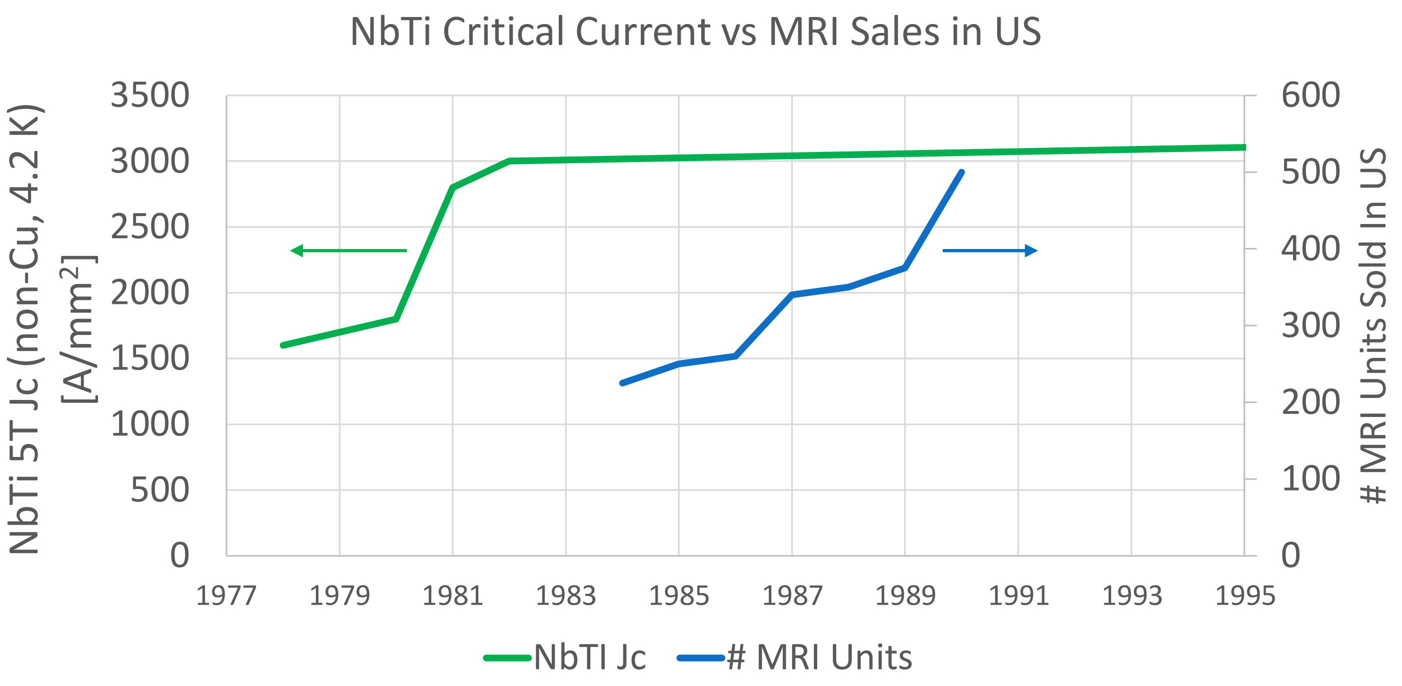
Increase in critical current of NbTi superconducting wire and subsequent sales of MRI machines in the US



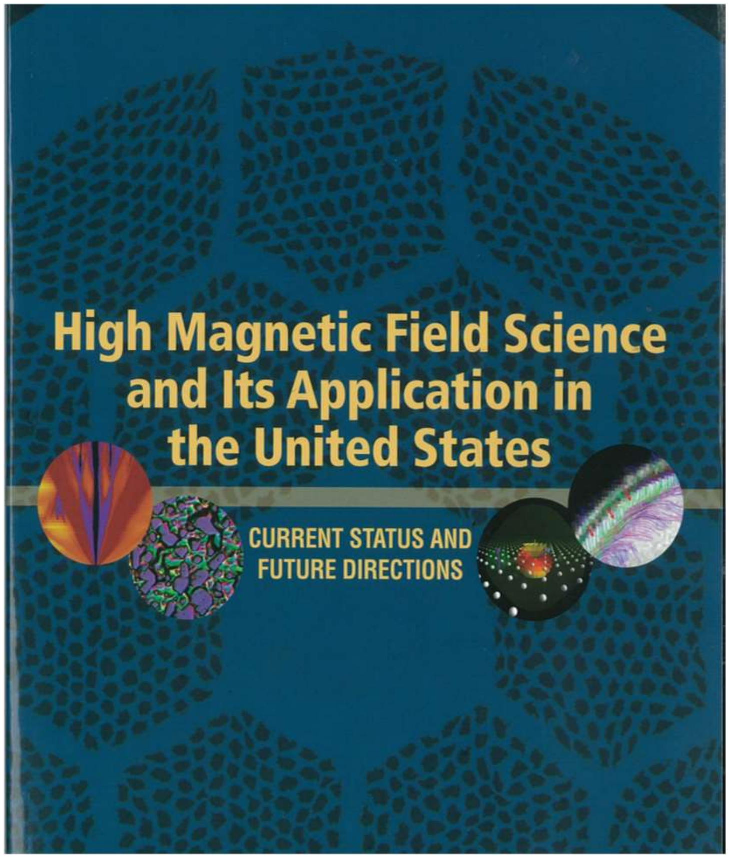
The Discovery Science Community not only discovered NbTi superconductor, but it provided the funding and assumed the risk associated with developing it to the point that commercial MRI magnets became feasible.

MRI magnets have revolutionized medicine.

Grand Challenges – High Fields

The US National Academy of Science appointed a committee to “Assess the Current Status and Future Direction of High Magnetic Field Science in the United States”

The “MagSci” Report was published in 2013


High Magnetic Field Science and Its Application in the United States
CURRENT STATUS AND FUTURE DIRECTIONS

Type	Recommendations
Pulsed	150, msec
	40 T, 30 s rep rate, neutrons or x-rays
Res/SC Hybrid	25 - 35 T for neutrons or x-rays
	60 T
NMR	1.3 GHz – 1.6 GHz (30.5 T – 37.6 T)
SC	Regional 32 T facilities
	40 T
	40 T for neutrons or x-rays
	20 T large animal & human MRI

A newer committee on this subject released a similar “pre-publication” version of their report in August 2024.

Grand Challenges – Particle Physics

In 2021 the European Laboratory Directors' Group published an Accelerator R&D Roadmap to meet the goals laid out previously by the 2020 European Strategy for Particle Physics.

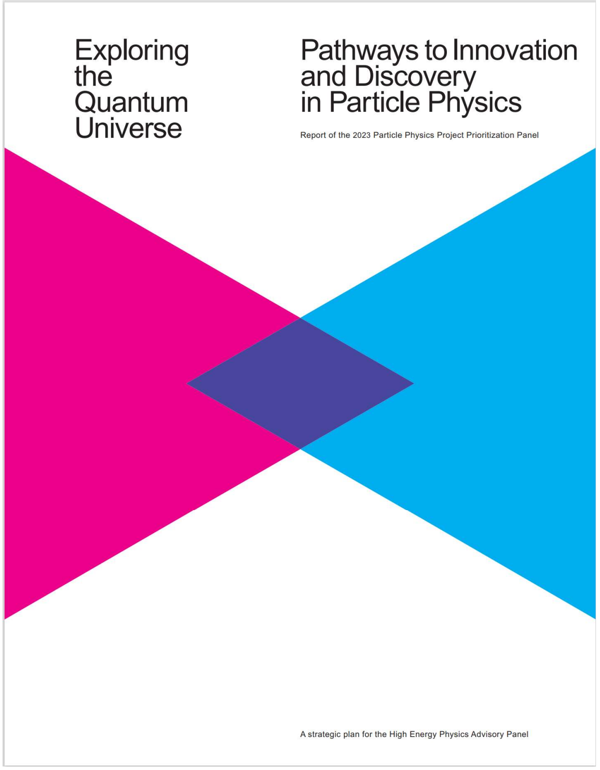
CERN-2022-001

EUROPEAN STRATEGY FOR PARTICLE PHYSICS

Accelerator R&D Roadmap

European Strategy Update

LDG Laboratory Directors Group



Exploring
the
Quantum
Universe

Pathways to Innovation
and Discovery
in Particle Physics

Report of the 2023 Particle Physics Project Prioritization Panel

A strategic plan for the High Energy Physics Advisory Panel

In 2023 the US Particle Physics Project Prioritization Panel (P5) published "Pathways to Innovation and Discovery in Particle Phaysics"

Discovery Science Grand Challenges - Goals

A number of Grand Challenges for Discovery Science that require superconductivity have been identified by organizations worldwide

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AREA	Challenge	Goal or Justification
High-Magnetic Field Research	40 T SC Magnet	A lower noise environment and longer hold times than present resistive magnets should enable discoveries in high-temperature superconductivity, re-entrant superconductivity, non-abelian quasiparticles, topological materials in the extreme quantum limit, among others. Exploring quantum critical points is one of several research frontiers requiring higher dc fields than are presently available.
	60 T Hybrid Magnet	
	>20 T cryogen-free magnets	The rising cost of helium is an obstacle to most researchers worldwide, particularly in less affluent environments. These magnets will therefore democratize participation in basic research.
High-Energy Particle Physics	20 T Dipole Magnets	Next generation colliders will require higher field dipole magnets and higher gradient rf cavities to reach the energies needed for an electron-positron Higgs factories and future hadron colliders.
	SC RF cavities	
	20 T Large bore solenoid for muon capture	A muon collider appears to be the most effective means of reaching 100 TeV collisions which are required to reach physics beyond the standard model.
	40 T SC for muon cooling	
Nuclear Physics	10 T, 100 cm bore magnet for Axion Detector	~27% of the universe is believed to be dark matter. The Axion is a leading candidate to explain the "missing mass". Different combinations of field and bore are needed to search different mass ranges using different resonator technologies.
	30 T, 15 cm bore magnet Axion Detector	
	SC RF cavities	Higher gradient rf cavities will enable an expansion of our understanding of the stability of atomic nuclei.

Discovery Science Grand Challenges – Technology Readiness

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AREA	Challenge	Technology Readiness
High-Magnetic Field Research	40 T SC Magnet	SC magnets >30 T are under development at a number of (high field) labs. Tremendous progress is being made in appropriate technology for 40 T user magnets.
	60 T Hybrid Magnet	A 60 T hybrid will require HTS technology on a scale similar to what is being developed for fusion, where tremendous progress is underway with private funding.
	>20 T cryogen-free magnets	Cryogen-free technology is routine for magnet up to ~15 T. Higher field system will emerge as HTS magnets become cost-effective for this market.
High-Energy Particle Physics	20 T Dipole Magnets	HEP is making major investments in multiple technologies with both REBCO and Bi-2212 conductor.
	SC RF cavities	Multiple groups at HEP laboratories and academic institutions gradients exceeding 20 MV/m. Advancements in material structure, heat treatments, surface polishing, clean-room preparation, and diagnostics. Nb3Sn and REBCO are being explored.
	20 T Large bore solenoid for muon capture	The fusion community is developing magnets with similar field and bore. HEP is starting to consider requirements for a muon collider.
	40 T SC for muon cooling	CERN has initiated a design study that has identified a new approach not previously employed by the high field labs. It will require R&D.
Nuclear Physics	10 T, 100 cm bore magnet for Axion Detector	Magnets of this field and bore have been built for MRI. At least one is being re-purposed for axion detection.
	30 T, 15 cm bore magnet Axion Detector	This goal can nearly be reached by removing the innermost coil from the 40 T, 3 cm bore High Field magnet.
	SC RF cavities	See above.

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Discovery Science Strategic Roadmap

(All timelines are best-case scenarios with estimated durations after receipt of funding)

AREA	GOALS	4 years	7 years	10 years
High-Magnetic Field Research	40 T SC Magnet	Design	Construction	Operation
	60 T Hybrid Magnet	Conceptual Design	Preliminary Design	
	High field cryogen free magnets	HTS magnets >20T	Cryogen-free HTS magnets >20T	
High-Energy Particle Physics	20 T Dipole Magnets	Design	Short prototype	Long prototype
	SC RF cavities		Operational at high gradients	High gradient at high frequencies
	20 T Large bore solenoid for muons	Design and Tests	Prototype	Integrated Coil
	40 T SC for muons	Design and Tests	Prototype	Integrated Prototype
Nuclear Physics	10 T Axion Detector	Design	Prototype	Integrated Prototype
	30 T Axion Detector	Design	Construction	Construction

Partnerships & Consortia

AREA	Facilities	Research Projects
High Energy Physics	State-of-the-art accelerators are highly centralized: CERN and few others worldwide. New facilities frequently require CERN to collaborate with US DOE and other partners.	Hundreds of researchers might collaborate on a single experiment.
Nuclear Physics	Multiple facilities exist in the USA, Europe, Asia. New facilities are developed at different labs.	Dozens of researchers may collaborate on an experiment.
High-Magnetic Field Research	Much research is conducted in University-based labs which support one or a few research groups. National facilities exist in the USA, France, The Netherlands, Germany, China, and Japan. The European labs coordinate activities via the European Magnetic Field Lab. New facilities are typically developed by individual national labs.	Experiments frequently involve a single principal investigator accompanied by their graduate students and/or postdoctoral assistants.

Partnerships & Consortia

AREA	Partnerships & Consortia
Particle Physics	State-of-the-art accelerators are so costly hundreds or even thousands of researchers must share the LHC at CERN. CERN itself represents a collaboration of 23 countries. Each experiment at CERN typically involves dozens of researchers from various institutions. As a result, CERN plays a crucial role in advancing the development of next-generation accelerators. Given the immense size and expense of these machines, CERN collaborates with other institutions, including US Department of Energy (DOE) labs, to develop advanced magnets for upgrades and future accelerators.
High-Magnetic Field Research	experiments and instruments are significantly smaller in scale compared to those in high energy physics. Researchers often work more independently, with many operating high field magnets up to around 15 T in their university laboratories. For experiments requiring even higher fields, they applied for access and travel to specialized high magnetic field facilities located around the world—such as those in Tallahassee, Hefei, Grenoble, Nijmegen and Sendai. In Europe, scientists benefit of large experimental expertise across four different high-magnetic field laboratories as part of the European High Magnetic Field Laboratory (EMFL) [13]. The high-field experiments frequently involve a single principal investigator accompanied by their research team (graduate students or postdoctoral assistants), a much smaller scale compared to the large collaborative efforts seen in high energy physics.

Summary

- SMART Discovery Science is **the** prime motor for advancing superconductivity and superconducting technologies. Its role has been demonstrated and recognized. SMART Discovery Science
  - discovers basic concepts and materials
  - develops the technology, and assumes the associated risk, to the point that commercial applications become feasible, and low-risk.
- Present demands are mainly on HTS materials (REBCO, BSCCO and further): homogeneity and isotropy, mechanical resilience and quench management
- Moving discoveries from the lab to the factory and into the economy and society requires highly skilled and knowledgeable personnel. The scientific community creates this workforce via education and training.

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