IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), January, 2023.
This presentation was given at EFATS 2022, August 30-31, 2022.

Superconducting Technologies for Cleaner and Sustainable Future

Ziad Melhem
Oxford Quantum Solutions Ltd,
Oxford, UK

2nd EFATS, Glasgow, Scotland, UK

31st Aug 2022

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The challenge

Global Environmental Challenges


Europe 15th July 2021


California 18th July 2021


UAE 17th July 2021

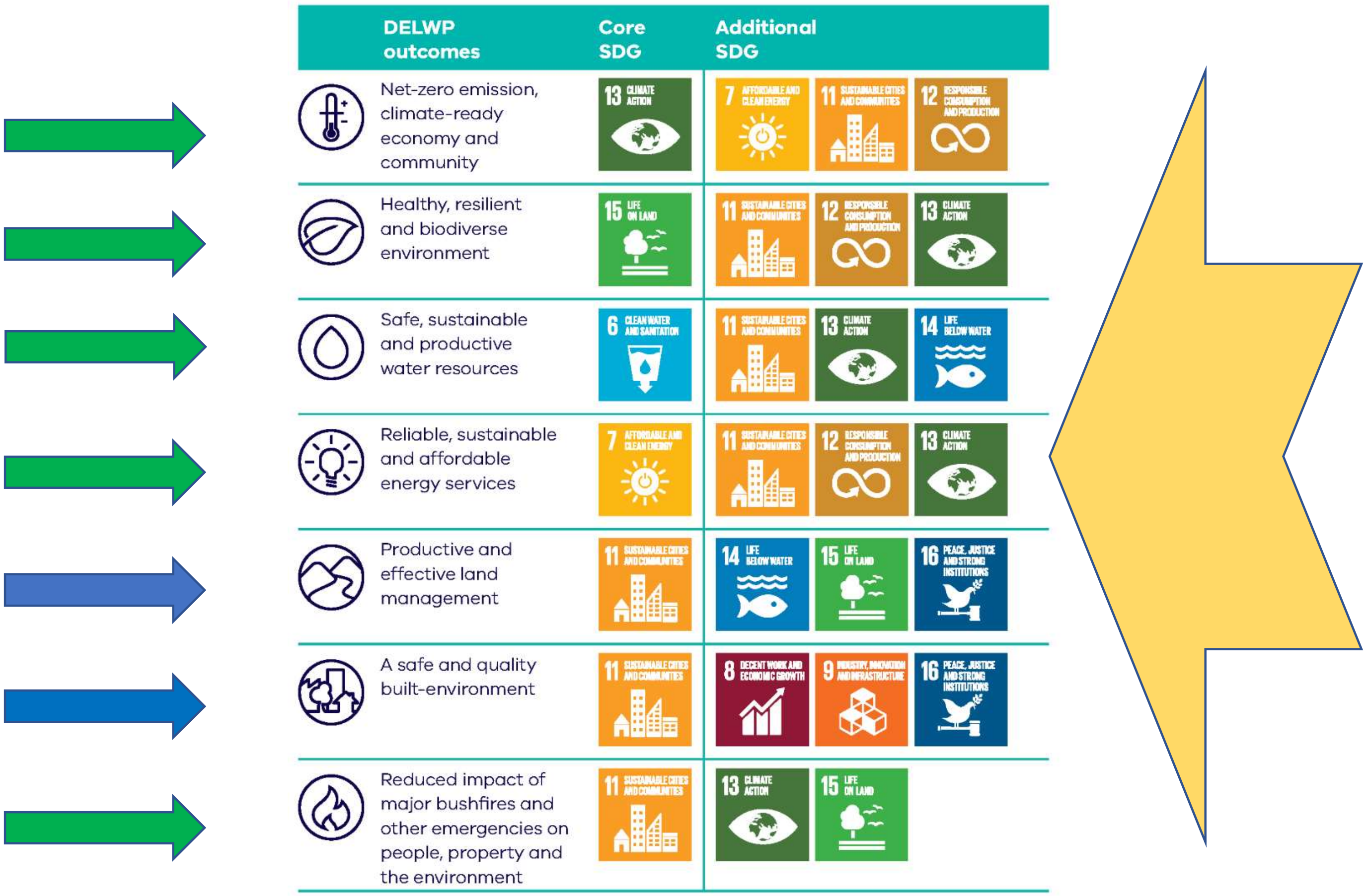
Greenland 2021 - melting
6 X times faster than 1990

Antarctica Icebergs
melting fast!

Key takeaw Need new innovations!....
Superconducting materials and technologies can and will help

UN Sustainable Development Goals – 17 in total

Superconducting Technologies and the SDG goals



DELWP outcomes	Core SDG	Additional SDG		
Net-zero emission, climate-ready economy and community	13 CLIMATE ACTION	7 AFFORDABLE AND CLEAN ENERGY	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION
Healthy, resilient and biodiverse environment	15 LIFE ON LAND	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION
Safe, sustainable and productive water resources	6 CLEAN WATER AND SANITATION	11 SUSTAINABLE CITIES AND COMMUNITIES	13 CLIMATE ACTION	14 LIFE BELOW WATER
Reliable, sustainable and affordable energy services	7 AFFORDABLE AND CLEAN ENERGY	11 SUSTAINABLE CITIES AND COMMUNITIES	12 RESPONSIBLE CONSUMPTION AND PRODUCTION	13 CLIMATE ACTION
Productive and effective land management	11 SUSTAINABLE CITIES AND COMMUNITIES	14 LIFE BELOW WATER	15 LIFE ON LAND	16 PEACE, JUSTICE AND STRONG INSTITUTIONS
A safe and quality built-environment	11 SUSTAINABLE CITIES AND COMMUNITIES	8 DECENT WORK AND ECONOMIC GROWTH	9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	16 PEACE, JUSTICE AND STRONG INSTITUTIONS
Reduced impact of major bushfires and other emergencies on people, property and the environment	11 SUSTAINABLE CITIES AND COMMUNITIES	13 CLIMATE ACTION	15 LIFE ON LAND	

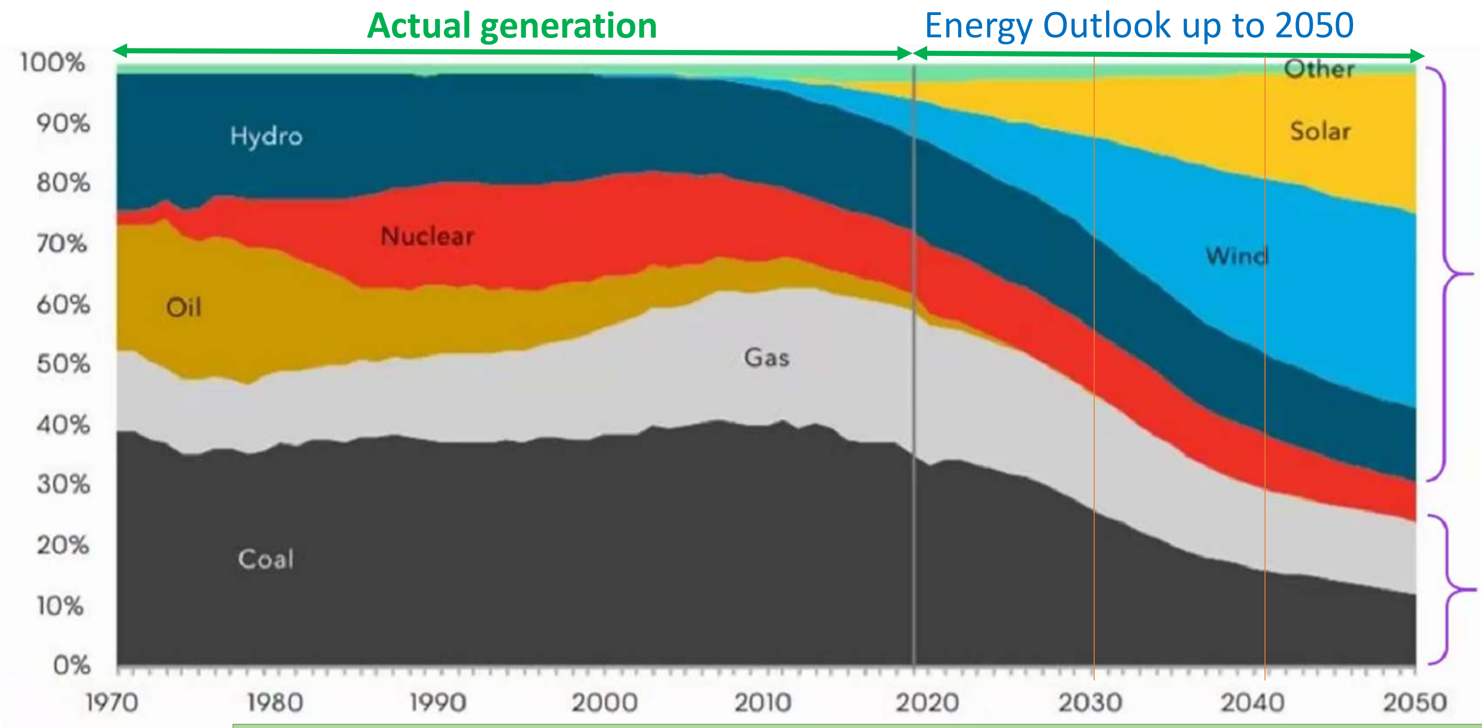
SC for
Energy generation &
power management

SC for
Medical diagnostics ,
medical treatment
And drug discovery

SC for
Digital age

Estimated Global Electricity Generation Mix

New Energy Outlook 2020 report by Bloomberg (2020)



Renewables
- 2020: 38%
- 2030:53%
- 2040:60%
- 2050: 70%

Fossil (Target for Clean energy like Fusion)
- 2020: 62%
- 2030:47%
- 2040:40%
- 2050: 30%

Key takeaway
- Estimated investment in Electricity generation ~ $20 Trillion by 2050
- ~ 30% generation by Fossil fuels equivalent to $ 6.6 Trillion
  - Potential addressable market for Fusion VERY LARGE !

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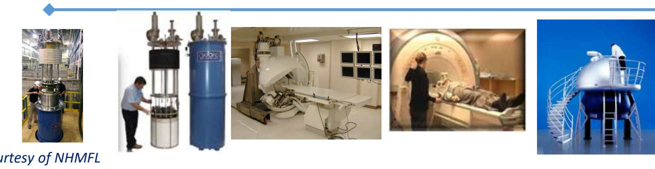
Overview

Innovation in Superconducting applications

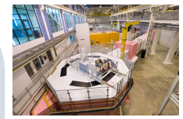
Oxford Quantum Solutions



Courtesy of NHMFL

Research & Medical Magnets

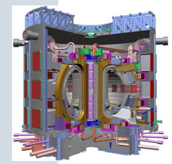
- Medical- MRI, NMR , Proton Bean Therapy
- Basic Research- Physical sciences RM
- HEP- Beamlines/Accelerates/ Detectors
- Fusion – LTS & HTS
  - UHF >25T (LTS+HTS)
  - 5T-20T >20K (HTS)
  - Bench Top Applications (LTS+HTS)
    - 0.5-5T >20K-77K



Courtesy of ISIS

Courtesy of TE Courtesy of CERN

Courtesy of Varian



Courtesy of ITER

Industrial applications

- Non-destructive Testing
- Inductive Heaters
- Magnetic separation
- Crystal Growth

Superconducting (SC) Applications

Power & Energy Applications

- Fault Current Limiters (FCL)
- Transmission Cables
- SC Magnet Energy Storage
- Generators (Wind/Utility)
- Transformers
- Motors
- Synchronous Condensers

Courtesy of Envison

Courtesy of AMSC

Courtesy of Nexans

Courtesy of Dwave

Microelectronics

- Quantum Computing
- Faster Computers
- Power Electronics

QMICS Cryolink @ 35 mK for SC cable
Courtesy of Oxford Instruments and WMI

Communications

- Satellite channels
- Wireless devices
- Antennae

Defence & Security

- Detectors/Sensors
- Rail gun
- Degaussing cables

Transportation

- Electric planes
- Maglev
- Ships
- Rocket propulsion

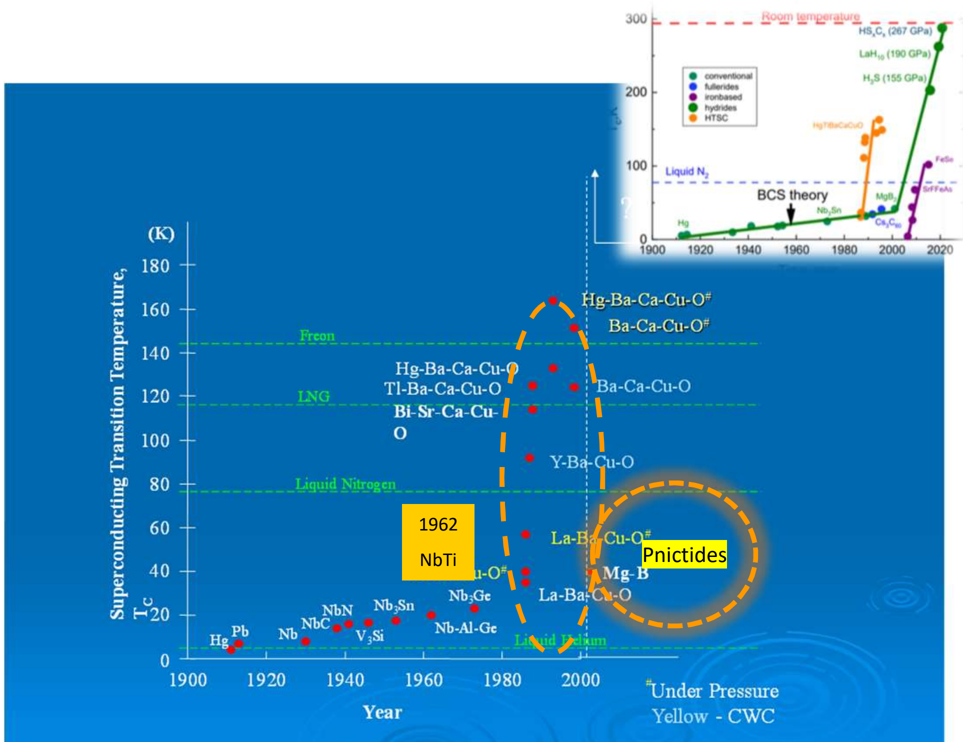
Chuo Shinkansen Maglev train

NASA N3-X

Superconducting materials

From Nanomaterials to SC materials for applications

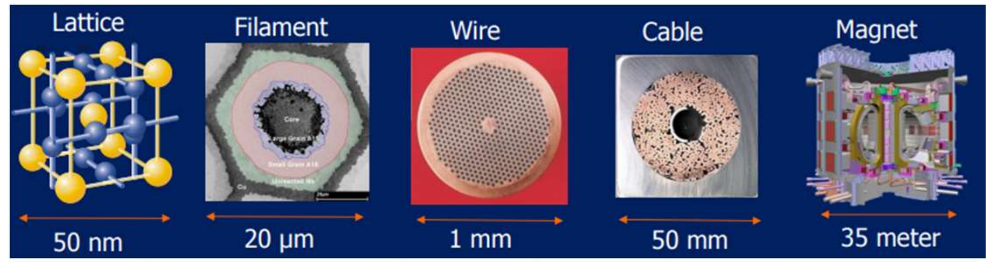
Oxford Quantum Solutions



Key takeaway –

- LTS wires are the dominant material for SC applications (MRI, NMR, HEP, RM).
- HTS introduction will extend SC use and lead to new applications @ 20-77 K
- Reducing cost of HTS is critical for commercial applications

Science → Processing → Wires for small scale applications → Cables for large scale applications → Large scale applications



	NbTi	Nb_3Sn	MgB_2	$Bi_2Sr_2CaCu_2O_8$ (Bi-2212)	$Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223)	$YBa_2Cu_3O_7$ (ReBCO)
T_c (K)	10	18.5	39	95K	110	92
B_{max} (T)	9.5 @4.2 K 11.5 @1.8 K	20 @ 4.2 K 23 @2 K	5-10 @4.2K 2-5 @10 K	>40 @4.2K 8 @ 20 K 4 @65 K	>40 @4.2K 8 @ 20 K 4 @65 K	>40 @4.2K 20 @ 20 K 8 @ 65 K
Material type	Ductile metal alloy	Brittle inter-metallic	Brittle inter-metallic	Ceramic oxide	Ceramic oxide	Ceramic oxide
Conductor shape		Multi-filamentary Rnd wire	Multi-filamentary Rnd wire	Multi-filamentary Rnd wire, flat tape	Multi-filamentary flat tape	Thin film coated conductor
Production Supply	Mature	Mature	Prototype-R&D	Prototype-R&D	Prototype-R&D	Prototype-R&D

Opportunities

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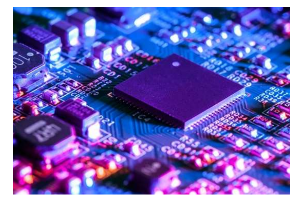
Expected Emerging SC markets by 2030

- Fusion
- Electric planes
- SC magnetic storage
- Renewables
- Compact and portable HF magnet systems for Physical and Life Sciences
- SC quantum computing
- Superconducting Electronics
- Medical diagnostics and therapy
- Industrial
- Transport

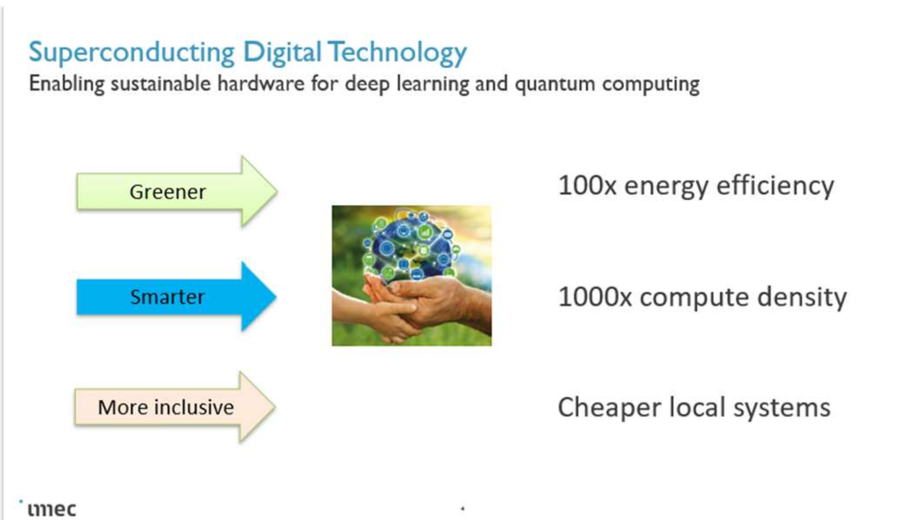







Quantum Computing – Superconducting Qubits

> 10 B $ commitment over the last 2 years

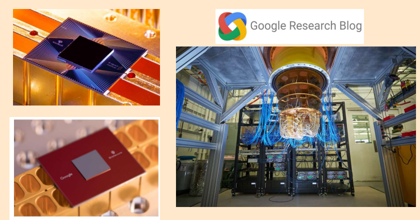


Key takeaway –

- Superconductivity critical for the digital aged based solutions
- SC qubits leading the way towards Quantum computers and embraced by big industrials

Google unveiled the world's largest quantum computer processor to date

- Dubbed **Bristlecone**, it's a **72-qubit** gate-based superconducting system

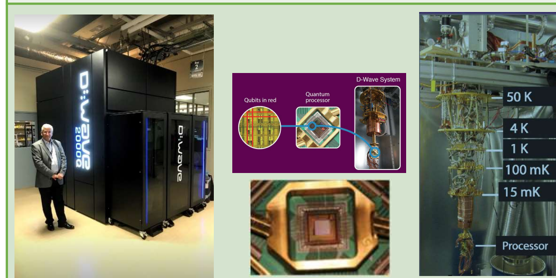


IBM demonstrated a 127 Qubit Quantum Computer

- **Already providing users with 20 Qubit comp**

The D-Wave 2X system implements a quantum annealing algorithm

- D-Wave systems are being used, for example, by Lockheed Martin, Google, NASA, & the University of Southern California.

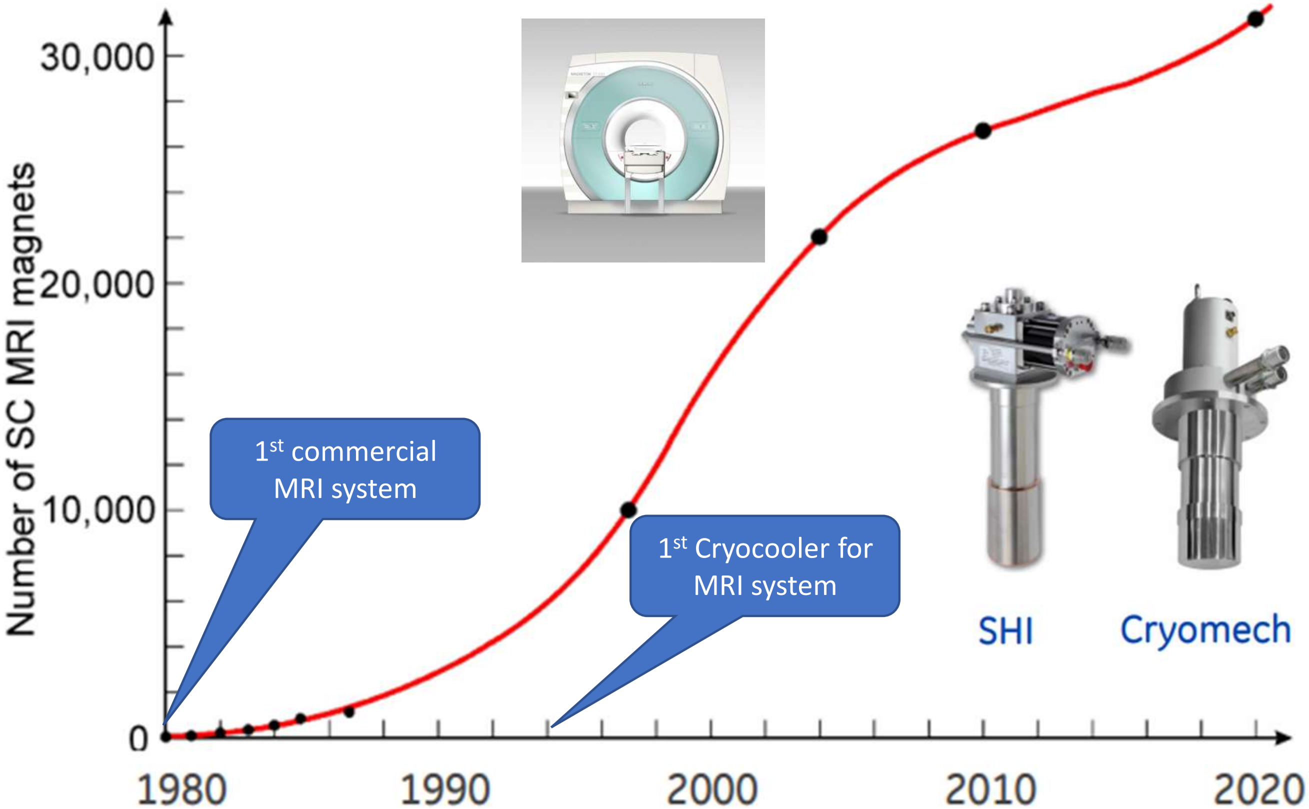


With 1000 qubits, the D-Wave 2X system can search through 2^{1000} possible solutions

Superconducting Qubit Devices

- **Commercial Leaders:**
  D-Wave, IBM, Google, Rigetti, Quantum Circuits Inc, Intel and others
- **Academic Leaders:**
  UCSB, UC Berkley, Yale, ETH Zurich, TU Delft, MIT, and others

MRI is a large volume production business- Led to new standard in Wire Supply, Cryogenics and Instrumentation



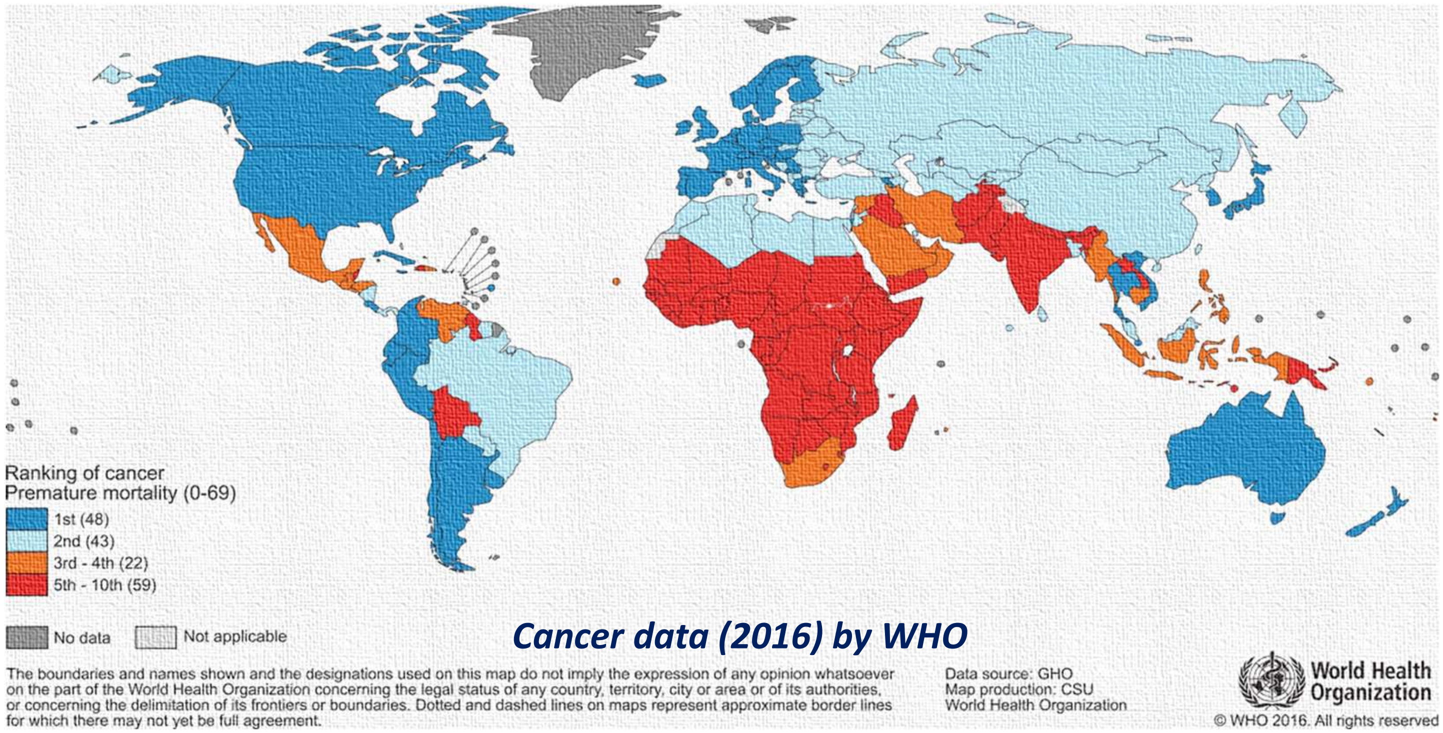
> 36,000 4 K GM SHI cryocoolers delivered, since 1995

Key takeaway:
MRI scale up led to significant enhancement in:
- NbTi wire supply
- Cost effective NbTi wire
- Cryogenics management
- New cryogen free enabling technologies
- Good example of SC use for commercial products

W Stautner IWC-HTS, 10/14-16/2015, Matsue, Japan
file:///C:/Users/melhe/Downloads/IWC-HTSPlenarytalk1version9.pdf

SC – Accelerators for cancer treatment

- > 19 million new cancer cases in the world (2020)
  - >4M in Europe
  - The probability to develop (die of) cancer <75 y old in Europe is ~28% (12%)
- By 2040, expected 27.5 M new cases and 16.3 M deaths, simply due to the growth of the population and increasing life expectancy
- 1st cause of mortality in higher income countries, 2nd cause of mortality worldwide



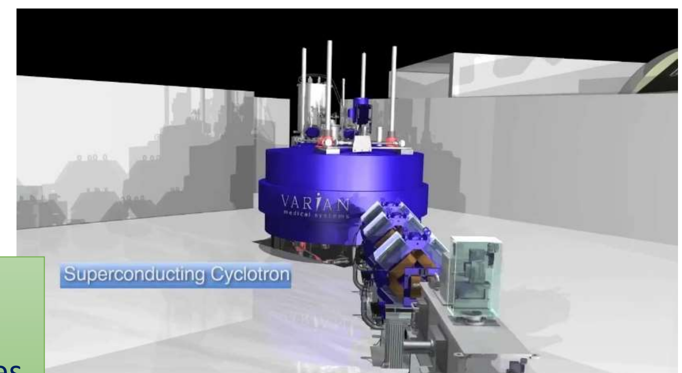
Cancer data (2016) by WHO

Key takeaway
Superconducting based solutions can and will help

Medical Therapy

Commercial accelerators for proton therapy: cyclotrons (by IBA and Varian/Accel) and synchrotrons (by Mitsubishi and Hitachi).

Oxford Quantum Solutions

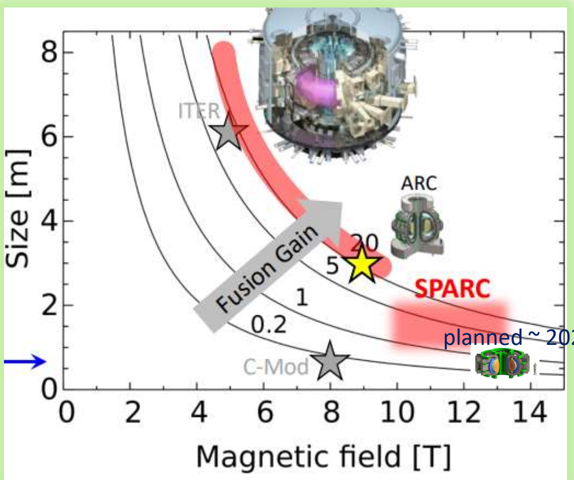


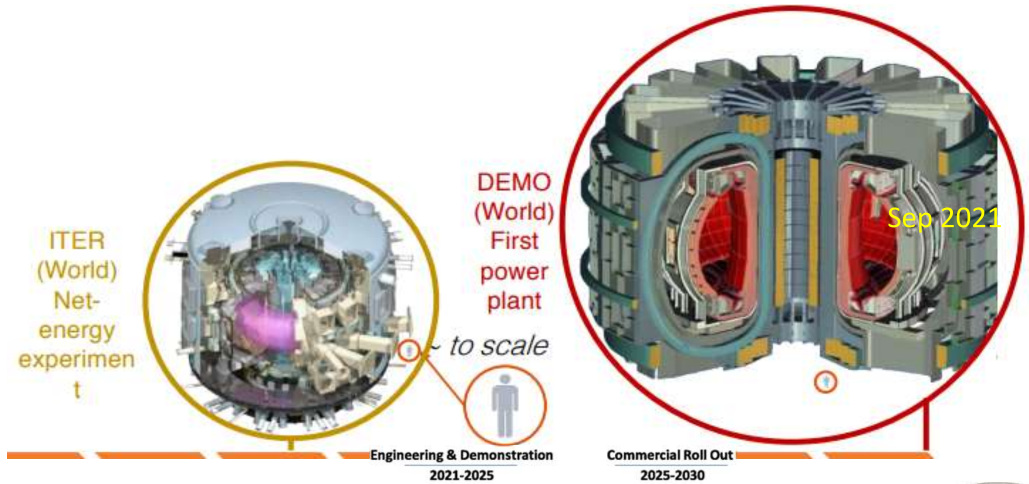
Key takeaway

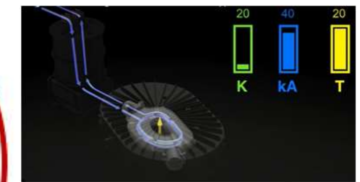
- Will provide step change in medical care and improve quality of life for so many
- Potential to be very large commercial market with high field and compact devices

Future fusion devices using HTS – Led by private funds

Source -Joseph V. Minervini Massachusetts Institute of Technology
Plasma Science and Fusion Center Cambridge, MA USA



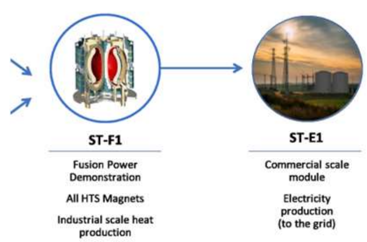


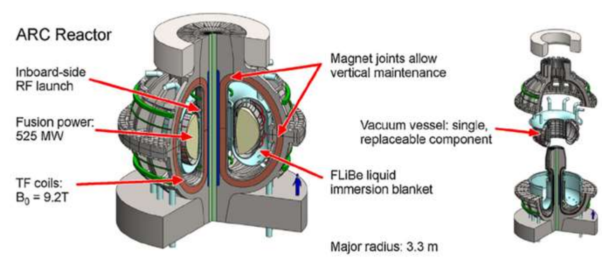


Key takeaway – HTS impact

Fast tracking development of new power stations

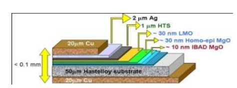
- Clean energy and environmentally friendly
- Safe power generation
- Potential for smaller fusion power devices





https://indico.cern.ch/event/775529/contributions/3309887/attachments/1828600/2993908/Minervini_HTS-for-Fusion-WAMHTS-5.pdf

tokamak energy
a faster way to fusion

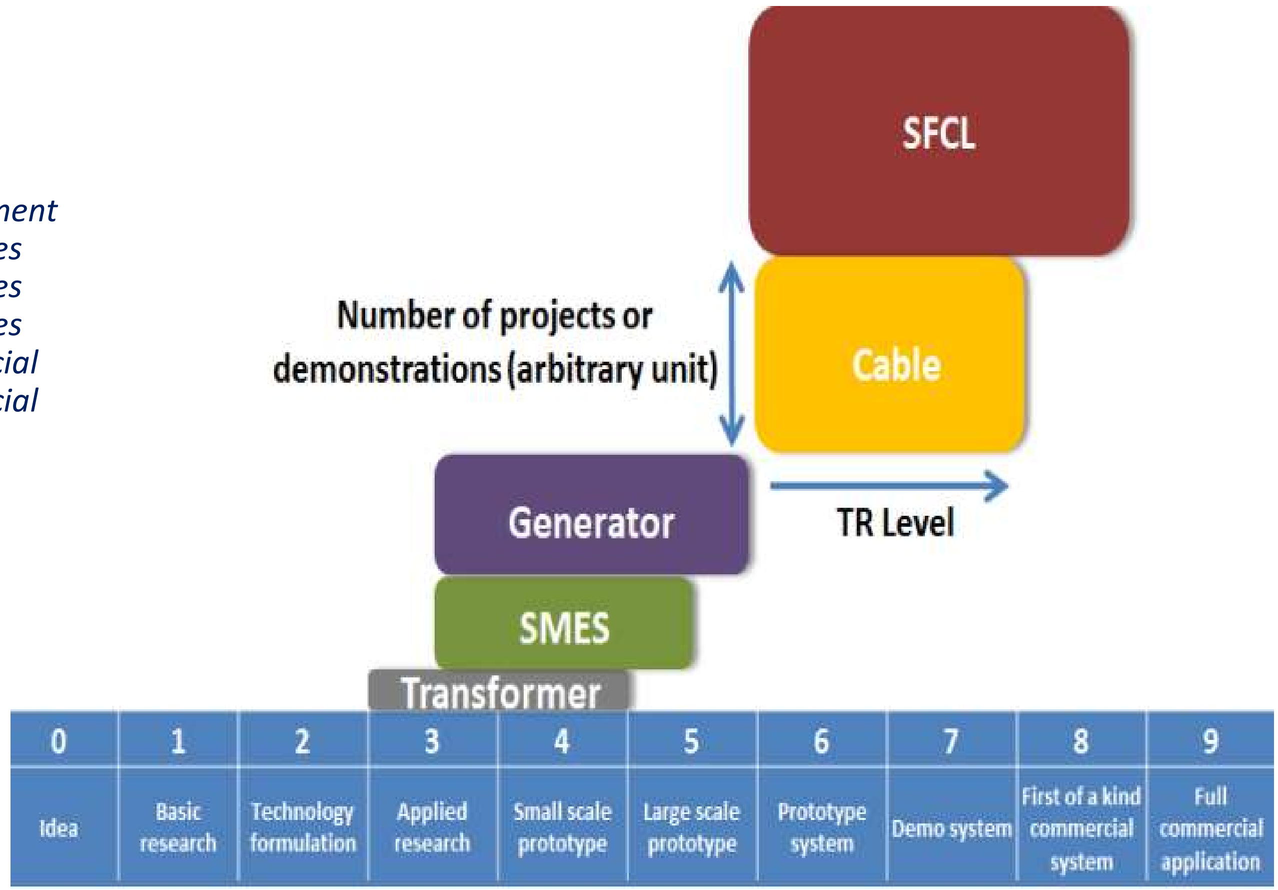


Commonwealth Fusion Systems , MIT

https://www.vtt.fi/sites/finnfusion2018/Documents/3-02%20Salmi%20Tokamak%20Energy.pdf

Power applications - Technology Readiness Level (TRL)

1. *Transformers* -*Development*
2. *Generators* -*Prototypes*
3. *Rotator for Wind Farms* -*Prototypes*
4. *SMES* -*Prototypes*
5. *SFCL* -*Commercial*
6. *Transmission lines* -*Commercial*



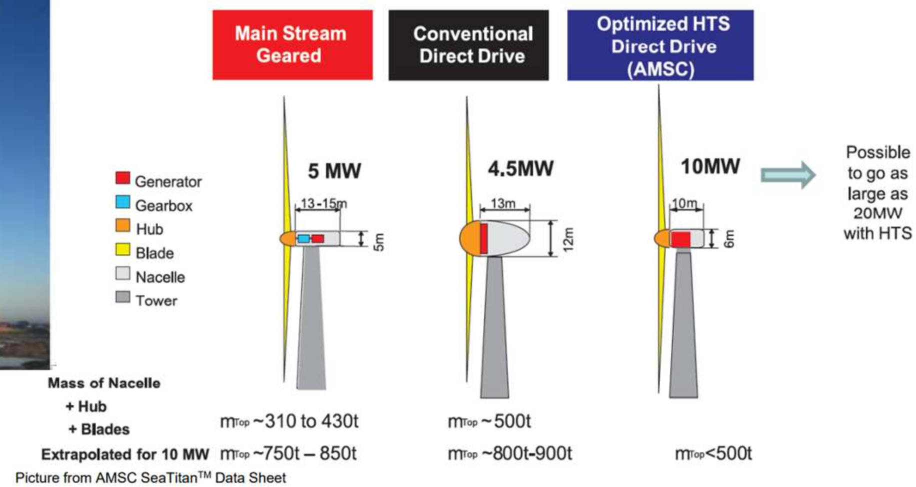
Key takeaway
- HTS cables and SFCL are > TRL 6 and available as a commercial products
- SMES and Generators are next to be commercialised

ecoswing – SC wind power generation

Oxford Quantum Solutions

- HTS Conductor
- All roads capability
- Low cost design
- Low weight design
- Mainstream markets
  - 3.6 MW for onshore and off-shore.
- Cryostat system integration
- Cryogen free for cooling

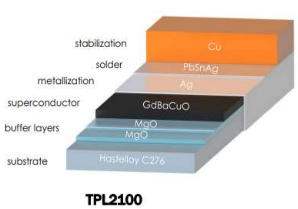
Horizon 2020
European Union Funding
for Research & Innovation

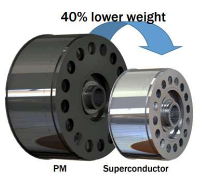


Source - Prof. M Noe- HTS Power Applications - _CERN [Microsoft PowerPoint - noe-hts power applications-2013-04-28 [Kompatibilitätsmodus] (cern.ch)]

Markus Bauer et al.
TUE-AF-OR17-05

THEVA





HTS wire with thick copper stabilization for superior electrical stability and high mechanical robustness

- 9 Partners from 5 countries working for a common goal

ENVISION, ECO5, JEUMONT Electric, DELTA, THEVA, SHI Cryogenics Group, Fraunhofer, UNIVERSITY OF TWENTE., DNV·GL

Key takeaway

- More MW power per footprint –
  - reduced in volume by 25%
  - Reduced weight by 40%
- HTS current density > 100 x Cu leading to HF and low energy loss
- Retrofitting existing infrastructure with enhanced generation

https://indico.cern.ch/event/445667/contributions/2558522/attachments/1521011/2376146/PI7-01_Kellers_EcoSwing_final_for_release.pdf

HTS transmission cables > 70

20 projects in the US/>20 Projects in the EU/>20 Projects in South Korea/> 10 Projects in China

Table 1: HTS Cable Projects in the United States

Project	Long Island 2	HYDRA Phase 2[1]	HYDRA Phase 3[2]	US Navy DC Cable
Location	Long Island, NY, USA	Yonkers, NY, USA	Chicago, IL, USA	Florida State University
Site	Holbrook Substation	Granite Hill–Rockview Substations	Chicago downtown area	Center for Advanced
Status	Abandoned[3]	Under construction at ConEd substation	Undergoing detailed feasibility assessment	Laboratory testing
Developer	AMS			
Utility/Host	LIPA			
In-Grid Start Date	NA			
End Date	LIPA c oper			
Type (AC or DC)	AC			
Phases	3			
Geometry	Coa			
Voltage	138			
Rated Current	240((Cab 800			
Length	600			
Fault Current	51 k (~14(			
Dielectric Design	Cold			
Dielectric Material	LPP			
HTS Material	YBC(			
HTS Conductor Supplier/Fabricator	AMS			
AC Loss	Not			
Cable Fabrication	Nexc			
Refrigeration	6 kW syster			

Table 3: HTS Cable Projects in Europe

Project	AmpaCity	BEST PATHS	St. Petersburg
Location	Essen, Germany	Germany and Switzerland	St. Petersburg, Russia
Site	Dellbruegge and Herkules Substations	Nexans, Hannover and CERN	Tsentralnaya and RP-9 Substations
Status	Operational	In design stage	Cable fabrication underway
Developer	Nexans, RWE Deutschland, and KIT[1]	See Note[2]	R&D Center of FGC UES[3]
Utility/Host	RWE Deutschland	Not applicable	FGC UES
Start Date	March 2014[4]	2015	Commercial operation in 2016
End Date	~ 2016		
Type	AC		
Phases	3		
Geometry	Tri-axial		
Voltage	10 kV		
Rated Current	2.3 kA (		
Length	1 km		
Fault Current	20 kA (		
Dielectric Design	Cold die		
Dielectric Material	LPP		
HTS Material	BSCCO		
HTS Conductor Supplier/Fabricator	Sumitom		
AC Loss	1 W/m		
Cable Fabrication	Nexans		
Refrigeration	4 kW @ (Messer)		

Table 5: HTS Cable Projects in Japan and South Korea

Project	Asahi	JeJu Island DC
Location	Yokohama, Japan	Jeju Island, South Korea
Site	Asahi Substation	GumAk–Hanlim Substations
Status	Completed initial test[1]	Operational
Developer	METI/NEDO/Sumitomo[2]	KEPCO/LS Cable/KERI
Utility/Host	TEPCO	KEPCO
Start Date	Oct. 30, 2012[3]	October 2014
End Date	Dec. 2013 (see note on Status)	2016
Type	AC	DC
Phases	3	1
Geometry	Triad	Coaxial DC
Voltage	66 kV	± 80 kV DC
Rated Current	5 kA (200 MVA)	3125 A DC
Length	240 m	500 m
Fault Current	31.5 kA_{rms} for 2 sec[4]	Not available
Dielectric Design	Cold dielectric	Cold dielectric
Dielectric Material	LPP	LPP
HTS Material	BSCCO	YBCO
HTS Conductor Supplier/Fabricator	Sumitomo	AMSC
AC Loss	0.9 W/m/phase @ 2 kA (50 Hz), 77 K	Not applicable
Cable Fabrication	Sumitomo	LS Cable
Refrigeration	6 kW @ 77 K. Closed-loop Stirling cycle, six machines (Mayekawa)[5]	Not available

Cable at Holbrook, Long Island USA, operational 2009

- 20 projects in the US
- >20 Projects in the EU
- >20 Projects in South Korea
- > 10 Projects in China

3002007192_Strategic Intelligence Update_ Superconductivity for Power Delivery Applications_ December 2015.pdf

MAGLEV with SC – Serious in Japan and China

Japan - 18 May 2011

- Japanese Government authorizes Central Japan Railway Co to proceed with high speed Maglev link from Tokyo to Osaka by 2045
- speed 580 kph

Japan - June 2015

- Chuo Shinkansen Maglev train Achieved 603 Kph (375 miles/hr) in Jun 2015
  - 1st phase complete by 2027 – Tokyo to Nagoya (40 min for 270 Km)
  - 2nd Phase by 2045 – Tokyo to Osaka (67 min hr for 500 Km)
  - Total cost ~ $55B
  - Using NbTi wire @4K

China - 2030

- Plans for two maglev lines to connect the south China province (Guangdong) with Beijing & Shanghai.
- The new maglev lines will cut travel time
  - Guangzhou to Shanghai to two and a half hours.
  - Guangzhou to Beijing will require just over three hours, halving current travel time by high-speed rail,

Key takeaway – Superconductors will have a significant impact on land transport and environment

Electric planes with SC – Selected examples

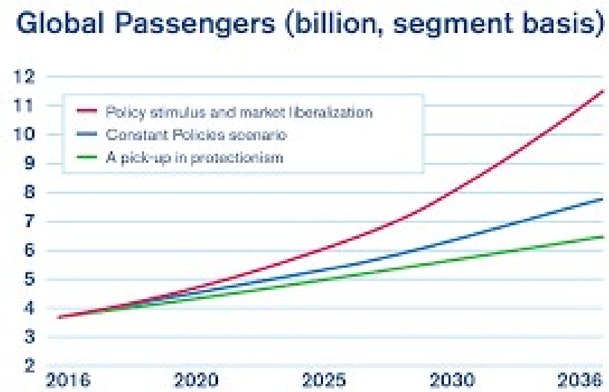
OQS Oxford Quantum Solutions

Fully Turbo-electric plane: NASA N3-X

- fuel burn reduction 70%, same range, speed, airport infrastructure.
- Technology: Hybrid Wing Body, **Fully distributed 50MW, Superconducting, 7500V, power system**

Partial Turboelectric

- Boeing SUGAR Freeze: fuel burn reduction **56% for 900 mile mission,** utilizes a truss-braced wing combined with a boundary-layer ingesting fan in an aft tail cone to maximize aerodynamic efficiency.
- The aft fan is powered by a **solid oxide fuel cell topping cycle** and driven by a **superconducting motor with a cryogenic power management system**



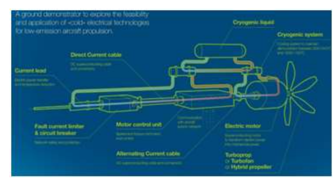
Empirical Systems Aerospace ECO–150R

- Matching and significantly exceeding current aircraft fuel burn.
- Technology considered ranges from **superconducting electrical machines cooled with liquid hydrogen** to conventional machines at various technology levels.

Airbus **A**dvanced **S**uperconducting & **C**ryogenic **E**xperimental powertrai**n** **D**emonstrator (ASCEND) project

Zero-Emission aircraft require

1. Energy storage,
2. Conversion from energy to propulsion - "ASCEND is focus"



https://www.flightglobal.com/aerospace/airbus-explores-cryogenic-superconducting-powertrain-for-electric-thrust/143097.article

Key takeaway – Serious effort to develop electric planes. Opportunities for National Facilities to speed up risk retirement

Superconductivity for the Future Initiative

Need new thinking on the role of Superconductivity in our future

SC Summit initiative - The Vision

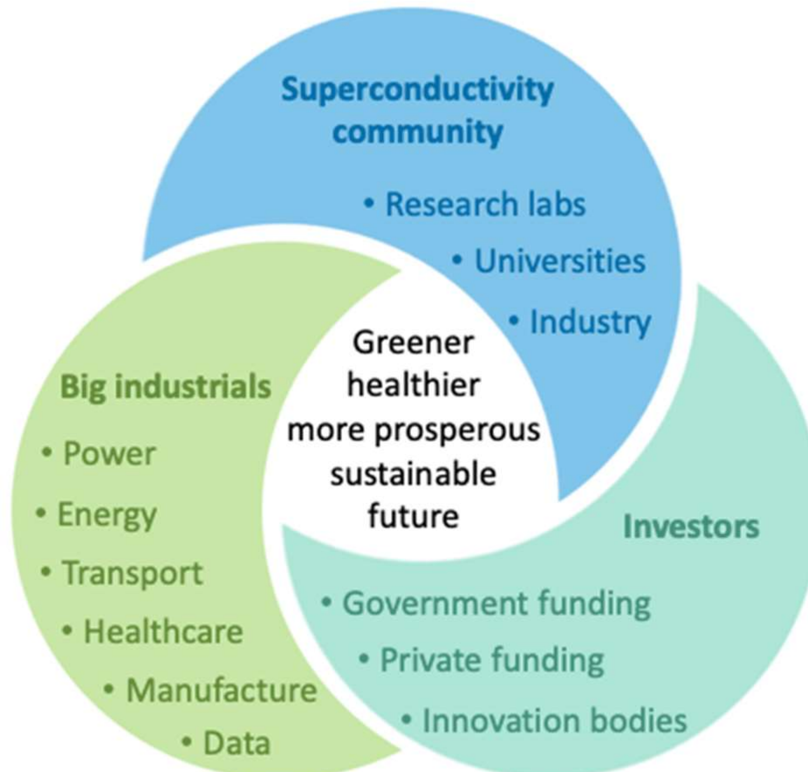
Superconductivity has already enabled major advances and capabilities such as MRI, NMR, high magnetic field research and high energy physics accelerators which otherwise would not be possible. In the future, superconductivity will provide a means towards zero emission targets, for example by enabling fusion power, expanding usage of wind power, and facilitating zero-emission transportation, as well as enabling new technologies such as superconducting classical and quantum computing, water purification, new medical diagnosis and therapy tools, and new scientific breakthrough

↓

Superconductivity from the Frontiers end to mainstream technologies

SC Summit initiative - The Proposal

- We wish to catalyse this process and fast-track development through an "Initiative for Superconductivity" towards a greener, healthier, prosperous, and sustainable future.
- We propose to hold a Superconductivity Summit at senior executive and decision-making level with the following objectives:
  - Develop and agree on a strategic roadmap for superconducting solutions and commercial products, including a concise list of grand challenges where SC can make a step change and significant impact. This will include:
    1. Define and found a collaboration partnership between the SC Science and industrial community, Government, Private Funding, and Big Industries.
    2. Develop an "Initiative" including funding on Superconductivity for the Future.
    3. Establish a mechanism for sustaining the development of commercial SC solutions and products linked to the 17 SDGs.
- International Organising Committee (IOC)
  Dr. Ziad Melhem, Dr. Joe Minervini, Dr. Luca Bottura, Prof. Susannah Speller, Prof. Lance Cooley, Prof. Venkat Selvamanickam, Prof. Stephen Gourlay, Dr. Anna Herr, Dr. Kathleen Amm



SCSI – Proposed Deliverables

- White paper on grand challenges
- Strategic roadmap for 10 years directly linked with the SDGs including potential funding required
- SCSI targets:
  - **Target 1-** Superconducting summit at senior level to facilitate the proposed partnership (2023)
  - **Target 2-** Request for national and private funding of the proposed grand challenges (2023)
  - **Target 3-** Develop partnership between the SC Community, national and Private funding and Big industrials (2023)
- Mechanisms for raising awareness of the potential from Superconductivity
  - Aim to present the SC initiative at selected International forums, e.g.
    - World economic forum – Davos (Jan 2024?)
    - COP28 (Nov 2023) , COP29(Nov 2024)
    - Doha Forum (Mar 2024 ?)
  - Establish regular communications channels
  - Focused market research on grand challenges
- Establish mechanism for sustaining the initiative

Proposed timeline for SCSI

Oxford Quantum Solutions

Pre March 2022
- Consultation with SC experts

17 May 2022 V-Mtg 1
- Launch the SCSI
- Setup of actions and framework for activities

17 Jun 2022 V-Mtg 2
- WGs setup
- Agree on next steps

Jun 2022 to 11 Jul 2022
- WGs prepare for SC Workshop in Oxford

11-12 July 2022
- SC Workshop in Person at Oxford University

30 Sep 2022
- Report and Notes from SC Workshop

15 Oct 2022
- First draft of strategic RMap from each WG
- Draft outline of the White paper/WG
- Shortlist list of stake holders

30 Oct 2022
- Review at ASC + Online status of the first draft of the Strategic Rmap
- Draft outline of the White paper/WG
- Reach out to stakeholders

30 Oct 2022
- Review at ASC Potential dates for the Summit
- Review timeline for the Strategic RMap and white papers

30 Nov 2022
- Finalise the Roadmap to enable drafting the first draft of the white paper for the Summit
- Reach out to stakeholders
- Informal contact with COP organisers

30 Jan 2023
- First draft of the white paper for selected grand challenges

Mar-Jun 2023 ?
- Review potential dates for the Summit
- Informal contact with DAVOS WEF organisers

Strategic Roadmap for 10 years – suggested format/coverage

Identify List of known Roadmaps/reports exist/ available and can be used as a basis for compiling a top level roadmap

WG Theme Ambition			
	4 years	7 Years	10 Years
Ambition #1			
Ambition #2 …			
WG Theme Materials needs			
	4 years	7 Years	10 Years
Need #1			
Need #2 …			

- WG Technology needs
- Cryogenic needs
- WG Instrumentation needs
- WG End-user needs
- WG supply chain needs
- WG skills/training needs
- WG Societal needs

- WG ecosystem needs
- WG Cost needs
- WG competitor technologies
- WG Funding needs
- WH partnership and consortia
- WG Impact statement
- WG Regulations and global agreements

SCSI Working Groups Convenors (10 in total)

Oxford Quantum Solutions

I. Applications		
1. Energy		
a. Fusion	Prof. Chris Grovenor University of Oxford / UK	Dr Neil Mitchell ITER – International/France
b. Renewables	Dr Michael Parizh GE Research / USA	Dr. Cristian Boffo Fermi laboratory /USA
c. Power transmission, distribution, and energy storage	Prof. Sastry Pamidi Florida University/ USA	Dr. Pascal TIXADOR CEA-CNRS/France
2. Healthcare	Dr. Kathleen Amm Brookhaven National Laboratory /USA	Dr. Joe Minervini MIT –USA

3. Electronics and quantum information processing	Prof. Giampiero Pepe ESAS/European/Italy	Dr. D Scott Holmes IEEE-CSC – International/USA
4. Science discovery		
a. HEP/Nuclear science	Dr Luca Bottura CERN International/Switzerland/ France	Dr Pierre Vedrine CEA/France
b. HF research & Astrophysics (Dark Matter)	Prof. Amalia Coldea/ University of Oxford/UK John BURGOYNE Oxford Instruments/UK	Dr. Mark Bird NHMFL – Florida University/USA
6. Transport	Prof Marco Breschi Italy	Dr Mark Husband GKN/UK
II. Materials for the identified applications	Prof. Venkat Selvamanickam Houston University/USA	Prof Susannah Speller University of Oxford/UK

Members (> 70) of the workshop on SCSI initiative and Sponsors of Workshop held at Oxford University 11-12th Jul 2022

Current members of the SCSI

Sponsors of Workshop held at Oxford University 11-12th Jul 2022