Strategic Approach to Broaden the Use of Superconductivity in Society and the Potential Impact on a Cleaner, Healthier and Sustainable Future

Ziad Melhem
Oxford Quantum Solutions Ltd,
Oxford, UK

2022 All Engineers Retreat at Fermilab (FNAL), USA

23rd Feb 2022

1. The challenge
2. Overview
3. Superconducting materials
4. Market analysis
5. Opportunities
6. Concluding remarks

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 takeaway

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

UN Sustainable Development Goals – 17 in total

Superconducting Technologies and the SDG goals

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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

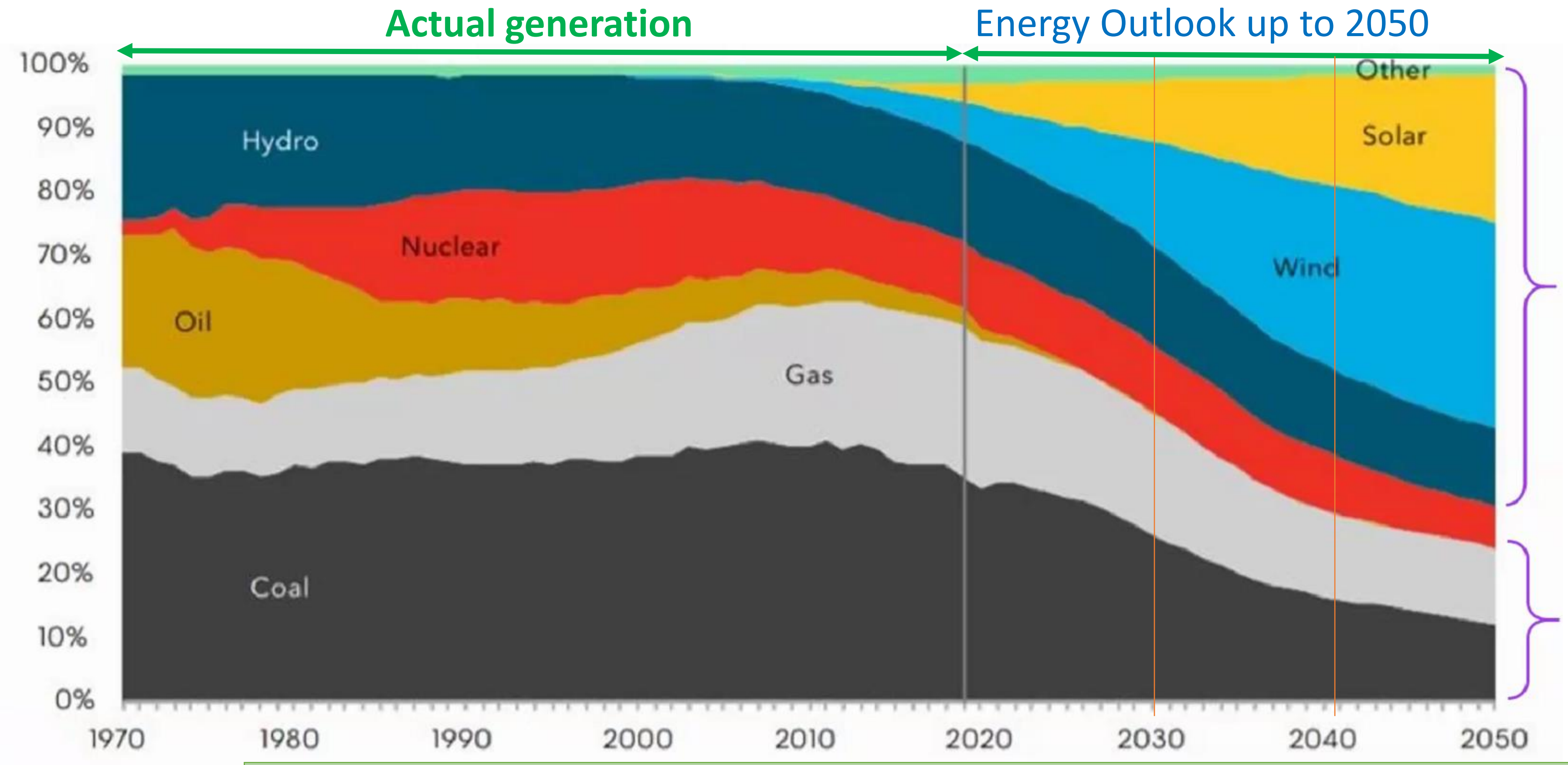
SC for
Energy generation &
power management

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)



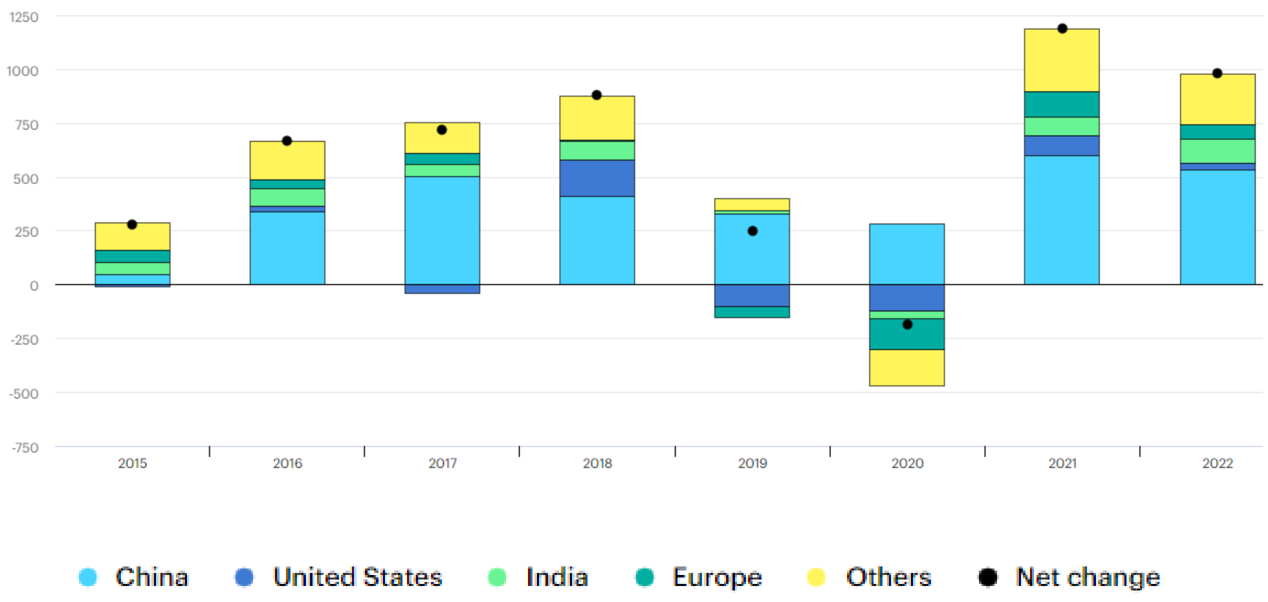
Renewables
- 2020: 38%
- 2030:53%
- 2040:60%
- 2050: 70%

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

Global change on electricity demand vs generation 2015-2022

Global changes in electricity demand (TWh), 2015-2022



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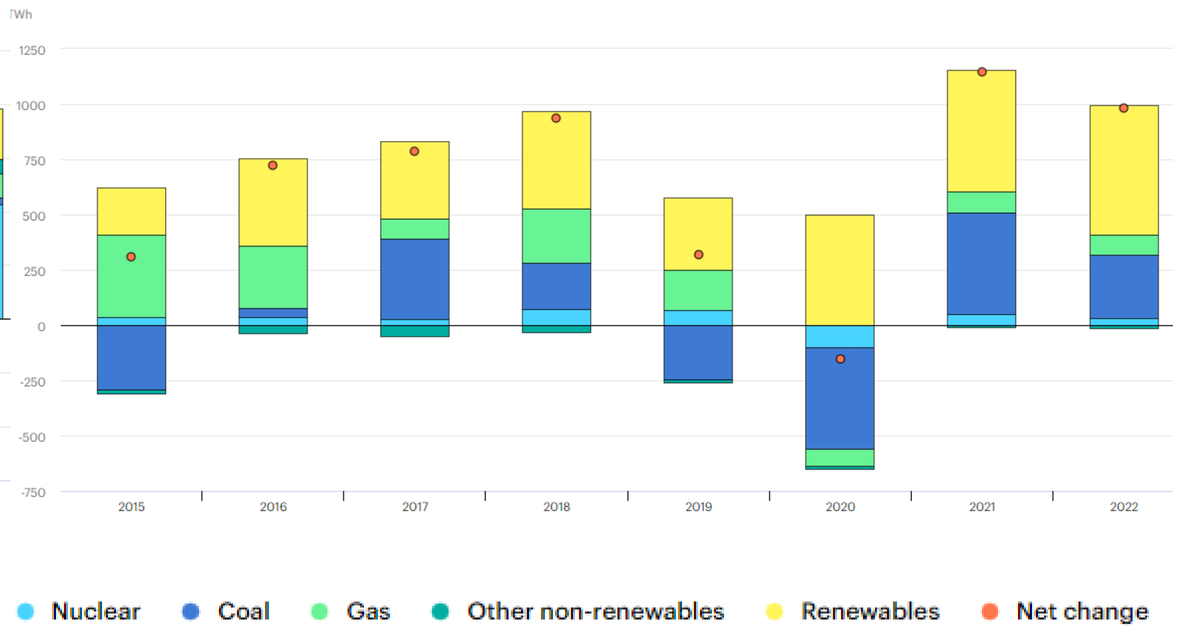

Key takeaway

- Steady increase in demand for electricity
- Use of Fossil is on the increase and supply from renewables are not increasing fast enough

https://www.iea.org/data-and-statistics/charts/global-changes-in-electricity-demand-2015-2022

Overview

From discovery by accident to commercialisation

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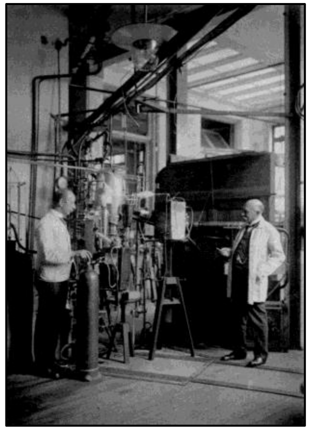
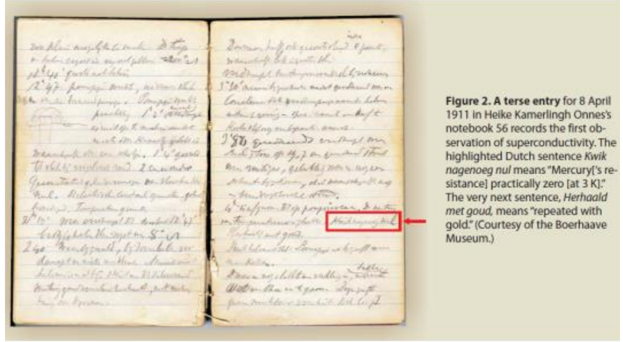
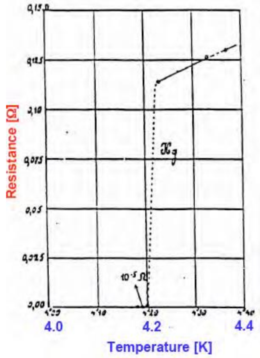
Heike Kamerlingh Onnes (1853-1926)
"Door meten tot weten"
("Through measurement to knowledge")



1908 Kamerlingh Onnes
Liquefies Helium



8 April 1911
"The Resistance of Mercury at helium temperatures"
0.034 W at 13.9 K, 0.0013 W at 4.3K and less than
0.0001 W at 3K



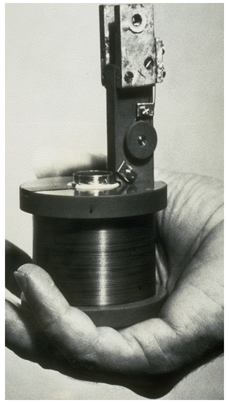
Oct 1911 (Reported in Nov 1911)
"On the sudden change in the rate at which the resistance of mercury disappears"

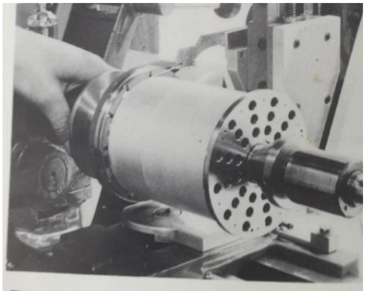
Global SC magnets delivered:

- >20,000 magnets (Research & NMR Magnets) (2-4K)
- >40,000 MRI (4 K)
- Total estimated SC market ~ £ 8 Billion (2021)

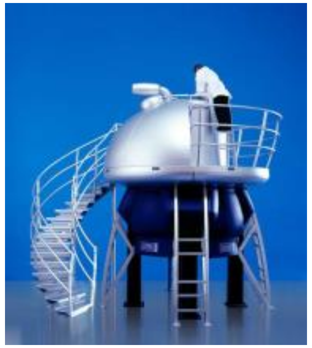
Humble beginnings … Oxford Instruments

in commercial Superconducting magnet technology – 4 Tesla



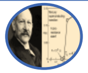


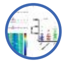
The winding of an early 10 Tesla magnet

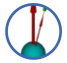


Courtesy of Oxford Instruments

> 25 Nobel Prizes - SC, Quantum & Cryogenics


1913 Superconductivity

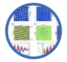

1922 Mass spectrograph


1943 Magnetic moment of the proton

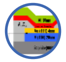

1944 NMR of isolated atoms & molecules, using molecular beams


1952 Nuclear magnetic resonance in condensed matter

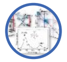

1955 Precision measurement of the electron’s magnetic moment


1970 Antiferromagnetic, ferrimagnetism


1972 Theory of superconductivity


1973 Superconducting tunnel junctions


1977 Theory of magnetic & disordered systems


1982 Critical phenomena, phase transitions


1985 Quantized Hall effect

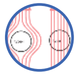

1987 High-Tc superconductivity


1991 High resolution Fourier-transform & two-dimensional


1996 Superfluidity of helium-3


1998 Fractional quantum hall effect, theory & experiment


2002 NMR spectroscopy of biological macromolecules in solution


2003 Type-II superconductors, superfluidity


2003 Magnetic resonance imaging


2007 for the discovery of Giant Magnetoresistance


2010 for ground-breaking experiments regarding the two-dimensional material graphene


2012 for ground-breaking experimental methods that enable measuring & manipulation of individual quantum systems


2013 for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, & which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS & CMS experiments at CERN’s Large Hadron Collider


2016 for theoretical discoveries of topological phase transitions & topological phases of matter”


2017 for developing cryo-electron microscopy for the high-resolution structure determination of biomolecules in solution

Key takeaway
Research using magnetic field, cryogenics & Quantum enabling new discoveries & 25 Nobel Prizes in Science & Medicine

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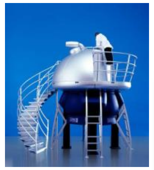
Innovation in Superconducting applications


Courtesy of NHMFL



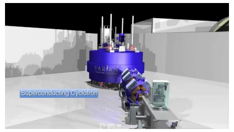
Research & Medical Magnets

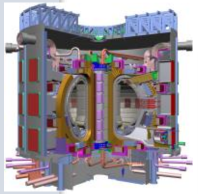
- Medical- MRI, NMR , Proton Bean Therapy
- Basic Research- Physical sciences RM
- HEP- Beamlines/Accelerates/ Detectors
- Fusion – LTS & HTS
  - UHF >25T (LTS+HTS)
  - 5T-20T >20K (HTS)
  - Bench Top Applications (LTS+HTS)
    - 0.5-5T >20K-77K


Courtesy of ISIS


Courtesy of TE


Courtesy of CERN

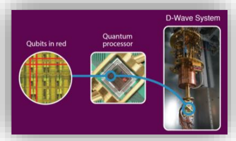

Courtesy of Varian


Courtesy of ITER

Industrial applications

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





Courtesy of Dwave

Microelectronics

- Quantum Computing
- Faster Computers
- Power Electronics

Superconducting (SC) Applications

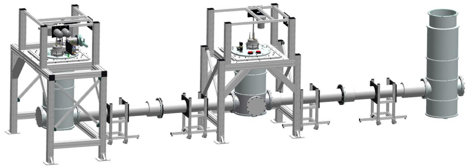
Power & Energy Applications

- 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


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

Communications

- Satellite channels
- Wireless devices
- Antennae

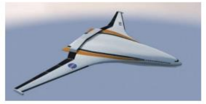
Defence & Security

- Detectors/Sensors
- Rail gun
- Degaussing cables

Transportation

- Electric planes
- Maglev
- Ships
- Rocket propulsion


Chuo Shinkansen Maglev train


NASA N3-X

Superconducting materials

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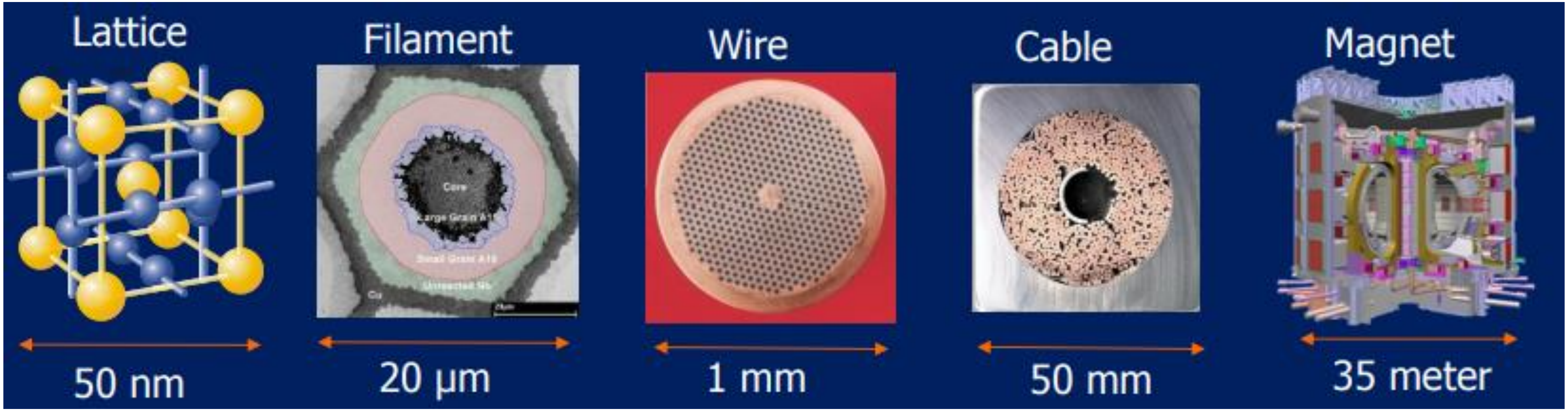
From nanomaterials to SC applications

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



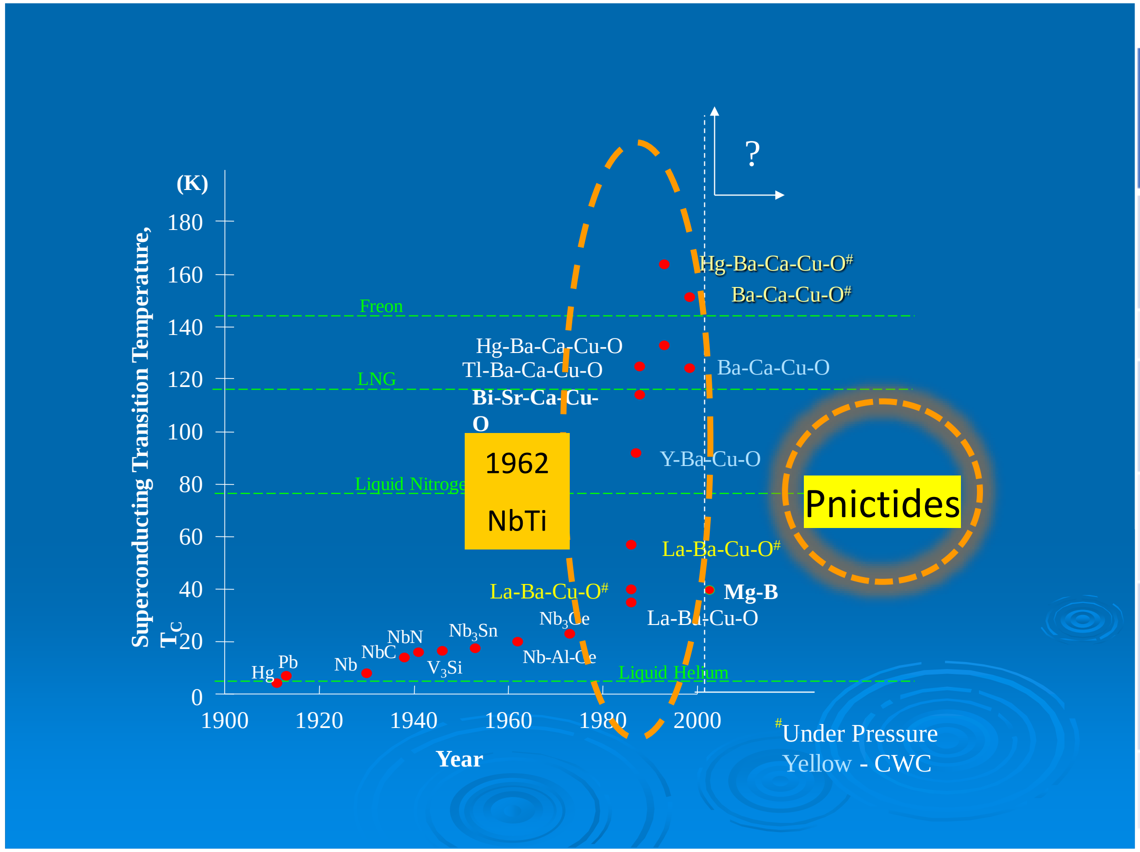
How to make performing 10 A - multi-kA conductors that guarantee the magnet not to quench or degrade ?

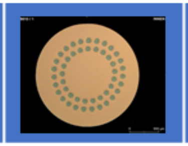
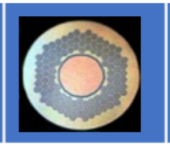
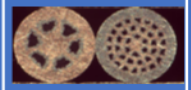
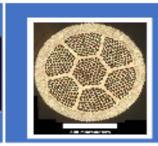
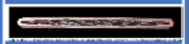
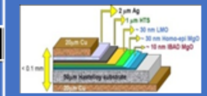
- Need to understand and control the entire production chain
  - An underdeveloped area of research, but essential to avoid surprises and degraded magnet performance
  - Striking examples exist of missing understanding putting large projects at risk or make them expensive

Key takeaway

Huge progress in translating new innovation in smart materials into large and advanced applications

Superconducting materials



						
	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

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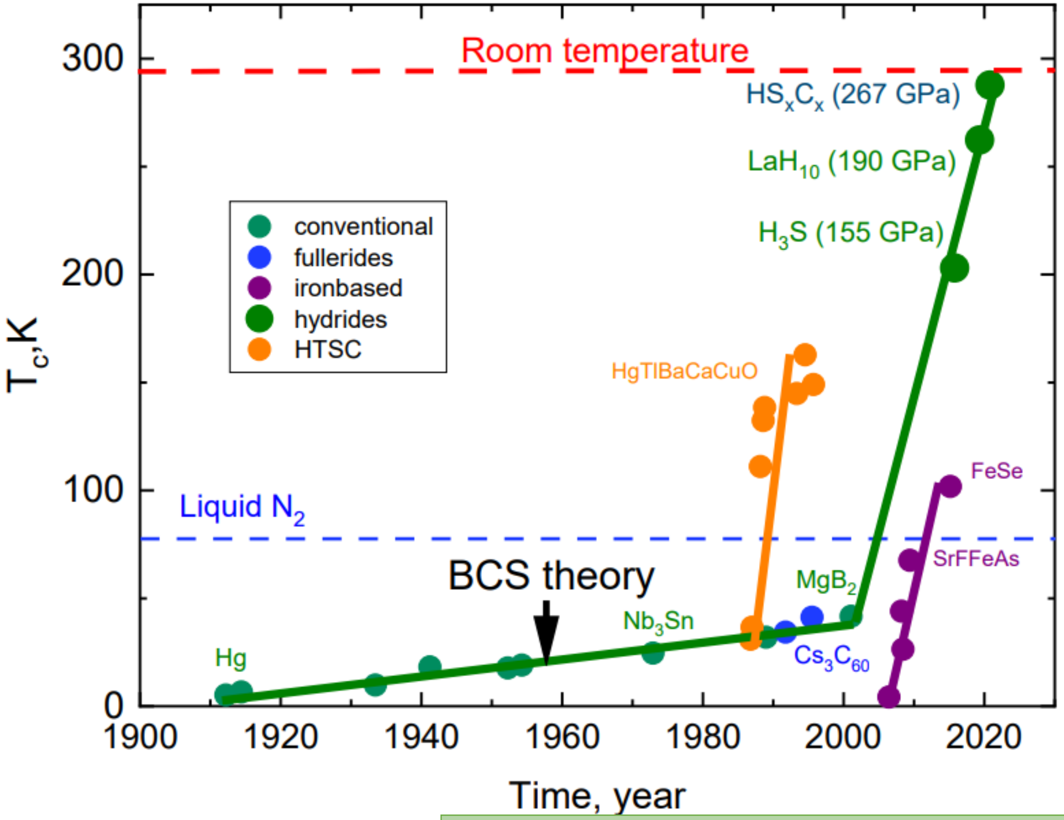
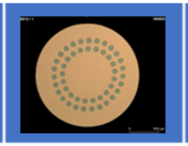
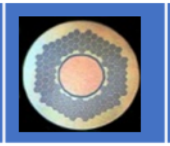
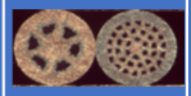
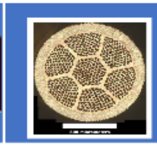
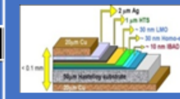
Superconducting materials – Performance and cost

Mikhail Eremets Plenary: A Path Towards Room Temperature – ASC 2020- 25th Nov 2020

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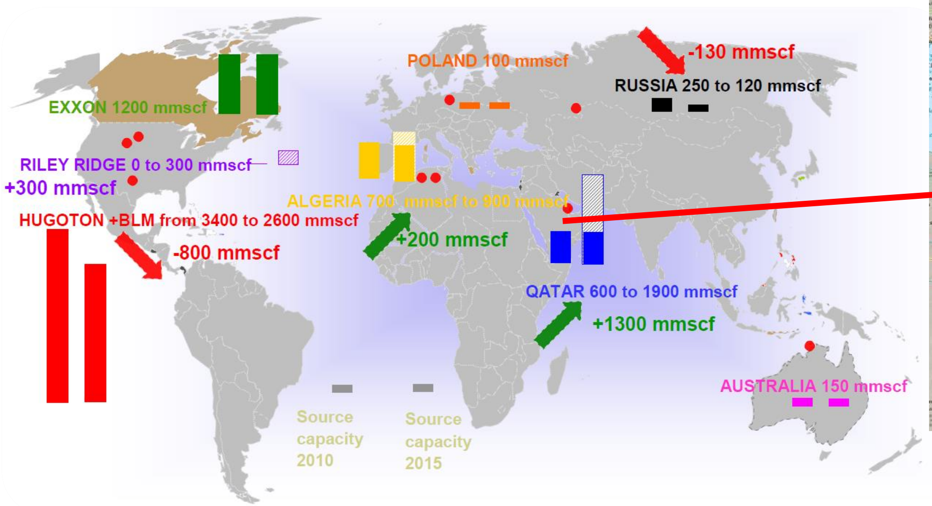
Production Supply	Mature	Mature	Prototype-R&D	Prototype-R&D	Prototype-R&D	Prototype-R&D

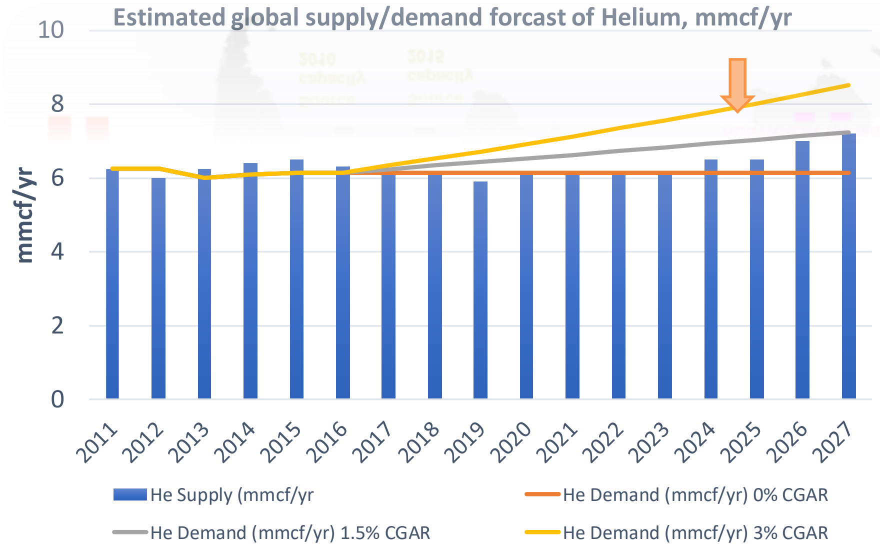
Key takeaway –

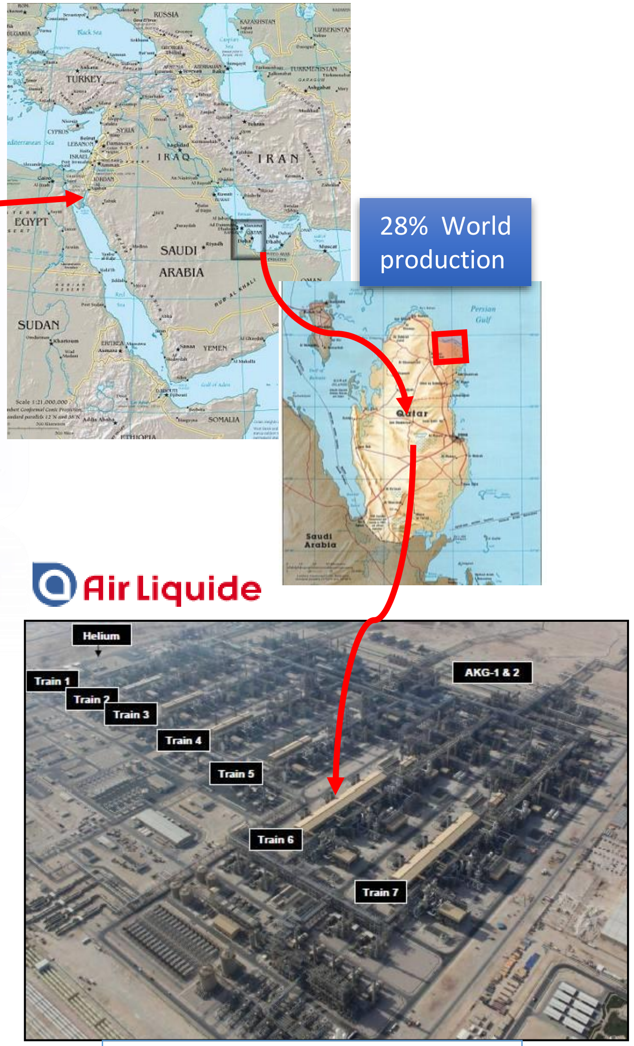
- LTS wires are the dominant material for SC applications (MRI, NMR, HEP, RM).
- HTS introduction will extend SC use and lead to new applications @ 20-77 K
- Reducing cost of HTS is critical for commercial applications

Major and Global Helium shortage (April 2020)
… Need new thinking on cryogenics

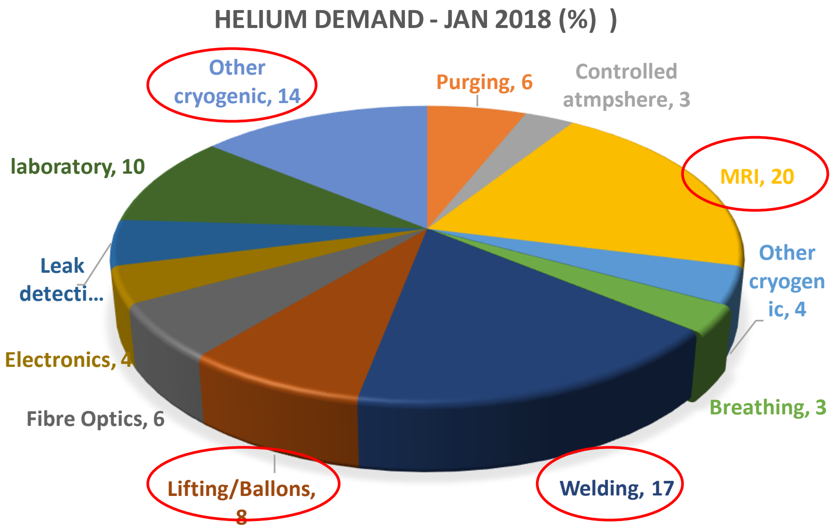
Oxford Quantum Solutions

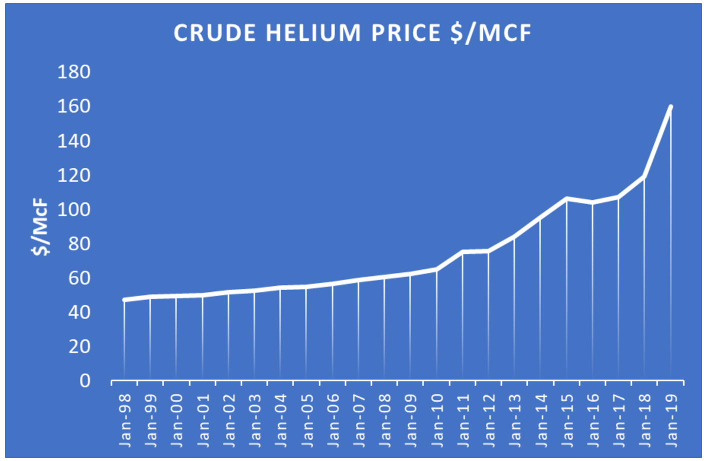






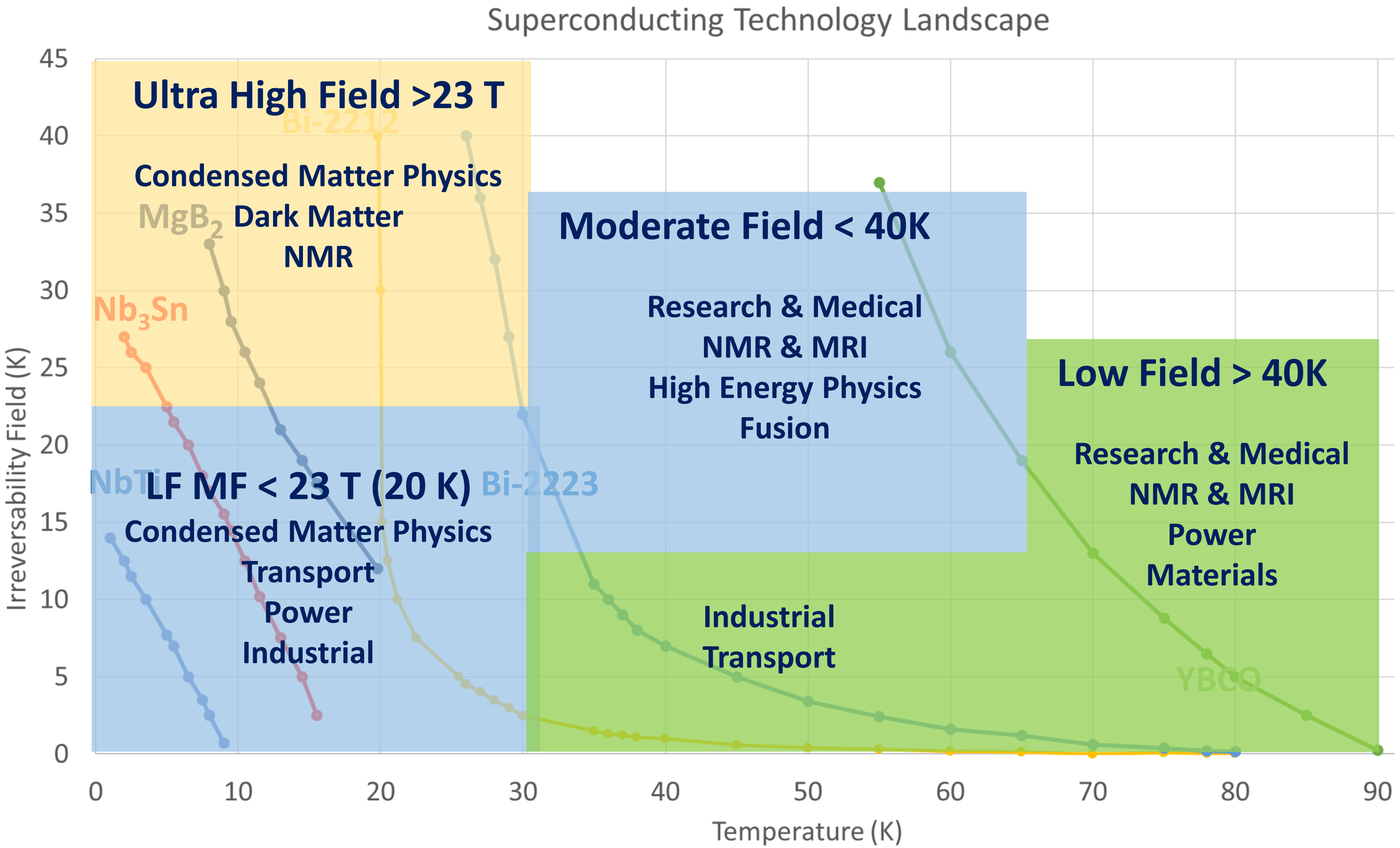
Courtesy of Air Liquide





High Temperature Superconductors (HTS) will lead to new market opportunities and enable new high field applications

- HTS will enable
  - HF systems >25 T
  - MF systems operating @20-40K
  - LF systems operating @ 40K
  - wide bore systems
  - compact magnets
  - Simplified cryogenics > 4K
  - Reduced footprint
  - Reduced overall cost



Market analysis

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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 - Fast growing application
- Superconducting Electronics
- Medical diagnostics and therapy
- Industrial and Transport

> $10 Billion by 2030

ziad.melhem@oxqsol.com

Opportunities

Nanotechnology Applications

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Opportunities …

Superconducting magnets for nanotechnology and materials research

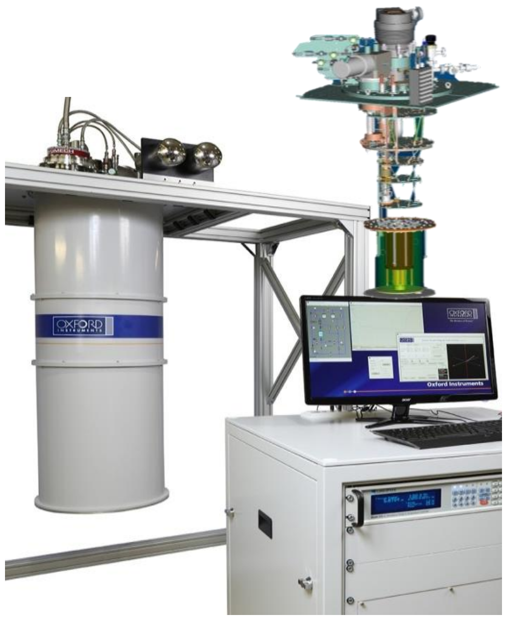
Oxford Quantum Solutions

Optics/DC	Optics/RF	New materials and new science

Courtesy of Oxford Instruments

Courtesy of RKUI-ISIS

Courtesy of Lancaster University



Courtesy of Oxford Instruments

Courtesy of Bruker

Courtesy of NHMFL

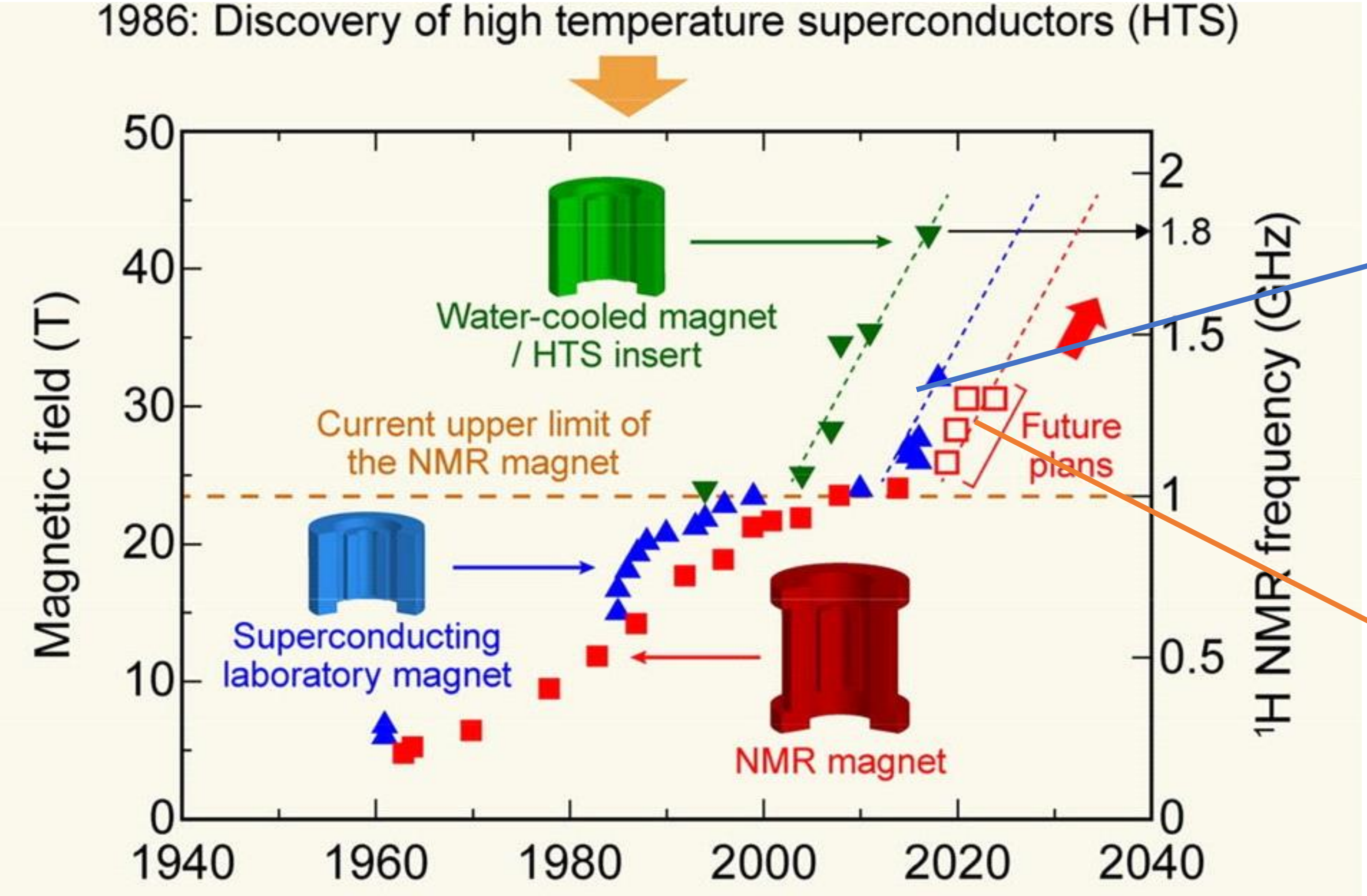
Courtesy of NHMFL and Oxford Instruments

Optics/DC		Optics/RF	New materials and new science
1.5-300 K		< 10 mK	2- 4 K
7 T	8-18 T	Up to 16 T	Up to 32 T

Key takeaway – Superconducting magnets are critical for materials research and discovery for physical and life sciences

SC magnet develop0ment timeline and high field

SOURCE: Maeda H., Yanagisawa Y. "Future prospects for NMR Magnets: A Perspective". Journal of Magnetic Resonance 306 (2019) 80-85



Courtesy of NHMFL

Courtesy of Bruker

Key takeaway – New era of HF magnets > 20 T using HTS leading the way to compact systems

Opportunities

Quantum applications

Quantum Computing – Superconducting Qubits

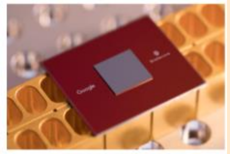
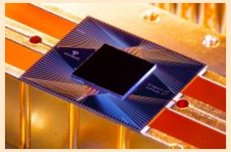
> 6 B $ commitment over the last 2 years

Superconducting Qubit Devices

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

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

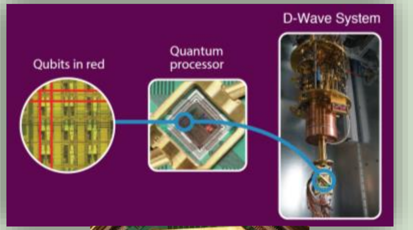
- Dubbed Bristlecone, it's a 72-qubit gate-based superconducting system

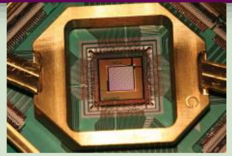
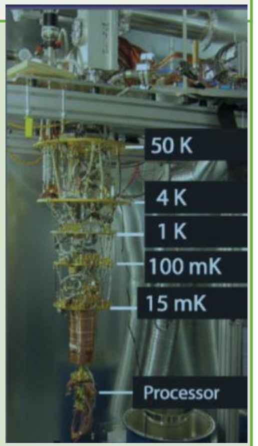




Google Research Blog

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

IBM demonstrated a 50 Qubit Quantum Computer

- Already providing users with 20 Qubit comp


Courtesy of IBM

Key takeaway – SC qubits leading the way towards Quantum computers and embraced by big industrials

ziad.melhem@oxqsol.com

Quantum metrology –
smart science to industrial applications

Smart science (Wet systems)

Technology demonstration (Cryofree systems)

1980
Discovery of QHE

2003
QHE as an electrical resistance standard

2010
Noble prize for Graphene

2011
NPL confirmed universality of QHE in 2D

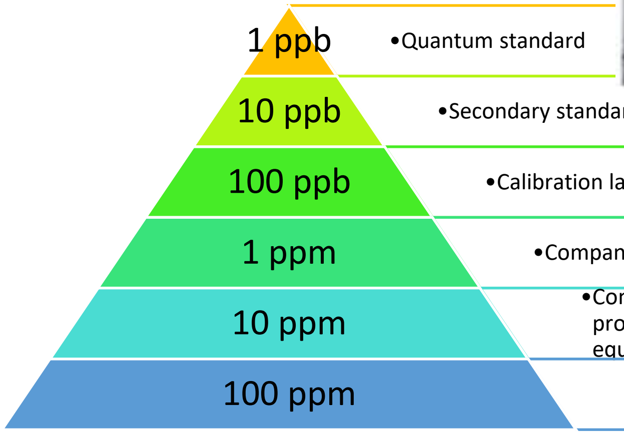
2015
NPL demonstrate Q Metrology

2017
OI+NPL+Chamers +_UoM – demonstrate industrial feasibility of QHR

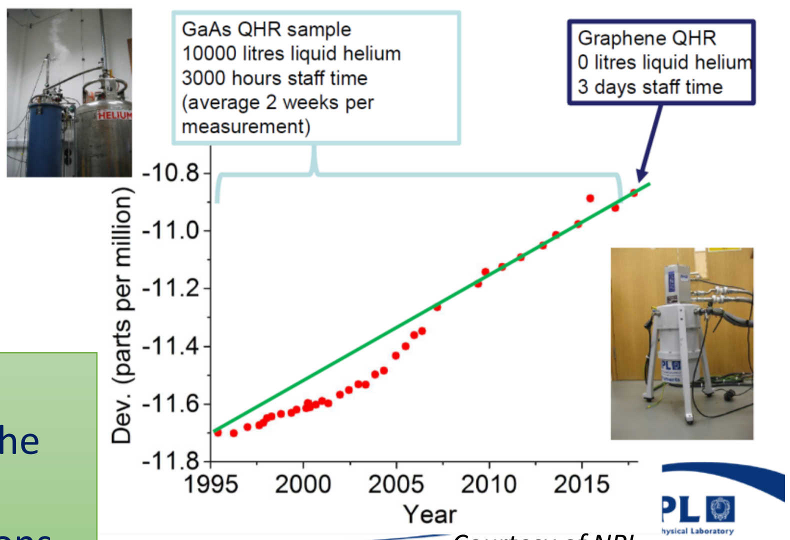
2019
OI+NPL + **Prototype** for TTQHR for Q Resistance standard

The primary standard for resistance is based on the Quantum Hall effect (QHE)

- Existing platforms use liquid Helium sub 1 Kelvin and require high field > 14 Tesla.
    - Expensive-*National facilities*
    - Large footprint
    - Require extensive additional services to operate.
- Setup ideal for research



23 years of resistance traceability: The history of one artefact resistor

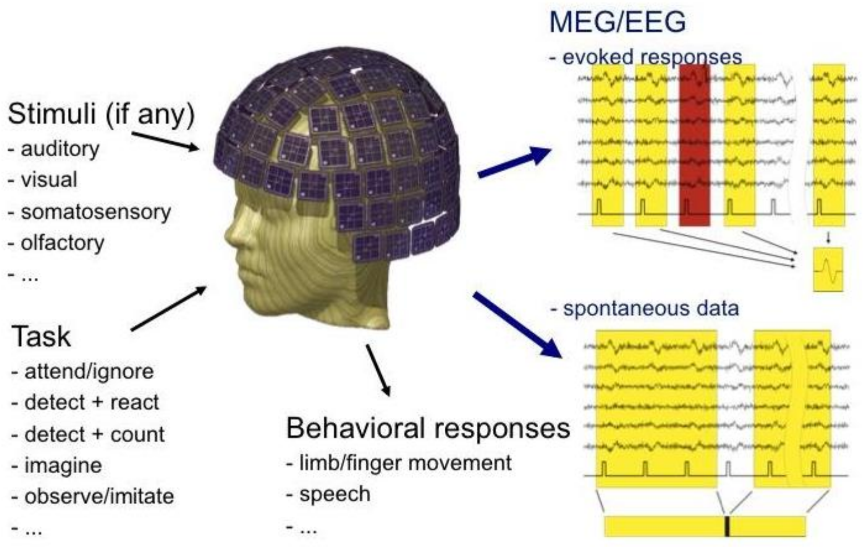


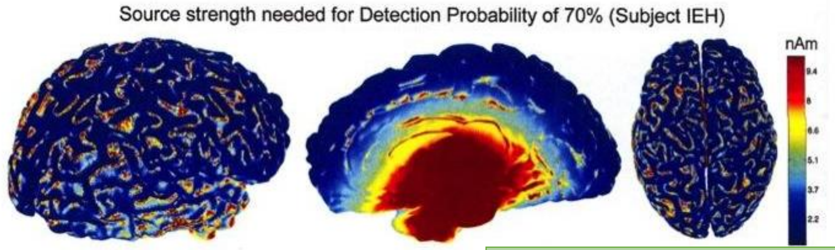
Courtesy of NPL

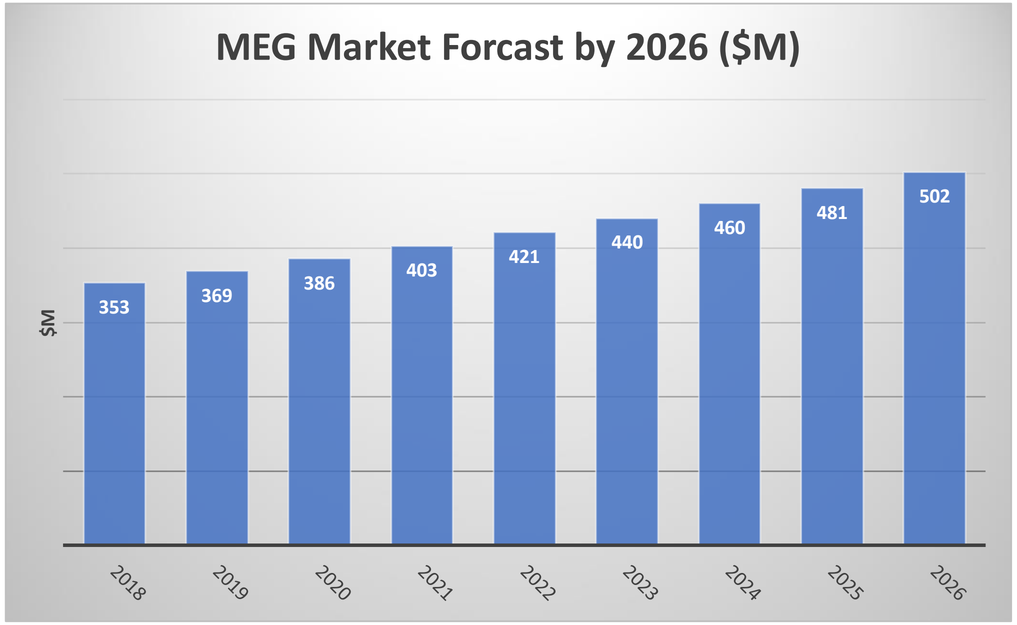
Key takeaway

- Moving primary metrology from the metrology labs closer to the factory floor leading to shorter traceability chain
- Measurements with Quantum accuracy for industrial applications

Quantum sensing - Magnetoencephalography (MEG)







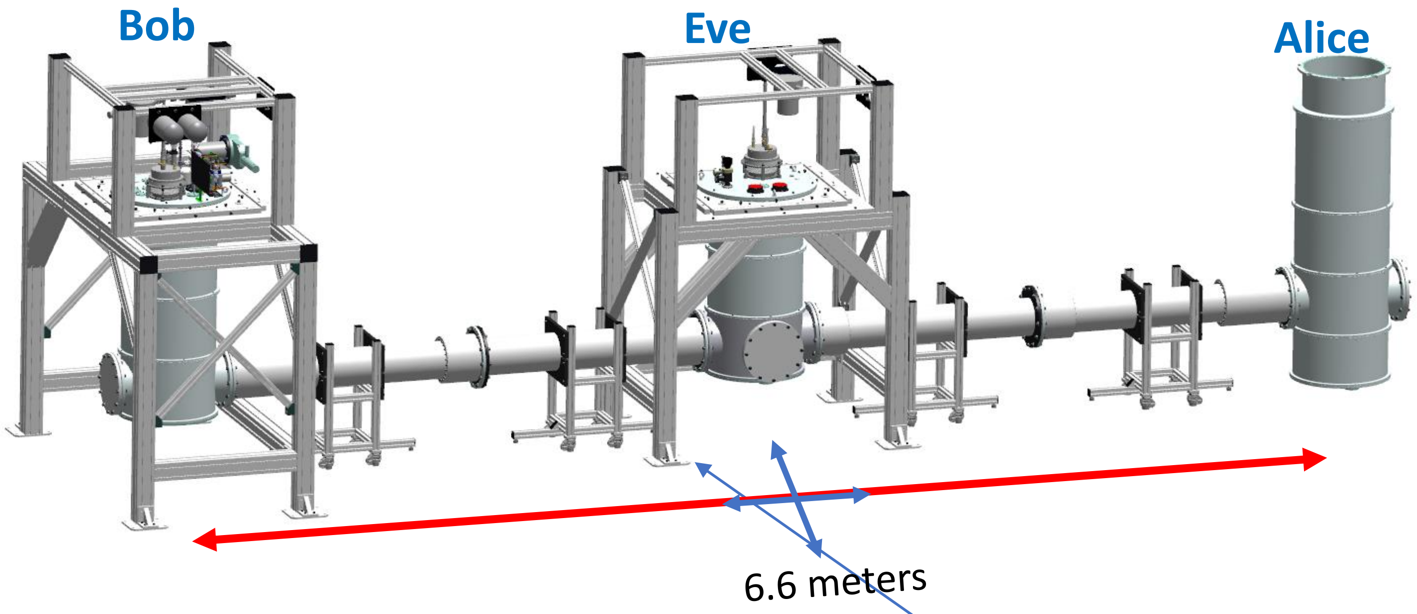
Key takeaway – SC electronic devices enabling a new class of advanced tools for health care with a decent market in 5 years from now

ziad.melhem@oxqsol.com

Q-LAN for Quantum Communications & Computing Scale up

- New innovations required Q Computing/Communications/Sensing
  - Quantum local area network (Q-LAN) - Cryogenic link between two dilution refrige
    - Enabling clustering of multiple fridges for large number of Qubits

Achieved ~35 mK (Specifications <100 mK)



Key takeaway – SC cables/wiring will enable advanced communications and transmission solution for advanced quantum solutions

Opportunities

Health care – MRI, NMR , Proton Therapy

MRI Magnets Development - Health Sector

- **All using LTS Materials**
- **>4000/yr. production**
- **>£ 5 Billion Euro/yr. market**

1980	1st MRI
1986	1st Active shield (AS)
1989	AS 1.5T
1994	1st Open MRI Magnet
1997	AS 3T
2000	AS 4T
2001	1.5T Small
2005	7T
2019	9.4T
2021	11.7T

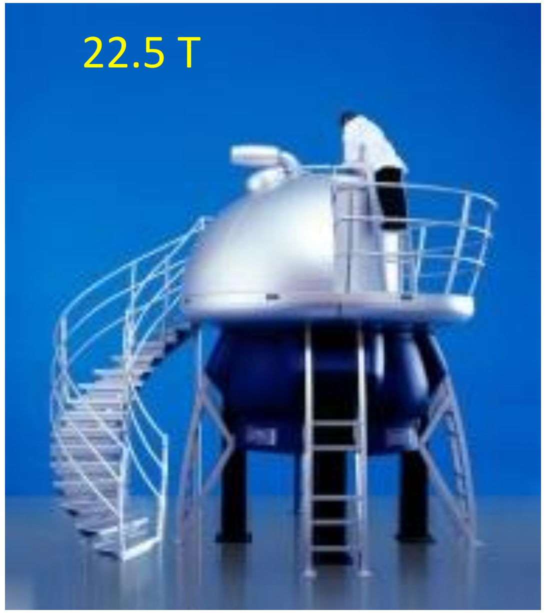
Courtesy of Siemens

Courtesy of CEA

Key takeaway

MRI scanning machines are commercial and > 70% of SC applications

New High Field NMR with HTS



NIMS-Jastec
LTS+HTS – NbTi, Nb3Sn & ReBCO

Oxford Instruments
Only LTS – NbTi, Nb3Sn

Bruker Biospin
LTS +HTS – NbTi, Nb3Sn, ReBco

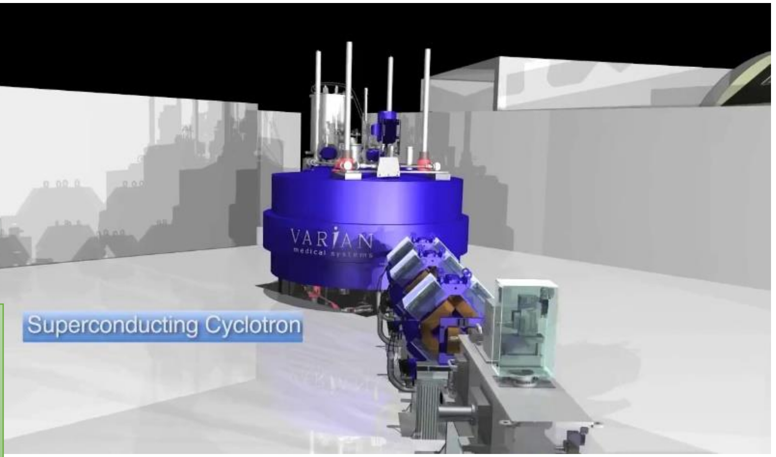
Key takeaway
New class of NMR devices impacting research and drug discovery for many difficult conditions and illness. E.g. Cancer, Dementia, Brain strokes, Heart conditions, etc

ziad.melhem@oxqsol.com

Medical Therapy

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

Now LTS
Plans for HTS



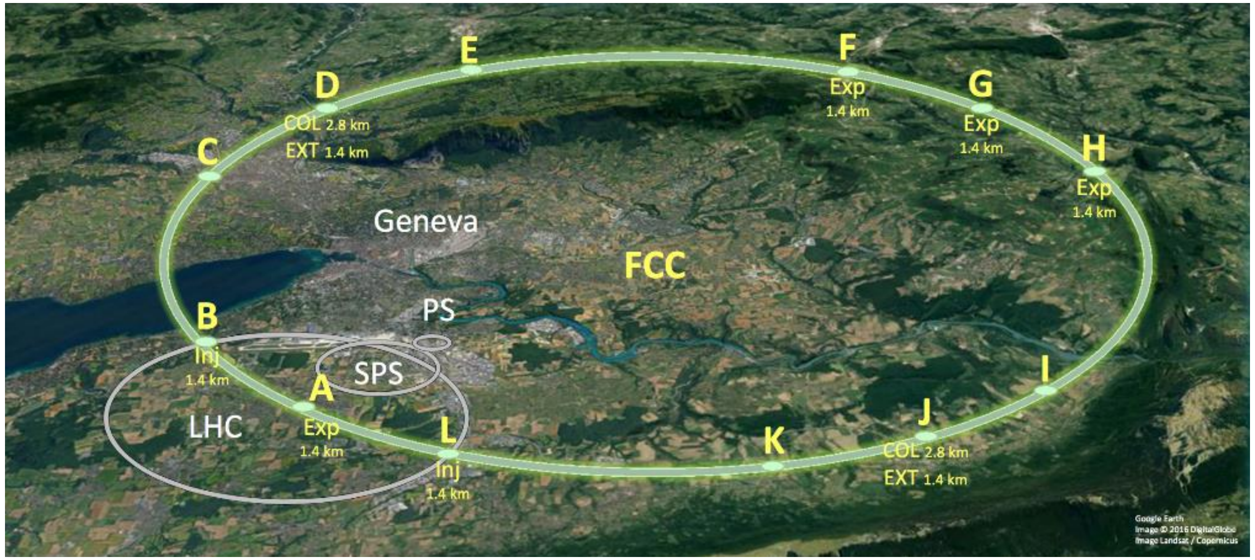
Key takeaway

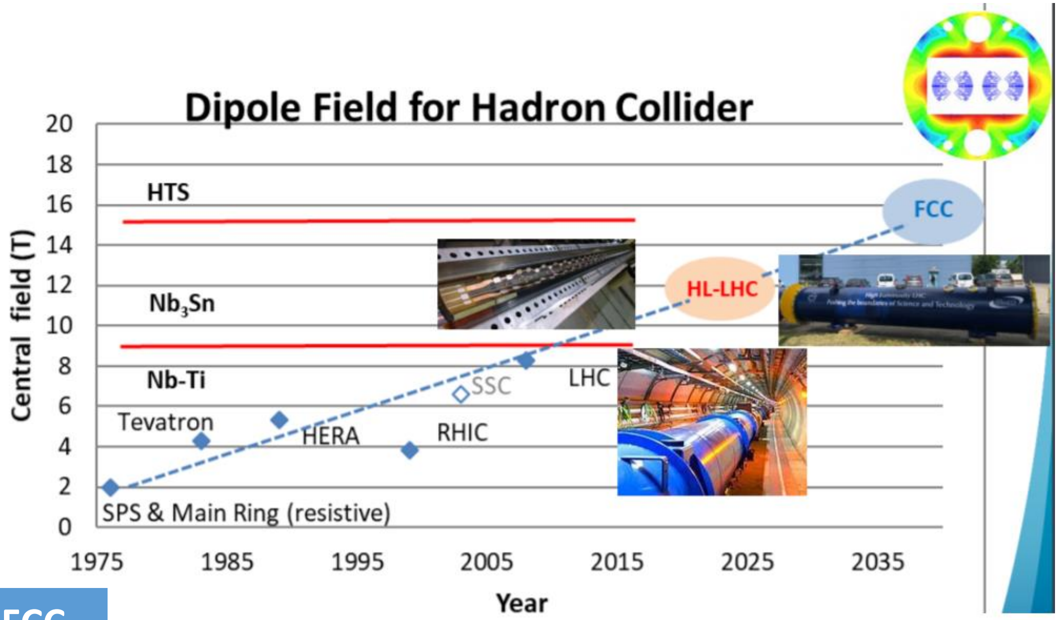
- Will provide step change in medical care and improve quality of life for so many
- Potential to be very large commercial market with high field and compact devices

Opportunities

Future High Energy Physics colliders with SC – EU, China, Japan

FCC – SC for future colliders – CERN (>20B Euro) – *Courtesy of CERN*





Challenges

- High Jc material
- Cost
- Length
- Operation at >16 T
- Materials availability

	LHC	FCC
Circumference (km)	26.7	97.5
Dipole field (T)	8.33	**16**
C.o.M. energy (TeV)	14	100

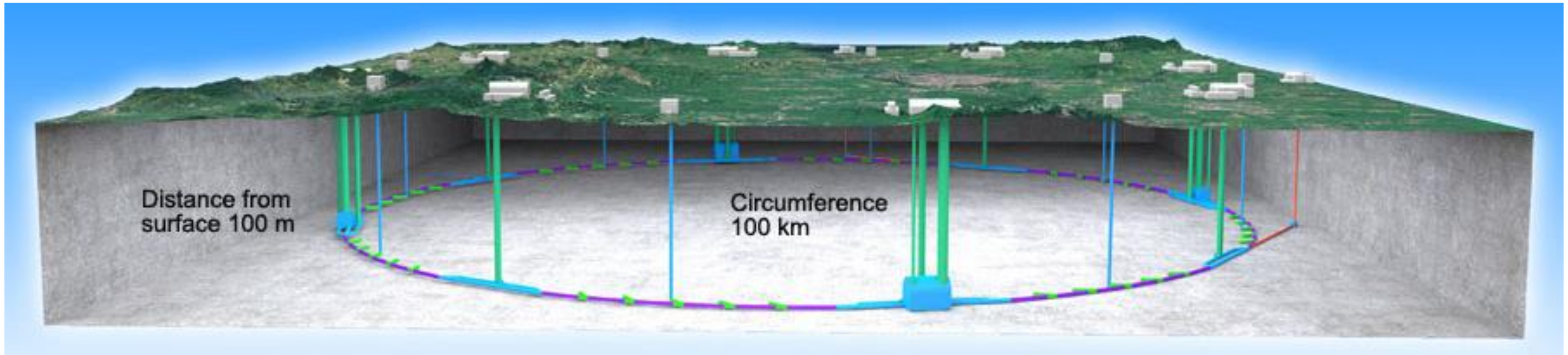
Using

- LTS for coils
  - NbTi
  - Nb3Sn
- HTS for Coils
  - YBCO
  - Bi-2212
- MTS for links
  - MgB2

Key takeaway and Impact on HTS

- Large and long term projects
- Not enough to fast track HTS deployment and cost reduction
- Critical in developing & demonstrating performance of new SC materials & technologies

Super Proton Proton Collider (SPPC) - China



- **Using Iron Based Superconductors (IBS)**
- Can operate at elevated temperatures
- 100 m of IBS conductor has been tested
- Cost ~ $5B

Baseline design

- Tunnel circumference: 100 km
- Dipole magnet field: 12 T,
  - iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV
- upgrade phase
  - Dipole magnet field: 20…24T, IBS technology
  - Center of Mass energy: >125 TeV
- Development of high-field superconducting magnet technology
  - Starting to develop required HTS magnet technology before applicable iron-based wire is available
  - ReBCO & Bi-2212 and LTS wires be used for model magnet studies and as an option for SppC:
  - stress management, quench protection, field quality control and fabrication methods

Key takeaway

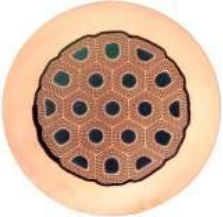
- Verification of IBS for High energy physics large scale projects will lead new commercial SC material with the potential
  - Cheap
  - High performance

Opportunities

Fusion

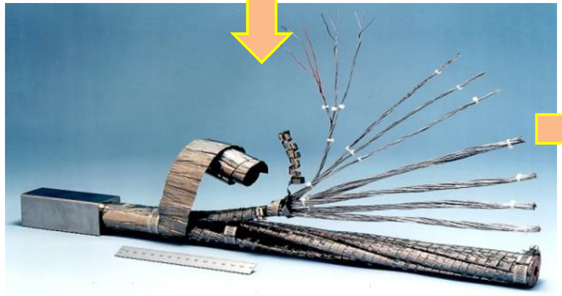
Nuclear Fusion – ITER using LTS

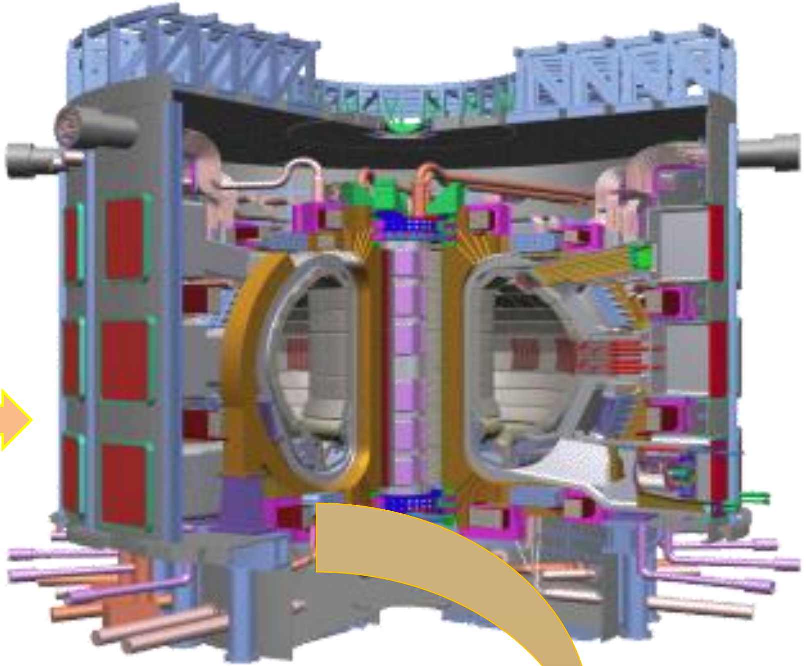
0.73mm ITER LTS strand



540mm cable

(1440strands)

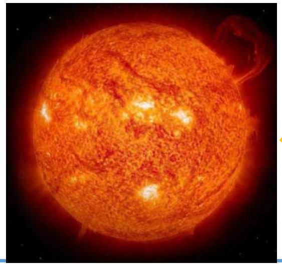




- **ITER strand** - new generation of LTS superconductors for energy applications
- 15B Euro development cost
- >20 yr development programme (10yr to build)
- 2027! date for 1st Plasma
- 74,000Km of superconducting wires

(*40,000 Km to circle the earth!* Almost twice around the earth!)

High field Superconducting magnets to contain plasma- Sun conditions 10 Million Degrees



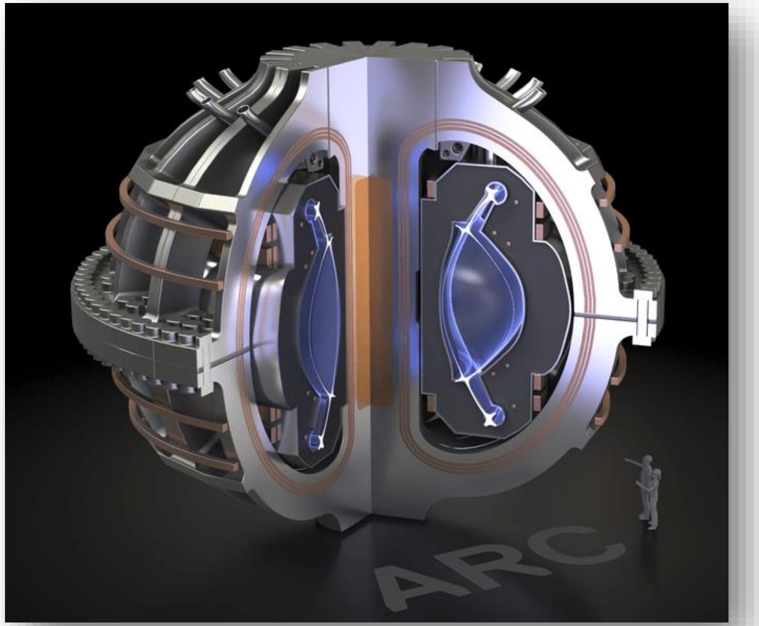
Power density: Fusion vs Renewables

Offshore wind

GE Haliade-X: 12 MW Turbine nacelle

Intermittent ~ 60 Capacity

Fusion



CFS ARC: 200 MWe Tokamak

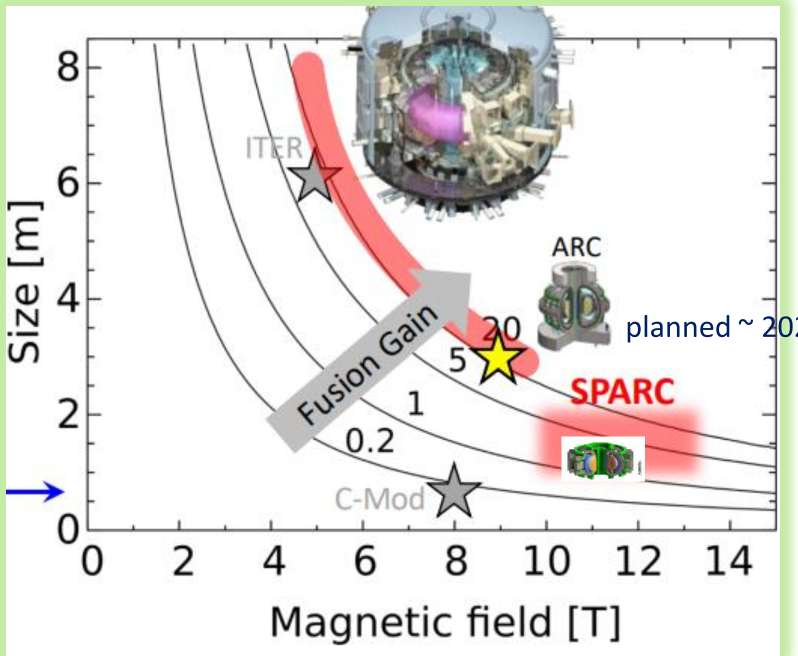
Firm 90% Capacity

https://w3.windfair.net/wind-energy/news/31919-he-haliade-x-nacelle-ore-catapult-test-site-uk-offshore-wind-turbine-large

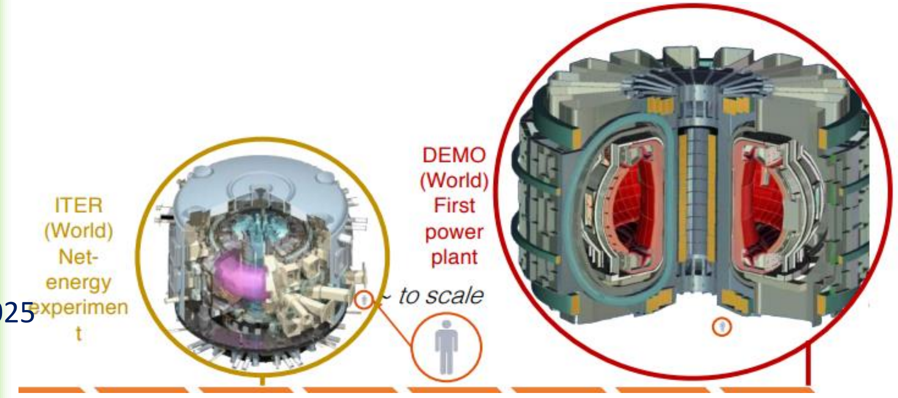
Future fusion devices using HTS – Led by private funds

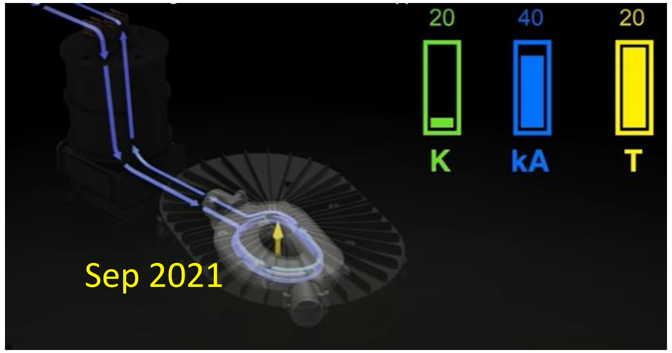
Source -Joseph V. Minervini Massachusetts Institute of Technology
Plasma Science and Fusion Center Cambridge, MA USA

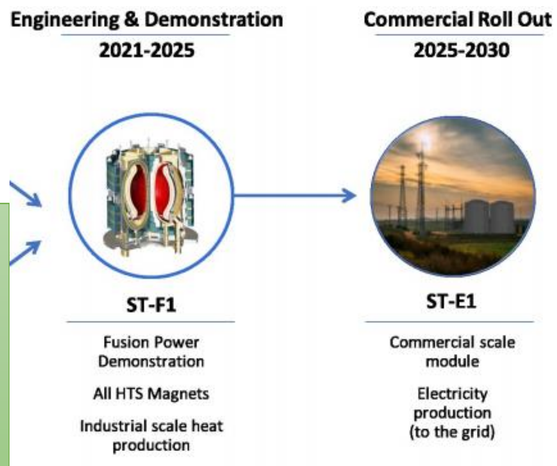
Oxford Quantum Solutions

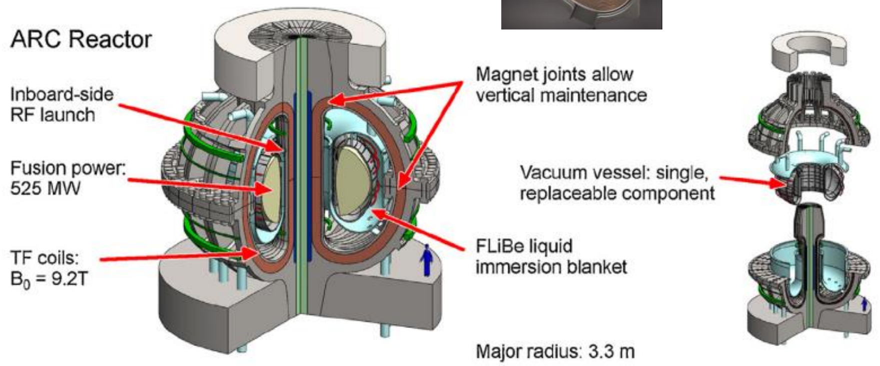


planned ~ 2025









Key takeaway – HTS impact

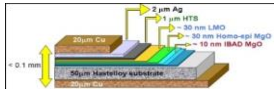
Fast tracking development of new power stations

- 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

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

tokamak energy
a faster way to fusion



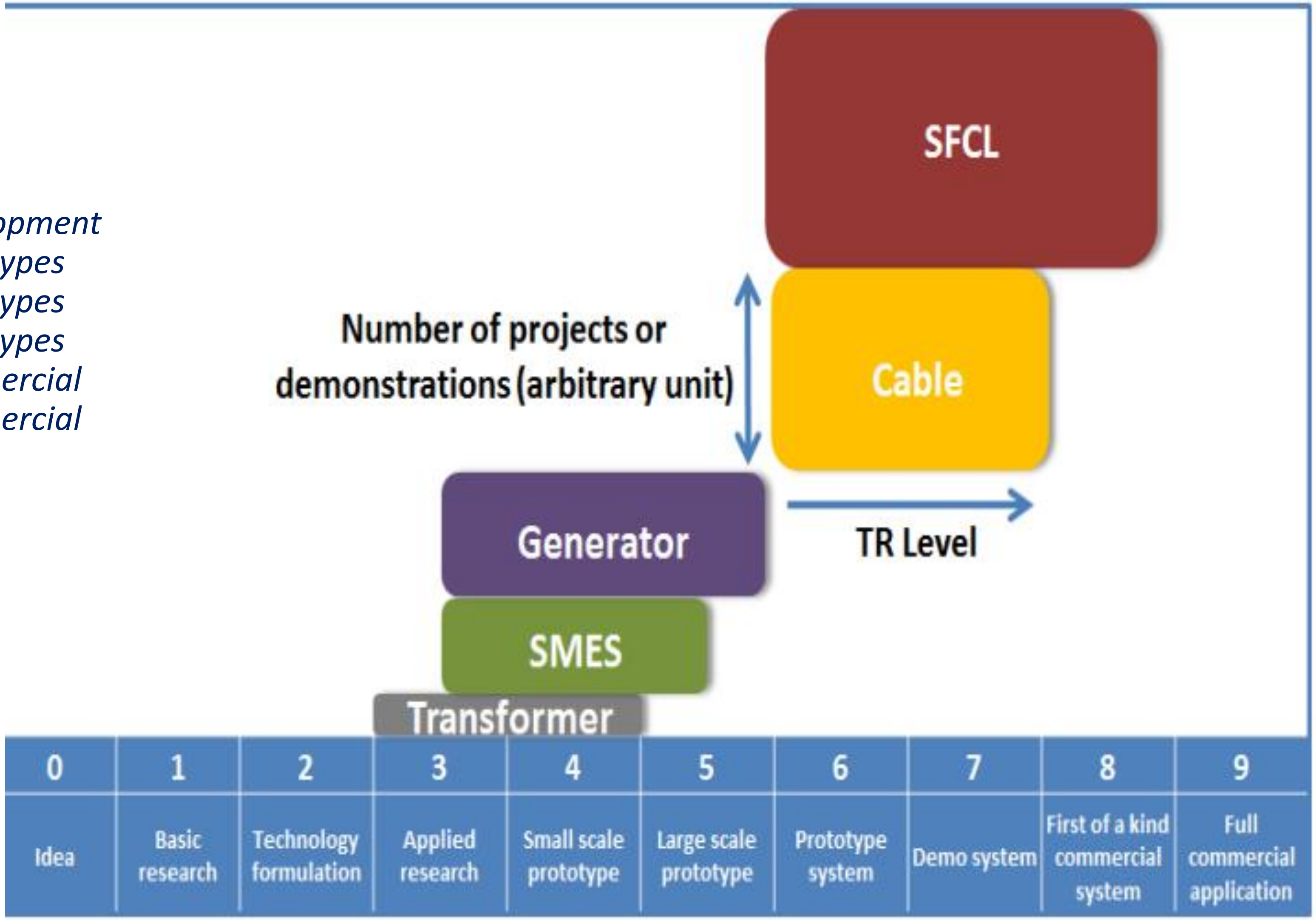
Commonwealth Fusion Systems , MIT

Opportunities

Power and Energy with HTS

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

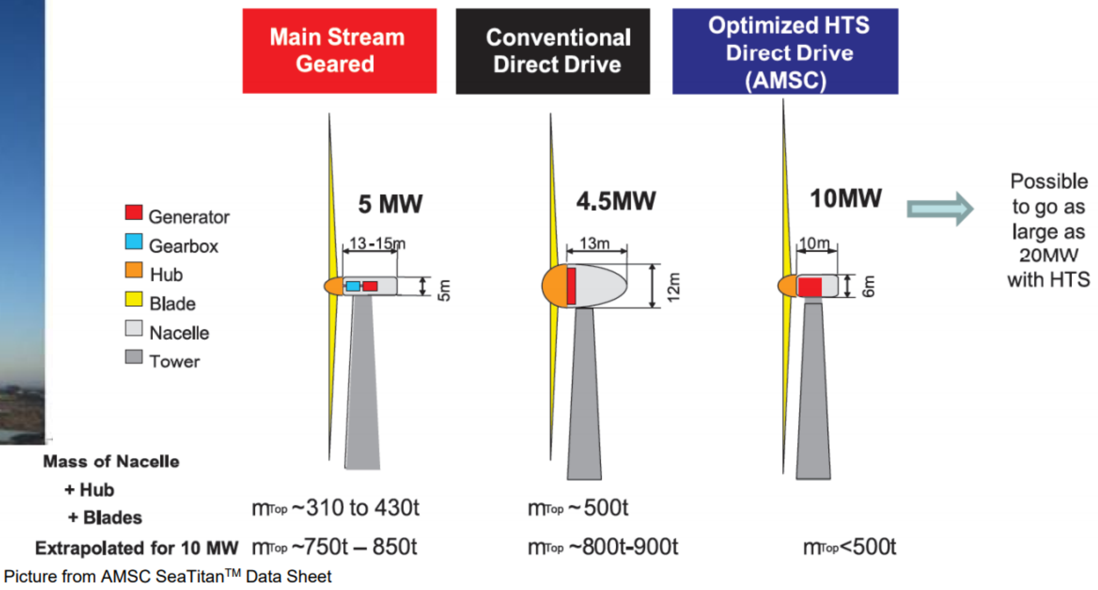
ziad.melhem@oxqsol.com

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

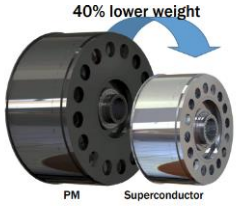
Horizon 2020 European Union Funding for Research & Innovation



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

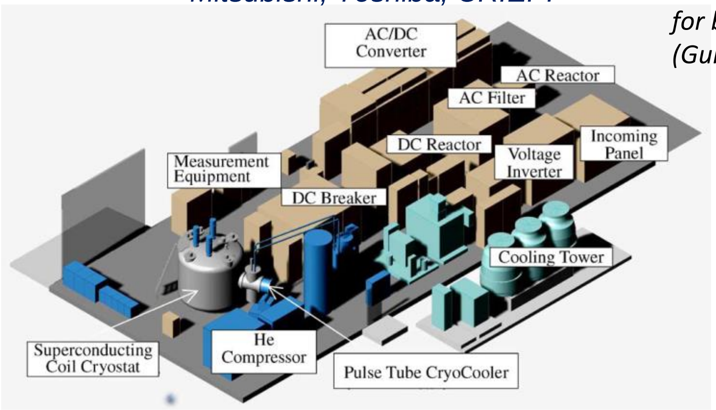
Energy storage and power transmission and distribution

2014

Ampacity ReBCO tape FCL 12kV 2.3kA

protecting superconducting cable in Essen city grid

Chubu Electric Power
Mitsubishi, Toshiba, CRIEPI



10 MVA/1 s SMES at Kameyama field test, in Japan.

S. Nagaya et al., "The state of the art of the development of SMES for bridging instantaneous voltage dips in Japan," Cryogenics (Guildf)., vol. 52, no. 12, pp. 708–712, Dec. 2012.

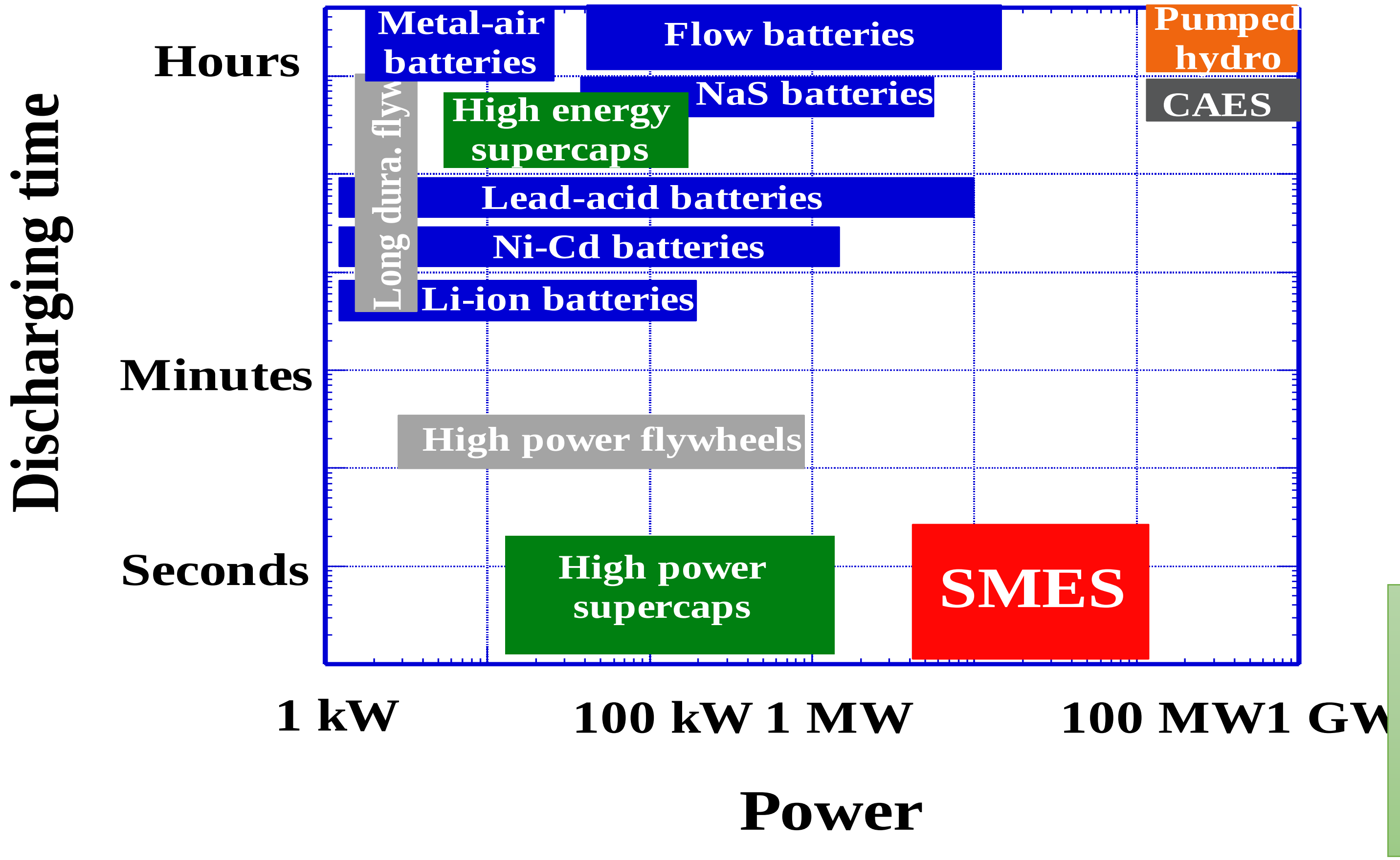
Field test of 500m long HTS cable (Furukawa Electric CRIEPI (Central Research Institute of Electric Power Industry) & Super-GM (Engineering Research Association for Superconductive Generation Equipment & Materials) 2005

Key takeaway – HTS Impact on Power Applications:

- New technology
- Improved energy efficiency
- Higher power density
- Higher power quality
- Essential for decarbonisation and zero emission targets

Discharging time versus power for various energy-storing devices

www.electricitystorage.org



Superconducting Magnetic Energy Storage

Pascal Tixador

Publisher : Woodhead-Elsevier
Editor: Ziad Melhem
Date 21st Dec 2011

Key takeaway

- SMES has superior performance vs other technologies
- Main barrier cost!
- SMES will be critical for Power conditioning

Superconducting Cables (>20 completed)

Field test of 500m long HTS cable (Furukawa Electric CRIEPI (Central Research Institute of Electric Power Industry) & Super-GM (Engineering Research Association for Superconductive Generation Equipment and Materials) 2005

Cable at Holbrook, Long Island USA, operational 2009

Note the elevation and the corners!

ziad.melhem@oxqsol.com

HTS transmission cables > 70

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

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 Su	Chicago downtown area	Center for Advanced
Status	Abandoned[3]	Ur Cc		
Developer	AMSC	AI		
Utility/Host	LIPA	Cc		
In-Grid Start Date	NA	20		
End Date	LIPA originally planned to operate system indefinitely	N te		
Type (AC or DC)	AC	AC		
Phases	3	3		
Geometry	Coaxial	Tri		
Voltage	138 kV	13		
Rated Current	2400 A_{rms} (Cable will operate @ 800 to 900 A_{rms})	40 (9		
Length	600 m	17		
Fault Current	51 kA_{rms} for 12 cycles (~140 kA_{peak} asymmetrical)	40		
Dielectric Design	Cold dielectric	Cc		
Dielectric Material	LPP	Cr		
HTS Material	YBCO fault current limiting	YE		
HTS Conductor Supplier/Fabricator	AMSC	AI		
AC Loss	Not available	N		
Cable Fabrication	Nexans	Ul		
Refrigeration	6 kW @ 65 K (advanced system proposed)	6. 4 (D		

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		
Developer	Nexans, RWE Deutschland, an KIT[1]		
Utility/Host	RWE Deutschland		
Start Date	March 2014[4]		
End Date	~ 2016[5]		
Type	AC		
Phases	3		
Geometry	Tri-axial		
Voltage	10 kV		
Rated Current	2.3 kA (40 MVA)		
Length	1 km		
Fault Current	20 kA (50 kA peak)		
Dielectric Design	Cold dielectric		
Dielectric Material	LPP		
HTS Material	BSCCO[8]		
HTS Conductor Supplier/Fabricator	Sumitomo		
AC Loss	1 W/m[10]		
Cable Fabrication	Nexans		
Refrigeration	4 kW @ 67 K. Open bath LN (Messer)[11]		

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

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

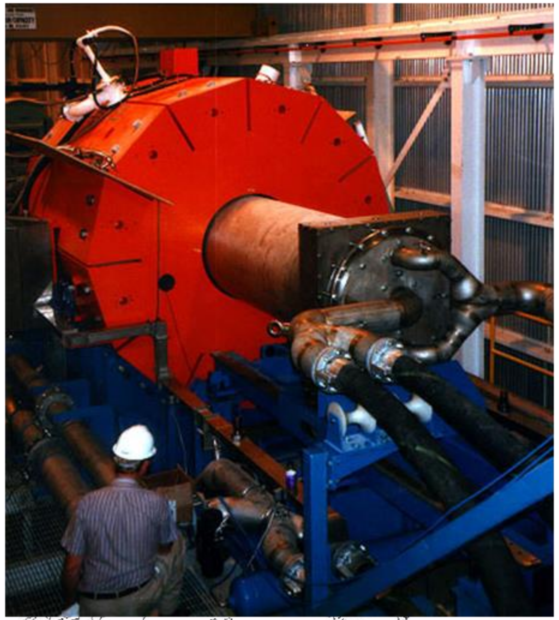
Opportunities

- Industrials with SC
- Non-destructive testing
- Inductive heaters
- Magnetic separation
- Crystal growth
- Quality control

Industrial Magnets

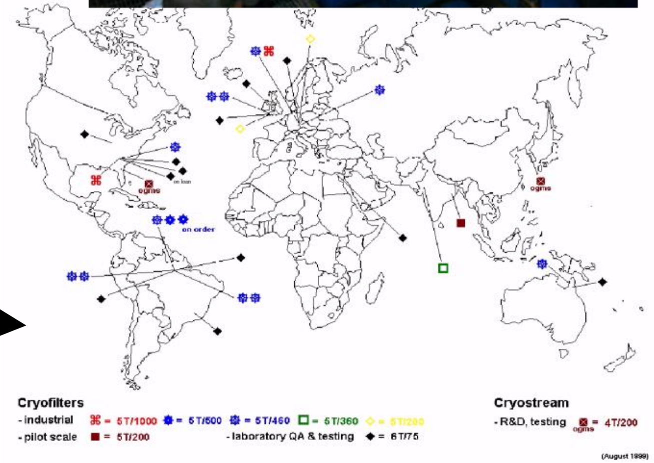
Magnetic separation - Carpco

- High gradient magnetic separation (HGMS)
- Primarily for kaolin processing
  - removing weakly magnetic impurities to improve whiteness (and therefore economic value)
- **5 T** magnets, 360 mm to 1000 mm bore



operate at the mining source

- Amazon rainforest, Brazil
- Queensland, Australia
- Cornwall, UK



Key takeaway

- Superconductors can operate in industrial and harsh environments

Opportunities

Transport with HTS

- MAGLEV
- Electric planes
- Electric ships

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

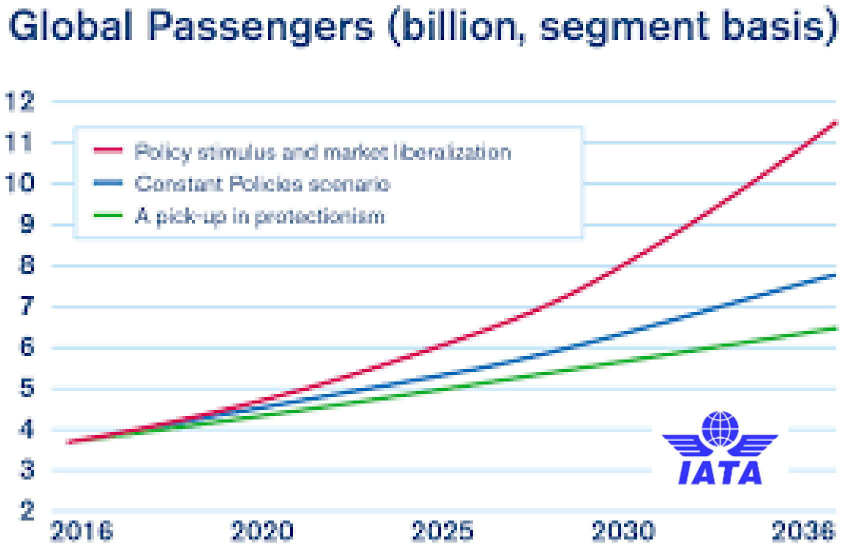
China - 2030

- 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,

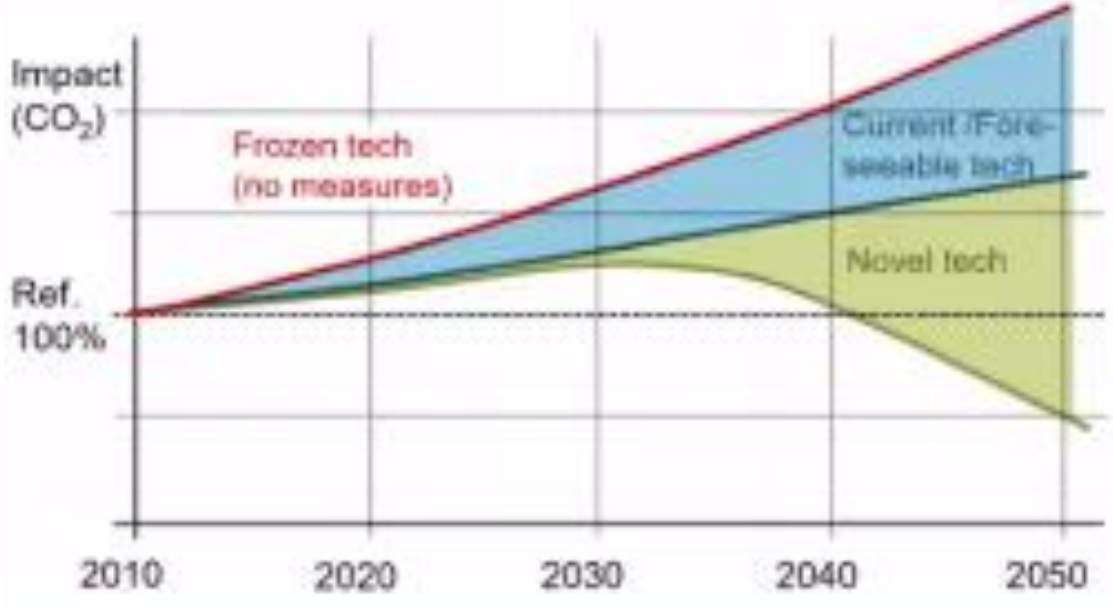
Key takeaway – Superconductors will have a significant impact on land transport and environment

Motivation for sustainable air transport
Global increase in air travel and greenhouse gas emissions

Oxford Quantum Solutions



Environmental impact (Co_2): forecast by mode of deployment



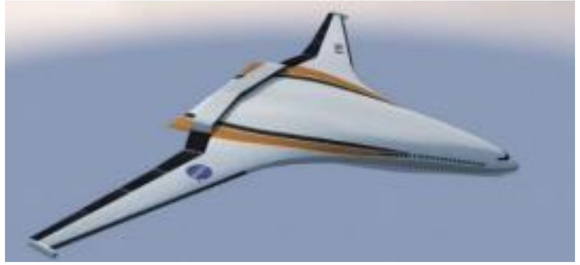
Key takeaway – Superconductors will have a significant impact on environment and decarbonisation

ziad.melhem@oxqsol.com

Electric planes with SC – Selected examples

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.

Progress with Electric planes

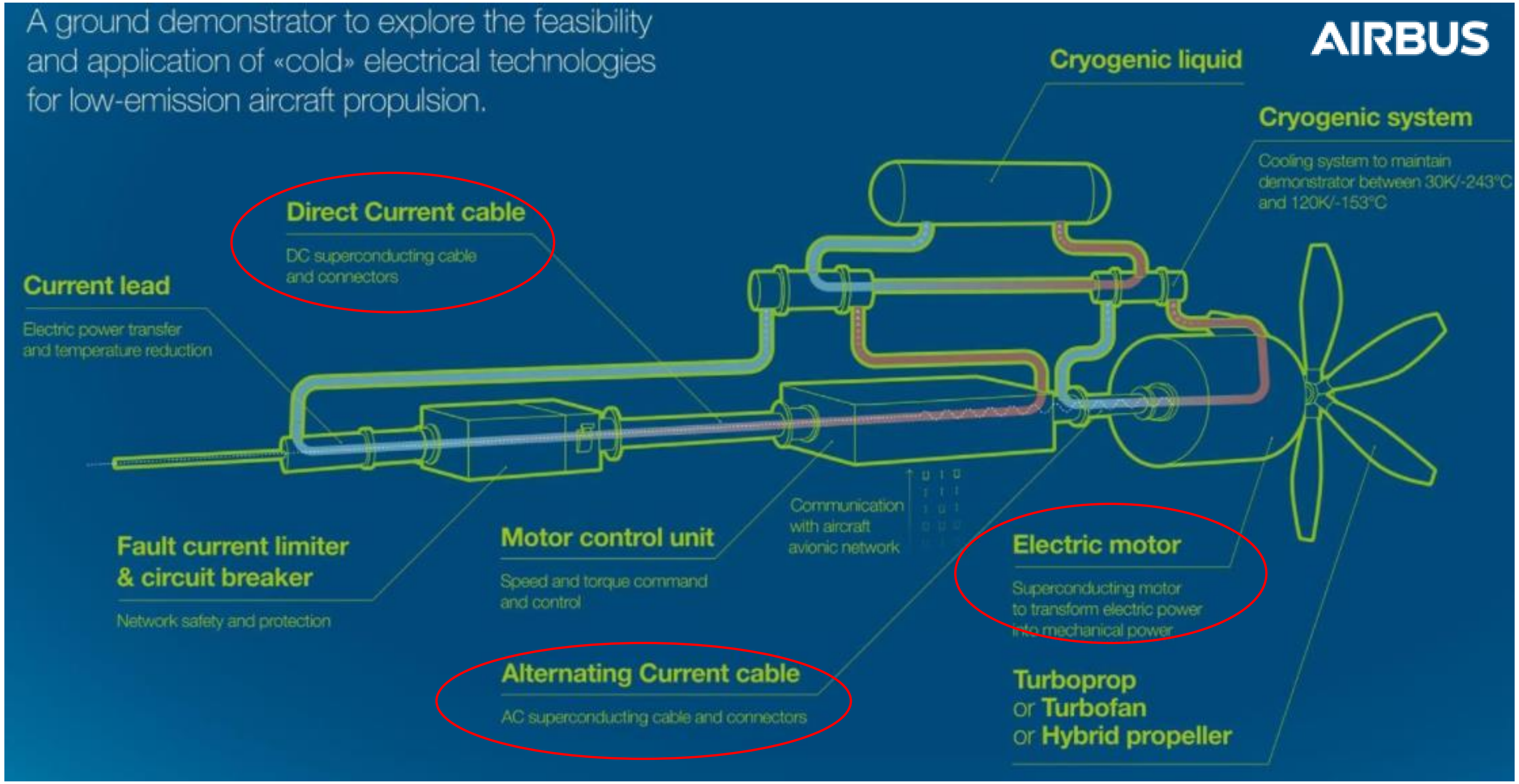
- Right building blocks are in place to have a viable large-plane EAP configuration tested by 2025
- Entry into service in 2035

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

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 focused on the conversion part.”



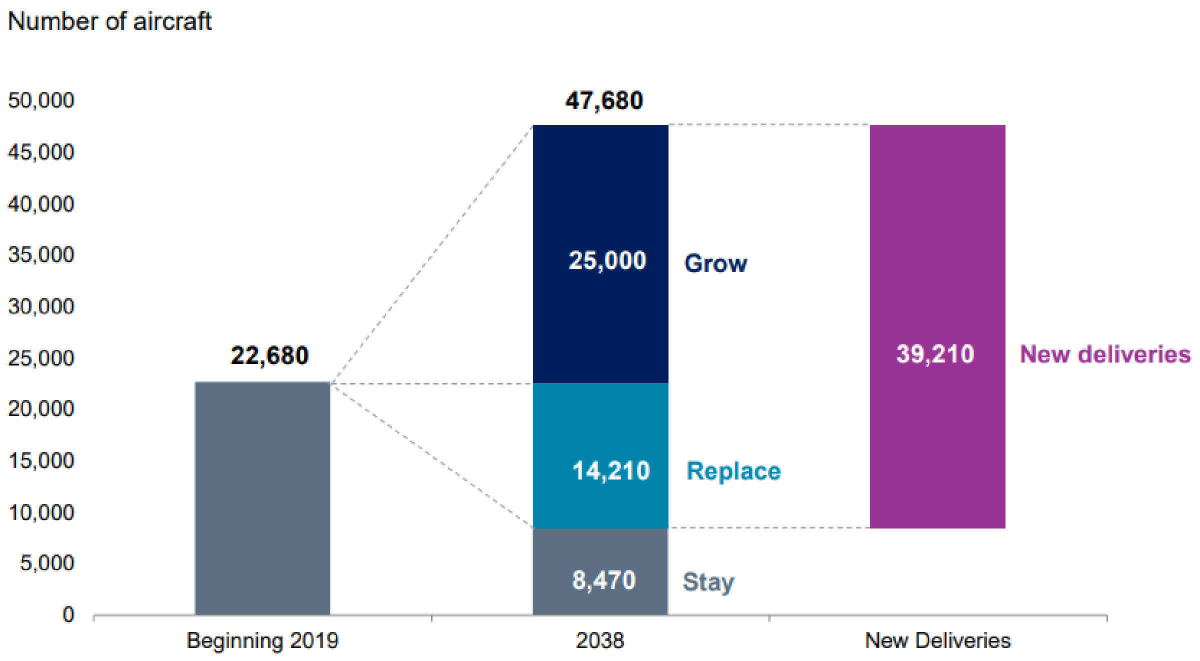
Key takeaway - Potential benefits from SC

- ~ 50% of powertrain weight,
- ~ 50% electrical losses
- reduction in the voltage required to less than 500V.

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

Opportunities for Electric Planes – Massive!

36% of new deliveries for replacement, 64% for growth



CAGR of 12.2%

Potential Electric Plane components

- **Superconducting Opportunity**
  - SC cables
  - Generators
  - Motors
  - Energy Storage
  - Propulsion

Key takeaway - Forecast of Electric Planes Opportunities

Superconducting/Cryogenics share ~ 20-30% by 2030 (~USD 3 B)

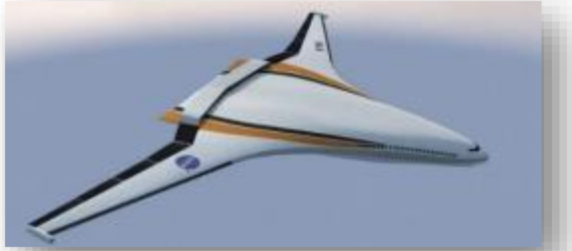
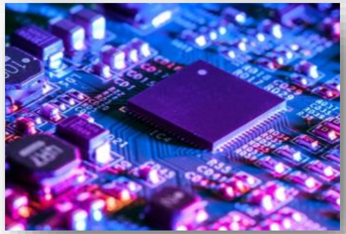
Airbus-GMF2019-presentation-Christian-Scherer.pdf

https://www.marketsandmarkets.com/Market-Reports/aircraft-electrification-market-31650461.html

Concluding Remarks

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

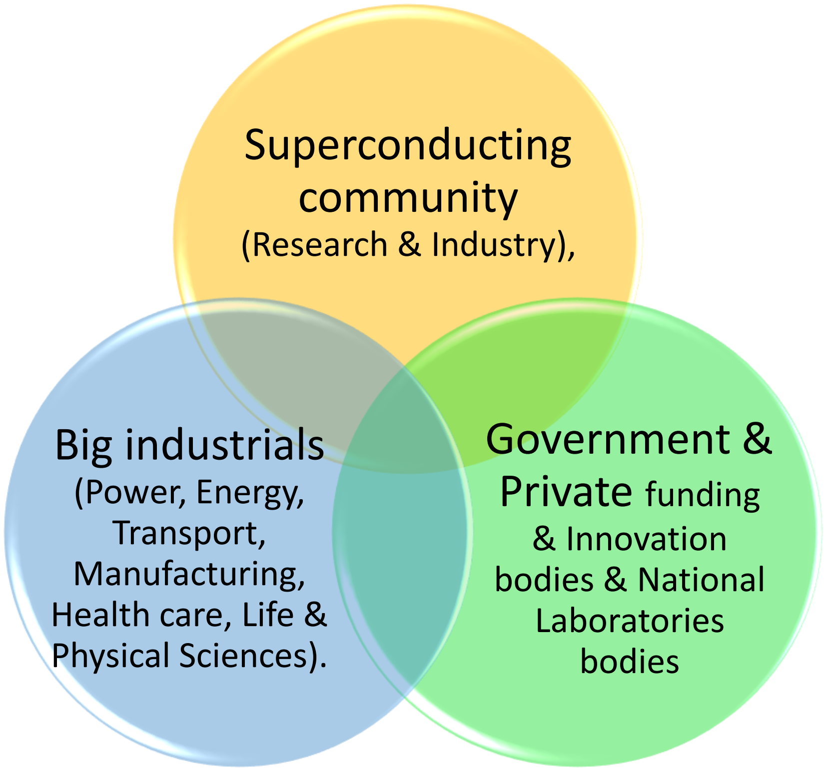







We need new thinking on developing Superconducting Products

- Diverse challenges identified by the UN 17 SDG's and the aggressive targets of decarbonisation by 2050 require a new initiative on developing SC products for
  - Cleaner, healthier and sustainable future
- Realising the potential of SC in addressing our societal future needs will require new thinking on capturing and harnessing the enormous potential of SC . At the heart of it is establishing a three-way partnership between SC Community, Government and Big Industrials
- We are developing an initiative to identify grand challenges and a mechanism to develop the role of SC in addressing the future societal challenges.
  - Planning for an International Summit on SC Products
  - A Focused Workshop on SC initiative will be held in July 2022 to plan for the summit
    1. Develop a Strategic Roadmap for SC solutions and commercial products
    2. Develop a partnership between the SC community, Government and Private Funding and Big Industrials
    3. Shortlist of grand SC challenges that can make a difference
    4. Establish working groups to draft proposals and mechanisms for the shortlisted SC challenges
    5. Establish a mechanism for sustaining the development of commercial SC solutions and products linked the 17SDGs



Such an initiative will significantly enhance the SC market