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

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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
Greenland 2021 - melting 6 X times faster than 1990

Antarctica Icebergs melting fast!

Europe 15th July 2021

California 18th July 2021

UAE 17th July 2021

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

<table>
<thead>
<tr>
<th>DELWP outcomes</th>
<th>Core SDG</th>
<th>Additional SDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net-zero emission, climate-ready economy and community</td>
<td>13 Climate action</td>
<td>7 Affordable and clean energy</td>
</tr>
<tr>
<td>Healthy, resilient and biodiverse environment</td>
<td>15 Life on land</td>
<td>11 Sustainable cities and communities</td>
</tr>
<tr>
<td>Safe, sustainable and productive water resources</td>
<td>6 Clean water and sanitation</td>
<td>11 Sustainable cities and communities</td>
</tr>
<tr>
<td>Reliable, sustainable and affordable energy services</td>
<td>7 Affordable and clean energy</td>
<td>12 Responsible consumption and production</td>
</tr>
<tr>
<td>Productive and effective land management</td>
<td>11 Sustainable cities and communities</td>
<td>13 Climate action</td>
</tr>
<tr>
<td>A safe and quality built-environment</td>
<td>8 Decent work and economic growth</td>
<td>10 Reduced inequality</td>
</tr>
<tr>
<td>Reduced impact of major bushfires and other emergencies on people, property and the environment</td>
<td>11 Sustainable cities and communities</td>
<td>15 Life on land</td>
</tr>
</tbody>
</table>

SC for Energy generation & power management

SC for Medical diagnostics, medical treatment And drug discovery

SC for Digital age
Estimated Global Electricity Generation Mix


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

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

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

Overview
From discovery by accident to commercialisation

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 4.3 K 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”

Humble beginnings ... Oxford Instruments
in commercial Superconducting magnet technology – 4 Tesla

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

Courtesy of Oxford Instruments

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> 25 Nobel Prizes - SC, Quantum & Cryogenics

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

**Industrial applications**
- Non-destructive Testing
- Inductive Heaters
- Magnetic separation
- Crystal Growth

**Microelectronics**
- Quantum Computing
- Faster Computers
- Power Electronics

**Communications**
- Satellite channels
- Wireless devices
- Antennae

**Defence & Security**
- Detectors/Sensors
- Rail gun
- Degaussing cables

**Research & Medical Magnets**
- Medical - MRI, NMR, Proton Beam 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

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

**Transportation**
- Electric planes
- Maglev
- Ships
- Rocket propulsion

**Research & Medical Magnets**
- Medical - MRI, NMR, Proton Beam Therapy
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**Transportation**
- Electric planes
- Maglev
- Ships
- Rocket propulsion

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Superconducting materials
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

<table>
<thead>
<tr>
<th>Material Type</th>
<th>NbTi</th>
<th>Nb₃Sn</th>
<th>MgB₂</th>
<th>Bi₂Sr₂CaCu₂O₈ (Bi-2212)</th>
<th>Bi₂Sr₂Ca₂Cu₂O₈ (Bi-2223)</th>
<th>YBa₂Cu₃O₇ (ReBCO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_c (K)</td>
<td>10</td>
<td>18.5</td>
<td>39</td>
<td>95K</td>
<td>110</td>
<td>92</td>
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<tr>
<td>B_{max} (T)</td>
<td>9.5 @4.2 K</td>
<td>11.5 @1.8 K</td>
<td>20 @ 4.2 K</td>
<td>23 @2 K</td>
<td>5-10 @4.2K</td>
<td>2-5 @10 K</td>
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<tr>
<td>Material type</td>
<td>Ductile metal alloy</td>
<td>Brittle intermetallic</td>
<td>Brittle intermetallic</td>
<td>Ceramic oxide</td>
<td>Ceramic oxide</td>
<td>Ceramic oxide</td>
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<tr>
<td>Conductor shape</td>
<td>Multi-filamentary Rnd wire</td>
<td>Multi-filamentary Rnd wire</td>
<td>Multi-filamentary Rnd wire, flat tape</td>
<td>Multi-filamentary flat tape</td>
<td>Thin film coated conductor</td>
<td></td>
</tr>
<tr>
<td>Production Supply</td>
<td>Mature</td>
<td>Mature</td>
<td>Prototype-R&amp;D</td>
<td>Prototype-R&amp;D</td>
<td>Prototype-R&amp;D</td>
<td>Prototype-R&amp;D</td>
</tr>
</tbody>
</table>

1962

NbTi

Pnictides

Under Pressure

Yellow - CWC

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Superconducting materials – Performance and cost

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.

<table>
<thead>
<tr>
<th>Material</th>
<th>NbTi</th>
<th>Nb3Sn</th>
<th>MgB2</th>
<th>Bi2Sr2CaCu2O8 (Bi-2212)</th>
<th>Bi2Sr2CaCu2O8 (Bi-2223)</th>
<th>YBa2Cu3O7 (ReBCO)</th>
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</thead>
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<tr>
<td>$T_c$ (K)</td>
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Mikhail Eremets Plenary: A Path Towards Room Temperature – ASC 2020-25th Nov 2020

Room temperature

Liquid N$_2$

BCS theory

$T_c$ K

Time, year

1900 1920 1940 1960 1980 2000

1962 NbTi

HgTIBa2CaCu3Ox

FeSe

MgB2

SiF FeA

$\text{Hg}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_8$

$\text{Hg}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_8$

$\text{Hg}_2\text{Pb}_2\text{Hg}$

La$_3$ $\text{Ba}_2$ $\text{Cu}_3$ $\text{O}_8$

$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3$ $\text{O}_8$

$\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3$ $\text{O}_8$ (Bi-2223)

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

28% World production

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
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
Opportunities

Nanotechnology Applications
Opportunities ...

Superconducting magnets for nanotechnology and materials research

Optics/DC

1.5-300 K

7 T

Optics/RF

< 10 mK

8-18 T

New materials and new science

< 10 mK

Up to 16 T

2-4 K

Up to 32 T

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

Courtesy of Oxford Instruments

Courtesy of Lancaster University

Courtesy of Bruker

Courtesy of NHMFL

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SC magnet development timeline and high field

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


 Courtesy of Bruker

 Courtesy of NHMFL
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

IBM demonstrated a 50 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

**Key takeaway** – SC qubits leading the way towards Quantum computers and embraced by big industrials
Quantum metrology – smart science to industrial applications

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+Chlamers+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

1 ppb • Quantum standard
10 ppb • Secondary standard
100 ppb • Calibration laboratory
1 ppm • Company ‘master’ item
10 ppm • Company production equipment
100 ppm • Product

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

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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
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 refrigerators
    - 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

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

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

1st MRI
1st Active shield (AS)
AS 1.5T
1.5T Small
AS 3T
AS 4T
11.7T
7T
9.4T
1.5T
Small
AS 3T
AS 1.5T
1st Open MRI Magnet
7T
11.7T

Courtesy of Siemens

1980
1986
1989
1994
1997
2000
2001
2005
2019
2021

Courtesy of
Siemens

Courtesy of
CEA

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New High Field NMR with HTS

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.

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

Oxford Instruments
Only LTS – NbTi, Nb3Sn

Bruker Biospin
LTS +HTS – NbTi, Nb3Sn, ReBco
Medical Therapy

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

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

**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

<table>
<thead>
<tr>
<th></th>
<th>LHC</th>
<th>FCC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference (km)</td>
<td>26.7</td>
<td>97.5</td>
</tr>
<tr>
<td>Dipole field (T)</td>
<td>8.33</td>
<td>16</td>
</tr>
<tr>
<td>C.o.M. energy (TeV)</td>
<td>14</td>
<td>100</td>
</tr>
</tbody>
</table>
Super Proton Proton Collider (SPPC) - China

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

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

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Opportunities

Fusion
Nuclear Fusion – ITER using LTS

• **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
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

Commonwealth Fusion Systems, MIT

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Opportunities

Power and Energy with HTS
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
– SC wind power generation

- 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

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

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

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

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Energy storage and power transmission and distribution

2014

**Ampacity**  ReBCO tape FCL 12kV 2.3kA
protecting superconducting cable in Essen city grid

**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

10 MVA/1 s SMES at Kameyama field test, in Japan.
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!
### Table 1: HTS Cable Projects in the United States

<table>
<thead>
<tr>
<th>Project</th>
<th>Long Island 2</th>
<th>HYDRA Phase 2</th>
<th>HYDRA Phase 3</th>
<th>US Navy DC Cable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Long Island, NY, USA</td>
<td>Norwalk, NY, USA</td>
<td>Chicago, IL, USA</td>
<td>Florida State University</td>
</tr>
<tr>
<td>Site</td>
<td>Hillside Substation</td>
<td>Granite Hill-Rockview</td>
<td>Chicago downtown area</td>
<td>Center for Advanced Technology</td>
</tr>
<tr>
<td>Status</td>
<td>Operational</td>
<td>Operational</td>
<td>Operational</td>
<td>Operational</td>
</tr>
<tr>
<td>Developer</td>
<td>AMSC</td>
<td>AMSC</td>
<td>AMSC</td>
<td>AMSC</td>
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<tr>
<td>Utility/Host</td>
<td>NYPA</td>
<td>NYPA</td>
<td>NYPA</td>
<td>NYPA</td>
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<tr>
<td>End Date</td>
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<td>2016</td>
<td>2017</td>
<td>2018</td>
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<tr>
<td>Type</td>
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<td>Phase</td>
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<tr>
<td>Voltage</td>
<td>10.5 kV</td>
<td>10.5 kV</td>
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<td>Current</td>
<td>2.3 kA (30 MVA)</td>
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<td>Length</td>
<td>100 m</td>
<td>100 m</td>
<td>100 m</td>
<td>100 m</td>
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<tr>
<td>Fault Current</td>
<td>5.8 kA, 8 cycles</td>
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</tr>
</tbody>
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### Table 2: HTS Cable Projects in Europe

<table>
<thead>
<tr>
<th>Project</th>
<th>Ampacity</th>
<th>Best Paths</th>
<th>St. Petersburg</th>
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<tbody>
<tr>
<td>Location</td>
<td>Essen, Germany</td>
<td>Germany and Switzerland</td>
<td>St. Petersburg, Russia</td>
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<tr>
<td>Site</td>
<td>Delbrück Substation</td>
<td>Hannover and CERN</td>
<td>St. Petersburg, Russia</td>
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<tr>
<td>Status</td>
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<td>Operational</td>
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<td>Developer</td>
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<td>AMSC</td>
<td>AMSC</td>
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<tr>
<td>Utility/Host</td>
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<tr>
<td>Voltage</td>
<td>10.5 kV</td>
<td>10.5 kV</td>
<td>10.5 kV</td>
</tr>
<tr>
<td>Current</td>
<td>2.3 kA (30 MVA)</td>
<td>2.3 kA (30 MVA)</td>
<td>2.3 kA (30 MVA)</td>
</tr>
<tr>
<td>Length</td>
<td>100 m</td>
<td>100 m</td>
<td>100 m</td>
</tr>
<tr>
<td>Fault Current</td>
<td>5.8 kA, 8 cycles</td>
<td>5.8 kA, 8 cycles</td>
<td>5.8 kA, 8 cycles</td>
</tr>
</tbody>
</table>

### Table 3: HTS Cable Projects in Japan and South Korea

<table>
<thead>
<tr>
<th>Project</th>
<th>Azuki</th>
<th>Jukju DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Yokohama, Japan</td>
<td>Jukju, South Korea</td>
</tr>
<tr>
<td>Site</td>
<td>Ashin Substation</td>
<td>Hannover Substations</td>
</tr>
<tr>
<td>Status</td>
<td>Operational</td>
<td>Operational</td>
</tr>
<tr>
<td>Developer</td>
<td>AMSC</td>
<td>AMSC</td>
</tr>
<tr>
<td>Utility/Host</td>
<td>JEPD</td>
<td>JEPD</td>
</tr>
<tr>
<td>Start Date</td>
<td>Oct, 2012</td>
<td>Oct, 2014</td>
</tr>
<tr>
<td>End Date</td>
<td>Dec, 2013</td>
<td>Oct, 2014</td>
</tr>
<tr>
<td>Type</td>
<td>AC</td>
<td>DC</td>
</tr>
<tr>
<td>Phase</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Voltage</td>
<td>10 kV</td>
<td>10 kV</td>
</tr>
<tr>
<td>Current</td>
<td>2.3 kA (30 MVA)</td>
<td>2.3 kA (30 MVA)</td>
</tr>
<tr>
<td>Length</td>
<td>240 m</td>
<td>240 m</td>
</tr>
<tr>
<td>Fault Current</td>
<td>5.8 kA, 8 cycles</td>
<td>5.8 kA, 8 cycles</td>
</tr>
<tr>
<td>Diode Design</td>
<td>Cold diode</td>
<td>Cold diode</td>
</tr>
<tr>
<td>Diode Material</td>
<td>YBCO</td>
<td>YBCO</td>
</tr>
<tr>
<td>AC Loss</td>
<td>Not available</td>
<td>Not available</td>
</tr>
<tr>
<td>Cable Fabrication</td>
<td>Not applicable</td>
<td>Not applicable</td>
</tr>
<tr>
<td>Refrigeration</td>
<td>6 kW @ 85 K (pillared system proposed)</td>
<td>6 kW @ 85 K (pillared system proposed)</td>
</tr>
</tbody>
</table>

- 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

Flightradar24’s 2019

Environmental impact (CO₂): forecast by mode of deployment

Key takeaway – Superconductors will have a significant impact on environment and decarbonisation
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 Advanced Superconducting & Cryogenic Experimental powertrain Demonstrator (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!

Key takeaway - Forecast of Electric Planes Opportunities
Superconducting/Cryogenics share ~ 20-30% by 2030 (~USD 3 B)

Potential Electric Plane components
- Superconducting Opportunity
  - SC cables
  - Generators
  - Motors
  - Energy Storage
  - Propulsion
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