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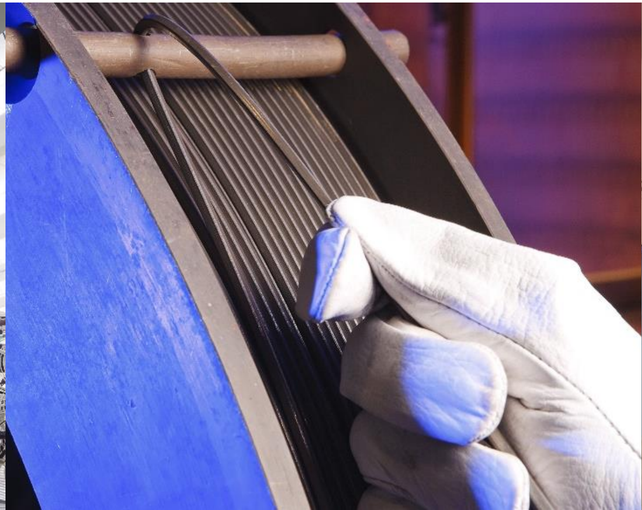
ASG SUPERCONDUCTORS



MgB_2 superconducting wires for electric aircraft: advantages and future perspectives

T. Spina, C.E. Bruzek and G. Grasso

August 2022

www.asgsuperconductors.com

OUTLINE

- Introduction: superconductors for Aircraft
- Status-of-art of Ex-situ MgB_2 wires at ASG superconductors
- MgB_2 improvement: the need of low AC losses conductor
- Conclusions

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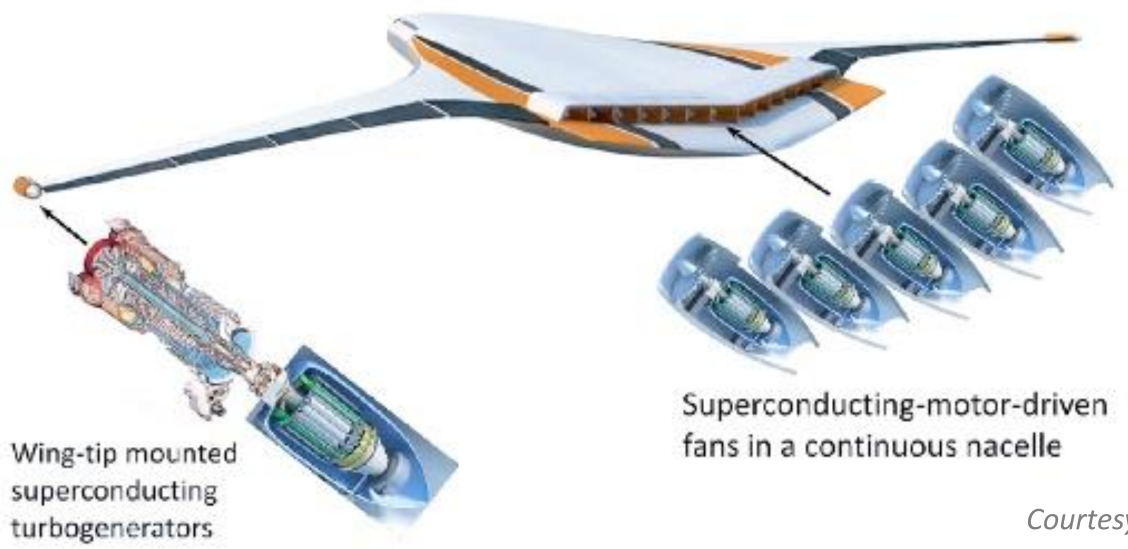
INTRODUCTION: THE N3X AIRCRAFT

https://www1.grc.nasa.gov/aeronautics/eap/airplane-concepts/n3x/



Courtesy by NASA

The N3X aircraft assessment predicted a nominally **20-percent fuel burn improvement** for the **superconducting**, fully distributed architecture over an equivalent vehicle with advance turbofan engines mounted on pylons.

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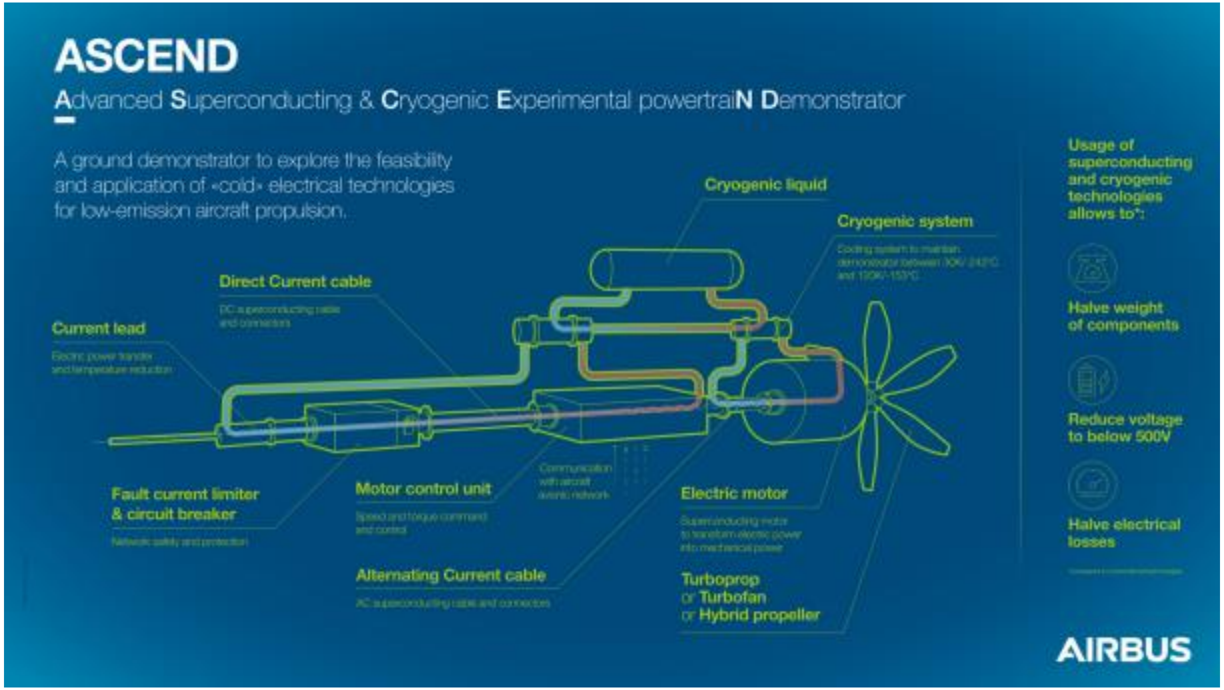
INTRODUCTION: ASCEND

The three-year demonstrator project aims to show that an electric- or hybrid-electric propulsion system complemented by cryogenic and superconducting technologies can be more than **2 to 3 times lighter than a conventional system**



To achieve this objective, ASCEND features a **500kW powertrain** consisting of the following components:

- A **superconducting distribution system**, including cables and protection item
- **Cryogenically cooled motor** control unit
- A **superconducting motor**
- A **cryogenic system**

https://www.airbus.com/en/newsroom/stories/2021-03-cryogenics-and-superconductivity-for-aircraft-explained

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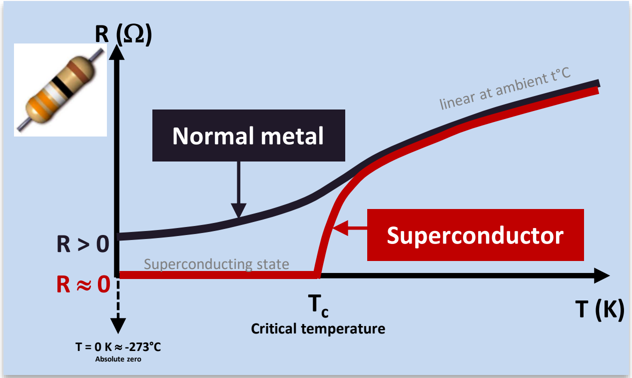
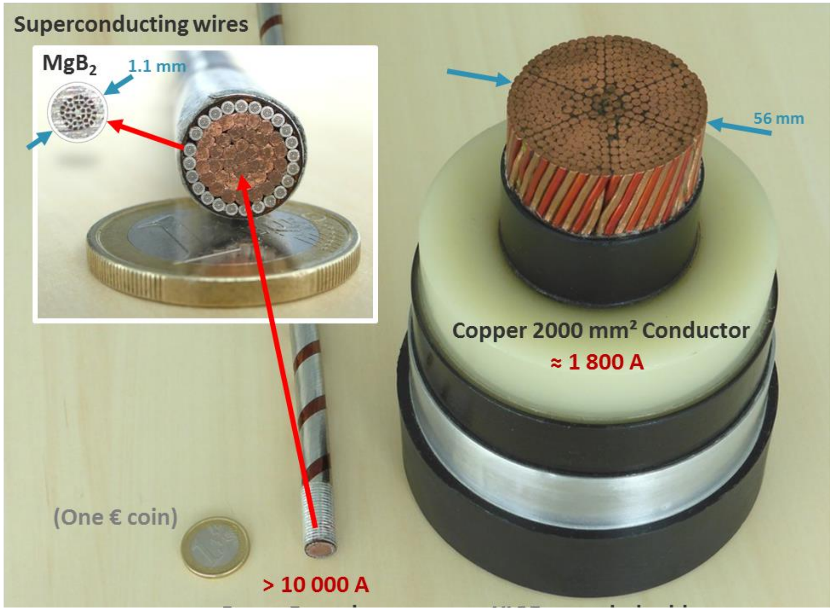
WHY SUPERCONDUCTORS FOR ELECTRICAL AIRCRAFT?

A superconductor is a material that shows zero resistance below a critical temperature (T_c)



zero resistance → **zero power dissipation**



ADVANTAGES of S.C. w.r.t N.C.:

1. Higher current
2. Lower (almost zero) Joule electrical losses

→

Superconducting machines can fundamentally achieve:

- **higher electrical efficiency**
- **higher specific power** (or power density)

than conventional machines

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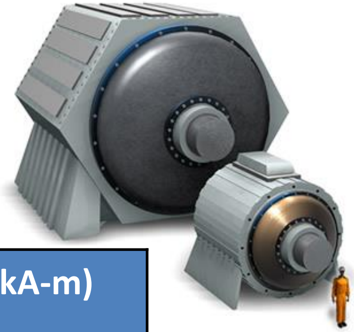
SUPERCONDUCTIVITY ENABLES A LIGHTWEIGHT TECHNOLOGY FOR AIRCRAFT



1. Superconductors are **lighter** than normal conductors (i.e. Cu, Al, etc.)
2. Superconductor **specific weight g/m** is mainly driven by the **metallic matrix**
3. MgB_2 wire specific weight could be reduce by a **factor 2** if titanium is used instead than nickel alloys matrix (on-going at ASG)

	Material	g/cm³	Shapes	Wire specific weight	I_c @1T; 20K	kg/(kA-m)
Resistive conductor	**Cu**	8,94	Tapes or Wires	Dependant on the diameter	1 A/mm²*	9
	Al	2,71	Tapes or Wires		0,4 A/mm²*	6,8
Superconductors	**MgB_2**	2,57	Tapes or Wires (1,33mm ø)	6-10 g/m	720 A	**~0,01**
	Bi2223	6,8	Tapes (0,3x4,3 mm)	8 g/m	1100 A	**~0,008**
	ReBCO	6,3	Tapes (0,2x4mm)	3,5-7 g/m	700-750 A	**0,006 to 0,01**

**air cooled*

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HTS enables Hydrogen powered aircraft

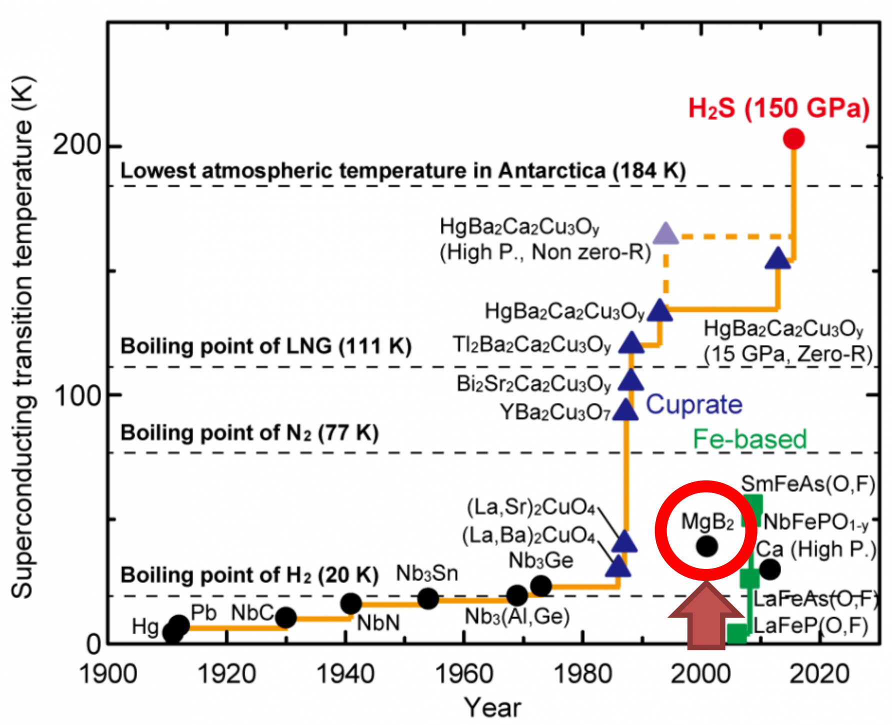
Low Density=low weight

*Values at 15 bar

Properties	LHe	LH_2	LN_2
Liquid T (K)	4.2K	20K	70K
Density (Kg/m³)	160	72	840
C_p (J/kg.K)	2600	9000	2000
Viscosity (µPa.s)	5,7	15,1	225
Solid T(K)	2,18 (superfluid)	14,5	64
Boil T(K)	5,2 (supercritical)	33	110

High C_p = Excellent coolant

Low Viscosity= Easy flow



Liquid H_2 is the best coolant for MgB_2 application (T_c=39K)

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SUPERCONDUCTING MACHINES (IN COLLABORATION WITH SAFRANTECH)

Superconducting machines

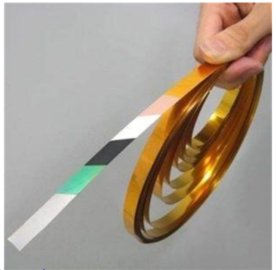
Superconducting rotors (DC) **And / or** **Superconducting stators (AC)**

Superconducting rotors (DC):
- Medium weight reduction potential
- Small efficiency improvement
- **Cryogenic cooling power required ~ 10 W**

Superconducting stators (AC):
- High weight reduction potential
- High efficiency improvement
- **Cryogenic cooling power required ~ 1000 W**

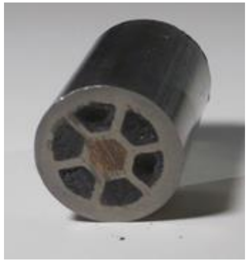
REBaCuO

- Highest current density potential
- **Critical temperature < 93 K**



MgB_2

- Highest efficiency potential
- **Critical temperature < 39 K**



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SUPERCONDUCTORS FOR AC STATOR WINDINGS: A RECENT COMPARATIVE STUDY

IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 31, NO. 9, DECEMBER 2021 5206807

Motors Employing REBCO CORC and MgB_2 Superconductors for AC Stator Windings

Swarn S. Kalsi, *Life Fellow, IEEE*, Rodney A. Badcock, *Senior Member, IEEE*,
James G. Storey, *Member, IEEE*, Kent A. Hamilton, *Member, IEEE*, and Zhenan Jiang, *Senior Member, IEEE*

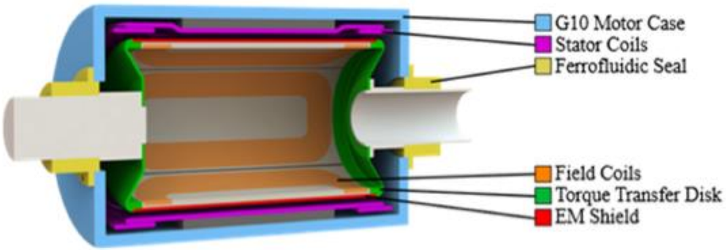

Fig. 1. Conceptual configuration of a superconducting synchronous motor.

TABLE I
SPECIFICATIONS FOR A 3 MW, 4500-RPM AIRCRAFT PROPULSION MOTOR

Parameter	Value
Motor Rating	3 MW
Motor Speed	4,500 RPM
Line Voltage	~1000 V
Rated power factor	0.9 lag
Motor diameter	< 500 mm
Axial length	< 800 mm
Field excitation winding	CORC
Armature winding	CORC and MgB_2
Operating temperature	20 K
Ambient temperature	120 K

TABLE VI
AC LOSSES IN STATOR COILS

Parameter	CORC	MgB_2
Hysteresis, W	23700	328
Coupling, W	0	364
Current Transport, W	7250	27
Total, W	**30900**	**727**

Both motors look attractive if the penalty of the cooling system is ignored—power density (>40 kW/kg) and efficiency (>99%). On the other hand, if refrigerators are needed then the REBCO CORC motor, with its higher AC losses, becomes less attractive.

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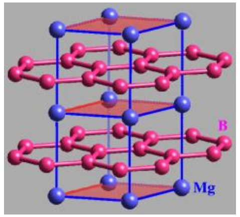
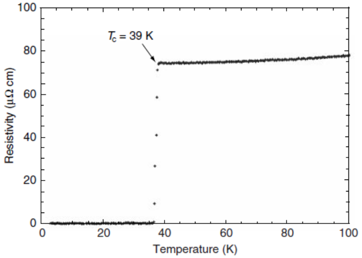
MgB_2 SUPERCONDUCTING PROPERTIES

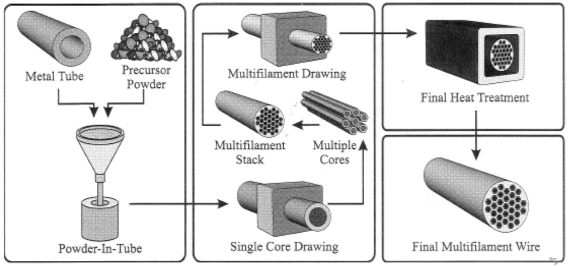
T_c compatible with operation in LH_2 simple structure and common materials

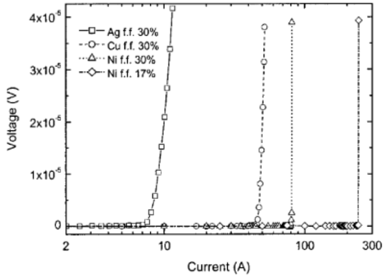




Nagamatsu et al. 2001
Superconductivity at 39K in magnesium diboride
Nature 410 63-4

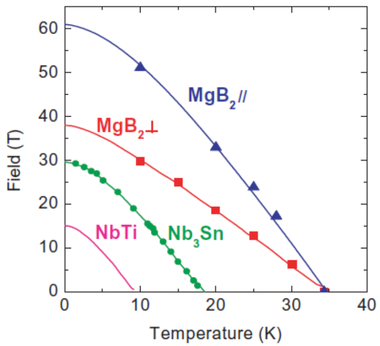
Easy process for wire fabrication (PIT: Powder In Tube)





G.Grasso et .al. 2001
Large transport current in unsintered MgB_2 SC tapes
APL Volume 72, number 9

High critical field (over 60T)



Iwasa Y et al. 2006
A round table discussion on MgB_2: towards a wide market or a niche production?
IEEE Trans. Appl. Supercond 16 1457-64

Low density

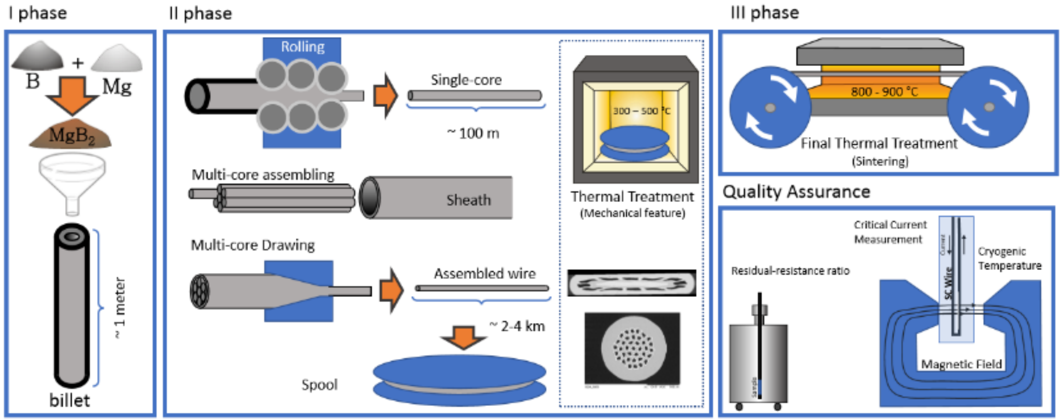
Compound	Mass density
Copper	8,96 g/cm^3
NbTi	6 g/cm^3
Nb3Sn	5,4 g/cm^3
YBCO	6,35 g/cm^3
BSCCO-2223	6,5 g/cm^3
MgB_2	**2,6 g/cm^3**

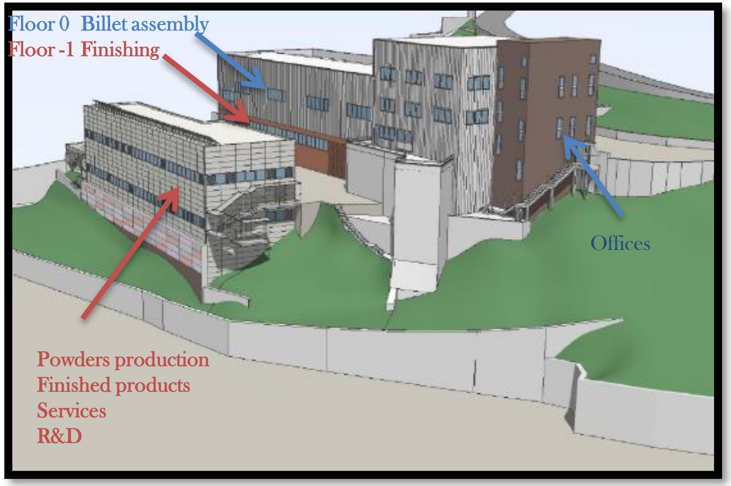
Advantages:

1. Material abundant and low cost (Mg , B, metallic sheaths,..)
2. Simple production process (no grain orientation required)
3. High mechanical properties in all direction (no need of reinforcements)
4. Higher T_c and T_{op} than other metallic materials (LTS)

MgB_2 EX-SITU «POWDER IN TUBE» WIRES

Ex-situ MgB_2 production process unique by ASG production plant installed entirely in Genoa, Italy;





- Actual plant is fully operational for **MgB_2 wire production**
- **MgB_2 chemical synthesis** is fully implemented and ready to be used **without final heat treatment** (**"React & Wind" technology, R&W**)
- Wire unit length today up to **8 Km in a single piece –length**
- It will be possible up to >**20 Km in a single piece-length** with the ongoing full scale up of the process and of the plant with a nominal full capacity exceeding >1000Km/y

ASG SUPERCONDUCTORS
columbus mgb2 unit

Wire manufacturing equipment

Clean synthesis of powders

Multistep rolling machine

High power drawing machine

20 meter in-line furnace

Multistep drawing machine

4 meter furnace
for annealing HT

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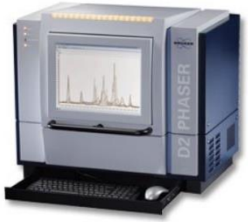
Quality Control (ISO 9001:2008)

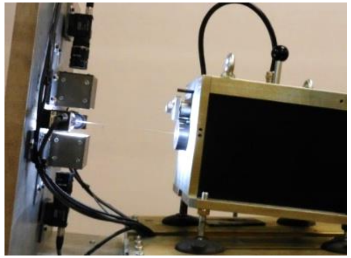
- Quality Control from **incoming raw material** to the **final product**
- Dedicated operative instructions and **procedure**
- **Real time** data collections of production and quality records
- **Materials analysis**:



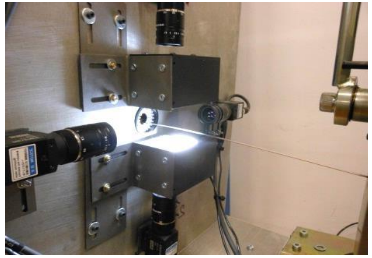
- SEM with EDX
- Optical stereomicroscopes
- Fast XRD
- Particle size analyzer

In-line defect detector

Eddy current detector
to check the product integrity



4 camera visual inspection
to check the surface appearance



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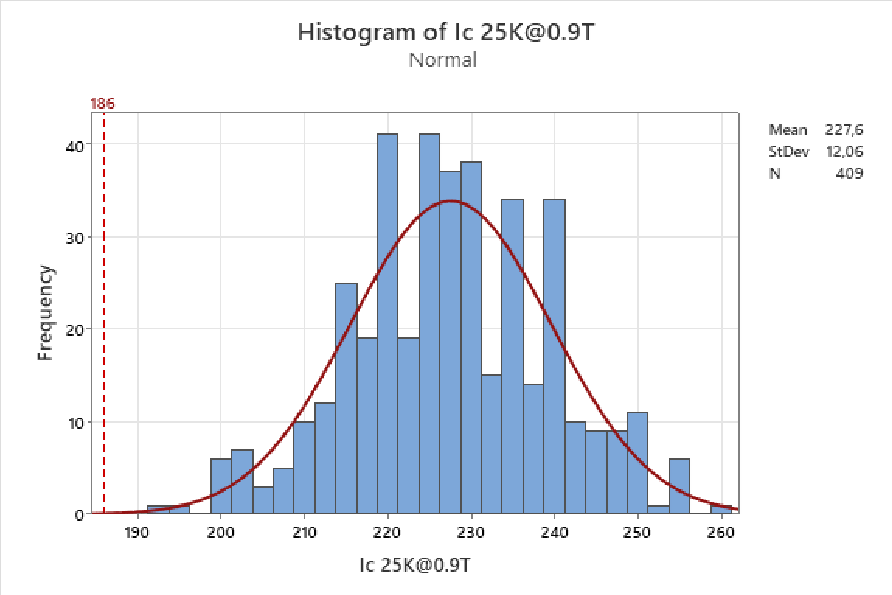
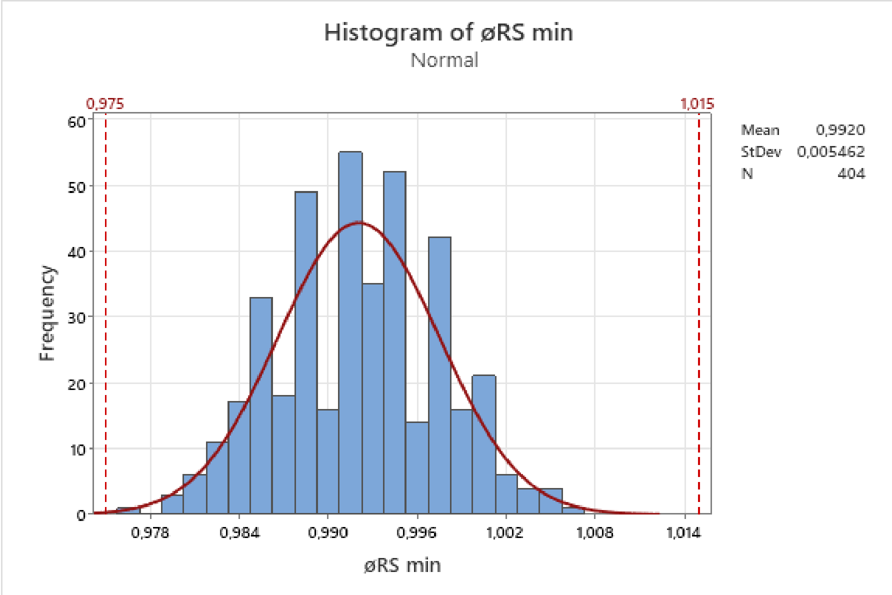
Stable and reproducible performances over 800 km of production

Critical current



I_c @25K/0,9 T = 227 A +/- 12

Wire diameter



D = 0,992 mm+/- 0,005

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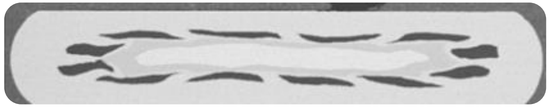
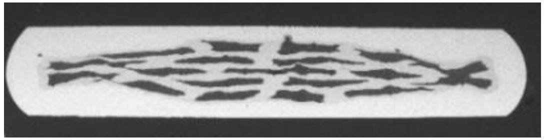
WIRE PRODUCTS PORTFOLIO

Production flexibility: different shape and materials possible

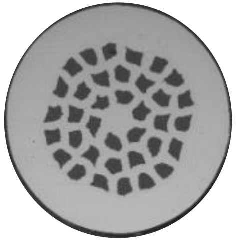
Tapes - Magnets

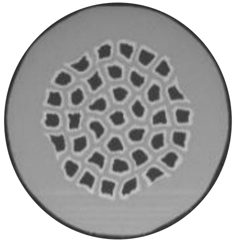




Materials	Unit piece length
Ni, Fe, Cu	typical 4km

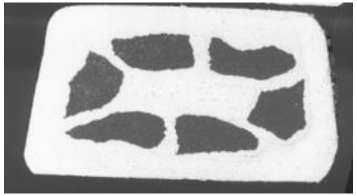
Round wires - cables





Materials	Unit piece length
Monel, Nb,Ni	typical 3,5km

Special/custom shapes



Materials	Unit piece length
Monel,Ni	Up to 8km

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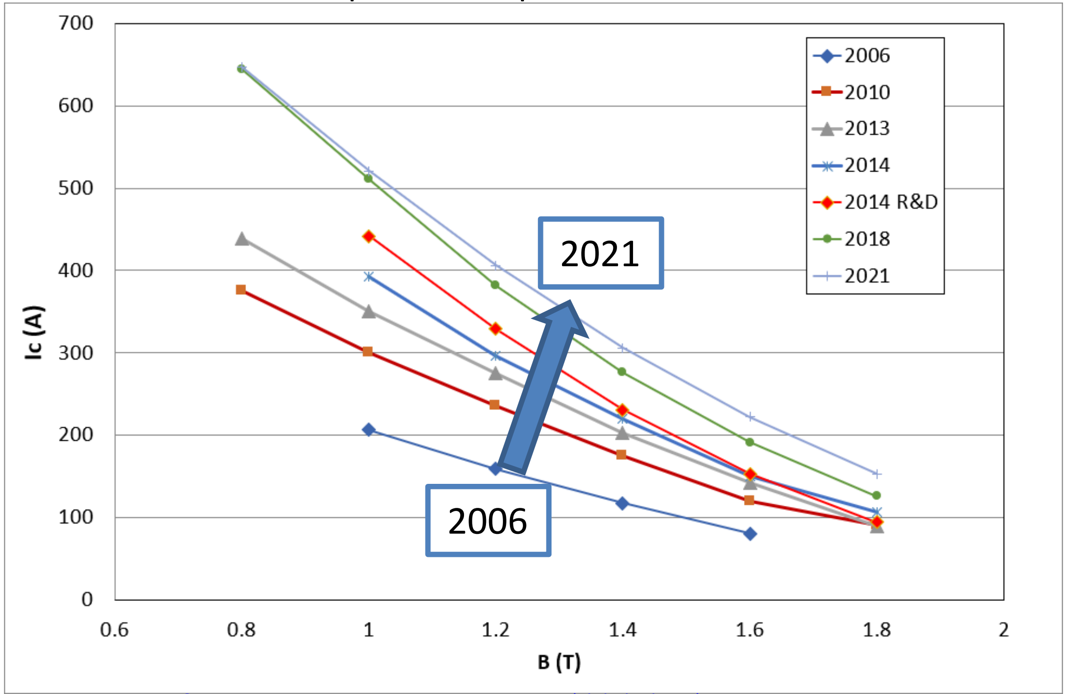
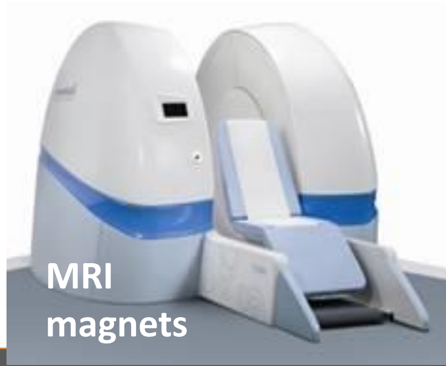
Performance Evolution enabled new technology

MR-Open conductor

- Validation of ex-situ ASG MgB_2 React & Wind technology
- Demonstrate the production of MgB_2 with high yield and low cost
- Two-fold improvement in performance over 15 years – reduction by 50% of wire needed
- Still a lot of space for improvements!

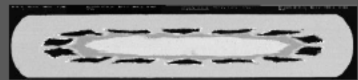


Reduction of volume possible thanks to s.c. performance improvement!



Wire layout in 2006:

- 14 filaments
- Unit piece length 1.6 Km



Updated wire layout:

- 12 filaments
- Improved fabrication process
- Unit piece length 4.0 Km

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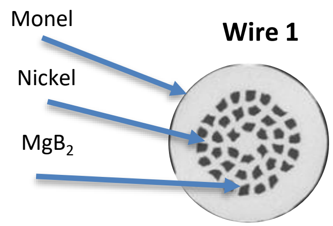
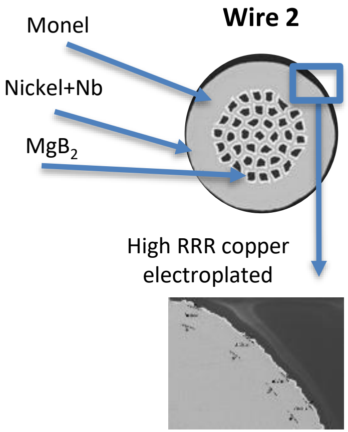
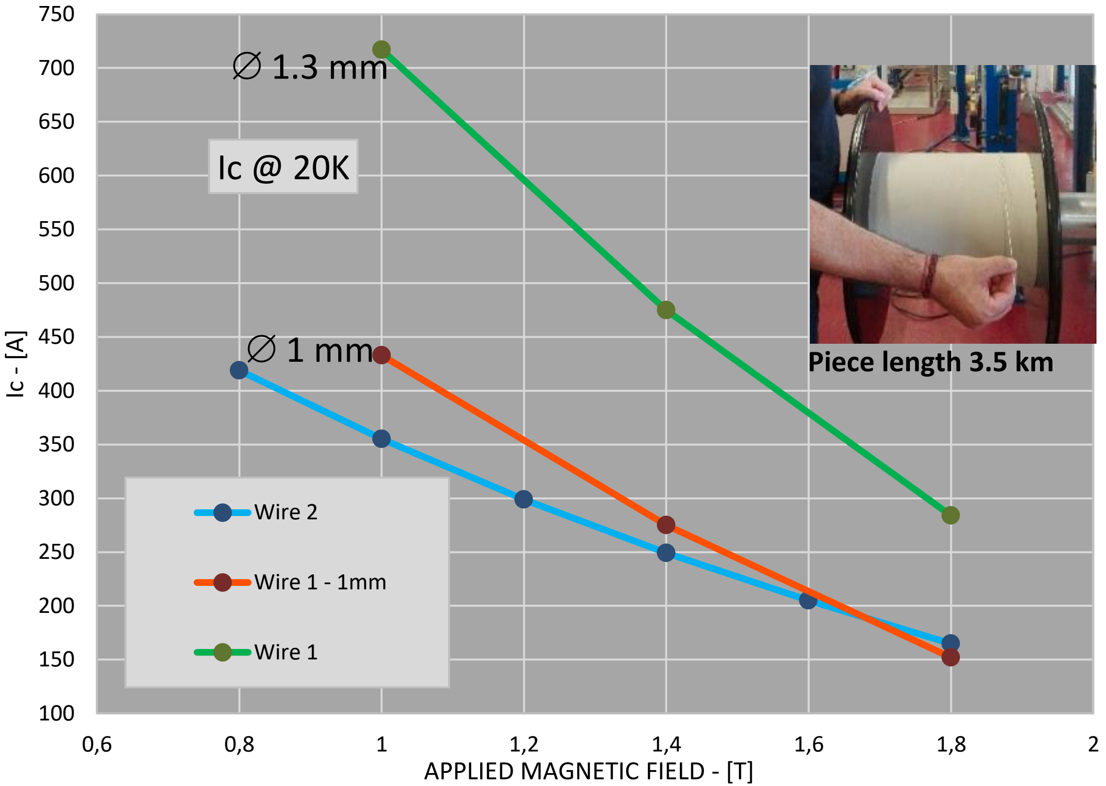
WIRES PERFORMANCE



Wire 1	
Diameter (mm)	1.3
Filaments	36
MgB_2	17%
Monel	53%
Nickel	30%



Wire 2	
Diameter (mm)	1
Filaments	37
MgB_2	12%
Monel	46%
Nickel	15%
Nb	13%
Copper	14%



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DC APPLICATIONS

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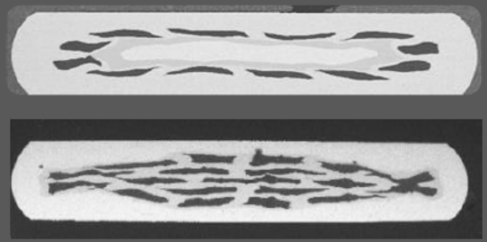
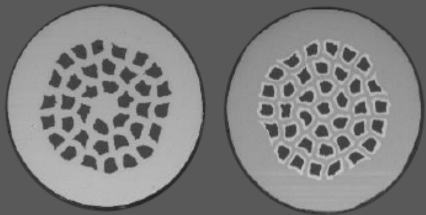
Tapes - Magnets



Materials	Unit piece length
Ni, Fe, Cu	typical 4km

Round wires - cables



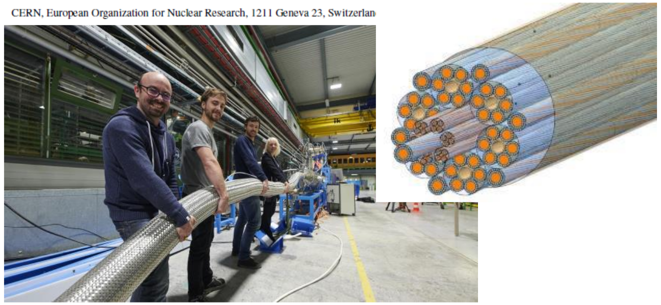
Materials	Unit piece length
Monel, Nb,Ni	typical 3,5km

IOP Publishing — Superconductor Science and Technology
Supercond. Sci. Technol. **27** (2014) 044024 (7pp) — doi:10.1088/0953-2048/27/4/044024

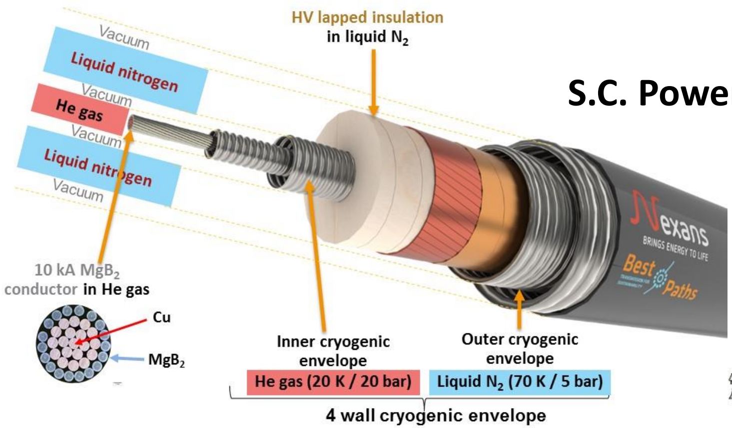
Development of superconducting links for the Large Hadron Collider machine

Amalia Ballarino

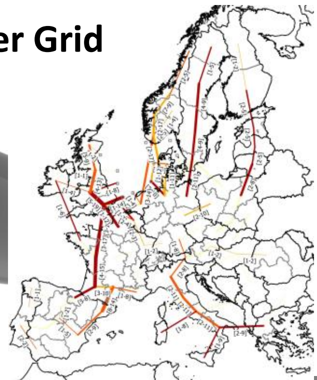
CERN, European Organization for Nuclear Research, 1211 Geneva 23, Switzerlan



PARAmed

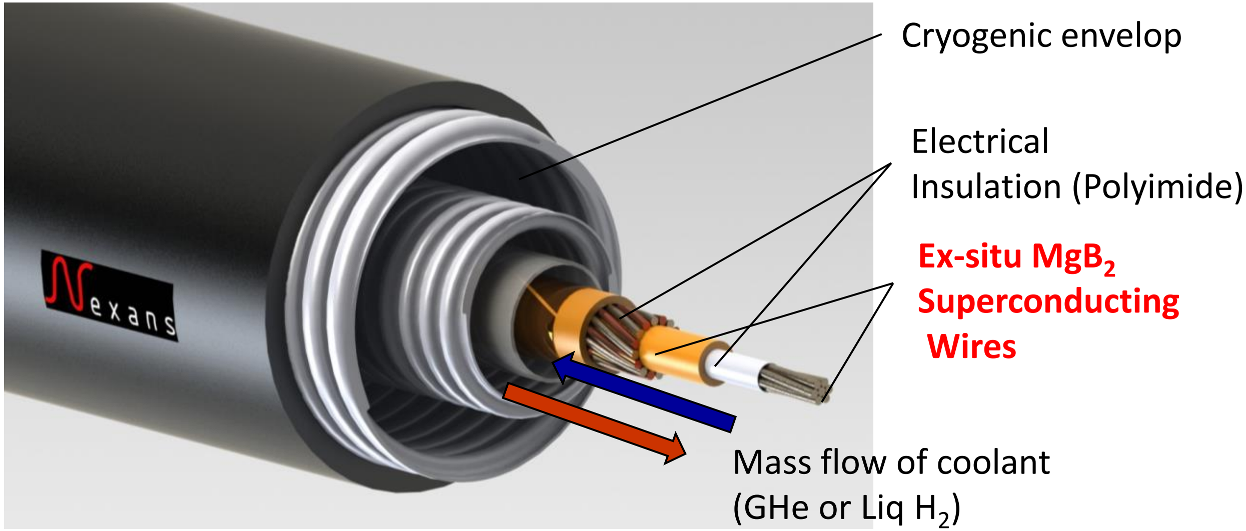


S.C. Power Grid



DC APPLICATION FOR AIRCRAFT

1. DISTRIBUTION OF SEVERAL MW POSSIBLE USING VERY HIGH CURRENT (SEVERAL KA) AT LOW VOLTAGE AND WITH LIMITED LOSSES
2. FAULT CURRENT LIMITING PROPERTIES SIMPLIFYING THE DISTRIBUTION SYSTEM (SUPERCONDUCTING-NORMAL TRANSITION)



Ready to be used!

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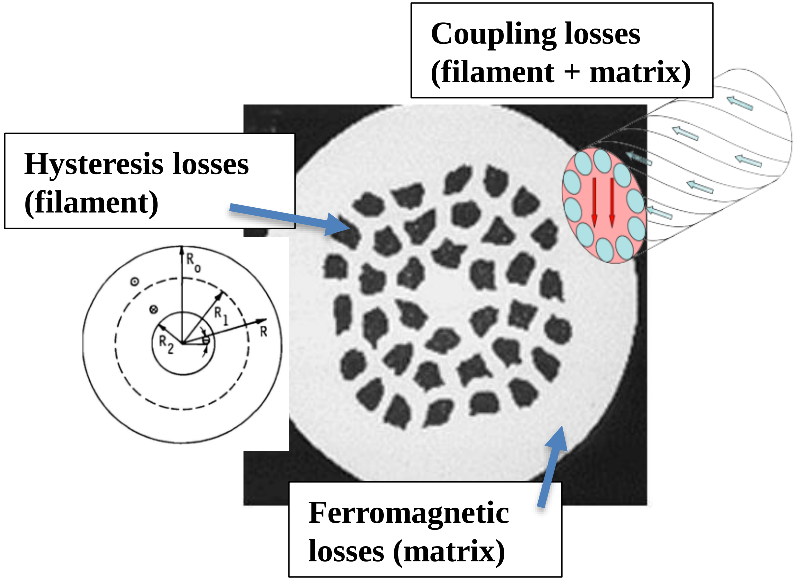
AC losses mechanisms in superconductors



Type	Source	Solution
Hysteresis losses (s.c. filament)	from superconducting screening currents	Smaller filament **diameter**
Coupling losses (s.c. filament)	from current loops crossing the matrix	Smaller **twist pitch** larger **transverse resistivity** (e.g. jacketing filaments with cupronickel)
Ferromagnetic losses (matrix)	hysteresis cycles in magnetic materials	Remove magnetic material (Ni, Monel, Fe) ➔ **non-magnetic matrix** (e.g. Ti)

AC losses reduction in superconductors by wire architecture optimization

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ASG SUPERCONDUCTORS columbus mgb2 unit

CONCLUSIONS

1. High-performance, high yield and low-cost conductor → ex-situ MgB_2 wires open unique opportunities to develop **affordable and efficient** superconducting technologies

2. MgB_2 wires present **critical current performances**, **handling** and **mechanical properties** suitable for most of the applications (Motors, DC cables, etc.)

3. MgB_2 technology is the perfect solution when associated with **Liq H_2** and will help our society to face the challenge toward **reduction of the CO_2 emission**

4. Despite MgB_2 was discovered only 20 years ago, ex-situ MgB_2 conductors are already commercially available and ready to be used in medical and other **DC applications** (power grids, links, energy storage, etc.)

5. To widen the application field of ASG ex-situ MgB_2 wires, an extensive R&D program is on-going at ASG superconductors in order to reduce **AC losses by wire architecture optimization**

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Thank you for your attention!