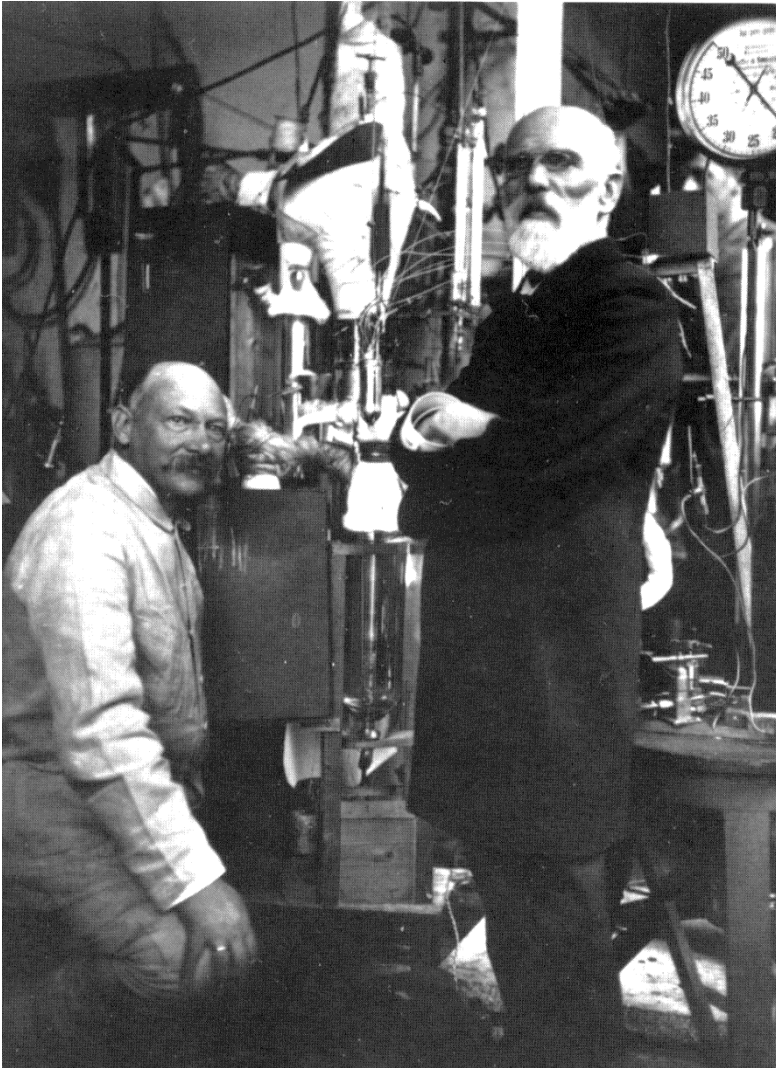


# High temperature superconductors for real world

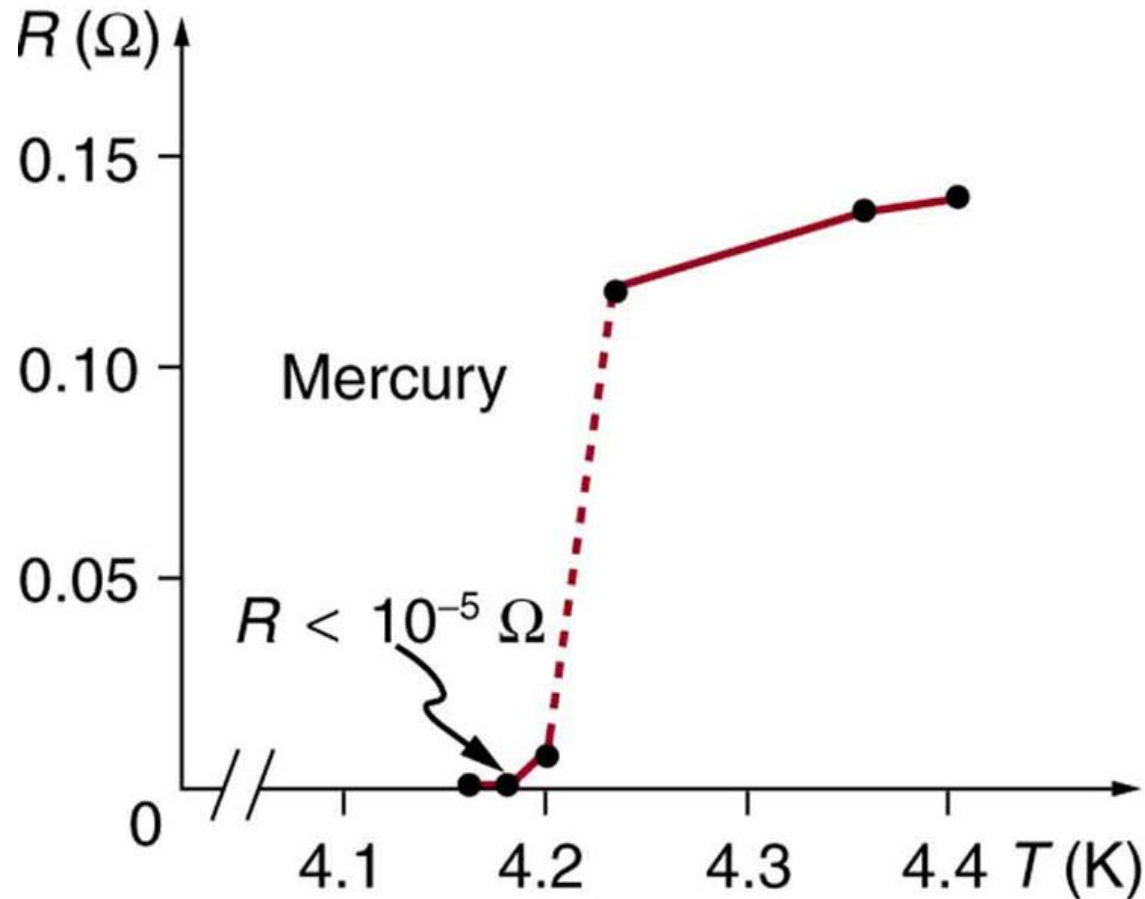
**From the amazing phenomenon  
to materials and applications**

- 1 Superconductivity: the amazing phenomenon**
- 2 Potential applications**
- 3 Low Temperature Superconductors**
- 4 High Temperature Superconductors:  
new wealth of commercial opportunities**
- 5 How to make useful HTS material**
- 6 2G HTS wire market**
- 7 HTS device market**



Heike Kamerlingh Onnes  
1853 -1926

Heike Kamerlingh Onnes discovered superconductivity in 1911

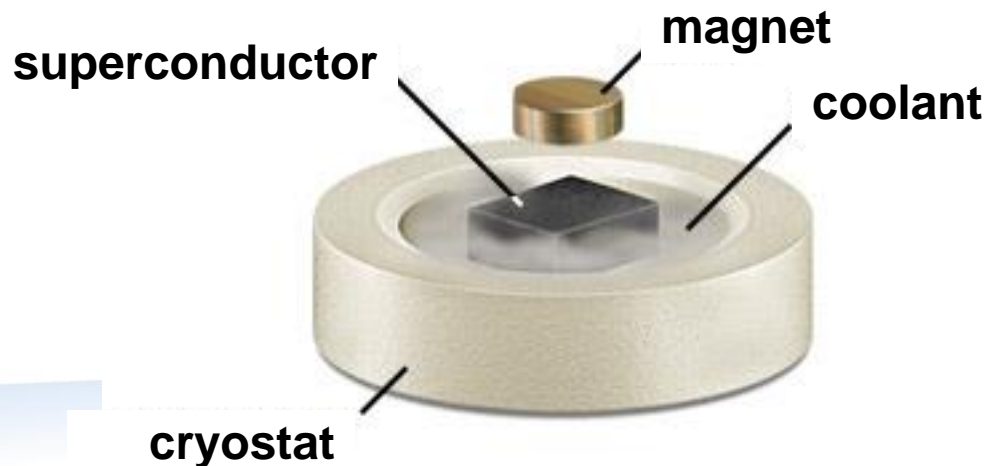
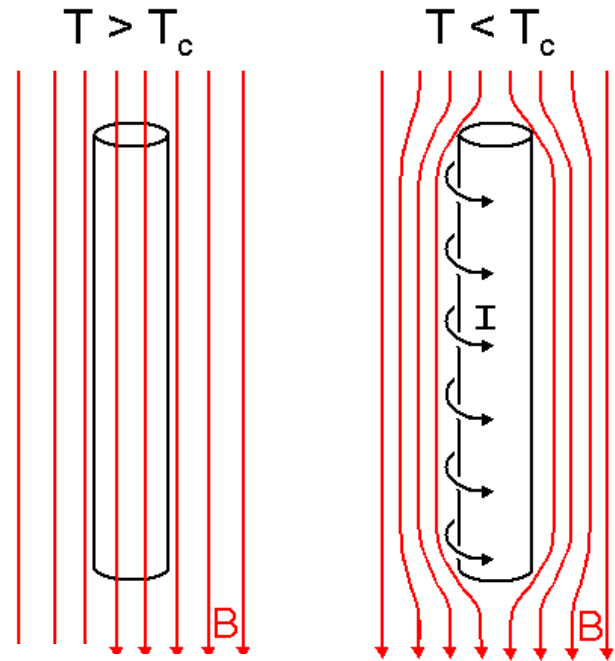


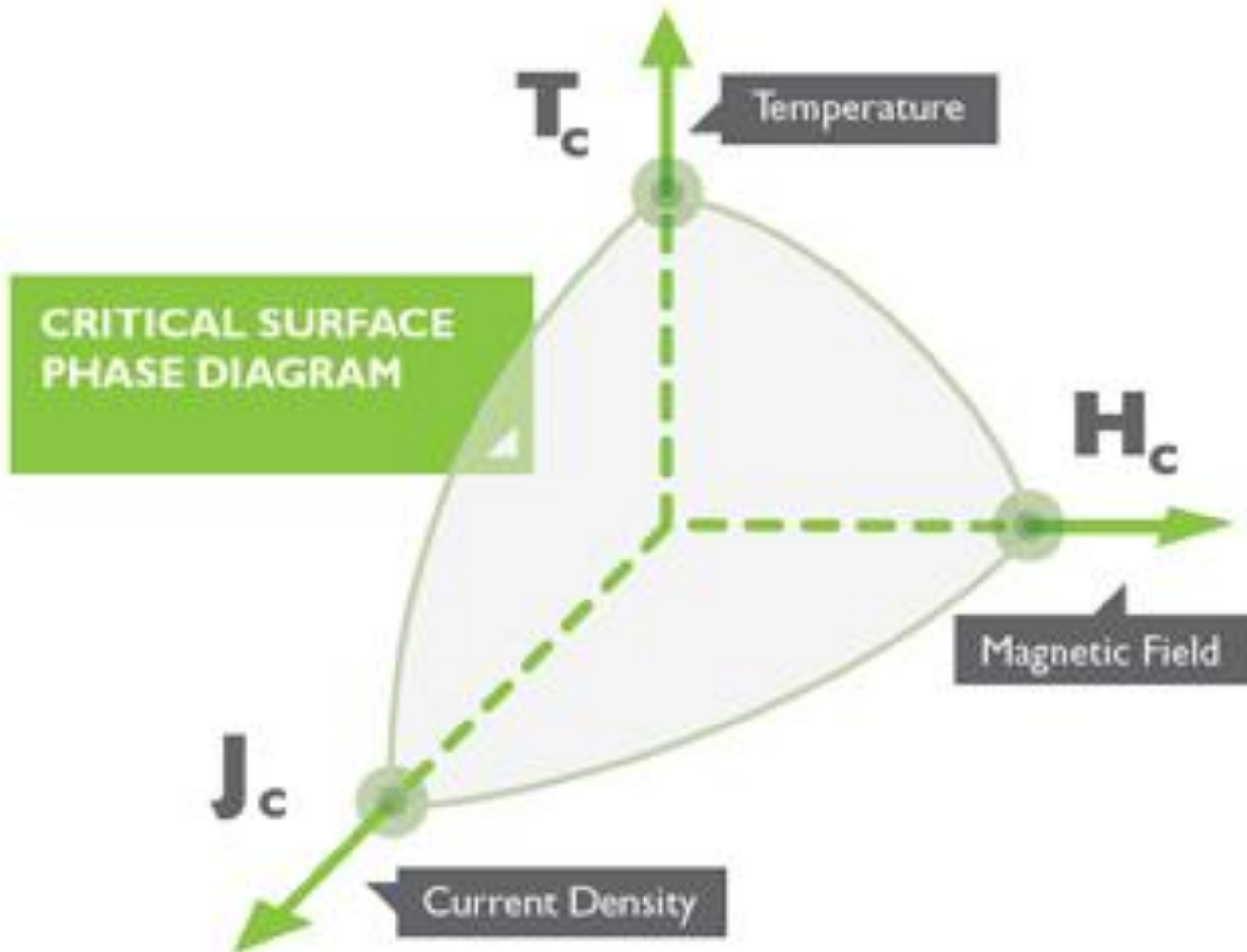
At  $T < 4.2$  K, the electrical resistivity of pure mercury drops to zero

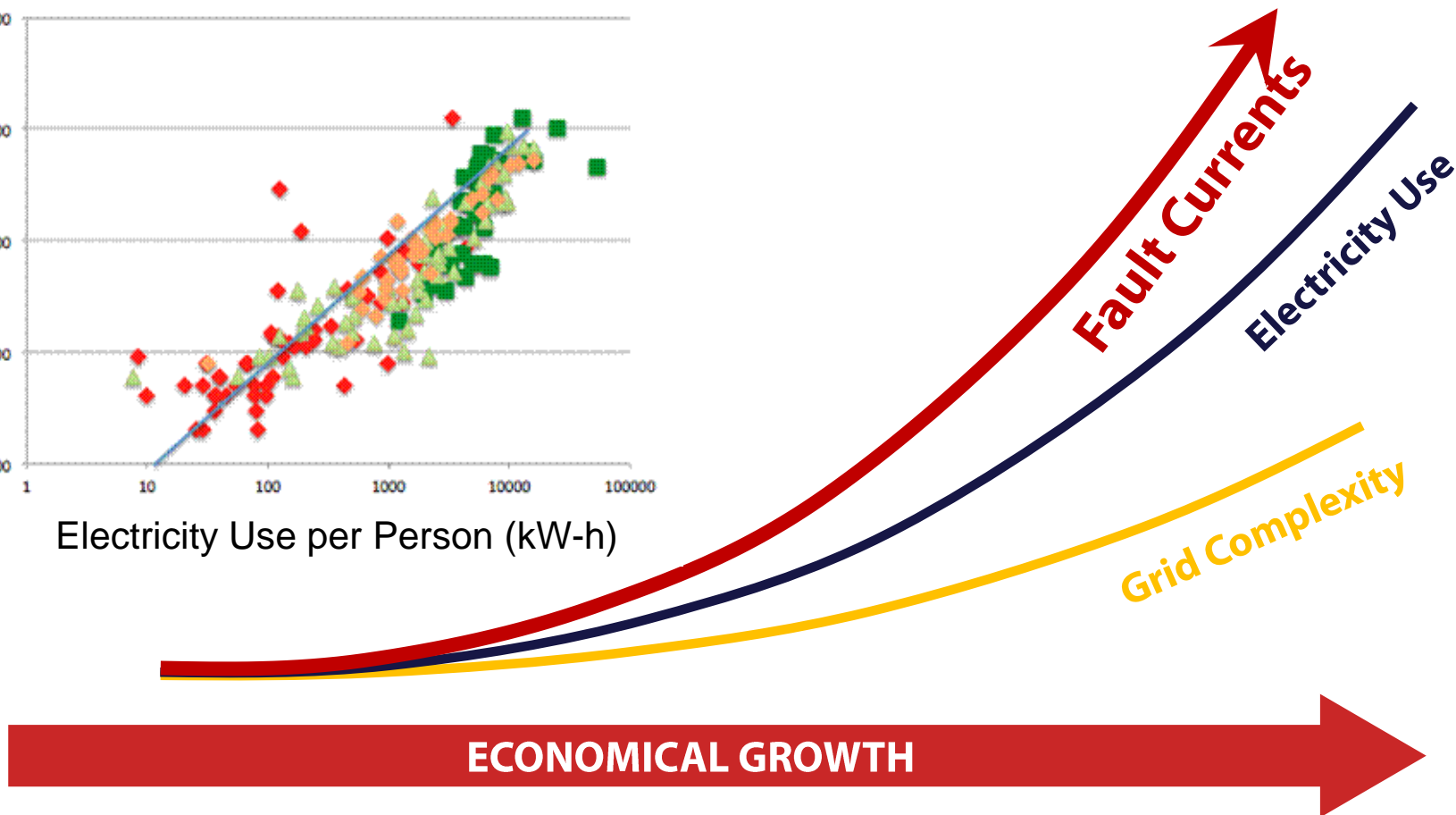
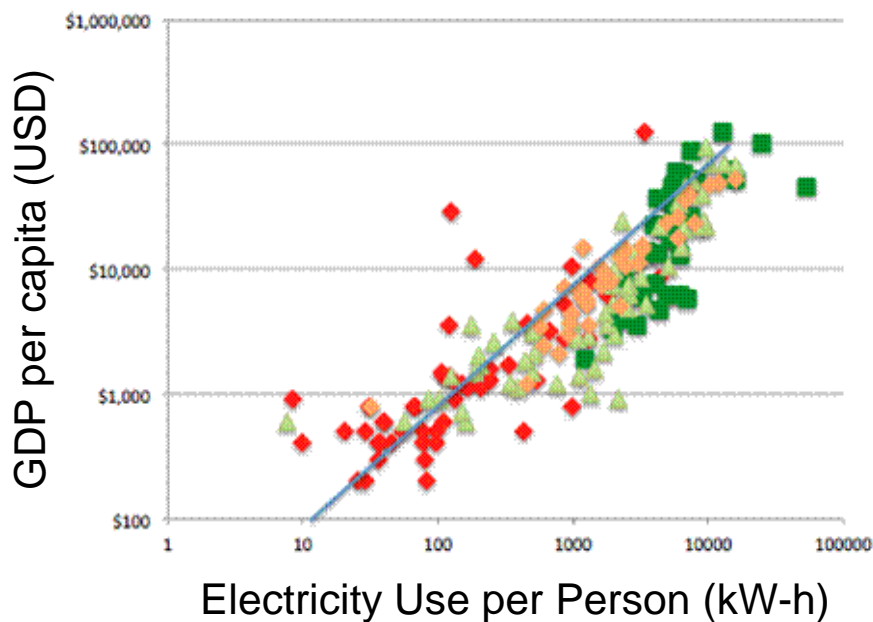
Superconductors repel magnetic field.

Superconducting eddy current generates magnetic field that cancels the external field.

**Superconductors are perfect diamagnetics.**








## ELECTRIC ENERGY

## Superconductor

## SCIENCE & INDUSTRY



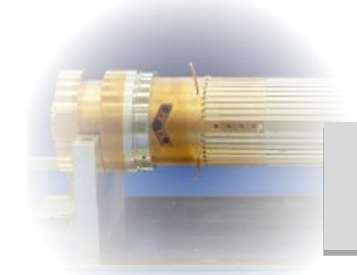
Power cables



High Field Magnets

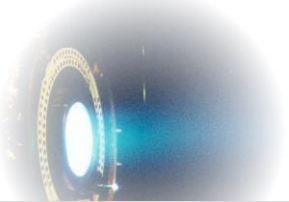


Fault Current Limiters



Current Leads

## SPECIAL APPLICATIONS



Plasma Engines



MagLev

## HEALTHCARE

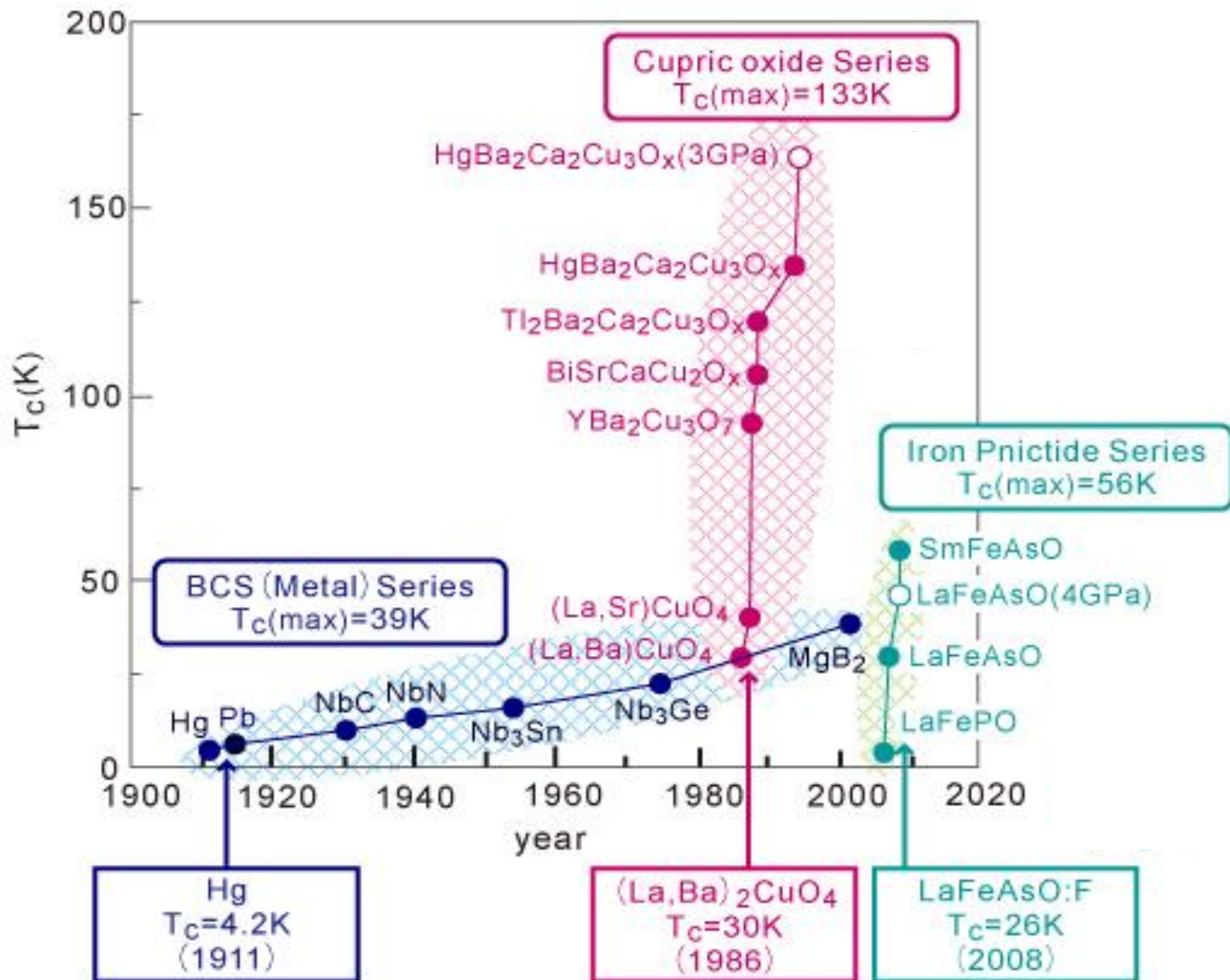


Radiotherapy

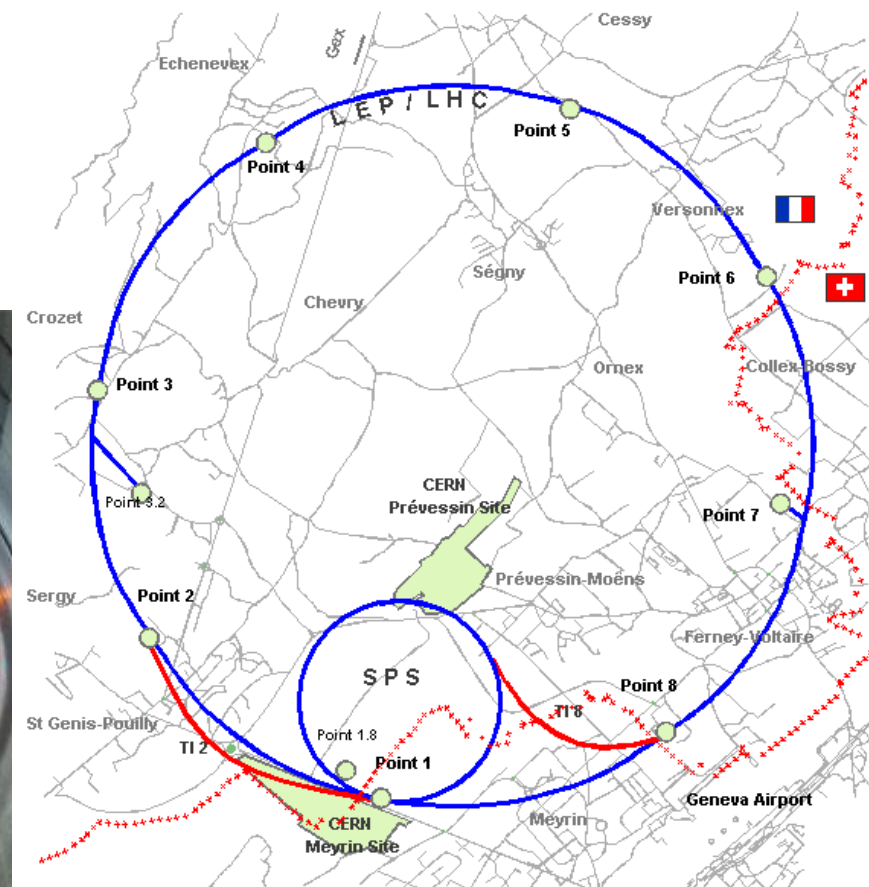


MRI



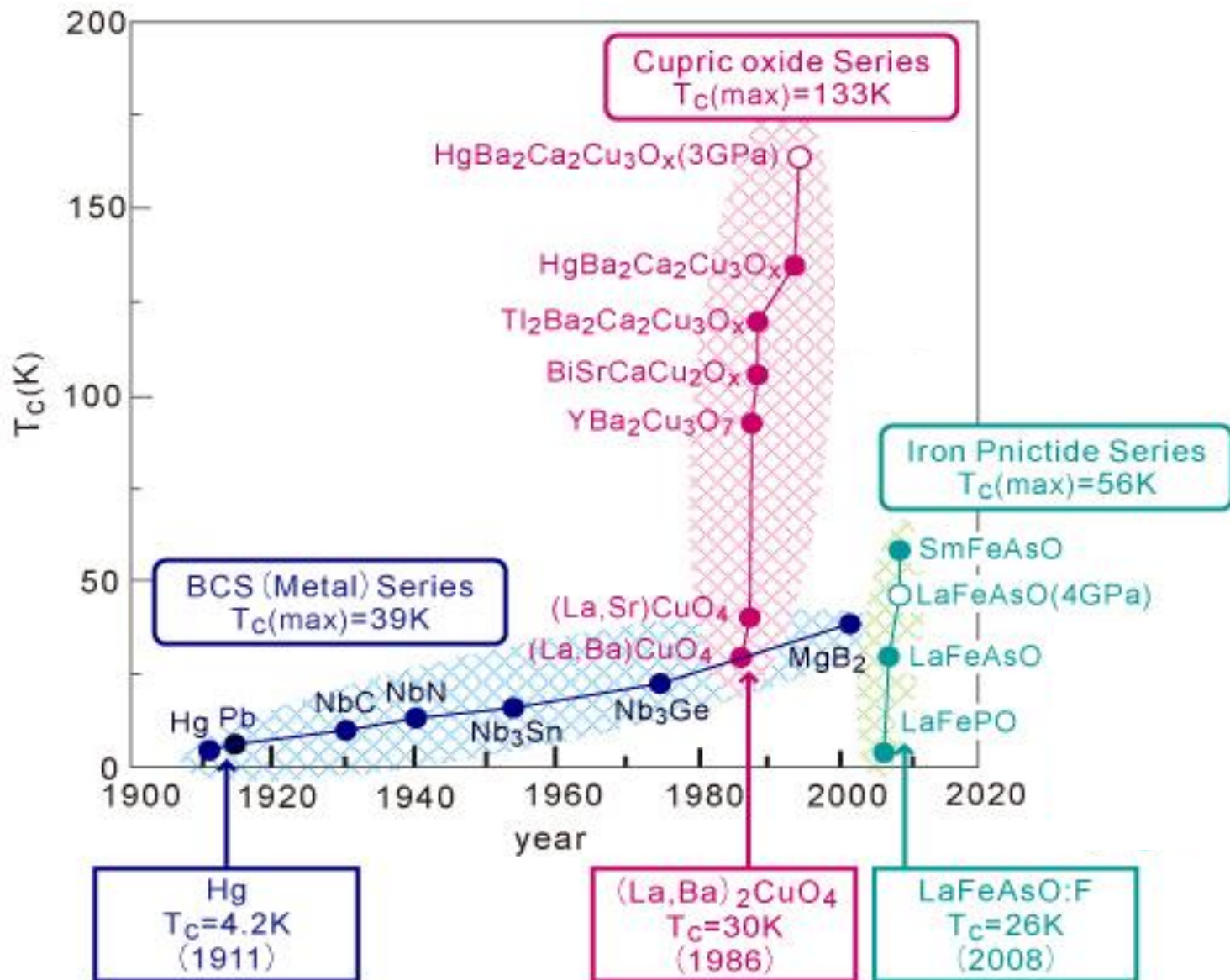


# LTS use: high (cost) energy physics



Map of CERN sites and LHC access points

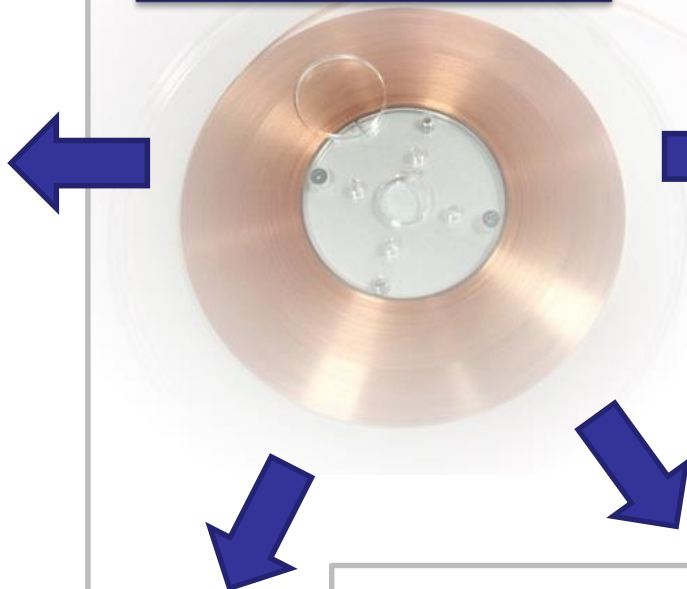
# High Temperature Superconductors (HTS) SuperOx



## ELECTRIC ENERGY

## HTS

## SCIENCE & INDUSTRY



Power cables

High Field Magnets

Fault Current Limiters

Current Leads

## SPECIAL APPLICATIONS

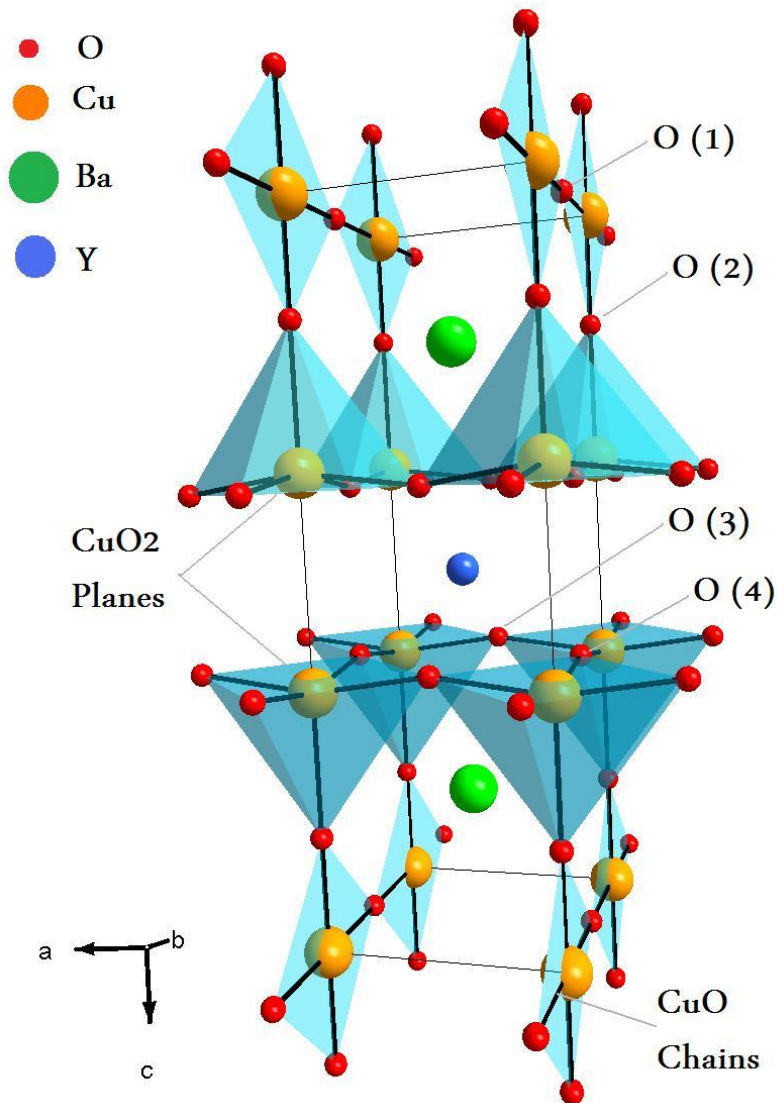
## HEALTHCARE

Plasma Engines

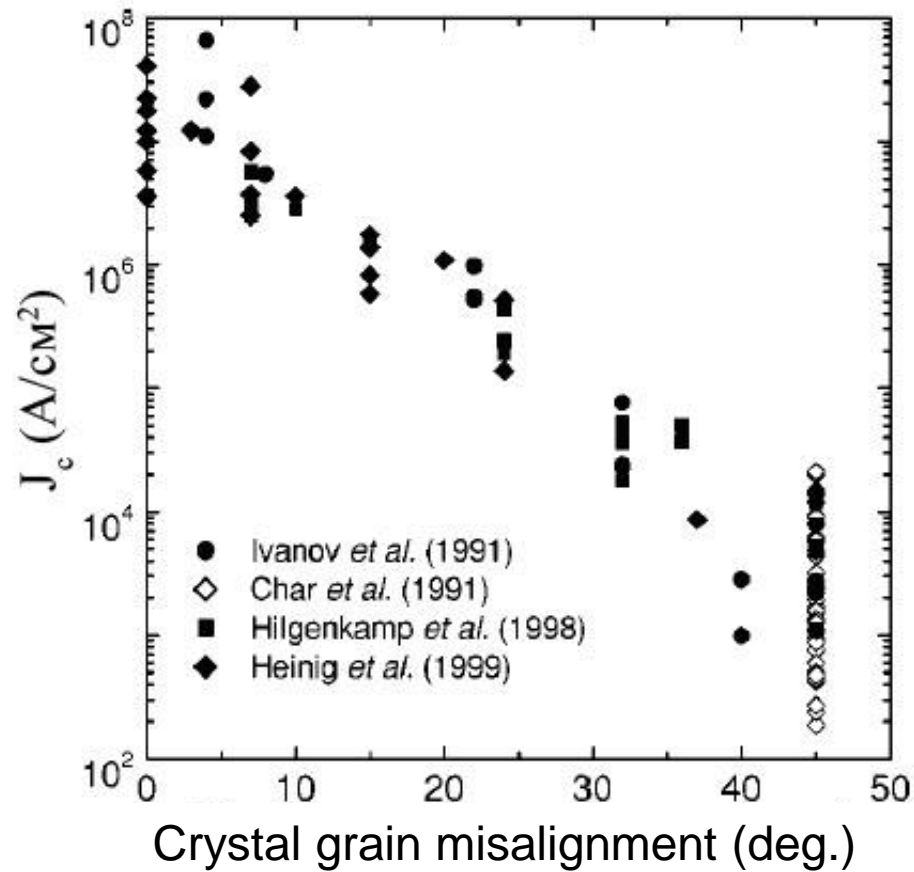
MagLev

Radiotherapy

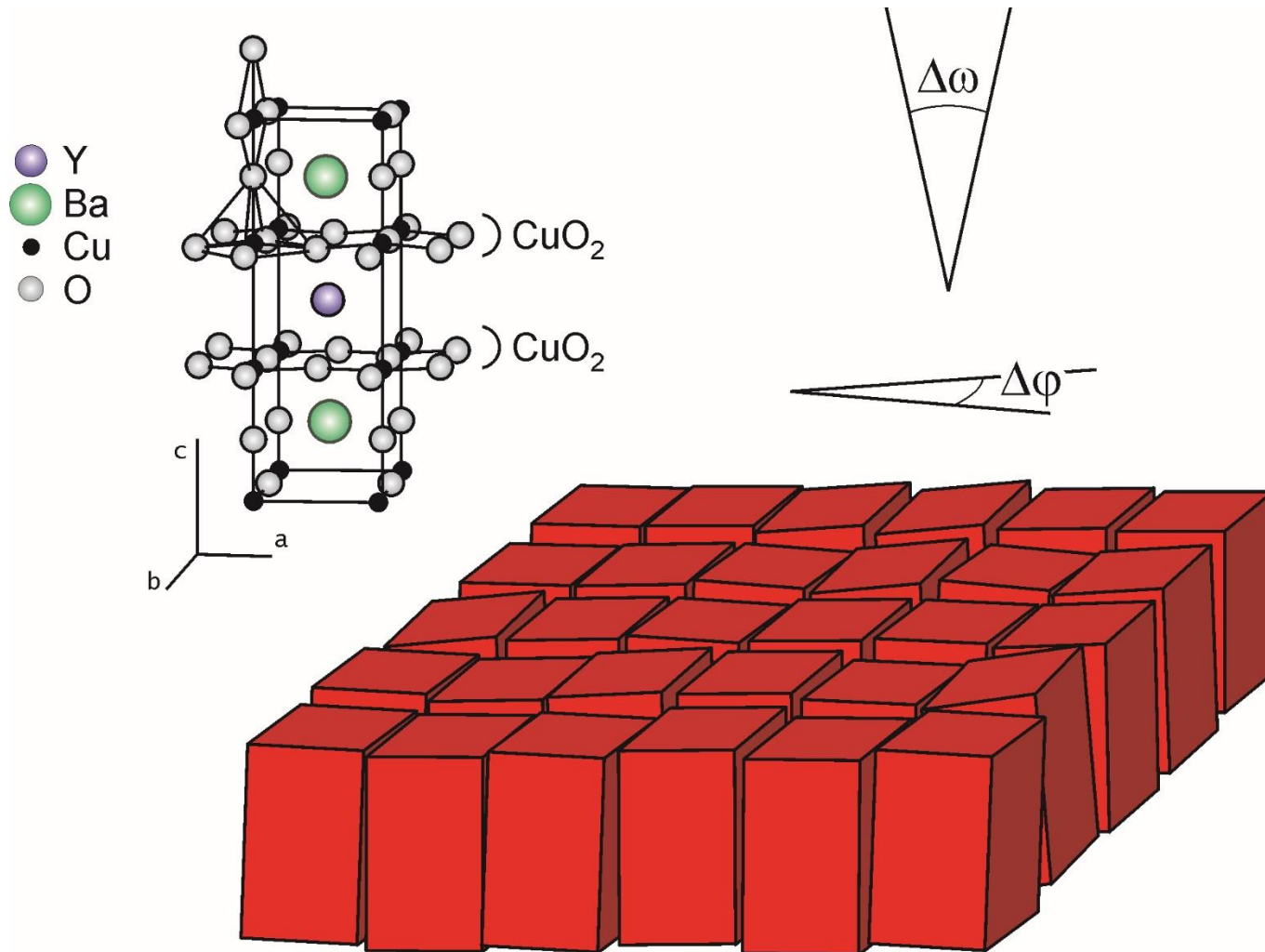
MRI



Crystal anisotropy in RE-Ba<sub>2</sub>Cu<sub>3</sub>O<sub>7</sub> leads to anisotropy of superconducting properties

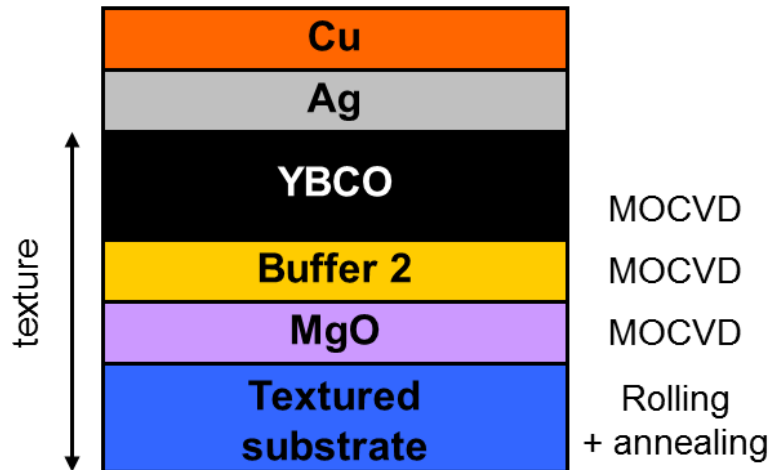


For high current HTS conductor, good grain alignment is essential

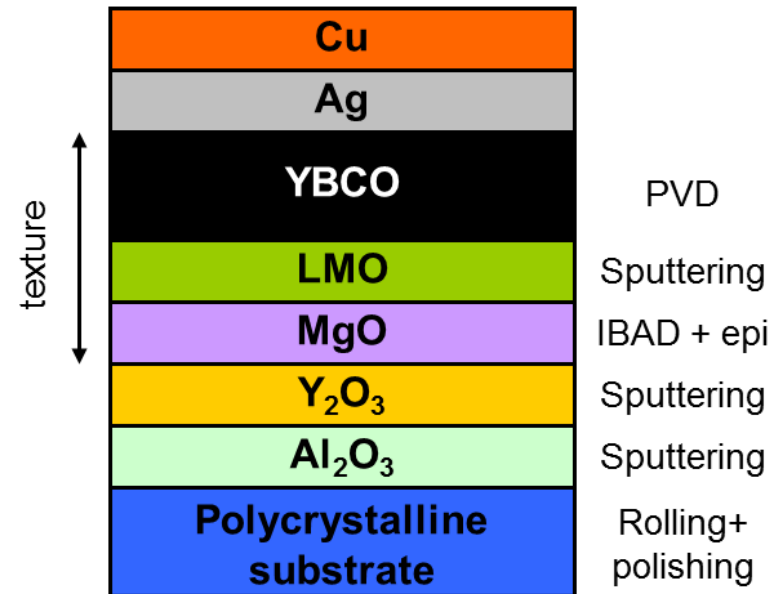


For high current HTS conductor, good grain alignment is essential

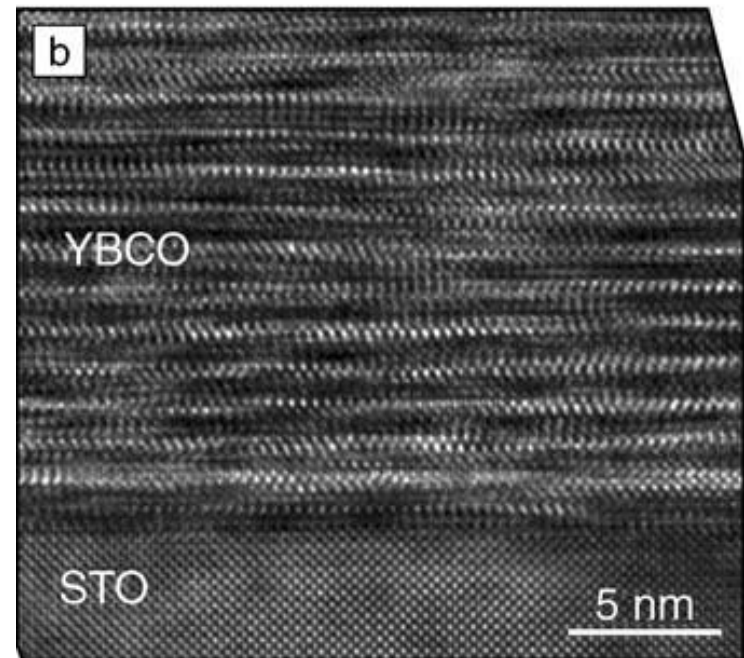
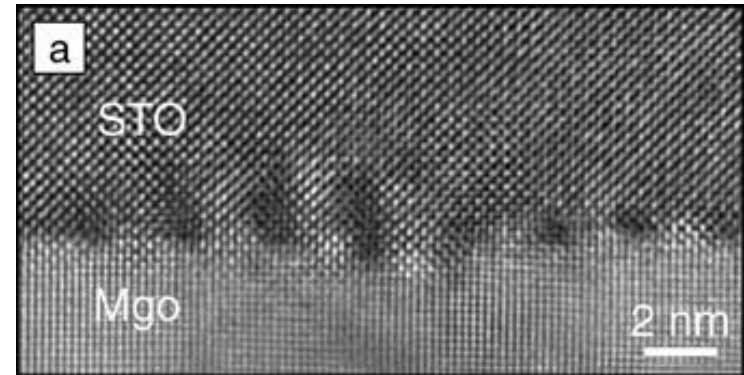
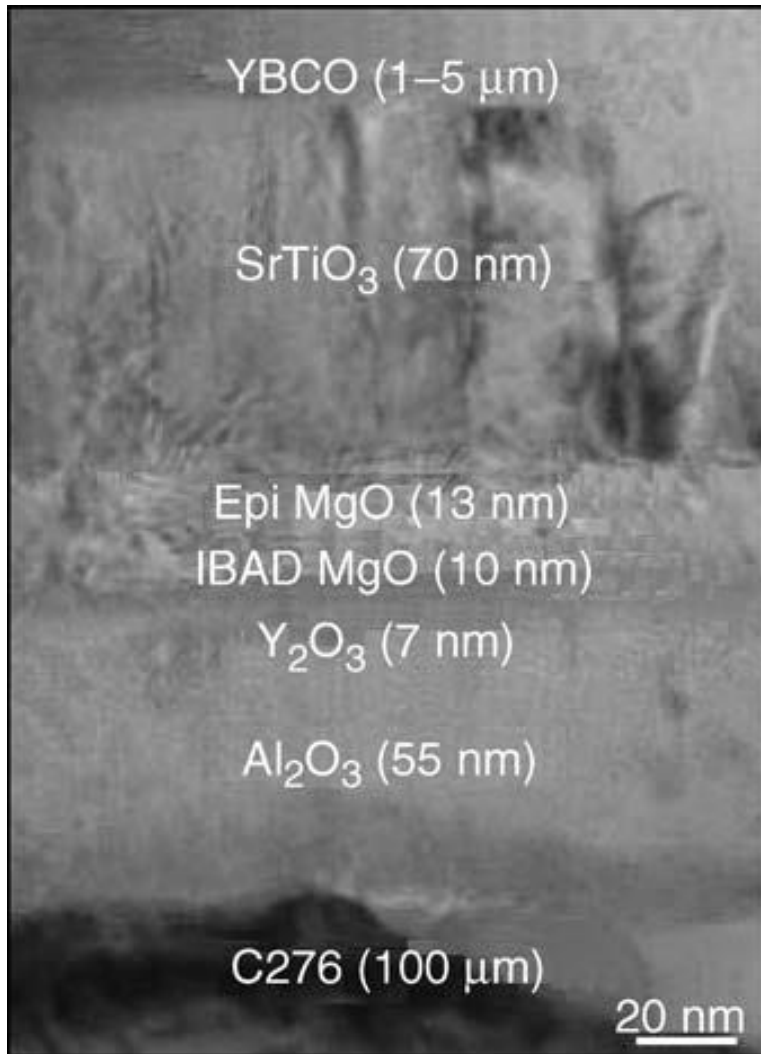
## RABiTS



## IBAD



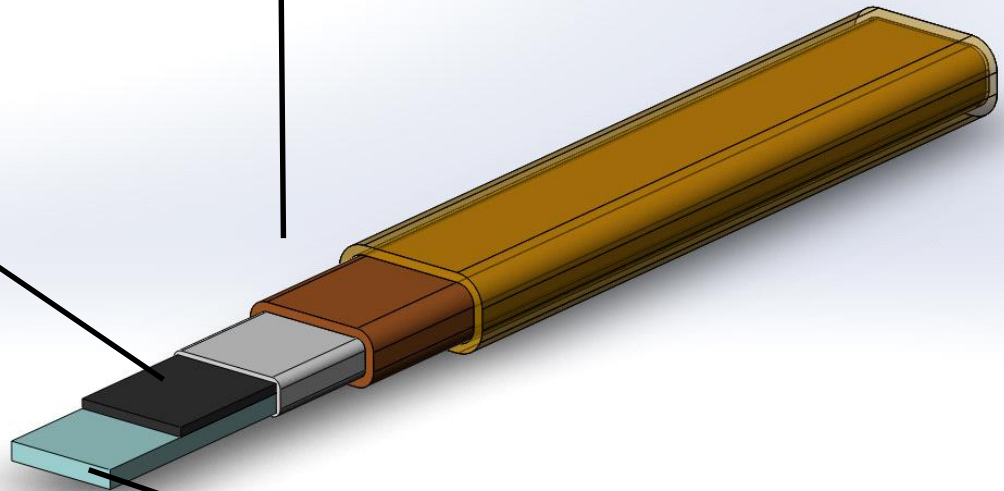




Transmission Electron Microscopy (TEM) images

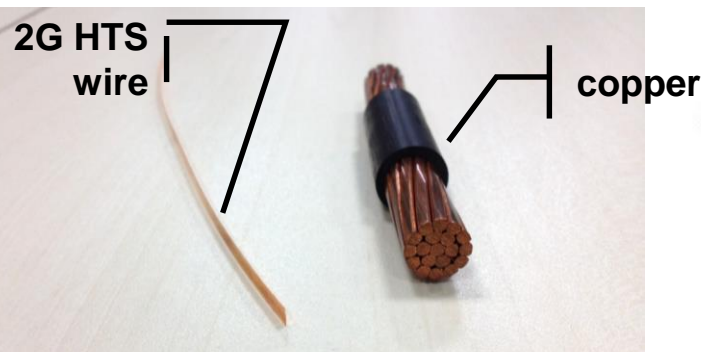
**Customisation**  
(silver/copper/solder/lamination/insulation)

**HTS layer**  
(1-3 microns)



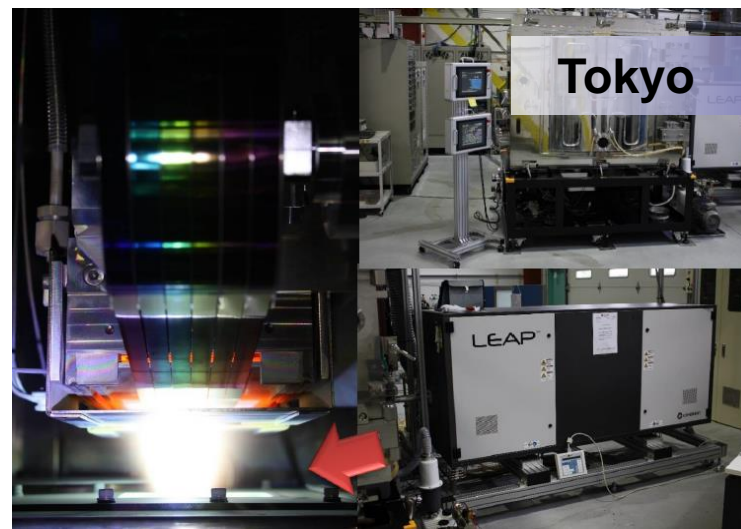
**Substrate (50-100 microns)**

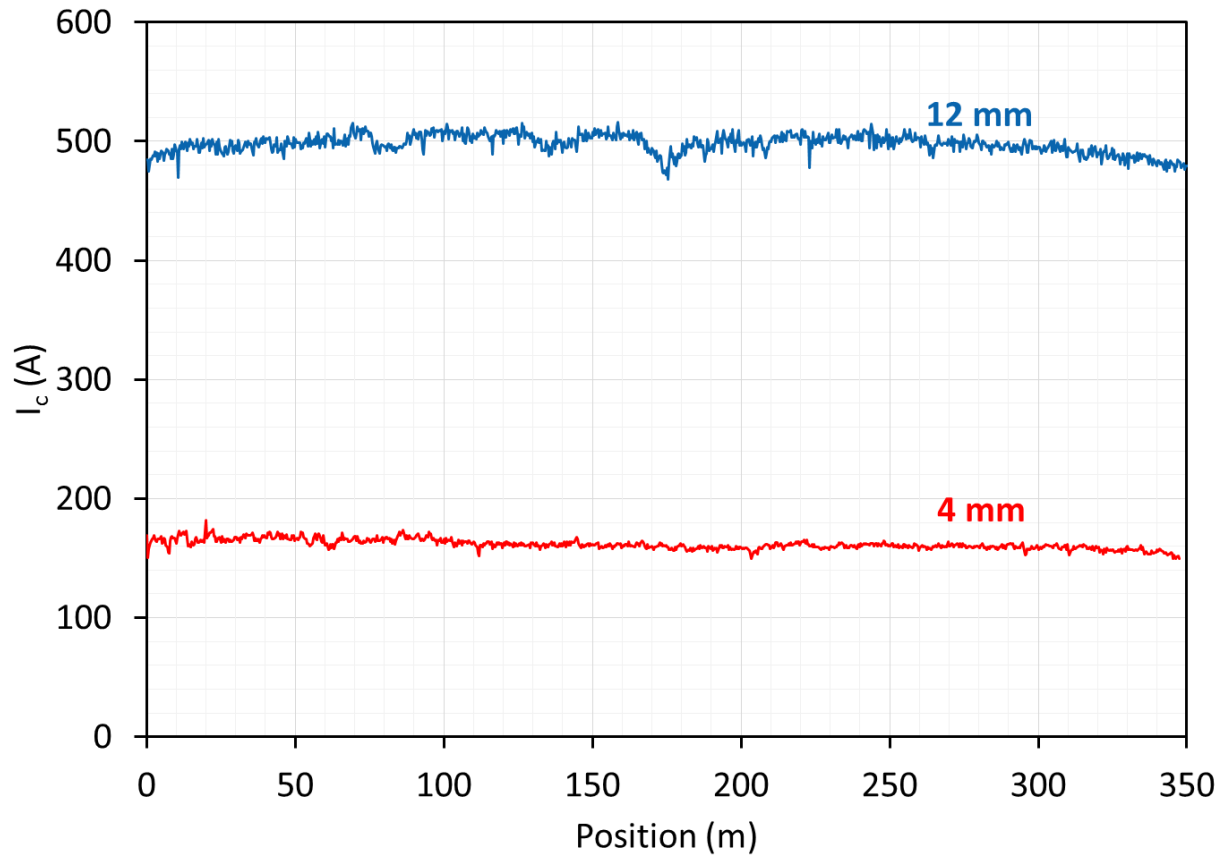
- electropolishing or planarisation
- buffer layers (100-200 nm)

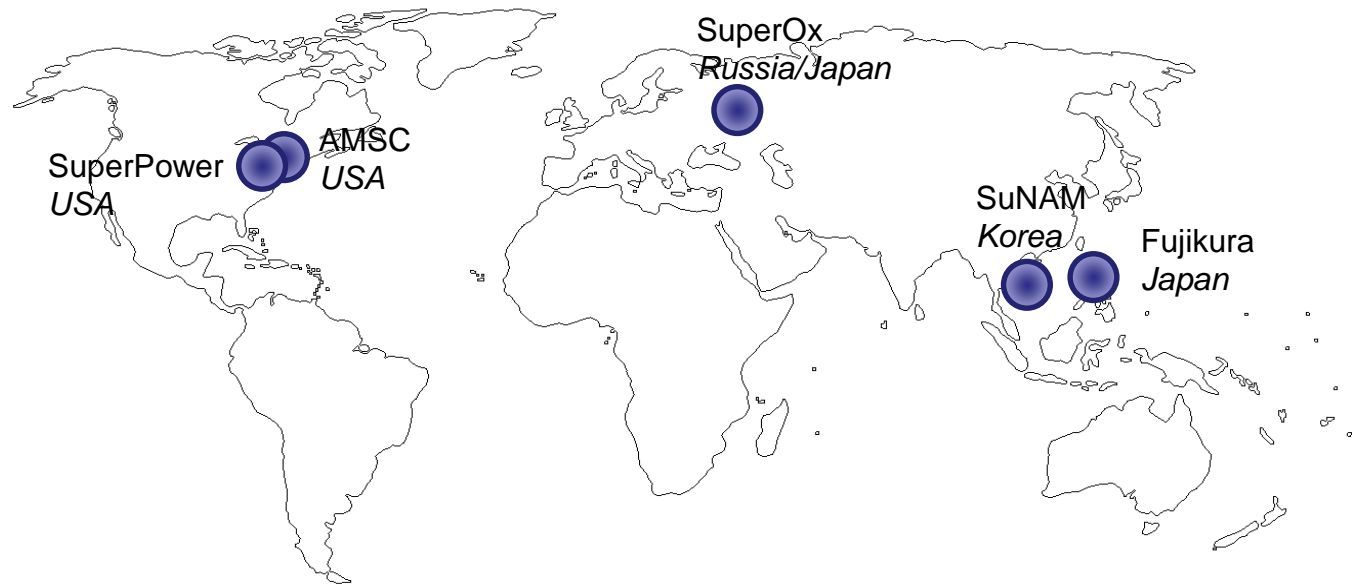


Up to 500 times  
current carrying capacity of copper

- 2006: SuperOx founded
- 2011: SuperOx Japan LLC founded
- 2011: SuperOx Innovations LLC becomes a Skolkovo resident
- 2012: start of 2G HTS wire production and sales
- 2013: relocation of SuperOx to Technopark Slava
- 2016: delivery of 2G HTS wire to customers around the world



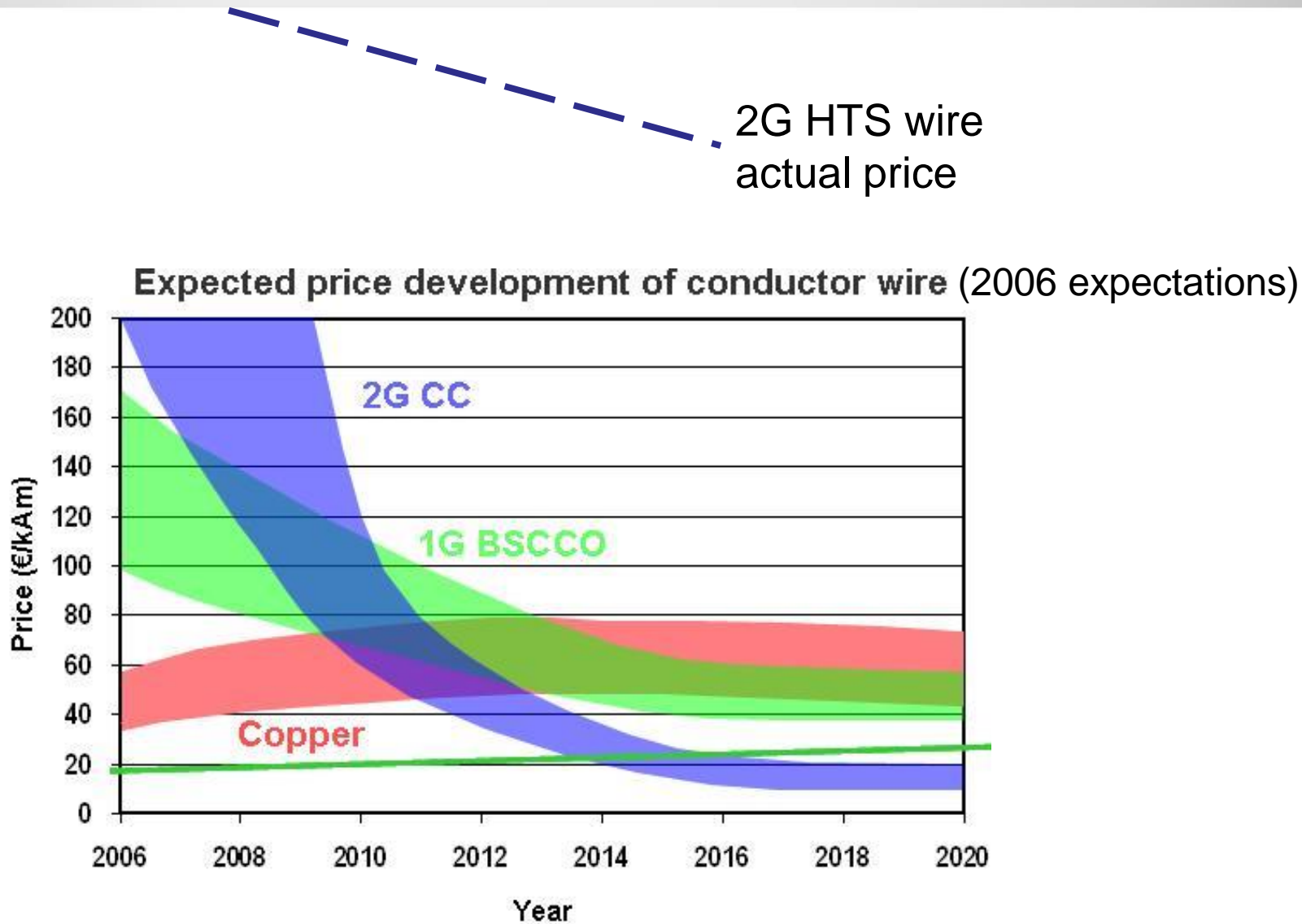




SuperOx is the only commercial 2G HTS wire manufacturer in Europe

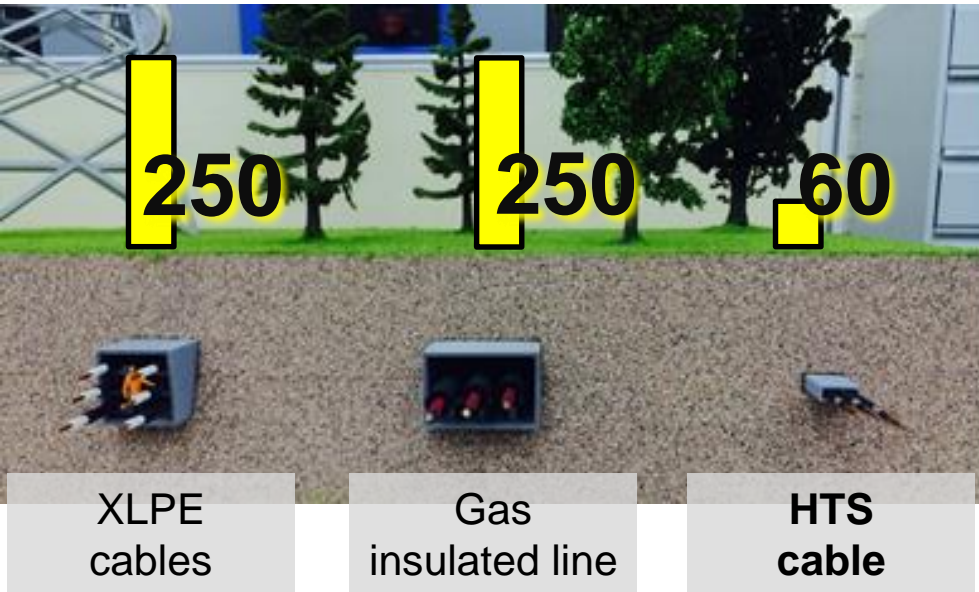
## SuperOx strategy:

- Enter the 2G HTS wire market
- Differentiate product by providing deep wire customisation
- Develop HTS applications to generate demand on wire and capture added value

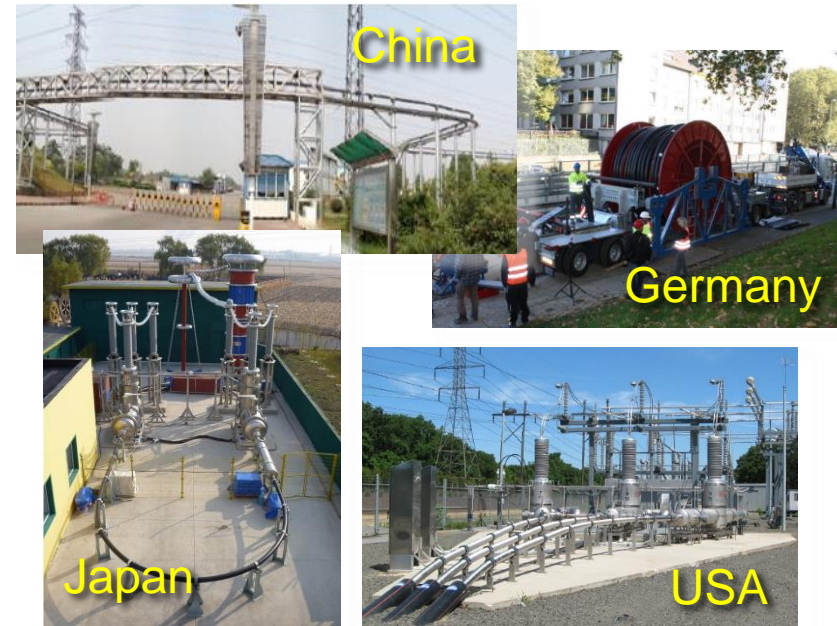


- Superconducting cable has **the lowest losses** and is the **most compact solution**

Yellow bars: **losses** in kW per km

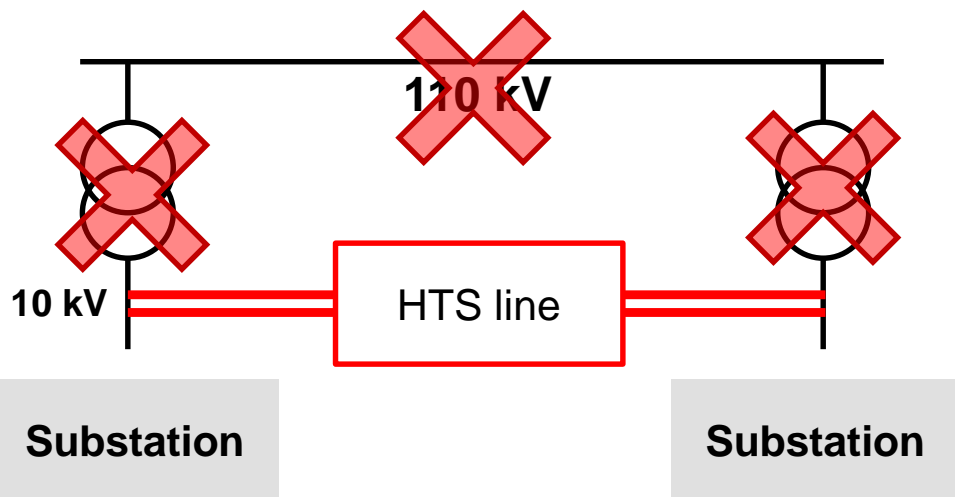


Most compact solution for energy transport for GWatt-level transmission



Over 15 pilot systems worldwide

- Superconducting cable can transmit 5 times more power in same cross-section
- Energy transmission at middle voltage instead of high voltage becomes feasible
- Big potential **to remove substations and high voltage lines from city centres**



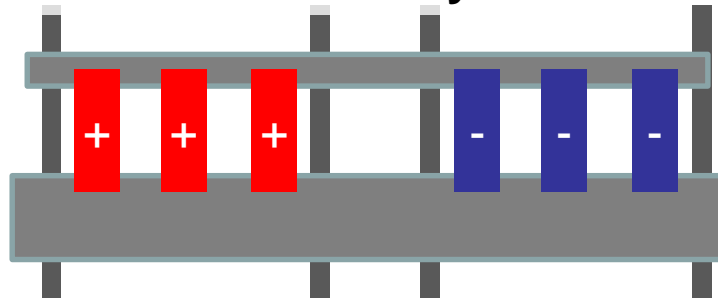
Making substations in cities superfluous

AmpaCity project (Essen/Germany)



- Due to zero resistance HTS decrease losses in current buses
- HTS help to reduce dramatically the size of transmission line
- Large potential is seen for **electrolysis plants (Al, Cu, Zn, Cl<sub>2</sub>)** and **data-centers**

## Conventional 60 kA DC system

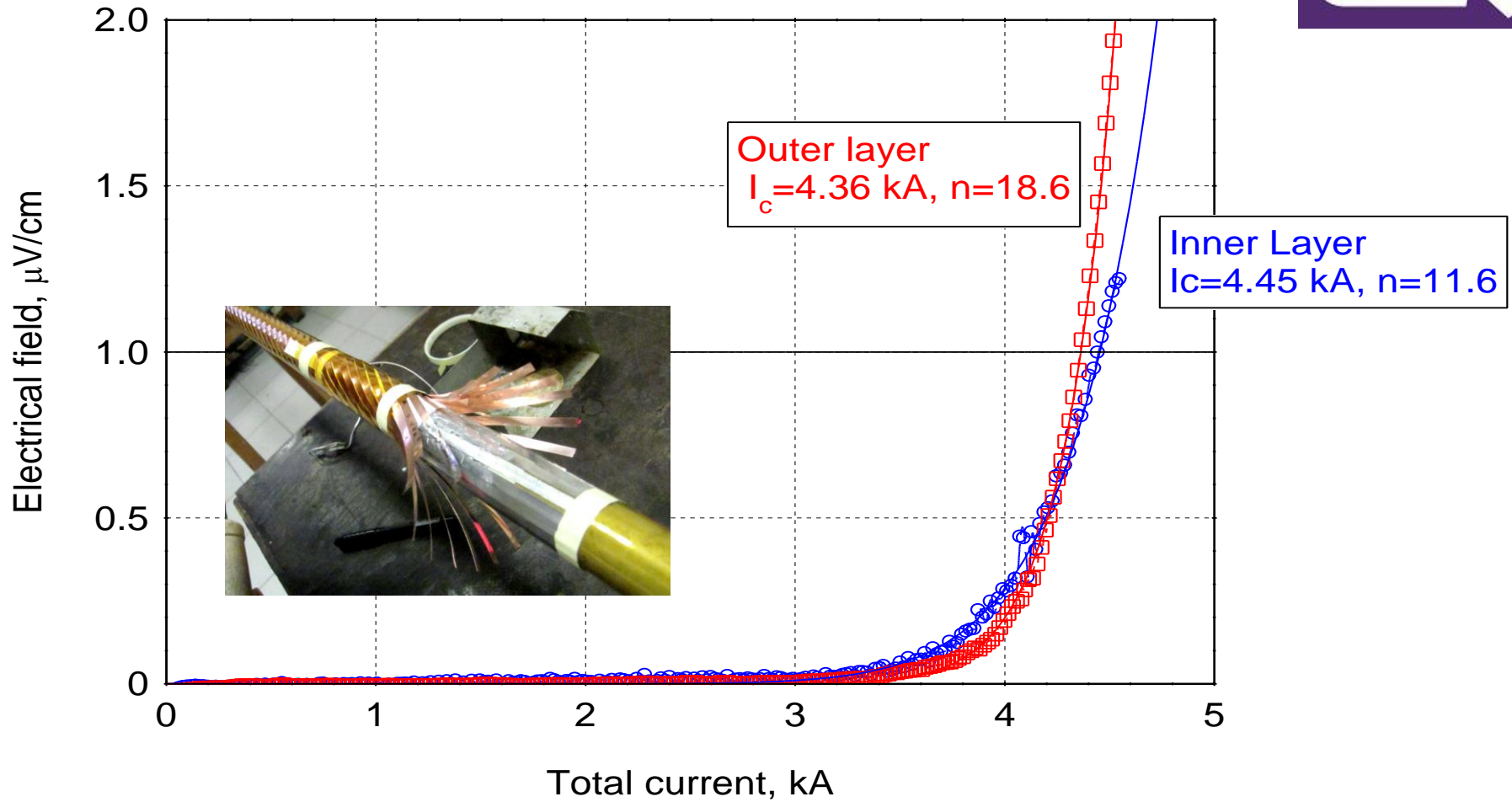


60 kA HTS cable line → 

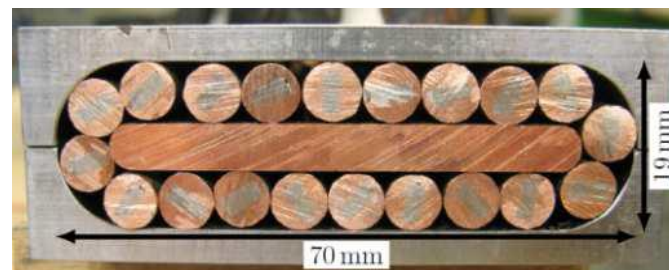
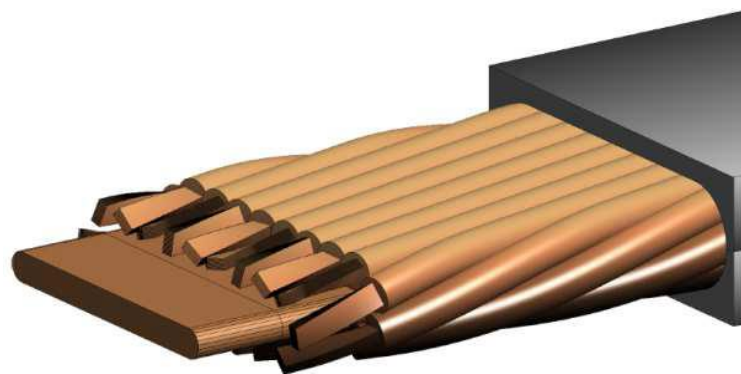
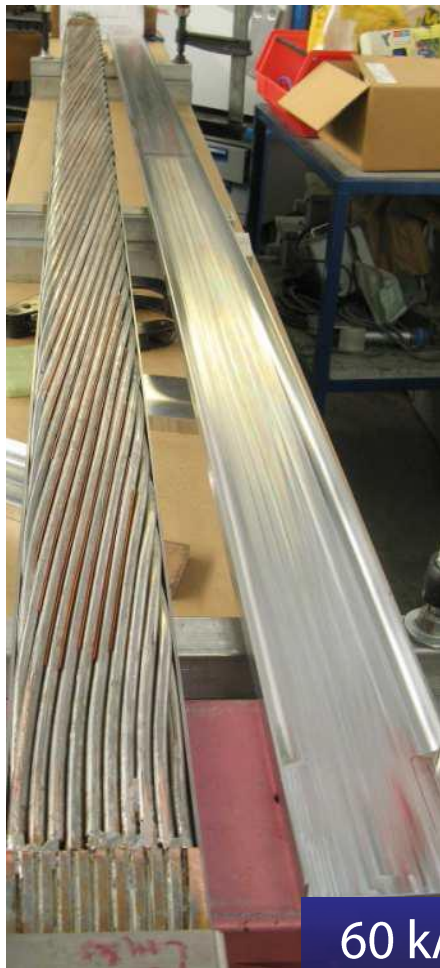


Cross-section is reduced by x20

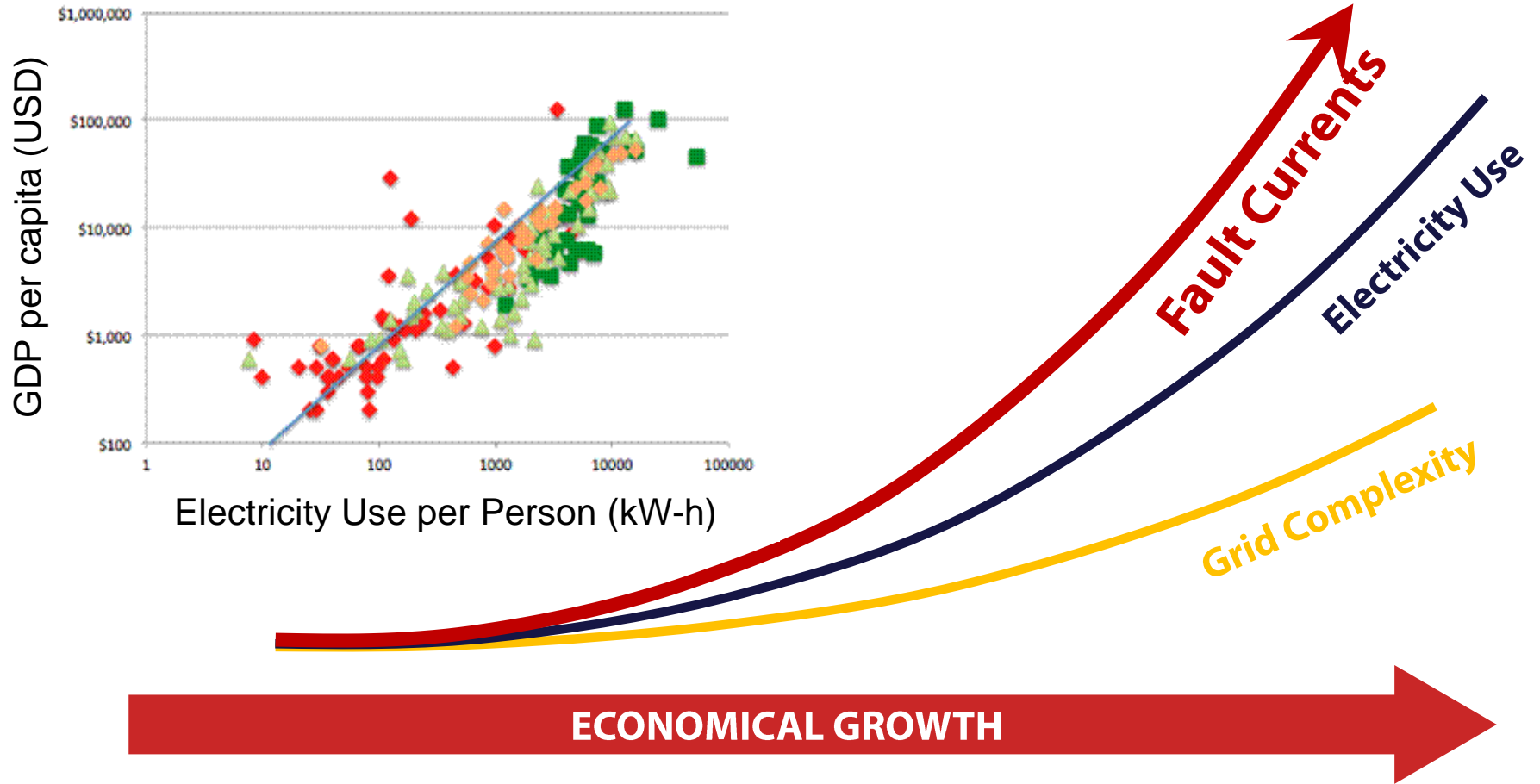
10 kA HTS Cable at aluminium electrolysis plant (China)



Courtesy of EPFL-CRPP, Dr. Bruzzone et al.

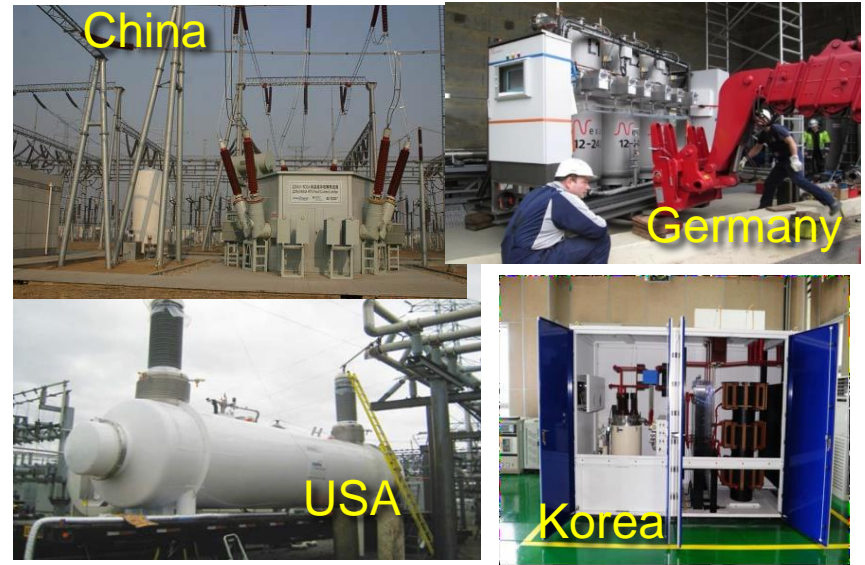
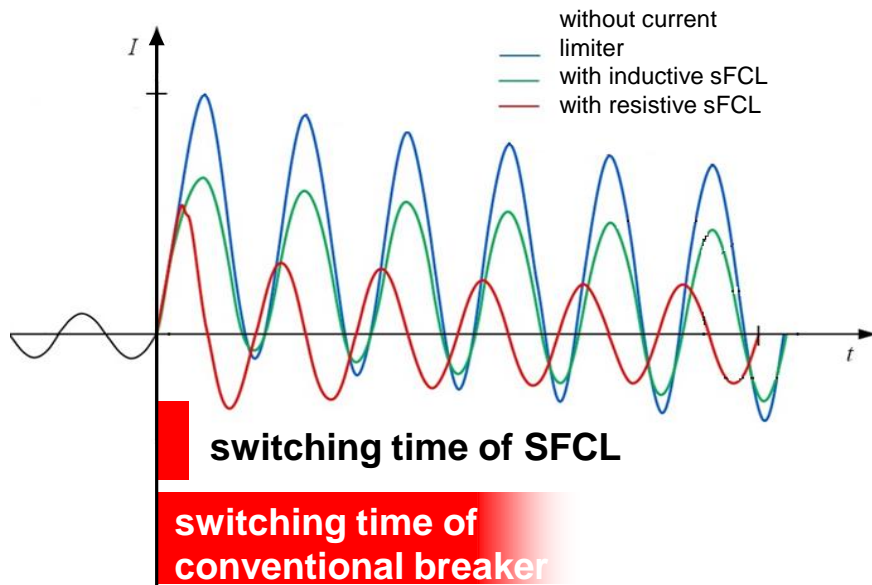


60 kA DC current lead Rutherford cable for fusion reactor coils made with SuperOx 2G HTS wire



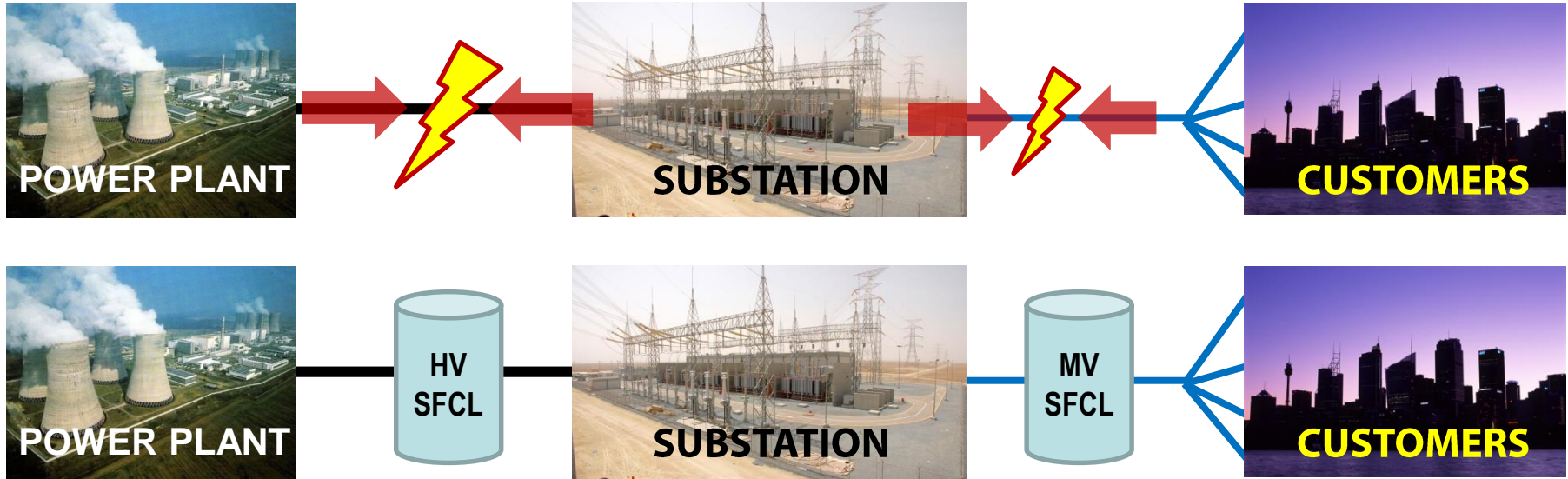
**Fault currents lead to blackouts and require \$\$\$ for grid upgrade**

- Extremely needed power equipment for electric power industry and Smart Grid
- **10-100 times faster** than any other existing system



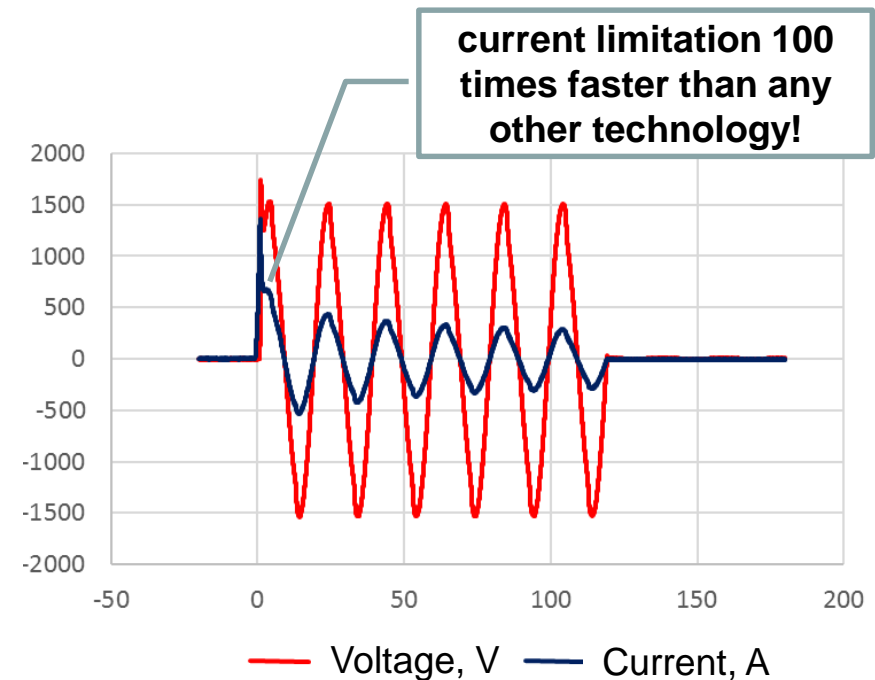
In many instances, there are no viable alternatives to SFCL

More than 15 successful pilots worldwide



**The market is growing with CAGR 30-100%.  
The largest share in densely populated Asia.  
Today is a perfect entry point.**

- SuperOx develops turn-key SFCL solutions for any grid
- SuperOx owns important IP in SFCL
- SuperOx is the only manufacturer of 2G HTS wire in Europe

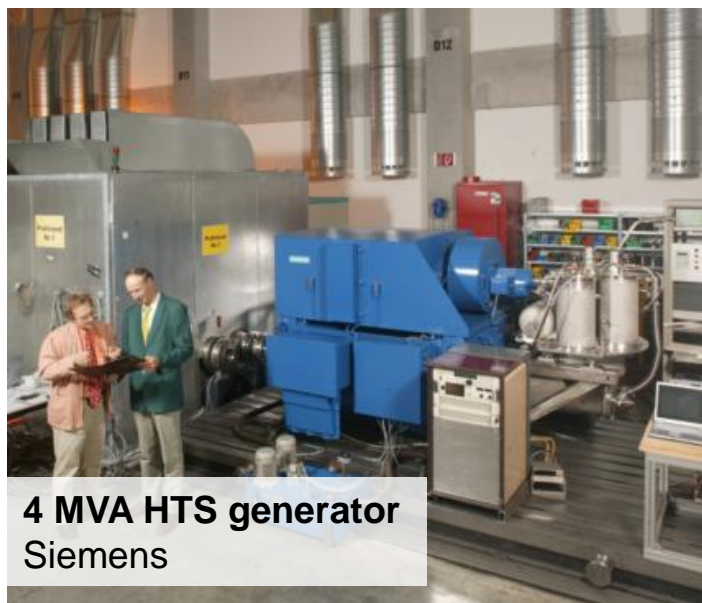




<i>Product type</i>	<i>Benefits for the Customer</i>
<p><b>High-Voltage SFCL</b> for transmission grid</p>	<ul style="list-style-type: none"> <li>➤ Very low probability of power outages</li> <li>➤ Reduce fault currents below 40 kA</li> <li>➤ Low electrical losses</li> <li>➤ <b><u>Reduce capital investment in circuit breaker replacement in large cities by more than 80%</u></b></li> </ul>
<p><b>Medium-Voltage SFCL</b> for distribution grid and coal power plants</p>	<ul style="list-style-type: none"> <li>➤ Reduce fault currents below 20 kA</li> <li>➤ High reliability of electrical power supply</li> <li>➤ <b><u>Yearly cost savings for coal plant at 200% of SFCL purchase price</u></b></li> </ul>

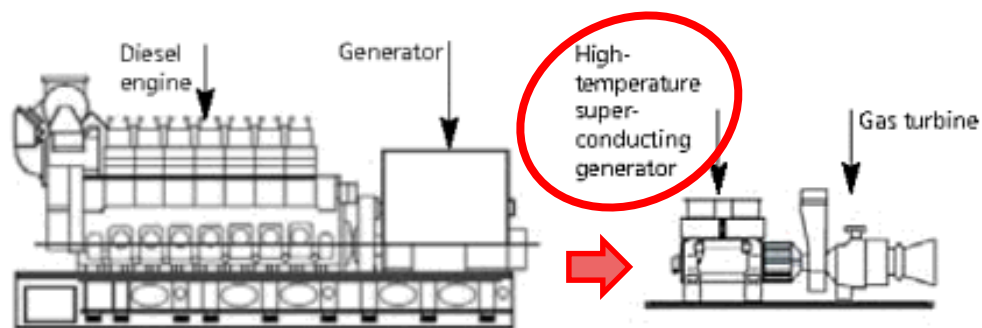


- HTS machines are significantly smaller in size and weight and have high efficiency even at low rotation speeds
- Especially attractive for **on-board generation** (e.g., ship) or **wind energy**

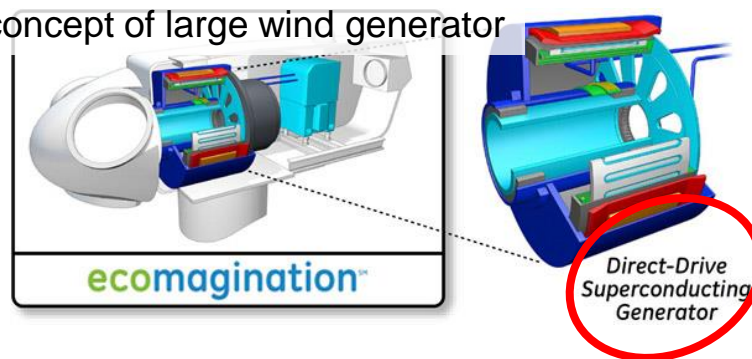


4 MVA HTS generator  
Siemens

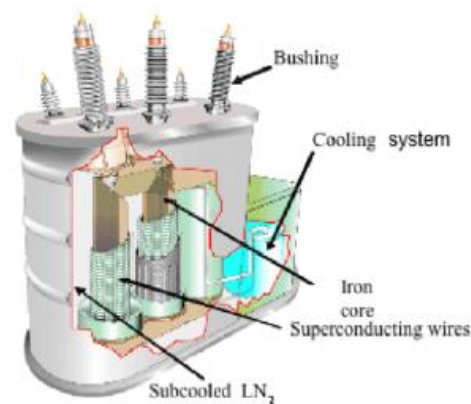
Source: Siemens, GE



GE concept of large wind generator



- HTS transformers are more energy efficient, reducing life-costs by 70%
- non-flammable and very compact (weight is reduced by 40%)
- can be designed with fault current limiting function (2 devices in one)

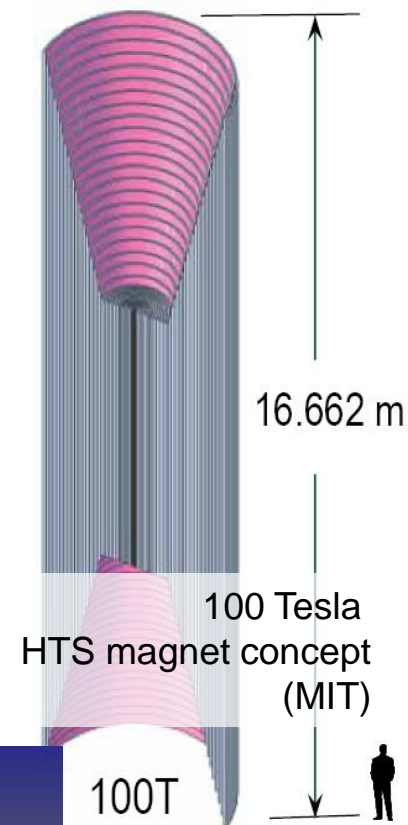
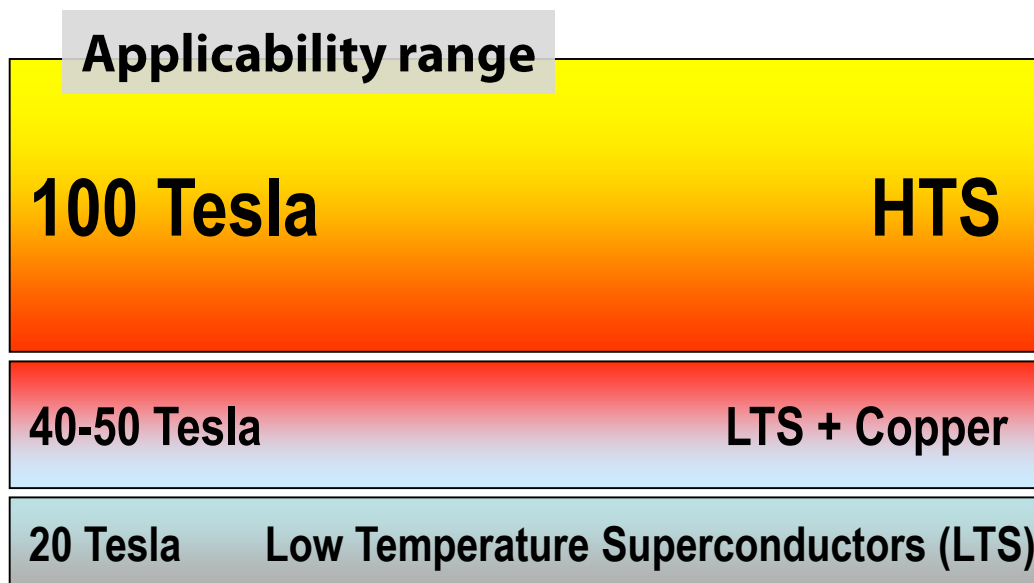


HTS enable new efficient transformers for future smart grid solutions

- Magnetic fields over >20 Tesla are essential for front-end research
- HTS magnets consume **0.1% of electric energy** of their copper counterparts



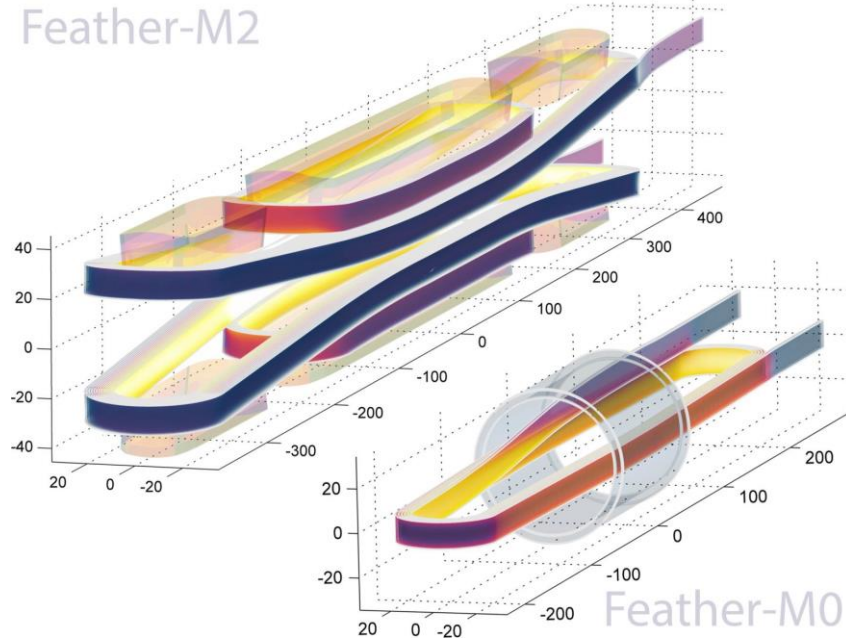
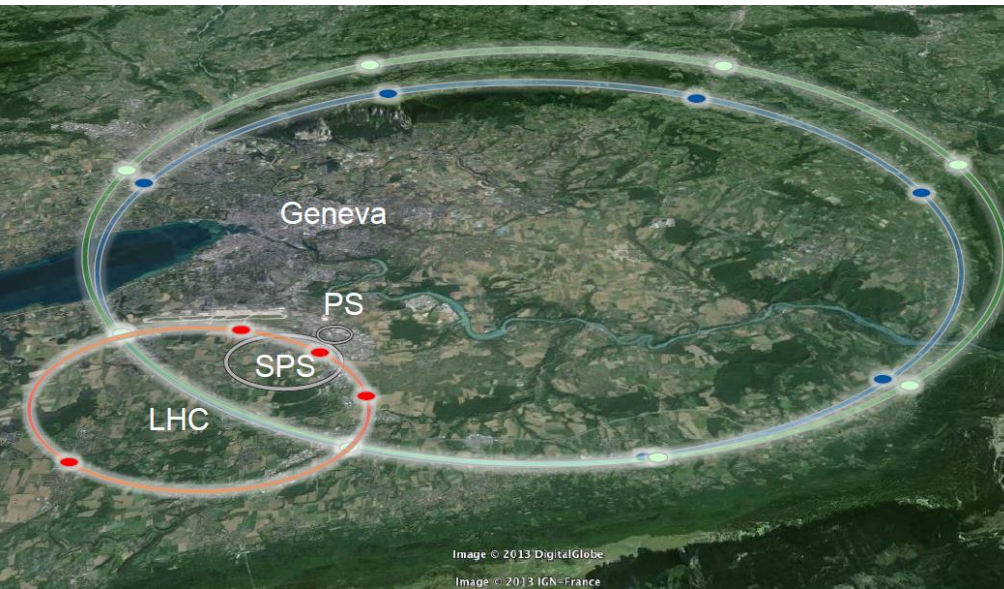
Record 35.4-Tesla HTS magnet (NHMFL)



Source: National High Magnetic Fields Lab, MIT

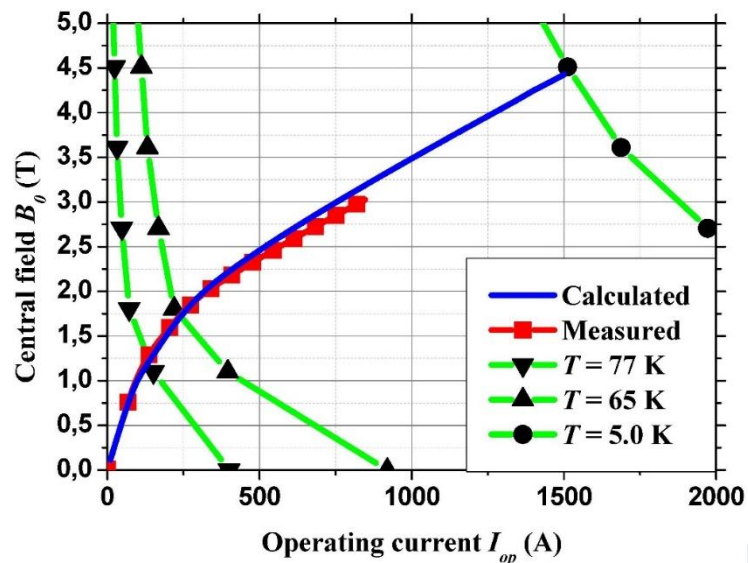
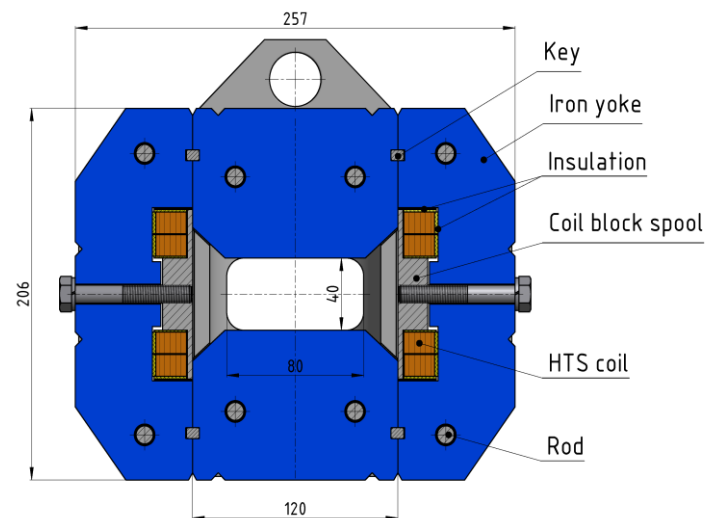
HTS enable magnets with fields over 50 Tesla – for the first time ever

- HTS magnets, cables and current leads make possible Future Circular Collider (to be built at CERN by 2035)



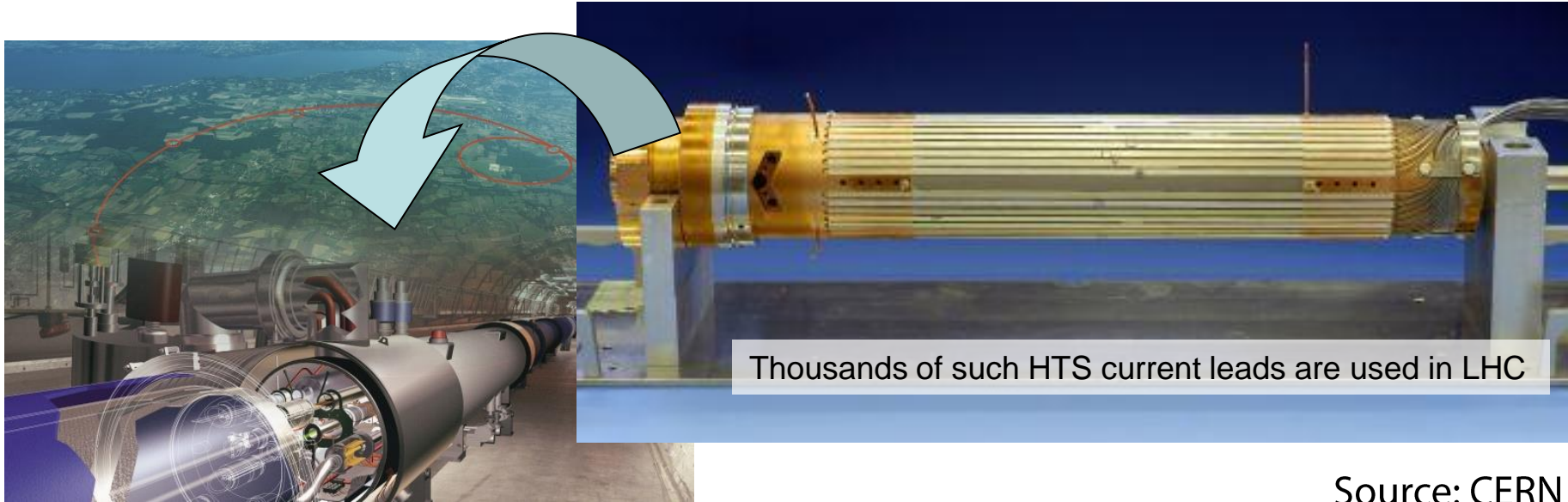
Source: CERN

HTS enable high magnetic fields, reduce energy consumption, facilitate power transmission in nearest future accelerators and colliders



With SuperOx wire, HTS dipole magnet was made by High Energy Physics Institute, Protvino (2015)  
**Measured 3+ T field, limited by current source**

- HTS current leads feed electrical current inside low temperature superconducting magnets without large heat inflow
- HTS is the only material to solve this task (low thermal conductivity)

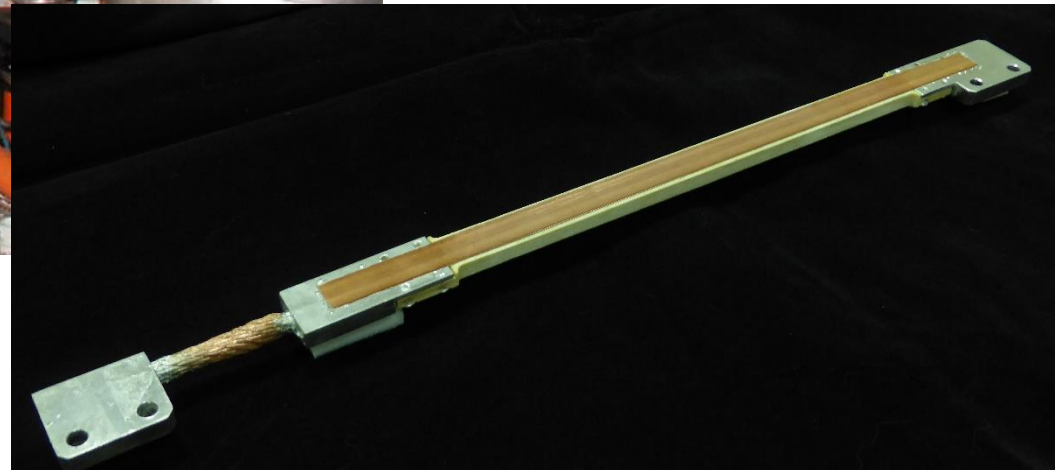


Source: CERN

HTS current leads reduced energy consumption of LHC cooling system 3-fold

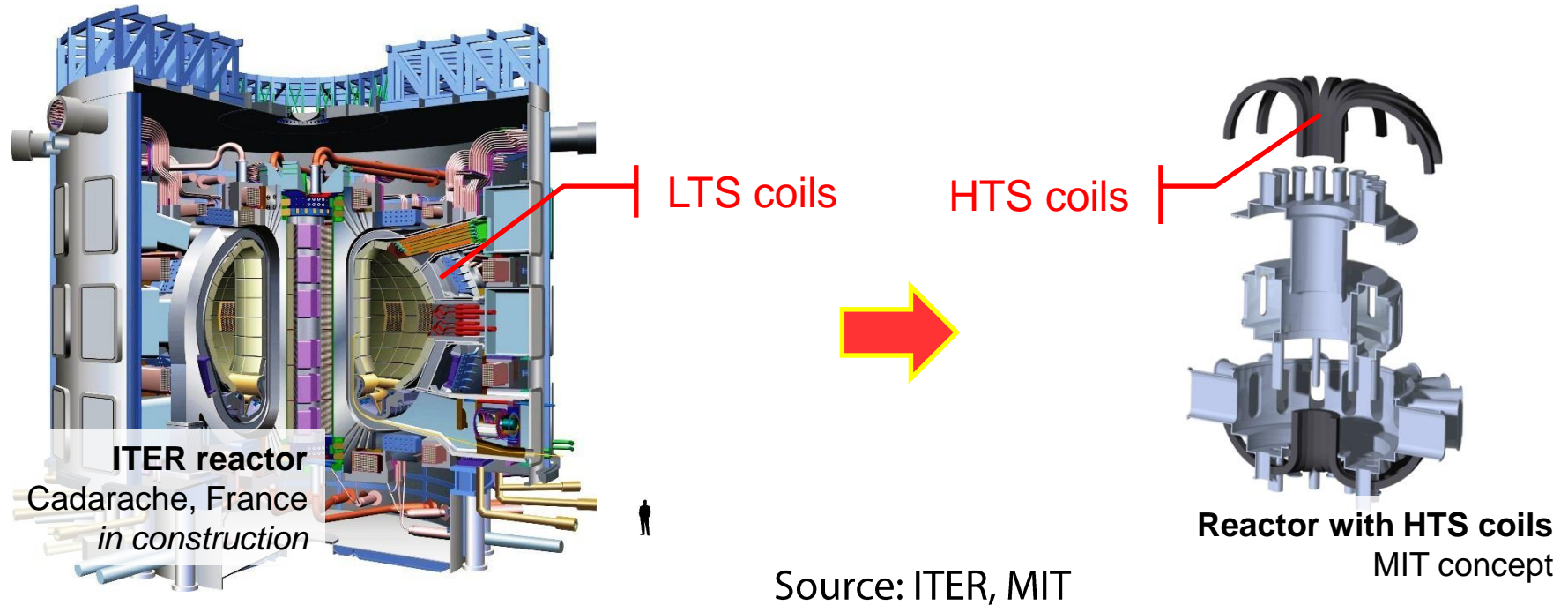


Nuclotron LTS magnets  
NICA collider, Dubna JINR



SuperOx's custom 100 A HTS current lead for a corrector coil of an LTS magnet

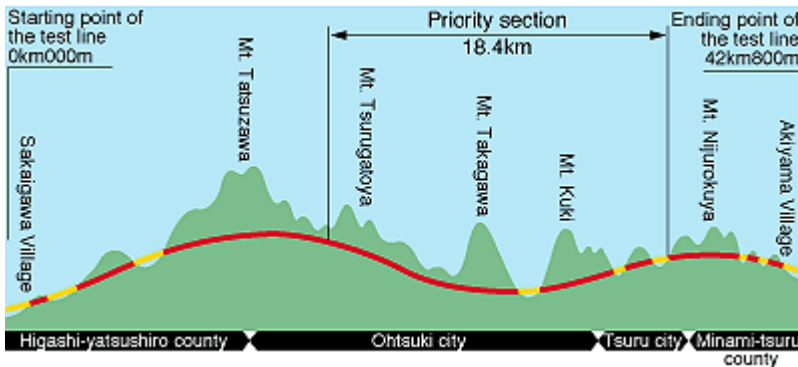
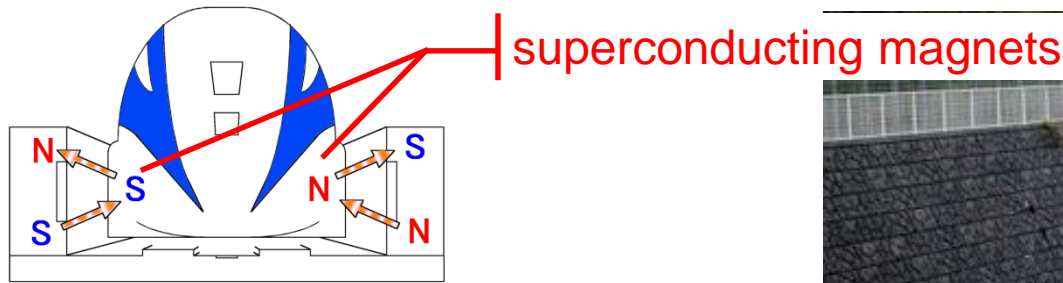
- In future, fusion reactors may provide clean energy for mankind
- ITER reactor will be built with LTS; **HTS is promising for next generation**



HTS magnets will enable higher fields for smaller, demountable fusion reactors



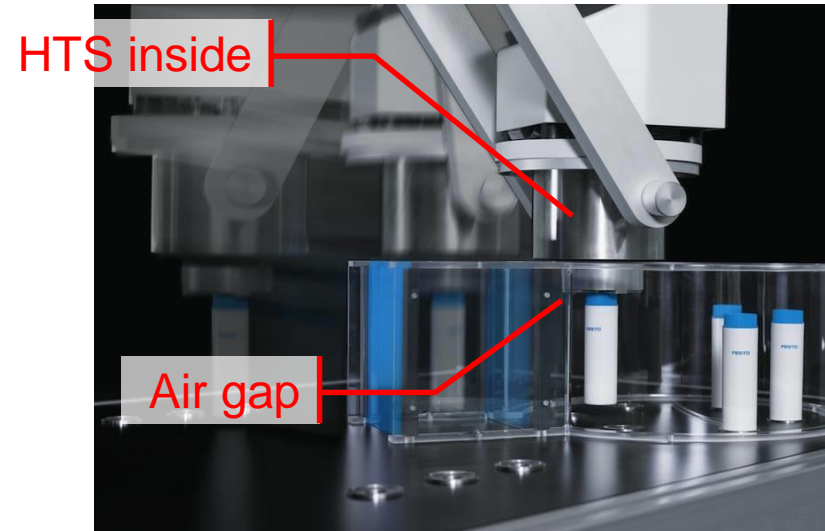
- Superconducting magnets with 5 Tesla field are necessary for levitation trains



43 km-long Yamanashi test line with top speed 603 km/h  
LTS magnets are upgradable to HTS

Source: Japanese Railway

- HTS provide stable levitation over permanent magnets
- Large potential contact-less manipulation systems for dangerous objects



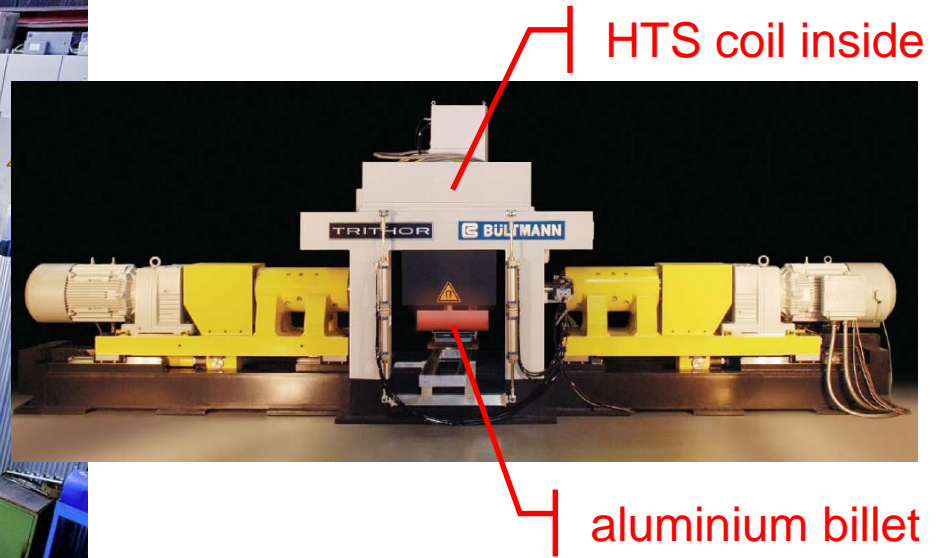
Source: FESTO

SuperOx developed new HTS material for levitation – 2G HTS composite blocks



<https://www.youtube.com/watch?v=sYMh0V7VMn8>

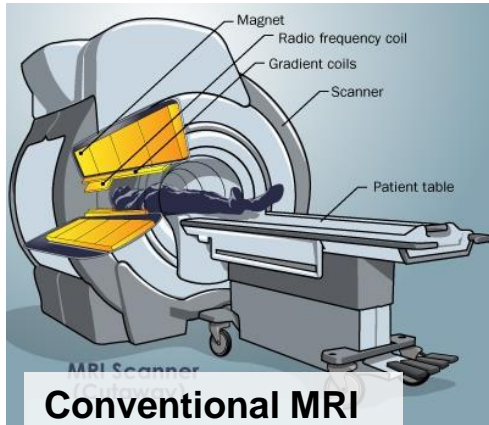
- HTS coils enable rapid heating of aluminium, copper, and brass billets
- Excellent uniformity, **operational costs are reduced by 50%**



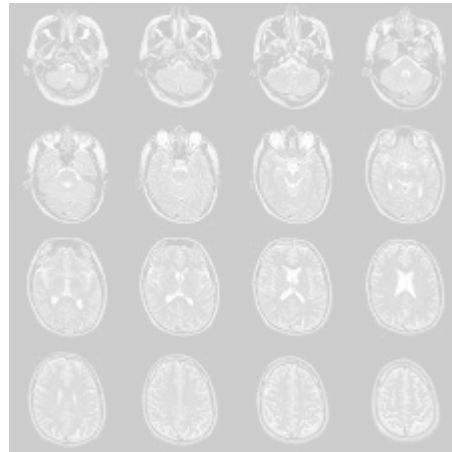
Source: Bueltmann/Trithor

HTS inductive heating saves 180,000 EUR/year for each 0.5 MW aluminium heater

- MRI is the largest market for low temperature superconductors now (about \$2B)
- HTS are the key materials for high resolution devices (field > 10 Tesla)



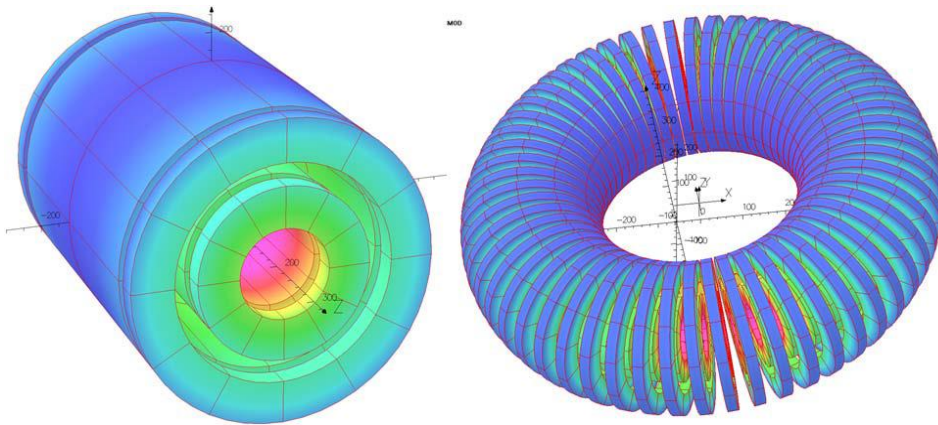
**Conventional MRI**  
since 1970s



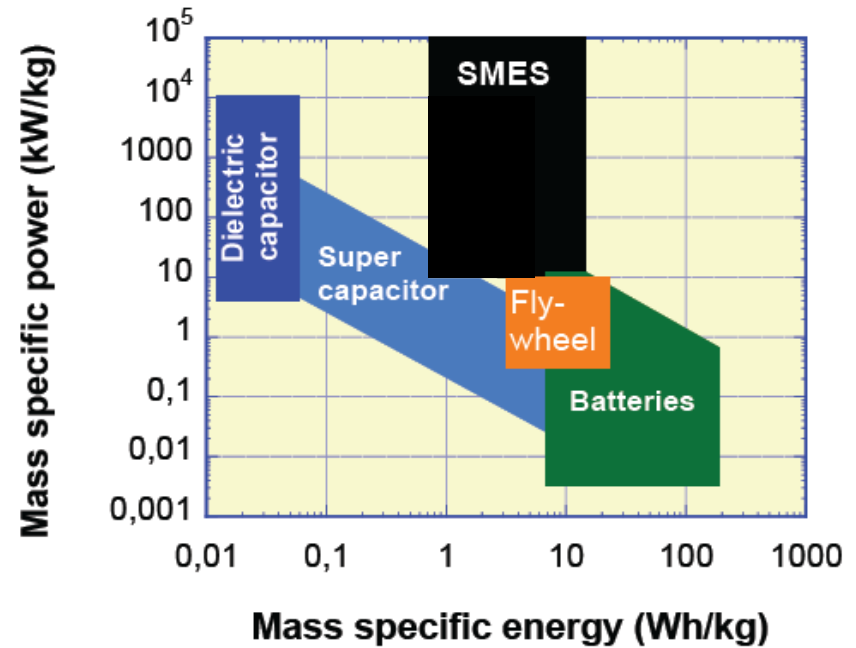
**Worlds-first  
HTS MRI magnet**  
2012  
IRL, New Zealand

HTS enable MRI machines that are cheaper in operation (no liquid helium)

- SMES is perfect for generating high power pulses



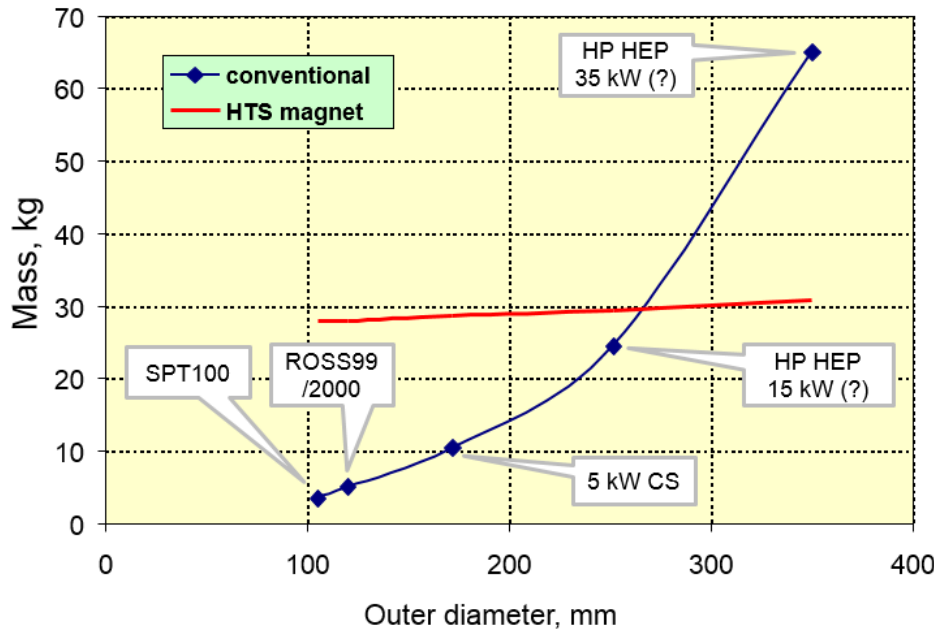
Source: Brookhaven Nat Lab



2.5 MJ SMES for military applications

Extremely fast charge/discharge

## ■ HTS magnets facilitate lightweight plasma propulsion engines

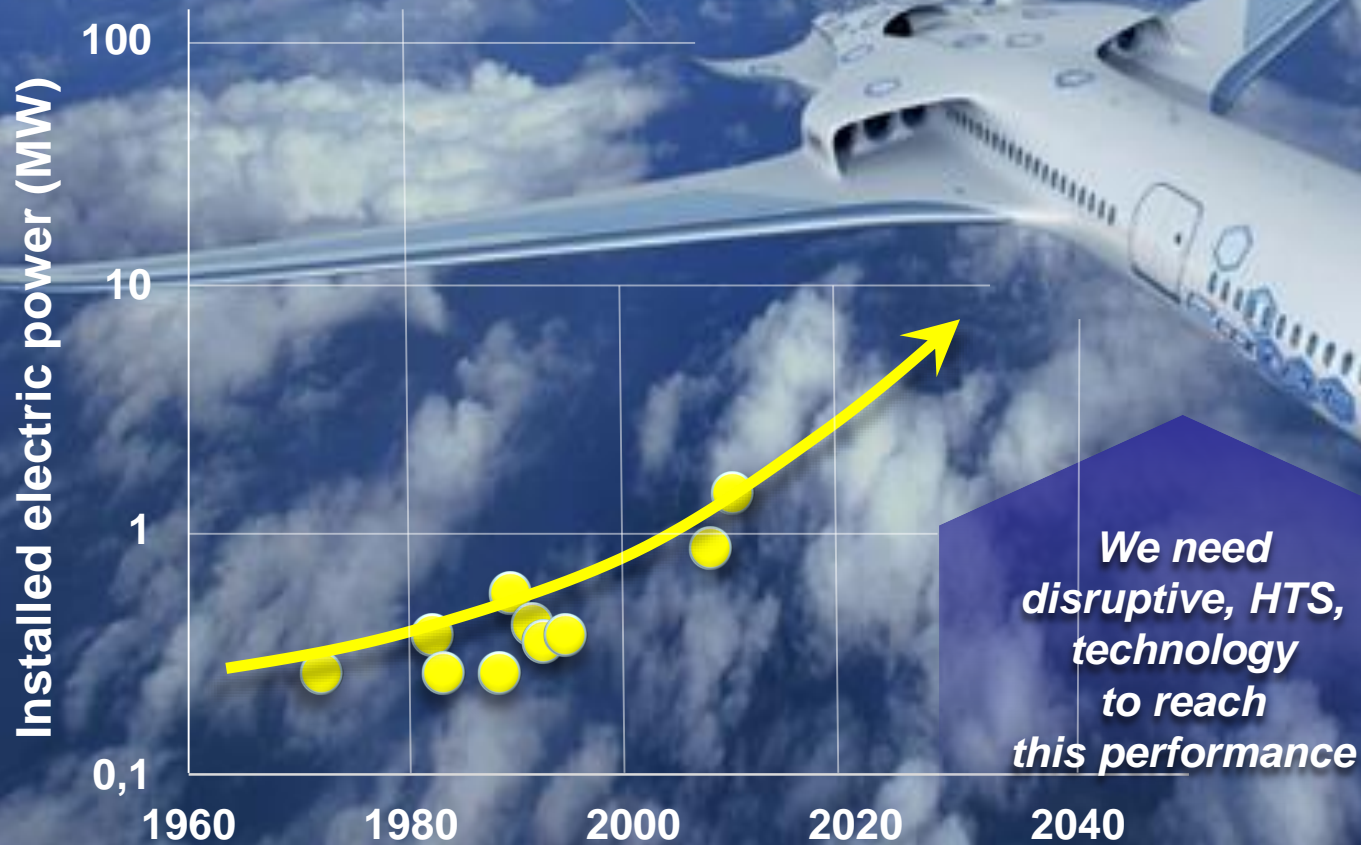


Source: Granados et al. / ISS2012

2 times lower weight for 35 kW engine

# HTS for future aircraft

Extreme fuel efficiency  
Very low noise





**Thank you for your attention!**

[www.superox.ru](http://www.superox.ru)  
[www.s-innovations.ru](http://www.s-innovations.ru)