Superconducting Materials
Learning outcome

<u>At the end of this lecture you will be able to</u>:

- Phenomenological describe the phenomenon of superconduction
- Explain how superconductors behave in magnetic fields
- Describe some applications of superconductors in Power Engineering

History of Superconductivity

- 1911 Kamerlingh Onnes discovered superconductivity while studying the resistance of metals at low temperatures (Hg mercury at 4.15K).
  - Resistance fall to zero at low temperature
  - the same phenomenon discovered in other materials

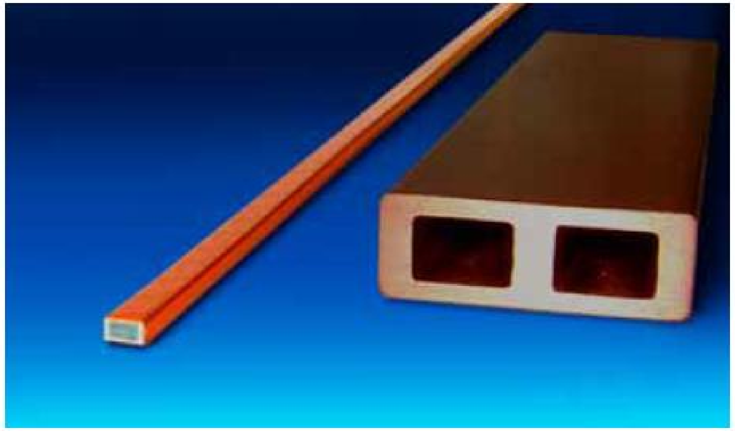
- Highest critical temperature yet 23 K in 1973
- Need of liquid Helium (4 K) or liquid Hydrogen (20 K)

- 1933 Walter Meissner & Robert Ochsenfeld discovered a magnetic phenomenon related to superconductivity

History of Superconductivity

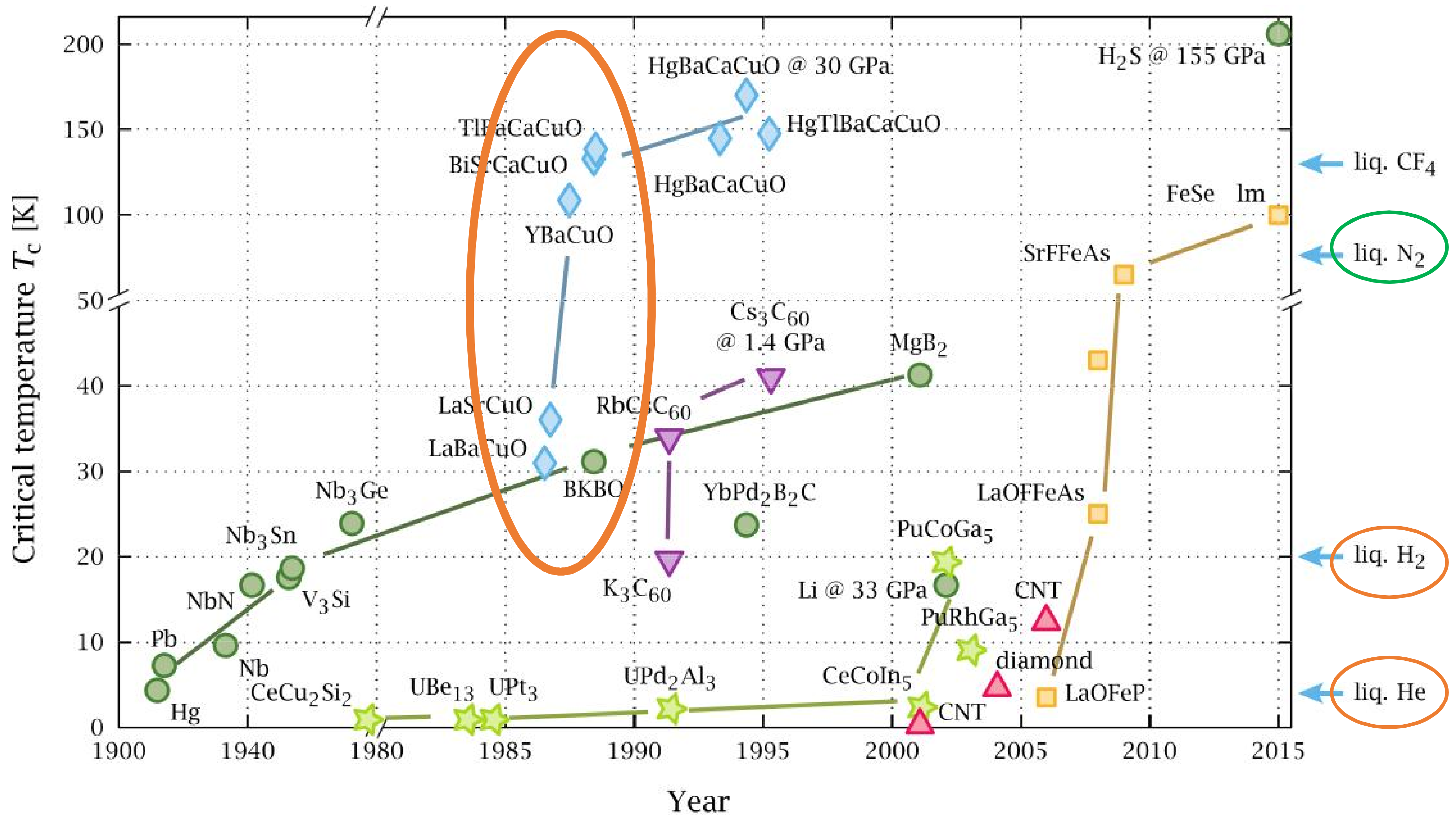
- 1986 J. Georg Bednorz & K. Alex Mueller discovered high temperature superconducting material
  - First @35 K and then @92 K
- Usage of liquid Nitrogen (77 K) became possible

- 1962 Josephson effect discovered a quantum phenomenon called after him

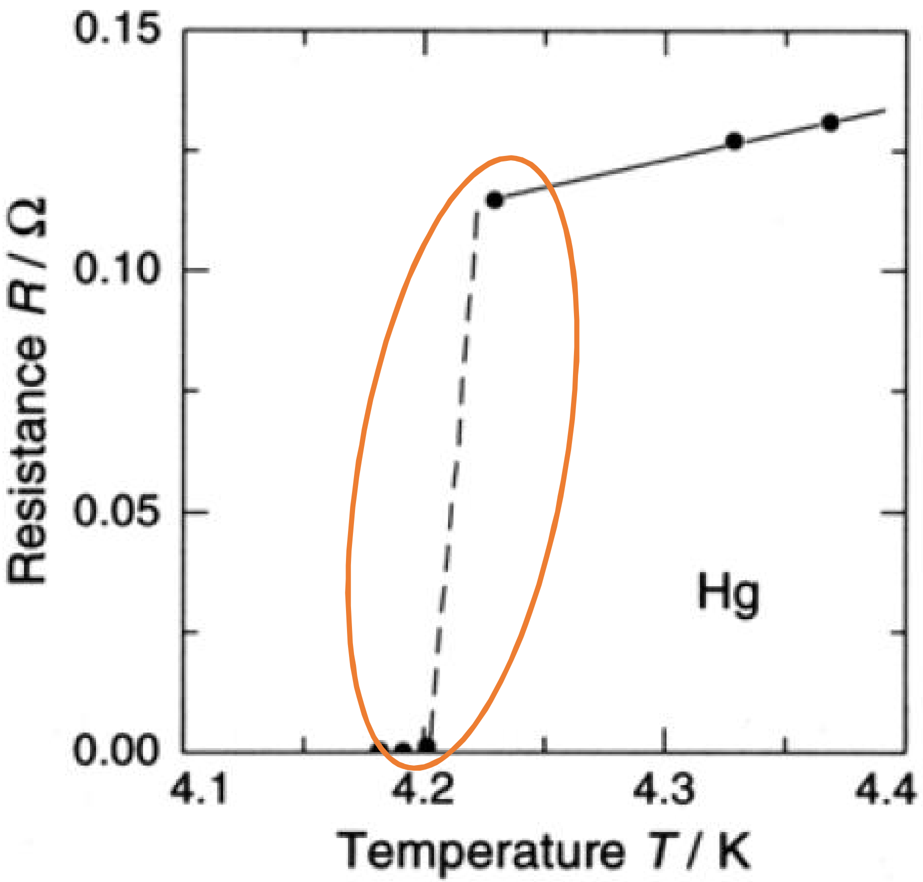


1,000 A HTS Wire   1,000 A Copper Wire

Development of Critical temperature



Electric Superconductivity phenomena



Measurement results as reported by Kamerlingh Onnes

Element	T_c (K)	Element	T_c (K)	Element	T_c (K)
Al	1.19	Nb	9.2	Tc	7.8
Be	0.026	Np	0.075	Th	1.37
Cd	0.55	Os	0.65	Ti	0.39
Ga	1.09	Pa	1.3	Tl	2.39
Hf	0.13	Pb	7.2	U	0.2
Hg	4.15	Re	1.7	V	5.3
In	3.40	Rh	0.0003	W	0.012
Ir	0.14	Ru	0.5	Zn	0.9
La	4.8	Sn	3.75	Zr	0.55
Mo	0.92	Ta	4.39		
Compound	**T_c (K)**	**Compound**	**T_c (K)**	**Compound**	**T_c (K)**
Nb_3Sn	18.1	MgB_2	39	UPt_3	0.5
Nb_3Ge	23.2	$PbMo_6S_8$	15	UPd_2Al_3	2
Cs_3C_{60}	19	YPd_2B_2C	23	$(TMTSF)_2ClO_4$	1.2
Cs_3C_{60}	40	$HoNi_2B_2C$	7.5	$(ET)_2Cu[Ni(CN)_2]Br$	11.5

High-T_c superconductor	T_c (K)	High-T_c superconductor	T_c (K)
$La_{1.83}Sr_{0.17}CuO_4$	38	$Tl_2Ba_2Ca_2Cu_3O_{10+x}$	125
$YBa_2Cu_3O_{6+x}$	93	$HgBa2Ca_2Cu_30_{8+x}$	135
$Bi_2Sr_2Ca_2Cu_3O_{10+x}$	107	$Hg_{0.8}Tl_{0.2}Ba_2Ca_2Cu_30_{8.33}$	134

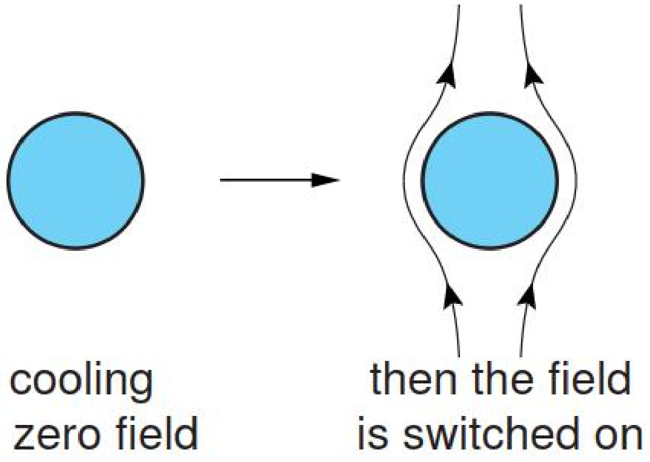
Electric Superconductivity phenomena

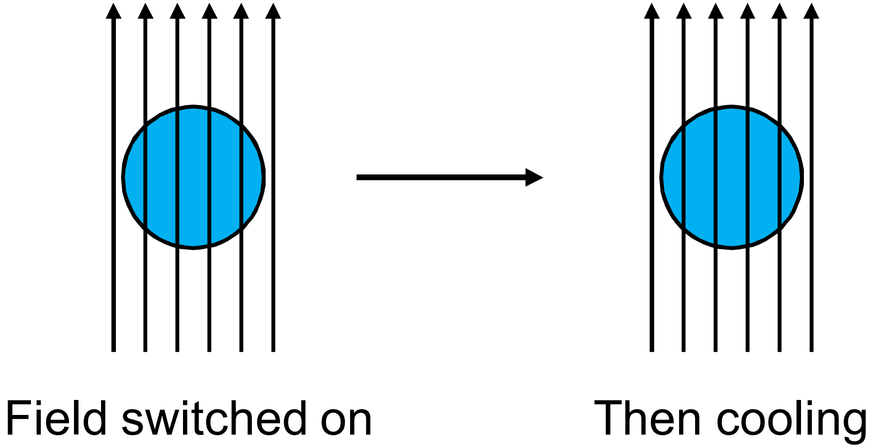
- Material in normal state

$$J = \sigma E \qquad \qquad \nabla \times E = -\frac{\partial B}{\partial t}$$

- Conductivy → 0, ***E*** → 0, thus ***B***=cte
- External field applied after cooling results in the flux not entering the conductor

Normal conductor at low temperature





- Superconductor does more than this! (Meissner effect)

Investigation work 20 min

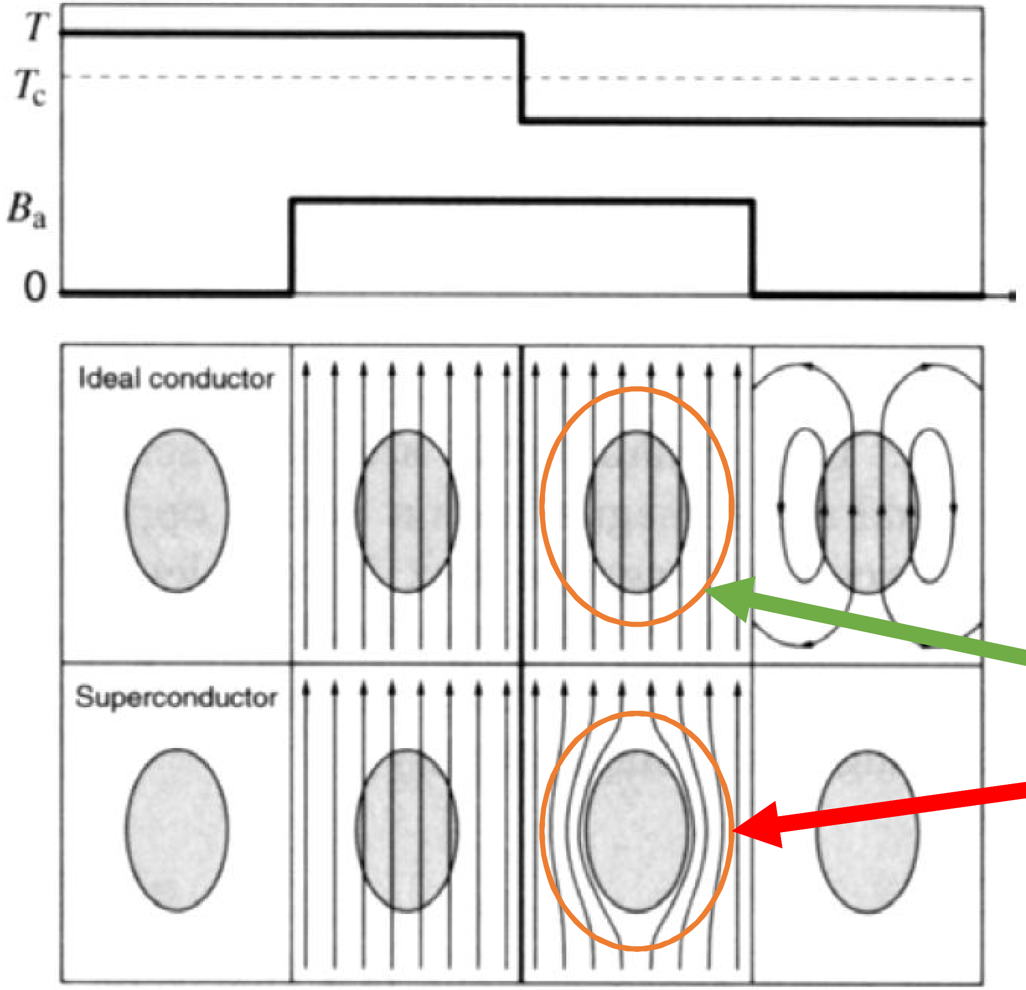
- Find an explanation of the Meissner effect in a superconductor and compare it with the behavior of a normal conductor at 0 K (5 min)

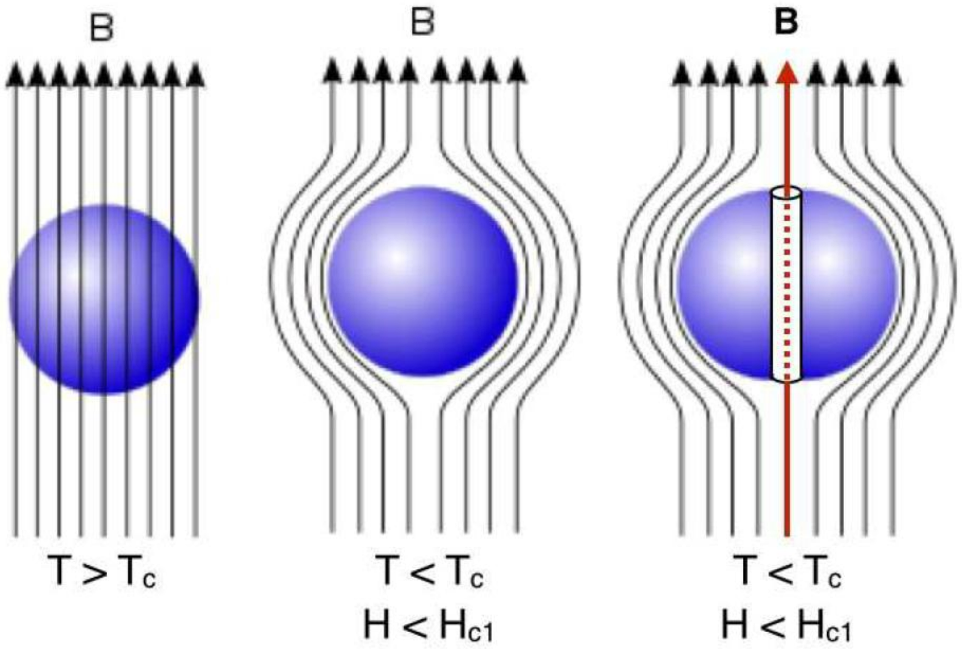
- Discuss your understanding with your mate (5 min)

- Merge your explanations and present them to the class

  - You might use internet

Meissner effect

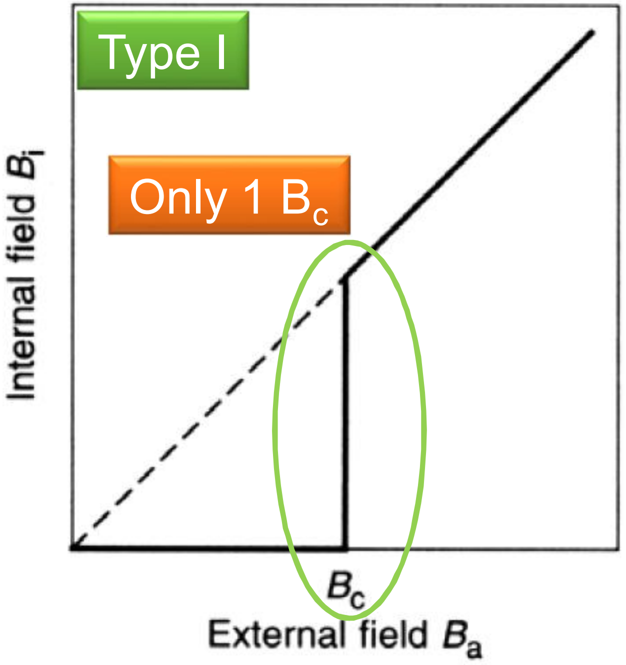


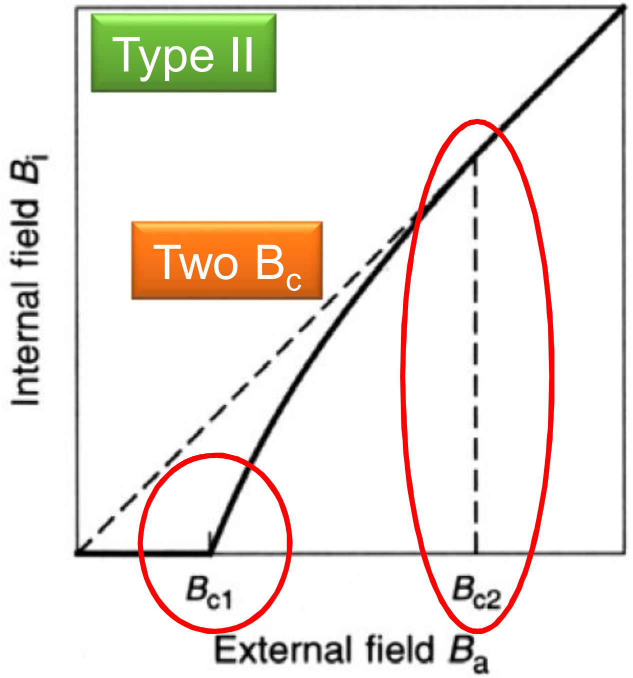


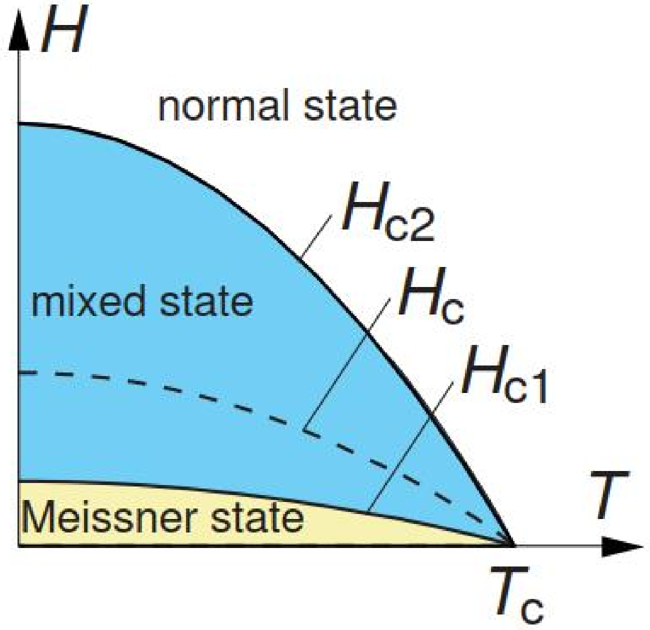
- Magnetic field applied and then temperature decreased
  - Normal conductor penetrated by the field
  - Superconductor expulses the field
- After field removal
  - Normal conductor induced current
  - Superconductor no induced currents
- If superconductor has a hole, the flux is trapped in the hole
- Meissner effect is noticed only if the field is not too high

Type I and type II superconductivity

- Natural elements are mostly type I superconductors while most compound are type II superconductors
- Superconductivity is destroyed by a high magnetic field (critical field)
- Two kind of behaviors are distinguished





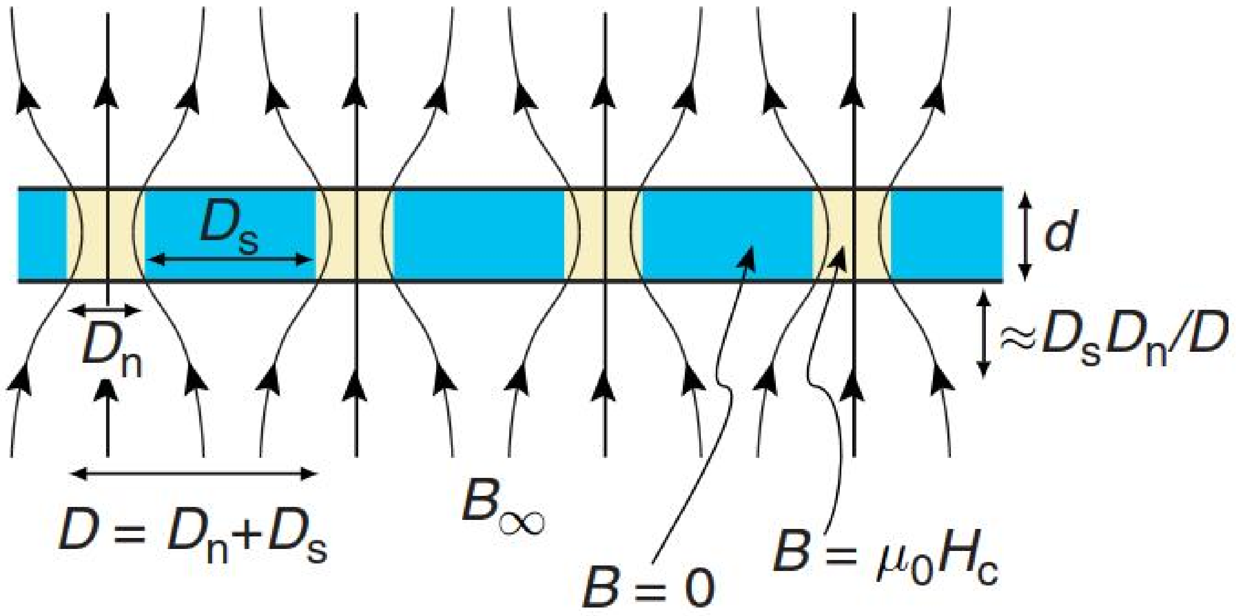


- Critical field is temperature dependent

$$H_c(T) = H_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

Type II superconductors

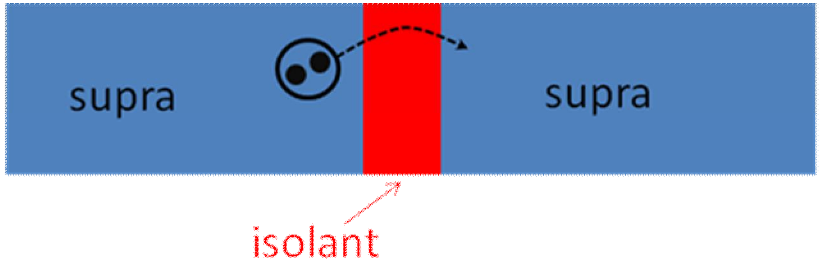
- In type II superconductors the flux is not completely repulsed
- The flux penetrates the superconductor to some extends
- In flat conductors the flux is split into normal conduction channels, it is quantized

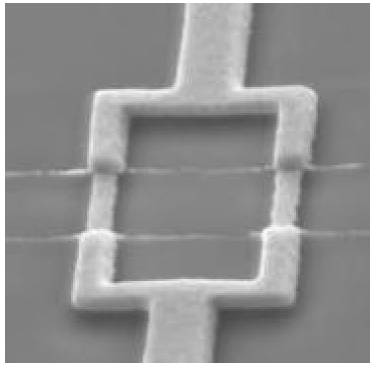


- Studying these superconducting phenomena in details requires a good background of quantum physics.

Josephson effect

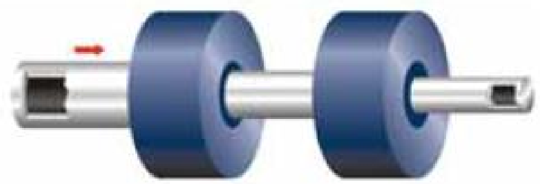
- Yet another quantum physics related phenomenon



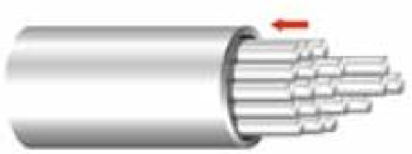


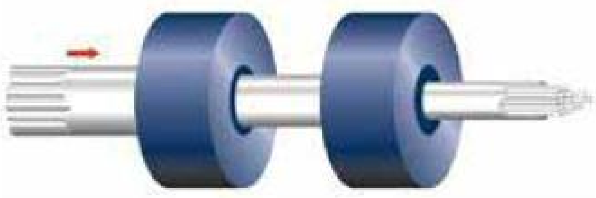
- Unexpected continuous electric current between two superconductors separated by a very thin insulating layer (few nm).
  - Electrons form Cooper pairs and condensate in a unique collective quantum wave
  - The wave can spill out of the superconductor
  - The electron pairs goes through the insulator thanks to the tunneling effect (quantum).
  - Current proportional to the sine of the phase difference between the superconductors.
- If a DC-voltage is applied, an alternating current will appear
  - Frequency depends only on voltage and fundamental parameters → U-measurement
  - Sensitivity to magnetic field makes it possible to measure low field → Squid

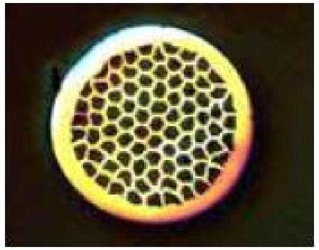
Manufacturing technology



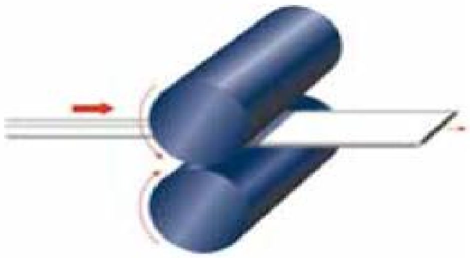
1. Ceramic and metal co-deformed to wire

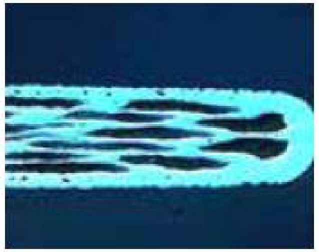






2. Multifilamentary architecture provides flexibility

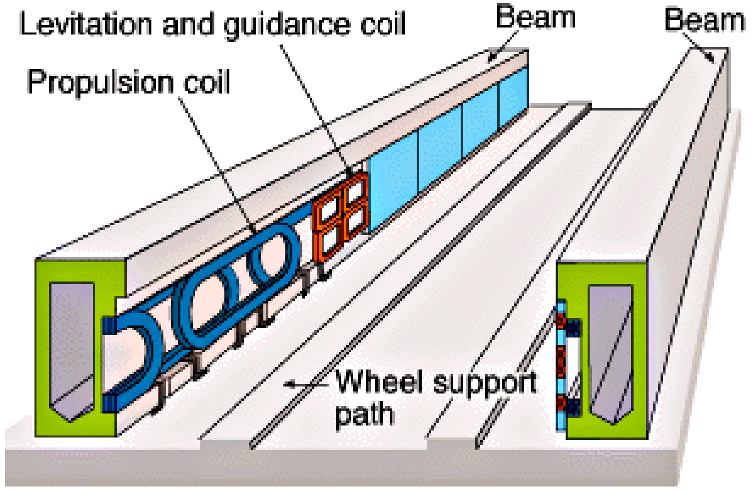




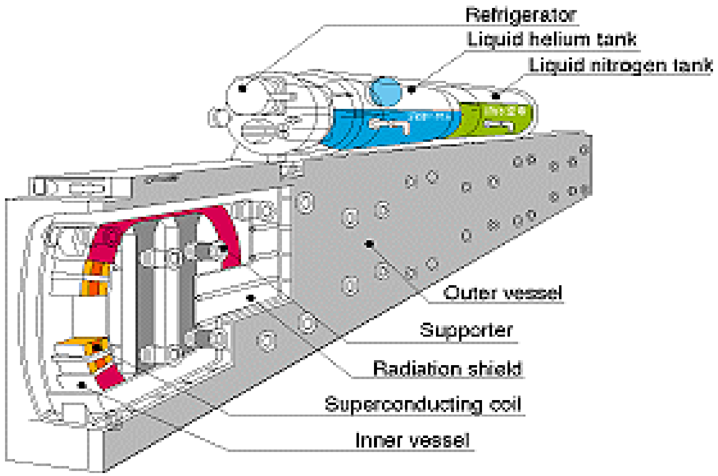
3. Rolling and heat treatment form the superconducting microstructure

Applications of superconductivity

- Maglev
  - Superconducting coil on-board
  - Active propulsion coils on-track
  - Passive levitation coils on-track
  - Flux density about 5 T
  - Low Temperature Superconducting technology

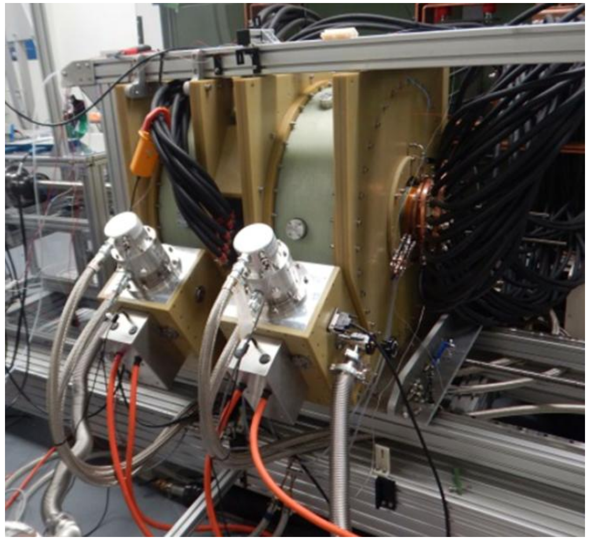


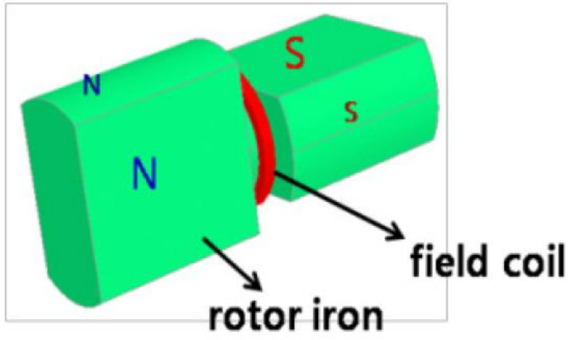
- Japan:
  - Tokyo-Osaka Speed record 603km/h
- China
  - Shanghai 1.2004, 431 km/h

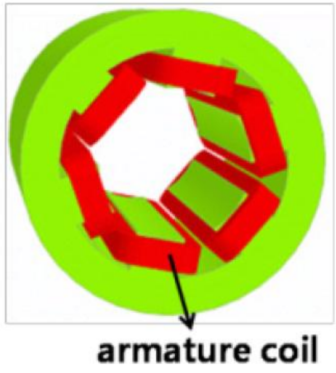


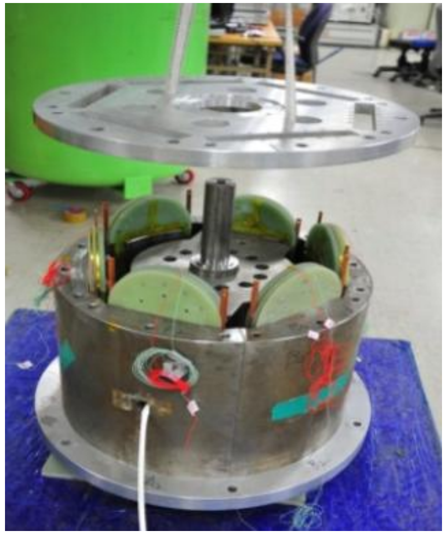
Applications of superconductivity

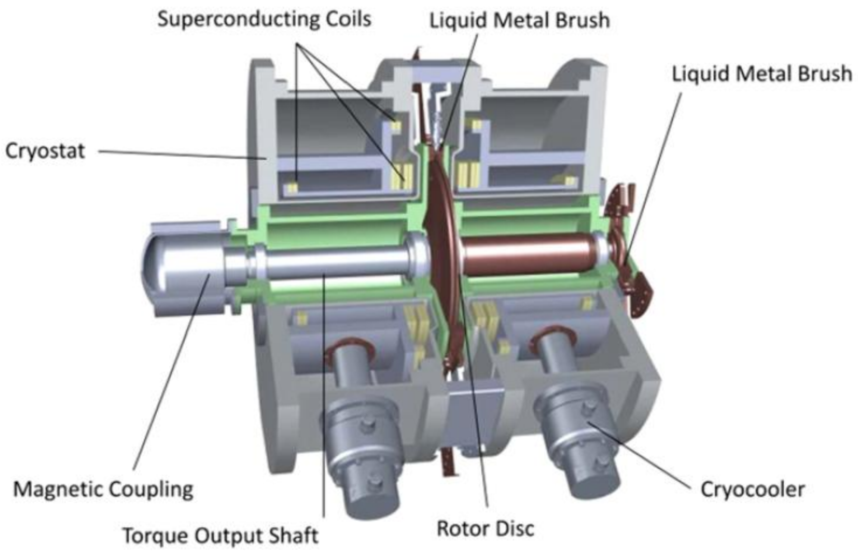
- Electrical machines
- Homopolar motors
  - 5 – 200 kW demonstrators
  - With and without iron core
  - 10-40 kA currents
  - Magnetic flux density 2-3T
  - Both Low and High Temperature superconductors





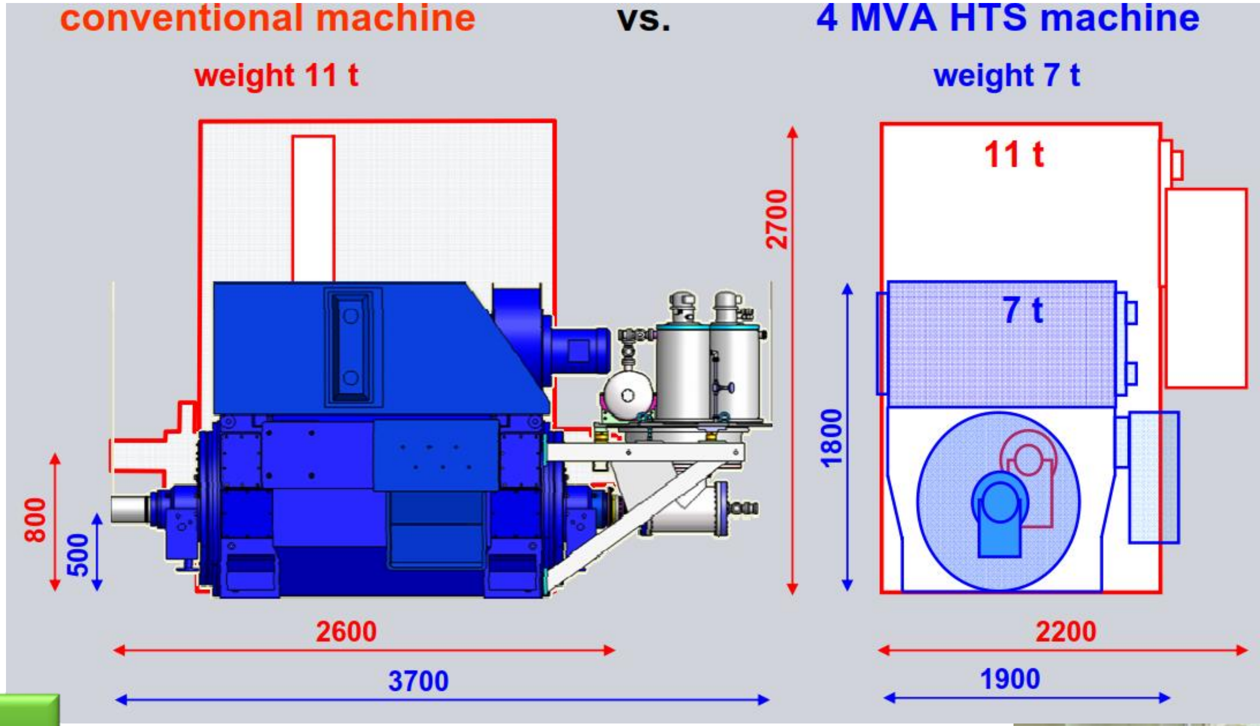


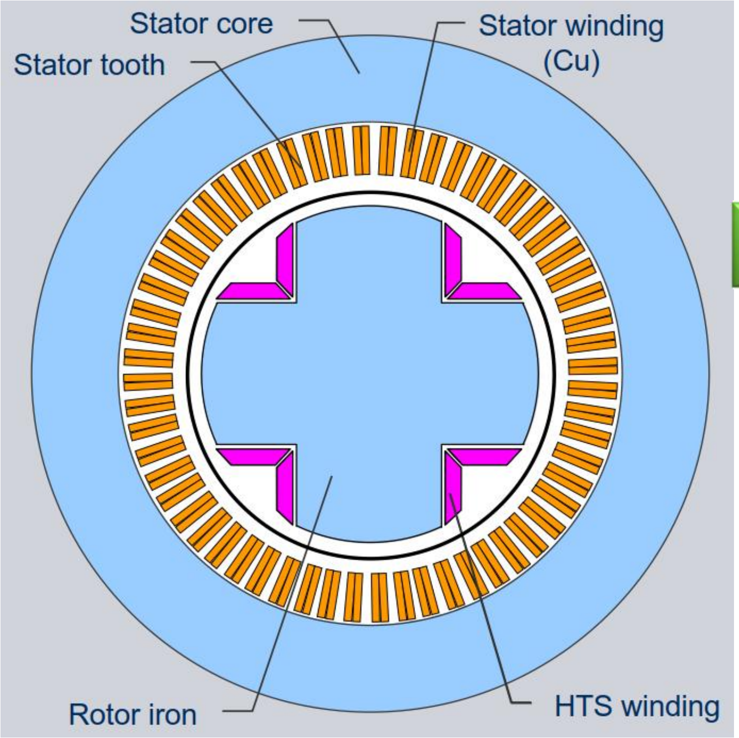




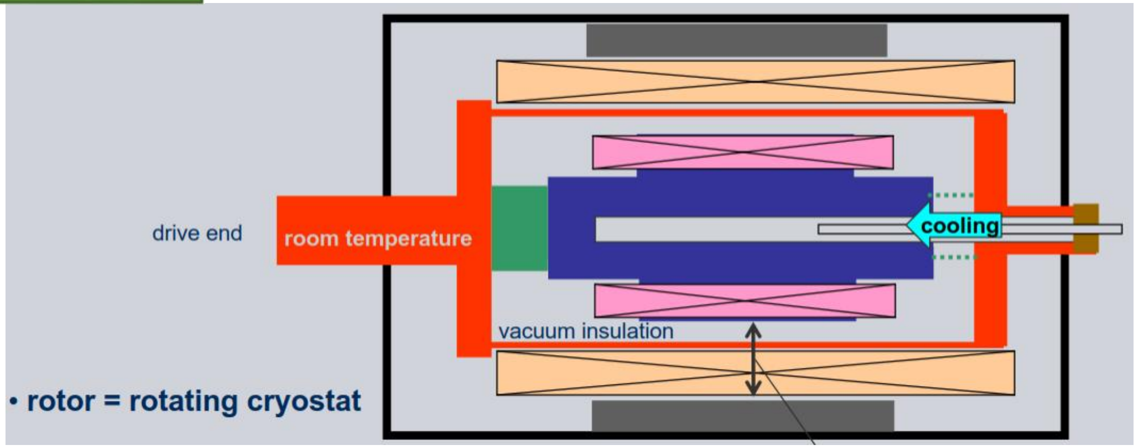
Applications of superconductivity

- Electrical machines
- Synchronous machines
  - With partial iron core
  - 1200 – 4000 kVA
  - Mostly demonstrators





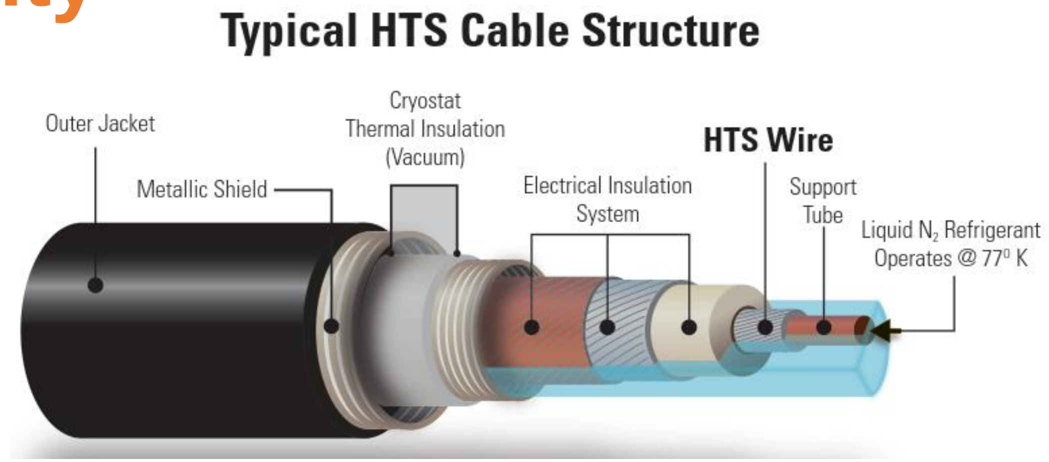
Siemens



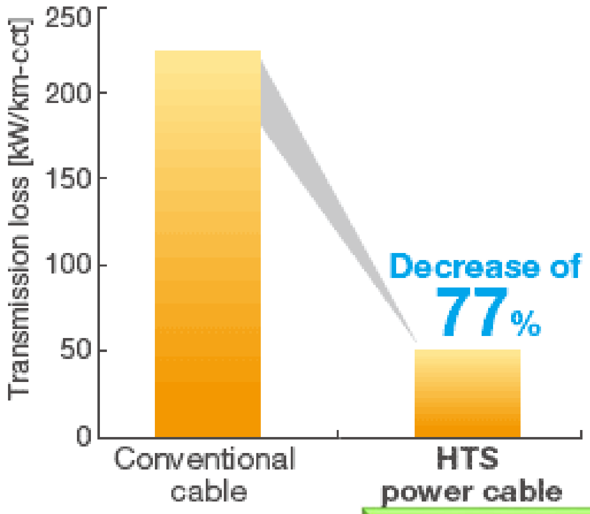
Trithor

Applications of superconductivity

- Cable demonstrators
- 2014, AmpaCity project, Essen, Germany
  - 1 km, 40 MW, 10kV instead of 110 kV
  - HTS ceramic technology, Liquid Nitrogen



- 2008, Long Island Power Authority, New York, USA
  - 600 m, 574 MW



Furukawa Electric

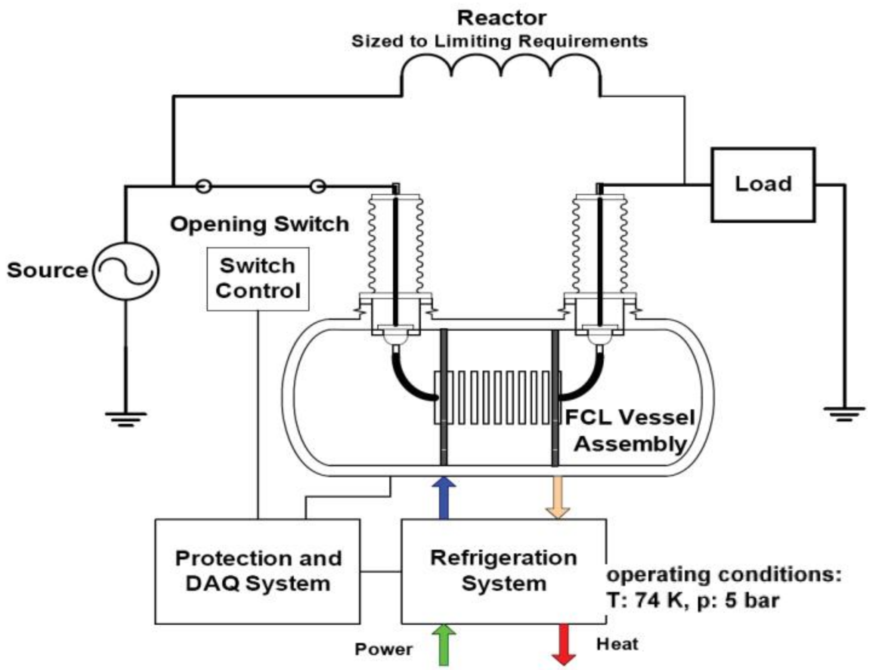
- In conventional cables, resistive losses are 2-8%
- In superconducting cables AC-losses are presents
  - Eddy-current in conducting matrix and hysteresis loss in ceramic material
  - Although very small, they hinder the cooling system

Investigation work 20 min

- Find an explanation of how superconducting based current limiters work
- Explain the working principle to your mate
- Merge your explanations and present them to the class
  - You might use internet

Applications of superconductivity

- Transformers and Current limiters
- Several designs for transformers, but no real application
- Several design and prototypes of current limiters



Applications of superconductivity

- Energy storage SMES