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## Hands-on Techno Economic Assessment: HTS Busbar

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# Techno Economic Assessment of an HTS Busbar System

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**Hi-SCALE**



# Content

- I. Motivation
- II. Aluminum and its Production
- III. HTS Busbar System
- IV. Conclusion

# I. Motivation

## II. Aluminum

# What is Aluminum?

- The most used metal after iron [1]
- Low density
- Soft, malleable
- Good thermal conductivity
- Good electrical conductivity
- Easily forms alloys with other metals
- Recyclable

A periodic table of elements where the element Aluminum (Al) is highlighted in red. The table shows the standard layout of elements with their symbols and atomic numbers. The groups are numbered 1 through 18 at the top. The lanthanide and actinide series are shown below the main table.



[1] [earth.com/earthpedia-articles/aluminum](http://earth.com/earthpedia-articles/aluminum)

# What is Aluminum - Uses

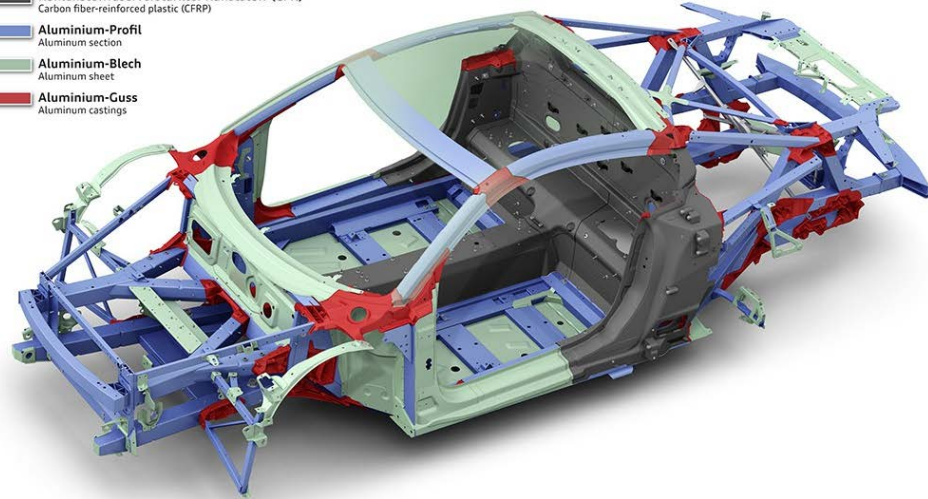


- Transportation Sector
  - Automotive
  - Aircraft
  - Spacecraft
  - Railway cars...
  
- Electrical Engineering
  - Cables
  - Overhead lines
  - Motors/generators...
  
- Construction
- Packaging

## Audi R8 Coupé

Audi Space Frame in Multimaterialbauweise  
Audi space frame in multimaterial construction  
03/15

-  Kohlenstofffaserverstärkter Kunststoff (CFK)  
Carbon fiber-reinforced plastic (CFRP)
-  Aluminium-Profil  
Aluminium section
-  Aluminium-Blech  
Aluminium sheet
-  Aluminium-Guss  
Aluminium castings



# Primary Aluminum Production

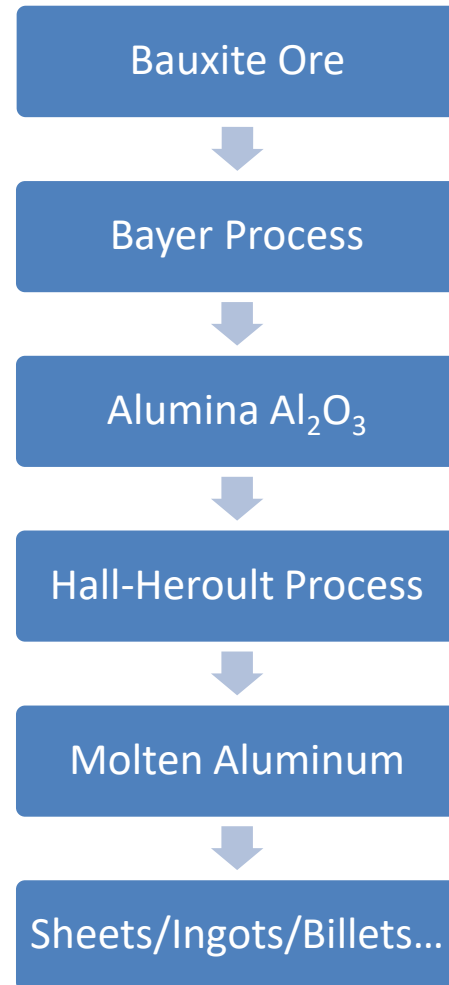
- Where does aluminum come from?
- Aluminum does not occur in its pure form!
- Most commonly found in bauxite
- Aluminum minerals in bauxite include largely:
  - Gibbsite
  - Boehmite
- With the **Bayer** and **Hall-Heroult** processes Aluminum is produced





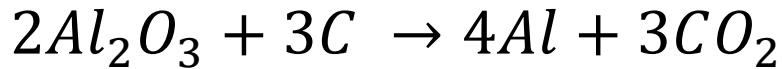
# Primary Aluminum Production

- This is process we can optimize with HTS!
- But why?

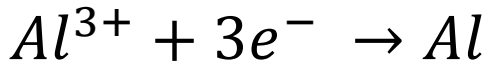


# Hall-Heroult-Process (Electrolysis)

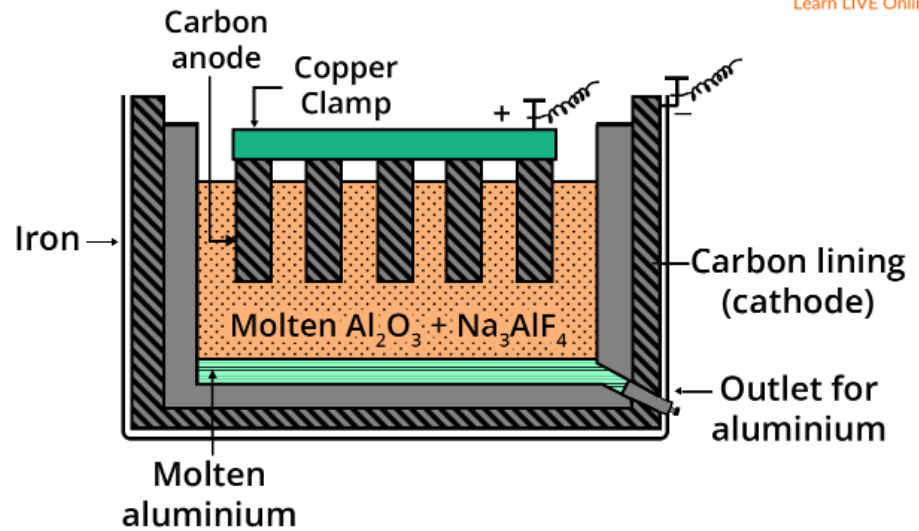
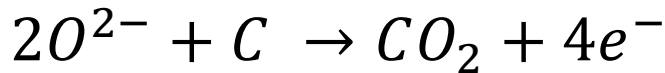
- The process is a redox-reaction:



- Cathode:



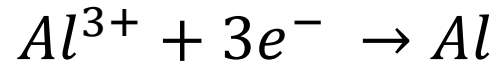
- Anode:



Cryolite is added to decrease the melting point of alumina (2000°C to 1000°C) and increase electric conductivity in the mixture

# Hall-Heroult-Process (Electrolysis)

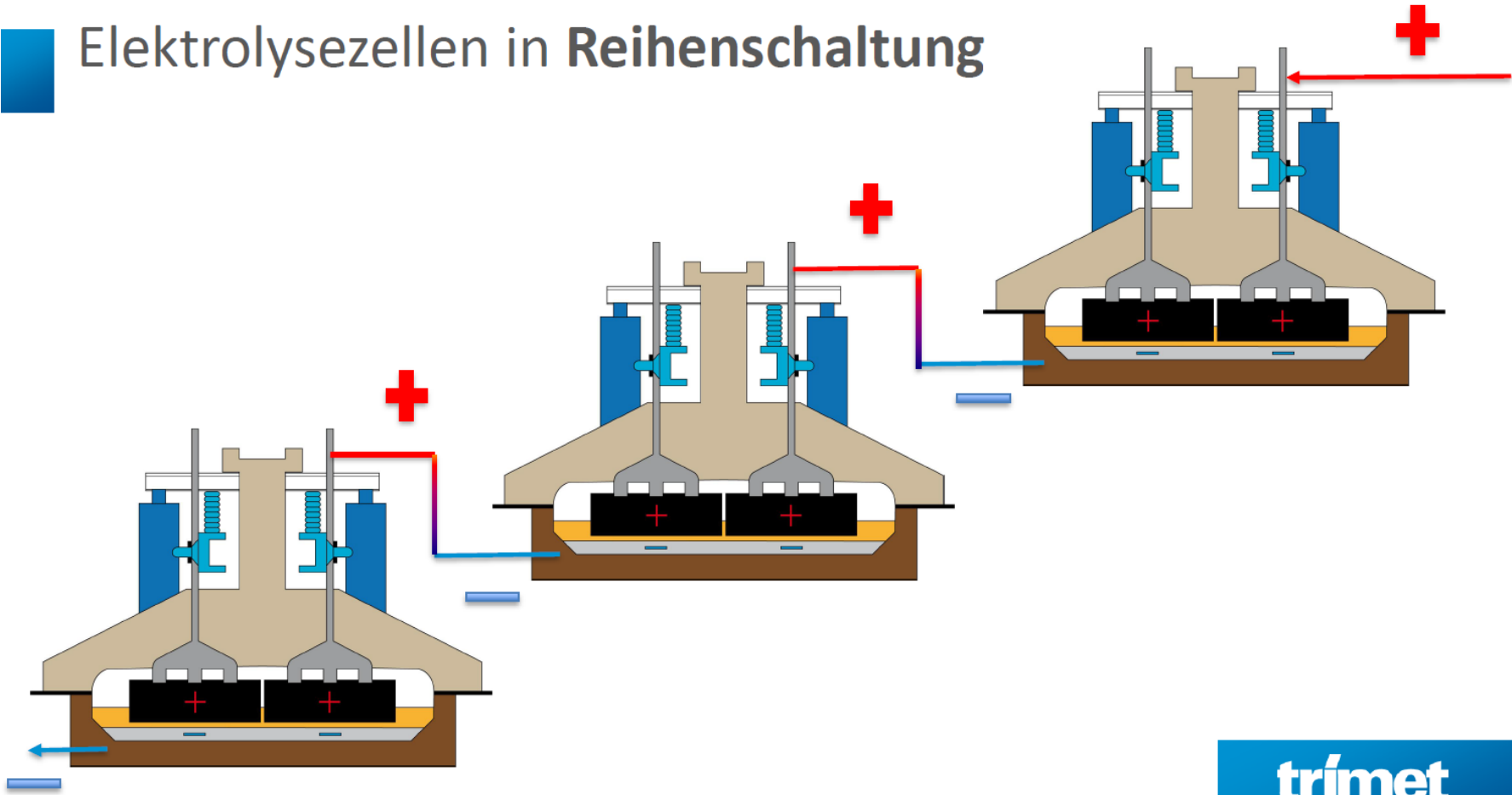
- Important take away going forward:



- The reaction scales with electron flow (**current**)
- Usual operating currents of around 200 – 400 kA (DC)
- Reaction takes place in electrolytic cell (5 V) at around 1000 °C
- Multiple cells are placed in series
- Electrical losses scale with current:  $W_{loss} = I^2 R$
- Highly energy intensive process!

# Example Aluminum Smelter

## Elektrolysezellen in Reihenschaltung



# Example Aluminum Smelter



100 % GeoBasis-DE/BKG (©2009) Landsat / Copernicus Data SIO, NOAA, U.S. Navy, NGA, GEBCO

60 m Kamera: 237 m 53°30'

[1] [earth.com/earthpedia-articles/aluminum](https://earth.com/earthpedia-articles/aluminum)

# Example Aluminum Smelter



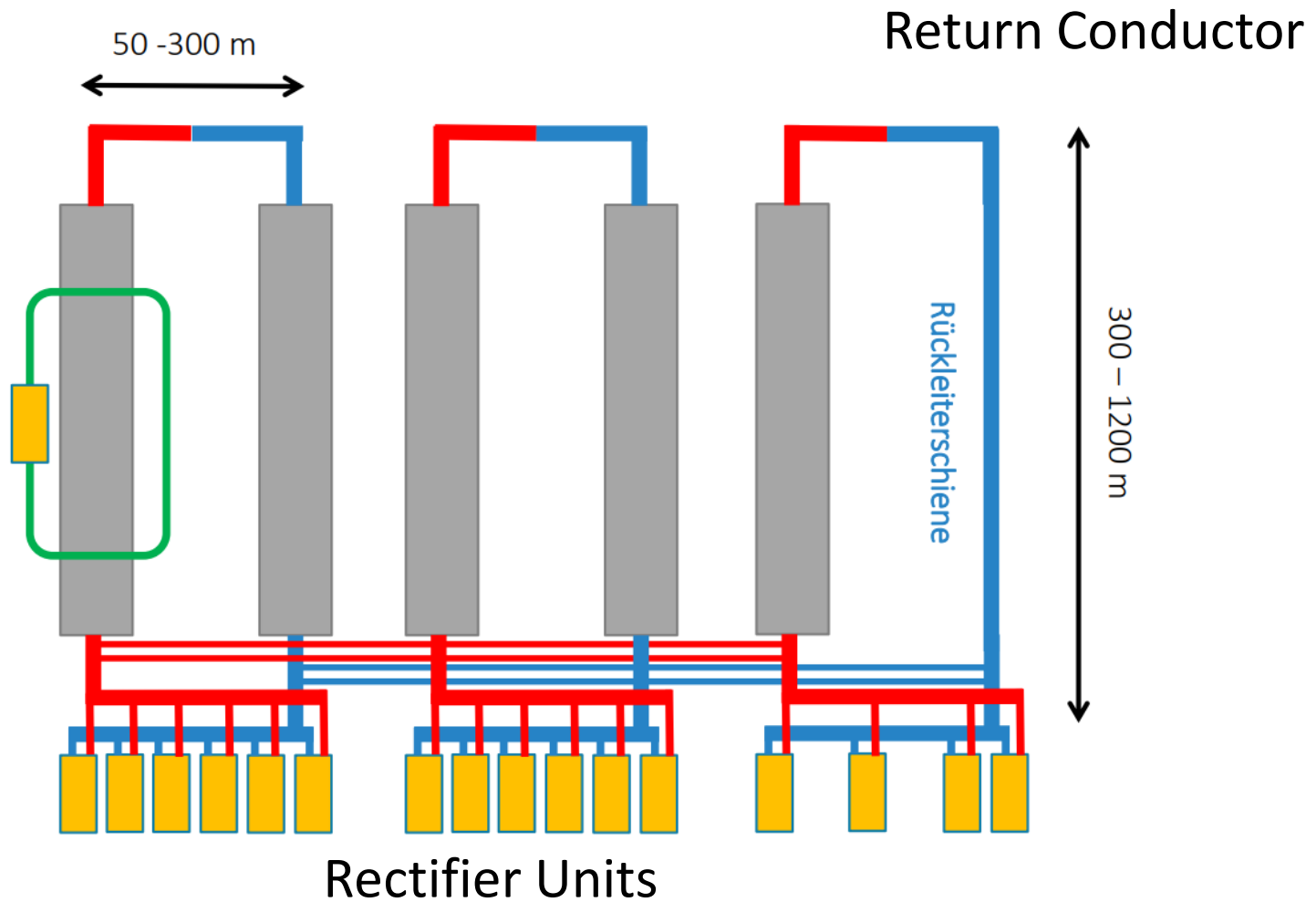
[1] [earth.com/earthpedia-articles/aluminum](https://earth.com/earthpedia-articles/aluminum)

# Example Aluminum Smelter



[1] [earth.com/earthpedia-articles/aluminum](https://earth.com/earthpedia-articles/aluminum)

# Example Aluminum Plant



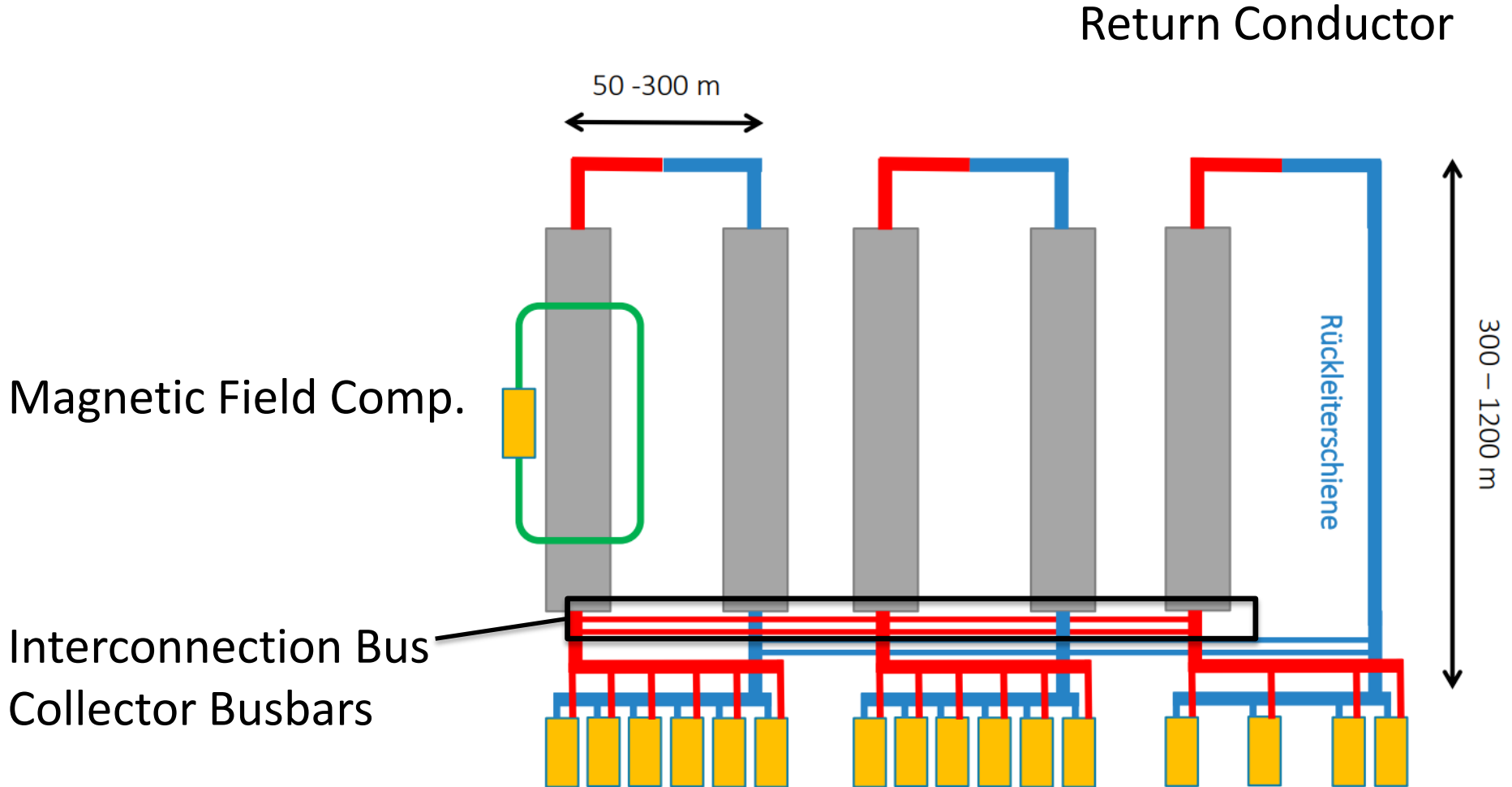
[1] [earth.com/earthpedia-articles/aluminum](http://earth.com/earthpedia-articles/aluminum)



# Example Aluminum Plant

- The **return conductor** carries roughly 200 kA
- 12 V are lost across a length of 600 m
- This results in a power loss of 2.4 MW!
- Yearly over 2 million kWh are lost!

# Multiple Possibilities for HTS Utilization!



[1] [earth.com/earthpedia-articles/aluminum](http://earth.com/earthpedia-articles/aluminum)

## III. HTS Busbar System

# HTS Busbar System – Goals

- To outline a system that utilizes the high current densities of HTS
- Showcase the various engineering considerations of:
  - Conductor
  - Cryostat
  - Cooling machine
  - Current lead

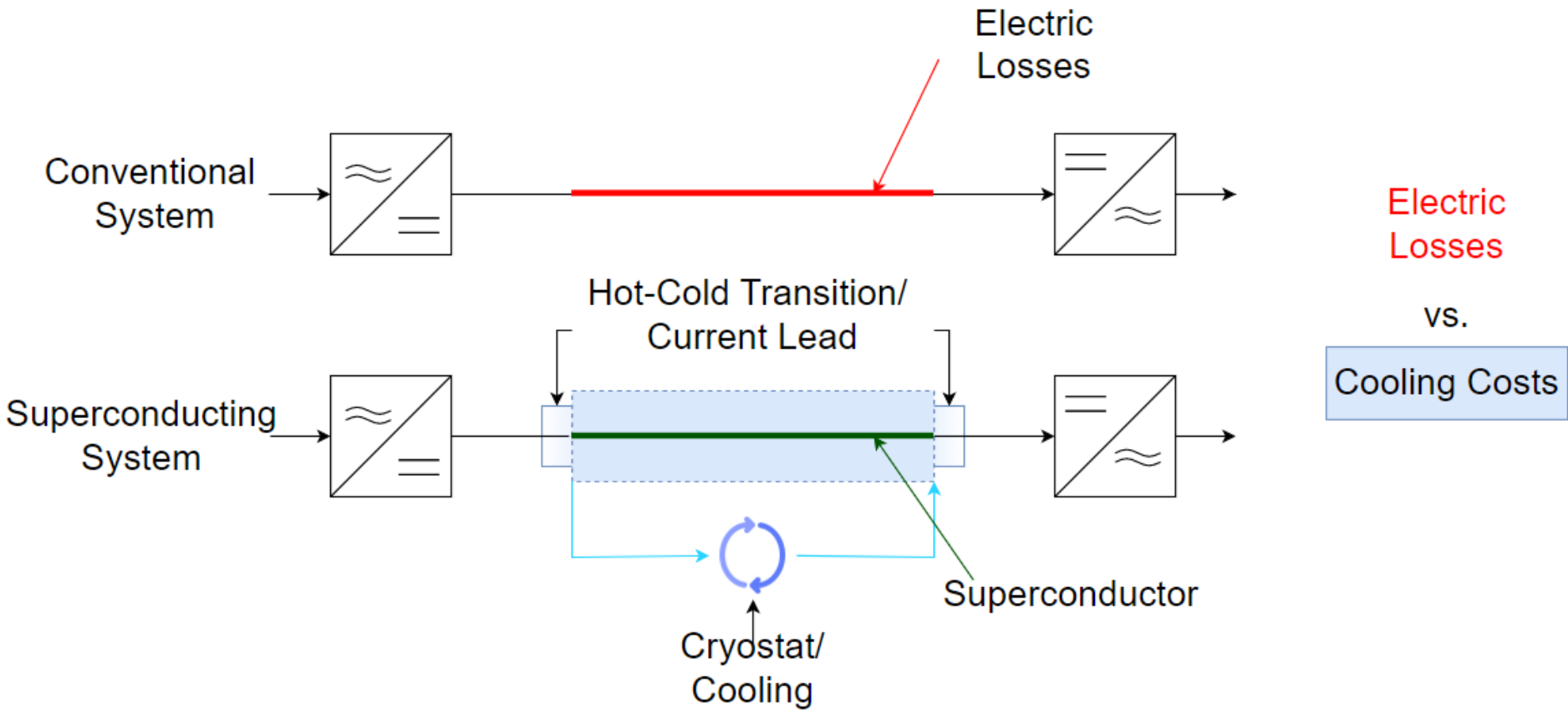


# HTS Busbar System – Overview

- A busbar system must fulfil several requirements:
  - Achieve a low temperature
  - Possess high thermal insulation
  - Insulate electrically
  - Be resistant to failures and changes in operation
  - System parameters must be measured, communicated and controlled
  - Reliable, controlled cooling system

[1] [earth.com/earthpedia-articles/aluminum](http://earth.com/earthpedia-articles/aluminum)

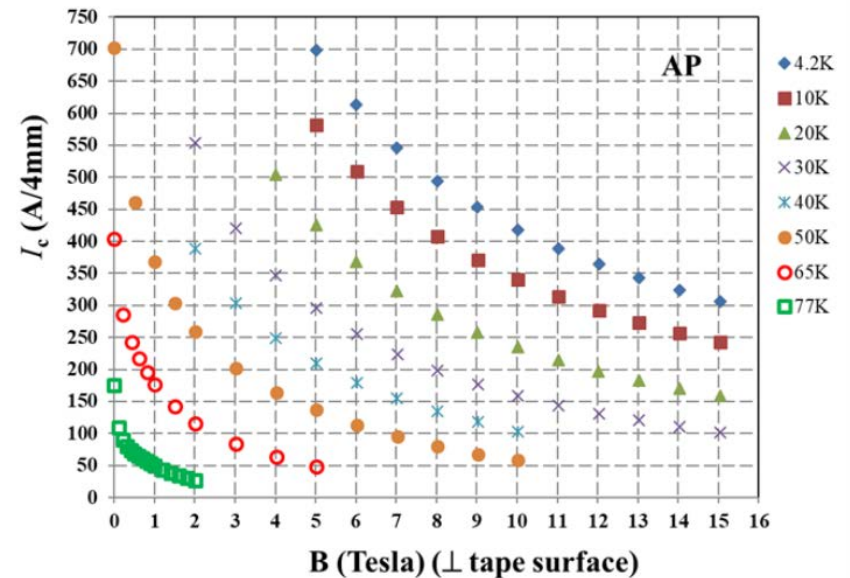
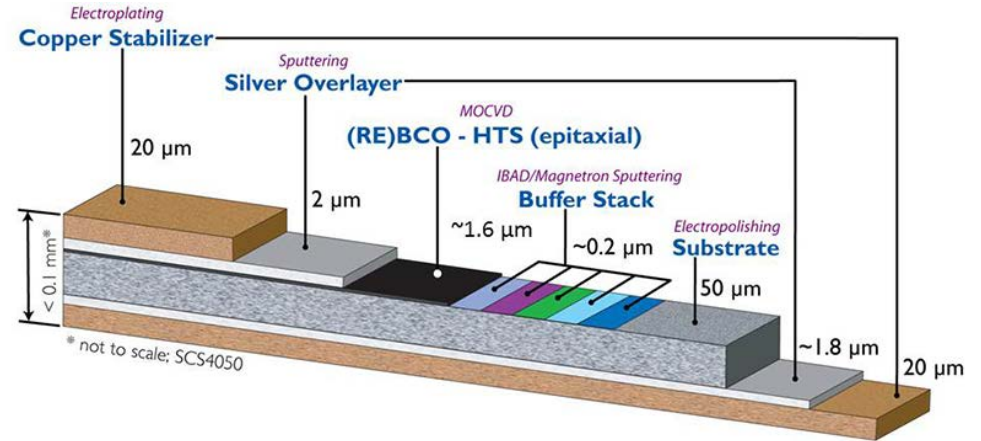
# HTS Busbar System – Overview



[1] earth.com/earthpedia-articles/aluminum

# HTS Busbar System – HTS

- YBCO HTS are used
- Quick Layer explanation

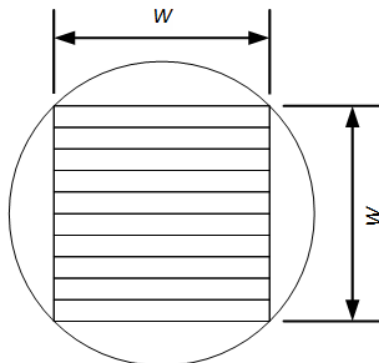


[1] <https://www.superpower-inc.com/specification.aspx>

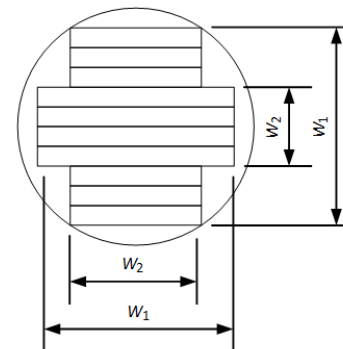
# HTS Busbar System – Conductor

- To achieve the wanted current at a certain temperature, multiple tapes are needed
- HTS are imbedded into copper to reduce short circuit current
- For DC current, two variations are possible:

Stack



Cross Conductor (CroCo)

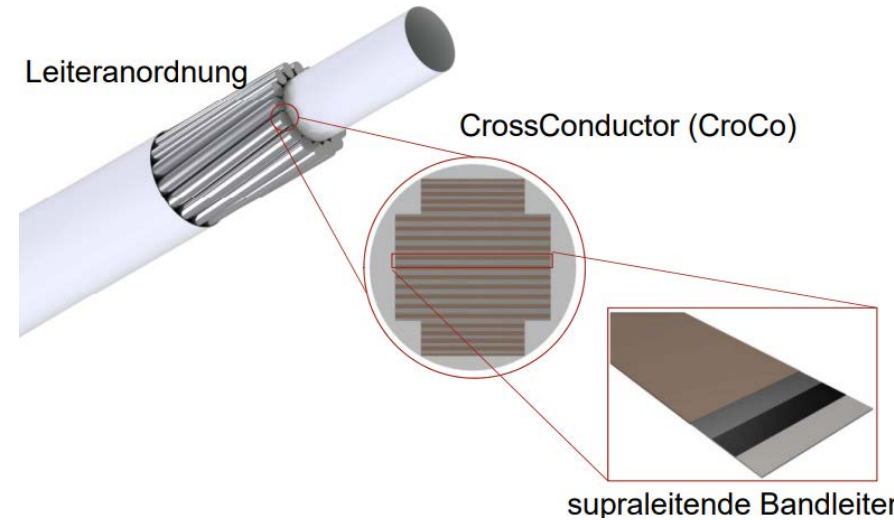


[1] <https://www.superpower-inc.com/specification.aspx>

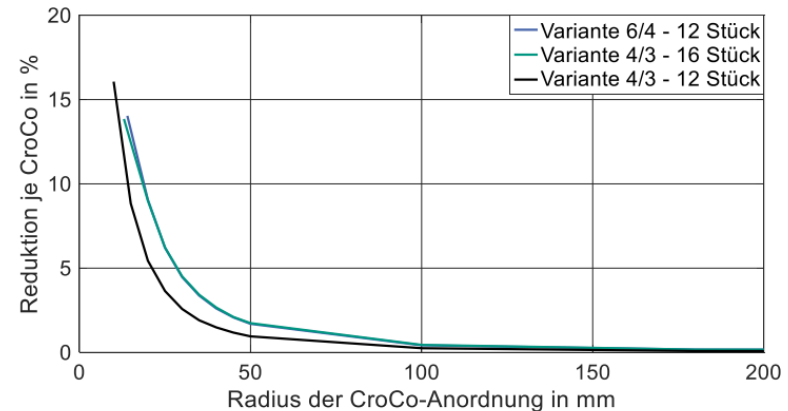


# HTS Busbar System - Phase

- The phase can then be comprised of multiple HTS conductors



- However, the closer the conductors are together, the higher the magnetic influence is:



[1] earth.com/earthpedia-articles/aluminum

# HTS Busbar System - Cooling

- Cooling to cryogenic temperature can only with low efficiency:
- Carnot Efficiency:

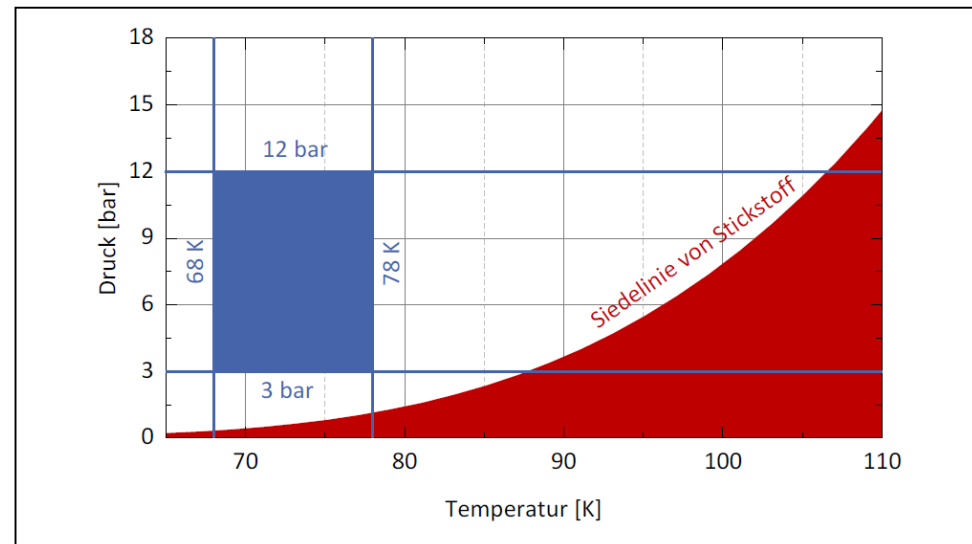
$$\eta_c = \frac{T_{cold}}{T_{hot} - T_{cold}} = \frac{77 \text{ K}}{300 \text{ K} - 277 \text{ K}} = 0.35$$

- Ideally, cooling 1 W at 77 K, requires almost 3 times as much power
- In practice, this number is much higher, at around 10 – 20
- There are alternatives to using cooling machines however...

[1] [earth.com/earthpedia-articles/aluminum](http://earth.com/earthpedia-articles/aluminum)

# HTS Busbar System - Cooling

- LN2 needs to be kept underneath its boiling state
- The boiling state is dependent on temperature, but also pressure
- The pressure inside the cryostat cannot be reduced below 3 bar
- An evaporation of LN2 would cause the HTS to lose their superconductivity



# HTS Busbar System - Cryostat

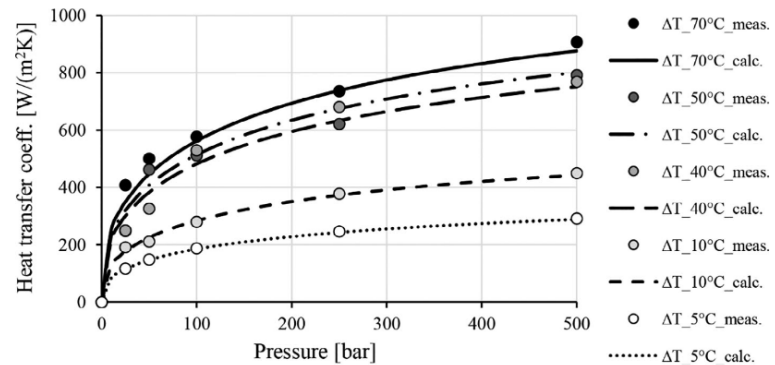
- Cryogenics – temperatures of below 120 K
- Cryostat – a device that maintains cryogenic temperatures
- Simplified, it is two pipes with a vacuum in between
- The vacuum is used to eliminate convective heat transfer



# HTS Busbar System – Thermal Insulation

- Convective heat transfer reduction through vacuum (low pressure)

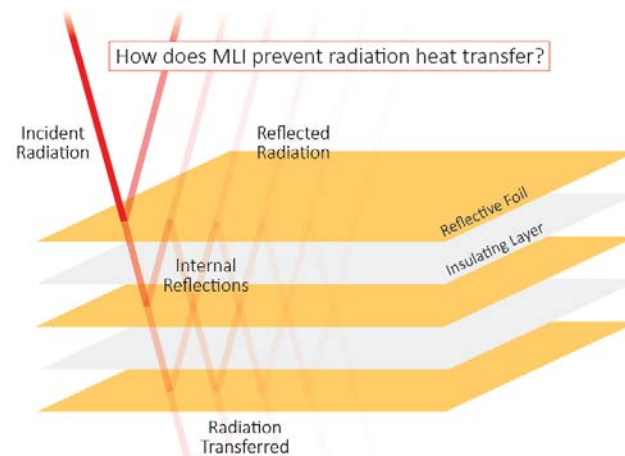
$$Q = k \cdot A(T_A - T_B)$$



- Radiative heat transfer reduction through multi layer insulation

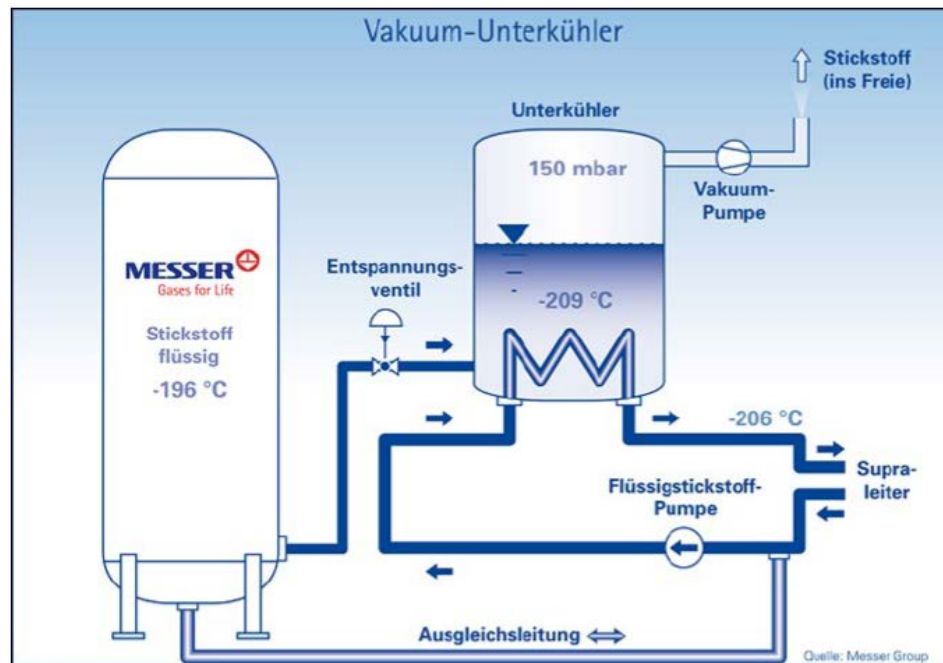
$$Q = k \cdot A(T_A^4 - T_B^4)$$

- A reduction to 2 W/m is possible



# HTS Busbar System – Closed Loop Cooling

- No LN2 escapes the system
- Cooling is done by a cooling machine



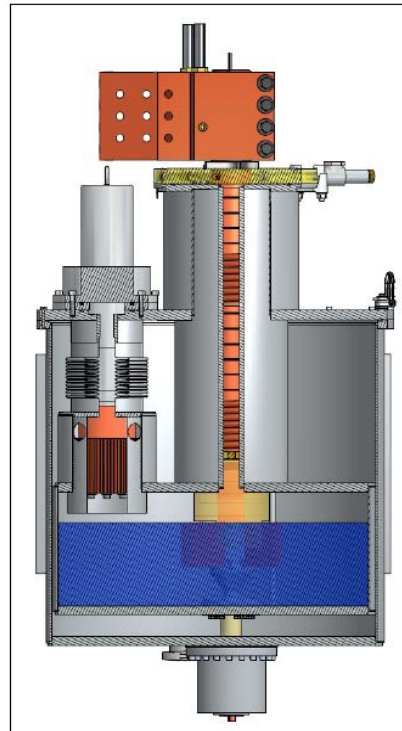
[1] Messer Group

# HTS Busbar System – Open Loop Cooling

- Only uses LN2 as a cooling medium
- LN2 absorbs heat and latent heat of vaporization cools HTS
- N2 is then expelled into environment
- A steady supply of LN2 is needed
- No cooling machine needed

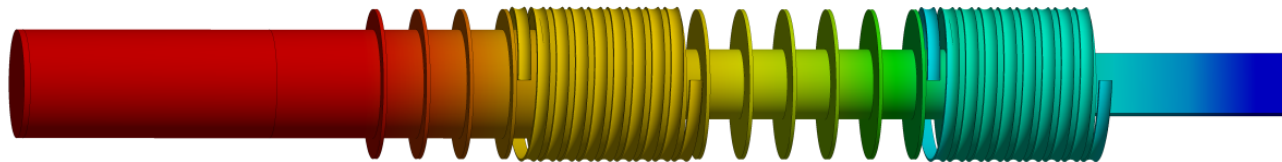
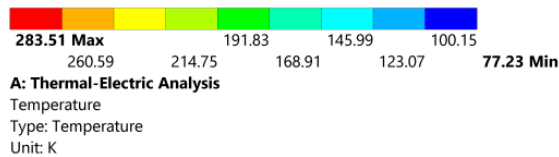
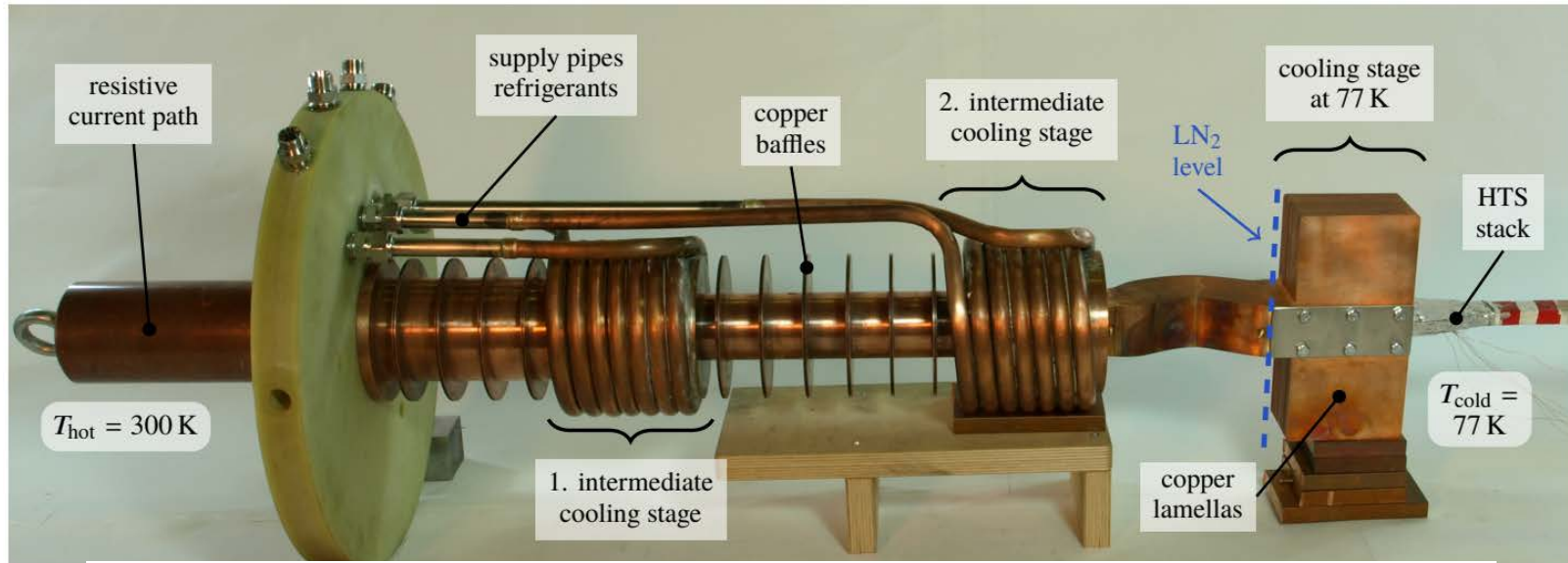
# HTS Busbar System – Current Lead ICE<sup>®</sup> Link

- The transition between room temperature conduction and cryogenic super conduction
- ICE Link Multi-Staged cooler
- Multiple cooling stages to increase electric efficiency
- Supports 20 kA





# HTS Busbar System – Current Lead ICE<sup>®</sup> Link



**Figure 6.7:** Temperature distribution at the surface of the resistive current path for a current of  $I = 20$  kA

## HTS Systems – Concluding Remarks

- There are many engineering trade-offs to consider when designing a HTS system, for example:
- Increasing the distance between HTS conductors means that they can carry more current due to the reduced magnetic field...
- ...however the size of the cryostat is increased...
- ...leading to more heat entering the system...
- ... increasing the size of the cooling machine and cooling power

# HTS Systems – Some Recent Projects Worldwide

Country	Project	Place	Year	Type	Voltage (kV)	Intensity (kA)	Length	Coolant	SC Tech.
EUROPE	SupraRail-SUPRASYS	SUPRASYS, Bilbao	2023	DC	3	1	20	GHe/LH2	MgB2 Wire
EUROPE	SupraRail-SUPRASYS	SUPRASYS, Bilbao	2023	DC	1.5	10	20	GHe/LH2	MgB2 Wire
EUROPE	SupraRail-SUPRASYS	SUPRASYS, Bilbao	2023	DC	0.5	20	20	GHe/LH2	MgB2 Wire
EUROPE	SuperRail (Nexans)	Francia	2021	DC	1.5	3	80	LN2	HTS-Tape
JAPON	<b>Chou line</b>	RTRI	2019	DC	1.5	10	310	LN2	-
EUROPE	<b>Ludwigshafen</b>	Alemania	2017	DC	1	20	25	LN2	YBCO
JAPON	<b>Ishikari</b>	Japon	2016	DC	20	2.5	1000	LN2	BSCCO
RUSIA	<b>St.Petersburg</b>	Sr. Petersburg, Russia	2014	DC	20	2.5	2500	LN2	BSCCO
EUROPE	<b>BesthPath</b>	Germany	2014	DC	320	10	20	LN2 / Ghe	MgB2 Tape

# HTS Systems – The Way Forward

- There are still challenges to overcome!
- More superconducting projects are needed to expand operational knowledge
- A need for specialized manufacturing and installation techniques
- HTS are still expensive (50+ €/kA/m)
- With increased demand, production will increase, causing the unit price to fall
- A greater prominence in society and industry is needed to

[1] [earth.com/earthpedia-articles/aluminum](http://earth.com/earthpedia-articles/aluminum)

**Thanks for the attention!**

**Questions?**

**Thoughts?**

**Ideas?**