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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 with Aluminum (Al) highlighted in red. The table shows elements from Hydrogen (H) to Oganesson (Og). The groups are numbered 1 through 18. Aluminum is located in group 13, period 3.



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

# What is Aluminum - Uses

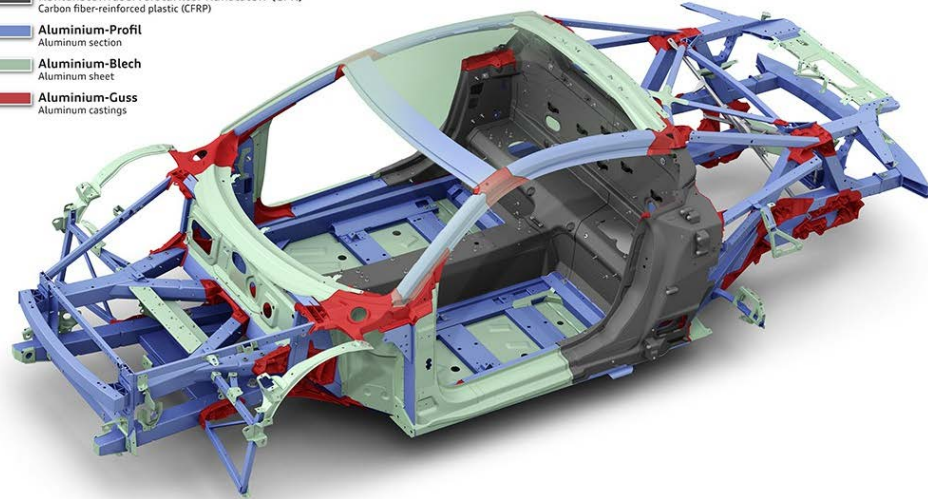


- Transportation Sector
  - Automotive
  - Aircraft
  - Spacecraft
  - Railway cars...
  
- Electrical Engineering
  - Cables
  - Overhead lines
  - Motors/generators...
  
- Construction
- Packaging

## 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

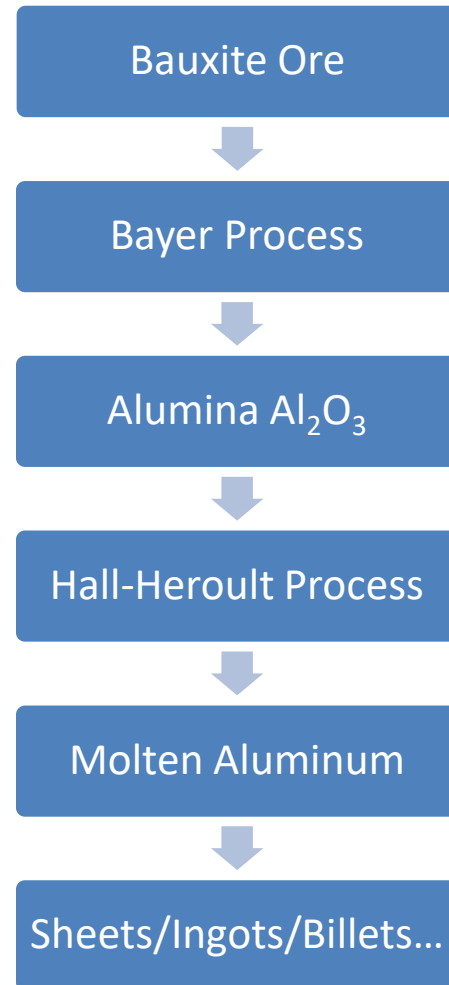
- Where does aluminum come from?
- Aluminum does not occur in its pure form!
- Most commonly found in bauxite
- Aluminum minerals in bauxite include largely:
  - Gibbsite
  - Boehmite
- With the **Bayer** and **Hall-Heroult** processes Aluminum is produced





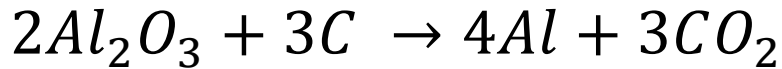
# Primary Aluminum Production

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

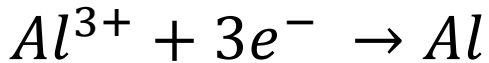


# Hall-Heroult-Process (Electrolysis)

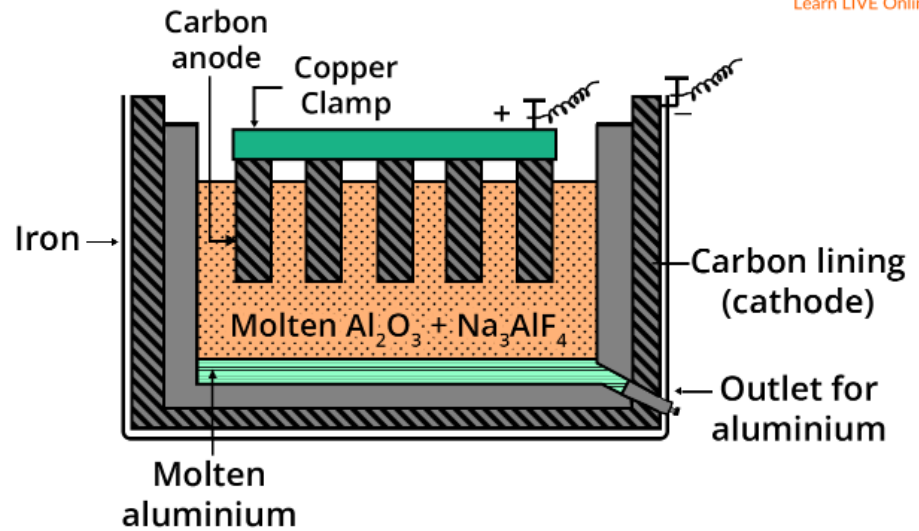
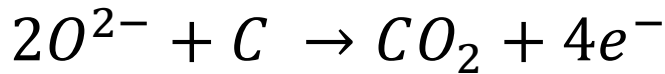
- The process is a redox-reaction:



- Cathode:



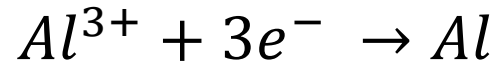
- Anode:



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)

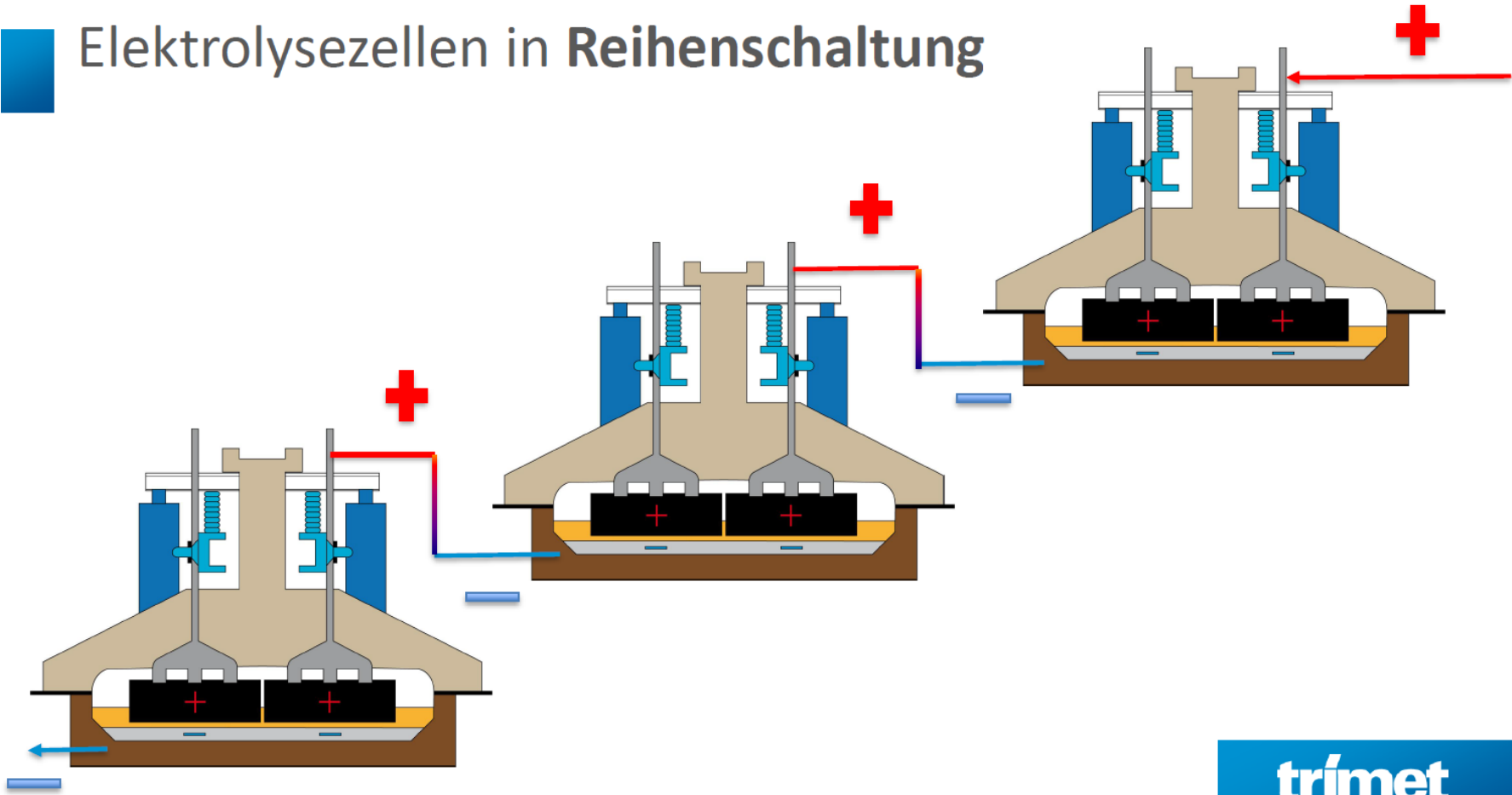
- Important take away going forward:



- 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)

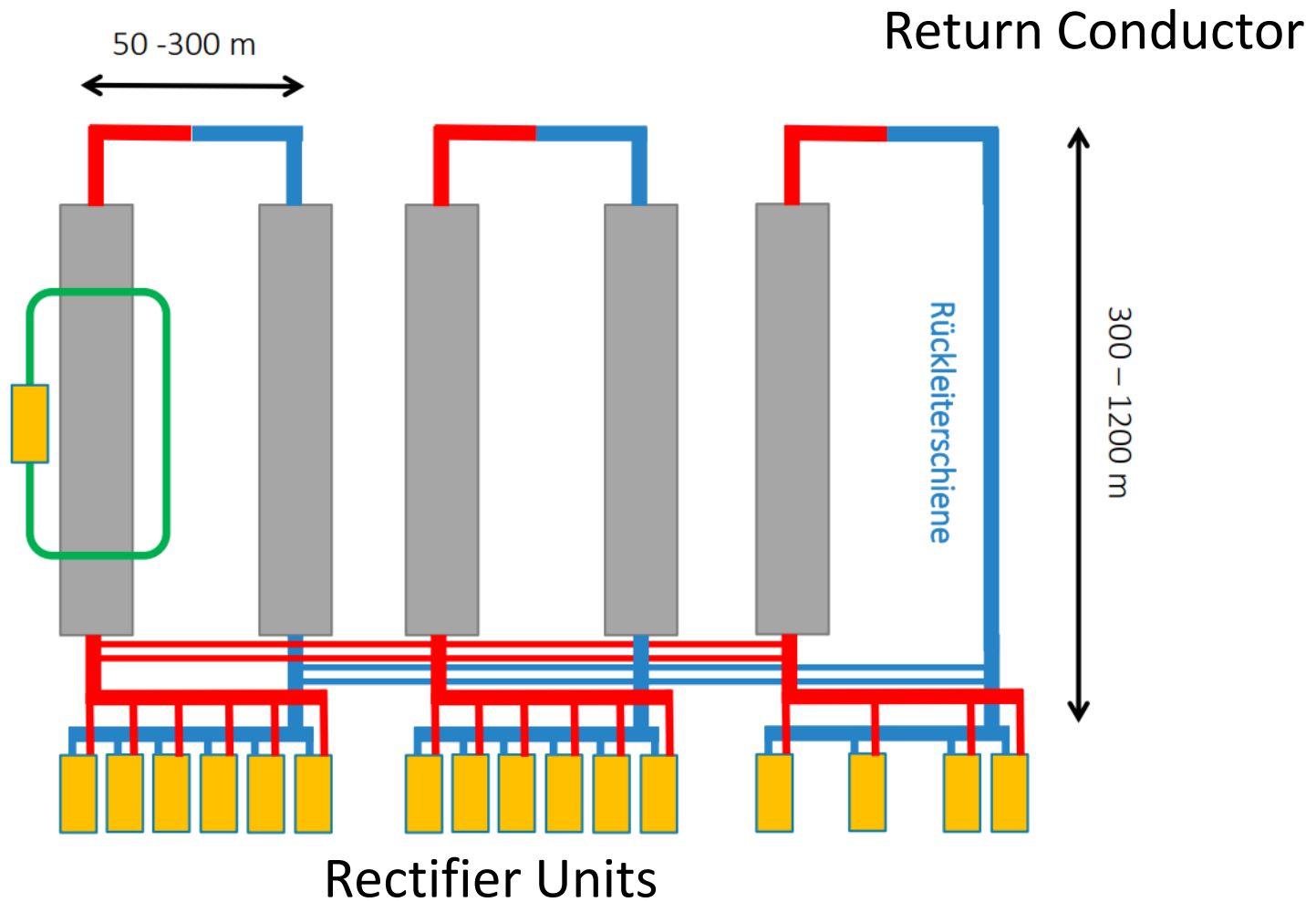


# Example Aluminum Smelter



[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)

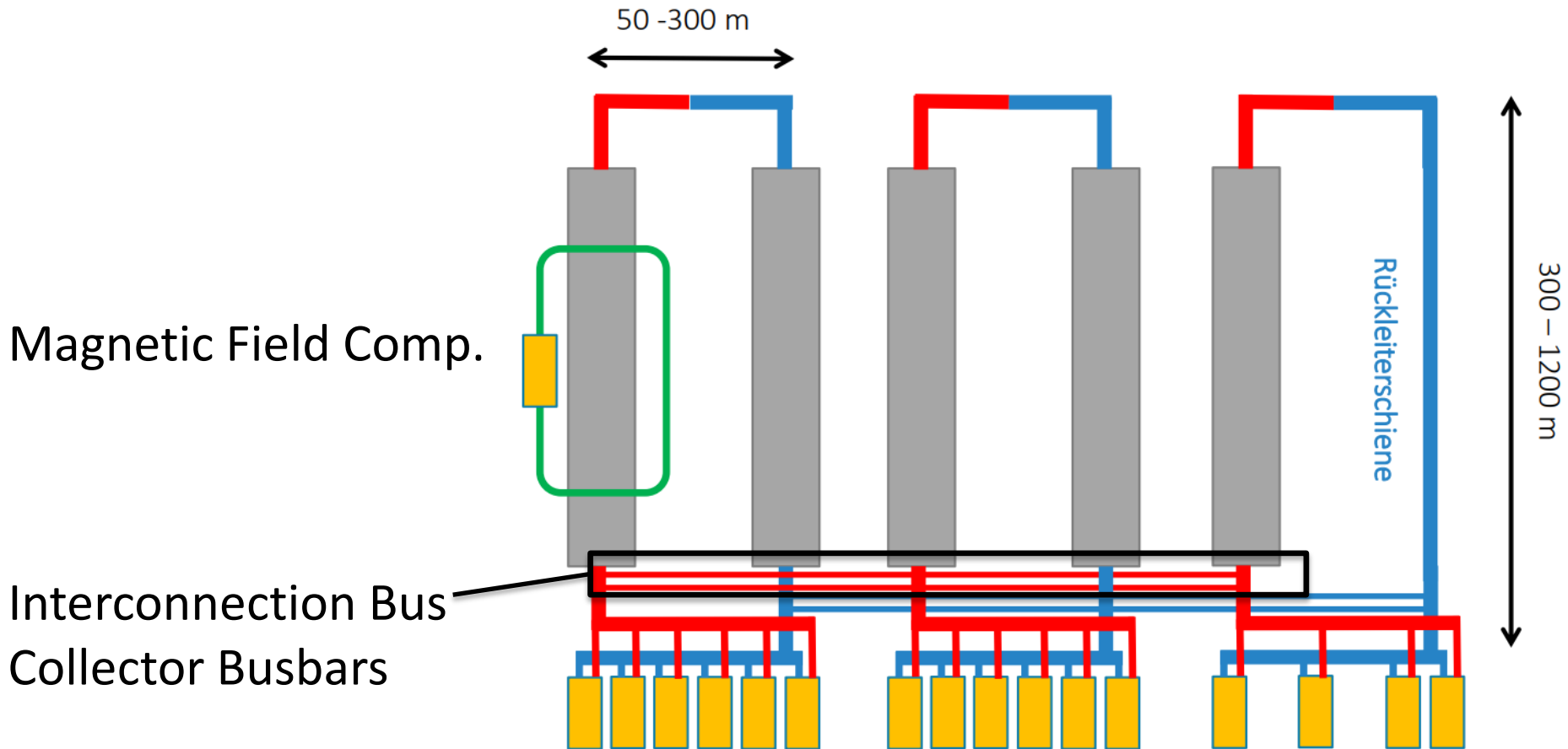


# Example Aluminum Plant

- 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!

Return Conductor



[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

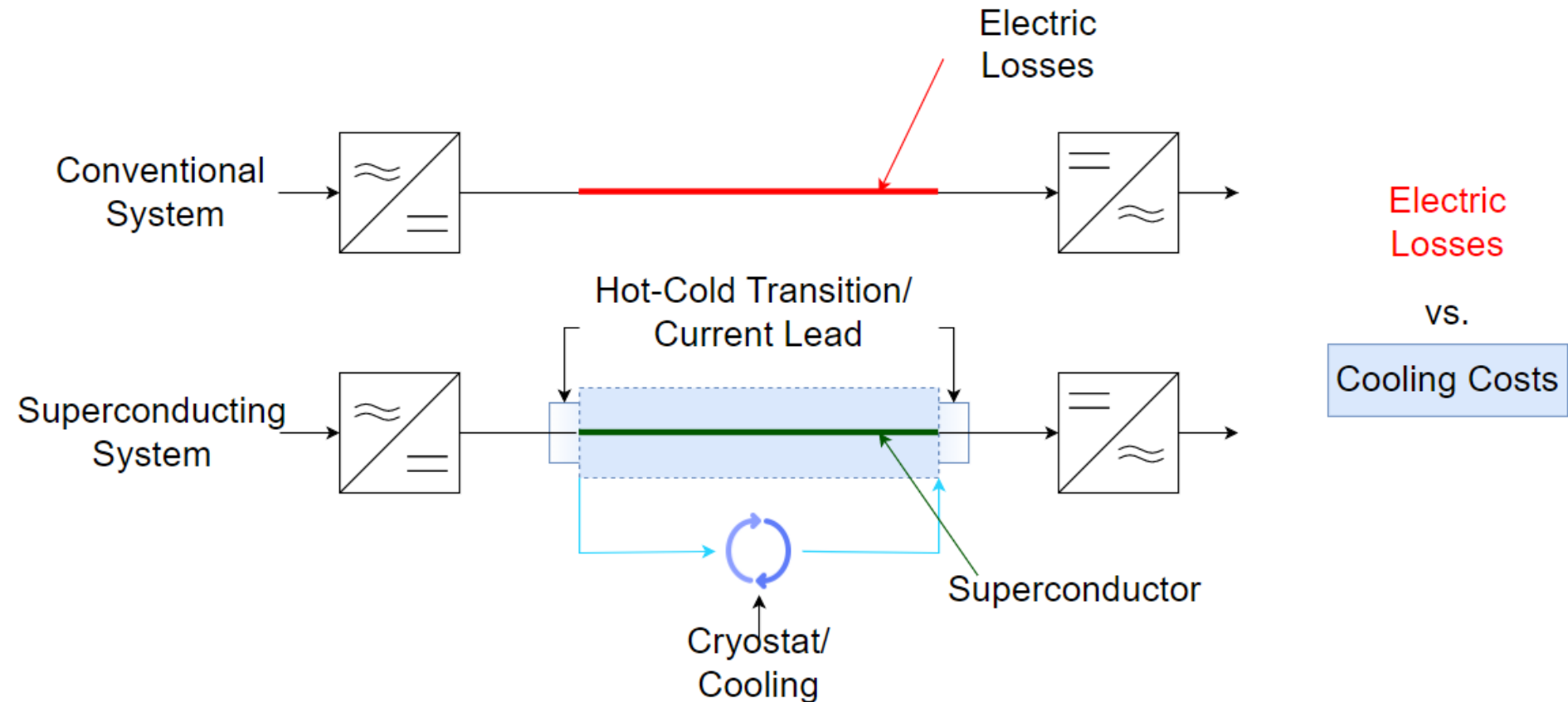


# HTS Busbar System – Overview

- 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)

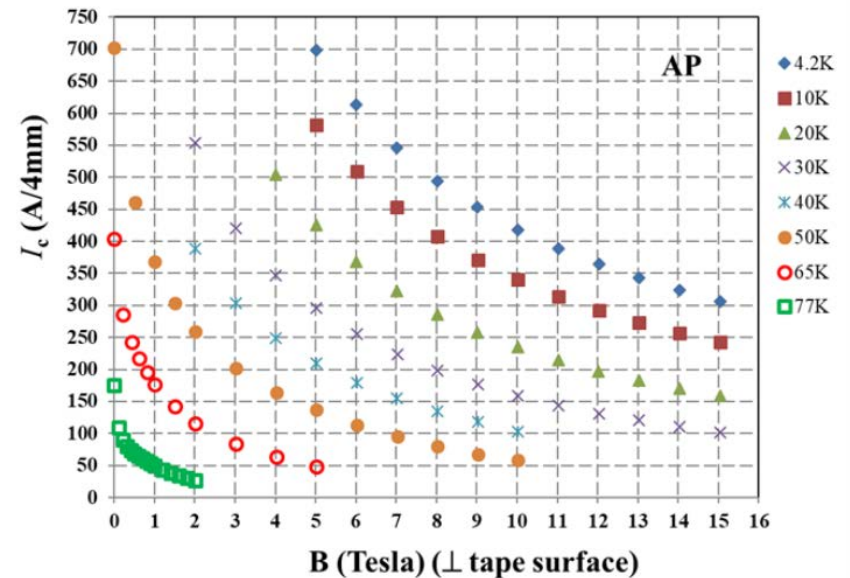
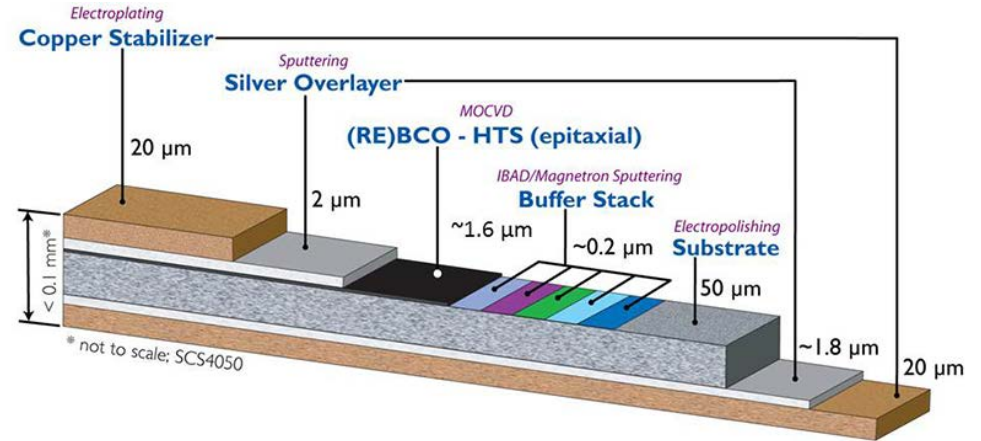
# HTS Busbar System – Overview



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

# HTS Busbar System – HTS

- YBCO HTS are used
- Quick Layer explanation

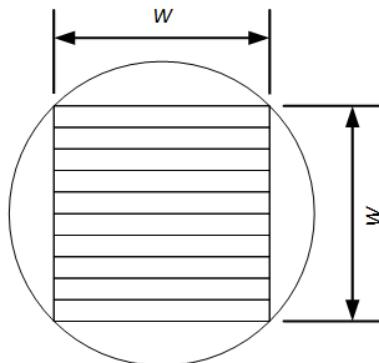


[1] <https://www.superpower-inc.com/specification.aspx>

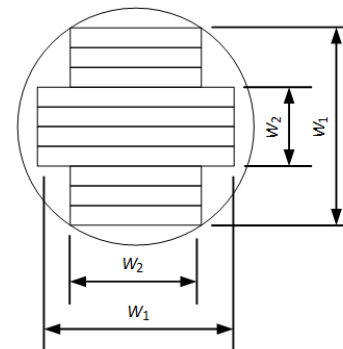
# HTS Busbar System – Conductor

- 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)

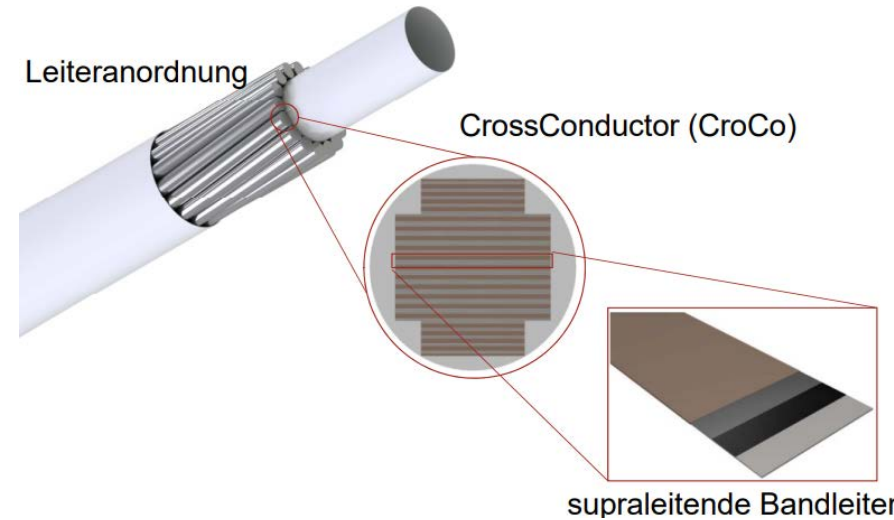


[1] <https://www.superpower-inc.com/specification.aspx>

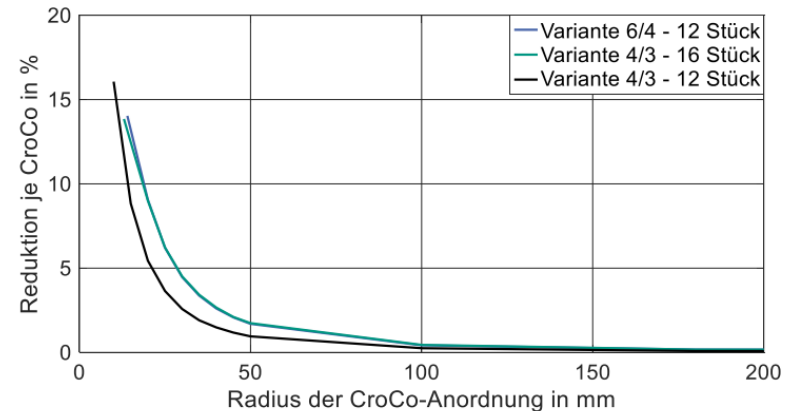


# HTS Busbar System - Phase

- 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:

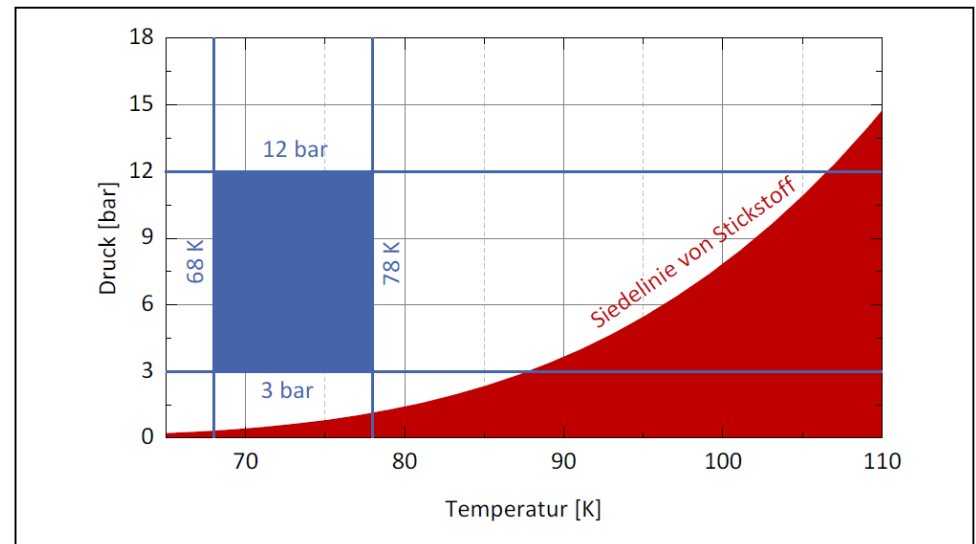
$$\eta_c = \frac{T_{cold}}{T_{hot} - T_{cold}} = \frac{77 \text{ K}}{300 \text{ K} - 277 \text{ K}} = 0.35$$

- 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

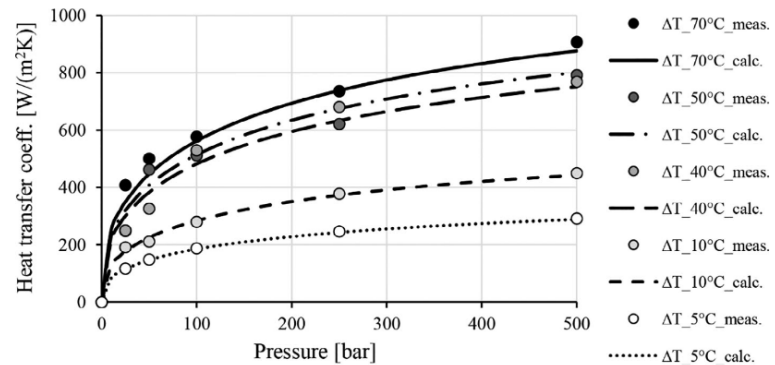
- Cryogenics – temperatures of below 120 K
- Cryostat – a device that maintains cryogenic temperatures
- Simplified, it is two pipes with a vacuum in between
- The vacuum is used to eliminate convective heat transfer



# HTS Busbar System – Thermal Insulation

- Convective heat transfer reduction through vacuum (low pressure)

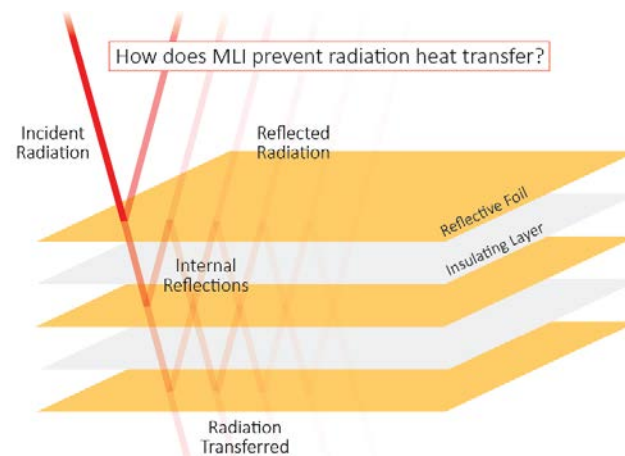
$$Q = k \cdot A(T_A - T_B)$$



- Radiative heat transfer reduction through multi layer insulation

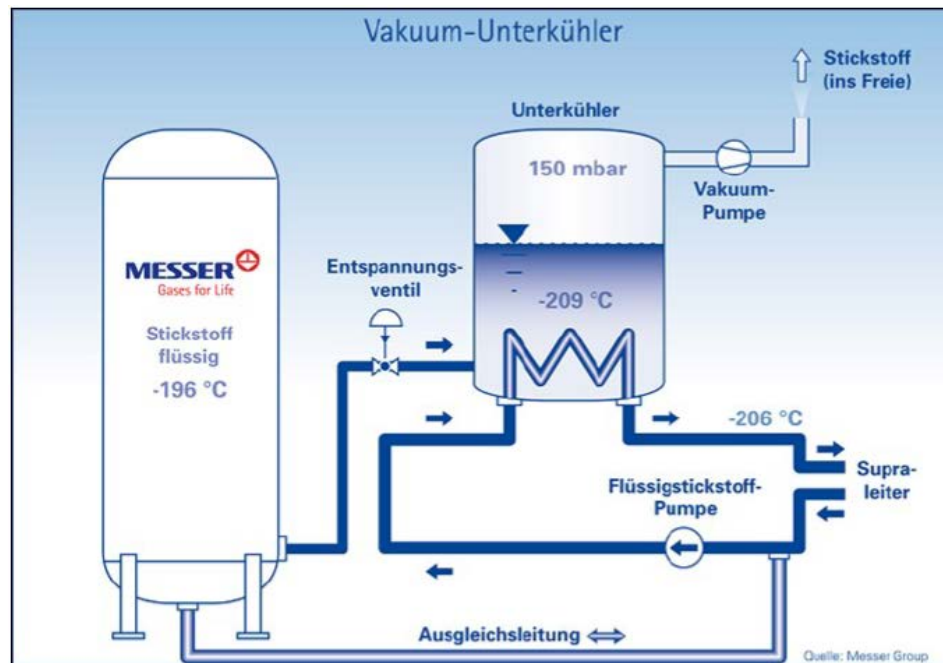
$$Q = k \cdot A(T_A^4 - T_B^4)$$

- 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



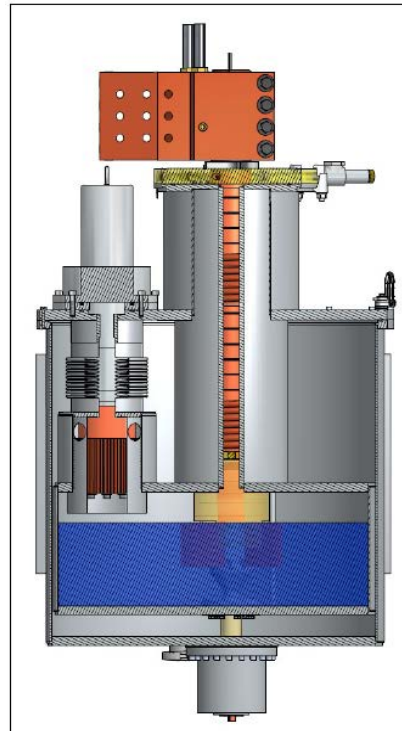
[1] Messer Group

# 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

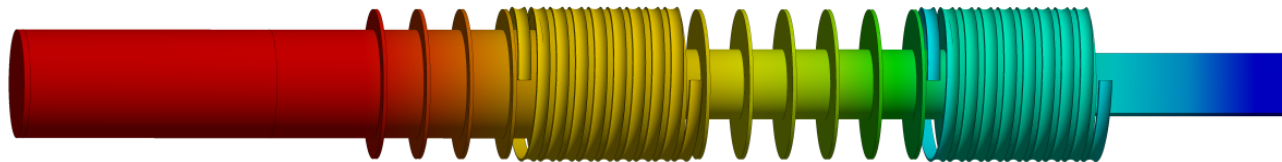
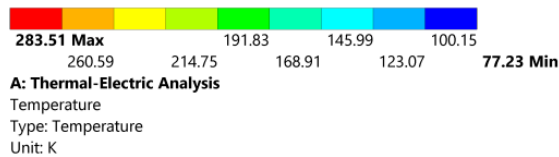
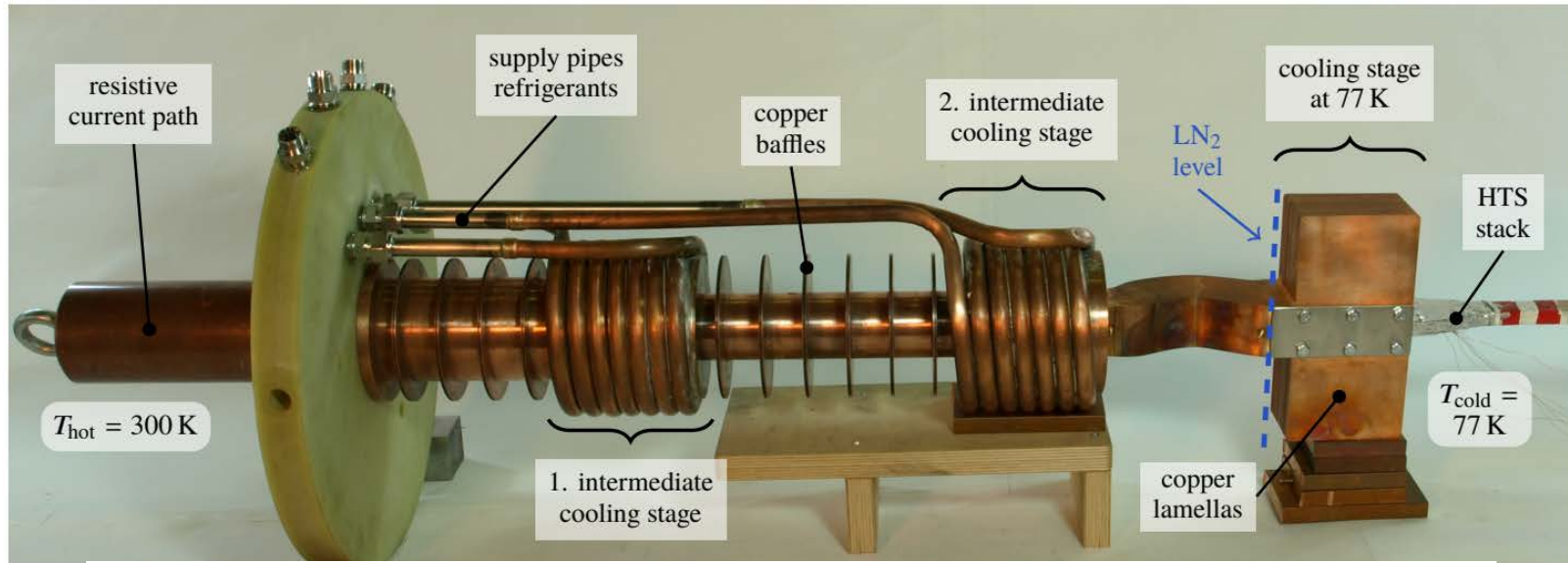
# HTS Busbar System – Current Lead ICE<sup>®</sup> Link

- 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

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

# 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

**Thanks for the attention!**

**Questions?**

**Thoughts?**

**Ideas?**