Research on High Current and Low inductance Laminated Transmission Busbar in High-power Long-pulse Steady-state Operations

By

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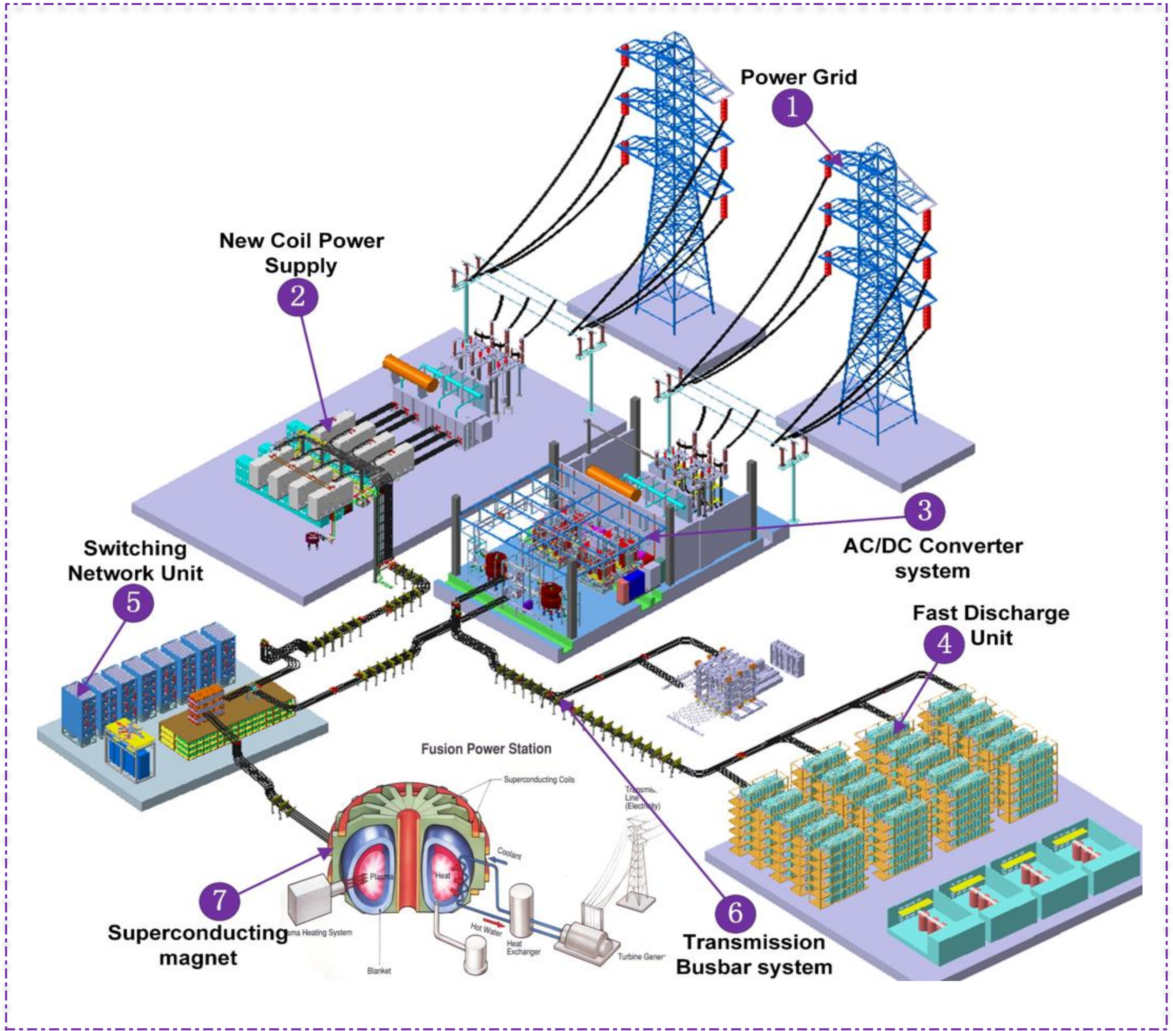
Outline

- Research Background
- Steady State Tokamak Research Aims at advanced laminated busbar system
- Experimental verification on laminated transmission busbar of steady state Tokamak operation
- Summary

Research Background



- **Long-pulse steady-state operation requires:**
  - **Low impedance and good heat dissipation.**
  - **High Rated voltage of transmission busbar system circuit during superconducting quenching.**
  - **Low electromagnetic interference (EMI).**
  - **High safety and reliability life-cycle.**

Shortcomings of traditional separated open busbar in LPO

Shortcomings of traditional separated open busbar

- **Large stray inductance:**

  Affects the response performance of power supply

- **Oxidation of the exposed transmission busbar:**

  Cause excessive ohmic loss

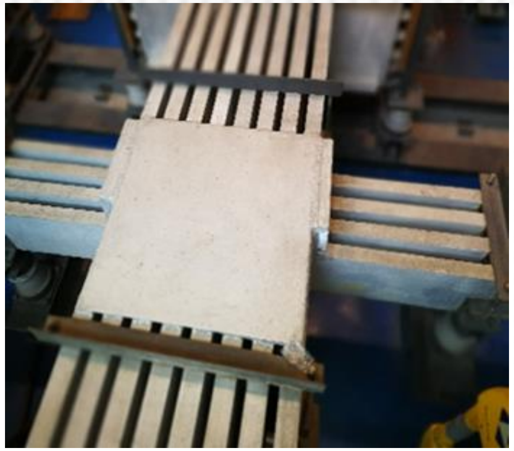
- **Separated transmission busbar:**

  High electromagnetic interference (EMI)

- **Large installation space:**

  High insulation level

EAST PF converter (15kA)



Multi conductor welding (120kA)

ITER test platform (120kA)

ITER test platform (DCDS 120kA)

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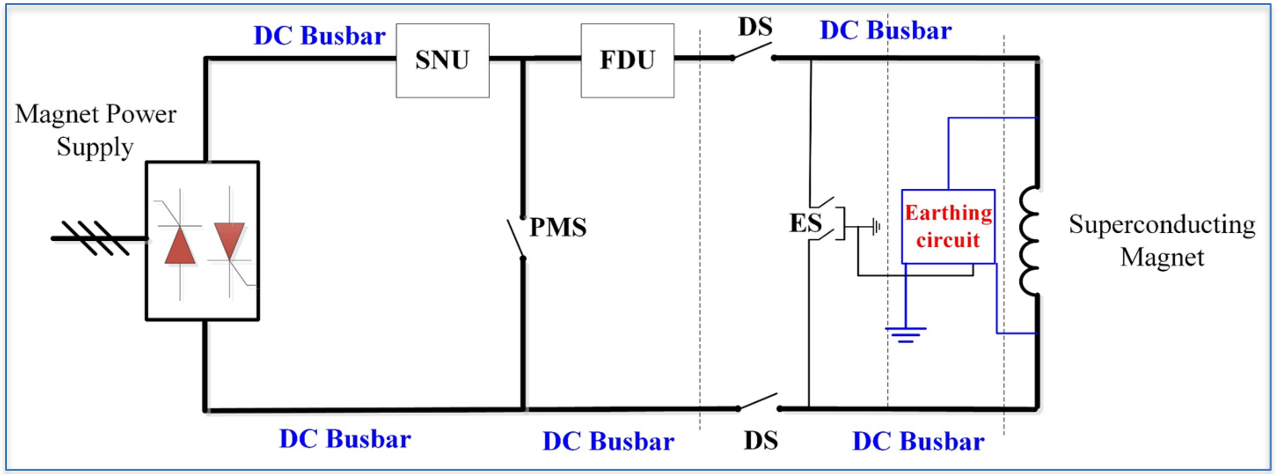
Steady State Tokamak Research Aims at high voltage and current advanced busbar system



Parameter	W7-X	EAST	ITER	JT-60SA	CFETR
Breaking Voltage	8kV	2kV	10kV	5kV	20kV (DC)
Rated Current	20kA	15kA	68kA	25.7kA	100kA

☐ High voltage and current advanced busbar system

- **The DC busbar can still operate normally under the quench protection of superconducting magnet:**

  More safety and reliability.

- **The low inductance busbar with good heat dissipation can transmit higher current:**

  Advantaged to improve **heat distribution** and keep steady state operation

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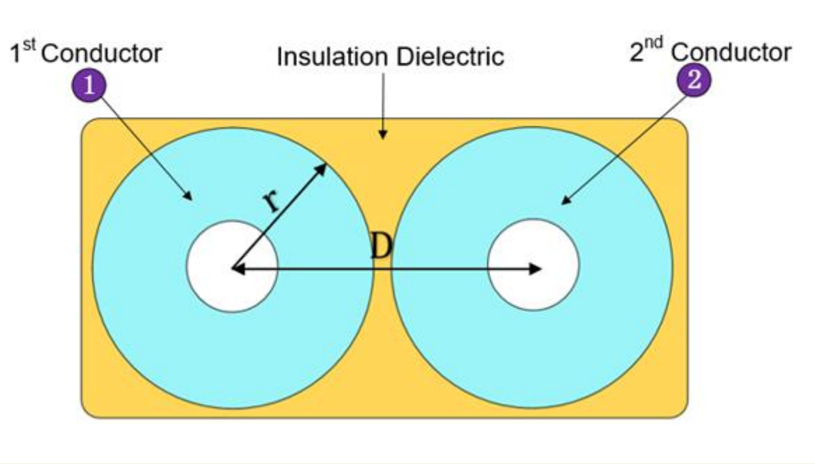
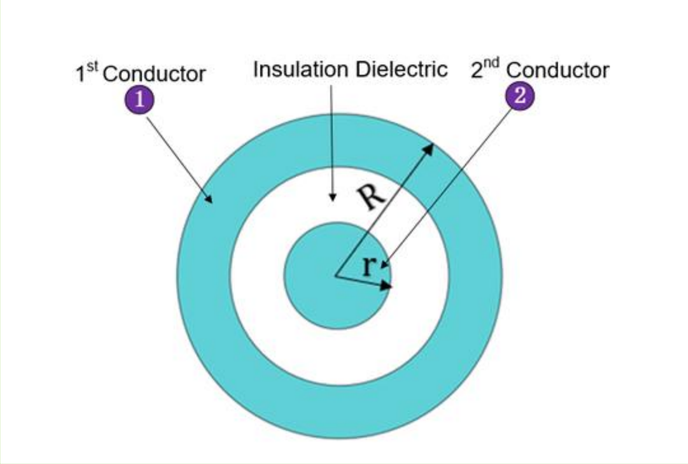
Steady State Tokamak Research Aims at Low inductance advanced busbar system

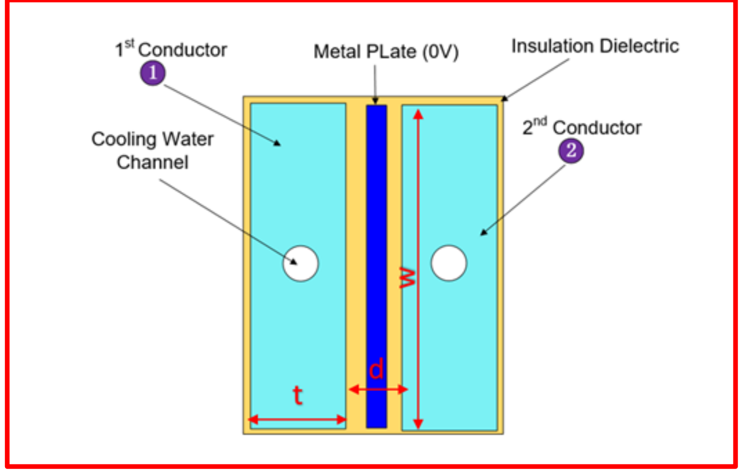
(a) Circle section laminated busbar



(b) Coaxial busbar



(c) Rectangular laminated busbar



Analysis for Low inductance advanced busbar system

- Low inductance depends on width/thickness, **distance** between two conductors.
- Insulation performance is determined by **insulation dielectric** and distance between two conductors.
- Long pulse steady-state operation requires good heat dissipation, determined by **width/thickness** of conductor.

$$\begin{cases} L_{P(N)} = \dfrac{\mu}{2\pi} l \left[\ln\left(\dfrac{2l}{w+t}\right) + \dfrac{1}{2}\ln\left(\dfrac{w+t}{l}\right) \right] \\ M_{PN} = \dfrac{\mu}{2\pi} \left[l \ln \dfrac{\sqrt{t^2+l^2}}{t}) - \sqrt{t^2+l^2} + t \right] \\ L_{total} = L_P + L_N - 2\, M_{PN} \end{cases} \quad (c)$$

$$\begin{cases} L_a = \dfrac{\mu_0 l}{2\pi}\left(\ln\dfrac{D}{r} + \dfrac{1}{4}\right) & (a) \\ L_b = \dfrac{\mu_0 l}{2\pi}\left(\ln\dfrac{R}{r} + \dfrac{1}{4}\right) & (b) \end{cases}$$

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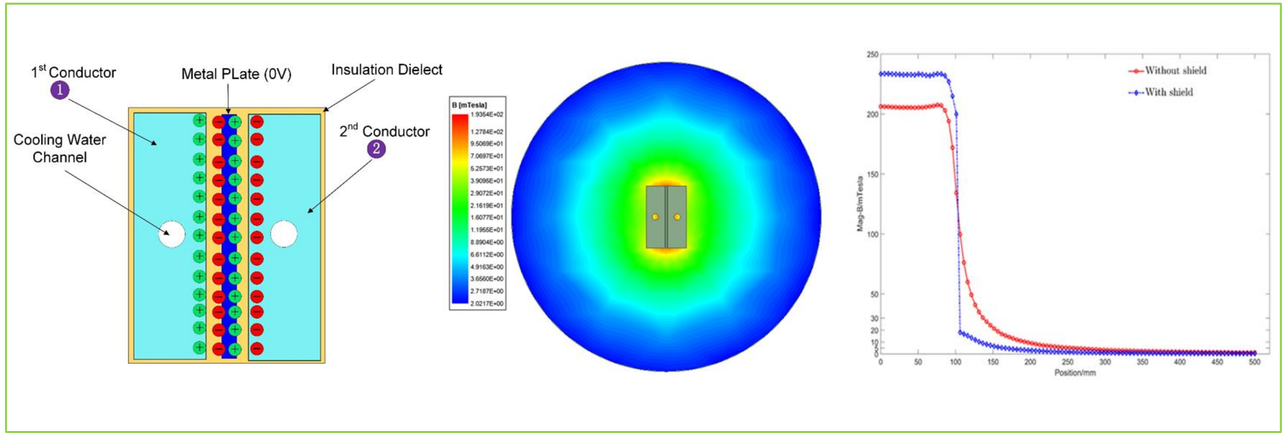
Steady State Tokamak Research Aims at Low impedance and EMI of advanced busbar system

◻ Positive and Negative:

- **Two conductors parallel array stacked arrangement:** Reducing stray inductance of transmission busbar
- **Change of magnetic field topology of busbar:** Reduce electromagnetic interference (EMI)
- **Middle plate between two conductors:**
  - Keep static balance
  - Increasing capacitance
  - Improve power supply performance
- **Cooling water channel Heat Dissipation in long-pulse steady-state operation**
- **Insulation dielectric to keep high insulation level.**



Tab.1. Inductance and impedance of laminated busbar at different frequency

Frequency (Hz)	Inductance (μH/m)	Resistance ($\mu\Omega$/m)
0	-	4.7
20Hz	0.162	10.2
50Hz	0.134	15.8
100Hz	0.118	23.30
200Hz	0.106	103.5
300Hz	0.102	213.8

◻ Regarding traditional separated busbar

- Inductance: **0.76 μH/m** at 20Hz $\rightarrow 0.162\mu$H
- Impedance: **51.1$\mu\Omega$/m** at 20Hz $\rightarrow 10.2\mu\Omega$

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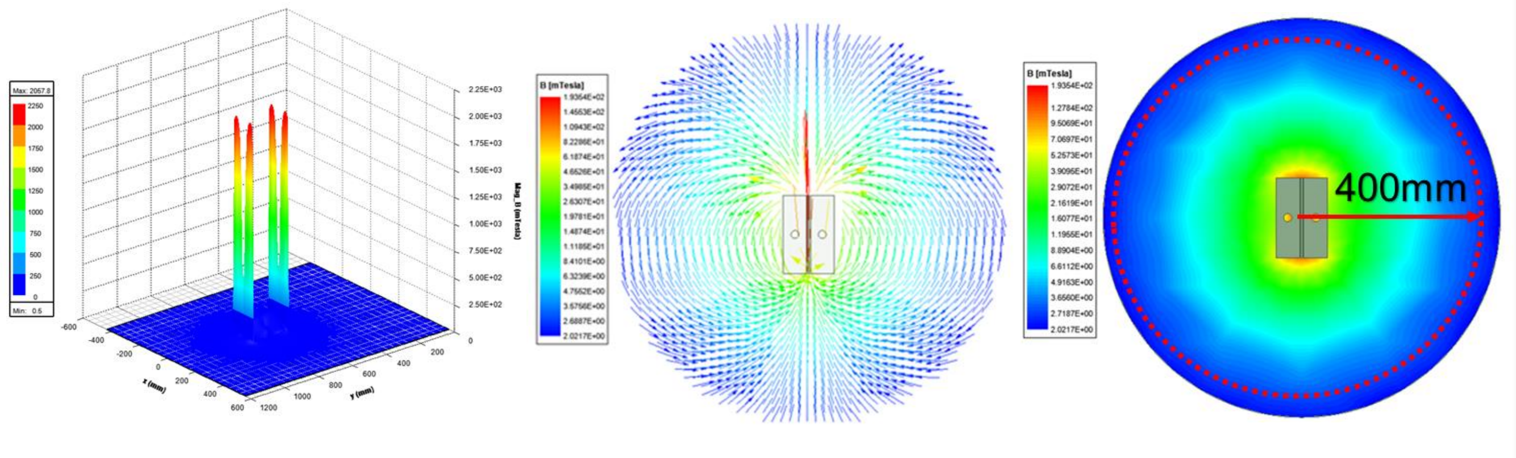
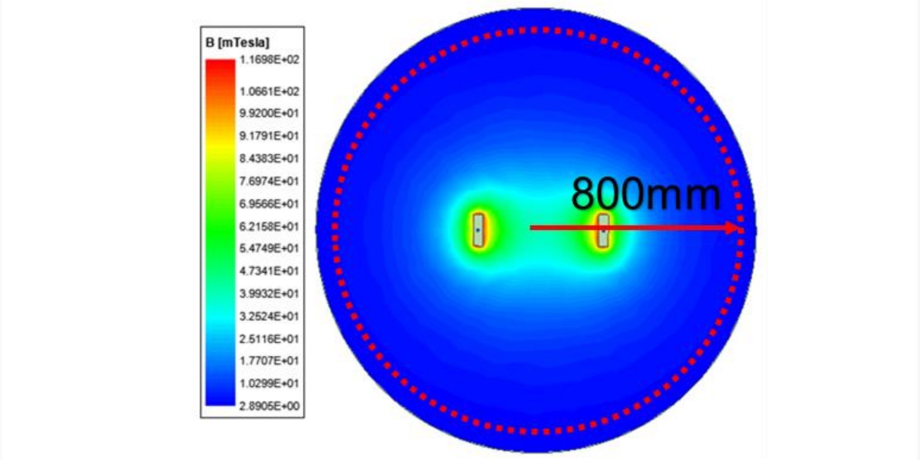
Analysis for electromagnetic topology of laminated and separated transmission busbar

The Electromagnetic distribution of laminated transmission busbar



Electromagnetic distribution of Separated Busbar



Electromagnetic topology analysis:

- Maximum Magnetic (193.5mT) is located in the Laminated Area of Busbar.
- The Isoline of Magnetic field 5mT is about 400mm from the center of the laminated busbar.(Far field regions offset each other)
- However, the separated busbar (800mm), the Isoline of the Magnetic field 5mT is about 800mm from the center of the laminated busbar.

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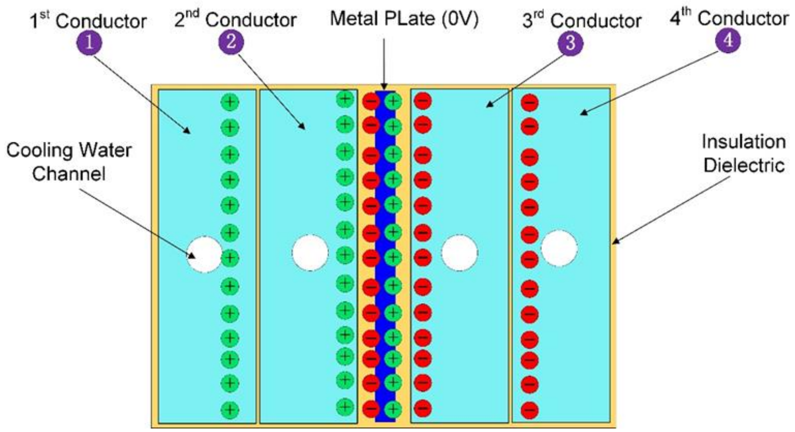
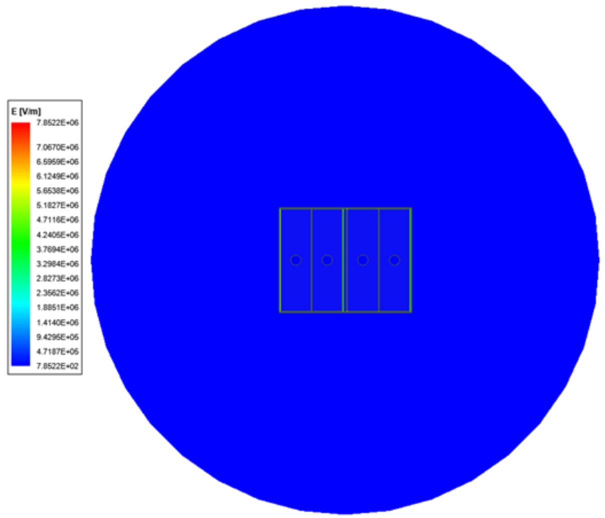
Research on current transmission expansion and electric topology of laminated busbar



Maximum Electric Field is 7.9E6 V/m (Glass fiber)



Current transmission expansion and electric field topology analysis:

- **The positive and negative conductors are respectively in close parallel structure, which increases the transmission capacity of rated current:**
  - Improve large current transmission capacity
- **Positive and negative conductors are filled with insulating materials (Glass fiber):**
  - Improve electric field distribution
- **Metal plate (0V, earthing) between positive and negative conductors:**
  - Keep static balance
  -Neutral grounding helps to balance the withstand voltage of superconducting magnet terminals to ground
- **Insulation dielectric to keep high insulation level.**
  Maximum Electric Field is 7.9E6 V/m (20kV)

Dielectric	Relative Permittivity ε	Breakdown field strength $\frac{E_{max}}{V/m}$
Air	1.0	3×10^6
SF_6	1.002	$(7\text{-}9)\times10^6$
Mica	5.4	100×10^6
Ceramic	5.3-6.5	10×10^6
Rubber	2.5-3	60×10^6
Glass fiber	4	35×10^6
Polyethylene	2.26	18×10^6

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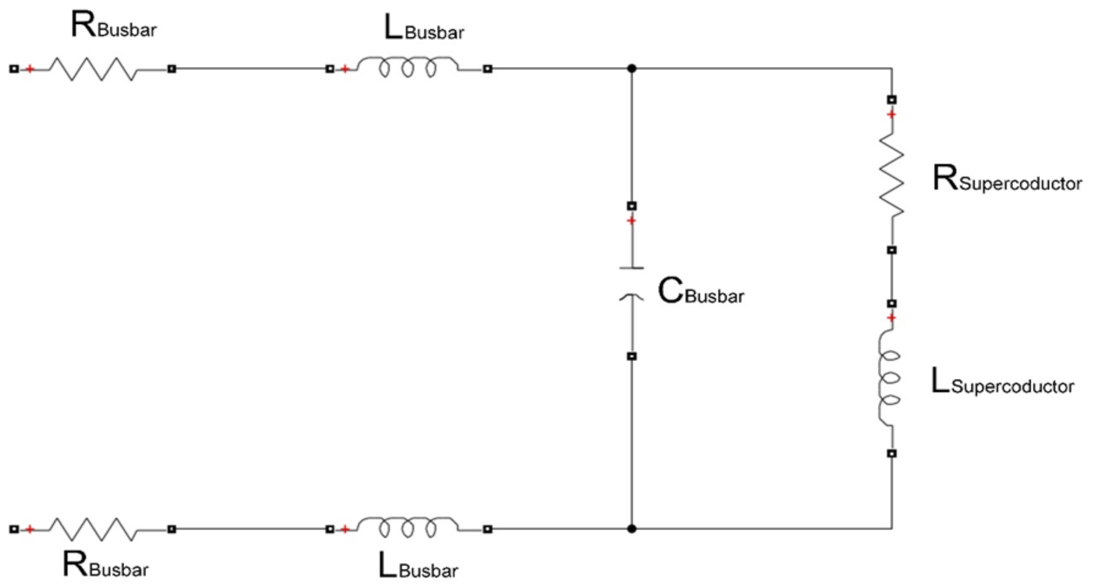
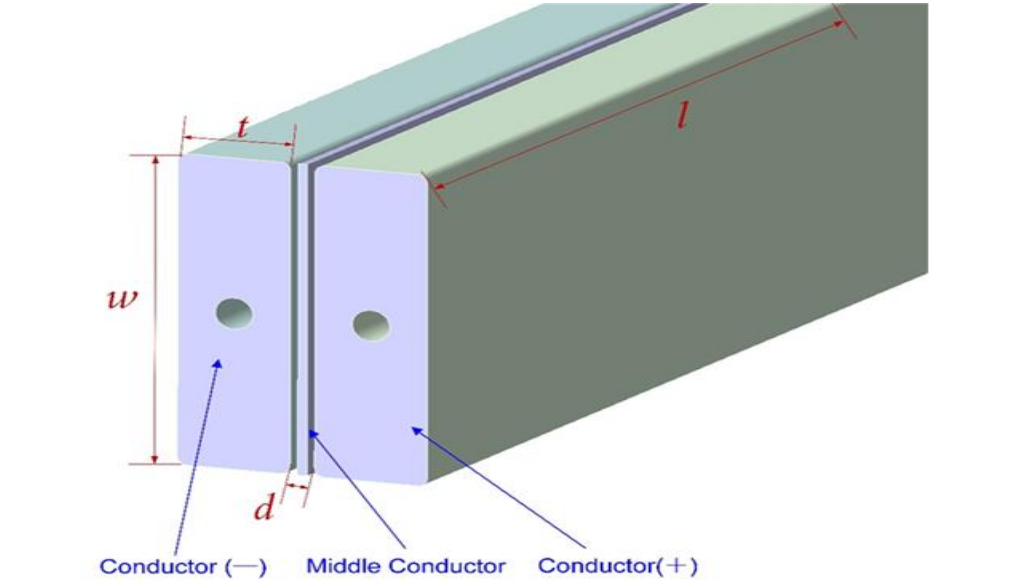
Research on equivalent circuit and proportion of magnetic energy of laminated transmission busbar

The equivalent circuit of transmission laminated busbar



Model of laminated busbar



Tab.1. Proportion of magnetic energy for laminated transmission busbar

Laminated area	Conductor area	Conductor joint	Far-field region
85.3%	11.3%	3.2%	0.2%

Equivalent circuit analysis:

- Two conductors parallel array stacked arrangement: reducing stray inductance of transmission busbar improve the dynamic response of current and voltage.
- Change of magnetic field topology of busbar: reduce electromagnetic interference (EMI).

Research on advanced laminated busbar aims at good working temperature zone

Research on advanced busbar aims at good working temperature zone

- Steady state operation requires good working temperature zone of aluminum and glass fiber.
- Working temperature zone of laminated busbar is controlled at the range of 42.52℃ to 52.34℃ accordingly.
- Flow velocity for cooling-water (Laminated busbar with length of 9m) $\rightarrow v = 2.0m/s$

$$\begin{cases} P = CQ\Delta T \\ Q = \pi\left(\frac{\mathrm{d}}{2}\right)^2 v\rho \end{cases}$$

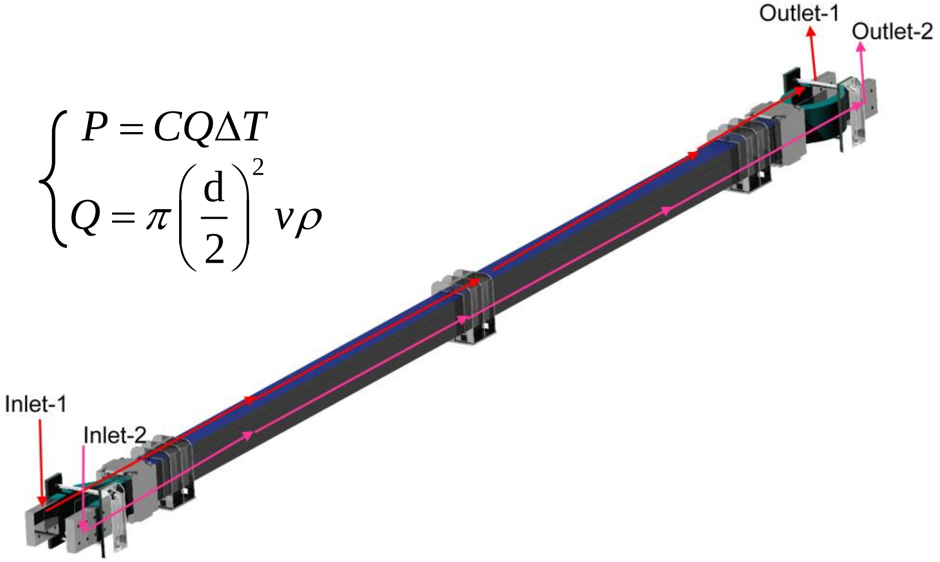


Fig.1. Cooling water circuit for laminated busbar(40kA)

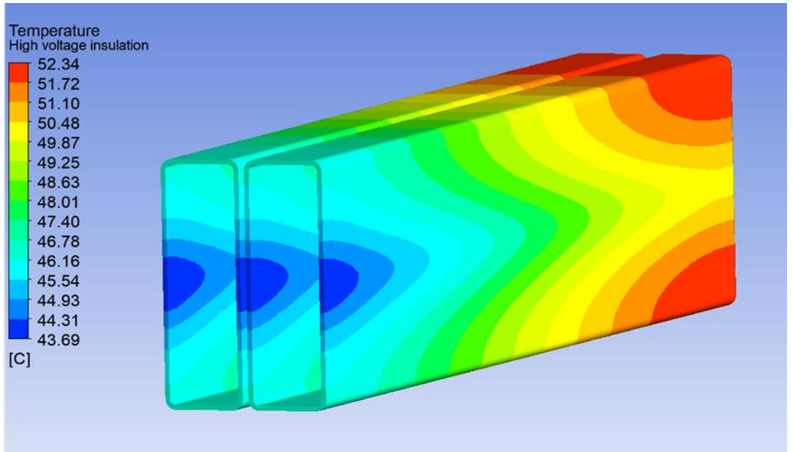


Fig.2. Temperature for 1st Glass Fiber (52.34/22.34℃)

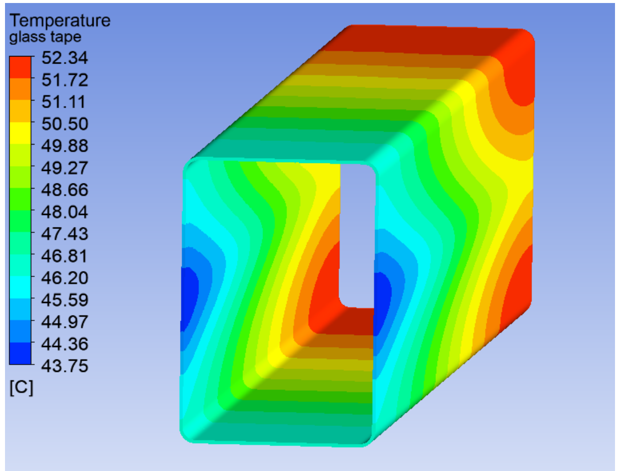


Fig.3. Temperature for 2nd Glass Fiber (52.34/22.34℃)

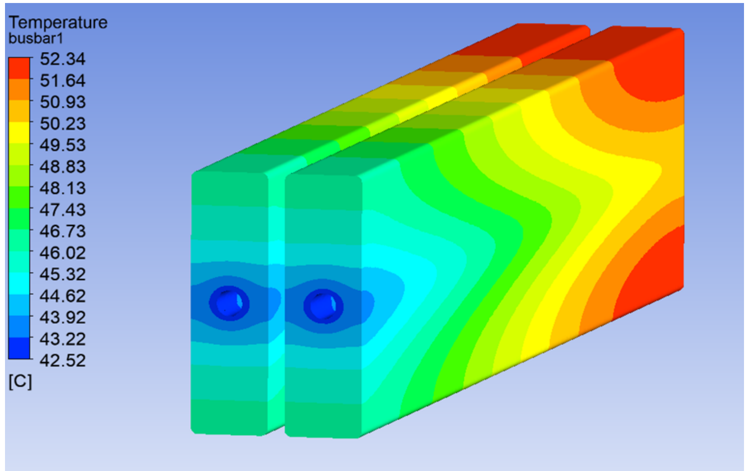


Fig.4. Temperature for 2nd Glass Fiber (52.34/22.34℃)

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Research on advanced laminated busbar Aims at high reliability for long-pulse steady state operation

Advanced laminated busbar Aims at high reliability for long-pulse steady state operation

- Steady state operation requires high reliability and stability in structure.
- Wrap the positive and negative electrode conductors with insulating materials, which is to achieve high insulation performance.

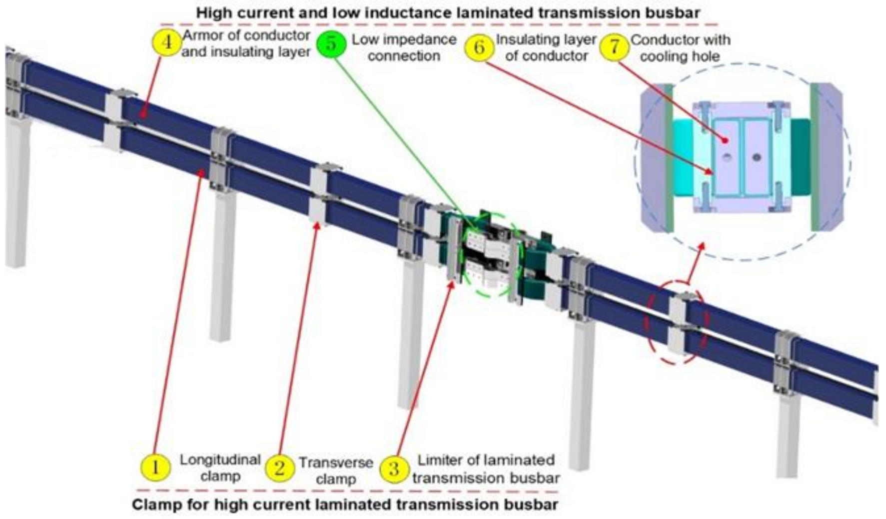

Fig.1. 40kA Laminated Busbar

Tab.1. Elements of topology of laminated transmission busbar

1	Conductor (3.5A/mm2)
2	The 1st insulation layer (Glass fiber)
3	The 2nd insulation layer(Glass fiber)
4	Epoxy plate
5	Strain clamp
6	Metal Plate(0V)
7	Cooling Water Channel

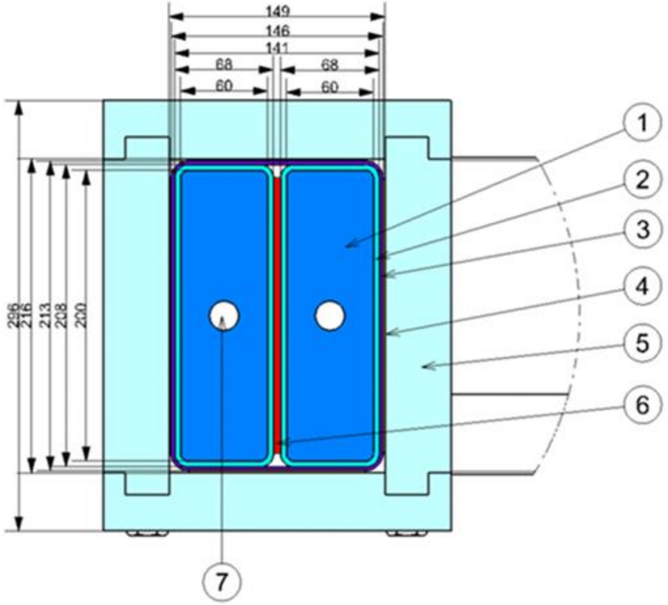

Fig.2. Laminated transmission busbar topology

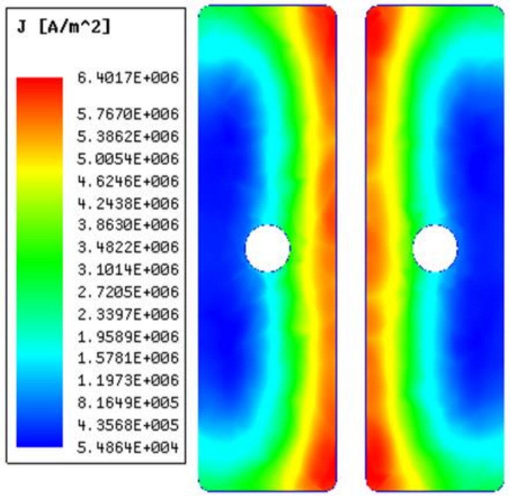

Fig.3. Skin Effect of laminated busbar at 20Hz

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Research on reliability of laminated busbar under Short-circuit Currents of power supply

Research on advanced busbar Aims at high reliability for long-pulse steady state operation

- Analysis of aluminum conductors stress (300kA), the Max. stress is 30.35MPa only.
- Max. intensity of the 1st and 2nd insulation dielectric glass fiber is 42.67MPa.

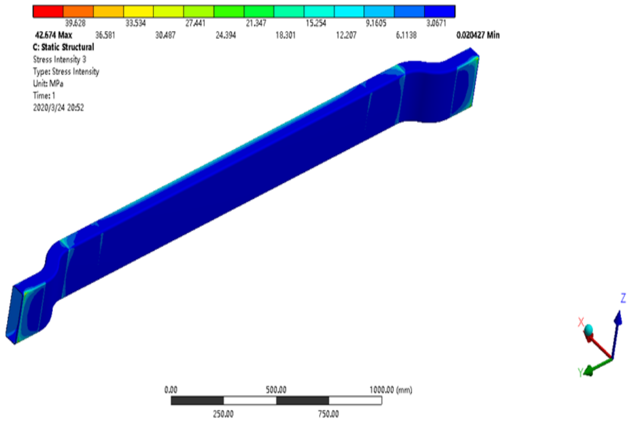

Fig.1. Stress distribution for the 1st Glass fiber(Max. 42.67Mpa/300kA)

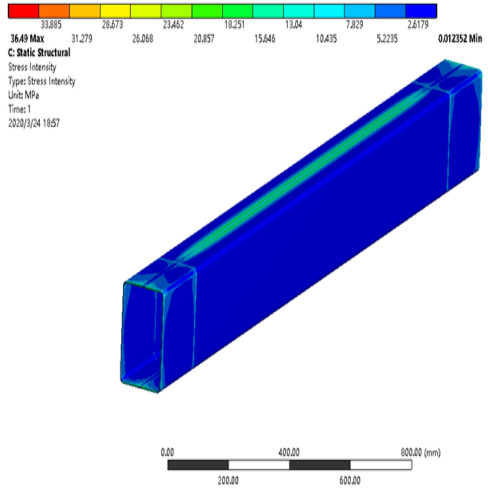

Fig.2. Stress distribution for the 2nd Glass fiber (Max. 36.49Mpa/300kA)

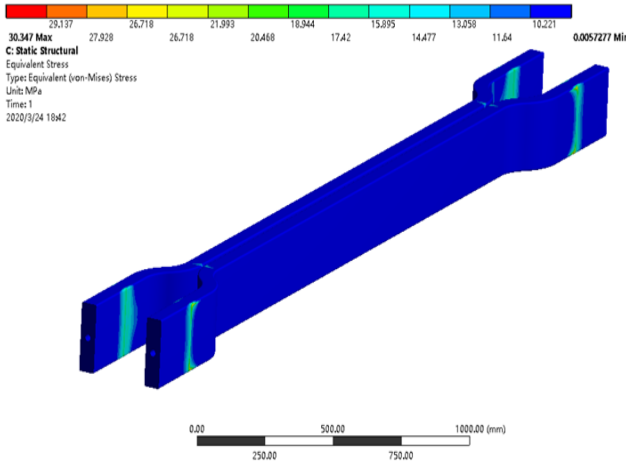

Fig.3. Stress distribution for the Aluminum conductor (Max. 30.347Mpa/300kA)

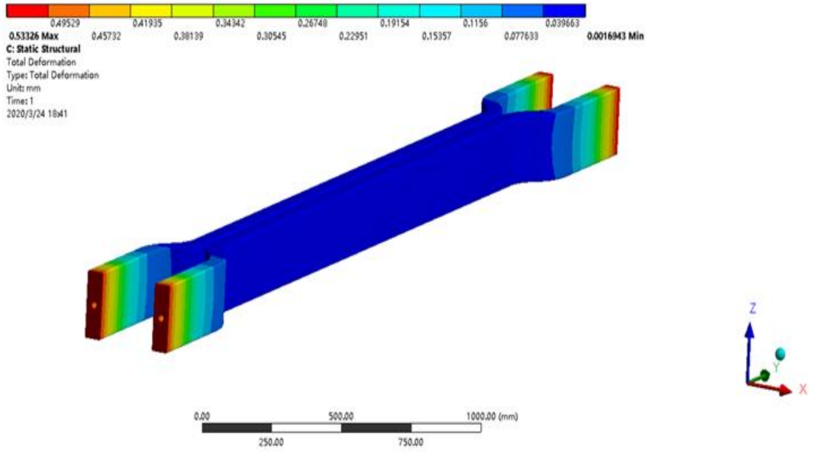

Fig.4. Deformation distribution for the Aluminum conductor (Max. 0.533mm/300kA)

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Research on fatigue analysis and method of laminated transmission busbar system

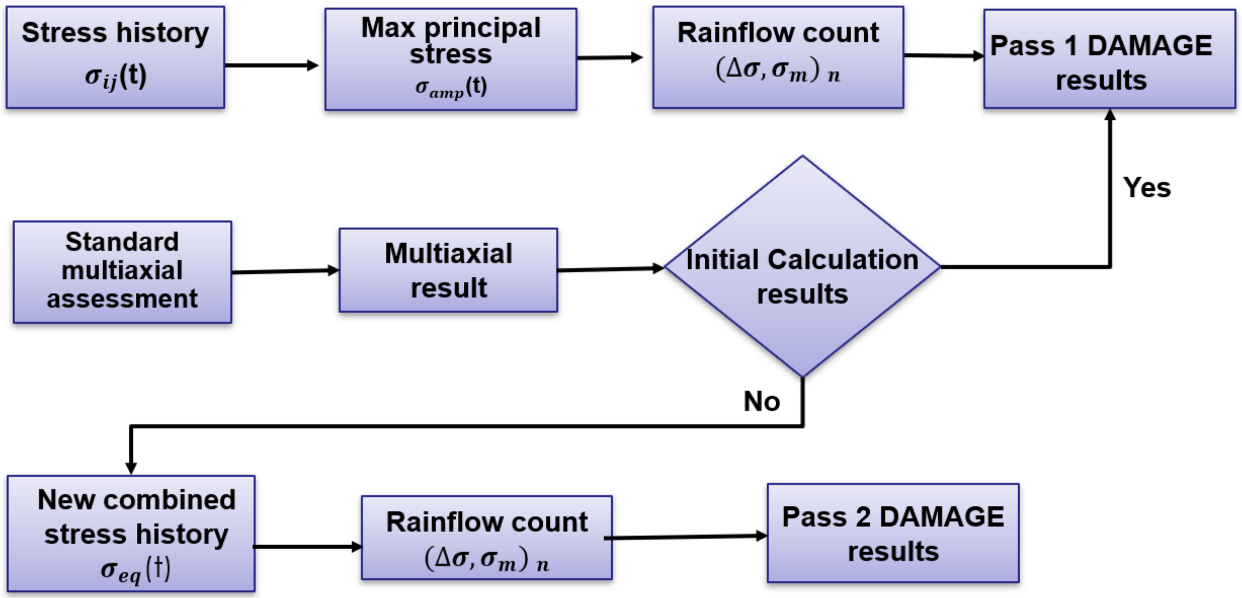

Fig.1. Fatigue Analysis Model and Method

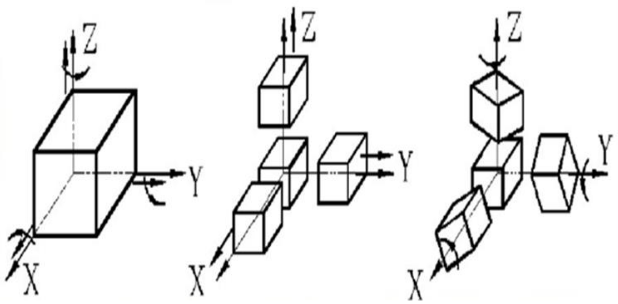

Fig.2. Degrees of freedom of space objects to be constrained

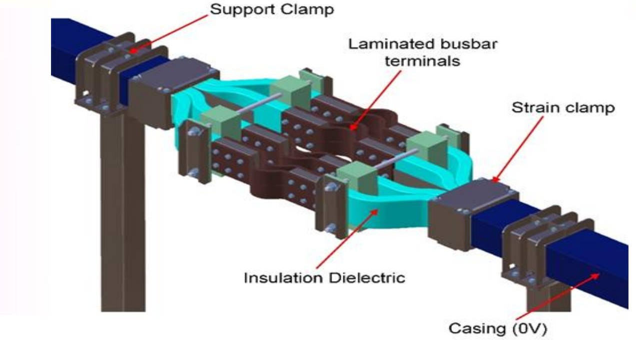

Fig.3. The model for fixture of the laminated busbar

Tab.1. Stress for Steel, aluminum, and glass fiber material

Material	Stainless steel	Aluminum (6101)	Glass Fiber
Ultimate strength	138MPa	60MPa	58Mpa

Fatigue analysis of laminated transmission busbar system for long-pulse operation

- Three supports and clamps are designed to constrain the six degrees of freedom of the laminated busbar.
- Analysis of aluminum conductors stress (300kA), the Max. stress is 30.35MPa only.
- Max. intensity of the 1st and 2nd insulation dielectric glass fiber is 42.67MPa.

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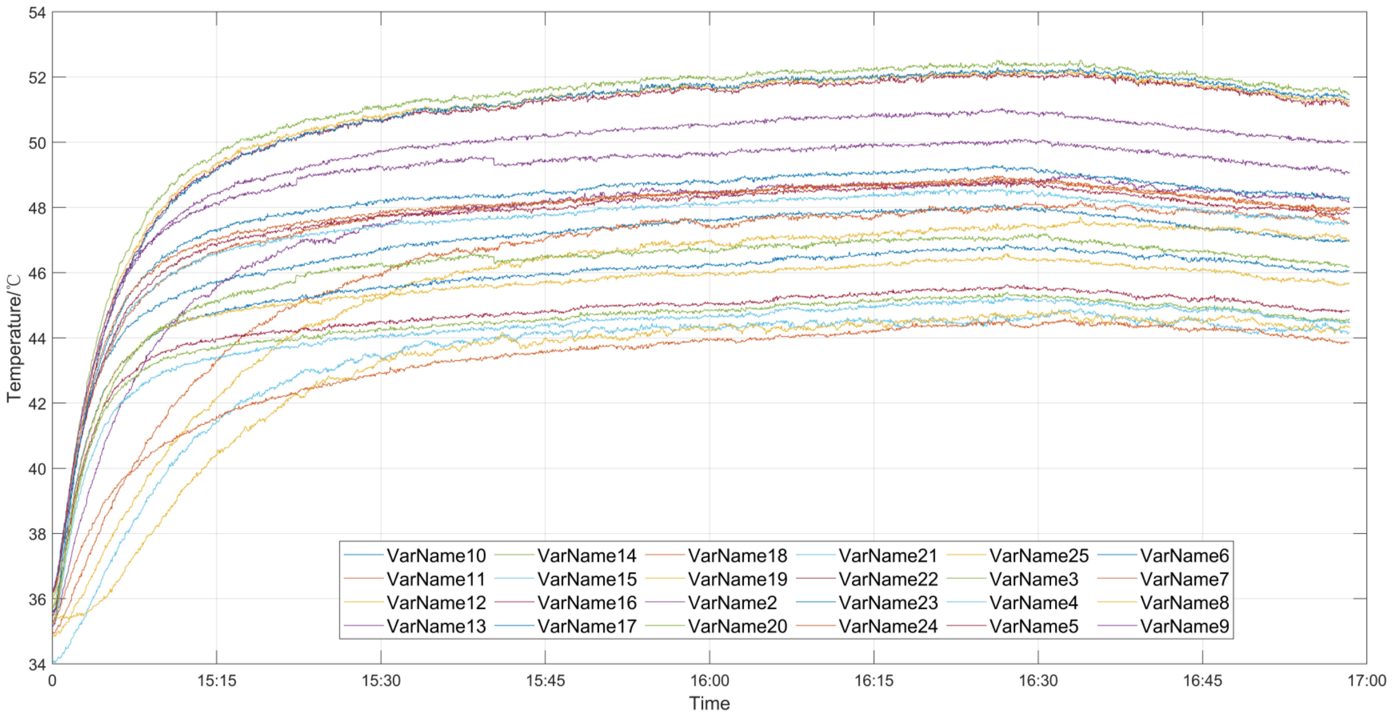
Experimental verification on laminated busbar for steady state Tokamak operation



- Set up an experimental test platform to test the laminated busbar under long pulse, and the temperature output is stable.
- The experimental results verifies the rationality of the laminated busbar design.

Summary

Research characteristics

- The conventional DC busbar occupies too much space, and the large inductance leads to **voltage drop**, **increase EMI** (Electromagnetic Interference).
- High current transmission laminated busbar, with **low inductance**, **low impedance**, **high power density** and **high current**, is available for long-pulse steady-state operation.

Research results

- Establish **mathematical model** to optimize the low inductance and insulation level, With same current and voltage, the new high current laminated transmission busbar can reduce **70% of the installation space**, **50% of the stray inductance**.
- "**Inherent capacitance**" of the laminated busbar can **reduce the current rise time** and **suppress the long-pulse current ripple** correspondingly.
- Establishing **Fatigue Analysis** Model and Method is applied for Life/Cycles Analysis of Laminated Busbar, to ensure the **reliability and safety** of long pulse operation.

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Thank you for your attention