Enhancing Efficiency and Reliability of Long-Pulse Tokamak DC Transmission Systems through Innovative Electromagnetic Topology Optimization

by

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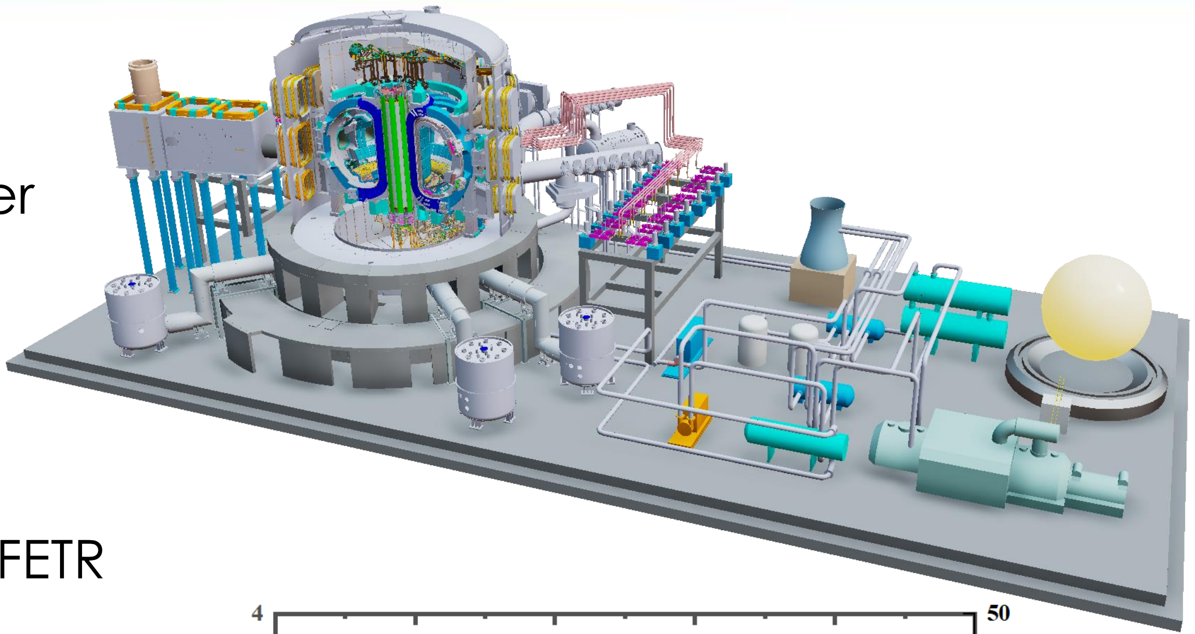
DCTS: Implement variable power transmission strategies and enhance magnet protection regime is key

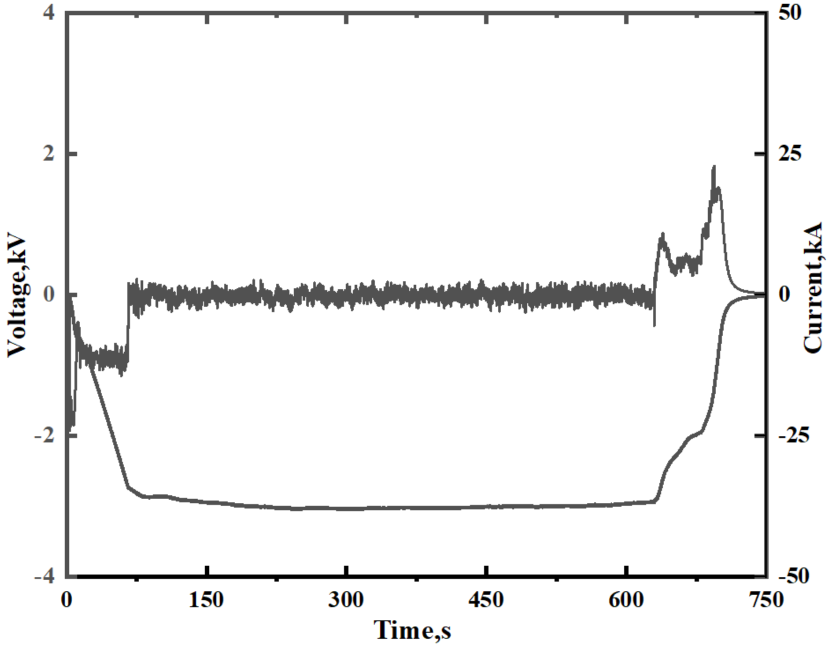


❑ Variable Power Transmission

- Transmission distance of several hundreds meter
- Low Inductance
- Low voltage drop
- TF/PF (55kA/10kV)
- CS (50kA/10kV)
- Thermal equilibrium of DCTS supported BEST&CFETR LPO

❑ High insulation level

- High reliability online protection system for DCTS
- Optimizing electric field distribution
- Quench protection system
- Compact Fusion devices, configuration of multiple systems



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Outline

- Motivation
- Innovative Electromagnetic Topology study for LPO
- Efficiency and Reliability study of DC Transmission system
- Summary and outlook

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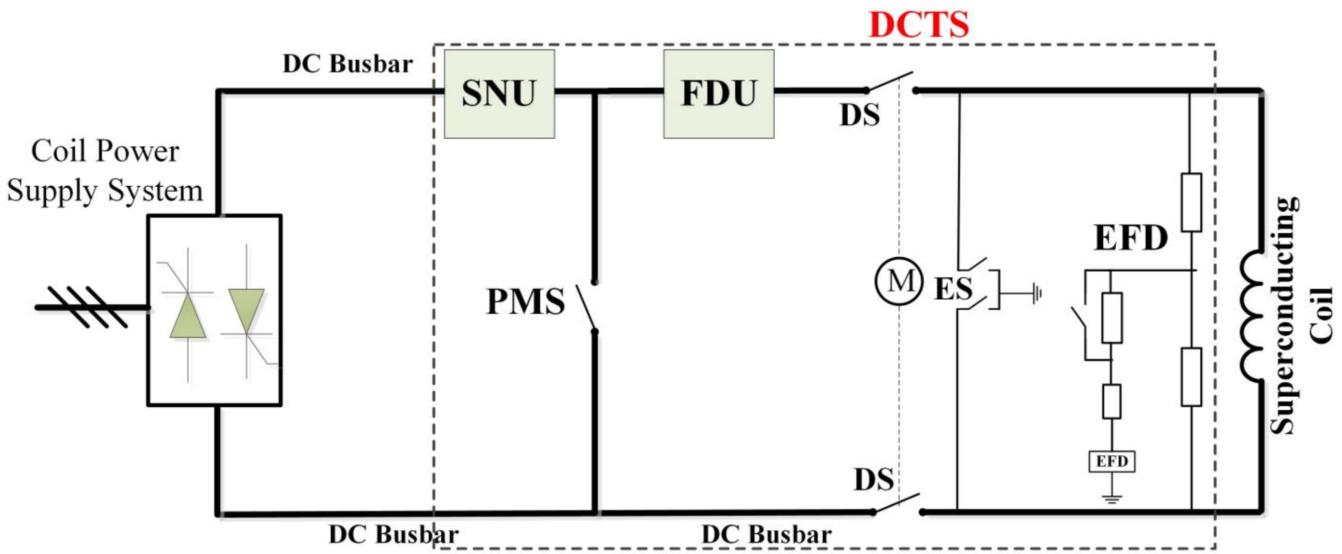
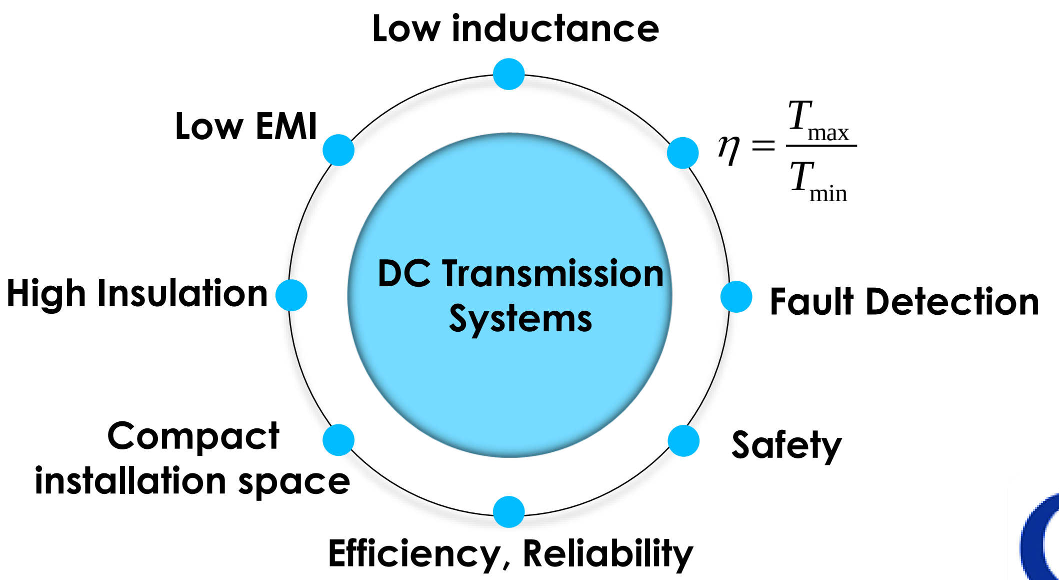
Motivation

- Steady state operation requires fully current I_{DC}.
- Reliability Operation requires High insulation level U_N.
- Enhancing Efficiency of DCTS requires low inductance and voltage drop.
- DC Transmission system can sustain energy release circuit to avoid damage when Superconducting coil quench.





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- Motivation
- **Innovative Electromagnetic Topology study for LPO**
  - ✓ Innovative Electromagnetic Topology of DC Link
  - ✓ Electric field Simulation and Analysis
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Innovative Electromagnetic Topology of DC Link

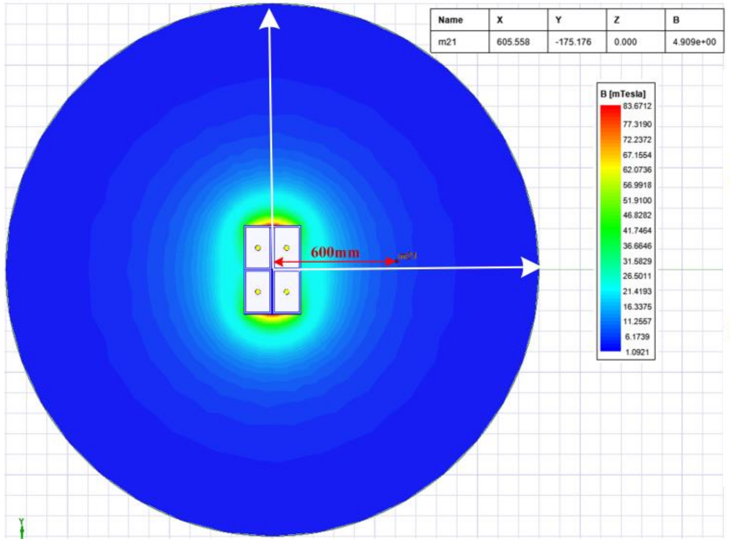
❑ Low EMI

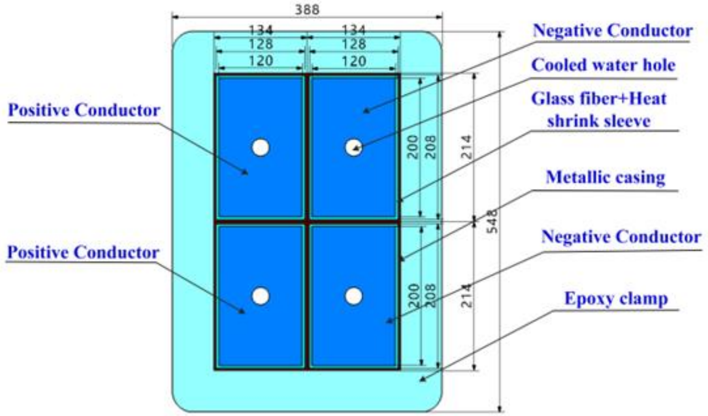
- Steady state current: **55kA/70kA**
- Electromagnetic field intensity

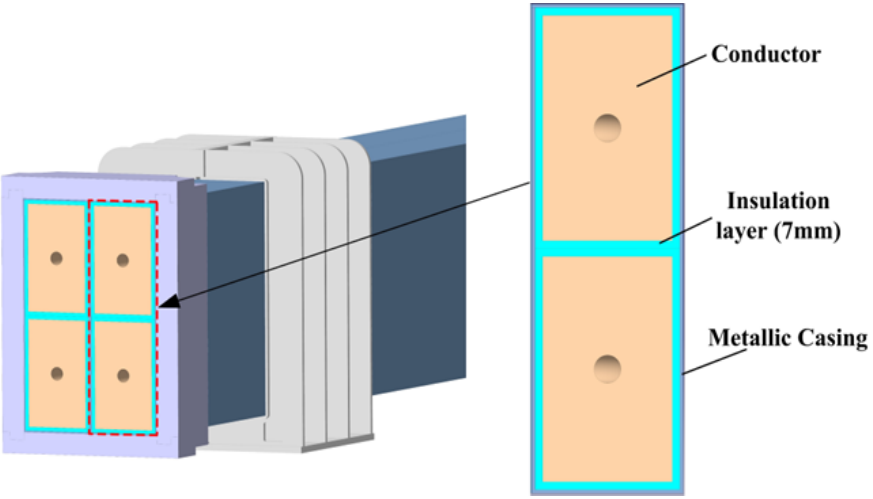
$$B_{0.6m} < 3\mathrm{mT}$$

❑ Core Parameter

- Resistance < **1.2 μΩ/m** (two poles)
- Inductance: $0.15\mu H/m$
- Stray capacitor: **32pF/m**
- Proportion of magnetic energy for Laminated area: **85.3%**







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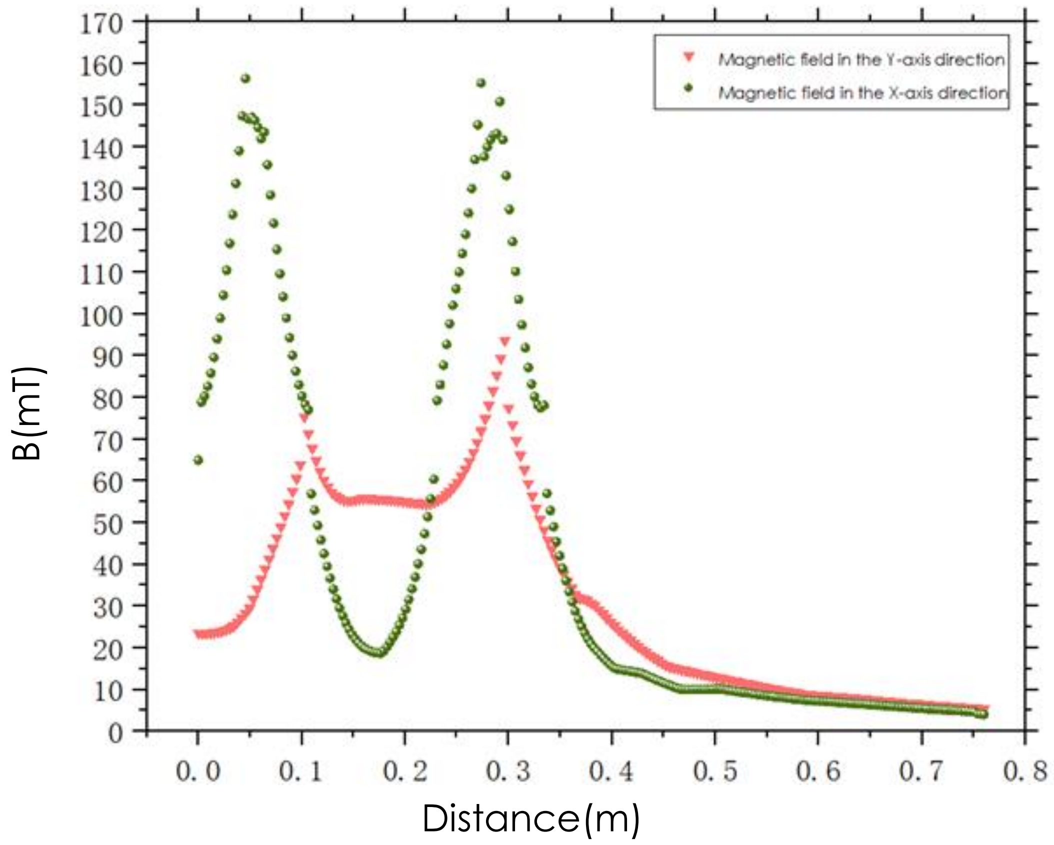
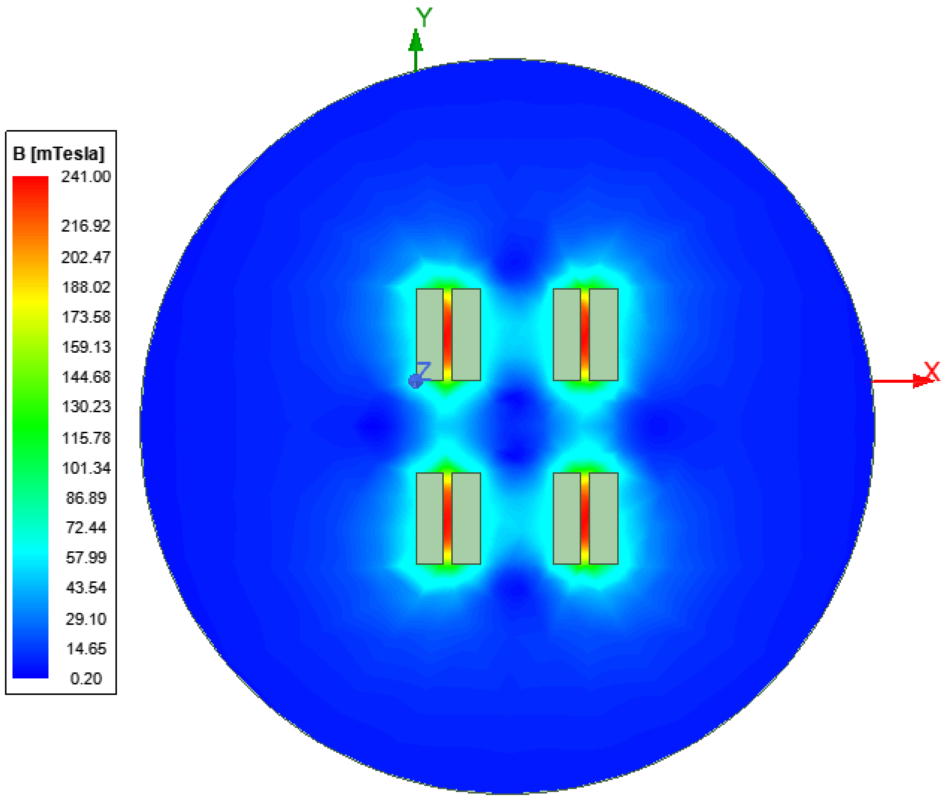
Innovative Electromagnetic Topology of DC Link

Low EMI

- Maximum magnetic field is mainly confined to the laminated region between the two poles
- Magnetic field distribution is distributed within the multiple segments busbar
- **$B_{0.7m(y)} < 3mT$, $B_{1.0m(x)} < 3mT$**





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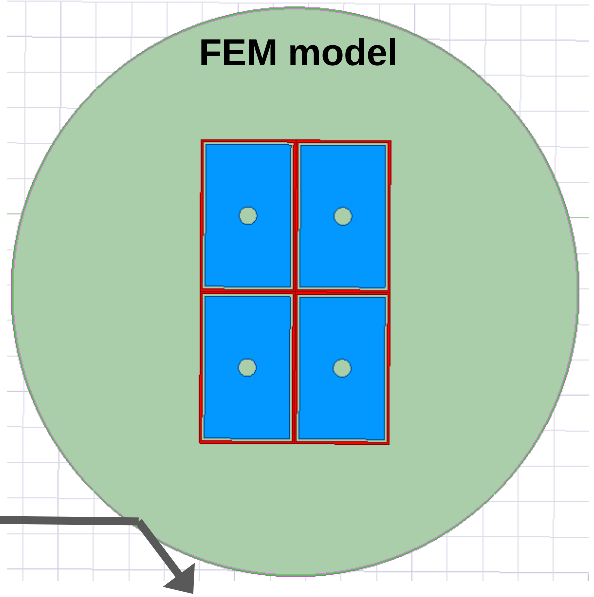
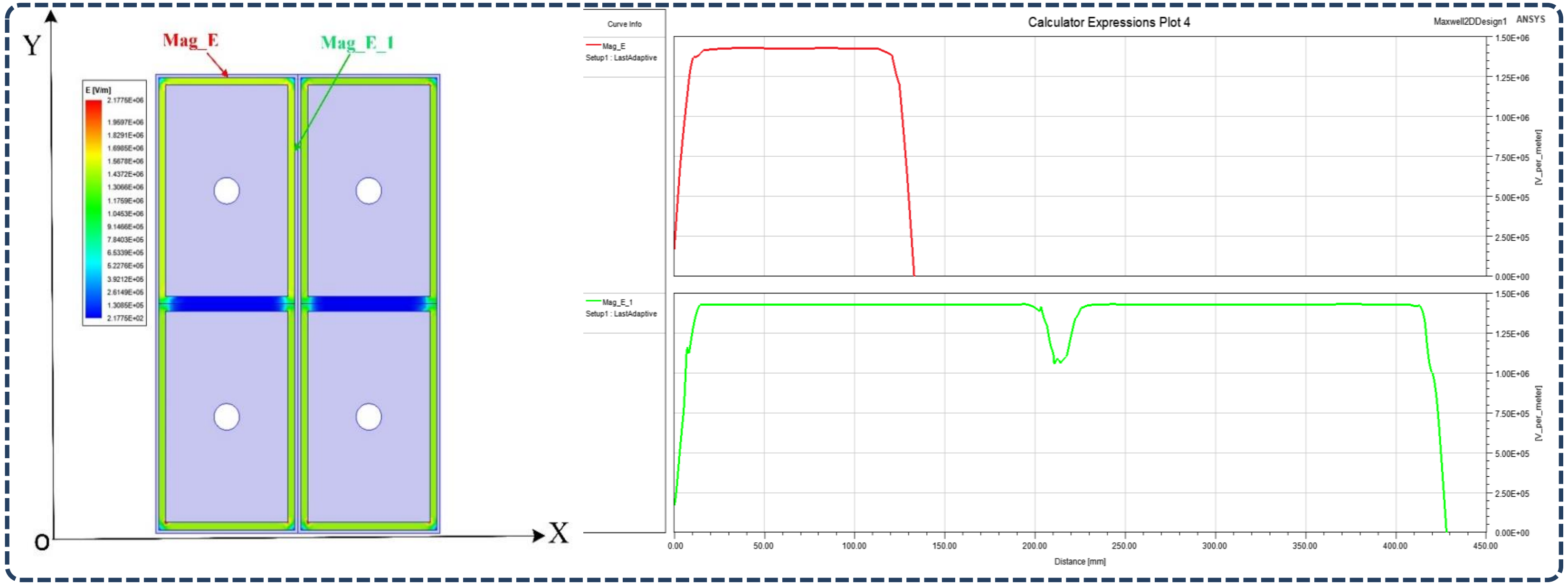
Electric field Simulation and Analysis

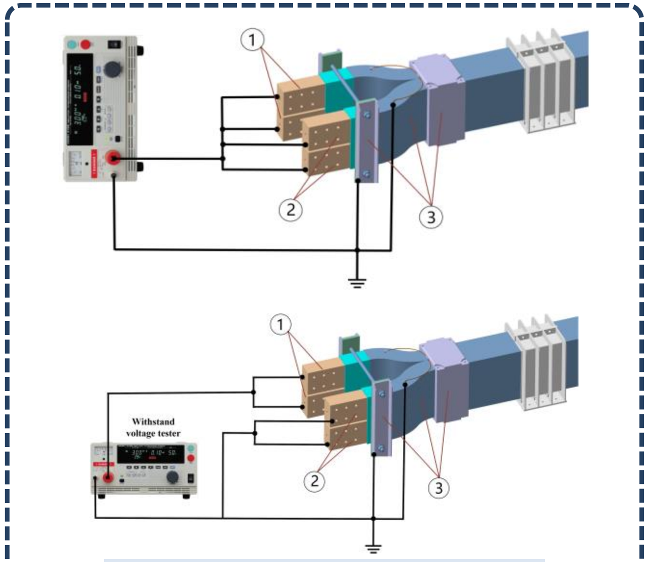
- **Enhanced insulation performance**
  - Boundary electric field: E_{max}~1.2kV/mm
  - Electric field between pole to pole: E ~0 kV/mm, prevent pole-pole fault
  - Potential of metallic casing U_B =0 V, reliability and safety

$$U_A - U_B = \int_A^B \vec{E}\,\vec{dl}$$

Electrostatic field potential 34kV







Analysis method

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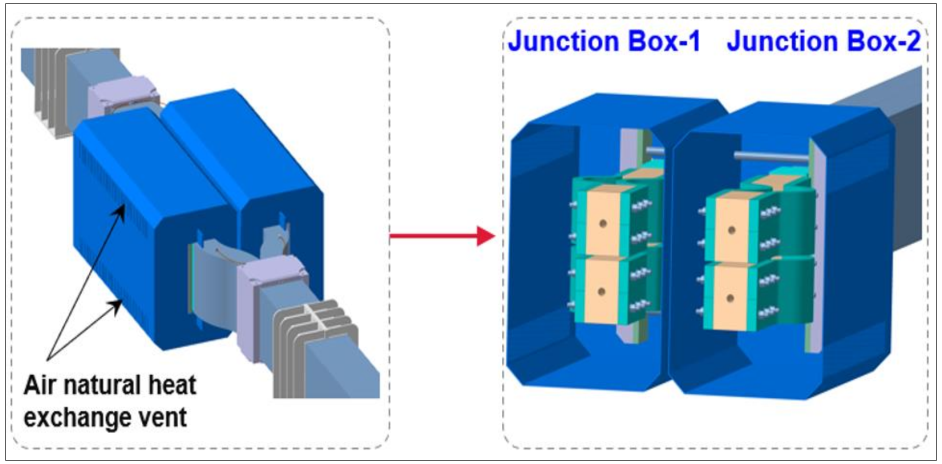
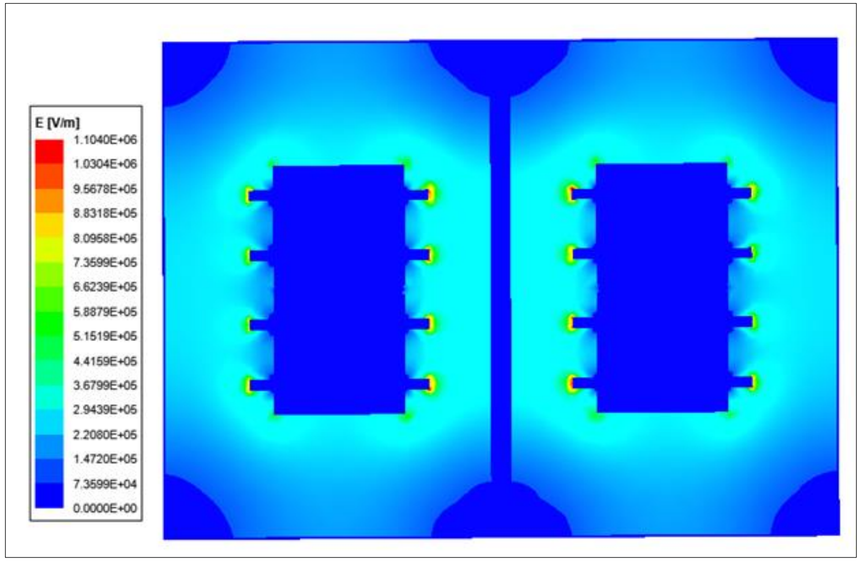
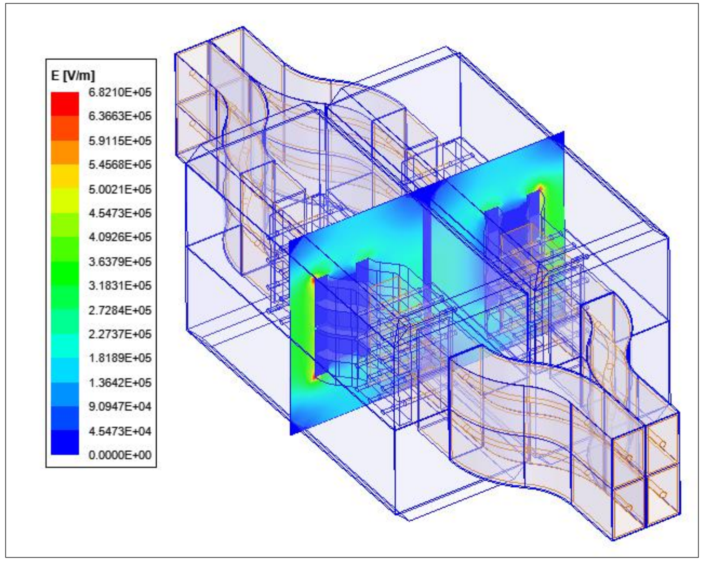
Electric field Simulation and Analysis

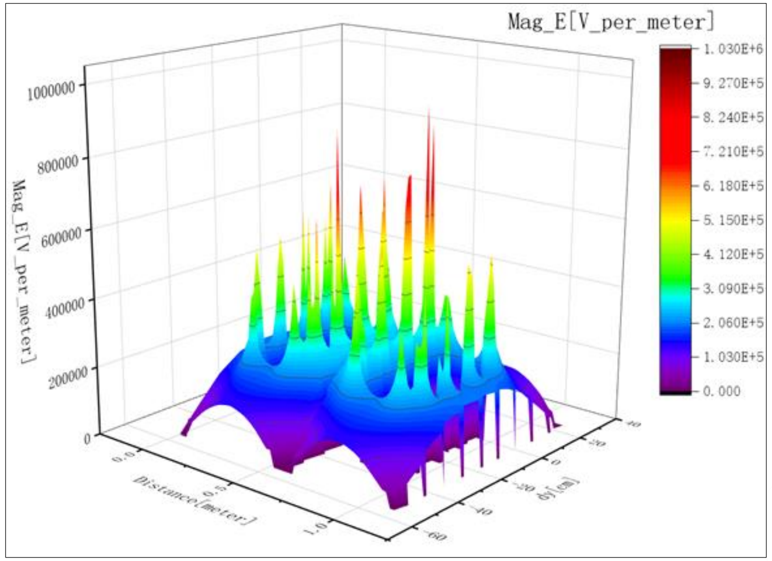
- **Enhanced insulation performance**
  - Connection bolts electric field: $E_{max} < 1.2$kV/mm
  - Copper Strip electric field : E ~0.69 kV/mm
  - Electric field at connection bolts substantial, electric field of corresponding zero-potential casing remains relatively small

FEM model









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Thermal simulation and analysis of DC Link

Busbar thermal model

Ohmic heating →

- Water channel wall heat transfer
- Air heat transfer

→

- Water cooling heat transfer
- Total thermal load on DC busbar(10m)
- Air heat exchange (~5W/m²·K)

Thermal conductivity of Aluminum

Temperature, °C	27	77	177	227
Thermal conductivity, W/(m×K)	207	210	217	222

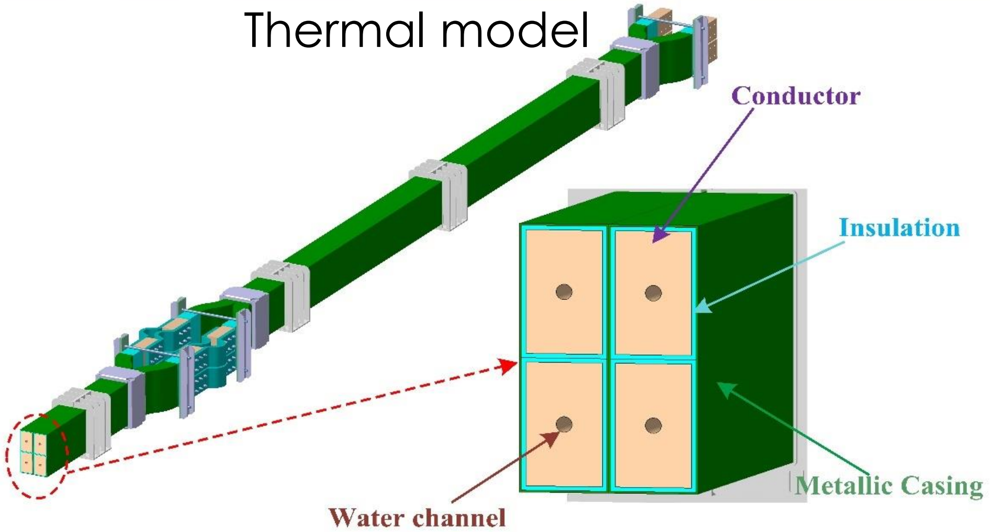
Thermal conductivity of Glass-fiber

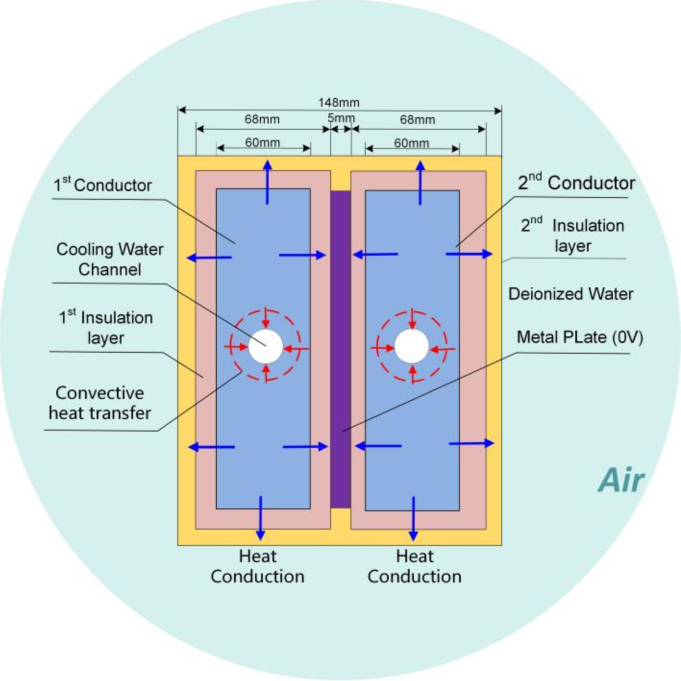
Temperature °C	Thermal conductivity (W/(m ·K))
20	0.035
40	0.036
80	0.038
100	0.039

Thermal conductivity of steel

Temperature °C	Thermal conductivity (W/(m ·K))
20	15.2
100	26.5
200	29.1

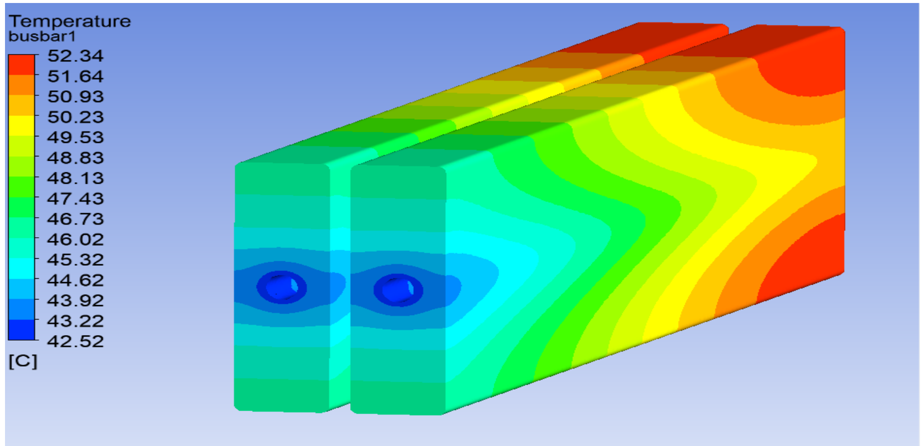
Thermal model



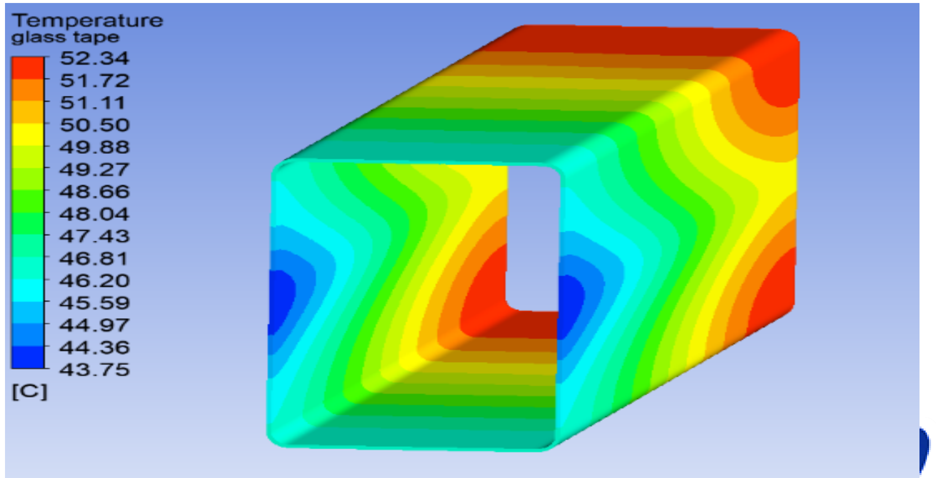


Thermal simulation and analysis of DC Link

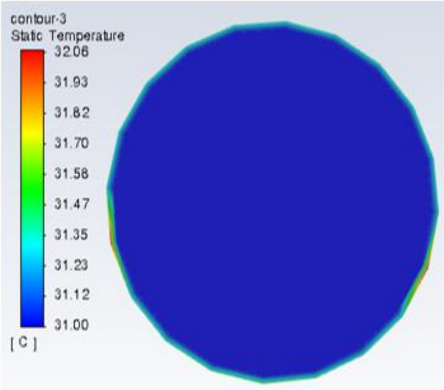
- **Thermal performance analysis**
  - Inlet pressure: P_{inlet}<0.45MPa
  - Pressure losses < 0.25MPa
  - Inlet flow rate： V~ 0.8m/s
  - Cooling water flow for each cooling channel:1.5m³/h
  - Maximum temperature of DC busbar : 53 ℃
  - Maximum temperature of Flexible link: 56.6 ℃

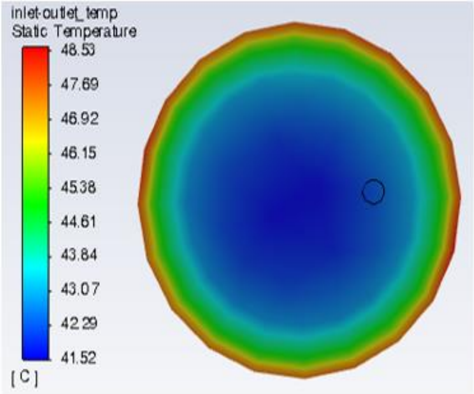


Temperature distribution of DC busbar

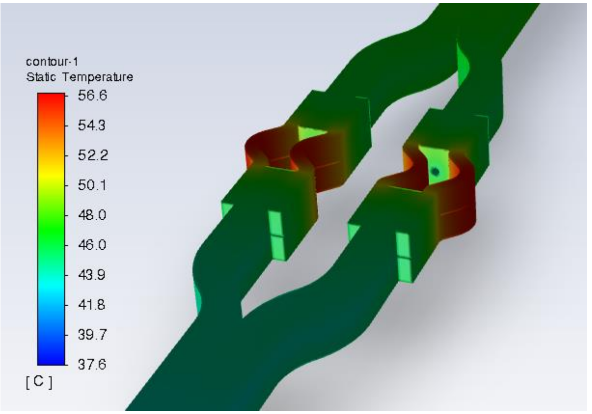


Temperature distribution of insulation layer





Temperature distribution of inlet&outlet water



Temperature distribution of Busbar connection

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Earthing fault analysis and study

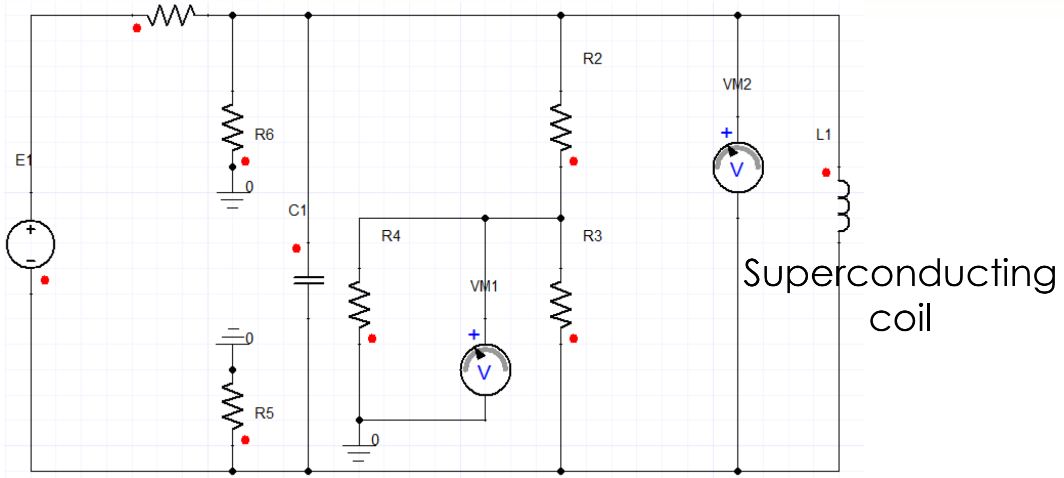
- **Earthing Fault simulation**

  Assumption: Peak voltage for ACDC converter is 1kV;

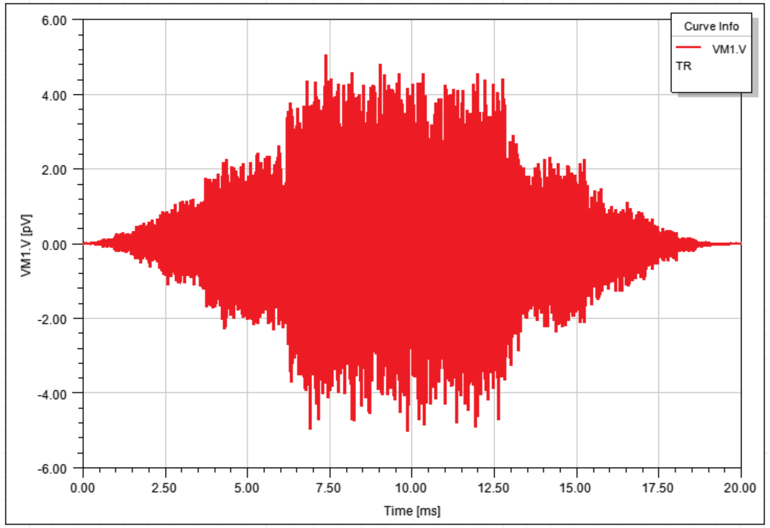
  – Case1: U_{EDF}=0V (peak voltage)

  – Case2: U_{EDF} ~40V (peak voltage)

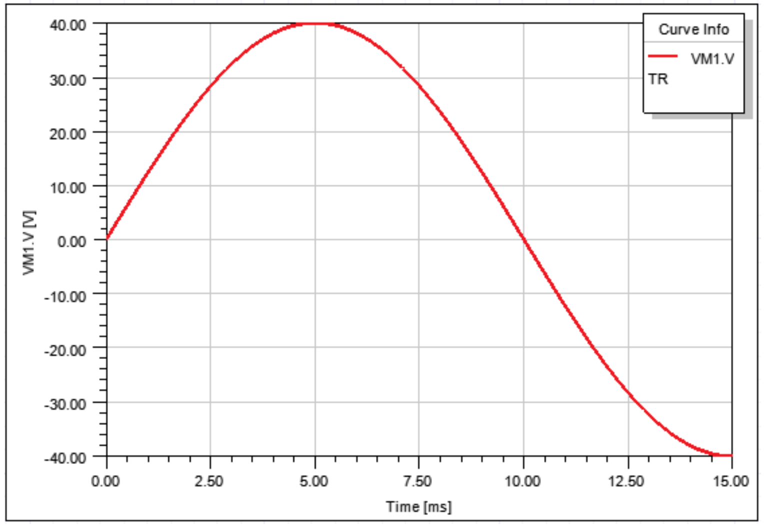
  – Case3:U_{EDF} ~ 450V (peak voltage)



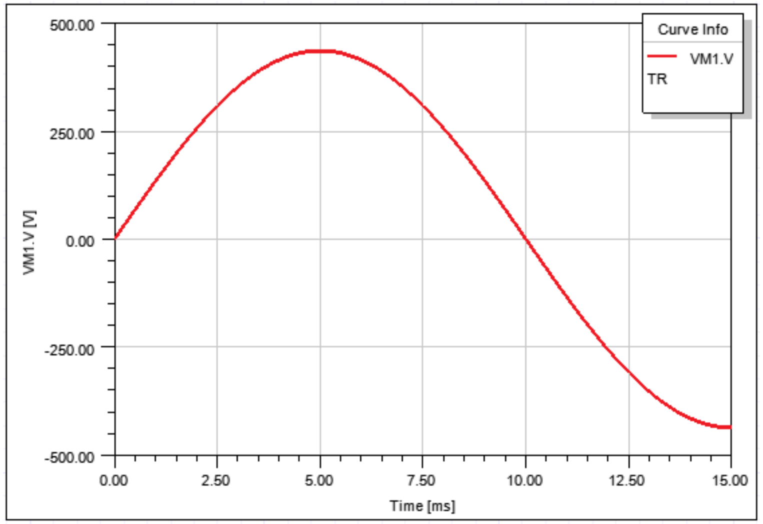
Simulation equivalent circuit



Case1: No grounding fault



Case2: Earthing resistance for one of two poles < 10kohm



Case3: Single pole busbar grounding fault

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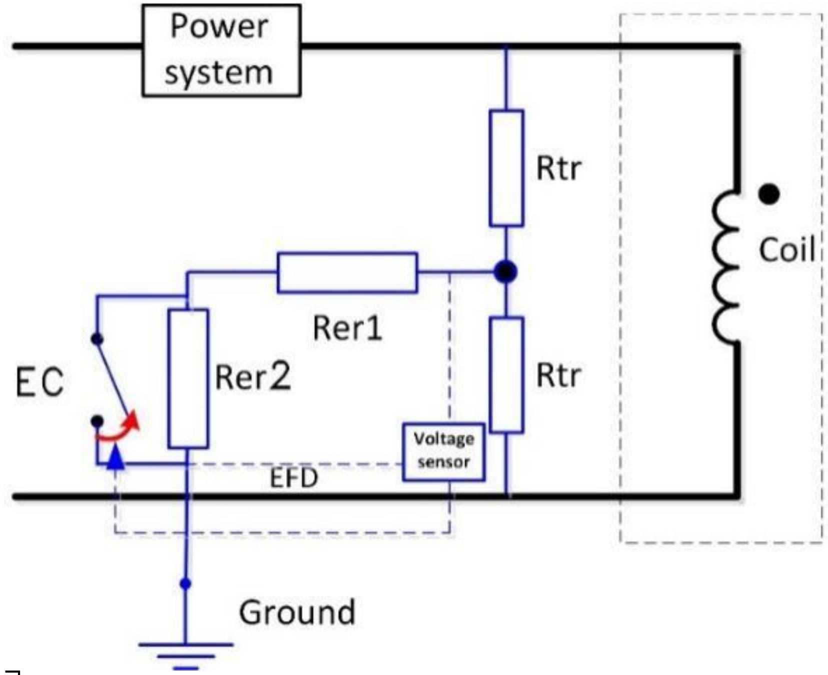
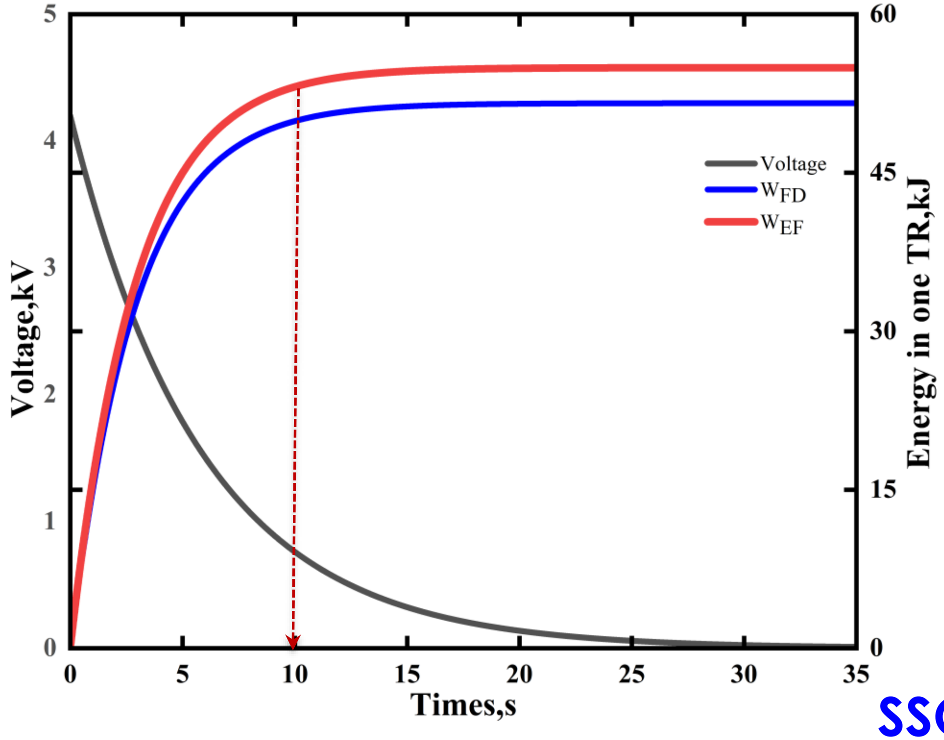
Earthing fault analysis and study

- **Fault detection**
  - Voltage measurement, Monitoring faults
  - Terminal resistors (R_{tr}), balanced voltage
  - Earth fault：current starts flowing in Rer1
  - Fault is detected, EC shall be opened to decrease the current to earth





$$\begin{cases} W_{FD} = \int_0^{t_n} U^2 dt \Big/ \left[2\cdot\left(R_{tr1}+R_{tr2}\right)\right] \\ W_{EF} = \int_0^{t_n} U^2 dt \Big/ \left[Rtr\cdot\left(1+\frac{R_{er1}}{R_{tr}+R_{er1}}\right)^2\right] \end{cases}$$

$$\begin{cases} U_{DC} = U_{CV} + U_{FDU} + U_{DCLINK} \\ U_{EDF} = \frac{U_{DC}\times R_{er1}}{2R_{er1}+R_{tr}} \\ P_{EDF} = \frac{U_{DC}^2\times R_{er1}}{(2R_{er1}+R_{tr})^2} \end{cases}$$

Scenario:
U_{DC}=9V,
U_{DC}=22.8V
U_{DC}=4.1kV

SSO: U_{EDF}=4V; Charge: U_{EDF}=10.6V, FD: U_{EDF}=1800V

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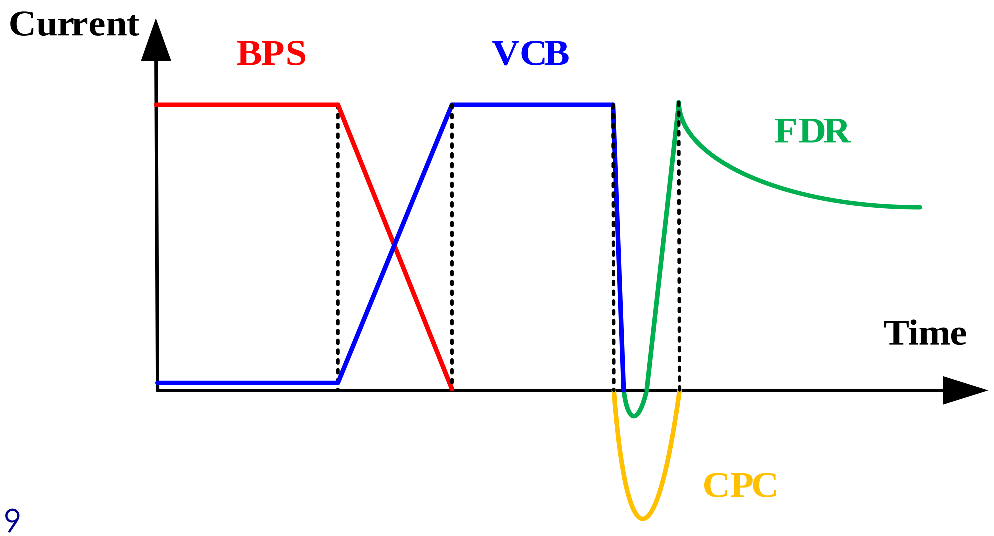
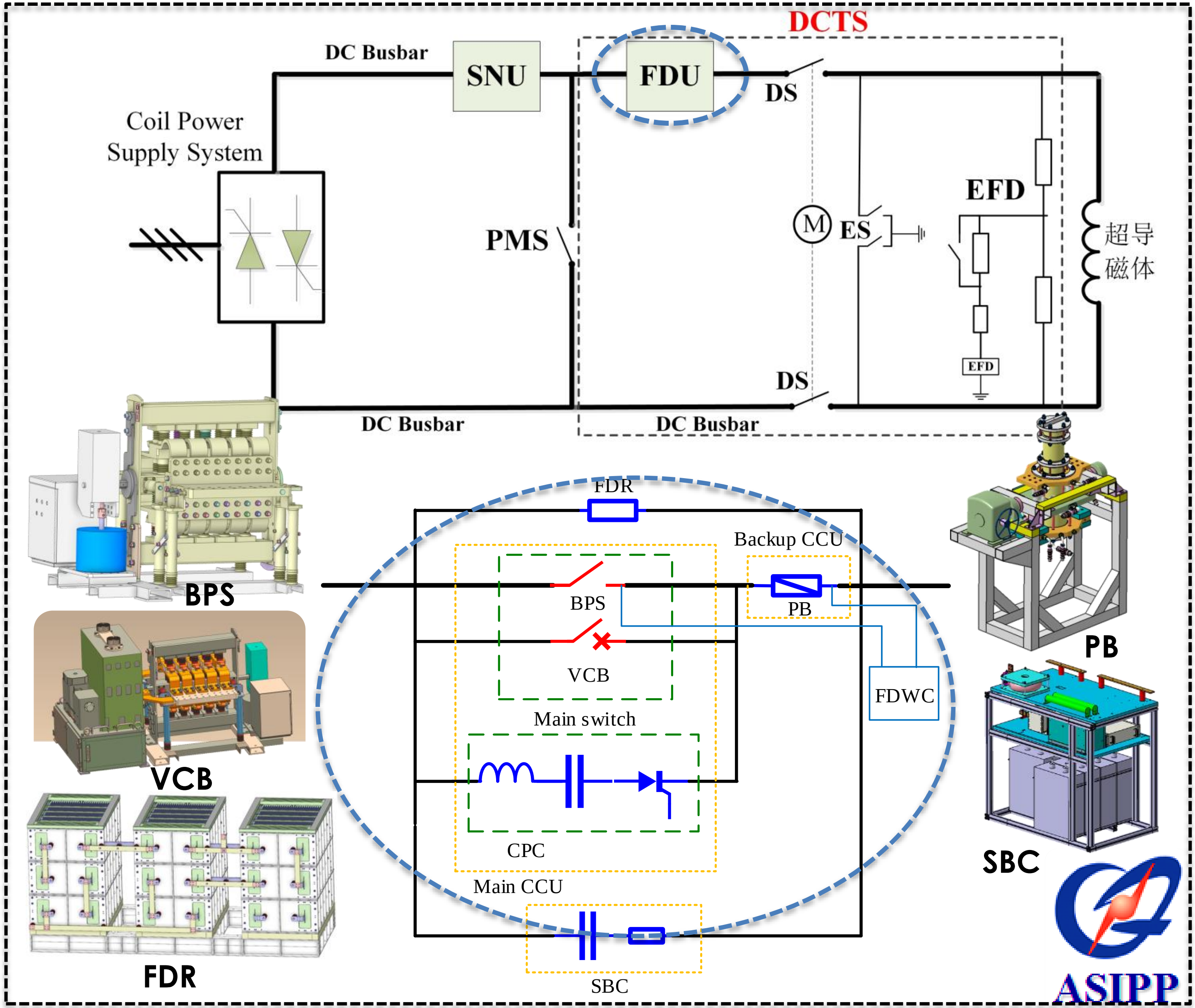
Progress of FDU in support of BEST and MCTB

FDU composition

- BPS and VCB: closed. BPS: high current.
- Coil quench accident, BPS turn off firstly, then the VCB turn off to extinguish arc and transfer current to FDR.
- If main switch fail, the backup PB must be triggered immediately.





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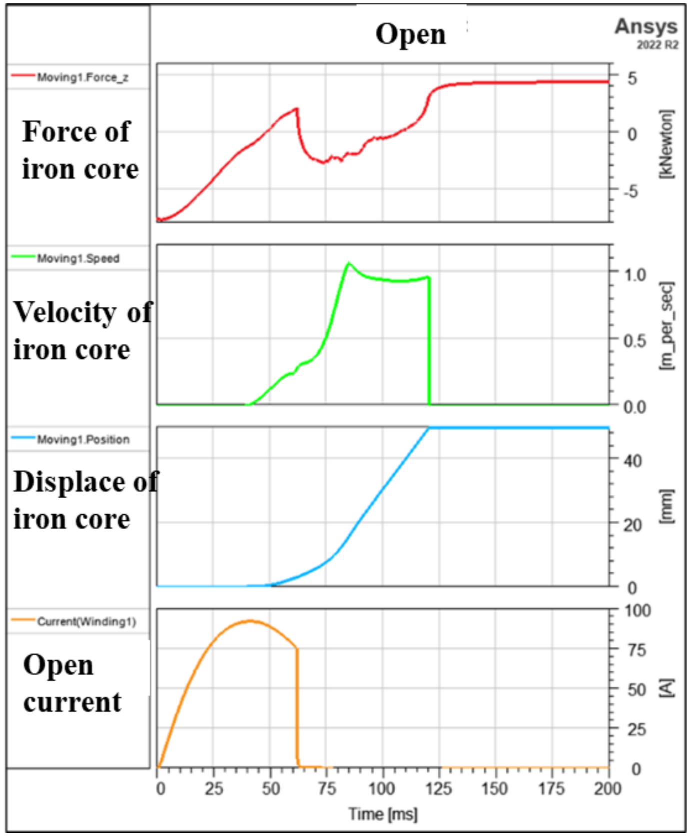
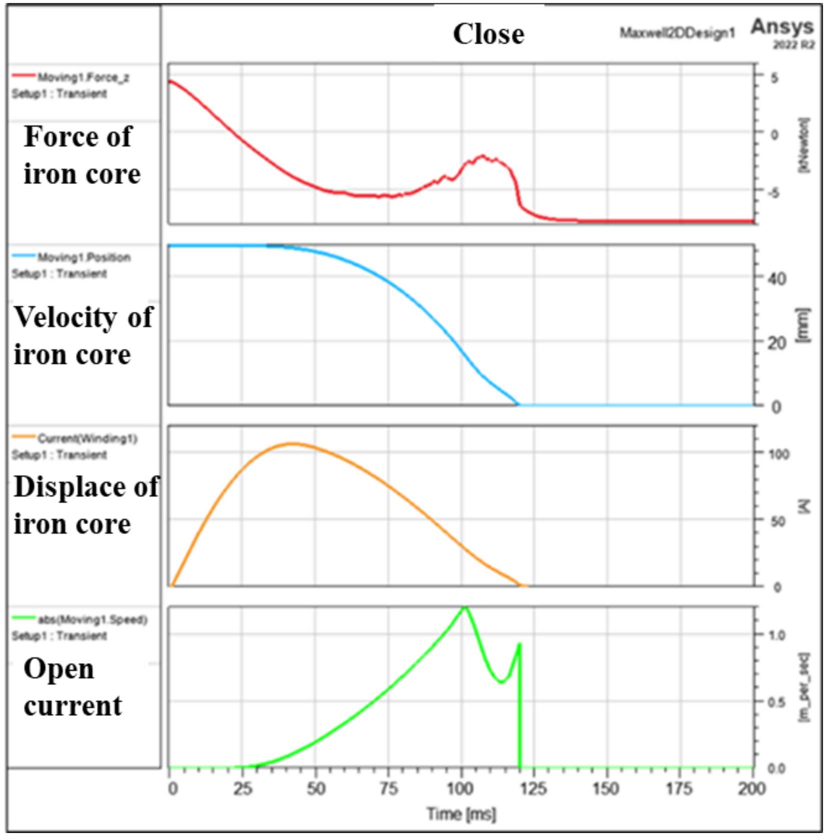
BPS simulation and test result

55 kA BPS





The opening performance:

1) At the opening stop position, the speed is 0.9m/s
2) Total travel time: 120ms

The closing performance :

1) At the closing stop position, the speed is 0.87m/s
2) Total travel time: 120ms

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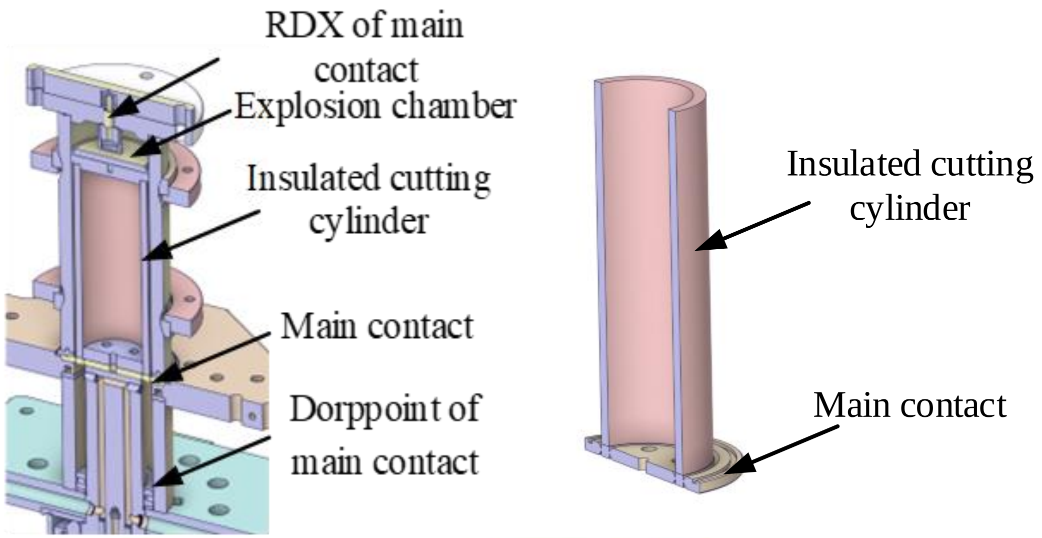
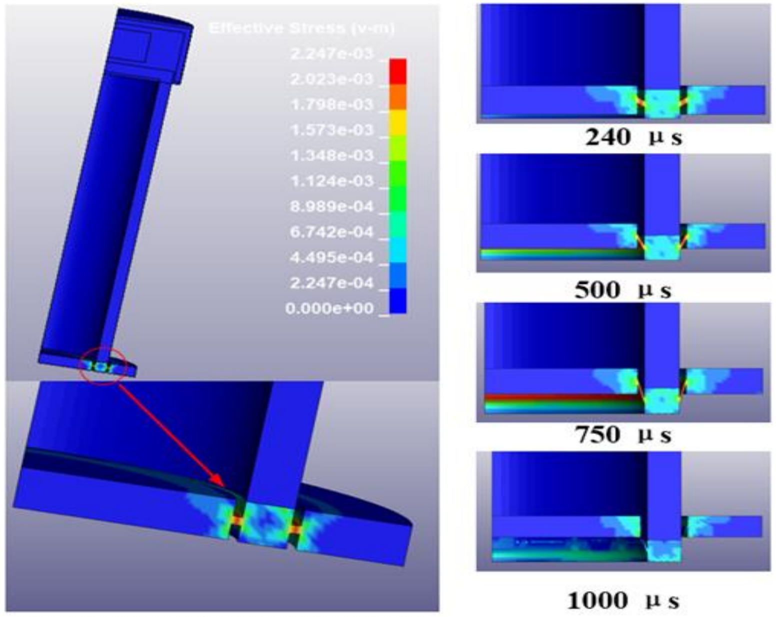
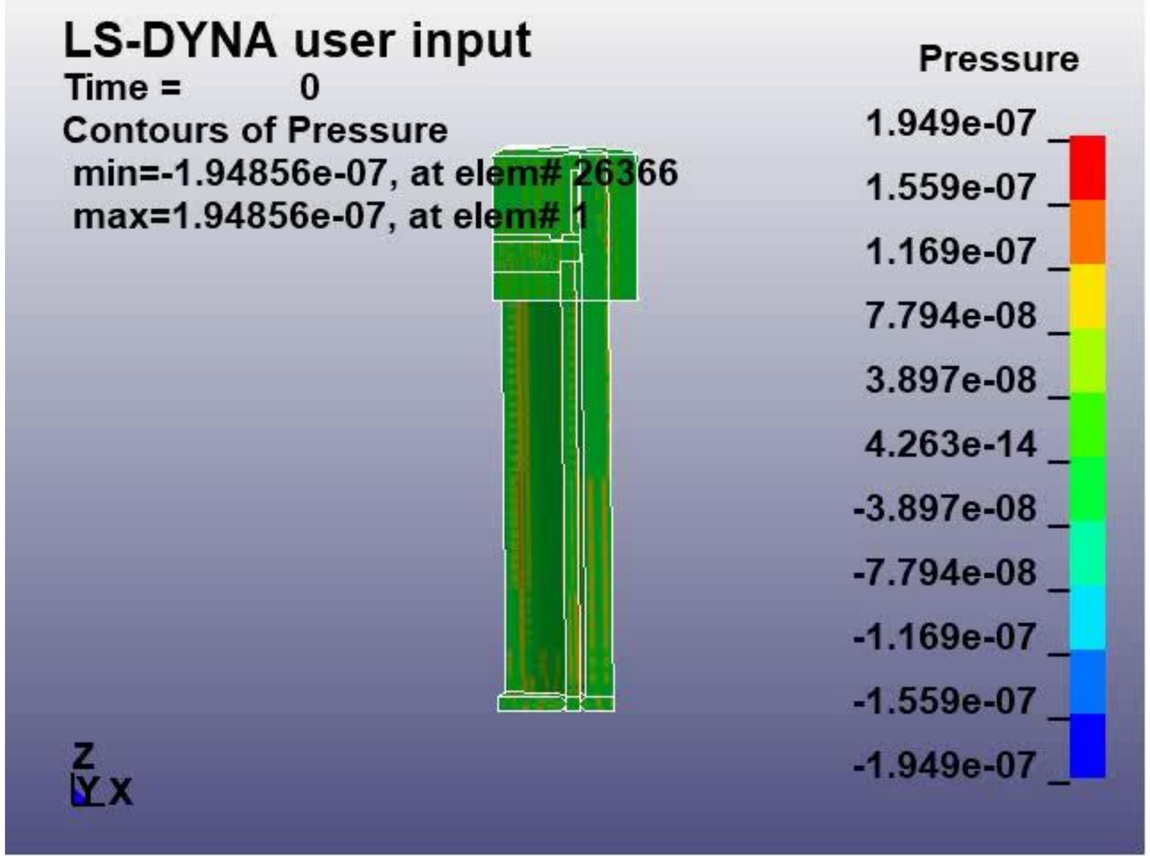
Pyro-breaker(PB) simulation and analysis







- The main contact use 8.5g RDX.

1.The disconnection of the main contact lags the arc contact.

2. The main contact is to establish long-lasting insulation

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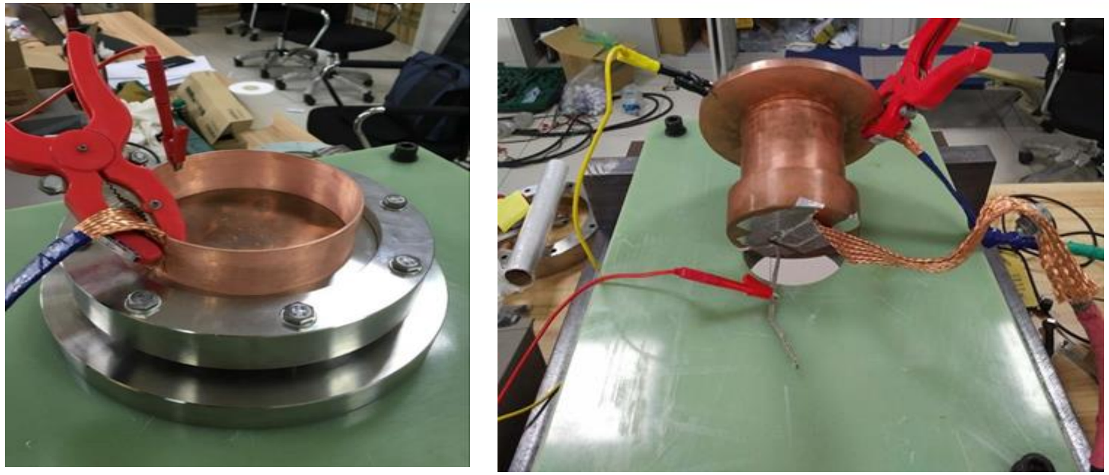
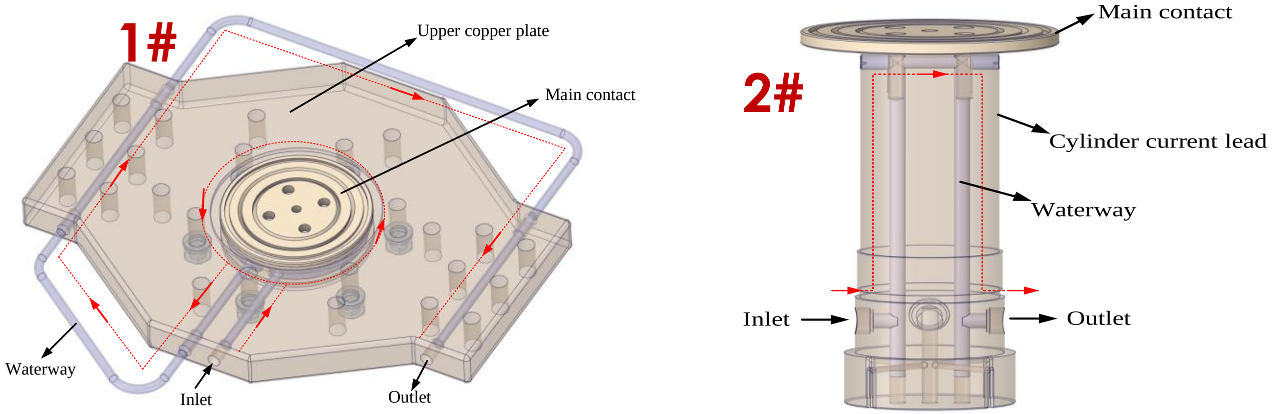
Pyro-breaker(PB) simulation and analysis

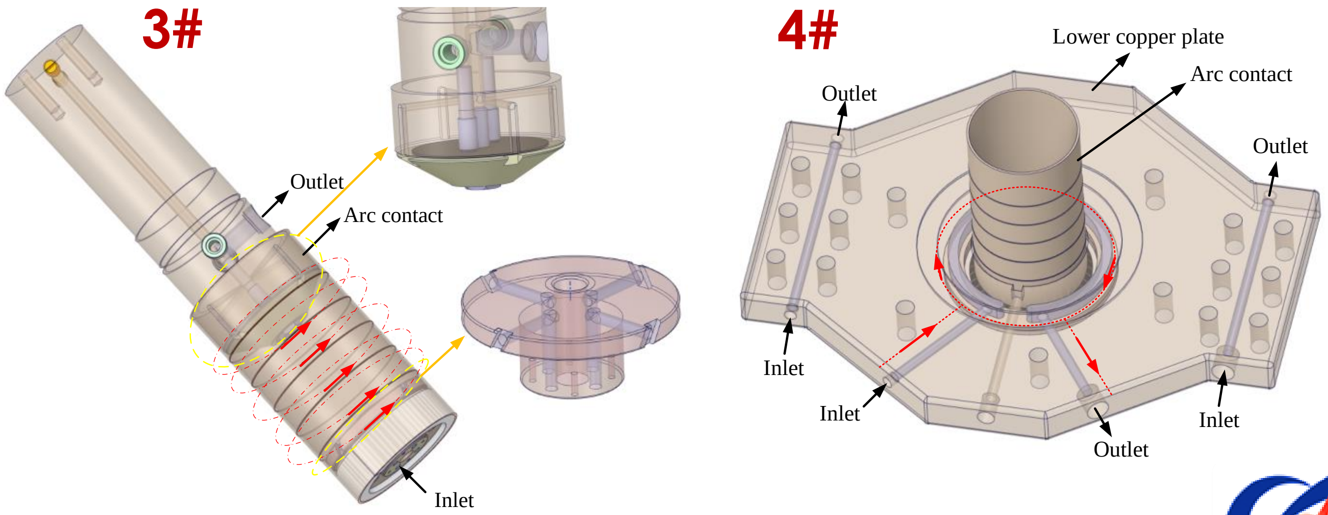


Contact resistance test diagram



Water channel for main contact

- The conductor resistance and contact resistance of each part of the the pyrobreaker, the total calculated resistance and the total measured resistance are less than 10 μΩ.
- In order to obtain better contact performance between conductors, pure silver coating was selected to reduce the contact resistance.



Water channel for arc contact

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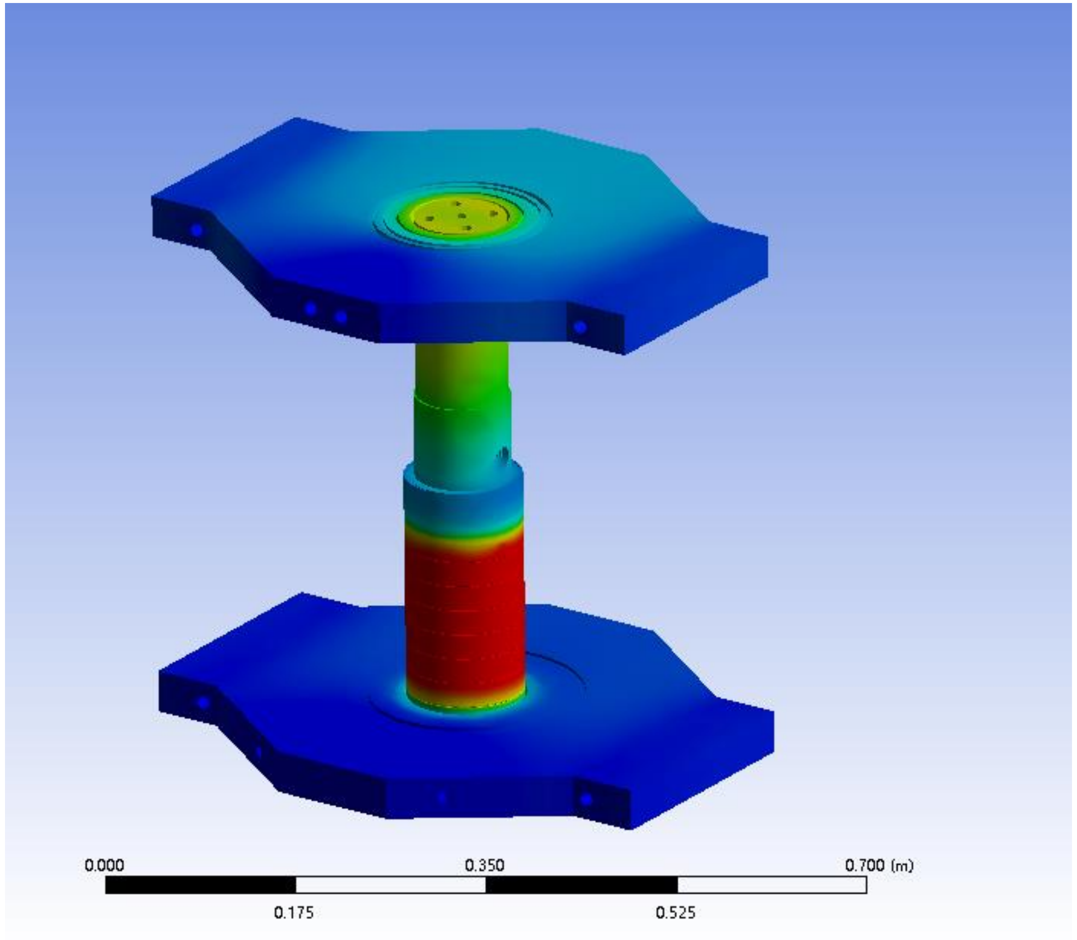
Pyro-breaker（PB）simulation and analysis



Cooling water(V) (m/s)	Water channel	Heat dissipation coefficient(h)(W/(m²*℃))	Tmax(℃)	Tmin(℃)	ΔT
1	1#、2#、4#	6035	76.27	35	41.27
	3#		99.62		64.62
1.2	1#、2#、4#	6982	72.73	35	37.73
	3#		91.01		56.01
1.5	1#、2#、4#	8374	69.20	35	34.20
	3#		81.90		46.90

1. Based on analysis, the 3# water channel flow rate is set to 1.5 m/s. The other water channel flow rate is set to 1 m/s.
2. The results show that the whole temperature of the pyrobreaker meets the design requirements.

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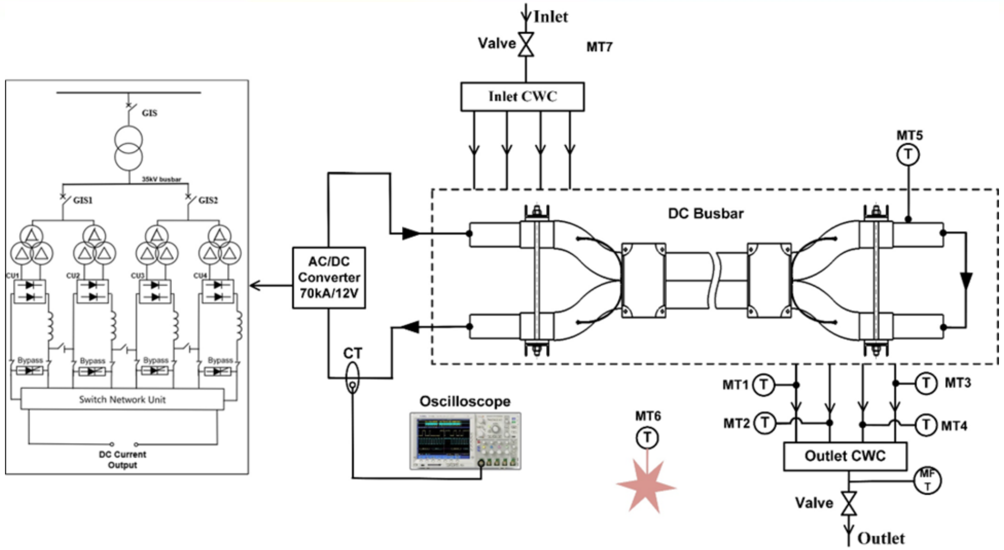
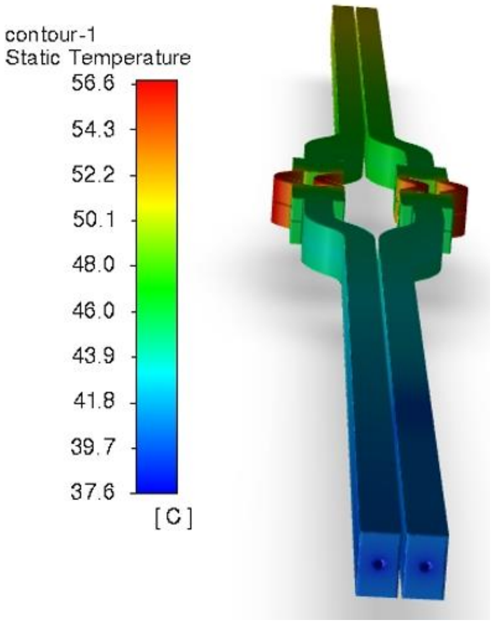
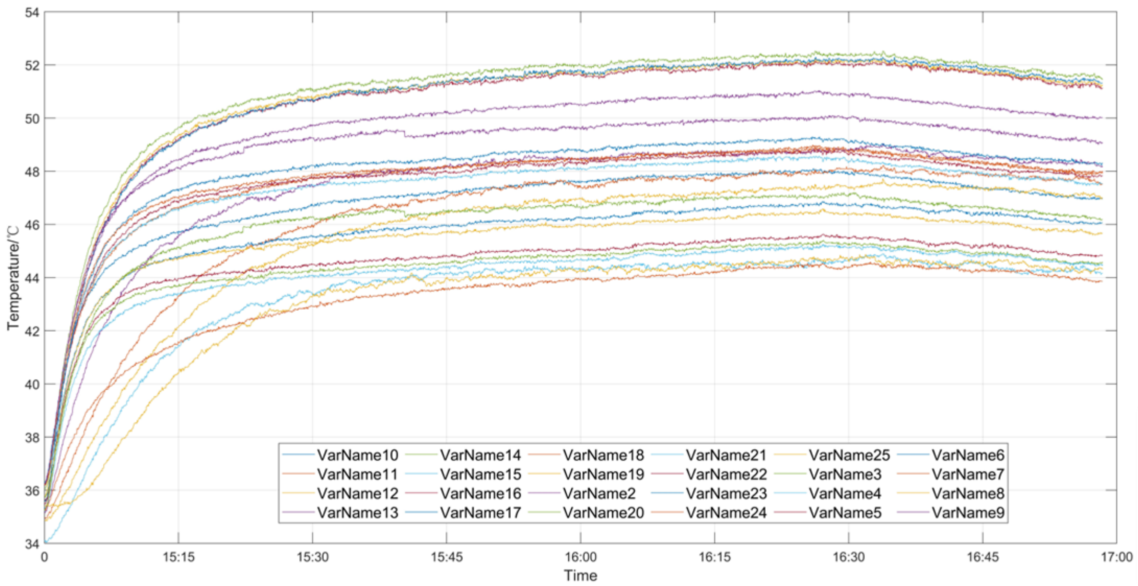
Experimental for thermal cycle test of DC Link

- **Test Result**
  - Coolant: Deionization water
  - Inlet pressure: P_{inlet}<**0.45MPa**
  - Temperature outlet water: **43℃**
  - Inlet flow rate： *V*~ **0.8m/s**
  - Maximum temperature of DC busbar and Insulation: **52 ℃**



Thermal cycling test topology circuit

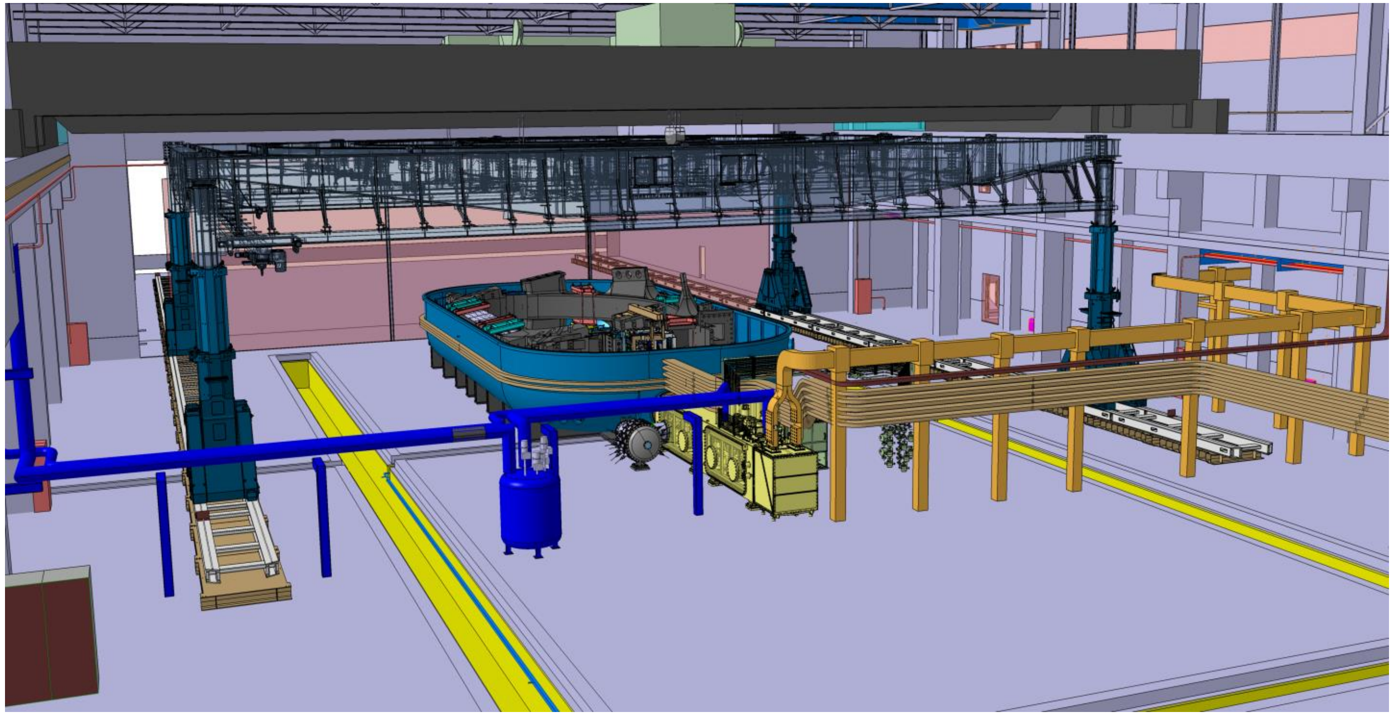




Risk Mitigation: Cold Testing of Superconducting Coil

The Magnet Cold Test Bench is a facility on ITER site that will allow a few (>3) TF coils and PF1 to be tested at nominal current before their integration.
What will be checked.

- Coil and Joint Performance.
- High voltage ground insulation at different T.
- Quench protection systems.



❑ DCTS

- Steady state current:**70kA**
- Electromagnetic field intensity
  $\boldsymbol{B}_{\mathbf{0.6m}} < \mathbf{3mT}$
- Resistance < **1.2 μΩ/m** (two poles)
- Inductance： $\mathbf{0.15}\boldsymbol{\mu H/m}$
- Stray capacitor: **32pF/m**
- Fault detection
- Quench protection systems

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Summary and plans

Summary:

- A novel study on electromagnetic topology has been applied to the DC transmission system, ensuring its reliability for long-pulse operation (LPO).
- This innovative busbar structure prevents insulation breakdown between the positive and negative terminals, mitigates single-point grounding faults, and ensures the safety and reliability of the electrical circuits.
- Low inductance and stray capacitor of DC busbar is analyzed.
- The Fast Discharge Unit (FDU) ensures prompt detection of superconducting quench events, enabling rapid power cutoff and the transfer of energy from the superconducting coil to the Fast Discharge Resistor (FDR).

Outlook:

- The DC transmission system should support a FD operation from maximum current without cooling water.
- Further research of LCR parameterization is needed to meet the electrical circuit response time requirements for different magnet operation scenarios.

Thank You For Your Attention!

Your Suggestion and Comments Will Be Appreciated.

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