IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), February 2020.
Presentation AT-4 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.

Korea Project for Developing Basic Technologies of a 10 MW Floating Wind Power Generator with HTS Magnet and Test Facility sponsored by KEPCO

Changwon National University
Prof. Minwon Park

Jan. 8th 2020

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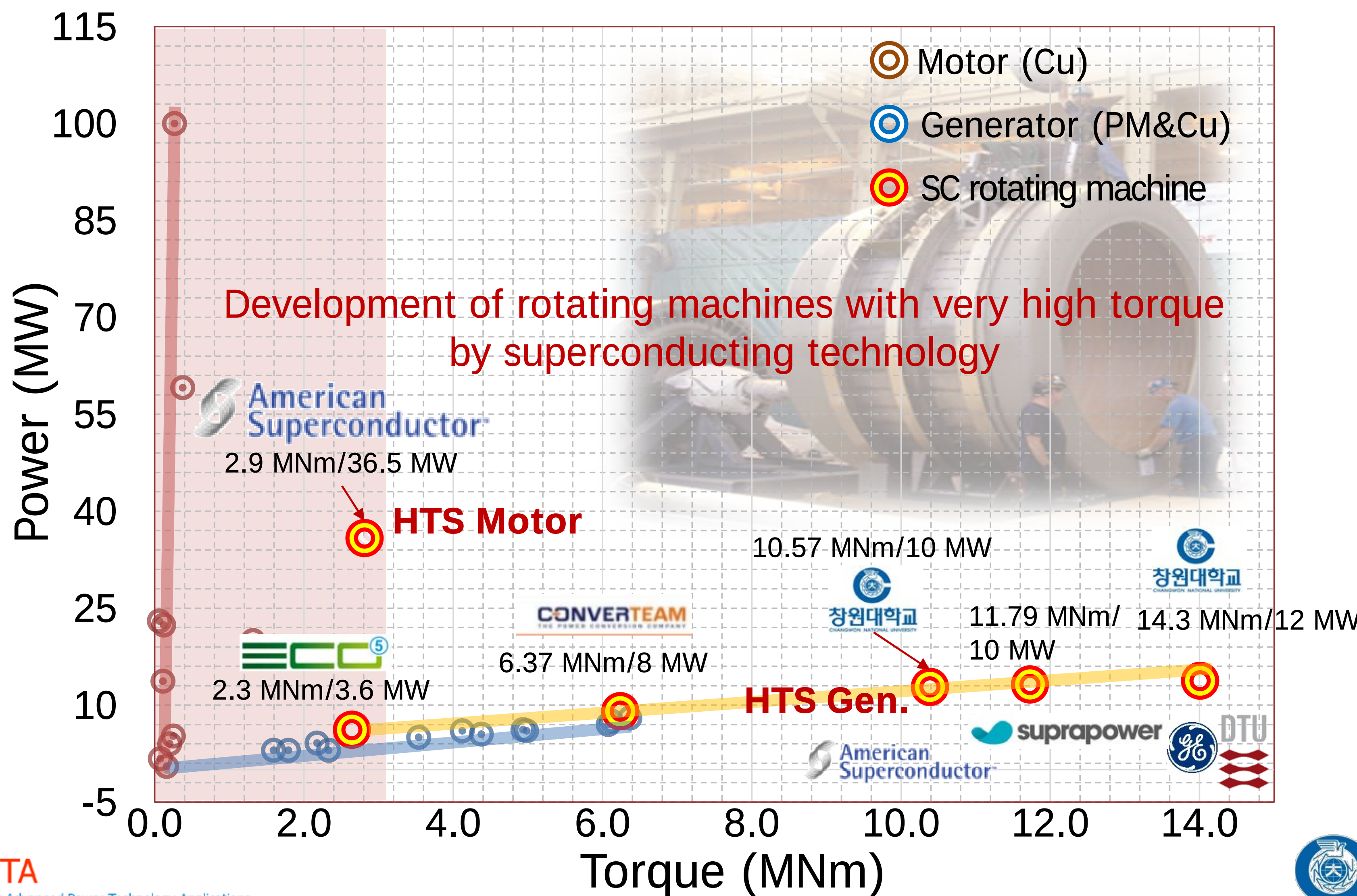
Output power & Torque of the wind power generators

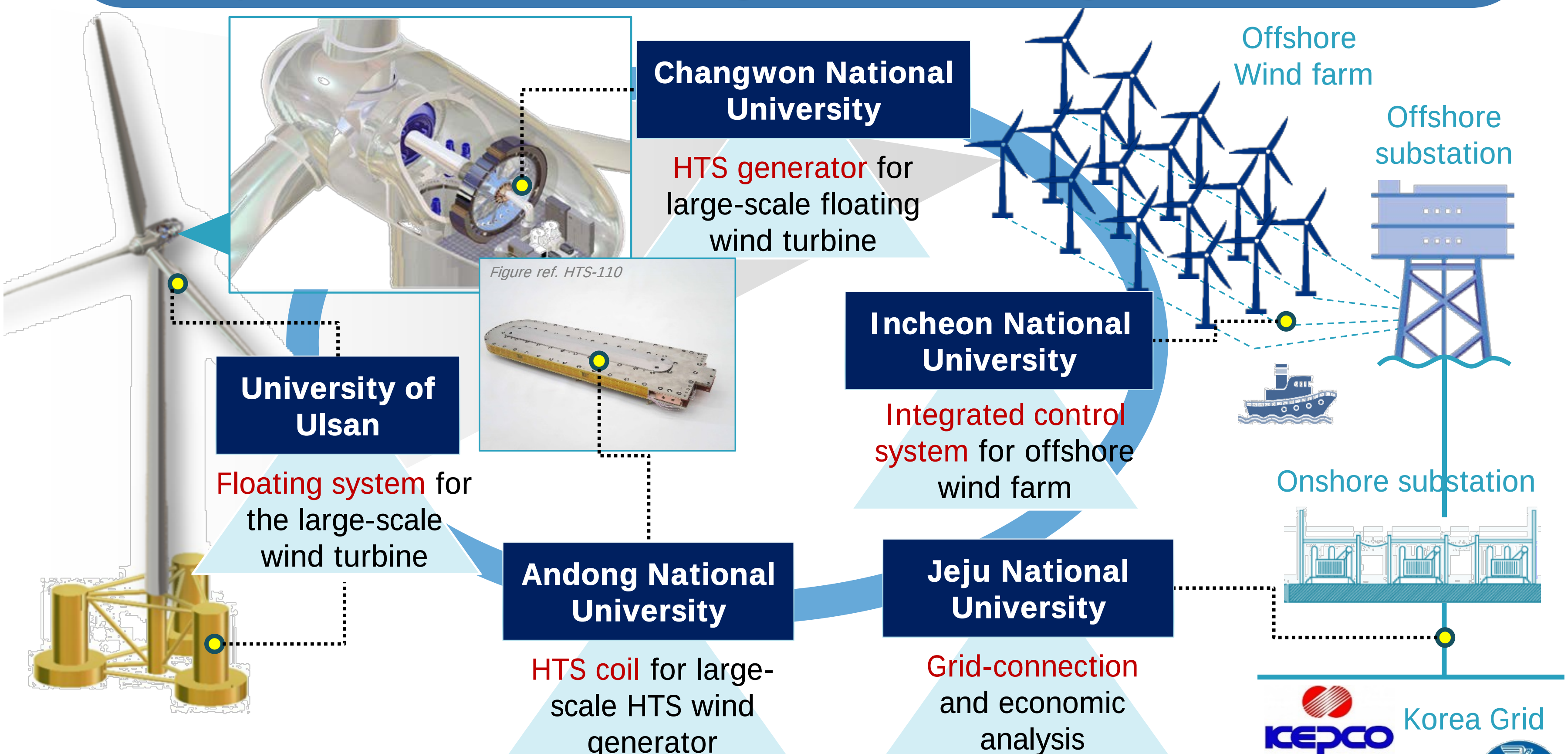
- Include new rotating machines



KEPCO project (From 2018.3 to 2021.2, about 6 M$ for 3 years)

- Project Title: Development of basic technology for floating offshore wind power system platform based on 10MW class superconducting wind power generator

Target: For 3020 new energy roadmap of Korean Government
Development of a 10MW class HTS generator for floating offshore wind turbine



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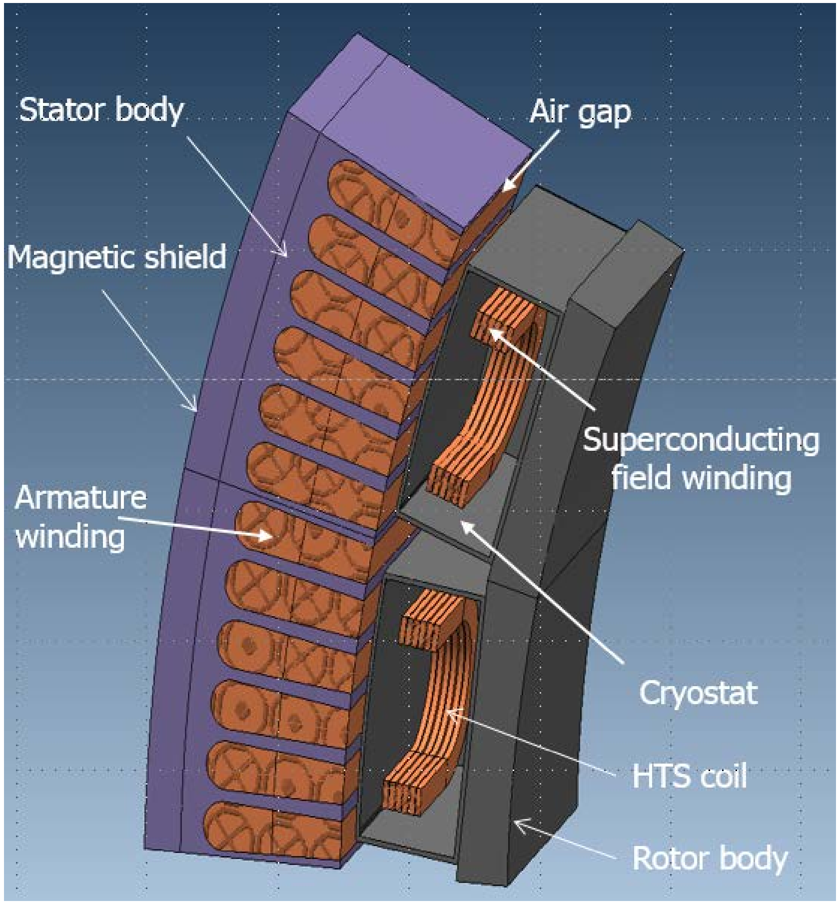
Electromagnetic design of the 10 MW wind generator

➢ Basic specifications & configuration of the superconducting generator

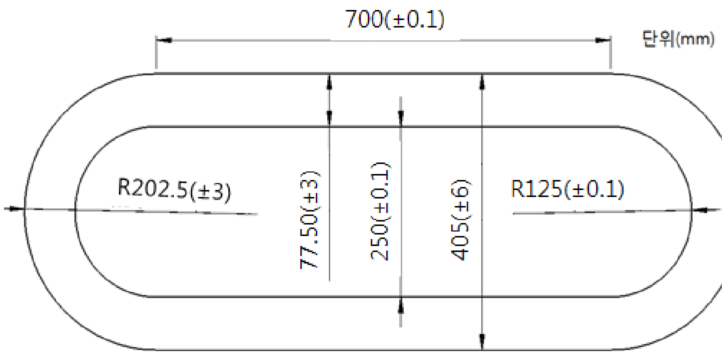
Parameter	Value
Rated power	10.5 MW
Rated L-L voltage	6.6 kV
Rated armature current (rms)	918.5 A
Rated rotating speed	9.69 RPM
Rated torque	10.34 MNm
The num. of rotor poles	40 ea
Effective length	700 mm
The length of air gap	15 mm
Cryostat thickness	20 mm
Air-gap between coil and cryostat	40 mm
Turns of stator coil	7 turn
Current density of copper wire	3 A/mm^2
Safety margin of operating current	40%



Electromagnetic design of the 10 MW wind generator

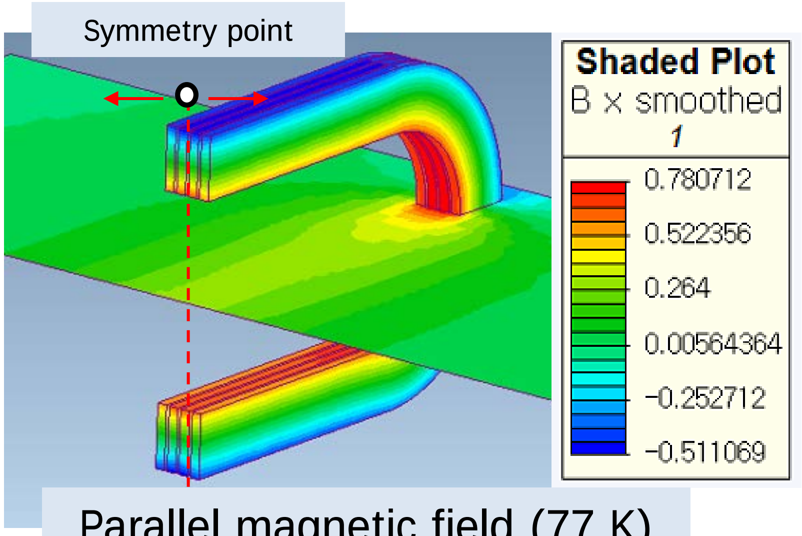
➢ Angular dependency of the HTS field coil for generator

<Dimensions of the HTS coil>

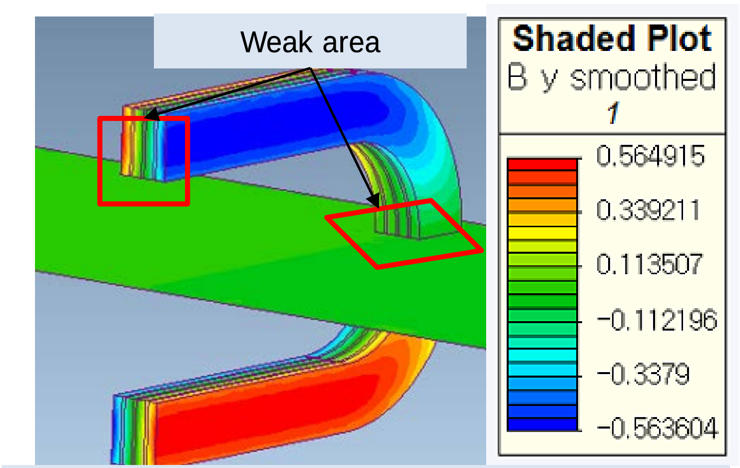


<Designed HTS coil>

Wire width	12.5 mm
Wire thickness	0.25 mm
Number of turn	310 turn
Length of wire (Total)	2.89 km
Critical current (77 K)	93 A
Critical current (35 K)	341 A
Max. perpendicular field (77 K)	0.56 T
Max. parallel field (77 K)	0.78 T
Max. perpendicular field (77 K)	2.07 T
Max. parallel field (77 K)	2.86 T



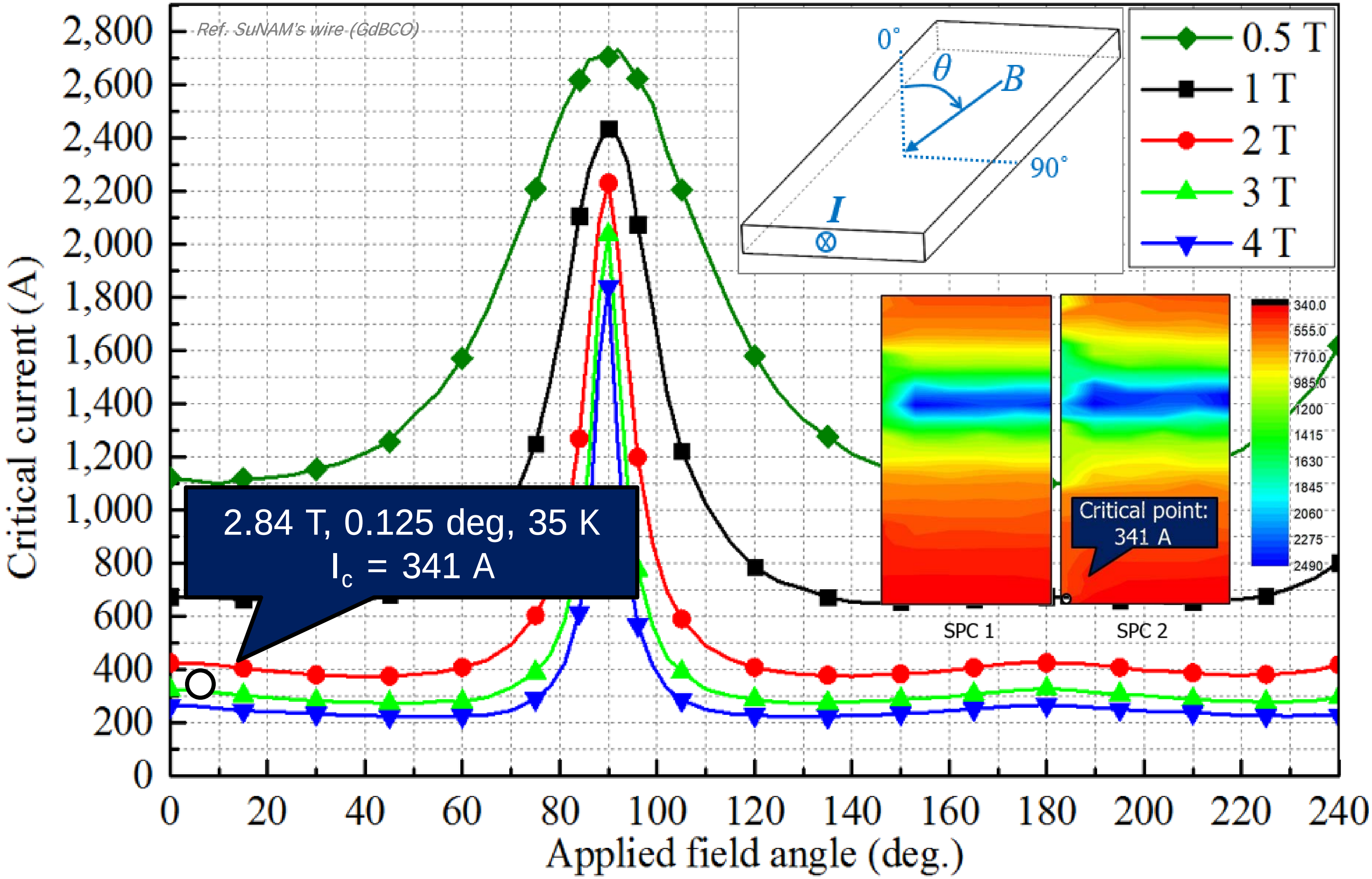
Parallel magnetic field (77 K)



Perpendicular magnetic field (77 K)

Electromagnetic design of the 10 MW wind generator

- Critical current of the HTS generator (@35 K) considering angular dependency



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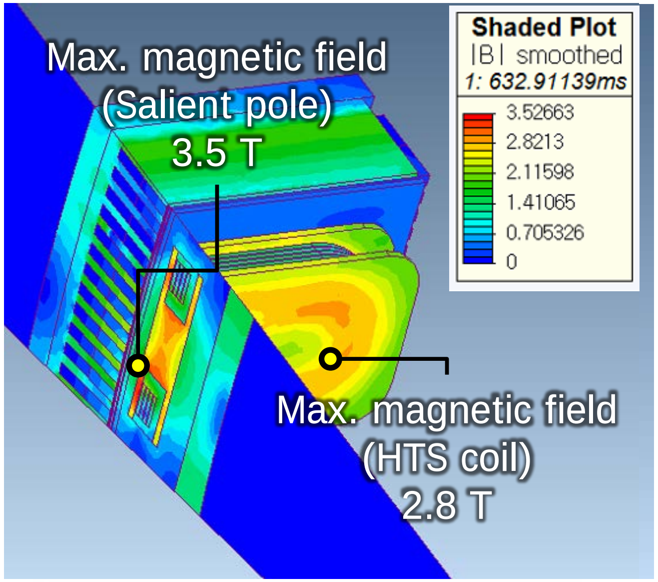
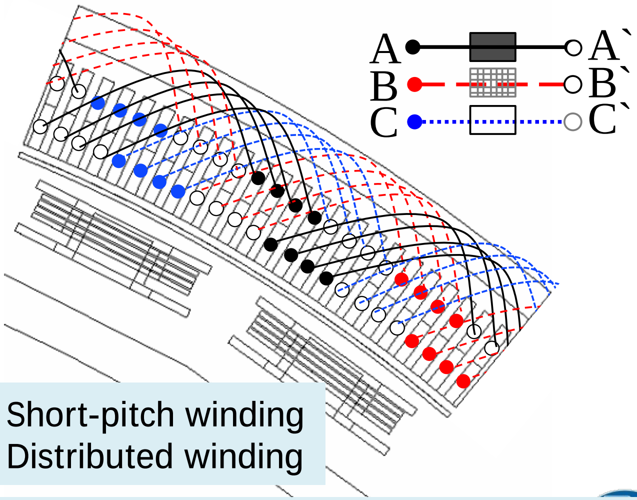
Electromagnetic design of the 10 MW wind generator

➢ Detail specifications and optimal design

Parts		S**'s wire
HTS wire	HTS wire width	12 mm
	HTS wire thick.	0.15 mm
	Ic @77K, S.F.	600 A
HTS coil	Num. of poles	40
	No. of HTS coil layers/pole	4
	Temperature	35 K
	Insulation type	Metal insulation
	Turns of HTS coil/layer/pole	310
	Effective length of HTS coil	700 mm
	Operating current	221 A (@35%margin)
	Total length of HTS wire	115.64 km
Results	Total diameter	8.23 m
	Total weight (incl.	124.8 ton
	Maximum magnetic field	2.8 T
	Perpendicular magnetic field	2 T



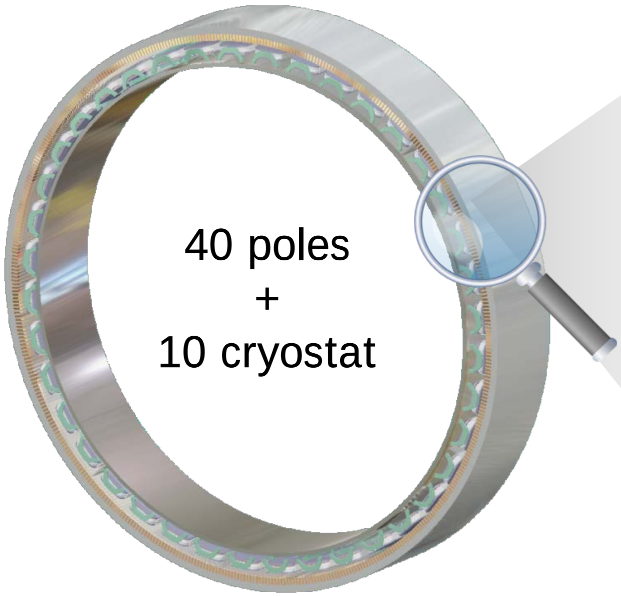


- Short-pitch winding
- Distributed winding

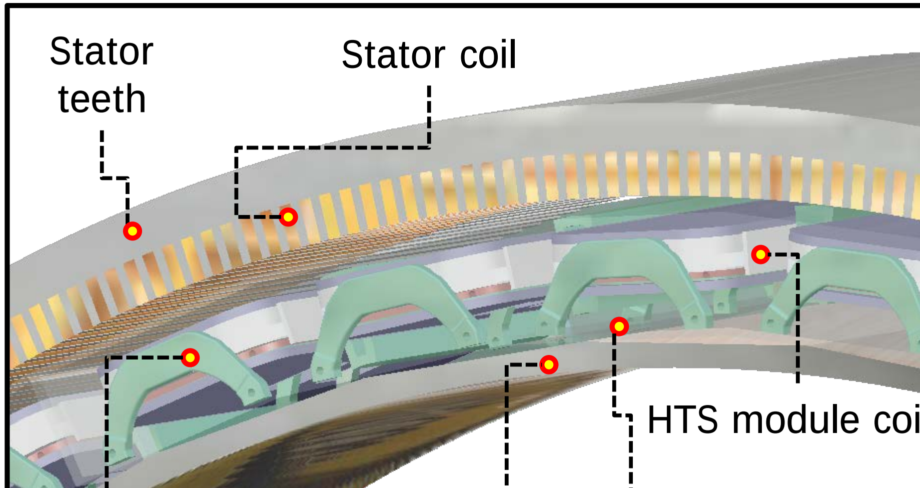
Stator winding of the 10 MW generator

Structure design of the 10 MW wind generator

➢ Detail configuration and materials



<10 MW HTS generator>



<Zoom in view of the 10 MW HTS generator>

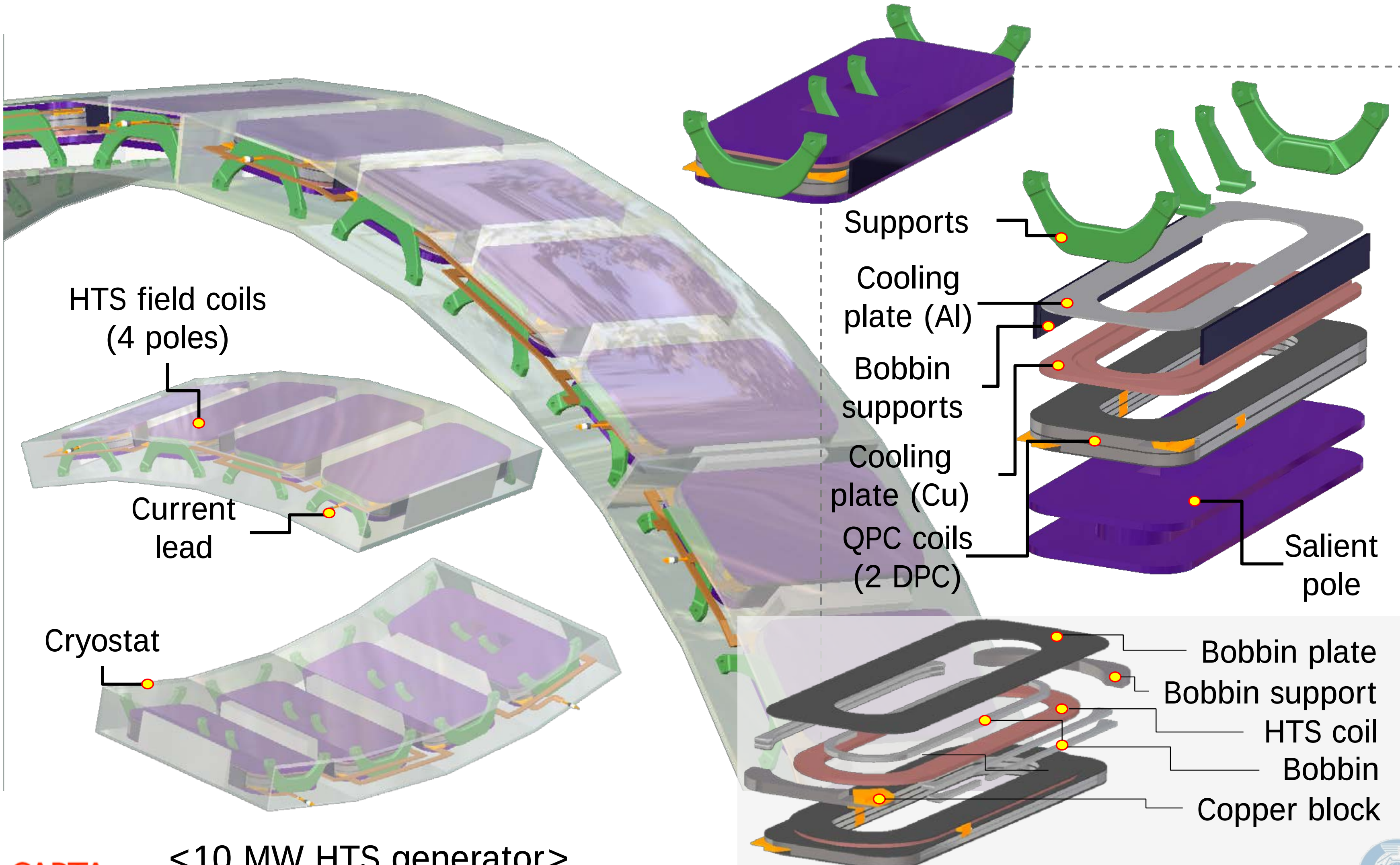
❖ Density of the solid material in HTS generator

	Parts	Materials	Density (kg/m³)
Stator part	Stator wire	Copper	8,940
	Stator teeth	35PN250	7,600
	Magnetic shield	35PN250	7,600

	Parts	Materials	Density (kg/m³)
Rotor part	HTS wire	YBCO	7,877
	Back iron	35PN250	7,600
	Cryostat	SUS 304	8,190
	Supports	FRP	2,400
	Bobbins	Al6061	2,700
	Current leads	Brass	8,550

Structure design of the 10 MW wind generator

- Detail configuration of the superconducting field coil

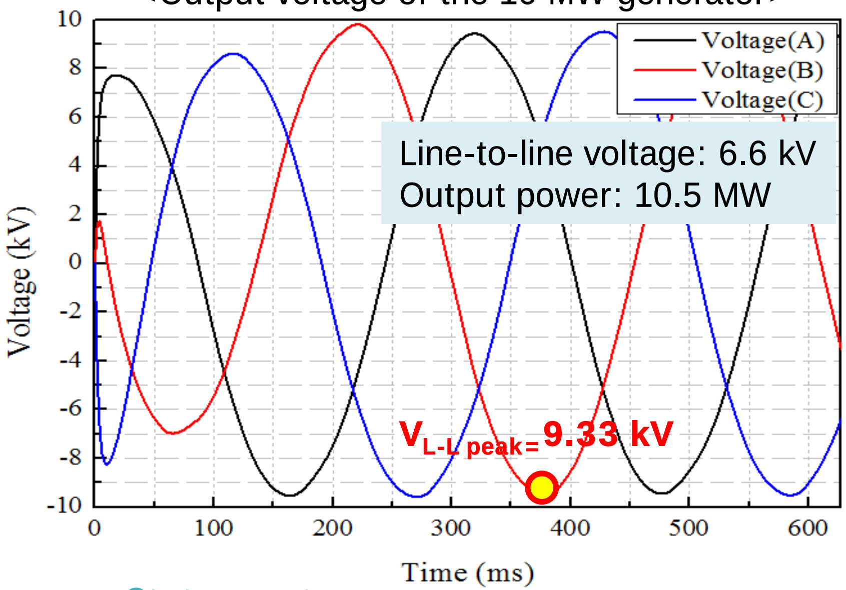


<10 MW HTS generator>

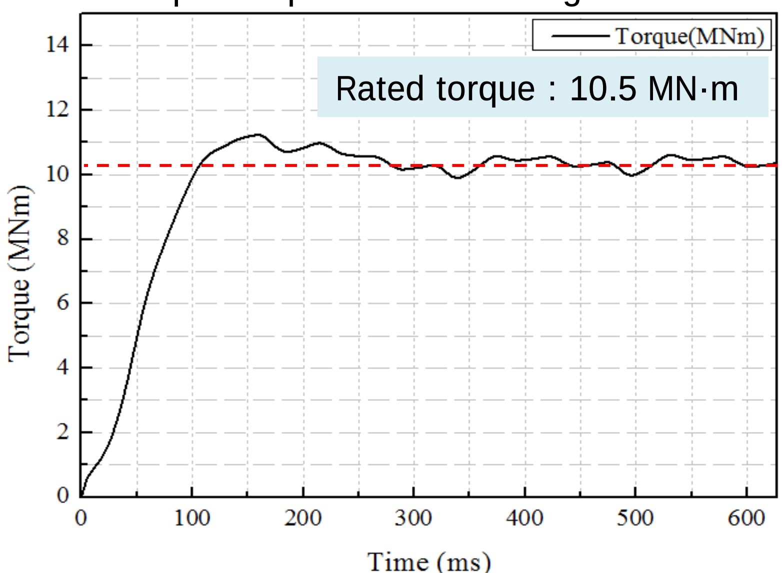
Simulation results of the 10 MW wind generator

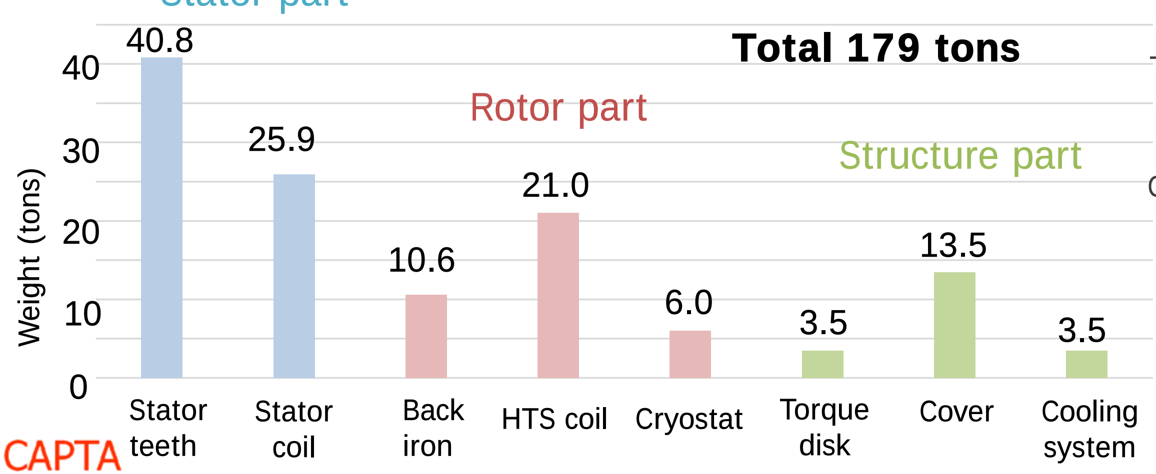
➢ Output power & torque & estimated weight with structures

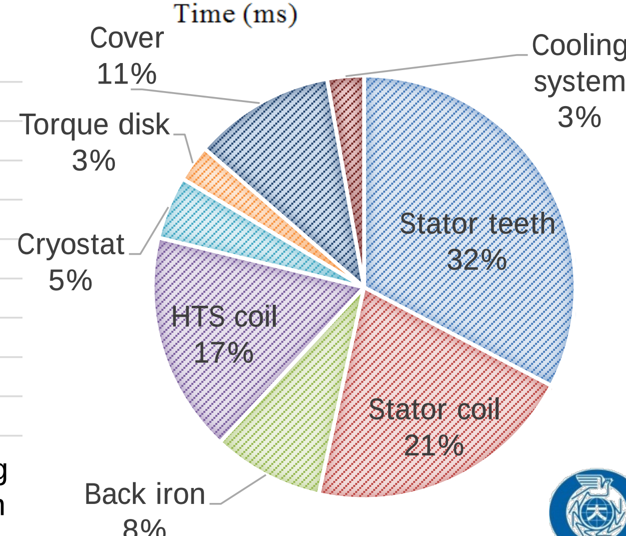
<Output voltage of the 10 MW generator>



<Output torque of the 10 MW generator>







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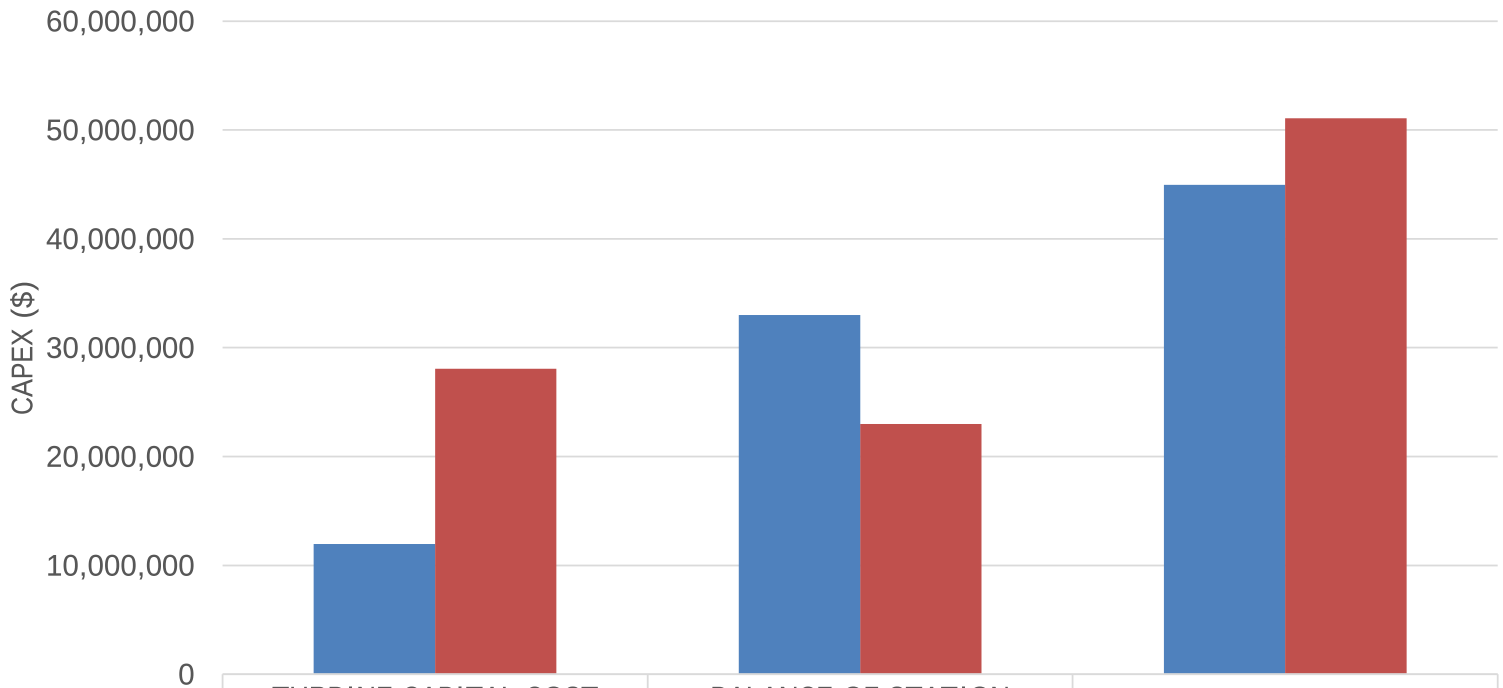
Economic evaluation of the HTS generator

➢ CAPEX(Capital expenditures)

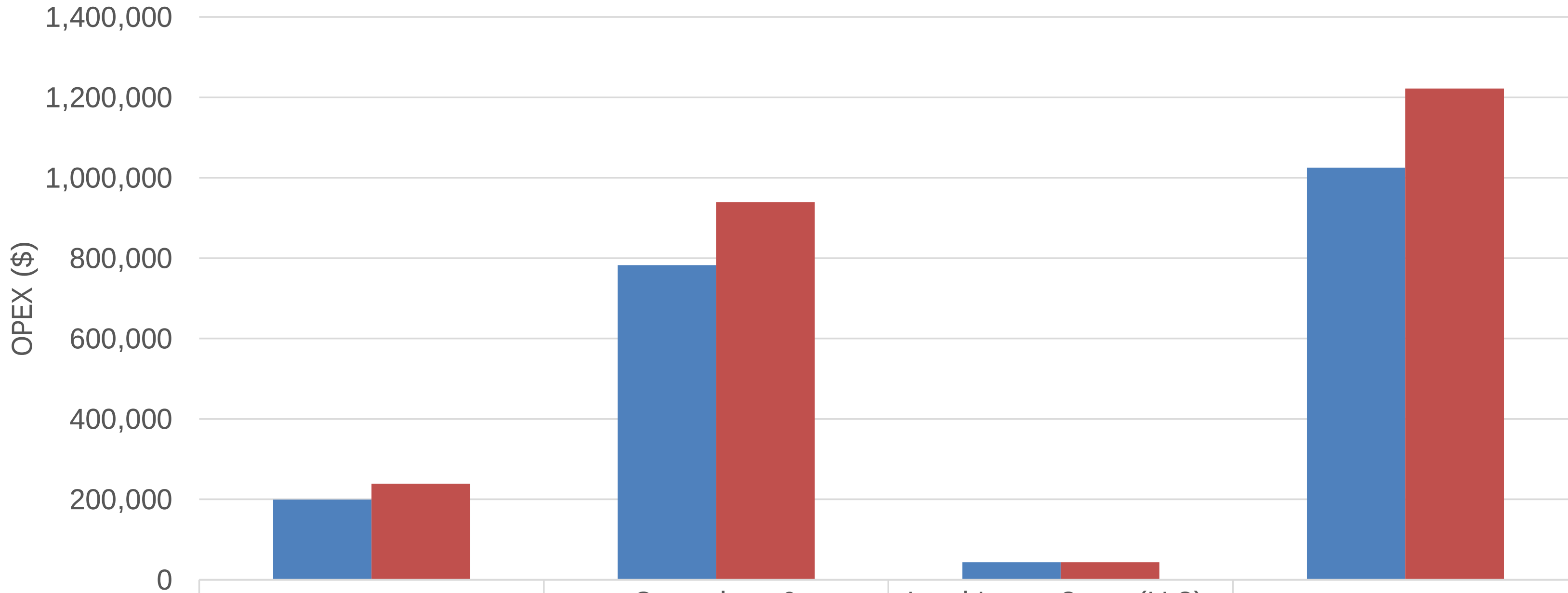


	TURBINE CAPITAL COST (TCC)	BALANCE OF STATION COST (BOS)	CAPEX (sum)
PMSG	11,961,519	32,996,635	44,958,154
SCSG	28,064,675	23,001,180	51,065,854

- ✓ Turbine capital cost: SCSG is $13.4 million higher than PMSG.
- ✓ Balance of station cost: SCSG is a $ 8.4 million savings from the reduction of SCSG's top head weight. (sea transport and construction costs such as crane installation and etc.)
- ✓ However, CAPEX is SCSG by $ 5 million higher than PMSG.

Economic evaluation of the HTS generator

➢ OPEX(Operating Expenditure)



	Levelized Replacement Cost(LRC)	Operations & Maintenance per turbine/year	Land Lease Costs (LLC); offshore bottom lease cost	OPEX (sum)
PMSG	199,219	782,857	43,289	1,025,364
SCSG	239,063	939,428	43,289	1,221,779

- ✓ Levelized Replacement Cost and O&M Cost: In the case of the SCSG, maintenance costs for cryogenic system are added. *(+20%)*
- ✓ Land Lease Cost: SCSG and PMSG are same.
- ✓ Therefore, OPEX has a SCSG of $ 170,000 higher than PMSG.

Economic evaluation of the HTS generator

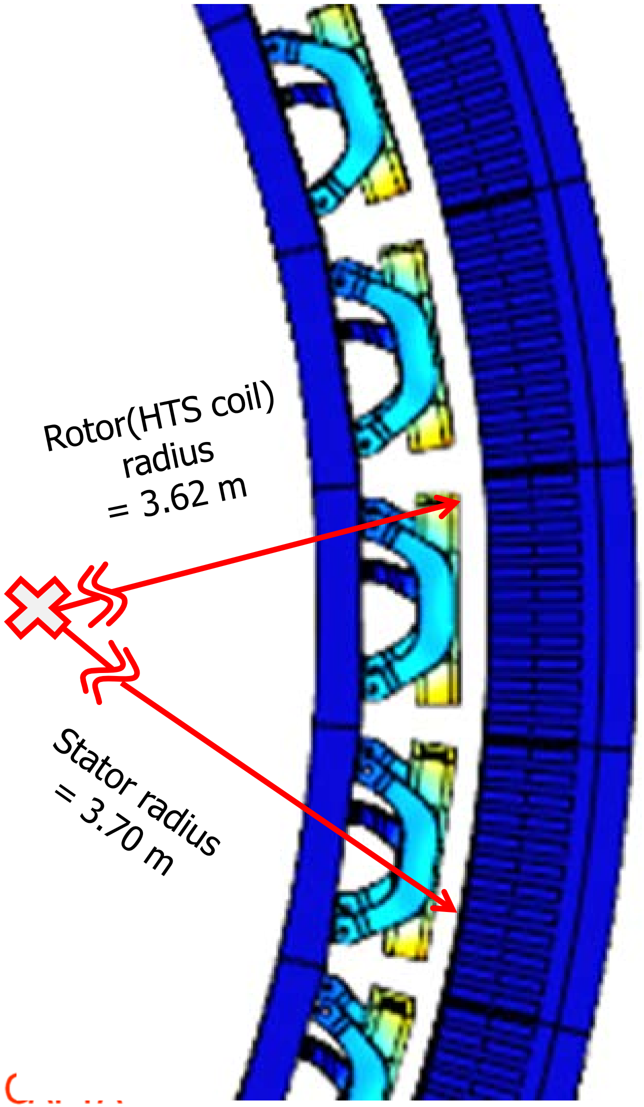
- LCOE(Levelized Cost of Energy)

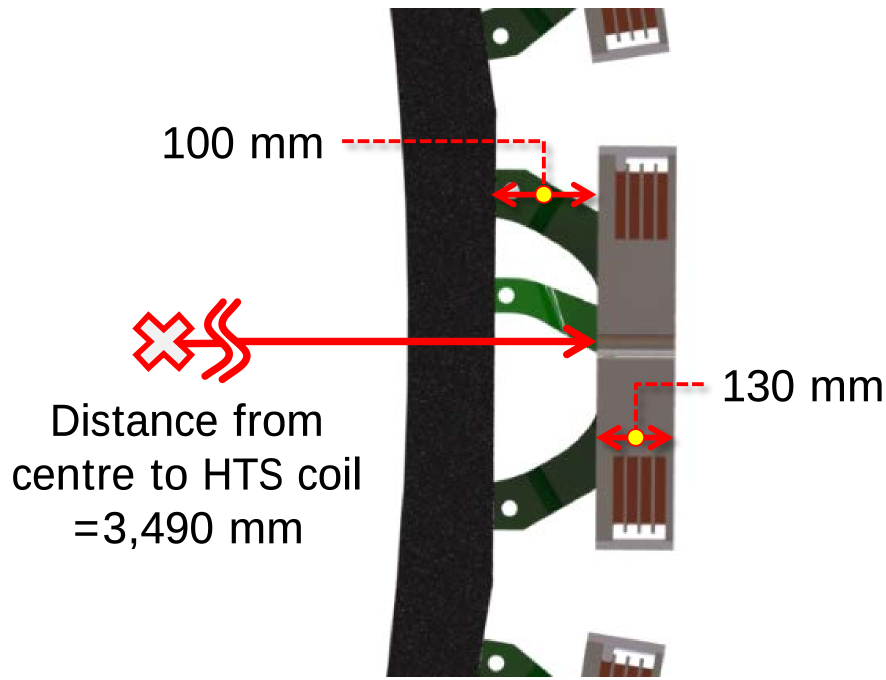
(HTS wire = 0.2$/A·m→0.05$/A·m)

Estimation	PMSG ($)	SCSG ($)	
		Current	Future
BALANCE OF STATION COST (BOS)	32,996,634.54	23,001,179.88	22,805,818.01
TURBINE CAPITAL COST (TCC)	11,961,519.29	28,064,674.56	21,552,612.06
INITIAL CAPITAL COST	**46,538,971.36**	**54,774,842.27**	**47,206,792.90**
Installed Cost per kW	3,878.25	4,564.57	3,933.90
Turbine capital per kW sans BOS & Warranty	996.79	2,338.72	1,796.05
Levelized Replacement Cost(LRC)	199,218.75	239,062.50	239,062.50
Operations & Maintenance per turbine/year	782,856.56	939,427.88	939,427.88
Land Lease Costs (LLC); offshore bottom lease cost	43,288.84	43,288.84	43,288.84
CAPACITY FACTOR	0.38	0.38	0.38
AEP (kwh)	**40,082,256**	**40,082,256**	**40,082,256.00**
AOE ($/kWh)	**0.0256**	**0.0305**	**0.0305**
FIXED CHARGE RATE (FCR)	5,389,212.88	6,342,926.74	5,466,546.62
LCOE ($/kWh)	**0.160**	**0.189** →	**0.167**

Lorentz force of the 10 MW wind generator

➢ Estimated force of the superconducting field coil

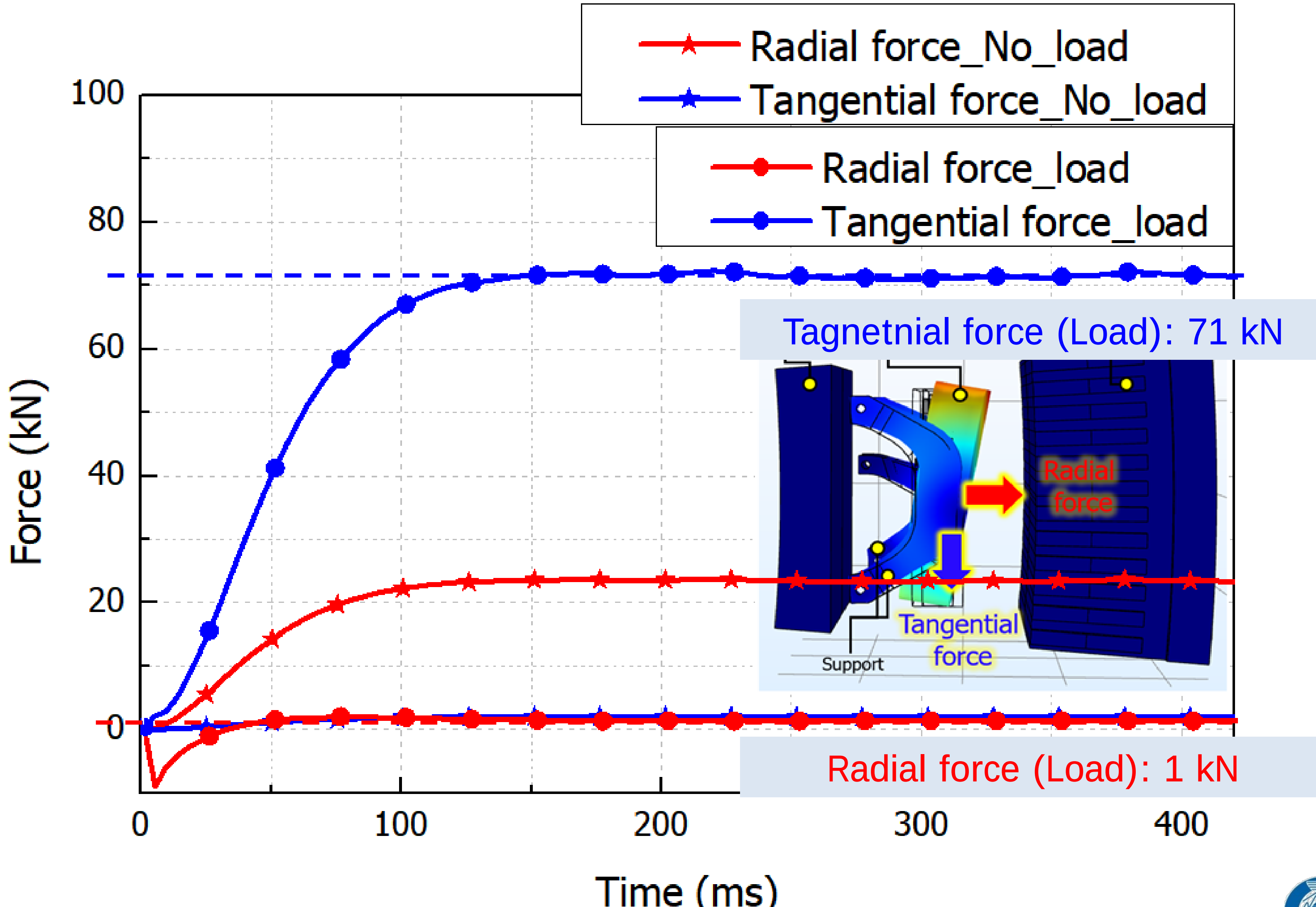




- $Distance\ of\ the\ 0\ to\ center\ of\ the\ HTS\ coil : 3{,}560\ mm$
- $Torque: 10.5\ MW / angularvelocity = 10.34\ MNm$
- $Torque\ per\ coil: 10.57\ MNm\ /\ poles\ (40) = 258\ kNm$
- $Tangential\ force = torque / Distance = 71.4\ kN$

Lorentz force of the 10 MW wind generator

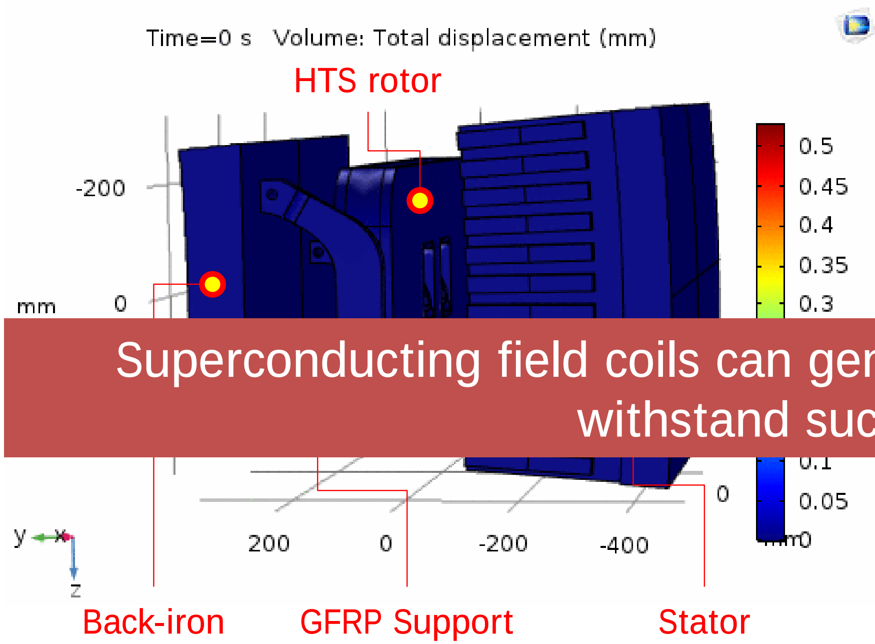
- Simulation results (Multiphysics; electromagnetic & mechanical)



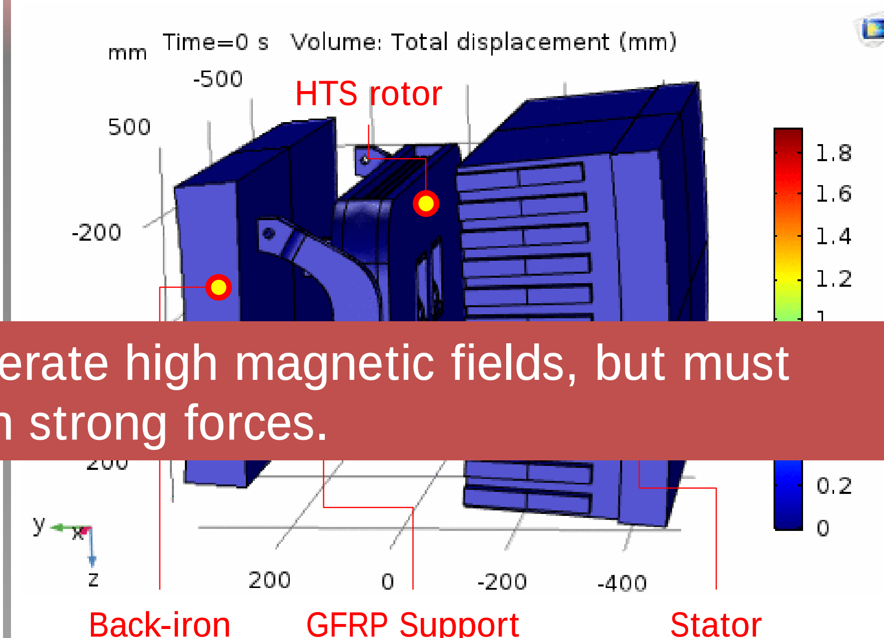
Lorentz force of the 10 MW wind generator

➢ Simulation results (Multiphysics; electromagnetic & mechanical)

<No-load condition>



<Load condition>



Superconducting field coils can generate high magnetic fields, but must withstand such strong forces.

No-load condition:

	Back-iron	Rotor	Stator
Radial	111 kN →	22 kN →	← 134 kN
Tangential	0 kN	2 kN ↑	2 kN ↓

Load condition:

	Back-iron	Rotor	Stator
Radial	105 kN →	1 kN →	← 106 kN
Tangential	0 kN	71 kN ↓	71 kN ↑

❖ 30 times displacement

→ Radial direction
→ Tangential direction

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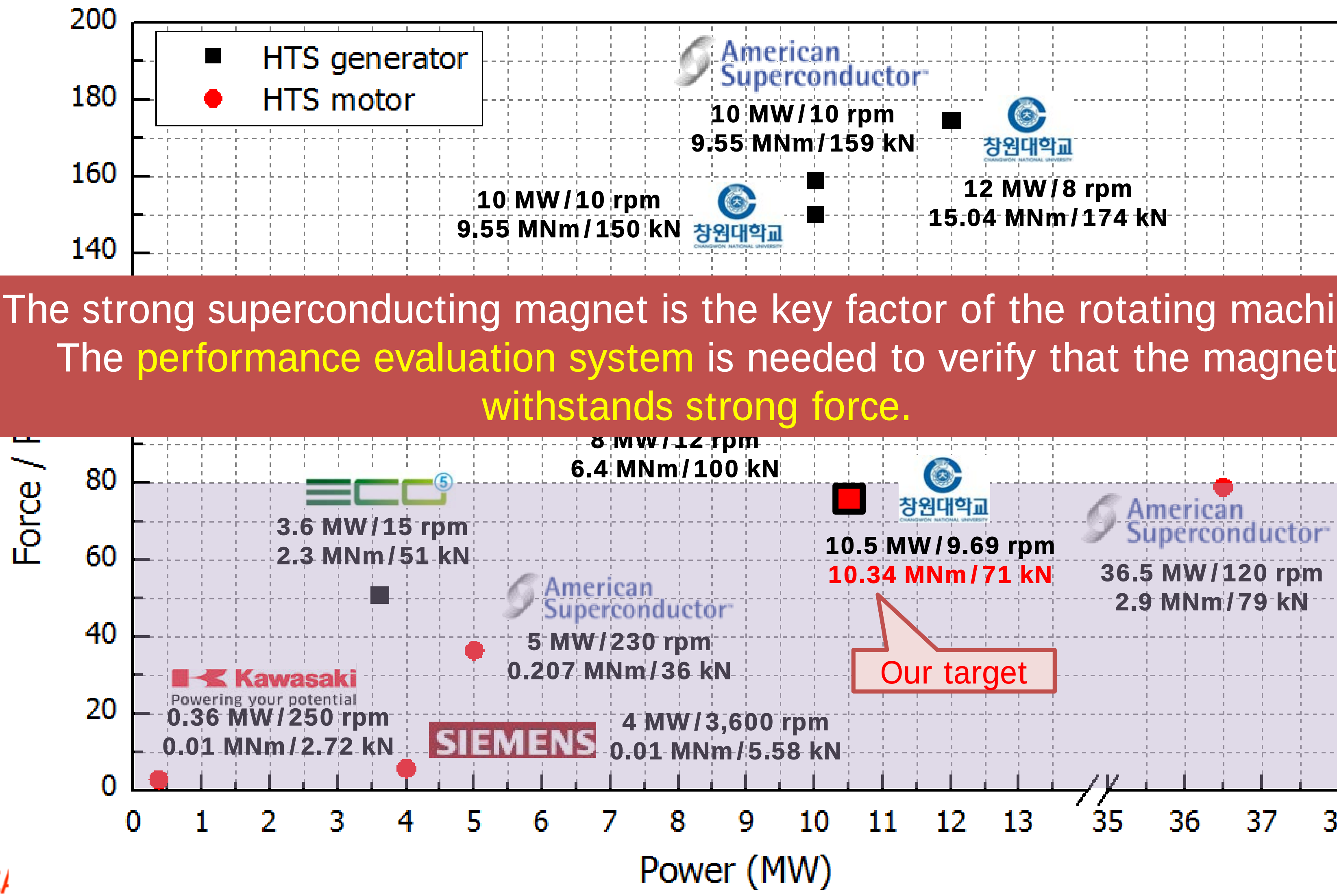
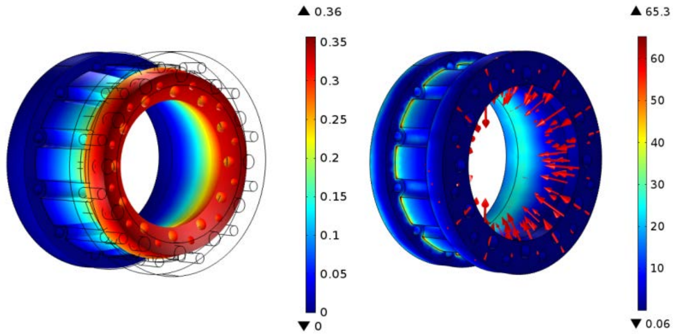
Lorentz force of the 10 MW wind generator

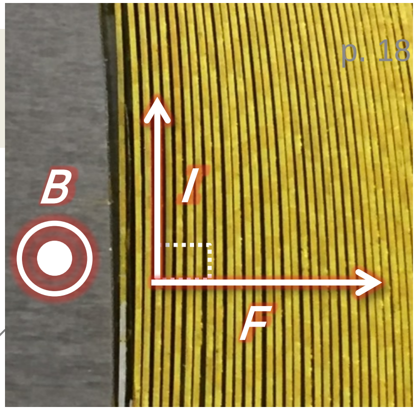
- Technical limitation due to high torque



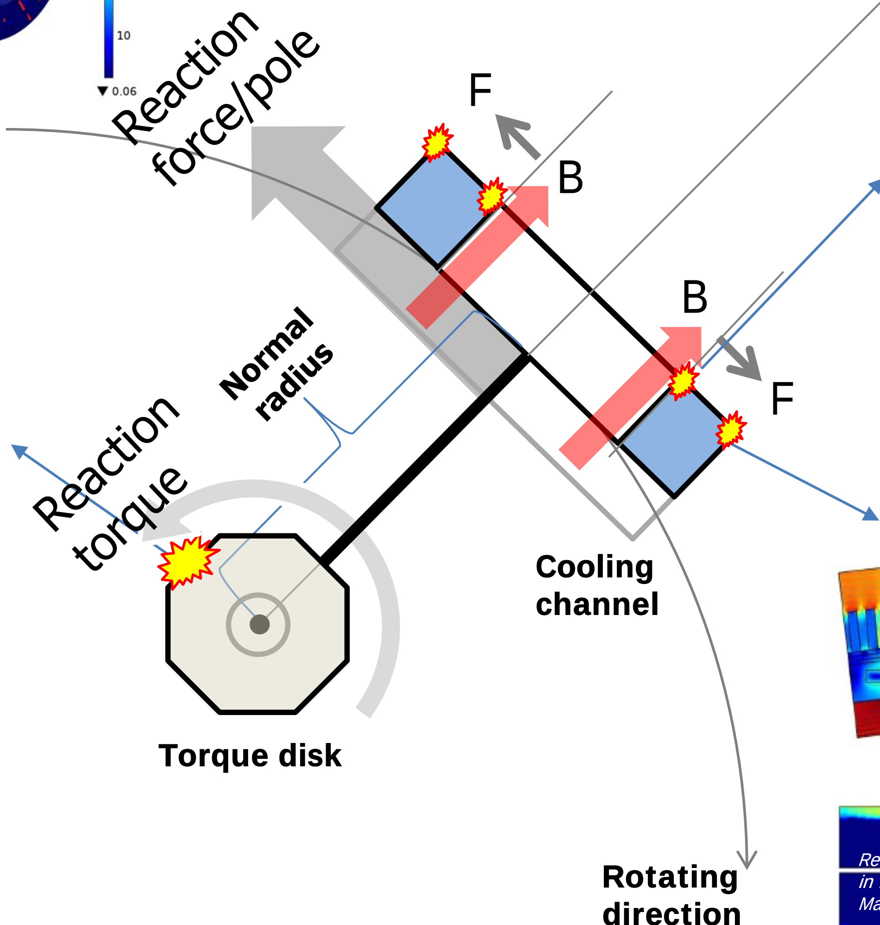
The strong superconducting magnet is the key factor of the rotating machine. The performance evaluation system is needed to verify that the magnet withstands strong force.

Short diameter machine



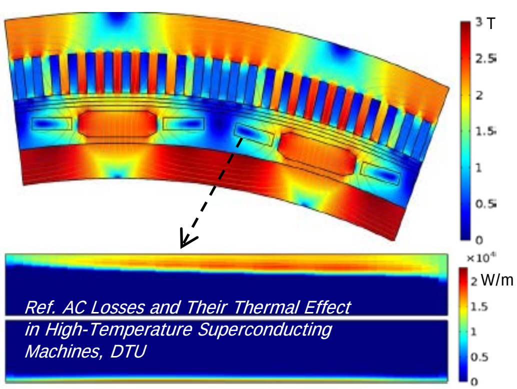


- Force/pole
- Strong structure, but paradox
- Torque disk all



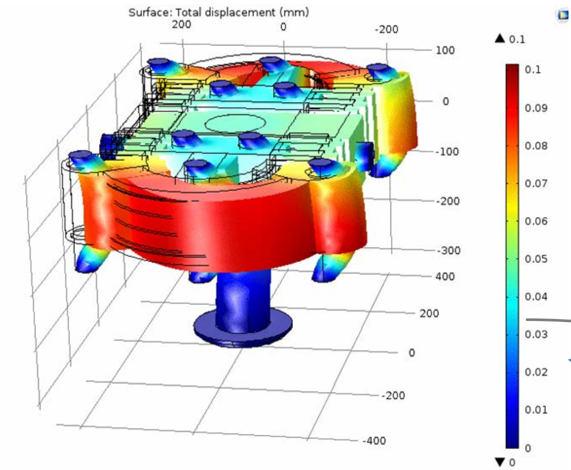
- In field property high Jc
- Strong winding
- Good cooling path

- AC loss
- Partial heat loss
- Eddy loss(structure)

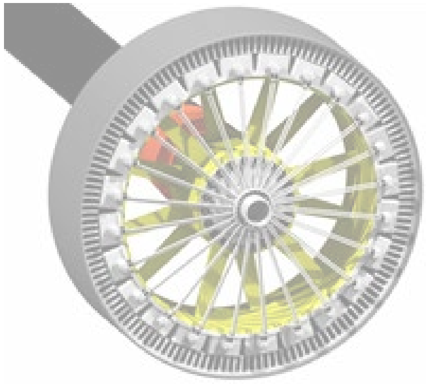


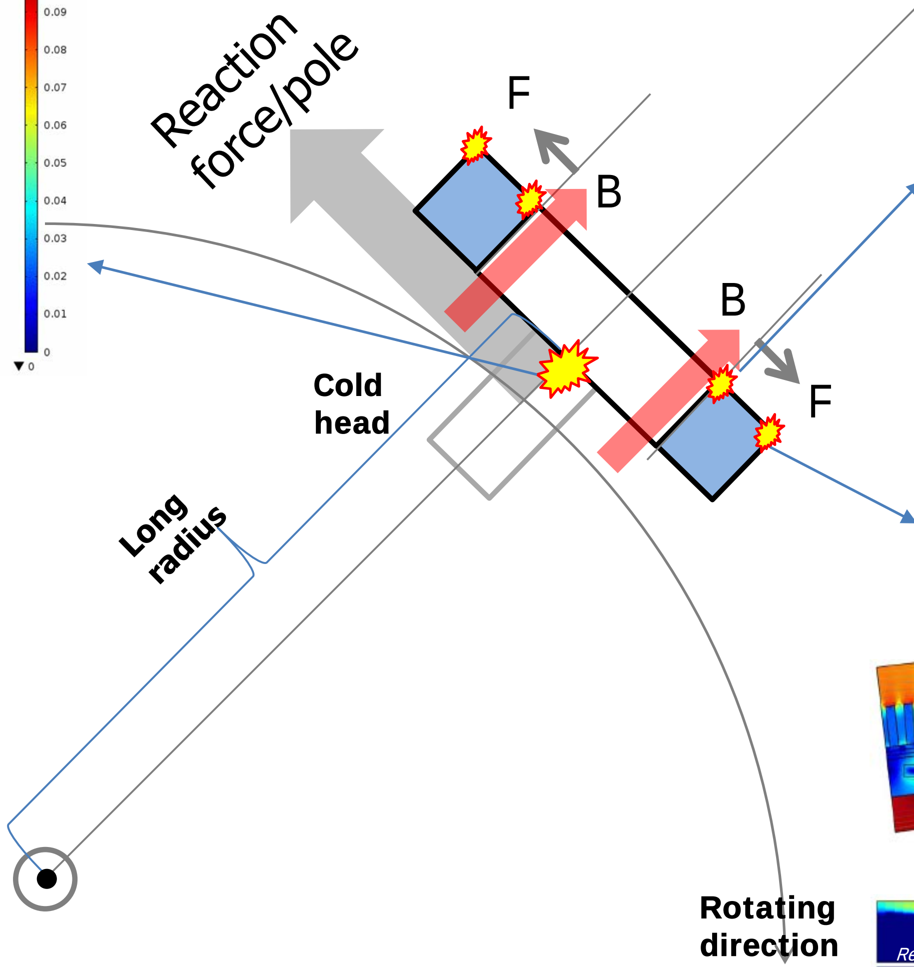
Example	force/pole
AMSC	79kN
5M motor	60kN
10M wind	100kN
15M wind	200kN

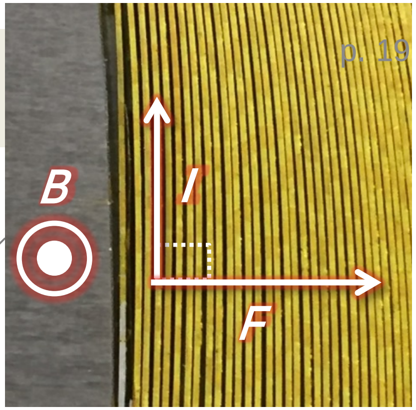
Long diameter machine



- Force/pole
- Strong structure, but paradox
- Torque disk all

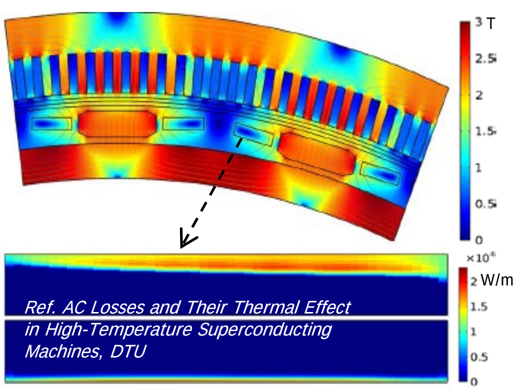






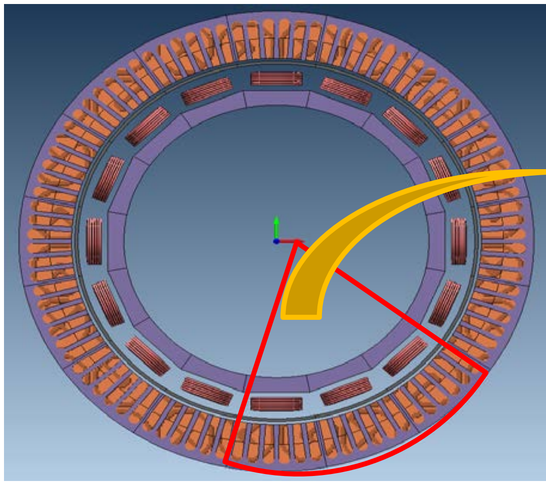
- In field property high Jc
- Strong winding
- Good cooling path

- AC loss
- Partial heat loss
- Eddy loss(structure)

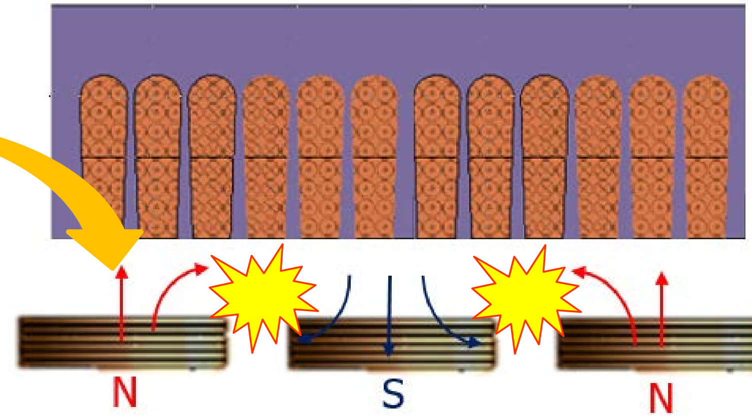


Performance Evaluation System (PES)

- Modeling of the PES based on the 10 MW wind generator



< Design of the superconducting generator >



< Design of the performance evaluation system>

Parameter	Value
Rated power	10.5 MW
Rated L-L voltage	6.6 kV
Rated rotating speed	10 RPM
The num. of rotor poles	40 ea

Parameter	Value
Rated power(apply 2 poles)	525 kW
Rated voltage(rms)	190.5 V
Rated velocity	3.91 m/s
The num. of rotor poles	3 ea

✓ Three HTS poles are required to make a pole pair (two poles).

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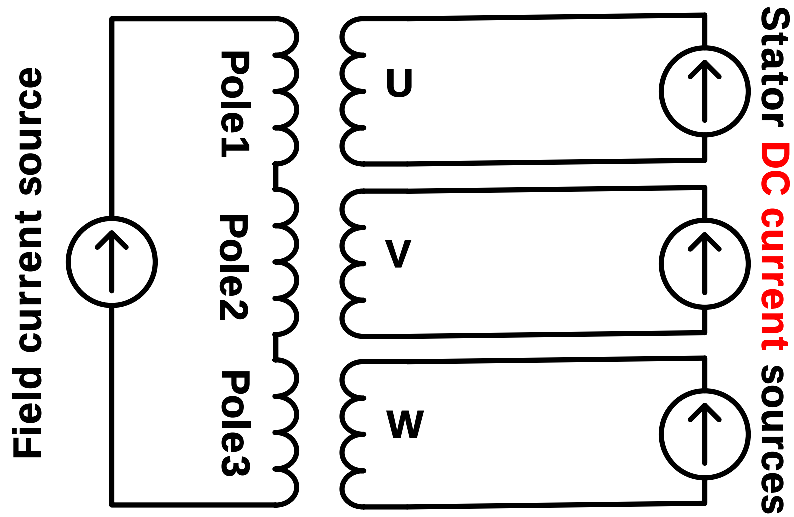
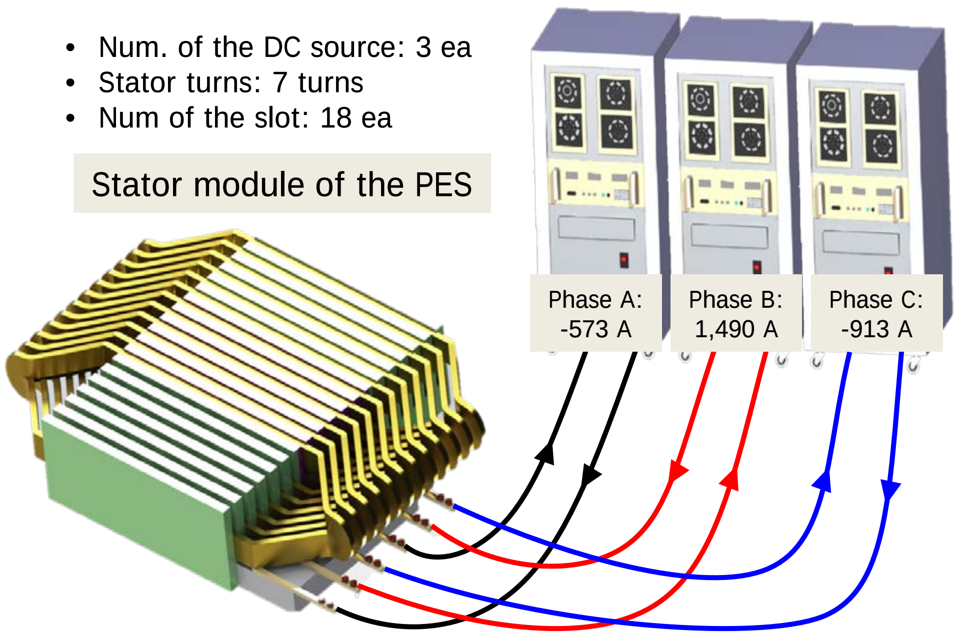
Performance Evaluation System (PES)

➢ Modeling of the PES based on the 10 MW wind generator



<PES Circuit diagram>

- Num. of the DC source: 3 ea
- Stator turns: 7 turns
- Num of the slot: 18 ea

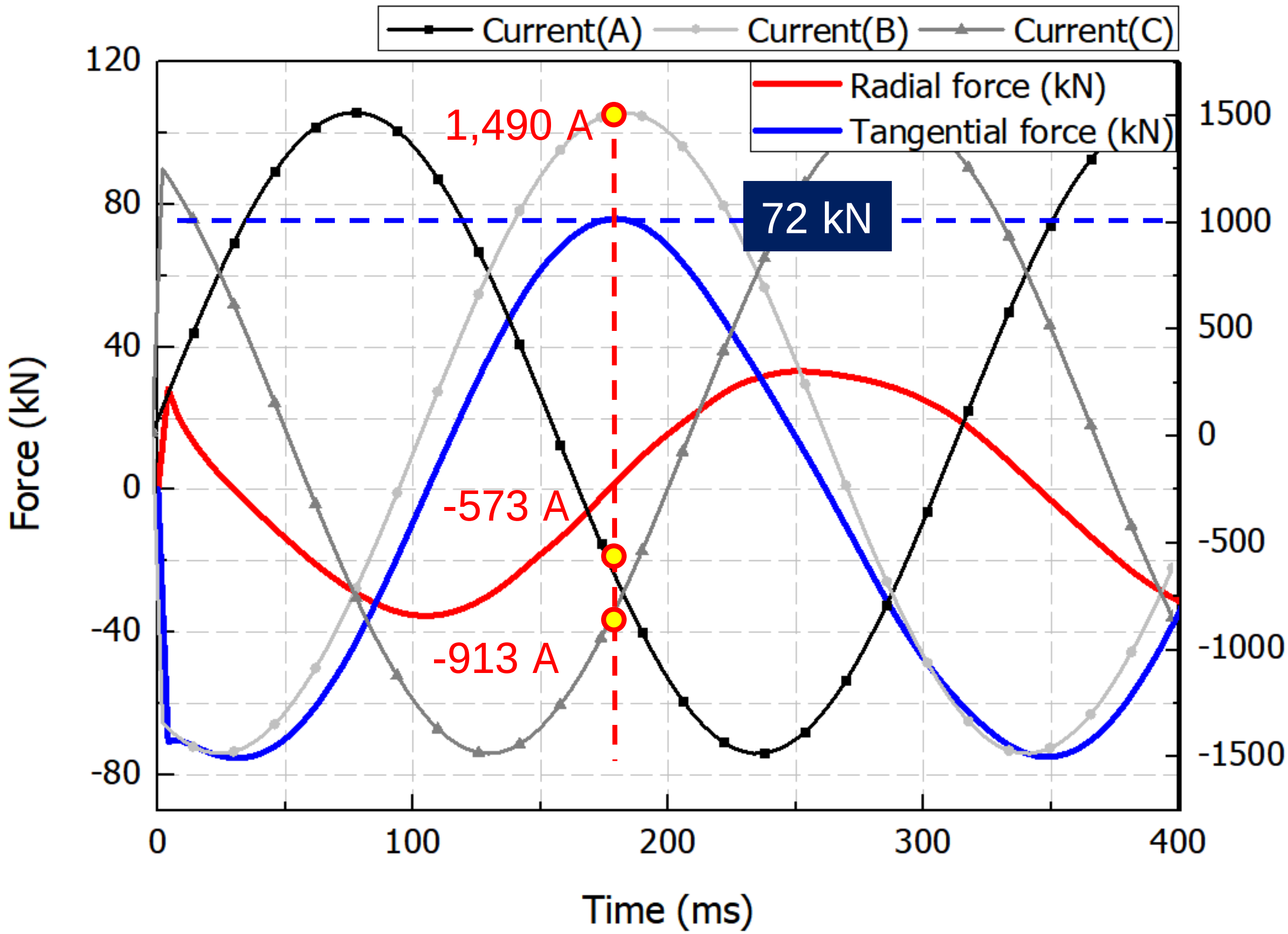


- Comparison of the force values between the generator and PES

Part	Generator	PES	Error
Tangential force of the Stator	71.5 kN	**72.2 kN**	0.98%
Total output power (×pole number)	10.5 MW	**10.6 MW**	0.98%

Performance Evaluation System (PES)

➢ Modeling of the PES based on the 10 MW wind generator



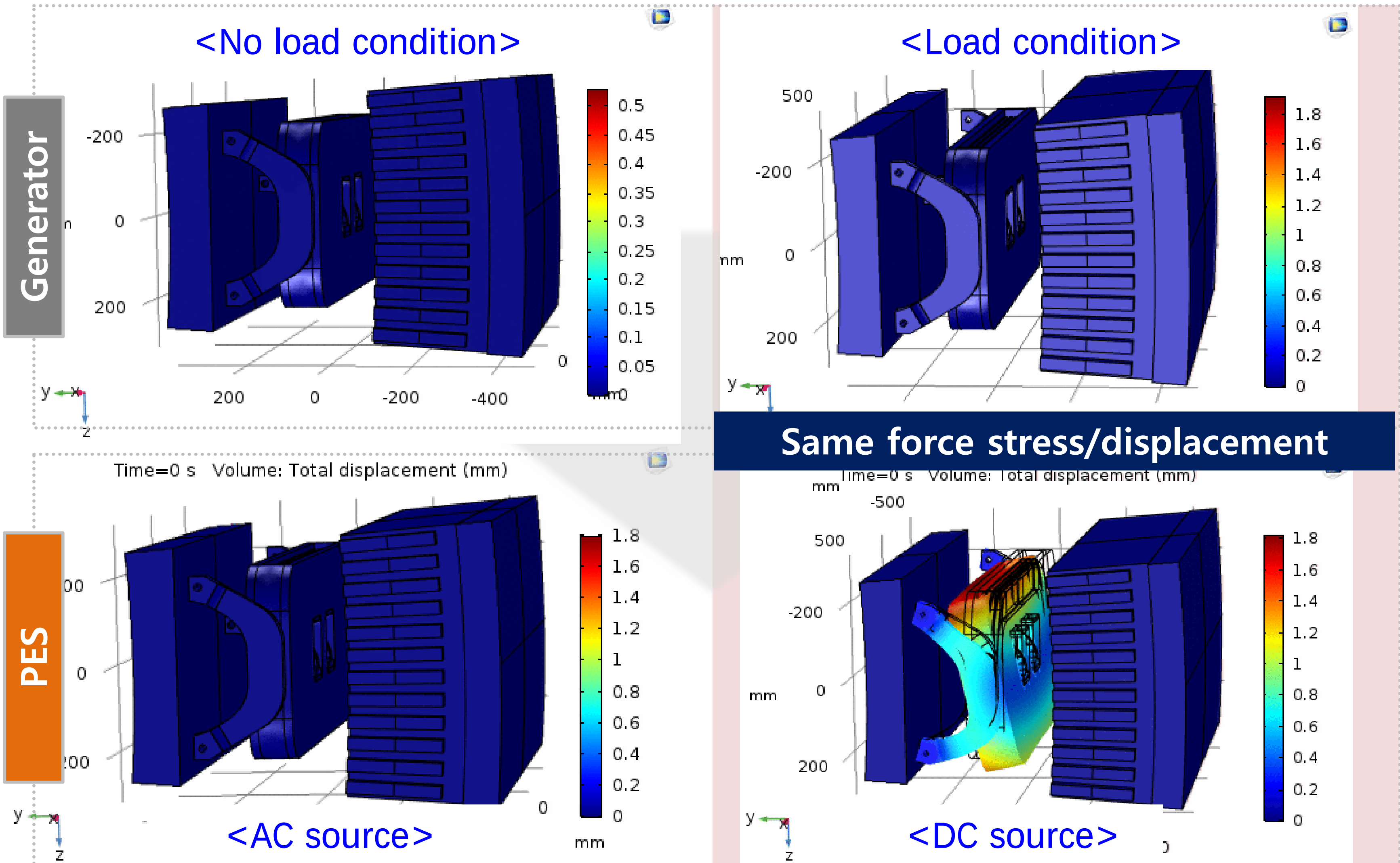
1. HTS generator
T_Force : 72 kN

2. PES (AC)
T_Force : 72 kN
R_Force : 1 kN

3. Input DC
Phase A: -573 A
Phase B: 1,490 A
Phase C: -913 A

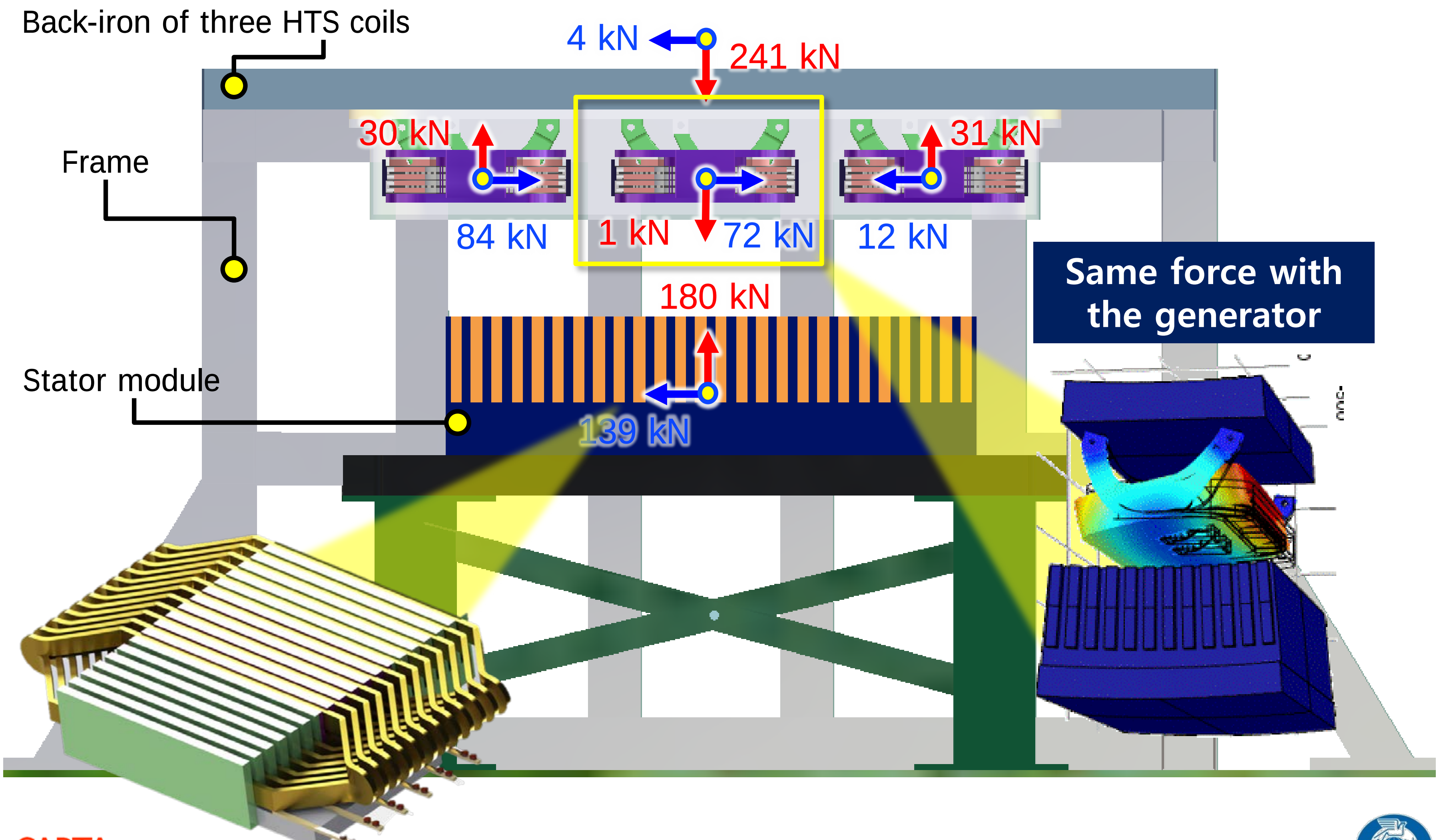
Performance Evaluation System (PES)

- Modeling of the PES based on the 10 MW wind generator
  - 30 times displacement



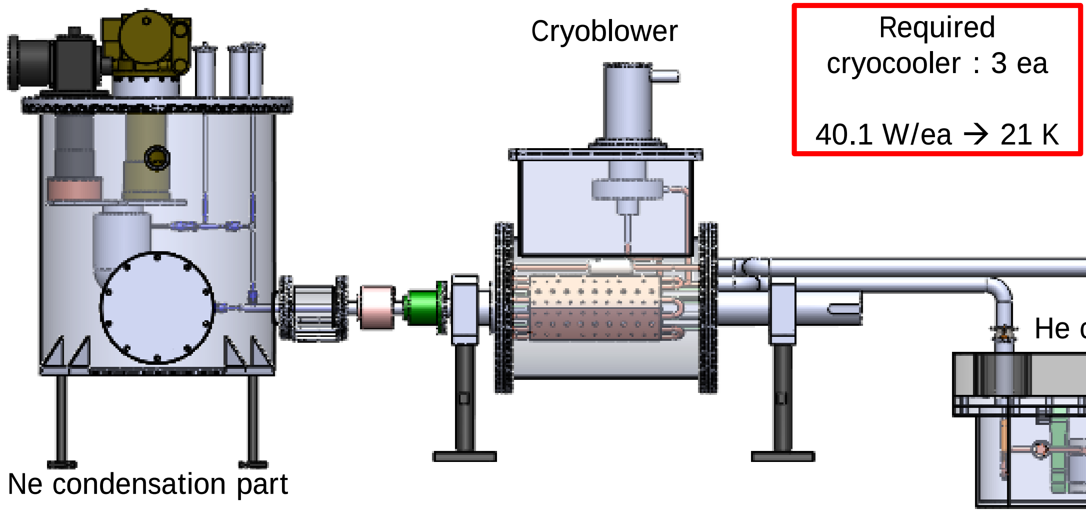
Performance Evaluation System (PES)

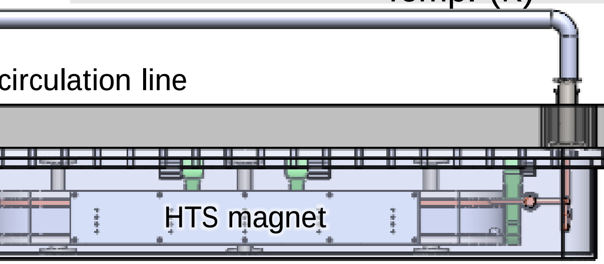
➢ Simulation results of the PES



Cooling system of the PES

- Cooling system with HTS modules

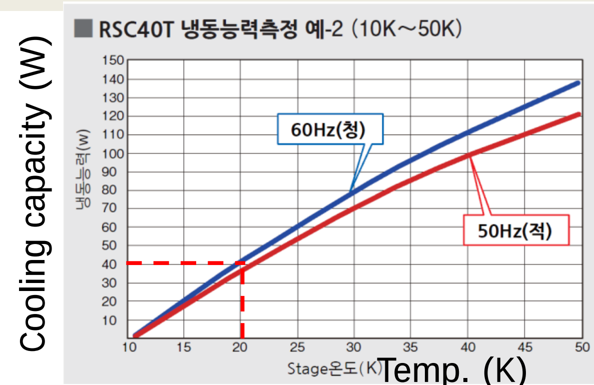




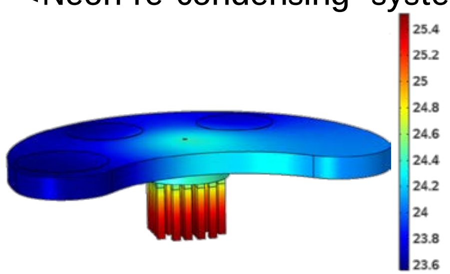
Required cryocooler : 3 ea

40.1 W/ea → 21 K

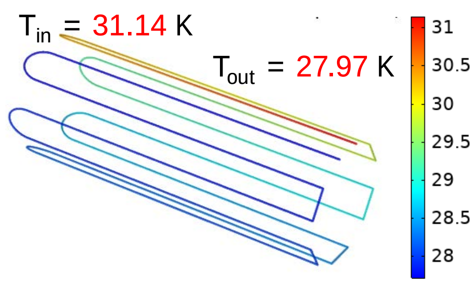
ULVAC RSC40T



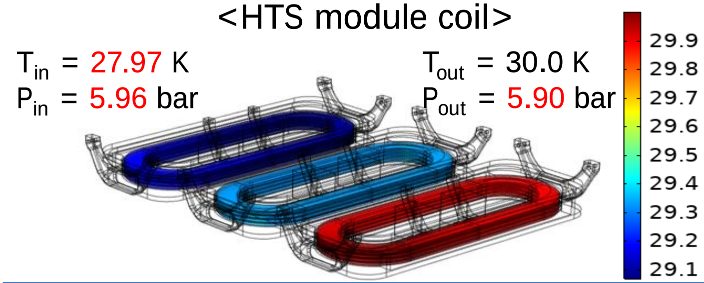
<Neon re-condensing system>



<Neon-Helium exchanger>



<HTS module coil>



24 K Operation	
ΔT	1.9 K
Heat exchanger T_{max}	25.5 K
Cryocooler capacity	164 W

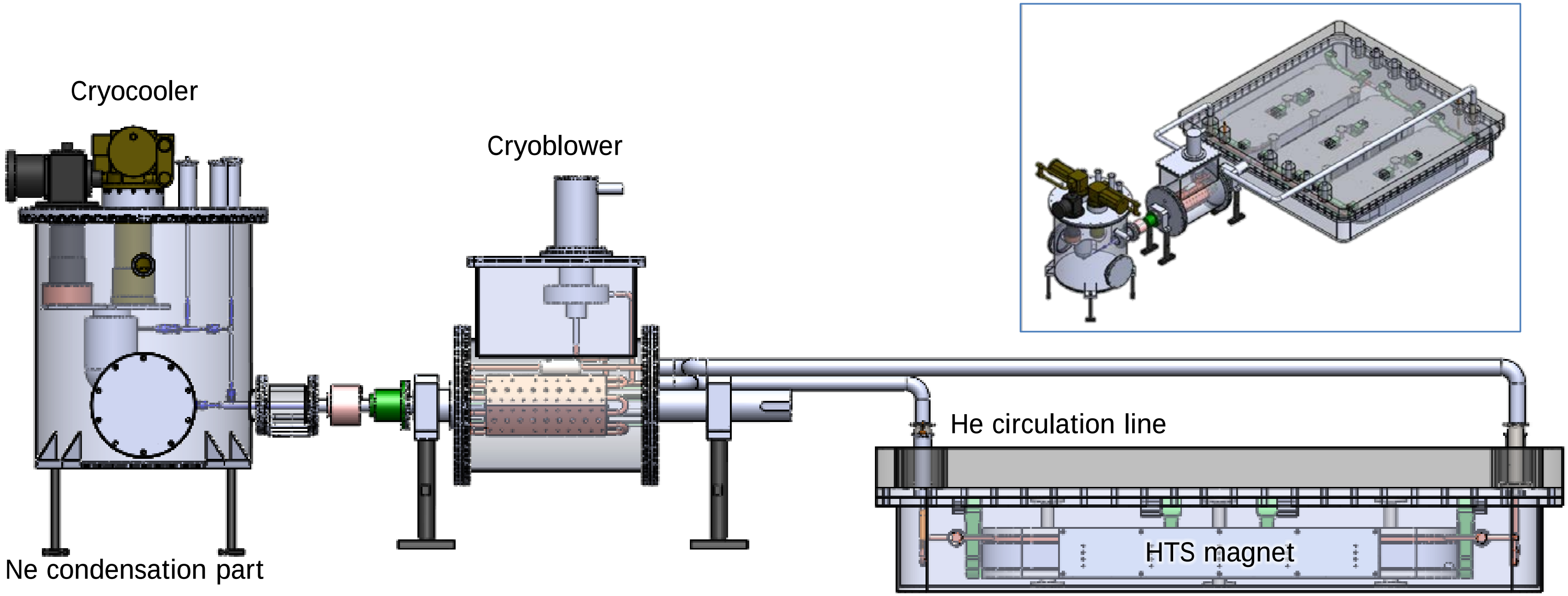
Parameters	Values
Pressure [bar]	6
Mass flow [g/s]	7.8
Velocity in tube [m/s]	9.29

Helium Parameters	Values
Heat load [W]	65 (+ 30%)
Mass flow [g/s]	7.8
Heat exchange length [m]	7
Pressure drop [kPa]	0.4

Cooling system of the PES

- Cooling system with HTS modules

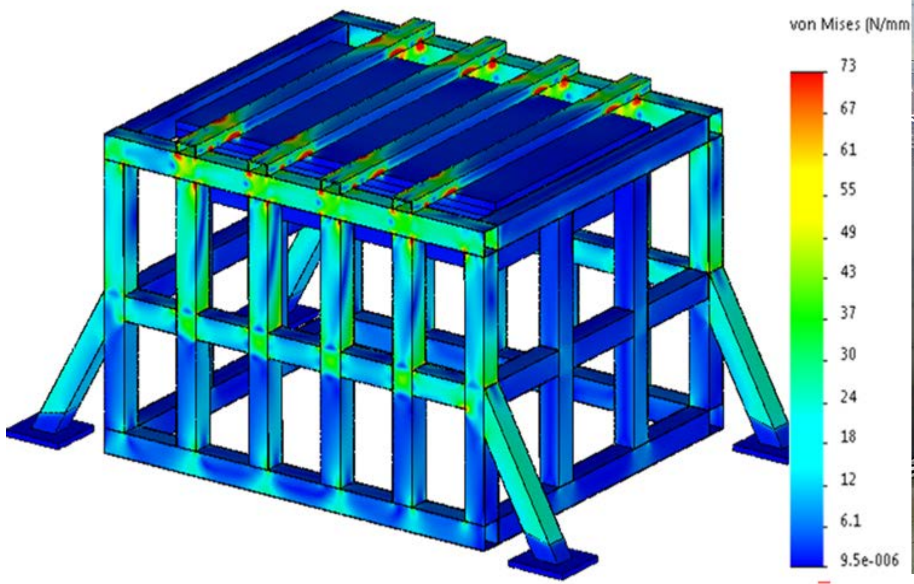
Part	Heat loss [W]	Operating Temperature [K]	Weight [kg]
Ne reconducting system	2.95	25 - 27	135.9
Ne-He heat exchanger	32.16	27 - 31	167.9
HTS module coil (with current lead)	85.35	28 - 30	2,465.8
Sum	120.46	-	2,769.6



<Neon re-condensing system> <Neon-Helium exchanger> <HTS module coil>

Frame structure of the PES

➢ Mechanical stress of the SUS frame



Maximum Stress: 73 Mpa
Maximum displacement: 1.63 mm

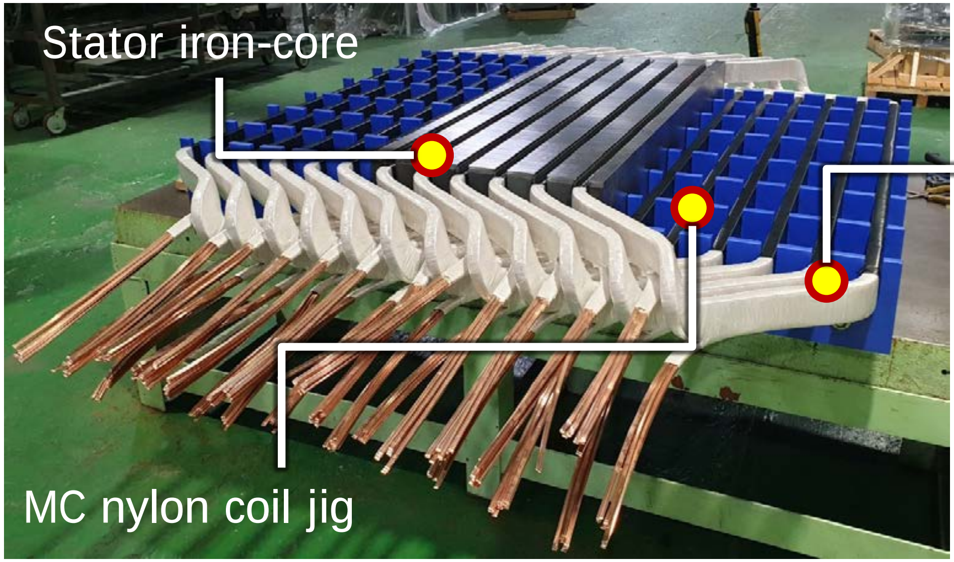
- ✓ Tensile strength: 550 MPa
- ✓ Allowable stress: 165 MPa
- ✓ Simulation result: 73 MPa

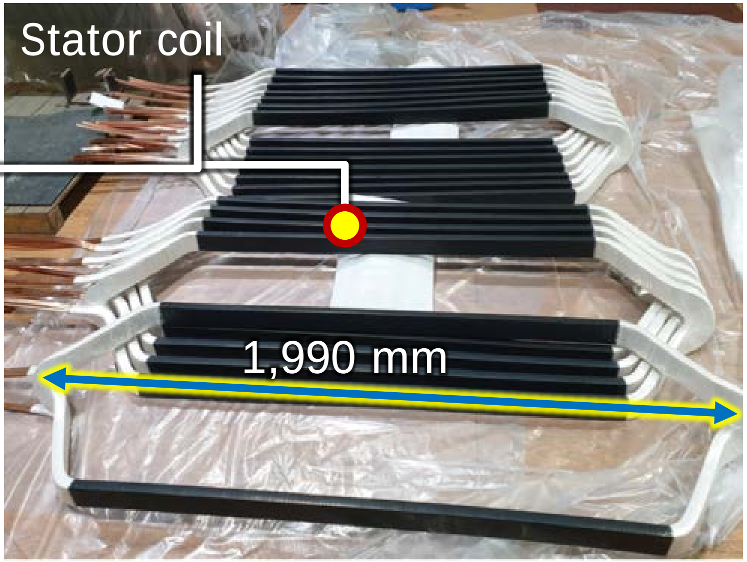
Items	Values
Tangential force	70 kN (7,138 kg)
Radial and weight force	99.35 kN (10,131 kg)

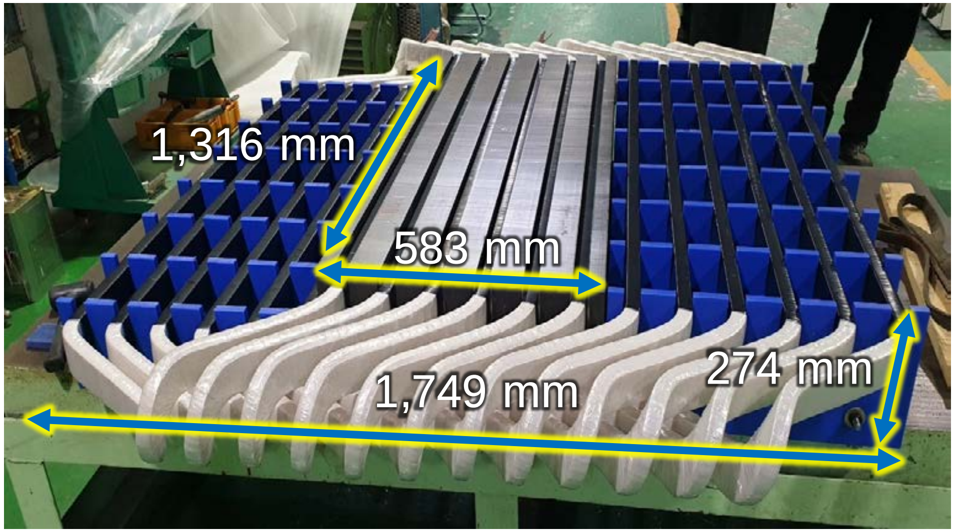
- ✓ The maximum stress of the frame structure of the PES generated by the HTS magnets is 73 MPa, that means the frame withstands the HTS magnet force. (therefore, it is stable.)

Stator module of the PES

➢Stator core and copper coils



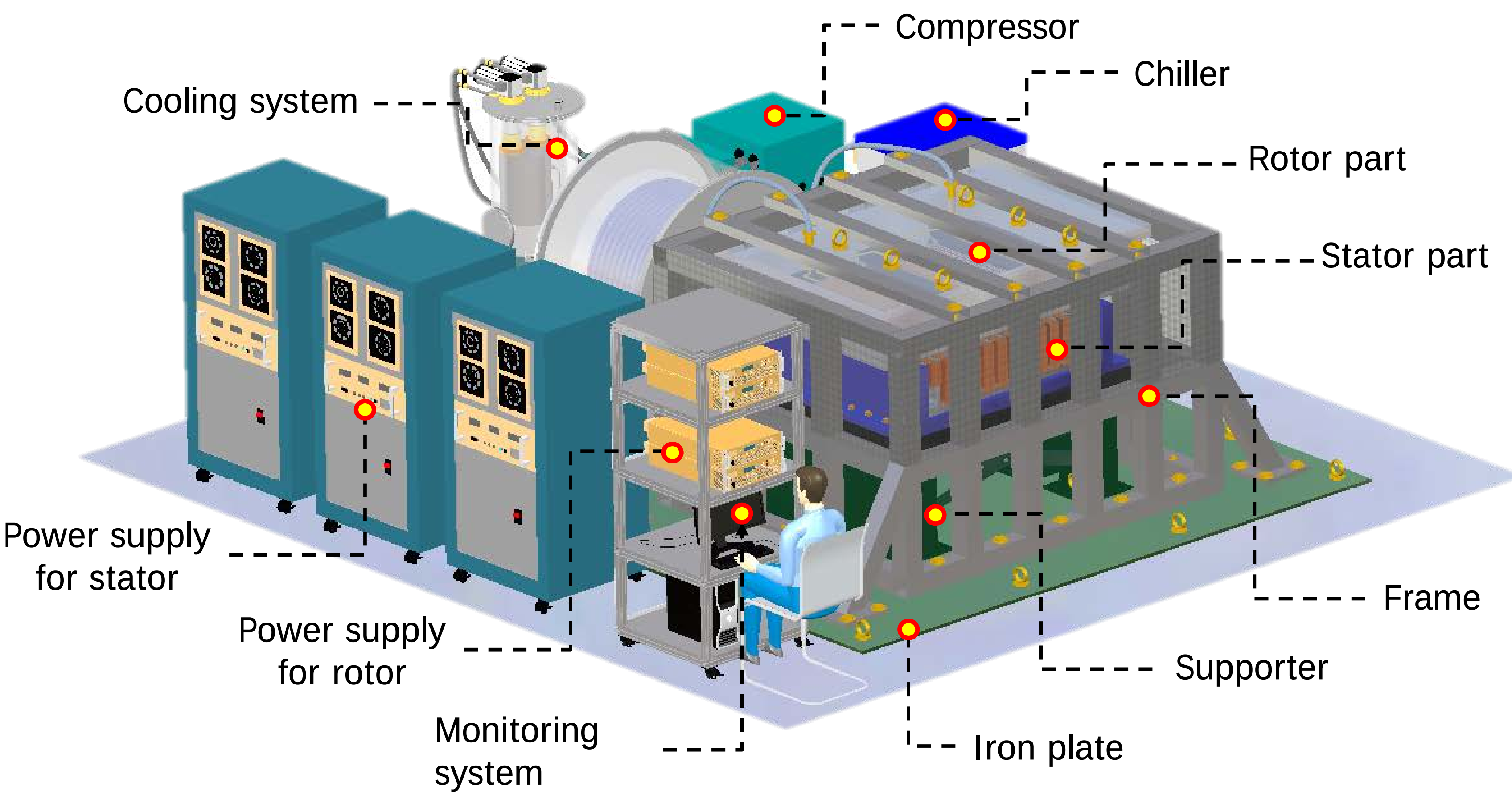




- ✓ MC nylong jig was mounted with the iron-core to support copper coils.
- ✓ The material of iron-core is 50PN470 which is silicon laminated steel and it is general material for the rotating machine.

Outlook of the PES1

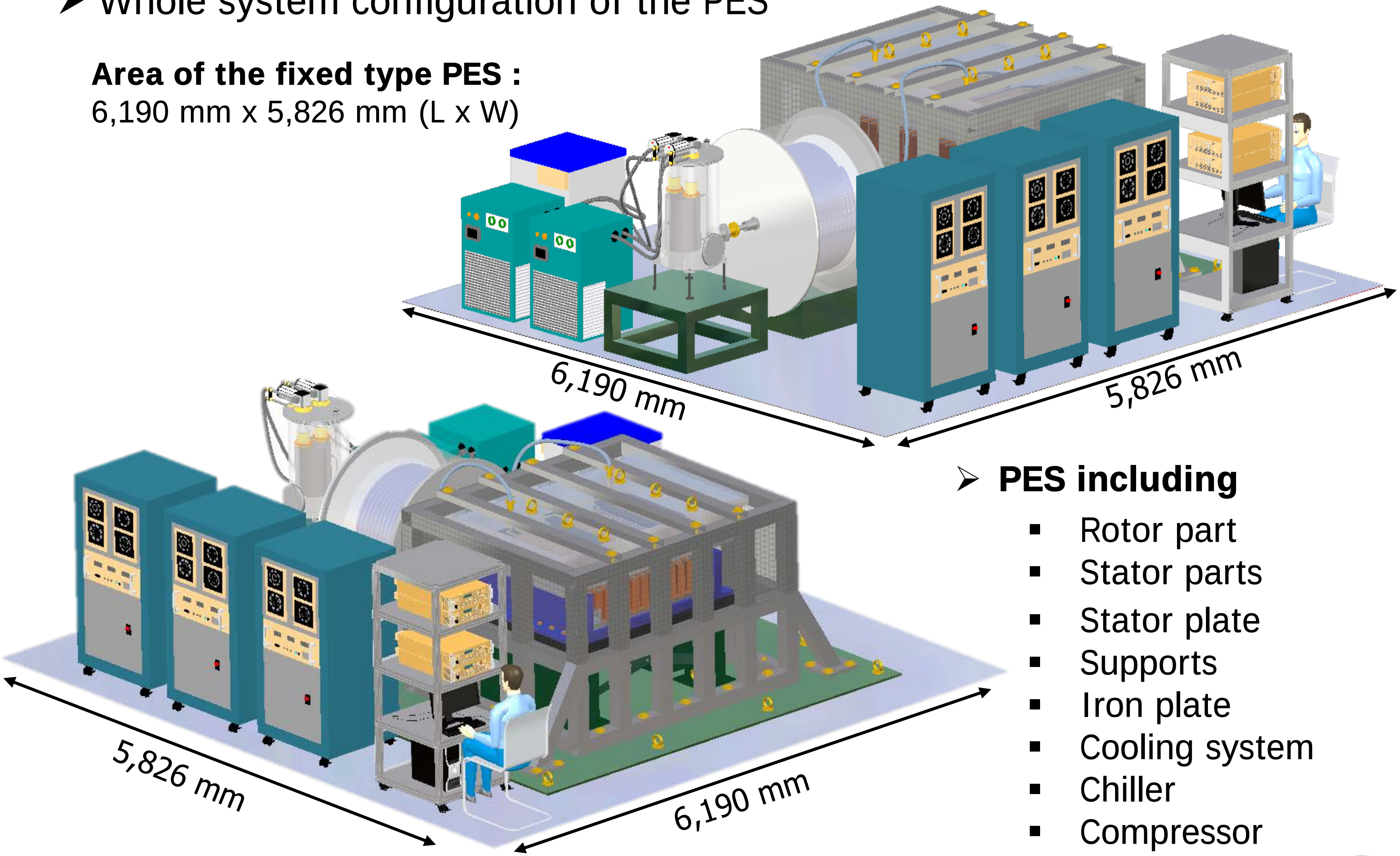
- Whole system configuration of the PES



Outlook of the PES2

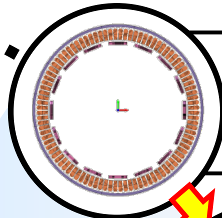
- Whole system configuration of the PES

Area of the fixed type PES :
6,190 mm x 5,826 mm (L x W)

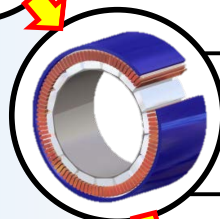


- **PES including**
  - Rotor part
  - Stator parts
  - Stator plate
  - Supports
  - Iron plate
  - Cooling system
  - Chiller
  - Compressor

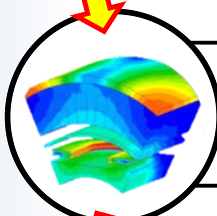
Scenario of the VR research



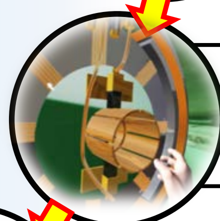
Designed and calculated MW class superconducting generator



3D model designed in the CATIA



Electromagnetic and mechanical analysis of the generator in **FEM**



Planned experiment system in the virtual reality using 3D graphic software

3D model and electromagnetic field observation to **VR environment**

Scenario of the VR research

- Collaboration method of the 3D model and FEM to the virtual reality

Design

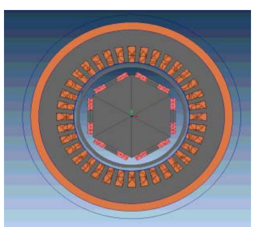
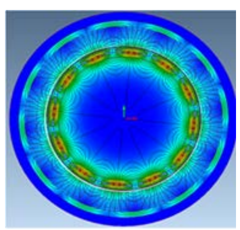
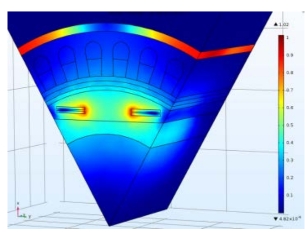
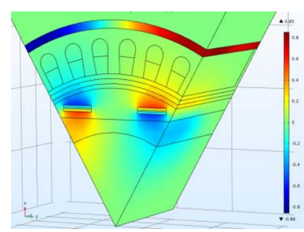
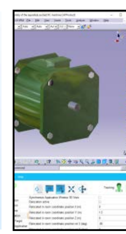
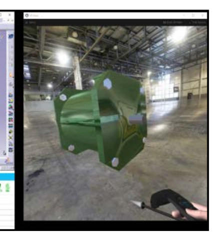
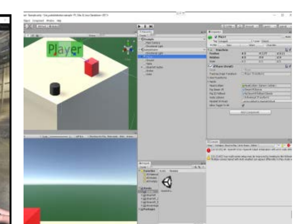
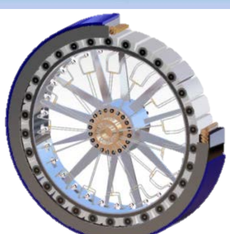
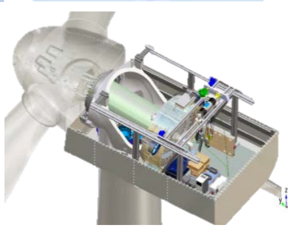
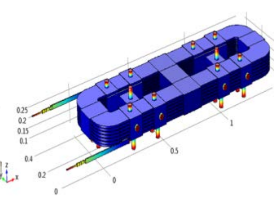
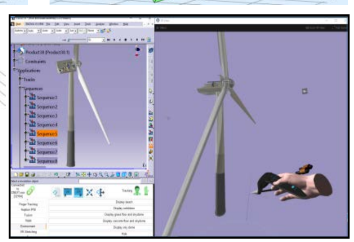
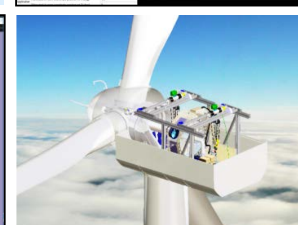
- Survey of the MW class generator
- Basic design and calculation of the MW class generator
- Basic design and calculation of the MW class generator
- Designed and calculated in Excel write script code
- Designed 3D model in the CATIA

Simulation

- Script run with MagNet and analysed distribution of the electromagnetic
- Confirmed output power and torque using MagNet and Origin
- To analyse mechanical stress of the generator using COMSOL
- To analyse heat load of the generator using COMSOL

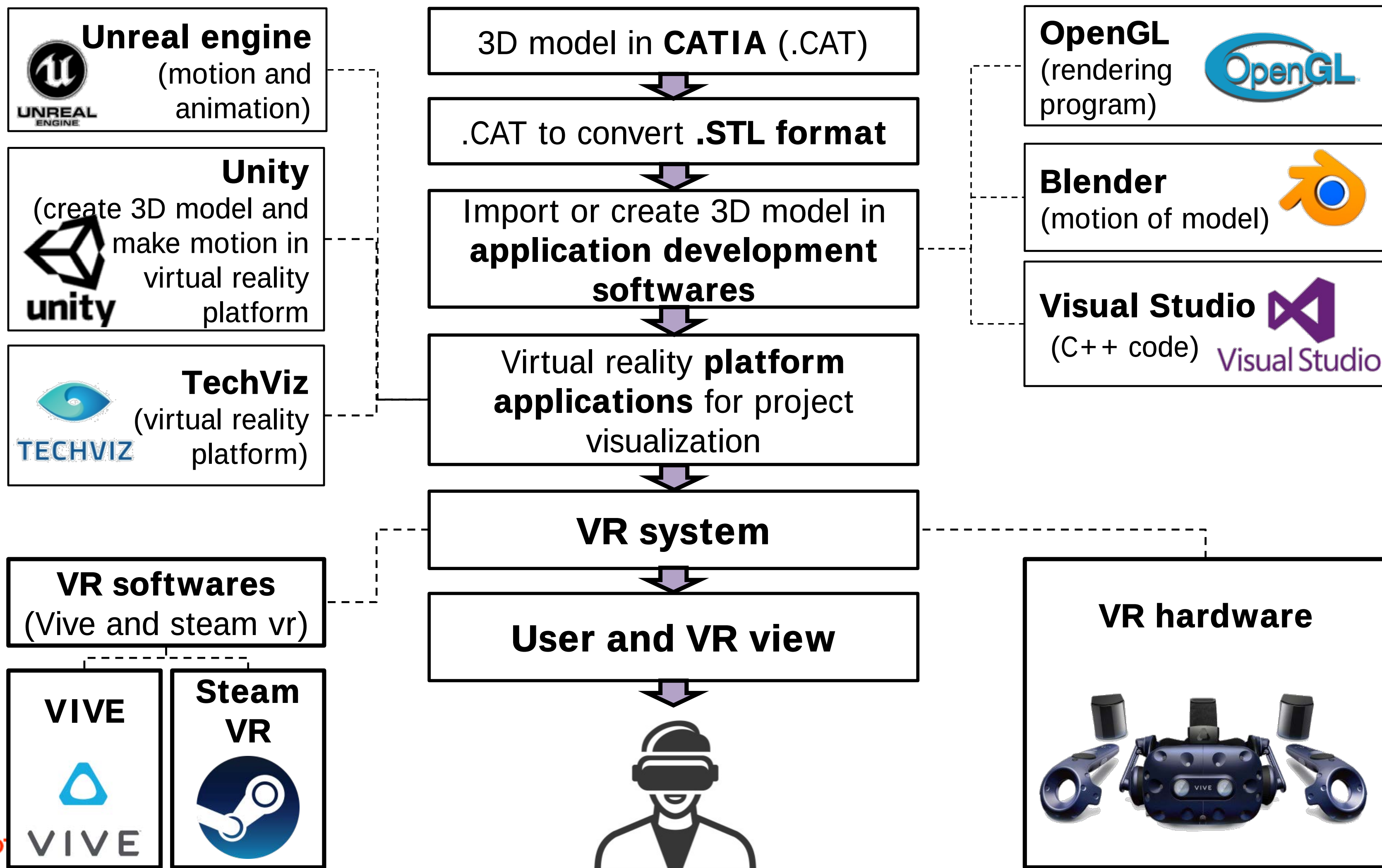
Virtual reality

- To convert 3D model format .CAT to .STL
- .STL file import to the Blender
- Make animation or action in the Blender or Unreal engine
- Animation or 3D file import to the Unity or TechViz
- Unity or TechViz connected with VIVE VR HMD
- 3D result collaborated with VR environment

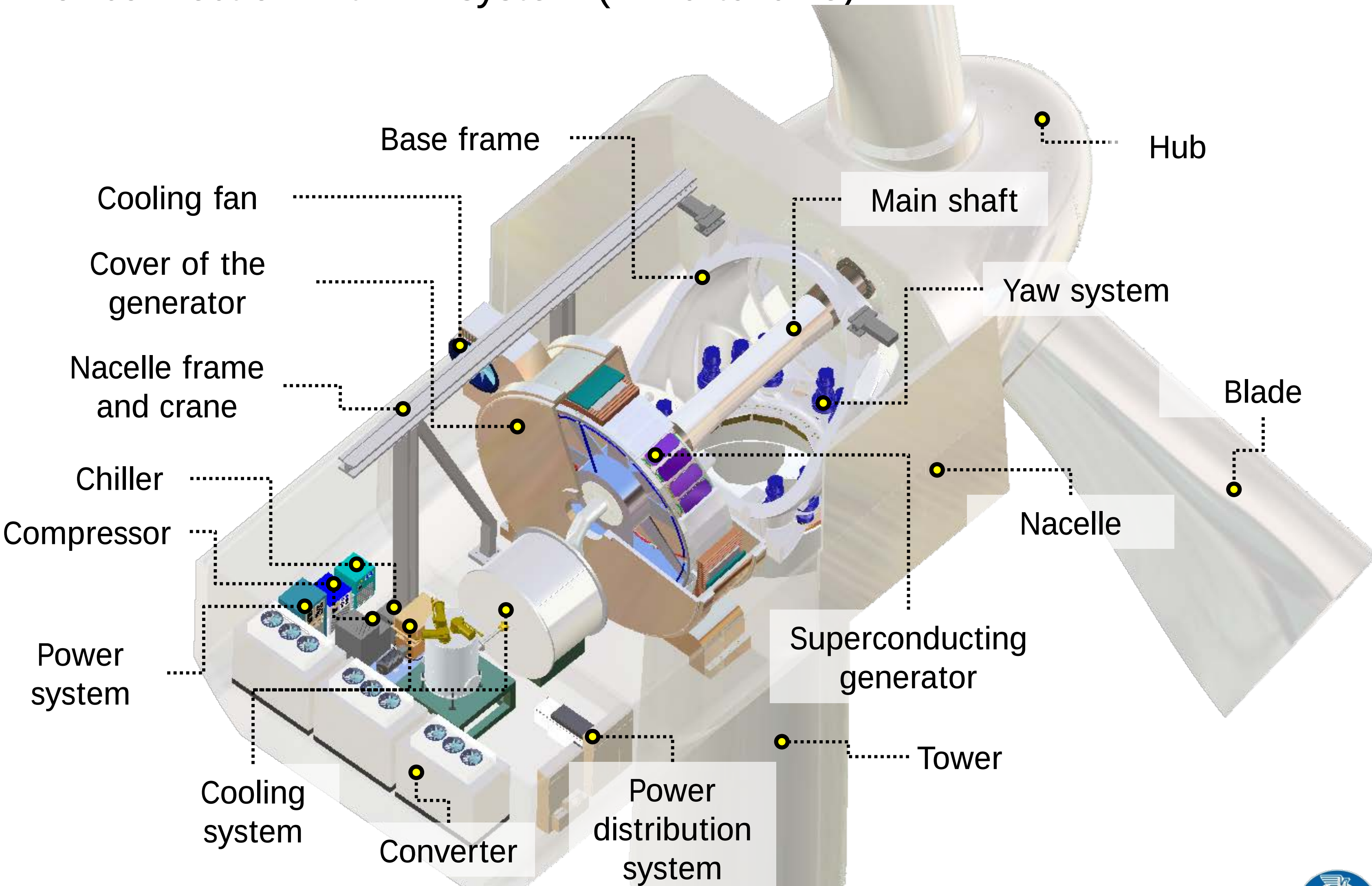

Flowchart of the virtual reality developing

- Following virtual reality software to use through virtual reality developing



3D model of a 10 MW wind turbine

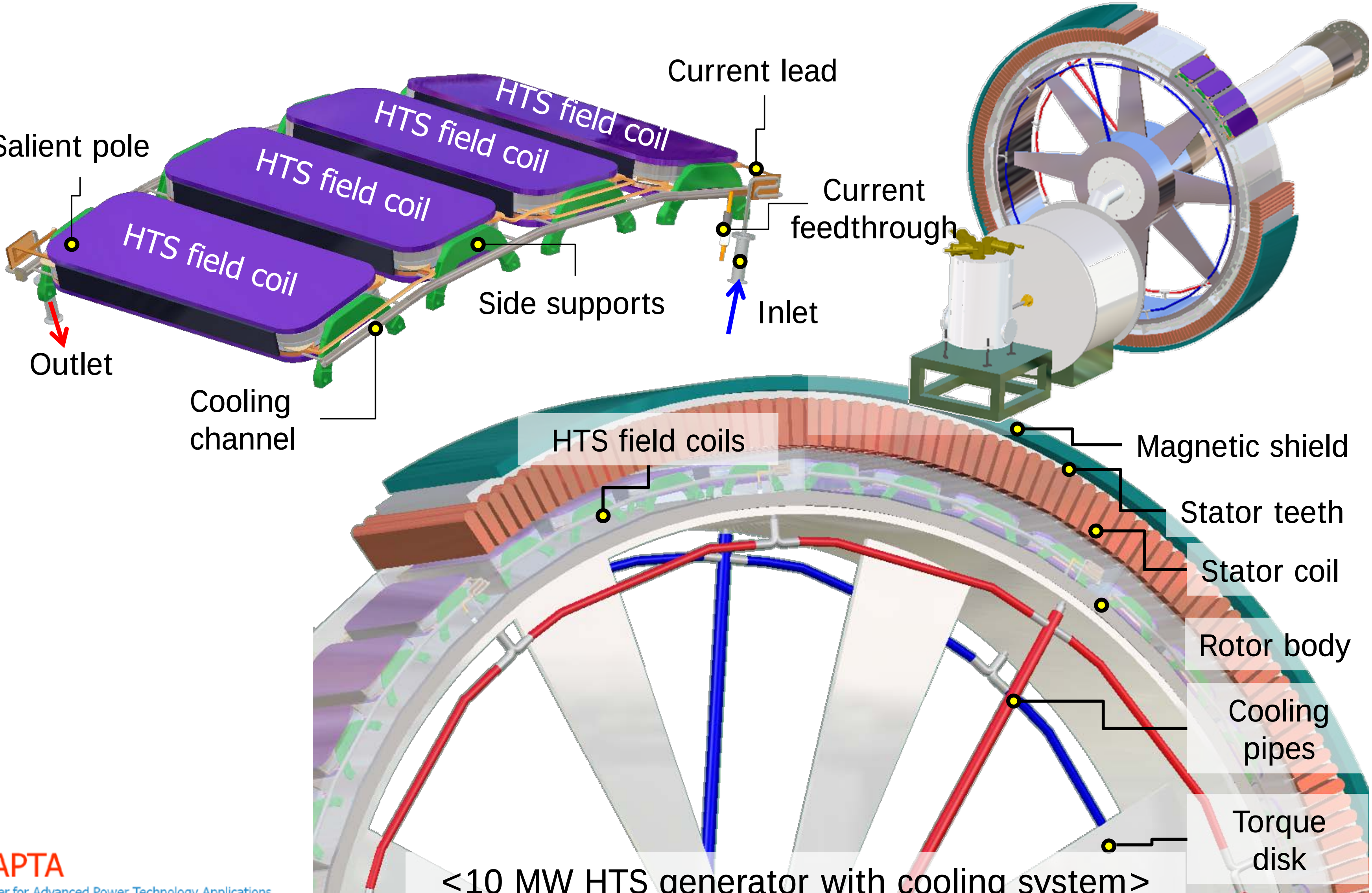
- For connection with VR system (Wind turbine)



<10 MW superconducting generator>

3D model of a 10 MW wind turbine

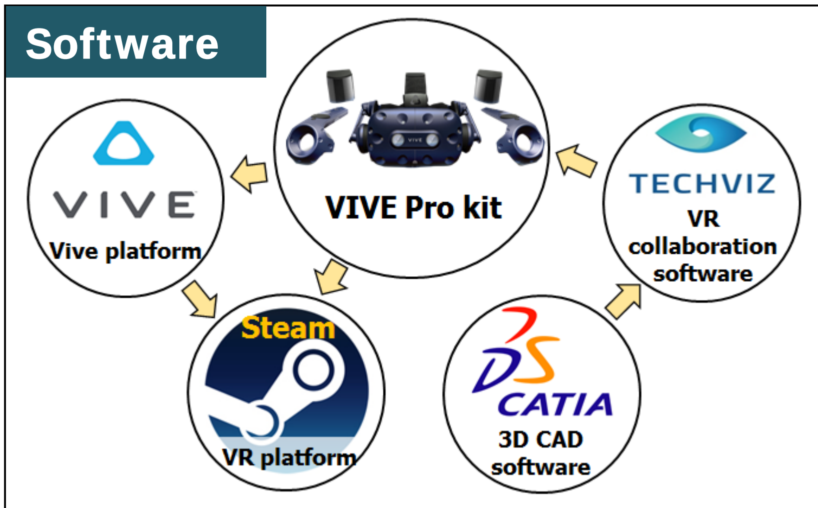
- For connection with VR system (Superconducting generator)



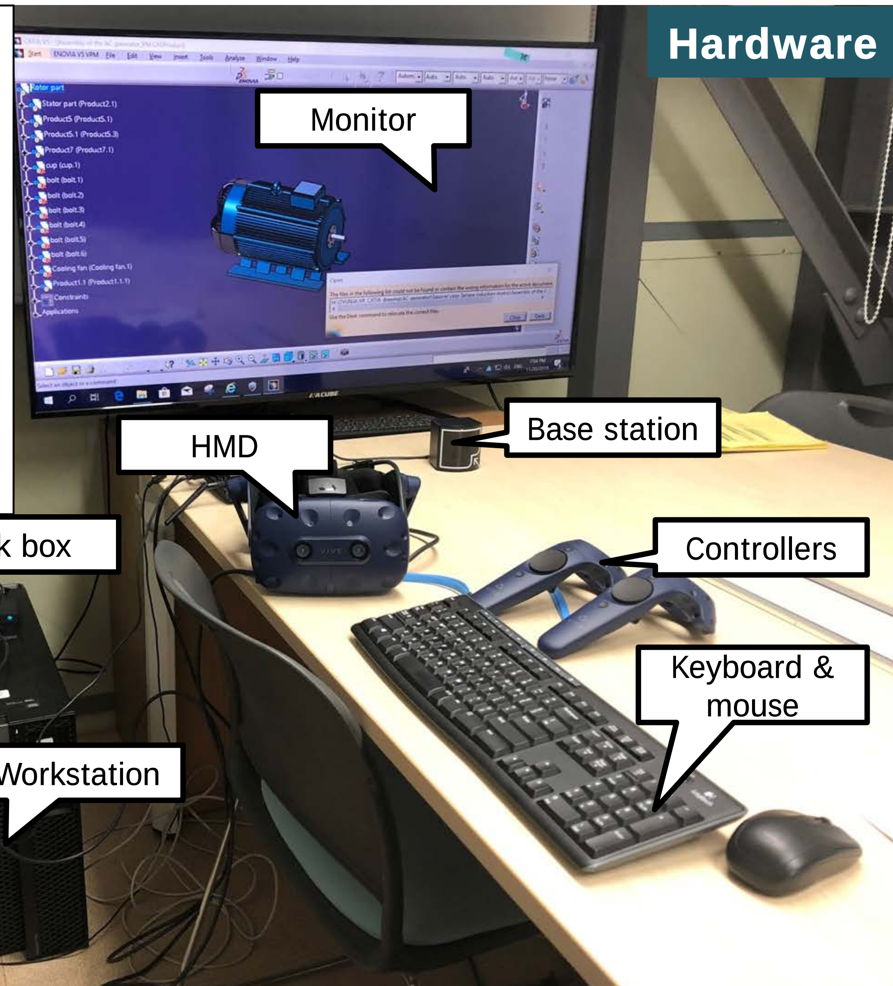
<10 MW HTS generator with cooling system>

VR hardware and software system

- Setup and installation of the VR devices and software

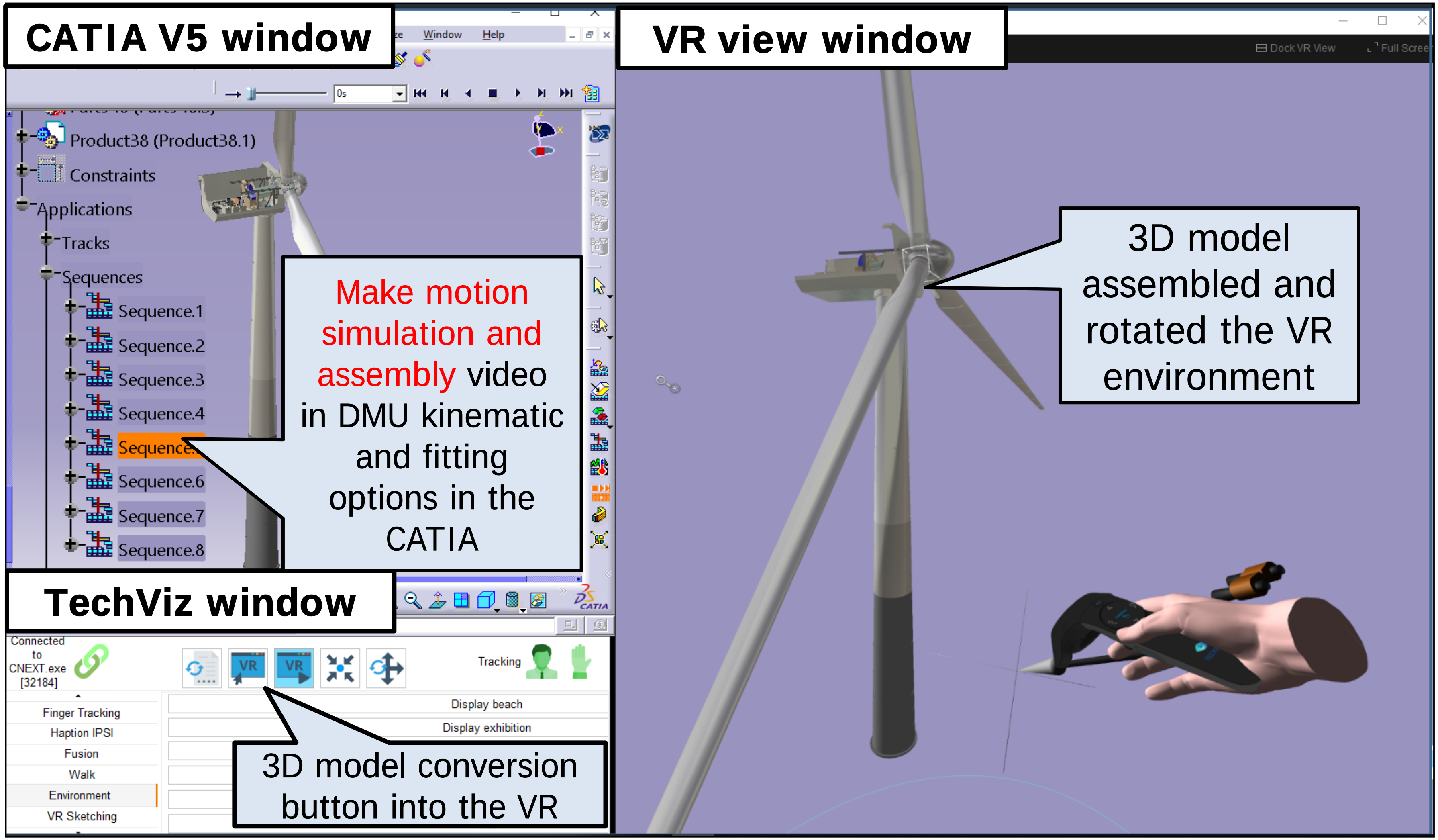


Installed software
Vive software
Steam software
CATIA V5
TechViz



VR with CATIA 3D program

- Collaboration with wind turbine 3D model and motion



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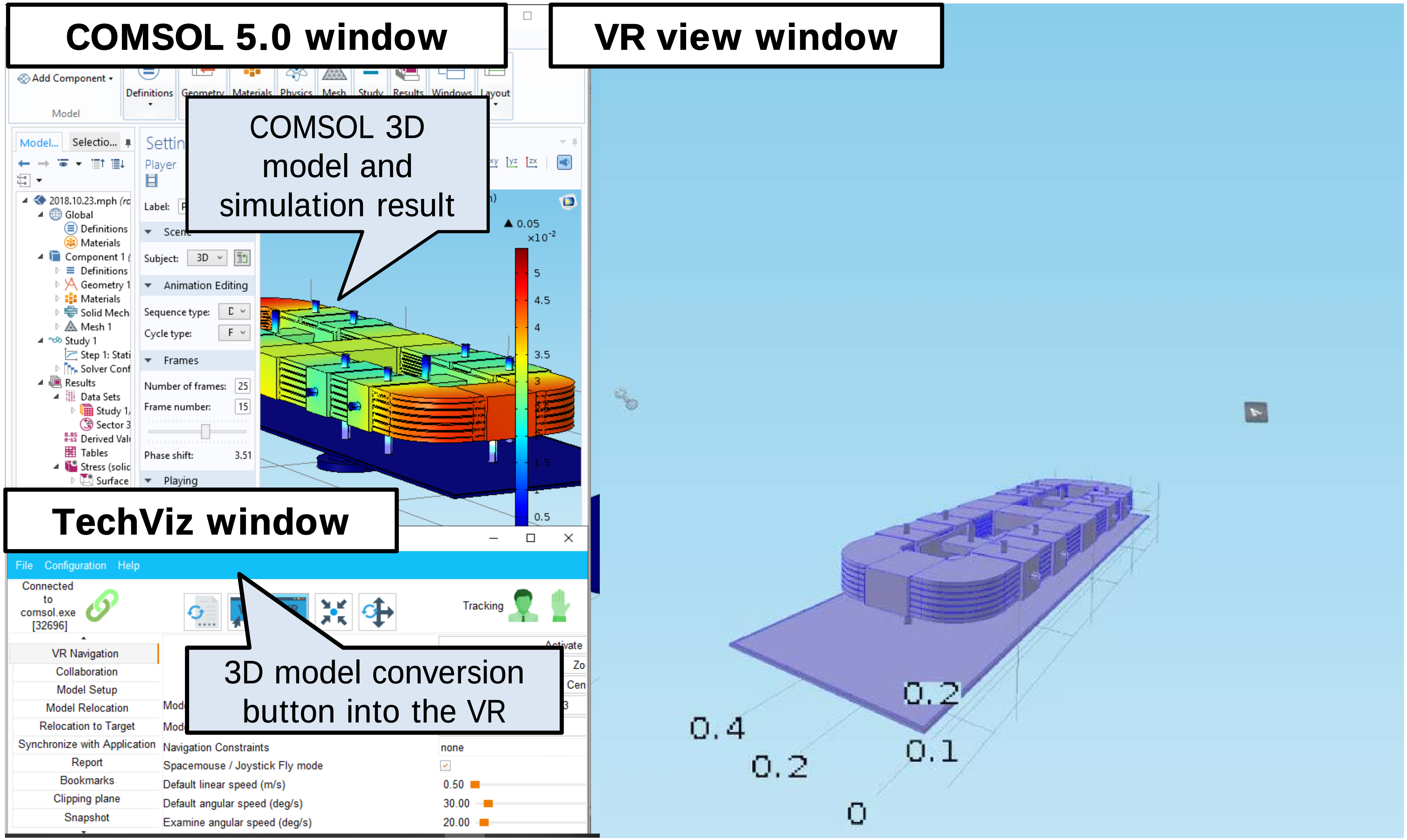
Presentation AT-4 given at ACASC/Asian-ICMC, 6-9 January 2020, Okinawa, Japan.

Motion of the 3D model in the VR

VR with COMSOL FEM program

- Collaboration with COMSOL



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Scenario of the research

➢ Scenario about wind turbine

Scenario (Virtual reality wind turbine)

1. Basic design and calculation of the MW class generator
2. Designed and calculated in Excel write script code
3. Designed 3D model in the CATIA
4. Script run with MagNet and analysed distribution of the electromagnetic of the gen.
5. Confirmed output power and torque using MagNet and Origin
6. To analyse mechanical stress of the generator using COMSOL
7. To analyse heat load of the generator using COMSOL

- To convert 3D model format .CAT to .STL
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- Make pushable and moving button and motion in the application development software

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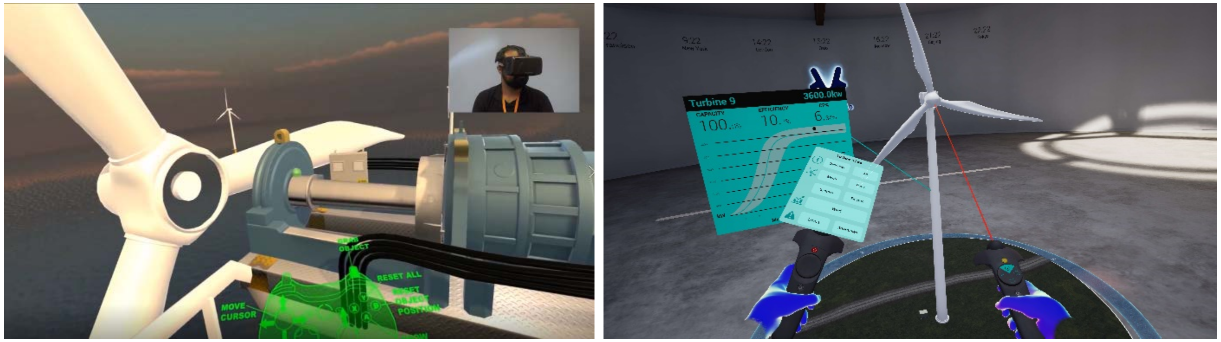

<Virtual reality wind turbine>


Thank you for your attention