# Process simulator development at ITER

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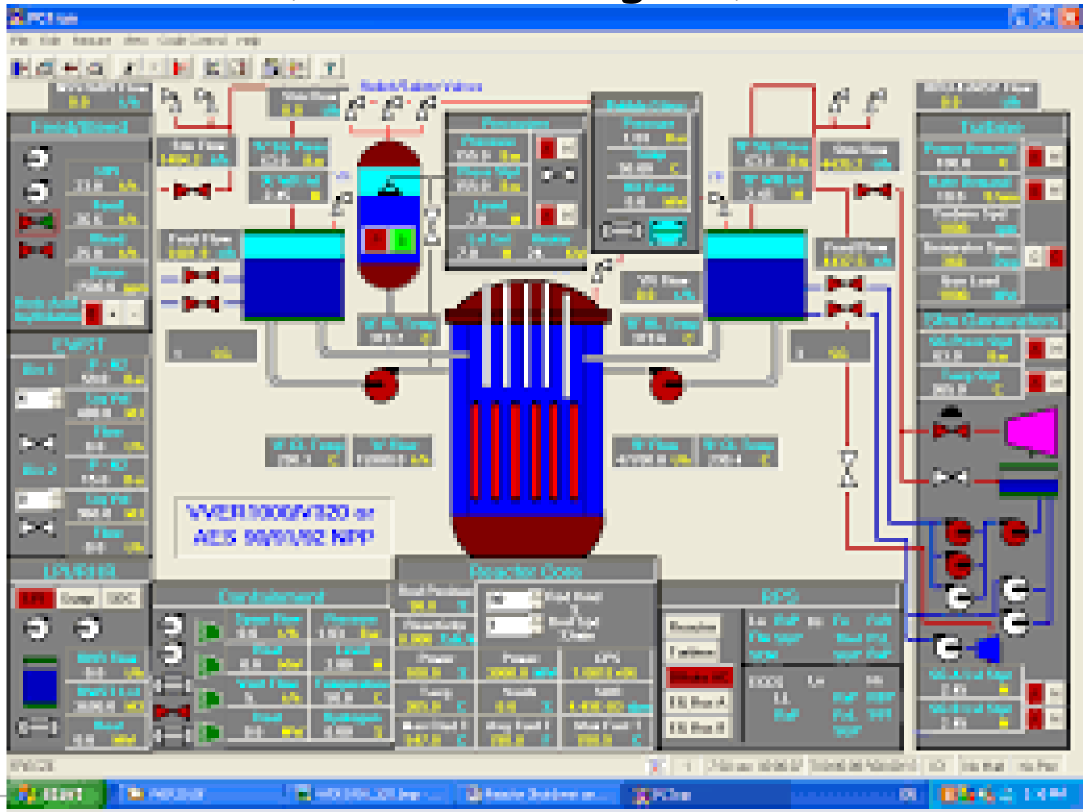
ITER Organization

Oct. 1, 2019 at EASISchool

CEA

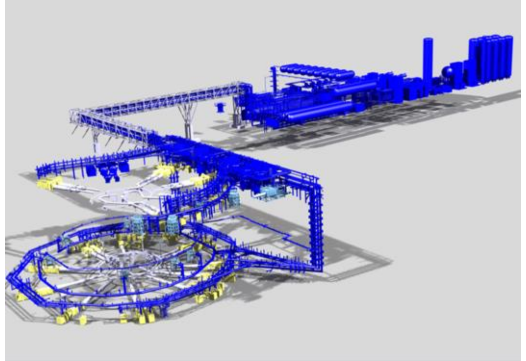
# Plant Simulator for TOKAMAK (Magnet & Cryoplant)

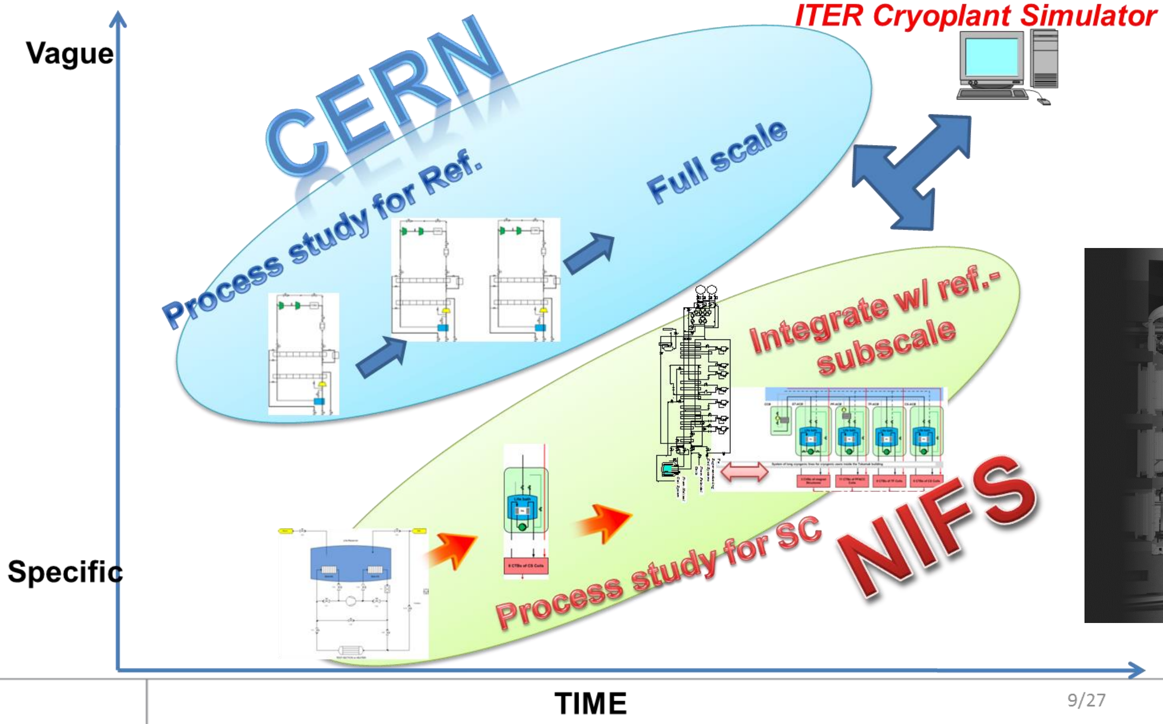
- Reproducing virtual plant operation in a real time (in WS/PC)
  - To understand the highly complex plant process
  - Versatile tool to verify control strategy
  - Focus on the most demanding operation & fast events (PD, FD of magnet)

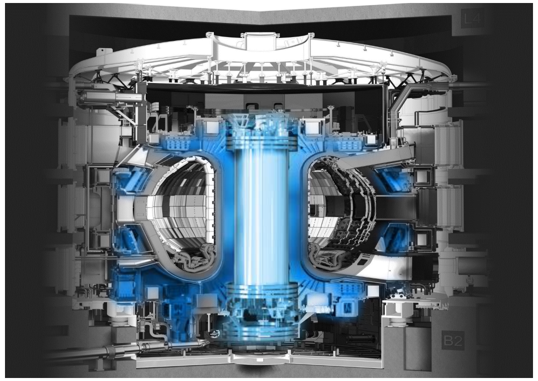


# Development Program

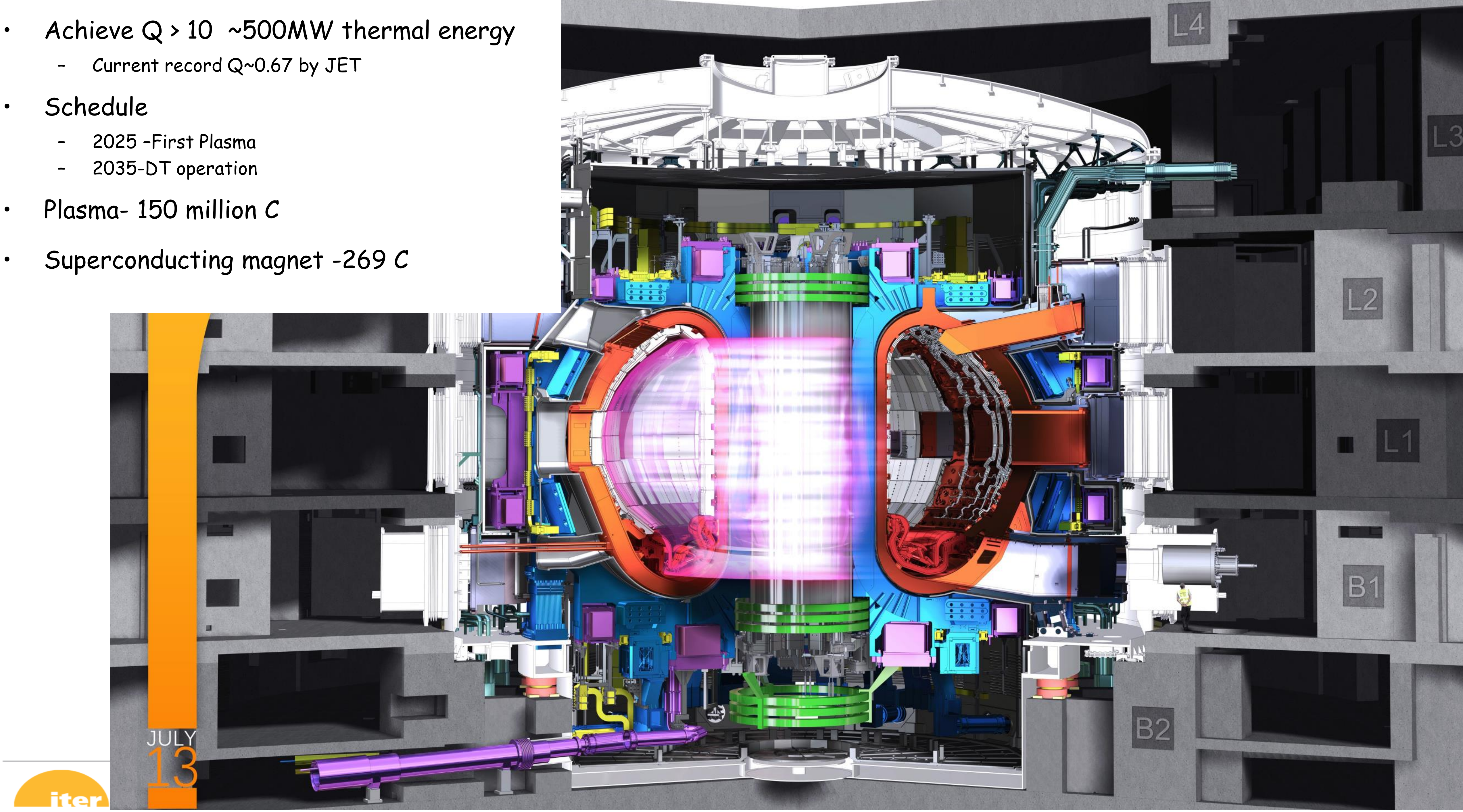
- ITER cryo-system simulator concept (back in 2011)
  - CERN (Refrigerator)-25 kW refrigerator model (2011-2013, 2016)
  - NIFS-development of Superconducting Magnet model w/ ACBs (2011-ongoing)
  - Coupling two models for Cryogenic system simulator (2017-2018)





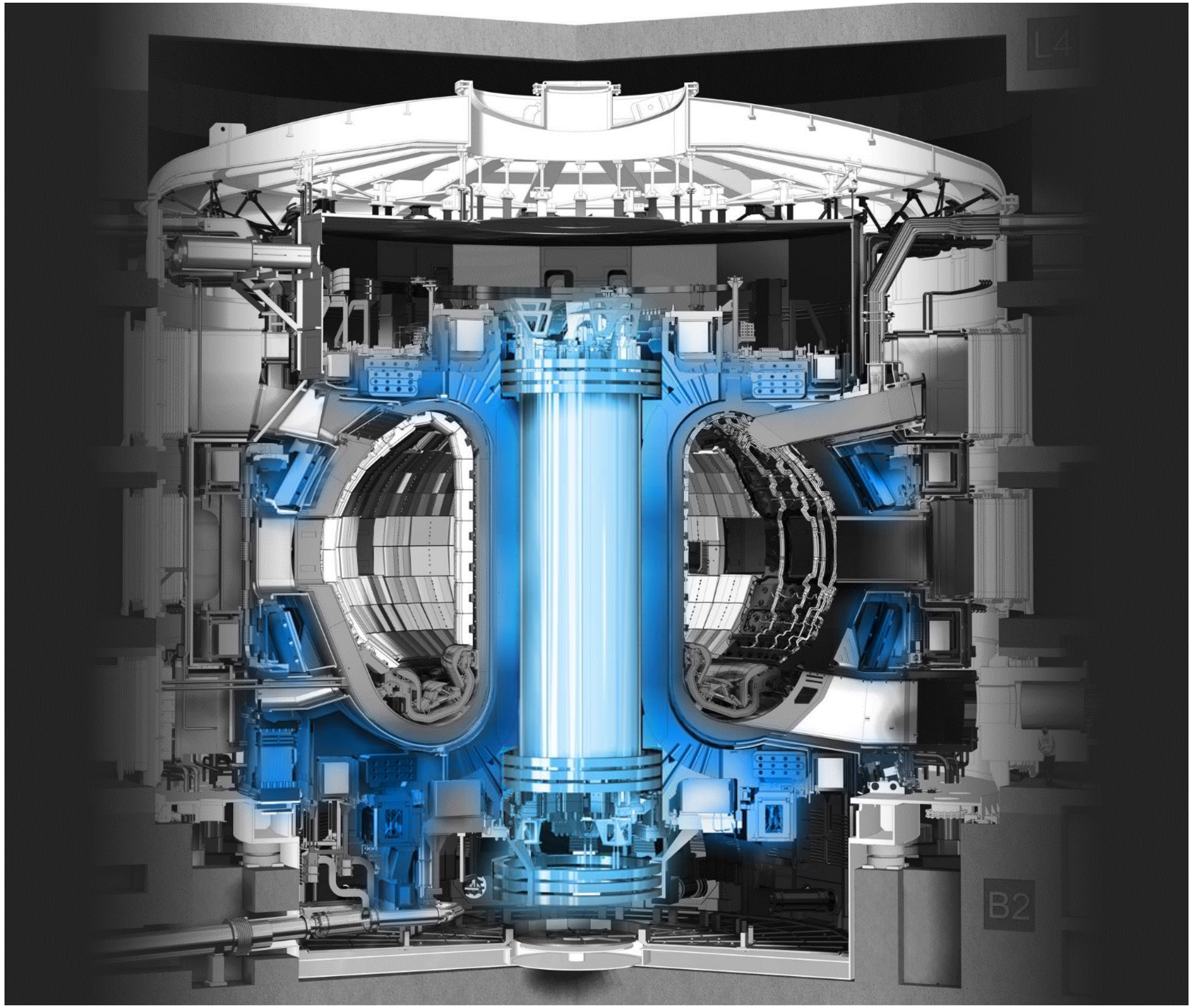
- Achieve Q > 10  ~500MW thermal energy
  - Current record Q~0.67 by JET
- Schedule
  - 2025 –First Plasma
  - 2035-DT operation
- Plasma- 150 million C
- Superconducting magnet -269 C



# CRYOGENICS-SUSTAIN OPERATION of TOKAMAK

- COLD-MASS
  - Approximately 10,000 tons
  - A forced-flow cooling w/ SHe

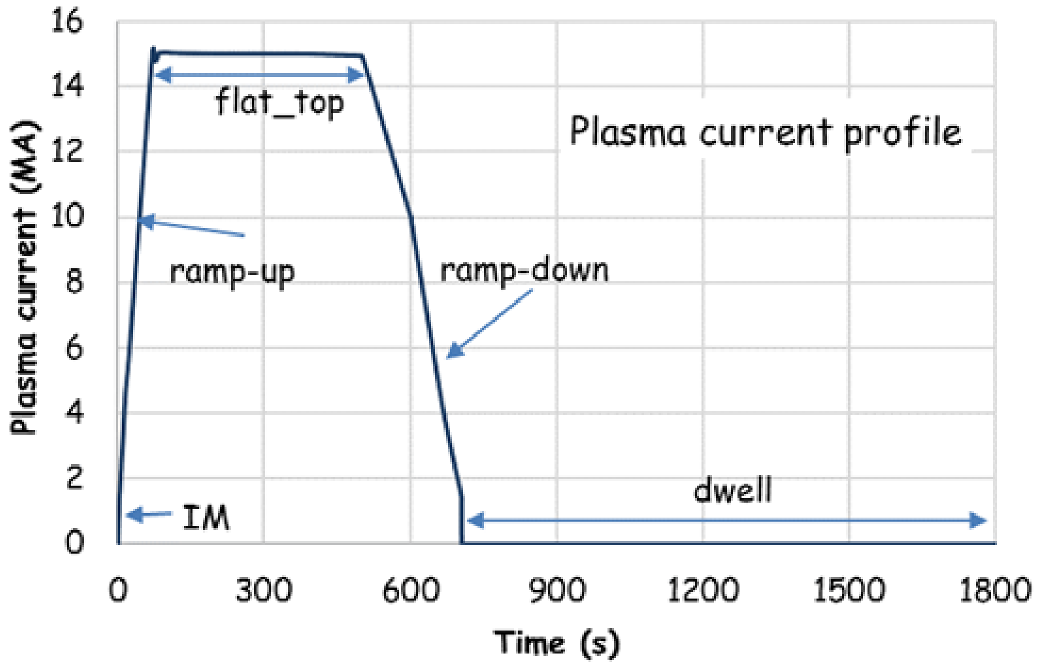
- Superconducting magnet system w/ dedicated ACB
  - Thermo-hydraulic length
    - TF-380 m
    - CS-152 m
    - PF-199-454 m
    - CC-130, 160, 200 m
    - TF structure ~20 m

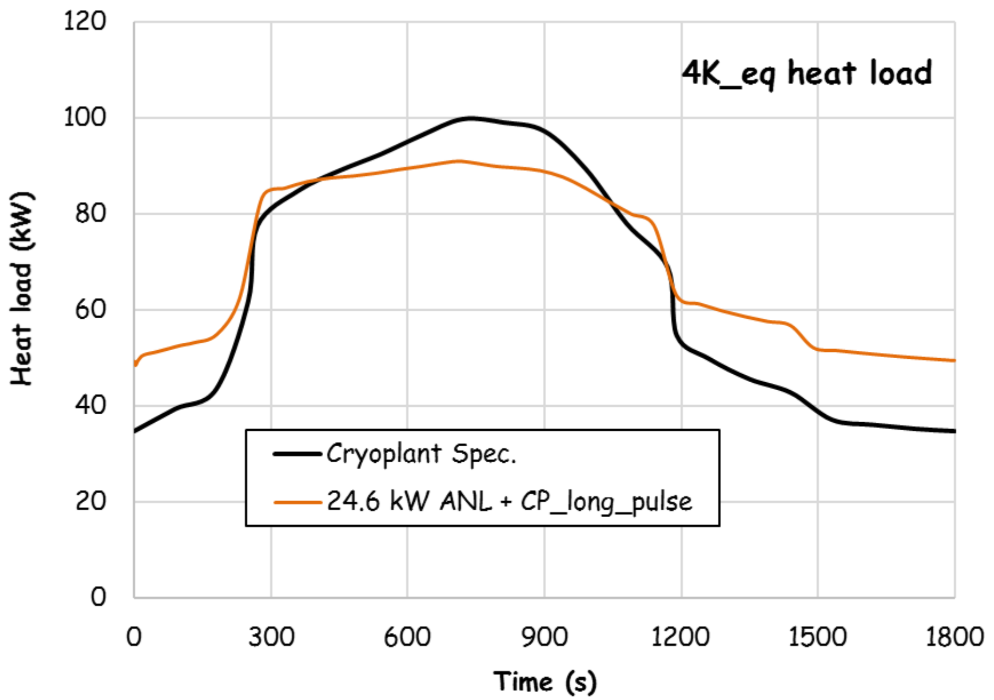


# Challenge for Cryogenics?

- Substantial dynamic heat load (>30 MJ)
  - Initial Magnetization by CS
  - Position control of plasma (PF/CS)
    - Eddy current generation and AC losses
  - Nuclear heat load; under assessment
    - 14.6 kW →now it goes up to > 20 kW…

Based on the Vincenta® simulation
Numerical code to look into the conductor stability



# Why plant simulator?

- $1^{st}$ time for Cryoplant to handle 35-100kW variation in 30 min
- 3 refrigerators connected in parallel to produce 100kW (max)
- Severe operation for CS (IM)
  - Cross check operation of cold-circulator/compressor
- Thermal energy mitigation in the case of plasma disruption

# OBJECTIVE-Plant simulator development

- To understand complex Cryogenic system for Tokamak (CRYOPLANT & MAGNET)
  - FULL SCOPE PLANT MODEL (INTERACTIVE) w/ SC magnet system

**Decision assistance for operation**

**Optimization**

**Controllability assessment**

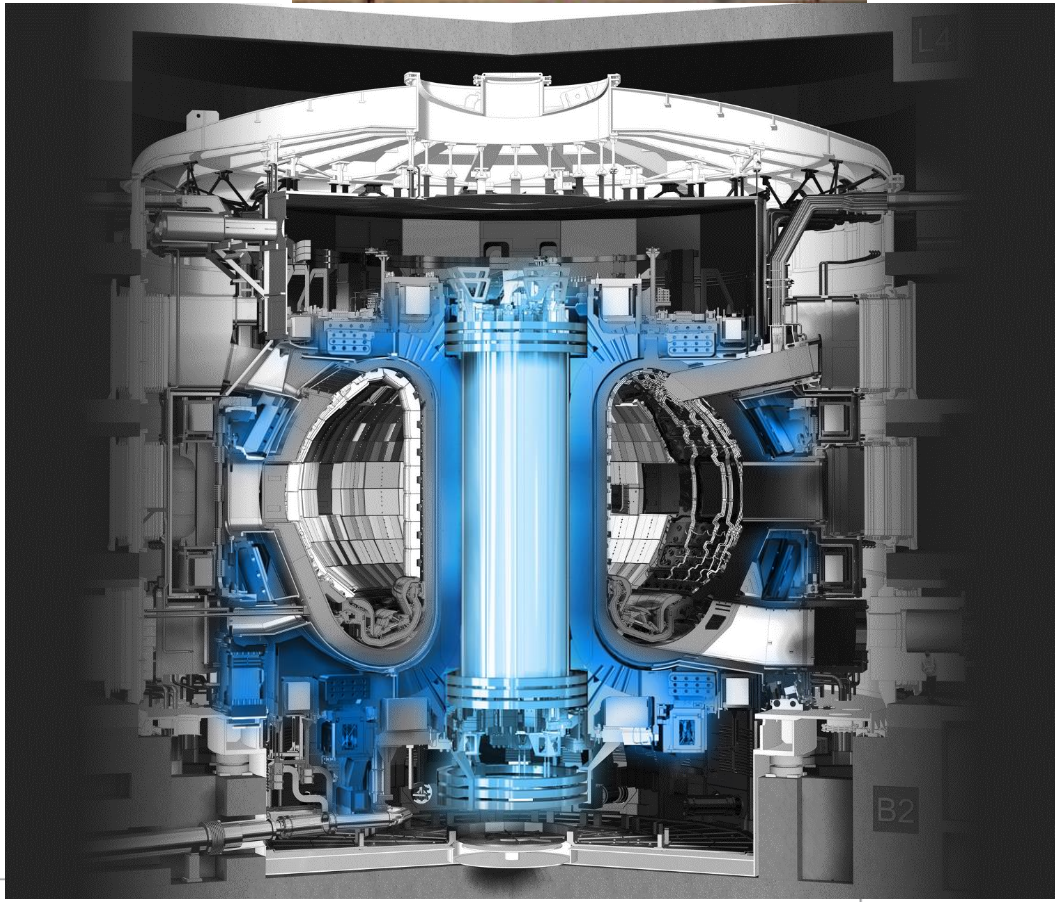
**Operator Training**

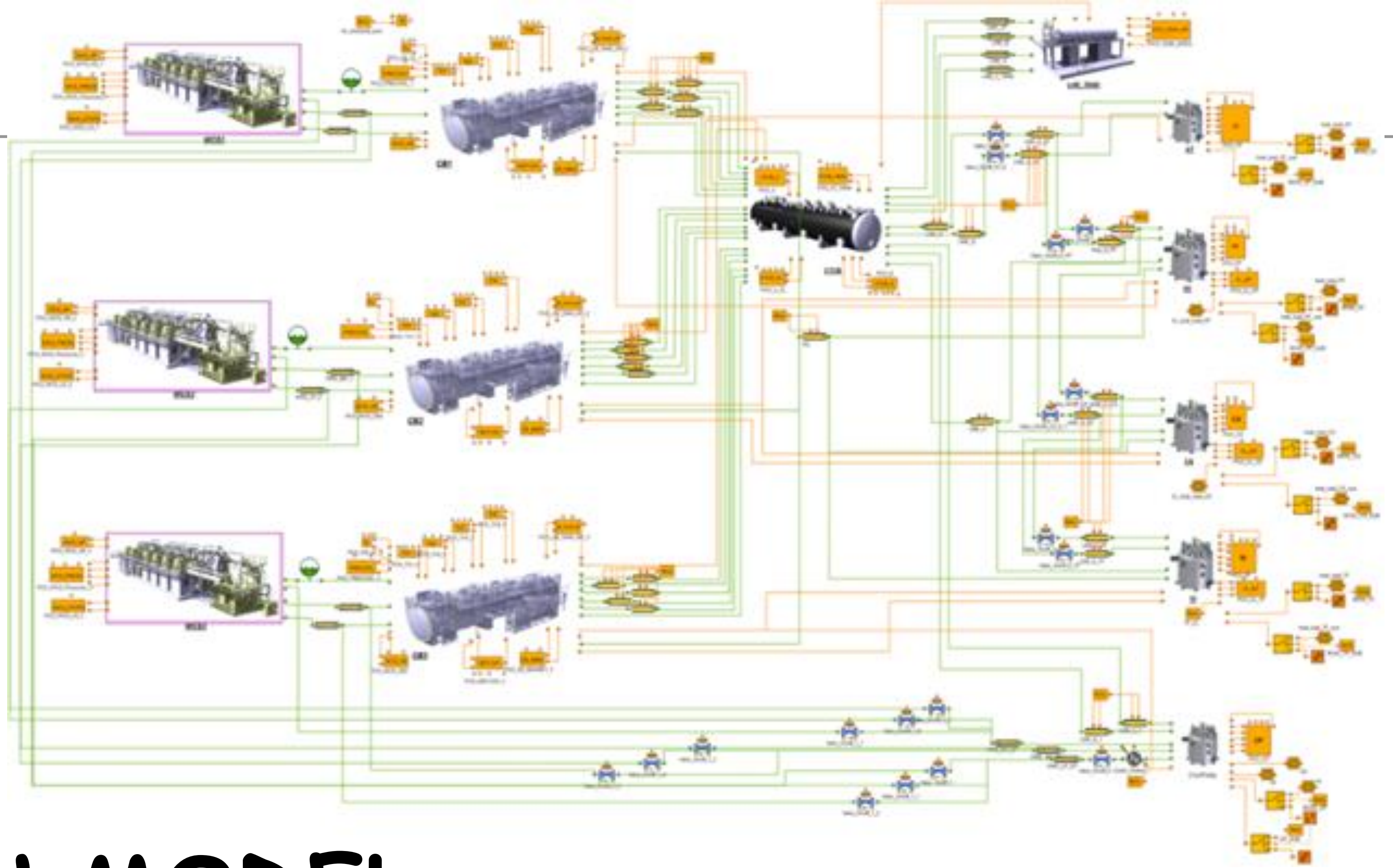
**Plant diagnosis**

**Fault Detection/Recovery**

# Outline

- Process simulator
- MODELING & RESULT
  - Magnet (CS, TF, PF/CC, TF structure) (Visual Modeler®)
- SUMMARY

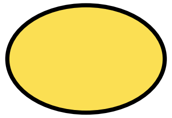
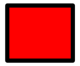


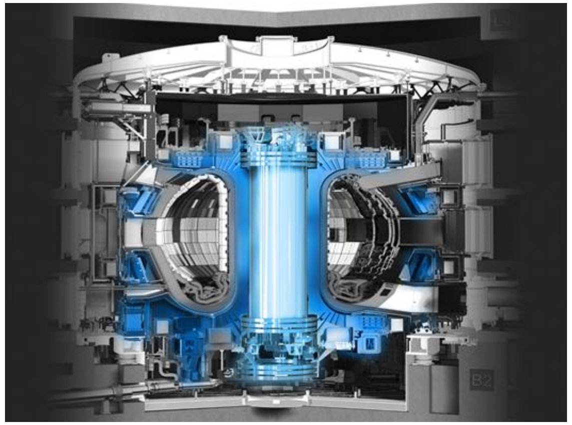


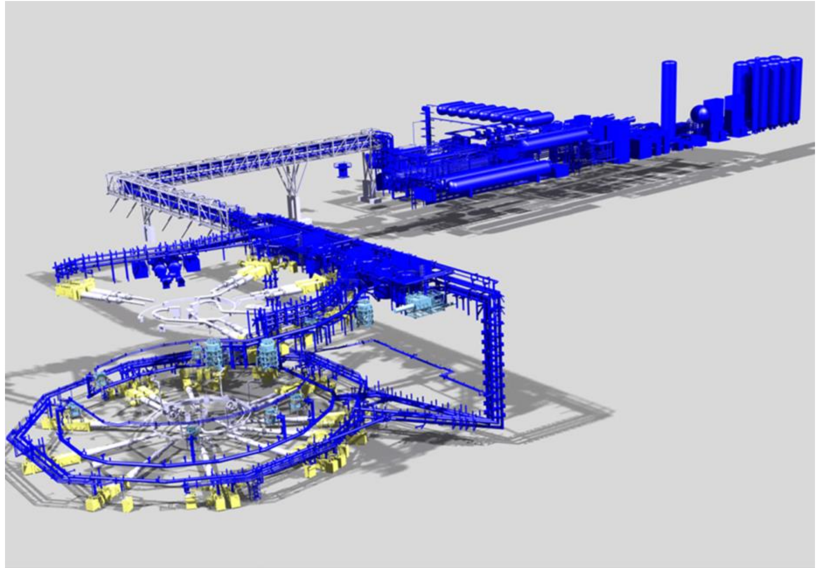
Fidelity?

# SIMULATION MODEL…

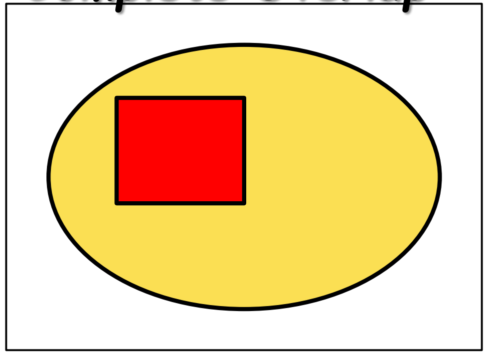
# How "Valid" are Simulation Model?

- Target system 
- Simulation Model 

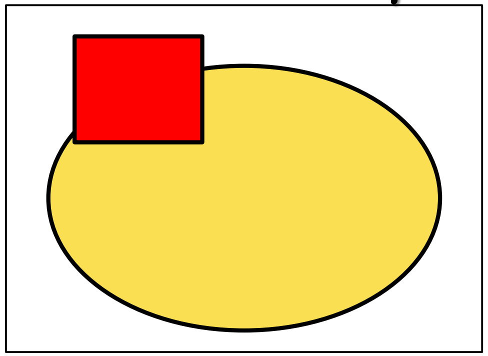




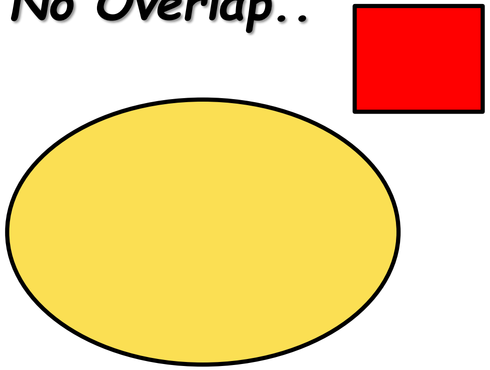
*Complete Overlap*



*Partial Overlap*

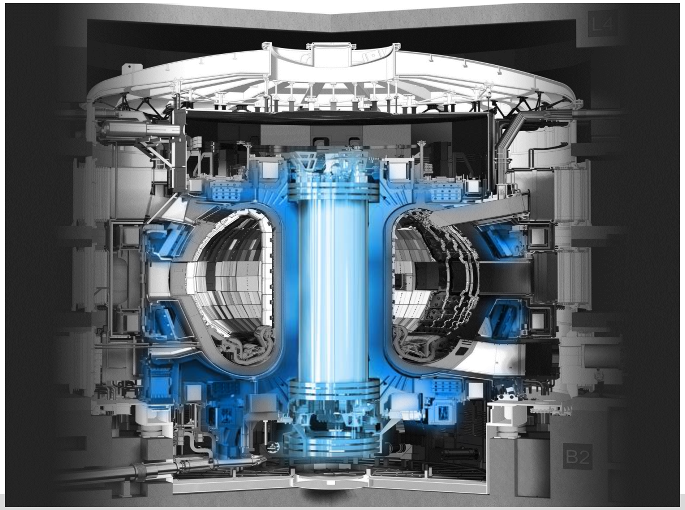


*No Overlap..*

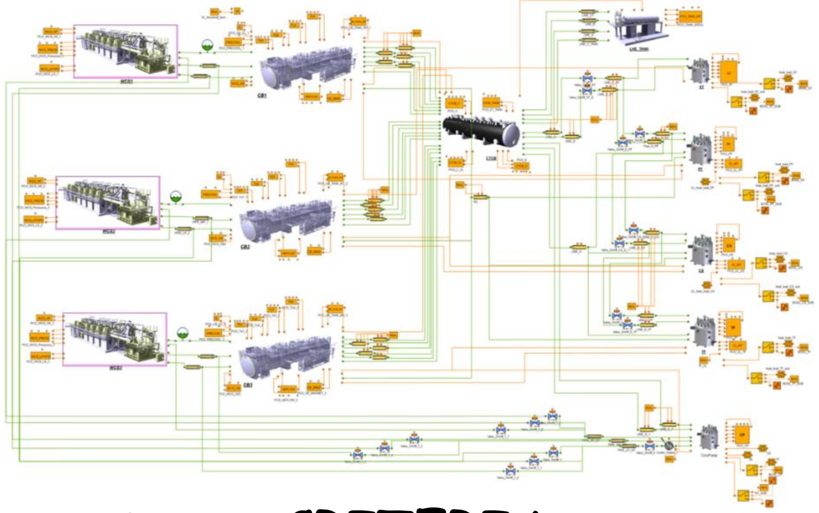


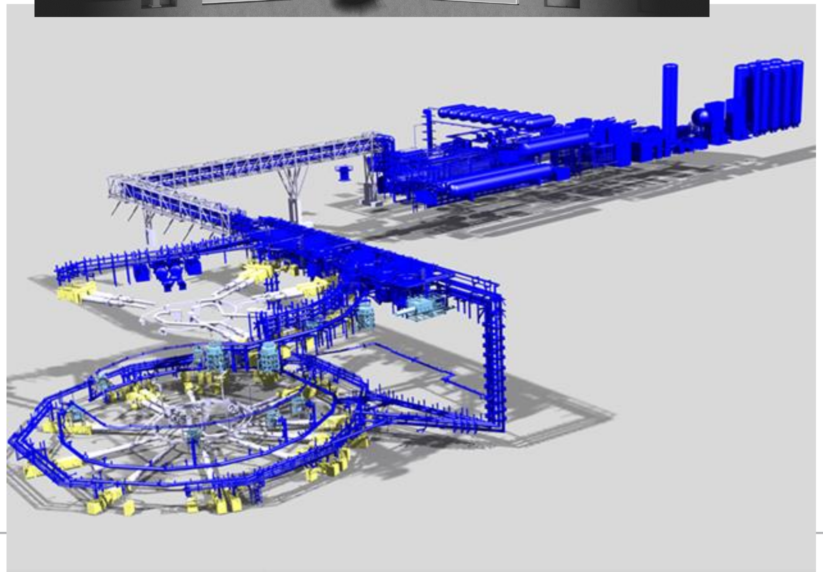
# Modeling and Validation/Benchmark

- Comparison of process simulation data w/ REAL SYSTEM
  - Agreement/Discrepancy
  - FEEDBACK→ Model revision



**Modeling & Simulation REQUIREMENT**

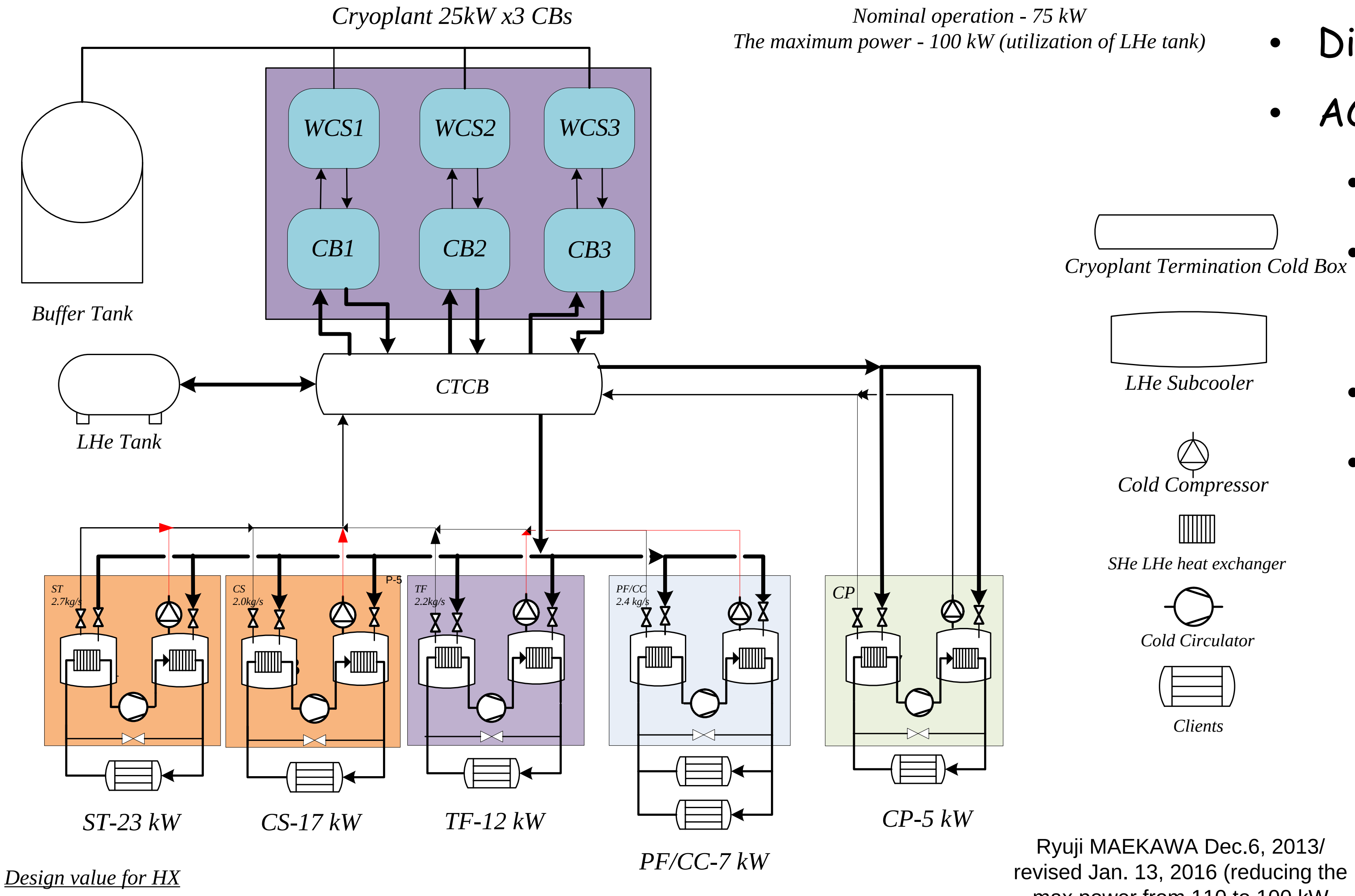




**Acceptance CRITERIA**

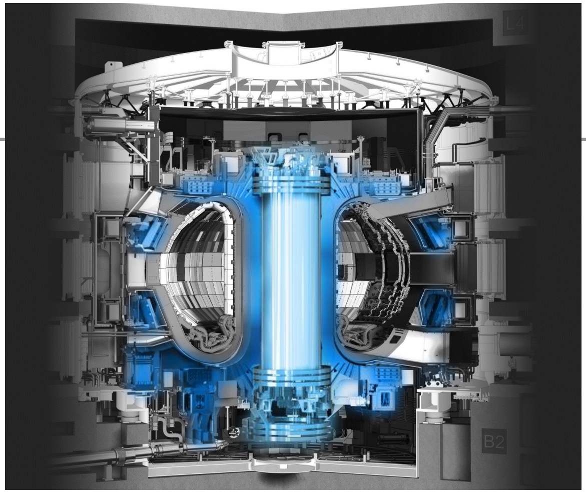
**TRADE OFF→ Accuracy vs Speed**

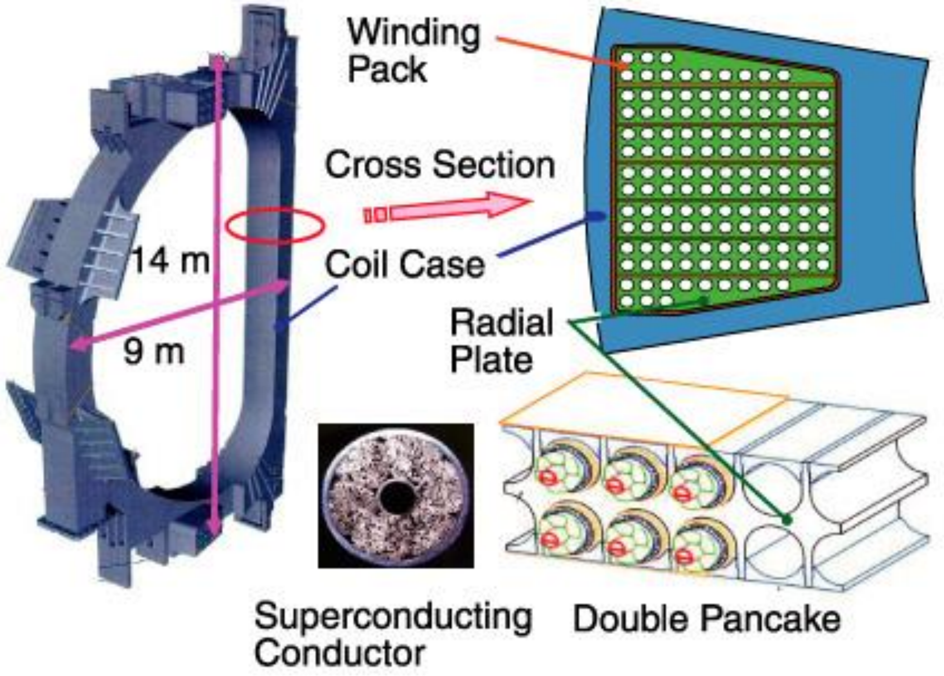
# Scope of development

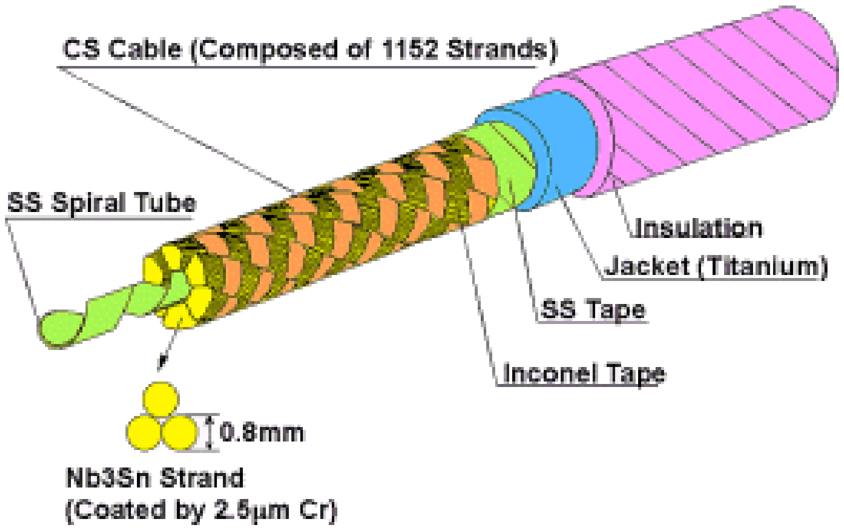



Ryuji MAEKAWA Dec.6, 2013/
revised Jan. 13, 2016 (reducing the
max power from 110 to 100 kW

- Distributed cooling for 5 sub-system
- ACB consists of;
  - Subcooler (saturated/subcooled)
  - SHE pump for circulation of coolant
  - Cold compressor/circulator
  - Control valves + process piping



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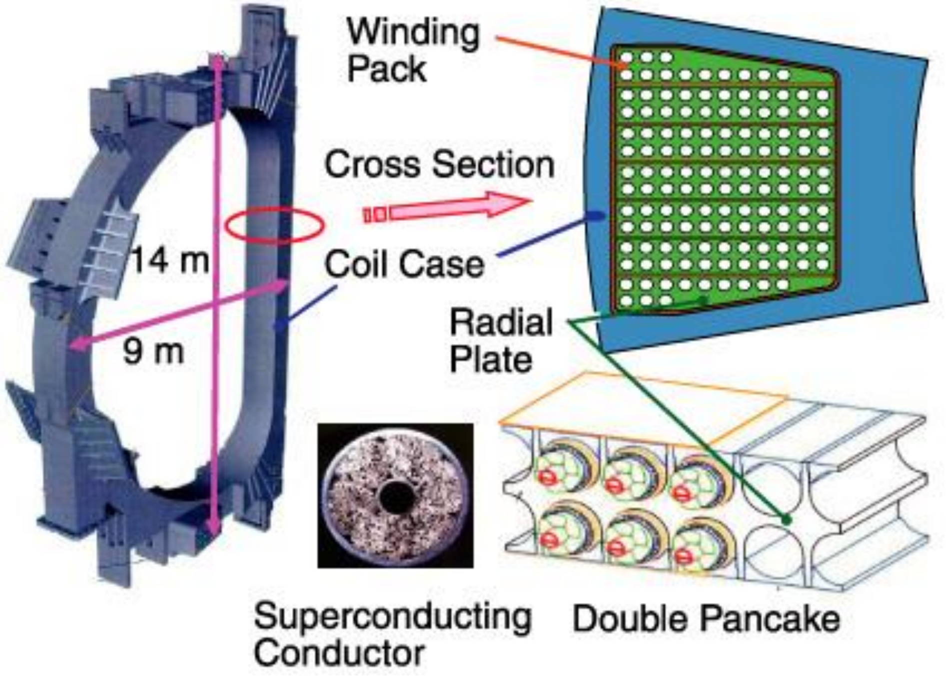
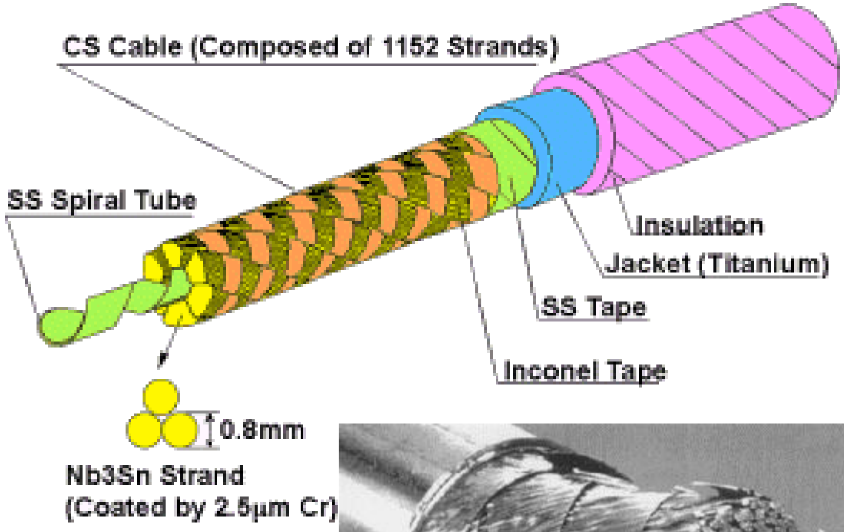
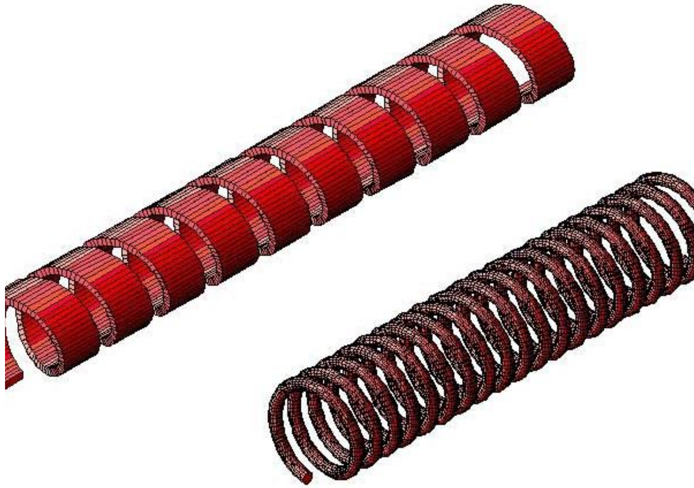
# MAGNET MODELING

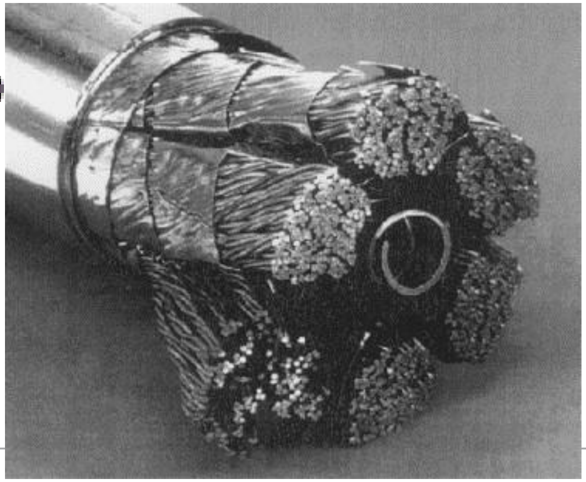
# Critical Issue for dynamic simulator

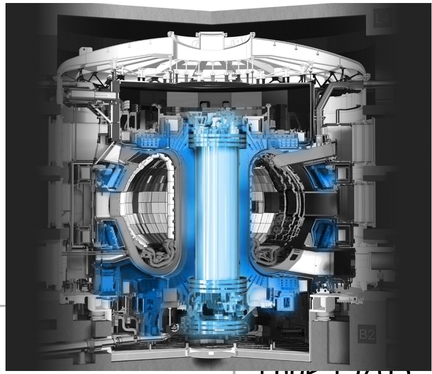
- How to model Cable-in-Conduit-Conductor (CICC)?
- N-S eqn?



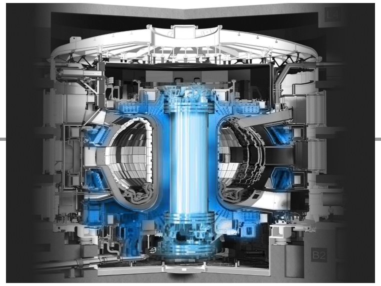



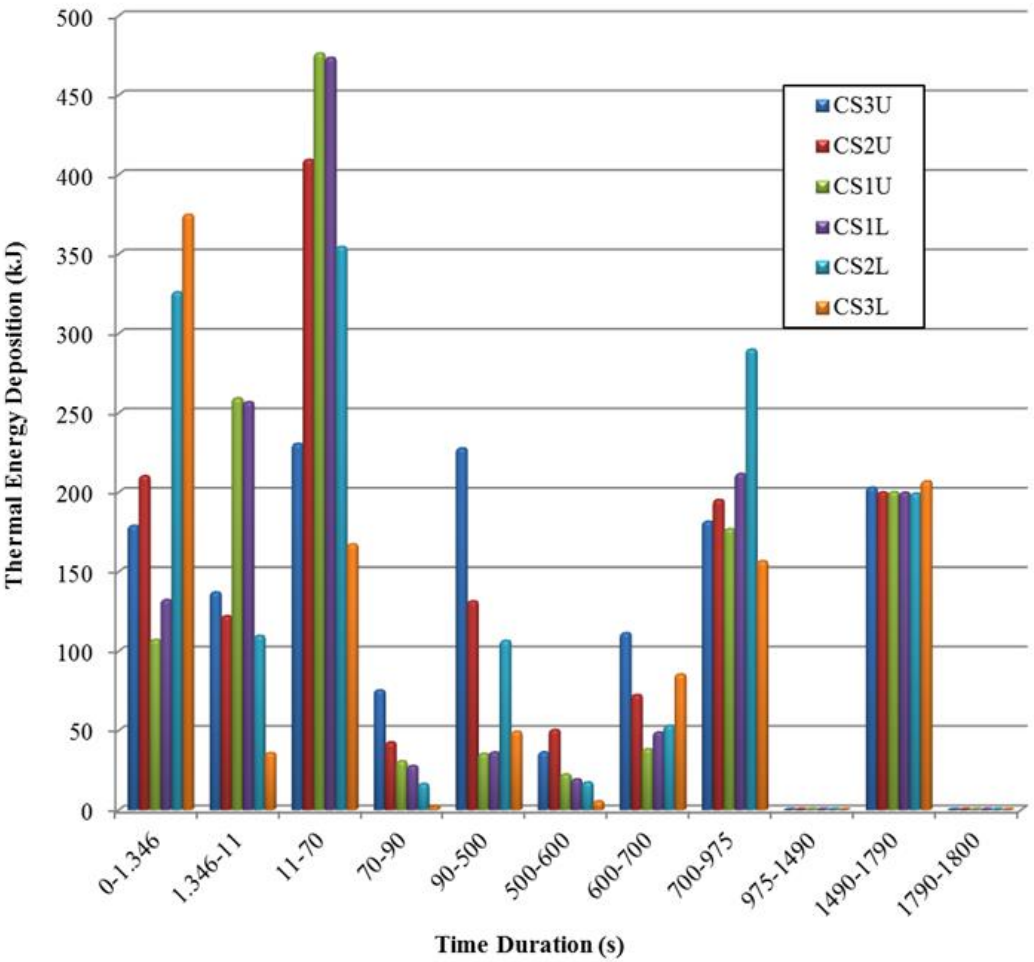


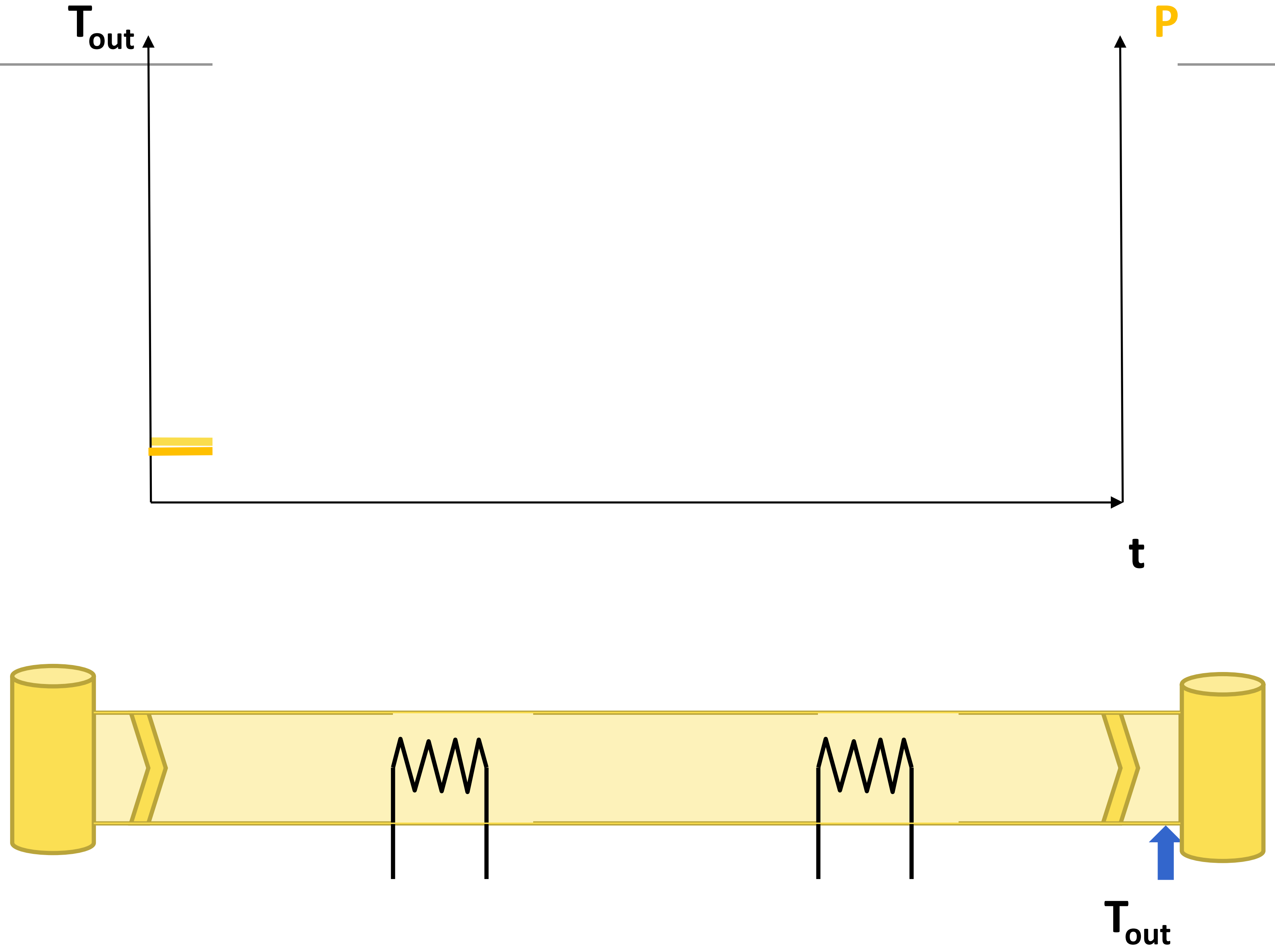


# Dynamic heat load on CS conductor



- 8 MJ in 1800 s - 50% deposition within 70 s





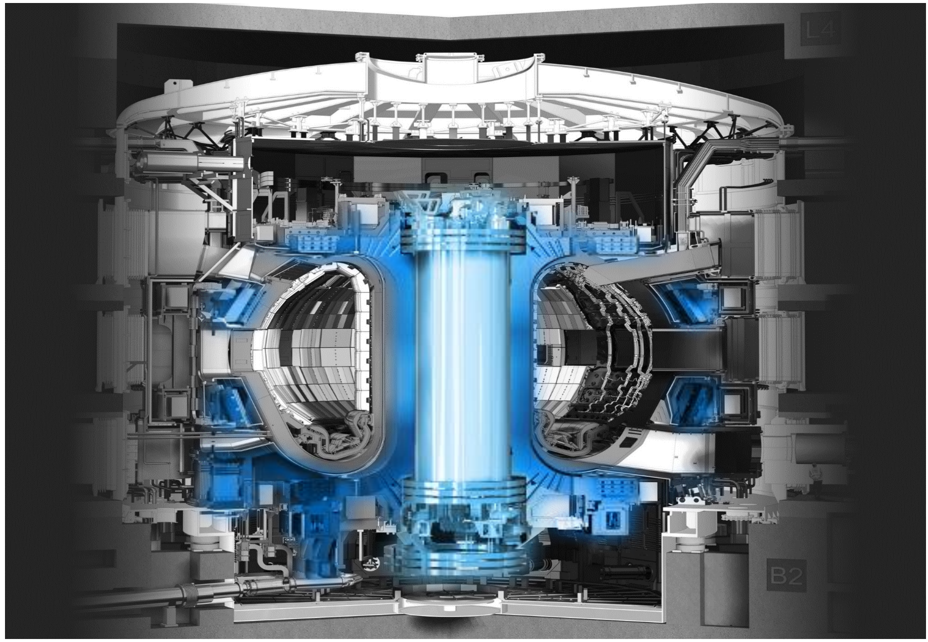

From CHATS 2011 presentation by B. Rousette CEA-Grenoble

# FORCED FLOW SHe COOLING

- Modeling of a forced-flow Supercritical Helium Cooling
  - Required for Magnet as well as structure cooling loop
  - Utilize 1st law of thermo-dynamics to describe energy balance in the loop

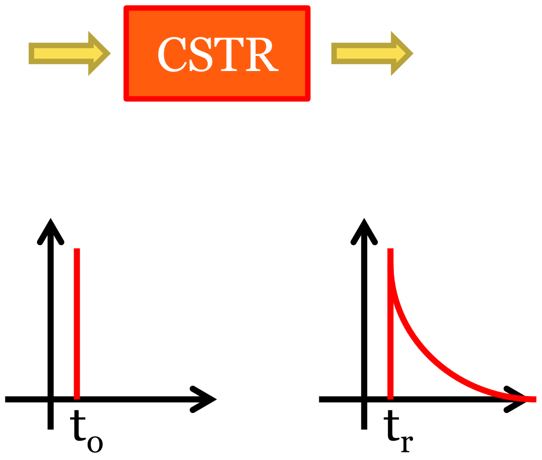
$$\dot{Q} - \dot{W} = \frac{dE}{dt}$$

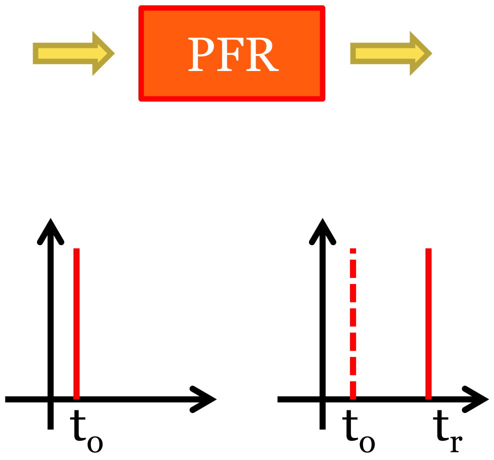
$$\dot{Q} - \dot{W} = \frac{\partial}{\partial t}\left( \int_{C-V} e\rho dV \right) + \int_{C-S} \left( e + \frac{P}{\rho} \right) \rho (\vec{v} \bullet \vec{n}) dA$$

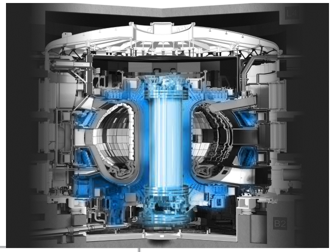


# MODELING CICC (CSTR; Continuous Stirred Tank Reactor)

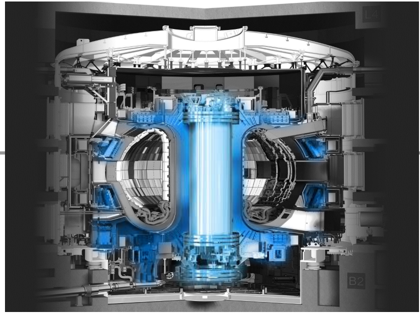
- Capture thermo-hydraulic behavior of forced flow SHe
  - Faster convergence with high accuracy
  - ST cooling (20m long), S/C cooling (>100m long)
  - CSTR MODELING to re-produce thermo-hydraulic behavior
    - QUANTIFY the rate of reaction in the given element
    - IMPULSE response (Continuous Stirred Tank Reactor/Plug Flow Reactor)

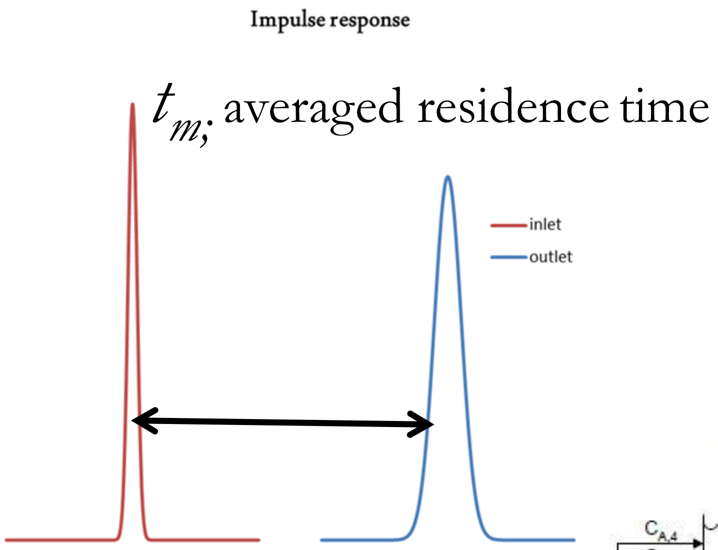


# Description of residence time and reaction






- Residence Time Distribution

$$E(\theta) = \frac{N}{(N-1)!}(N\theta)^{N-1} exp(-N\theta)$$

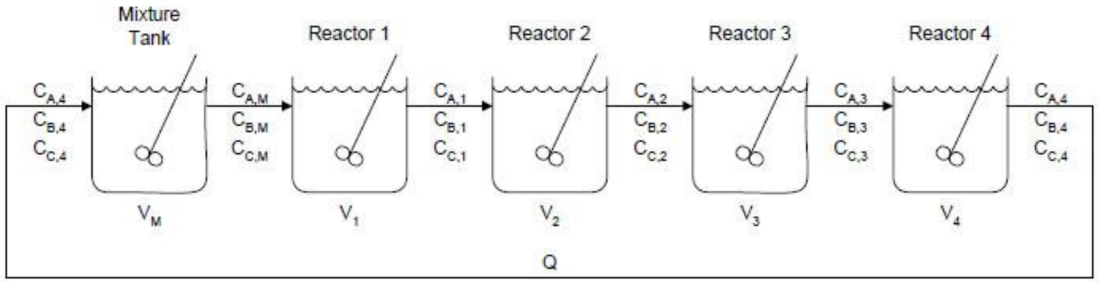
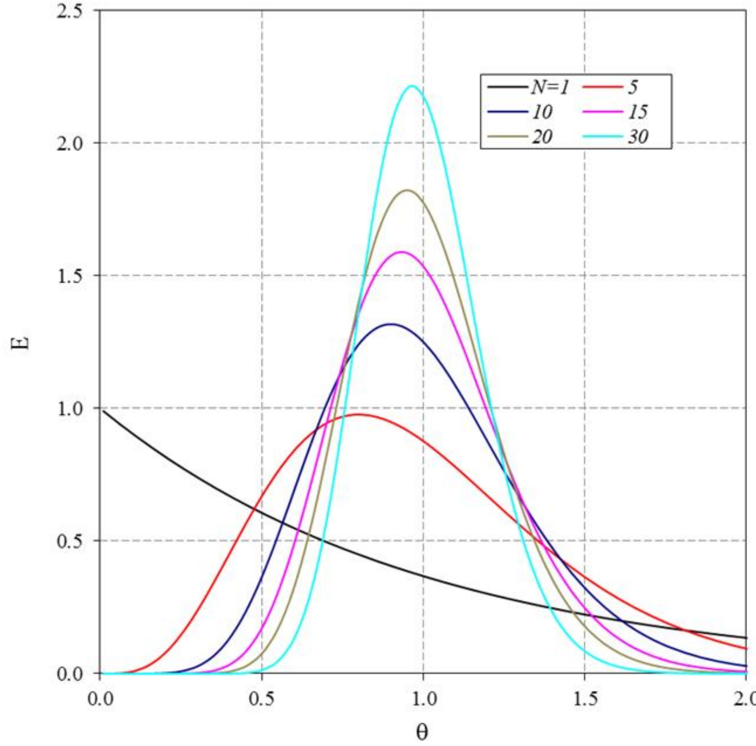
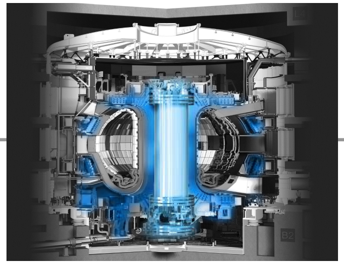


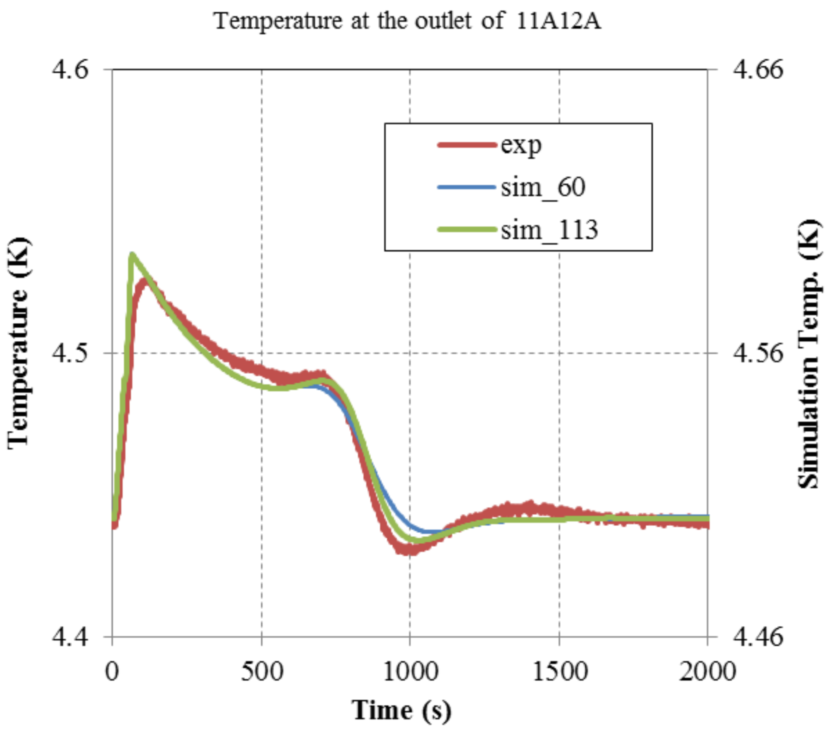

**Figure 8:** Scheme of the agitated-tanks-in-series model used for the reaction rate and adsorption constant estimation.

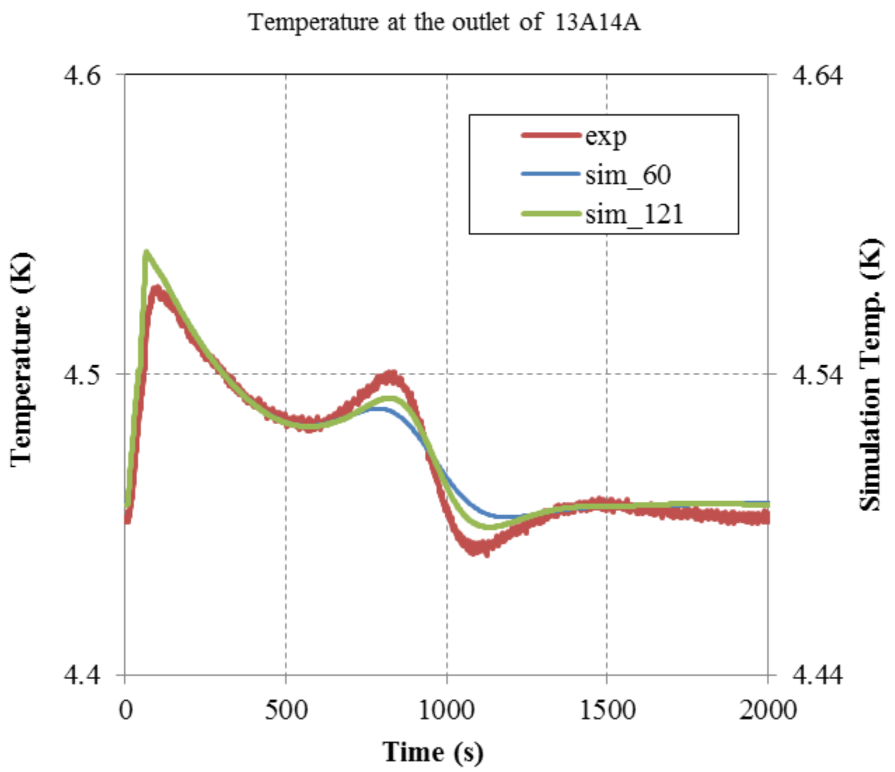


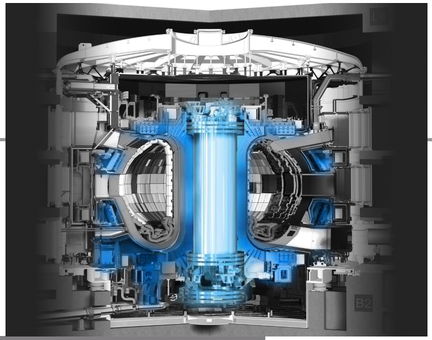
# Validation of module by CSMC test (NAKA-JARIE)

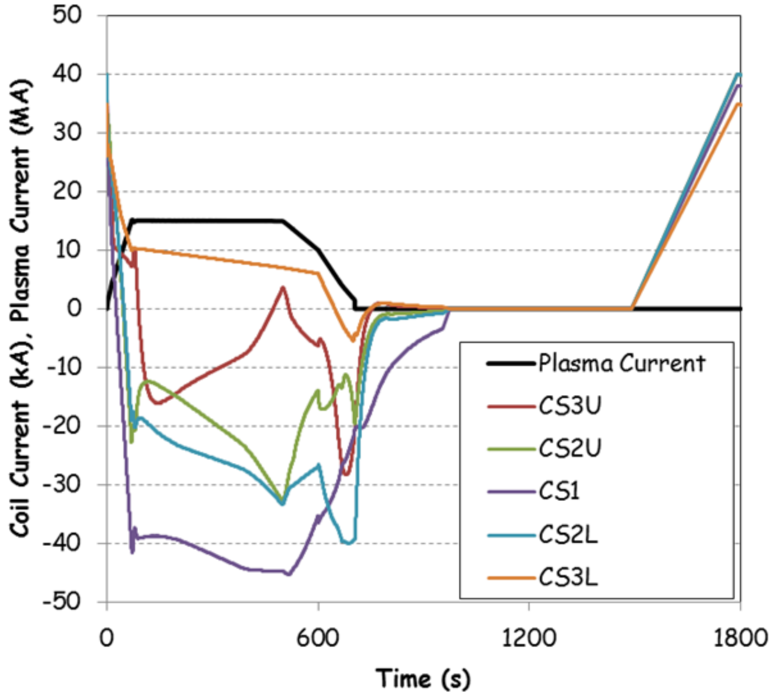


- CICC model based on # of CSTR unit connecting in series
- Temperature profile of CSMC test results compared w/ simulation

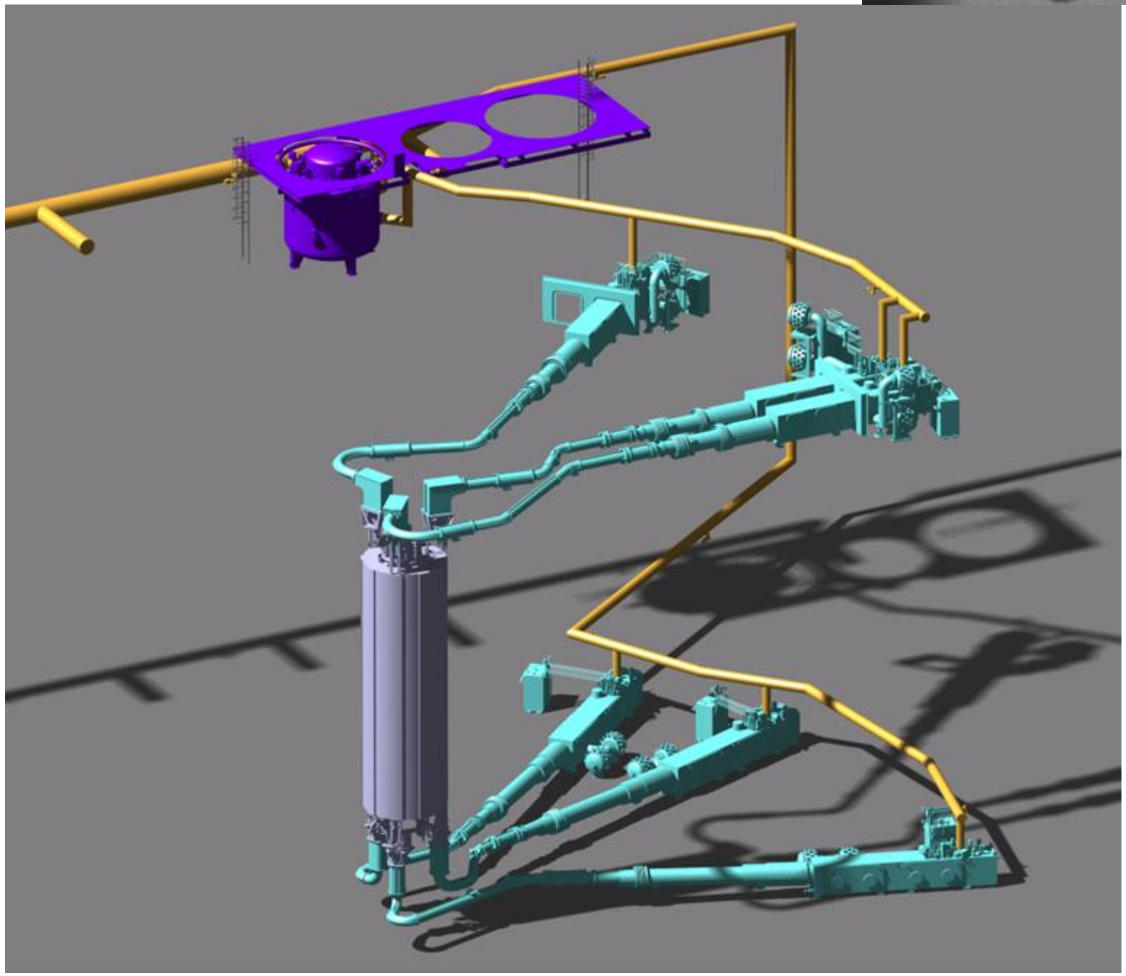




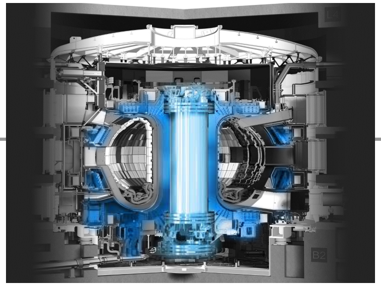



# CS SIMULATION

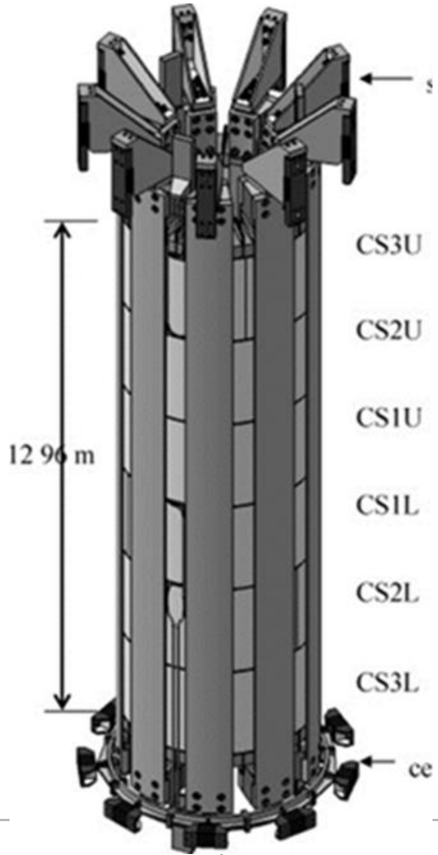


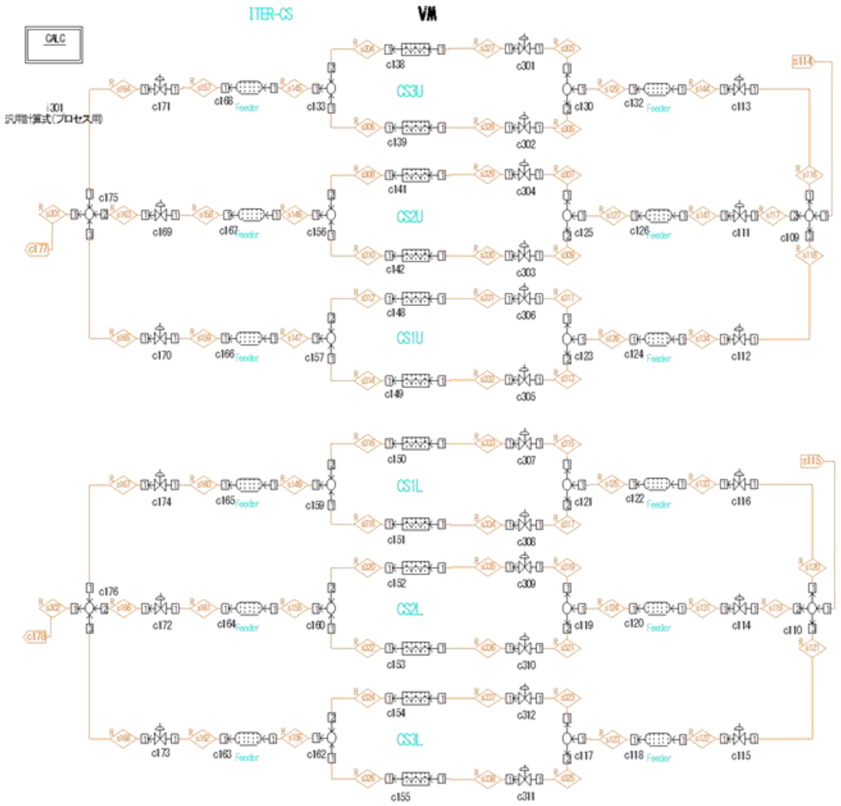
# Objective of CS process simulation

- Assess the impact on IM
  - Cold circulator operation
- Operation stability
  - Cross check functionality of ACB in terms of process control
  - Supply 4.3 K SHe to CS modules

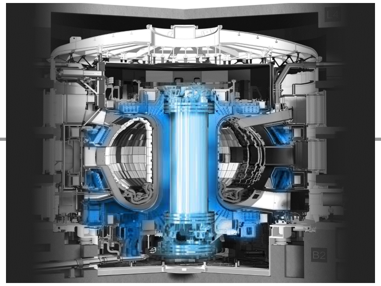


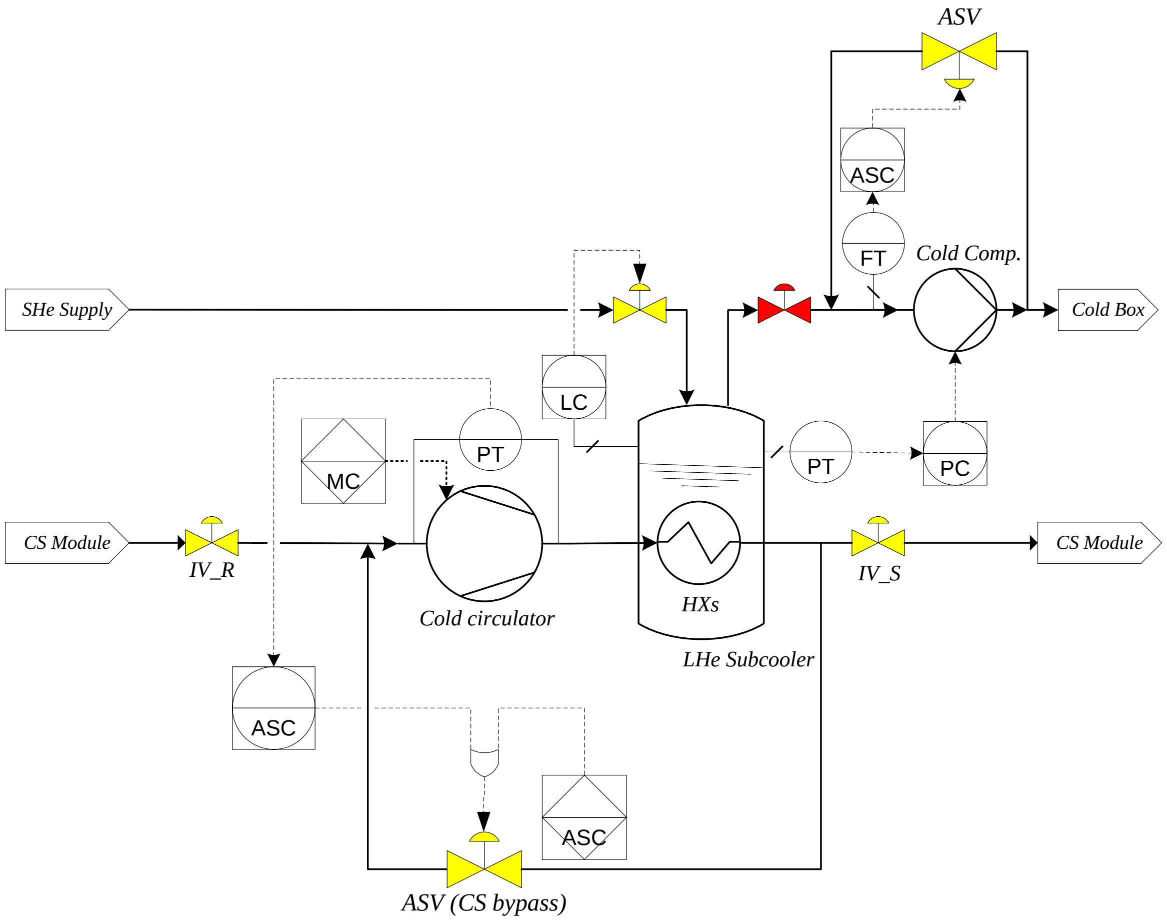
- CICC based on CSTR model
  - Spatial discretization 70 along the conductor length
  - Total of 480 discretization to capture thermo-hydraulic characteristics in CICC (CS)

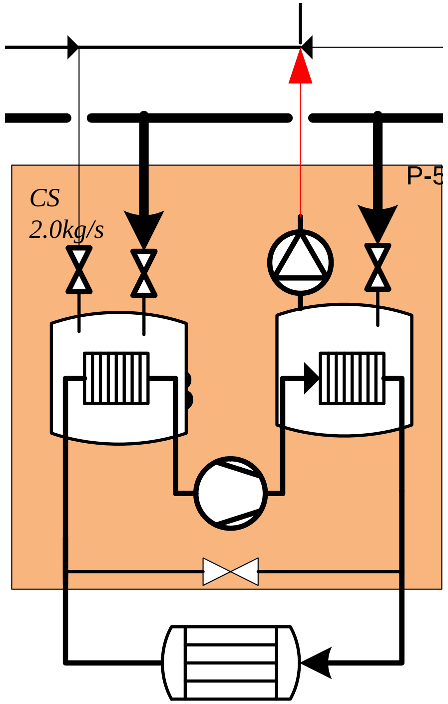


# Process control ACB






CS-17 kW

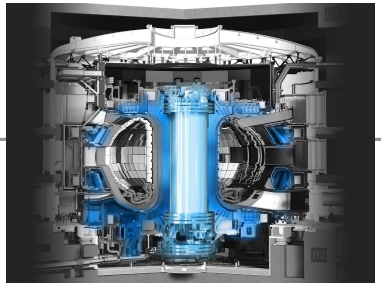
ASC: Anti-Surge Controller
PT: Pressure Transmitter
MC: Mitigation Control

ASV: Anti-Surge Valve
LC: Level Controller
FT: Flow Transmitter

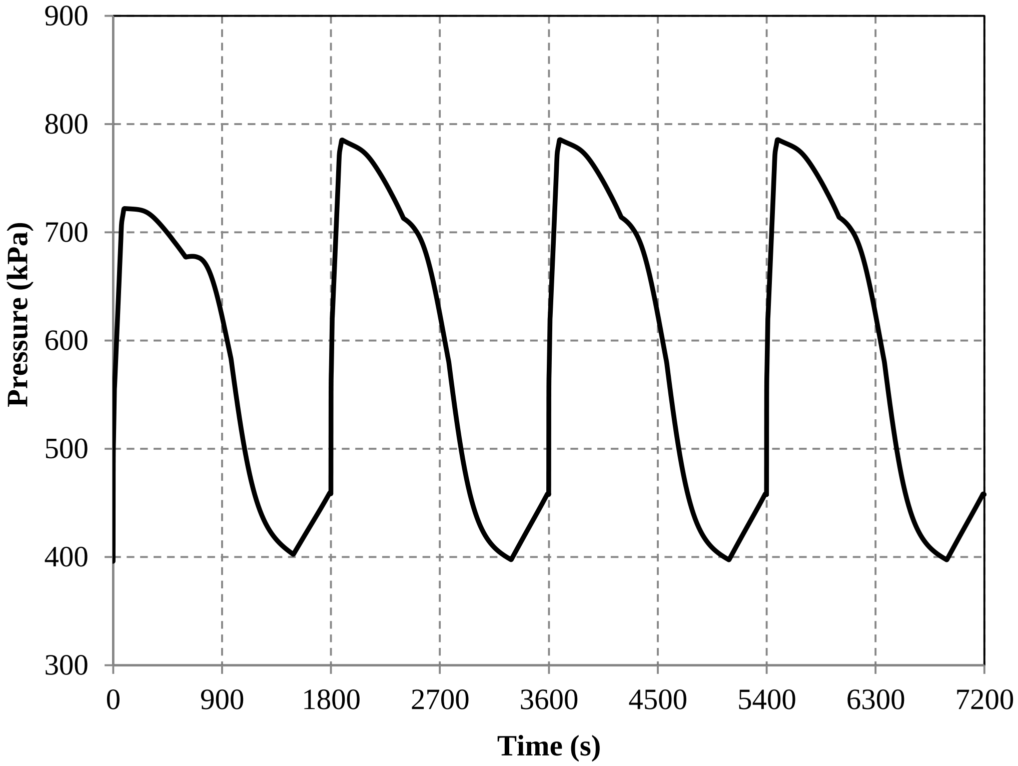
IV_S: Isolation Valve Supply
PC: Pressure Controller

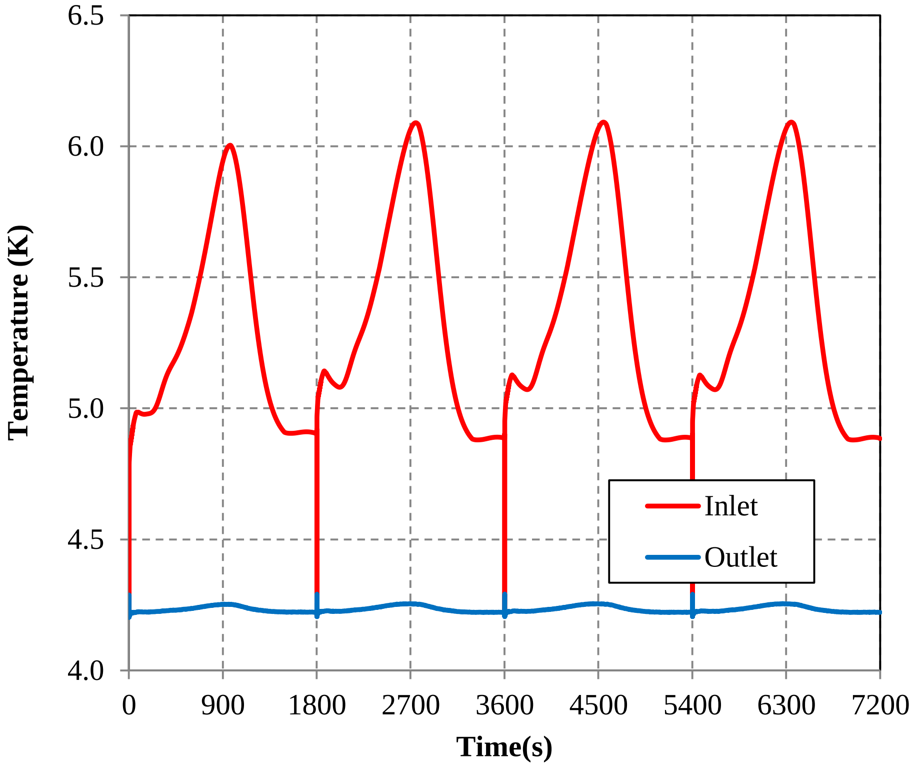
IV_R: Isolation Valve Return
HX: Heat Exchanger

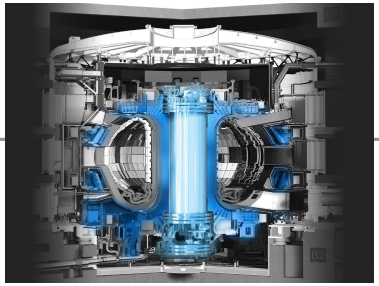
# CS cooling loop



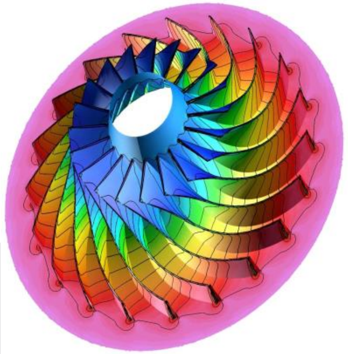
- Pressure (loop) and Temperature (at HX) variations

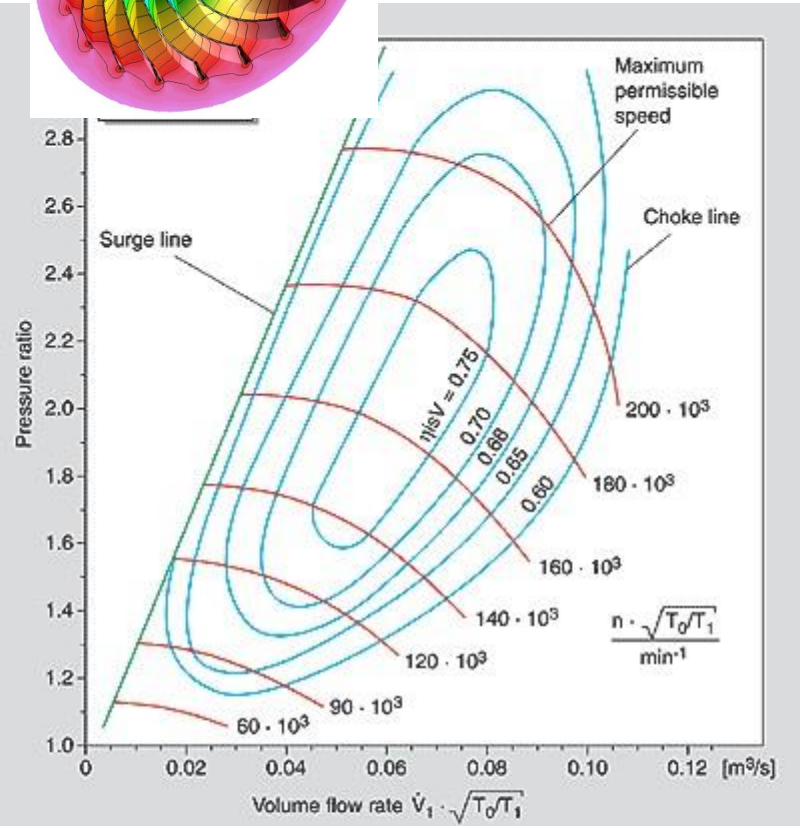


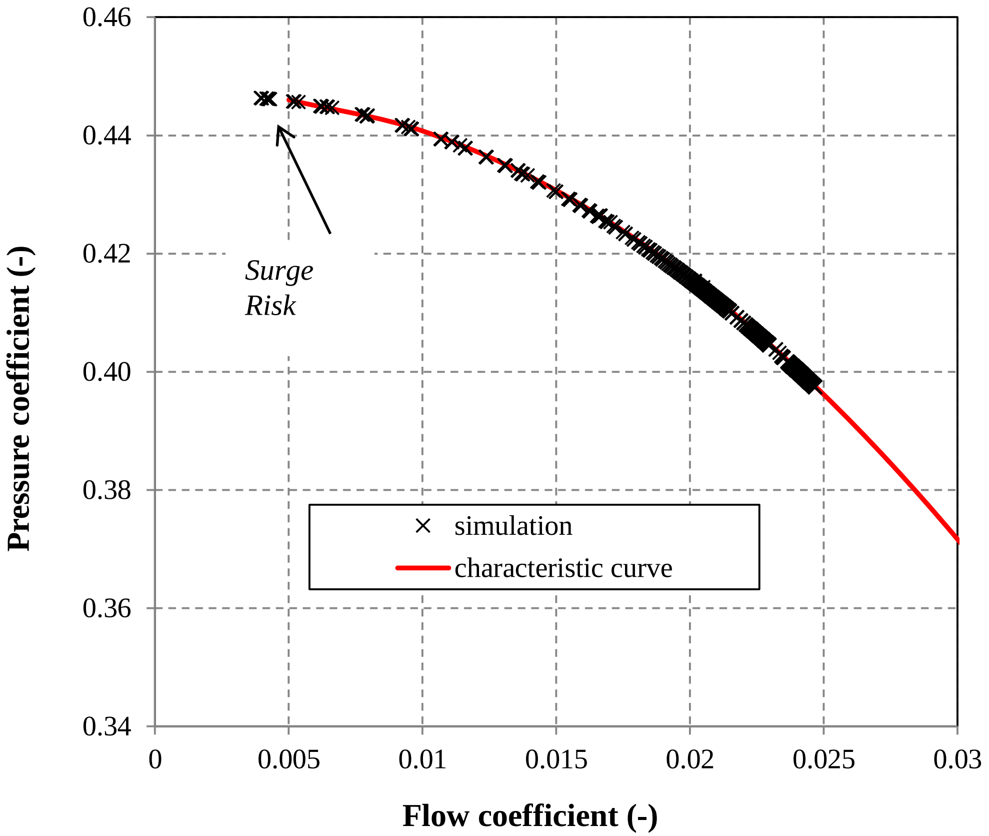


# Modeling of Cold circulator/compressor

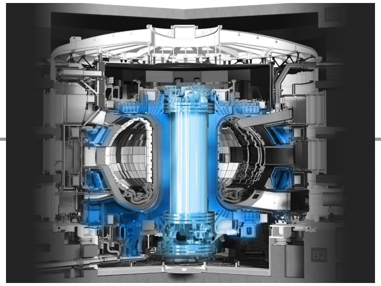




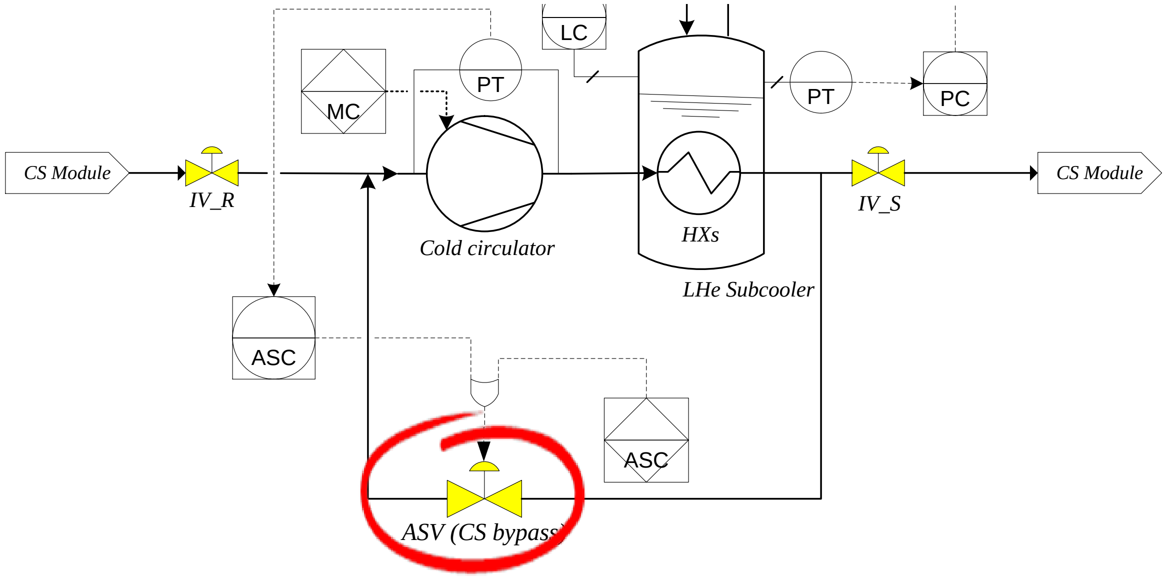

Characteristic Curve for circulator/comp. normalized



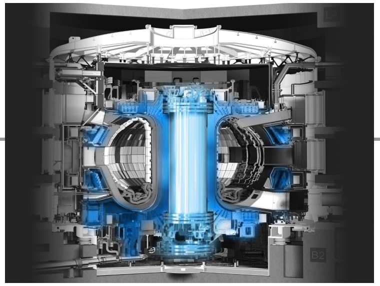
# Process control -ASV



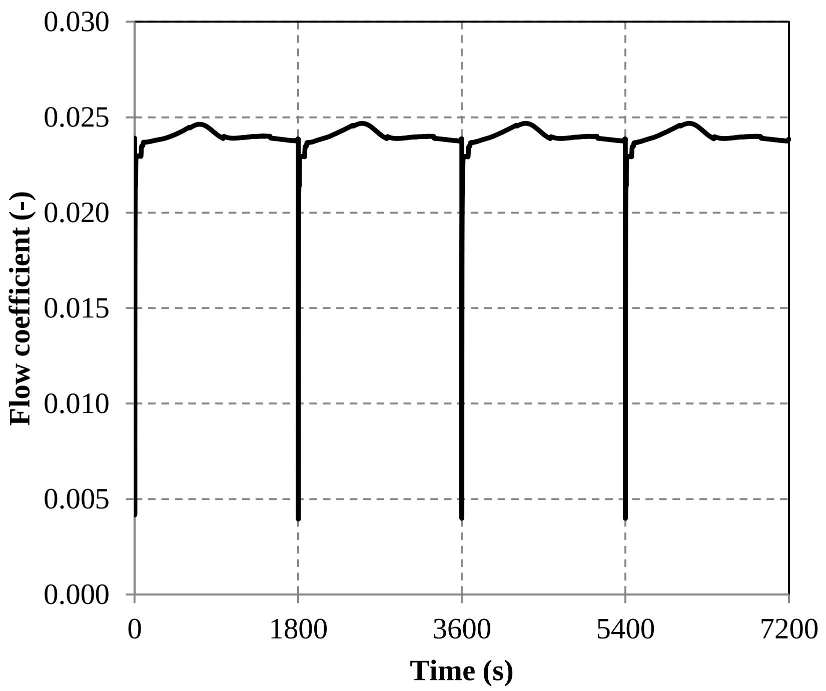
- Impose operation boundary to avoid surge
  - ASV
    - Active/passive
      - Simply open ASV at the onset of IM
      - Circulator dP regulation

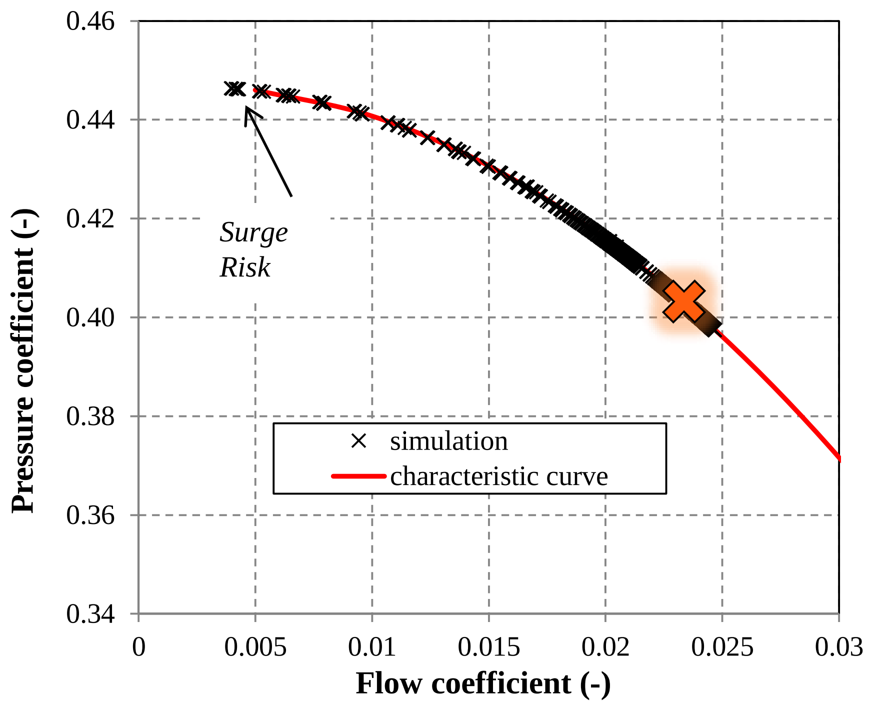


# Impact on SHe pump operation at IM



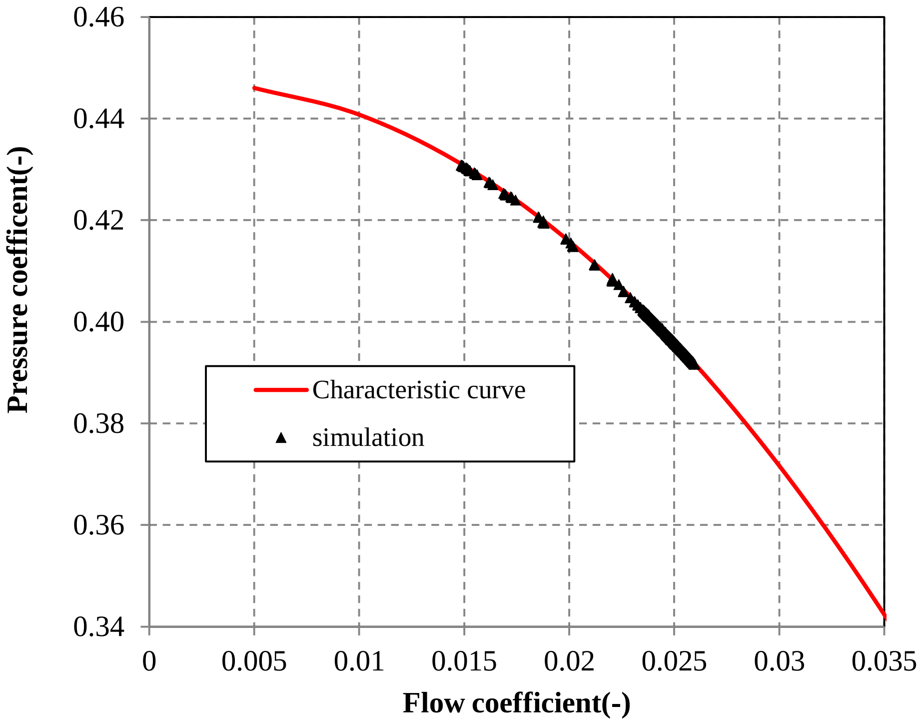
- Risk to go into surge at the IM due to drastic P increase
  - Driving operation point in a short time, a few seconds

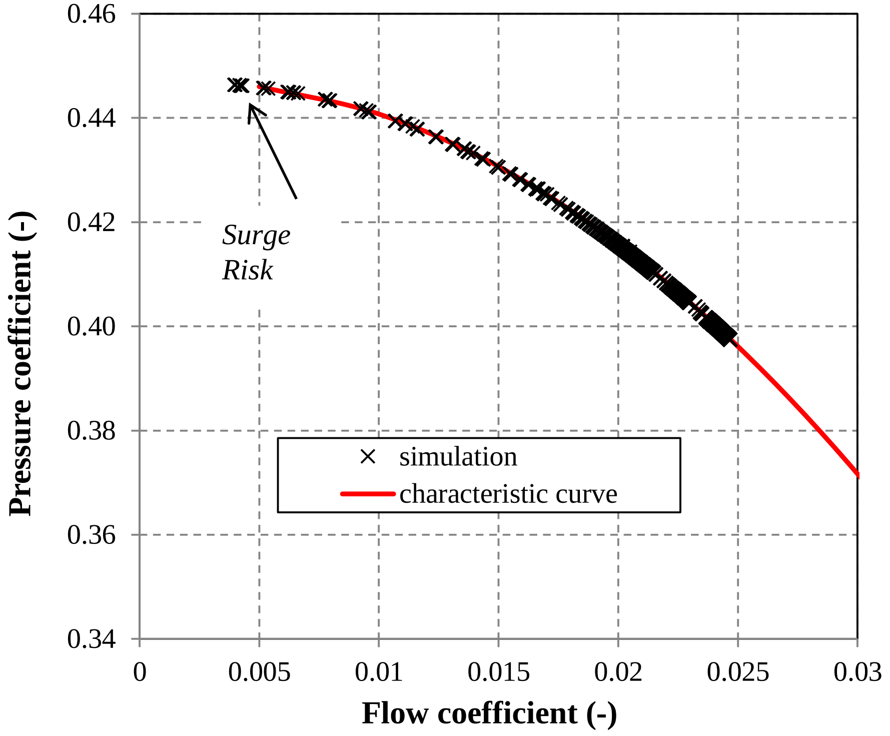


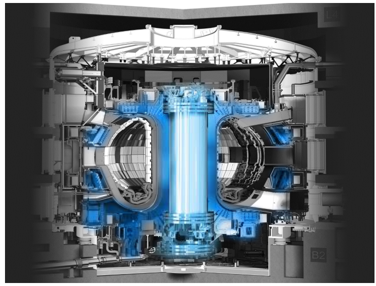



# Result of ASV

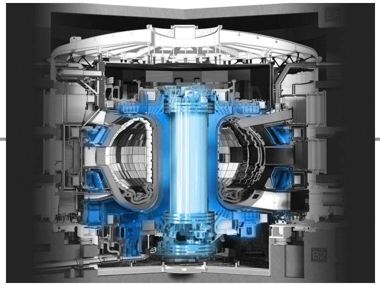
- Effective regulation via ASV to limit the operation range of SHe pump



# CS simulation brings…



- Identify the risk of operation
- Implement control logic
  - Simulation demonstrated successful mitigation of risk
  - Validation is required with the real system

# Rule of thumb!

- Model has to be validated before use!
- Simulation model represents the physical model based on the equations
- ITERATION/REVISION !!
  - SIMULATION ≠ REALITY
  - Engineering verification

# Summary-Current status

- Running global simulation under fast event
  - Plasma disruption followed by the fast energy discharge
- Complete the development for
  - He cryoplant (EcosimPro®)
    - 3 helium refrigerator operated in parallel
  - ACB (5 distribution boxes) (EcosimPro® & Visual Modeler®)
  - Superconducting magnet system (Visual Modeler®)
    - TF
    - TF structure (TF coil case + support)
    - CS
    - PF/CC
    - Benchmark against SUPERMAGNET®