# Dynamic simulation of the first cool down of the JT-60SA cryo-magnet system

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Creation of Harmonious Diversity

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# Context

In framework of the ITER Broader Approach research and development for fusion activities, involving Japan and Europe, the JT-60SA tokamak integrated commissioning started mid 2020 with a Japanese and European integrated team, following the assembly completion (March 2020).

The cool-down from 300 K to 4.5 K took more than one month following the requirements for cool-down speed and thermal gradients.

Dynamic simulations were performed during the cool down to support the operation and to optimize the cool-down process.

The first cool-down of the JT-60SA magnet system is presented and compared with simulation results performed with SIMCRYOGENICS models. SIMCRYOGENICS is the simulation library developed by CEA (Low Temperature Systems Department) on a Matlab/Simulink platform for modelling cryogenic processes.

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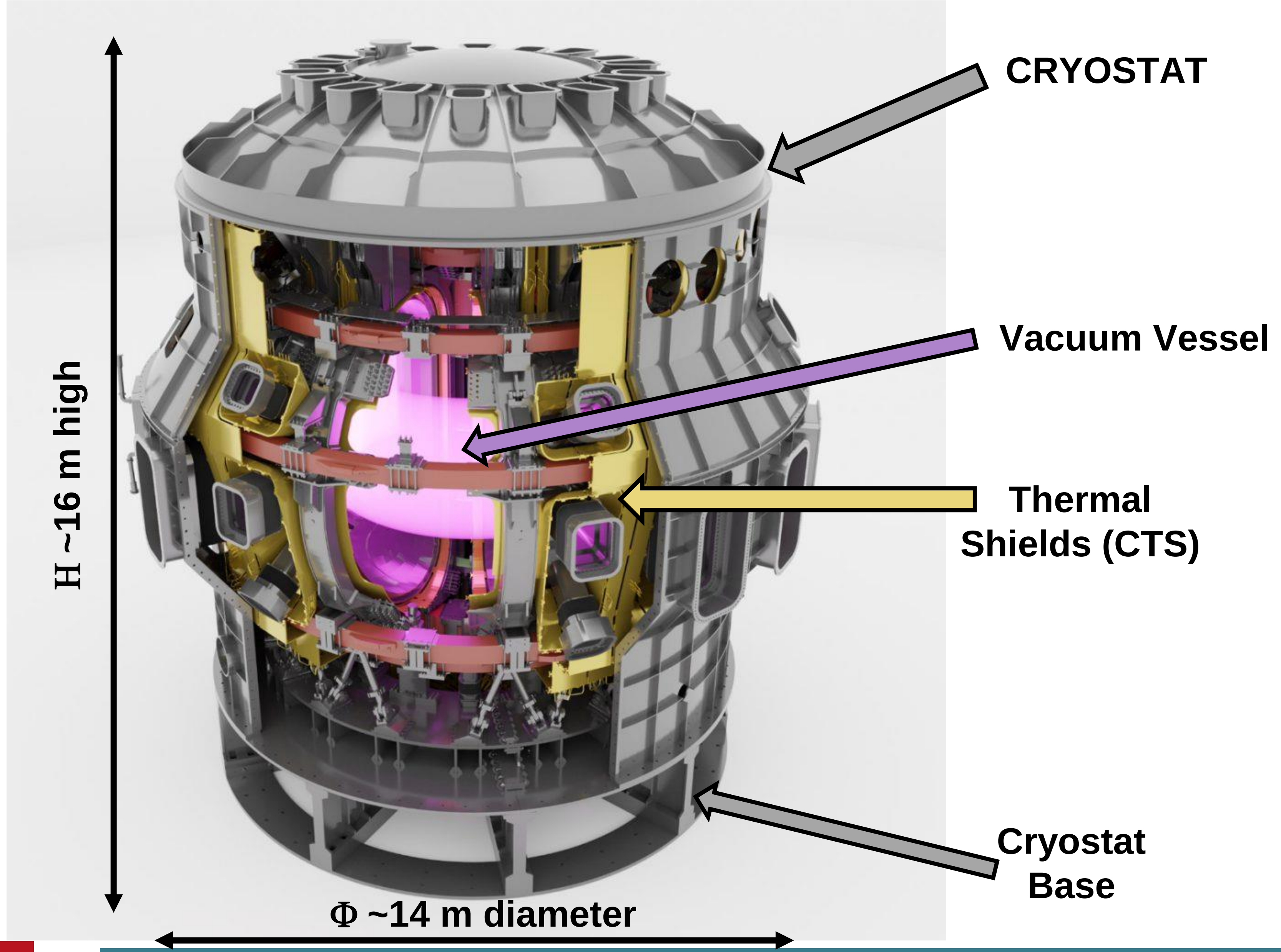
# The JT-60SA tokamak

The JT-60SA supraconducting tokamak was built on the QST Naka site (Japan, Ibaraki prefecture) in the framework of the Broader Approach Agreement between Japan and Europe signed in February 2007.

The JT-60SA tokamak fusion project aims to support the exploitation of ITER in resolving essential physics and engineering issues for DEMO reactors. DEMO is the advanced phase towards the industrial-scale fusion reactor.

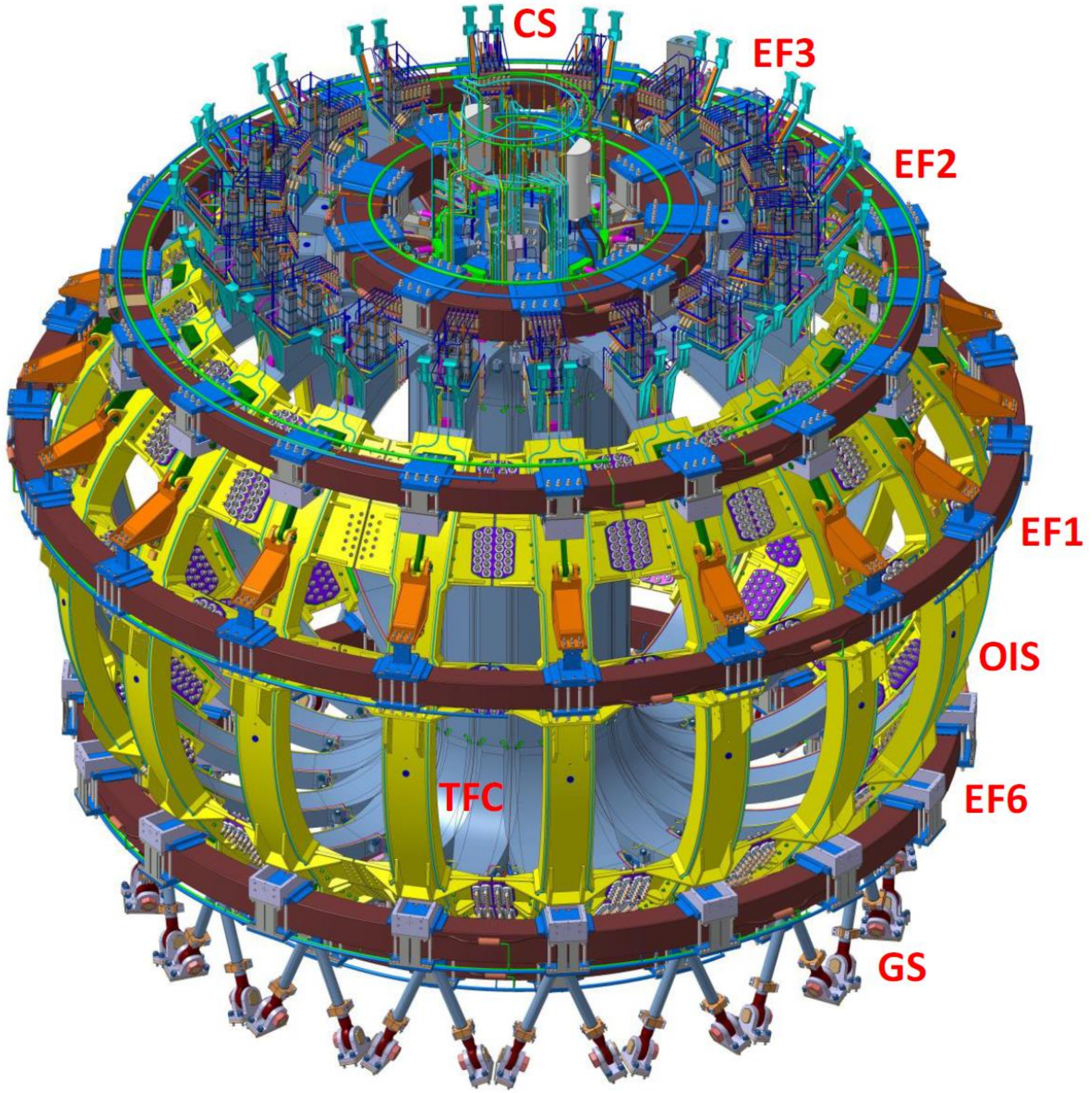




*Comparison of the plasma volumes : Courtesy from F4E*

# The JT-60SA magnet system

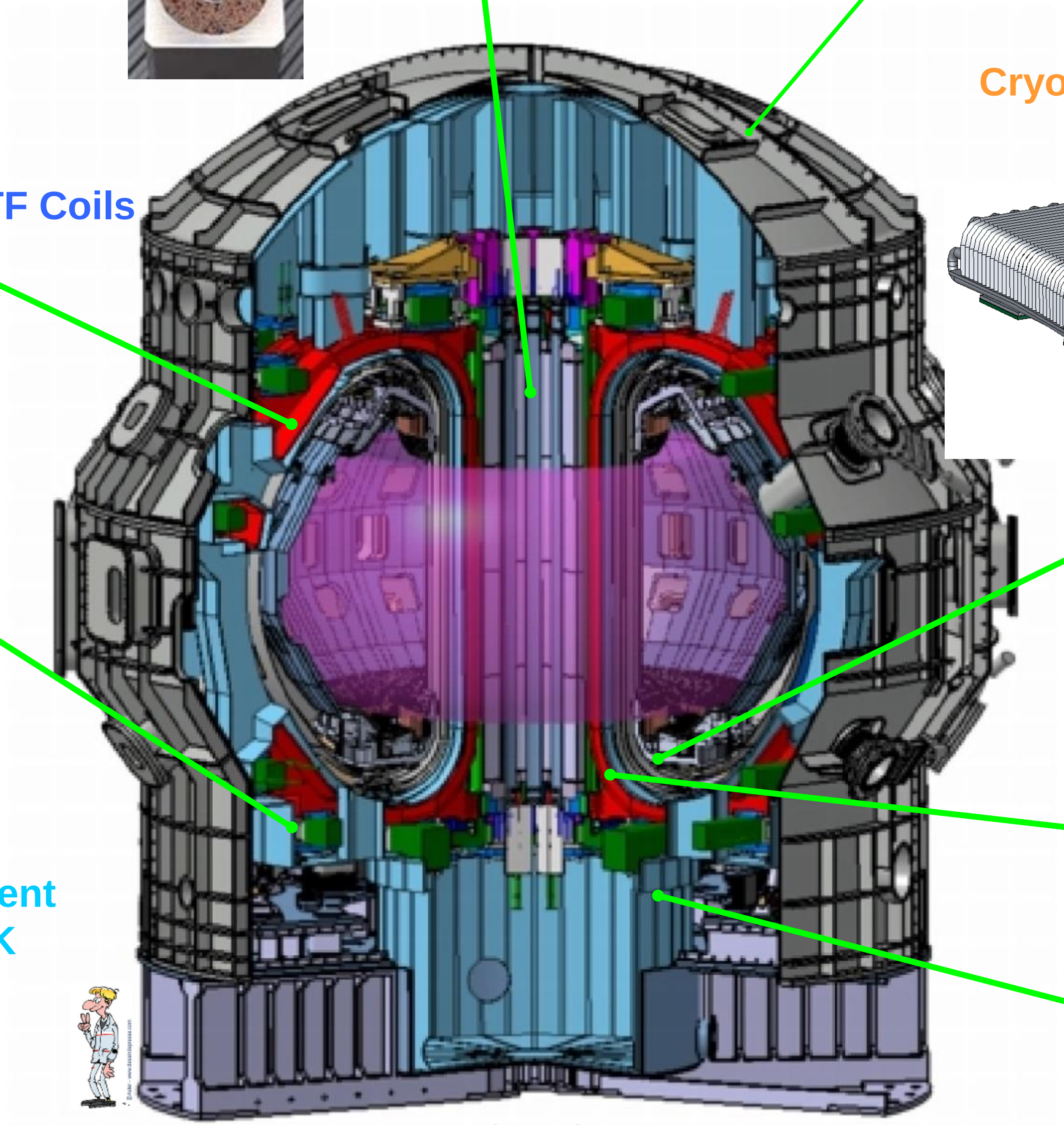
- 18 TF coils (NbTi)
  - Magnet energy of the 18 TF coils 1.06 GJ
  - Max field at conductor 5.65 T
  - Total Weight ~ 420 Tons
  - Nominal current 25.7kA
- 4 CS modules ($Nb_3Sn$)
  - Peak field 8.9 T
  - Total Weight ~ 100 Tons
  - Operating current 20kA
- 6 EF coils (NbTi)
  - Peak field 4.8T (6.2T for EF3/EF4)
  - Total Weight ~ 178 Tons
  - Operating current 20kA
- Current Leads 26 HTS-CL
  - 6 HTS-CL for TF coils
  - 8 HTS-CL for CS coils
  - 12 HTS-CL for EF coils



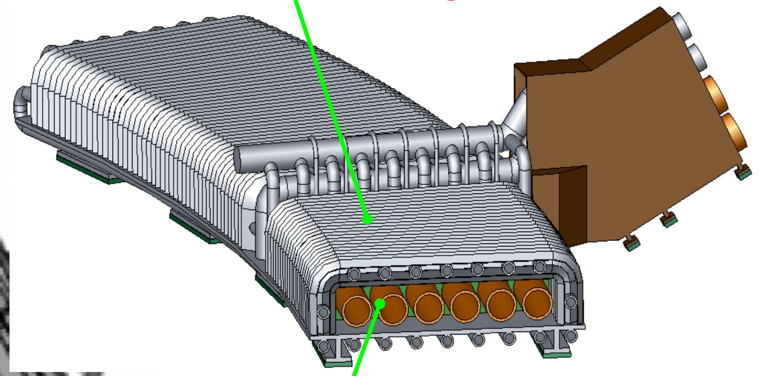

**TOTAL cold mass to cool-down until 4.5K (~700 Tons)**

# The JT-60SA cryogenic system: The main cryogenic users

Cable-In-Conduit Conductors (CICC)

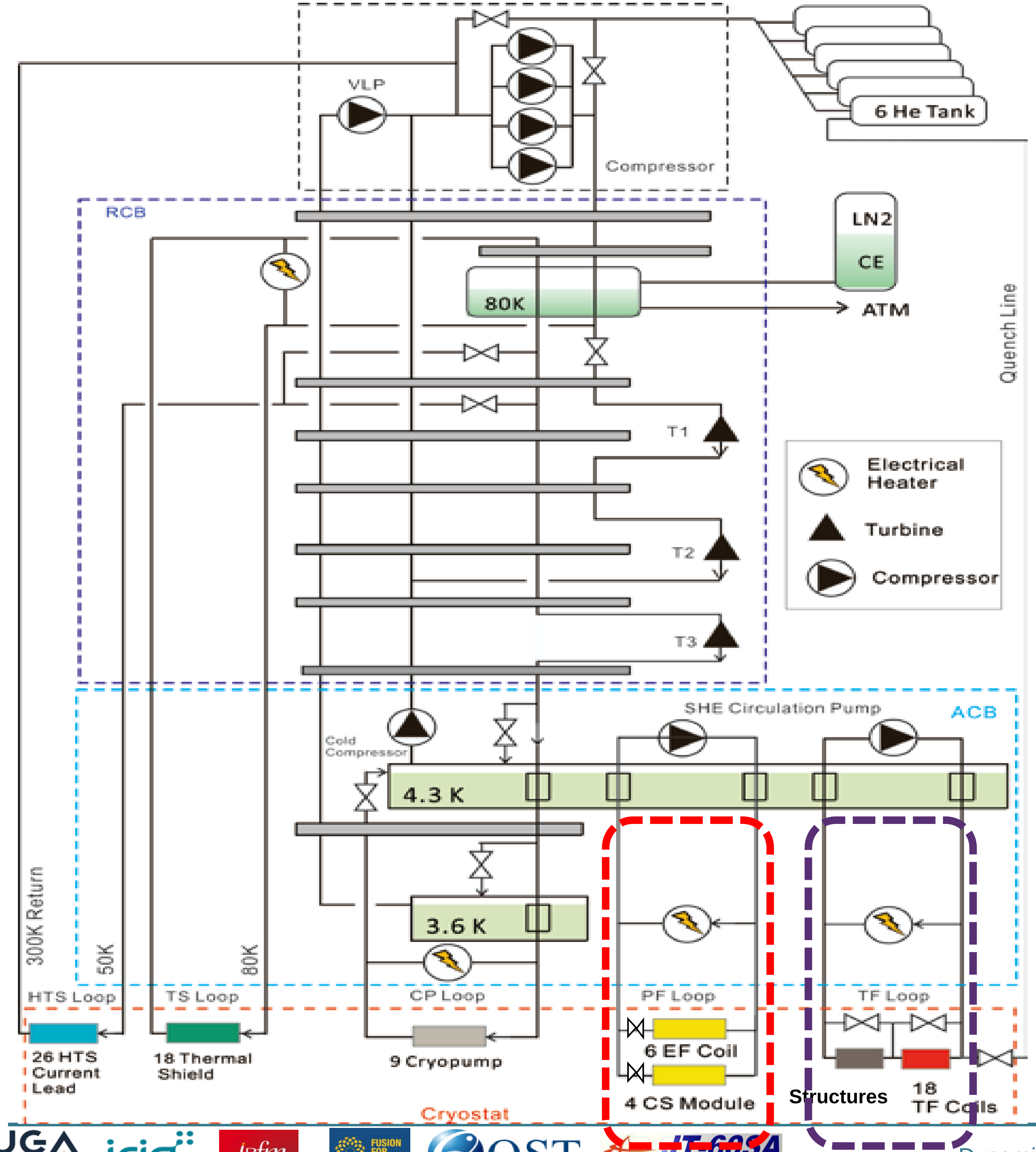



JT-60SA Tokamak




# The JT-60SA cryogenic system: The magnet cooling loops

Cryoplant power ~ 9kW eq. @ 4.5 K

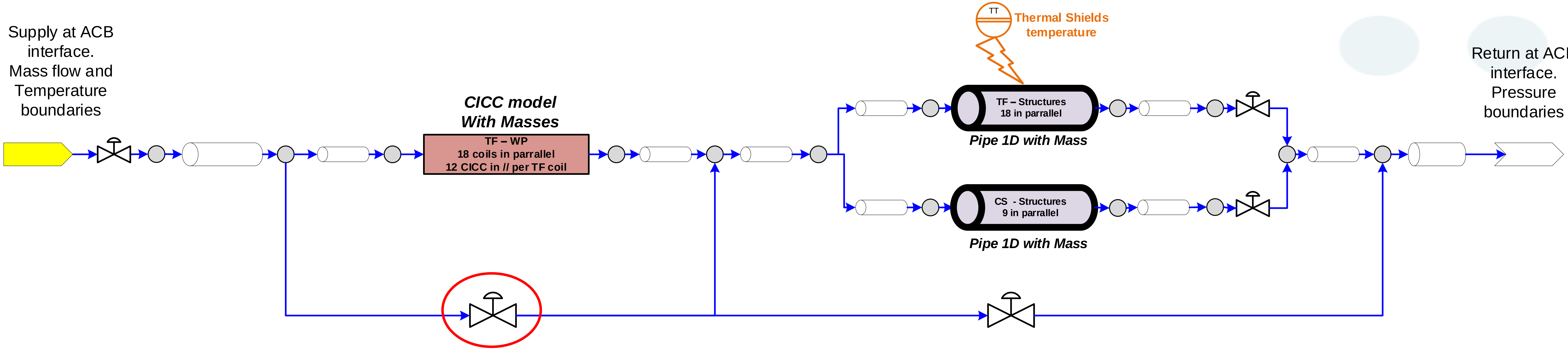



- **2 independent models had been developed for Cool-Down simulation using SIMCRYOGENICS**
- **1 model for the loop 1 dedicated to TF coils and structures and 1 model for the loop 2 dedicated to the EF and CS coils.**
- **Simulations are performed from 300 K to 5 K**
- **Boundary conditions for the simulation models:**
  - Supply boundary conditions: Temperature and mass flow rate imposed, based on real measurement all along the JT-60SA cool-down
  - Return boundary condition: Pressure imposed based on the real measurement all along the JT-60SA cool-down
  - Opening of the main process valves was based on the real valve opening measurements: except the number of changes reduced to ease the simulation
  - Thermal Shield temperatures used for the radiation heat loads estimates on TF Structures, EF coils

- **Cryoplant not included in the models.** (models include the magnet cooling circuits, cryodistribution from Auxiliary Cold Box (ACB))

# SIMCRYOGENICS Simulation models 1/2

## Simplified scheme of the Loop 1 simulation model

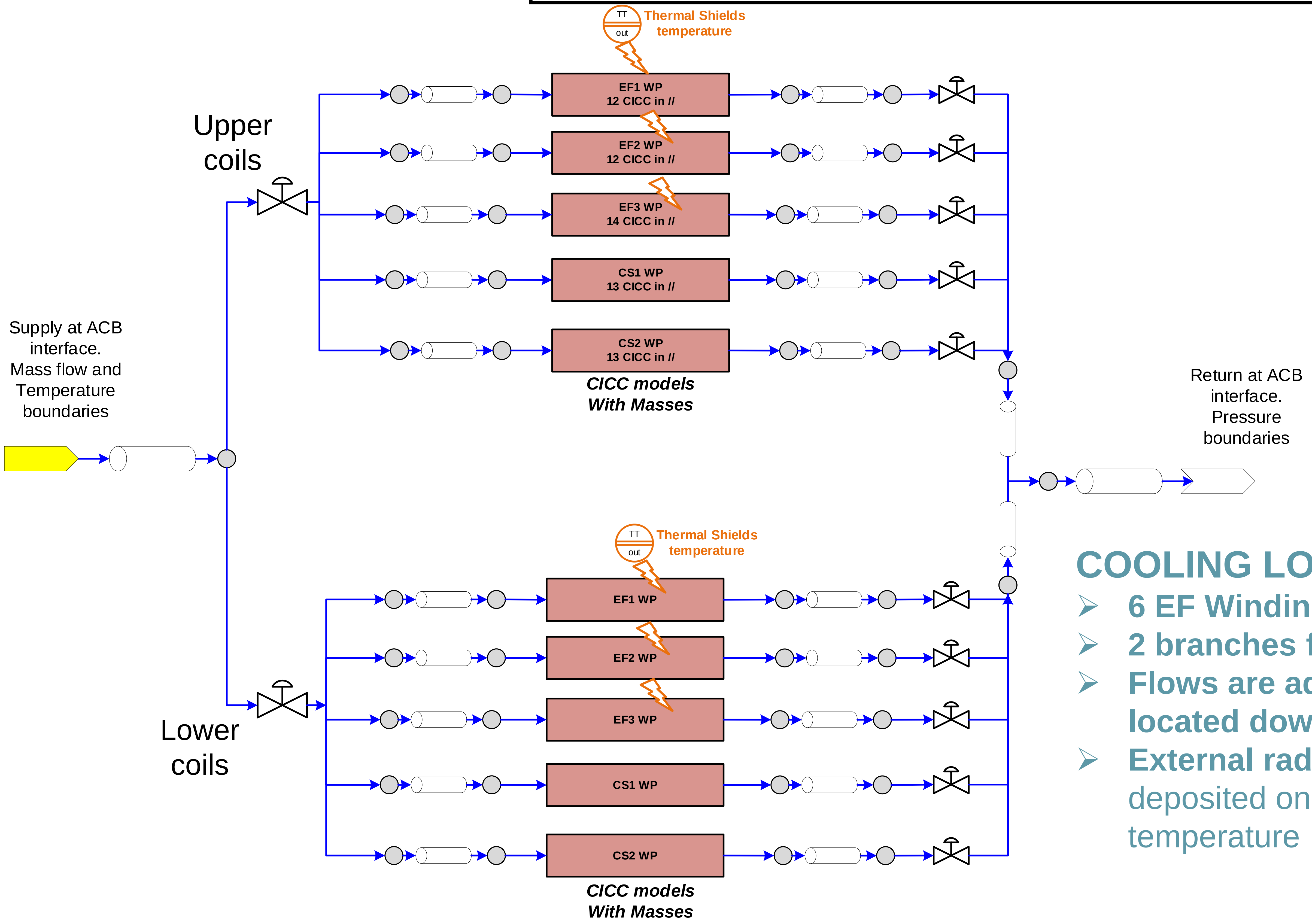



## <u>COOLING LOOP 1</u>: For TF coils and Structures

- **18 TF Winding Packs cooled in parallel** (12 conductors in // per TF coil)
- **Structures cooled in series with TF winding packs** (18 TF structures in parallel with 9 CS structures)
- **During cool-down, the full mass flow rate is required through structures** (larger masses and radiation heat loads) **and only ~1/3 to the TF-WP using the by-pass valve** (opposite to normal operation at 4.4K where larger flow goes to winding packs)
- **Radiation heat loads deposited on TF structures based on the Thermal Shields temperature measurement.**

# SIMCRYOGENICS Simulation models 2/2

## Simplified scheme of the Loop 2 simulation model




## COOLING LOOP 2: For EF and CS coils

- **6 EF Winding Pack and 4 CS Winding Pack in parallel**
- **2 branches for upper and lower** Poloidal Field Coils
- **Flows are adjusted for each coil by control valves located downstream each coil**
- **External radiation heat loads during cool-down** deposited on EF coils based on the Thermal Shields temperature measurements.

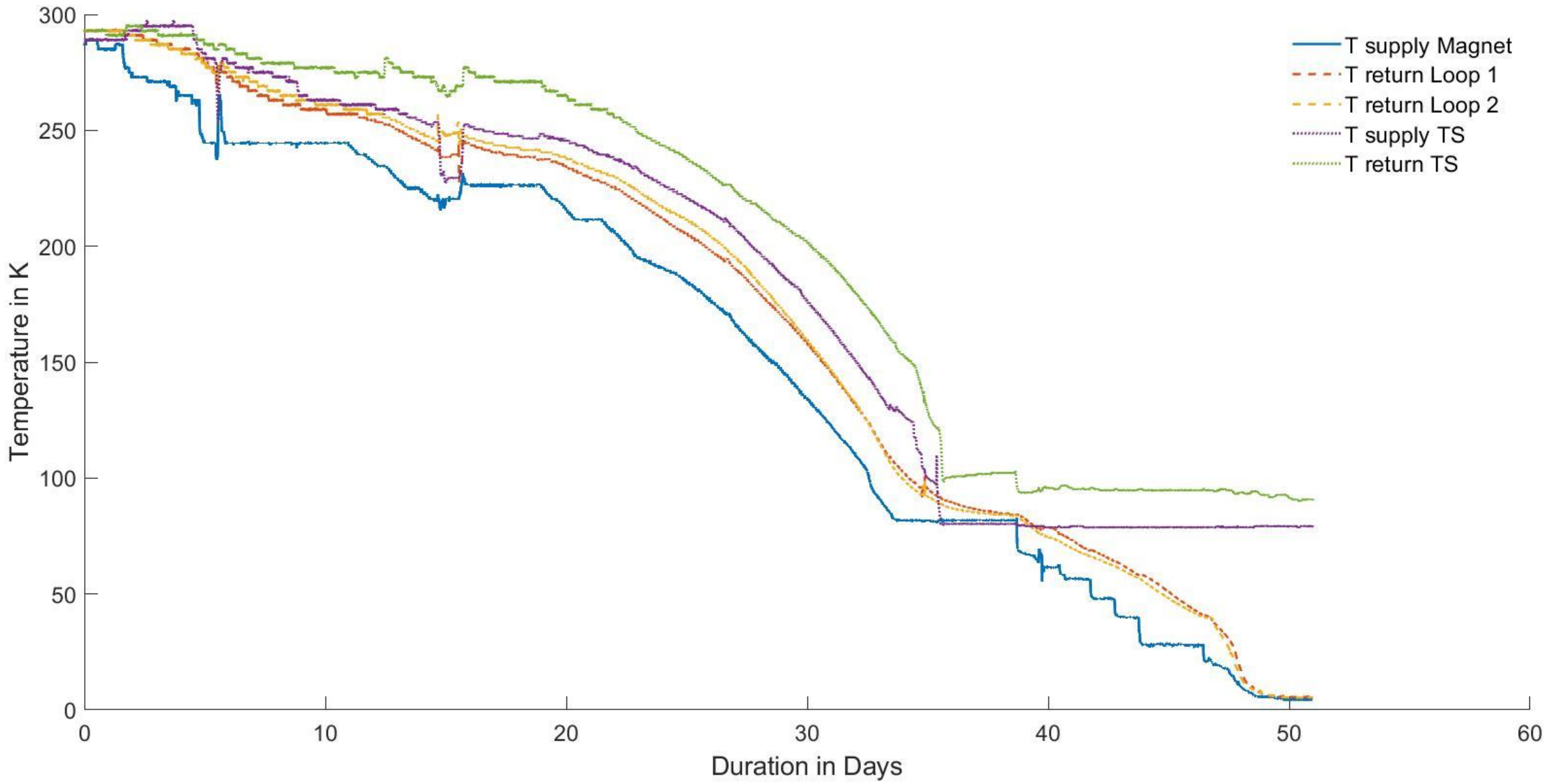
# The JT-60SA tokamak cool-down

## Main cool-down requirements

- Cool-down speed shall not exceed 1 K/h (**nominal cool-down speed is 0.6 K/h**) cool-down expected duration 20 days
- The temperature difference between inlet and outlet of thermal shields and coils should be less than 40 K
- The temperature difference between thermal shields and coils shall be kept within 50 K with the **thermal shield always warmer than the coils** in order to protect the shield surfaces from frozen impurities

## Main cool-down performances reached

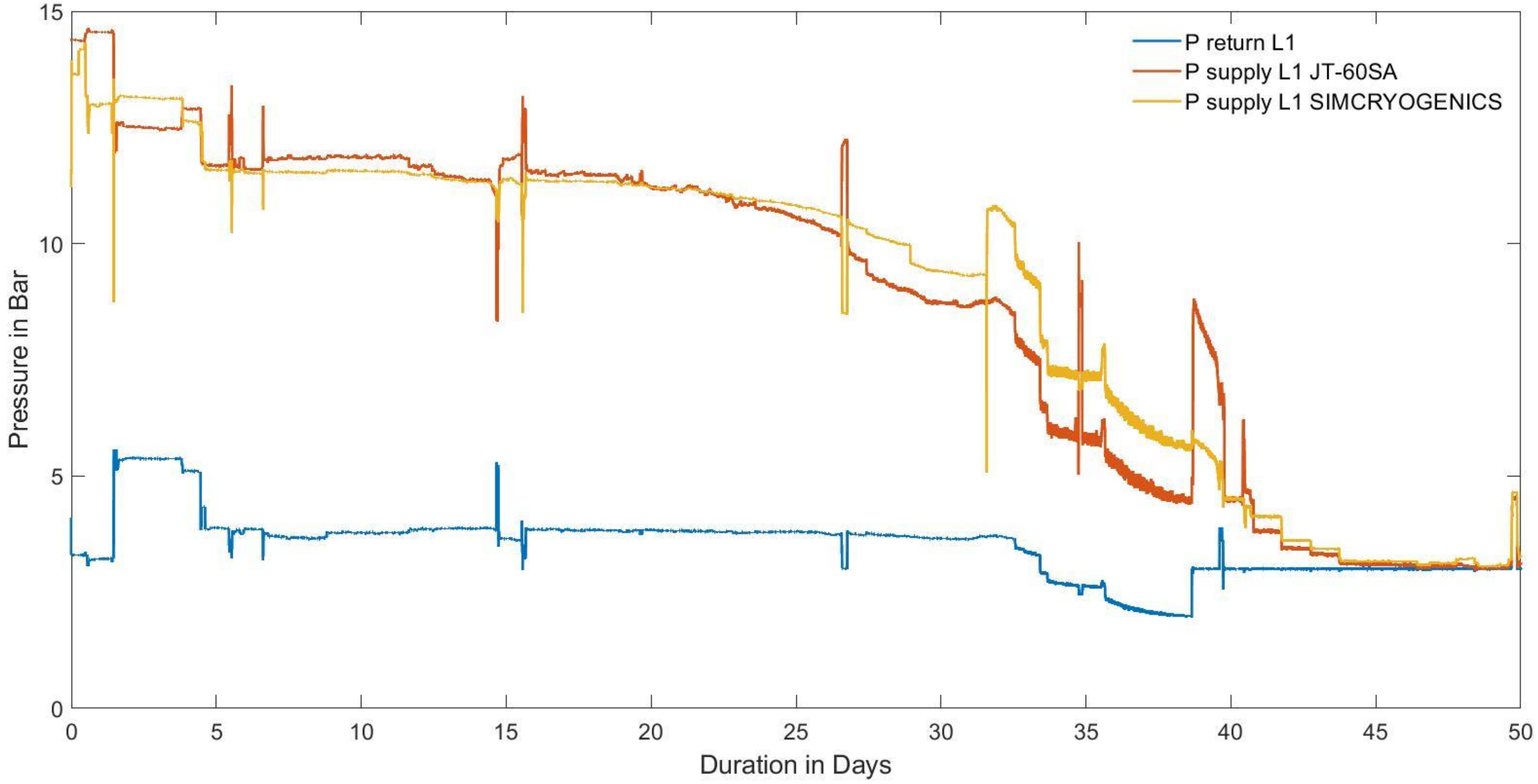
- This first cool-down of the JT-60SA was also used to check and assess the procedures, the instrumentation and the associated controls: we spent about 14 days of stop for checking instrumentation and various systems
- The tokamak cool-down took place in 47 days with 33 active cooling days. Therefore, the average cool-down speed was about **0.37 K/h** (based on active days).
- This cool-down was fully compliant with protection requirements concerning magnets and thermal shields (even more conservative requirements had been applied, which also impacted the cool-down speed).



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

**Pressure comparison on Loop 1 for TF-WP and structures**

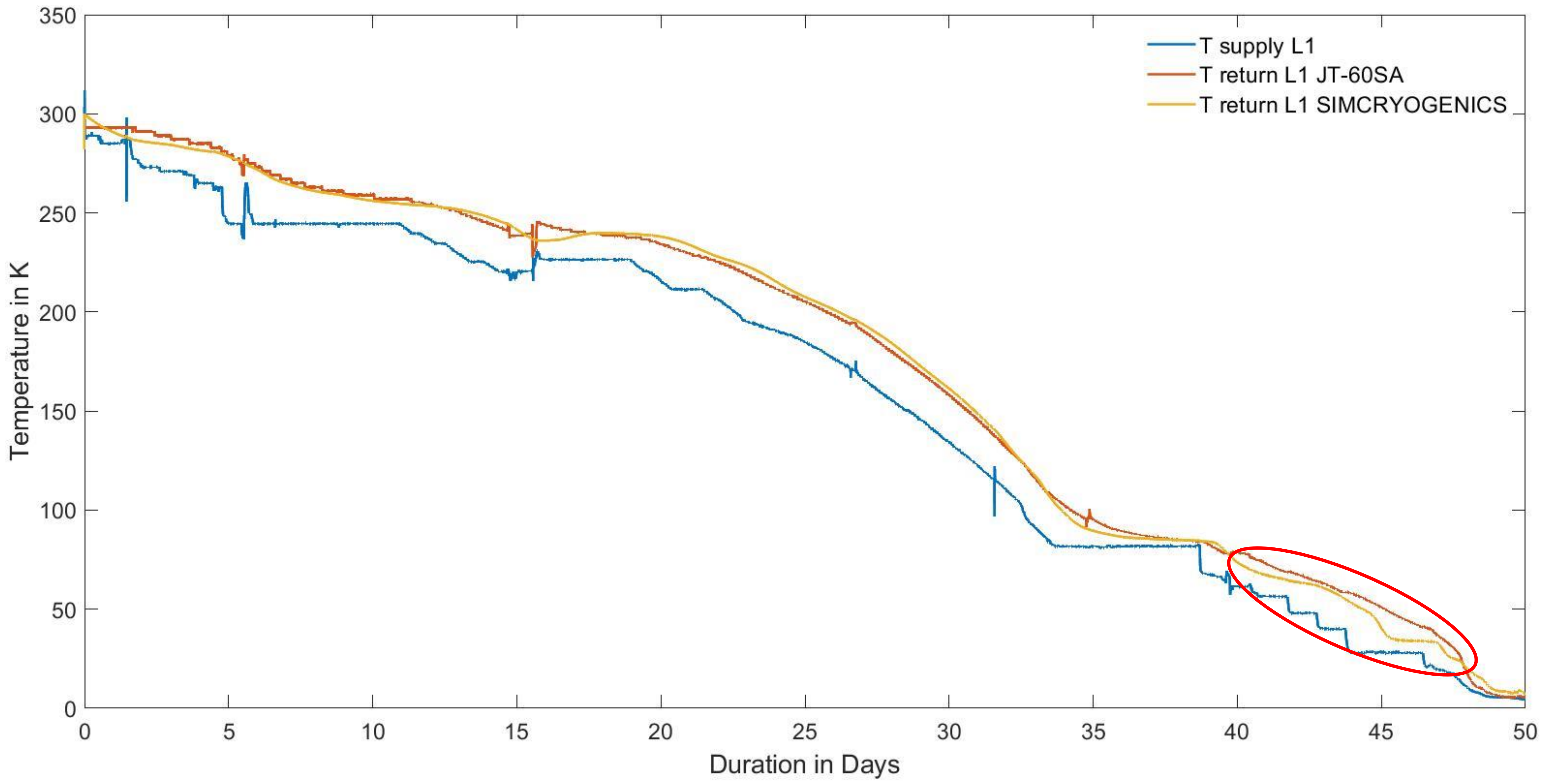
- Pressure return (Blue) is a boundary condition for the SIMCRYOGENICS model
- Pressures and corresponding pressure drops are properly simulated: The opening of the by-pass valves on the TF-WP impacts rapidly the pressure drops of the total circuits.



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

## Temperature comparison on Loop 1 for TF-WP and structures

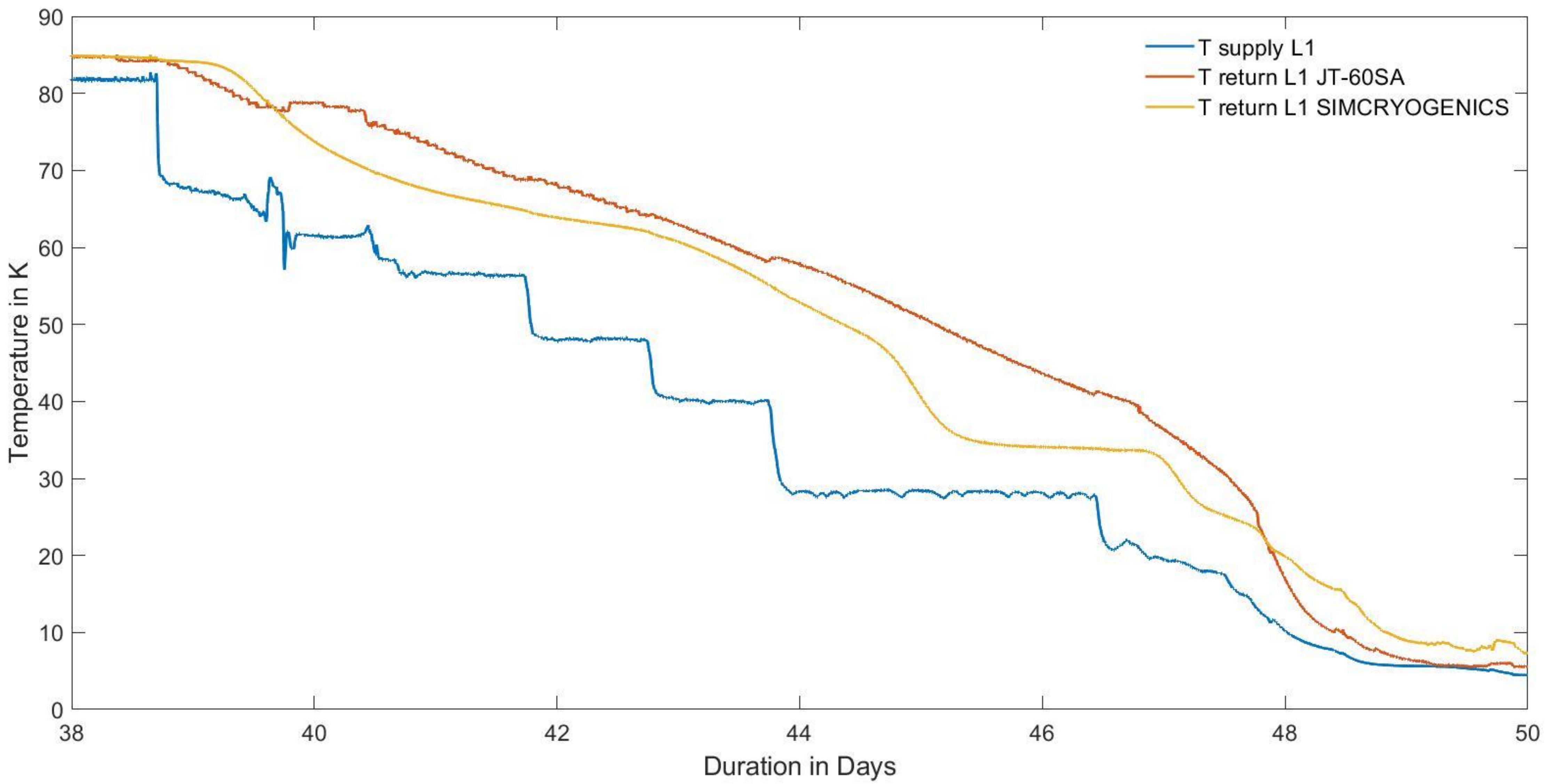
- Good agreement between simulated temperatures (Yellow) and measured temperatures (Red) during cool-down until 80 K



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

**Temperature comparison on Loop 1 for TF-WP and structures**
**Zoom in below 80 K**

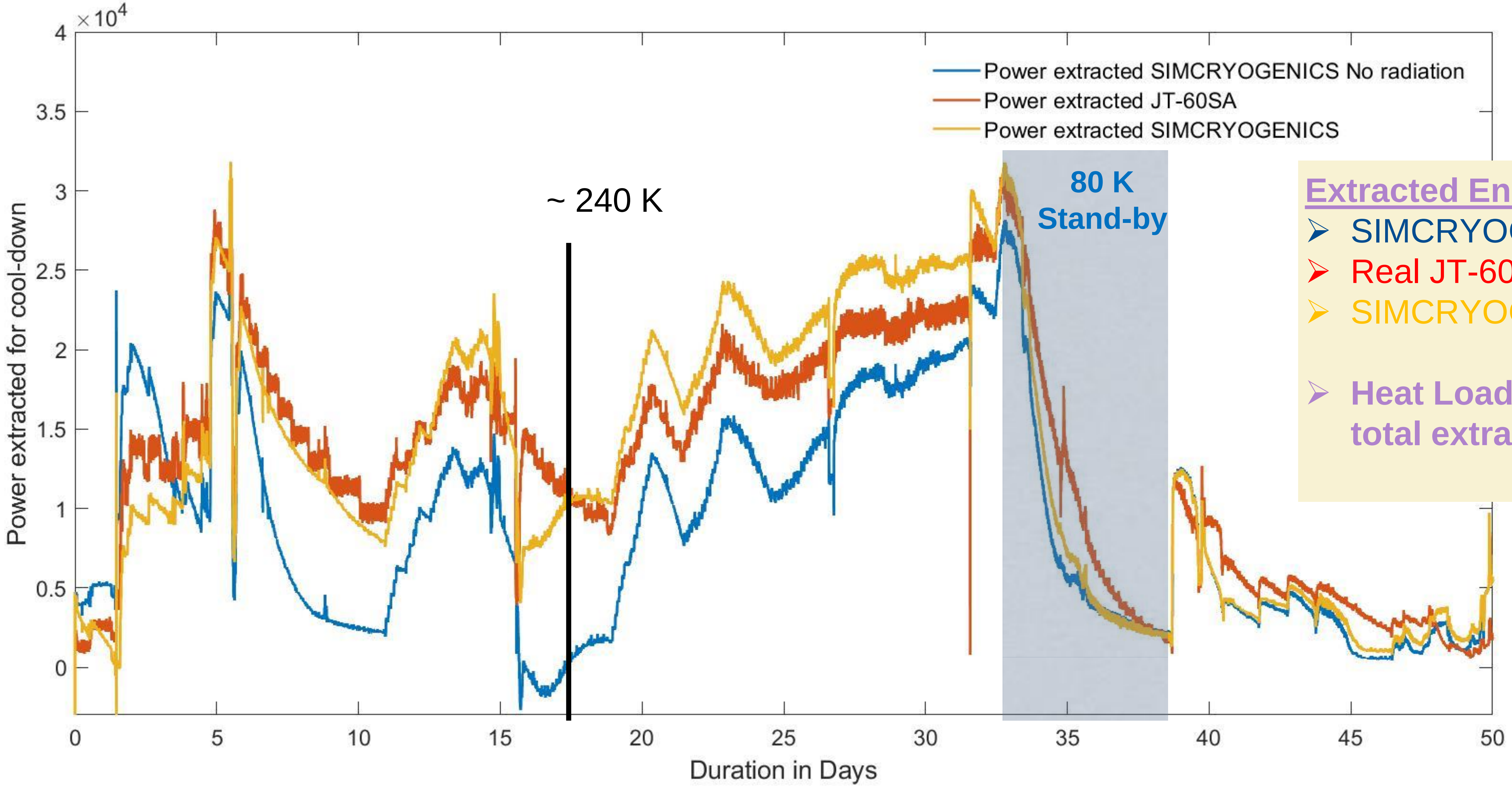
- Below 80K:
  - ❖ measured return temperature is a bit higher than SIMCRYOGENICS simulation
  - ❖ real extracted energy is about 12.5% higher than simulation (4.95 GJ for JT-60SA vs 4.36 GJ for simulation)
- This discrepancy is certainly due (at least partially) to the Gravity Supports supporting magnet system (which are not considered in the model and helped until 80K by the Thermal Shields).



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

## Extracted power comparison on Loop 1 for TF-WP and structures

- Additional simulation added without any external heat loads by radiation (Blue plot)
- It is **necessary to consider the heat loads during cool-down phase** (coming mainly from radiation)
- Only small discrepancies between SIMCRYOGENICS simulation (Yellow) and JT-60SA (Red) on extracted power
- Total extracted energy is well aligned.




**Extracted Energy L1 during Cool-down :**

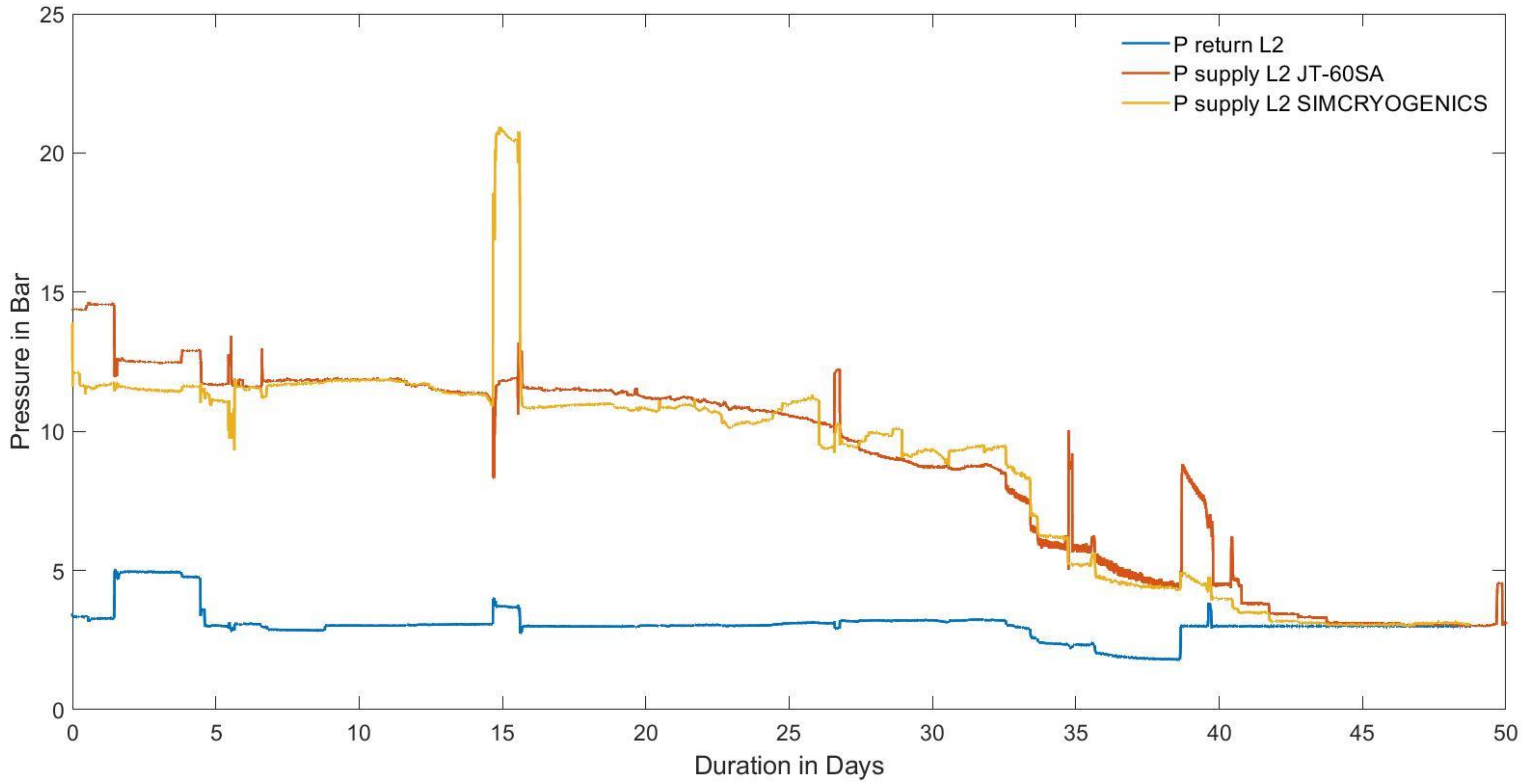
- SIMCRYOGENICS no radiation ~ 38.30 GJ
- Real JT-60SA data ~ 55.57 GJ
- SIMCRYOGENICS ~ 55.76 GJ

- **Heat Loads ~ 17.46 GJ about 31 % of the total extracted energy**

# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

## Pressure comparison on Loop 2 for EF and CS coils

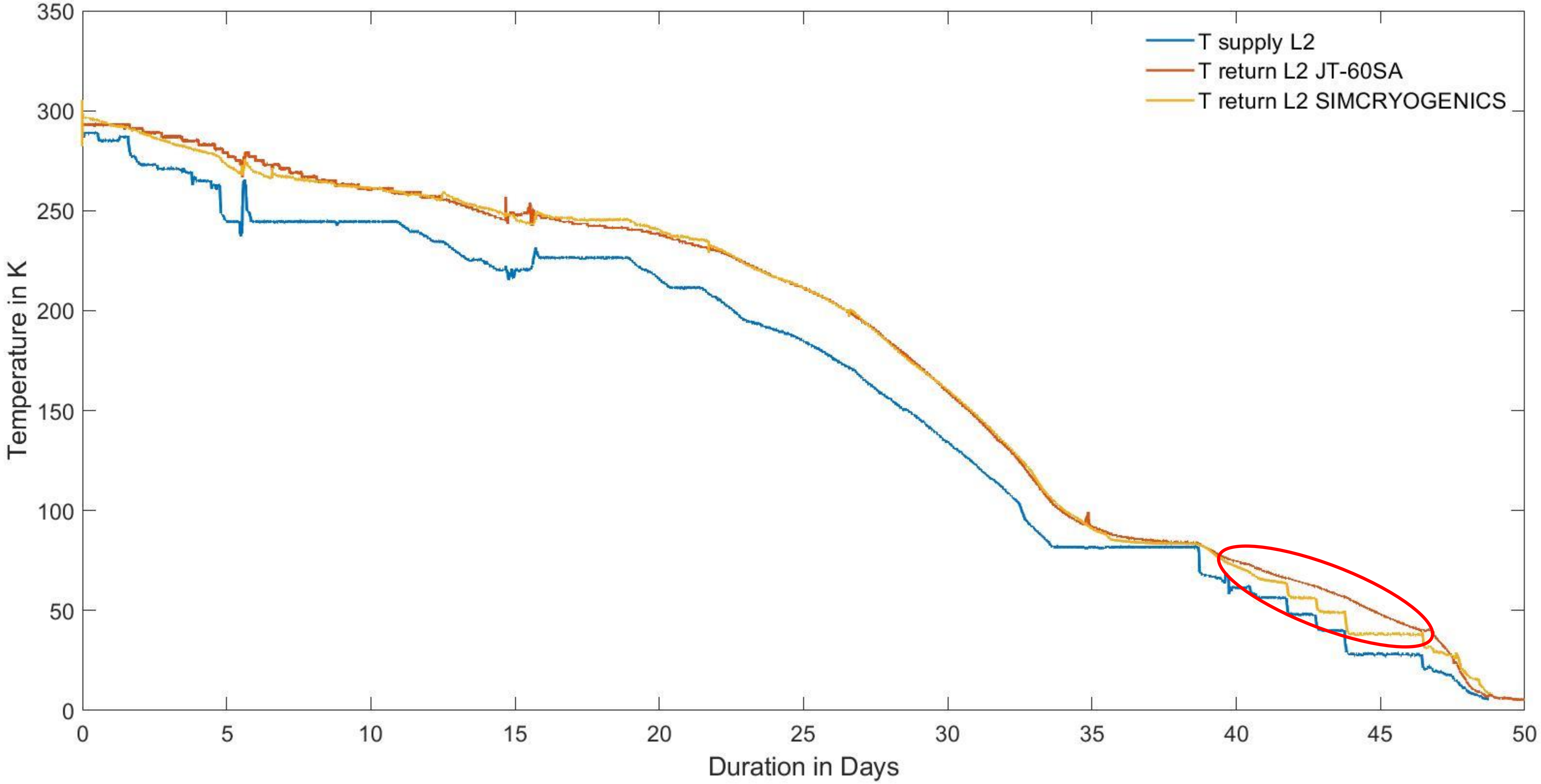
- Good agreement on pressure simulated values except some variable phenomenon (increase of mass flow…), often linked to changes in valve openings not all considered in simulation model.



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

## Temperature comparison on Loop 2 for EF and CS coils

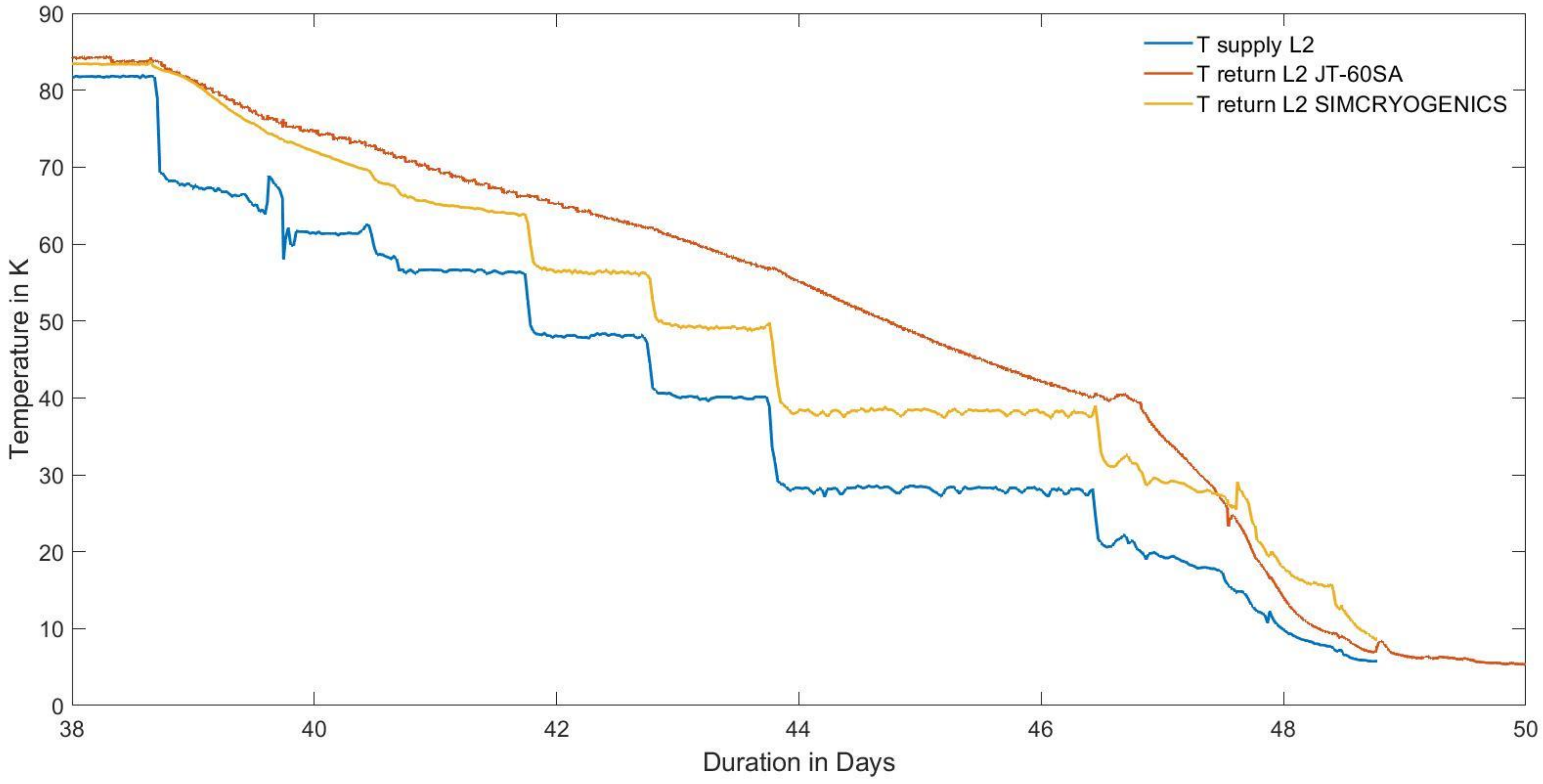
- Very good agreement for the return temperature estimates until 80K.



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

**Temperature comparison on Loop 2 for EF and CS coils**
**Zoom in below 80 K**

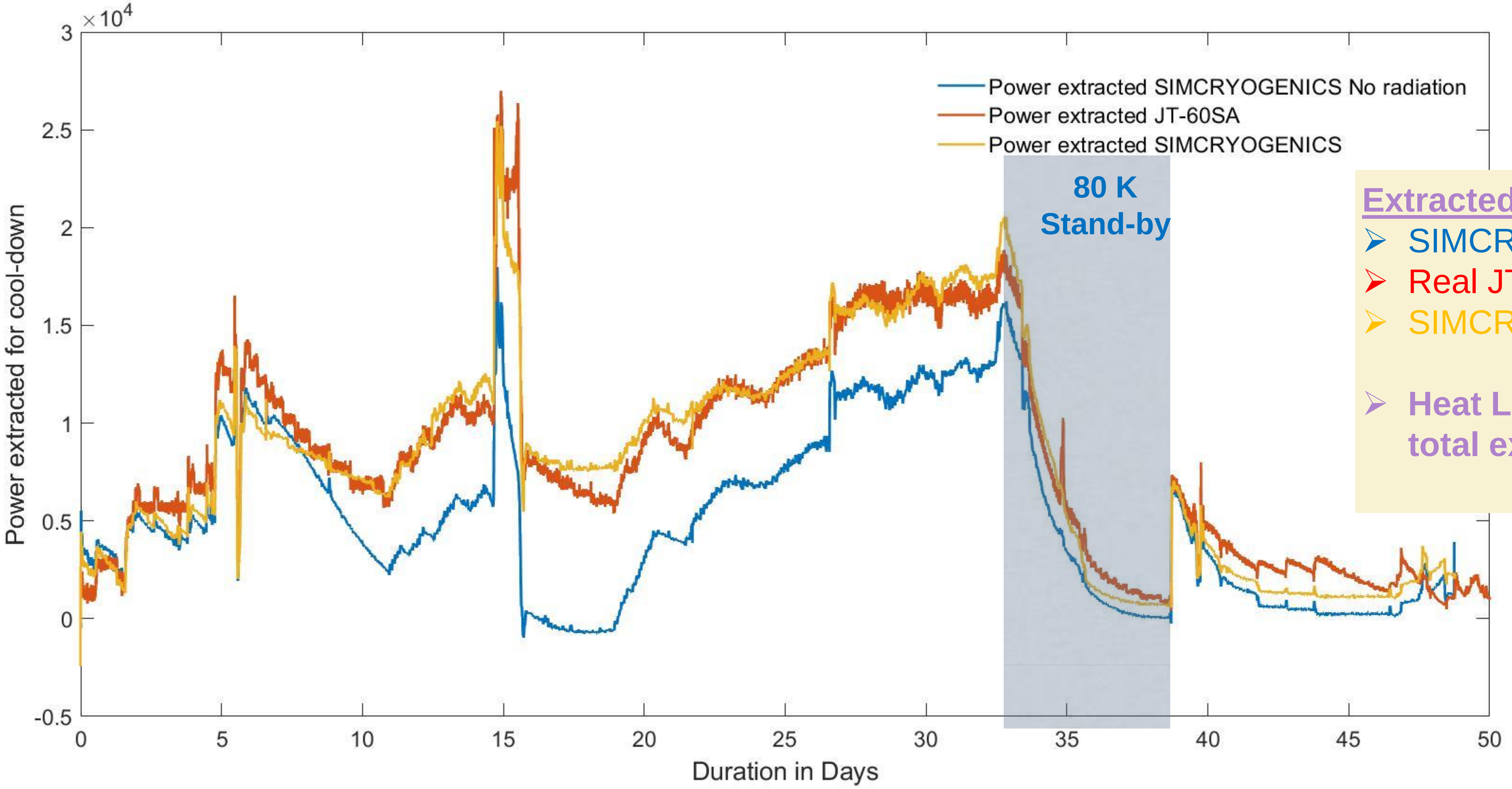
- Below 80K:
  - measured return temperature is a bit higher than SIMCRYOGENICS simulation
  - time constant feature is widely different (simplified model with parallel flows and model 1D against real 3D for masses)
  - real extracted energy is about 33% higher than simulation (2,88 GJ for JT-60SA vs 1,91 GJ for simulation)
- It is potentially due to some parts not properly considered in the simulation model (supports, masses, heat loads...)



# Comparison between JT-60SA cool-down and SIMCRYOGENICS simulations

## Extracted power comparison on Loop 2 for EF and CS coils

- **Additional simulation** added without any external heat loads by radiation (Blue plot)
- It is **necessary to consider the heat loads during cool-down phase** on loop 2 ~ 39% of the total extracted energy
- **Excellent agreement** between SIMCRYOGENICS simulation (Yellow) and JT-60SA (Red) concerning extracted power




Extracted Energy L2 during Cool-down :
- SIMCRYOGENICS no radiation ~ 21.60 GJ
- Real JT-60SA data ~ 35.39 GJ
- SIMCRYOGENICS ~ 34.48 GJ

- **Heat Loads ~ 13.79 GJ about 39 % of the total extracted energy**

# Conclusions and perspectives

- Simulation models using **SIMCRYOGENICS had been developed to support the JT-60SA cool-down**
- After cool-down, the models had been adapted (mainly boundary conditions changed) to reproduce and simulate the JT-60SA tokamak cool-down.
- **2 independent SIMCRYOGENICS models** had been used, one for TF coils and structures (Loop 1) and one for EF/CS coils (Loop 2)
- The simulation models using SIMCRYOGENICS are able to simulate with a **good agreement the full cool-down process**: pressure drops, temperatures, energy…
- It is **mandatory to consider the heat loads during cool-down** because it is not negligible in term of extracted energy (between 30-40 % of the total extracted energy).
- Below 80K, the real temperatures during cool-down are higher than the simulated ones.
    - The **energy to evacuate is larger** than those estimated by simulation models
    - The **reasons of additional heat loads below 80 K are not fully clear** but could come from several sources:
        - Heat load estimated from **radiation model based on the Thermal Shield temperature is not perfects**, (nevertheless 1 week after cool-down, the static heat loads were almost aligned with the expected design values)
        - **Additional mass cooled** by Thermal Shields until 80 K, which are cooled by magnet circuits below (eg. TF coil Gravity Supports …)
        - **Approximation on the mass ratios for coils and associated specific heat for materials**, but seems a second order.

- Perspectives:
    - Improve and reduce the duration of the next tokamak cool-down
    - Possibility to adjust the simulation model in order to be aligned with real cool-down (mainly below 80K).
    - Integrate cryoplant process in the simulation models for further cool-down improvements

# REFERENCES

[1] Shirai H, Barabaschi P., Yutaka K. and The JT-60SA team. Progress of JT-60SA Project: EU-JA joint efforts for assembly and fabrication of superconducting tokamak facilities and its research planning. Fusion Engineering and Design, Volumes 109–111, Part B, 1 November 2016, Pages 1701-1708. (https://www.sciencedirect.com/science/article/pii/S0920379615303136 ).

[2] Yoshida K., .Tsuchiya K., Kizu K., Murakami H., Kamiya K., Obana T., Takahata K., Peyrot M., Barabaschi P.. Development of JT-60SA superconducting magnet system. Physica C: Superconductivity and its Applications Volume 470, Issue 20, 1 November 2010, Pages 1727-1733. (https://www.sciencedirect.com/science/article/pii/S092145341000451X)

[3] Koide Y. et al., JT-60SA Superconducting Magnet System, Nuclear Fusion, IOP Publishing, 2015, 55 (8), pp. 86001-86007. https://iopscience.iop.org/article/10.1088/0029-5515/55/8/086001/pdf

[4] Michel F. ; Hitz, D. ; Hoa C. ; Lamaison V. ; Kamiya K. ; Roussel P. ; Wanner M. ; Yoshida K.. Cryogenic requirements for the JT-60SA Tokamak. Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference - CEC, Volume 57. AIP Conference Proceedings, Volume 1434. AIP Conference Proceedings, Volume 1434, Issue 1 June 2012, p.78-85, https://aip.scitation.org/doi/abs/10.1063/1.4706907

[5] Lamaison V., Beauvisage J., Fejoz P., Girard S., Gonvalves R., Gondé R., Heloin V., Michel F., Hoa C., Kamiya K., Roussel P., J-C.Vallet, Wanner M., Yoshida K.. Conceptual Design of the JT-60SA Cryogenic System: AIP Conference Proceedings, Volume 1573, 337 (2014). https://aip.scitation.org/doi/pdf/10.1063/1.4860720

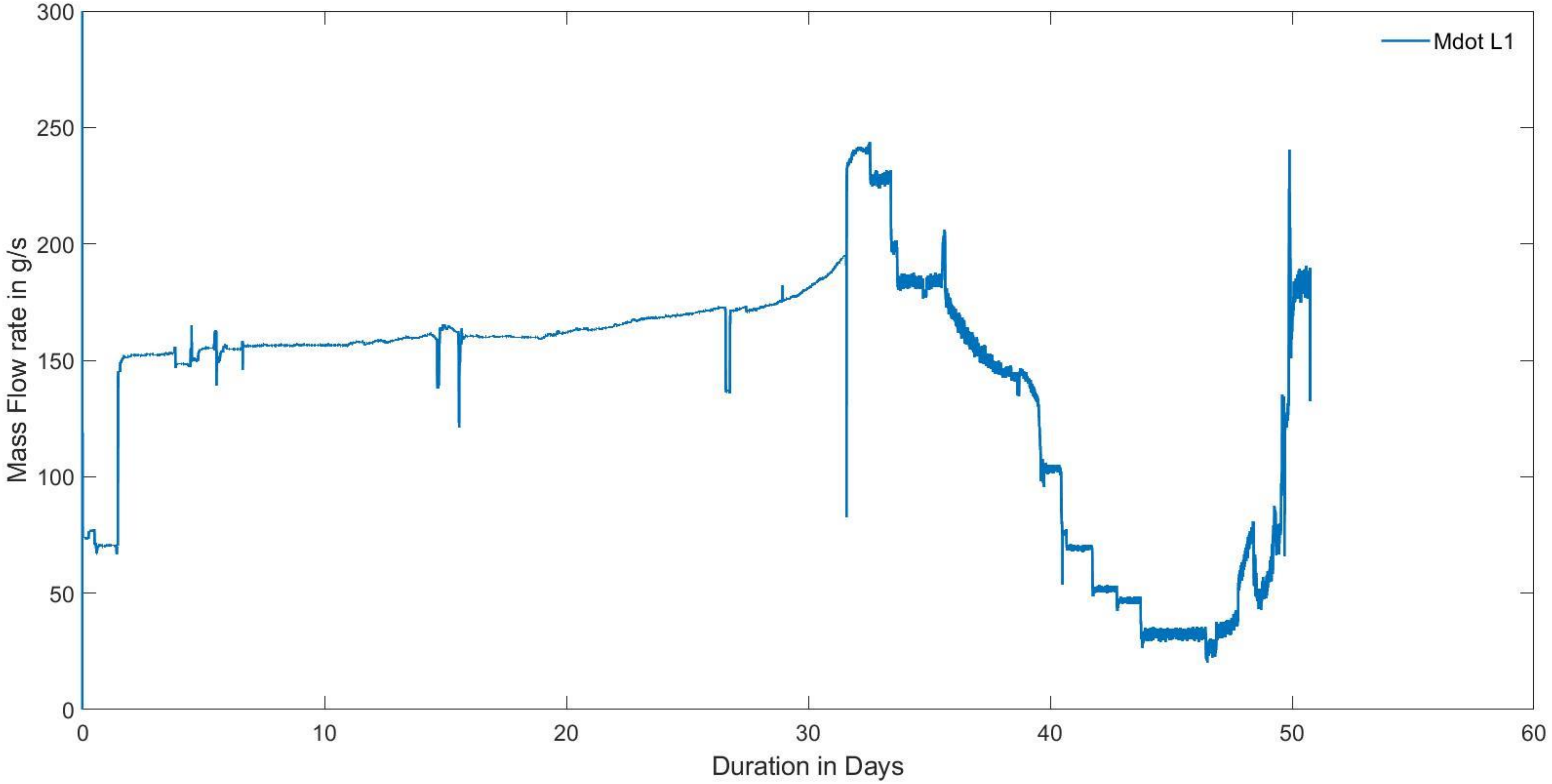
[6] Kamiya K., Natsume K., Ohtsu K., Oishi M., Honda A., Kashiwa Y., Kizu K., Koide Y., Hoa C., Michel F., Roussel P., Lamaison V., Bonne F., Dipietro E., Cardella A., Wanner M., Legrand J., Pudys V., Langevin B.. Commissioning of the JT-60SA helium refrigerator. IOP Conf. Series: Journal of Physics: Conf. Series 897, 2017.
https://iopscience.iop.org/article/10.1088/1742-6596/897/1/012015/pdf

[7] Bonne F., Varin S., Vassal A., Bonnay P., Hoa C., Millet F. and Poncet J.-M.. Simcryogenics: a Library to Simulate and Optimize Cryoplant and Cryodistribution Dynamics. CEC conference 2019. IOP Conf. Series: Materials Science and Engineering 755 (2020).
https://iopscience.iop.org/article/10.1088/1757-899X/755/1/012076

[8] Varin S., Bonne F., Hoa C., Nicollet S., Zani L., Vallet J.-C., Fukui K., Natsume K.. An update of dynamic thermal-hydraulic simulations of the JT-60SA Toroidal Field coil cooling loop for preparing plasma operation. CHATS on Applied Superconductivity 2019. Cryogenics Volume 109, July 2020.
https://www.sciencedirect.com/science/article/pii/S0011227520300941

# Additional slide

## Mass Flow rate in Loop 1 for TF-WP and structures



# Additional slide

**Mass Flow rate in Loop 2 for EF and CS coils**