# Multi-scale thermal-hydraulic modelling for the primary heat transfer system of a tokamak

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- GETTHEM applications
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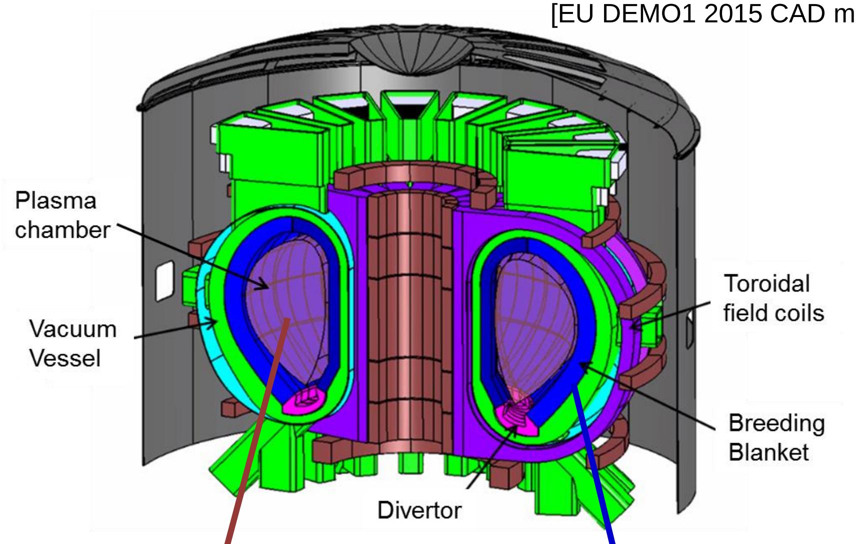
- Conclusions & perspective

# Introduction

- EU DEMO aims to prove economic feasibility of fusion electricity
  - First reactor to include Power Conversion System and to breed tritium in situ → Breeding Blanket (BB)
- BB is the first component facing the plasma → largest total thermal load from plasma + nuclear reactions

[EU DEMO1 2015 CAD model]



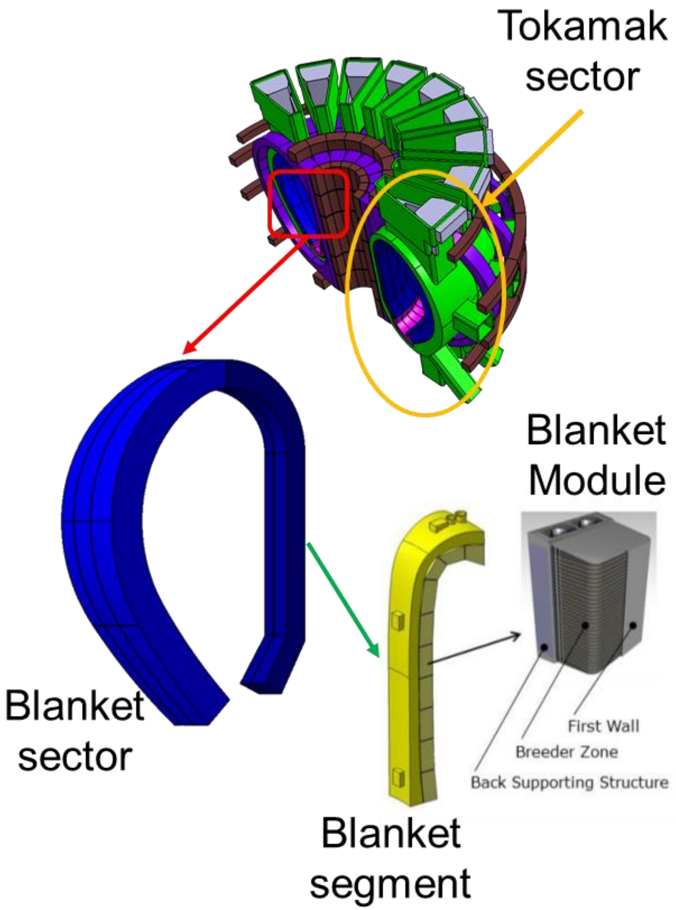
$\text{D(T,n)He} + 17.6\ \text{MeV}$

$^{6}\text{Li}(n,\alpha)\text{T} + 4.8\ \text{MeV}$

$^{7}\text{Li}(n,n'\alpha)\text{T} - 2.5\ \text{MeV}$

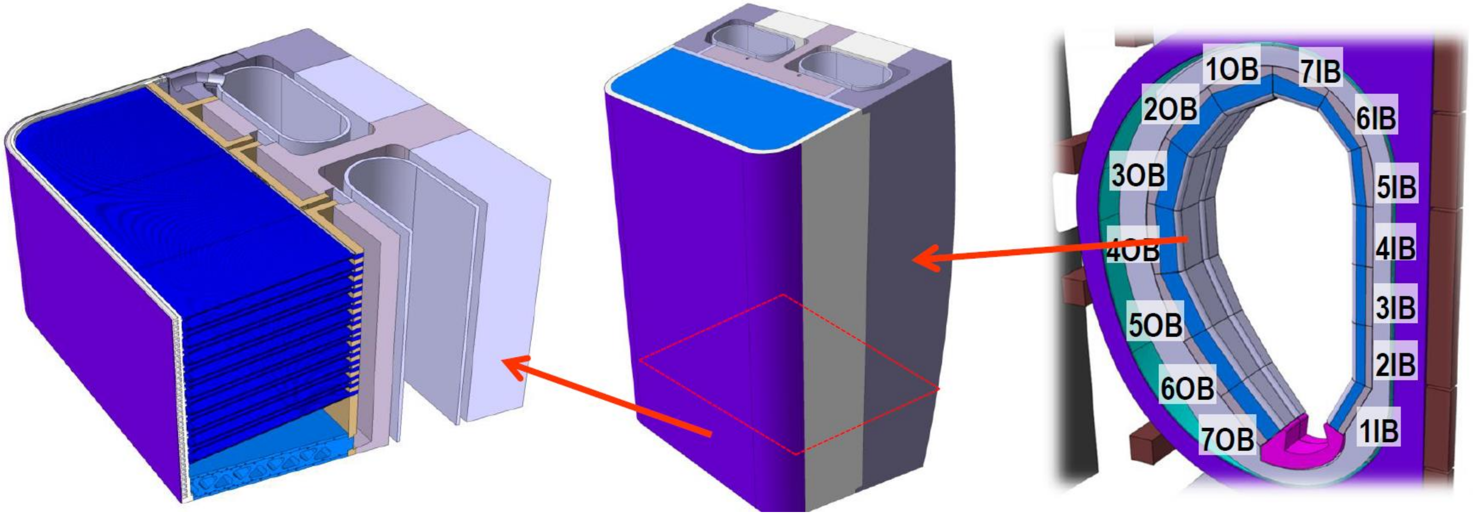
# The EU DEMO BB (2015 revision)

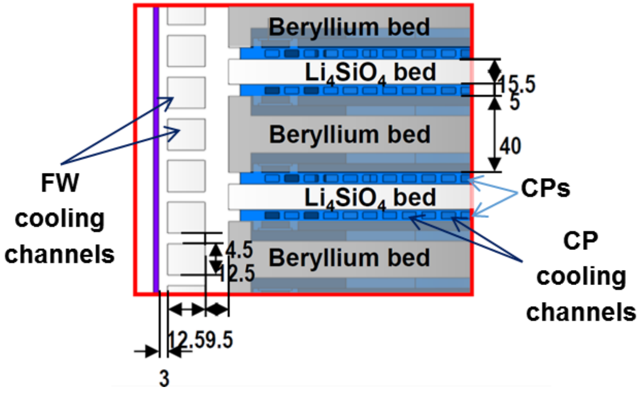
- Tokamak toroidally divided in sectors
- Each sector → 2 inboard (IB) and 3 outboard (OB) BB segments
- Each segment → several Blanket Modules (BMs)
- First Wall (FW) and Breeding Zone (BZ)
- 4 BB concepts:
  - Helium-Cooled Pebble Bed (HCPB)
  - Water-Cooled Lithium-Lead (WCLL)
  - Helium-Cooled Lithium-Lead
  - Dual Cooled Lithium-Lead



[EU DEMO1 2015 CAD model; L. V. Boccaccini, 2015]

# HCPB



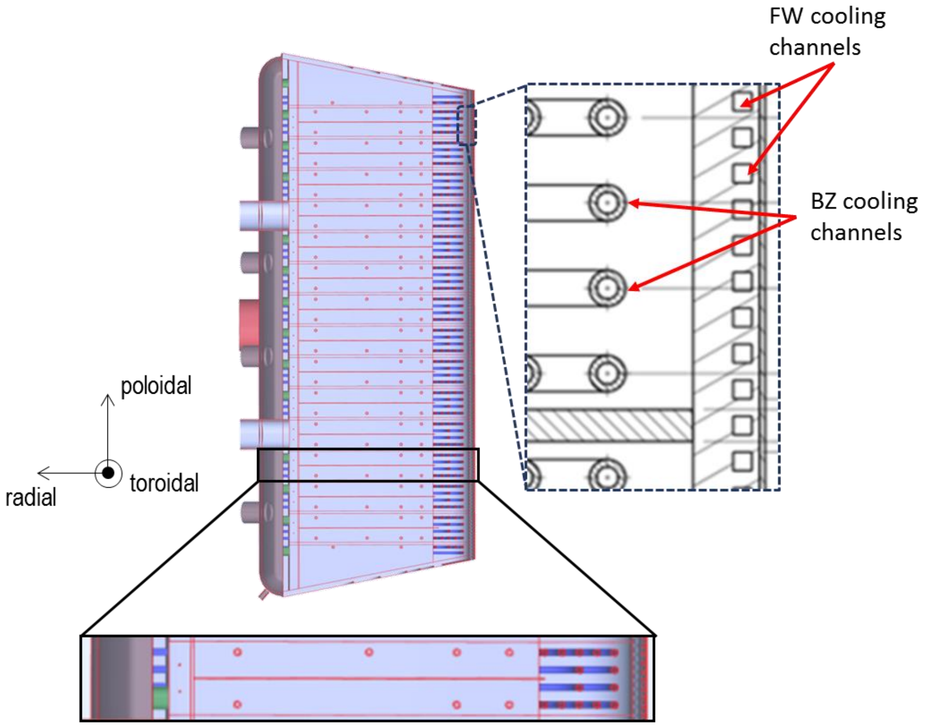


[F. A. Hernández González, 2016]

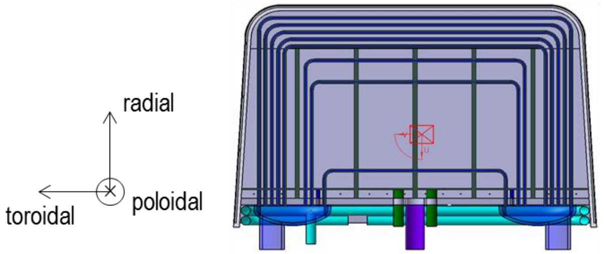
- Coolant: He (8 MPa, 300 – 500 °C)
- Breeding material: $Li_4SiO_4$ pebbles
- *n* multiplier: Be pebbles
- FW and BZ cooled in series (~2000 cooling channels per BM)
  - Square FW cooling channels
  - Rectangular BZ cooling channels, inside metallic Cooling Plates (CPs)

# WCLL

- Coolant: Water (15.5 MPa, 285 – 325 °C)
- Breeding & *n* multiplier material: PbLi eutectic (liquid)
- FW and BZ cooled by different loops (~500 cooling channels per BM)
  - Square FW cooling channels
  - Circular BZ cooling channels



[A. Del Nevo, 2016]



# Aim of the work

Problem: fast analyses are fundamental during design stage, to check effect of different parameters → need for a system-level thermal-hydraulic modelling tool, for transient analysis of the DEMO Primary Heat Transfer System (PHTS) and Balance of Plant (BoP):

- Allow parametric analyses → fast simulation
- Consider both normal and accidental transient scenarios
- Easy to update, to follow the design development → flexible
- Written in an object-oriented language
- User-friendly

# The GETTHEM code (I)

Solution: develop the GEneral Tokamak THErmal-hydraulic Model (GETTHEM) supported by EUROfusion

- Main features:
  - Fast simulation of thermal-hydraulic transients in the entire PHTS
  - At present, HCPB and WCLL modules
  - System-level code developed using the equation-based, object-oriented Modelica language → user-friendly
  - Developed in-house and relying on open source Modelica libraries
  - Runs on OpenModelica
  - Easy to update as the design evolves, thanks to its modular nature
- Solves mass and energy conservation equations:
  - 0D lumped modelling approach for manifolds, pumps, valves
  - 1D Finite Volumes modelling approach for cooling channels and pipes
    - Momentum balance is also solved in 1D models

# The GETTHEM code (II)

The tool must be applicable to nominal and accidental scenarios
→ use different modelling assumptions:

**NORMAL OPERATION:**

Look at the differences among the channels, due to geometry or heat load asymmetries → simplification of the physics:

- Thermophysical properties of water linearized around operating point
- Helium modelled as ideal gas
- Constant thermophysical properties of structural material

**OFF-NORMAL OPERATION:**

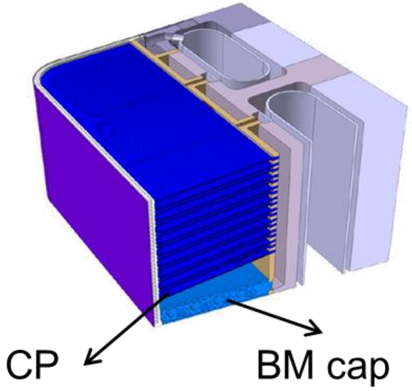
Keep into account the details of the thermodynamic evolution of the coolant during an in-vessel Loss-Of-Coolant Accident (e.g. evaporation, flashing, 2-phase flow, choked flow) → simplification of the geometry:

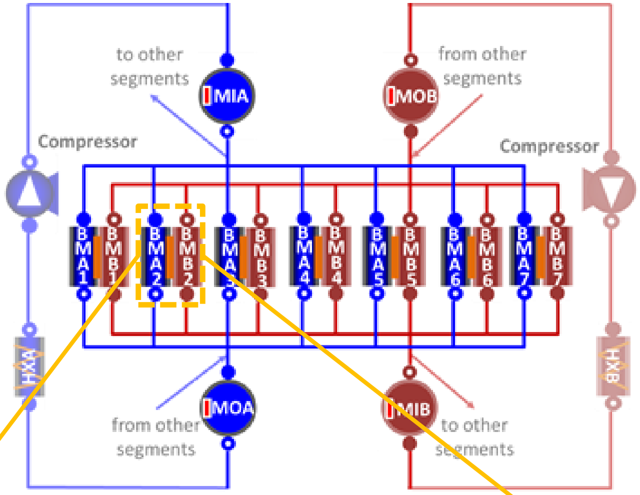
- All components (including PHTS) modelled with 0D approach

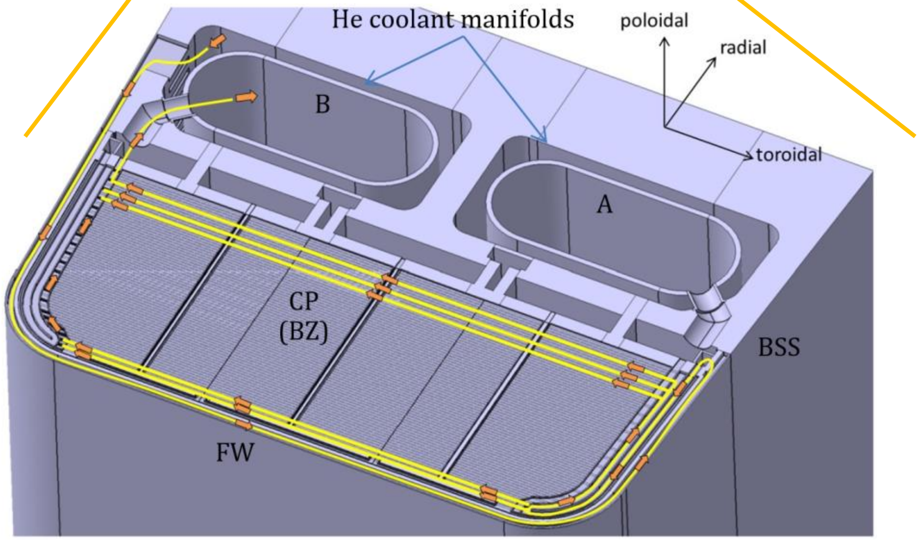
# GETTHEM applications: HCPB normal operation

- BM caps (2/BM) and CPs (~60/BM) cooled in parallel
- Aim: optimize mass flow rate distribution to keep temperatures in the design range

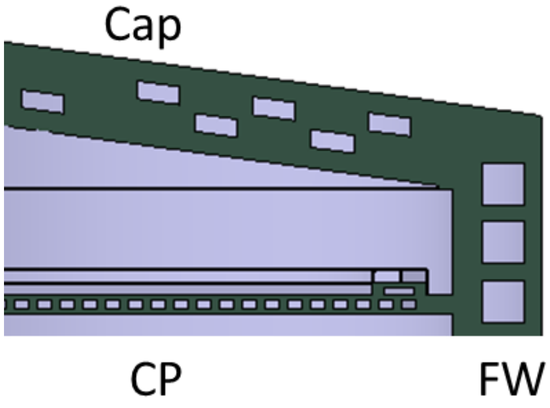
→ Apply GETTHEM to study temperature distribution



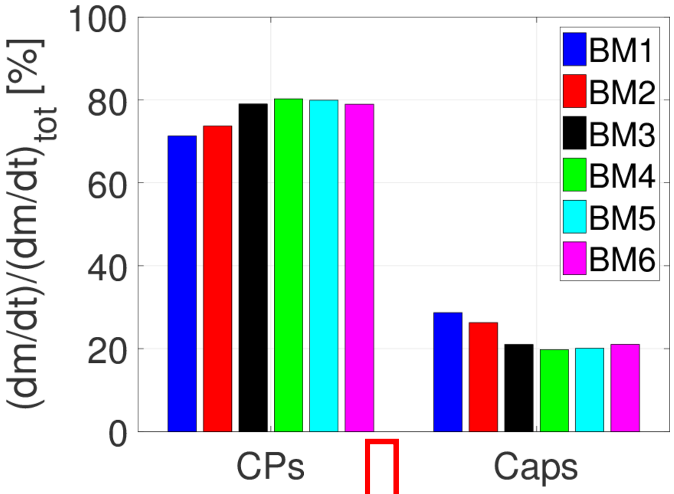


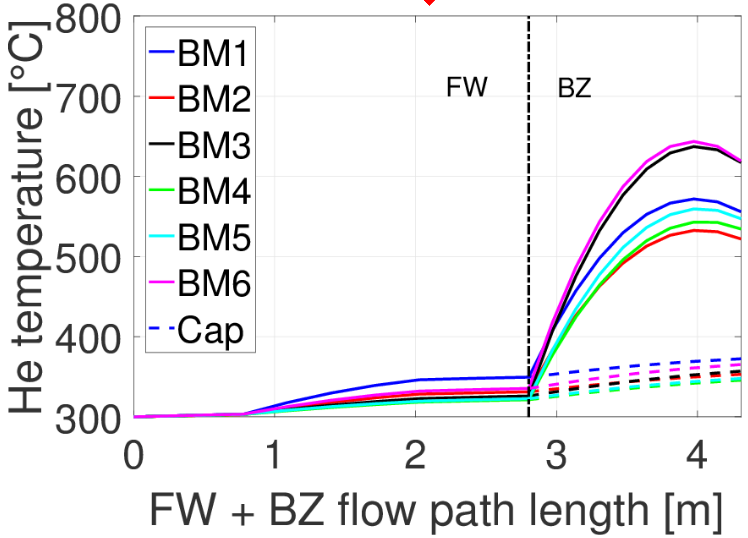


# GETTHEM applications:
# HCPB normal operation – Results (I)



- Cap channels have larger cross section → smaller hydraulic resistance
- The 2 caps receive ~20 % of the coolant, the 60 CPs only ~80 % → caps overcooled, CPs overheated

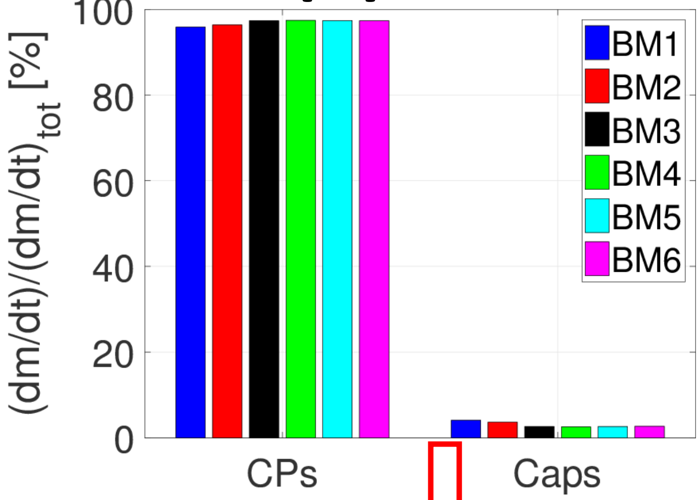




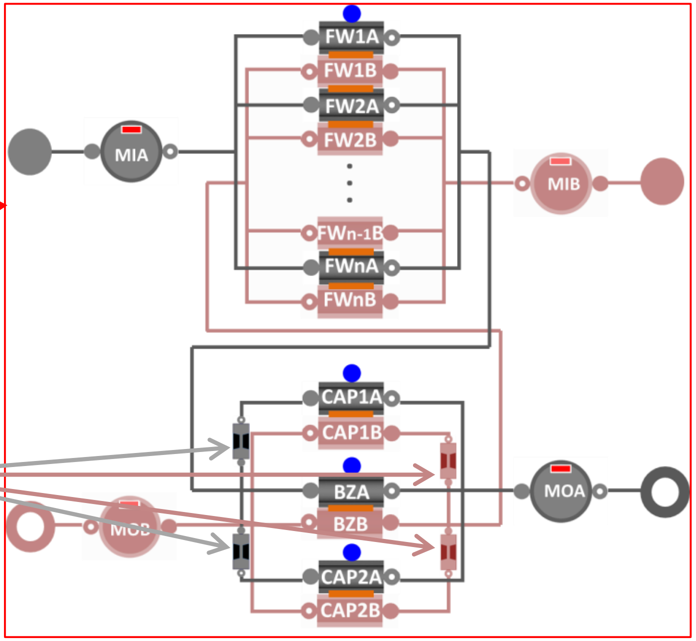
[A. Froio et al., 2016]

# GETTHEM applications:
# HCPB normal operation – Results (II)

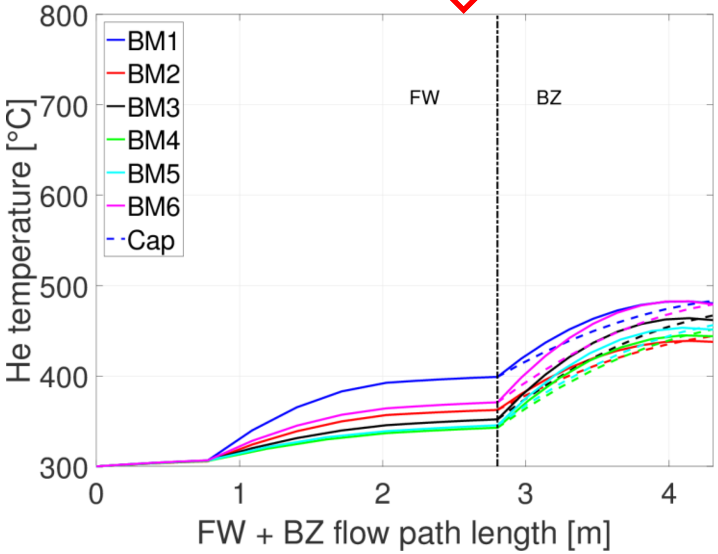
- Introduce orifices at cap inlet → parametric analysis on orifice aperture to optimize temperature distribution
- $T_{He}$ now always within design range → no overheating + higher plant efficiency



BM model



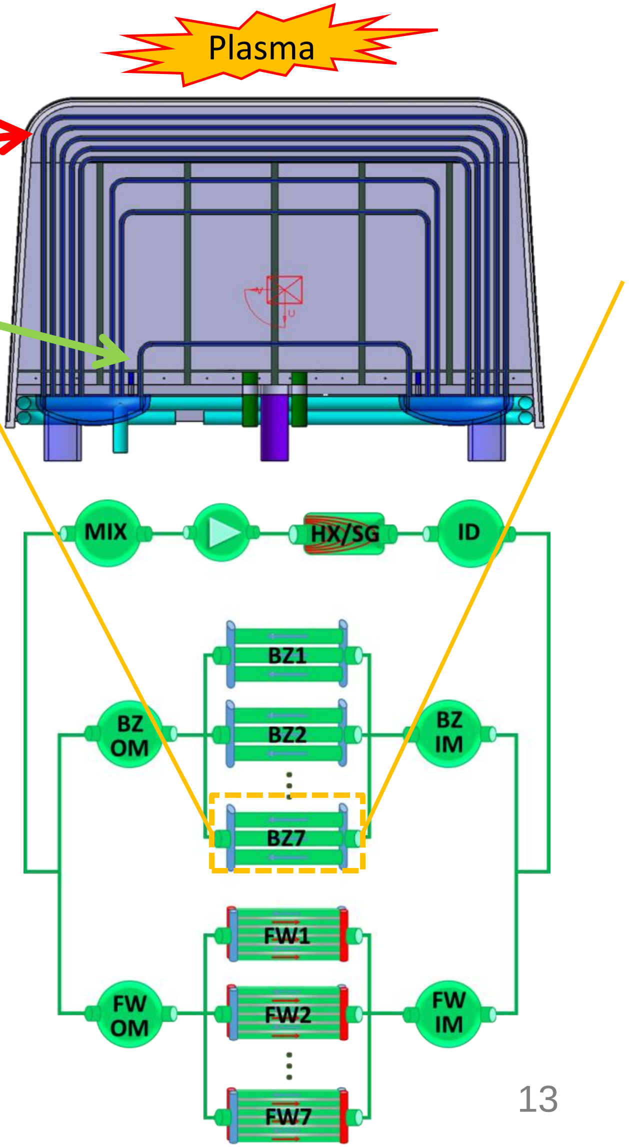
Orifices



[A. Froio et al., 2016]

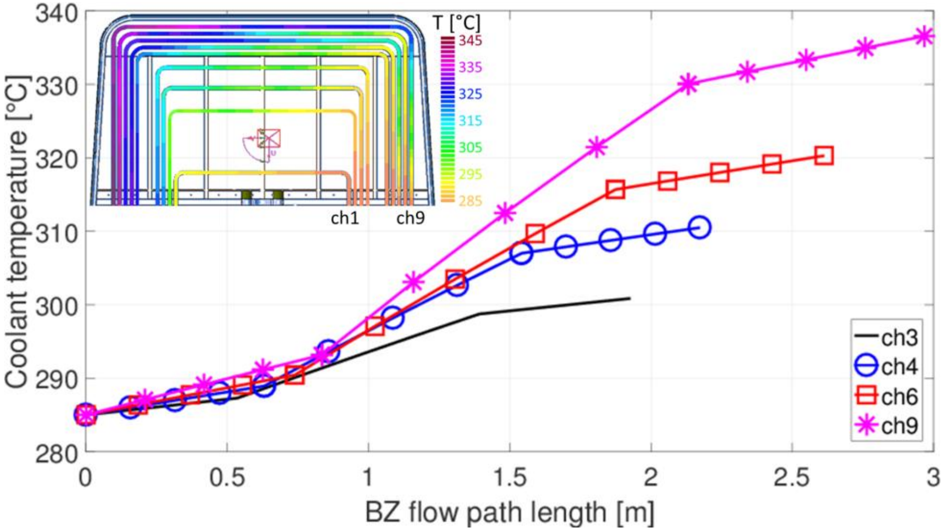
# GETTHEM applications: WCLL normal operation

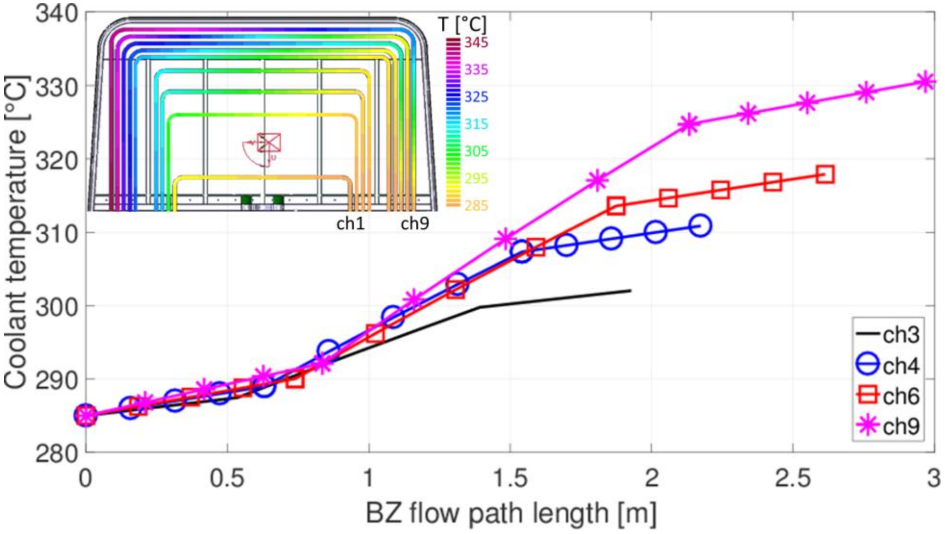
- BZ cooling channels have different lengths → different resistances
- Channels closer to the plasma get higher heat flux → need higher coolant flow rate
- Aim: optimize mass flow rate distribution



# GETTHEM applications: WCLL normal operation – Results

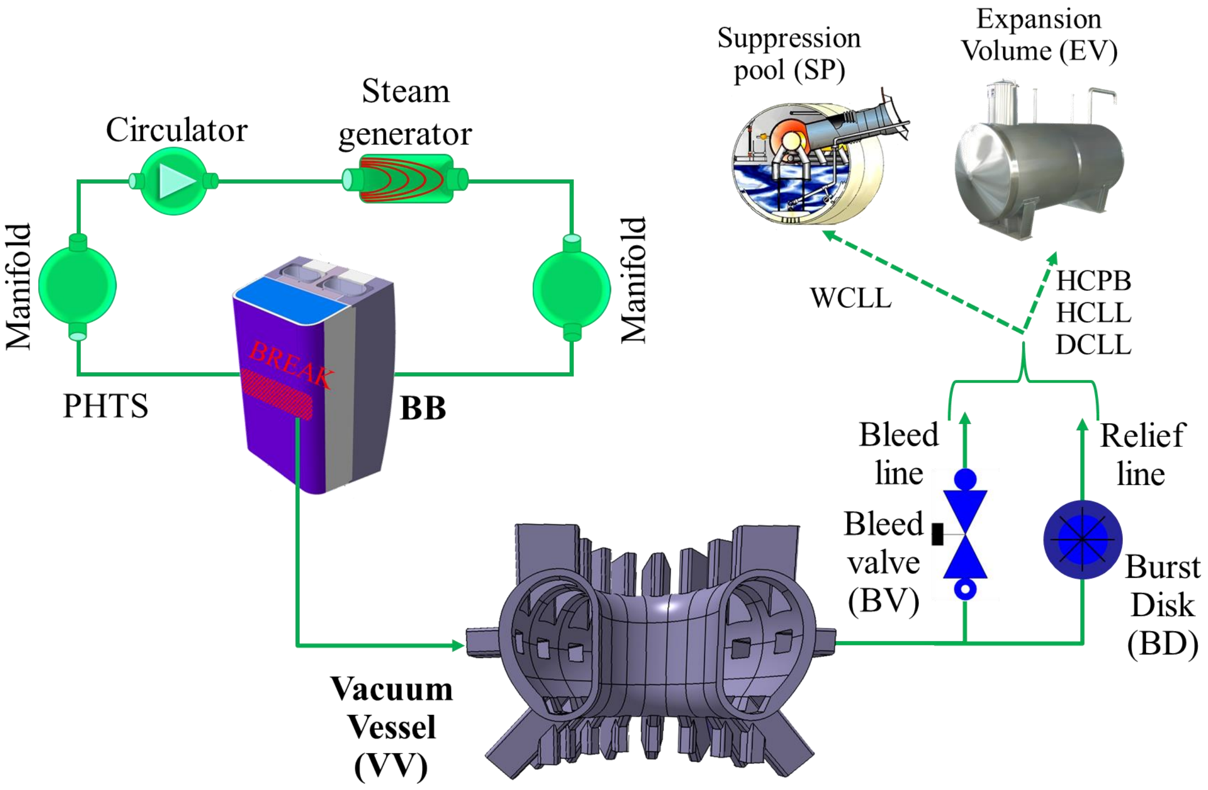
- Most loaded channels receive the least mass flow rate → temperature increases close to saturation (343 °C)
- Dimension orifices at channel inlet to optimize mass flow rate → more uniform outlet temperature distribution → 15 °C below saturation





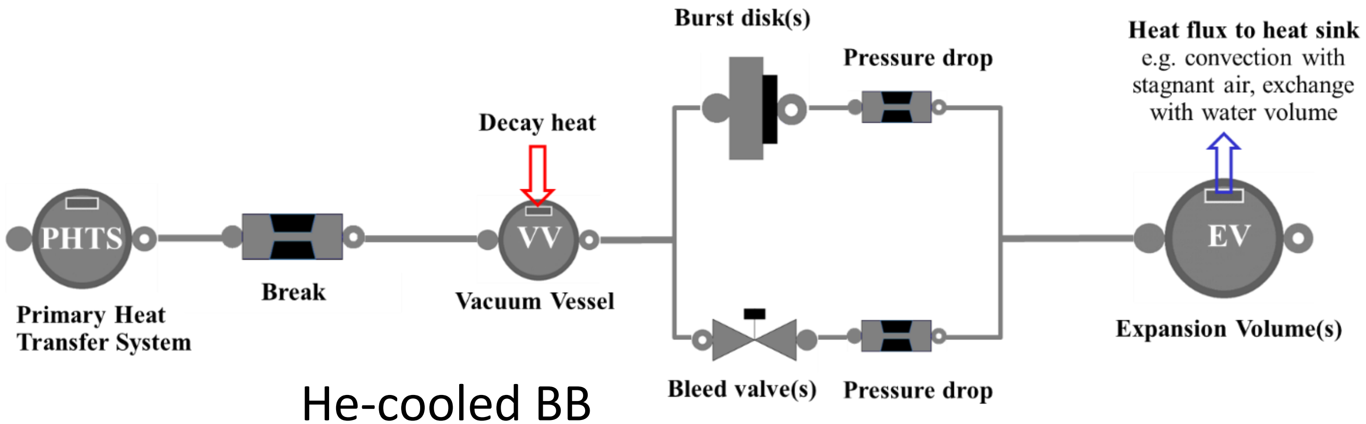
[A. Froio et al., 2017]

# GETTHEM applications: off-normal conditions – in-VV LOCA

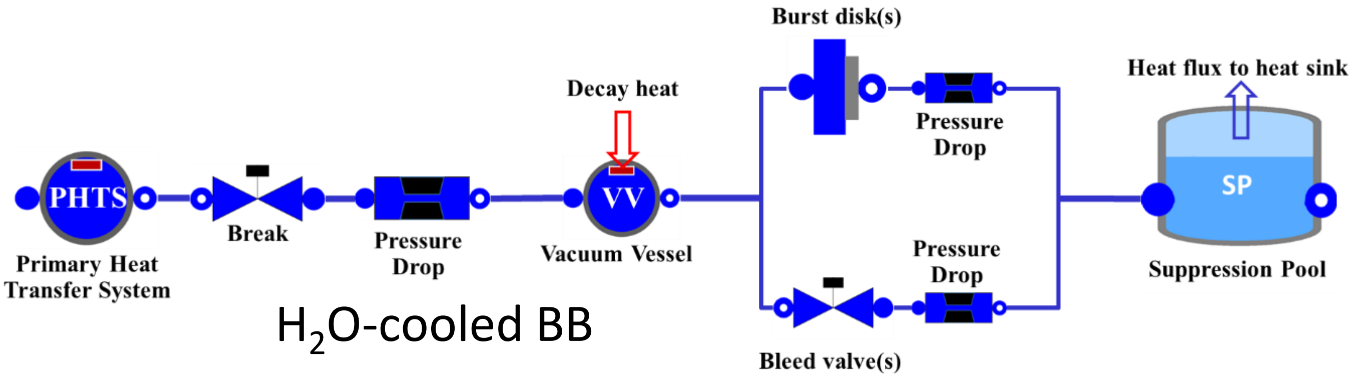


- Sudden energy deposition from plasma causes FW failure → release of coolant inside Vacuum Vessel (VV) → in-VV LOCA
  - VV operating pressure: ~10 mPa
  - VV maximum design pressure: 200 kPa
- VV → first containment barrier against release of radioactive materials → avoid overpressure!
- Aim: analyse pressure transient inside VV following in-VV LOCA for He-cooled and $H_2O$-cooled BBs

# GETTHEM applications: off-normal conditions – in-VV LOCA models



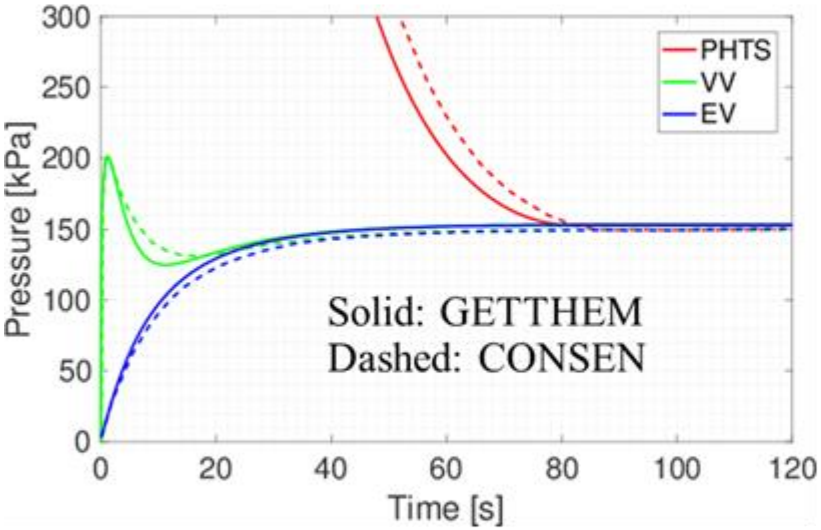
He-cooled BB

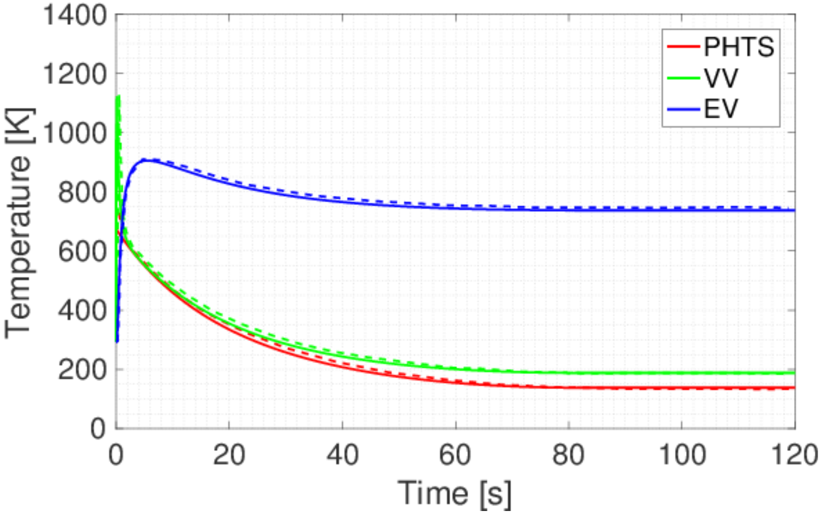


$H_2O$-cooled BB

# GETTHEM applications:
# in-VV LOCA step 1 – He model benchmark

- GETTHEM in-VV LOCA model for He-cooled BBs is applied in a scenario modelled with the validated CONSEN code (reported in [G. Caruso et al., 2017])
- Good agreement between the two models: discrepancy on relevant variables below 1 %

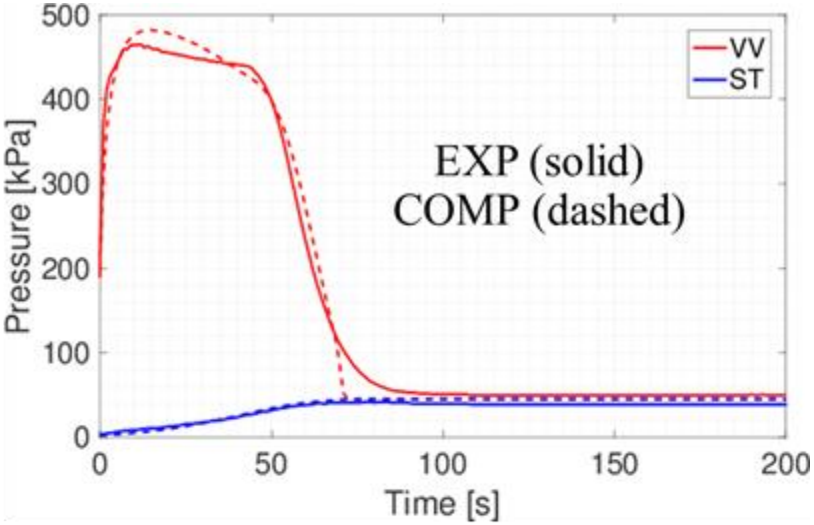




[A. Froio et al., 2017]

# GETTHEM applications:
# in-VV LOCA step 1 – $H_2O$ model validation

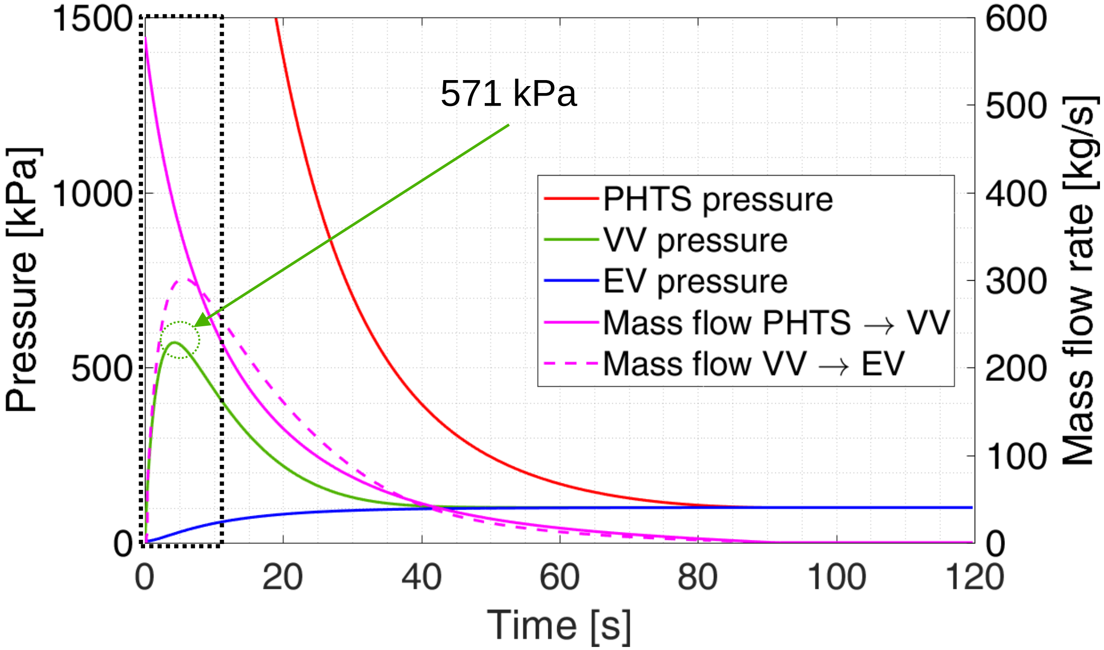
- GETTHEM in-VV LOCA model for $H_2O$-cooled BBs used to reproduce results of ICE experimental campaign (Japan, 2000)
- Excellent agreement on pressure evolution (within experimental uncertainty)



[A. Froio et al., 2017]

# GETTHEM applications: in-VV LOCA step 2 – application to DEMO (He)

- Peak pressure overcomes VV limit (200 kPa)
- Transient is too fast to consider active mitigation systems (peak reached after ~4 s)
- Even after BD opening coolant removed from VV is ~1/6 of coolant entering VV → insufficient mitigation



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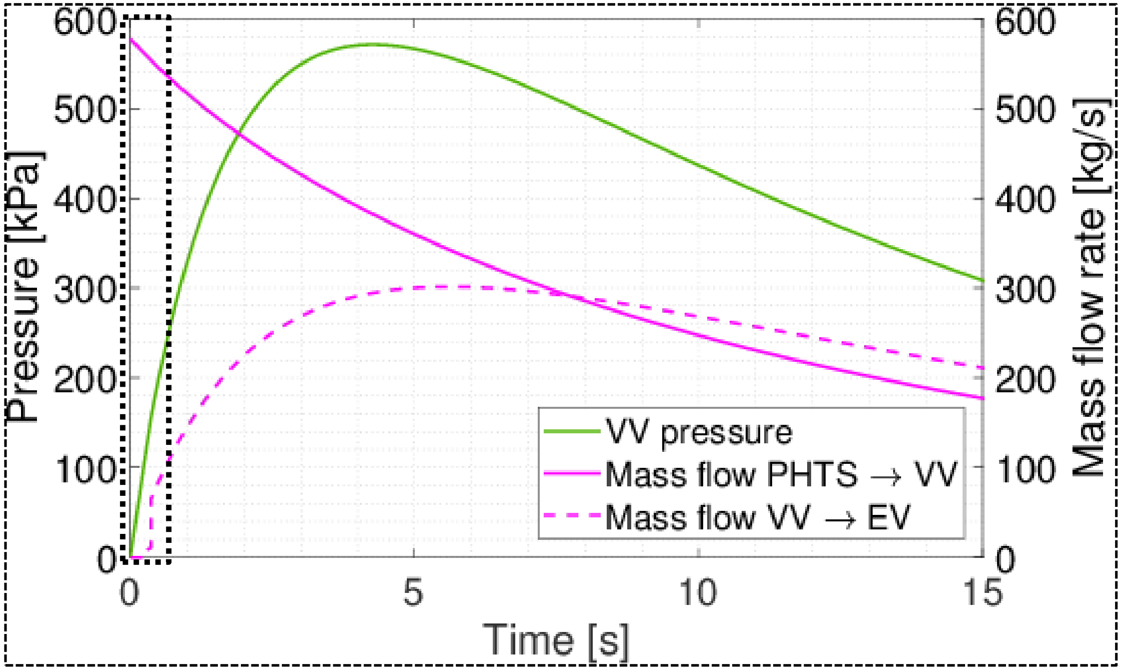

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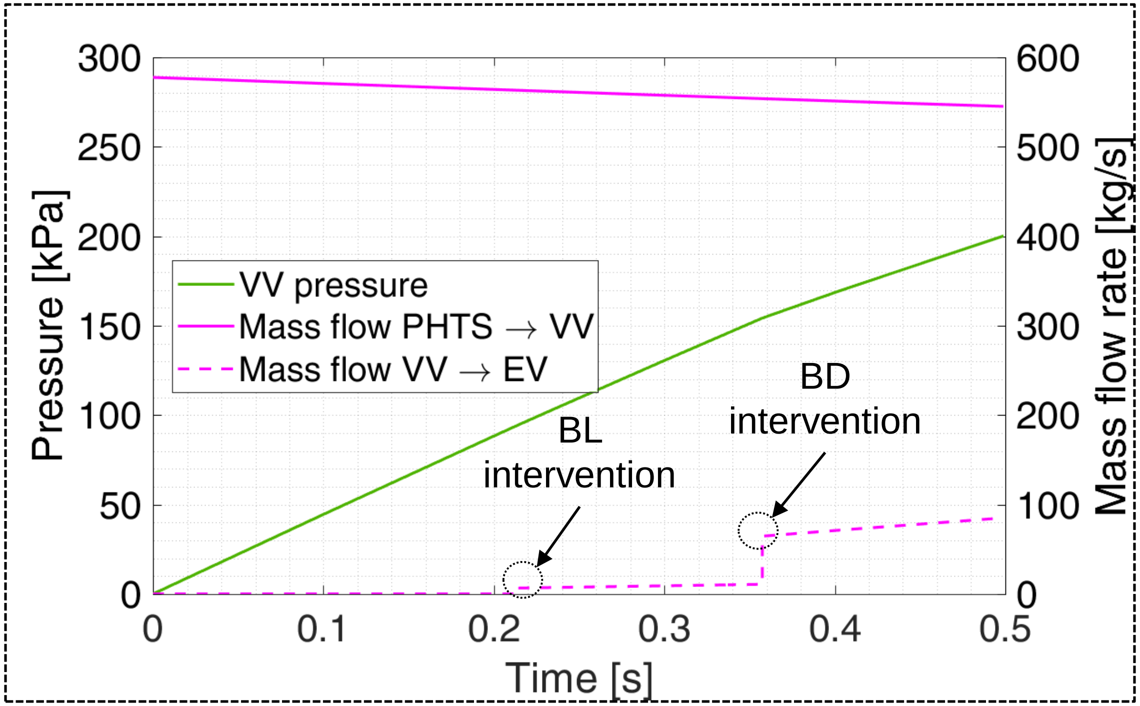
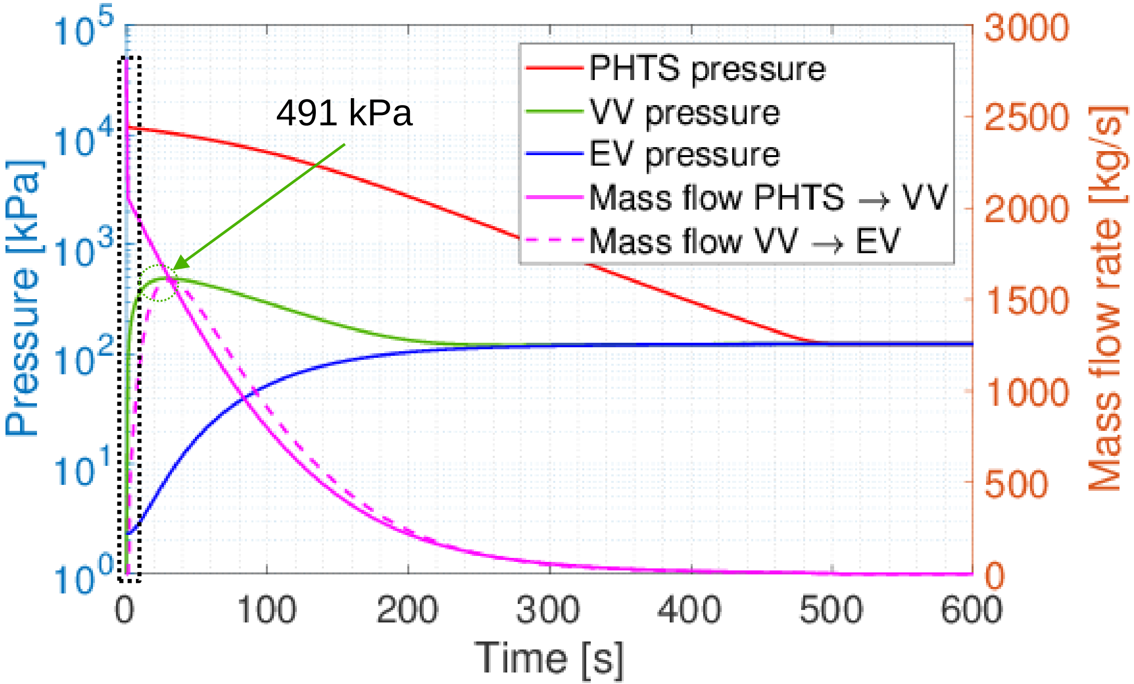


# GETTHEM applications:
# in-VV LOCA step 2 – application to DEMO ($H_2O$)

- Peak pressure overcomes VV limit
- Transient is *much slower* than He (peak reached at ~30 s)
- Saturation conditions reached at ~1 s → water boils inside PHTS → 2-phase flow → pressure increase in VV slows down



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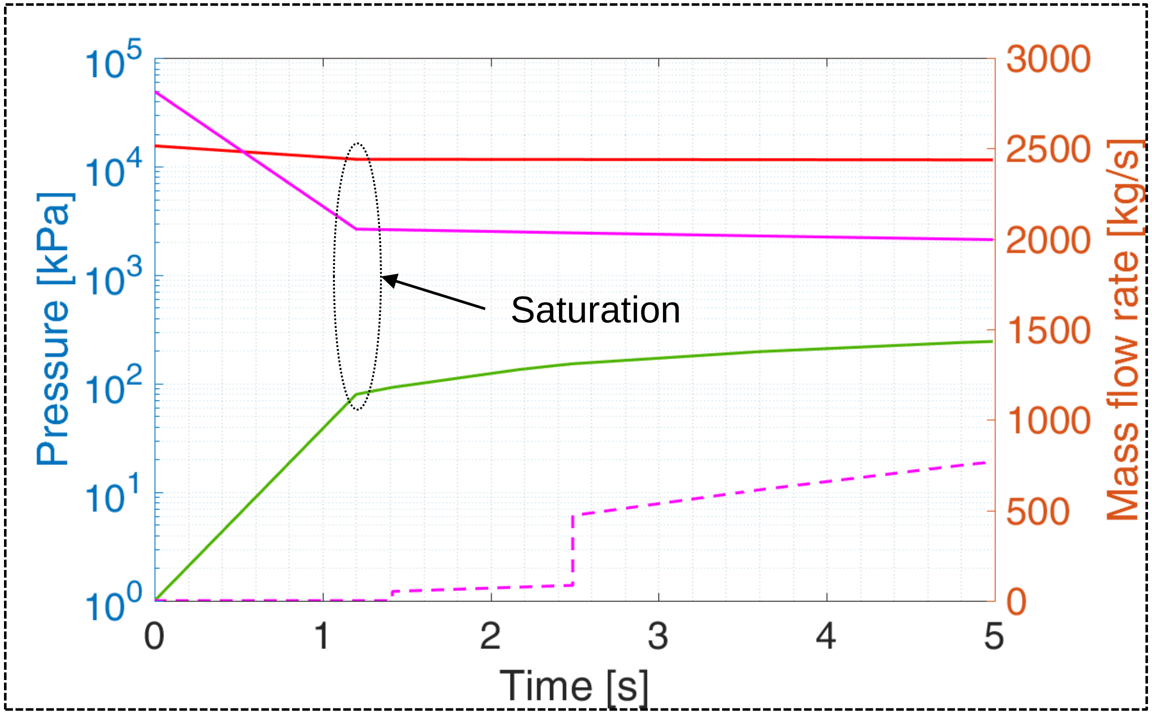

# Conclusions…

GETTHEM model developed during PhD to allow fast transient thermal-hydraulic simulations for DEMO

- ✓ Code benchmarked and validated in off-normal scenarios
- ✓ Successfully applied to optimize flow distribution in normal operation for HCPB and WCLL
- ✓ Code used to predict pressure behaviour following an in-VV LOCA

# …and perspective

- →Benchmark of code capabilities to predict hot-spot temperatures in solid materials during normal operation
- →Parametric analysis of different heat loads to FW
- →Parametric analysis of break size for in-VV LOCA
- →Include 1D PHTS model in LOCA analysis

# Acknowledgements

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- L. Savoldi for continuous support