Safety Analysis of the European Test Blanket Systems in ITER using MELCOR

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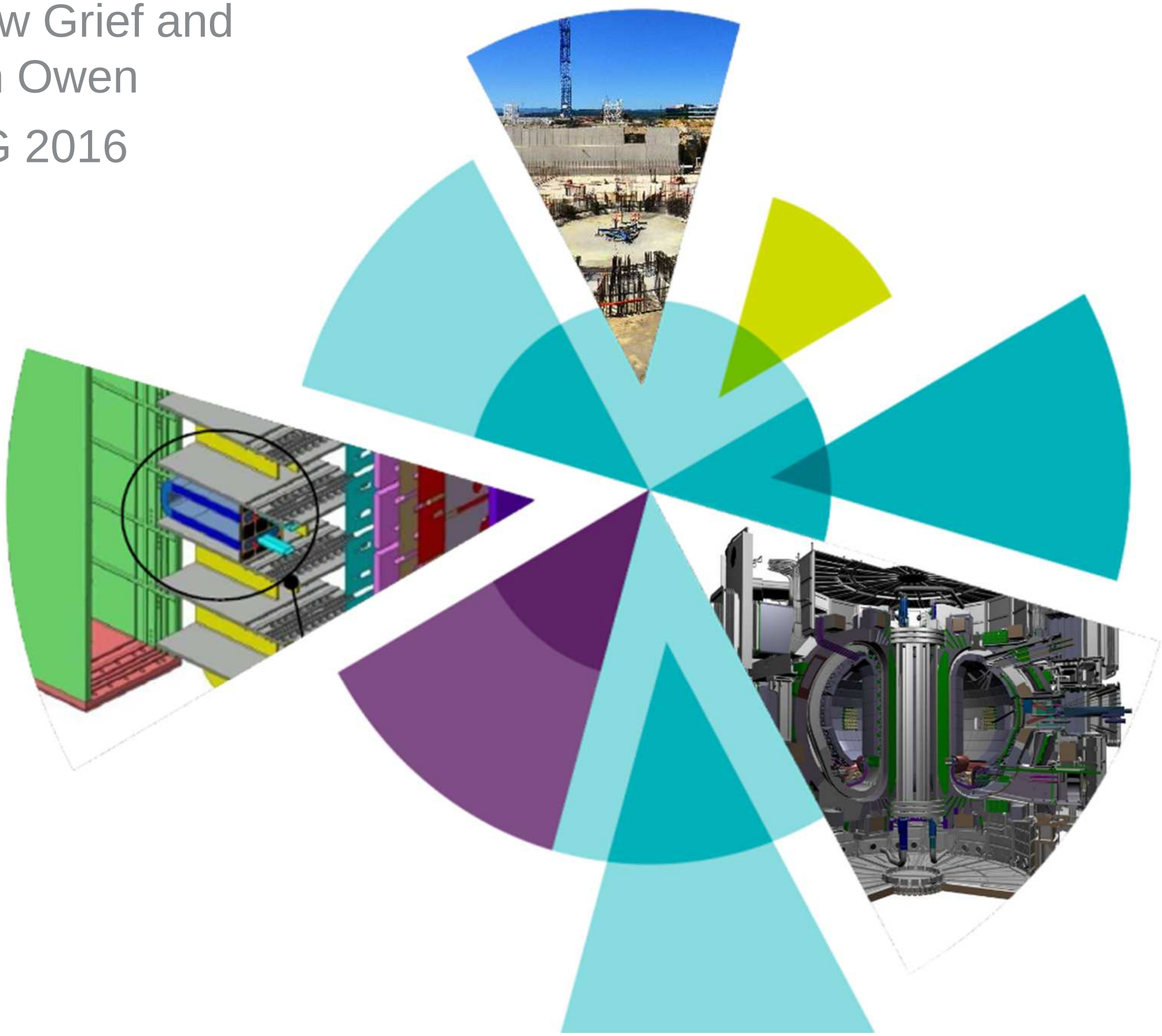
EMUG 2016



Overview

1. **Introduction to fusion and the ITER machine**
2. **Tritium self-sustainment and Test Blanket Modules (TBMs)**
3. **The Helium Cooled Pebble Bed (HCPB) and Helium Cooled Lithium Lead (HCLL) TBMs**
4. **Hazards and safety analysis modelling of TBMs using MELCOR**
5. **Methodology / approach**
6. **Case studies**

This presentation describes work conducted for Fusion 4 Energy under contract F4E-OMF-331-04-01-01. Amec Foster Wheeler wish to thank F4E for allowing us to present this work

Introduction to ITER

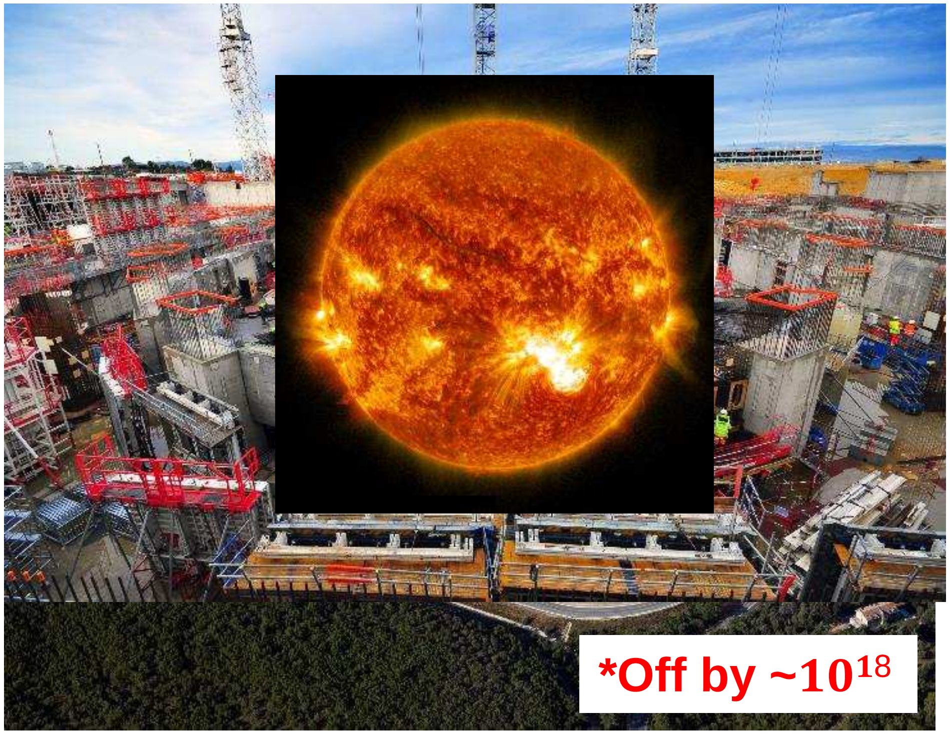
ITER (Latin for ‘The Way’, previously ‘International Thermonuclear Experimental Reactor’) under construction at Cadarache in southern France

- An experiment, not a power plant – no electricity generation
- Produce heat using magnetically confined deuterium-tritium fusion

International project led by the ITER Organisation (IO)

- European Union, India, Japan, China, Russia, South Korea, USA
- European contribution is through ‘Fusion for Energy’ (F4E)

Scientists developing 'Doctor Who-like' huge nuclear STAR to produce same power as SUN *



*Off by ~10^{18}

Images: http://www.iter.org/

The ITER Experiment

Aims

- Produce 10 times more energy than input (500 MW fusion power)
- Achieve a **burning plasma** – sustained reaction for a long duration (100s of seconds)
- Test integrated technologies and demonstrate safety

How?

- Use the largest ever **tokamak** (840 m^3) to magnetically confine a high temperature plasma (ionised gas)

Facts and figures

- **23,000 t** machine weight
- Temperature of the plasma: **150 million °C**
- Temperature of the magnets: **-269°C**
- **Cost ~ 13 billion $**
  - **Large Hadron Collider ~ 10 billion $**
  - **International Space Station ~ 150 billion $**

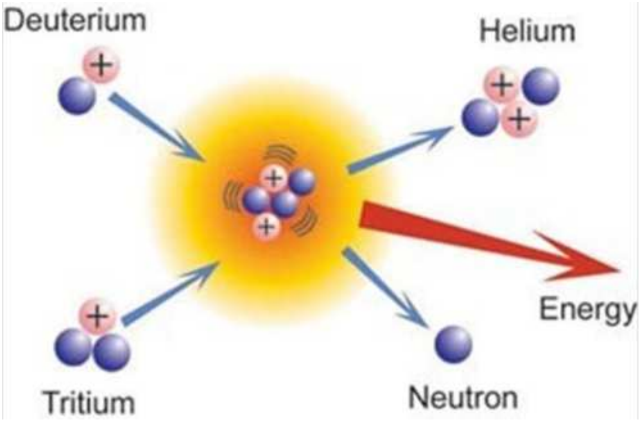


Image: http://www.iter.org/

The ITER Machine

Vacuum vessel

Magnets

- 48 magnets

Cryostat

- The vacuum vessel sits inside the cryostat

Blanket

- 440 water cooled modules, each 1 m x 1.5 m and ~4 tonnes
- Shields vacuum vessel from high energy neutrons and removes heat

Divertor

- This removes impurities (exhaust) from the plasma
- **Very** high heat loads
- At bottom of vacuum vessel

- Interactive graphics available: http://www.iter.org/mach

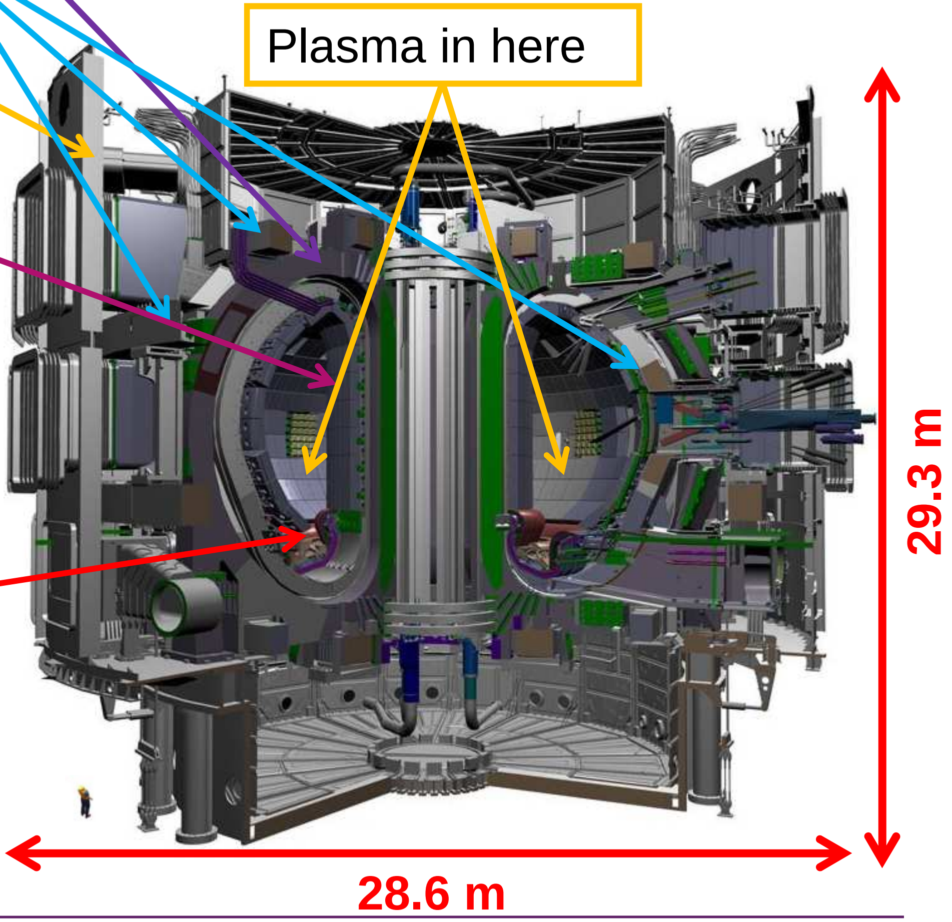


Image: http://www.iter.org/

Tritium Breeding

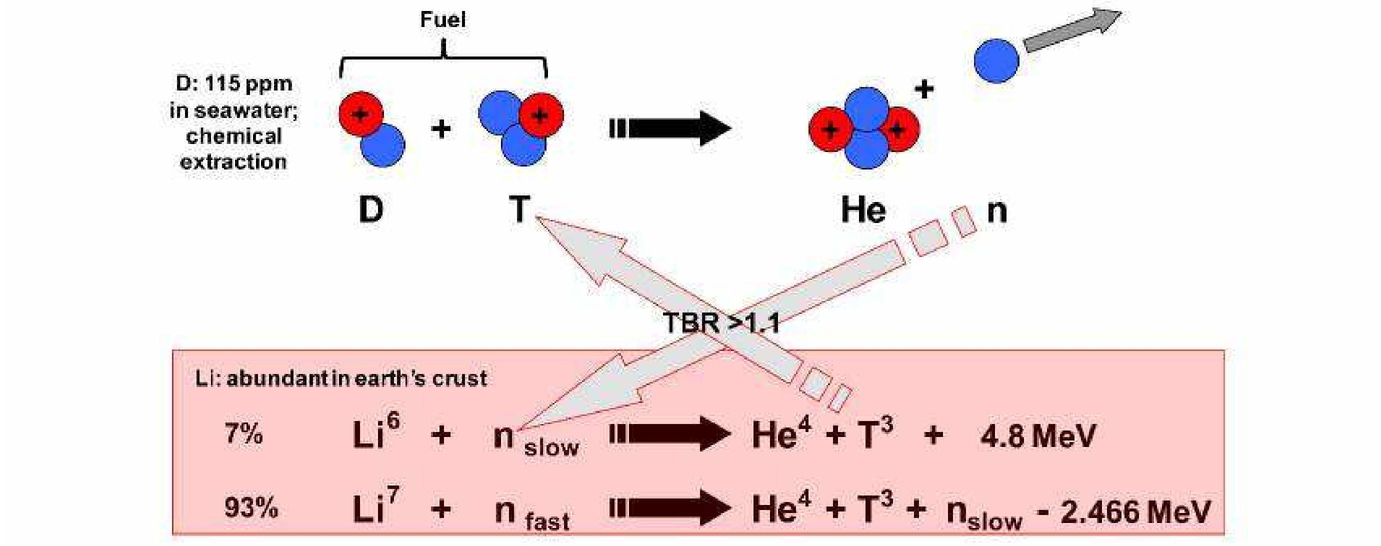
Tritium self-sustainment is a requirement of any commercial fusion plant

- Tritium resources currently estimated at **~20 kg**
- The envisaged fusion power demonstration plant (DEMO) will require **300 g per day** to produce 800 MW electrical power
- Approximate cost of tritium: **$100,000 per gram…**

Estimates: S. Willms, ITER Test Blanket Module Meeting, UCLA, Feb 2004

Tritium Breeding

ITER will use the high energy neutrons produced in the fusion reaction to test tritium breeding concepts



Six designs of Test Blanket Module (TBM) will be tested at ITER

► The TBMs all contain lithium; Beryllium and lead are used as neutron multipliers

Europe will provide two designs:

- Helium-Cooled Pebble Bed (HCPB) TBM
- Helium-Cooled Lithium Lead (HCLL) TBM

Image: http://www.hiper-laser.org/

The Test Blanket Modules

Test Blanket Module (TBM)

Test **B**lanket **M**odule

This is a technology test programme

The aim is to test technology that will be used heavily in the next fusion reactor after ITER (which will be called DEMO)

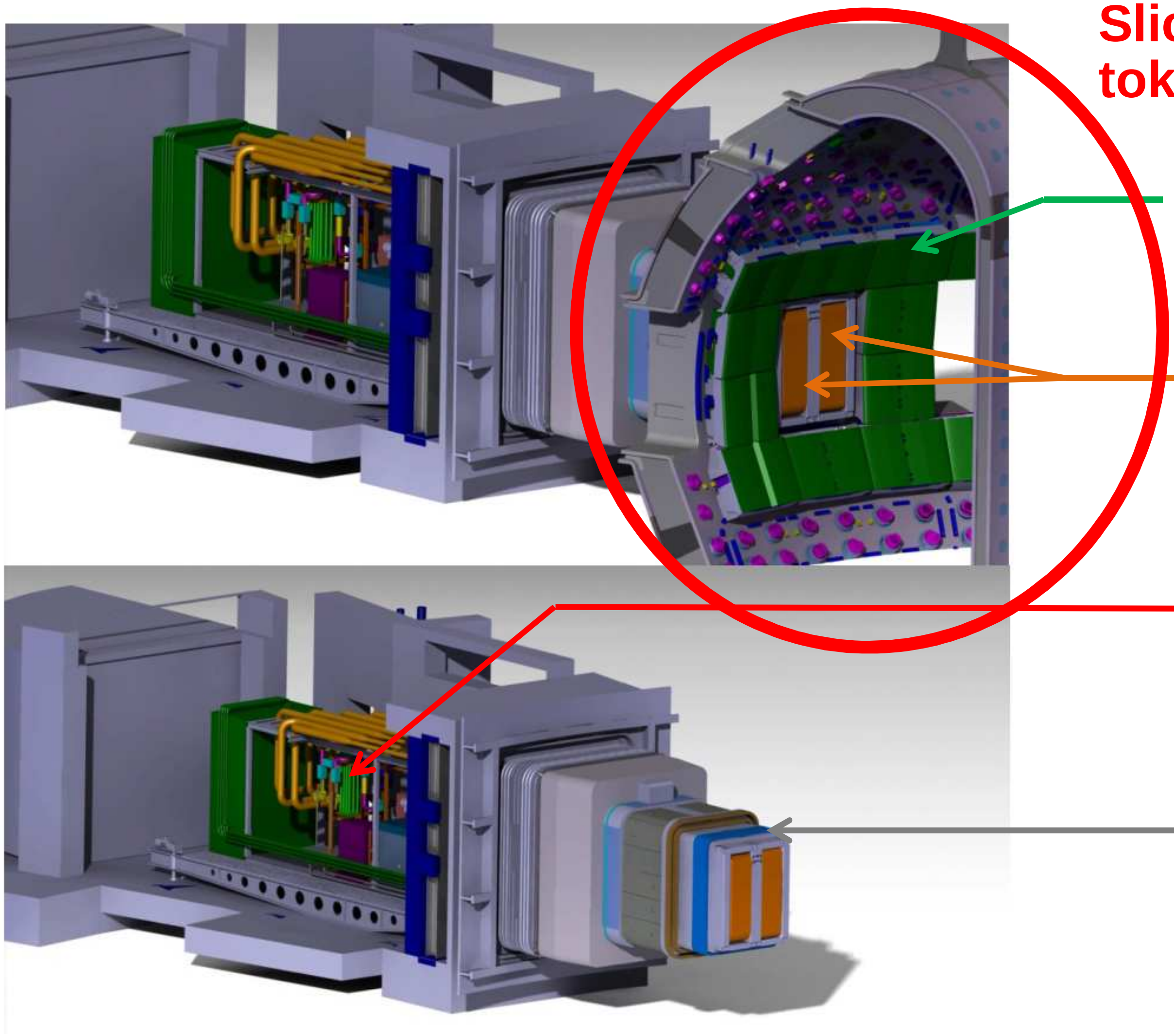
In future reactors these components will be arranged in the ‘blanket’ around the plasma chamber

A full blanket of tritium breeding modules will be needed to create enough tritium to run a power reactor

The curved wall of the plasma chamber is lined with many hundreds of individual ‘modules’

At ITER most modules are just for shielding and cooling – these are called ‘blanket shield modules’. There are 6 tritium-producing test blanket modules

Location of HCLL and HCPB TBM



Slice of the tokamak

Water-cooled blanket shield module

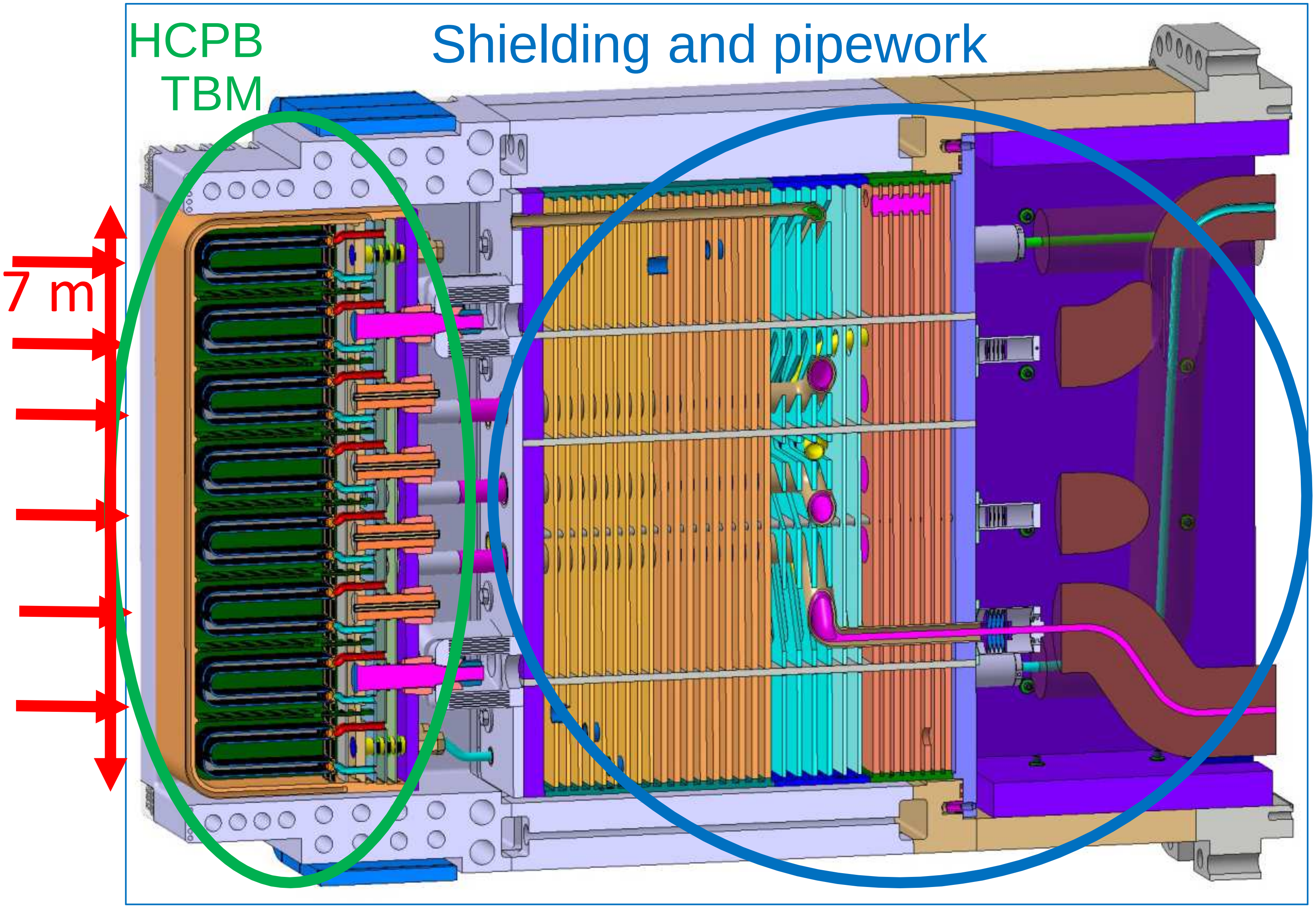
Test Blanket Modules

Supporting systems

Port Plug

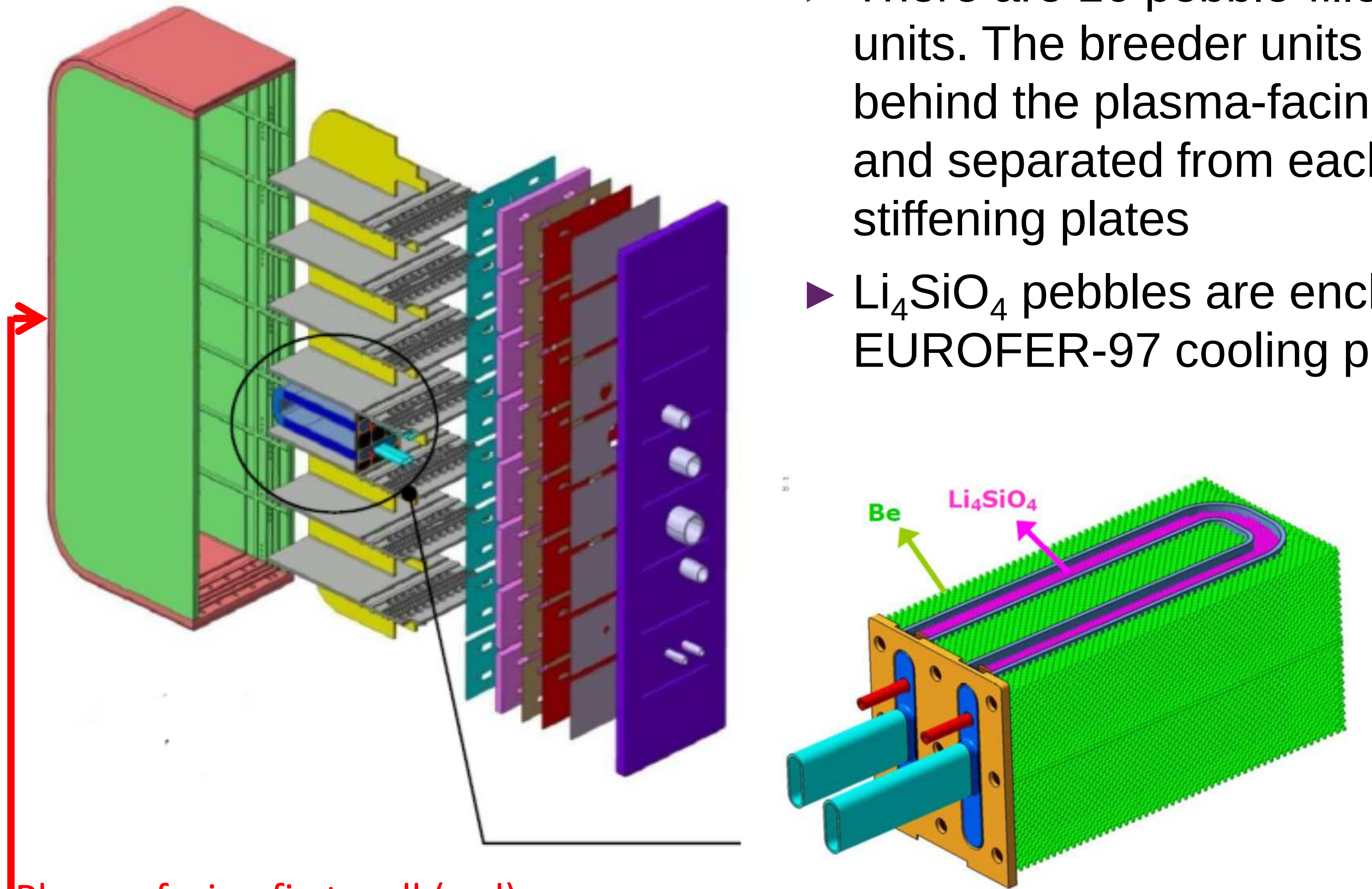
Helium-Cooled Pebble Bed TBM

Heating and neutrons from plasma



Helium-Cooled Pebble Bed TBM

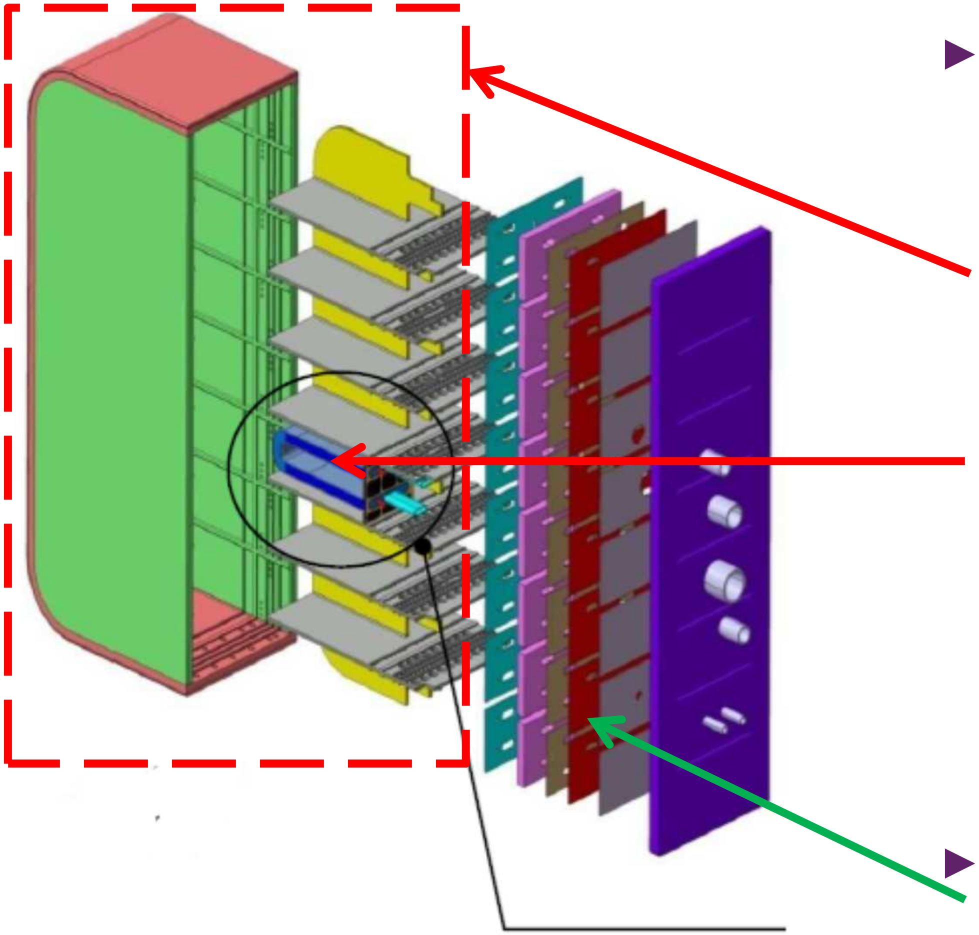
- There are 16 pebble-filled breeder units. The breeder units are held behind the plasma-facing ‘first wall’ and separated from each other by stiffening plates
- Li_4SiO_4 pebbles are enclosed by EUROFER-97 cooling plates



Plasma-facing first wall (red)

Images: F. Cismondi *et al.*, ‘Design Description Document of the HCPB TBM generic box (Part.1 TBM Box)’, F4E report;
F. Cismondi *et al.*, ‘Design Description Document of the reference option for the HCPB-In TBM Breeder Units’,F4E report

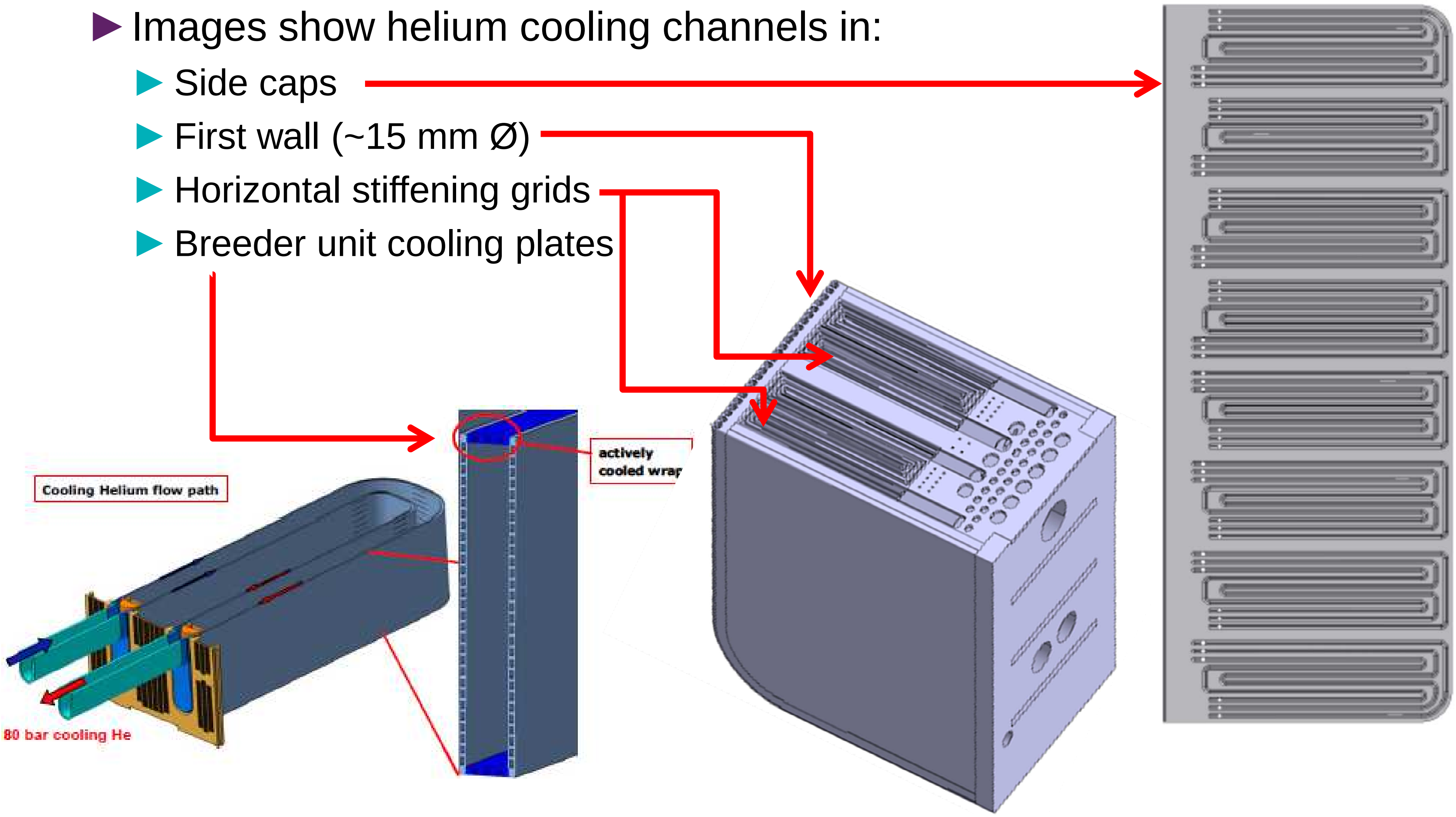
Helium-Cooled Pebble Bed TBM



- Due to the high heat loads most of the structural components contain helium coolant channels
  - All component in red box have coolant channels within them
  - The curved plates separating the beryllium pebbles and the lithium pebbles also contain helium coolant channels
  - These multiple sets of coolant channels are the main heat removal system for the whole TBM
- Spaces between plates at the back of the TBM box form 4 manifolds for the helium coolant

Images: F. Cismondi *et al.*, 'Design Description Document of the HCPB TBM generic box (Part.1 TBM Box)', F4E_D report; F. Cismondi *et al.*, 'Design Description Document of the reference option for the HCPB-In TBM Breeder Units',F4E report

Helium-Cooled Pebble Bed TBM



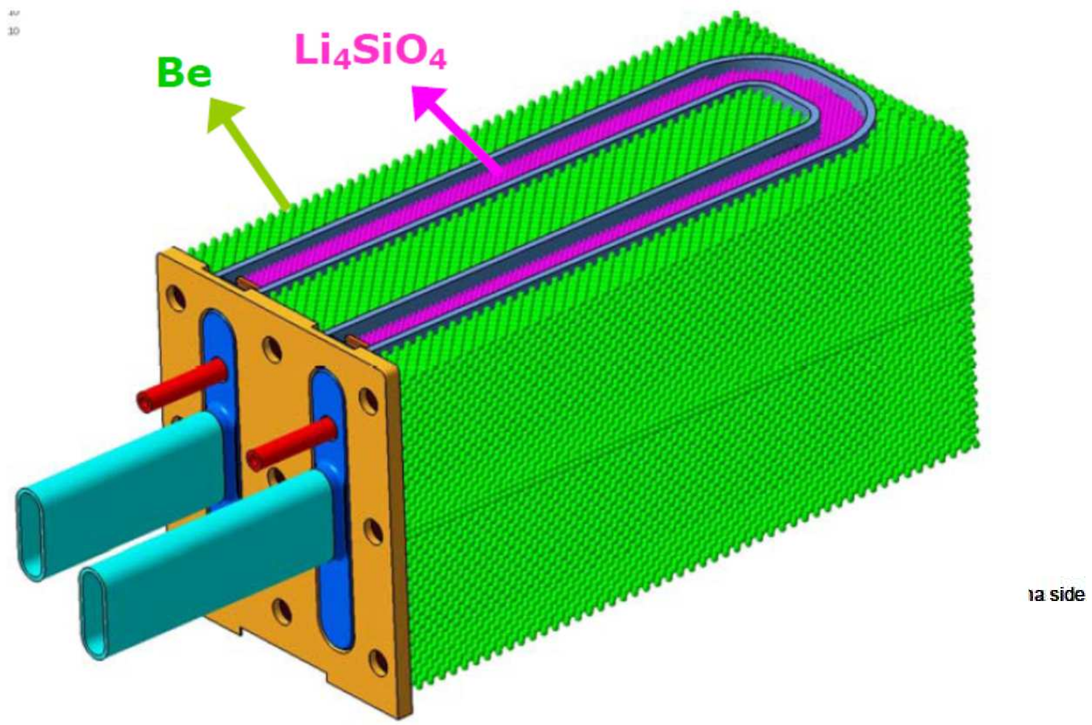
- Images show helium cooling channels in:
  - Side caps
  - First wall (~15 mm Ø)
  - Horizontal stiffening grids
  - Breeder unit cooling plates

Images: F. Cismondi *et al.*, 'Design Description Document of the HCPB TBM generic box (Part.1 TBM Box)', F4E report
F. Cismondi *et al.*, 'Design Description Document of the reference option for the HCPB-In TBM Breeder Units',F4E report

Helium-Cooled Pebble Bed TBM

How is the tritium extracted?

- A second, separate, slow low pressure (~1 bar) helium flow is passed through the beryllium and lithium pebble beds in each of the 16 breeder units
- Tritium diffuses out from the pebbles, into this ‘purge gas’ flow
  - Carried off to the Tritium Extraction System (TES)



- Yellow arrows show purge gas flow
- The plates and caps (not shown) around the beryllium and lithium pebbles constrain the purge flow

Images: F. Cismondi *et al.*, ‘Design Description Document of the HCPB TBM generic box (Part.1 TBM Box)’, F4E report;
F. Cismondi *et al.*, ‘Design Description Document of the reference option for the HCPB-In TBM Breeder Units’,F4E report

Helium-Cooled Lithium Lead TBM

- Basic box structure very similar to the HCPB TBM
- Liquid lithium lead (PbLi) used to breed tritium and transport it from the TBM
  - High tritium breeding capability, relatively high thermal conductivity, immunity to irradiation damage
- Lithium lead flow strongly affected by magneto hydrodynamics (MHD)

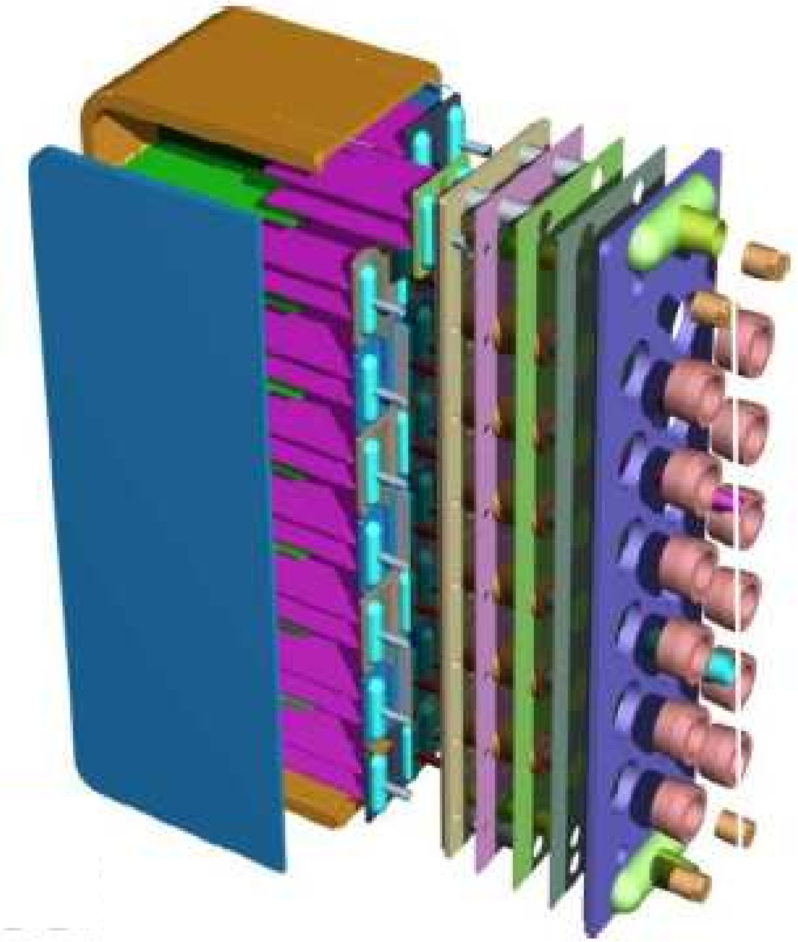


Image: G. Aiello, A. Li Puma, G. Rampal, H. Simon, 'Design Description Document of the Reference Option for the HCLL TBM Generic Box, Version 1.0, F4E report

Auxiliary systems

- Helium Coolant System (HCS) – primary TBM heat removal system
- Coolant Purification System (CPS)
- Lithium lead ancillary system (for HCLL)
- Tritium extraction system (for HCPB)
- Port plug – water-cooled structure that houses the TBMs
- Instrumentation and control systems

Image: G. Aiello, A. Li Puma, G. Rampal, H. Simon, 'Design Description Document of the Reference Option for the HCLL TBM Generic Box, Version 1.0, F4E report

TBM Hazards

As complex nuclear systems, we must demonstrate the TBMs will operate safely in operational and accident scenarios.

Examples of key hazards include:

- For both HCPB and HCLL systems
  - Leaks or pressure relief systems releasing helium / tritium / activated corrosion products / dust into ITER buildings
- HCLL
  - Hazardous PbLi leak into Vacuum Vessel (VV) / ITER buildings
  - Hydrogen production through PbLi chemical reaction (with steam/water)
- HCPB
  - Hydrogen production through beryllium chemical reactions (with air or steam)

Plasma ‘disruptions’ can deposit large amounts of energy on the TBM:

- Plasma control is difficult!
- May damage the TBM and the water-cooled blanket shield modules

Accident Analysis Methodology

Accident analysis for fusion systems is not as highly developed as for most fission reactors

- Common elements (choked flow, decay heat, convective heat transfer, …) but also many ‘novel’ phenomena
- Validation is much less developed than for LWRs
- Necessary to develop a coherent methodology that addresses these challenges and maintains consistency with ITER licensing approach

Outline of the methodology

- Selection of accident scenarios based on failure modes and effects analysis (FMEA) studies
- Development Accident Analysis Specifications (AAS)
  - Use of Phenomena Identification and Ranking Table (PIRT) to identify required physical models to aid selection of the analysis code
  - Objectives / Acceptance criteria
  - System assumptions
- Development of TBS models using the selected analysis codes
- Qualification of the models via comparison with finite, element calculations, code-to-code comparisons, and sensitivity studies
- Application of the qualified models to the selected accident scenarios
  - Ongoing sensitivity studies to address uncertainties, demonstrate conservatism
  - Iterative updates as knowledge improves

Requirements for TBM Accident Analysis

Key requirements for the analysis code:

- ‘Typical’ flow / convection heat transfer models for gases, heat structure models for solids
- ‘Typical’ control system models
- Multi-dimensional heat conduction modelling
- Flow of molten PbLi
  - PbLi as working fluid
  - Pressure drops induced by magnetic field (MHD)
- Chemical reaction modelling (Beryllium – steam / air reaction)
- Robust numerics
- Modelling flexibility
- Consistency with ITER accident analysis desirable

Use of MELCOR

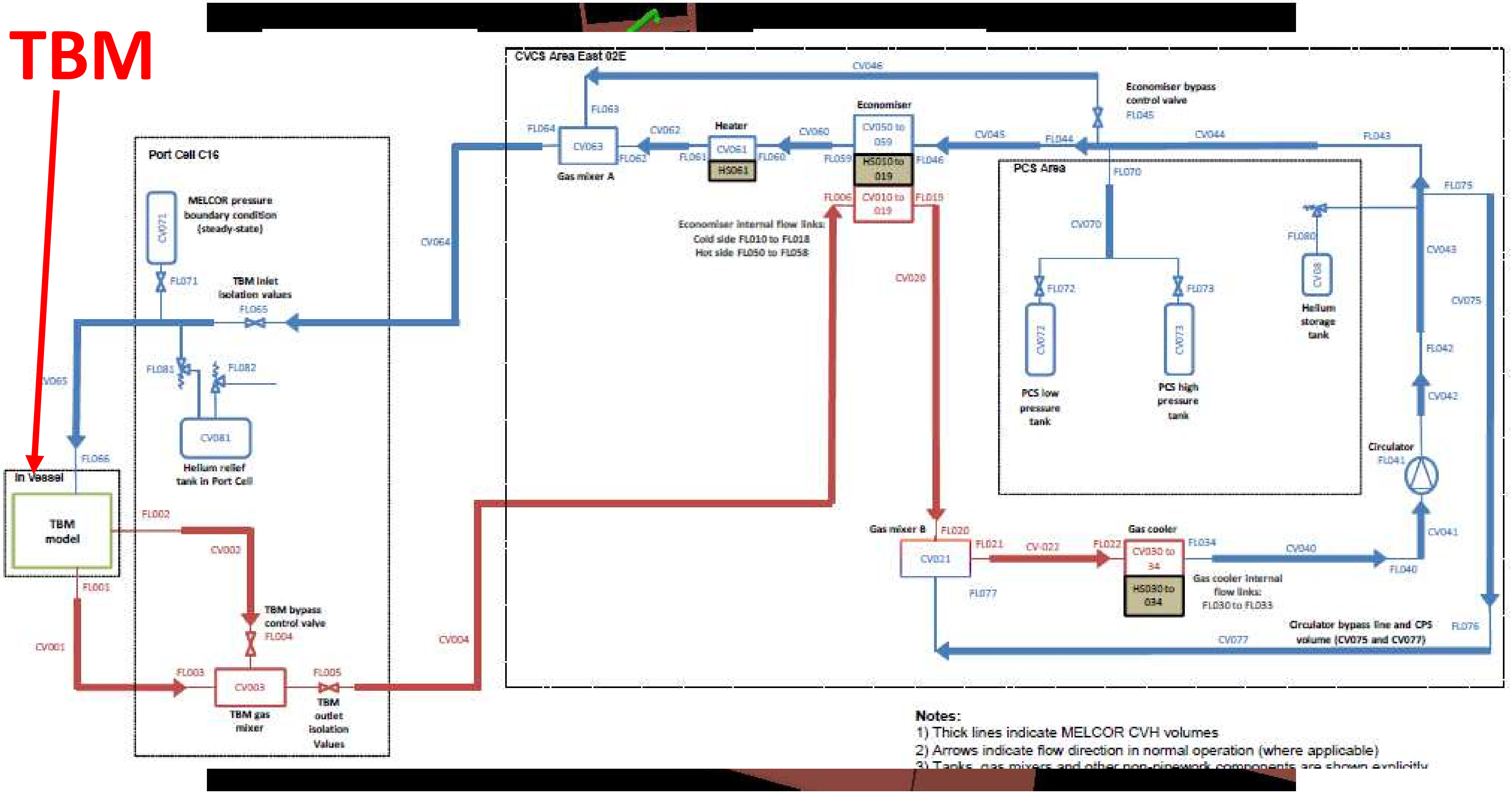
The fusion-adapted MELCOR codes, produced by Brad Merrill at Idaho National Laboratory based on the MELCOR 1.8.x code base meet the key requirements

- Work described today uses fusion-adapted 1.8.2 and 1.8.5 MELCOR code versions
  - Multi-fluids 1.8.5 code for HCLL TBS (ability to simulate liquid PbLi)
  - ITER 1.8.2 code version for HCPB TBS (sufficient control functions for modelling complex thermal conduction network in pebble bed)
- We look forward to using the new (double precision) fusion adapted 1.8.6 code in upcoming work… (and maybe a fusion-capable MELCOR 2.x code in due course!)
- Main MELCOR packages used so far: CVH, FL, HS, TF and CF modules
- MELCOR models qualified against finite element analysis and RELAP5-3D model

In this talk we present MELCOR work – however, Amec Foster Wheeler have also developed RELAP5-3D models of these systems and performed code-to-code comparisons

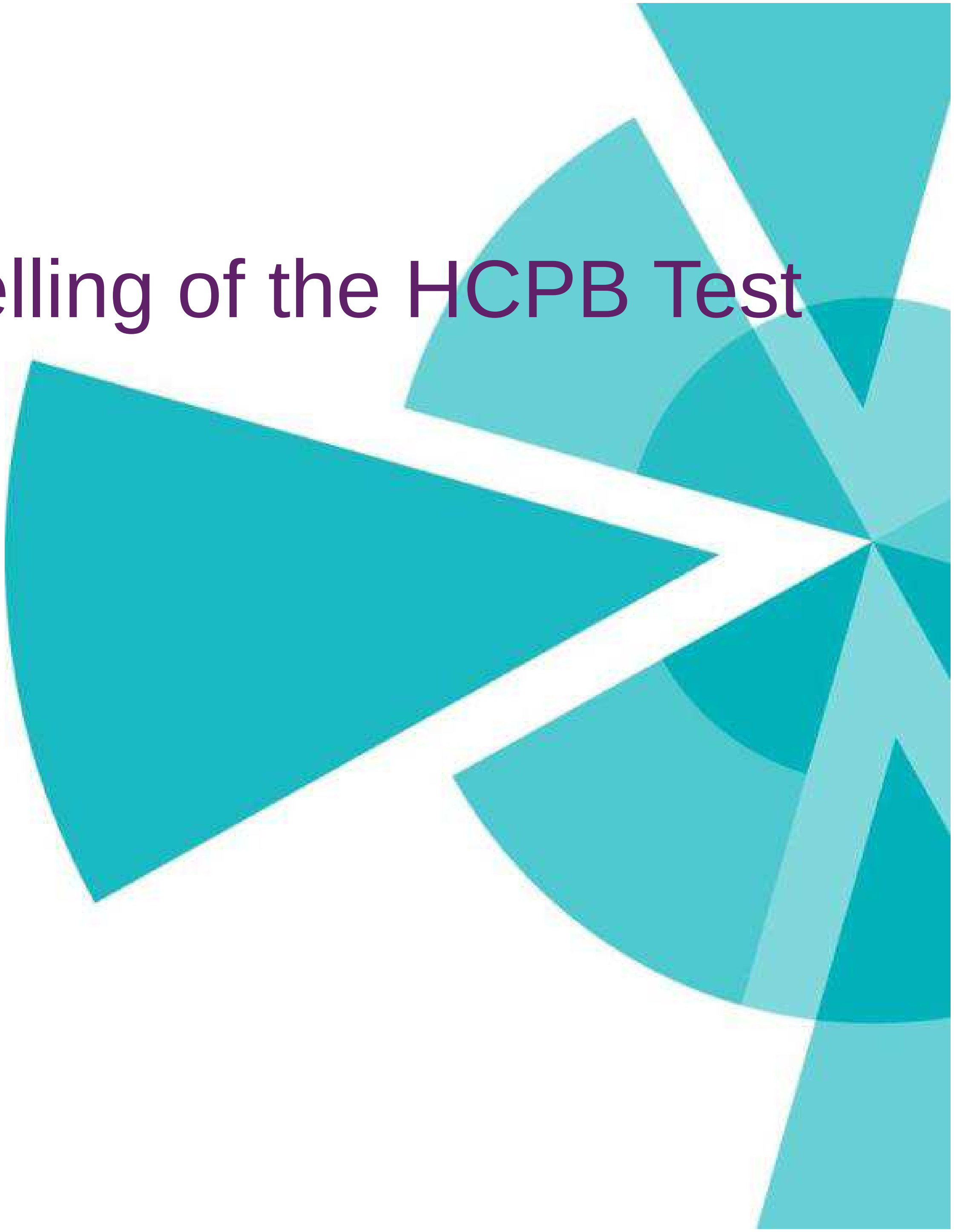
Modelling the Helium Coolant System (HCS)

- ► Start simple – modelling the cooling system:

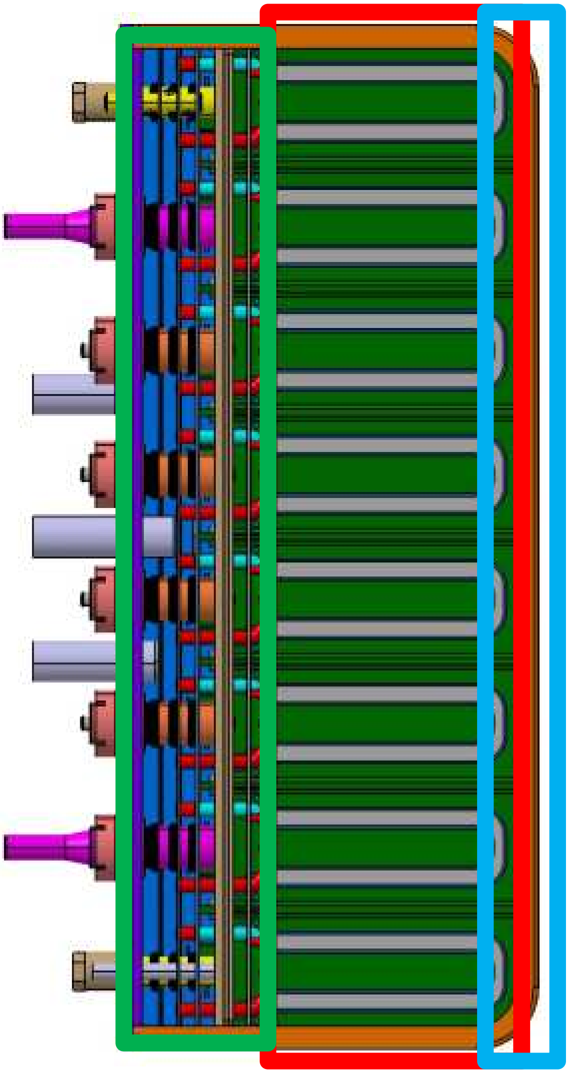


Notes:
1) Thick lines indicate MELCOR CVH volumes
2) Arrows indicate flow direction in normal operation (where applicable)
3) Tanks, gas mixers and other non-pipework components are shown explicitly

MELCOR modelling of the HCPB Test Blanket System



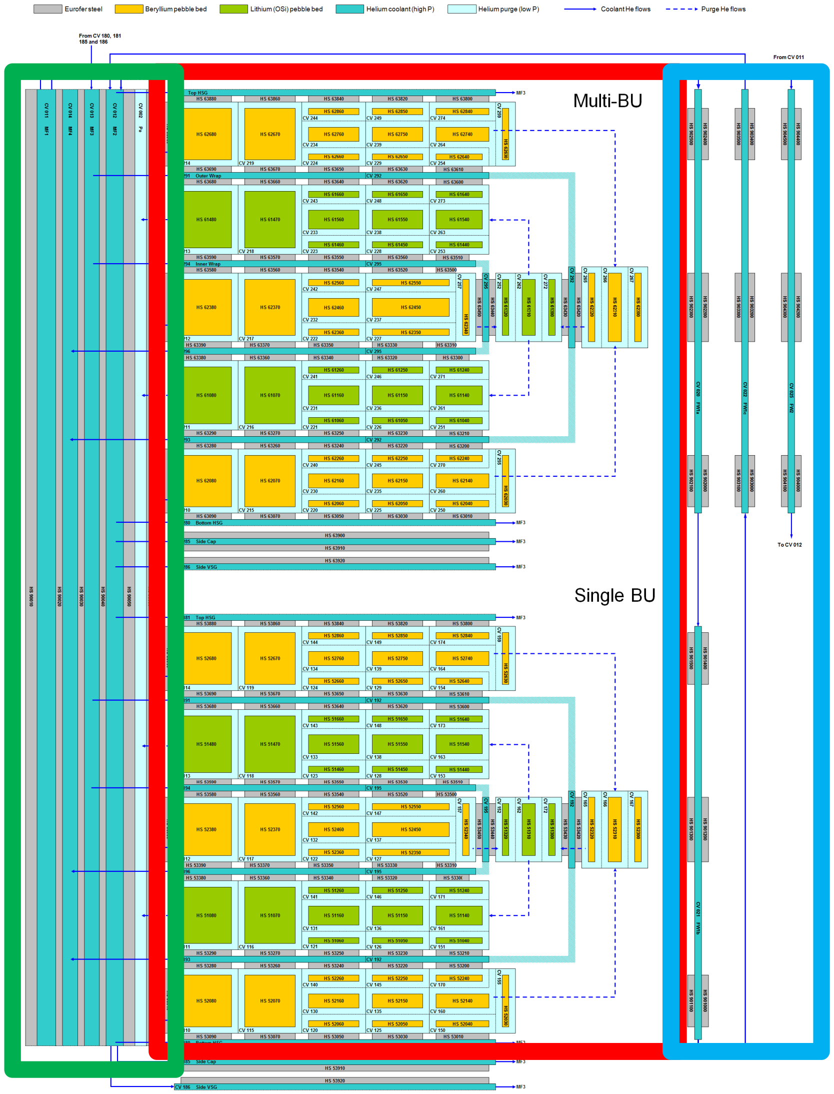
Modelling the HCPB TBM



Plasma-facing First Wall (FW)

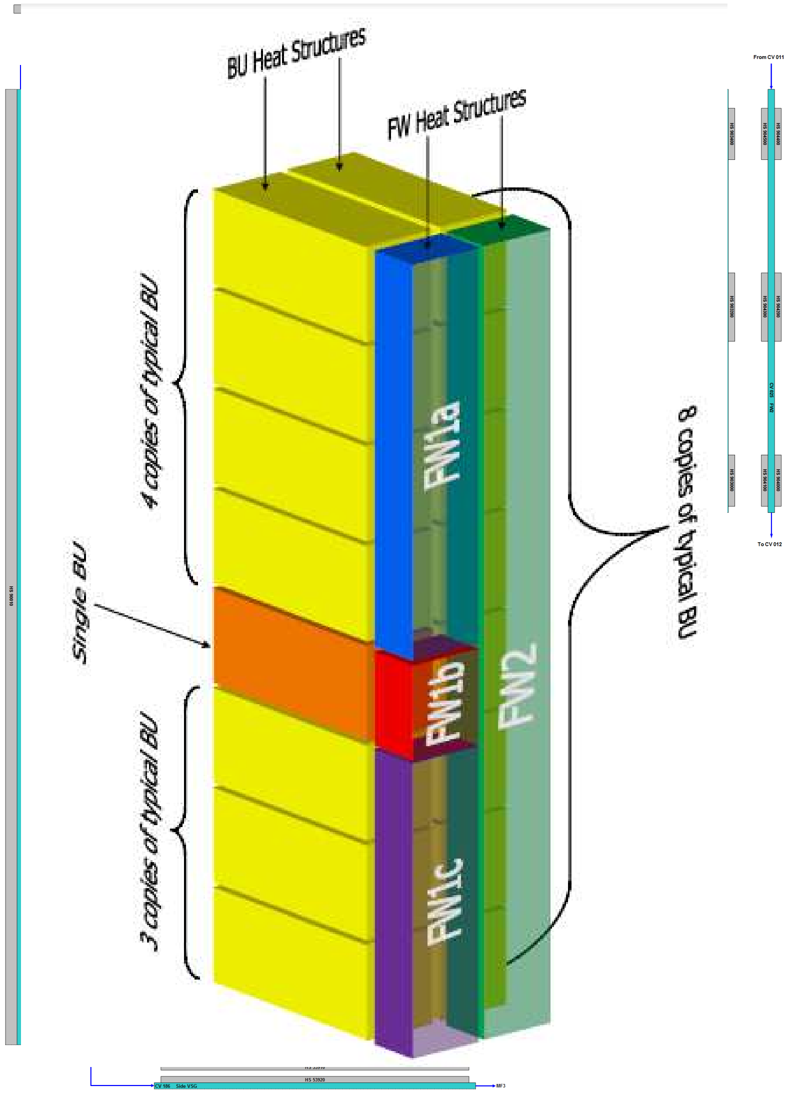
16 Breeder Units (BUs)

Helium manifolds

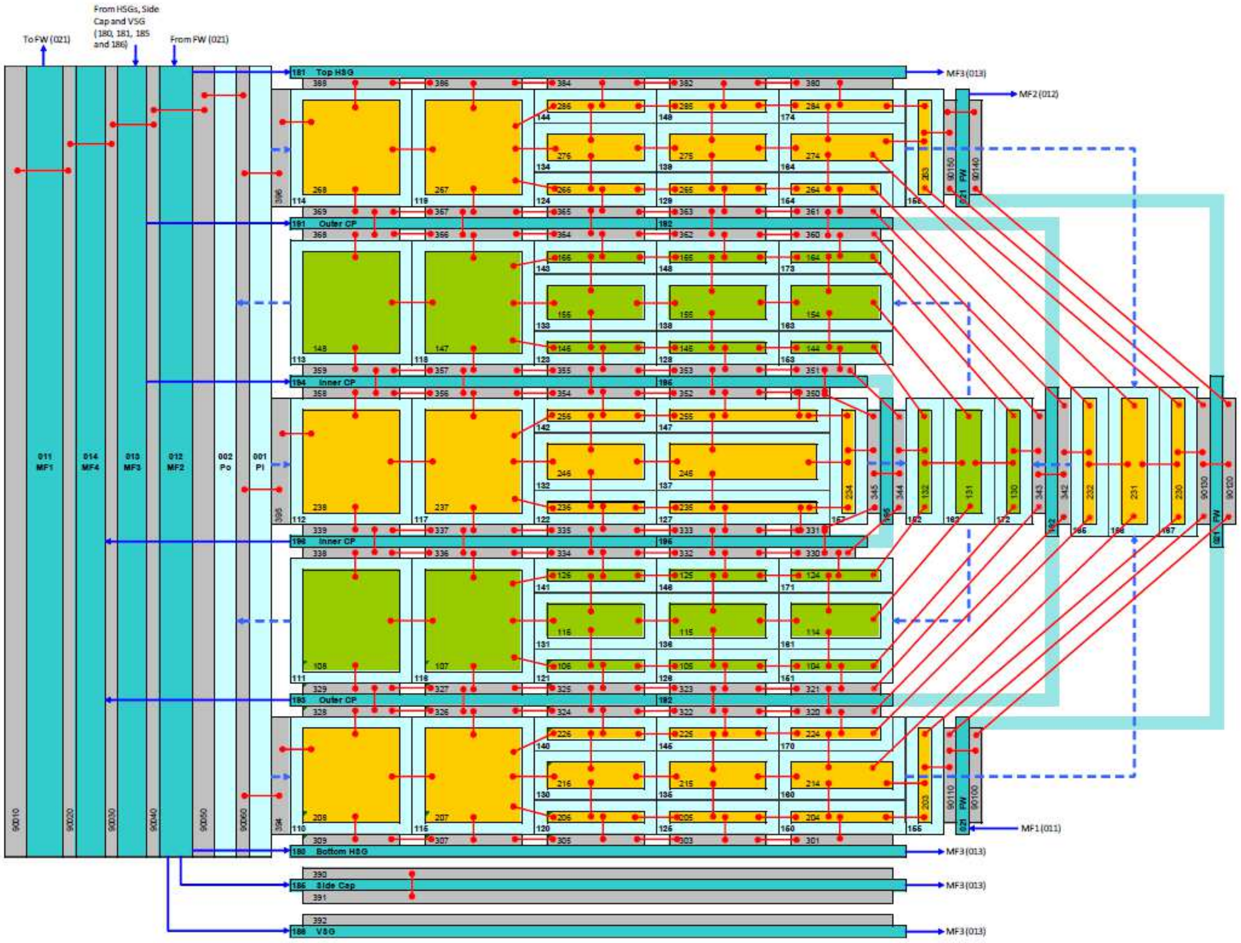


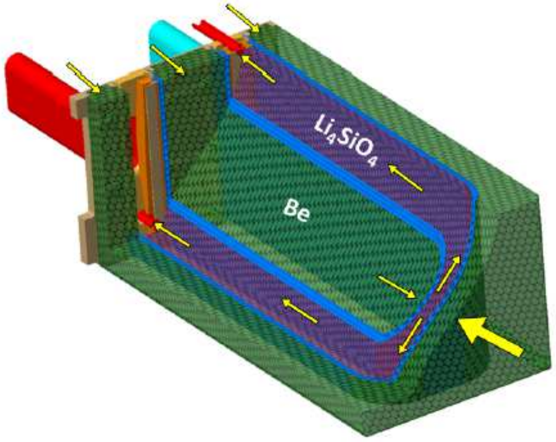
Helium-Cooled Pebble Bed Model Design

- ‘Single BU’ and ‘Multi BU’ nodalisation allows us to separately analyse the behaviour of a damaged Breeder Unit (BU) from the fifteen intact BUs
  - Interaction between damaged BU and the ITER VV differs from the intact BUs
  - The damaged BU may receive enhanced cooling in the case of a coolant leak
- Developed a nodalisation of the TBM First Wall (FW) which accounts for the different behaviour of the (thermally) connected BUs



Modelling the HCPB Breeder Units





⬜ Eurofer Steel
🟨 Beryllium Pebble Bed
🟩 LiOS Pebble Bed
🟦 Helium Coolant
⬜ Helium Purge Gas

→ Coolant He Flows
⇢ Purge He Flows
●—● CF Heat Transfers

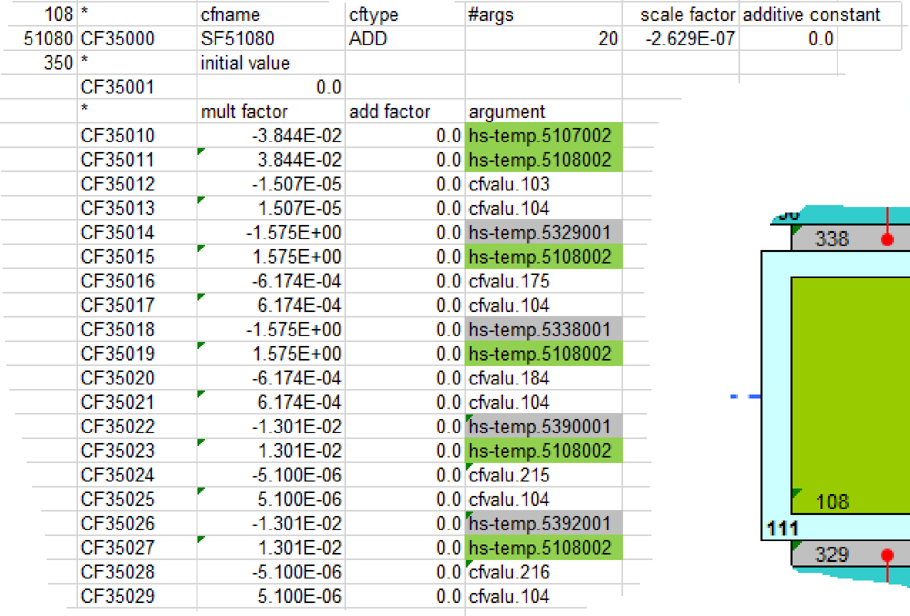
Modelling the HCPB Breeder Units

Modelling conduction in the pebble bed

- Heat transfer between two pebble bed zones: $H_{12} = \frac{A_{12}}{d_{12}} k_{12}(T_1 - T_2)$

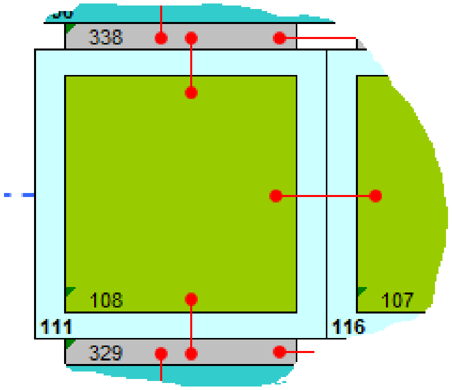
- Conductivity of a pebble bed zone: $k_i(T) = a_i + b_i T$

- A single MELCOR 'ADD' control function computes heat source for each heat structure (four terms for each conduction path):



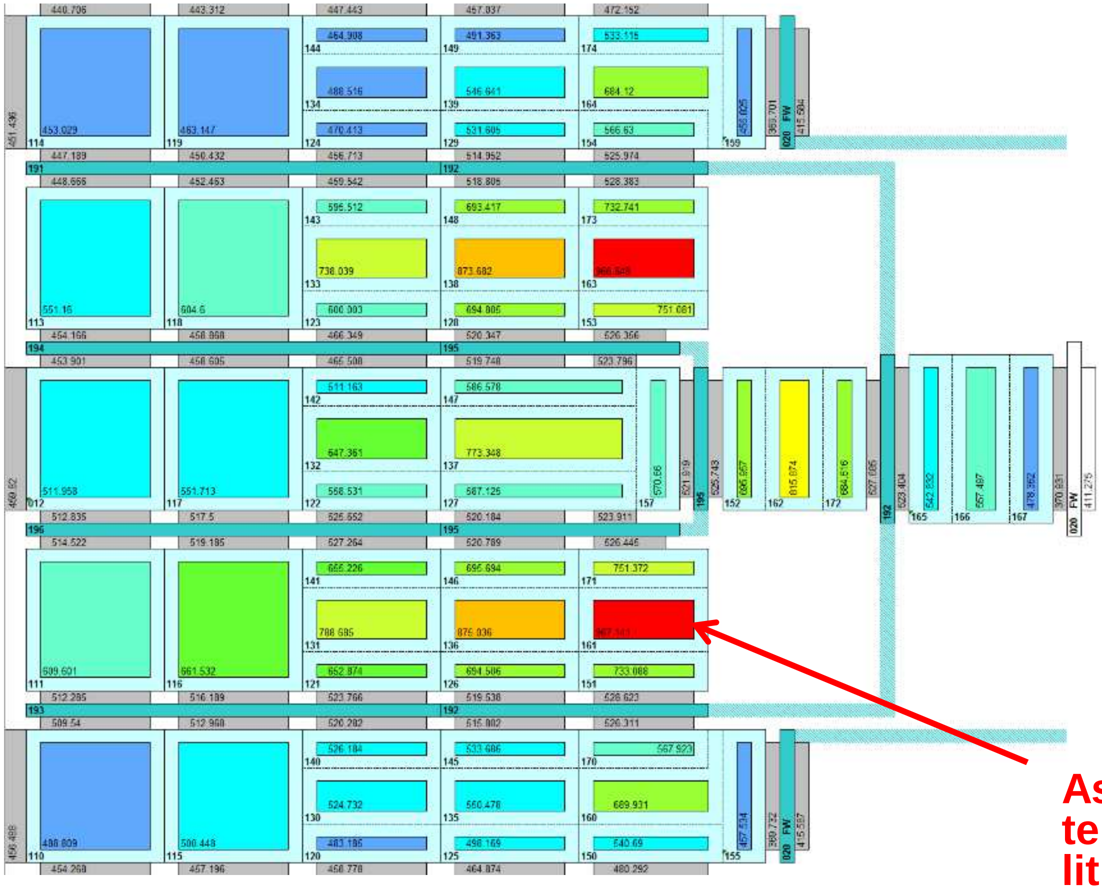
108	*	cfname	cftype	#args	scale factor	additive constant
51080	CF35000	SF51080	ADD	20	-2.629E-07	0.0
350	*	initial value				
	CF35001	0.0				
	*	mult factor	add factor	argument		
	CF35010	-3.844E-02	0.0	hs-temp.5107002		
	CF35011	3.844E-02	0.0	hs-temp.5108002		
	CF35012	-1.507E-05	0.0	cfvalu.103		
	CF35013	1.507E-05	0.0	cfvalu.104		
	CF35014	-1.575E+00	0.0	hs-temp.5329001		
	CF35015	1.575E+00	0.0	hs-temp.5108002		
	CF35016	-6.174E-04	0.0	cfvalu.175		
	CF35017	6.174E-04	0.0	cfvalu.104		
	CF35018	-1.575E+00	0.0	hs-temp.5338001		
	CF35019	1.575E+00	0.0	hs-temp.5108002		
	CF35020	-6.174E-04	0.0	cfvalu.184		
	CF35021	6.174E-04	0.0	cfvalu.104		
	CF35022	-1.301E-02	0.0	hs-temp.5390001		
	CF35023	1.301E-02	0.0	hs-temp.5108002		
	CF35024	-5.100E-06	0.0	cfvalu.215		
	CF35025	5.100E-06	0.0	cfvalu.104		
	CF35026	-1.301E-02	0.0	hs-temp.5392001		
	CF35027	1.301E-02	0.0	hs-temp.5108002		
	CF35028	-5.100E-06	0.0	cfvalu.216		
	CF35029	5.100E-06	0.0	cfvalu.104		

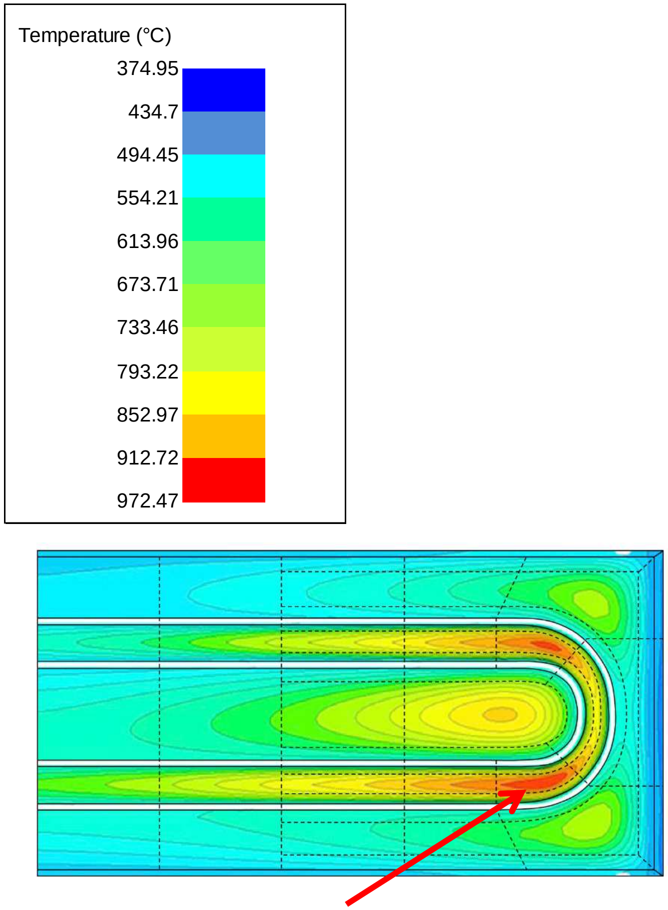
$$= a_i \frac{A_{12}}{d_{12}} (T_{\mathrm{HS1}} - T_{\mathrm{HS2}}) + b_i \frac{A_{12}}{d_{12}} \frac{(T_{\mathrm{HS1}}^2 - T_{\mathrm{HS2}}^2)}{2}$$



Modelling the HCPB TBM

Breeder unit temperature distribution predicted using MELCOR





As in CFD, highest temperatures in lithium pebbles

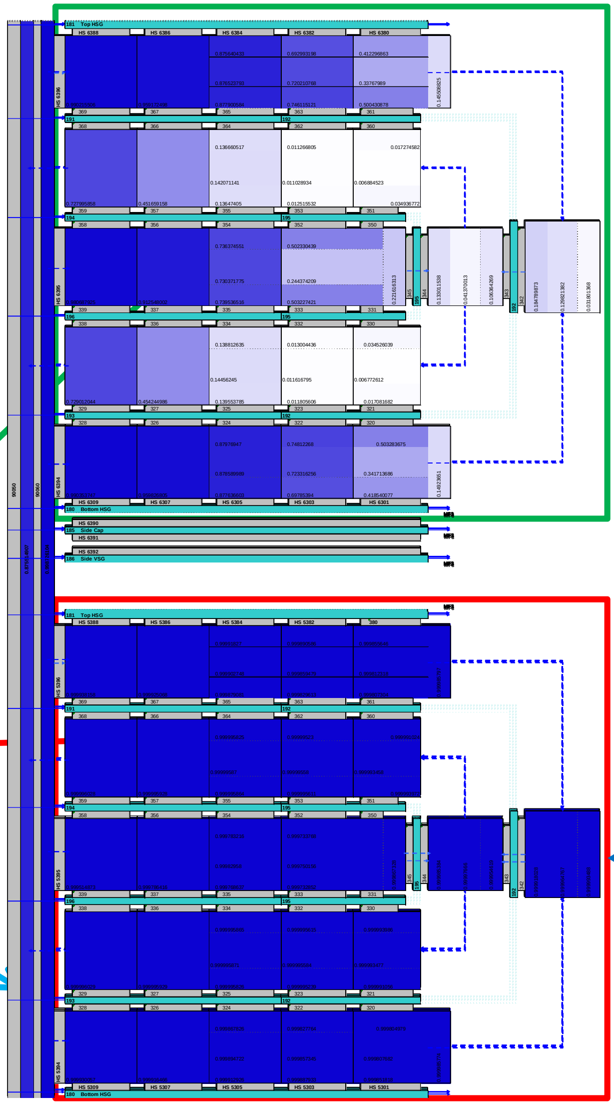
Steam Ingress into HCPB TBM

A plasma ‘disruption’ ruptures an ITER water-cooled blanket module and the first wall of the TBM

- ▶ Plasma chamber fills with steam
- ▶ Steam can enter the TBM and react with beryllium pebbles, producing H_2

- ▶ 15 intact breeder units
- ▶ 1 damaged breeder unit
- ▶ Connecting manifolds

- ▶ Steam concentration in pebble regions shown by dark blue shading



46 s

100% helium

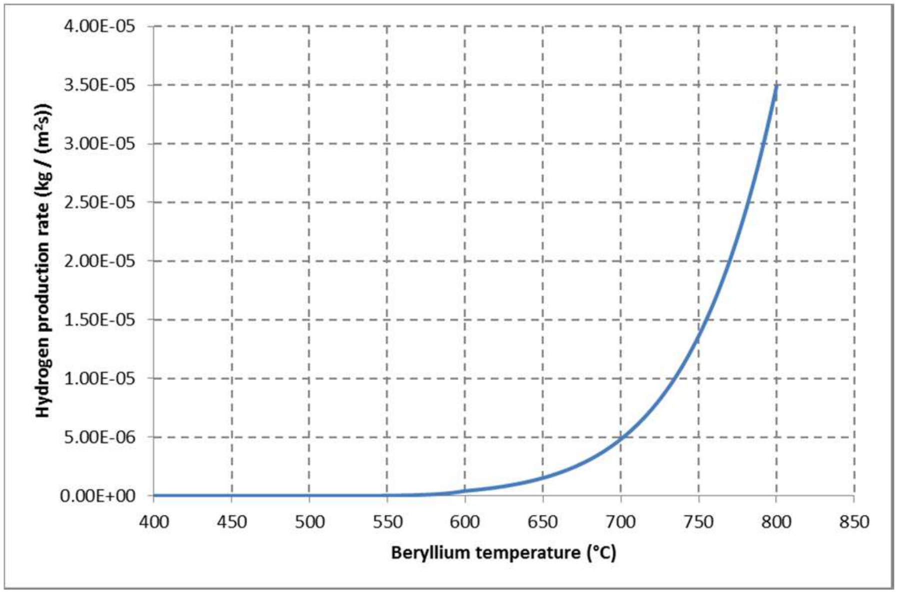
100% steam

Steam from plasma chamber

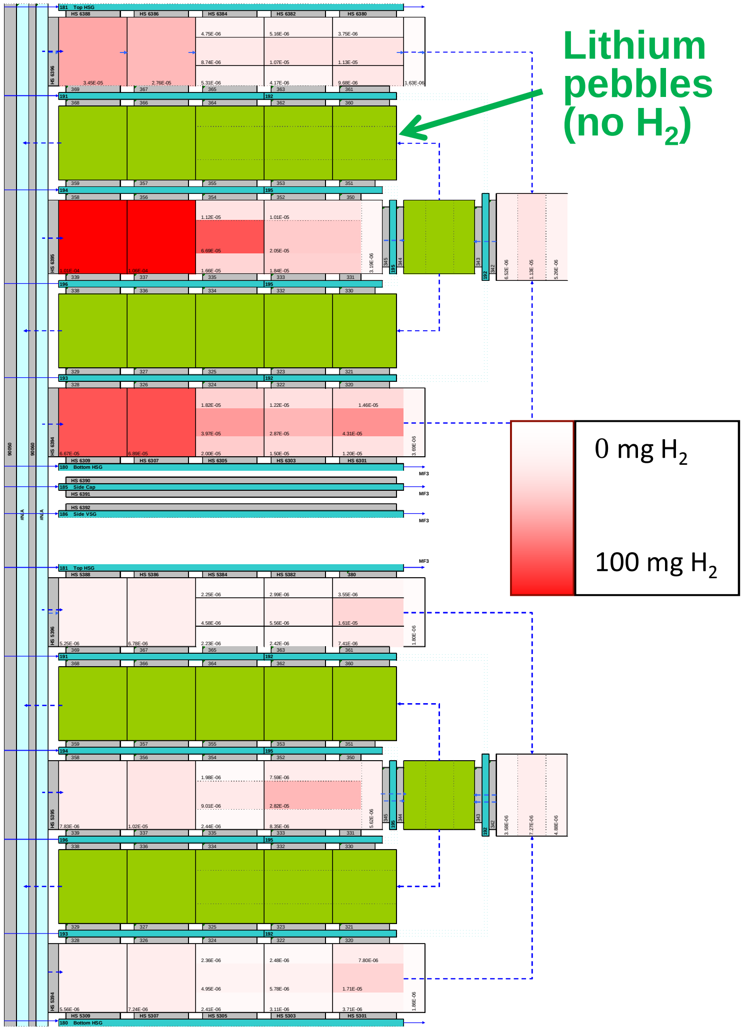
Hydrogen production

- Red colouring indicates mass of hydrogen produced over the duration of a simulation
- Hydrogen production is dependent on **pebble temperature** and **steam partial pressure**

Hydrogen production correlation



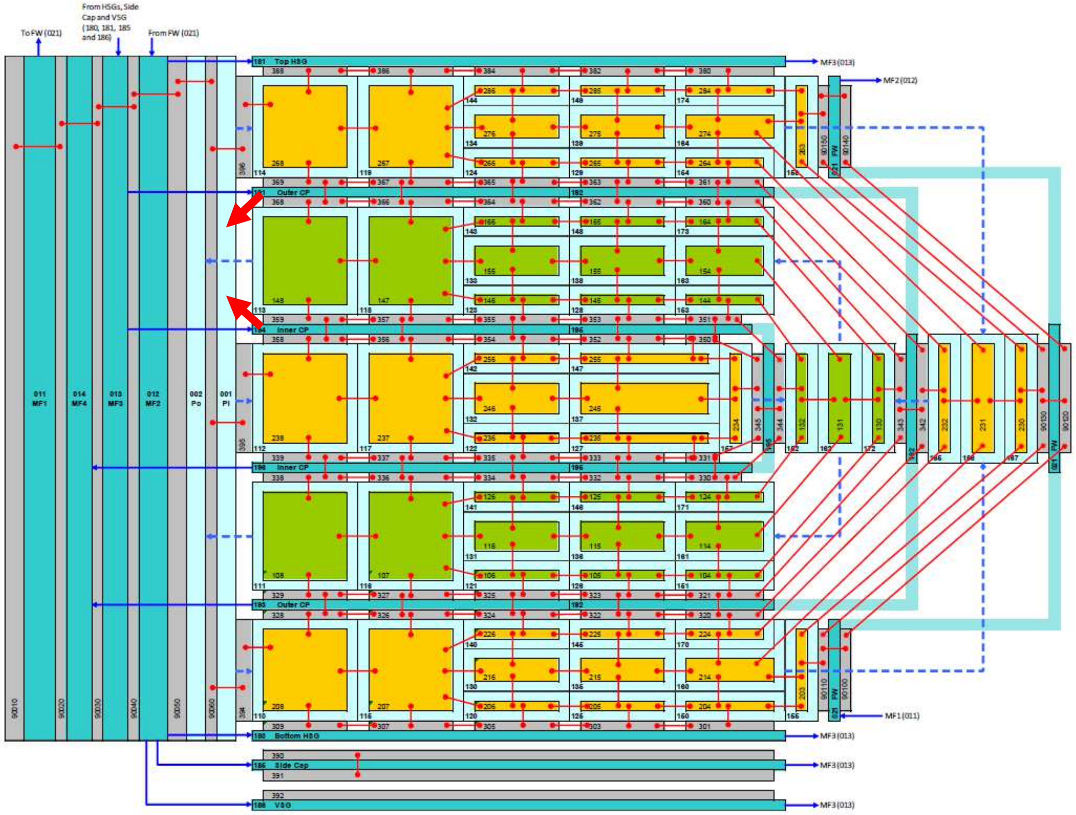
MELCOR model prediction

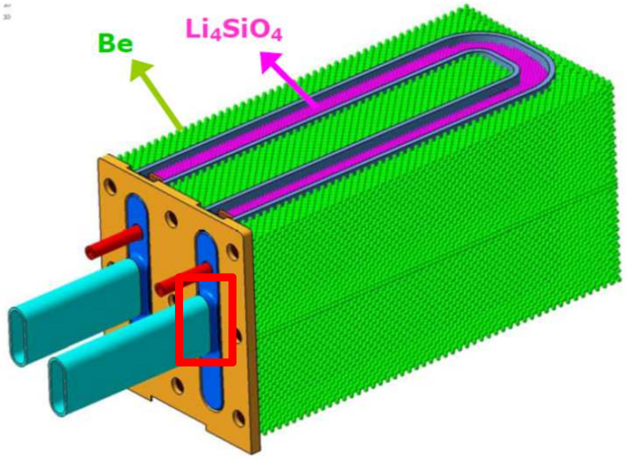


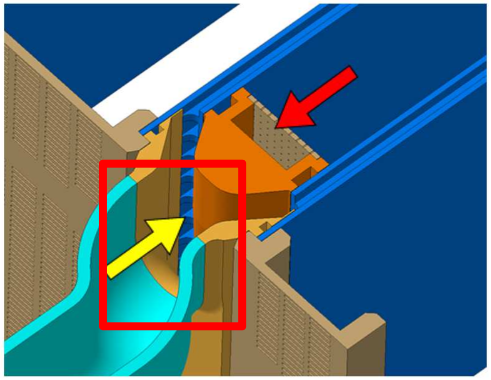
HCPB in-box LOCA

In-box LOCA

- High pressure coolant helium leaks into (pebble-filled) low pressure purge gas region of TBM.

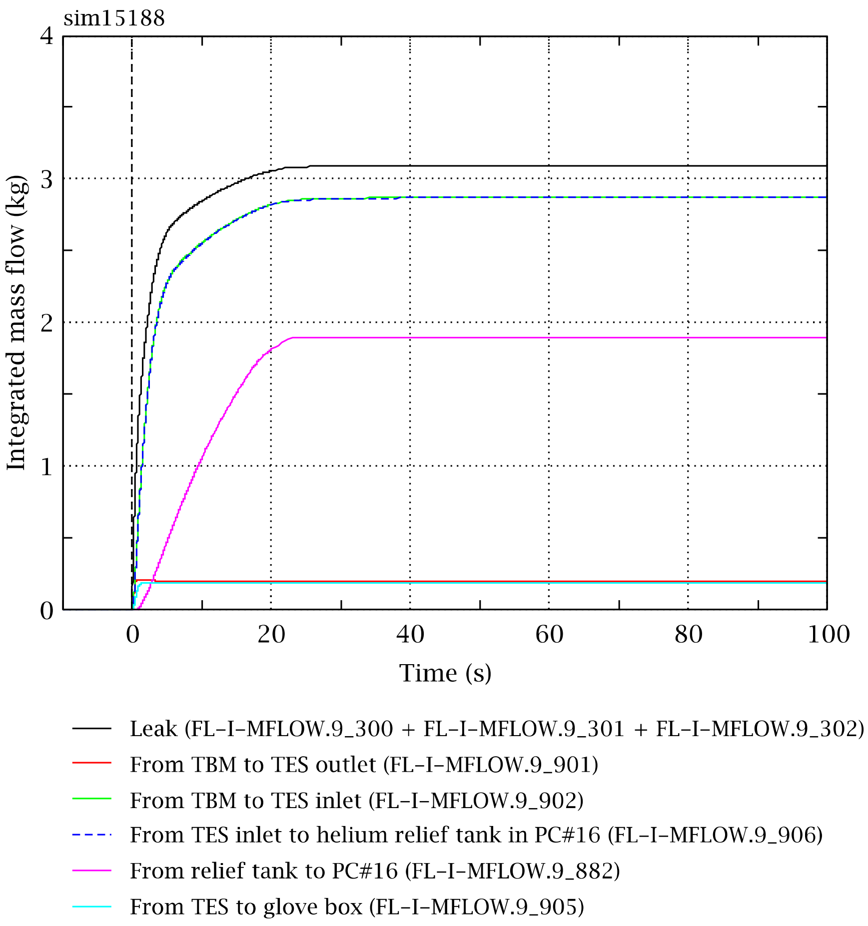




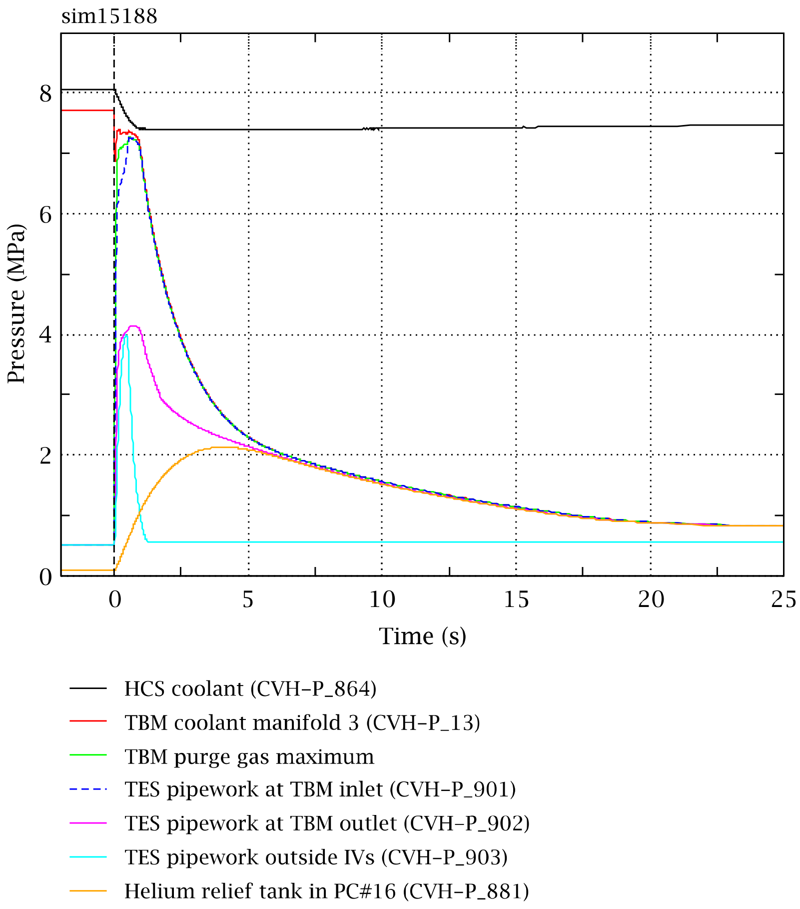


HCPB in-box LOCA

Leak integrated mass flow

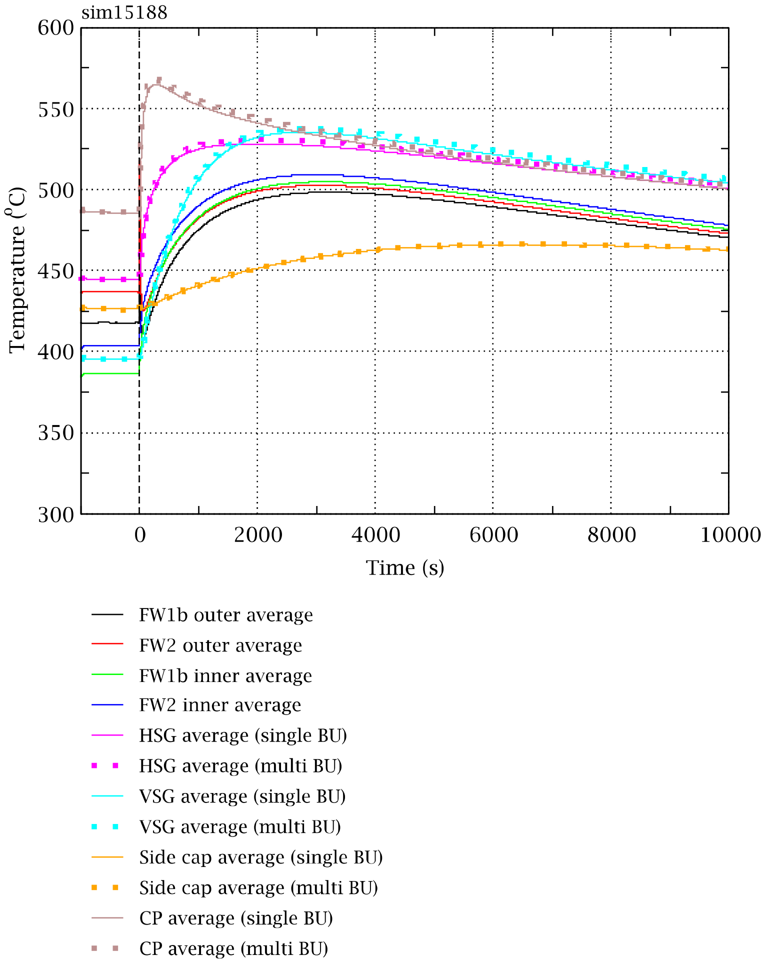


Pressurisation of TBM

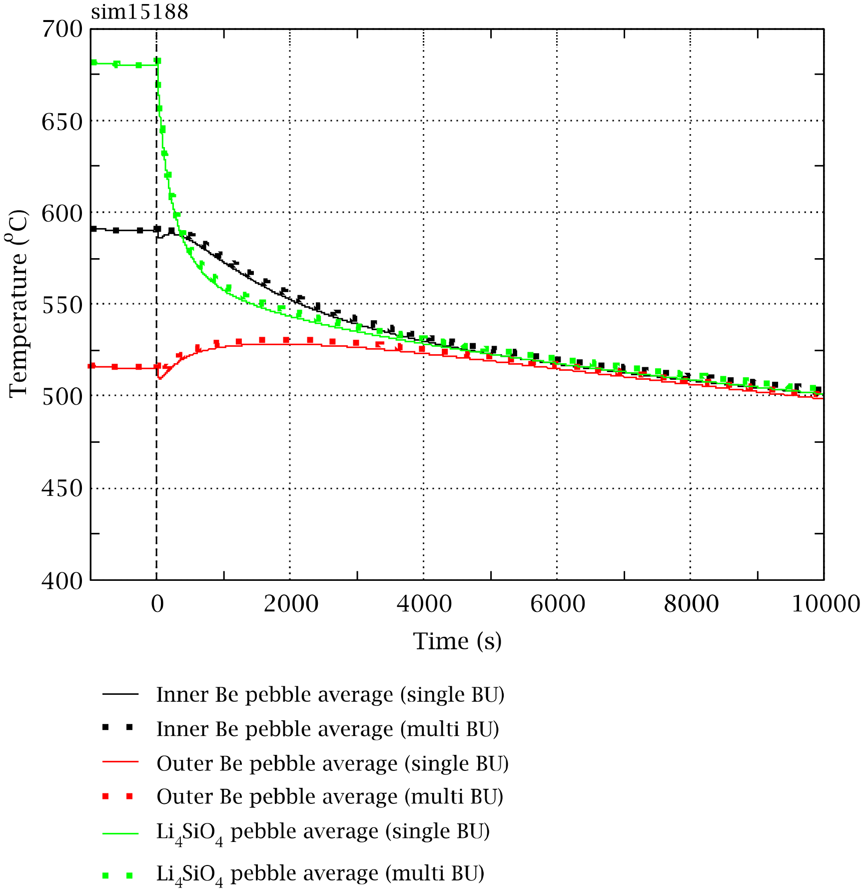


HCPB in-box LOCA

TBM EUROFER-97 temperatures



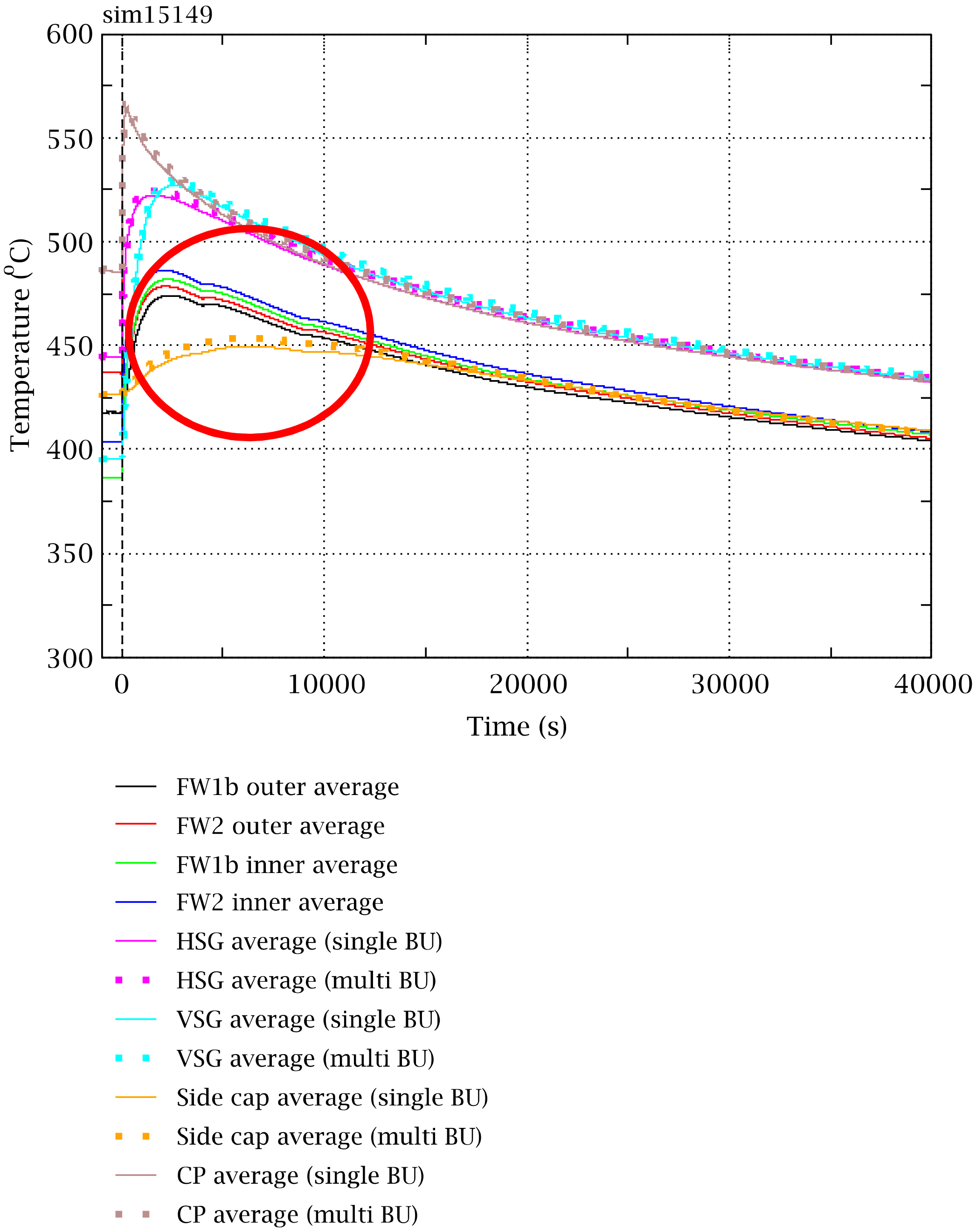
TBM pebble temperatures



Impact of Round-off Error

Average TBM temperatures

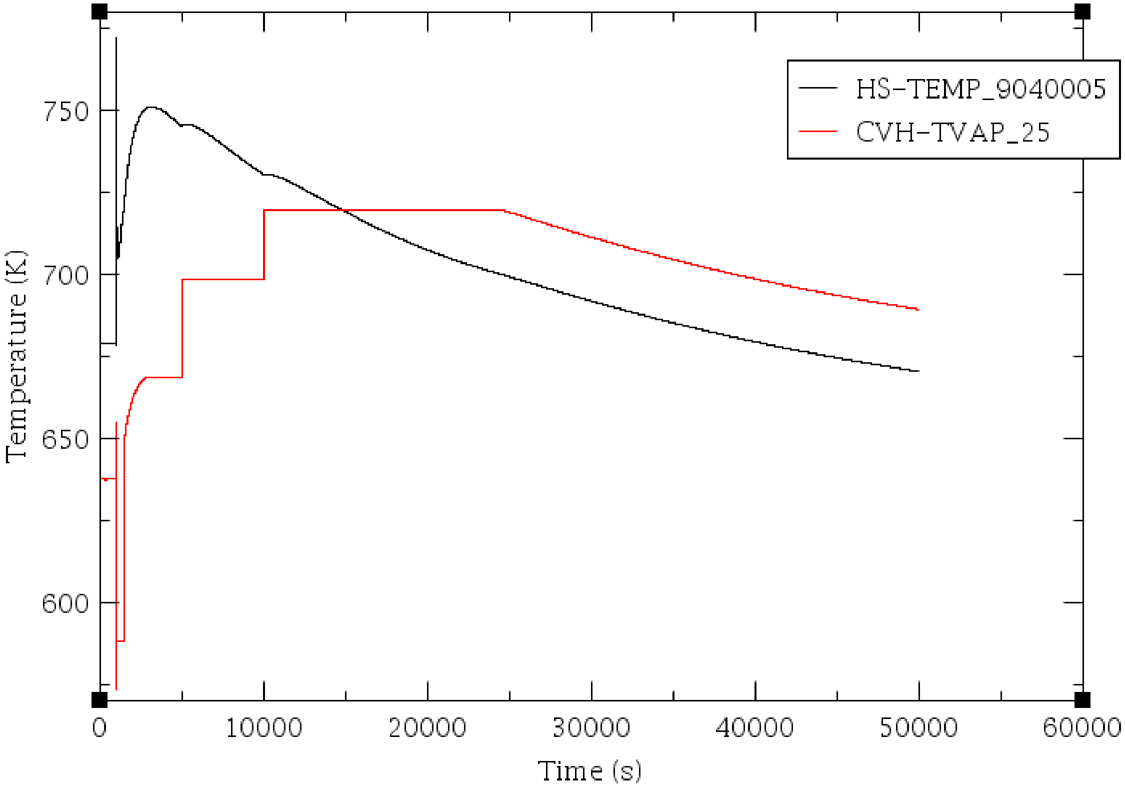
- **We noticed discontinuities in the average TBM first wall temperatures.**
- **The discontinuities occur at the same time as changes to the user-defined maximum timestep.**



Impact of Round-off Error

Investigating the issue

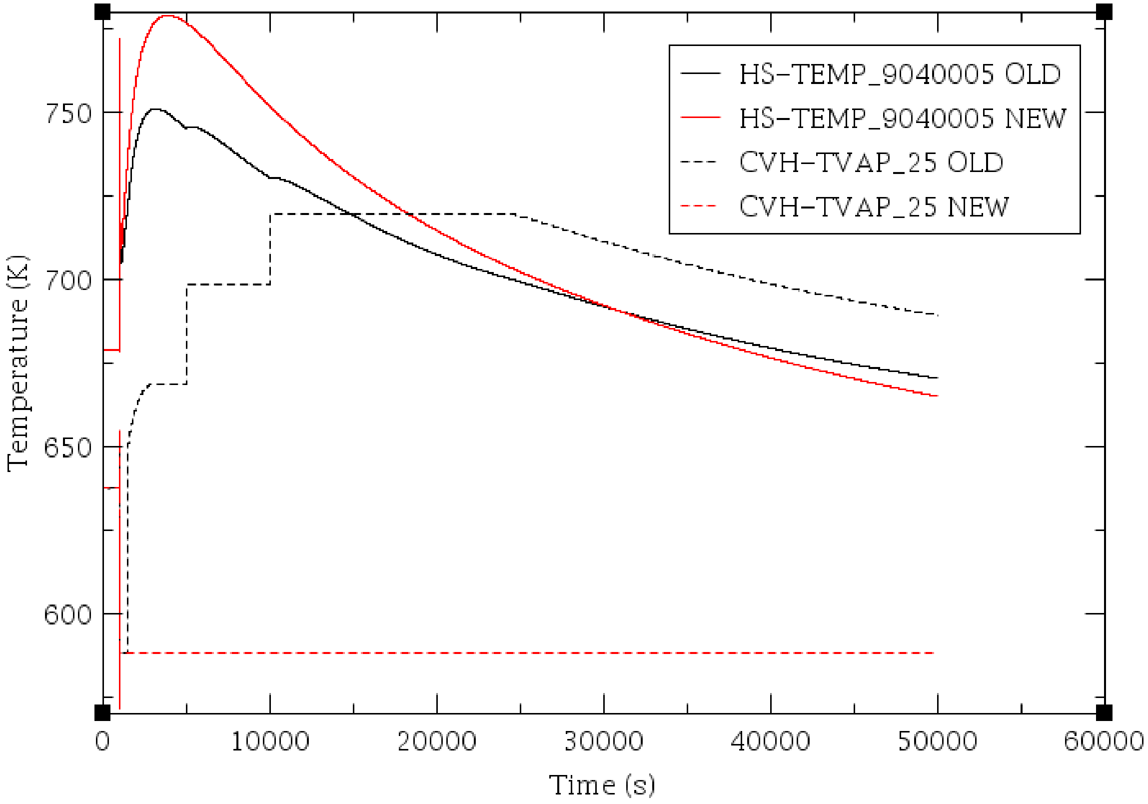
- **The discontinuities occur at the same time as large changes in the helium coolant temperature.**
- **This coolant is stationary and at ~1 MPa.**
- **Flat-lining behaviour in MELCOR 1.8.2 simulations is usually a sign of round-off error, due to the code being single precision.**



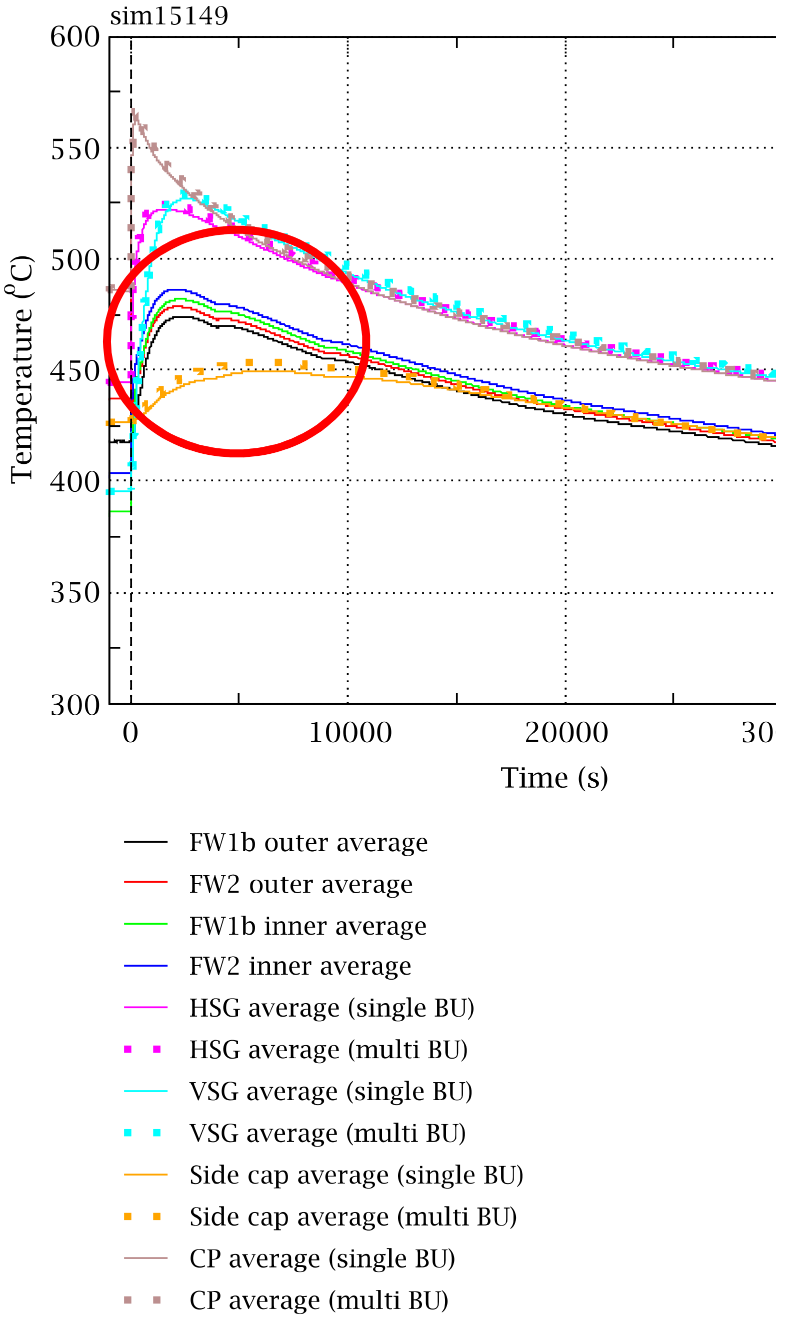
Impact of Round-off Error

Mitigating the issue

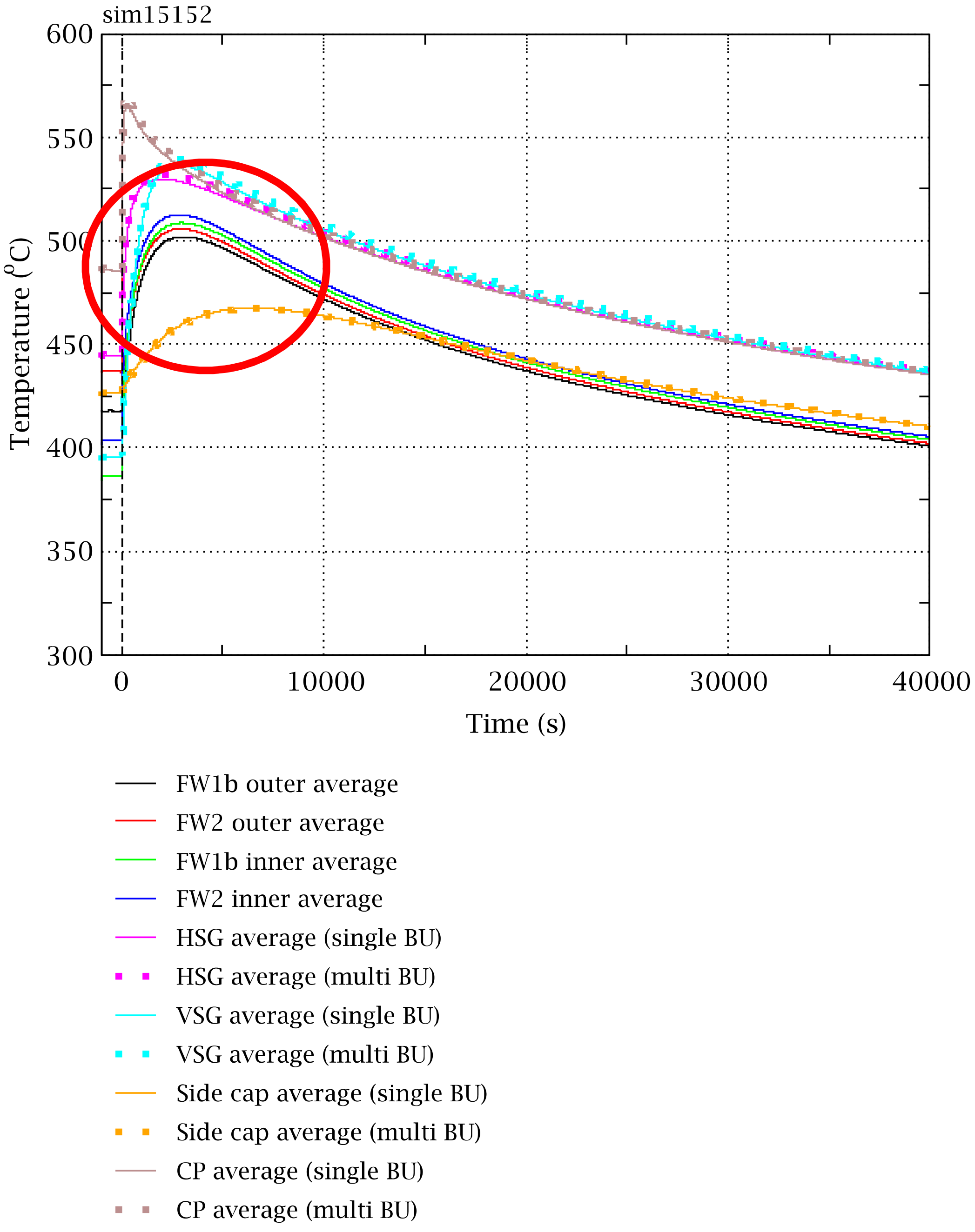
- **Reduce natural convection heat transfer (for rectangular heat structures, internal flow)**
- **In the new simulation (in red), the FW heat structures reach higher temperatures and the coolant temperatures do not change after 1020 s.**
- **Behaviour in the zero transient and first 20 s is unaffected.**



OLD average temperatures



NEW average temperatures



MELCOR modelling of the HCLL Test Blanket System

HCLL TBM Model

Nodalisation of the TBM

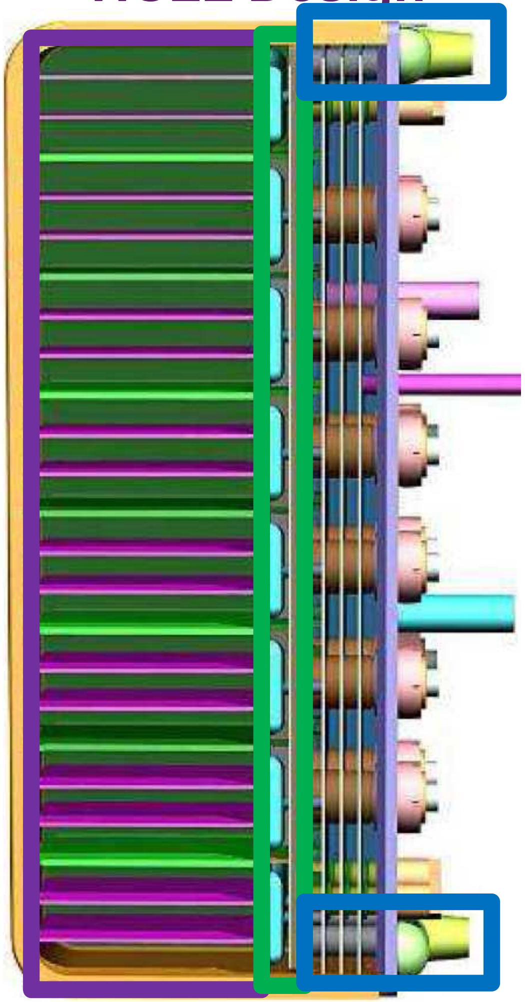
- Must balance **accuracy / detail** against **complexity / computer time**.
  - FW nodalisation (Courant limit)
  - Represent 16 BUs with 8 modelled BUs. Nodalisation allows simulation of PbLi drain-down during an accident.

Modelling PbLi

- Incompressibility of PbLi results in very small timesteps (~10^{-9} s) required for numerical convergence in MELCOR 1.8.5 in PbLi filled volumes!
- We include very small volumes of gas in each CVH (<0.1% by volume) to resolve these issues for normal operation cases
  - We refer to these as ‘buffer gas’ volumes
  - ‘Trap’ this gas through careful specification of junction elevations

HCLL In-Box LOCA

HCLL Design

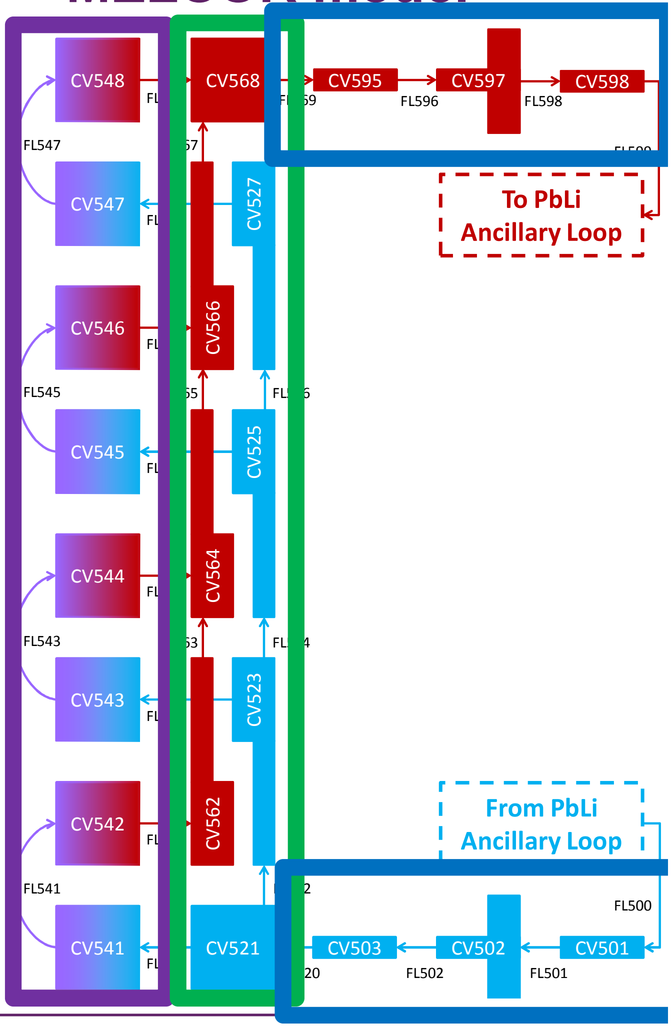


16 PbLi-filled breeder units (8 shown)

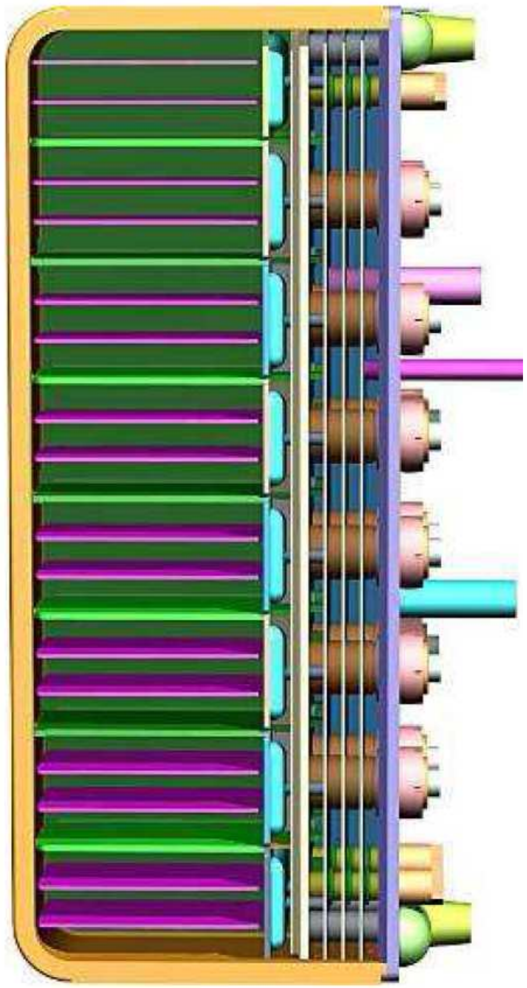
PbLi distribution / collection manifolds

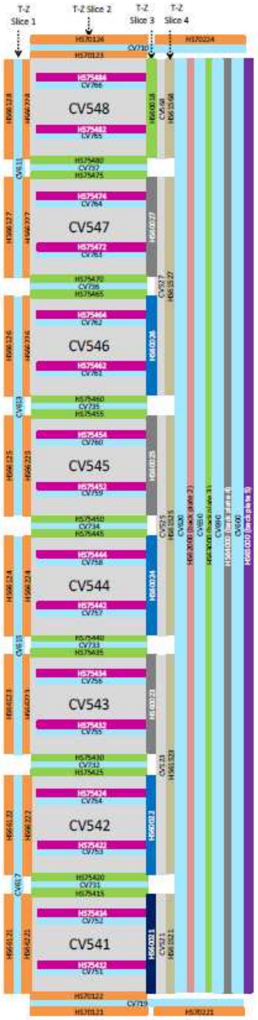
PbLi inlet / outlet pipes

MELCOR model



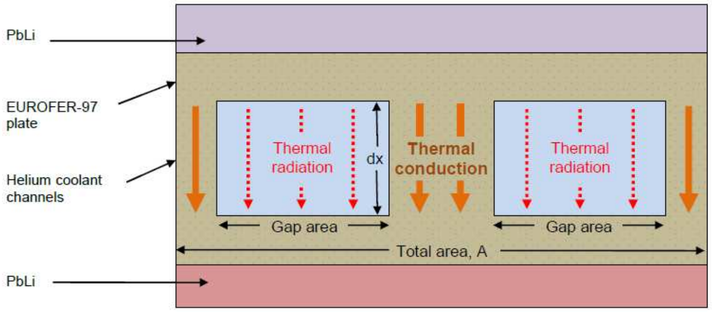
HCLL TBM Model



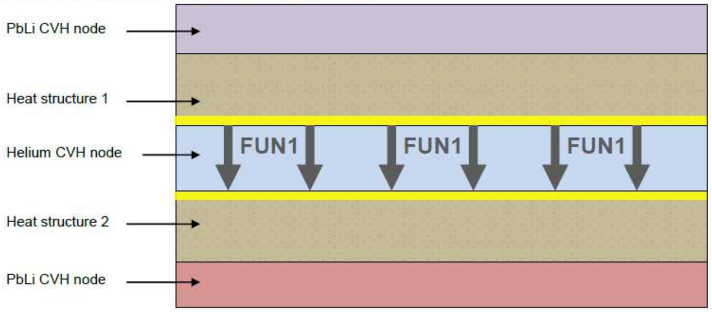


- Fusion-adapted codes include ‘FUN1’ control function
  - Very valuable for modelling combined conduction and thermal radiation

Typical TBM Stiffening Grid Geometry:



Equivalent MELCOR model using FUN1:



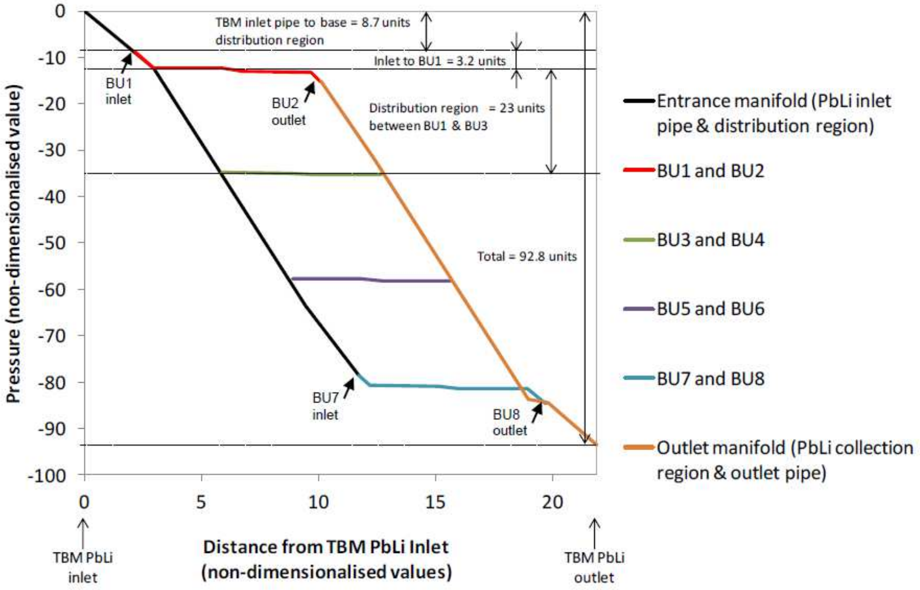
HCLL TBM Model

Modelling MHD

- Use control functions to reproduce MHD pressure drops observed in:

L. Bühler et al., ‘Magnetohydrodynamic Flow in a Mock-Up of a HCLL Blanket. Part II Experiments’, Forschungszentrum Karlsruhe, Report FZKA 7424, September 2008.

- Pressure drop proportional to velocity
- ‘Quick-CF’ pump input used to produce the appropriate pressure drop in MELCOR PbLi flow paths.
  - Under-relaxation scheme implemented for numerical stability.
  - But this method crashes in a transient situation with voided control volumes.
- INL have implemented implicit MHD model in new version of fusion-adapted MELCOR 1.8.5.
  - Also in 1.8.6



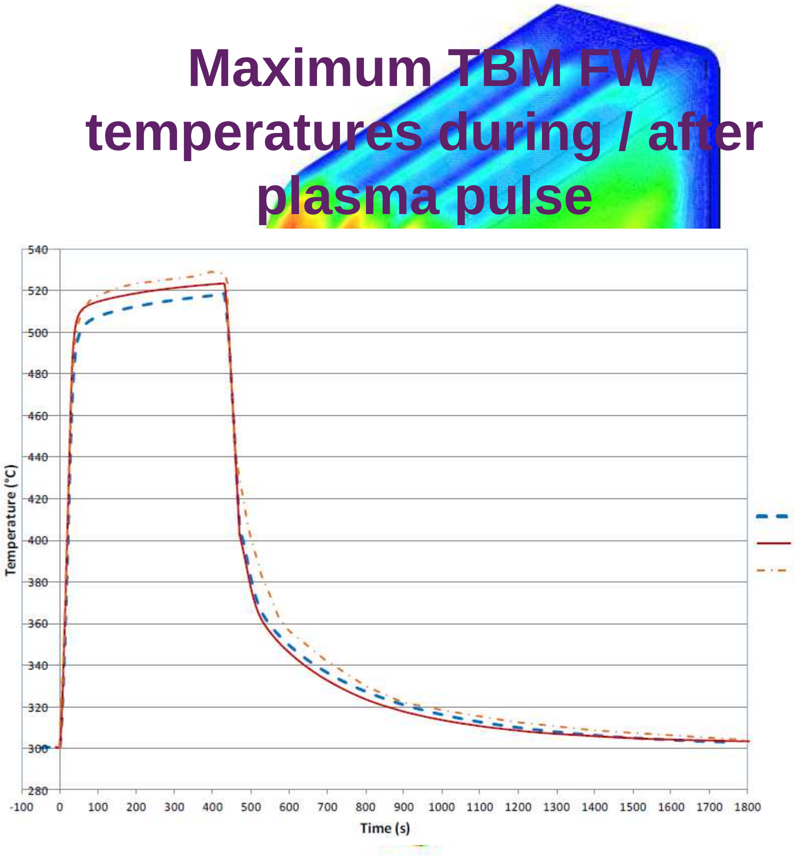
Note: BU1 = Bottom layer BUs
BU2 = 2nd layer of BUs
: : : :
BU8 = Top layer of BUs

HCLL Qualification

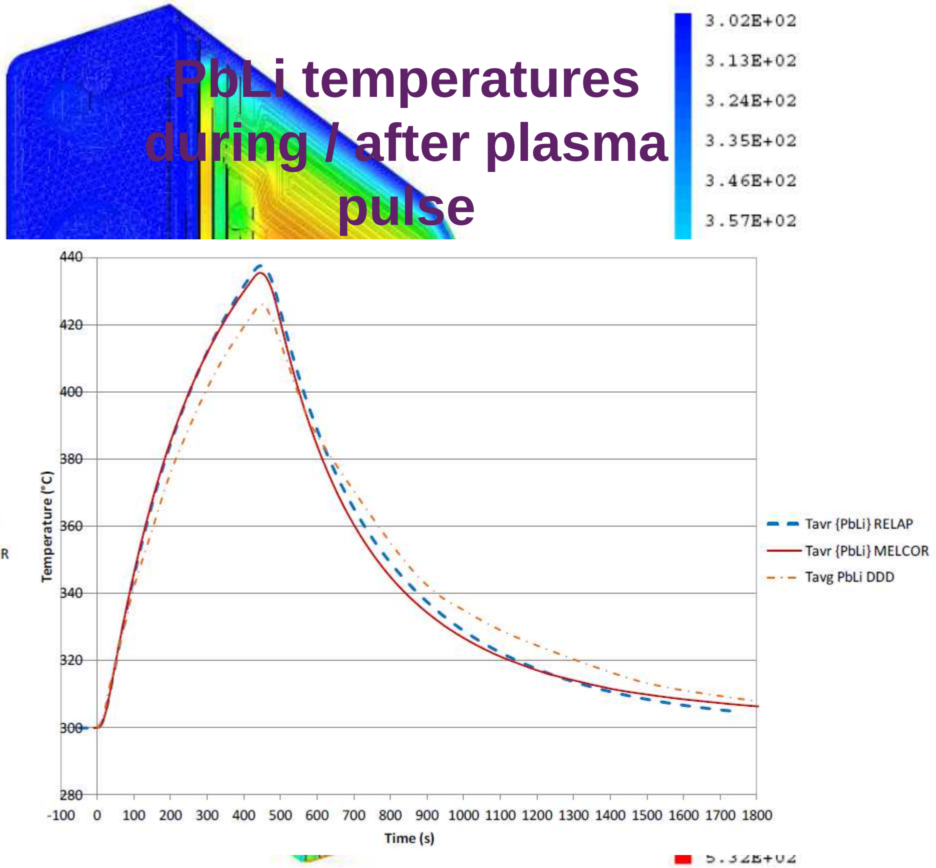
TBM temperatures during an ITER power pulse

- Compared to RELAP5 simulation and design finite element analysis

Maximum TBM FW temperatures during / after plasma pulse

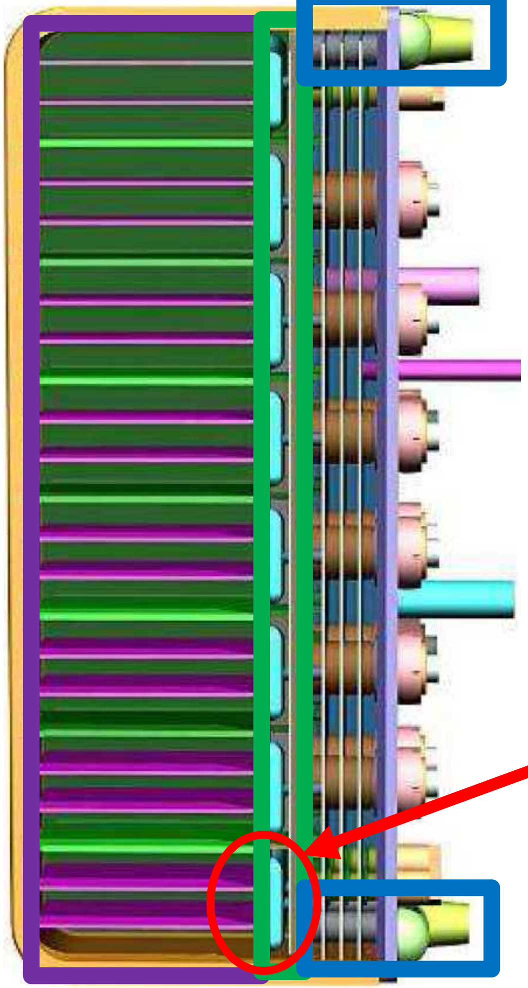


PbLi temperatures during / after plasma pulse



HCLL In-Box LOCA

HCLL Design



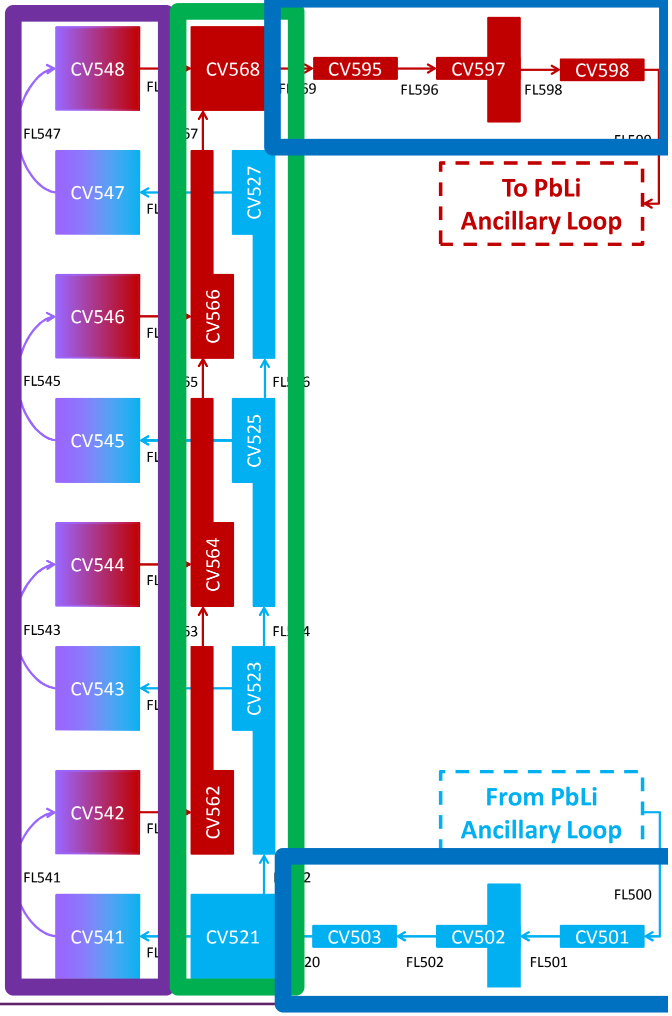
16 PbLi-filled breeder units (8 shown)

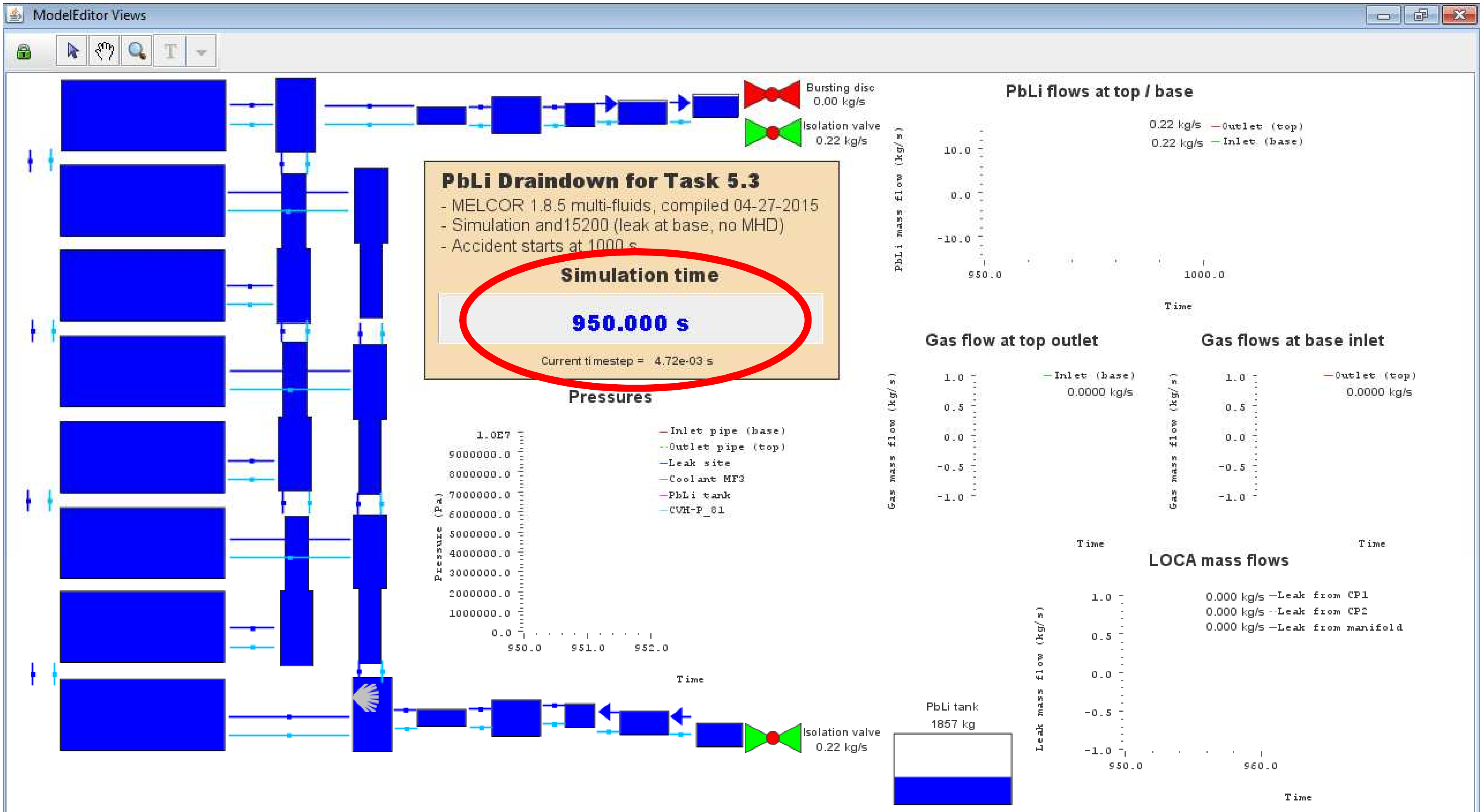
PbLi distribution / collection manifolds

PbLi inlet / outlet pipes

Simulate leak of helium coolant into PbLi compartment

MELCOR model





PbLi Draindown for Task 5.3

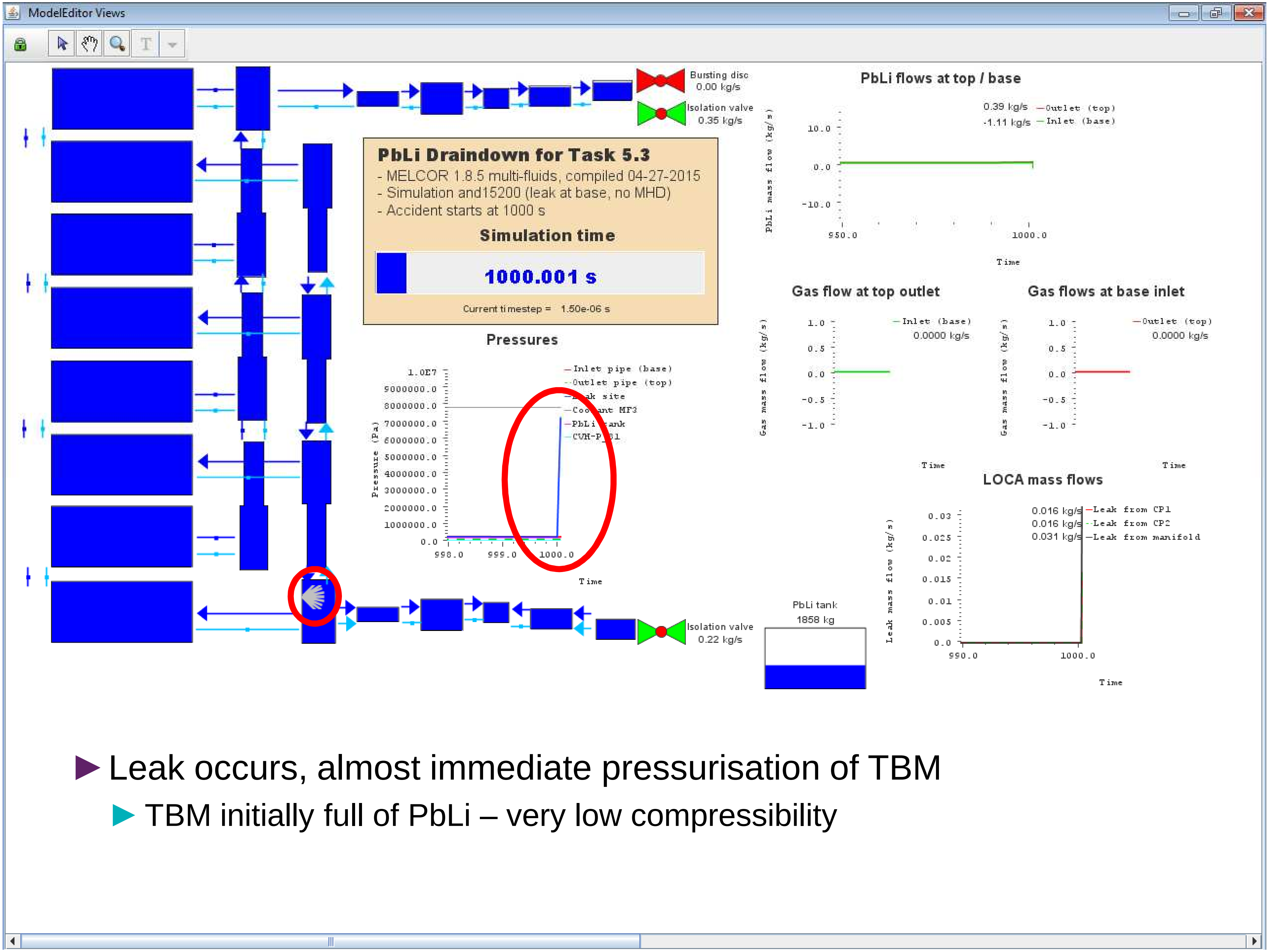
- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

950.000 s

Current timestep = 4.72e-03 s

- Prior to accident - full power steady state conditions
- Solid blue shows that TBM is full of lithium lead (PbLi)
- Accident starts at 1000 s
- **Results shown for analysis with MHD effects off**



PbLi Draindown for Task 5.3

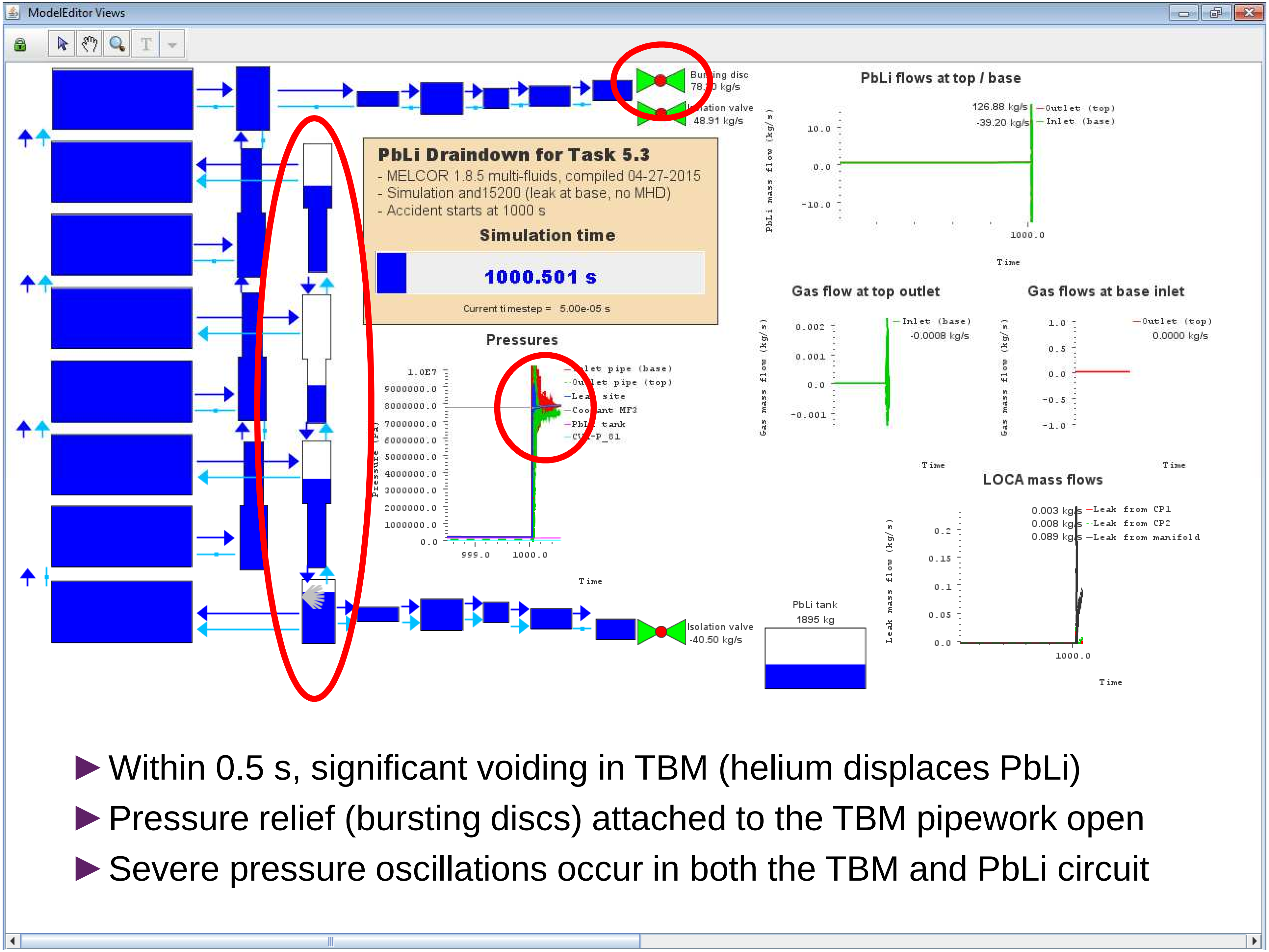
- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1000.001 s

Current timestep = 1.50e-06 s

- Leak occurs, almost immediate pressurisation of TBM
  - TBM initially full of PbLi – very low compressibility



PbLi Draindown for Task 5.3

- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1000.501 s

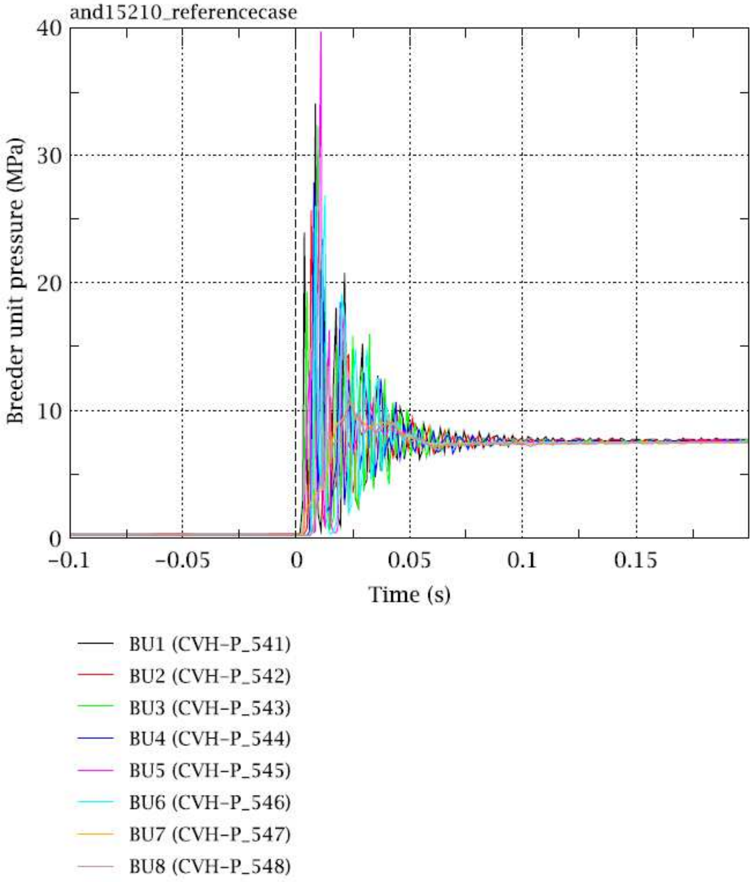
Current timestep = 5.00e-05 s

- ▶ Within 0.5 s, significant voiding in TBM (helium displaces PbLi)
- ▶ Pressure relief (bursting discs) attached to the TBM pipework open
- ▶ Severe pressure oscillations occur in both the TBM and PbLi circuit

Pressure Oscillations

Severe pressure oscillations when the LOCA occurs

- Breeder unit pressures exceed 30 MPa despite the helium coolant pressure being only 8 MPa.
- The sizing of gas buffer volumes (which are used to give numerical stability) plays a role.
- Some ‘PbLi hammer’ may be expected, but how is this affected by MHD, elasticity of structures?
  - Open issue.



PbLi Draindown for Task 5.3

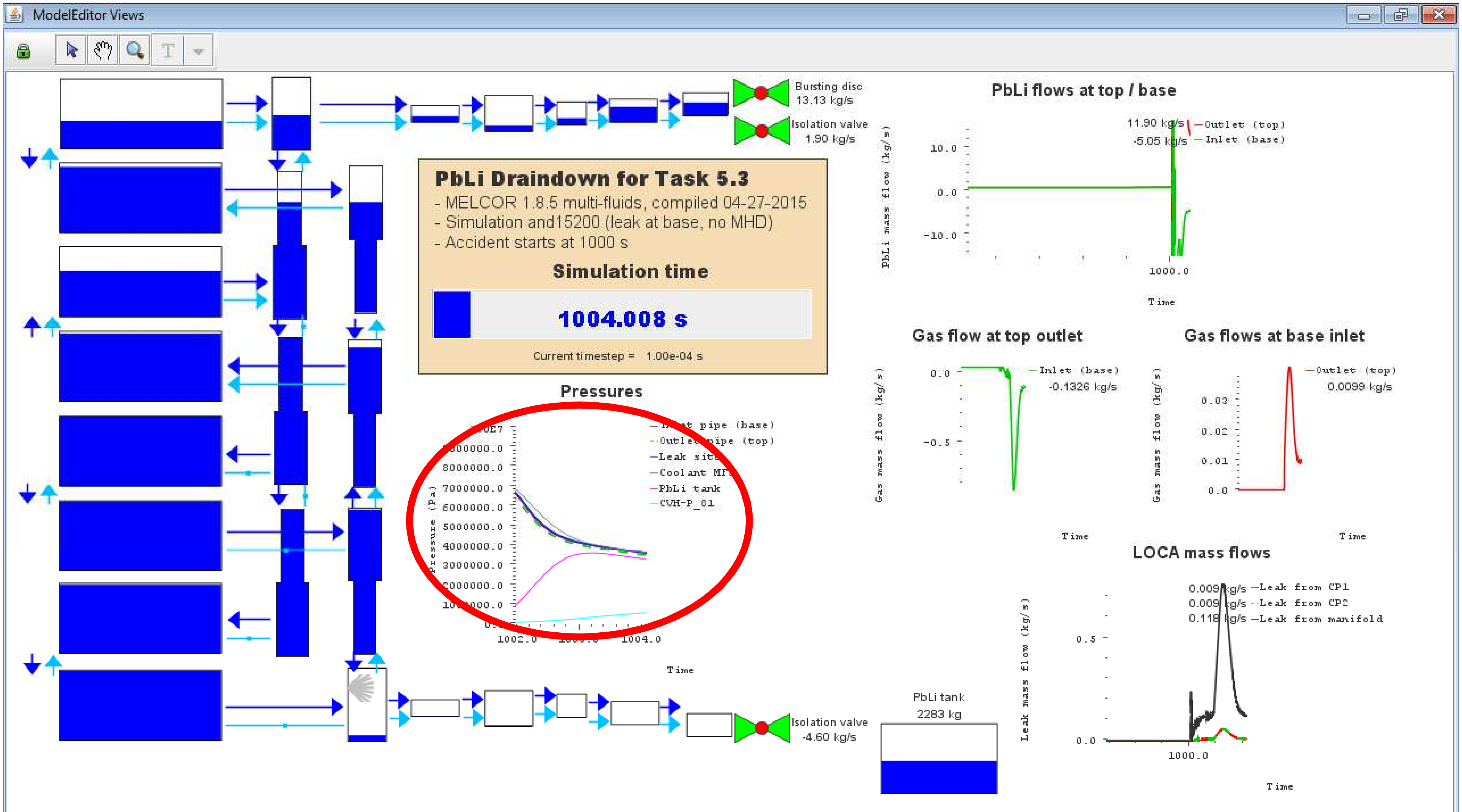
- MELCOR 1.8.5 multi fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1002.000 s

Current timestep = 1.00e-04 s

- After 2 s, leaked helium can vent through TBM outlet pipework without needing to displace further PbLi
  - This allows the helium leak mass flow to increase rapidly



PbLi Draindown for Task 5.3

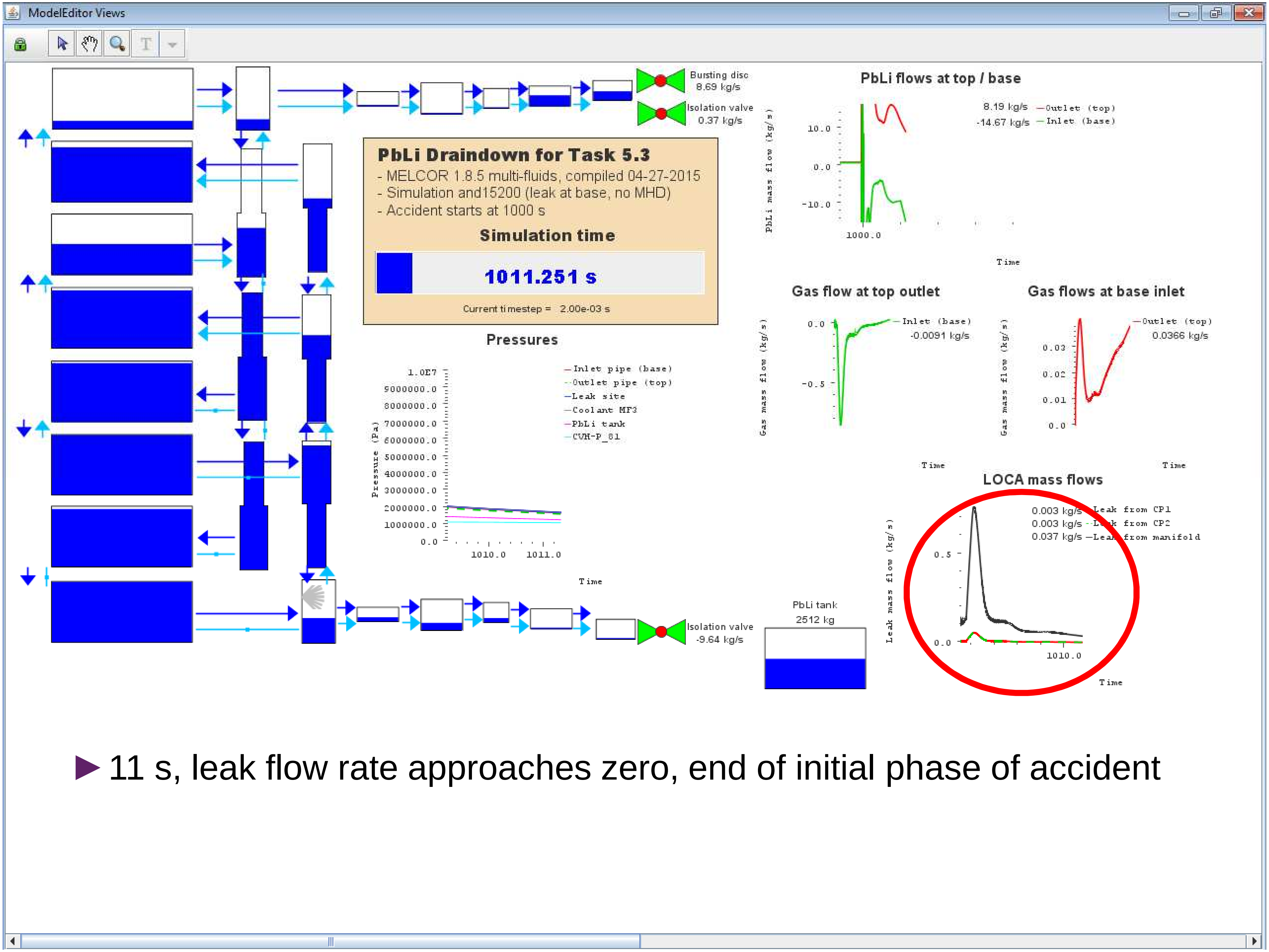
- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1004.008 s

Current timestep = 1.00e-04 s

- ▶ 4 s after the start of the accident the TBM pressure reduces
- ▶ Helium supply through leak drops (helium coolant system is isolated)
- ▶ Leaked helium vented first to PbLi storage tank then relief tank



PbLi Draindown for Task 5.3

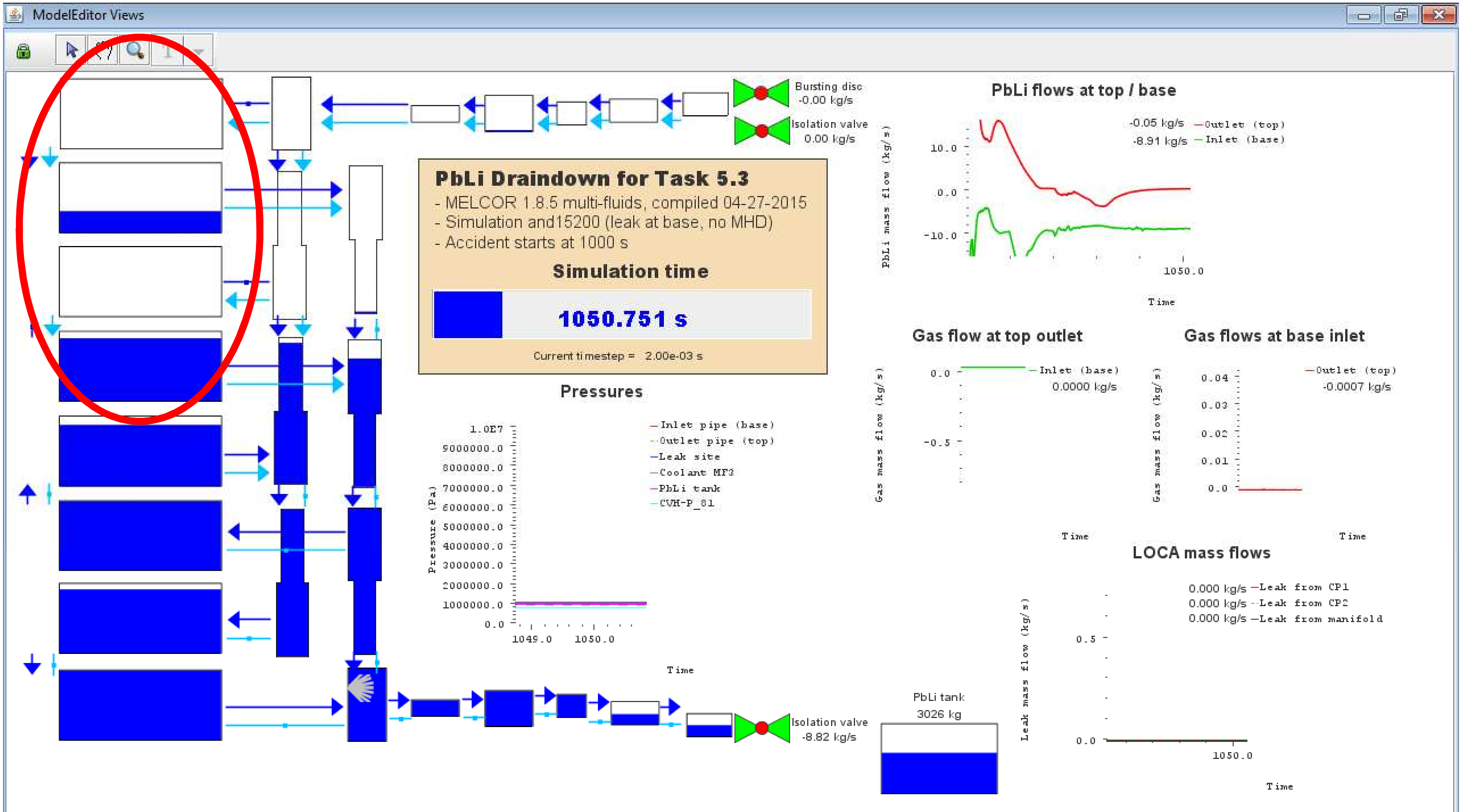
- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1011.251 s

Current timestep = 2.00e-03 s

▶ 11 s, leak flow rate approaches zero, end of initial phase of accident



PbLi Draindown for Task 5.3

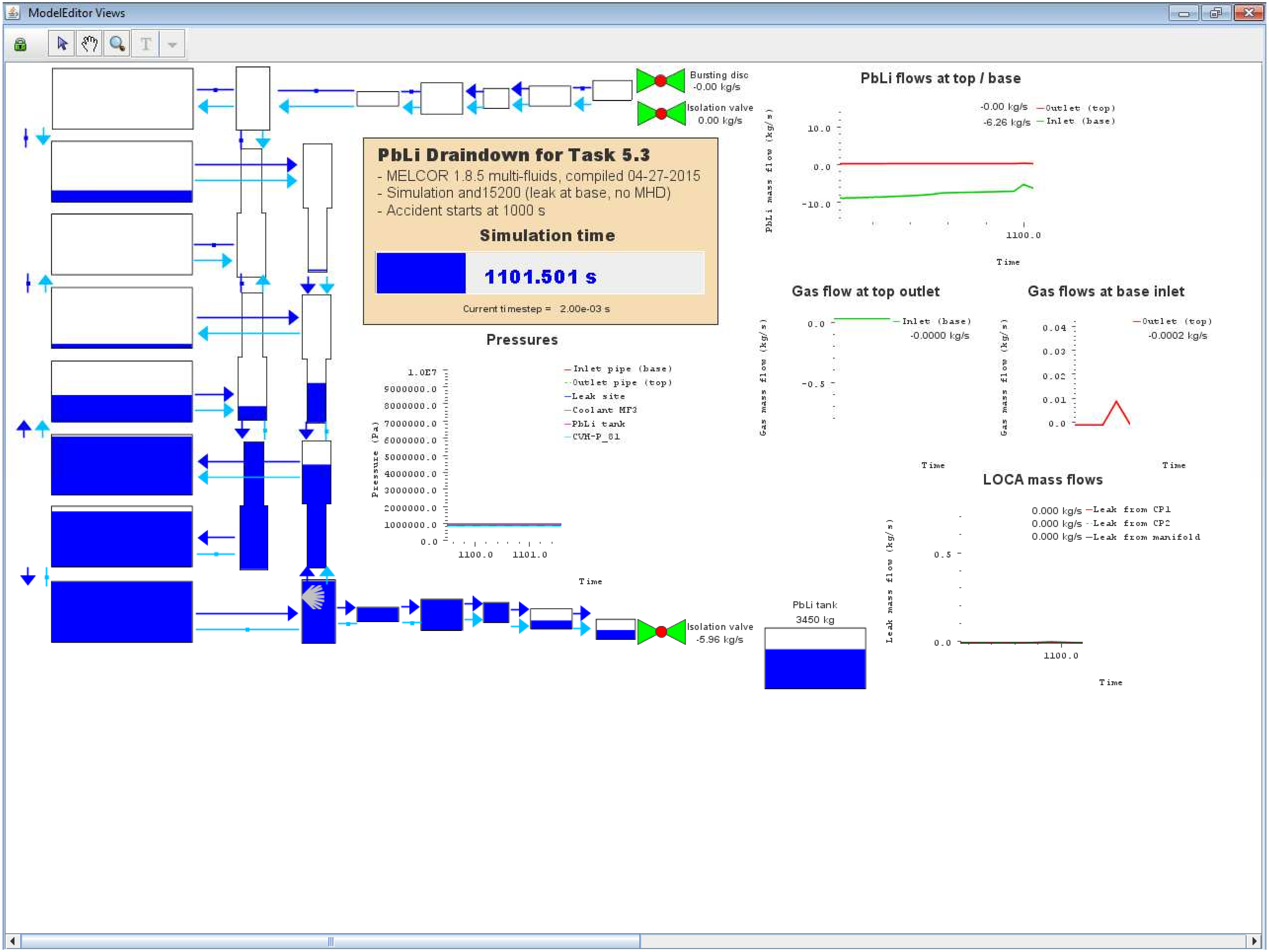
- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1050.751 s

Current timestep = 2.00e-03 s

- ▶ 50 s, long term drain-down of PbLi into storage tank is occurring
- ▶ Temperatures of TBM structures reducing (not shown)



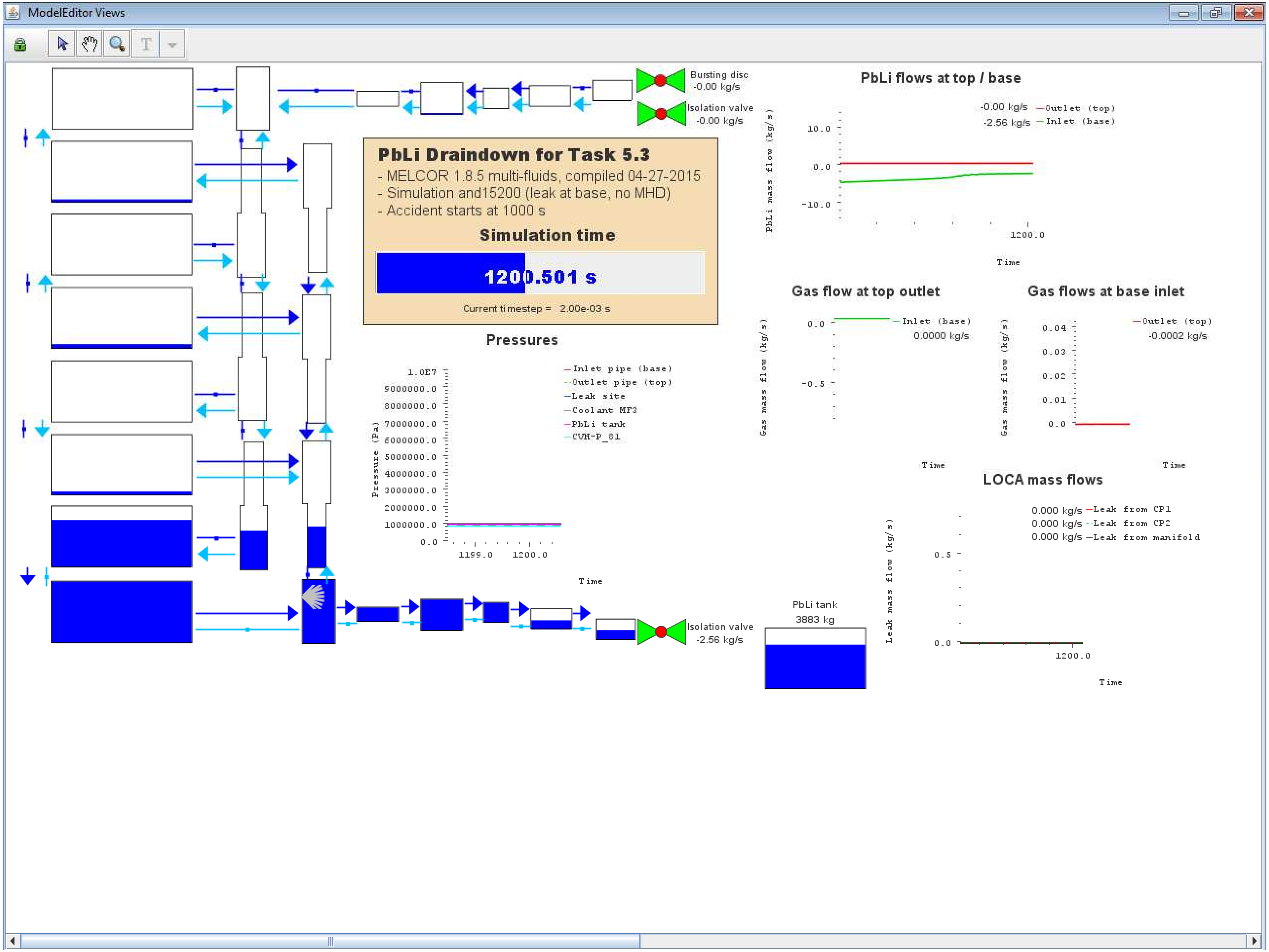
PbLi Draindown for Task 5.3

- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1101.501 s

Current timestep = 2.00e-03 s



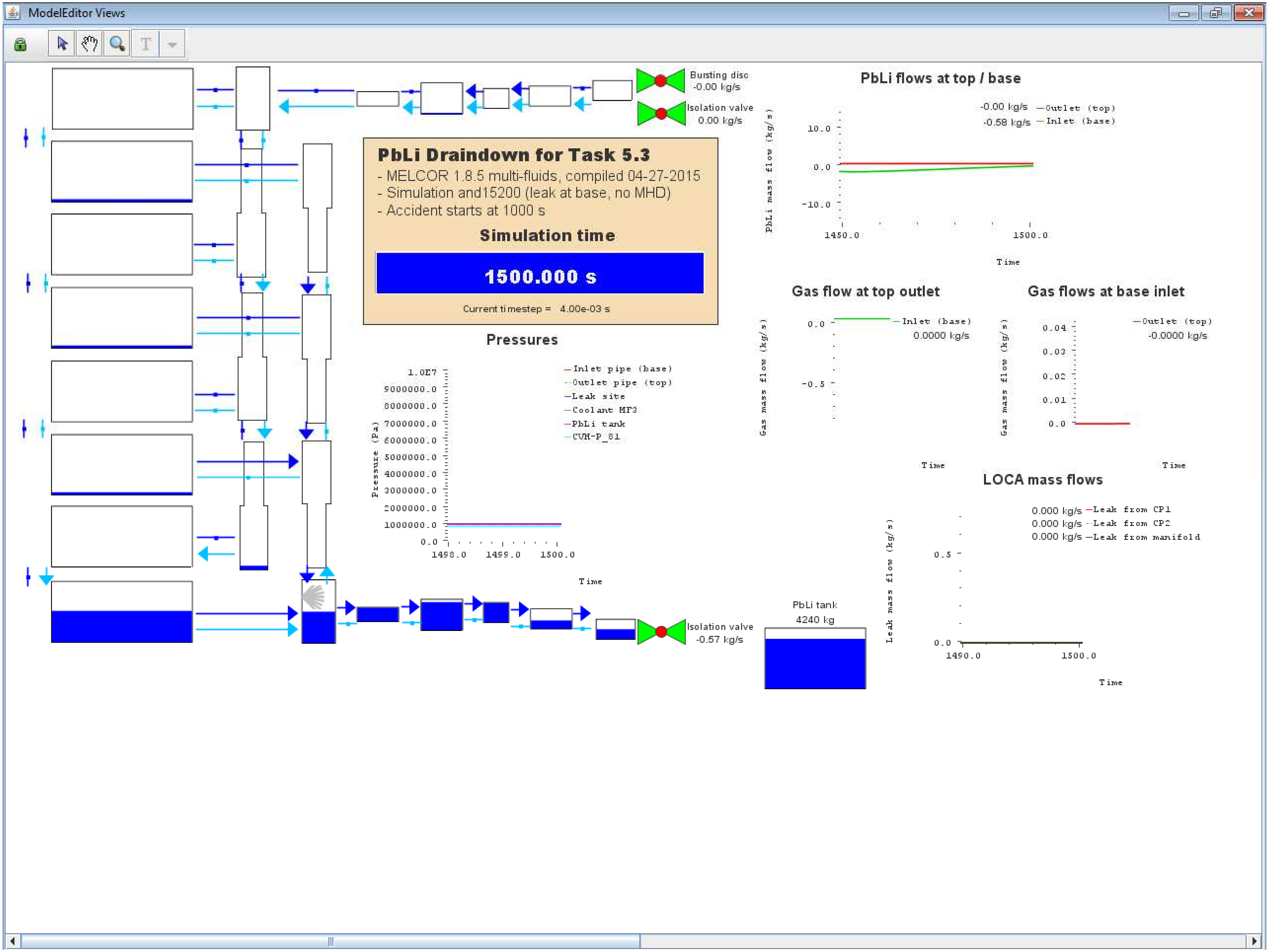
PbLi Draindown for Task 5.3

- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1200.501 s

Current timestep = 2.00e-03 s



PbLi Draindown for Task 5.3

- MELCOR 1.8.5 multi-fluids, compiled 04-27-2015
- Simulation and15200 (leak at base, no MHD)
- Accident starts at 1000 s

Simulation time

1500.000 s

Current timestep = 4.00e-03 s

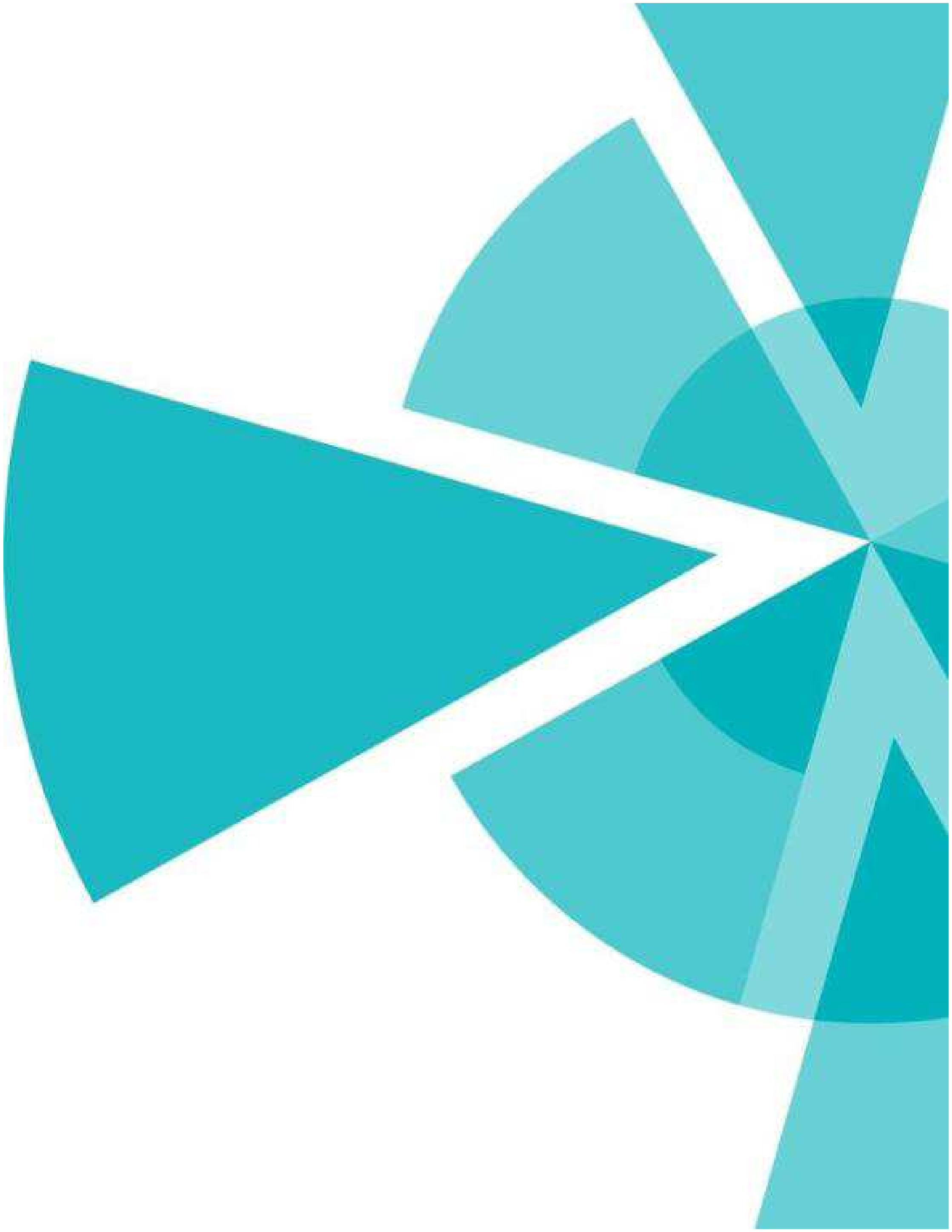
Summary

- ITER will be the world’s largest fusion reactor, and the first to produce more energy than is required to sustain its operation. It will provide the test data required for designing a prototype commercial reactor.
- Tritium self-sustainment will be required for a commercial fusion plant. ITER will test tritium breeding concepts in its TBM programme
- Analysis of the TBMs require us to simulate a range of physics including:
  - Gas flow and heat transfer in a pebble bed
  - Flow of liquid lithium-lead in strong magnetic fields
  - Chemical reactions in accident scenarios
- The fusion-adapted MELCOR codes provide a good platform for this analysis
- Our initial work:
  - Qualified accident analysis models of the HCPB and HCLL TBMs
  - Six accident analyses (so far)
  - Further modelling and accident analyses anticipated….

Further Reading

“Methodology for Accident Analyses of Fusion Breeder Blankets and its Application to Helium-Cooled Pebble Bed Blanket”. D. Panayotov *et al.*, Fusion Engineering and Design, DOI: 10.1016/j.fusengdes.2015.11.019, November 2015

Q&A



Back-up Slides