SMART SLB analysis with OpenFOAM/TRACE/PARCS

Kanglong Zhang

Institute for Neutron Physics and Reactor Technology (INR)

Outlines

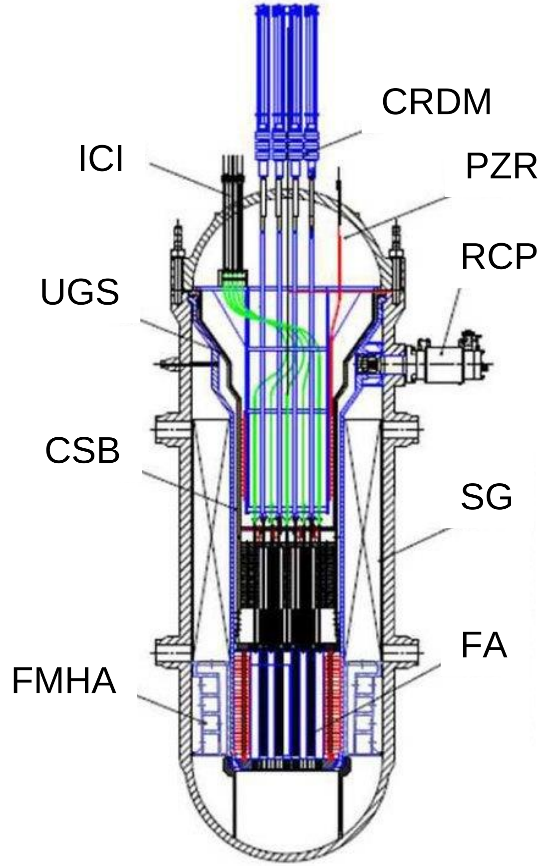
Karlsruhe Institute of Technology

SMART SLB** analysis with **OpenFOAM/TRACE/PARCS

- SMART – introduction to the overall system
- SLB transient sequence (+ steady-state parameters)
- OpenFOAM/TRACE/PARCS
  - Codes coupling methodologies
  - Modeling
  - Computational configuration
  - Steady-State (SS) results
  - Transient (TS) results
- Conclusion and Outlook

SMART Reactor

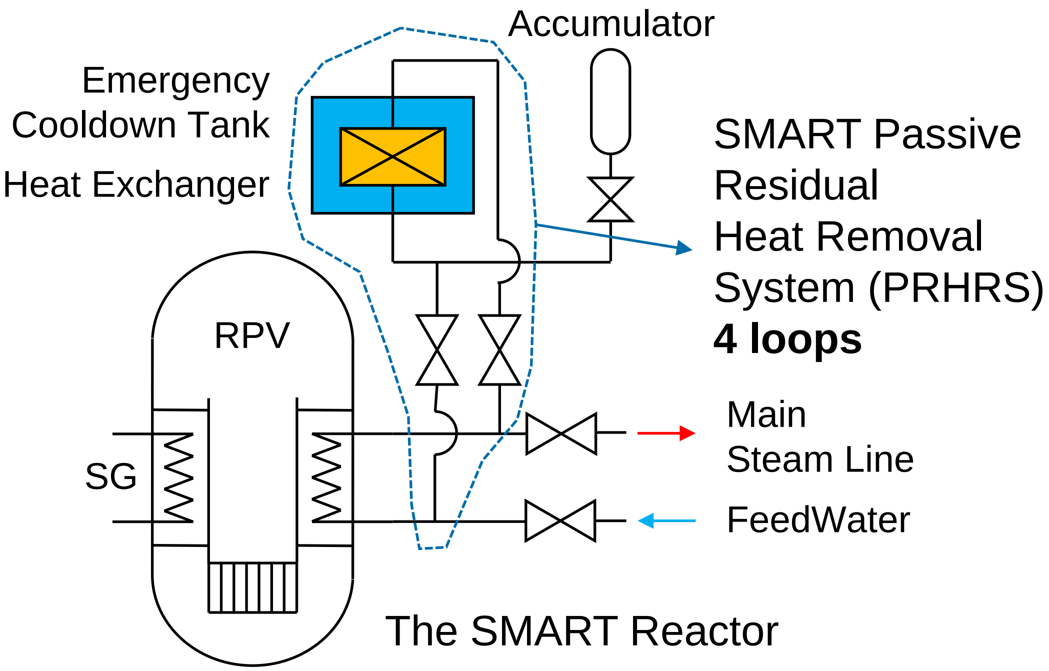
System-Integrated Modular Advanced Reactor (KAERI, South Korea)



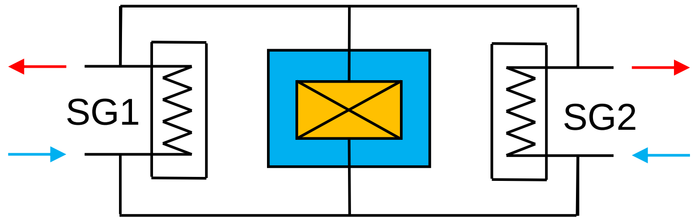
The SMART RPV

4 RCP
8 SG

CRDM: Control Rod Drive Mechanism
ICI: Incore Instrumentation
UGS: Upper Guide Structure
CSB: Core Support Barrel
FMHA: Flow Mixing Header Assembly
PZR: Pressurizer
RCP: Reactor Coolant Pump
SG: Steam Generator
FA: Fuel Assembly



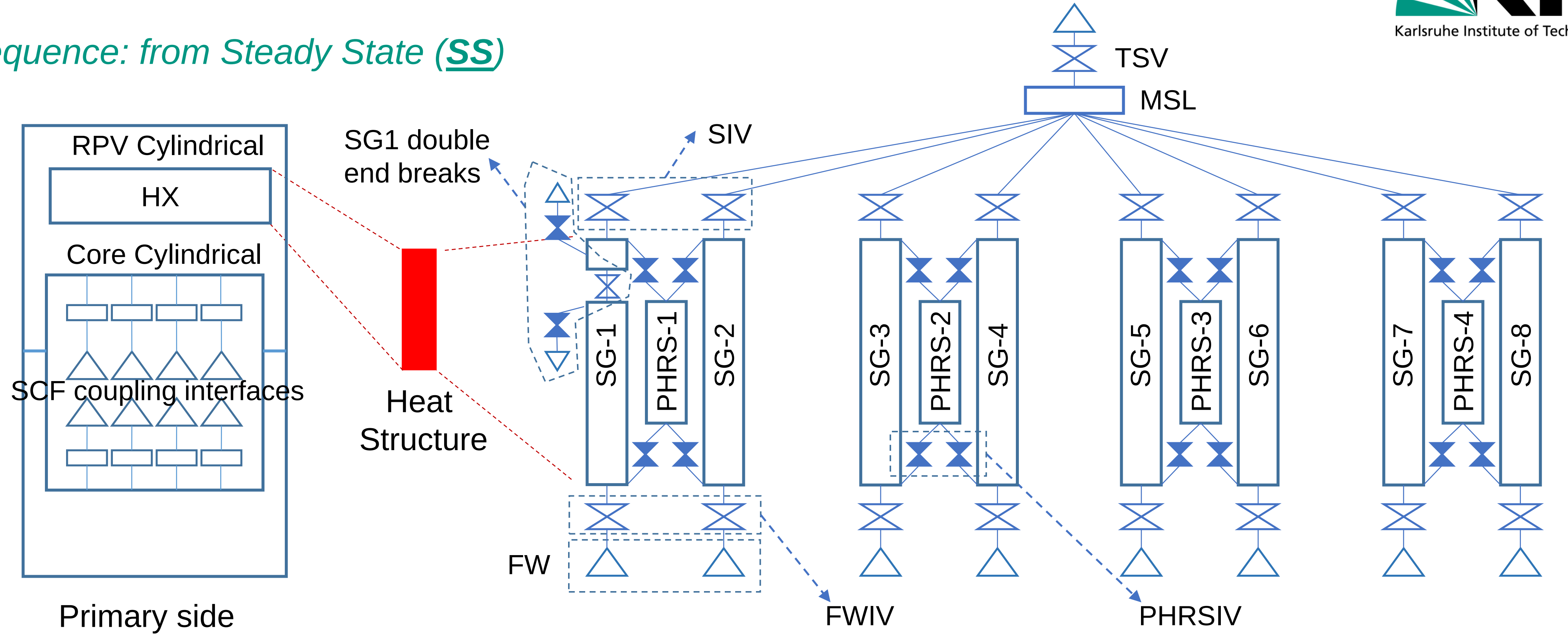
The SMART Reactor



Two SGs share one PRHRS loop

SMART SLB transient sequence

*SLB sequence: from Steady State (**SS**)*



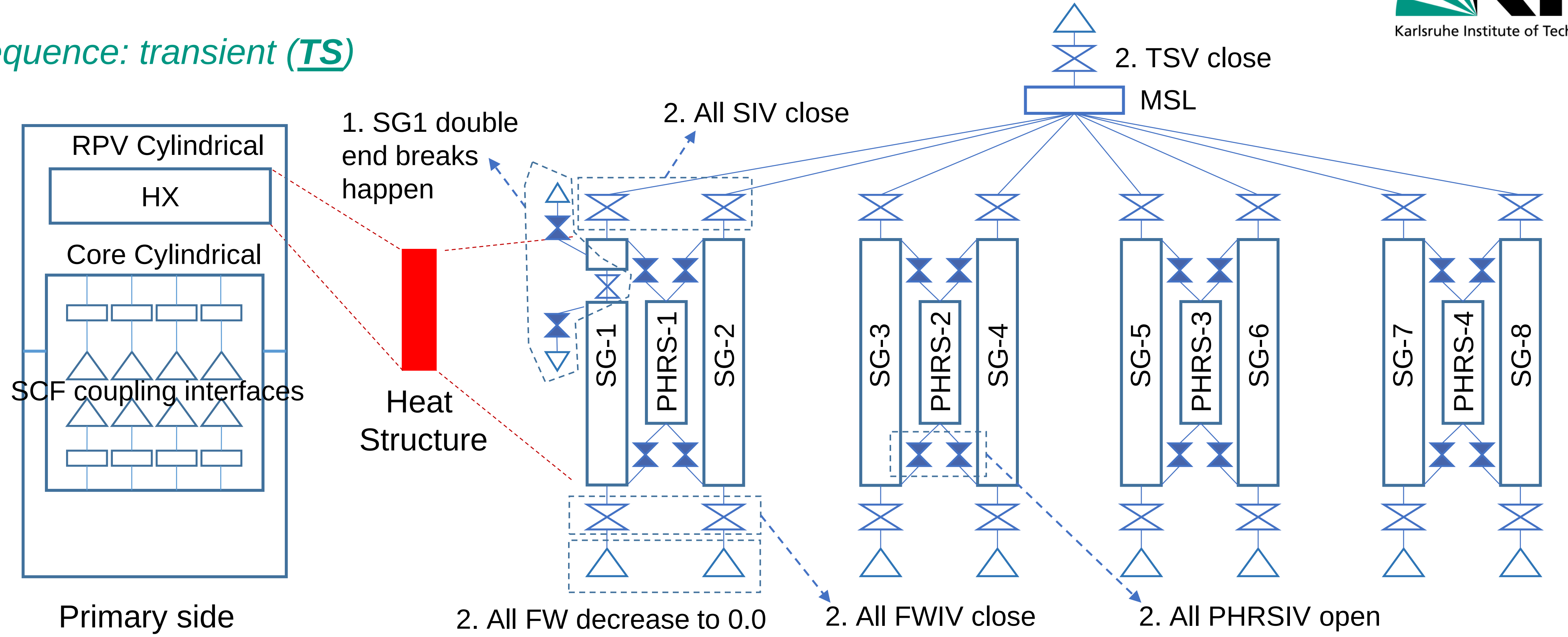
Initial Conditions

Thermal power (MW)	330.0	Core outlet temperature (K)	596.15
Core mass flow rate (kg/s)	2006.4	Main steam line mass flow (kg/s)	160.8
Core inlet temperature (K)	568.6	Main steam line pressure (MPa)	5.2

Solid shapes – close
Empty shapes – open

SMART SLB transient sequence

*SLB sequence: transient (**TS**)*



1. SG1 double end break happen, Loss of offsite power , at the same time;
2. Pumps coasting down, SG1 pressure decrease under 2.0 MPa;
3. SCRAM, SIV / FWIV / TSV close, PHRSIV open.

Solid shapes – close
Empty shapes – open

*The total transient is **500s** and the SLB happens at **100s**.*

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Karlsruhe Institute of Technology

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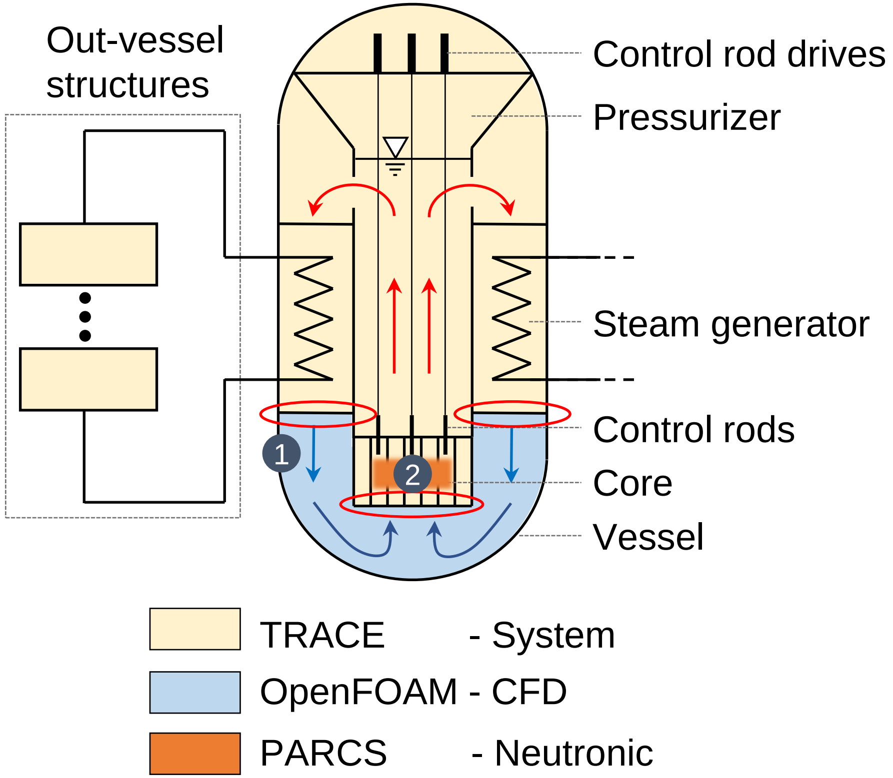
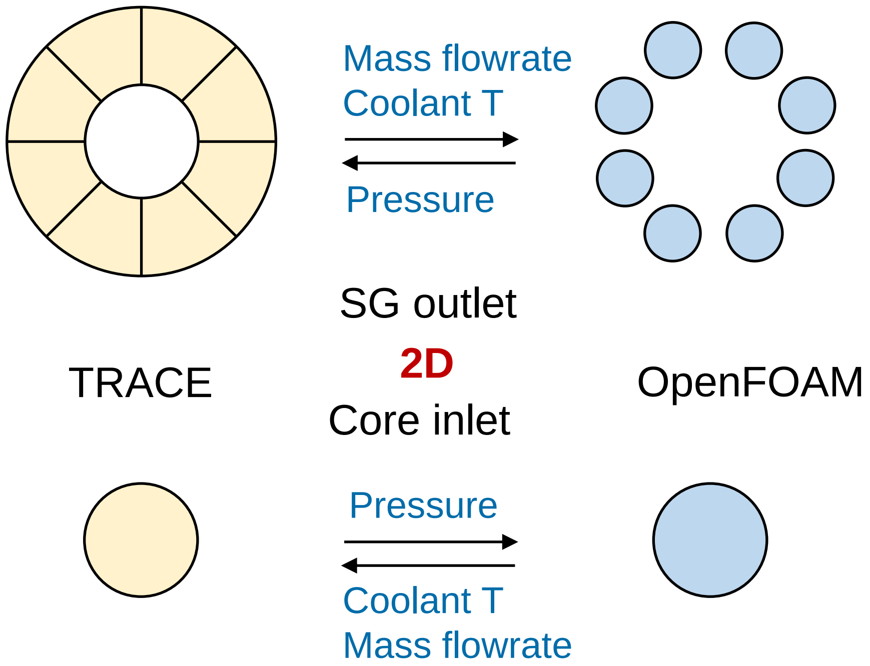
OpenFOAM/TRACE/PARCS

*Codes coupling methodology – via **ICoCo***



1. Interface between TRACE and OpenFOAM
2. Interface between TRACE and PARCS

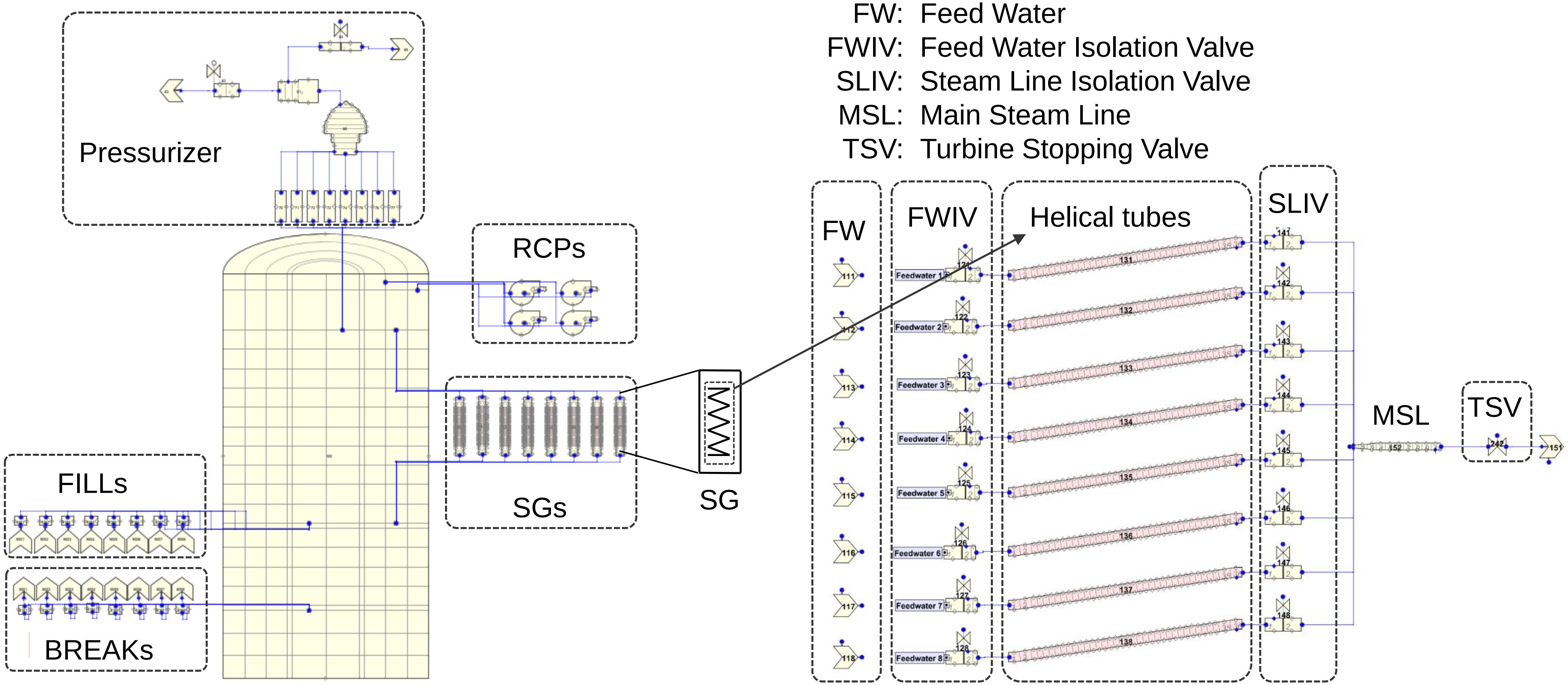


The field mapping between codes are by MEDCoupling

OpenFOAM/TRACE/PARCS

*Modeling: TRACE– **RPV TH**, OpenFOAM– **downcomer lower plenum TH**, PARCS– **Core NK***

FW: Feed Water
FWIV: Feed Water Isolation Valve
SLIV: Steam Line Isolation Valve
MSL: Main Steam Line
TSV: Turbine Stopping Valve



TRACE model - RPV

TRACE model - SGs

OpenFOAM/TRACE/PARCS

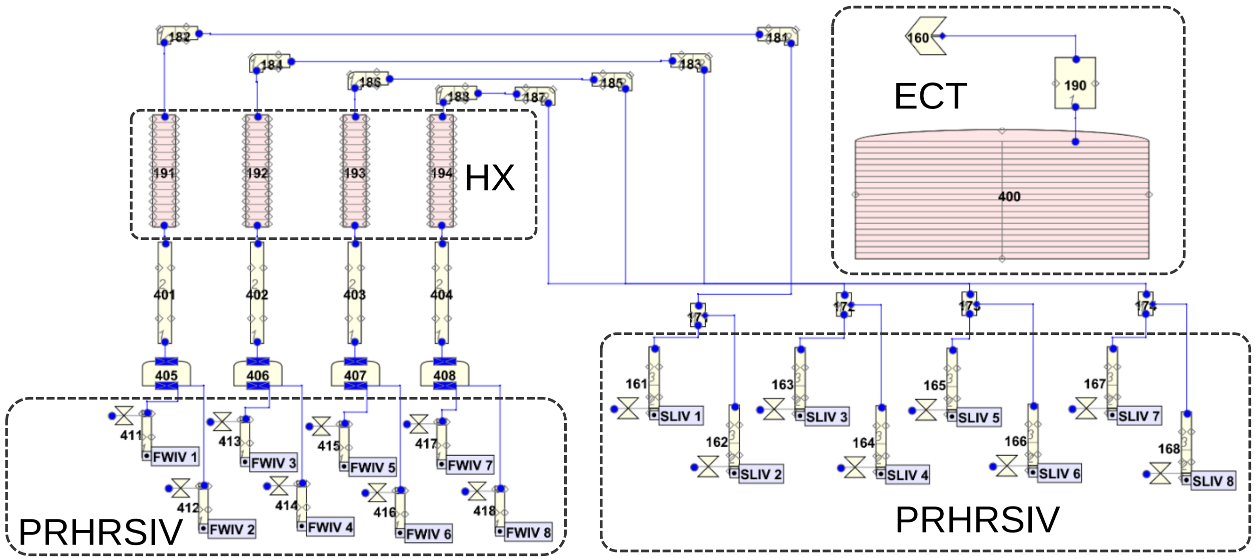
*Modeling: TRACE– **RPV TH**, OpenFOAM– **downcomer lower plenum TH**, PARCS– **Core NK***

PRHRS: Passive Residual Heat Remove System

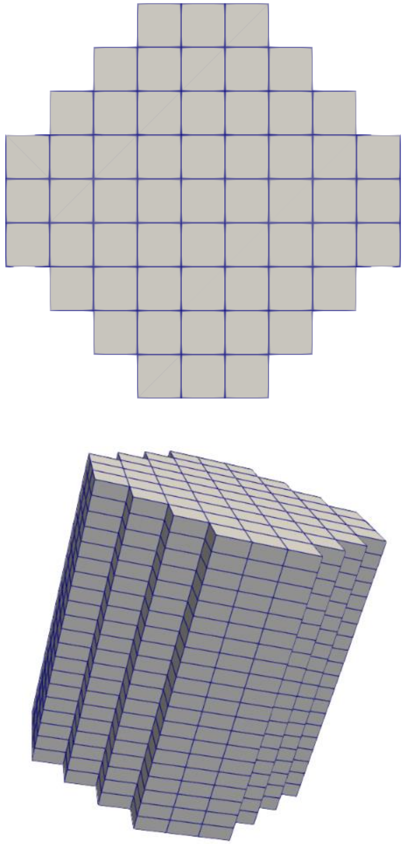
PRHRSIV: Passive Residual Heat Remove System Isolation Valve

ECT: Emergency Cooldown Tank

HX: Heat Exchanger



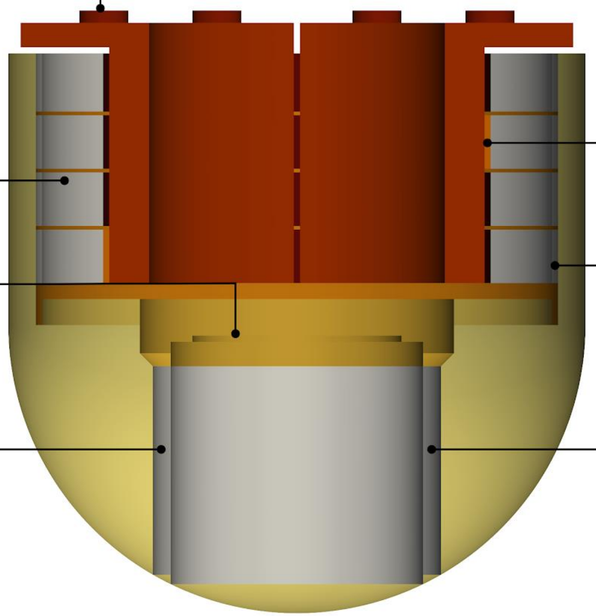
TRACE model - PRHRS



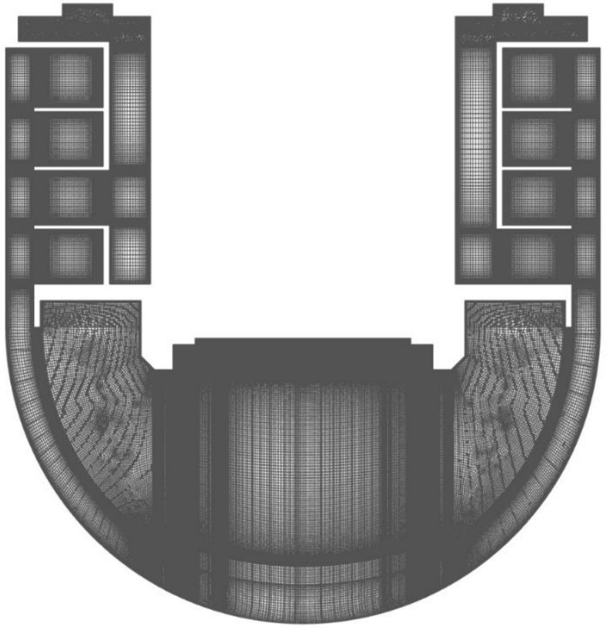
PARCS/SCF model - Core

OpenFOAM/TRACE/PARCS

*Modeling: TRACE– **RPV TH**, OpenFOAM– **downcomer lower plenum TH**, PARCS– **Core NK***



OpenFOAM model - CAD



OpenFOAM model - Mesh

Element count	Aspect Ratio	Skewness	Orthogonal Quality
40 million	Avg. 2.64	Avg. 0.11	Avg 0.944

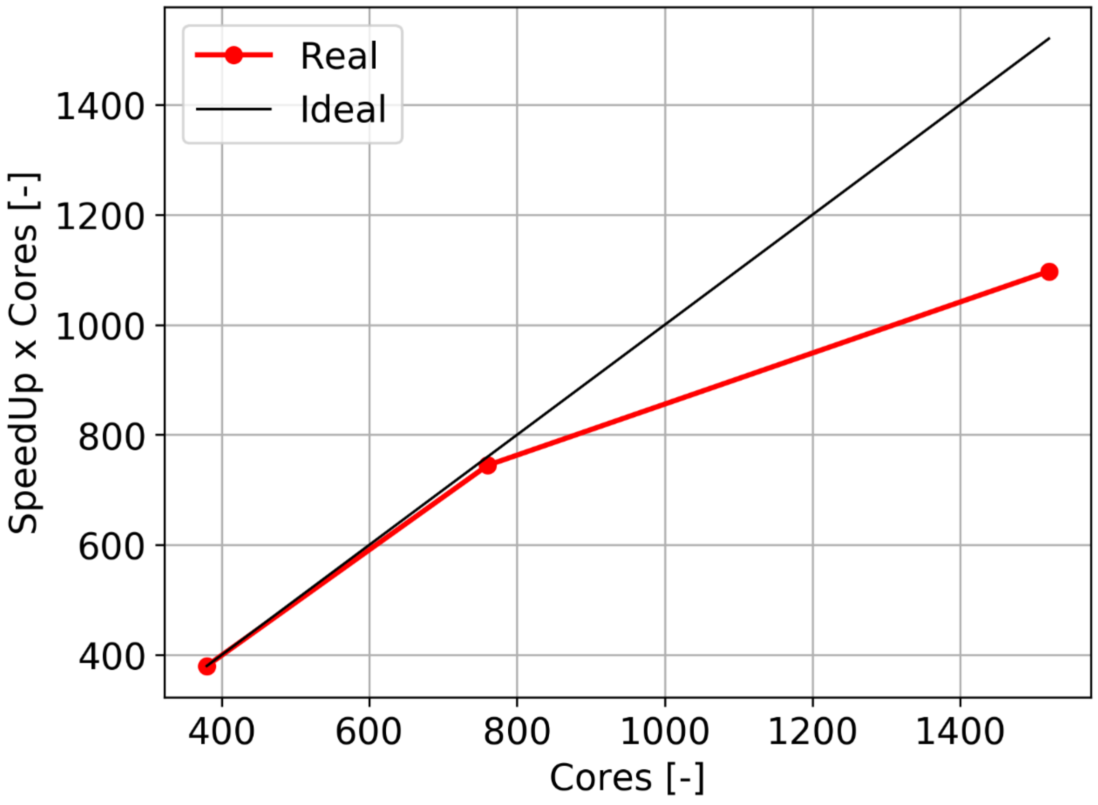
OpenFOAM/TRACE/PARCS

Computational configuration

CPU	Time (h)	CPU x Time	Speed-up Ratio
380	51.45	19551	1 (Ref)
760	26.26	19958	0.9796
1520	17.82	27086	0.7218

- We use **1520** cores (20 nodes x 76 cores).
- Wall-time applied is **70** hours.
- The transient time runs up to around **104** s.

Speed-up Ratio



OpenFOAM/TRACE/PARCS

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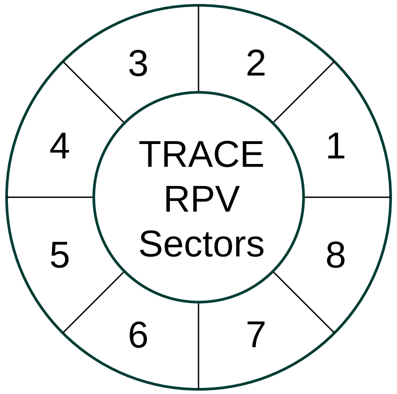
*Results: Steady State (SS) - **Global***

Parameter	TRACE/PARCS (ref)	TRACE/PARCS/OpenFOAM	Diff %
Primary pressure (MPa)	15.0	15.0	0.0
Core Power (MW)	330.0	330.0	0.0
Core inlet T (K)	567.36	566.62	0.13
Core outlet T (K)	594.76	594.15	0.10
Core mass flow rate (kg/s)	2090	2092	0.09
Core pressure drop (kPa)	35.1	35.1	0.0

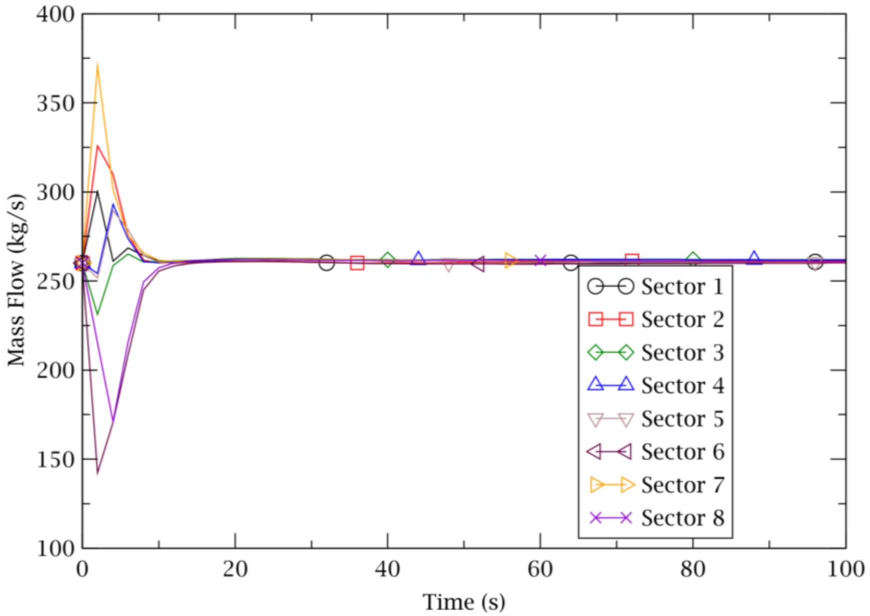
Diff = abs(TRACE/PARCS/OpenFOAM - TRACE/PARCS)/100

OpenFOAM/TRACE/PARCS

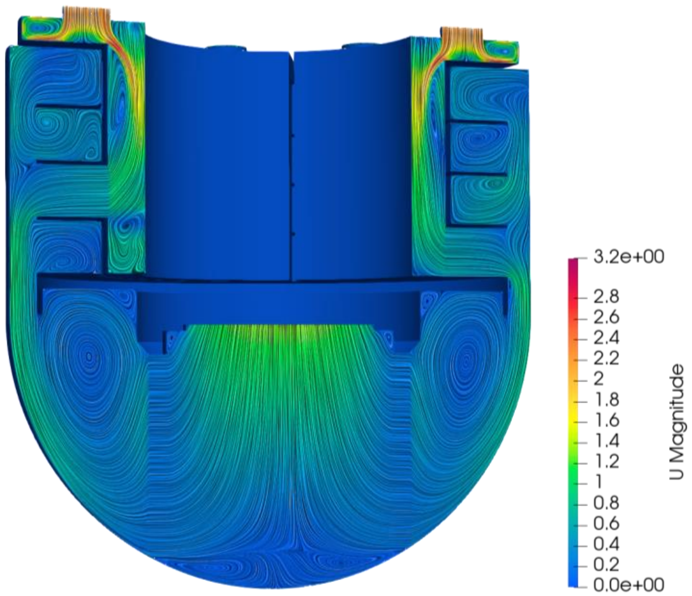
*Results: Steady State (SS) – **Detail***



The RPV mesh of TRACE has **8 sectors** azimuthally, corresponding to **8 SGs**



Mass flowrate at the core inlet **(Coupling interface)**

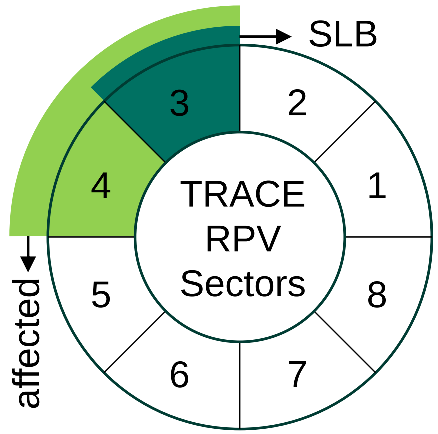


Coolant velocity in OpenFOAM domain

- The hydraulic field converges quickly proving **well**-established **models** and coupling **schemes**.
- Large **vortex** in the lower plenum because of the **skirt**.
- Obvious **low-velocity** area at the **bottom** of the lower **plenum**.

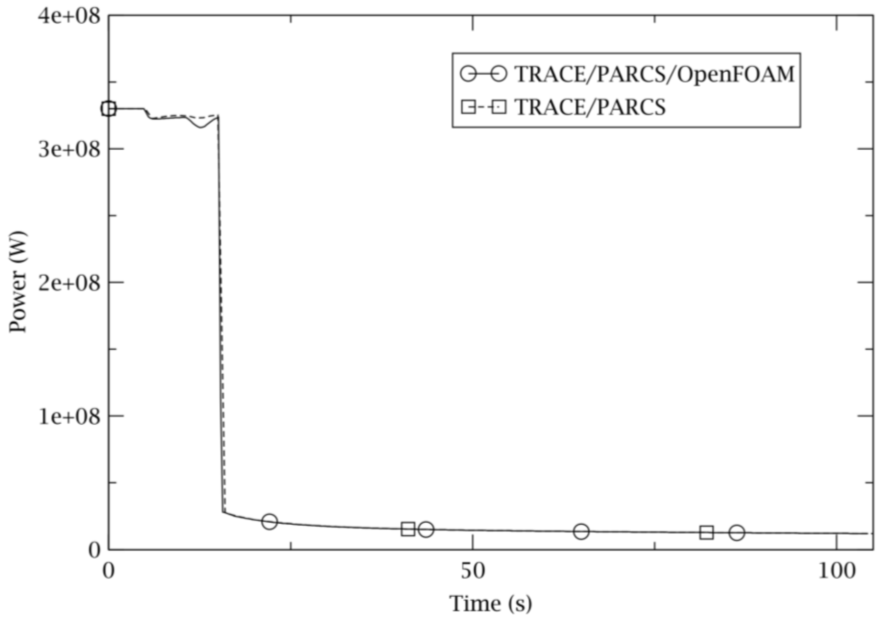
OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **Global***

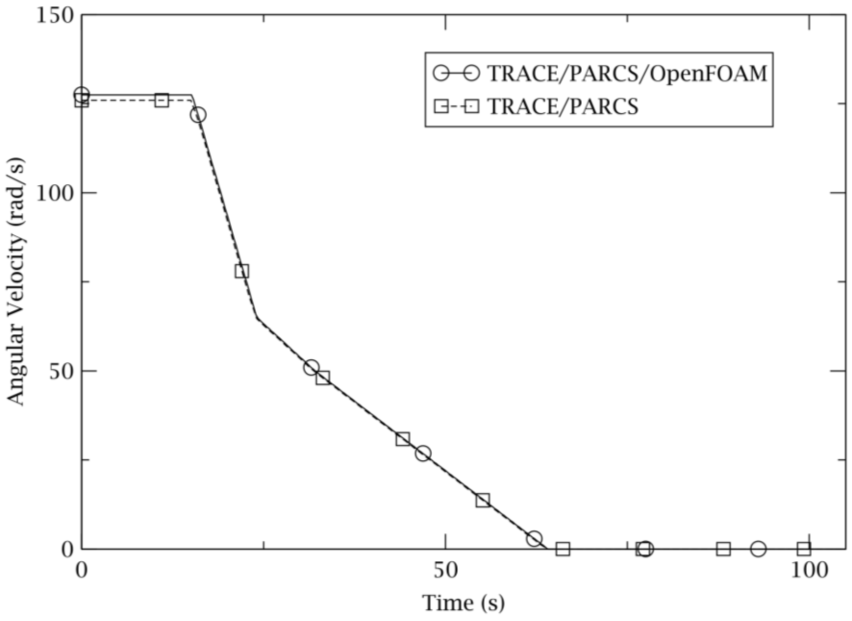


SLB happens in sector **3**, influencing **3** and **4** (PRHRS)

SG1 2 connect to sector 3 and 4



Core total power

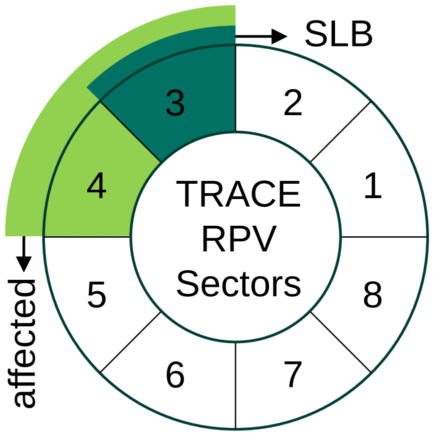


Pump speed

- SLB happens:
  - Total power quickly decreased to ~6% nominal power, then gradually decreased to ~3.5% at 100s;
  - Four main pumps gradually coasting down to 0.0 rad/s at 165s.
- TRACE/PARCS/OpenFOAM and TRACE/PARCS have almost the **same** global behavior.

OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **Global***



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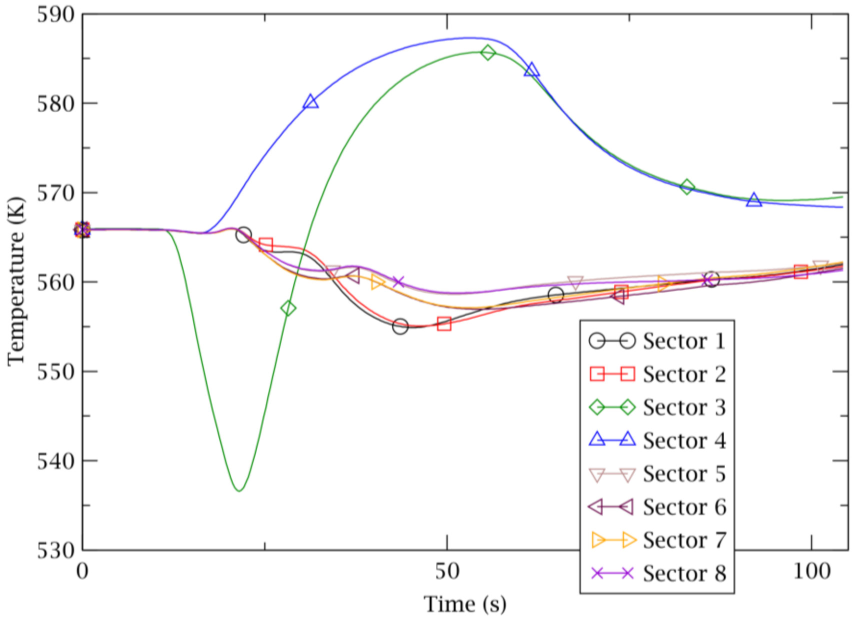
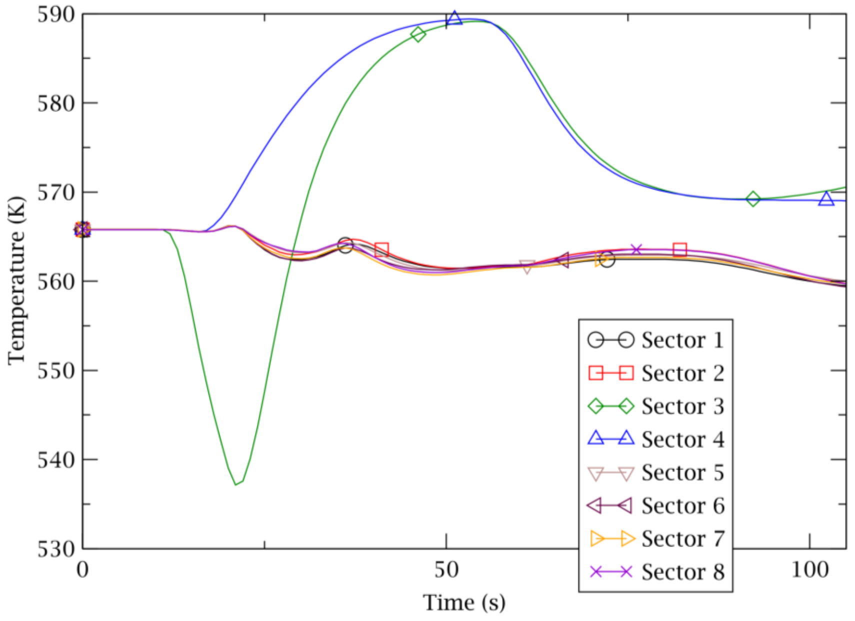


SG outlet T – TRACE/PARCS/OpenFOAM

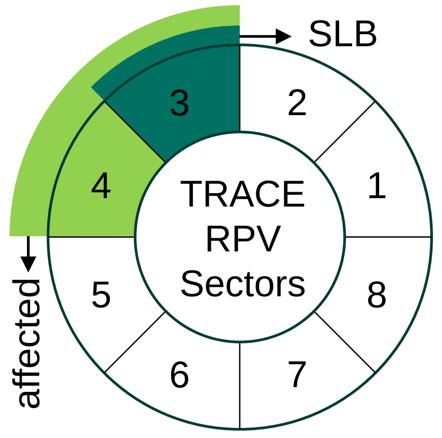


SG outlet T – TRACE/PARCS

- SLB happens:
  - SG1 – T **decrease** due to vaporization, T **increase** due to failure of PRHRS1;
  - SG2 – T **increase** due to failure of PRHRS1;
  - SG3-8 – T **slight perturbation** thanks to PRHRS2-4.
- TRACE/PARCS/OpenFOAM predict **similar** results as TRACE/PARCS.

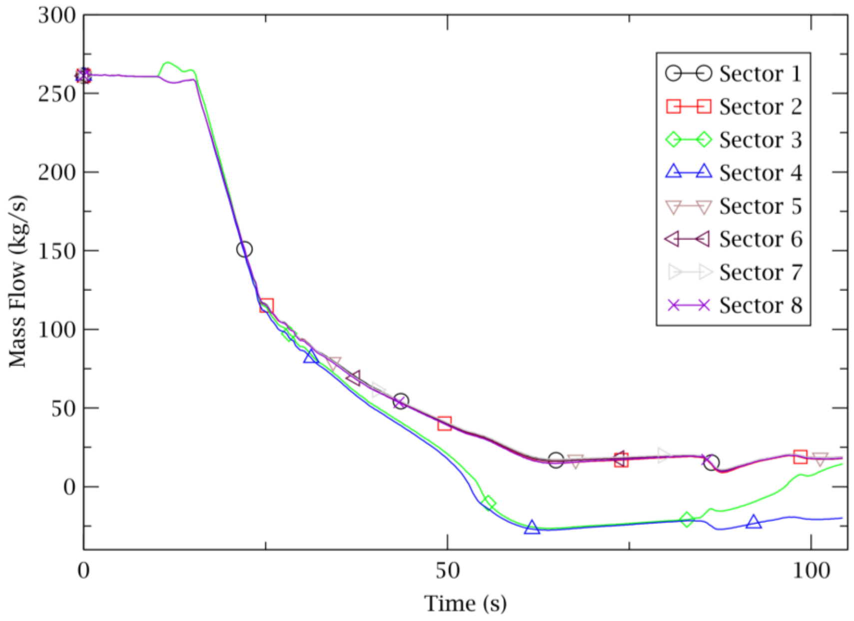
OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **Global***

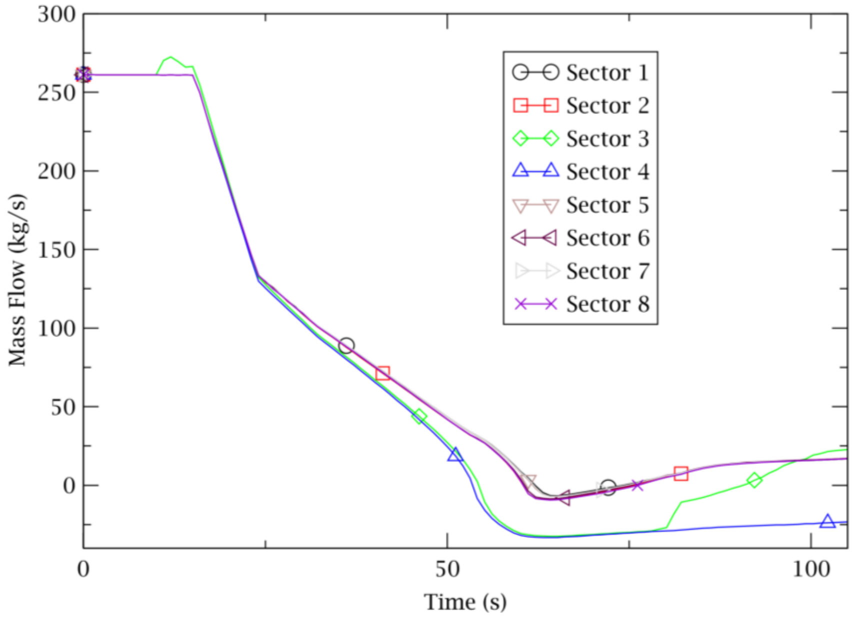


SLB happens in sector **3**, influencing **3** and **4** (PRHRS)

SG1 2 connect to sector 3 and 4



SG mass – TRACE/PARCS/OpenFOAM

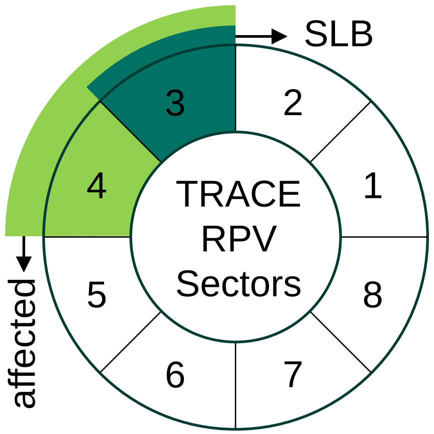


SG mass – TRACE/PARCS

- SLB happens:
  - SG1 – M **increase** due to lower T, **decrease** due to failure of pumps, **increase** thanks to natural circulation;
  - SG2-8 – M **decrease** due to failure of pumps, **increase** thanks to natural circulation;
  - SG1-2 – M goes **lower** due to a higher T.
- TRACE/PARCS/OpenFOAM predict **similar** results as TRACE/PARCS.

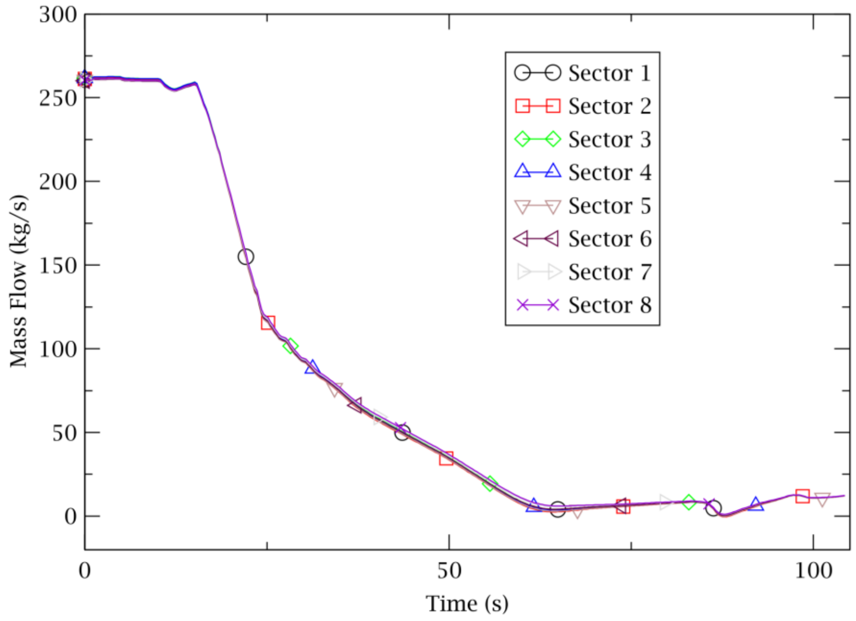
OpenFOAM/TRACE/PARCS

Results: Transient (TS) – __Global__

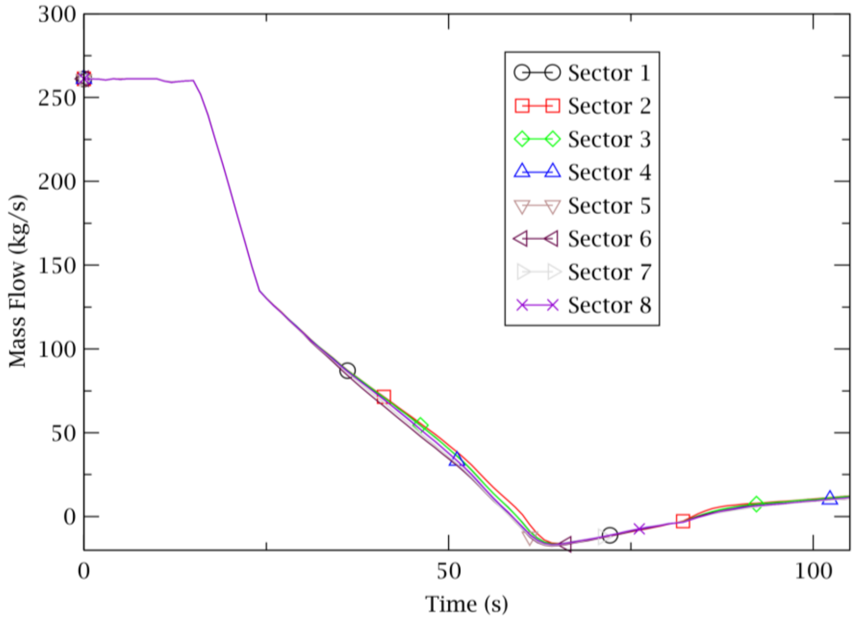


SLB happens in sector **3**, influencing **3** and **4** (PRHRS)

SG1 2 connect to sector 3 and 4



Core mass – TRACE/PARCS/OpenFOAM

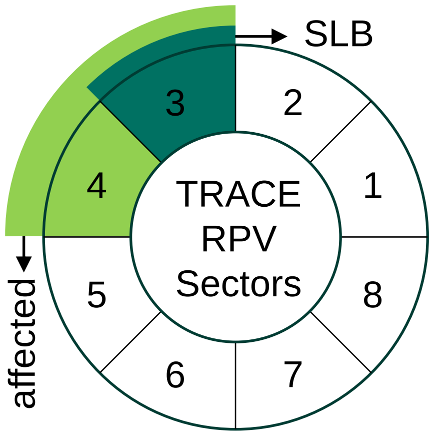


Core mass – TRACE/PARCS

- SLB happens:
  - Core inlet sector 1-8 – Synchronously, M **decrease** - failure of pumps, **increase** - natural circulation;
- TRACE/PARCS/OpenFOAM predict **similar** global results as TRACE/PARCS, but:
  - TRACE/PARCS predict **reverse flow** at the core inlet;
  - TRACE/PARCS/OpenFOAM gives always **upward flow** though very low.

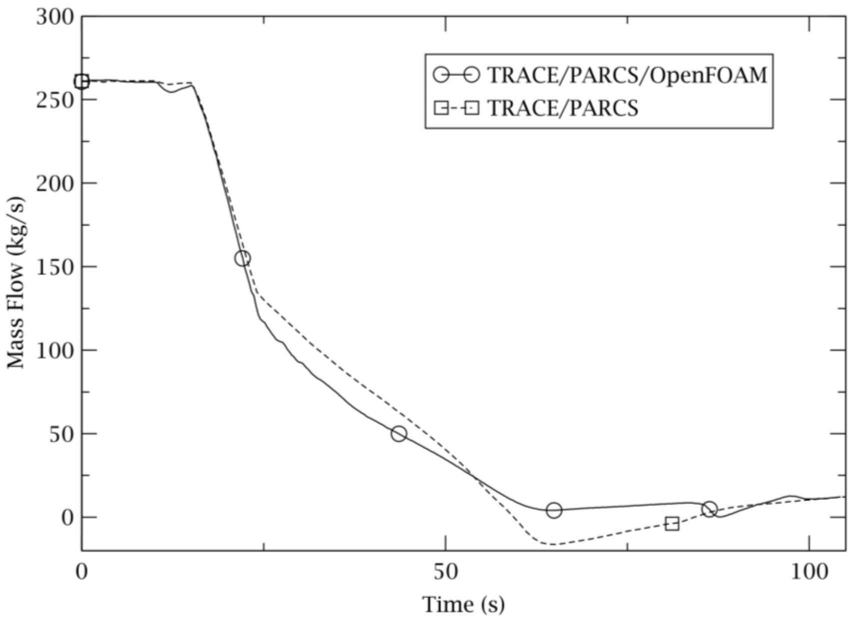
OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **Global***

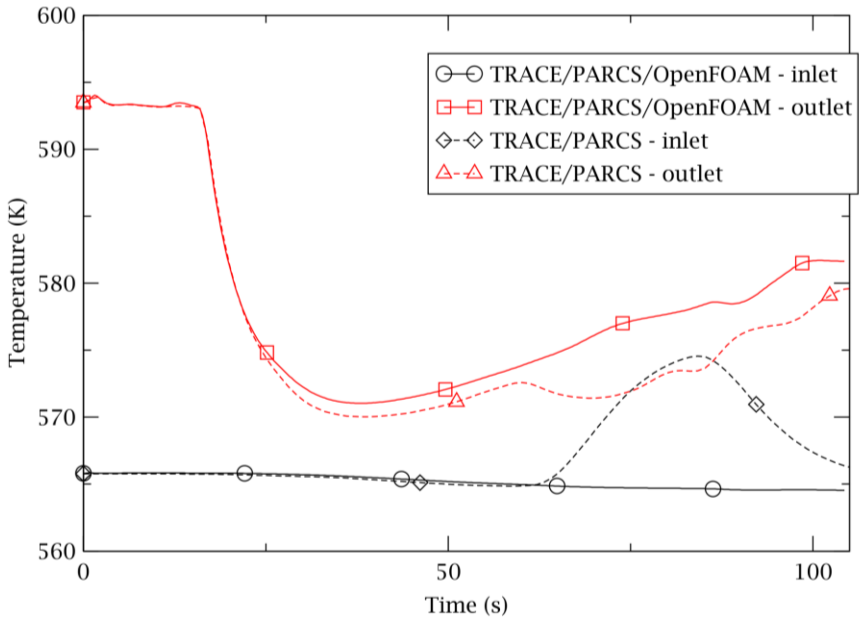


SLB happens in sector **3**, influencing **3** and **4** (PRHRS)

SG1 2 connect to sector 3 and 4



Core 1/8 mass

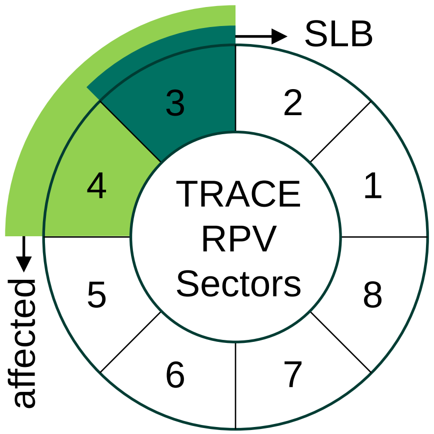


Coolant average T at core inlet and outlet

- SLB happens:
  - Core inlet sector 1-8 – Synchronously, M **decrease** - failure of pumps, **increase** - natural circulation.
- TRACE/PARCS/OpenFOAM:
  - Core **inlet** T - **tiny** changes; Core **outlet** T **decrease** – SCRAM, **increase** – M decrease.
- Coolant T curves of TRACE/PARCS indicate the reverse flow.

OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **Global***



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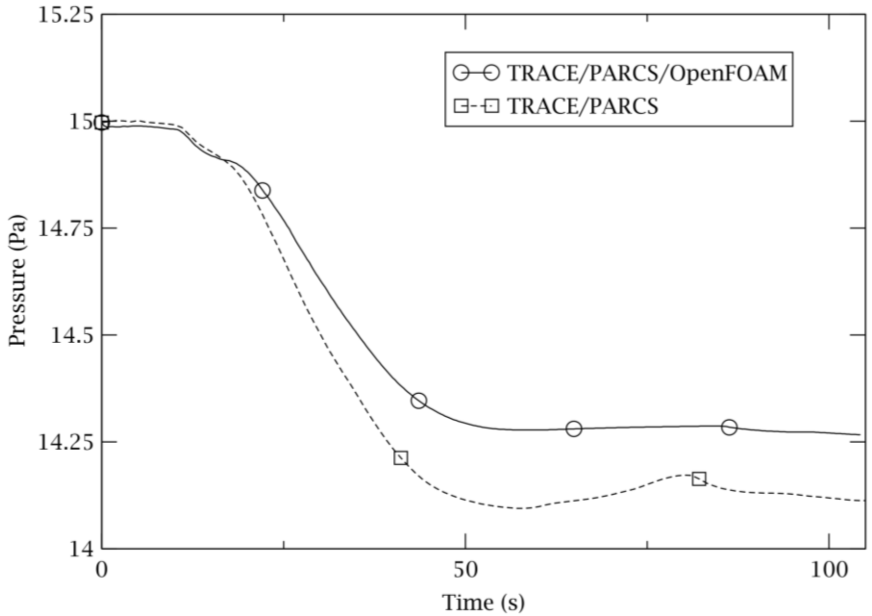
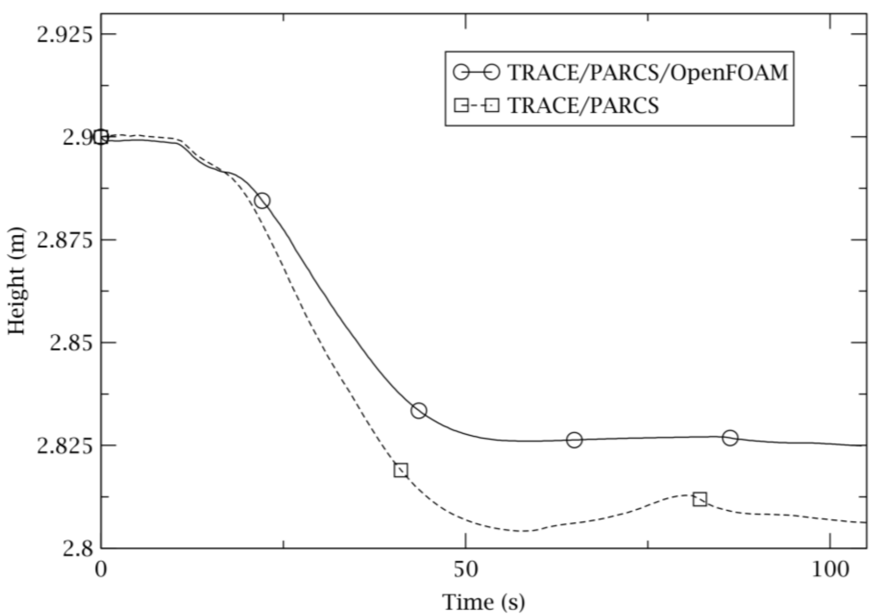


Pressure – pressurizer bottom

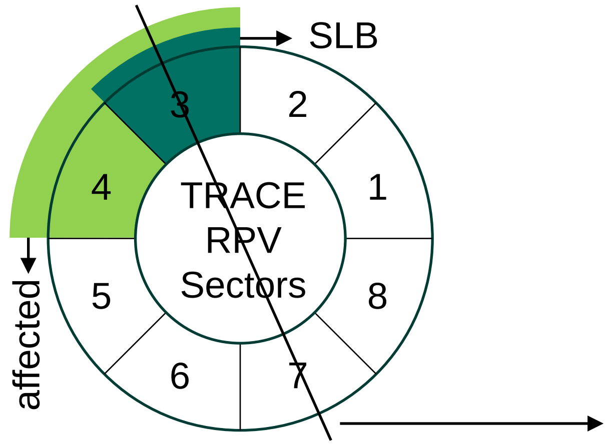


Water level in the pressurizer

- SLB happens:
  - Primary pressure gradually goes from 15 MPa down to around 14.25 Mpa;
  - The water level in the pressurizer gradually goes from 2.9 m down to around 2.825 m.
- TRACE/PARCS/OpenFOAM predict **similar** results as TRACE/PARCS.

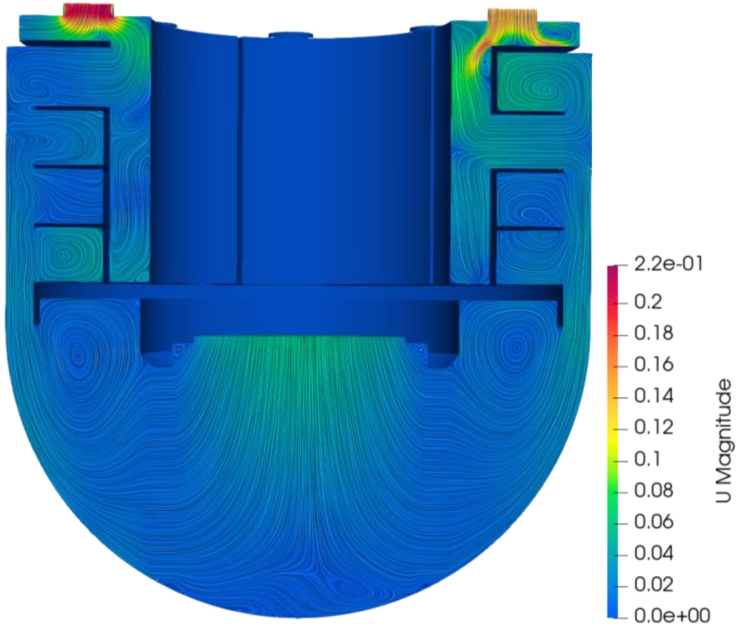
OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **CFD** – **100s***

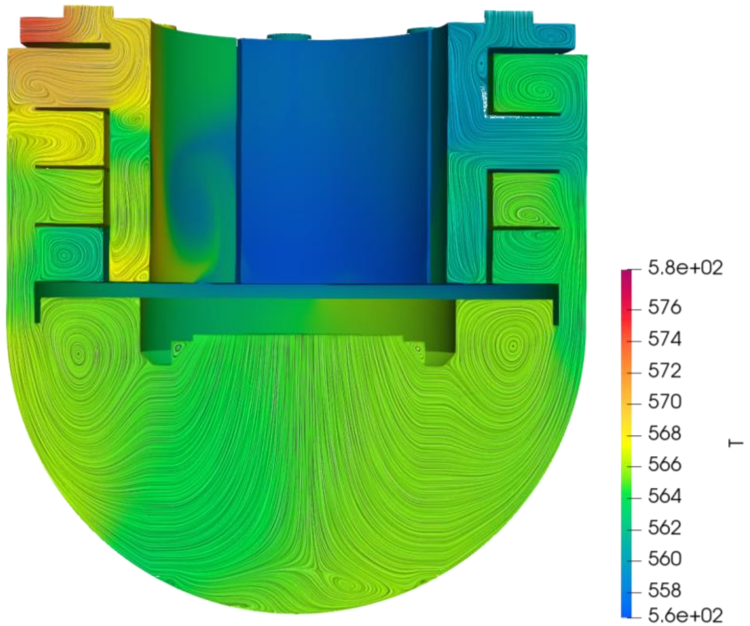


SLB happens in sector **3**, influencing **3** and **4** (PRHRS)

SG1 2 connect to sector 3 and 4



Velocity magnitude

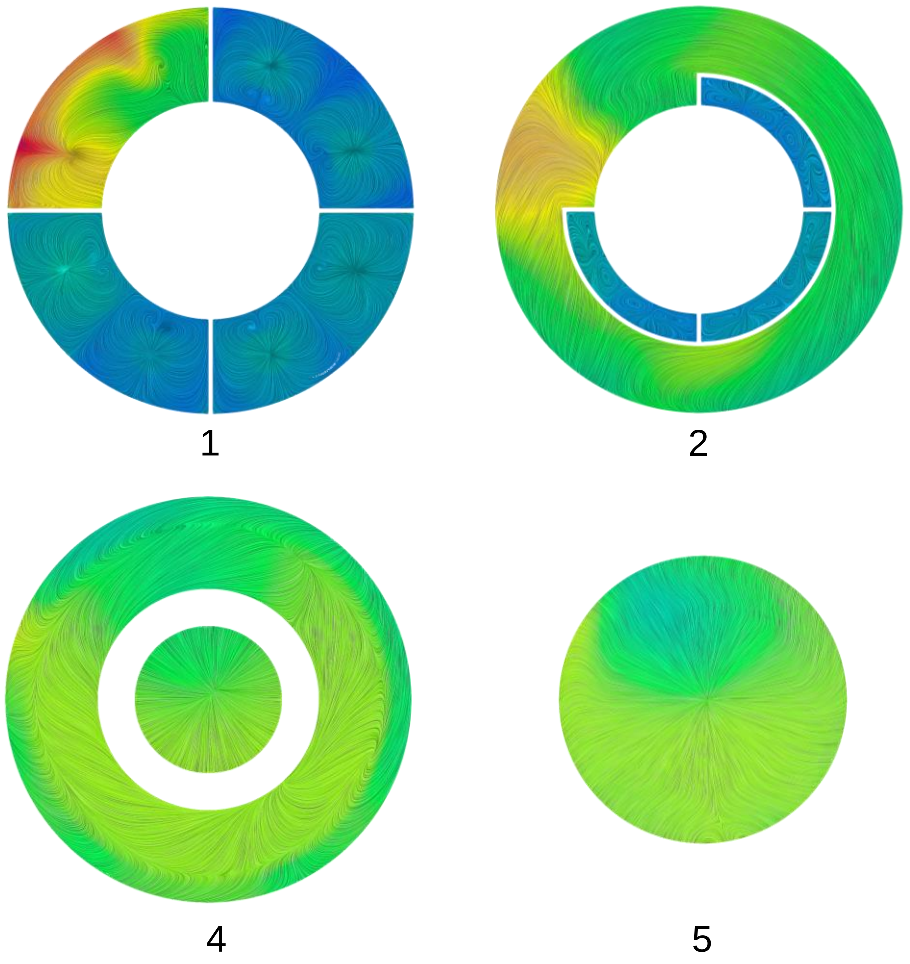


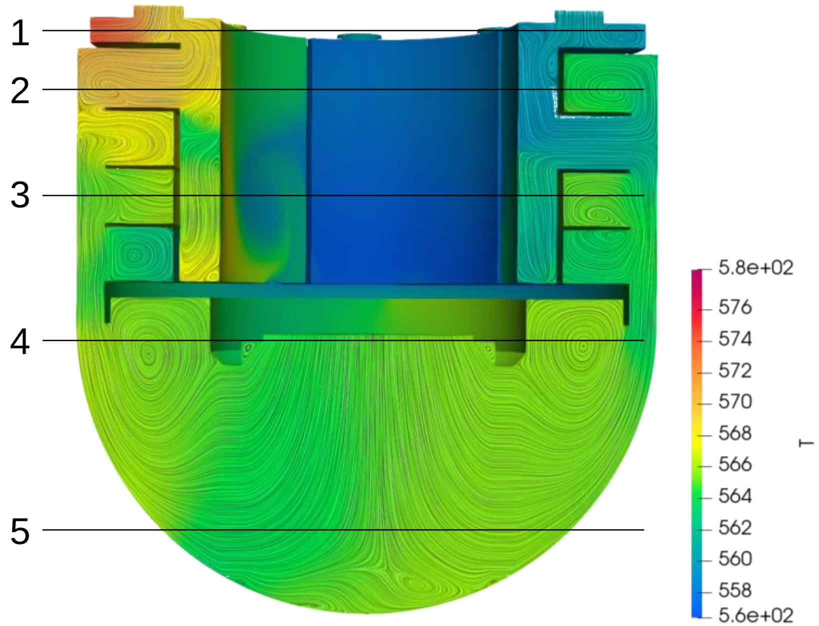
Coolant temperature

- 100s:
  - Natural circulation preliminarily established;
  - Obvious 3D **unsymmetrical** effect in coolant **velocity** and **temperature** observed.
- The strong **unsymmetrical** flow condition at the downcomer inlet is sufficiently **flattened** in the downcomer and further **omitted** by the skirt, while still a slight **uneven T** at the **core inlet**.

OpenFOAM/TRACE/PARCS

*Results: Transient (TS) – **CFD** – **100s***



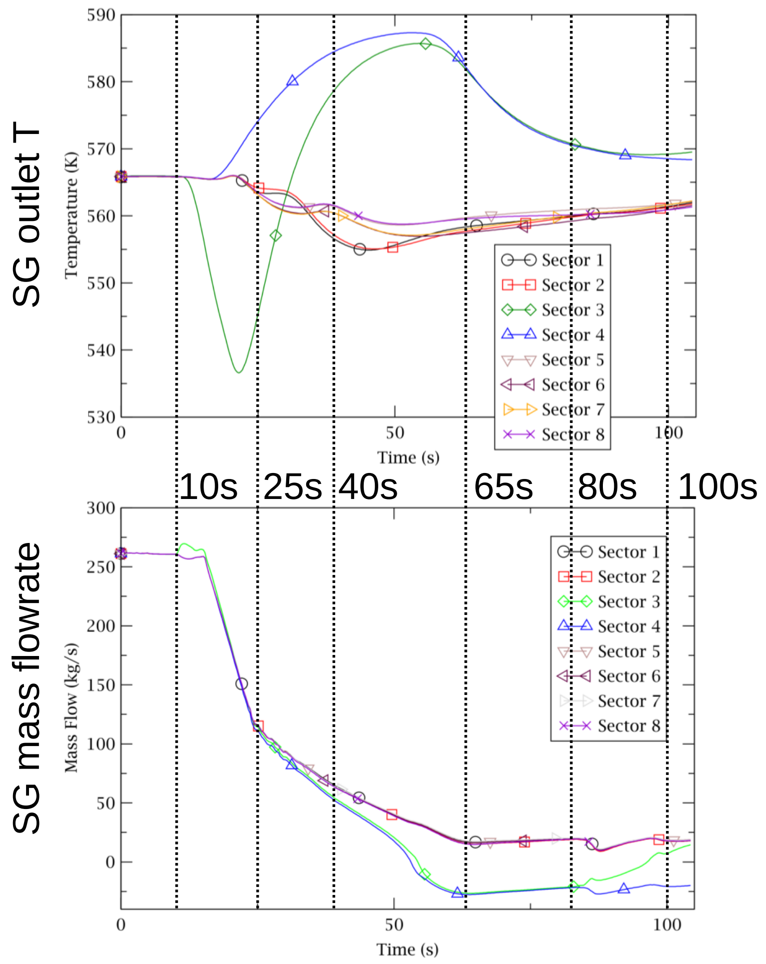


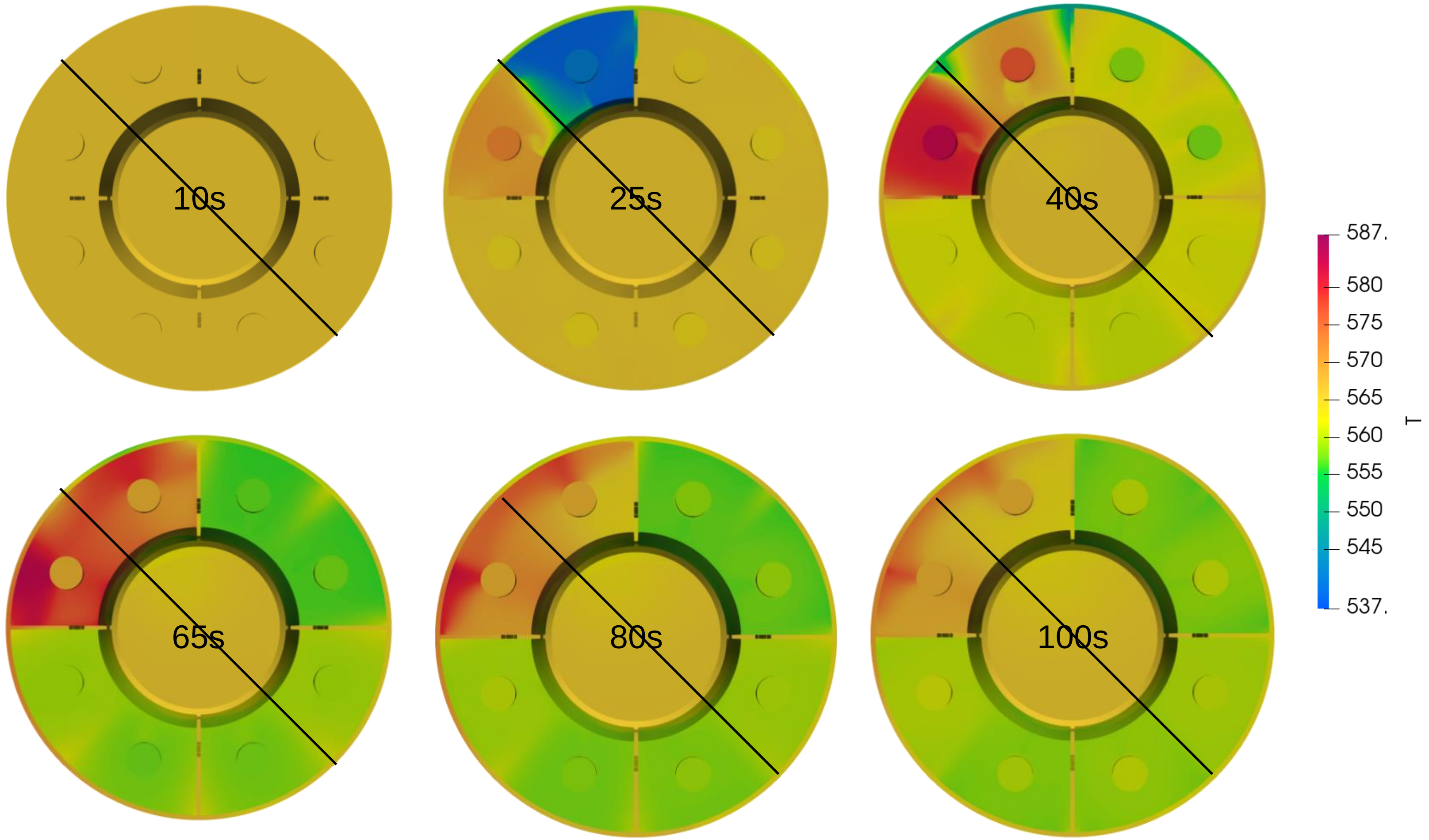
Coolant temperature

- 100s:
  - The strong **unsymmetrical** flow condition at the downcomer inlet is sufficiently **flattened** in the downcomer and further **omitted** by the skirt, while still a slight **uneven T** at the **core inlet**.

OpenFOAM/TRACE/PARCS

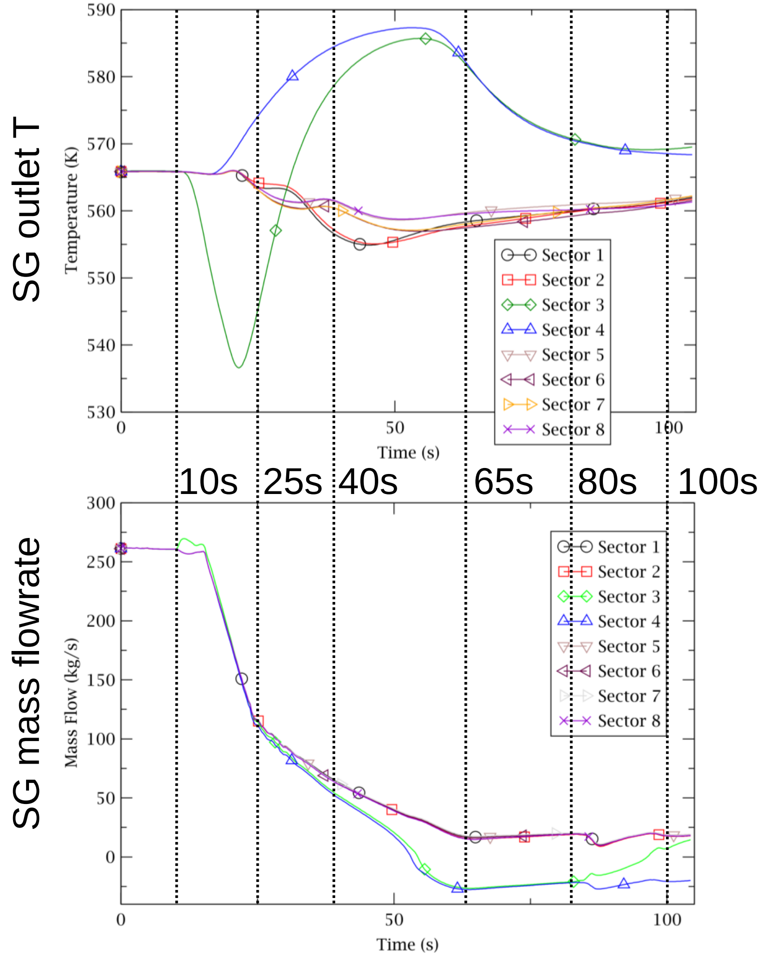
*Results: Transient (TS) – **CFD** – **T evolution** with time*

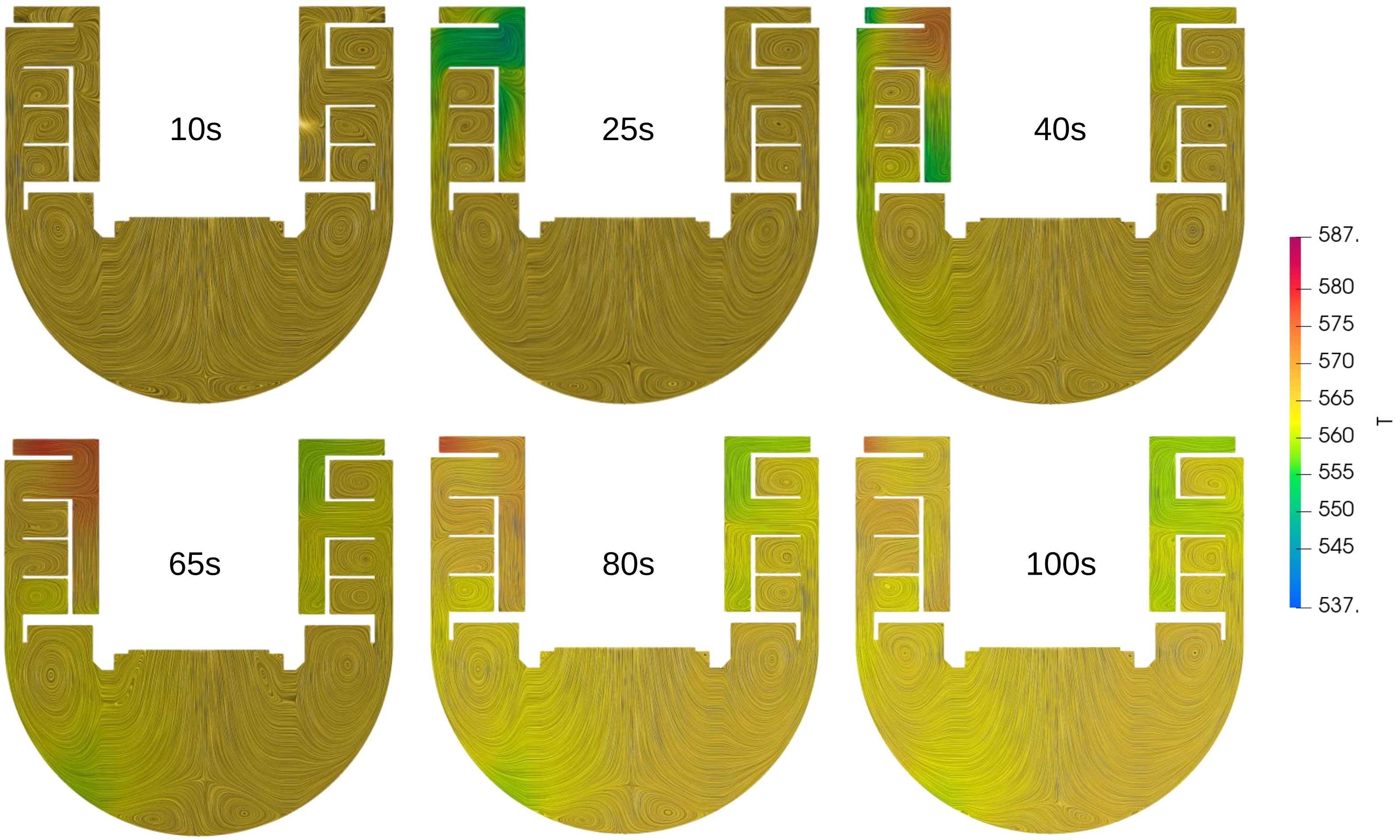




OpenFOAM/TRACE/PARCS

Results: Transient (TS) – CFD – T evolution with time





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Temporal Coupling of TRACE/PARCS/OpenFOAM

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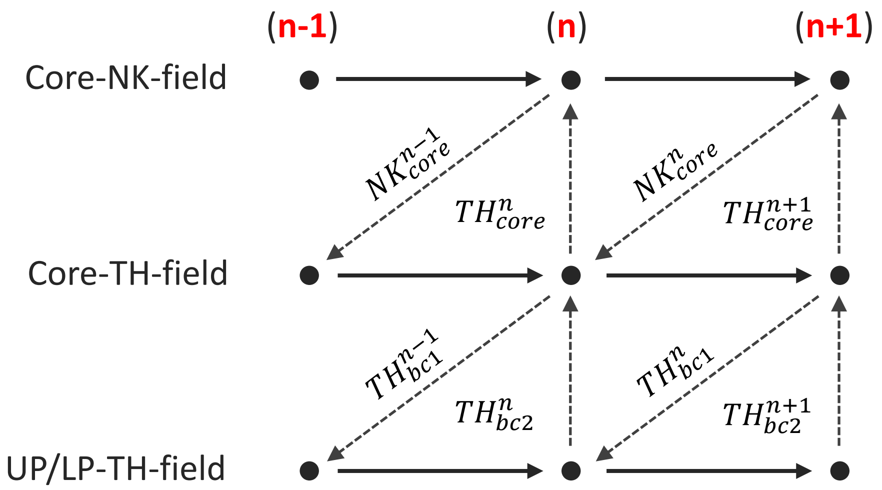


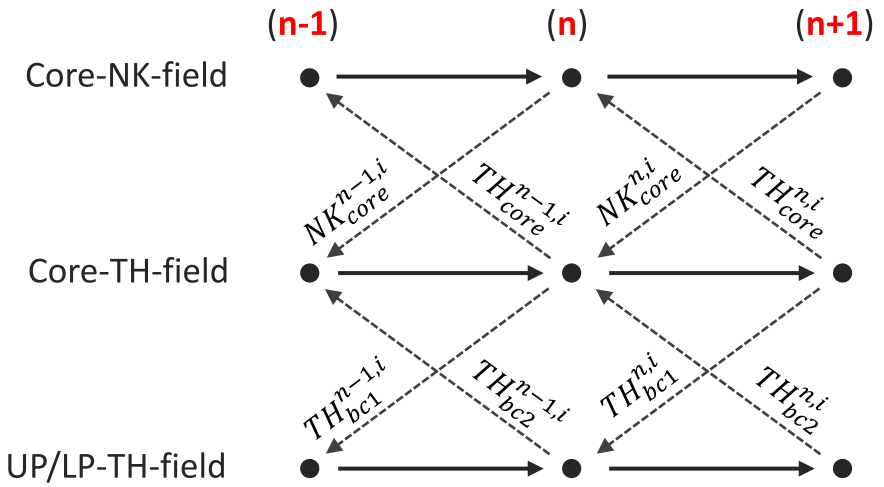
$NK_{core}^{n+1} = f(NK_{core}^{n}, TH_{core}^{n})$

$TH_{core}^{n+1} = f(NK_{core}^{n}, TH_{core}^{n}, TH_{bc2}^{n})$

$TH_{up,lp}^{n+1} = f(TH_{up,lp}^{n}, TH_{bc1}^{n})$

Explicit Coupling

$Field^{unknown} = f(Field^{known})$



$NK_{core}^{n+1} = f(NK_{core}^{n}, TH_{core}^{n+1})$

$TH_{core}^{n+1} = f(NK_{core}^{n+1}, TH_{core}^{n}, TH_{bc2}^{n+1})$

$TH_{up,lp}^{n+1} = f(TH_{up,lp}^{n}, TH_{bc1}^{n+1})$

Semi-implicit Coupling

$Field^{unknown} = f(Field^{known}, Field^{unknown})$

Temporal Coupling of TRACE/PARCS/OpenFOAM

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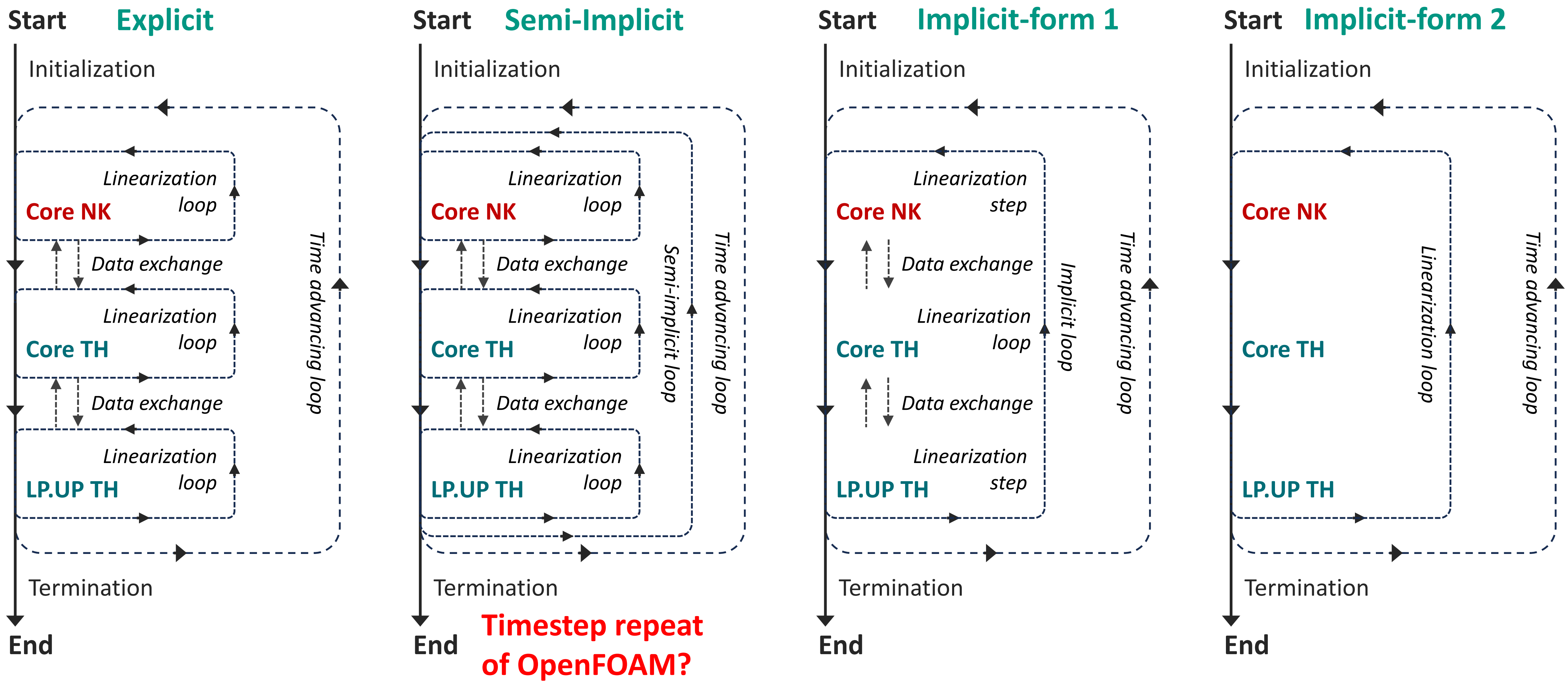
What we are using now | **What we have now** | **What is promising**



Conclusion and Outlook

*Conclusions from the SLB - TRACE/SCF/OpenFOAM-ICoCo from a **physical** viewpoint:*

- During the SLB, **Globally**:
    - SLB happens in SG1 secondary loop, SCRAM, and main pumps coasting down;
    - SG1 primary T decrease(SLB) – increase (1^{st} PRHRS fail, pumps fail) – decrease (other PRHRS);
    - SG2 primary T increase (1^{st} PRHRS fail, pumps fail) – decrease (other PRHRS);
    - SG3-8 primary T slight perturbation (2^{nd} 3^{rd} 4^{th} PRHRS).
- During the SLB, **CFD**:
    - Strong 3D unsymmetrical flow conditions observed in the CFD domain;
    - From downcomer inlet to core inlet, coolant well mixed.
- The reactor **stay safe** in and after the SLB accident.

*Conclusions from the SLB - TRACE/SCF/OpenFOAM-ICoCo from a **technical** viewpoint:*

- Significant instability issue for low-pressure drop condition, OpenFOAM timestep repeat problem.

Future work:

- Finalize semi-implicit coupling, and implement implicit coupling, thus enhancing stability.

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