Operation of the helium cooled DEMO fusion power plant and related safety aspects

1st IAEA workshop on ***"Challenges for coolants in fast spectrum system: Chemistry and materials, Vienna, July, 5-7 2017***

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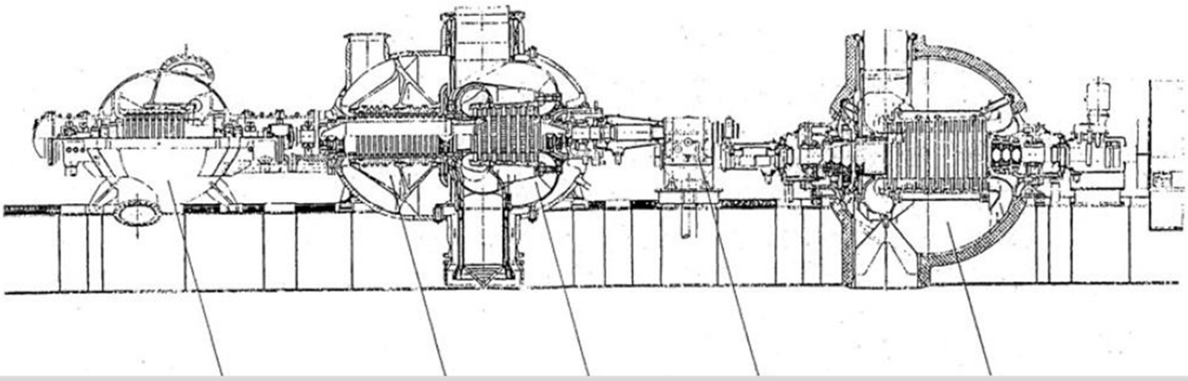

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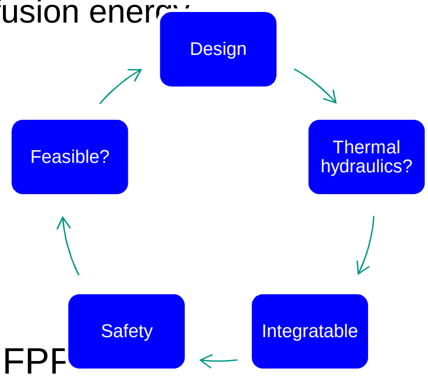
Activities

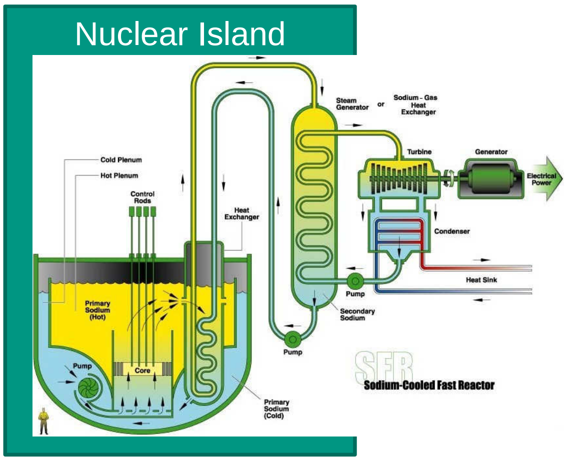
- **European Fusion Roadmap**
  Realization of fusion energy source for electricity (and heat) by 2050 → Integration of a FPP in Multimodal Energy systems 2050+
- **Horizon 2020: European research framework programme**
  - Power Plant Physics and Technology (PPPT) conducted by the EUROfusion Consortium for the development of fusion energy
  - Activities:
    1. BOP: Balance of plant
    2. BB: Breeding blanket incl. FW
    3. DIV: Diverter
    4. SAE: Safety and environmental protection

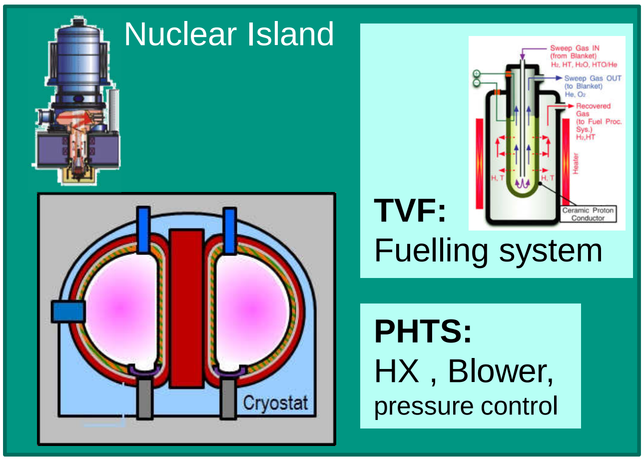


Objectives:

- Extension of ITER by power plant technology → FPP
- Integration of safety provisions from the beginning
- Involvement of industry to participate in ongoing developments

Fast reactor ←→ Fusion reactor (DEMO)



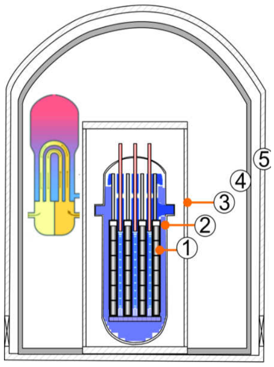


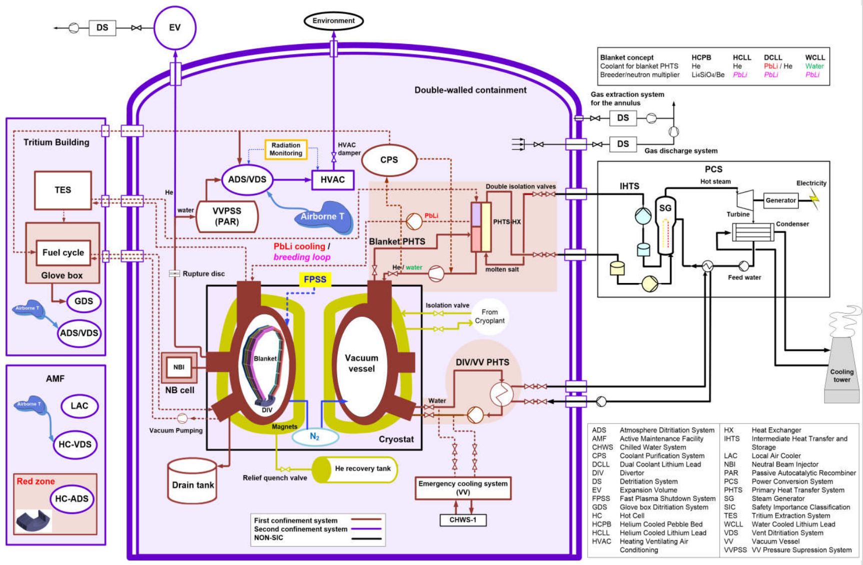
- **Fast reactors:** easily defined interface at nuclear island: Secondary coolant, cables, decay heat removal systems
- **Fusion reactor:** IHTS, Divertor and vacuum vessel (VV) cooling, plasma heating systems, tritium transport, decay heat removal, VV relieve lines

→ Contact with WENRA Reactor Harmonization Working Group (RHWG)

Primary safety functions of a nuclear plant

- Confinement
- Control of releases
- Limitation of releases





- 4/5 static subsequent enveloped barriers
- Static barriers for release control (mainly related to barriers + PAR+ PRS)
- „practical elimination“ of level 5 by design + core catcher + mitigation chains

- Two static barriers extended over large scale
- Mixture of static and dynamic barriers (DTS, TES, HVACS)
- Large sets of active + passive systems (but lower inventory and energy content and larger time for intervention)

Fusion facts

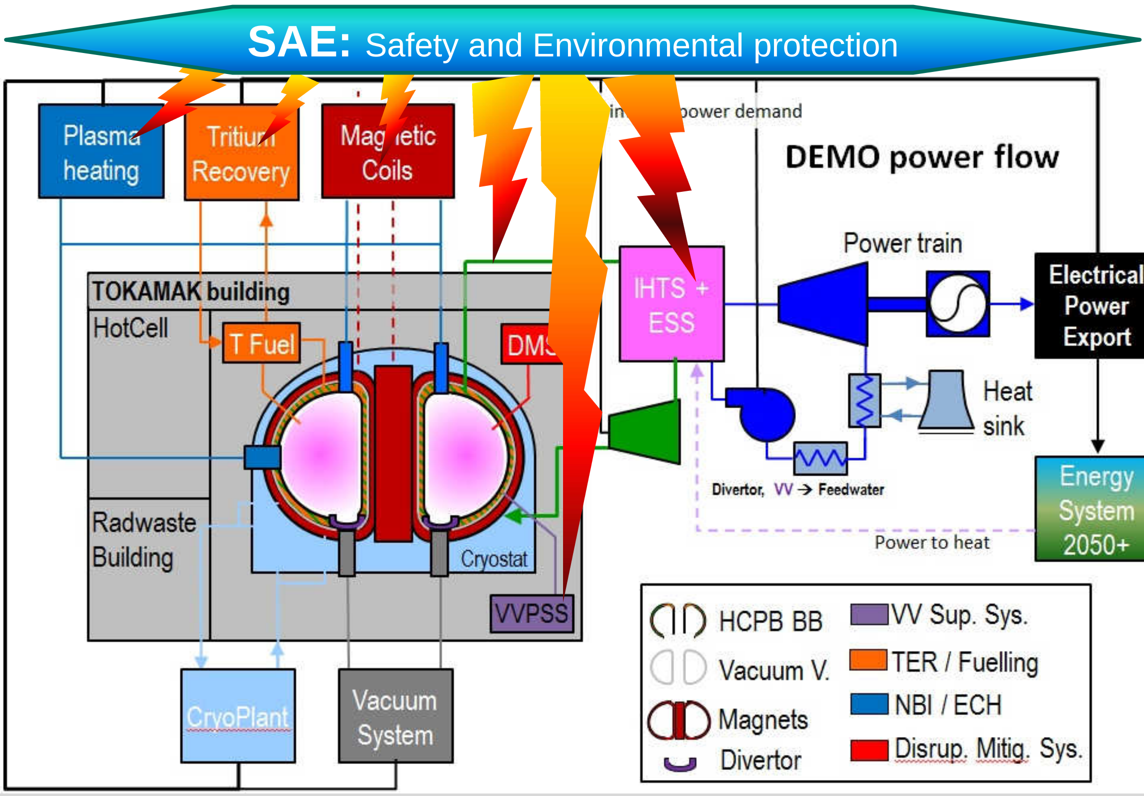
Internals

- Tokamak operate in pulsed mode:
  presently 2h plasma pulse +
  15-30 min dwell time (central solenoid loading and vacuum)
- Plasma power density small, temperatures very high, but risk of disruptions etc.
- Additional plasma heating required (neutral beam or microwaves)
- Plasma localized dynamically inside tokamak vessel
- Permanent vacuum pumping to divertor
- Vacuum vessel with multitude penetrations
  → needs to be cooled by water

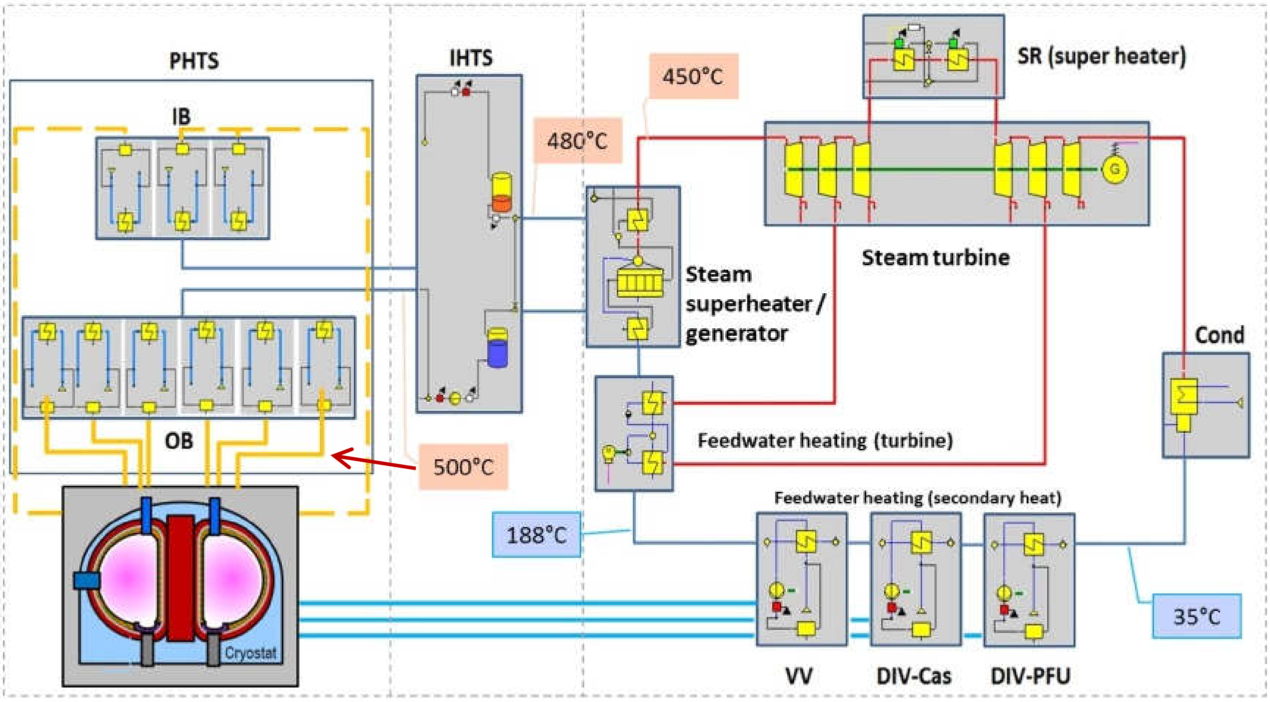
Externals

- Loading of central solenoid requires energy ramp (> 50MW/min)
  → robust grid or internal (thermal) energy buffer (in IHTS)

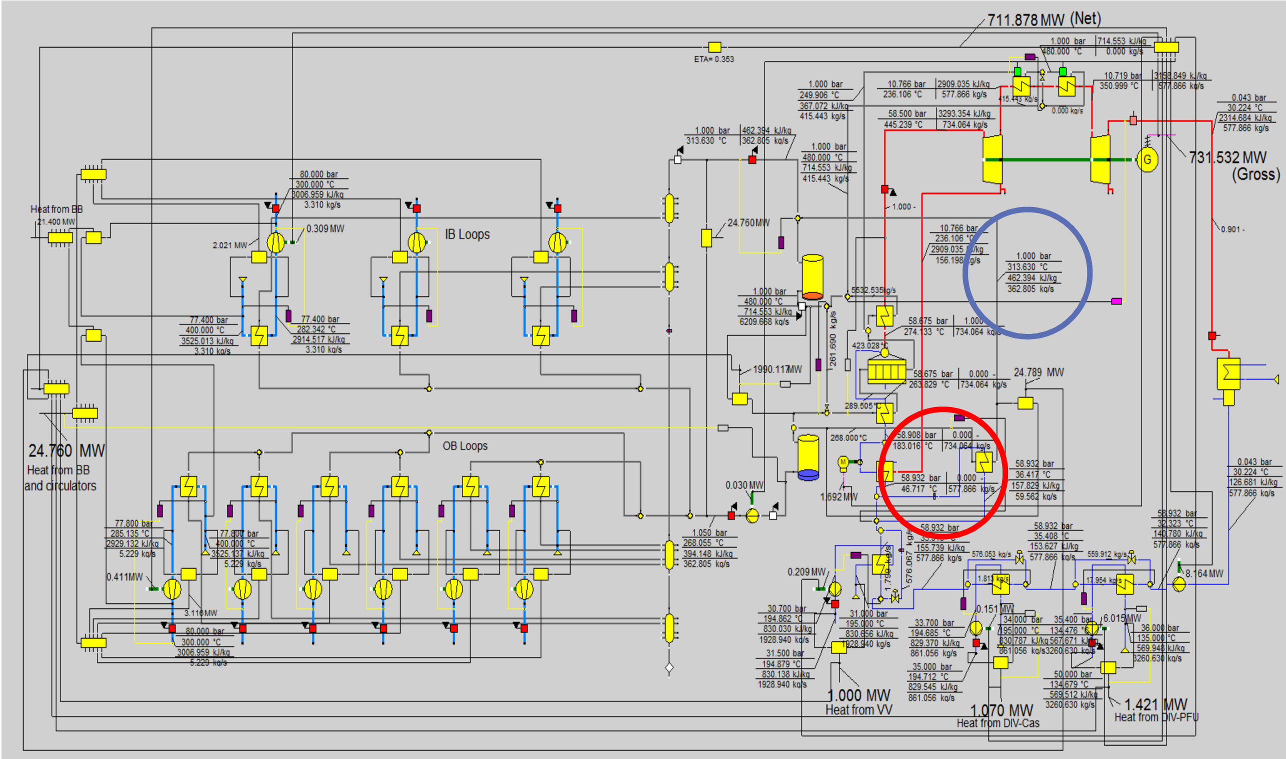
Systems & interfaces



Energy transfer BB → Balance of plant (BOP)



Central backbone: Balance of plant (BOP)



Present state of BOP for HCPB

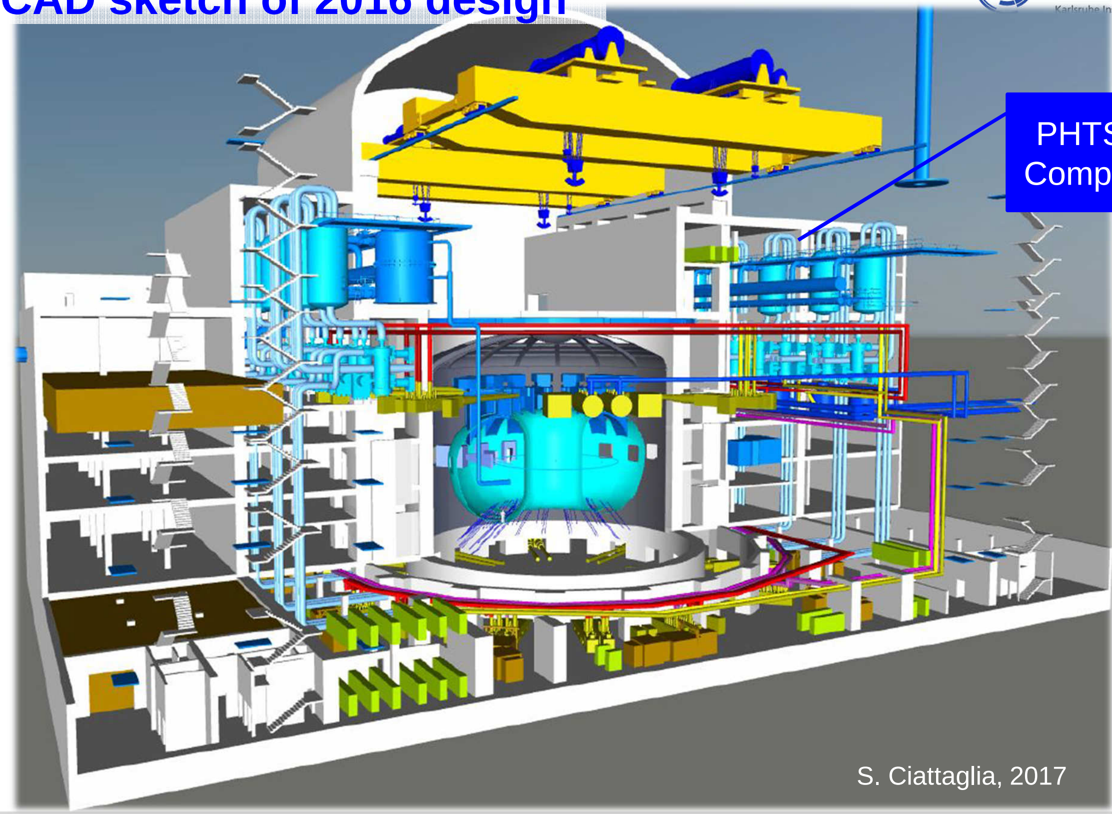
Today:

- 18 sectors: 3 in-board loops each for 6 sectors
  6 out-board loops each for 3 sectors
  (power variation ~20%)
- Two versions of BOP:
  1. with a thermal energy storage (ESS) in the IHTS (low pressure, technology from Concentrating solar power)
     → lifetime for FPP possible
  2. without ESS: steam generator inside Tokamak, steam line penetrates confinement, power train (Turbine + generator power by grid during dwell time), req. heating of turbine and steam generator
     → extrapolation to FPP difficult

Upcoming challenges:

- Change of tokamak design → back to 16 sectors (22,5°)
  new segmentation of IB/OB PHTS to level sector power to loop power

CAD sketch of 2016 design



DEMO HCPB Safety

EUROfusion PPPT - WPSAE

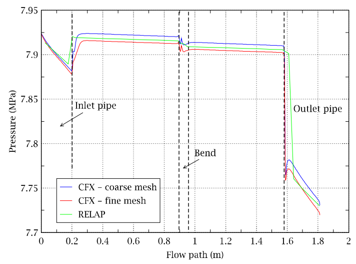
- Proposal of a confinement strategy for DEMO
- Identify safety functions categorized in a Safety Importance Classification (SIC) scheme
- Assess impact of design choices on fulfillment of safety objectives and criteria
- Functional Failure Mode Effect Analysis (FFMEA) and selection of representative accident scenarios
- Code validation experiments
  - *First wall (FW) behavior and* Loss of flow accident (LOFA)
  - *Tritium migration inside the breeding zone (BZ)*
  - *Tritium trapping and release of beryllium-based neutron multiplier materials*
- Activation analyses for decay heat calculation
- Deterministic analysis of selected accident sequences and evaluation of consequences
- Study of provision of expansion volume (EV) combined with the vacuum vessel pressure suppression tank (VVPSS)

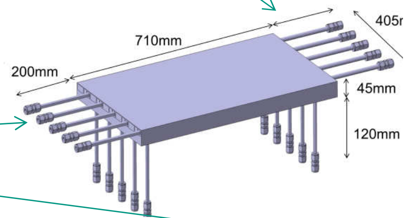
Safety analyses – design based accident (DBA)

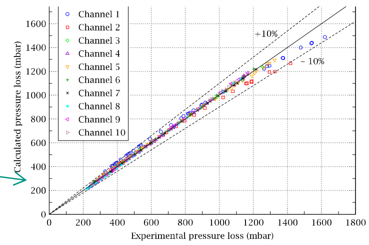
LOFA in the FW

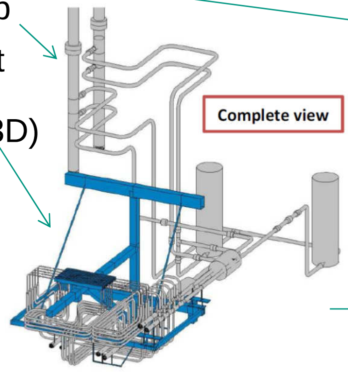
Sequence

- CFD model set-up for one / two channels
- Reduction to simplified model – system code
  - ➡ *Verification*
- Experimental development
  - Design of the test mock-up
  - Isothermal validation
- Integration in the helium loop
- Full scope single experiment
- System analysis (RELAP5-3D)
- Full 3D safety analysis
  - ➡ *Validation*









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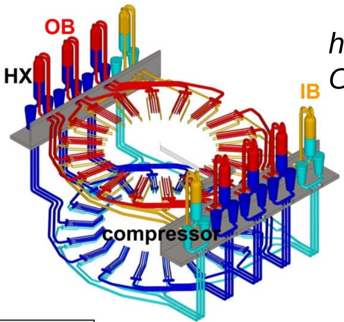
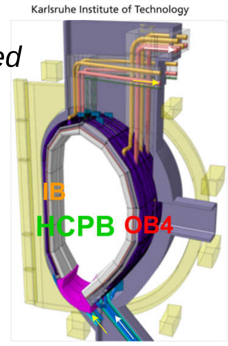
In-box / in-vessel LOCA using MELOCR186 for fusion

Karlsruhe Institute of Technology

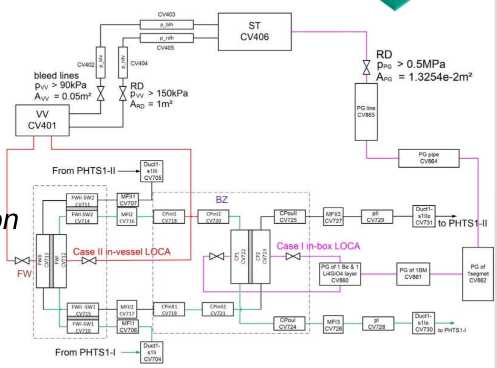
- Started with HCPB 2014
- HCPB 2015 integrated in one OB loop of the PHTS
  - break sizes of the FW / CP-BZ in one OB4
  - Plasma shutdown conditions



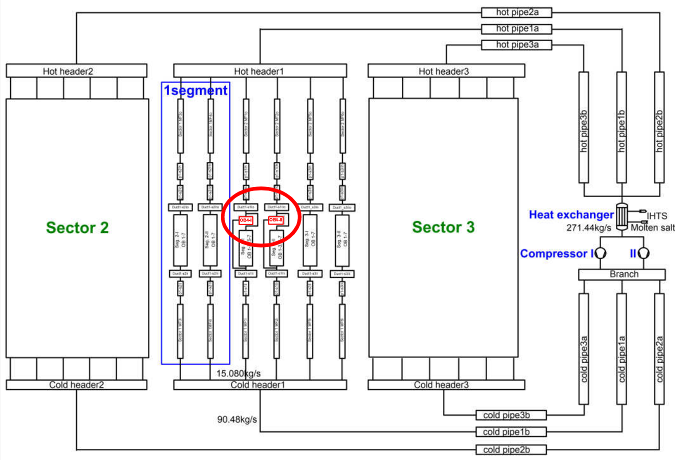
highest loaded OB blanket



One OB4 with LOCA conditions



Integration



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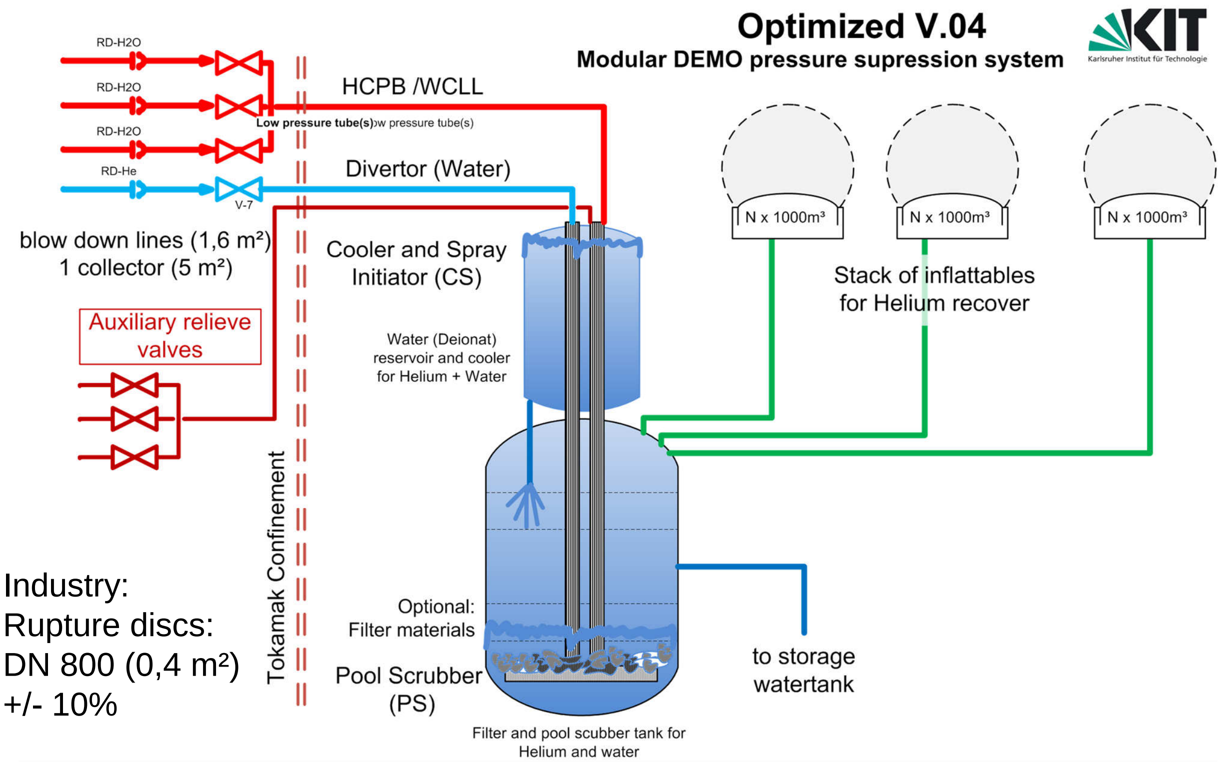
Safety provisions: extended VVPSS + EV



Summary: Requirements for VV safety

1. Eliminate practically the over-conservative 10m² leak (RE) by experiments and/or preemptive measures
2. Define:
   1. 3 blow down channels (size ~1,6 m²)
   2. a corridor like collector ~5m² (can be used for maintenance)
   3. Low pressure zone valves to ESS/VVPSS
3. Investigate segmentation for WCLL PHTS like HCPB
4. Back-up solution: relieve valves:
   Investigate fast acting valves to depressurize PHTS so that the pressure drop in the first wall can be used to reduce the threat to the VV

The worst plasma event due to the runaway electrons

- Affected FW surface area of 10m² in strip form of the toroidal direction: would affect all outboard blankets → all 6 PHTS loops
  → *is considered to be to conservative*

- Heat flux load on the FW due to the plasma disruption power
  → over-pressurization of the vacuum vessel
  → failure of diamond windows of plasma heating system
  → failure of all OB blankets
  ➔ costly repair during long time maintenance

- VV overpressurization presently **not** covered reliably by vacuum vessel pressure supression system plus expansion volume (Water and Helium)

→ To reduce uncertainty → experiments on FW behaviour:

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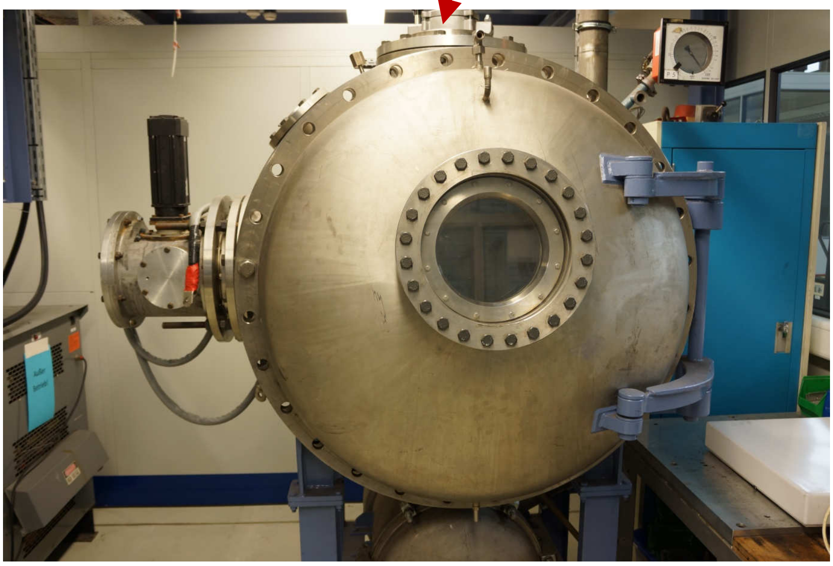
FW failure test set-up

Using prototypic materials and structures of present FW designs:

- FW and Divertor non-failure: E-gun (B. Ghidersa, He-flow)
- FW failure and damage progression (static)

~20 kW



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Summary: safety issues

- He inventory in normal operation
  - one OB loop: 1.5848e3kg
  - 6x OB loop: 9.509e3kg
- EV in failure of one OB loop to confine the final pressure of the in-vessel LCOA at 200kPa (VV pressure limit)
  - Required volume: 12.4 x 10^3 m^3
  - 6x OB loop: 47.6 x 10^3 m^3
- Termination time of the plasma power after the LCOA ?
  → Plasma quench by first ejection of He / steam
- Heat load due to the REs (TOKES) and the affected FW surface area
- Verify & validate the FW temperature
  - 3D thermal analysis (ANSYS)
  - FW failure experiments

Summary and Outlook

Safety

- Interferes with nearly all subsystems of DEMO
- Accidental scenarios during the pulsed operation:
  → need to model the HCPB BB plus associated PHTS and auxiliary systems of BOP using RELAP5-3D
- Update of MELCOR model based one DEMO Baseline 2017
- Check each heat source how it affects safety

Heat transfer and power train

- Update simulation on new designs : 16 sectors , new BB design
- Pulse to dwell time simulation required using RELAP5-3D
- Industry involvement to address component feasibility

That's all for today, Questions?