The computer-aided design of cooling system for MPD detector of NICA

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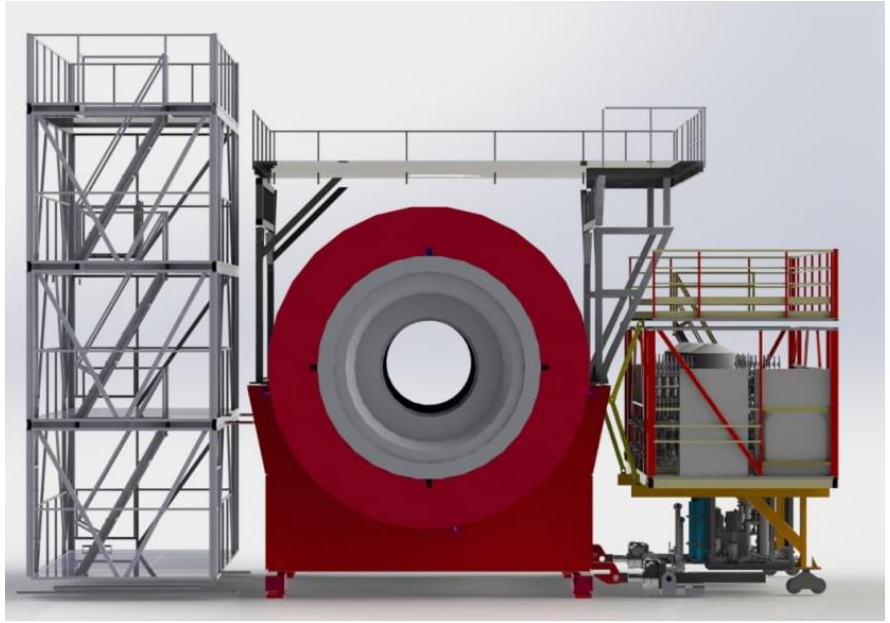
delivered by A.S.Fedotov

The outline

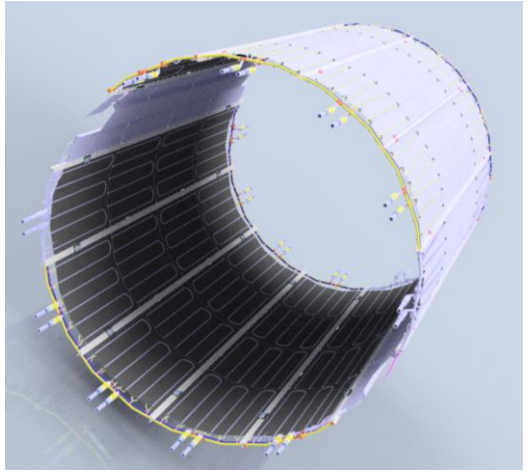
Structure of the talk (30 mins’):

1. Specifics of MPD cooling system design;
2. Finite-element modelling;
3. Model for control systems;
4. Verification results;
5. Conclusions and upcoming challenges;
6. Gratitudes.

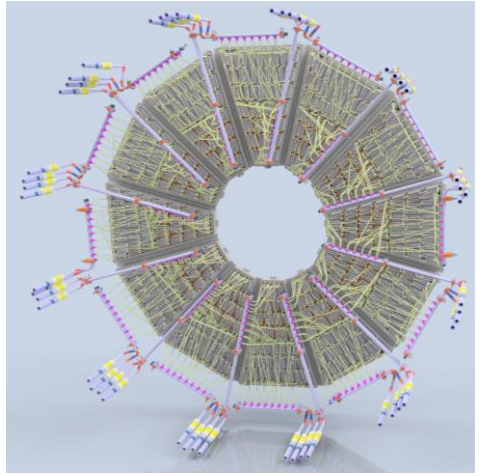
The systems



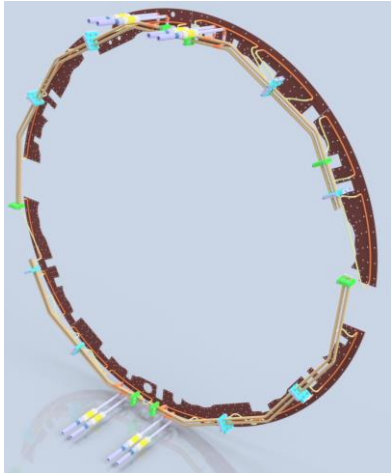
MPD setup concept



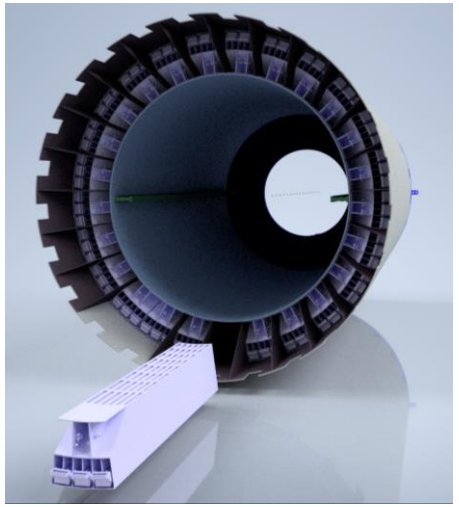
Outer thermal screen



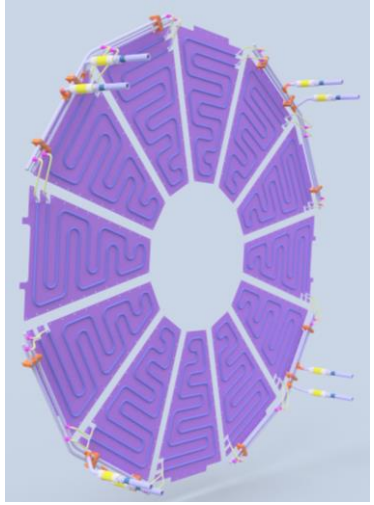
SAMPA & FEC electronics + ROC cases



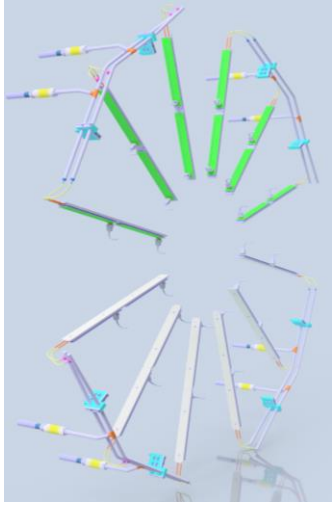
Flanges



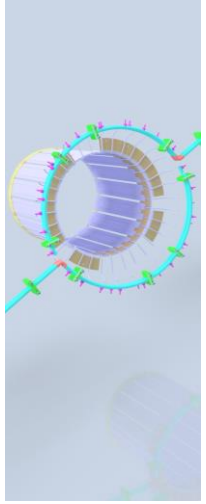
ECAL



Frontal thermal screen



LVDB and reading controllers



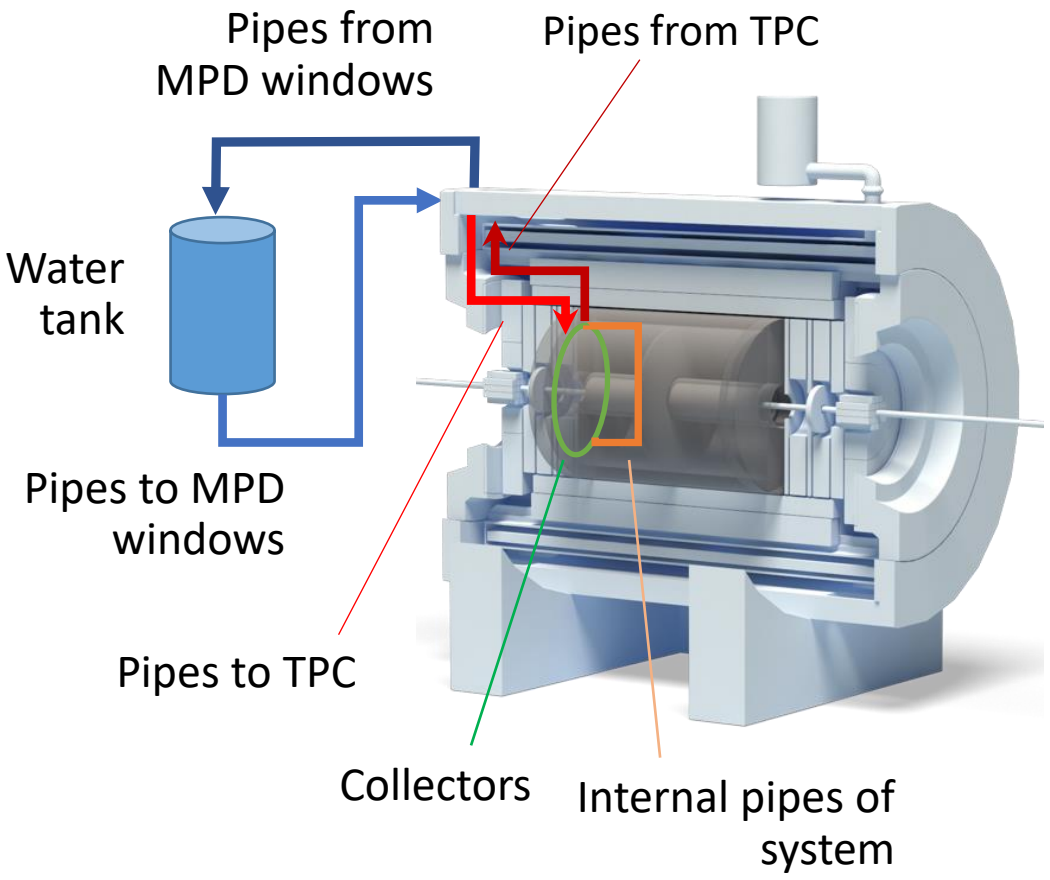
Internal thermal screen

The goal and the scheme

- The **goal** is to provide water supply both to cooling and thermostabilization systems;

Cooling: FPGA, ECAL, LVDB

Thermostabilization: SAMPA, ROC cases, Outer thermal screen, Internal thermal screen, Flanges



Principal scheme of cooling design

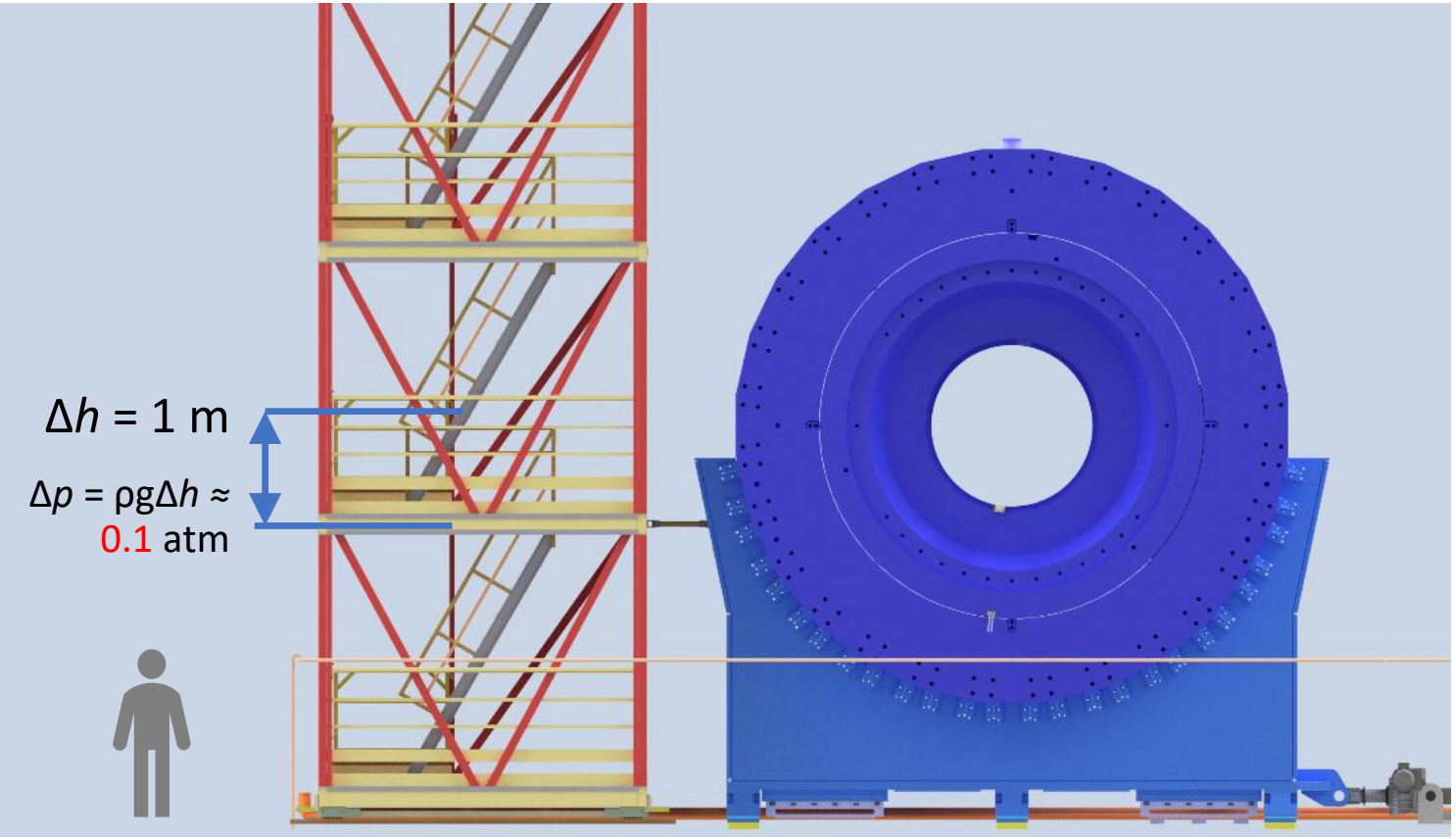
The challenge

Leakless regime of operation requires absolute pressure in TPC & ECAL < 1 atm.

- Each meter of water column adds or substracts about 1⁄10 atm;
- Height of MPD ≈ 8 m;

- Pressure higher than 1 atm may cause leak;
- Pressure lower than 0.1 atm may cause stagnation or cavitation.

Need to simulate the flow in details!



The model for physics

Navier-Stokes equations for pipes:

$$\begin{cases} \dfrac{\partial \vec{u}}{\partial t} + (\vec{u}\cdot\nabla)\vec{u} = -\dfrac{\nabla P}{\rho} - \dfrac{1}{2} f \dfrac{|u|\vec{u}}{D} + \vec{g} \\ \dfrac{\partial \rho}{\partial t} + \nabla\cdot(\rho\vec{u}) = 0 \\ \rho c_l \left(\dfrac{\partial T_l}{\partial t} + \vec{u}\cdot\nabla T_l \right) = \nabla\cdot\left(\lambda_l \cdot \nabla T_l\right) + \dfrac{1}{2} f \dfrac{\rho |u| \vec{u}}{D} + Q_{\text{wall}} \\ \rho c_s \dfrac{\partial T_s}{\partial t} = \nabla\cdot\left(\lambda_s \cdot \nabla T_s\right) + Q_{\text{heat}} \end{cases}$$

$\vec{u}$ – velocity,
P – water pressure,
T_l – water temperature,
T_s – solid body temperature,
λ – heat conduction coefficient,
c – heat capacity,
Q – heat source,
g – gravity constant,
ρ – density,
D – pipe diameter,
f – Darcy factor.

Colebrook-White equation for Darcy factor:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{f}} \right)$$

Re – Reynolds number;
ε – roughness of pipe walls.

Pressure drop from an elbow:

$$\Delta p = \frac{1}{2} K_f \rho u^2$$

K_f – loss coefficient.

The computations

Example of SAMPA boundary value problem

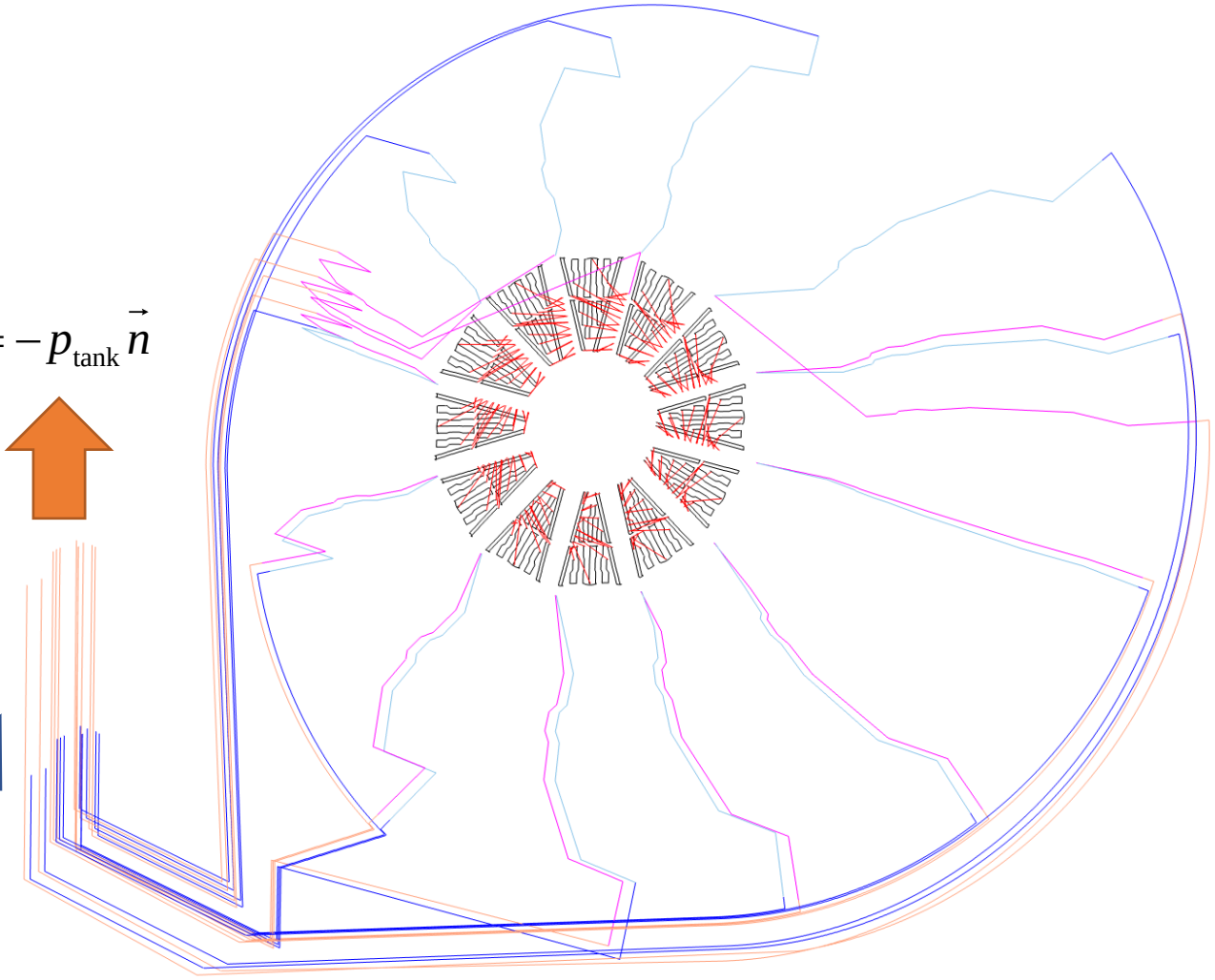
Outlet: $$\begin{cases} \left(-p\mathbf{I} + \mu\left(\nabla\vec{u} + (\nabla\vec{u})^T\right)\right)\vec{n} = -p_{\text{tank}}\vec{n} \\ p_{\text{tank}} = 0.35\ \text{atm} \end{cases}$$

Inlet: $$-\rho\frac{\pi D^2}{4}\vec{\mathrm{u}}\cdot\vec{n} = \dot{m}$$

Mass flow rate $\dot{m}$ is known from technical specifications

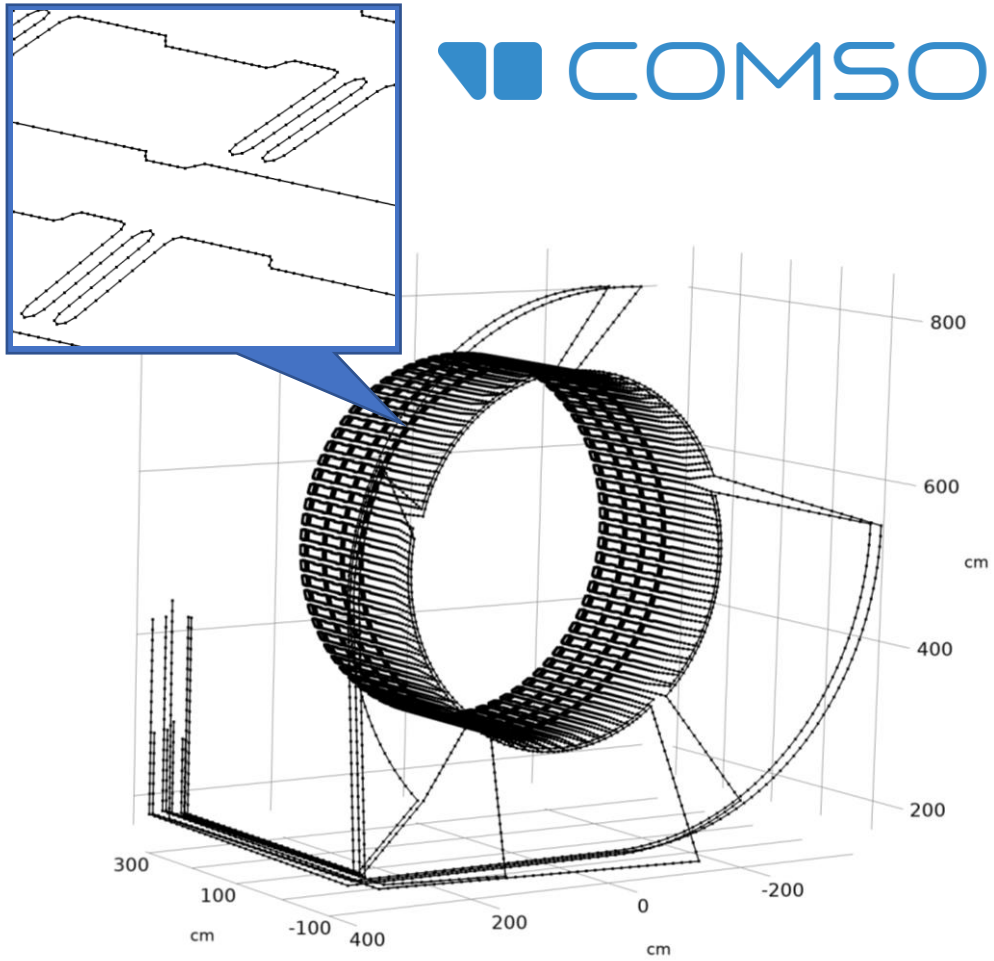
We explore for **two questions**:

- What pressure must be supplied to the inlet?
- Will it be in 0.15 atm < p < 1 atm range?



Example of SAMPA boundary value problem

The computations



Example of ECAL mesh
(similar for each of 8 systems)

- Finite-element method with 2nd-order polynomial approximations;
- Computational domain graphs was created by handwritten scripts with possibility of quick rearranging;
- Pressure difference is taken into an account:
  - **Hydrostatic** difference;
  - Pressure loss due to **wall friction**;
  - Local pressure drops from **elbows**.

The internal thermal screen

Computational study report:

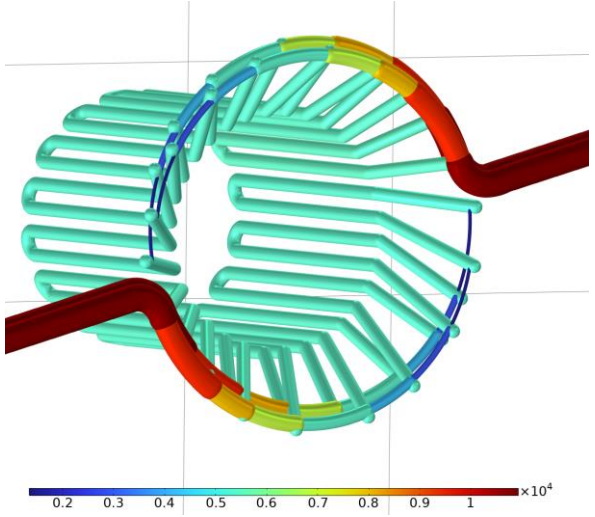
Parameter	Value
Pipe diameter tank-MPD	20 mm
Pipe diameter MPD-tank	20 mm
Pipe diameter MPD-TPC	20 mm
Pipe diameter TPC-MPD	20 mm
Volume flow for whole system	2 m^3/h
Tank upper collector height h_{c-u}	4.1 m
Tank lower collector height h_{c-d}	2.6 m
Pipe roughness ε	0.046 mm

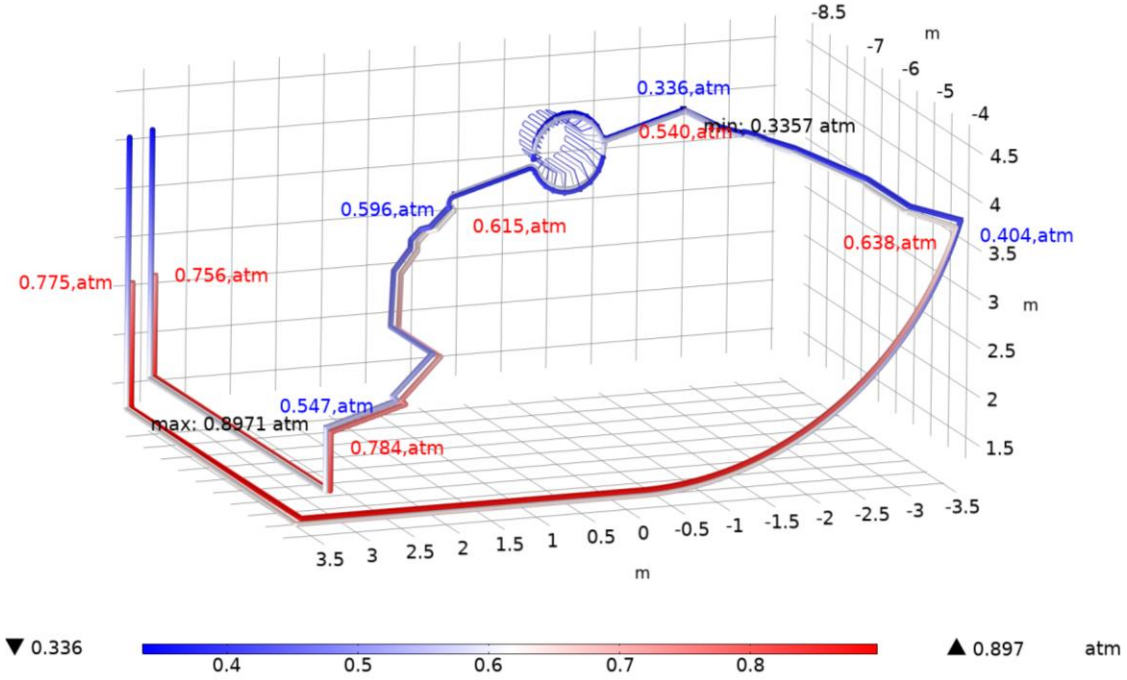
Boundary condition	Value
Volume flow per 1 subsystem	0.5 m^3/h
Pressure in tank p_{tank}	0.35 atm

Found from model	Value
Pressure at entrance to subsystem I p_{itsI}	0.775 atm
Pressure at entrance to subsystem II p_{itsII}	0.756 atm
Reynolds number Re	$5 \cdot 10^3$

Desired volume flow 2 m^3/h is achieved (may reach up to 2.8 m^3/h) for pressure in 1 atm range

Reynolds number:

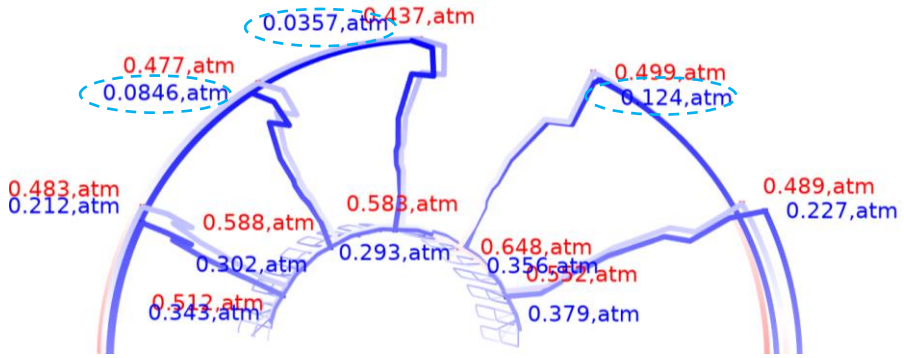




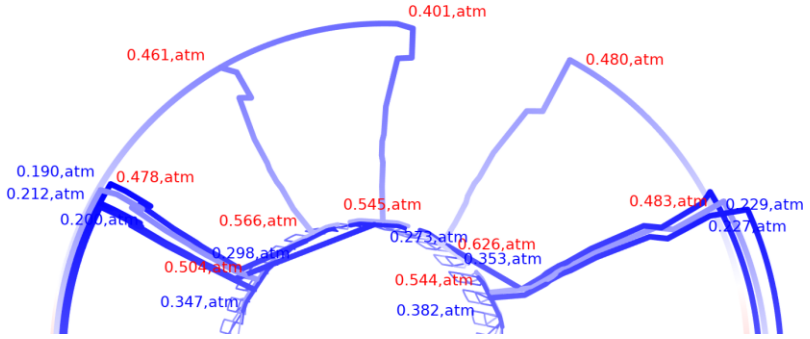
Absolute pressure distribution

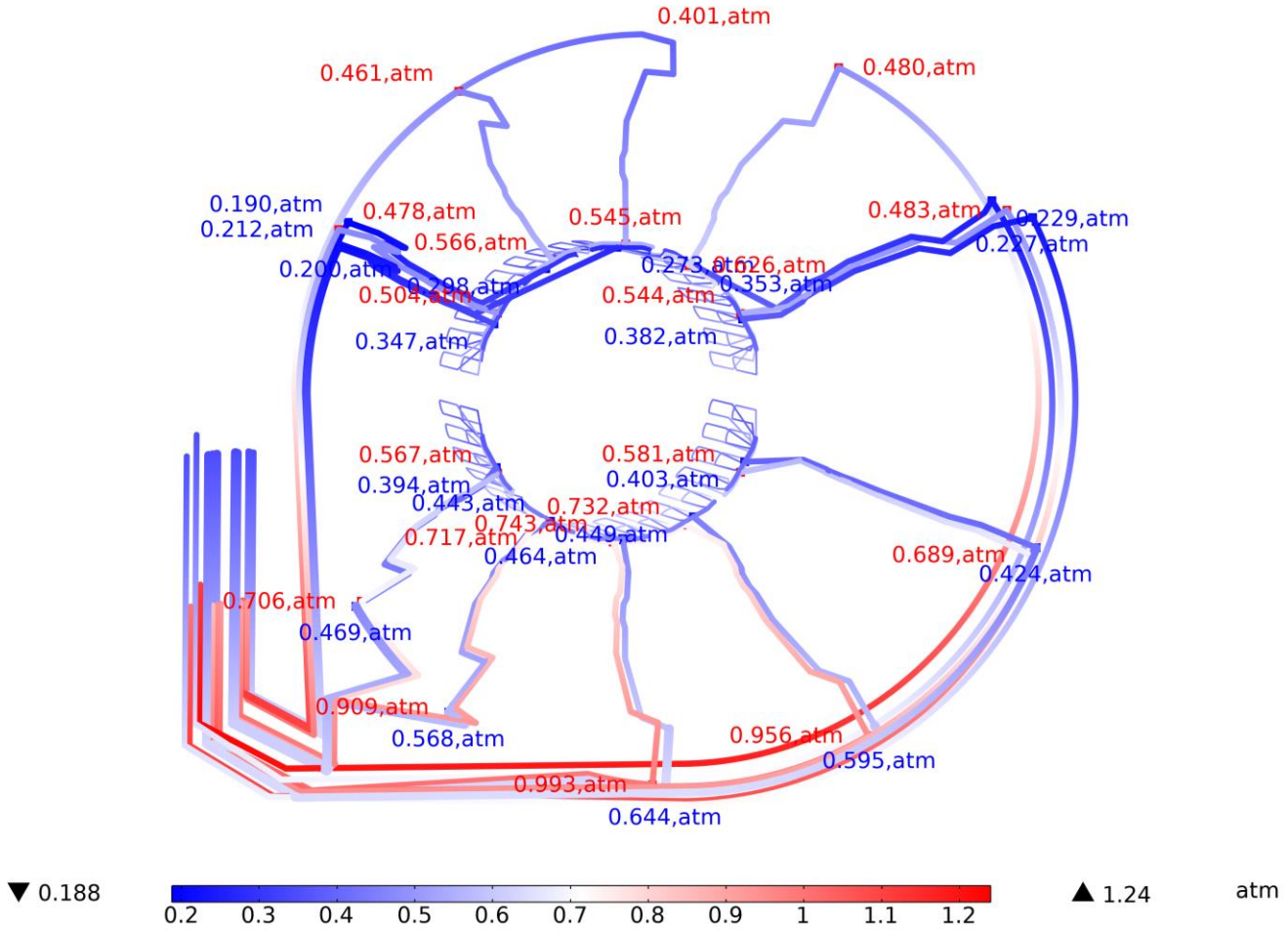
The outer thermal screen

Initial concept: “same MPD window for enter and exit of pipes” – too low pressure on return



New concept: “return pipes in upper part go to side windows” – pressure is OK

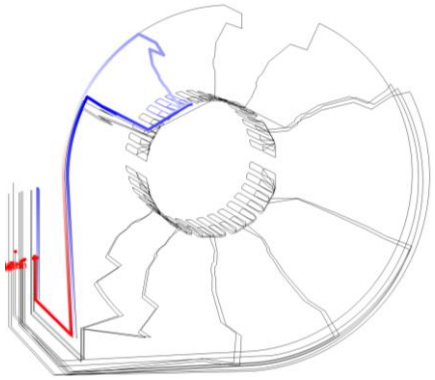




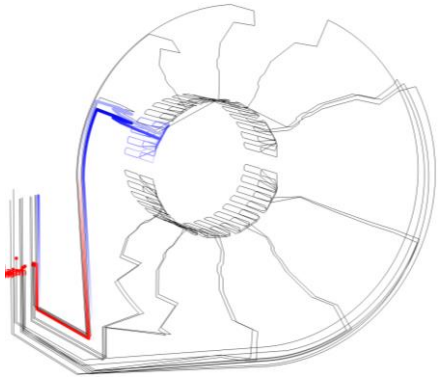
Absolute pressure distribution in new concept

The outer thermal screen

Two types of subsystems:

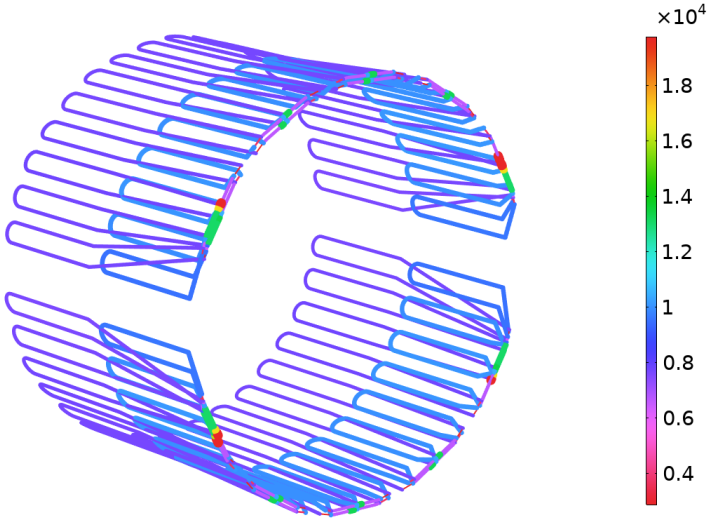


4-panel subsystem

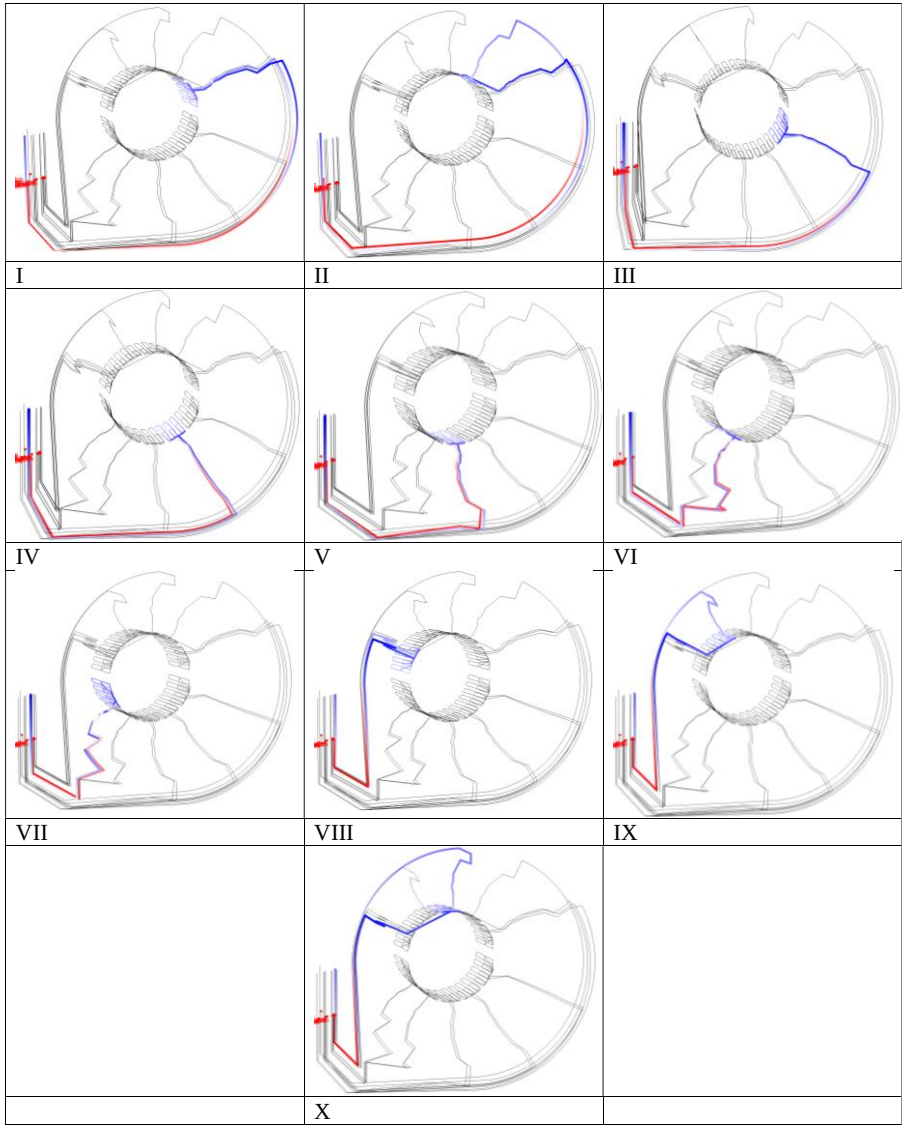


3-panel subsystem

Pressure was optimized for each subsystem to achieve same Reynolds number & cooling efficiency
(table in additional slides)

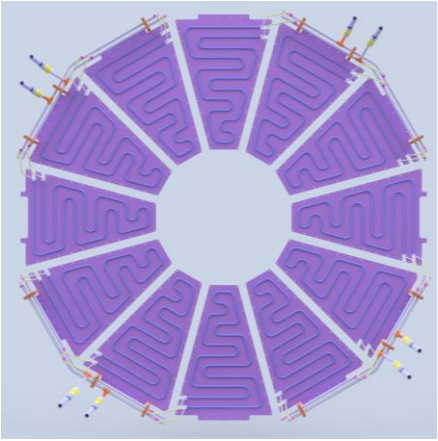


Reynolds number

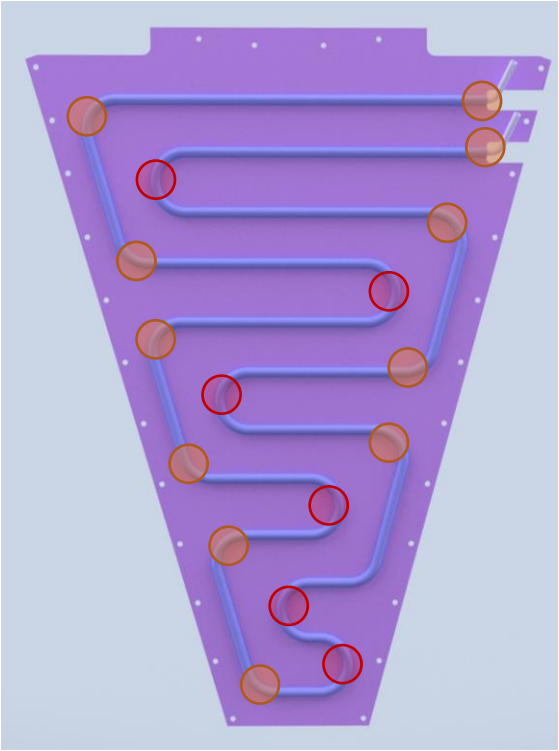


10 subsystems per side

The frontal thermal screen



Frontal thermal screen



Single panel

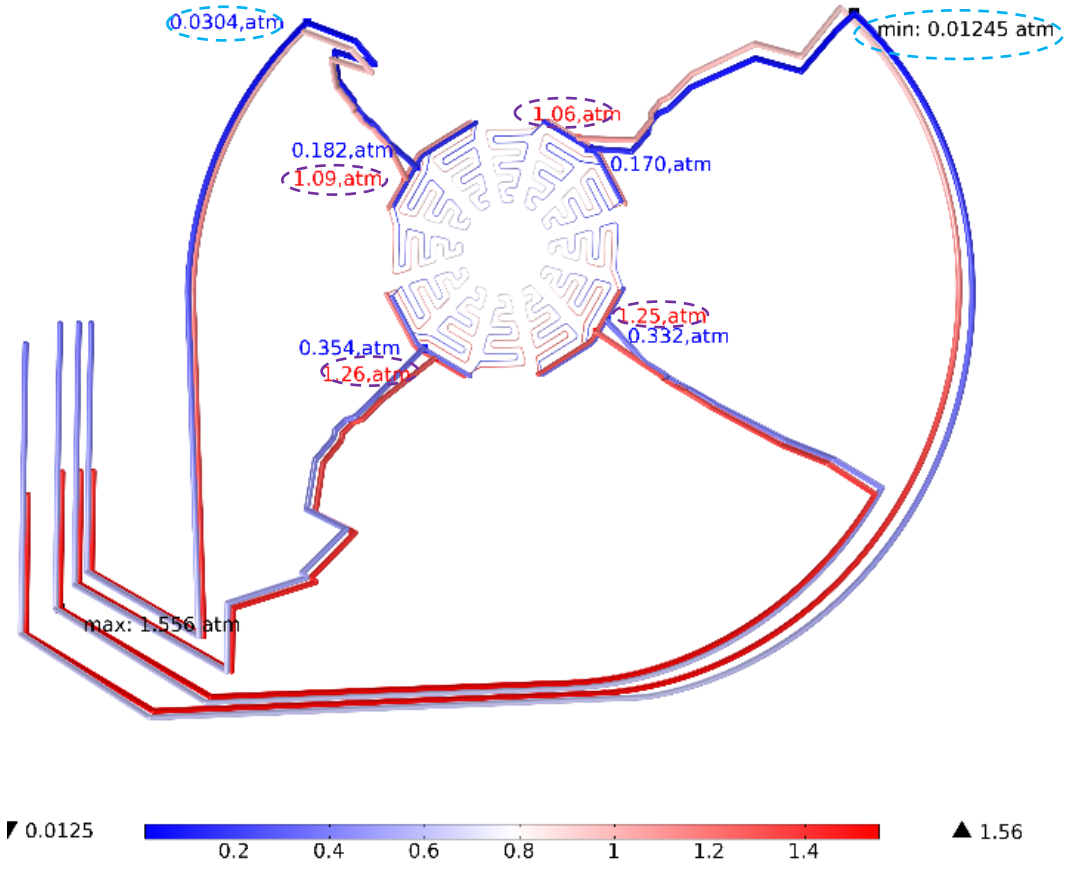
High losses in panels:

6 elbows of 180° and

11 elbows of 90°

Flow per manifold = 0,25 m^3/h

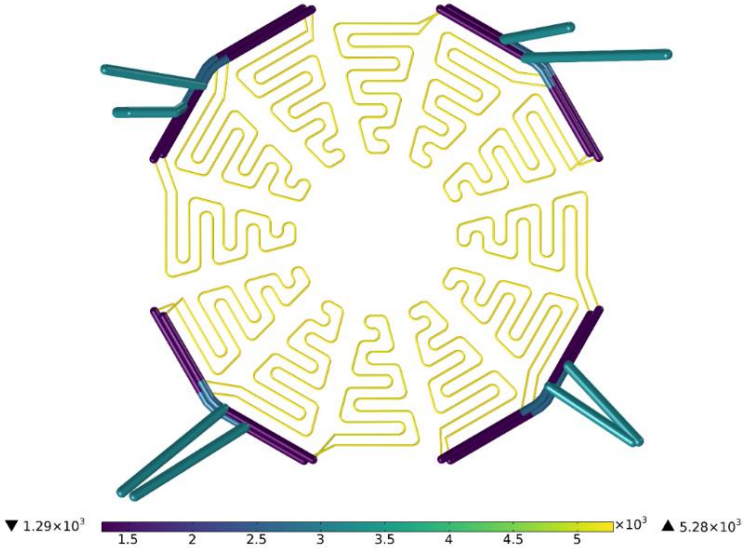
Initial concept: “same MPD window for enter and exit of pipes” – too low pressure on return and leakless is violated!



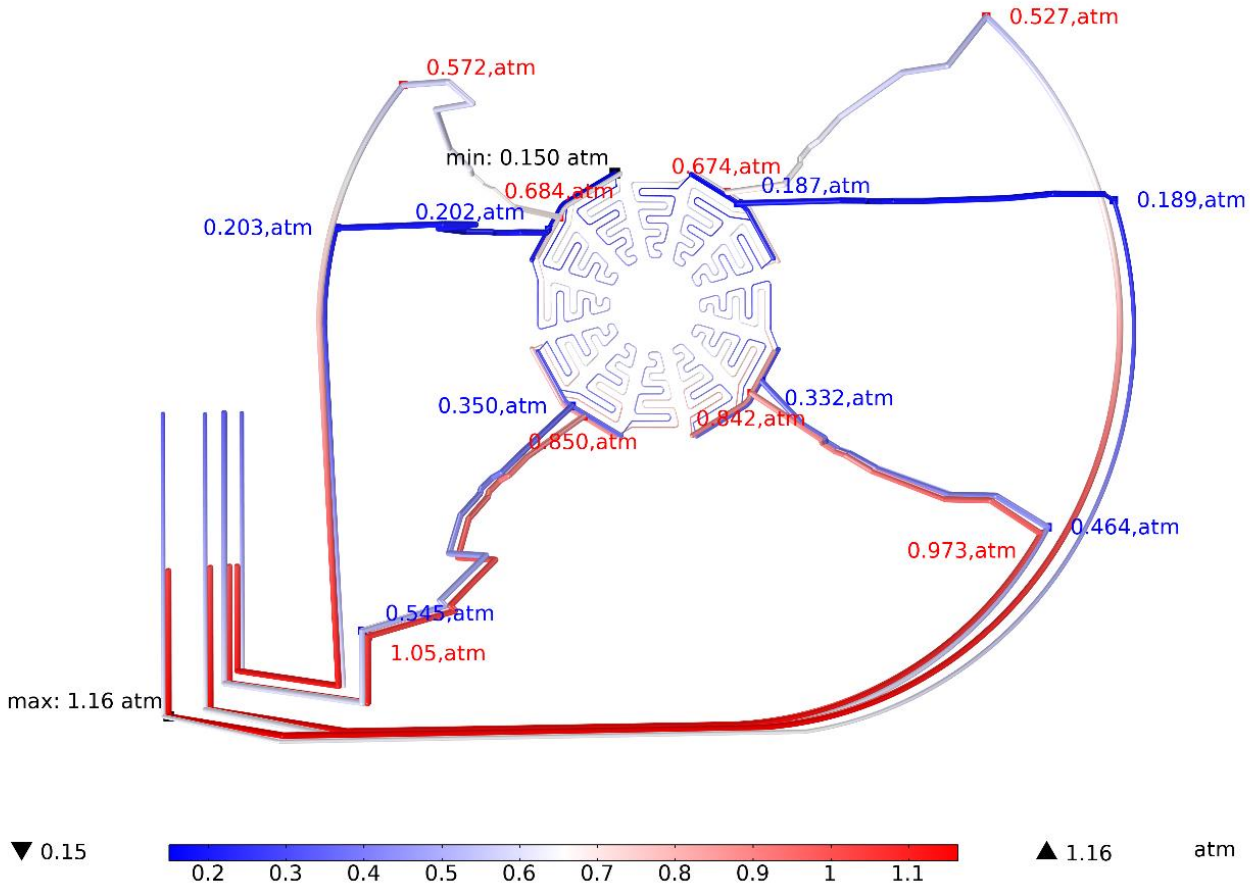
The frontal thermal screen

New concept:

1. Increase pressure on return by using side windows and narrow pipes on MPD-tank line (14 mm);
2. Decrease flow from 0.24 m^3/h to 0.18 m^3/h



Reynolds number

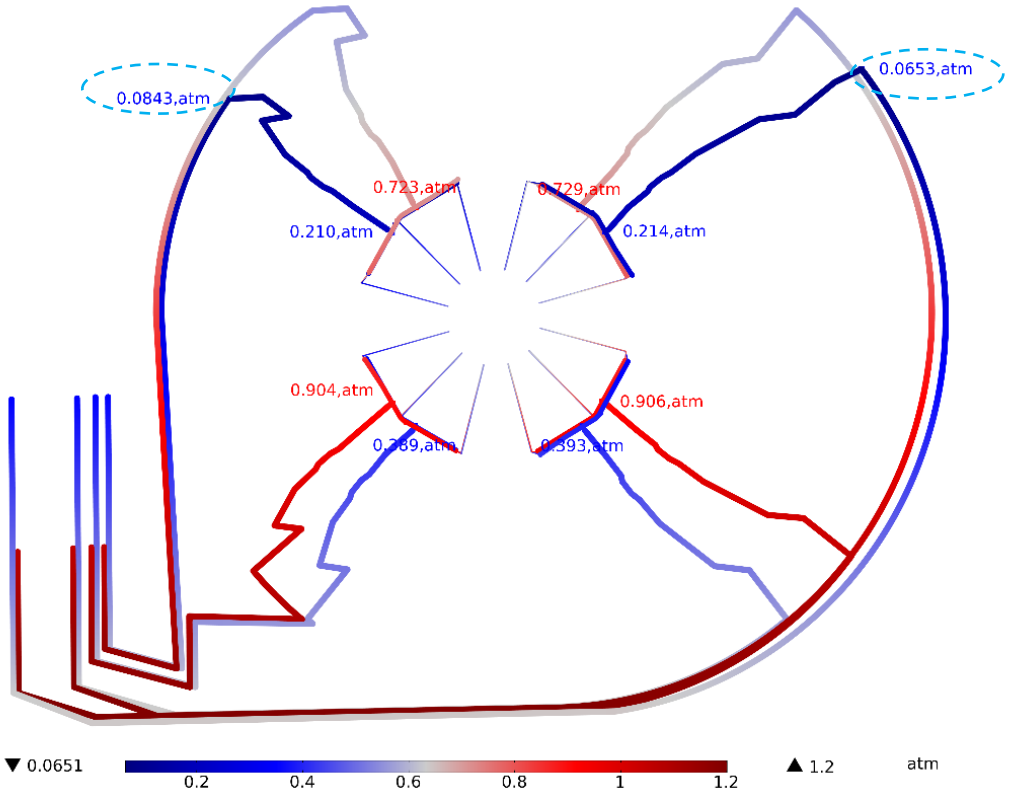


Absolute pressure distribution in new concept

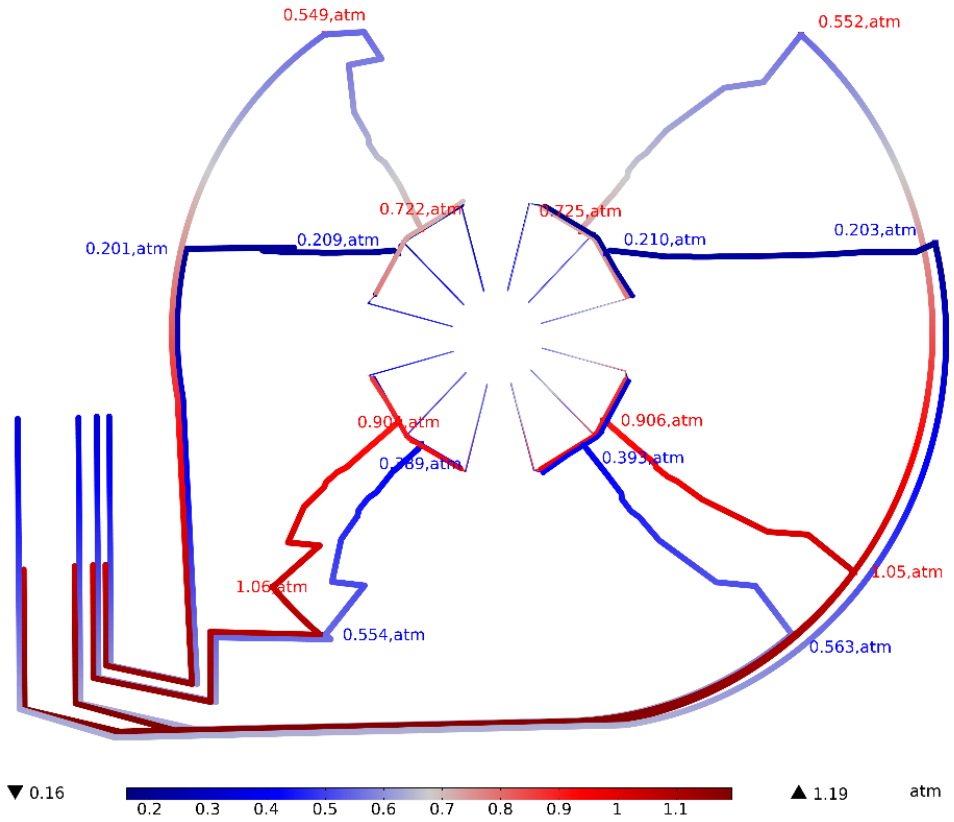
Ergo: forced to decrease volume flow due to resistance of screen panels, still Reynolds number is $5.3 \cdot 10^4$

The LVDB

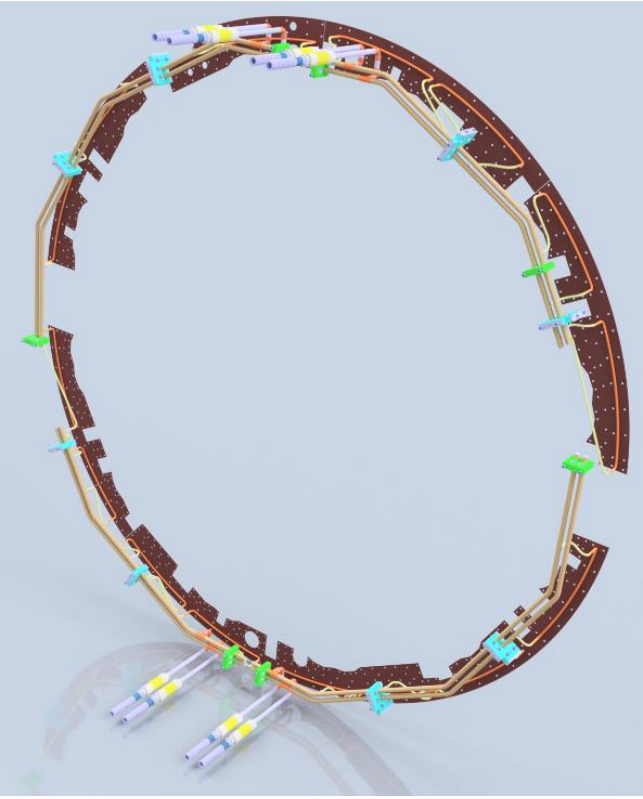
Initial concept: “same MPD window for enter and exit of pipes” – too low pressure on return



New concept: “return pipes in upper part go to side windows” – pressure is OK

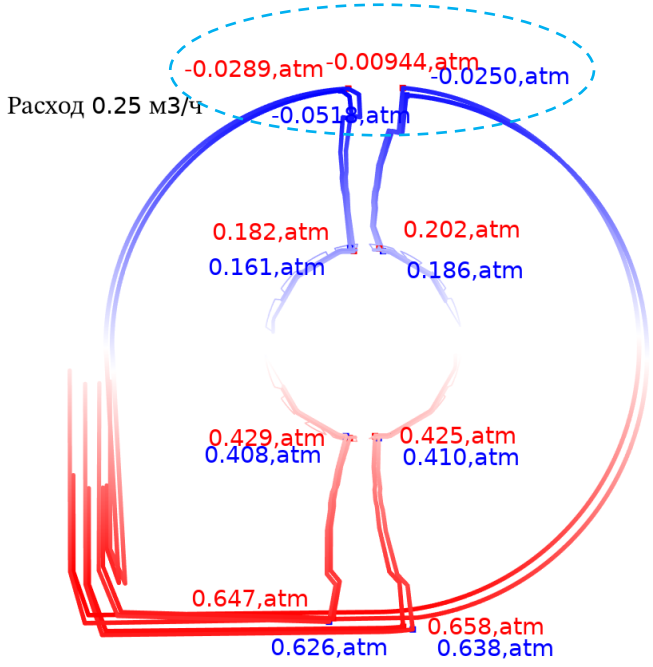


The flanges

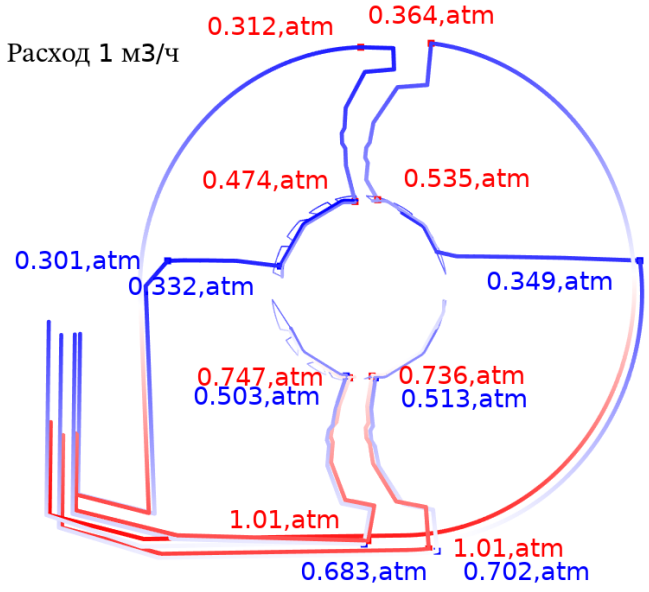


Flange pipes & plate

Initial concept: flow 0.25 m^3/h per single manifold – too low pressure both on enter and return!



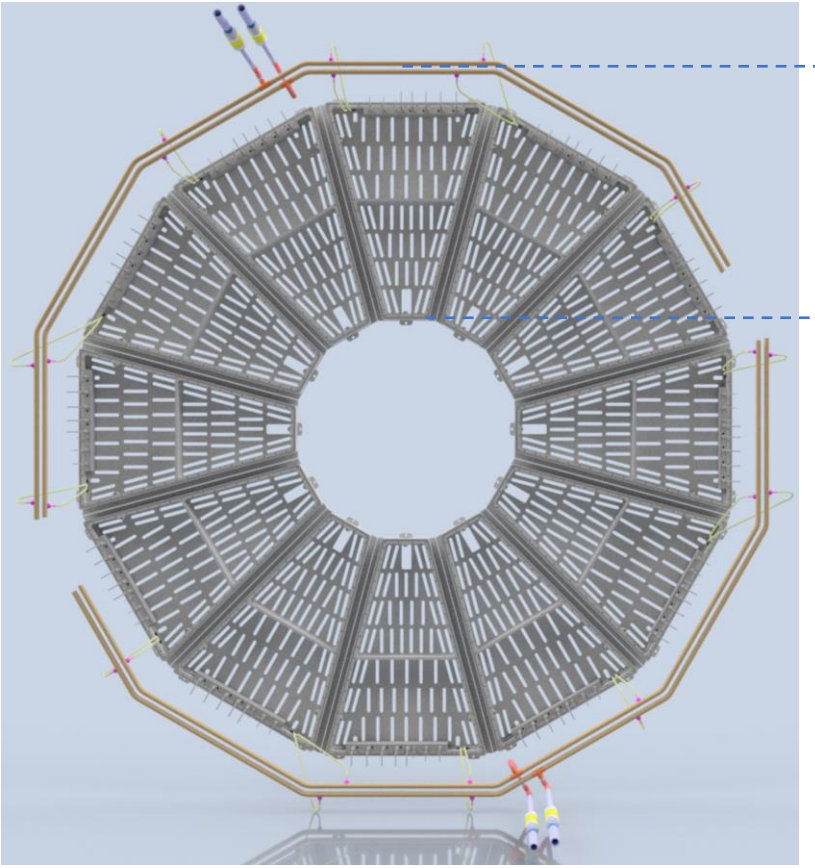
New concept: “return pipes in upper part go to side windows” and increase flow up to 1 m^3/h – pressure is OK



Ergo: increase of flow (up to 1.38 m^3/h) and rearranging return pipes in upper half with Re $2\cdot10^4$

The ROC cases

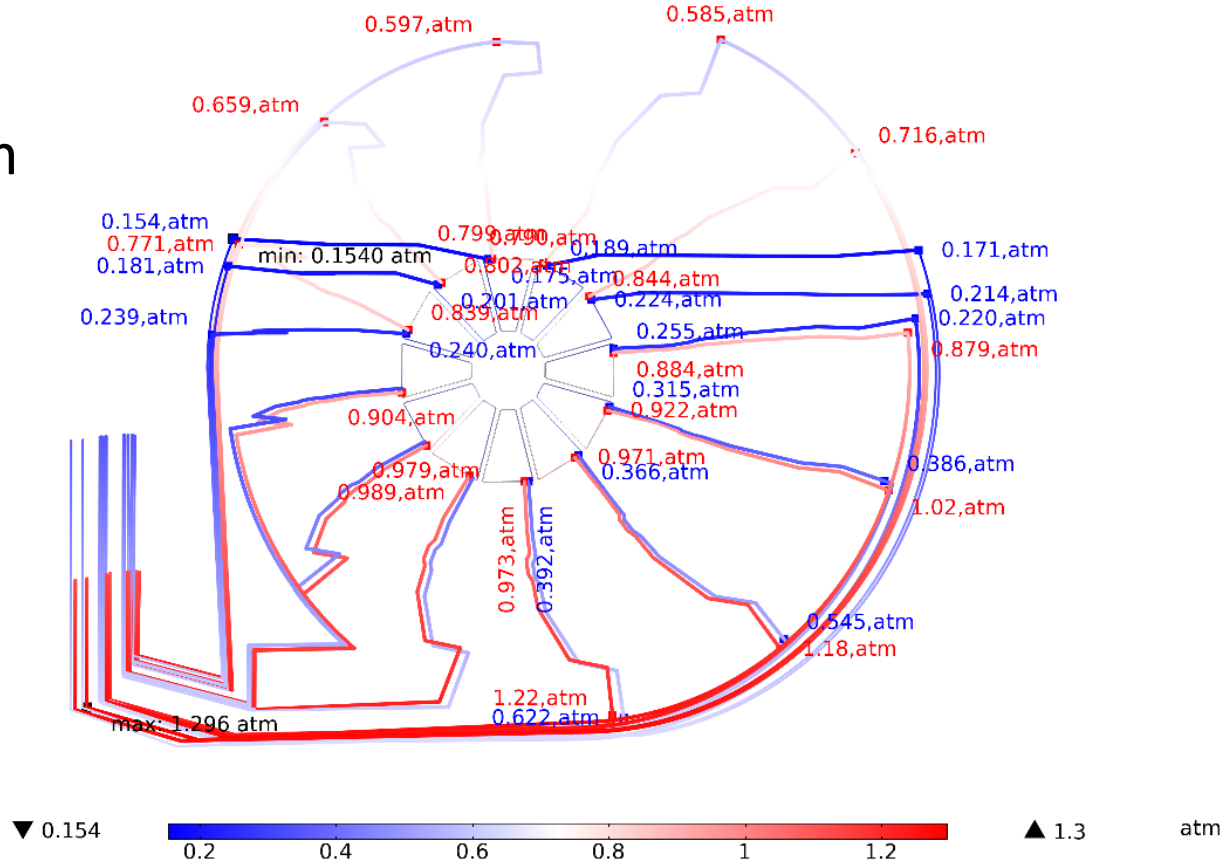
Initial concept: large manifolds (6 ROC each) make impossible to ensure proper pressure regime for every ROC



0.15 atm

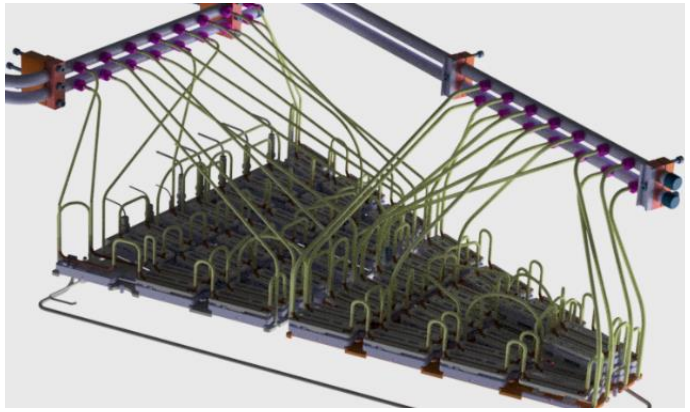
New concept:

1. individual water supply with no manifold;
2. return pipes in upper part go to side windows.



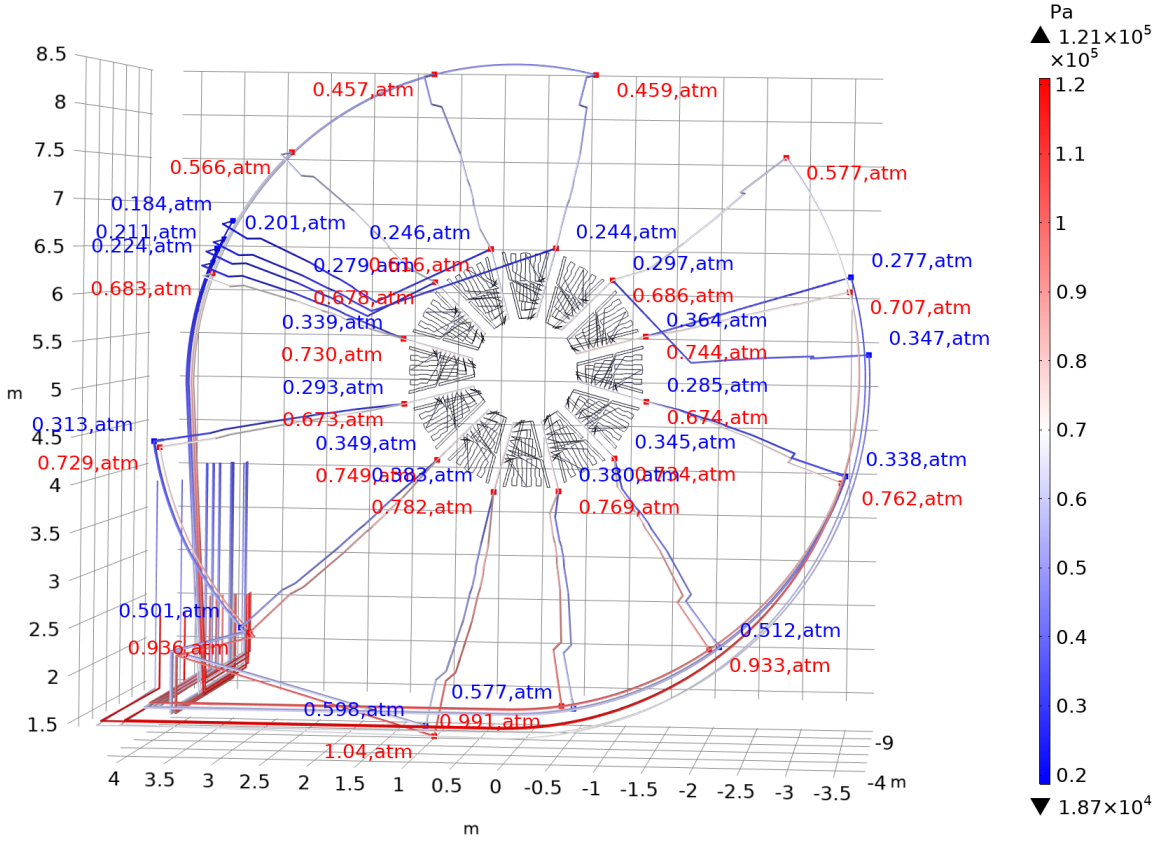
The FPGA & SAMPA electronics

Initial concept: united in same manifolds, which does not allow to distinguish cooling (FPGA) and thermostabilization (SAMPA)



New concept:

1. Separate FPGA & SAMPA;
2. Return pipes in upper part go to side windows.



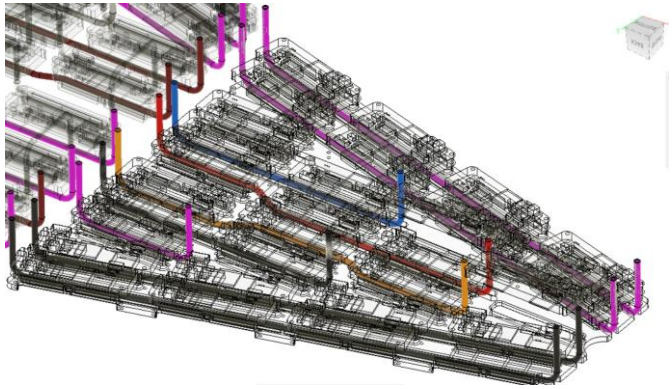
Pressure distribution in SAMPA thermostabilization system

It is possible to increase volume flow for SAMPA from 0.23 up to 0.6 m^3/h !

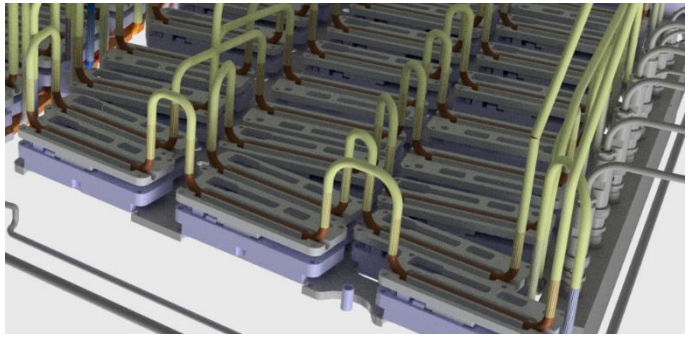
The FPGA & SAMPA electronics

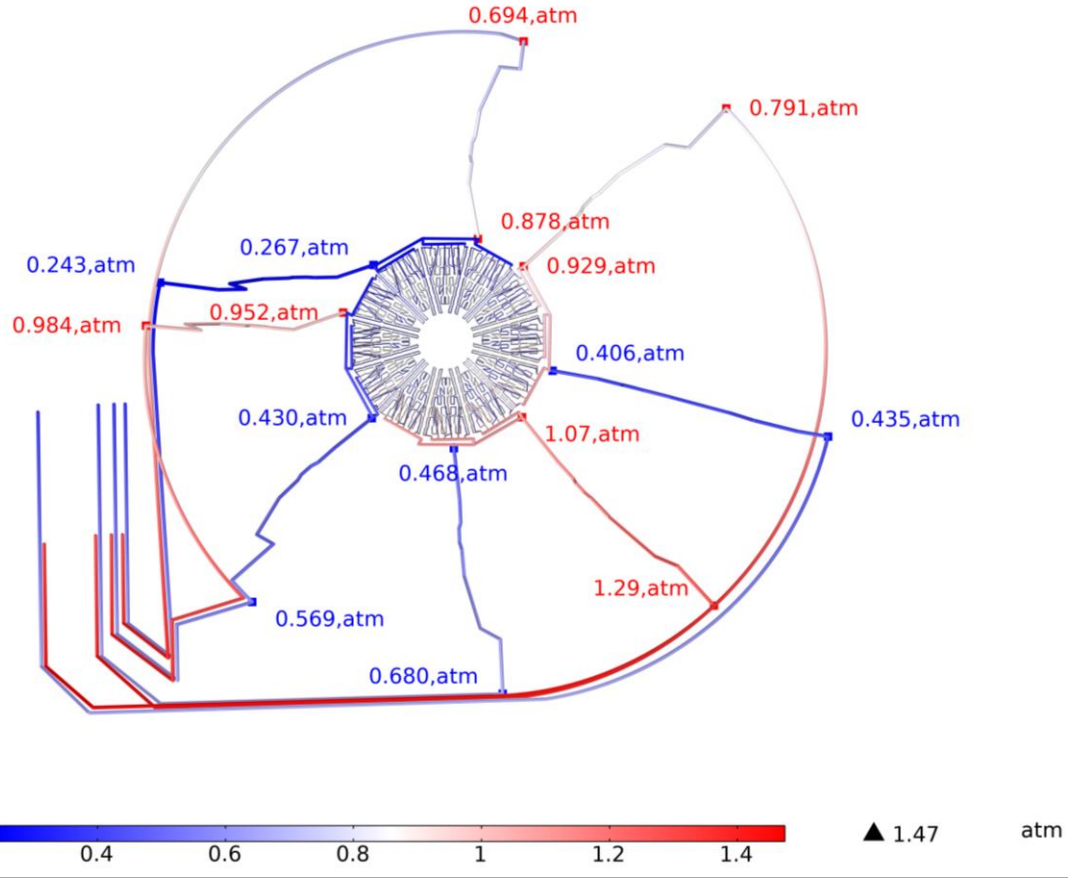
FPGA has higher flow resistance

SAMPA system:
long straight pipes



FPGA system:
short pipes and lot of fittings

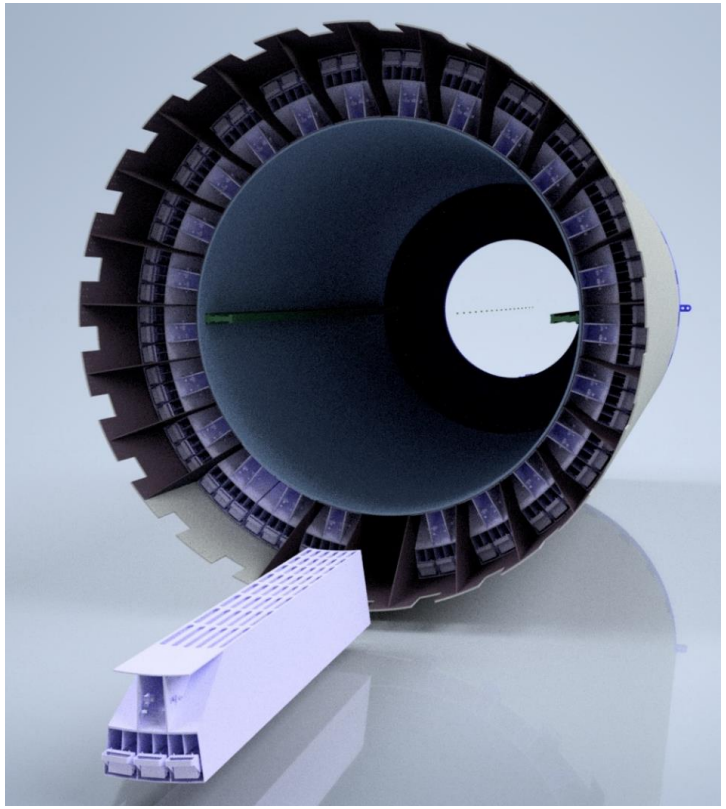




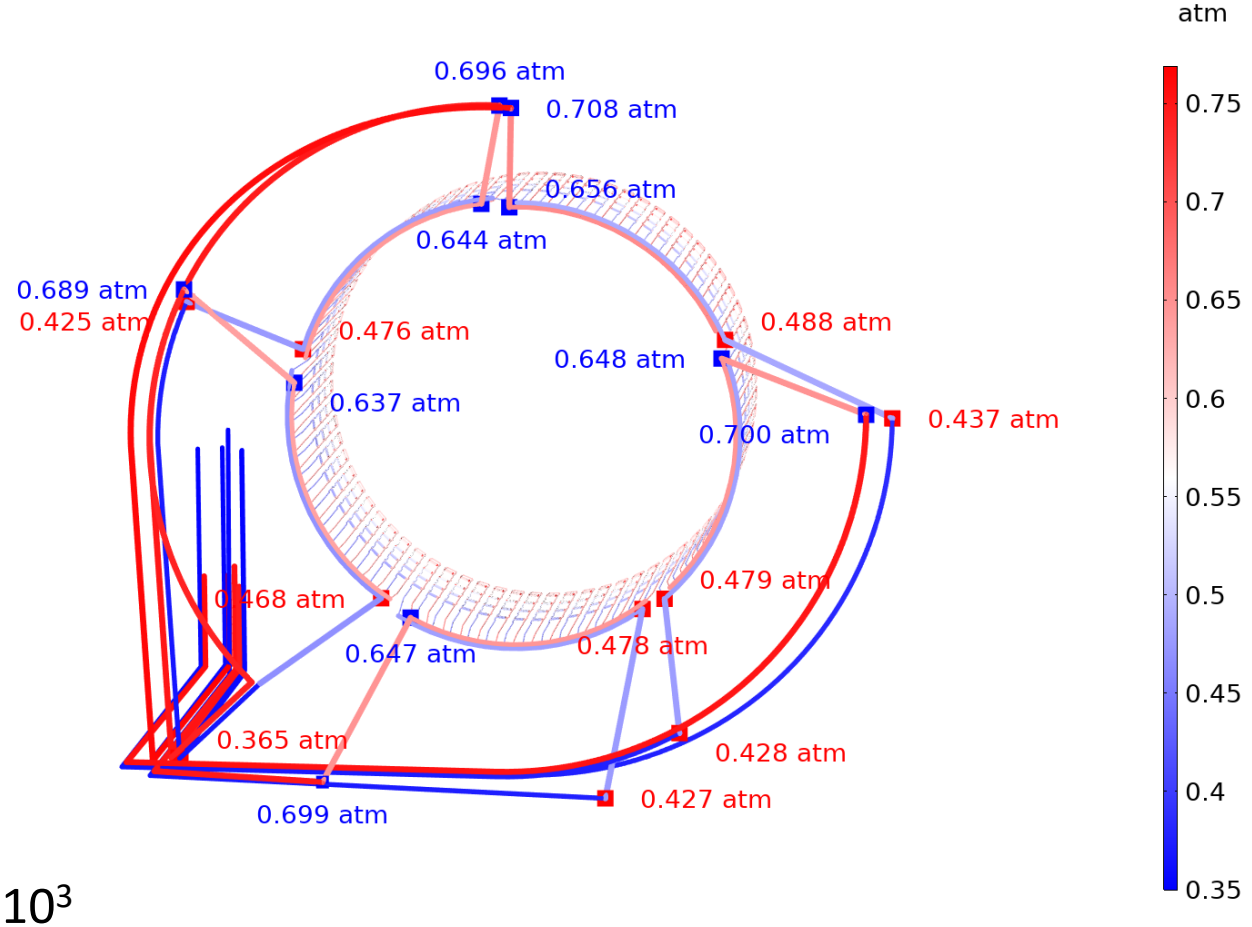
Due to high FPGA flow resistance lower subsystem is at 0.79 m^3/h while others meet target specification was 0.84 m^3/h

The ECAL

Initial concept: no manifolds



New concept: 5 manifolds to save space in windows



ECAL works in nominal regime at Re $2 \cdot 10^3$

The model for engineering

Mass conservation equations

$$\Delta p_{f,A} = \frac{64\nu}{2D^2 S}\frac{L + L_{add}}{2}\dot{m}_A$$

$$\Delta p_{f,B} = \frac{64\nu}{2D^2 S}\frac{L + L_{add}}{2}\dot{m}_B$$

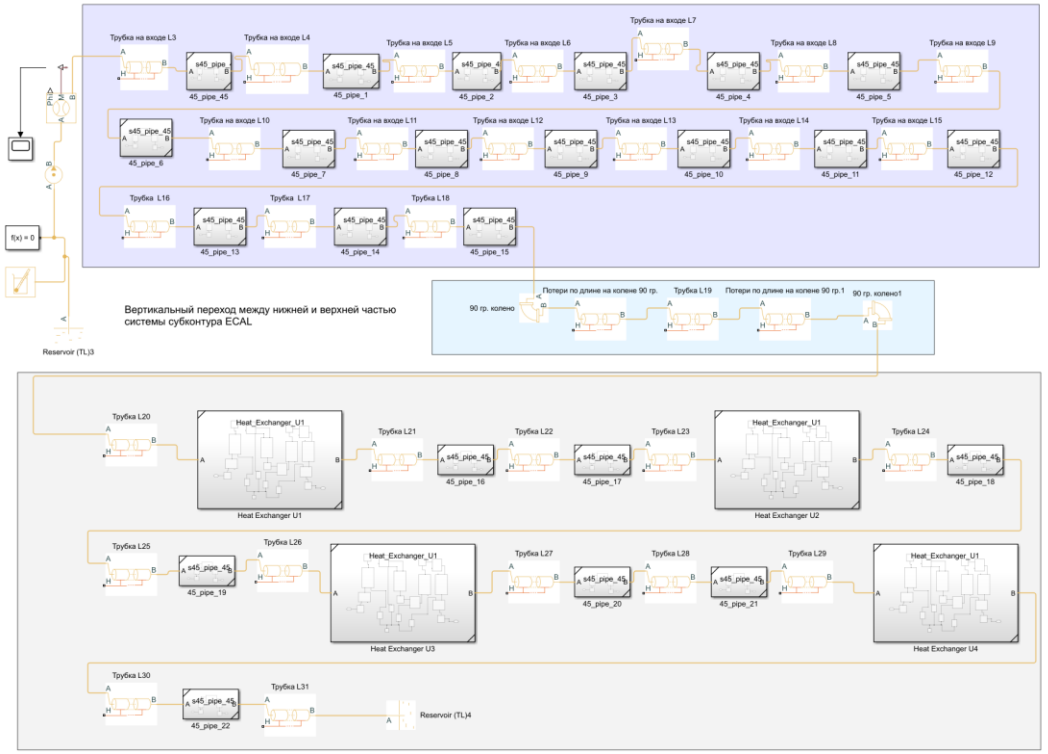
$$\dot{m}_A + \dot{m}_B = 0$$

$\dot{m}_A$ – mass flow rate at the entrance,
$\dot{m}_B$ – mass flow rate at the exit,
$\Delta p_{f,A}$ – pressure drop at the entrance,
$\Delta p_{f,B}$ – pressure drop at the exit,
υ – kinematic viscosity,
D – pipe diameter,
L – pipe length,
L_{add} – equivalent length for local losses

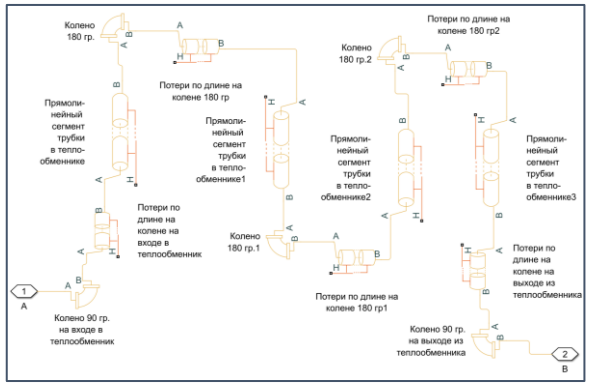
Systems of ordinary differential equations are solved with Matlab Simulink (Simscape).

- Additional verification of finite-element simulations;
- Easier-to-handle engineering model for virtual testing of equipment;
- Automatics can be added to model.

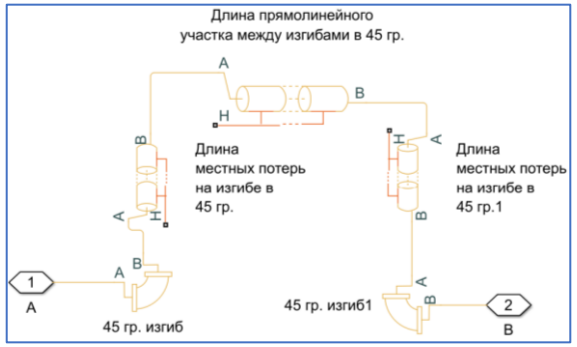
The example of single subsystem



Equivalent fluid dynamics scheme of ECAL panel

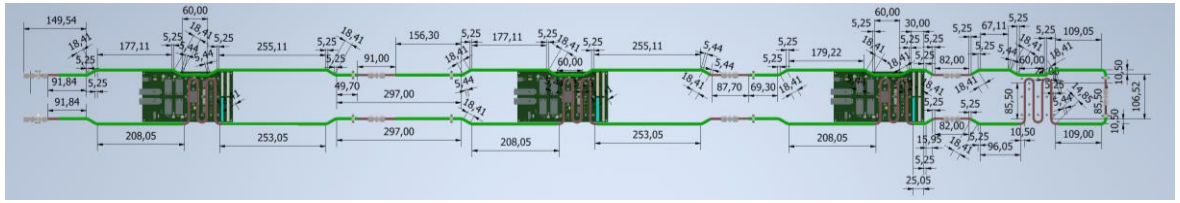


ECAL heat exchanger subsystem



ECAL elbow subsystem

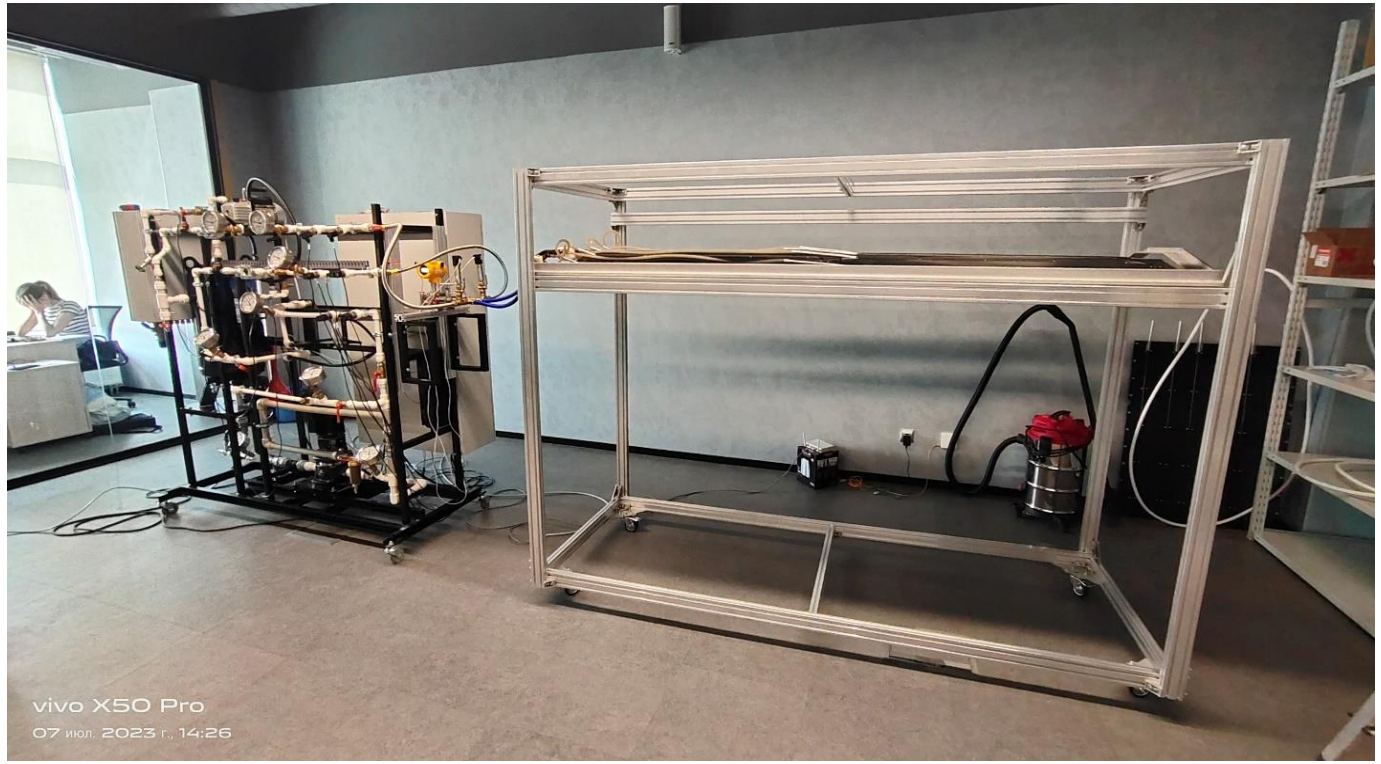
For ΔP = 0.12 atm
Mass flow from technical specifications: 0.006 kg/s
Mass flow from COMSOL: 0.0059 kg/s
Mass flow from Simscape: 0.0057 kg/s



Geometry of ECAL panel

The experiment

Experimental setup



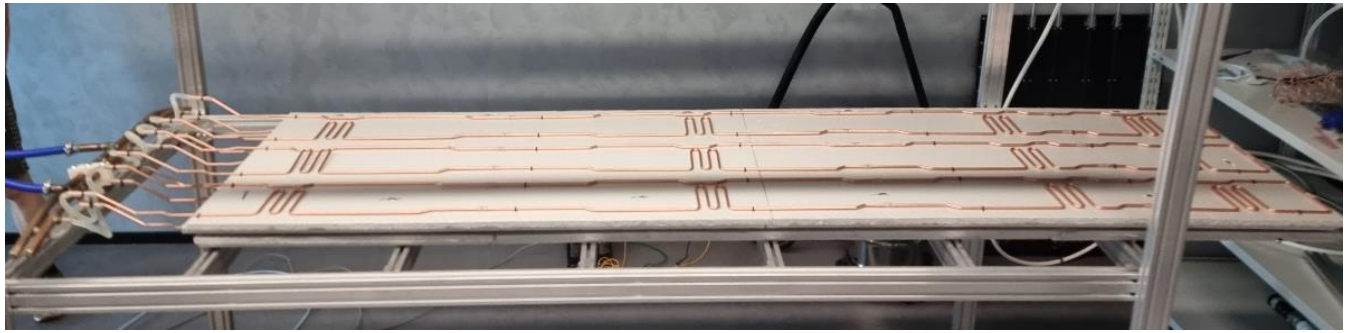
Touch panel of data logger

Equipment:

- Pump Wilo MHIL903-E-3-400-50-2/IE3, Q=16 m^3/h;
- Flowmeters SV3150 and F608 Flexus;
- PC-28 pressure sensors.

The experiment

ECAL (6 panels)

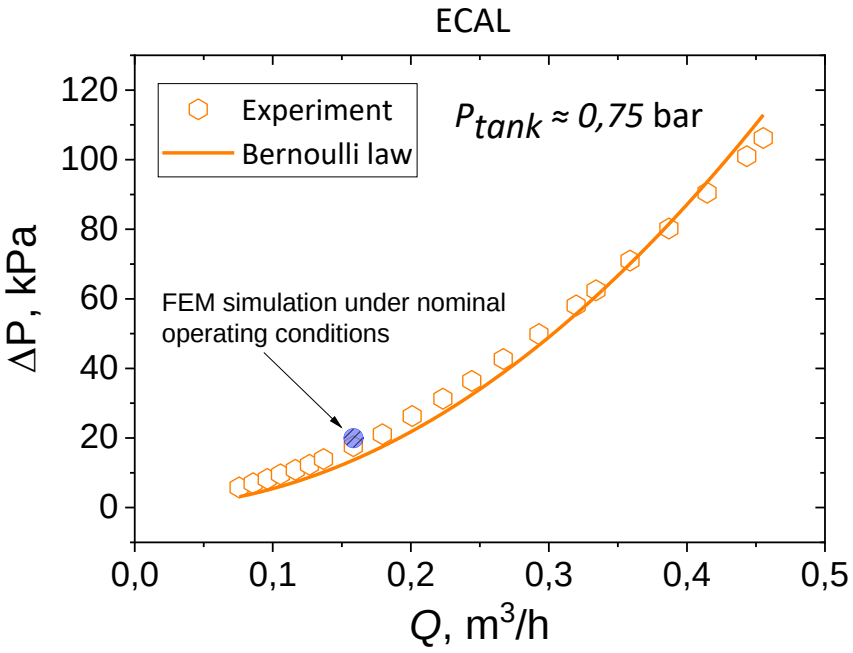


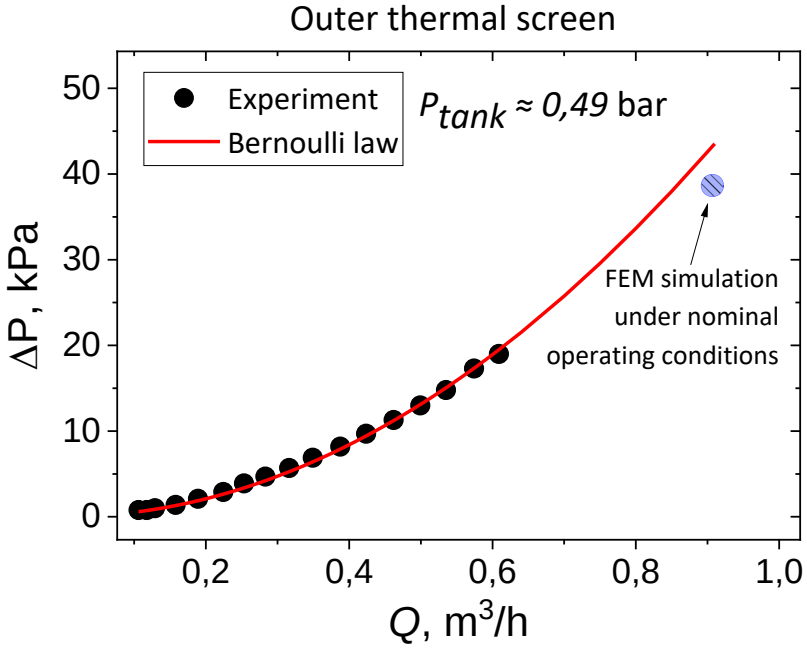
Outer thermal screen (3 panels)

Bernoulli law:

$$\Delta p \approx \frac{\rho v^2}{2}$$

- Subsystems obey Bernoulli law.
- The difference between experimental and simulated values is about 3% and 6%





The conclusions

1. The problem of water supply to TPC & ECAL detectors was studied. The important parameters were established and optimized in order to keep leakless regime and sufficiently high pressure:
   - tank height;
   - straight and return pipes design;
   - pipe diameters;
   - manifold design.

2. Ordinary differential equations-based model of Simscape can mimic the features of the flow computed by Navier-Stokes equations and provide great potential for the development of control models for virtual testing of flow regimes.

3. Experimental verification showed divergence between computed and measured flow at nominal pressure about 3% for ECAL and 6% for outer thermal screen.

Спасибо за внимание!

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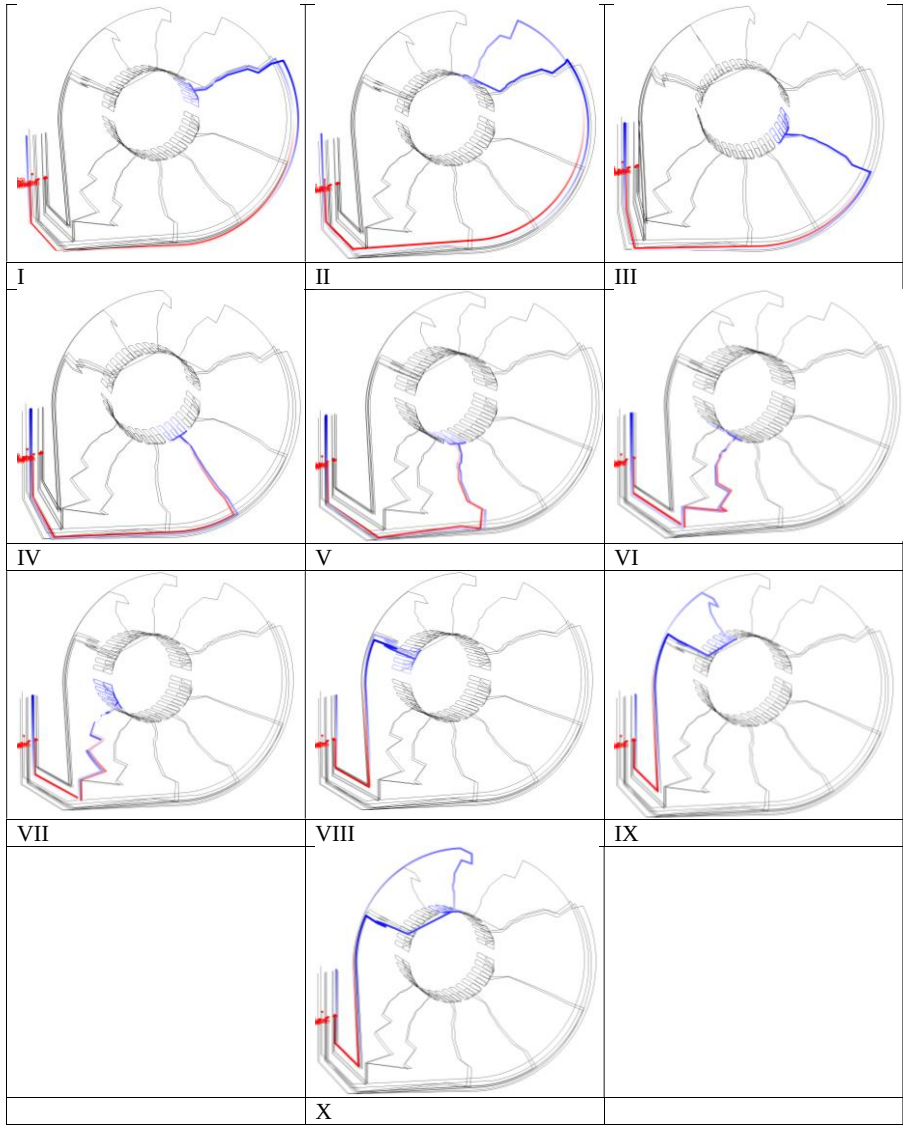
- Самсонов В.А.

Параметры внешнего теплового экрана

Параметр	Значение	Комментарий
Диаметр подводов MPD d_MPD_in	20 мм	
Диаметр отводов MPD d_MPD_out для контуров III, IV, V, VI, VII	30 мм	
Диаметр отводов MPD d_MPD_out для контуров I, II, VIII, IX,X	20 мм	
Диаметр подводов TPC d_TPC_in	20 мм	
Диаметр отводов TPC d_TPC_out	20 мм	
Расход на подконтур q_out_th_scr	1.08 $м^3$/ч	Граничное условие
Суммарный расход на всю систему	21.6 $м^3$/ч	
Высота верхнего коллектора $h_{c\text{-}u}$	4.1 м	
Высота нижнего коллектора $h_{c\text{-}d}$	2.6 м	
d_out_th_scr	6 мм	
Шероховатость трубок ε	0.015 мм	Гладкий термопластик COMSOL
Давление в баке p_{tank}	0.35 атм	Граничное условие
Давление на вход в контур I p_{itsI}	0.996 атм	Рассчитано для обесп. расхода
Давление на вход в контур II p_{itsII}	1.11 атм	Рассчитано для обесп. расхода
Давление на вход в контур III p_{itsI}	0.85 атм	Рассчитано для обесп. расхода
Давление на вход в контур IV p_{itsII}	0.94 атм	Рассчитано для обесп. расхода
Давление на вход в контур V p_{itsI}	0.92 атм	Рассчитано для обесп. расхода
Давление на вход в контур VI p_{itsII}	0.90 атм	Рассчитано для обесп. расхода
Давление на вход в контур VII p_{itsI}	0.80 атм	Рассчитано для обесп. расхода
Давление на вход в контур VIII p_{itsI}	0.92 атм	Рассчитано для обесп. расхода
Давление на вход в контур IX p_{itsI}	1.04 атм	Рассчитано для обесп. расхода
Давление на вход в контур X p_{itsI}	1.04 атм	Рассчитано для обесп. расхода
Число Рейнольдса в нагрузке Re	$(0.5 – 1.2)\cdot 10^4$	



Параметры фронтального теплового экрана

Параметр	Значение	Комментарий
Диаметр подводов MPD d_MPD_in	20 мм	
Диаметр отводов MPD d_MPD_out	14 мм	Важно!
Диаметр подводов TPC d_TPC_in	20 мм	
Диаметр отводов TPC d_TPC_out	20 мм	
Расход на подконтур q_out_th_scr	0,18 $м^3$/ч	Граничное условие
Суммарный расход на всю систему	1,44 $м^3$/ч	
Высота верхнего коллектора h_{c-u}	4,2 м	
Высота нижнего коллектора h_{c-d}	2,7 м	
d_front_th_scr	4 мм	
Шероховатость трубок ε	0,046 мм	Коммерческая сталь COMSOL
Давление в баке p_{tank}	0,35 атм	Граничное условие
Давление на вход в контур I p_{itsI}	0,99 атм	Рассчитано для обесп, расхода
Давление на вход в контур II p_{itsII}	1,01 атм	Рассчитано для обесп, расхода
Давление на вход в контур III p_{itsI}	1,01 атм	Рассчитано для обесп, расхода
Давление на вход в контур IV p_{itsII}	0,99 атм	Рассчитано для обесп, расхода
Число Рейнольдса в нагрузке Re	$5 \cdot 10^3$	
Диаметр трубок термоэкрана d_{tube}	4 мм