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LEAKLESS COOLING AND THERMAL STABILIZATION SYSTEM FOR THE MPD TPC

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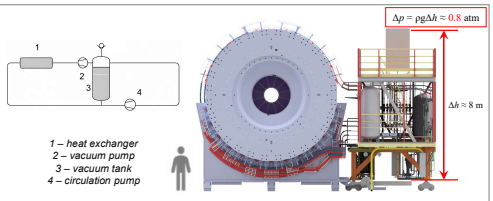
MOTIVATION

The Multi-Purpose Detector (MPD) is the flagship experiment of the heavy-ion collider program at the Nuclotron-based Ion Collider fAcility (NICA). For the first run, MPD will comprise six subdetectors: the Time Projection Chamber (TPC), Electromagnetic Calorimeter (ECAL), Time-of-Flight detector (TOF), Forward Hadron Calorimeter (FHCal), Fast Forward Detector (FFD). With the total power consumption of MPD reaching 1 MW, including more than 20 kW dissipated inside the detector volume, a significant amount of heat may be released during operation, and therefore efficient and reliable thermal management is required.

Leakless water-based cooling systems (LCS) are widely used in large particle detectors to remove high heat loads while protecting unique electronics from water leaks. The sub-atmospheric leakless concept was proposed by M. Bosteels in 1994: the coolant pressure is kept below ambient pressure, so any local breach draws air into the circuit instead of expelling water into the detector volume. A typical LCS consists of a vacuum tank, circulation pump, heat exchanger, and vacuum pump connected in a closed loop. Water is stored in the vacuum tank, delivered by the circulation pump to the heat exchanger to set the inlet temperature, then supplied to the detector cooling circuits and returned back to the tank.

For MPD, this approach is required to cool densely packed high-power detector readout electronics, minimize temperature gradients, and provide stable thermal conditions for the TPC gas system, whose operating temperature must be stabilized within ±0.1 °C. The system must operate within a narrow pressure window: the absolute pressure has to remain below 1 atm in the detector volume to maintain leakless operation, but not fall too low (<0.1 atm) to avoid cavitation or flow stagnation. Since the MPD height is about 8 m, hydrostatic pressure variations become significant, making computational hydraulic design necessary.

To this end, the Leakless Cooling and Thermal Stabilization System for the MPD was designed based on numerical simulations and tested on an experimental test bench (stand). The full-scale system is currently undergoing commissioning tests on the detector in leakless operation mode. LCS consists of three independent primary water circuits, each equipped with its own vacuum tank: aluminum thermal stabilization (Al-TS), copper thermal stabilization (Cu-TS), and copper cooling (Cu-Co). Aluminum piping is used in the thermal screens closest to the TPC gas volume to minimize the material budget, whereas copper piping is used in the remaining radiators for easier fabrication. Since copper and aluminum must not share the same water volume because of galvanic corrosion, the Al-TS and Cu-TS circuits are hydraulically separated. The detector assignments of the three primary circuits are summarized in table.

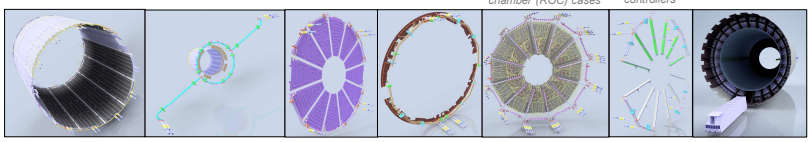


1 – heat exchanger
2 – vacuum pump
3 – vacuum tank
4 – circulation pump

Conceptual scheme of LCS

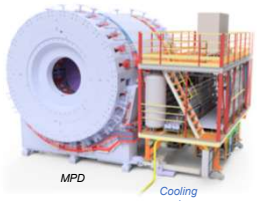
MPD and a service platform

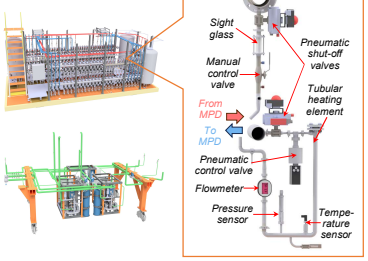
Outer thermal screen | *Internal thermal screen* | *Frontal thermal screen* | *Flanges* | *SAMPA & FPGA electronics + Readout chamber (ROC) cases* | *LVDB + reading controllers* | *ECAL*



Primary circuit	Al-TS				Cu-TS			Cu-Co		
Assigned elements	Frontal thermal screen	Internal thermal screen	Outer thermal screen	Flanges	ROC cases	SAMPA	FPGA	LVDB & FPGA	ECAL	Total for LCS
Total heat load per element P, kW	1.04	0.05	0.5	0.1	0.24	0.3	0.38	8.5	7.5	>18.6
Total flow rate per element Q, m³/h	2	2	30	8	2.4	13.2	6.5	2.7	3.2	60

SYSTEM DESIGN AND EQUIPMENT







Piping layout | *Completed assembly of 1st floor*

All equipment on the 1st floor has been installed, including steel manifolds, subcircuit enclosures, vacuum tanks, circulation and vacuum pumps, temperature and pressure sensors, flowmeters, heaters, pneumatic shut-off and control valves, and electronic cabinets. The electronic cabinets have been equipped with Siemens 1500 series PLCs, hADC and I/O modules, and power supplies; all cables and piping have been routed. A dedicated software has been developed to display all sensor readings and pneumatic valve states on a monitoring interface and to enable remote adjustment of heater power and flow rate in the subcircuits, either manually or through an automatic tuning mode.

COMPUTATIONAL SCHEME AND RESULTS

Each LCS subcircuit was simulated as a 1D hydraulic pipe network, accounting for hydrostatic pressure variations, distributed friction losses, and local losses in elbows.

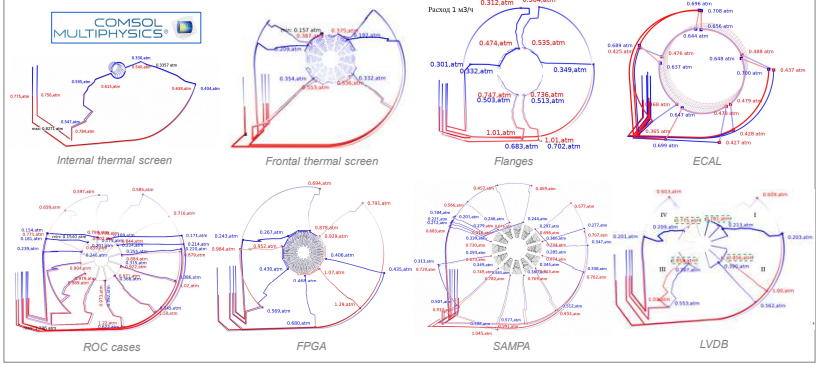
$$\frac{\partial u}{\partial t} + (u \cdot \nabla)u = -\frac{\nabla P}{\rho} - \frac{1}{2} f \frac{|u|u}{D} + g,$$

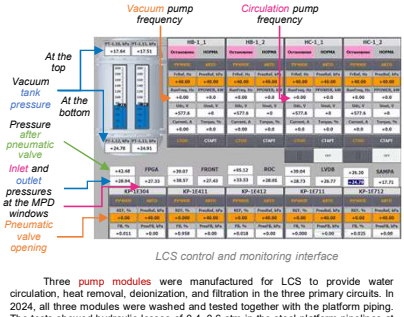
$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0,$$

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

u – cross-section averaged velocity
P – pressure
t – time
ρ – water density
g – gravity constant
f – Darcy friction factor
D – pipe diameter
ε – pipe wall roughness
Re – Reynolds number

The model confirmed leakless operation and defined the required pump operating points, vacuum-tank pressures, pipe diameters, and pipe-routing modifications.





LCS control and monitoring interface

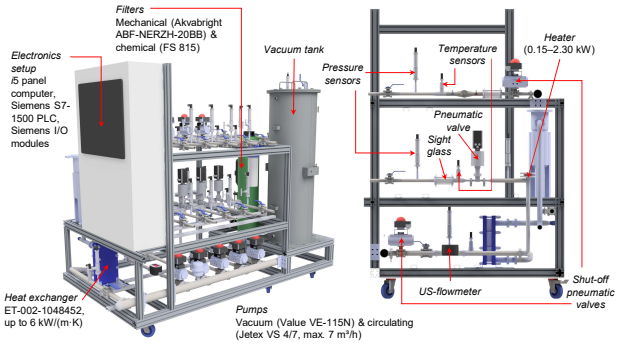
Three pump modules were manufactured for LCS to provide water circulation, heat removal, deionization, and filtration in the three primary circuits. In 2024, all three modules were washed and tested together with the platform piping. The tests showed hydraulic losses of 0.4–0.6 atm in the steel platform pipelines at nominal flow rates. The system remained stable under high-pressure testing up to 10 atm, with no leaks or mechanical failures. At nominal flow, the circuits retained a pressure margin of about 1.5 atm, sufficient for reliable water supply.



Pump module at the factory | *All pump modules installed at the 0th floor*

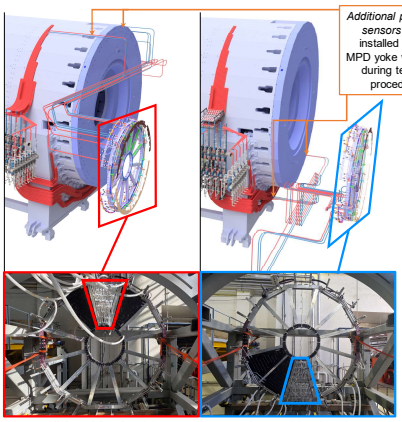
EXPERIMENTS

A team of scientists and engineers from JINR, LLC ArcoLab and INP BSU (Belarus) designed and built a dedicated experimental test bench (stand): a scaled prototype of the MPD LCS. The prototype reproduces key design features of the full system and enables the experimental program summarized in the table.



Stand gen.	Experiments	Results
1st	Cooling performance tests for mock-ups of ECAL, outer/frontal thermal screen panels, FPGA, SAMPA, LVDB radiators, and ROC subcontour	Numerical pressure-drop estimates validated at nominal flow rates; hydraulic resistance measured for each radiator type
	Low-pressure collapse tests for pipes of different materials/diameters	Pipe materials selected
2nd	Pad-plane thermal stabilization tests on the ROC mock-up	Feasibility of maintaining pad-plane thermal stability within ±0.1 °C confirmed by adjusting the water inlet temperature in FPGA, SAMPA, ROC, and LVDB subcontours at nominal flow rates
3rd	Water-filling procedures for cooling loops	Water-filling procedure developed
	Pneumatic valve tests. Fault-scenario tests: shut-off valve actuation under water-hammer conditions	Required valve opening ranges determined. No connector failure under water-hammer conditions; system remained stable
	PID control of heater power	PID tuning procedure and automatic control algorithm developed; optimal PID coefficients defined
	Air-ingress tests in pipes	Influence of bubble size and velocity on hydraulic resistance quantified; ML-based bubble-detection method developed using camera recordings of flow in a sight glass

Upcoming experiments: upgraded pad-plane thermal stabilization tests on the ROC mock-up; water-to-gas heat-exchanger tests for the TPC gas system



The extreme positions of ROC

LEAKLESS TEST RUN

After final assembly of LCS, including tests of pump modules, sensor response, control interface, as well as verification of pipeline leak-tightness, full-scale system test runs were initiated. The runs were performed for the cooling circuits of a single ROC, including frontal electronics and thermal-screen panels installed on the service wheel near the MPD, at their real operational height but still outside the final detector position, as shown in the scheme. Two extreme ROC positions were considered: of the lowest and the highest configurations. For these runs, the water-supply pipelines were approximately twice as long as in the nominal layout. Pressure drops were evaluated from the difference between the readings of pressure sensors installed at the inlet and outlet windows of the MPD yoke under the nominal operating regime with the vacuum-tank pressure set to $p_{\mathrm{tank}} = 0.35$ atm.

Main test results:

- Leakless operation was successfully achieved and stably maintained.
- The cooling sub-circuit for the SAMPA and frontal thermal screen satisfied the expected flow requirements in both extreme positions with a more than 10% operational margin.
- The ROC case, FPGA and LVDB subcircuits performed as expected in the highest position. In the lowest position, the measured flow rate was 5% lower than expected, but remained within the acceptable range for achieving the required cooling performance.
- A rapid water-filling procedure for vacuum pipelines was tested. The method is based on preliminary evacuation of the system down to 0.05 atm to remove air, followed by sequential filling and opening of each subcircuit. A 2-minute holding period was applied after each step to stabilize pressure oscillations and establish the operating regime, while maintaining leakless operation and removing air pockets;
- A key feature of direct leakless-mode pressure monitoring at the MPD windows was identified: special dead-end impulse lines transmitting pressure from the window taps to the sensors provide reliable readings only when the sensors are located below the corresponding taps. If a sensor is placed higher, the hydrostatic pressure decrease in the line can release dissolved air as a gas phase, distorting pressure transmission.
- Minor adjustments (1–2%) to the pneumatic control valves were found to trigger stiction-induced limit cycling within the actuator's mechanical stopper system. These self-regulating oscillations can cause opening fluctuations of up to 10%, potentially threatening the leakless operation. A safety threshold was implemented to protect the sub-atmospheric regime. To bypass this mechanical limitation, tailored control algorithms are being developed to translate small setpoint adjustments into a sequence of larger, stable steps that achieve the same final state.

CONCLUSIONS

- A dedicated 1D graph-based Navier-Stokes model was developed to optimize the TPC and ECAL sub-atmospheric cooling networks. Simulations demonstrated that replacing the standard radial pipe routing with a combined layout - utilizing horizontal return lines in the upper detector section - eliminates hydrostatic head losses. This modification drastically improves leakless stability, raising the minimum pressure from a critical to a safe −0.1 atm.
- A laboratory test benches – research stands – have been designed and assembled to investigate hydrodynamic and thermal processes in leakless thermal stabilization systems. The components, instruments, and architecture of the test bench correspond to the thermal stabilization system of the TPC and ECAL detectors and can be controlled via a computer or a Siemens PLC. In total, three generations of test benches have been developed to sequentially address engineering challenges.
- Full-scale leakless test runs of the assembled LCS confirmed stable sub-atmospheric operation for a single ROC and frontal thermal-screen panels at their actual operating height. The required flow conditions were achieved with sufficient margin; minor reductions in the lowest position were attributed to the extended pipeline length. The tests also validated the rapid filling procedure and revealed key safety-control features of pressure monitoring and pneumatic valve actuation.