The 29th International Scientific Conference of Young Scientists and Specialists
AYSS-2025
JINR, Dubna, Russia, 27 – 31 October, 2025

JOINT INSTITUTE FOR NUCLEAR RESEARCH

HIGH-PERFORMANCE COMPUTATIONS FOR CONVECTIVE FLOW ANALYSIS IN THE TPC DRIFT VOLUME OF MPD/NICA

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NICA PROJECT. MPD

At the Joint Institute for Nuclear Research (JINR, Dubna, Russia), the NICA (Nuclotron-based Ion Collider fAcility) mega-science project is underway, aiming to create a next-generation ion collider utilizing the upgraded accelerator “Nuclotron”.

Trackers: Time-Projection Chamber (TPC) and Inner Tracker (IT) - 3D track reconstruction (incl. at small radii), momentum determination, and pattern recognition.

PID-systems: Time of Flight System (ToF) - search for charged hadrons and nuclear clusters, Electromagnetic calorimeter (ECal) - measurement of electron and photon energy.

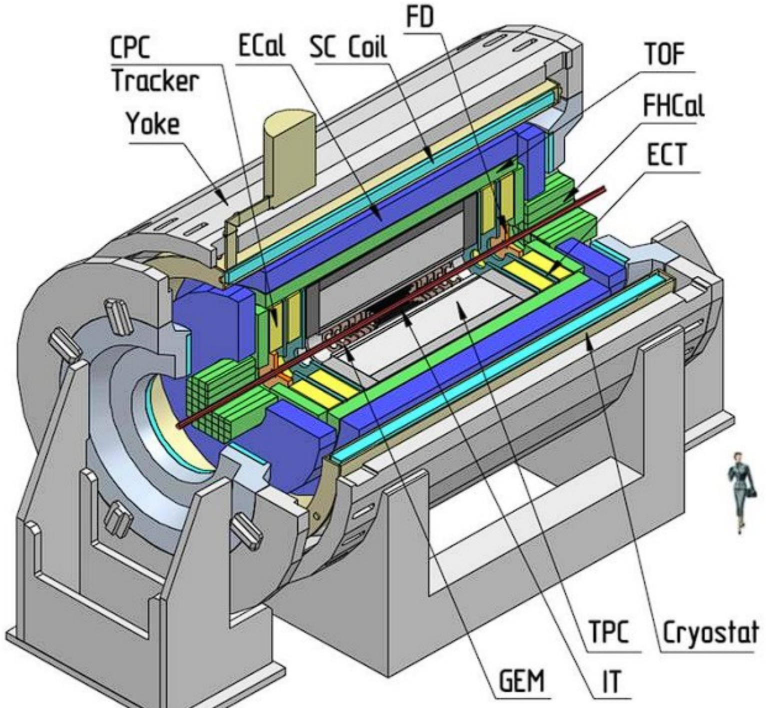


Figure 1. MPD setup design[1]

One of the detectors of the NICA complex — the Multi-Purpose Detector (MPD) — is designed to perform unique measurements of heavy-ion collision events, including high-precision particle tracking and comprehensive particle identification over a wide range of experimental conditions.

1. The MultiPurpose Detector – MPD to study Heavy Ion Collisions at NICA : Conceptual Design Report / JINR / res. sup. Sissakian A.N., Sorin A.S., Kekelidze V.D. — Dubna. — 260 p.

TPC THERMAL STABILIZATION SYSTEM

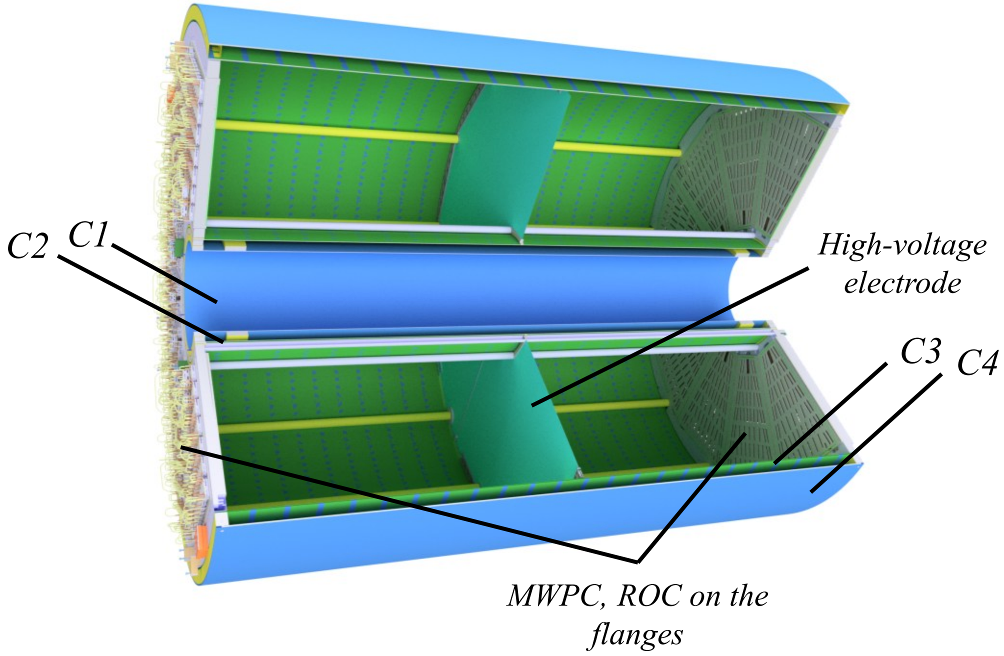
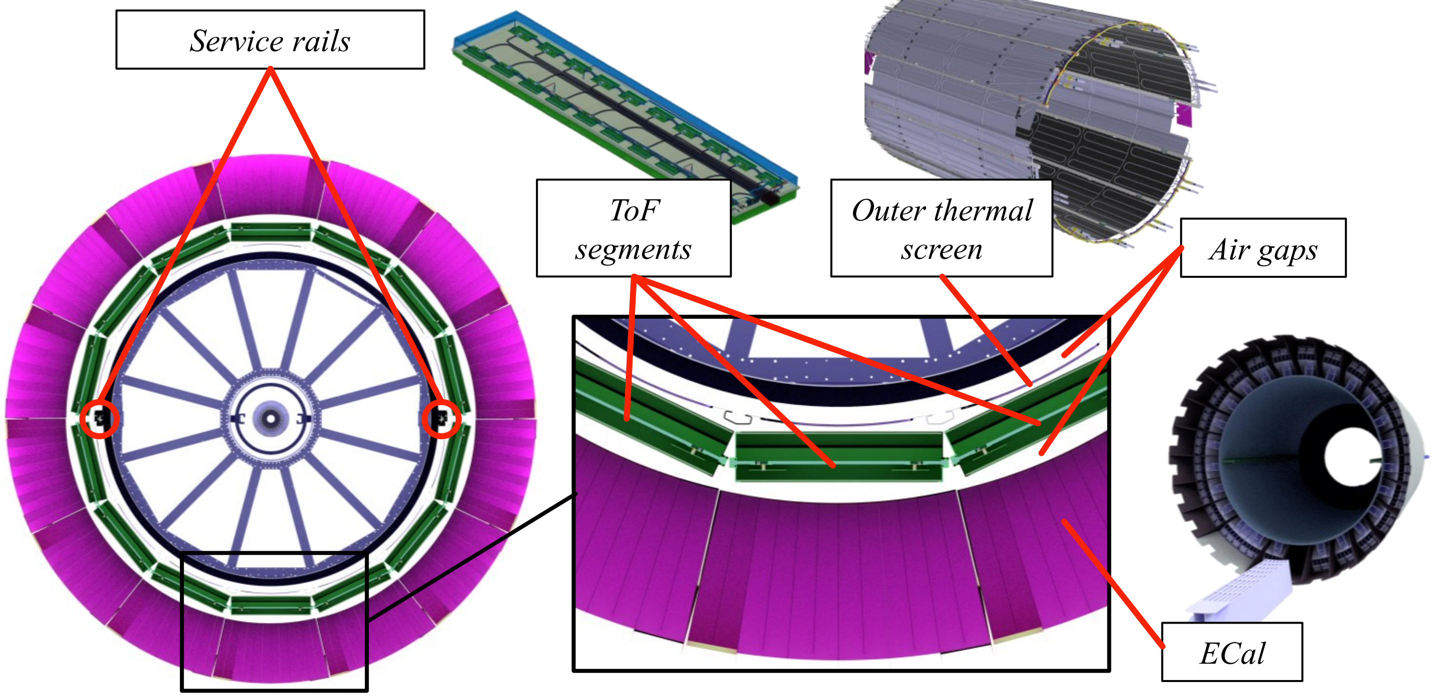


Figure 1. TPC design (sectional view)



The kevlar shells C1–C2 and C3–C4 are mechanically coupled in pairs via aluminum flanges to establish gas-tight interfaces. These interstitial volumes are purged with nitrogen to mitigate the risk of high-voltage discharges and to inhibit the ingress of O_2 and H_2O into the TPC gas volume.

According to preliminary estimates, the permissible amplitude of temperature fluctuations should not exceed **±0.25 K** when using the **Ar/CH_4 (90:10)** gas mixture and **±0.10 K** when using the **Ar/CO_2 (80:20)** gas mixture[1].

1. Time Projection Chamber for Multi-Purpose Detector at NICA : Technical Design Report / JINR / res. sup. A. Averyanov, S. Chernenko, F. Levchanovskiy — Dubna, 2018. — 107 p.

MOTIVATION

The purpose of the research:

To determine the temperature and velocity distributions in the TPC drift volume for Ar/CH_4 (90:10) and Ar/CO_2 (80:20) gas mixtures.

Objectives:

1) To perform HPC-driven CFD simulations to investigate the convective dynamics of the specified gas mixtures, taking into account heat release from the ToF system and the design of the outer thermal screen;
2) To obtain 3D temperature and velocity fields and analyze the convective flow structure.

FREE CONVECTION MODEL

System of equations of motion of a viscous incompressible non-isothermal gas in **the Boussinesq approximation**:

$$\begin{cases} \dfrac{\partial \vec{\upsilon}}{\partial t} + (\vec{\upsilon}\nabla)\vec{\upsilon} = -\dfrac{\nabla P}{\rho_0} + \nu\Delta\vec{\upsilon} + g\beta T\vec{e}_z, \\ \dfrac{\partial T}{\partial t} + (\vec{\upsilon}\nabla)T = \chi\Delta T, \\ \mathrm{div}\ \vec{\upsilon} = 0, \\ \rho = \rho_0\left(1 - \beta(T - T_0)\right) \end{cases}$$

$\vec{\upsilon}$ – velocity,
P – pressure,
T – temperature,
ν – viscosity,
ρ – density,
ρ_0 – density at a reference temperature T_{mean},
β – thermal expansion coefficient,
χ – thermal diffusivity,
g – gravity coefficient,
$\vec{e_z}$ – unit vector along the z axis.

The present study investigates the gas dynamics in half of the TPC volume (from the endplate to the HV electrode).

Case geometry and temperature ranges

	R_{inner}	0,341 m	Inner radius of the TPC volume
	R_{outer}	1,330 m	Outer radius of the TPC volume
	L_{half}	1,650 m	Half length of the TPC
Ar/CH_4 (90:10)	T_{mean}	293,50 K	Mean temperature inside the TPC
	T_{min}	293,32 K	Temperature minimum on the TPC surface
	T_{max}	293,68 K	Temperature maximum on the TPC surface
Ar/CO_2 (80:20)	T_{mean}	293,35 K	Mean temperature inside the TPC
	T_{min}	293,20 K	Temperature minimum on the TPC surface
	T_{max}	293,50 K	Temperature maximum on the TPC surface

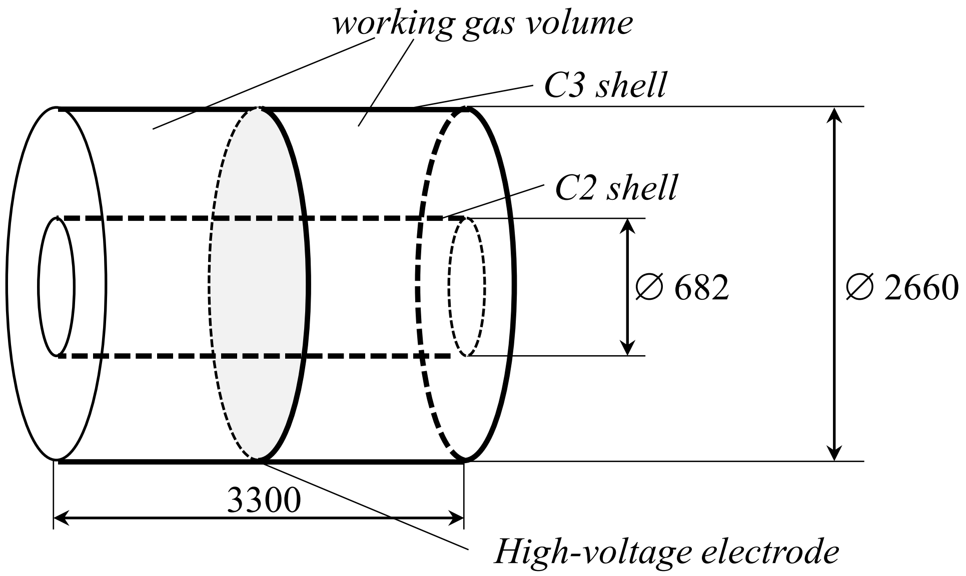


Figure 2. TPC detector dimensions

CASE PARAMETERS. MESH

Ar/CH_4 (90:10) & Ar/CO_2 (80:20) gas mixtures

The thermophysical properties (ρ, v, κ, C_P) of the gas mixtures were calculated using the following expressions:

$$K_{eff} = \frac{K_1\eta_1 + K_2\eta_2}{\eta_1 + \eta_2} \qquad \kappa_{eff} = \frac{\kappa_1\eta_1 M_1^{1/3} + \kappa_2\eta_2 M_2^{1/3}}{\eta_1 M_1^{1/3} + \eta_2 M_2^{1/3}}$$

K_{eff} – effective property of the binary gas mixture,
$K_{1(2)}$ – property of the 1st (2nd) component of the binary mixture,
$\eta_{1(2)}$ – fraction of the 1st (2nd) component in the mixture,
$M_{1,2}$ – molar mass of the 1st (2nd) component of the mixture,
$\kappa_{1,2}$ – thermal conductivity coefficient the 1st (2nd) component of the mixture.

SEM + BDF2 with adaptive time stepping
SEM polynomial order: N = 7
ILES filtering: decreases the amplitude of the 2 highest modes by 5%
8 CPU cores
8 MPI processes

NEK
fast high-order scalable CFD

Gmsh

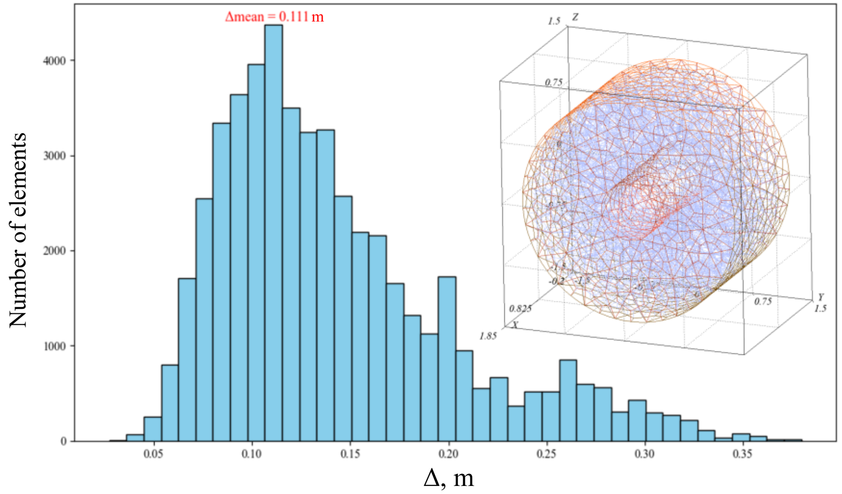
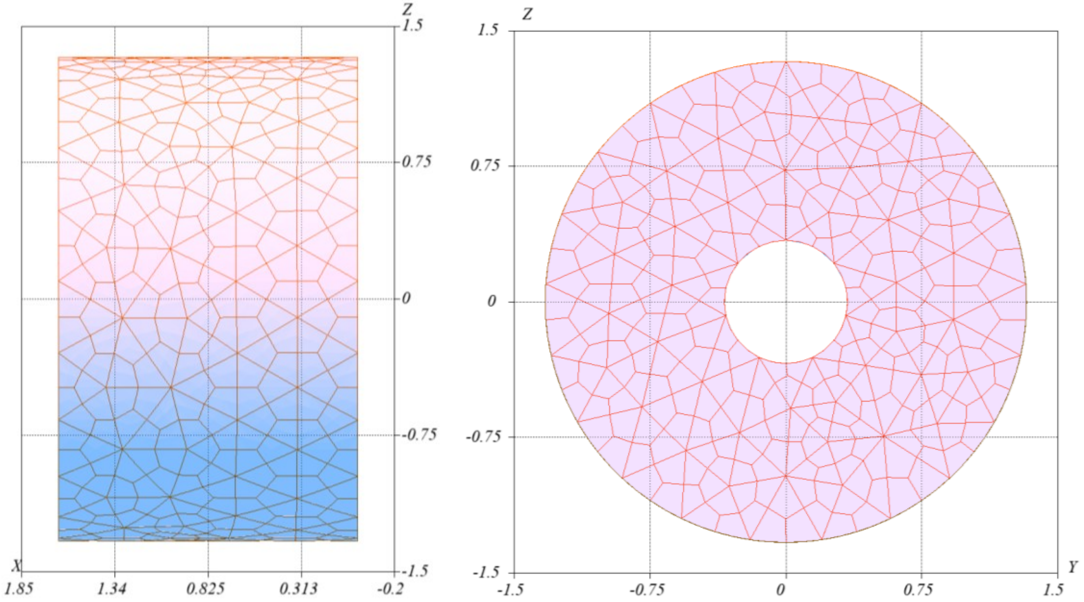


Figure 3. Distribution of characteristic sizes Δ of mesh elements

The 3D computational mesh contains $5.8 \cdot 10^3$ hexahedral 2nd order elements



BOUNDARY CONDITIONS ON C3 SHELL

I. Balashov and G. Meshcheryakov experiment

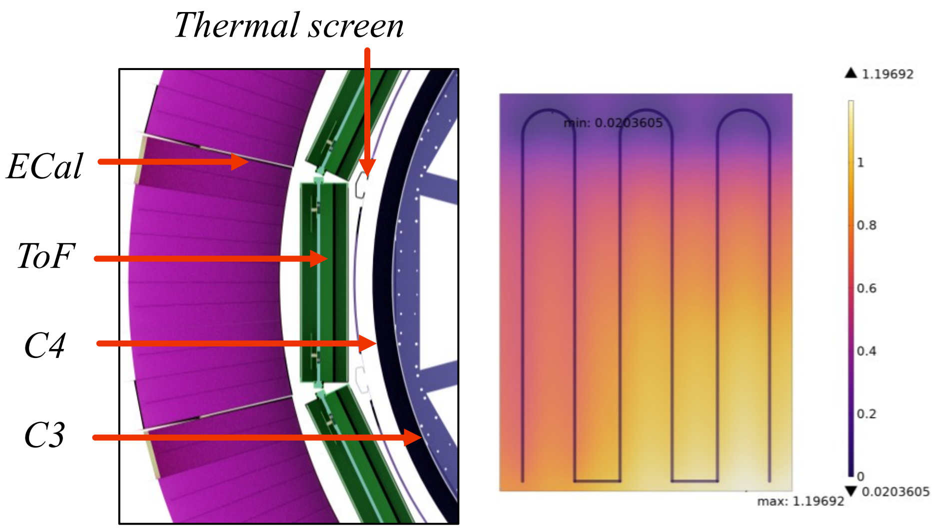


Figure 4. Fragment of the TPC endcap (left); temperature distribution on a single outer thermal screen panel (right)

Thermal conductivity of 1 mm contact layer between the outer thermal screen and coolant-carrying tubes **vary** from 0.12 to 0.2 W/(m·K) at different points on the screen.

To predict the temperature distribution on the C3 shell, the following must be taken into account:

- Heat load from ToF system;
- Non-uniform temperature distribution on the outer thermal screen.

A. Fedotov COMSOL computations

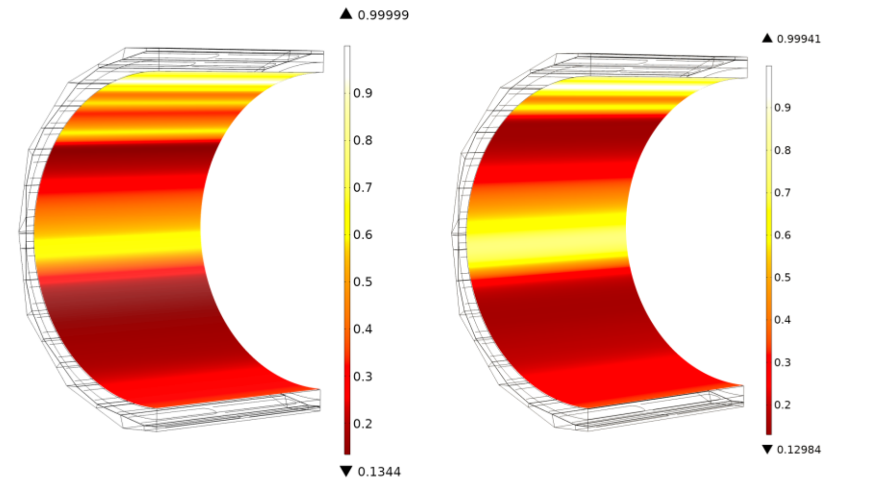


Figure 5. Normalized temperature distributions on half of the C3 shell

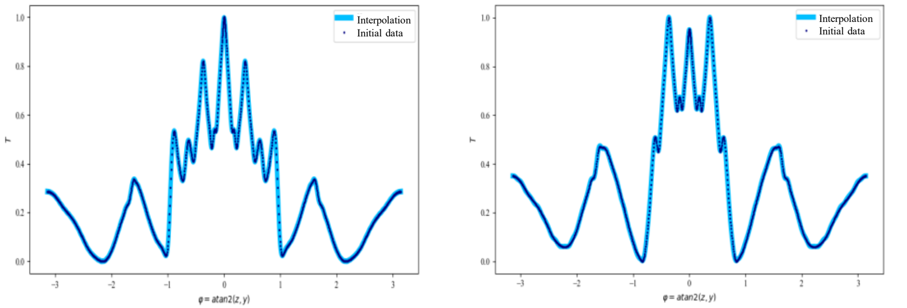
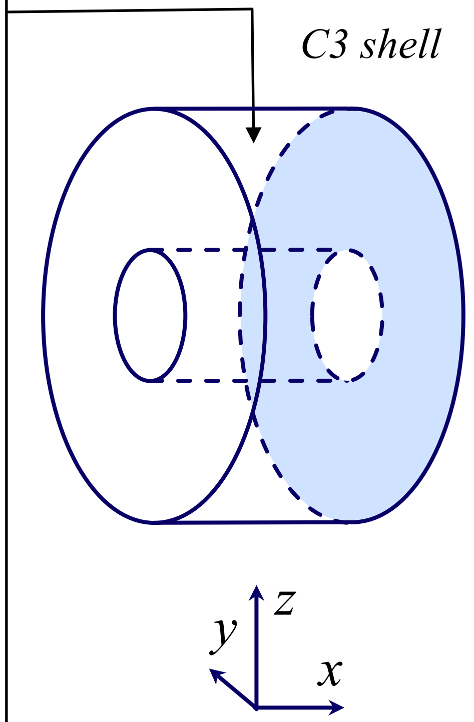
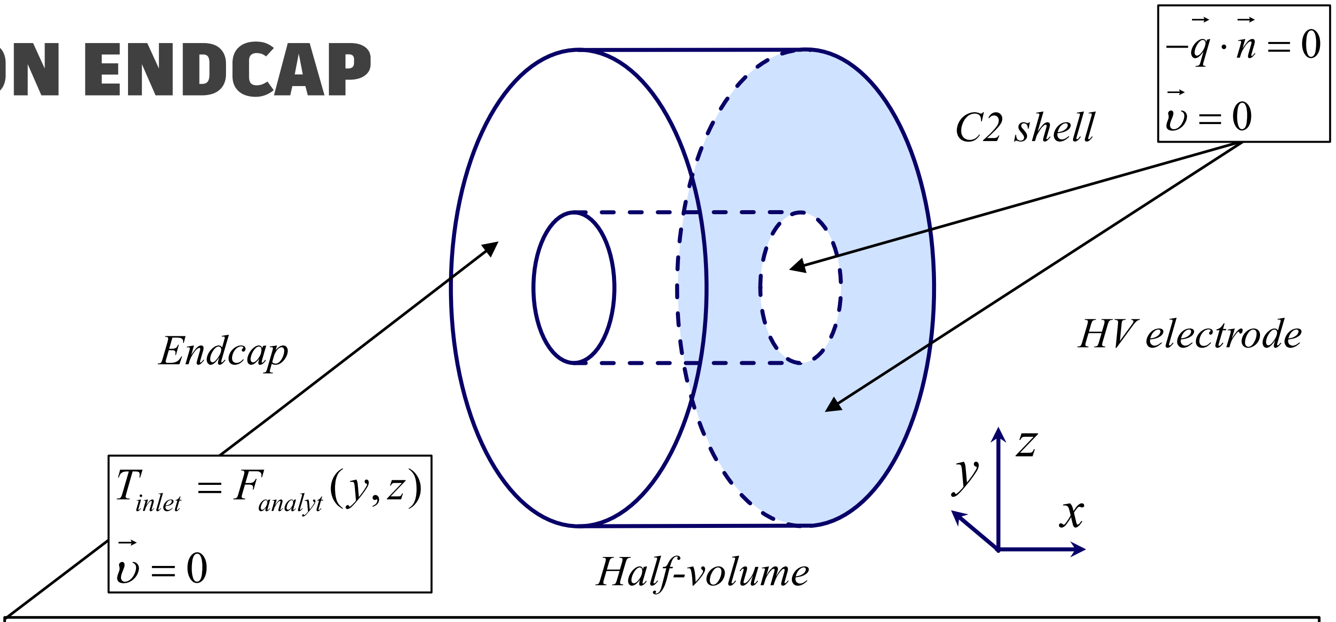


Figure 6. Angular distributions of normalized temperature in section *yz* (φ is measured in radians)

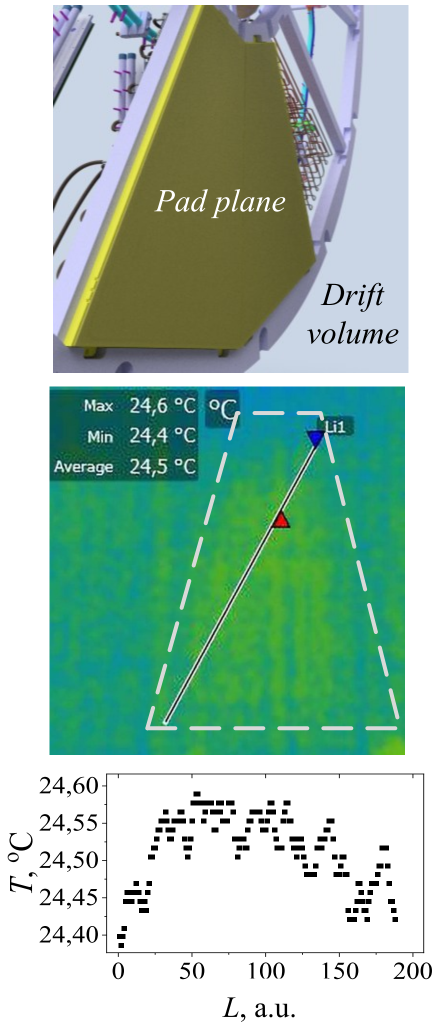
$$T_{outer\ wall} = F_{inter}(y,z)$$
$$\vec{\upsilon} = 0$$



BOUNDARY CONDITIONS ON ENDCAP



V. Chehovsckiy [et al.] experiment



The feasibility of achieving **temperature uniformity within ±0.1 °C on the ROC pad plane** has been confirmed, while keeping the FPGA boards' temperature below the recalibration threshold of 45 °C.

With effective cooling, the pad plane exhibits **a temperature profile that peaks at the center and decreases toward the edges**.

Figure 7. View of the pad plane from inside the TPC (top); thermal image of the pad plane at the optimal operating mode of the ROC cooling circuit (center); pad plane temperature profile along the cutline (bottom)

$$F_{analyt}(y,z)=\frac{1}{2}\left(1-\cos\left(0,6\pi(y^2+z^2)+\frac{\pi}{4}\right)\cdot\left|\frac{y^6-15y^4z^2+15z^4y^2-z^6}{\left(y^2+z^2\right)^3}\right|\right)$$

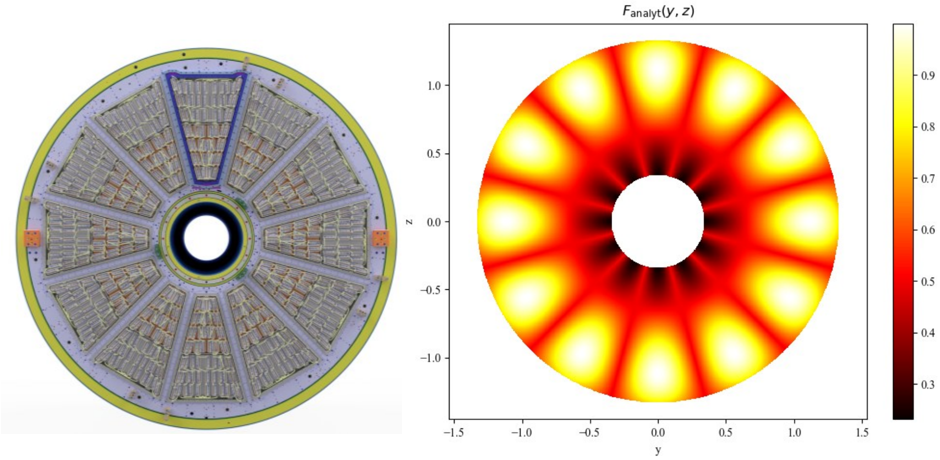


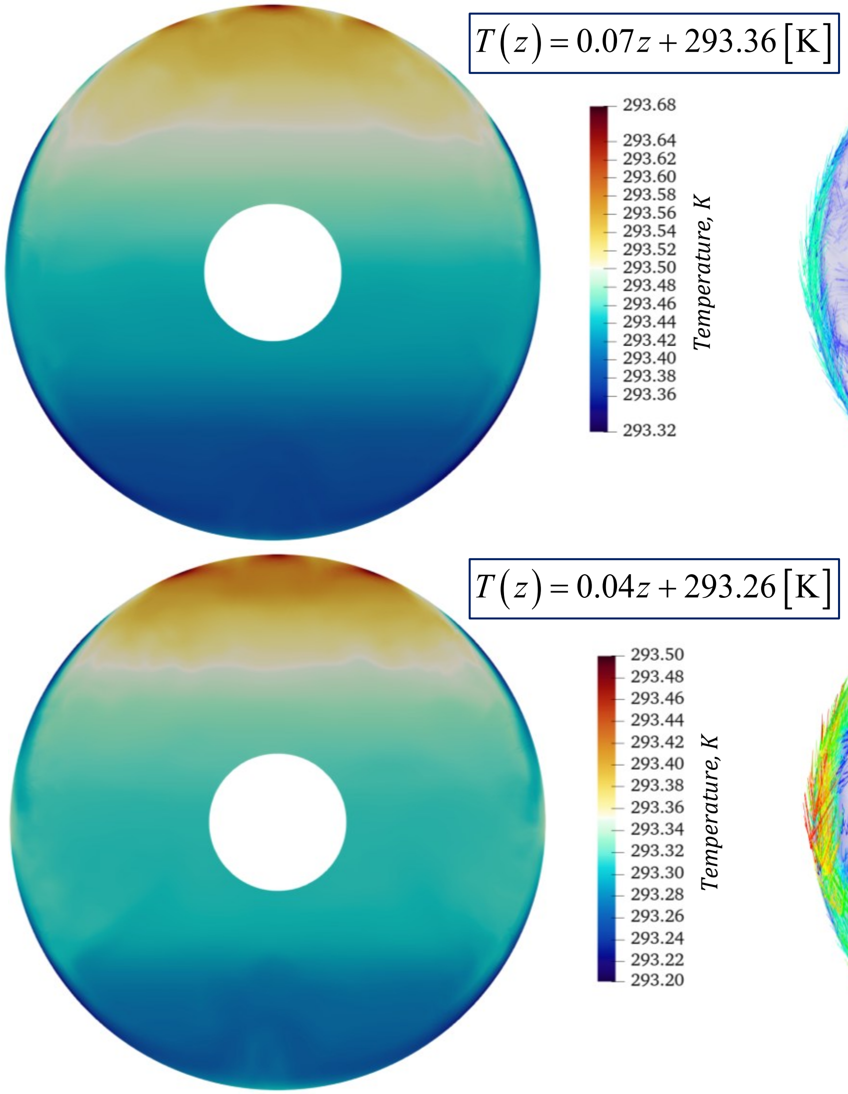
Figure 8. Front view of the ROC and FEE of the TPC, and the analytically specified temperature distribution on the endplate

FREE CONVECTION IN WORKING GAS

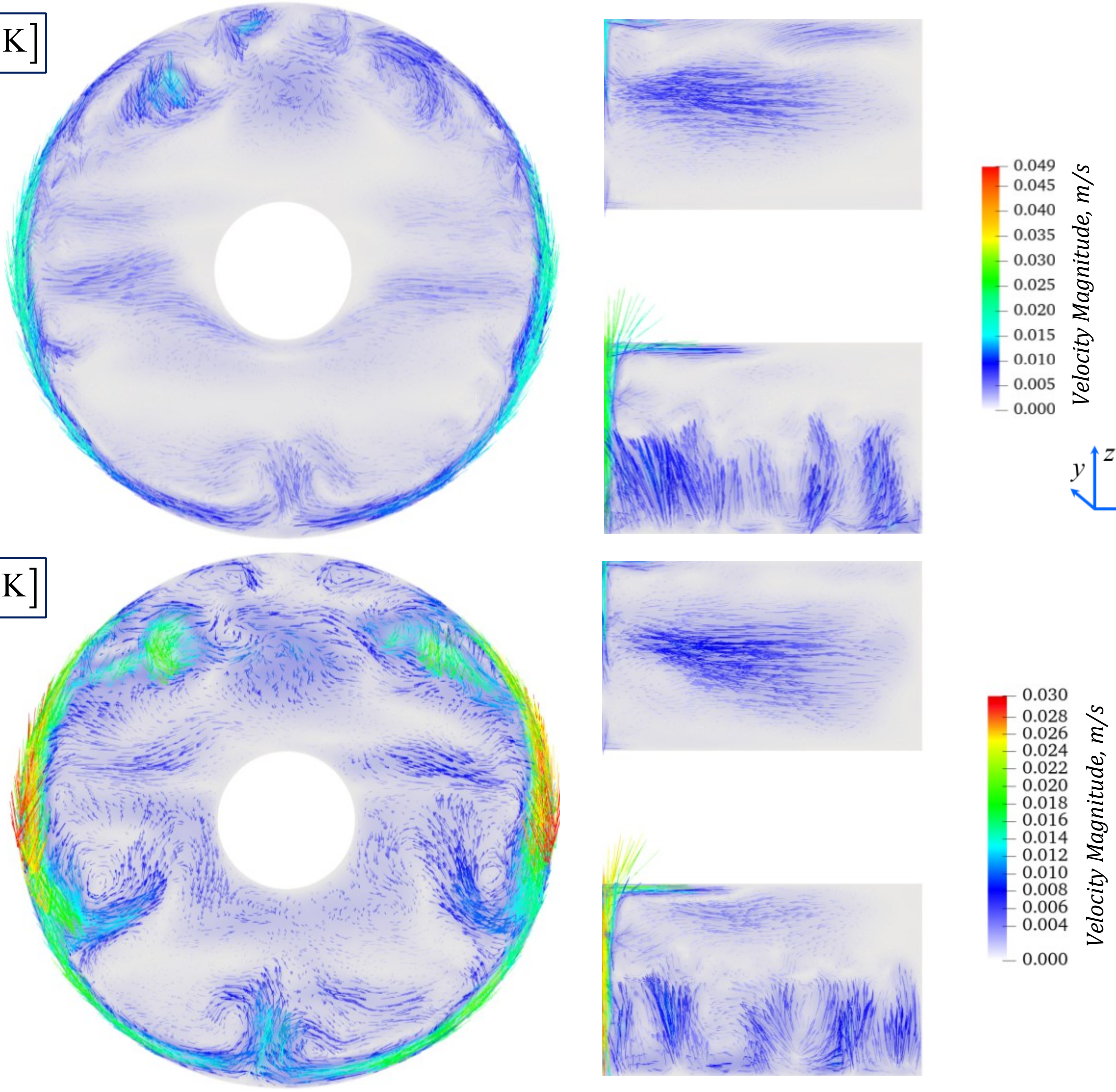
ParaView – Parallel Visualization Application

Ar/CH_4 (90:10)

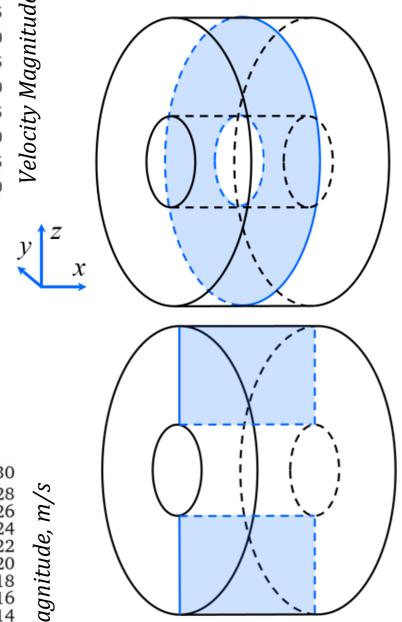
Ar/CO_2 (80:20)



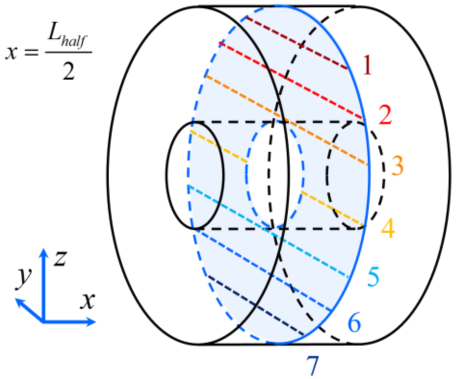
Temperature fields

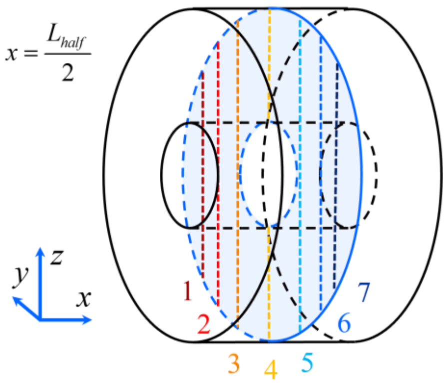


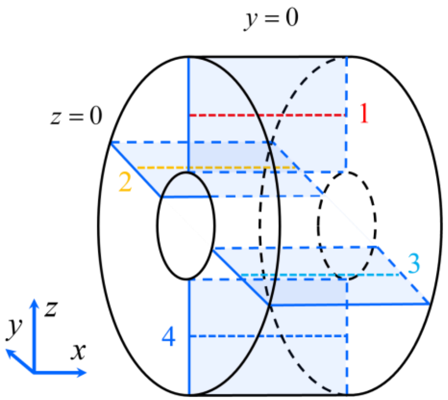
Velocity vector fields



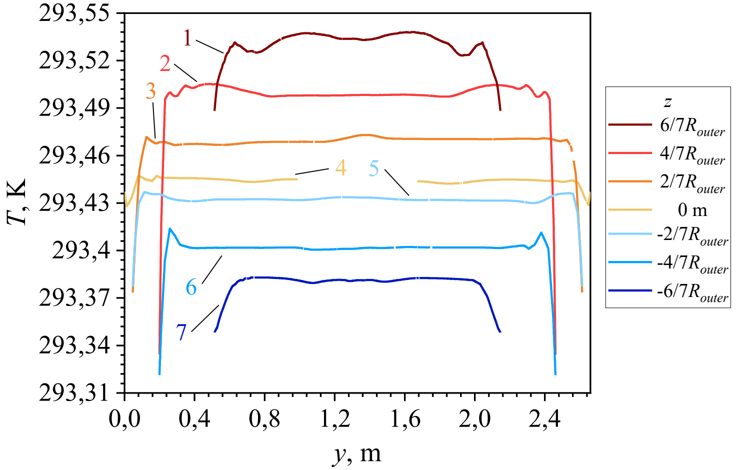
LINEAR TEMPERATURE PROFILES COMPARED

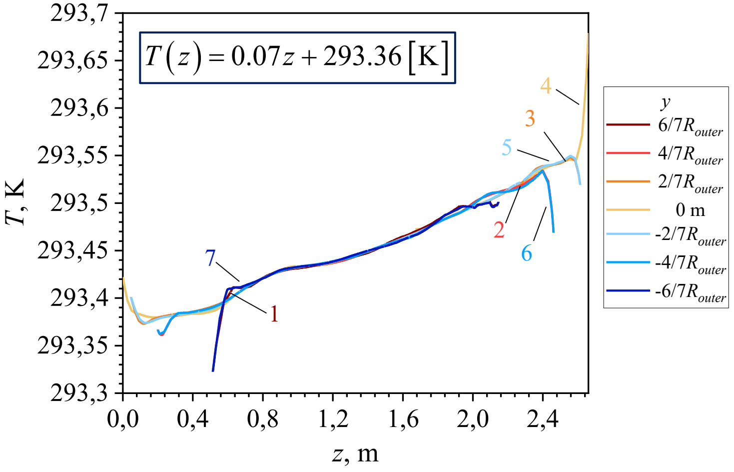


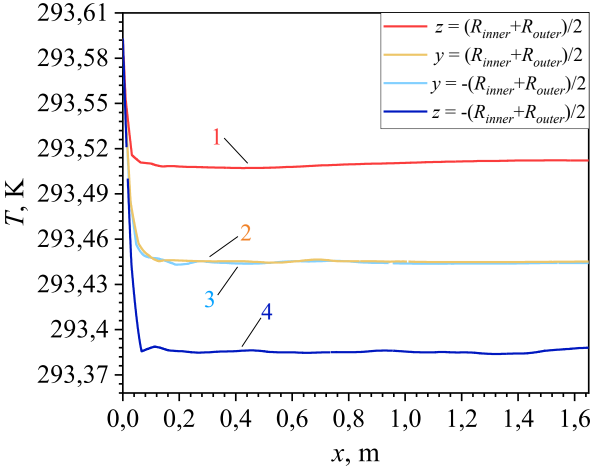




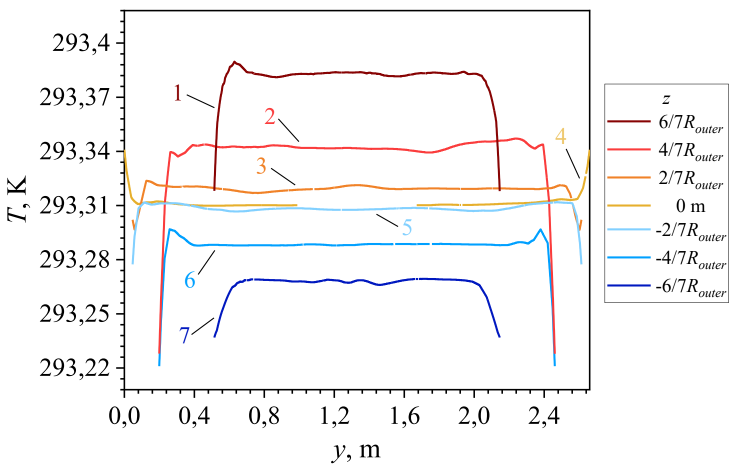
Ar/CH_4 (90:10)

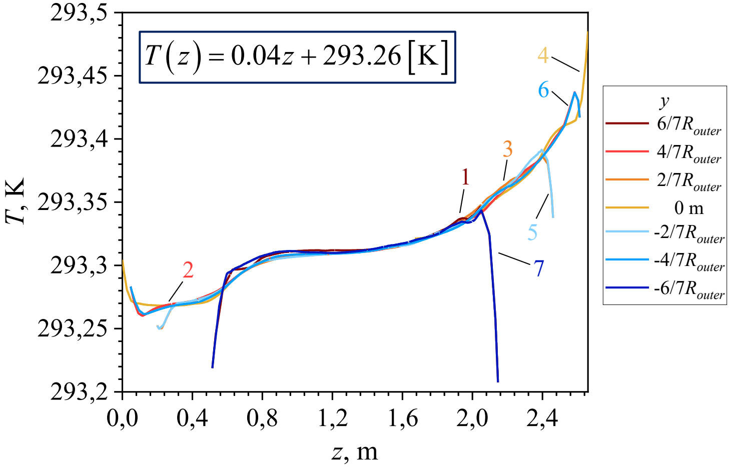


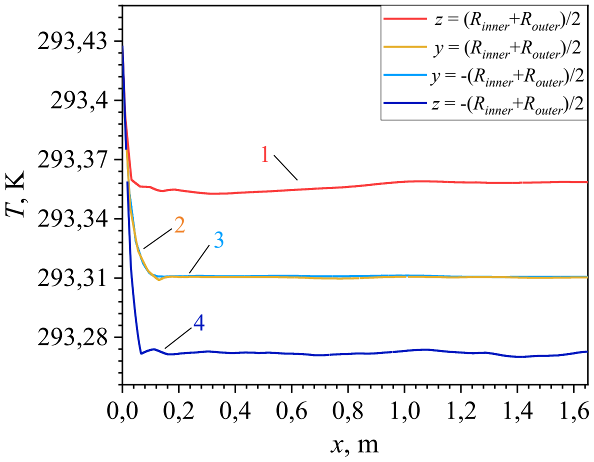




Ar/CO_2 (80:20)



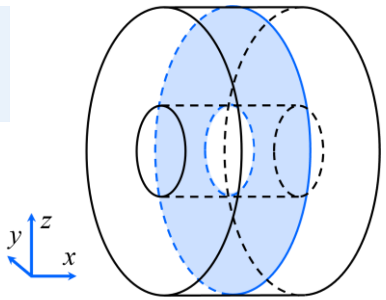




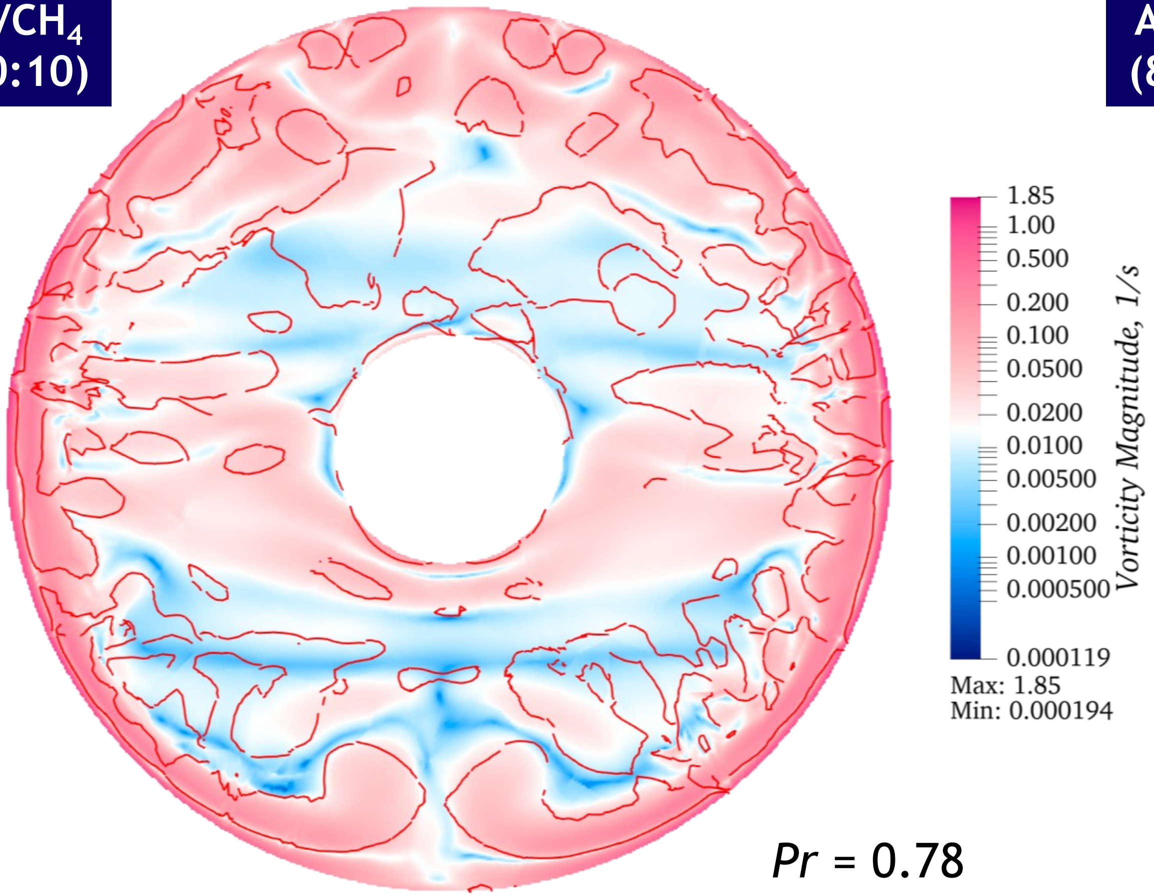
$$\mathrm{Pr} = \frac{\nu}{\chi}$$

Q-CRITERION

Vorticity $\Omega = \frac{1}{2}\left(\nabla\vec{\upsilon} - \left(\nabla\vec{\upsilon}\right)^{\mathrm{T}}\right)$ **&** **Strain** $S = \frac{1}{2}\left(\nabla\vec{\upsilon} + \left(\nabla\vec{\upsilon}\right)^{\mathrm{T}}\right)$ → $Q = \frac{1}{2}\left(\|\Omega\|^2 - \|S\|^2\right)$

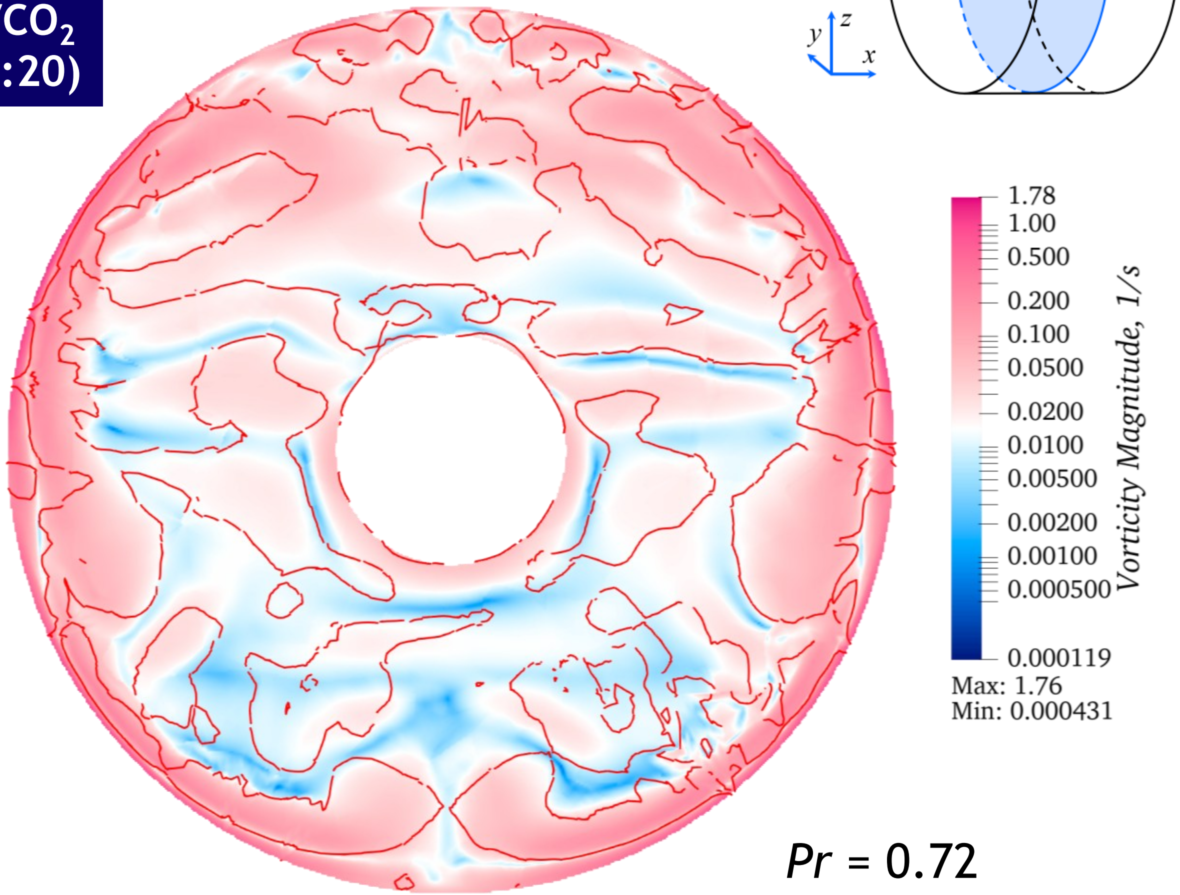


Ar/CH_4 (90:10)



Pr = 0.78

Ar/CO_2 (80:20)



Pr = 0.72

CONCLUSIONS

1. For the free convection problem inside the TPC, the temperature boundary conditions were formulated on the basis of experimental measurements and preliminary 2D simulations;
2. Computational analysis revealed that ToF detector (in absence of cooling) and endcap electronics of TPC heat up working gas with inhomogeneity of **±0.18 K** for **Ar/CH_4 (90:10)** and **±0.15 K** for **Ar/CO_2 (80:20)**;
3. Despite meticulous boundary conditions, temperature in the working gas depends on vertical coordinate linearly. At the chosen height, temperature remains constant excluding the thin region of **5-10 cm** directly near the pad planes and C3 shell.

XVI MPD Collaboration Meeting
VBLHEP, JINR, 28 - 30 October, 2025

THANK YOU FOR YOUR ATTENTION!

Related talk:
XVI MPD Collaboration Meeting, Oct 29th, Wed
M. Medvedeva [et. al] HIGH-PERFORMANCE COMPUTATIONS FOR CONVECTIVE FLOW AND ELECTRON DRIFT ANALYSIS IN THE TPC OF MPD/NICA