VENECIA-VINCENTA modelling of cryopumps and their operation in regeneration and cool-down modes

VENECIA-VINCENTA FOR TH ANALYSIS OF FORCED FLOW COOLED CRYOPUMPS.

A demo-model of 4K sorbent quilted panels of one design option of ITER Torus Cryopump (T-CP) demonstrates that Venecia code is useful and reliable tool for thermal hydraulic (TH) analysis of CP, including its regeneration, in particular:

- Rapid exhaust of 4K helium from one CP back to a cryoplant (recovery),
- Rapid warm up of one CP from 4K to 100K,
- Rapid cool-down of one CP from 100K down to 4K.

The Demo figures show the helium flow dynamic and evolution of time dependant temperature profiles along 28 quilted panels (4 parallel loops, each with 7 panels in series), their in-pump manifolds and external supply/return cryogenic lines. The time limit for each stage of regeneration is 150 s. Cryogenic control valves for providing different stages of regeneration are included in the demo-model.

The geometry of panels and cryogenic lines is fixed for this demo-model. A user of demo-model could investigate personally the time evolution of cryogenic parameters in T-CP (helium P, T, flow rate and pressure drop) in a way to calculate the necessary helium mass flow rates that allow providing each of three different stages of regeneration in shorter or longer period of time than for the chosen time limit of 150 seconds.

This demo example illustrates that Venecia code could be easily adopted for description all of other necessary details of cryopump design, namely:

- Description of 80-100K cooling loop with chevrons and thermal shields cooled by gaseous helium (or nitrogen if needed).
- Description of all 80K and 4K cryogenic components of FZK test facility (or others), namely liquid helium bath with SHe heat exchangers immersed in a bath, 4K helium circulator with its working characteristic, cryogenic control valves for regeneration at 100K and for nominal 4K cooling during CP pumping ,
- Description of heat exchangers, heaters and valves for high temperature regeneration at 300K and 470K,
- Variable vacuum conditions inside CP for different regeneration stages (especially for 4K helium exhaust (recovery) during which a decrease of vacuum could be resulted in large additional heat load on the quilted panels and hence could greatly increase temperature of helium return back to the cryoplant).

It should be stated that VENECIA package has no limitations for description of large dimensioned cryopumps as NB cryopumps for ITER (or others).

The VENECIA package is ready for studies of cryopump options cooled by forced flow of supercritical helium or by two-phase helium, when needed.

The Venecia is an advanced modification of previously used Vincenta. The programming procedures of VENECIA package is greatly improved in a way to include the advanced pre- and post- processor and visualization programs and be essential to provide more information to establish the process control strategies. This code makes it possible to perform multi-parameter optimisation and synthesis taking into consideration all process and design constraints for both the cryopumps and their cryogenic circuits.

At present the VENECIA package is commercially available.

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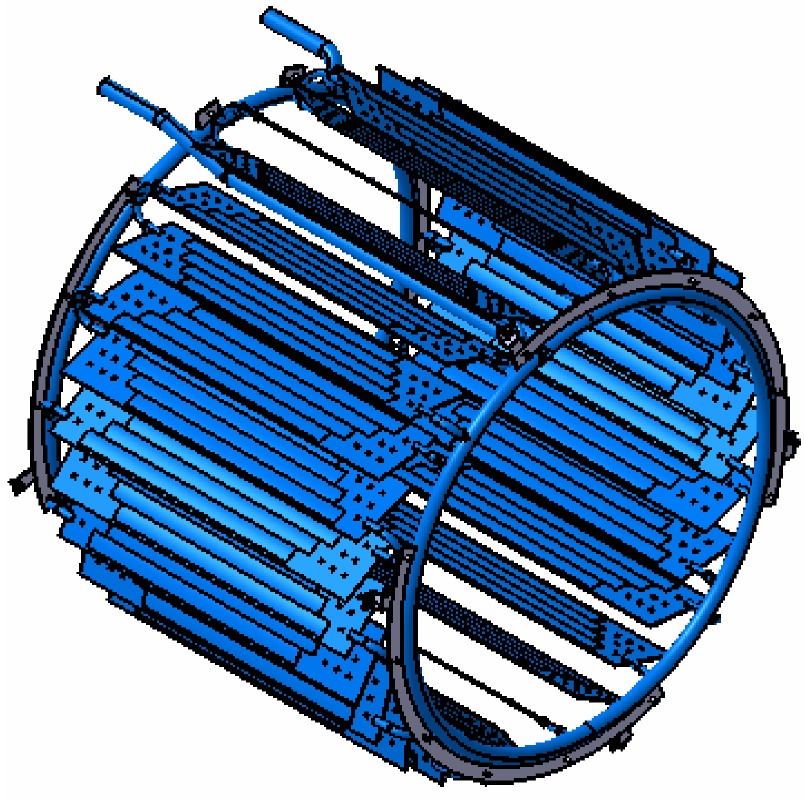
The VENECIA package is ready for analysis of magnets and cryopumps. According to FZK recommendations the VENECIA package could be oriented on the TH analysis of cryopumps only. This modification could be useful for maximal simplification of the pre- and post-processor and visualization programming.

It should be emphasized that FZK recommendations on more suitable pre- and post- processing could be included in modified version of Venecia. A small service contract to support usage of Venecia by FZK personal is recommended in order to be maximally close to FZK practice.

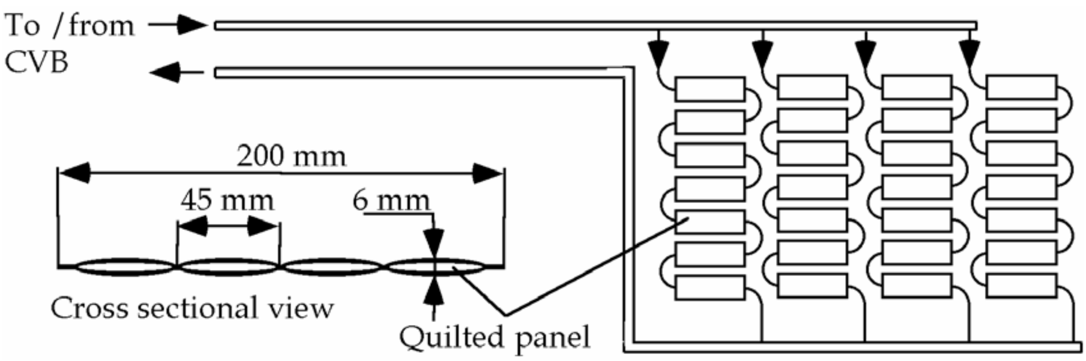
The ALPHYSICA is also ready for tasks with FZK to study different specific operating scenarios of regeneration and nominal cooling for different options of cryopumps. As example the efficiency of usage of regeneration stage named “cold helium exhaust (recovery)” should be examined in details in order to guarantee that vacuum decrease during this stage of regeneration does to lead to great increase of temperature of helium flow returned back to cryoplant and hence to great reduction of helium quality of this return helium flow.

VENECIA provides modelling of cryopumps and analysis of their behaviour in basic modes. As an example, a simplified version of the ITER torus cryopump model is presented.



Cryopump with cryopanels, ring manifolds and helium supply/return pipes

The torus cryopump consists of 28 charcoal coated cryopanels hydraulically grouped into 4 parallel branches. Every branch has 7 cryopanels connected in series.

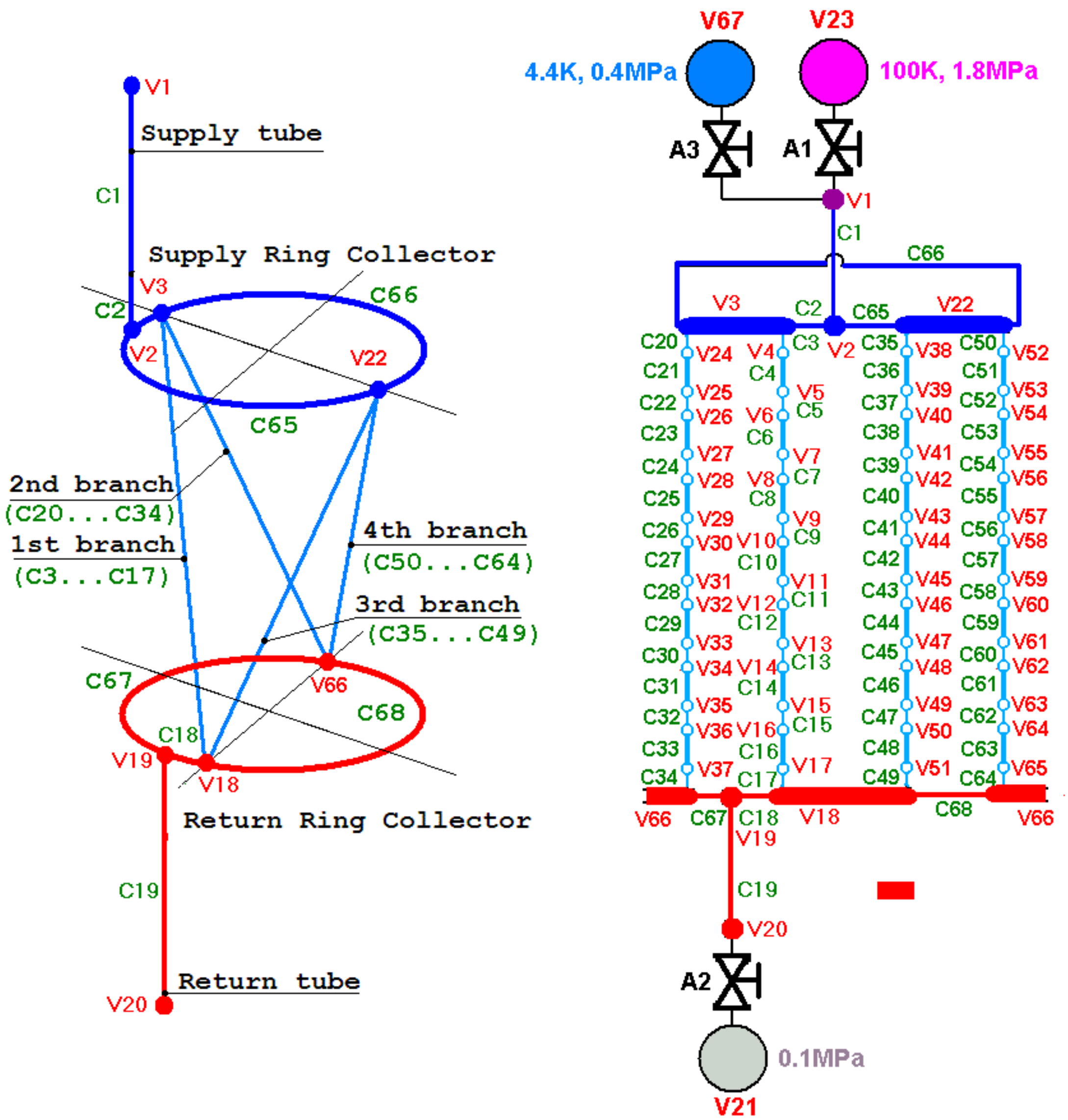


Hydraulic scheme of torus cryopump.

Table 1 Basic parameters of cryopump components

Components	Length, m	Cross section area for He flow, mm^2	Wall cross section area, mm^2	Wetted perimeter, mm	Material
Supply/return pipes	-	1063	193	94.25	Stainless steel
Ring manifolds	3.8	1100	313.4	125.7	Stainless steel
U-shaped pipes	0.17	235.3	121.3	54.3 x4	Stainless steel
Quilted cryopanels	1.0	120.0 x4	760	90.5 x4	Stainless steel

The model includes all components of the cryopump: 28 cryopanels, 32 U-shaped pipes, 2 ring manifolds each formed with 3 elements, and helium supply/return lines. Every component is described individually.



VENECIA model of torus cryopump for analysis of different operating modes

Table 2 Basic parameters of model elements

	Length, m	**Cross section area,** mm^2	**Wetted perimeter,** mm	**Comments**
Helium flows				
C1, C19	10.0	1063	94.25	Supply/return pipes
C2, C18	0.25	1100	125.7	Ring manifold parts
C65, C67	1.9	1100	125.7	Ring manifold parts
C66, C68	1.65	1100	125.7	Ring manifold parts
C3, C5, …, C17 C20, C22, …, C34 C35, C37, …, C49 C50, C52, …, C64	0.17	235.3	54.3 x4	U-shaped pipes
C4, C5, … C16 C21, C23, …, C33 C36, C38, …, C48 C51, C53, …, C63	1.0	120.0 x4	90.5 x16	Cryopanels
Walls				
W1, W19	10.0	193.	-	Supply/return pipes
W2, W18	0.25	313.4	-	Ring manifold parts
W65, W67	1.9	313.4	-	Ring manifold part s
W66, W68	1.65	313.4	-	Ring manifold part s
W3, W5, … W17 W20, W22, …, W34 W35, W37, …, W49 W50, W52, …, W64	0.17	121.3	-	U-shaped pipes
W4, W5, … W16 W21, W23, …, W33 W36, W38, …, W48 W51, W53, …, W63	1.0	190. x4	-	Cryopanels

Volumes

	Volume, cm^3	**Comments**
V4, V5, … V17 V24, V25, … V37 V38, V39, … V51 V52, V53, … V65	15.7	The cryopanel collectors
V2, V3, V18, V19, V22, V66	53.2	Connections between the ring manifold parts
V1, V20	354	Connections between the valves and supply/return pipes

Here C1 and C19 simulate respective helium flows in the supply and return pipes, each 10 m long with the inner diameter of 45 mm;
C2, C65, C66 and C18, C67, C68 simulate helium flows in different parts of the supply and return ring manifolds;
C4, C6, C8, … , C16 correspond to the helium flows in cooling channels of 7 quilted cryopanels hydraulically linked in series via U-shaped pipes C3, C5, C7, … , C17.

Channels C1-C19 are thermally linked with corresponding walls W1-W19 which are actual walls of pipes and cryopanels.

All cryopanels are modelled as straight channels. The inlet/outlet pressure drop in the cryopanels defines mainly the total cryopanel hydraulic resistance. Local hydraulic resistances of cryopanels are taken into account by means of additional friction in the friction factor of the U-shaped pipes.

In addition, the hydraulic circuit includes control valves A1, A2, A3 and some artificial components: infinite helium volumes V23, V67, V21 in order to model the helium supply under different operating conditions.

Table 3. Helium parameters in artificial infinite volumes

Volume	Pressure, MPa	Temperature, K
“hot” line V23	1.8	100
“cold” line V67	0.4	4.4
“LHe bath”/collector V21	0.1	

The model enables simulation of 3 basic operating modes in the regeneration and cool-down stages of the cryopump:

A. LHe push-out: when valve A1 is open, “hot” helium supplied from the 100K volume V23 at 1.8MPa expels the cold helium out from the cryopump into the “LHe bath” V21. The push-out of cold helium allows saving some part of liquid helium by transferring it through a J-T valve A2 directly into the LHe bath.;
B. warm-up from 4.4 K to 100 K: “hot” helium is supplied from the volume V23 till the cryopump temperature reaches 100K;
C. cool-down from 100 K to 4.4 K: when the valve A3 is open, cold helium is supplied from SHe line V67 at 0.4 MPa till the cryopump temperature falls to 4.4 K.

First two modes provide the cryopump regeneration.

Every operating mode takes 150 s. In all simulations the heat associated with the re-sorption process and radiation is neglected.

Mode A (PUSH-OUT)

The inlet of the cryopump supply pipe with 4.4K SHe is connected through the valve A1 with a fixed opening to a high pressure manifold modelled as an infinite volume V23 with GHe at 1.8MPa and 100K. During the push-out stage such connection provides practically constant mass flow rate at the inlet of the supply pipe due to the critical ratio of pressures in the high pressure manifold and the supply pipe. The outlet of the cryopump return pipe is connected through the “J-T” valve A2 to the LHe bath modelled as an infinite volume at 0.1 MPa. A2 also operates as a relief valve to keep the pressure at the return pipe outlet, and therefore in the cryopanels, close to the initial level of 0.4 MPa. The push-out mode of regeneration is assumed finished when the outlet temperature (upstream A2) starts rising up. The opening of this valve is assessed as 1 mm^2

to provide an appropriate mass flow rate during 150 s. Initial conditions for simulation of the cryopump push-out stage are zero helium velocity, 4.4 K and 0.4 MPa for all channels of the cryopump.

The full set of inputs for the push-out simulation is available in the input file **DEMO3A.IN**.

Mode B (WARM-UP)

In 150s after the beginning of regeneration, when the cryopump outlet temperature starts rising up, the openings of both valves A1, A2 sharply enlarge to new fixed positions of 100 mm^2 and 40 mm^2 respectively, and the warm-up starts. Larger openings of valves A1, A2 cause a pressure rise between the valves from 4 bar to a value that is slightly lower than the pressure in volume V23.

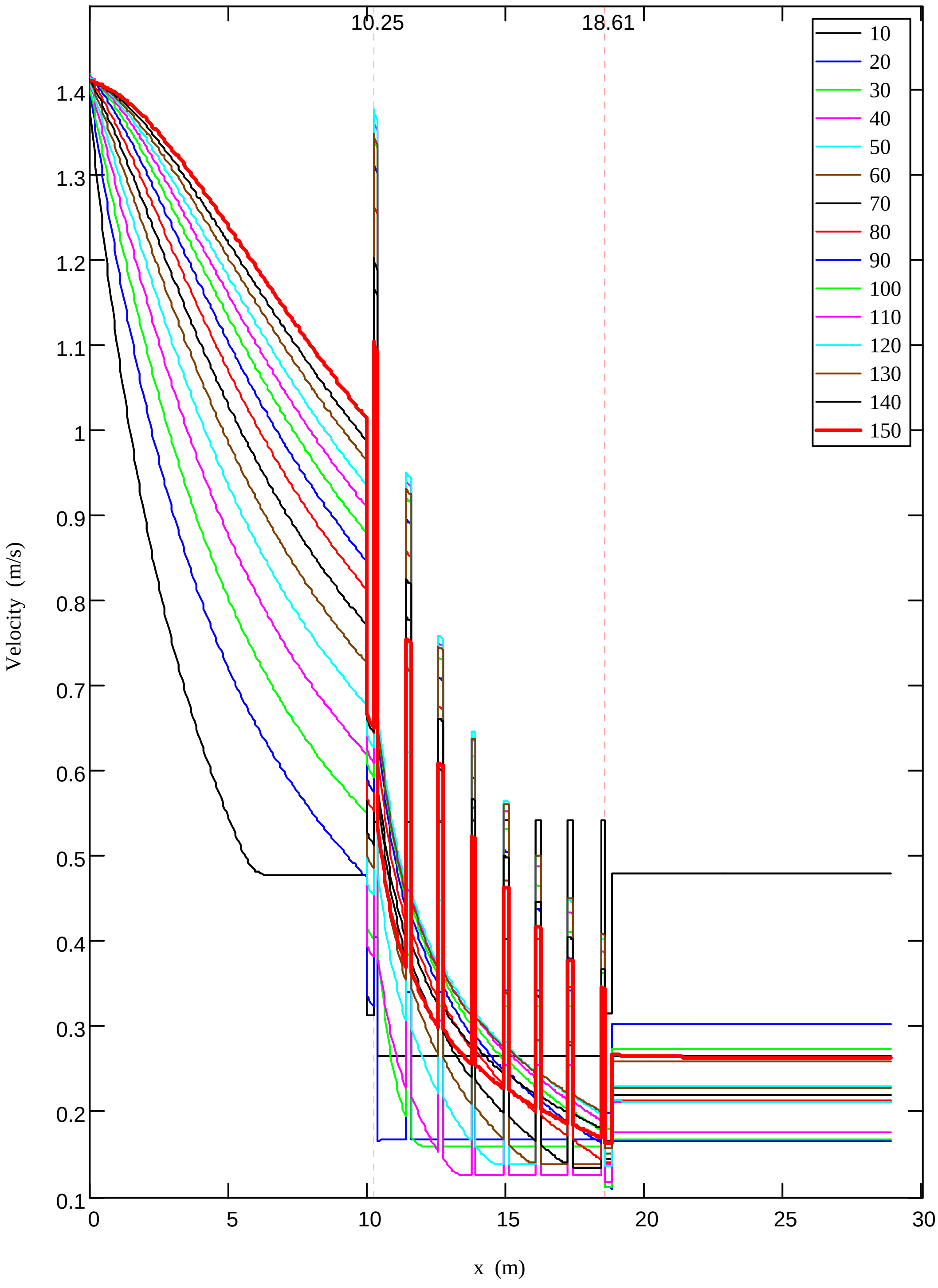
For taken parameters of A1 and A2 valves this stage will finish in 150 s (at 300s from beginning) when the temperature at the outlet of return pipe will close 100K.
The full set of inputs for the warm-up simulation is available in the input file **DEMO3B.IN**.

Mode C (COOL-DOWN)

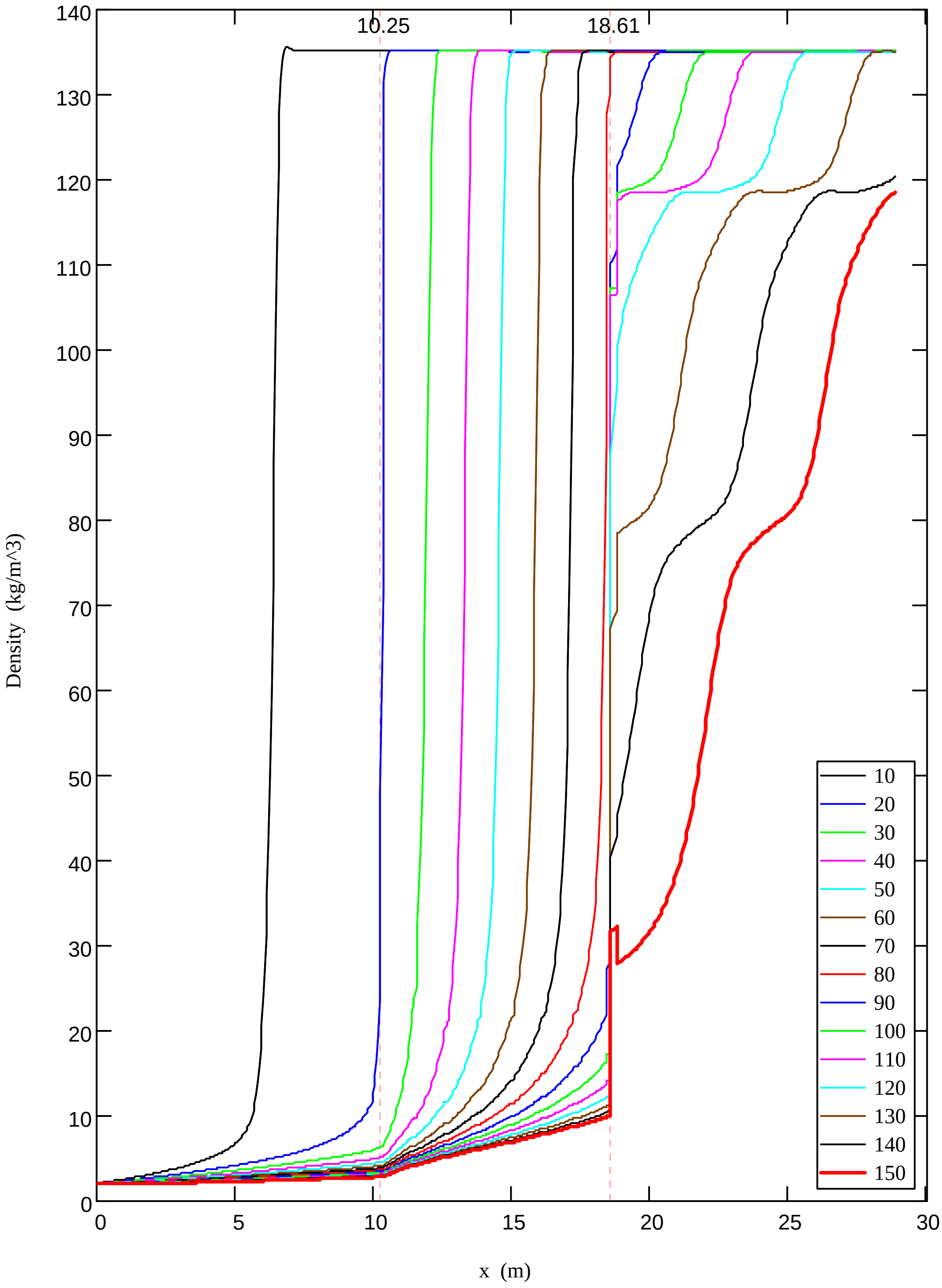
Immediately after the outlet temperature reaches 100K at the warm-up stage, the cool-down from 100K to 4.4K is simulated. Valve A1 is assumed to instantly close, while valve A3 fully opens. Simultaneously valve A2 starts operate as a safety valve so as to keep the helium pressure at the outlet of the return pipe at level of 0.365 MPa. With such cool down control algorithm the outlet temperature of the return pipe reaches 4.4K at 150 s (at 450s from beginning).
The full set of inputs for cool-down simulation is available in the input file **DEMO3C.IN**.

Simulated results

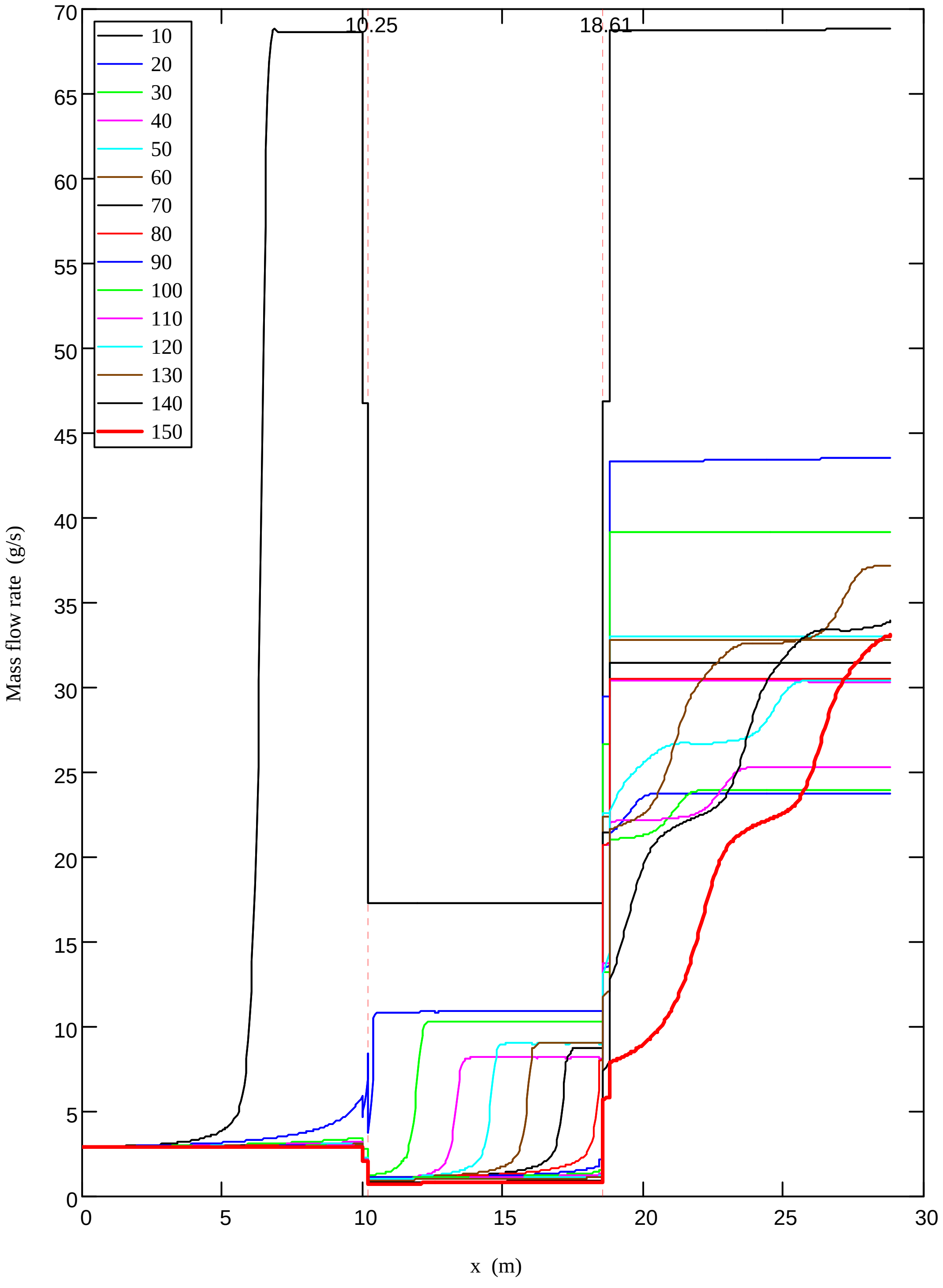
Below main simulated results are presented for the 3 operating modes of the cryopump: push-out, warm-up, and cool-down. The helium behaviour is presented along the supply pipe C1(0 to 10m) with ring manifold C2 (10m to 10.25m), first quilted cryopanel branch C3…C17 (10.25 m to 18.61 m), and ring manifold C18(18.61m to 18.86m) and return pipe C19 (18.86m to 28.86m).



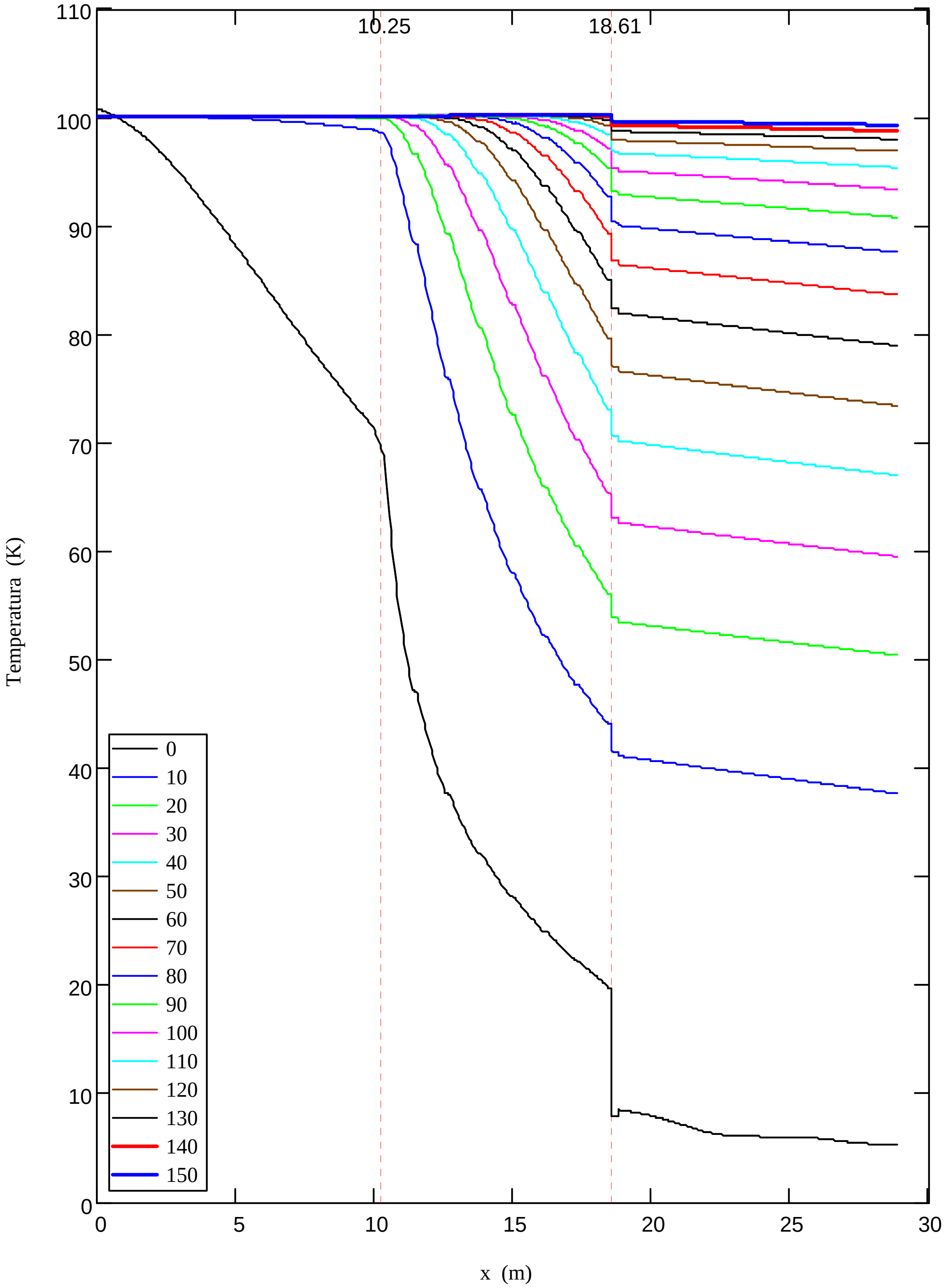
Cryopump push-out: variations of helium velocity along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



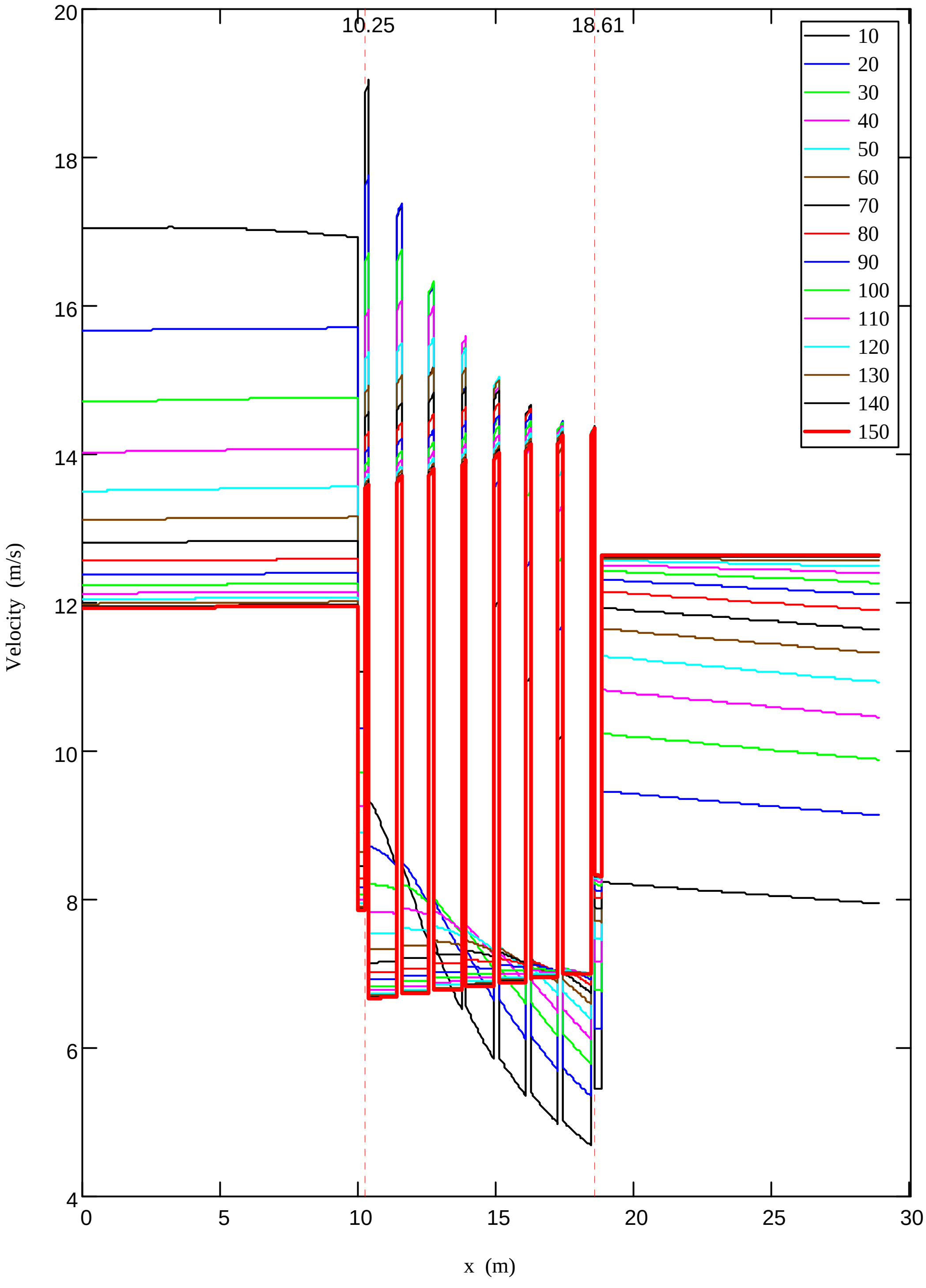
Cryopump push-out: variations of helium density along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



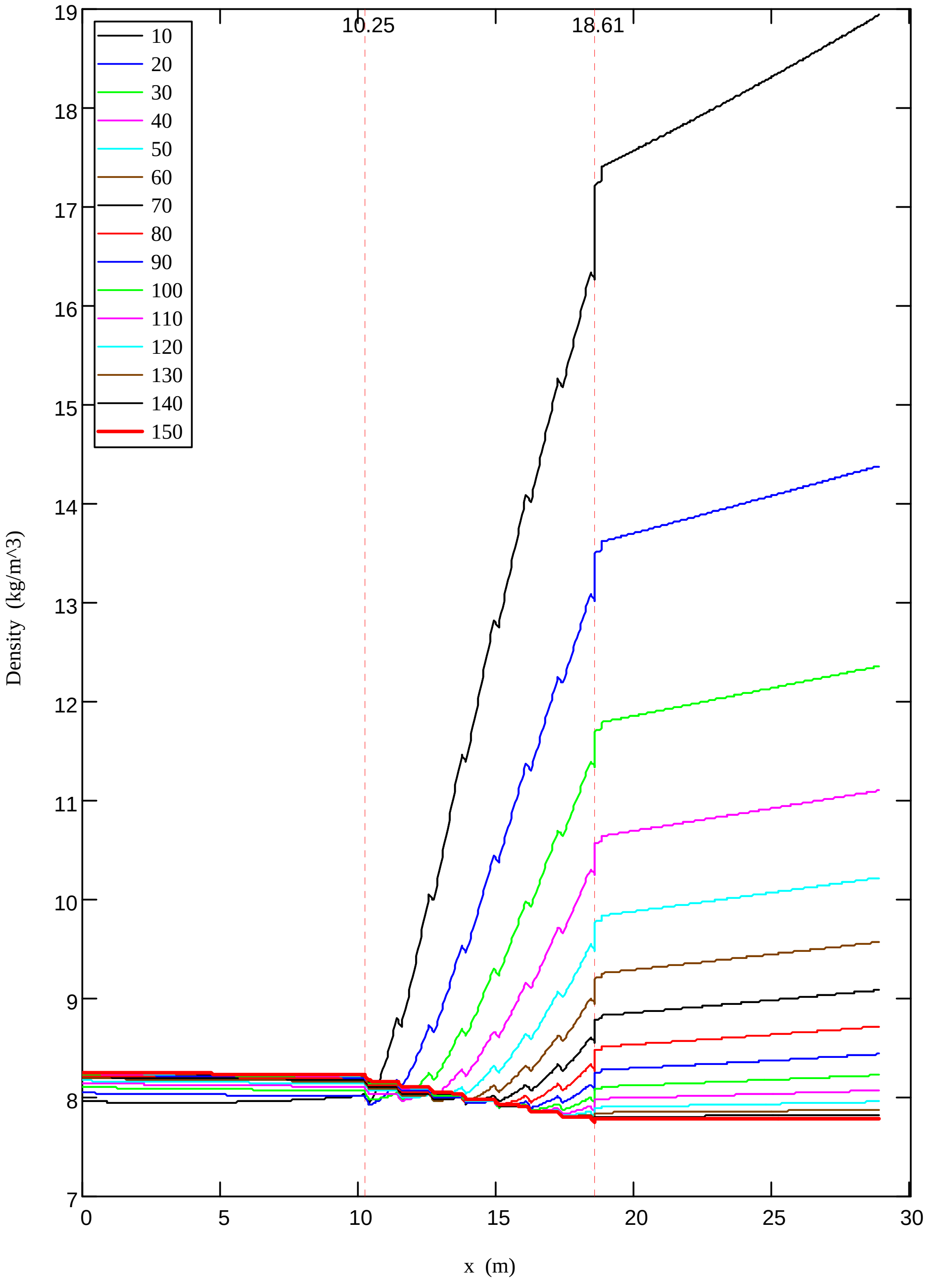
Cryopump push-out: variations of helium mass flow rate along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



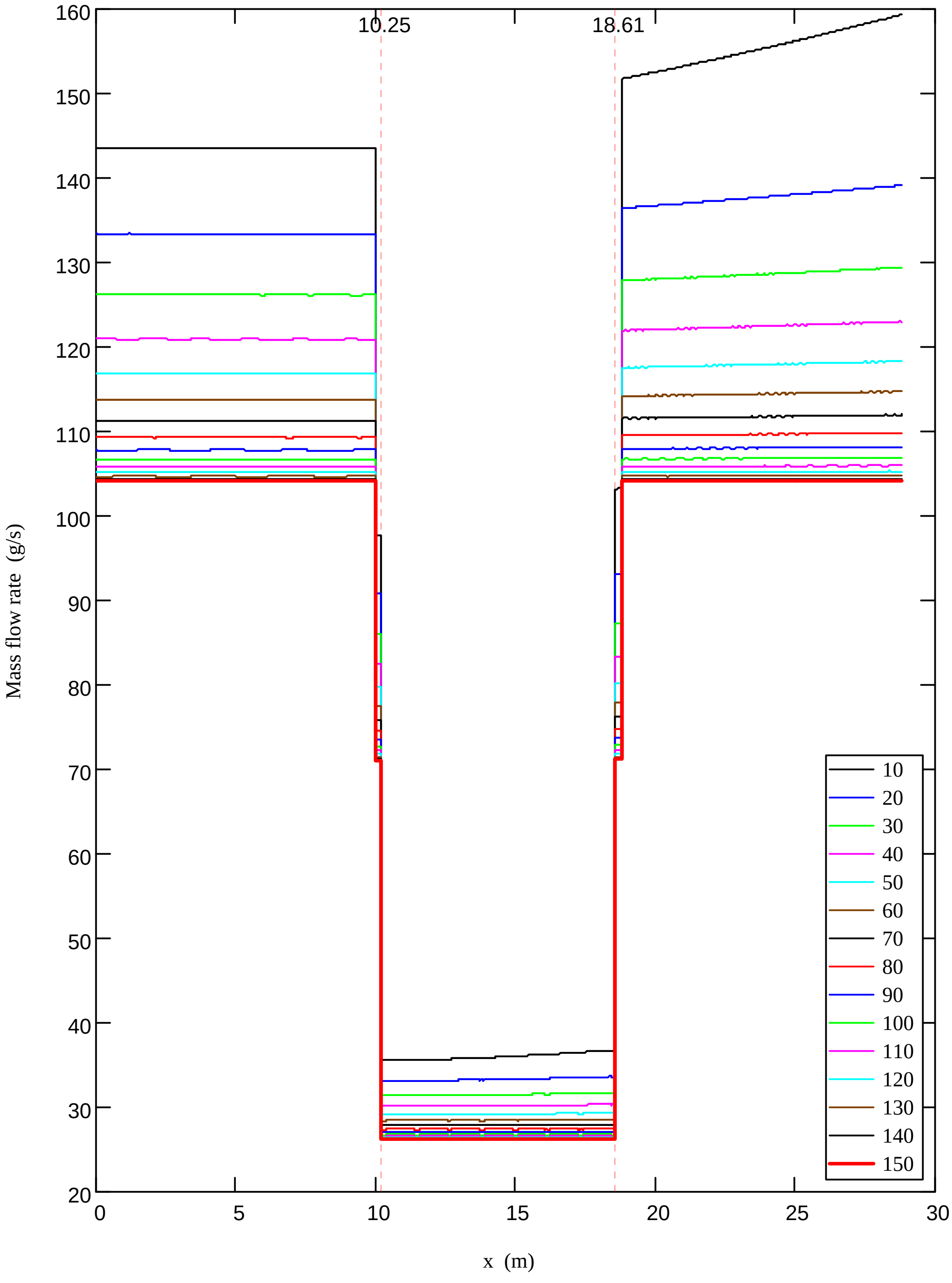
Cryopump warm-up: variations of helium temperature along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



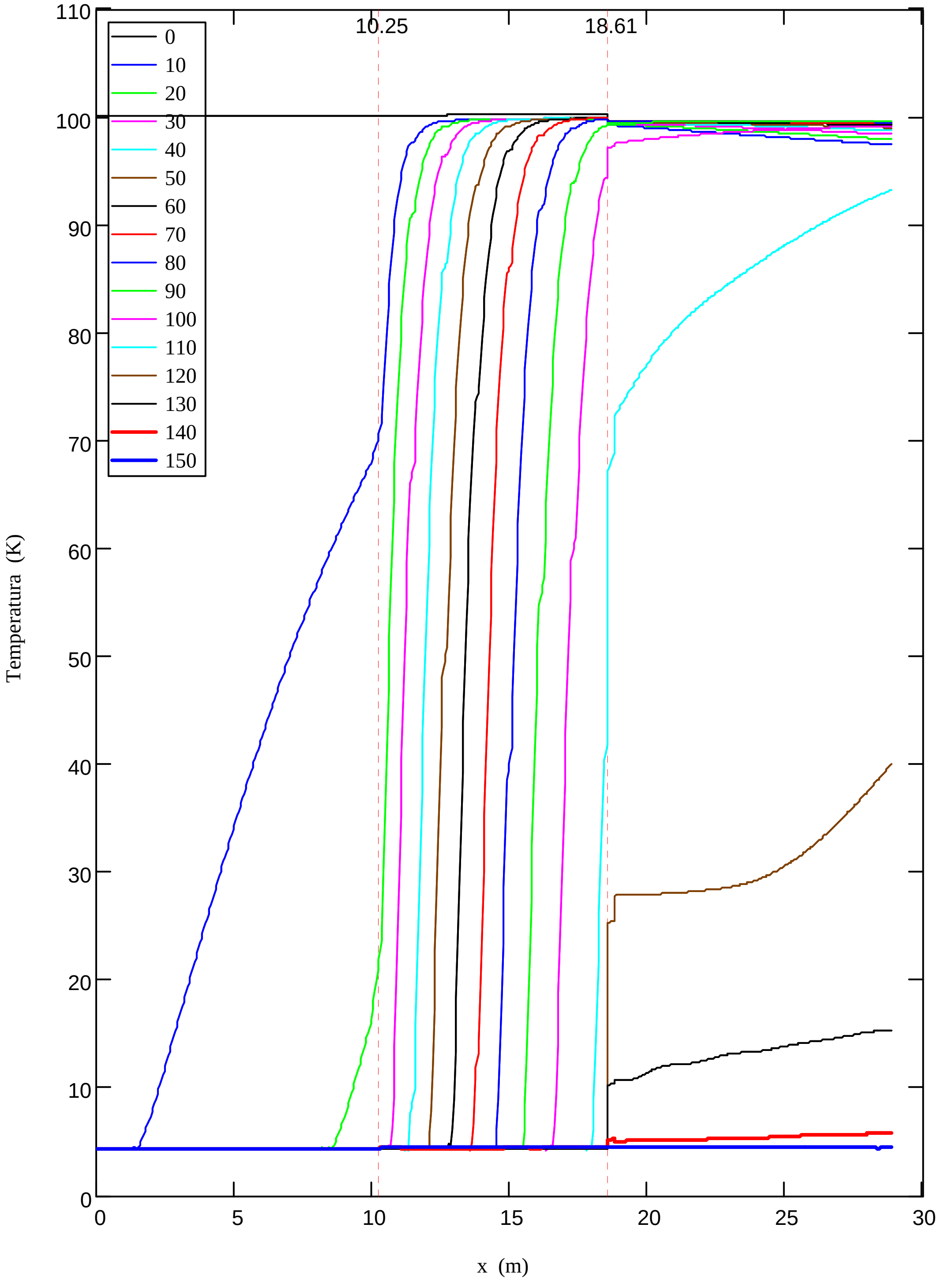
Cryopump warm-up: variations of helium velocity along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



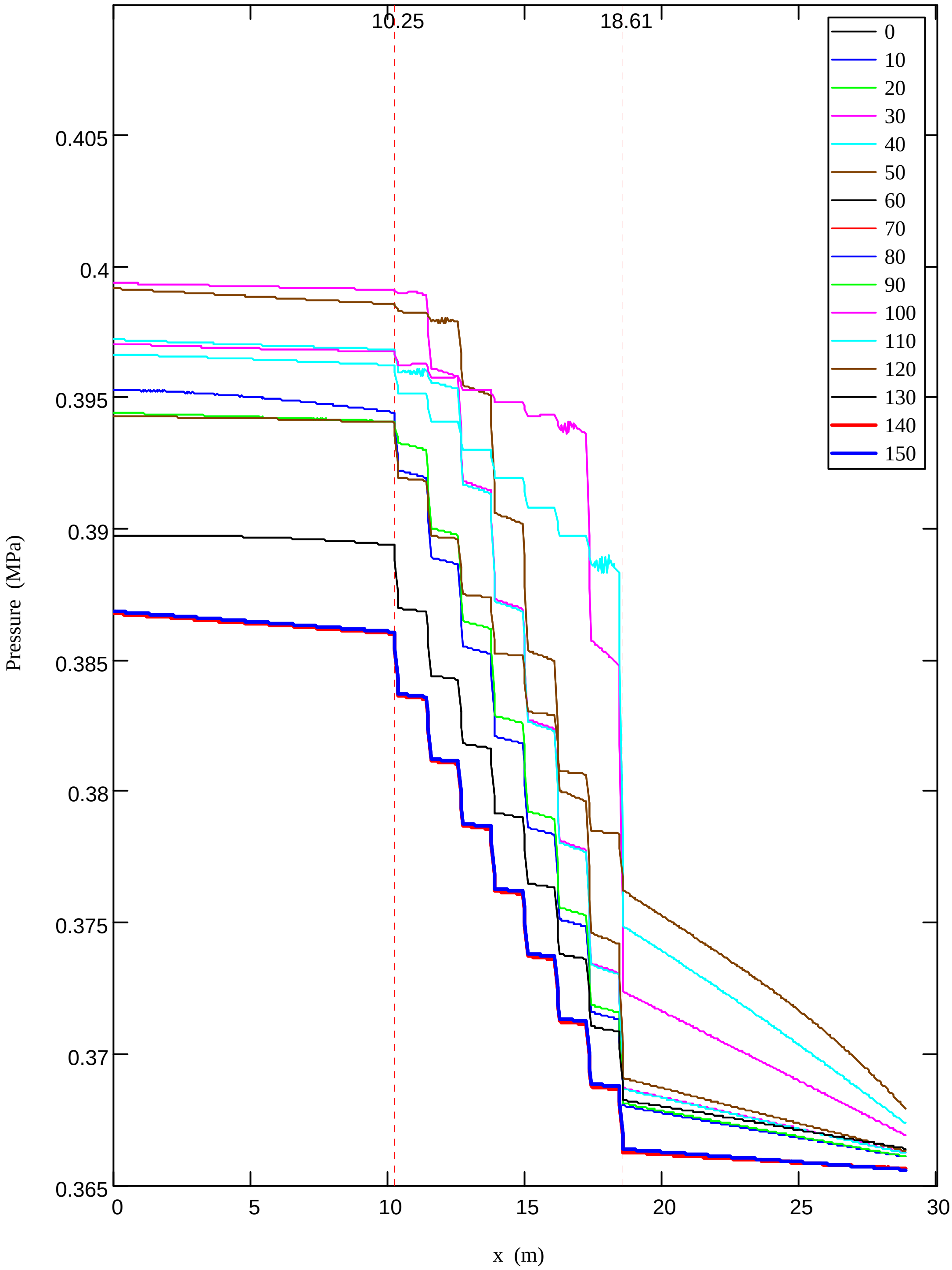
Cryopump warm-up: variations of helium density along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



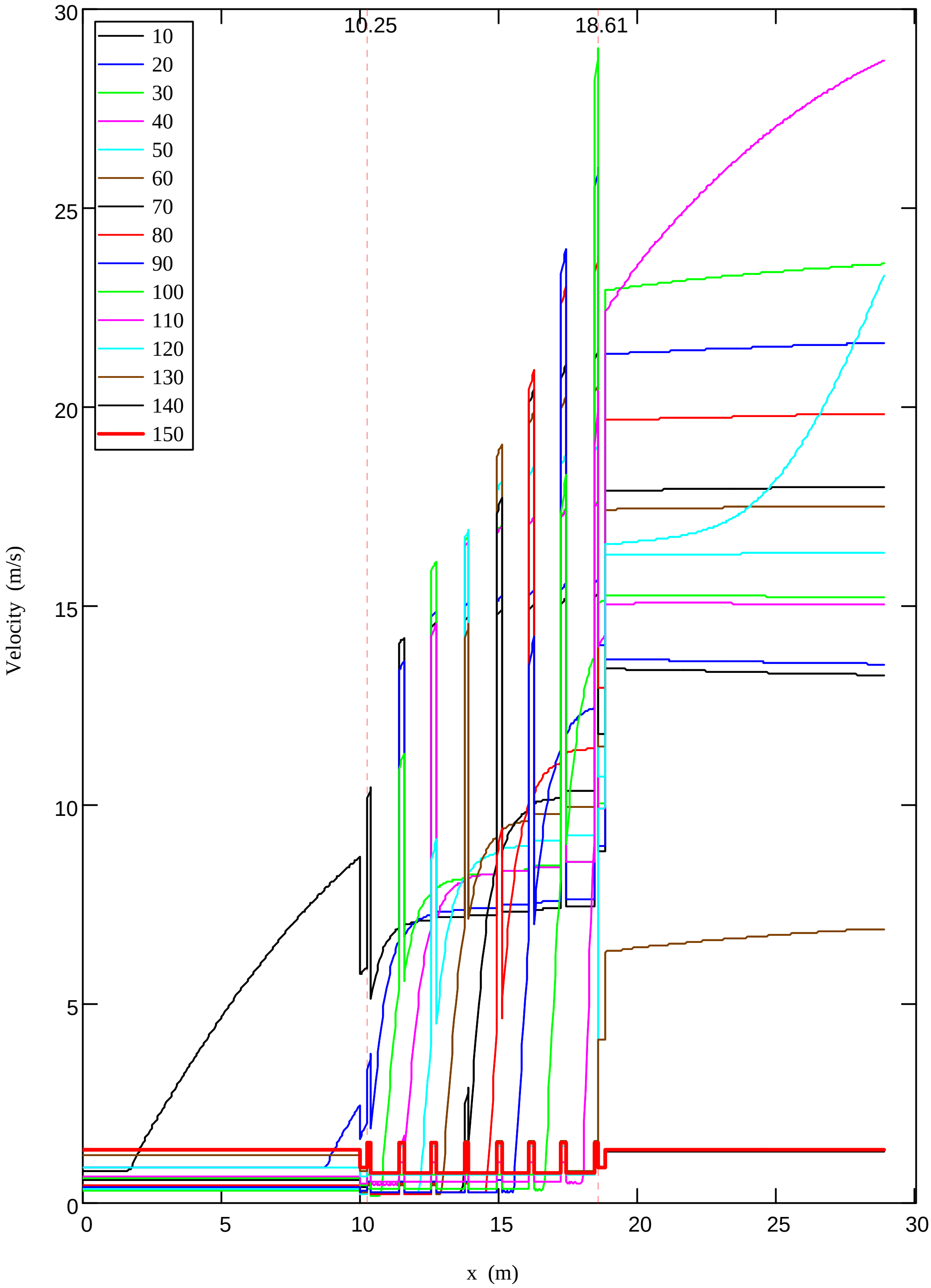
Cryopump warm-up: variations of helium mass flow rate along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



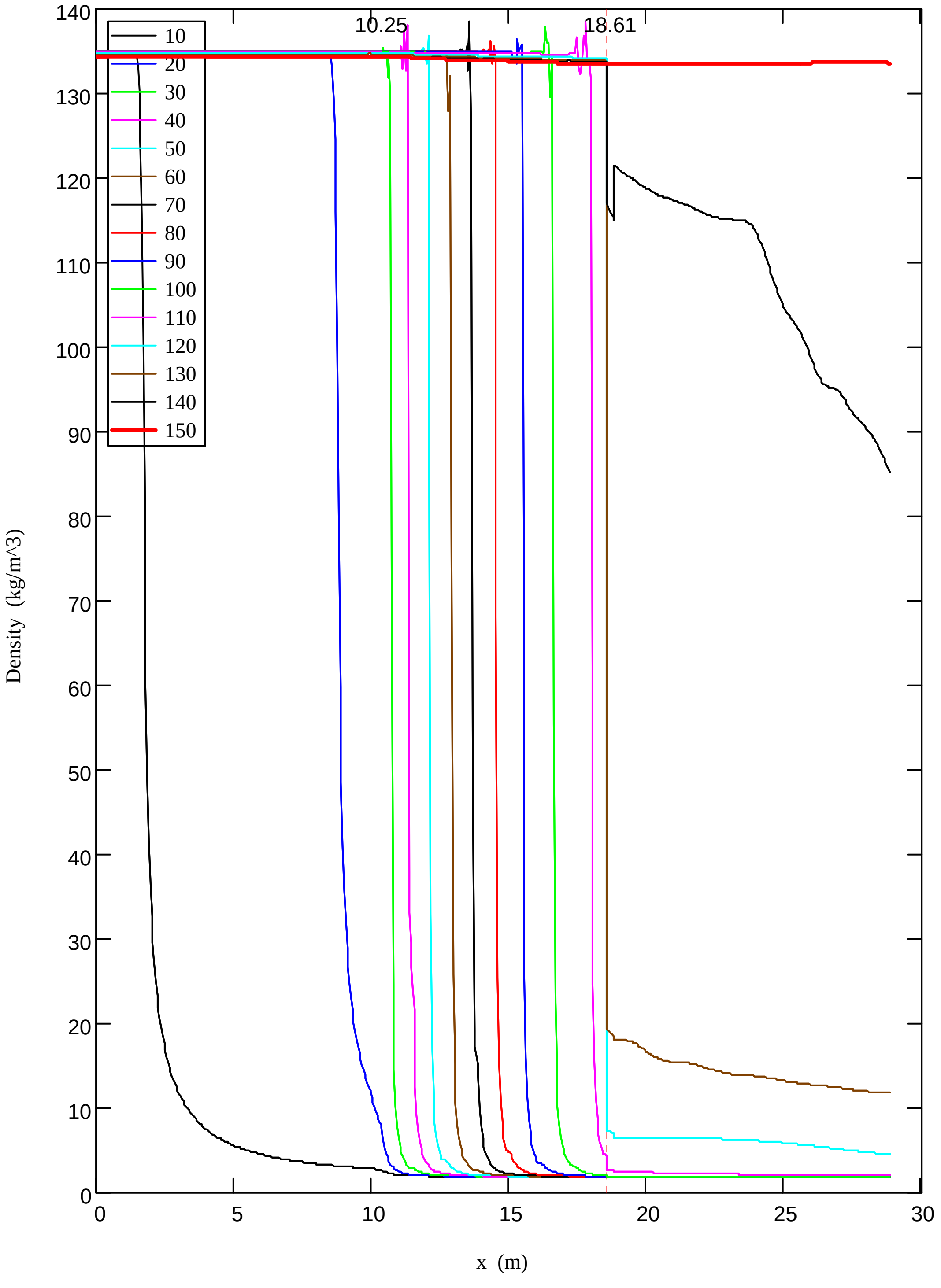
Cryopump cool-down: variations of helium temperature along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



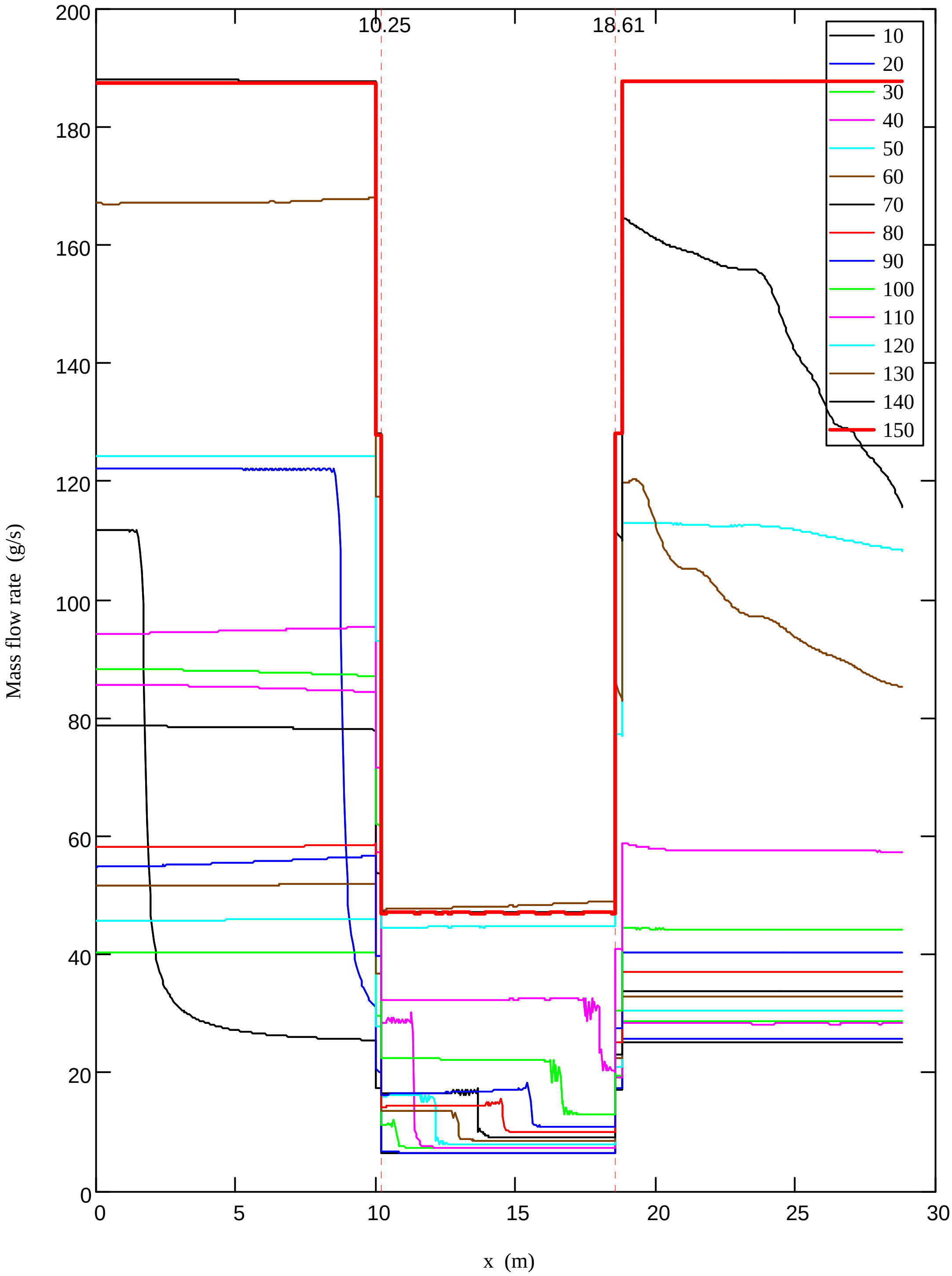
Cryopump cool-down: variations of helium pressure along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



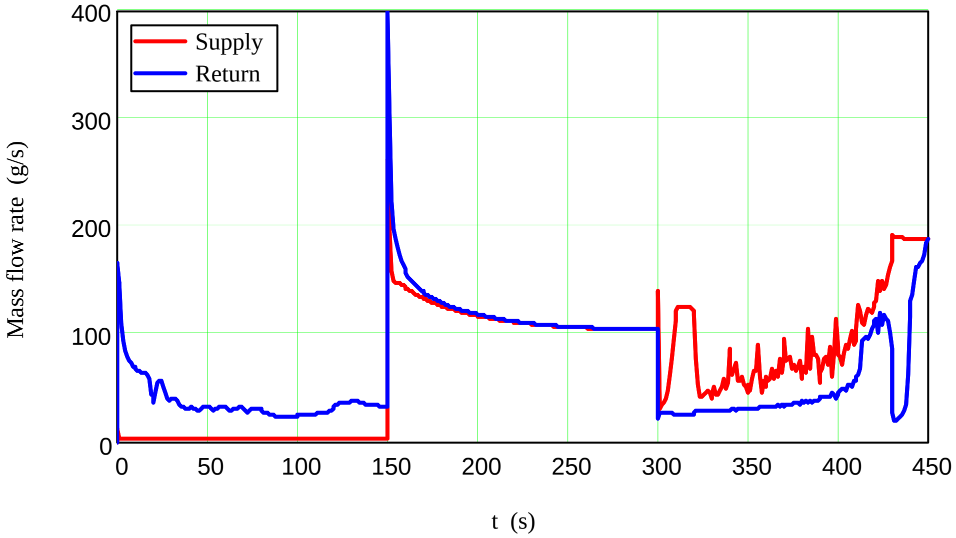
Cryopump cool-down: variations of helium velocity along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



Cryopump cool-down: variations of helium density along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19

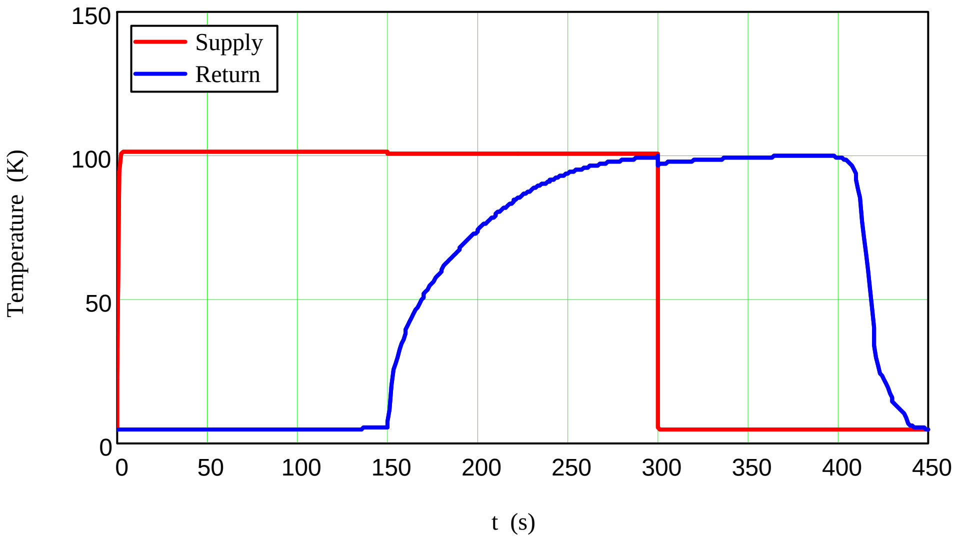


Cryopump cool-down: variations of helium mass flow rate along supply pipe C1, ring manifold C2, first cryopanel branch C1…C17, ring manifold C18 and return pipe C19



Evolution of the helium mass flow rate at the inlet of the supply pipe and outlet of the return pipe during 3 modes:

- 0-150s: push-out
- 150s-300s: warm-up
- 300s-450s: cool-down



Evolution of the helium temperature at the inlet of the supply pipe and outlet of the return pipe during 3 modes:

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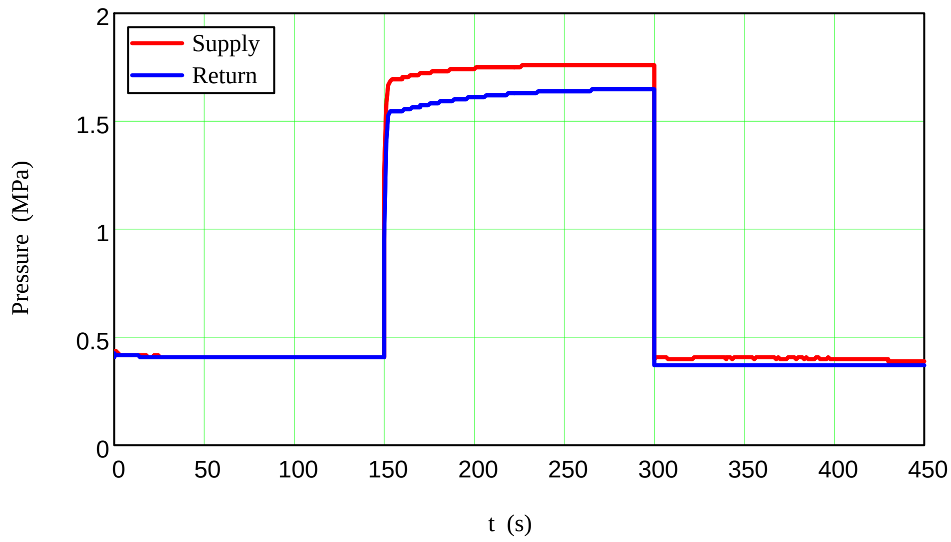

Evolution of the helium pressure at the inlet of the supply pipe and outlet of the return pipe during 3 modes:

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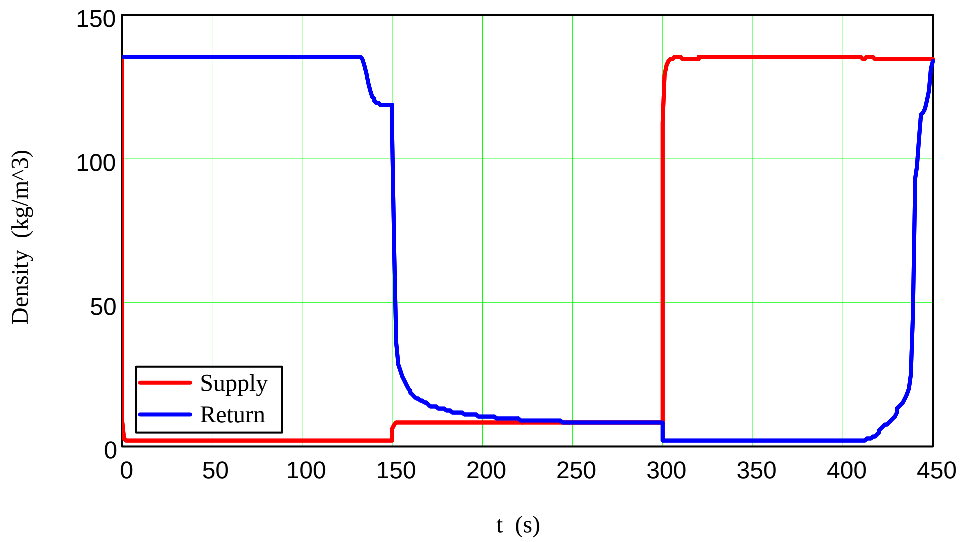
- 300s-450s: cool-down



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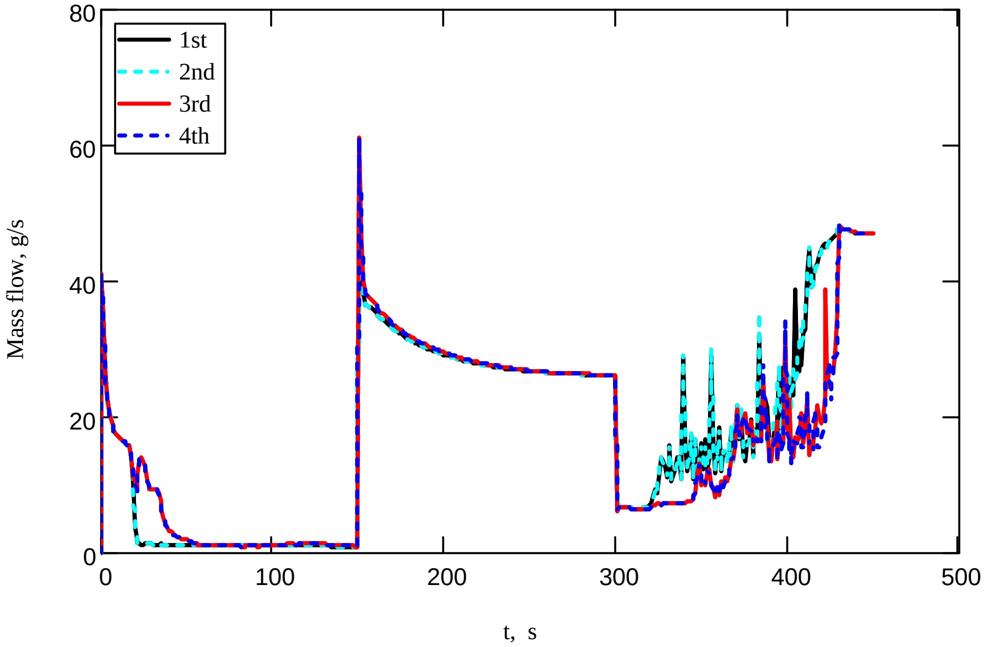
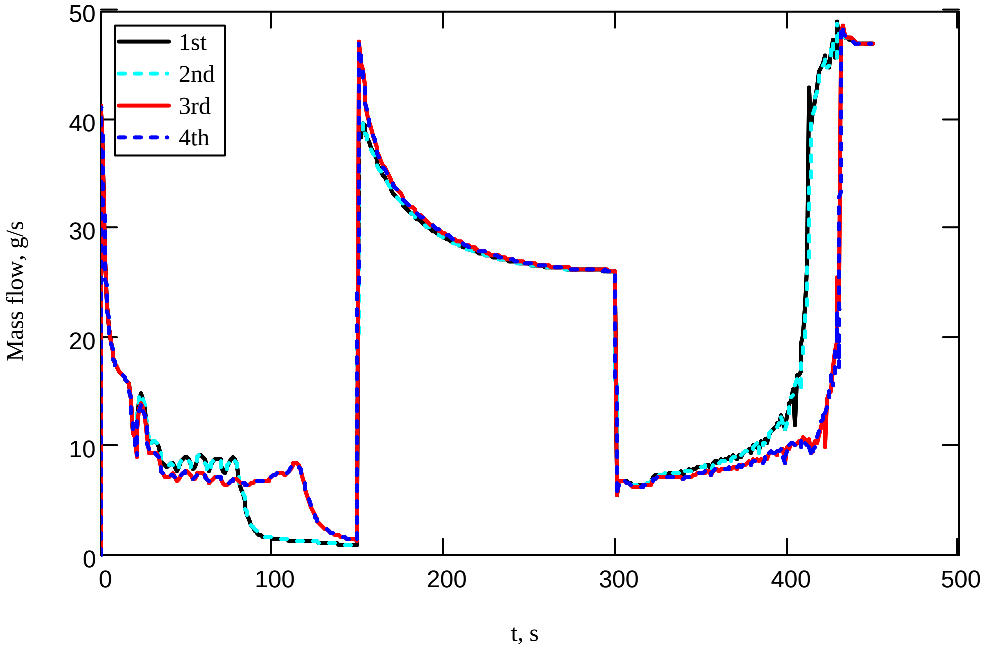


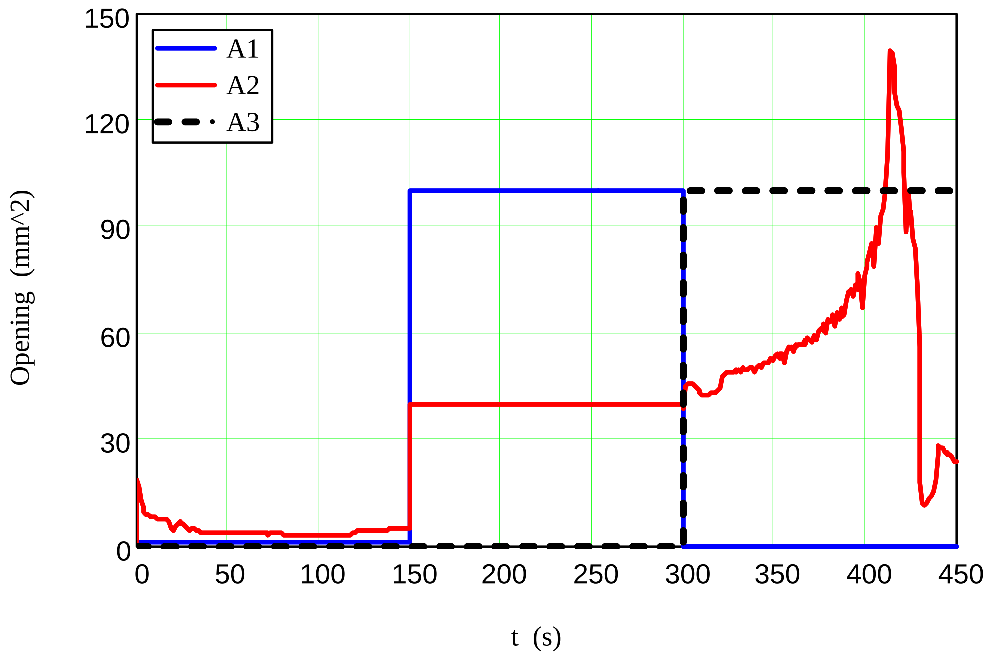
Evolution of the helium mass flow rate at inlet of different cryopanel branches during 3 modes:

- 0-150s: push-out
- 150s-300s: warm-up
- 300s-450s: cool-down



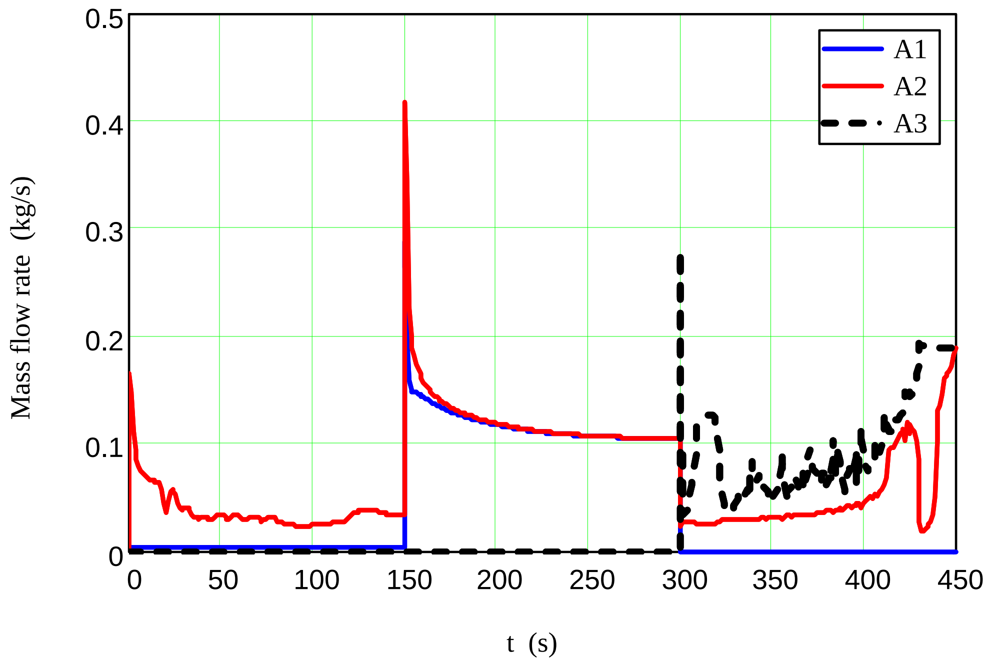
Evolution of the helium mass flow rate at outlet of different cryopanel branches during 3 modes:

- 0-150s: push-out
- 150s-300s: warm-up
- 300s-450s: cool-down



Evolution of the control valves opening during 3 modes:

- 0-150s: push-out
- 150s-300s: warm-up
- 300s-450s: cool-down



Evolution of the mass flow rates through control valves during 3 modes:

- 0-150s: push-out
- 150s-300s: warm-up
- 300s-450s: cool-down