Features of Reaching the Operating Vacuum in the Accelerators of the NICA Project

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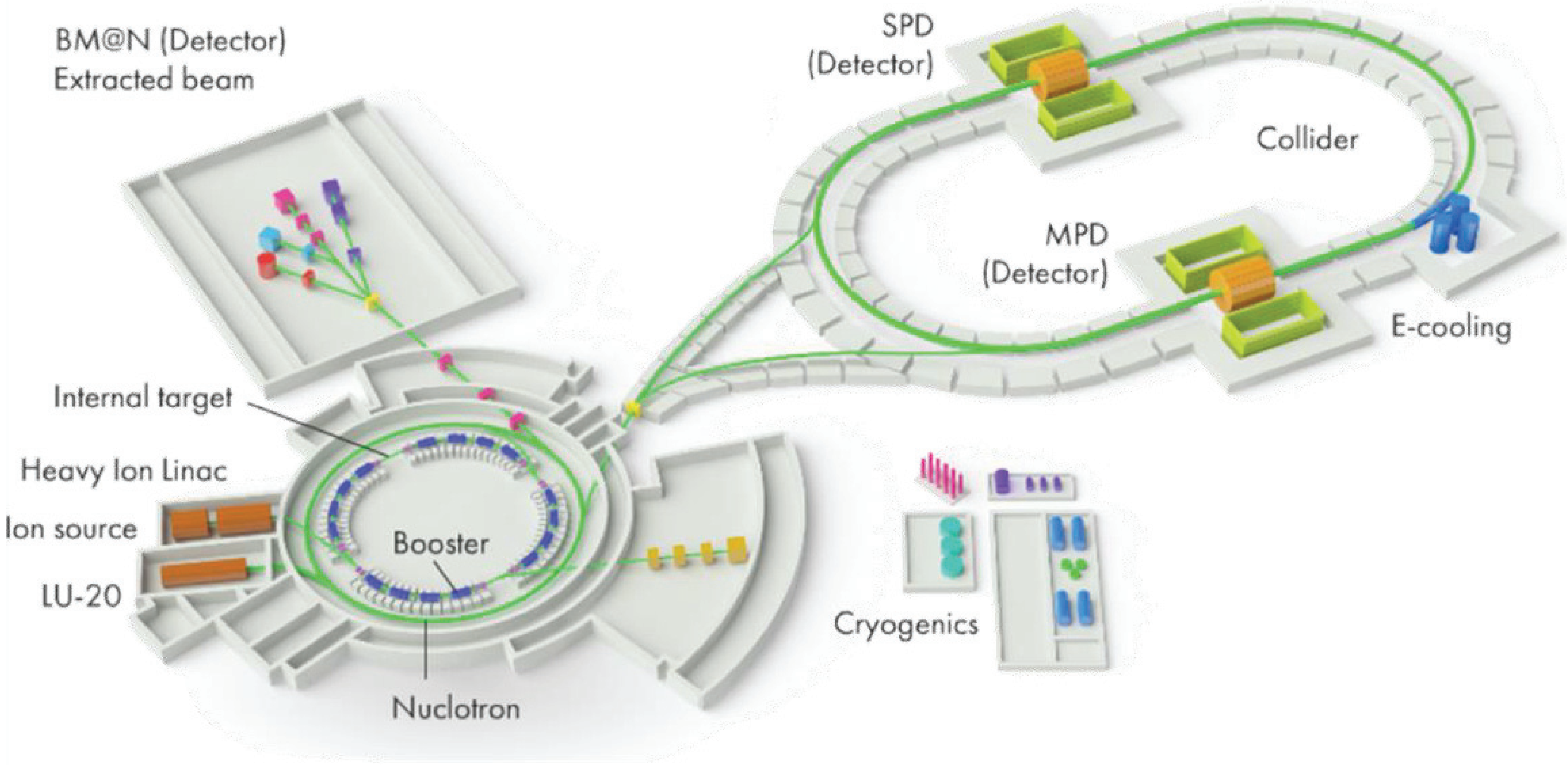
Content

- Requirements for vacuum conditions
- Factors that affect on reaching the ultimate vacuum
- Technological stages of obtaining an operating vacuum
- Examples and results

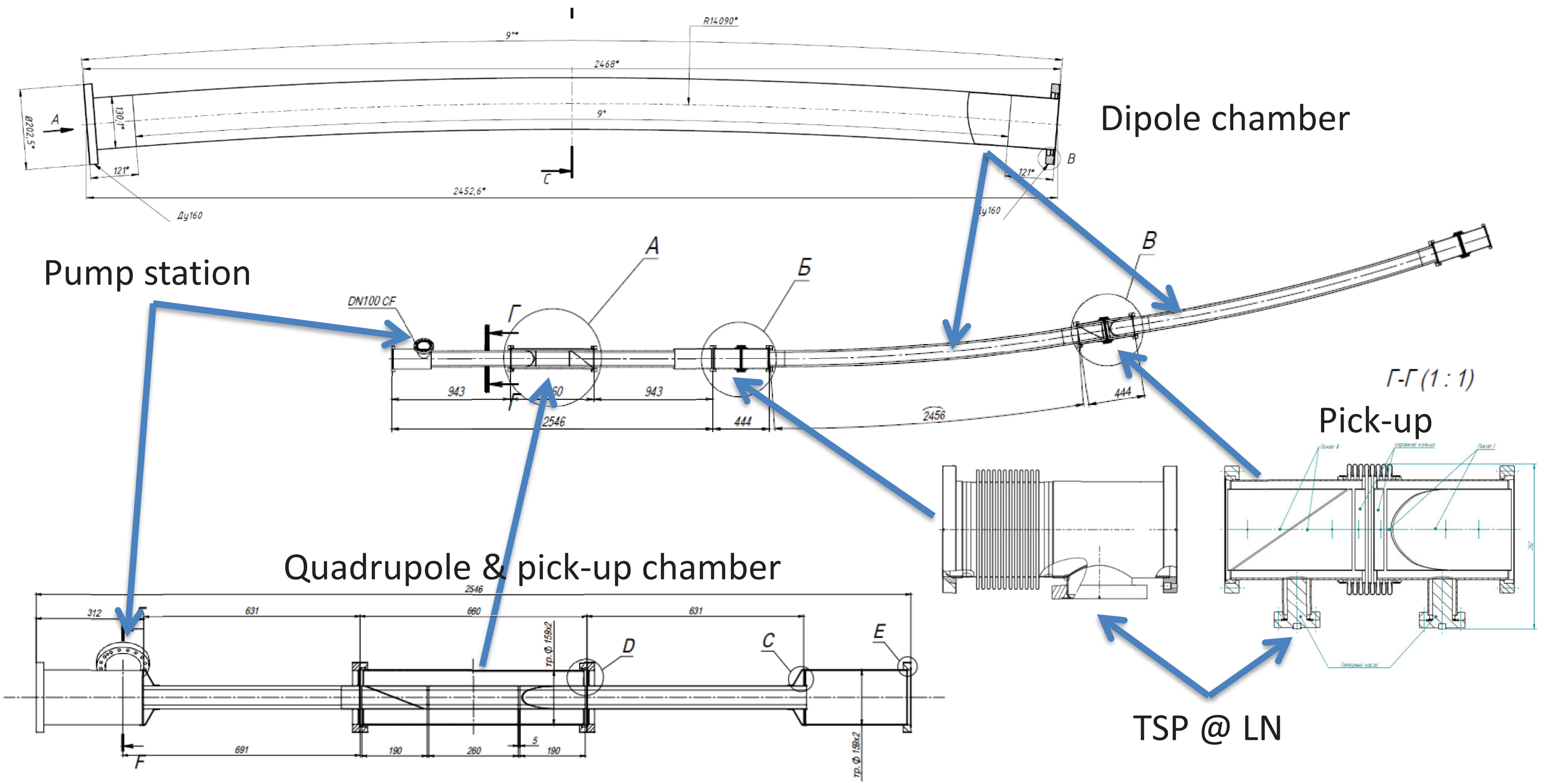
Accelerator complex NICA



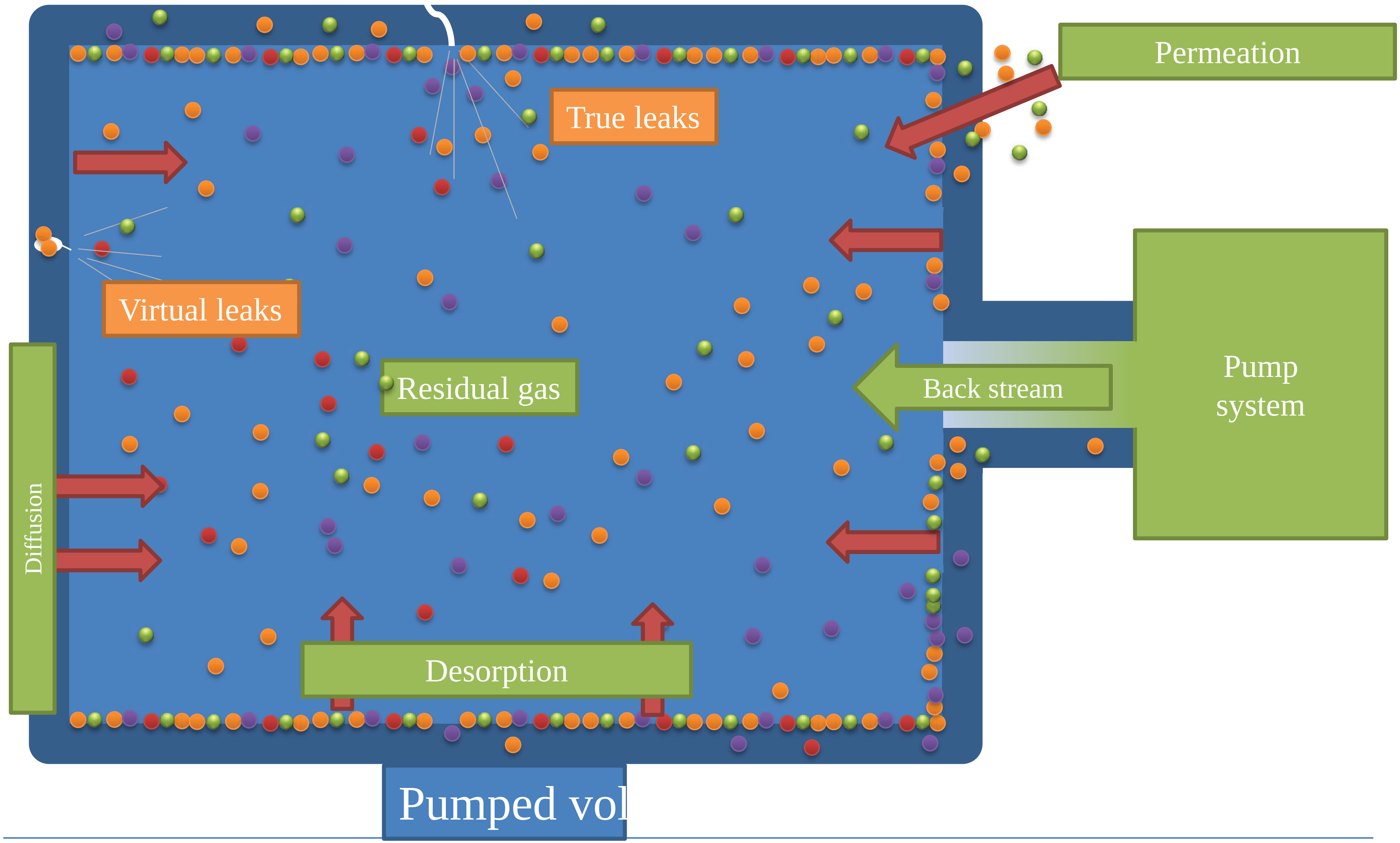
Vacuum volumes

Volume	Length, m	Pressure, Pa
Transport channels (b.205)	~150	$\leq 1\times10^{-1}$
Transport channels (between accelerators)	20-100	$\leq 1\times10^{-5}$
LU-20	20	$\leq 1\times10^{-4}$
HILAC	11,5	$\leq 1\times10^{-5}$
LILAC	~10	$\leq 1\times10^{-5}$
Nuclotron	251,5	$\leq 1\times10^{-7}$
Booster	211	$\leq 2\times10^{-9}$
Collider	503	$\leq 2\times10^{-9}$
MPD (beams collision)	9	$\leq 2\times10^{-9}$
Isolating volume		$\leq 2\times10^{-4}$

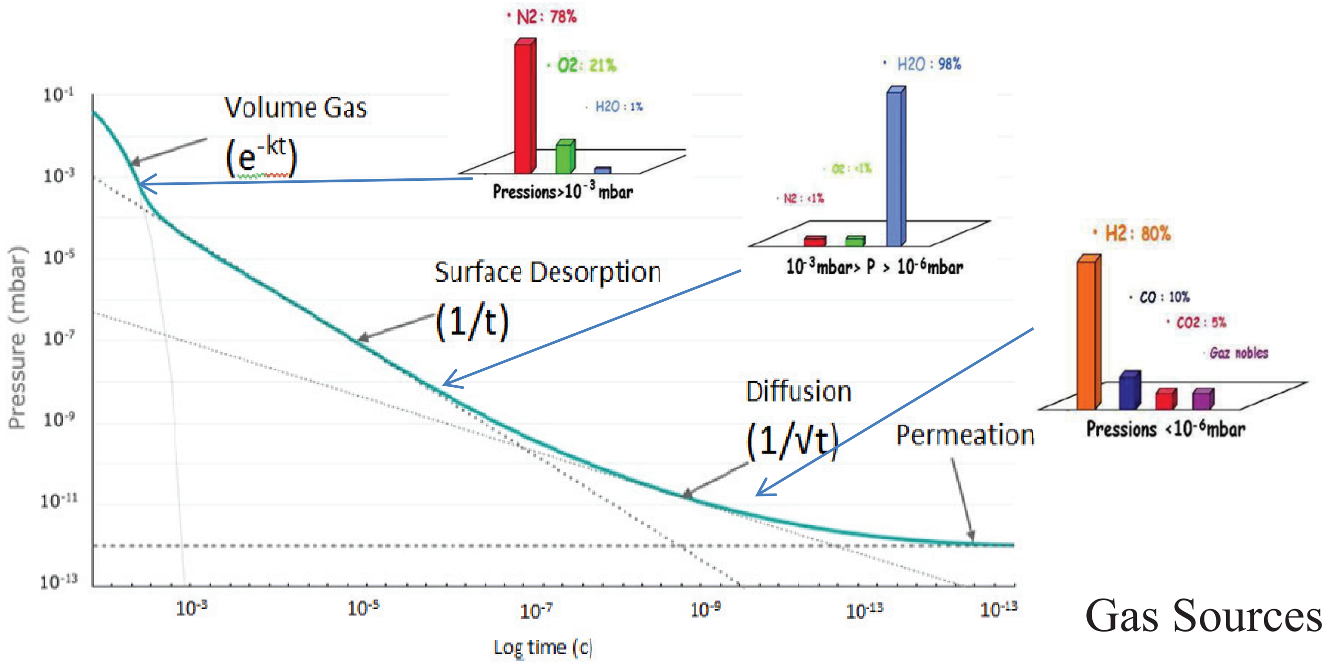
Examples of vacuum chambers



Sources of gas loads

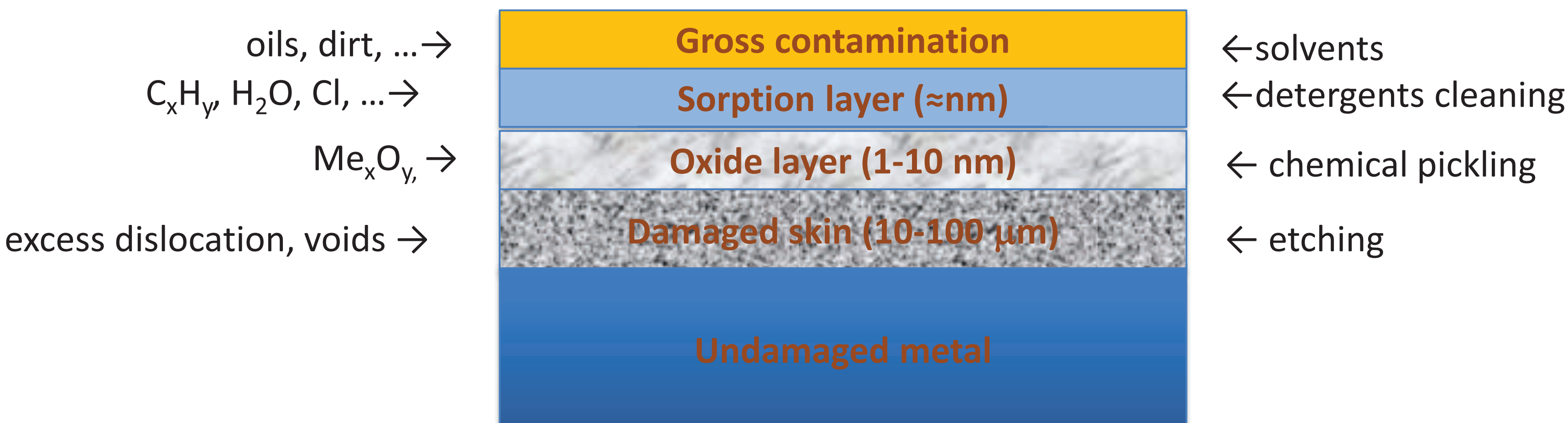


Limiting mechanisms during pumping down



$$P_{min} = \frac{Q_c}{S_e}$$

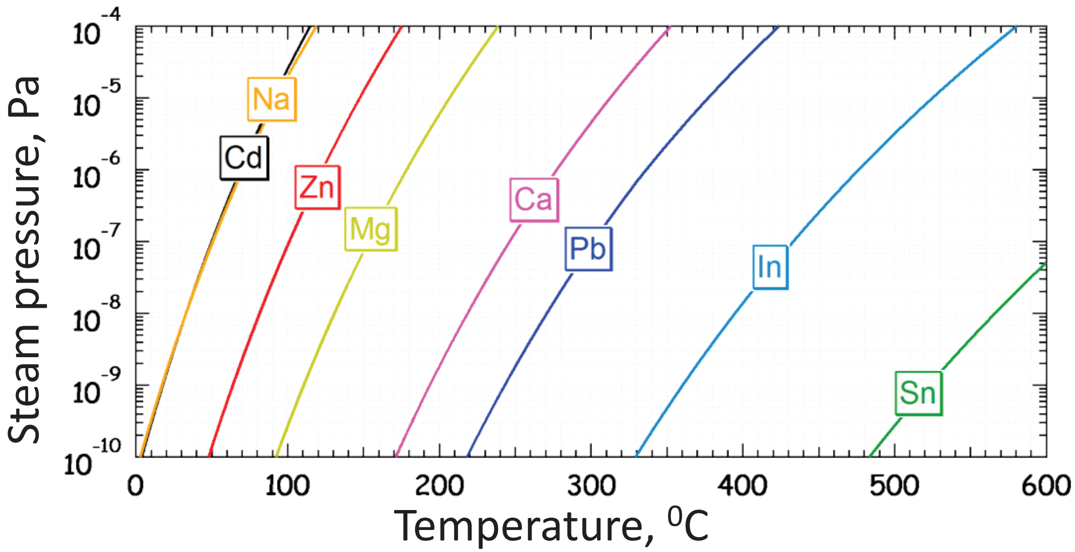
Gas Sources from surface



Materials and saturated steam pressure

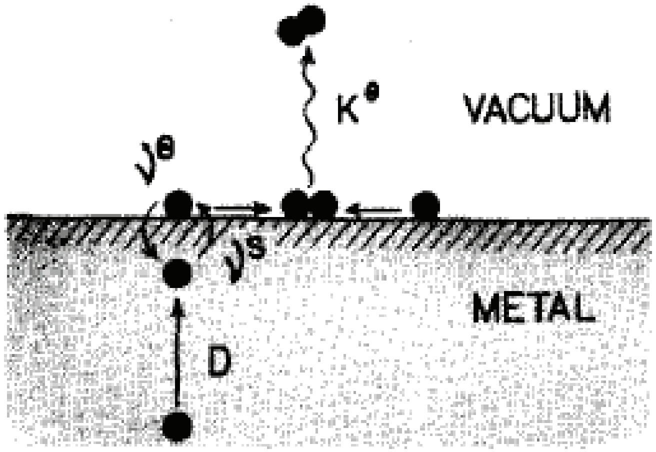
At room temperature

Material	q (mbar l s^{-1} cm^{-2})	Main gas species
Neoprene, not baked, after 10 h of pumping	order of 10^{-5}	H_2O
Viton, not baked, after 10 h of pumping	order of 10^{-7}	H_2O
Austenitic stainless steel, not baked, after 10 h of pumping	3×10^{-10}	H_2O
Austenitic stainless steel, baked at 150°C for 24 h	3×10^{-12}	H_2
OFS copper, baked at 200°C for 24 h	order of 10^{-14}	H_2



$$\log_{10} P_E = A - \frac{B}{C+T}$$

Outgassing of molecules dissolved in the bulk of metals



- Gas molecules are dissolved into the bulk of materials during the production processing and during their permanence in air.

- Only H atoms have enough mobility in metals to attain the surface where they recombine to form H_2.

Factors that affect on the final result

Stages of obtaining an operating vacuum:

- Design (selection of materials, requirements for outgassing flow, design features)
- Production (material quality, welding, polishing, cleaning, heating and control)
- Incoming inspection (full or random control)
- Mounting preparation and assembly (clean room, assembly culture, nitrogen blowing, leakage control)
- Mounting (clean room, assembly culture, nitrogen blowing, leakage control)
- Obtaining the required vacuum (warm-up, prolonged pumping)

- Clean conditions
- Vacuum hygiene
- Dry purified nitrogen
- Leakage control
- Material requirements
- Manufacturer requirements

- Assembly
- Air filling
- Leaks
- Production

Typical Requirements

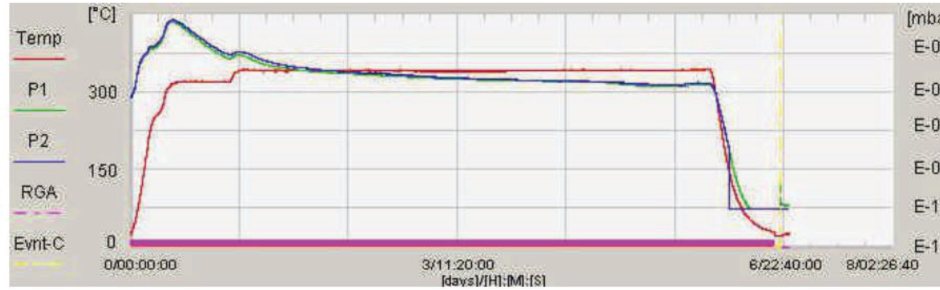
№	Specified domain	Specified values and description
1	Inside environment	Vacuum: <$2*10^{-9}$ [Pa]
2	Outside environment	Vacuum: 10^{-5} [Pa]
3	Operating temperature	(a) 4 ÷ 300 K (b) bakeout temperature up to 450°C
5	Materials (see attached drawing)	For stainless steel elements - AISI 316L/316LN or similar alloy specified for the operating environment For other elements oxygen-free copper (OFHC)
4	Welding of elements	(a) TIG/WIG welding according to ISO 13920 – BF. (b) The contractor can advise other standards.
5	Brazing of elements	(a) Brazing must be suitable for operating in XHV environment. (b) The contractor, based on design review, can advise other production standards and procedures.
6	Cleaning	Standard XHV cleaning
7	Leakage testing	Leak rate at room temperature lower than: $5*10^{-12}$ [$Pa*m^3/s$]
8	Flow rate	Flow rate must be measured with Membrane method: <$2*10^{-11}$ [$Pa*m^3/s*m^2$]
9	Bellows expansion joints	(a) We propose to use pressed bellows expansion joints instead of welded type. We observe to have enough stiffness for these elements to support the middle part with chevron heat shield. (b) See the Related documents section for supplier proposal (3.2 Spring_bellows_supplier.pdf)
10	Delivery specials	(a) QTY – 100 psc. of complete items (b) Filled with dry nitrogen (c) Closed with blank flange DN100QCF (incl. clamb chain VaCFix) and one Pinch off flange 100CF (d) Packed in plastic bag and ready-to-install condition after delivery

Production

- TIG welding
- Vacuum Furnaces
- UHV-cleaning
- Vacuum testbenches

- FMB (FrakoTerm)
- BINP
- VakuumPraha

BAKEOUT REPORT

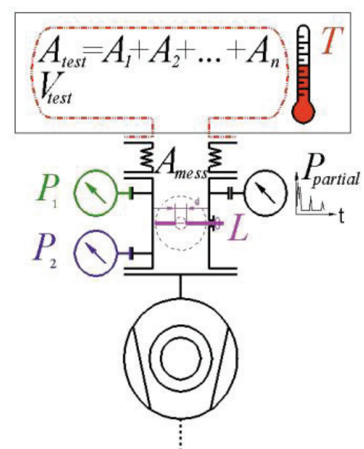


A	RGA active	P1 = 1.2E-10 mbar	A = 21000 cm² (Inner surface)
B	Heating Off	P2 = 1.0E-10 mbar	Qspez = 4.24E-15 mbar*l/s*cm² (Outgasing rate)
C	Pinhole closed/ Final pressure determined	dP = 2.0E-11 mbar	P = 1.00E-10 mbar (Final pressure)

Explanation

[redacted]

$$L = 9.1 \cdot 10^{2} \cdot d^{2}$$
$$\Delta P = P_1 - P_2$$
$$Q = \Delta P \cdot L$$
$$Q_{spez} = \frac{Q}{A_{test} + A_{mess}}$$



The bakeout commences with opened aperture, i.e. at max. suction speed of the pump stand, and is monitored from a defined total pressure (less than 10E-06 mbar) using a mass spectrometer.
The desorption rate and the permissible helium leak rate are determined at room temperature after cooling down.

Desorption rate: Q = 8.90e-12 Pa·m³/s

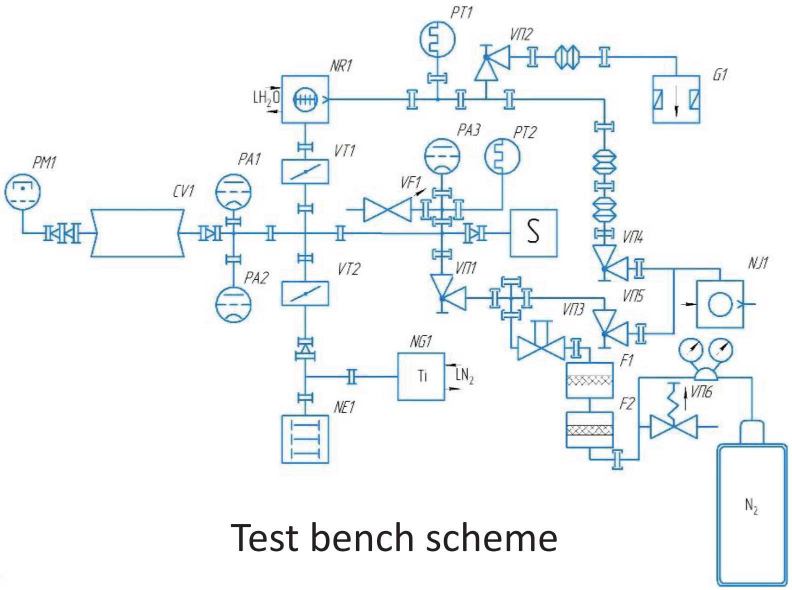
Specific desorption rate: Qspez = 4.24e-16 Pa·m³/s·cm²

d=7mm, A_mess=2000cm²

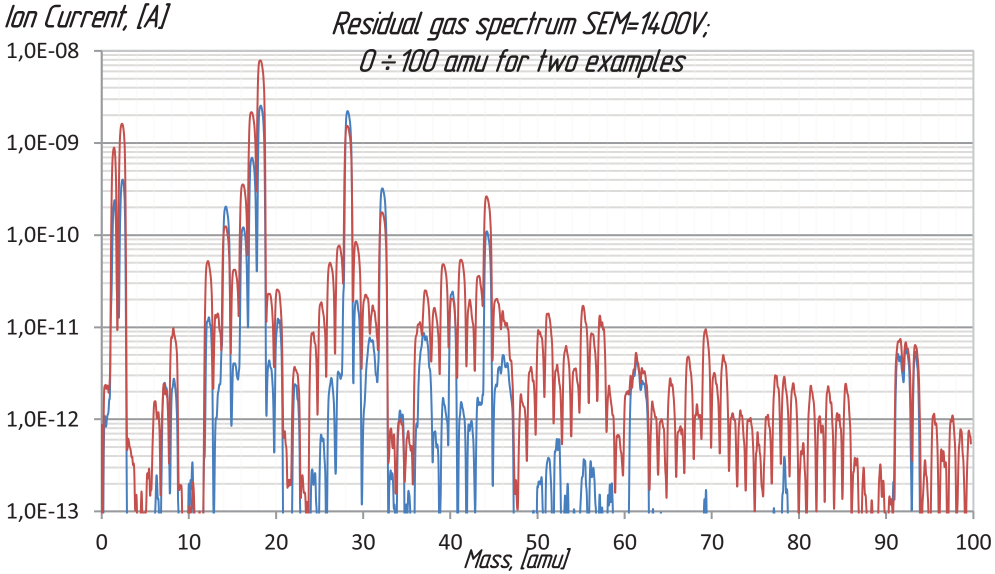
Acceptance tests

Clean zone
for assembling

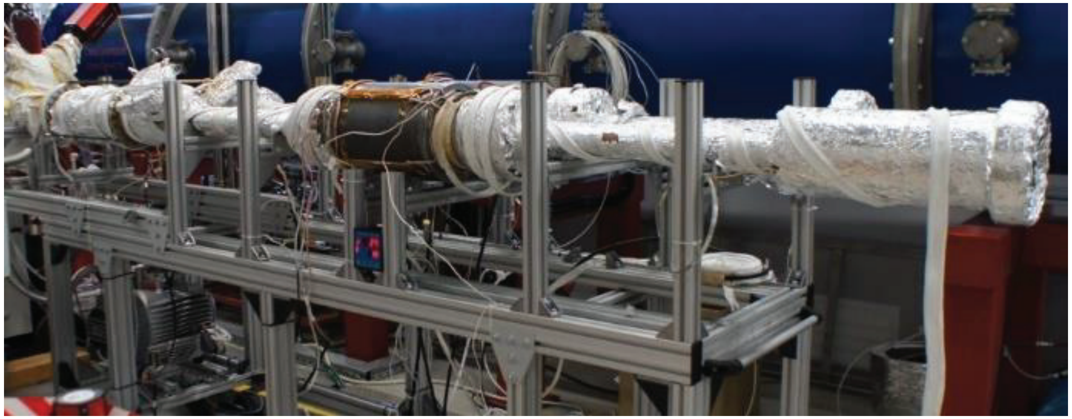
Vacuum testbench
with examples

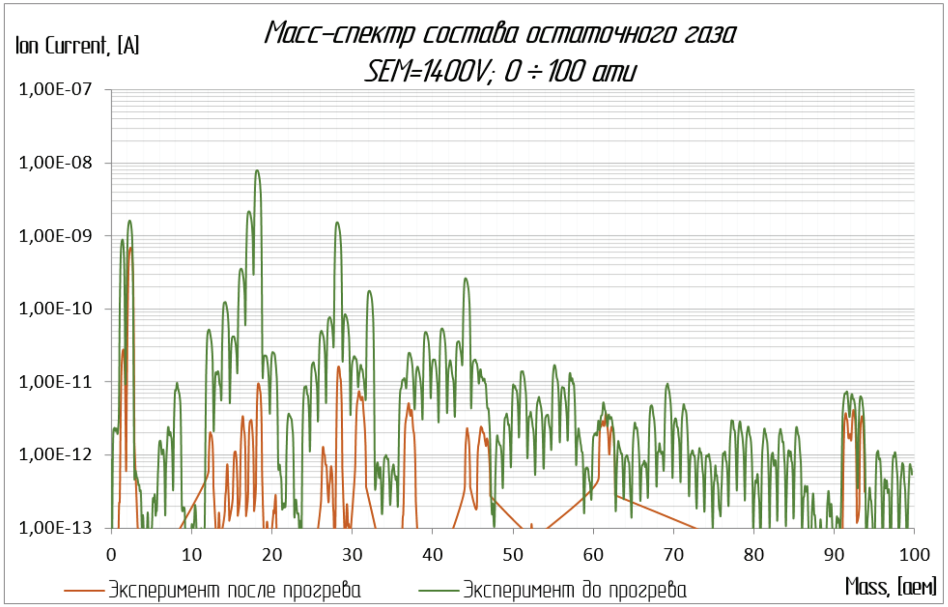


Test bench scheme

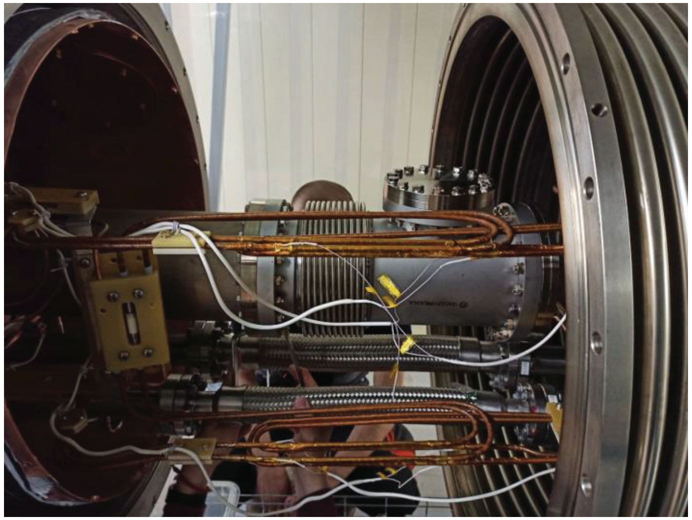


Assembling

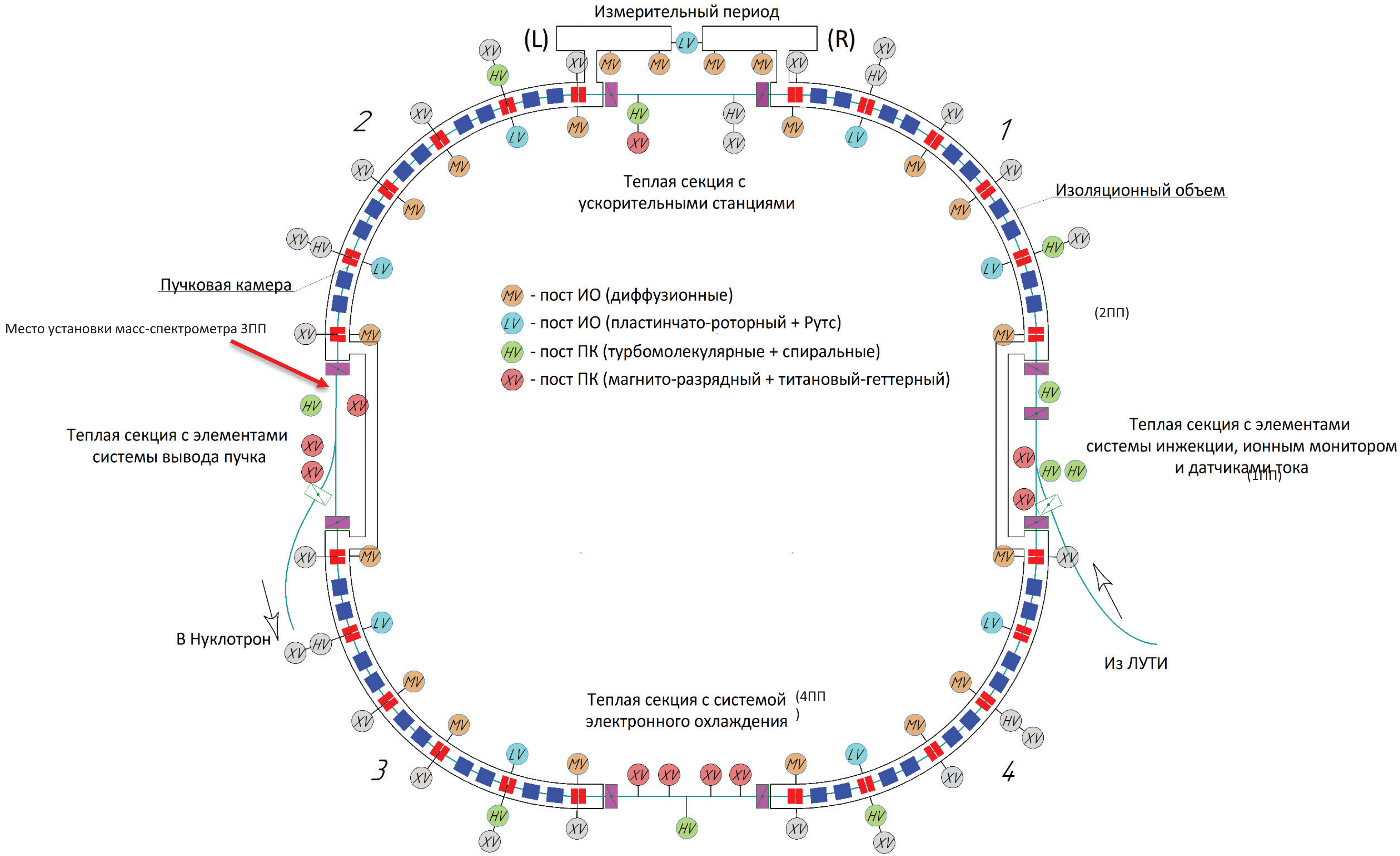



Масс-спектр состава остаточного газа
SEM=1400V; 0 ÷ 100 amu
Ion Current, [A]
1,00E-07
1,00E-08
1,00E-09
1,00E-10
1,00E-11
1,00E-12
1,00E-13
0
10
20
30
40
50
60
70
80
90
100
Mass, [аем]
Эксперимент после прогрева
Эксперимент до прогрева

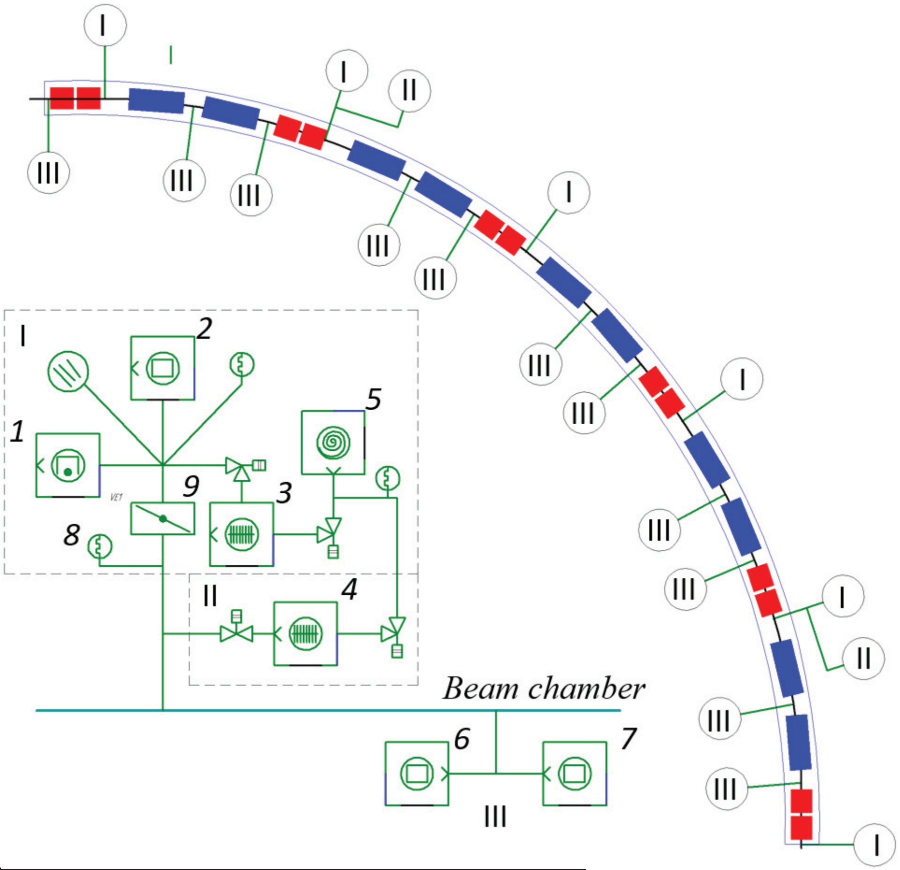
Mounting



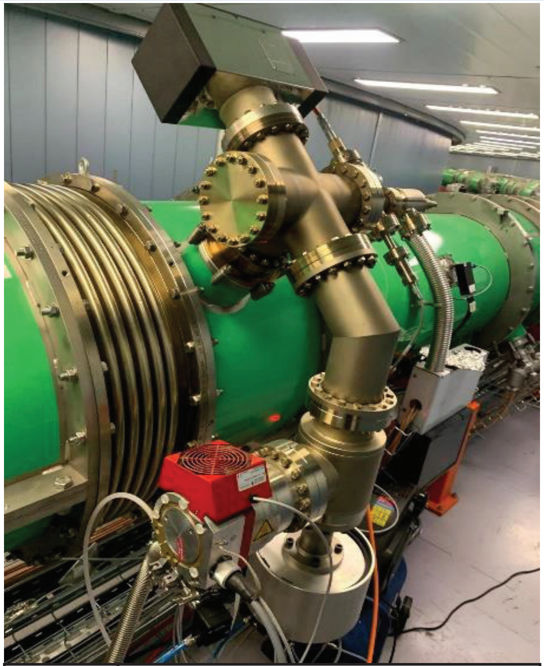

Booster vacuum scheme



Vacuum system principle scheme of beam chamber`s cold part

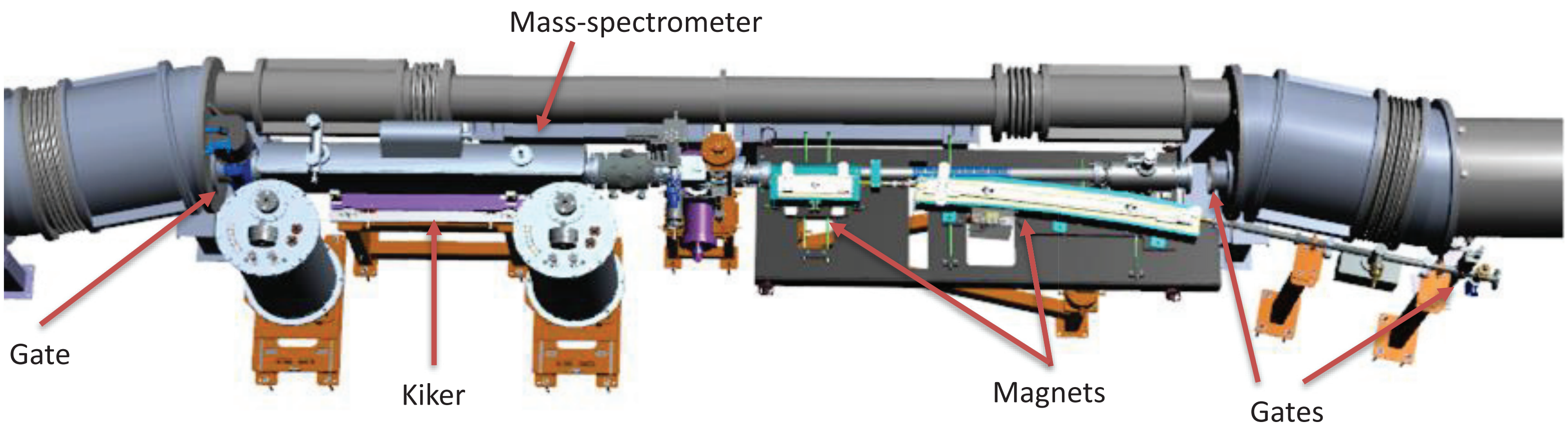


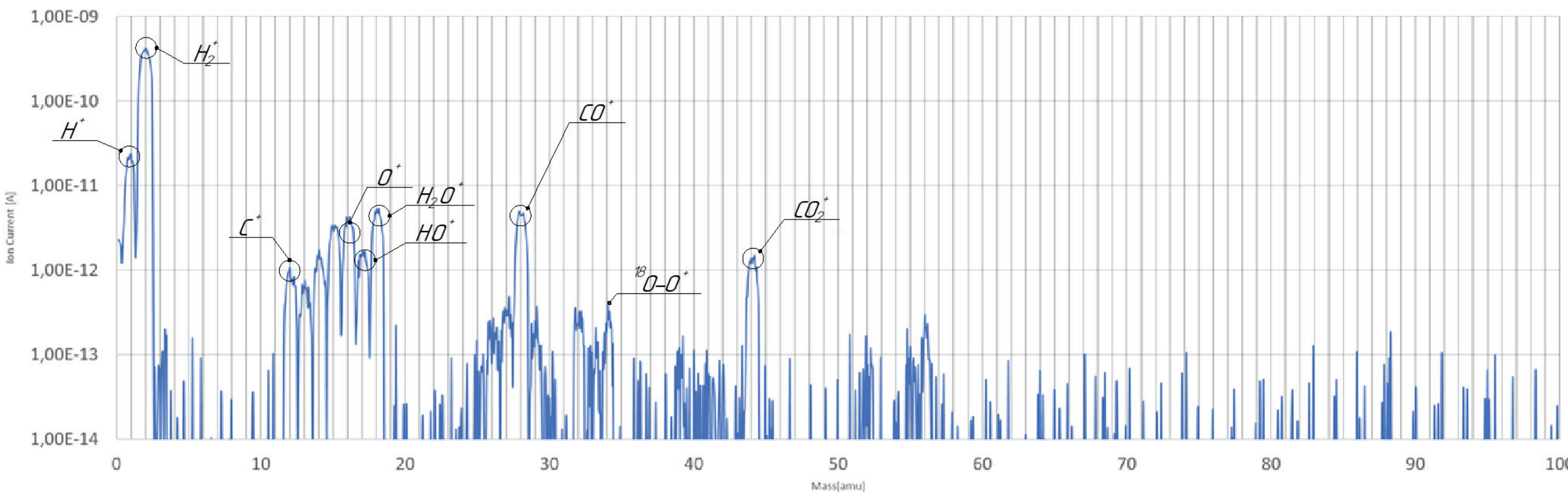
Pos.	Item
I	Main pump plant
II	Auxiliary pump plant
III	Titan-sublimation pumps



Pos.	Item
1	Ion pump
2	NEG pump
3	Turbomolecular pump 1
4	Turbomolecular pump 2
5	Dry scroll pump
6,7	Titan-sublimation pumps
8	UHV gauge
9	All metal gate

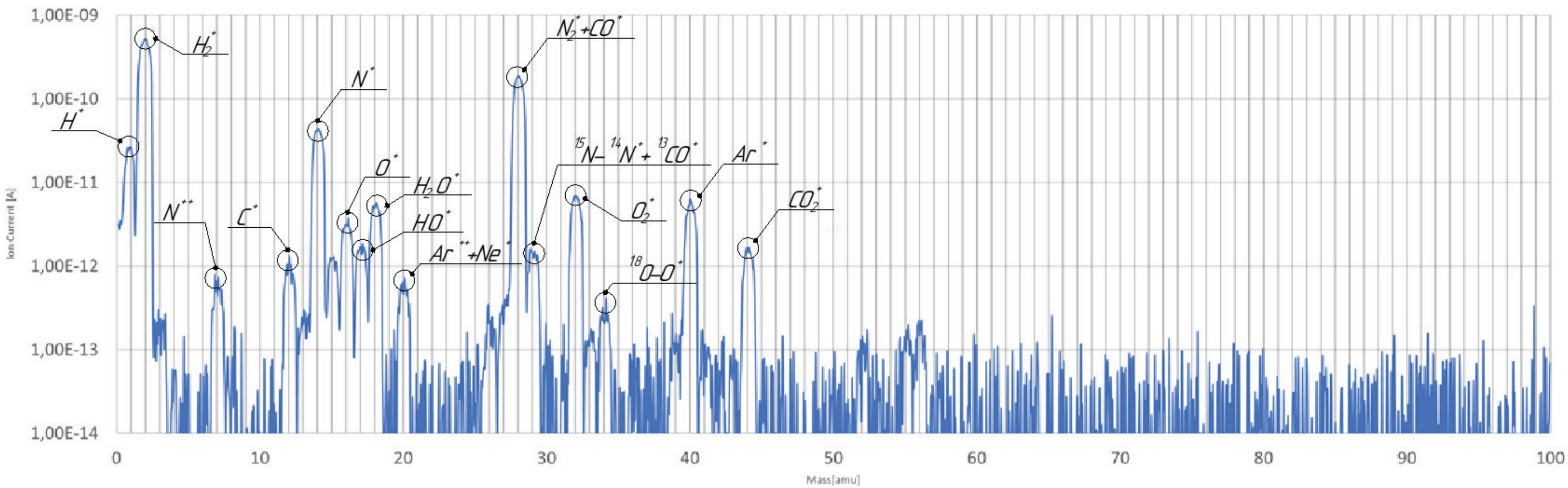
Residual gas spectrum in the fast extraction system (BINP)





$P=3{,}3\cdot10^{-9}$Па;

Residual gas spectrum in the fast extraction system with leak

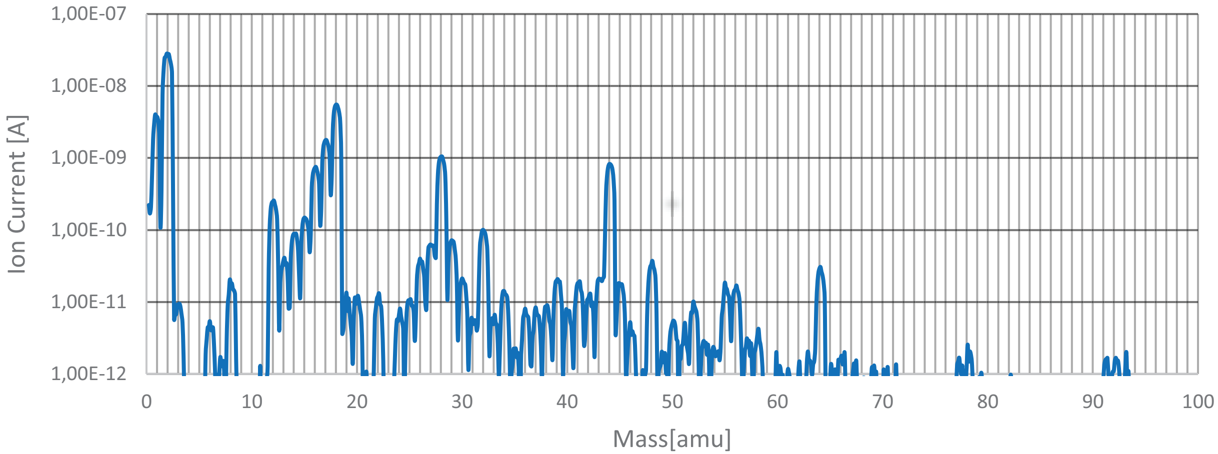


P=$6\cdot10^{-8}$Pa

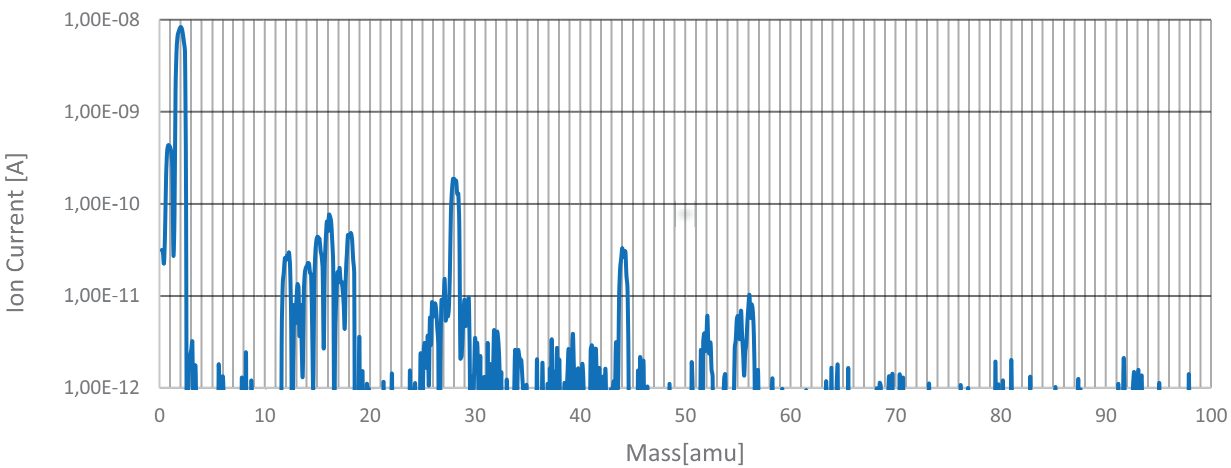
Beam gates was opened → 17.12.2020

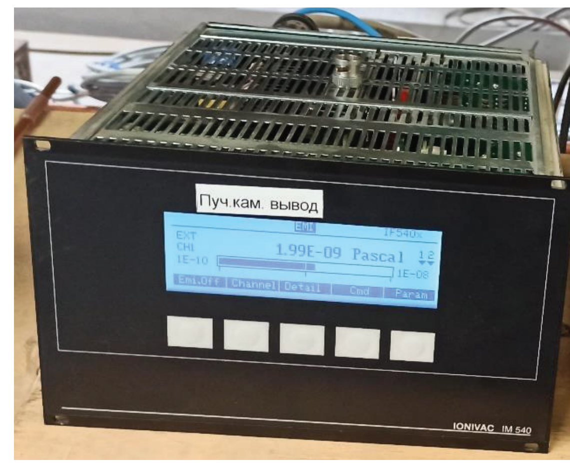
Date	SS 1	Arch 1	SS 2	Arch 2	SS 3	Arch 3	SS 4	Arch 4
4.12.2020	$2.7\cdot10^{-9}$	$1\cdot10^{-6}$	$1.6\cdot10^{-8}$	$5.2\cdot10^{-7}$	$3.3\cdot10^{-9}$	$9.6\cdot10^{-7}$	$1.6\cdot10^{-8}$	$1.1\cdot10^{-6}$
10.12.2020	$1.7\cdot10^{-9}$	$6.8\cdot10^{-9}$	$1.6\cdot10^{-8}$	$6.0\cdot10^{-9}$	$3.3\cdot10^{-9}$	$7.1\cdot10^{-9}$	$1.3\cdot10^{-8}$	$1.1\cdot10^{-8}$
17.12.2020	$1.2\cdot10^{-8}$	$4.3\cdot10^{-9}$	$1.3\cdot10^{-7}$	$3.4\cdot10^{-9}$	$3.5\cdot10^{-9}$	$4.4\cdot10^{-9}$	$2.9\cdot10^{-8}$	$6.7\cdot10^{-9}$
19.12.2020	$4.5\cdot10^{-8}$	$4.2\cdot10^{-9}$	$3.4\cdot10^{-7}$	$3.3\cdot10^{-9}$	$4\cdot10^{-9}$	$4.3\cdot10^{-9}$	$3.5\cdot10^{-8}$	$6.6\cdot10^{-9}$
21.12.2020	$6.3\cdot10^{-8}$	$4.2\cdot10^{-9}$	$4.0\cdot10^{-7}$	$3.0\cdot10^{-9}$	$4.2\cdot10^{-8}$	$4.0\cdot10^{-9}$	$3.0\cdot10^{-8}$	$5.0\cdot10^{-9}$
25.12.2020	$6.6\cdot10^{-8}$	$3.5\cdot10^{-9}$	$4.1\cdot10^{-7}$	$2.6\cdot10^{-9}$	$5.4\cdot10^{-8}$	$3.5\cdot10^{-9}$	$3.0\cdot10^{-8}$	$5.0\cdot10^{-9}$
27.12.2020	$6.3\cdot10^{-8}$	$3.5\cdot10^{-9}$	$4.4\cdot10^{-7}$	$2.6\cdot10^{-9}$	$5.3\cdot10^{-8}$	$3.3\cdot10^{-9}$	$2.8\cdot10^{-8}$	$4.5\cdot10^{-9}$

Life-time of 3.2 MeV/u He^{1+} is about 1.3 s Equivalent pressure of residual gas is about $3\div4\times10^{-8}$ Pa *(Middle vacuum $2\text{-}3\times10^{-8}$ Pa)*



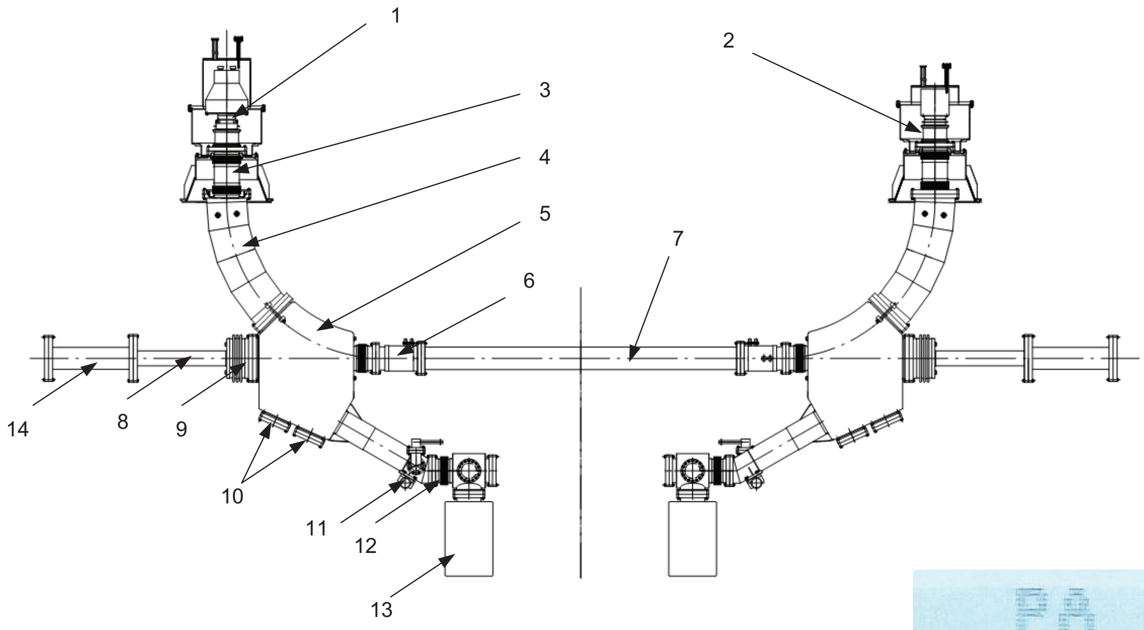
P ≈ $4.5 \cdot 10^{-9}$Pa (before bake out)

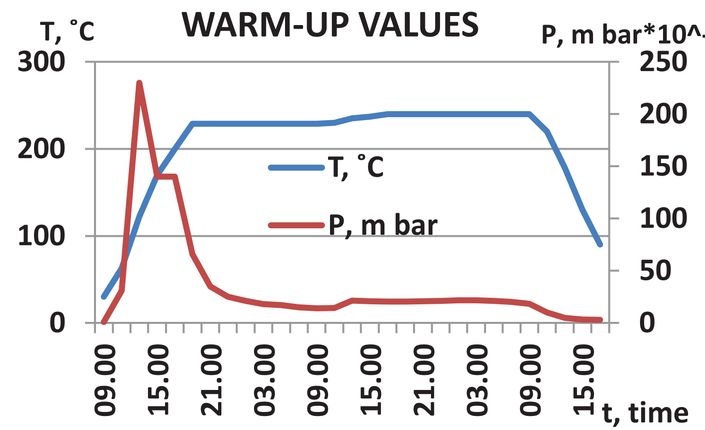




P≈$2.0 \cdot 10^{-9}$Pa (after bake out)

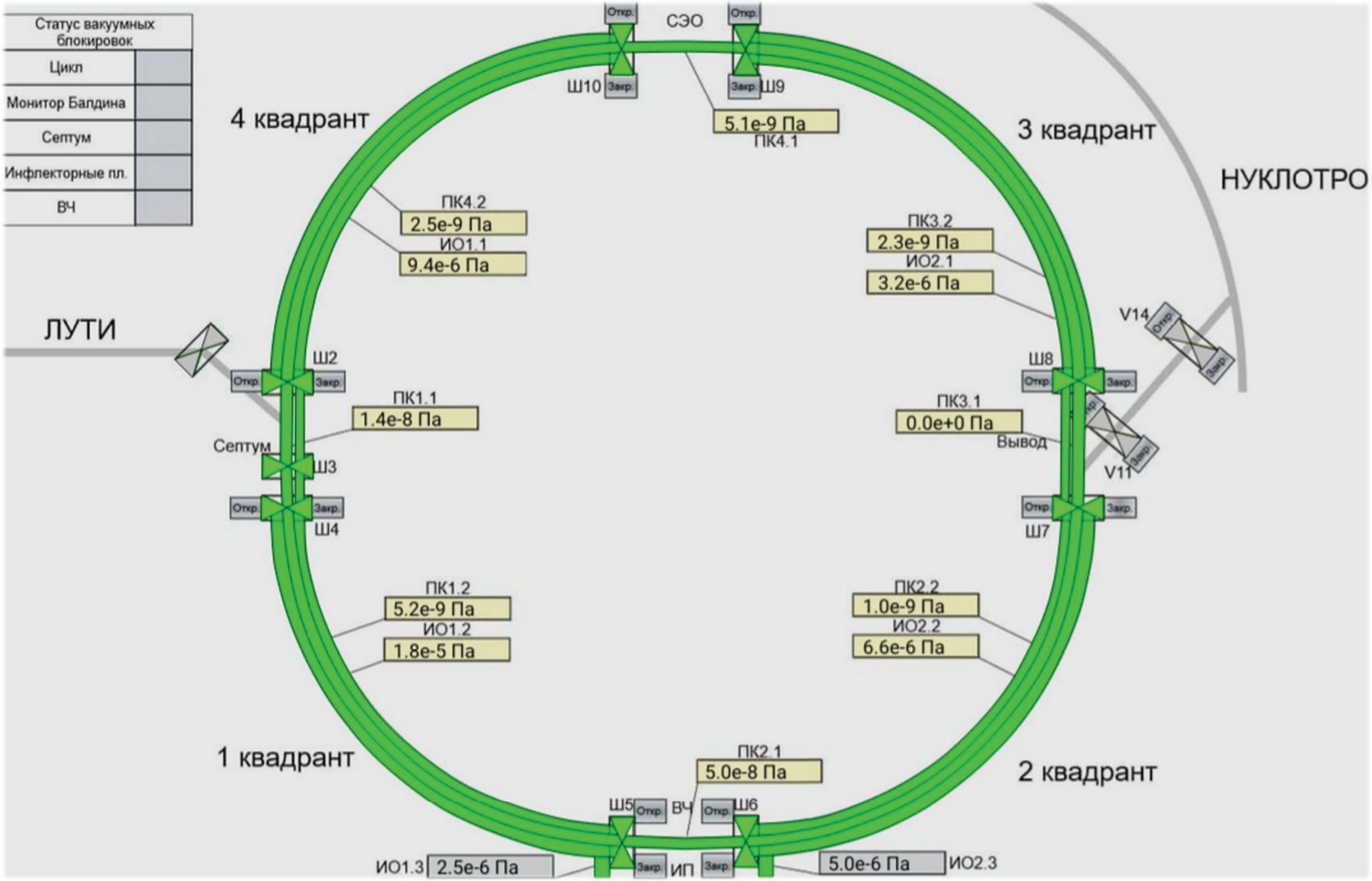
Vacuum chamber of electron cooling system (BINP)





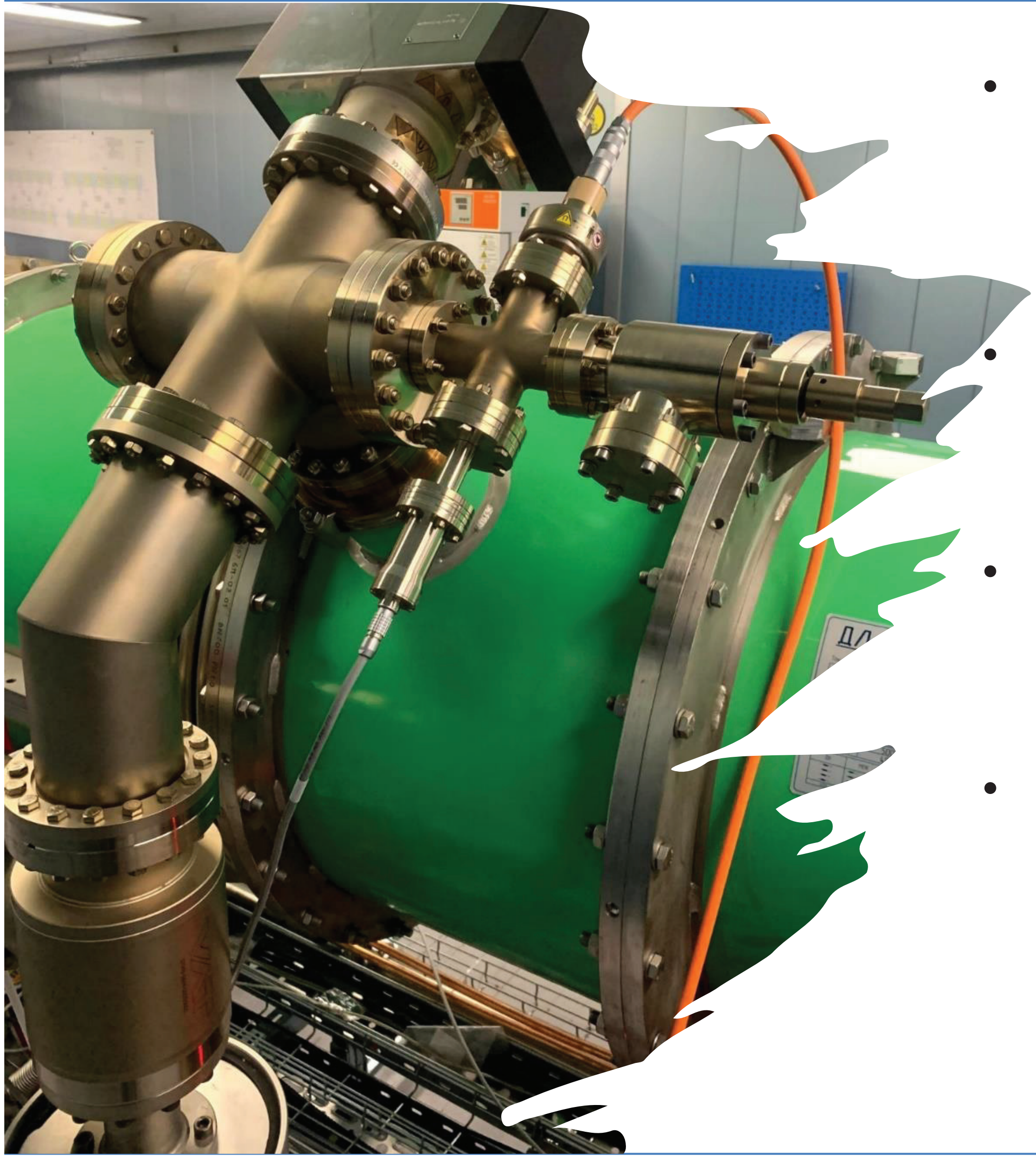
1. Gun, 2. Collector, 3. Sublimation pump TSP-IKG «VACOM», 4. Bent chamber, 5. Toroid section, 6. Pick-up station, 7. Cooling section, 8. Dipole section, 9. Bellows, 10. NEG position, 11. Vacuum valve, 12. Bellows, 13. Ion pump, 14. Connector.

Booster vacuum at the end of work



Life-time of 3.2 MeV/u He^{1+} up to 10 s, equivalent pressure of residual gas is about $8 \div 9 \times 10^{-9}$ Pa (*Middle vacuum 5-6×10^{-9} Pa*)

Summary



- Without the possibility of installing distributed pumping systems, the main task is to reduce the level of desorption from the surfaces of the chamber walls.
- This requires compliance at every stage the design requirements, vacuum hygiene and material selection.
- In the booster assembled under these conditions the vacuum was obtained, measured by the loss of helium +1 at the level of $8\text{-}9 \cdot 10^{-9}$Pa;
- As practice has shown, the main difficulty is maintenance and preservation the required vacuum during the accelerator operation.

Obtaining the vacuum in the warm beam chambers

- Requirements:
  - Working pressure ≤ 2 × 10^{-9} Pa;
  - Residual gas composition: m/e>15 ≤ 20%; m/e>46 ≤ 0,1% of the total ion current;
- Conditions for achieving
  - Total outgassing flow ≤ 2×10^{-11} Pa·m^3/s·m^2;
  - Leaks ≤ 1×10^{-12} Pa·m^3/s;
  - Use of materials with low saturated vapour pressure;
  - Coating the surfaces with titanium nitride films or non-sprayed getter to achieve a low coefficient of secondary electron emission;
  - Preliminary annealing of products at temperatures above 350 °C in vacuum or washing in an ultrasonic system and warming up at 250 °C;
  - Compliance with the requirements of vacuum hygiene at all stages of product manufacture;
  - Pumping systems:
    - Ion pumps (IMG);
    - Titanium Sublimation Pumps (TSP);
    - Non-evaporable getters (NEG): surface coating, cartridge use
  - Pressure sensors
    - With hot cathode (type Extractor)
  - Gate and valves
    - All-metal gates and valves
  - Assembly in clean conditions (clean area and blowing of dry clean nitrogen, if necessary);
  - Compliance with the requirements of vacuum hygiene when assembling the section;
  - Warming up at 250-350 ° C for at least 48 hours.

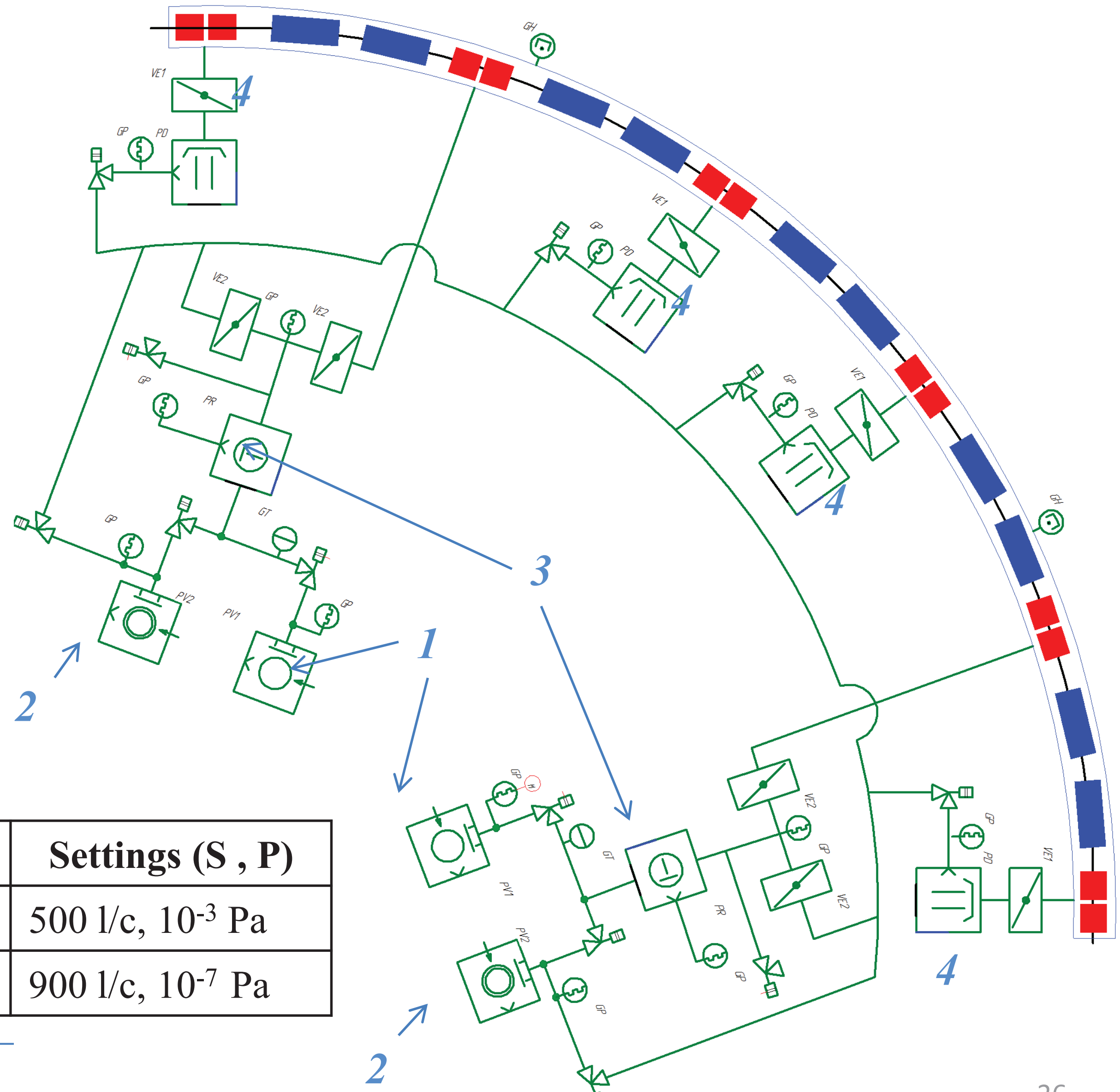
Obtaining the vacuum in the cold beam chambers

NO POSSIBILITY OF HEATING AFTER ASSEMBLY

- Requirements:
  - Working pressure ≤ 2×10^{-9} Pa;
  - Residual gas composition : m/e>15 ≤ 20%; m/e>46 ≤ 0,1% of the total ion current;
- Conditions for achieving
  - Total outgassing flow ≤ 2×10^{-11} Pa·m³/s·m²;
  - Leaks ≤ 1×10^{-12} Pa·m³/s;
  - Use of materials with low saturated vapour pressure;
  - Washing the products in an ultrasonic system, warming up at 250 ° C or at above 350 ° C in a vacuum.
  - Compliance with the requirements of vacuum hygiene at all stages of product manufacture. Delivery of products under seal and filled with dry pure nitrogen;
  - Pumping systems (distributed):
    - Ion pumps (IMG);
    - Titanium Sublimation Pumps (TSP);
    - Cryosorption of cold surfaces (chamber temperatures below 10K);
  - Pressure sensors
    - With hot cathode (type Extractor)
  - Gate and valves
    - All-metal gates and valves
  - Assembly in clean conditions in compliance with the requirements of vacuum hygiene (clean area in compliance with the requirements of a purity class of at least 7 and blowing of dry pure nitrogen is required!);

Vacuum system of insulating volume for the booster regular section

Pos.	Item
1	Single stage rotary vane pump
2	Double stage rotary vane pump
3	Roots pump
4	Diffusion pump



Item	Qnt.	Settings (S , P)
Roughing pump plants	10	500 l/c, 10^{-3} Pa
Diffusion pump plants	20	900 l/c, 10^{-7} Pa

Outgassing of Metals

- **Unbaked metals**
  - Water is the main gas desorbed by unbaked metals.
  - The outgassing rate of water decreases following a 1/t law: the outgassing of unbaked metals is not an intrinsic value.
  - The water outgassing does not depend significantly on the nature of metals, on surface treatments and on temperature (for temperatures lower than 110° C).
  - At present no methods, except heating, exist to quickly remove water from unbaked metals.
- **Baked metals**
  - Hydrogen is the main gas desorbed by baked metals.
  - The value of the outgassing rate of hydrogen is stable at room temperature; when the thermal history is known the outgassing of hydrogen is an intrinsic property of metals.
  - The diffusion model predicts values for the hydrogen outgassing that are in accord with experimental observations.
  - Firing decrease the hydrogen outgassing rate by more than 2 orders of magnitude.

Hydrogen diffusion in metals

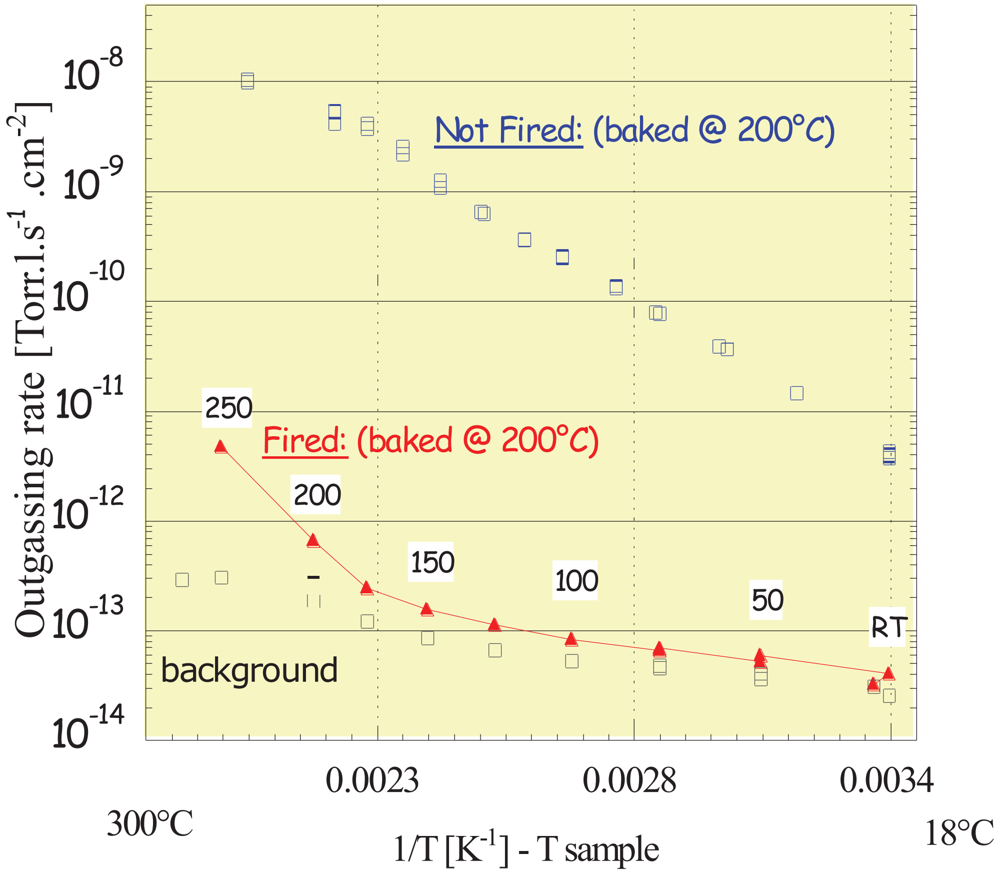
Material: 316LN

Wall thickness: 2 mm

Vacuum firing:

950° C x 2 h, 10^{-5} Torr H_2

For the fired chambers, the outgassing rate is limited by the background signal. The result was so intriguing that the experiment was repeated in a second system. On both systems, the upper limit at RT is 10^{-14} Torr.l.s^{-1}.cm^{-2}.



Beam lifetime due to recombination on rest gas at booster

$P = 10^{-9}$ Pa, $T = 293$ K, $k = 1.38\ 10^{-23}$ J/K, $\beta = 0.083$ (3.2 MeV/u)

$\tau = P\sigma\beta c / Tk$ – beam lifetime

t_life = 1000 s, $\sigma = 1.63\ 10^{-22}\ m^2$ (Au^{31+}, H_2 rest gas)

t_life = 25 s, $\sigma = 68.6\ 10^{-22}\ m^2$ (Au^{31+}, N_2 rest gas)