# Ultrahigh Vacuum in Superconducting Synchrotrons

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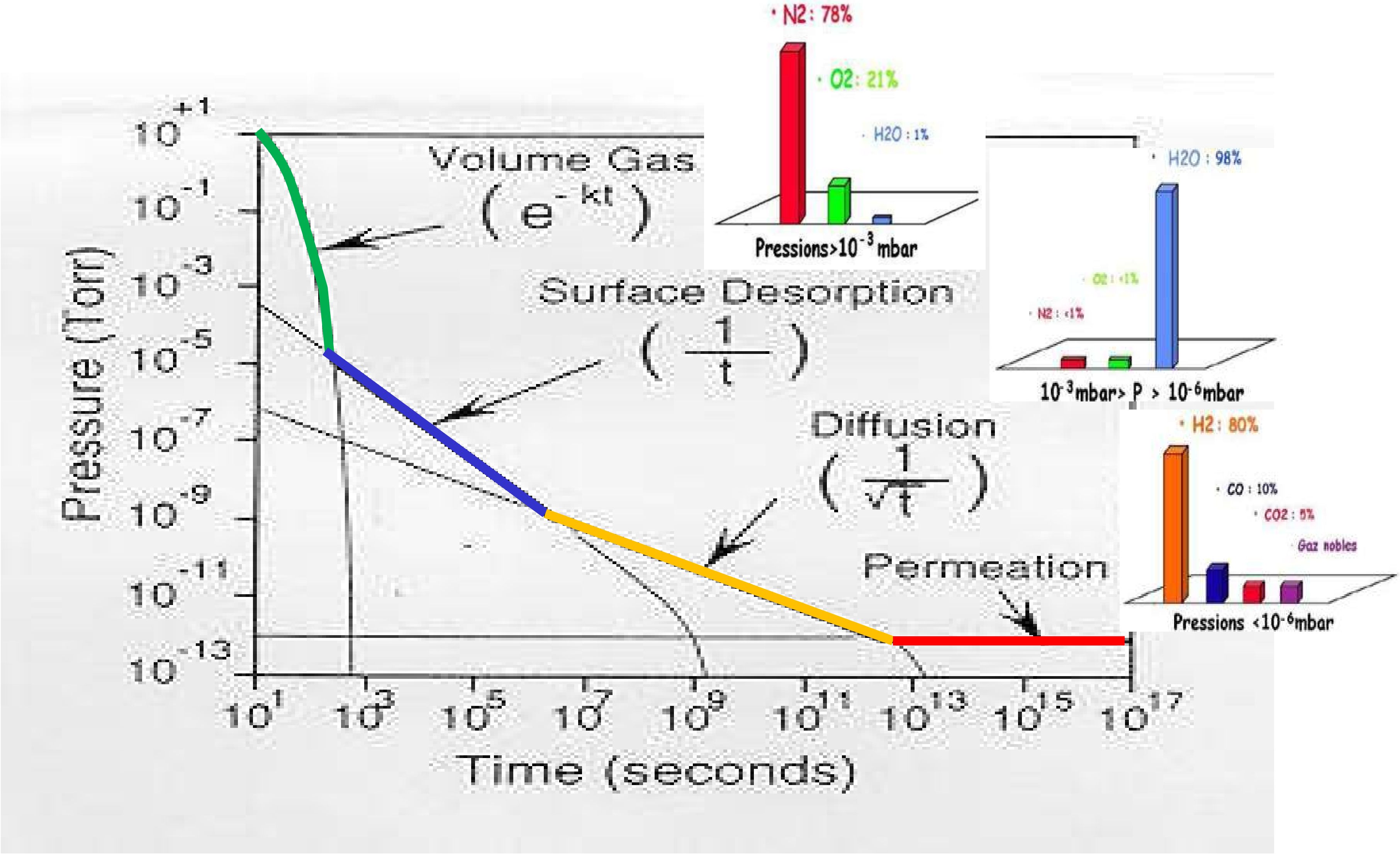
Topics:

- Pumping & outgasing of hydrogen
- Cryogenic pumps & non evaporable getters for UHV
- Superconducting accelerators: LHC, RHIC, SIS100, Nuclotron
- Vacuum system for NICA Booster

Russian Particle Accelerator Conference
Obninsk, October 5 -10, 2014

# Limiting mechanisms during pump down



# Out gassing 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: Firing

CERN unpublished results

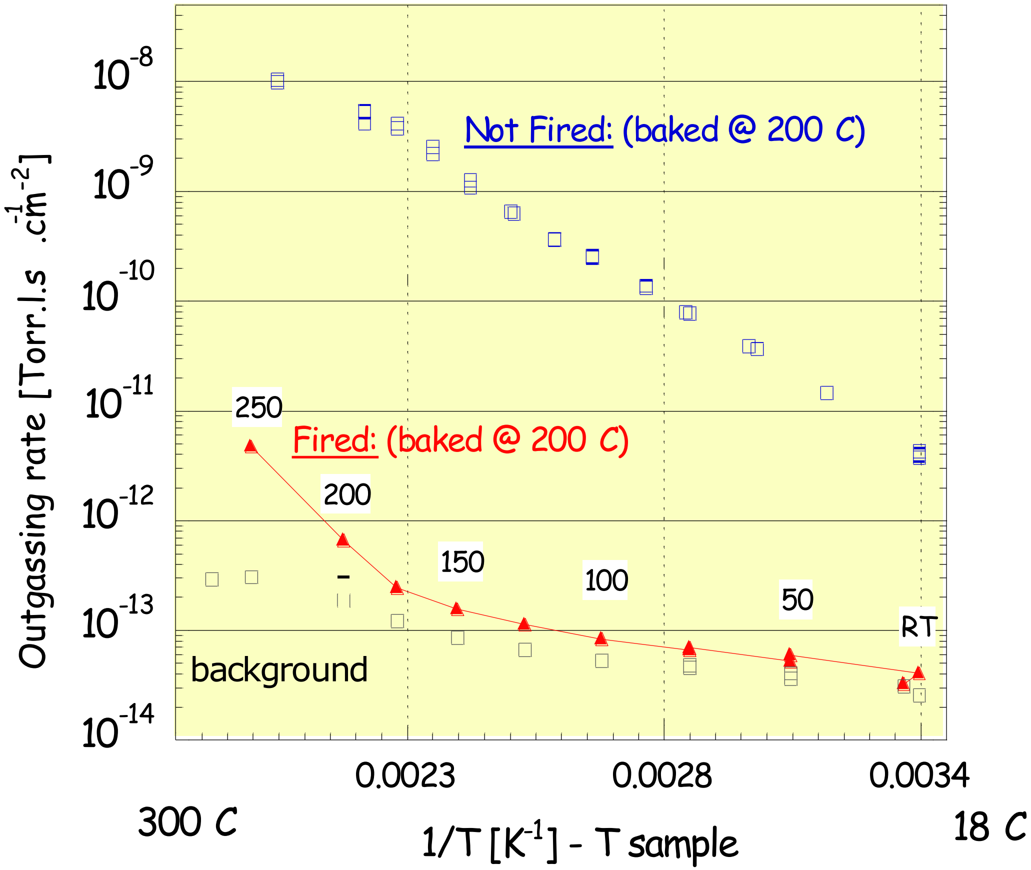
Material: 316LN

Wall thickness: 2 mm

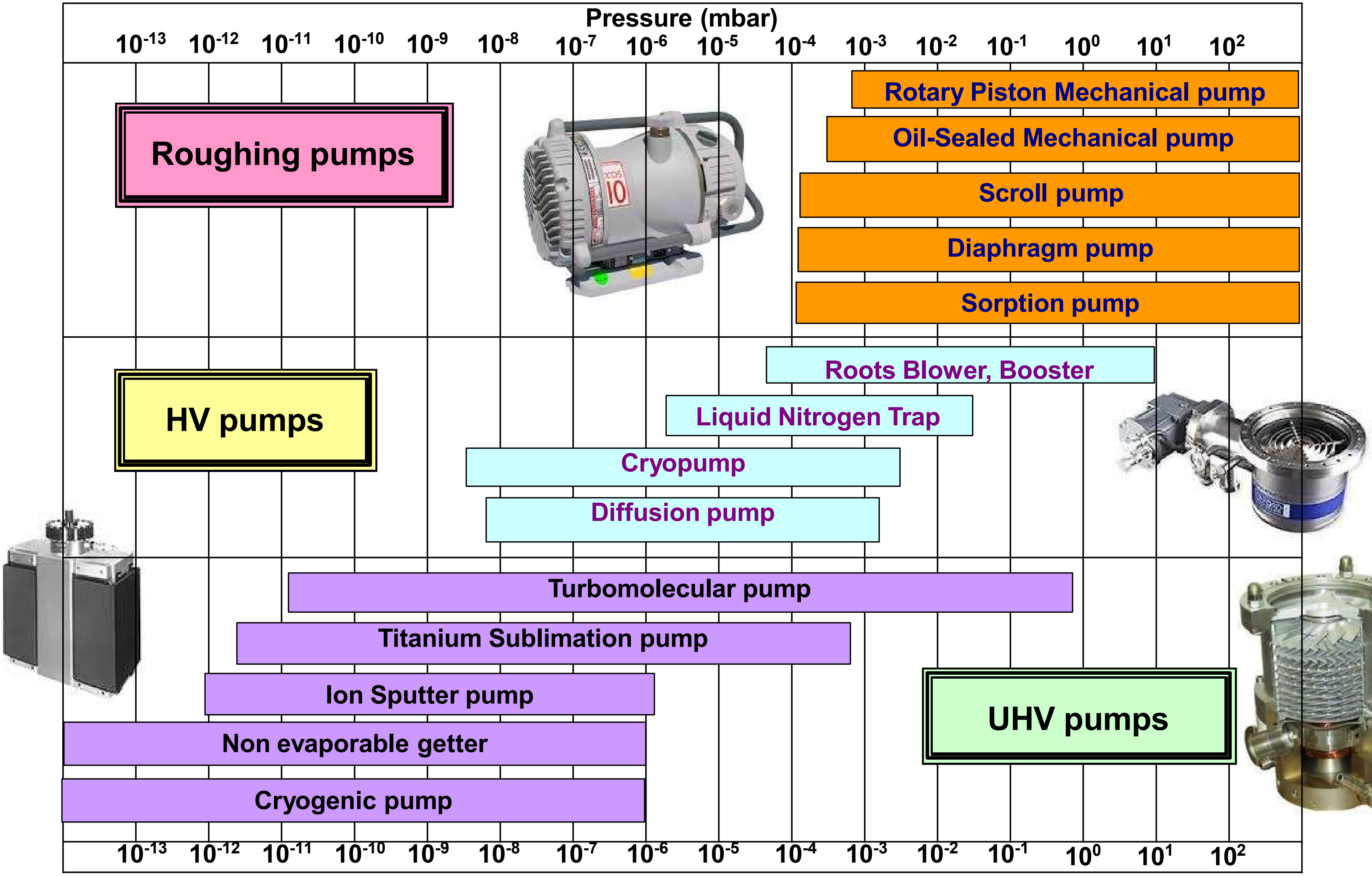
Vacuum firing:

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.$s^{-1}$.$cm^{-2}$.



# Pressure Ranges of Vacuum Pumps



Pressure (mbar)

$10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$

**Roughing pumps**

Rotary Piston Mechanical pump

Oil-Sealed Mechanical pump

Scroll pump

Diaphragm pump

Sorption pump

**HV pumps**

Roots Blower, Booster

Liquid Nitrogen Trap

Cryopump

Diffusion pump

**UHV pumps**

Turbomolecular pump

Titanium Sublimation pump

Ion Sputter pump

Non evaporable getter

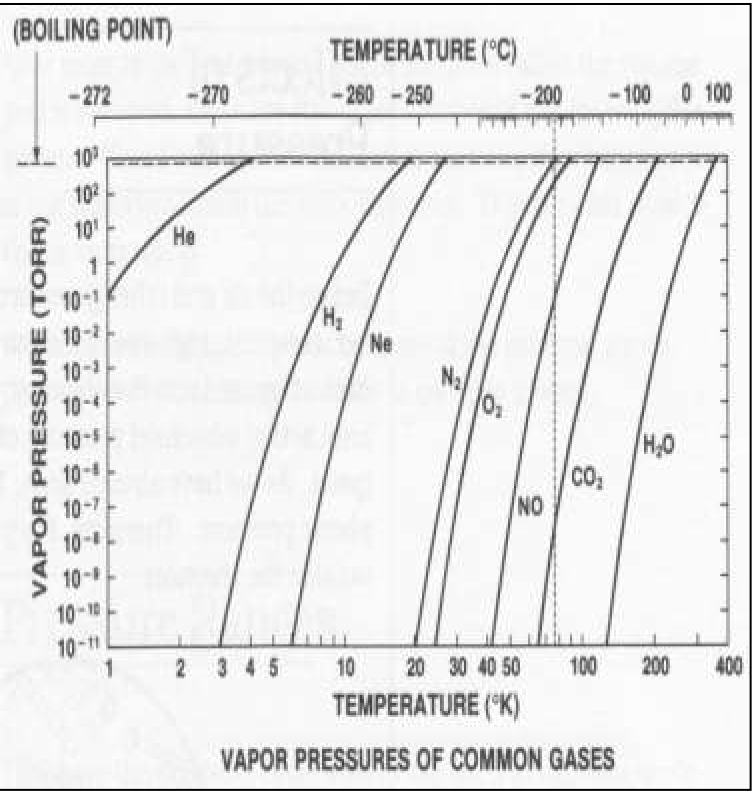
Cryogenic pump

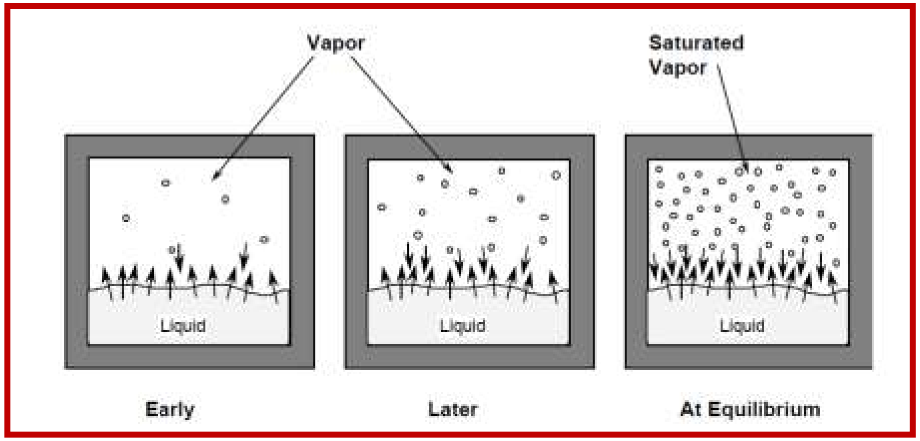
$10^{-13}$ $10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ $10^{0}$ $10^{1}$ $10^{2}$

# Cryopumping

Cryopumping relies on three different pumping mechanisms:

1. **Cryocondensation**: is based on the mutual attraction of **similar** molecules at low temperature:
   a. the key property is the **saturated vapour pressure**, i.e. the pressure of the gas phase in equilibrium with the condensate at a given temperature. It limits the attainable pressure.
   b. Only Ne, $H_2$ and He have saturated vapour pressures higher than $10^{-11}$ mbar at 20 K.
   c. The vapour pressure of $H_2$ at 4.3 K is in the $10^{-7}$ mbar range, at 1.9 K lower than $10^{-12}$ mbar.
   d. Large quantity of gas can be cryocondensed (limited only by the thermal conductivity of the condensate phase and the thermal flow)





*Courtesy of F. Dylla, CAS vacuum 2006*

# Cryopumping

2. **Cryosorption**: is based on the **attraction between molecules and substrate**. The interaction is much stronger than that between similar molecules:

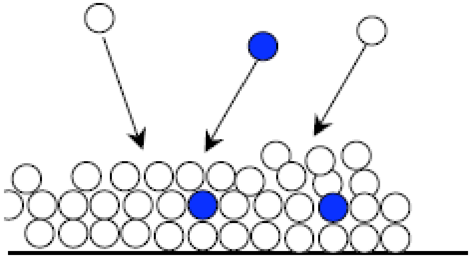
   a) Gas molecules are pumped at pressures much lower than the saturated vapour pressure providing the adsorbed quantity is lower than one monolayer.

   **a) Porous materials** are used to increase the specific surface area; for charcoal about 1000 $m^2$ per gram are normally achieved.

   b) The important consequence is that significant quantities of $H_2$ can be pumped at 20 K and He at 4.3 K.

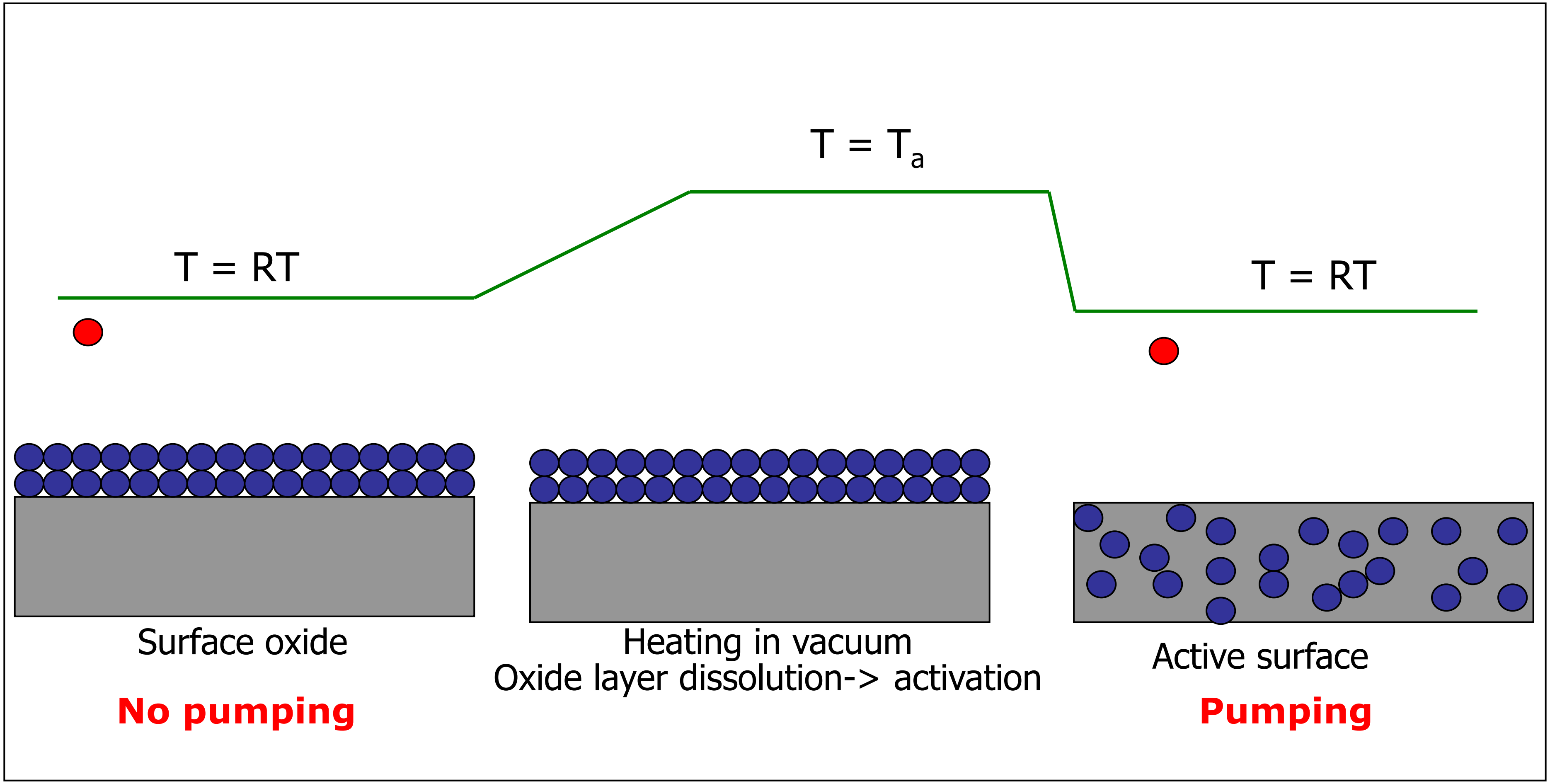
   c) Submonolayer quantities of all gases may be effectively cryosorbed at their own boiling temperature; for example at 77 K all gases except He, $H_2$ and Ne.

3. **Cryotrapping** : low boiling point gas molecules are trapped in the layer of an easily condensable gas. The trapped gas has a saturation vapor pressure by several orders of magnitude lower than in the pure condensate. Examples: Ar trapped in $CO_2$ at 77 K; $H_2$ trapped in $N_2$ at 20 K.



# Non-Evaporable Getter (NEG) Pumps

The dissolution of the oxide layer is possible only in metals having very high oxygen solubility limit, namely the elements of the 4th group: Ti, Zr and Hf.



Surface oxide

**No pumping**

Heating in vacuum
Oxide layer dissolution-> activation

Active surface

**Pumping**

# Non-Evaporable Getter Pumps

Gases are categorized into four families based on their interactions with NEGs:

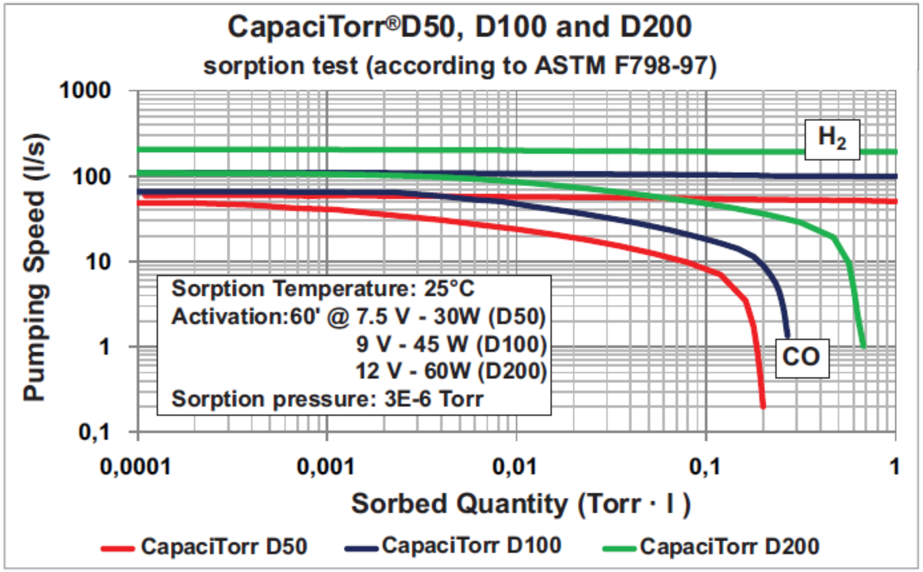
1. Hydrogen and its isotopes - sorbed reversibly.
2. $CO$, $CO_2$, $O_2$, and $N_2$ - sorbed irreversibly.
3. $H_2O$, hydrocarbons - sorbed in a combination of reversible and irreversible processes.
   Hydrocarbons are sorbed very slowly.
4. Rare gases - not sorbed at all.
   Ion pumps are required in combination with NEGs

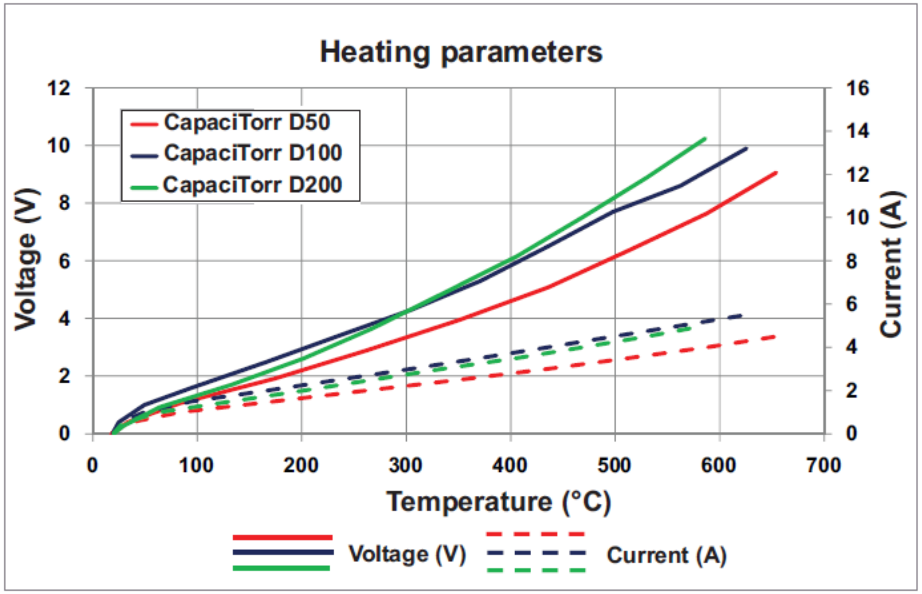
A typical alloy produced by SAES Getter is St707:

| Element | Concentration [wt. %] | Main role in the alloy |
|---|---|---|
| **Zr** | 70 | - High O solubility limit.<br>- Chemical reactivity |
| **V** | 24.6 | - Increases O diffusivity,<br>- Chemical reactivity |
| **Fe** | 5.4 | - Reduces pyrophoricity |

Full pumping speed is obtained after heating at 400°C for 45’ or 300°C for 24h

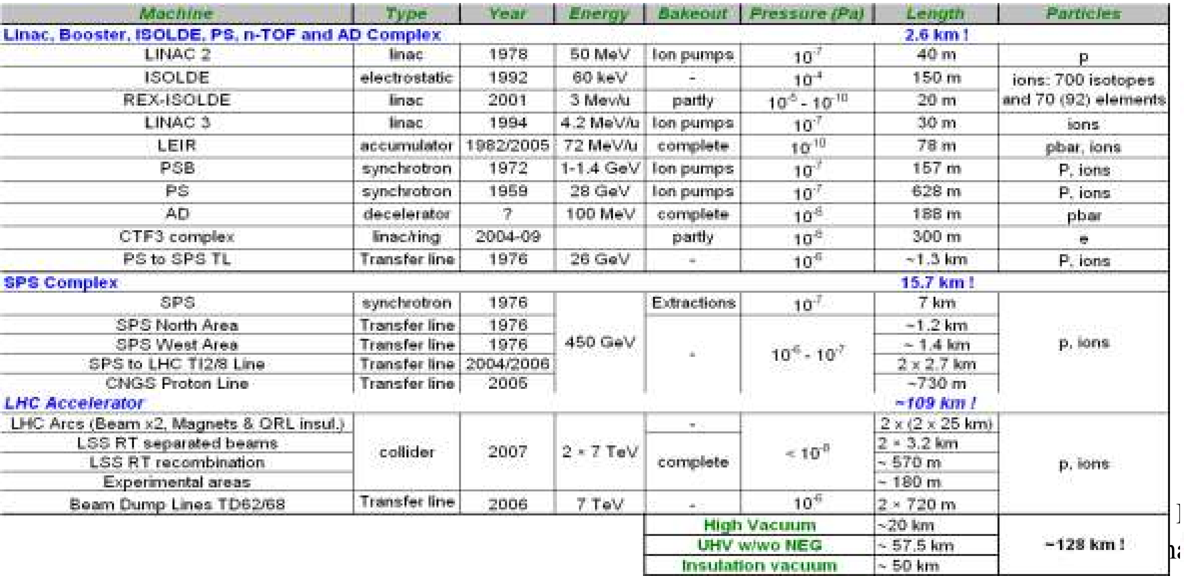
# CapaciTorr® , NEXTorr® (SAES Group)



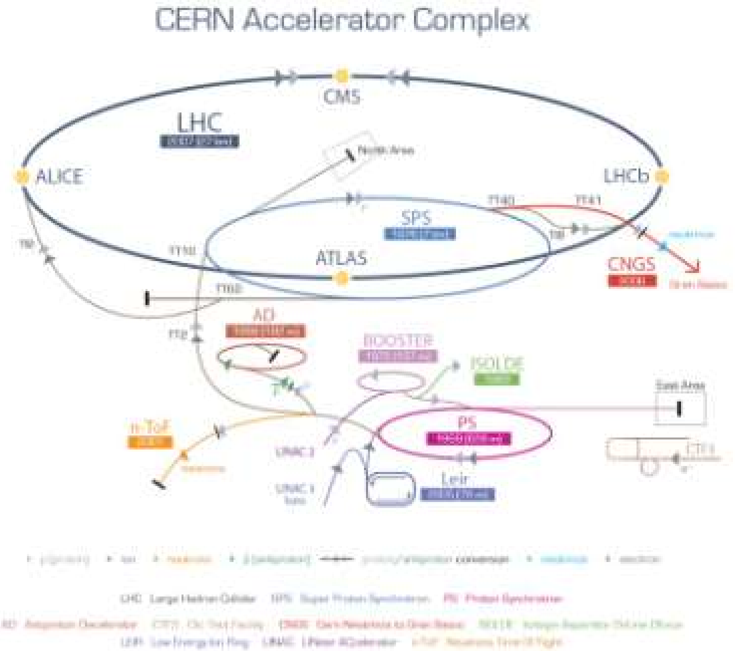


# Vacuum, Surfaces & Coatings Group

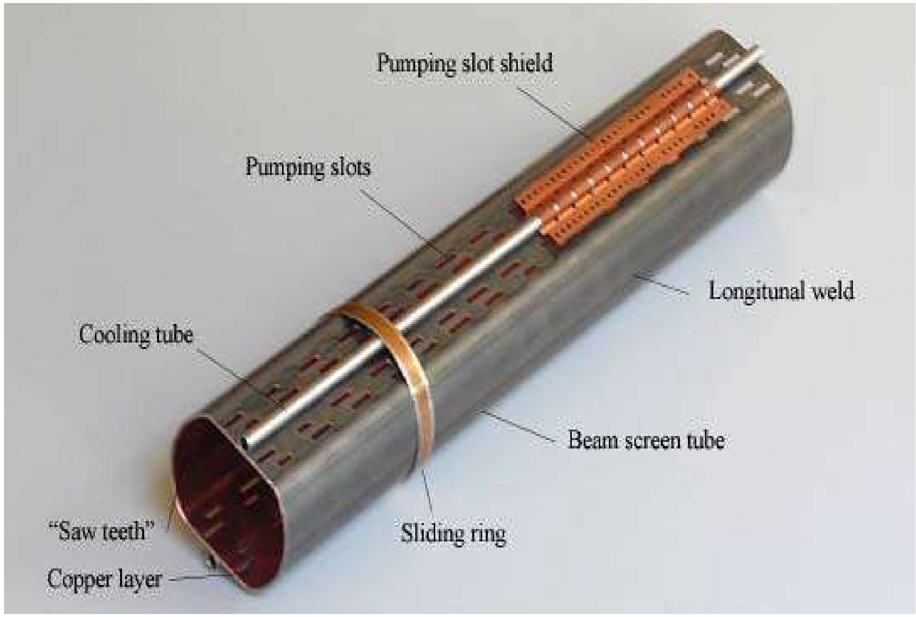
- **A CERN-wide responsibility for the operation of accelerators and detectors vacuum systems**
  - 128 km of vacuum:
    - 78 km of high/UHV vacuum for beams w/wo NEG coated beam pipes
    - 50 km of high vacuum for insulation
- **A large quantity of gauges, instrumentation, pumps and leak detectors**
  - 2850 ion pumps, 450 turbo molecular pumps and 325 Ti sublimation pumps
  - 2750 pressure gauges, 40 leak detectors and 50 RGAs
  - 1930 roughing valves and 510 gate sector valves

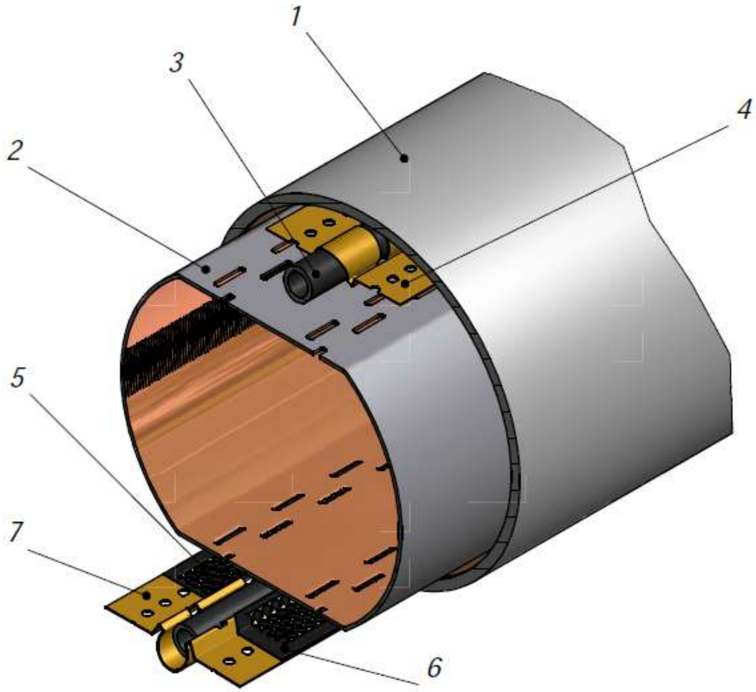


| Machine | Type | Year | Energy | Bakeout | Pressure (Pa) | Length | Particles |
|---|---|---|---|---|---|---|---|
| **Linac, Booster, ISOLDE, PS, n-TOF and AD Complex** | | | | | | **2.6 km !** | |
| LINAC 2 | linac | 1978 | 50 MeV | Ion pumps | $10^{-7}$ | 40 m | p |
| ISOLDE | electrostatic | 1992 | 60 keV | - | $10^{-4}$ | 150 m | ions: 700 isotopes and 70 (92) elements |
| REX-ISOLDE | linac | 2001 | 3 Mev/u | partly | $10^{-5}$ - $10^{-10}$ | 20 m | |
| LINAC 3 | linac | 1994 | 4.2 MeV/u | Ion pumps | $10^{-7}$ | 30 m | ions |
| LEIR | accumulator | 1982/2005 | 72 MeV/u | complete | $10^{-10}$ | 78 m | pbar, ions |
| PSB | synchrotron | 1972 | 1-1.4 GeV | Ion pumps | $10^{-7}$ | 157 m | P, ions |
| PS | synchrotron | 1959 | 28 GeV | Ion pumps | $10^{-7}$ | 628 m | P, ions |
| AD | decelerator | ? | 100 MeV | complete | $10^{-8}$ | 188 m | pbar |
| CTF3 complex | linac/ring | 2004-09 | | partly | $10^{-8}$ | 300 m | e |
| PS to SPS TL | Transfer line | 1976 | 26 GeV | - | $10^{-6}$ | ~1.3 km | P, ions |
| **SPS Complex** | | | | | | **15.7 km !** | |
| SPS | synchrotron | 1976 | 450 GeV | Extractions | $10^{-7}$ | 7 km | p, ions |
| SPS North Area | Transfer line | 1976 | | - | $10^{-6}$ - $10^{-7}$ | ~1.2 km | |
| SPS West Area | Transfer line | 1976 | | | | ~ 1.4 km | |
| SPS to LHC TI2/8 Line | Transfer line | 2004/2006 | | | | 2 x 2.7 km | |
| CNGS Proton Line | Transfer line | 2005 | | | | ~730 m | |
| ***LHC Accelerator*** | | | | | | ***~109 km !*** | |
| LHC Arcs (Beam x2, Magnets & QRL insul.) | collider | 2007 | 2 × 7 TeV | - | < $10^{-8}$ | 2 x (2 x 25 km) | p, ions |
| LSS RT separated beams | | | | complete | | 2 × 3.2 km | |
| LSS RT recombination | | | | | | ~ 570 m | |
| Experimental areas | | | | | | ~ 180 m | |
| Beam Dump Lines TD62/68 | Transfer line | 2006 | 7 TeV | - | $10^{-6}$ | 2 × 720 m | |
| | | | | **High Vacuum** | | ~20 km | **~128 km !** |
| | | | | **UHV w/wo NEG** | | ~ 57.5 km | |
| | | | | **Insulation vacuum** | | ~ 50 km | |



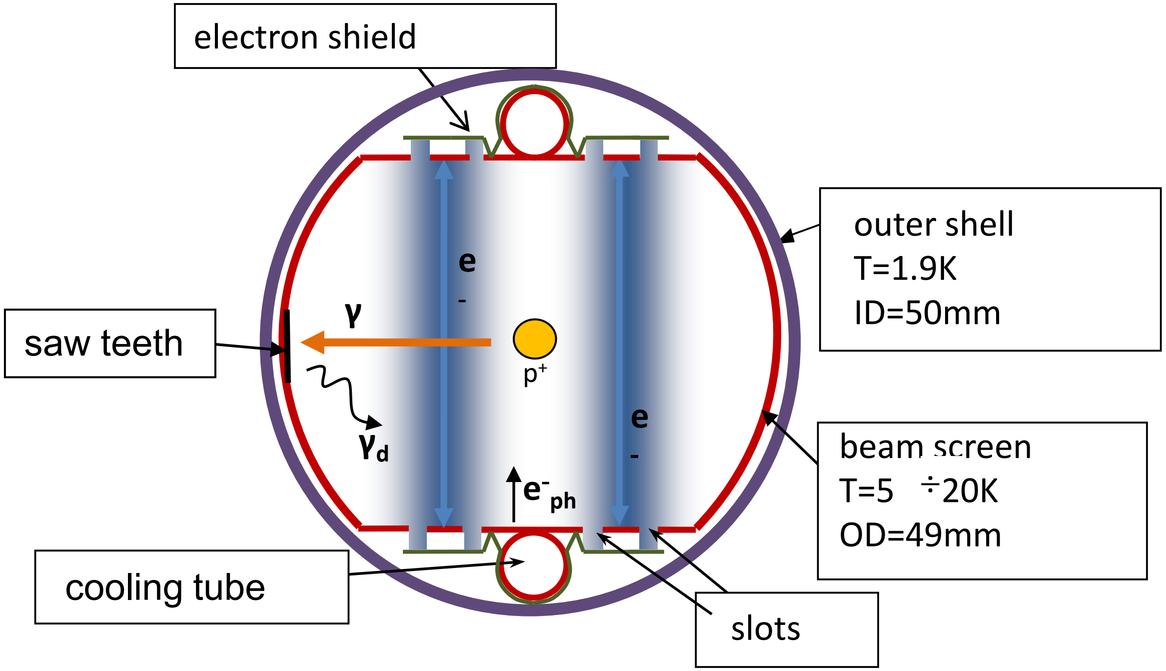
CERN Accelerator Complex





# Cold vacuum chamber with cryosorber

**1- outer shell, 2 – beam screen, 3 – cooling tube, 4,7 – pumping slot shield, 5 – charcoal fiber, 6 – grid for charcoal fixing**



electron shield

outer shell
T=1.9K
ID=50mm

saw teeth

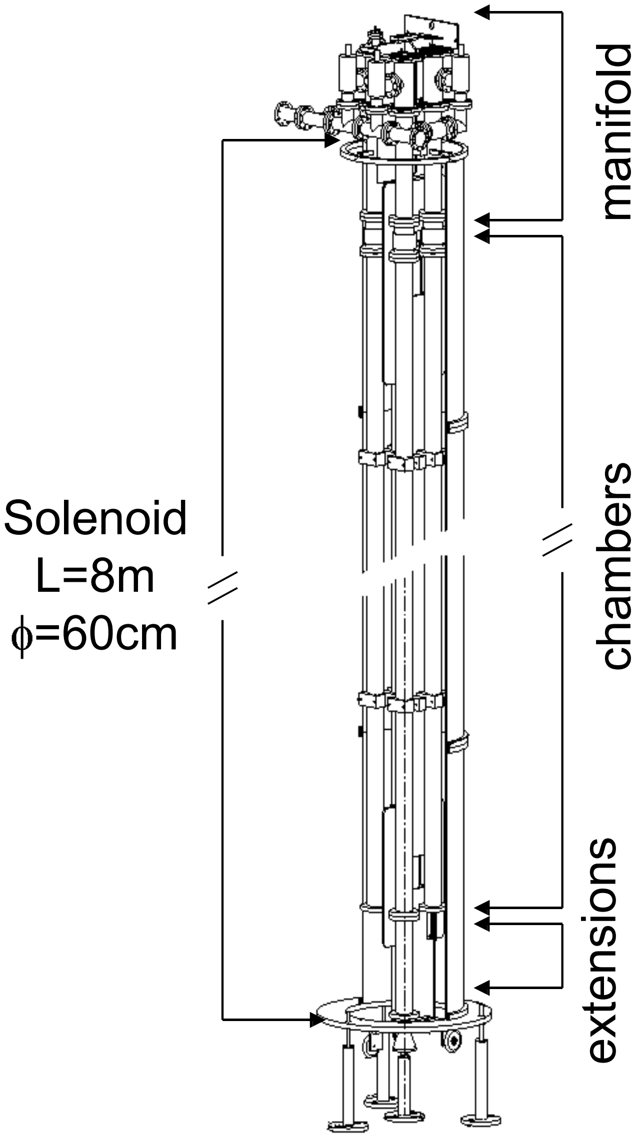
beam screen
T=5 ÷20K
OD=49mm

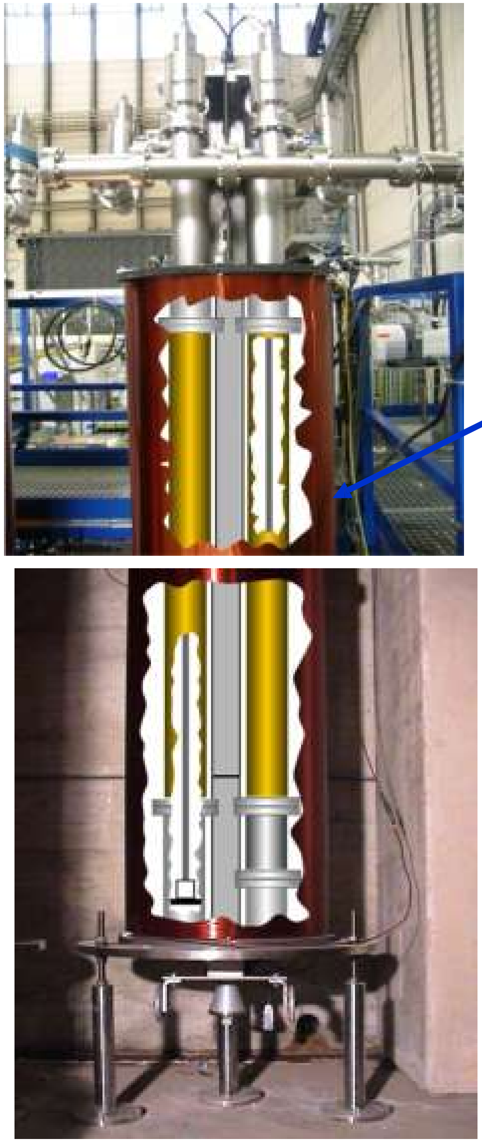
cooling tube

slots

More than 1300 chambers coated with TiZrV NEG for the LHC.

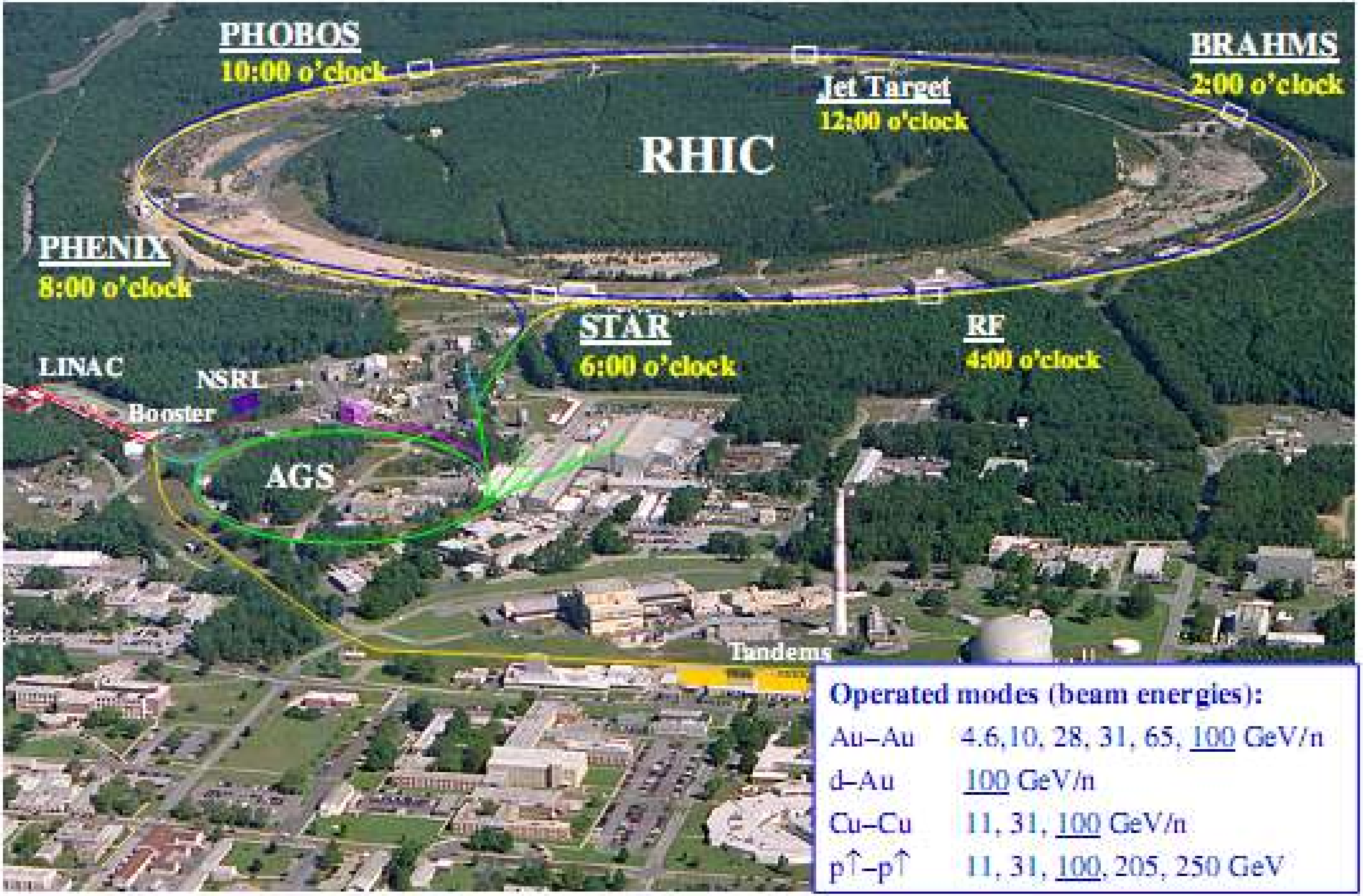
Standard chambers are 7 m long, 80 mm diameter.





CERN’s NEG Coating Facility

# RHIC @ BNL, Long Island, New York



**Operated modes (beam energies):**

| | |
|---|---|
| Au–Au | 4.6,10, 28, 31, 65, <u>100</u> GeV/n |
| d–Au | <u>100</u> GeV/n |
| Cu–Cu | 11, 31, <u>100</u> GeV/n |
| p↑–p↑ | 11, 31, <u>100</u>, 205, 250 GeV |

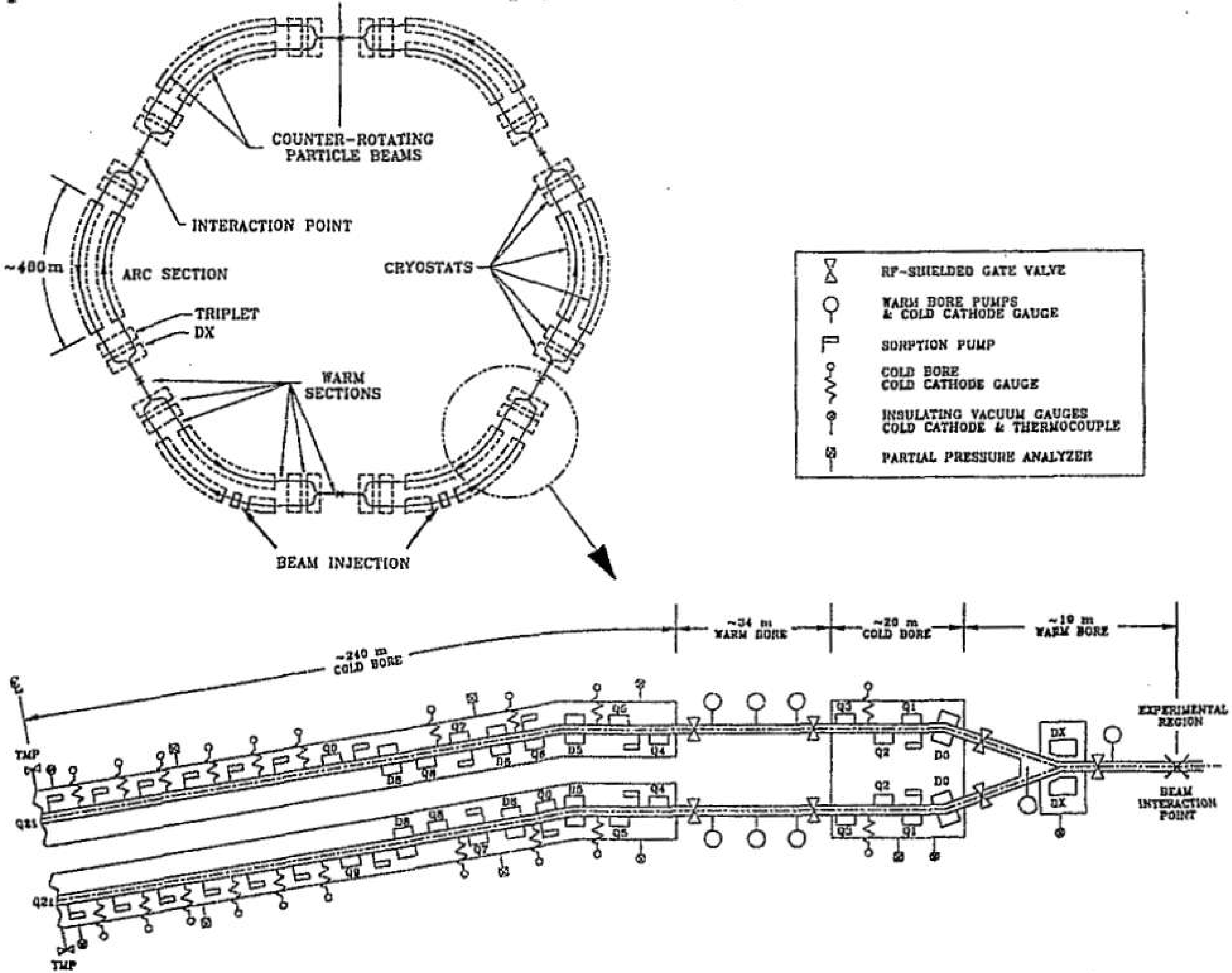


**FIGURE 1.** Schematic layout of RHIC ring and one-half of sextant showing the three types of warm vacuum regions, the Q3-Q4 insertion, the final DX focusing and the interaction region.

# Sorption pumps containing activated charcoal are mounted to the pull through ports of the RF-shielded bellows at every fourth interconnect (B30 m intervals) to pump He and H2.

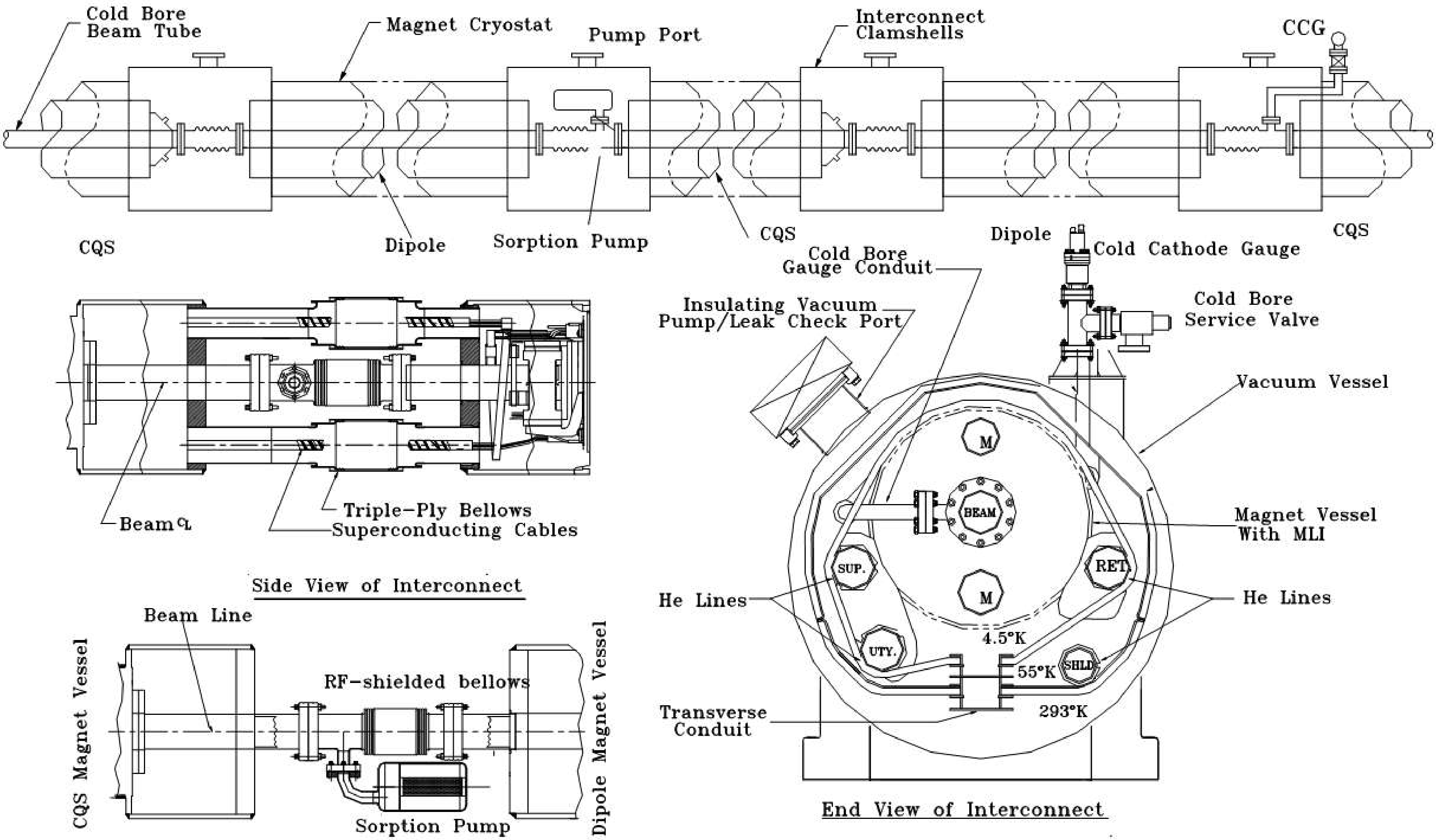
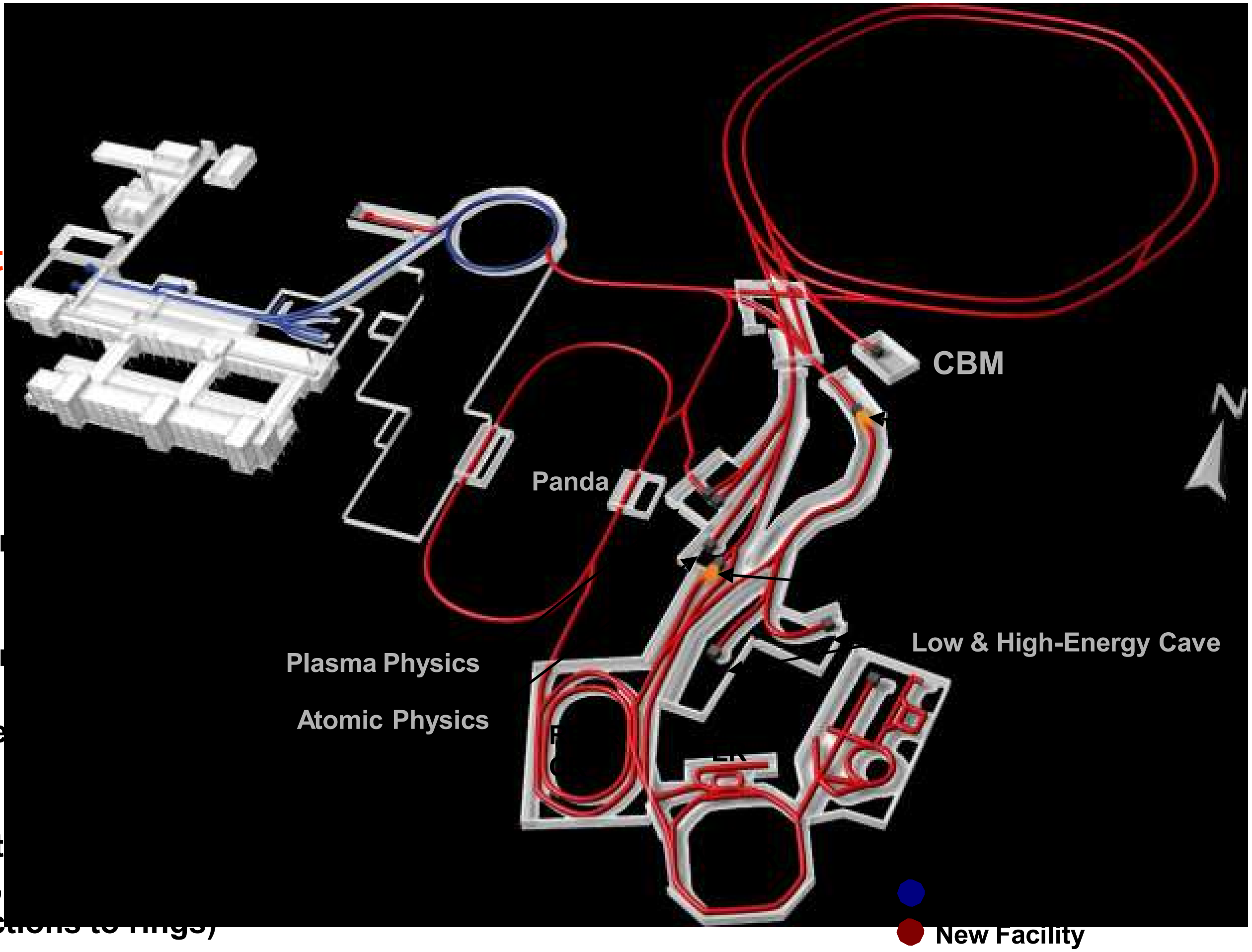


Fig. 2. Vacuum layout of arc sections, and the magnet and beam tube interconnects.

# FAIR Vacuum Requirements

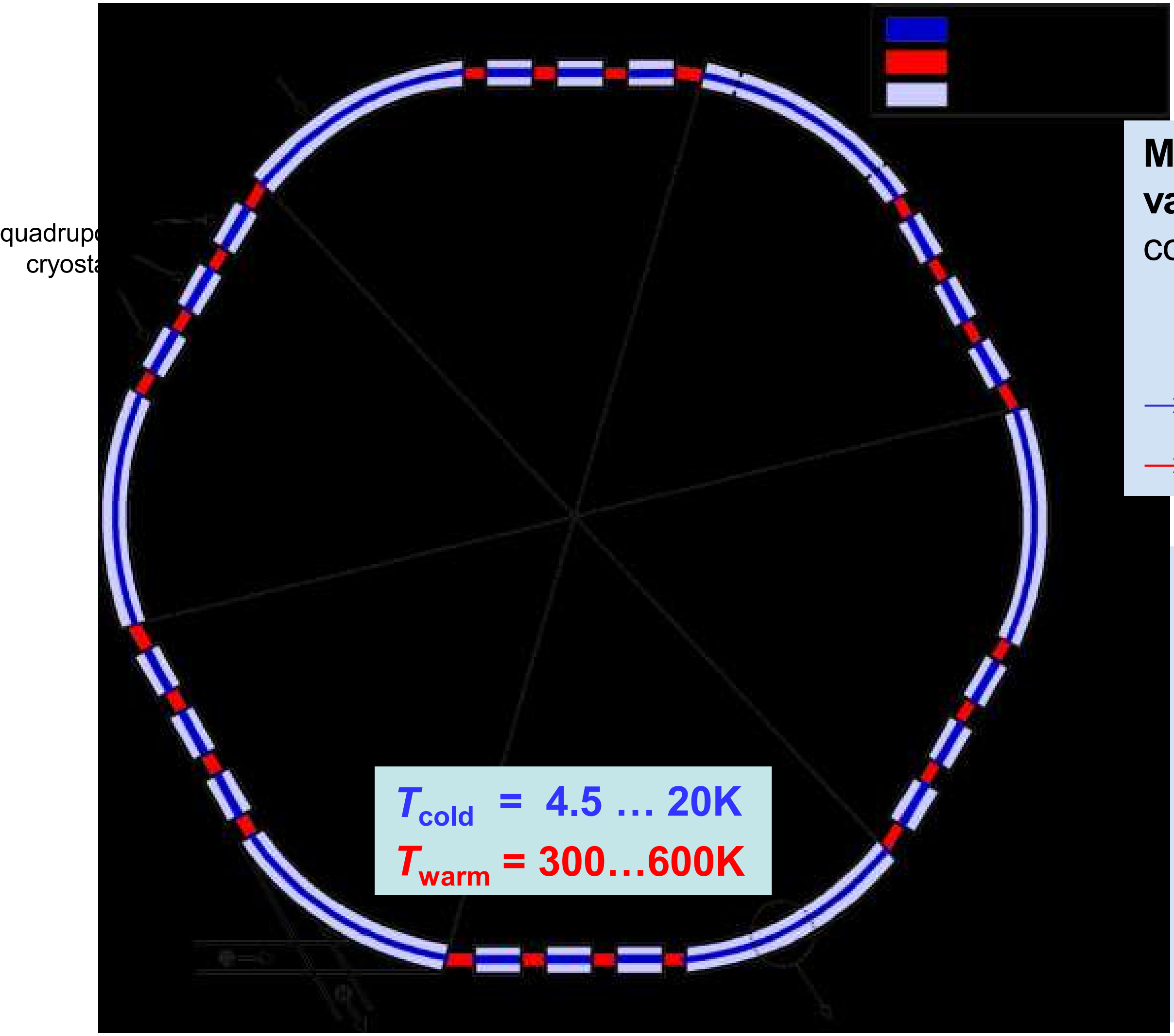


Due to ion beam lifetime requirement
(e.g.: $U^{28+}$ in SIS18):

| | |
|---|---|
| SIS18 (216m): | bakeable $p \approx 5 \cdot 10^{-12}$ mbar |
| ESR (108m): | bakeable $p \approx 5 \cdot 10^{-12}$ mbar |
| SIS100 (1084m): | cold arcs $T_{OP}$=7-20K<br>bakeable straight sectio<br>$p \approx 5 \cdot 10^{-12}$ mbar |
| SIS300 (1084m): | cold arcs $T_{OP}$=4.2K<br>bakeable straight sectio<br>$p \approx 5 \cdot 10^{-12}$ mbar |
| NESR (223m): | $p \approx 5 \cdot 10^{-12}$ mbar (bakeable |
| HESR (550m): | $p \leq 10^{-10}$ mbar (bakeable) |
| RESR (240m): | $p \leq 10^{-10}$ mbar (bakeable) |
| CR (221m): | $p \leq 10^{-9}$ mbar (no bakeout |
| HEBT/Super-FRS: | length 2.4 km, 10% cold,<br>differential pumping sections to rings)<br>$p \approx 1 \cdot 10^{-9}$ mbar |
| P-Linac: | $p \approx 1 \cdot 10^{-9}$ mbar |

*all pressures: $N_2$ equivalent

# Vacuum Systems of SIS100



$T_{cold}$ = 4.5 … 20K
$T_{warm}$ = 300…600K

**Maximum** allowed average beam **vacuum pressure** under dynamic conditions is given by beam life time

$$N_{max} < 4\cdot10^{+12}\ \mathrm{m}^{-3}\ (\mathrm{H}_2)$$

→ $p_{cold} < 5\cdot10^{-12}$ mbar ($T$ = 10K)
→ $p_{warm} < 1\cdot10^{-10}$ mbar ($T$ = 300K)

Total length of SIS100: 1083.6 m (82% cold, 18% warm)

basic structure: hexagonal

six straights and six arcs

25 warm sections (24 x 9.1 m long, 1x 3.3 m)

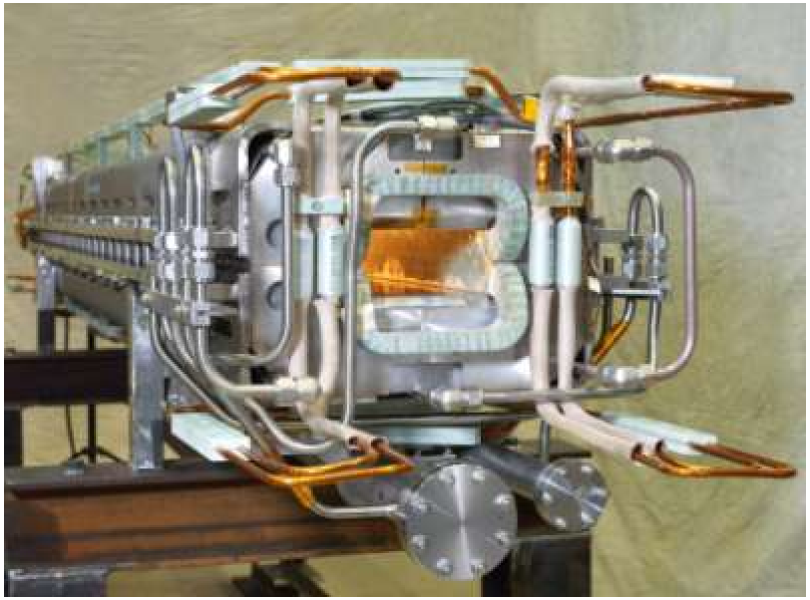
25 cold sections (6 long arcs: 5x 135m, 1x 122.6m), 19 short straight, 18 x 4.3m, 1 x 9.2m)

# SIS100 Dipole Chamber Design

**Vacuum physical requirements on the magnet chamber design**

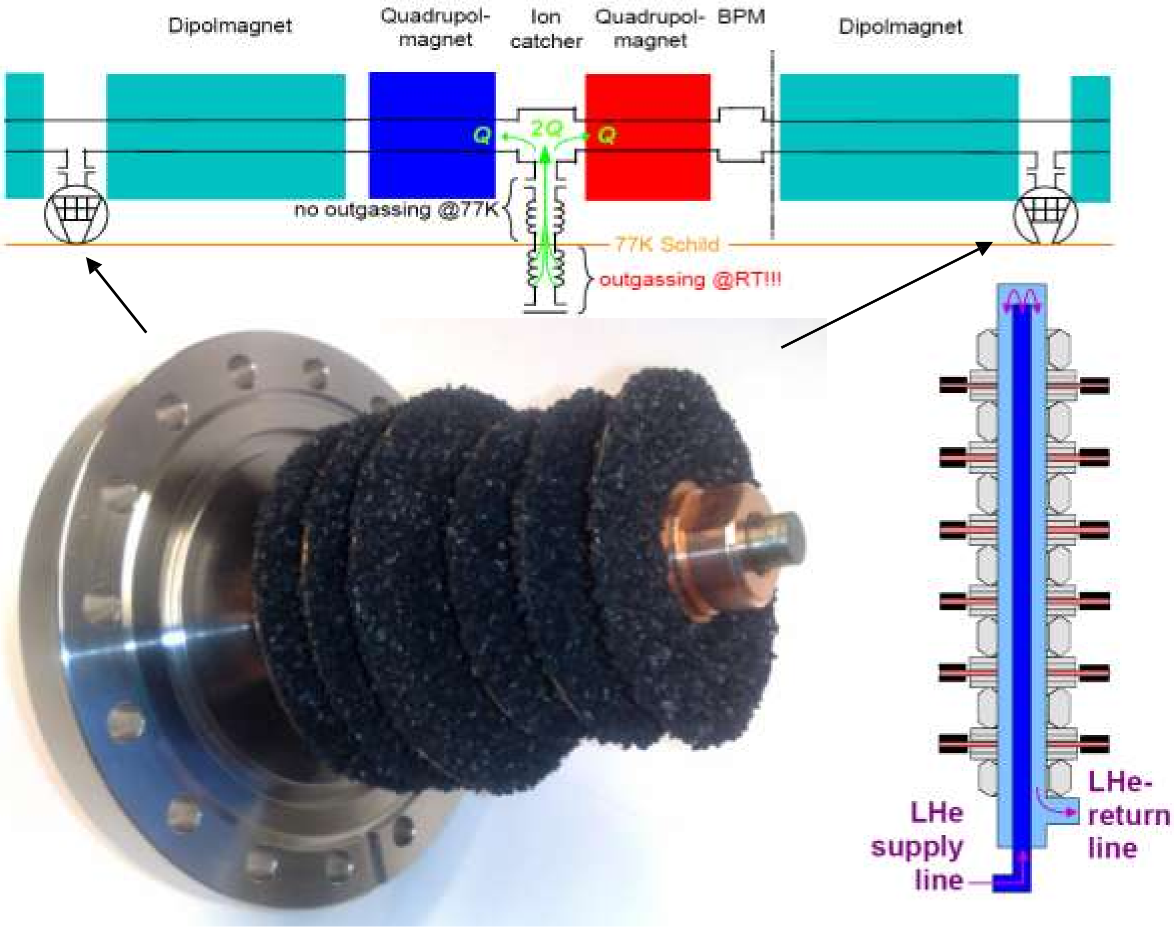
- all dipole chambers represent 45% of the total cold surface in the cryogenic arcs
- the inner beam pipe wall will be used as expanded cold surface of an efficient cryopump with practically infinite capacity for nearly all condensable gas species -> wall temperatures as low as possible
- static vacuum pressure inside the chamber $10^{-12}$ mbar, under dynamic conditions < $10^{-11}$ mbar
- due to the fast magnet ramping eddy currents heat up the chamber wall to temperatures > 20K

Length of chamber: 3.35 m
Aperture: 120 x $60 mm^2$
Wall thickness: 0.3mm
Rib thickness: 3.0 mm



# Cryosorption Pumps

- **auxiliary pumps** are used primarily to lower the partial pressures of $H_2$ and He
- **10 cryosorption pumps per arc** (each 13 m) and **one per short quadrupole doublet in the straight sections**
- **2 different pump layouts**
- cryosorption pump consists of several round cryopanels (i.e. copper disks coated with charcoal of SC2 type made by CHEMVIRON, coating by KIT, Karlsruhe, Germany)
- panels stacked on a central cooling tube cooled down to $T \sim 4.5$K
- $S_{He} \sim 1$ ℓ/s cm² for He and $S_{H2} \sim 10$ ℓ/s cm² for $H_2$

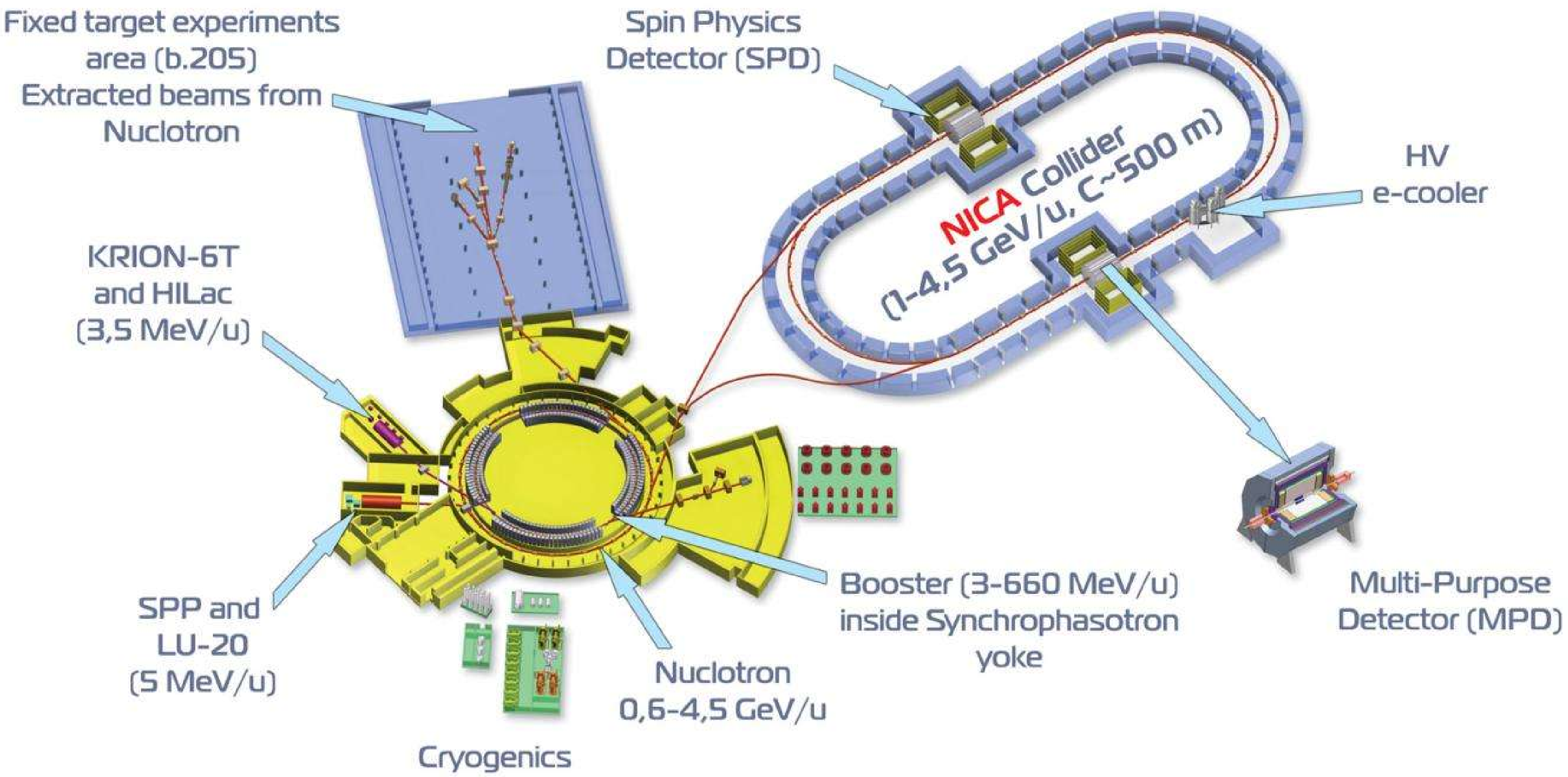


| $m_{char}$ | $A_{char}$ | $C_{char}$ | $S_{pump}$ |
|---|---|---|---|
| ~ 24 g | ~ 34000 m² | ~ 0.25 mbar.ℓ | ~ 50 ℓ/s |

Layout_1
(to be used in cryogenic arcs)

# Superconducting accelerator complex NICA

## (Nuclotron based Ion Collider fAcility)



Fixed target experiments
area (b.205)
Extracted beams from
Nuclotron

KRION-6T
and HILac
(3,5 MeV/u)

SPP and
LU-20
(5 MeV/u)

Cryogenics

Nuclotron
0,6-4,5 GeV/u

Booster (3-660 MeV/u)
inside Synchrophasotron
yoke

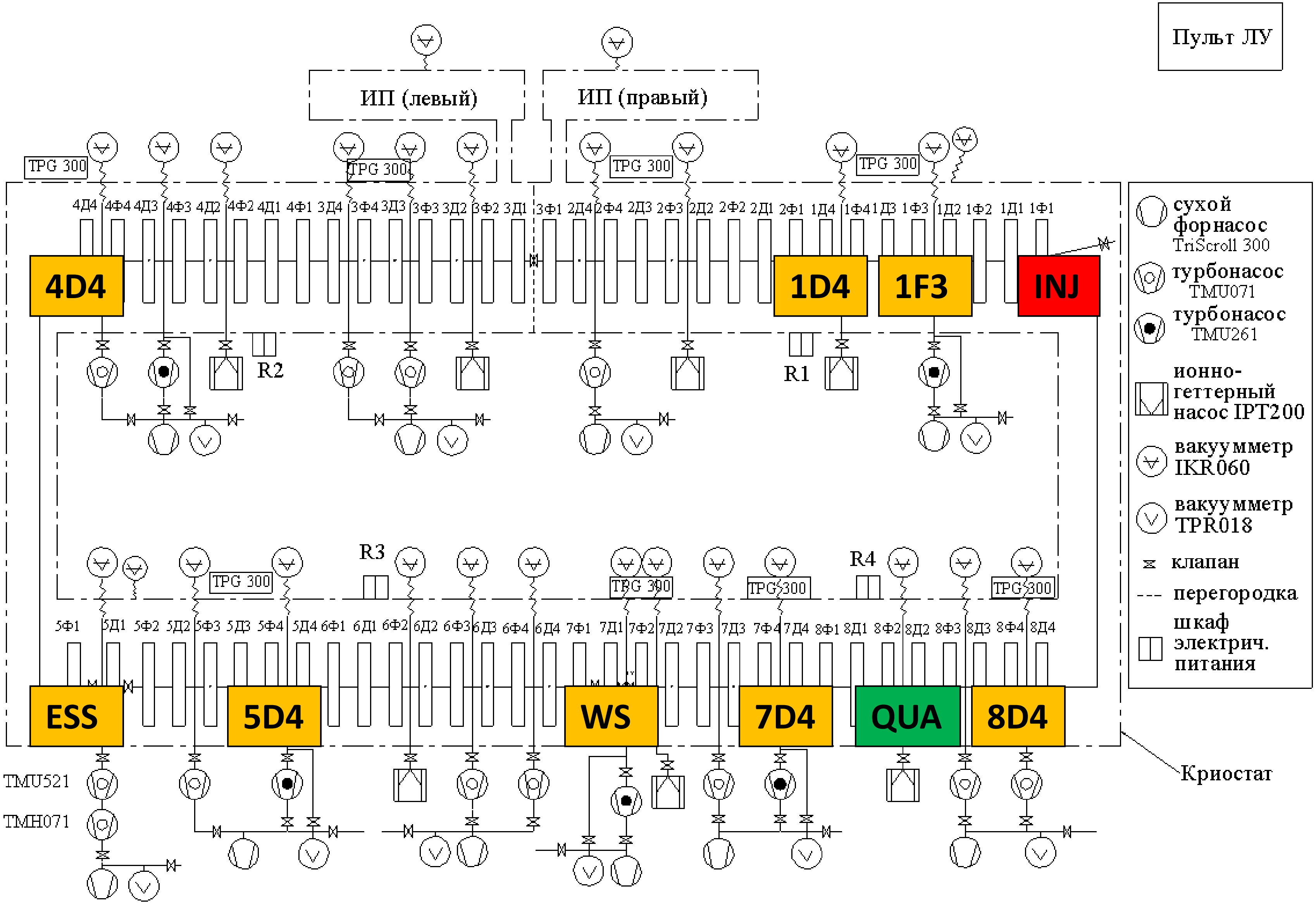
Spin Physics
Detector (SPD)

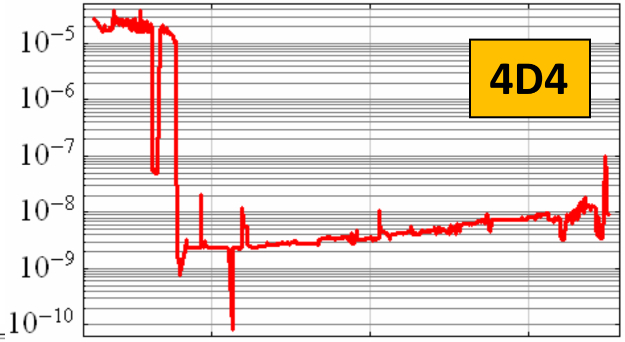
NICA Collider
(1-4,5 GeV/u, C~500 m)

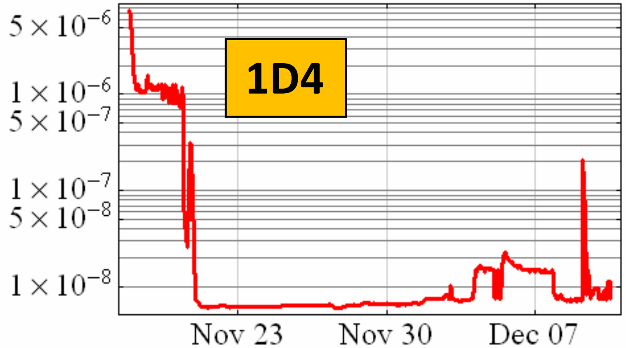
HV
e-cooler

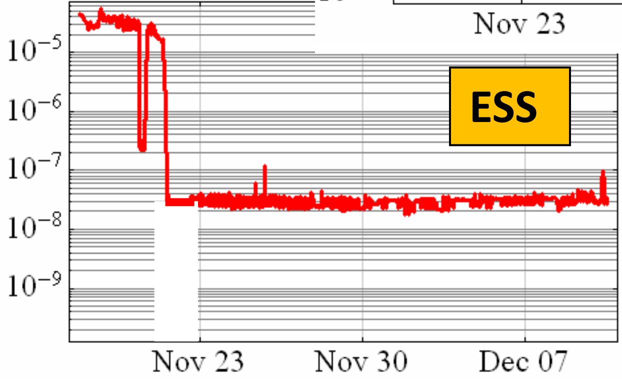
Multi-Purpose
Detector (MPD)

# Upgrade of Nuclotron vacuum system

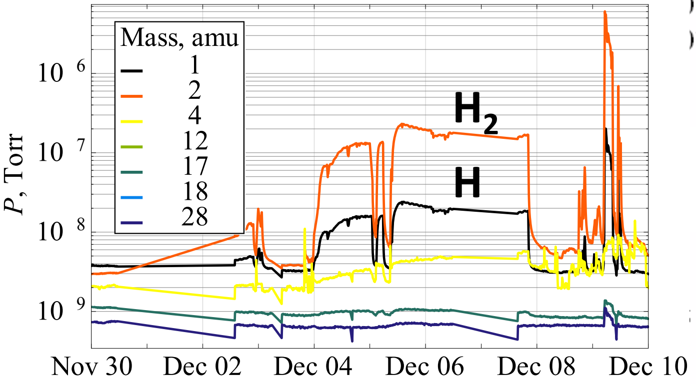


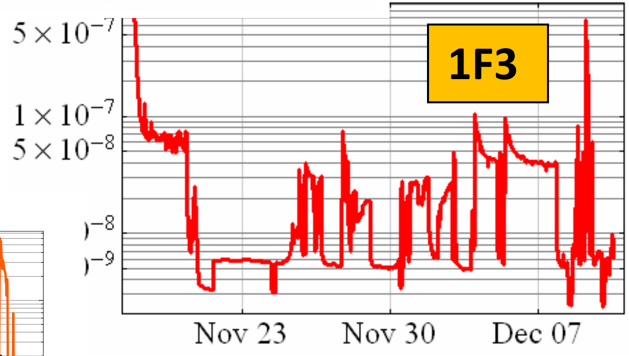




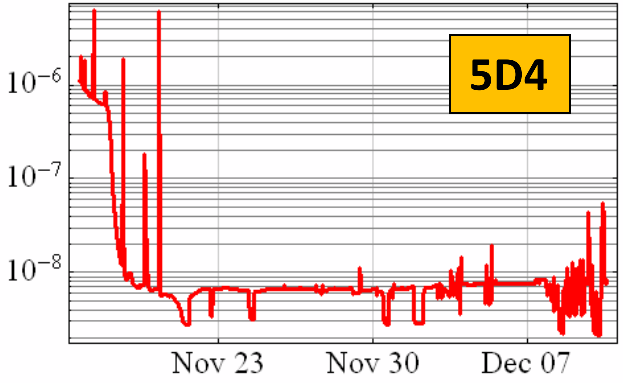


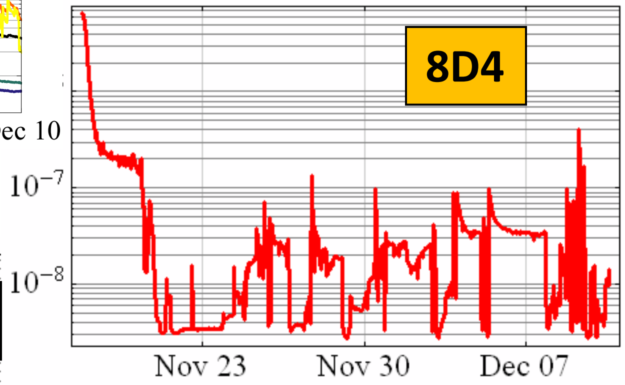
## Mass analyzer QUADERA

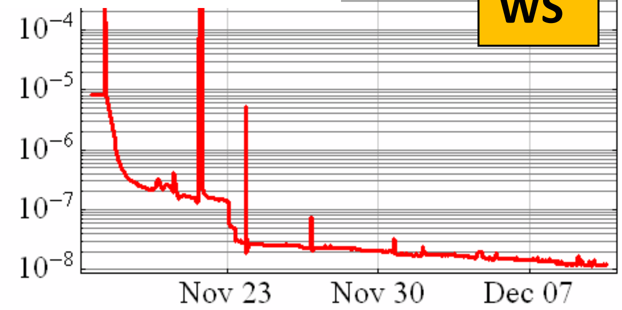


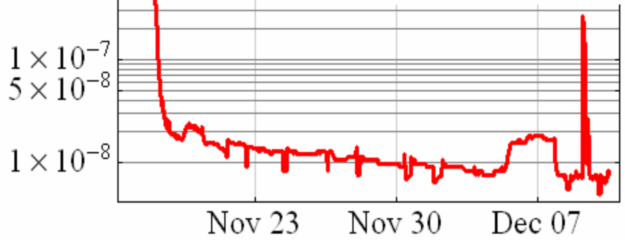


**INJECTION**





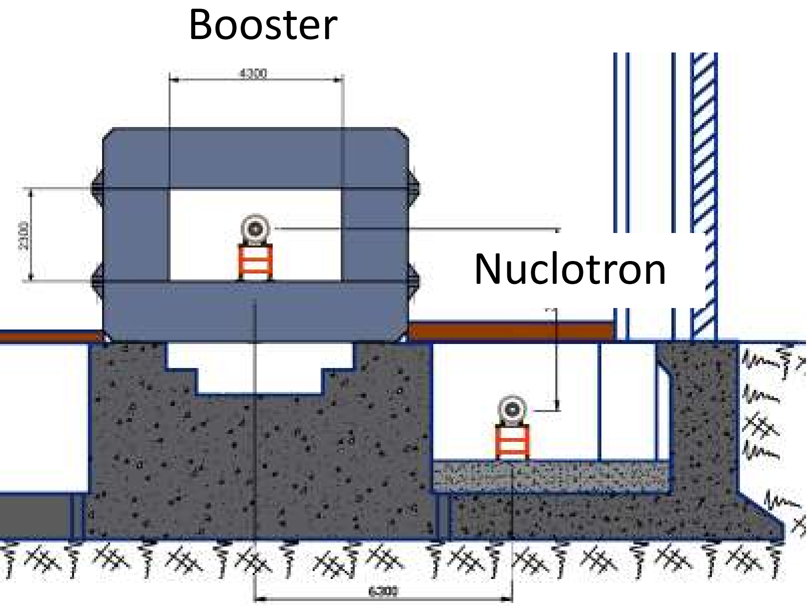


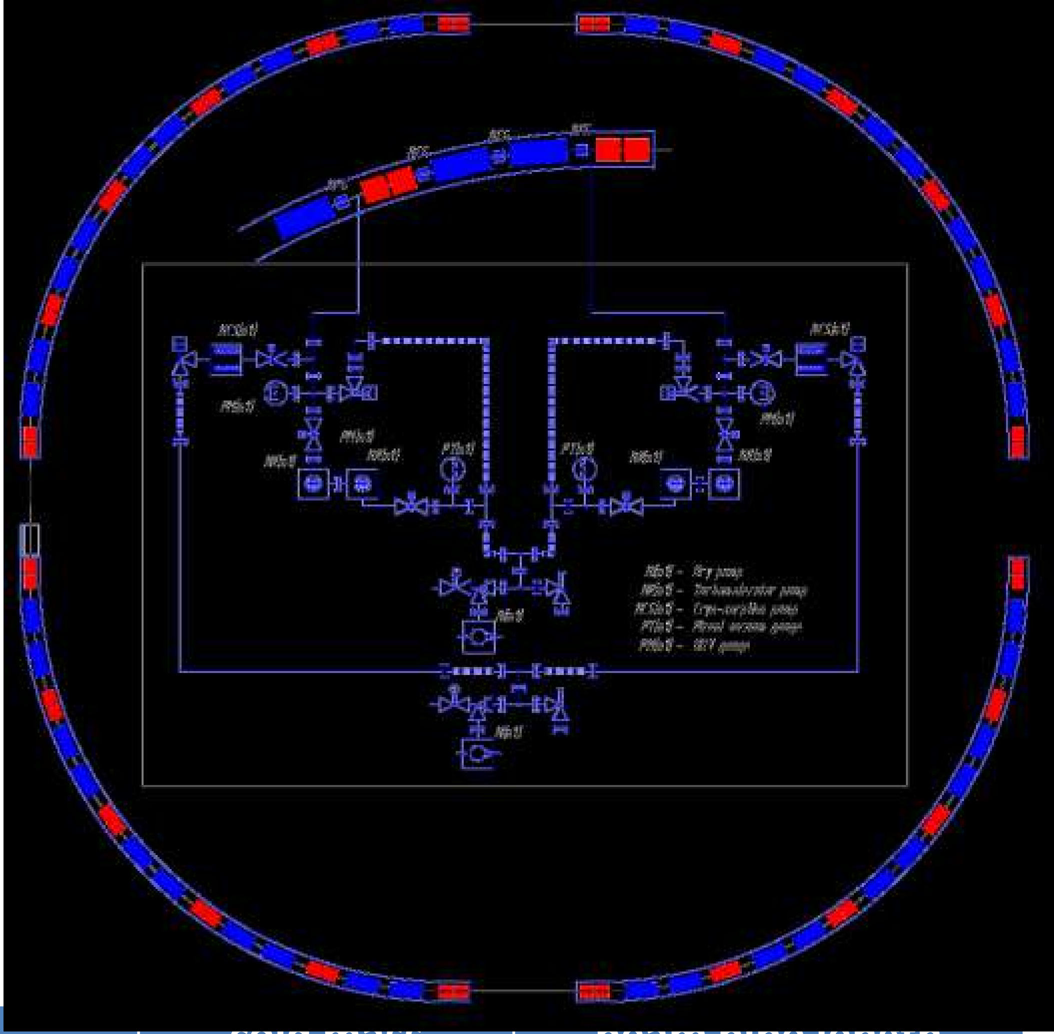


**QUADERA**

**8D2**

# Booster optics structure

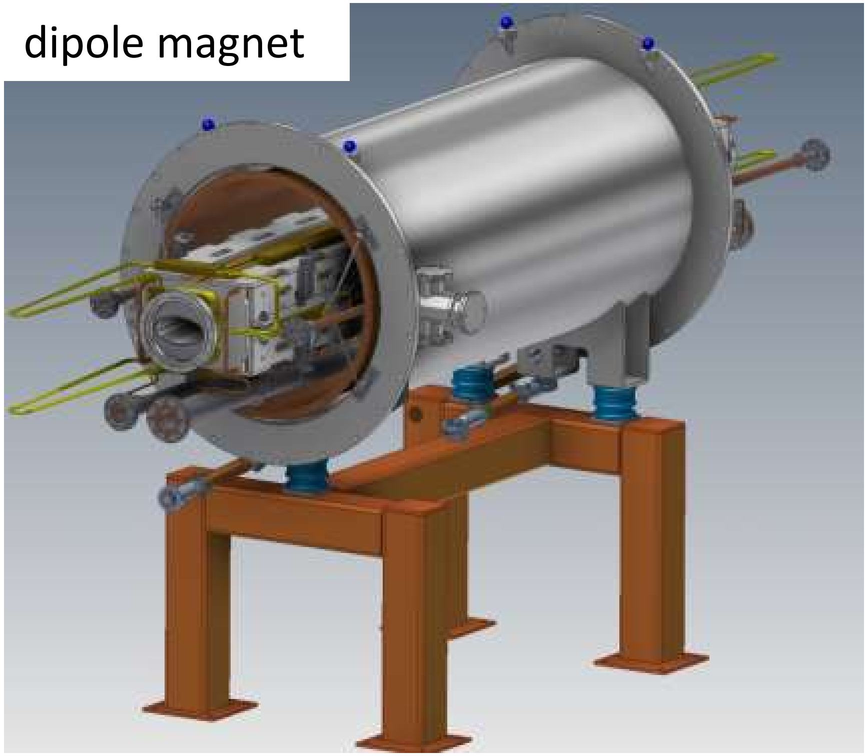




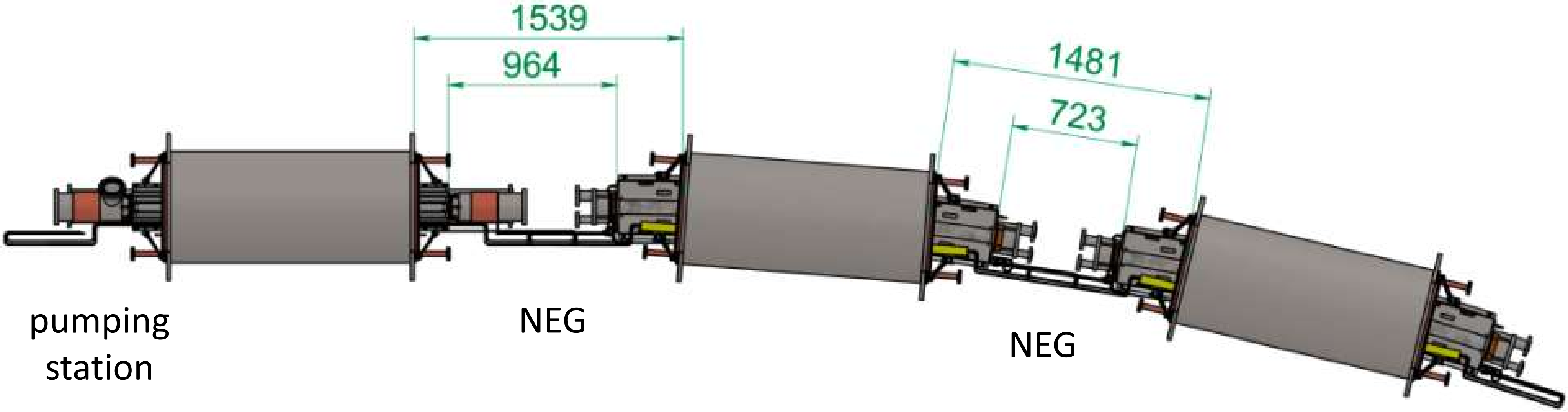
| | | quantities | cold mass (kg) | beam pipe length (м) |
|---|---|---|---|---|
| **Dipole magnet** | | 40 | 1000 | 2,7 |
| **Double quadrupole magnet** | one corrector | 16 | 365 | 2,45 |
| | three correctors | 8 | 470 | 2,45 |

# Booster magnet connection

double quadrupole magnet



dipole magnet



# NEG pumps at cryogenic temperature

## NEG still have good pumping speed for H2 close to liquid nitrogen temperature

3444 Boffito *et al.*: Gettering in cryogenic applications

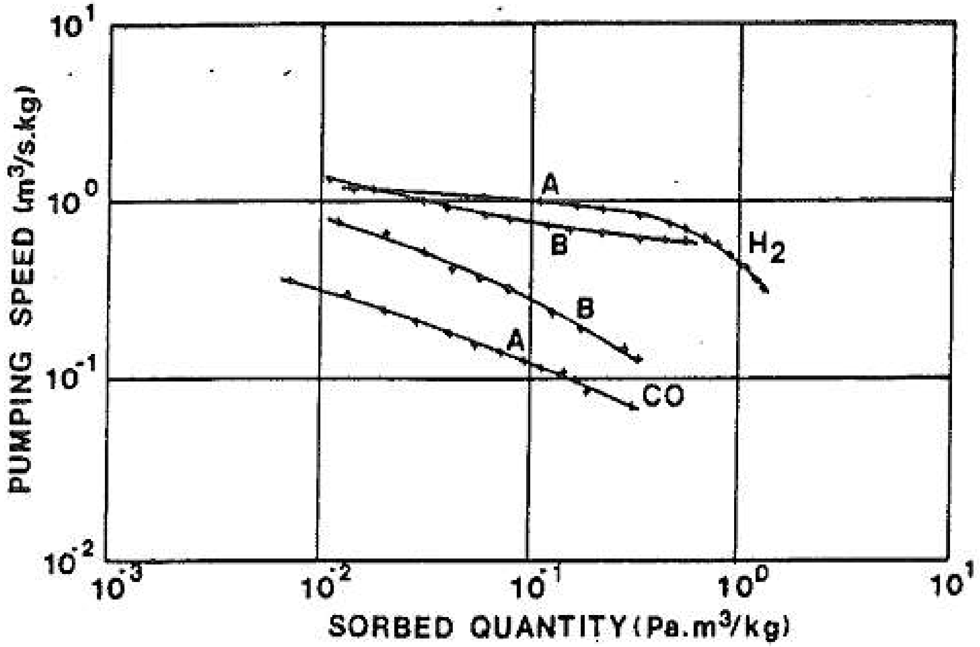
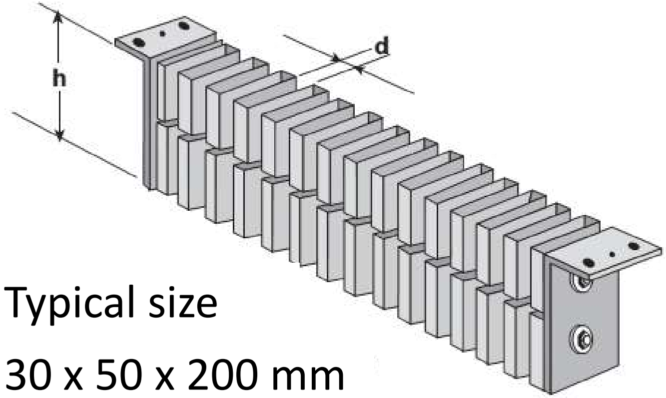


FIG. 3. $H_2$ and CO sorption characteristics for the Zr–V–Fe getter alloy at (A) room and (B) $LN_2$ temperature, after activation at 400 °C for 30 min.

## SORB-AC® Getter Wafer Modules and Panels

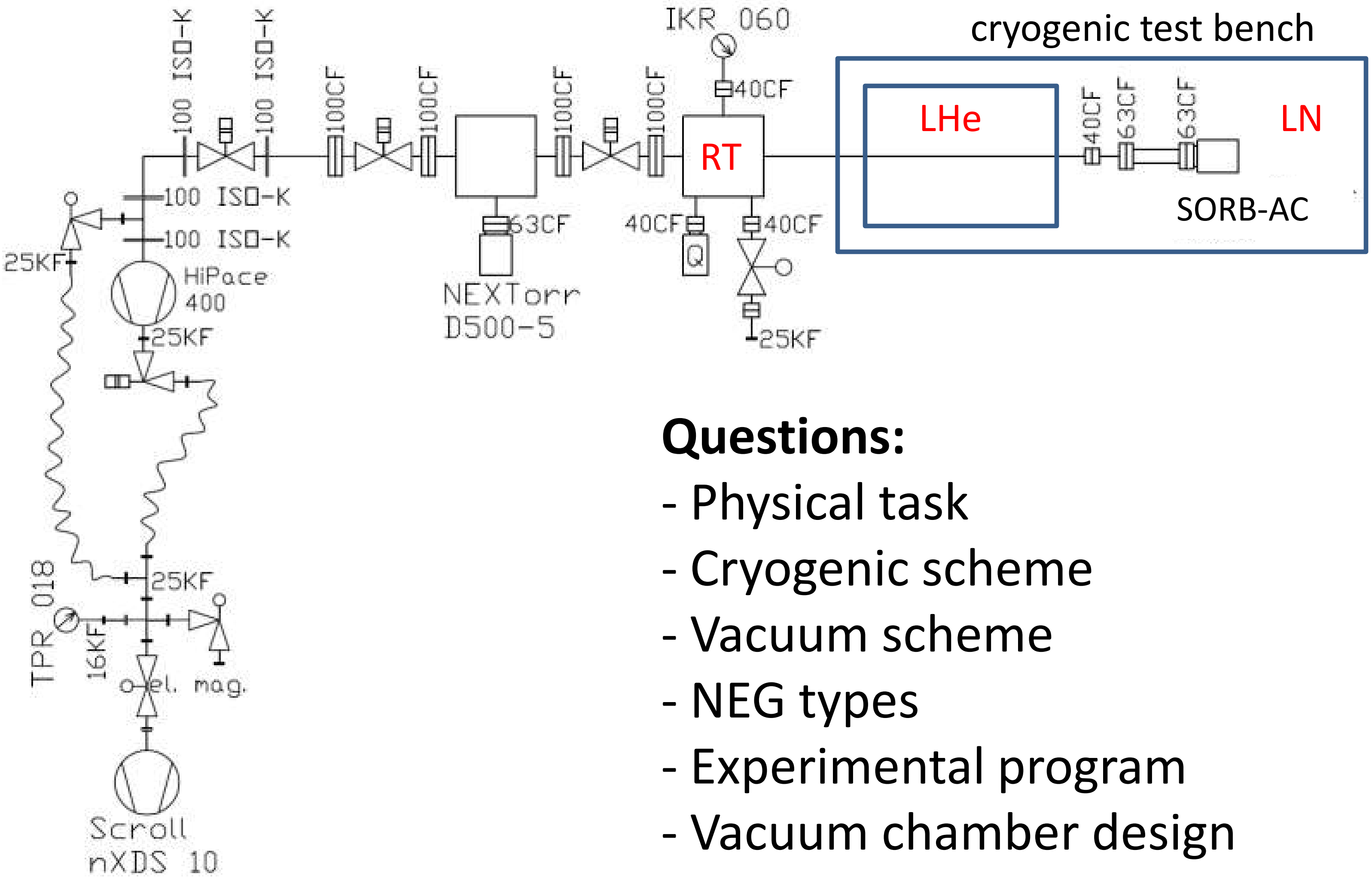


Typical size

30 x 50 x 200 mm

# Vacuum scheme for NEG test under cryogenic temperatures

**in collaboration with SAES Group**

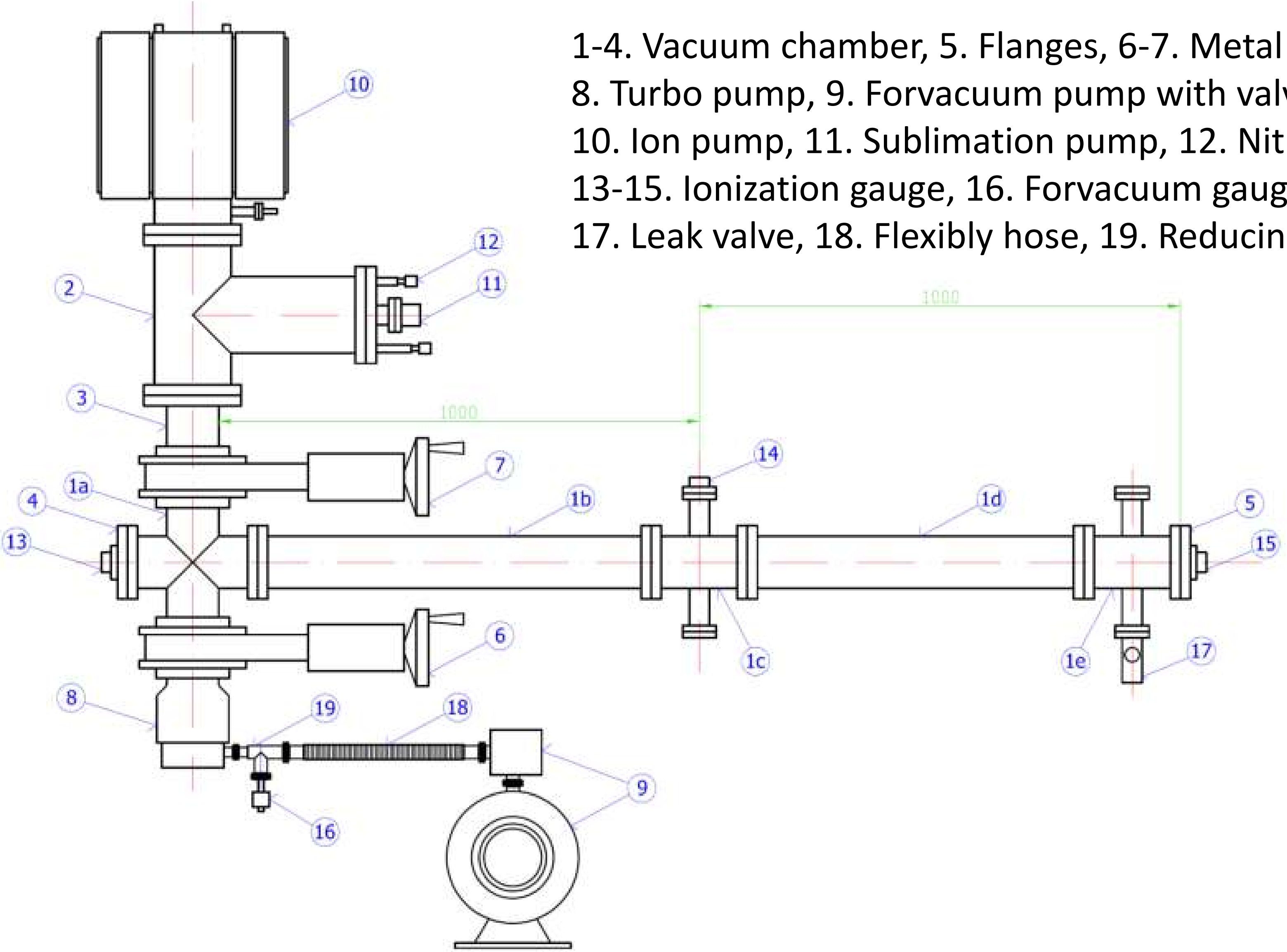


**Questions:**

- Physical task
- Cryogenic scheme
- Vacuum scheme
- NEG types
- Experimental program
- Vacuum chamber design

# Warm test bench at JINR

**in collaboration with Vakuum Praha (Czech Republic)**
**and ФГУП СКБ ИРЭ РАН (г.Фрязино, МО)**



1-4. Vacuum chamber, 5. Flanges, 6-7. Metal valve,
8. Turbo pump, 9. Forvacuum pump with valve,
10. Ion pump, 11. Sublimation pump, 12. Nitrogen trap,
13-15. Ionization gauge, 16. Forvacuum gauge,
17. Leak valve, 18. Flexibly hose, 19. Reducing T-piece

# Backing of Test Bench at JINR

After baking during 30 hours with 280$^{o}$C
vacuum was reached value about **$10^{-11}$ Torr !**