SIMULATION OF VACUUM CONDITIONS AND ION BEAM LOSSES FOR DESIGNING VACUUM

SYSTEMS OF HEAVY ION ACCELERATORS AND IRRADIATION FACILITIES

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Determination of basic parameters and technical requirements for the vacuum system of the cyclotron complex:

- ✓ **the level of average pressure in vacuum chambers that provides ion beam intensity needed for goals of nuclear and applied physics;**
- ✓ **the optimal geometry of vacuum chamber (effective dimension, for instance, diameter);**
- ✓ **the optimal location of pumps with optimal pumping speed;**
- ✓ **the adequate level of gas loading (gas flow to the vacuum chamber, ion beam stimulated gas desorption, specific outgassing rate from surfaces of constructed materials)**
- ✓ **the optimal (rational) cost of vacuum equipment.**

The computer simulation code VACLOS using Microsoft EXCEL and Visual Basic software has been developed to determine the beam loss caused by the charge-changing collisions between various heavy ions and residual gas molecules during acceleration in a cyclotron. This code includes :

- ✓ **the determination of the pressure distribution inside the cyclotron;**
- ✓ **the evaluation charge changing cross section of the ion on molecules of the residual gas;**
- ✓ **the calculation of the transmission efficiency for ion beams.**

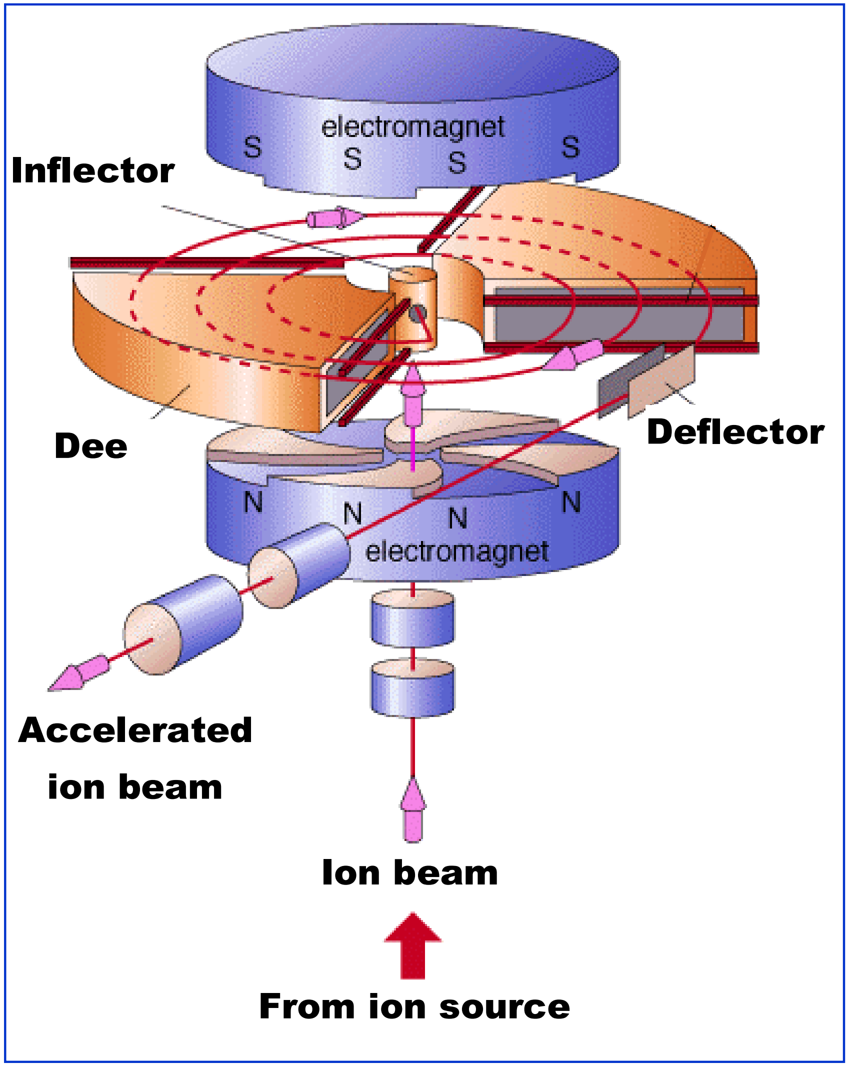
GENAP carries out analogous procedures for oblong vacuum chamber, such as ion beam transport lines, linear accelerator etc., and for fixed ion energy.

VACLOS & GENAP have been developed and tested on the basis of experiments in four cyclotrons of heavy ions at the Flerov Laboratory of Nuclear Reactions (FLNR). They have been used for design of the vacuum systems for the number of new cyclotron complexes in order to maximize an efficiency of accelerated ion beams.

Vacuum chambers of cyclotron complex typically include

- the channel of the ion injection to the cyclotron from the external ion source or the line of low energy ion beams,
- the cyclotron's vacuum chamber and
- transport lines of accelerated ion beams to the experimental facilities.

Ion beam movement during beam's acceleration in vacuum chambers of cyclotron complex



RADIAL PRESSURE DISTRIBUTION IN CYCLOTRON

The total gas loading in the cyclotron vacuum chamber involves the following main components (typically in working regimes):

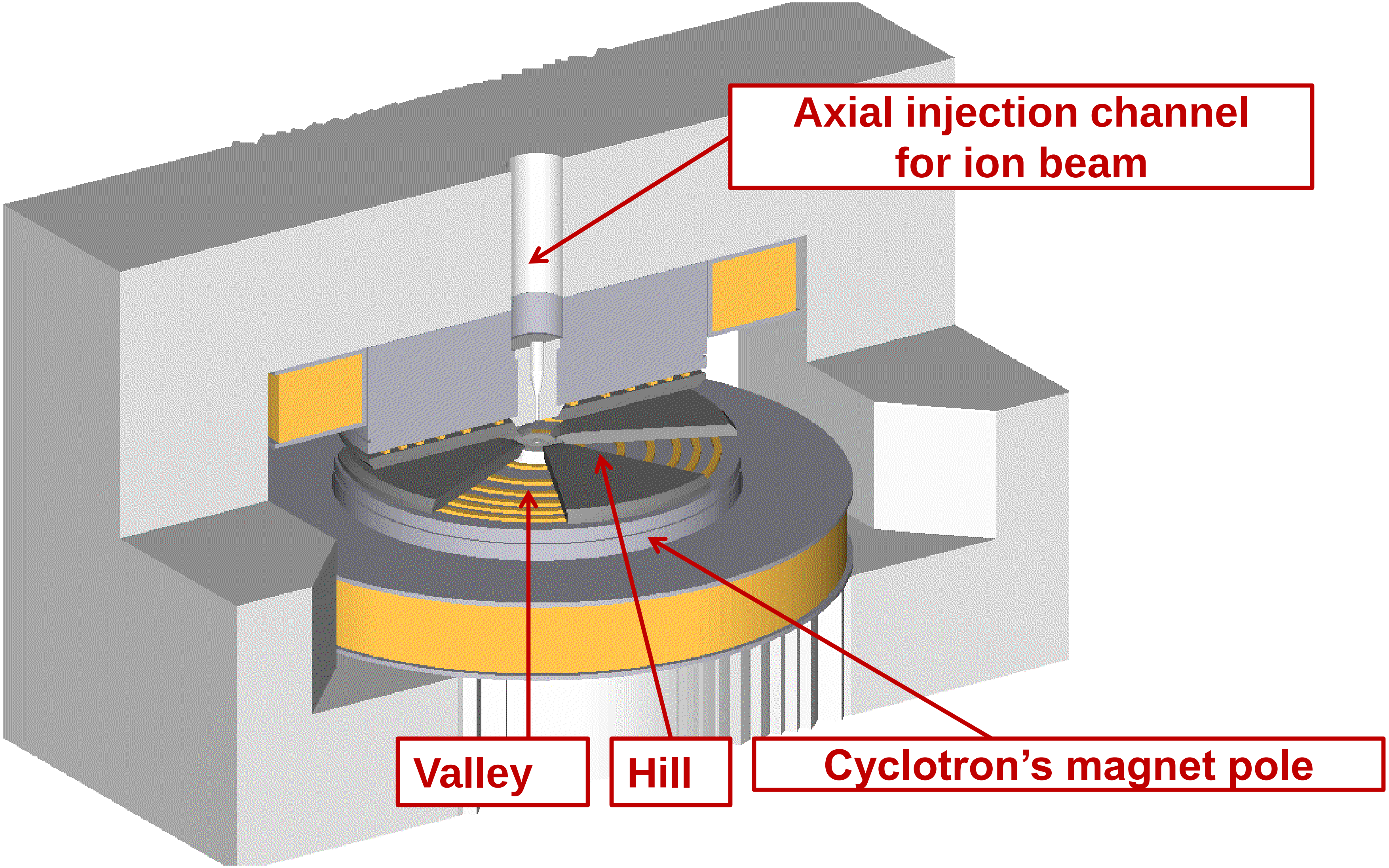
- **the working gas flow from the internal ion source (usually for a PIG source, $Q \cong (3 \div 6) \cdot 10^{-3}$ Torr·l·s^{-1} for Xe or Kr working gas and $Q \cong (6 \div 9) \cdot 10^{-3}$ Torr·l·s^{-1} for Ar or N_2),**

- **the thermal outgassing from the surfaces of the constructional materials (the specific static outgassing $q \cong 1 \cdot 10^{-5}$ Torr·l·s^{-1}·m^{-2} in the steady state),**

- **the atmospheric gas flow through the micro-defects in the vacuum chamber (about 10% of the thermal outgassing as it was found experimentally),**

- **the ion stimulated desorption. We can disregard it in the optimal regime of beam focusing, when it is significantly less than the thermal outgassing for ion beam intensities of $1 \cdot 10^{11} \div 1 \cdot 10^{12}$ s^{-1}.**

Structure of vacuum chamber that is defined by the azimuthally periodical structure of cyclotron's magnet poles



For the case of the cyclotron geometry with azimuth symmetry and an internal gas flow inside the cyclotron, the pressure profile is expressed by the equation:

$$P(r) = P_0 + \frac{Q}{G_{R\text{-}r}} \quad , \qquad (1)$$

where $P_0 = P(R)$ is the pressure at the pump's positions, Q is the gas flow rate due to the ion source, $G_{R\text{-}r}$ is the conductance, R is the vacuum chamber radius.

The radial conductance inside the vacuum chamber of the cyclotron can be obtained from the Knudsen formula:

$$G_{R-r} = \frac{4}{3} \nu_a \frac{1}{\int_r^R \frac{\Pi(x)}{F^2(x)} dx} \quad , \qquad (2)$$

where ν_a is the molecular average thermal velocity, Π, F are the perimeter and cross section of the azimuth periodic segment (hill and valley of the magnet poles) of the vacuum chamber.

From equations (1) and (2), we can get the pressure profile resulting from the gas loading of the internal ion source:

$$P(r) = P_0 + \frac{3nQ}{2\pi\nu_a}\frac{1}{h^2}\left[\ln\frac{R}{r} + \frac{nh(R-r)}{\pi Rr}\right] \quad , \quad (3)$$

where n is the number of the pole sectors, h is the axial gap between the magnet poles.

The pressure produced by the thermal outgassing is presented by :

$$P_0^{'}(r) = P_0^{'} + \int_r^R \frac{q\Pi}{G_{R-r}^{'}}dx + \frac{1}{G_{R-r}^{'}}\int_0^r q\Pi dx \quad , \quad (4)$$

where q is the specific static outgassing, and P_0 or is the pressure at the pump's position.

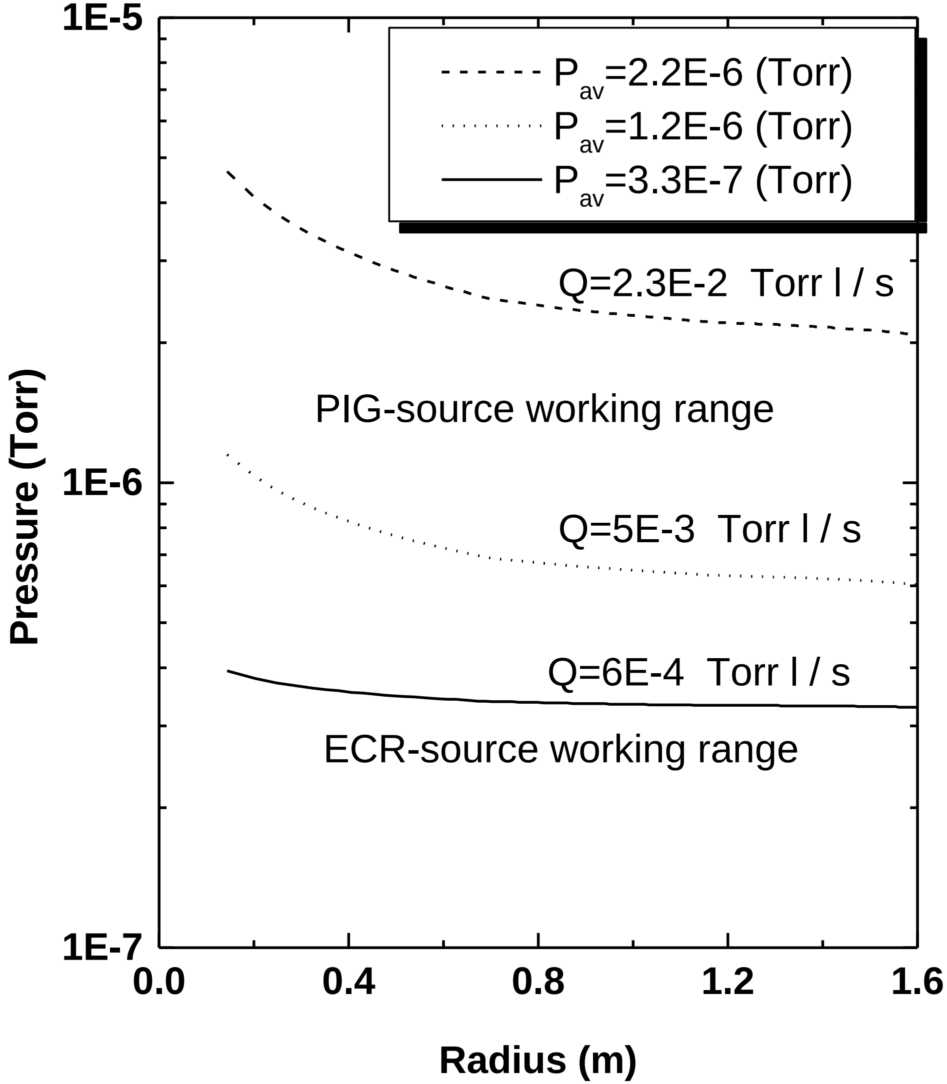
Last equation leads to:

$$P'(r) = P_0' + \frac{3nq}{\pi h^2 \nu_a}\Bigg[\frac{\pi}{4n}\left(R^2 - r^2\right) + \frac{3}{2}h(R-r) + \frac{nh^2}{\pi}\ln\frac{R}{r}\,\frac{\pi}{2n}R_0^2\ln\frac{R}{r} - hR_0\ln\frac{R}{r} - \frac{hR_0^2(R-r)}{2Rr} - \frac{nh^2R_0(R-r)}{\pi Rr}\Bigg] \quad (5)$$

where r changes from R_0 to R.

Then the average pressure in the periodic segments (hill, valley and regarding the dee's position) of the vacuum chamber was calculated. The results are in good accordance with previous measurements.

The intervals of working pressure for the U-400 cyclotron equipped with either an ECR or a PIG ion source:



The calculated radial pressure distribution for the U-400 cyclotron, being equipped with an ECR or a PIG ion source, at the corresponding average pressure at the extraction radius R=160 cm ($q = 1 \cdot 10^{-5}$ Torr·l·sec^{-1}·m^{-2}).

PRESSURE DISTRIBUTION IN OBLONG VACUUM CHAMBERS

The pressure distribution *p(x)* over an oblong vacuum chamber of the length L can be found as a solution of differential equation:

$$\frac{d^2 p}{dx^2} = -\frac{Q}{G(L)} \qquad (6)$$

where *Q* is a gas flow to the vacuum chamber and *G(L)* is its conductance.

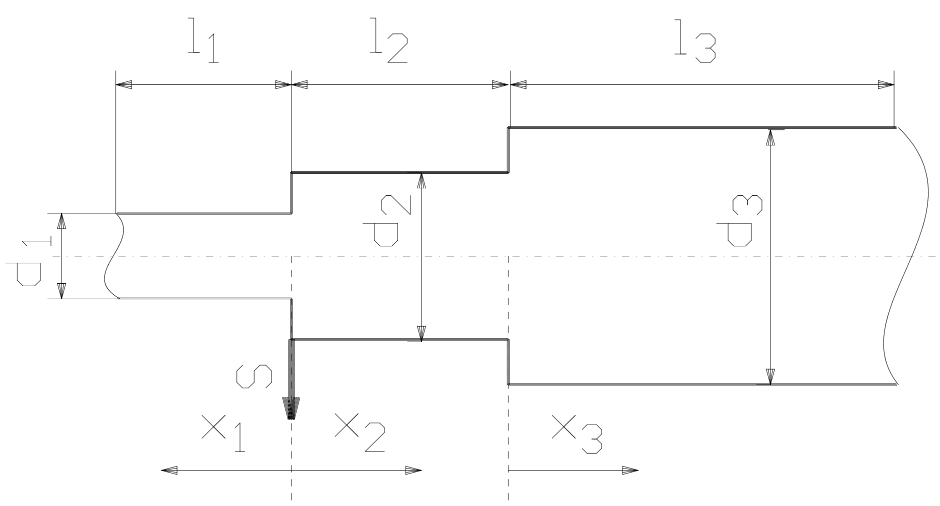
To explain the algorithm itself let us consider the vacuum chamber consisting of three parts, each part being of length l_i, and diameter d_i. The specific outgassing in the i-part will be q_i, i=1,2,3. The pressure distribution along the coordinates x_1, x_2, and x_3 will be defined by the equations:

$$P_q(x_1) = \sum_{i=1}^{3} \frac{q_i F_i l_i}{S} + \frac{q_1 F_1}{G_1}\left(x_1 - \frac{x_1^2}{2l_1}\right)$$

$$P_q(x_2) = \sum_{i=1}^{3} \frac{q_i F_i l_i}{S} + \frac{q_3 F_3 l_3 x_2}{l_2 G_2} + \frac{q_2 F_2}{G_2}\left(x_2 - \frac{x_2^2}{2l_2}\right) \qquad (7)$$

$$P_q(x_3) = \sum_{i=1}^{3} \frac{q_i F_i l_i}{S} + \frac{q_3 F_3 l_3}{G_2} + \frac{q_2 F_2 l_2}{2G_2} + \frac{q_3 F_3}{G_3}\left(x_3 - \frac{x_3}{2l_3}\right)$$

where S is the pumping speed.



Scheme of a vacuum system with static outgassing.

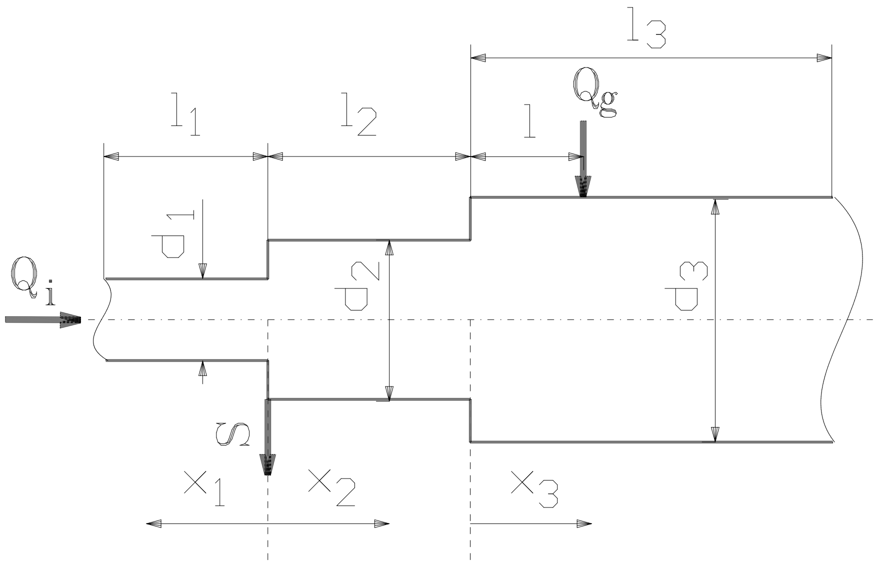
S - pumping speed,

d_I - diameter of the chamber segment of length l_i.

Having in mind the accelerator technique, another gas source connected with the ion beam must be taken into account, too. It consists of the gas flowing from the ion source and the stimulated gas desorption from the surface due to the collisions with the scattered ion beam. The gas desorption rate *Qg* due to the lost beam can be calculated according to the expression:

$$Q_g = 1000 \frac{I}{Z} \gamma_i kT \quad (8)$$

where *I* is the lost beam intensity, *Z* is the average charge state of the lost ions, γ_i is the gas desorption yield, *k* is the Boltzmann constant and *T* is gas temperature.



Scheme of a vacuum system with dynamic gas loading.
Q_i- ion source gas loading,
Q_g- stimulated gas desorption,
S- pumping speed, d_i- diameter of the chamber segment of length l_i.

The pressure distribution caused by this additional gas load will be:

$$P_Q(x_1) = \frac{Q_g}{S} + Q_i\left(\frac{x_1}{l_1 G_1} + \frac{1}{S}\right)$$

$$P_Q(x_2) = \frac{Q_i}{S} + Q_g\left(\frac{x_2}{l_2 G_2} + \frac{1}{S}\right)$$

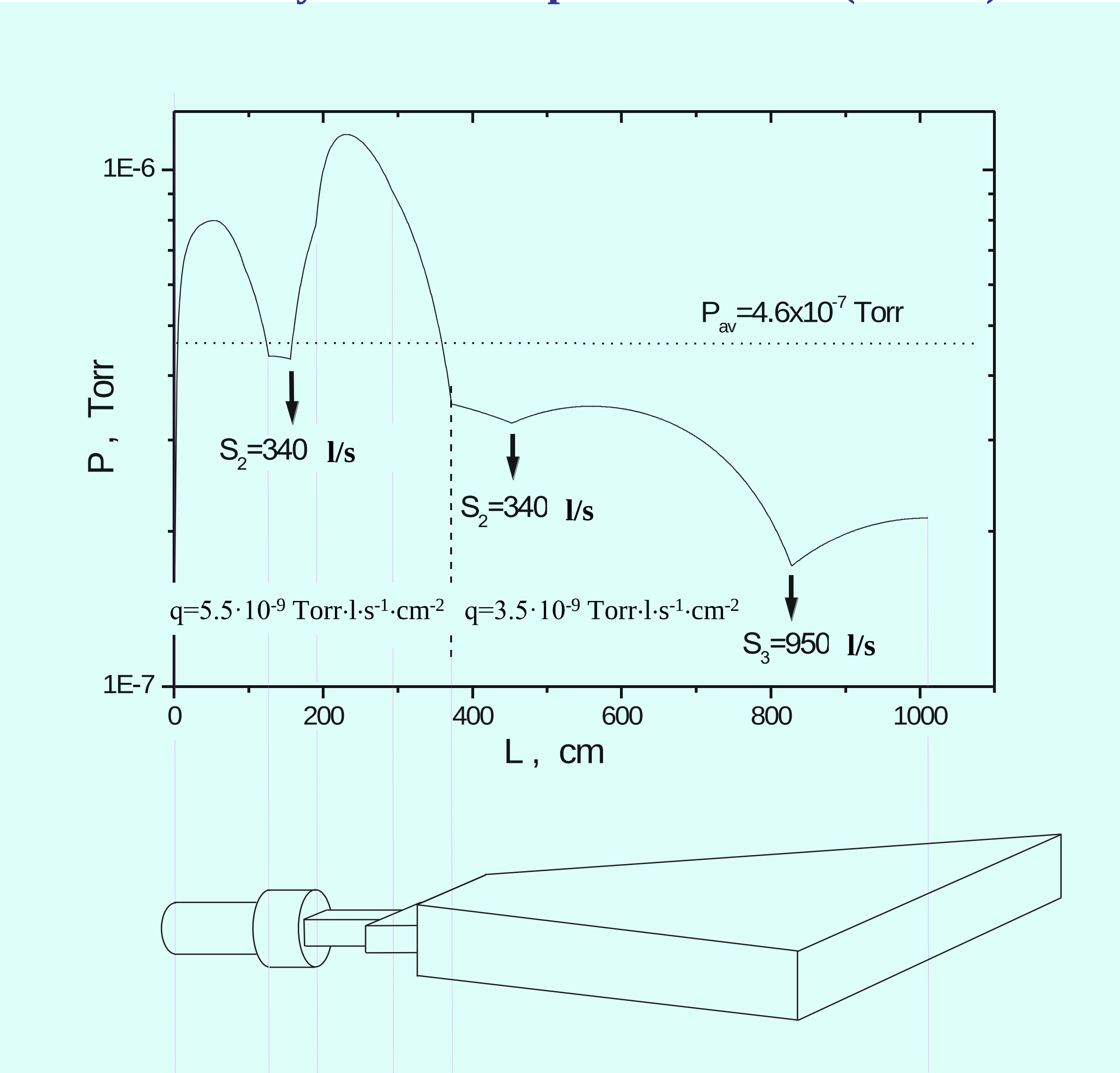
$$P_Q(x_3) = \frac{Q_i}{S} + Q_g\left(\frac{1}{G_2} + \frac{1}{S} + \frac{x_3}{l_3 G_3}\right) \quad \textbf{if } x<l$$

$$P_Q(x_3) = \frac{Q_i}{S} + Q_g\left(\frac{1}{G_2} + \frac{1}{S} + \frac{1}{G_3}\right) \quad \textbf{if } x>l \qquad \textbf{(9)}$$

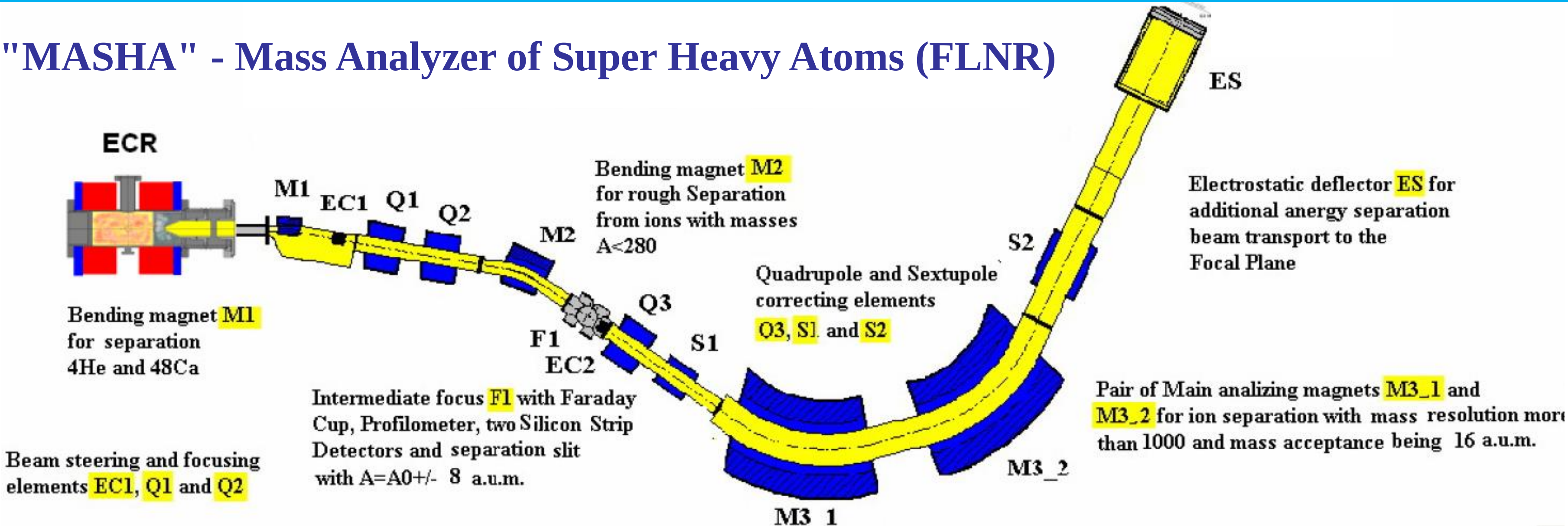
In the case of both static and dynamic outgassing the pressure distribution can be found combining equations (7) and (9) :

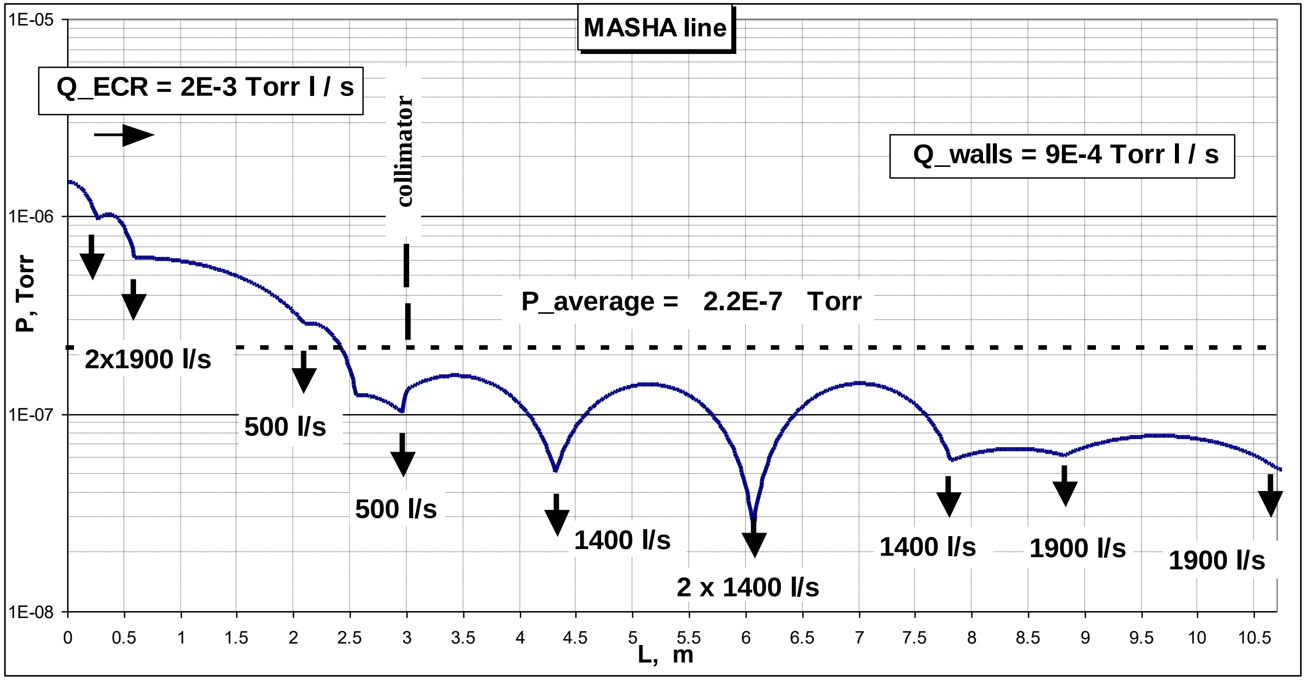
$$P_j(x_i) = P_q(x_i) + P_Q(x_i) \qquad \textbf{(10)}$$

Calculated pressure distribution along the experimental installation for irradiation of polymer films with heavy ions of the cyclotron complex CYTREC (Dubna)



"MASHA" - Mass Analyzer of Super Heavy Atoms (FLNR)





ION BEAM LOSS

In the case of beam losses due to the charge exchange between the ions and the residual gas the transmission efficiency T of an accelerator over pathlength L is:

$$T = \exp\left\{ -3.3\times 10^{16}\int_0^L P(\ell)\,\sigma(\beta)\cdot d\ell \right\}$$

where P is the pressure in Torr, dλ is an element of the pathlength in cm, β is the relative velocity (v/c) and σ is the sum of all the relevant capture and loss cross-sections in cm^2/molecule.

Several analytical and semi-empirical models have been applied to the calculation of the cross-sections. Obtained as a result, the transmission factors of every model were compared with the experimental data on the vacuum losses of accelerated heavy ions in the U-400 and U-400M cyclotrons.

The best accordance with the experimental data has been found for the joint model of the two following models:

I.

$$\sigma_{\mathrm{C}} = 2 \times 10^{-15} \mathrm{z}^{2} (137\beta)^{-5}$$

$$\sigma_{L} = 2 \times 10^{-15} (1 + z)^{2} (137\beta)^{-5} \times \exp\left(-\frac{2(z - z) + 1}{2d^{2}}\right)$$

Where the mean charge $\bar{\mathrm{z}}$ **value is approximated by**

$$\bar{\mathrm{z}} = \mathrm{Z_p} \{1 - \mathrm{C} \cdot \exp(-137\beta\delta)\}$$

C≅1 has a very weak dependence on the atomic number Z_P,

$$\delta = 0.3443 - 0.0667 \ln(\mathrm{Z_p})$$

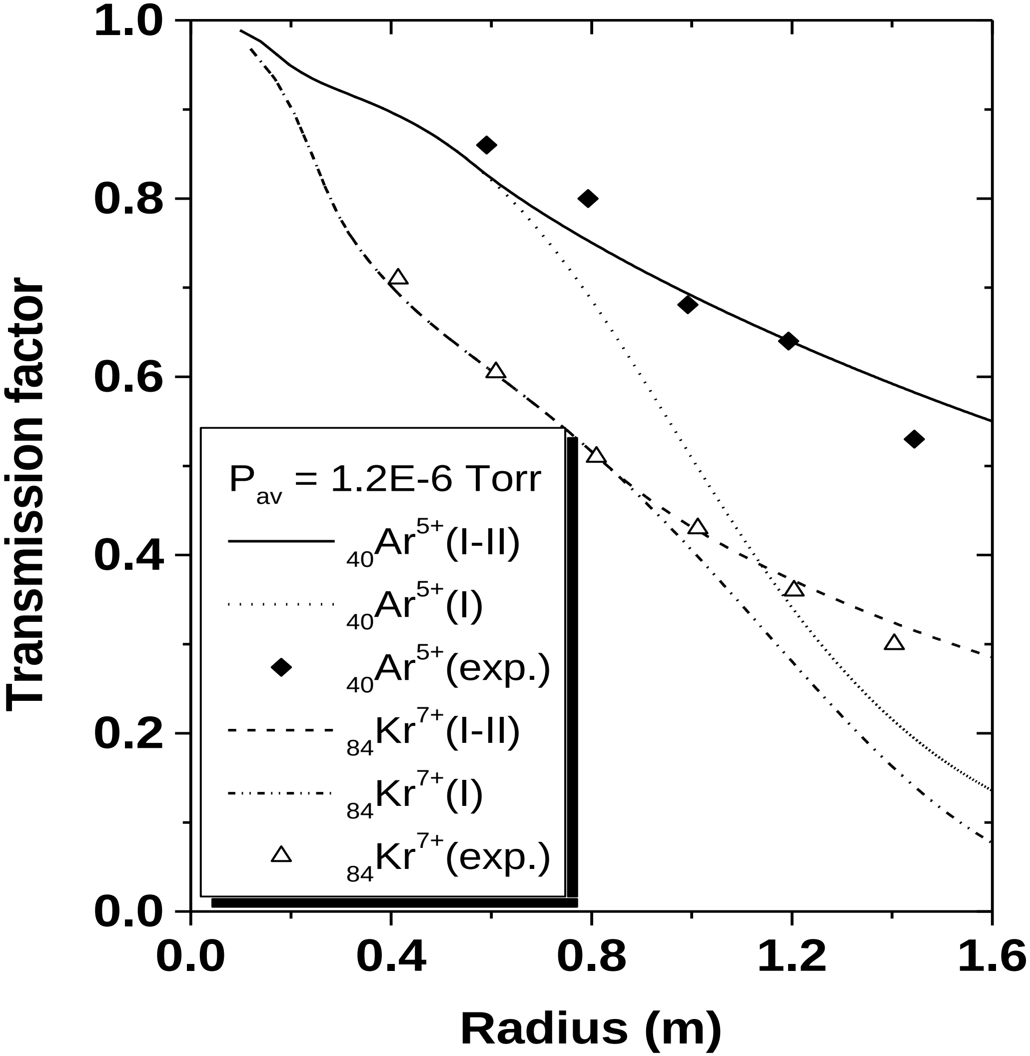
and the standard deviation $\mathrm{d} = 0.27\sqrt{\mathrm{Z_p}}$ **is given by in a residual gas such as N_2 or air;**

II.

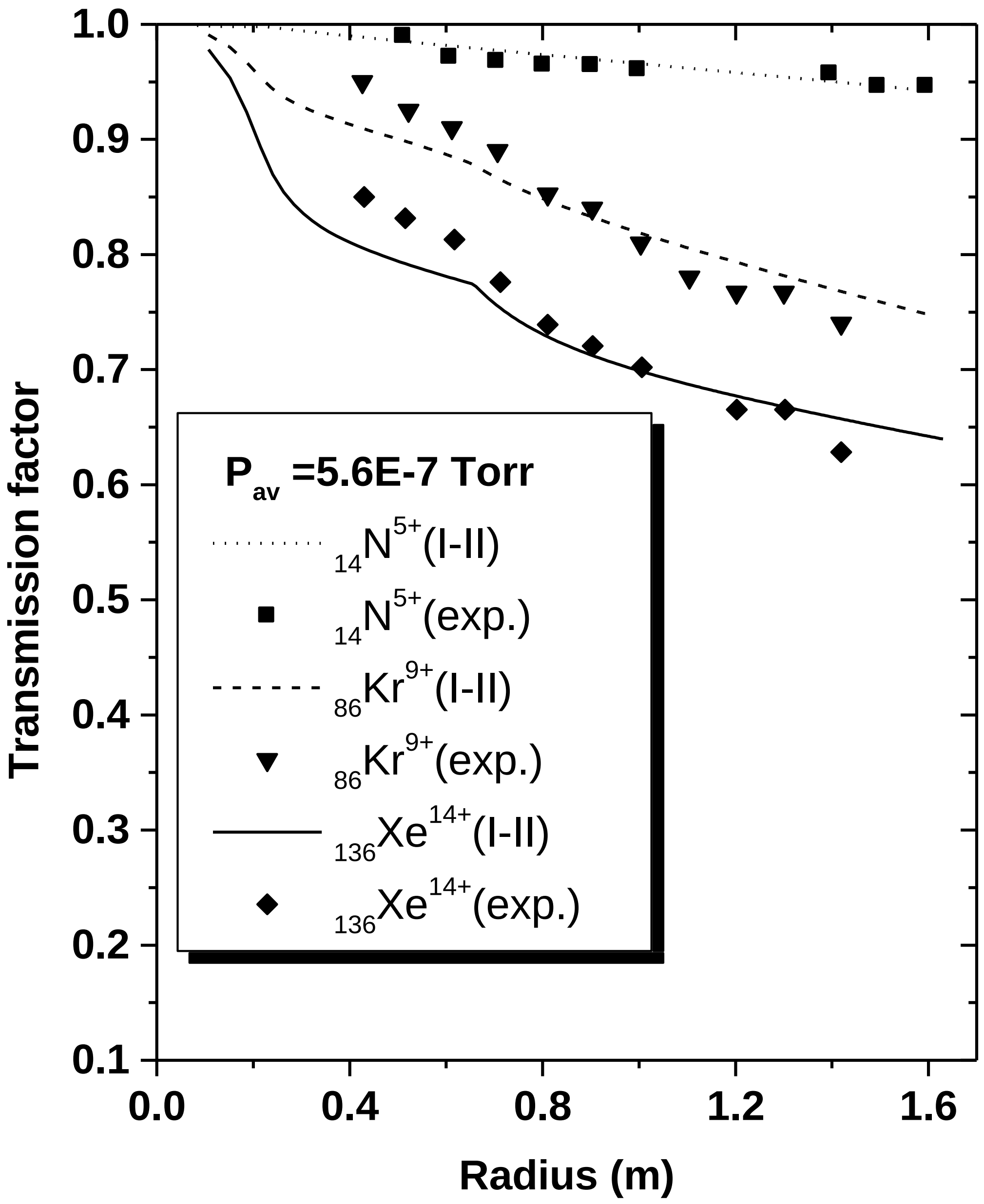
$$\sigma_{\mathrm{C}} \cong 3 \times 10^{-28} \mathrm{z}^{5/2} \beta^{-7} \qquad \sigma_{\mathrm{L}} \cong 9 \times 10^{-19} \mathrm{z}^{-2/5} \beta^{-2}$$

In the joint (I-II) model we used the first (I) model for ions energy up to 1.5 MeV/amu and the second (II) model for higher energy.

Such an approach allowed us to obtain quite satisfactory accordance with the experimental data as shown in figure. It also shows the comparison between the two models.



The transmission factor for the cyclotron equipped with a PIG ion source, calculated in accordance with the two models (joint I-II and I), as compared with the experimental data for accelerated ions $^{40}Ar^{5+}$ (up to 9 MeV/amu, Q=6.5·10^{-3} Torr·l·s^{-1}) and $^{84}Kr^{7+}$ (up to 4 MeV/amu, Q=6·10^{-3} Torr·l·s^{-1}) at an average pressure of P_{av}=1.2·10^{-6} Torr (considering radial pressure distribution) at the extraction radius R=160 cm in the U-400 cyclotron.



The transmission factor for the cyclotron equipped with an ECR ion source, calculated in accordance with joint model I-II, as compared with the experimental data for accelerated ions $^{86}Kr^{9+}$ (up to 6 MeV/amu) and $^{136}Xe^{14+}$ (up to 6 MeV/amu) in the U-400 cyclotron and $^{14}N^{5+}$ (up to 53 MeV/amu) in the U-400M cyclotron at an average pressure of P_{av}=5.6·10^{-7} Torr (considering radial pressure distribution) at the extraction radius R=160 cm.

For the low energy of ions it is possible to apply the Muller-Salzborn formula:

$$\sigma_{z,z-1} = 1.43 \times 10^{-12} z^{1.17} P^{-2.76}$$

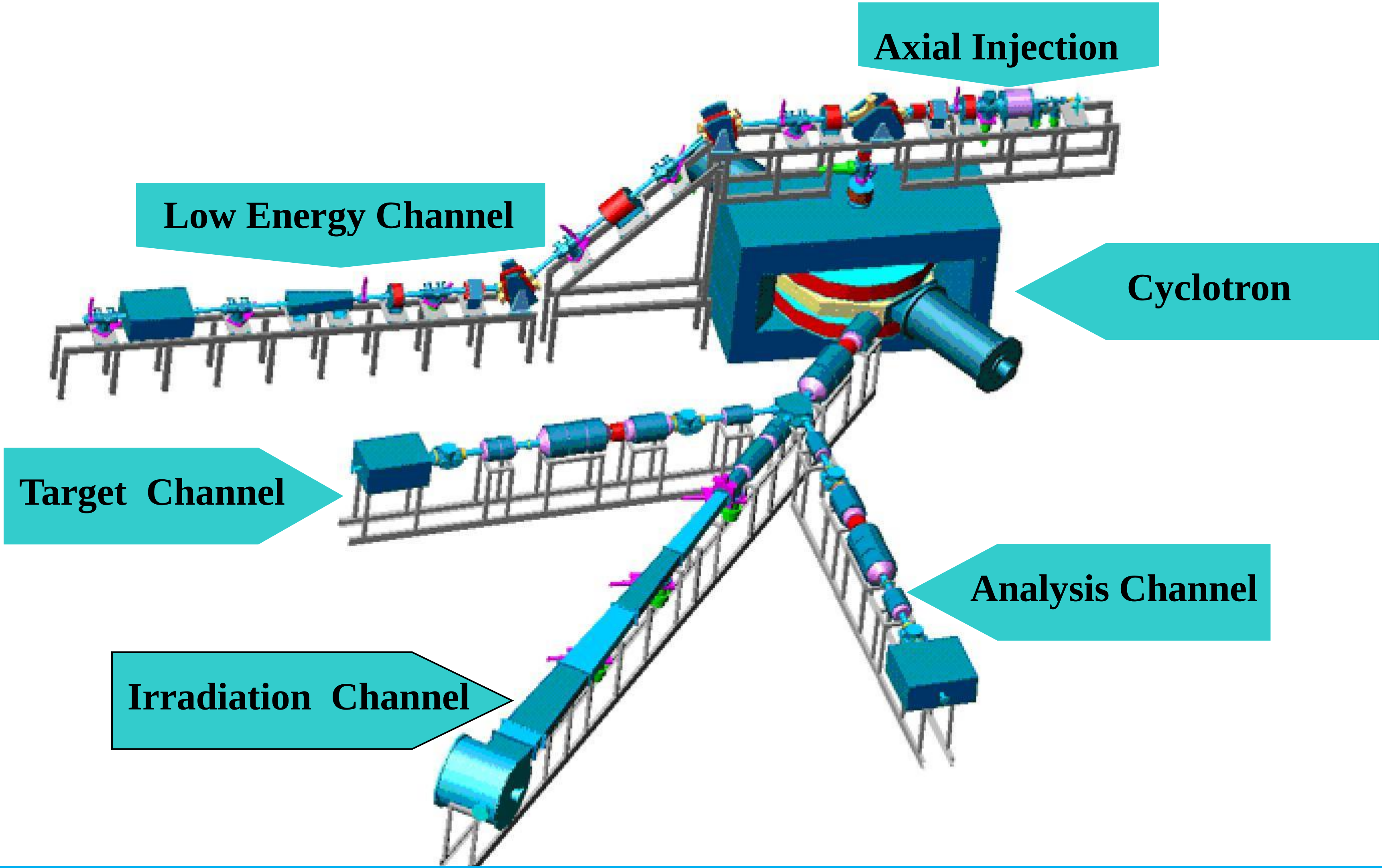
where

$\sigma_{z,z-1}$ (cm^2/molecule) the single electron capture cross section,

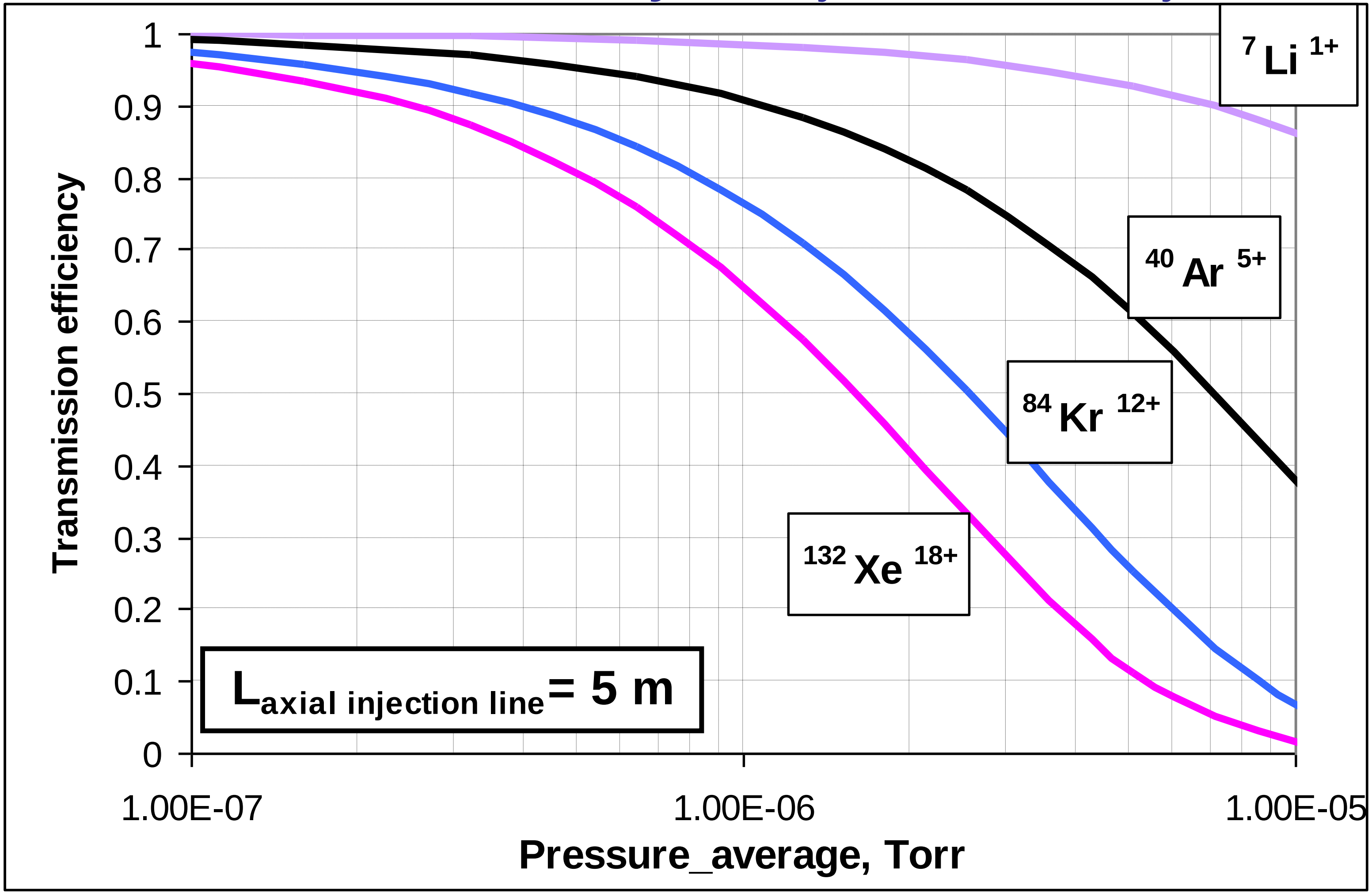
z (coulomb) the ion (projectile) charge,

P (Joule) the first ionization potential of the target (residual gas)

THE DC-60 CYCLOTRON COMPLEX DESIGNED AND CREATED BY FLNR JINR FOR RESEARCH CENTER AT STATE UNIVERSITY IN ASTANA, KAZAKHSTAN

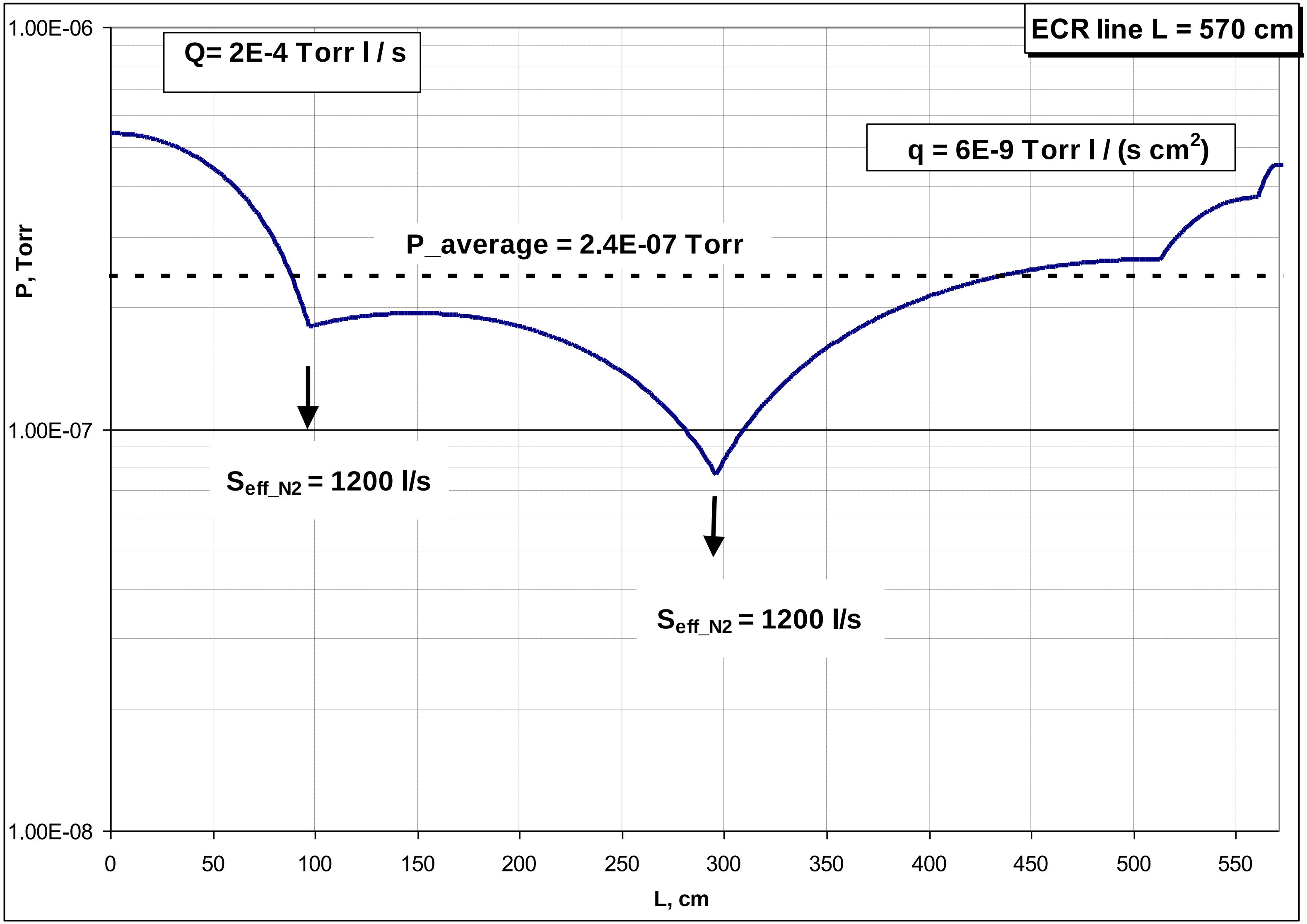


The transmission efficiency of ions $^{7}Li^{1+}$, $^{40}Ar^{5+}$, $^{84}Kr^{12+}$, $^{132}Xe^{18+}$ in the channel of axial injection system of DC-60 cyclotron

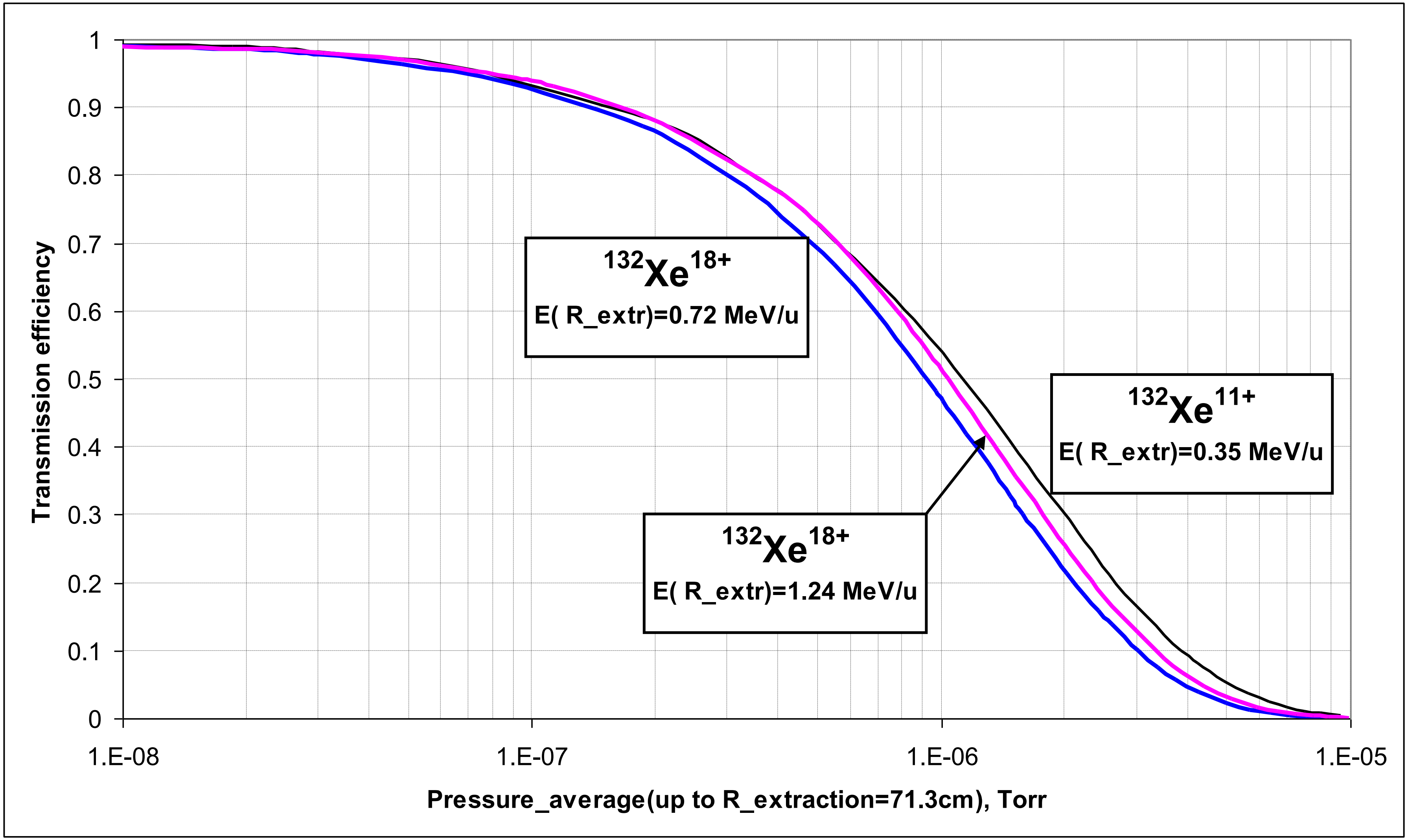


$T \geq (80 \div 95)\%$ $\Rightarrow$ $P_{average} \leq (2\div5)\cdot10^{-7}$ Торр

The pressure distribution along the injection line



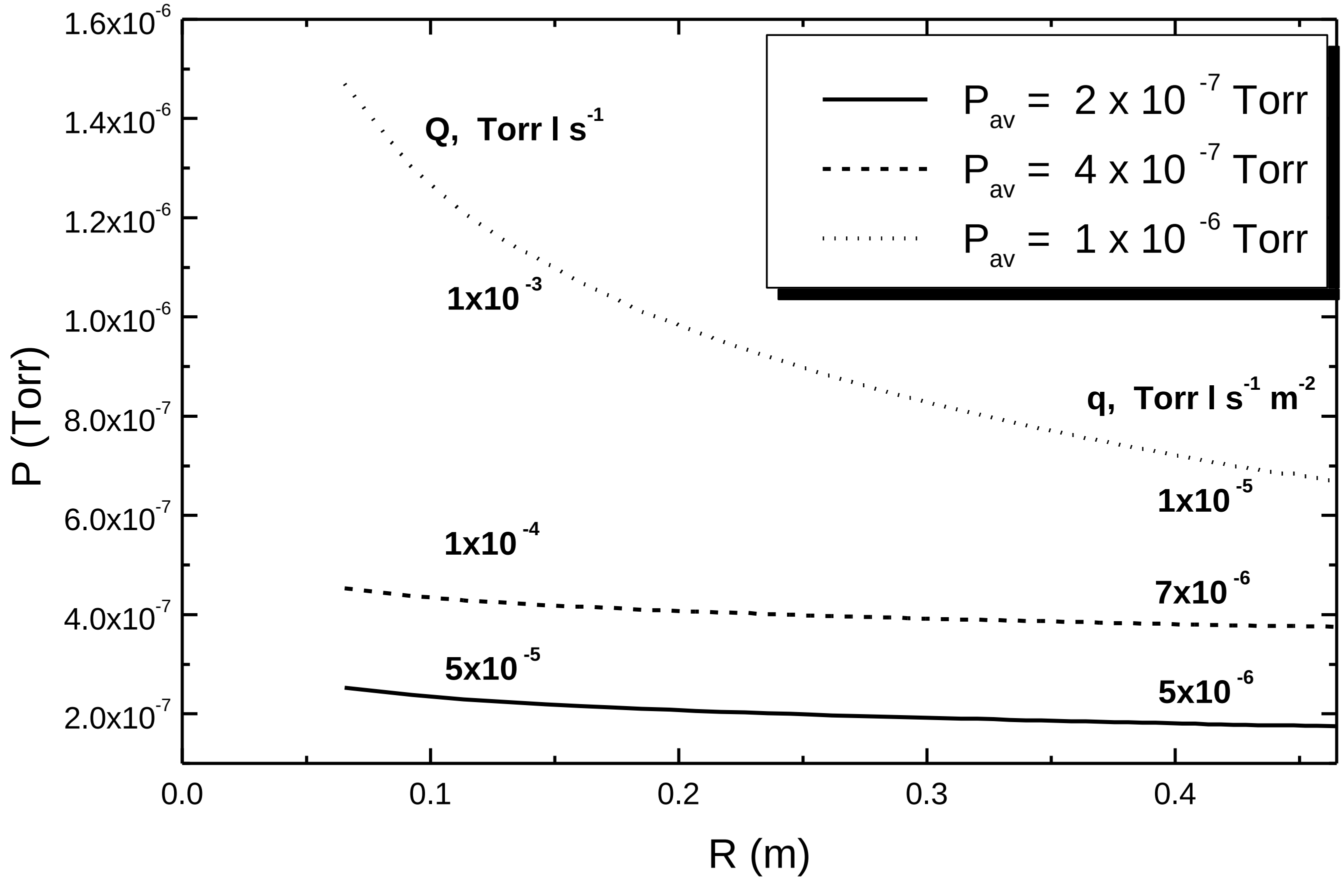
Beam transmission in DC-60 cyclotron's vacuum chamber



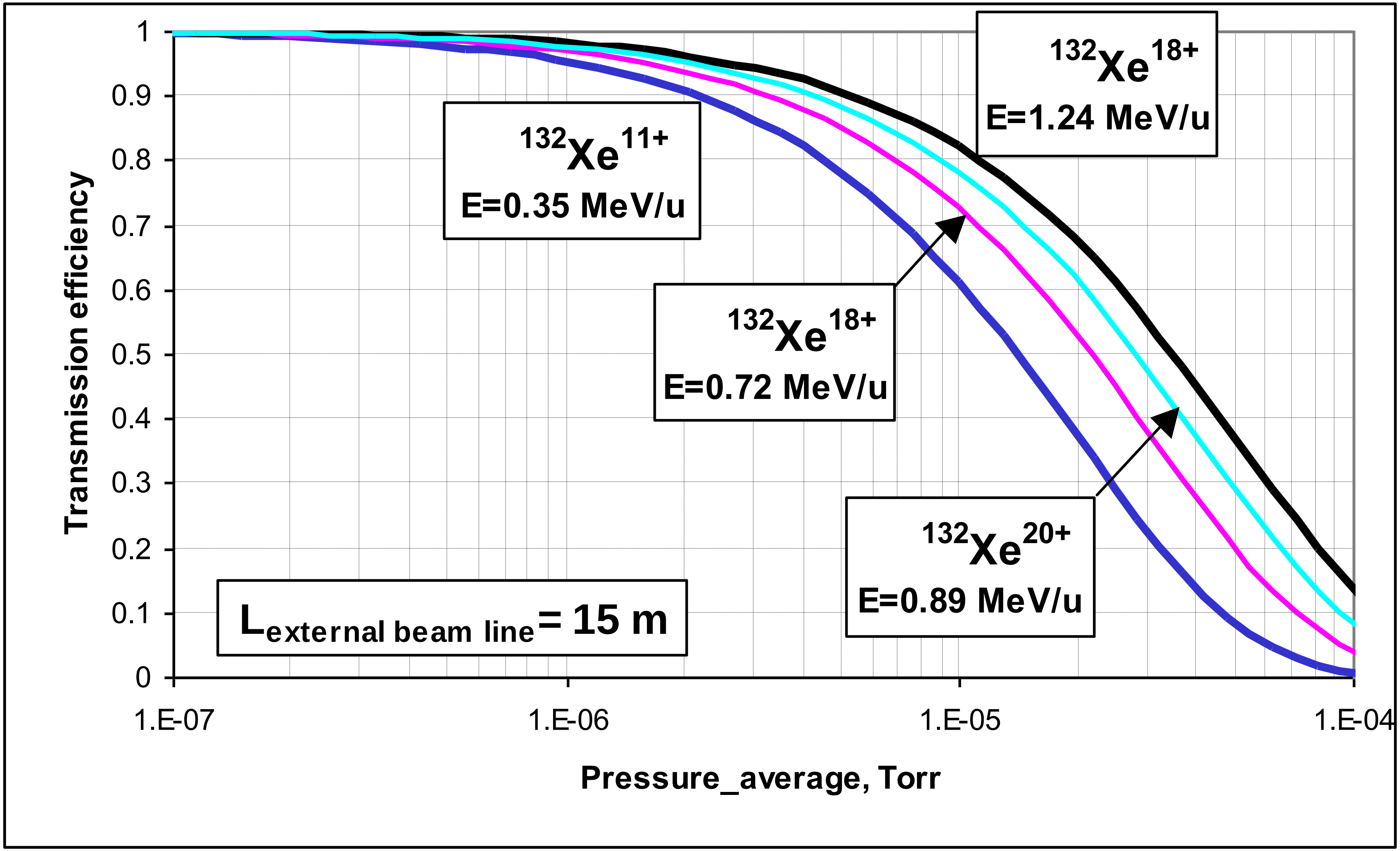
$T \geq (85 \div 90)\%$ ⇒ $P_{average} \leq (1 \div 2) \cdot 10^{-7}$ Торр

The radial pressure distribution in the cyclotron vacuum chamber under different gas loading conditions for the gas flow in the cyclotron's central region Q, Torr·l/s and specific outgassing rate q, Torr·l·s^{-1}·cm^{-2}:

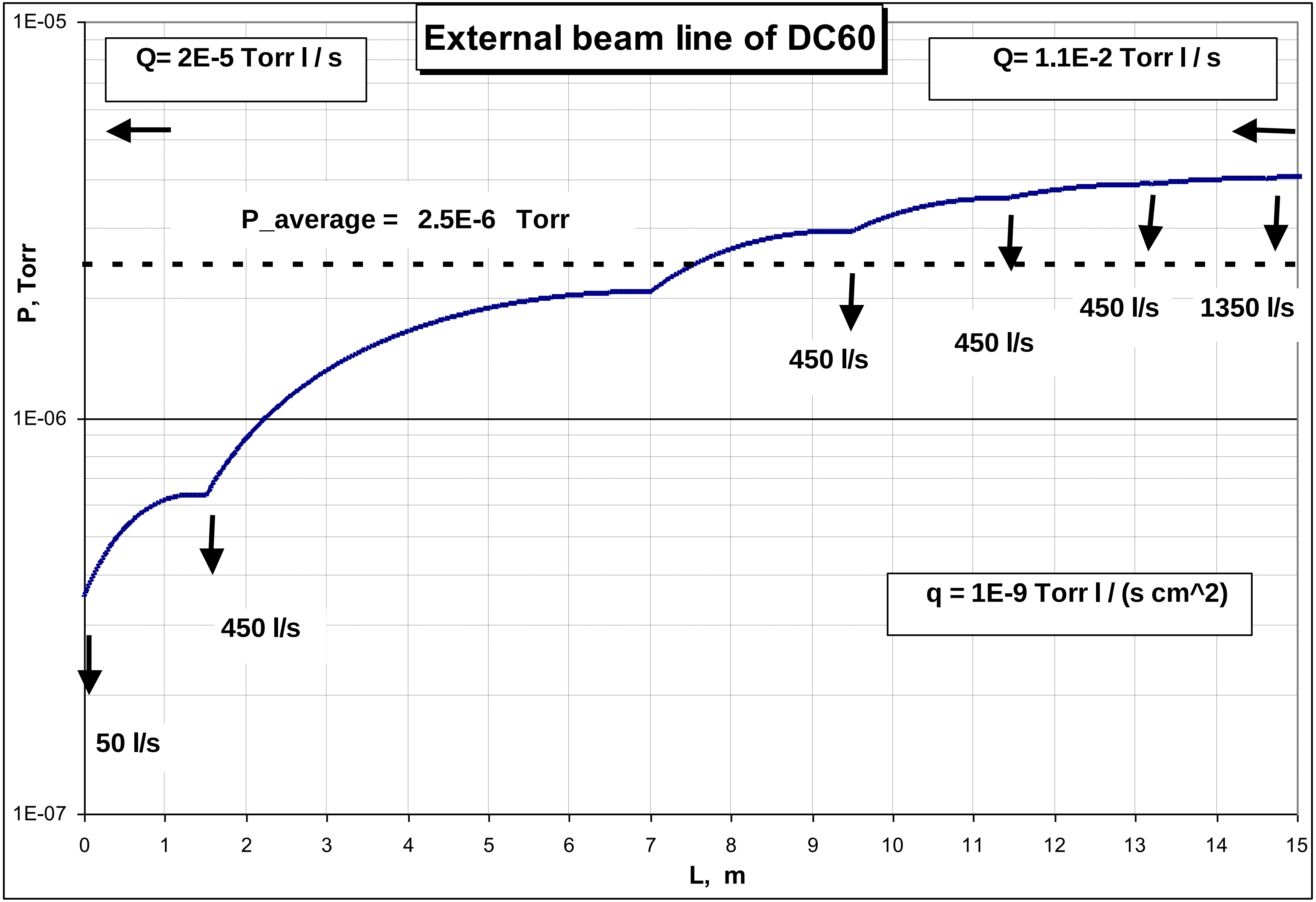
1) $Q=5\cdot10^{-5}$, $q_1=5\cdot10^{-6}$ and $P_{average}=2\cdot10^{-7}$ Torr;
2) $Q=1\cdot10^{-4}$, $q_1=7\cdot10^{-6}$ and $P_{average}=4\cdot10^{-7}$ Torr;
3) $Q=1\cdot10^{-3}$, $q_1=1\cdot10^{-5}$ and $P_{average}=1\cdot10^{-6}$ Torr



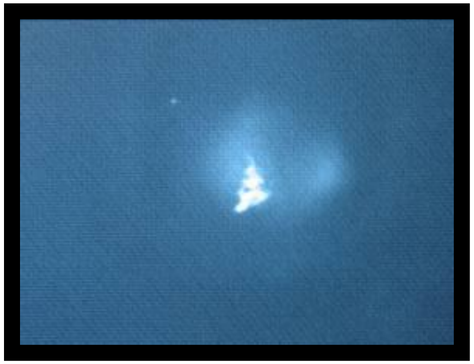
Transmission efficiencies of extracted ion beams



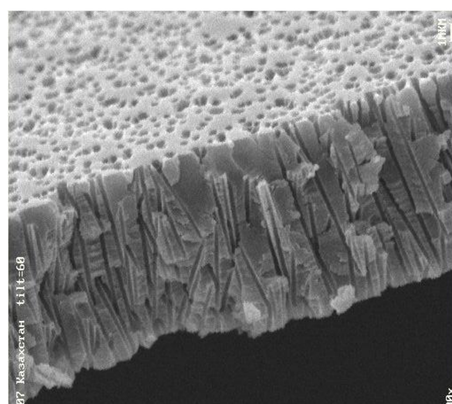
The pressure distribution along the extracted beam channel



DC-60 CYCLOTRON COMPLEX was created during 2004-2006



Accelerated ion beam monitor

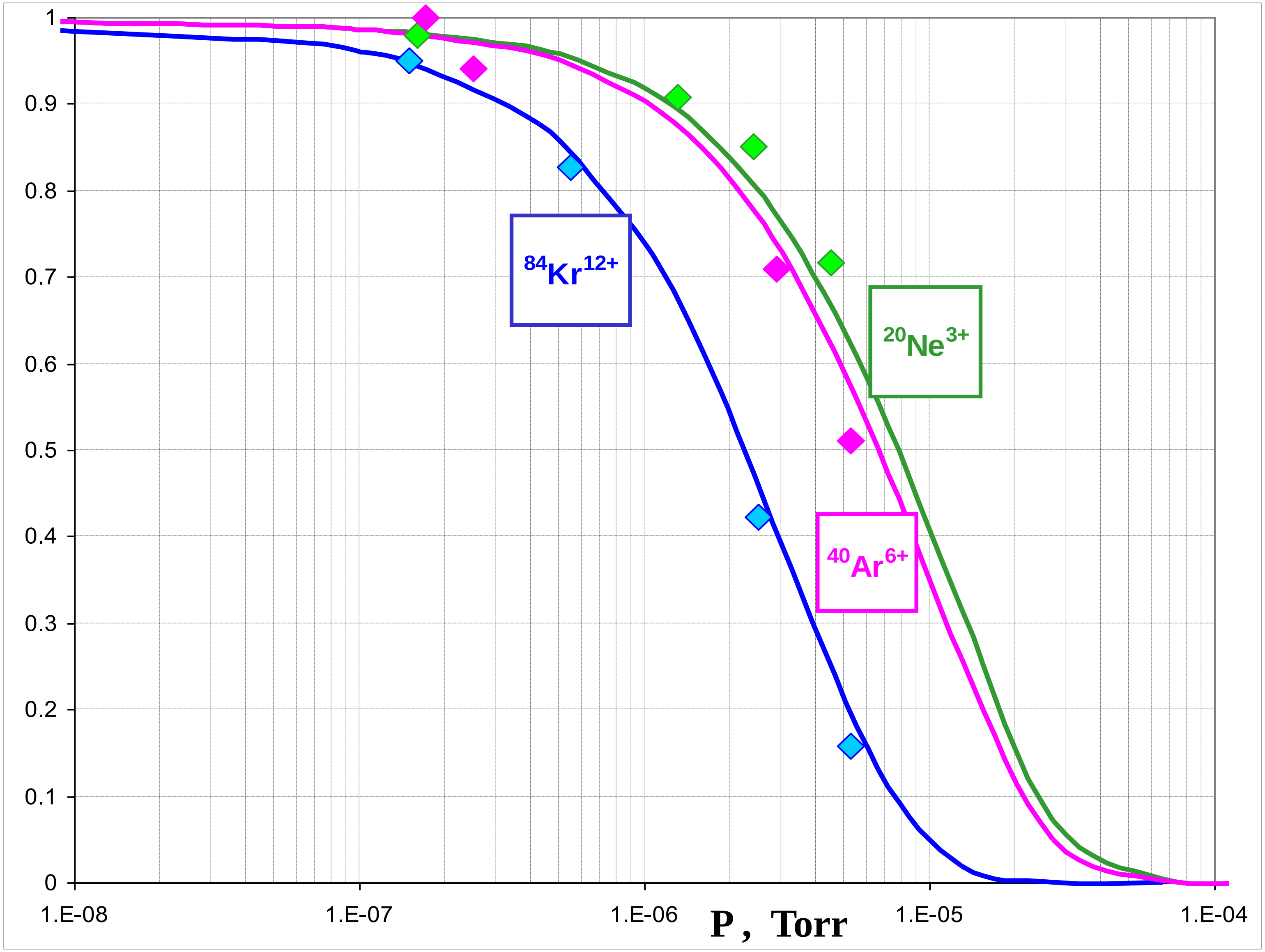


Produced nuclear filters

Accelerated ions :

$^{14}N^{2+}$	$^{22}Ne^{2+}$
$^{20}Ne^{\ 3+}$	$^{40}Ar^{4+}$
$^{40}Ar^{5+}$	$^{40}Ar^{6+}$
$^{40}Ar^{7+}$	$^{84}Kr^{+12}$

Experimental (symbols) and calculated (lines) transmission efficiencies for accelerated ion beams in the launched DC-60 complex



DC-110 cyclotron complex was successfully launched in 2012

for acceleration of ions Ar, Kr & Xe

(Dubna Center of Nano- &Nuclear Technologies)

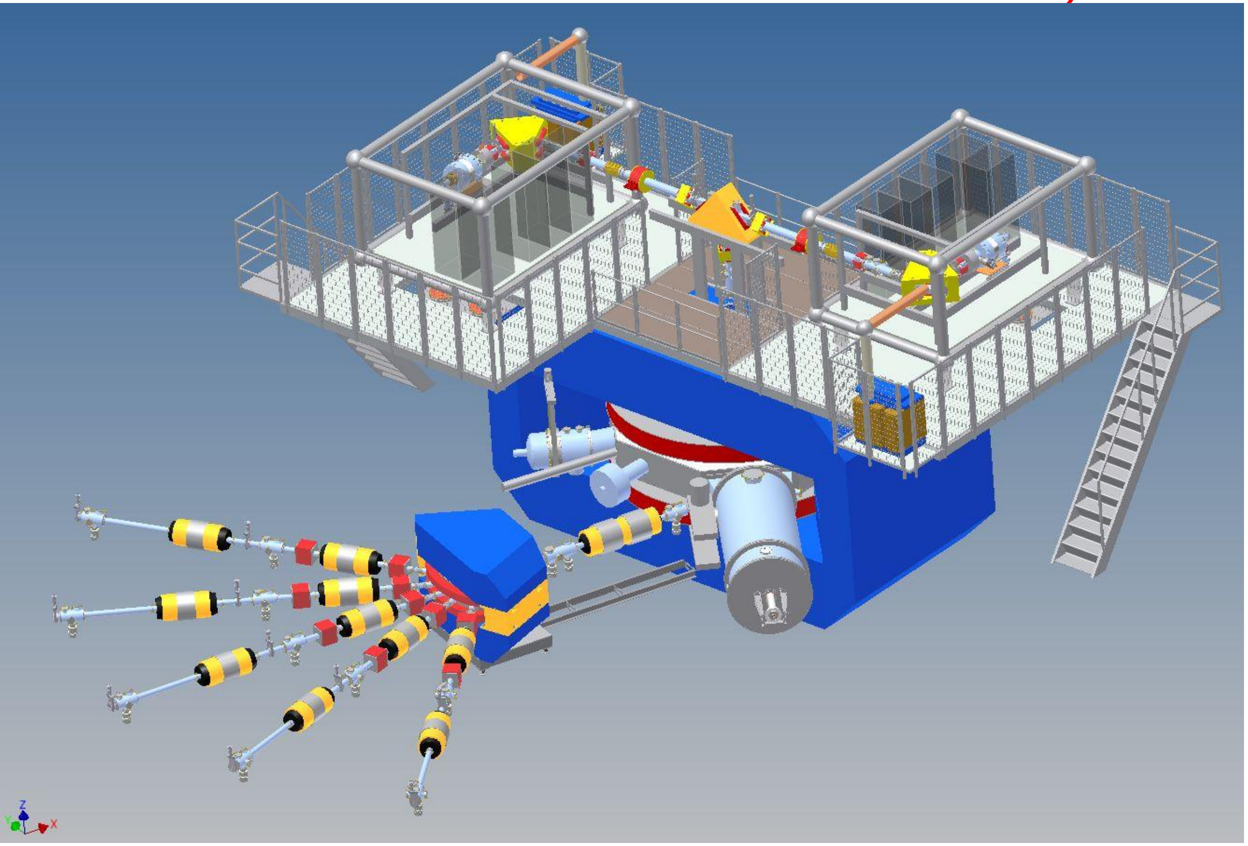
Prototype : DC-60 cyclotron complex

Accelerated ion energy : 2.5 MeV/amu

New DC-280 cyclotron complex for acceleration of ions from He to U

Prototypes : U400-U400M, DC-60, DC-110, DC-350 cyclotron complexes

Start of the first ion beam: December 26, 2018

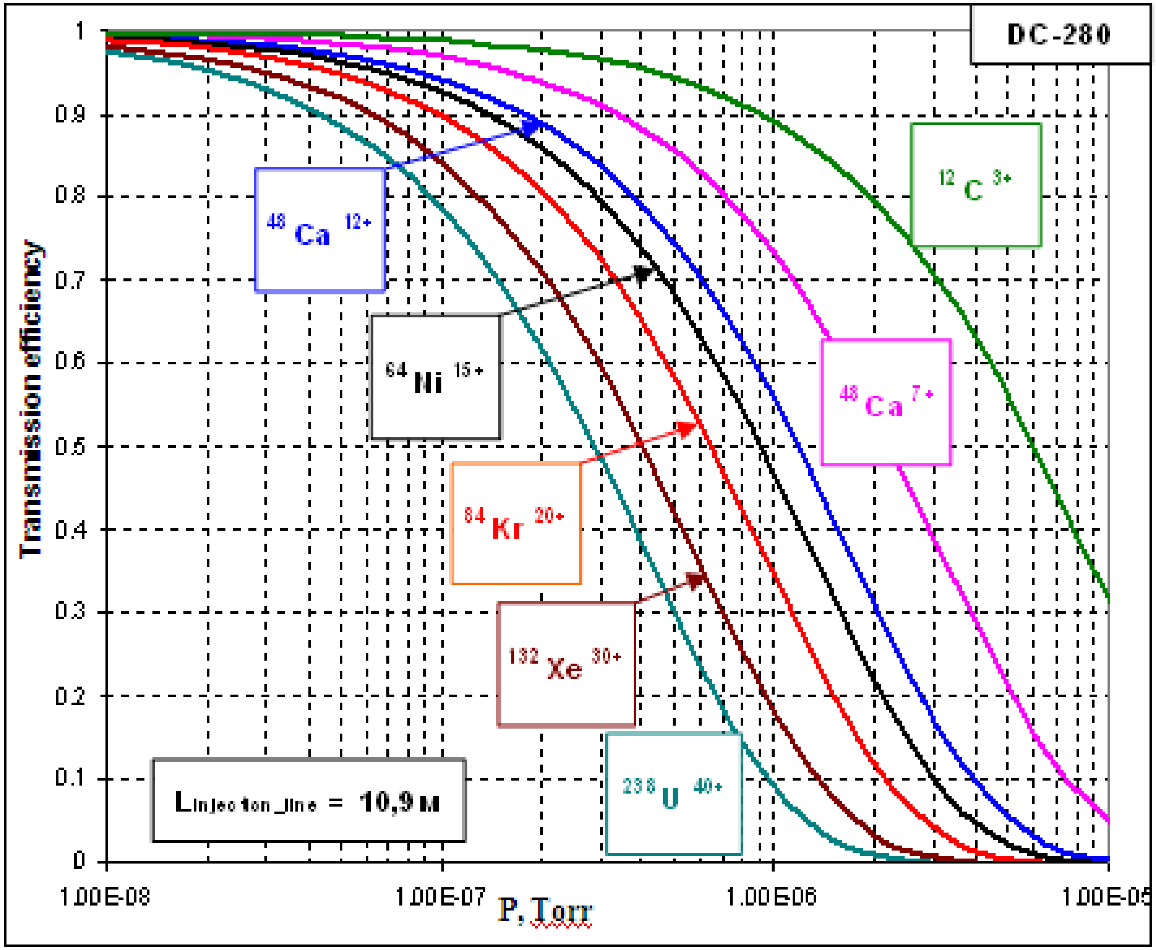


DC280 (expected)		
Ion	Ion energy, MeV/A	Output intensity, pps
^{7}Li	4	1×10^{14}
^{18}O	8	1×10^{14}
^{40}Ar	5	6×10^{13}
^{48}Ca	5	$0{,}6\text{-}1{,}2\times10^{14}$
^{54}Cr	5	2×10^{13}
^{58}Fe	5	1×10^{13}
^{124}Sn	5	2×10^{12}
^{136}Xe	5	1×10^{14}
^{238}U	7	5×10^{10}

- Synthesis and study of properties of super heavy elements.
- Search for new reactions for SHE-synthesis.
- Chemistry of new elements.

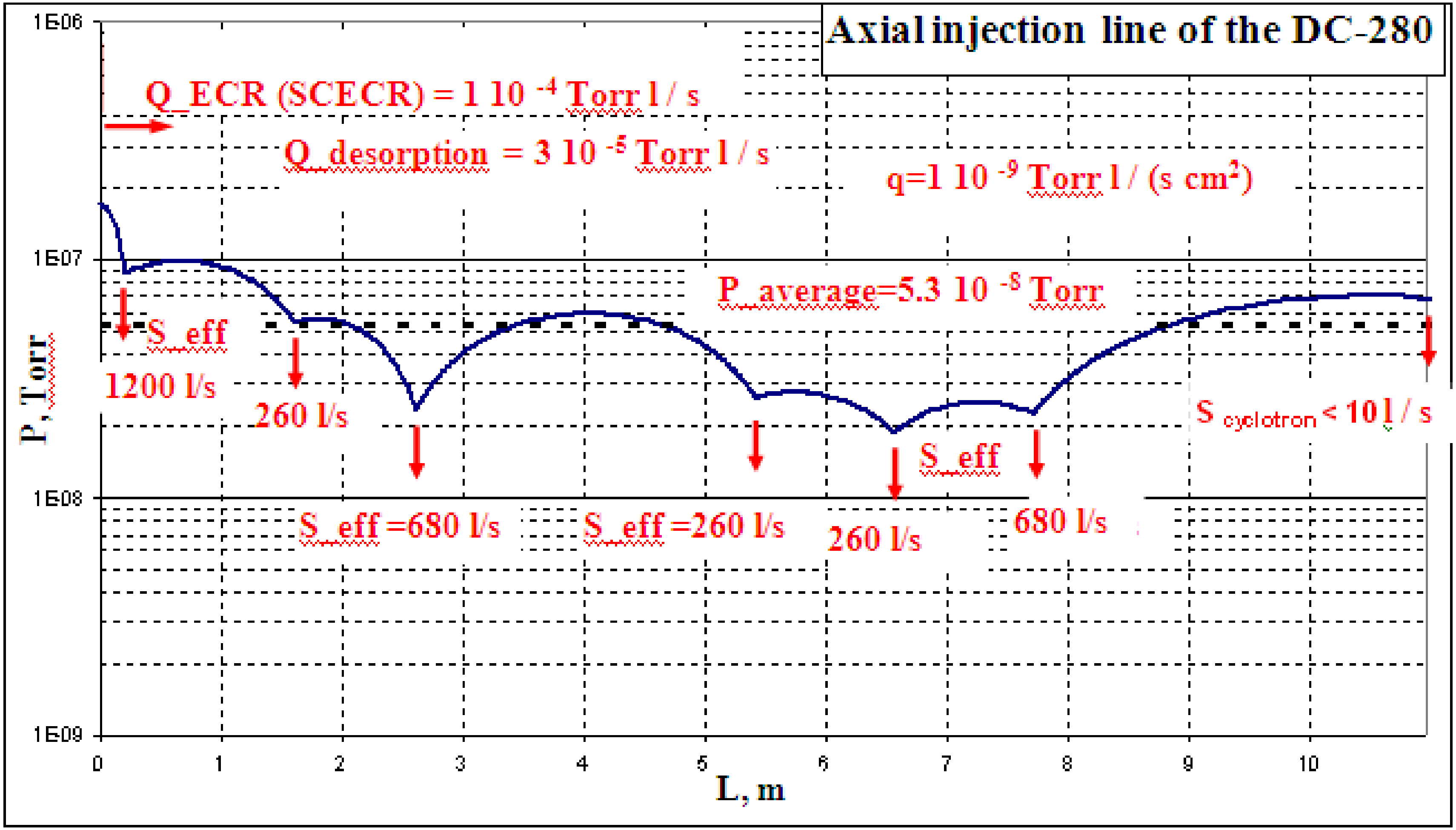
Energy of accelerated heavy ions: 4 ÷ 8 MeV/A
Ion mass: 4 ÷ 238
Intensity: 10 pμA (for 48Ca)
Efficiency of beam transfer: > 40%

Transmission efficiency of ions in the axial injection channel of the DC-280 cyclotron



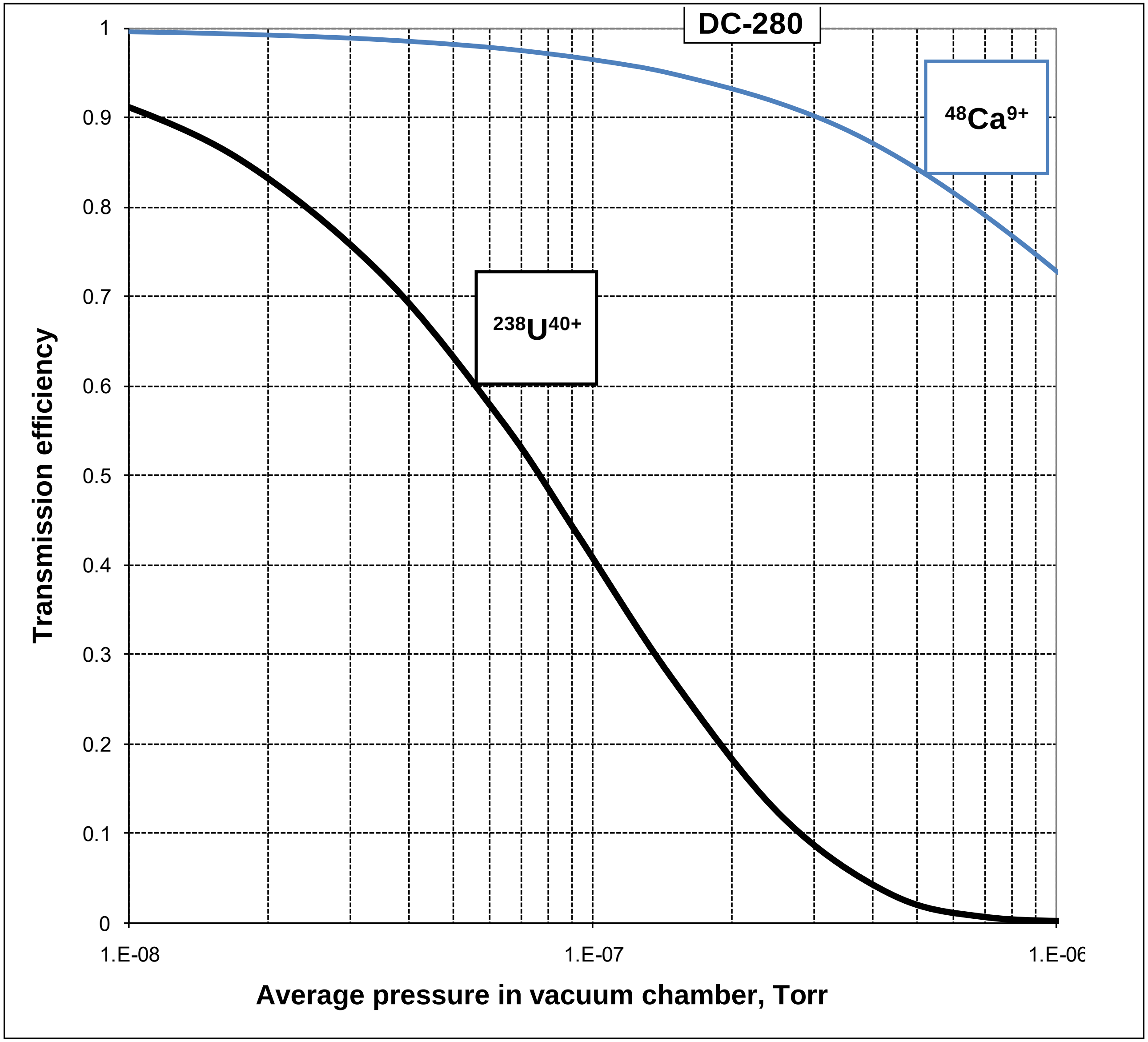
$T \geq (85 \div 99)\%$ $\Rightarrow$ $P_{average} \leq 6 \cdot 10^{-8}$ Торр

Pressure distribution along the axial injection line of the DC-280



$T \geq (85 \div 95)\%$ $\Rightarrow$ $P_{average} \leq 5.3 \cdot 10^{-8}$ Торр

Beam transmission in the DC-280 cyclotron's vacuum chamber



$T \geq 60\%$ ($^{238}U^{40+}$) ÷ 98% ($^{48}Ca^{9+}$) $\Rightarrow$ $P_{average} \leq 6 \cdot 10^{-8}$ Торр ($S_{\_eff}$ =37 000 l/s)

CONCLUSIONS

1. Based on the results of experimental studies at the cyclotrons of the Flerov Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research and the analysis of published data obtained at accelerators of other research centers, a method for numerical modeling of vacuum ion losses during beam injection into the cyclotron, acceleration and transportation of the beam to physical irradiation installations has been developed.

- **The method describes the process of ion charge exchange from hydrogen to uranium with energy from 1 keV/nucleon to 100 MeV/nucleon.**
- **The developed method is applicable to the calculation of vacuum chambers of arbitrary cross-section with arbitrary arrangement and number of vacuum pumps.**
- **Combination of GENAP & VACLOS provide solution for optimization of vacuum systems for practically arbitrary geometries of vacuum chambers.**

2. Using the developed numerical modeling technique:

- **vacuum systems of the U-400, U-400M and IC-100 cyclotron complexes of the FLNR were optimized,**
- **vacuum systems of the DC-72 cyclotron complex were developed for the Slovak Cyclotron Laboratory, Bratislava, Slovak Republic,**
- **new cyclotron complexes were developed and created:**
  the DC-60 heavy ion cyclotron complex for Interdisciplinary Research Complex, Astana, Kazakhstan,
  the DC-110 heavy ion cyclotron complex at the Dubna Center of Nano & Nuclear Technologies,
  the DC-280 heavy ion cyclotron complex for the Flerov Laboratory of Nuclear Reactions,
- **a channel of about 130 m in length has been created for transporting radioactive beams of the Dubna radioactive ion beams (DRIBs) accelerator complex based on the U-400 and U-400M cyclotrons,**
- **the vacuum system of the experimental physical installation of the MASHA (Mass Analyzer of Super Heavy Atoms) mass separator was calculated and optimized,**
- **developed projects for creation of the DC-140 heavy ion cyclotron complex and for the reconstruction of the U-400 cyclotron complex into the U-400R (R - reconstructed) for the Flerov Laboratory of Nuclear Reactions is currently in the implementation stage.**

3. The completed studies and the developed calculation methodology allow for the optimal design of vacuum systems for accelerator complexes and physical irradiation installations.

SOME OF PUBLICATIONS

1. M.N. El-Shazly, B.N. Gikal, G.G. Gulbekian, A.V. Tikhomirov. Beam loss due to the charge exchange with the residual gas in the FLNR heavy ion cyclotrons. Proceedings of EPAC 98, Stockholm, 1998, P.2199.
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