Numerical procedure permitting calculation of how a vacuum chamber influences Electric Propulsion Thruster jet expansion.

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Abstract: It is known that ERT integral parameters depend on the test conditions. This is especially true for the SPT. We know that the same thruster's model demonstrates different performances in different chambers. Unfortunately up to now there are no criteria, which permit the comparison of a thruster operation under different test conditions. In this work we have tried to develop a numerical procedure permitting the calculation of how the vacuum chamber influences SPT jet parameters. In the vacuum chamber, if the thruster operated, the residual gas pressure increases in order. Therefore first of all it was necessary to simulate ion motion in a residual gas atmosphere, which formed as a result of ion flow interaction with the chamber walls. Also with the help of the PIC model the concentration of the particles flew out the thruster and distribution of charge-exchange particles in the chamber volume were calculated. In order to calculate the electric field density in the ion jet, a fluid model was developed. The model was based on the solution of continuity, momentum and mass conservation equations. The results of calculations were compared with experiment. Also the charge-exchange ion current was compared with the experimental data obtained with the help of Faraday probes located in the thruster back hemisphere. The possibility, if it is possible to correct probe performances inaccuracy happening due to residual gas influence was examined with the help of developed software.

I. Introduction

This project researches the operation of the Hall thruster in vacuum chamber and the processes which occurred in the chamber.

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The thruster emits a predetermined number of ions and neutral particles. Ions were emitted by predetermined function j=f (a), where a – angle between the direction of the ion and the normal direction to face of the thruster; j – density of ion’s current. Neutrals were emitted in all directions to normal direction of start face with equal probability. Ions of working gas become neutral atoms after interaction with the chamber wall and leave the wall with the velocity taken by Maxwell’s distribution for temperature of the wall.

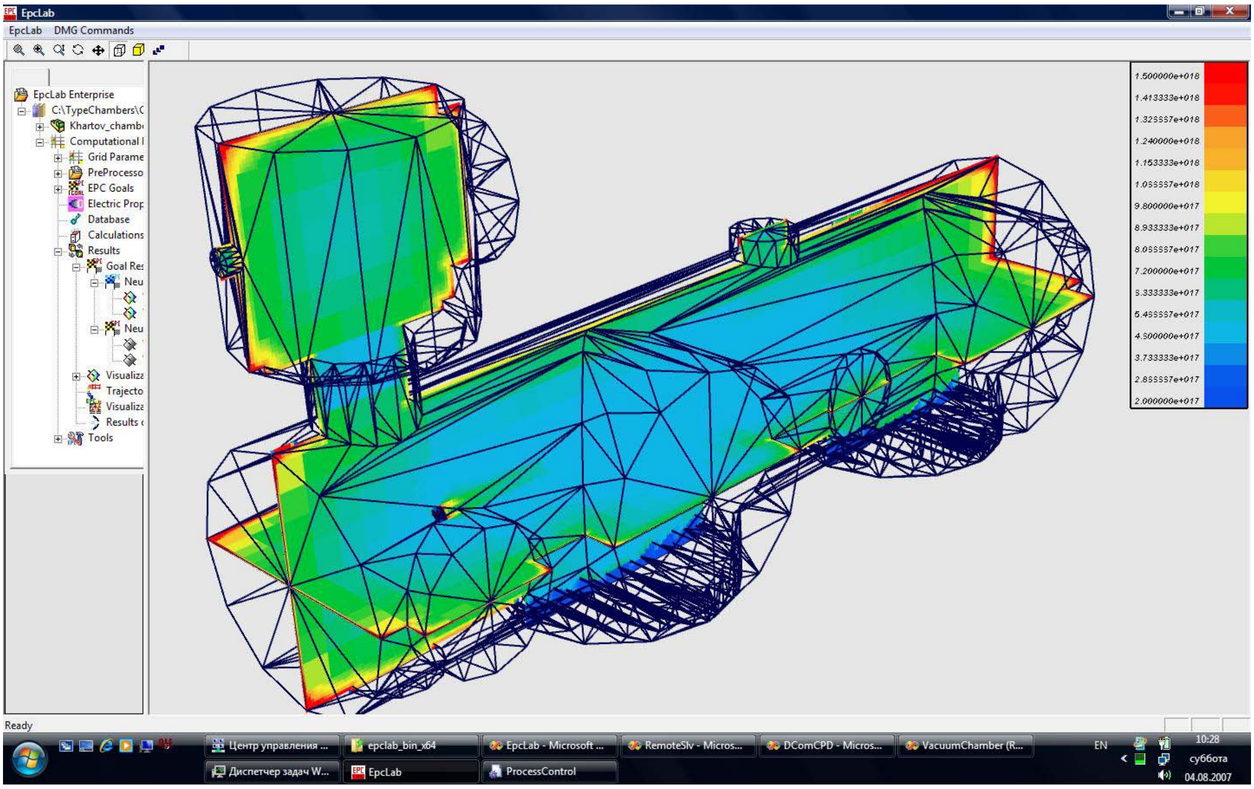
A Particle which touches the wall reflects with equal probability in all directions to normal of the face in the point of touching. All particles move by straight lines (After the first iteration tensity of calculated electric field was considered). Reflections occurred until particle touched the face of pump.

It must be considered also that for finding out the concentration of neutral atoms, ions, and charge exchanged ions there was used trajectory algorithms for determined number of simulated particles with definite boundary conditions (angle distribution for fast ions flow simulation, determined number of charge exchanged neutral particles in definite cell for charge exchanged particles (CEX) distribution (the initial values of CEX particles in cell we determined after neutral particles distribution calculation and tracing the fast ion using charge exchange cross section for current ion energy and average energy of neutral particles in cell).

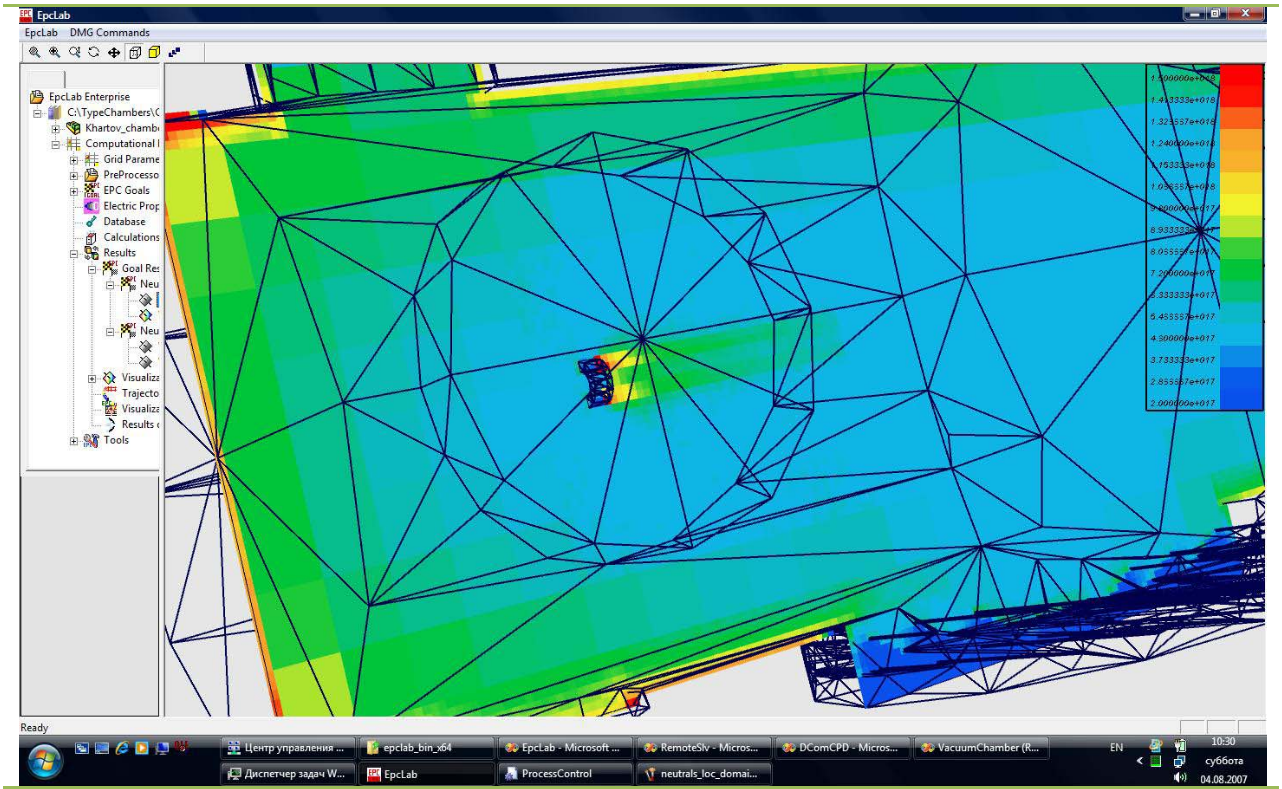
II. Experiment

The experiment was carried out on the stend in MAI university in the testing purposes of the results of calculations. In the experiment we were interested of measuring 3 items: 1) pressure of neutral gas in the definite point; 2) Ion current on the boom 400mm off from thruster; 3) ion current on the boom which is located in the same surface as thruster outlet section. Because of the length of boom was only 100 mm we’ve made 2 measurements. First was on the distance 100mm-200 mm from thruster axis. Second one we carried out on the distance 300mm-400mm from thruster axis (close to the wall of chamber).

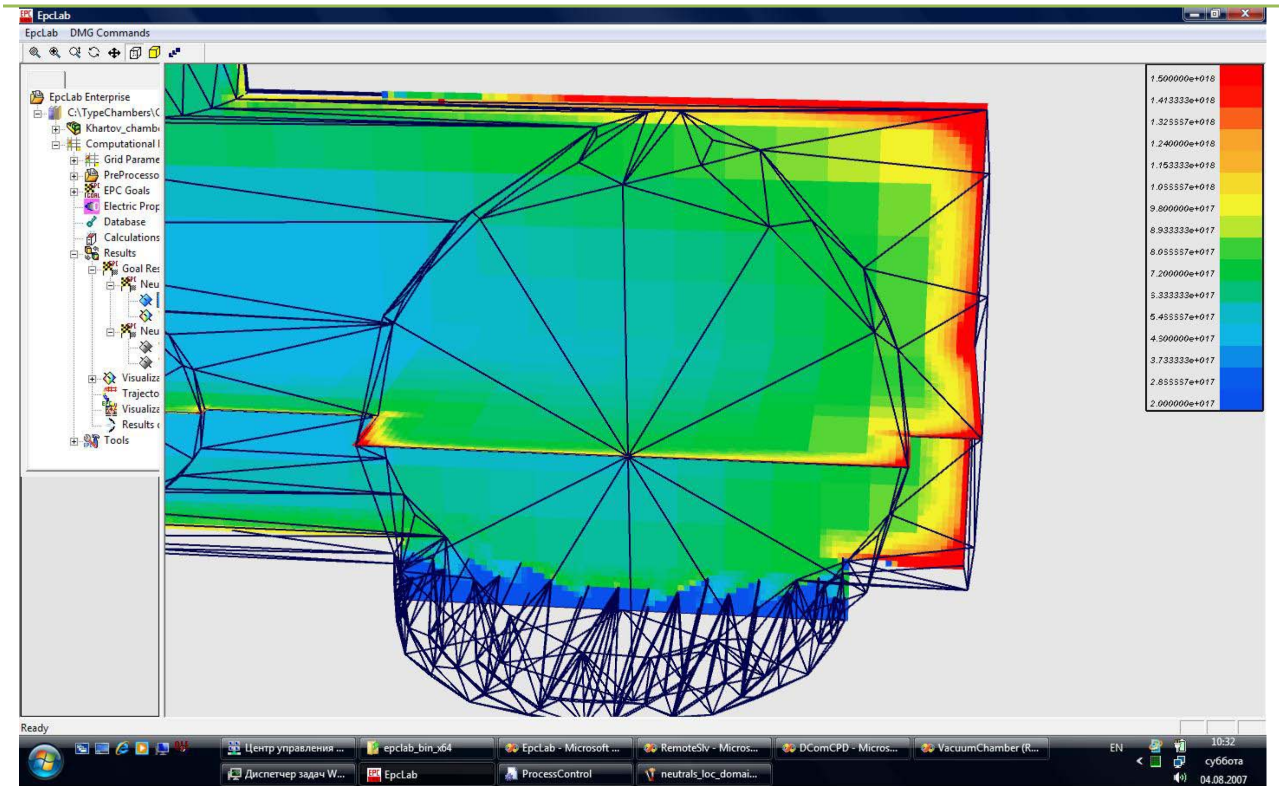
We used two Faraday probes for the current measurements. One was 7 mm diameter, which was used on the arc boom. For the measurement of CEX (Charge-exchange ions) on the boom in the thruster outlet surface we have used 18.2 mm diameter probe.



Calculated distribution of neutral particles (general view)(1/m^3)



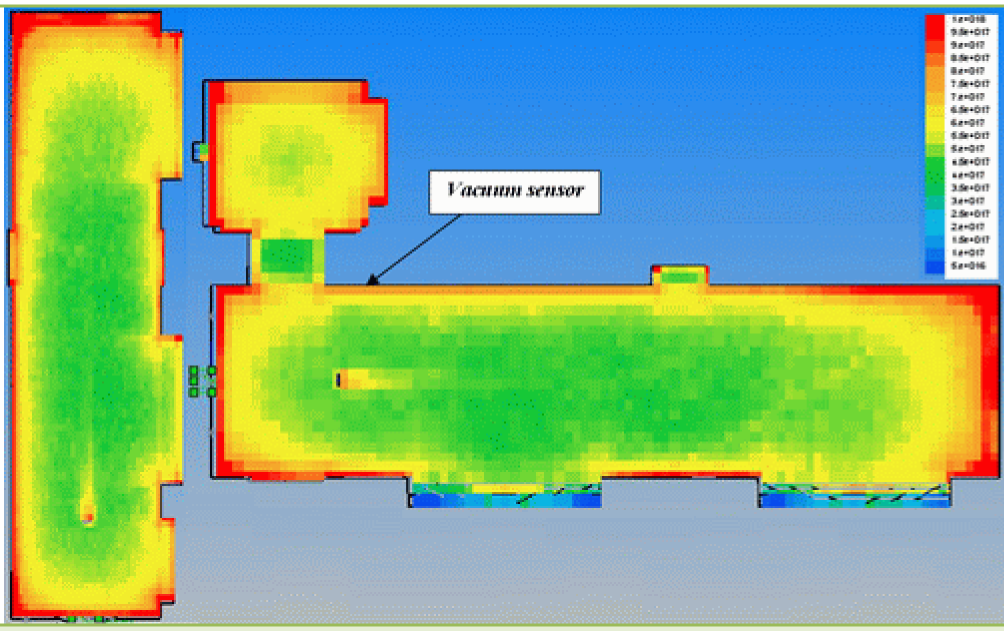
Concentration of neutral particles (Thruster and vacuum sensor area)(1/m^3)



Concentration of neutral particles (The wall and pump section)(1/m^3)

The vacuum sensor neutral gas distribution analysis

The initial distribution of neutral gas:



Position of vacuum sensor (simple grid calculation)

The calculated value in the point of sensor was 1e18 1/m^3.

There are two reasons for this divergence: 1) Static vacuum 2) the incorrect measurement because of construction of sensor itself.

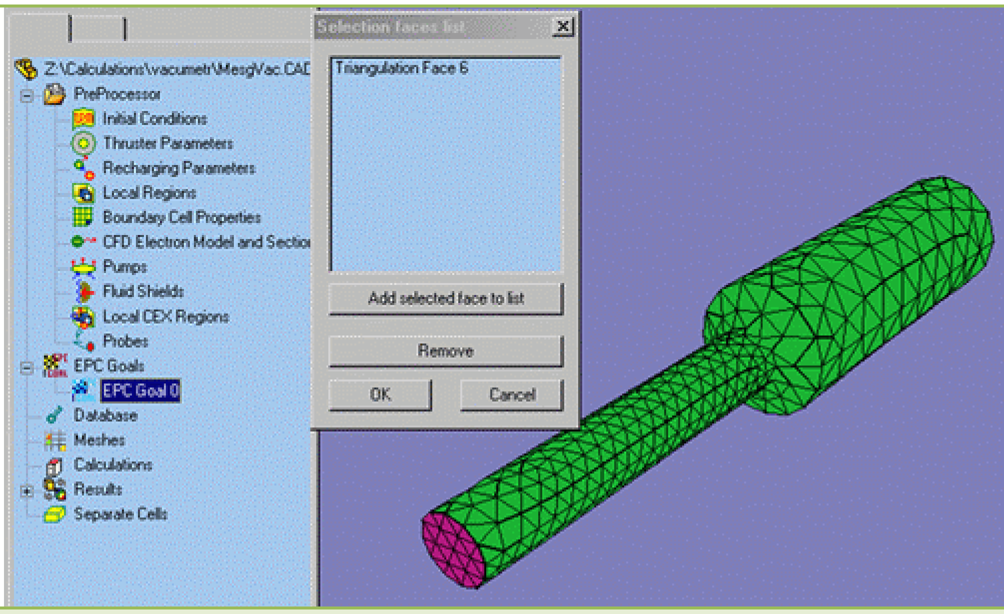
The mass consumption of gas flowing into sensor calculated by the next formula:

$$\dot{N} = \frac{u \cdot \pi \cdot r^2 \cdot n}{2}; \dot{m} = \nu \cdot M; \nu = \frac{\dot{N}}{N_a} \Rightarrow \dot{m} = \frac{u \cdot \pi \cdot r^2 \cdot n \cdot M}{2 \cdot N_a},$$

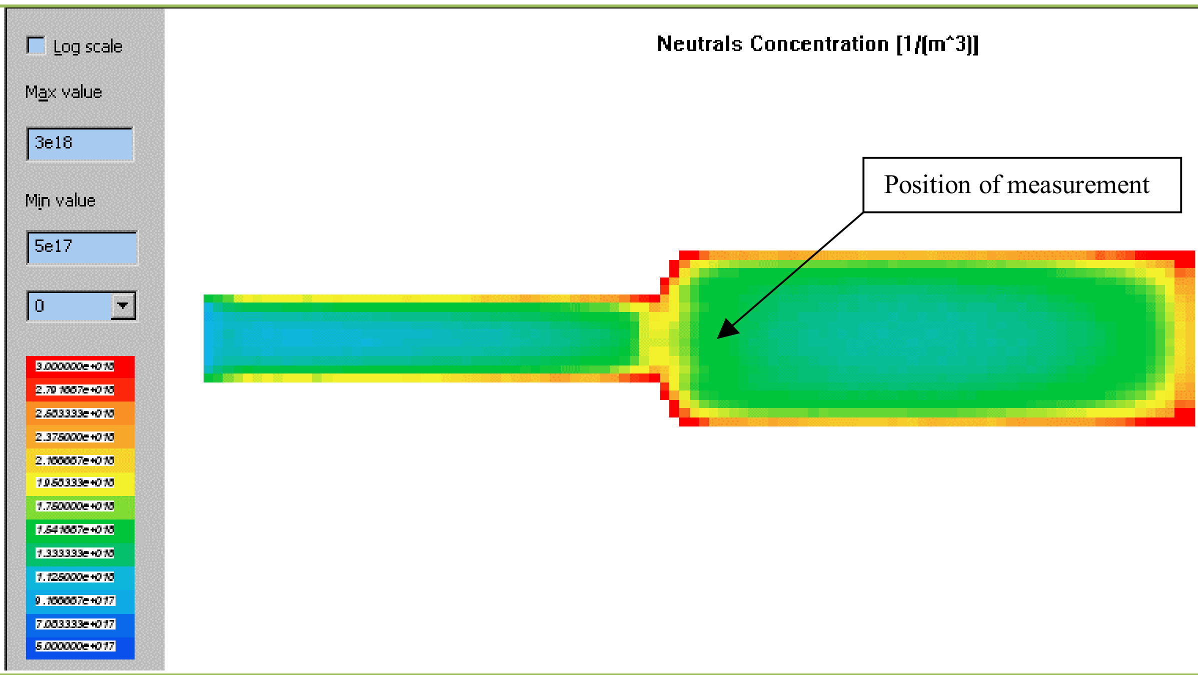
Where u – average velocity of particles; r – radius of entry hole; n – concentration of neutral particles near the entry hole of sensor; M – molecular mass of particles; Na – the Avogadro constant.

Average velocity equals 220 m/s (for 300K). There was used cosine distribution of emitted particles.

The simulation was made for 10e6 particles and 40x20x100 cells grid.



Sensor geometry



The neutral particles distribution in vacuum sensor($1/m^3$)

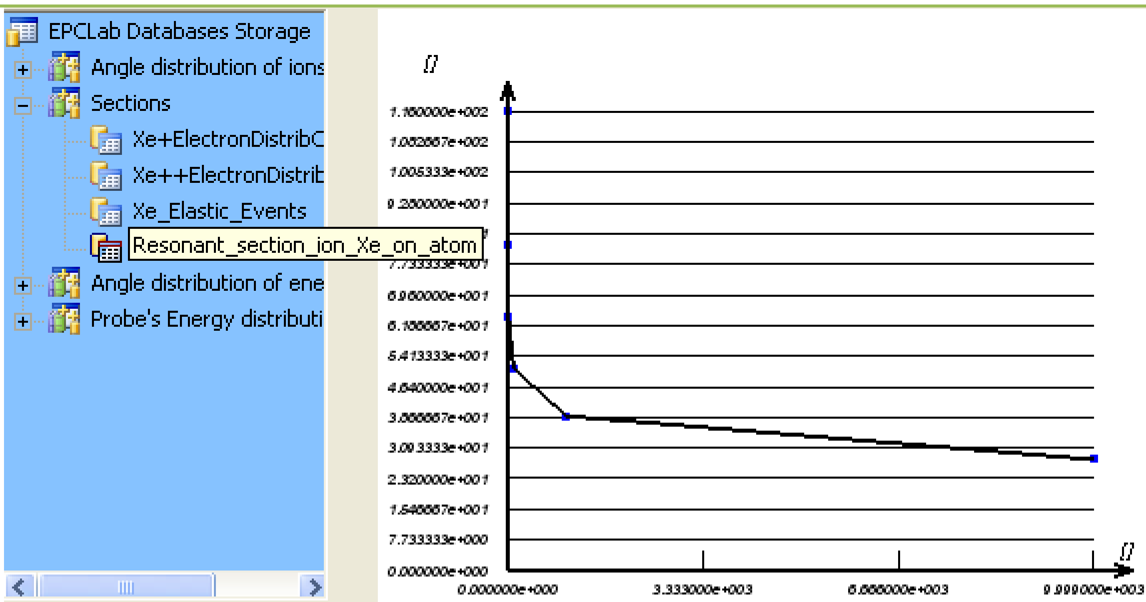
The result of concentration of neutral particles in the measure point is 1.3e18 which give us possibility to assume conservative value of pressure in the sensor of about 25%.

Short description of initial data and calculation comparison with experimental data with analysis of result

The initial data of calculation:

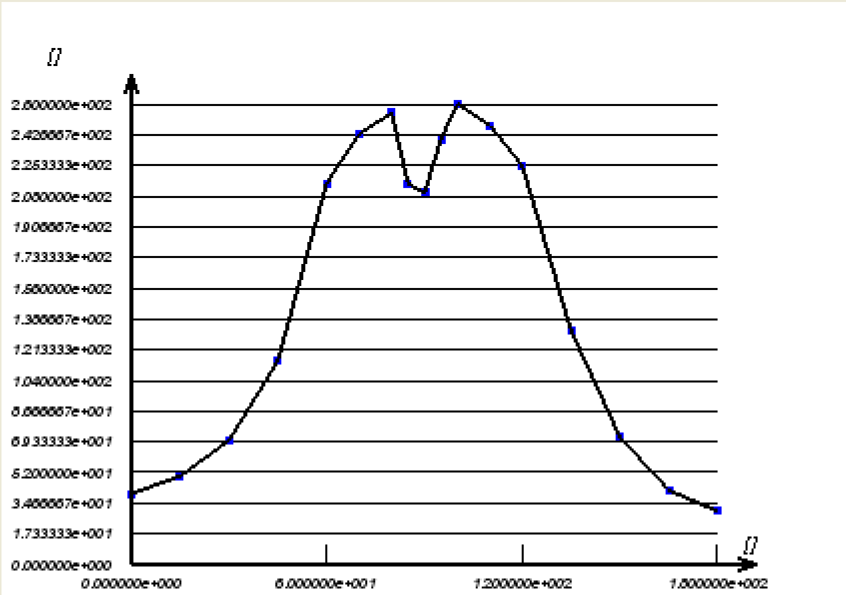
1) The average temperature of neutral gas in chamber 300K.
2) The only gas in chamber is Xe, the model doesn't consider static vacuum.
3) Anode mass consumption 2.2 mg/s
4) Cathode mass consumption 0.22 mg/s
5) 5% of total current was neutral particles with anode's temperature 1000K

Also we've used in calculations charge exchange cross section of Xe ion on Xe atom. The distribution is show below:



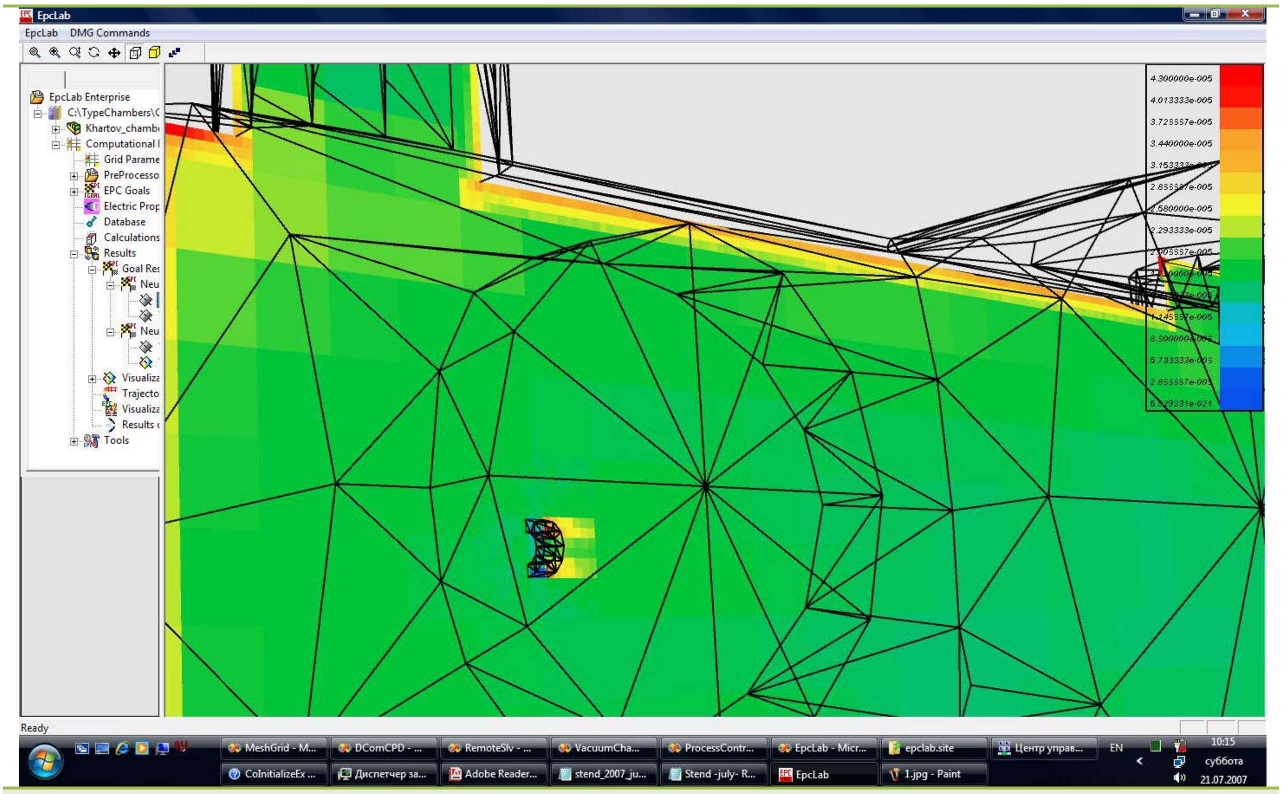
Xe – Xe+ charge exchange collision section ($x10^{-20}$ m^2) of energy in eV

Also as initial data for direction of ions determination we used experimentally[15] measured angle current distribution (it is figured on the comparison with the result current) and angle energy distribution shown on the next figure.

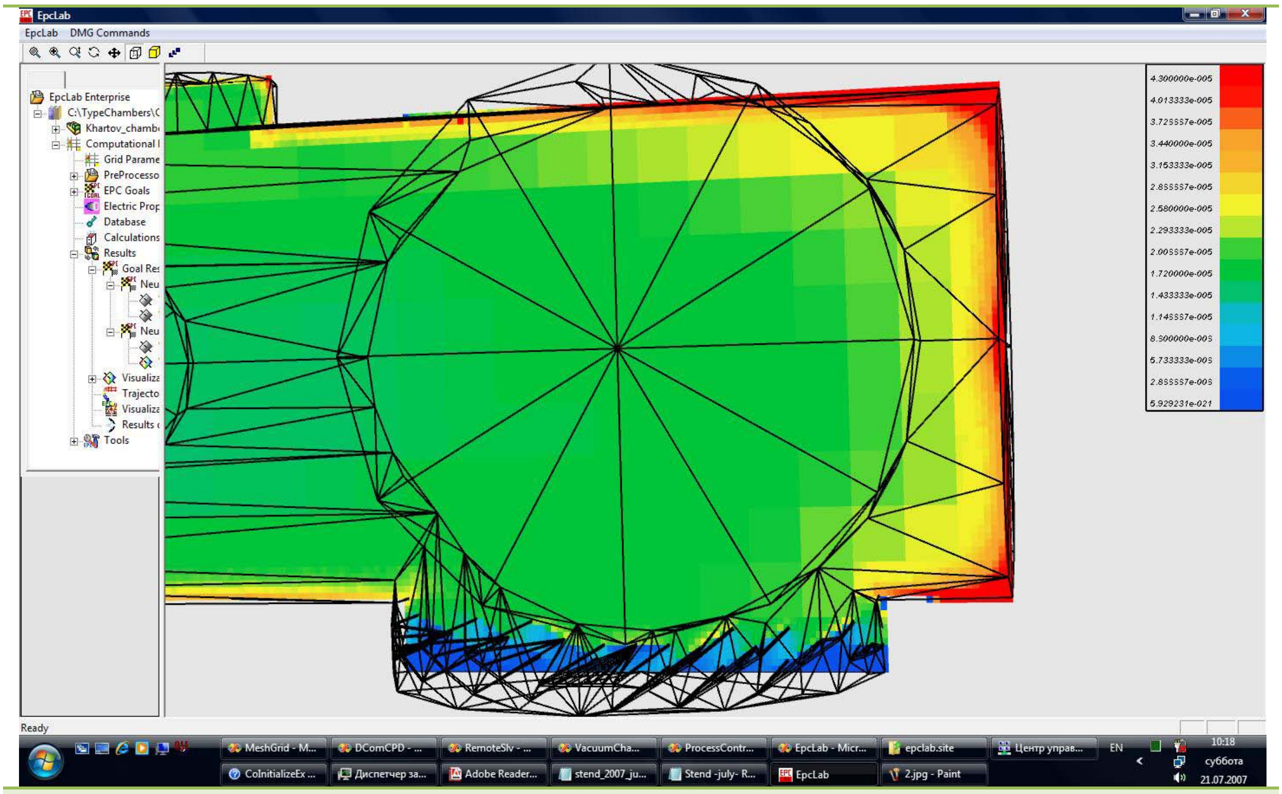


Angle's energy distribution(eV)

The analysis of neutral particles concentration calculation



Pressure in chamber (Tor)



Pressure in chamber (Tor)

Experimental measurement fluctuated from 5e-5 Tor till 6.2e-5 Tor with operated thruster.
The static vacuum during experiment also fluctuated from 0.7e-5 Tor till 1.2e-5 Tor

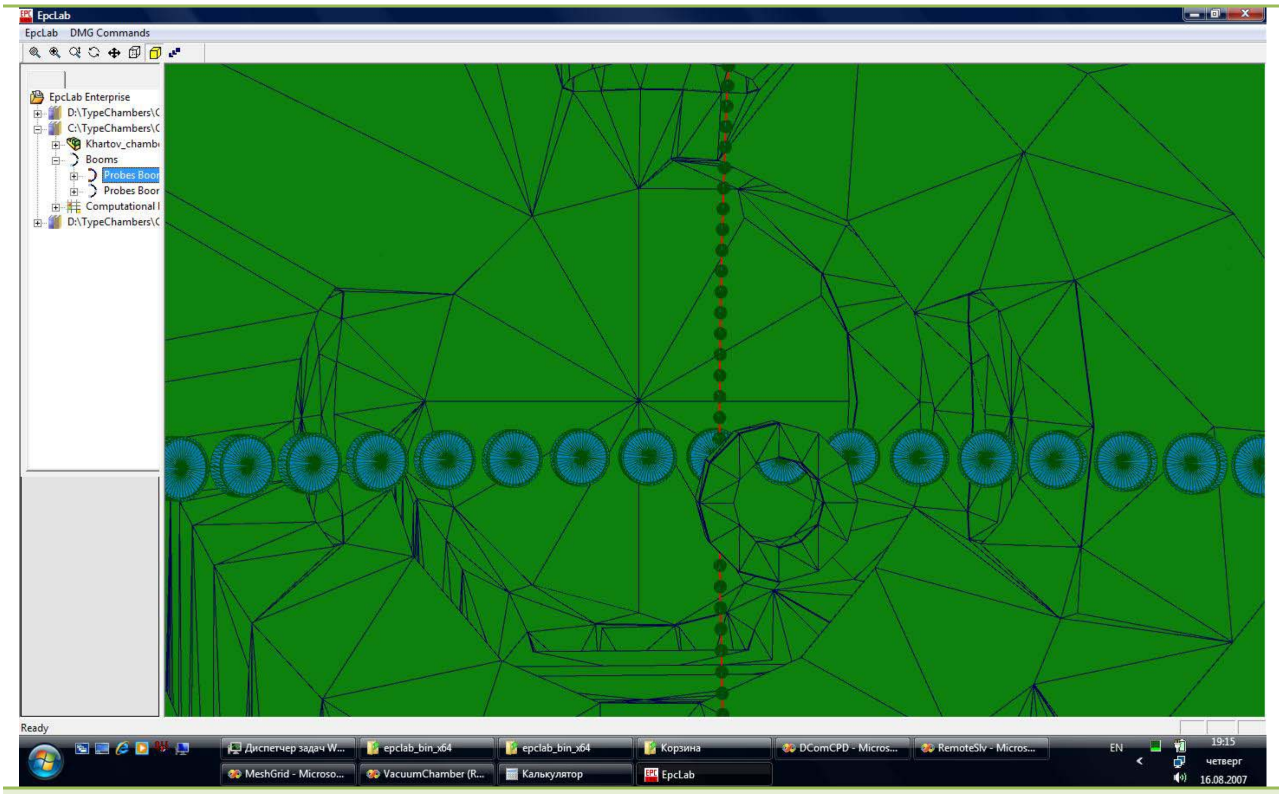
Calculated values of neutral pressure in chamber were about 1.4÷1.7e-5 Tor. The value in the sensor point was about 3.3e-5 Tor. This value doesn't consider static vacuum.

As we assume the sensor gives us 1.3 times more data values.

P (calculation) = [3.3*1.3] e-5= 4.29 e-5Tor
P(experiment) = [(5.0÷6.2)-(0.7÷1.2)] e-5 = [3.8÷ 5.5]e-5 (Tor(мм.рт.ст.))

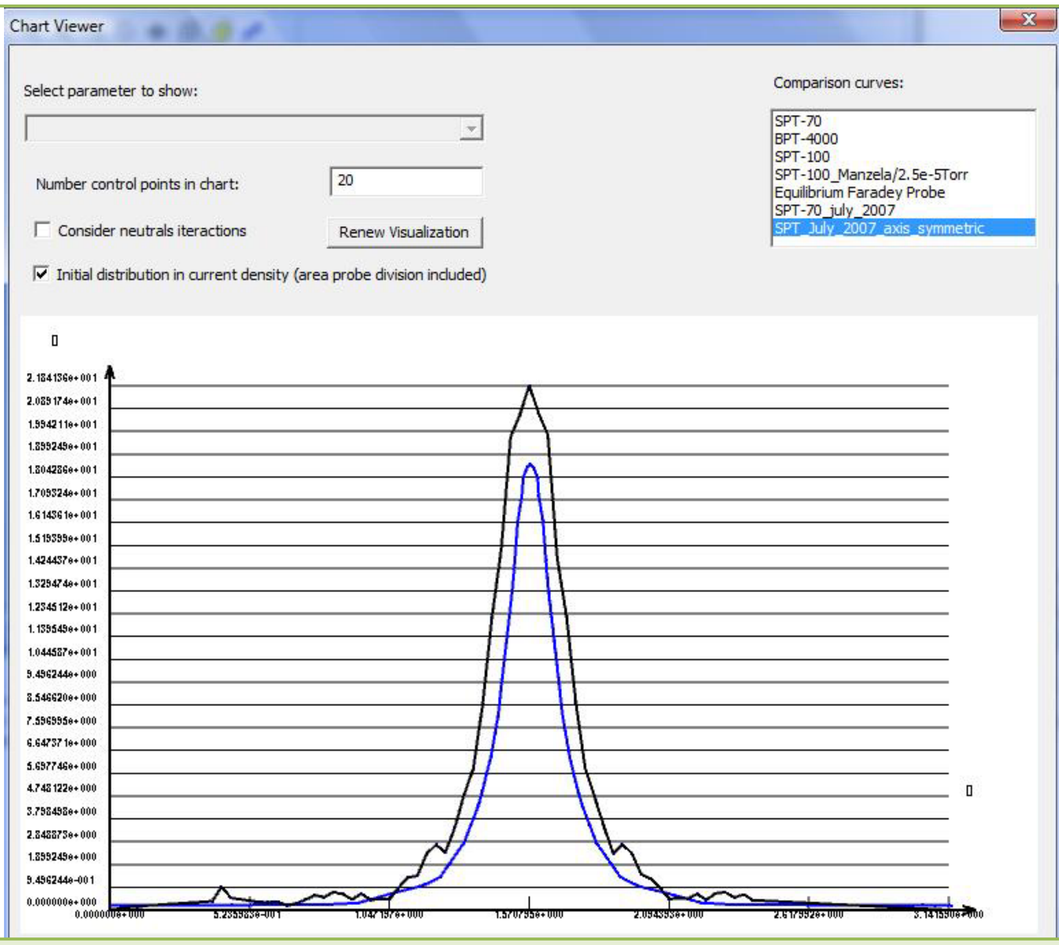
The primary ions calculation

For the comparison with experiment there were used two simulated booms of probes. The first one had probes which comprehend the real experiment probe with diameter 7mm. We used it for the simulated ions current measurement. The other boom had 35 mm diameter probes which were used for the energy distribution on the certain angle.



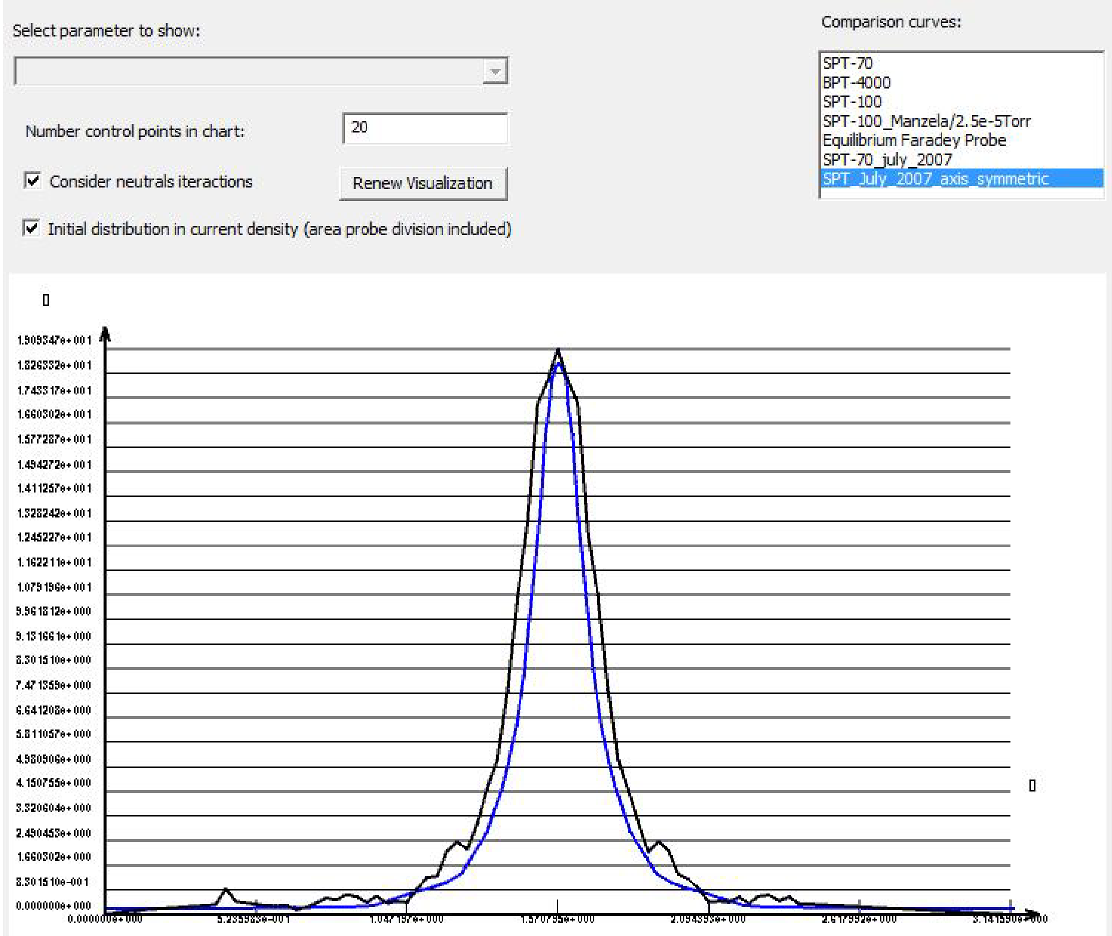
Visualization of probes system

Results comparison:



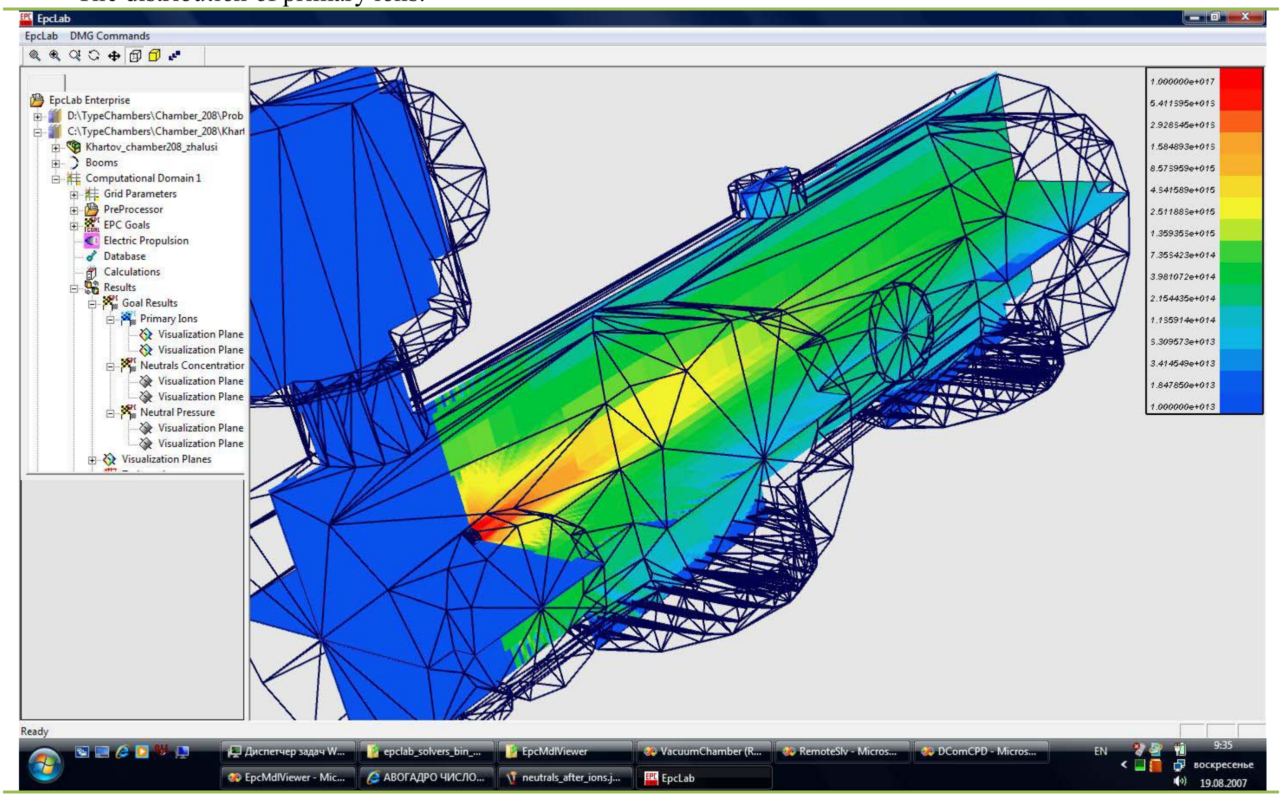
Comparison of primary ions current distribution (the blue is initial experimental distribution). The black one is calculated without considering neutrals interaction loss.

I have to make two comments to this figure. Actually the probe's system was on the distance 390 mm from thruster, and we consider all anodes' mass consumption as ionized primary gas.

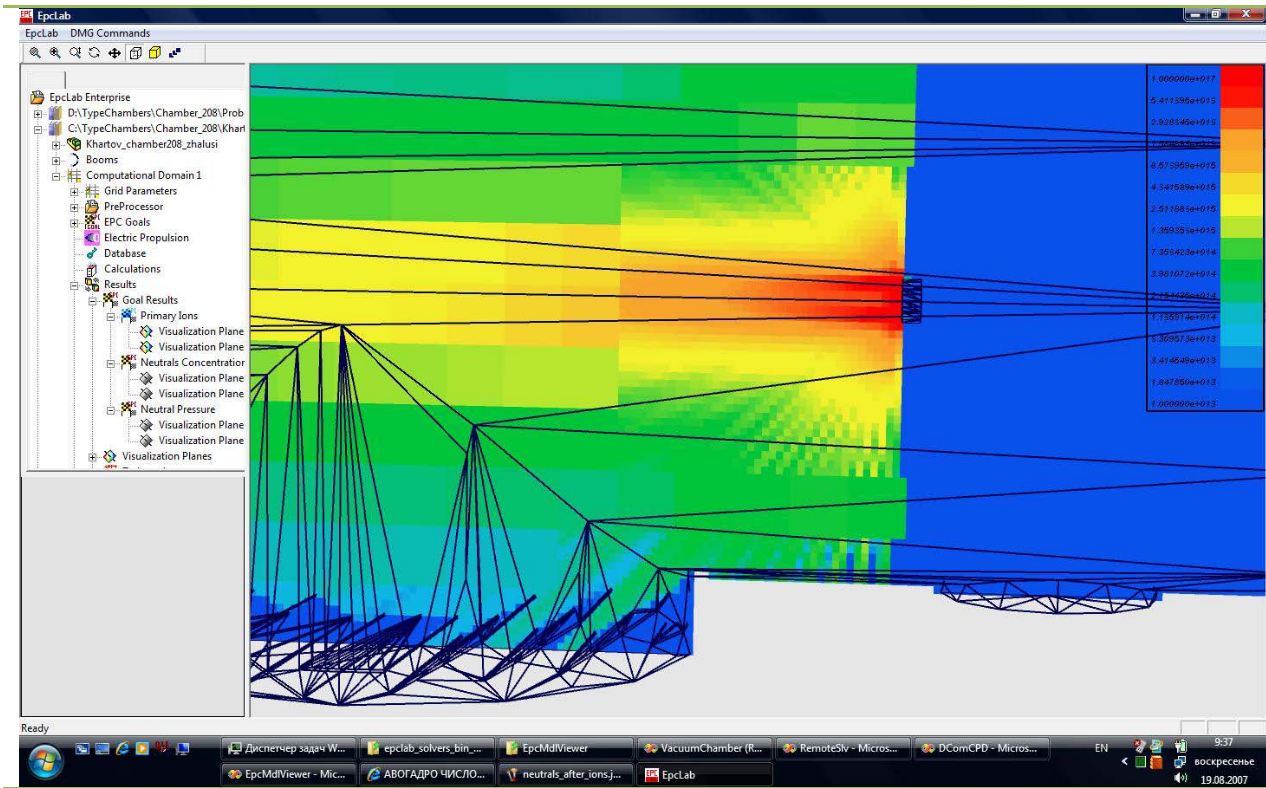


Comparison of primary ions current distribution (the blue is initial experimental distribution). The black one is calculated with considering neutrals interaction loss.

The distribution of primary ions:

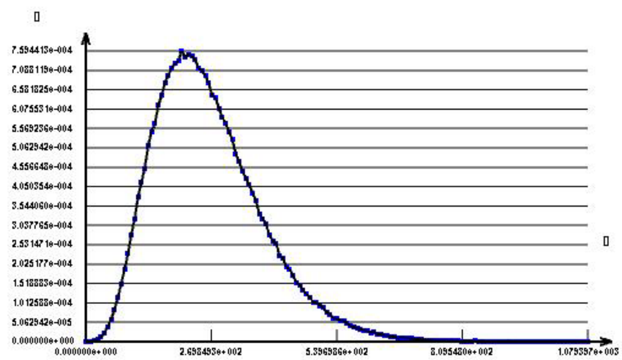


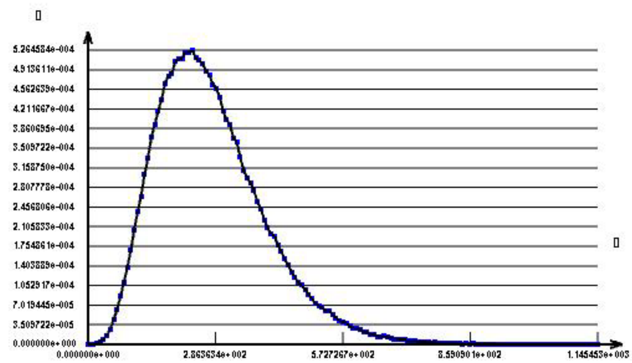
The distribution of primary ions (general view)(1/m^3)



The distribution of primary ions (local domain) (1/m^3)

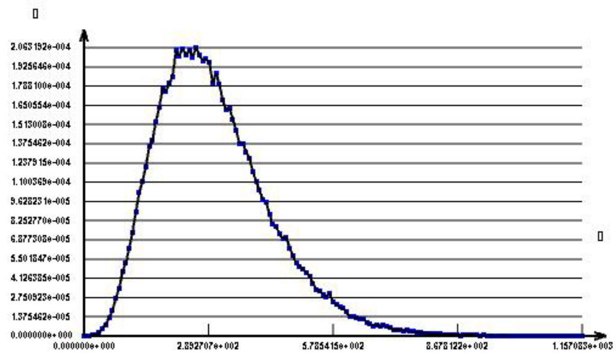
The Energy distribution of ions at the specified angles (characteristics taken from simulated probes):



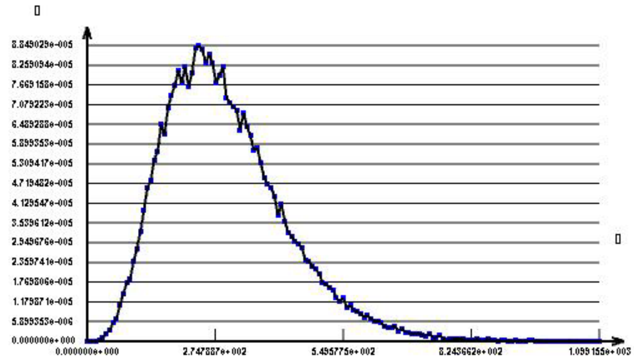


0 degrees (thruster axis)(bottom chart axis: energy of ions in eV)

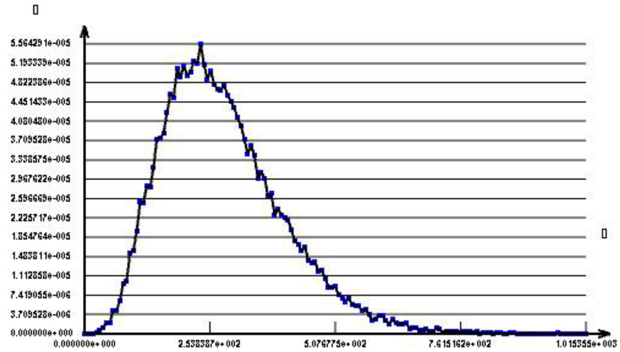
6 degrees from thruster axis



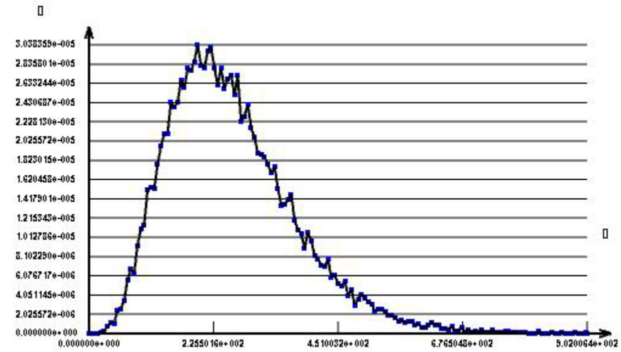
12 degrees from thruster axis



18 degrees from thruster axis

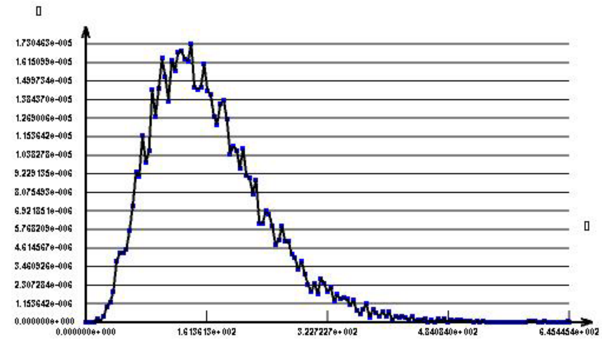


24 degrees from thruster axis

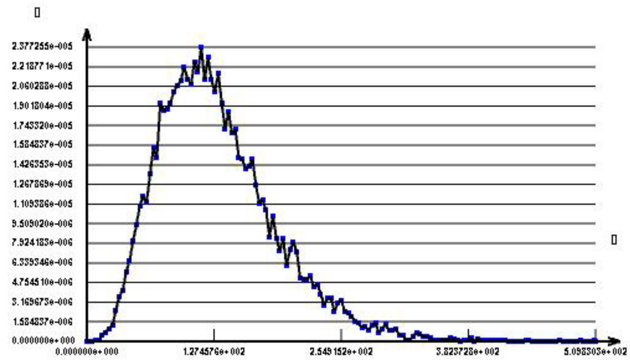


30 degrees from thruster axis

36 degrees from thruster axis

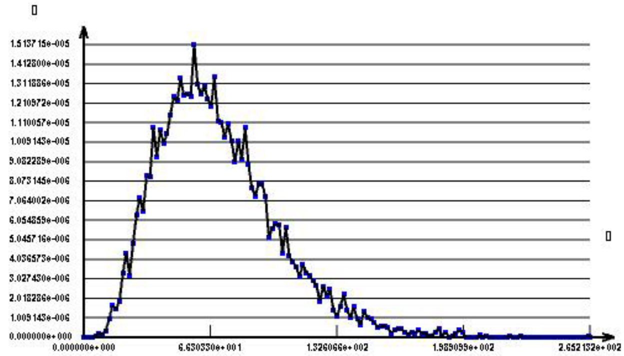


42 degrees from thruster axis

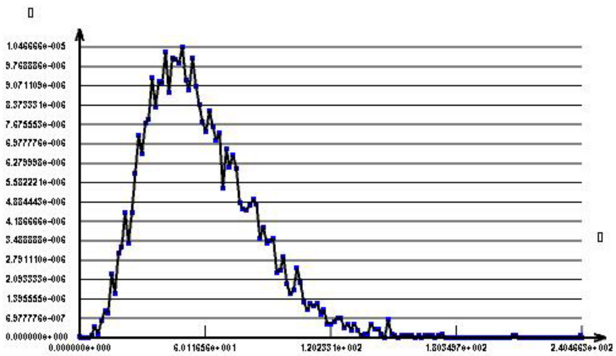


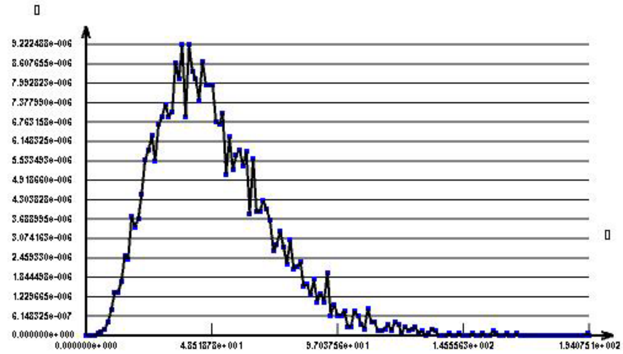
48 degrees from thruster axis

54 degrees from thruster axis

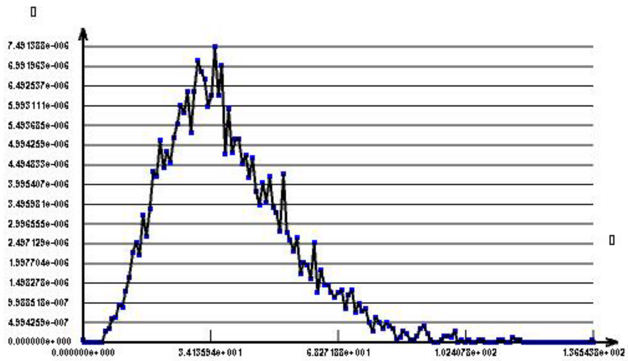


60 degrees from thruster axis | *66 degrees from thruster axis*





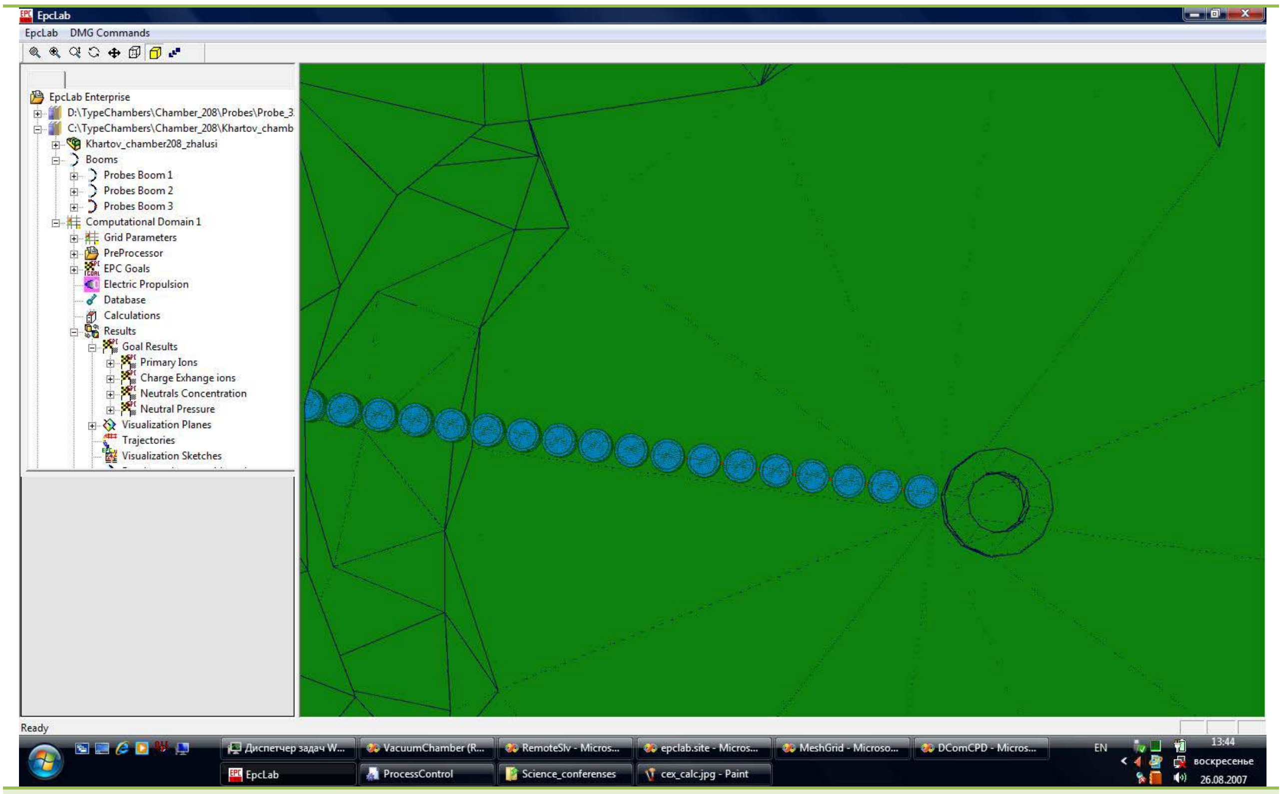
72 degrees from thruster axis | *78 degrees from thruster axis*



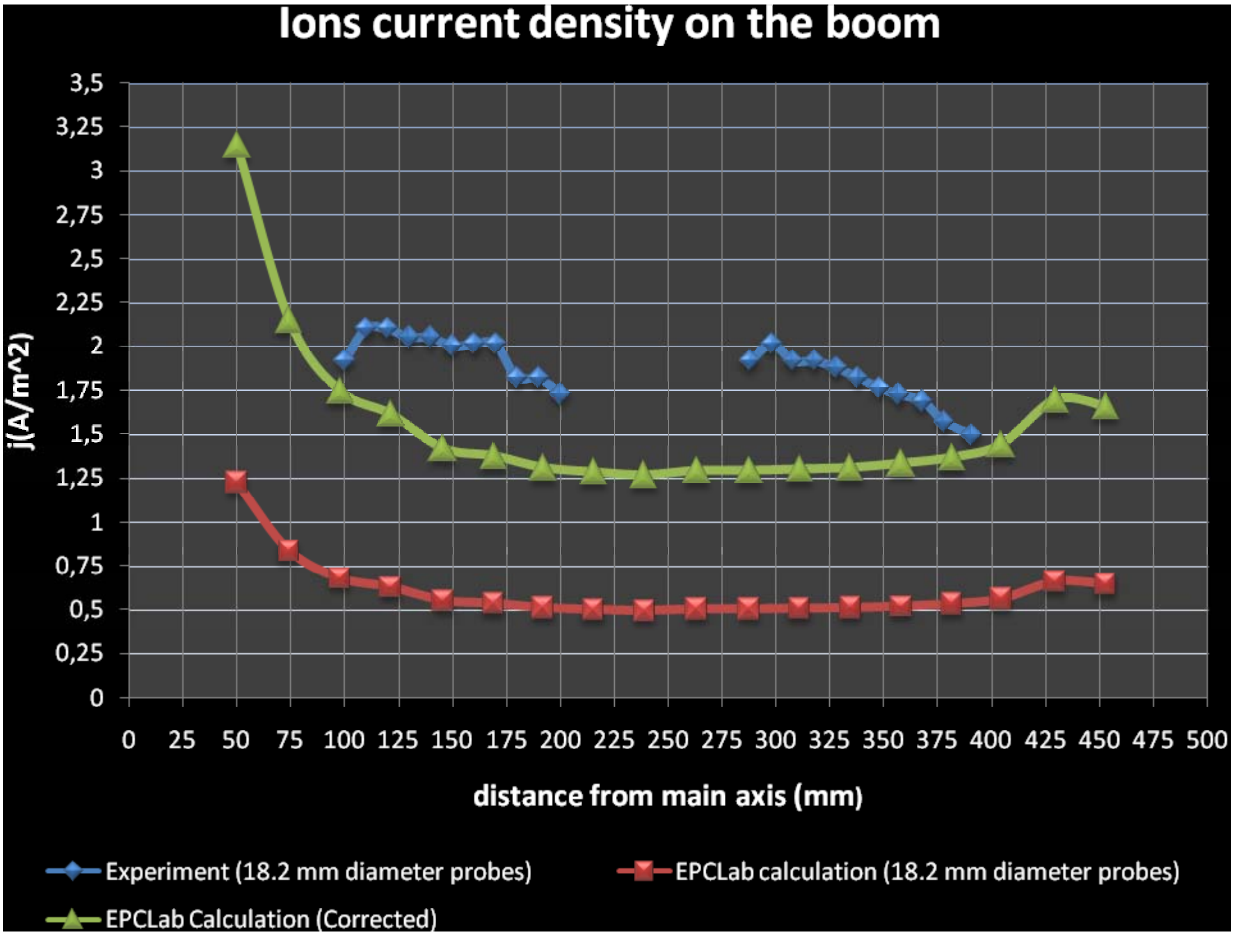
84 degrees from thruster axis

CEX ions distribution

For the determination of total amount of CEX ions we've precalculated arrays of neutral particles distribution and during the analysis of trajectory of primary ions with use of CEX cross section determine amount of CEX ions. Then we've made a procedure which analyzes the distribution of the CEX ions particles in the chamber volume. Because of our assumption the velocity of CEX particles of about 220 m/s (average for 300K) the concentration CEX particles arrays cannot be calculated properly. For the solving of this problem it should be calculated or measured experimentally a potential distribution. Our fluid model of potential distribution simulation is in process. There were some successful simulations but till September we cannot launch it in chamber. Though concentration array is not true the total amount of CEX particles were calculated properly. So the simulation probe current can be trusted.



Simulated boom with probes in the outlet surface of thruster



Ion current density on the boom

The shown results (red line) lead us to find out the reason of 3 times more experimental data than calculated. The fields which we didn't consider can only change trajectory but cannot change the amount of charge exchanged particles. Our resonant cross sections which had been taken from [13] and were calculated by 30% mistake theory as was published in the source actually has much more mistake.

We also tried to find out some other data for cross section Xe – Xe+ charge exchange collision. The cross sections measured by Miller at al[18] are employed:

$\sigma_{CEX}(Xe, Xe+) = (175.6 - 27.2\log_{10}(g)) \times 10^{-20} m^2$, where g is relative velocity.

The Cross section by this equation gives us 2.5 times more cross section than we have used before for our energies. And the corrected green line calculated by this distribution is more close to the experimental data. Also we should add that the experimental charged exchanged current on the probes also includes static vacuum pressure ions recharged by primary ions beam, which we did not consider in calculation so the experimental current higher than calculated one.

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