On the focusing of ion beams using micro- and nano porous structures

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Abstract

Recently, many publications [1–6] have appeared, in which the mechanism of focusing of ion beams in porous dielectric structures is experimentally investigated. This self-organizing charge-up mechanism is called the capillary guiding effect. It consists in the fact that the ion beam induces a layer of surface charges on the walls of such structures, which forms an analog of the waveguide that reflects the beam from the walls. Thus, the initial ion beam is not only focused inside the channel, but also is able to change the direction of its movement in the direction along the axis of the channels, if these channels are located at an angle to the direction of the initial movement of the beam. A detailed study of this mechanism is possible only on the basis of a meaningful theoretical model that takes into account the probabilities of elastic reflections and charge exchange of ions when they collide with pore walls, depending on the parameters of the initial beam and the properties of the material of the porous structure. The author's experience in numerical modeling of charged particle beams in microchannel plates [7-8] allowed him to develop algorithms and programs for modeling guiding effects of ion beams and to carry out calculations to study the details of the guiding mechanism and compare numerical results with experimental data.

Guiding effect in the micro pores

The *capillary guiding* of the ion beam provides evidence that the inner walls of the capillaries become charged and electron capture from the surface is suppressed in a self-organizing process. Surprisingly, the majority of ions were found to survive the surface scattering events in their initial charge state. The angular distributions of the transmitted particles indicate propagation of the ions along the capillary axis [1].

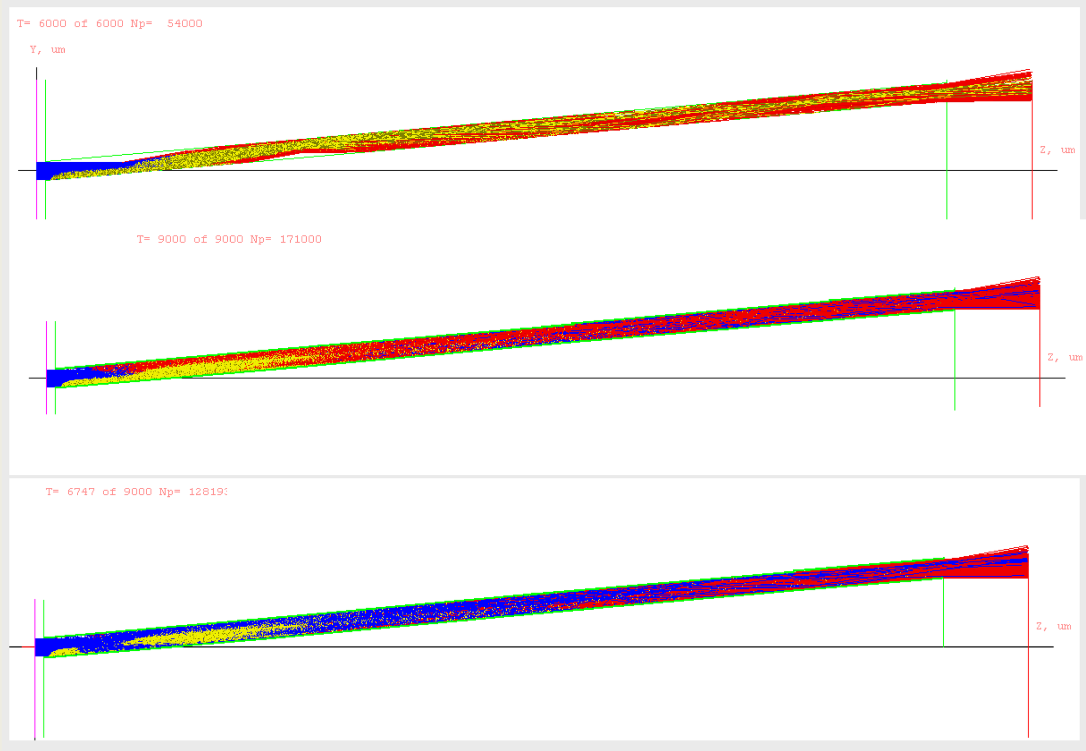
When ions pass through micro channels with dielectric walls, the following processes take place:

1. The absorption of an ion when it collides with the channel surface with a probability R_a, which depends on the energy of the incident ion, the angle of incidence, and the characteristics of the wall material. In this case, the ion charge "sticks" to the wall, inducing an electric field in the channel, which will affect the particles moving in the channel.
2. The relaxation of charges on the channel wall at a characteristic time τ_r.
3. An ion that touches the wall with a certain probability P_e is elastically reflected from the wall.
4. For an ion of multiplicity n that hits the wall, there is a probability P_n of quasi-elastic Rutherford scattering on the atoms of the wall with a loss of charge, that is, converting it into an ion with a multiplicity of one less (recharging process). The lost charge "sticks" to the wall, creating an induced field. The probabilities of more than a single charge loss at the first stage can be neglected.

Numerical model of guiding effect

The induced fields create a channeling effect when a plate or film with channels, inclined at angles of 0-20 degrees to the axis of the incident ion beam, captures the beam, changing the initial direction of its movement, leading to the channel axis, while maintaining a sufficiently large coefficient of ion transmission through micro channels. This effect takes place for small initial ion energies (up to several kilovolts) [1-4].

In simulations by Monte-Carlo method the beam of 3 keV Ne7+ ions with random initial data comes to the pore of 0.2 um diameter, 10 um length, 5 degrees tilt angle. Particle injection stops at the time moment t=1/3 τ. The surface charge growth and particle dynamics shown below.



Initial, intermediate and final stages of surface charge accumulation. Blue – trajectories of primary particles, red – back scattered particles, yellow – surface charges.

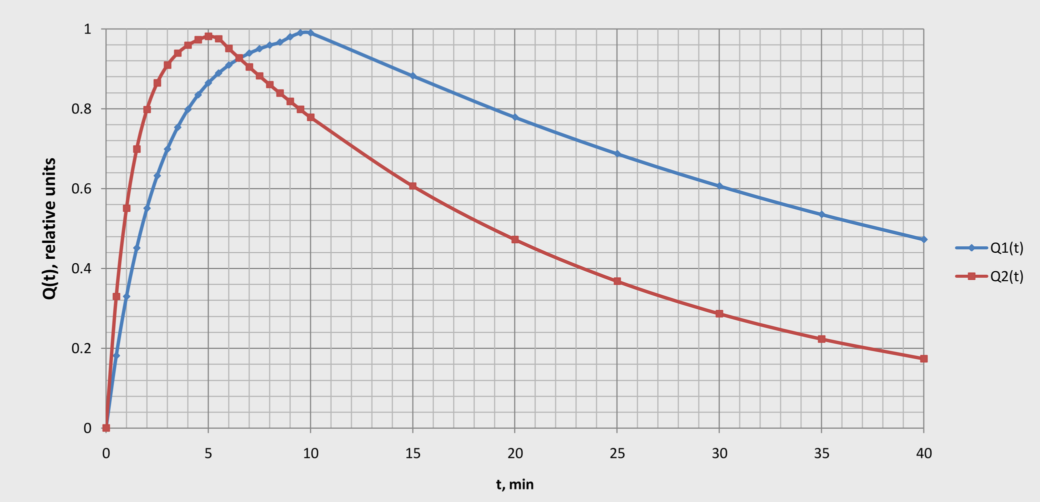
Charging equation

$$\frac{dQ}{dt} = J_{in} - \tau_c Q(t), \quad \tau_c = \left(\frac{1}{\tau_p} + \frac{1}{\tau_r}\right).$$

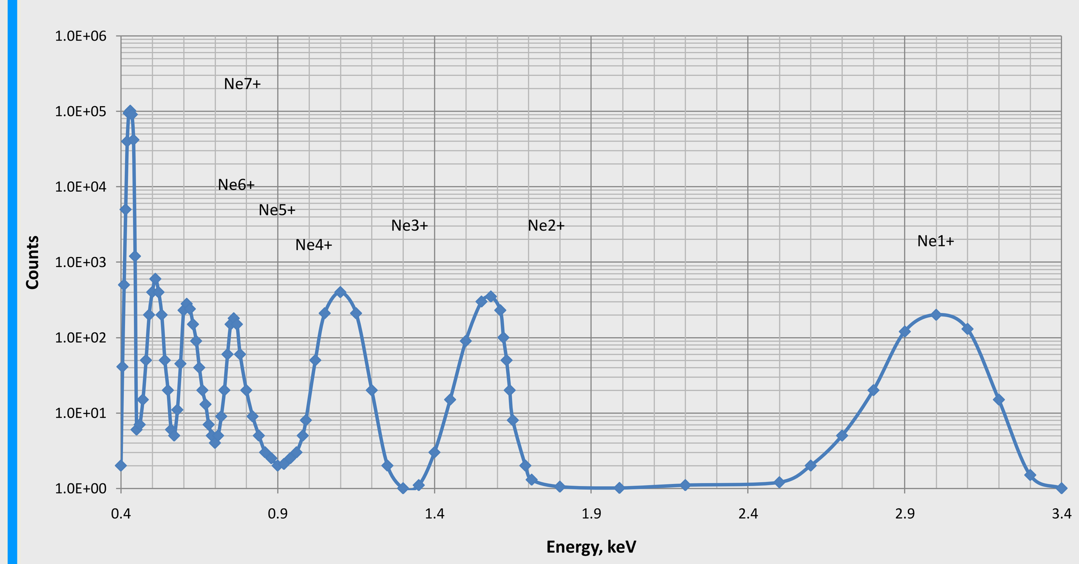
Q – charge on the wall, I_{in} – injection current, τ_c - charging time, τ_r - relaxation time.

Solution

$$Q(y) = \begin{cases} Q_m\left[1 - \exp\left(\frac{t}{\tau_c}\right)\right], t < \tau_c, \\ Q_m \exp\left(-\frac{t-\tau_c}{\tau_r}\right), t > \tau_c. \end{cases}$$



Charging process for τ_c = 1.25 min, τ_r = 20 min (red); τ_c = 2.5 min, τ_r = 40 min (blue).



Energy spectrum for multi-charged ions at the exit of micro channel. Initial energy of the beam equals to 3 keV.

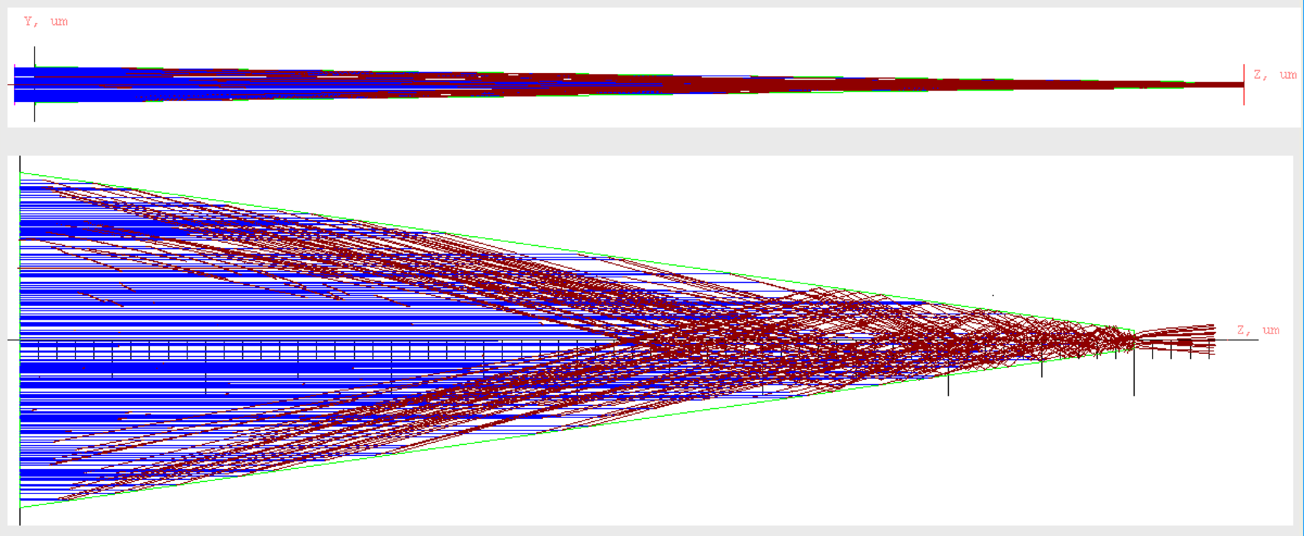
Focusing effects

Slightly tapered glass capillaries with micro or submicro order outlet diameters attract much attention as ion beam focusing lens. It is well accepted that slow highly charged ions such as 8 keV Ar8+ are guided due to the charging up of the inner wall [5-6]. During this guiding the ions are gently deflected, therefore, the transmitted ions suffer no energy loss and the charge state is maintained. The focusing factor of a glass capillary, defined as the ratio of areal current density at the inlet and outlet, depends on the ion species, the incident energies and the shape of glass capillary. For example, the focusing factor of 2 MeV He+ beam is about 1000 and for 8 keV Ar8+ it is about 10. Two factors are conceivable as the mechanism of focusing, one is the above-mentioned charging up of the inner wall and the other is the small angle scattering by the surface atoms nuclei.

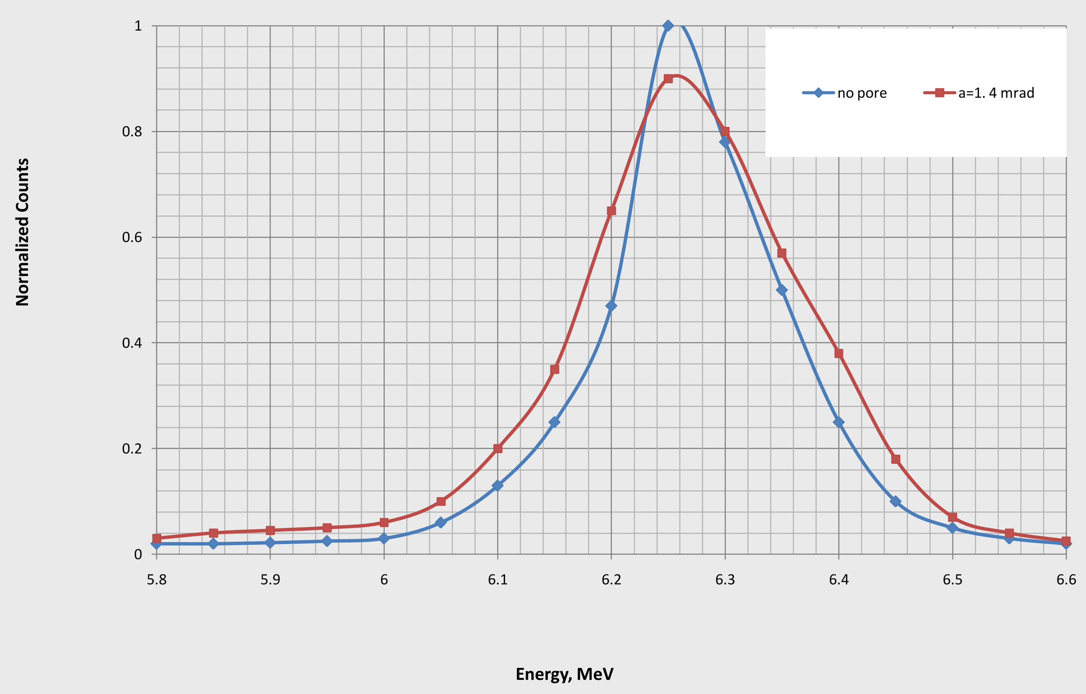
The dependence of focusing effect on capillary taper angles were examined. The results suggest that the small angle scattering plays a significant role in focusing of 6.4 MeV ions. The capillary is made of borosilicate glass pipe, which has 1.8 mm and 3.0 mm inner and outer diameter, respectively. The outlet diameter is 100 lm for energy spectrum measurements [5]. Differently tapered capillaries are prepared by changing the pulling force of the puller.

Results of numerical simulations

Figures below shows the capillary focusing effect for 6.4 MeV N2+ ions in the conic capillary of borosilicate glass with input diameter of 1.8 um and output diameter of 0.2 um.



Primary ions shown with blue color, back scattered ions – with red color. Top picture has x:Y scale 1:1, .bottom picture has scale 1:10 Current density compression is 91.



Energy spectrum of transmitted ions with and without capillary.

Computer code Monte Carlo Simulator "MSC-ions" under Linux and Windows platforms

The code MCS is full 3D Monte Carlo simulator with friendly user's interface and graphical post-processor. Numerical models include the angular, energy and spatial distributions for the injected multi-charged ions. They include also the fringe fields, recharging, absorption and secondary emission effects in cylindrical and conic-shape micro- and nano pores. The code can provide the numerical study in order to evaluate all needed parameters of realistic devices: gain, transit time spread, angular, energy and spatial distributions of primary and secondary particles in pre defined cross-sections. Typical CPU-time for simulation of 1 million particles is 1 to 10 minutes at desktop or laptop computer with 1.8GHz CPU. The massive computations of. statistical properties of amplifiers demand parallel computations at super computers or PC-clusters.

References

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