Transportation and focusing of accelerated proton beams by means of dielectric channels

2006 J. Phys. A: Math. Gen. 39 4775

(http://iopscience.iop.org/0305-4470/39/17/S73)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND GENERAL

J. Phys. A: Math. Gen. **39** (2006) 4775–4779 doi:10.1088/0305-4470/39/17/S73

Transportation and focusing of accelerated proton beams by means of dielectric channels

K A Vokhmyanina[1], L A Zhilyakov[2], A V Kostanovsky[2],
V S Kulikauskas[1], V P Petukhov[1] and G P Pokhil[1]

[1] D V Skobeltsin Institute for Nuclear Physics, MSU, 119892, Moscow, Russia
[2] Institute for High Energy Density RAS, 125412, Izhorskaya St 13/19, Moscow, Russia

E-mail: lev@iht.mpei.ac.ru

Received 16 September 2005, in final form 16 February 2006
Published 7 April 2006

Abstract

The present paper gives an experimental and theoretical study of the transmission process of protons within the 100 keV to 300 keV energy range through a quartz tube, 100 mm in length and 1.6 mm in diameter. It has been established that protons pass through the tube without energy losses. The proton beam goes through the tube even when the tube axis is tilted from the beam axis. The angular width of the protons' transmission curve versus the angle of incidence makes about 3°. As the authors suggest, this effect is due to self-organization of a beam–wall charge system. Computer simulation has shown that distribution of the charge on the wall is axially symmetric and oscillates along the tube. It is known that when a charge moves inside the oscillating field which has a gradient, it is subjected to the action of a unidirectional force. This force provides protons movement through the channel without collisions with the wall.

PACS number:

1. Introduction

The possibility of transporting relativistic impulse heavy-current electron beams through dielectric channels was experimentally shown in the 1980s [1–4]. The authors explained abnormal transmission of the beam by formation, from the wall material, of plasma compensating Coulomb electron bunch repulsion forces.

Transfer of positive ions via a dielectric channel without collision with walls was for the first time observed only in 2002 [5]. This paper showed that multi-charge ion beam (Ne^{7+}) passes through dielectric micro capillaries without collision with channel walls. In the paper [6] an experiment was performed on transportation of Mev helium ions through a conic glass capillary and compressed beam up to 0.3 μm in diameter. The beam density in the ions

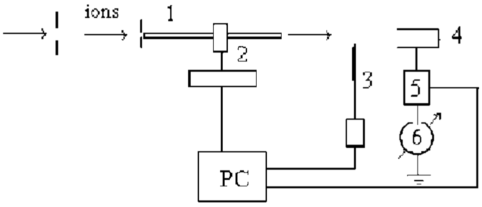

Figure 1. Layout of the experimental set-up: 1—capillary; 2—goniometer; 3—shutter; 4—Faraday cup; 5—current integrator; 6—micro amperemeter, PC-computer

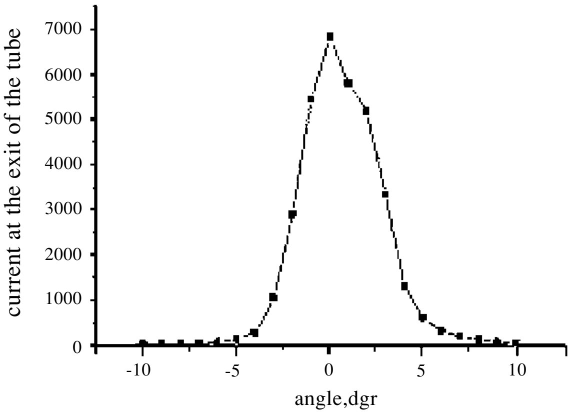

Figure 2. Dependence of the current of proton beam passing through the tube on the angle between the tube axis and beam direction (tube length $L = 10$ cm, diameter $d = 1.6$ mm).

experiments is too small and the beam's volume charge does not play any role at the beam behaviour in the capillary. A different explanation is needed.

In our works [7, 8], we studied the interaction between sliding proton beams and dielectric surface. Computer simulation and experimental results have proven that the property of self-organization–dielectric surface electrization goes in a way providing conditions for beams sliding along the surface with no energy losses due to ionization. Since possible transporting of ions through dielectric capillaries and tubes has practical interest, we investigate the process of protons transportation through a glass tube.

2. Experiment and results

Using the ion accelerator KG – 500 at the Moscow State University Institute of Nuclear Physics, transportation of beams of accelerated protons through a dielectric (quartz) tube was studied. Protons' energy was from 100 to 400 keV, beam current 0.1 to 2 μA, tube length 100 mm, diameter 1.6 mm. An experimental layout is given in figure 1. It was discovered that in the case of the paraxial position of the tube relatively to the beam direction, the passed beam current value is very close to the initial beam current, transmission is about 80%. Beam transmission through the tube was also observed when the tube axis did not coincide with the beam direction. The dependence of the tube transmission coefficient on the angular displacement is shown in figure 2. Transmission curve half-width makes about 3°. It should be noted that at a 3° angular tilting and an initial beam energy of 200 keV, the energy of the transverse proton motion (normal towards the wall) is about 500 eV only.

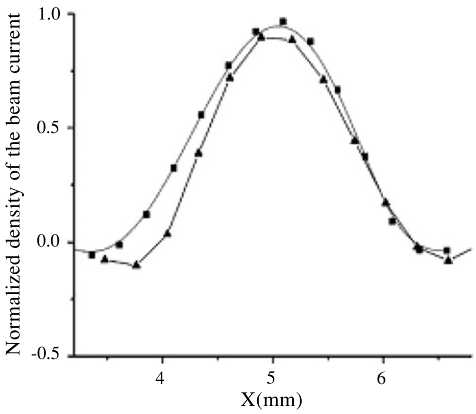

Figure 3. Measured beam profile: ■—at tube inlet, ▲—at tube outlet.

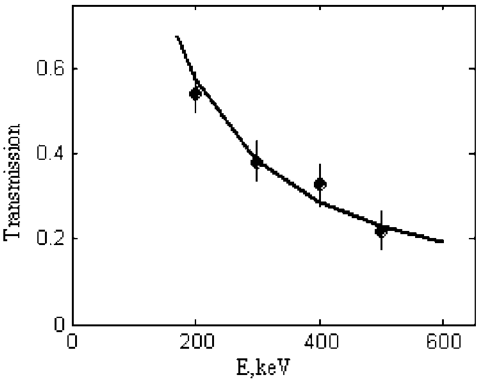

Figure 4. Transmission coefficient for different energies of ion beam: points—experimental results', solid line—E^{-1}.

Comparing proton beam cross-sectional dimensions at the tube inlet and outlet, which are shown in figure 3, shows that the dielectric tube somewhat lowers down the cross-sectional dimension of the beam during its transportation (small focusing action).

The above experimental results can be due to the formation of an electrostatic field deflecting ions away from the wall and preventing close collisions of protons with the tube walls surface as the inner surface of the channel (tube) is charged. It follows from the experiment that the depth of 'effective' potential well keeping ions from colliding with walls under said conditions is about $\sim$ 500 eV. The fact that channel walls are charged by the incident beam is supported by N Stolterfoht *et al* (2002) as well. At the same time, the process of walls electrization should be self-organizing. It should be noted that beam transportation through a dielectric channel cannot be explained based on the assumption that the charge is uniformly distributed on the inner surface of the channel because, in this case, the electric field inside the channel should be equal to zero.

The next experiment was performed with a conic capillary at the same geometry as in figure 1. The conic capillary was 10 cm of length, 1.5 mm input diameter and 0.5 mm output diameter . We measured the transmission coefficient for different energies of ion beam. Results are shown in figure 4. We see that at energy 200 keV, for example, the transmission

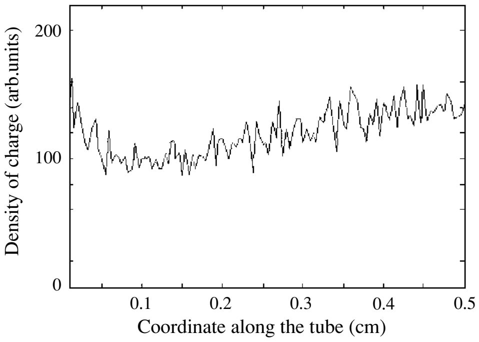

Figure 5. Calculated distribution of charge along the tube.

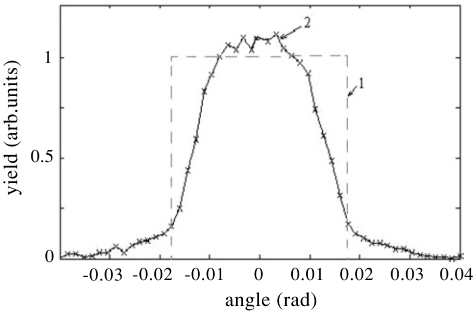

Figure 6. Calculated angular distribution of protons beam at inlet (curve—1) and outlet (curve—2) of the tube.

is about 50% and the exit square is nine times smaller than the inlet square, so the current density is about five times higher. We can conclude that the current density at the exit of the capillary is higher by a few times than at the entrance; there is a focusing of the beam [6]. It is interesting that the dependence E^{-1} fits experimental data very well (figure 4).

3. Model

To understand the mechanism of this phenomenon, a computer model has been developed simulating the movement of charged particles inside the channel. A similar modelling was made in our previous paper [8]. The model is based on a solution by the Runge–Kutt method of Hamilton equations for protons moving in the Coulomb field generated in the channel at the wall produced by the charge produced by ions collision with walls at the initial stage of protons' transport through the channel. Proton collision with the wall is fixed if the particle's transverse coordinate becomes equal to the tube radius. In this case, a charge is generated on the wall, whose value is determined in reality by the number of electrons emitted from the surface. The model provided for a self-organizing interaction of ions with a dielectric channel is similar to that occurring in the experiment. The model has shown that the tube wall is charged in an axially symmetric manner and the charge is oscillating along the tube around any value which approximately is a constant (see figure 5). The mean axially symmetric charge can be excluded because it does not create a field inside the channel. The oscillating force with mean value equal to zero acts on the particle as some effective unidirectional force—a so-called gradient force [9]. This force creates an ‘effective’ potential well keeping particles inside the tube; in this case, the potential well is established in a self-agreed manner so as to prevent contact of particles with the wall. The depth of this ‘effective’ potential depends on experimental conditions. We used the model to calculate the angular distribution of protons at the tube exit too. A more detailed description of our model is given in [10].

Figure 6 gives simulation results for protons with 0.3 MeV energy passing through a capillary 2.5 cm long and 0.1 cm in diameter. Simulation has shown that dielectric channel is a focusing device for a beam of charged particles, which also agrees with the experiment—intensity distribution along transverse coordinate of the output beam is narrower in comparison with the input beam (figure 3). This conclusion also in agreement with the results of the work [5], where the directing action of micro capillaries on the motion trajectory of ions (Ne^{7+}) was investigated.

4. Conclusion

As a result of experimental and theoretical studies performed, it was demonstrated that the high transmission coefficient of protons through a dielectric channel is explained by electrization of the tube during protons irradiation. It is important to underline that there is a self-organization of a beam–wall charge system, i.e., a charge is generated, at which there are no more collisions of protons with the wall and no more changes in the charge distribution. The experiment shows as well that more beam self-isolation takes place also at tilting angles of the channel axis toward the beam direction. It seems interesting to continue investigation of the registered phenomenon and study its dependence on various conditions, such as channel geometry, material properties, particles’ energy and so on.

The phenomenon of self-isolation of accelerated charged particles from the wall of a dielectric channel served as a basis of the suggested device for transporting beams of charged particles [11, 12].

Acknowledgment

This work was done with support from the Russian Fund of Basic Researches, grant no 05-02-16007.

References

[1] Akopov R A, Antablyan O G and Khanikyants E K 1983 *JTP* **53** 2269 (in Russian)
[2] Akopov R A, Antablyan O G, Davtyan S V and Khanikyants E K 1986 *JTP* **56** 552 (in Russian)
[3] Krastelev E G and Yablokov B N 1977 *Lett. JTP* **3** 775 (in Russian)
[4] Agafonov A V *et al* 1981 *Phys. Plasma* **7** 267
[5] Stolterfoht N *et al* 2002 *Phys. Rev. Lett.* **88** 133201–1
[6] Nebiki T 2003 *J. Vac. Sci. Technol. A* **21** 1671
[7] Zhilyakov L A *et al* 2002 *Surface* **11** 65 (in Russian)
[8] Zhilyakov L A *et al* 2003 *Surface* **4** 6 (in Russian)
[9] Landau L D and Lifshits E M 1988 *Mechanics* (Moscow: Nauka)
[10] Vokhmyanina K A, Zhilyakov L A, Petukhov V P, Pokhil G P, Fridman V B and Tulinov A F 2006 *Izv. RAN* to be published (in Russian)
[11] Zhilyakov L A, Kostanovsky A V, Kulikauskas S V, Petukhov V P and Pokhil G P 2003 *Patent RU* No 34056
[12] Zhilyakov L A, Kostanovsky A V, Kulikauskas S V, Petukhov V P and Pokhil G P 2004 *Patent RU* No 45199