MASS-SPECTROMETER FOR SPACE DUST EXPLORATION

Novikov L.S. (1), Semkin N.D. (2), Pomelnikov R.A. (2), Voronov K.E. (2), Rotov S.V. (2)

(1) Scientific Research Institute of Nuclear Physics, Moscow State University, Moscow, Russia, 119899, Email: novikow@npi.msu.su

(2) Samara State Aerospace University, Moskovskoe shosse, 34, Samara, Russia, 443086, Email: semkin@ssau.ru

ABSTRACT

Micrometeoroids and artificial particles effect on space vehicle construction poses the task of physical parameters and chemical composition studying. Time-of-flight mass-spectrometers are used for these purposes.
The mass-spectrometers parameters computing is based on definition of field potentials and ion movement in this field. Libman method is used for this computing.

The exploitation of mass-spectrometer instruments in space and laboratory experiments on studying micrometeoroids, artificial particles and processes of interaction with solid body is of important scientific and practical interest.
According to known particles distribution in space the probability of particle impact with equipment is sufficiently small, thus, the most important requirements for registration of the particles are the large area of sensor surface of mass-spectrometer, the independence of output characteristics and impact location, the minimum losses of ions generated by impact, the high resolution and experimental results validity.
Experiments on studying of space dust particles are conducted in condition of own external atmosphere (OEA) influence onto space vehicle. It effects on measurement results. Thereby the development direction is in close touch with experiment clarity and resolution increasing. Alternating in time and space electrical fields are used for realization of these characteristics.
Alternating electrical field can be used for decreasing of initial ion dispersion during emission from ion source. This focusing method is called the dynamical compensation method. This method envisages increasing of time-of-flight mass-spectrometer resolution using alternating electrical field in accelerating gap between target and grid for dynamical compensation of initial ion dispersion by coordinate and emission time. The example of dynamical compensation described in [1], where the step-by-step calculation of particle acceleration is developed by authors of this paper. This method is required for decreasing of initial particle dispersion on speed and coordinates

$$a(t)=\begin{cases} a_0=\dfrac{eV_0}{m\,D}, t\le 0; \\ a_{k-1}+\dfrac{a_k-a_{k-1}}{\Delta t}\left(t-(k-1)\Delta t\right), t\in\left[(k-1)\Delta t, k\Delta t\right] \end{cases} \tag{1}$$

where Δt is the discretization step, a_k are unknown values. They can be derived, on the one hand, from the following condition: at $t_1 = kt$ the speed of ion emission $V_1(t_1)$ must be equal to zero for interval $x \in [0,l]$

$$V_{1k}=\frac{a_t}{4}\left(T-k\Delta t+\sqrt{(T-k\Delta t)^2-\frac{8d}{a_t}}\right) \tag{2}$$

On the other hand, a_k must implement the situation when ion emitted at moment of time t (that is previously unknown) achieves the bound x =1 at time $t = k\cdot\Delta t$. Therefore the acceleration $a(t)$ can be found from equations system (in assumption $x = 0$, $V_0 = 0$)

$$\begin{cases} V_{1k}=\int\limits_t^{t_1} a(t)=\int\limits_t^{k\Delta t} a(t)dt \\ l=\int\limits_t^{t_1}\int\limits_t^{t} a(z)dzdt=\int\limits_t^{k\Delta t}\int\limits_t^{t} a(z)dzdt \end{cases} \tag{3}$$

In (3) values t и $a(t)$ are unknown. The double integral in (3) can be represented as

$$\int\limits_t^{t_1} d\tau\int\limits_t^{\tau} a(z)dz=\int\limits_t^{t_1} dz\int\limits_z^{t_1} a(z)d\tau=\int\limits_t^{t_1}(t_1-z)a(z)dz \tag{4}$$

Unknown values $a_0, a_1 \ldots a_n$ can be sequentially found.

Proceedings of the 3rd European Conference on Space Debris, ESOC, Darmstadt, Germany, 19 - 21 March 2001
(ESA SP-473, August 2001)

At first values t_0 и a_0 can e found from equations

$$V_b = V_1(t_1 = 0) = -a_0 t_0;$$
$$l = \frac{a_0}{2} t_0^2; a_0 = \frac{2l}{V_0^2}; t_0 = -\frac{V_b}{a_0} \tag{5}$$

where $V_b = \sqrt{\frac{2lV_0}{m_b}}$.

Then at $t_1 = \Delta t$ ion got started at moment of time t achieves the bound $x = 1$ with determined speed $V_1(t_1 = \Delta t)$. We can derive values t and a_1 from this condition. With computed a_0 и a_1 we can find a_2 etc. The usage of dynamical compensation method in classical time-of-flight design of instrument allows to achieve the resolution about $R = 400$ for particles of 200 atomic mass unit.

Usage of alternating electrical field in reflector allows to decrease the length of particles flight to required energy dispersion compensation and, consequently, time-of-flight analyzer size. It is very important for natural experiment. Analytical calculation of axial potential distribution in non-linear reflector calculation is done in [2]

$$z = \frac{1}{\pi}\left\{ t_0 \alpha \sqrt{\tilde{\varphi}} - L_0 \arcsin \sqrt{\frac{\tilde{\varphi}}{1+\tilde{\varphi}}} - \right.$$
$$\left. - L_1 \left[\sqrt{\tilde{\varphi}} + (1+\tilde{\varphi}) \arcsin \sqrt{\frac{\tilde{\varphi}}{1+\tilde{\varphi}}} - \frac{\pi}{2}\tilde{\varphi} \right] \right. \tag{6}$$

where $\alpha = \sqrt{-\frac{2e}{m}\varphi_1}$ is the speed of a particle got started from origin of coordinates with zero initial speed after area [0,1]; φ_1 is the pushing field potential; $L_0 = l_{12} + l_{52}$ is the full length of particle free flight in non-field space; $\tilde{\varphi} = \frac{\varphi}{-\varphi_1}$ is the dimensionless potential.

The applying of non-linear electrostatic field in mass-reflectron allows to increase resolution up to $R = 550$ for particles of 200 atomic mass unit.

The Libman extrapolation method can be used for mass-spectrometer field simulation.

The Libman extrapolation method is the most universal and useful one as compared to other fast convergent iteration methods. This method is equivalent to consecutive node relaxation with search (extrapolational method). It is an extension of Libman method based on introduction of coefficient a

$$A_{n,k}^{n+1} = A_{n,k}^{n} + \frac{a}{4}\left(A_{n+1,k}^{n} + A_{n,k+1}^{n} + A_{n-1,k}^{n} + A_{n,k-1}^{n} \right.$$
$$\left. + h^2 W - A_{n,k}^{n}\right) \tag{7}$$

where a is the convergence (relaxation) coefficient defining the search degree. It can be shown that value a must be from 1 … 2 range. If $a = 1$ then Eq. (1) can be converted to an equation of ordinary Libman method, if $a \geq 2$ the solution process becomes unstable. If a lies in specified range then the convergence is better than a=1, and with some optimal a that differs for any particular task the speed of relaxation essentially rises. The numerical computation of particle path implies discrete particle movement in field with determined time step (the step estimation is shown later), but we can logically assume that particle coordinates are not equal to potential grid node coordinates.

Thus, the improved calculation of field intensity in particle location is required. Particle coordinates can be found from equations

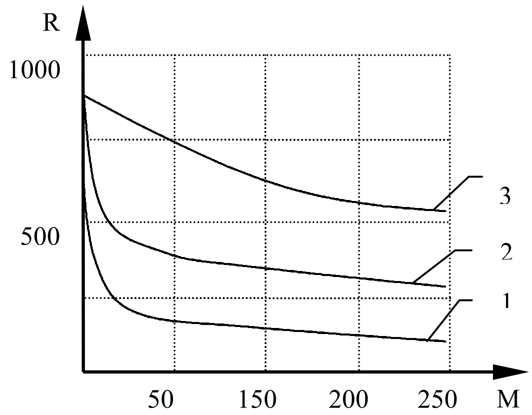
$$\left.\begin{aligned} x &= x' + \left(v'_x + \frac{qE_x}{m} dt \right) dt, \\ y &= y' + \left(v'_y + \frac{qE_y}{m} dt \right) dt. \end{aligned}\right\} \tag{8}$$

Descending from differential to time increment we get equations

$$\left.\begin{aligned} x(t+\Delta t) &= x(t) + \left(v_x(t) + \frac{qE_x}{m} \Delta t \right) \Delta t, \\ y(t+\Delta t) &= y(t) + \left(v_y(t) + \frac{qE_y}{m} \Delta t \right) \Delta t. \end{aligned}\right\} \tag{9}$$

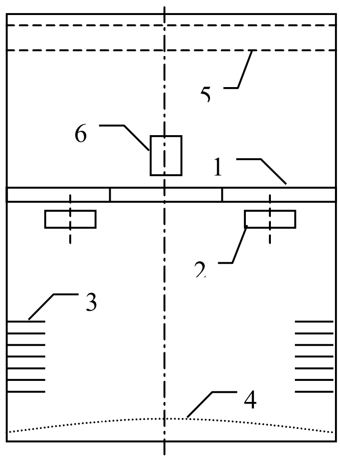
The time step selection Δt is sophisticated problem but we should note that time step must provide coordinate increment (x or y) to be less than potential grid step at least on one order. Thus, Δt is defined during the time of particle's flight to be able to correct input time step Δt_{in} assigned by an operator.

Using this mathematical model, the dependencies for resolution of different mass-spectrometer designs on element mass are built (Fig. 1). The design of combined gas-dust-impact mass-spectrometer is shown in Fig. 2. The distinction of this mass-spectrometer is separate focusing of ion packet in space and by energies executed in electronic immersion lens 5 and non-linear mass-reflectron 3.



1. The classical electrostatic reflector;
2. The reflector with non-linear electrical field;
3. The dynamical compensation method.

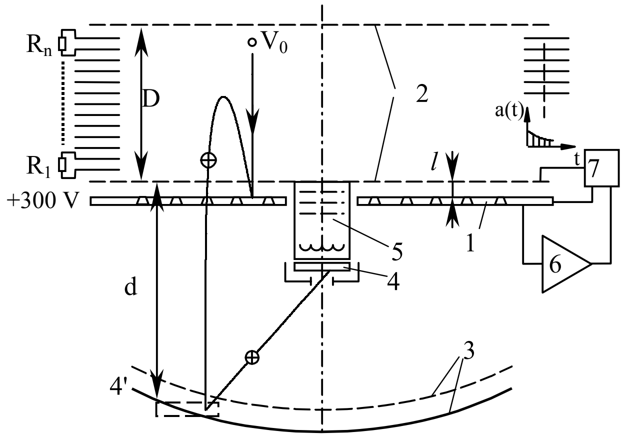
Fig.1. The resolution of mass-spectrometer as a function of the ion mass



1. Target; 2. Ion receiver; 3. Non-linear reflector; 4. Reflecting grid; 5. Immersion lens; 6. Ion source.

Fig.2. Gas-dust-impact mass-spectrometer

The additional ion focusing towards receivers is executed by reflective grid 4.



1 – target; 2 – focusing reflector; 3 – parabolic reflector; 4 – ion reciever; 5 – ion source; 6 - amplifier; 7 – control block (hi-voltage impulse generator).

Fig.3. Gas-dust-impact mass-spectrometer design scheme with parabolic reflector.

To compare focusing methods the experiments were conducted on electrostatic accelerator EG-8 with accelerating voltage 1.6 MV using the techniques described in [3,4]. Fig. 3 shows ion spectrums obtained with usage of the mass-spectrometer in Fig. 4.

Al, Fe, SiO_2 particles with size 0.05…0.25 μm and speeds 2…20 $km{\cdot}s^{-1}$ were used. The target material was Nb. The potential mechanism of ion generation (the discharge in particle-target gap) dominates for speed range 0.2…2 $km{\cdot}s^{-1}$. In case of discharge of particles with the help of electron beam ions practically do not exist for speed range 0.1…2 $km{\cdot}s^{-1}$. With the speed range greater than 4 $km{\cdot}s^{-1}$ the impact mechanism acts [4].

The dynamical compensation method has some advantages relatively other methods. However, due to earlier particle focusing (see Fig. 5) the collection coefficient of this method is 30% lower than the method using non-linear reflector.

Dependencies in Fig. 5 show the resolution of combined design of the mass-spectrometer. With new focusing conditions R = 600 for particles of 200 atomic mass unit. The combined design shown in Fig. 3 is more preferable (see Fig. 5). The reflective grid 4 has radius about r =7 m and allows to perform additional focusing of the ion beam to receivers 2.

Immersion lens vastly decreases the dependence of the mass-spectrometer resolution on impact location on target 1.

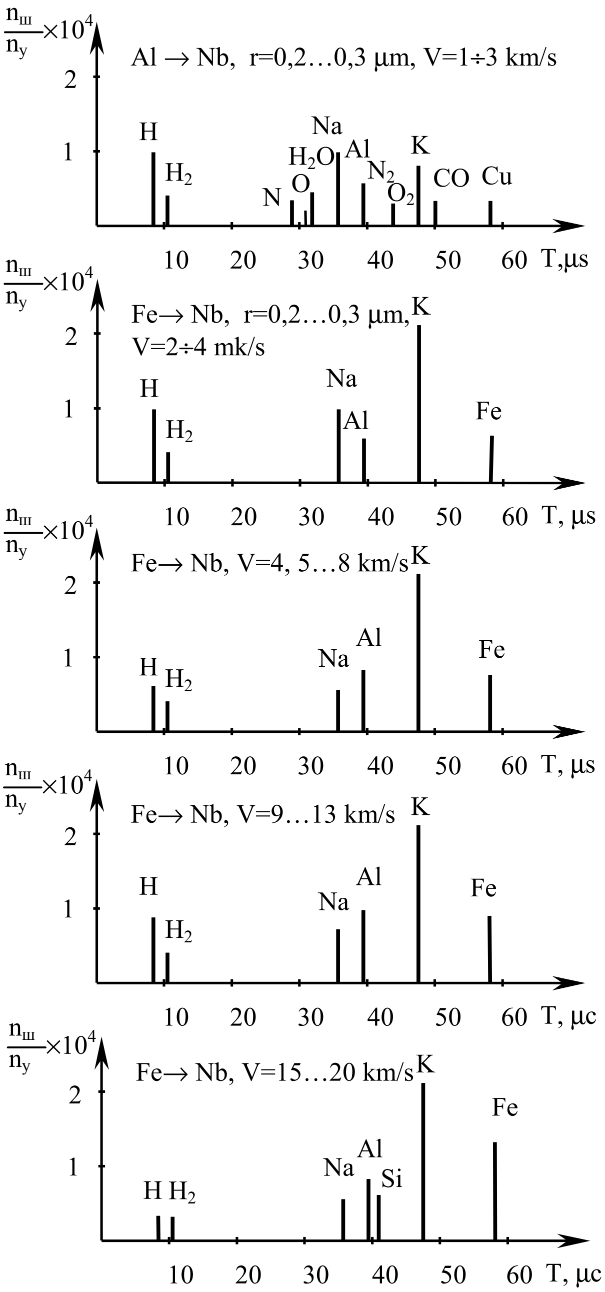


Fig.4. Ion spectrums

Thereby, analyzing the designs of the instrument and methods of ion packet focusing we can conclude that time-of-flight mass-spectrometers using separate focusing of particles by energies and in space are perspectives for studying of space vehicle's own external atmosphere particles. The most favorable methods are the dynamical compensation and particle's flight in non-linear electrical field.

Since the calculations for such designs are rather com-

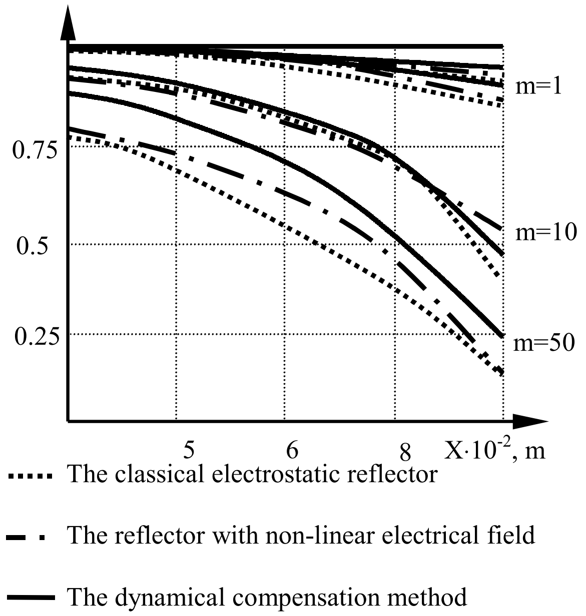


Fig.5. The resolution of mass-spectrometer as a function of the impact location

plex special software is required, in particular products using Libman method for computation of field potential.

REFERENCES

1. N.D. Semkin, K.E. Voronov. Patent № RU-212257 (Russian Federation) *The dust-impact mass-spectrometer*, *BI*, Vol. 32, 1998.
2. N.D. Semkin, K.E. Voronov, S.V. Myasnikov. Analytic computation of non-linear electrostatic reflector distribution in mass-reflectron. *VINITI*, Deposit № 3225-B97, 1997.
3. N.D. Semkin. Study of dust particles characteristics using electrostatic accelerator. Deposit № 6709-B87, 48, 1987.
4. N.D. Semkin et al. Mass-spectrometry of ions emitted during impact of accelerated dust particles on target. ZhTF, Vol. 58 Issue 6, 1231–1239, 1988.