Tandem analyzer of plasma flow ions by energy, mass and charges

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Abstract. This article introduces the concept of a new analyzer of a multicomponent ion beam by energy, mass, and charge. The analyzer is constructed as a tandem, i.e. combining a Wien linear velocity filter (WLF) and a retarding field analyzer (RFA). The system is effective at separating the elements or the groups of elements in various experiments, for example, for plasma mass separation in the such design variants as WLF-RFA and RFA-WLF. It is worth noting that the device can work with ions characterized by a wide energy range. The results of experimental testing of the TANDEM analyzer (WLF-RFA) in a three-component plasma flow (Ne + Ar + Kr) generated by an anode layer plasma accelerator are presented. In the ion flow characterized by the energies ranging from 100 to 1500 eV, the TANDEM separated ions with relative masses ranging from 20.17 to 83.8 with a resolution of ~7 and charges ranging from 1 to 5. The resolution of WLF-RFA increases upon the growth in ion density in a multicomponent stream.

1. Introduction

Ion energy and mass analyzers can predominantly be applied in the study of the surface of solids, the research on the structure of matter and interaction processes in collisions of particles in gases and plasma, particularly where the analyzer is localized in the plasma-occupied area [1]. The devices for ion separation use electric and magnetic fields when analyzing particles with regard to the ratio of the ion mass to its charge \( M/z \) [2–8]. The method of indirect ion charge registration by means of an electronic system external to the analyzer containing a charge sensitive amplifier [7, 9] has been designed for a beam of ions of one mass. All [1–8] diagnostic methods and devices require that the ions in the flow be characterized by the same energy \( W_0 \). If this is not the case, ions characterized by \( W_0 \) are isolated at the first stage of the measurement process by means of so-called “Tandem-in-Time” and “Tandem-in-Space” schemes [2, 3, 6, 8] when the measurement data from two consecutive energy and mass analyzers (on a time scale or in space) is employed to identify the ion mass. For example, on the mass spectrometer, consisting of a cylindrical electrostatic energy analyzer and a sector magnetic mass analyzer, the ions characterized by \( M/q = (B^2/2U) r^2 \) are separated. \( B \) stands for the induction of the magnetic field of the sector magnet, \( U \) is the accelerating voltage for the ion, and \( r \) is the radius of curvature of the ion trajectory.
Determining the distribution of the multicomponent ion flow by space is one of the key tasks in the process of separation of the plasma substance into elements or groups of elements. During plasma-optical mass separation [10, 11], a plasma accelerator is used as the source of the multicomponent flow of ions. In the unit POMS-E-3 [11, 12], where the experiments were conducted, a thruster with an anode layer (TAL) served as an accelerator. Conceptually, the ions generated by TAL are characterized by a wide range of energies. Therefore, in this project we set the task to provide the analysis of ion beams by energy, mass, and charge, in the device (let us call it “TANDEM” – WLF-RFA). It was also deemed crucial to arrive at the possibility of working with non-energy ion flows which possess a large initial angular spread in the analysis by masses and charges. The article focuses on the description of the TANDEM operation for determining the charge state of ions and the joint analysis of ion distribution measurements by masses and charges.

2. The concept of the device

The concept of the device allows for consecutive operation of a Wien linear velocity filter (WLF) [4, 5] and a retarding field analyzer (RFA) [13–15] upon the registration of the ions on the detector located at the outlet of the TANDEM. In respect of the task, the result will not change if the sequence of the analyzers in tandem is reversed: RFA – WLF. The tests conducted on WLF-RFA, first on a three-component ion beam generated by a duoplasmatron source, and then in a multicomponent plasma flow demonstrated the capacity of the device in accomplishing the task.

Let us briefly describe the measurement method and the TANDEM in the mass analysis (WLF-RFA variant). The device diagram is shown in figure 1.

![Analyzer scheme: 1 – permanent magnet; 2 – pole tip; 3 – plates of WLF capacitor; 4 – RFA analyzing grid; 5 – Faraday cylinder.](image)

“Short” Wien filter is characterized by the minimally possible length; the input slit of the RFA is not located in the WLF focus, which is set at the output – far beyond the zone of the crossed electric field of $E$ intensity and magnetic field characterized by magnetic induction $B$. This is necessitated by a large aperture ($\gamma \geq 105^\circ$) of the device. Such a property of the analyzer is essential for the registration of ions, which are distinguished by three-dimensional trajectories as opposed to rectilinear ones. The detector is to have a wide aperture with an input window, the area of which overlaps the output slit of RFA, for example, Faraday cylinder, secondary emission multiplier or microchannel plate. WLF and RFA are separated by a wall with a magnetic core that has an input slot for the input flow of ions (only ions) into the RFA. Therefore, the dividing grid $G_2$ in the RFA is deemed unnecessary, and only the analyzing grid $G_3$ is present in WLF-RFA configuration.

If WLF is set to the drift velocity $v_0 = \frac{E}{B}$ (for the ion having the mass of $m_1$ – for a certain energy $W_1 = (m_1v_0^2)/2$ ) and in case no retarding potential $U_{an}$ is observed on the analyzing grid $G_3$ of RFA, all the ions $m_1 ... m_k$ pass to the detector, provided their velocity $v_k$ satisfies the passing condition

$$\frac{W_k}{m_k} = \frac{v_k^2}{2} = \frac{E^2}{2B^2}.$$

(1)
The current from the detector will be maximum. When $U_{an}$ is applied, the detector current will decrease stepwise. From the total current, the currents of ions reflected in RFA will be consecutively subtracted, starting from the lightest values. The number of stages should be equal to the number of different masses of ions, and the speed of ions should correspond to the speed settings of WLF. The retardation curve and the ion energy spectra will have the form as shown in figure 2.

![Figure 2. The retardation curve RFA $I = f(U_{an})$ and the ion spectra of the three-component ion flow $-dI/dW = \phi(W)$ are constructed analytically.](image)

At the known values of $E$ and $B$ and the most probable energy of $W_k$, based upon the passing condition (1), the masses of ions on the detector are calculated as follows: $m_k = 2W_k(B^2/E^2)$. Integration of the ion distribution functions separated by the analyzer gives the density values of the particles of a specific mass:

$$n = \int_{W_1}^{W_2} \left(\frac{qM}{2}\right)^{1/2} \frac{1}{qA} \left(\frac{dI}{dW}\right) \left(\frac{1}{W^{3/2}}\right) dW.$$

Upon registration of the ion flow characterized by a wide energy spectrum, different charges as well as the absence of retarding potential $U_{an}$ on the analyzing grid G3 of RFA, and when WLF is configured for the energy $W_1$ of a singly charged ion, the ions with all charge multiplicities are able to pass to the detector. The energies of the ions should satisfy the passing equation (1). Then, the detector current is maximum. Upon the increase in $U_{an}$, the ion characterized by a large charge in the RFA electric field will be inhibited more significantly, since the force applied to the ion $F = qE_{an}$ is directly proportional to its charge $q$ and the electric field strength $E_{an}$ which is determined by the potential of the analyzing grid G3 of RFA. When $eU_{an} \approx W_1/3 + \Delta W$, the ions characterized by $q = 3$ will be released from the WLF aperture; when $eU_{an} \approx W_1/2 + \Delta W$, the ions characterized by charge $q = 2$ will be released; if $eU_{an} \approx W_1 + \Delta W$, the ions characterized by $q = 1$ will be released (where $\Delta W$ stands for resolution of the analyzer by energy). Thus, the detector current in the presence of ions with different charge multiplicity will gradually decrease upon the growth in $U_{an}$ (the retardation curve of RFA will be similar to the curve shown in figure 2). The maximum charge multiplicity will be equal to the number of steps on the retardation curve. The amplitude of the current steps will be proportional to the content of ions in the flow with different charge multiplicity. Differentiation of the retardation curve will describe a quantitative characteristic, namely, the density of ions characterized by different charge multiplicity. In this case, the RFA + WLF tandem becomes the analyzer of the “charge multiplicity” of the ions in the plasma flow.

3. The test of the analyzer in the flow of multicomponent plasma

The linear Wien filter has the following dimensions: the distance between the capacitor plates is 6 mm; the distance between the pole tips of the magnets is 16 mm; the length of the permanent NeFeB magnets is $L = 50$ mm. The magnets are equipped with the pole tips made of soft magnetic steel, which are needed to equalize the amplitude of the magnetic field induction over the entire area of
NeFeB magnets. The WLF has an armored magnetic core. The average magnetic field induction along the length of WLF is $B \approx 0.25$ T. The width of the input and output slots are $s_1 = s_2 = 1$ mm. Faraday cylinder was used as a detector. The resolution of the analyzer by masses $R_M$ and energies $R_W$ is determined by WLF and is calculated in the following way: for example, at $W_1 = 500$ eV for Ne$^+$ $R_M = R_W = 10.1$, Ar$^+$ − 6.93, Kr$^+$ − 4.56.

The registration of the retardation curve of the analyzer is provided by the hardware-software complex [16], the hardware of which consists of a personal computer NI PXIe-8115, ADC, and DAC, combined in a complex device NI PXIe-6361 and an adjustable voltage source 0–4 kV. Communication between the computer and the ADC/DAC is carried out via the PXI interface in the NI PXIe-1078 chassis.

The program performs the task of identifying energy, mass and charge composition of the multi-component plasma flow by referring to a data file obtained during the measurement process of the ion current-voltage characteristics (retardation curves) of the ion beam conducted by a TANDEM analyzer. During the measurement course, the program controls the generation of analyzing electrical voltages and the registration of the ion currents on the analyzer detector using the NI PXIe-6361 complex. Input and output data are visualized via graphs and tables. For each detected peak of the ion current in the mass or charge spectrum, the ion and its charge are identified and visualized by means of the built-in library of mass and charge ions.

Figure 3 shows a typical energy distribution of the ions of the mixture of the three plasma gases Ne$^+$ Ar$^+$ Kr, measured at the output of the TANDEM. For comparison, the energy distribution of ions at the input of the tandem is also provided. The devices were located at a distance of 5 cm from the output of the TAL. It is observed that the total spectrum (curve 3 – RFA TOTAL) has been generated by the ions characterized by energies of 500 ≤ $W$ ≤ 1200 eV, therefore it has not been deemed possible to register ions of the three gases with a single setting of WLF. Upon selecting a narrow energy interval (configuration WLF: a specific voltage $U_{WLF}$ on the WLF capacitor), the current of the ion beam decreases. Figure 3 illustrates the instantaneous amplitudes of argon and neon ion spectra multiplied by 100, while the total spectrum is multiplied by 2 as to fit into the adopted coordinate system.

**Figure 3.** Energy distributions of ions in the Ne$^+$ Ar$^+$ Kr mixture. TAL discharge parameters: $U_d = 900$ V; $B_{an} \approx 0.072$ T; $P = 12 \times 10^{-5}$ Torr; inlet speed 10 cm$^3$.c$^{-1}$ for Ne, 5 cm$^3$.c$^{-1}$ − Ar and 12 cm$^3$.c$^{-1}$ − Kr. Curve 1: $U_{WLF} = 70$ V; 2 − $U_{WLF} = 60$ V. Curve 3: the original (3) spectra of the ions in Ne$^+$ Ar$^+$ Kr mixture passing through the input of the analyzer.
The program for processing spectra 1 and 2 provided the data given in figure 4 and in table 1. When $U_{WLF} = 70 \text{ V}$ which corresponds to the drift velocity $v_{0.70} \approx 4.7 \times 10^4 \text{ m·c}^{-1}$, five peaks on the energy distribution of ions were identified – all matching the ions Ne$^+$, Ar$^+$, Fe$^+$, and Kr$^+$. The first and the lowest energy peak is not assigned to any of the masses available in the program library. The peak of Fe$^+$ ions appeared unexpectedly. When $U_{WLF} = 60 \text{ V}$ and $v_{0.60} \approx 4 \times 10^4 \text{ m·c}^{-1}$, three peaks of the plasma gas ions Ne$^+$, Ar$^+$ and Kr$^+$ were determined respectively (on the other energies in comparison with the previous instance). The ions Fe$^+$, which have the energy $W_{Fe^+} \approx 489 \text{ eV}$ when $v_{0.60} \approx 4 \times 10^4 \text{ m·c}^{-1}$, were not observed on the retardation curve and the ion spectra 2 (figure 3), possibly due to the relatively coarse degree (25) of the polynomial approximation. In this case, spline approximation is required.

| № peak | Spectrum “a” figure 4 | Spectrum “b” figure 4 |
|--------|-----------------------|-----------------------|
| W (eV) | Mass (amu) | Atom | W (eV) | Mass (amu) | Atom |
| 1      | 121.54 | 11.03 | undefined | 160.42 | 19.92 | Ne |
| 2      | 240.01 | 21.79 | Ne | 338.63 | 41.84 | Ar |
| 3      | 388.82 | 35.29 | Ar | 657.97 | 81.29 | Kr |
| 4      | 598.24 | 54.30 | Fe |      |      |    |
| 5      | 827.67 | 75.13 | Kr |      |      |    |

With regard to the appearance of the ions of iron in the spectra, one can conclude the following. The discharge in TAL burns in the axially symmetric anode-cathode gap. The size of the anode along the radius is $\Delta R_a \approx 15 \text{ mm}$. The plasma flow passes through the slit in the steel cathode (iron content $C_{Fe} \geq 98.5\%$), the size of the slit is $\Delta R_c \approx 5 \text{ mm}$. The central axial line of the anode and cathode are the same. Upon the application of energetic ions of the plasma stream, secondary ions (which amount to about $10^{-5}$ of the primary ions) are generated along with the sputtering of the iron particles in the atomic phase from the inner and outer rings of the cathode surface; the width of each ring equals $\Delta r \approx 5 \text{ mm}$. The coefficient of sputtering of iron with ions of the inert gases, in given energy range of the ions in the discharge, is $\gamma \geq 1$ (for example, when sputtering ions characterized by $W = 600 \text{ eV}$ the coefficients of sputtering $\gamma_{Ne^+} \approx 0.97$ for Ne$^+$ and $\gamma_{Kr^+} \approx 2.0$ for Kr$^+$). Iron atoms have the potential of the first electron impact ionization $\varphi_{Fe} \approx 7.9 \text{ eV}$, which is two-three times less than the electron temperature in the discharge plasma. Therefore, the probability of ionization of the iron atoms approaches 1. There also exists a high possibility of double and triple ionization of Fe: $\varphi_{2Fe} \approx 16.2 \text{ eV}$; $\varphi_{3Fe} \approx 30.7 \text{ eV}$. 

![Figure 4. Mass distribution of ions for spectra 1 (panel “a”) and 2 (“b”) given in figure 3.](image-url)
Measurement-identification of the charge state of the multicomponent ion beam is carried out sequentially by the data processing program for each of the ions identified upon measuring the spectrum by mass. The velocity (energy $W_0$) of the WLF setting is chosen so that the spectra of all the ions of the plasma-forming gas possess the energies near $W_0$. In the future, a joint analysis of the mass and charge spectra and refinement-identification of the ions, unidentified at any step of data processing, is conducted. Table 2 (part “Charge analysis”) shows the energy or energy ranges of the ions when the processing program identified the ion of the specified charge while taking into account the energy resolution of WLF. Energy ambiguity can be explained by averaging the value of the induction of the analyzing magnetic field along the trajectory of the ion in WLF as well as its heterogeneity at the boundaries of WLF. Table 3 demonstrates the data when the ions of different charge multiplicities at one energy were identified.

| Spectrum “a” figure 4. Mass analysis | Spectrum “a” figure 4. Charge analysis |
|-------------------------------------|--------------------------------------|
| $W$ (eV) | Mass (amu) | Atom | $W$ (eV) | Charge (e) | Ion |
|---------|------------|------|---------|-----------|-----|
| 121.54  | 11.03      | undefined | 220.33 $\div$ 230.23 | 1 | $Ne^+$ |
| 240.01  | 21.79      | $Ne$ | 438.62  | 1         | $Ar^+$ |
| 388.82  | 35.29      | $Ar$ | 568.48 $\div$ 598.24 | 1 | $Fe^+$ |
| 598.24  | 54.30      | $Fe$ | 309.37  | 2         | $Fe^{2+}$ |
| 827.67  | 75.13      | $Kr$ | 200.5   | 3         | $Fe^{3+}$ |
|         |            |      | 797.71 $\div$ 817.71 | 1 | $Kr^+$ |
|         |            |      | 438.62  | 2         | $Kr^{2+}$ |
|         |            |      | 289.53 $\div$ 338.99 | 3 | $Kr^{3+}$ |

Table 3. Energies, masses and charges of atoms and ions for spectra illustrated in figure 4.

| Spectrum “b” figure 4. Mass analysis | Spectrum “b” Figure 4. Charge analysis |
|-------------------------------------|--------------------------------------|
| $W$ (eV) | Mass (amu) | Atom | $W$ (eV) | Charge (e) | Ion |
|---------|------------|------|---------|-----------|-----|
| 160.42  | 19.92       | $Ne$ | 170.31  | 1         | $Ne^+$ |
| 338.63  | 41.84       | $Ar$ | 348.61  | 1         | $Ar^+$ |
| 657.97  | 81.29       | $Kr$ | 488.63  | 1         | $Fe^+$ |
|         |             |      | 229.66  | 2         | $Fe^{2+}$ |
|         |             |      | 150.37  | 3         | $Fe^{3+}$ |
|         |             |      | 618.12  | 1         | $Kr^+$ |

Only an atom with a mass of 11.03 amu was unidentified. This may be attributed to the instability of the electrical discharge parameter or the supply systems when defining the retardation curve of the RFA TANDEM.

The work with the multi-charged ions in one device was possible due to the contribution of RFA in the “movement” of multi-charged ions from the high-energy part of the spectrum (spectrum 3 on figure 3 ions entering the analyzer input) in the low-energy one.

4. Conclusion

Figure 5 shows a diagram of the processing-interpretation of the output signal of the analyzer based on the example of the discharge observed in Ne + Ar + Kr mixture. Naturally, the atoms of light masses have smaller energies than that of the heavy ones; single-charge ions in the measured spectra have energy greater than that of multicharged ions. Their separation is carried out according to these characteristics, along with the matching of the identified ion masses with the ones stored in the database. Ne ($M = 20.55; W = 231$ eV), Ar ($39.95; 449.2$), Fe ($59.3; 666.4$) and Kr ($88.74; 997.8$) were isolated during the mass analysis in the experiment resulted in the data presented in figure 5. The analysis of the charges resulted in the following values: Ne – undefined; Ar$^+ – W = 617$ eV; Ar$^{3+} – 201.5$; Fe$^+ – W =$
785.1 eV; Fe$^{2+}$ – 429.3; Kr$^{+}$ – W = 990 eV; Kr$^{2+}$ – 634.9 eV. Reduced ion energies lie within the energy range of the spectrum illustrated in figure 5. The final accuracy of the approximation did not allow the separation of neon ions and two-charge argon (yet, the atoms of neon were present).

As expected, the ions of three plasma-forming gases and iron are present in the charge spectrum of the ion flow. The highest degree of ionization is observed for iron (Fe$^{3+}$) and krypton (Kr$^{3+}$): 30.65 and 36.95 eV respectively, as in the atoms with the lowest third ionization potentials.

Figure 5. The distribution of ion energy at the outlet of the TANDEM. TAL discharge parameters: $U_d = 900$ V; $B_{an} \approx 0.072$ T; $P = 12 \times 10^{-5}$ Torr; inlet speed 20 cm$^3$.c$^{-1}$ for Ne, 7 cm$^3$.c$^{-1}$ – Ar and 4 cm$^3$.c$^{-1}$ – Kr. $U_{WLF} = 80$ V.

The results summarized in figure 3 and tables 1–3 prove the potential of using a combination of Wien linear filter and a retarding field analyzer. The constructed analyzer can successfully be applied with a view to determine the mass and charge composition of the multicomponent flow of ions of elements (groups of elements) characterized by a wide range of energies. Naturally, the quality of the TANDEM increases upon the rise in ion density in the multicomponent flow (due to the partial pressure of plasma-forming gases).

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