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Research Article

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An ion beam system for calibration of space low-energy ion detectors

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Abstract: Low-energy ion detection in space is one of the most important interests of space exploration. An accurate calibration of this type of instrument is necessary to ensure the effectiveness and scientificness of the obtained data. And the ion source is the most critical equipment in a calibration facility. In this study, an ion beam system based on Kaufman ion source is designed, which can meet the ground calibration of space low-energy ion detection instrument in the low-energy range of 100–1,000 eV. The experimental research shows that when the beam intensity of the ion source is about 100 mA, the Faraday Cup collects about 1 mA of current, and the generated ion beam fluctuates less than 5% within 60 min, which can meet the ground calibration requirements of space low-energy ion detection instruments.

Keywords: Kaufman ion source, calibration, space ion detector, payload

1 Introduction

Space low-energy ion detection is one of the most important interests of space science detection. It has great significance to scientific research such as space science and planetary science. Most space exploration plans, such as Ulysses (Gloeckler *et al.* 1992), WIND (Lin *et al.* 1995), SOHO (Hovestadt *et al.* 1995), ACE (Stone *et al.* 1998), Parker Solar Probe (Kasper *et al.* 2016), Mars Express (Barabash and Lundin 2006), Venus Express (Barabash *et al.* 2007), China's Double Star Project (Reme *et al.* 2005), Chang'e Project (Ouyang *et al.* 2010), and Tianwen-1 (Kong *et al.* 2020), have carried low-energy ion detection payloads and have made a lot of scientific achievements in recent decades. The manufacture of these space crafts and instruments has greatly stimulated the development of space plasma low-energy ion detectors.

Generally, these instruments measure the energy to charge ratios and mass to charge ratios of ions, and record the ion count rates detected by the instrument in a particular field of view. In order to derive the physical parameters such as ion flux, density, and temperature from the data, the transfer functions of the instrument should be obtained as precisely as possible. The transfer functions depend on several physical parameters of the incident ions such as direction, energy, mass, and charge. Although more powerful software is available to simulate the ion optical characteristics of the instrument, the ground calibration experiments are still necessary for deductions of the transfer functions. Throughout the decades of space explorations, calibration experiments about most of the scientific instruments, which obtained important space scientific achievements, have been published in relevant literature (Wüest *et al.* 2007). The calibration data have important reference value for understanding the raw data detected by the instrument. Without scientific and accurate calibration data, it is impossible for space low-energy ion detectors to obtain credible scientific result.

The ion source is one of the most important components in a ground calibration facility of space low-energy ion detection instruments. The ion beam generated by the ion source is used to test or calibrate the instrument or its sensor components continually. Those tests build up a solid foundation for the final in-flight instrument and also ensure the realization of the scientific objectives. Therefore, the ion source is the most critical component in a ground calibration facility, which also affects the reliability and scientificity of the detected data during the on-orbit operation.

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Due to the first mover advantage, researchers in European and American countries have built many calibration facilities focused on the calibration of space low-energy ion detection instruments, and the types of particle beams have been extended to heavy ions, electrons, neutral atoms, dust particles, *etc*. The energy also has covered most of the energy ranges of space low-energy particle detection, which greatly supports the development and upgrading of space low-energy particle detection instruments (Biddle and Reynolds 1986, Ghielmetti *et al.* 1983, Graf *et al.* 2004, Marti *et al.* 2001, Westermann *et al.* 2001, Wüest *et al.* 2007). Since the space environment exploration in the 1970s, some research on ground calibration facilities have also been reported in China (Shi 2014, Yang *et al.* 2015, Zhang *et al.* 2020). Currently, the ion beam system which could be used to calibrate the space low-energy ion detectors are the EBIS ultra-low-energy heavy ion experimental platform in the Institute of Modern Physics of the Chinese Academy of Sciences and the calibration facility for space proton detectors in The National Space Science Center of the Chinese Academy of Sciences. But the particle types and energy range of those facilities cannot fully cover the calibration needs of space low-energy ion detection instruments.

At present, the space payload development platform in the School of Earth and Space Sciences at the University of Science and Technology of China (USTC) also built two calibration facilities for space low-energy ion detection instruments. Those facilities have a 5 keV Penning ion source and a 30 keV dual-plasma ion source, which can provide ion beams in the energy range from several hundred eV to 30 keV so as to provide calibration services (Hu *et al.* 2019, Qiu *et al.* 2018, 2020, Shan *et al.* 2023, Shi 2014). However, maybe affected by the pressure fluctuation in the gas supply system and the voltage ripple in power supply system, those two ion beam systems have the problem of operating instability when the ion energy is lower than 500 eV. The low-energy ion beam intensity and direction fluctuates frequently, which cannot meet the calibration requirements of any instrument. During calibrating a low-energy ion spectrometer onboard a Chinese geosynchronous satellite, only the method of ion optical simulation can be adopted to partially replace the ground calibration. This also leads to the inaccurate transfer functions of the instrument when the ion energy is lower than 500 eV (Hu *et al.* 2019, Qiu *et al.* 2020). In this study, an ion beam system is designed for testing and calibrating space low-energy ion detectors. This ion beam system based on the Kaufman ion source can generate low-energy ions in the range of 100–1,000 eV (the working gas can be He, Ar, O_2, *etc.*). This ion beam system can make up for the gap of low energy range from 100 to 500 eV for calibration of the space plasma payload developed by USTC.

2 Design of a calibration facility based on Kaufman ion source

The entire low-energy ion calibration facility is shown in Figure 1, and it consists of an ion source, a velocity selector, a beam expansion system, and a deflection system. In the ion source, the low-energy ions are generated and accelerated to a certain energy. An ion filter is used to purify the ion beam, since it may contain unwanted impurities or multiple charge states ions. Then, the purified ion beam will be modified by several Einzel lenses, so the spot size and beam intensity of the ion beam can meet the requirements of calibration test. Finally, before the ion beam enters the target chamber, a deflection system is needed to eliminate the energetic neutral atoms generated by charge exchange collision.

2.1 Ion source

There are many types of ion sources, which are commonly used in space low-energy ion calibration, such as dual-plasma ion source, electron collision ion source, electron cyclotron resonance ion source, radio frequency ion source, *etc.* (Wüest *et al.* 2007). Considering the need of ion energy of order 100 eV and easy maintenance during equipment operation, a set of K-17 Kaufman ion source is used. The original diameter of the ion beam spot is about 17 cm. And the ion energy is continuously adjustable between 100 and 1,000 eV. When the working gas is argon or other inert gases,

Figure 1: The schematic diagram of an ion beam system.

the continuous operating time is several hundreds of hours. The time is long enough for a calibration test.

Figure 2 shows the schematic diagram of the installed ion source. The vacuum chamber is a long column, with a total length of about 1,000 mm and an inner diameter of 350 mm. The center line of the chamber is about 1,500 mm (±15 mm adjustable) from the ground. The knife edge flange directly below the middle of the cavity is connected to the vacuum pumping system. The Kaufman ion source is located on the left of the vacuum cavity, and is fixed on the left flange, while the right flange is reserved, which can be docked with E × B speed selector in the later stage. A Faraday disk, which is a single layer aluminum plate with 2 inches in length and 1 inch in width, is installed in the middle of the vacuum chamber by the KF40 quick coupling flange, closed to the outer edge of ion beam cross section. The Faraday disk can be used for long-term monitoring of the working status of the ion source and for measuring the strength and stability of the ion beam, without causing obstruction and interference near the center of the beam section.

Figure 3 shows the schematic diagram of the Kaufman ion source structure, which is mainly composed of discharge chamber, cathode, and ion optical elicitation system. The discharge chamber adopts the structure of permanent magnet and magnetic permeable pole shoe to improve the discharge efficiency of the ion source. The cathode filament is located in the center of the discharge chamber and produces primary electrons that maintain discharge after heating. The ion extraction system, called a double grid structure, consists of a screen grid and an acceleration grid. The electrons emitted from the heated cathode are accelerated by the voltage between the axisymmetric anode and the cathode added to the perimeter of the discharge room, and the energy corresponding to the potential difference between the plasma and the cathode is obtained. The potential of the plasma is close to that of the anode. Such high-speed electrons collide and discharge with the working gas atoms entering the discharge room to form plasma. The ions in the plasma enter the acceleration zone through the sheath and are extracted by the ion optical extraction system to form an ion beam. The neutralization filament emits electrons into the ion beam, which can keep the ion beam neutral, increase the stability of the process and reduce the divergence angle of the ion beam.

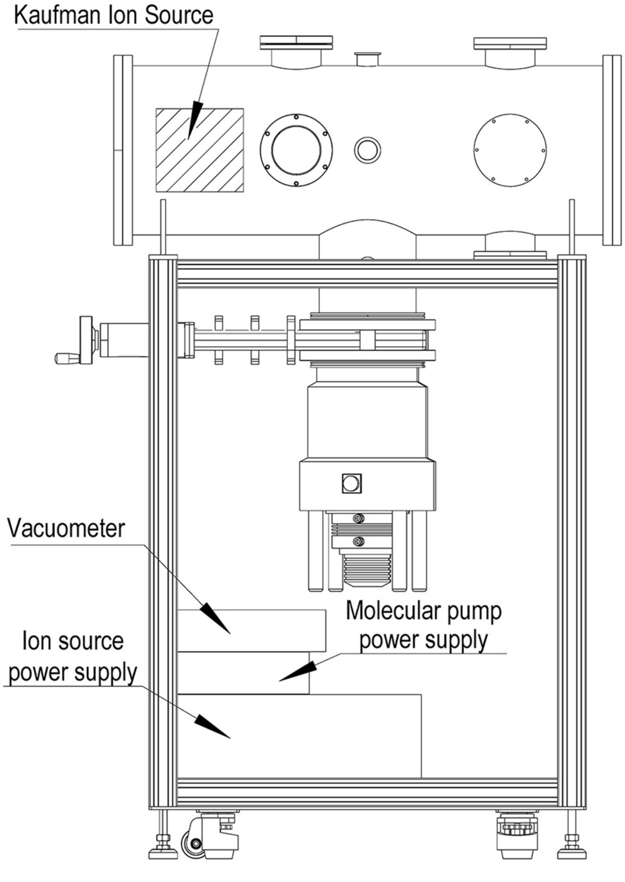

Figure 2: The diagram of ion source appearance.

2.2 Ion filter

The ion beam generated by the ion source contains neutral atoms, electrons, and ions in a variety of charge states. The calibration test requires an ion flux in a certain energy and a certain charge state. So the Wien filter is used to separate out the ions according to the different mass-to-charge ratios (Plies *et al.* 2011). There are orthogonal electric and magnetic fields inside the Wien filter, and the directions of electric and magnetic fields are perpendicular to the direction of ion velocity. Only when the electric and magnetic forces received by ions are equal, ions can pass through the ion filter smoothly. When the magnetic field intensity is fixed, the unwanted ions can be filtered out by controlling the electric field strength of the ion filter, and only ions with a specific charge-to-mass ratio can pass through to improve the purity of the ion beam.

2.3 Beam expansion system

The intensity of ion beam after screening is generally in the order from μA to mA, which is too high for calibration of space low-energy ion detection instruments. The ion optical lenses can be used to expand the ion beam, which reduce the ion beam intensity by 3–6 orders of magnitude so that it can meet the calibration requirements of space low-energy

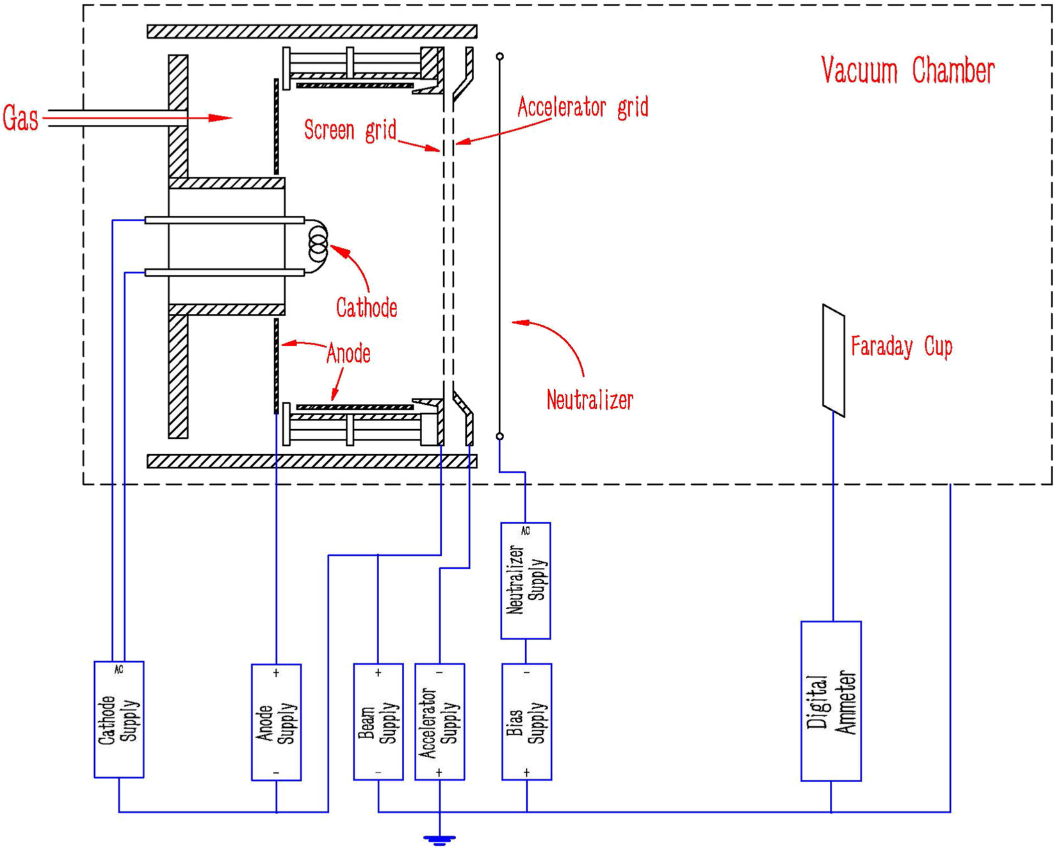

Figure 3: The schematic diagram of Kaufman ion source.

ion detection instruments. Generally, the ion optical lens is a single-lens structure, which is composed of three coaxial cylindrical electrodes. Multiple single lenses are combined to form a beam expansion system, which can achieve the purpose of reducing beam intensity, and the divergence angle of outgoing ions can be adjusted, so that the ion beam entering the subsequent system is quasi-parallel.

2.4 Deflection system

For the ion beam adjusted by the beam expanding system, due to the influence of machining and assembly errors, the center line of the ion beam and the central axis of the system do not necessarily coincide, and the ions do not completely move along the central axis. If the direction of ion movement is not adjusted, the ion beam will deviate greatly when entering the target chamber and cannot reach the detector entrance system to be calibrated. At the same time, due to the impact of charge exchange collision, the ion beam may carry certain energy neutral particles, which are equivalent to the energy of ions, which will interfere with the calibration test and affect the reliability of calibration data. Therefore, the center axis of the ion beam system and the center axis of the target chamber are generally installed at a certain angle, and the movement path of the ion beam is controlled by the deflection plate electrode. By adjusting the electrode voltage of the deflection plate, the direction of the ion beam can be changed, while the neutral particles move in the original direction and separate from the ion beam, so that only the required ion beam can reach the predetermined test area of the target chamber.

3 Ion source stability test and analysis

Based on the design above, the stability test of the K-17 Kaufman ion source was carried out first. As shown in Figure 3, the collected current of the Faraday disk was measured and recorded by a Keithley 6485 picoammeter to monitor the beam strength and stability of the ion source. In the experiment, the working gas was high

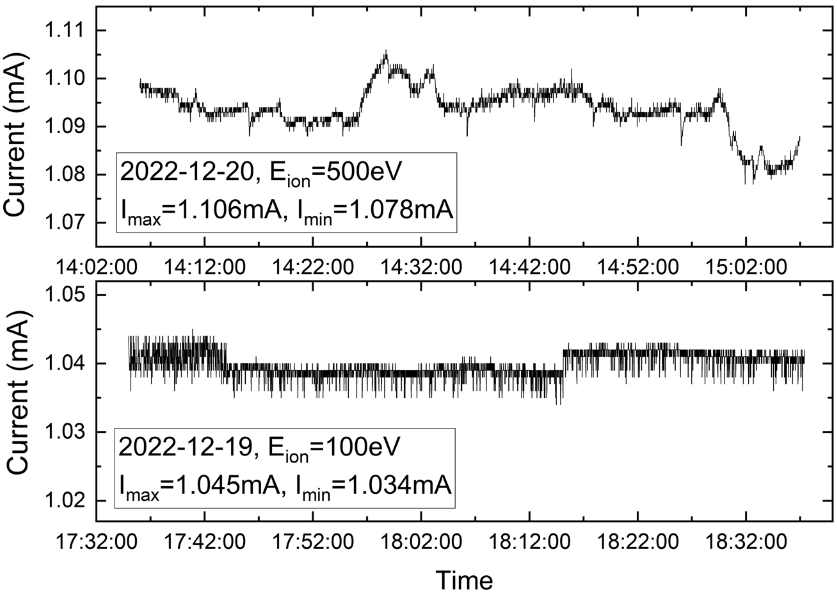

Figure 4: Variation in the current collected by the Faraday cup with time.

pure argon, the accelerating electrode voltage was 200 V, and the neutralizing filament current was 1 A (the emission electron was negligible). The ion energy is changed by changing the screen voltage, and the ion beam current for different ion energy is modulated to about 100 mA by adjusting the cathode filament current.

The total beam current is controlled to be 100 mA. As shown in Figures 4 and 5(a), the collected current of the Faraday disk is slightly higher than 1 mA. Assuming the beam cross section of the ion source is evenly distributed, the current collected by the Faraday disk should be 100 mA × 1,290/22,686 = 5.7 mA. It can be seen that the beam cross section of the ion source should be high in the center and decreasing outwards, and the ion beam cross section distribution of different energies has little difference, so the current collected by the Faraday disk is smaller than the current obtained by the average area. It also shows the ionic beam intensity of 1 cm^2 at the center of the beam

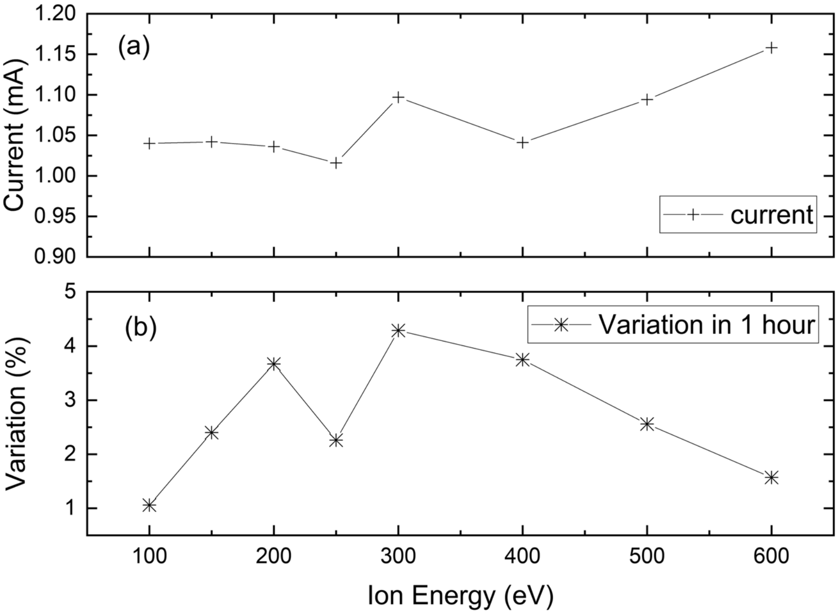

Figure 5: (a) The change in average current collected by Faraday disk with ion energy. (b) The change in ion beam stability with ion energy.

may be higher than 1 mA, and subsequent attenuation of the beam should be carried out several times to conform to the detection flux range of the detector.

At the same time, $\tau = (I_{\max} - I_{\min})/I_{\text{avg}}$ represents the stability of the ion beam in 1 h, where $I_{\max}$ is the maximum value of the current collected by the Faraday disk in 1 h, $I_{\min}$ is the minimum value, and I_{avg} is the average value. As shown in Figure 5(b), the change in ion source beam is less than 5% within 1 h, and the stability is good, which can meet the calibration needs of low-energy ion detection instruments in the future. It can be also observed that the change in ion beam within 1 h is less than 2% at 100 and 600 eV energy, but close to 5% at around 300 eV, which may be affected by the ripple change in the power system provided by the manufacturer at different voltage combinations. And the influence of molecular pump power supply and water cooling system on the measurement of the entire circuit and picoammeter is also the focus of future work.

4 Summary

In this study, a low energy ion beam system for ground calibration of space low-energy ion detectors is developed based on a commercial Kaufman ion source. The ion beam system showed good time stability. Within the range of 100–600 eV ion energy tested, the 1 h change rate was less than 5%, the beam current fluctuation was small, and the ion source energy could be controlled by continuous adjustment of plate potential. In the follow-up work, the power supply system of ion source, the power supply of molecular pump, and the water-cooling system can be improved to further improve the working stability of ion source and meet the requirements of accurate ground calibration test of space low-energy ion detection instruments.

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Conflict of interest: The authors declare no competing interest.

Data availability statement: The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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