A NEW 6MV TANDEM ACCELERATOR IN TRNAVA

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Abstract

This article is focused on the explanation and description of the complex system of a new 6 MV electrostatic accelerator in Trnava. The main part is focused on the arrangement explanation of the 6MV tandem accelerator and its fundamental principle, ion beam production and also ion beam transport through the system from ion source to the experimental chambers. In the next part, each facility of the whole system is described. Every single facility has a special function (ion beam creating, focusing, bending, accelerating, polarity changing, charge state separating) for the system running. The beam properties as well as possible applications of the accelerator in research and industry are sketched. The construction of the new accelerator system will be completed in autumn 2015.

Key words

accelerator, tandem, ion sources, ion beam, analyzing magnet,

1. INTRODUCTION

Since its first mention in the late 1920s, particle accelerators have grown to become the backbone for the science and technology development in modern society. These versatile and powerful instruments contribute to many areas, and exist in a large variety of size and capacity, each type fitting to a particular application. Energetic ion beams and the related tools are powerful instruments for research and the wide area of the fabrication and materials characterization techniques. They were basically developed to probe and to understand the nuclear structure, but later on, in the past few decades, they have given rise to many key techniques for materials engineering and analysis (1).

In the most simple case, an ion accelerator includes basic elements of high-voltage supply, an ion source, an accelerating electrostatic field between the ion source and a grounded electrode, and a vacuum tube in which the ions move to the target with an energy of $E = q \cdot e \cdot V$, where q is the charge state of the ion (q = 1, 2, 3, . . .), e the elemental charge unit, and V the voltage between the ion source and the grounded electrode (1).

2. 6MV TANDEM ACCELERATOR SYSTEM IN TRNAVA

In the close future, the Slovak University of Technology, Faculty of Material Science and Technology in Trnava will obtain a new 6MV tandem accelerator. Nowadays, it is one of the versatile tools that offer a variety of powerful analytical techniques for materials analysis and modification. The opportunities provided by this device open the door and lead to the new possibilities at the frontier of different scientific areas.

The concept of the Tandem accelerator was invented in order to achieve higher beam energies than with single ended machines. It has been specifically proposed by Bennett (2), Kallmann (3) and Alvarez (4). A Tandem accelerator utilizes the terminal high voltage twice in sequence in order to obtain output energies of two or more times that available in a single acceleration (5). The 6MV Tandetron is a compact, multipurpose electrostatic tandem accelerator system produced by High Voltage Engineering Europa B.V., The Netherlands (HVEE). It operates via a Cockcroft-Walton type high voltage generator providing the terminal voltage varying from 300 kV to 6 MV. The device provides a high terminal voltage stability of at most ±600 V with a maximal ripple ±500 V. Due to an effective suppression of the X-ray level (<2 μSv/hr), the accelerator can be operated in the typical laboratory conditions without a need of extra shielding (6).

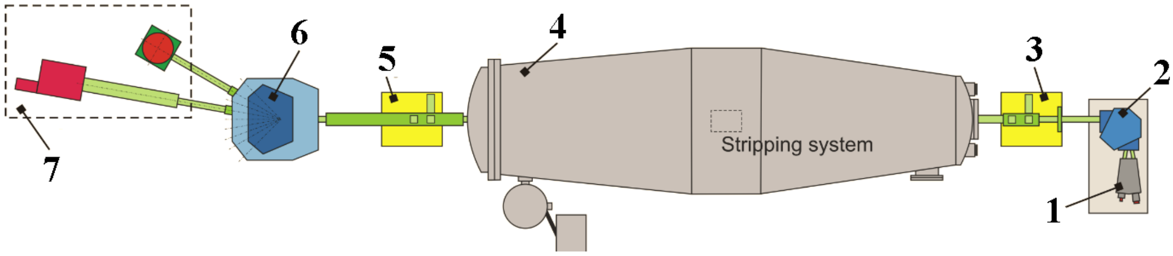

Fig. 1 *System arrangement of the 6MV tandem accelerator (High energy ion accelerator) 1) Ion sources, 2) Mass analyzing magnet, 3) Focusing system in front of the accelerator, 4) 6MV tandem accelerator, 5) Focusing system behind the accelerator, 6) Switching magnet, 7) Analyzing and modification chambers*

Detailed system arrangement of the 6MV tandem accelerator is showed in *Fig. 1*. For better understanding of the whole system functionality, the system can be divided into seven basic subsystems (showed in *Fig. 1*), where each unit has a special function described below. The system working and the transport path of the ions is shortly described in the following seven steps: *Part 1* – at the beginning, it is necessary to create (extract) a negative ion beam. Ion sources are used to create the ion beam (in our case: sputtering ion source or duoplasmatron ion source). From the particle source, the ions pass through the mass analyzing magnet (*Part 2*), where ions are separated by mass (for instance "Si"). Ions with the low or high mass are deflected and stopped. *Part 3* - in this section, the ion beams are focused with lenses, X and Y steerers, beam profile monitor (BPM), aperture, Faraday cups and slit to the required shape of the beam. BPM is provided before the slit. It provides the continuous display of the shape and position of the beam in both the X- and Y-coordinates. *Part 4* - in this step, the negative ions in 6MV tandem accelerator are accelerated in the first tube from ground potential to a positively charged high-voltage terminal in the middle of the tank. Then, in the middle inside the accelerator, stripper system changes the injected negative ions into positive ions. Positively charged outgoing ions are accelerated in the second tube, away from the terminal, back to the ground potential. *Part 5* - second focusing system (in principle the same as focusing system in part 3), placed between the 6MV accelerator and switching magnet, prepares the ion beams (with required shape and current) for the last two steps. *Part 6* - the ions are reflected and charge separated (for example only ^{36}Cl) to one of nine canals in the switching magnet. *Part 7* in the final step, ions are passing to the analyzing or modification devices, where scientific experiments are carried out.

3. ION SOURCES

Ion source is one of the most important parts of the whole system. The main reason of these devices is to generate and extract negative ions with two separate ion injectors.

The first one is *duoplasmatron ion source*. This is an arc discharge ion source using both magnetic and electric fields to govern the plasma. Concerning the source principle (showed in *Fig. 2)*, the ions are axially extracted from the plasma of the low pressure plasma discharge between the hot cathode and anode. The emission aperture (d ≈ 0.3–0.6 mm) in the anode on the discharge axis provides the extraction of positive ions. In order to obtain an enhanced plasma density and a high ionization degree in front of the anode aperture, the discharge is strongly concentrated successively by the focusing action of an intermediate electrode and the effect of a strong axial magnetic field set up by the lens, the poles of which are the anode and intermediate electrode. In the case of positive ion extraction, ion currents of 1 mA for hydrogen can be achieved (1).

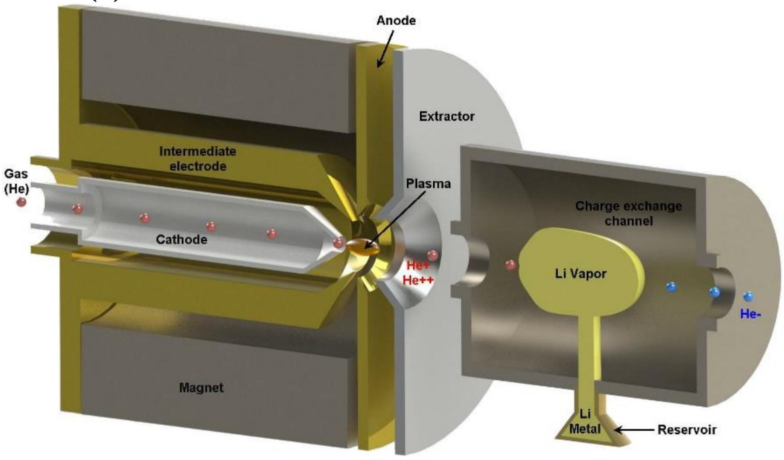

Fig. 2 *The principal scheme of a Duoplasmatron ion source*

Positive ion source operation is required for helium, for which only He^+ can be created with good efficiency inside the duoplasmatron. In the case of ion source application in high energy ion accelerators, He^+ ions after extraction pass through the so-called charge exchange channel, in which vapor of lithium is present. The result is that about 1 % of the incoming He beam turns negative and can be thus further accelerated in a tandem accelerator. Obviously, this limits the maximum current available for He ions to a few mA. Negative ion currents (H^-, D^-, T^-) of 50 – 150 mA are possible to be extracted from the source (1).

The second one is *Sputtering ion source*. The most widely used ion source providing a wide variety of negative ion beams for the injection into Tandem accelerators is the Cesium Sputtering source with spherical or ellipsoidal geometry of the ionizer (7, 8). *Fig. 3* shows the principal scheme of Cs sputtering ion source with spherical geometry of the Cs ionizer, which will be also topical in our case.

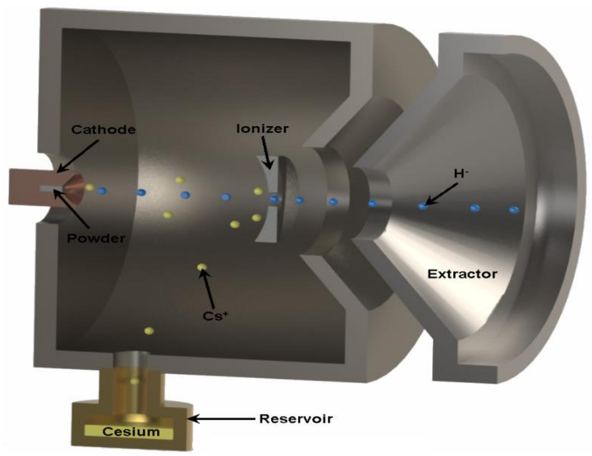

Fig. 3 *The principal scheme of a Cs sputtering ion source*

4. ANALYZING MAGNET

The ion beam which is extracted from the ion source feed material usually consists of many ion species. But almost all ion beam applications request only one type of accelerated ions in the ion beam. Requested ions (2 in Fig. 1) must be spatially separated from the mixture of all ions according to their mass and charge state. All other ions (1 and 3 in Fig.1) must be rejected (1).

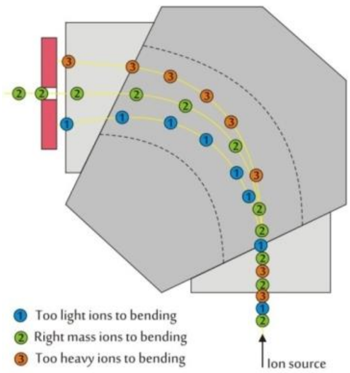

Fig. 4 *Conceptual diagram of ion mass separation*

The ion mass separating devices perform the separation and analysis of accelerated ions through a flight tube (beam line) usually in analyzing 90° sector magnets. The principal of energetic ions separation is beam bending with magnetic field by charge to mass ration. If the ion is subject to a constant and uniform magnetic field of induction ***B*** at 90° to its trajectory, it is subject to a Lorentz force $\boldsymbol{F}_{\mathbf{L}}$ (1, 9):

$$F_L = |\boldsymbol{F}_L| = |q(\boldsymbol{v} \times \boldsymbol{B})| = qvB$$

q – charge state, $\boldsymbol{v}$ – ion velocity, ***B*** – magnetic induction

For ions of constant velocity v, this leads to a constant radial acceleration of the ion a_r at 90° to its trajectory (Fig.5).

$$a_r = \omega v = \frac{v}{R} v = \frac{v^2}{R}$$

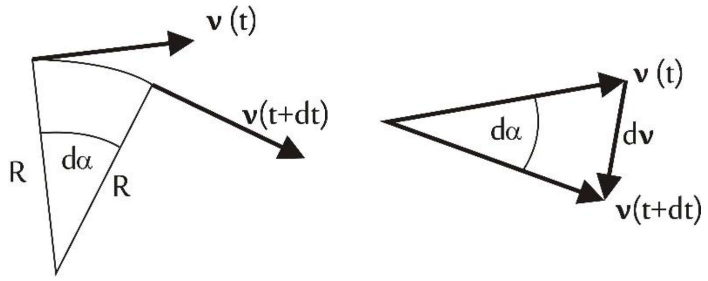

Fig. 5 *Definition of tangential velocity v and radial acceleration a_r* (9)

The fundamental equation of motion $F_L = ma_r$ therefore leads to

$$qvB = \frac{mv^2}{R}$$

and the ion (Fig. 6) describes a circle of radius

$$R = \frac{mv}{qB} = \frac{p}{qB} = \frac{\sqrt{2Em}}{qB}$$

In all practical cases, for ion beams (protons, deuterons, etc.) at energies $E_0 \leqslant 10$ MeV, the relation between the magnetic rigidity "*B.R*" where *B* is the magnetic field and "*R*" is the orbit radius of the particles with electric charge "$q = z{\cdot}e$" and mass "m_0", is given in appropriate units, as follows:

$$BR = 144\sqrt{\frac{m_0 E_0}{z^2}}$$

where, *BR* is kG cm, m_0 is in atomic mass unit (amu), $z = 1, 2, 3, \dots$, and E_0 the beam kinetic energy in MeV (14).

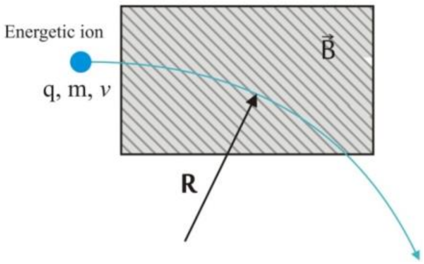

Fig. 6 *Beam bending with magnetic field* (10)

5. FOCUSING SYSTEM

Without focusing, only a small fraction of the ion beam injected into the accelerator from the ion source would be available at the exit of the accelerator, because thermal distribution of velocity, convex plasma sheets at the source exit and repulsion between ions cause ion beam divergence. Electrostatic or magnetic lenses are usually used as focusing elements in many application cases of ion beam, which can be designed as (1, 9):

- single lenses,
- quadrupole lenses (electrostatic or magnetic),
- multiple arrangement quadrupole lenses (doublet, triplet).

Electrostatic single lens (Einzel lens) – usually consists of three plates or rings held at different potentials that can focus a beam of electrons to a single point without changing the energy of the beam. The focusing is accomplished through the electric field manipulation by changing the voltage applied to the middle electrode (Fig.7).

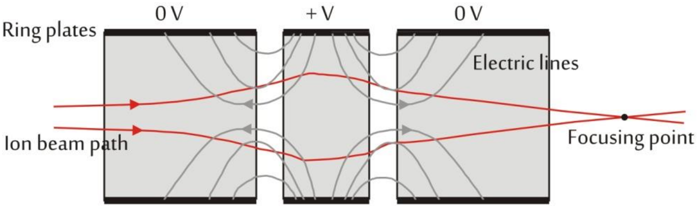

Fig. 7 *Principle of an electrostatic Einzel lens* (11)

Electrostatic and magnetic quadrupole lenses – consist of four identical poles with length dimensions in the order of the distance between poles. Their fields have two planes of symmetry, and their field vectors in the region where the charged particles move are nearly perpendicular to the velocity vectors of the charged particles. Such lenses focus the ion beam only in one direction and cause it to diverge in another one perpendicular to the first one, creating a linear image of a point object (Fig. 8).

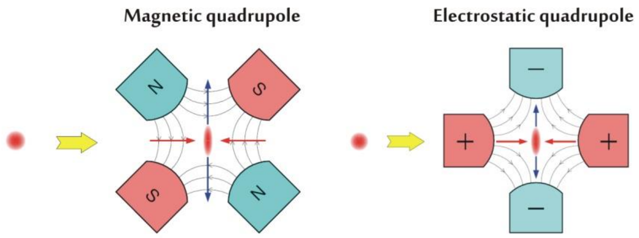

Fig. 8 *Principle of buildup of magnetic and electrostatic quadrupole lenses (10)*

Two quadrupole lenses whose fields are turned 90° to each other about the ion beam can be mounted one behind the other to form a doublet or three quadrupole lenses can form a triplet (Fig.9) - (quadrupole triplets are normally operated symmetrically, the field strengths of the first and third singlets being identical).

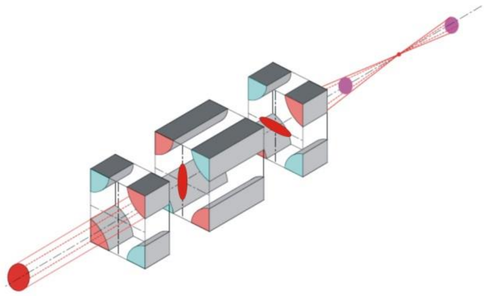

Fig. 9 *Arrangement of three single quadrupoles farming a quadrupole triplet (10)*

6. THE 6MV TANDEM ACCELERATOR

The Tandem accelerator utilizes the terminal high voltage twice in sequence in order to obtain output energies of two or more times that available in a single acceleration.

In tandem accelerators, negative ions injected from the ion source are accelerated in a first tube from ground potential to a positively charged terminal at high-voltage in the middle of the tank (*Fig. 10*) (1).

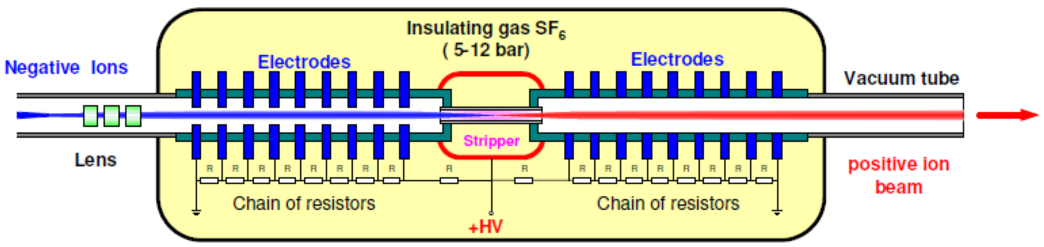

Fig. 10 *Schematic of the 6 MV tandem accelerator (10)*

Inside the terminal is a *stripper system* (*Fig. 12*), which uses a gas canal (usually nitrogen or argon) or a very thin carbon foil (areal density about 5 μg/cm2) (5). In the stripper system, a few electrons are stripped off from the negative ions converting them to positive ions (single or multiple charged) *charge exchange processes* (*Fig. 11*). The beam is now composed of positive ions with a distribution of different charge states and these ions are accelerated in a second tube, away from the terminal, back to ground potential. The acceleration of each ion depends on its charge state q (q = +1, +2, +3, +4, +5, ...) so that the final energy E of the ions $E = (q + 1)\cdot e\cdot V_T + eV_I$, where $e\cdot V_I$ is the injection energy of the ions before entering the tandem, V_T is the terminal potential (high voltage), and q is the positive charge state (1, 12).

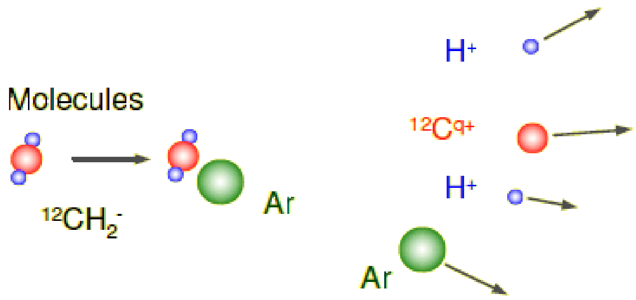

Fig. 11 *Charge exchange (10)*

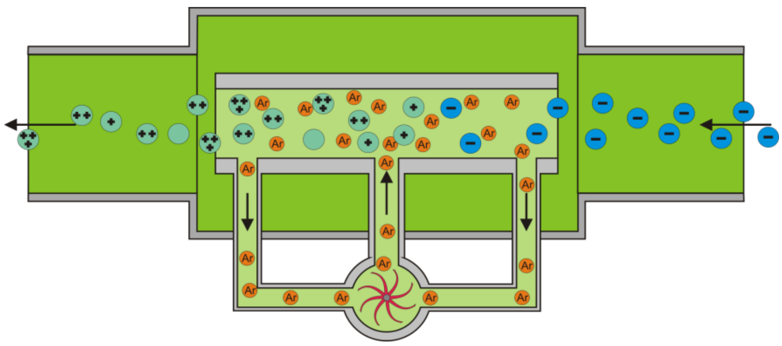

Fig. 12 *Stripping system (charge exchange processes)*

Ensuring elimination of undesirable phenomena (sparks, corona phenomena, humidity, etc) is possible by using insulating electronegative gas, sulfur hexafluoride (SF_6), whose dielectric strength is 2.7 times higher than that of air at 1 atm (101 kPa). The pressure of SF_6 inside of the steel pressure acceleration vessel is up to 12 bar. Pressurized vessel is used to contain the high-voltage components. This allows working with much higher electric fields and thus reduces the physical size of the apparatus (1, 13).

7. SWITCHING MAGNET

As shown in *Fig. 13*, after ion beam formation and at the accelerator exit, the positive ions with different charge states are energy analyzed by the high energy analyzing magnet (9- port switching magnet).

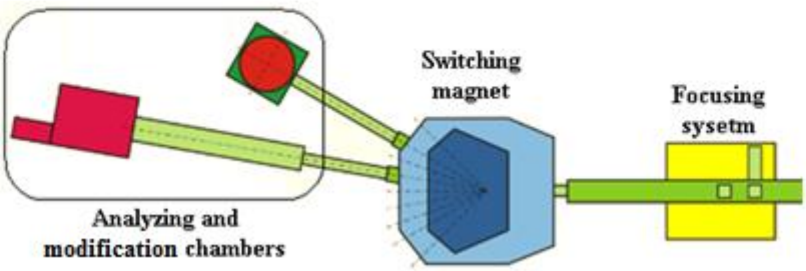

Fig. 13 *Schematic picture of switching magnet (10)*

For many research applications, the high energy analyzing magnet (switching magnet) can switch the ion beam in different beam lines connected with different chambers of ion beam analysis or ion beam irradiation of different materials (1).

The main aim of the whole system is to transport our focusing beam to the analyzing and modification chambers, where scientific experimental measurements are carried out.

8. CONCLUSION

A 6 MV tandem machine can give energy of more than 50 MeV to an ion. In this energy region, new ion beam analyses and ion beam modifications of materials can be done. The accelerator will be used for ion beam analysis such as Rutherford Backscattering Spectrometry (RBS), Particle-Induced X-ray Emission (PIXE), nuclear reaction analysis (NRA) and elastic recoil detection (ERD) as well as for material modification via high-energy ion implantation. Material modification on the nanoscale as well as the treatment of large areas is likewise possible as ion beam and plasma methods are scalable with respect to materials dimension. The next application is material property modification by using swift heavy ion irradiation. With the availability of high energy heavy ions from accelerator, swift heavy ion beams have been widely used in various fields, particularly for the modification of materials through dense electronic excitation following the slowing down of swift heavy ions in the material.

Acknowledgement

This paper was funded by the ERDF - Research and Development Operational Programme under the project "University Scientific Park Campus MTF STU - CAMBO" ITMS: 26220220179.

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