

## SENSITIVITY OF THE ION BEAM FOCAL POSITION WITH RESPECT TO THE TERMINAL HIGH VOLTAGE RIPPLE IN AN FN-TANDEM PARTICLE ACCELERATOR

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*Lucrarea investighează abaterea de la axa optică principală a fasciculului de particule accelerate, în zona de analiză energetică a unui accelerator electrostatic Van de Graaff tandem. Această abatere, măsurată în planul focal imagine al magnetului analizor, se datorează în principal ondulantei („ripple”) tensiunii înalte de accelerare. Studiul a fost efectuat atât prin calcule analitice cât și cu ajutorul programului de simulare opto-ionică „SIMION”. Rezultatele obținute furnizează o mai bună înțelegere a funcționării sistemului de analiză în energie și crează premizele unor dezvoltări tehnologice ulterioare, necesare îmbunătățirii stabilizării energetice a fasciculelor de ioni la acceleratoarele electrostatice.*

*The work investigates the beam shift from the main optical axis in the energy analyzing region of a tandem Van de Graaff particle accelerator. This shift measured at the image focal plane of the analysing magnet is mainly produced by the ripple of the accelerating high voltage. The study has been performed by analytical calculation and by numerical simulation with the SIMION opto-ionic code. The results provide a basis to better understand the energy analysis system of an electrostatic accelerator, creating the basis for future technological*

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*developments, necessary for the improvement of the particle beam energy stabilization.*

**Keywords :** Electrostatic accelerators, beam energy stabilization, high voltage charging system, energy analyzing system.

## 1. Introduction

Many nuclear physics experiments with accelerated particles require a very good beam energy resolution while the beam energy is required to be continuously adjustable. The high beam energy resolution is obtained by the inclusion of a magnetic ion beam analysis between the accelerator and the experiment in order to select the required ion beam in what concerns the ion mass, charge state and energy and to obtain an error signal if the ion beam energy slightly deviates from the nominal value.

The main objective of this paper is to investigate the ion energy analyzing system based on a 90° magnetic field deflection used at the Tandem Van de Graaff accelerator of IFIN-HH [1]. The radius  $R$  of the circular trajectory of a charged particle of mass  $m$ , charge state  $q$  and velocity  $v$  in an uniform magnetic field of induction  $B$  is given by the well known equation:

$$R = m \cdot v / q \cdot B \quad (1)$$

In an electrostatic tandem accelerator where the particles are accelerated in the electrical field generated by a high voltage electrode (terminal) whose potential is  $U_T$  (for the IFIN-HH tandem accelerator  $U_T = 1 \div 9$  MV), the particles energy is:

$$E = (q+1) U_T \quad (2)$$

that reflects the acceleration principle in two stages, the first one as a negative ion and a second stage as a positive ion of charge state  $q$  obtained by a stripping process that take place in the terminal when the beam crosses a very thin carbon foil. The negative ions are always in the charge state 1.

By combining equations (1) and (2), the following relation may be derived:

$$R \cong \frac{0,144}{B} \left[ U_T m \frac{(q+1)}{q^2} \right]^{\frac{1}{2}} \quad (3)$$

where  $R$  is in meters,  $m$  in amu,  $q$  in elementary charges,  $B$  in T and  $U_T$  in MV.

A magnetic analyzing system detects the position of the beam in the focal plane of the analyzing magnet where special slits are installed. If the beam deviates from the position that corresponds to the required energy due to a variation or oscillation of the high voltage on the accelerator terminal, the resulting error signal processed in a stabilizing system described later restores the value of the high voltage to the nominal value. The sensitivity of the beam position in the image focal plane of the analyzing magnet with respect to small

variations of the terminal voltage was analytically calculated and also investigated by using the Simion 3D v7.0 code [2] for ion beam simulation. The output of these calculations and simulations allows to optimize the particle beam energy slit stabilization system [3].

## 2. Principles of the beam energy stabilization systems at tandem accelerators

In Fig. 1 is presented a schematic layout of the Bucharest IFIN-HH tandem Van de Graaff accelerator. The accelerated ion beam trajectories and the beam transport components are represented at a certain level of details.

The injection system comprise two negative ion sputter sources [4] for protons and heavy ions and a  $\text{He}^-$  duoplasmatron type source [5]. The injection ion energy ( $E_i$ ) in the accelerator obtained by a pre-acceleration process is between 50 keV and 80 keV. The injection system is equipped with an inflection magnet that can select ions through a  $20^\circ$  deflection process.

The ion beam transport system of the tandem accelerator, also known as "tubular extensions", is divided into three distinctive zones:

- a) The low energy (LE) extension located between the inflection magnet and the entry point in the accelerating system installed in a pressurized tank that allows to load the terminal to a high voltage adjustable between 1 MV and 9 MV by using a Van de Graaff generator;
- b) The high energy extension (HE) located between the exit of the accelerating system and the object slit (OS) of the analyzing magnet system;
- c) The seven final extensions are located between the image slit of the analyzing magnet system and the target area. The switching magnet is able to select one desired extension by simply changing the angle of beam deviation. For the Bucharest tandem accelerator, this angle can be set at:  $0^\circ$ ,  $\pm 15^\circ$ ,  $\pm 30^\circ$  or  $\pm 45^\circ$ . The ion beam has five minimal dimension points (also known as cross-over or nodal points) of the beam. The analyzing and energy stabilization systems perform the beam energy selection through a  $90^\circ$  beam deflection within a double-focusing analyzing magnet. The radius of the beam deflection for this analyzing magnet is 1 m. Two pairs of adjustable slits are placed in the focal object and image points of this analysis system. An error signal is obtained by a differential amplifier as the difference of the electrical currents intercepted by each of the two legs of the image slit. This error signal is sent on the grid of a corona triode [6] able to tune-up the terminal voltage by means of the corona discharge. Due to the electrical behavior of the Van de Graaff generator which is practically a constant current source, the terminal voltage can be controlled through this corona discharge that is as a load for the generator [7].

Apart the slit stabilization, the tandem may derive an error signal too from a generating voltmeter (GVM), a device installed in the wall of the tandem pressurized tank and that measures the terminal voltage [7].

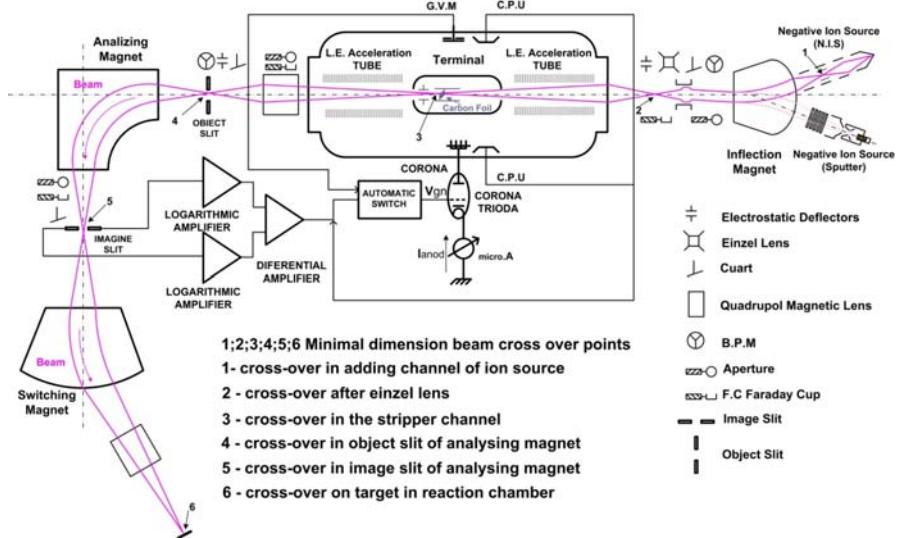


Fig. 1. Schematic layout of the ion beam trajectories and the related parts of the beam transport system at the Bucharest FN Tandem Accelerator.

According to the origin of the error signal applied to the grid of the corona triode, the electronic system may work in one of the three following modes: GVM mode – the high voltage stabilization is based on the GVM signal; SLIT mode – the high voltage stabilization is based on the signal provided by the image slit of the analyzing system; AUTO mode – which is an automated switching between the SLIT and GVM modes, according to the presence or absence of the beam at the image slit.

In figure 2 is schematically shown how the beam is intercepted by the image slits.  $V_{TN}$  is the nominal working voltage associated with the beam required energy;  $V_T$  is a slightly deviated value of the terminal high voltage;  $V_{gn}$  is the nominal voltage applied on the grid of the corona system triode, corresponding to  $V_{TN}$ ;  $V_{grid}$  is the triode grid voltage when  $V_T$  deviates from  $V_{TN}$ .

In figure 2.a, is presented a scenario of  $V_T < V_{TN}$  and thus the beam energy is lower than the required value. As a result the beam deviation angle is larger than  $90^\circ$  in the analyzing magnet and so it will hit more in the low energy (LE) side of the image slit. According to figure 1 in this case an unbalance of the beam current on both image slits will appear  $I_{LE} > I_{HE}$  producing a differential error signal  $V_{OUT} < 0$ . So the triode grid potential is more negative than normal, the current  $I_{anod}$  of the triode decreases due to the phenomenon of „transfer resistor” and the terminal voltage  $V_T$  increases until it becomes equal to  $V_{TN}$ . The beam

position between the two legs of the image slit reach the center (see fig. 2.b), corresponding to the required value of the beam energy.

In Fig 2.c, the terminal voltage  $V_T$  is higher than  $V_{TN}$ , leading to the beam energy increase. The beam will exhibit a smaller deviation in the magnetic field of the analyzing system, as a result it will strike more in the high energy side of the image slit, and a current unbalance on the two slits will occur again. The effect is compensated by a less negative grid potential ( $V_g$ ) of the triode and a higher  $I_{anod}$  restores the nominal terminal voltage  $V_{TN}$ .

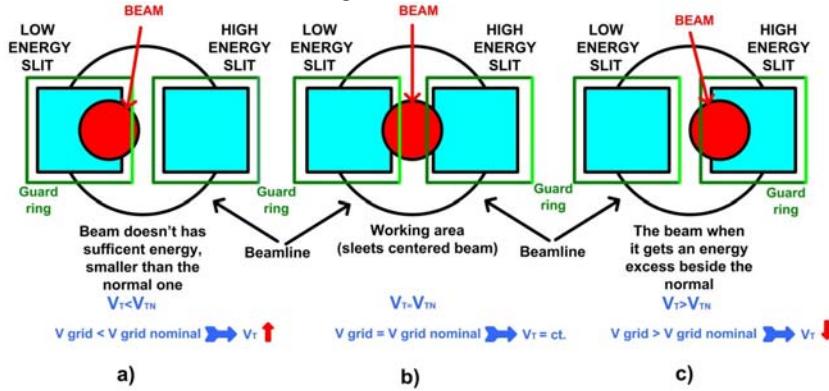


Fig. 2. Schematic representation of the image slits and the deviations from the optical axis of the beam in the image focal plane of the analyzing magnet, corresponding to the acceleration voltage variations

### 3. Numerical calculations and simulations

As mentioned before, the main component of the magnetic beam analysis system is the 90° double focalization dipole magnet. This system is equipped with two slits mounted in the “object” focal point placed in front of the dipole, and in the “image” focal point after the dipole. The focal distances for this dipole magnet are given by the relation [2]:

$$f_x = R/\tan\beta \quad (4)$$

where  $R$  is the radius of the beam curvature and  $\beta$  is the pole face rotation angle (see figure 3). In our case considering the design values  $\beta = 26.5^\circ$  and  $R = 1$  m, the focal distance is  $f_x \approx 2$  m measured from the pole face. The double focalization property refers to the property of beam focalization both in the horizontal and vertical planes. The focalization in the vertical plane depends on the magnetic pole profiles at the entrance and/or the exit that create specific fringe-fields. The analytic relation for the vertical focusing distance is [2]:

$$f_y = R / \tan(\beta - \psi) \quad \text{with} \quad \psi = k_1(g/R) \left[ \frac{1 + \sin^2 \beta}{\cos \beta} \right] \quad (5)$$

where :  $g$  is the dipole gap and  $k_l$  is the fringe field integral.

For a proper particle analysis with the dipole, the ion beam has to have a cross-over in the “object” focal point, as may be seen in Figure 1. This task is accomplished by the magnetic quadrupole doublet lens placed in front of the “object” slits.

Assuming that a given beam is centered on the image slits at the terminal high voltage  $U_T$  (fig. 2.b), the horizontal shift  $\Delta x$  of the beam position at the image slit location (fig. 2.a or 2.c) at very small variations  $\Delta U_T$  of  $U_T$  can be calculated with the approximate equation:

$$\Delta x \approx \gamma [(R + L)/2] (\Delta U_T / U_T) \quad (6)$$

where  $R$  is the beam trajectory radius in the analyzing magnet,  $L$  is the distance from the magnet pole exit face to the image slit and  $\gamma$  is a constant that depends on the magnetic fringing field of the magnet, that is of the magnet gap and pole face geometry. This equation may be derived from equation (3) by simple mathematical considerations. As can be seen from equation (6) the beam shift  $\Delta x$  does not depend on the mass or charge state of the particles. For the  $90^\circ$  magnet of the IFIN-HH tandem whose gap is 25.4 mm,  $L = 2R$  and  $\gamma = 1.33$ , so equation (6) becomes :

$$\Delta x \approx \gamma (3 R/2) (\Delta U_T / U_T) \quad (7)$$

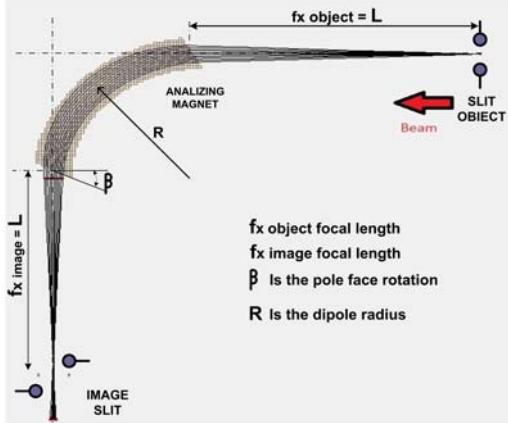


Fig. 3. Schematic representation of the  $90^\circ$  dipole analyzing magnet for an ion beam with an angular divergence of  $2^\circ$ . It is observed that the cross-over obtained in the “object” slit is “transported” by the magnetic field to the “image” slits point.

The accuracy of adjusting the slit opening is 0.02 mm.

The terminal high voltage is always subject to a ripple whose amplitude  $\Delta U_T$  is usually  $0.001 - 0.004$  of  $U_T$ . This ripple has a negative influence on the stability of the beam energy and position on the target of experiments and it may be reduced by slit stabilization of the terminal high voltage. In order to estimate this influence, the shift  $\Delta x$  was calculated for different values of  $U_T$ . The results of

these calculations are given in table 1 in the case of the IFIN-HH tandem accelerator where  $R = 1$  m. These results were verified by simulating the beam trajectory in the magnet for three species of particles ( $^4\text{He}$ ,  $^{12}\text{C}$  and  $^{32}\text{S}$ ) and 4 terminal voltages, using the SIMION ion optics code. The shift  $\Delta x$  obtained by simulation for the three particles were practically identical, verifying thus the theoretical observation that the shift does not depend on the ion species and their charge states. In table 1 are given the results of the simulation too. A very good correlation with the analytical calculations is observed.

*Table 1*  
**Beam shift from the optical axis in the image focal plane of the analyzing magnet of the IFIN-HH tandem accelerator due to the acceleration voltage ripple.**

$U_T$ (MV)	$\Delta x$ (mm)					
	$\Delta U_T = 1$ kV		$\Delta U_T = 2$ kV		$\Delta U_T = 5$ kV	
	Calculated	Simulated	Calculated	Simulated	Calculated	Simulated
1	2.000	2.003	4.000	3.980	10.00	10.11
2	1.000	1.003	2.000	2.005	5.000	4.99
3	0.670		1.330		3.330	
4	0.500	0.502	1.000	1.004	2.500	2.47
5	0.400		0.800		2.000	
6	0.330	0.335	0.670	0.670	1.670	1.65
7	0.285		0.570		1.430	
8	0.250		0.500		1.250	
9	0.220		0.440		1.110	

In Fig. 4 is a graphic of the horizontal position dispersion created by the terminal high voltage ripple at the image slits as resulted from our calculations. In this figure is represented only one half of the image slit and the abscissa is the slit symmetry axis that is the beam axis for the nominal high voltage on the terminal. The image slits opening is usually 1 mm (that is  $\pm 0.5$  mm). Comparing the shift  $\Delta x$  with this opening, one may derive the limitations of the slit stabilization. As results from figure 4, at an image slit of 1 mm, a terminal voltage ripple amplitude smaller than 2 kV will not be reduced by slit stabilization for  $U_T > 6$  MV because the shift  $\Delta x$  is much smaller than the slit opening and no error signal will be obtained from the slit. At small terminal voltages (1 – 6 MV), the slit stabilization is effective even for  $\Delta U_T < 1$  kV because the beam position shift is comparable or larger than the slit opening and thus an error signal is obtained as the beam is differently intercepted by the two legs of the slit. These observations are valid for any particle (ion species) or any ion charge state.

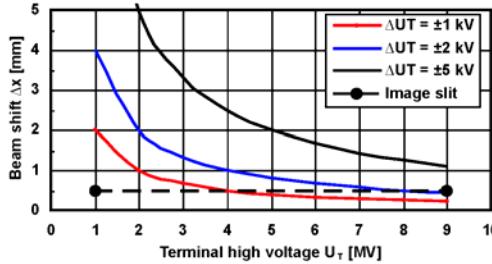


Fig. 4. Variation of the beam position in the image slit plane for different acceleration voltages  $U_T$ .

#### 4. Conclusions and perspectives

In the present work a practical problem of the high voltage terminal variations influence on the position of the accelerated beam in the image focal plane of the analyzing magnet has been approached. In this respect, extensive numerical simulation with the computer code SIMION has been performed and compared to analytical calculations.

It has been found that due to the terminal high voltage ripple, a horizontal shift of particles position in the focal point where the image slits are located occurs. This shift is larger at low acceleration voltage than the shift at high voltage acceleration for the same ripple amplitude.

From this study can be concluded that the greatest influence on the beam position has the voltage instabilities of the high voltage terminal. There are several physical processes and technical reasons contributing to this voltage instability. The ripple amplitude of the terminal high voltage is the main cause of beam position instabilities and it has to be minimized.

The results obtained in this study are relevant for the design of on improved energy stabilization systems at the Bucharest FN-Tandem accelerator as reported in Ref [3].

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