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A low-cost, accurate and non-intercepting continuous method for beam current measurements in a high-current ion implanter

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Abstract

The development of a low-cost, accurate, non-intercepting continuous method for measuring the beam current in a high-current ion implanter is described. The method, named a differential current monitor, is based on the electric charge conservation principle, applied to the currents that flow in the implanter electrical system, due to the acceleration voltage applied to the ion beam and the leakage currents to ground. This method allows for continuous measurement of the ion beam current without intercepting it. Since its installation, it is possible to accurate measure ion beam currents from tens of μA to mA, which is the normal range for this type of system.

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Keywords: Ion implantation; High-current ion implanter; Positive ion beam; Beam current measurement method

1. Introduction

The high-current ion implanter (HCII), shown in Fig. 1, model 1090, manufactured by Danfysik [1], was installed at the Nuclear and Technological Institute (ITN), Sacavém, Portugal. This facility has been mainly used to implant samples for research applications, where low beam current isotopes are used [2–10]. The HCII system is equipped with a cold hot reflex discharged ion source (CHORDIS), model 920, originally developed at GSI, Germany. The operating flexibility of the ion source (sputter, gas and vapor version), makes it possible to obtain ion beams of nearly all elements of the periodic table [11,12]. However, for safety reasons, radioactive or very hazardous elements are not handled. For the elements used, ion beams currents up to several mA can be obtained.

The maximum ion beam acceleration voltage is 210 kV (50 kV extraction plus 160 kV post-acceleration). Hence for singly charged ions an energy of 210 keV can be obtained. The beam can be focused on the target in a 2 cm^2 rectangle and can sweep an area of approximately 900 cm^2, depending on the mass-energy product. The isotope purity of the beam is controlled by a double-focusing 90° magnet with a mass resolution of $M/\Delta M = 250$ [1].

For implantation, the precise measurement of the ion beam current on target is the key point in order to calculate the implanted dose. Hence, the system shown in Fig. 1 was originally equipped with a Faraday cup and a beam-stop device to measure the current. However, their use resulted in the ion beam being intercepted and subsequent disturbance of the experiment. In consideration of this, the implanter manufacturer subsequently developed a non-intercepting continuous measuring device based on a

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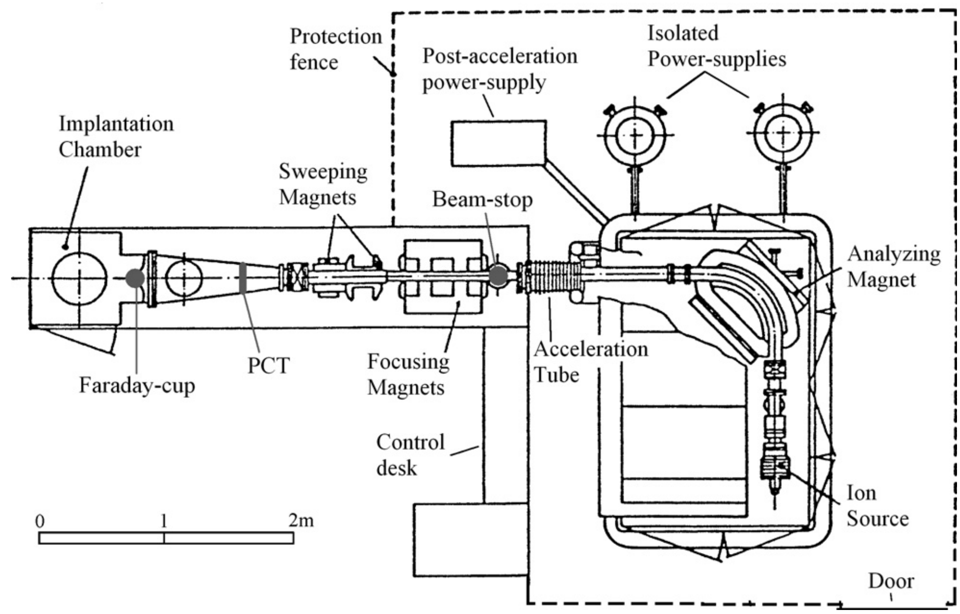

Fig. 1. Layout of the high-current ion implanter installed at the Nuclear and Technological Institute, Sacavém, Portugal. The PCT is not included.

parametric current transformer (PCT), with a maximum error in the current reading of 10 μA [13], allowing for precise implanted dose control.

Since this implanter runs mainly on research-oriented projects, the ion beam currents normally implanted are of the order of tens of μA. Hence, the PCT has not the required accuracy, added to the fact that the device is very expensive. Consequently, an alternative method called a differential current monitor (DCM) was developed to measure the ion beam current. This low-cost and accurate method allows for the continuous ion beam current measurement without intercepting the beam before the target, based on the principle of charge conservation in the implanter system. Electric currents that flow in the implanter electrical system, which depend on the acceleration voltage applied to the ion beam and the leakage currents to ground are continuously integrated. Consequently, it is possible to accurate measure ion currents from tens of μA to mA. To determine the precision of the ion current measurements the doses implanted in the samples are calculated by RBS.

2. Ion beam current measurement

One of the most important parameters to be controlled in ion implantation is the dose, D, which is the number of atoms n_a implanted for unit area s in the surface of a sample (atoms/cm^2), normally s represents the area scanned by the beam. The dose can be defined as

$$D = \frac{n_a}{s}. \tag{1}$$

The number of atoms n_a implanted into the surface can be calculated, measuring the current integral, as

$$n_a = \frac{Q}{qe} = \frac{\int_0^T i\,dt}{qe}, \tag{2}$$

where Q is the total charge deposited, which can be related to the current i of the beam and the total time T of the irradiation, q is the charge state of the implanted ion and e is the electron charge. Considering Eq. (2), if during the implantation period, the current i changes, the total implantation time T has to change in order to provide the intended charge Q. Consequently, it is important to continuously measure the ion beam current to account for any changes that will affect the dose implanted.

Also, precise dose determination is essential to obtain reproducibility in ion implantation. Hence, since the dose depends on the deposited charge, as shown in Eq. (2), it is necessary to know precisely the beam current intensity.

The HCII is equipped with two devices for measuring the ion beam current: a beam-stop and a Faraday cup. They are positioned in such a way that can intercept the ion beam, respectively, just after the post-acceleration and just before the implantation chamber, as shown in Fig. 1. The beam-stop, shown in Fig. 2, is a water-cooled isolated copper plate connected to ground and in series with an ammeter, which is used to control the implantation process and to get a rough idea of the beam current, since it has no electronic suppression.

If the beam-stop is hit by a positive beam (I_b) it becomes positively charged and there is an electric current (I_t) from it to earth to neutralize this charge, as shown in Fig. 2. However, if this electric current is measured, by the ammeter in series, its value is not the real beam current

$$I_t = I_b + I_e. \tag{3}$$

This measured current can be several times higher than the beam current, depending on the energy and mass of the

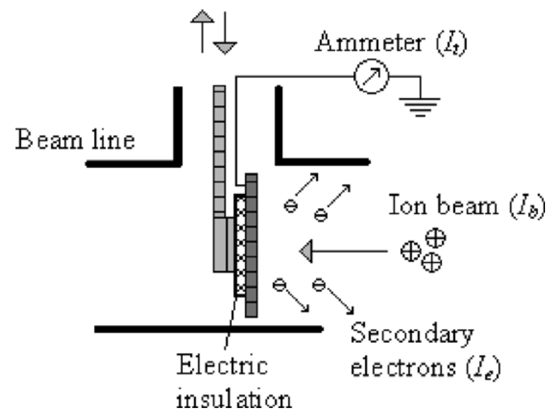

Fig. 2. Schematic of the beam-stop device in the HCII showing the interaction of the ion beam with copper plate: I_t, current measured by the ammeter; I_b, ion beam current; I_e, secondary electron current.

incoming ions and the target material. This is because, when the beam strikes the target, secondary charged particles are emitted, mainly secondary electrons (I_e), which are electrically equivalent to an incoming positive current [14]. Due to this the ammeter indicates an electric current larger than the real beam current, as in Eq. (3).

To obtain an exact current measurement it is necessary to use a more complex apparatus to avoid that these secondary electrons being counted. This can be done by polarizing the beam-stop with a positive direct voltage of about 200 V. Usually, the device used to measure the ion beam current is the Faraday cup, specially assembled to avoid the effects of beam interactions with the target. Electric or magnetic fields are used to keep the secondary electrons from exiting the system and being counted [14].

To measure the ion beam current in the high-current implanter, there is a Faraday cup, shown in Fig. 3, with magnetic suppression, placed at the entrance of the implantation chamber. The use of electron suppression by magnetic fields instead of electric fields is mainly to prevent additional complexity due to the use of high voltage. In Fig. 3, the copper volume of the Faraday cup is water-cooled and there is a mechanism that allows for vertical displacement for beam interception.

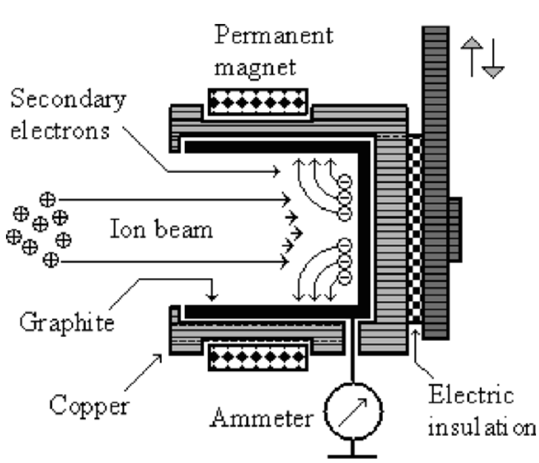

Fig. 3. Schematic of the Faraday-cup device in the HCII.

For accurate beam measurement by the Faraday cup it is necessary to focus the beam inside in a $1 \times 1\ cm^2$ aperture. Normally, for mono-isotopic ion beams it is possible to focus 90% in the Faraday-cup. However, for multi-isotope beams, particularly for low mass elements, due to the mass resolution of the analysing magnet the distance between isotopes can be larger than this aperture. In this case, two situations can occur: (i) each individual mass is focused but separate from the adjacent one with a value equal to the dispersion of the magnet; (ii) the beam is defocused to include all the masses in one image, but of great dimensions.

Even if the current measurement errors are not considered, the main disadvantage of the Faraday cup or beam-stop methods is that any beam current fluctuations are not reflected in the dose calculation, Eq. (2). So the implanter operator should be always be present, since an increase or decrease of the beam current can introduce errors in the dose up to 20% or more.

To increase the accuracy in the beam current measurements, the implanter manufacturer developed a non-intercepting device based on a parametric current transformer (PCT) [13]. This is a toroidal transformer designed for non-intersecting beam current measurement. It is normally used to measure the beam current in beam lines and accelerators. The current measurement is based on very precise compensation of the magnetic field created by the beam current. The assembly consists in a sensitive magnetometer that determines the resolution and zero drift of the PCT [15]. Hence, the modulator is sensitive to external magnetic fields. Therefore these fields should be attenuated by extensive magnetic shielding. The PCT is protected from external magnetic fields by multiple multilayer composite magnetic shields composed of amorphous and crystalline alloys. This is important when small currents have to be monitored [13].

The location of the PCT in the 1090 model implanter is shown in Fig. 1. To allow for the larger square conical cross-section of the beam tube, a specially designed, large-aperture (340 mm in diameter) was developed. The PCT needs to be mounted around the beam scanning chamber, 1.5 m away from the target position. The zero offset of the PCT is 1 AT^{-1} and its magnetic shielding is not sufficient to shield it from the stray fields of the beam scanning magnets. A key development was the introduction of additional magnetic shielding between the magnets and the PCT. This limits the magnetic field at the PCT to 10^{-5} T, corresponding to a maximum error in the current reading of 10 μA [13]. The PCT was developed mainly for ion beam currents greater than 1 mA, which is normally the case for service implantation facility, for improving tribological and corrosive behaviour of materials [13,16]. Our machine is mainly used for research projects where currents are normally less than 0.1 mA, so the 10 μA error in the current measurement described above is far greater than what is tolerable [2–10]. Also, the cost of the PCT is a big disadvantage.

Hence, a new method had to be developed for precise ion beam current measurements in the range between tens of μA to mA. The answer was the DCM method described below.

3. Differential current monitor method

Fig. 4 shows the simplified equivalent electric circuit of the implanter, Fig. 1. The ion source is represented by a current source. The extraction power supply has a serial resistance, R_{S1}, for protection, and a parallel resistance, R_{P1}, for stabilization. The post-acceleration power supply has a serial resistance, R_{S2}, for protection. The two parallel resistances, R_{L1} (150 MΩ) and R_{L2} (137.5 MΩ), represent, respectively, the set of stabilization resistances placed along the cooling oil tube for terminal cooling and the net resistances placed along the accelerating tube for distributing the potential. These parallel resistances are currently named stabilization resistances or leakage resistances.

Considering the equivalent electric circuit of Fig. 4, the ion beam current, I_B, can be determined as

$$I_B = I_{PA} - (I_{L1} + I_{L2}), \quad (4)$$

where I_{PA} is the post-acceleration power supply current, I_{L1} and I_{L2} represent, respectively, the currents in the leakage resistors R_{L1} and R_{L2}.

In Fig. 4, junction M represents the point where the total beam current, I_{EX}, extracted from the ion source is divided, due to the mass analysis. A part is retained in the analyzing magnet and beam collimators, I_M, and the remaining part is the ion beam that goes all the way through the line to the target, I_B. The connection between points M and H represents the beam current that passes from the terminal potential to ground through the beam line vacuum system. Two situations can happen:

- The post-acceleration voltage is zero. In this case $I_{L1} = I_{L2} = 0$, as no voltage is applied to the leakage resistors. In this case current I_{PA} is equal to the beam current, I_B, as shown in Eq. (4), in order to compensate the lost charge by the terminal.
- The post-acceleration is not zero. In this case I_{L1} and I_{L2} are different from zero and proportional to the voltage applied by the post-acceleration power supply. The current I_{PA}, across the post-acceleration power supply (i.e. the current supplied by the power supply) is equal to the currents across the stabilization resistances, $I_{L1} + I_{L2}$, plus the beam current, I_B, as in Eq. (4).

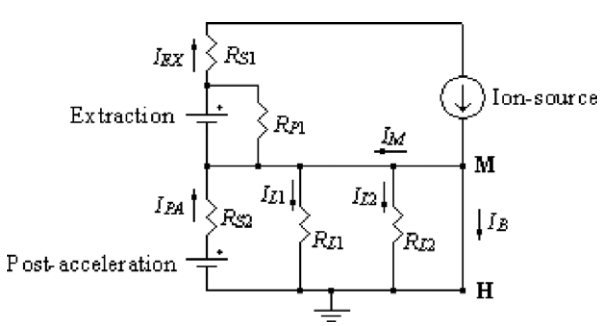

Fig. 4. Simplified equivalent electric circuit for the electrical currents circulation in the HCII.

Therefore, to measure the beam current, an electronic circuit was assembled that subtracts from the total current supplied by the post-acceleration power supply the current that crosses the stabilization resistors, R_{L1} and R_{L2}. Currents I_{L1} and I_{L2} are directly monitored in the system. Additionally, current I_{PA} is taken directly from the post-acceleration power supply.

4. Results and discussion

With the DCM, it becomes possible to continuously integrate the beam current without intercepting it. This device has operated for many years with good results, with errors less than 10%, in the dose for beam currents from tens of μA to mA. The results are checked on a regular basis by RBS on the implanted samples, and by comparing the beam current measurements between the Faraday cup and the DCM device for a mono-isotopic, well-focused Ar^+ ion beam.

Fig. 5 shows the percentage error between the current measured in the Faraday-cup (I_{FC}) and the current measured in the DCM (I_{DCM}), $((I_{FC}/I_{DCM}) - 1) \times 100$. It is a function of the beam current measured in the DCM (I_{DCM}), for an Ar^+ beam with energies higher than 100 keV (these data points were collected for a period of several years). The current measured by the DCM is always higher than the Faraday cup, as expected since the DCM device measures all the current that goes to ground potential and, also because for the Faraday cup it is necessary to focus the beam in a 1 cm^2 square hole. In addition, the precision of the DCM is higher for high intensity beam currents, with the limitation that all the current must be focused in the Faraday cup.

The main limitation of this method occurs when the beam strikes the beam line walls. Since all the ion current that leaves the high voltage potential and comes to ground is measured as beam current that hits the target, this method measures a current higher than the real one, resulting in dose shortage in the implanted sample.

Another problem, common to most implantation systems, happens if the focussing and beam sweeping area definition are not well set, due to a low intensity and low energy of the ion beam. This results in dose non-uniformity in the implanted sample, due to the fact that this beam current measuring system measures all the current that hits the ground potential and not a certain area. These errors can be as high as 20% in the implanted dose.

In addition, with this method, since the leakage currents in the implanter are being continuously observed, as well as the post-acceleration power supply current, it is possible to check their performance. Considering this, variations in the leakage currents in the order of more than 10% were

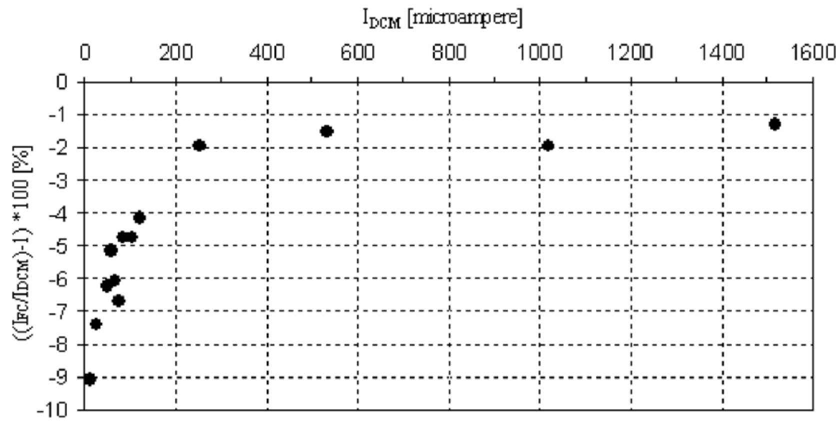

Fig. 5. Error in percentage between the Faraday-cup and the DCM beam current measurement.

observed, mainly, depending on the implanter humidity conditions.

5. Conclusions

The operation of a low-cost, accurate DCM device, for measuring the ion beam current in an implanter has been discussed. With this it is possible to continuously measure the ion beam current without intercepting it. This method has significant advantages compared to existing intercepting devices (i.e. beam-stop and Faraday cup). Due to its simplicity it is a low-cost device with great accuracy, being a good alternative for the existing methods and the PCT device.

This device operates with good results with errors less than 10% in the dose for beam currents from tens of μA to mA. In addition, the way the current measuring system is implemented makes it possible to check the performance of the high voltage power supplies and the leakage resistors that control the applied voltages in the implanter.

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References

[1] B.R. Nielsen, P. Abrahamsen, S. Eriksen, Mater. Sci. Eng. A 116 (1989) 193.
[2] A. Kling, J.G. Marques, J.C. Soares, M.F. da Silva, E. Dieguez, F. Agulló-López, Nucl. Instr. and Meth. B 127/128 (1997) 520.
[3] L.M. Redondo, C.M. de Jesus, J.G. Marques, M.F. da Silva, J.C. Soares, M.M. Pereira de Azevedo, J.A. Mendes, M.S. Rogalski, J.B. Sousa, Nucl. Instr. and Meth. B 139 (1998) 350.
[4] E. Alves, R.C. da Silva, M.F. da Silva, J.C. Soares, Nucl. Instr. and Meth. B 147 (1999) 226.
[5] A. Kling, M.F. da Silva, J.C. Soares, Nucl. Instr. and Meth. B 166/167 (2000) 280.
[6] C. Marques, M.M. Cruz, R.C. Da Silva, E. Alves, Nucl. Instr. and Meth. B 175–177 (2001) 500.
[7] E. Alves, C. Liu, E.B. Lopes, M.F. da Silva, J.C. Soares, C. Boemare, M.J. Soares, T. Monteiro, Nucl. Instr. and Meth. B 190 (2002) 625.
[8] E. Alves, C. Marques, R.C. da Silva, T. Monteiro, J. Soares, C. McHargue, L.C. Ononye, L.F. Allard, Nucl. Instr. and Meth. B 207 (2003) 55.
[9] C. Marques, E. Alves, R.C. da Silva, M.R. Silva, A.L. Stepanov, Nucl. Instr. and Meth. B 218 (2004) 139.
[10] A.R. Ramos, C. Marques, E. Alves, A.C. Marques, R.M. Almeida, Nucl. Instr. and Meth. B 240 (2005) 415.
[11] R. Keller, B.R. Nielsen, B. Torp, Nucl. Instr. and Meth. B 37/38 (1989) 74.
[12] B. Torp, B.R. Nielsen, D.M. Rück, H. Emig, P. Spädtke, B.H. Wolf, Rev. Sci. Instr. 61 (1990) 595.
[13] B. Torp, P. Abrahamsen, S. Eriksen, P.L. Hoeg, B.R. Nielsen, Surf. Coat. Technol. 66 (1994) 361.
[14] J.F. Ziegler, in: J.F. Ziegler (Ed.), Ion implantation science and technology, second ed., Academic Press, Inc., Harcourt Brace Jovanovich, Publishers, San Diego, California, 1988, ISBN 0-12-780621-0,, Cloth bound.
[15] K. Unser, IEEE Trans. Nucl. Sci. NS-16 (1969) 934.
[16] B. Torp, P. Abrahamsen, S. Eriksen, B.R. Nielsen, Surf. Coat. Technol. 51 (1992) 556.