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## Mass spectrometry improvement on an high current ion implanter

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## ABSTRACT

The development of accurate mass spectrometry, enabling the identification of all the ions extracted from the ion source in a high current implanter is described. The spectrometry system uses two signals ( $x$ - $y$  graphic), one proportional to the magnetic field ( $x$ -axes), taken from the high-voltage potential with an optic fiber system, and the other proportional to the beam current intensity ( $y$ -axes), taken from a beam-stop. The ion beam mass register in a mass spectrum of all the elements magnetically analyzed with the same radius and defined by a pair of analyzing slits as a function of their beam intensity is presented. The developed system uses a PC to control the displaying of the extracted beam mass spectrum, and also recording of all data acquired for posterior analysis. The operator uses a LabVIEW code that enables the interfacing between an I/O board and the ion implanter. The experimental results from an ion implantation experiment are shown.

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## 1. Introduction

Nuclear physics applications in materials science using combined methods of hyperfine interactions for the observation of the magnetic and electric interactions between nuclear moments of excited states in specific radioactive probe nuclei as well as the internal fields of the material and ion channeling for lattice location investigations can be excellent and unique tools for basic studies of defects in single crystals [1]. The high current ion implanter installed at Nuclear and Technological Institute (ITN) is dedicated to materials research which makes isotope selection an important requirement. Being also specially oriented for surface engineering studies, the ion implantation facility has been optimized to implant the isotope  $^{186}\text{W}$ . Then the  $^{187}\text{W}$  radioactive probe is obtained using the thermal neutron flux of the Portuguese Nuclear Research Reactor. The selectivity of the implanted chemical species is one of the most relevant advantages of ion implantation. In order to guarantee beam purity avoiding the contamination of the implanted samples, the mass spectrometry is essential in this process [2–5].

A new system, that was not included in the original configuration of the equipment, was developed in order to obtain precise identification and recording of all elements extracted from the ion source. This system allows the user to control and analyze

the mass spectrometry through a developed PC application, using the program LabVIEW, allowing an instantaneous correction of the experimental parameters in order to maintain the beam purity, and enabling the export of the data acquired. Nowadays, Danfysik implanters are fully computer controlled with increased mass spectrometry performance. In this work details are given about the implantation of  $^{186}\text{W}^+$  and  $^{186}\text{W}^{++}$  and the respective characterization of the samples using neutron activation analysis (NAA) used to prepare radioactive samples for hyperfine interactions studies.

## 2. System description

The high current ion implanter installed at ITN, represented in Fig. 1, is the Danfysik model 1090 [6,7]. The ion source, gas and sputter version, operating flexibility makes it possible to produce ion beams from nearly all elements of the periodic table [8]. This high current ion implanter is equipped with a beam profiler, an analyzing magnet and  $x$ - $y$  analyzing slits, enabling a beam envelop imaging and coarse mass analyses of the extracted ion beam. This device, located between the exit of the  $90^\circ$  analyzing magnet and a pair of analyzing slits consists of a probe that intersects the beam, giving an image of the beam horizontal and vertical contours and its position relative to the beam line.

The application of a magnetic field to the ion beam, as show in Fig. 2, ensures that ions of different masses extracted from the same source spot hit the analyzing slits in different spots. This physical separation,  $\Delta y$ , between two adjacent ion beams with

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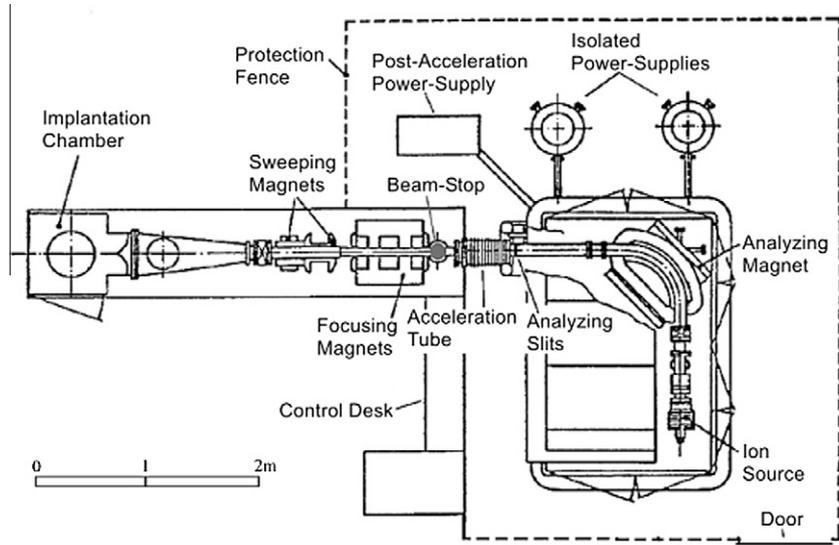


Fig. 1. Layout of the high-current ion implanter installed at the Nuclear and Technological Institute, Sacavém, Portugal.

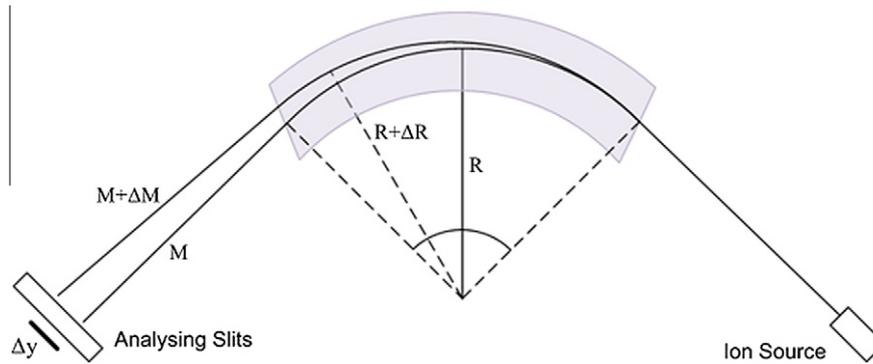


Fig. 2. Schematic of the analyzing magnet ion mass dispersion.

masses  $M$  and  $M + \Delta M$ , in the analyzing slits, due to the analyzing magnet deflection, is known as the magnetic dispersion  $D$  [8]

$$D = 2R \frac{M_2 - M_1}{M_1} \quad (1)$$

where  $M_1$  and  $M_2$  are two adjacent masses (in a.m.u.) and  $R$  is the magnet deflection radius.

The dispersion is measured in the analyzing slits, comprising two L-shaped copper bars that are simultaneously moved, having a 0–25 mm variable horizontal aperture and 25 mm constant vertical aperture. It can be seen from Eq. (1) that the dispersion depends only on the magnet geometry and the ion mass.

With the beam profiler is possible to observe the physical separation between the different beam masses, with the possibility of calibration to obtain the mass separation in length units that corresponds to the dispersion value.

The final width,  $L$ , of the beam image in the analyzing slits, which depends on: (i) the extraction power supply stability ( $dE/E$ ); (ii) the magnet current power supply stability ( $dB/B$ ), (iii) the beam divergence  $\alpha$ ; (iv) the initial object width  $S$ , is given by [9]:

$$L = R \frac{dE}{E} + R \frac{dB}{B} + R\alpha^2 + S \quad (2)$$

where  $dE/E = dB/B = 5 \times 10^{-4}$ ,  $R = 500$  mm,  $\alpha = 20$  mrad and  $S = 4.5$  mm (according to [10] for the extraction configuration used, the initial object width,  $S$ , for a focus beam is about half the extraction

electrode aperture), resulting in a beam width of approximately 5.5 mm.

Experimentally, the beam width can vary depending on the system operating conditions, where the  $\alpha$  and  $S$  parameters change in every run. The beam divergence depends on the ion source optimization and the initial extraction aperture width, of 9 mm, which becomes wider and loses its circular shape due to the ion bombardment. All these factors result in an increasing image size and a decrease in the mass separation. Hence, a slit aperture of 7 mm is usually required to transmit about 90% of a mono isotopic beam to the target.

In order to obtain a mass spectrum, two signals are required, one proportional to the analyzing magnet magnetic field ( $x$ -axes) and another proportional to the beam current intensity ( $y$ -axes). The first signal is taken from a voltage proportional to the analyzing magnet, available from the magnet power supply. The use of this signal comprises two difficulties: (i) the magnet current has hysteresis, thus it is advisable to continuously scan the current during a mass spectrum; (ii) the analyzing magnet is located on the post-acceleration potential. Therefore, an optic-fiber based circuit was developed to send the magnet current signal to the ground potential.

Whereas, on the post-acceleration potential, the d.c. voltage proportional to the magnet current is converted through a voltage-to-frequency ( $V/F$ ), in a number of voltage pulses with a frequency proportional to its amplitude.

This signal is applied to an infrared LED connected to one side of an optic fiber. On the other side, placed at ground potential, a photo-transistor converts the light pulses to a number of voltage pulses with the original frequency. This signal is finally converted in a frequency-to-voltage ( $F/V$ ) d.c. voltage with the same initial amplitude.

The current signal is taken from a beam stop located just after the acceleration tube, Fig. 1, and not from the non-intersecting device usually used to measure the beam current. The beam stop has no electron suppression but it gives a high accuracy fast electrical signal, considering that the current amplitude is not critical.

### 3. Results and discussion

All the system improvements are controlled through an application developed using the National Instruments program LabVIEW. For establishing the connection between the PC and the ion implanter, a multifunction input/output board by National Instruments, model USB-6251, was used. The application created for user interface is shown in Fig. 3, where the mass spectrum corresponds to a tungsten ( $W^+$ ) implantation. Due to the fact that LabVIEW is a graphical programming language specially created for instrumentation and measurement [11], a straightforward interface with switches to control the ion implanter and numerical and graphical indicators was developed. With this application the user can control the ion implanter through a PC and export the data obtained by mass spectrometry.

The mass spectrometry PC application displays the mass spectrum and offers the possibility to analyze the results online. For accurate element identification, the calibration of the horizontal axis is done using known reference elements.

For the calibration the user needs the values of two different elements, the lowest calibration peak and the highest calibration peak. In this case the value obtained for nitrogen was used as the lowest calibration peak because it is the first element deflected by the analyzing magnet. The value obtained for argon, which has the most intense ion current in the beam, was used as the highest calibration peak.

The developed application allows the user to export all the  $x$ - $y$  data acquired by the DAQ into a text (.txt) format file, and the mass spectrometry obtained into a bitmap (.bmp) format file.

For the calibration calculus, considering the horizontal axes as a reference, the different line points are given by

$$\text{Calibration} = \sqrt{\frac{M}{q}} \quad (3)$$

where  $M$  is the isotope mass (in a.m.u.),  $q$  is its charge and the calibration units are arbitrary. It is important to mention that, in order to guarantee the precision of this calculus, the values exported to the .txt file that are used.

During analysis of a mass spectrum the following should be taken into account: (i) the ion charge state and if it is a molecule; (ii) the magnetic field dependence on  $\sqrt{E}$ , which results in mass distance change with ion energy, so if the extraction energy is lower, the elements are closer; (iii) that element peak lines are wider for heavier elements. Considering a constant value for  $dB/B$ , then for increasing magnetic fields  $B$  (i.e. heavier elements) the magnetic dispersion  $dB$  increases, increasing the beam width; (iv) the slits aperture should be smaller than the dispersion to avoid overlapping between adjacent masses that leads to the broadening of the element peak lines in the spectrum.

Fig. 4 shows the beam spectrum, with the different  $W$  isotopes resolved, done with 0.5 mm aperture on the analyzing slits. The calculation of the  $W$  isotope abundance from the  $W^+$  peak intensities in the spectrum gives values similar to the natural abundances, as shown in Table 1.

The only exception is the value obtained for  $^{180}W^+$  which is justified by the  $^{180}Hf^+$  contamination (due to a previous Hf implantation).

Considering that we use the  $^{186}W$  implantation for hyperfine interactions measurements, and therefore one needs to activate the sample in a high flux of neutrons in the reactor, it is important that the contamination, if exists, should be reduced to a minimum. The  $^{186}W^+$  was implanted in Si samples, which were successively analyzed by neutron activation analysis (NAA). Fig. 5 shows a  $\gamma$ -ray spectrum from one of these samples implanted with  $^{186}W^+$ . The  $\gamma$ -ray energies shown in the spectrum of Fig. 5 are characteristic of the excited states of  $^{187}Re$  from the  $\beta^-$  decay by the radioactive  $^{187}W$ .

If higher implantation energy is needed, a  $W^{++}$  beam should be used. The mass dispersion is the same in  $W^+$  and  $W^{++}$ , as it depends only in the ion mass. In the specific case of selecting a  $W^{++}$  beam, one should additionally consider the contamination by  $Zr^+$  (also a

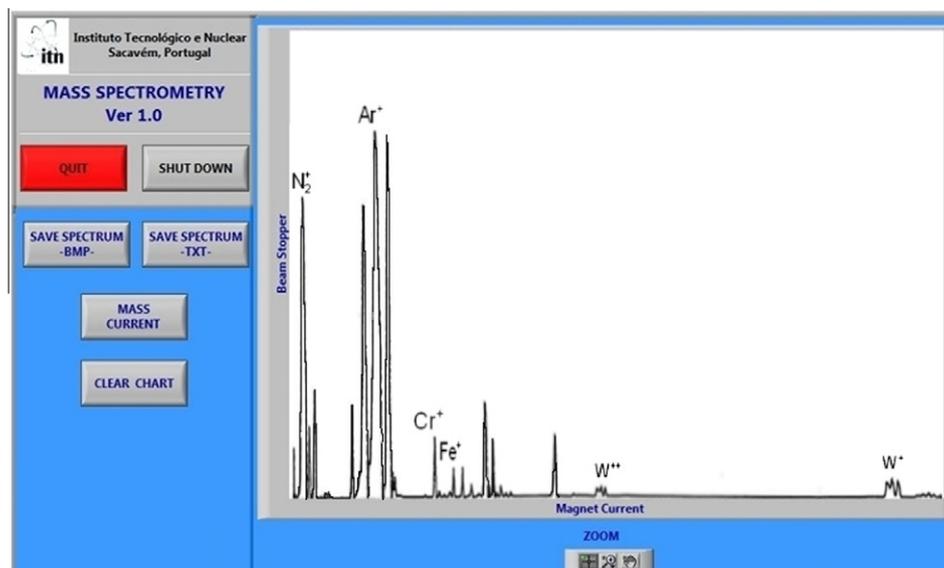


Fig. 3. User interface of the control and monitoring application.

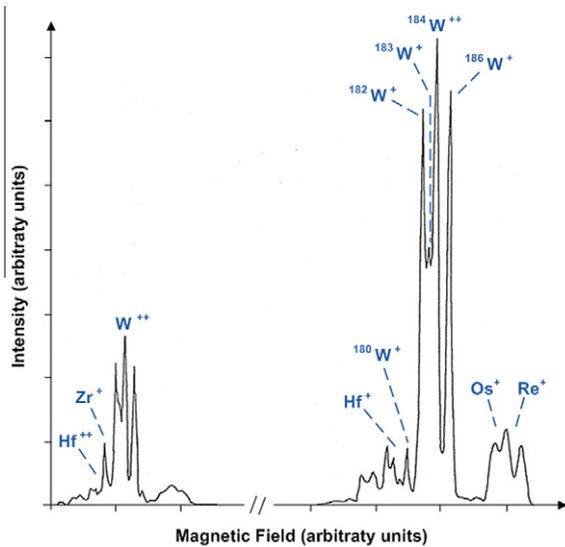


Fig. 4.  $W^+$  and  $W^{++}$  mass spectrum, with 25 kV extraction and 0.5 mm slits aperture.

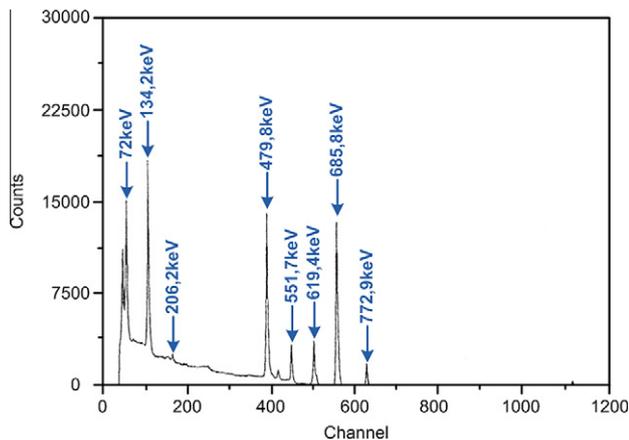


Fig. 5. Implanted  $^{186}W^+$ ,  $10^{16}$  atoms/cm<sup>2</sup>, Si sample and  $\gamma$ -ray spectrum, after neutron activation.

Table 1  
Natural abundances of W isotopes.

W	180	182	183	184	186
Natural abundance (%)	0.13	26.3	14.3	30.67	28.6

natural contaminant of Hf). In this case we must consider that only  $^{186}W^{++}$  is not contaminated. However, it is important to remember

that, due to the proximity of other isotopes, we may not be able to use the global current of this isotope.

#### 4. Conclusion

The development of an accurate mass spectrometry system enabling the registration (i.e. a mass spectrometry) of all ion species extracted from an ion source of a high current ion implanter has been described. The developed system uses a personal computer, one multifunction input/output board, some custom made electronic interface modules and a LabVIEW application presenting the acquired ion implanter signals to the user.

Currently, the user is able to: (i) monitor the mass spectrum by a PC; (ii) acquire  $x$ - $y$  values with higher accuracy; (iii) calibrate the mass spectrum more efficiently and quickly; (iv) print and save the mass spectrum.

The system allows the precise implantation of  $^{186}W$  for hyperfine interactions experiments. This system together with a pair analyzing slits and a beam profiler operation, allows for further increase of implantation accuracy. Since its installation, we have been able to record mass spectra from all the implanted elements and accurate implant specific isotopes. The precision of the ion implantation was determined by NAA.

In the system presently in use, new developments will be made in the future in order to proceed with the full automation of the mass spectrometry process. For that, the system must be able to self-calibrate and to do the automatic classification of the elements in the mass spectrum.

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