ION SOURCES AT THE MICHIGAN ION BEAM LABORATORY: CAPABILITY AND PERFORMANCE

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Abstract

The Michigan Ion Beam Laboratory (MIBL) at the University of Michigan has instruments equipped with ion sources capable of generating a wide variety of ions. The 1.7-MV Tandem accelerator can operate with three different sources: a Torvis source, a Duoplasmatron source and a Sputter source. The 400-kV ion implanter is equipped with a CHORDIS source that can operate in three different modes (gas, sputter, and oven) and is capable of producing ion beams for most of the elements in the periodic table. In this work, we discuss the principle of operation of each source, their performances and the latest applications and projects conducted at MIBL using these sources.

INTRODUCTION

The Michigan Ion Beam Laboratory is located in Ann Arbor, Michigan, and is part of the Department of Nuclear Engineering and Radiological Sciences at the University of Michigan. The laboratory is equipped with two major instruments: the 1.7-MV tandem accelerator (General Ionex Corporation) and the 400-kV ion implanter (National Electrostatic Corporation).

The accelerator is a solid-state gas insulated high frequency device, capable of operation between 0.4 and 1.7 MV (see Figure. 1). It can operate with three different ion sources: the Torvis source (National Electrostatic Corporation), the 358 Duoplasmatron source (General Ionex Corporation) and the PS120 Sputter source (Peabody Scientific). The accelerator has two ion injection beamlines attached to the low-energy bending magnet, each one at 30º to the accelerator beamline direction. The Torvis source is installed in one of this injection beamlines and in the other one is installed either the Duoplasmatron or the Sputter source. After the bending magnet at the high energy end of the accelerator there are two beamlines: the 15° beamline for ion beam modification (ion implantation, ion mixing and radiation damage), and the 30° beamline for ion beam analysis.

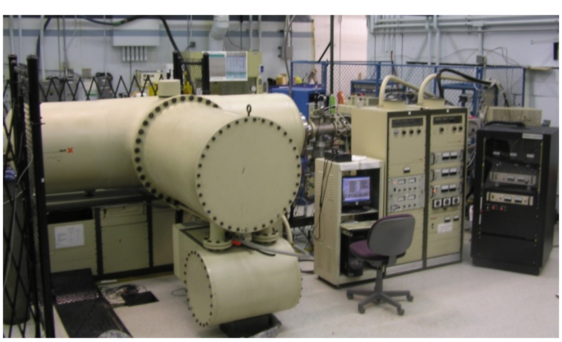

Figure 1: Picture of the 1.7-MV tandem accelerator and the area where the ion sources are located.

The ion implanter is air-insulated (see Figure. 2) and is designed to produce high current and high brightness ion beams. The implanter's ion source is a CHORDIS source model 921 made by Danfysik. The source can provide beams for most of the elements in the periodic table. The implanter's design allows obtaining implantation energies between 10 and 400 kV.

Figure 2: 400-kV ion implanter.

In the next sections we describe in more detail each of the ion sources mentioned including their principle of operation, performance in producing different ion beams and applications to current research projects.

TORVIS SOURCE

TORVIS stands for TORoidal Volume Ion Source. Figure 3 shows a schematic of the Torvis source. This source is used in MIBL to create negative ion beams using H_2 and D_2 gases.

Principle of Operation

The gas is leaked into the source volume and the molecules are ionized by electrons emitted from a tungsten filament to form a plasma of charged particles.

The body of the source is formed by the upstream and downstream flanges and a cylinder between these two flanges. Inside the flanges and cylinder there are concentric rings of magnets in which the poles of the magnets alternate by ring (see Figure. 3). This magnet assembly produces cusp fields that surround the entire plasma chamber. In addition, the source incorporates a conical magnetic filter field to separate the plasma into two distinct regions. In the outer toroidal region, the abundant fast electrons produce highly vibrationally excited molecules in the gas discharge. The conical magnetic dipole field separating the toroidal region from the axial region prevents fast electrons from entering the axial region, while allowing the excited hydrogen molecules to enter. This filtering prevents the fast electrons from destroying the negative atomic ions which are subsequently formed in the axial region by dissociative attachment of slow electrons. This complicated magnetic field is the critical feature of the source [1].

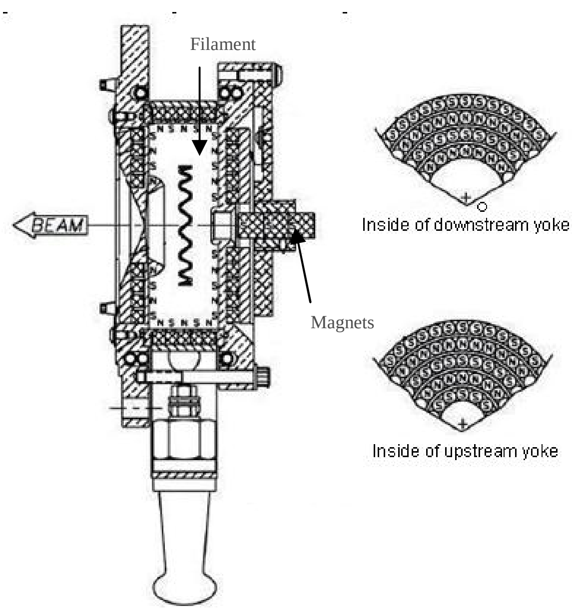

Figure 3: Torvis source schematic.

Maintenance

The most frequent service is the replacement of the tungsten filament after ~1000 hours of usage. When this task is done, the inside volume of the source is cleaned to remove a thin tungsten layer deposited on the walls due to sputtering of the filament by the plasma.

Performance and Applications

The Torvis source is used to produce H^- and D^- ion beams. Current of ~100 μA can be easily obtained for each ion on the target after a ~50% ion transmission through the accelerator.

MeV-Proton (H^-) beams are used to study the effects of irradiation on materials, with emphasis on material issues related to the nuclear power industry: materials degradation and design for advanced reactor systems [2]. These experiments run at proton beam currents of ~65 μA on the sample. The beam is scanned continuously on the sample 24 hours a day (with no beam interruption) over an area of 24 mm × 16 mm. The irradiation times range between 1 to 10 days. The damage rate accumulated on the sample surface is ~1 DPA (displacement per atom) per day.

MeV-Deuterium ion (D^-) beams are used to do nuclear reaction analysis (NRA). Recent measurements were done using the $^{12}C(d,p)^{13}C$ and $^{14}N(d,\alpha)^{12}C$ nuclear reactions to obtain the depth profile distributions of C and N in different samples. Also, deuterium beams were used to do NRA-ion channelling to measure the substitutional fraction of N in GaAs samples [2].

DUOPLASMATRON SOURCE

This source, as the Torvis source, produces ion beams using gases. Both sources can be configured to extract either positive or negative ions. Negative ions coming out of the source can be injected directly into a tandem accelerator without using a charge-exchange system. At MIBL, the Duoplasmatron source is configured to extract positive ions. In this case, the charge-exchange system uses sodium vapor to form negative ions. Figure 4 shows a schematic diagram of the source.

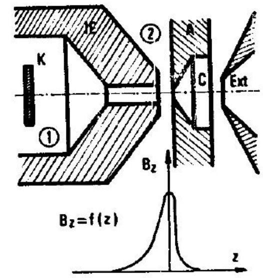

Figure 4: Schematic diagram of the Duoplasmatron source. (1) Cathode region. (2) Anode region. K: hot cathode. IE: intermediate electrode. A: anode. C: expansion cup. Ext: extractor. Below the schematic is the plot of the magnetic field intensity along the axial direction [3].

Principle of Operation

A gas is leaked into the source and the molecules are ionized by electrons emitted from the filament to create a discharge. The arc has a dual compression: geometrically and magnetically. The ions are axially extracted from the plasma of the low pressure arc between a hot cathode K and an anode A. In the case of positive ion extraction the emission aperture is bored in the anode on the discharge axis. 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 the intermediate electrode IE and the effect of a strong axial magnetic field between IE and A. The dense arc plasma protrudes through the anode aperture. The form of the emissive surface of this "expansion ball" maybe shaped in order to improve the ion beam optical properties if the diffusion processes in an "expansion cup" placed just behind the anode are adequately controlled [3].

Maintenance

At MIBL the filament of the source is done with a platinum mesh (gauge 52, 0.1-mm diameter wire) with dimensions of 1"×4" rolled up as a scroll**.** The mesh is coated with high calcium triple carbonate (Ba-Sr-Ca CO_3). The most frequent service on this source is to recoat the filament after ~80 hours of operation. A less frequent task is to reload sodium in the charge-exchange system.

Performance and Applications

We use this source to produce helium ion beams to do ion beam analysis: Rutherford Backscattering

Spectrometry (RBS), Elastic Recoil Detection Analysis (ERDA), and RBS-ion channelling [2]. Typical He^{++} current on the target ranges from ~5 to ~50 nA depending upon the sample composition and the detector's count rate. The helium ion transmission through the accelerator is ~15% for both +1 and +2 charge states.

SPUTTER SOURCE

Sputter sources are adequate for a wide variety of nuclear experiments but some exceptions do occur particularly with elements having small electron affinities. Sputter sources have found broad application in areas such as ion implantation, radiation damage studies and accelerator mass spectrometry. Figure 5 shows the schematic of the Sputter source at MIBL which has a cylindrical ionizer.

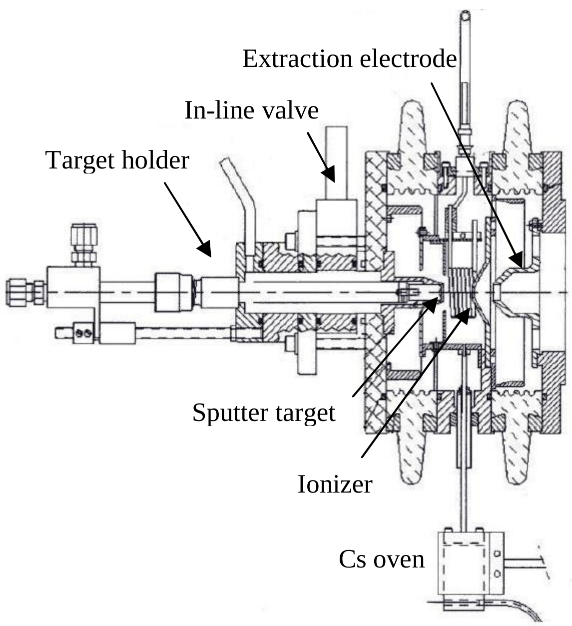

Figure 5: Sputter source schematic.

Principle of operation

Cesium is heated in the Cs oven and the resulting vapor enters the source region which contains the ionizer assembly. The ionizer and chamber are at the same voltage while the sputter target is held in an insulated holder assembly at a voltage negative compared to the ionizer. Cesium ions are formed by surface ionization and are then attracted to the sputter target holder assembly. This beam of cesium sputters the target with a large fraction of the sputtered components being negative ions of the target material [4]. These negative ions are extracted up to 40 keV. The ionizer and source chamber can be biased up to 30 kV and the sputter target up to 10 kV. To change the sputter target, the target holder is retracted through the rear plate and the in-line valve is closed to preserve vacuum in the source.

Maintenance

The main maintenance task done on this source is to reload the cesium oven and change the sputter target.

Performance and Applications

The PS120 sputter source has been recently acquired by MIBL. Our experience with it is still limited. So far we have produced Si and Fe beams. The Si beam was produced to test the source after its installation. We obtained ~110 μA after the 30° bending magnet located 2 m from the source. The only optical element between the source and the magnet was a 5"-diameter greeded lens located 1.4 m from the source and 0.5 m from the magnet. We are particularly interested in producing iron beams to study the effects of irradiation on materials as in the case of proton beams produced with the Torvis source. The Fe beam has the advantage of a much higher damage rate on the sample surface than the proton beam. A 5-MeV Fe^{++} beam at a current of ~1 μA scanned over the same area than the proton beam will accumulate a damage dose of ~100 DPA per day. We have produced Fe beams using two different cathode target materials: Fe_3O_4 and pure metallic Fe. In the first case we obtained in the Faraday cup after the 30° bending magnet a maximum $(^{56}Fe^{16}O)^-$-molecular-ion beam current of ~22 μA, and in the second case ~10 μA of Fe^- ions.

By installing an Einzel lens immediately after the sputter source the beam currents after the 30° bending magnet have increased by a factor of ~2 for the same source parameters. Also, the installation of the Einzel lens improved the transmission of the Fe beam through the tandem accelerator by a factor of ~2.

In the latest test we obtained a current of ~1.5 μA of 2.7-MeV Fe^{++} ions after the analyzing magnet in the high energy end of the accelerator.

CHORDIS SOURCE

CHORDIS stands for Cold of Hot Reflex Discharge Ion Source. The Model 921A ion source is designed for the production of high current and high brightness ion beams for applications in particle accelerator injection, ion implantation, isotope separation, ion beam mixing, sputtering, fusion plasma diagnostics, etc.

Principle of Operation

A schematic of the CHORDIS source is shown in Figure. 6. The primary ionizing electrons are emitted from tungsten-filament cathodes. The source chamber walls form the anode for the discharge. The plasma is confined radially by an array of permanent magnets that form a multicusp field and axially by two biased reflector electrodes. The front reflector forms the first electrode of the extraction system. Particles are fed through the rear electrode in the form of gases to produce different ion beam [5,6].

Alternatively, ion beams can be produced by mounting a metal disk inside the discharge chamber in front of the outlet hole. The disk may be biased to a negative potential with respect to the cathode. With an argon gas discharge in the source, sputtered atoms from the disk will be ionized and mixed with the discharged plasma, causing the extracted beam to contain a large fraction of them. The sputter version is particularly well suited for producing ions of medium and high melting point materials. Elemental materials as well as alloys and sintered mixtures may be used for the sputter disks.

The CHORDIS source in MIBL is also equipped with an internal oven which makes it ideal for production of pure ion beams from elements with low melting point and at least 2 Torr vapour pressure at 1000 °C. The oven temperature is regulated independently of the other operating parameters, and condensation of charge materials is avoided by making all other internal source parts hotter than the oven itself. The charge can be introduced from the rear end, with the source mounted in operating position. Auxiliary gas (e.g. argon) may be used to stabilize the discharge. The oven version is suitable for materials like the alkalines and earth-alkalines, aluminium, indium, thallium, tin, lead, antimony, and bismuth.

Maintenance

The most frequent maintenance task is the replacement of the filaments in the plasma chamber. The lifetime of the filaments depends upon the intensity of the plasma and beam currents needed. On average in MIBL we replace the filaments every ~100 hours.

Every time a new ion beam is required the source has to be opened to either change the gas bottle, the sputtering target, or the material in the oven to be evaporated into the plasma chamber.

Performance and Applications

The 400-keV implanter was installed in MIBL two years ago. Since then we have produced 19 different ion-type beams to do ion implantation for a wide variety of research projects in material science and medical applications [2]. The implanted species using gases are: H, He, and N; using a sputtering target: B, Si, Cr, Fe, Co, Cu, Pd, Ag, In, Ce, Er, Yb, Ta, and Au; and using the oven: Sn and Bi. Other ion beams have been produced: Be^+, C^+, O^+, O^{++}, Ne^+, Ar^+, Ar^{++}, Ni^+, Sm^+, and W^+.

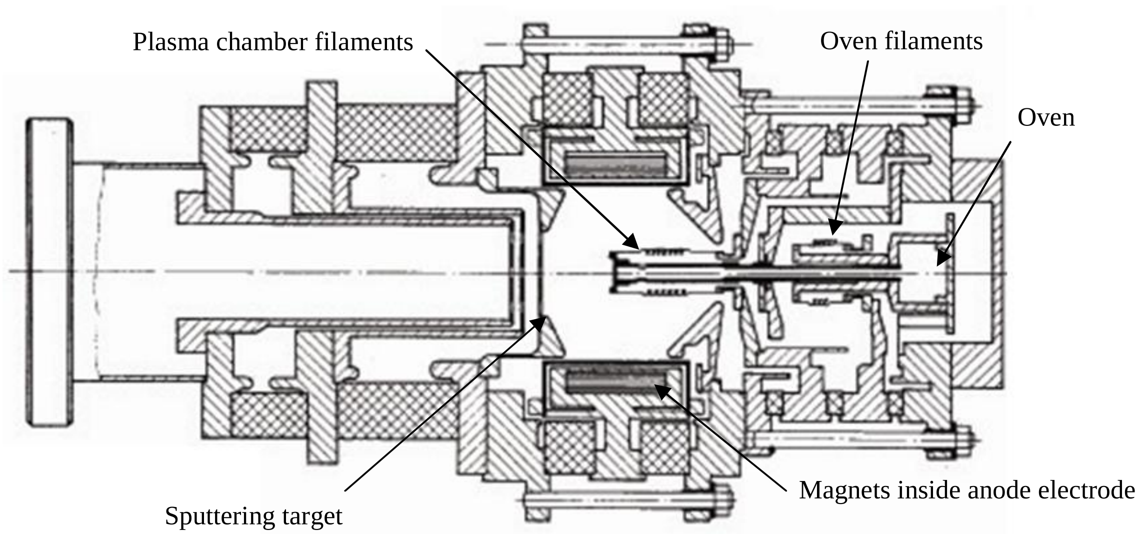

Figure 6: Schematic of the CHORDIS source.

Summary

The Michigan Ion Beam Laboratory was established for the purpose of advancing the understanding of ion-solid interactions by providing unique and extensive facilities to support both research and development in the field. Every year the laboratory's activities involve about thirty research projects including research groups in the University of Michigan, other universities in USA and around the world, and private companies. All of these activities are related with the use of ion sources. These facts show how important is to understand the basic principles of operation of ion sources and achieve a good performance for each of them.

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