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New ion beam materials laboratory for materials modification and irradiation effects research

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ABSTRACT

A new multifunctional ion beam materials laboratory (IBML) has been established at the University of Tennessee, in partnership with Oak Ridge National Laboratory. The IBML is currently equipped with two ion sources, a 3 MV tandem accelerator, three beamlines and three endstations. The IBML is primarily dedicated to fundamental research on ion–solid interaction, ion beam analysis, ion beam modification, and other basic and applied research on irradiation effects in a wide range of materials. An overview of the IBML facility is provided, and experimental results are reported to demonstrate the specific capabilities.

1. Introduction

Ions with keV to MeV energies can be used to controllably change electrical, optical, structural, mechanical and chemical properties of materials in the surface region up to a few micrometers. Ion irradiation has the advantage of having well-controlled conditions that allow for fundamental studies on ion–solid interaction and material response to extreme radiation environments. Applications of such energetic ions include advanced electro-optical device fabrication, nanostructure engineering, and radiation effect studies for nuclear materials and space exploration [1–10]. For nuclear energy applications, controlled ion irradiation approaches can be utilized to explore a wide range of irradiation conditions (e.g. dose, dose rate, damage energy density, and temperature) in nuclear materials and achieve better understanding from separate effects evaluation and testing, as well as combined or simultaneous effects of integrated irradiation studies. Advances in understanding the response of materials to energetic ions have significantly contributed to the knowledge of irradiation damage from high-energy neutrons on microstructure evolution, and changes in chemical and physical properties in advanced structural steels, fuels, and cladding materials. Progress made in ion–solid interactions, including defect production, microstructure evolution and damage recovery, has led to many technological advances to create new functionalities in metals, semiconductors, ceramics and polymers [1–10].

Diminishing research and training capabilities in the USA for ion beam analysis (IBA), ion beam modification, fundamental understanding of ion–solid interaction, and irradiation effects research in materials have prompted the University of Tennessee (UT), in partnership with Oak Ridge National Laboratory (ORNL), to develop a new multifunctional Ion Beam Materials Laboratory (IBML, http://ibml.utk.edu/) located on the UT campus. The primary mission of the UT-ORNL IBML is to address the scientific challenges associated with both fundamental and applied programs, as well as educational and training needs. Since operation of this laboratory began in the fall of 2012, it has been utilized to support various research needs for national energy and security missions. The purpose of this paper is to describe the capabilities in this new facility with some recent studies on defect formation and damage accumulation.

2. Overview of IBML facility

The IBML, with laboratory space of ~300 m^2 (45 ft × 70 ft), is equipped with two ion sources, an injection magnet, an electrostatic tandem ion accelerator, an analyzing magnet, three high-energy beamlines, and three endstations, as shown Fig. 1. In addition, one low-energy beamline and its endstation after the injection magnet are in the development stage. The IBML has a separate sound-proof control room with a glass wall overlooking the

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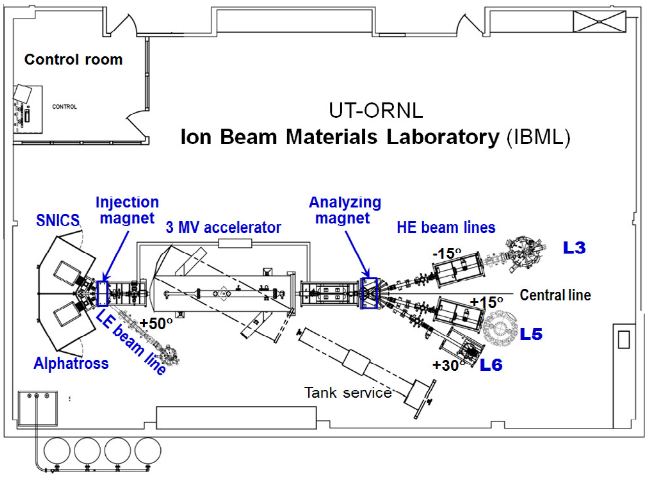

Fig. 1. Schematic layout of the UT-ORNL IBML, including a separated control room, the two ion sources, a 3 MV tandem accelerator, beamlines and end-stations.

accelerator, beamline and endstation areas. This facility is capable of accelerating a variety of ion species over a range of energies from a few hundreds of keV to a few tens of MeV to meet the needs for education, fundamental research and applied programs.

One ion source is a radio frequency (RF) charge exchange ion source (Alphatross) for producing gas ions. At the IBML, this ion source is used to produce helium ions. The other ion source is a Source of Negative Ions by Cesium Sputtering (SNICS) II. Most heavy ions, as well as hydrogen ions, are produced from a solid cathode by Cs$^+$ sputtering. Elemental or compound cathode material containing the required elements is compacted inside a cathode rod, normally made out of Cu due to its high thermal and electrical conductivity. For Ni or Fe ions, pure Ni or Fe cathodes are used to avoid difficulties of mass separation from Cu. The negative ion beam, produced from either the Alphatross or the SNICS source with pre-acceleration energies of a few tens of keV, is bent at a 30° angle (Fig. 1) by the injection magnet into the central beamline of the accelerator. The accelerator is a 3.0 MV Pelletron (model 9SDH-2) tandem electrostatic accelerator, manufactured by National Electrostatics Corporation (NEC, WI, USA, http://www.pelletron.com). Calibration of ion energy was carried out in generating voltmeter (GVM) mode using a resonant reaction ^{16}O(α,α)^{16}O [11]. The resultant peak energy is well within the error for the reported resonant peak energy with an overall error of ±10 keV.

A unique design of the injection magnet at the low-energy end of the accelerator is the three bending ports, which makes low-energy ion beam capabilities available at an insignificant additional cost. A 0° port is positioned along the central line where the ions travel to the accelerator (Fig. 1). The other two ports are at ±50°. One low-energy (LE) beamline is shown in Fig. 1 downstream from the injection magnet along the +50° port away from the central beamline of the accelerator. Such a design enables 100° bending of light ions (He at this IBML) from the Alphatross ion source, and modest bending (20°) of heavy ions from the SNICS source. Based on the voltage (up to 80 keV) and current capabilities (up to a few tens μA) of both ion sources, this LE beamline allows applications, such as low-energy high-current implantation, shallow doping, and surface modification. Specifically, the penetration depth from H and/or He implantation from this low-energy capability can be controlled to match that from heavy ion irradiation produced from the high-energy end of this accelerator. Such overlap of the ion ranges meets the requirements to investigate cavity formation under heavy ion irradiation with and without H and He present in various nuclear materials for reactor applications. Moreover, low-energy implantation of certain fission products into the surface region from this low-energy capability will also enable migration studies of fission products to the surface and to the bulk under subsequent irradiation conditions at elevated temperature. As a preliminary test, 50 keV He ion implantation into a glass sample was performed, and the beam shape and uniformity was monitored by the luminescence from the sample. Further development of this LE beamline will include adding an electrostatic steerer to deflect the beam, an einzel lens to focus the beam, a beam profile monitor to observe beam shape, a Faraday cup for current measurement, double slits or collimator to define beam size. A customized position- and temperature-controlled target chamber will allow H and He implantation, or other surface modification by heavy ions to be performed at temperature ranging from 150 to 1000 K.

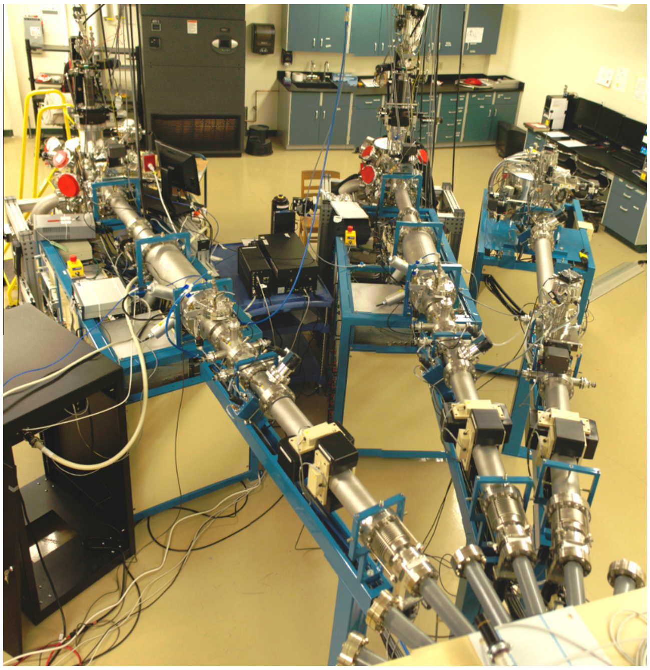

Fig. 2. A photograph of the three high-energy research beamlines with L3 on the left, L5 in the middle, and L6 on the right.

The analyzing (switching) magnet at the high-energy end of the endstation has seven ports at −45° (L1), −30° (L2), −15° (L3), 0° (L4), +15° (L5), +30° (L6), and +45° (L7), with respect to the accelerator. Three high-energy beamlines are located at the L3, L5, and L6 ports downstream from the analyzing magnet, as shown in Figs. 1 and 2. The energetic positive ions after the accelerator are focused using a magnetic quadrupole and a *Y*-axis electrostatic steerer into the analyzing magnet and bent into one of the three research beamlines. The L6 beamline and its endstation are devoted to rapid routine ion beam analysis at room temperature. Two other beamlines (L3 and L5) with temperature-controlled endstations are equipped with some unique capabilities for ion beam analysis, modification, and radiation effects studies that will be described in the following section.

3. Endstations and capabilities

There are three operational endstations. The manipulators or goniometers in these endstations are computer-controlled, and the working pressure is in the low 10^{-5} Pa range. Higher vacuum conditions are possible, if needed.