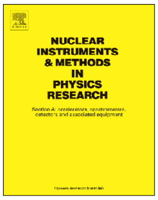
Nuclear Instruments and Methods in Physics Research A 763 (2014) 266–271

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima



Copper K-shell x-ray emission induced by the impact of ion beam from an electron cyclotron resonance ion source

S.K. Jain *, V. Arora, R. Rathore, S. Bagchi, P.A. Naik

Raja Ramanna Centre for Advanced Technology, Indore 452 013, India

ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form
26 May 2014
Accepted 18 June 2014
Available online 27 June 2014

Keywords:
Electron cyclotron resonance ion source
Characteristic x-ray emission
Bremsstrahlung spectrum

ABSTRACT

The K-α and K-β x-ray emission (at 8.05 keV and 8.9 keV respectively) produced from a copper target by the impact of 25 keV hydrogen (H^+) and nitrogen (N^+) ion beams, and 200 keV for argon (Ar^{+8}) beams from an electron cyclotron resonance ion source (ECRIS), has been studied experimentally. The K-α x-ray line intensity exhibited an increase with increasing ion beam energy with a scaling law $I_{K\text{-}\alpha} \propto E^{\gamma}$, where the scaling exponent γ was 4.0, 4.2, and 4.1 for hydrogen, nitrogen, and argon ion beam respectively. The results can be explained by considering the K-shell ionization cross-section for ion impact. The peak to background ratio of x-ray line intensity was observed to increase rapidly with the ion beam energy and highest ratio of 6×10^5 was observed for hydrogen ions. The study is important for optimizing ECRIS for generating a low cost, long life x-ray source for applications in material science.

1. Introduction

There is an active research interest in the generation of keV x-ray line emitting sources yielding high photon flux with high peak to background ratio for various scientific and technological applications in material science [1], medical applications like radiology, mammography, radio-biology, phase contrast imaging etc. [2–4], calibration of thermo-luminescent dosimeters [5], trace elemental analysis [6], and non-destructive testing [7]. The conventional sources like Coolidge tube or rotating anode x-ray generator [8], which use filament and high voltage power supply have disadvantages like reduction of the intensity of the x-ray output with time, limited photon flux, and high divergence. Although synchrotron radiation x-rays sources [9] are efficient and the intensity of the x-ray radiation is also several order magnitude higher than in conventional sources, such sources are capital intensive large central facilities and not accessible for applications such as elemental analysis or detector calibration etc. on routine basis. The other alternative is the laser produced plasma based x-ray source [10]. It requires moderate infrastructure and gives fairly high peak brightness, but has low repetition rate limited by the driving laser. On the other hand, an electron cyclotron resonance ion source (ECRIS) based x-ray sources are rapidly gaining popularity [11–15]. The reasons for this are: its simplicity in use, compactness, lesser cost, easy control of photon flux etc. Moreover, it does not have any filament, and hence there is no reduction in intensity of x-rays generated with continuous operation of the source. In ECRIS [16–18], the electron cyclotron resonance (ECR) plasma is produced by the interaction of the microwave radiation, by matching the cyclotron frequency of an electron (ω_{ce}) in an externally applied DC magnetic field to the microwave frequency (ω_{rf}) i.e. $\omega_{ce}=eB/m$, where e is the electron charge, m is the mass of the electron, and B is the magnetic field. The ion beam from the ECR plasma is extracted electrostatically.

The ECR plasma can generate x-ray radiation by de-excitation of the plasma constituents for highly charged plasma like argon plasma (Ar^{8+}). X-rays can also be produced inside the plasma chamber due to the high energy electrons hitting the chamber walls. High energy electrons can be produced by multiple collisions/passages in the resonance zone. When these electrons hit the chamber walls, bremsstrahlung radiation is produced [2,19–23]. The generation of x-rays is also by the collision of ion beam produced by ECRIS with a solid target. In this process, referred to as particle induced x-ray emission (PIXE) [6], x-rays are generated when a high current ion beam strikes on a target (tungsten, molybdenum, copper etc.) and loses its energy to generate characteristics line radiation, and continuum emission (bremsstrahlung) extending up to the energy of the ion beam. The energetic ions bombarding the target knock out electrons from inner shells of the atoms creating vacancies in those shells, which when filled by the electrons from the outer shells result in the characteristic x-ray line radiation. The energy of the line radiation depends on the target material, and the flux of line radiation depends on the energy of the ion beam. A tightly focused ion beam can generate an x-ray source of microns order, useful for applications such as phase contrast imaging. Next, for use in imaging

---

* Corresponding author.
E-mail address: skjain@rrcat.gov.in (S.K. Jain).

http://dx.doi.org/10.1016/j.nima.2014.06.057
0168-9002/© 2014 Elsevier B.V. All rights reserved.

applications, a nearly monochromatic source with high peak line intensity to background continuum radiation intensity ratio is desirable.

In this paper, we report investigation of the generation of copper *K*-shell x-ray emission by the impact of ion beam from an ECRIS. The dependence of the x-ray line radiation intensity on the hydrogen, nitrogen and argon ion beam extraction voltage was studied. It may be noted that the energy of a positive ion beam (E_i) is related to the extraction voltage (V_{ex}) by the relation $E_i = ZeV_{ext}$, where e is the electron charge, *Z* is the ion charge state. The extraction voltage was varied from 5 to 25 kV. It was observed that the copper *K*-α, and *K*-β intensity increases with energy for all the three types of ions. The *K*-α line intensity was found to follow a scaling law of $I_H^{4.0}$, $I_N^{4.2}$, $I_{Ar}^{4.1}$ for hydrogen, nitrogen and argon ions respectively, where I is the ion beam energy. The above results have been explained on the basis of particle induced x-ray emission, by considering the cross-section for *K*-shell ionization by ion impact. The paper is organised as follows: a brief description of the ECRIS based x-ray source is given in Section 2, the experimental setup in Section 3, and the results and discussion are presented in Section 4.

2. Description of ECRIS based x-ray source

An Electron cyclotron resonance ion source called as RRCAT-ECRIS operating at 2.45 GHz frequency has been built to extract proton beam current up to 30 mA for 50 keV beam energy from hydrogen produced plasma [24,25]. The use of 2.45 GHz frequency, which is routinely used in microwave ovens and does not require any high voltage, makes the ECRIS cheaper and compact.

A schematic block diagram/3D-view of the RRCAT-ECRIS is shown in Fig. 1. An ECRIS consists of a microwave system to produce and heat the plasma, an evacuated plasma chamber, solenoid coils for generating the desired magnetic field, a gas flow system, beam extraction electrodes to get an ion beam out of the plasma, and a water circulation unit for cooling the microwave components, solenoids coils, plasma chamber, and beam extraction electrodes. The microwave system consists of a microwave generator (magnetron operating at 2.45 GHz frequency, providing up to 2 kW continuous mode power) with a suitable microwave power transfer line. The power transfer line has an isolator to protect the magnetron from any power reflected from the plasma due to impedance mismatch, a directional coupler for measurement of forward and reflected power, a triple stub tuner for precise impedance matching, a high voltage break to electrically isolate the microwave line from the plasma chamber floated at high voltage, a microwave vacuum window made of quartz used for vacuum sealing the microwave line at atmosphere pressure from the evacuated plasma chamber, and an open ended waveguide is used to feed the microwave power to the plasma chamber. The design details of the microwave system have been described elsewhere [26]. Three solenoid coils were used to produce magnetic field for the plasma confinement, heating, and to tune the electron cyclotron frequency to match with the microwave frequency for resonant energy transfer to the plasma. The magnetic field configuration to achieve flat, beach, off-resonance, and mirror, was designed using Poisson software, the details of which are described elsewhere [27]. The flat, beach, off-resonance field configurations are effective for singly charged ion beams, and the mirror field for multiply charged ion beams. High purity experimental gas was used and the gas flow was regulated with a fine precision valve. The source had three-electrode beam extraction system consisting of a plasma electrode biased at 25 kV DC, an extraction electrode negative 1 kV DC, and a ground electrode. A Faraday cup with biased suppression voltage was used for the true measurement of the ion beam. During the course of experiment for singly charged ion beam the mirror field was not used or kept at a low value, this in turn reduces the chance of producing higher charge states.

3. Experimental setup

The experimental setup of the x-ray source using RRCAT-ECRIS is shown in Fig. 2. The plasma chamber was evacuated to $\sim 10^{-6}$ mbar,

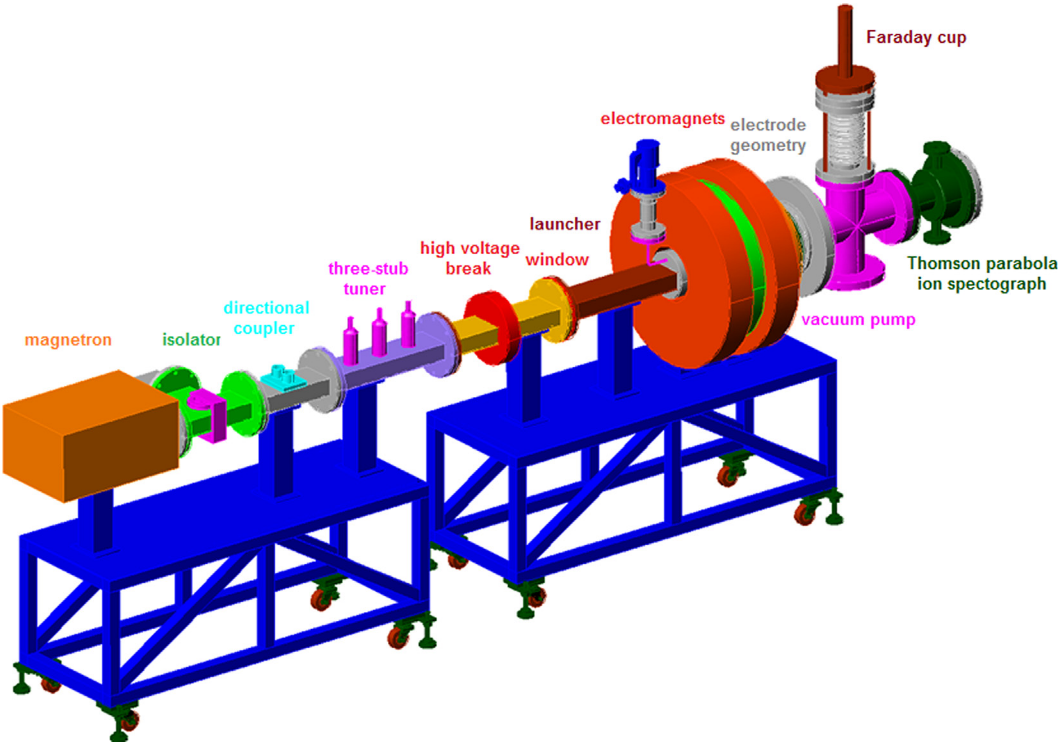


Fig. 1. A schematic 3D-view of the RRCAT-ECRIS.