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UNFOLDING OF BREMSSTRAHLUNG PHOTONS ENERGY SPECTRA EMITTED FROM 28-GHz ECR ION SOURCE

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Abstract

The aim of present study is to determine end-point energies of the bremsstrahlung photons energy spectra emitted from 28-GHz Electron Cyclotron Resonance Ion Source (ECRIS) by using inverse-matrix unfolding method. Azimuthal angular distribution of the bremsstrahlung photons from 28-GHz ECR ion source were measured at Busan Center of Korean Basic Science Institute (KBSI). Gamma-ray detection system consists of three round type NaI(Tl) scintillation detectors positioned 62 cm radially from the beam axis and another detector placed at the extraction port for monitoring photon intensity along the beam axis. Bremsstrahlung photons energy spectra were measured at six azimuthal angles at RF power of 1 kW to extract ^{16}O beam with a dominant fraction of O^{3+} and O^{4+}. Monte Carlo simulation based on Geant4 simulation package was performed to take the geometrical acceptance and energy-dependent detection efficiency into account due to large non-uniformity in the material budget. We extracted true bremsstrahlung energy spectra using the inverse-matrix unfolding method. The unfolding method was based on a full geometry of the Geant4 model of the ECR ion source. The highest end-point energies after unfolding method were found at angles 90° and 330° which both reaches 1.690±0.030 MeV. Therefore, the high end-point energies intensity at angles 90° and 330° were associated with the shape of the ECR plasma.

INTRODUCTION

Electron cyclotron resonance ion sources (ECRIS) are magnetized plasma ion source used to produce intense multiply charged ions taking advantage of accelerating electrons in the magnetic field with a GHz range radio frequency microwave [1]. The magnetic field of the morden ECRIS consists of mirror field (generated from 3 solenoid coils) combined with a hexapole field forming the so-called minimum-B structure. The magnetic field serves two purposes, it fulfills the condition for resonant interaction between plasma electrons and high frequency microwaves launched into the plasma chamber. Due to the resonant nature of the heating process electrons can gain energy beyond those required for efficient ionization which make ECRIS intense sources of bremsstrahlung. This is considered as an unfortunate consequence as it increases heat load of the cryostats of superconducting devices and poses a safety hazard [2].

In the ECRIS high energy bremsstrahlung photons are generated on the plasma chamber walls as a result of the interaction between the wall material and electrons escaping the magnetic confinement and, in the plasma, due to the deceleration and collision of the charged particle. The generated bremsstrahlung photons deposits energy in the structure of ion sources and turns out to be substantial heat load to the cryostat in case of superconducting ECRIS [3]. The cryogenic system can remove only a limited amount of heat from the cryostat. If more heat is added to the system than can be removed, the temperature of the liquid helium rises and can cause the superconducting coils to quench [4].

Bremsstrahlung photons measurements produced in the ECRIS have been made since late 60s. However, many of these experiments used to measure the bremsstrahlung photons energy in only one direction (axially) using one or two detectors but under different conditions [5]. Therefore, this study aims at determining end-point energies of the bremsstrahlung photons energy spectra emitted from 28-GHz ECRIS using the three round type NaI(Tl) scintillation detectors positioned 62 cm radially from the beam axis.

EXPERIMENTAL SETUP

The experiment setup to measure bremsstrahlung photons energy intensity from 28 GHz superconducting ECRIS of the compact linear accelerator facility at the KBSI. ECRIS developed at the KBSI is composed of a six racetrack hexapole coils and three mirror solenoid magnets. The axial magnetic field is about 3.6 T at the beam injection area and 2.2 T at the extraction region, respectively. A radial magnetic field of 2.1 T can also be achieved on the plasma chamber wall. A higher current density NbTi wire was selected for winding of sextupole magnet. The inner face of the 0.05 m thick solenoid coil is placed at a distance of 0.44 m from the beam axis. The 0.10 m thick iron shielding structure is 1.20 cm wide, 1.22 cm high and 1.70 cm long [6].

Bremsstrahlung photons energy spectra were measured using three round type NaI(TI) detection system as shown in Fig. 1 facing the edge of the ECRIS at the injection side. The detectors were labeled with letters D1, D2, D3 and D4, which were operated at +1300 V. The first three detectors were attached on supporting structure as shown in Fig. 1, while D4 was at the view port for monitoring the intensity of the ECR plasma. The photon energy intensity was measured at six angles in a 30° interval. The three detectors system were placed at the two sides of the ECRIS, on the top and left as depicted in Fig. 1.

Each NaI(Tl) detector was placed in a lead (Pb) collimator of a 0.5 cm hole. The Pb collimator covered a full dimension of the NaI(Tl) crystal. The 500 MHz FADC system was used for data acquisition as shown in Fig. 2. The detector signal was fed to splitting module and then to a NKFADC500 and recorded in a coincidence with a reference signal from the detector D4 placed at the view port. The 4-channel flash ADC module (Notice Co.) recorded full pulse information

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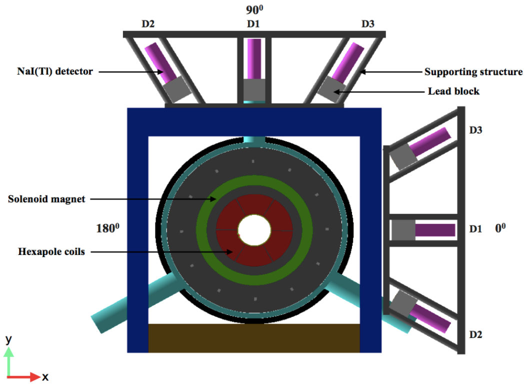

Figure 1: NaI(Tl) scintillation detectors at the injection side of the ECR ion source.

from four NaI(Tl) detectors in every 1000 ns. The ring-buffer data were then fed to a PC. Due to a huge data size the measurement was performed in every 3 minutes. Trigger logic OR provide event triggering condition. The data recorded by using the NKFADC500 flash ADC were in raw binary form. The raw binary data were decoded to get ROOT format data for analysis [7].

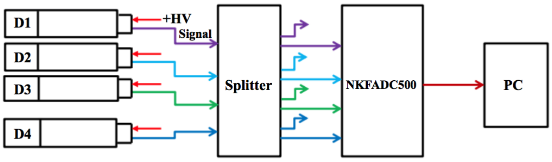

Figure 2: Electronic readout showing the signal from each detector.

DATA ANALYSIS

Energy Calibrations

Throughout the measurement the energy calibration of the spectrum was taken using standard radioactive gamma rays' sources namely, ^{60}Co source with gamma-ray energies of 1173 keV and 1332 keV and ^{137}Cs source gamma-ray energy of 662 keV. Then, the three calibrated data points were fitted using a least-squared chi-square linear fit to convert channel number to its corresponding energy value. The background photon energy spectrum was measured for 10 hours and was normalized with the data taking time and subtracted from the raw spectra for bremsstrahlung photon measurement.

Deconvolution Procedures

The measured spectrum in physical experiment are usually distorted and transformed by different detector effects, such as finite resolution, perturbations produced by the electronic device, etc. In order to reproduce true photon spectrum from the measured distributions it is necessary to take into accounts these effects by means of response function [8]. Normally the response functions are obtained by response matrix. From the basic mathematical relationship, the measured spectrum M(E) can be given as follows:

$$M(E) = R(E, E_0)T(E_0) \,, \tag{1}$$

where T(E_0) is the original or true energy distribution of gamma rays emitted by the source and R(E,E_0) is the response function or sensitive matrix of the detector.

The task is to obtain the true gamma ray spectrum given the measured energy spectrum. Thus, the desired photon spectrum T(E_0) is calculated from the matrix equation as follows:

$$T(E_0) = R^{-1}(E, E_0)M(E) \,, \tag{2}$$

R^{-1} is the inverse of the response matrix.

The procedure for obtaining T(E_0) from M(E) is known as the unfolding (Deconvolution) of the measured spectrum.

Unfolding of Energy Spectrum of Bremsstrahlung Photons

Fig. 3 is describing the comparisons of the unfolded (red histogram) and experimental measured (black histogram) bremsstrahlung photons energy spectra for the detectors D1, D2 and D3 at the injection side of the ECRIS. All measured spectra were normalized to the number of events taken in the same time interval by the detector D4. It is observed that the number of photons yields at the end of the high energy region of the spectrum increases after unfolding technique.

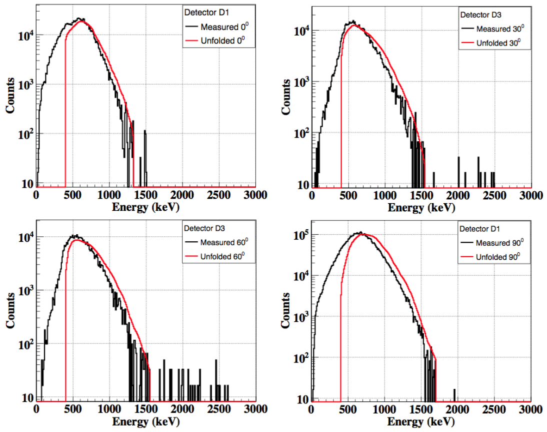

Figure 3: Energy spectra obtained unfolding method.

By the application of inverse matrix unfolding method to the continuous spectrum, the results show a more precise identification of the bremsstrahlung photons end-point energy intensity in the spectrum. The highest end-point energies in a radial direction was observed at angles 90° and 330° which both reaches energy of 1.690 MeV, and this energy value is beyond predicted maximum energy of 1.330 MeV. The maximum energy (T_{max}) that an electron can attain from ECR heating at cyclotron frequency ω can be given as follows:

$$T_{\max} = E_{\max} - m_e \,, \tag{3}$$

where m_e is the mass of an electron and E_{max} is the total energy of an electron.

RESULTS AND DISCUSSIONS

The end point of the spectrum reaches (1.690±0.030) MeV in the radial direction as shown clearly in Fig. 4 for angles 90° and 330° which is beyond the maximum kinetic energy available in the ECR heating. The ECR ion source at the KBSI is operated with f=28 GHz and B_{max}=3.6 T, based on equation (3) the maximum kinetic energy that an electron can attain from the ECR heating at the given frequency is 1.3 MeV which means measured photons energy should have energy less than 1.330 MeV, which is inconsistent with experimental measured energy spectra of the bremsstrahlung photons. It should be noted that, the maximum energy of the bremsstrahlung photons is defined by the energy of the incoming electron.

Moreover, the ECR plasma is formed in the shape of the twisted triangular prism, due to sextupole magnetic fields, [9]. The cross section of the ECR plasma was triangle at the injection side and therefore, the three corners of the plasma triangle correspond to angles 90°, 210° and 330°, this implies that after every 120° there should be a maximum angle. Electrons at three corners of the triangles are accessible to hit the chamber wall and produce the bremsstrahlung photons. The corners at 90° (1.690±0.030) MeV and 330° (1.690±0.030) MeV correspond two of the maximum angles of the plasma triangle while the angles at 210° was not accessible during the measurements. Thus, the high photon intensities at 90° and 330° are associated with the shape of the ECR plasma. The high photon intensity at 30° and 60° cannot be explained with the shape of the ECR plasma. The modulation phase should rotate by 60° between the inverted triangle at the extraction section and the triangle at the injection side.

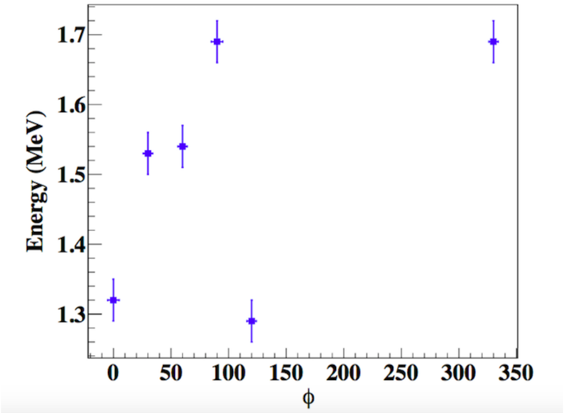

Figure 4: The end points energies distributions of the bremsstrahlung photons at the injection side of the ECR ion source.

CONCLUSIONS

Bremsstrahlung photons energy spectra from the 28-GHz ECR ion source were measured at the injection side. The gamma-ray detection system consists of three NaI(Tl) scintillation detectors placed 62 cm radially from the beam axis and one NaI(Tl) scintillation detector at the extraction port for monitoring photon intensity along the beam axis. At the injection side, the ECR plasma is formed in the shape of the twisted triangular prism, due to the hexapole magnetic fields. The the three corners of the plasma triangle correspond to angles 90°, 210° and 330°, that means after every 120° there should be maximum angle. Electrons at two angles namely 90° and 330° of the triangular shapes at the injection side of the ECRIS can collide easily with the chamber wall and produce the bremsstrahlung photons. Hence, the high photon intensities at angles 90° and 330° can be explained by the shape of the ECR plasma. The gaps between the adjacent hexapole coils could account for high end-point energies observed at angles 0°, 30°, 60° and 120°.

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