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BREMSSTRAHLUNG PHOTONS EMISSION IN 28-GHz ELECTRON CYCLOTRON RESONANCE PLASMA

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Abstract

Radial measurements of bremsstrahlung photons show high-energy intensity beyond a critical energy from electron cyclotron resonance (ECR) heating and its nature is not well understood so far. For the first time we have measured the bremsstrahlung photons energy intensity from 28-GHz ECR ion source at Busan Center of KBSI. Three round type NaI(Tl) detectors were used to measure the bremsstrahlung photons emitted at the center of the ECRIS at the same time. Another NaI(Tl) detector was placed downstream from the ECR ion source for monitoring photon intensity. The ECR ion source was operated at Radiofrequency (RF) power of 1 kW to extract ^{16}O beam with a dominant fraction of O^{3+}. Bremsstrahlung photons energy spectra were measured at the center of the ECR ion source. We studied possible systematic uncertainties from different characteristics among the three NaI(Tl) detectors by repeating measurements alternatively. Geant4 simulation 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 from the 28-GHz ECR ion source using the inverse-matrix unfolding method. The unfolding method was based on a full geometry Geant4 model of the ECR ion source. The high energy intensities of the bremsstrahlung photons at the center of the ECRIS were explained by the internal structure and shape of ECR plasma.

INTRODUCTION

An electron cyclotron resonance ion source (ECRIS) is one of the most used ion source types for high charge state heavy ion production [1]. Most electron cyclotron resonance (ECR) ion source including Korea Basic Science Institute (KBSI), rely on the superposition of solenoid and hexapole magnetic fields for plasma confinement [2]. The ECR plasma state depends on various operation conditions such as radiofrequency (RF) power, the pressure of the injected gas and the solenoid coil current. Also, ECR on sources are usually built for a specific maximum resonance frequency, e.g 28 GHz [3]. The ECR plasma used in this study is 28 GHz was developed as injector equipment for the heavy ion linear accelerator at the KBSI.

In ECR radio frequency microwaves heat plasma electrons in order to provide ionization of neutral gases. As a result of ECR heating very high electron energies are produced which can generates a large amount of bremsstrahlung photons [1,4]. Two process in the ECR plasma lead to the emission of bremsstrahlung radiations in the form of x-rays. First bremsstrahlung is created by electron-ion collisions within the plasma volume. The second process is when electrons are lost from the plasma, collide with the plasma chamber wall and radiate bremsstrahlung due to their sudden deceleration [1,5].

The produced bremsstrahlung photons deposits energy in the structure of ion sources and turns out to be substantial heat load to the cryostat in the case of superconducting ECR ion sources [4,6]. The cryogenic system can remove only a limited amount of the 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 [2].

Bremsstrahlung photons produced in ECR ion source have been made since late 1960s [7]. Nevertheless, many of these experiments used to measure the bremsstrahlung photons in only one direction, axially using one or two detectors but under different conditions. However, since the bremsstrahlung photons emitted from the ECR is expected to be anisotropic due to various effects [5]. This paper presents the first measurements results of the bremsstrahlung photons energy intensity at the center of the ECR ion source at three azimuthal angles.

EXPERIMENTAL SETUP

The data that is presented in this paper was carried out to measure bremsstrahlung photons energy intensity from 28 GHz superconducting ECR ion source of the compact linear accelerator facility at Korea Basic Science Institute (KBSI), cyclotron research centre.

ECR ion source developed at KBSI is composed of a six racetrack hexapole coils and three mirror solenoid magnets [8]. 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 5 cm thick solenoid coil is placed at a distance of 44 cm from the beam axis. The 10 cm thick iron shielding structure is 120 cm wide, 122 cm high and 170 cm long [9].

The experiment setup to measure bremsstrahlung photons spectra in this study is totally different from previous experiment conducted by other researchers. Photon energy spectra were measured using three round type NaI(TI) detectors as shown in Fig. 1 facing the edge of ECRIS at the center of the ECR ion source.

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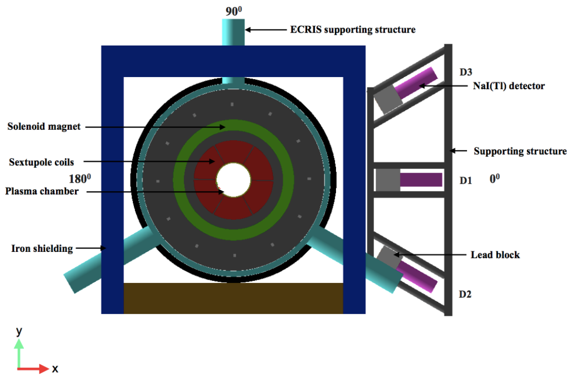

Figure 1: The three NaI(Tl) scintillation detectors at the center of the ECR ion source.

For easy reference, all detectors are labeled with letters D1, D2, D3 and D4, which were operated at +1300 V. The three detectors (D1, D2 and D3) were mounted on the support structure for measurements at azimuthal angles, as shown in Fig. 1, while the D4 detector was mounted at the view port for monitoring the intensity of ECR plasma (Fig. 2).

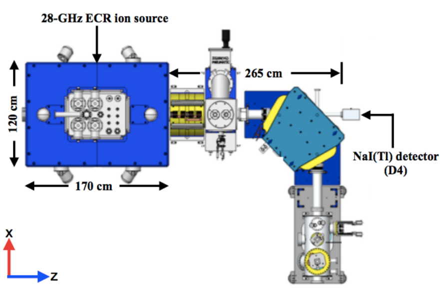

Figure 2: Detector D4 at the view port. The D4 detector was used to monitor a possible variation in ECR plasma intensities throughout the measurements.

The photon energy intensity was measured at 3 angles in a 30° interval at the ECR ion source. The three detectors were attached at a single support structure, and changed the positions, in order to cover the angular region. For a systematic study among the three detectors, the three detectors were replaced at the same angular position.

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 illustrated in Fig. 3.

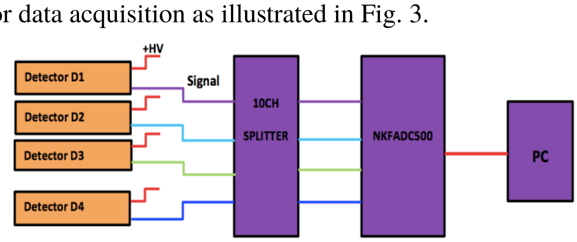

Figure 3: Schematic of an electronic illustration showing the signal from each detector was fed to the splitting module and then to other electronic devices.

The detector signal was fed to splitting module and then to a (500 MHz flash ADC) NKFADC 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 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 [10].

DATA ANALYSIS

Energy and Efficiency 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 [11]. 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.

In order to take the geometric acceptance and also the energy-dependent detection efficiency into account a Monte Carlo simulation based on Geant4 package was performed. To perform a Monte Carlo simulation based on Geant4 package a fully Geant4 model based on the KBSI ECR ion source design was considered during the simulation. Monte Carlo simulation was performed due to complicated structure of the ECR ion source, the material budget differs largely depending on the azimuthal angles.

In the first step Geant4 simulation was performed with gamma ray spectra ranging from 0.1 to 2 MeV with an interval of 0.1 MeV. Then each peak was fitted to the Gaussian functions and the peak region were calculated by taking 1.96σ value which makes 95 % confidence level for the peak region. The peak regions boundary was established as $(\mu - 1.96\sigma, \mu + 1.96\sigma)$ and counts under this region were recorded for each peak and angle.

Unfolding 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 [12–15]. Normally the response functions are obtained by response matrix. From the basic mathematical relationship, the measured spectrum M(E) can be given as follows:

$$M(E) = R(E, E_0)T(E_0)\,, \qquad (1)$$

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.

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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:

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

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. The matrix multiplication of M(E) and $R^{-1}(E, E_0)$ matrices gives another row matrix, which is true gamma ray spectrum of the detector. The pulse height distributions from various mono-energetic gamma ray spectra were obtained from Monte Carlo simulation based on Geant4 package using NaI(Tl) scintillation detector.

RESULTS AND DISCUSSIONS

Deconvolution of Mono-energetic Measured Spectrum

We have checked the correctness of the response matrix by multiplying R and R^{-1} and we have found that all elements along the diagonal are unity while in the inverse matrix all elements above the diagonal are negative numbers. These are physically justifiable. When measured spectrum (column vector M) is multiplied by the inverted matrix R^{-1} due to photons of a given energy the number of photons fall entirely in the channel corresponding to the given energy in the true spectrum (column vector T). Since the diagonal elements are positive the above statement can be true only if all elements above the diagonal are negative [16].

In order to check the practicality of the inverted matrix in the analysis of the continuous gamma ray spectrum we have first used it for the inversion of the spectrum from standard mono-energetic gamma ray source. The use of inverse matrix approach which shifts low pulse height counts into their photo-peak energy region by unscrambling the energy distribution recorded by NaI(Tl) scintillation detector. The typical measured and deconvolute gamma ray spectra are overlaid in Fig. 4. By means of the direct matrix inversion unfolding method, the backscattered peak and Compton continuum are significantly eliminated from the measured spectra into the corresponding photo-peak. In order to quantify the efficiency of the deconvolution technique the peak-to-total ratio (P/T) after applying direct matrix inversion unfolding method was calculated and was increased to 0.93 from 0.50 (0.43 increment) for ^{137}Cs radioactive source. Therefore, the number of counts in the photo-peak region increased approximately by factor of 0.43 after deconvolution.

Unfolding of Energy Spectrum of Bremsstrahlung Photons

This subsection is describing the bremsstrahlung photons energy spectra at the center position of the ECR ion source as represented in Fig. 5. All the measured spectra in azimuthal angles were normalized to the number of events taken in the same time interval by the detector D4. It is observed that

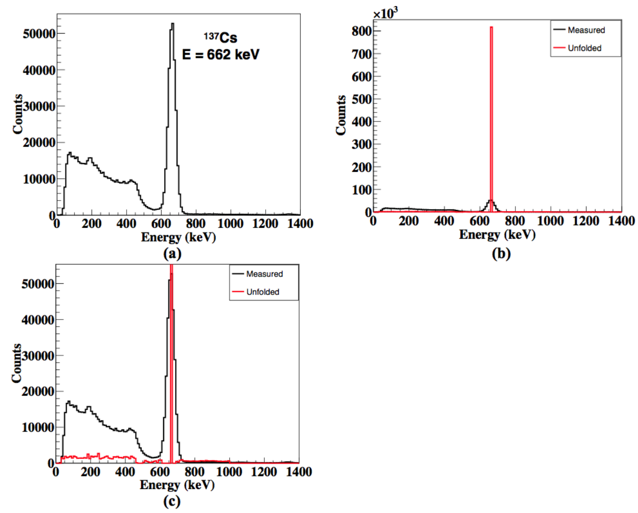

Figure 4: (a) The measured energy spectrum of ^{137}Cs (overlaid as black histogram) (b) The deconvoluted spectrum (overlaid as red histogram) using matrix inversion method.

both spectra at angles 30° and 330° shows the bump around 0.25 MeV for all three configurations.

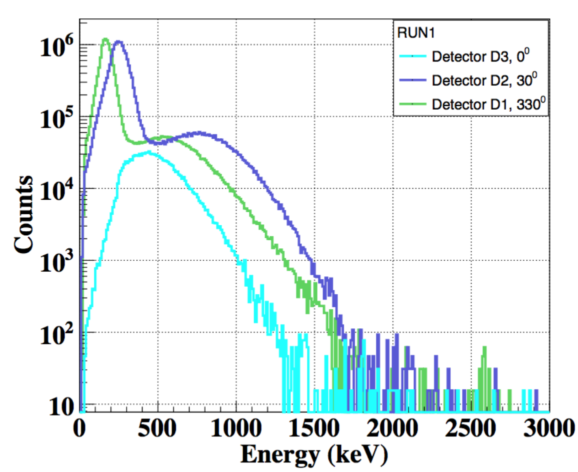

Figure 5: Bremsstrahlung photons energy intensity measured in three angles for detectors D1, D2 and D3.

The comparisons of unscrambled spectra after the application of inverted response matrix to the experimental measured bremsstrahlung photons for the detectors D1, D2 and D3 at the center position of the ECR ion source to all three azimuthal angles are well described by Fig. 6 for RUN1, the other two configurations namely RUN2 and RUN3 shows similar behavior. By the application of inverse matrix deconvolution method to the continuous spectrum, the results show a more precise identification of the bremsstrahlung photons end-point energy intensity in the spectrum. The end-point energies in a radial direction at angle 0° reaches 1.450 MeV while 30° and 330° reaches 1.710 MeV and 1.690 MeV respectively, which 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:

$$T_{\max} = E_{\max} - m_e\,, \qquad (3)$$

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

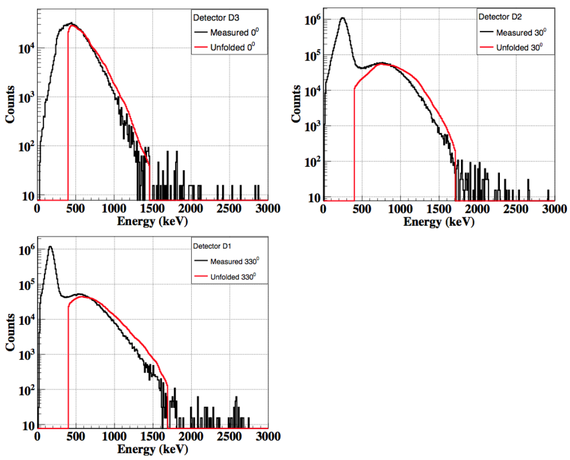

Figure 6: Deconvoluted energy spectra at angles 0° (D3), 30° (D2) and 330° (D1) respectively obtained after unfolding.

CONCLUSIONS

For the first time we measured bremsstrahlung photons energy intensity from the 28-GHz ECR ion source at Busan Center of KBSI at the center position. The detection system consists of three NaI(Tl) scintillation detectors placed 620 mm radially from the beam axis and one NaI(Tl) scintillation detector framed 3500 mm away at the extraction port for monitoring the photon intensity along the beam axis. At the center position, the ECR plasma is formed in the shape basically the same with the six-arm star (hexagon) [17, 18], due to the hexapole magnetic fields. The six corners of the plasma shape correspond to the angles of 30°, 90°, 150°, 210°, 270° and 330°, that means after every 60° there should be maximum angle. During the data measurement, we managed to measure three angles 0°, 30° and 330° other angles were not accessible due to the ECR supporting structure. Electrons at two angles namely 30° and 330° of the hexagon shapes at the center position of the ECR ion source can collide easily with the chamber wall and produce the bremsstrahlung photons. Hence, the high photon intensities at angles 30° and 330° can be explained by the shape of the ECR plasma. The gaps between the adjacent hexapole coils could account for high photon intensity and end-point energy observed at angles of 0°.

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