Characteristic X-ray Radiation Excited by 450 MeV/nucleon C^{+6} Ions and 1.3 GeV Protons in Extracted and Circulated Beams of Accelerator U70

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Abstract
The results of the experimental observation of characteristic X-ray radiation (CXR) excited in solid targets by the extracted and circulated 450 MeV/u C^{+6} ions beams and circulating 1.3 GeV protons beam are presented. The spectra of X-ray radiation measured from different targets are presented and discussed. It was found that the background radiation near the beams is low enough that allows the observation of the CXR spectral peaks with energies from a few to tens keV by semiconductor X-ray detectors. Applications of the CXR for monitoring of the number of accelerated particles in experimental applied and basic research, including radiobiology and radiation medicine as well as the relativistic nuclear physics and steering of beams by bent crystalline deflectors are proposed.

Keywords: characteristic X-ray radiation, proton beam, carbon beam, beam monitoring

1. Introduction

X-ray radiation produced in a target by accelerated particles can be used for a number of purposes. For instance, the characteristic X-ray radiation (CXR) can be applied for monitoring of the number of particles passed through a target, see e.g. [1,2]. The parametric X-ray radiation from a crystalline target can be applied for measurements of the beam transverse dimensions [3] and for online diagnostics of the beam deflection in a bent crystal as well as the bent crystal state [4,5]. However, the radiation background in the vicinity of the accelerator can be significant at measurements of X-ray spectra, see e.g. [6,7]. In present paper we describe results of our measurements of CXR spectra excited in different targets by beams of moderate relativistic energy available in runs 2013/2014. The measurements were performed at 1.3 GeV proton beam and recently developed 450 MeV/u C^{+6} ions beam [8] at accelerator U70, Protvino, Russia.

2. Experimental

The experiments with extracted 450 MeV/u C^{+6} ions beam were performed at channel #25 of the accelerator U70. The beam of diameter about 100 mm passed through the air and crossed the targets. The beam intensity was about $5*10^8$ ions per cycle. The beam pulses of duration 1200 ms were emitted by the accelerator every 8 s. The targets and the X-ray detector were installed in air, as it is shown in Fig. 1. The targets usually consisted of two foils/plates of different materials installed close one to another. The transverse size of the targets was about 20 – 50 mm. The X-ray spectrometer consisted of the silicon X-ray detector XR100SDDfast and digital pulse processor PX4. Some of measured X-ray spectra are shown in Figs. 3–6. The targets and experimental conditions for every measurement are described in the figure captions.

The experiments with circulating 450 MeV/u C^{+6} ion and 1.3 GeV proton beams were performed at 32th section of the main accelerator ring. The beam pulses of duration 0.3–2 s followed every 8 s. The transverse beam sizes were 15 and 10 mm in horizontal and vertical directions respectively, the divergence was ±0.5 mrad in both directions. Experiments with two targets and two X-ray spectrometers were performed simultaneously in two X-ray stations installed at distance 0.8 m one from another in 32th section of the ring. The thin foil targets of size 20×50 mm were inserted into the beam in vacuum and covered all cross section of the beam, as it is shown in Fig. 2. The CdTe X-ray detector XR100T and digital pulse processor PX4 were used for measurements of spectra of X-ray radiation from 20 μm thick W target and silicon X-ray detector XR100CR with digital pulse processor PX5 were used for measurements of spectra of X-ray radiation from 60 μm Ti target. The detectors were installed in vacuum at distance 180 cm from the targets. Measured spectra of X-ray radiation excited by carbon beam are shown in Figs. 7,8 and ones excited by proton beam are shown in Figs. 9,10.

The semiconductor X-ray detectors and digital pulse processors produced by Amptek were used in all applied X-ray spectrometers. The energy calibration of the X-ray spectrometers has been performed with use of the radioactive source ^{241}Am.

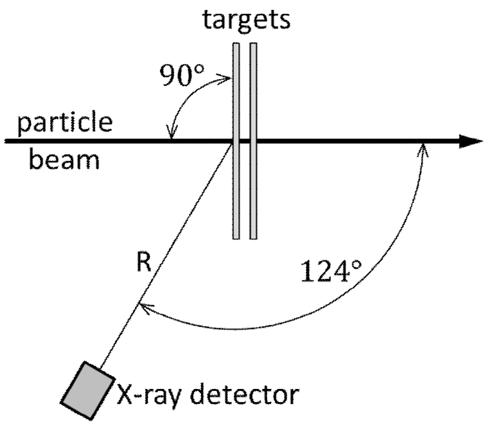

Figure 1. Experimental arrangement in measurements of CXR excited by extracted carbon beam.

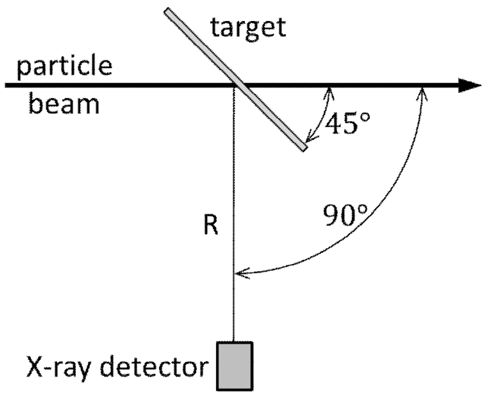

Figure 2. Experimental arrangements in measurements of CXR excited by circulating proton and carbon beams.

3. Results and discussion

Measured spectra of X-ray radiation are shown in Figs. 3-10 without any background subtraction. The spectral peaks of K- and some L- lines of the CXR from the atoms of the targets are clearly seen in all spectra. Besides, K-radiation of Br atoms from the dosimetric film is seen in Fig. 5. The escape peaks in Figs. 8,10 arise due to properties of the CdTe detector.

Note a good energy resolution of the X-ray spectrometers. The full width at half of maximum (FWHM) of the Ti K_α spectral peak is equal to 150 eV in the spectrum measured with the extracted carbon beam by the Si detector XR100SDDfast (Fig. 5) and 220 eV in the spectra measured with the circulating carbon beam by the Si detector XR100CR (Figs. 7,9).

The lowest spectral background was observed at application of Si X-ray detectors. The peak/background ratio reaches values about 100 in spectra measured with carbon and proton circulating beams shown in Figs. 7,9. The spectral background increases at application of CdTe detector, especially at energies below 10 keV, see Fig. 10.

The Ge singlecrystal plate target was installed in a goniometer. Our attempts to observe the orientation dependence of the Ge crystal CXR yield relative to Nb foil CXR yield (see Fig. 3) in the vicinity of the main crystallographic axes and planes of the crystal were not succeed. The reason could be in a significant divergence of the extracted carbon beam.

The results of spectrometric measurements with different intensities of circulating 1.3 GeV proton beam are shown in Figs. 9,10. One can see that the registered CXR yield increases nonlinearly on the proton beam intensity. The nonlinearity could arise due to the overloading of the digital pulse processors of the X-ray spectrometers during the beam pulses.

The result of the measurements of the spectral background without any target in circulating proton beam is shown in Fig. 10. One can see that the most of the spectral background arises due to insertion of the high-Z target into the beam.

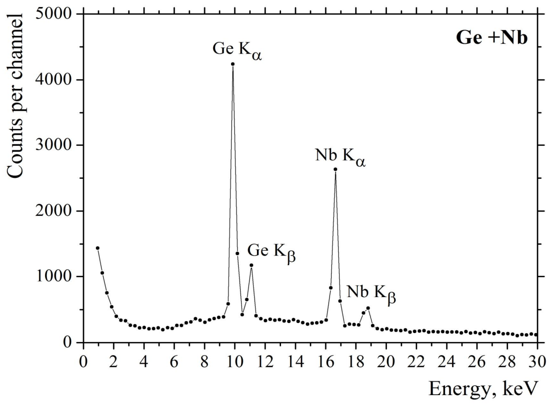

Figure 3. The spectrum of X-ray radiation measured at interaction of extracted 450 MeV/u carbon beam with 0.5 mm thick Ge crystal plate and 15 μm Nb foil. The detector was at distance 56 cm from the target. The exposure time was 193 min.

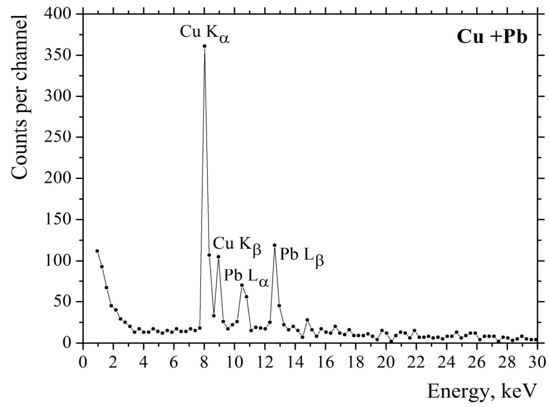

Figure 4. The spectrum of X-ray radiation measured at interaction of extracted 450 MeV/u carbon beam with 0.5 mm thick Pb plate and 20 μm Cu foil. The detector was at distance 56 cm from the target. The exposure time was 59 min.

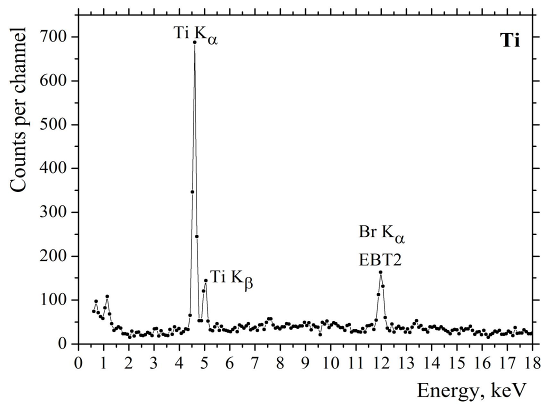

Figure 5. The spectrum of X-ray radiation measured at interaction of extracted 450 MeV/u carbon beam with 60 μm Ti foil and dosimetry film EBT2. The detector was at distance 20 cm from the target. About 4×10^9 carbon ions passed in the beam during the measurements. The exposure time was 732 s.

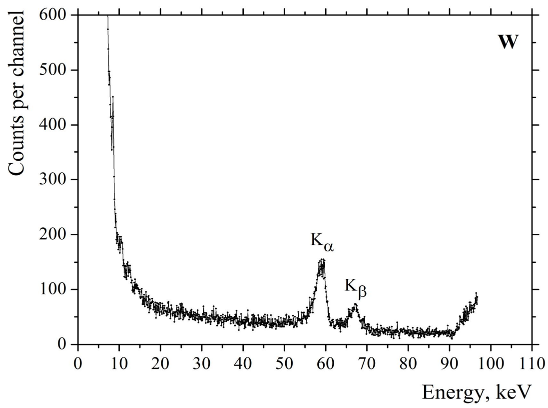

Figure 6. The spectrum of X-ray radiation measured at interaction of extracted 450 MeV/u carbon beam with 1.5 mm W plate. The detector was at distance 20 cm from the target. About 7×10^9 carbon ions passed in the beam during the measurements. The exposure time was 678 s.

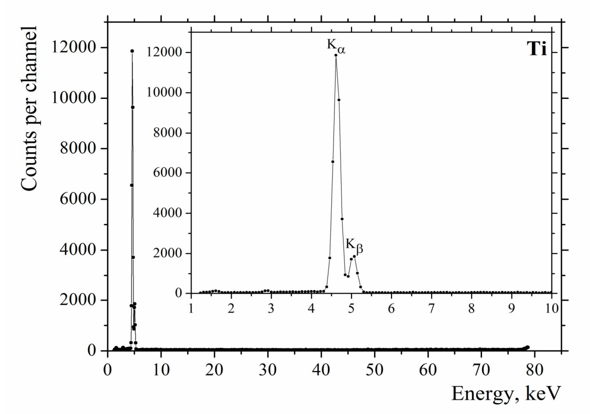

Figure 7. The spectrum of X-ray radiation measured at interaction of 36 cycles of circulated 450 MeV/u carbon beam with 60 μm Ti foil at 2.5×10^9 ions/cycle.

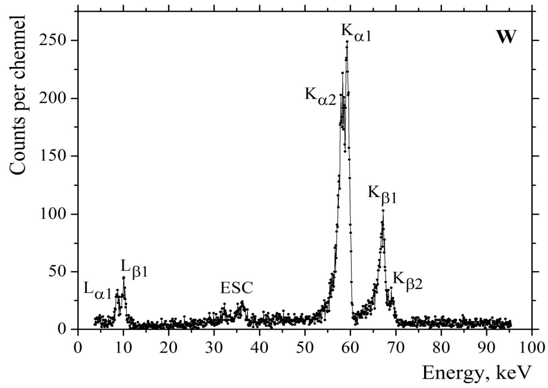

Figure 8. The spectrum of X-ray radiation measured at interaction of 36 cycles of circulated 450 MeV/u carbon beam with 20 μm W foil at 2.5×10^9 ions/cycle.

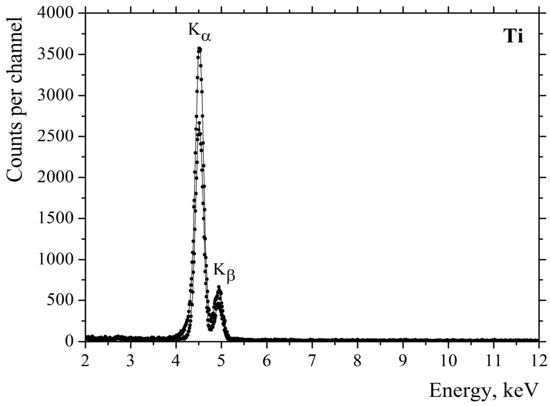

Figure 9. Spectra of X-ray radiation measured at interaction of 434 cycles of circulated 1.3 GeV proton beam with 60 μm Ti foil. Upper line shows the spectrum measured at 2×10^{11} protons/cycle, lower line shows the spectrum measured at 1×10^{11} protons/cycle.

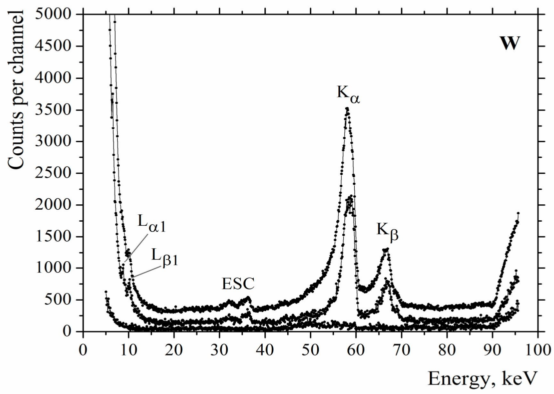

Figure 10. Spectra of X-ray radiation measured at interaction of 434 cycles of circulated 1.3 GeV proton beam with 20 μm W foil. Upper line shows the spectrum measured at 3×10^{11} protons/cycle, the middle line shows the spectrum measured at 1×10^{11} protons/cycle, the lowest line shows the spectral background measured with removed target at 3×10^{11} protons/cycle.

4. Applications of the CXR

We propose application of the CXR for online monitoring of the number of particle in both circulating and extracted beams.

In the circulating beam, a thin foil target can be installed across the beam in the ring. The CXR yield from the target would provide information about the number of interactions of the circulating particles with the target.

In the extracted beam, a thin foil target can be installed across the extracted beam before the object under irradiation. The CXR yield from the foil would provide information about the number of particles incident the object. For example, the dose of radiation provided by the beam for medical objects can be controlled by the CXR yield from a thin foil.

In the experiments on steering of the beam by a crystalline deflector, the CXR from the deflector can give information about the number of particles that passed through the deflector.

5. Conclusion

In present paper, we have demonstrated experimentally the real possibility to perform spectrometric measurements of the characteristic X-ray radiation excited in solid targets by extracted and circulating 450 MeV/u carbon and circulating 1.3 GeV proton beams at accelerator U70. Spectra can be measured in the energy range from a few to tens of keVs, the energy resolution in measured spectra may be up to about 150 eV, the peak/background ratio can reach about 100. The spectral background may be low enough at installation of the X-ray detectors at distance a few tens of centimeters from the beam. Silicon X-ray detectors provide better peak/background ratio. The experiments with full energy of accelerated at U70 particles are desirable to clear up the features of the CXR, PXR and spectral background at higher beam energies.

Applications of the CXR for monitoring of the number of accelerated particles in experimental applied and basic research, including radiobiology and radiation medicine as well as the relativistic nuclear physics and at interaction of particles with bent crystalline deflectors are proposed. The applications are possible in the accelerator U70 and other similar machines, e.g. in CERN.

6. Acknowledgements

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