BUNCH LENGTH DETECTOR BASED ON X-RAY PRODUCED PHOTOELECTRONS*

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Abstract

We have developed and tested an X-ray based Bunch Length Detector (X-BLD) for application in ion accelerators. X-rays produced as a result of ion beam interactions with matter are used to generate photoelectrons. The photoelectrons are analyzed by an RF deflector synchronized with the master-oscillator, similar to the BLDs based on secondary electrons. The expected time resolution is several picoseconds. The proposed X-BLD is particularly useful for the measurement of CW heavy-ion beams passing through a stripper foil or film in a high-power driver accelerator. The results of the X-BLD commissioning and beam bunch profile measurements at the ANL heavy-ion CW ATLAS accelerator are presented.

INTRODUCTION

One of very important beam parameters in accelerators to be measured is bunch time distribution or bunch length as it is most commonly referred. In proton and ion accelerators, the beam instrumentation for the measurements of beam parameters in the transverse planes, beam energy and phase centroids are well established while there are no devices to provide picoseconds-level measurements of bunch time structure. Bunch length measurements are especially important in high-intensity ion accelerators for appropriate accelerator tuning and preventing excessive beam losses.

Currently, the bunch length measurements of proton, H-minus and ion beams are most commonly performed using a Bunch Length Detector based on secondary electrons (SE-BLD) [1, 2]. The secondary electrons are produced as an interaction of the ion beam with a thin wire inserted into the beam. The time resolution of the SE-BLD is about 15 psec and limited by time delay of secondary electron production, non-uniform field for the electron acceleration, and energy and angle distributions of the electrons. Also, this detector requires a thin wire which can not withstand under high-intensity beam irradiation due to overheating. In this paper we propose an X-ray based Bunch Length Detector (X-BLD) with expected time resolution less than 5 psec.

X-RAY BASED BUNCH LENGTH DETECTOR

The general layout of proposed X-BLD is shown in Fig. 1. The detector utilizes X-rays that are produced due to the interaction of ions with a stripper foil (or flowing liquid metal film) in heavy-ion linacs. A low-density pulsed gas target can be used as a source of X-rays in high-power linacs. Ion-atom collisions produce inner shell vacancies of both projectile ions and target atoms with subsequent emission of characteristic X-ray spectra [3, 4].

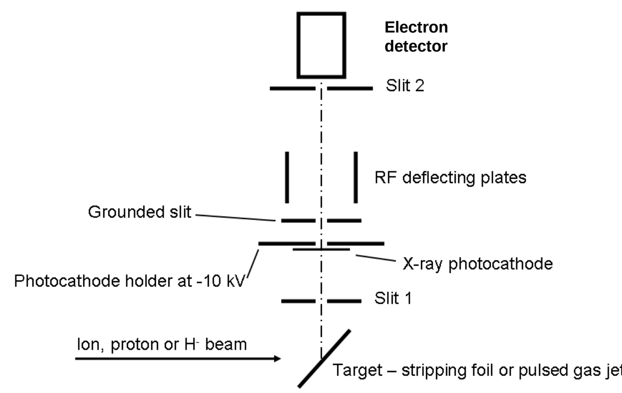

Fig. 1. General layout of the X-BLD.

The decay time of K-shell vacancies are of the order of $10^{-10}/Z^4$, where Z is atomic number of projectile ion or target atom [4]. The decay time of K-shell vacancies are below 1 ps for all elements heavier than helium. The energies of characteristic K lines are, typically, in the range of 1–20 keV and their intensities are one-two orders of magnitude higher than the continuum [5].

A CsI X-ray photocathode can be used to convert X-ray photons with energies in the range of 0.1–10 keV into low energy electrons with narrow energy dispersion (about 1.5 eV) [6]. Time structures of both X-rays and photoelectrons are identical to the time structure of bunched ion, H-minus or proton beam with very high accuracy. A slit in the front of the photocathode (see Slit 1 in Fig. 1) can be used to minimize the effect of ion beam and target size on the time resolution. The time distribution of the ion, H-minus or proton bunch is coherently transformed into a spatial distribution of the photoelectrons through transverse modulation by the RF voltage as is done in SE-BLD [1, 2]. A transverse deflection angle of the electrons depends on the phase of deflecting field. The intensity of the electron beam downstream of the slit 2 (see Fig. 1) can be measured by a Secondary Electron Multiplier (SEM). This intensity is a function of the phase of the RF deflector field and equivalent to the bunch time profile. Total ion beam longitudinal charge distribution is obtained by changing the phase of the RF deflecting field. Transverse deflection and registration principle are similar to those used in a SE-BLD [1, 2].

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Heavy-ion accelerators usually require a stripping foil. X-rays generated by ion beams at stripping foil can be utilized for the bunch length measurements. In this case, the measurements are completely non-destructive. Similar approach can be used to measure bunch length at the location where H-minus is converted to protons. For proton beams and high power ion beams a pulsed gas jet [7] can be used as a target to generate characteristic X-ray spectra. Heavy gases, like xenon, are more preferable as they provide higher output of characteristic X-rays [4]. Pulsed gas jet with a nozzle opening of about 1 ms, typical diameter of about few mm and pressure of about 1 Torr is suitable for this purpose. This technology is very well established and widely used in different applications. Energy loss of ion or proton beam can be kept below tolerable level by adjusting gas pressure. Another attractive approach for high power beams can be utilization of metal microparticles with a size in the range of 0.1 – 100 µm dropping across the beam. Such low-cost metal microparticles are commercially available.

The proposed X-BLD has a number of significant advantages as compared to the SE-BLD:

- X-BLD can be used for high power ion, H-minus and proton beams where SE-BLD is not applicable due to overheating or damage of the wire target.
- The X-BLD does not require any additional space or targets along the beam line if stripping foil is used as a target.
- Time resolution of the X-BLD is higher than time resolution of SE-BLD because
  a) X-ray generation is much faster process than secondary electron generation,
  b) energy dispersion of photoelectrons is about factor of 10 lower than the energy dispersion of secondary electrons.

X-BLD TESTING AT ANL ATLAS FACILITY

We have developed and built an X-BLD to conduct a proof-of-principle experiment at Argonne Tandem Linear Accelerating System (ATLAS). General view of the X-BLD incorporated into ATLAS beam line downstream of the booster linac and X-BLD 3D model are presented in Figs. 2 and 3 respectively. Commercially available CsI photocathode [8] is sensitive in energy range of 0.1-10 keV and is used to convert X-rays to photoelectrons. Thick water-cooled copper target was driven by compressed air cylinder between two positions: “in” and “out” of the beam. Ion beam hits target at 45º incident angle and X-rays are detected normally to the target surface. The RF deflector and dual MCP – phosphor screen is the same as used previously for the SE-BLD [9]. An electron beam image produced on phosphor screen was acquired by a CCD camera and sent to the control PC for analysis. The LabVIEW based software is used to control all power supplies and provide on-line data analysis.

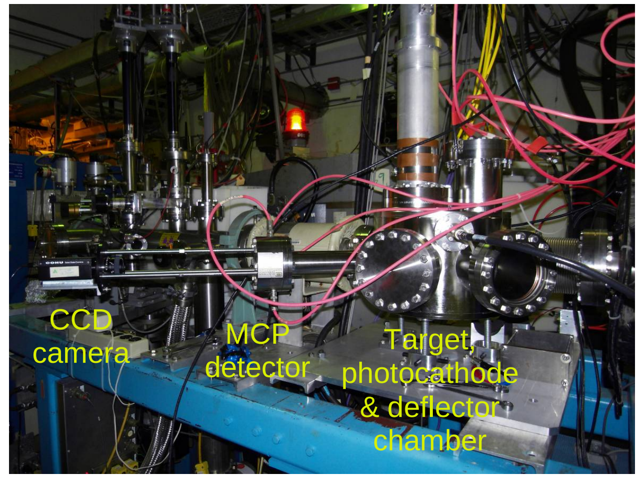

Fig. 2. General view of the X-BLD incorporated into the ATLAS beam line.

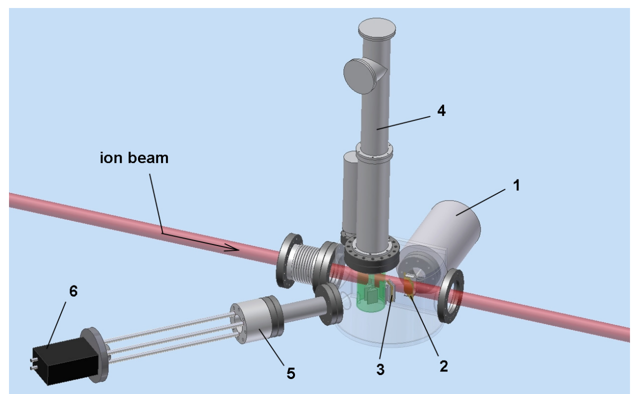

Fig. 3. 3D model of the X-BLD: 1 – target translator, 2 – Cu target, 3 – CsI photocathode, 4 – RF deflector, 5 – dual MCP – phosphor screen, 6 – CCD-camera.

The CsI photocathode dimensions are 1×10 mm^2. The photoelectrons are collimated to the width of 0.1 mm by the grounded slit downstream of the photocathode forming electron beam with initial dimensions of 0.1×10 mm^2. Fig. 4 shows the image of photoelectron beam on the phosphor screen obtained before the RF deflector is turned on. The RF deflector plates are isolated and biased to provide one-dimensional focusing of electrons onto the phosphor screen. The FWHM electron beam image width is ~0.4 mm as is seen from Fig. 4.

The X-BLD has been used to measure bunch length of low-energy oxygen beam with intensities up to 0.5 eμA. Particularly, Fig. 5 shows a bunch length of 1.6 MeV/u oxygen beam. We have also measured bunch center of 9 MeV/u oxygen beam as a function of the RF phase in the last accelerating resonator of the ATLAS booster. The X-BLD is located ~4 m downstream of this cavity. Variation of the resonator RF phase results in a beam energy change. Consequently, the bunch center phase depends on the resonator phase as is plotted in Fig. 6.

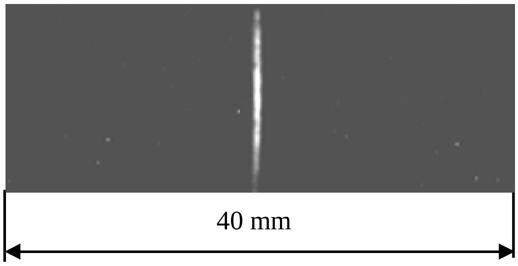

Fig. 4. Image of photoelectrons on the phosphor screen without RF deflection.

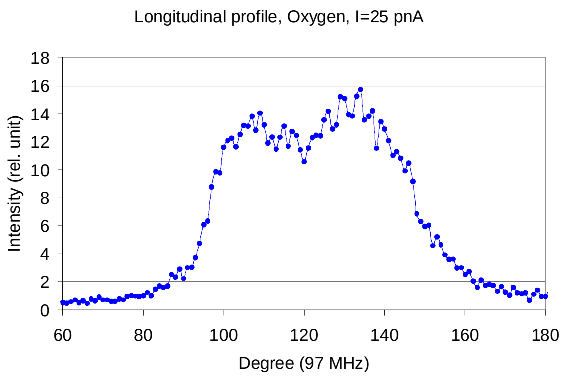

Fig. 5. Typical longitudinal profile of the 1.6 MeV/u oxygen beam.

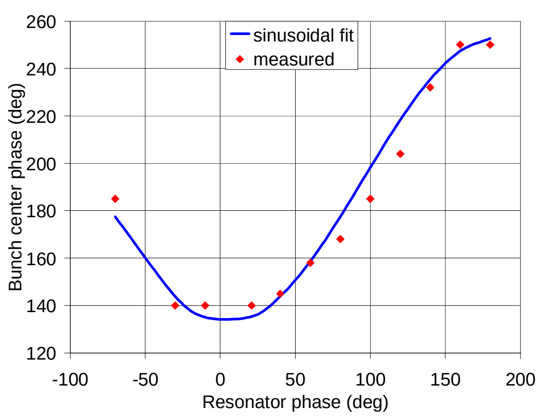

Fig. 6. Bunch center phase as a function of the RF phase in the last RF cavity (97 MHz) of the booster.

POSSIBLE IMPROVEMENTS OF X-RAY BLD FOR HIGH INTENSITY ION BEAMS

The X-BLD has been built to prove the concept and we have not expected high resolution of bunch time structure measurements in this particular design performance. Due to the very low intensities of available ATLAS beams, the detector was designed to collect as much of X-rays produced on the target as possible. The time resolution is limited by large dimensions of the X-ray production area and the lack of an X-ray collimation upstream of the photocathode. X-rays produced over whole area of beam-target interaction are responsible for photoelectron production with the X-ray energy-dependent efficiency defined by the photocathode.

Temporal resolution and X-ray selectivity of X-BLD can be further improved by incorporating into the detector an X-ray spectrometer based on spherically bent mica crystals. The spectrometer should be installed between beam target and X-ray photocathode. The spherically bent crystals combine the Bragg reflection properties of the crystal lattice with regular reflection optics of spherical mirrors [10], thus providing high luminosity together with high spatial and spectral resolutions. It is very attractive for bunch length measurements to use the K-shell projectile and target atom X-ray radiation lines induced due to ion-atom collisions because the decay time of an inner shell vacancy is extremely short (below 1 ps for all elements heavier than helium). One can mention potential advantages of X-BLD combined with X-ray spectrometer due to full suppression of background x-ray continuum spectra, which may have longer decay time than decay time of inner shell vacancies.

CONCLUSION

We have developed and tested an X-ray based Bunch Length Detector (X-BLD) for application in ion accelerators. The sensitivity of X-BLD is high enough to measure bunch length even for ion beams with quite low intensities such as 210 enA/25 MeV $^{18}O^{7+}$. Temporal resolution of an X-BLD can be improved for high intensity ion beams by incorporation of an X-ray spectrometer into the device. The electron beam detection based on MCP-phosphor system used has low dynamic range and requires improvement.

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