DEVELOPMENT OF A BEAM PROFILE MONITOR USING NITROGEN-MOLECULAR JET FOR INTENSE BEAMS *

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Abstract

A non-destructive beam profile monitor using a sheeted jet beam of nitrogen molecule as a target has been developed for intense proton beams. The pressure of the sheeted target was 5e-4 Pa at the beam collision point. For beam core region, light emitted from nitrogen excite-deexcite process by proton beam collision is measured by a high sensitive camera with a radiation resistant image intensifier. For beam tail region, ionized electrons are used for detecting. Design study of such a hybrid type detector is discussed mainly in this paper.

INTRODUCTION

By using molecular jet as a thin planer target for beam profile measurement, the collision point with the proton beam is able to determine clearly. In addition two-dimensional beam profile can be obtained. Mainly two physical processes of ionization and excitation (and deexcitation) in the collision can be considered for beam profile detection.

Detecting method of using electron or ion produced by ionization due to proton beam collision is ordinal [2]. In this method detecting efficiency is higher and measurement can be done in short time as within a bunch length of 100ns. If confinement for electron or ion collection is possible, this method has advantage than light detection. On this method an electron or an ion is entered into multiplication device like a micro channel plate (MCP). Because yield of electron or ion is extremely high in case of high intensity proton beam, the gain of multiplication easily becomes lower due to hitting damage, so the gain should be calibrated as accurate as possible. This is additional problem to the electron or ion detection.

In measuring beam profile of high intensity beam, beam tail's signal is important as well as beam core's. Because beam tail has an effect on limiting on performances of the accelerator such as beam loss and some beam instability.

In former design [1], only beam core's signal detection with deexcitation light of nitrogen molecule was considered for fast detection as within a bunch separation time. If precise beam tail measurement is able at the same detecting point, it has advantageous characteristics for accelerator operation and beam physics.

Considering above points of view, we are now studying design on hybrid method of electron and photon detection for simultaneous profile measuring of beam core and tail using molecular-jet beam.

HYBRID TYPE DETECTION

Our monitor employs a sheeted nitrogen molecular target. In collision on the target with proton beam, reaction of ionization and excitation occurs on the nitrogen molecules. These phenomena produce the ionized pair of electron and nitrogen-molecule ion, and photon respectively. It is an effective method that using the deexcitation light in the part of beam core having rich proton density, and on the other, using ionized nitrogen molecule in the part of beam tail having poor proton density. At the former part, accurate collection of ionized electron or ion is rather difficult because of strong induced electro-magnetic field by dense proton beam, so the light detection has an advantage as free from such a violate field. On the contrary, at the latter part, a light detection becomes difficult because of poor photon yield. In this part beam field's effect also be reduced by distance from beam center, so a method using the produced electron or ion is advantageous than the light detection. Besides collecting efficiency at a detector is almost full in case of using electron, it is about 10% in case of using photon in which solid angle of a first optical element limits the detection yield.

Number of produced pair of electron and ion on ionization is larger than produced photon number on deexcitation at the same energy of incident proton beam. Production energies of electron with ion and photon of visible light region are 35 eV and 3.6 keV respectively [3].

Concerning these detection methods, we have already demonstrated. The light detection method was verified with low energy ion beams [1], and ion detection type monitor has been already realized in the medical ion synchrotron of the HIMAC [2].

DETECTION EQUIPMENT DESIGN

Horizontal and vertical cross-sectional views of colliding region of the jet beam with the proton beam are presented in Fig. 2 and Fig. 3 respectively. The jet beam of nitrogen molecule is formed as a sheeted target at the collision point.

Nitrogen Molecular Jet Beam

Expected dimensions of the target are as follows: thickness of 1-3 mm, width of 50-100, and length of 100-200 mm (in duration time of 140-280 μs). The jet runs with a terminated velocity by jet process of about 730 m/s after skimmer. The target thickness is determined by width of final slit located exit of the jet generator. Due to the thickness yields an error on measured beam size, it is

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desired be as thin as possible, but produced light becomes lower.

Bench tests are running for developing denser molecular target (Fig. 1), and present obtained specification shows in Table1. Molecular density on the target which is about located 500 mm away from nozzle is reached 5e-4 Pa in pressure at room temperature. Five or ten times larger density to the current is expected.

Table 1: Obtained Specification of the Jet Generator

Parameter	**Value**
Pressure of Molecular Beam	5e-4 Pa @ 4th chamber
Pulse Duration	100-1000 µs
Source Pressure	0.8 MPa
Nozzle Size	2.4 mm dia.
1st/2nd Skimmer Size	3.5^H x 3.5^V/40^H x 6^V mm^2
Target Cross Sectional Size	53^W x $(1\text{-}5)^t$ mm

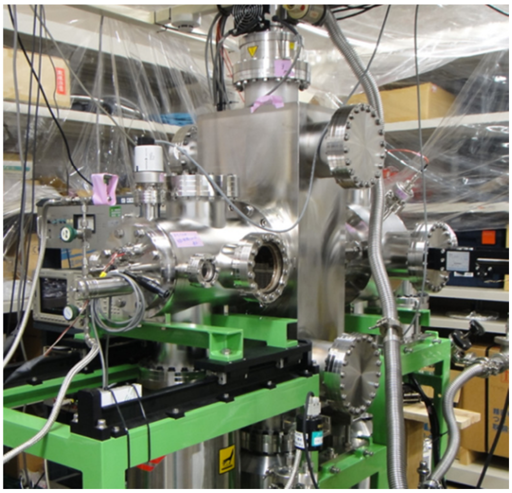

Figure 1: Molecular jet generator for developing dense target. Four chambers line up: from leftside, first nozzle and skimmer chamber, rectangular chamber which is joined second chamber including second skimmer and third chamber including collimating slit, and this chamber has thickness of 220 mm, and final fourth detector chamber.

Beam Core Detection

The jet target has a cross angle of 45 degree to the circulating proton beam (Fig. 2). In the collision, ionization and excitation-deexcitation will occur. Beam core is measured with using deexcitation light of nitrogen molecule [3]. Its wavelengths of 390-410 nm are employed because of its shorter decay time of about 60 ns [3].

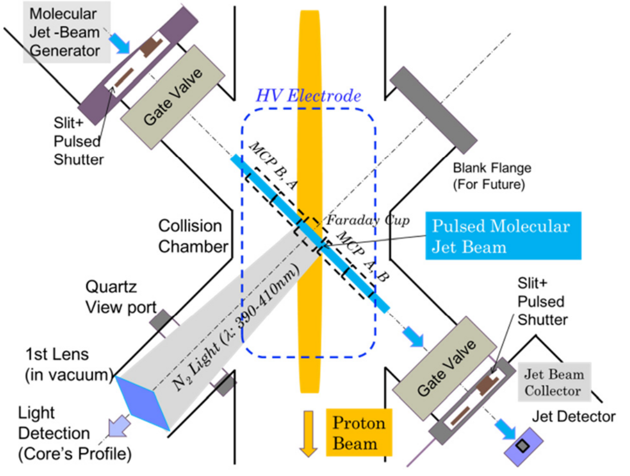

Figure 2: Horizontal cross-sectional schematic view of collision point.

Normal direction of the target is to be the axis of an optical measurement system. For high speed measurement such as one bunch detection, due to poor light yield, the first element of the system to be positioned as close as possible to the target, and its aperture is to be as larger as possible. One suitable choice is an Offner relay system having large aperture of 300 mm [4]. Without deformation and any aberration, its covered area for imaging could be amounts to 90 x 160 mm^2. This optics should be install in a vacuum separated with accelerator's, because of avoiding light produced by collision of atmospheric nitrogen with loss particle or so. Behind the optics, a radiation-hard image intensifier (I.I.) [1] having two micro channel plates receive the light and multiple its photoelectron. An estimation of produced photon number is about 5e5-5e6 /bunch with conditions as follows: bunch population of 1.6e13 proton, beam energy of 3 GeV, target thickness of 1mm, and nitrogen molecule density in the target of 5e11-5e12/cm^3.

After the I.I., a camera having high sensitivity and high dynamic range of 4 orders or higher is suitable, like HARP electron tube device (57 dB in signal to noise ratio)[1]. Because that an overlap area between beam core and tail is to be recognized as precisely as possible. If necessary, by using image bundle fiber made of quartz, the camera should be located far from hot radiation area (over several-tens kGy).

Beam Tail Detection

By using high electric fields which are generated in normal direction to the beam median plane (Fig. 3), the ionized particles run toward the electrode which has opposite polarity to the particle itself. In this situation, the ionized nitrogen molecule is more affected than electron by the beam-induced field, because the transport velocity of molecules is very slow due to the larger mass. So electrons are employed for the beam tail detection. In case that the electrode gap is 150 mm, it is enough to set +/- 30 kV at the upper and lower electrodes respectively. In electron collection scheme the guiding magnetic field is also added for confinement. By the field, cyclotron motion will occur during electron transportation, such that a radius of the motion is about 1mm at the kinetic energy of about eV with field strength of 0.01 T.

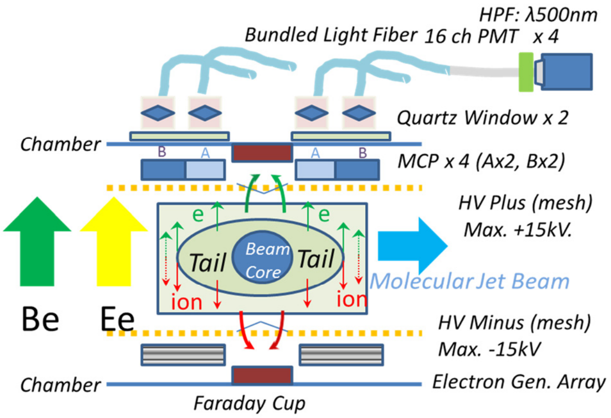

Figure 3: Vertical cross-sectional schematic view of collision point.

Key point is distinction between beam core and tail region. In beam tail detection region some electrodes and micro-channel plates will be needed to employ. On their geometry and fields design for ionized particle collection, simulation of proton beam field and tracking of generated ionized particle are needed. A simulation for electron transportation calculation was done with CST studio suite [5] using time domain solver.

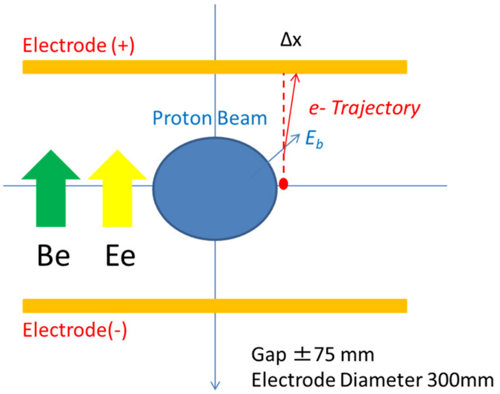

Figure 4: Transient analysis on electron collection.

In the simulation, specifications of Gaussian proton beam bunch were as follows: longitudinal σ was 20ns, intensity was 2e13 protons, and radius is 9 mm. Simultaneously during proton running time of about 200 ns, electrons were produced in the beam median plane (Fig. 4). Reached position of electron at 75 mm distance of upper positive electrode (this point was supposed to our detector) was calculated. Energy distribution of electron was Maxwellian and the energy was truncated at 1eV.

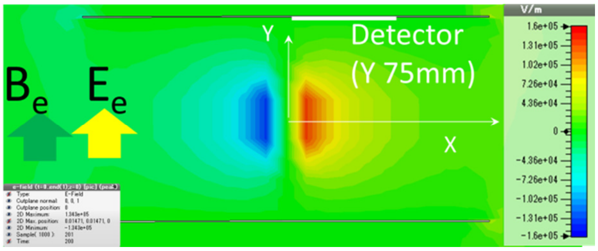

Figure 5: Electric field strength at bunch peak.

Figure 5 shows electric field induced by bunch at the time of peak current. Maximum strength value of electric field is 1.6e5 V/m at 9 mm apart from beam center in the median plane. At outside of beam, the strength is inversely proportional to the distance.

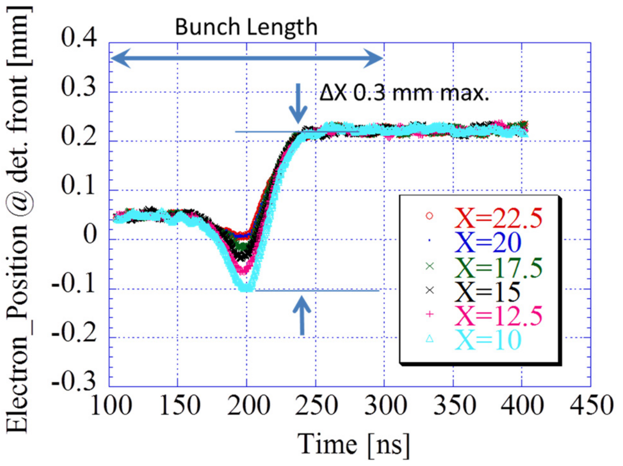

Figure 6: Horizontal position deviation of electron.

Figure 6 shows horizontal position deviation of collected electron at the upper positive electrode. The X axis means distance from beam centre on the beam median plane. These electrons were produced from beam fringing of X= 10 towards outside of the beam with a step of 2.5 mm. Plotted value is deviation of generated X position from reached X position at the upper electrode. This calculation was intended to estimate electron collection accuracy at beam fringing and beam tail part under condition as follows: electric collection field of 30 kV/ 75 mm, and guiding magnetic field strength of 0.05 T. This result shows the deviation of electron collection position is only within 0.3 mm at a region of beam fringing. Note that plotted data after time of 250 ns of +0.23 mm means some effect by wake field, it should be refined for actual model.

In this way beam profile of so called tail part of the proton beam is detected with electron. Actually foursome micro channel plates (MCP) attached to the positive electrode are employed as shown in Fig. 3. For entire scheme on beam profile measurement, Fig. 7 shows detection ranges with segmentation concerning for detection method and detection sensitivity. Like this segmentation, dynamic range of detection is up to 5 orders or higher.

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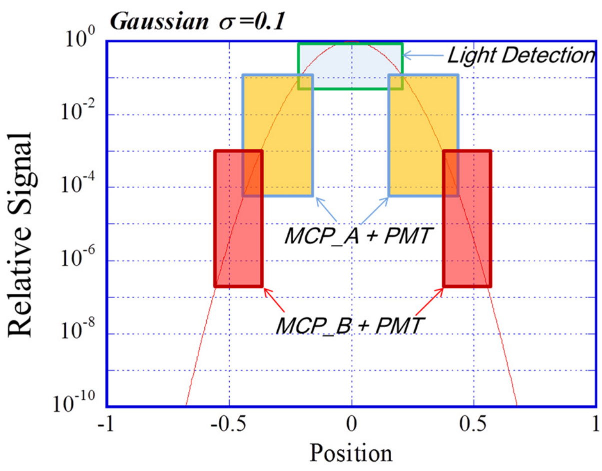

Figure 7: Dynamic range for universal Gaussian beam assumed bunch intensity of 2e13 proton or higher, colored by detector segment.

In electron collection any other electrons which are produced at outside of the target like residual gas collision should be kept out. For this purpose, the electron reachable area on the electrode's surface will be made of thin wire mesh, and MCPs are positioned behind of it. In such MCPs having two stages, secondary electrons produced in the channel are able to be multiplied until 1e6 in maximum. After the exit of MCP, electrons are accelerated with electric field of 4~6 kV, then they are made to bombard to the phosphor screen having light decay time of shorter than about 300 ns. Such a time is within the time of bunch separation of 600 ns at 1.7 MHz of rf frequency. Generated light is made to be concentrated with tapered lenses made of quartz and is transported to photomultiplier tube via light fibre. These materials are radiation hard to avoid browning and colour centre. But inside of quartz fibre and other optical element, any Cherenkov light is likely of producing by some charged particles around the accelerator. The wavelength of such a Cherenkov is mainly from ultra-violet range to visible light range. Avoiding the effect of Cherenkov light, emission wavelength of the screen is suitable to a longer wavelength than ultra-violet's. In addition, if the screen has an afterglow characteristic, it is able to measure the light at the absent time of beam bunch.

SUMMARY

Concerning to light detection method in beam core's region was discussed. Electron collection field as simulated result suggests adequately for electron detection accurately. From latter result, also a method using electron detection for beam core measurement is seemed to be worth considering.

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