OPTICAL BEAM PROFILE MONITOR AT THE RHIC POLARIZED HYDROGEN JET

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Abstract

A gas fluorescence beam profile monitor has been realized at the relativistic heavy ion collider (RHIC) using the polarized atomic hydrogen gas jet. RHIC proton beam profiles in the vertical plane are obtained as well as measurements of the width of the gas jet in the beam direction. We estimate the fluorescence cross-section of 100 GeV protons and Au ions on hydrogen gas to be 6.6×10^{-21} cm^2 and $\sim1.7\times10^{-16}$ cm^2, respectively, and calculate the beam emittance to provide an independent measurement of the RHIC beam. This optical beam diagnostic technique, utilizing the beam induced fluorescence from injected or residual gas, represents a step towards the realization of a simple and truly noninvasive beam monitor for high-energy particle beams.

INTRODUCTION

The use of optical gas fluorescence beam profile monitors for high-energy proton and heavy ion accelerators and storage rings have been implemented in several machines [1,2]. Often, gas must be introduced to create a pressure bump to enhance the fluorescence signal strength. In some cases, residual gas in the beam chamber generates sufficient light from interactions with particle beams. At the 12 o'clock position of the RHIC, a polarized atomic hydrogen jet (H-jet) polarimeter is used as one of the proton polarimeters for the measurements of the proton beam polarization. By taking advantage of the fluorescent light emitted by the hydrogen atoms excited by the proton beam, we have implemented an independent beam profile monitor attached to the H-jet, see Figure 1, albeit in the vertical plane of the accelerator only. First beam profile results from the hydrogen gas target were successful; and subsequent improvements in optics, CCD, and optical calibrations resulted in a much improved image quality [3]. Further optimization on the optical system and the installation of a fiber-coupled spectrometer to spectrally resolve the fluorescent light allowed us to determine an upper limit on the impurity of the gas in the H-jet, a background contribution for polarimeter correction measurements. In FY2009, we upgraded our CCD to a firewire camera interfaced with a high-speed fiber-optical link to display the beam profile in the RHIC main control room. In addition, an image intensifier was added to provide a visual observation of the proton beam in real time limited only by the 0.5 ms decay time of the intensifier. The projected profiles are used to determine the beam size, position, and movement that are important for the RHIC operation and beam characterization. We compare our beam emittance measurements to a system of ionization profile monitors (IPMs). In additional, we obtained the fluorescence cross section values in the 100 GeV beam energy range for proton and gold ion beams [4]. The Au ion fluorescence cross section is shown to be sufficiently large to produce usable images in the absence of the atomic jet, but only with long integration times.

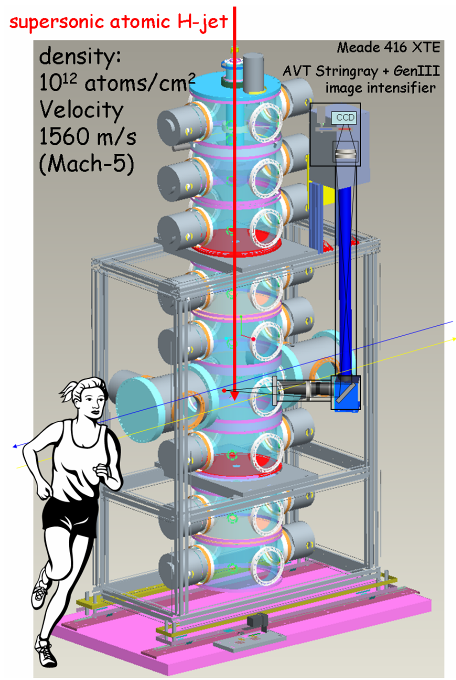

Figure 1: H-jet with external modification including the attachment of an optical imaging system (not to scale).

BEAM PROFILE MEASUREMENTS

The optical field-of-view (26.9 x 17.9 mm), the sensitivity of the camera (3.64×10^4 photons/CCD brightness level/mm^2 at 650 nm), the imaging scaling factor (34.9 µm/ pixel), the overall optical transmission of the imaging system (0.58), and its spectral response were established from a mock-up system in a laboratory. These parameters are important for the cross-section calculations. Figure 2 shows a 656 nm filtered fluorescence profile of a typical 100 GeV polarized proton beam. Information obtained in the x-axis corresponded to the width of the supersonic H-jet column, 6.57 mm FWHM in diameter after correcting for the 45° viewing angle, in agreement with other measurement techniques. The y-axis projection of the image profile corresponds to the vertical beam size of the proton, σ=0.54 mm, in good agreement with the value expected at this location. The light emission process exhibits a linear dependence on the proton intensity with no indication of saturation, even up to the highest beam intensities. The proton beam profile has a near Gaussian shape. However, careful examination on all raw image data shows ~7% of the integrated fluorescence intensity developed on the downstream side of the H-jet has a 0.9 μs exponential decay tail, which we attributed to the lifetime of a metastable state of the hydrogen. This qualitative image illustrates that one can use the H-jet fluorescence for routine beam monitoring. The H-jet fluorescence image gives a visual observation of the RHIC beam. Moreover, using the calculated FOV, the photon sensitivity of the CCD, the total number of particles, and the density of the gas jet, we calculated a photon production cross section of $6.6\text{x}10^{-21}$ cm^2 at 100 GeV.

A fiber-optics spectrometer installed directly across the image path of the H-jet camera recorded spectral information during the RHIC runs. In addition to the much stronger 656 nm hydrogen Balmer line, a total of six Balmer series lines down to 390 nm were observed. But no other spectral impurity line was observed. By analyzing the H-jet images using different spectral filters, we established an experimental upper limit of 0.15% for the ratio of the impurity gas relative to the hydrogen gas.

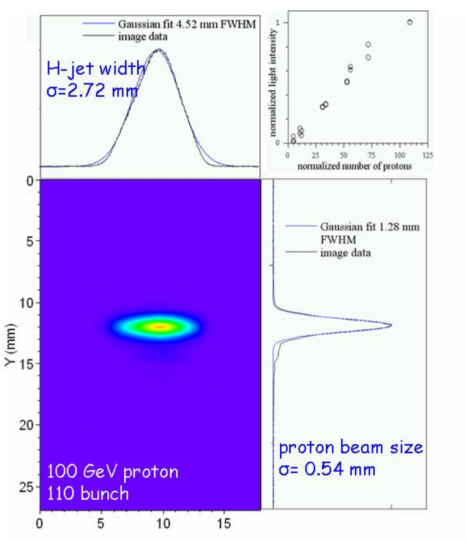

Figure 2: False color fluorescence image profile for a RHIC proton beam, 656 nm filtered. The x and y projections of the image profile correspond to the width of the H-jet and the vertical beam size, respectively. The brightness of the fluorescence increases linearly with proton beam intensity.

During the 100 GeV deuteron-gold runs and the 4.6 GeV Au–Au runs with the H-jet off, the H-jet camera fortuitously recorded a streak of light after a long exposure time. This light streak is absent, or below the sensitivity of the CCD camera, when only deuteron beam is circulating in the RHIC ring. This fluorescence is unambiguously due only to the interactions of Au ion beams with residual gas in the vacuum at the center of the interaction chamber at a vacuum level of 10^{-9} Torr. Spectral analysis of the image suggested that hydrogen was the main constituent of the residual gas for the production of Au ion induced fluorescence. Figure 3 shows typical beam profiles of 100 GeV and 4.6 GeV gold ion beams. No interference band-pass filter was used; hence, the CCD camera collected all fluorescent light, limited only by the spectral response of the CCD chip. The fluorescence intensity depends linearly on the Au ion intensities, indicating the residual gas fluorescence involves a single step excitation. Using the CCD brightness level calibration, we calculated a photon production cross section of $\sim 1.7\text{x}10^{-16}$ cm^2 for the 100 GeV Au ion beam. While the gas density of the residual hydrogen gas several is orders of magnitude lower than that of the supersonic hydrogen gas jet, the photon production of Au ion is higher by a factor of 3 than that of the H-jet but is accounted for by the larger fluorescence cross section due to the higher atomic number of the Au ion. Figure 3 displays a representative fluorescence image of low energy 4.6 GeV Au ion beams. Although this Au ion beam energy was lower than that of the previous d-Au runs, it generated sufficient fluorescence photons with a slightly higher efficiency by a factor of 1.7 than that of the higher energy Au ion beam. Because of the lower Au ion beam energy, a larger beam size by a factor of $\sqrt{100\,GeV/4.6\,GeV}$ =4.7 is anticipated, which is in good agreement with the observed beam size increase of 4.8.

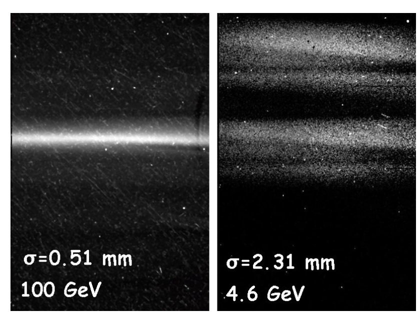

Figure 3: Fluorescence image profile and the width of RHIC Au ion beams.

EMITTANCE MEASUREMENTS AND COMPARISON WITH IPMS

A system of four ionization profile monitors (IPMs) located at the 2 o'clock location are the major emittance measurement systems in RHIC. Since the transverse emittance is a constant value around the RHIC ring, using the measured beam size, the known betatron function at the H-jet location, and assuming there is no vertical dispersion, the normalized 95% transverse vertical emittance can be calculated from

$$\varepsilon_{H-jet} = \frac{6\pi\gamma\sigma^2_{H-jet}}{\beta_{H-jet}} \tag{1}$$

Table 1 summarizes and compares the beam profile measurements with the IPM results. At low beam energies, the agreement of the emittance between the H-jet and the IPM is reasonably good. At high beam energies, the beam emittance inferred from the H-jet deviated significantly from that of the IPM results.

Table 1: Summary of H-jet Beam Profile Measurements

Mode	p - p	p - p	d - Au	Au - Au
energy (GeV)	250	100	100 Au	4.6
β function	7.83	10.3	3	10
γ function	266	106.8	107.4	4.9
$\sigma_{H\text{-jet}}$ (mm)	0.40	0.54	0.51	2.3
$\varepsilon_{H\text{-jet}}$ (π mm mrad)	34	18.1	55.8	15.5
ε_{IPM} (π mm mrad)	6.9	16.0	13.5	15.6

Despite the reduction of the beam size follows the $1/\sqrt{beam\ energy\ (GeV)}$ dependence, it appeared to have reached a minimum of 0.40 mm during the recent proton beam runs at 250 GeV/nucleon, see Figure 4(a). In order to understand this limitation we used ZEMAX to simulate the imaging system and to confirm the resolution of the imaging system to be <5 μm, represented by the point spread function (PSF) shown in Figure 4(d). Furthermore, object size well below 0.2 mm in dimension, which is the expected proton beam size at 250 GeV, is well resolved by the current imaging system, see inset of Figure 4(d). An independent image resolution test on an identical mock-up optical system supports the results of the ZEMAX simulation. Therefore, the observed minimum beam size is not limited by the optical resolution of the imaging system and the fluorescence is not saturated. Because the imaging system is attached to the H-jet where many vacuum pumps are constantly running, hence there are some issues on the rigidity of the camera system. However, initial test does not indicate any noticeable image blurring due to any mechanical vibration.

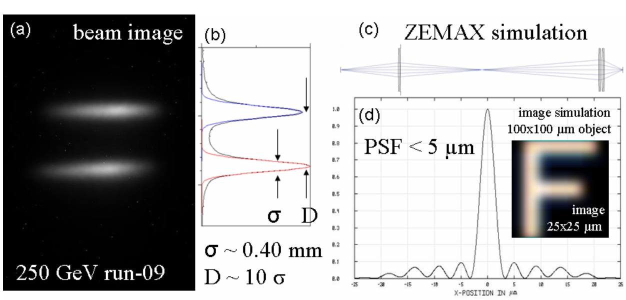

Figure 4: (a) 250 GeV proton beam image and (b) the corresponding width of the blue and yellow beams. (c) ZEMAX optical simulation of the imaging system and (d) the PSF, inset shows the image simulation.

We hypothesize that possible beam intensity related phenomena might have blurred the fluorescence image and caused an increase on the beam size, thus a larger beam emittance at the highest beam energies. Although beam intensity dependent behavior on the fluorescence of scintillating crystals used in the beam profile monitor of electron accelerators was observed [5], the use of injected or residual gas at low gas densities in our beam monitor should have levitated any saturation of the emission sites. However, collective effects such as space charge may play a role in the observed image blurring at the highest beam energies.

CONCLUSION

Beam profile monitors based on the fluorescence of injected or residual gas excited by the passage of particle beams are a promising approach for the diagnosis of low energy to high energy particle beams, including protons, ions, and possibly deuterons. The H-jet fluorescence camera system gives a real-time guidance for RHIC beam injection, tuning, and physic experiment run. We estimate the fluorescence cross sections that are not known in this ultrarelativistic regime and calculate the beam emittance to provide an independent measurement of the RHIC beam. While optical fluorescence beam profile monitors are still being developed at some laboratories, our results represent a step toward the realization of a simple and truly noninvasive beam monitor for high-energy particle beams. By implementing a vertical curtain-like flat gas jet orientated at 45° to the beam, a single imaging system would provide a 2-D map of the beam cross section.

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