RESIDUAL GAS FLUORESCENCE MONITOR AT RHIC

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Abstract

A residual gas fluorescence beam profile monitor at the relativistic heavy ion collider (RHIC) has successfully recorded vertical beam sizes of Au-ion beams from 3.85 to 100 GeV/n during the 2010 beam runs. Although the fluorescence cross section of Au-ion is sufficiently large, the low residual gas in a typical vacuum chamber of $<10^{-9}$ torr produces necessary weak fluorescence photons. However, with adequate CCD exposure time, the vertical beam profiles are captured to provide an independent measurement of the RHIC beam size and emittance. This beam diagnostic technique, utilizing the Au-ion beam induced fluorescence from residual gas where hydrogen is still the dominant constituent in nearly all vacuum system, represents a step towards the realization of a truly noninvasive beam monitor for high-energy particle beams.

INTRODUCTION

The use of injected gas to enhance the fluorescence signal for beam profile monitors in high-energy proton and heavy ion accelerators and storage rings have been implemented in the past [1]. In some cases, residual gas in the beam chamber alone generates sufficient light from interactions with particle beams. Recently, we reported some of these initial results and found that the fluorescence cross section is sufficiently large to produce usable images with long integration times [2]. Here, we demonstrated the non-invasiveness, passive, and the robustness of the Residual Gas Fluorescence beam Monitor (RGFM) technique by continuously recording vertical beam sizes of Au-ion beams from 3.85 to 100 GeV/n during the 2010 beam runs at RHIC.

At the 12 o'clock position of the RHIC, an independent beam profile monitor optical system is attached to the hydrogen gas jet apparatus. With the hydrogen gas jet turned off, the residual gas pressure of the vacuum chamber reached $\sim 10^{-9}$ Torr. The circulating Au-ion beams, named as Blue and Yellow beams, excite the residual gas along their beam paths and the fluorescence light was captured by imaging relay optics onto a CCD camera (AVT Allied Vision Technologies, Stingray F145B, 16-bit, 1388x1038 pixels, 6.45 µm pixel size). Because of limited viewports available, the camera sustains a 45-degress viewing angle to the beam directions, see left of Figure 1. And because of this 45-degress viewing angle, the resulting images show a slight skew of the fluorescence beam path, see right of Figure 1. Nevertheless, projected Au-ion beam profile in the vertical plane of the accelerator is unambiguously obtained. These results are used to determine the beam size, position, and movement that are important for the RHIC operation and beam characterization. Furthermore, we compare our beam emittance measurements to a system of ionization profile monitors (IPMs).

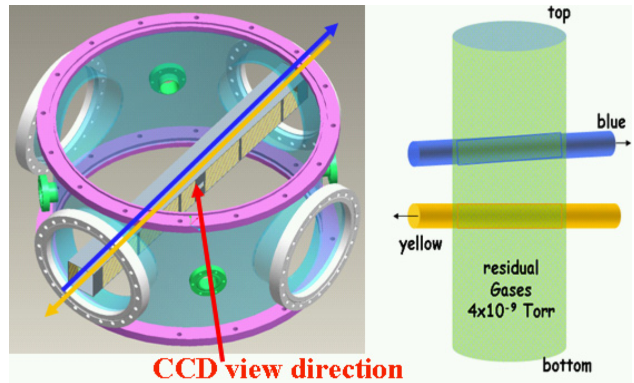

Figure 1: Left: drawing of the interaction chamber showing the rf cage at the beam centre and the 45-deg viewing angle of the CCD. Right: image orientation of the Au-ion beams showing the slight skew of the beam image paths as a result of the 45-deg viewing direction.

BEAM PROFILE MEASUREMENTS

The imaging system has an optical field-of-view of 36.5 x 27.3 mm^2 with an in-situ and bench image pixel calibration of 0.0263 mm/pixel. And the sensitivity of the camera is $\sim 3.6 \times 10^4$ photons/CCD brightness level/mm^2 at 650 nm. These parameters are important for the calculation of the cross-section. Figure 2 shows the selected fluorescence beam images of Au-ion beams from 100 to 3.85 GeV/n and their corresponding beam sizes by plotting a vertical line-out at the centre of each image. We note that the fluorescence light is collected by the entire spectral response of the CCD, it increases linearly with Au-ion beam intensity with no indication of saturation [2], and it is markedly present only when Au ion beams circulating the RHIC rings.

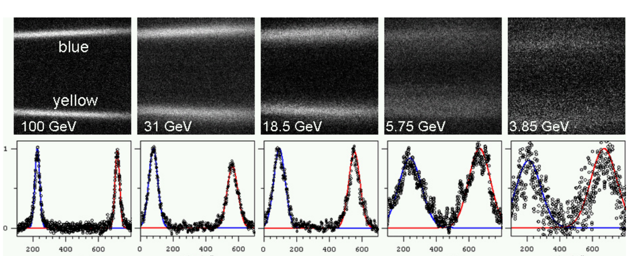

Figure 2: Top: residual gas fluorescence beam images of Au-ion beams from 100 to 3.85 GeV/n. Bottom: their corresponding vertical beam sizes. All images are captured with 1 minute CCD exposure time and without band-pass filter. Image calibration: 26.3 µm/pixel.

All Au-ion beam profile has a near Gaussian shape. Previously, by using different narrow bandpass filters to select individual hydrogen Balmer series lines, we determined [2], and confirmed here again, that hydrogen is the main constituent residual gas in the chamber. Thus, beam images similar to that of Figure 2 were also obtained with 656 nm, 486 nm, and 390 nm bandpass filters (H_α , H_β , and H_ζ lines of the Balmer series), but with longer exposure time. However, residual gases other than hydrogen are also present and participated in this fluorescence process. The fluorescence decay time of hydrogen and other gases are typically in a few to tens of nanosecond, while the gas velocity is much below supersonic; therefore, no significant image blurring deteriorates the vertical width of the Au-ion beams.

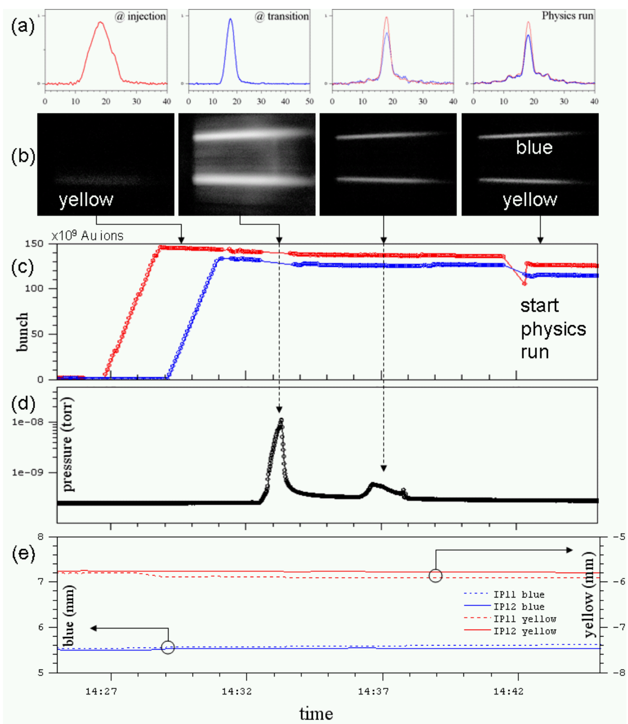

Figure 3: Timeline events of (a) bunch duration in nanoseconds recorded by a wall current monitor, (b) fluorescence beam images with identical 1-minute CCD exposure time, (c) Au-ion beam intensities at injection, ramping, transition, and finally at store at 100 GeV/n, (d) their corresponding vacuum pressure in the chamber and (e) beam position from an independent beam position monitor. Red and blue traces correspond to Yellow and Blue RHIC Au-ion beams, respectively. Data are obtained from beam fill # 11598.

Figure 3 displays the timeline events on one representative beam fill at the first ~20 minutes from injection to store. When Au-ion beam went from injection to transition with a shorter bunch width (10 ns to 4 ns), see Figure 4(a), a pronounced pressure bump was detected at the 12 o'clock of RHIC, see Figure 3(d). While Au ions transit from long to short bunch, the increase of spatial charge density ionizes the surrounding gas molecules. It is speculated that the ejected electrons and the ionized molecules could propel towards the lining of beam pipes and vacuum chambers causing a release of excess residual gases molecules [3], thus a transient pressure surge.

Since our RGFM is sensitive to the amount of residual gas, the intensity of the beam image also increases linearly with the pressure surge, shown in the 2nd image of Figure 3(b). Ironically, the intensity of the fluorescence signal can now also function as an ultrahigh vacuum monitor but requires a relativistic ion beam. The designation of Au-ion beams on the beam images are unambiguously determined by the start of the beam fill. For instance, the beam intensity plot from respective direct-current current transformer as shown in Figure 3(c) indicates Yellow beam starts first (but not always on every beam fill) resulting in fluorescence streak appears at the bottom of the beam image, see left image of Figure 3(b). Despite a 1-minute long exposure time was used to capture all beam images, additional independent measurements from beam position monitors located upstream at 11 and downstream at 12 o'clock positions, see Figure 3(d), detect negligible beam movement, if any, within the CCD exposure time. Consequently, not only the RGFM gives a visual observation of the RHIC beams, it can also provide beam emittance information to cross check with IPMs.

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 [4]. Using the measured beam size σ, the known betatron function β, and assuming there is no vertical dispersion, the normalized transverse vertical emittance ε can be calculated using data from RGFM and IPM,

$$\varepsilon_{RGFM\ or\ IPM} = \frac{6\pi\gamma\sigma^2_{RGFM\ or\ IPM}}{\beta_{RGFM\ or\ IPM}} \qquad (1)$$

where γ equals 106.8, β_{RGFM} equals 4 meters, and β_{IPM} equal 143.9 and 150.6 meters for the Yellow and Blue rings, respectively.

Table 1: Summary of beam size and beam emittance for Au ion beams of energies 100 to 3.85 GeV/n. Data obtained from RGFM and IPM of the same beam runs.

#	Au-ion beam energy (GeV/n)	Residual gas fluorescence monitor (RGFM): beam size & emittance				Ionization beam profile monitor (IPM) : beam size & emittance			
		σ_{yellow}	ε_{yellow}	σ_{blue}	ε_{blue}	σ_{yellow}	ε_{yellow}	σ_{blue}	ε_{blue}
1	100	0.37	22.0	0.39	24.5	1.88	15.65	2.18	20.38
2	31	0.87	30.6	0.73	21.9	3.6	20.56	3.2	15.7
3	18.5	0.92	21.2	0.92	21.5	5.93	34.9	4.3	18.3
4	5.75	1.76	11.4	1.84	12.1	3.41	13.3	2.91	10.0
5	3.85	2.1	10.4	2.0	10.2	3.27	8.18	3.54	9.73

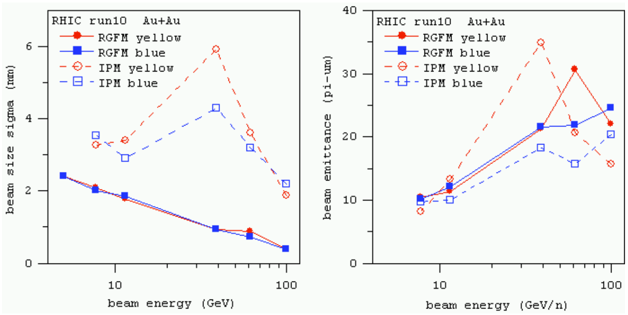

Figure 4: Plot of beam sizes (left) and beam emittances (right) against the logarithmic of the Au ion beam energies from 100 to 3.85 GeV/n. Data obtained from RGFM and IPM of the same beam runs. Lines are connected for clarity.

Table 1 compares the RGFM measurements with the IPM results and Figure 4 plotted those values against the logarithmic of the Au ion beam energies. We note that beam sizes obtained from IPM and RGFM in two different locations at the RHIC ring are inherently different because of beam optics. Although beam emittance can vary on various RHIC beam runs, however, the transverse emittance is a constant value around the ring for the same beam run [5]. At low beam energies, the agreement of the emittance between the RGFM and IPM is good. At high beam energies, the beam emittance inferred from the RGFM deviated from that of the IPM. But at the same time the IPM results also shown some inconsistence. Nevertheless, the beam sizes obtained from residual gas fluorescence monitor follows closely the $1/\sqrt{beam\ energy\,(GeV)}$ dependence; a slope close to -2 is obtained from the RGFM results shown on the left of Figure 4. The observed minimum beam size of σ_{RGFM}=0.37 mm at the highest 100 GeV Au ion beam energy is not limited by the optical resolution of the imaging system, which has been independently confirmed using ZEMAX simulation. Furthermore, the rigidity of the imaging system to mechanical vibration has been verified.

CONCLUSION

Beam profile monitors based on the fluorescence of residual gas excited by the passage of particle beams are a promising approach for the diagnosis of low energy to high energy particle beams. The residual gas fluorescence monitor can provide a real-time guidance for RHIC beam injection, tuning, and physic experiment run. While optical fluorescence beam profile monitors are still being developed at some laboratories with injected gases [6], our results represent a step toward the realization of a truly noninvasive, passive, and robust monitor for high-energy particle beams. With higher photon sensitivity instruments, a near real-time beam monitoring system can be devised to provide beam sizes and beam emittance information to support the operation of particle accelerators.

REFERENCES

[1] A. Variola, R. Jubg, and G. Ferioli, Phys. Rev. ST Accel. Beams 10, 122801 (2007).

[2] T. Tsang,, S. Bellavia, R. Connolly, D. Gassner, Y. Makdisi, T. Russo, P. Thieberger, D. Trbojevic, and A. Zelenski, "Optical beam profile monitor and residual gas fluorescence at the relativistic heavy ion collider polarized hydrogen jet," Review of Sci. Instrument 79, 105103 (2008).

[3] U. Iriso and W. Fischer, "Electron-impact desorption of the RHIC beam pipes," Proceedings of EPAC09, paper MOPCH134, 2006.

[4] R. Connolly, J. Fite, S. Jao, S. Tepikian, and C. Trabocchi, "Residual-gas ionization beam profile monitors in RHIC," BIW10 Conference Proceedings, paper TUPSM010, 2010.

[5] A. Zelenski, G. Atoyan, G. Bunce, A. Bazilevshiy, R. Connolly, D. Gassner, R. Gill, H. Huang, G. Mahler, Y. Makdisi, B. Morozov, S. Nemeshure, T. Russo, D. Steski, M. Sivertz, S. Tepikian, R. Todd, and K. Yip, "Beam emittance measurements in RHIC," Proceedings of PAC09, paper TH5RFP020, 2009.

[6] F. Becker, C. Andre, P. Forck, R. Haseitl, A. Hug, B. Walasek-Hoehme, F. Bieniosek, and D. Hoffmann, "Beam induced fluorescence monitor and imaging spectrography of different working gases." DIPAC 2009 Conference Proceedings, paper TUPB02, 2009.