BEAM LIFETIME AND EMITTANCE GROWTH MEASUREMENTS OF GOLD BEAMS IN RHIC AT STORAGE*

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Abstract

During stores of gold beams, longitudinal and transverse beam sizes were recorded. Longitudinal profiles were obtained with a wall current monitor. Transverse profiles were reconstructed from gold-gold collision rates at various relative transverse beam positions. The total beam lifetime was measured with a beam current transformer, the bunched beam lifetime with the wall current monitor. Diffusion rates in the beam halo were determined from the change in the loss rate when a scraper is retracted. The measurements are used to determine the lifetime limiting effects. Beam growth measurements are compared with computations of beam-growth times from intra-beam scattering.

1 INTRODUCTION

For physics runs, colliding gold beams are stored for several hours in the Relativistic Heavy Ion Collider (RHIC), with "blue" beam circulating clockwise and "yellow" beam counter-clockwise. During stores beam intensities and emittances change due intra-beam scattering, beam-beam forces and nonlinear magnetic fields in the interaction region (IR) magnets. In this article we report on beam lifetime and emittance growth measurements and compare these with growth time computations from intra-beam scattering, which is expected to be the dominant effect. Growth times are defined as $\tau_{x,y,s} = ((1/\sigma_{x,y,s})(d\sigma_{x,y,s}/dt))^{-1}$ where $\sigma_{x,y,s}$ denote the rms beam sizes in the transverse and longitudinal directions.

In Tab. 1 the basic machine parameters during a store are given (see Ref. [1] for a complete list). In 2000, its first year of operation, RHIC collided beams below the design energy since the beam splitting dipoles in the IRs were not yet fully quench tested. Of the two rf systems only the accelerating rf system was used, accounting for longer buckets and less gap voltage than in the design. While the transverse emittances had the design values, the longitudinal emittance was enlarged due to an imperfect transition crossing (the nominal γ_{tr}-jump scheme was not yet commissioned). On average, bunch intensities during stores reached 25% and the average luminosity 10% of the design value.

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Table 1: Machine parameters for gold beams at storage.

parameter	unit	design	run 2000
kinetic energy E	GeV/u	100	64.3
harmonic no. h	...	7×360	360
gap voltage V	MV	6	0.3
no. of bunches	...	60	55
ions per bunch N_b	...	10^9	$0.25\cdot10^9$
emitt. $\epsilon_{N\,x,y\,95\%}$	μm	10	10
bunch area $S_{95\%}$	eV·s/u	0.3	1.0
av. luminosity L	cm^{-2}s^{-1}	$2\cdot10^{26}$	$2\cdot10^{25}$

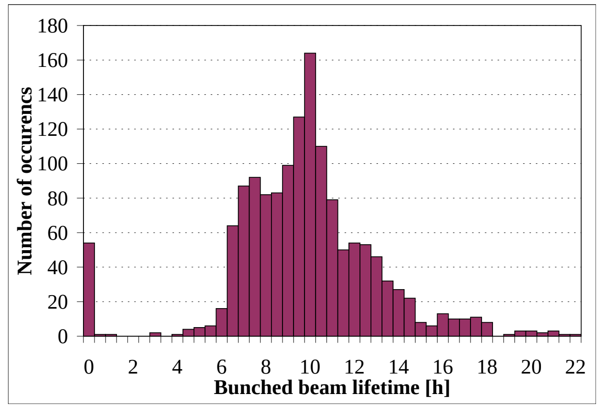

Figure 1: Distribution of average bunched beam lifetimes.

2 BEAM LIFETIME MEASUREMENTS

Luminosity fills in RHIC typically lasted 3 to 10 h and were terminated upon request from the experiments. For luminosity production only bunched beam is relevant. In Fig. 1 a histogram of the bunched beam lifetimes of 1495 bunches in 36 fills is shown, averaged over the fill time. The distribution has a long tail up to 44 h. Excluding bunches with extremely short lifetimes and the long tail, the average bunched beam lifetime is 10 h. Typically, the bunched beam lifetime did not change significantly during a fill.

During a long store a substantial part of the beam escaped the rf buckets. In Fig. 2 the unbunched portion is shown as a function of the store time. While there is a wide

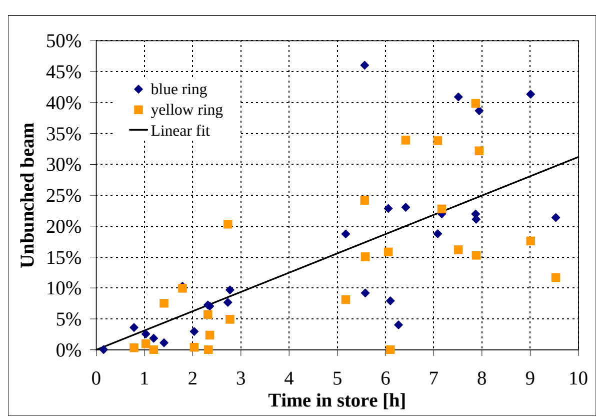

Figure 2: Unbunched beam as a function of store time.

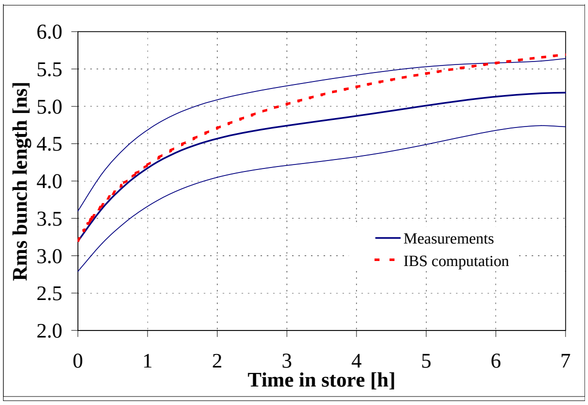

Figure 3: Rms bunch length increase during stores. The thick solid line shows the average, the thin solid lines the average plus and minus one standard deviation of a distribution.

spread for the unbunched portion at any given time, on average, 30% of the beam was unbunched after 10 h. The storage rf system (see Tab. 1) will provide more longitudinal focusing and should reduce the debunching. A higher bunch intensity will increase the debunching.

3 EMITTANCE MEASUREMENTS

Longitudinal Bunch lengths were measured routinely with a wall current monitor [2] at 4 s intervals and with a resolution of 0.25 ns. Each longitudinal bunch profile was later fitted to a Gaussian distribution. In Fig. 3 the average rms bunch length of 314 bunches is shown as a function of store time. The bunches were selected from a larger distribution to have initial longitudinal growth times between 1 h and 3 h (see below). From the measured bunch length and the known rf parameters the longitudinal bunch area and emittances can be computed.

In order to obtain the bunch length growth times τ_s, all available bunch length curves were fitted to a 5^{th} order polynomial. The growth time can then be obtained as a the derivative of the fitted polynomial functions. The chosen polynomial order was a compromise between a good fit, which calls for a high order, and robustness in the derivative, which calls for a low order. Fig. 4 depicts a distribution of initial longitudinal growth times. Excluding bunches with extremely short initial growth times and the long tail in the distribution, an average initial longitudinal growth time of 2.4 h was observed. In section 5 a comparison is made with growth times expected from intra-beam scattering.

Transverse In 2000, the transverse emittances during stores could only be obtained from so called Vernier Scans [3]. During such a scan beams are transversely swept stepwise across each other. The sweep is achieved by applying orbit bumps in the interaction region with typical step sizes of 200 μm. The collision rate is recorded as a function of the relative distance between the two bunches. A Gaussian fit yields the the maximum achievable collision rate, the location of the maximum and the effective beam size at the IR. Since this method cannot distinguish between the blue or yellow contribution, equal beam sizes in both beams were assumed. A total of 8 scans at various times within the store were performed, each scan including both, a horizontal and a vertical sweep.

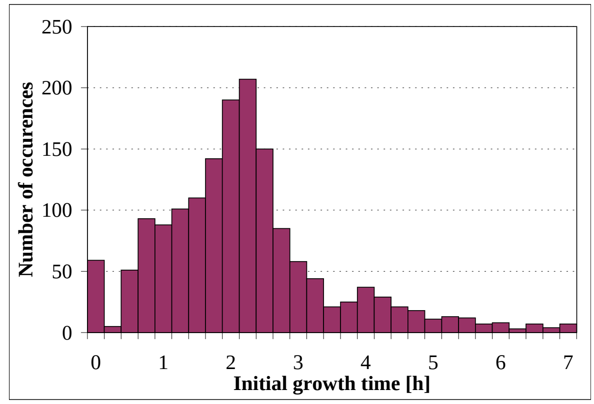

Figure 4: Distribution of initial longitudinal growth times of 1719 blue bunches. The tail goes up to 350 h.

In 2000 two IRs had a β^* of 3 m, four IRs had 8 m. Because of a typical rms bunch length of 4.5 ns or 1.5 m (see Fig. 3) we corrected for the “hour-glass” effect [4], which causes beam sizes to appear a few percent larger than they are. The store time is the time after reaching flat top and is based on the center between start and end of a full Vernier Scan. The measurements right after reaching flat top are in relatively good agreement with emittance measurements at injection energy (typically 10-13 μm).

4 DIFFUSION MEASUREMENTS

The transverse diffusion rate at a collimator [5] can be determined from a fit to the time-dependent loss rate when the collimator is moved by a small amount [6]. A number of such measurements were done in the yellow ring. Fig. 6 shows the measured diffusion coefficient as a function of

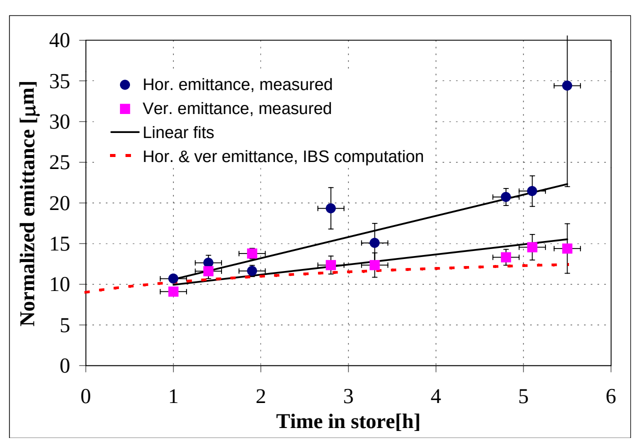

Figure 5: Transverse emittance measurements as a function of store time. Note that measurements were taken during different stores.

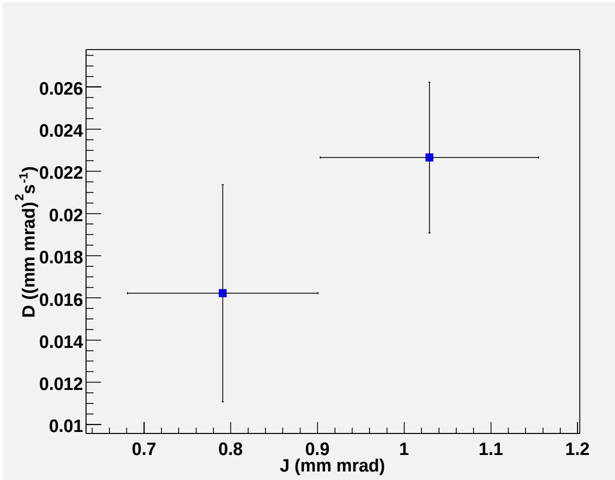

Figure 6: Measured diffusion coefficients. Both data points were taken in the same fill.

particle action. The uncertainty of the position of the collimator relative to the beam and statistical signal fluctuations contribute to the shown errors. These measurements can be compared with beam-beam simulations [6].

5 INTRA-BEAM SCATTERING COMPUTATIONS

To compute initial beam growth times and the evolution of the beam size resulting from intra-beam scattering, a computer program was used [7, 8]. In the program it is assumed that the whole machine consists of FODO cells. The input consists of the FODO cell parameters, particle parameters like mass and charge state, beam parameters such as transverse and longitudinal emittances and the bunched intensity. In Tab. 2 the input parameters used in the computations are listed. The given errors are the rms value of the measured distributions for intensity, bunch length and momentum spread. The error of the transverse emittances is only a rough estimate.

Table 2: Input parameters for IBS computations.

parameter	unit	value
bunch intensity N_b	10^9	0.27 ± 0.09
rms bunch length σ_s	ns	3.19 ± 0.40
rms momentum spread σ_p	10^{-4}	3.89 ± 0.49
transv. emittances $\epsilon_{N\,x,y\,95\%}$	μm	9.0 ± 2.0

Tab. 3 shows a comparison between measured initial growth times and growth times computes with the IBS model. The difference in the longitudinal plane is about 50%, similar to the one achieved at injection [9]. Note that the transverse data have a large error.

In Figs. 3 and 5 the computed time evolution is shown for the average input values (see Tab. 2). The particle loss computed from the average bunched beam lifetime (see Fig. 1) was explicitly included in the simulation since the computer program does not compute particle losses.

Table 3: Initial growth times, measured and computed with an IBS model. A transversely fully coupled machine is assumed in the computation.

	measured [h]	computed [h]	difference [%]
τ_s	2.3 ± 1.0	1.8 ± 1.0	-22
τ_x	8.1 ± 1.5	33.7 ± 13.2	$+316$
τ_y	16.0 ± 5.0	33.7 ± 13.2	$+110$

6 SUMMARY

In this paper we compared average lifetimes, and average longitudinal and transverse beam growth with expectations from intra-beam scattering computations. While there is relatively good agreement between measured and computed longitudinal growth times, observed transverse growth times are far larger than those obtained from IBS calculations. This is an indication that intra-beam scattering is the dominating effect for longitudinal bunch growth, but not for transverse. The transverse beam growth may be dominated by the beam-beam interaction (compare Ref. [6]) or nonlinear field errors in the interaction regions.

The quality and accuracy of the experimental data can be greatly improved if transverse profile monitor data are available on an average of even bunch-by-bunch basis during stores. Refined IBS calculations should make predictions of debunching as a function of time.

7 ACKNOWLEDGMENTS

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