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FEB/SBE: Commissioning with Au Beam and Run for the FY1996 AtR Transfer Line Commissioning

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Technical Note

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ABSTRACT

A new system for fast extracted beam (FEB) has been installed in the AGS to deliver a beam with characteristics appropriate for the BNL g-2 muon storage ring and the filling of the RHIC heavy ion collider. The old system was limited to perform only fast one-turn extraction for the neutrino experiments and no longer exists. The new FEB extraction system is capable of performing single bunch *multiple* extraction of either a heavy ion beam or a high intensity proton beam at a rate of 30 Hz up to at least 8 times per AGS cycle. The new system consists of a fast multi-pulsing kicker and a thick ejector septum magnet with local extraction orbit bumps. On 6 November 1995, the new system was successfully commissioned with Au^{77+} beam by extracting one bunch/cycle to the U-line at 11.23 GeV/c/N, following the run that continued *prasitically* with the HIP/SEB program in the so-called *context switching on-request mode* for the AGS-to-RHIC transfer line (AtR TL) commissioning for 6 weeks. The beam intensity was initially ~0.05×10^8 ions per bunch and was gradually increased up to ~2.5×10^8 ipb by the end of the run. The extracted beam emittance was measured by the AtR TL commissioning team to be $\varepsilon^*_{h,v}(95\%)$ = ~10 π mm-mrad, consisting with an estimated internal emittance of ~7-8 π.

I. INTRODUCTION

Since the old fast extracted beam (FEB) and single bunch extraction (SBE) systems [1] are no longer available due to the AGS improvement program, the new FEB system [2] serves as the AGS extraction system not just for the muon g-2 experiment [3] but also for RHIC [4]. The AGS complex accelerates slow-extracted (SEB) Au^{77+} beam at 11.6 GeV/c/N for the heavy ion physics program and the high intensity SEB proton beam up to $6 \cdot 10^{13}$ ppp at 25.5 GeV/c for various high energy physics experiments.

With the new FEB system the AGS complex will serve as an injector for RHIC. The circumference of the RHIC ring is 19/4 times larger than the AGS and its harmonic number at injection is 342, compared to 12 of the AGS. The AGS may accelerate three bunches per pulse and transfer individual bunches one by one into the waiting rf buckets in RHIC through AtR TL. Each RHIC ring can be filled with 57 (or 114) bunches one after another in a few minutes every 10 hours or so and accelerate heavy ions to energies of 250·(Z/A) GeV/N with the luminosity $\mathcal{L} = 2 \cdot 10^{26}$ cm^{-2}s^{-1}.

For the BNL muon g-2 experiment (E825), which has constructed a 14 m diameter superferric muon storage ring with B = 1.5 T in order to improve the previous CERN measurement of the anomalous muon magnetic moment (a_μ) by a factor of 20, the FEB must meet the following requirements: (1) extract the bunched proton beam at 24 GeV/c and up to full intensity to the newly constructed V-target through the U-line for 3.1 GeV/c π/μ production, and (2) perform single bunch multiple extraction (SBME) at 33.3 ms intervals up to 8 times per AGS cycle.

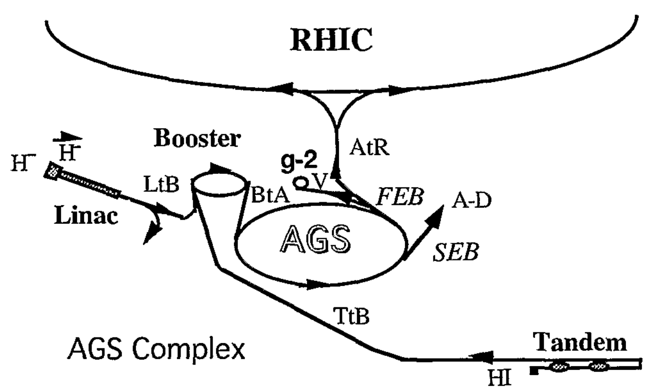

Figure 1: Schematic view of the AGS-RHIC complex.

In the fall of 1995, both the new FEB system and the AtR TL were commissioned with Au beam. The schematic layout of the AGS-RHIC accelerator complex is shown in Figure 1.

II. The *New* FEB EXTRACTION SYSTEM

II.A. Machine and Beam Parameters

Due to its high intensity operation for the g-2 experiment, it is critical that the FEB system achieves a high extraction efficiency of ~100 %. On the other hand, for RHIC injection, the beam intensity is rather low but pulse-to-pulse and cycle-to-cycle modulations in the extracted bunched beam parameters must remain within acceptable levels otherwise any excess modulations will directly influence RHIC performance. Therefore, stability and reproducibility of the extracted beam parameters are crucial for RHIC injection. Table 1 lists the expected or assumed beam parameters and performance of the AGS Complex for FEB operation.

Table 1: FEB beam parameters.

User	g-2/V	RHIC/AtR	RHIC/AtR	
Particle	Protons	Protons	Heavy ions	
Momentum	22-24	28.0†	28.0†	x[Z/A]GeV/c/N
		(24.5 for pol. p)	28.0x(79/197)†	for (Au^{77+})
N_{SBE}	1,2, , ,8,(12)	3 x (19x2)	3 x (19x2)	for 2 rings
N_{ion}/bunch	5000	100	1(Au), 6(Si)	[10^9]
$\varepsilon^*_{h,v}(95\%)$	~50 π	20 π	10 π	[mm-mrad]
		1.0	0.3	[eV-s/N]
$l_{bunch(full)}$	~50	12	17	[ns]
$(dp/p)_{full}$	± 0.2	± 0.06	±0.10	[%]
Oper. Mode	(with HEP/SEB)	filling 2 rings	every 10 hr	

†The value was changed from the original RHIC design value of 29.0 [4] to **28.0** so that the FEB can operate at a desirable working point even with the limited capability of the AGS tune and chromaticity controls[6]. For Au^{77+}, p = 11.23 GeV/c/N. N.B. the AGS becomes an extremely non-linear machine as the momentum increases beyond 25 GeV/c/charge.

The new system was designed based on the 1991 FEB conceptual design report [5] which had assumed that

1. the operational momentum range: $22 \le p \le 29$ GeV/c/charge,
2. the maximum 95% normalized transverse emittance of the high intensity proton beam:
   $\varepsilon^*_{h,v}(95\%) = 6\cdot\sigma^2/\beta\cdot(p/m) \cong \sim 50\ \pi$ mm-mrad,
   where σ is the standard deviation of the beam size due to the transverse emittance,
3. the maximum total momentum spread: $(dp/p)_{full} \cong \pm 0.2$ %,
4. the maximum full bunch length: $l_b \cong \sim 50$ ns,
5. the rf harmonic number: h = 12.

In 1994 the AGS rf harmonic number was changed from h =12 to 8 in AGS (from 3 to 2 in Booster) for high intensity proton operation in order to accelerate the high intensity beam without difficulties along with increasing the bunch length, momentum spread and transverse emittance. It should be noted that for the SEB users, their main interest is uniformity of the beam spill and beam intensity. The actual measured values of ε*, dp/p and l_b for the AGS beam strongly depend on the machine condition, especially the exact high intensity setup. Though the high intensity values for the FEB(p) operation have not yet been optimized, it is now apparent that the values of ε^*, dp/p and l_{bunch} are much larger than the FEB design values and may cause some problems (i.e., beam loss). For RHIC injection, the values of ε^n, dp/p and l_b for both protons and ions are substantially smaller than the high intensity values since the AGS Booster can deliver much more intensity than that assumed for the RHIC design parameters. The Au beam intensity is expected to increase from present value of 10^8 to 10^9 ipb to meet the design value. The AGS basic machine parameters and performance of the FY1995-96 proton (Au^{77+}) SEB operation are summarized in Table 2.

II.B. Extraction Scheme

The new system consists of a fast multi-pulsing kicker at straight section G10 [FKG10] followed by a thick septum ejector magnet at ssH10 [SMH10] in order to utilize the existing U-line and due to severely limited availability of straight sections at the AGS. To minimize the required voltage on pulsing the fast kicker, the kicker is a C-type open ferrite magnet with a pole tip. The center of the kicker aperture is placed about 64 mm from the central orbit at the middle of ssG10. A few msec before each single bunch extraction two extraction bumps [BLWG09 and H11] and SMH10 are excited to bring the beam into the aperture of the kicker and adjacent to the septum of the ejector. During extraction, the kicker is synchronized and phased to the bunches and triggered every 33.3 ms to send one bunch at a time into the ejector, which gives an additional larger kick to extract the bunch out of the ring. In Figure 2, we show a schematic layout of the FEB extraction components and the extraction orbit bumps. The basic parameters of the kicker, ejector and extraction bumps are summarized in Table 3. The optical functions and the extraction bump orbit at the FEB(Au^{77+}) working point in the AGS are shown in Fig. 3a. and the optical functions and the orbit for the extracted beam in Fig. 3b.

Table 2: AGS Machine and SEB Beam Parameters

Circumference	$C = 807.075$		[m]
Curvature	$\rho = 85.37$		[m]
Revolution time	$t_{rev} = 2.692$		[μs]
Tune	$Q_h \cong Q_v \cong 8.7$		
Beta functions	$\beta_{h,v} = 22.5 - 10.5$		[m]
Dispersion Fun.	$D_x^{max} = 2.20$		[m]
No. of bunches	$N_b = 8$ (2x4)† for p	12 for Au^{77+}	before debunching
Gap bet. Bunches	$t_s = 336$	224	[ns]
Typical intensity	$\sim 5.5 \cdot 10^{13}$	$\sim 2 \cdot 10^{8}$	[ipp]
Typical cycle	3.2	3.6	[s]
Typical spill length	1.2	1.2	[s]
Typical mom.	$p = 25.5$	11.6	[GeV/c/N]
Trans. emittance	$\varepsilon^*_T(95\%) \cong 90\pi$?	10π ?	[mm-mrad]
Long. emittance	$\varepsilon_L \cong 1.2$?	0.3 ?	[eV-s/bunch/N)
Bunch full length	$l_b \cong 100$	20?	[ns] bf debunching

† 4 Booster transfers, each has 2 bunches.

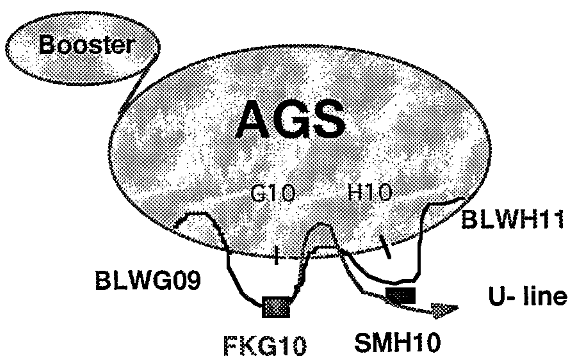

Figure 2. Layout of the AGS FEB components.

Table 3. FEB magnet parameters.

	Kicker	Ejector	Bumps
Name	FKG10	SMH10†	BLWG09/H11††
Location	ssG10	ssH10	F8/9-G2/3, G16/17 H4/5, H18/19-I12/13
θ_{max} [mrad]	2.0	22.0	2(4)/pair
Waveform	half sine	half sine	half sine
B_{max} [T]	0.1	1.0	0.05(0.1)
$t_{base\text{-}width}$	380 ns	2.4 ms	7 ms
I_{max} [kA]	2.0	23	0.6 (1.2)
Tolerance [%]	< 0.9	< 0.09	< 0.8

† Its power supply does not yet have a resonant charging module.
†† Without trim backleg windings.

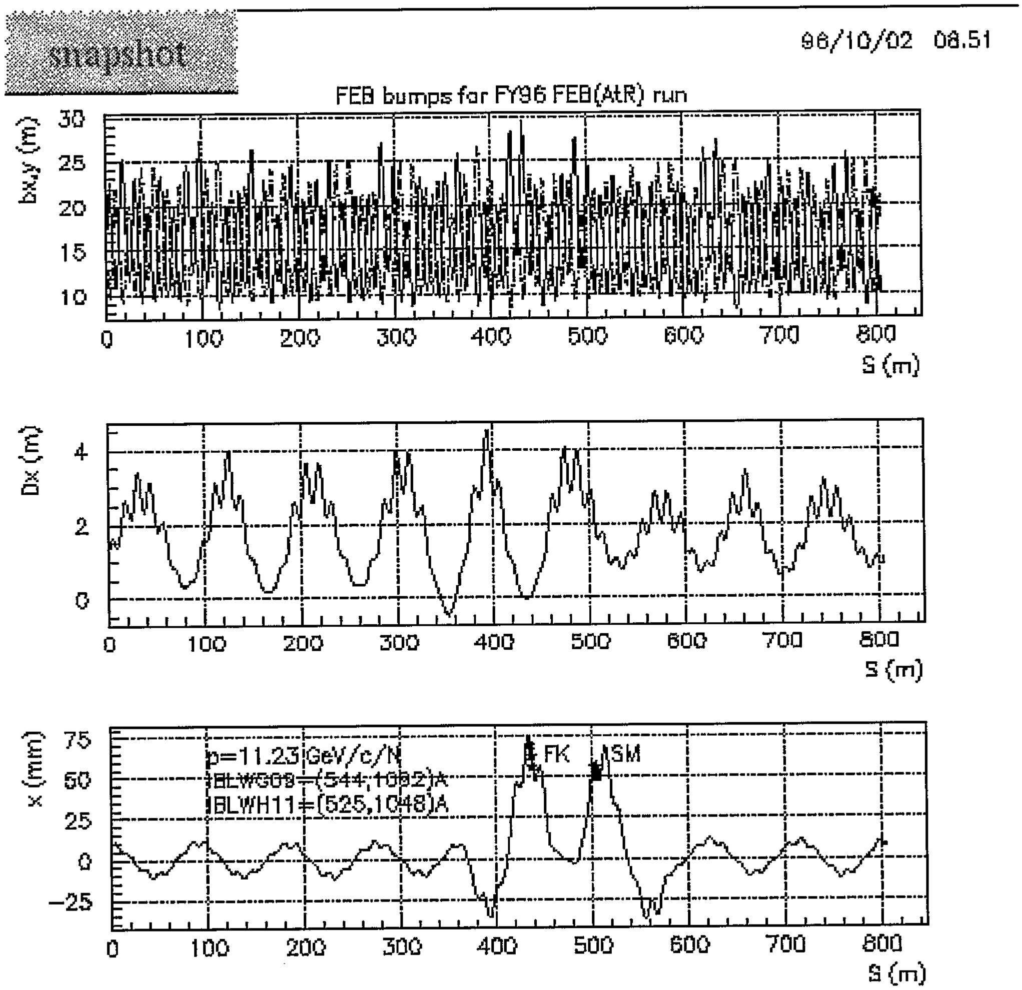

Fig. 3a. $\beta_{h,v}$, D_X and x(bumps) as a function of S starting from ssL20ds at the working point.

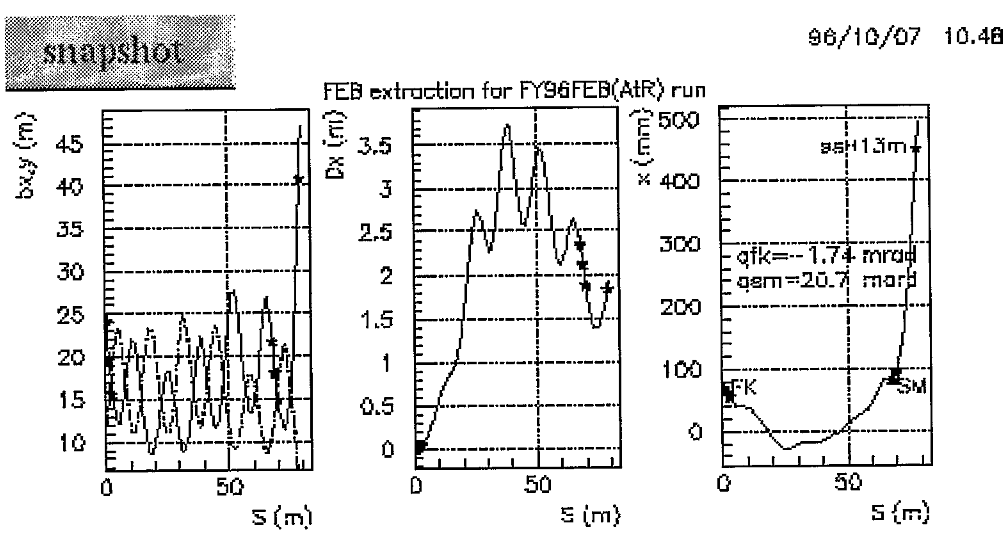

Fig. 3.b. $\beta_{h,v}$, D_X and x as a function of S starting from ssG10us for the extracted beam.

II.C . Instrumentation

There are essentially *minimum* beam instruments that are specific to FEB:

- two pairs of standard AGS short local loss monitors both at the upstream and at downstream end of ssG10; one is connected to the G10 beam inhibit system for FKG10 protection, and another is to monitor possible beam loss through analog signals.

- one pair of short local beam loss monitors at ssH10us and ds.

- a standard AGS flag (1 mm thick) at the upstream end of SMH10 to monitor the position and profile of the bunch that is kicked by FKG10.

In addition to the AGS-type loss monitors, some spare movable RHIC-type loss monitors have been installed at ssG11, ssG19, ssH09 and ssH10ds to enhance diagnostic capability since the present AGS ring loss monitor system is not sensitive to gold beam. The extracted beam profile was measured by digitizing images on the first flag at the beginning of the U-line (uf1). The extracted Au beam will be fully stripped to Au^{79+} by FlagH10 as well as one of the first two thick flags, uf1 or uf2, and transferred to the beam dump at the end of the W-line. The AtR TL is intensively equipped with various types of instruments (loss monitors, position monitors, flags, current transformers etc.) to measure the extracted beam parameters and losses, and is controlled by the new RHIC control system, independent from the AGS control system [7,8].

As the present AGS orbit display system is not sensitive to Au beam, PUEs at F04, F14, G08 and H08 are selected to have high gain electronics sensitive to Au beam so that we can assure that we have proper FEB extraction bumps through analog signal.

III. COMMISSIONING And RUN With Au^{77+} BEAM

On 6 November, the FEB(Au) commissioning was successfully performed following the AGS-OPM-TPL 95-09 manual, extracting one of the 12 Au^{77+} bunches at the design momentum of 11.23 GeV/c/N to the first flag on the U-line(uf1) in a few hours once AtR TL was secured and the beam was enabled for setup. The FEB(Au) run started at 24:00 as scheduled using the context switching mode, performing FEB/SBE for one AGS cycle following nine consecutive cycles without interrupting the HIP/SEB program. Then run mode was changed from the ping-pong mode to the on-request mode and continued to deliver the single bunch Au beam for AtR commissioing for six weeks. At 04:39, 9 November, the AtR commissioning team led by M. MacKay managed to get the beam down to the last flag (wf3) and beam position monitor(wb7) in the W-line, and dumped the beam on the beam dump [7]. On average the AtR commissioning team used less than a few hundred pulses per 8-hour shift to achieve its goal.

Since the beam intensity was $0.05\text{-}0.1 \cdot 10^8$ ipb at the early stage of the run and it was not good enough for position measurements with the AtR BPM system, the bunched beam was allowed to make a longitudinal coherent quadrupole mode oscillation (quadrupole pumping) and was extracted when the bunch length was at the minimum (i.e., highest peak intensity but with the largest $\Delta p/p$ spread) for the BPM system. Later, the beam intensity was gradually increased by improving the Tandem's ion output, changing rf harmonic $h = 12$ to 16 at injection and coalescing bunches at $h = 8$ up to $\sim 2.5 \cdot 10^8$ ipb by the end of the run with two bunches circulating on the flattop. The intensity requested for the AtR commissioning was $\geq 0.5 \cdot 10^8$ ipb and the RHIC design value is $1 \cdot 10^9$ ipb for Au beam.

The following picture shows analog outputs from the selected PUEs with a high gain at F04,F14,G08, and H08, qualitatively agreeing with the FEB bumps predicted by MAD (Figure 3a).

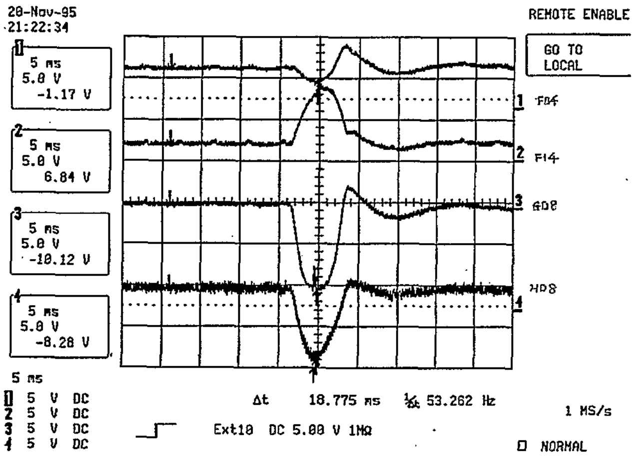

Fig.4: Analog signals from the selected PUEs.

A typical bunch shape is shown in the Figure 5 when the quadrupole pumping is off and on.

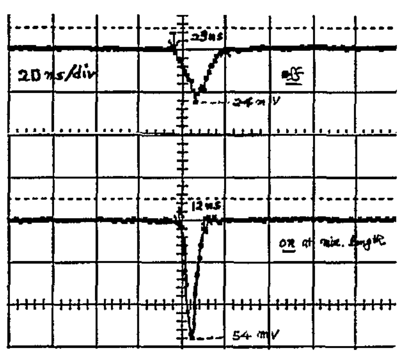

Fig. 5: Bunch shape when the quadrupole pumping is on and off.

A mountain range display of circulating bunches on the flattop is shown in Figure 6, which exhibits a bunch shape oscillation due to the quadrupole pumping and a clean single bunch extraction. The left-over bunches are dumped (to the E20 beam catcher) at the end of the flattop.

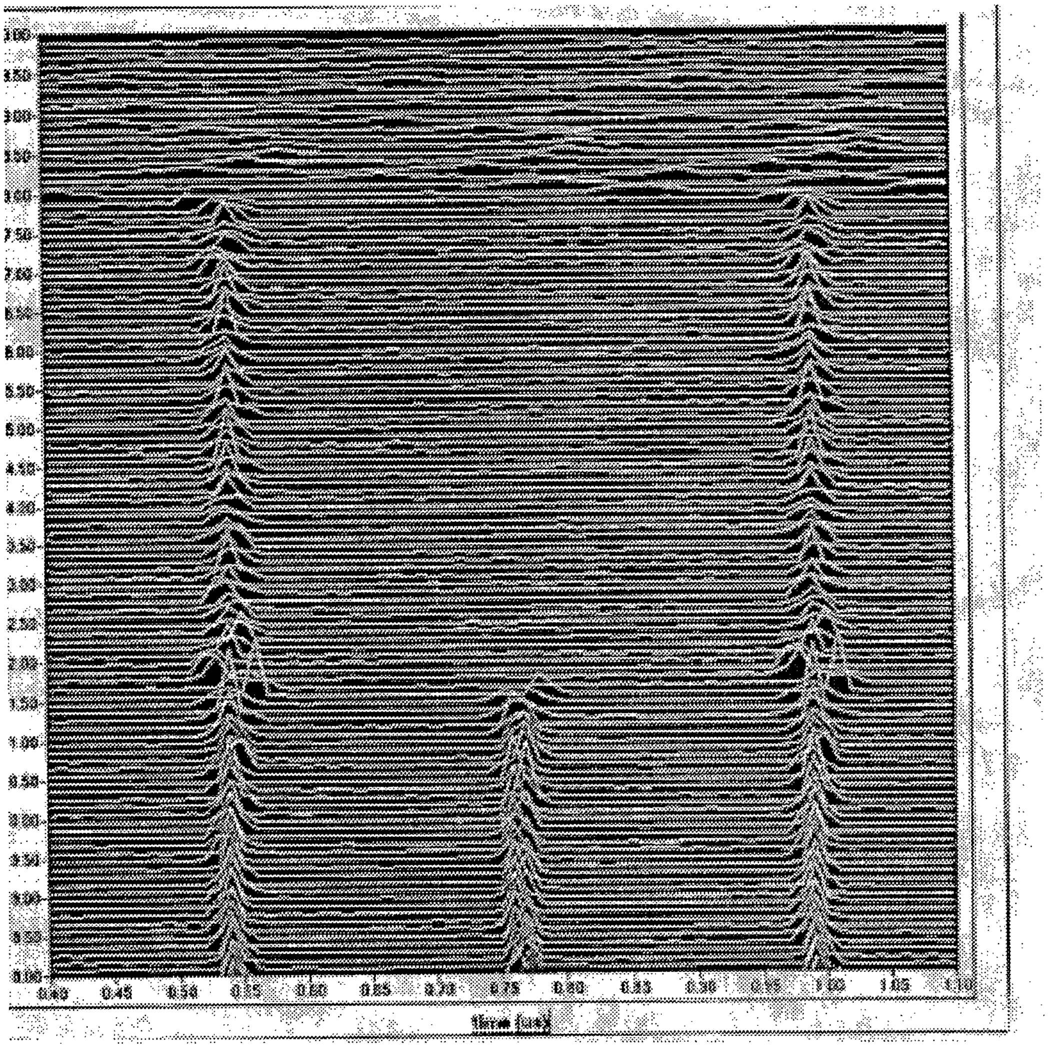

Fig. 6: A mountain range display of circulating bunches on the flattop with one bunch is extracted by the FEB extraction system.

A typical beam profile observed on uf1 (the first U-line flag) is shown in the following picture.

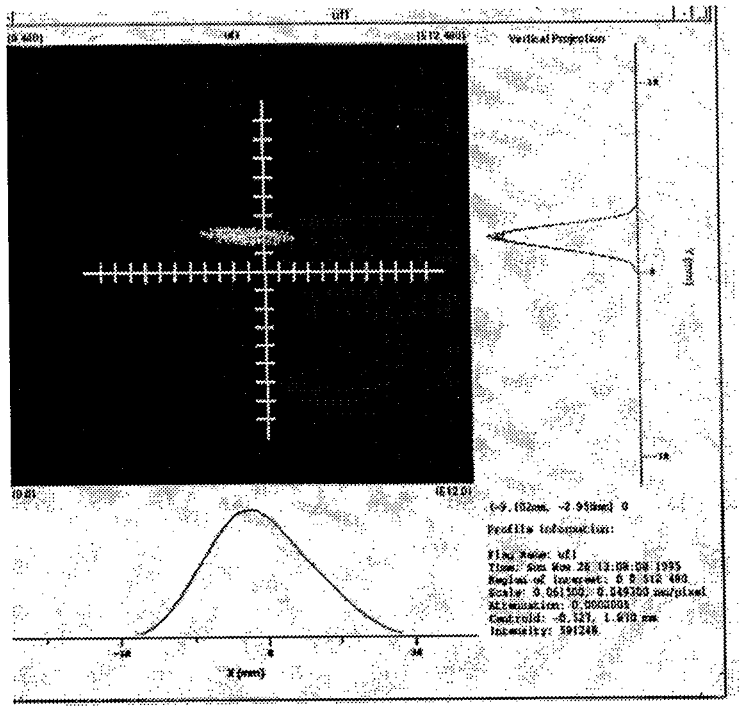

Fig. 6: A typical beam profile on uf1 at the beginning of the U-line.

Figure 7 shows the centroid distribution of the extracted beam observed over six random FEB/SBE pulses on uf1 to investigate the pulse-to-pulse modulation: The vertical position (y) appears to be quite stable within ± 0.1 mm, and the horizontal position (x) varies within ± 0. 35 mm. See ref.[7] for a more detailed study of stability as a function of beam intensity.

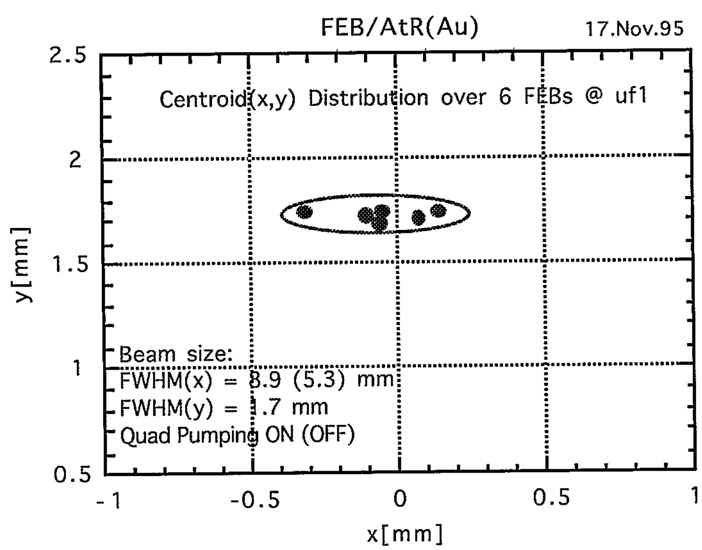

Fig.7 : The distribution of the beam position obsereved on uf1.

Table 4 summarizes the machine conditions and performance for the FEB(Au) run for the AtR commissioning.

Table 4. A summary for FY96 FEB(AtR) Commissioning and Run

User	RHIC	AtR TL (W. MacKay)
Comm. Date and Period	06.Nov.95, 17:00-24:00	beam on uf1
Run started/ended	07.Nov.96-18.Dec.95	~6 weeks
First Beam on the dump	09.Nov.95, 04:20	at the end of W-line
Run Mode	Context Switching with SEB	on request mode
Ions[A,Z]	$_{197}Au^{77+}$	$_{197}Au^{79+}$ after uf1
Momentum[p]	28.0x(79/77)x(77/197)=11.23	GeV/c/N, (B=1.1225 T)
Intensity	0.05 -> 2.5	10^8 ipb
Flattop Length	1260-1485	ms
FEB Time Window	1400-1485 (1432.25)	ms from To
AGS Repetition Rate	3.60	sec
Harmonic[h]	8 (16 @ inj. -> 8 @ accel.)	22.Nov.95 (was 12)
e^*_T(95%)	~7-8 π	mm-mrad (internal)
e^*_L	~0.3?	eV-sec/N
N_{SBE}	1	one bunch/cycle
Navg of SBEs	~ 600 -> ~ 200	per 8h-shift (10K total)
Working Point	$\{Q_h,Q_v\}=\{8.73, 876\}$ at R=0	$\{I_{Qh}, I_{Qv}\}=\{564, -445\}$ A
Highfield Sexts	$\{I_{Sh},I_{Sv}\}=\{50, 0\}$	A, $\{\xi_h, \xi_v,\} = \{-3.7,1.6\}$
BLWG09	$\{I_a,I_b\}=\{544,1092\}$	A
BLWH11	$\{I_a,I_b\}=\{556,1104\}$	A
FKG10	~1.8	kA (1.8 mrad)
SMH10	~20.	kA (20. mrad)
FlagH10	@ssH10us	
BPMs	@PueF04,F14,G08 & H08	+ turn-by-turn PueG14
AGS LMs	@ssG10us&ds and ssH10us&ds	
RHIC LMs	@ssG11,G19,H09 & H10ds	

IV. CONCLUSIONS AND OUTLOOK

• The new FEB extraction system was installed in the AGS and was commissioned with Au^{77+} beam, extracting one bunch/cycle to the U-line at 11.23 GeV/c/N and run for the AtR TL commissioning using the context switch on-request mode for 6 weeks without any serious problems.

• There was no sign of beam loss during FEB/SBE extraction.

• The context switch on-request mode worked fine even if after no activity over a week. (N.B. Due to the limited ppm capability of the main magnet power supply, the magnet cycle setup must be satisfied with the condition on power comsumptions: $\Delta W = |W_{mm}(SEB)-W_{mm}(FEB)| \leq 1.5$ MW).

• The maximum extracted beam intensity was ~ $2.5 \cdot 10^8$ ipb so that to meet the RHIC design intensity of $1 \cdot 10^9$ ipb it might need one more coalescing.

• The AtR commissioning and its measurements on extracted beam characteristics are described in ref.[7,8]:

- K =10.33 GeV/N (p =11.23 GeV/c/N) which is exactly the same with the FEB setup value. (N.B. the updated AGS design energy of Au beam is 10.33 GeV/N not 10.8 GeV/N, see Table 1. or ref.[6]).

- $\varepsilon^*_h(95\%) = (10.3 \pm 0.5)\ \pi$ and $\varepsilon^*_v(95\%) = (9.5 \pm 0.6)\ \pi$ mm-mrad. The internal emittance was estimated to be $\varepsilon^*_{h,v} \approx 7\text{-}8\ \pi$ mm-mrad from the beam spot size on FlagH10 and IPM data for the HIP/SEB beam before debunching. (IPM was not available during the AtR commissioning).

- $\sigma_p/p = 0.3\%$, $l_b = 20$ ns at high intensity. If σ_p/p means a rms value, then 0.3 % is too large even if assuming the qudrupole pumping was on. We estimate that internal $(\sigma_p/p)rms \approx$ ~0. 02-0.03 % or $(dp/p)full \approx \pm 0.1$ % or less based on the beam spot size on the FlagH10 and known beta and dispersion functions at the flag. The internal l_b(full) varies from 12 to 36 ns depended on exact machine conditions.

- the vertical beam poistion observed on uf1 is quite stable but the horizontal position varies within ± 0.5 mm, and shows some intensity dependence.

• For the next run (RHIC Sextant Test), we hope that we can

- perform *multiple* single bunch extraction (2 or 3 SBEs/cycle) at 30 Hz with the design Au intensity,

- test the trim backleg windings for better FEB bumps,

- measure fully the *internal* beam parameters (ε_T, ε_L, σ_p/p) and pulse-to-pulse, day-by-day beam stability,

- have a full synchronization between FKG10 and the RHIC injection kicker firings.

V. ACKNOWLEDGMENTS

The FEB and AtR TL commissioning with Au beam was performed collectively by the accelerator staff in the AGS Department and the RHIC Project.

The new FEB extraction system was designed by the AGS/AD/Extraction Group and the optimal FEB extraction parameters for RHIC injection were developed together with H. Foelsche, E. Forsyth and N. Tsoupas.

We would like to thank many members of the AGS Department who have helped to construct the new FEB system and make its commissioning successful, especially: A. Dunbar (bumps), J. Tuozzolo (kicker), E. Rodger (ejector), W. Zhang (kicker PS), R. Lockey (ejector PS), E. Gill (injection bump), E. Keith-Monnia (controls-software) N. Schumburg(controls-hardware), J. Skelly (controls-datacon), P. Ingrassisa and MCR staff, and many others.

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