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Libera Hadron: Demonstration at RHIC (BNL)

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Introduction

Libera Hadron has been tested at Brookhaven National Laboratory. The tests took place on February 28th and March 1st 2011 at RHIC (yellow) ring. Furthermore, laboratory measurements of the unit were carried out on a stepper-motor controlled micrometer wire-BPM test-bench.

The Libera Hadron system implements the following basic functionalities*:

- *Single Pass – High Resolution, Single Bunch Transversal Beam Position measurement of individual bunches*
- *Single Bunch Precise Charge measurements*
- *Turn by Turn – High Resolution, Turn averaged Beam Position and Charge measurements*
- *Slow Acquisition - Beam Position Slow streaming for monitoring purposes***

In addition, it can offer the following advanced functionalities:*

- *Single Pass - High Resolution, Individual Bunch Arrival Time measurement*
- *Fast Acquisition – Very High Resolution Beam Position measurement streaming at 10 kHz rate on dedicated output for Fast Feedback purposes***
- *Bunch Map and Bunch Fill Pattern measurements*

* The prototype, used for RHIC measurements, is performance wise fully functional. However, it had the DSP implemented on the on-board PC, limiting the speed of processing and the acquired buffer sizes. The processing will be transferred to on-board FPGA for the regular product.
** Due to the above described reason, the streaming data flows were not functional on this prototype.

The Libera Hadron system is implemented on a uTCA based 19" 2U platform chassis. The chassis can populate up to 4 BPM modules in order to acquire simultaneously the position from 8 BPM planes. The instrument consists of a high performance stabilized RF front-end and state-of-the-art analog to digital converters. The digital signal processing is implemented on Virtex_5 FPGA and a computing module that can access to large data buffers (up to 8 Gbits per BPM) through a PCIe bus. The data acquired by the BPM modules can be transferred through dedicated low latency LVDS links to FPGA based real time DSP modules for further processing and SFP streaming for feedback purposes.

Fig 1.: Libera Hadron: A Hadron Beam Processing System in 19" 2U rack-mount chassis implementing a high performance RF front-end, FPGA real-time processing, computing module and auxiliary slots for further processing, SFP data streaming and other purposes.

Measurements at RHIC

Libera Hadron was installed on one of the RHIC BPM pickups, through power splitters. Only two electrodes corresponding to horizontal plane were connected to the channels A and C of the instrument. Channels B and D were therefore not connected. Figure 2 shows the acquired raw BPM signals.

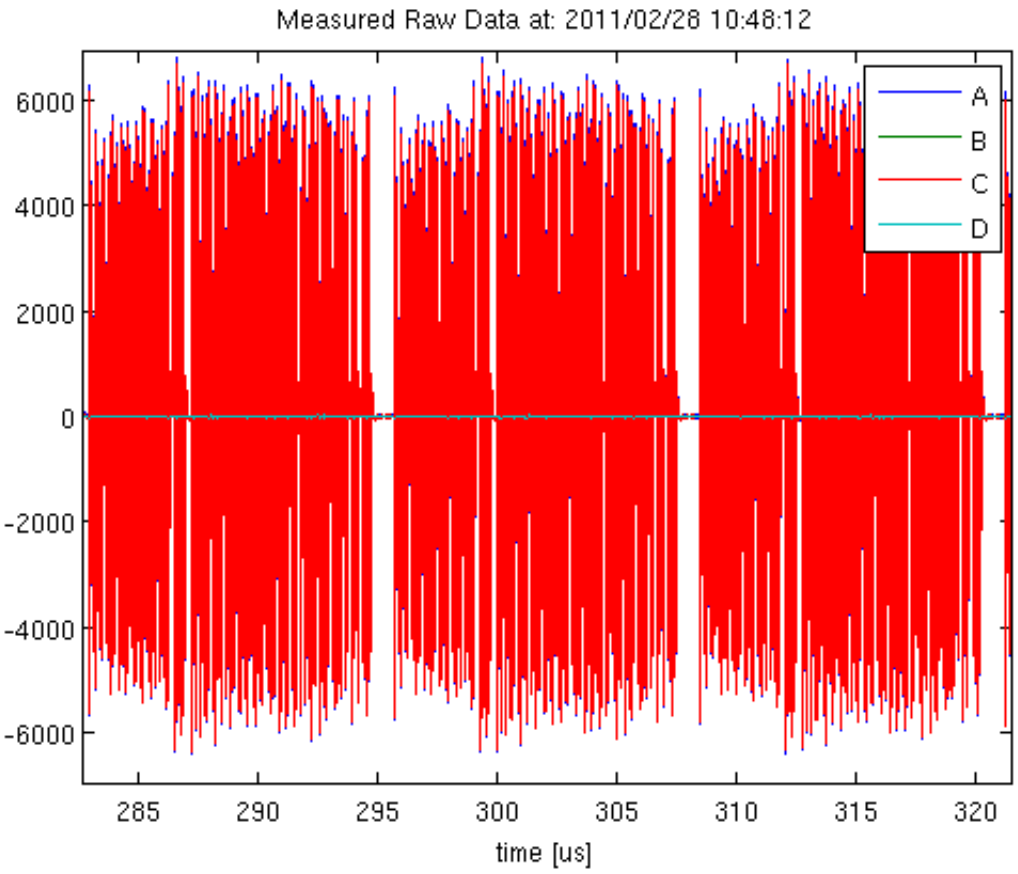

Fig 2: Acquired RAW BPM signal, the picture presents a zoom-in of 3 turns and shows already the characteristic bunch fill pattern. Due to the installation of power splitters and the operation of the machine at relatively low current the measurements were carried out at approx 6000 counts (19% of the instrument full scale). However, the full scale can be further adjusted to optimize the measurements.

The Libera Hadron system digitally processes the acquired data in order to provide the acquired signals at different rates and present different information content. The available signals are:

- Raw data: (refer to figure 2)
- Single Pass: the Libera Hadron system automatically detects the bunches in the acquired signals, isolates them, extracts each bunch charge information, the position information in the transversal plane and the beam arrival time information. Figure 3 represents the measured Single Bunch (Single Pass) signal.

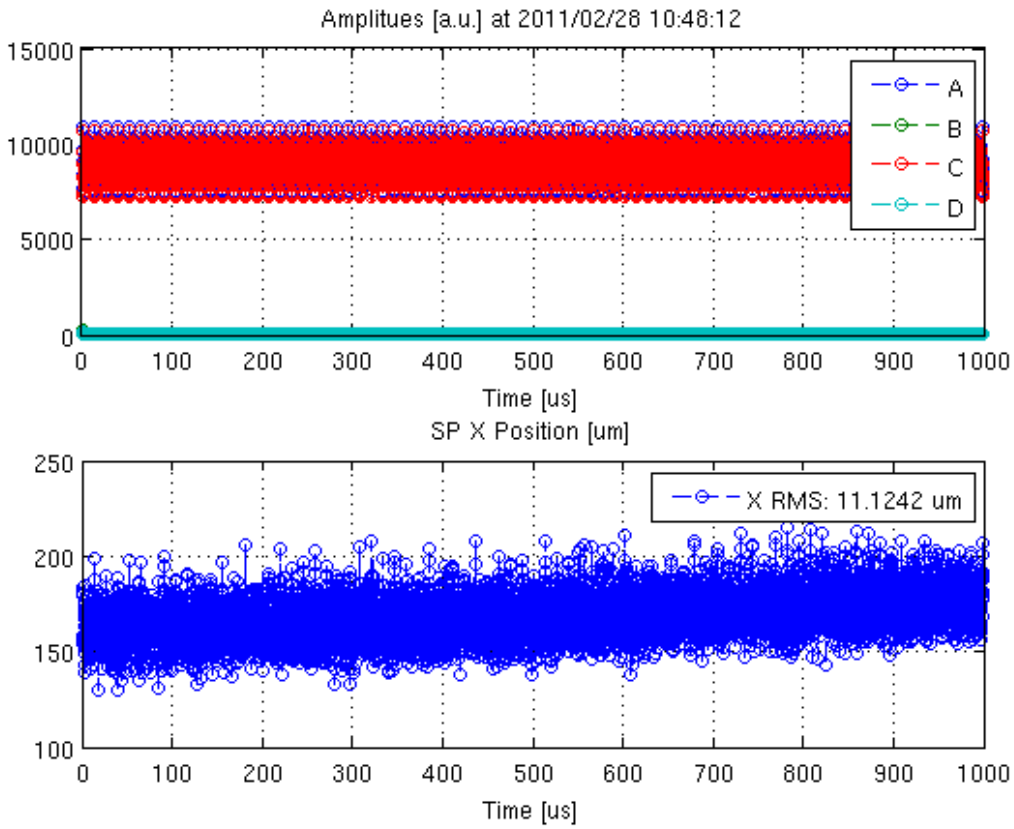

Fig 3: Acquired Single Bunch (Single Pass) signal in the time frame of 1 ms (corresponding to approx. 80 RHIC turns). The upper plot represents the amplitude samples for individual bunches. The lower plot represents the position measurements for individual bunches. The standard deviation (calculated in the 1 ms time-frame) of the Single Bunch position is approx 11 um.

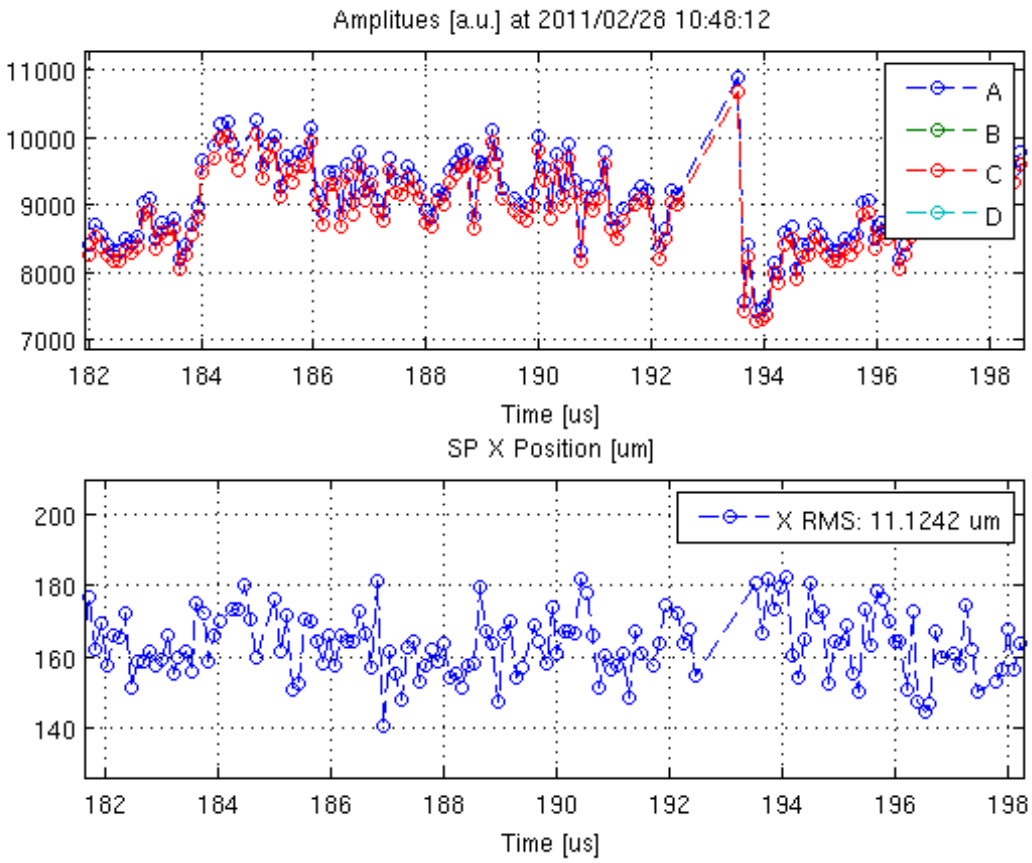

Fig 4: Zoom in of the acquired Single Bunch (Single Pass) signal over a turn. The amplitude plot shows the charge distribution among bunches and the relative position measurements are available from the second plot.

- Bunch Map: The individual bunches were tracked over 78 turns and the information is provided as a map of filled buckets.

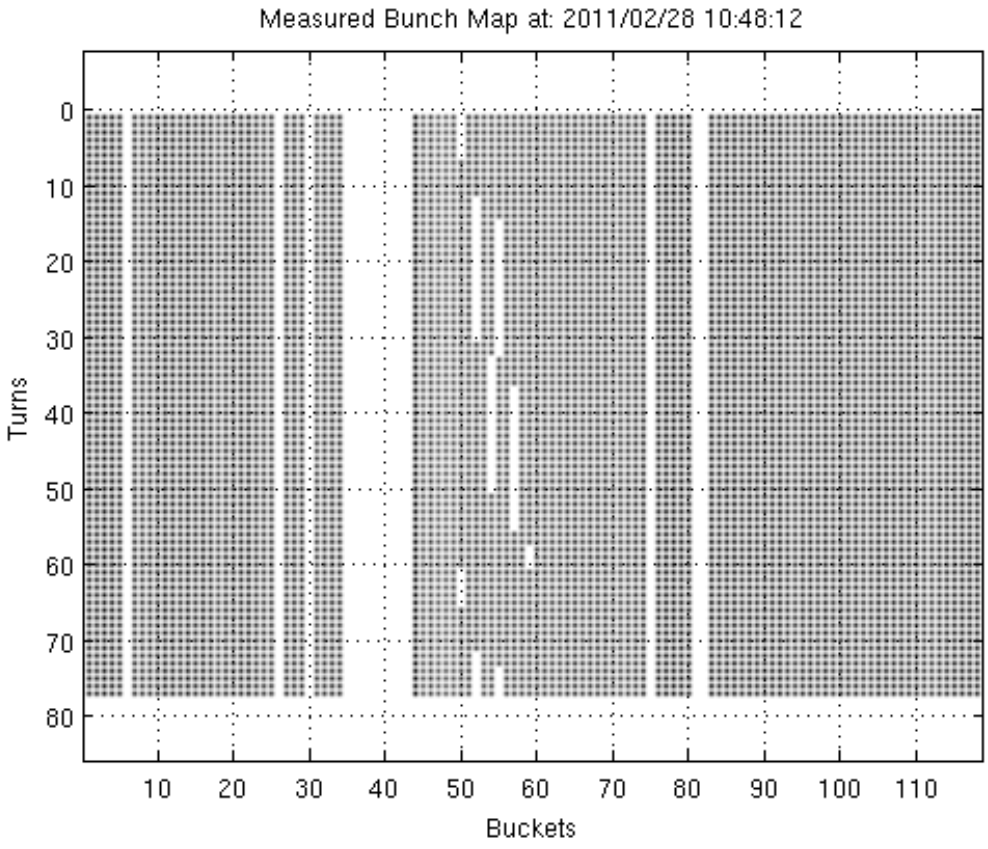

Fig 5: The bunch map show over many turns the charge detected in each bucket. The bucket 44 of the Libera Hadron enumeration has the highest charge. Bunches in the buckets between the 50th and 60th are sometimes missed because of the default setting of the bunch detection threshold. If bunches at lower charge are expected a lower threshold needs to be applied to the Libera Hadron in order to detect all bunches.

- The bunch map information can be averaged over many turns to get the average bunch fill pattern:

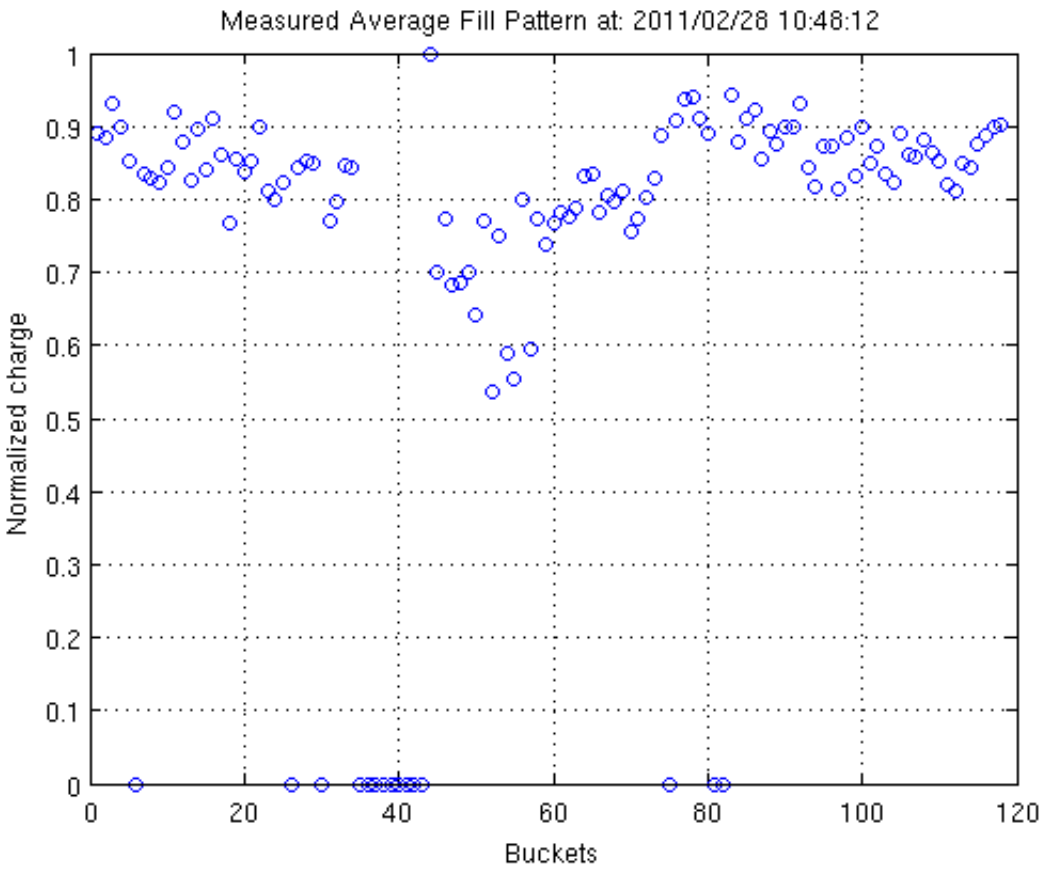

Fig 6: The RHIC average fill pattern over 78 turns. The measurement shows the normalized charge, stored in the individual buckets. The maximum charge was injected in bucked 44, the other buckets store between 70 – 90 % of the maximum charge. The buckets between 35 and 43 are empty.

The Single Pass (Single Bunch) acquisitions have been used also to observe the injection into RHIC. Figures 7-9 show some frames of the "injection movie". Please contact Instrumentation Technologies if you are interested in the movie.

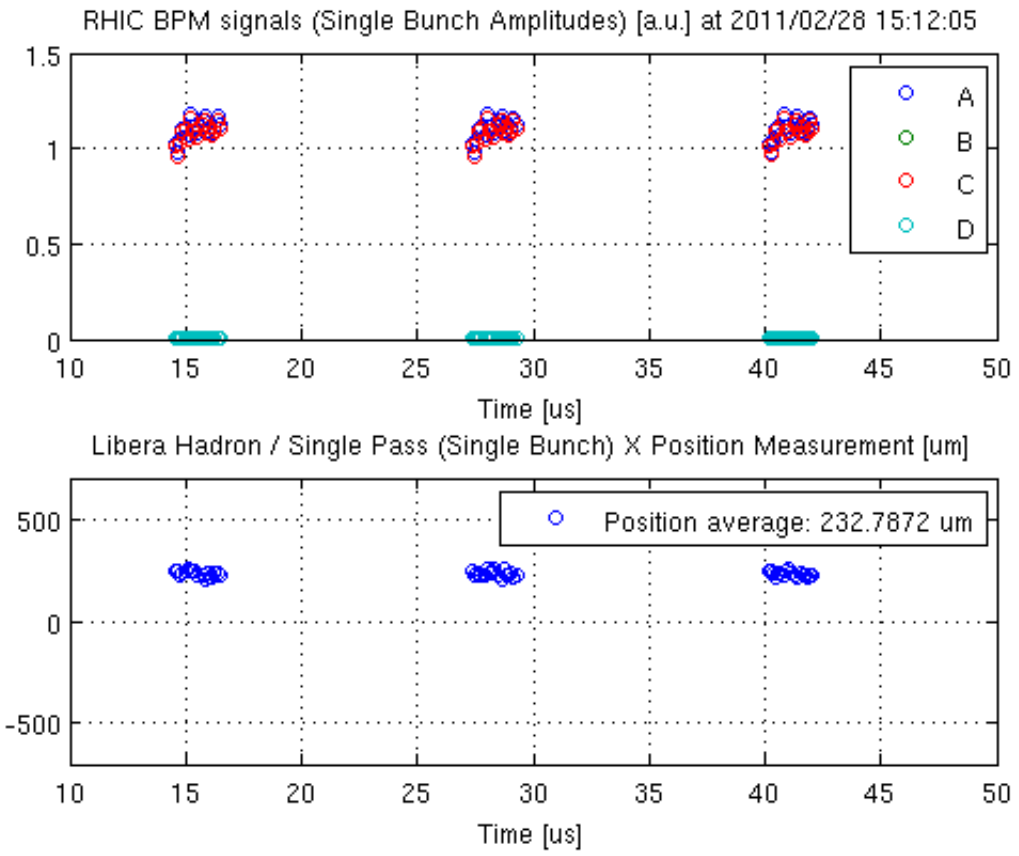

Fig 7: RHIC injection "frame A": Libera Hadron, Single Bunch measurement during RHIC injection. In the picture are represented 3 turns with an approx. fill of 10 %. The maximum charge, expressed in arbitrary units, is approx. 1.2.

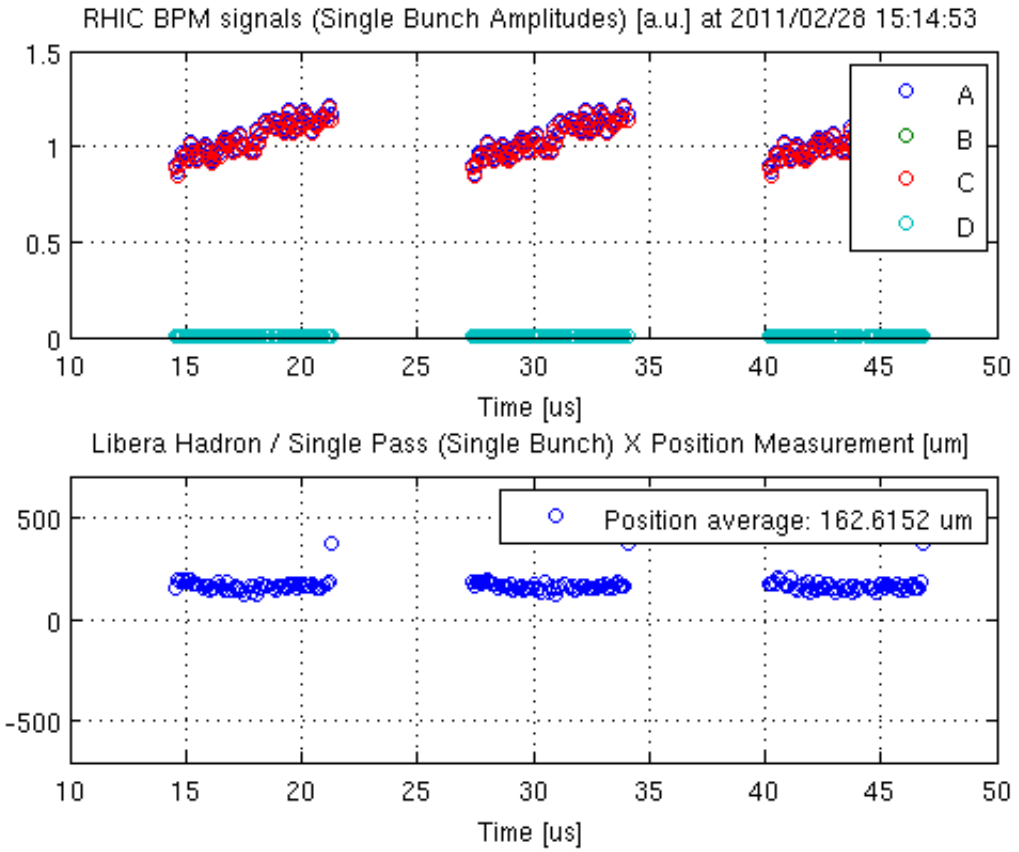

Fig 8: RHIC injection "frame B": Libera Hadron, Single Bunch measurement during RHIC injection. Three turns with an approx. fill of 60 % are shown. In less than 3 minutes there were injected further bunches with the same charge, the maximum charge is still 1.2 a.u., but the local maximum of figure 7 decayed down to approx. 1.05. The last bunch injected in the frame (the last in the turn) is displaced from the others due to injection transient oscillation effects. In figure 9, the next frame taken after 4 seconds shows that bunch already aligned with the others.

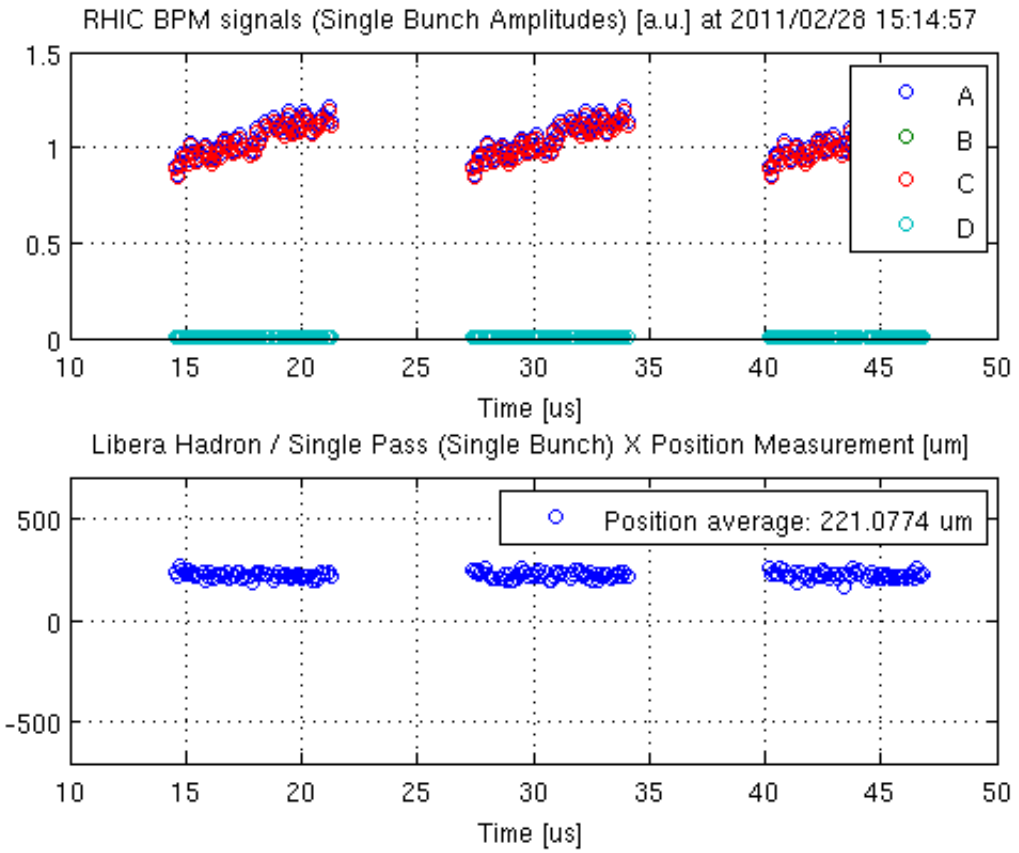

Fig 9: ***RHIC injection "frame C": Libera Hadron, Single Bunch measurement during RHIC injection. By comparing the average position of the 3 frames, a slow transversal motion was observed of the beam that was better characterized in the measurements that follow.***

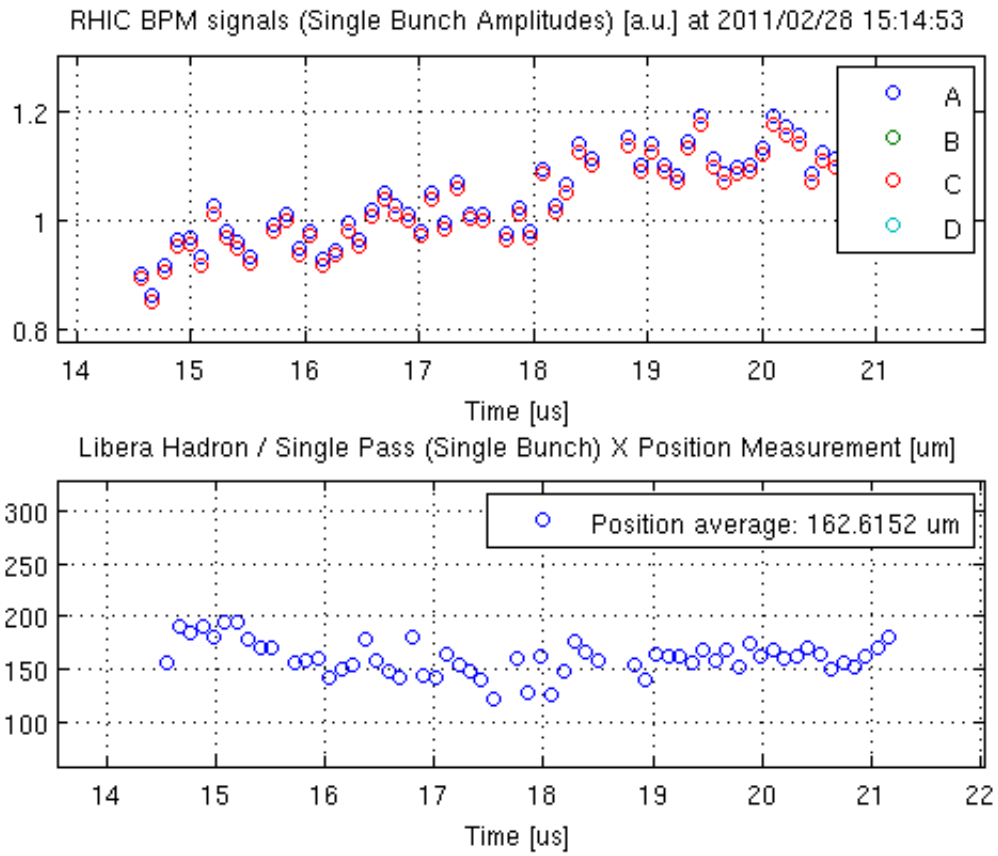

Fig 10: The injected beam measured over a single turn shows the bunch charge and position distribution. The slope of the amplitude is produced by the beam decay in the storage ring during the injection process.

The RHIC injection Single Bunch measurements were also represented on a longer timescale in figure 11.

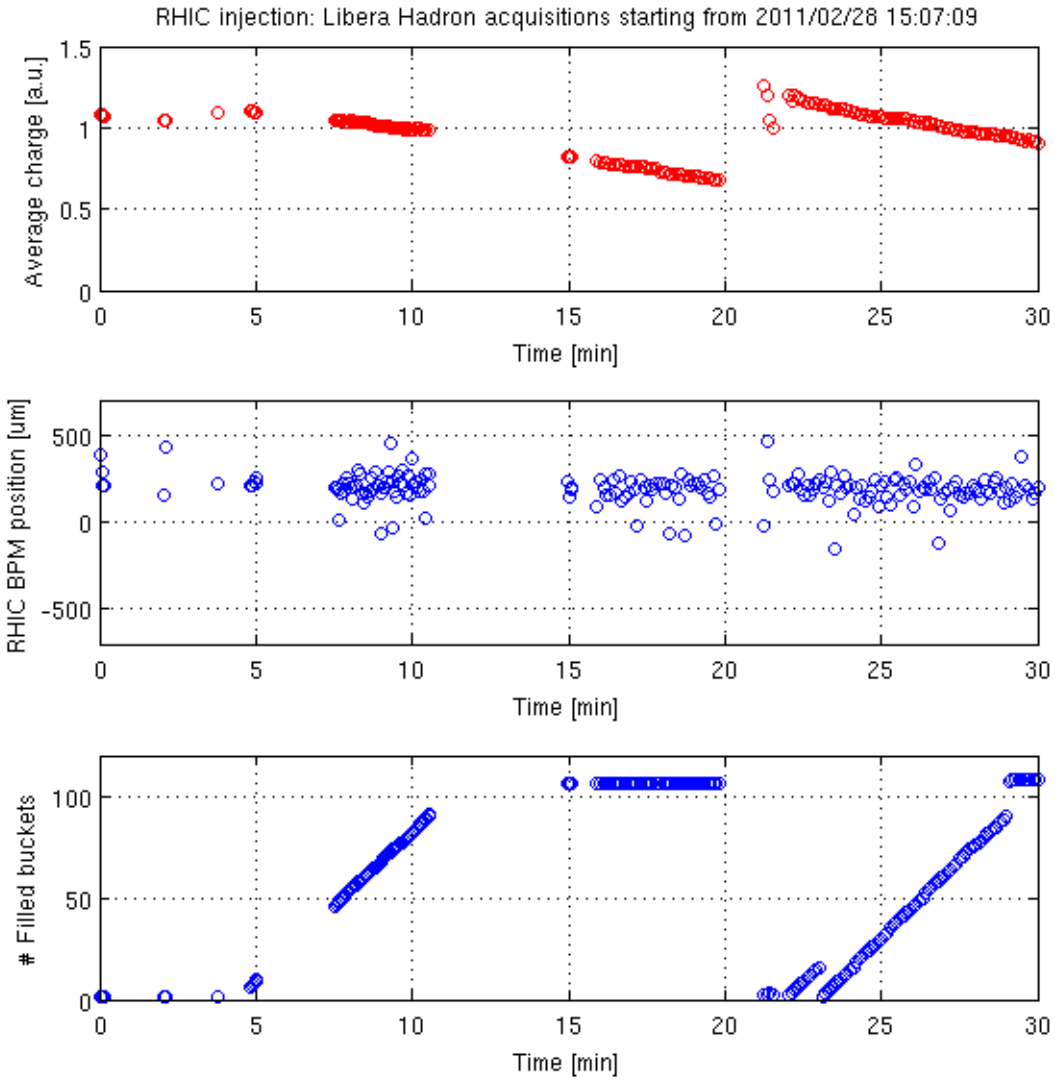

Fig 11: RHIC injections over longer timescale: Averaged Libera Hadron, Single Bunch measurement during RHIC injection. The first plot represents the average stored charge per bucket expressed in arbitrary units. The charge decay during the injection process can be clearly distinguished. The second plot represents the average beam position. Slow fluctuations of the beam were observed in these measurements and subsequently better characterized. From this preliminary measurements average peak to peak excursions of the beam position in the order of 300 um were measured. The third plot shows the number of stored bunches during 3 injections.

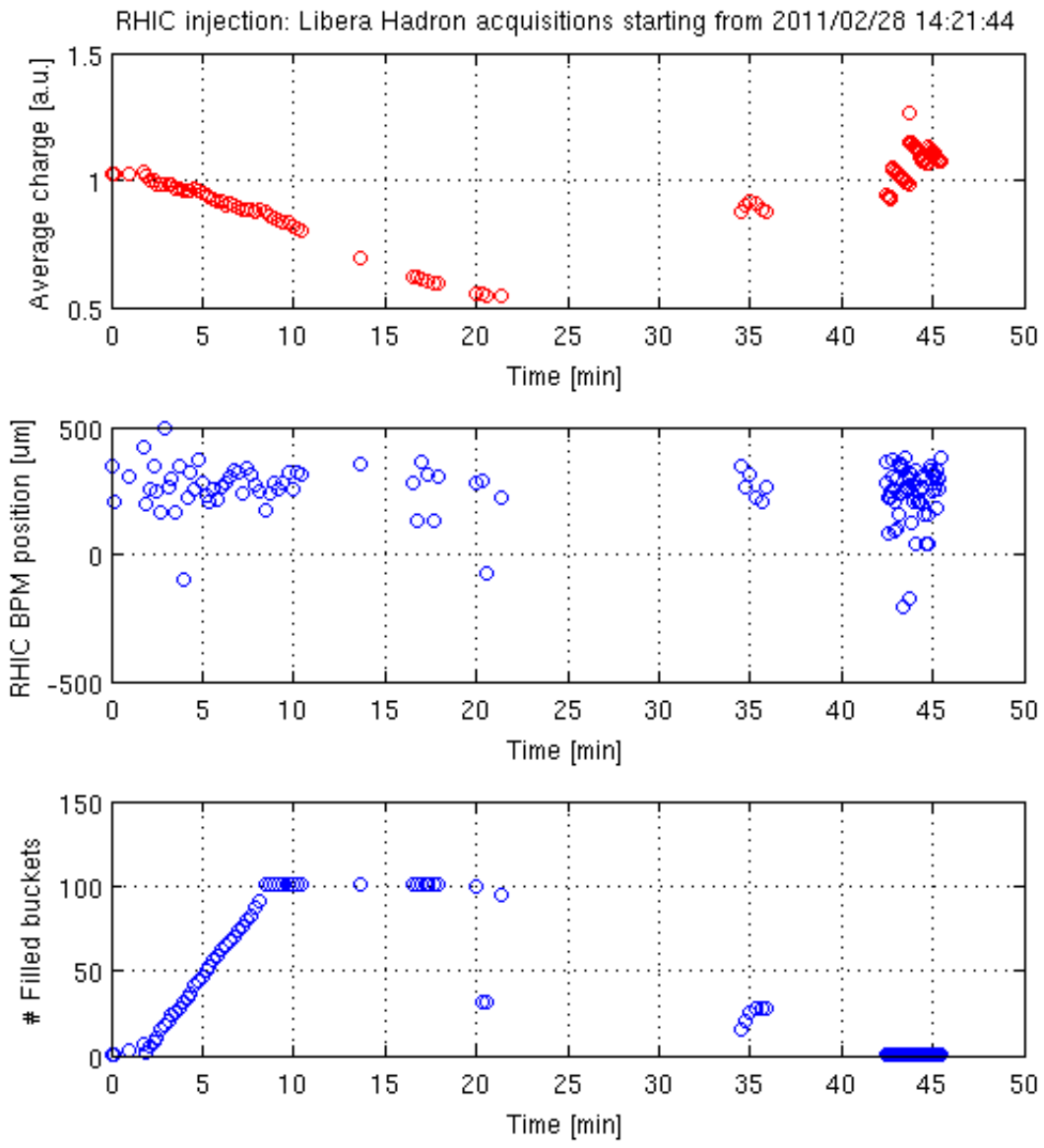

Fig 12: Another sequence of injections and beam current decays measured from averaged Libera Hadron, Single Bunch data. At time 42 min, single bunch injections were performed.

Some Measurements from the Laboratory

- Beam Arrival Time measurements: Libera Hadron also provides for each detected bunch a beam arrival time measurement. Figure 13 shows a laboratory measurement of the beam arrival time.

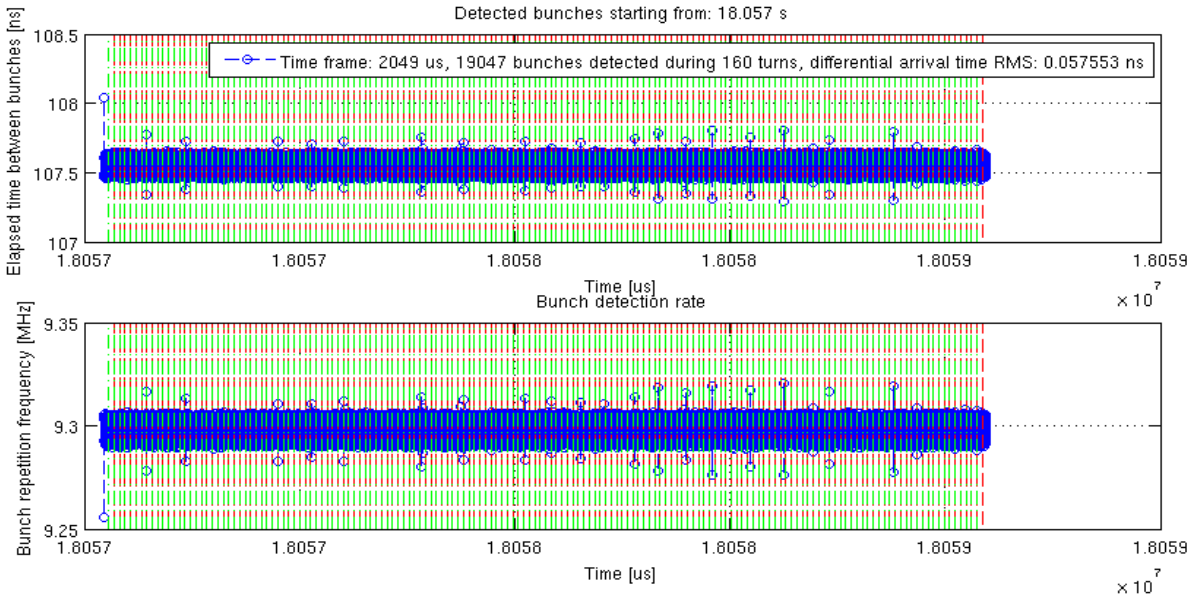

Fig 13: Libera Hadron laboratory Beam Arrival Time measurement represented as elapsed time between consecutive bunches and the resulting local bunch repetition rate frequency. The standard deviation of the elapsed time measurements is 57.55 ps.

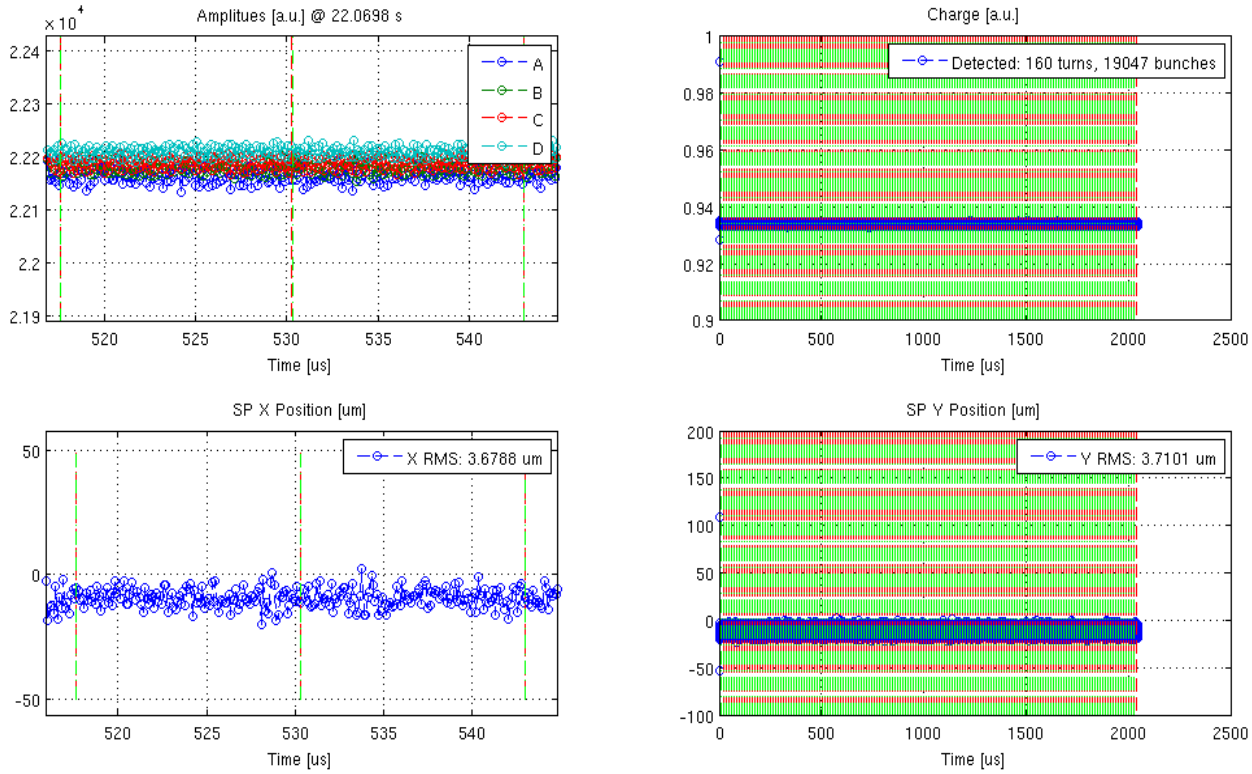

Fig 14: Libera Hadron laboratory Single Pass (Single Bunch) position measurement. The laboratory Single Bunch position measurement standard deviation at half full scale is 3.7 um. The main difference between the presented RHIC measurement (Figure 3: RMS=11.1 um) is in the signal level difference.

Presented measurements describe instantaneous individual bunch motion in the transversal and longitudinal planes. There is a potential in the instrument to further process these signals inside the Libera Hadron unit and

generate a low latency analog output signal that acts back on the beam in order to damp oscillations of individual bunches or clear predefined buckets.

The same unit also provides the averaged Single Pass stream over many turns in order to track slower beam motions and for orbit correction purposes.

Similarly like figure 14, the Turn by Turn data was acquired by means of laboratory measurements:

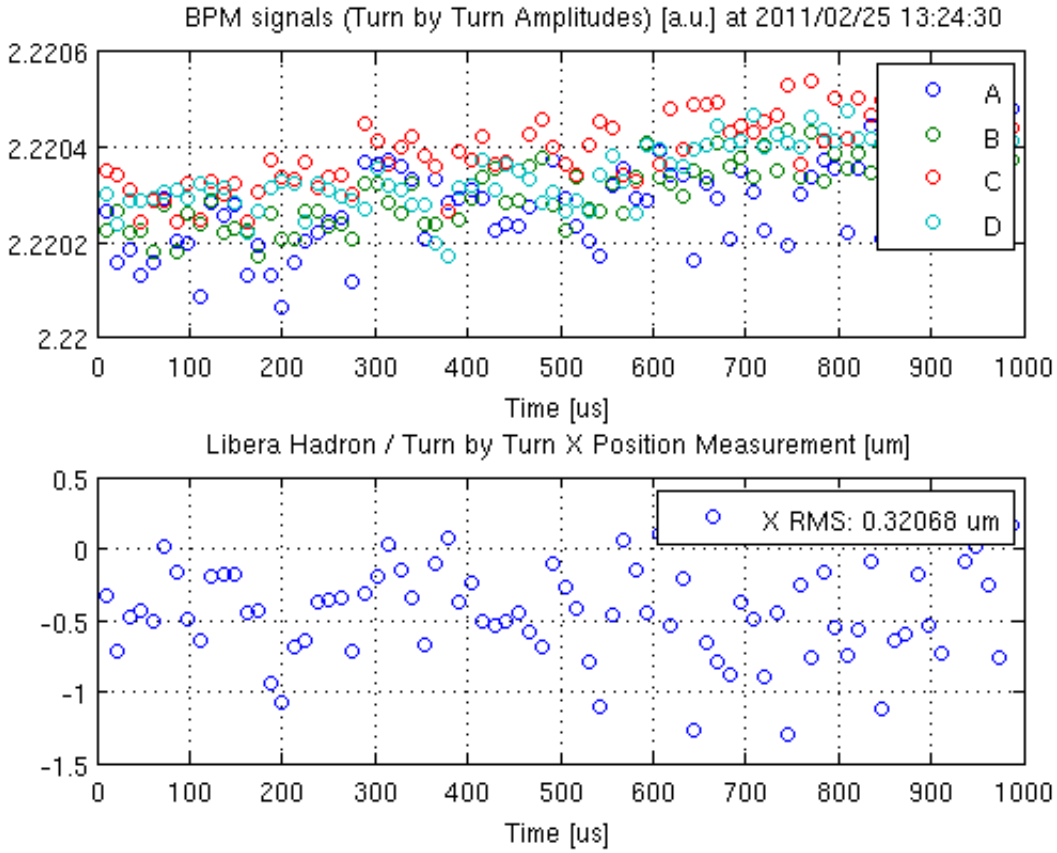

Fig 15: Libera Hadron laboratory Turn by Turn position measurement shows a submicron position resolution. The measured position standard deviation was 0.32 um.

Measurements at RHIC (continued)

- Turn by Turn acquisition: Another acquisition supported by the Libera Hadron system is the turn based averaged data known as "Turn by Turn" measurements. The averaging can involve predefined buckets. Figure 16 shows a Turn by Turn measurement at RHIC.

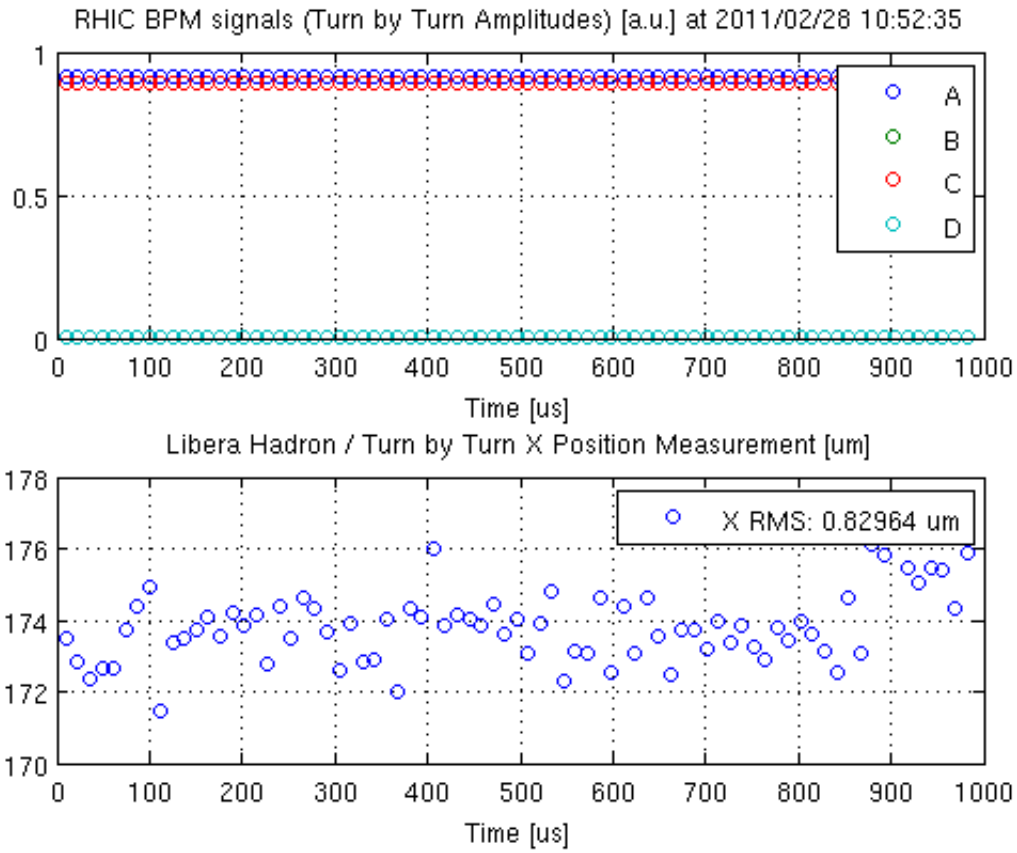

Fig 16: Libera Hadron Turn by Turn position measurement at RHIC. The first diagram shows the average amplitudes and the second diagram the average position. Each sample corresponds to a RHIC turn over a frame of 1 ms. The position measurement standard deviation is 0.83 um.

The Turn by Turn acquisitions were used to investigate the position fluctuations describe during the injections measurement.

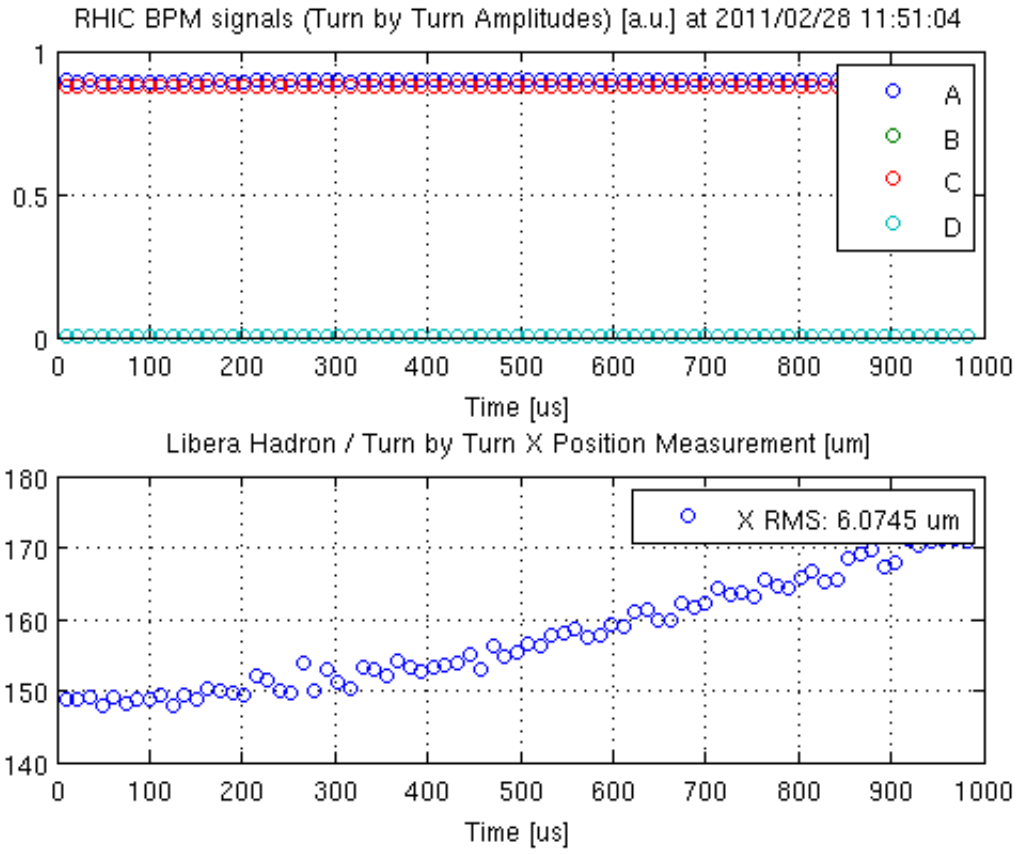

Fig 17: Libera Hadron Turn by Turn position measurement at RHIC. Some Turn by Turn measurement showed a slope in the position.

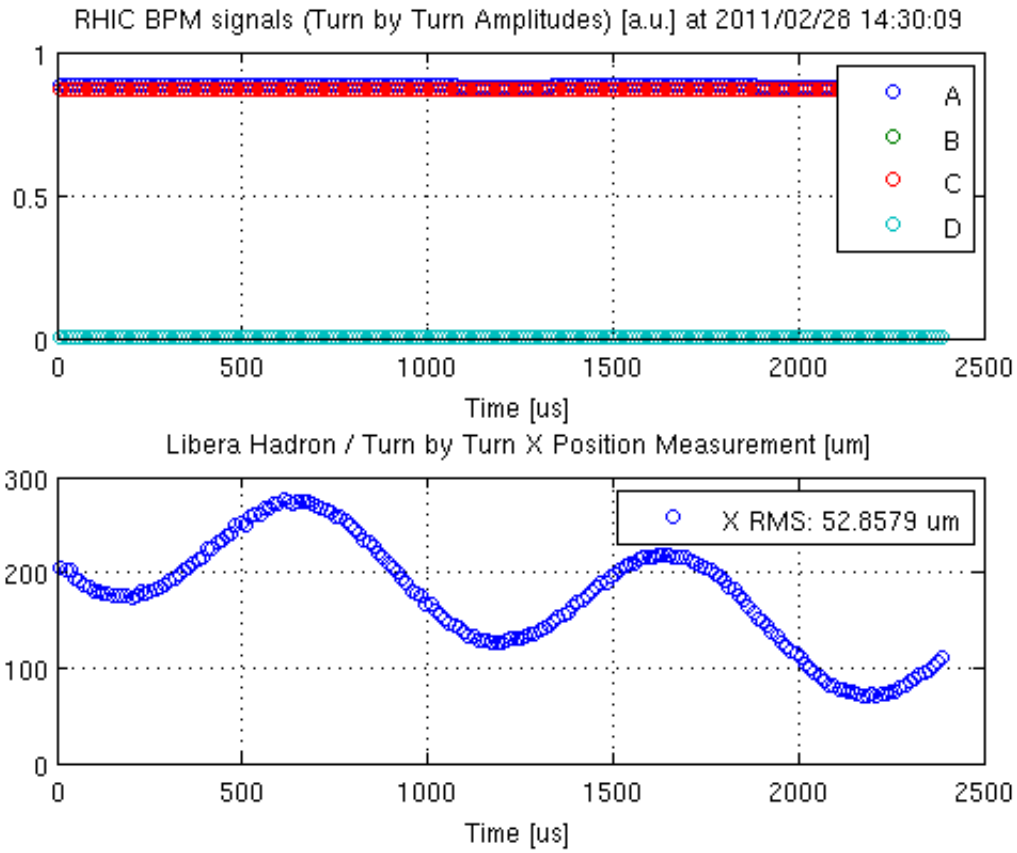

Fig 18: Libera Hadron Turn by Turn position measurement at RHIC. Subsequently the acquisition length was increased to 2.4 ms in order to track slower changes in beam motion. At least two frequency components of the beam position were identified. The fastest oscillation period was 1 ms, resulting in a 1 kHz frequency component producing beam motion with peak to peak excursions of 100 um. Superimposed to that oscillation much slower modulation of the beam position was measured. A comparison with the acquired Single Pass data locates the acquired Turn by Turn oscillating position in the middle of the injection depicted in figure 12. Figure 12 at times between 5 a 10 minutes also shows a sine pattern in the position samples taken at distances of few seconds. The pattern results from the aliasing of one of the two frequency components.

Fast Acquisition: The Libera Hadron also supports a 10 kHz data streaming obtained by means of further averaging of the Turn by Turn stream over 8 turn in the case of RHIC.

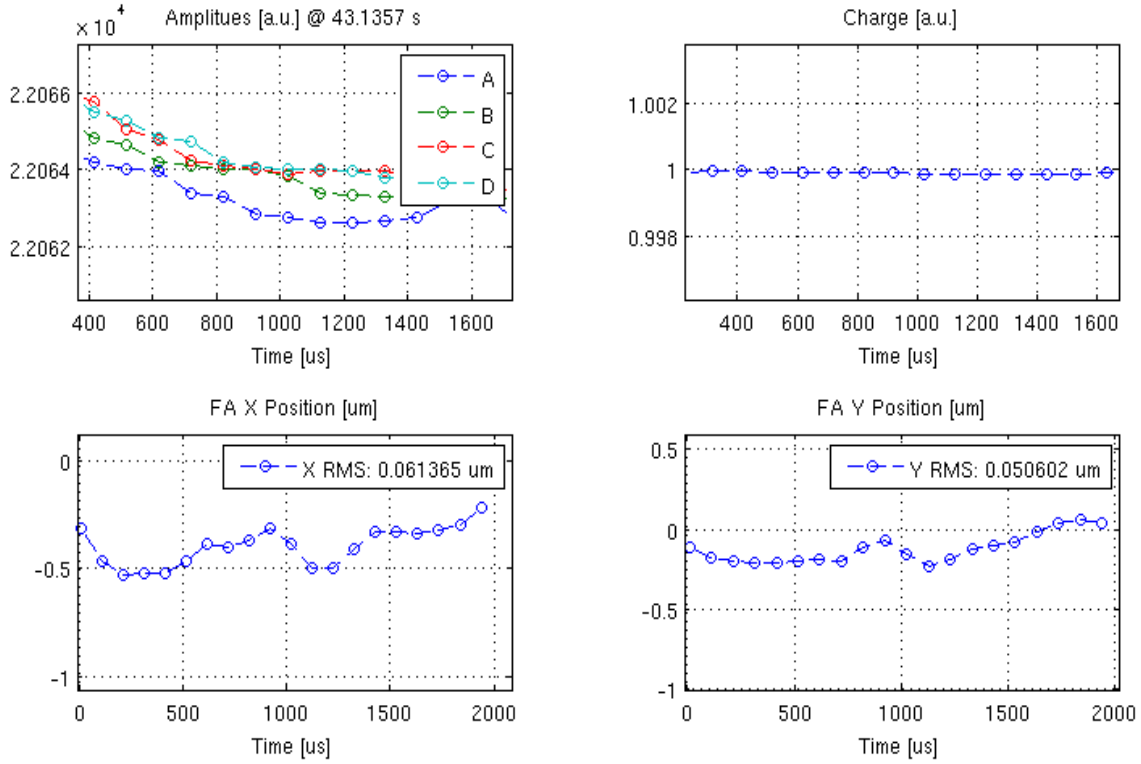

Fig 19: Libera Hadron laboratory Fast Acquisition position measurement. The measured position standard deviation is in the worst case 61 nm.

Measurements at RHIC Laboratory Test bench

The second day the Libera Hadron was installed on one of the RHIC BPM pickups, in the laboratory test bench in order to measure the system response to deterministically controlled signals. The wire test bench controlled by stepper motors was fed by generator driven pulses, simulating the beam. The Libera Hadron system was configured for TBT measurement and two position sweeps were performed:

- a position sweep measurement in the range of ±5 mm in steps of 100 um

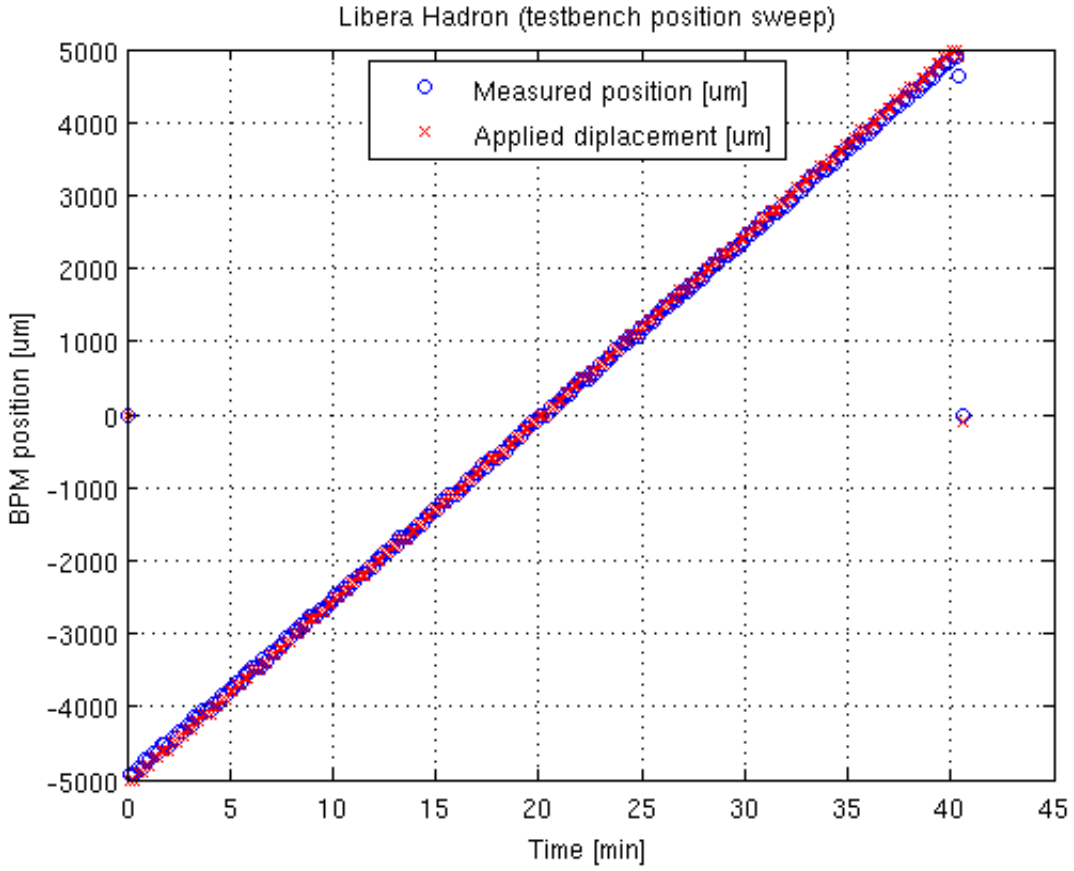

Fig 20: Libera Hadron test bench position sweep measurement. The blue marks represent the applied position by the stepper motors and the red crosses correspond to the Libera Hadron measurements. The isolated blue circle on the upper-right corner corresponds to the Libera Hadron measurement during the last test bench motion on the way back to the center.

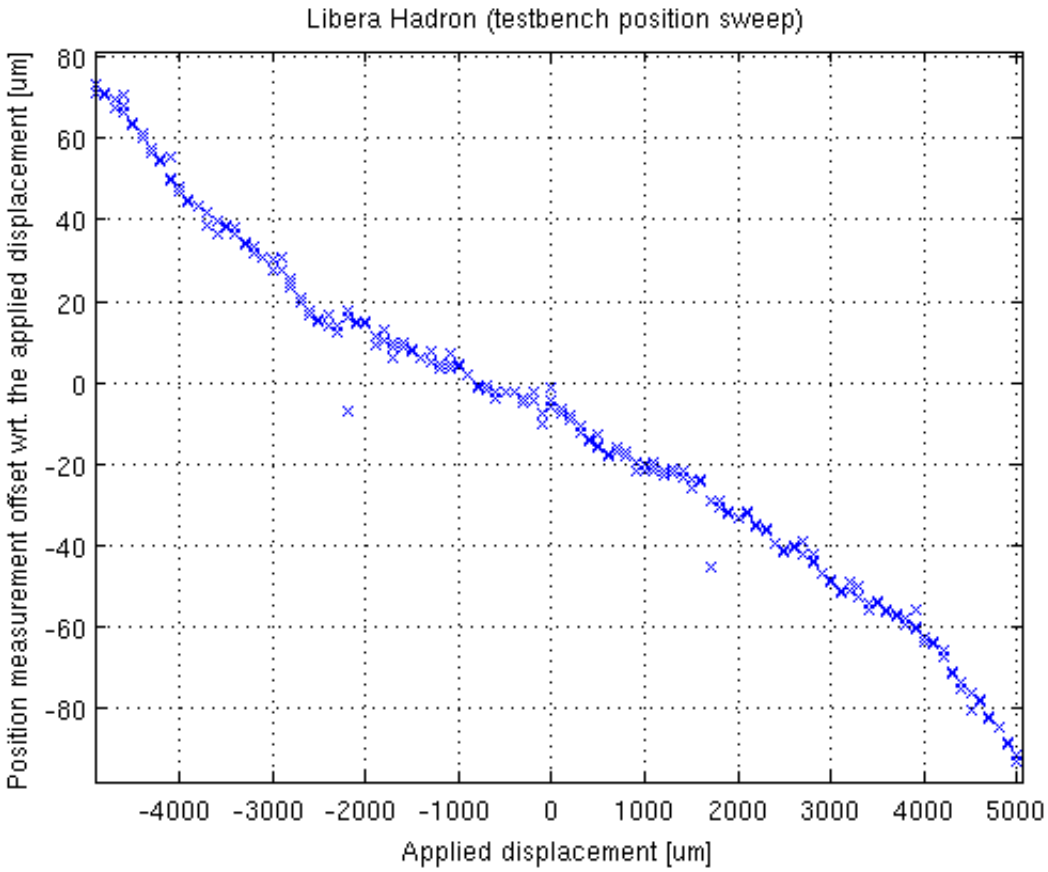

Fig 21: Libera Hadron test bench position sweep measurement represented as position offset with respect to the applied test bench displacement. The measurement shows the limitations of the Libera Hadron linear position model. From the first order fit of the curve a static position offset (zero order term) for the specific BPM geometry can be calculated and applied to the Libera Hadron unit. The slope of the curve (through the first order term) can be applied to the unit as correction of the nominal geometrical factor. The third order term can be used in the implementation of a cubical correction term as extension of the pickup linear model.

- a position sweep measurement in the range of ±15 mm in steps of 1 mm

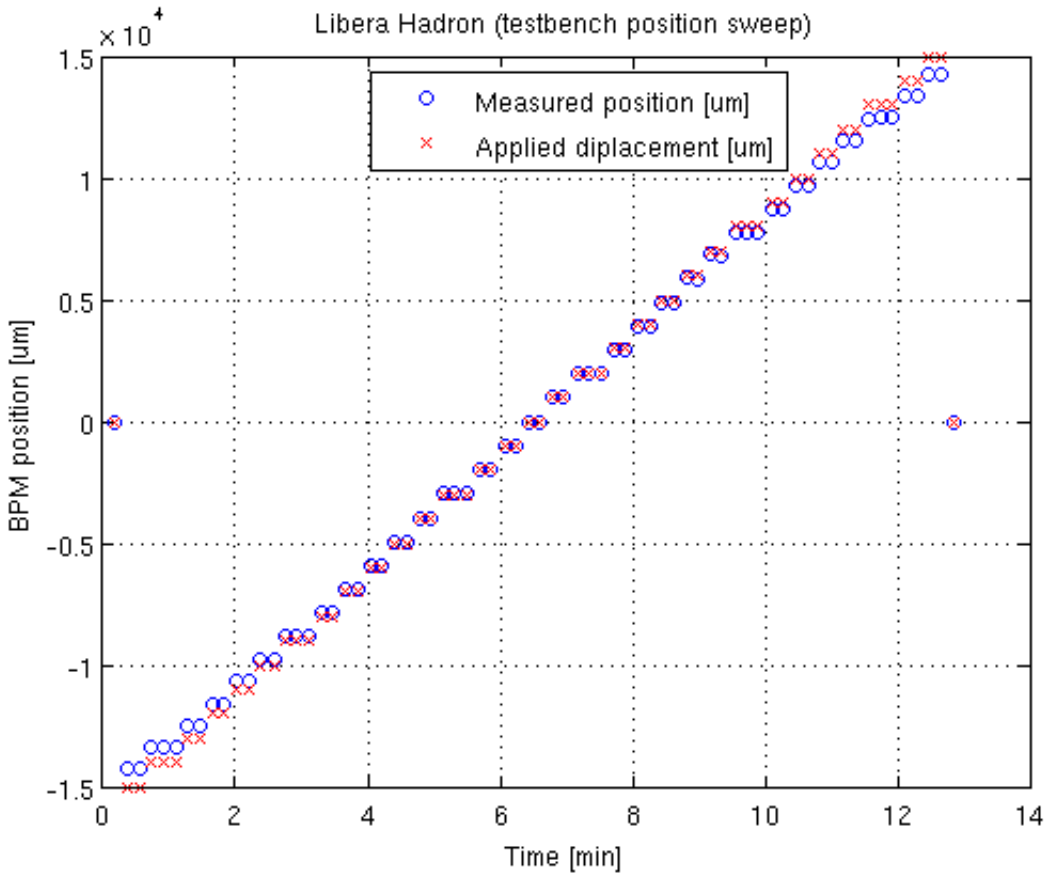

Fig 22: Libera Hadron test bench position sweep measurement. The blue marks represent the applied position by the stepper motors and the red crosses correspond to the Libera Hadron measurements. The non linear response of the BPM pickup is clearly visible in the figure for the case of a of 30 mm span.

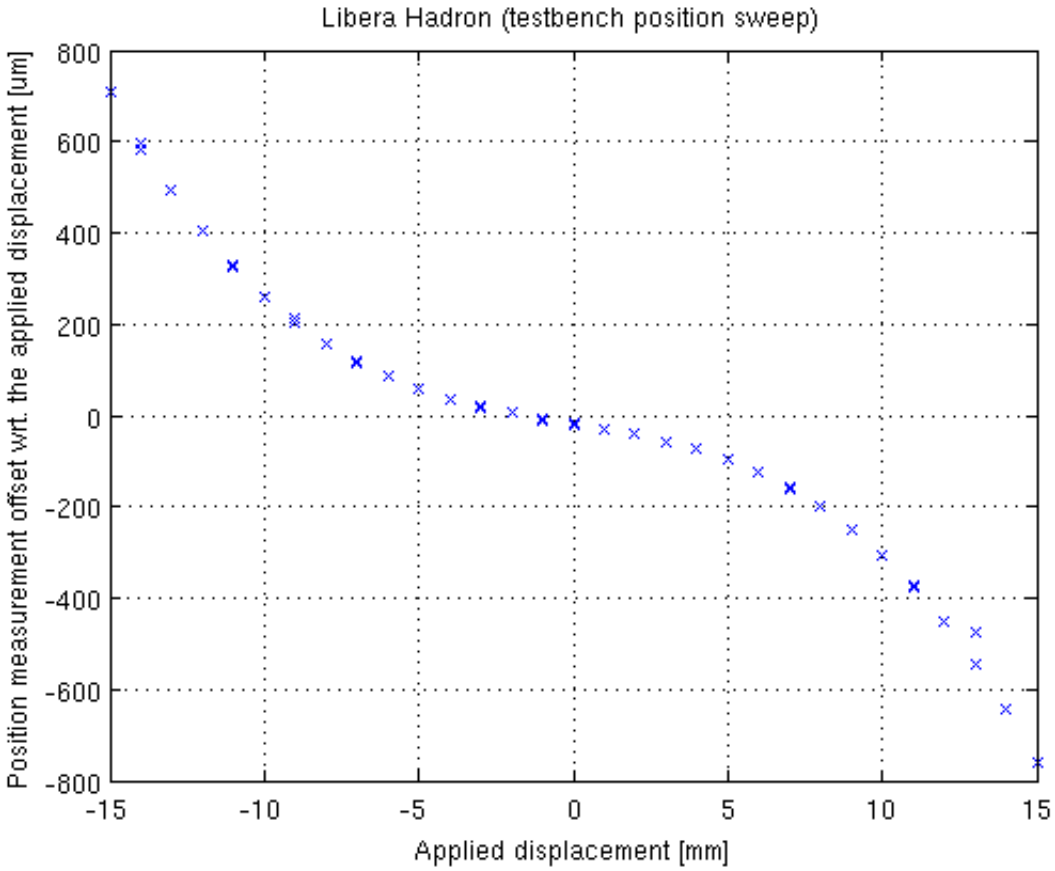

Fig 23: Libera Hadron test bench position sweep measurement represented as position offset with respect to the applied test bench displacement showing the non linear response of the BPM pickup. One of the samples for the displacement of +13 mm was taken during the test bench motion between +12 mm and +13 mm.

Acknowledgements:

We acknowledge whole the RHIC diagnostics team that supported us during the measurements, particularly we acknowledge Robert J. Michnoff and Robert Hulsart.