Libera

MEASUREMENTS AT CNAO WITH THE LIBERA SPARK "HR" PROTOTYPE

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Libera

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- CNAO facility and existing BPM system
- Libera Spark “HR” BPM
- Test bench and beam tests at CNAO
- Data analysis
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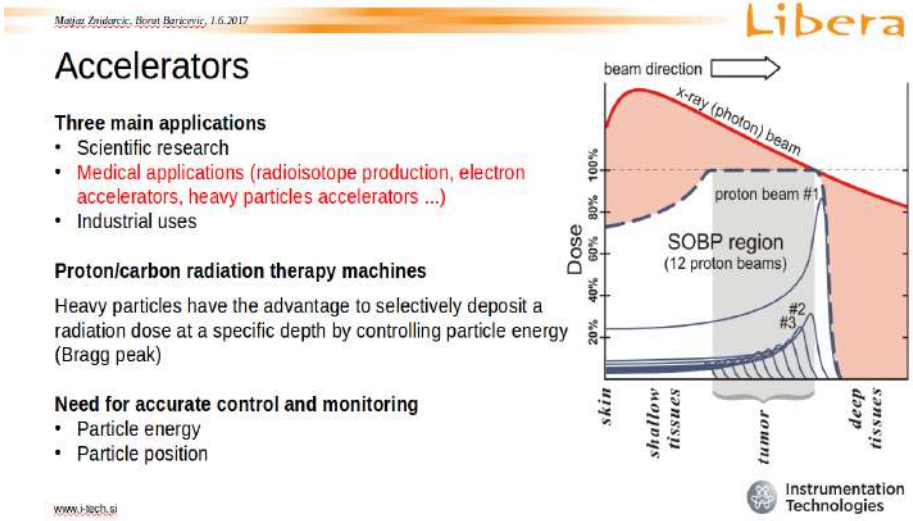
Instrumentation Technologies

Motivation

Libera entering in medical field - Proton/Carbon radiation therapy

- Libera Hadron BPM – proven and in usage at several circular machines around the globe
- Medical machines – requirements
  - Simple to use
  - Usually slow monitoring and bunch-by-bunch data is needed
  - Quiet instruments
  - No maintenance
- CNAO medical facility
  - Analise data at bunch-by-bunch rate
  - Tune frequency



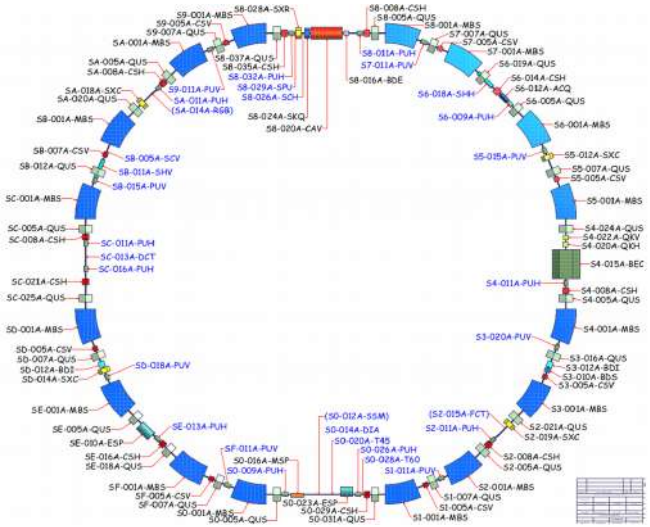
Libera Spark "HR" PROTOTYPE

Instrumentation Technologies

The National Center of Oncological Hadrontherapy (CNAO)

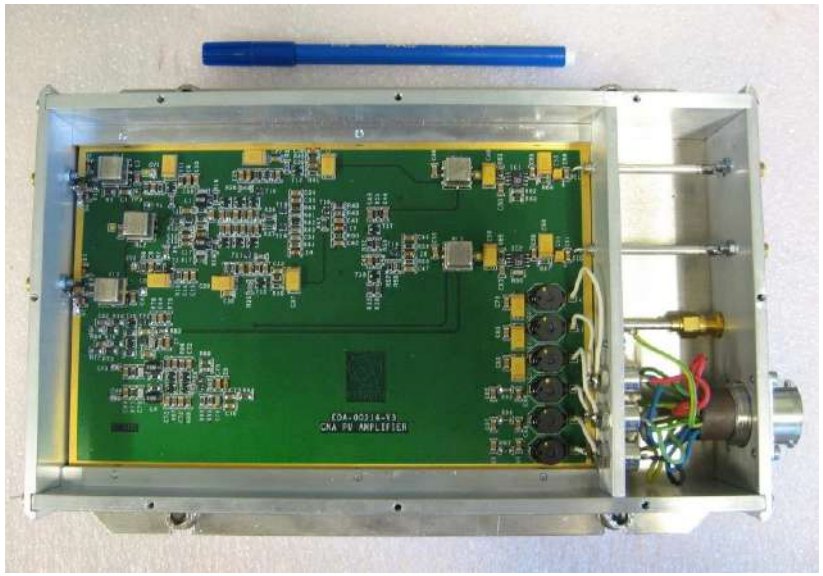
CNAO in Pavia is one of the first centers for hadron therapy in Europe, treating patients since 2011.

- Synchrotron ring with circumference 76.84 m
- 2 Sources – Protons and Carbon IONs
  - Protons extracted at 60 – 250 MeV
  - Carbon IONs extracted at 120 – 400 MeV
- 3 horizontal + 1 vertical treatment line
  - Complex cases of cancer and pediatric tumors

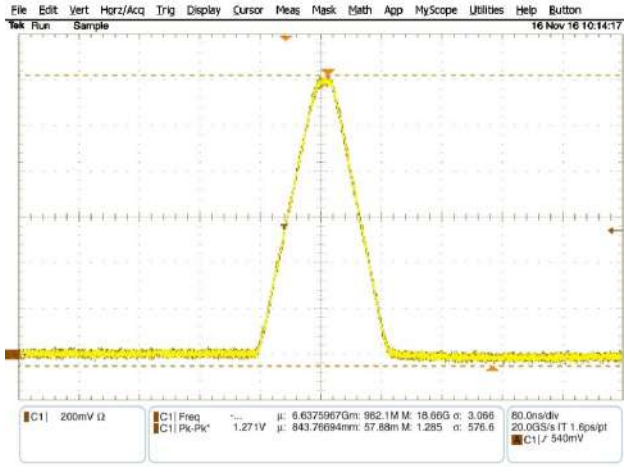


CNAO BPM system

- Modular BPM system
  - CNAO front end – calculates Sigma and Delta
  - Back end - calculates analog division between integral of Delta and integral of Sigma
  - PXI digitizer
- Position delivered at **fixed rate** – **1 kHz**



Libera Spark “HR” prototype



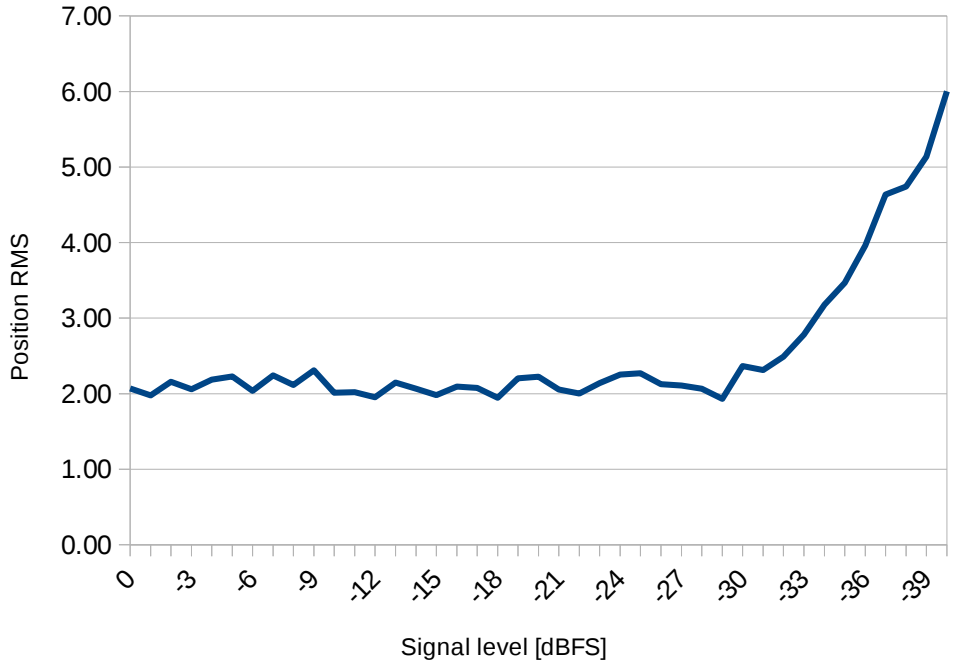
Signal FWHM = 100 ns

Direct acquisition of BPM pickup signals

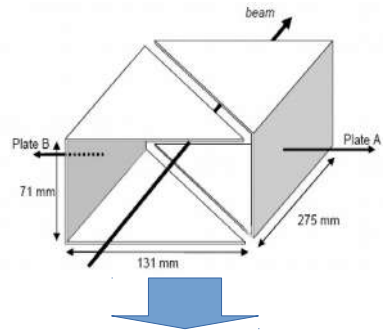
- 35 MHz low pass front end
- Sampling @ 125 MHz
- 8 Msamples data buffer / Off-line DSP
- Position calculated at Bunch-by-bunch rate

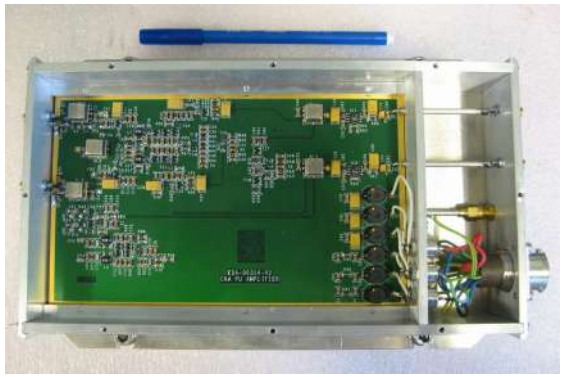
	Spark
Dimensions (H x W x D) mm	44 x 210 x 210
A/D conversion	125 MHz / 14 bit
FPGA / CPU	Zynq-7020, ARM Cortex-A9
Cooling	Passive
Power supply	PoE
Input gain / attenuation	Programmable, 31 dB
Temperature stability	0.3 micrometer / °C
Long term stability [8 h]	< 0.3 micrometer (kx = ky = 10 mm)
Data processing	Bunch-by-bunch (Offline)

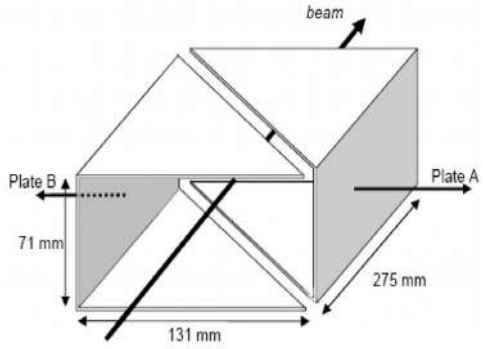
Kx = Ky = 10 mm



CNAO and Libera BPM systems



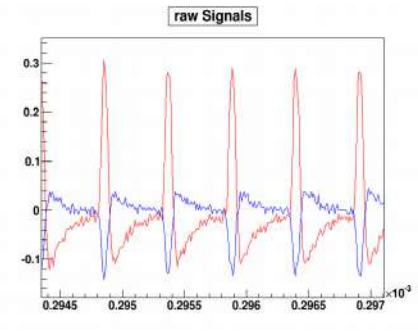


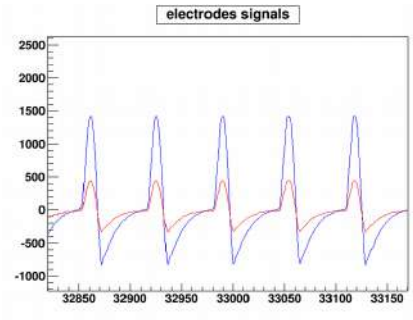


sigma and delta

A B C D

DSO was connected to the CNAO front end

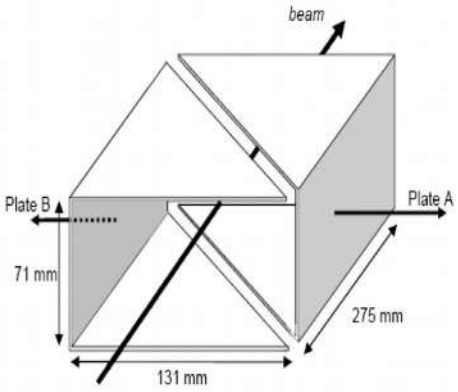


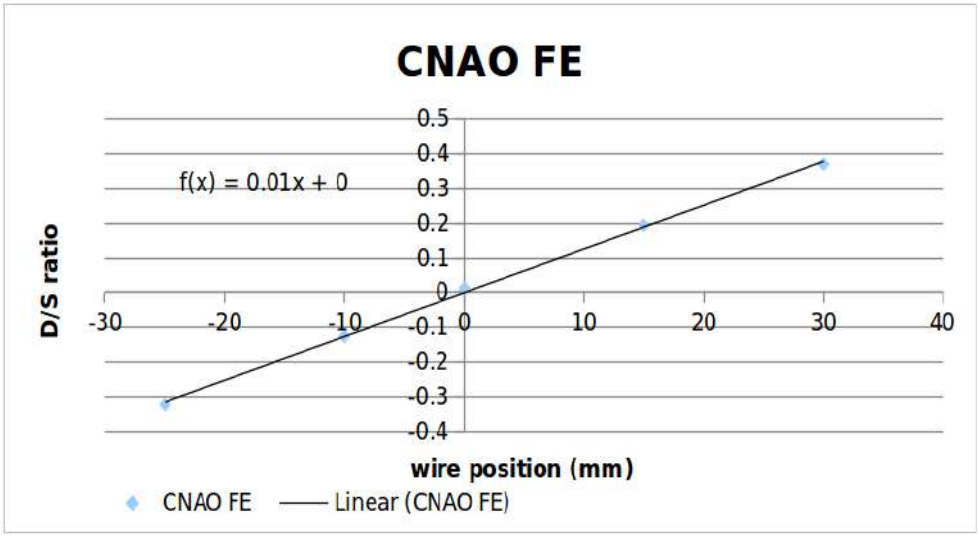


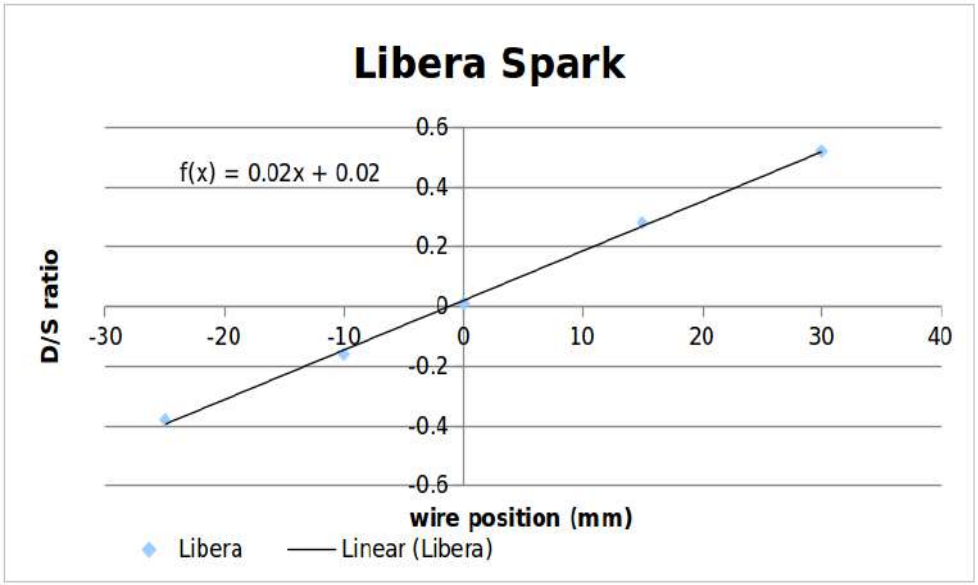
Test bench

Shoe-box pickup

- 5 wires – 5 different transverse positions (not a standard coordinate table)
  - Mechanical accuracy problems
  - Connectors + cables connection
- Sine wave injected into each wire
  - Amplitude and frequency was changing
- Geometrical coefficients for both systems





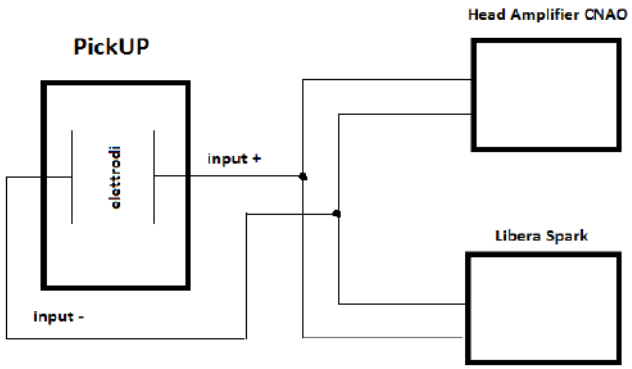


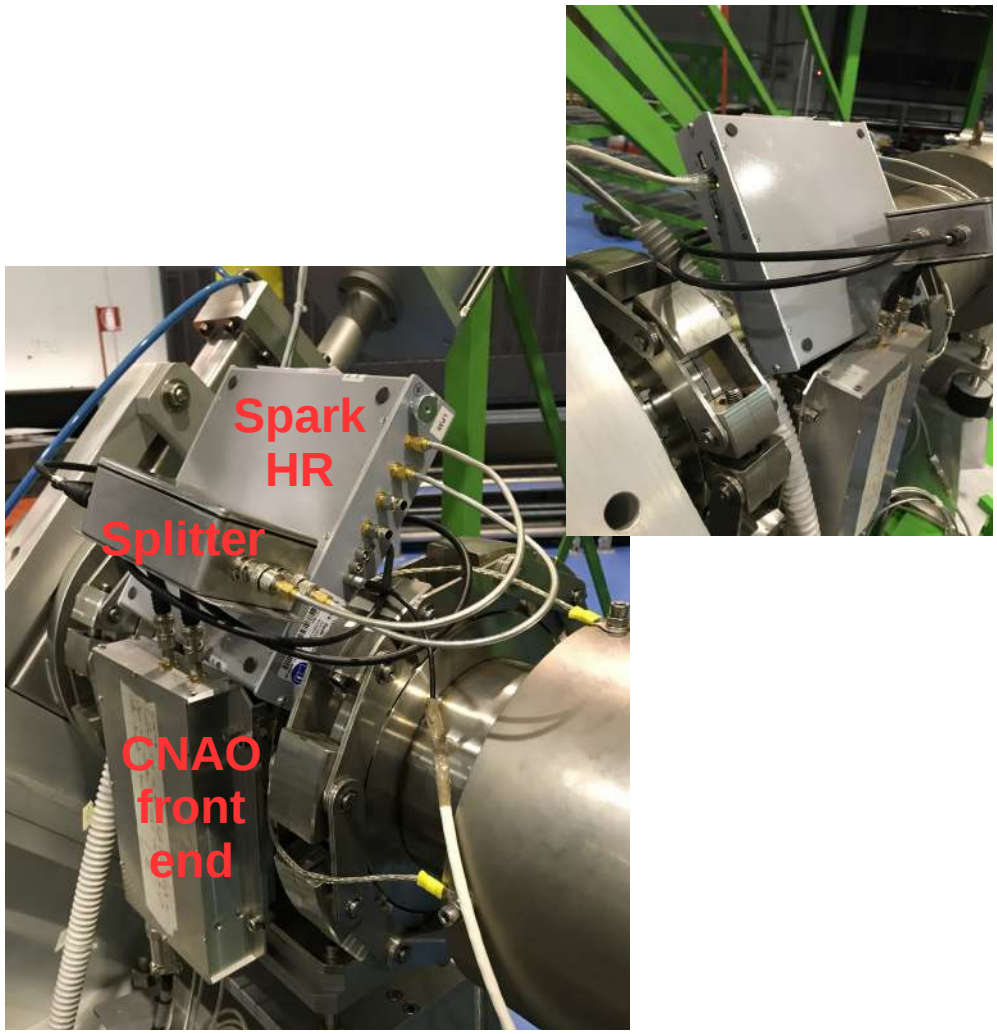
Instrumentation Technologies

Beam tests

Instruments placed in a high dispersion region

- Single bunch (one bucket) 0.5 – 3 MHz
- Only horizontal plane measured (2 channels)
- Signal spitted to both systems
  - Difference in the impedance (10 MOhm vs. 50 Ohm – attenuators added)
- 1 ms ADC data chunks acquired
  - Spark HR @ 125 MHz
  - CNAO front end (Lecroy DSO @ 100 MHz)





Measurements (data acquisitions)

PROTONS and CARBON IONS

- Measurements during injection (micro bunches)
  - 1 us of beam at 500 kHz
- Measurements during beam acceleration
- Measurements at flat-top with fixed energy before extraction
  - Different energies – constant frequency
- **Measurements at flat-top changing the LLRF position set point**
  - **Stable beam (3 MHz)**
  - **The beam was displaced in 5 different positions spaced by ~5 mm**

Data analysis (horizontal plane)

CNAO algorithm

Input = Delta / Sigma

- Integration of Sigma and Delta
- Bunch signal extraction (finding the two local minimals before and after the bunch peak)
- Offset subtraction
- For each bunch the integral of Sigma and Delta are computed using a fixed threshold
- Position calculation

$$X = K_x \frac{\Delta}{\Sigma} + X_{OFFSET}$$

Libera Bunch-by-bunch algorithm (implemented in Libera Hadron)

Input = Pickup signal L, Pickup signal R

- Useful data extraction (from the ADC data from individual channels, the samples belonging to individual bunches are identified)
- For each channel and for each bunch, the amplitude is calculated with sum-of-squares formula

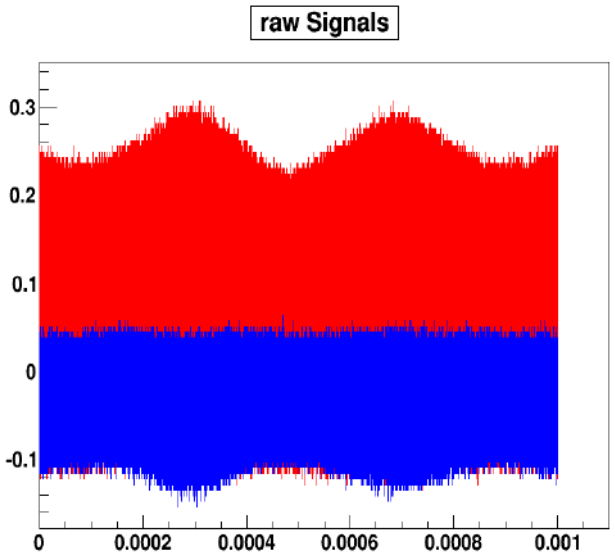
$$V_A = \sqrt{\sum_{PROC\ WIN.\ START}^{PROC\ WIN.\ END} A^2} \qquad V_C = \sqrt{\sum_{PROC\ WIN.\ START}^{PROC\ WIN.\ END} C^2}$$

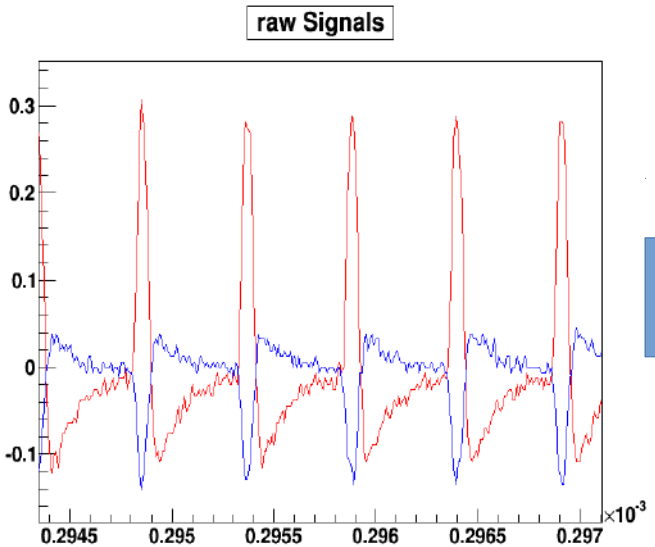
- Position calculation

$$X = K_X \frac{(V_A' - V_C')}{(V_A' + V_C')} + X_{OFFSET}$$

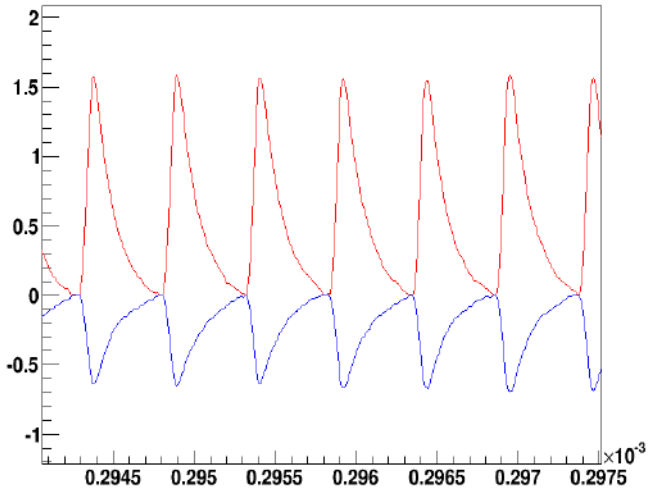
Data analysis - CNAO front end

Sigma (red) and Delta (blue) acquired directly from the CNAO front end





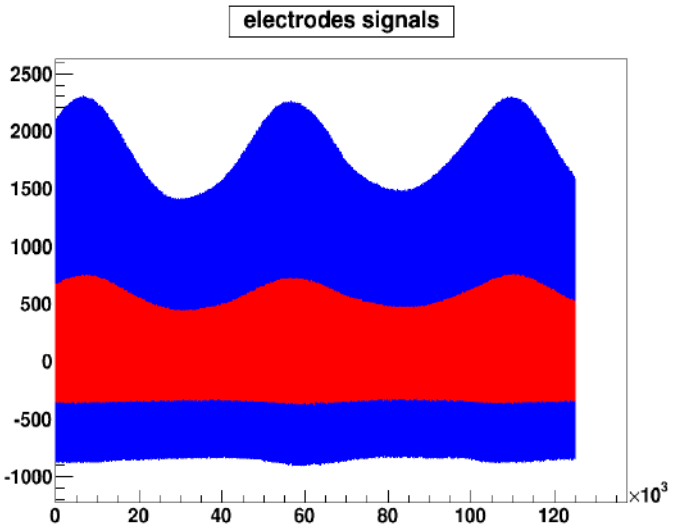
CNAO algorithm -Integrated signal

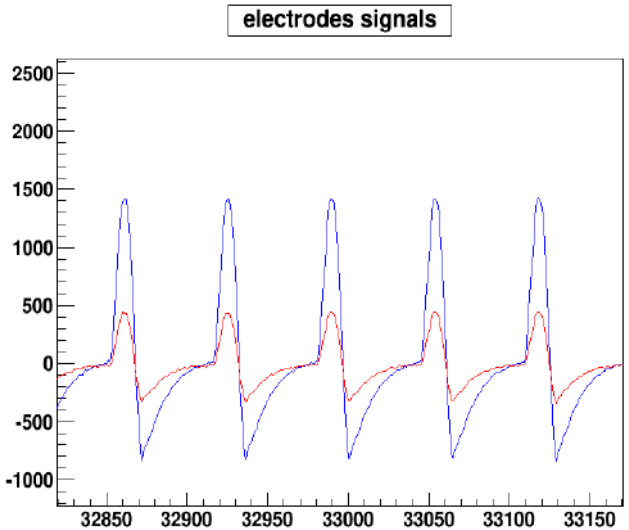


Instrumentation Technologies

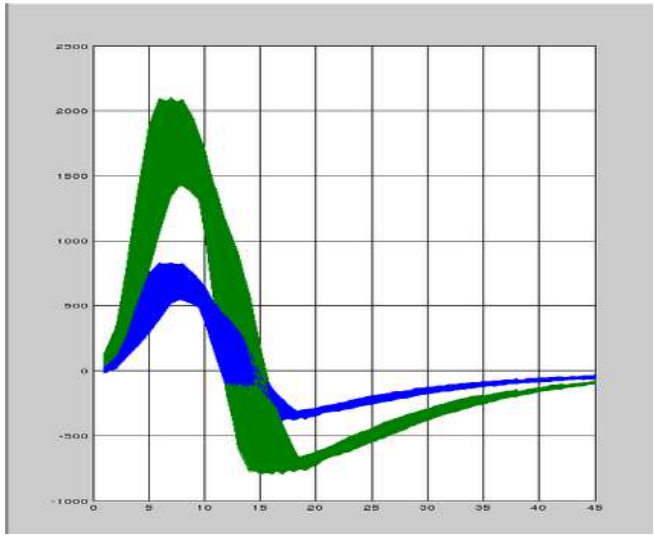
Data analysis - Libera Spark

Channels Left (red) and Right (blue) acquired with Spark HR

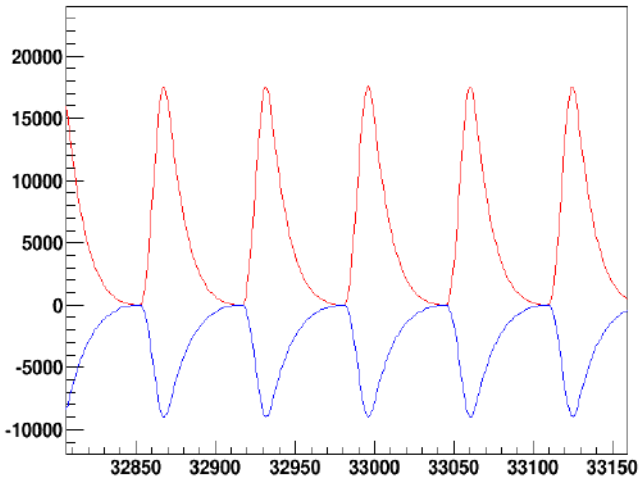




Libera bunch-by-bunch algorithm
– Extracted bunches



CNAO algorithm -Integrated signal

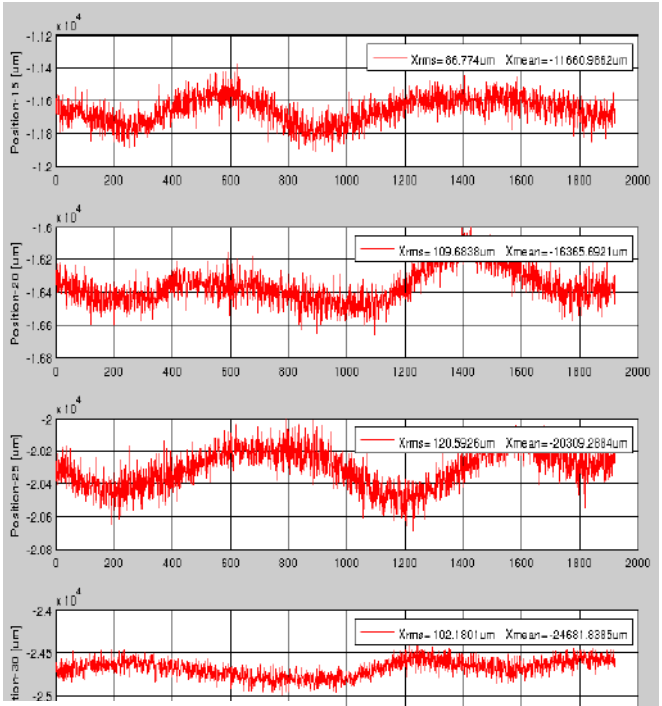


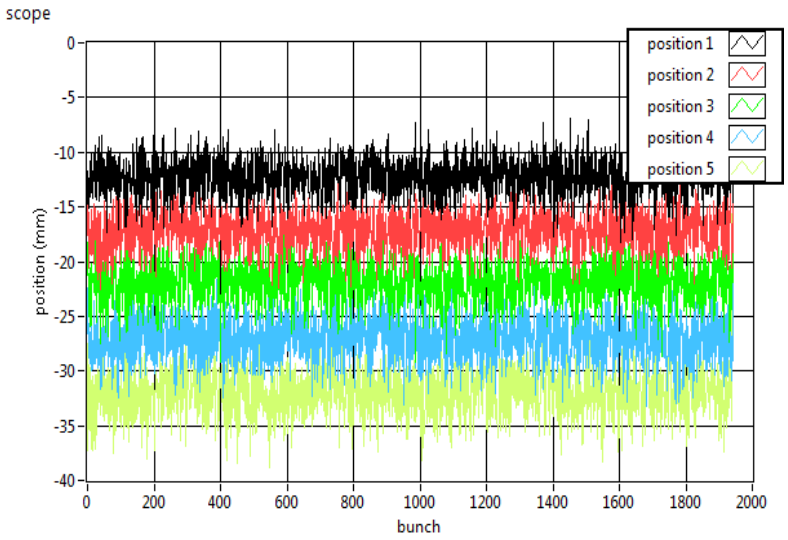
Results I (Protons)

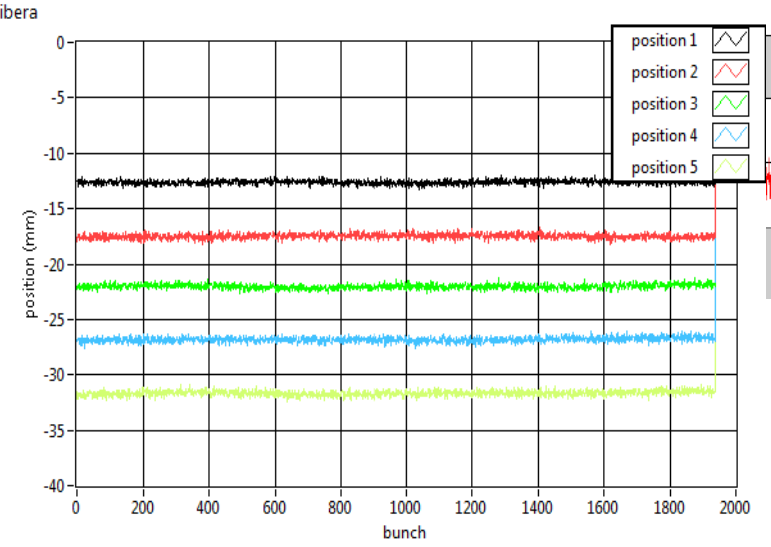
- Standard deviation of the instruments differs for a factor of ten
- Libera is “all in one” low noise system
- CNAO front end + cabling + oscilloscope.
- Signal level provided to the Spark HR instrument was low

Standard deviation

Set beam position [mm]	CNAO front end CNAO DSP [mm]	Libera Spark HR CNAO DSP [mm]	Libera Spark HR Libera DSP [mm]
- 35	2.21	0.24	0.14
- 30	2.18	0.23	0.10
- 25	1.99	0.21	0.12
- 20	1.79	0.22	0.11
- 15	1.79	0.19	0.08





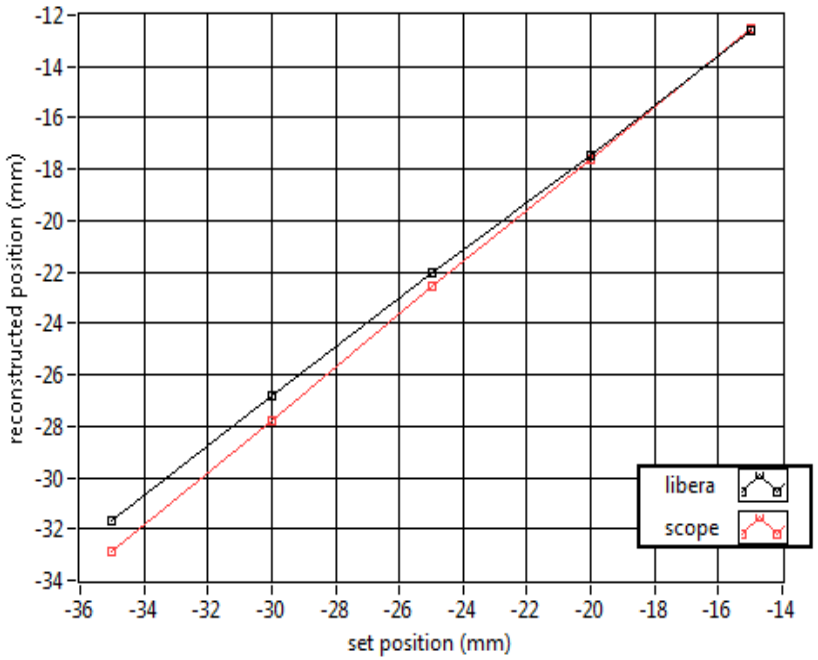


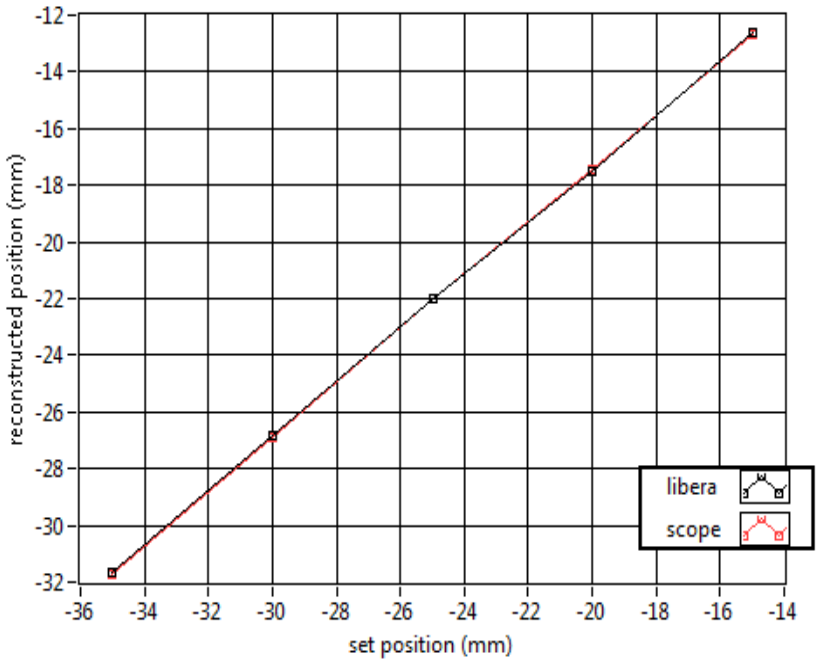
Results II (Protons)

- Positions achieved with Spark HR and CNAO front end are slightly different. The reconstructed position after rescaling is equal.
    - Signal splitting and not equal cables

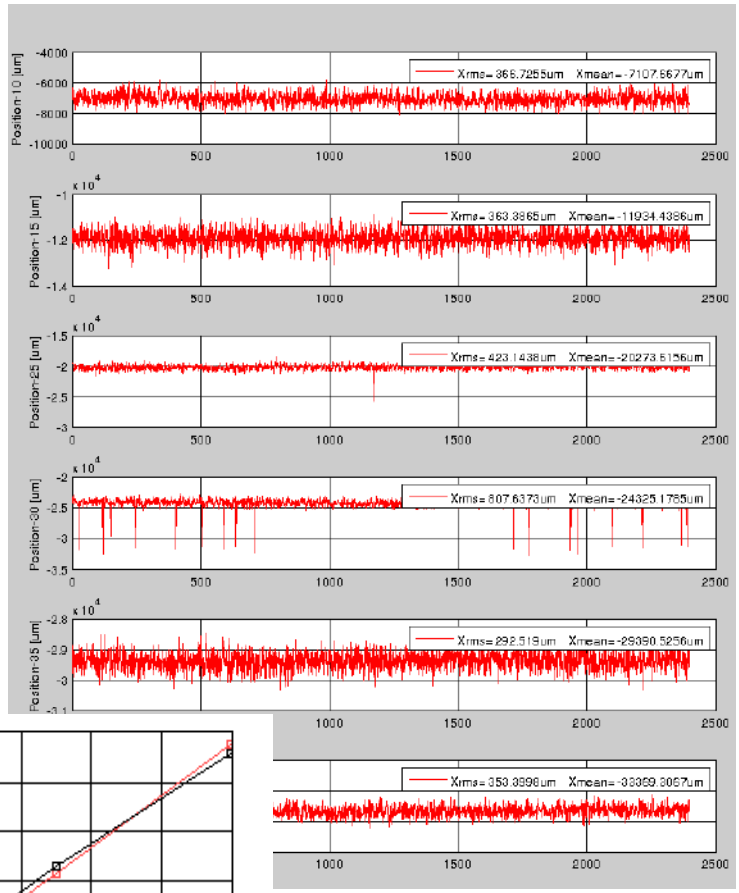
Position measurement

Set beam position [mm]	CNAO front end CNAO DSP [mm]	Libera Spark HR CNAO DSP [mm]	Libera Spark HR Libera DSP [mm]
- 35	-32.91	-31.66	-29.06
- 30	-27.79	-26.81	-24.68
- 25	-22.52	-22.02	-20.31
- 20	-17.63	-17.49	-16.37
- 15	-12.5	-12.62	-11.67





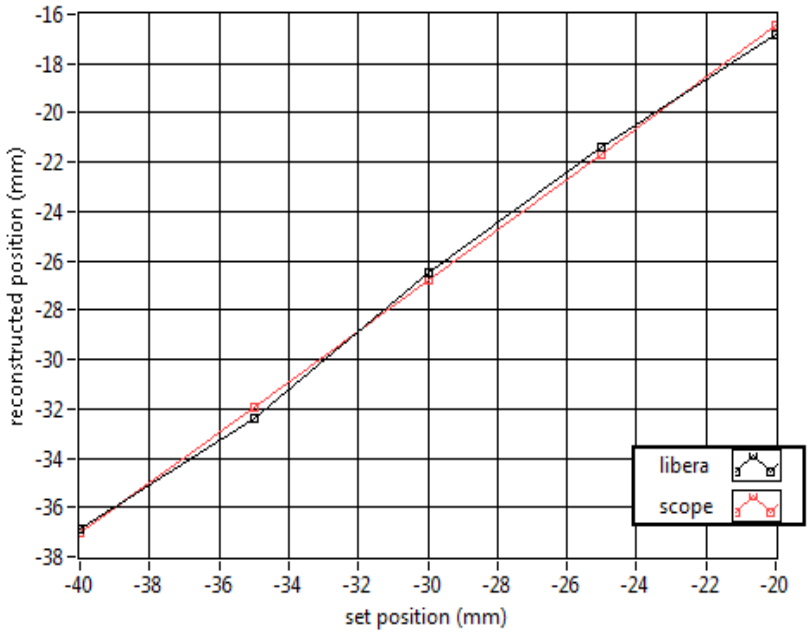
Results – Carbon IONs



Same tests repeated with Carbon IONs

- Small signals
- Due to DSO wrong settings, tests were repeated later
  - Libera + splitter + CNAO front end
  - CNAO front end

- Measurements can not be directly compared
- Same slope

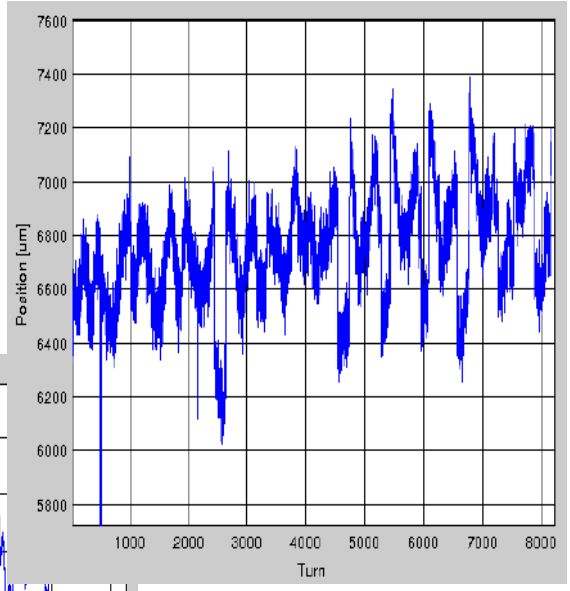


Instrumentation Technologies

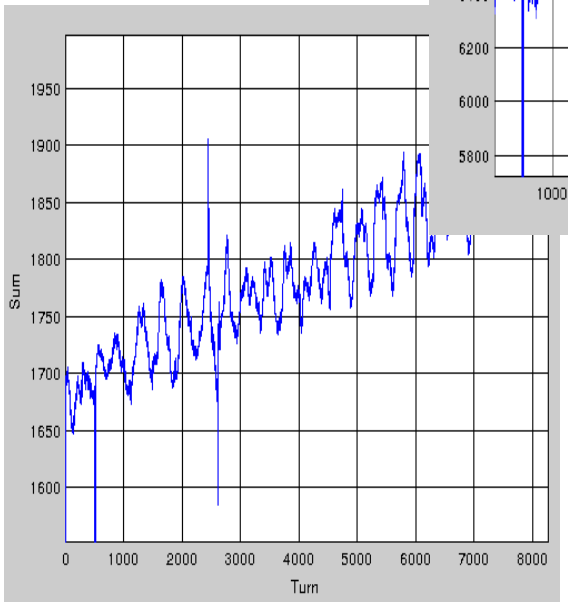
Measurement during acceleration – Protons

- Acceleration starts at 500 kHz
- ~8500 turns are plotted

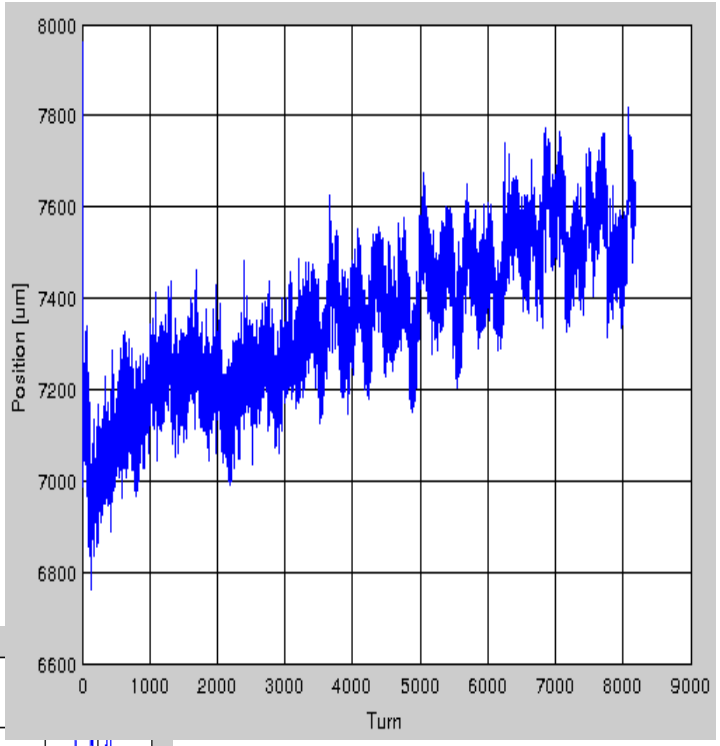
Horizontal Position



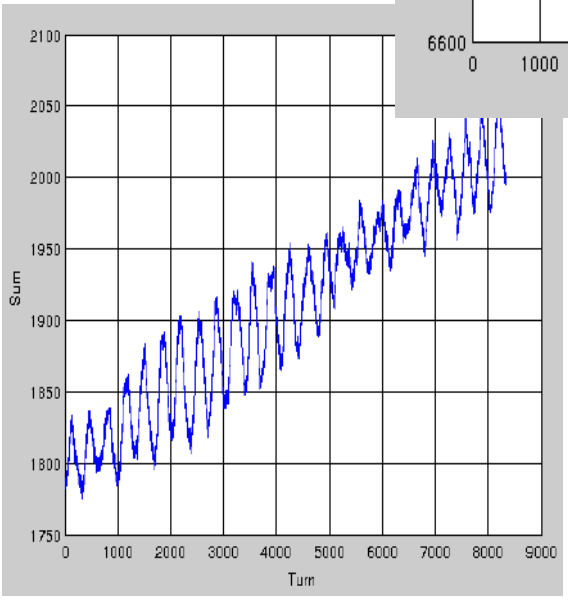
Charge



Horizontal Position (+ 8 ms)



Charge (+ 8 ms)

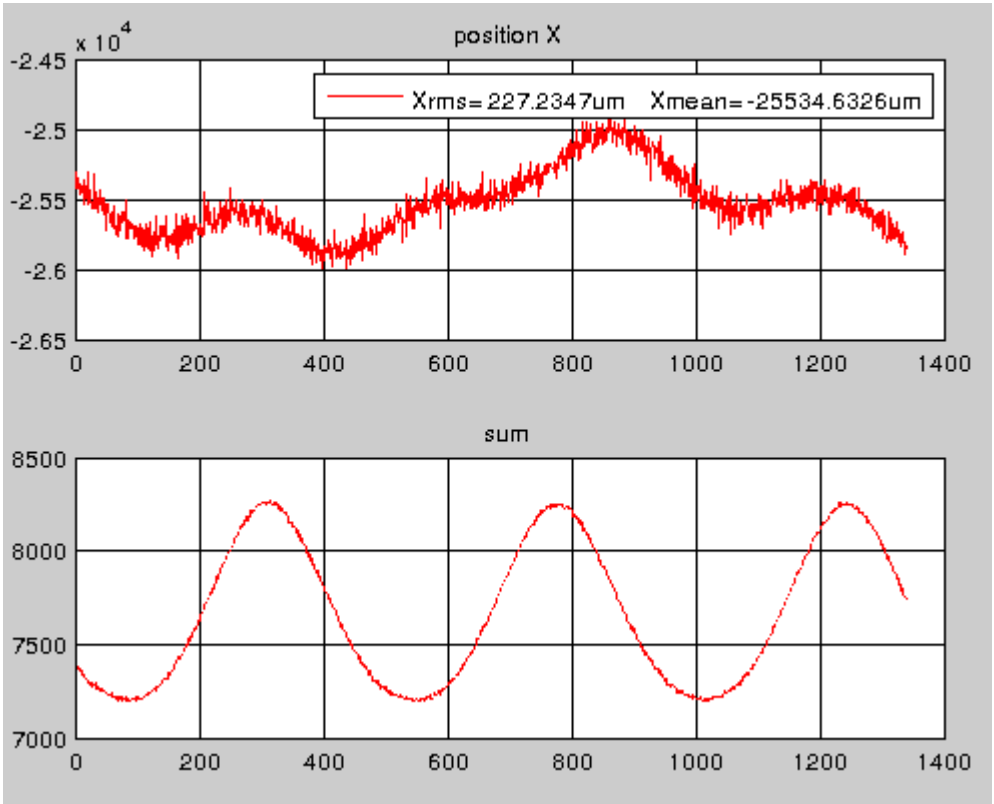


Instrumentation Technologies

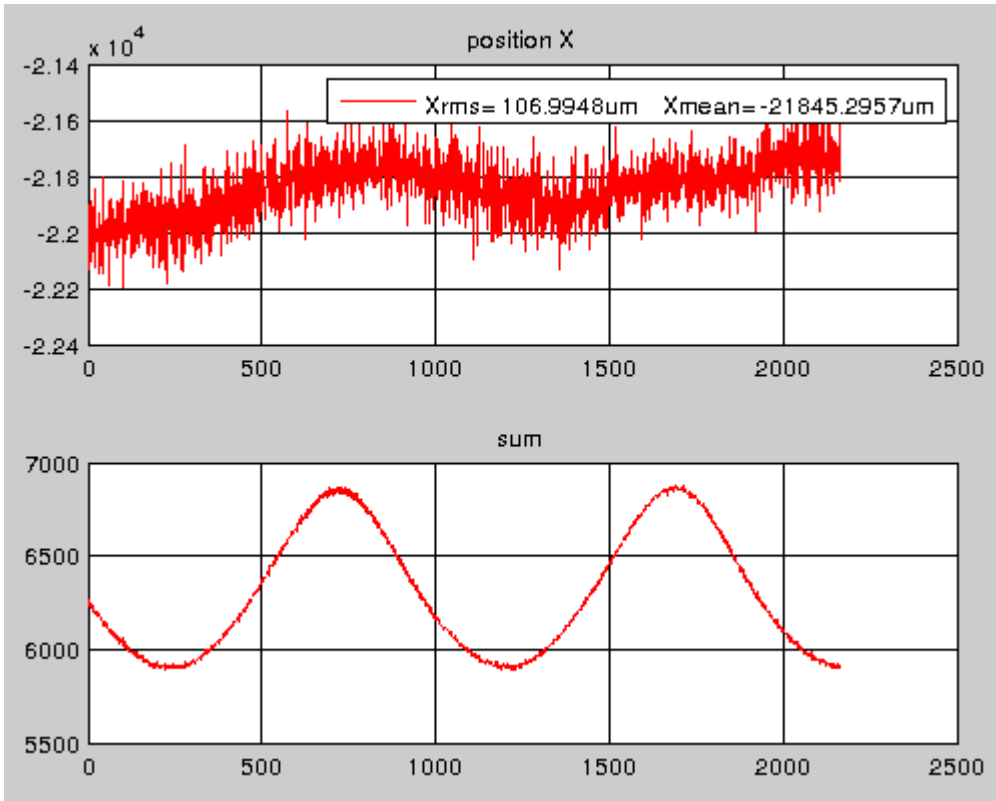
Measurements right before the extraction – Protons

- 3 MHz constant beam circulates in the machine at fixed energy - extracted to the patient
  - < 10 % fluctuation in the amplitude related to the synchrotron fluctuations i.e. bunch shape fluctuation
  - Integral of SUM i.e. accelerated charge is constant = **constant dose to the patient**

62 MeV beam



196 MeV beam



Conclusion

- The tests at CNAO provided clean results with a turn-by-turn beam position resolution of hundred micrometers, with still margin for improvement.
- The idea of using Libera Spark as a BPM readout system for hadron therapy machines has been confirmed.
- Implementation of the DSP in the FPGA and further tests will follow