TRIUMF

Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

# Low Frequency Position Monitoring at the TRIUMF cyclotron injection line

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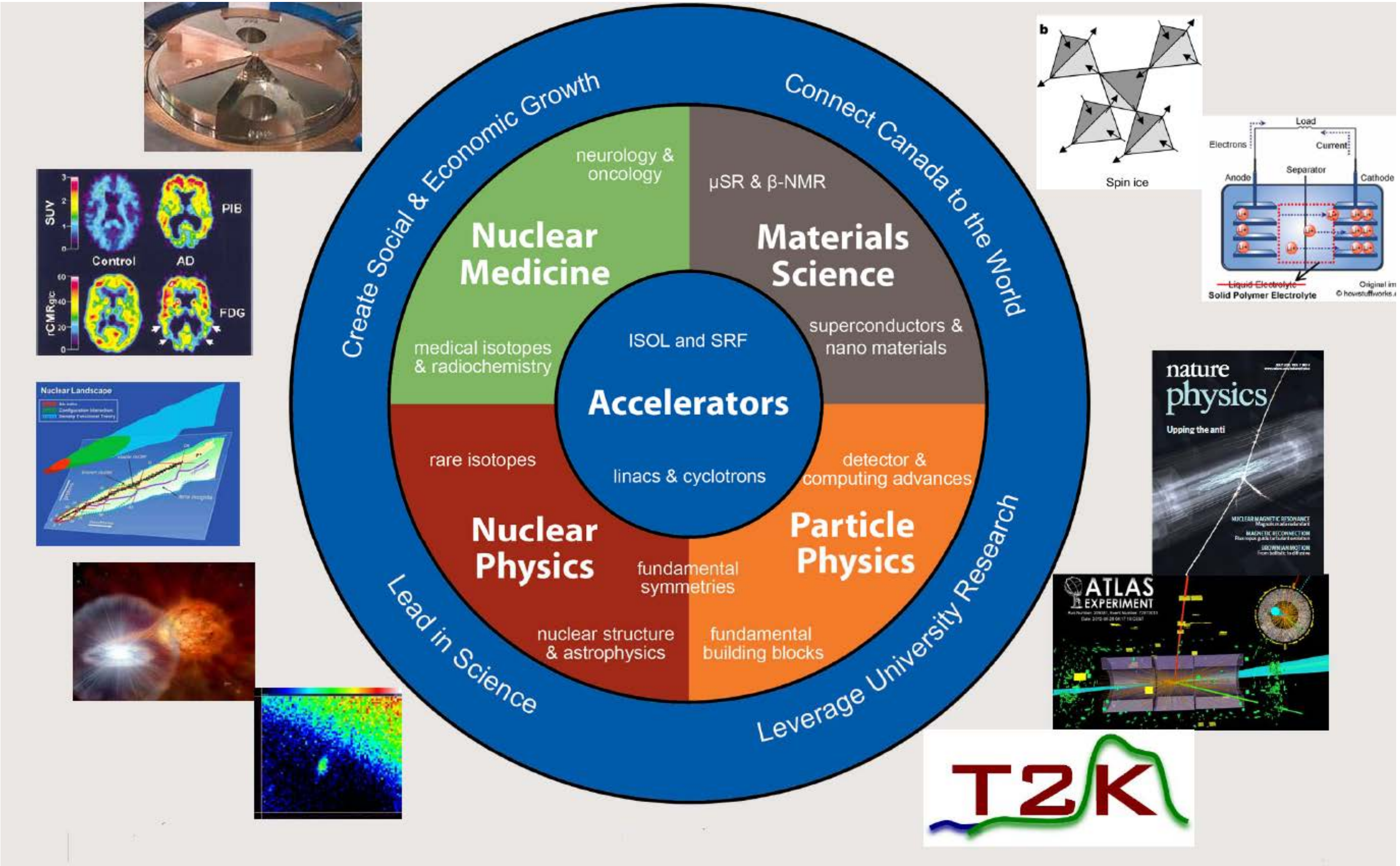
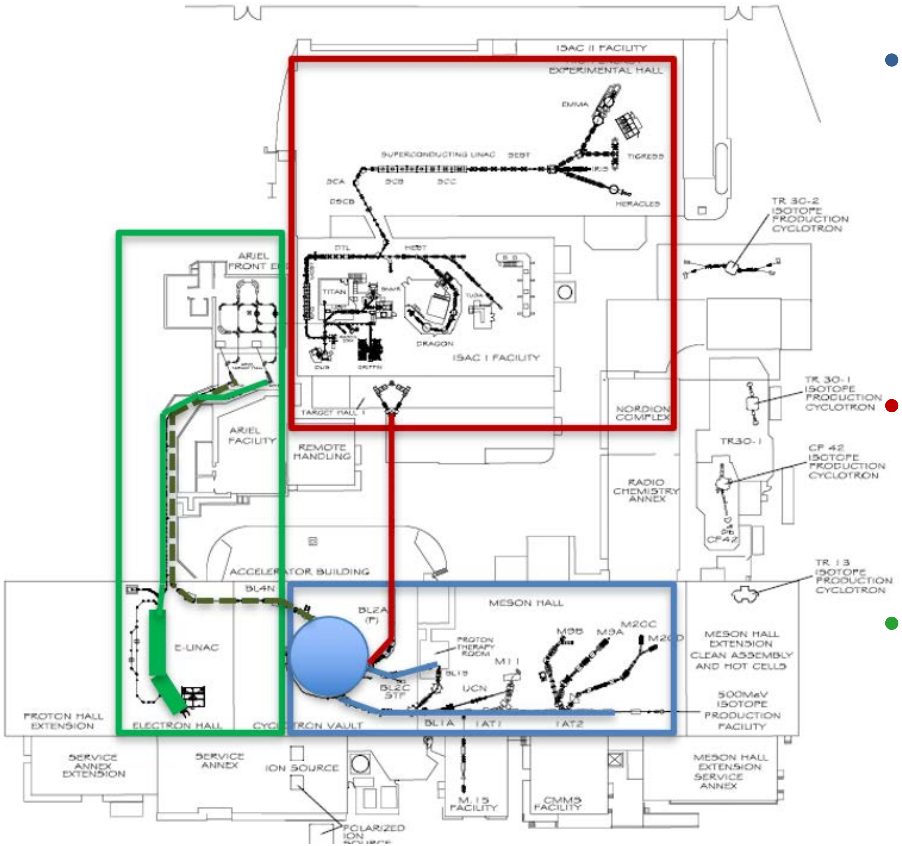
# TRIUMF: Canada's National Laboratory


- Canada's Particle Accelerator Center
- Founded in 1968
- Located in the west part of Vancouver at the campus of UBC
- IBIC 2026 will be held in Vancouver

# TRIUMF Research Program



# TRIUMF accelerators




- 500MeV cyclotron since 1974

  ~300-400μA distributed to multiple beamlines. Still a main workhorse. A program is ongoing to upgrade aging systems

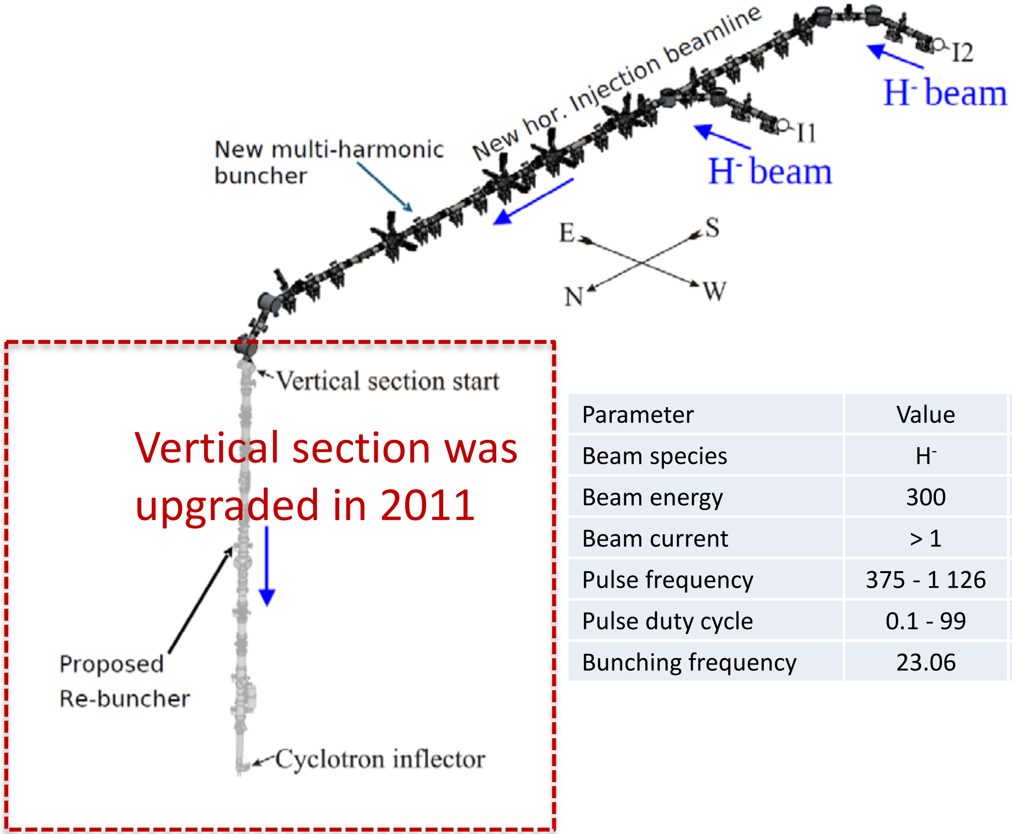
- ISAC since 1995

  Radioactive ion beam (RIB) facility with a heavy ion accelerator complex

- ARIEL in progress (2010-2024)

  Electron linac since 2014

# Cyclotron injection line upgrade program




| Parameter | Value | Unit |
|---|---|---|
| Beam species | $H^-$ | |
| Beam energy | 300 | keV |
| Beam current | > 1 | mA |
| Pulse frequency | 375 - 1 126 | Hz |
| Pulse duty cycle | 0.1 - 99 | % |
| Bunching frequency | 23.06 | MHz |

- 34 m long injection line connects $H^-$ sources with the cyclotron
- The vertical section was upgraded in 2011
- New horizontal section and the second ion source I2 are presently under construction
- DC $H^-$ beam is chopped at the source into pulses of variable frequency and duty cycle and bunched at 23.06 MHz halfway to the cyclotron

- We would like to measure the beam position of our chopped DC beam in a non-intercepting way
- Non-intercepting beam position monitor designs are widely used at tens of MHz and above, but much less common for kHz pulsed beams ( see, e.g. K.Johnson et all, NIM 14(1961),p.125 and H.S.Camarda, NIM 161(1979),p183, both use inductive pickups).
- Several options (inductive pickups, wall current) were evaluated, and the final decision was in favor of a capacitive pickup loaded with a high input impedance circuit.

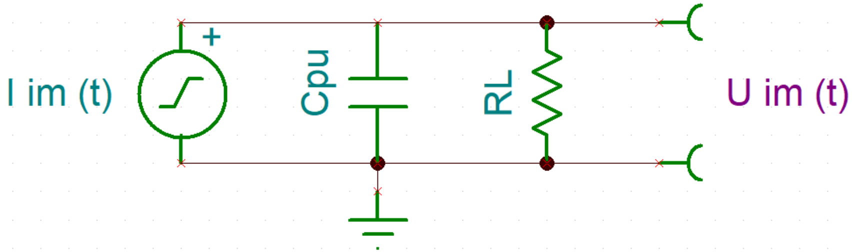
The principle has been known for years, e.g. in review by P.Forck, P.Kowina, D.Liakin, CAS-CERN 2009

## Frequency domain

$$|Z_t| = \frac{1}{\beta c}\frac{1}{C_{PU}}\frac{A}{2\pi r}\frac{\omega/\omega_c}{\sqrt{1+\left(\omega^2/\omega_c^{\,2}\right)}}$$

$$\omega_c = (R_L C_{PU})^{-1}$$

Cut-off frequency can be lowered by increasing $C_{PU}$ and $R_L$

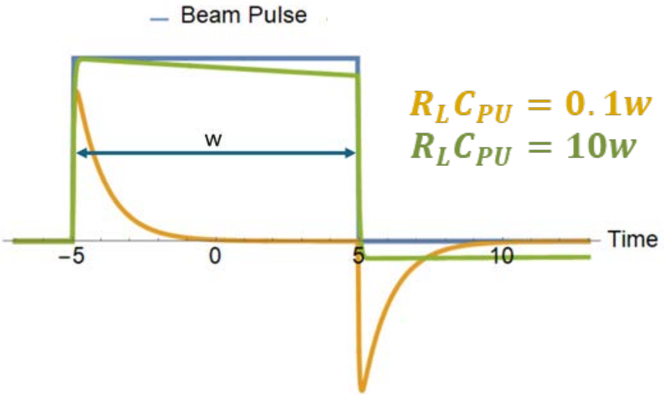



## Time domain

$$U(t) = \Theta(t) U_0 e^{-\omega_c t}$$ $\Theta(t)$ - step function

$$I(t) = I(t \geq -w/2) - I(t \geq w/2)$$

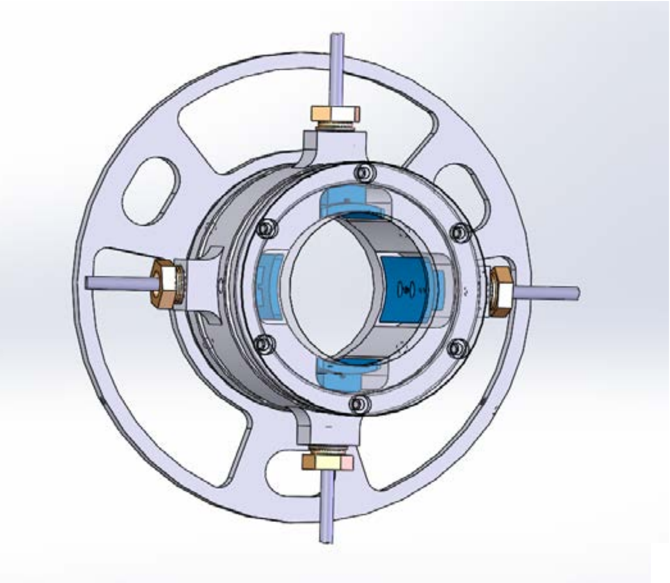
$$U(t) = \Theta(t + w/2)\, U_0 e^{-\omega_c t} - \Theta(t - w/2)\, U_0 e^{-\omega_c t}$$

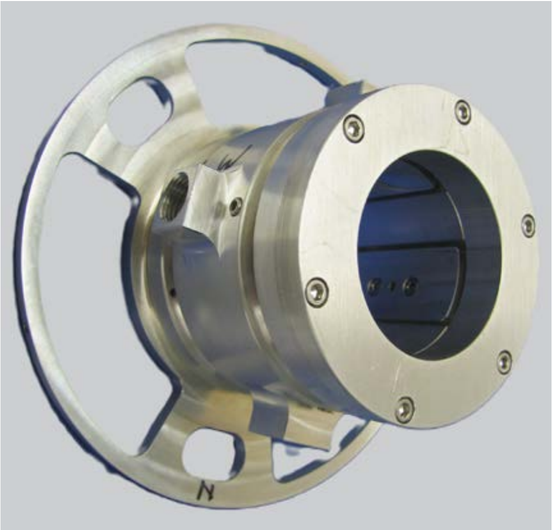


# Concept

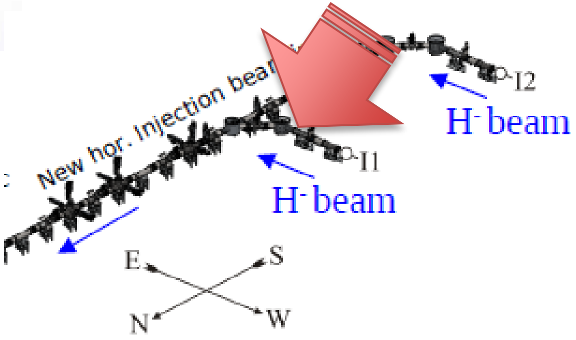
- For a given beam pulse structure we can shape the response via $R_L C_{PU}$, to build the measuring system based on sampling signals in the time domain.
- Given that $C_{PU}$ can be only varied in the limited range, tuning of the response in a broad range is done via $R_L$.
- In practical sense this leads us to $R_L$ >> 50 Ω.
- To implement the concept we need a capacitive pickup and a high input impedance circuit

# Capacitive pickups





| Parameter | Value | Unit |
|---|---|---|
| Button shape | rectangular | |
| Button length | 50 | mm |
| Button width | 60 | degrees |
| Inner diameter | 50 | mm |
| Button capacitance | 12 | pF |
| Position sensitivity | 1.35 | dB/mm |

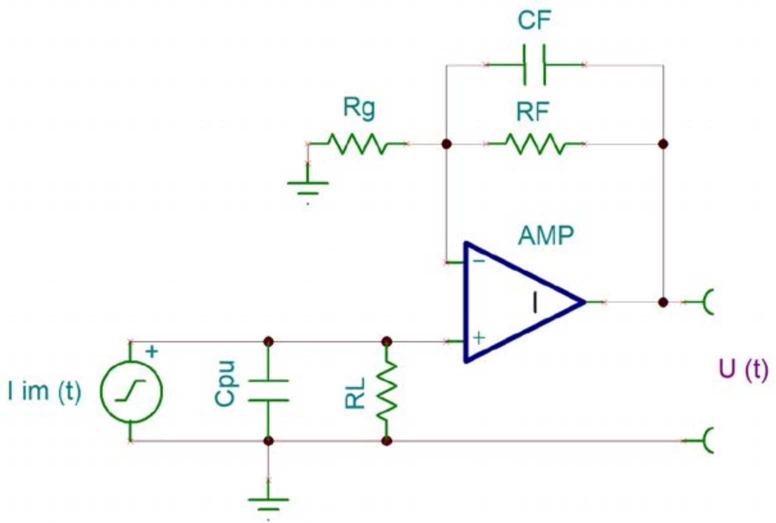


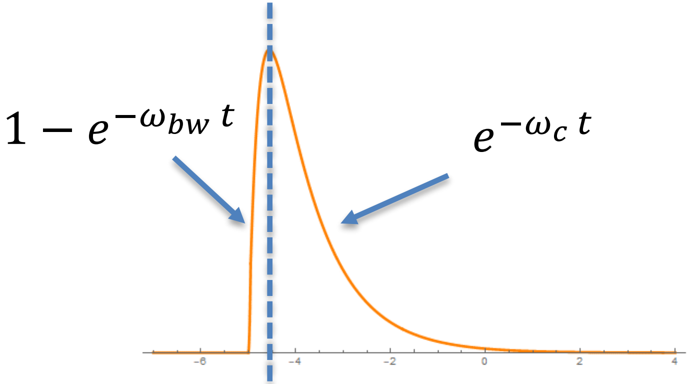

- Developed in 2011 for the vertical section of the injection line
- Five such devices have been in operation since then
- Designed to operate at 46 MHz
- Adequate for kHz operation as well

A high input impedance amplifier with a JFET input stage and a gain of G = 200 was developed. The bandwidth was set to $f_{bw}$ =100 kHz to suppress the signal overshoot and form the signal shape.

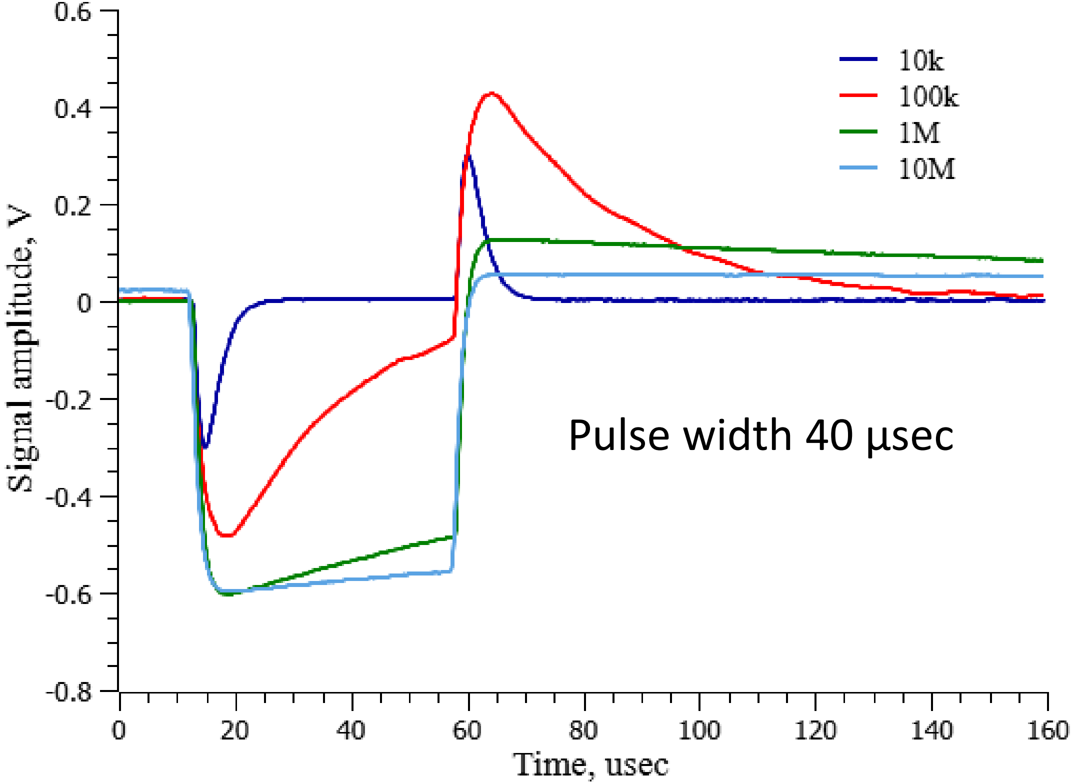
$$U(t) = \Theta(t)\, U_0\, \left(1 - e^{-\omega_{bw}\, t}\right) e^{-\omega_c\, t}$$

$$\omega_{\mathrm{bw}} = (R_{\mathrm{F}} C_{\mathrm{F}})^{-1}$$



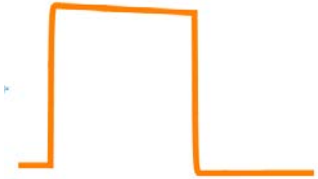



# First measurements



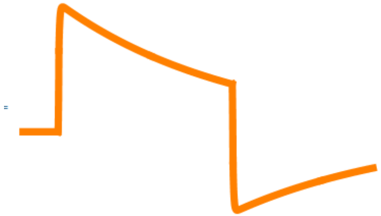

- First measurements were done with various $R_L$ and 300 keV $H^-$ beam at 0.5mA beam peak current
- Signals are generally in agreement with predictions
- For quantitative comparison stray capacitance has to be known

# From signal processing point of view



1) $R_L C_{PU} \gg w$. Signal follows the beam pulse with minimum distortion. Most interesting option. Baseline easily identified.

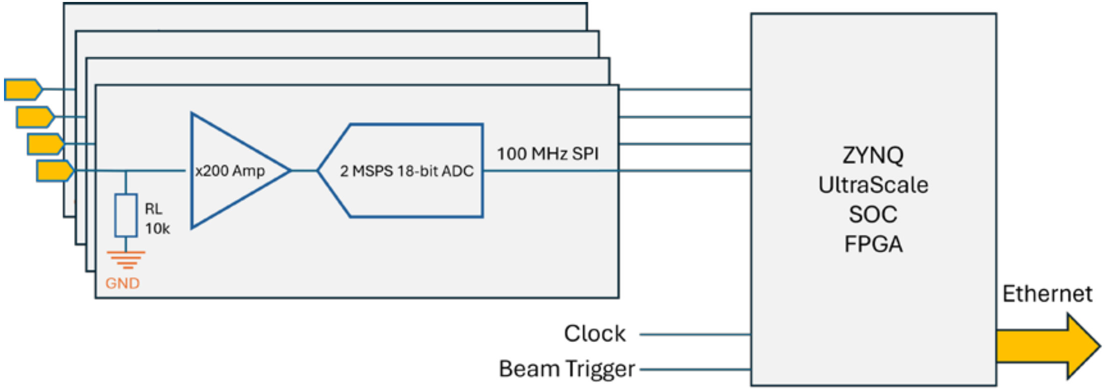
2) $R_L C_{PU} \ll w$. Signal from each edge of the pulse decays to the baseline before the next one arrives. Baseline easily identified.



3) In the intermediate case finding the baseline is not generally straightforward.

*Option 2 is presently pursued due to time constraints*

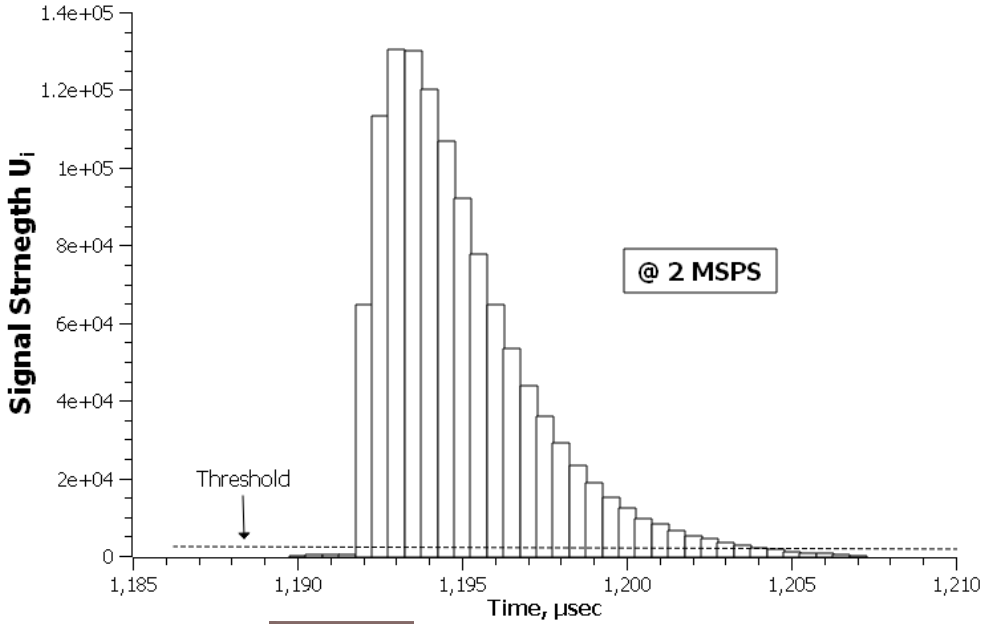
# DAQ and processing

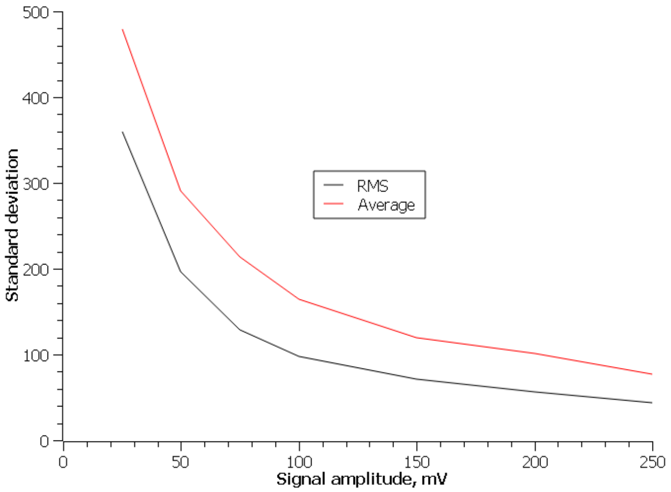




- 10 kOhm input impedance for operation with 1% - 99% of 1126 kHz pulse.
- Signals are sampled with 2MSPS 18-bit SAR ADC
- 100MHz SPI interface to ZYNQ UltraScale SOC FPGA
- Firmware development is still in progress.
- External clock and trigger are foreseen for synchronization to the beam
- Standalone unit placed within 0.3 m from a device

# DAQ and processing

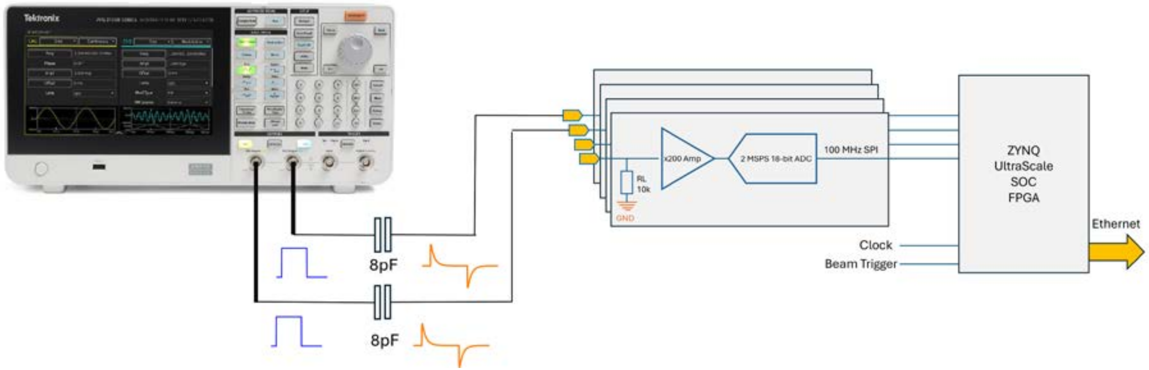


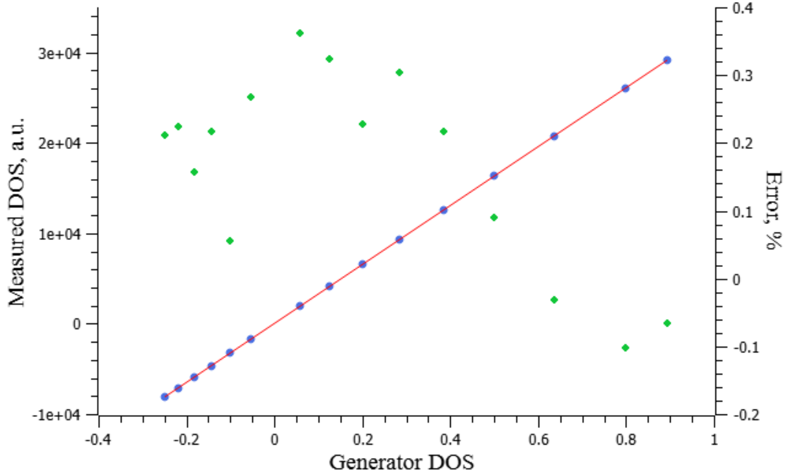

$$U_{rms} = \sqrt{\sum_{i=1}^{N} {U_i}^2}$$

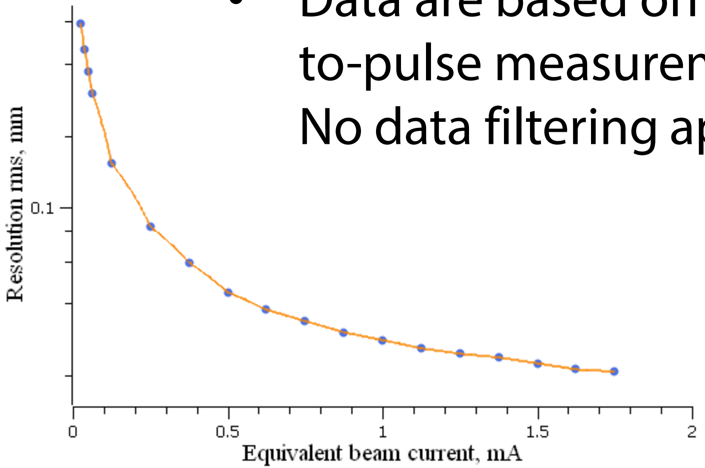
$$DOS = \frac{U_{rms_L} - U_{rms_R}}{U_{rms_L} + U_{rms_R}}$$

The RMS value gives up to 50% better signal-to-noise ratio compared to the average one

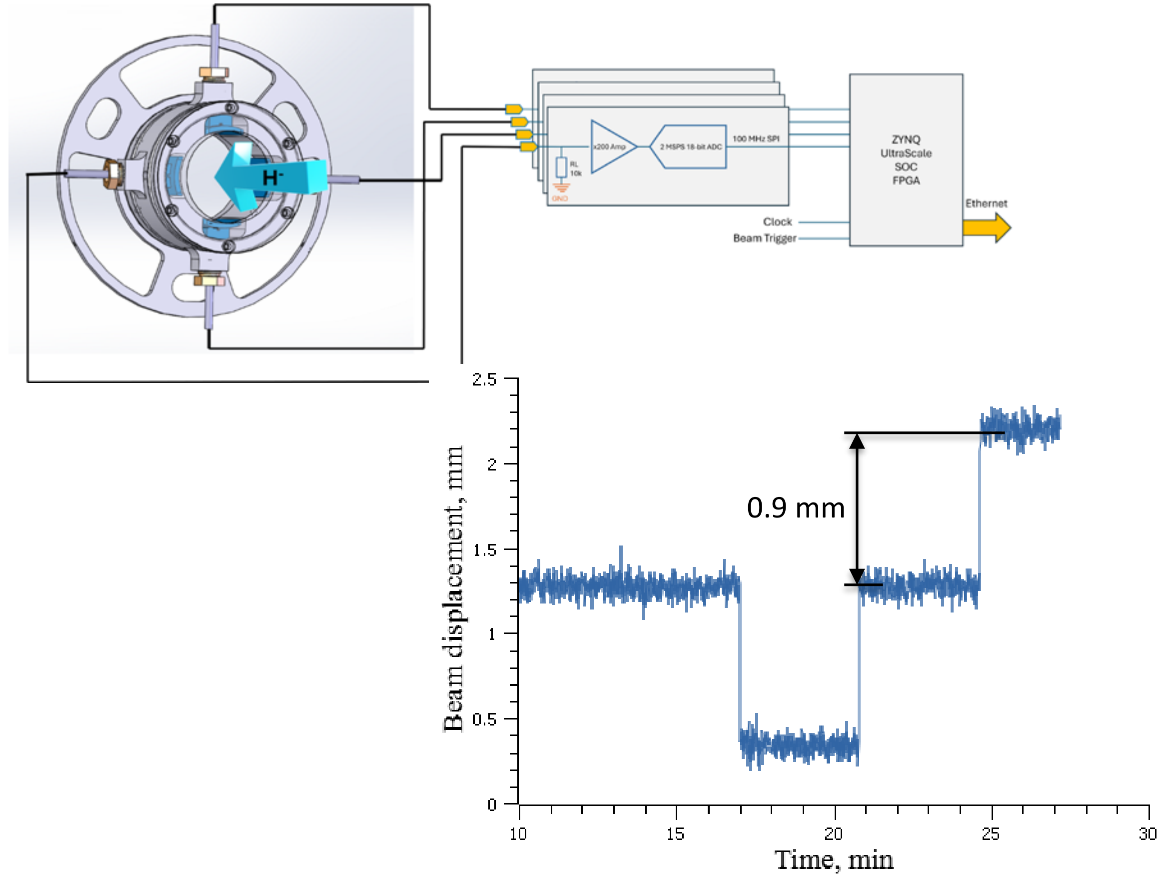



- Electronics linearity of <0.4% and rms resolution of 0.07mm @ 0.5mA (equivalent )were measured at the bench
- Data are based on pulse-to-pulse measurements. No data filtering applied.



# Beam-based position measurements




In beam-based measurements 0.5mA $H^-$ beam was steered with electrostatic dipole

The observed position noise was 25% higher than that measured on the bench

- A simple system was developed for non-intercepting beam position monitoring of the pulsed ion beam in the TRIUMF cyclotron injection line. The system is based on capacitive pickups and high input impedance electronics and operates in wide range of audio frequencies and duty cycles.
- The system was tested on the bench and with the actual beam and demonstrates a high linearity within a reasonable dynamic range and a resolution adequate for the application
- The system performance is believed to further improve with applying appropriate data filters.

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