BPM Systems at Brookhaven National Laboratory

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

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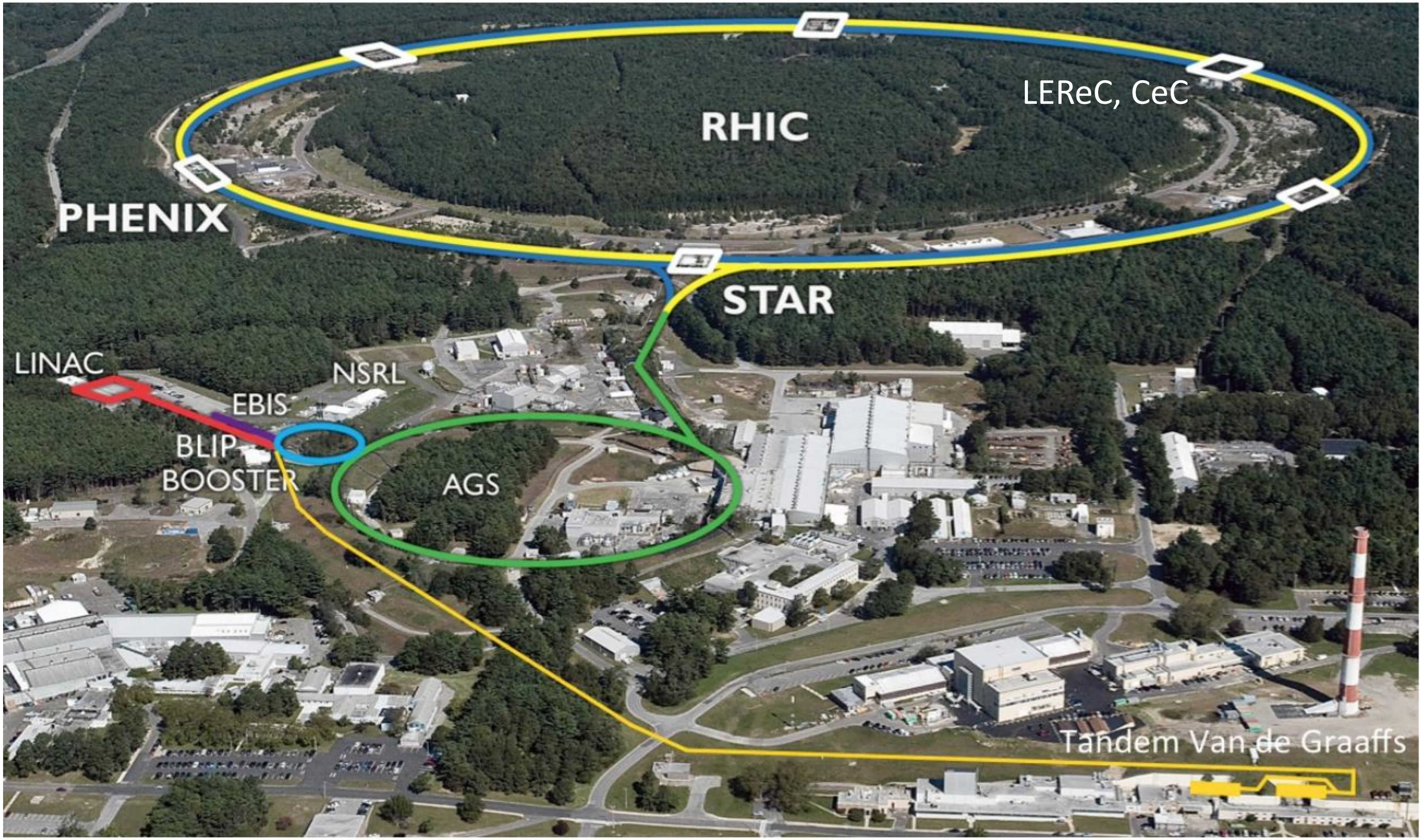
The RHIC Complex



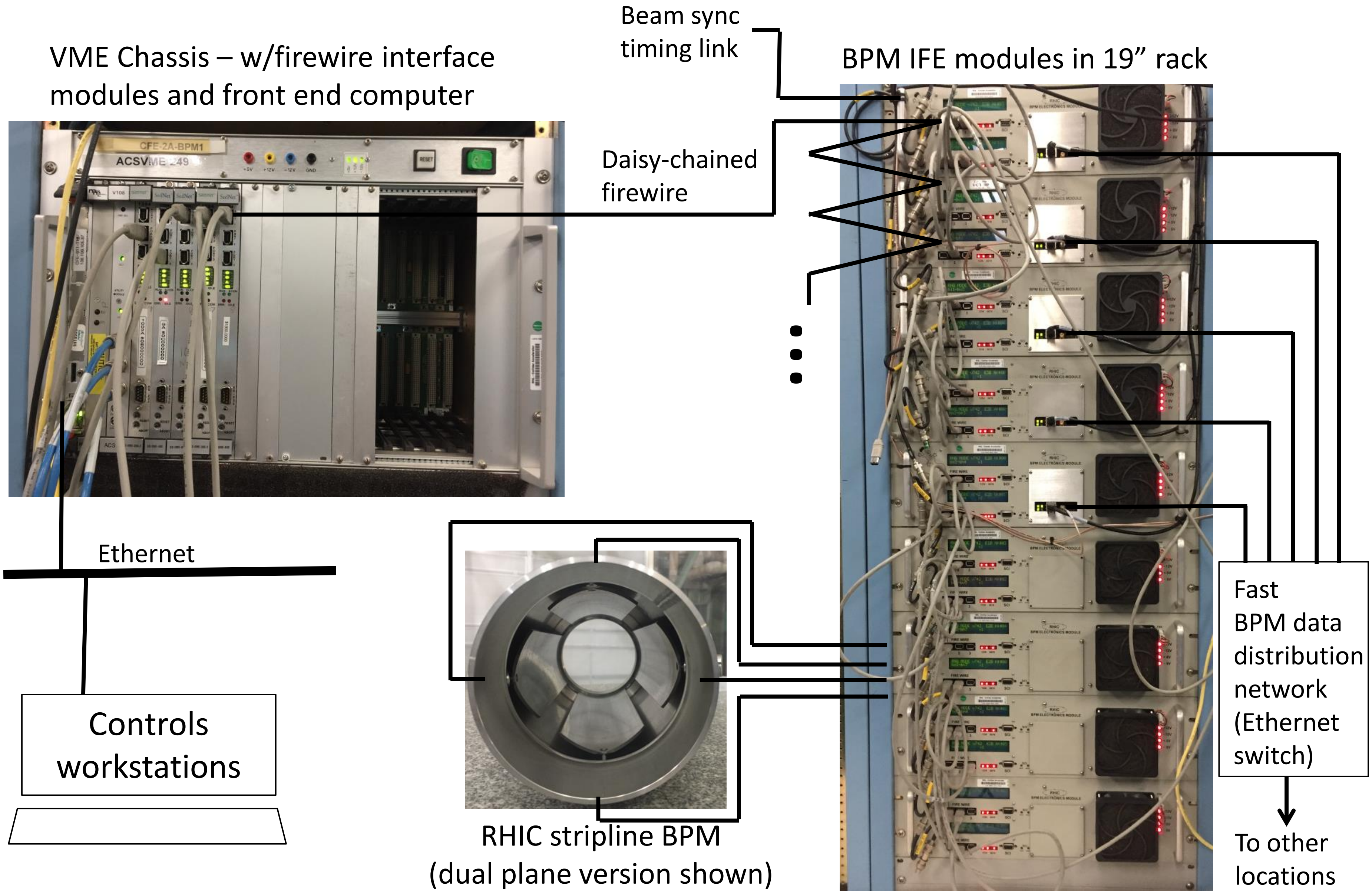
BPM Systems for the BNL Collider-Accelerator Machines

Machine	Beam	Machine circumf/length	Beam repetition rate	BPM Electronics processing
AGS/Booster	Ions, Protons	AGS: 807.1253 m circumf. (4/19 of RHIC) Booster: 201.78m circumf. (1/4 of AGS)	AGS Rev period: ~2.7 us Harmonic: 1 up to 12	Older analog systems (Not discussed in this talk)
LINAC/BLIP	H^-, Protons	LINAC: 144.8 m, 9 accelerating tanks	200 MHz bunch train, 450 us long, 6.67 Hz rep rate	**V301**: 200 MHz low-pass filter, under-sampled, bunch train sliced into ~150 segments for position calculations, 30 MSPS ADC clock rate
RHIC	Ions, Protons	3833.845 m	Rev period: ~12.8 us Harmonic: 360 (28 MHz with max of every 3rd bucket filled)	**IFE**: 28 MHz low-pass filter, single sample on bunch peak, 100kHz ADC (1990s) **V301**: 39 MHz or 200 MHz low-pass filter, oversampled w/ 400 MSPS ADC
LEReC (Low Energy RHIC electron Cooling)	Electrons, mixed with RHIC Ions	100 m	704 MHz bunch trains, 9 MHz train rate; trains overlaid with RHIC ion beam	**V301 for electrons**: 700 MHz band-pass filter, under-sampled w/400 MSPS ADC **V301 for electron bunch trains and ions**: 39 MHz low-pass filter, oversampled **Libera single pass for some electron-only BPMs**: 700 MHz band-pass filter, under-sampled
CeC (Coherent electon Cooling)	Electrons, mixed with RHIC Ions	~36 m	Electrons: 78 kHz (RHIC revolution frequency)	**Libera Platform B**: 500 MHz band-pass for electrons, 9 MHz band-pass for ions
CBETA (Cornell-Brookhaven ERL Test Accelerator)	Electrons	79 m circumference	41.9 MHz, up to 8 different energy beams in same beam pipe (4 accelerating, 4 decelerating)	**V301**: 800 MHz Bessel low-pass filter, single sample on bunch peak; different timing values for each of 8 different energy bunches, ~400 MHz ADC clock locked to RF

RHIC Integrated Front End (IFE)

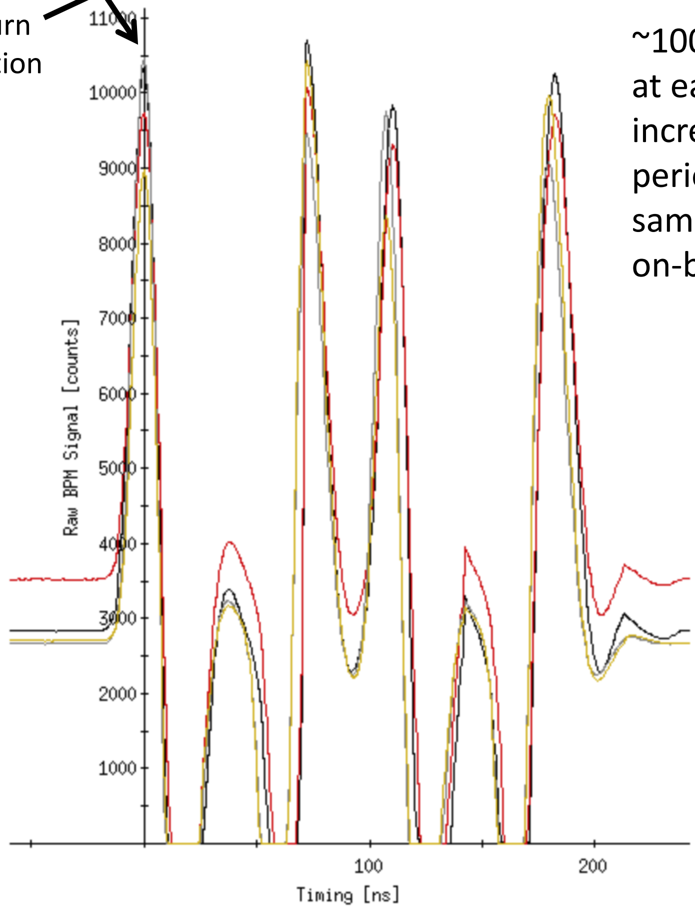
- Designed in 1990s during RHIC construction
- 100 kHz ADC
- Supports self-trigger and fixed-trigger timing
- Single sample at peak of bunch
- Provides matching of input signals to 20ps using digital delay generators
- Approx. 700 boards are installed in RHIC, each board supports a single measurement plane

RHIC Integrated Front End (IFE) BPM Architecture



RHIC IFE profile scans for configuring ADC clock timing to peak

Single ADC sample per turn used for position calculation

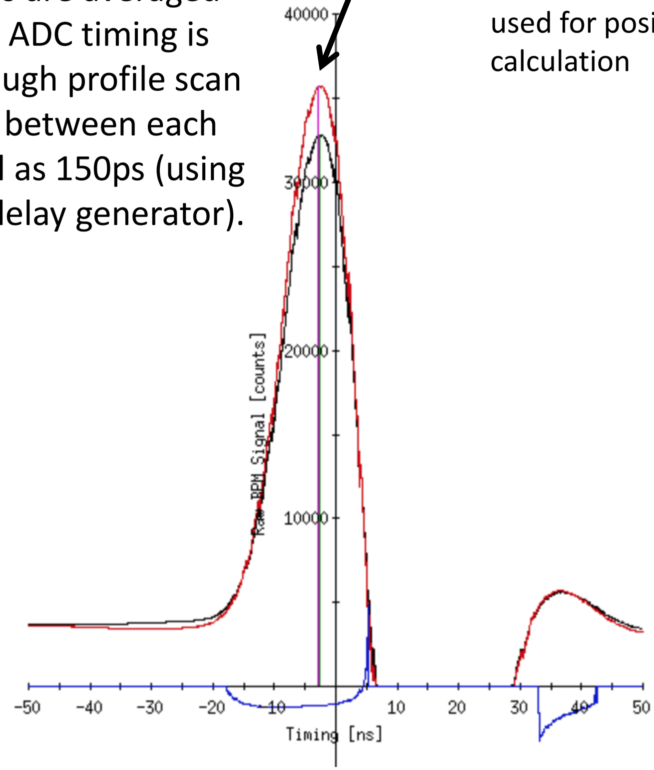


Beam profile scan of DX BPM which installed in common beam pipe at collision area. Two different beams are detected moving in opposite directions.

For profile scan

~100 ADC samples are averaged at each point and ADC timing is incremented through profile scan period. The time between each sample is as small as 150ps (using on-board digital delay generator).

Single ADC sample per turn used for position calculation



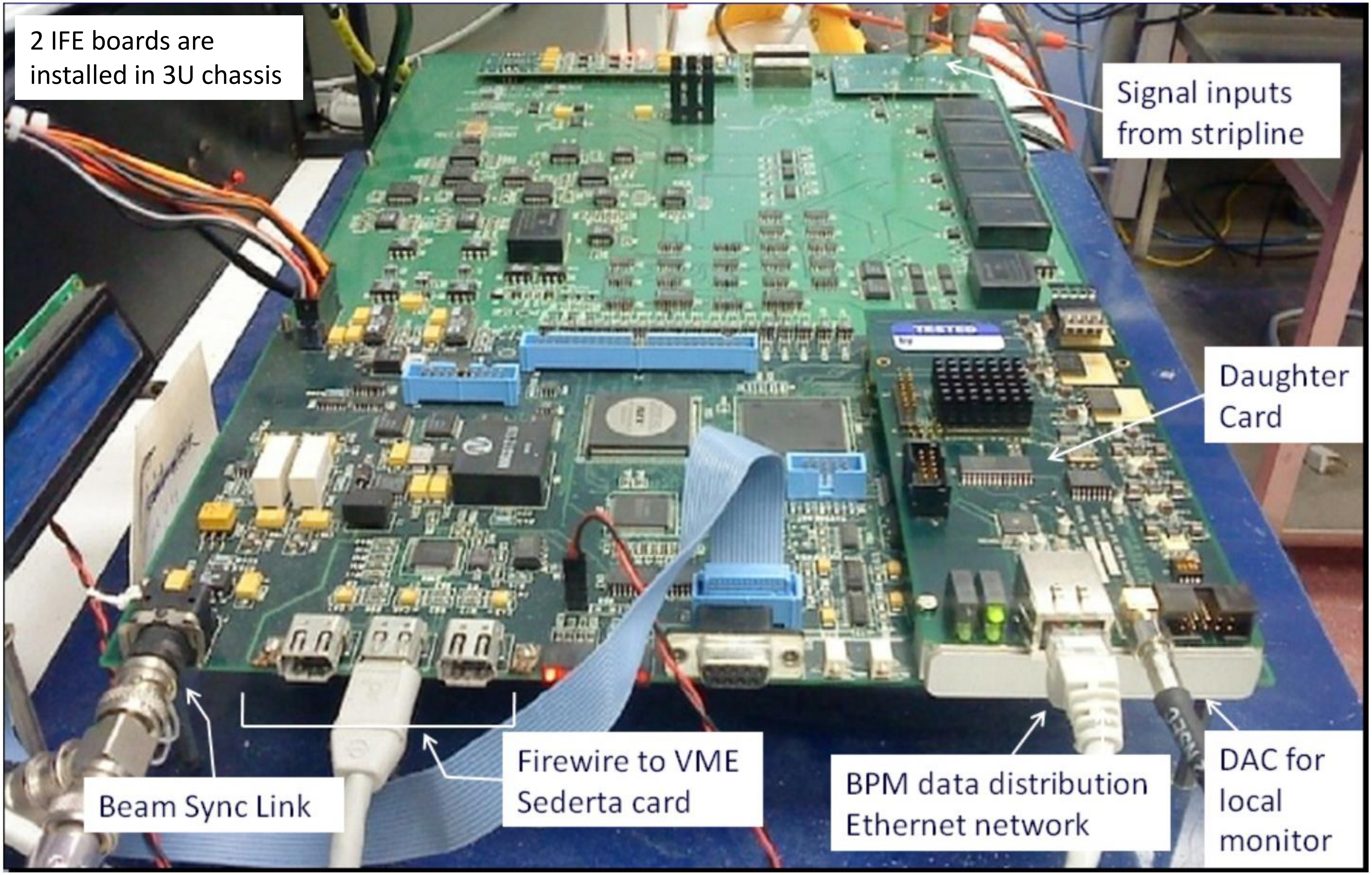
Typical beam profile scan of BPM showing ion beam with pulse width of ~15 ns.

RHIC 10 Hz Global Orbit Feedback (GOFB)

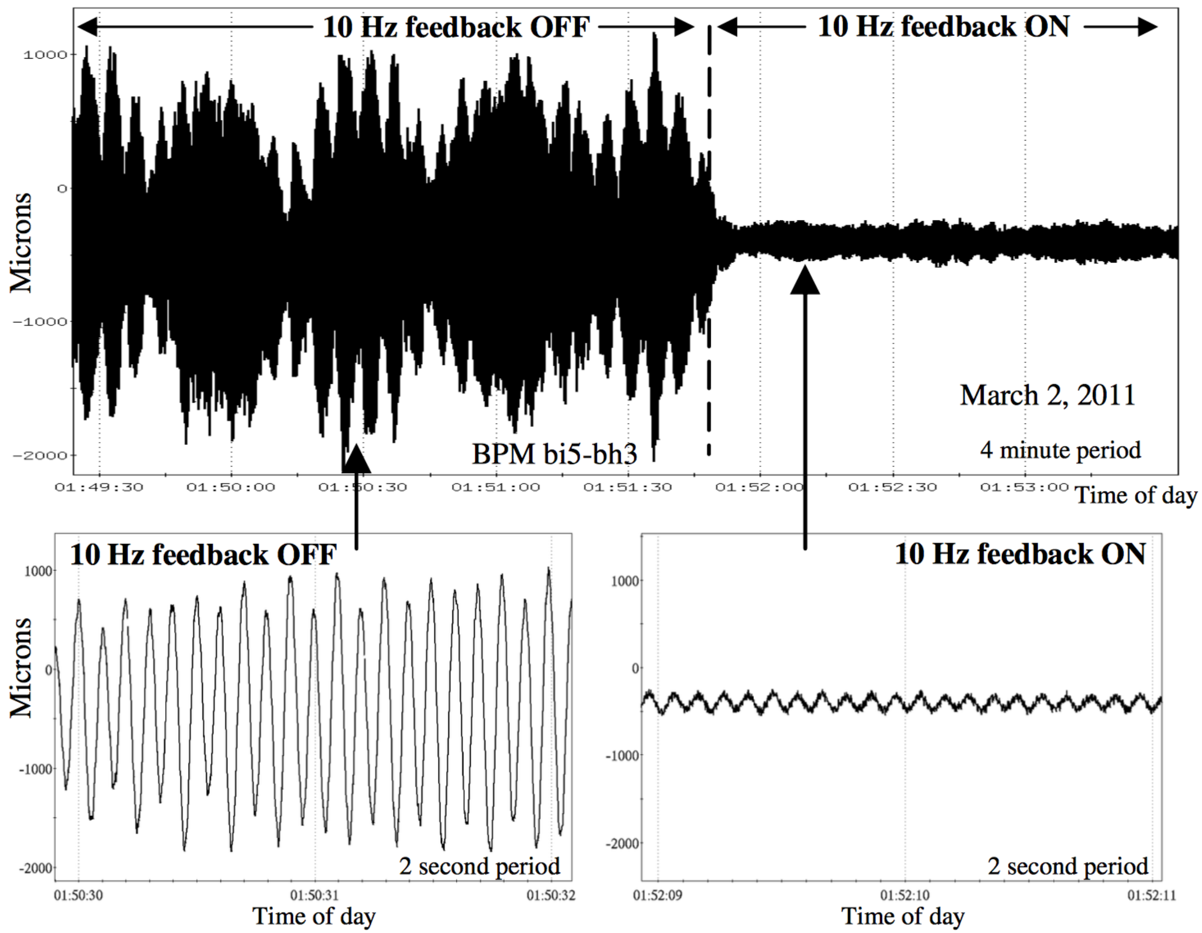
Purpose: To correct 10 Hz beam oscillations induced by triplet cryostat vibrations

- 72 BPM measurements distributed around 3.8 km ring via dedicated Ethernet network
- Developed custom daughter card for IFE board for dedicated BPM data distribution network
  - Used low level Ethernet protocol to allow use of commercially available network switches
- All position measurements distributed around RHIC ring at 10 kHz rate
- Matrix calculations at 6 locations around the ring to provide setpoints to local corrector magnet power supplies

RHIC 10 Hz GOFB
IFE Board with Daughter Card



RHIC 10 Hz Global Orbit Feedback



Typical BPM measurement with 10 Hz feedback OFF vs. ON (1000 data points per second).

BNL Designed V301 BPM Module

Motivation: RHIC complex upgrade & electron applications

- VME form factor – backplane used for power and machine clock distribution, VME data bus not used
- Based on Xilinx Zynq gate array
- Linux runs directly on one Arm processor in the gate array, which is tightly coupled to gate array logic
- Linux boots from on-board microSD card, which fetches gate array code and software executables from network server
  - This allows simple deployment of gate array code and onboard software by simply copying the new version to the server and rebooting all devices.
- Each module has 2 Ethernet connections
  - One for controls communication
  - One for custom use like high speed position distribution
- 1st production run 2016 for LEReC, RHIC (qty:80); 2nd completing now for CBETA (qty:160); 3rd for addnl CBETA, Linac and other applications (qty:50)

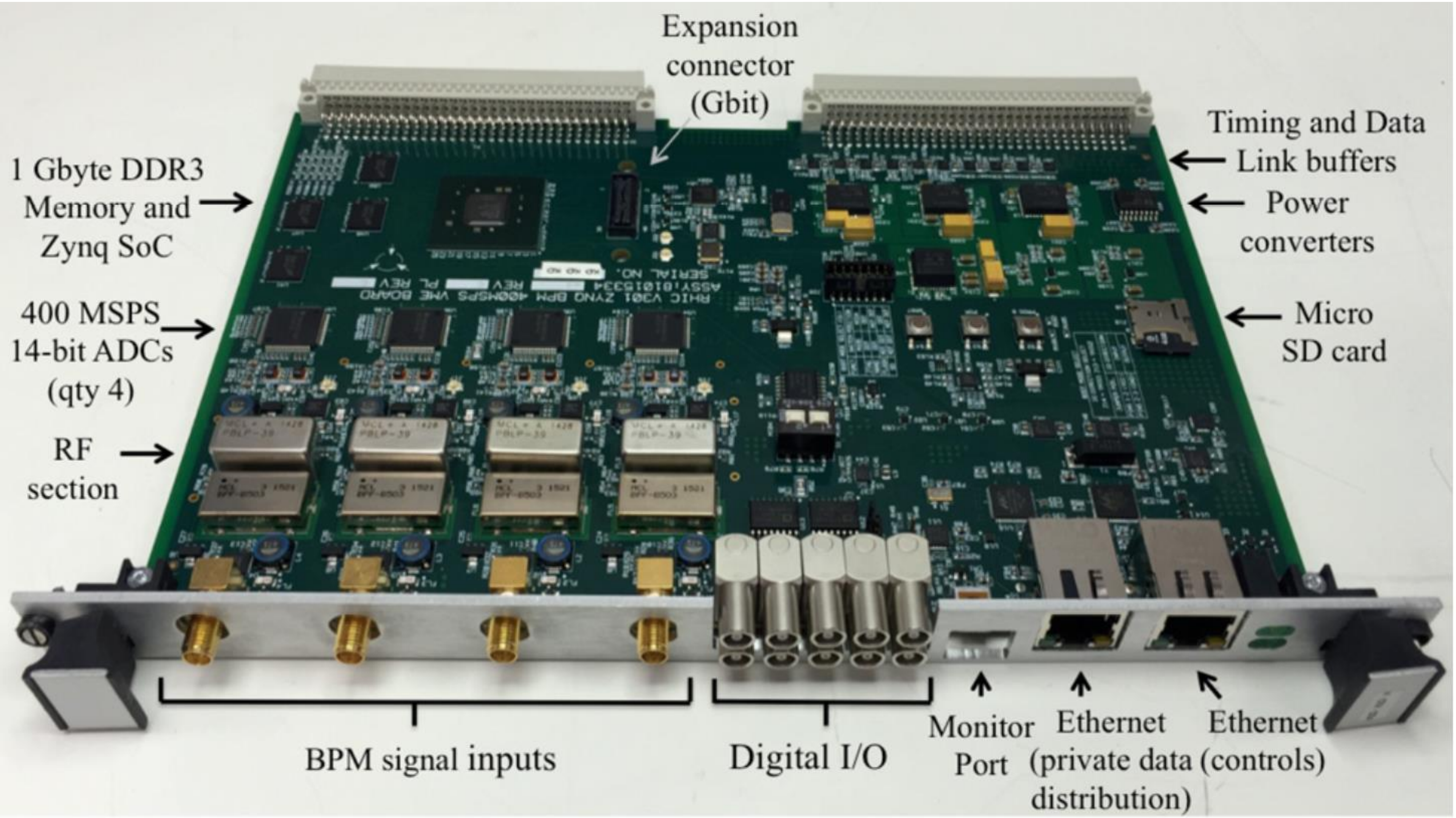
BNL Designed V301 BPM module

Short list of features

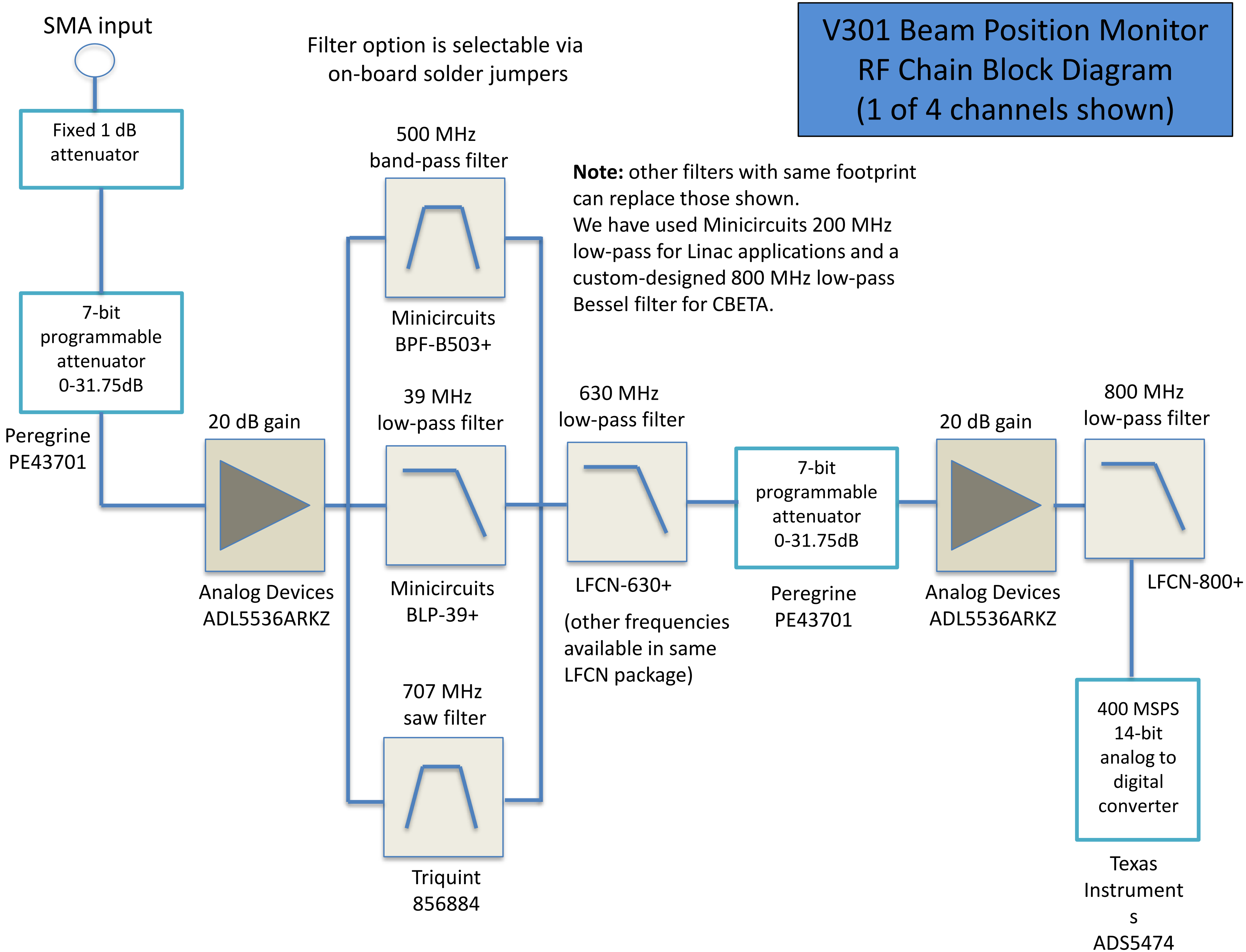
- Capable of measuring Electrons and/or ions
- Under-sampling, over-sampling, single point
  - (RHIC ion beam, DX BPMs, LEReC electrons 700 MHz, LEReC electrons 39 MHz, LEReC ions, CBETA electrons)
- 500 MHz band-pass, 700 MHz band-pass, 39 MHz low-pass, 200 MHz low-pass, 800 MHz low-pass Bessel
- Bunch-by-bunch, turn-by-turn
- Machine protection interface based on position threshold excursions

V301 RF front end modeled from NSLS II design

BNL Designed V301 BPM module



V301 Beam Position Monitor RF Chain Block Diagram (1 of 4 channels shown)

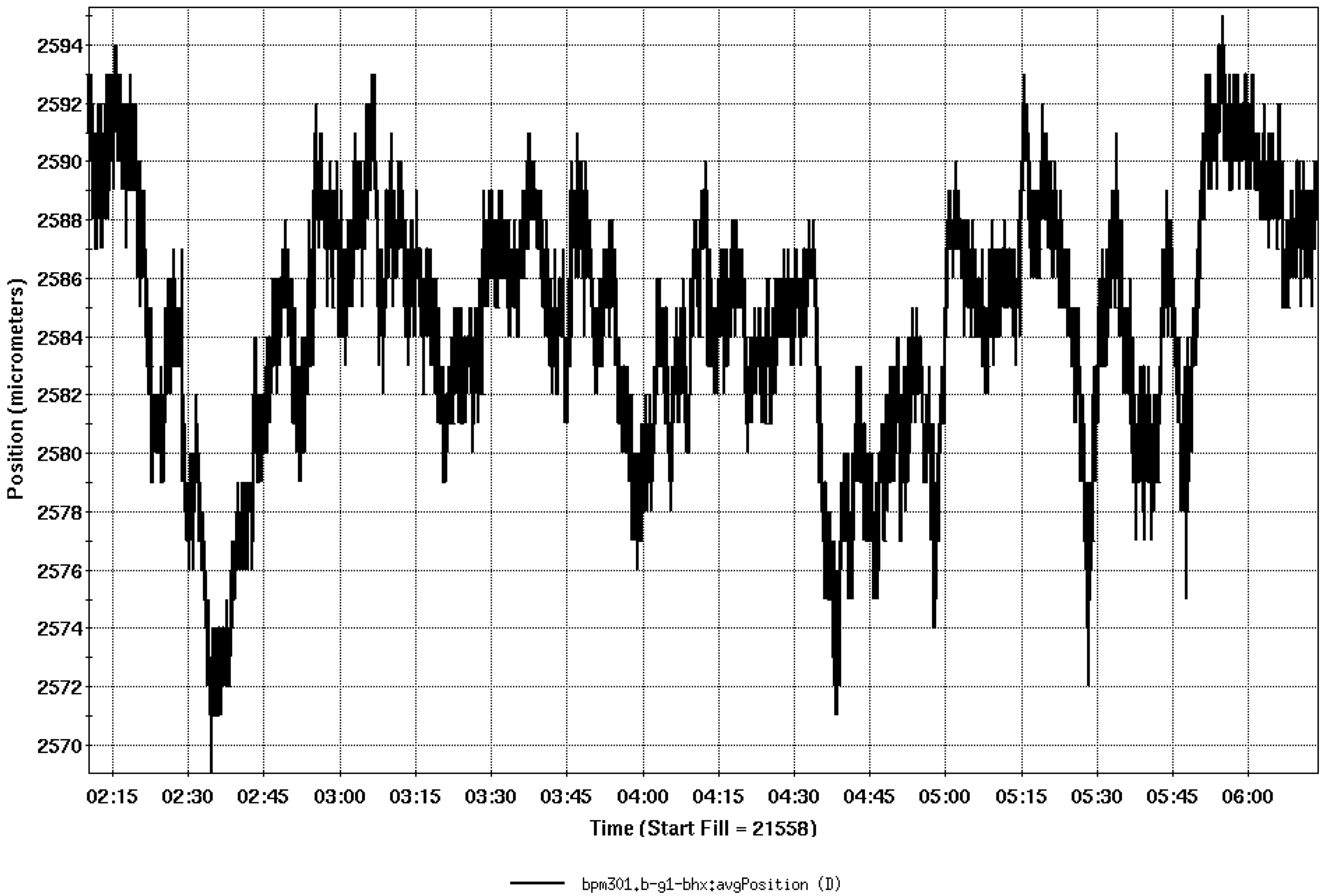


Note: other filters with same footprint can replace those shown.
We have used Minicircuits 200 MHz low-pass for Linac applications and a custom-designed 800 MHz low-pass Bessel filter for CBETA.

V301 for RHIC ions

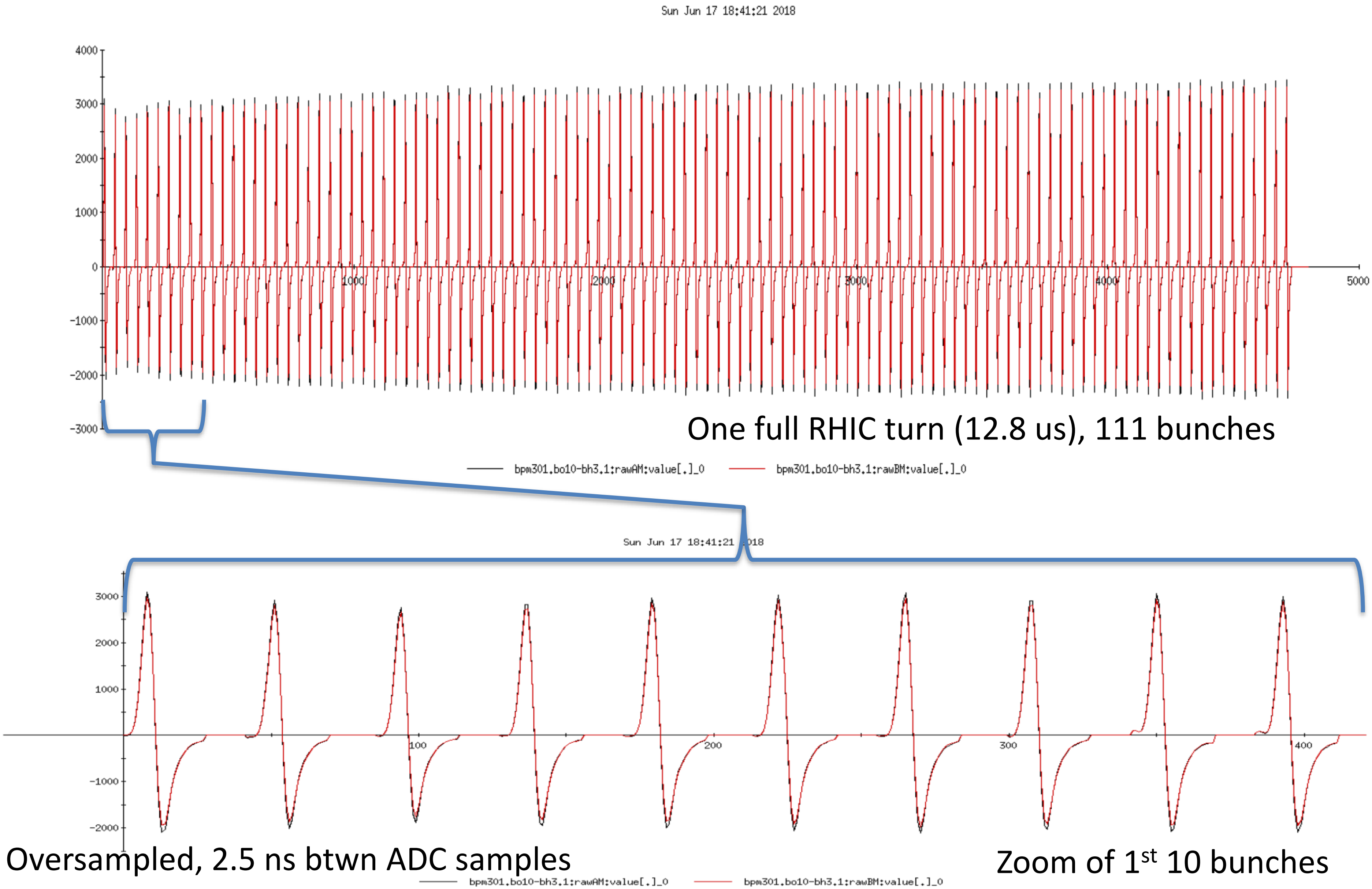
- Measurements being provided with V301 modules:
  - 1 second average orbit position
  - Buffer of 1000 position values delivered each second, 1 ms per sample
  - Bunch by bunch position measurements
  - Bunch by bunch coherence (peak-to-peak variation every x turns)
  - Turn-by-turn position measurements
  - Bunch-by-bunch position measurement for last turn as beam is dumped
  - Bunch measurements for 2 different beams as needed for DX BPMs in the common beam pipe of the collisions sections.
    - One V301 measures both beams.
  - Bunch-by-bunch luminosity (counting digital pulses from experiment ZDC coincident signals and binning to each bucket)
  - Bunch-by-bunch loss monitor (counting digital pulses from loss monitor system and binning to each bucket)

V301 for RHIC (ions), Position



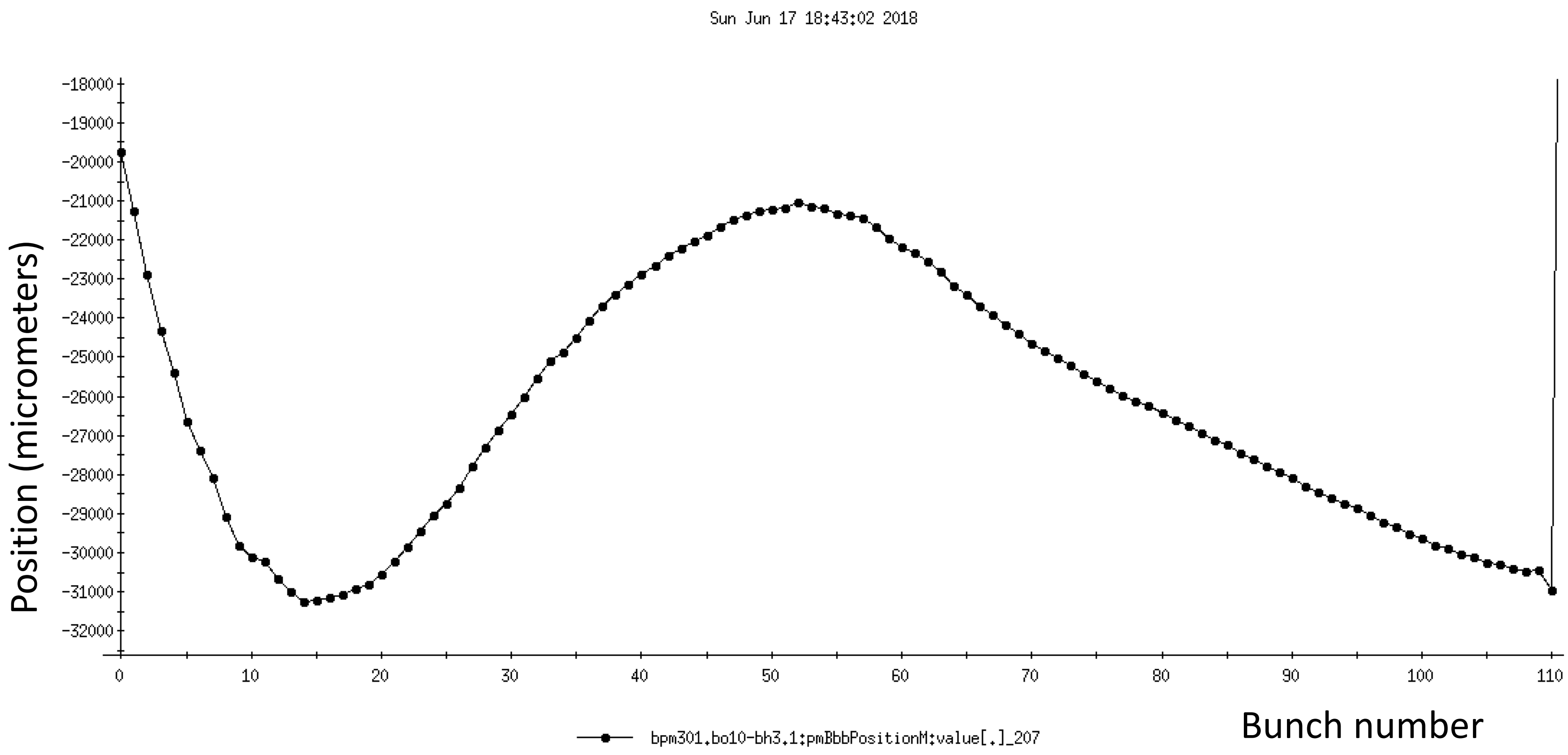
Plot of V301 average orbit beam position data during a segment of a RHIC store.
Single digit micron variations are detectable. (4 hour period shown)

V301 for RHIC (Ions), Raw Data Plots



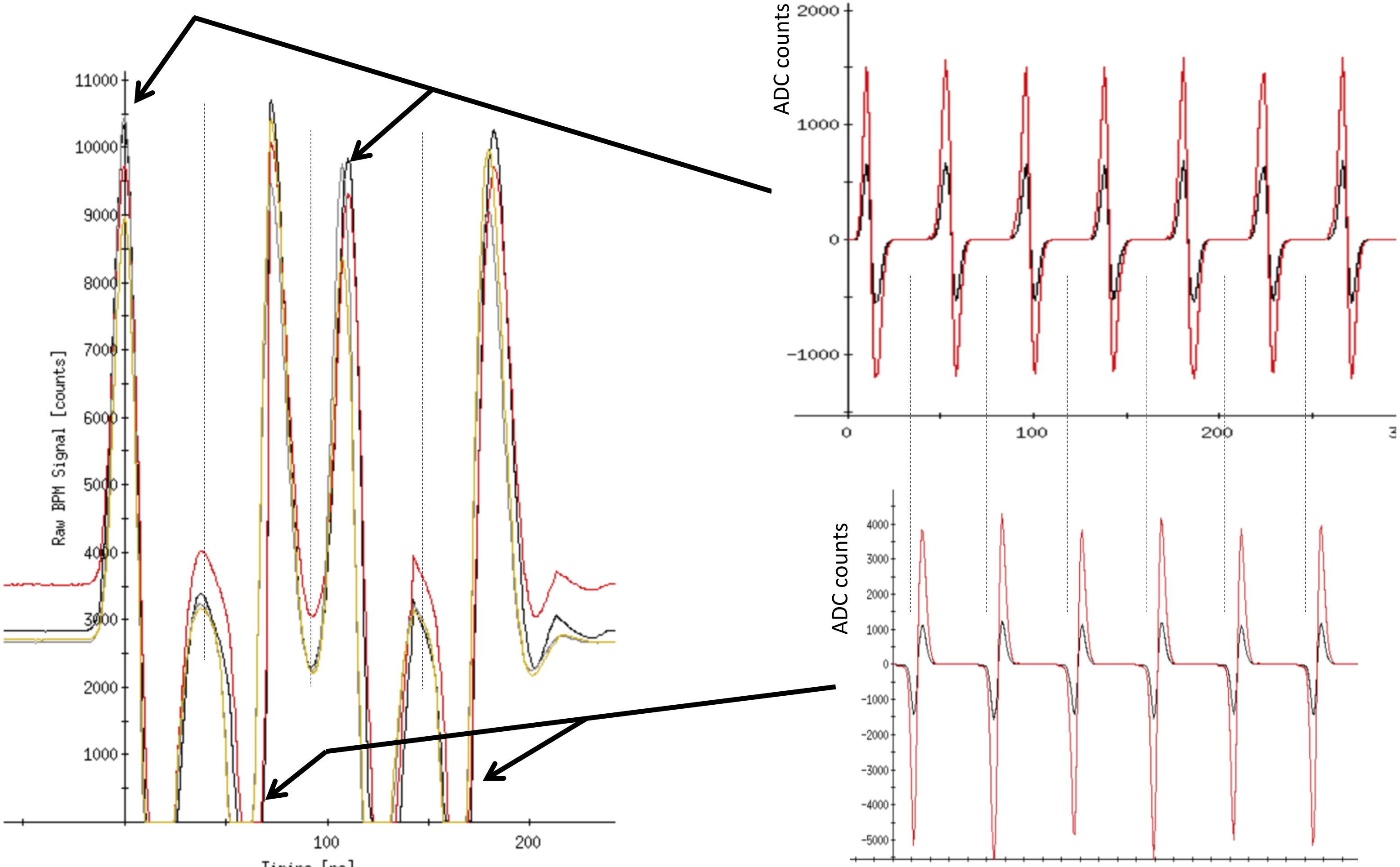
V301 for RHIC dump (ions)

Bunch-by-bunch position for dumped beam



The waveform shown correlates with the dump kicker high voltage output.

V301 for RHIC DX BPMs
(2 ion beams traveling in opposite directions)



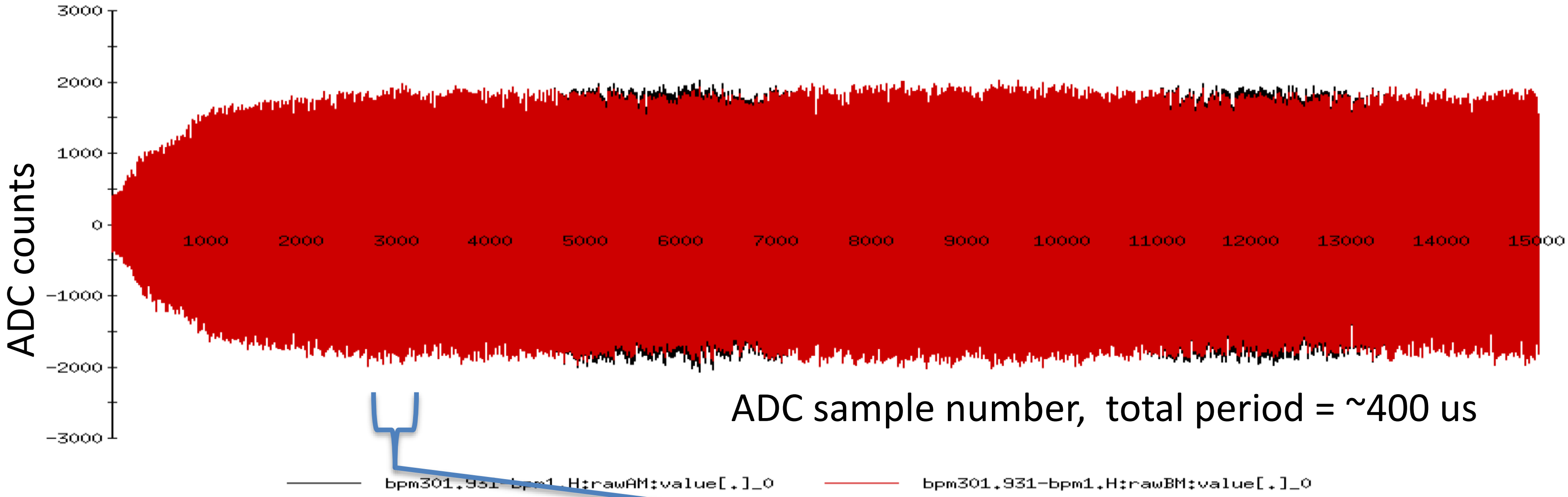
Timing configured to process all positive going pulses

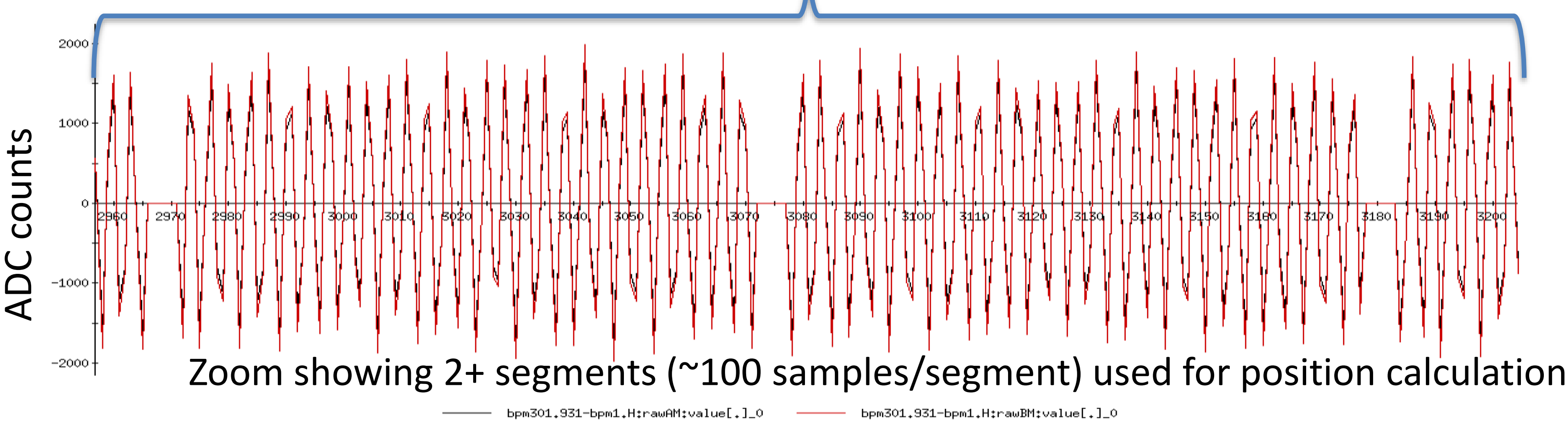
Timing configured to process all negative going pulses

Plot of stripline signal at DX BPM installed in the common collision area beam pipe, which detects 2 ion beams traveling in opposite directions. Beam in one direction generates positive going pulse and beam in opposite direction generates negative going pulse.

One V301 module is used to independently measure both beams. 200 MHz low pass filter is used to provide better beam separation than the standard 39 MHz low-pass filter

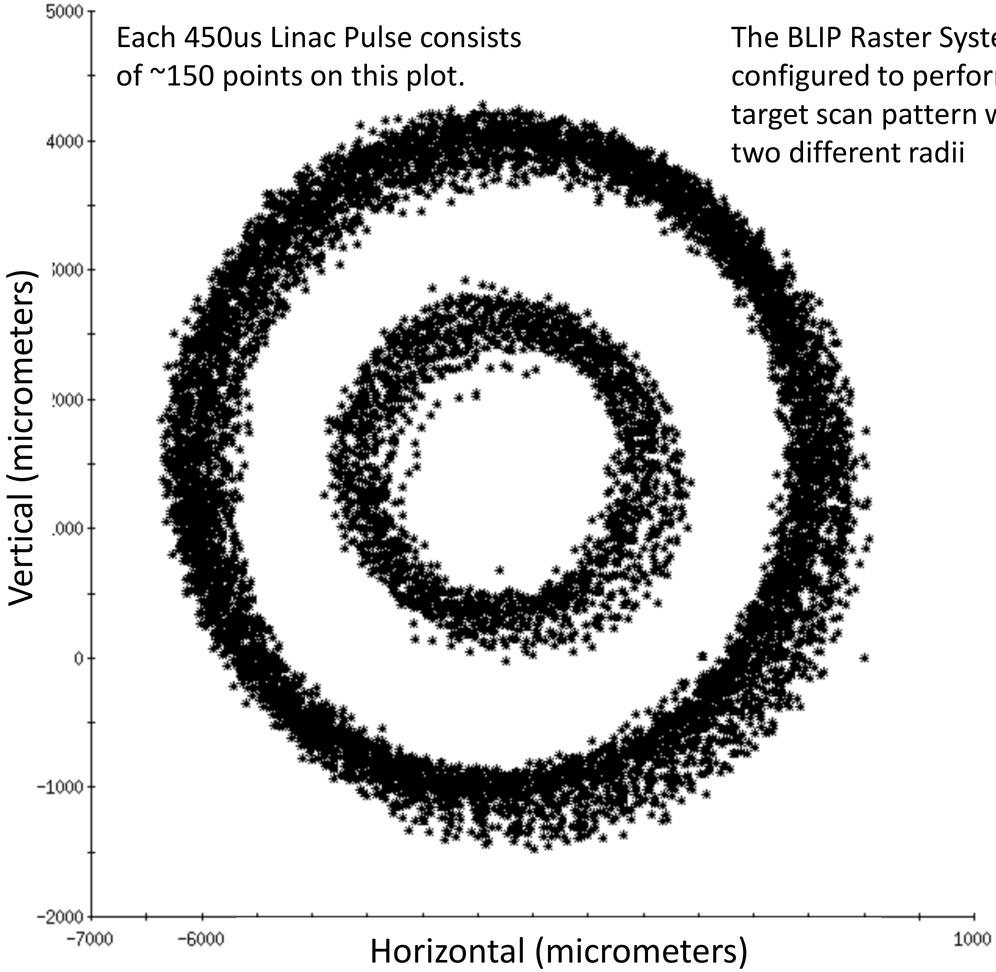
V301 for BLIP beam from LINAC protons

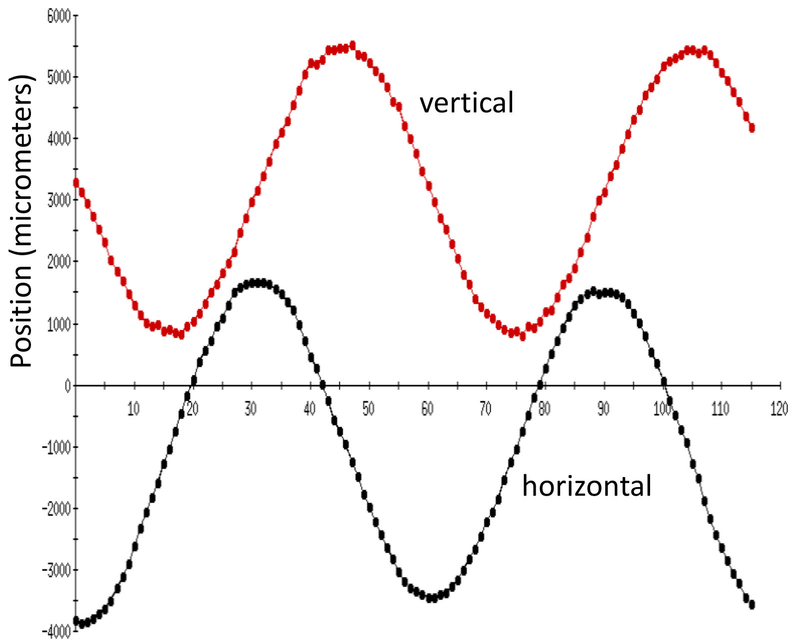




200 MHz RF signal, undersampled, ADC clock = 30 MHz internal clock (not locked to RF)

BLIP Raster X vs. Y
(Proton beam from Linac)





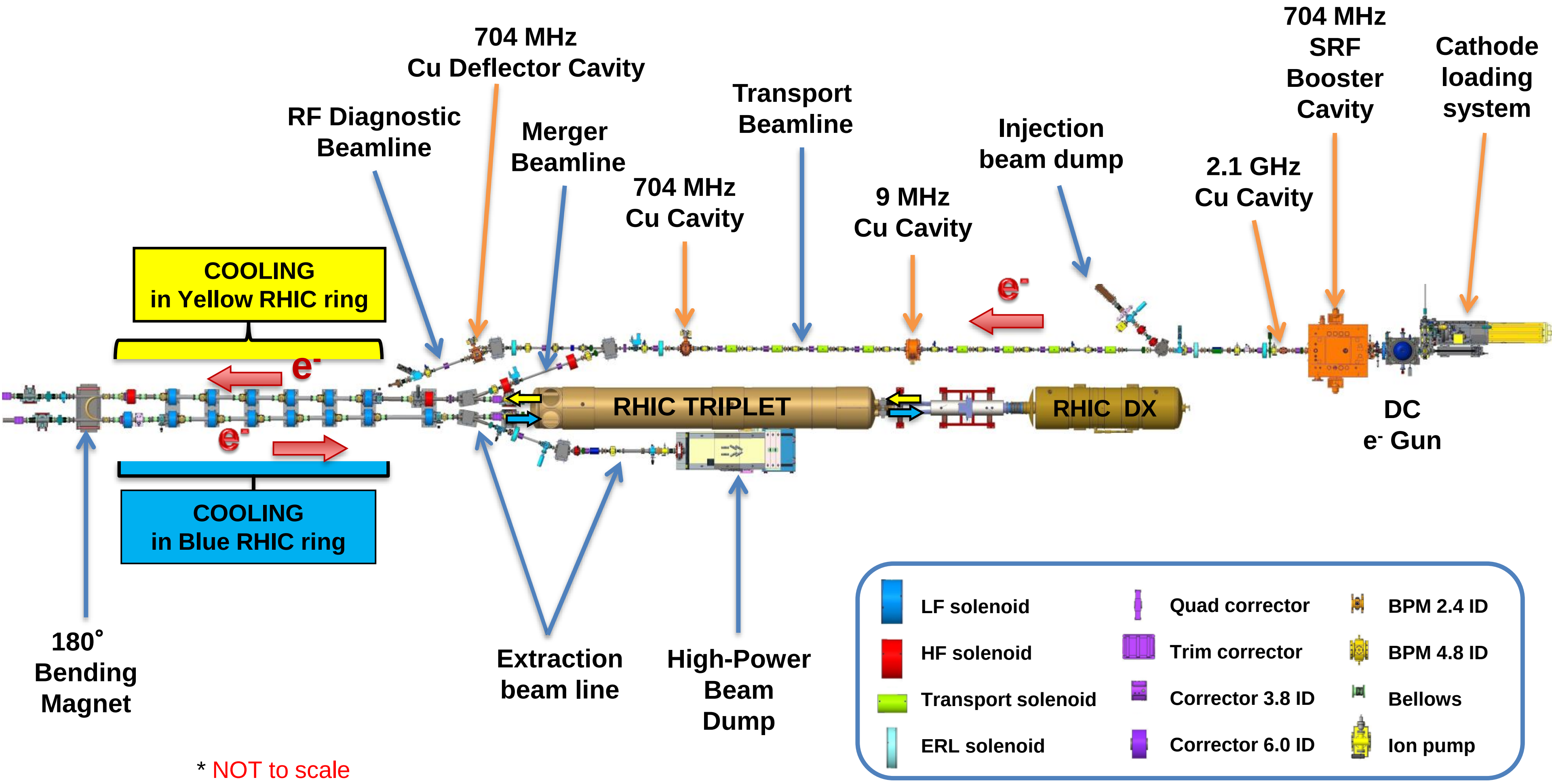
Horiz and Vert positions for one single 450 us long LINAC beam pulse, divided into 100+ measurement segments.

Raster pattern generates 2 5 kHz periods with 90 deg phase separation between horiz and vert.

X vs. Y plot of BLIP BPM data showing the most recent ~10k points of beam position measurements

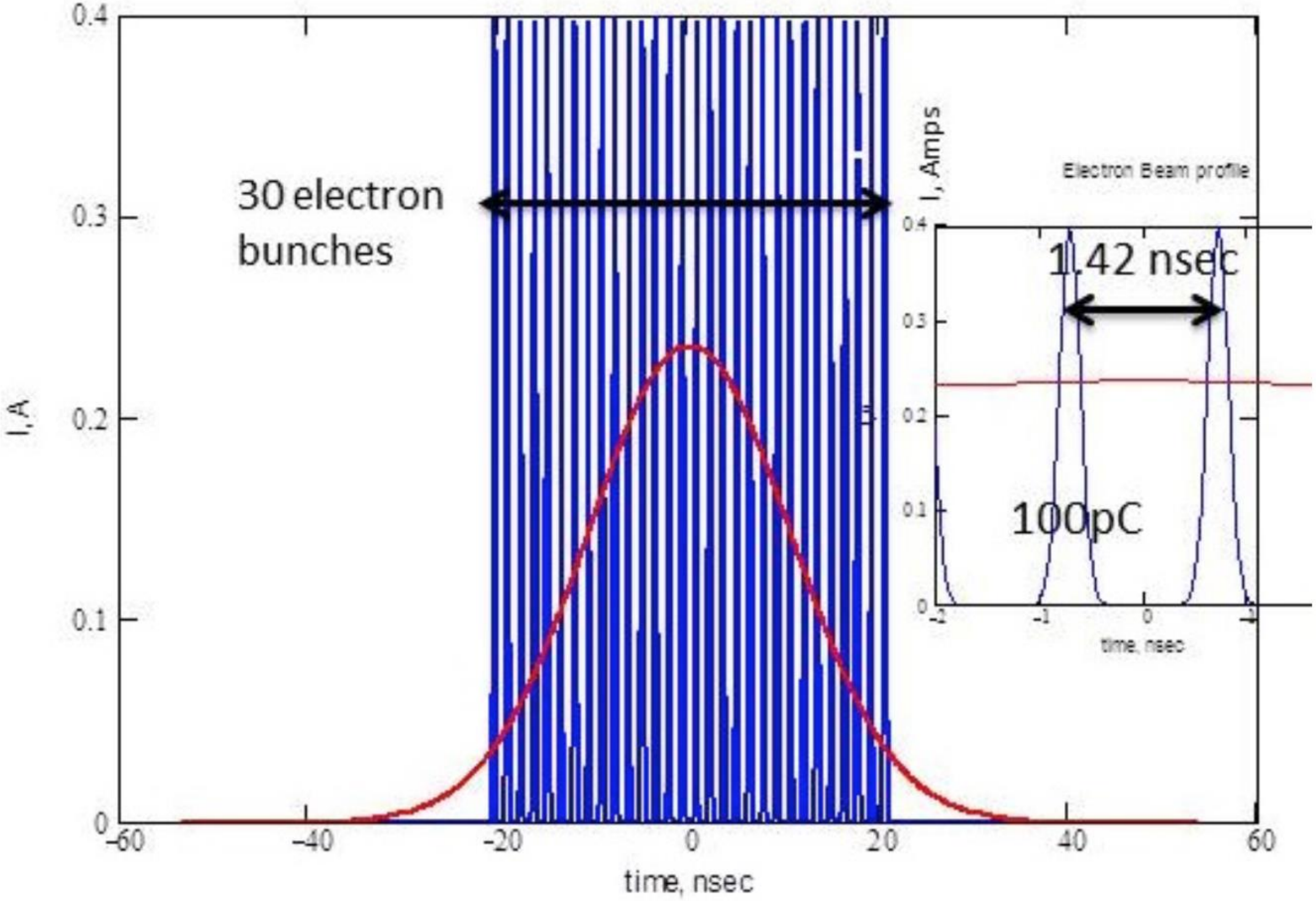
LEReC Accelerator (Low Energy RHIC electron Cooling)

Presently being commissioned



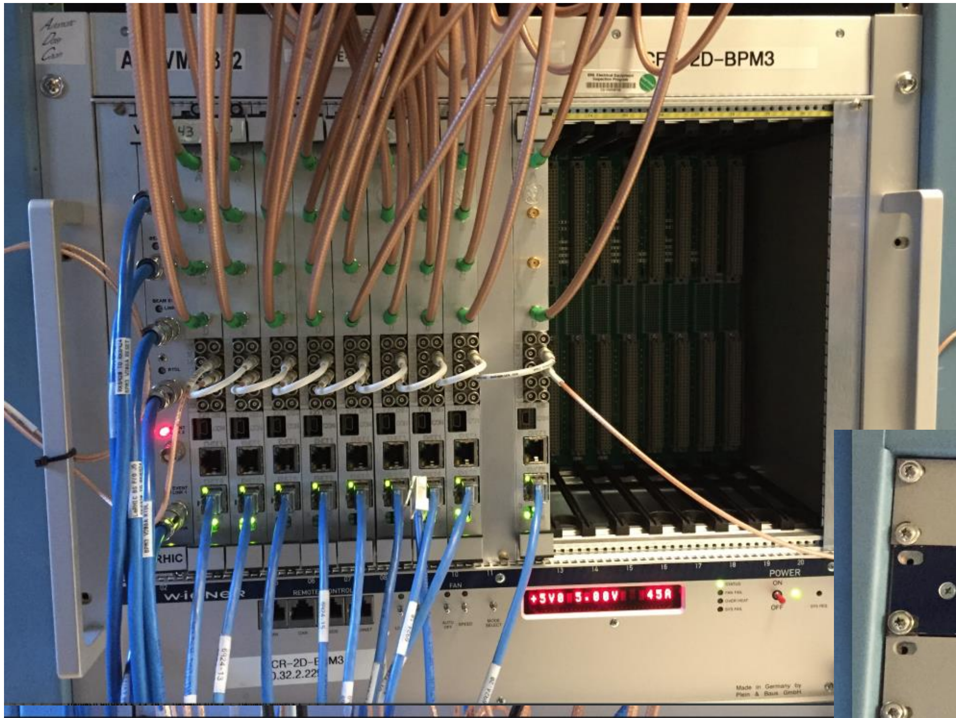
100 meters of beamlines with the DC Gun, high-power fiber laser, 5 RF systems, including one SRF,magnets and instrumentation

LEReC electron & ion bunch overlay



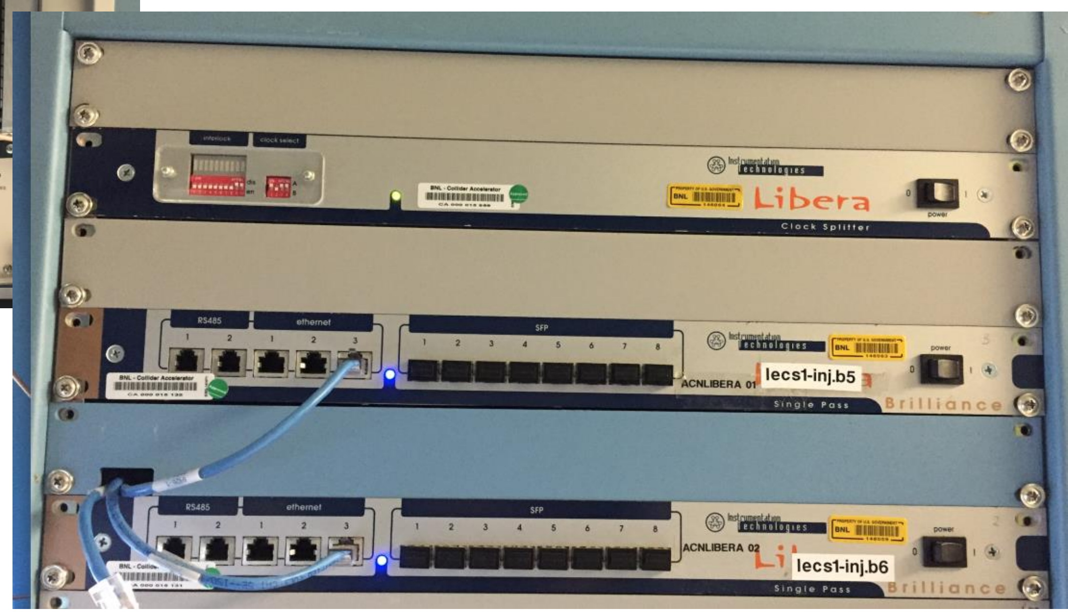
Longitudinal representation of several electron bunches (blue) overlaid with single ion bunch (red)

LEReC BPM electronics



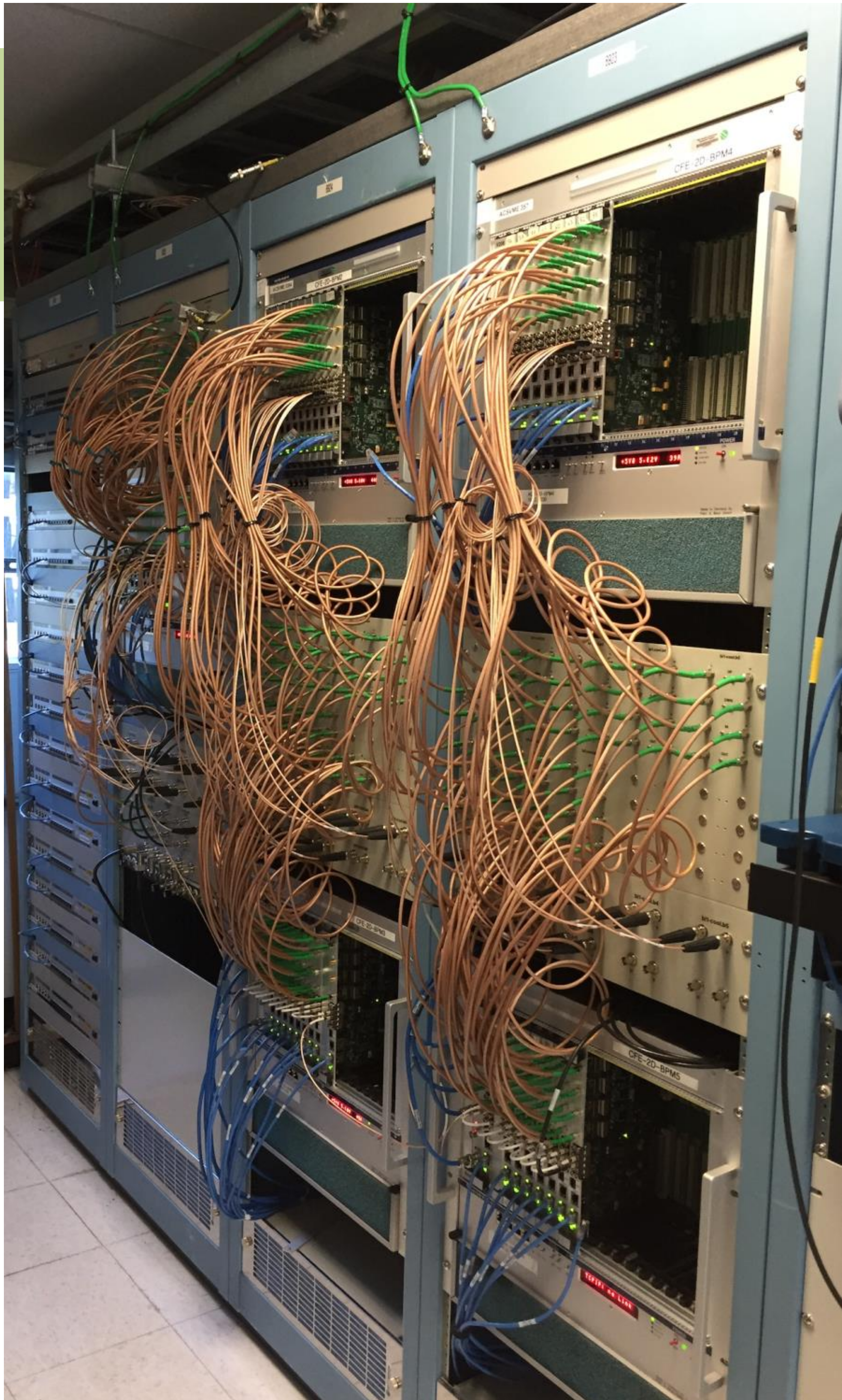
V301 modules in VME chassis for measuring electrons and ions

Libera Brilliance single pass modules for measuring some of the electron buttons in the transport line. These units were available from a previous project.

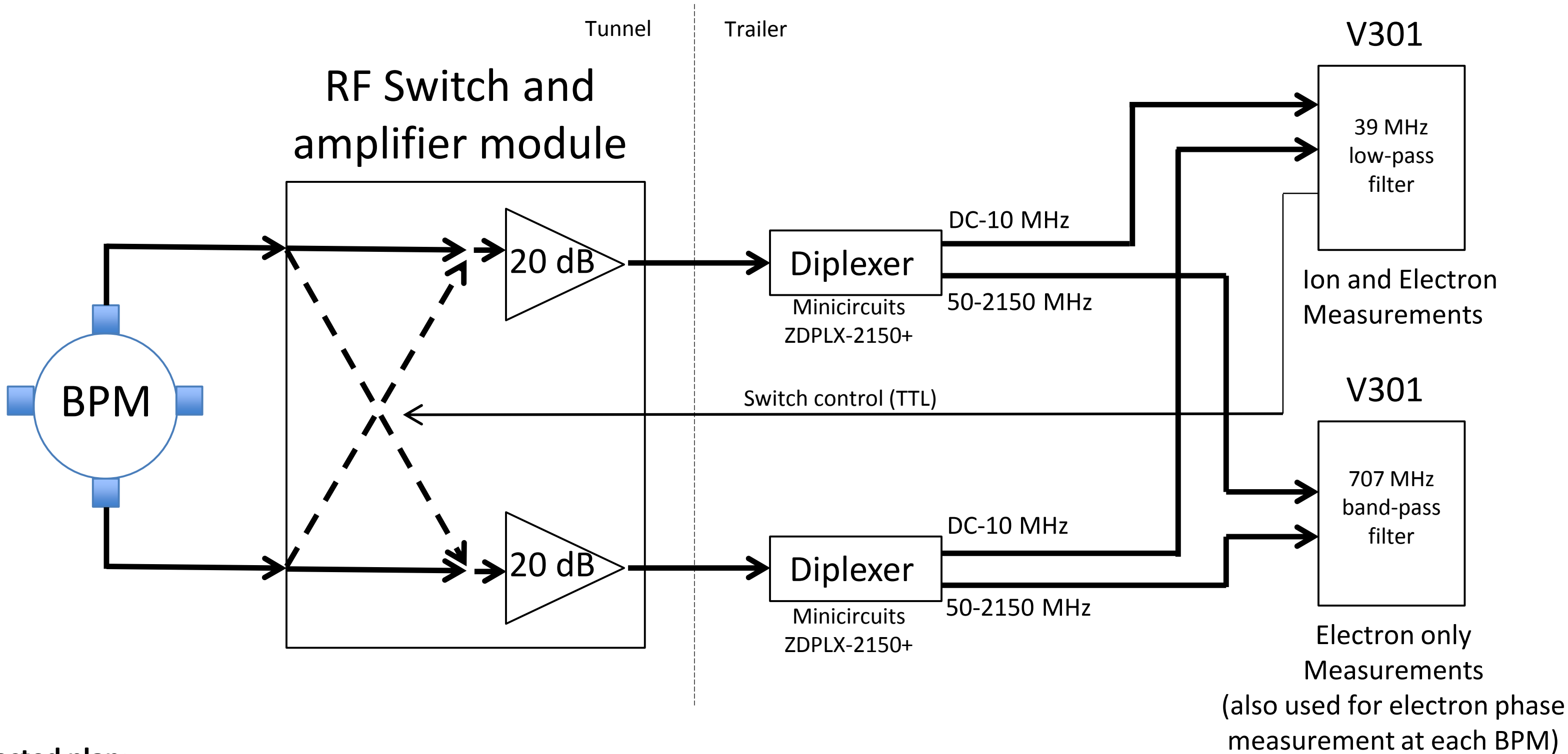


V301 for LEReC electrons and Ions

- Ions
  - 9 MHz bunch spacing
- Electrons
  - 9 MHz bunch trains
  - 700 MHz bunch spacing within each train
- Button signals are split to 2 differently configured modules
  - Modules configured with <u>700 MHz band-pass filter</u> only allow electron beams to be detected.
    - Note: This is only the case for long ion bunches which are planned to be used for LEReC. Short ion bunches with 200 MHz RF do generate a signal on the 700 MHz band-pass filter.
  - Modules configured with <u>39 MHz low-pass filter</u>, detect both ion signal and electron bunch train signals. A gap in one or the other must be present to distinctly measure only one of the beams.
- Time of flight (phase diff btwn 2 BPMs)
- Machine protection



LEReC
Position Measurement Hardware Architecture



Expected plan:

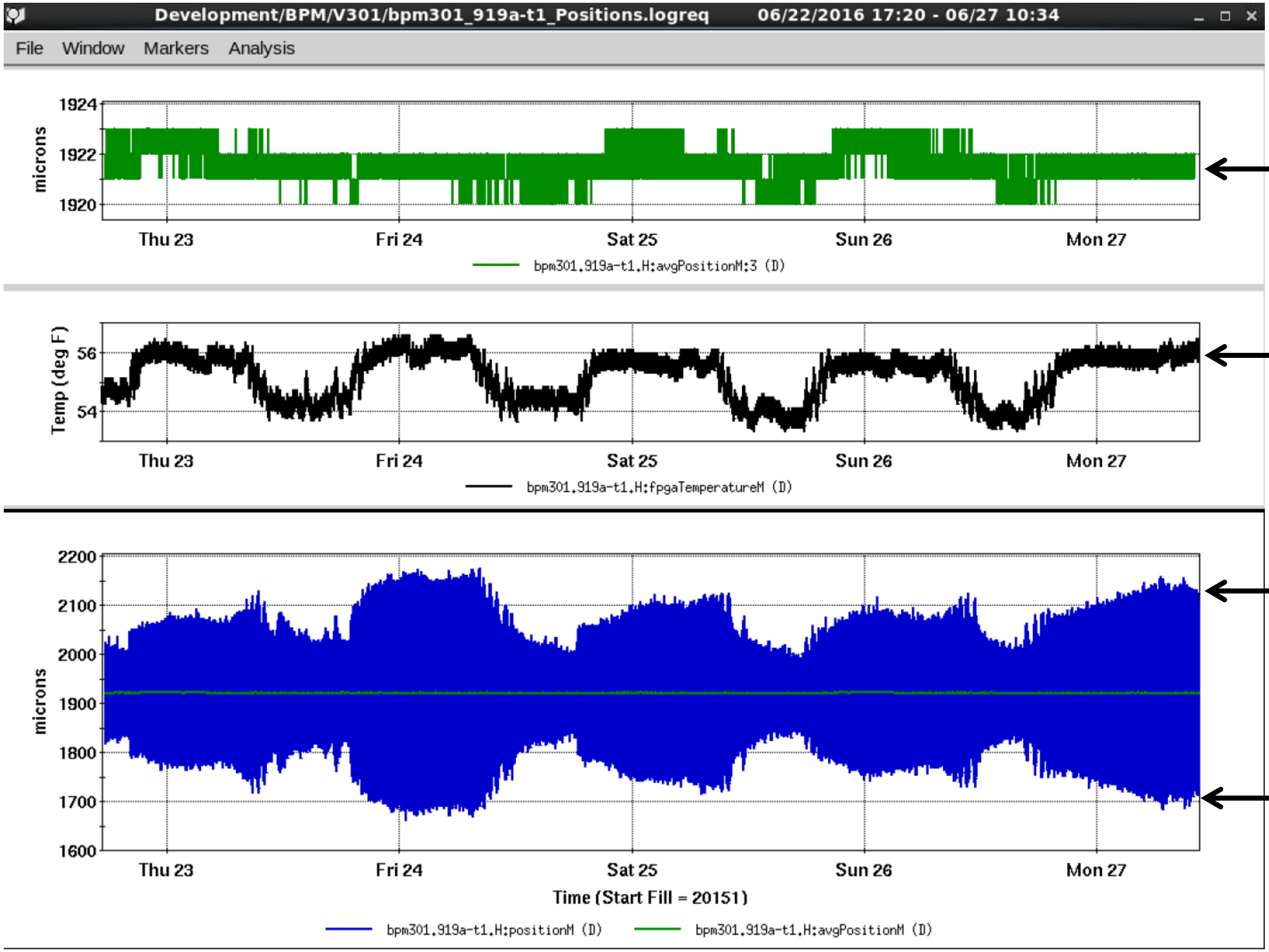
- Continuously cycle RF switch to provide real-time calibration of input signals. This can provide automatic compensation of amplitude variations due to electronics and cables when temperature varies.
- Switches provide compensation for all components downstream of switch.
- Cables from BPM to switch module must be matched (length expected to be about 6 ft.)
- Offline calibration of switches including cables from BPM to switch is required.

However:

- This is presently not being done due to machine protection system requirements.

Continuous Switching of Input Signals

(with simulated electron beam signal and 700 MHz band-pass filter)



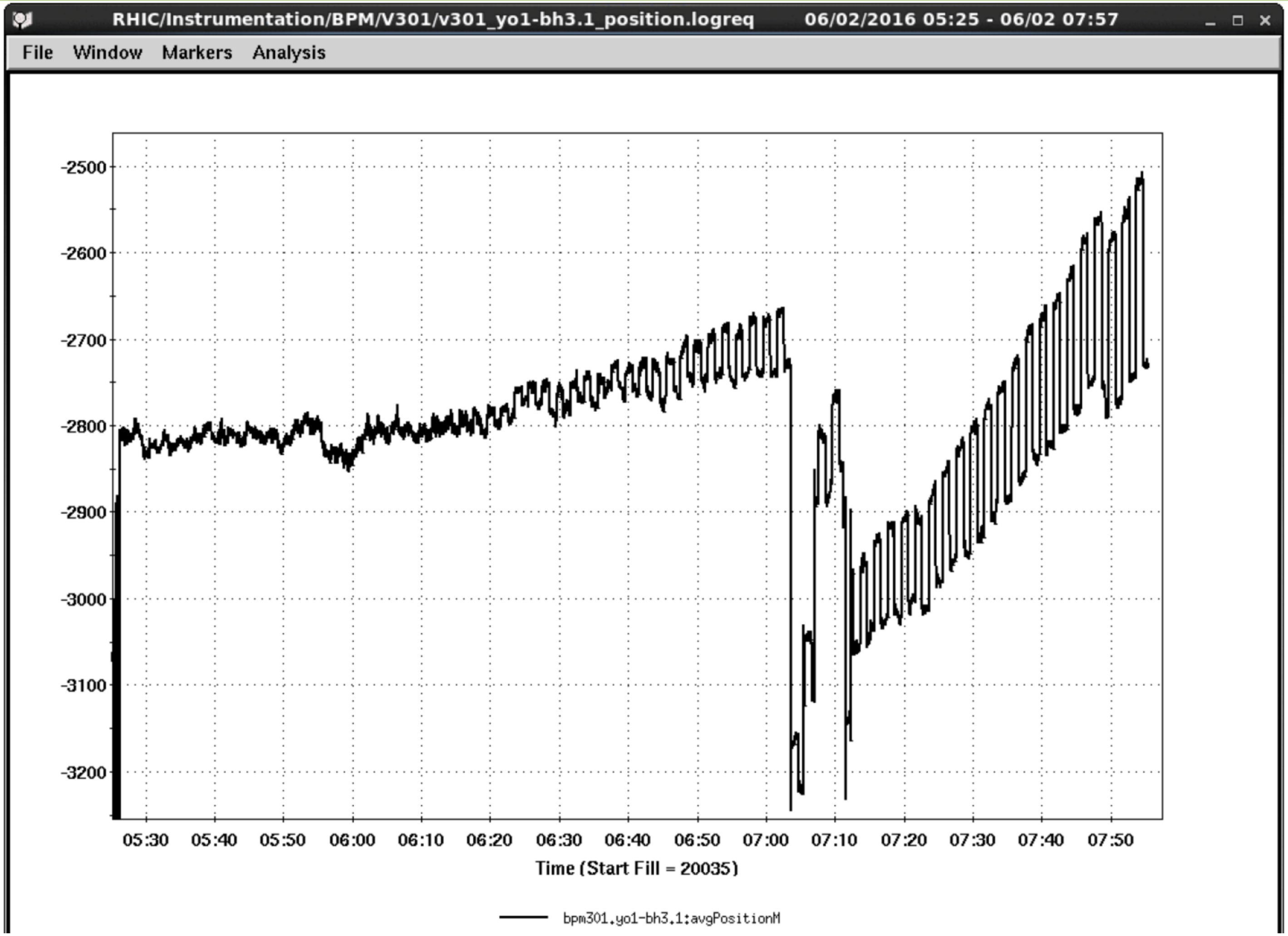
Continuous average of position data – averaging position values from both RF switch states. Note that average is very stable.

BPM board temperature – note that position variations are somewhat correlated with temperature

Top of envelope – RF switch in normal state

Bottom of envelope – RF switch in reverse state, with position calculation multiplied by -1

Yellow LEReC button measurements with 40dB attenuators, analog switch and 20 dB amplifiers in tunnel (9.8 Gev, gold)

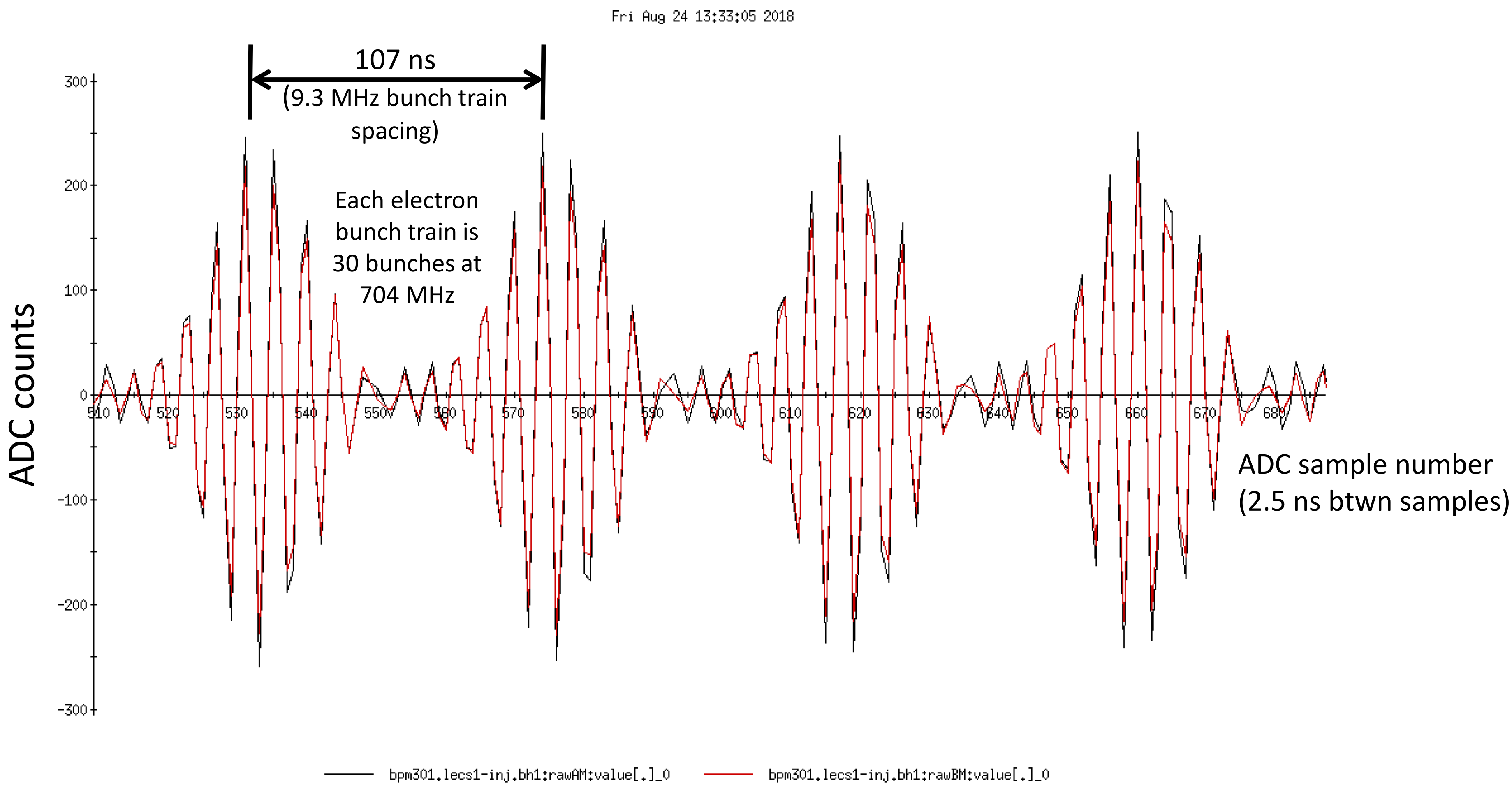


Attenuators were used at buttons to test low amplitude ion beam expected for operations

200 microns

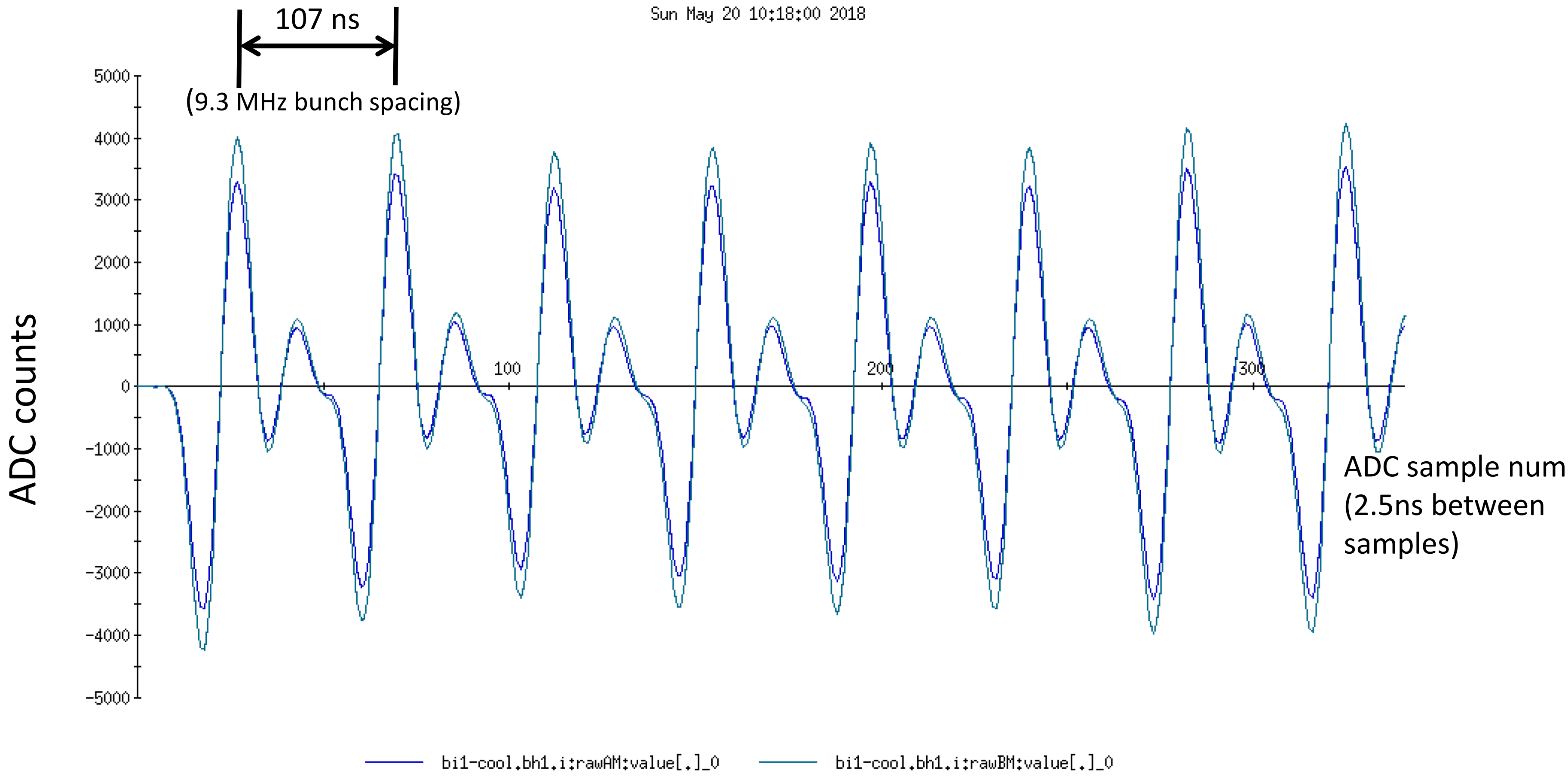
Analog switch changing state every 1 minute during a RHIC store. Note that the position changes due to switching increase during the store. This seems to indicate that the calibration changes during the store due to beam conditions, for example beam frequencies affecting filter response. Electronic component temperature variations could also explain changes, but in this case the variations seem to be beam related. (This signature was different store to store.)

LEReC electron Beam w/ V301
Raw ADC data



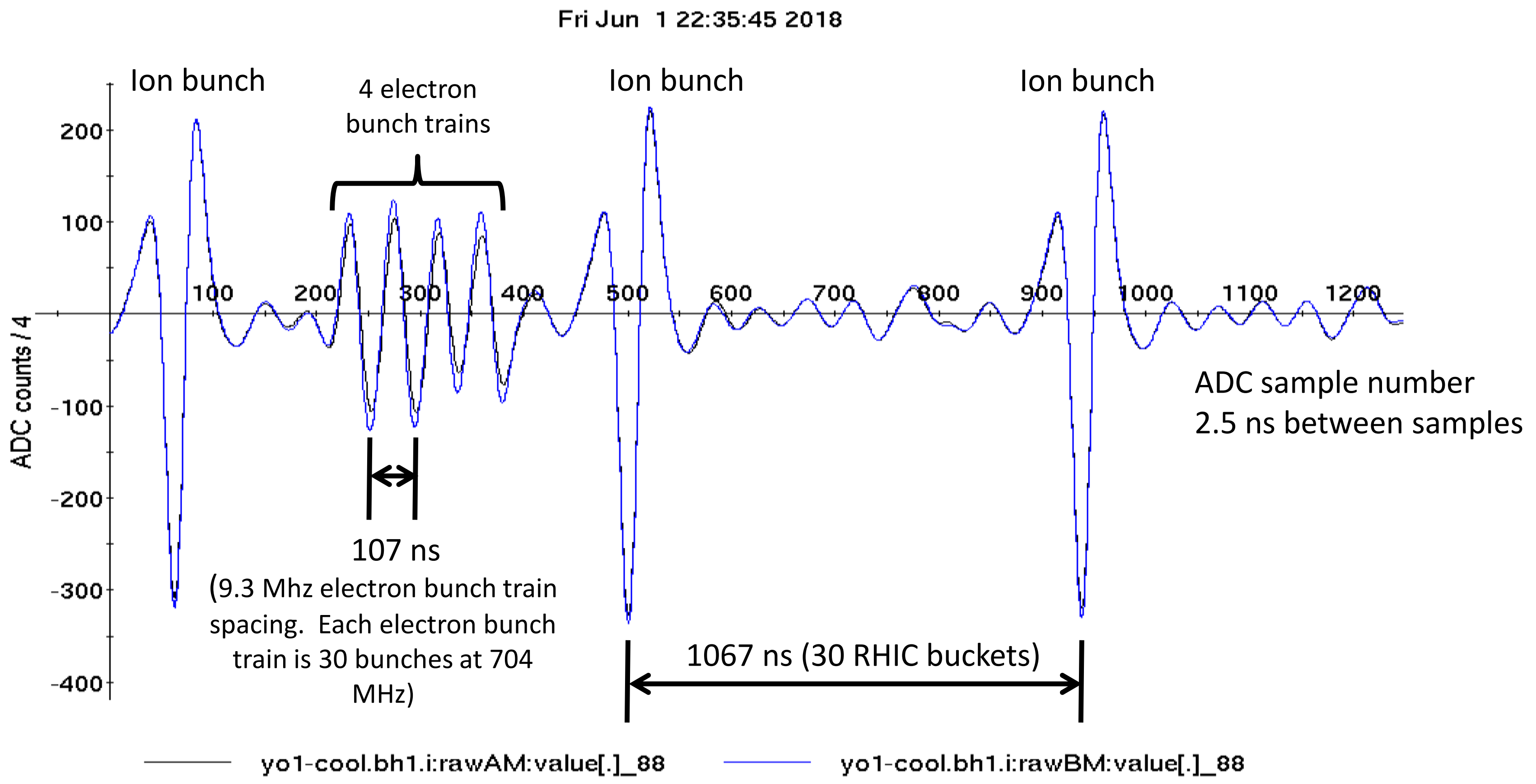
Raw ADC data for LEReC electron beam, measured with V301 (4 bunch trains shown)
Undersampled 700 MHz band-pass filtered signal, 2.5 nS between ADC samples

LEReC ion Beam w/ V301 Raw ADC data



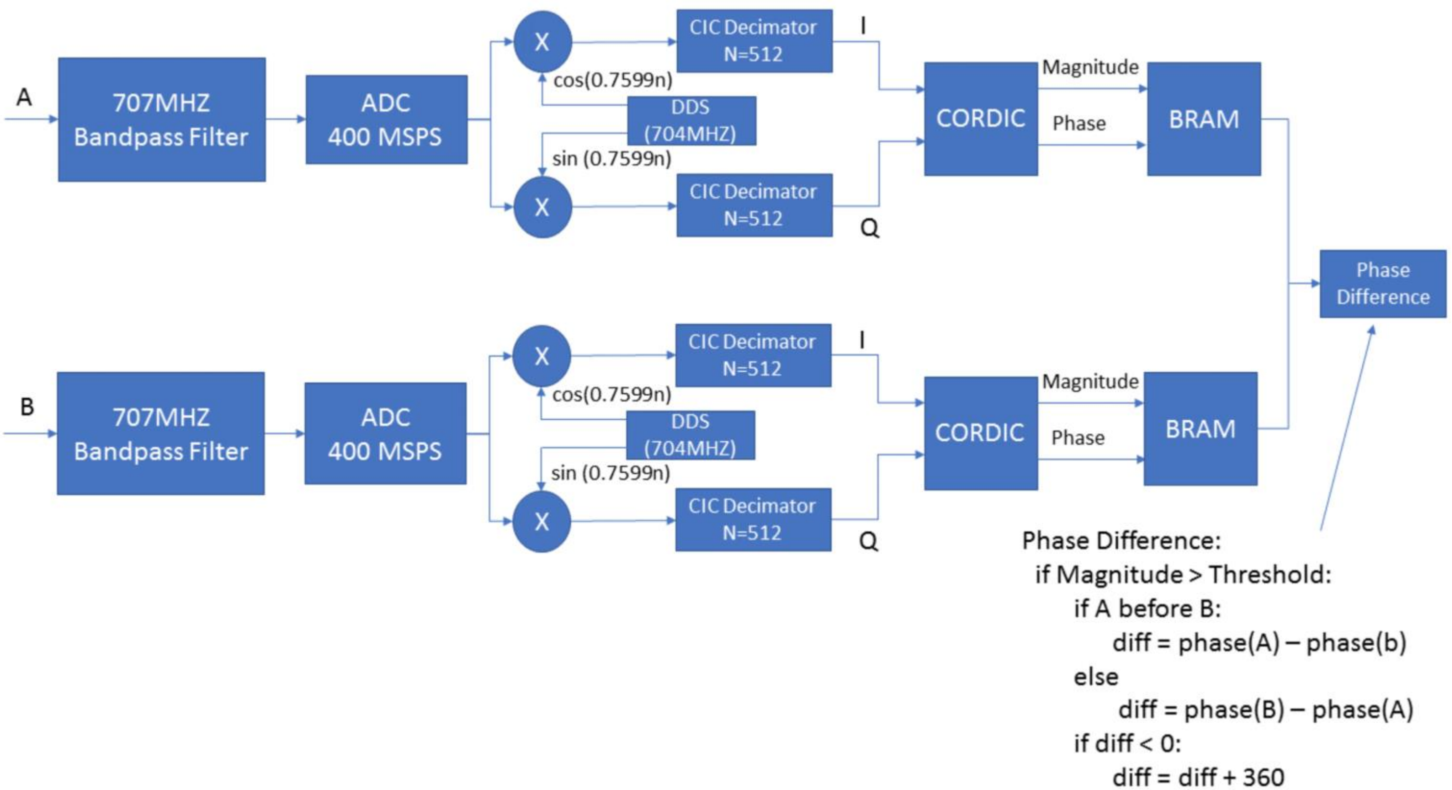
Raw ADC data for LEReC ion beam in cooling section, measured with V301 (8 bunches shown) Oversampled 39 MHz low-pass filtered signal, 2.5 nS between ADC samples. The 10 MHz low-pass diplexer output broadens the width of the signal.

LEReC ion and electron Beam w/ V301 Raw ADC data



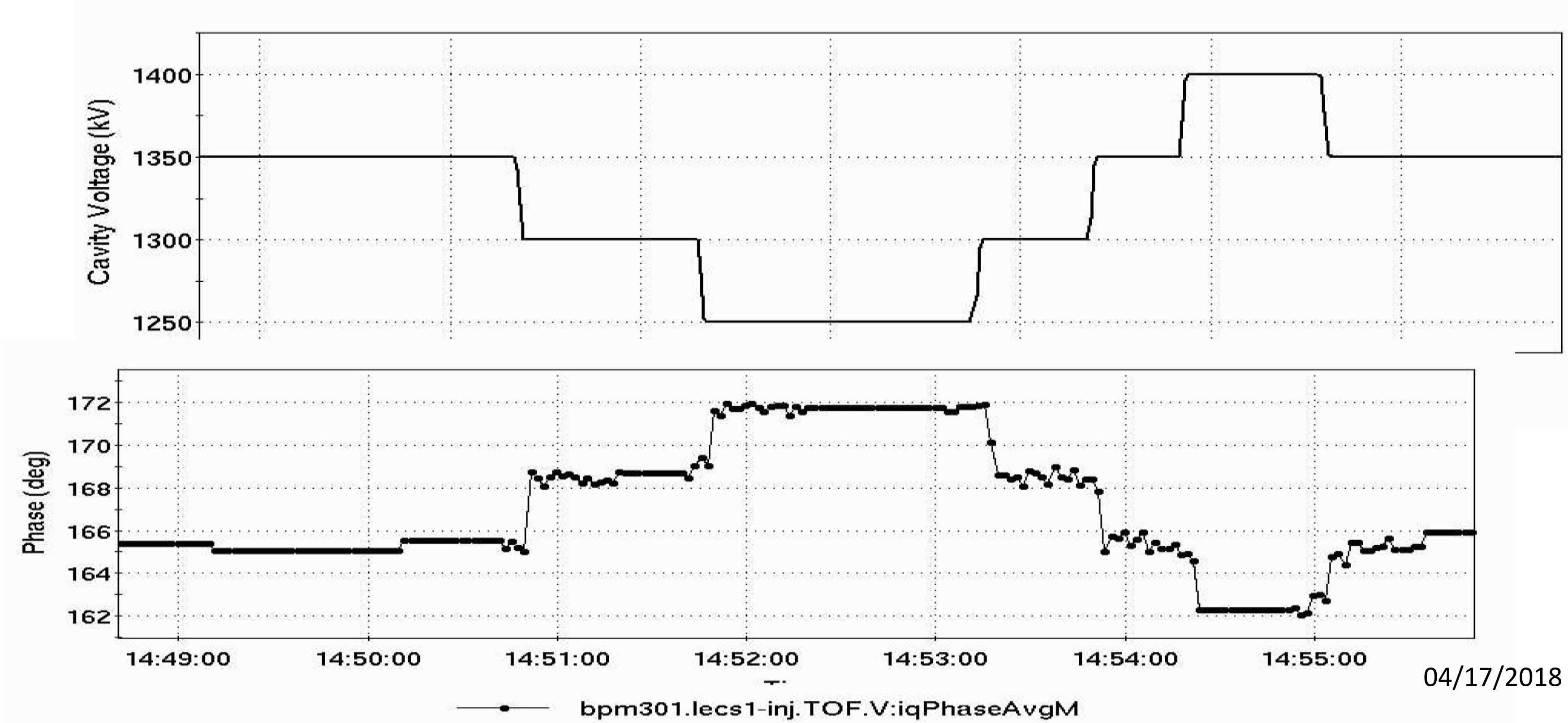
Raw ADC sample for LEReC ion beam and electron beam in cooling section, measured with V301 39 MHz low-pass filtered signal, 2.5 nS between ADC samples. A 500 kHz digital high pass filter is included in the gate array code to filter out low frequency noise.

LEReC Time-of-Flight w/ V301 electrons



Block diagram of gate array code to compute phase difference between 2 button signals (from 2 different BPM locations)

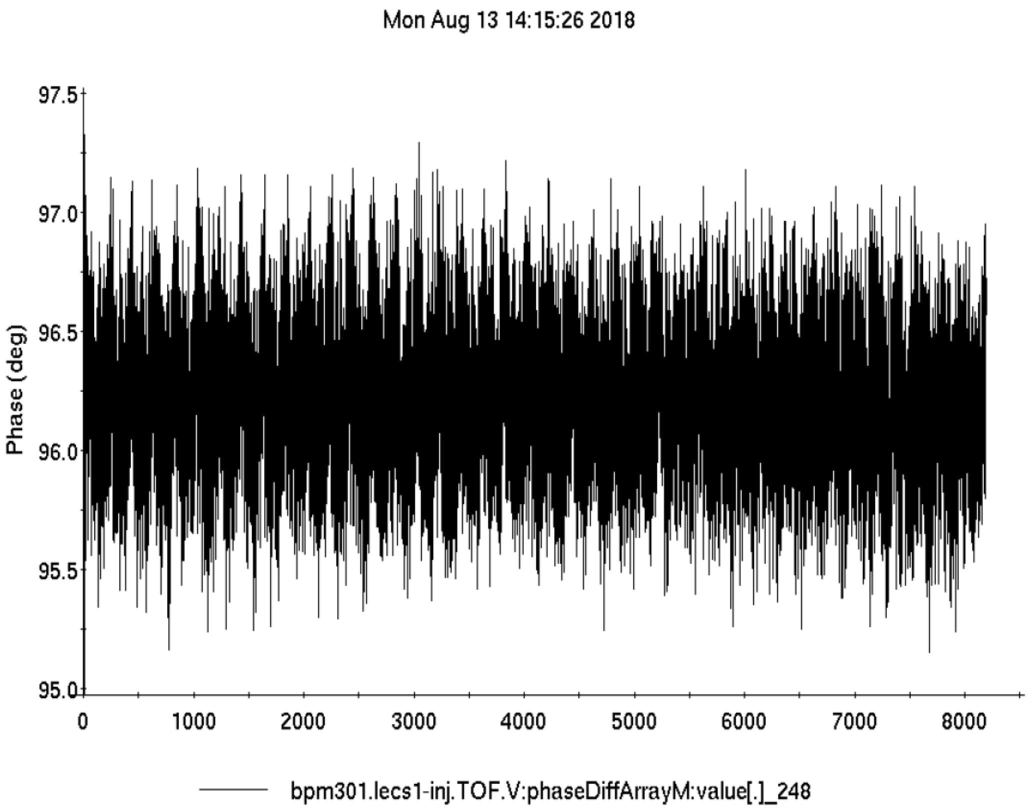
LEReC Time-of-Flight w/ V301 electrons



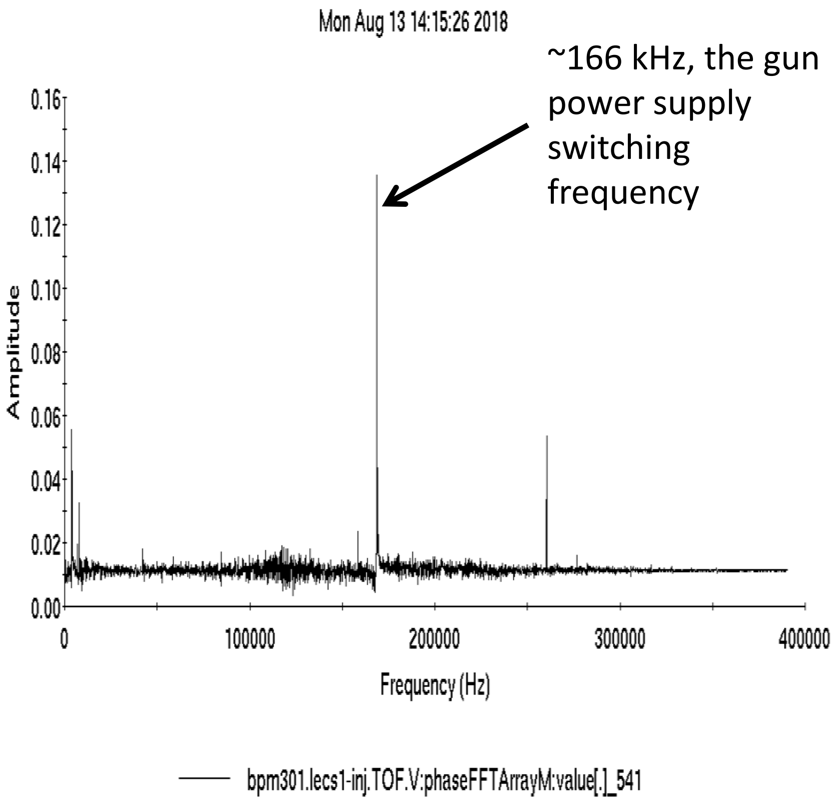
04/17/2018

Phase measurement from V301 correlates very well with RF cavity voltage variations. Note: Lower cavity voltage decreases beam energy which translates to longer beam travel time and therefore larger phase difference, so decreasing the cavity voltage increases the phase.

LEReC Time-of-Flight w/ V301 electrons



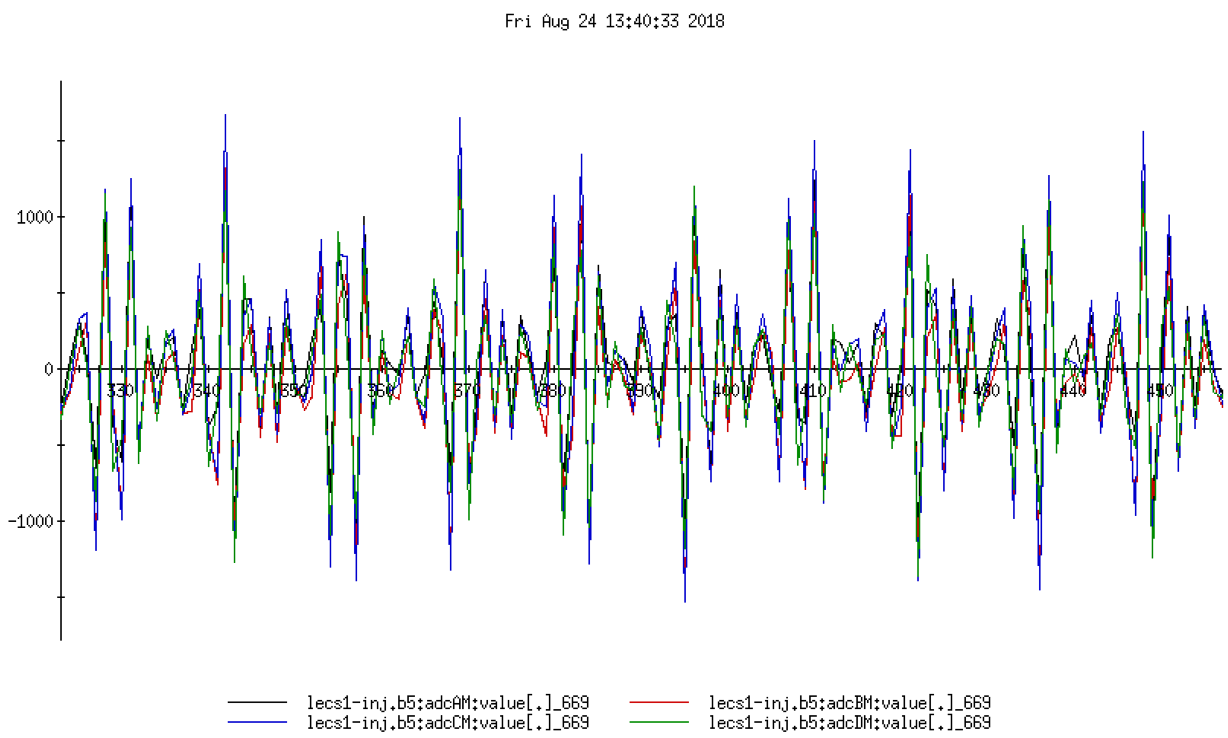
Phase data showing peak-to-peak variations of about 2 degrees.
1 deg = 1/700MHz /360 = ~4ps



FFT of phase data

V301 configured with 707 MHz bandpass filter. Button signals from 2 different BPMs are connected to one V301 module for dedicated phase measurement.

LEReC electron beam w/ Libera Brilliance Raw ADC data

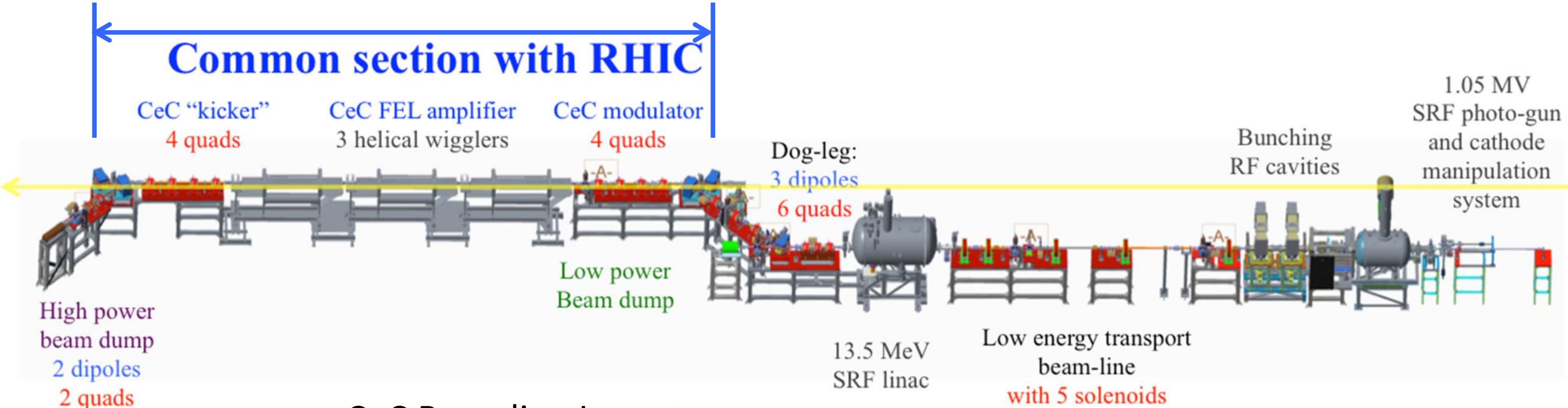


Raw electron ADC data from Libera Brilliance (8ns between ADC samples)

Libera Platform B for CeC

(Coherent electron Cooling Proof of principle)

electrons and Ions

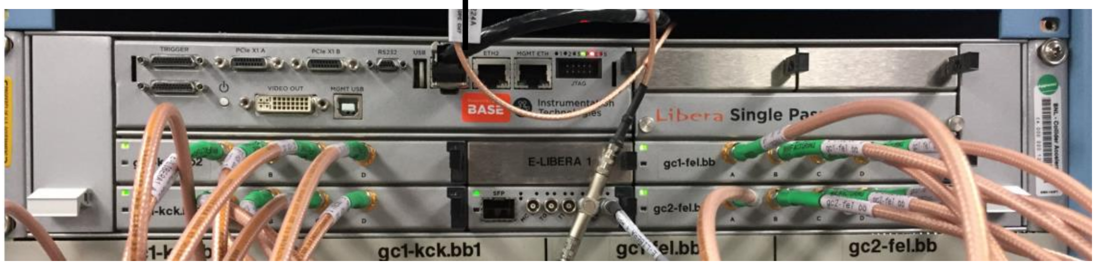


CeC Beamline Layout

CeC BPM electronics

Ethernet

Libera Platform B
One chassis supports
up to 4 BPMS



BPM button cables

RF clock and trigger

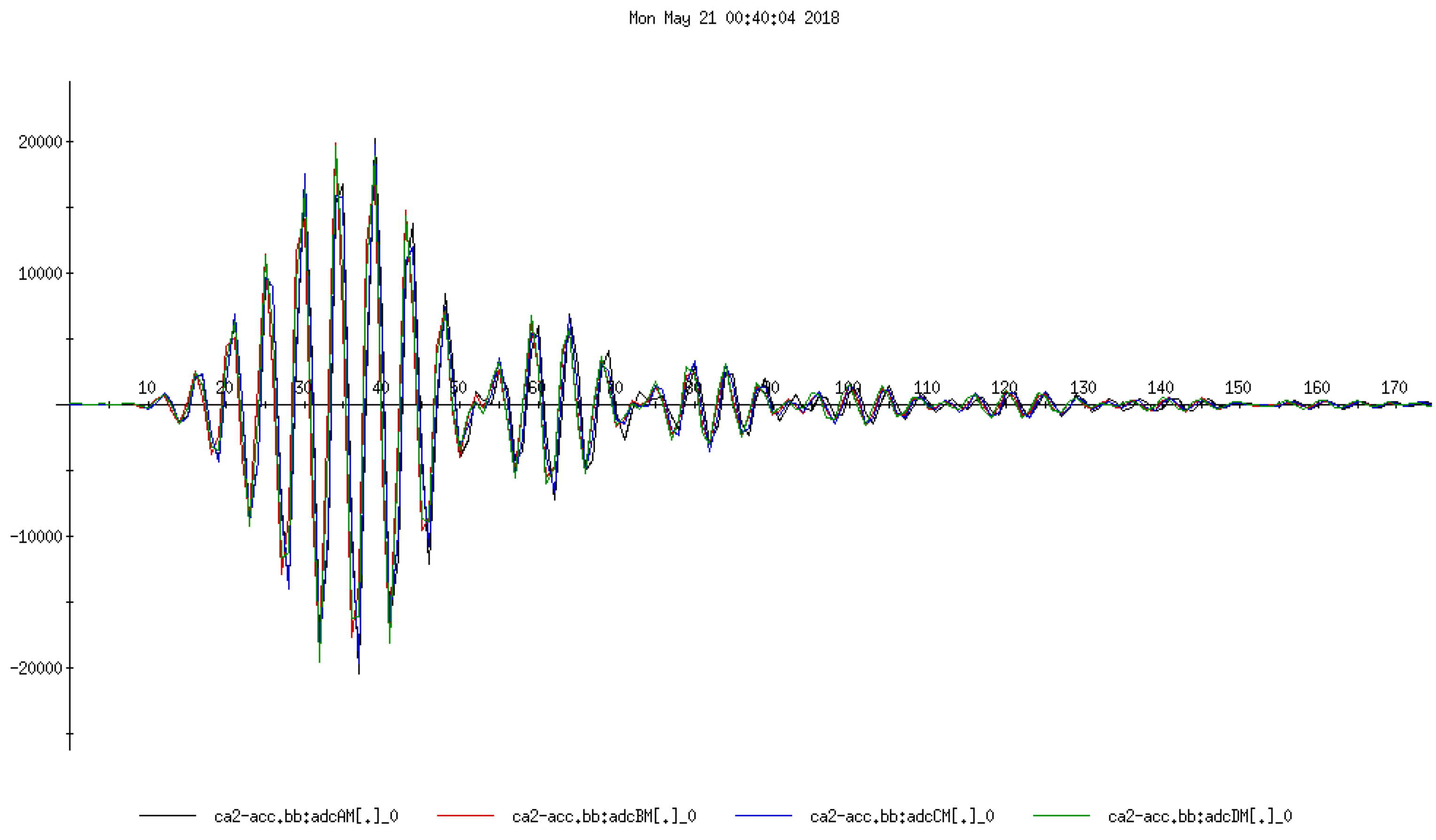
BPM button cables

For Electrons: 500 MHz band-pass filter

For Ions: 9 MHz band-pass filter

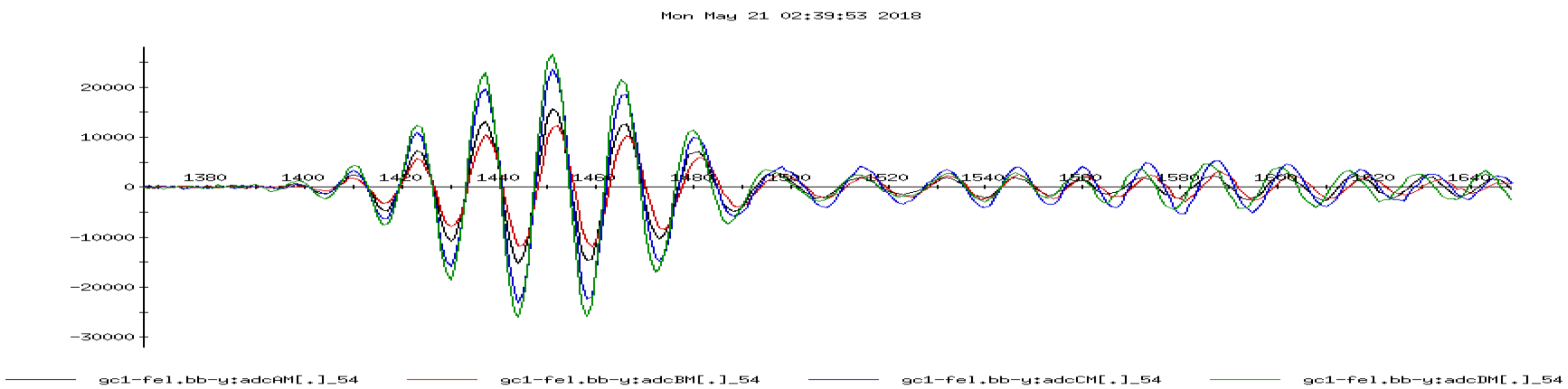
CeC BPM Rack

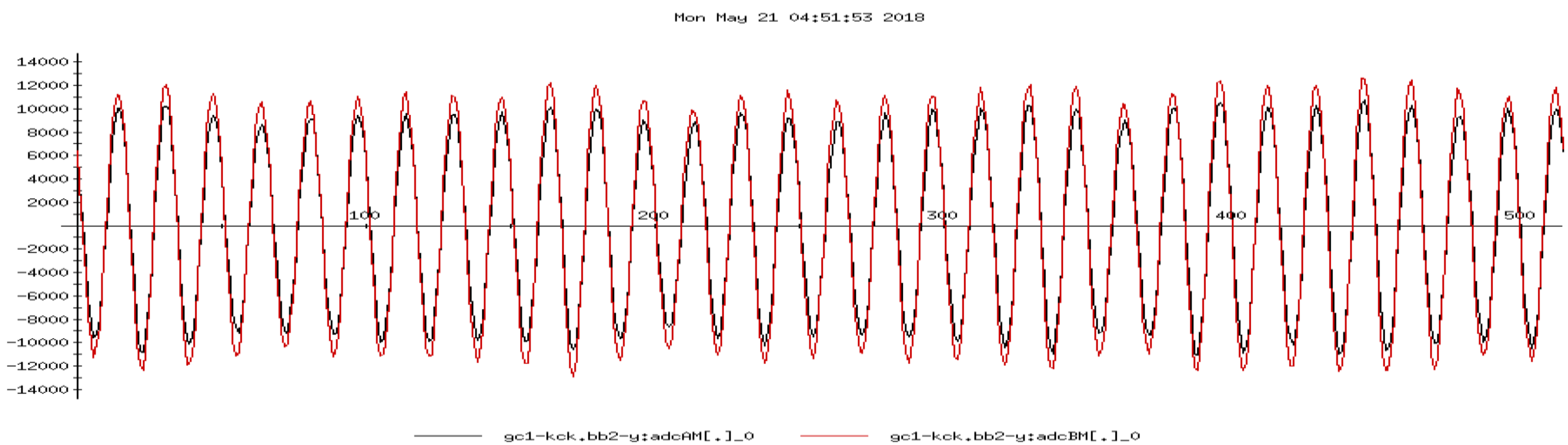
CeC electron Beam w/ Libera Platform B



Raw ADC sample for single CeC electron bunch, measured with Libera Platform B
Under-sampled 500 MHz band-pass filtered signal

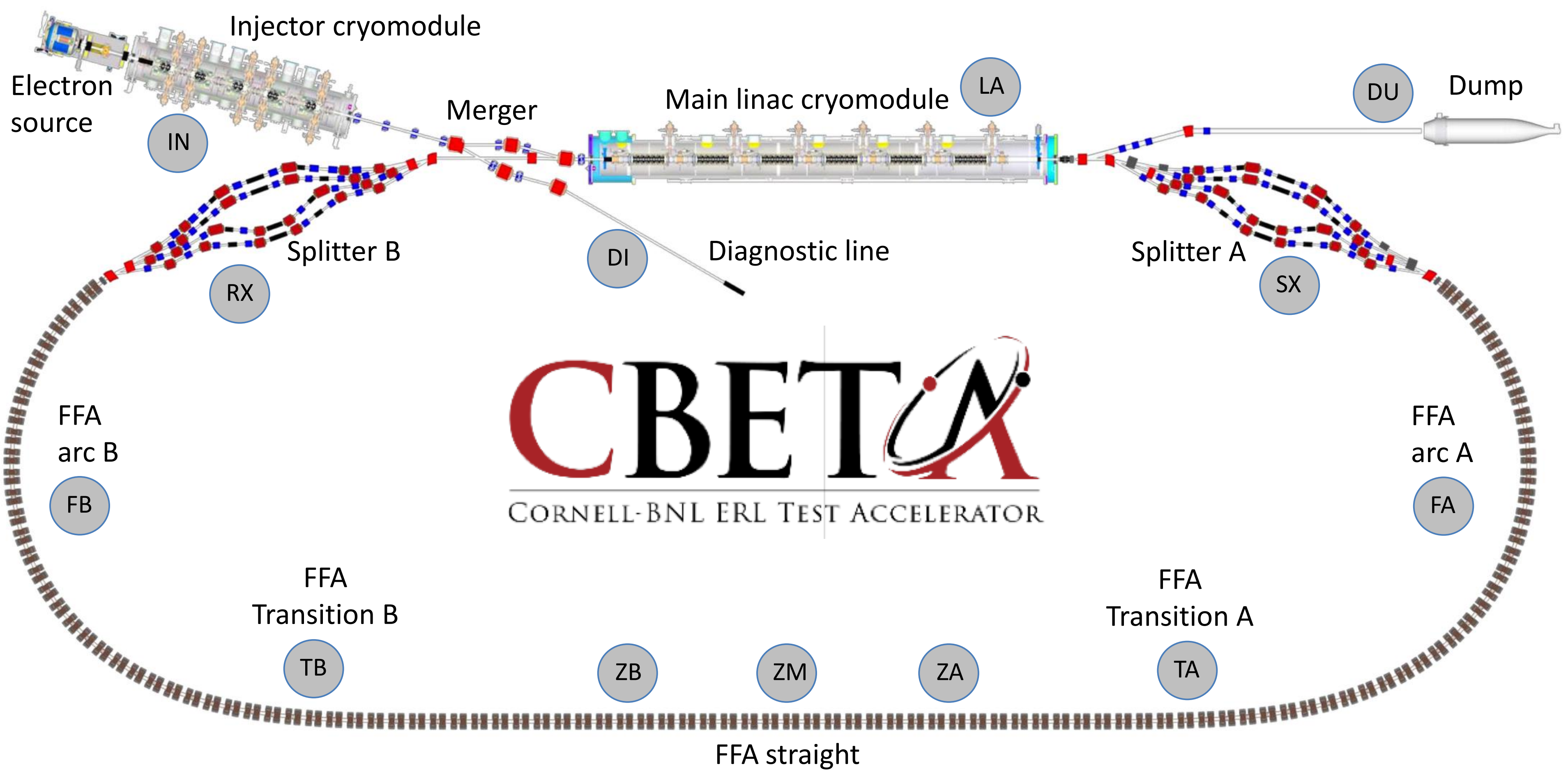
CeC ion Beam w/ Libera Platform B





Raw ADC sample for single CeC ion bunch (top) and many ion bunches (bottom)
Measured with Libera Platform B
Over-sampled 9 MHz band-pass filtered signal

CBETA Machine Layout
BNL and Cornell University Collaboration



CBETA bunch pattern

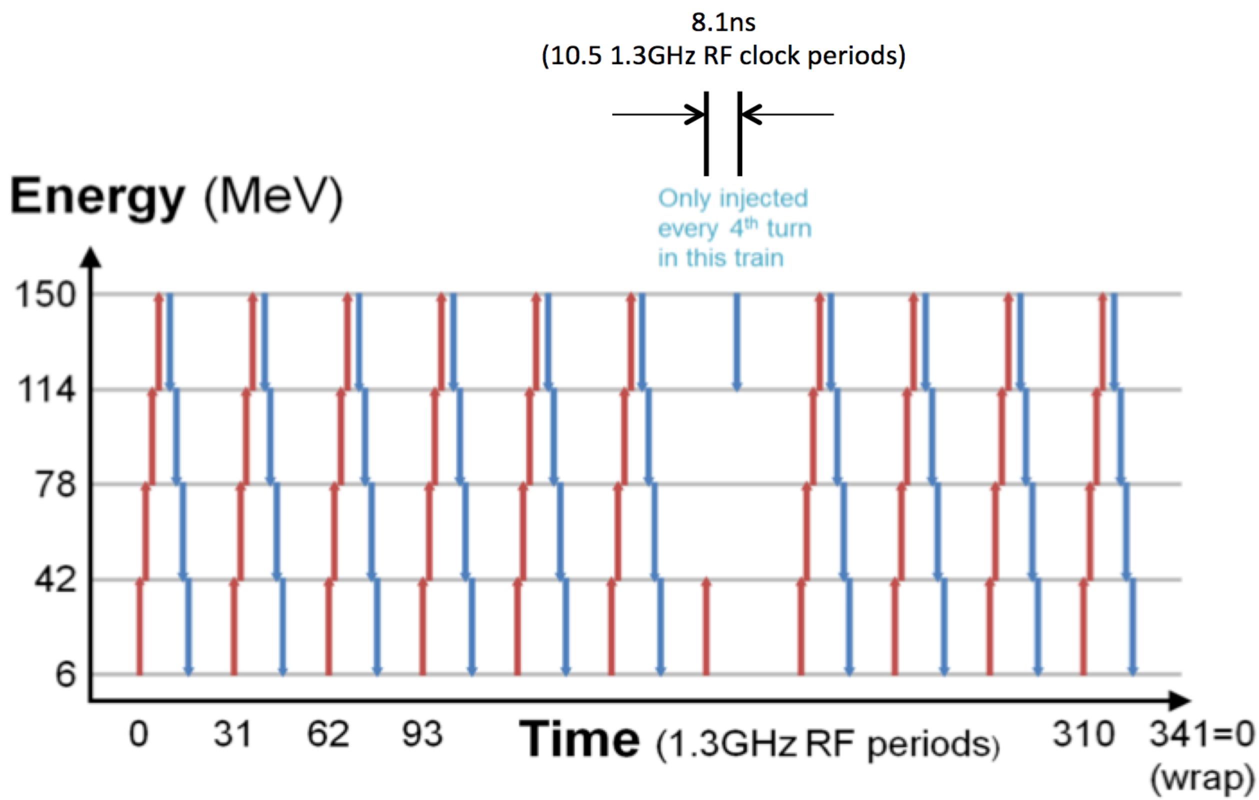


Figure 2.8.1: Bunch pattern produced in the eRHIC-like mode that has a circumference of $h = 343$ RF wavelengths but a time periodicity of 341 RF periods.

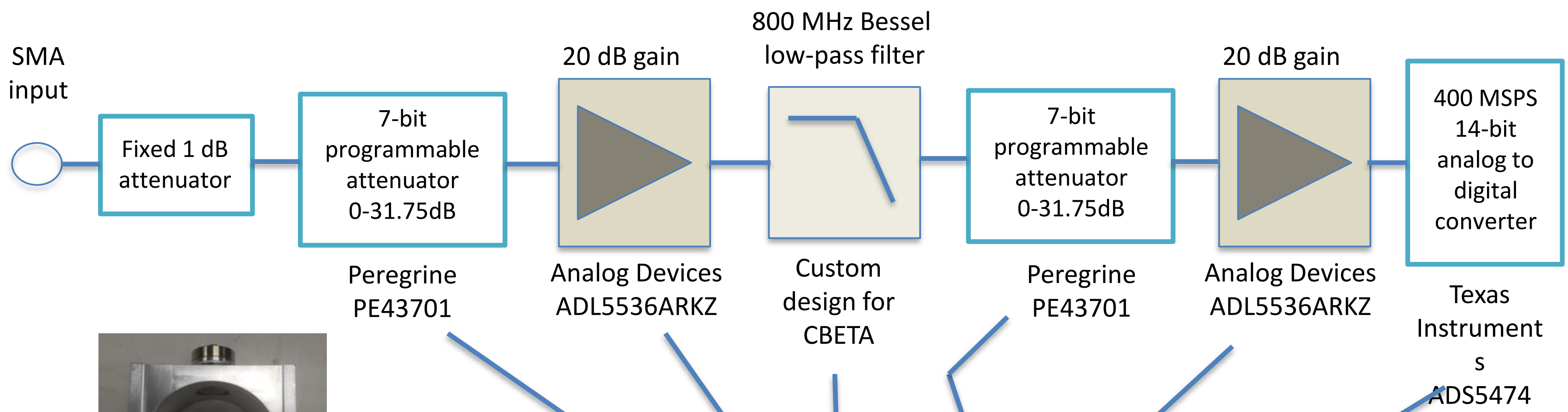
Up to 8 different energies (4 accelerating, 4 decelerating) must be independently measured

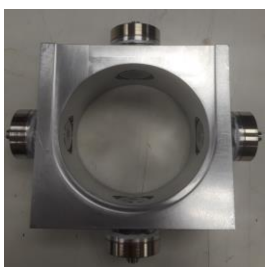
Figure from CBETA design report

V301 for CBETA (electrons)

- Single sample is taken on the peak of the bunch
- Developed custom 800 MHz Bessel filter
- Measuring up to 8 different energies at each BPM is required
- Each energy requires different timing setup
- Mixer chassis has been developed for several dedicated modules to provide phase measurements for bunch arrival monitoring
- Developed EPICS IOC for this application

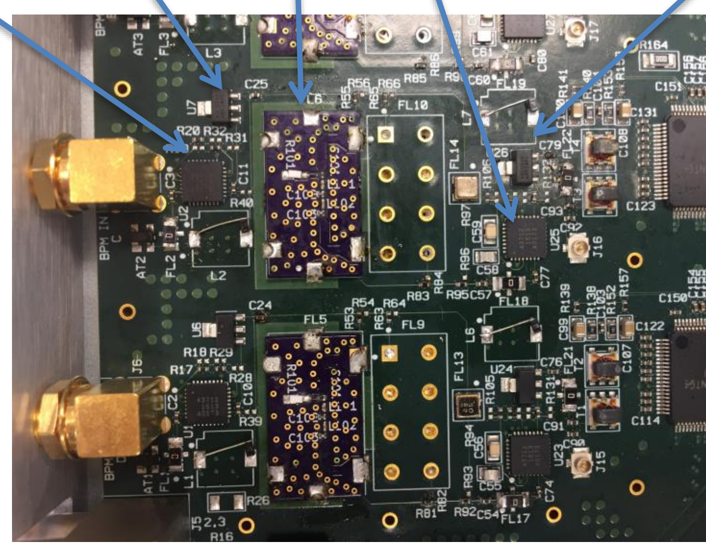
V301 BPM
CBETA RF Chain Block Diagram
(1 of 4 channels shown)





Round FFA loop button chamber

Oval splitter line button chamber



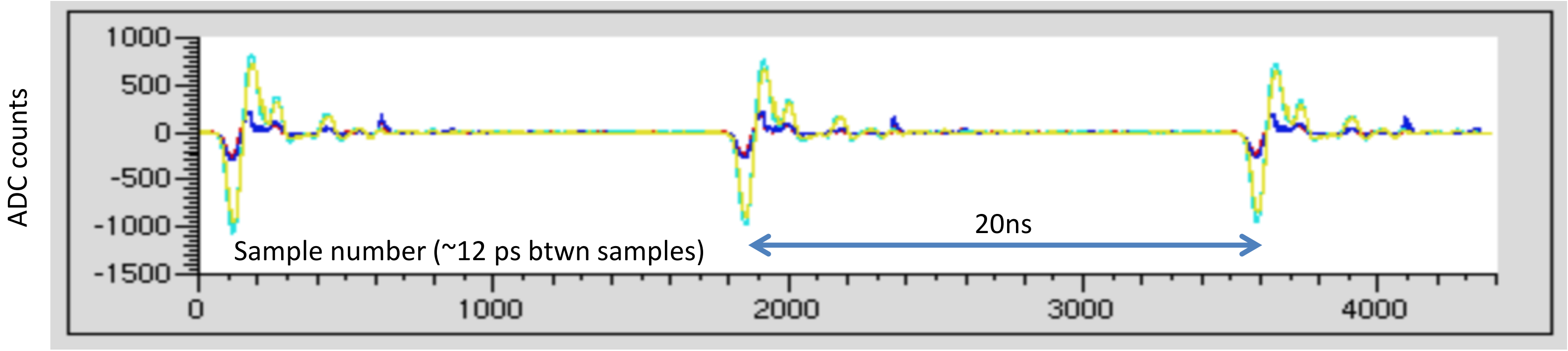
Fully populated CBETA BPM VME chassis

Recent tests have confirmed that up to 17 V301 BPM modules can be installed in each VME chassis, driven by 1 clock distribution board.

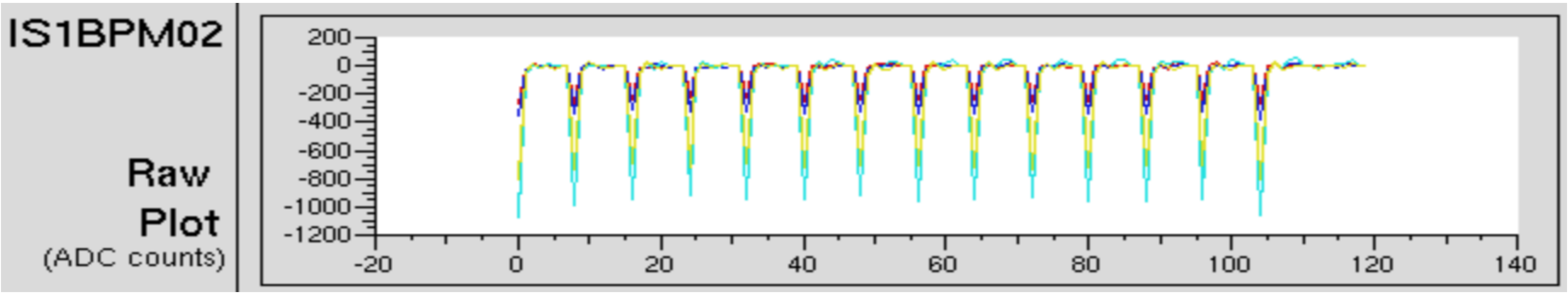
Total current on +5V backplane supply with 16 V301 modules is ~80 A.

Weiner VME Chassis supports up to 115 A for +5V

CBETA profile scans for configuring ADC clock timing to peak



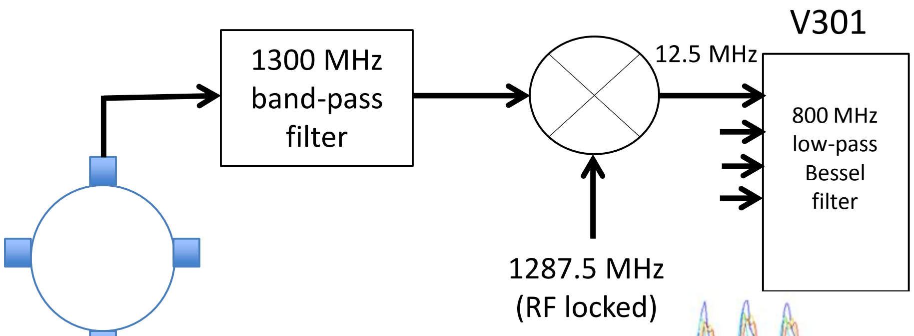
Splitter 1 BPM 04 beam profile scan during fractional arc test, April-May 2018. Each sample is an average of 10 samples (programmable). ADC clock is then stepped in about 12ps increments to fill in data between 2.5 ns ADC clock periods.



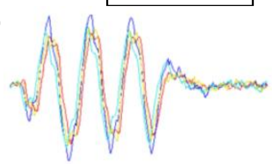
Splitter 1 BPM 02 raw ADC data for beam during fractional arc test, April-May 2018. Time between samples is one ADC clock, 2.5 ns. The time between bunches is 20 ns (50 MHz bunch rate), so a bunch is detected every 8 ADC samples.

V301 for CBETA (electrons) Bunch Arrival Monitors (BAMs)

CBETA RF clock: 1300 MHz



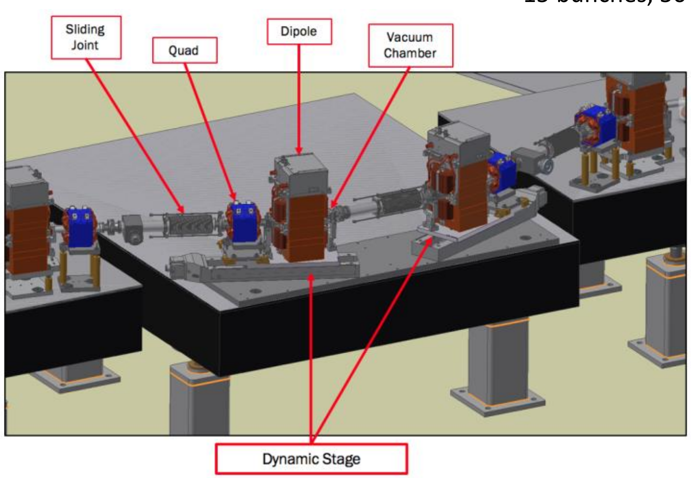
BAM mixer block diagram
(1 of 4 channels shown)



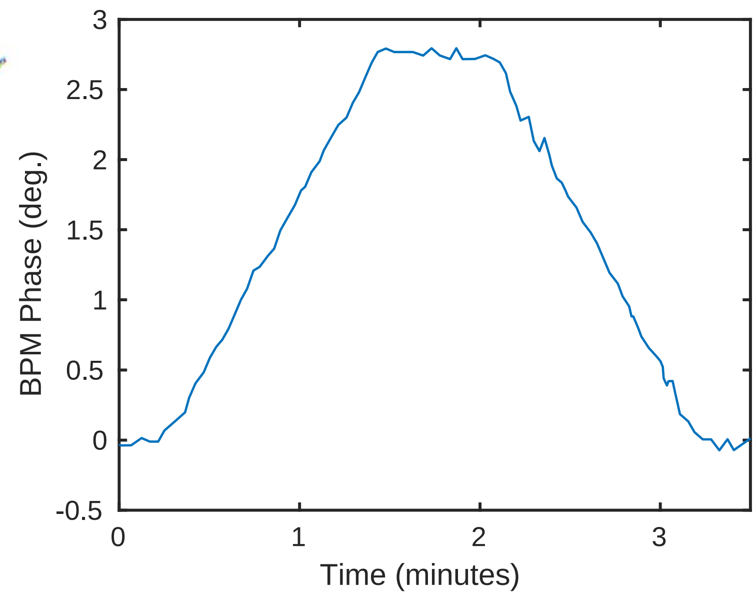
Measured 12.5 MHz signal
15 bunches, 50 MHz spacing

Configuration tested during fractional arc test April-May, 2018

BAM measures phase and position



Splitter 1 path length adjustment stage



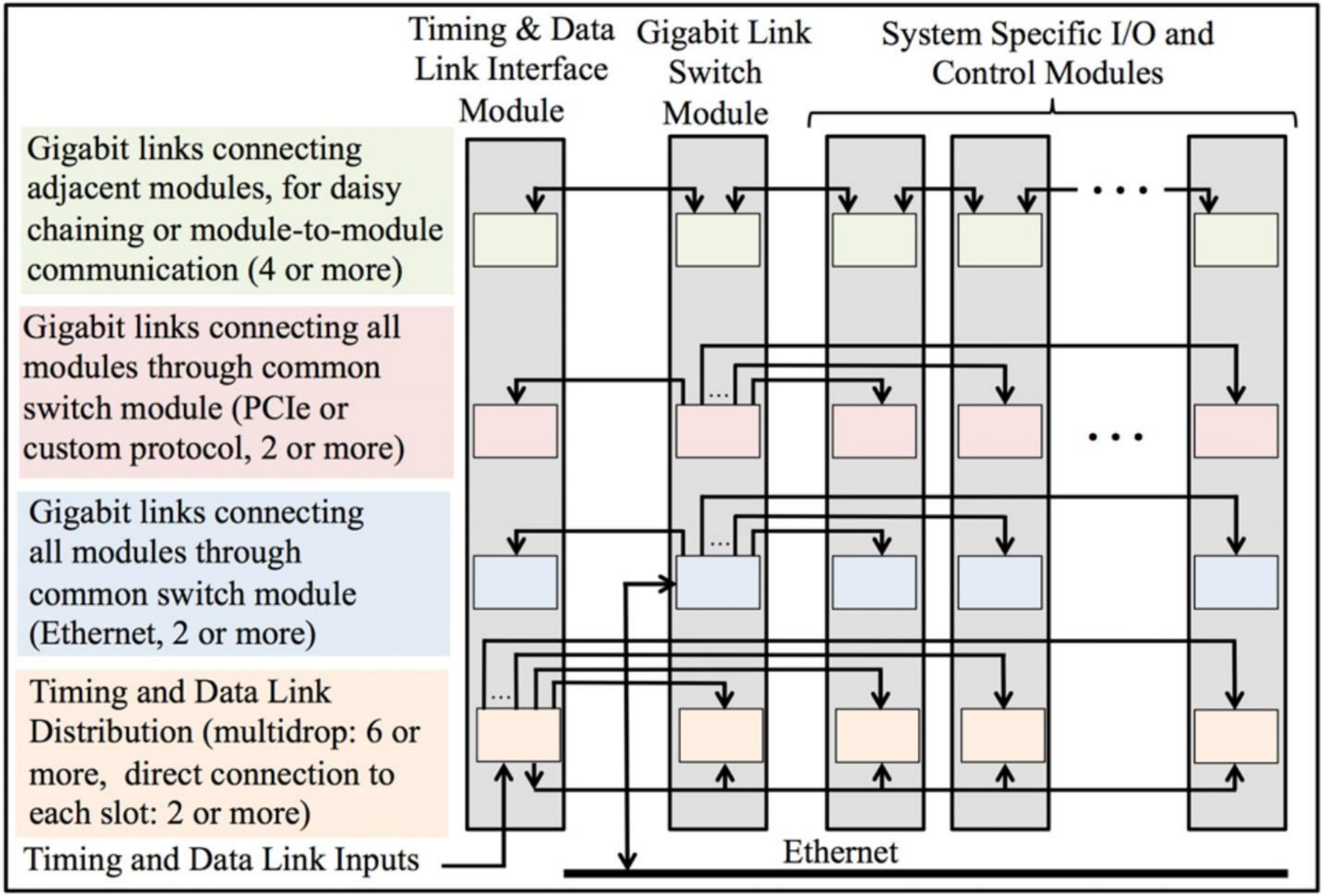
Beam arrival phase on S1 BPM 5 during a splitter stage movement forward and back of 1 cm

1 deg = 1/1300e6 /360 = ~ 2ps

The future – eRHIC electron-ion Collider

- Anticipate similar architecture to V301
- Modules housed in separate 1U chassis are not desirable
- uTCA is not our favorite – doesn't have quite the industrial robustness as VME or other industrial chassis and accommodates limited channels per chassis
- VME is not optimal – old technology, old parallel bus that will not be used
- The multi-module chassis approach is highly desirable for simplified serviceability. Specific chassis architecture has not yet been selected.
  - openVPX?, custom?, other?
  - Need capability to distribute timing signals across backplane

Draft chassis architecture for eRHIC



Draft design of inter-module communication for eRHIC BPMs and other control system modules

Summary

- Original RHIC BPM IFE system designed in 1990s is still in use
- V301 BPM module has recently been designed in-house and supports a wide range of applications
  - Ions, electrons
  - Variety of acquisition techniques – oversampling, undersampling, single sample on bunch peak
  - Bunch-by-bunch, turn-by-turn, average orbit, coherence
  - Phase measurements
  - Machine protection
  - Multiple beams
- Libera BPMs have been integrated for some applications
- eRHIC is in our future (hopefully)

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[4] K. Vetter, et. al., NSLS-II Beam Position Monitor, Beam Instrumentation Workshop, Santa Fe, New Mexico, 2010

[5] R. Michnoff, et. al., The Brookhaven Linac Isotope Production (BLIP) Facility Raster Scanning System First Year Operation with Beam, International Beam Instrumentation Conference, Barcelona, Spain, September 2016

[6] Collider-Accelerator Department, BNL, Low Energy RHIC Electron Cooler (LEReC), White Paper, September 19, 2013

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