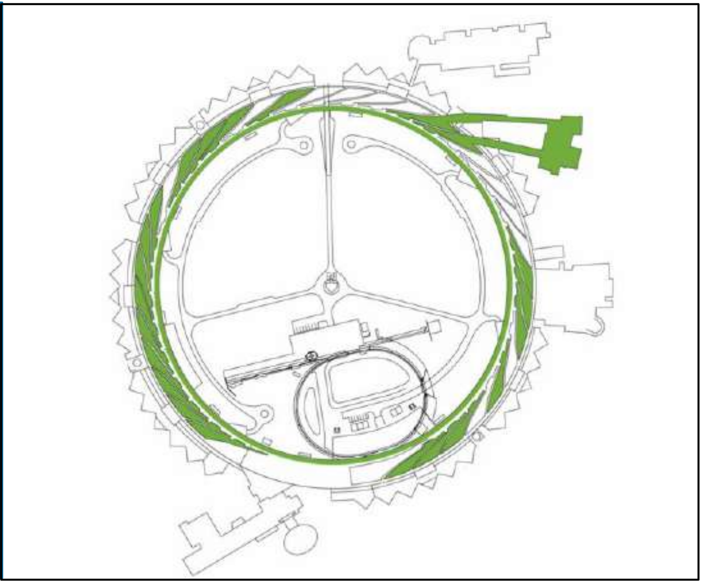
Comparison of Instrumentation Technologies Libera LLRF and APS Operations Beam-RF Phase Measurements



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Libera Workshop 2023

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Outline

- Introduction: APS Operations Phase Detector Circuit, Hardware and Controls
- Applications at the Advanced Photon Source (APS)
  - **Linac beam-rf phase controllaw**
  - Photocathode Gun (PCGun) laser-rf phase measurement
  - Beam tilt measurement in the APS Storage Ring (SR)
  - **Booster to Storage Ring (BTS) transport line arrival time measurement (APS-Upgrade)**
- Comparison of Libera LLRF and Operations Phase Detector Measurements
- Libera LLRF Setup in the APS Linac Gallery
- Experimental Results
- Summary
- Acknowledgements

Introduction: Phase Detector Circuit, Hardware and Controls

- APS phase detector system is based on a commercially available analog phase detector chip AD8302
- System operates at S-Band (2856 MHz) which is the linac rf frequency and has a resolution of a few ps
- Phase reference is obtained from an S-Band coupled signal as close to the beam as possible
- Beam signal is obtained from bpm striplines or buttons and is converted to an S-Band signal using a cavity filter
- Small signal bandwidth DC-30 MHz
- Systematic phase measurement errors depending on reference/test signal input and other factors

ANALOG DEVICES

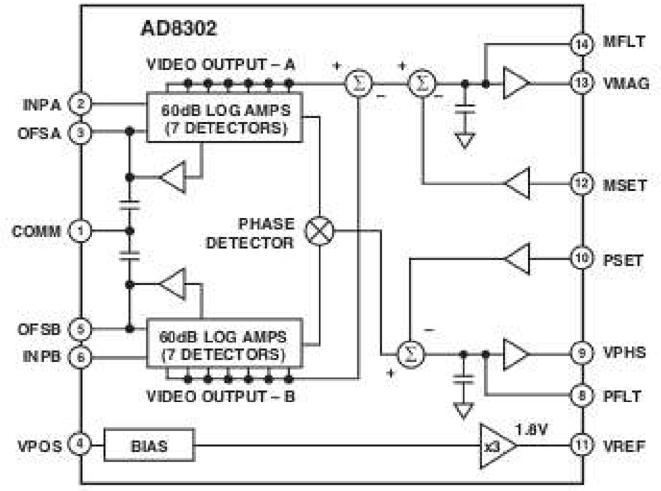
LF–2.7 GHz
RF/IF Gain and Phase Detector

AD8302

FEATURES
Measures Gain/Loss and Phase up to 2.7 GHz
Dual Demodulating Log Amps and Phase Detector
Input Range –60 dBm to 0 dBm in a 50 Ω System
Accurate Gain Measurement Scaling (30 mV/dB)
  Typical Nonlinearity < 0.5 dB
Accurate Phase Measurement Scaling (10 mV/Degree)
  Typical Nonlinearity < 1 Degree
Measurement/Controller/Level Comparator Modes
Operates from Supply Voltages of 2.7 V–5.5 V
Stable 1.8 V Reference Voltage Output
Small Signal Envelope Bandwidth from DC to 30 MHz

APPLICATIONS
RF/IF PA Linearization
Precise RF Power Control
Remote System Monitoring and Diagnostics
Return Loss/VSWR Measurements
Log Ratio Function for AC Signals

FUNCTIONAL BLOCK DIAGRAM

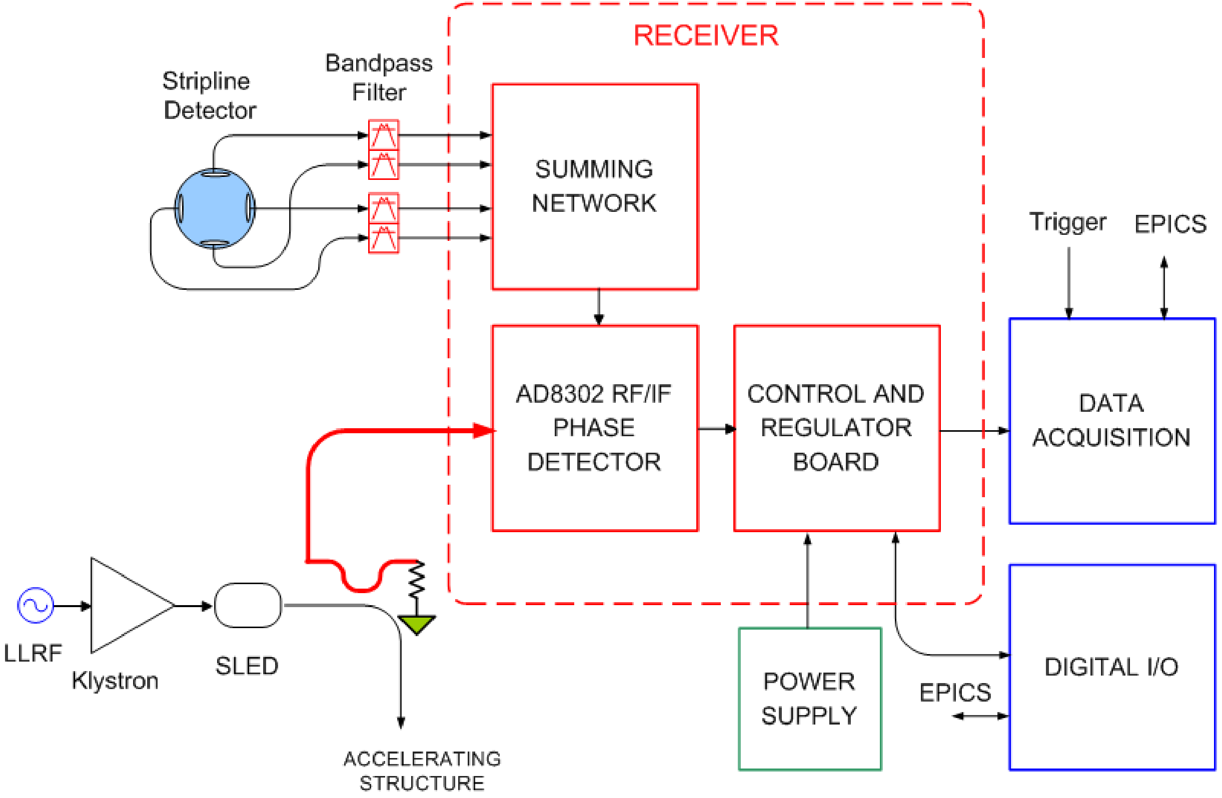


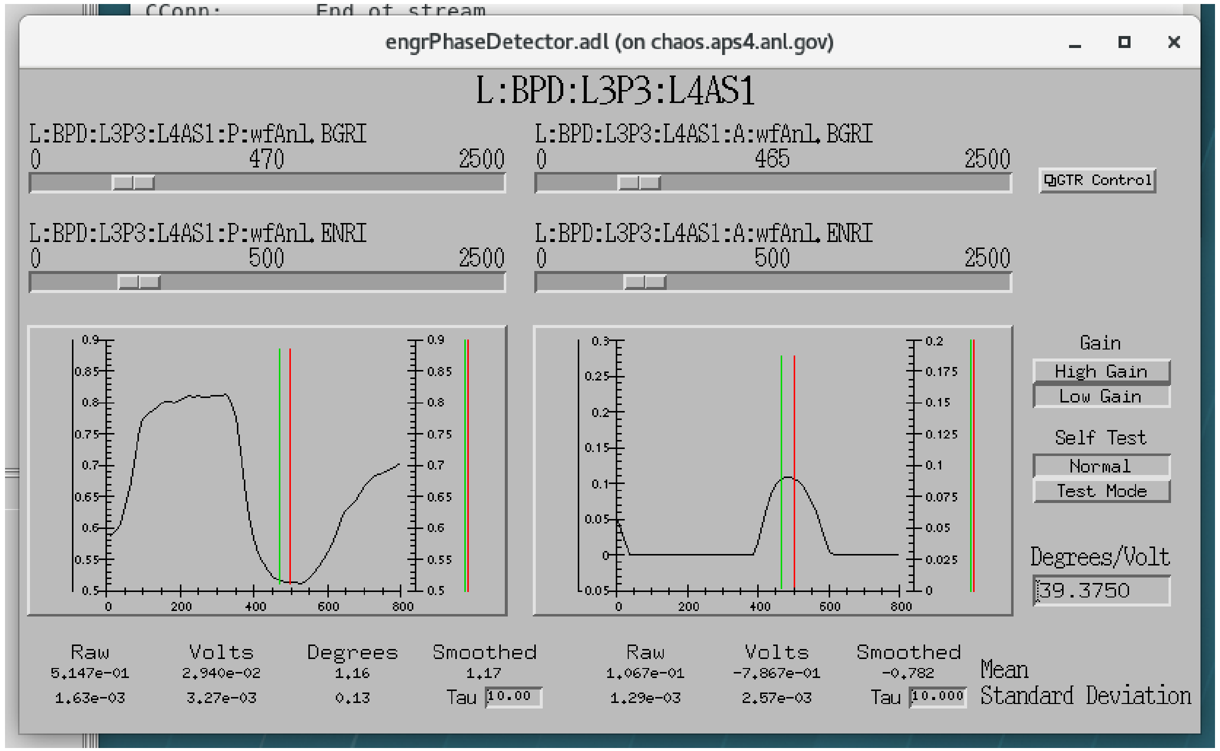
PRODUCT DESCRIPTION
The AD8302 is a fully integrated system for measuring gain/loss and phase in numerous receive, transmit, and instrumentation applications. It requires few external components and a single supply of 2.7 V–5.5 V. The ac-coupled input signals can range from –60 dBm to 0 dBm in a 50 Ω system, from low frequencies up to 2.7 GHz. The outputs provide an accurate measurement of either gain or loss over a ±30 dB range scaled to 30 mV/dB, and of phase over a 0°–180° range scaled to 10 mV/degree.

The signal inputs are single-ended, allowing them to be matched and connected directly to a directional coupler. Their input impedance is nominally 3 kΩ at low frequencies.

The AD8302 includes a phase detector of the multiplier type, but with precise phase balance driven by the fully limited signals appearing at the outputs of the two logarithmic amplifiers. Thus, the phase accuracy measurement is independent of signal level over a wide range.

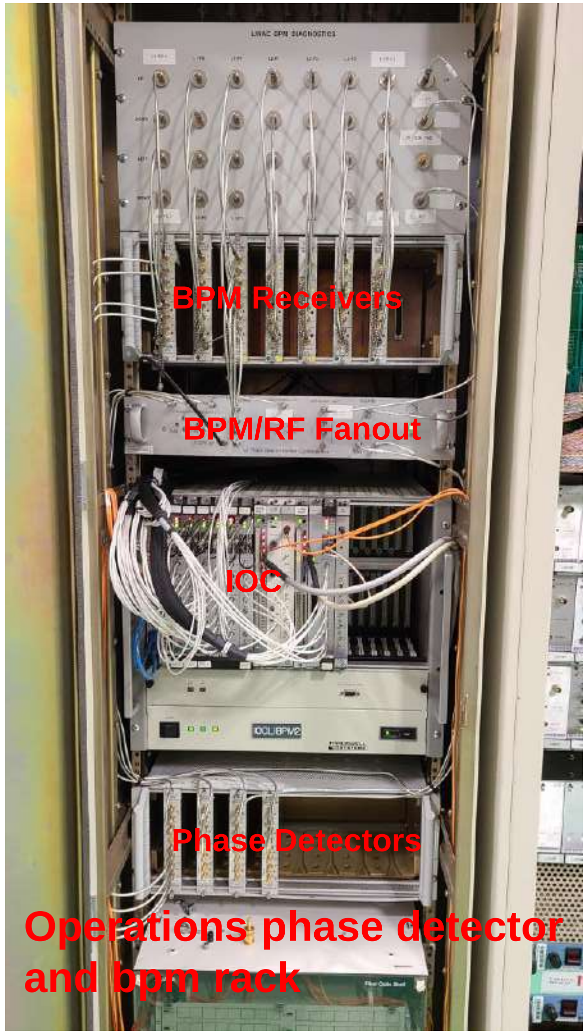
Introduction: Phase Detector and Circuit, Hardware and Controls



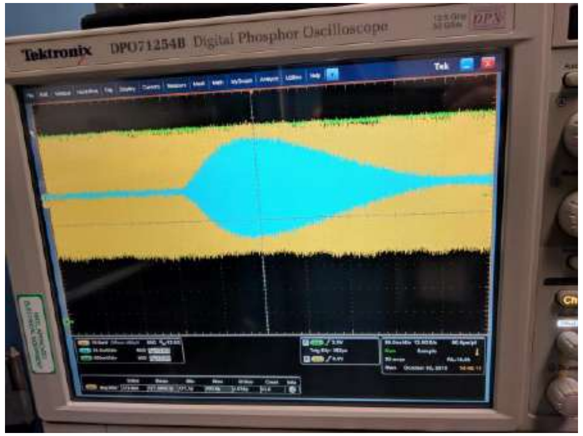


- APS phase detector system is based on a commercially available analog phase detector chip AD8302
- RF reference power of -20 dBm, bpm S-band signal power needs to be between -10 to -30 dBm

Introduction: Phase Detector and Circuit, Hardware and Controls



S-Band Cavity Bandpass Filter, 4 pole 3 MHz BW

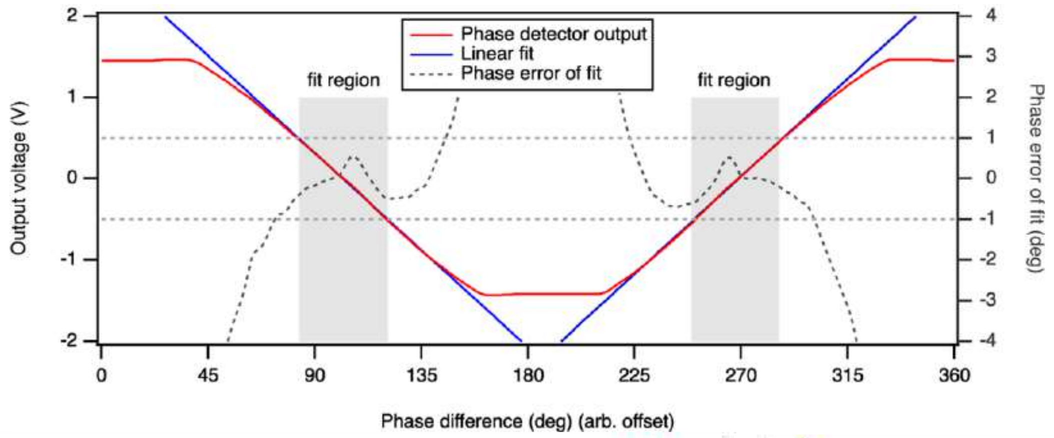


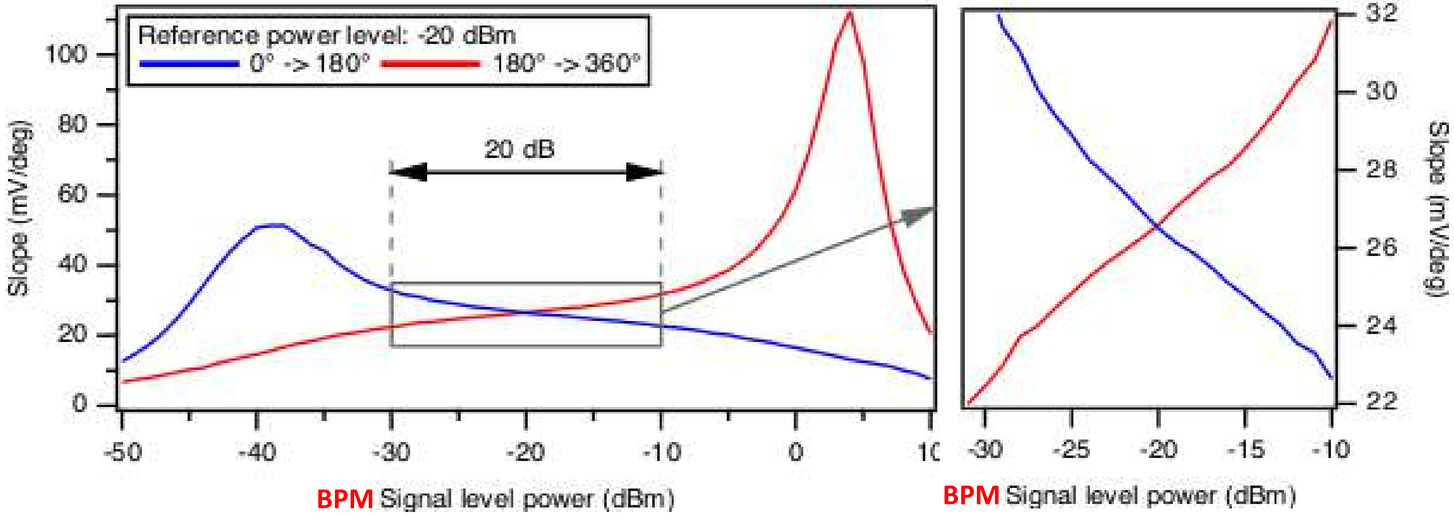
S-Band BPM Signal after S-Band Filter (Blue) and RF Reference Signal (Yellow)

- APS phase detector system hardware in linac

Introduction: Phase Detector and Circuit, Hardware and Controls

- Typical performance of the AD8302 phase detector for a The reference signal at -20 dBm and a beam signal which varies from -10 to -30 dBm (corresponds to roughly 0.3 nC to 5 nC)
- The phase detector slope varies by +/- 15 %
- At S-Band (2856 MHz) 1 degree of phase ~ 1 ps arrival time



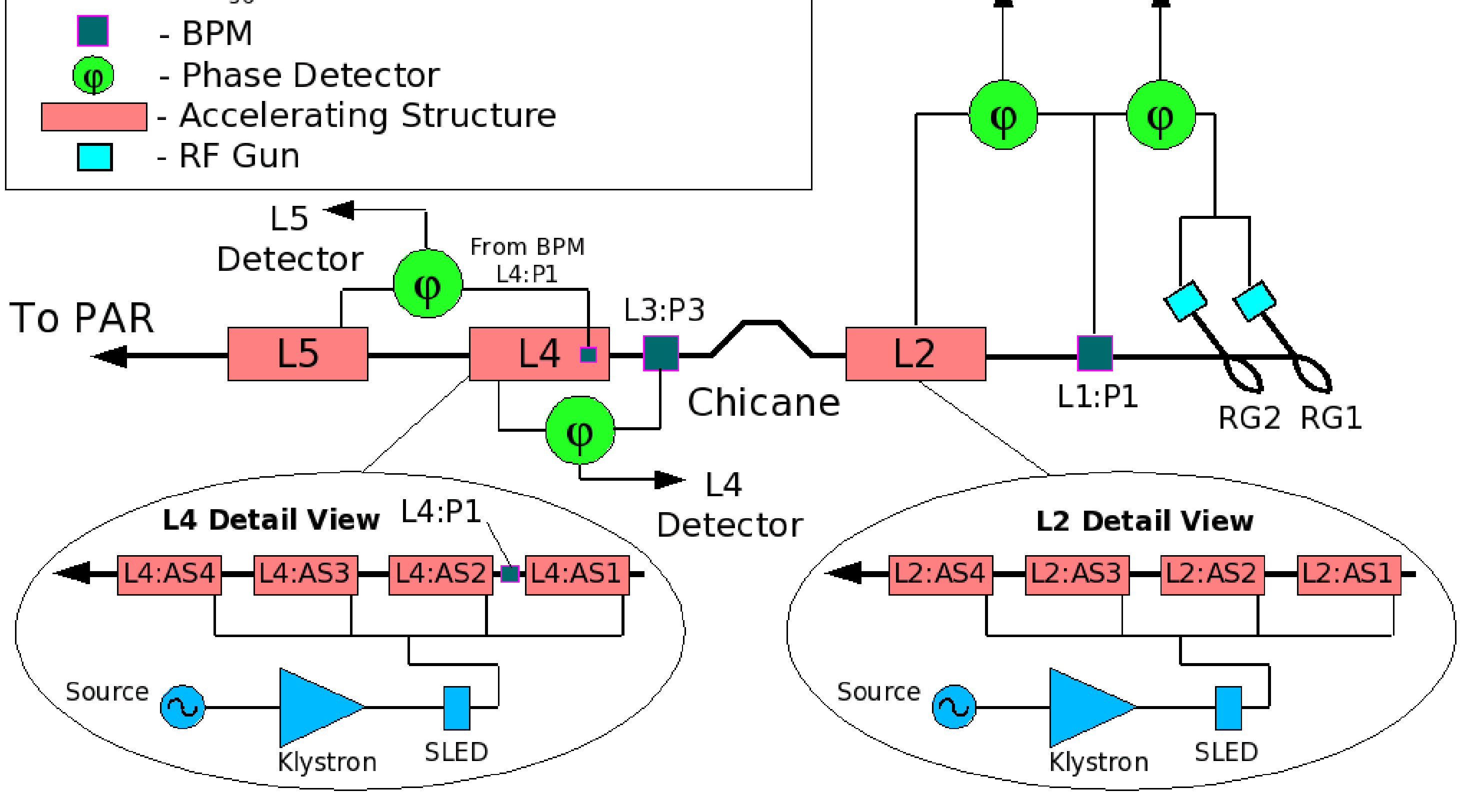


Applications: Linac Beam-RF Phase Controllaw[1]

- APS linac phase detector system has been in use since 2006
- Used to keep beam on crest from the rf guns though the accelerating structures
- Phase reference is obtained from an S-Band coupler on waveguide at each gun or linac accelerating structure
- Phase reference is obtained as close to the beamline as possible or downstream of any rf drift sources
- Beam signal is converted to an S-Band signal for comparison to the reference using a cavity filter
- BPM used is upstream of phase detector accelerating structure rf reference

LINAC Parameters:

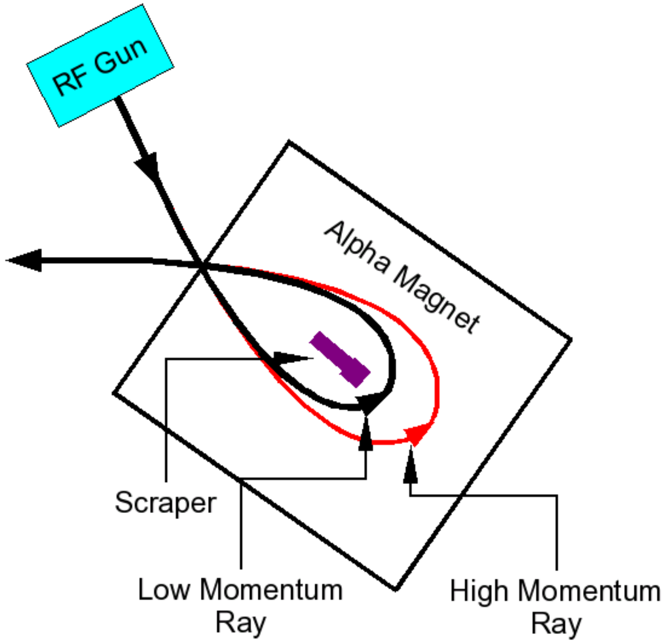
Pulse Rate: 2 - 12 Hz
RF Frequency: 2856 MHz
Extracted Charge per pulse: 0.3 - 1 nC
Extraction Energy: 325 - 450 MeV
RF Gun Macropulse Length: 11 - 40 ns
Chicane R_{56}: -65 mm



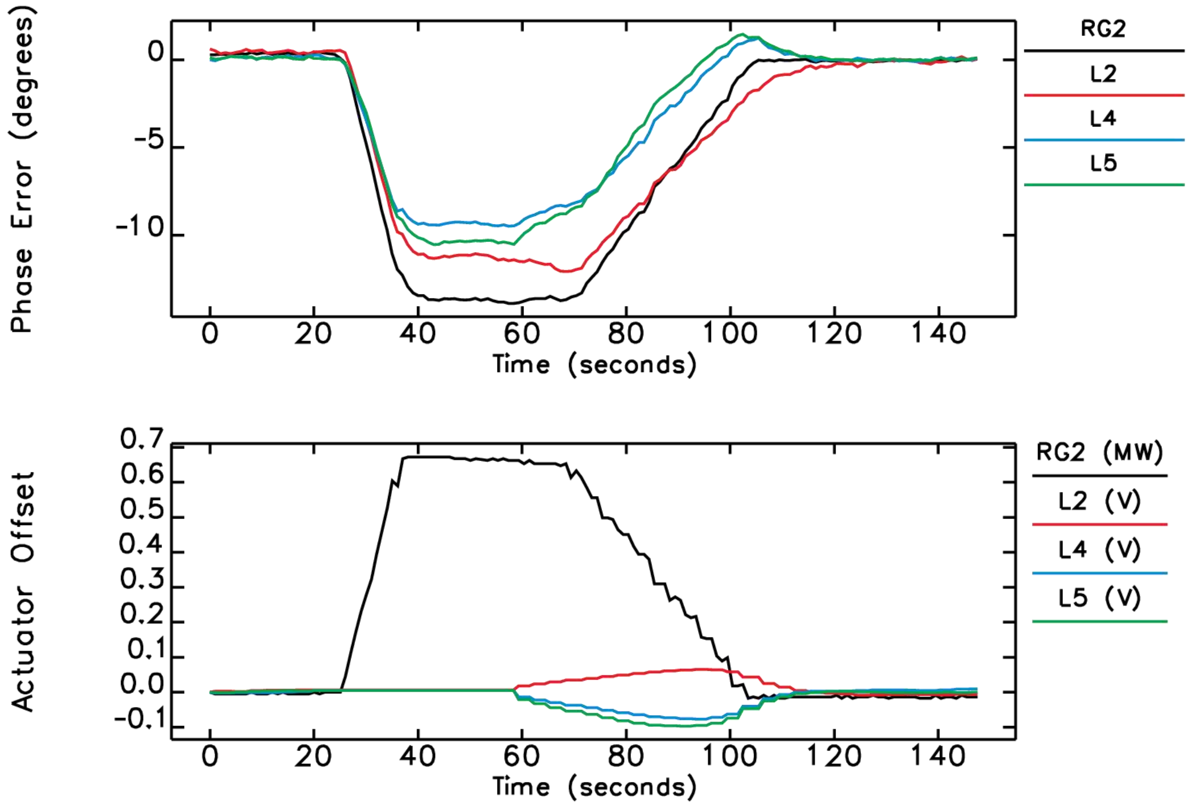
[1] **N. S. Sereno etal., PRST-AB 11, 072801 2008**

Applications: Linac Beam-RF Phase Controllaw cont.

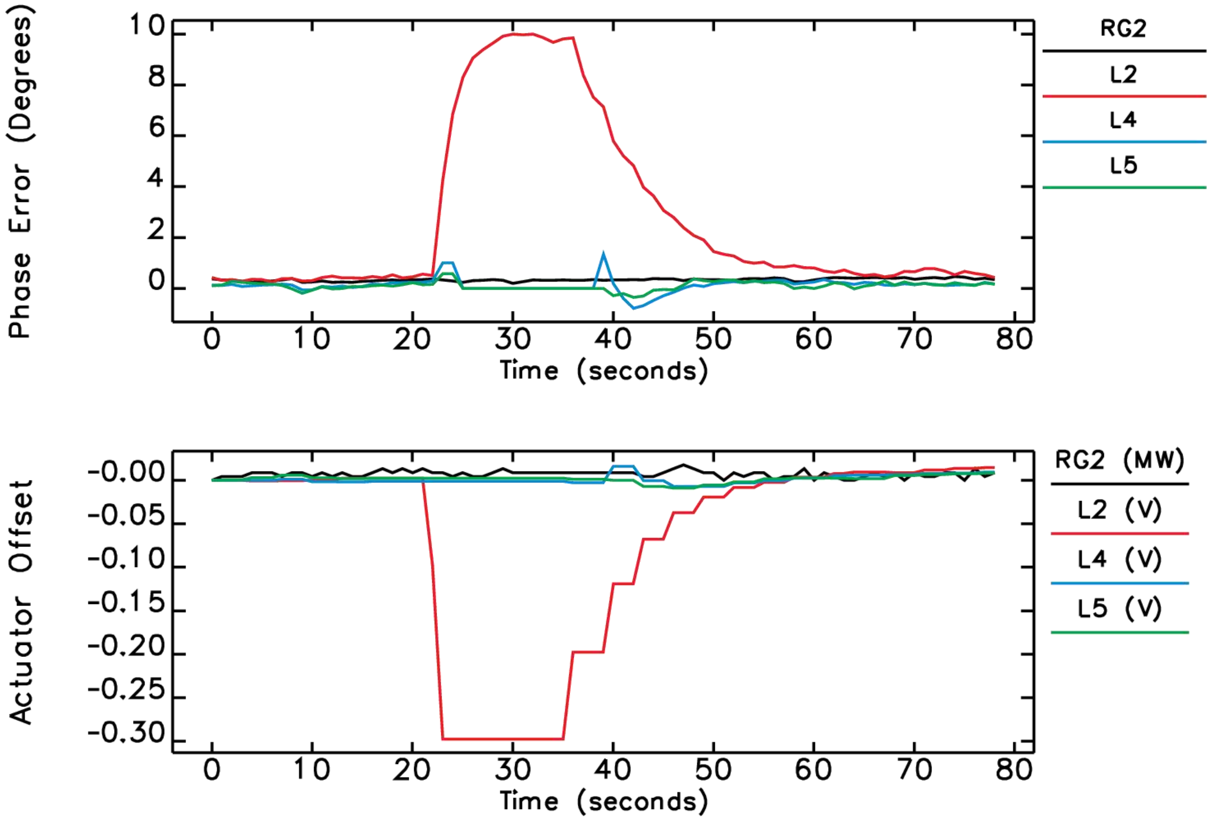
- Since the beam is relativistic, after the rf guns, the beam arrival time is determined by dispersion in the linac chicane and the the rf gun alpha magnet
- Can define a controllaw using as actuators the rf gun power and linac station L2, L4 and L5 phase shifters
- The gun power actuator affects arrival time for all phase detectors in the linac
- Due to dispersion in the chicane, the arrival time at linac sections L4 and L5 is altered due to an rf gun power change



Applications: Linac Beam-RF Phase Controllaw cont.



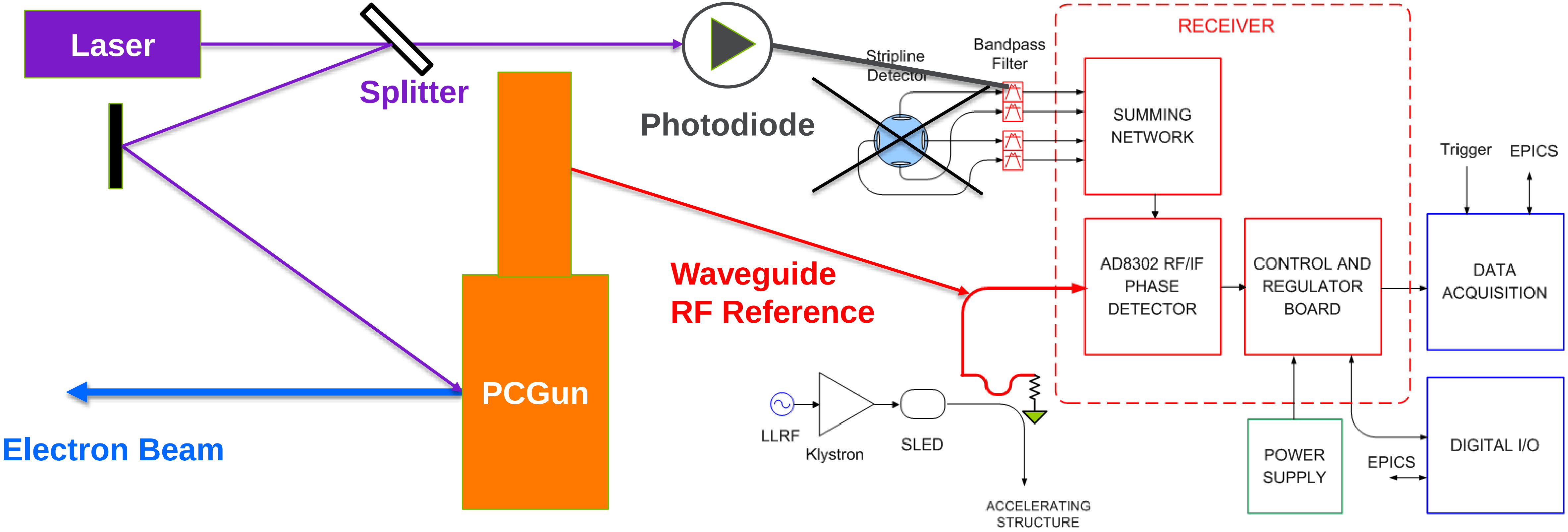
RF Gun Power Change and Recovery



Linac Section L2 Phase Change and Recovery

- RF Gun and linac L2 section phase error recovery using the controllaw
- System in operation in the APS injector linac since 2006

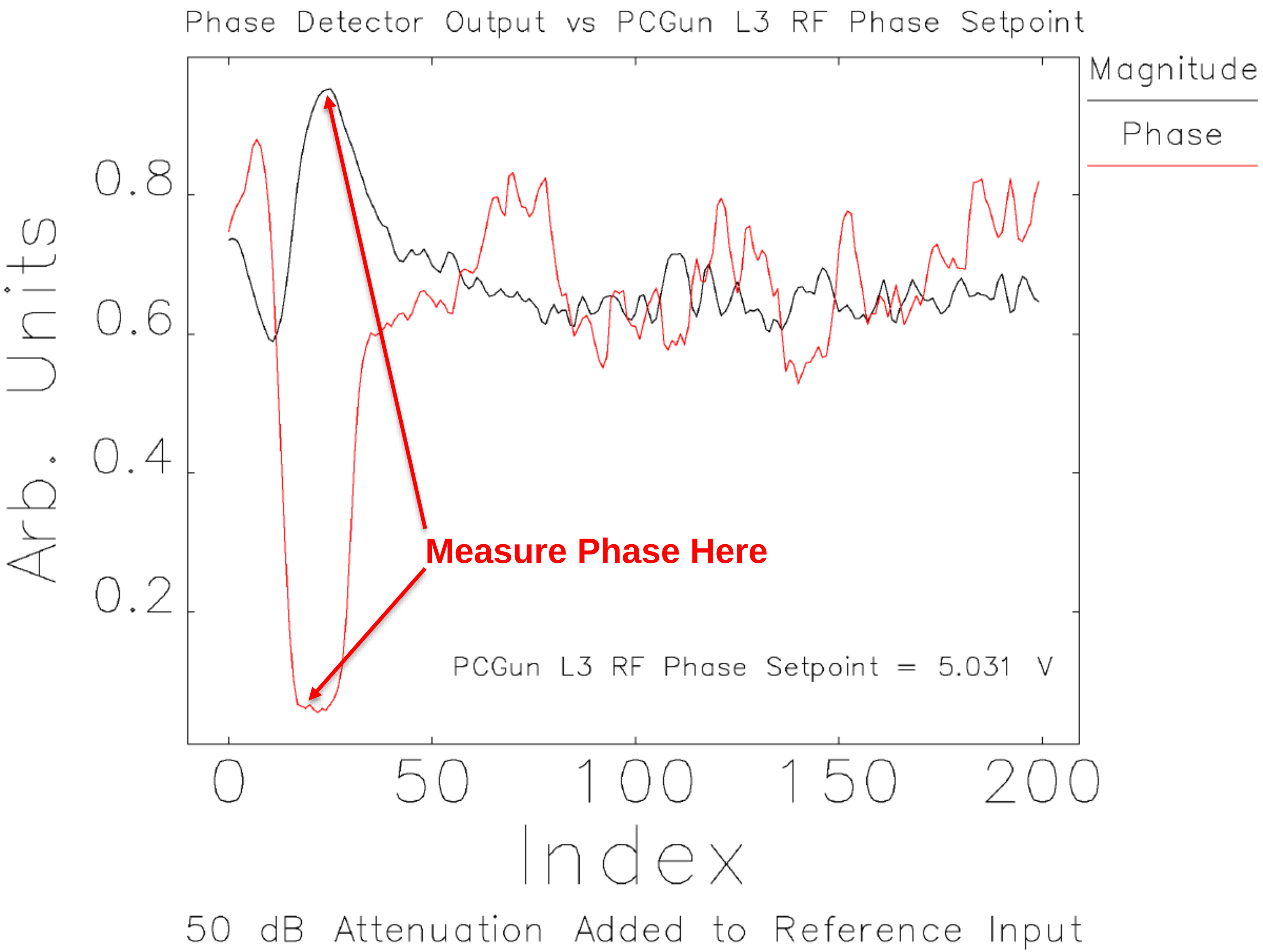
Applications: PCGun Laser-RF Phase Measurement



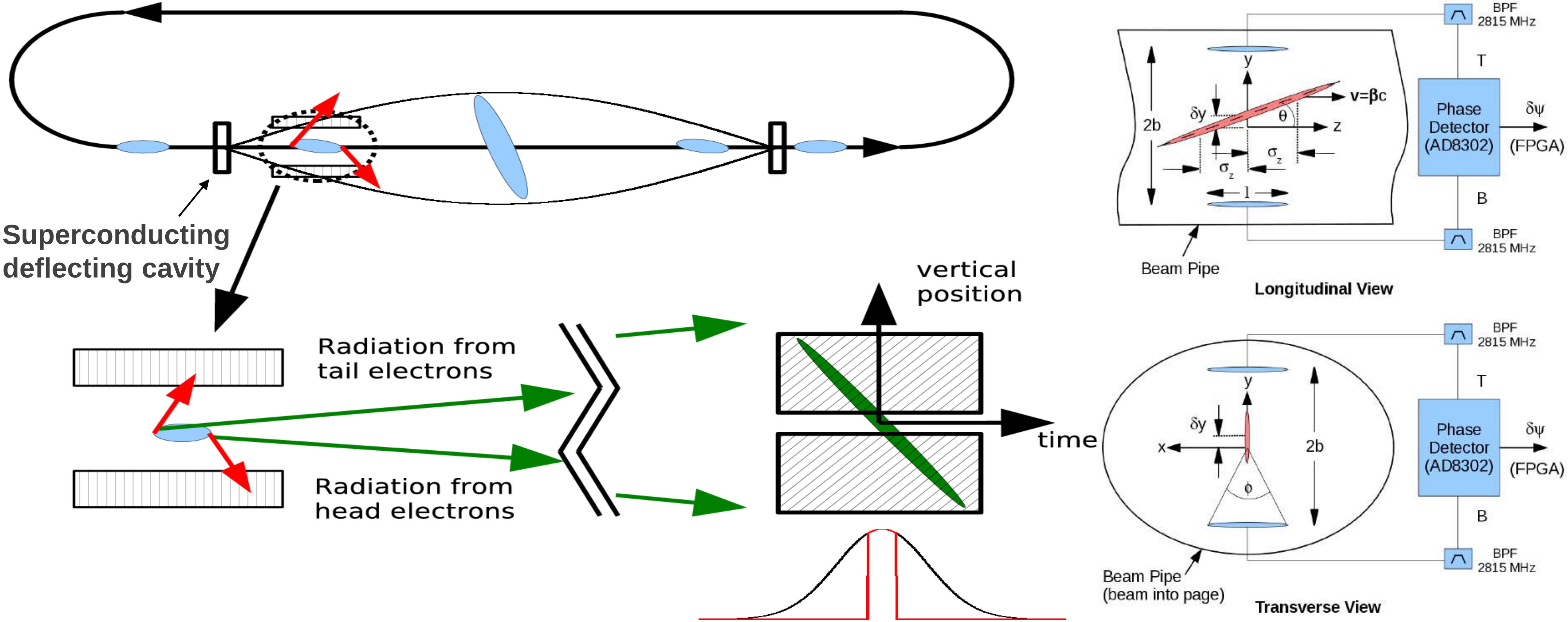
- Proof of principle experiment to measure the laser beam arrival time wrt PCGun rf phase
- The laser arrival time wrt PCGun rf phase sets the emittance of the electron beam
- Incorporate into a future controllaw using linac phase detectors

Applications: PCGun Laser-RF Phase Measurement cont.

- Proof of principle experiment varied the PCGun rf waveguide phase using the klystron LLRF phase shifter
- Need to boost the photodiode signal as it was rather small (made due by attenuating the reference signal)
- Plot horizontal axis is for 88 MHz digitizer sample rate (Index Unit = 11 ns)



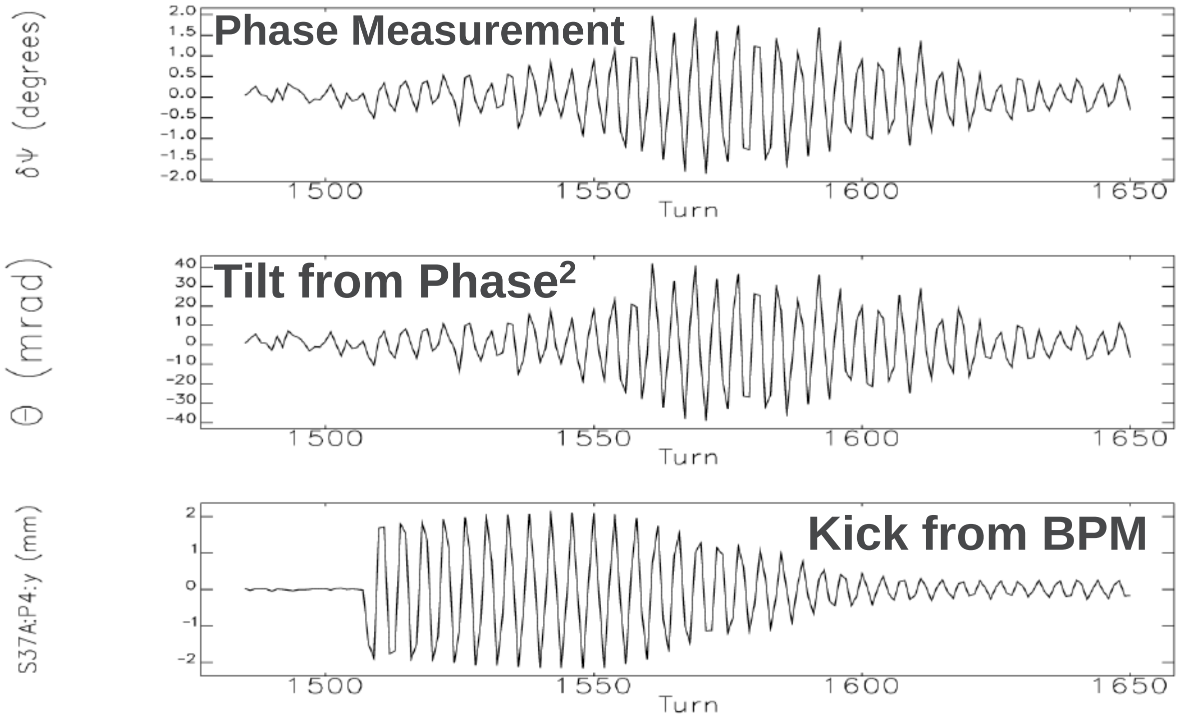
Applications: Beam Tilt Measurement in the APS SR[1,2,3]



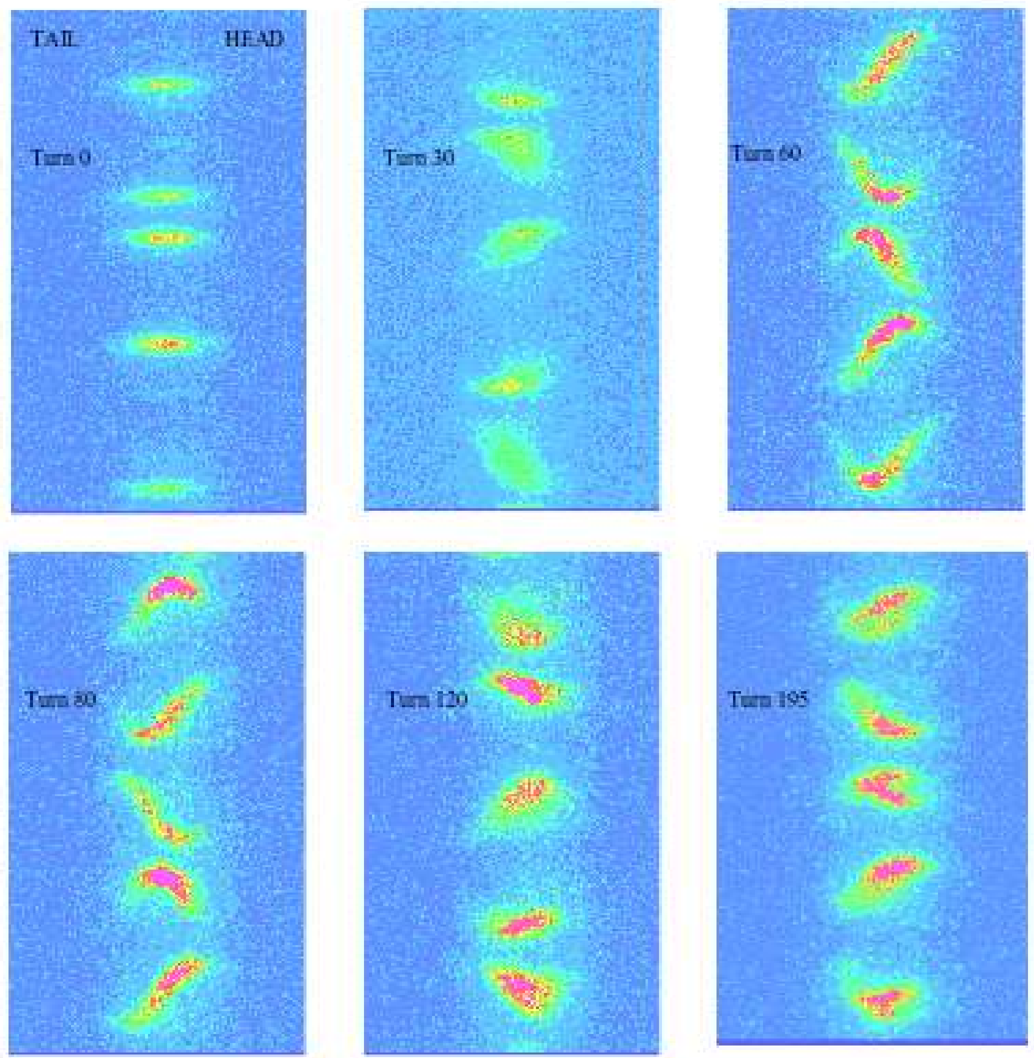
[1]A. Zholents *et al*.NIM A 425, 385 (1999).
[2] M. Borland, Phys. Rev. ST Accel Beams 8, 074001 (2006).
[3] N. Sereno etal. 2012 BIW, Newport News, VA

- Motivation was to measure residual beam tilt after the deflecting cavities in original APS-Upgrade

Applications: Beam Tilt Measurement in the APS SR[1] cont.



- Experiment to measure bunch tilt by kicking the beam vertically
- Tilt is generated due to machine chromaticity and energy difference between the bunch head and tail

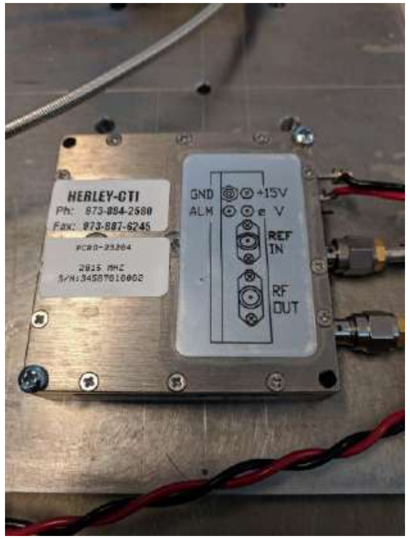


Streak Camera “Synchroscan” Tilt Measurement

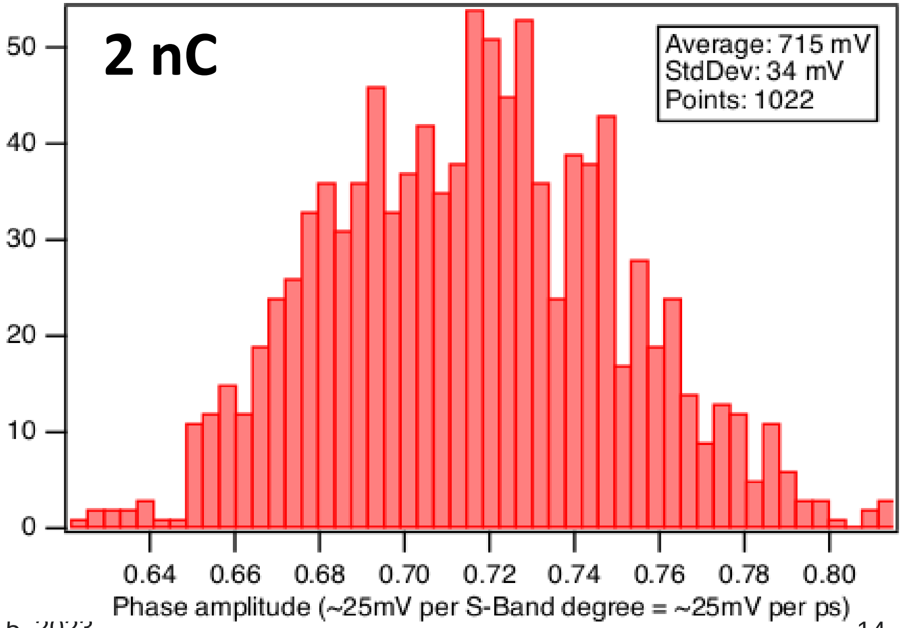
[1] **B. X. Yang, PAC 2005**
[2] **W. Guo etal., PRST-AB 10, 020701, 2007**

Applications: BTS Arrival Time Measurement

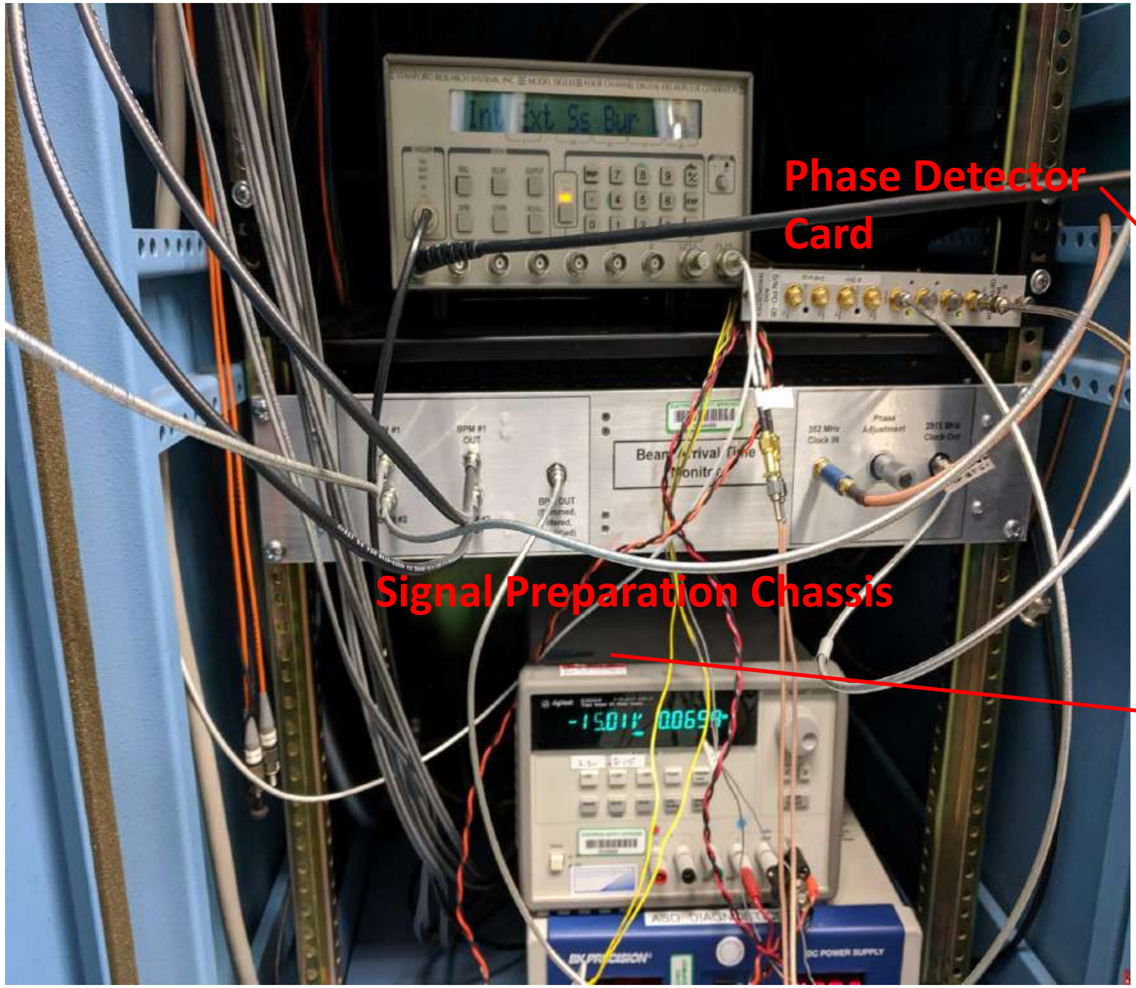
- Setup is the same as for the linac phase detectors except the phase reference is 352 MHz
- Use a PDRO to multiply 352 MHz x 8 to get 2815 MHz S-band reference
- Uses a stripline bpm in the BTS as the beam signal (two striplines oriented either horizontally or vertically)
- Beam rate is 1 Hz and 6 GeV for APS-U in the BTS line
- For APS-U arrival time jitter specification is 50 ps rms
- Histogram plot shows 1.4 ps rms for present APS performance
- APS-U uses booster frequency ramping to do bucket targeting (different rf sources for Booster and SR)

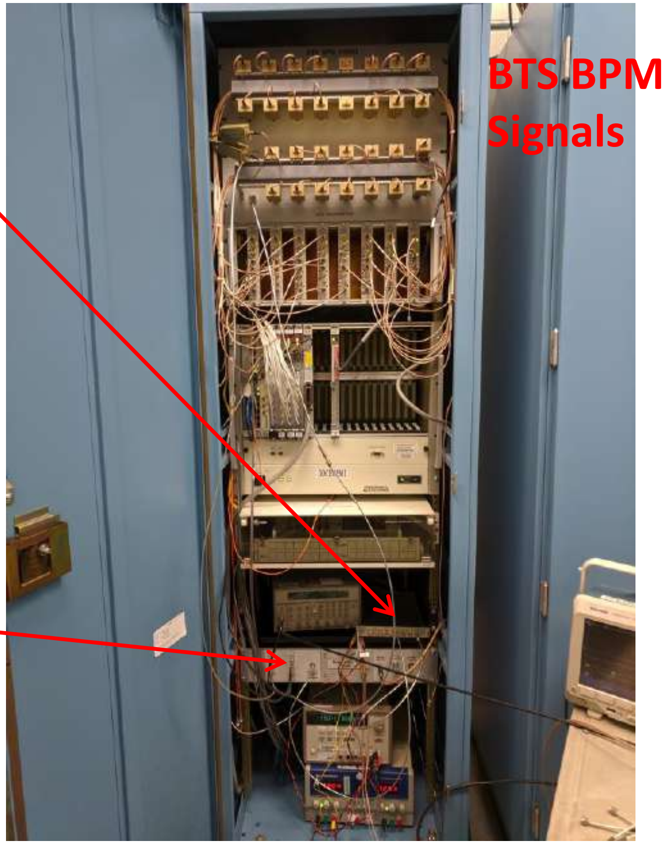


PDRO (Phase Locked Dielectric Resonant Oscillator)



Applications: BTS Arrival Time Measurement cont.

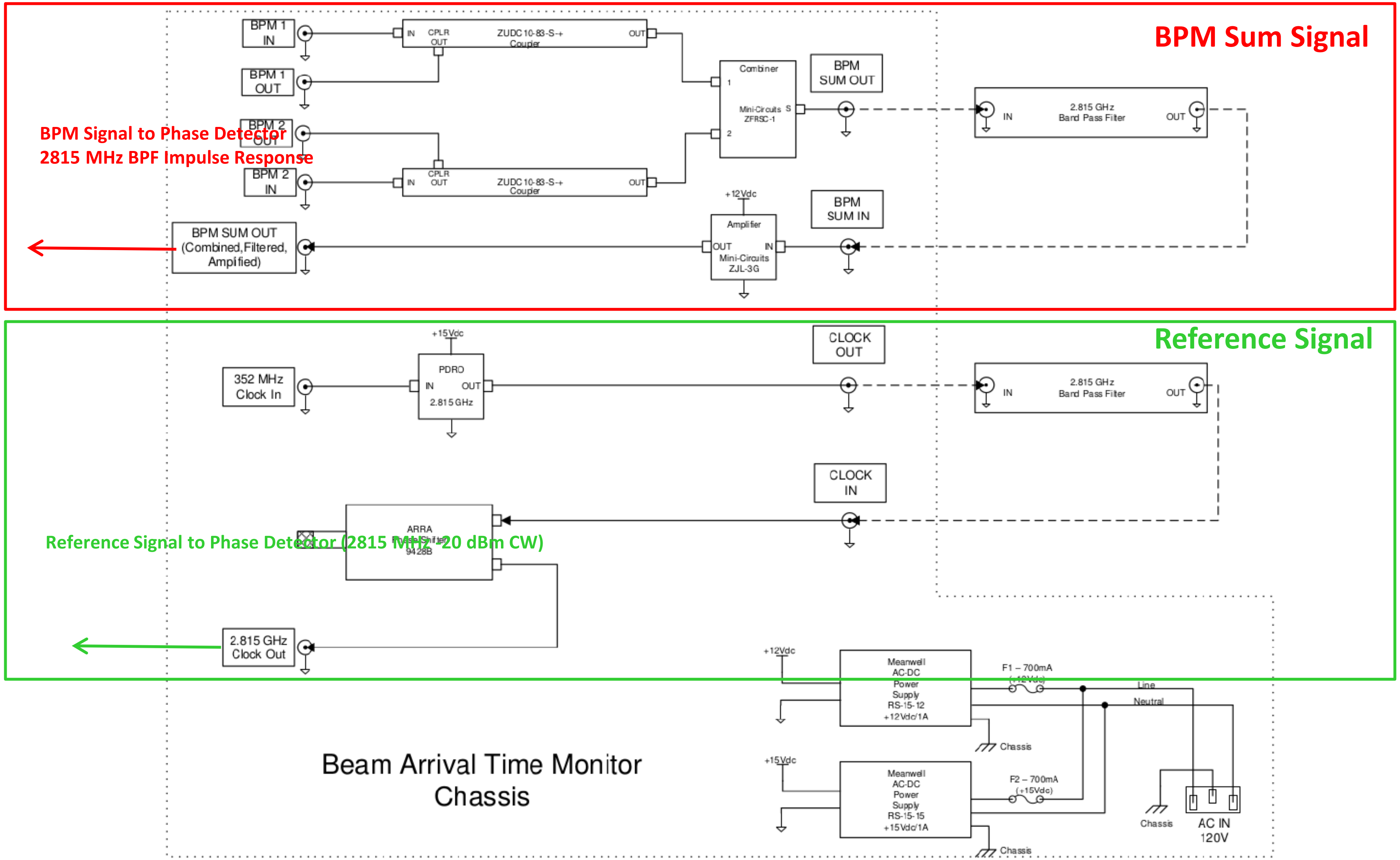




- Hardware setup in SR LLRF and timing room

Applications: BTS Arrival Time Measurement cont.

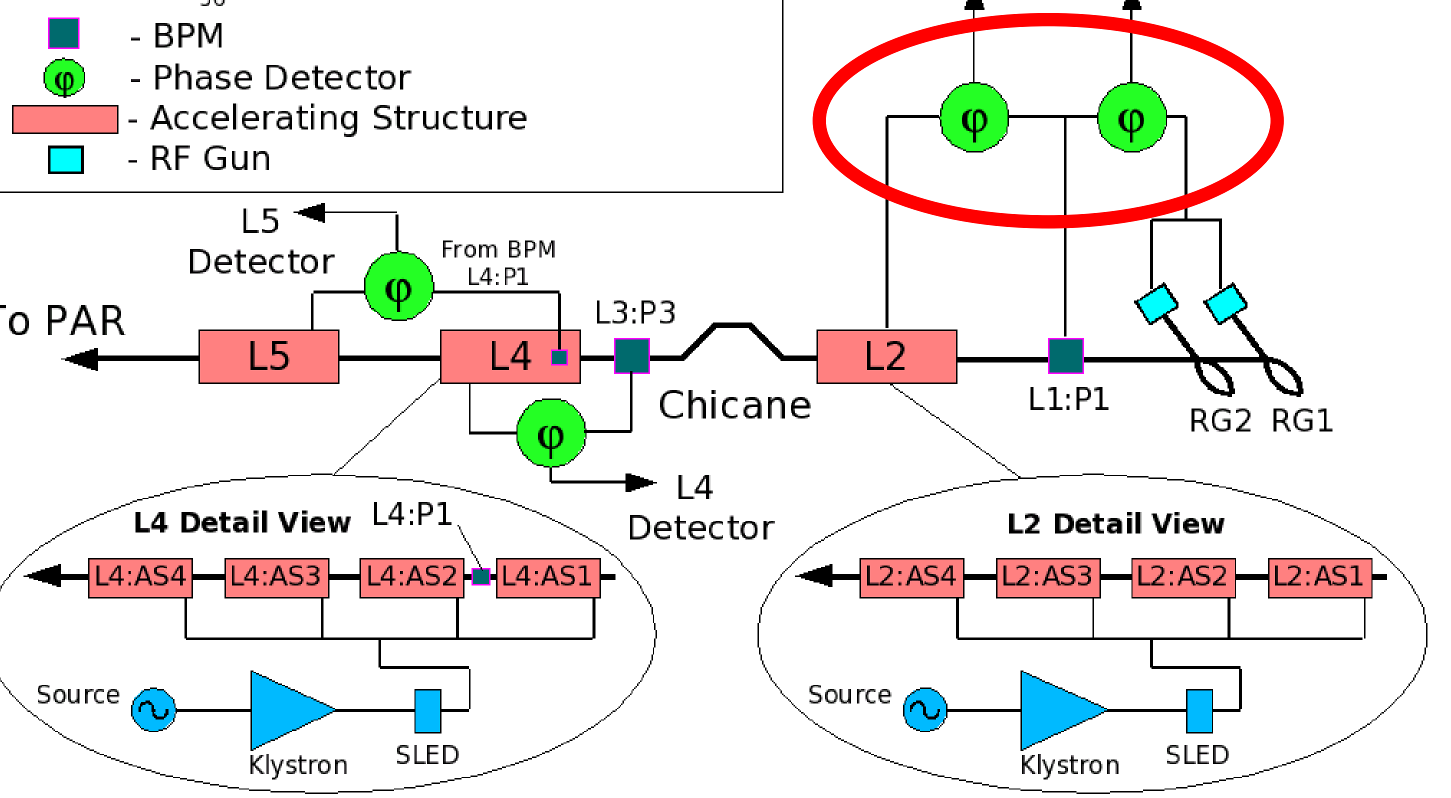
- Setup is similar to the linac phase detectors except the phase reference is 352 MHz SR master oscillator
- Built special chassis to prepare bpm and rf reference signals for this application



Comparison of Libera LLRF and Operations Phase Detector Measurements

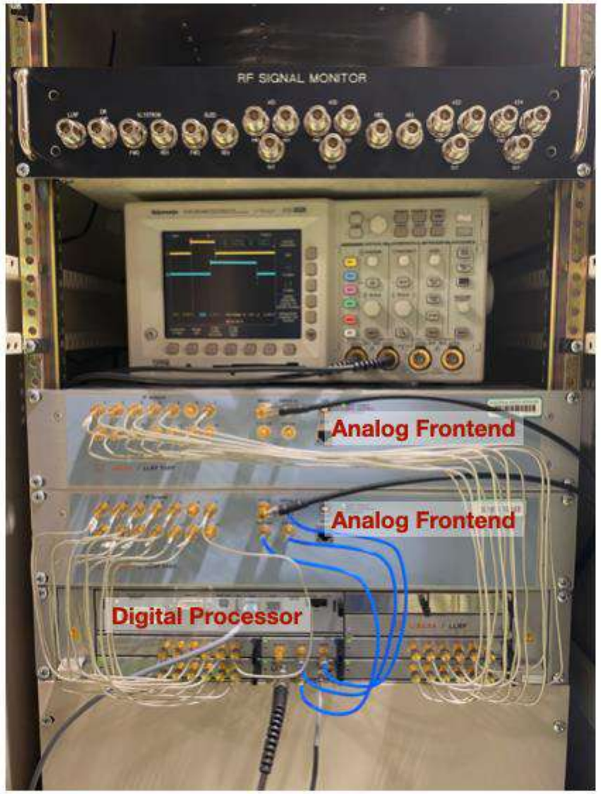
- For this test, we used the linac phase detectors connected to L1:P1
  - L:BPD:L1P1:RFGUN2
  - L:BPD:L1P1:L2AS1
- Used nominal operations charge at L1:CM2: 1.1 nC
- Changed RG2 power to change arrival time at L1P1
- Waited for gun current to stabilize after each change in gun power
- Recorded 500 LLRF phase waveforms at each RG2 power setting covering a 30 degree (ps) range in the phase detector system
- Of the 500 waveforms could get between 50 and 200 with beam signal (no beam trigger to LLRF system)

LINAC Parameters:
Pulse Rate: 2 - 12 Hz
RF Frequency: 2856 MHz
Extracted Charge per pulse: 0.3 - 1 nC
Extraction Energy: 325 - 450 MeV
RF Gun Macropulse Length: 11 - 40 ns
Chicane R_{56}: -65 mm



Argonne NATIONAL LABORATORY

Libera LLRF Setup in the APS Linac Gallery

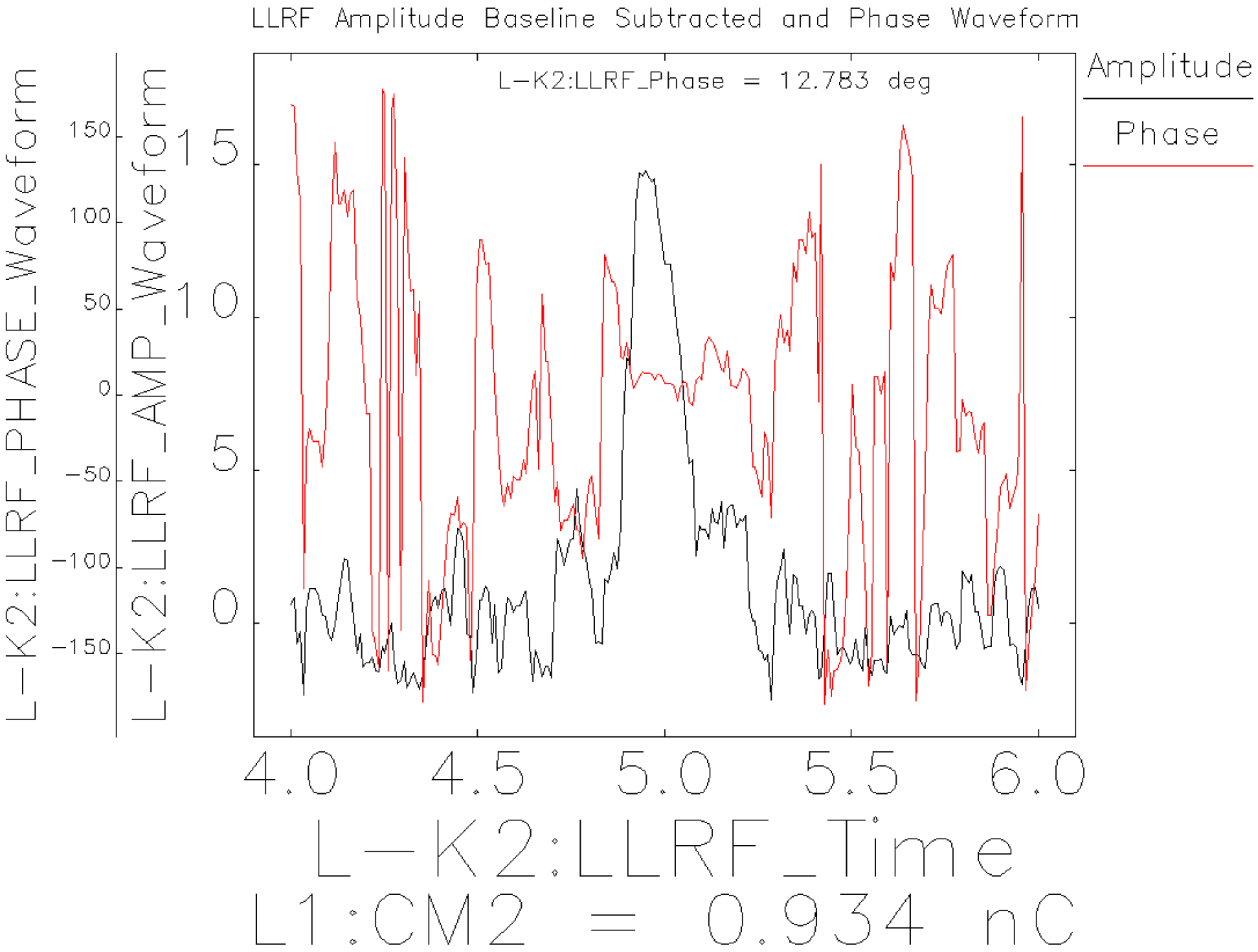


ITech LLRF electronics in rack

New K2 modulator, klystron and LLRF racks in Linac Gallery

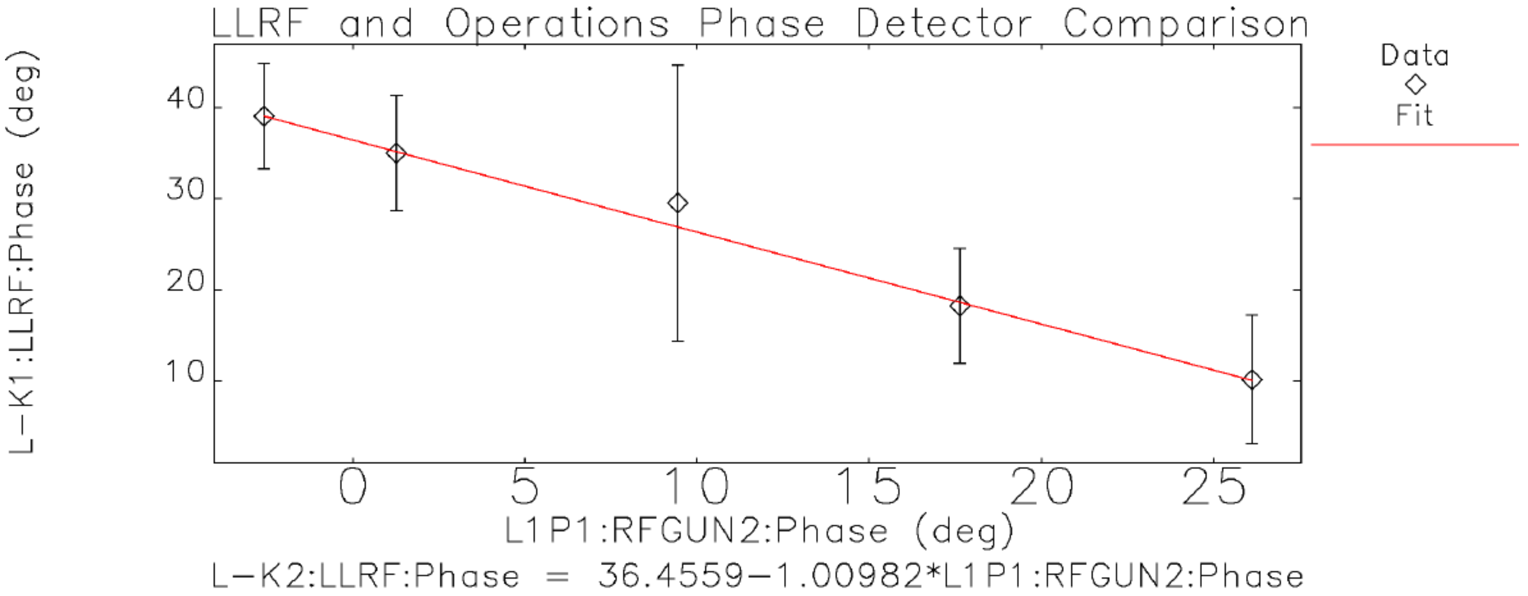
Experimental Results

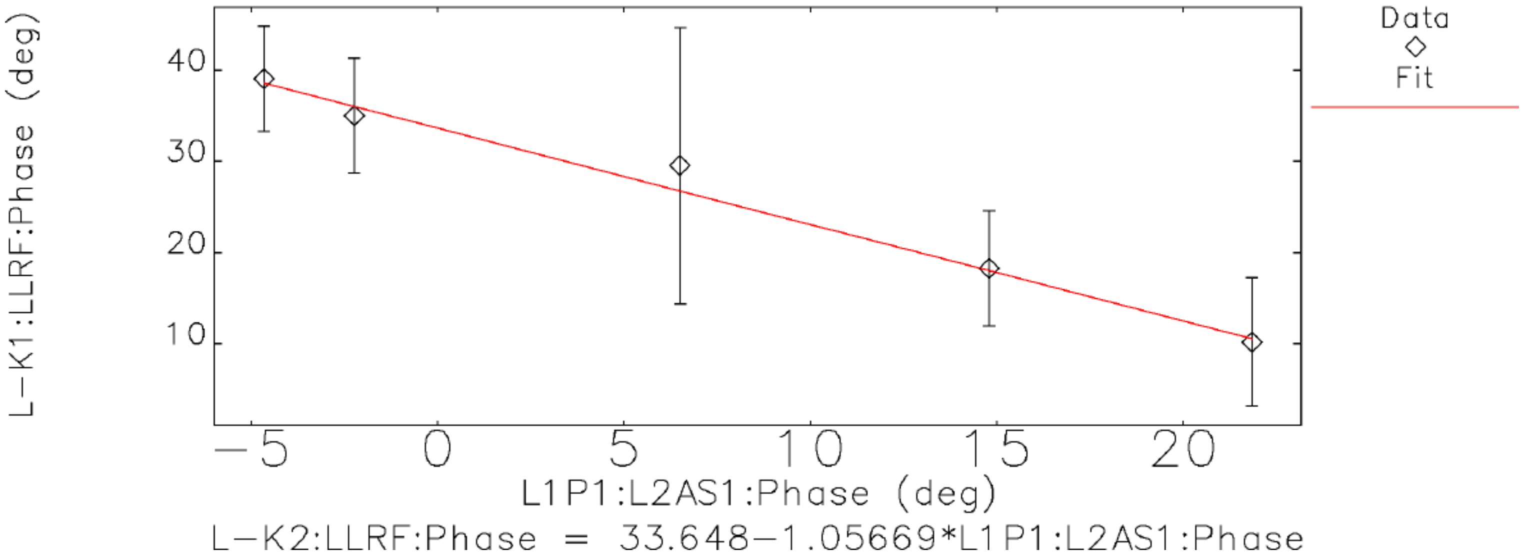
- ITech LLRF outputs amplitude and phase waveforms
- Measurements relative to the S-Band linac master oscillator reference
- Data processing:
  - Remove baseline offset of amplitude waveform
  - Determine the peak amplitude and only keep waveforms above 12 counts (very small signal as max range is 25000 counts)
  - Process the phase waveform by taking the phase value at the peak of the amplitude waveform
  - Compute phase mean and standard deviation and plot vs operations phase detector phase output
  - Fit a line to the data, check slope and intercept



Experimental Results cont.

- Top Plot: LLRF phase measurement vs operations L1P1:RFGUN2 phase measurement
- Bottom Plot: LLRF phase measurement vs operations L1P1:L2AS1 phase measurement
- Large error bars likely due to:
  - Small signal available to ITech LLRF system
  - A few large outlier phase measurements
- Fits nearly identical for the plots: Unity slope and similar intercepts





Summary

- Presented the APS operations phase detector system based on the AD8302 phase detector chip
  - **Main APS operations application is linac phase detectors used in a phase controllaw (since 2006)**
  - **New beam arrival time measurement in the BTS to diagnose APS-U timing system performance**
  - Used for two other proof-of-principle experiments: Laser-beam rf phase for PCGun and SR beam tilt measurements
- Compared Libera LLRF system and operations phase detector measurements
  - Proof of principle measurement limited by lack of a beam trigger for Libera LLRF
  - Large error bars due to small beam signal level input to Libera LLRF and large unexplained outliers
  - Libera LLRF compared favorably in performance to operations phase detector (unity slope when each phase detector compared directly)
- Could this be a possible future product?
  - Long linacs could potentially make use of quite a few of these devices
  - Rings could use them to diagnose sources of tilt due to kicks
  - Photon-rf signal photodiodes could allow use in PCGun systems
- Could this be a possible future “hybrid” or “fully” digital product?
- A hybrid product would be to use the AD8302 or equivalent and use an FPGA to control it and correct for systematic errors

Acknowledgements*

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