Digital BCM Receiver

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Beam Instrumentation Challenge

Requirements on the beam asymmetry: Δx or $A_Q = (Q_R - Q_L)/(Q_L + Q_R)$

Parameter	Jitter requirement	Achieved	Resolution requirement	Achieved
Charge	< 1000 ppm	500 ppm	< 10 ppm	65 ppm
Energy	< 108 ppm	6.5 ppm		
Position	< 47 μm	48 μm	< 3 μm	2.4 μm
Angle	< 4.7 μrad	1.4 μrad		

Source: MOLLER CDR. Requirements quoted for 1920 Hz helicity flip rate

LBNL direct-sampling RF receiver is designed to satisfy the requirements on the beam charge resolution

Development of a direct-sampling RF receiver for precision beam charge measurements in the MOLLER experiment

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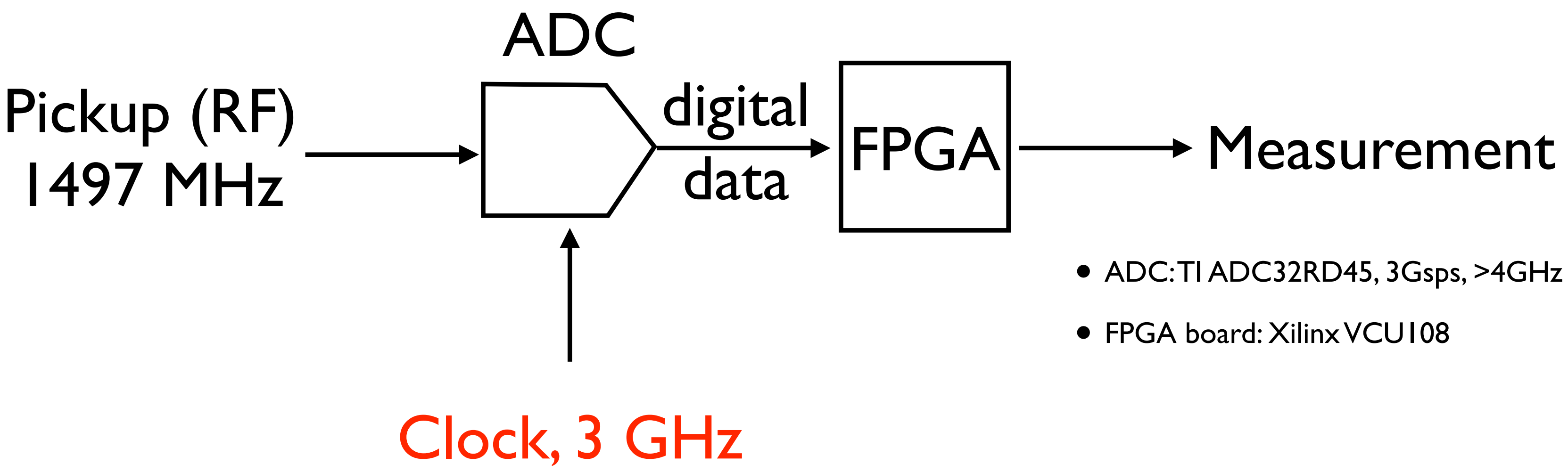
System architecture: digital RF receiver

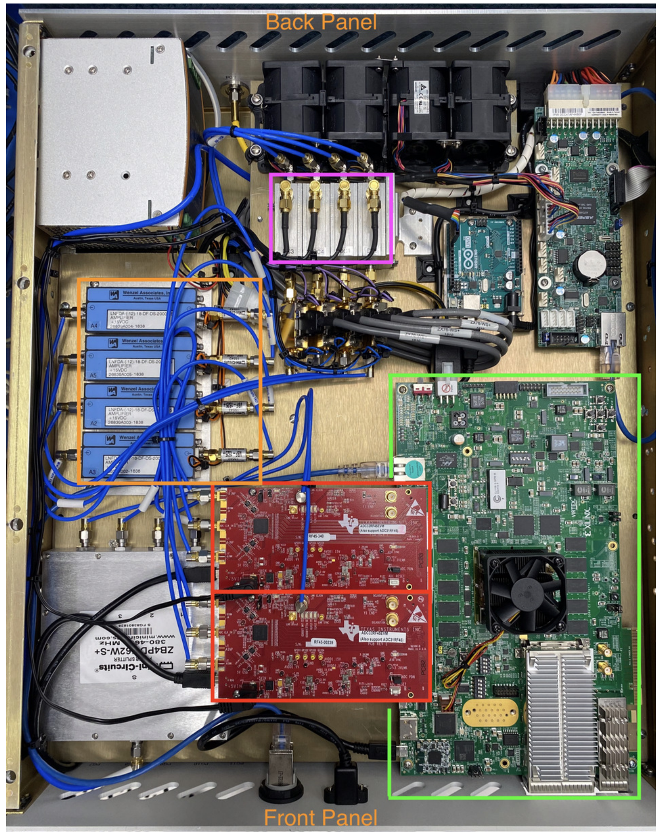


- ADC: TI ADC32RD45, 3Gsps, >4GHz BW, 14bit
- FPGA board: Xilinx VCU108

- High sampling rate (>~3Gsps) and high dynamic range (>10bits) ADCs that are capable of direct RF sampling
- Amplitude fluctuation of LO doesn't contribute. Phase noise is small; modest contribution to the final uncertainty
- Filtering and decimation done digitally in ADC and/or FPGA
- Output: decimated data stream, integrated in 0.5 msec windows in FPGA or offline
- Implemented in a 4-channel prototype receiver box

Prototype

4 RF channels



- VCU108 FPGA board
- ADC32RF45EVM
- Amplifier and filter
- Directional coupler

Single channel chain

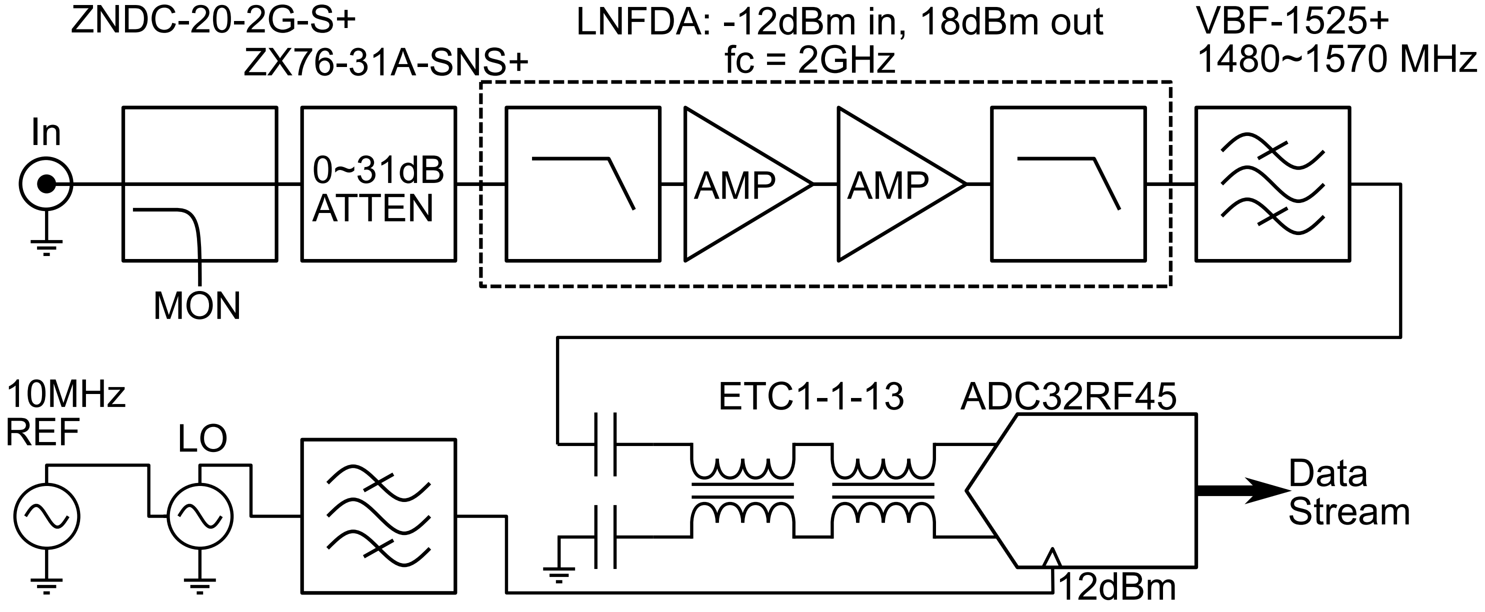


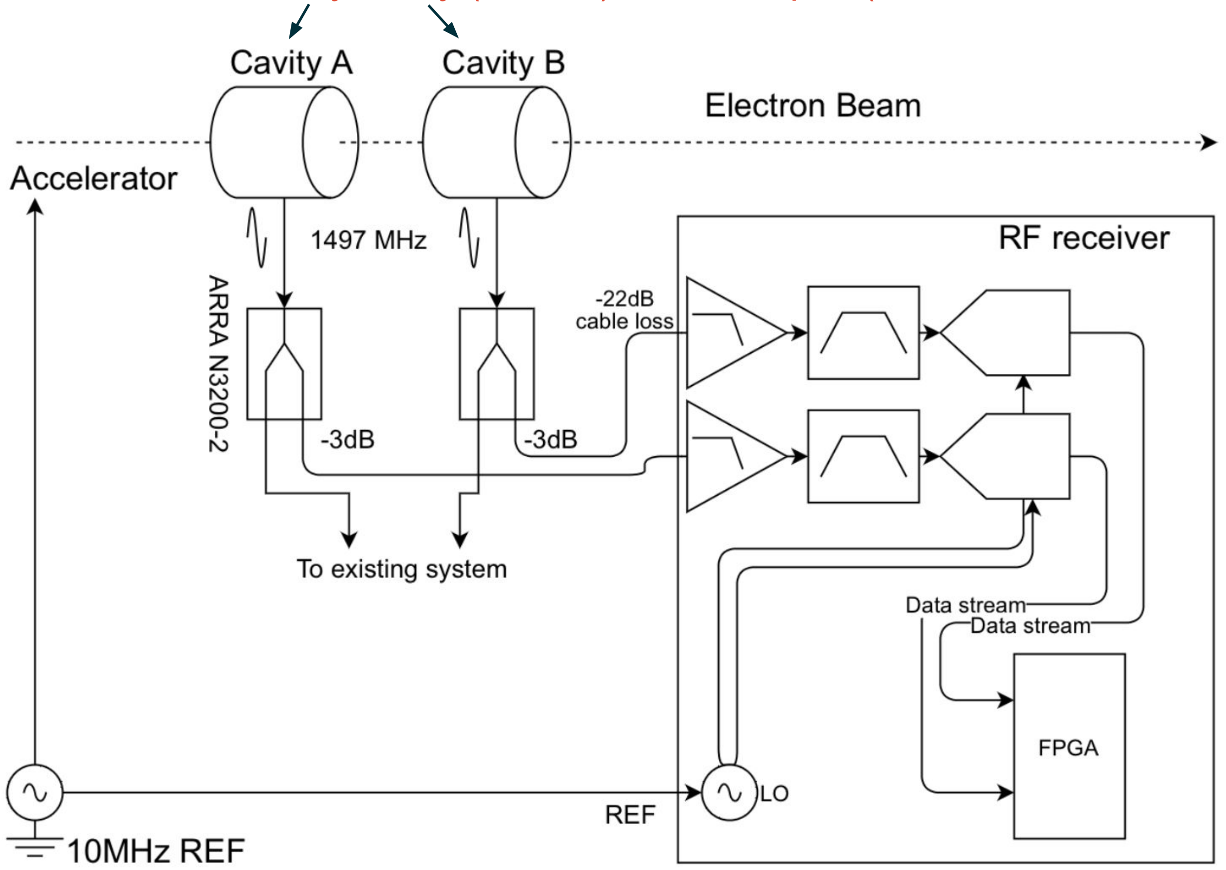
Figure 3. The RF front-end signal processing chain of the sampling system with the part numbers.

Beam Test in Hall A in Sept 2020 (CREX)

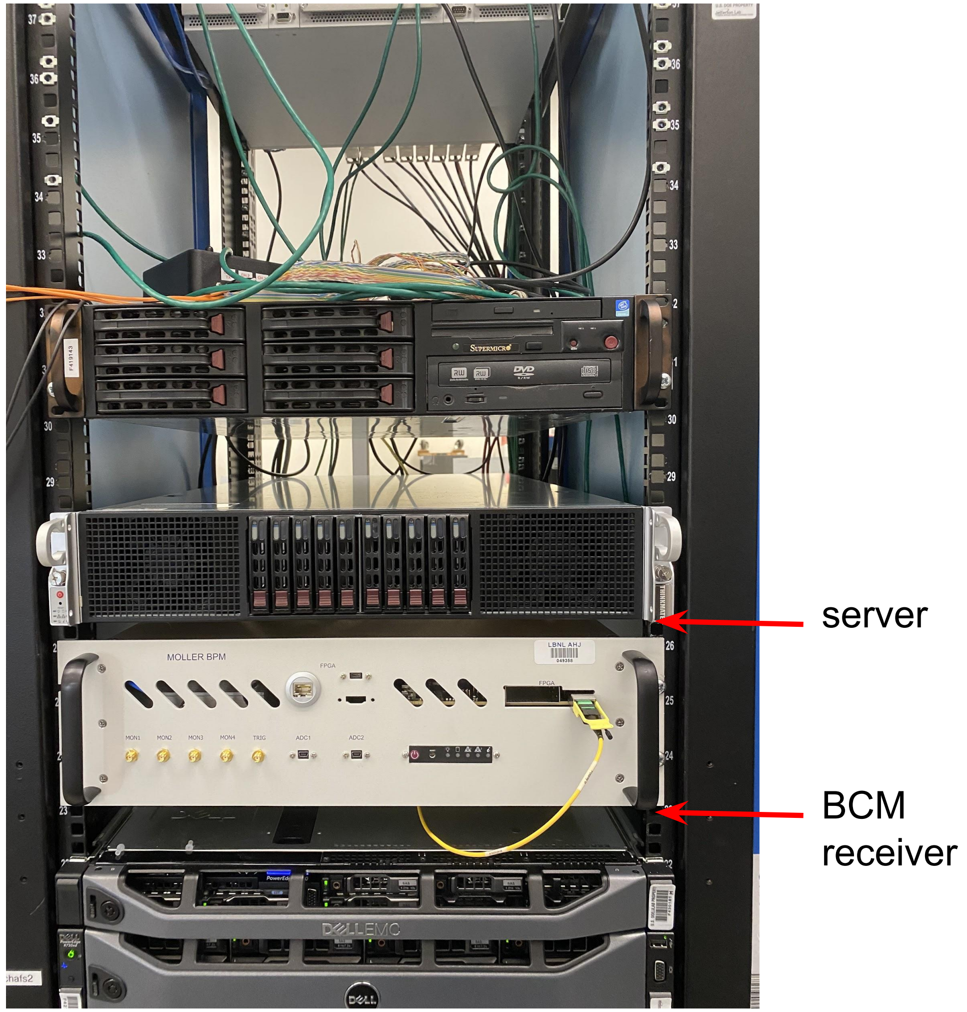
- Beam test in Hall A : Parasitic running during CREX (September, 2020)
  - no beam, tune beam, 0-150uA
  - didn't sync with 120 Hz helicity flips

- 2 channels to take 2 RF signals from BPM4B and 4D (-40dBm@1μA)
  ⇒ splitter (-3dB) ⇒ cable to counting house (-22dB)
  ⇒ -22dBm@-150μA at BCM box

Intensity cavity (TM010) of BPM triplet (located after rasters!!)



middle room of Hall A counting house



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DSP chain

Input: 1497 MHz RF signal

1. Direct sampling at 3072 Msps (14-bit, 10-bit ENOB)

$$x_i = A\cos(2\pi f_0 \theta_i)$$

where $f_0 = 1497$ MHz, $fs_0 = 3072$ MHz, $\theta_i = \frac{i}{fs_0}$

2. Digital Down Conversion (DDC) with tunable (numerical) LO

$$I_i = x_i\cos(2\pi f_1\theta_i + \phi), Q_i = x_i\sin(2\pi f_1\theta_i + \phi).$$

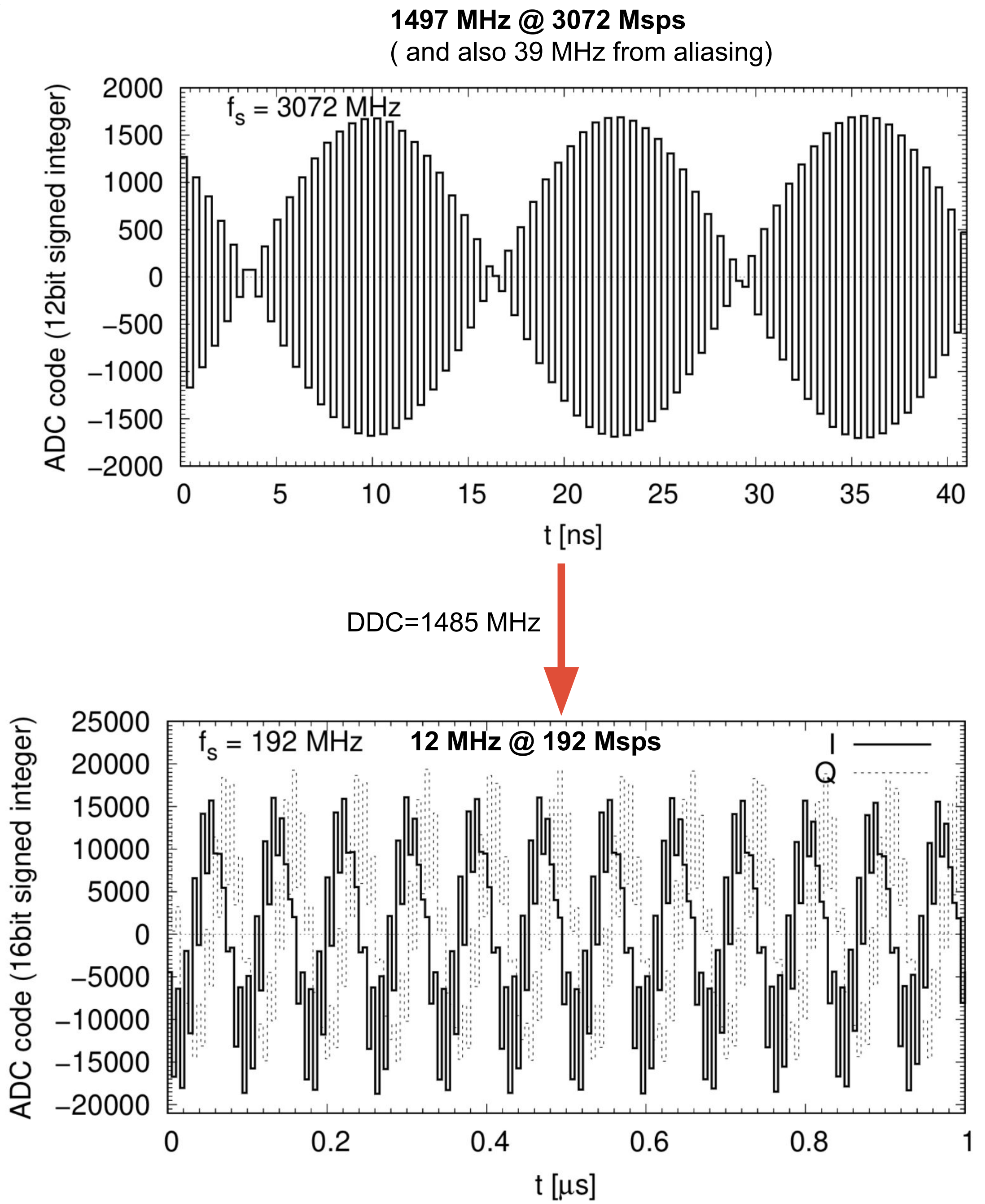
$y_i = I_i + \mathbf{j}Q_i$, two freq. $f_0 + f_1$ and $f_0 - f_1$.

filtered out

3. /16 decimation: keep 1 sample every 16 samples (selectable between 4-32)

$$fs = fs_0/16 = 192 \text{ MHz}$$

Final data stream: I/Q (16-bit each) at **192** Msps rate (~ 2 x 400 MB/s)



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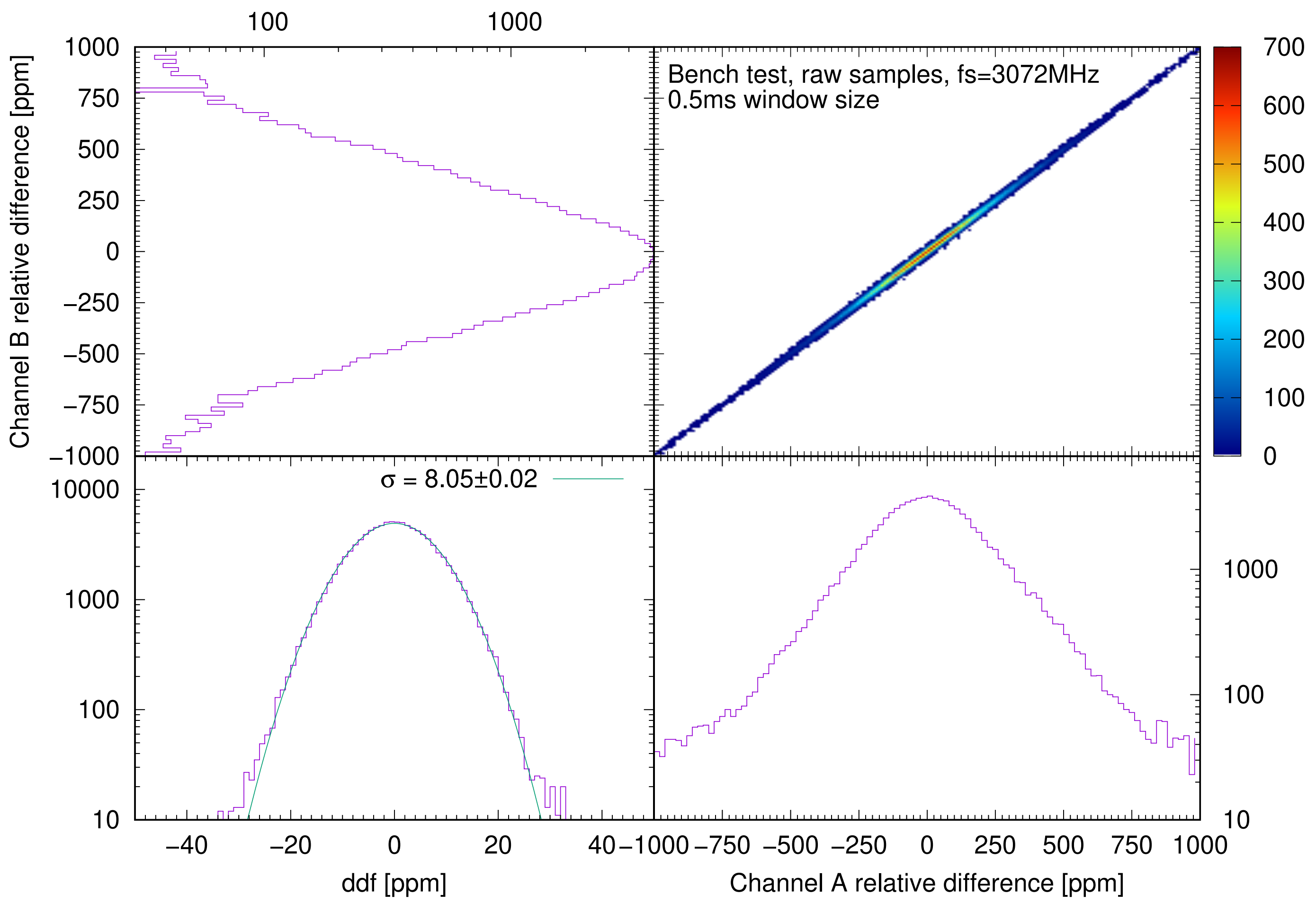
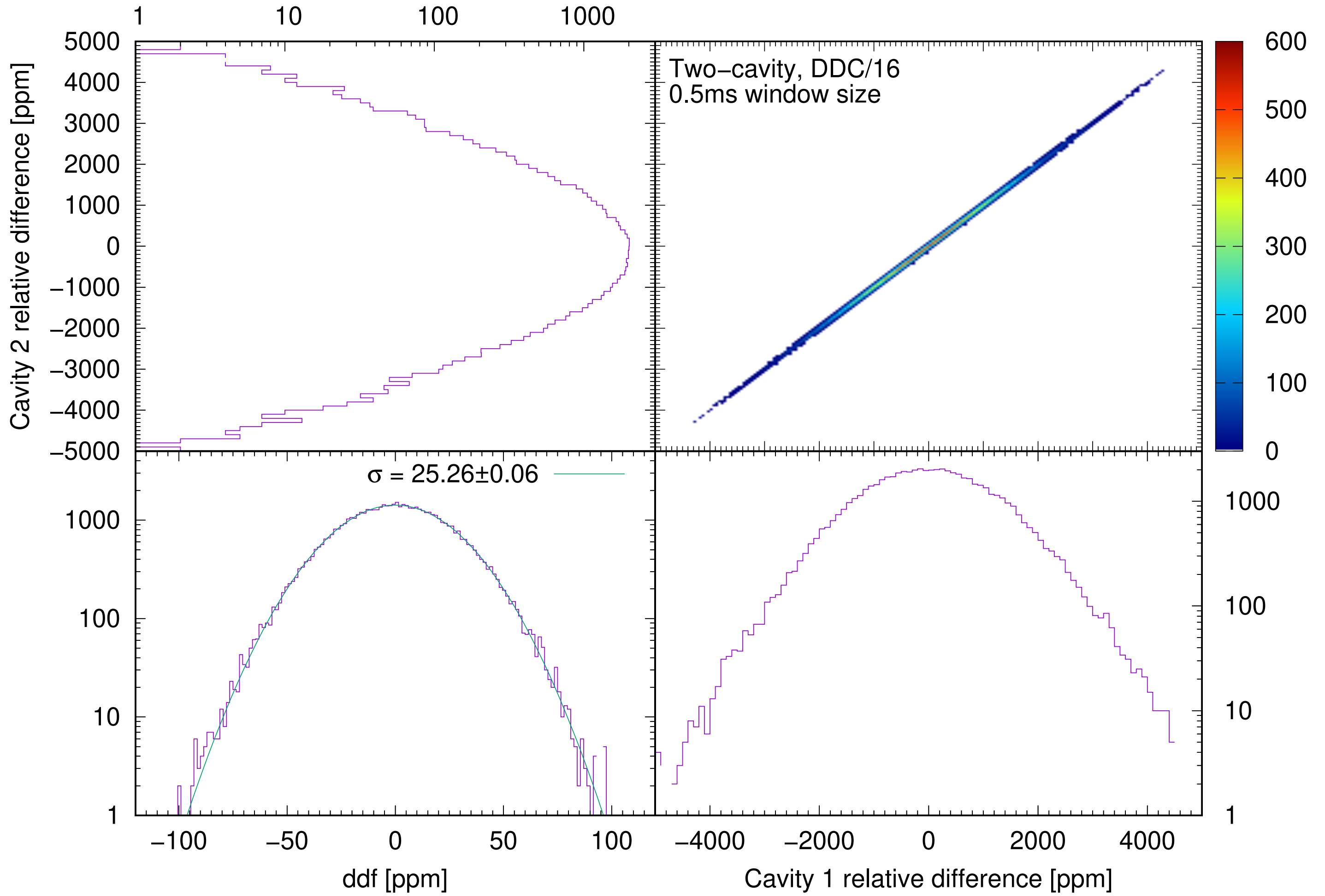
Performance

Define resolution as double-difference (ddf): $ddf = (A_A - A_B)/\sqrt{2}$

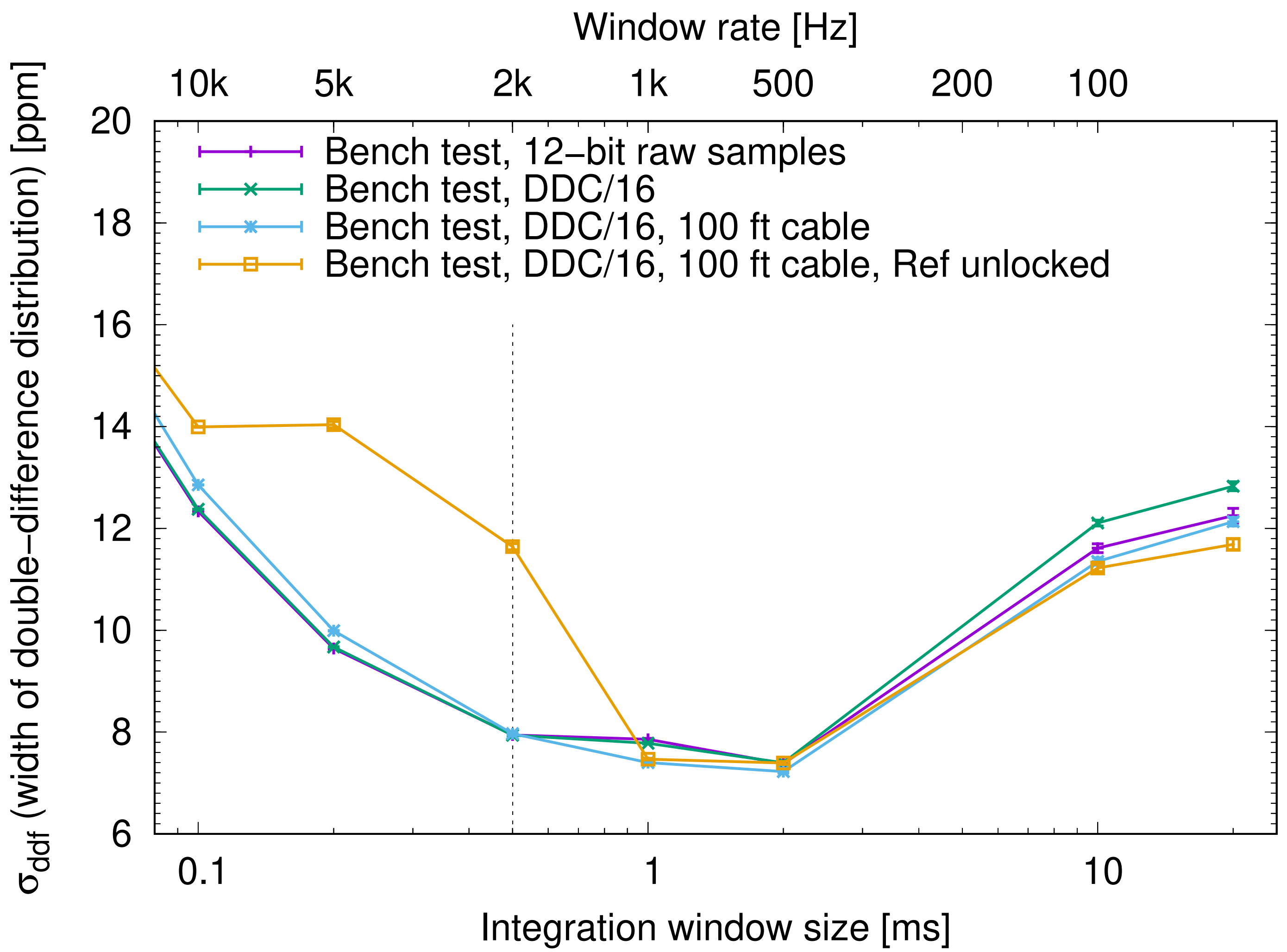


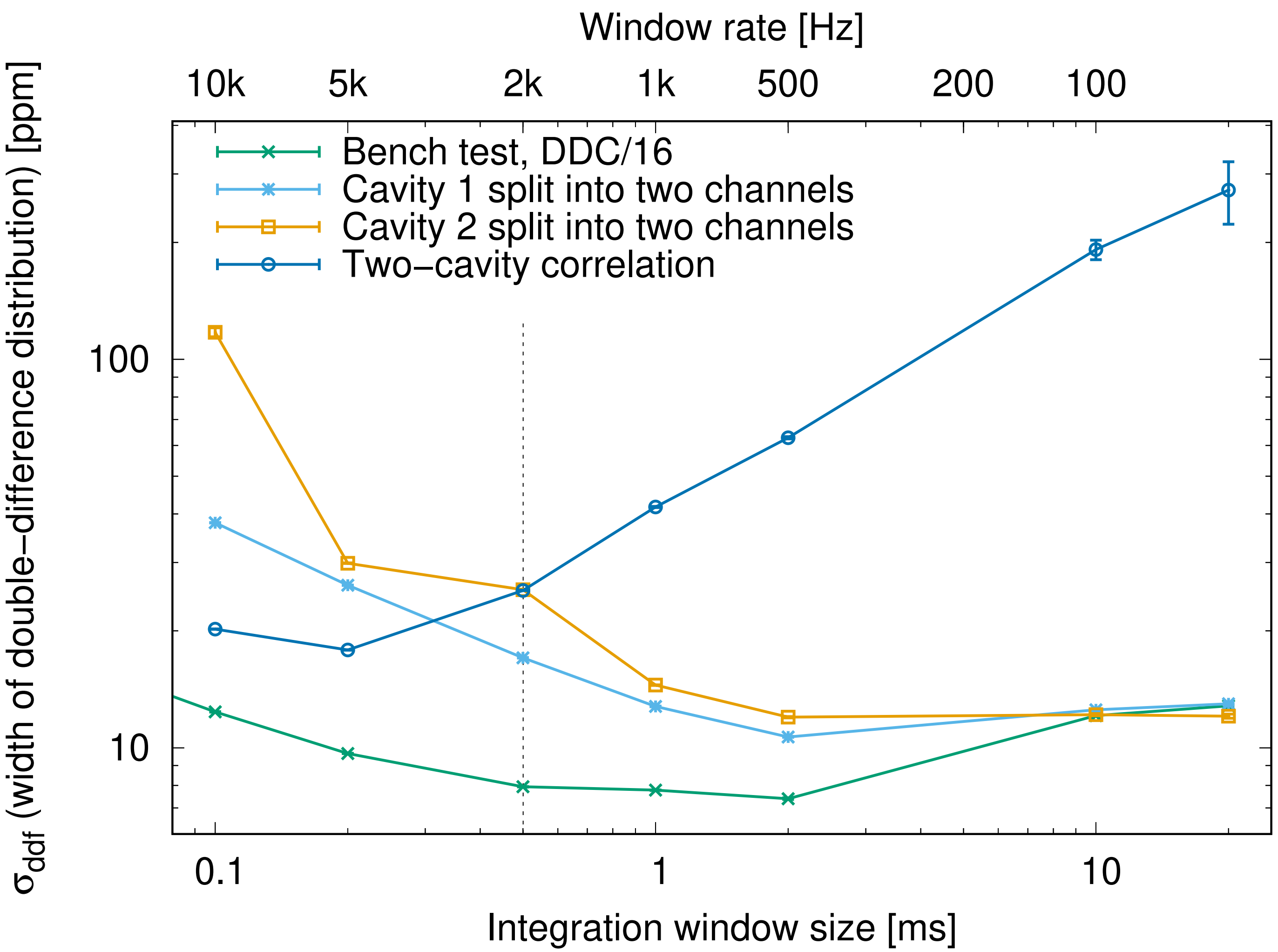


Bench test with beam generator:
8 ppm @ 2 kHz helicity rate

Beam test with cavity signals:
25 ppm @ 2 kHz helicity rate

Potential sources of Beam Noise





Additional ~20 ppm of beam-induced noise; appears to scale as 1/f

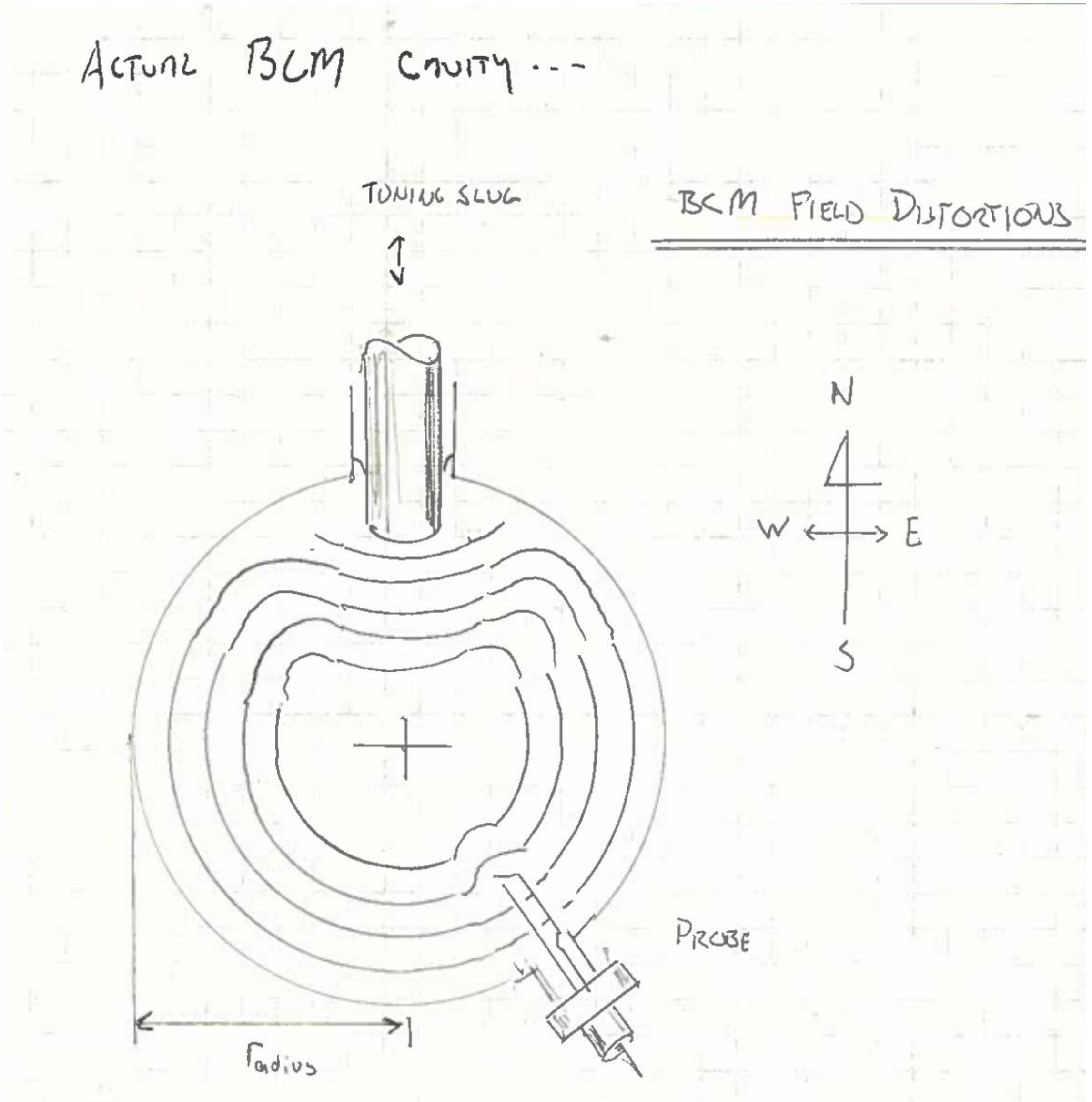
Not seen (?) in CREX at ~120 Hz, but see caveats below

MOLLER

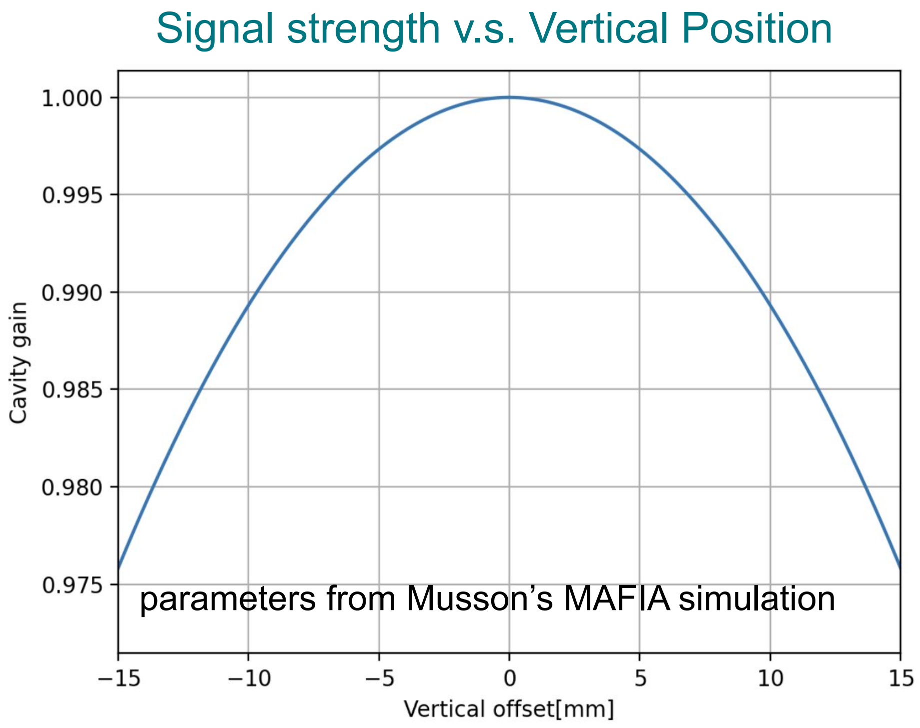
Potential sources of noise

- Large beam jitter (in particular position) during transition between the helicity windows
  - We did not sync to the helicity windows and we integrate over these transitions
  - If this is the source, it would be (fairly easily, FLW) handled by feeding the helicity signal into our data stream (needs to be done for MOLLER anyway)
  - Not clear though why it scales as 1/f
- Systematics in the BCM-based measurement ?
  - Halo and other losses between cavities — that could scale as 1/f
  - Phase and tune drifts ? — also scales as 1/f.
    - Tested cables on the bench at LBNL but not in situ — did not see a smoking gun

Position dependence of BCM signal



Courtesy of John Musson



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To contribute to asymmetry, requires

1. cavity mis-alignment, and
2. time-dependent beam position
   a. beam position fluctuation
   b. raster

Implies requirement on relative alignment of the cavity electrical centers to ~1mm or regression of BCM signal against BPM signals

Lessons Learned

- There is nontrivial beam structure around the 1497 MHz carrier frequency: AM-modulated intensity
  - Time-multiplexing beam signals at ~1 MHz is dangerous and should be avoided
  - In discussion with JLab beam instrumentation group to remove mux from the JLab BCM readout (written in requirements document)
- Important to integrate BCM signals over the correct helicity windows
- Being able to regress/correct against beam position would be useful

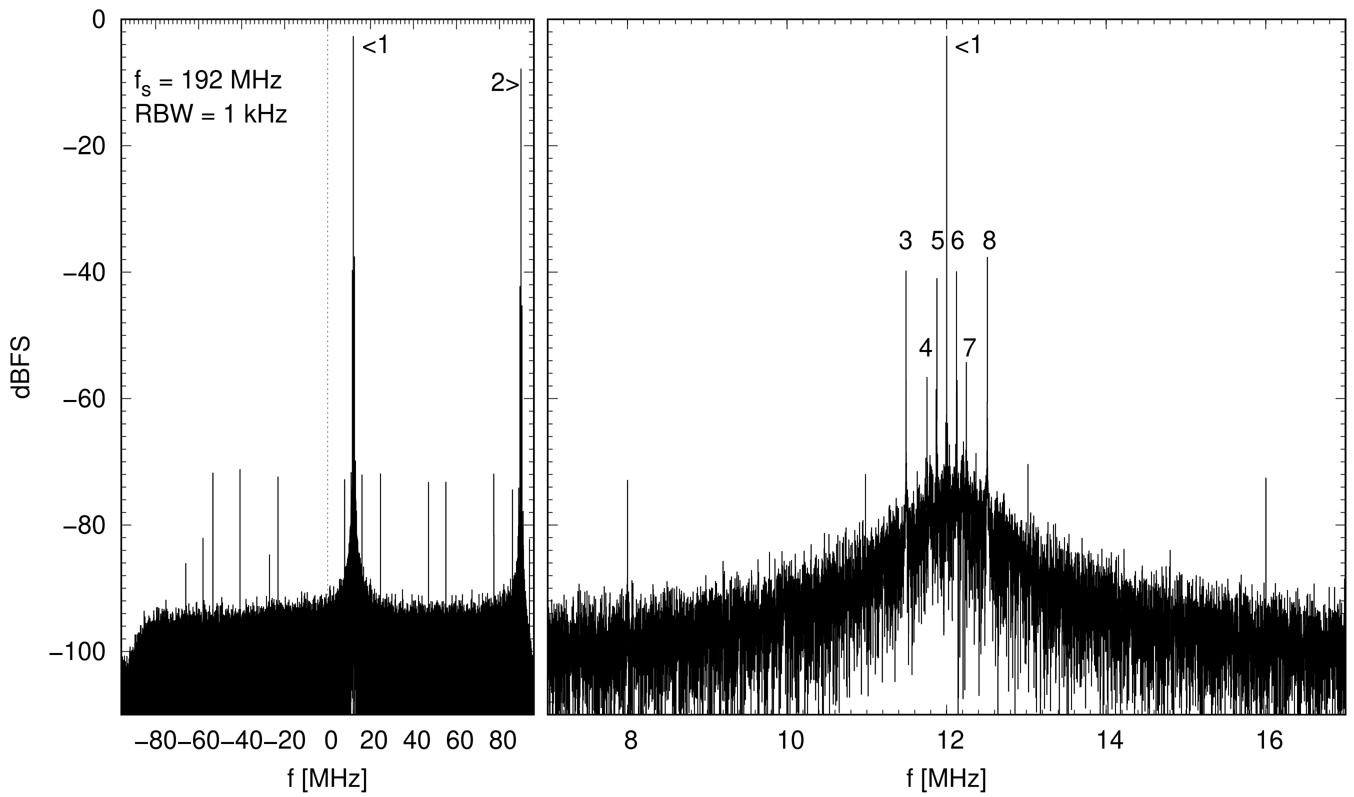


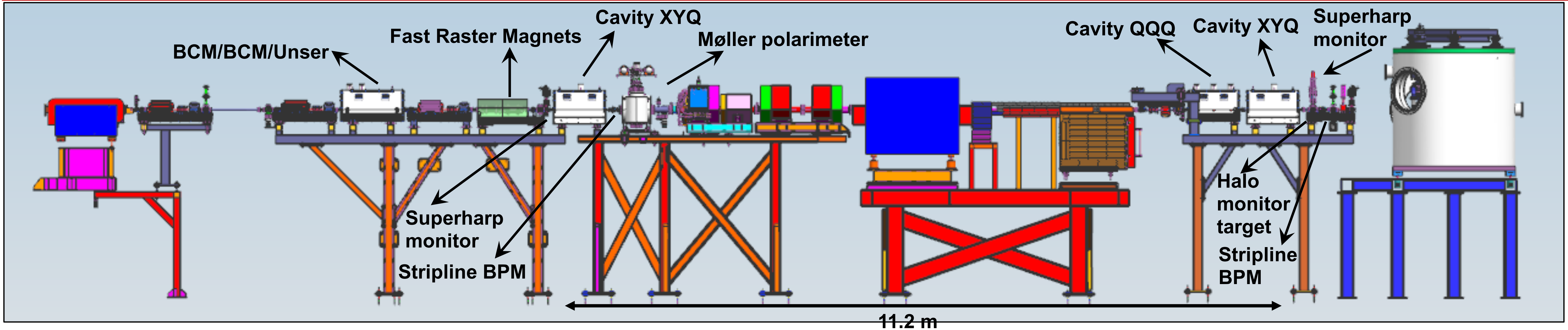
Figure 8. Power spectrum of a representative cavity signal induced by 130 μA beam. NCO is set to 1485 MHz and is digitally mixed with the input and then decimated by a factor of 16, resulting in an effective sampling rate of 192 MHz. The 1497 MHz input signal appears as two mixing product peaks marked 1 and 2 at 12 MHz and 90 MHz, respectively. Both I and Q are recorded and combined to compute the power spectrum via complex-input FFT, as shown in the left panel. The right panel shows a zoomed-in view around peak 1, which is of primary interest.

Implementation in MOLLER

- Would ideally upgrade from NI digitizer+Xilinx FPGA to an integrated Xilinx Zynq RFSoC (e.g. ZU48DR on a ZCU208 eval board)
  - 8 channels @ 5 GSPS, 14 bits: sufficient specs
  - FMC mezzanine slot, e.g. for helicity sync
  - ARM processor can run an instance of CODA
  - Similar architecture to the TRIUMF digitizers: can share firmware/software
  - Would need 1 module for BCMs, 2 if include BPMs

- Alternative is to duplicate our existing 4-channel box to read out 5 BCMs (and possibly 6 BPMs)
  - Would need 1-2 additional boxes
  - Helicity sync and DAQ interface more complicated
- Need to plan commissioning/beam tests carefully

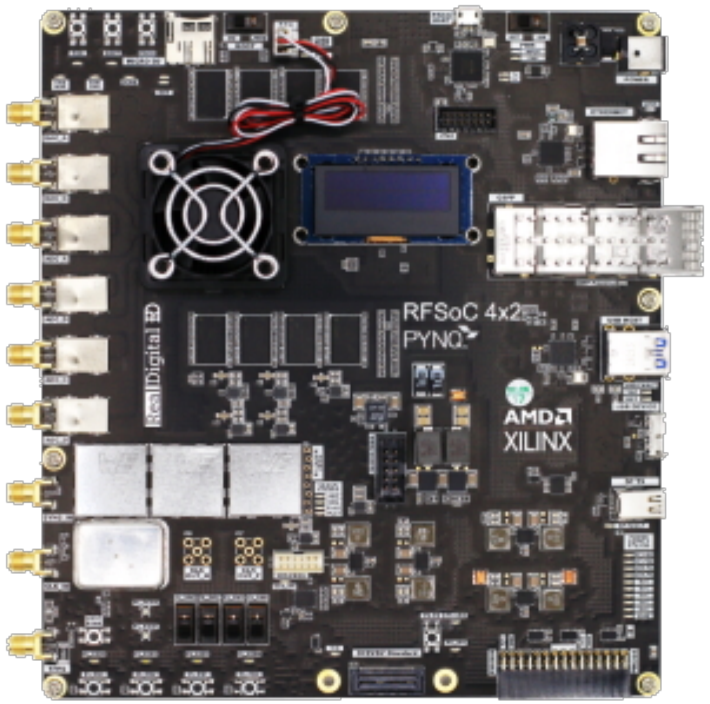
Implementation in MOLLER



- 11 cavity monitors (5 BCMs, 6 XYQ)
  - Some used for beam feedback and control: would need to split signals between MOLLER and JLab processors/DAQ
  - Could instrument all or some: absolute minimum would be 2 BCMs
- Ideally would amplify the signals in the Hall A labyrinth
- Ideally would retune BCMs for higher Q

Progress Since 2022

- No funding at Berkeley for this work — have to scavenge for resources
- Procured RFSoC 4x2 kit (RFSoC-PYNQ) to test functionality
  - A student brought it up, measured amplitude and phase noise — seems adequate
  - Developments synergistic with my other projects (and Aled is working with this board at UCSB) — can make some progress without MOLLER-specific funds
  - Incoming Berkeley graduate student interested in MOLLER will (hopefully) start working with this system in the Fall
- Ultimately, if MOLLER is interested in this technology, we'll need to find a way to pay for the development



Summary

- Internal noise (8 ppm) of the digital BCM processor satisfies MOLLER specs, could be further improved
- Noise performance in the beam test not (quite) up to spec; needs to be understood
- Need implementation and deployment/commissioning plan
- Started discussions with the DAQ group about integration with the DAQ
  - Ideally, BCM processor would look very similar to the MOLLER digitizers with the new Zynq RFSoC

Backup

Noise Budget

- Noise budget/requirements for σ_Q/Q<14 ppm: assume fs=3 GHz and ΔT=0.5 msec
- Digitizer (white) noise

$$\frac{\sigma_Q}{Q} = 2^{-\mathrm{ENOB}+3/2} \cdot \frac{1}{\sqrt{f_s \Delta T}} \rightarrow \text{ENOB} > 8 \text{ bits}$$

- Thermal noise: -124 dB @ 2 kHz for beam signal of -18 dBm → σ_Q/Q ~ 0.6 ppm
- Phase noise (uncorrelated time jitter, though mindful of *1/f* contributions):

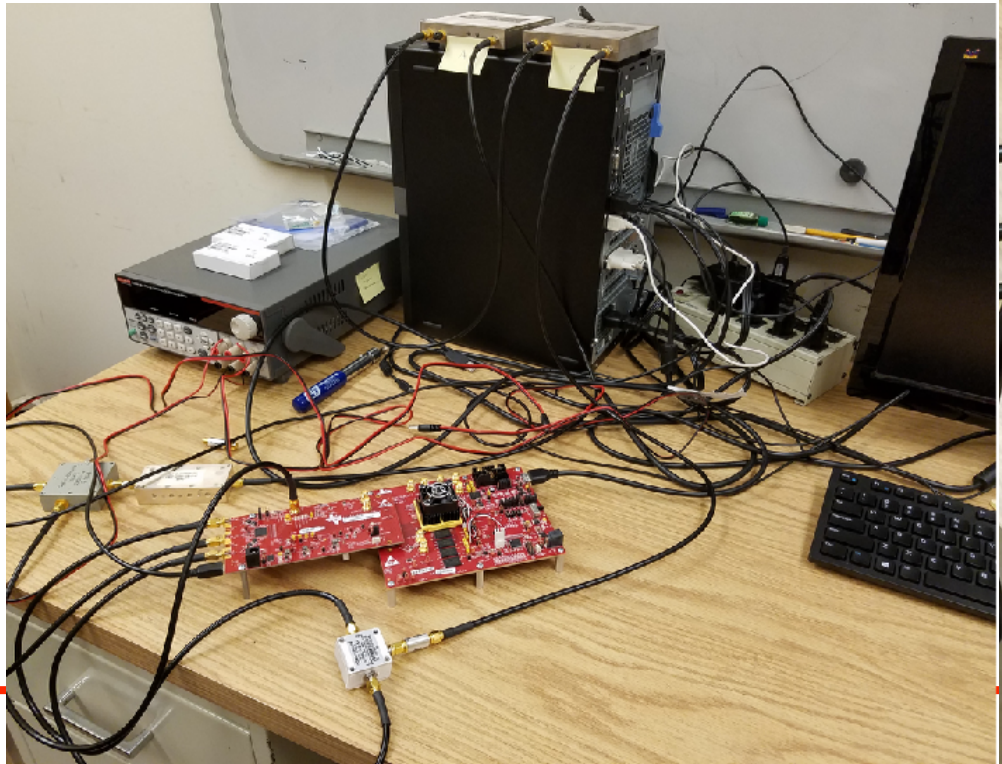
$$\frac{\sigma_Q}{Q} \sim \frac{\pi f \sigma_t}{\sqrt{f_s \Delta T}} \rightarrow \sigma_t < 3.6 \text{ psec}$$

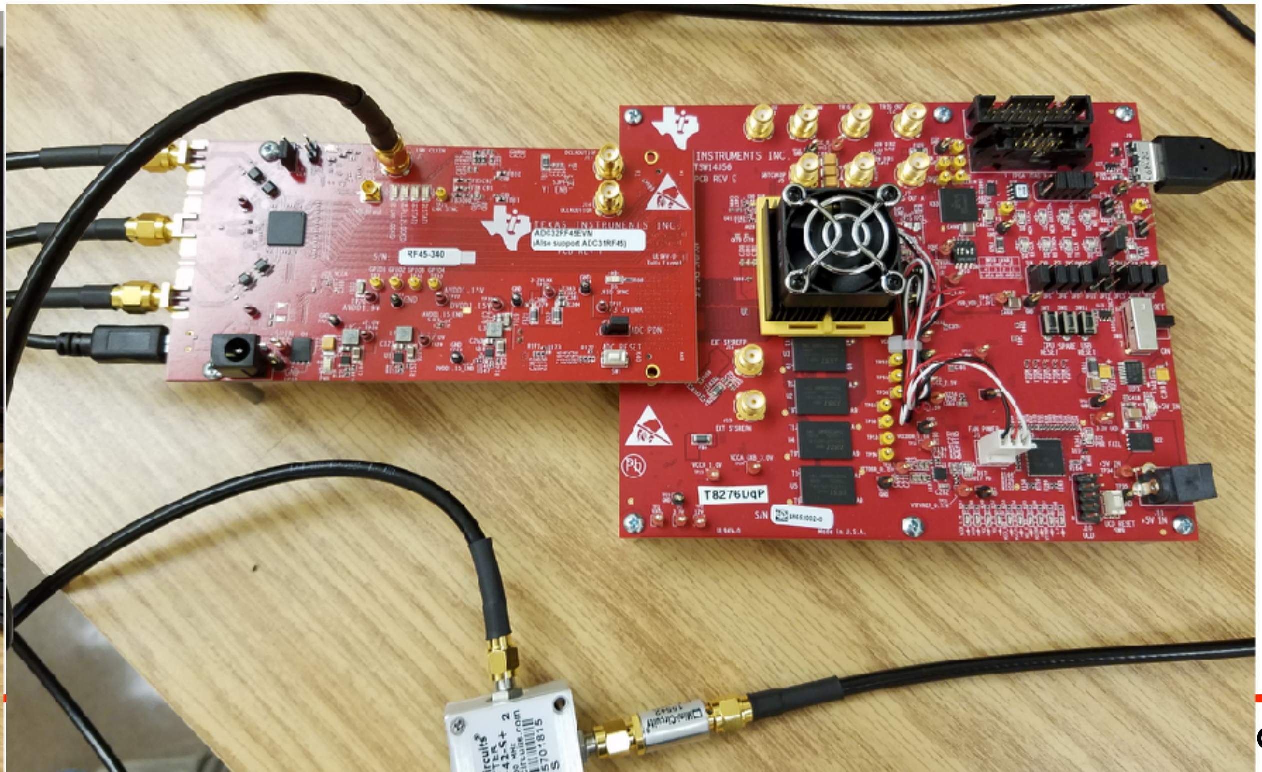
  - Simulation by Joe Camilleri: σ_t <~ 1 psec
- Spec of σ_Q/Q<14 ppm achievable with currently available hardware

BCM Digital Receiver Prototype

Joe Camillieri

- LDRD at LBNL
  - FY18: prototyping, bench tests
  - FY19: full hardware/firmware implementation, beam tests
- Prototype based in TI ADC32RF45 evaluation board and ADC capture card; stream raw data to disk (~200 msec → 2 GB)
  - 14-bit ADC but limited to 12 bits by JESD204B interface with capture card
- Offline analysis (DDC, averaging, asymmetry analysis)





RF Clock

- ERA Instruments ERASynth+: software-configurable, low-jitter RF generator; oven-controlled oscillator
- Use two phase-locked generators
  - 3 GHz clock
  - RF signal (<1.5 GHz)
  - Split signal between 2 input channels of the ADC (typically 9 dBm/channel)

RF clock: phase noise

Adequate for 10 ppm resolution

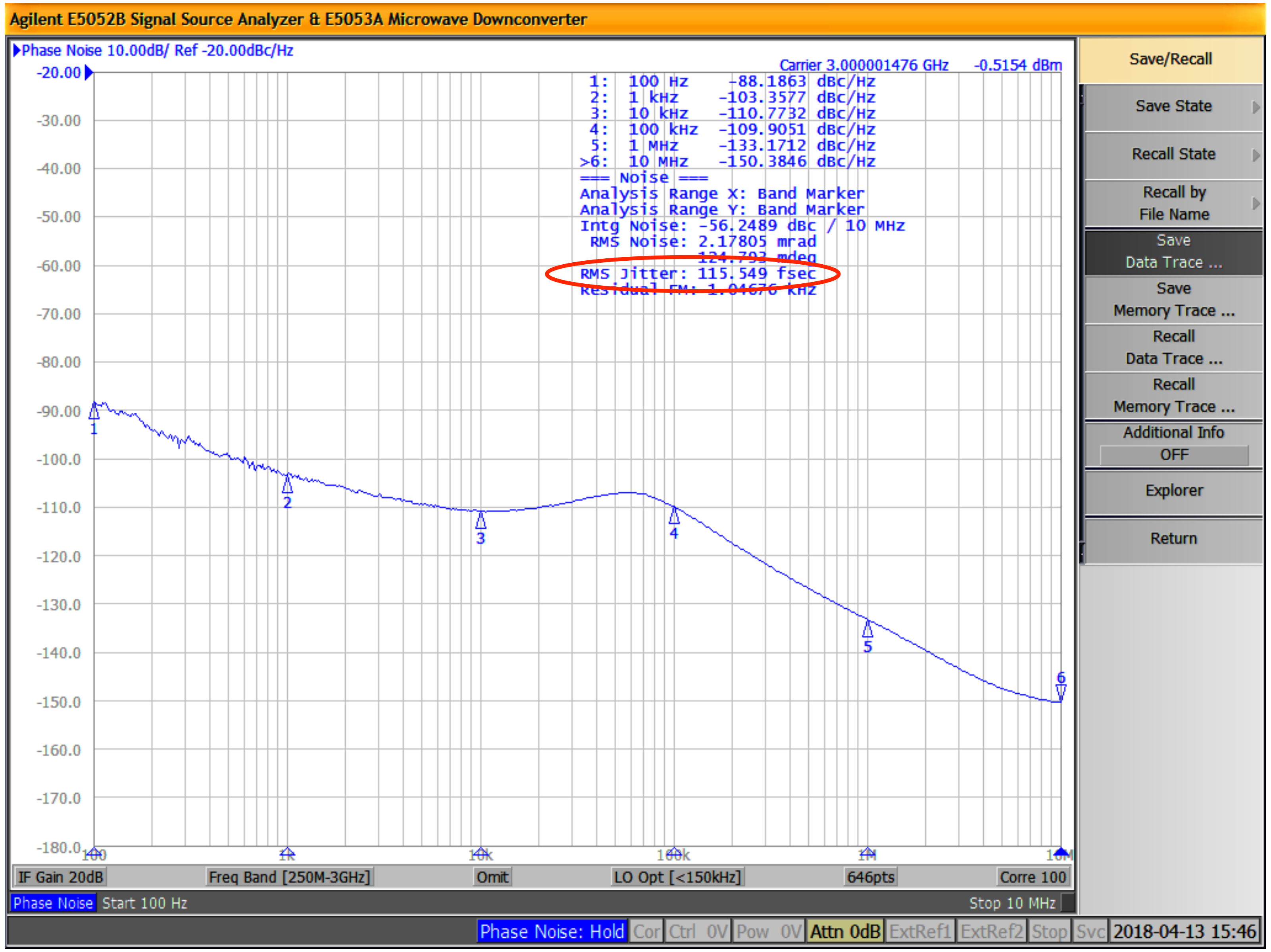
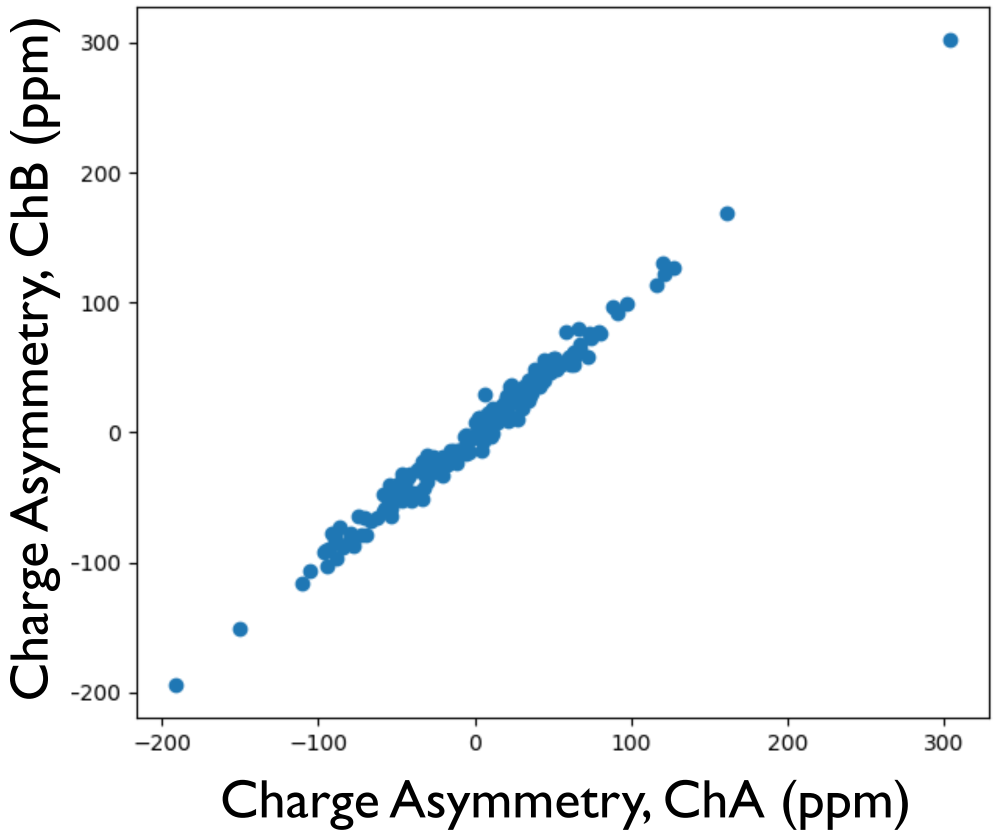


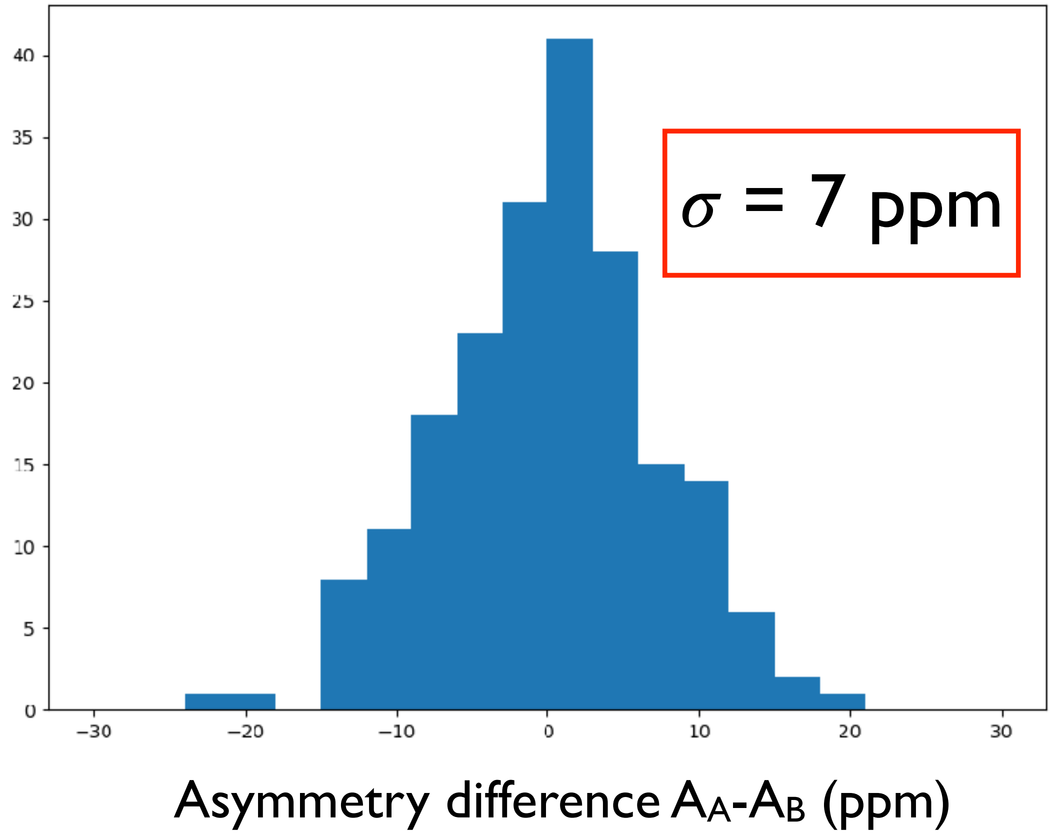
Figure 27: ERASynth+ Phase Noise Performance at 3 GHz RF Output

Performance

James Egelhoff

1 kHz pairs
1497 MHz, +9 dBm input signal per channel
3000 Msps, 12 bit digitizer





Performance

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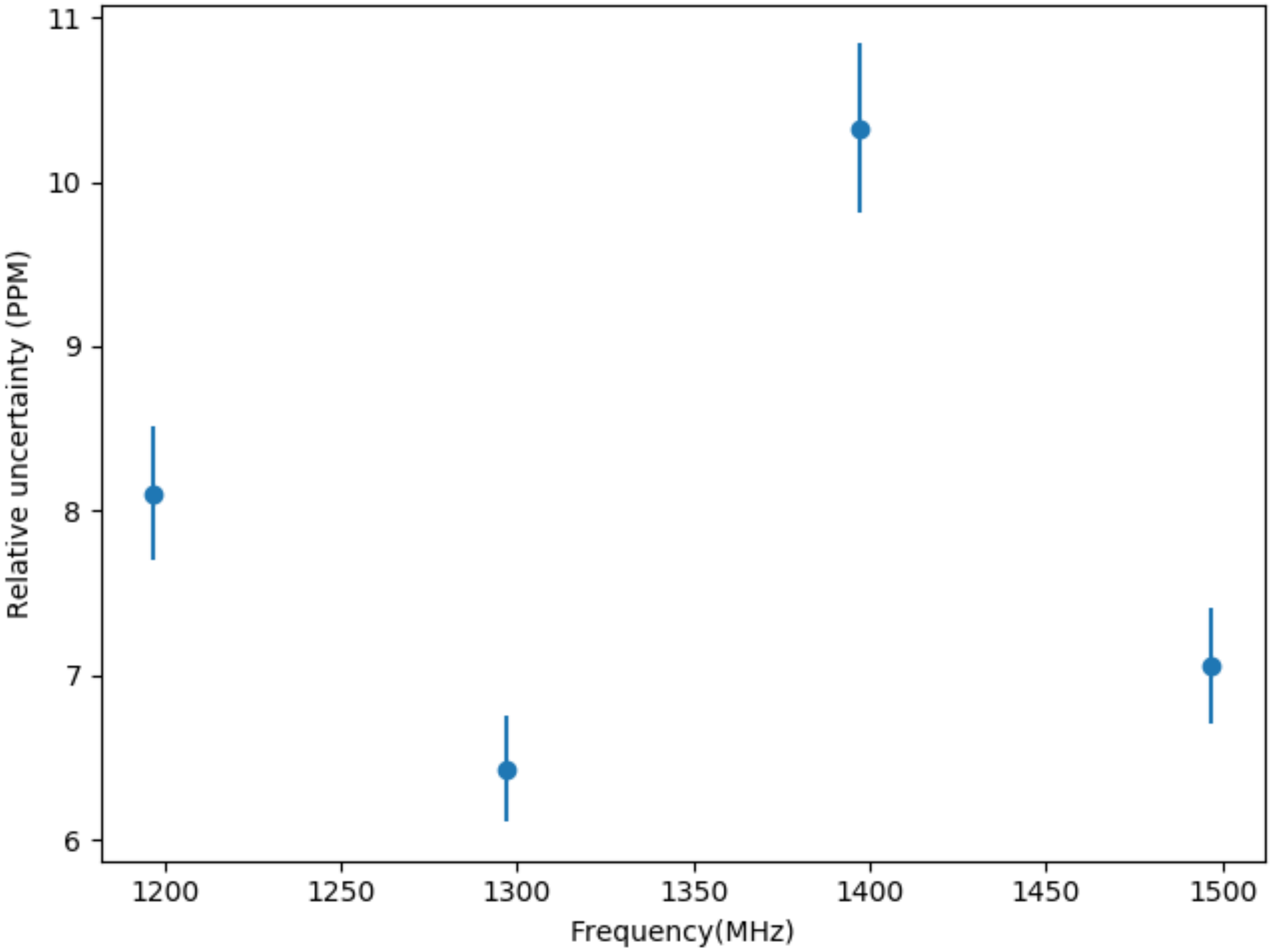
Resolution (ppm)



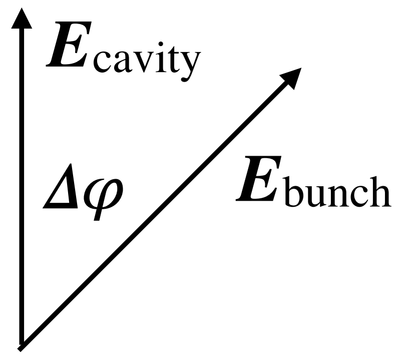
Systematics: phase drifts

- Quadrature sum of I/Q demodulated signals is relatively insensitive to slow phase drifts

$$A = \sqrt{I^2 + Q^2}$$

  - at the cost of 3 dB increase in noise
- Slow phase drifts with f<500 Hz cancel out to good precision in helicity quads
- Will simulate residual sensitivity to drifts of the cable delay (phase drift) and drifts of the cavity frequency
- Will develop firmware to monitor/calibrate cavity frequency
- If necessary, can deploy phase stabilization hardware developed for LCLS-II

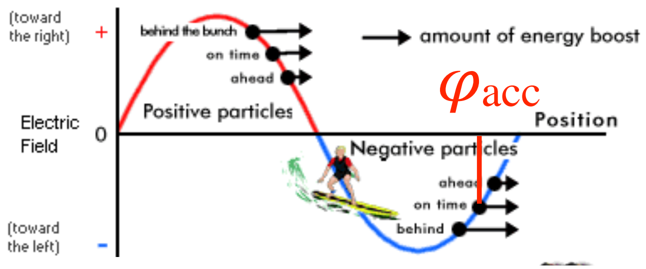
Potential Systematics: beam phase jitter



- Cavity BCMs introduce one potential systematics into the measurement of charge: they do not measure beam charge directly
- Signal induced by each bunch is a projection of the its phasor onto the EM field phasor of the cavity, i.e.

$$\mathbf{E}_c \cdot \mathbf{E}_b \propto q_b \cos \Delta\phi$$

  - Naive calculation: assume that the phase shift is *uncorrelated* bunch-to-bunch, i.e. it is dominated by white noise
  - Then $\sigma_Q/Q<14$ ppm → to $\sigma_\varphi<0.1$ rad for bunch frequency of 250 MHz and 0.5 msec
  - Such jitter seems unlikely: beam energy spread is $\sim\sigma_\varphi \sin\varphi_{acc}$, and σ_E of a few percent seems large
  - However, correlated phase shifts could be a problem (correlates energy spread and charge error from cavity BCM)



Do We Need to Worry ? (thanks Kent)

- Consult beam physicists: they should know what the bunch phase jitter is and whether there is a large *1/f* component
- If the phase jitter is large for us to worry about, can measure its effect on the BCMs by comparing cavities tuned to different harmonics of the bunch frequency

$$\sigma(\phi_{\mathrm{BCM}}) = 2\pi f_{\mathsf{cavity}}\sigma(t_{\mathrm{bunch}}) = \frac{f_{\mathsf{cavity}}}{f_{\mathsf{acc}}}\sigma(\phi_{\mathrm{bunch}})$$

  - E.g. build a pair of cavities tuned to 4th harmonic, 998 MHz.
  - They should not be that large, and can be anywhere in A-line