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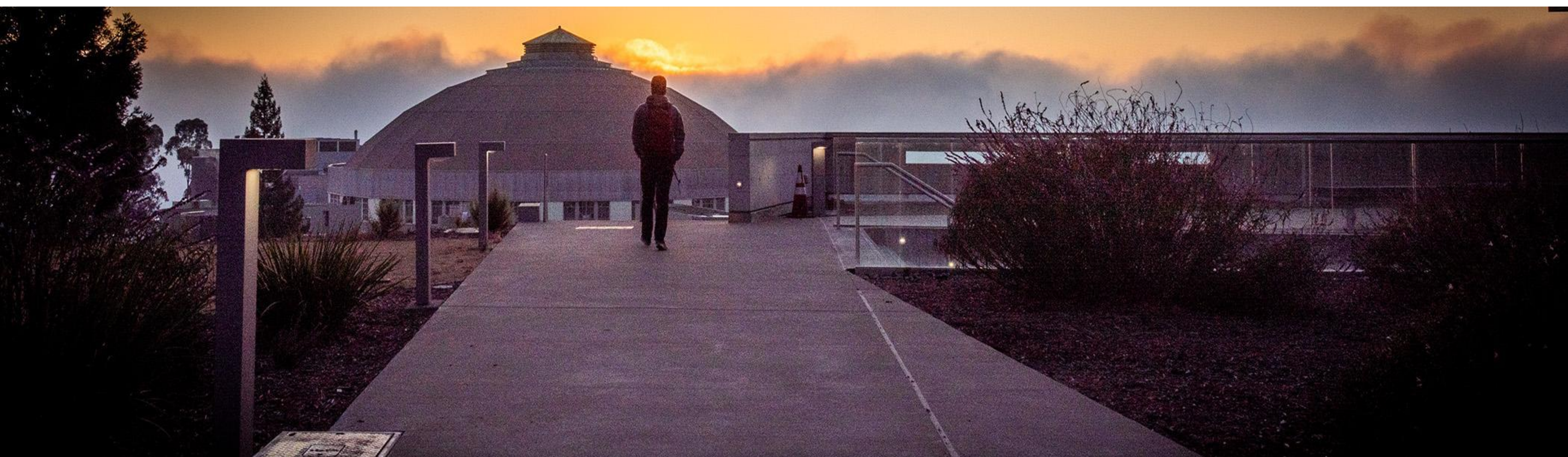
The Direct RF Sampling Digital BCM for the MOLLER Experiment at Jefferson Lab

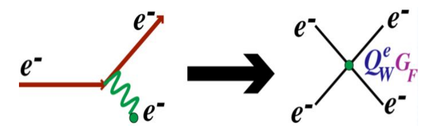
Shujie Li, John Arrington, Joe Camilleri, Kerri Campbell, Aled Cuda, James Egelhoff, Yury Kolomensky, Yuan Mei, Ernst Sichtermann, Vamsi Vytla

Feb 10, 2022

JLab Hall A Winter Meeting

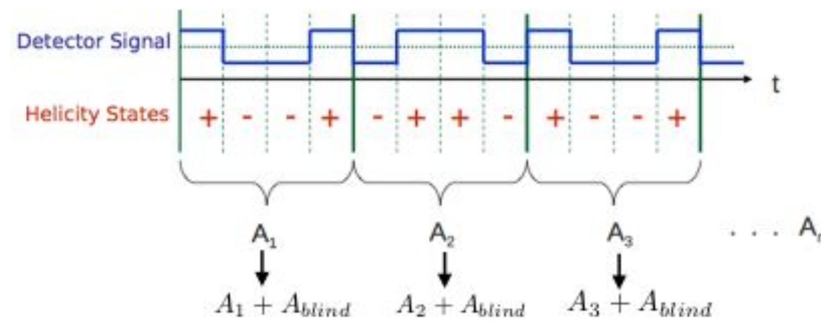


JLab E12-09-005: The Measurement of a Lepton-Lepton Electroweak Reaction (MOLLER)



Parameter	Value
E [GeV]	≈ 11.0
E' [GeV]	2.0 - 9.0
θ_{cm}	$50°$-$130°$
θ_{lab}	$0.26°$-$1.2°$
$< Q^2 >$ [GeV^2]	0.0058
Maximum Current [μA]	70
Target Length (cm)	125
ρ_{tgt} [g/cm^3] (T= 20K, P = 35 psia)	0.0715
Max. Luminosity [cm^{-2} sec^{-1}]	$2.4 \cdot 10^{39}$
σ [μBarn]	≈ 60
Møller Rate @ 65 μA [GHz]	≈ 134
Statistical Width(1.92 kHz flip) [ppm/pair]	≈ 91
Target Raster Size [mm]	5 x 5
Production running time	344 PAC-days = 8256 hours
ΔA_{raw} [ppb]	≈ 0.54
Background Fraction	≈ 0.10
P_{beam}	$\approx 90\%$
$< A_{pv} >$ [ppb]	≈ 32
$\Delta A_{stat} / < A_{expt} >$	2.1%
$\delta(\sin^2\theta_W)_{stat}$	0.00023

MOLLER CDR



- Integrate counts over each helicity state at 1.92 kHz
- Yields normalized to the Beam Charge Monitors

- counting statistical width = **91 ppm** , to keep the beam intensity measurement an insignificant source of noise:
  BCM resolution ~ **10 ppm**

Experiment Requirements on BCM

MOLLER science goals require precision measurement of (false) beam-induced asymmetries:

- Rapid flips of the longitudinal polarization of electrons: **2 kHz (0.5 ms)** helicity flip rate
- Beam charge asymmetry measurement with 10ppm resolution:
  - $asym = \frac{RMS_{n+1} - RMS_n}{RMS_{n+1} + RMS_n}$
  - **"double difference" b/w two BCMs (asym_A - asym_B)/√2 < 1e-5**

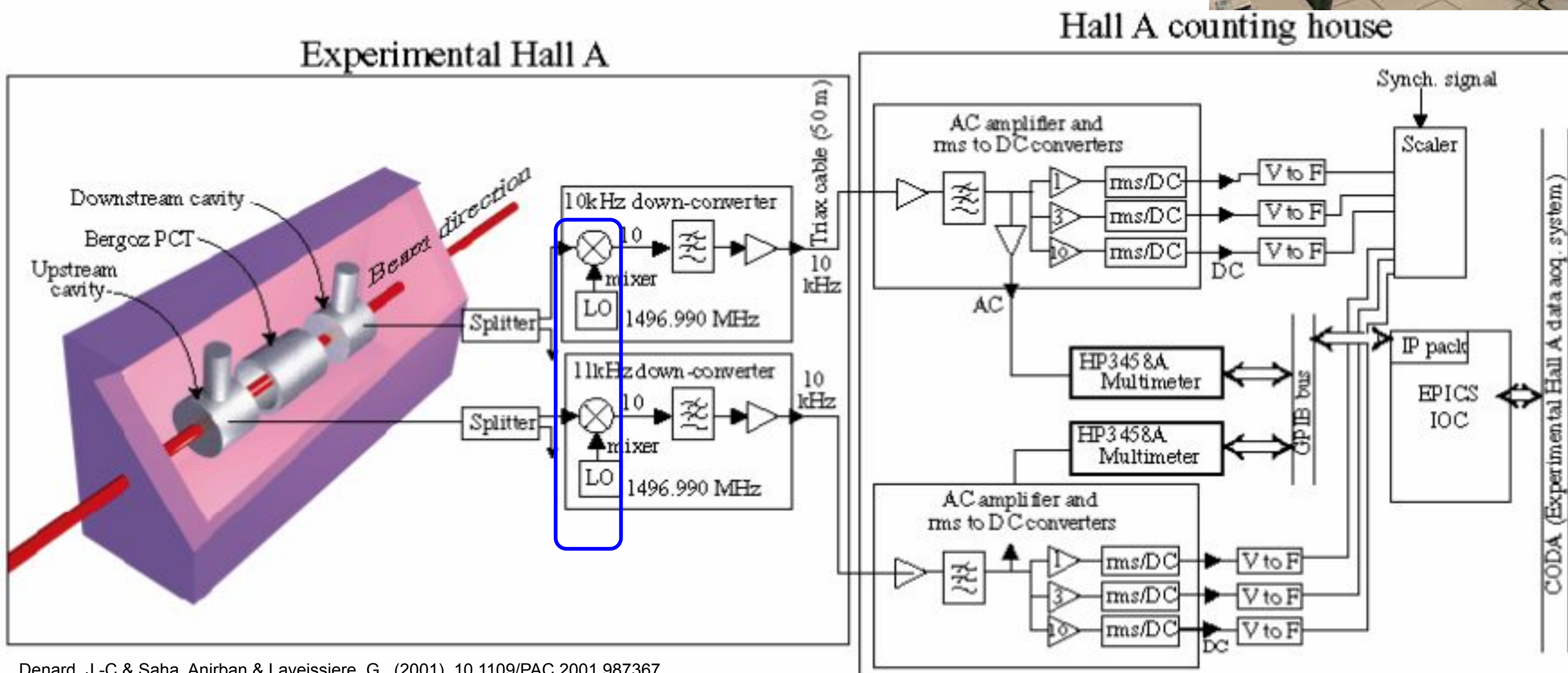
Parameter	Jitter requirement	Achieved	Resolution requirement	Achieved
Charge	< 1000 ppm	500 ppm	< 10 ppm	65 ppm
Energy	< 108 ppm	6.5 ppm		
Position	< 47 μm	48 μm	< 3 μm	2.4 μm
Angle	< 4.7 μrad	1.4 μrad		

Information from Moller CDR

- Current state of the art (Qweak): **~65ppm** for 480 Hz window pairs (960 Hz helicity flip)
- Best bench test result (Moller CDR): **~42ppm** for 960 Hz window pairs (1920 Hz helicity flip)
- This new BCM device: bench test **8.1ppm**, beam test **24.5ppm** for 2kHz helicity flip

Standard Hall A BCM System

- Analog mixer
- Limitation (most likely): Local Oscillator amplitude and phase noise



Denard, J.-C & Saha, Anirban & Laveissiere, G.. (2001). 10.1109/PAC.2001.987367.

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- Analog mixer
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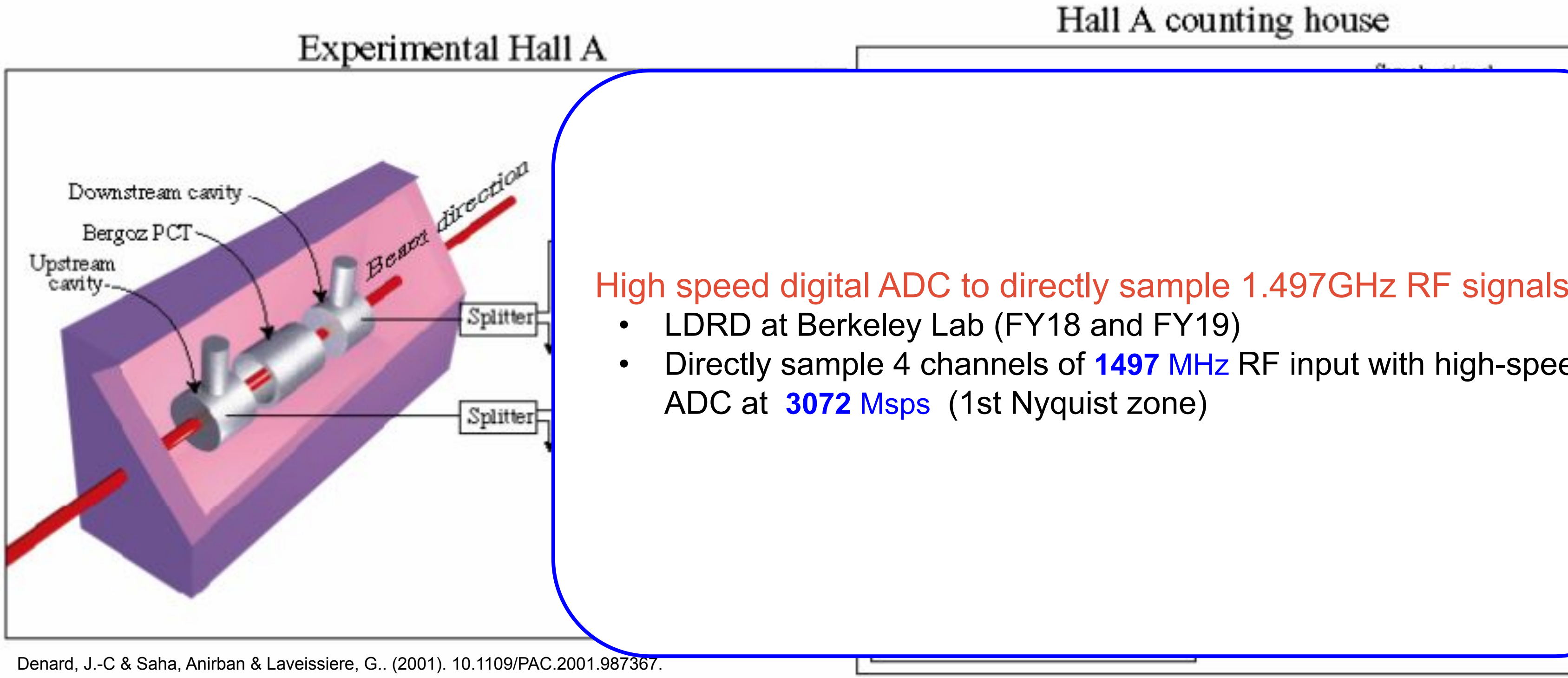


High speed digital ADC to directly sample 1.497GHz RF signals

- LDRD at Berkeley Lab (FY18 and FY19)
- Directly sample 4 channels of **1497** MHz RF input with high-speed ADC at **3072** Msps (1st Nyquist zone)

Denard, J.-C & Saha, Anirban & Laveissiere, G.. (2001). 10.1109/PAC.2001.987367.

Y. Mei et al. arXiv:2110.09575, submitted to JINST

Beam test in Hall-A in Sept. 2020

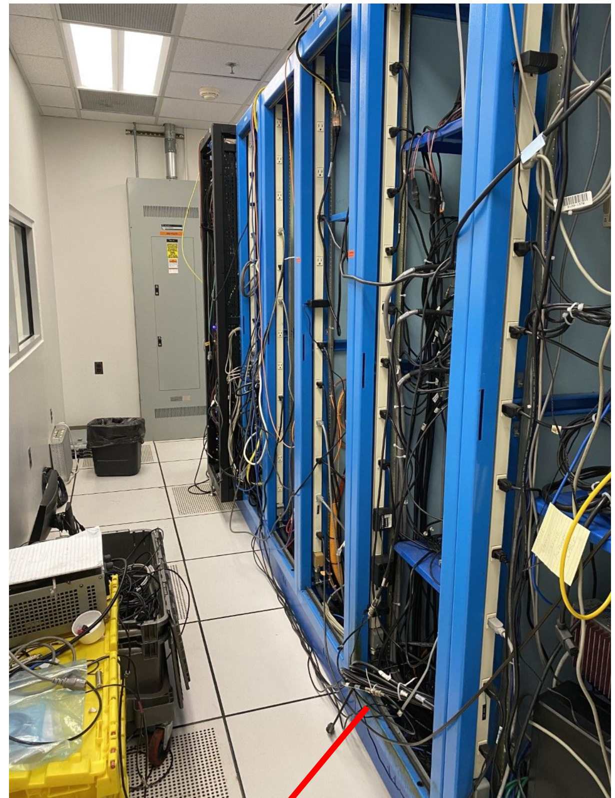
Temporary installation location

3 pieces:

- 1 RF receiver box (3 rack-unit)

- 1 server (2 rack-unit)

- 1 small desktop (can be stack on top of the rack)



with a lot of help from John Musson, Ole Hansen,Caryn Palatchi, Kent Paschke

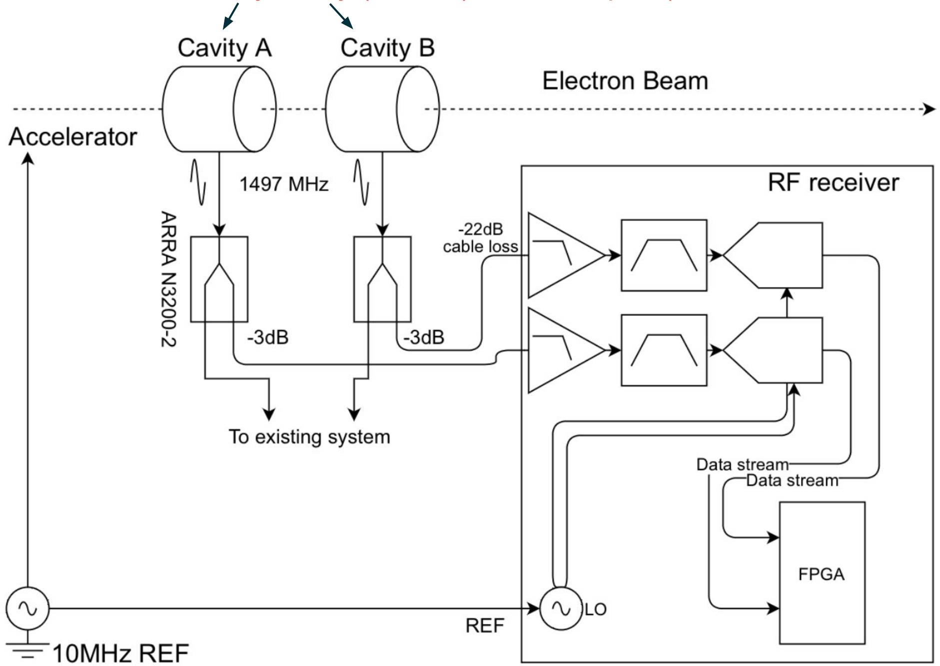
2 copies of cavity signals

Beam test in Hall-A in Sept. 2020

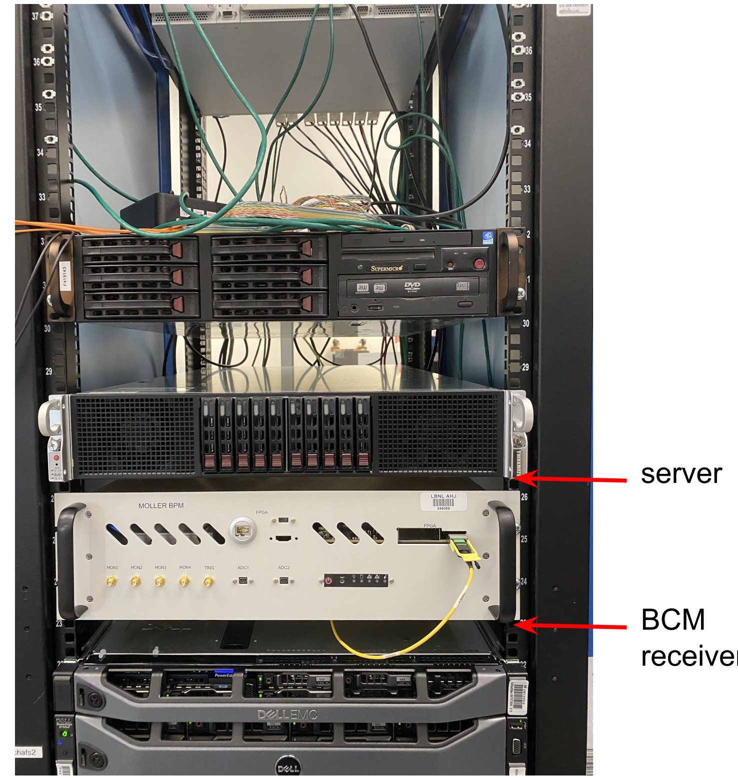
- Beam test in Hall A : Parasitic running during CREX (September, 2020)
  - no beam, tune beam, 0-150uA
  - didn't sync with 120 Hz helicity flips

- 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



Signal Processing within ADC

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

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

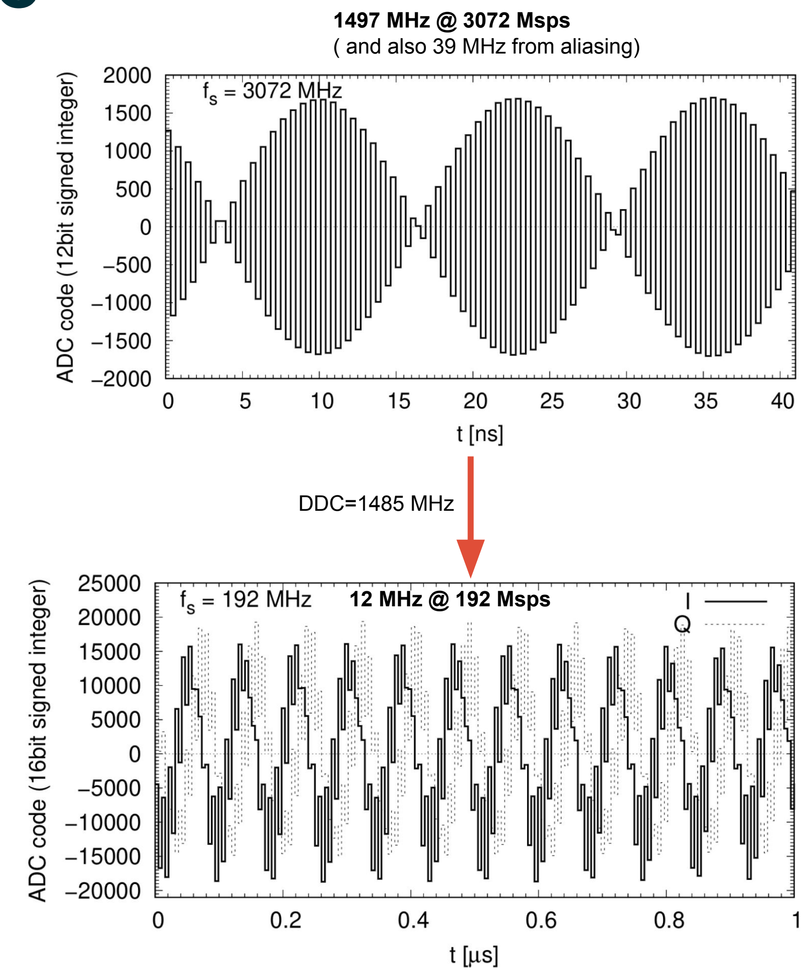
$y_i = I_i + \mathbf{j}Q_i$, two freq. $f_0 + f_1$ and $f_0 - f_1$.

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)



System Linearity test 1: in-hall test with two tones

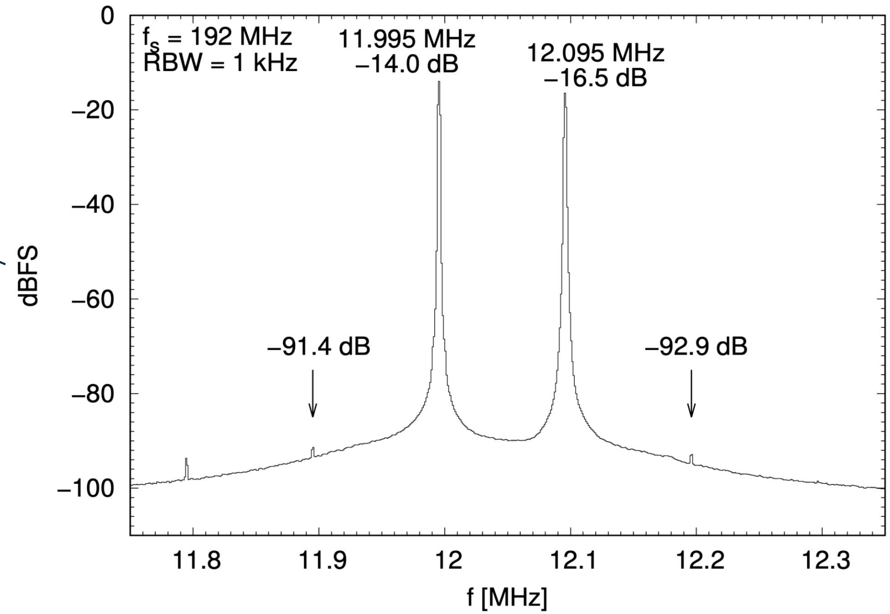
Injected signals: 1497, 1497.1 MHz

3rd order intermodulation:
increases 3dB when main signal increased 1dB

	f1=11.995 MHz	f2=12.095 MHz	2*f1-f2	2*f2-f1
dBFS	-14.0	-16.5	-91.4	–92.9

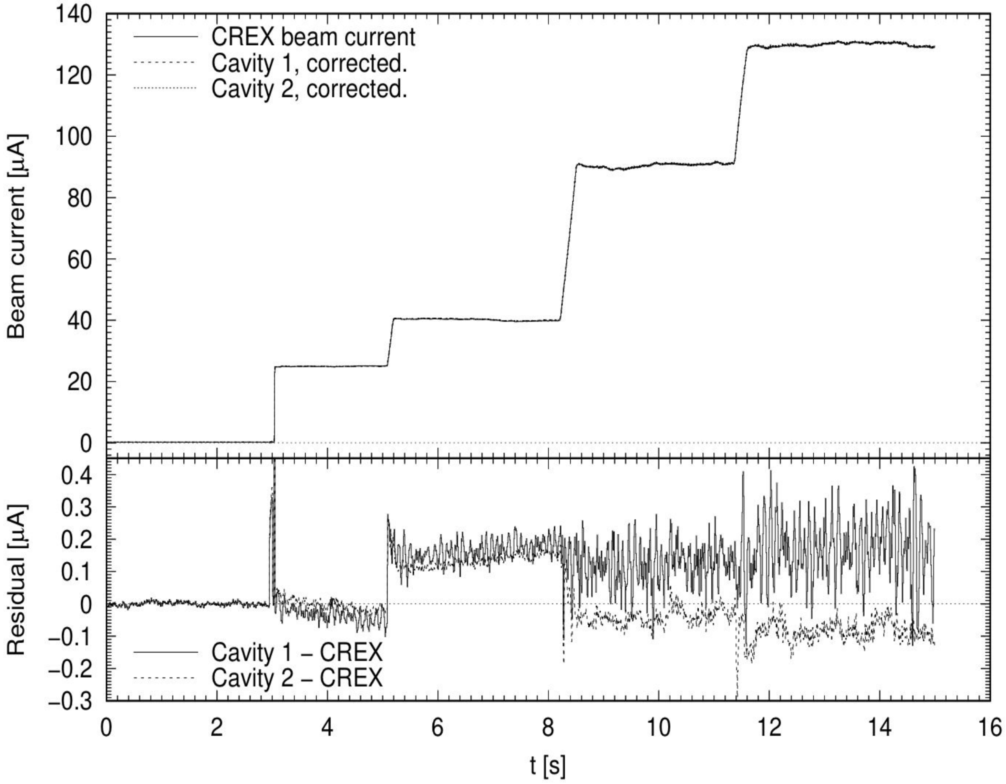
The **3rd order intercept point** IP3 ~ -14+(-14-91.4)/2 ~ 23 dB
Non-linearity = power(-2*IP3) / power(0 dBFS) ~ 1e-5

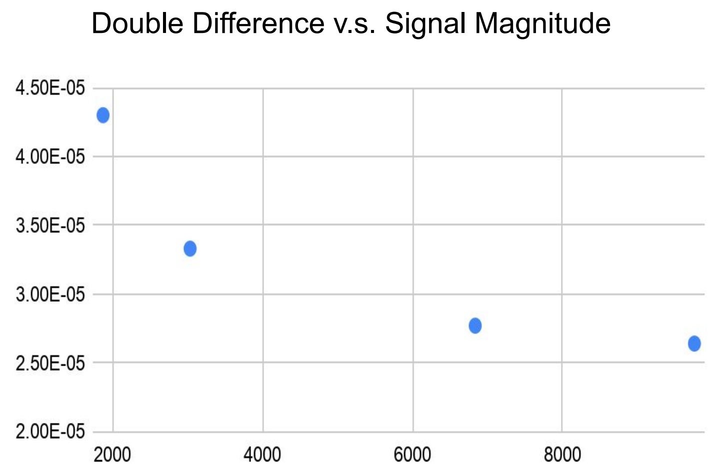
signal power
relative to full scale
sine wave



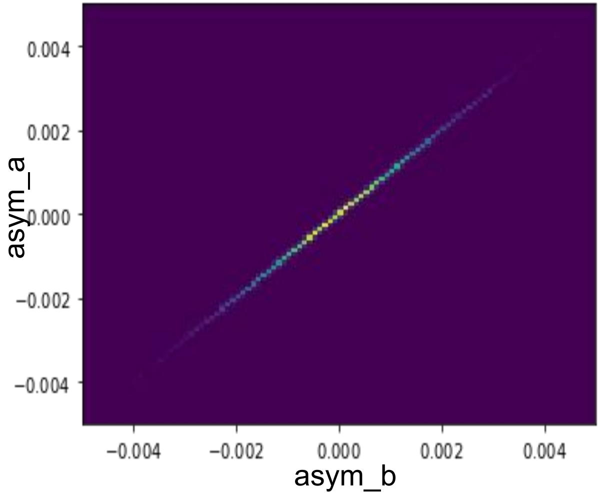
System Linearity test 2: Comparison of beam current measurements

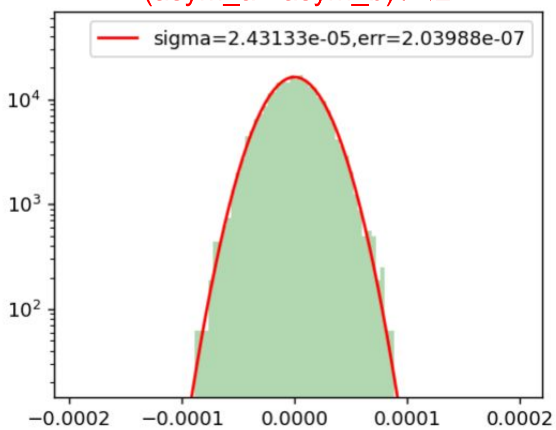
Beam current from this work v.s. CREX BCM (run 8548)





“Double-difference”





With 2000 Hz (0.5 msec) integration window:

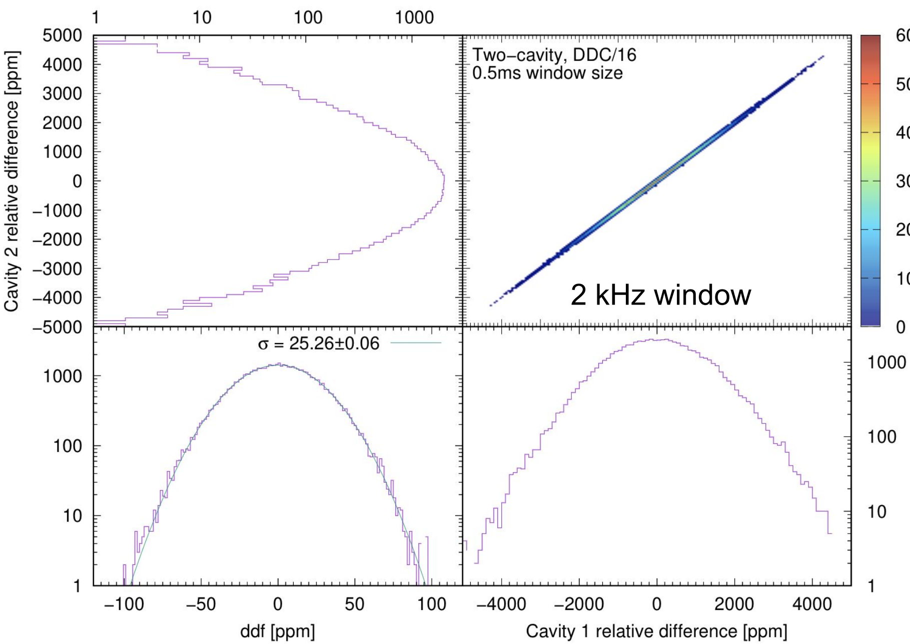
- Calculate RMS and asymmetry for each RF signal (“I” and “Q”)

$$asym = \frac{RMS_{n+1} - RMS_n}{RMS_{n+1} + RMS_n}$$

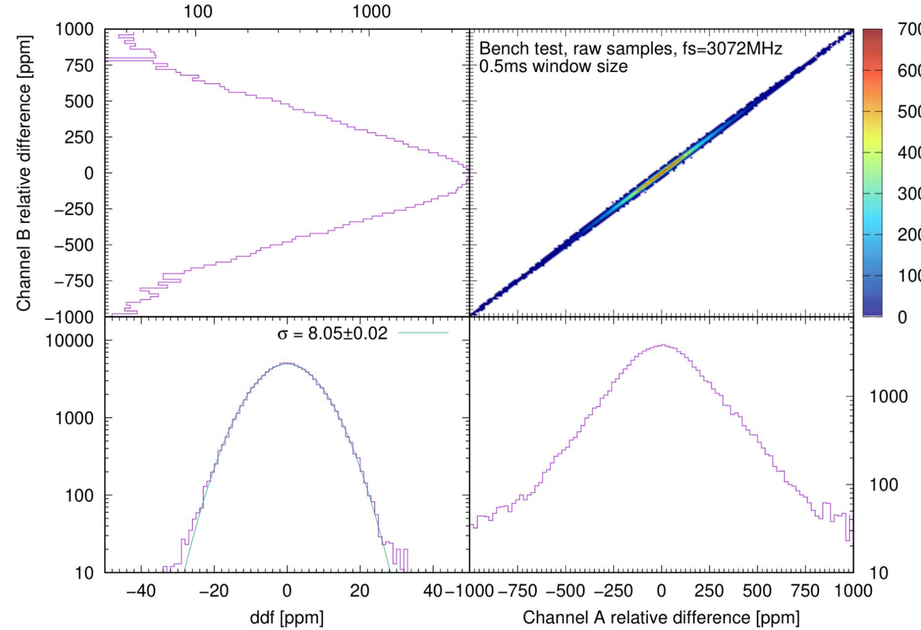
- Correlate signals from two BPMs (channel a and channel b), the width of asymmetry ellipse (double difference) indicates the contribution from white noise:
  - use “I” or “Q” signal from each channel: **25 ppm**
  - use : $\sqrt{(I^2 + Q^2)}$ from each channel: **24.5 ppm**
- “I” and “Q” are numerically computed in ADC. There appears to be sizable numerical “error”**:**
  - correlate “I” and “Q” from the same channel: **8 ppm**

Performance

Best beam test result @ 2kHz: **24.5 ppm**

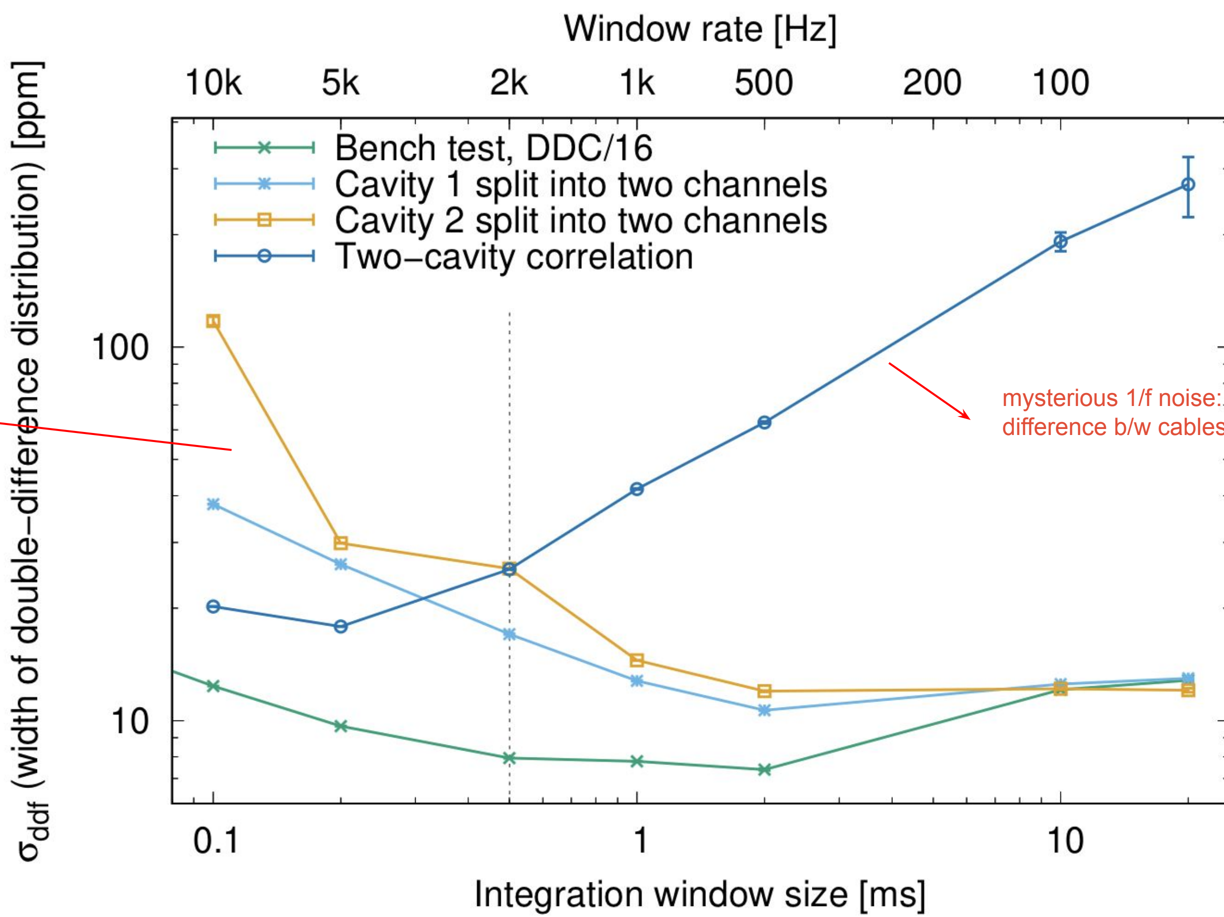


Best bench test result @ 2kHz: **8.1 ppm**



** After beam test, the BCM box was shipped back to LBL for more bench tests.

Double Difference v.s. Integration Window Size

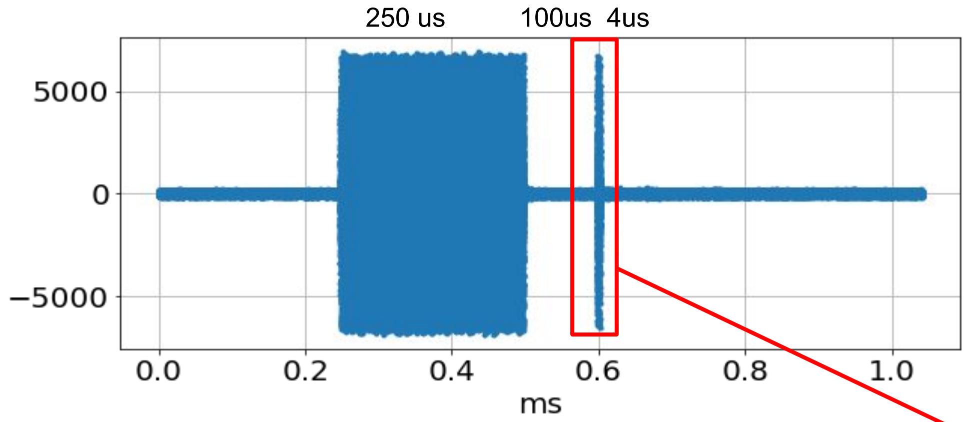


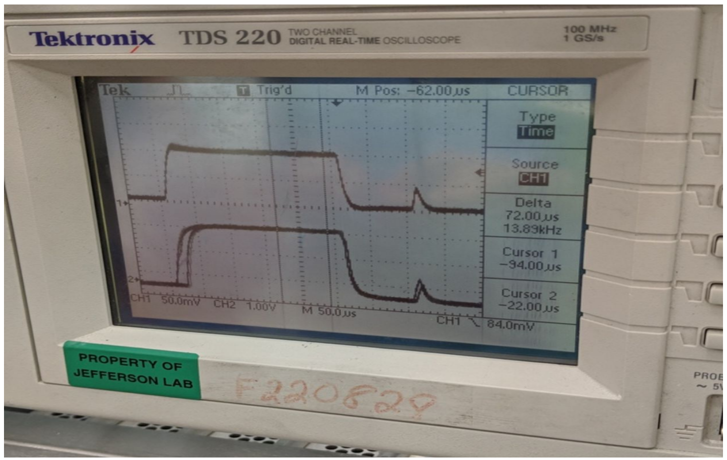
excessive amount of noise due to the lack of 10MHz reference.

mysterious 1/f noise: also seen by Qweak. Possible difference b/w cables/ cavities

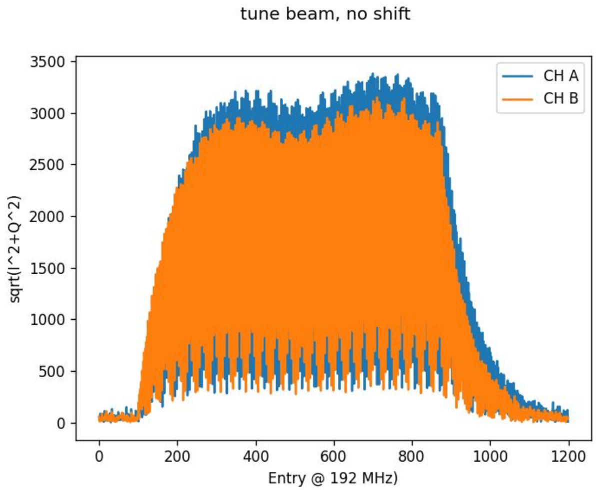
Possible Sources of Noise:

Time Dependence: 60 Hz tune beam check



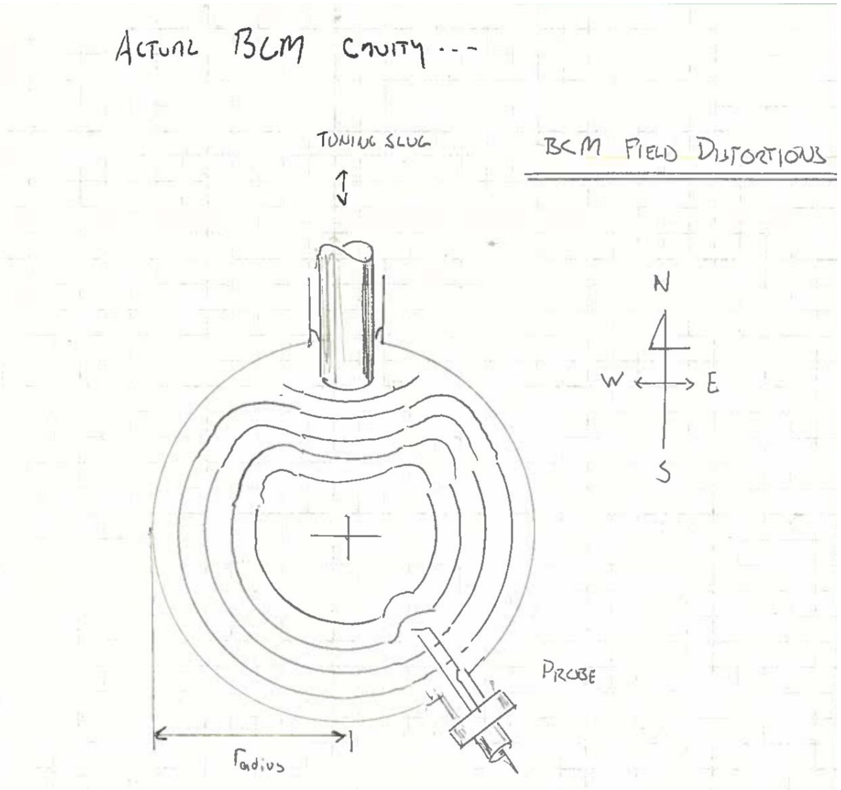


difference in cavity response time



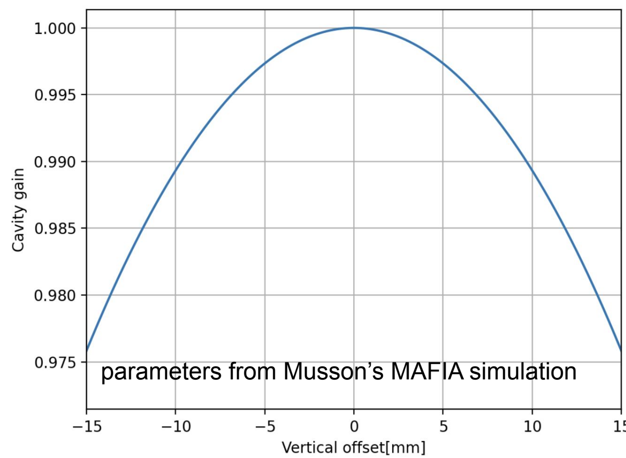
Possible Sources of Noise:

Beam position dependence: model



Courtesy of John Musson

Signal strength v.s. Vertical Position



To contribute to asymmetry, requires

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

Possible Sources of Noise:

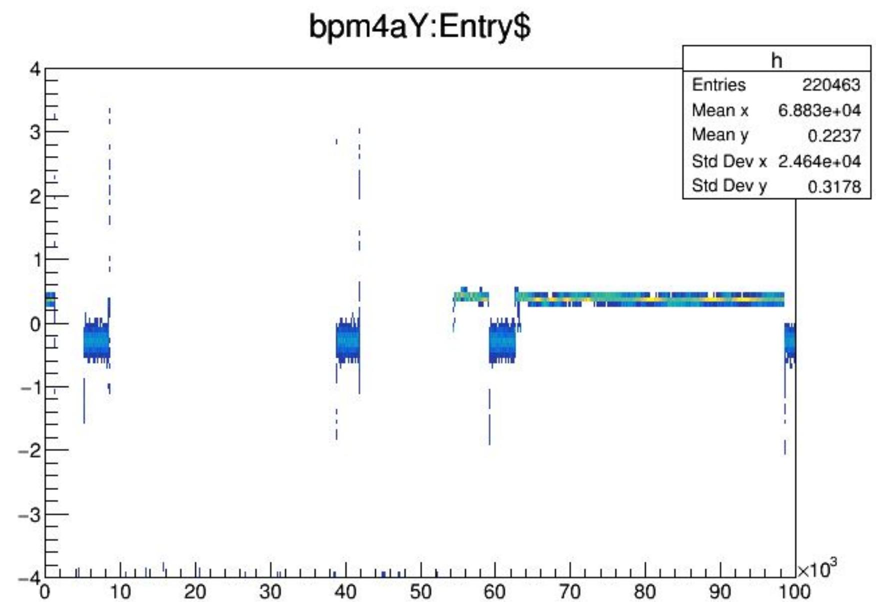
Beam position dependence: known beam conditions

CREX **raster**:

- frequency (close to 25kHz, and not repeating too often), see logbook
  - 213*120Hz = 25.559949 kHz
  - 205*120Hz = 24.599951 kHz
- Beam Size: 2mm x 2mm (beam spot: 200 um x 200 um)

CREX **BPM**:

beam position measured at 120Hz. Fluctuation could be averaged.



Summary and Future Plan

The BCM box is demonstrated to have 8 ppm resolution in bench test, but we observed 25 ppm noise with JLab beam (check our arxiv paper! https://arxiv.org/abs/2110.09575). That is already a big improvement from QWEAK (65 ppm)

next beam test (preferable in Hall A in 2022)

a. beam current > 50 uA
b. put receiver box closer to cavities e.g. in the labyrinth (less signal atten. better SNR ratio)
c. helicity sync (study the potential noise from helicity transition)
d. raster frequency sync (reduce beam jittering effect)
e. measure BPM to control the beam position effect

2. BCM configuration for MOLLER
   a. Integration into the MOLLER DAQ
   b. FPGA firmware development

Meetings with the MOLLER DAQ group
https://moller.jlab.org/wiki/index.php/DAQ_Meetings

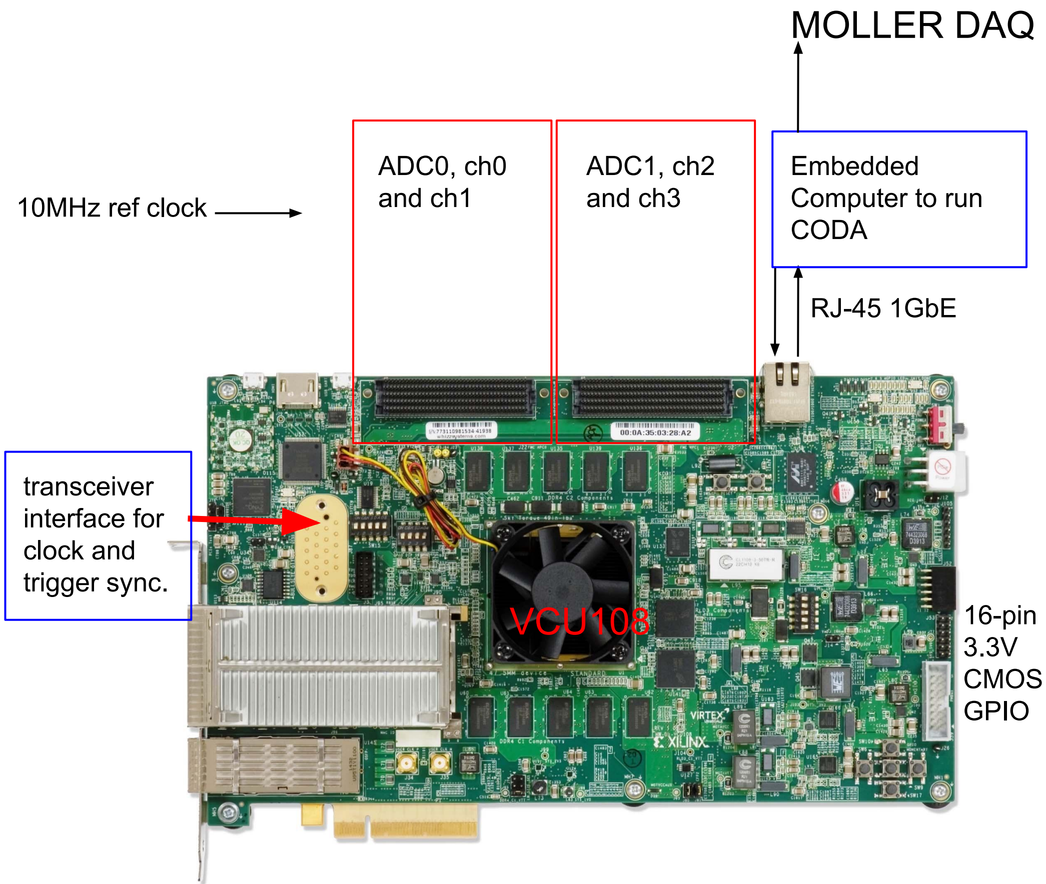
THANK YOU!

Thanks for the help from Kent Paschke, Caryn Palatchi, Cameron Clarke, PREX-II/CREX collaboration and run coordinators,

John Musson, Bob Michael, Ole Hansen, Chris Cuevas, Jessie Butler, Robert Tucker

Data interface blue: planned integration work

[Meetings with MOLLER DAQ group](https://moller.jlab.org/wiki/index.php/DAQ_Meetings)
https://moller.jlab.org/wiki/index.php/DAQ_Meetings



- RJ-45 1GbE
  - Slow control and configuration (inward flow)
  - BCM data (outward flow)
    - 1x 32-bit number per channel every 0.5ms helicity window
    - 4-channel data rate: 256 kbps (normal operation mode, streaming)
    - Debug mode: up to 1Gbps, download ADC raw waveform snippets from onboard memory
  - A TCP server running inside the FPGA
- QSFP28 optical link - FPGA MGT
  - Receive synchronization signals
  - Need to check compatibility with overall signaling specs
- 3.3V CMOS GPIO
  - Receive synchronization signals
  - Likely requires converter
- Embedded computer
  - Run software logic for trigger interface
  - Connect to the FPGA board via RJ-45 ethernet
- Improvement on FPGA firmware for online analysis

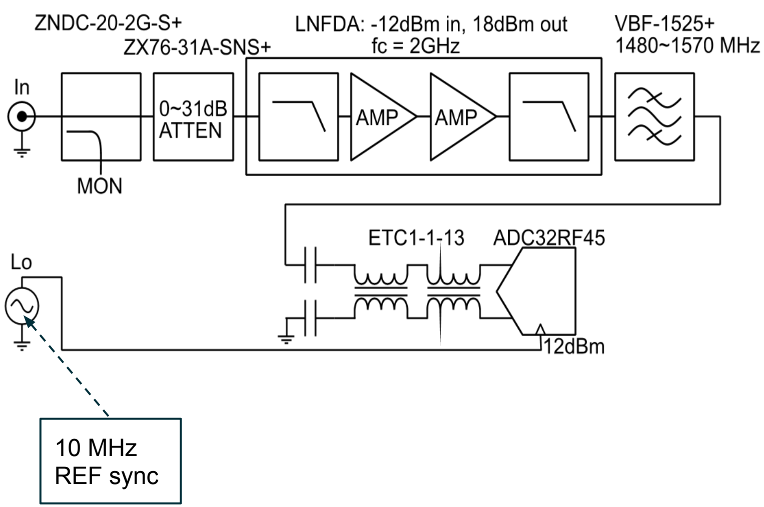
Y. Mei et al. arXiv:2110.09575, submitted to JINST

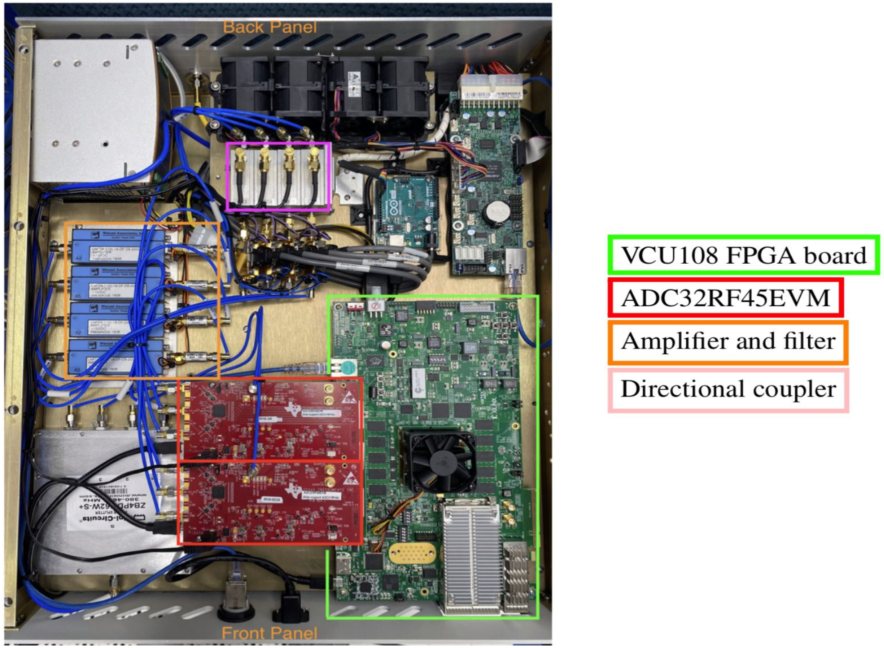
Direct RF-Sampling Digital BCM by LBNL

New idea to address outstanding beam instrumentation issues for MOLLER

- LDRD at Berkeley Lab (FY18 and FY19)
- Directly sample 4 channels of **1497** MHz RF input with high-speed ADC at **3072** Msps (1st Nyquist zone)

RF chain. ADC f_s=3072Msps, BW>4GHz





Beam test in Hall-A in Sept. 2020

- 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

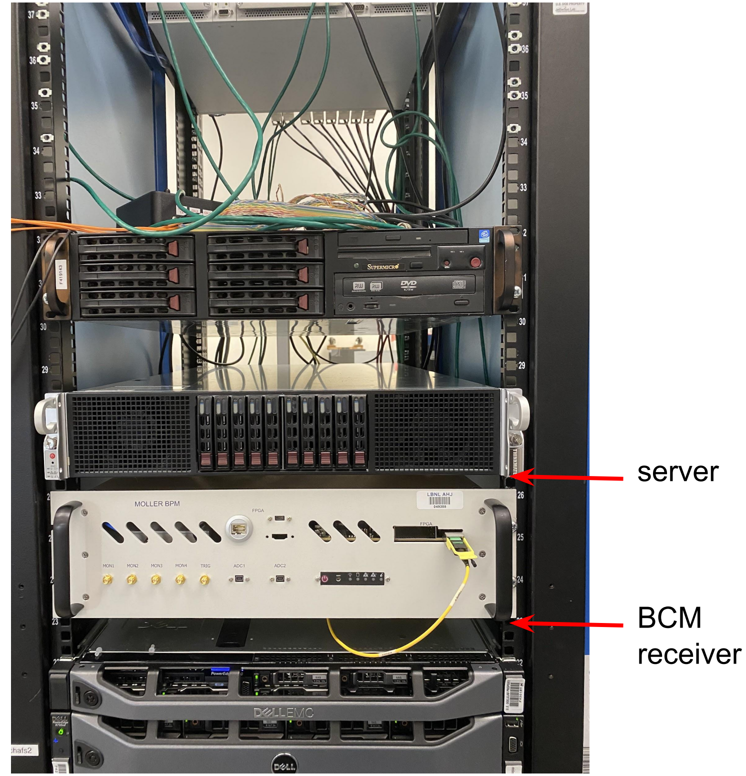
- 2 channels to take 2 RF signals from BPM4B and 4D (-40dBm@1μA)
  ⇒ splitter (-3dB) ⇒ cable to counting house (-22dB)
  ⇒ -22dBm@-150μA at BCM box

- ADC
  - 1497 MHz RF signal digitally down-converted to 2 ,7, 12 MHz
  - /16 decimation
  - I and Q components transmitted to FPGA then to the server

- Server
  - real-time signal processing parallelized by DPDK
    - read data from network as raw packet
    - band-pass filter and RMS check
    - write data to disk (400MB/s/channel)

- Sampling clock sync to 10 MHz reference

middle room of Hall A counting house

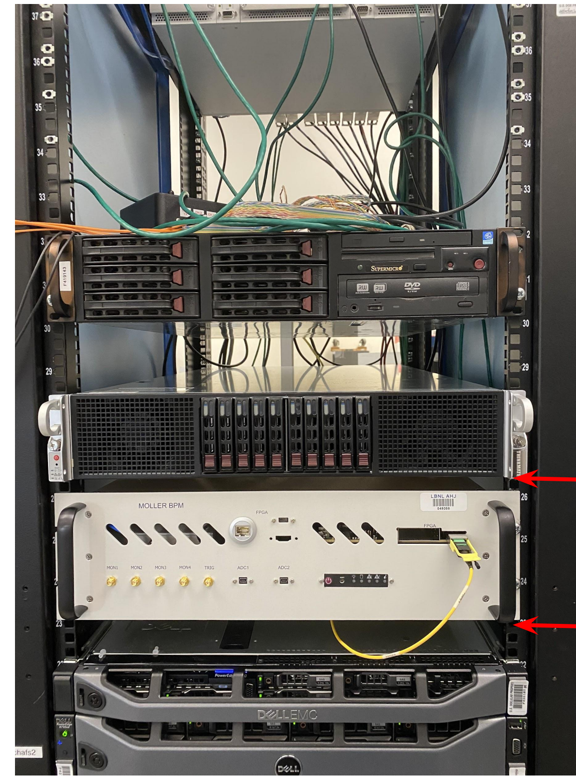


Beam test in Hall-A in Sept. 2020

2 weeks of data-taking, 700 GB data on disk

- Beam conditions:
  - no beam, tune beam, 0-150uA
- Hardware configuration:
  - Attenuators
  - two RF signals, or one RF signal splitted to two channels
  - in-hall test with signal generators
- Software configuration:
  - DDC gain
  - DDC frequency to 2, 7, 12 MHz
  - run-time filter and decimation
  - record only I signal, or I and Q
  - sync (or not) to 10 MHz reference

middle room of Hall A counting house



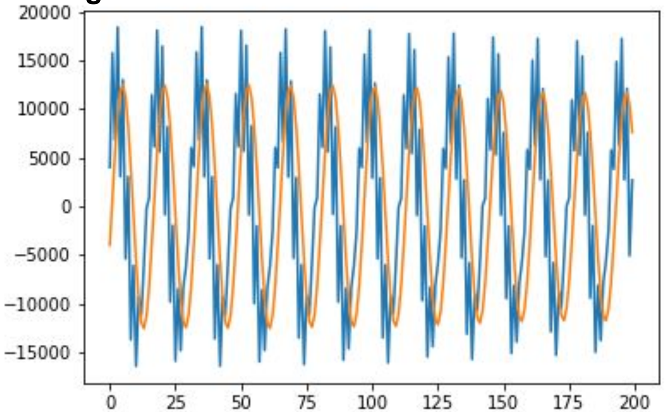
server

BCM receiver

Beam Signal and Spectrum

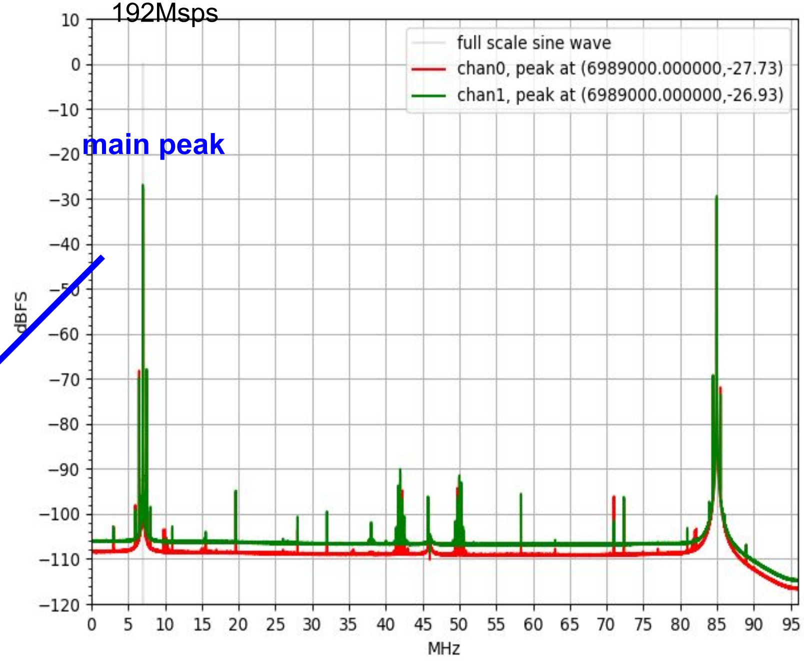
raw signal before/after filter

ADC range: +-32768



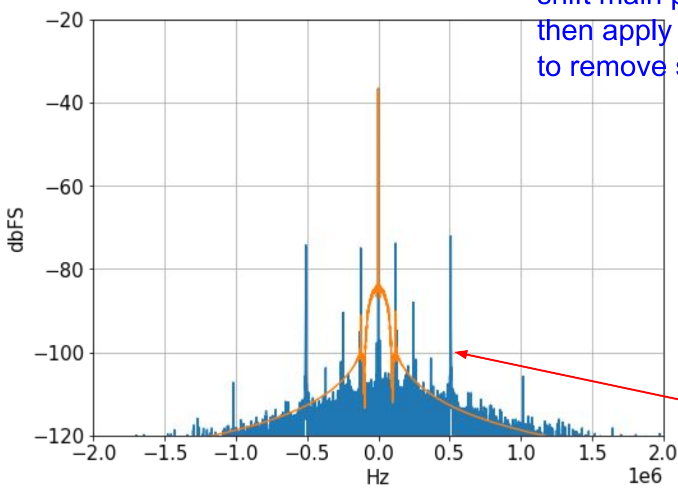
sample @ 192Msps

Power spectrum after DDC (7MHz), decimated to 192Msps



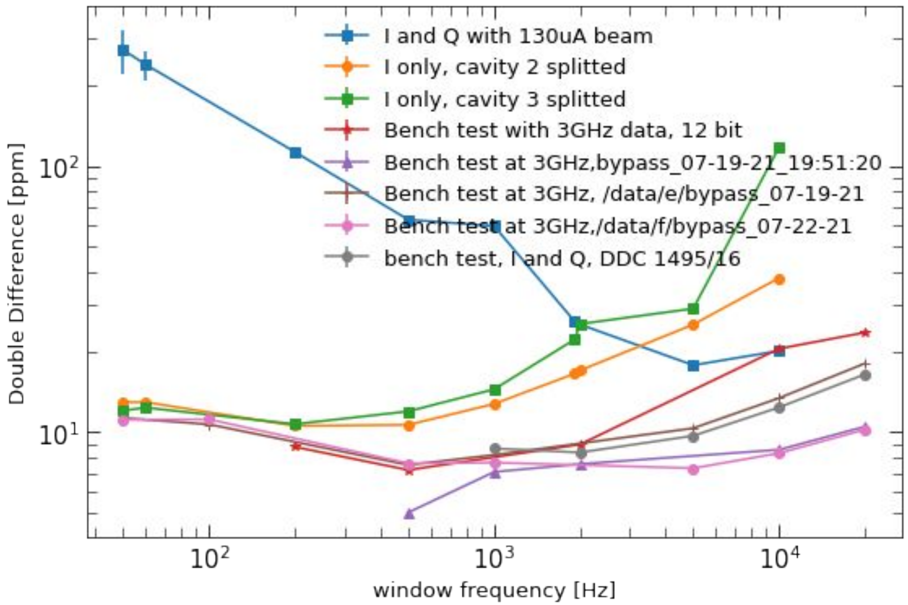
main peak

shift main peak to DC,
then apply lowpass filter
to remove side peaks



Note on the 0.5 MHz side peaks:
Appears with beam signal only, seen with this device as well as spectrum analyzer
Absent with test signal injection
Doesn’t contribute to `double-difference’ width when included

Bench Tests at Berkeley



From beam test 09, 2020:

Blue: 192MHz, I and Q, locked, signals from two cavities

Orange (green): 192MHz, I only, cavity 2(3) signal splitted to two channels. Not locked. Window truncation applied in analysis.

From bench test 07,2021(3GHz, 12bit)

Red: 1497MHz test signal generated with our ERASynth powered by a desktop computers power supply, signal split to two channels and amplitude set near saturation

Brown: Breakout Board signal generator powered from servers supply (as opposed to ERASynth from desktop power supply) signal split from single output channel. Amplitude about ⅓ of saturation amplitude

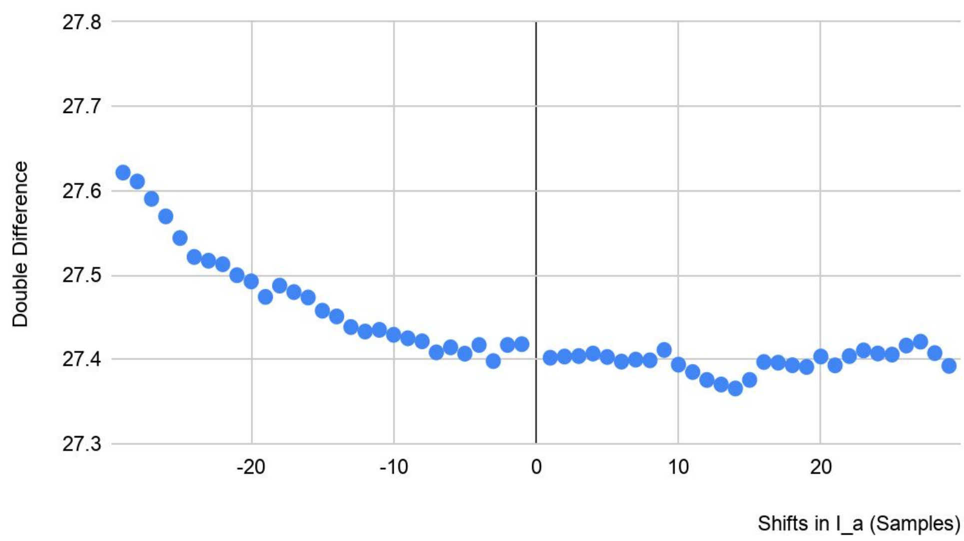
Purple: Breakout Board signal generator (server supply) fed each input channel on the FPGA from separate outputs on the generator. Amplitude about ⅔ of saturation amplitude (didn't see 60Hz noise)

Pink: ERASynth powered from the Server supply, splitter for two channels, amplitude set very near saturation

Possible Sources of Noises:

Time Dependence: simulation results

- Calculate double difference between channel a and b:
  - only “I” components were used
  - integration window = 1920 Hz
  - 4 seconds of data
- Repeat this calculation with manually shifted I_a
  - 1 sample @ 192MHz ~ 5 ns



Possible Sources of Noises:

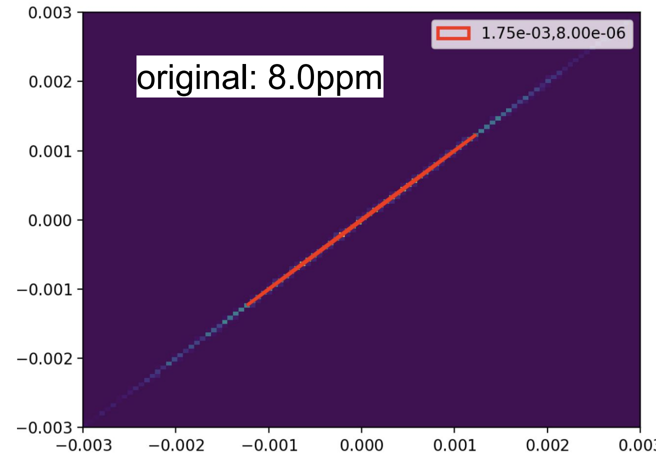
Beam position dependence: simulation results

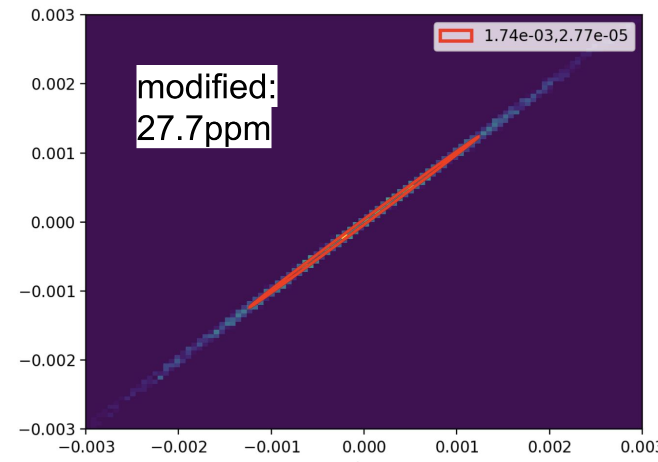
Take 1 second of I and Q signal from the same channel:

- Calculate the vertical beam offset:
  - I: 2mm raster + 12mm const
  - Q: 2mm raster
- Apply corresponding gain factor on I and Q
- Calculate double difference at 2 kHz (before/after)

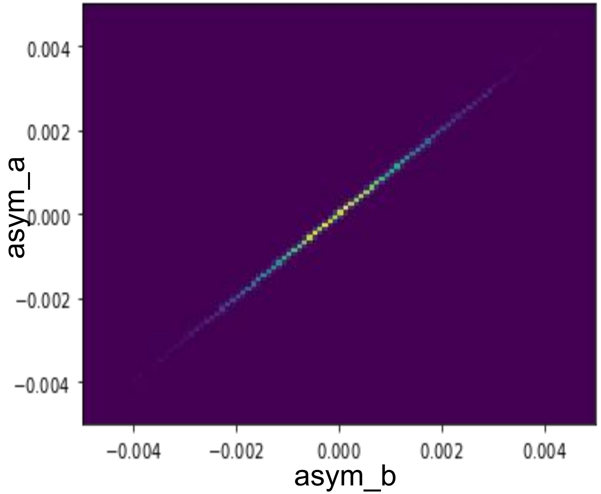
⇒ Need **~10 mm** misalignment between two cavities to bring the double difference from 8ppm (bench test result) to 28ppm (beam test result)

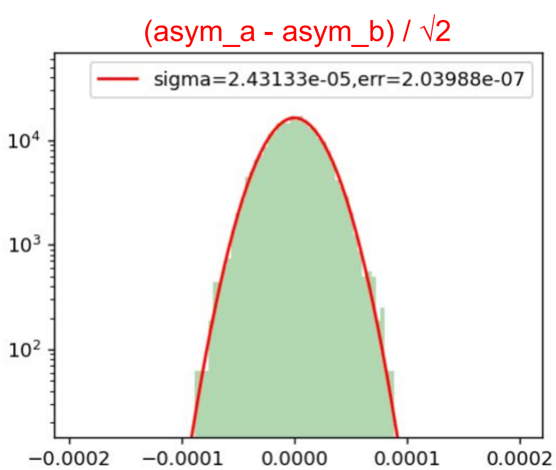
** According to John Musson, cavity misalignment is usually ~1mm, >4mm is not likely to happen





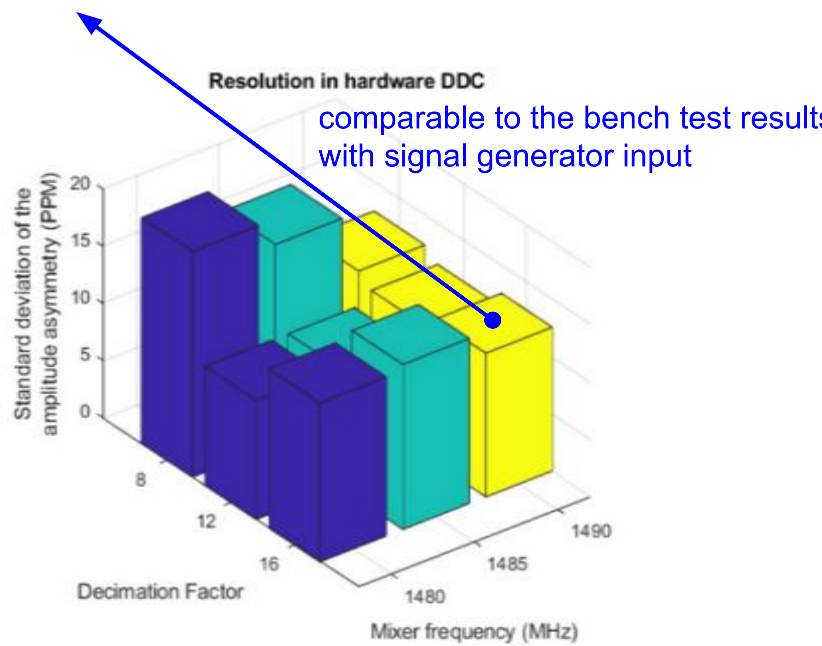
“Double-difference”



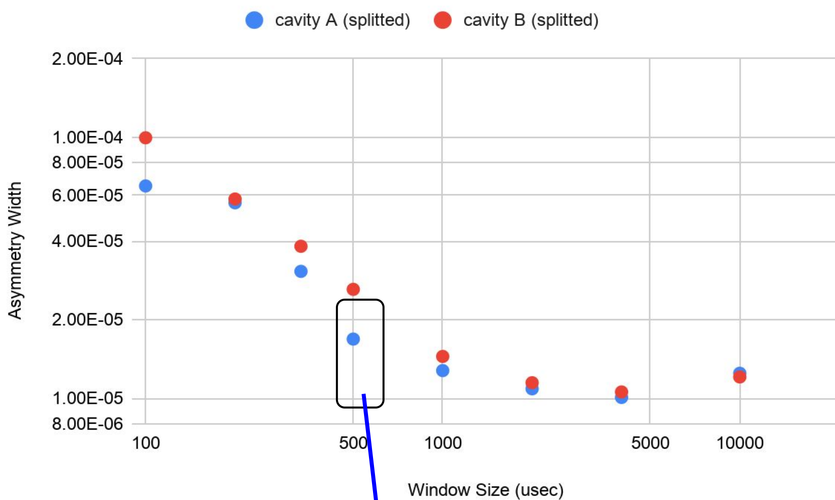


With 2000 Hz (0.5 msec) integration window:

- Correlate signals from both BPMs (double difference):
    - “I” or “Q” signal only: **25 ppm**
    - “I” and “Q” together: **24.5 ppm**
    - “I” and “Q” are numerically computed in ADC. There appears to be sizable numerical “error”
- if split one cavity signal to two channels, and correlate their “I” signals:
    - **16 ppm (measured noise floor of this BCM setup)**



One cavity signal splitted to two channels.
“I” only, not locked. 7 MHz

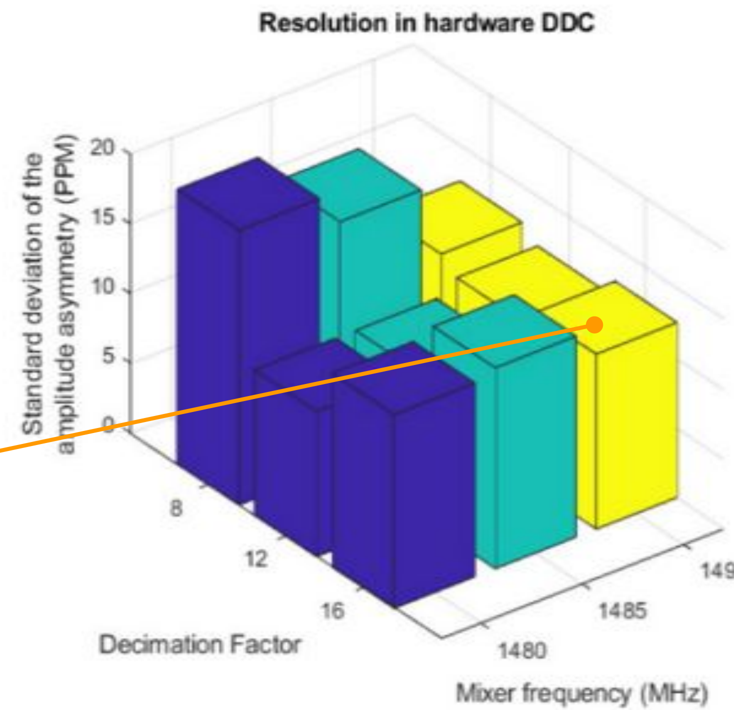


16 ppm at 2000 Hz

comparable to the bench test results with signal generator input

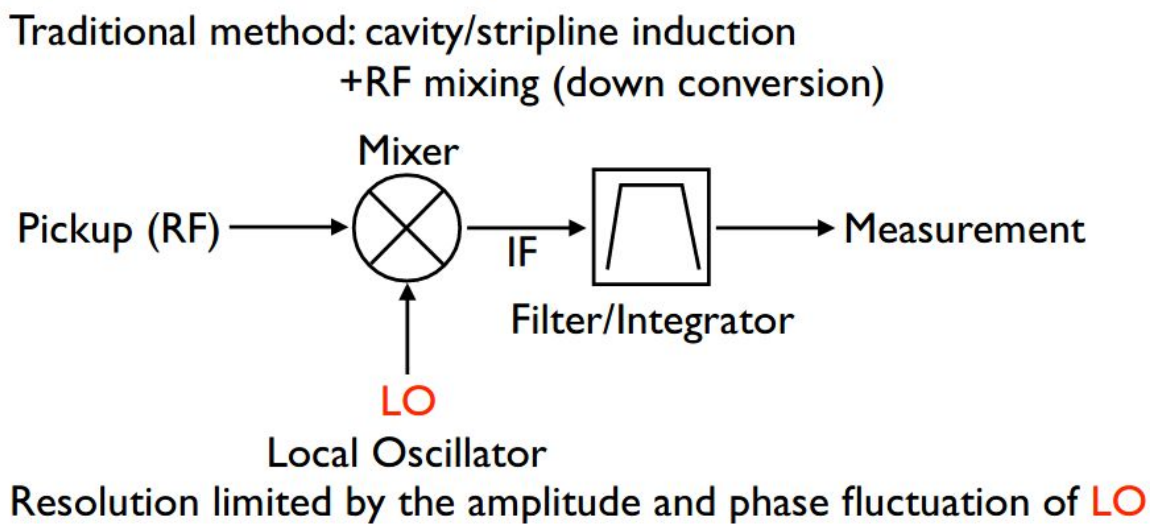
White noise dominates: correlation width decreases with increasing window size

Cavity A vs B: possible difference in cable or cavity itself?



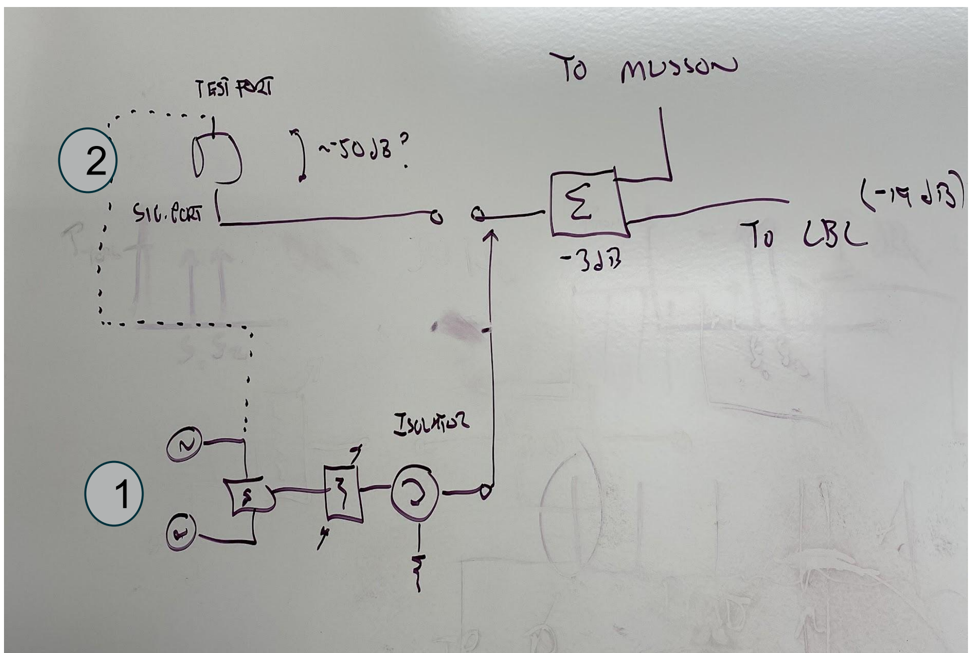
Current Hall A BCM System (Yury and Yuan)

- Limitation (most likely): LO amplitude and phase noise,(add more here)

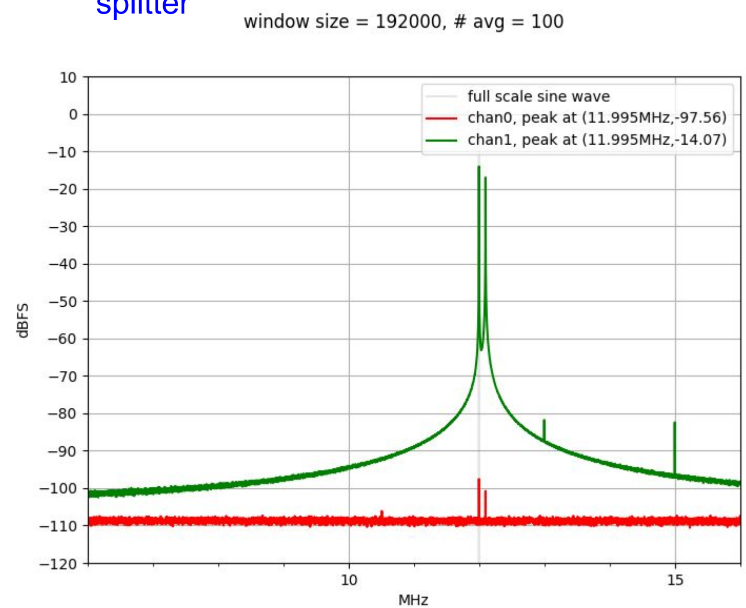


In-hall test, no side peaks

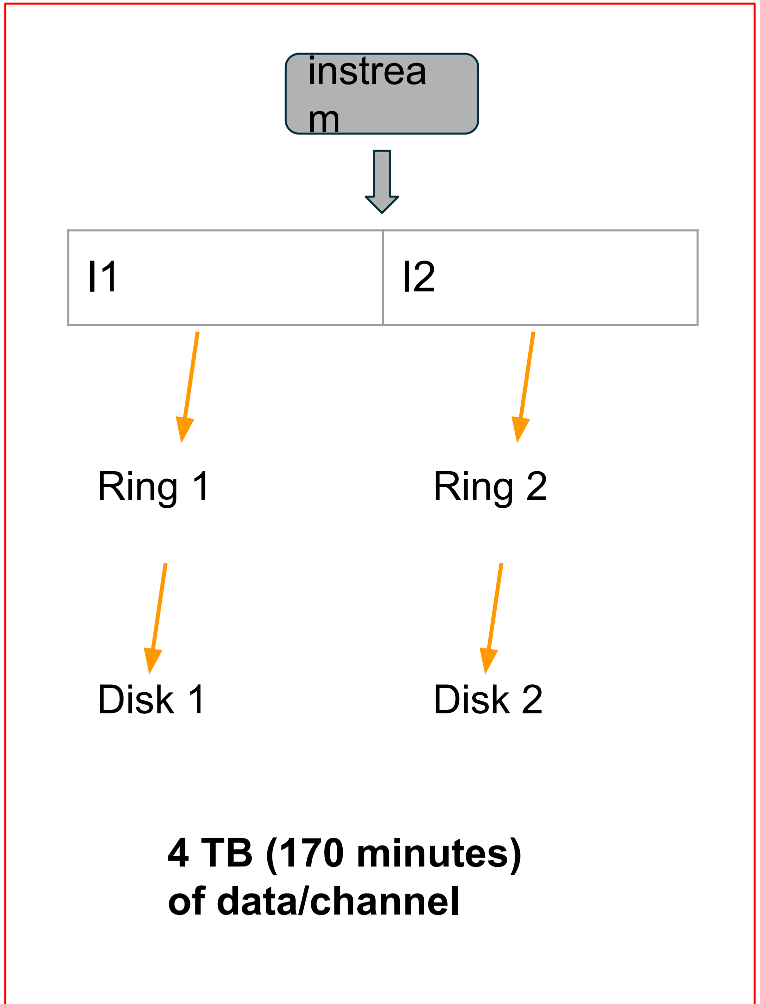
1. signal(s) ⇒ 3db splitter ⇒ 19 db cables (“spare” 2, 3) ⇒ BCM
2. Signal ⇒ cavity ⇒ splitter and cables ⇒ BCM

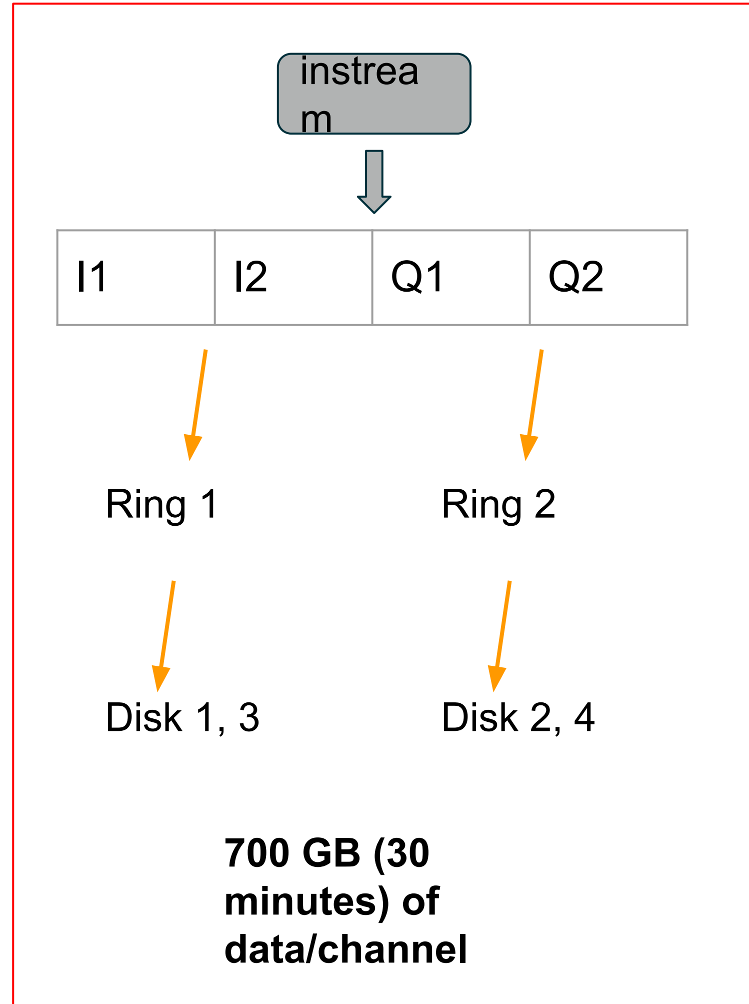


Two signals at 1497 and 1497.1 MHz to splitter



Tune beam, no beam, CW beam
Ref clock locked or not
DDC gain, frequency
External generator





From Moller CDR:

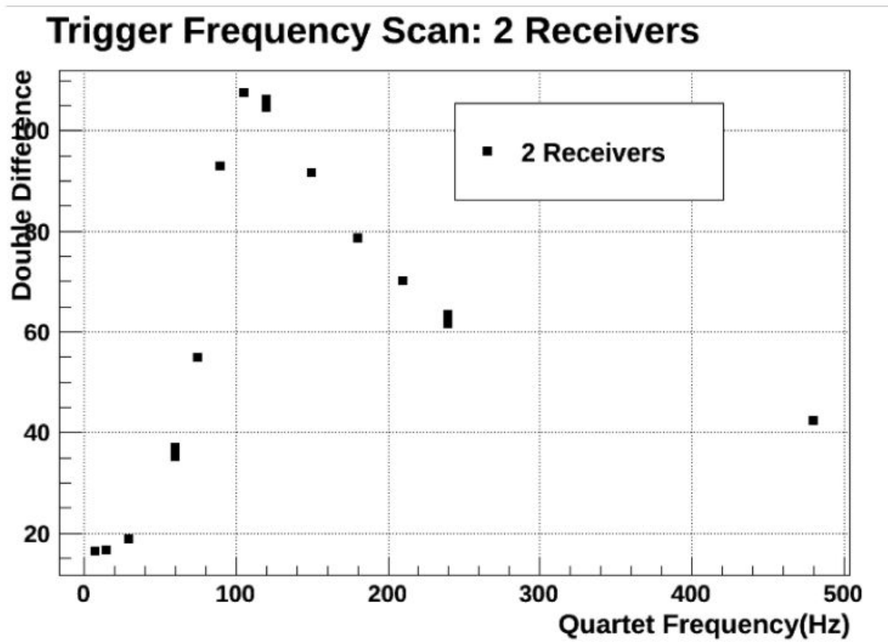
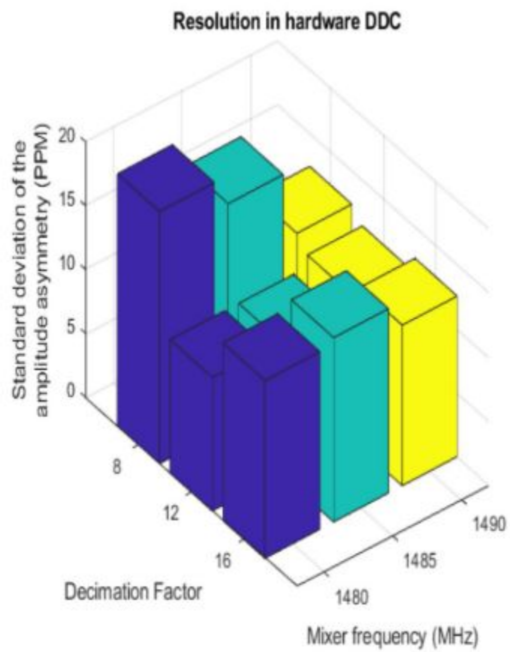


Figure 38: *Bench study of Q_{weak} digital receivers with two receivers and a common rf source to simulate the beam signal. The observed double difference versus quartet frequency is shown.*

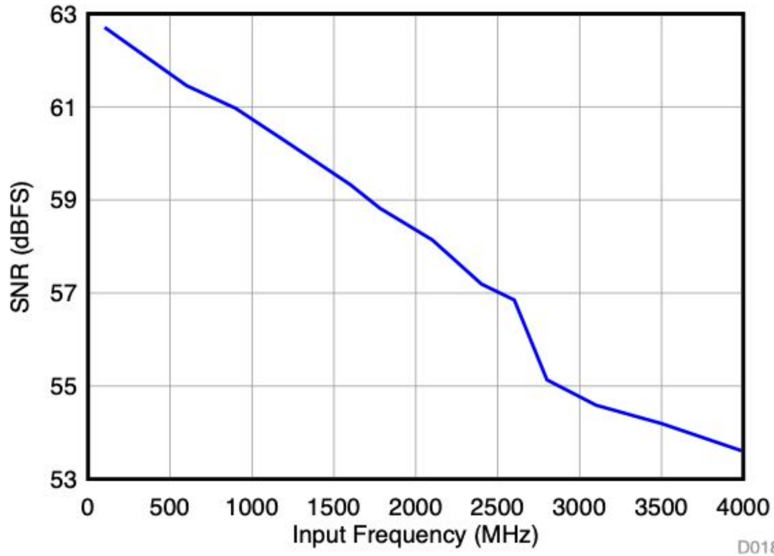
Update from James Egelhoff:

BCM ADC Resolution Results



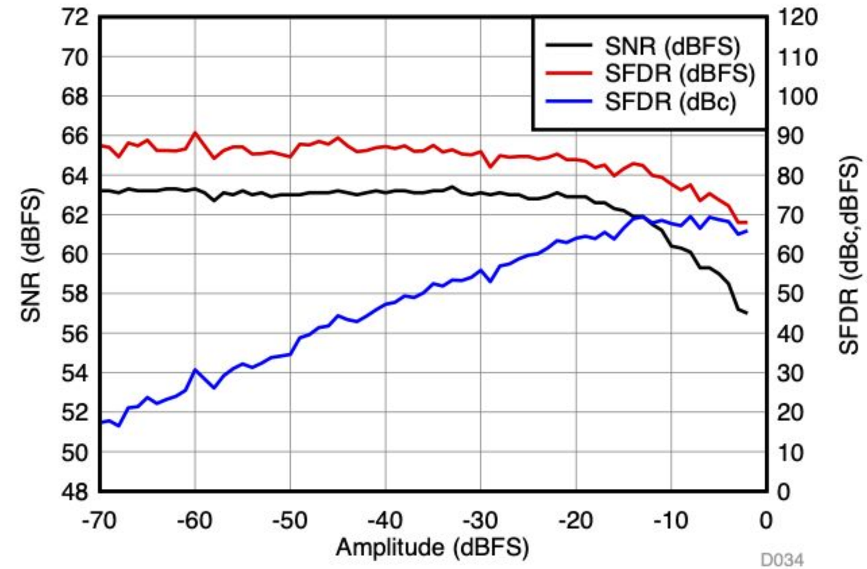
- Current ADC testing setup utilizes two ERASYNTH signal generators (one for clocking, one for signal)
- Signal is split and fed into two independent channels, both sampling at 3GBPS with 12 bit resolution and optional digital down conversion. Amplitudes are averaged over half-ms windows and differences between channels are compared to determine resolution.
- Typical resolution of ~10PPM with room to improve (for instance, moving from simple voltage RMS calculation for signal amplitude to quadrature reconstruction, improving RF isolation of the electronics, etc.)

ADC quantization noise



A_{OUT} = –2 dBFS with 0-dB gain for the first and second Nyquist,
A_{OUT} = –3 dBFS with 2-dB gain for the third Nyquist

Figure 22. Signal-to-Noise Ratio vs Input Frequency



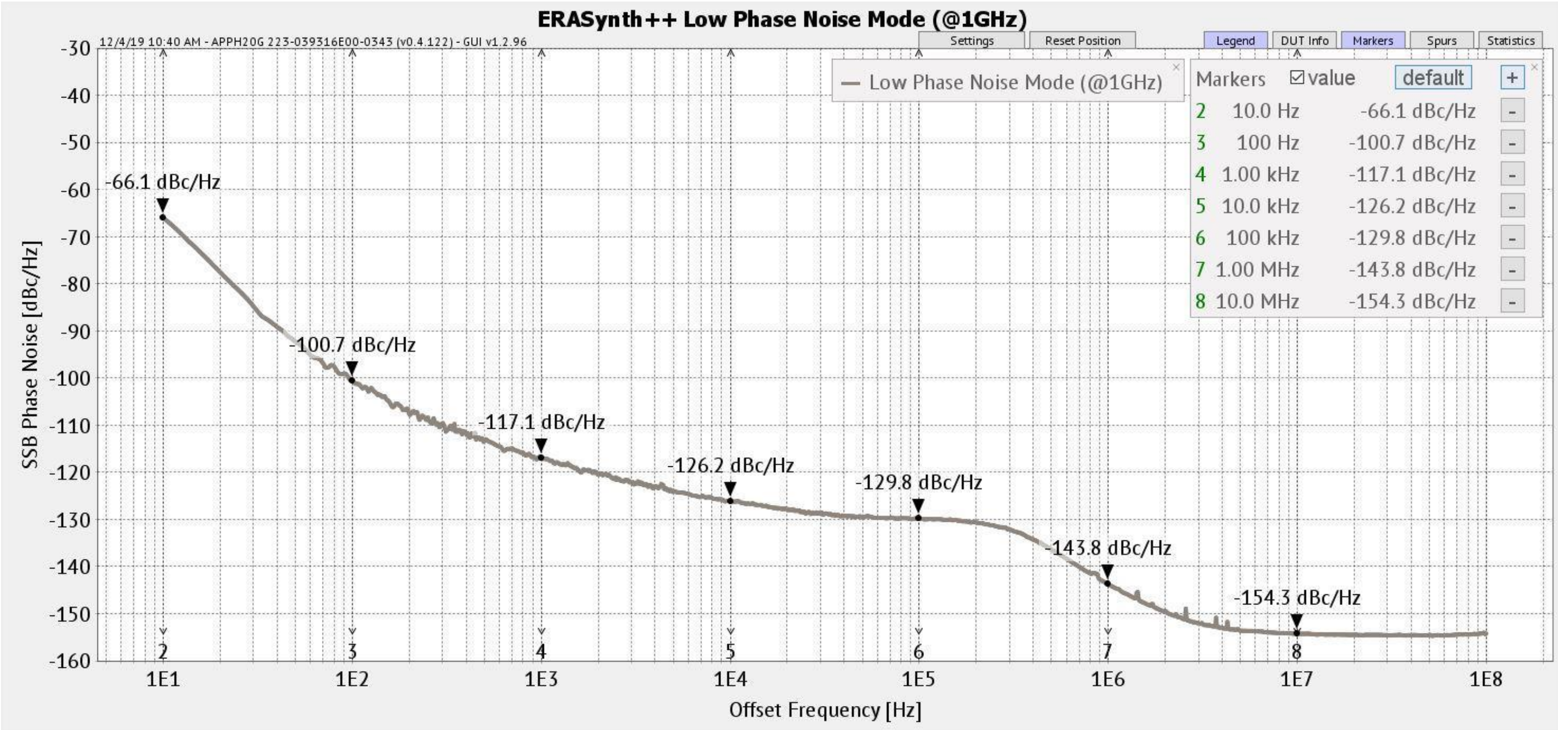
f_{IN} = 1.78 GHz

Figure 38. Performance vs Amplitude

$$\text{ADC noise floor}: -155\text{dBFS/Hz} \rightarrow \sqrt{10^{-\frac{155}{10}} \times 2000} = 8.0 \times 10^{-7}$$

~10.2 bit equivalent ADC (consider noise only) $$20\log_{10}\left(\frac{\sqrt{2/3}}{2^{10.2}} \Big/ \sqrt{\frac{3072\times10^6}{2}}\right) = -155.0$$

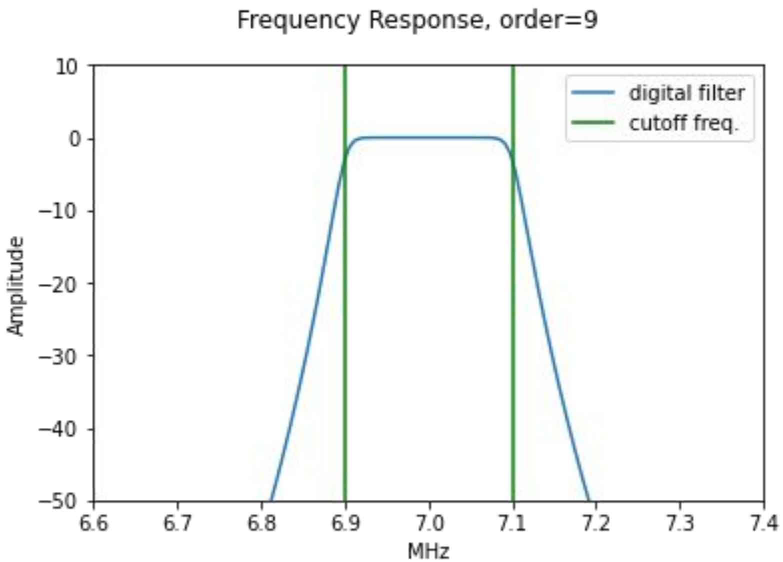
Phase noise

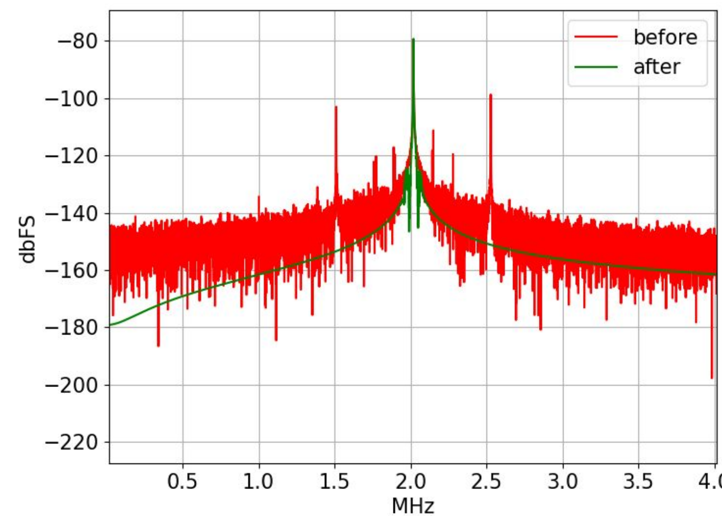


$$\sqrt{\int_{10\mathrm{Hz}}^{2\mathrm{kHz}} \Phi(f)df} = 1.67 \times 10^{-3} \qquad \sqrt{\int_{100\mathrm{Hz}}^{2\mathrm{kHz}} \Phi(f)df} = 1.47 \times 10^{-4}$$

ADC aperture jitter 90 fs -> 156 dBc/Hz equivalent

Bandpass filter for I only data



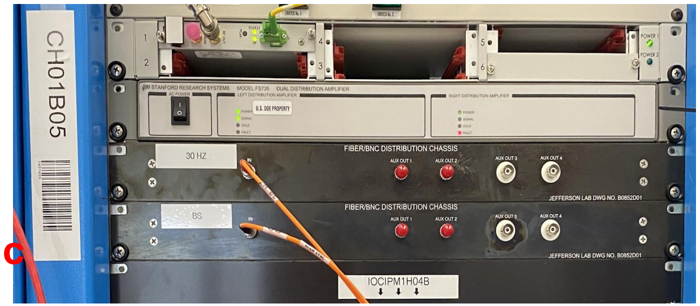


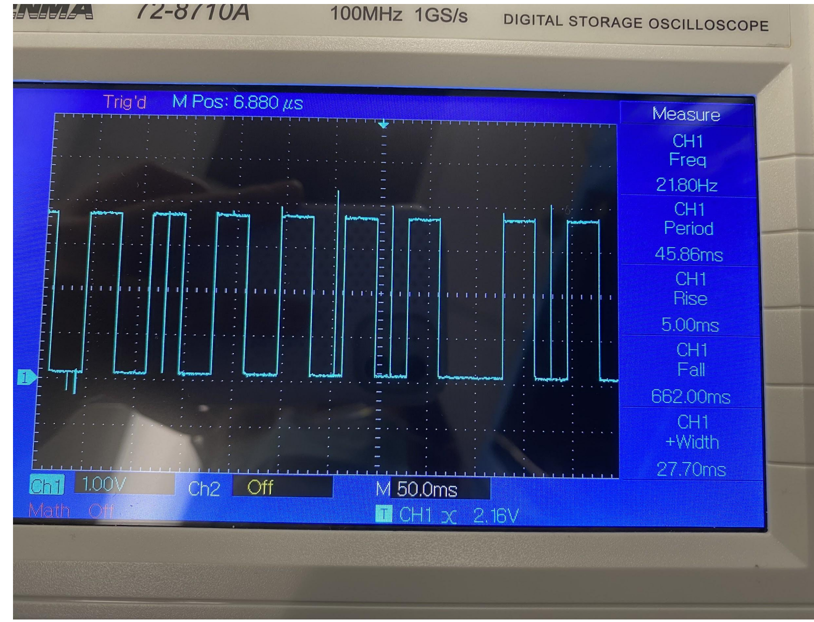
Helicity signal in counting house

Front

Helicity

Beam sync





Back

Possible in-hall installation location:

In the labyrinth next to the BCM BPM modules.