HOM Based Diagnostics at the TTF

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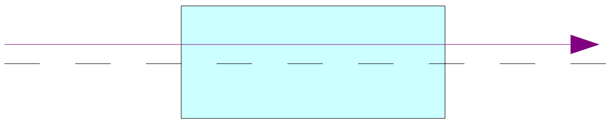
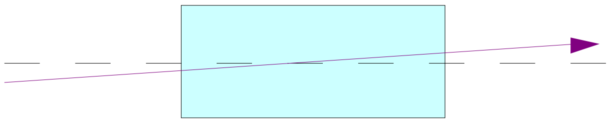
(SLAC, DESY, CEA Saclay)

With many contributions from the TTF team

Dipole Mode Response to Beam

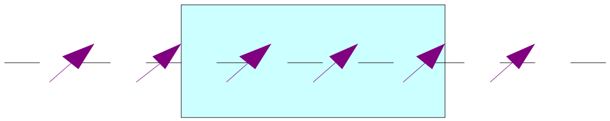


Beam position offset produces mode amplitude proportional to (position) X (charge)



Beam at angle produces signal at start of structure, cancels at end of structure: Result is “derivative” like signal, 90 degrees out of phase with position signal

Amplitude is proportional to (Angle) X (charge) X (cavity length)



Bunch tilt signal produces a signal with the same phase as the beam angle signal

Amplitude is proportional to (Tilt) X (charge) X (bunch length)

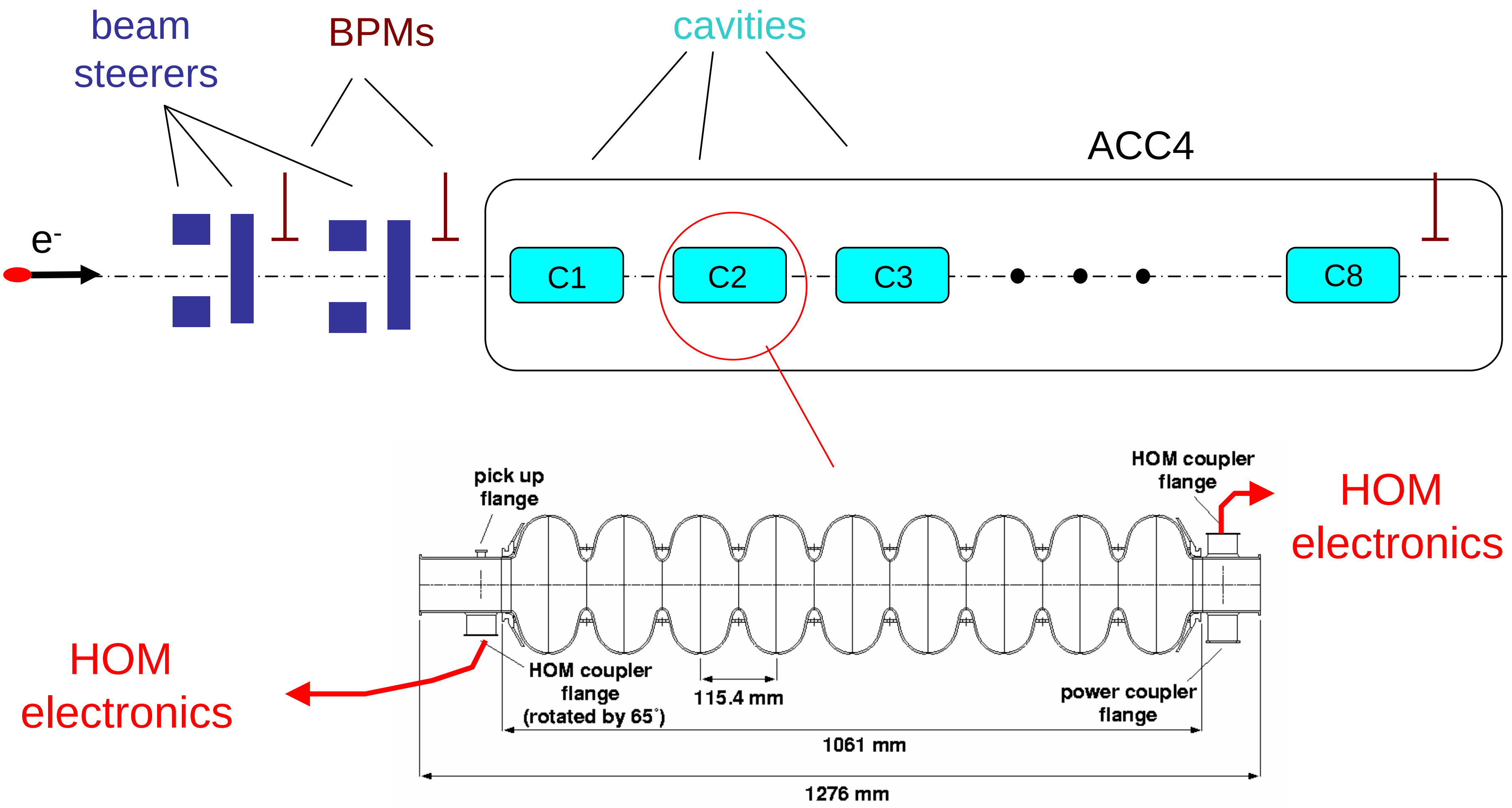
Not significant for the DESY TTF (bunches are very short)

Note that centers (position / angle for zero signal) of HOM modes are modified by asymmetric couplers at the ~100 micron level

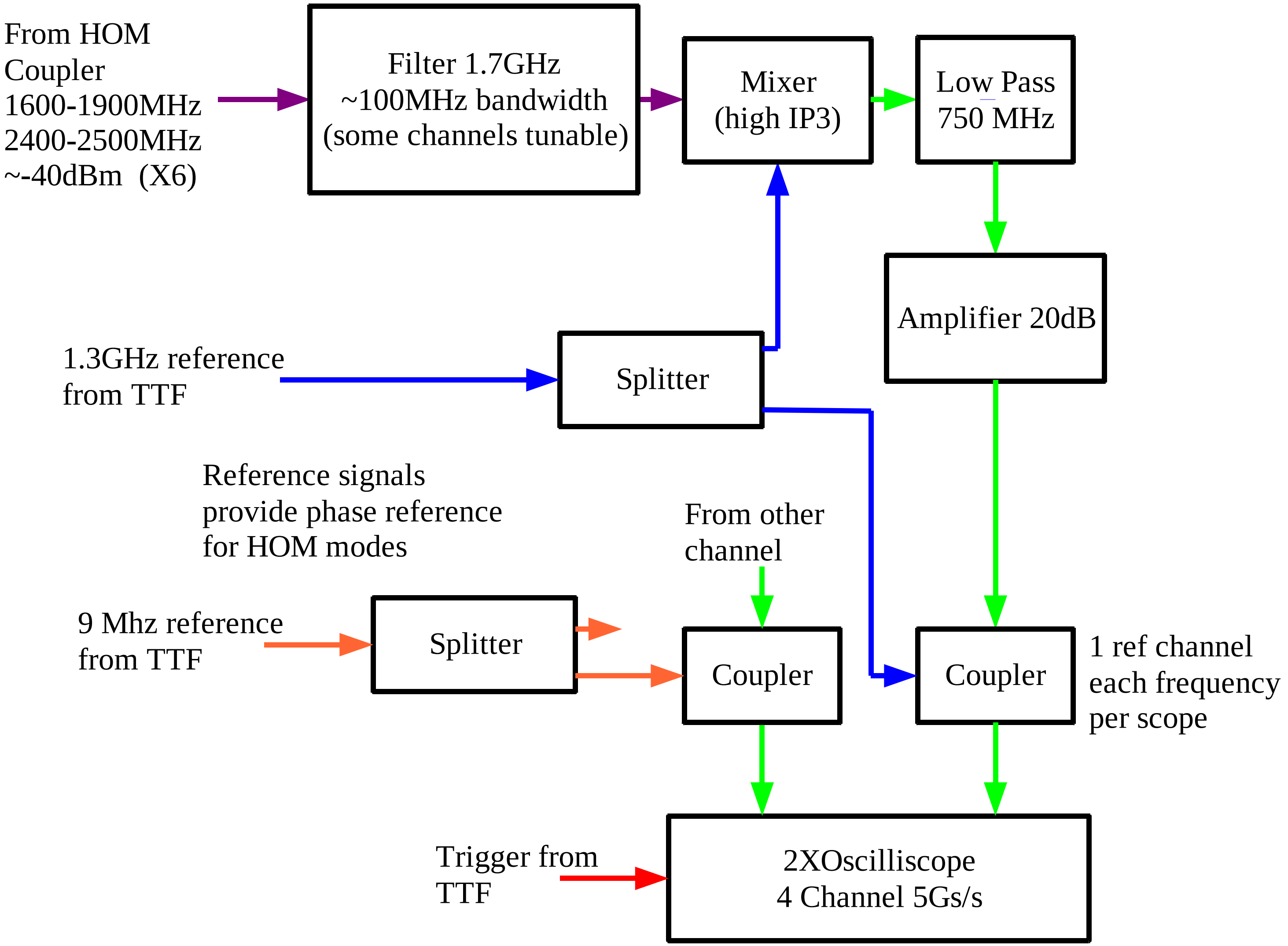
HOM Modes For This Study

- In addition to the 1.3 GHz accelerating mode, the SC cavities support higher order modes with frequencies above approximately 1.6 GHz.
- We primarily use the Dipole TE111-6 (~1700MHz), TE111-7 (~1730MHz) Modes, and the TM110-4 (~1860MHz) mode. These are the near-speed-of-light dipole modes which couple most strongly to the beam.
- Experiments were done primarily in ACC4, with some tests in ACC1.

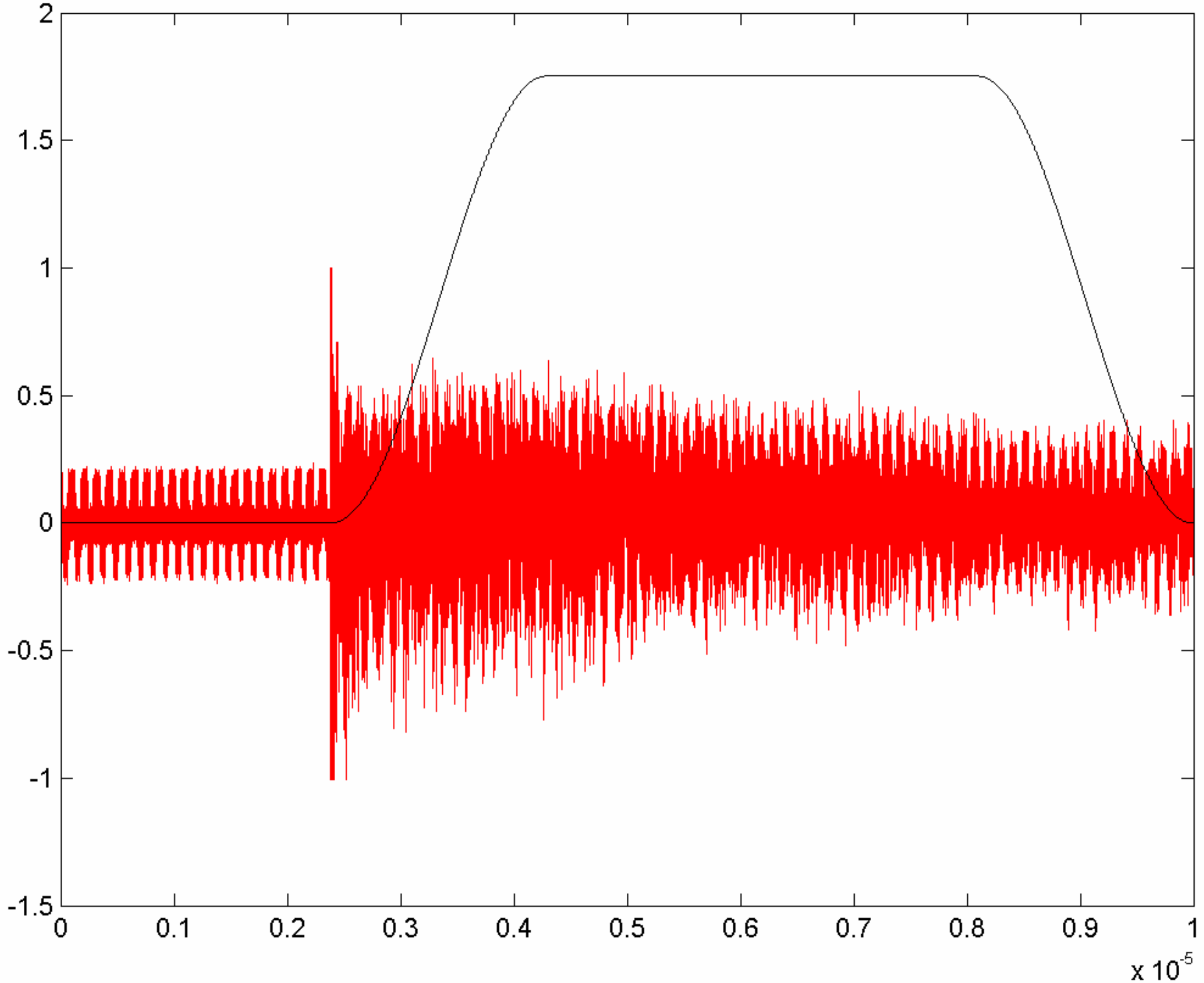
Experimental Setup - ACC4



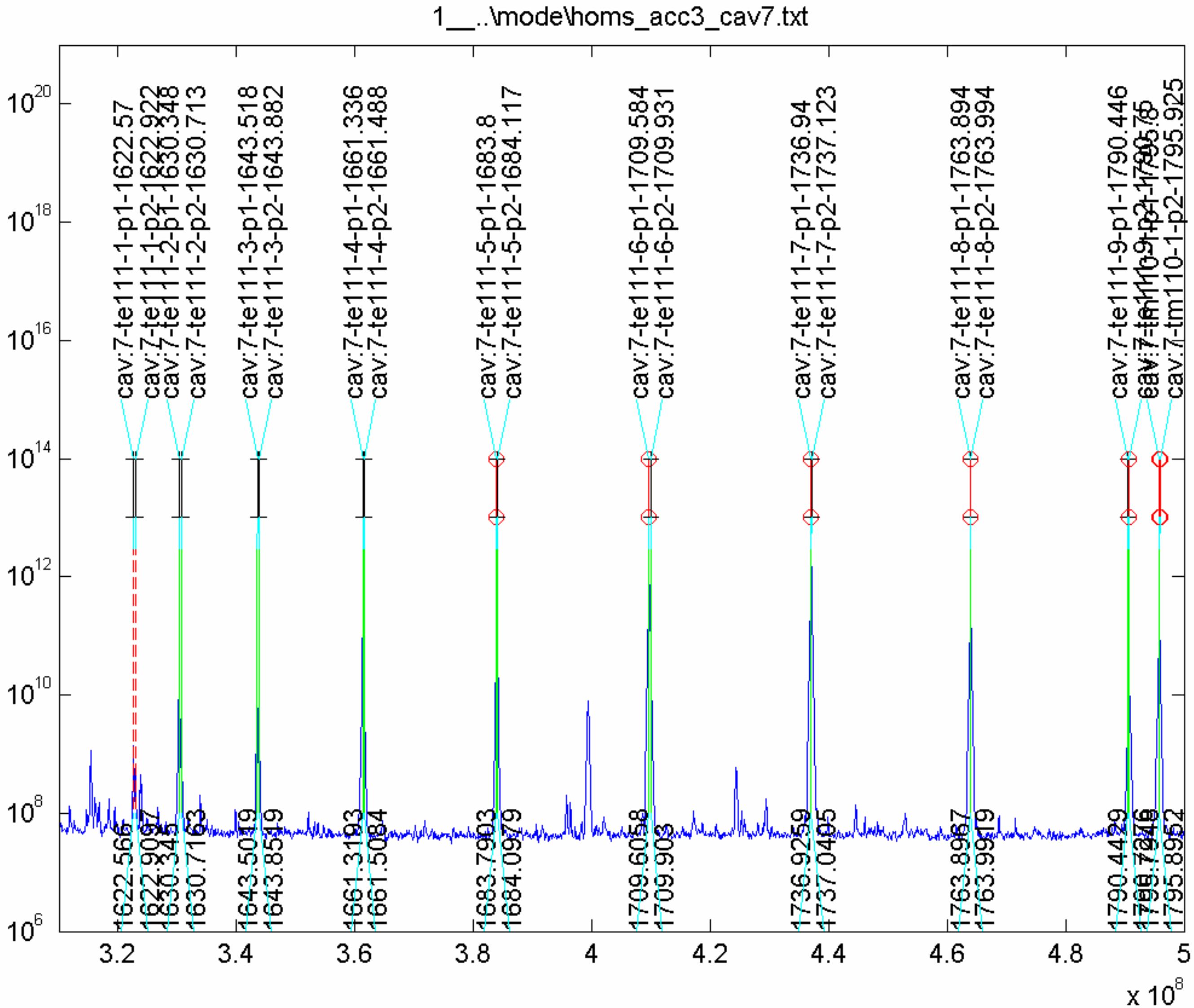
HOM Measurement Electronics



Raw Scope Waveform



HOM Spectrum near TE111 modes



Signal Analysis for Beam Position

- Use conventional BPMs before and after structure to define beam position and angle at the cavities.
- For HOM signals, measure complex amplitude at line frequencies
  - Each “line”, e.g. TE111-6 has 2 polarizations, at slightly different frequencies
  - Each cavity has 2 HOM ports
  - Complex signal has 2 real degrees of freedome
  - Get 8 real measurements / cavity (for 1 mode).

Linear Regression

- Given a set of measurements for a set of variables, predict the measurements for one variable based on the others.
- Prediction is a linear combination of the other variables for that measurement.
- Linear combination is chosen to minimize the RMS error of the prediction of the variable over all measurements.
- Need more measurements than variables!!!
- Can also use to predict X and Y, from mode components.

Set of Measurements $M_{a,b}$ on the "reference" mode where "a" is the data set (1:100 for our data), and "b" is one of the 8 components of the mode:

- Polarization 1 or 2
- Coupler 1 or 2
- Real or Imaginary part

Set of measurements from the BPMs X is a single component (out of X,X',Y,Y') for the target mode.

$$
\begin{bmatrix} M_{1,1} & \cdots & M_{1,8} & 1 \\ M_{2,1} & \cdots & \cdots & 1 \\ \cdots & \cdots & \cdots & 1 \\ M_{100,1} & \cdots & M_{100,8} & 1 \end{bmatrix} \begin{bmatrix} R_1 \\ \cdots \\ R_9 \end{bmatrix} = \begin{bmatrix} M_{1,x} \\ M_{2,x} \\ \cdots \\ M_{100,x} \end{bmatrix}
$$

"Ones" allow for offsets
In modes vs. BPMs

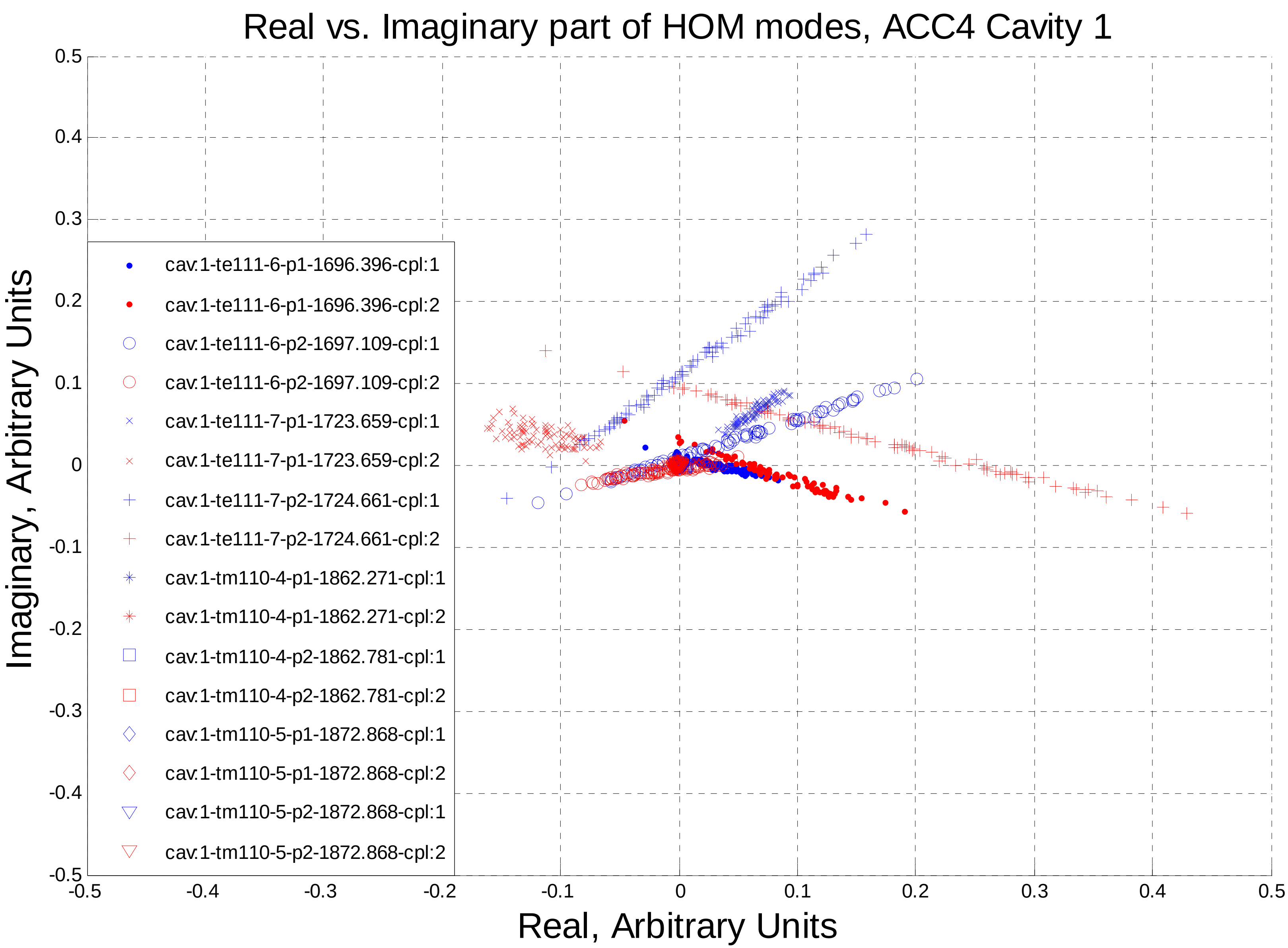
Set of coefficients which best (in a "least squares" sense) predict the BPM measurement

These coefficients R are found by "linear regression", in our case the arithmetic is done by *Matlab*.

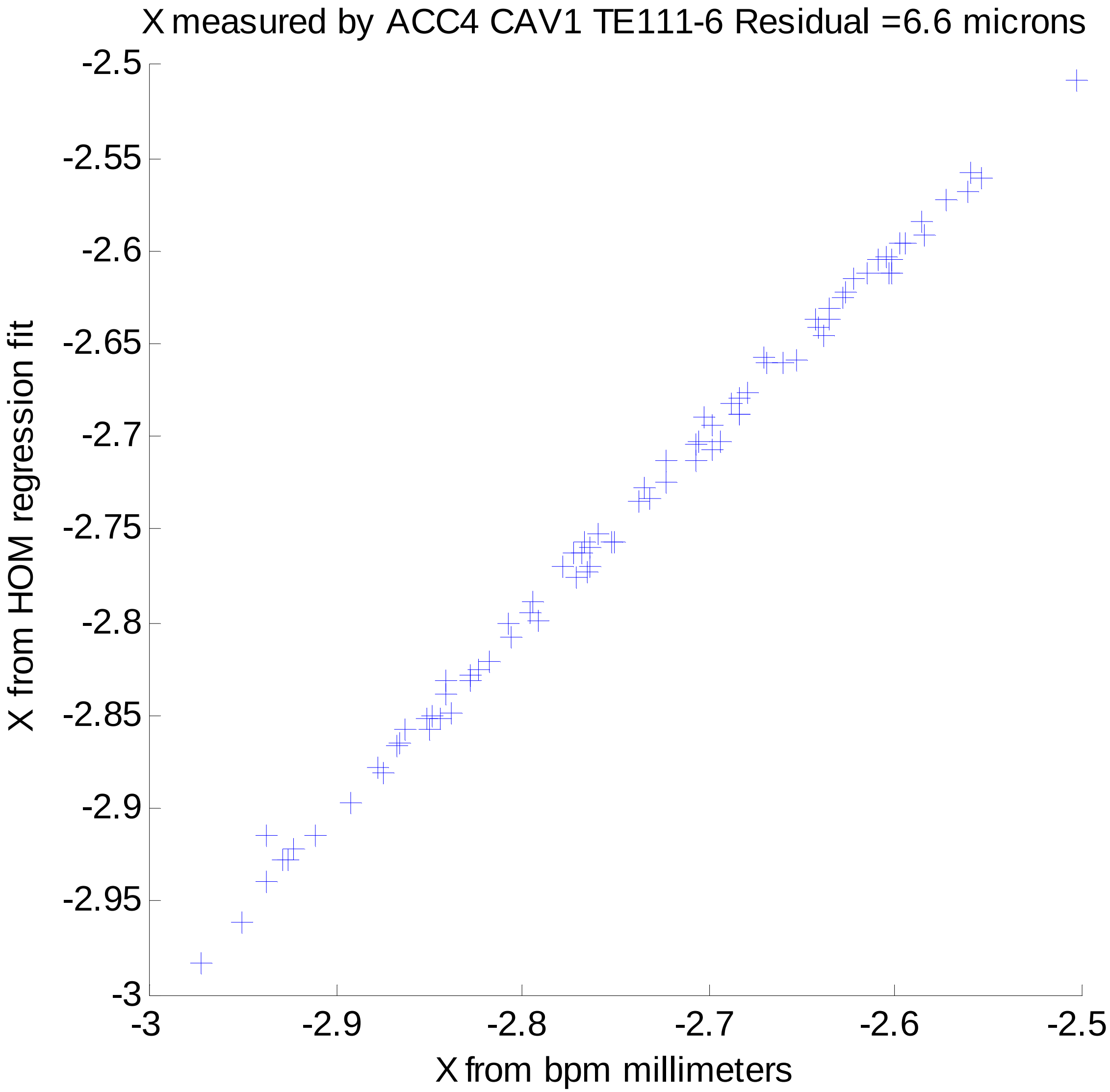
Experimental setup for HOM Mode Regression against BPMs

- Use ACC4. All cavities measured, several modes. CAV1 measurements, TE111-6 shown.
  - Really "typical": haven't had time to find plots with best resolution
- Use BPMs just upstream and downstream of ACC4
- HOM signals measured without pre-amplifiers to provide larger range (for cavity alignment studies).
  - Approximately 10dB increase in noise figure.
- Resolution measurements include conventional BPM resolution

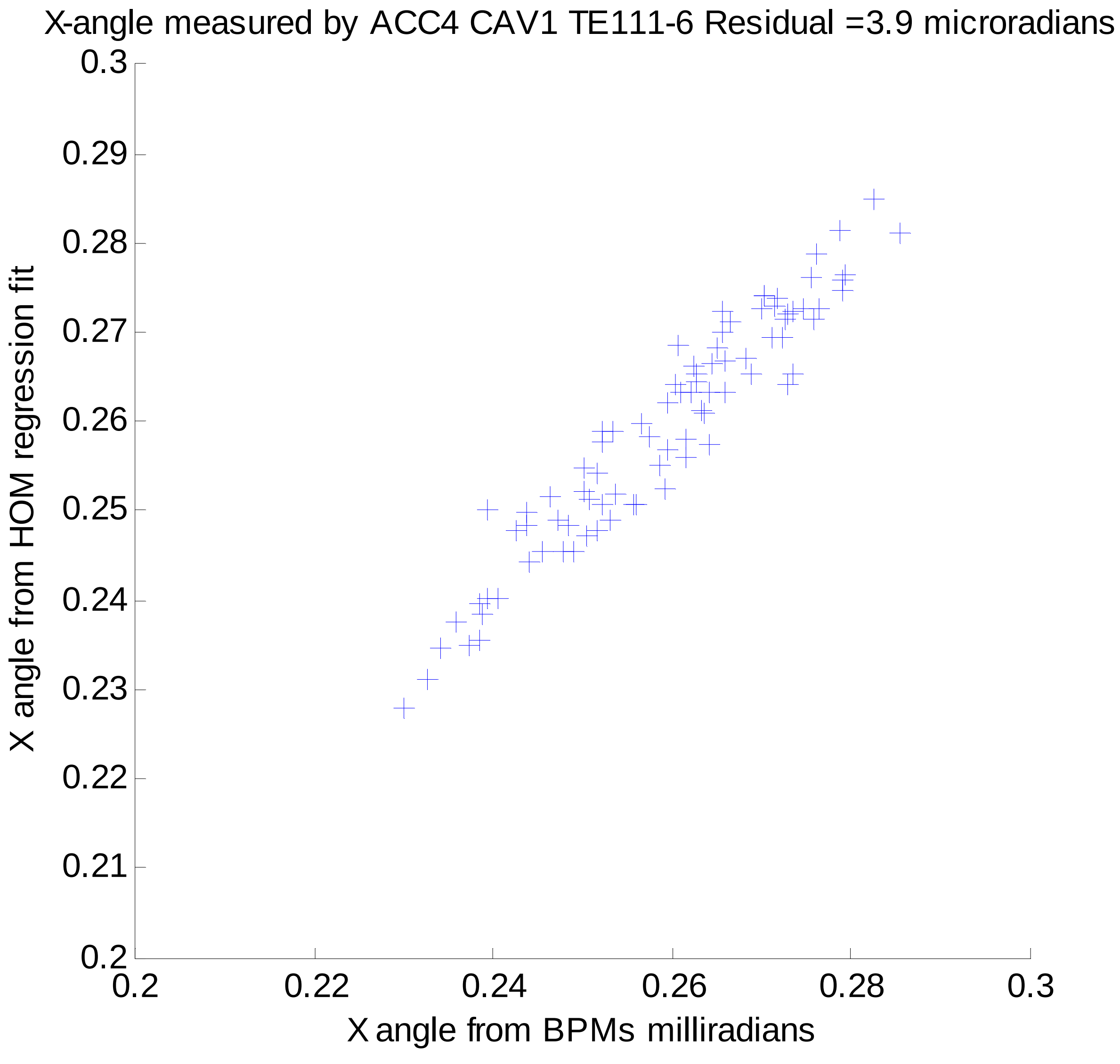
Hom Mode vectors during corrector scan (4-d scan)



HOM Mode regression for X

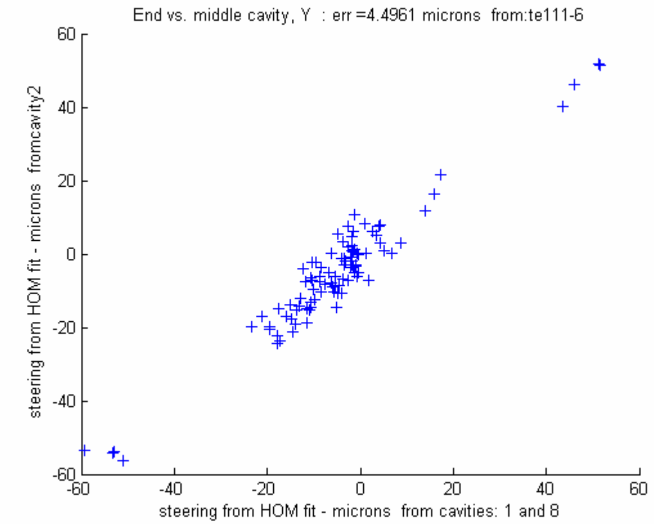


HOM mode regression for X angle.



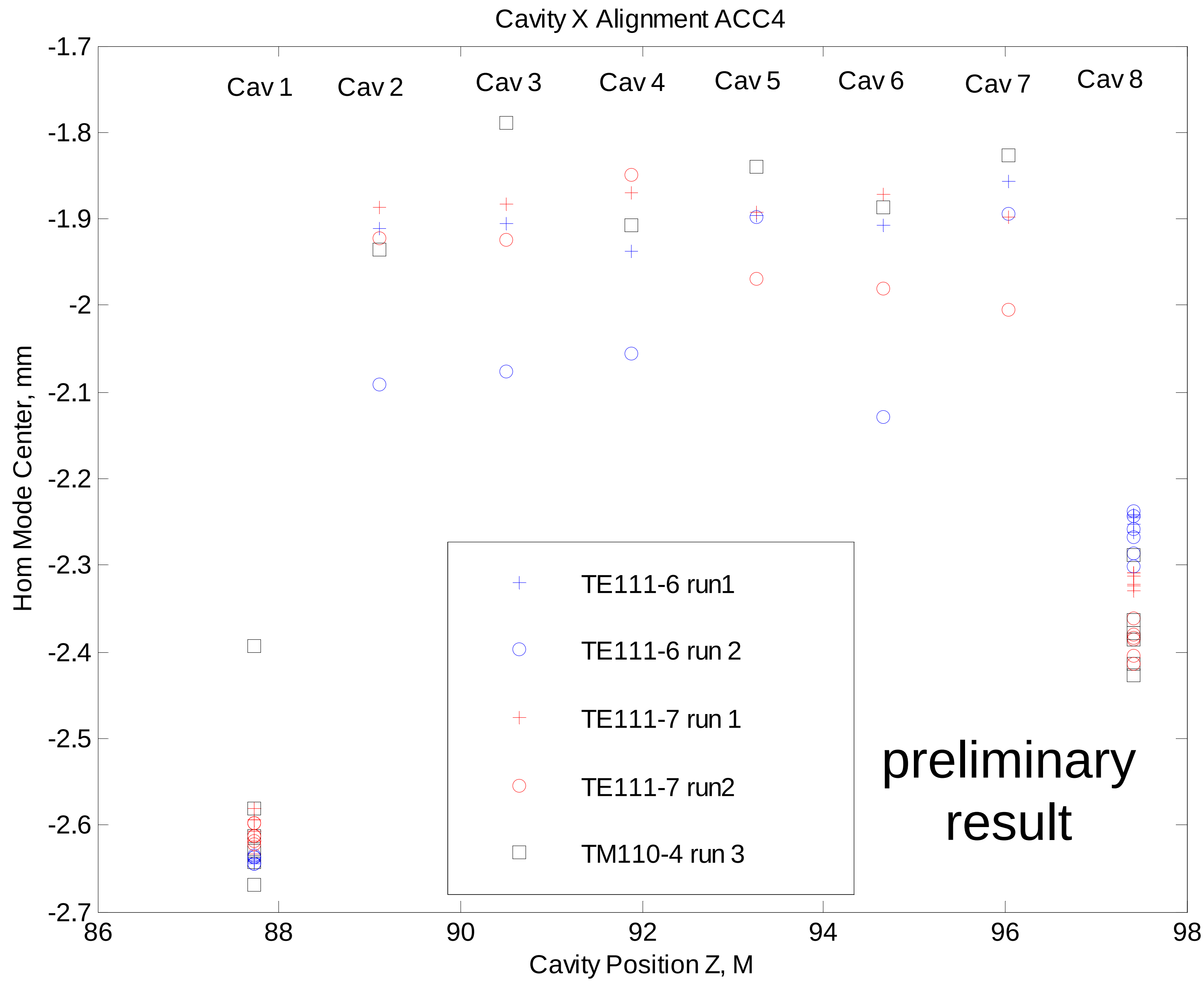
HOM BPM resolution

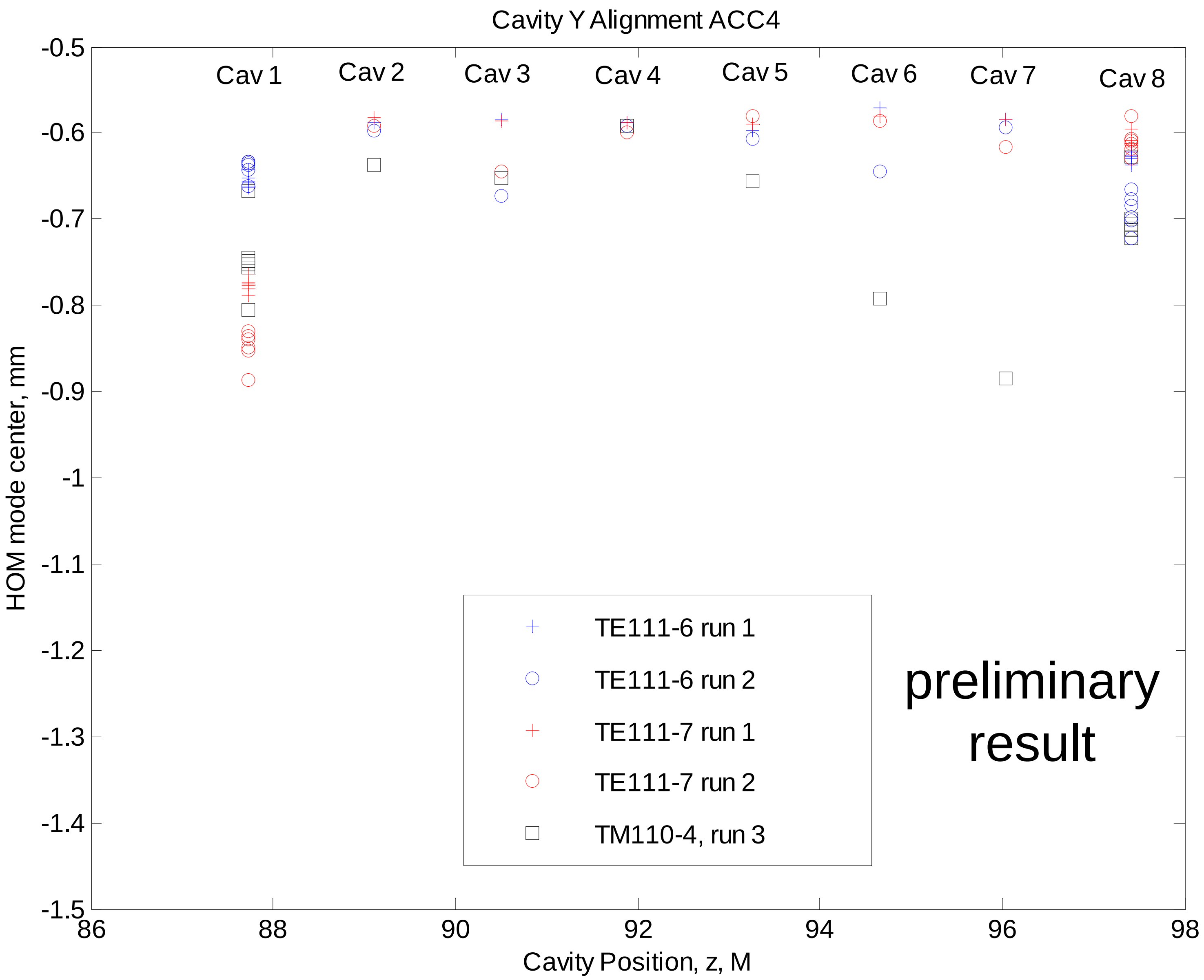
- 7 micron, 4 micron-radian resolution.
  - Consistent with ~1 meter lever arm for angular resolution
  - Indicates that conventional BPM resolution better than ~10 microns. (not limited)
- Dynamic range ~ 1 millimeter (with this gain / attenuation)
- Previous test of HOM mode resolution (end cavities vs. center cavity) gave 3 micron resolution
  - Test done with preamplifiers – but in an earlier hardware configuration



Cavity Alignment from HOM modes

- Several analysis methods tried – so far best appears to be:
  - Record HOM signals and conventional BPMs for a series of machine cycles
  - Find HOM (complex) amplitudes as a function of frequency (from FFT)
  - Linear Regression / Singular Value Decomposition to find matrix between HOM amplitudes and BPMs
  - Find beam position / angle corresponding to zero HOM signals in each cavity.
- Work still preliminary


Cavity X Alignment ACC4
Cav 1
Cav 2
Cav 3
Cav 4
Cav 5
Cav 6
Cav 7
Cav 8
-1.7
-1.8
-1.9
-2
-2.1
-2.2
-2.3
-2.4
-2.5
-2.6
-2.7
Hom Mode Center, mm
86
88
90
92
94
96
98
Cavity Position Z, M
TE111-6 run1
TE111-6 run 2
TE111-7 run 1
TE111-7 run2
TM110-4 run 3
preliminary result



Cavity Y Alignment ACC4
Cav 1
Cav 2
Cav 3
Cav 4
Cav 5
Cav 6
Cav 7
Cav 8
-0.5
-0.6
-0.7
-0.8
-0.9
-1
-1.1
-1.2
-1.3
-1.4
-1.5
HOM mode center, mm
86
88
90
92
94
96
98
Cavity Position, z, M
TE111-6 run 1
TE111-6 run 2
TE111-7 run 1
TE111-7 run 2
TM110-4, run 3
preliminary result

Cavity Center Measurement Issues

- HOMs have few micron resolution
  - Would expect cavity resolution to similar level
  - See resolution worse than 100 microns

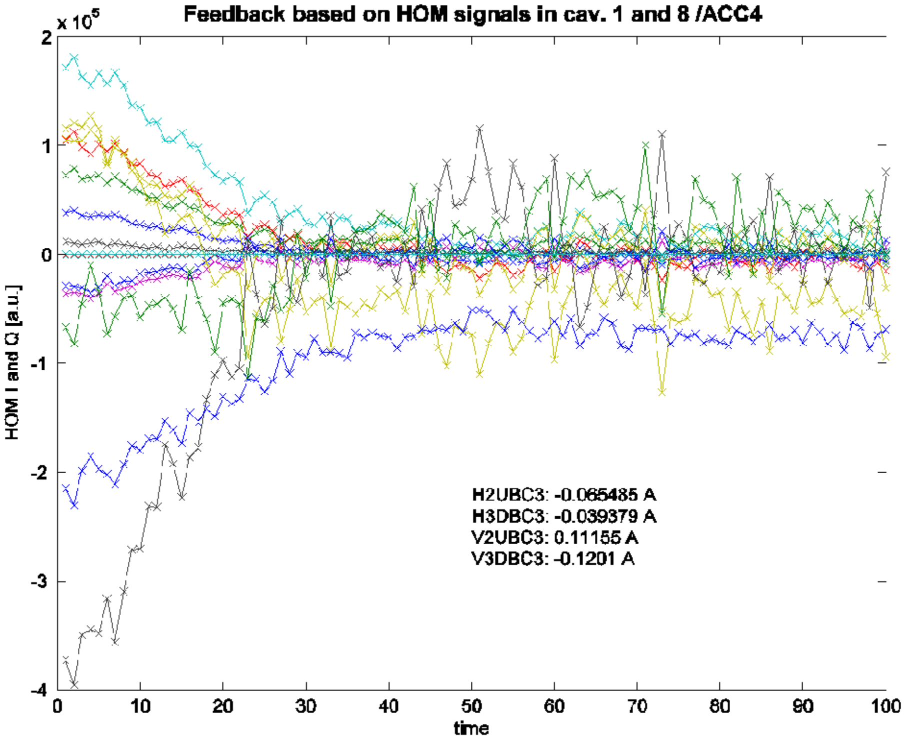
WHY?

- Beam trajectories not steered through zero in angle.
  - Must project angles to zero – introduces errors
  - Can't "ignore" angle – it is related to position by RF phase angle.
  - In future (this week?) use feedback to stabilize on position and angle for each cavity in sequence
- 8 HOM degrees of freedom (2X coupler, 2X mode polarization, 2X real / imaginary), represent 4 real degrees of freedom (X, X', Y, Y')
  - Need to understand how to treat correctly
  - Some cavities, polarization frequencies are degenerate
    - Need both couplers, but only 1 lne
  - Some cavities polarization frequences are well separated
    - Need both lines, but only 1 coupler.
  - Many cavities are partially degenerate
  - Need help with the math.

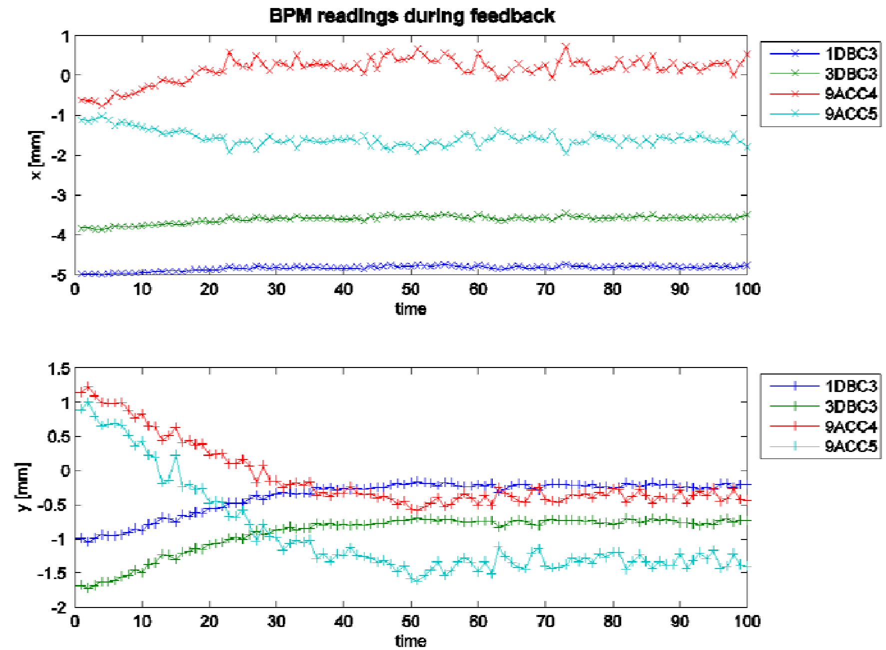
HOM Based Beam Feedback

- Do a calibration of HOM mode (complex) amplitudes against two sets of X,Y correctors.
  - Linear regression, similar to what we did for BPMs described earlier
  - Use first and last cavity in a structure
- Feedback adjusts the correctors to minimize HOM amplitudes.
  - 2 cavities, have 16 real measurements
  - 4 control degrees of freedom
  - Combine feedback signals for all modes -> minimizes RMS
- Two experiments:
  - ACC4, cavities 1 and 8
  - ACC1, cavities 1 and 8
- In each case plot the 16 real amplitudes (2 cavities X 2 couplers X 2 frequencies X real / imaginary part) for each machine cycle.

ACC 4 Feedback



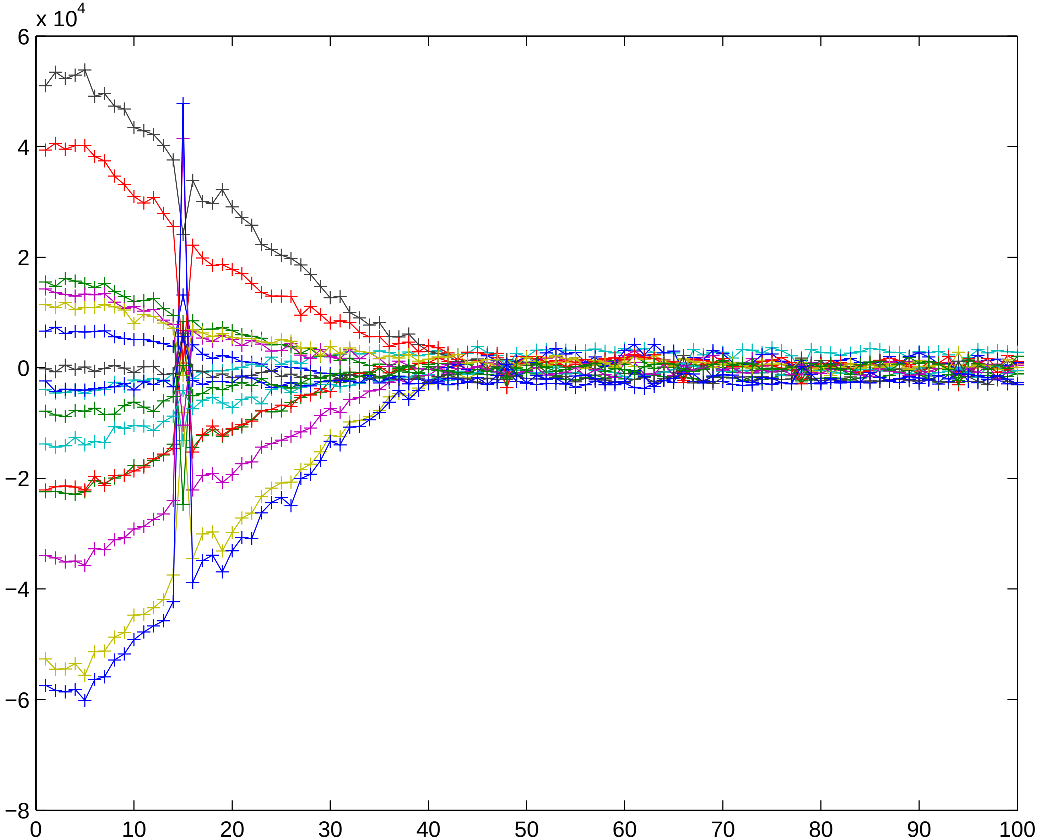
HOM mode component amplitudes during feedback, vs. machine cycle



Conventional BPMs during feedback

Beam position and angle set to minimize total power in TE111-6 modes in Cavities 1 and 8 of ACC4

ACC1 Feedback



HOM mode component amplitudes during feedback, vs. machine cycle

Feedback minimized HOM Power.

Emittance optimized before feedback operation 1.6X1.8 (90%)

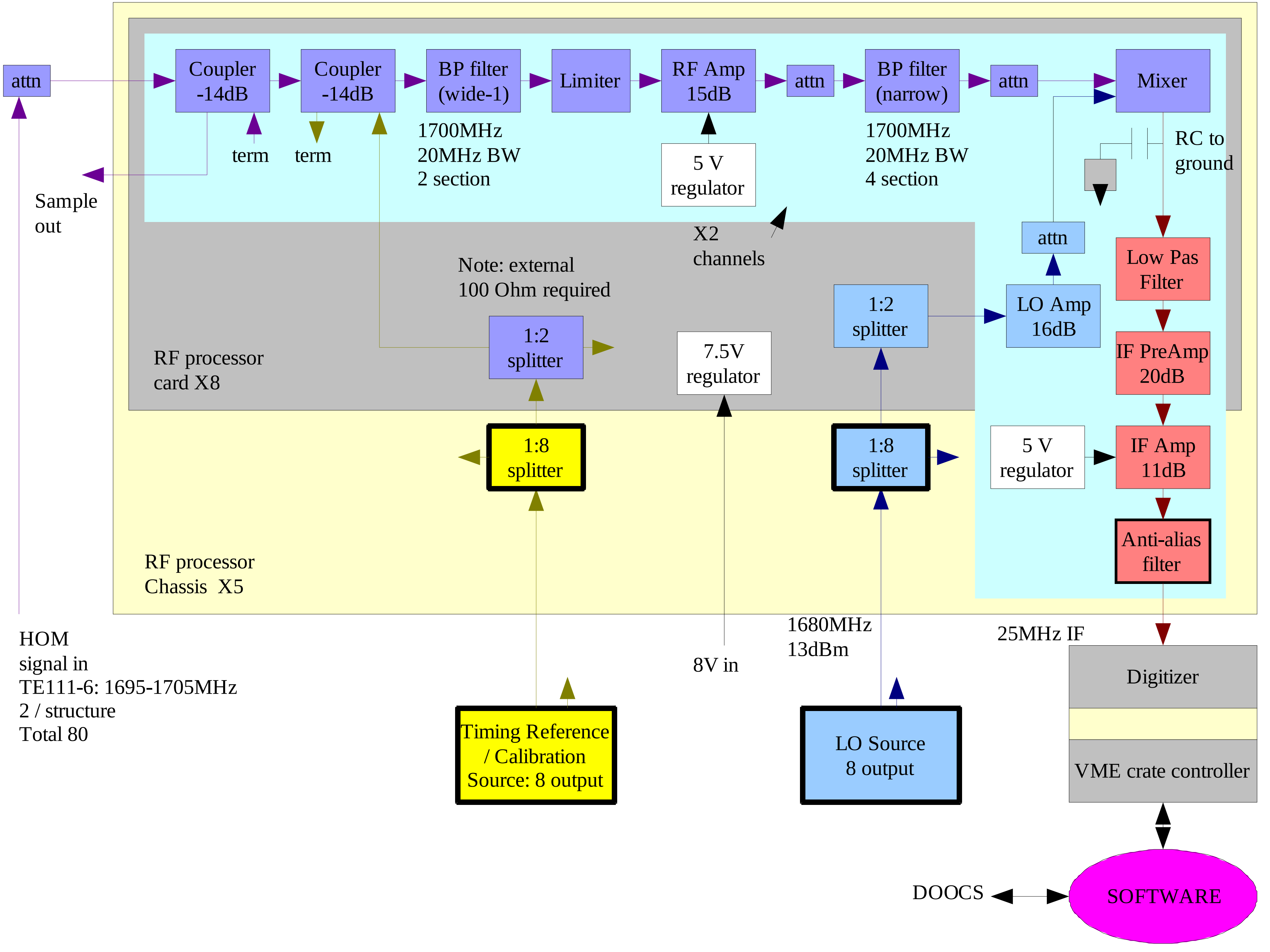
After feedback, Emittance slightly improved 1.6X1.6 (90%) (not clear if this is statistically significant)

Beam not tuned after feedback

Note, jump due to phase error (2 π wrap problem)

HOM Diagnostic System for Full TTF Linac

- Want to simultaneously instrument all 40 cavities in the TTF
  - Need 80 channels of data acquisition
- Scope based system (used for previous measurements) requires one (4 channel, 5Gs/s) scope for 2 cavities.
  - 20 scopes, at ~30,000 € is too expensive
- Build narrow band (10MHz BW) system
  - Dowmix to 25MHz IF
  - Digitizer with 100Ms/s, 14 bit digitizers (SIS3301 8 channel VME modules)
  - System hardware cost ~ 100,000 € for full system.
- Narrow band system can only measure 1 mode – choose TE111-6
  - 10 MHz bandwidth input filters
- Theoretical noise similar to existing HOM system
- Linearity / dynamic range expected ~20dB better than existing system.
- Expect 1 micron resolution at 1 millimeter dynamic range.


attn
Coupler -14dB
Coupler -14dB
BP filter (wide-1)
Limiter
RF Amp 15dB
attn
BP filter (narrow)
attn
Mixer
term
term
1700MHz
20MHz BW
2 section
5 V regulator
1700MHz
20MHz BW
4 section
RC to ground
Sample out
X2 channels
attn
Low Pas Filter
Note: external 100 Ohm required
1:2 splitter
LO Amp 16dB
1:2 splitter
7.5V regulator
IF PreAmp 20dB
RF processor card X8
1:8 splitter
1:8 splitter
5 V regulator
IF Amp 11dB
Anti-alias filter
RF processor Chassis X5
HOM signal in
TE111-6: 1695-1705MHz
2 / structure
Total 80
1680MHz
13dBm
25MHz IF
8V in
Digitizer
Timing Reference / Calibration Source: 8 output
LO Source 8 output
VME crate controller
DOOCS
SOFTWARE

HOM Downmix Board

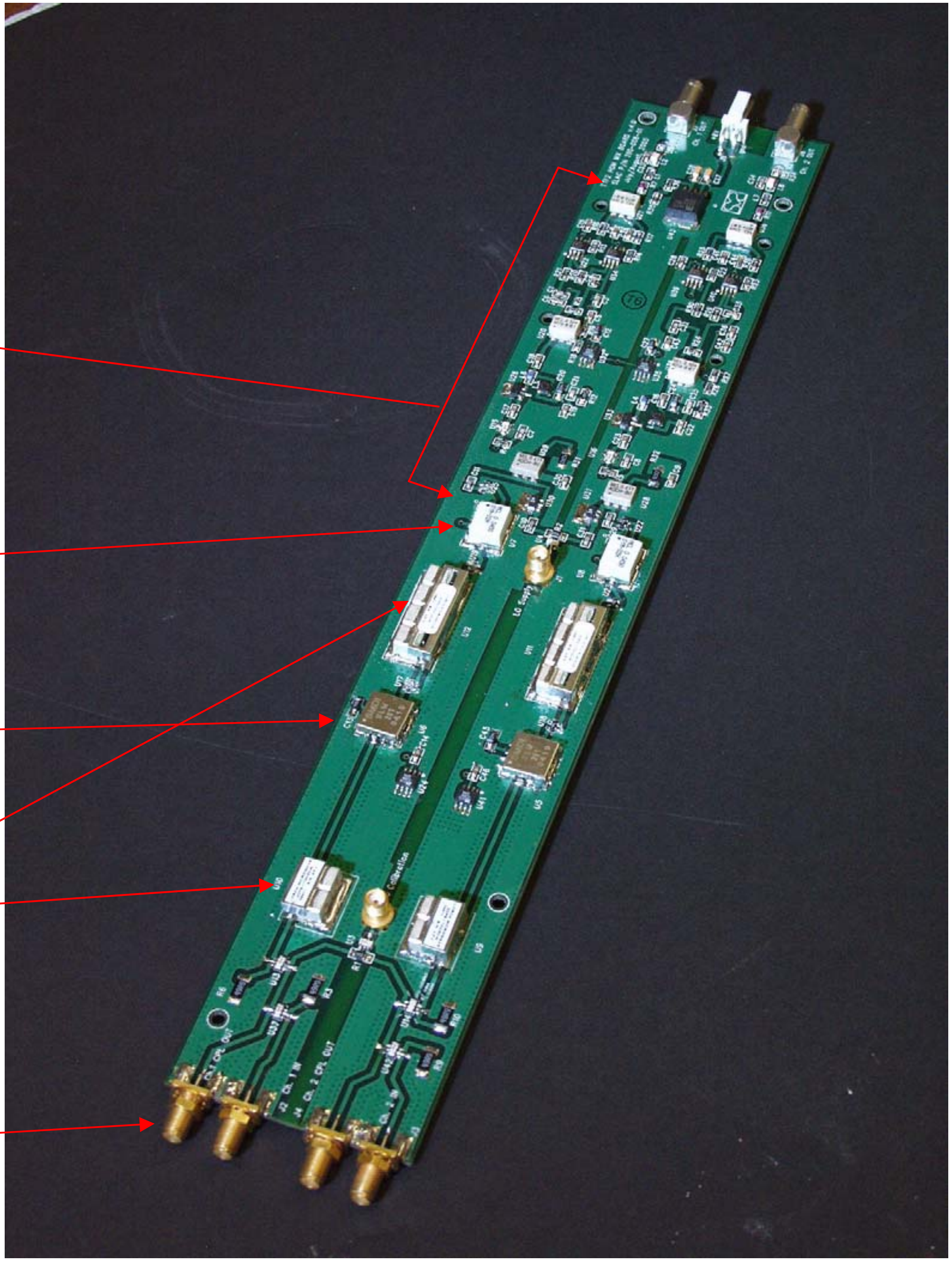
IF output amplifier

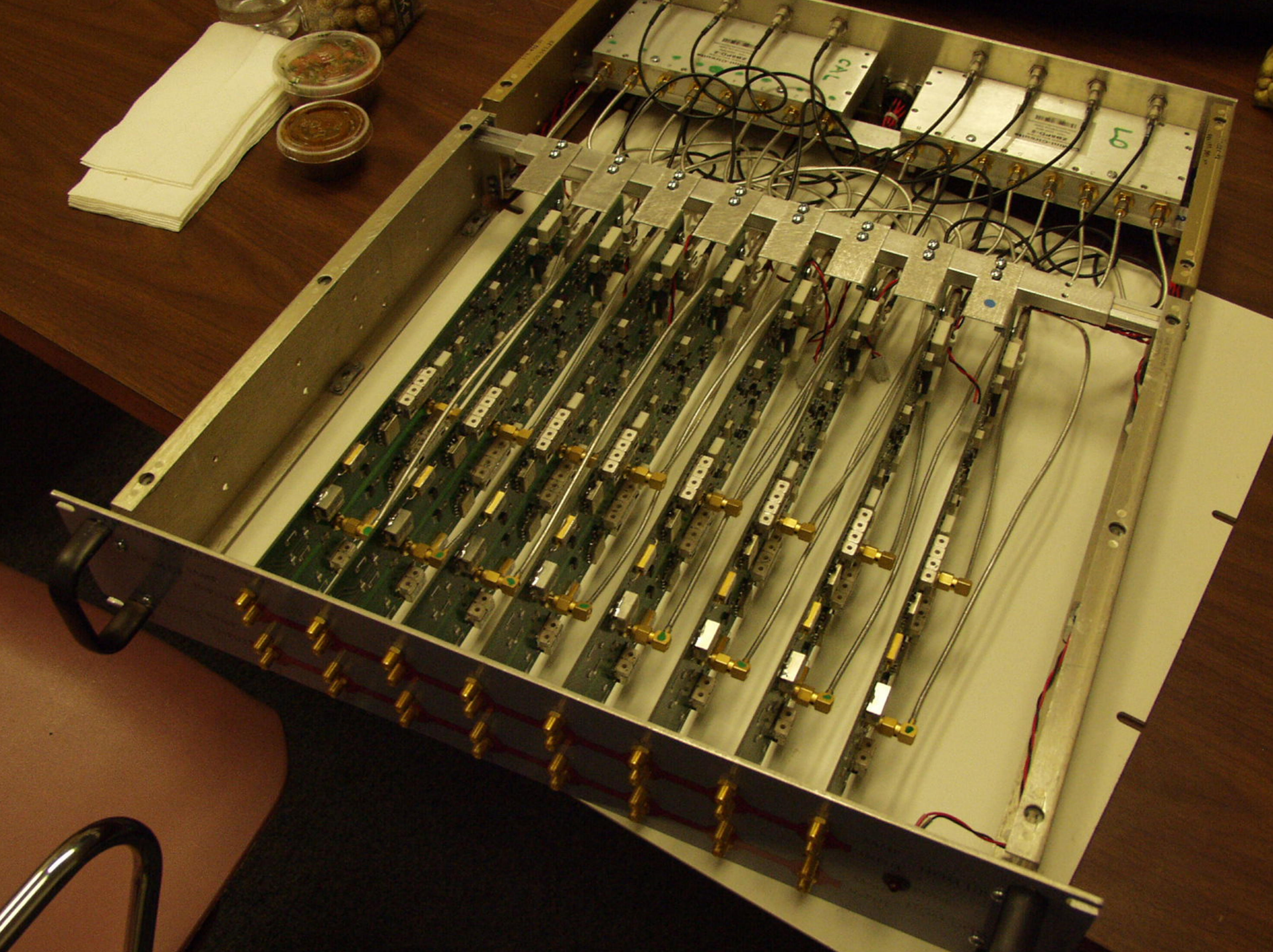
Mixer

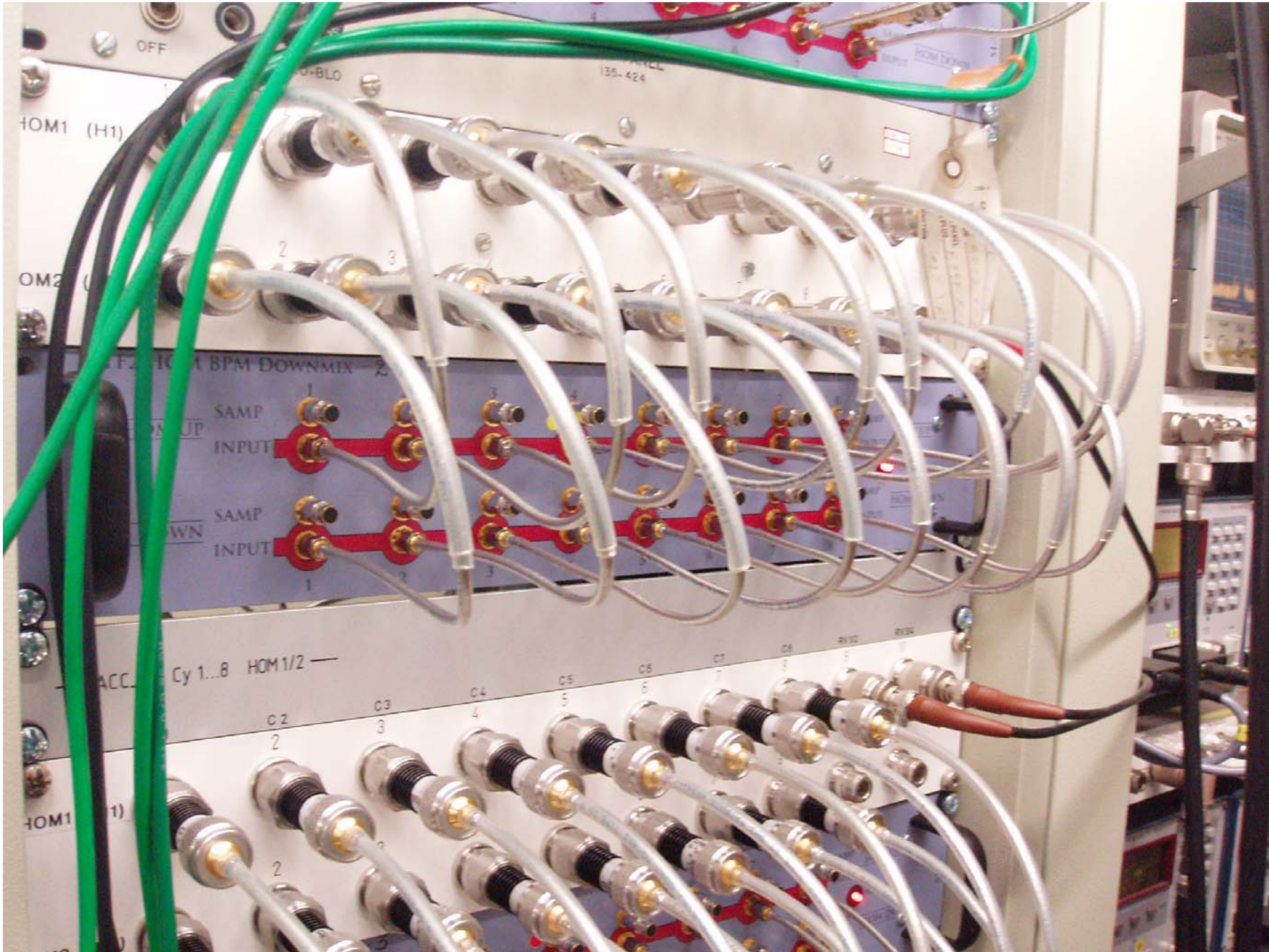
Pre-amplifier

Bandpass filters

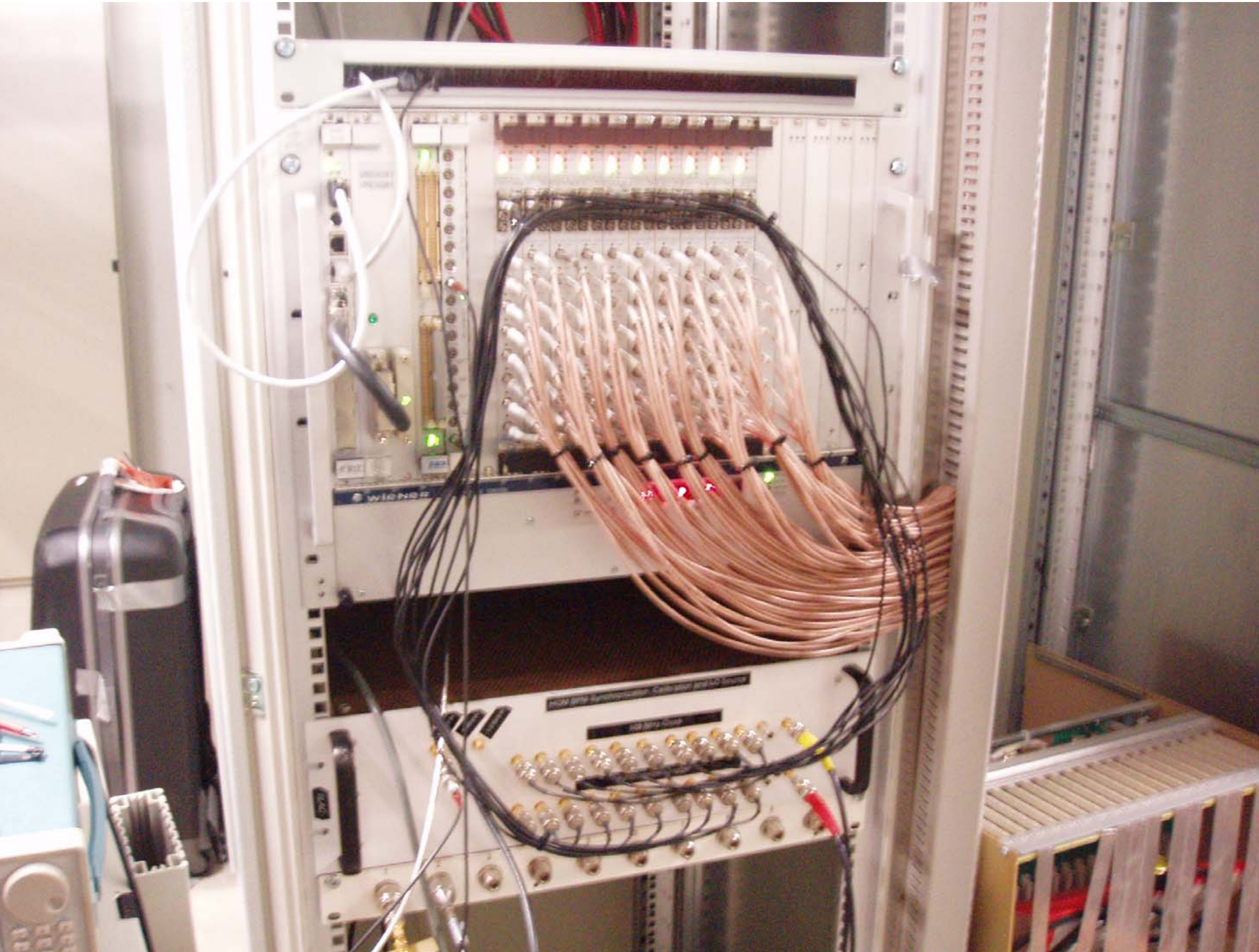
Input and sample out

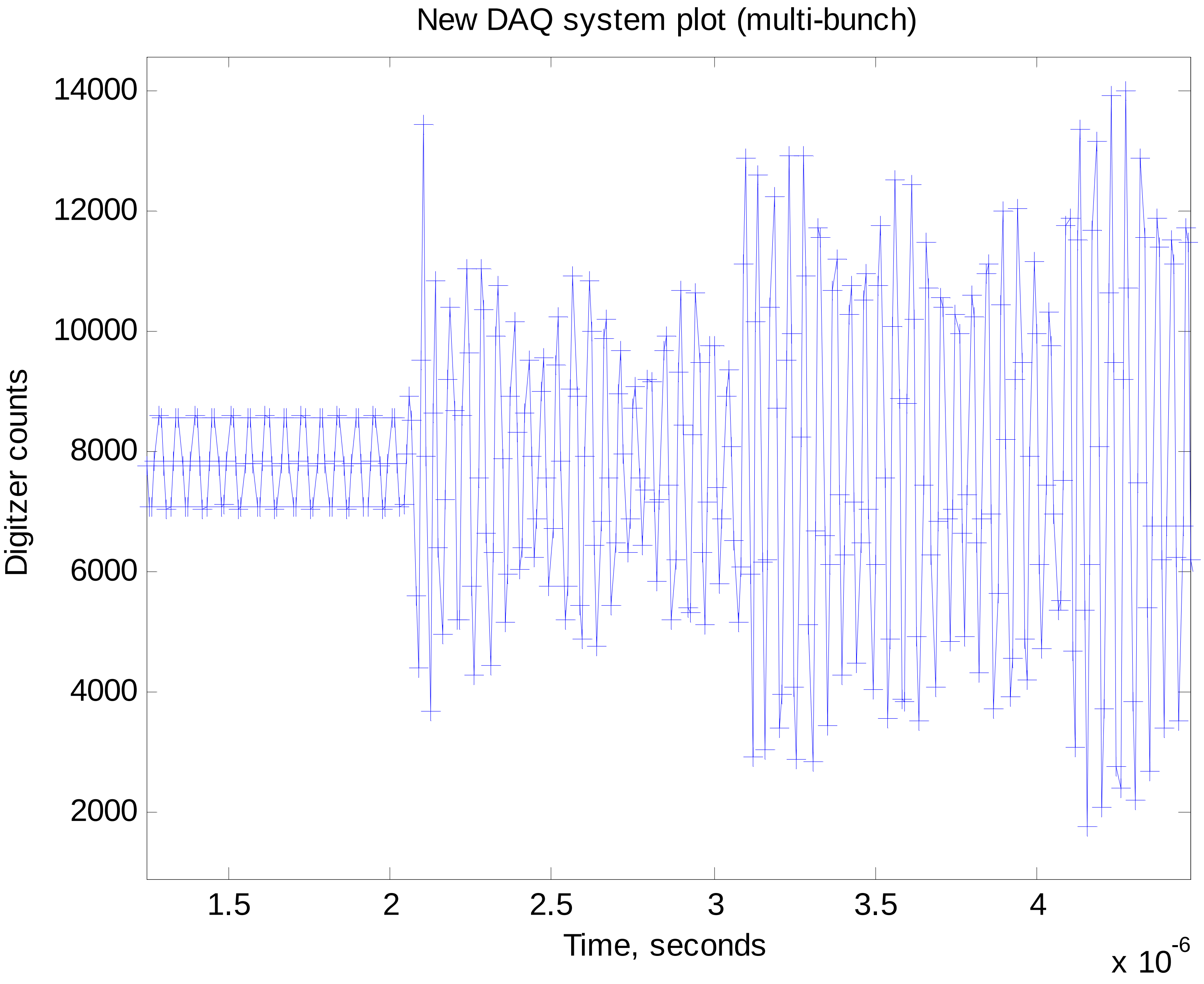



CAL



OFF
135-424
HOM1 (H1)
BPM DOWNMIX
SAMP
INPUT
SAMP
INPUT
Cy 1...8
HOM 1/2
C 2
C3
C4
C5
C6
C7




New DAQ system plot (multi-bunch)
Digitizer counts
14000
12000
10000
8000
6000
4000
2000
1.5
2
2.5
3
3.5
4
Time, seconds
x 10^-6

Multi-bunch operation

- New hardware can digitizer signals for the full length of the TTF bunch train. >1 millisecond.
- At each bunch passage, field amplitude from the bunch addes to the existing field amplitude.
- Fields from previous bunches decay at a predictable rate
- Only care about field after passage of previous bunch – History does not matter.
- Can subtract (decayed) fields at time of previous bunch to find new contribution.
- Effective integration time ~1 microsecond (rather than ~10 currently used). Will reduce resolution, but still expect <10 microns.

HOM System Applications

- Real time BPM – all cavities in TTF
  - Expect single bunch resolution ~1 micron
    - 3 micron demonstrated
  - Measure each bunch in train to ~10 microns
    - Multi-bunch measurement not yet demonstrated
  - Need automated calibration and integration with DOOCS.
- HOM mode minimization feedback
  - Should improve emittance
  - Demonstrated for 2 cavities in one structure
  - Should be possible to feedback to beam orbit which minimizes HOM power in full machine.
  - Need to integrate with DESY feedback system
- Measure / monitor cavity alignment within structures
  - Preliminary results suggest ~100 micron resolution
  - Expect few micron results
  - Work ongoing.