Cavity BPM studies at ATF and CALIFES

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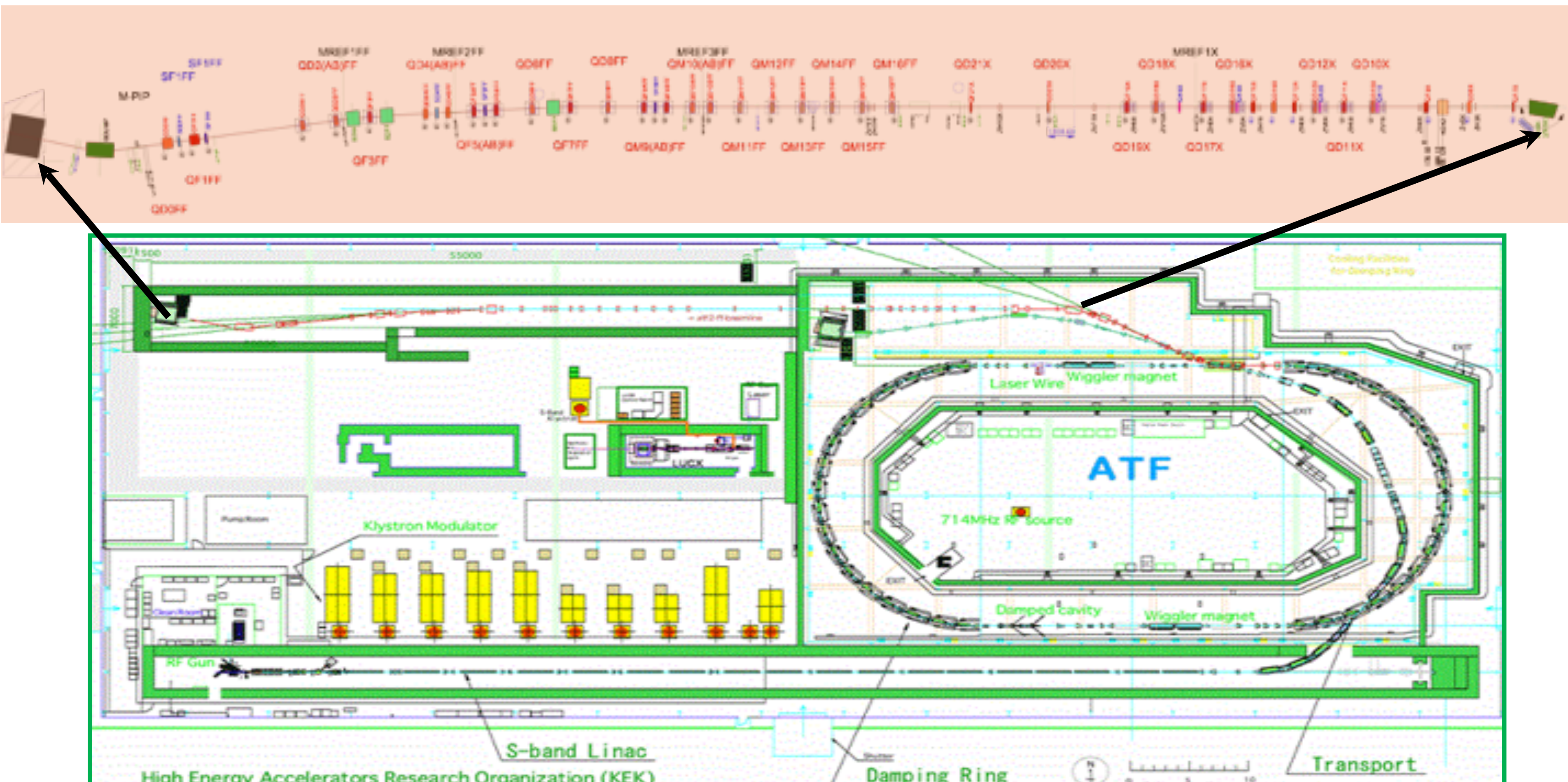
- 1.3 GeV low-emittance beam, a scaled model of the next Linear Collider beam delivery system aimed at delivering 37 nm beam size
- Very dense with advanced beam instrumentation (WS, OTR, LW, BSM, CBPM)

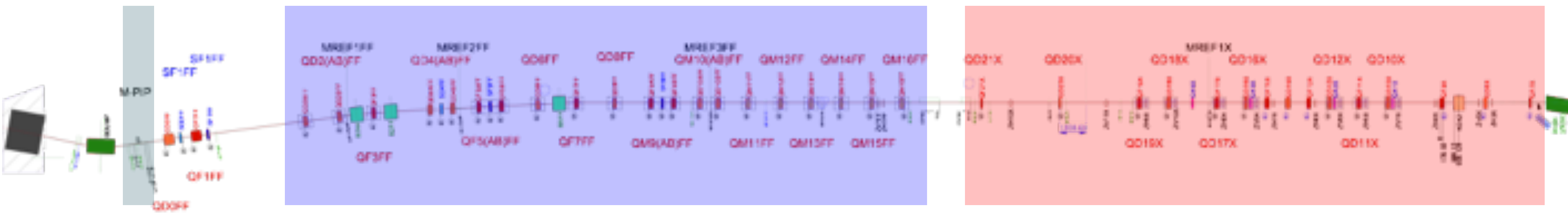


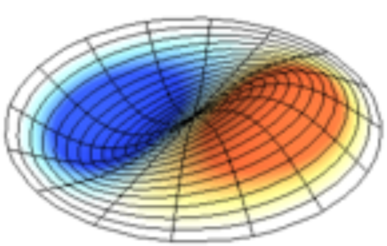
Cavity BPMs at ATF2

IP region
(4 BPMs)

C-band BPMs
(on movers)

Strip line/Cavity BPMs
(mounted rigidly)

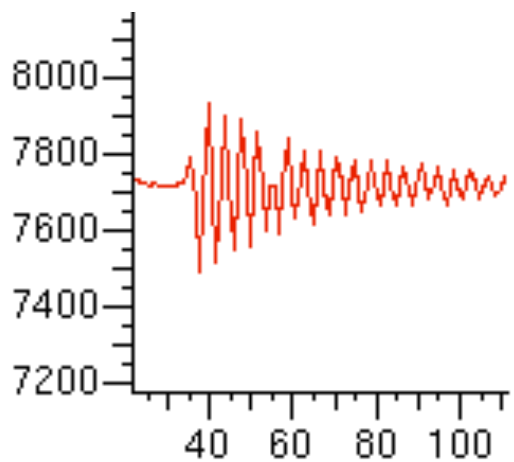




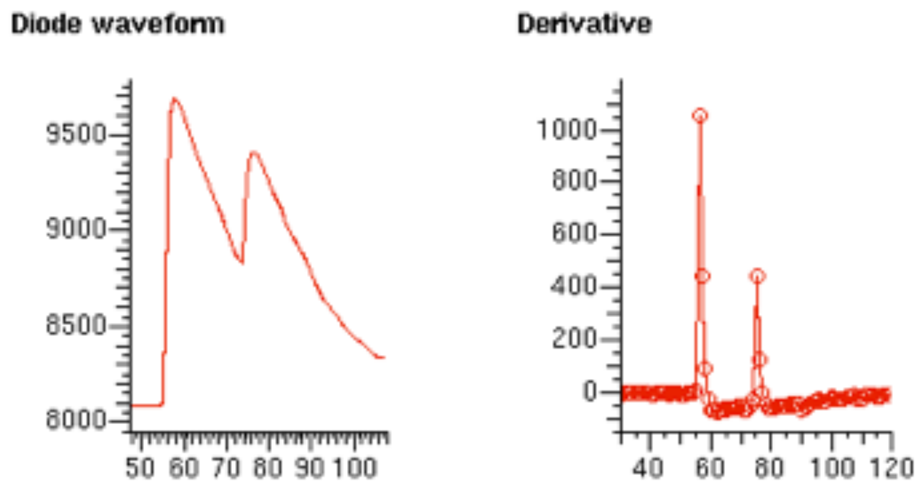
http://www.acs.psu.edu/drussell/
demos/membranecircle/circle.html

Position measurements of multiple bunches at ATF2

- Need to measure positions of multiple bunches with bunch spacing smaller or comparable with the decay time of the signal in the cavities
- Position measurement includes measuring both amplitude and phase, so subtraction needs to be done on phasors

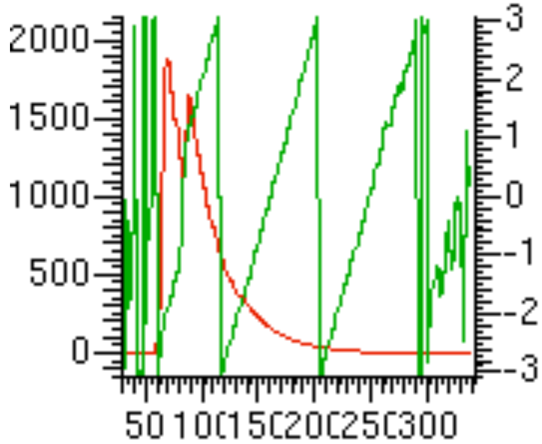


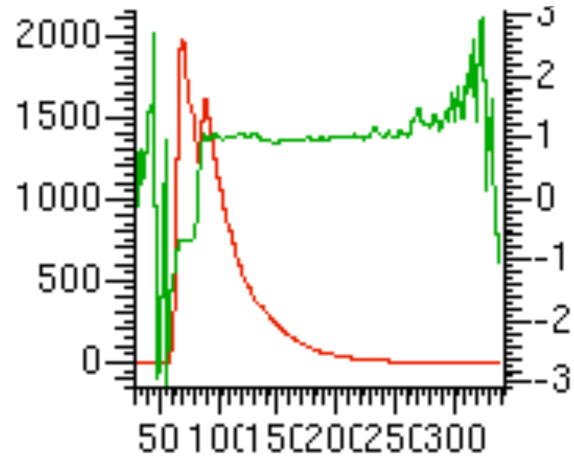
Bunch search



- Number of bunches and timing between them may vary shot-to-shot (missing bunches, timing drifts)
- Use diode-rectified signal from the reference cavity
- Detect the bunches using the front of the signal
- Upper limits of resolution: bunch 1 ~20 ps bunch 2 ~60 ps
- At around 3 MHz frequency difference this means 0.02 and 0.06 degree respectively

Frequency, decay and sampling time tuning





- Precision measurement of the frequency of the signal, decay time of the processed amplitude and choice of the sampling time relative to the arrival time needed for processing and subtraction

What that technically means

- Need to detect the bunches
- Every number becomes an array
- Every 1D array becomes a 2D array
- Speed and transparency important

- Result: complete re-design of the low-level software
- Significant changes to the infrastructure (higher-level scripts)
- No dramatic change in interfaces (for better or worse)

EPICS IOC implementation

- Subroutines integrated in EPICS IOC
- Using aSub
- Advantage: easy synchronisation, no overhead in code
- Disadvantage: not easy to debug

```
record(waveform, "$(name):i") {
  field(NELM, "$(nb)")
  field(FTVL, "DOUBLE")
}

record(waveform, "$(name):q") {
  field(NELM, "$(nb)")
  field(FTVL, "DOUBLE")
}
```

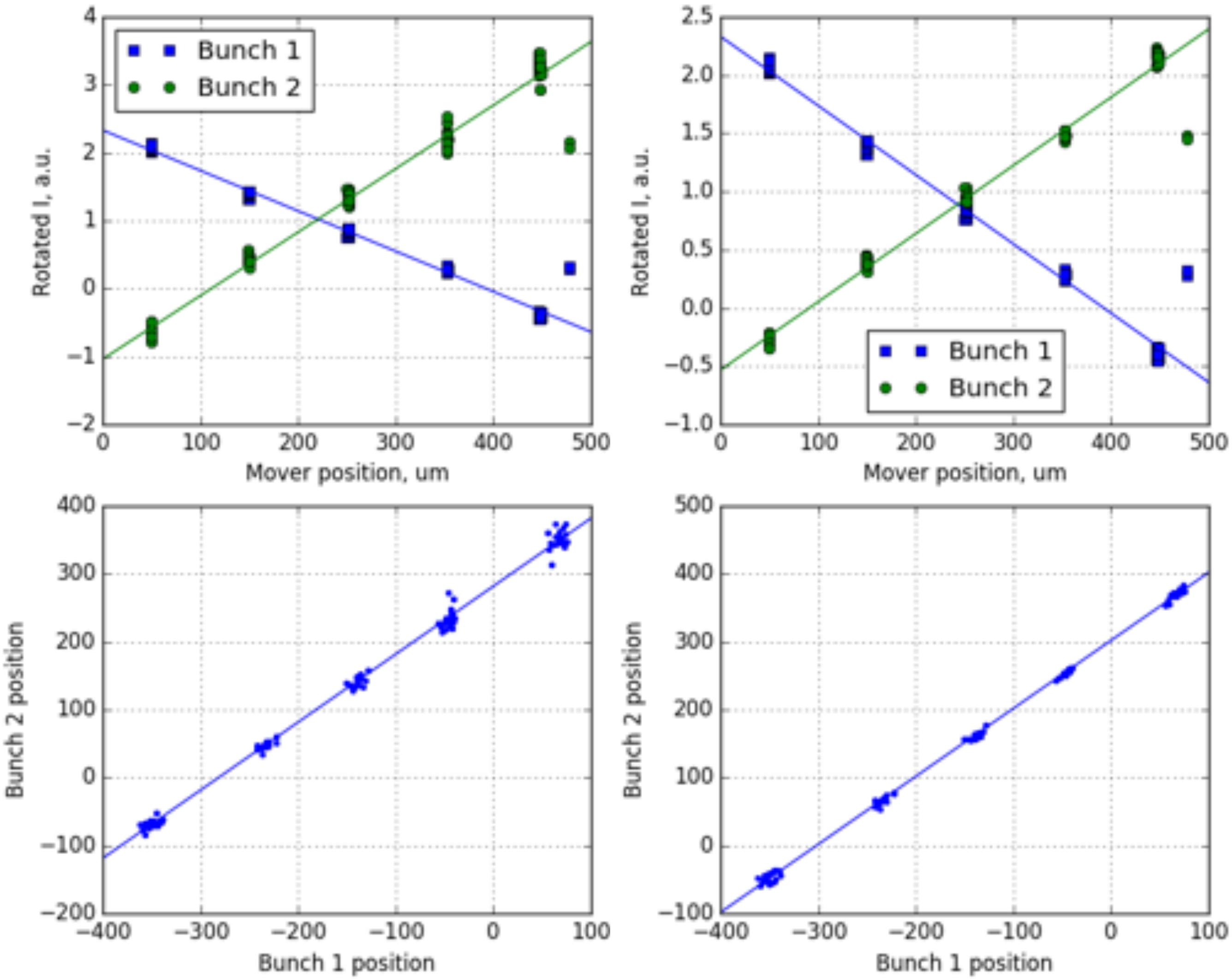
```
record(waveform, "$(name):posscale") {
  field(NELM, "$(nb)")
  field(FTVL, "DOUBLE")
}

record(waveform, "$(name):tiltscale") {
  field(NELM, "$(nb)")
  field(FTVL, "DOUBLE")
}
```

```
record(aSub, "$(name):CalcPos") {
  field(INAM, "CalcPosTiltInit")
  field(SNAM, "CalcPosTiltProc")
  field(INPA, "$(name):sAmp CP")
  field(NOA,  "$(nb)")
  field(INPB, "$(name):sPhi")
  field(NOB,  "$(nb)")
  field(INPC, "$(name):sAmpCal")
  field(INPD, "$(name):sPhiCal")
  field(INPE, "$(rname):sAmp")
  field(NOE,  "$(nb)")
  field(INPF, "$(rname):sPhi")
  field(NOF,  "$(nb)")
  field(INPG, "$(rname):sAmpCal")
  field(INPH, "$(rname):sPhiCal")
  field(INPI, "CDIODEnew:nob")
  field(FTI,  "LONG")
  field(INPJ, "$(name):usecal")
  field(FTJ,  "LONG")
  field(INPK, "$(name):iqrot")
  field(NOK,  "$(nb)")
  field(INPL, "$(name):posscale")
  field(NOL,  "$(nb)")
  field(INPM, "$(name):tiltscale")
  field(NOM,  "$(nb)")
  field(INPN, "$(name):posflip")
  field(NON,  "$(nb)")
  field(INPO, "$(name):bbaoffset")
  field(INPP, "$(name):bbaflip")
  field(OUTA, "$(name):pos CA")
  field(NOVA, "$(nb)")
  field(OUTB, "$(name):tilt CA")
  field(NOVB, "$(nb)")
  field(OUTC, "$(name):i CA")
  field(NOVC, "$(nb)")
  field(OUTD, "$(name):q CA")
  field(NOVD, "$(nb)")
  field(OUTE, "$(name):ical CA")
  field(OUTF, "$(name):qcal CA")
}
```

Subtraction effect on calibrations

- Using an example (typical, not the best) calibration for QM16FFx, processing with subtraction ON and OFF
- Comparing the calibration scales for bunch 1 and 2: can differ by up to 3% as sampling time differs by up to 1 sample, but not more
- Comparing bunch 1 and 2 positions during calibration

Calibration with subtraction OFF/ON



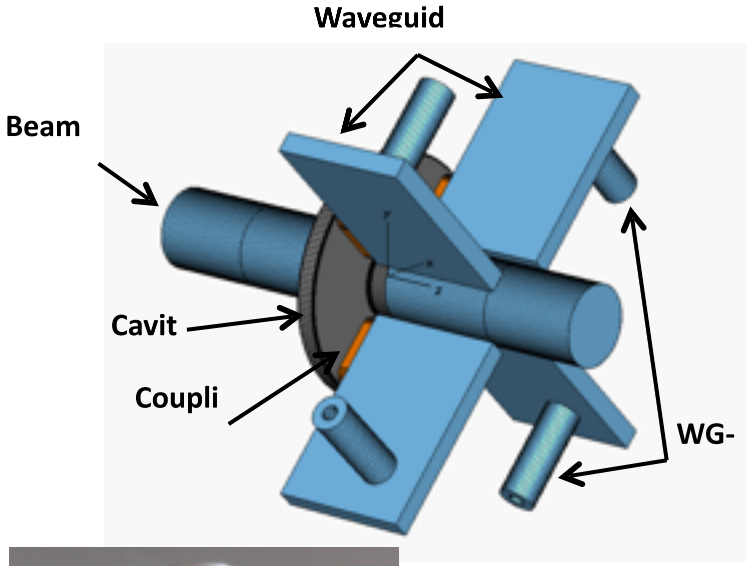
OFF:
Scales: 168 um/a.u. and 107 um/a.u.
Residual within +/- 100 um: 12.8 um

ON:
Scales: 168 um/a.u. and 171 um/a.u.
Residual within +/- 100 um: 2.9 um

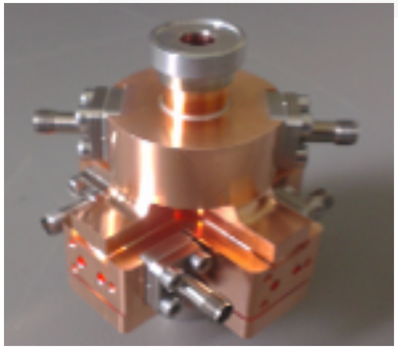
Status & Outlook

- Subtraction confirmed with many CBPMs
- With subtraction, calibration scales for bunch 1 and 2 differ by less than 3%, which is expected as sampling time differs by up to 1 sample, but not more
- With many calibrations in place, one can correlate the scales to the difference between the arrival and sampling times
- Resolution limit (from the best calibration) around 1.2 um, but still need a dedicated measurement (data being analysed)
- Resulting algorithms are being implemented in the online code

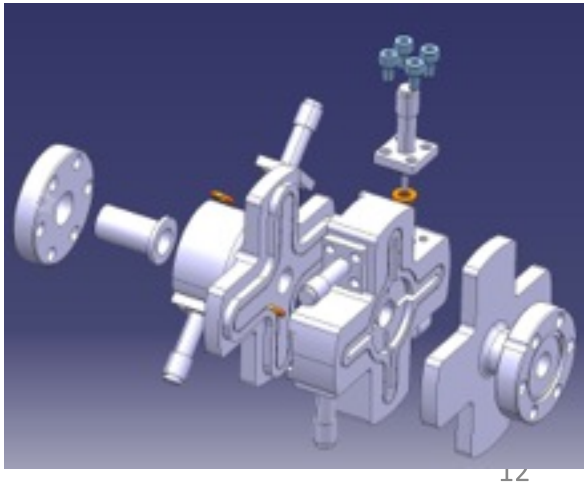
CLIC main beam CBPM @CALIFES



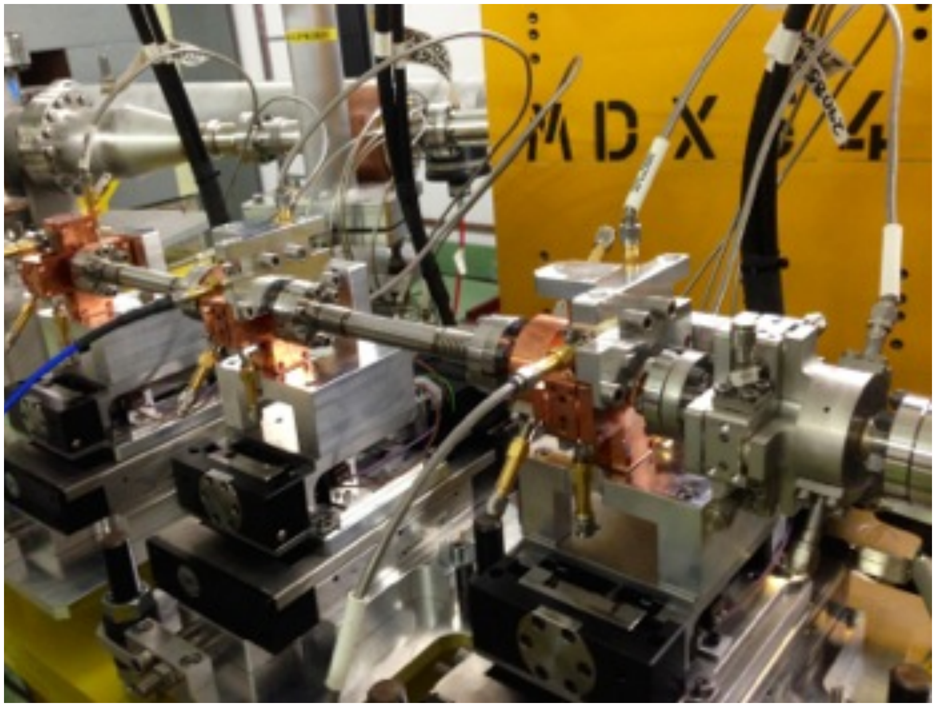
- Required for precision positioning of main linac components
- High spatial (50 nm) and high temporal (50 ns) resolution needed for interesting machine tuning measurements such as beam-based alignment, wakefield-free steering and *online dispersion correction* via energy chirped trains
- High sensitivity low-Q cavities as sensors



Cavity	Q	F
Reference	*938*	*14.772*
Predicted	*500*	*15.0*
Position	*~830*	*14.996*
Predicted	*524*	*15.0*

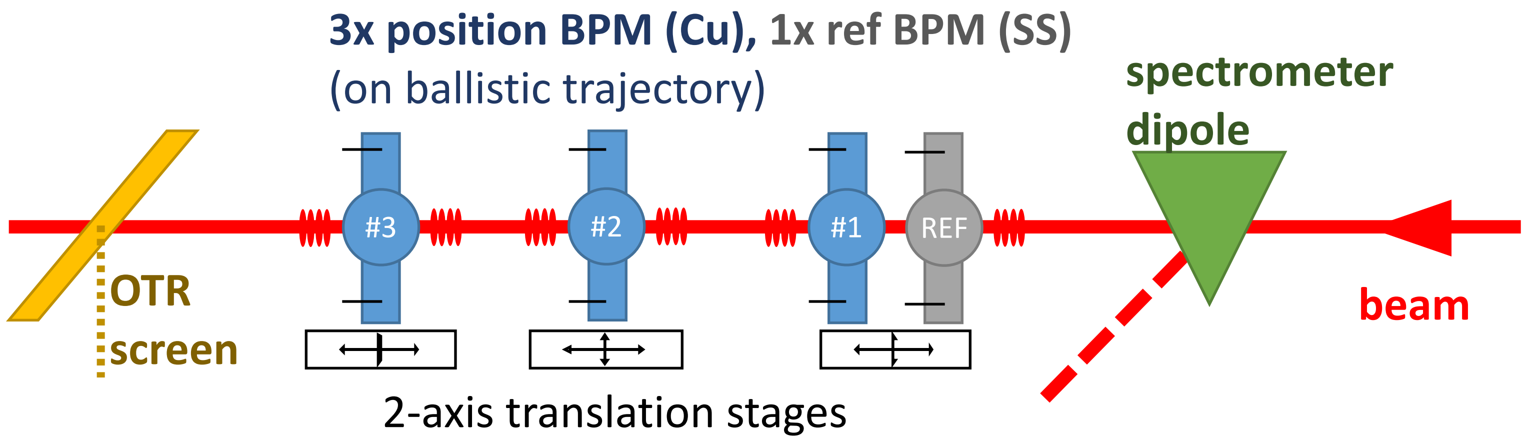


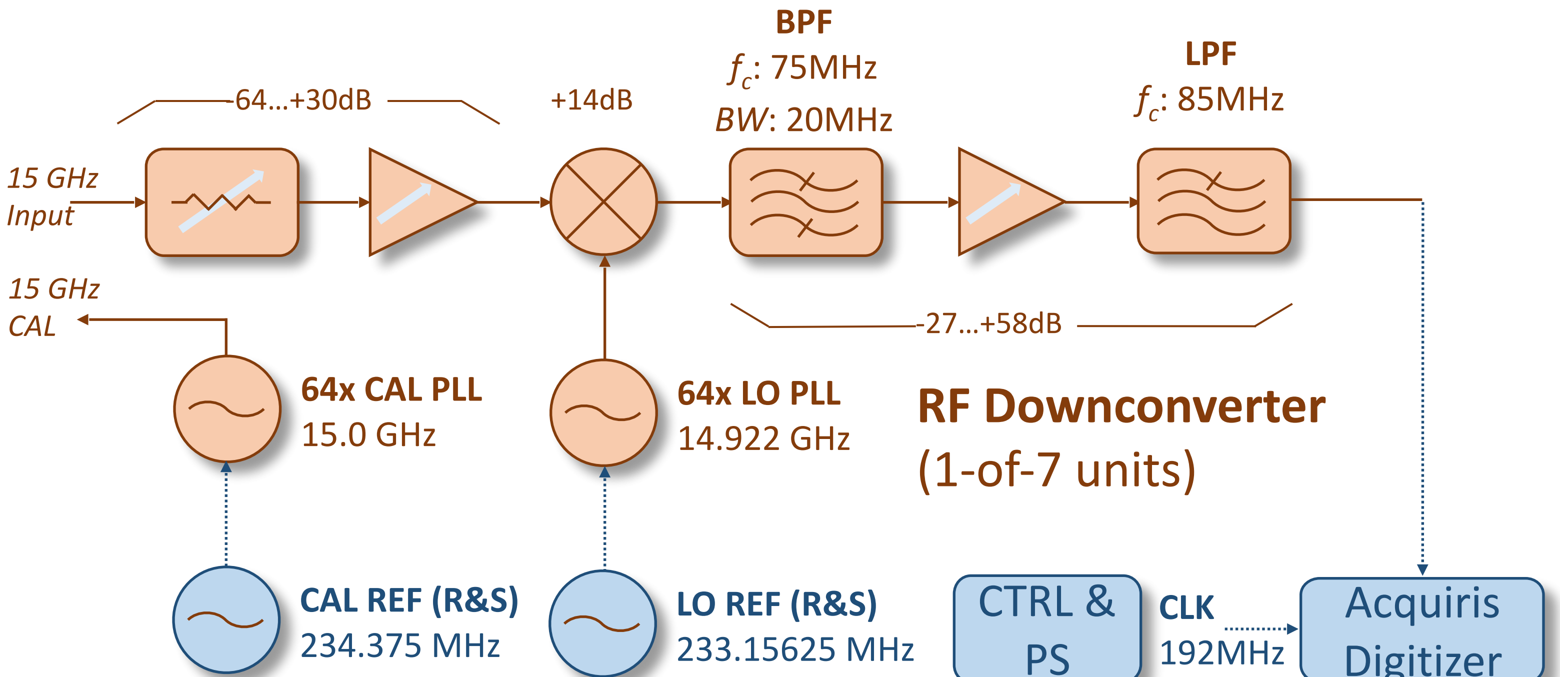
BPM triplet in CALIFES



- CBPM triplet installed in CALIFES (CTF probe beam) + old stainless prototype used only as a reference
- Located downstream due to small aperture next to the beam dump

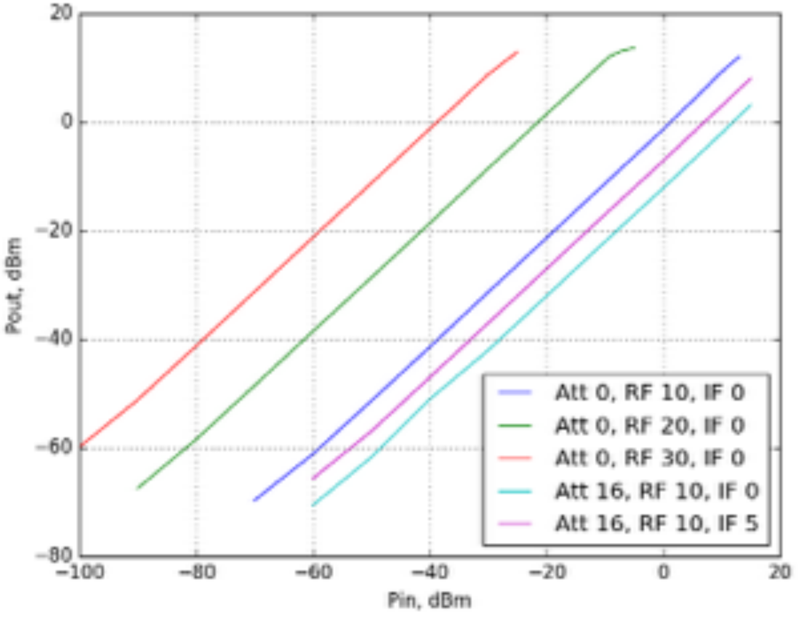
CBPM triplet and analog processing





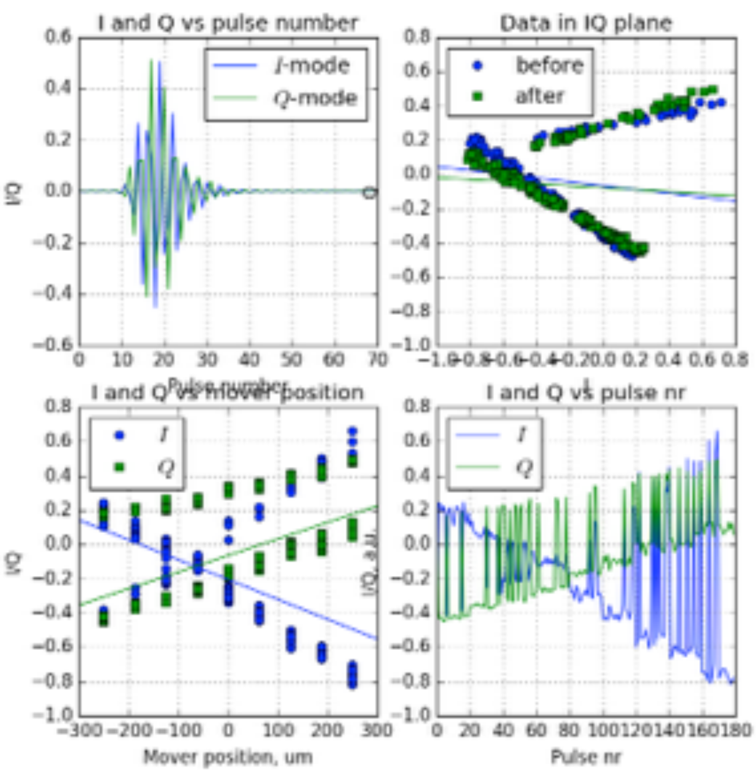
Analog electronics

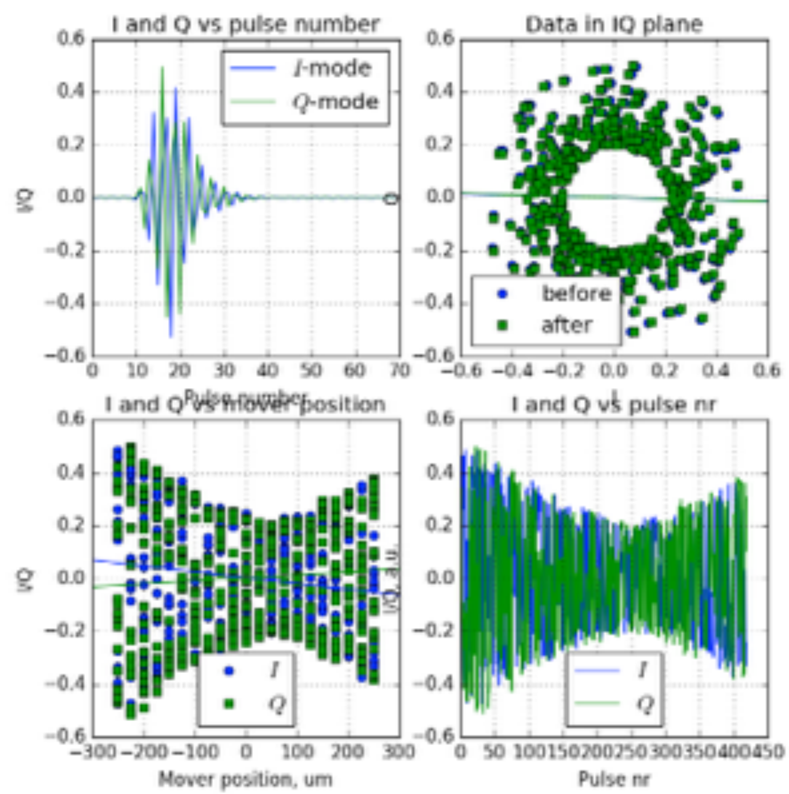
- Single stage of conversion
- A lot of gain control
- The figure shows the output power vs. input power for various settings of control in a CW measurement
- In April 2016 relocated from next to the beam line to behind concrete as observed multiple failures due to radiation damage



Beware: problematic digitisers

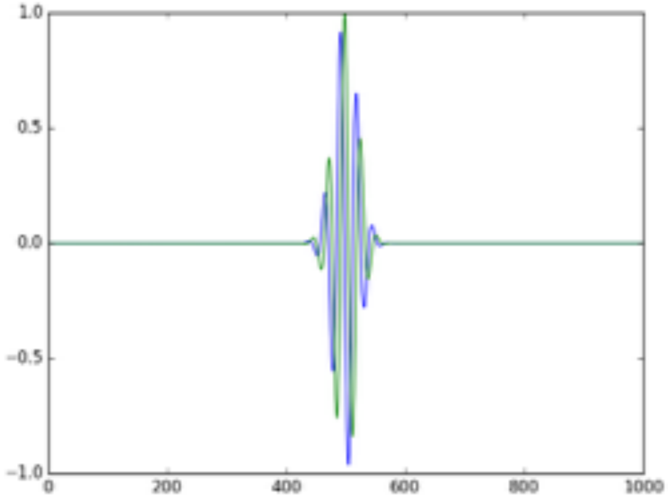
- Observed a malfunction in our 12-bit high-speed digitisers
- The observation was as if there was de-phasing between the electronics channels
- Firmly diagnosed by simply splitting a test tone into 2 digitiser inputs
- Problem being investigated
- Using an 8-bit digitiser, so the dynamic range is reduced despite faster acquisition

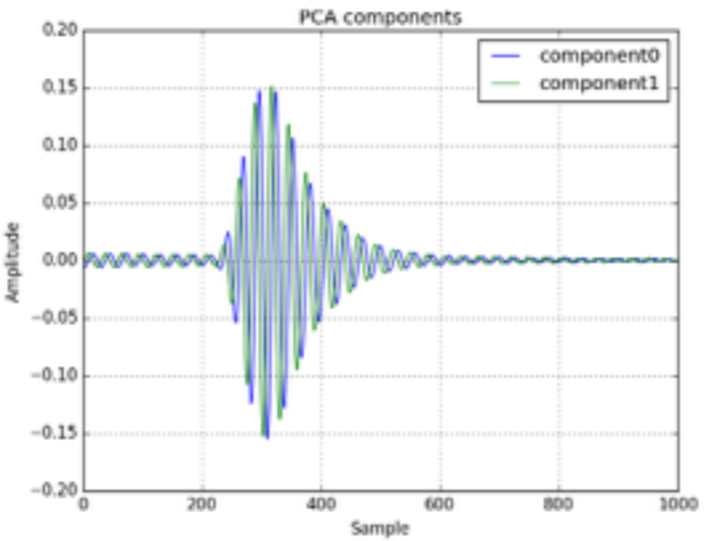




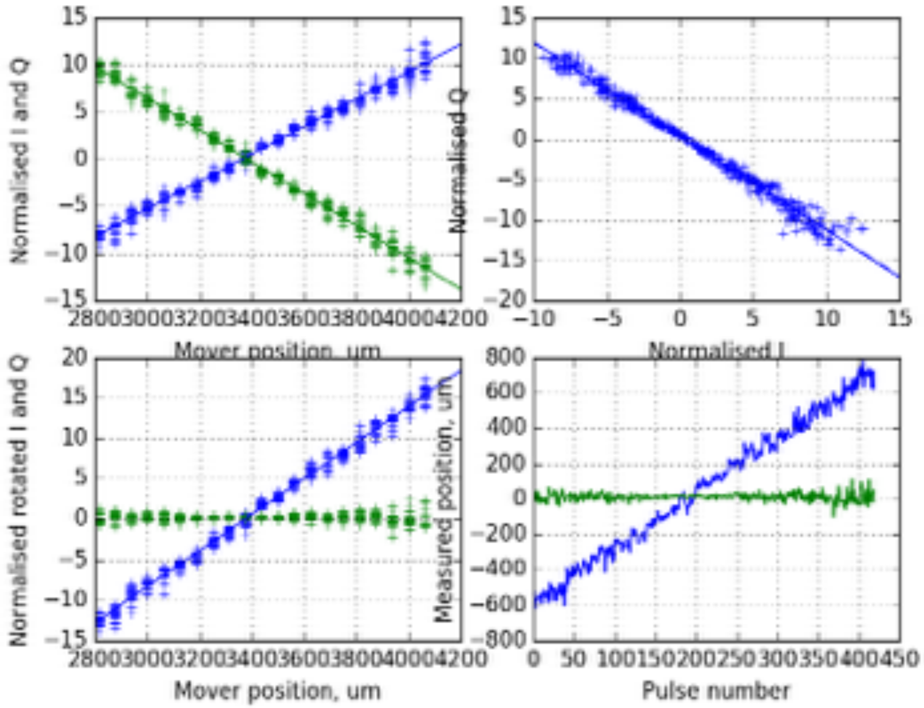
Digital processing

- 2 types of analysis used: Digital Down-Conversion (DDC) and Principal Component Analysis
- In both cases use a basis of windowed 2 orthogonal sin/cos-like signals
- DDC: Gaussian window, positioned arbitrarily
- PCA: Signal-derived window
- Concentrating on DDC for now as it is more robust and better understood



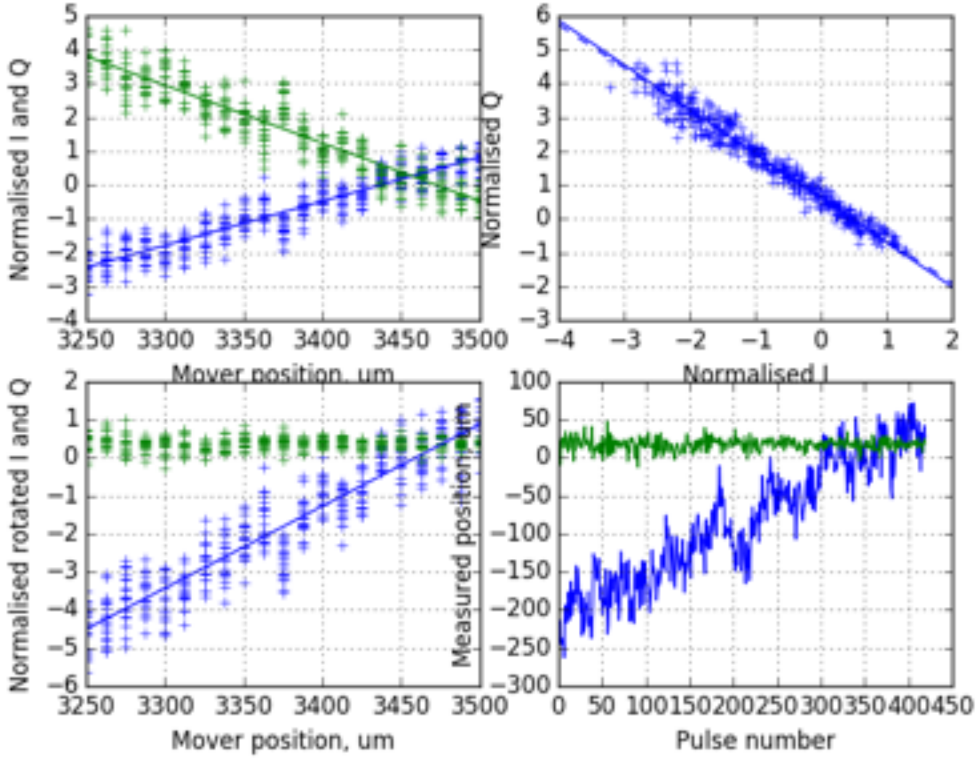


Wide range calibration, low gain



- Use mover stages to ensure pure position offset (no angle) and high precision
- Find the phase corresponding to the position in the complex IQ plane
- Determine the position scale
- Non-linearities can be observed as increased phase noise (bow-tie) in the IQ plane, or compression in the calibration plots
- Work in the central region or reduce gain

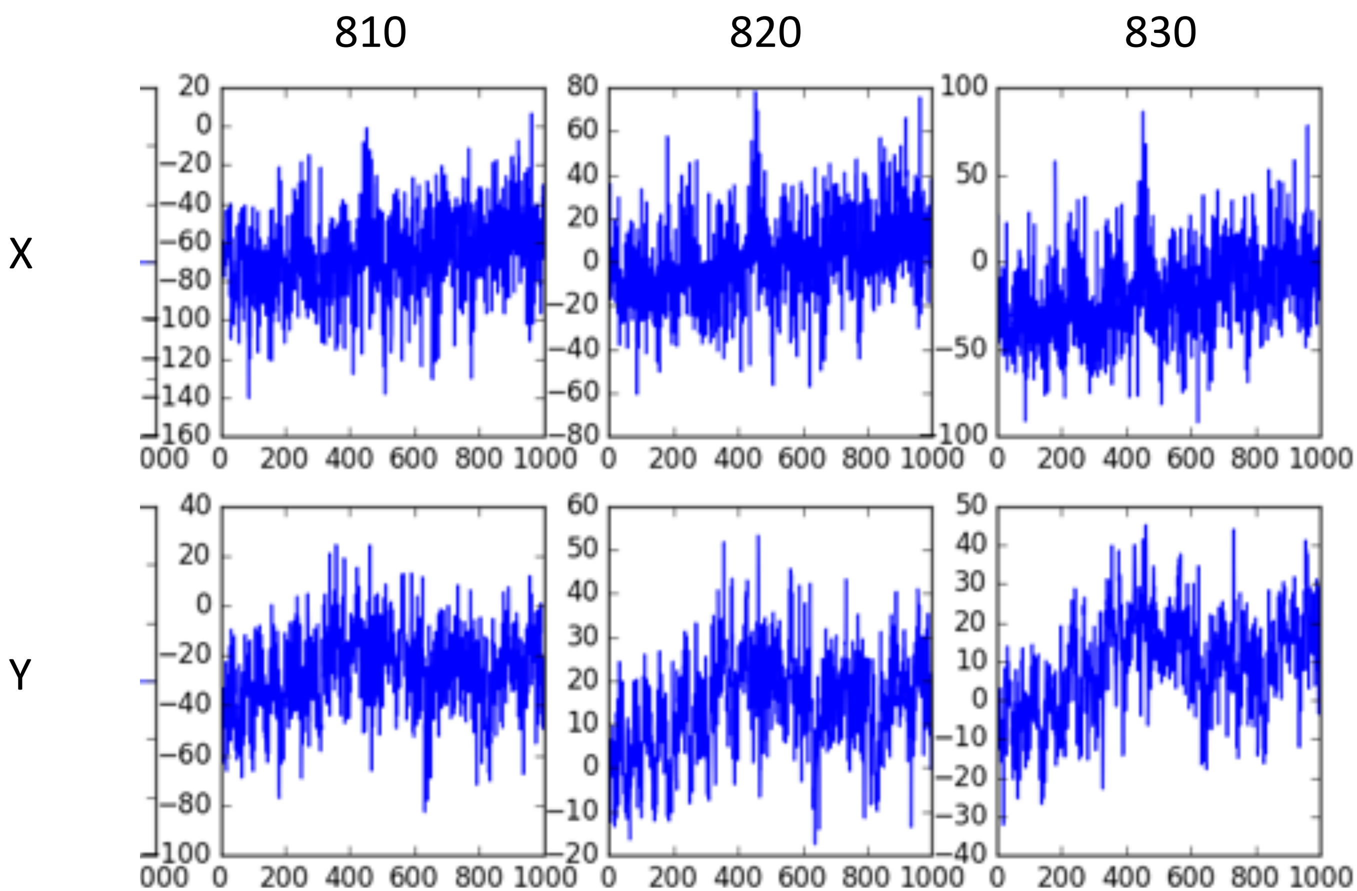
Calibrations narrow range



- Still observe an increased phase noise at higher amplitudes, but much reduced
- The resulting phase noise can be confused with the angular jitter, its signature is the amplitude dependence

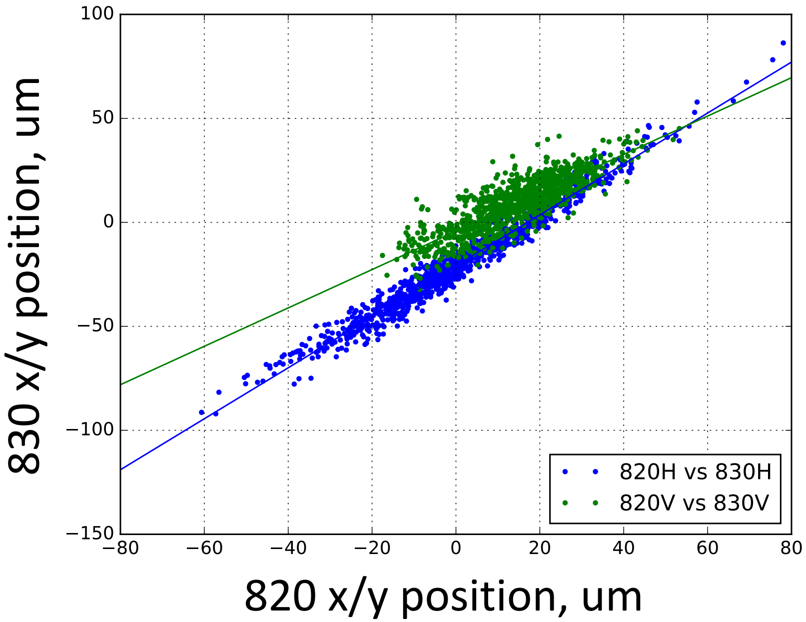
CBPM correlation

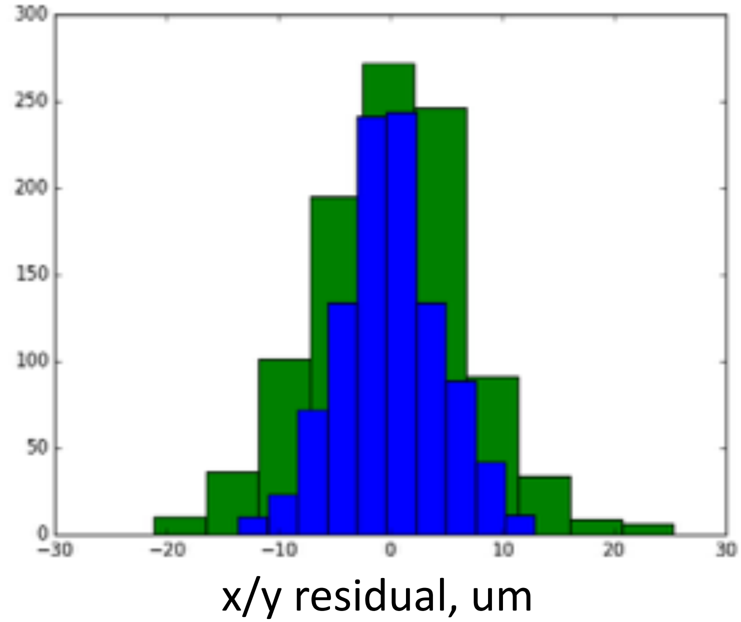
- CBPM 810 did not provide good correlation due to systematic offset, so it sensitivity could not be increased for maxim resolution without reaching into saturation
- 820 and 830 appear well correlated, but can not subtract the angle with 2 BPMs



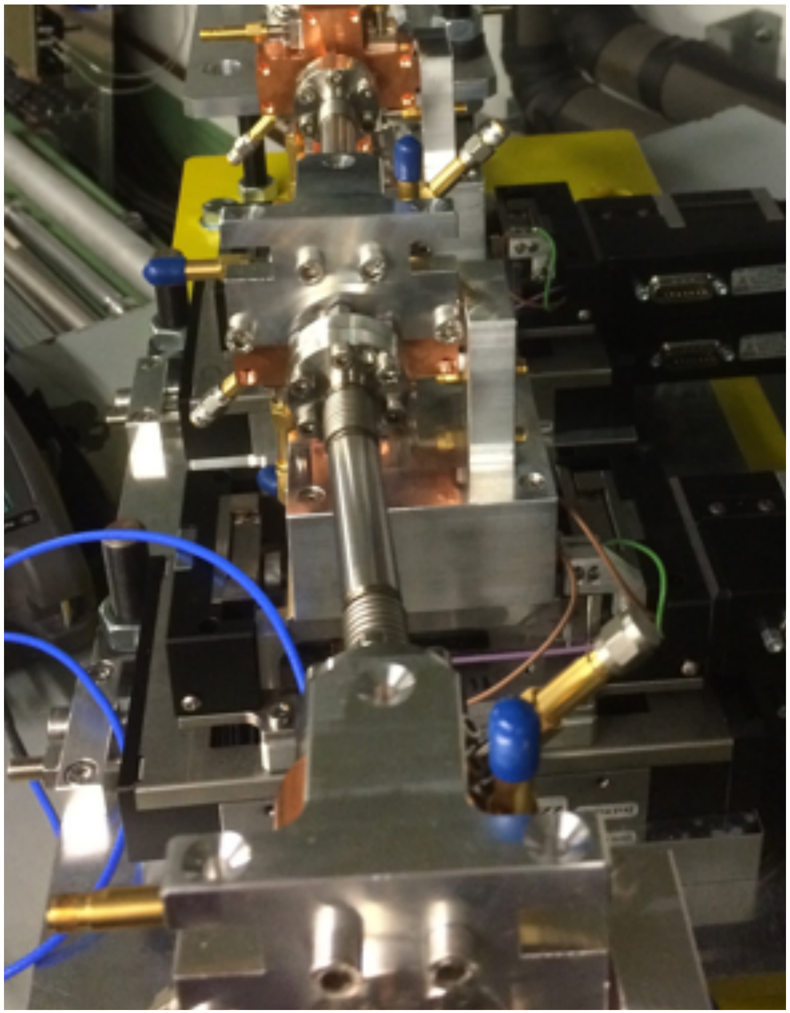
Resolution estimate

- With only 2 BPMs, and no means of subtracting the angular jitter, the best resolution estimate so far is about 6 um, while at best one may expect ~1 um in the current setup

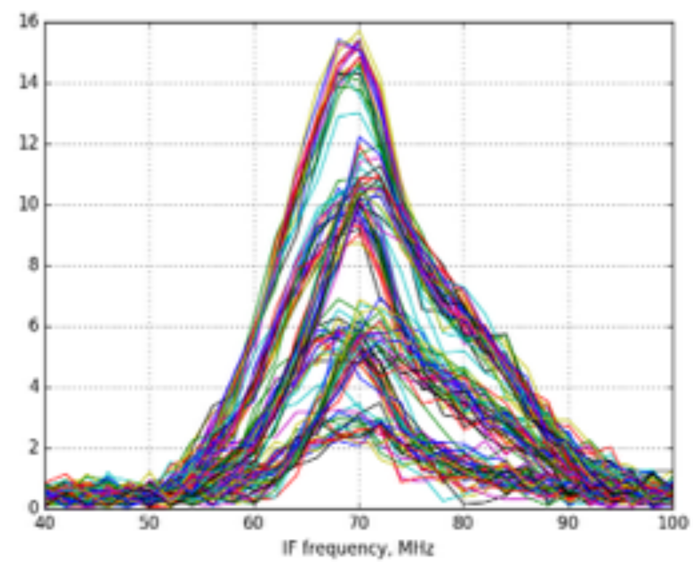




First cavity alignment



- The first cavity proved to be difficult to align in order to minimise its signal
- Minimum position far away from the middle
- Two possible issues:
    - Angular misalignment
    - Signal leakage
- A measurement campaign using a handheld VNA did not discover any leakage above -60 dB
- Frequency content suggests a leaked mode



Summary of troubleshooting

- Reference cavity frequency off
  - Used the old reference cavity, fix: small correction to the radius
- First CBPM misalignment/leakage
  - No parasitic coupling found above 60 dB, frequency spectrum suggests interference
  - Increase distance between the first CBPM and the stainless reference cavity
  - Check the alignment in the new location in CLEAR
- Electronics saturation
  - Measured ranges via thorough calibrations
  - Improved alignment
  - Still a problem, especially for multiple bunches
  - The source is difficult to locate with many active components
  - Phase noise not as apparent as amplitude compression
  - Electronics may need a re-design
  - Relocation of the electronics reduced radiation damage induced problems with failing chips
- Digitiser malfunction
  - Used an alternative available
  - Bit resolution not sufficient for achieving the required performance
  - Checking with Controls and the vendor

Status & Outlook

- System commissioned at reduced resolution, several ways of improving the system performance have been identified
- There is still some data to process
- Currently the system is being relocated to be used with wakefield monitors in CLEAR
- Re-commissioning later this year