Orbit Observations and Transparency with Crab Cavities in the SPS

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Acknowledgements: T. Levens, M. Gasior

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Outline

- Crab orbit measurements to compare all available diagnostics.
- Crabbing transparency

Orbit Measurements

- Crab orbit measurements made during MD7 (17-10-2018 12:20-12:40)
  - 1MV in Cavity 1 with fixed phase,
  - 1MV in Cavity 2 with phase varied in steps of 45 degrees. ~2 cycles per step.

- For each cycle we have the DOROS BPMs, the headtail monitor and the orbit from the MOPOS BPMs.

- We also have the power sensors on cavity 1 and cavity 2.

- Will compare the results from each of these devices.

Calculation of Orbit from Crab Kick

- Closed orbit at location i caused by a kick at location j. β is the beta function at the specific location, ψ is the phase (in tune units), θ is the kick, Q is the tune.

$$u_i = \frac{\sqrt{\beta_i}}{2\sin(\pi Q)} \sum_{j=i+1}^{i+n} \theta_j \sqrt{\beta_j} \cos(\pi Q - |\psi_i - \psi_j|)$$

- For only one kick at the location of the crab cavity, where V_1 and V_2 are the cavity voltages, φ_1 and φ_2 are the cavity phases and E is the beam energy.

$$V_{CC} = V_1 \sin(\omega t + \phi_1) + V_2 \sin(\omega t + \phi_2)$$

$$\theta_j = \Delta x' = -\frac{V_{CC}}{E}$$

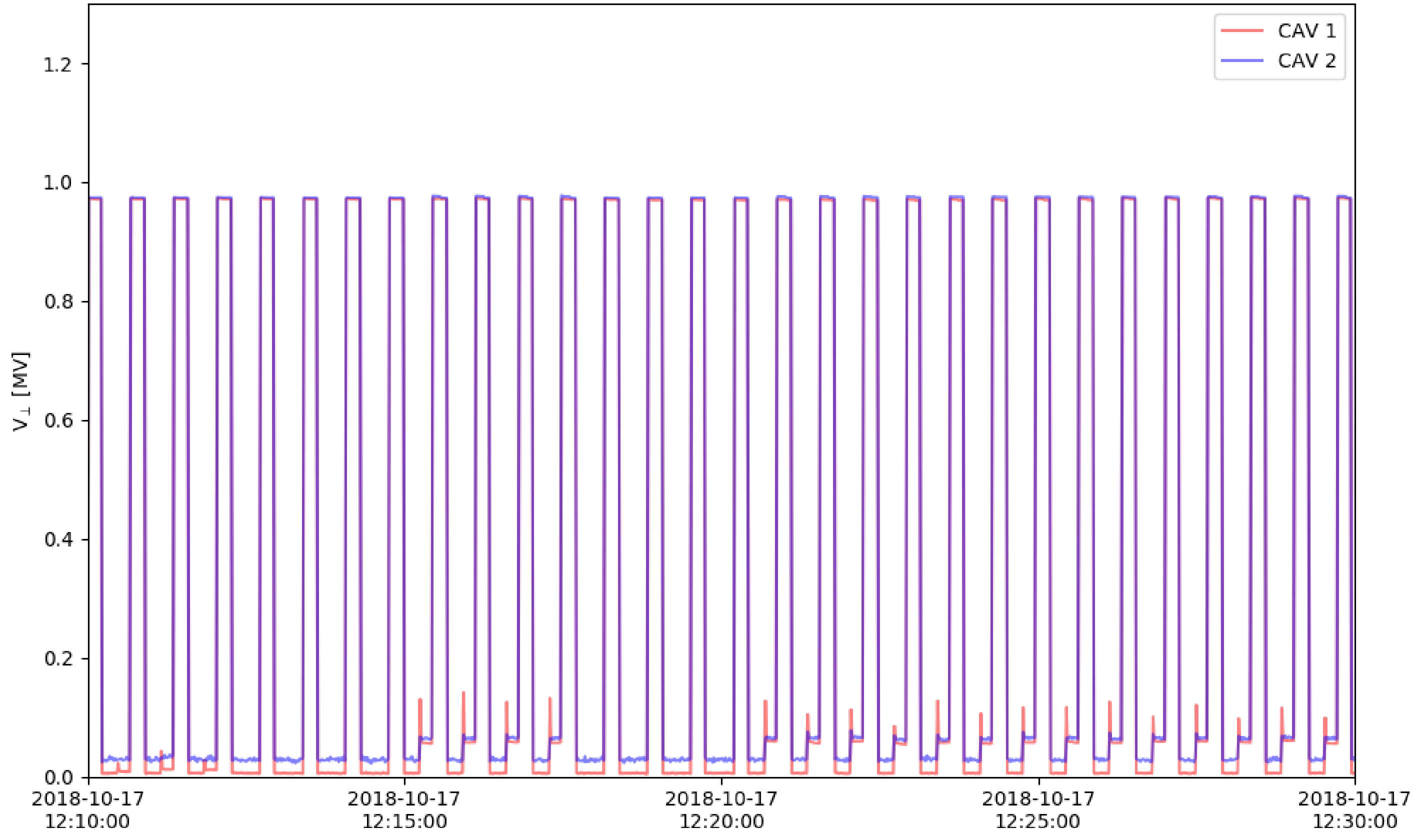
Diagnostic Information

- https://docs.google.com/document/d/1kpqnNSXJv7Ro7iQ6OtxvnT4EUOSfYEWxjqUxqEZVIG0/edit

Device	Location [m]	β_y [m]	ψ_y
Headtail Monitor	4145.03	49.4	15.680
DOROS BPM 51805	5182.62	22.0	19.627
DOROS BPM 51999	5245.20	24.1	19.860
DOROS BPM 61736	6311.66	82.4	23.901
Crab Cavity 1	6312.72	78.2	23.903
Crab Cavity 2	6313.32	75.9	23.904
DOROS BPM 61751	6314.52	71.3	23.907

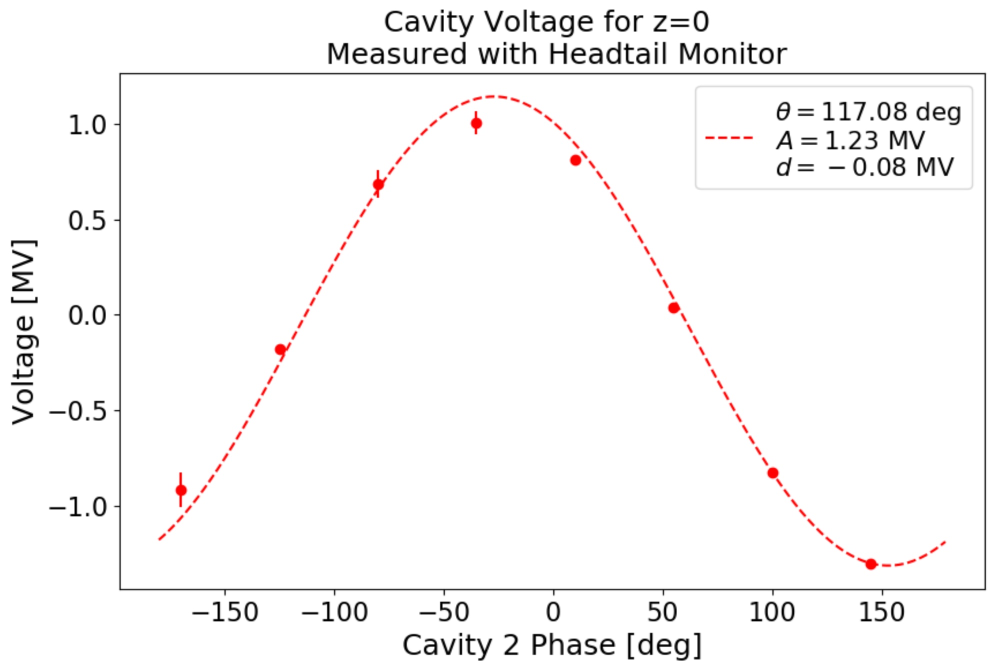
Power Sensors

- Measurement of FWD Power from each IOT.
  - Translated to cavity voltage assuming a conversion factor from simulation from Joules to Volts, and a given external quality factor Qe=1.6e10.



Headtail Monitor

- Headtail monitor measures intra-bunch offset.
  - Calibrated with MOPOS BPMs without crabbing at end of 2017 and start of 2018.
- One measurement per cycle, how the calculation is made has been shown in previous talks (see: https://indico.cern.ch/event/735504/contributions/3033524/).
- Below is a plot of the cavity voltage for the peak of the charge distribution, i.e. for a particle at z=t=0.
- Measurement below shows sinusoidal fit and shows 1.23MV amplitude in cavity 2, more than the 0.98MV from the power sensors.



A=Amplitude
d=Offset
θ=Phase Offset

for ω=2π400MHz.

Headtail Monitor

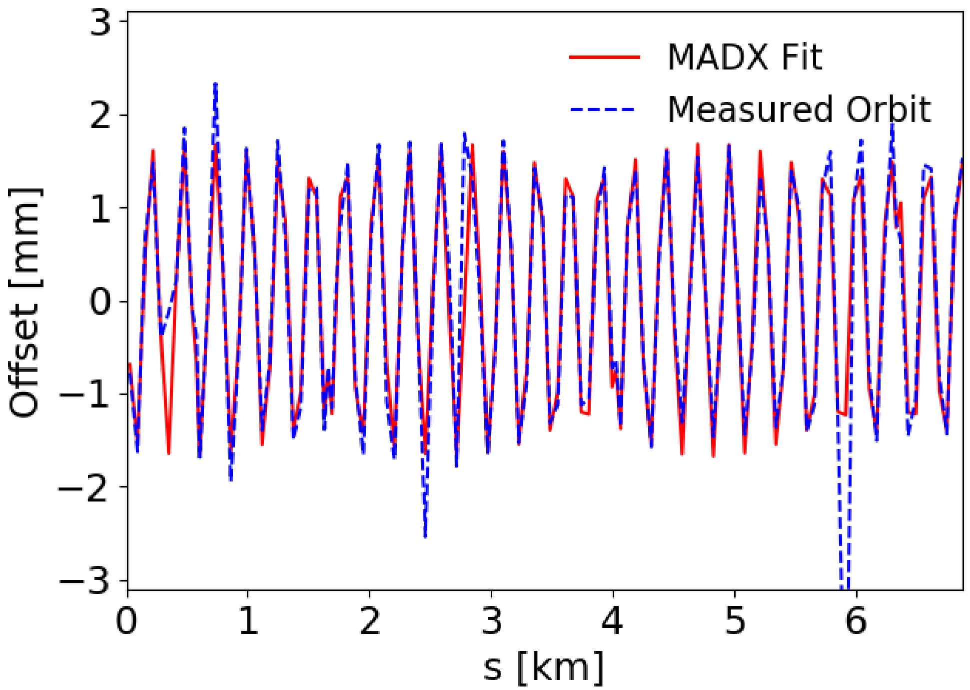
- The scaling of the power sensor reading is $\propto \sqrt{Q_e}$
- Qe = 1.6e10, V = 0.98 MV
- Qe = 1.79e10, V=1.23 MV

- This is a reasonable error on the Qe and so could explain the discrepancy.

- Either way the beam is the best diagnostic so we assume we have 1.23 MV in Cavity 2 (Cavity 1 voltage and phase are fixed so not important).

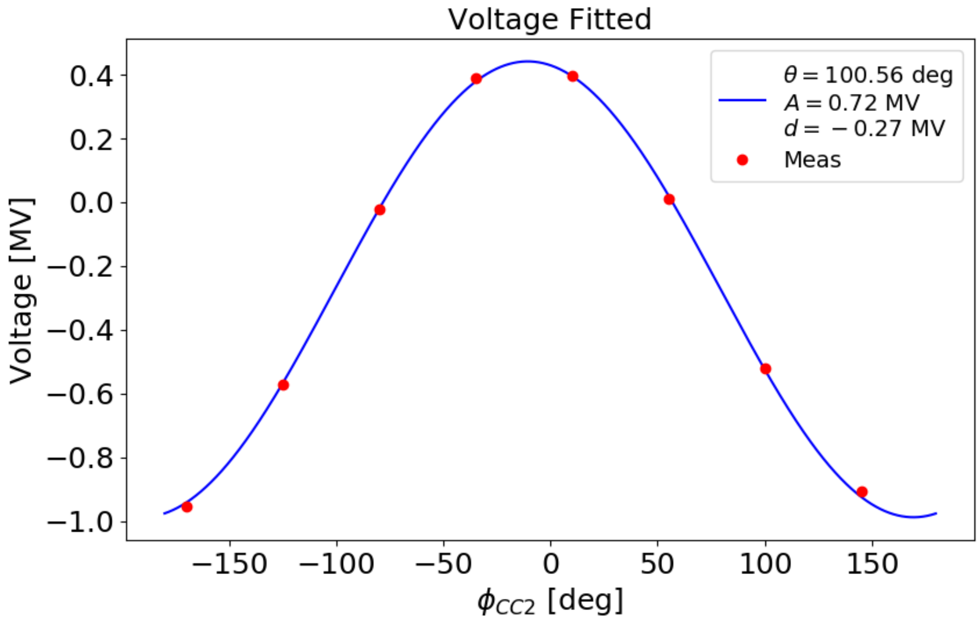
MOPOS

- For each cycle we acquire the orbit from MOPOS BPMs.
- Take one orbit step as a reference and subtract it from all points to remove closed orbit without crab cavities.
- Can then fit a kick using MADX twiss parameters and find the equivalent voltage to recreate the closed orbit from the crab cavities for each step.



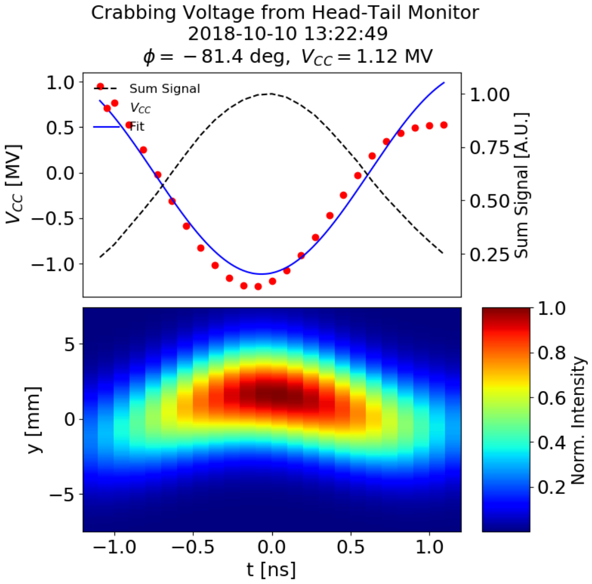
MOPOS

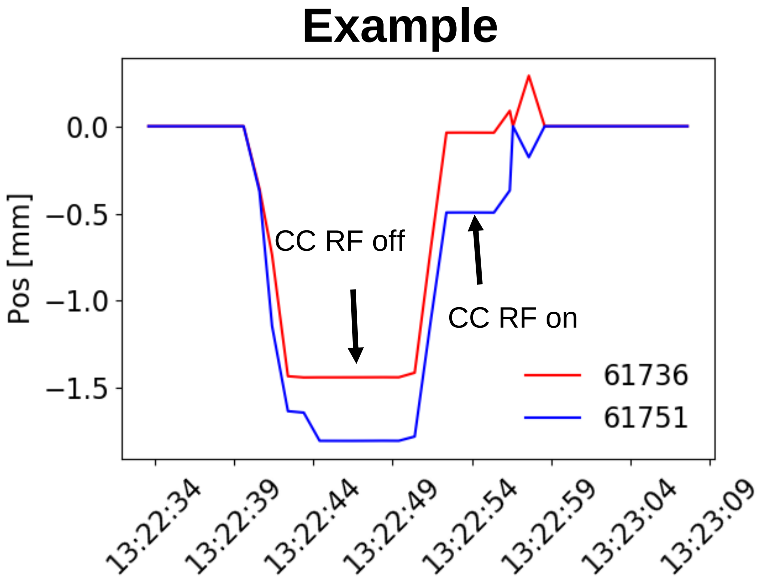
- Amplitude of oscillation is 0.72MV, compared to the expected value of 1.23MV.
- The fitted MADX model does **NOT** include any effect of the bunch length.



DOROS

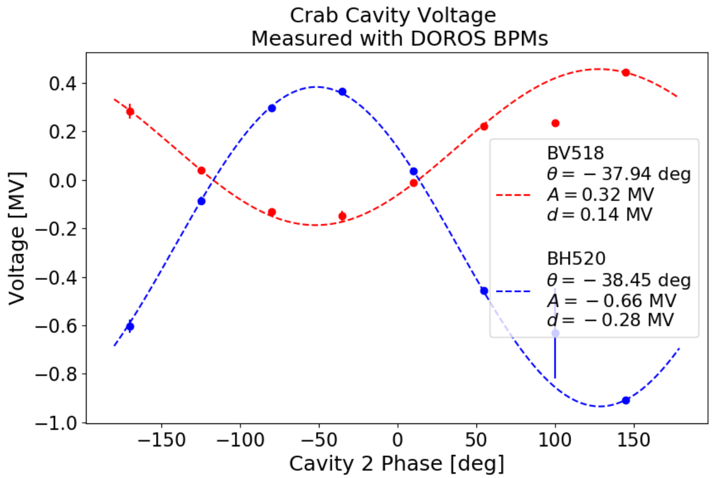
- 4 DOROS BPMs in total. 2 ~1m either side of crab cavity cryomodule and 2 in ring.
- Acquires every 1s but averages over previous 2 seconds (polarity switching frequency of 1Hz).
- CC RF is off for first half of 26GeV cycle, then switched on after all bunches are injected.
- Orbit shift at crab cavity is observed. Required kick for this shift can be calculated.

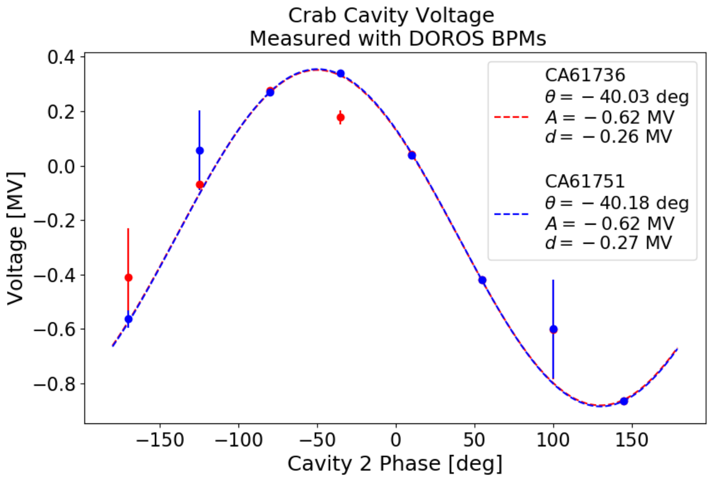




DOROS

- Application of equations on slide 3 allows the required kick that gives the observed shifts to be calculated.
- Yet again, a smaller kick than expected. Bunch length effect NOT included.
- BV518 is ~ factor 2 lower than for all other BPMs. This is a software issue where FESA does not consider the correct aperture (H instead of V). Can be rescaled with 156mm/83mm.





Summary of Measurements

Device	Measured Voltage [MV]	Note
Power Sensors	0.98	Error on Qe
Headtail Monitor	1.23	For z=0, No CTF
MOPOS BPMs	0.72	No Bunch Length
DOROS @Crabs	0.62	No Bunch Length
DOROS @518,520	0.60, 0.66	No Bunch Length

Bunch Length

- A reduction is expected that comes from the long bunch which probes the non-linear crab cavity rf fields.
- Studies have been performed into the effect of the BPM filters on the readout in the presence of intra-bunch motion.

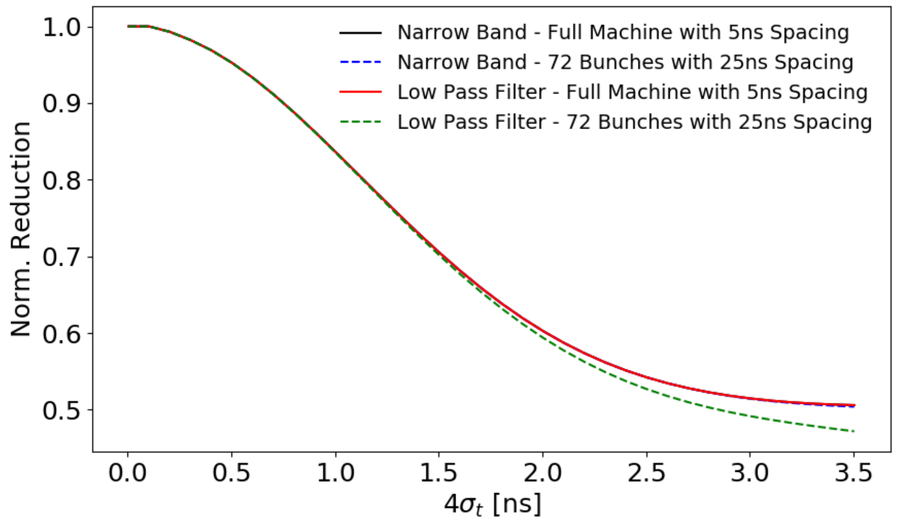
- The MOPOS BPMs have a 200MHz narrow band (resonant) filter.
  - Only the 200 MHz component of the beam is taken.
- The DOROS BPMs have a low pass filter with cutoff at 200MHz (and a high pass filter at 60 MHz).
  - All frequencies of the beam between 60MHz and 200MHz are taken.

Bunch Length

- Taking the idealized signal from the BPM buttons and computing a sum and delta signal and filtering on the sum and delta signals gives:

$$A = C_1 I(t)(C_2 + X(t)) \qquad \Delta = A - B$$
$$B = C_1 I(t)(C_2 - X(t)) \qquad \Sigma = A + B$$
$$\longrightarrow \quad \frac{\Delta}{\Sigma} = \frac{F\big(I(t)X(t)\big)}{F\big(I(t)\big)}$$

- Where X(t) is the intrabunch motion, I(t) is the charge distribution and F is an operator that performs the necessary filtering.



For $4\sigma_t$=2.9ns:
Low Pass = 0.4972
Narrow Band = 0.5183

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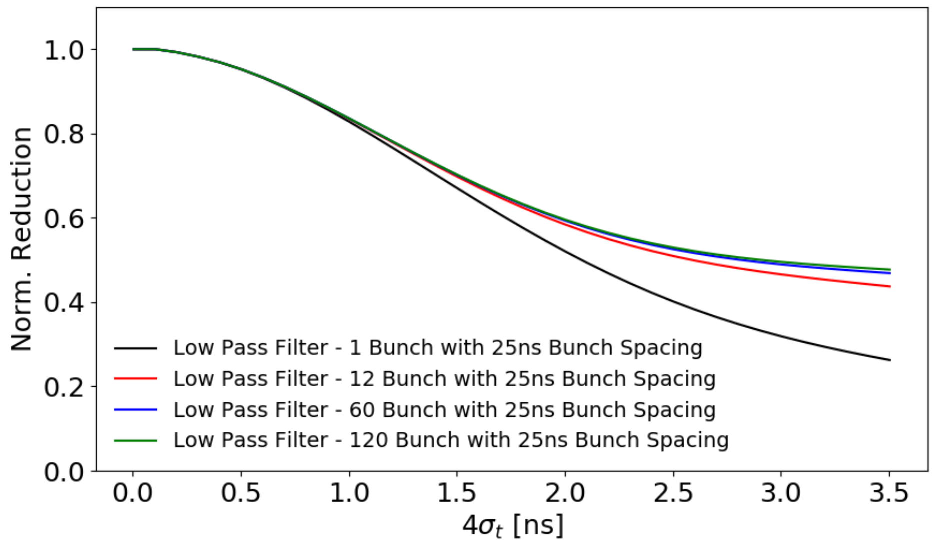

HiLumi HL-LHC PROJECT
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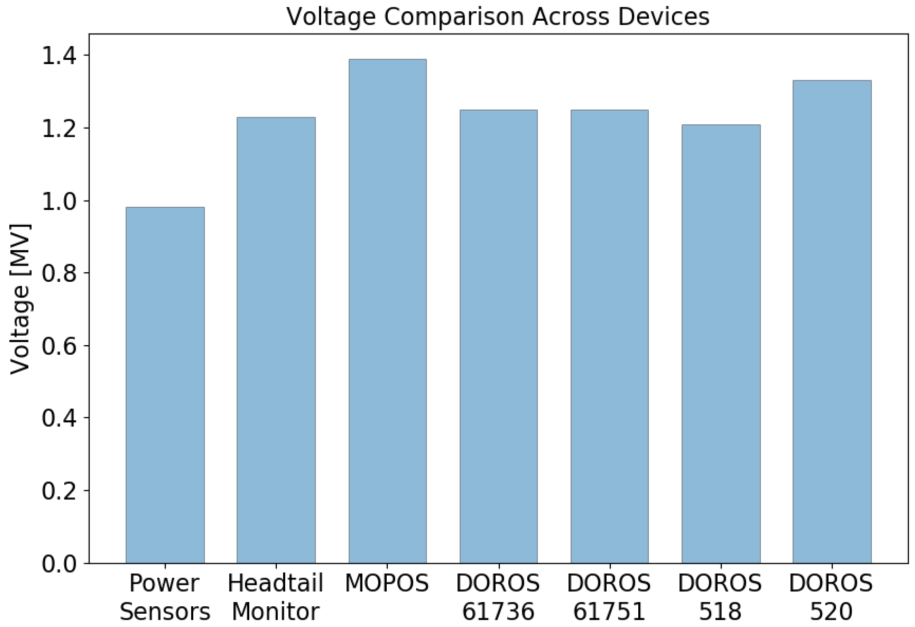
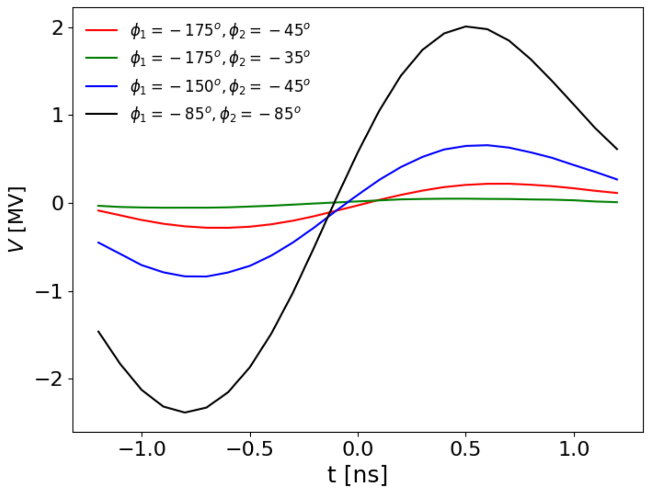
Summary of Measurements

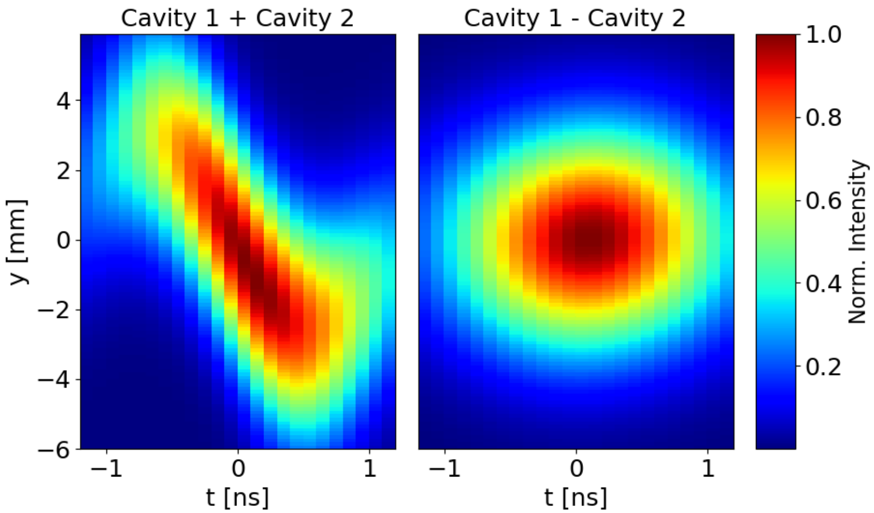
Device	Measured Voltage [MV]	Note
Power Sensors	0.98	Error on Qe
Headtail Monitor	**1.23**	For z=0, No CTF
MOPOS BPMs	**1.39**	**BL Corrected**
DOROS @61736 & 61751	**1.25**	**BL Corrected**
DOROS @518, 520	**1.21,1.33**	**BL & Aperture Corrected**



Transparency

- For a period during MD7 (17/10/2018 ~10:30 – 11:30) we had both cavities with feedback and tuning loops operational at 2K pulsing with 1MV per cavity.
- Set both cavities individually to approximate crabbing phase.
- Set them in anti-phase and try to fine tune the phases (minimum step size 5 deg) to minimize the observed crabbing.
- Lowest measured crabbing amplitude was ~60kV (with 1MV per cavity).





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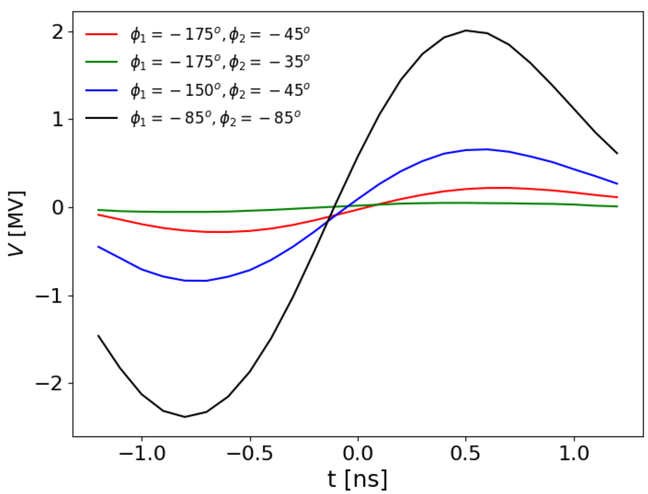
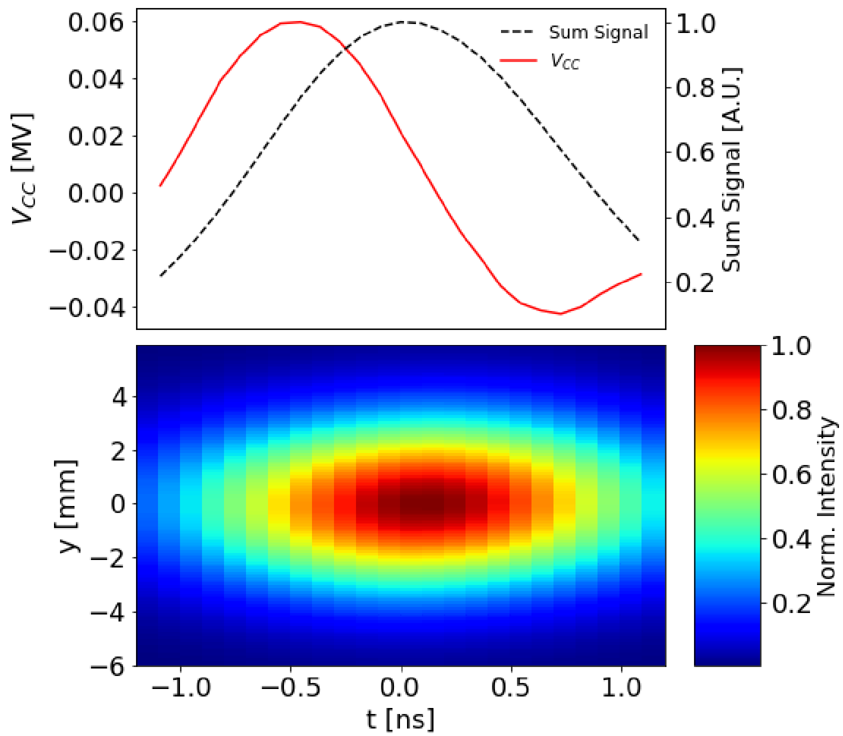
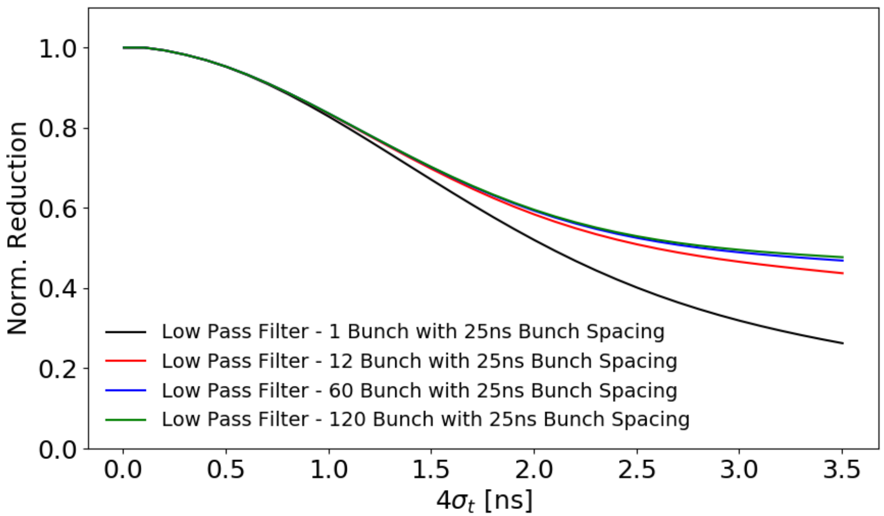




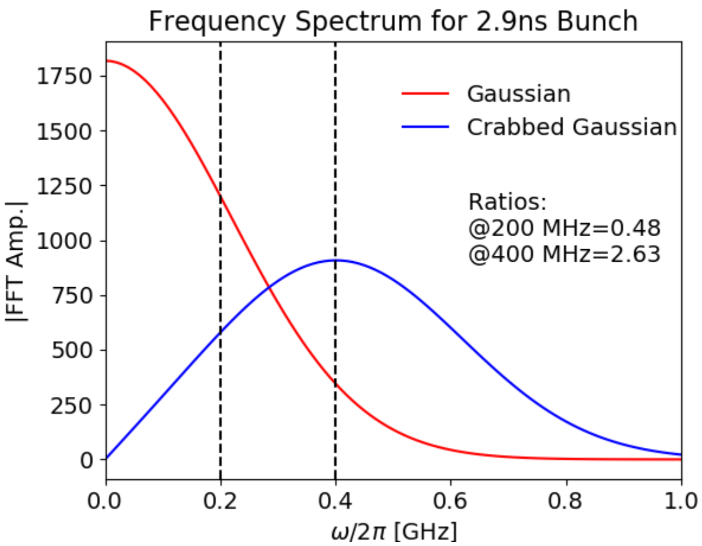
Merci et au revoir

- Don’t forget to come to my BE seminar on 1st March 2019.

Backup



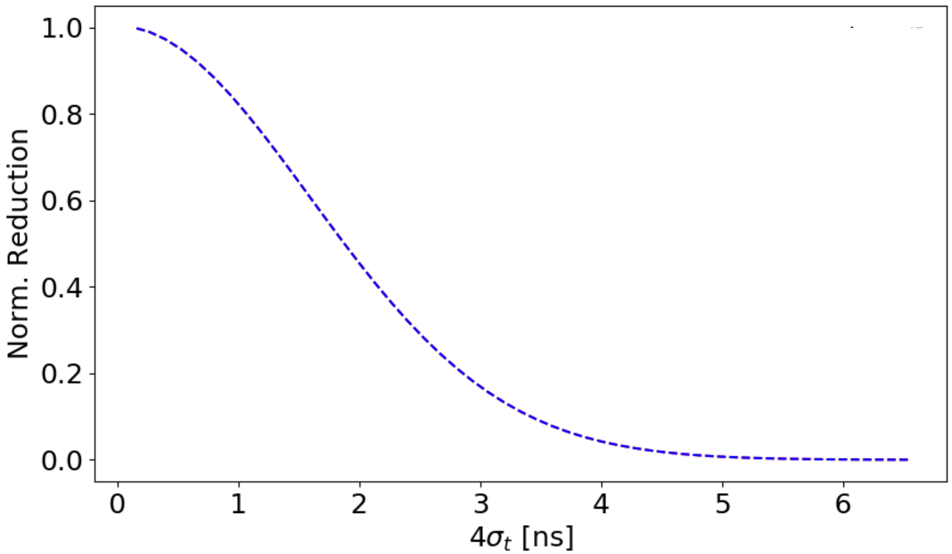
Norm. Reduction
$4\sigma_t$ [ns]
Low Pass Filter - 1 Bunch with 25ns Bunch Spacing
Low Pass Filter - 12 Bunch with 25ns Bunch Spacing
Low Pass Filter - 60 Bunch with 25ns Bunch Spacing
Low Pass Filter - 120 Bunch with 25ns Bunch Spacing



Frequency Spectrum for 2.9ns Bunch
|FFT Amp.|
$\omega/2\pi$ [GHz]
Gaussian
Crabbed Gaussian
Ratios:
@200 MHz=0.48
@400 MHz=2.63

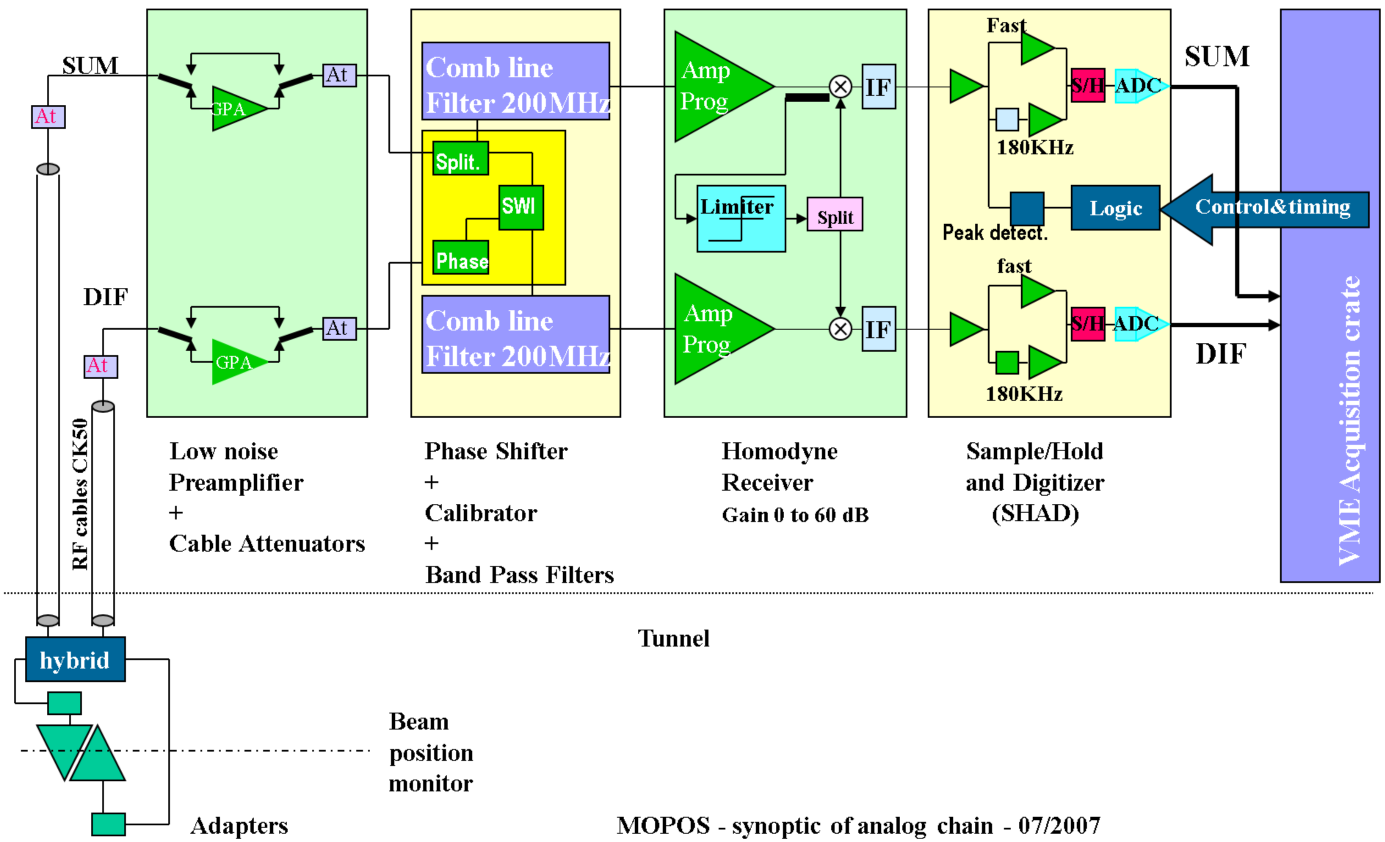
Bunch Length

- A reduction is expected that comes from the long bunch which probes the non-linear crab cavity rf fields.
- Propagate equation 3 as a function of z around the ring to calculate z-dependent closed orbit.
- The BPM readout is simply the charge weighted average of the intrabunch motion i.e. $< I(t)x(t) >$
- For the measurements in question $4\sigma_t = 2.9\ \mathrm{ns}$. This gives a reduction factor of 0.17.
- 1.23MV*0.17=0.209 MV, reduction is far too large!



Bunch Length

- Is this really what the BPMS are doing?
- Information below received from Christian Boccard. It is the analog chain of the MOPOS BPMs.



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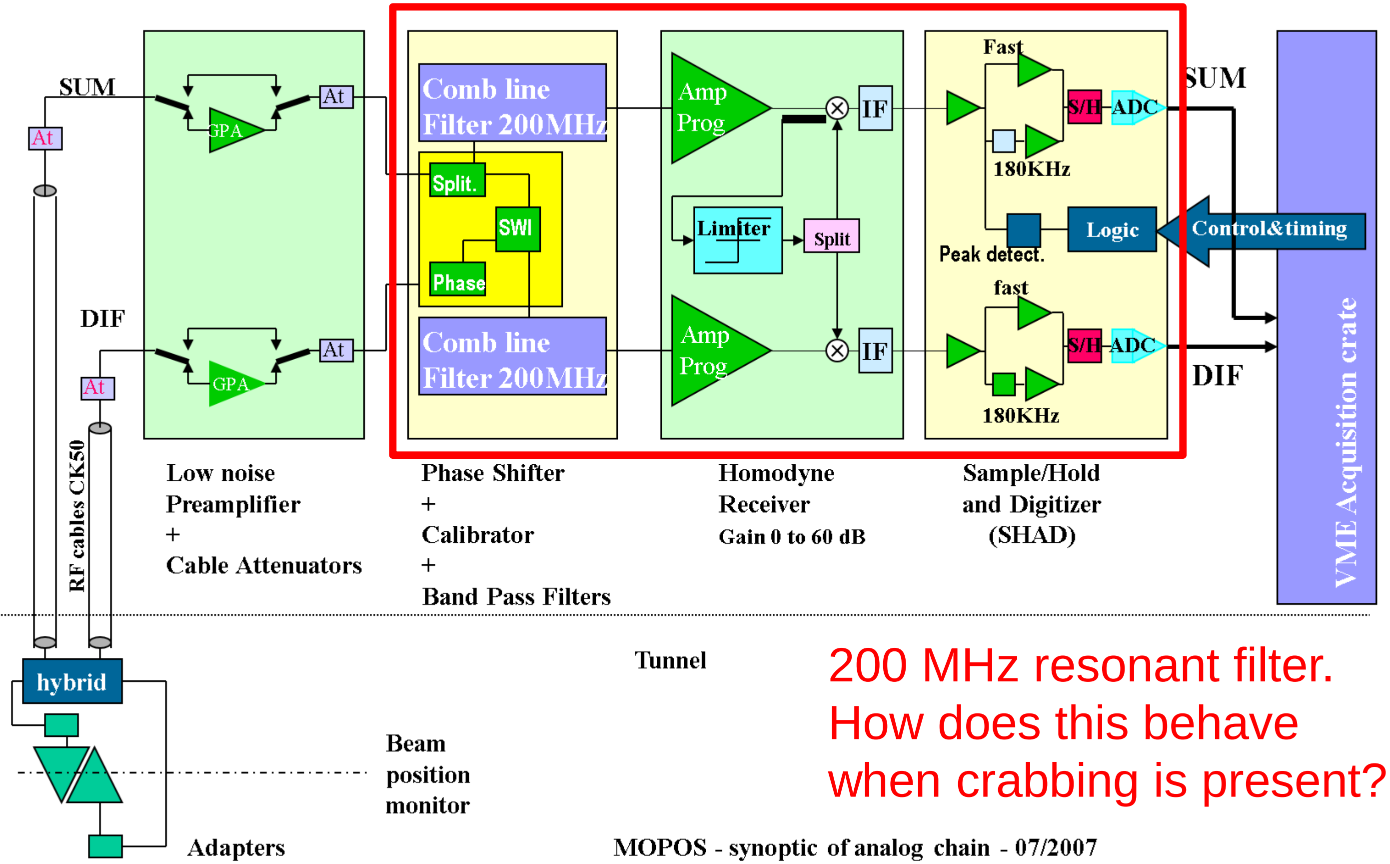

200 MHz resonant filter.
How does this behave
when crabbing is present?