First Proton Beam Dynamics Results with Crab Cavities

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Material for this presentation summarized from more detailed BE seminar: https://indico.cern.ch/event/800428/

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Outline

- Introduction
- Operational Setup
- MD Overview
- Diagnostic Comparison
- Cavity Transparency
- Emittance Growth in Coast
- Conclusions

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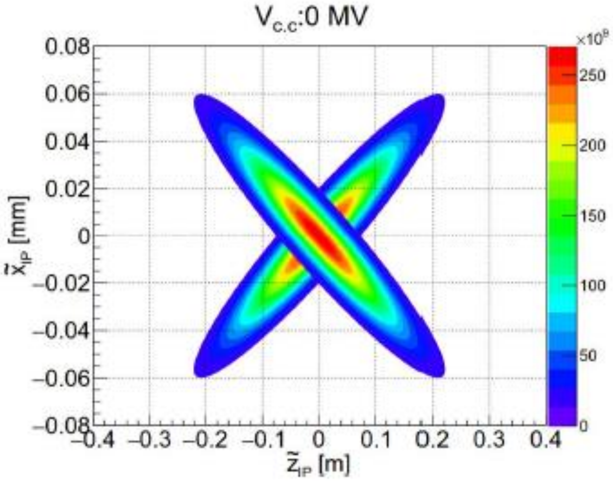
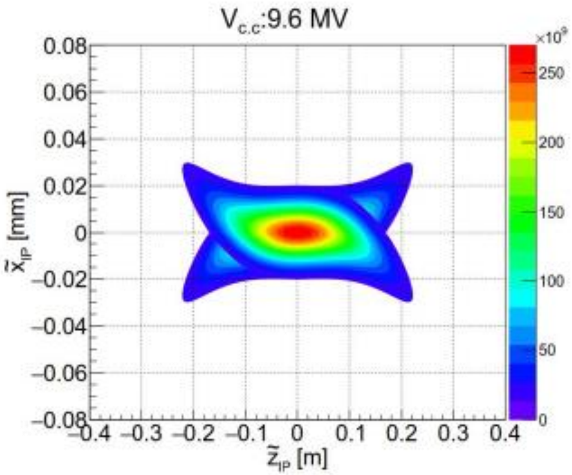
Introduction

- High-Luminosity LHC is the planned upgrade of the LHC to provide a large boost to the luminosity output of the machine.
- Bunches do not currently collide head-on due to the crossing angle which reduces the number of collisions per crossing.
- Providing a rotational kick either side of IP1 and IP5 (ATLAS & CMS) can create a bunch rotation that will restore head-on collisions and therefore improve the luminosity.

- This rotational kick can be provided by any device that provides a positive kick for the head of the bunch and negative for the tail (or vice versa) -> **Crab Cavities**.
- 2 superconducting crab cavities at 400 MHz have been fabricated and installed into the SPS and were tested in 2018.

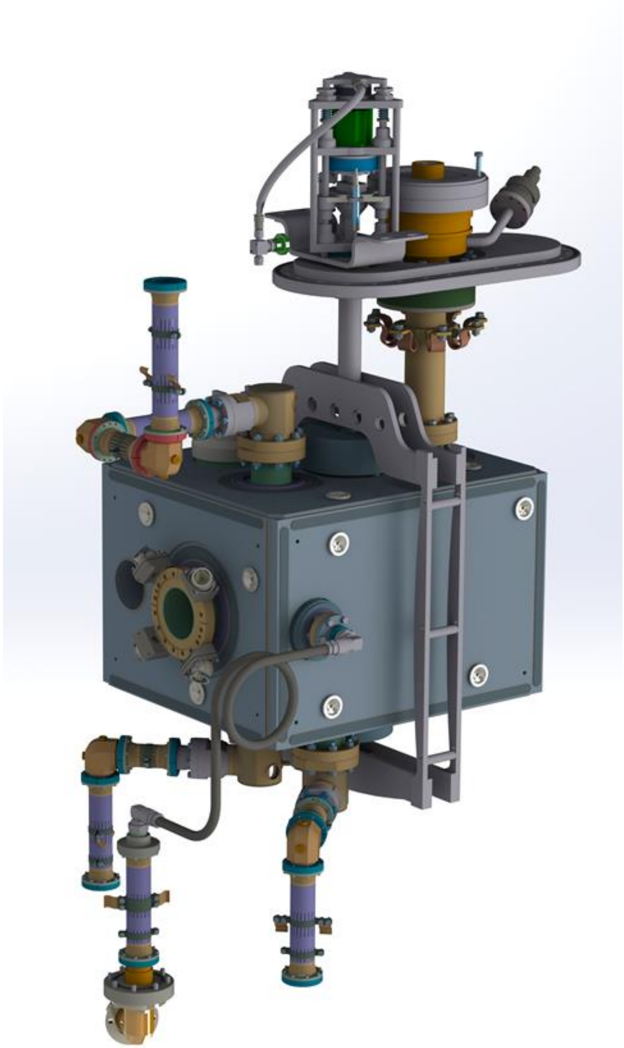


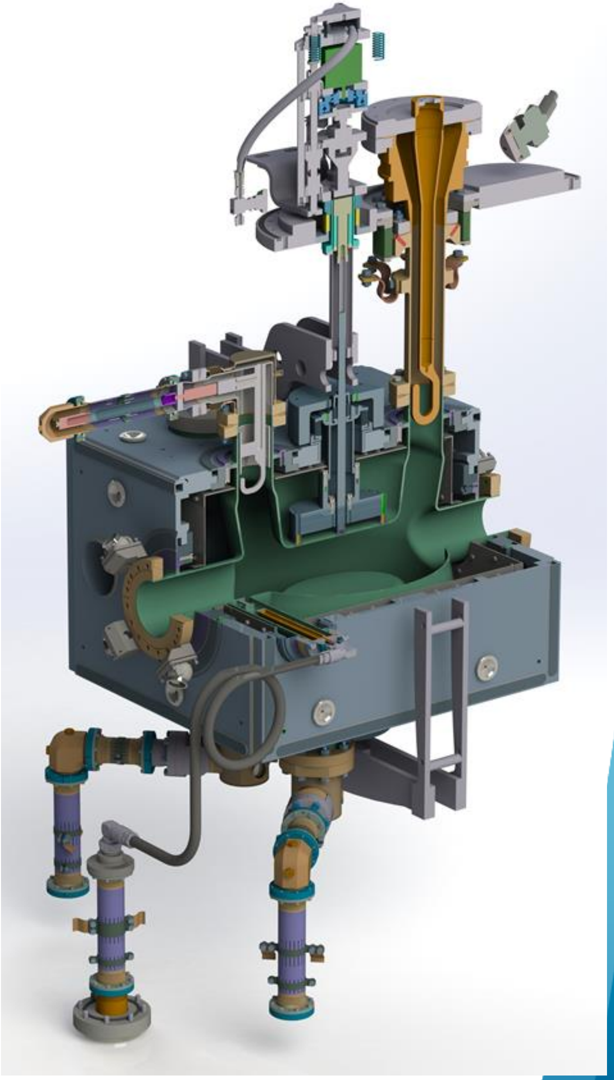


DQW Cavity

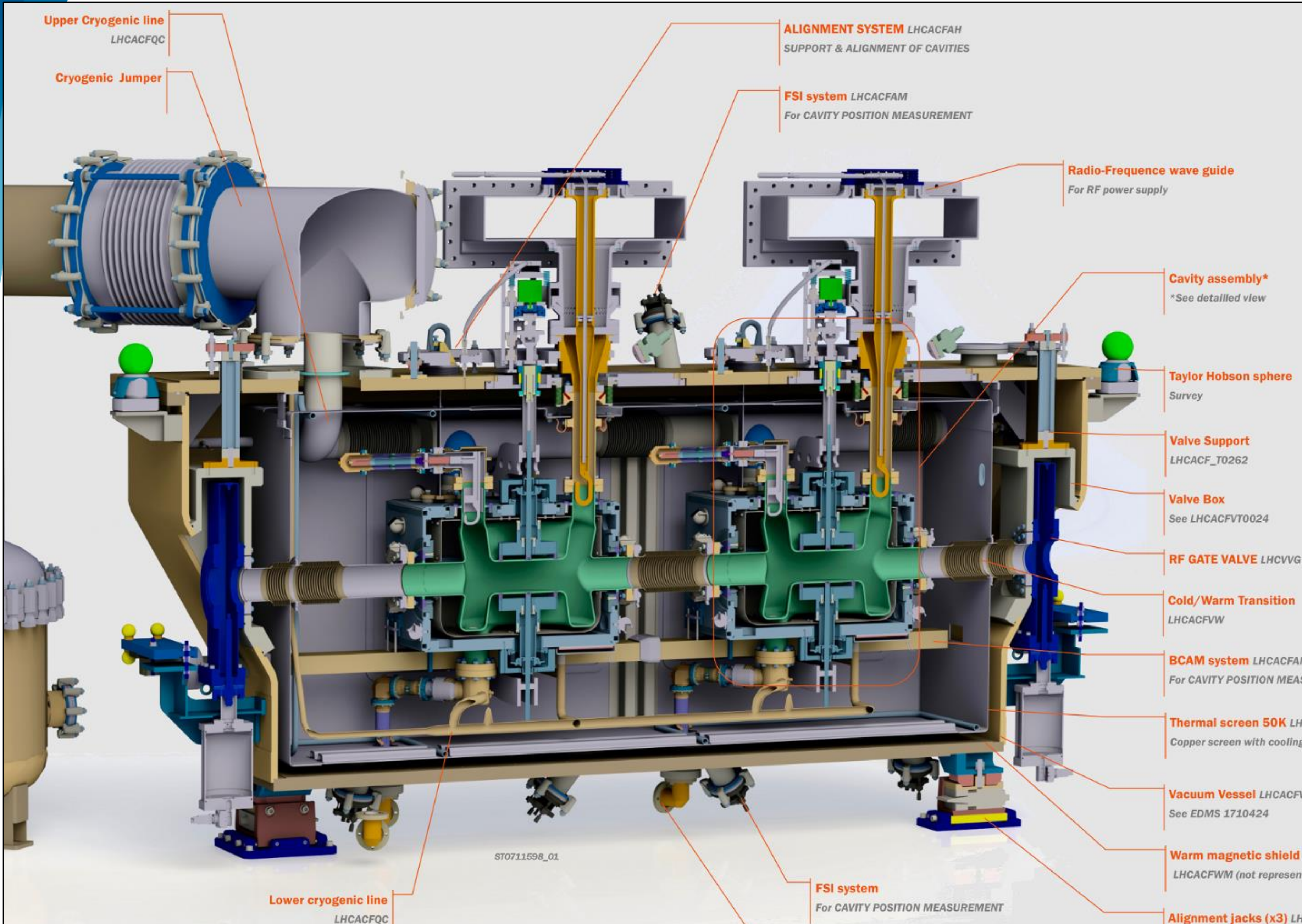
Bare DQW cavity (400MHz)

Dressed DQW cavity





Courtesy: EN-MME



Courtesy: EN-MME

SPS Installation

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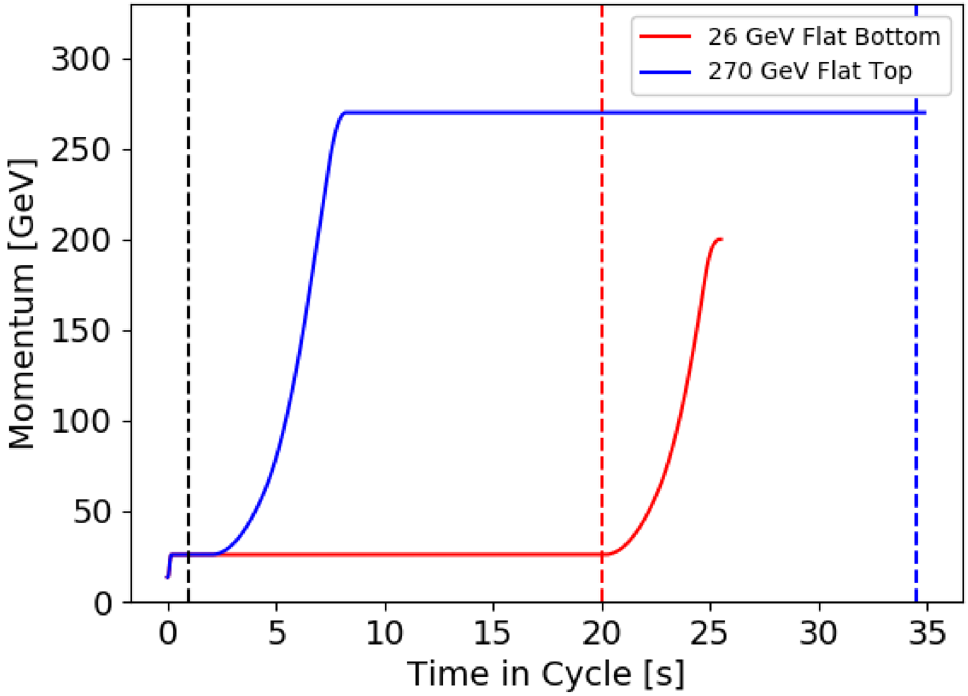
SPS Cycles

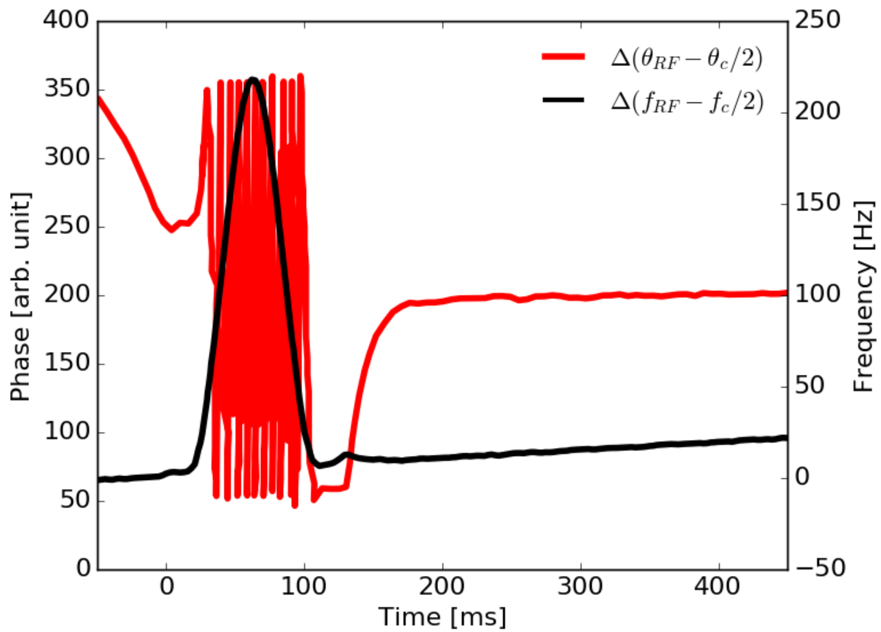
- SPS is a medium-speed cycling machine, typical cycles ranging from 4s-50s.
- Two cycles were setup specifically for the crab cavity MDs.

- MD_CRAB_26_L26400_**Q26**_2018_V1 - 26 GeV with **19.12s FB**.
- MD_CRAB_26_270_L30000_**Q26**_2018_V1 - 270 GeV with **26.6s FT**



Crab-RF Sychronisation

- Crab cavity RF set point from BA6 to BA3 (several km away)
- CC ~400 MHz - narrow, SPS RF ~200 MHz - broad
- Re-phasing of SPS RF to become synchronous with CC RF.
- Occurs at the beginning of every 26 GeV cycle (normally ~1s after injection).
- Occurs at the end of the ramp for every 270 GeV cycle (normally ~1s after reaching flat top).



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.

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

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

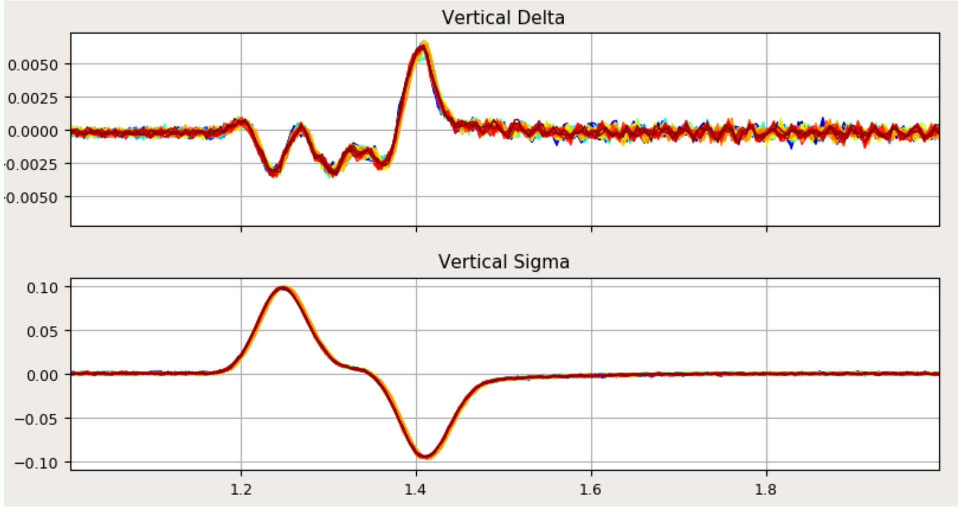
- For optics information at crab cavities and diagnostic devices, see backup.

Head-Tail Monitor

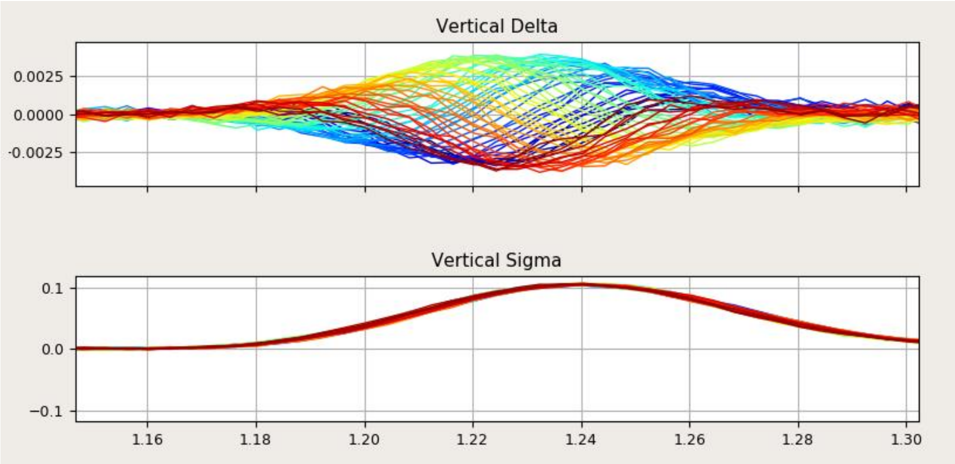
- The Head-Tail monitor gives two data sets
  - A sigma (or sum) signal, which is the longitudinal line density for a given window (often ~10,000 turns with 100ps sampling)
  - A delta (or difference) signal, which is a measure of the transverse offset within the bunch.
- When synchronised with the main rf, the crab signal vanishes into the baseline signal.
  - Need to remove the baseline without removing the crab signal.
- Step 1: Calculate baseline from delta signal acquired **before synchronisation**.
- Step 2: Take delta signal acquisitions of interest and subtract baseline. Divide by the sum signal and apply normalisation factor to acquire intra-bunch offset in mm.

Head-Tail Monitor

- Example of delta signal without baseline removal. Crabbing is in here somewhere…

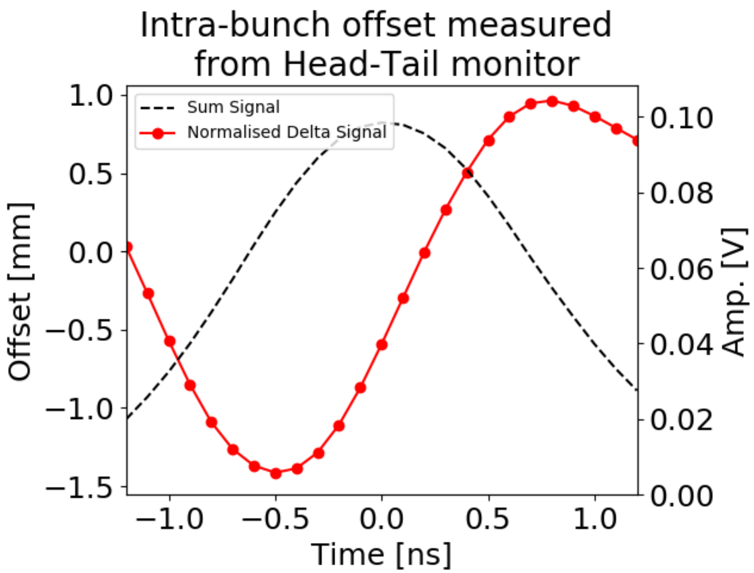


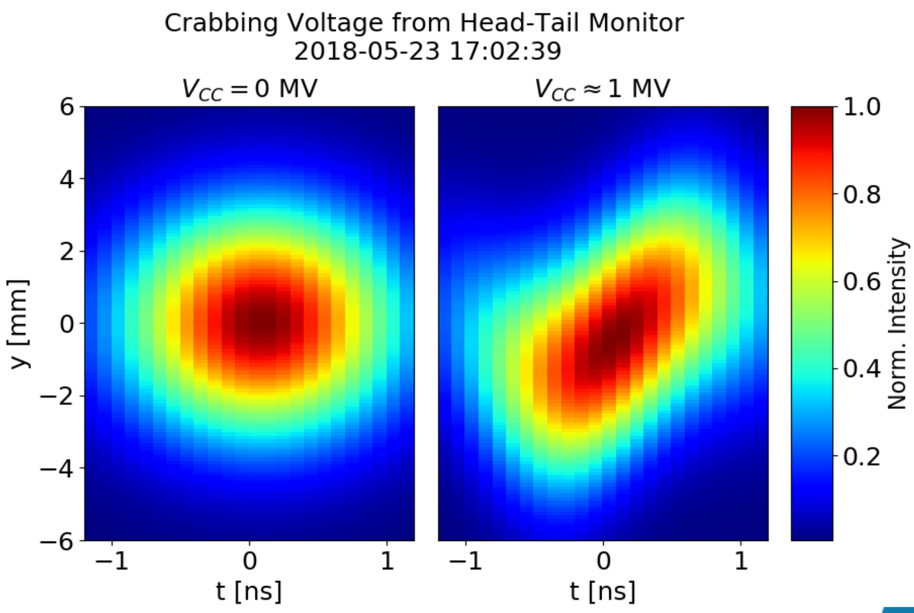
- Example of delta signal when cavity is <u>not synchronous</u> with beam. The baseline can be removed without affecting the crab signal because we only remove the average signal.



Head-Tail Monitor

- Dividing delta signal (with subtracted baseline) with sum signal gives intra-bunch offset.
- Take the measured profile in z. Assume a Gaussian profile in y with sigma taken from wirescan.
- Modulate in z with intra-bunch offset.
- Make plot of reconstruction of crabbing!





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MD Overview

*** Operating temp is 2K, V=3.4 MV**

MD#		Cav1 [MV[	Cav2 [MV]	Temp [K]	Energy [GeV]
1	First crabbing, phase and voltage scan	0.5	0	4.5	26
2	270 GeV ramp with single bunch	1-2	0	4.5	26, 270
3	Intensity ramp up	1	~0.3	4.5	26
4	270 GeV coast setup	1.0	0.5	2.0	270
5	Emittance growth at 270 GeV with induced noise	0	1.0	2.0	270
6	Intensity ramp up to 4-batches	-	1.0-1.5	2.0	26
7	Intensity/Energy ramp up	1.0	1.0	2.0	26, 270

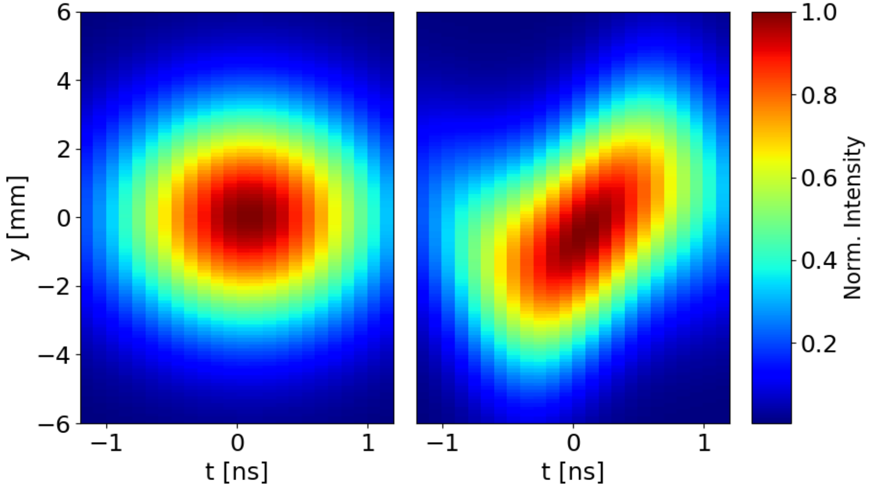
10 MDs: 2 for cycle and table setup, 1 lost due to cavity issues

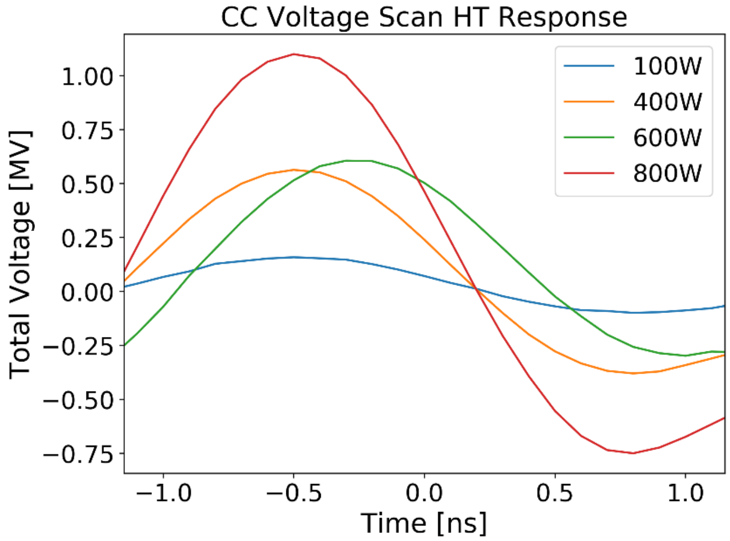
Protons meet Crabs

First injection – 12:55, May 23
Cavity 1 only.

Worked w/o RF feedback
$0.2 - 0.8 \times 10^{11}$p/b

Crabbing reconstruction from Head-Tail monitor





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Diagnostic Comparison

- 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:
  - DOROS BPMs (4 special LHC-type BPMs that accurately measure the orbit every 1s)
  - Headtail monitor
  - MOPOS BPMs (SPS standard BPMs, ~100 per plane, one measurement per cycle).
  - Power sensors for Cavity 1 and Cavity 2
- Will compare the results from each of these devices (specific results in backup).

Interim Summary of Measurements

Device	Measured Voltage [MV]	Note
Power Sensors	0.98	Dependence 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.

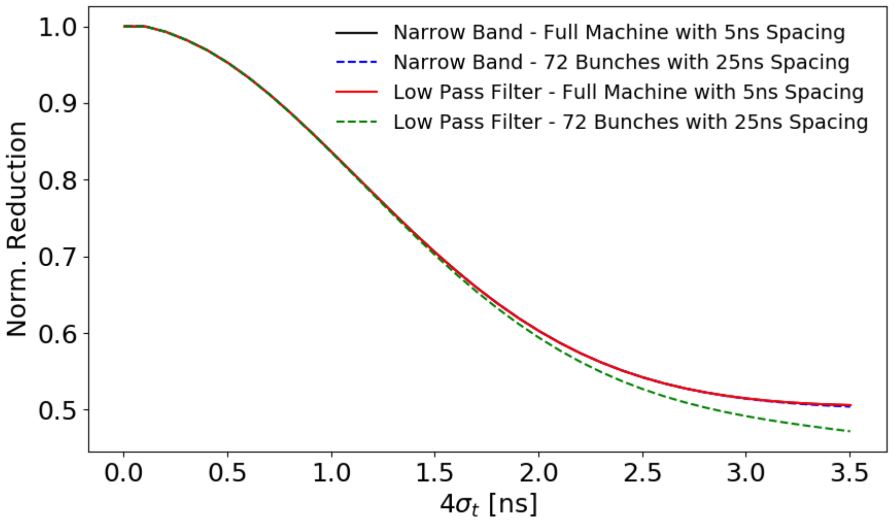
- The MOPOS BPMs have a 200MHz narrow band (resonant) filter.
  - Only the 200 MHz component of the beam is taken.
- The DOROS BPMs have a low pass filter with cutoff at 200MHz (and a high pass filter at 60 MHz).
  - All frequencies of the beam between 60MHz and 200MHz are taken.

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

Bunch Length

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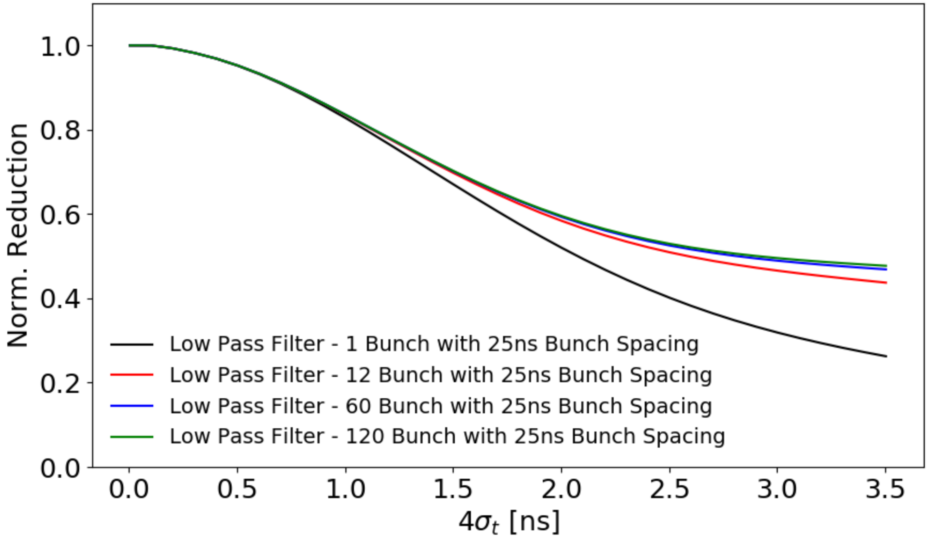
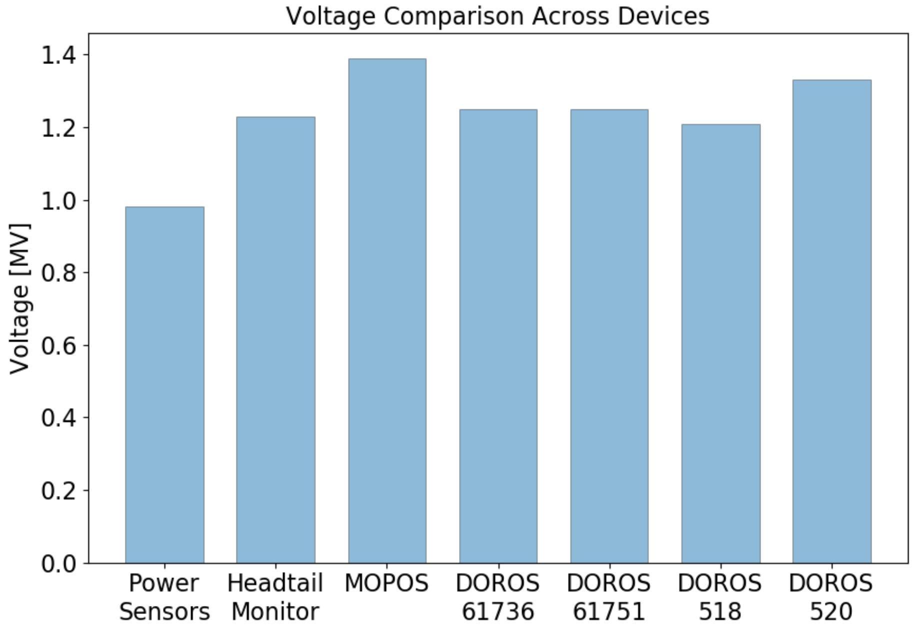


Summary of Measurements

Device	Measured Voltage [MV]	Note
Power Sensors	0.98	Dependence on Qe
Headtail Monitor	**1.23**	For z=0
MOPOS BPMs	**1.39**	**BL Corrected**
DOROS @61736 & 61751	**1.25**	**BL Corrected**
DOROS @518, 520	**1.21,1.33**	**BL Corrected**



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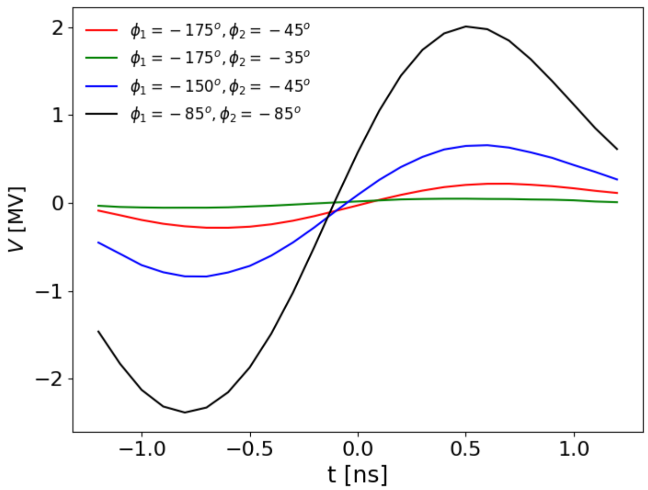
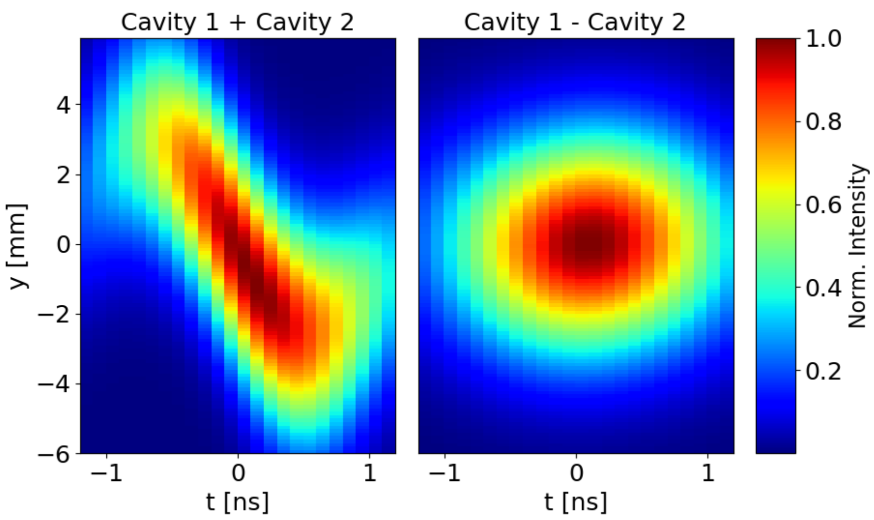
Transparency

- 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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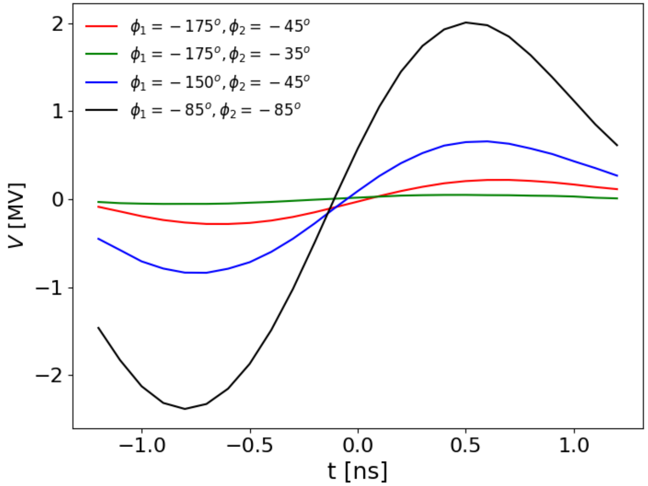

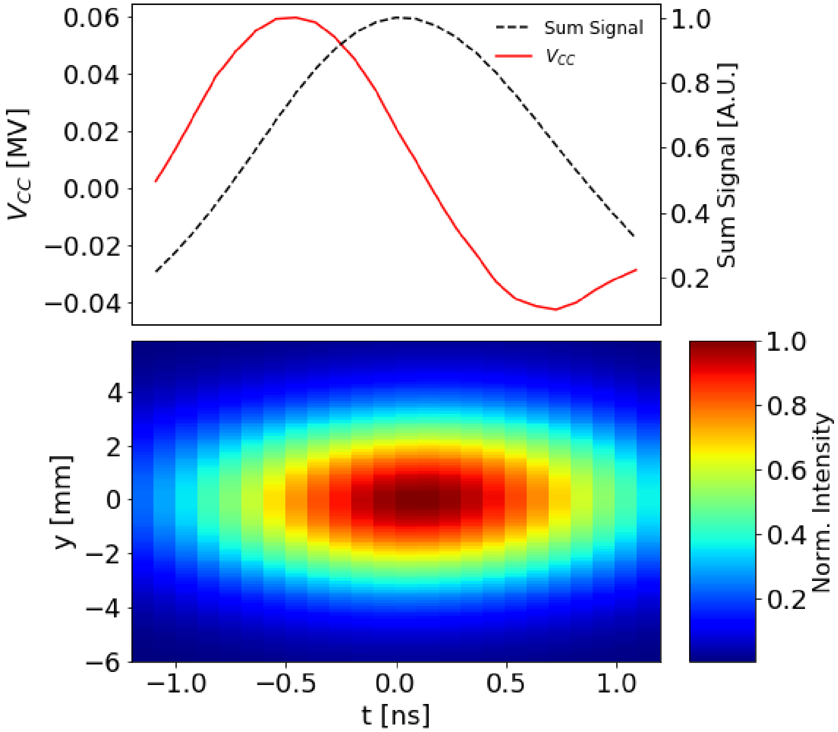

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Emittance Growth in Coast

- Crab cavity is a transverse kicker with a feedback system.
- The feedback spectrum spreads over a wide range of frequencies which includes the first betatron sideband.
- Crab cavity feedback means the bunch is being kicked at the tune, which causes emittance growth. Needs to be quantified!
- Measurements were made of the emittance growth in coast as a function of the strength of the feedback spectrum at the tune.

Emittance Growth in Coast

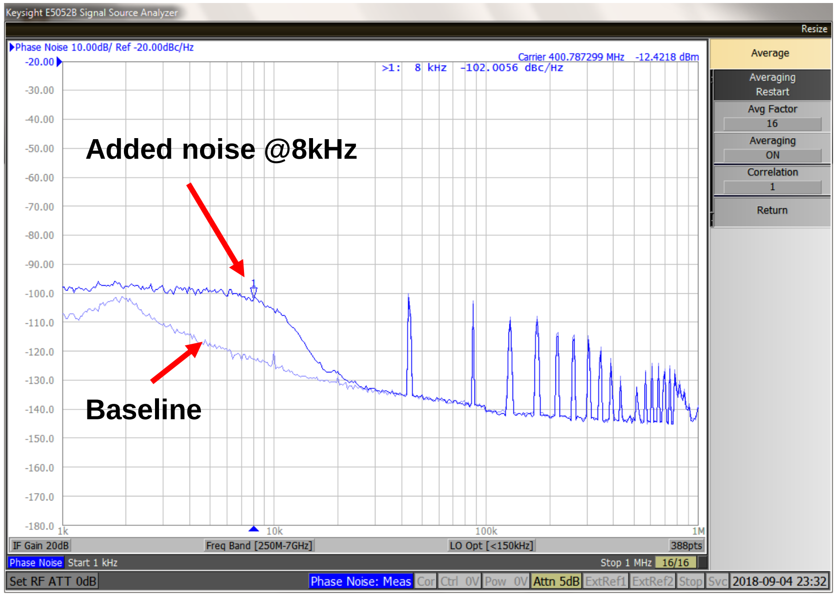
- CC1 idling (no RF), CC2 field at ~1 MV
- 4 coasts with some varying settings during each coast.
- Transverse profile is measured with Wire Scanners
  - Emittance is calculated by fitting the measured profile and bringing in the relevant optics parameters.
  - Average emittance over 4 bunches is used

- Coast MDs in 2017 defined the optimum settings for these kinds of measurements.
- ADT off, 800 MHz off, longitudinal feedback and damper off, Qh=0.13, Qv=0.18, Q'h = 2, Q'v = 2.

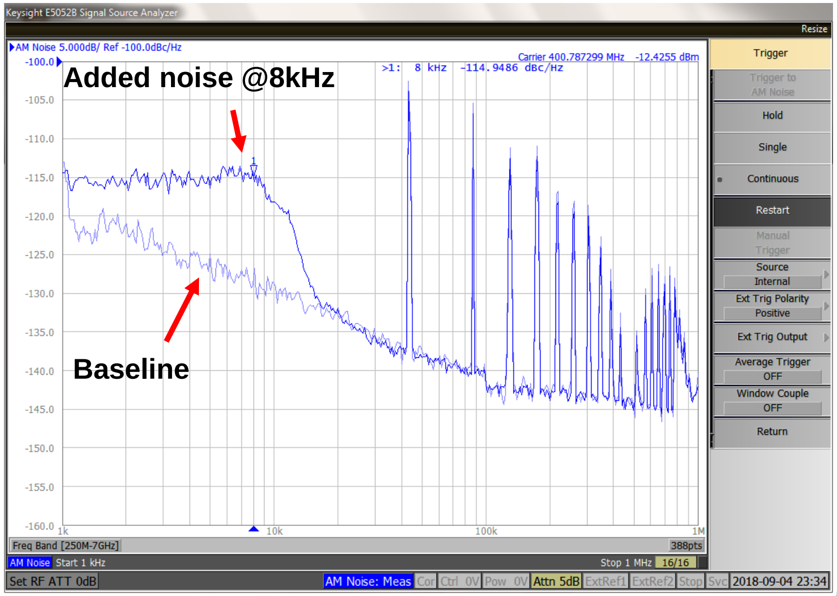
Injected Noise

- RF noise added vectorially -> always a mixture of phase and amplitude noise. Phase noise was always dominant but some amplitude noise present.
- RF noise (PM and AM) covered a band from DC to 10 kHz only -> excites the first betatron band only (around 8 kHz)
- CC2 phase and amplitude noise Power Spectral Density measured with Signal analyser.
- Below is the power spectral density measured in the cavity antenna.

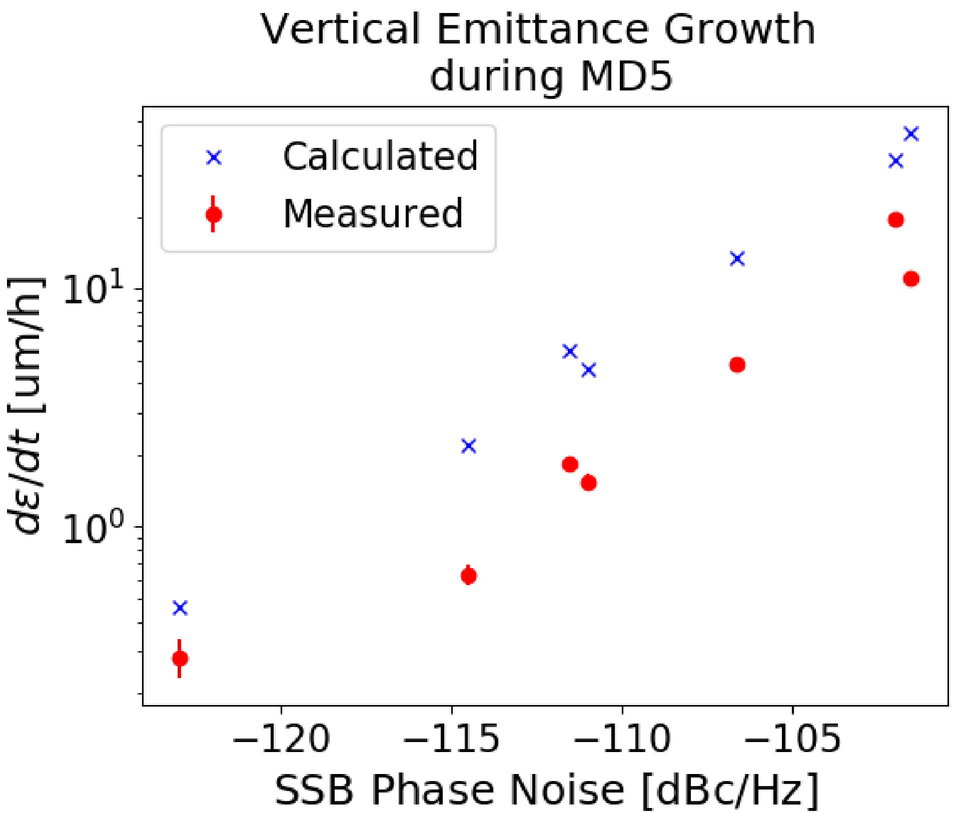
Phase



Amplitude



Results



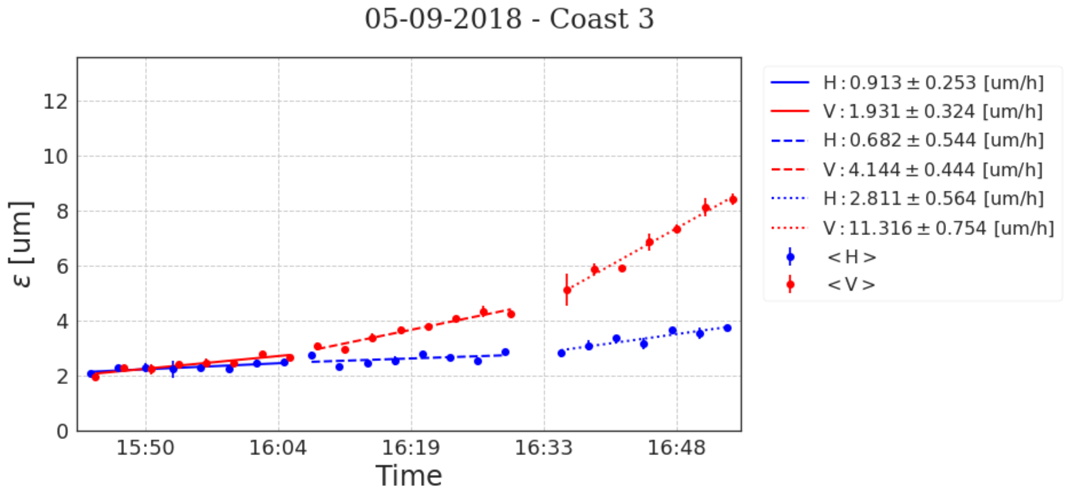
Measured (Wire Scan) and calculated during the coasts with different noise levels.

- The x-axis is the Phase Noise PSD. Although always smaller, the Amplitude Noise PSD varied during the successive coasts. This explains the different calculated values for very similar Phase Noise PSD, and may partly explain the different measured emittance growth.

- The calculations over-estimate the growth by factor 2-4

Possible reasons for the difference

- Differences between definition of emittance between the measured and the calculated.
- The measured emittance does not include beam losses: The bunch population from the fit decreases by 8-11% during the excitation. Could be real loss or moving particles from the core to the tails where the wirescan cannot detect it.
- An additional source of error is the apparent coupling between the horizontal and vertical planes, which is not included in the calculations
- The horizontal emittance growth rate is clearly increasing as we inject noise on the vertical plane.



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Conclusions

- Successful MD program entirely down to the huge amount of work put in by all people involved.
- Demonstrated the worlds first crabbing of a proton beam.
- Able to provide answers to some of the beam dynamics questions surrounding the use of crab cavities in the LHC.
- Provided some vital experience for future testing of crab cavities, relevant for both future SPS tests and for installation into the LHC.

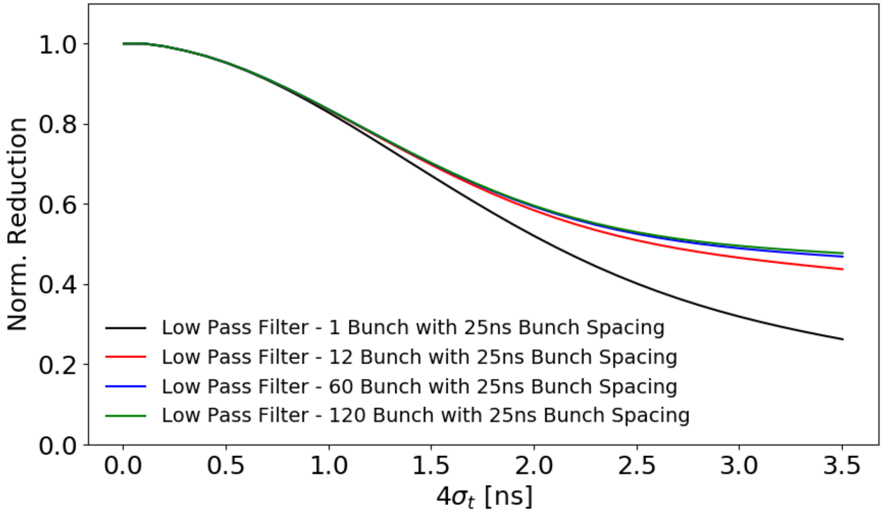
Thanks for listening!

Diagnostic Information

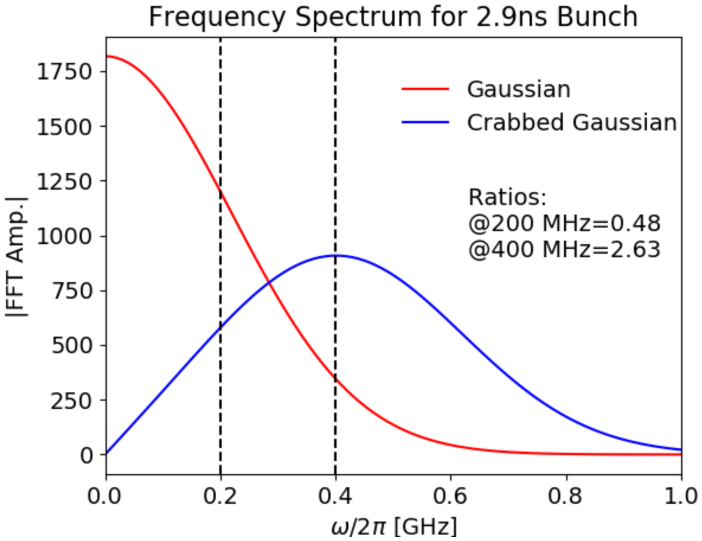
- https://docs.google.com/document/d/1kpqnNSXJv7Ro7iQ6OtxvnT4EUOSfYEWxjqUxqEZVIG0/edit

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

Backup

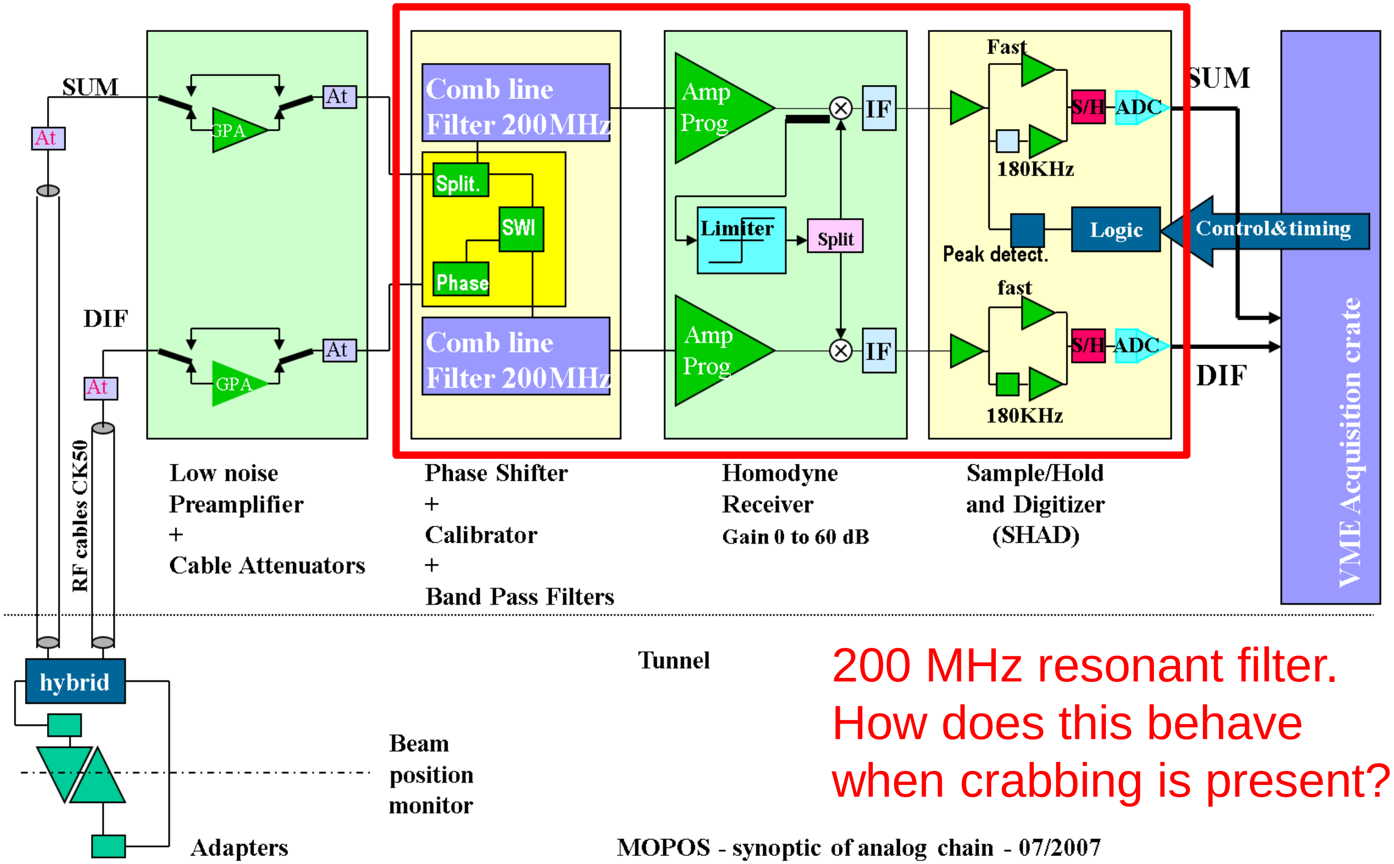


Norm. Reduction
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
$4\sigma_t$ [ns]
Low Pass Filter - 1 Bunch with 25ns Bunch Spacing
Low Pass Filter - 12 Bunch with 25ns Bunch Spacing
Low Pass Filter - 60 Bunch with 25ns Bunch Spacing
Low Pass Filter - 120 Bunch with 25ns Bunch Spacing



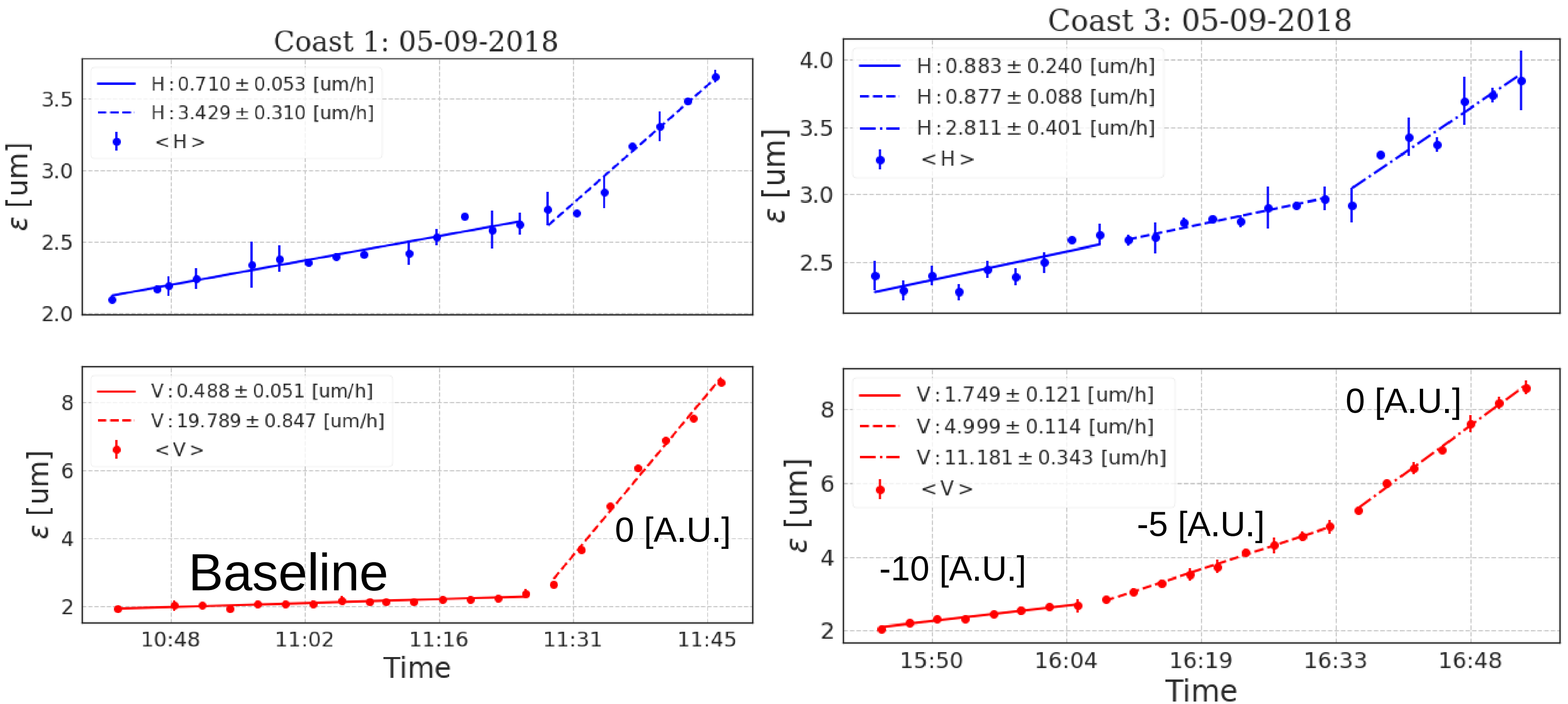
Frequency Spectrum for 2.9ns Bunch
|FFT Amp.|
1750
1500
1250
1000
750
500
250
0
0.0
0.2
0.4
0.6
0.8
1.0
$\omega/2\pi$ [GHz]
Gaussian
Crabbed Gaussian
Ratios:
@200 MHz=0.48
@400 MHz=2.63

Bunch Length



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

MD5: Summary of Coasts



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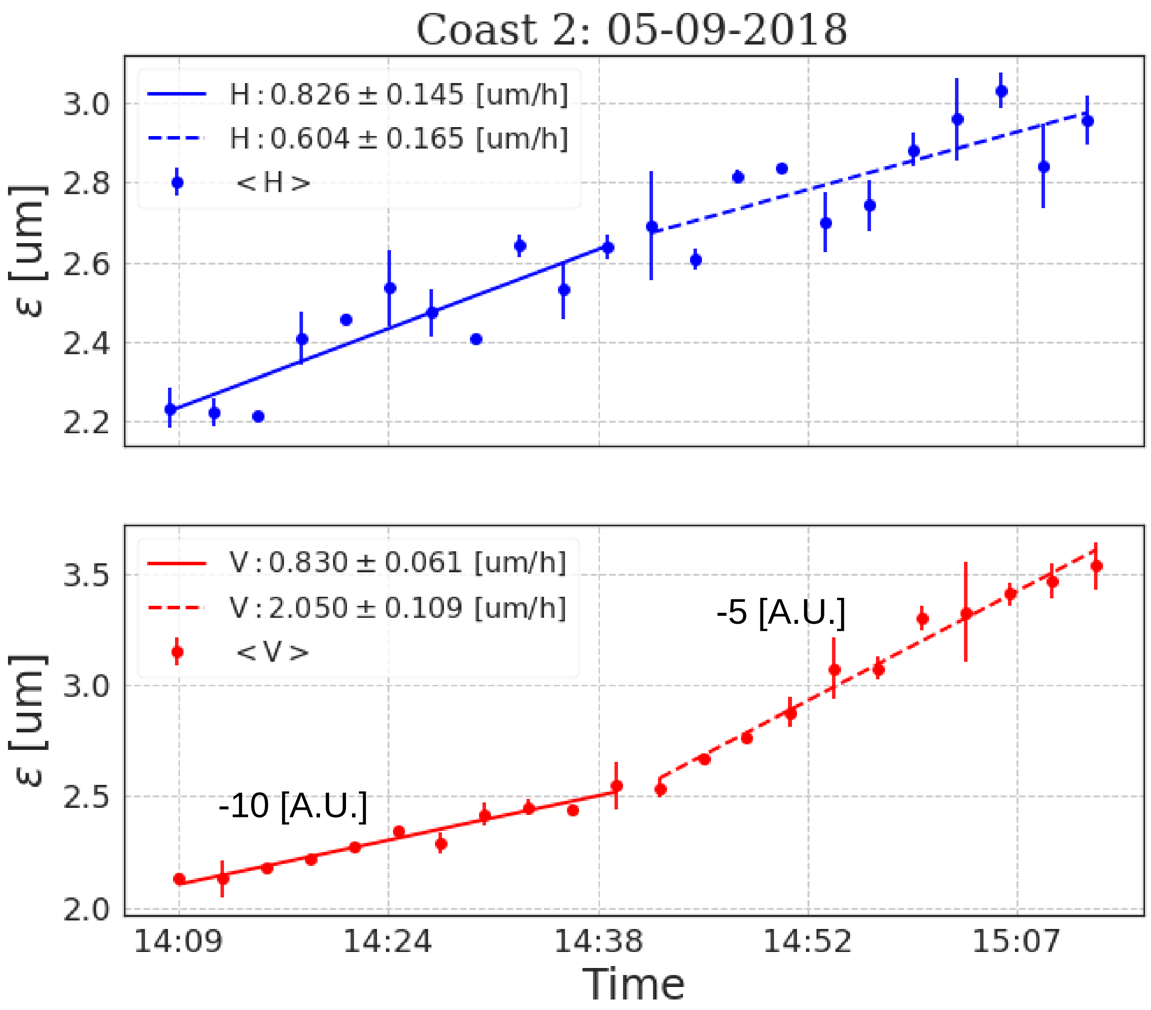


Ramp to 270 GeV

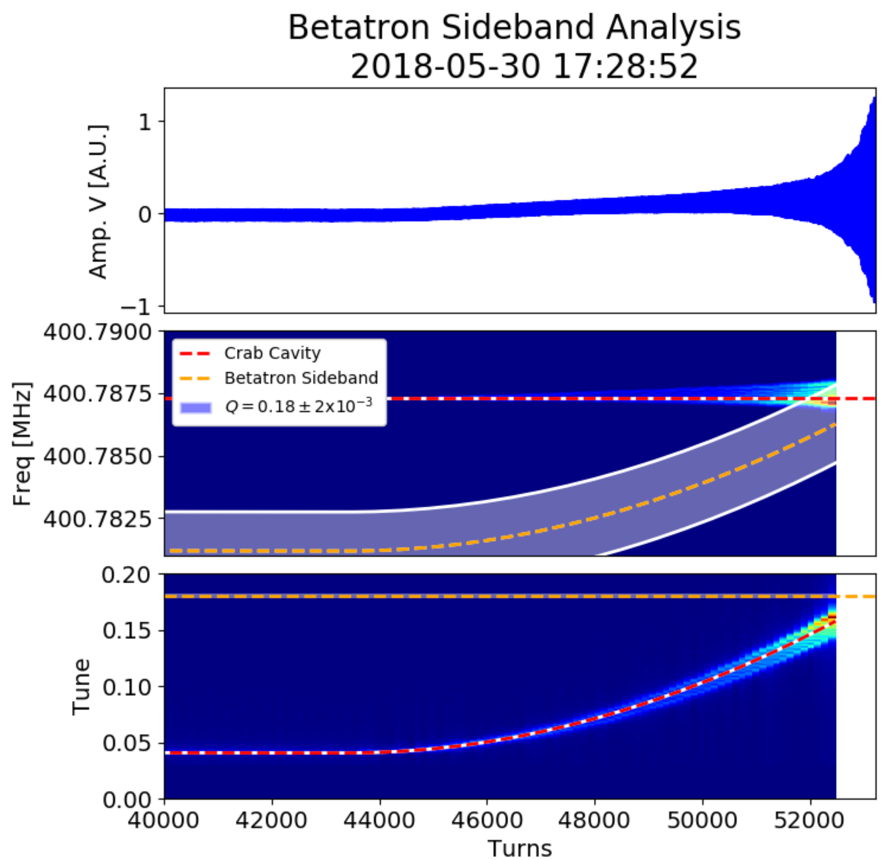
Vertical tune: $Q_y = 0.18$

RF Freq:
Cavity 1: 400.787 MHz (~1 MV)
Cavity 2: 400.528 MHz (almost zero)

Resonant excitation observed as we cross the vertical tune (black dotted lines).

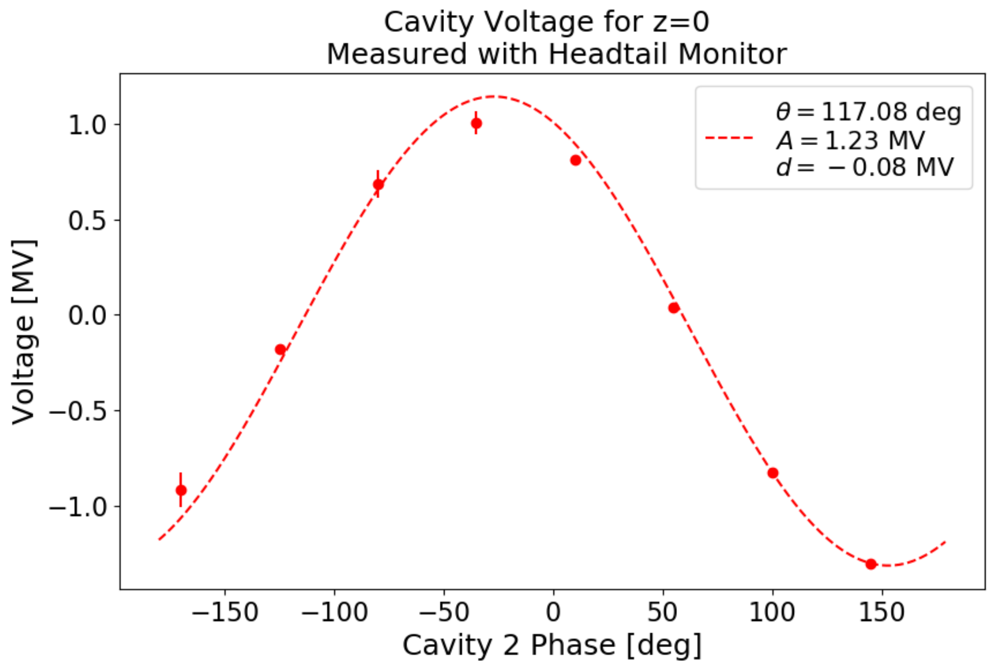
Kicking the beam at 270 GeV equivalent frequency , while sweeping the beam frequency from 26-270 GeV

After setting the correct cycle start voltage to 270 GeV equivalent, beam circulated w/o any issue



Diagnostic Comparison: 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
- 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.

Diagnostic Comparison: 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.
  - Power sensor reading very reproducible at V=0.98MV.

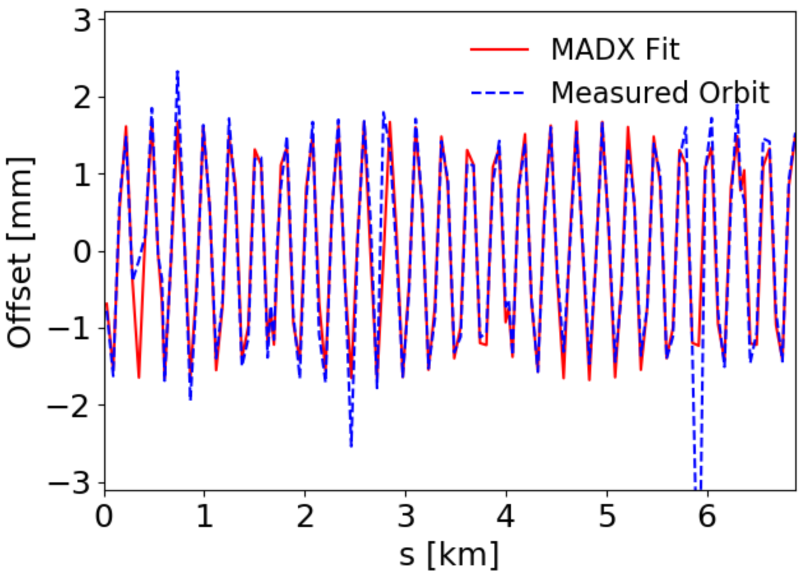
- The scaling of the power sensor reading is $\propto \sqrt{Q_e}$
- Qe = 1.6e10, V = 0.98 MV
- Qe = 1.79e10, V=1.23 MV

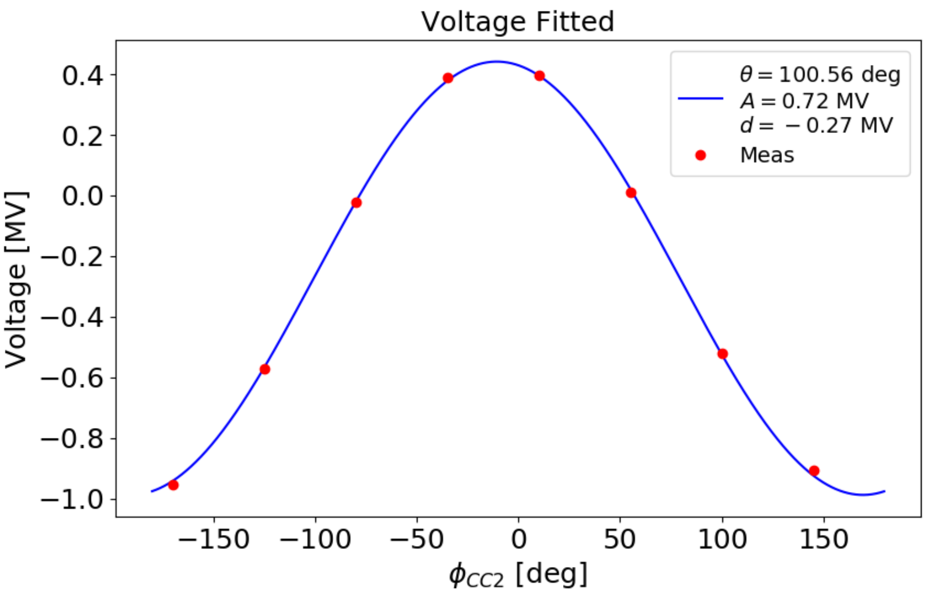
- This is a reasonable error on the Qe and so could explain the discrepancy.

- 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).

Diagnostic Comparison: 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.

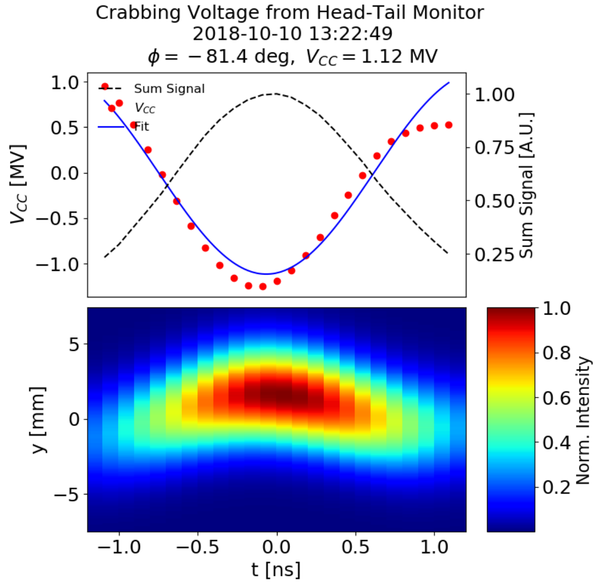


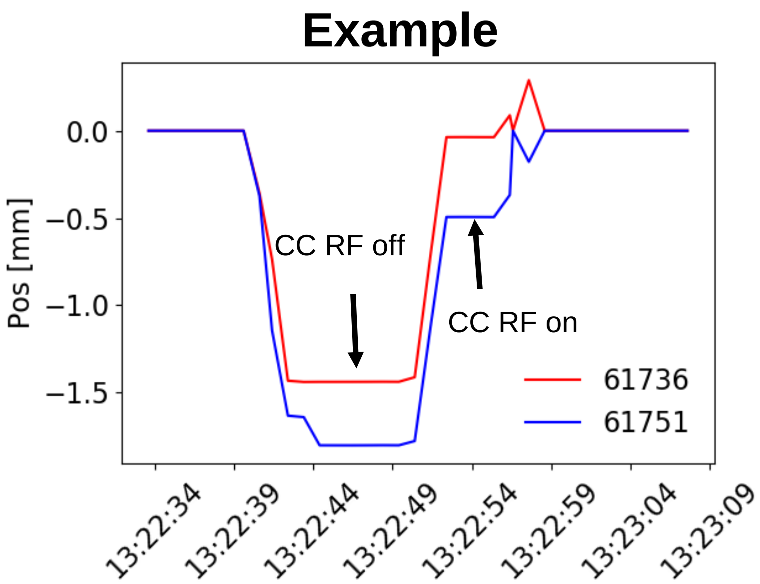


The fitted MADX model does **NOT** include any effect of the bunch length.

Diagnostic Comparison: DOROS

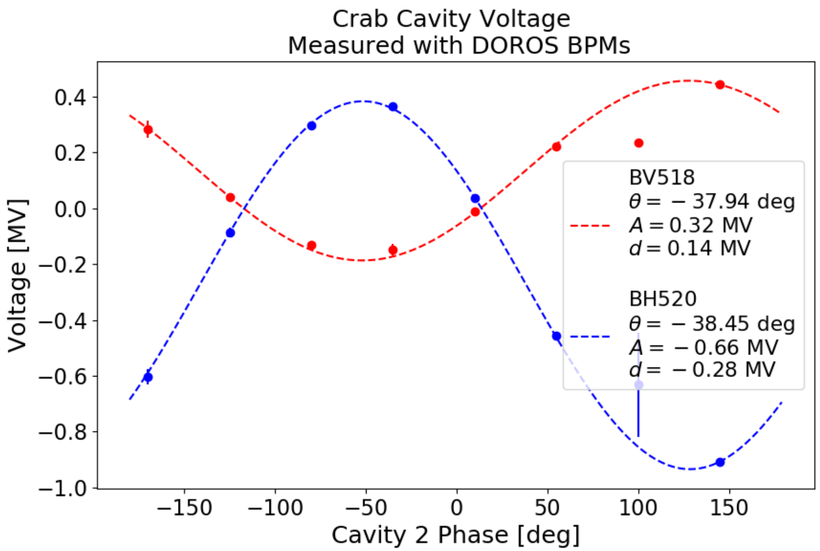
- 4 DOROS BPMs in total. 2 ~1m either side of crab cavity cryomodule and 2 in ring.
- Acquires every 1s but averages over previous 2 seconds (polarity switching frequency of 1Hz).
- CC RF is off for first half of 26GeV cycle, then switched on after all bunches are injected.
- Orbit shift at crab cavity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

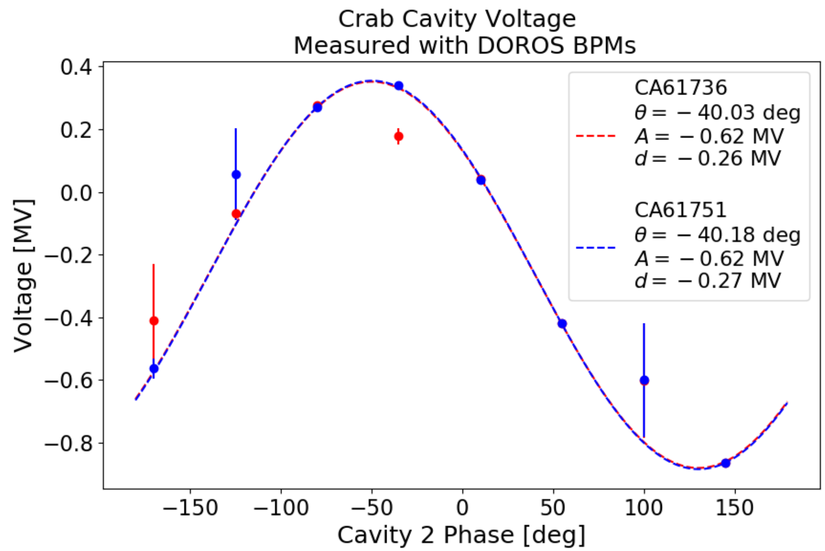




Diagnostic Comparison: DOROS

- 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.





Emittance Growth Calculations: Unnormalized Emittance

Phase noise

Beam parameters

Geometric factor (bunch length)

$$\frac{d\varepsilon_x}{dt} = \beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta\phi}\left(\sigma_\phi\right)\sum_{k=-\infty}^{\infty}\int_0^{\infty} S_{\Delta\phi}\left[\left(k \pm \nu\right) f_{rev}\right]\rho\left(\nu\right)d\nu$$

- Depends on the overlap between phase noise spectrum and betatron tune distribution
- Noise spectrum is aliased at f_{rev}
- The "phase-noise geometric factor" decreases with bunch length

Amplitude noise

$$\frac{d\varepsilon_x}{dt} = 2\beta_{cc}\left(\frac{eV_0 f_{rev}}{2E_b}\right)^2 C_{\Delta A}\left(\sigma_\phi\right)\sum_{k=-\infty}^{\infty}\int_0^{\infty} S_{\Delta A}\left[\left(k \pm \nu \pm \nu_s\right) f_{rev}\right]\rho\left(\nu\right)d\nu$$

- Depends on the **overlap** between phase noise spectrum and synchro-betatron tune distribution
- The "amplitude-noise geometric factor" **increases** with bunch length.

See P. Baudrenghien and T. Mastoridis, "Transverse emittance growth due to rf noise in the high-luminosity lhc crab cavities," Phys. Rev. Accel. Beams 18, 101001 (2015).https://journals.aps.org/prab/abstract/10.1103/PhysRevSTAB.18.101001