Beam dynamics preparation studies for the crab cavity experiment in the SPS

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Many thanks to the SPS OP team

Motivation

- Outline the CC test program in SPS (2018) and preparation
- Demonstrate feasibility with protons
- Recent results
    - Characterization of the natural emittance growth in the SPS
    - Validation of the already existing instrumentation in the SPS that will be used during the CC experiment is of paramount importance!

HLLHC-UK collaboration

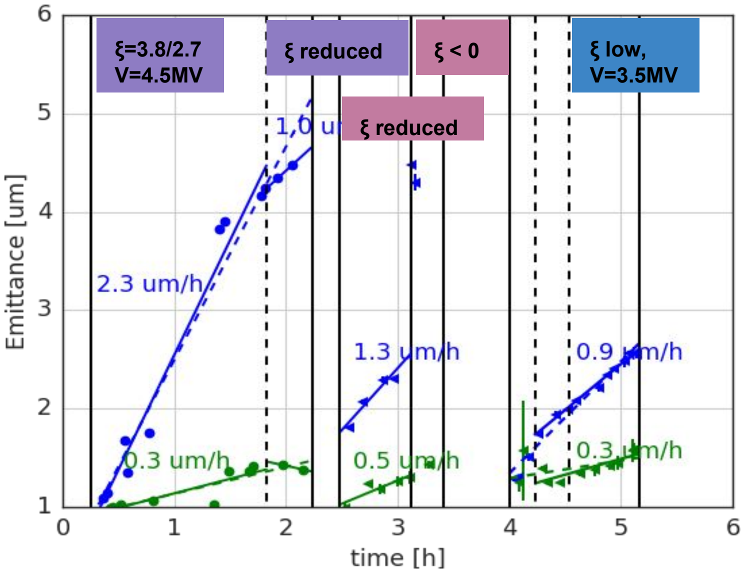
Natural emittance growth studies until 2012

	Unit	Sep 2010	Oct 2010	May 2011	July 2011
Energy	GeV	55	120	120	270
Qx,y	-	0.13/0.18	0.13/0.18	Several tunes	0.13/0.18
$\xi x,y$		2-3	2	0.5	0.5
Intensity	$\times 10^{11}$	1.1	0.5	0.2	0.2
# Bunches	-	1	12	1	1
$\varepsilon_{x,y}$	µm	3.1/2.8	1.5-2.0	2.5	2.5
V_{RF}	MV	3.0	4.0 (1)	4.6 - 6.5	4.6 - 6.5

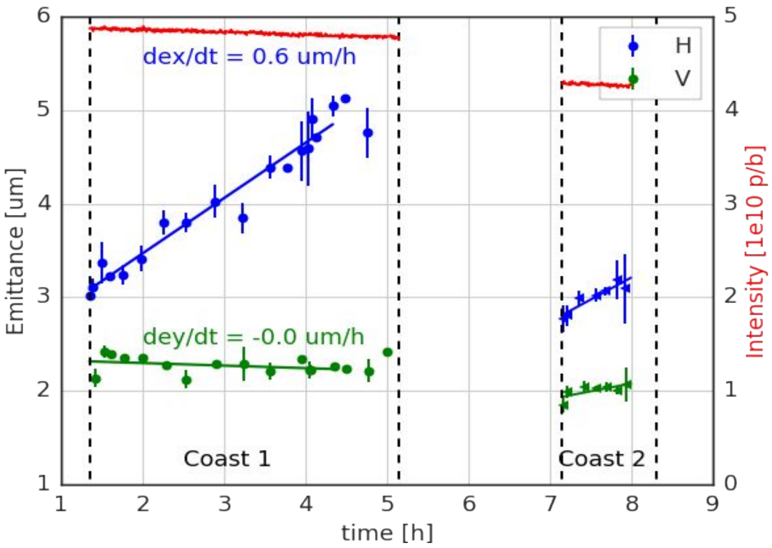
Energy [GeV]	Intensity [$\times 10^{11}$]	Qx/Qy	Voltage [MV]	$d\varepsilon_x/dt$ [/hr]	$d\varepsilon_y/dt$ [%/hr]	$d\varepsilon y/dt$ [µm/h]
55	1.0	0.13/0.18	3.0	140-370%	57%	1.6
120	0.5 (12b)	0.13/0.18	2.0-4.0	100-300%	40-90%	0.6-1.8
120	0.1	0.13-0.33	2.0-4.0	18%	17%	0.43
270	0.4	0.13/0.18	3.0	20-23%	14-24%	0.35-0.6

- **Different energy** coasts, primarily **single bunch** and **low intensity**
  - Distinguish between collective effects and natural emittance growth
- Best spots identified to be 120/270 GeV with 1-4 e10 ppb
  - The lowest emittance growth
  - Similar results in both planes
- Lower energies and higher intensities always gave worse results

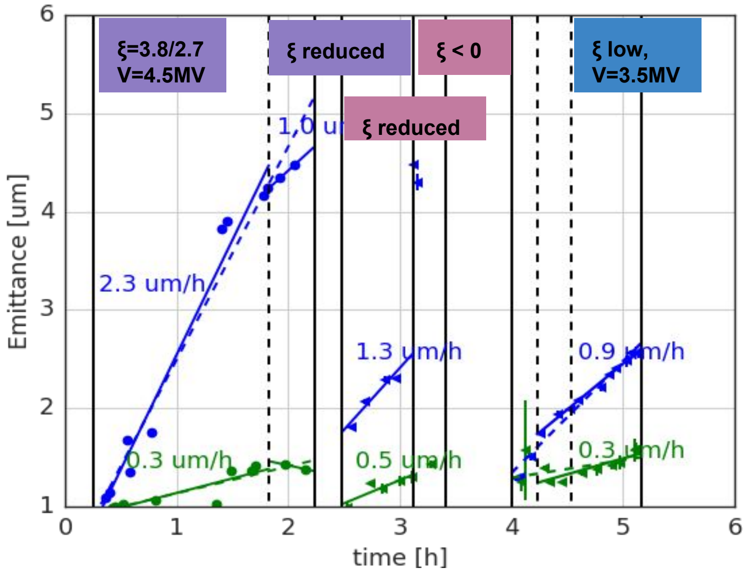
Natural emittance growth studies in 2015



- 2 MDs with coast beams in the SPS at 270 GeV took place in 2015
- **Different growth rates in the 2 planes**



Natural emittance growth studies in 2015



- Clear impact of chromaticity on the horizontal emittance slope
  - No dramatic impact on the vertical emittance growth
- No clear impact of RF voltage change

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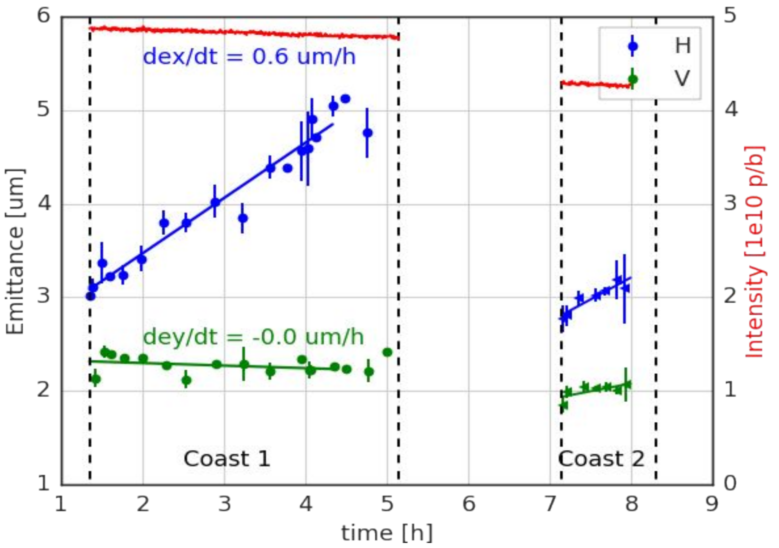
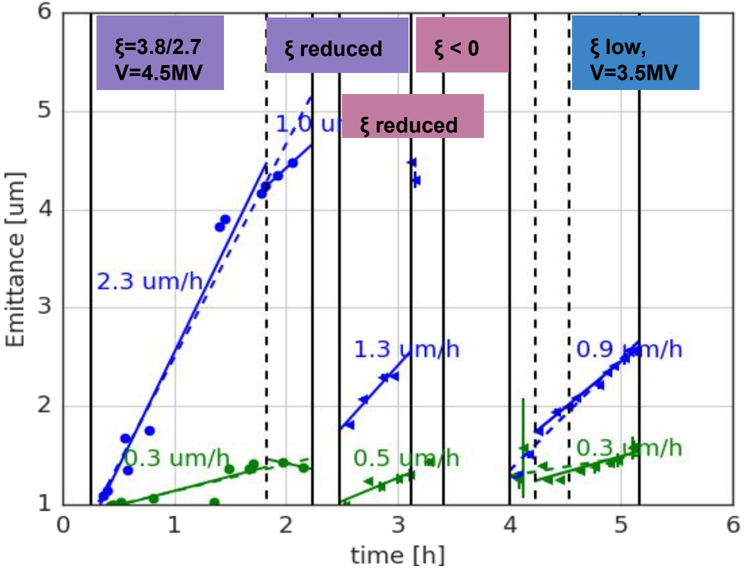


Natural emittance growth studies in 2015



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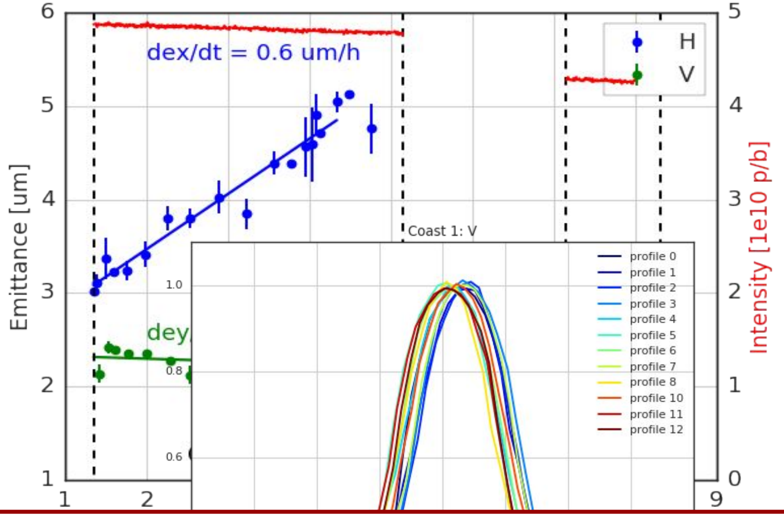


Zero vertical emittance growth observed, probably due to **saturated vertical profiles**

CC SPS Test Program Day, Jan. 2016
Potential MDs for 2016-17

1. Emittance growth studies with chromaticity scan and transverse damper
2. Lowest emittance/shortest bunch at injection via scraping (Q20 and Q26 for scaling)
3. Wideband feedback kicks in a crab like pattern to measure the sensitivity from the existing instrumentation
4. Beta-bump with relocated independent quadrupoles
5. SPS operation feasibility at fractional Q~0.04
6. Q30-Q40 OPTICS (OPTIMUM TO BE FOUND FROM MADX/ SIMULATIONS) provided the options above are not feasible

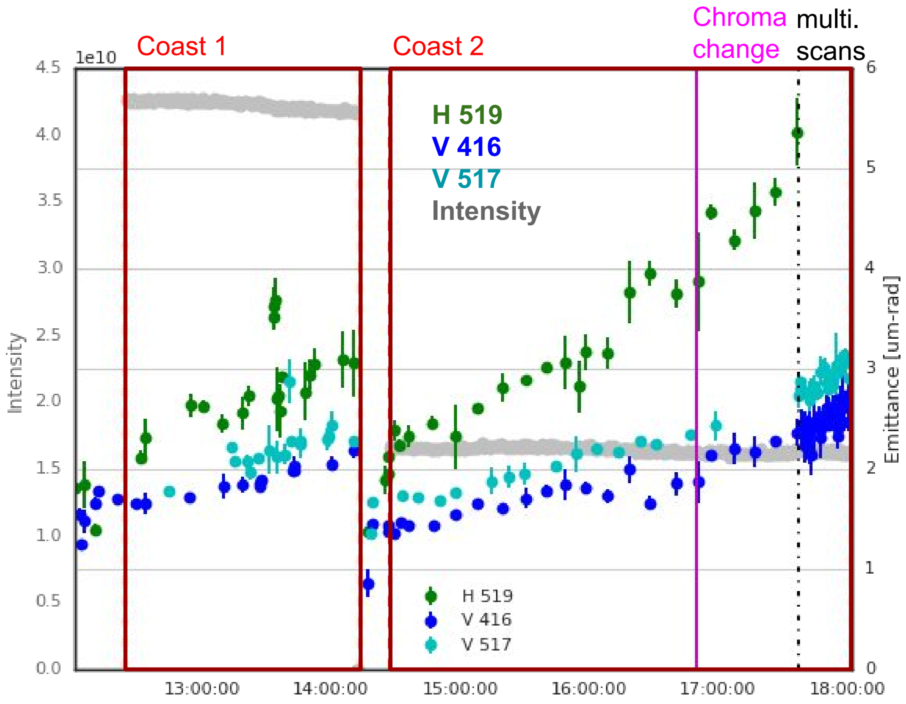
Emittance evolution in coast MD: 7 Dec. 2016

- 2 MDs took place in 2016
  - July and Dec 2016
- MD conditions for Dec. 2016:
  - Energy of 270 GeV
  - **Two different intensities**
    - Coast 1: 4.2e10
    - Coast 2: 1.6 e10
  - Chroma H/V: 0.5/1
  - Wire scanners used: 519H, 416V, 517V

➔ Chroma change by 2 units performed after 2 hours in coast 2

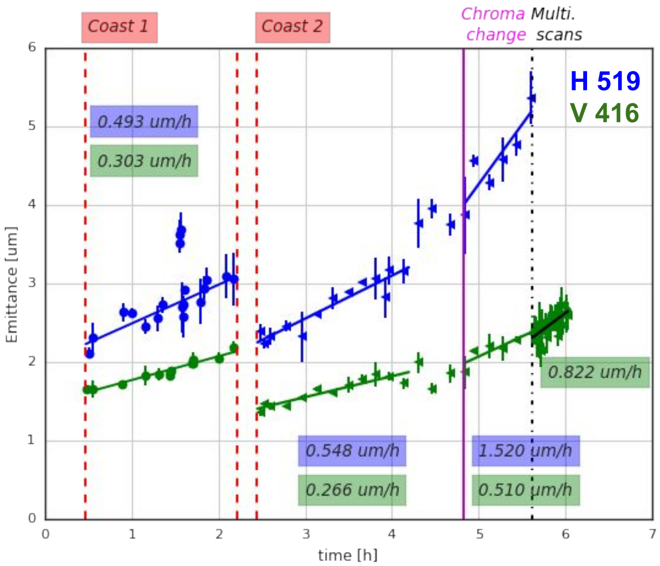
➔ **Multiple wire scans** performed the last 15 min. of the MD

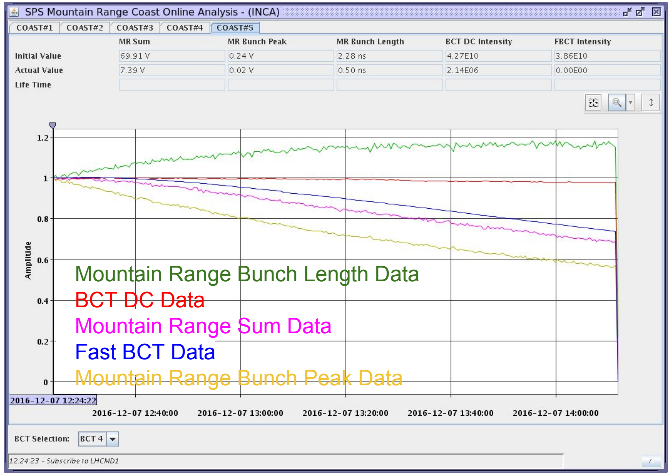
- ◆ Study the impact of the WS to the natural emittance growth



Emittance evolution along the MD

- Transverse plane
  - **Linear fit** applied for 4 different cases:
    - Coast 1
    - Coast 2 before chroma change and for same time-window as in coast 1
    - Coast 2 after chroma change
    - Coast 2 during the multiple WS
  - Clear **slope increase** after the **chroma change** in both planes
  - Slope increase during the multiple scans, however the spread is also large
- Longitudinal plane
  - Slow **off-bucket losses** observed
  - **Bunch length increase** by ~20% in 1.8h for coast 1 and ~10% in 1.8h for coast 2





Studies plan for 2017

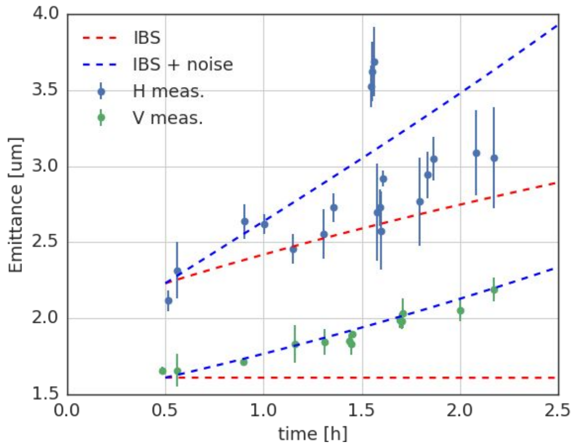
- Natural emittance evolution in coast
    - If possible one MD at the beginning of the year where the vacuum levels could be worse
        - At optimal conditions (low chroma and low intensity) to see if the situation for the emittance evolution is also worse
    - Commissioning and cross-calibrate the BGI monitors (similar with ion beams last year)
    - Repeat the WS multiple scans experiment of F. Roncarolo in a more systematic way
    - Systematic chroma scan
    - Different intensities
    - Effect of transverse damper: Identify the effect of the damper on the emittance evolution on coast without the CC
    - At the end of the year, dedicate few hours to degrade the vacuum levels and study the impact on the emittance evolution
    - vacuum and power supply monitoring during each MD and subsequent simulations

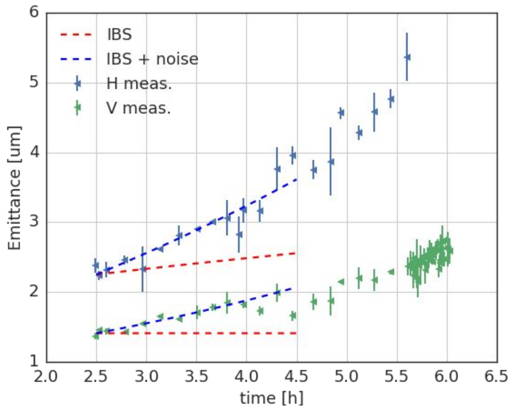
Studies plan for 2017

- Head - tail monitor
  - Study the accuracy of the monitor at different energies and intensities
  - Identify the minimum kick that can be measured
  - Simulations are currently in progress to use them as guideline (A. Alekou et al)
- Closed-orbit correction
  - In past MDs an rms orbit of 3-5mm. Verify if we can do better than this
  - Verify if the normal YASP can be used efficiently at 270 GeV
    - Is it more efficient to use the extraction kickers?
  - Identify the optimal kickers and the sensitivity of the BPMs around the crab lo
    a varying closed orbit in the cavity region to identify the electrical center.
- Collimation studies
  - Verify if the system works as it should (scrapers, BLMs, ...)
- Studies with shorter bunch length
  - look at effects of non-linearity of the RF curvature (the CC have an RF freq. of 400 MHz)

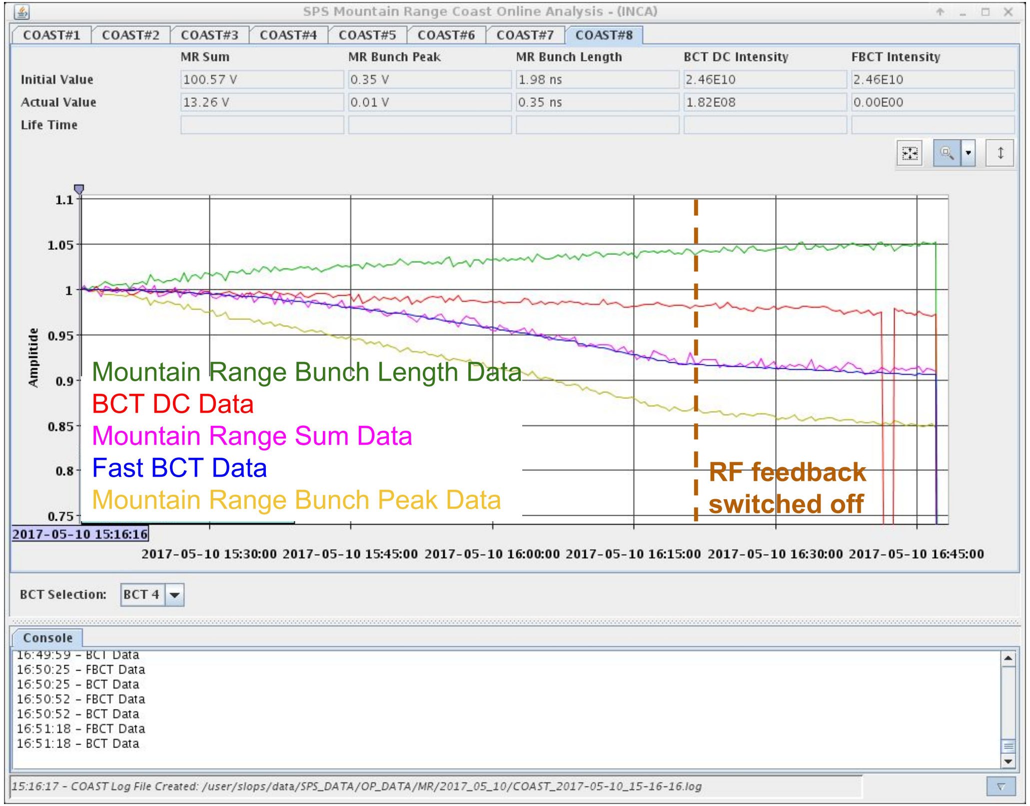
Emittance growth due to intrabeam scattering (IBS) - Dec. 2016

- **IBS calculations** using the SPS lattice and the bunch characteristics during the MD
  - IBS can only explain a small part of the horizontal emittance growth
- **Assumption**: vertical emittance growth due to a **noise source** acting in both planes
- **Interesting notice:** Combining IBS + extra growth term same as in the vertical plane → emittance evolution better reproduced





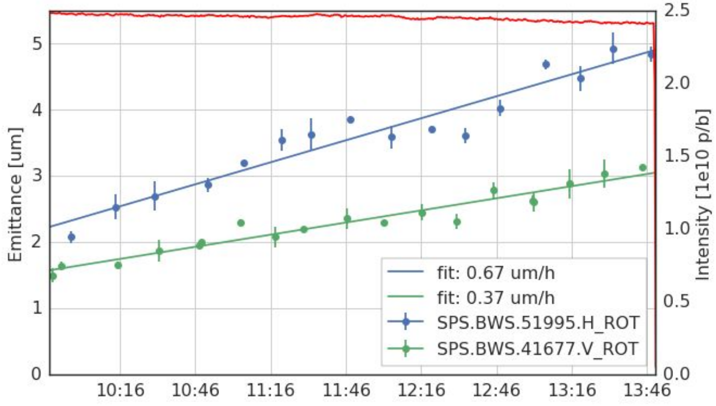
Experimental studies in 2017 - 10 May

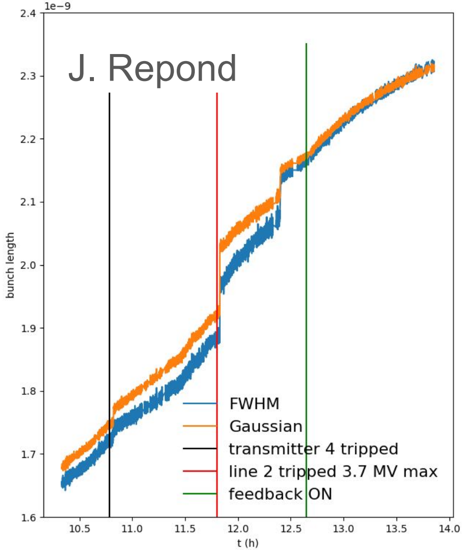


- Not able to do any transverse emittance studies, due to “bad” transverse beam size profiles
  - Focus in the slow off-bucket losses
    - Very helpful input and participation of the RF group!
- **Source of off-bucket losses was identified → RF feedback**

Experimental studies in 2017: 21 June

- 21 June: MD with coast at 270 GeV, low intensity and low chromaticity
  - The RF feedback was off for the first 2.5h and then switched on verifying that the off-bucket losses are caused by the RF feedback
  - Large growth in all planes observed
    - The RF system was not behaving very well during the MD
  - IBS can predict only part of the H growth. Assuming another source of growth, similar with the one in the vertical plane, we can reproduce the H growth much better (dashed blue line) (with low chroma)
- 22 June:
  - Calibration studies for the Head Tail monitor at high intensity (T. Levens, T. Lefevre, M. Krupa)





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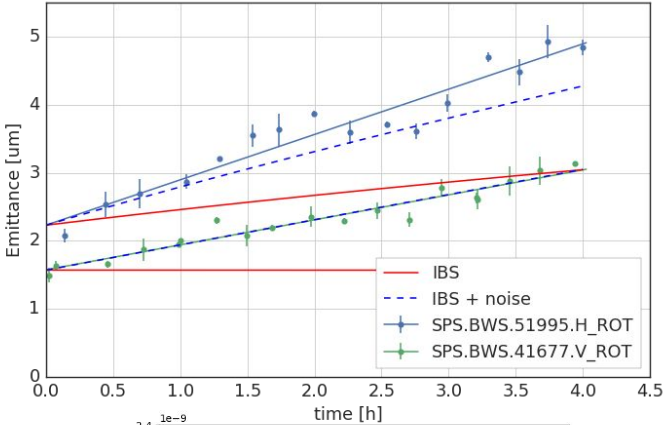
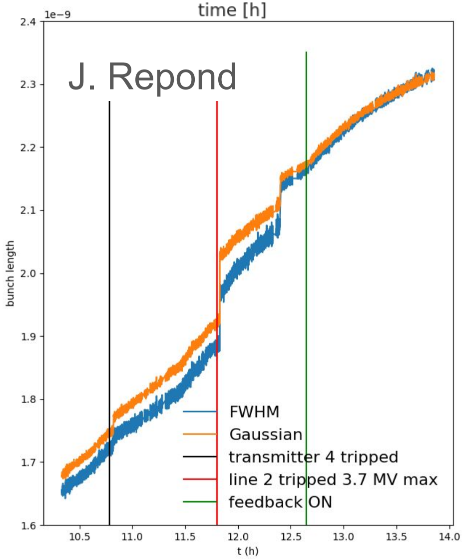
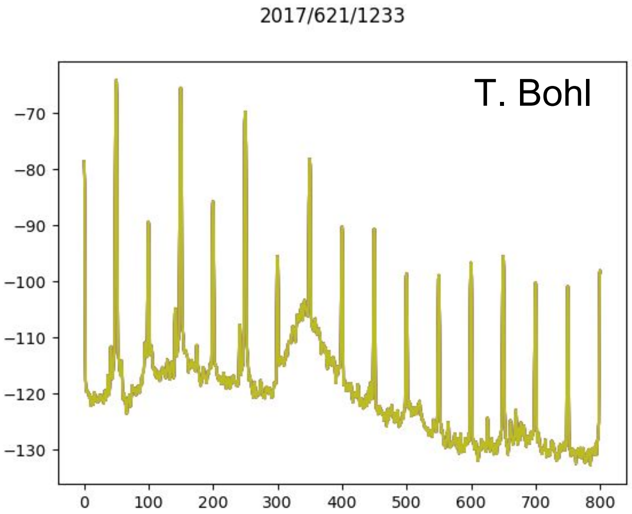
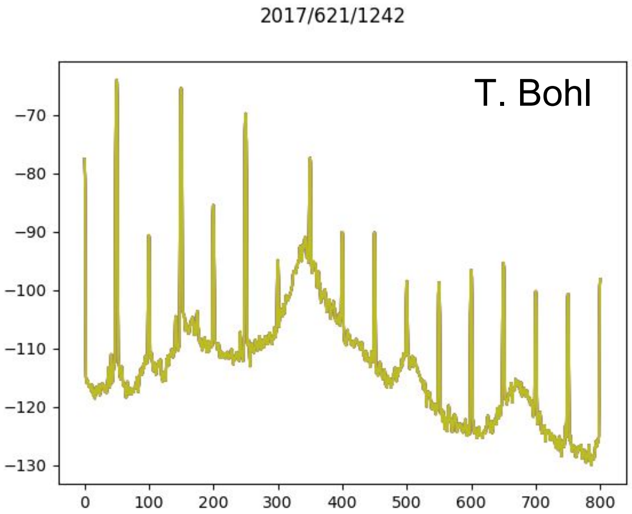




Longitudinal signals

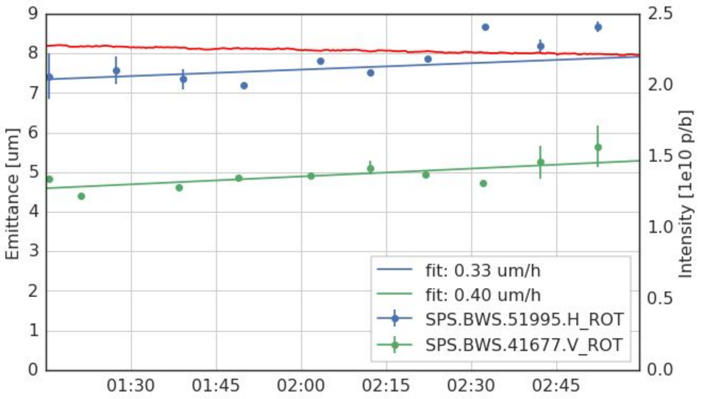


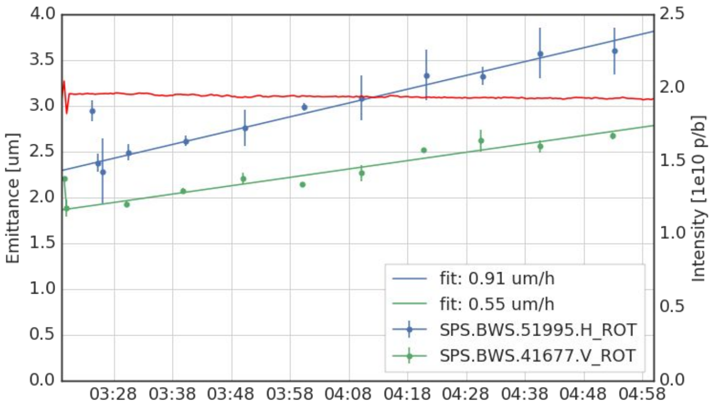


- Peak detected Schottky signals were also acquired with the RF feedack off and on in order to see if the spectrum is changing
- No obvious difference. Simulations to be followed up by Joel

MD with Q20 Optics: 4 July

- The Q20 optics was tested!
- RF voltage of 5MV
- 2 coasts at low intensity and low chroma
  - Coast 1:
    - emit. H/V = 7.35 / 4.59 um
    - Nb=2.2e10 ppb
    - σl = 1.7 ns
  - Coast 2:
    - emit. H/V = 2.29 / 1.86 um
    - Nb=1.95e10 ppb
    - σl = 2 ns





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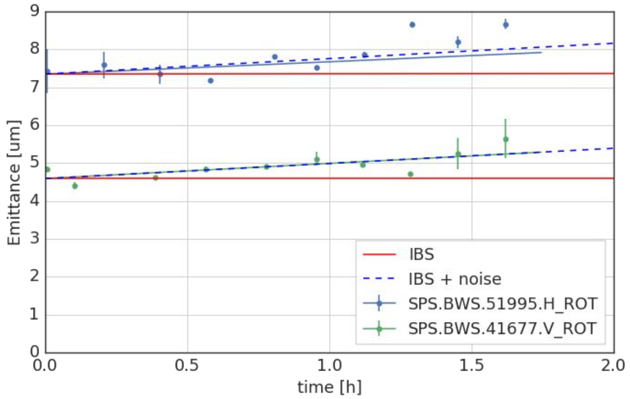
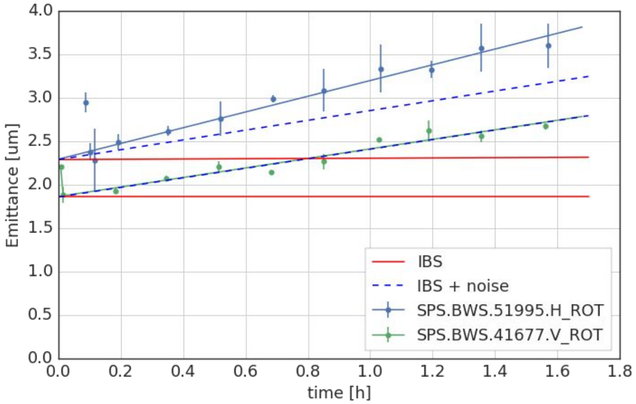
    - σl = 2 ns
- Q20 and Q26 behave similarly!





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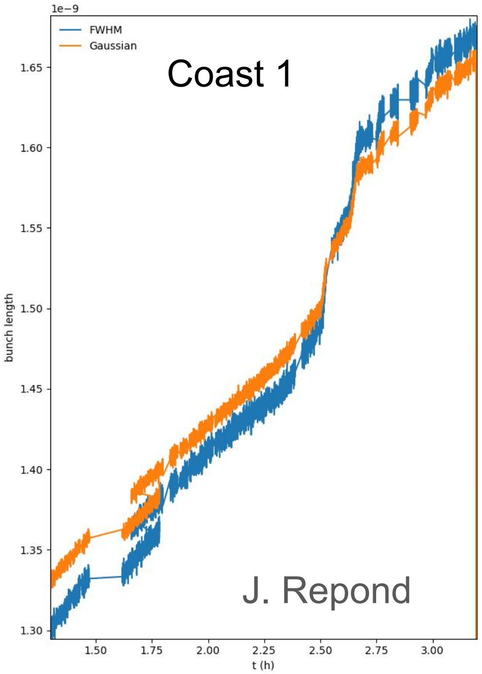
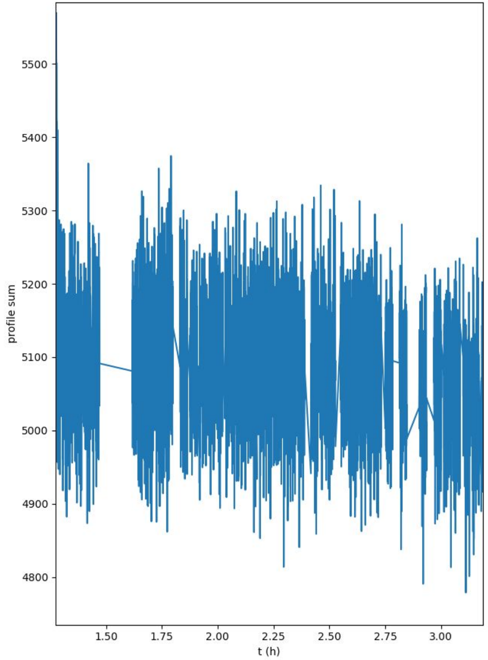
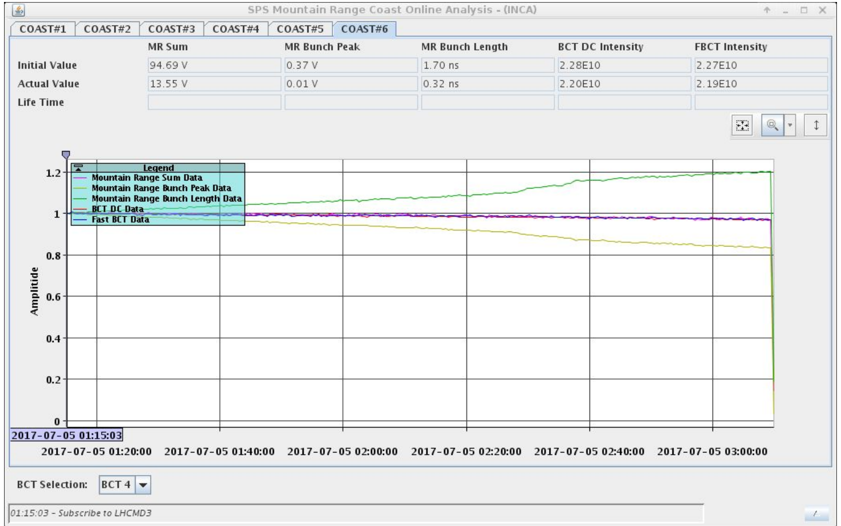




- Sudden jump in bunch length needs to be understood
- The effect is visible in the horizontal plane as well
- Analysis in progress



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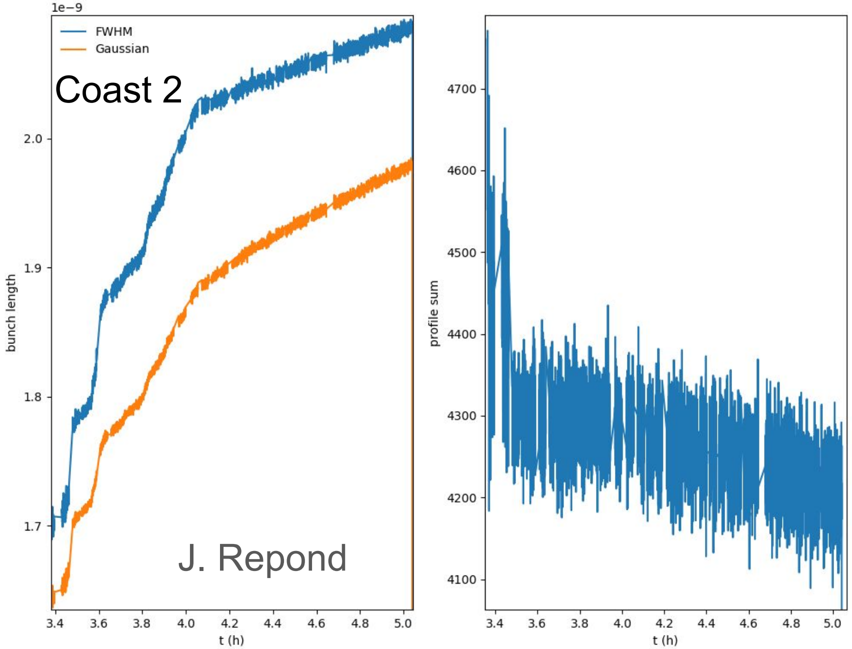
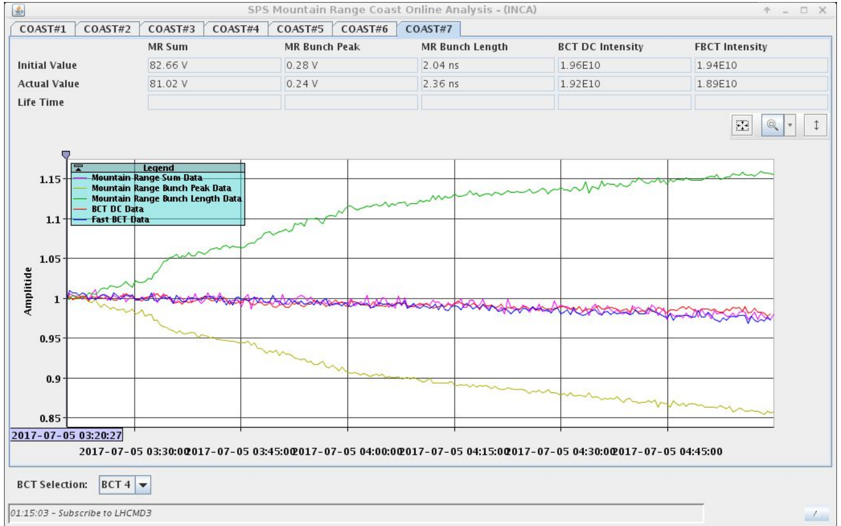
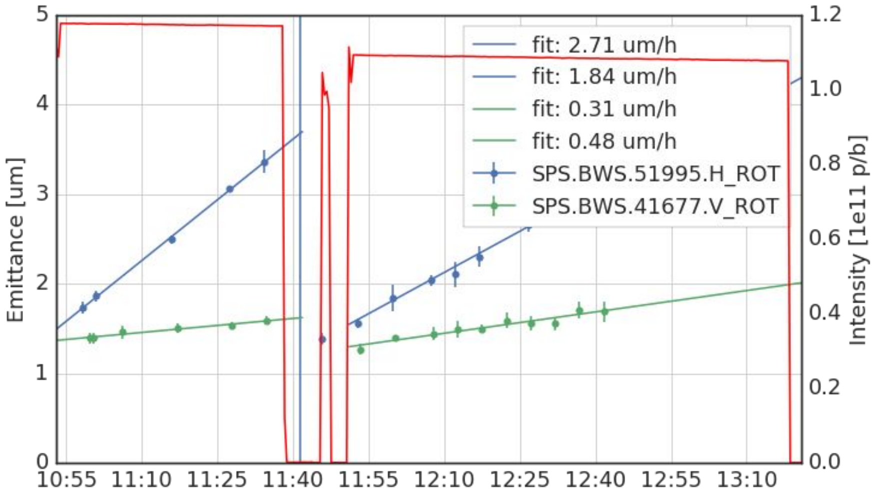


- Sudden jumps in bunch length which starts earlier in time than coast 1
  - The bunch length is also larger
- Analysis in progress

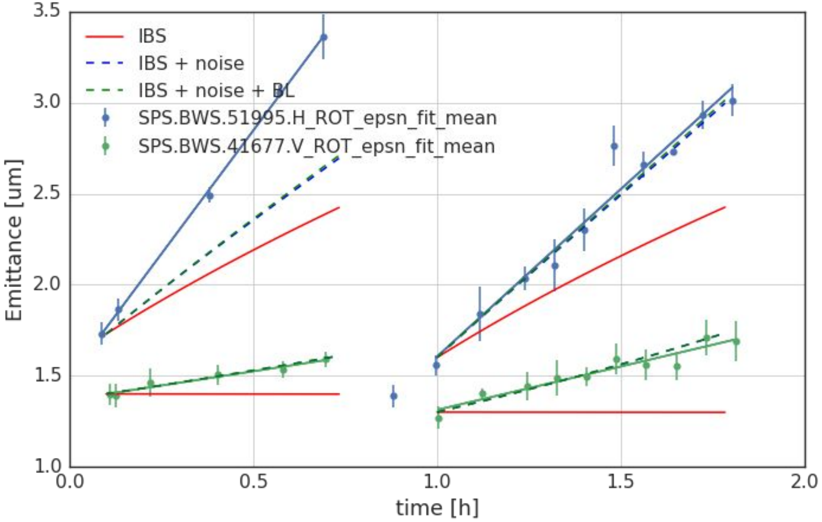


Parasitic MD, Q26, nominal intensity: 9 August 2017



- Parasitic MD with nominal intensity
  - Main user: Collimation studies
- Very nice emittance measurements! Big improvement of the quality of the data from the WS!!

9 August 2017: Parasitic MD, Q26, nominal intensity



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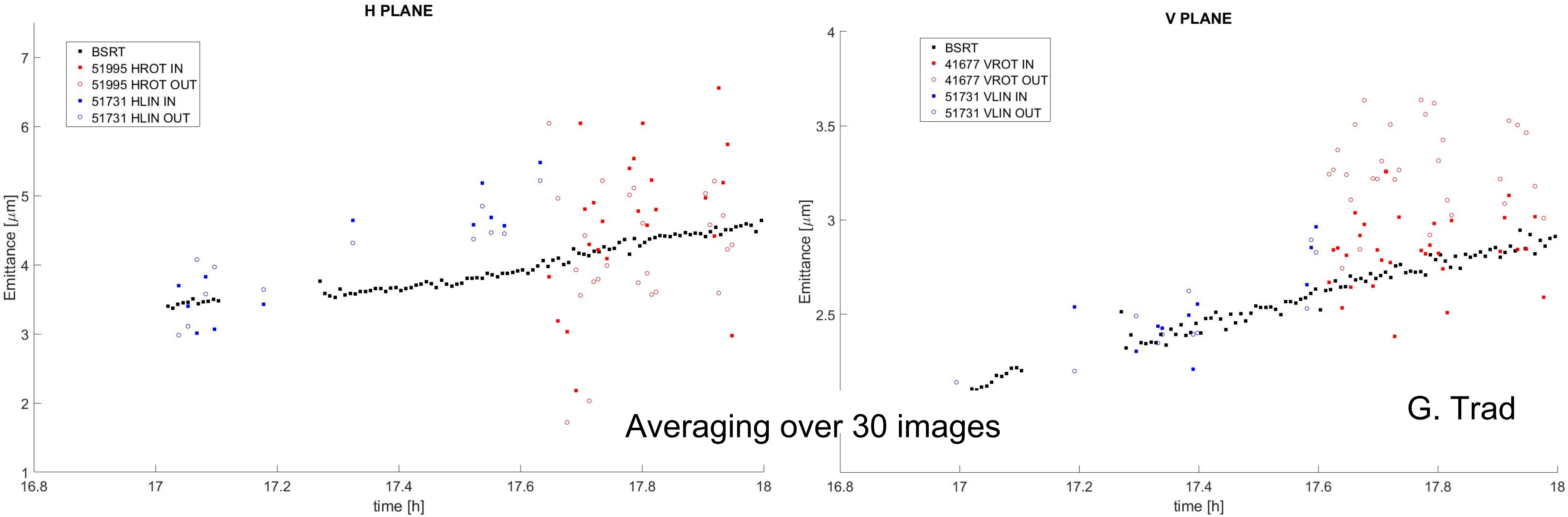
Experimental studies in 2017 - Use of the BSRTs



Averaging over 30 images

G. Trad

- BSRT calibration for the coast beams (many thanks to G. Trad)!!
- Ideal tool to observe slow ramping of the CC voltage!

Head tail monitor

- Calibration of the Head Tail monitor at low intensities (removing attenuators) (T. Levens, T. Lefevre, M. Krupa)
  - Very nice signals and promising results

Transverse damper

- G. Kotzian has set up the scripts for logging the damper data during coast
  - First orbit data
- MDs with and w/o transverse damper foreseen for next MDs

Summary table (Preliminary)

	Emit. H/V [μm]	Nb [1e10]	Chroma H/V	RF voltage [MV]	Bunch length [ns]	Long. emit. [eV.s]	H growth [μm/h]	V growth [μm/h]	Bunch length growth
May 2015									~10%/h
Coast 11	0.8/0.9	1.5	3.8/2.7	4.5	1.5		2.3	0.3	
Coast 12	4.2/1.5	1.5	Reduced	4.5	1.5		1.0	-0.2	
Coast 2	1.8/1.0	1.25	Reduced	4.5	1.5		1.3	0.5	
Coast 3	1.7/1.2	1.7	Reduced	3.5	1.5		0.9	0.3	
July 2016	2.85/2.16	2.25	2.5/2.5	5.1	1.96	0.41	0.59	0.23	~10%/h
Dec. 2016									
Coast1	2.23/1.61	4.25	0.5/1		2.28	0.36	0.49	0.30	~10%/h
Coast 2	2.25/1.41	1.65	0.5/1	2	2.3	0.36	0.55	0.27	~10%/h
ξ increase	4.0/1.98		2.5/3		-		1.52	0.51	-
multi-scans	-/2.3		2.5/3		-		-	0.82	-

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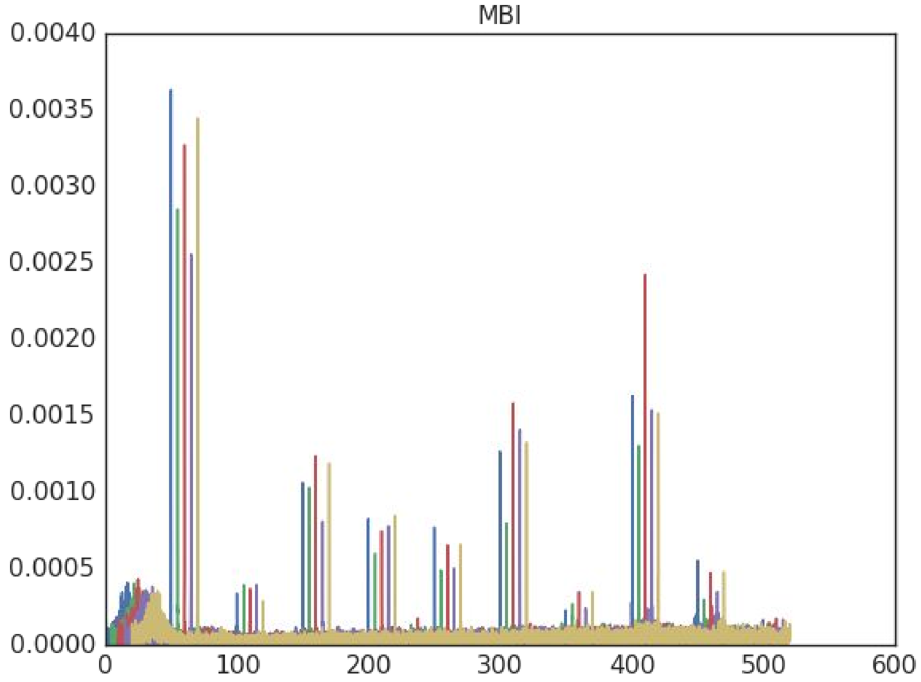
May 2017	Focus on the off bucket losses, no transverse emittance measurements								
June 2017	2.1/1.7	2.5	1/1.6	5	1.9	0.41	0.67	0.37	~10%/h
4 July 2017 Q20 Coast 1 Coast2	7.3 / 4.8 2.5/2.0	2.2 2.2	0.7/1.4	5	1.7 2.0	0.33 0.45	0.33 0.83	0.4 0.5	~10%/h ~10%/h
9 Aug. 2017 **Coast 1** **Coast 2**	1.73/1.4 1.6/1.3	12 11	No chroma measurem ents				2.71 1.84	0.31 0.48	

Analysis of the ripple data



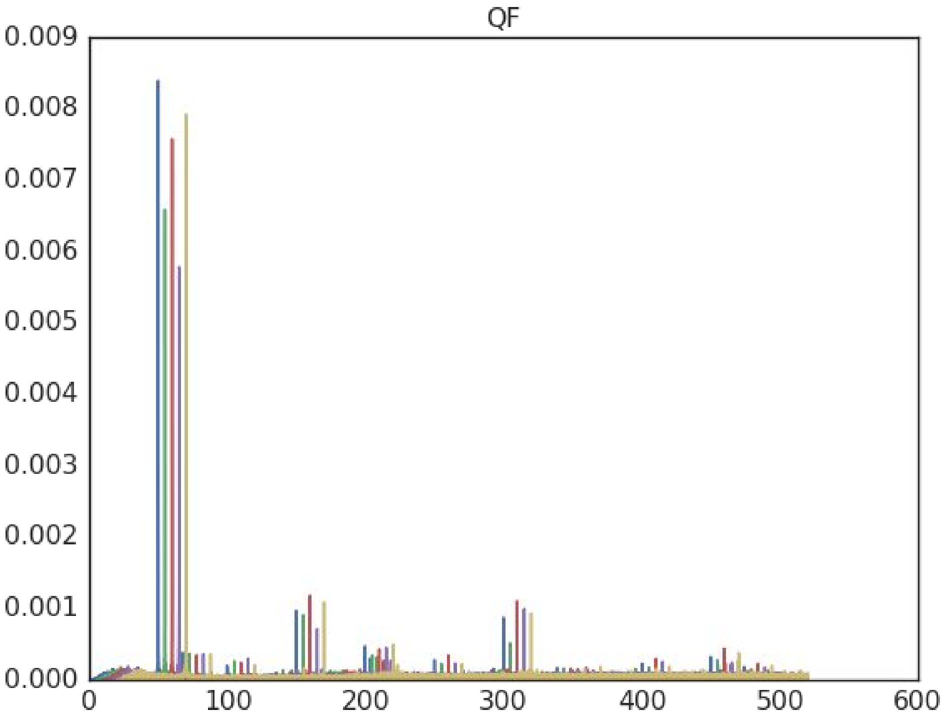
Data from June MD

- Frequency spectrum of the power supply current for the MBI, QF and QD
- 50Hz line is the main frequency
  - higher harmonics also present

Red: The time moment where the RF feedback was switched-on

- The results for two cycles before and 2 cycles after are also plotted
  - The frequency lines are moved by 5 Hz just to be able to observe any changes

Power supply ripple



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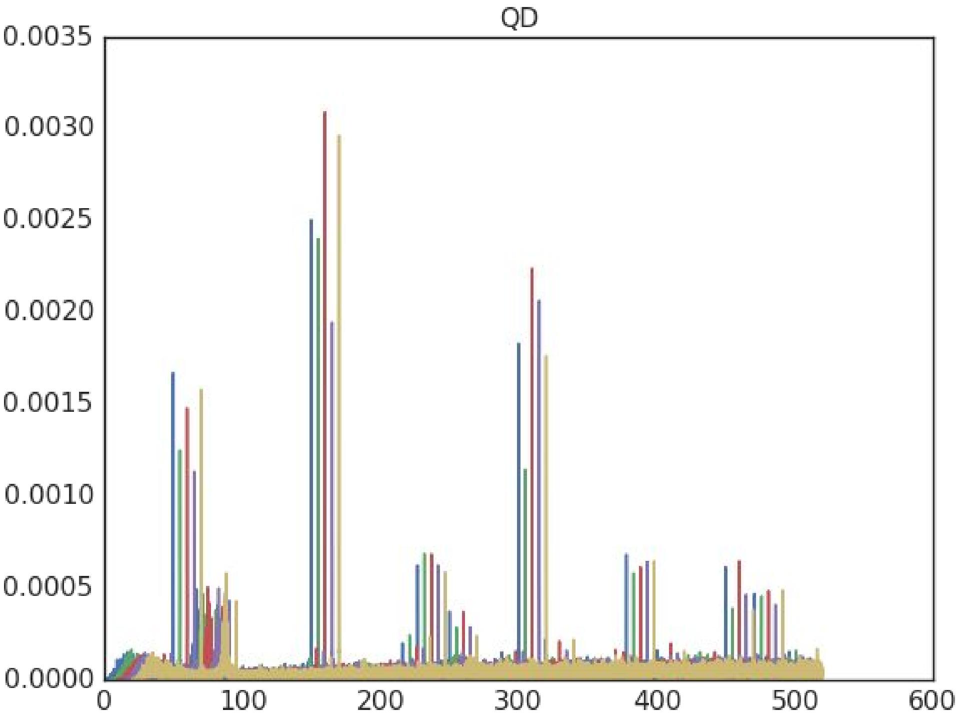

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- The results for two cycles before and 2 cycles after are also plotted
  - The frequency lines are moved by 5 Hz just to be able to observe any changes
- A technical student starting the 1st of Oct. will work on the simulations

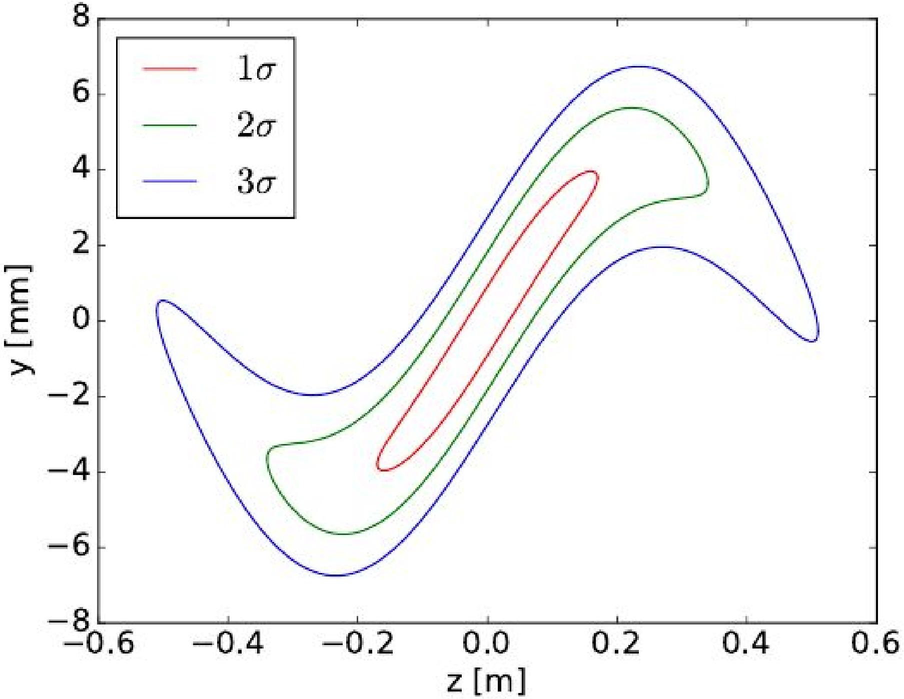
Expected emittance growth due to the CC noise during the SPS test

We are in contact with **T. Mastoridis** and **P. Baudrenghien**. They are working on the calculations and soon we will have their estimations

Some preliminary statements:

- The prototype CC LLRF was tested in SM18. The measured noise spectrum would lead to unsustainable transverse emittance growth
- Efforts are ongoing to improve the LLRF performance
- A combination of reducing the regulation bandwidth to 10 kHz and adding a notch filter at the first betatron sideband (-12dB) would lead to an emittance growth rate of 50% per hour (40% due to amplitude and 10% due to phase noise)

Instrumentation validation for measuring the crabbing



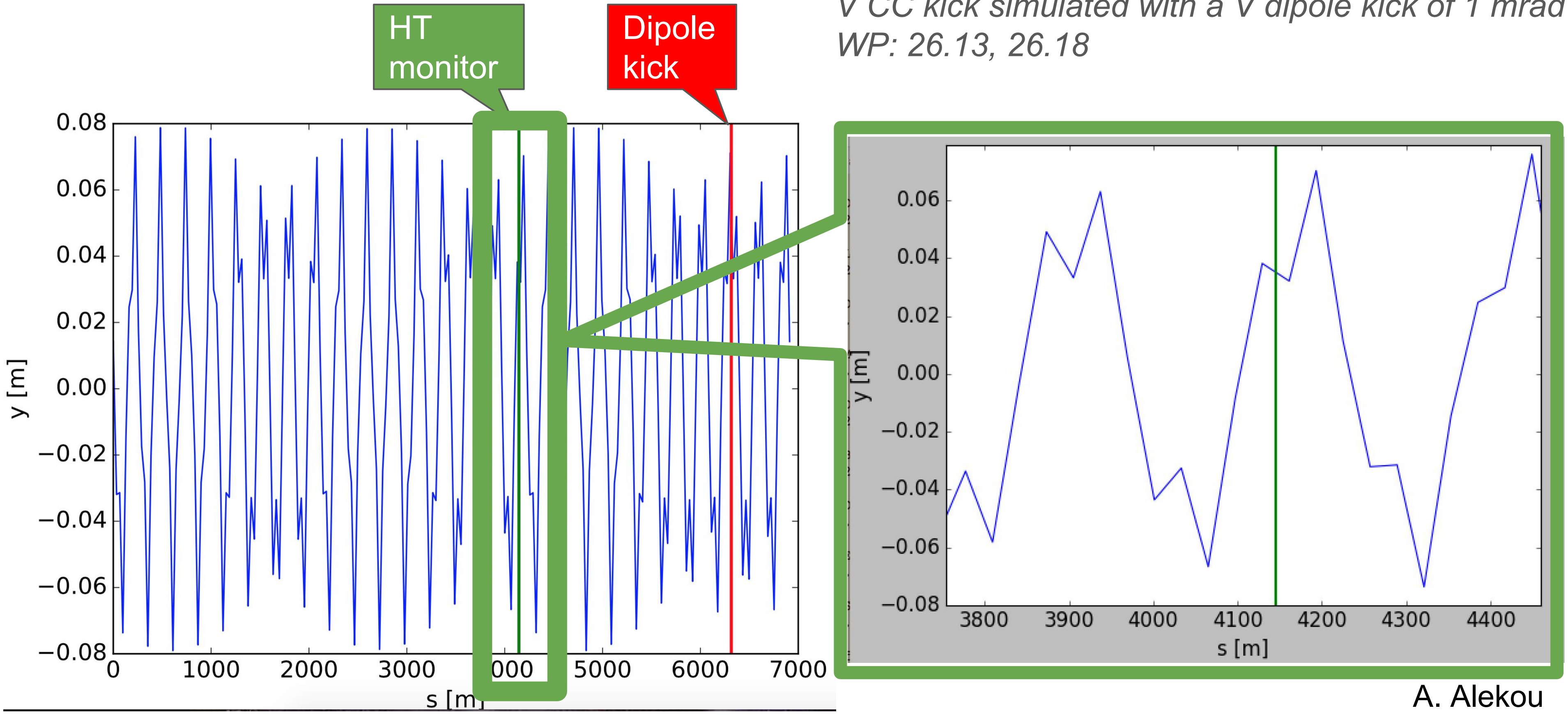
The bunch profile of the crabbed beam at the HT monitor location (55GeV, V=6.8MV)

- The most sensitive instrument available in the SPS that we can use to measure the kick of the crab cavity is the Heat-Tail monitor
- It has been used mainly to detect instabilities → Large intra-bunch motion
- Preparation studies are in progress to prove that it can be used to measure the crabbing of the bunch

A. Alekou

CO deformation due to dipole error compatible with the CC kick

V CC kick simulated with a V dipole kick of 1 mrad
WP: 26.13, 26.18



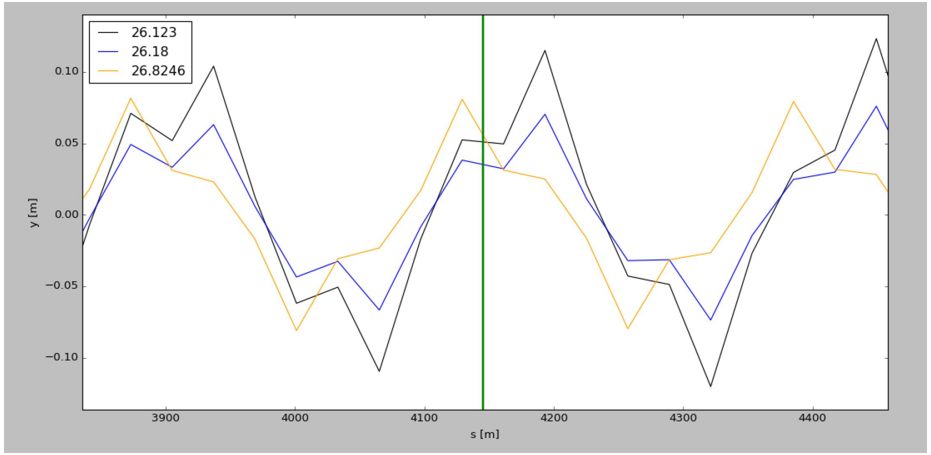
A. Alekou

Head-Tail (HT) monitor reading

- We would like to have a **good y-reading at HT monitor position**
- For higher y-signal at HT we could physically move the HT (only if absolutely necessary, to be avoided), or change the SPS WP

Impact of the SPS working point

- Can increase overall y-CO and therefore the CO at the HT monitor location
- Changes ph-Advance between HT and kick, HT can be at crest of wave

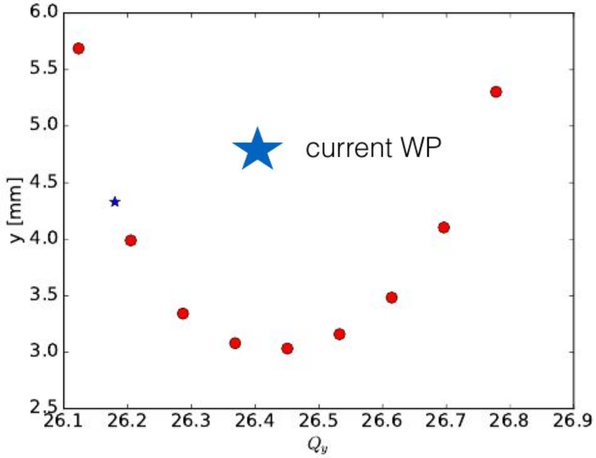


$$z(s) = \frac{\theta}{2} \frac{\sqrt{\beta(s)}\sqrt{\beta(s_k)}}{\sin \pi Q} \cos\left(\left|\Phi(s) - \Phi(s_k)\right| - \pi Q\right)$$

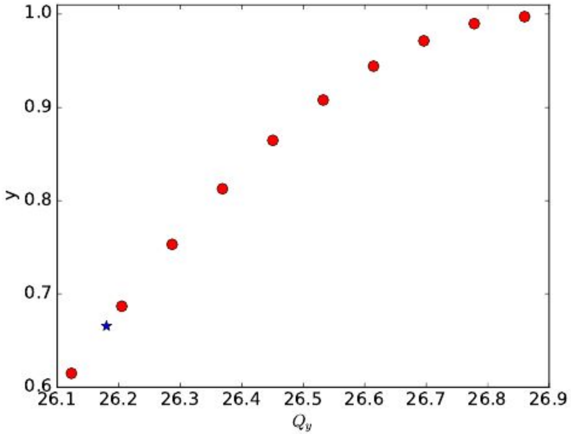
A. Alekou

Head-Tail monitor reading with respect to WP change

y-amplitude at HT monitor



normalised y-amplitude at HT monitor
y_norm=(y@HT/ymax)*√(βmax/β@HT)

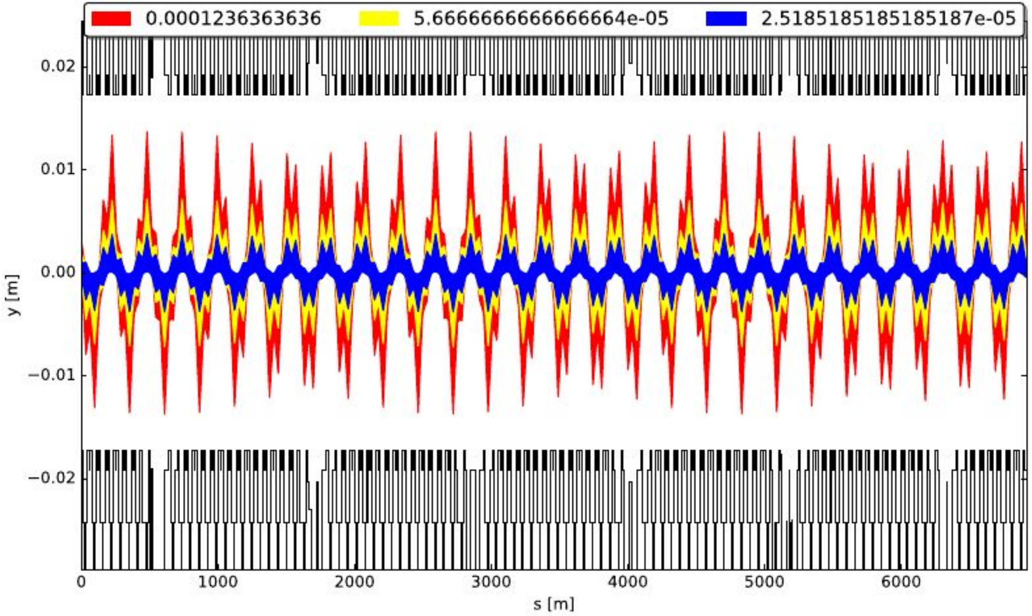


- 30% “loss” of reading does not justify WP change or change of HT monitor location.
- In contact with the BI group (T. Lefevre, T. Levens et al) to study HT limitations
  - First parallel MD already took place the 22nd of June and next one foreseen for the 4th of July

A. Alekou

Aperture limitation vs kick size vs energy

55 GeV 120 GeV 270 GeV



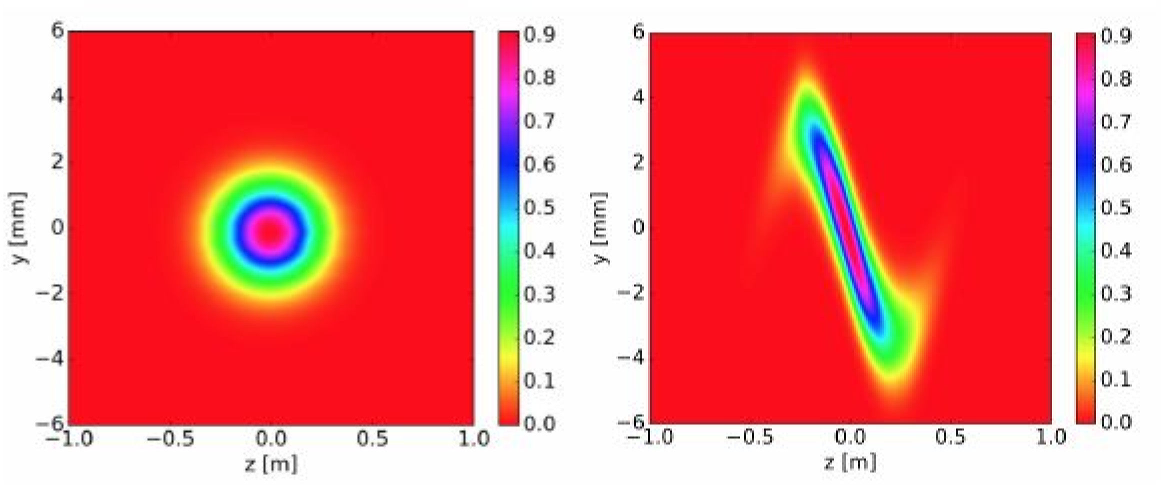
V=6.8MV

Energy [GeV]	Kick [mrad]
55	0.1236
120	0.0567
270	0.0252

Conclusion: for max V (6.8 MV), nominal WP, at 55, 120, 270 GeV, there is no aperture limitation.

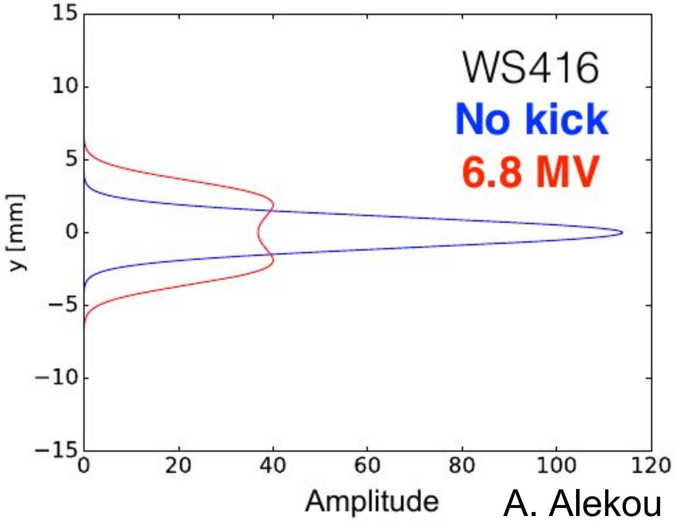
A. Alekou

Using the Wire scanners to measure the crabbing



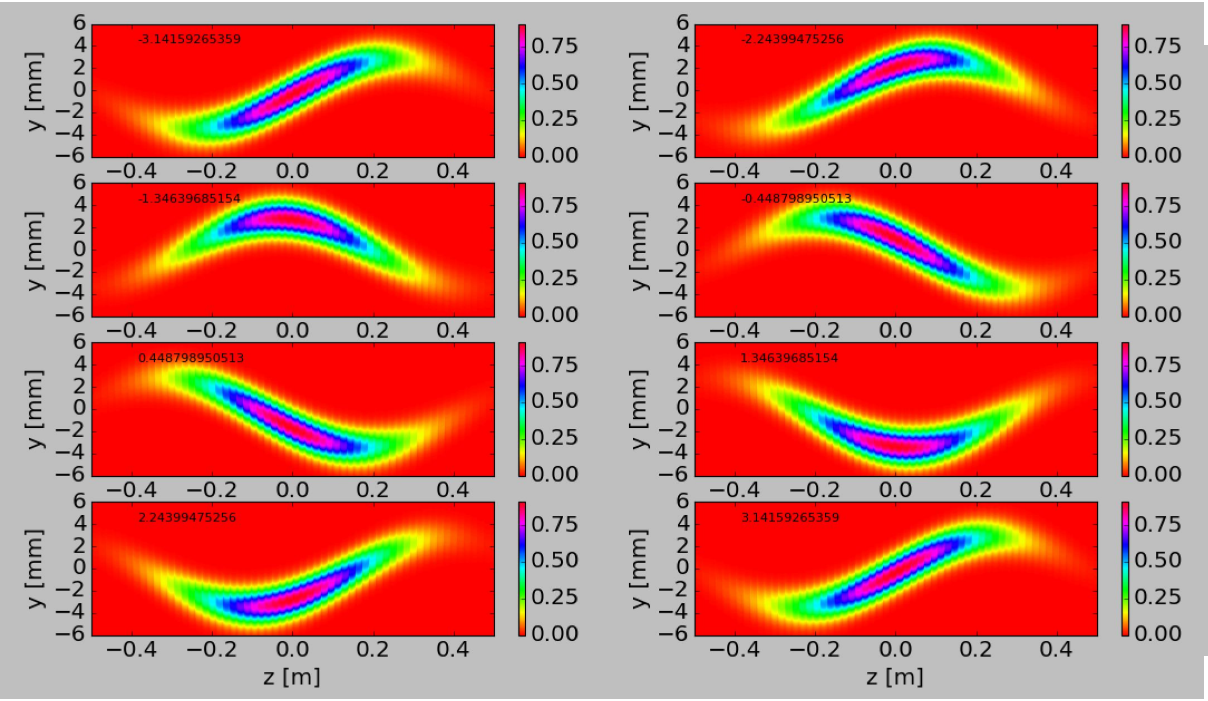
2D gaussian beam in y and z, without (left) and with a kick corresponding to 6.8 MV (right).

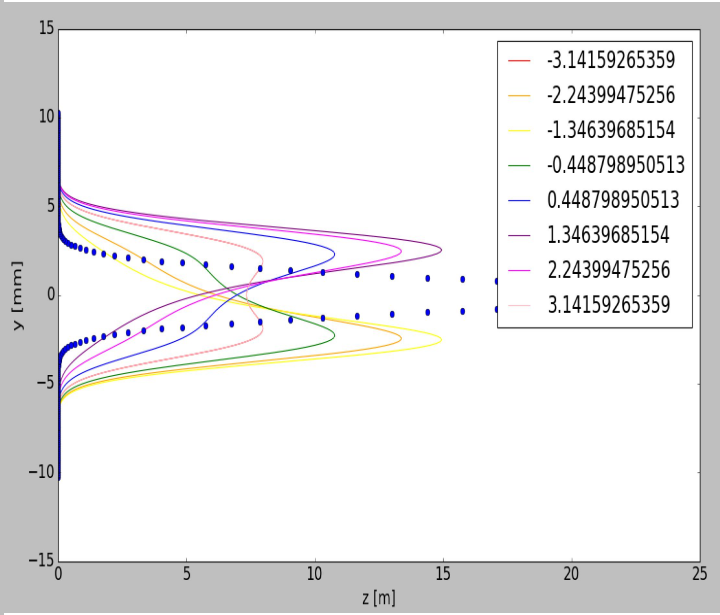
- An alternative approach is under investigation → Use the Wire scanners to measure the effect of the CC on the bunch profile



A. Alekou

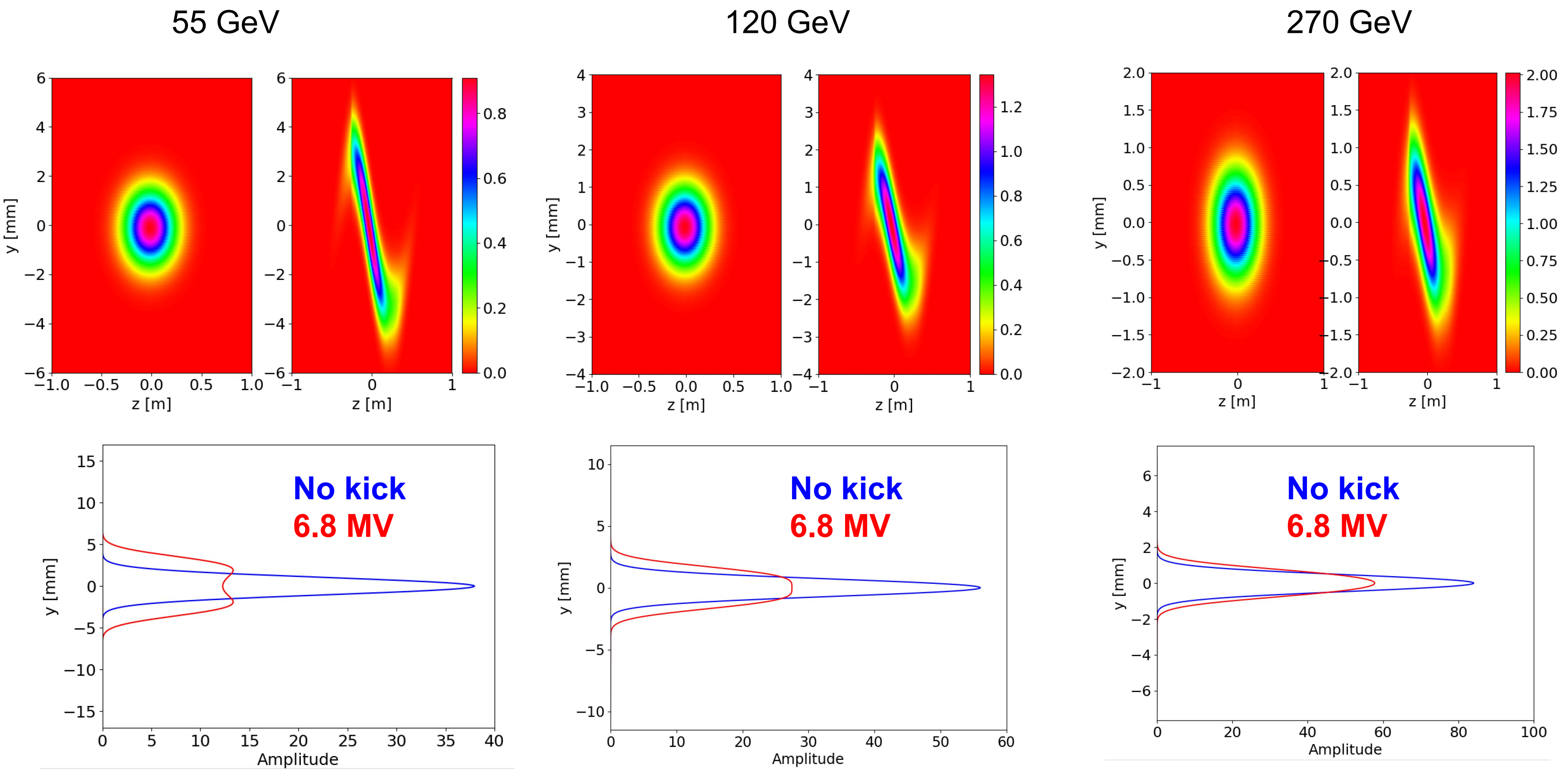
Impact of the CC phase on the bunch profile at the WS location



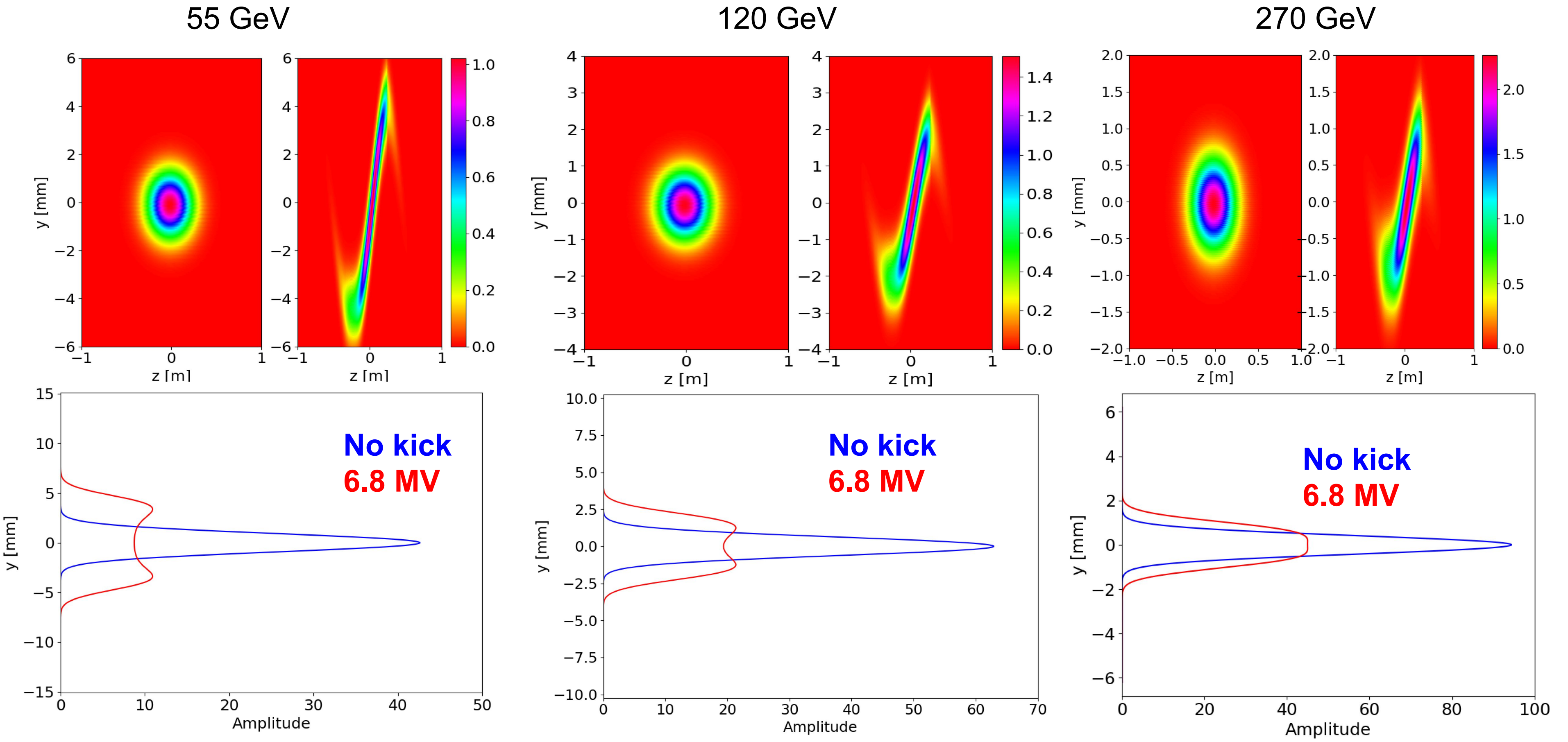


A. Alekou

WS, 6.8MV



HT, 6.8MV



55 GeV
120 GeV
270 GeV
y [mm]
z [m]
Amplitude
No kick
6.8 MV
No kick
6.8 MV
No kick
6.8 MV

Current Conclusions

- Clear dependence of the emittance growth on the chromaticity
- Off-bucket losses correlated with the RF feedback
  - The effect was eliminated switching the RF feedback off
- IBS plays a role in the horizontal and long. planes
- Extra H emittance growth (on top of IBS) is very similar to the vertical emittance growth observed
- Vertical emittance growth does not seem to be correlated with the bunch intensity (to be verified in the next MDs)
- Vertical and longitudinal emittance growth similar between Q20 and Q26 optics
  - We will continue with Q26 which is well set up for the coast beams

Next studies in dedicated and parallel MDs

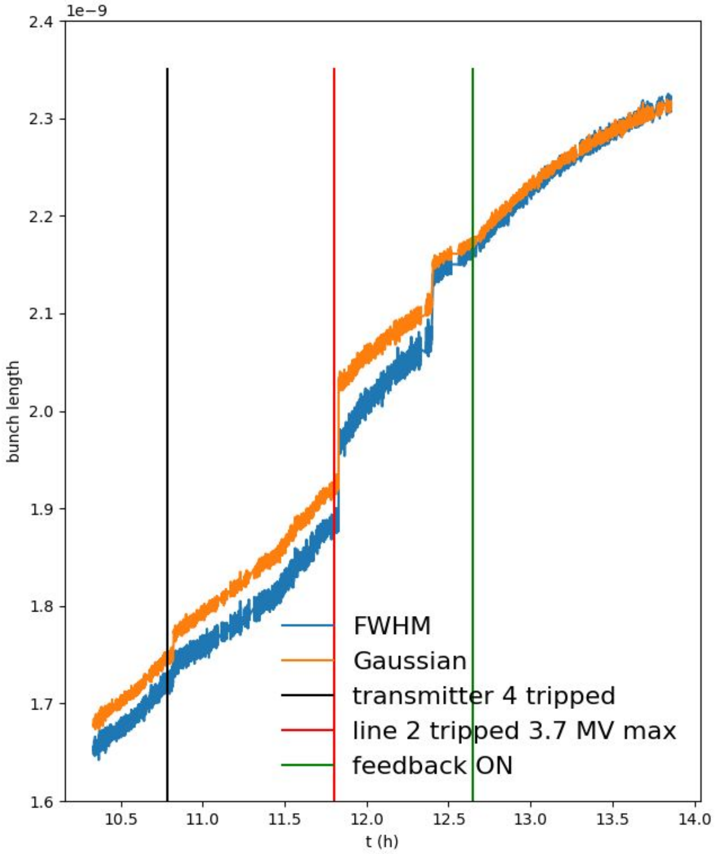
- Systematic chromaticity scan in order to define optimal chroma settings in both planes
    - We will try to inject 4 bunches, well spread in the machine, with different intensities
- Linear WS multi-scan to verify dependence on the number of scans
- Vacuum degradation and emittance evolution correlation
    - During the last dedicated MD of the year
- In parallel MDs we would like also to study in the next weeks:
    - Orbit correction around the CC location
    - Identify the optimal kickers and the sensitivity of the BPMs around the crab lo
      a varying closed orbit in the cavity region to identify the electrical center.

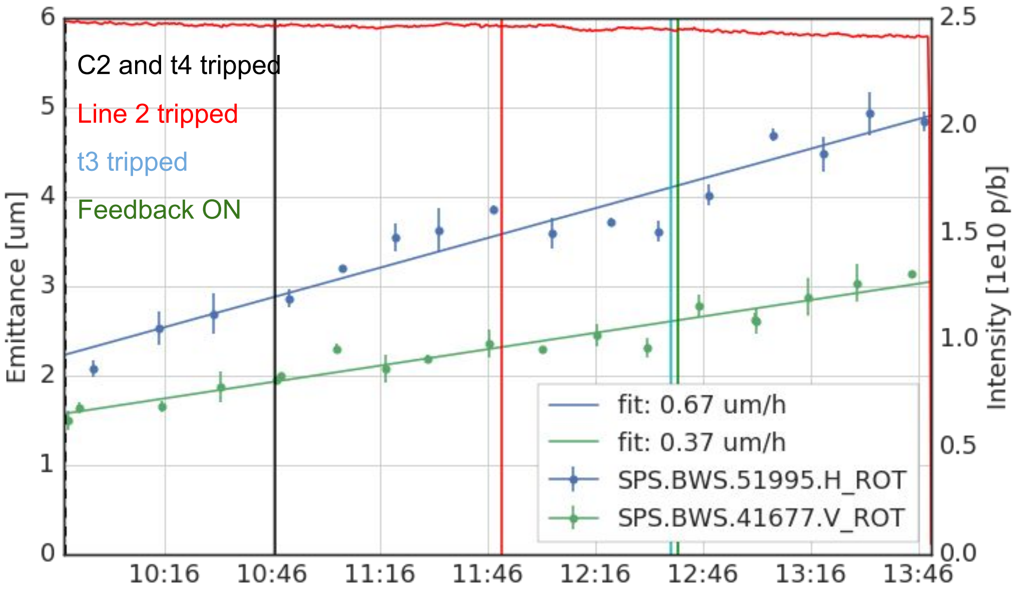
Thank you for your attention!

CC SPS Test Program Day, Jan. 2016
Open issues and action items

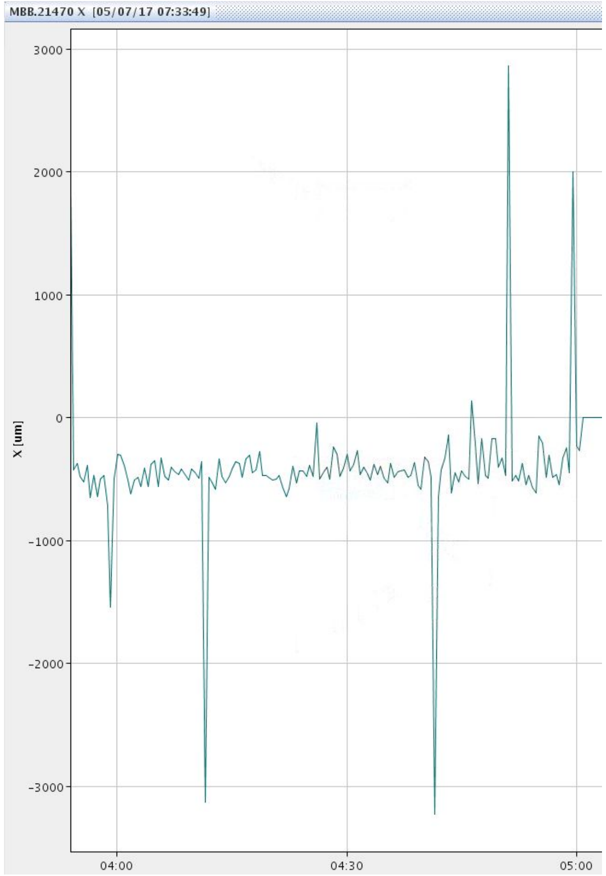
1. The crab cavity ECR including any major modifications required for the layout near the nominal location in LSS6 should be drafted by the March 2016. The responsibility of collecting the needs from all equipment and services groups is within WP4.
2. Some immediate simulations and specifications to be decided within 2-3 months to understand the need of additional instrumentation. The responsibility of which can be undertaken by WP2 with joint support from WP4, WP13 and others as necessary.
3. The request to carry out the LSS6 improvement of the MOPOS should be recommended before 2018.
4. The local orbit and optics insertion favourable for the CC's should be checked in early 2016 MDs. The use of the extraction bumpers and the full extent of the orbit manipulation near the CC region should be validated.
5. HT monitor resolution MD.
6. A follow up meeting in a few months to revisit the various aspects to further converge on experimental program and beam parameters is needed. In this meeting, the minimum subset for the input to the HL-LHC production modules should be defined.

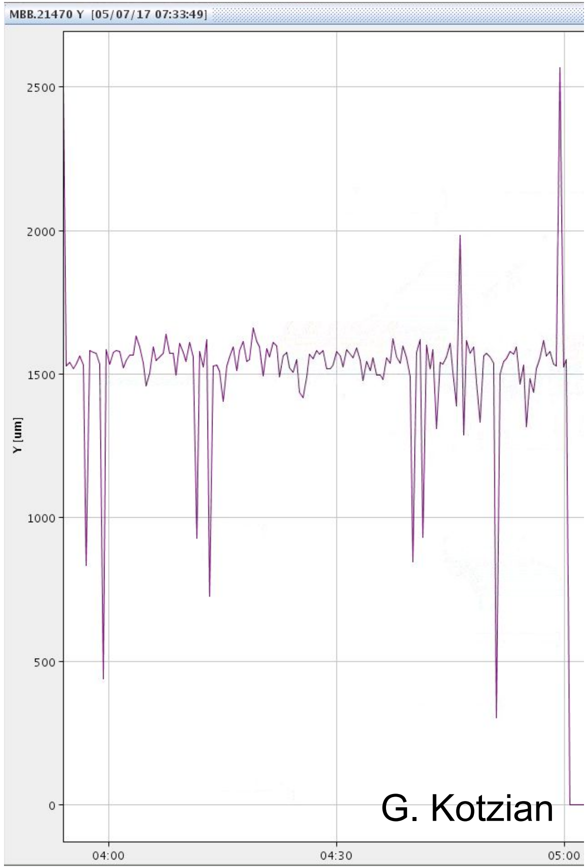
Longitudinal profiles analysis by Joel





Transverse Damper





- G. Kotzian has set up the scripts for logging the damper data during coast
- MDs with and w/o transverse damper foreseen for next MDs