Transient beam loading in crab cavities

Experience from SPS & predictions for HL-LHC

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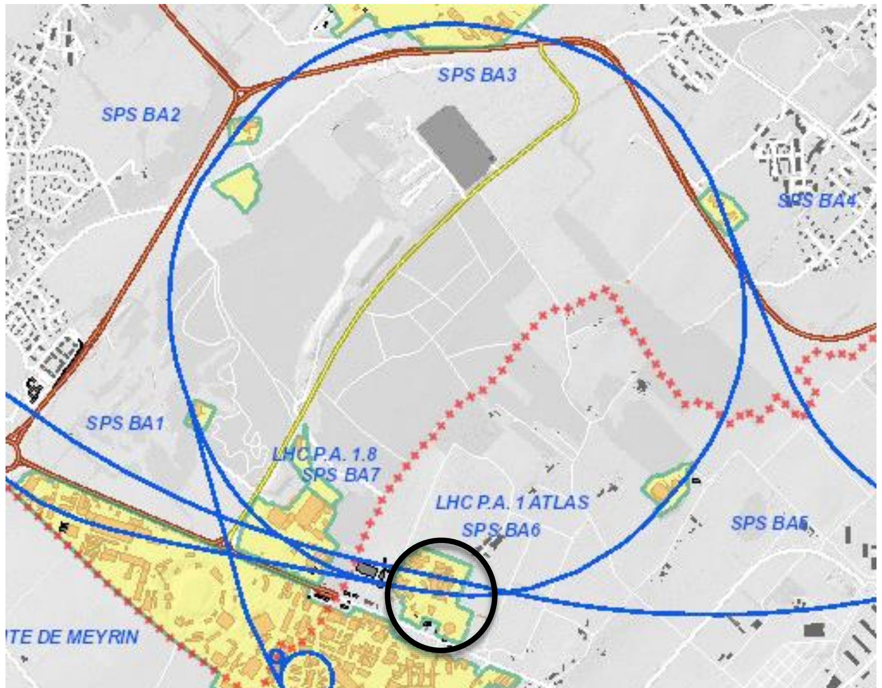
Content

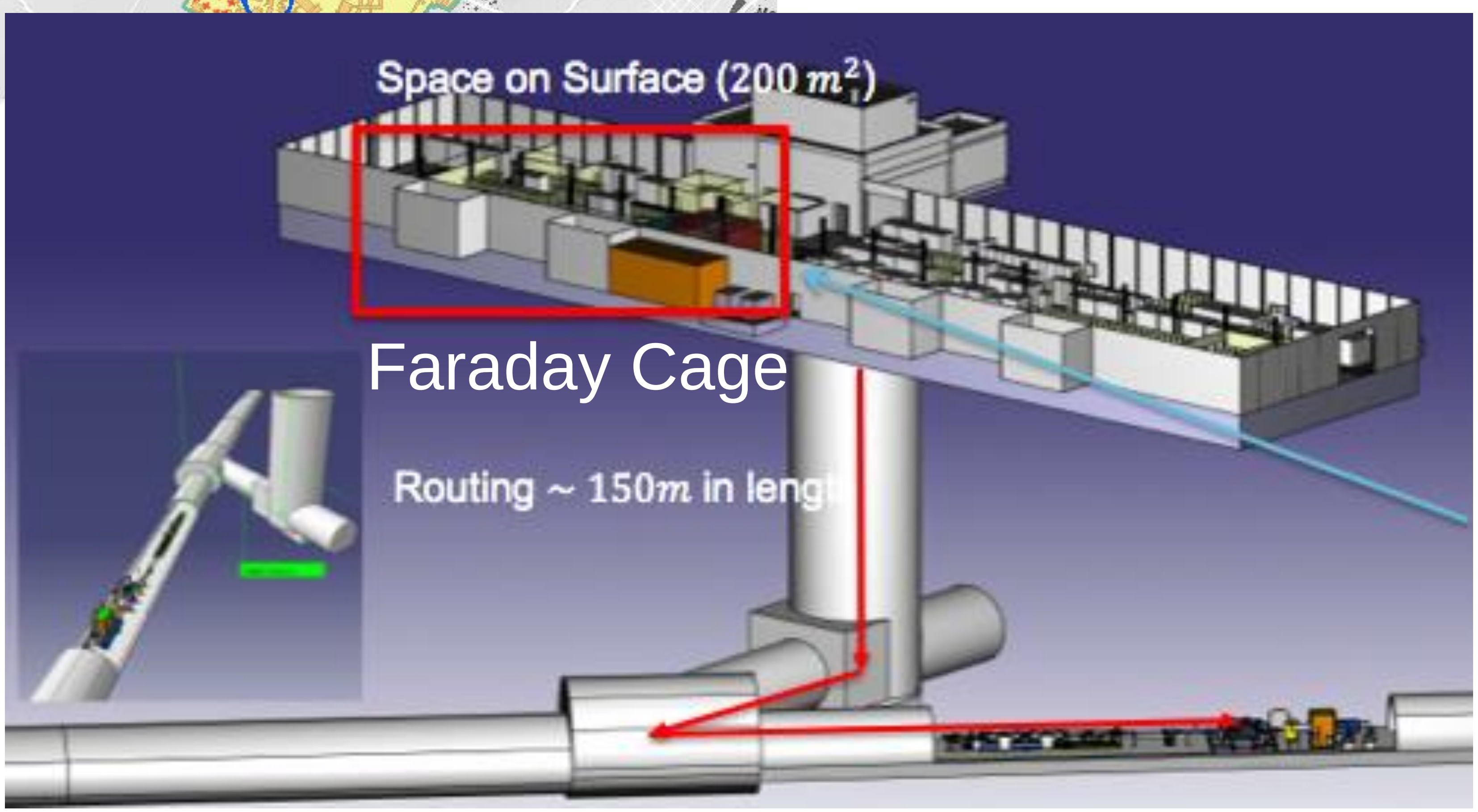
- Beam loading measured in the SPS-CCs
- HL-LHC beam loading calculations
- Microphonics measured in the SPS-CCs
- Ponderomotive instabilities observed in the SPS-CCs
- Conclusions

SPS-CCs



- Crab cavities are in the SPS tunnel underneath the faraday cage
- LLRF controls are located in Faraday Cage at BA6.

(Details are in Philippe's talk)



LLRF SPS-CCs

Beam loading measured in the SPS-CCs

$$J_g(t) = \frac{A_\perp(t)}{2(R/Q)}\left(\frac{1}{Q_{ext}} + \frac{1}{Q_0} - 2i\frac{\Delta\omega}{\omega}\right) + \frac{dA_\perp(t)}{dt}\frac{1}{\omega(R/Q)} + \frac{x(t)\omega}{c} I_{b,dc} F_b e^{-i\phi_{ext}(t)} \quad \text{(Eq.1)}$$

- Induced cavity amplitude after the M-th turns without compensation of beam loading:

$$A_\perp(nT_b) = -I_{b,dc}F_b\frac{\omega^2}{c}\left(\frac{R}{Q}\right)\tau\left[1 - e^{-\frac{T_b}{\tau}}\right]\frac{1 - e^{-\frac{MN_bT_b}{\tau}}}{1 - e^{-\frac{N_bT_b}{\tau}}}\sum_{k=0}^{N_b-1} e^{-\frac{kT_b}{\tau}} \cdot x((n-k)T_b).$$

- DC beam current is bunch intensity <u>averaged over one 25ns period</u>. (LLRF cannot regulate microstructure beam loading that is harmonics of 40 MHz.)

$$I_{b,dc} = \begin{cases} 0 & \textbf{no beam} \\ \frac{n_p q}{T_b} & \textbf{beam.} \end{cases}$$

- Power (P_g) required to compensate full beam loading (A(t)=0 in Eq.1)

$$J_g(nT_b) = \frac{x(nT_b)\omega}{c} I_{b,dc}F_b$$

$$P_g(nT_b) = \frac{1}{2}\left(\frac{R}{Q}\right)Q_e|J_0 + J_g(nT_b)|^2$$

$$J_0 = \frac{V_0}{2(R/Q)Q_L}$$

Bunch Spacing T_b	25 ns
available bunch number N_b	924
Bunch intensity N_p	1.0×10^{11}
RF frequency @ 26GeV f_{RF}	400.5288 MHz
Bunch length (4σ)	3.0 ns
Bunching factor F_b (@26GeV)	0.17
$I_{b,DC}$	0.64 A
R/Q (circuit-ohm)	210
Q_L	500,000
Time constant τ	397 us

Table 1: SPS-CCs parameters

* J. Tuckmantel, Cavity-Beam-Transmitter Interaction Formula Collection with Derivation, CERN-ATS-Note-2011-002, 2011

Beam loading measured in the SPS-CCs

- 10th October MD

  - 12bx1, 12bx2, 12bx3, 12bx4, 24bx2, 24bx3, 24bx4, 36bx1, 36bx4, 48bx1, 48bx2

  - Beam trajectory is offset from the closed orbit in SPS-CCs locally : ±10 mm (measured by BPM)

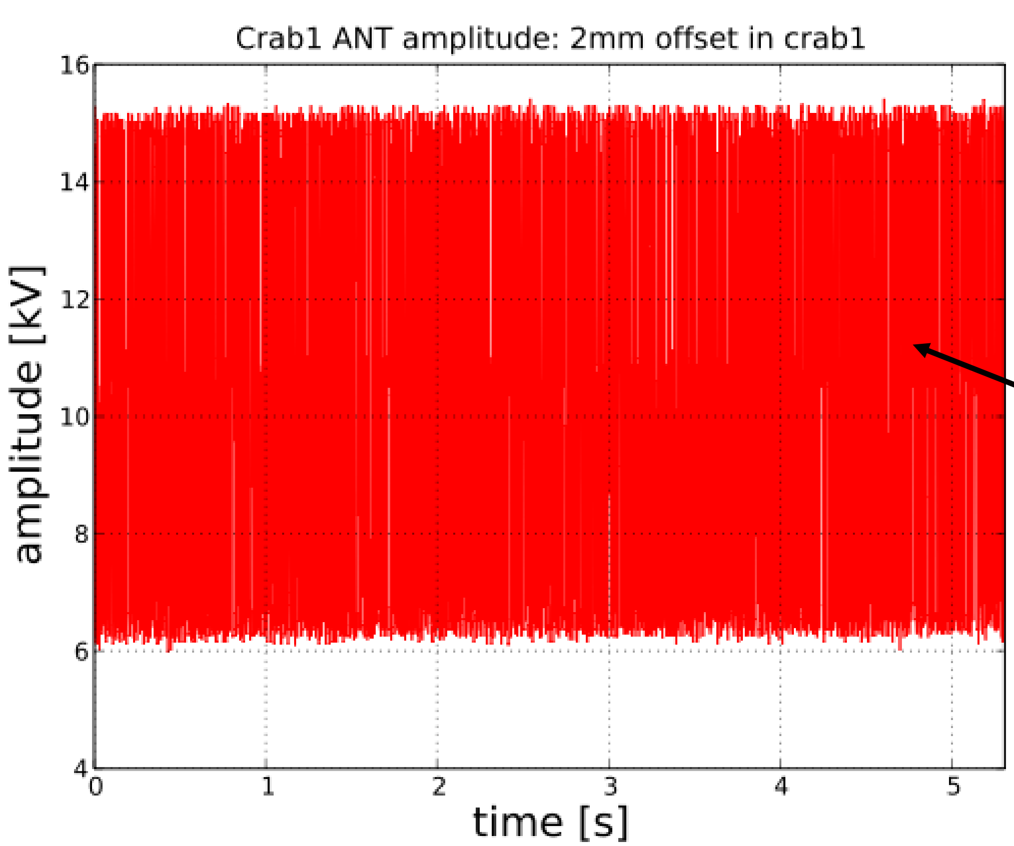
- Setup measurements

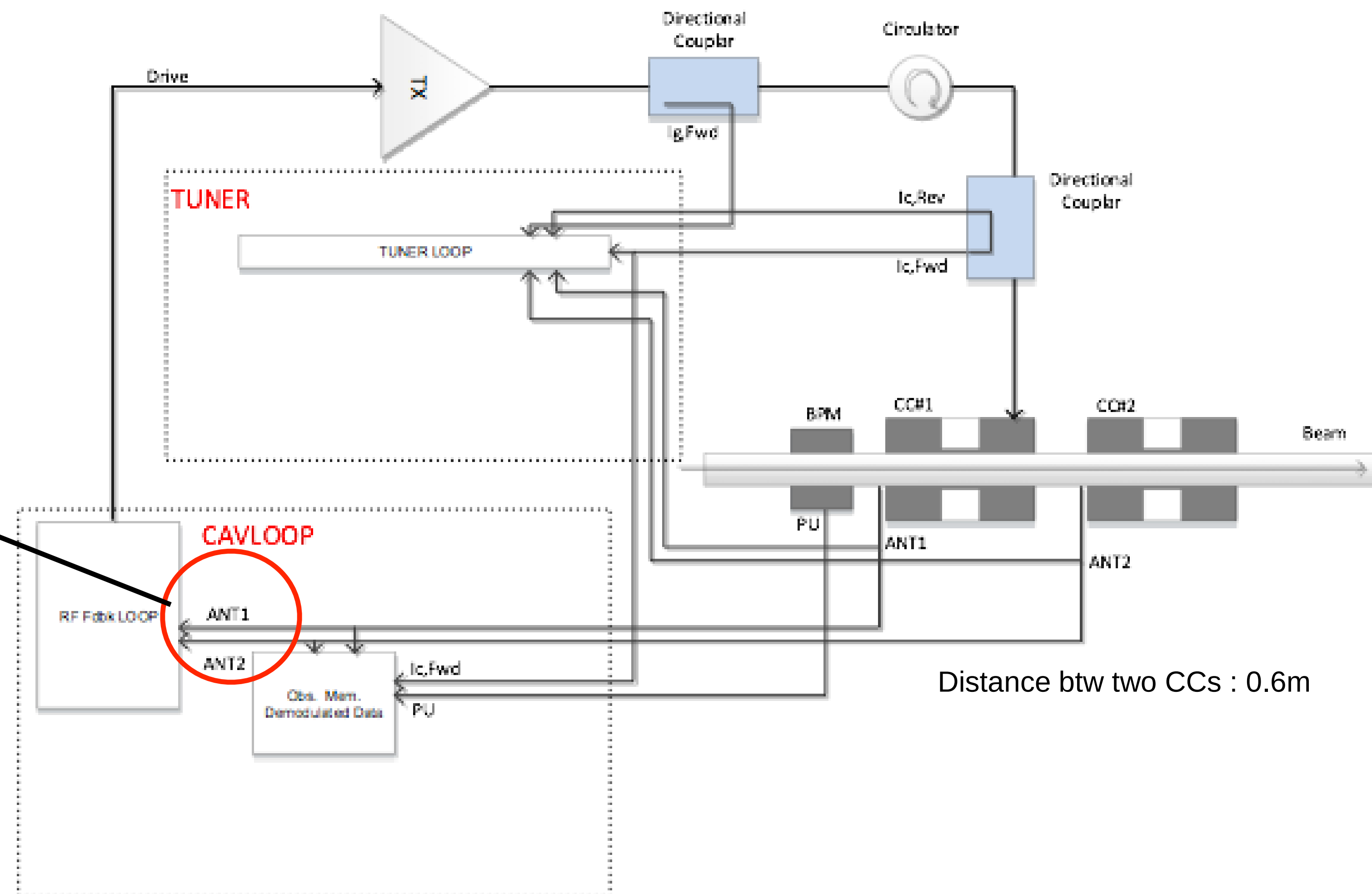
  Both cavies are turned off -> cavity field is Zero

  Reading ANT signal to measure beam induced voltage in the CCs

  ANT amplitude (averaged over 5 seconds) is plotted with respect to the offsets. -> Calibration and attenuation due to the cavity not being tuned perfectly, corrected.

  97.6 kHz sampling and 5.3 s time window.

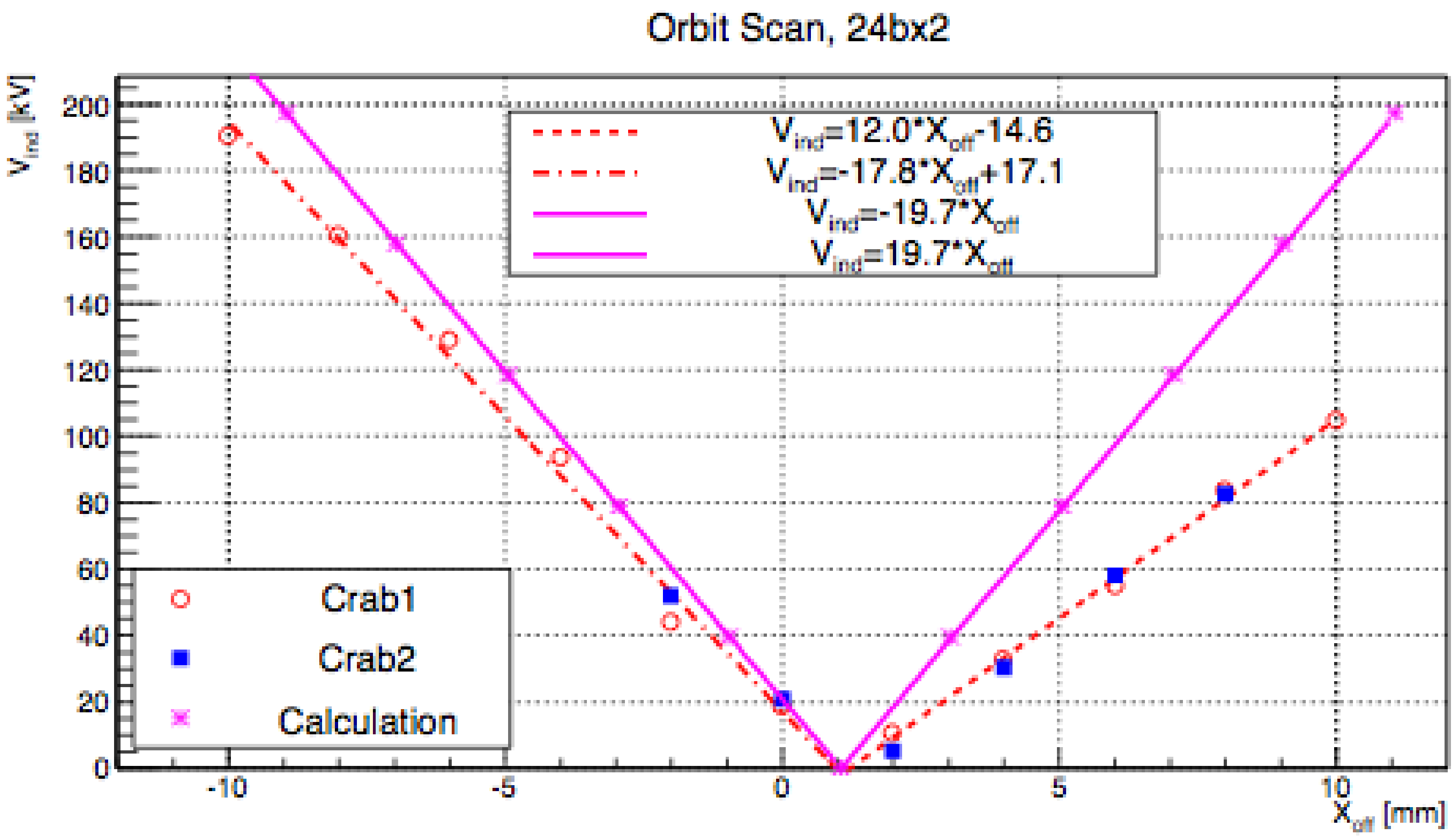




Distance btw two CCs : 0.6m

Beam loading measured in the SPS-CCs

- Calculations
  - Bunch filling scheme - initial bucket for each batch is fixed at 1/81/161/241.
  - Calculated induced voltage is averaged over one turn.

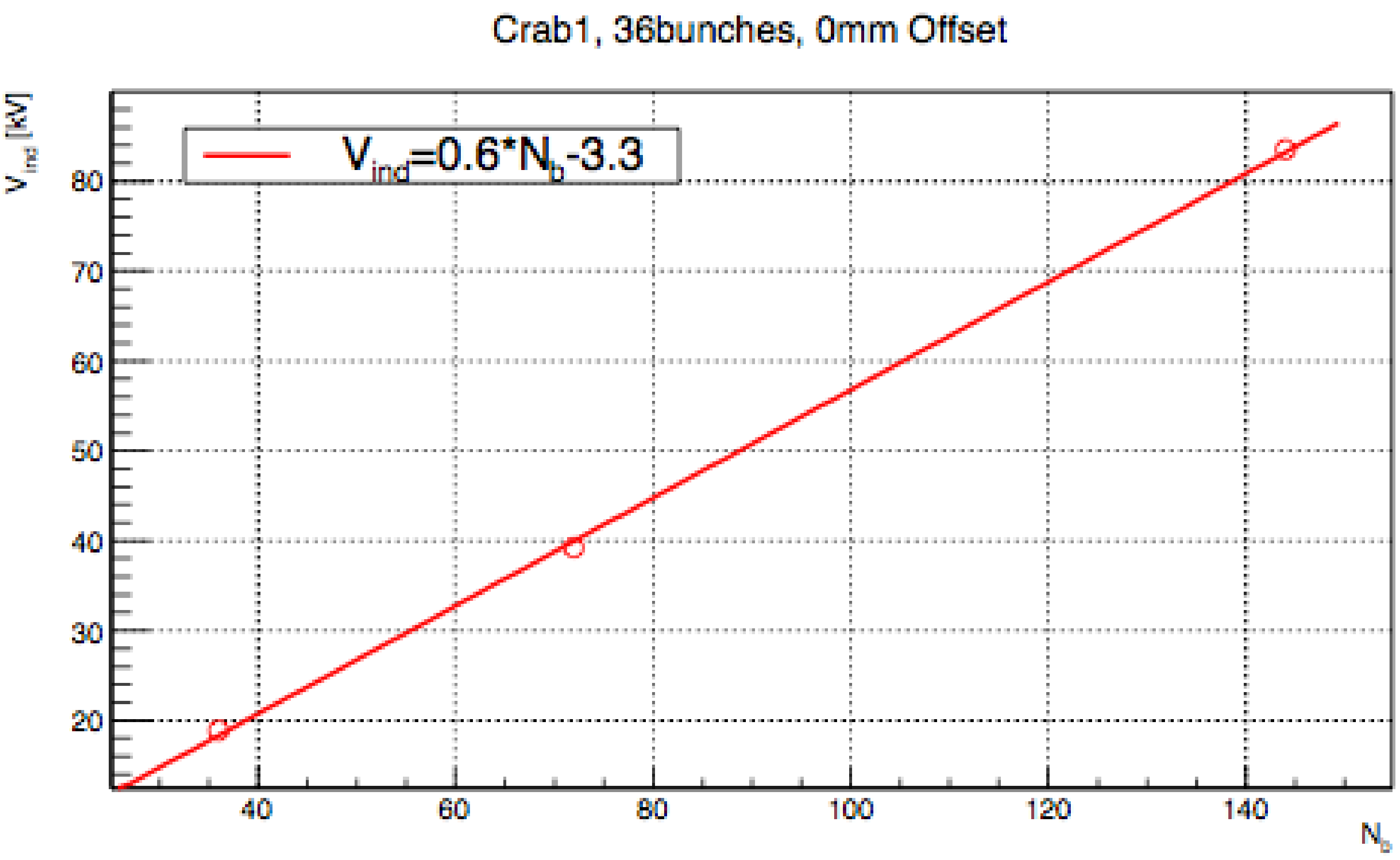


- Electric centre of cavities are +1.06 mm for both cavities.
- Calculation plot is shifted to the estimated electrical centre (in the figure).
- There is an asymmetry in measured data between negative and positive offsets (why?).

Beam loading measured in the SPS-CCs

- 36bx1, 36bx2, 36bx4 at 0 mm, intensity scan

Induced voltage is linearly increasing with beam intensity.



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  - Long-range beam-beam effect
  - Injection oscillation
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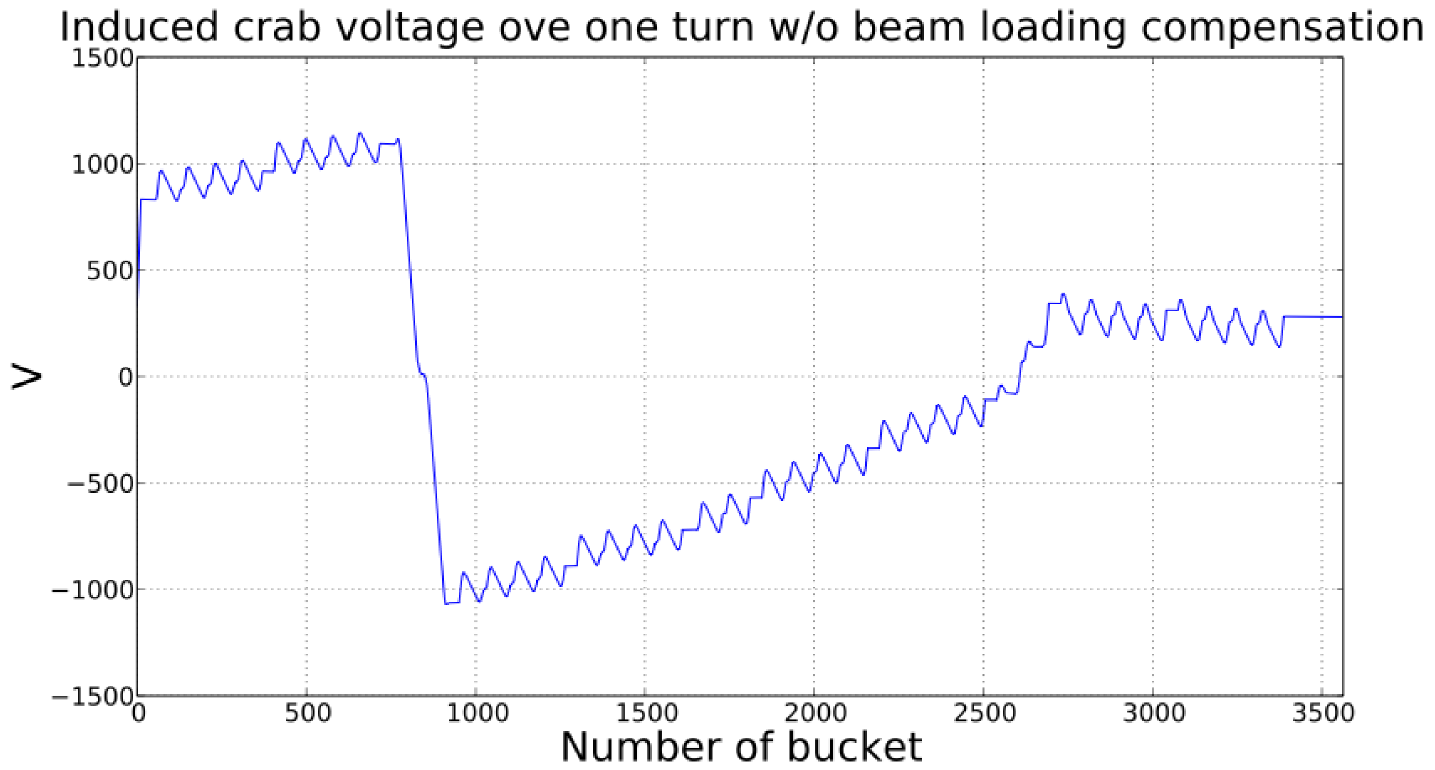
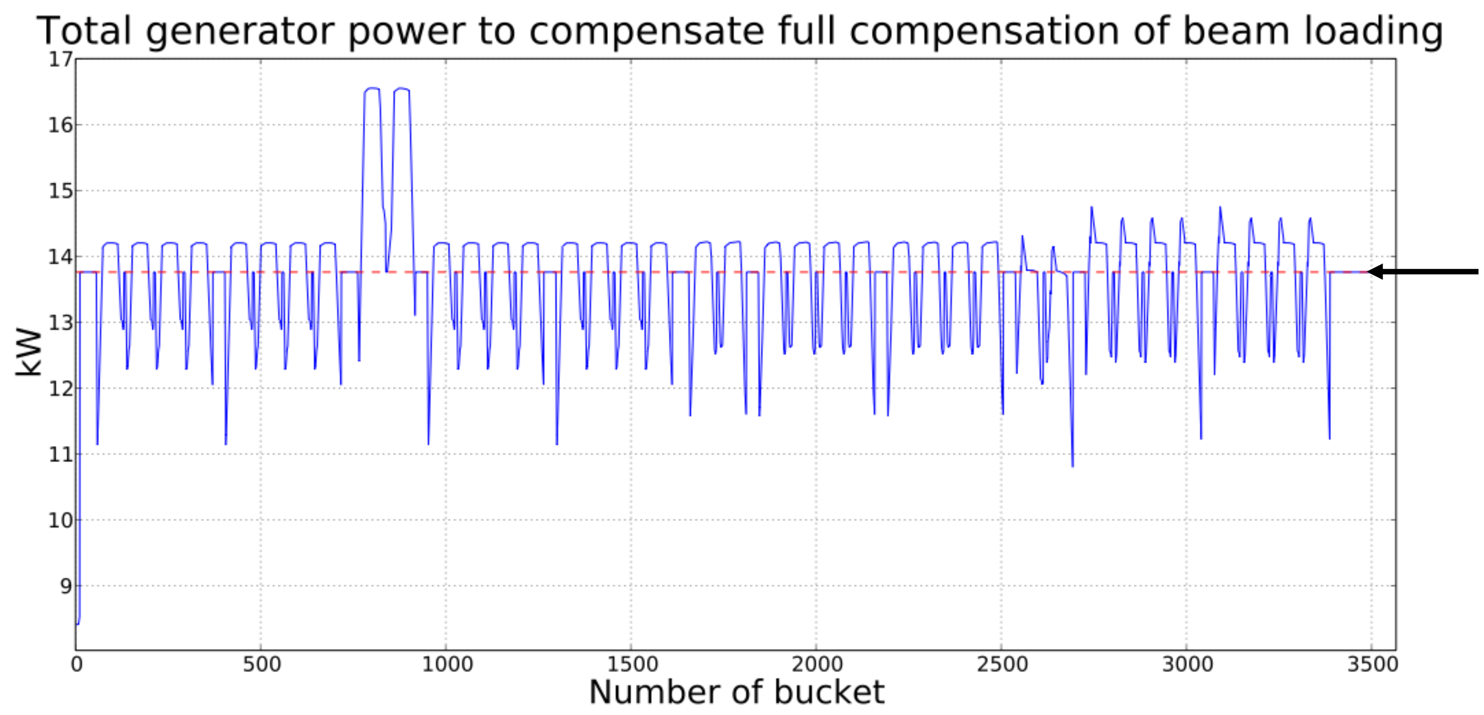
HL-LHC beam loading calculations due to the Long-Range Beam-Beam



Bunch Spacing T_b	25 ns
available bunch number N_b	3564
Bunch intensity N_p	2.3×10^{11}
RF frequency f_{RF}	400.789 MHz
Bunch length (4σ)	1.2 ns
Bunching factor F_b (@7TeV)	0.75
$I_{b,DC}$	1.47 A
CC voltage V_{cc}	3.4 MV
R/Q (circuit-ohm)	210
Q_L	500,000
Time constant τ	397 us

Table 2: HL-LHC parameters

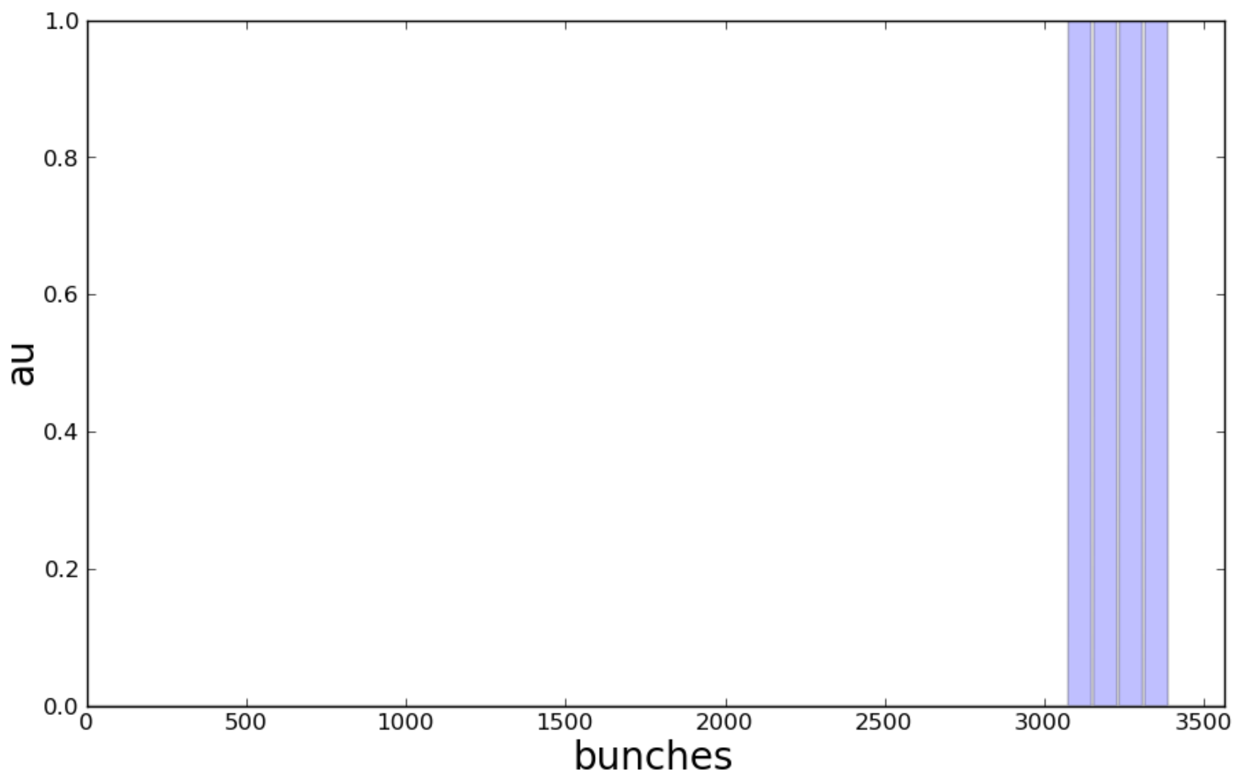


Driving term (P_0) = 13.8 kW (V_{cc}=3.4MV)

- Generator power required to compensate full beam loading due to LRBB is small.

HL-LHC beam loading calculations due to the injection oscillation

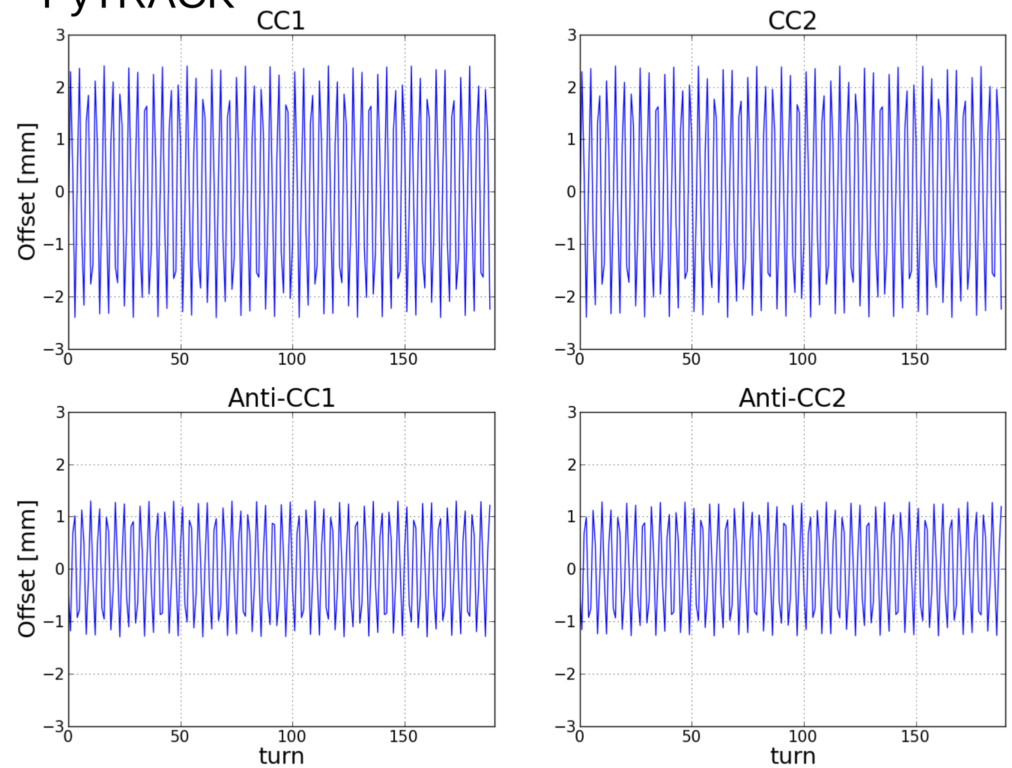
- Injection mismatch causes injection beam oscillations along the ring -> Orbit offset in the CC.
- Apply simulation to calculate transverse offsets and induced voltage in the CCs using PyTRACK



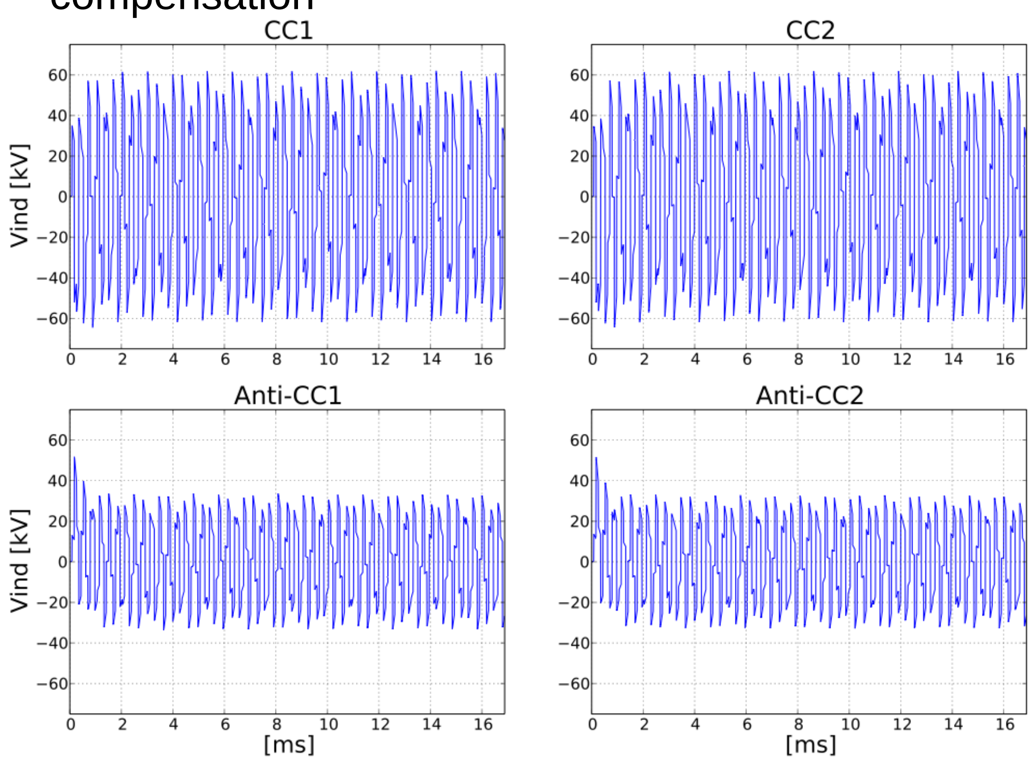
- Single particle tracking
  - Injection offset at IP1 is at 0.35mm in horizontal
- Injection optics (HLLHCV1.3)
  - φ_{adv} (between CC and CC_{ant}): 220deg
- 4 CCs: 2 x crabbing, 2 x anti-crabbing (IP5)
- Nominal CC voltage: 0 V
- Induced voltage is computed every time the particle enters the CCs
  - Assuming all the bunches follow the same orbit
- Filling: one batch only (the other batches assumed to be circulating on the closed orbit)

HL-LHC beam loading calculations due to the injection oscillation

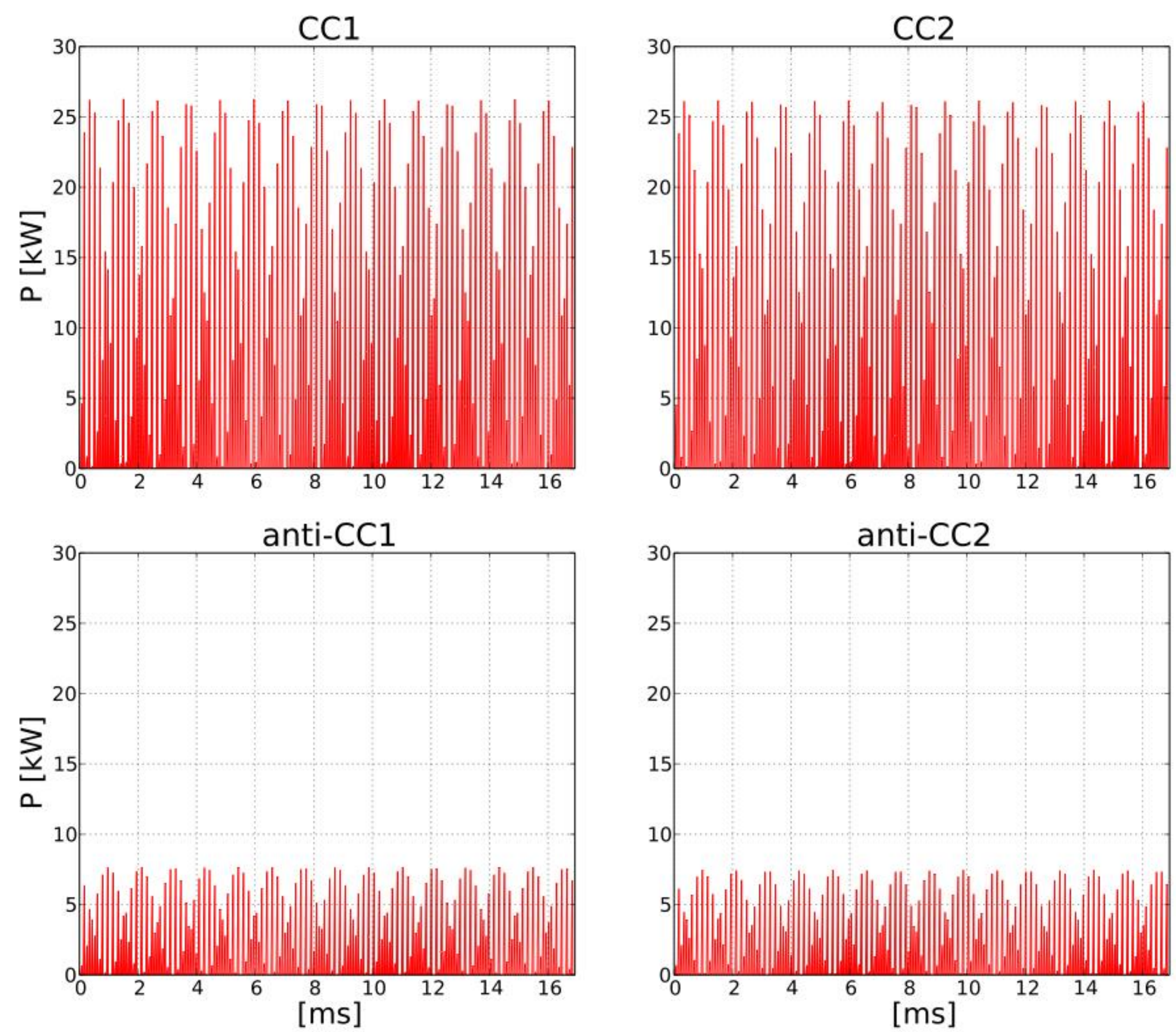
Particle offset in CCs over 190 turns computed by PyTRACK



Induced crab voltage over 190 turns w/o beam loading compensation



Generator power required to compensate full beam loading over 190 turns.



- Demanded power to compensate full beam loading is 26 kW maximum.

But, injection offsets will be damped by ADT

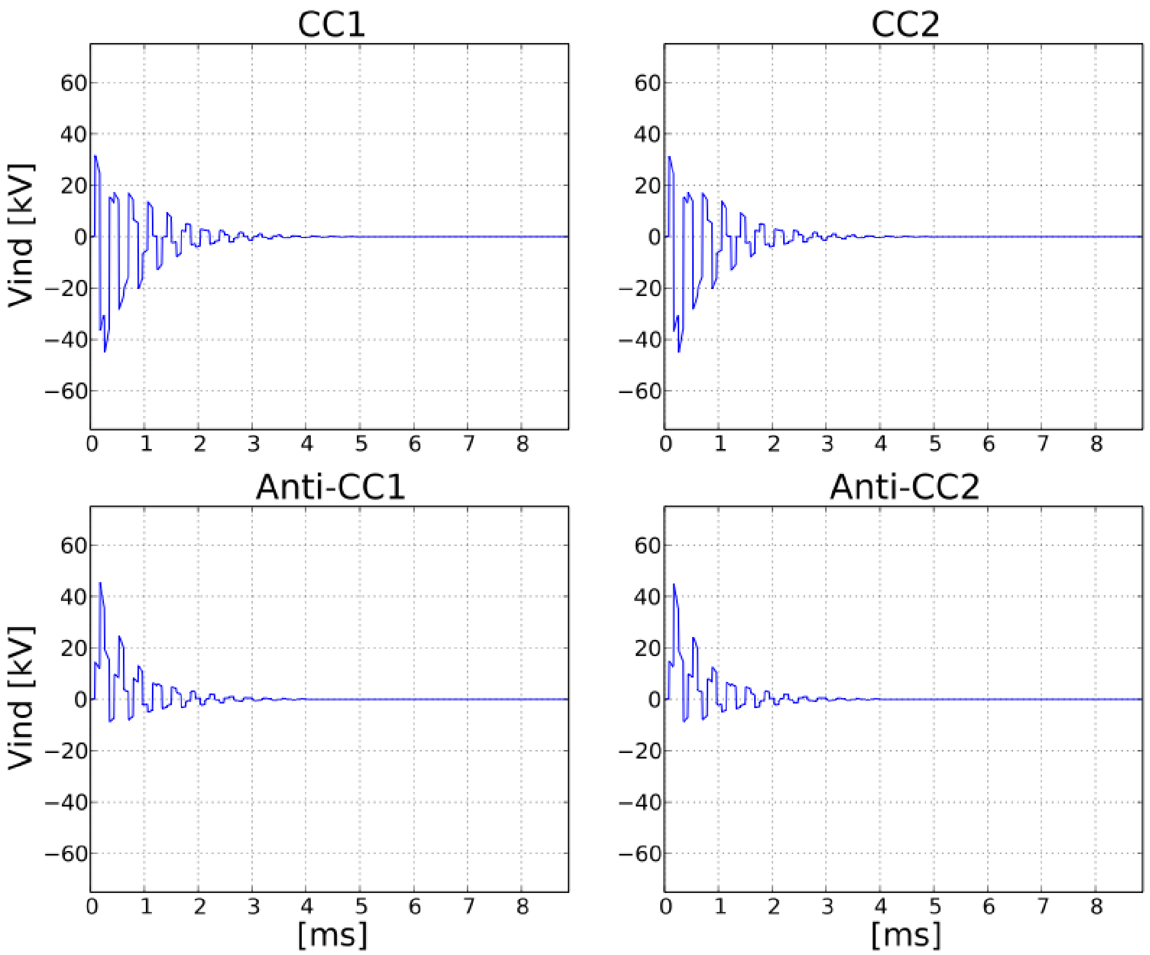
- Horizontal transverse damper is applied in the calculation.
- Momentum kick ($\Delta x'$) at ADT is computed using BPM (x_{BPM}) at quad. magnet (Q7).

$$\Delta x' = -g \cdot \frac{x_{BPM}}{m_{12}} \qquad g = \frac{2T_{rev}}{T_d}$$

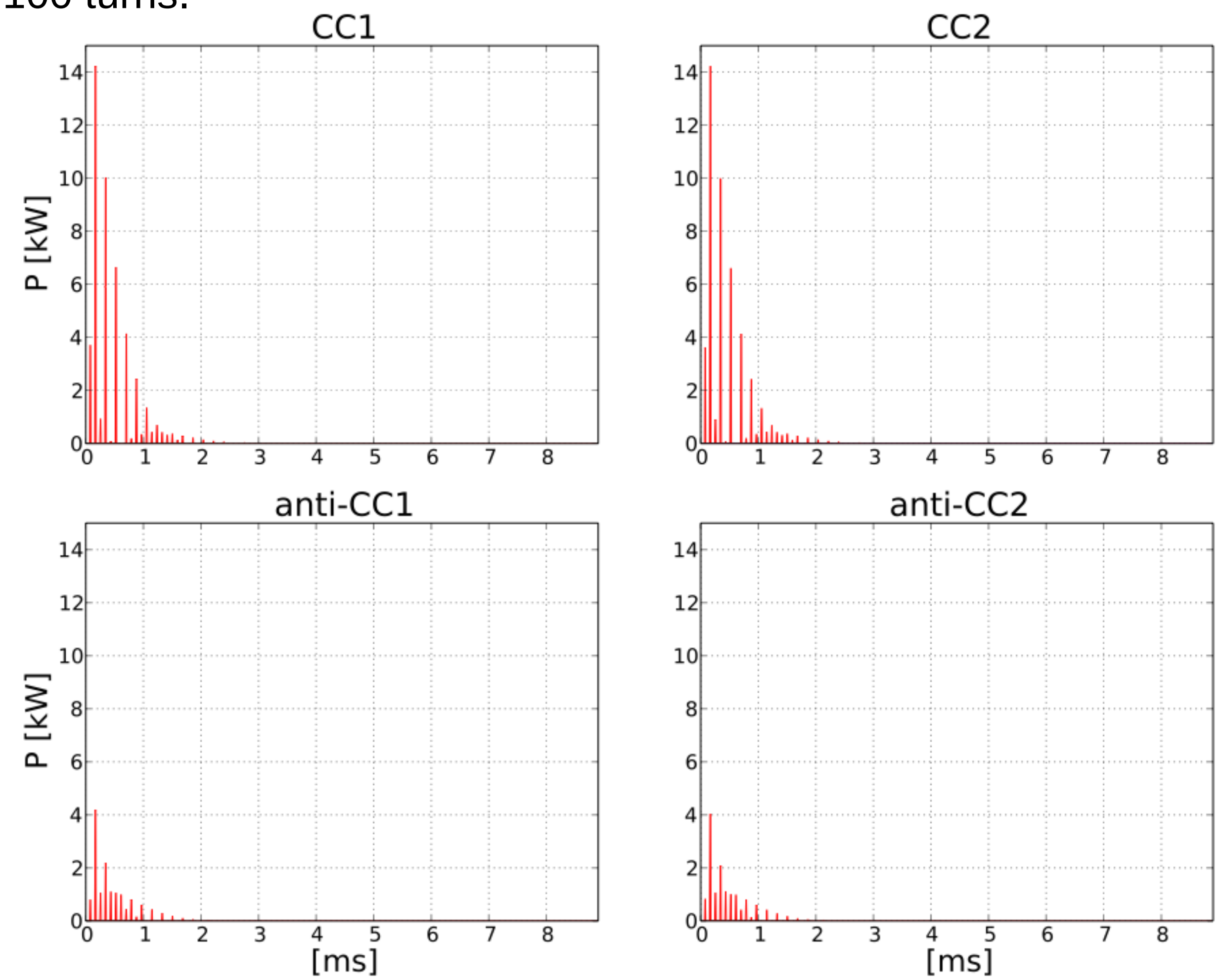
m_{12}: inverse transfer matrix from BPM to ADT

T_d:10xT_{rev}

Induced crab voltage over 100 turns w/o beam loading compensation



Generator power required to compensate full beam loading over 100 turns.



- Required generator power is acceptable (14kW) when using transverse damping system.

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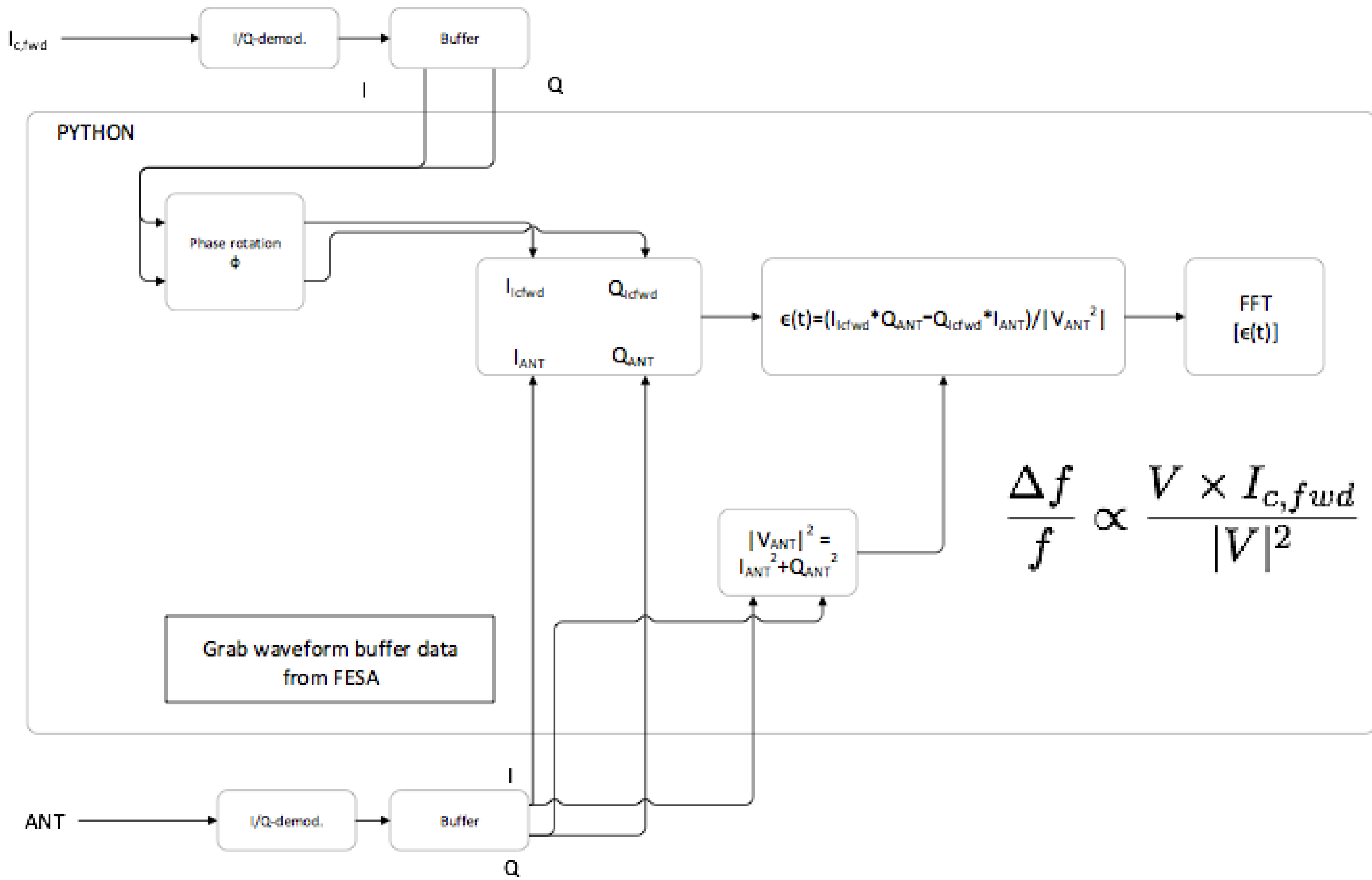
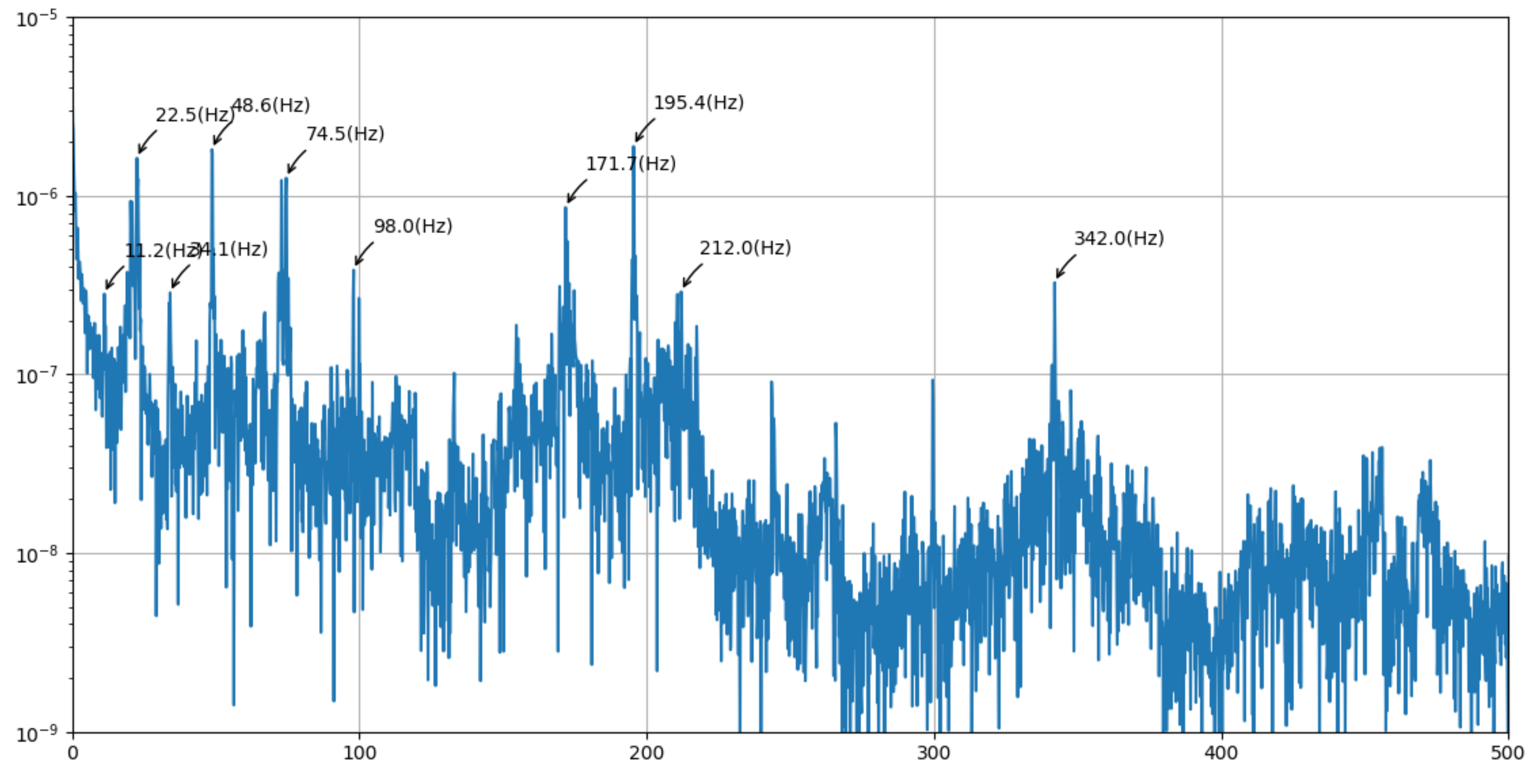
Microphonics measurement in SPS CCs



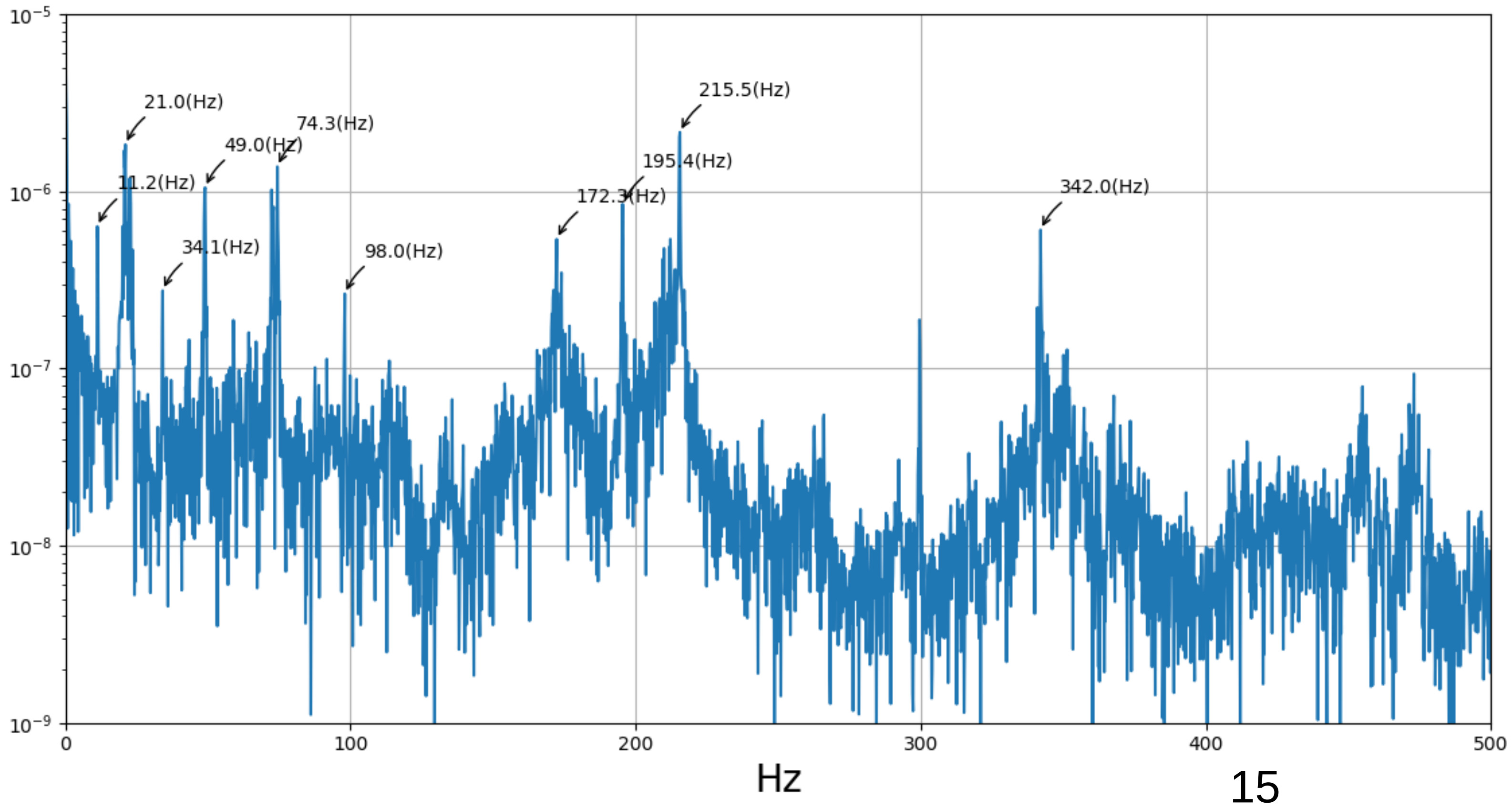
- RF FDBK is OFF: michrophonics modes measured in the ANT
- RF FDBK is ON: michrophonics modes measured in the $I_{c,Fwd}$
- Sampling frequency: 97.7 kHz
- Recording time window: 5.3 s

Microphonics in Crab1

RF-FDBK is OFF (Vcrab1:1.1 MV)

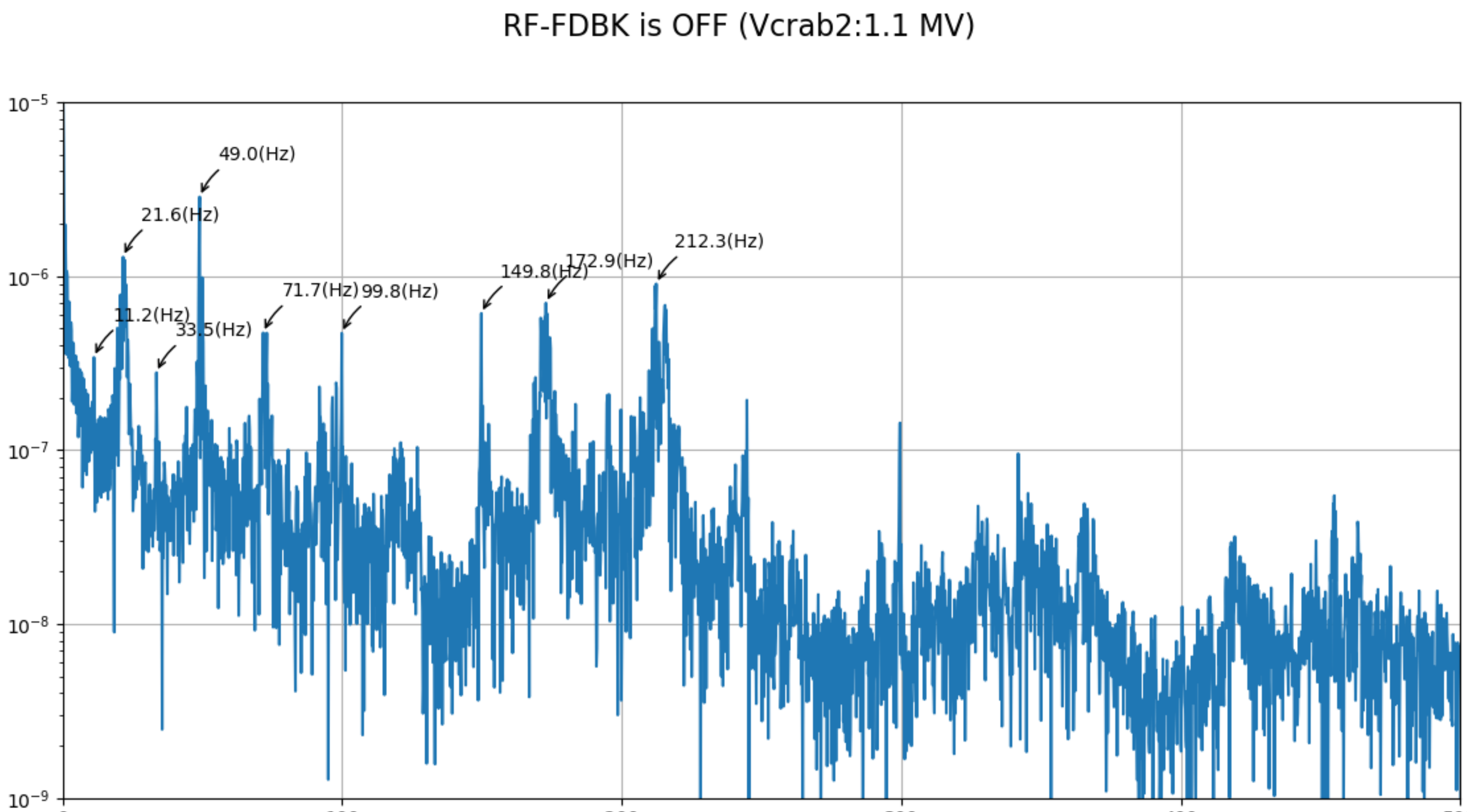


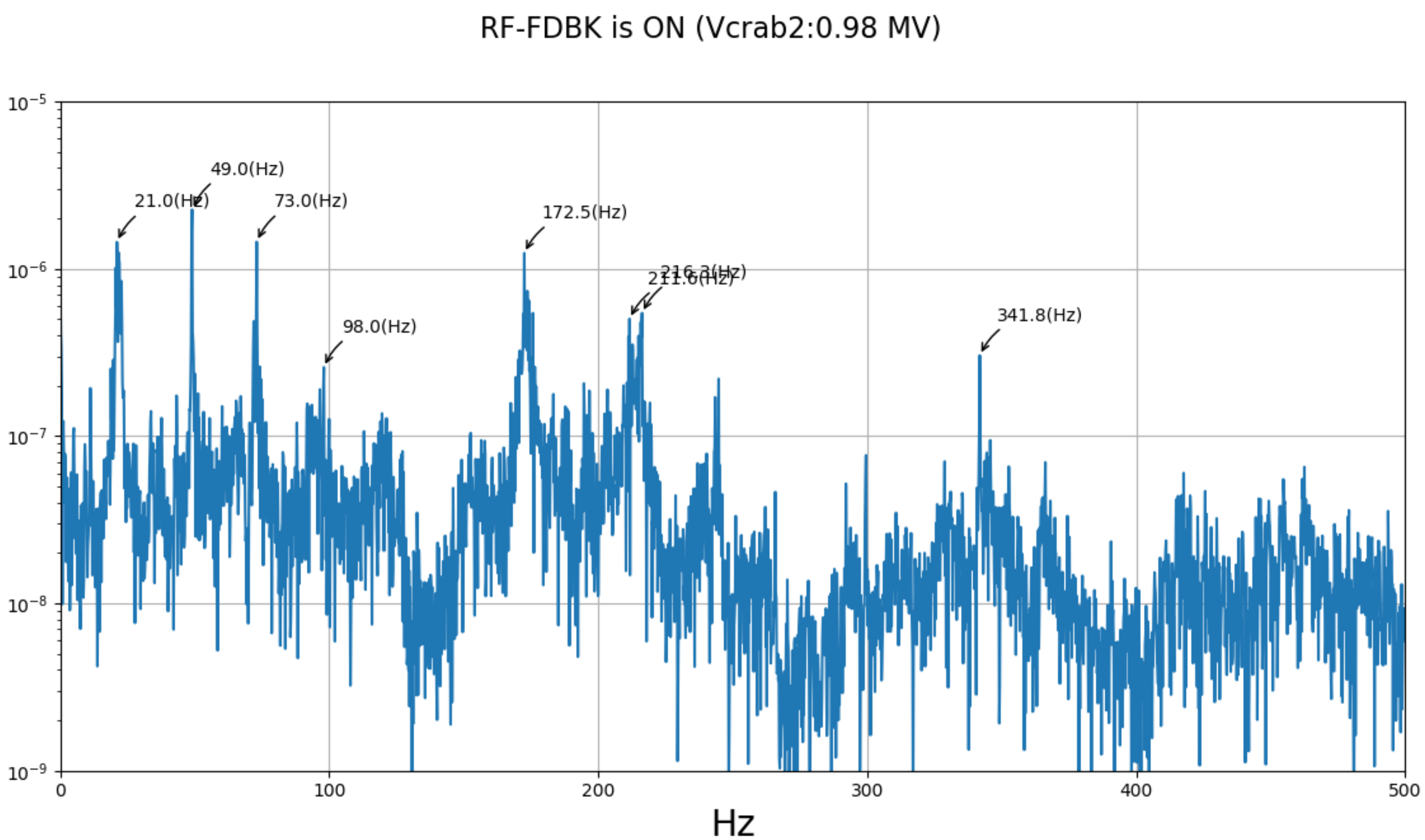
RF-FDBK is ON (Vcrab1:1.1 MV)



- 20-30 Hz: Cryo-pump
- 49 Hz: TX high voltage ripples (50Hz)+ Tuner mode (Mechanical 47.7Hz)
- 74 Hz: Mechanical mode (78.5)
- 98 Hz: Harmonics of TX high voltage ripples
- 171 Hz: Not identified
- 195 Hz: could be harmonics of TX high voltage ripples
- 210 Hz: Mechanical mode (209Hz)
- 342 Hz: Not identified (could be TX high voltage ripples)

Microphonics in Crab2





- 20-30 Hz: Cryo-pump
- 49 Hz: TX high voltage ripples (50Hz) + Tuner mode (Mechanical 47.7Hz)
- 73 Hz: Mechanical mode (78.5)
- 98 Hz: Harmonics of TX high voltage ripples
- 172 Hz: Not identified
- 212 Hz: Mechanical mode (209Hz)
- 342 Hz: Not identified (could be harmonics of TX high voltage ripples)

Ponderomotive instabilities measured in SPS-CCs

- The oscillation is not seen in the ANT when the cavity field is below 1 MV. (Fig.1, FDBK is OFF).
- When the cavity voltage is above 1 MV, we observe huge oscillations (210 Hz) in the ANT. (Fig.2, FDBK is OFF).

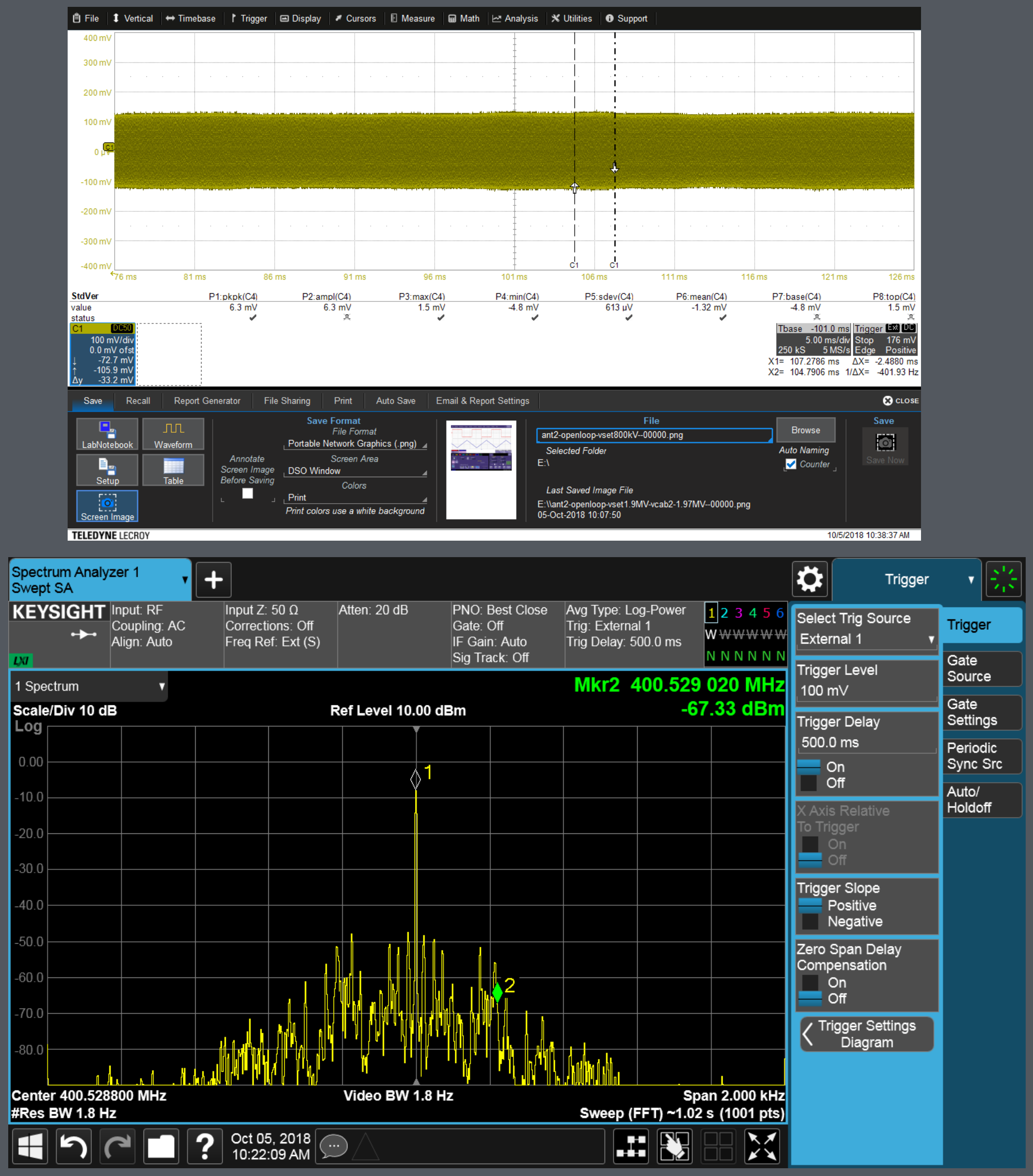


Fig1. ANT (800kV)

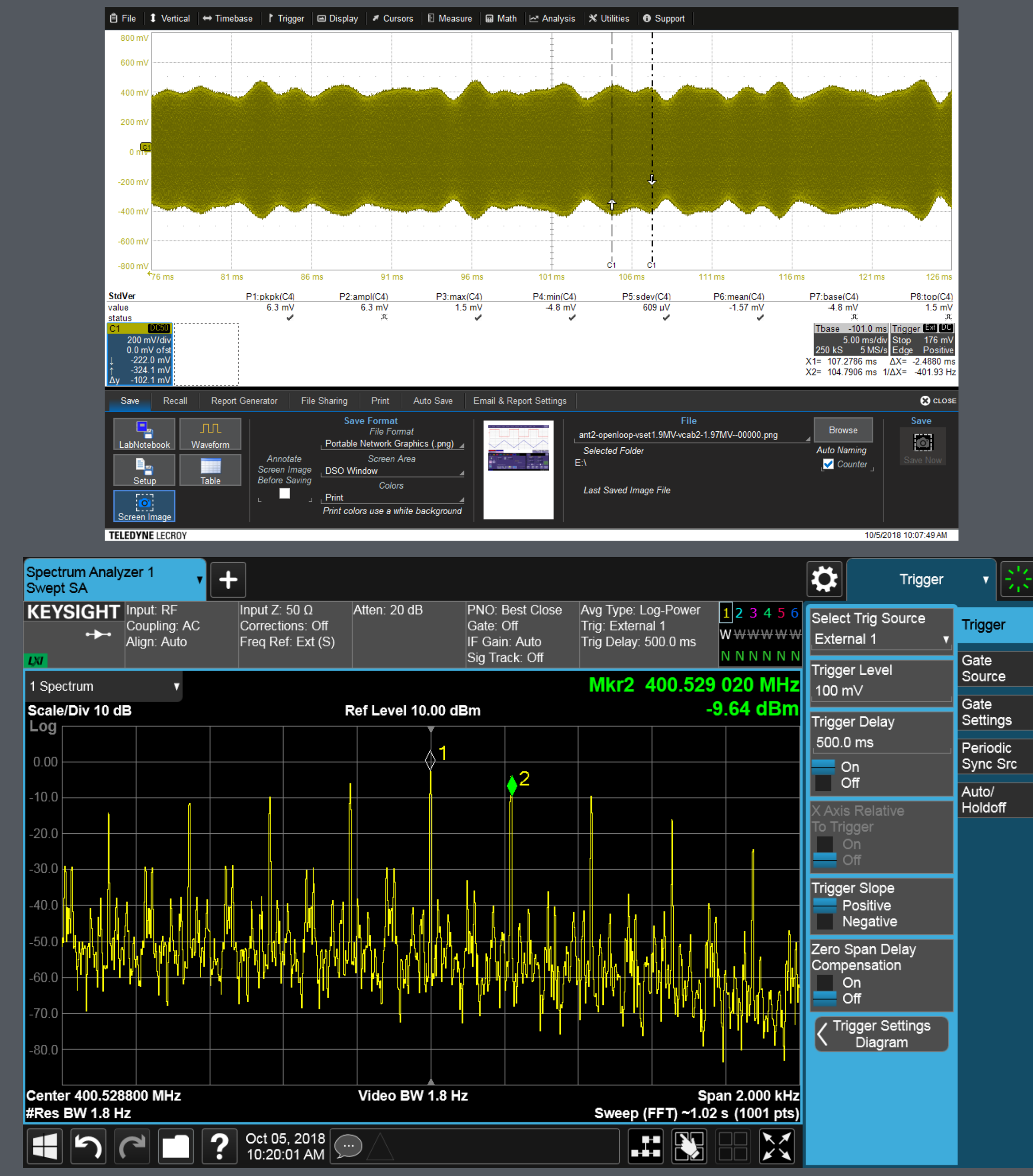


Fig2. ANT (1.9MV)

Ponderomotive instabilities measured in SPS-CCs

- The same (ponderomotive) oscillation has been observed in the HIE-Isolde QWR cavities and LEP* (around 100Hz) at CERN.

Proceedings of the 12th International Workshop on RF Superconductivity, Cornell University, Ithaca, New York, USA

PONDEROMOTIVE INSTABILITIES AND MICROPHONICS – A TUTORIAL*

J. R. Delayen#, Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA

ELECTROACOUSTIC OSCILLATIONS IN THE LEP SC. CAVITIES

D. Boussard, P.Brown, J. Tückmantel, CERN, Geneva, Switzerland

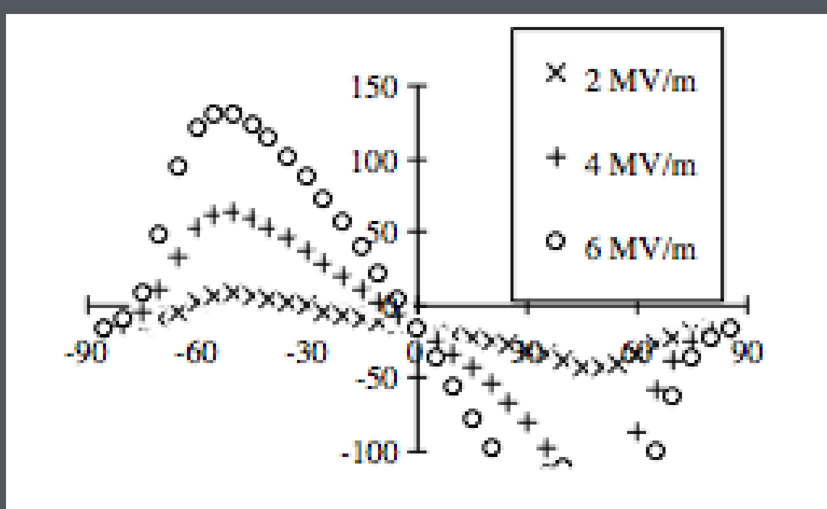
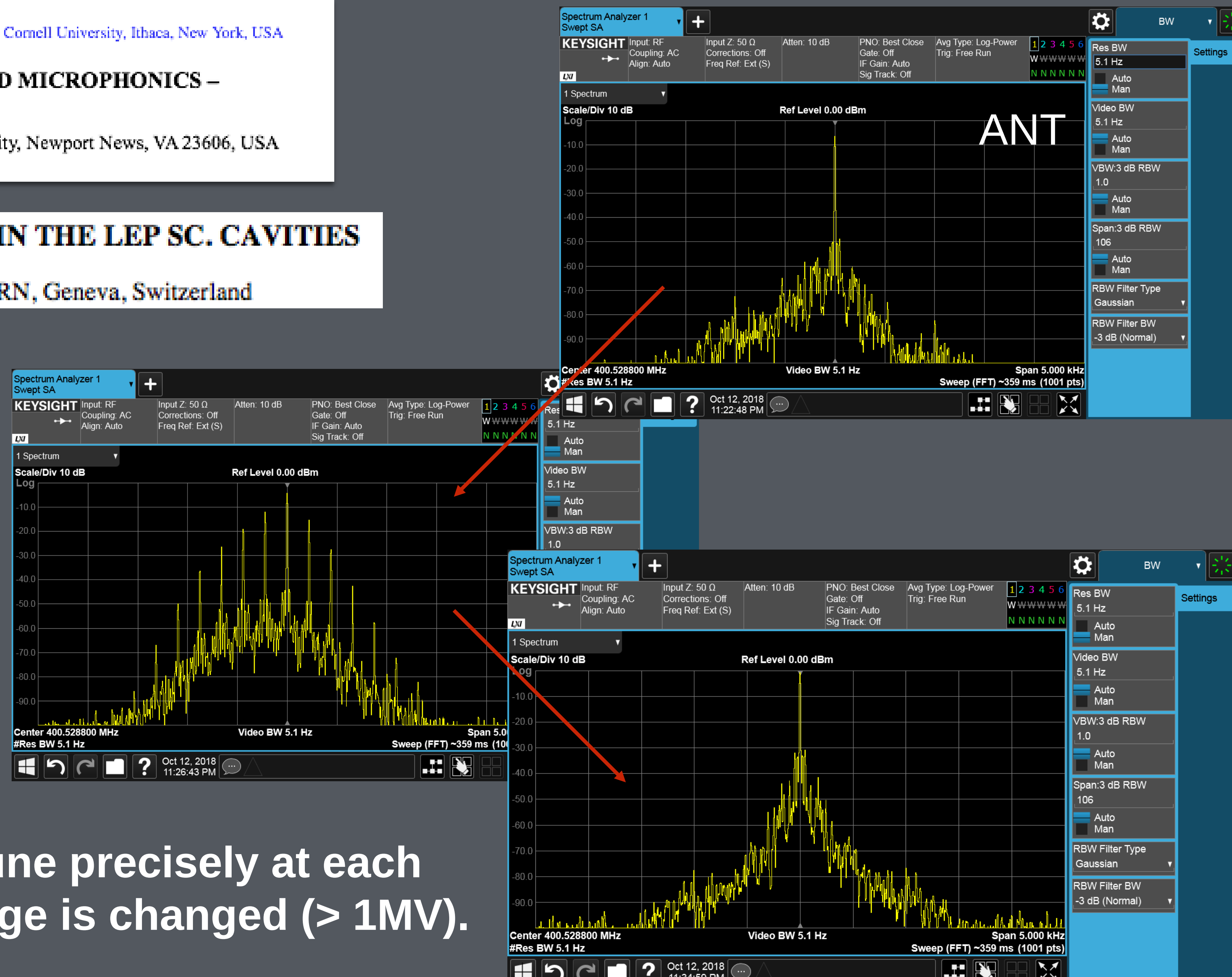


Fig. 2: Growth rates [s^{-1}] as function of ϕ_z[deg] for three different cavity field levels. The chosen parameters match the actual conditions of the LEP2 sc. cavities



The cavity should be on tune precisely at each time when the cavity voltage is changed (> 1MV).

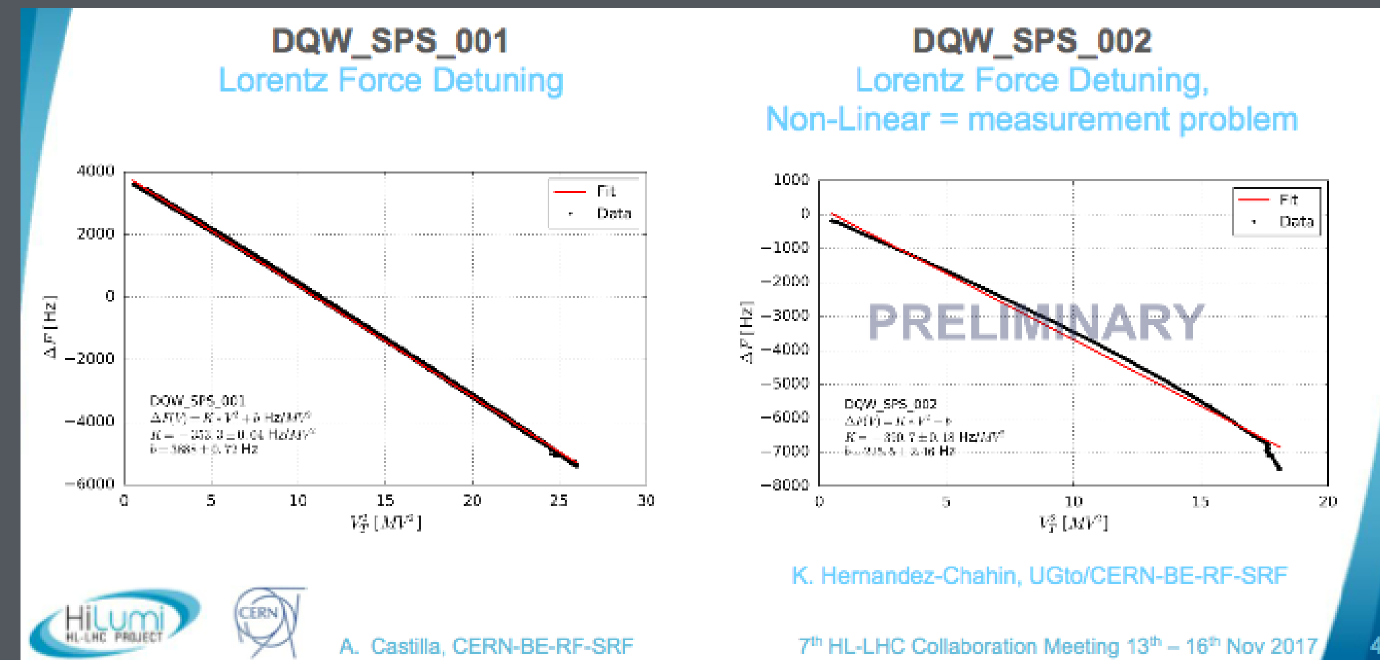
Ponderomotive instabilities measured in SPS-CCs

CERN DQW TESTS SUMMARY

Alejandro Castilla
on behalf of
BE-RF-SRF section and the crab cavity project.

LFD is -350 Hz/MV^2 (crab1), -390 Hz/MV^2 (crab2) measured at SM18.

When the cavity field is close to 1 MV, the detuning frequency is about one cavity bandwidth, that is the worst case for ponderomotive oscillation (-400Hz).



- To close the RF FDBK, we need to tune the cavity precisely.
- When the RF FDBK is closed, FDBK stabilises the cavity field (no more problem of ponderomotive oscillation. The 210Hz mechanical mode is just seen as very small modulation sidebands (Fig.3)).

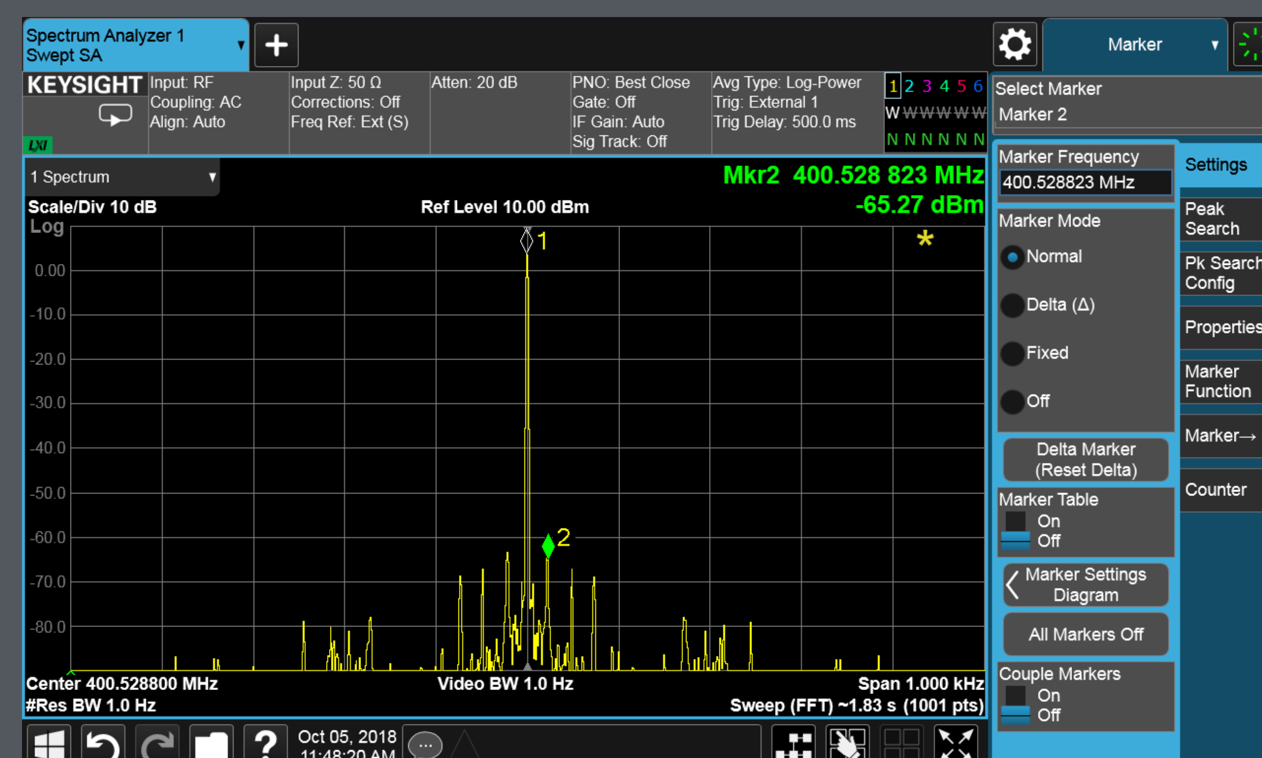


Fig3. ANT: 1600kV, RF FDBK is ON

Conclusions

- <u>Beam loading has been measured in the SPS-CCs.</u> Measurements are in reasonable agreement with the calculation. Further analysis is necessary.
- Beam loading due to the LRBB and injection oscillation in HL-LHC CCs is computed. <u>For LRBB the required power is negligible. For Injection oscillation, it peaks at 26kW without ADT down to 14kW with ADT.</u>
- Microphonics modes have been identified in the SPS-CCs
  - Fluctuation of cryo-pressure, TX high voltage ripple and several mechanical modes.
- Ponderomotive oscillations have been observed around 210 Hz in the SPS-CCs
  - They are completely damped when operating exactly on tune or with RF FDBK ON.