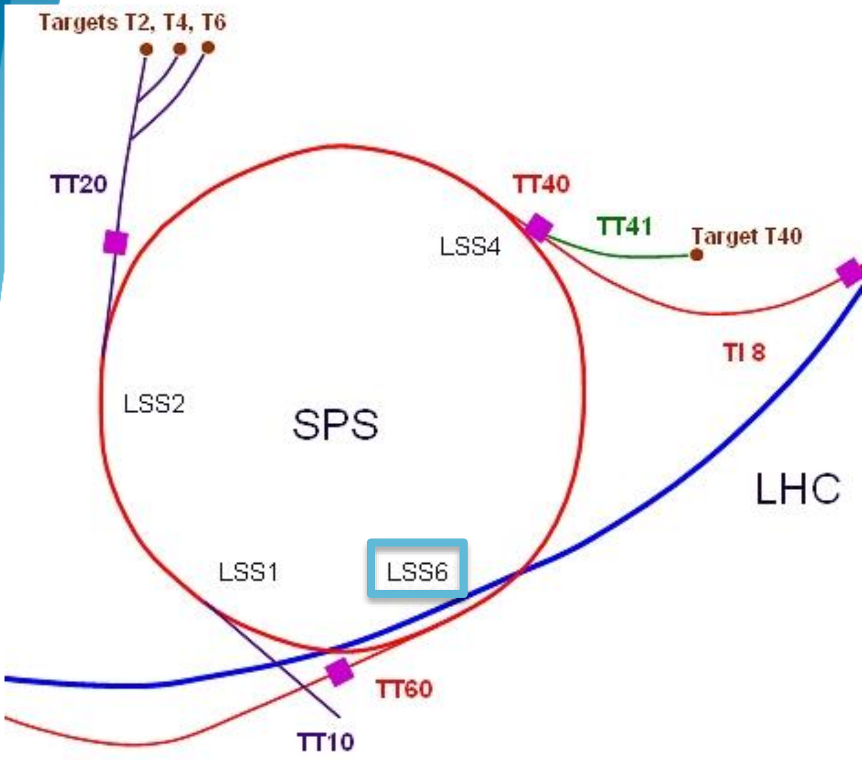
SPS beam measurements & Operational challenges

On behalf of BE-ABP/BI/RF/OP & MPP, UK/US

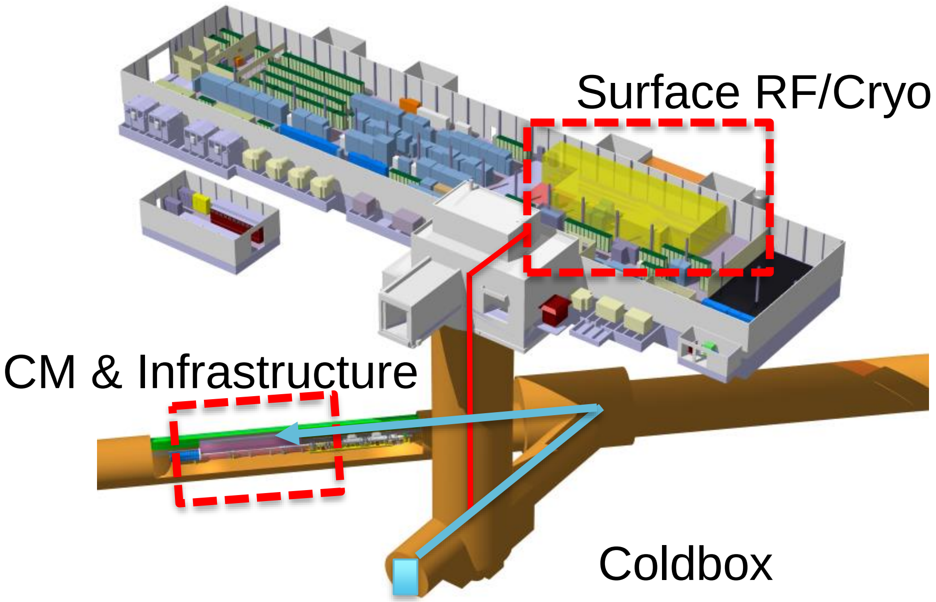
HL-LHC WP4

20 June 2019 - CERN

Super Proton Synchrotron, SPS

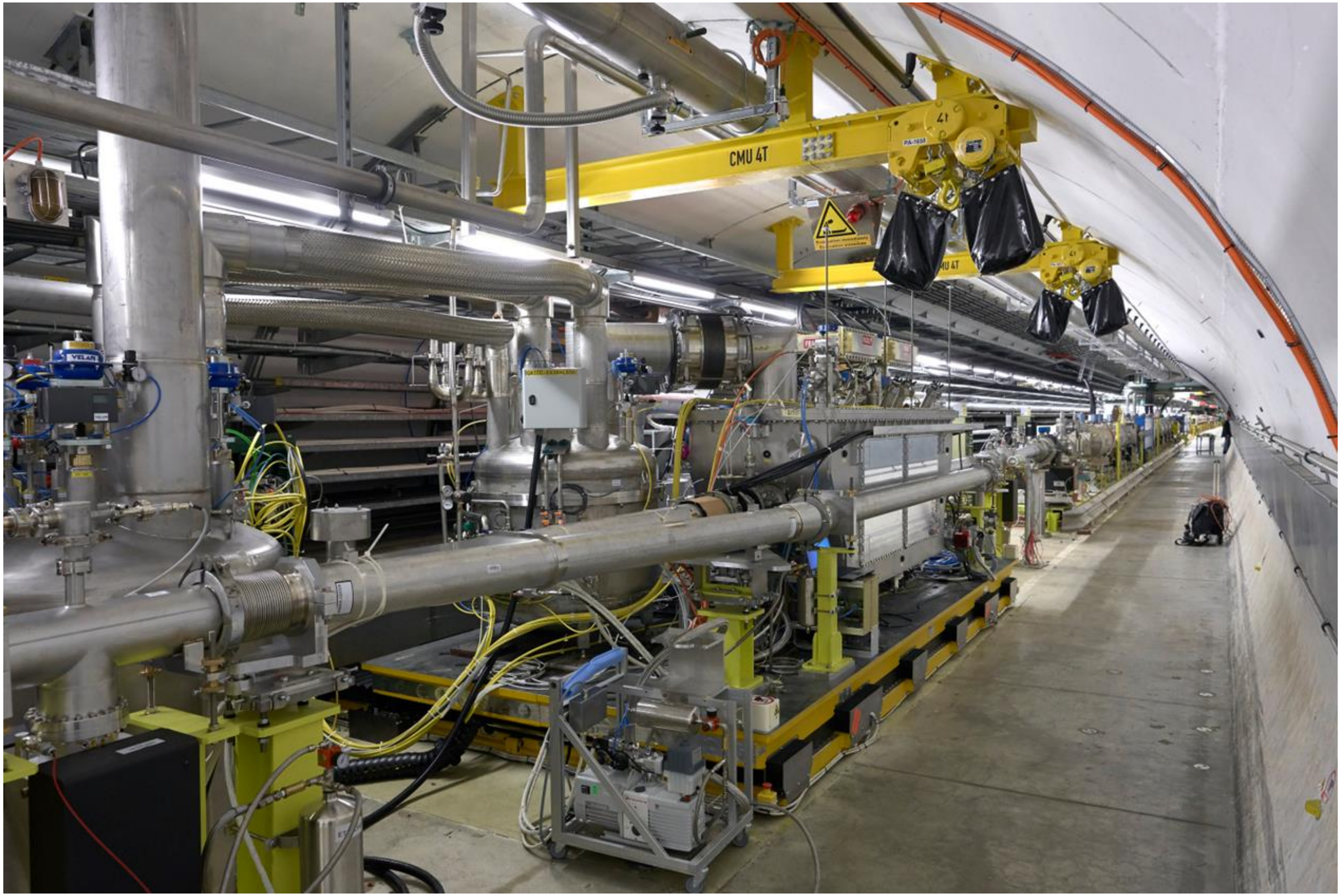


Circumference	7 km
Injection-Extraction energy	26-450 GeV
Main RF Frequency	200 MHz, TW
CC Frequency swing	400.528 – 400.788 MHz
CC bandwidth	800 Hz



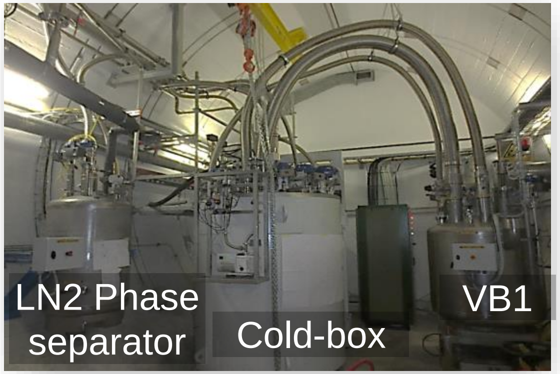
SPS-LSS6 before crabs

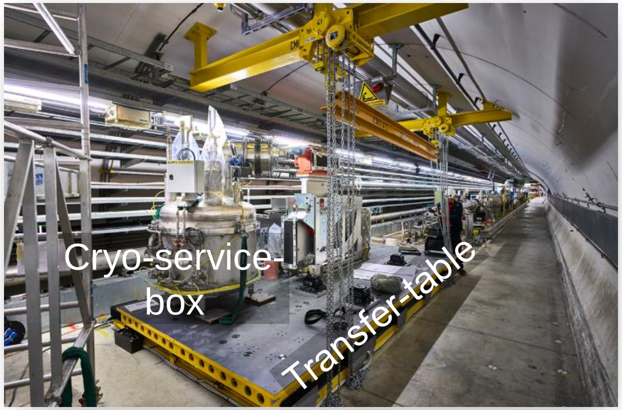
SPS-LSS6 - 2018

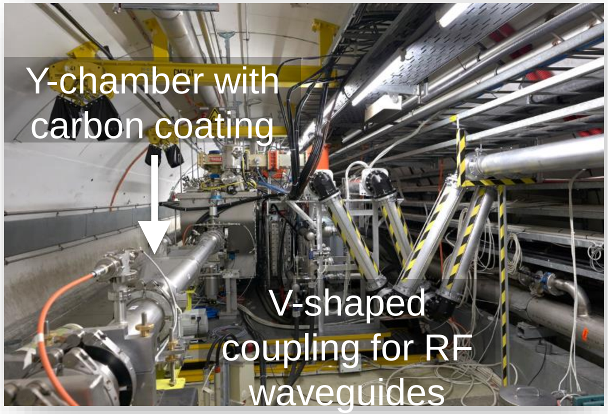


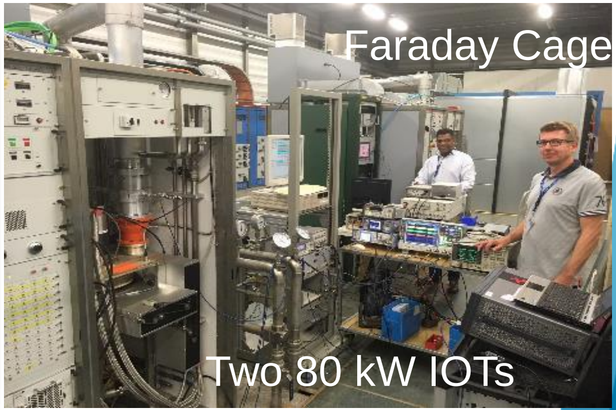
SPS-Crab Installation

- Massive installation of a new RF & Cryo plant in BA6 in parallel to the cryomodule into the beam line









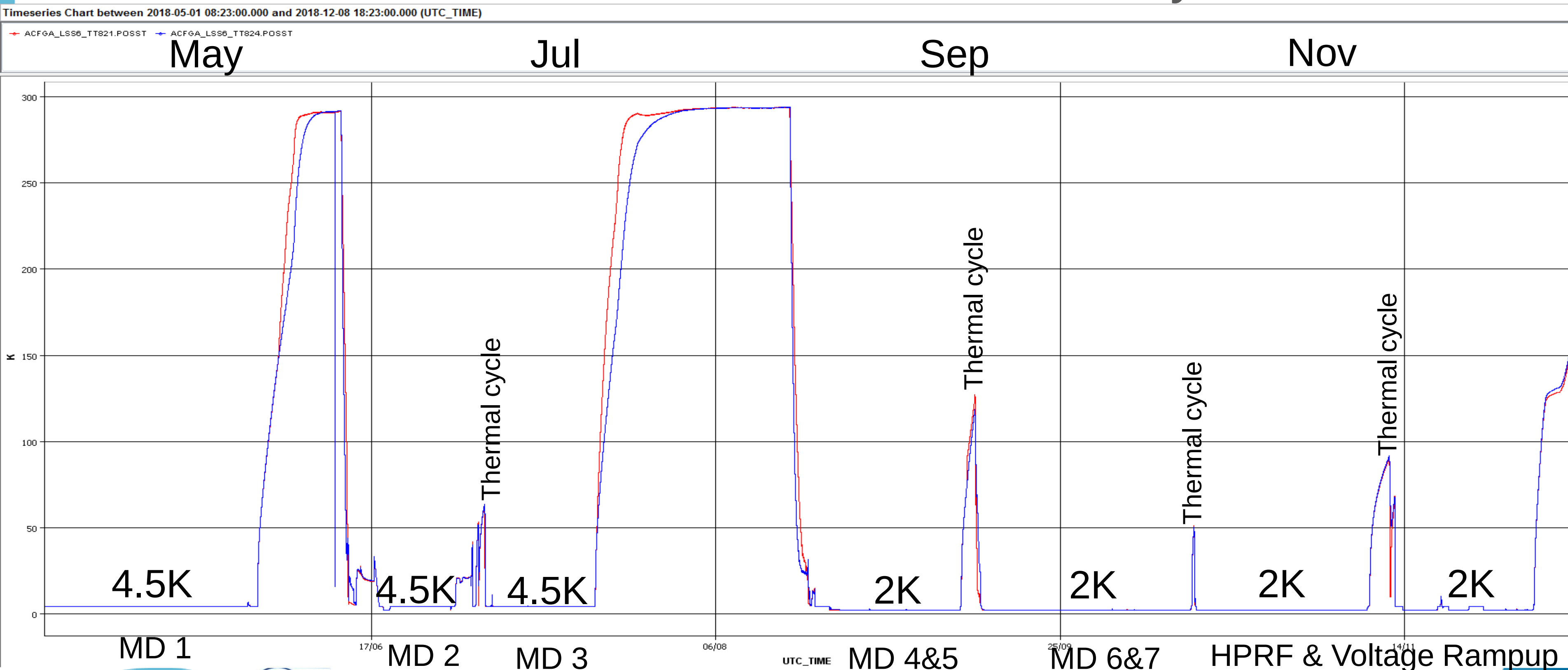
Expected SPS Test Sequence

- 4 main phases foreseen – 10 machine development sessions (MDs) requested
- 2 slots were for table and RF setup in-beam
- 7 MDs of 10 hrs each were performed

	What	When	MD slots
0	RF commissioning (no-beam)	Mar-Apr	~ 4 weeks
1	RF-beam synchronization	Apr-May	2-4 x 10h
2	Transparency to beam	Jun-Jul	2-4 x 10h
3	Performance & Stability	Aug-Sep	4 x 10h
4	High intensity RF operation	October	2 x 10h

Cryo Availability

- Issues with LN_2 meant operation at 4.5K before the Summer
- 4.5K not ideal due to large pressure modulation, higher than 1 MV caused vacuum-thermal runaway



MD Overview

* Operating temperature is 2K

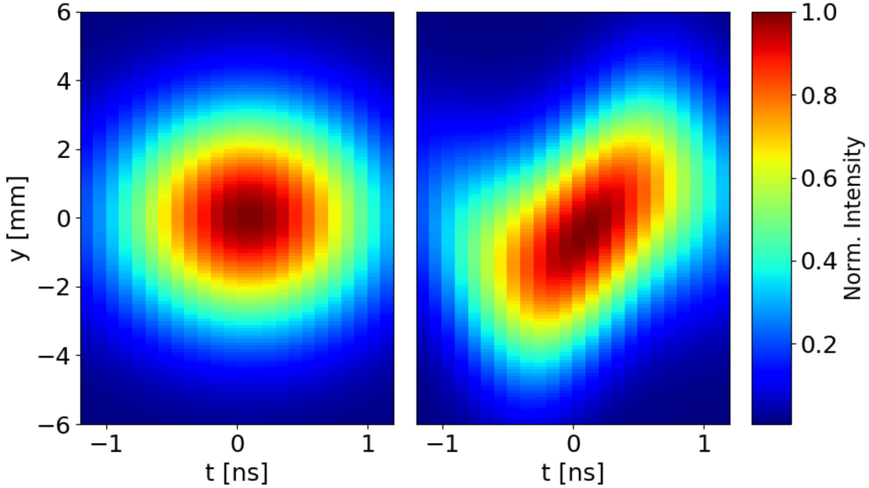
MD#		Cav1	Cav2 [MV]	Temp [K]	Energy [GeV]
1	First crabbing, phase and voltage scan	0.5	0	4.5	26
2	270 GeV ramp with single bunch	1-2	0	4.5	26, 270
3	Intensity ramp up	1	~0.3	4.5	26
4	270 GeV coast setup	1.0	0.5	2.0	270
5	Emittance growth at 270 GeV with induced noise	0	1.0	2.0	270
6	Intensity ramp up to 4-batches	-	1.0-1.5	2.0	26
7	Intensity/Energy ramp up	-	1.0	2.0	26, 270, 400

Protons meet Crabs

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

Single bunch
$0.2 - 0.8 \times 10^{11}$ p/b

Crabbing reconstruction
(assuming Gaussian transversely)



Head-tail monitor as main beam diagnostic

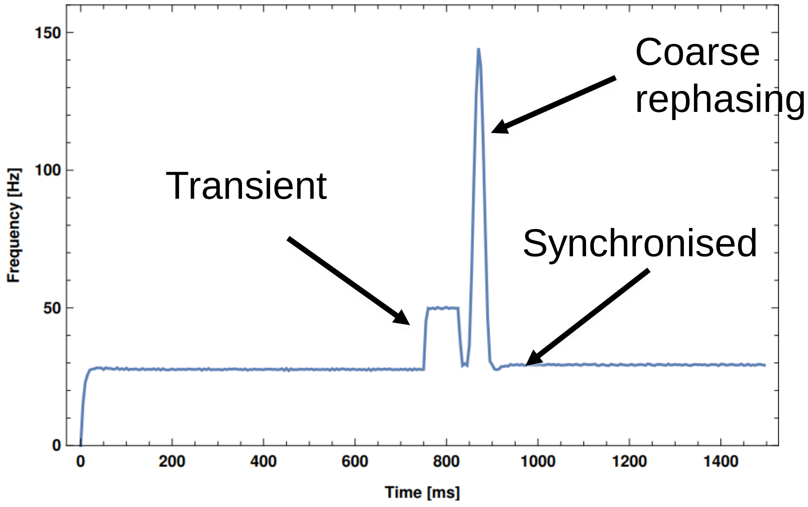
In general, beam measurements showed 10-20% larger voltage than RF signals

L. Carver, T. Levens et al.

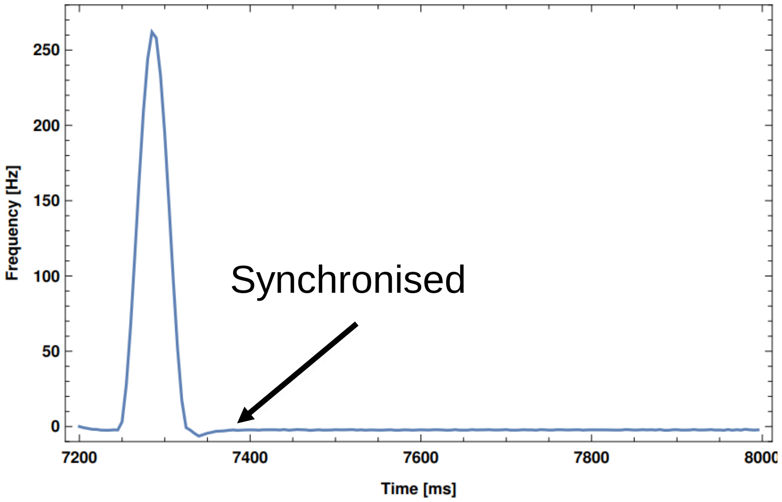
How to synchronize Crab-RF ?

- Crab cavity is at fixed frequency
  - Freq (400.53 – 400.78 MHz): 26 – 450 GeV
  - SPS RF ~200 MHz is rephased to crab Freq

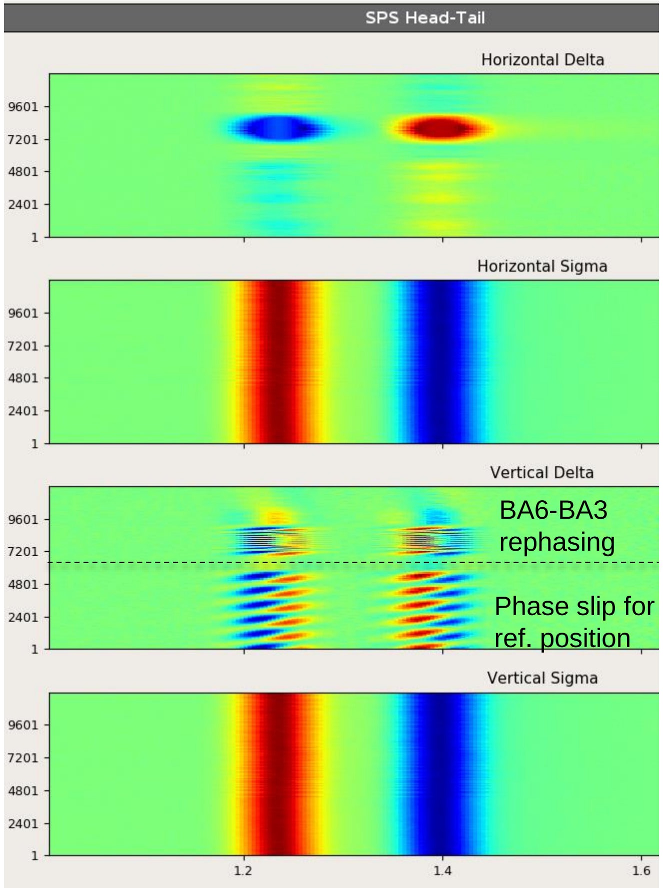
26GeV rephasing
Synch after ~1s after injection

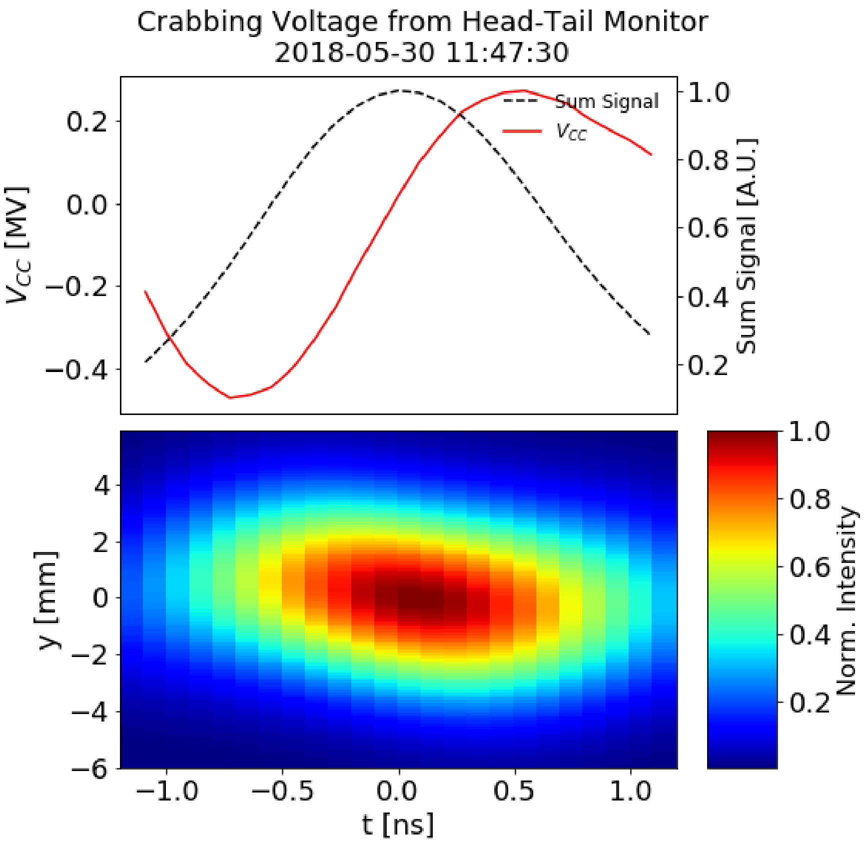


270GeV, Synchronized after ~7.4s
i.e. 0.2s after reaching flat top



Reconstruction of Crabbing using HT



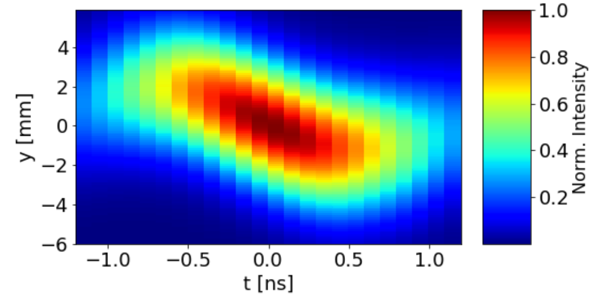


# of turns for ref position along the bunch ~ 2k turns

RF re-synchronization ~ 1s after injection

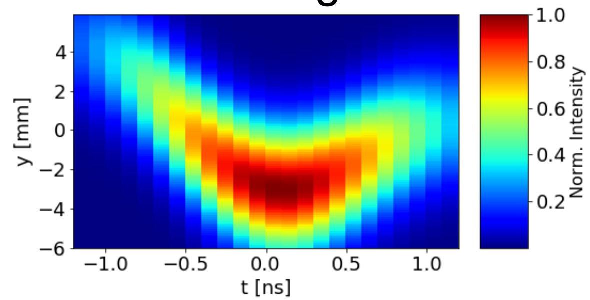
Phase Scans & “Transparency”

0 Deg

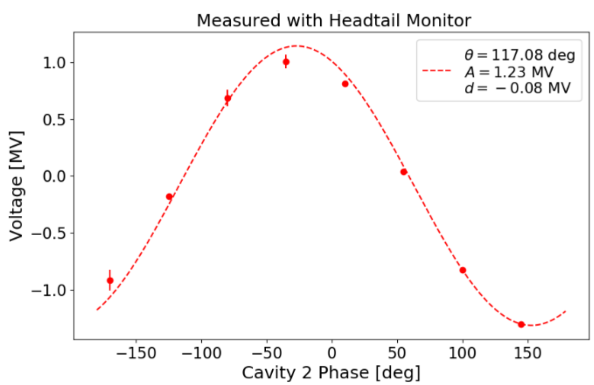


RF phase scan w.r.t the beam phase with cavity 1

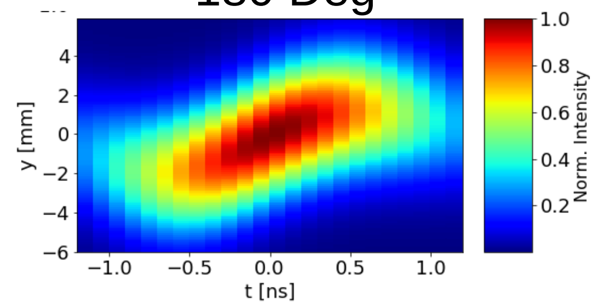
90 Deg



CAV2 Voltage/Phase

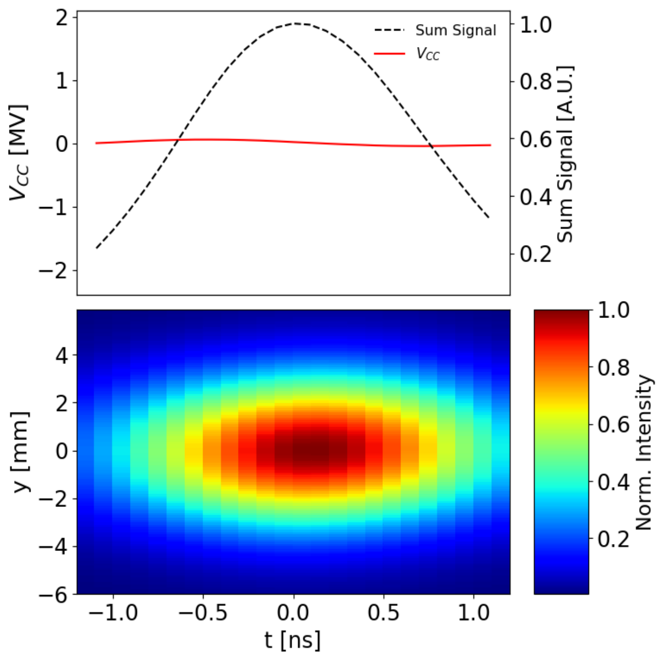


180 Deg

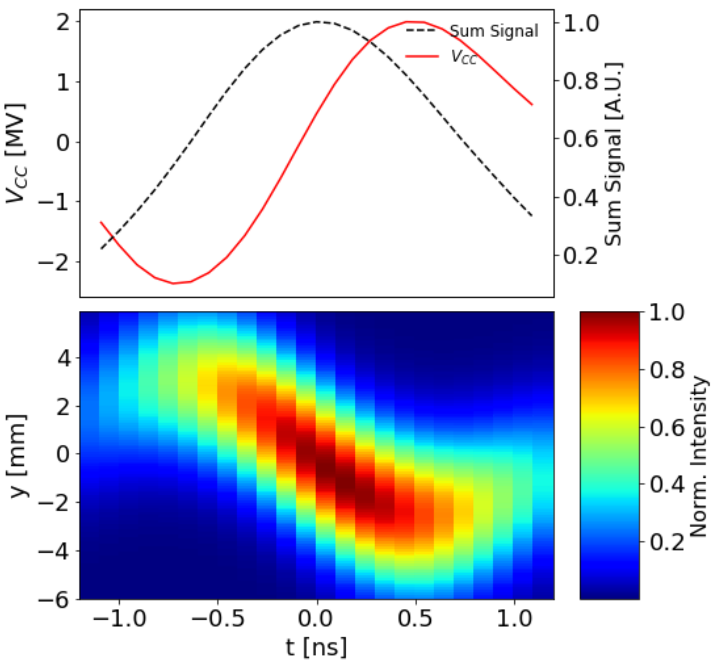


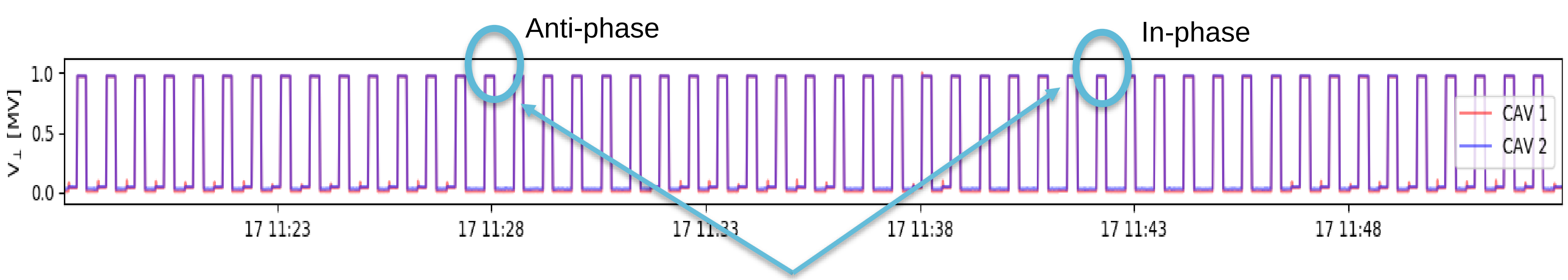
Transparency: V=1MV in both cavities

Cavity 1 - Cavity 2



Cavity 1 + Cavity 2



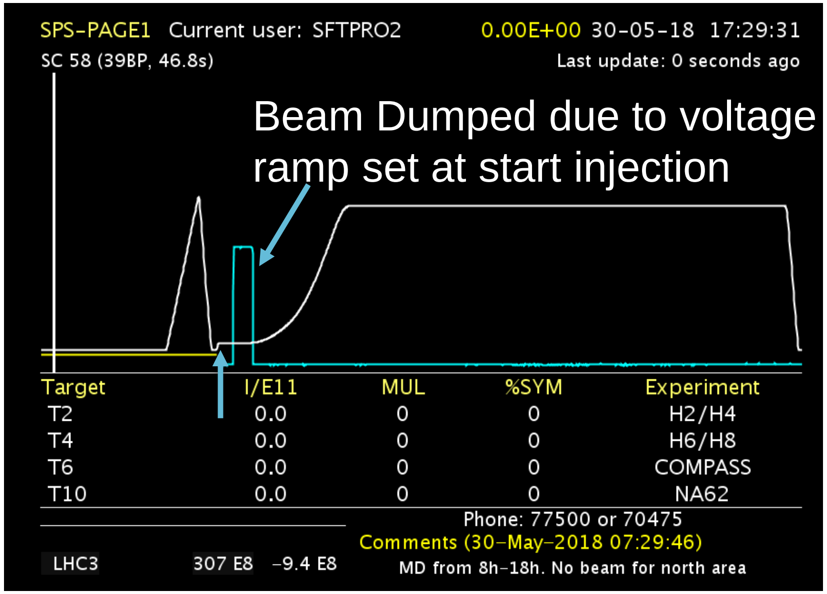


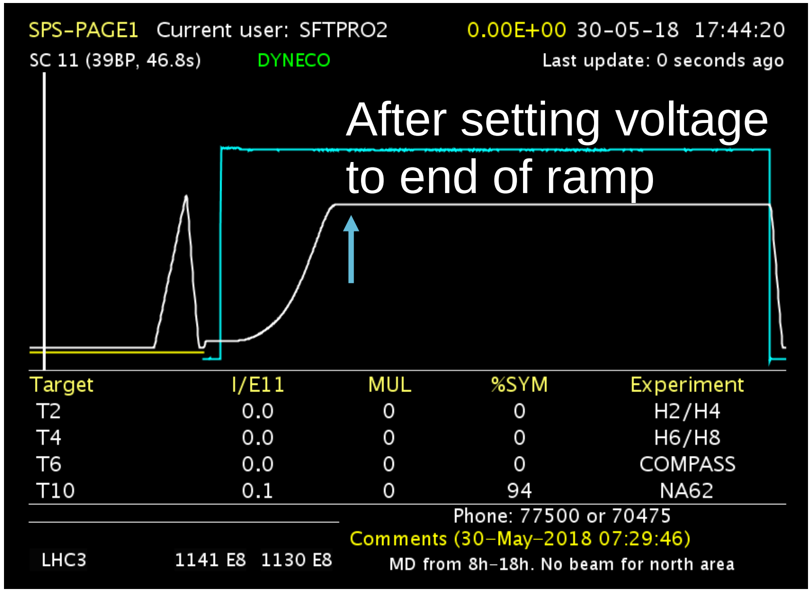
SPS MD cycle (~20 sec flattop)

270 GeV Ramp

- With cavities powered during the energy ramp and without synchronization to main RF, the beam is rapidly lost due to resonant excitation at the betratron frequency.
- With cavities off during the ramp the beam makes it through without losses. New operational scenario for HL-LHC

Cav1 ~1MV (400.787 MHZ), Cav2 off (400.528 MHz)





HiLumi HL-LHC PROJECT CERN

Ramp to 270 GeV

Vertical tune: $Q_y = 0.18$

RF Freq:

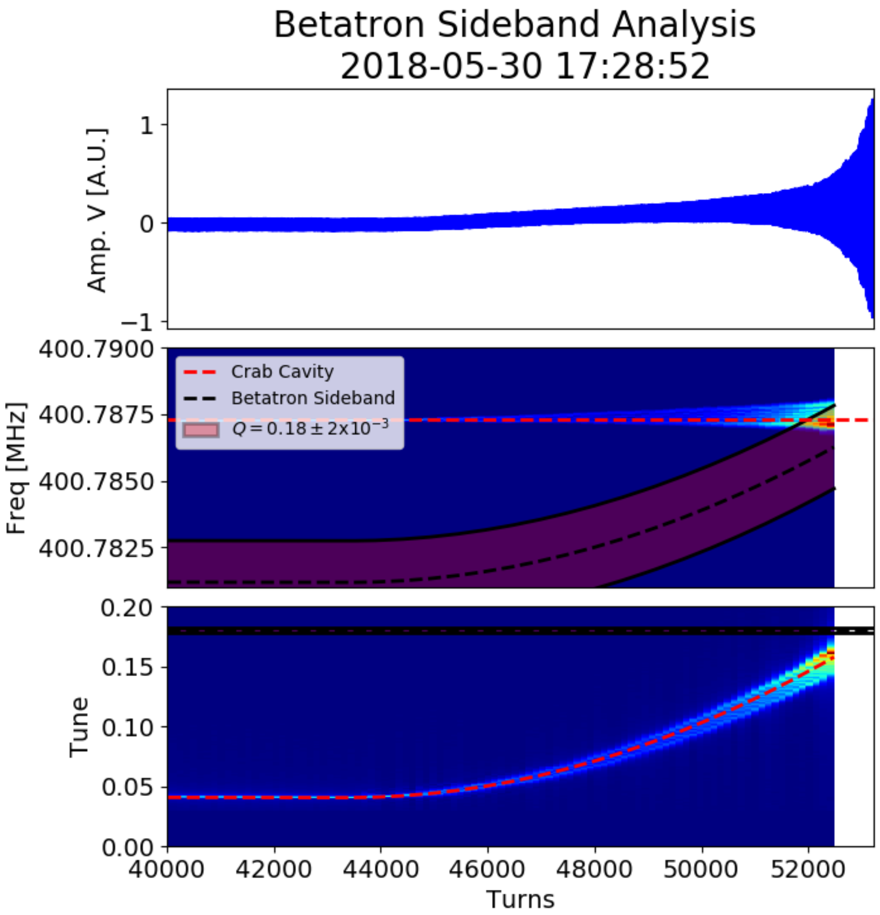
Cavity 1: 400.787 MHz (~1 MV)

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

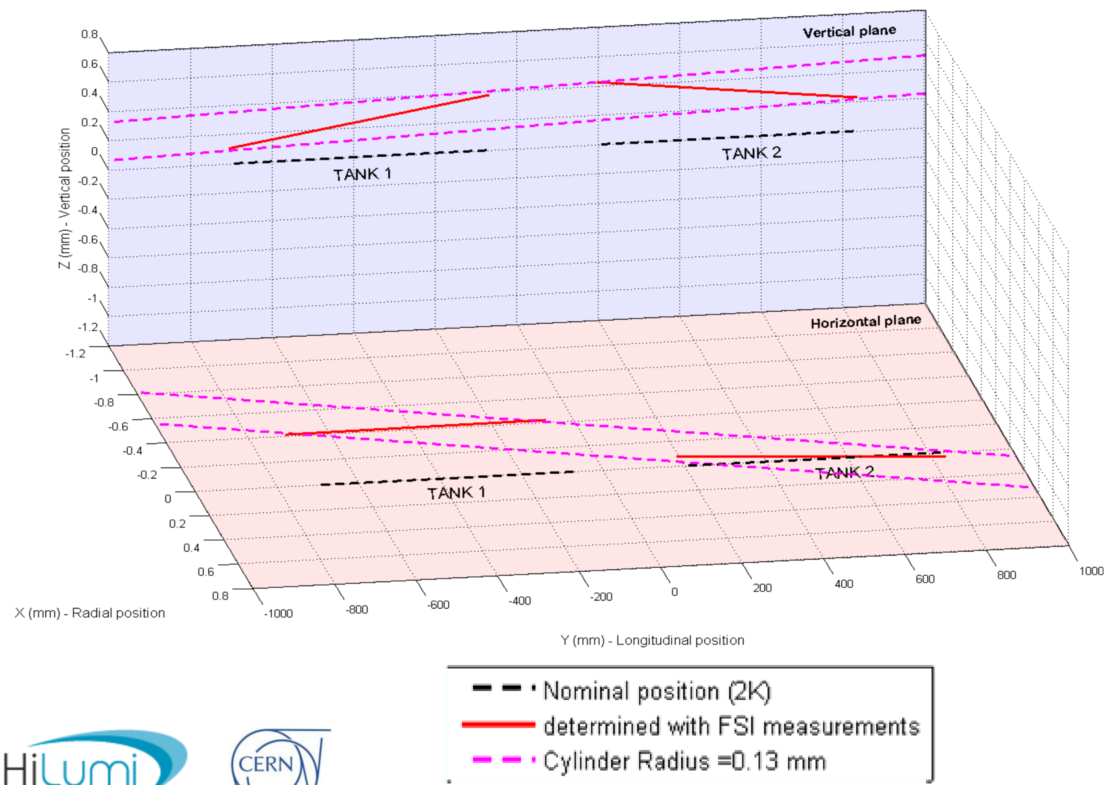
After setting the correct cycle start voltage to 270 GeV equivalent, beam circulated w/o any issue

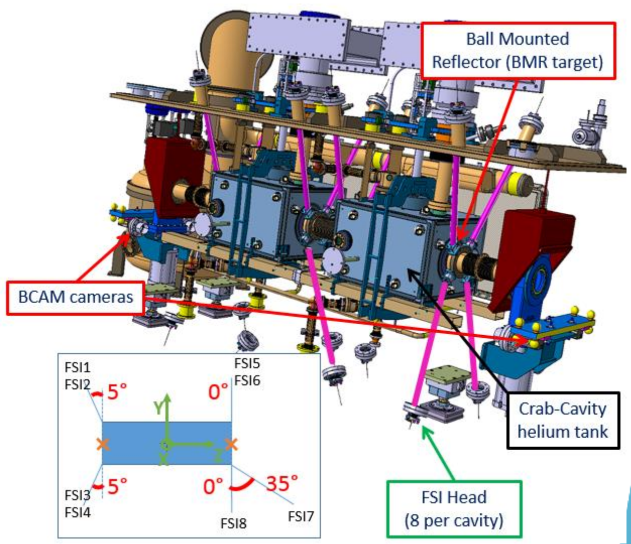


Cavity Alignment

- Tight alignment tolerances ($\pm 0.5\,\mathrm{mm}$, intra-cavity misalignment at $2\mathrm{K}$) for HL-LHC.

• Alignment between the 2 cavities : Radius = $130\ \mu\mathrm{m}$

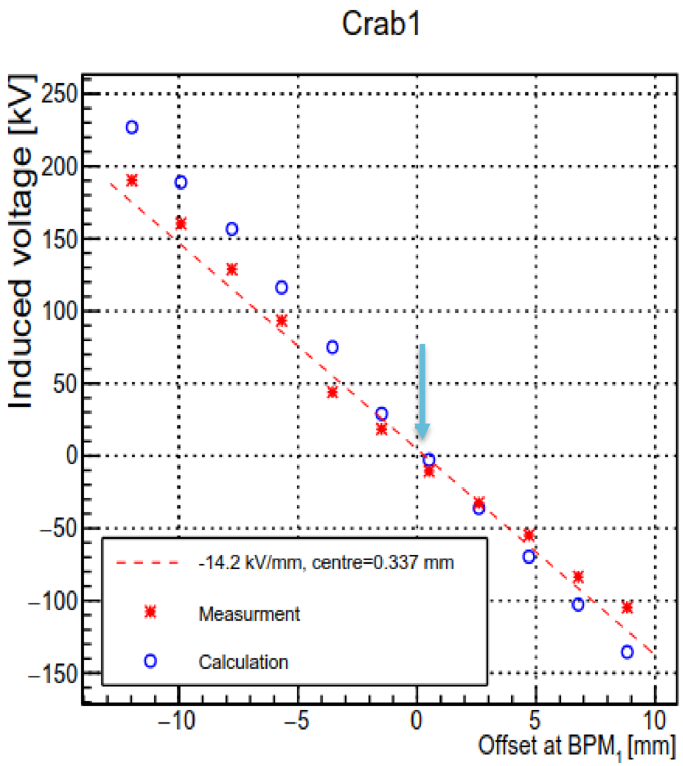


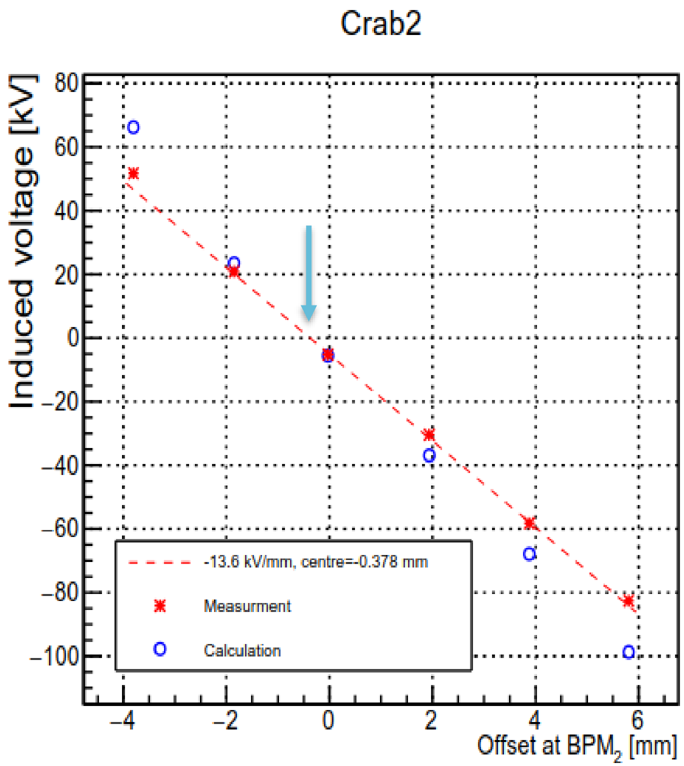


Courtesy: EN-ACE-SU/MME

Beam Loading & Electrical Center

- Beam induced voltage with cavities off performed to determine the magnitude & electrical center

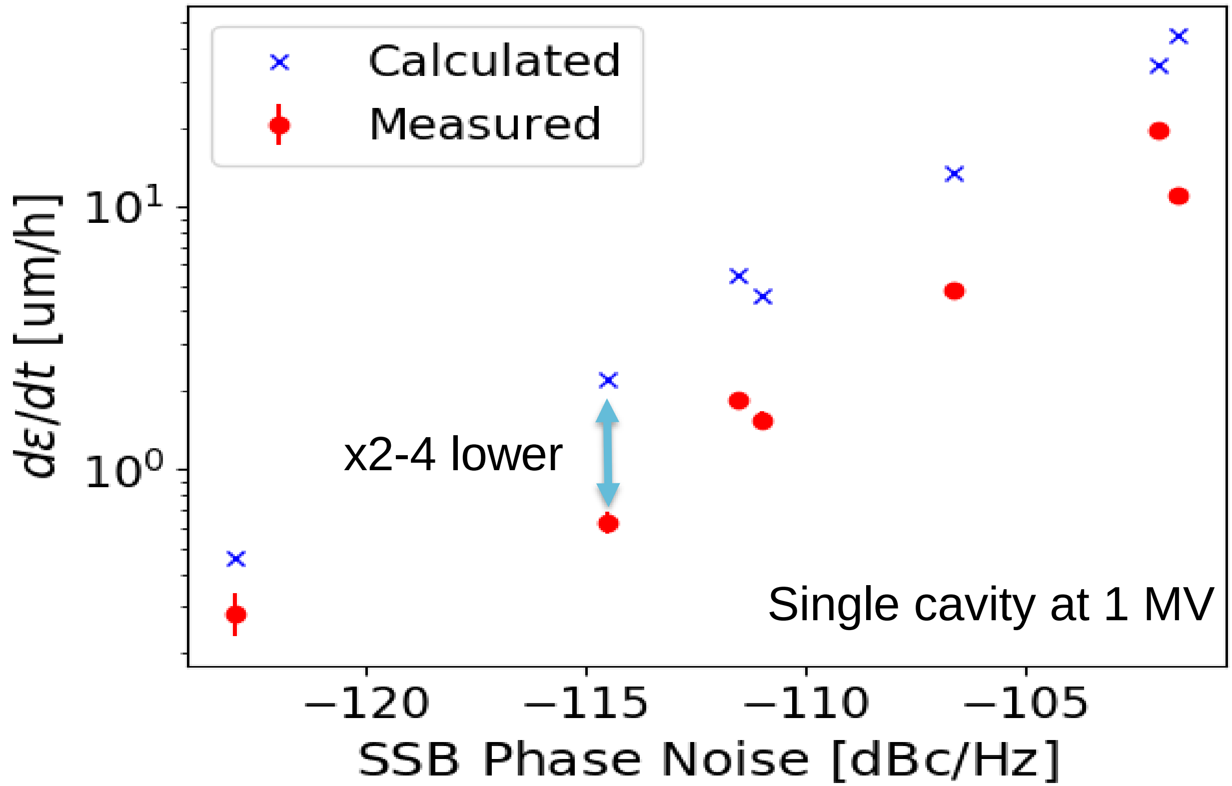




E. Yamakawa et al.

Emittance Growth

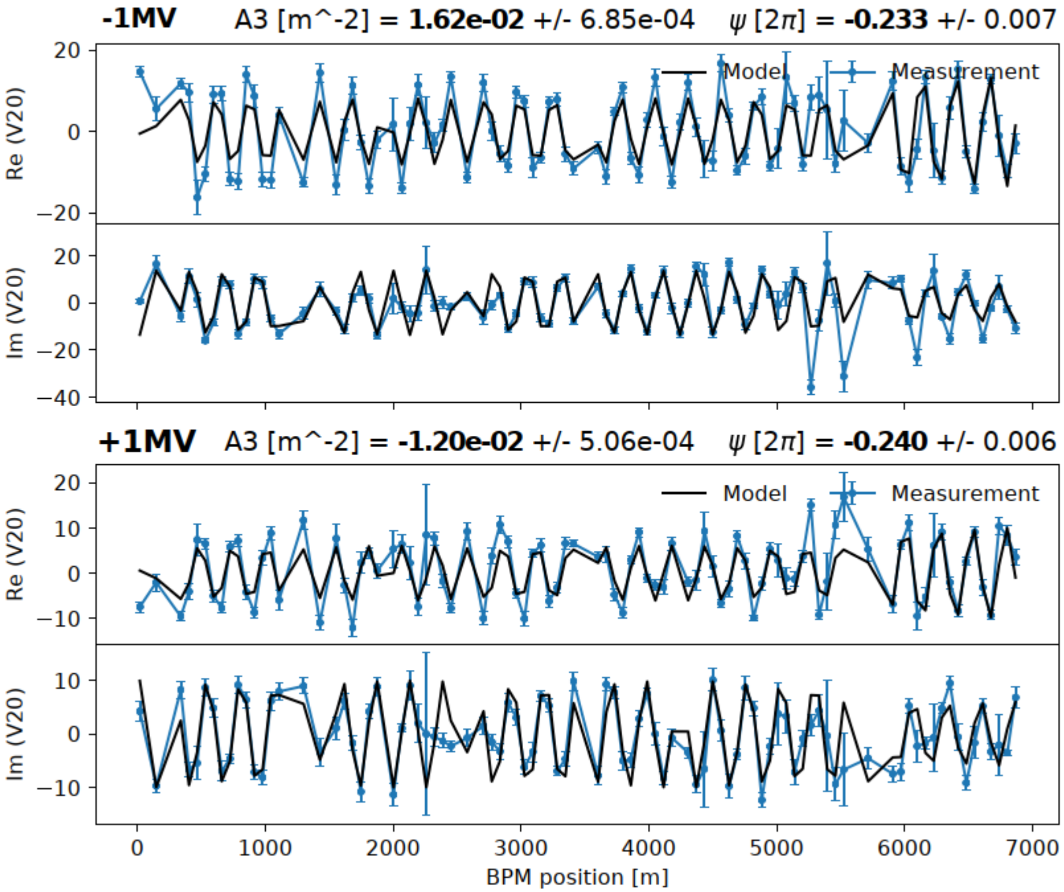
- SPS natural emittance growth at 270 GeV, $\leq 0.5\ \mu\text{m}/\text{h}$
  - HL-LHC we need to be below $0.05\ \mu\text{m}/\text{h}$
- CC Expected growth with existing electronics (noisy!)
  - Ph. noise up to $8\ \mu\text{m}/\text{hr}$, amp noise: $1.4\ \mu\text{m}/\text{hr}$ (σ_t: 2.0 ns)
  - Scaling with additional induced noise is qualitatively reproduced but more pessimistic than measured growth



P. Baudrenghien, L. Carver et al.

RF Multipoles

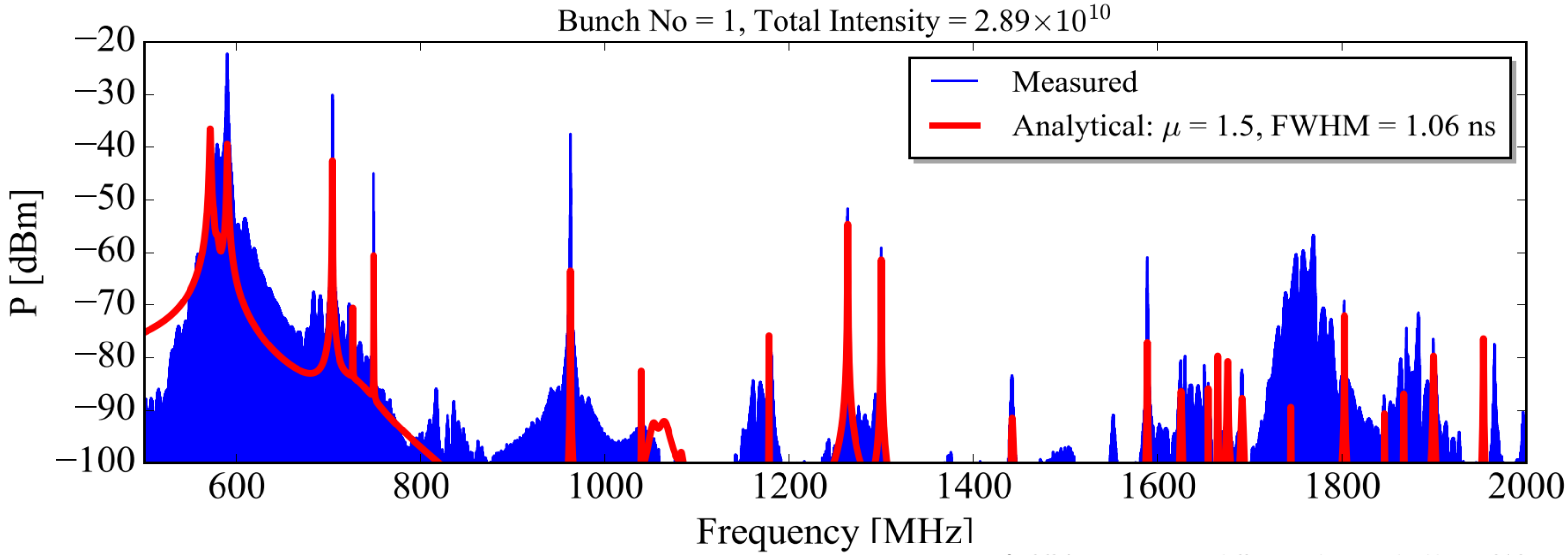
- Very promising results to measure RF multipoles with beam, but still require careful separation between existing components



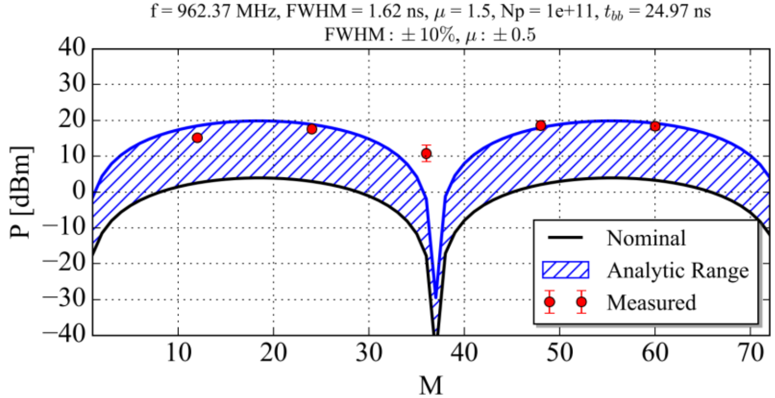
M. Carla et al.

Higher Order Modes

- Integrated max HOM power measured < 3 W. More than 75% from ~960 MHz.
- Overall HOM power & scaling to the HL-LHC looks reasonable, some deviations from expectations



(including bunch length/distribution range)



J. Mitchell et al.

High Intensity

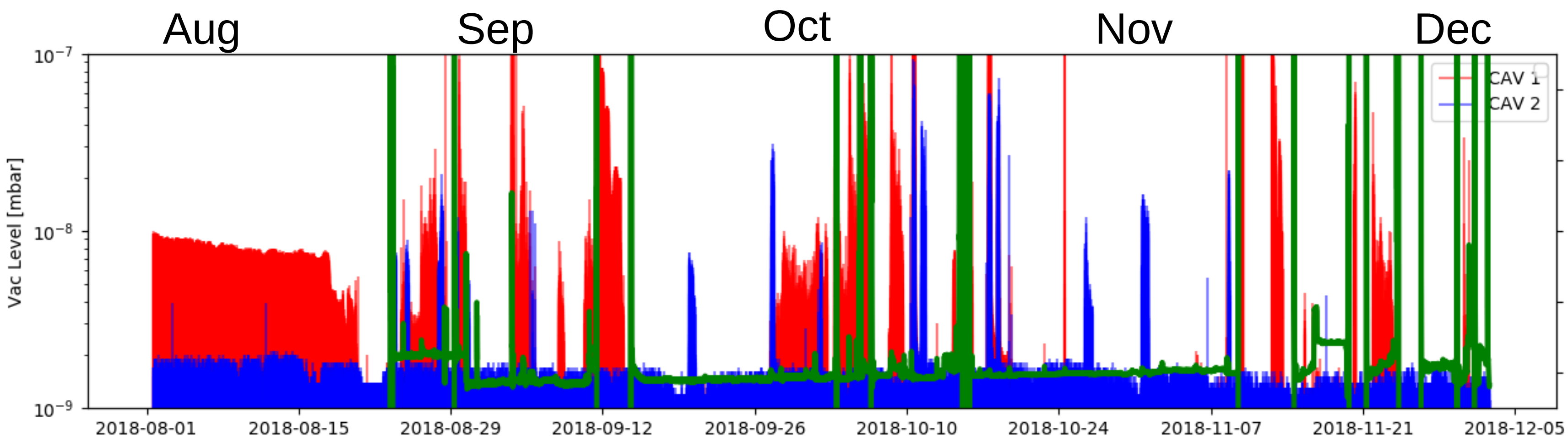
- MD6: 72 bunches at 2×10^{10} p/b increased to 4×36 at 1×10^{11}p/b (1/2 the max intensity)
  - Limited by crab by-pass pressure rise 10^{-6}mb
  - With moderate voltage (1 MV), no beam induced failures or fast transients seen except for pressure rise
- MD7: 2×60 bunches at 1×10^{11}p/b
  - Also limited by vacuum pressure rise in by-pass
  - Cavities on/off at 1MV didn't make any difference on pressure dynamics
  - Ramp the multi-bunches to 270-400 GeV to reach closer to LHC like bunch lengths – longitudinally unstable beyond 12-bunches, required more setup time

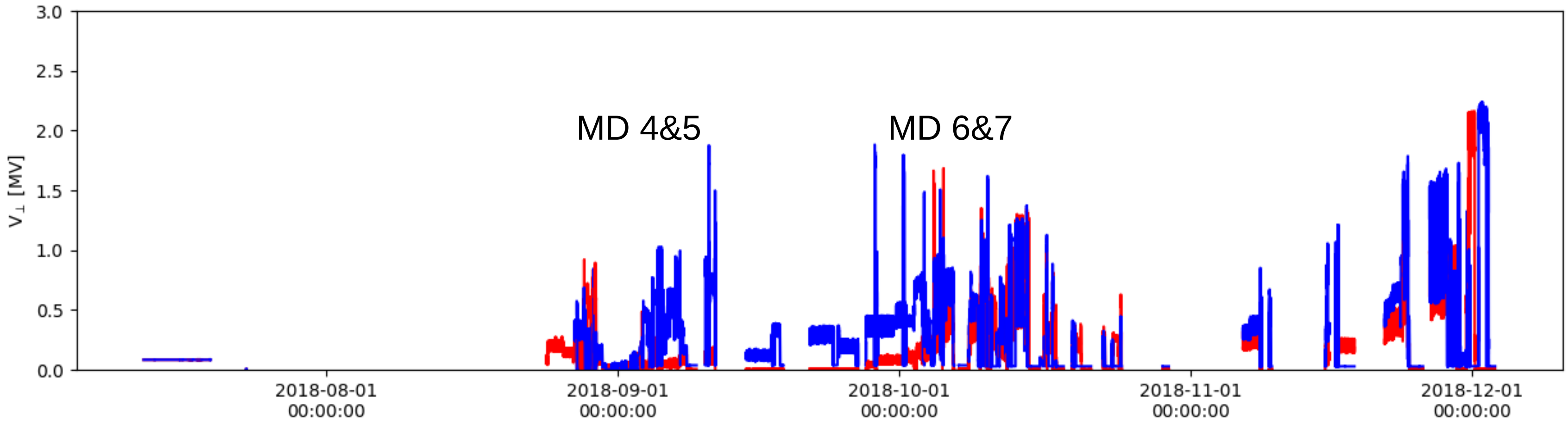
Some Challenges to Consider

- Cavity voltage reach
- RF linearity at low power and optimization of RF chain including interlocks
- Direct beam coupling with field probe for field regulation
- Electro-acoustic instabilities above 1MV, recall LFD $\sim 300 - 800\ \mathrm{Hz/MV^2}$
- Microphonics measured but not an issue

HiLumi HL-LHC PROJECT CERN

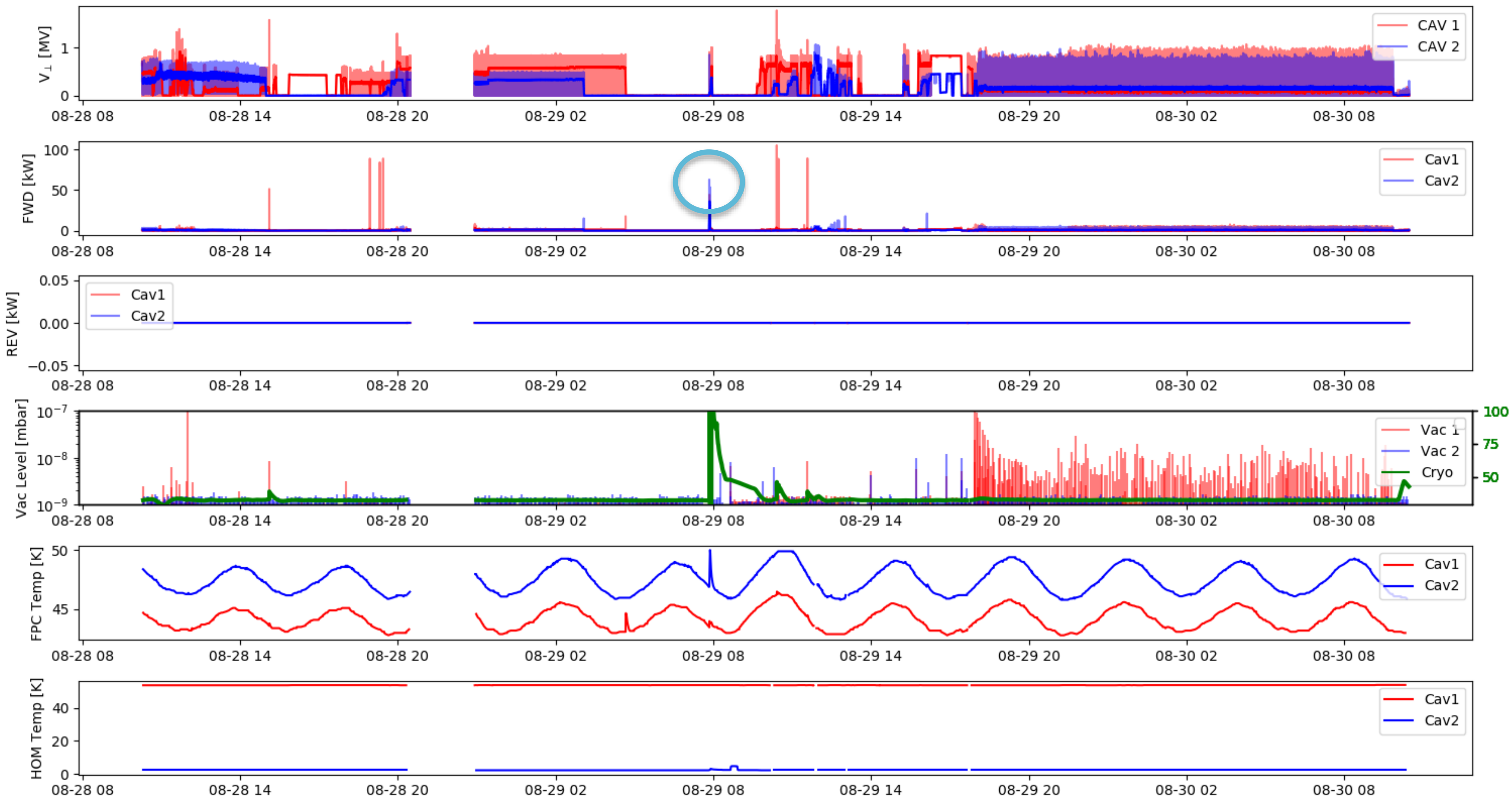
Average Voltage Evolution (2K)





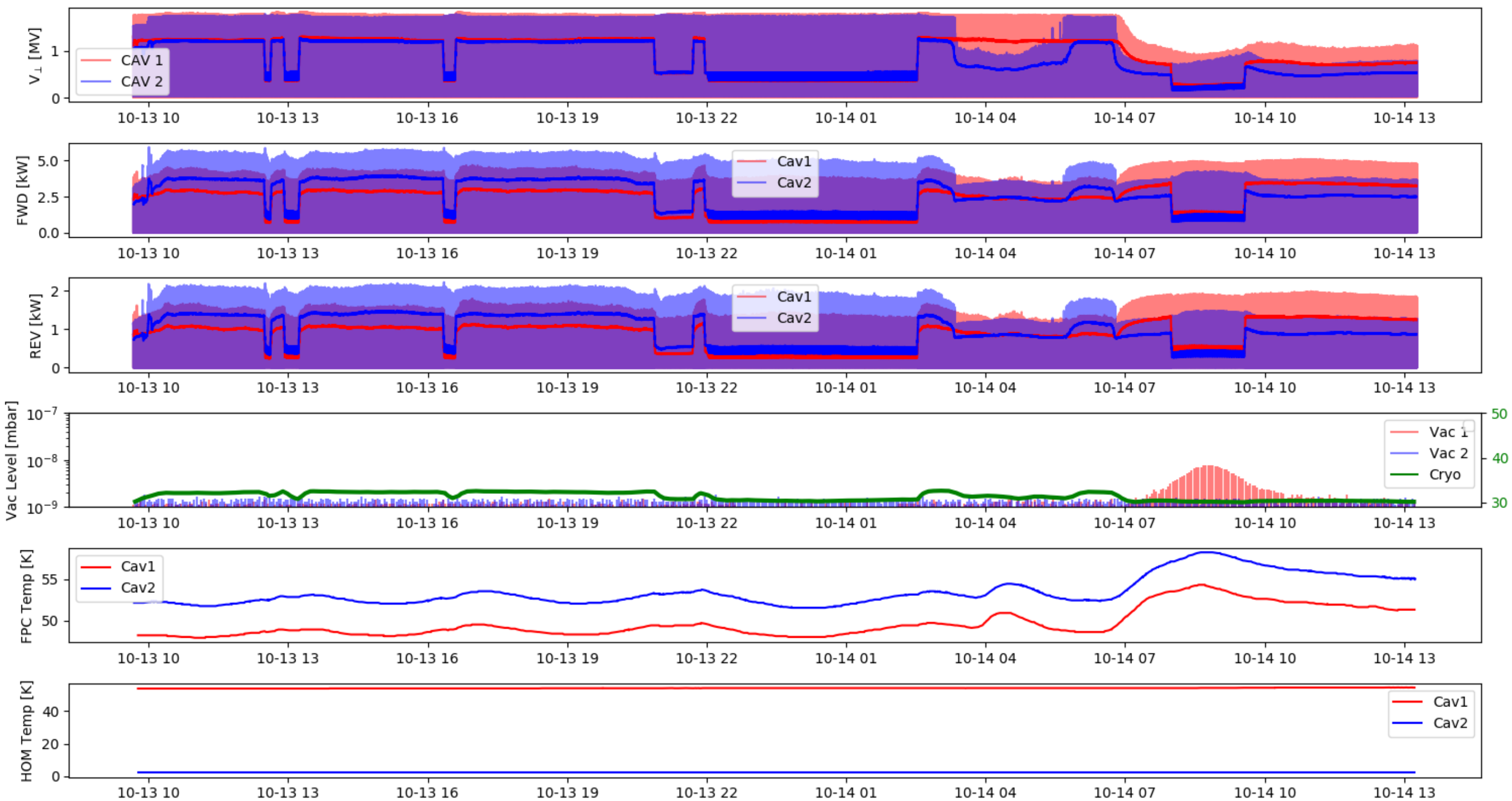
First 2K operation, Aug 29 (MD4)

- With LLRF feedback, sudden request of power on cavity 2 but this cavity did not see any significant power yet through conditioning



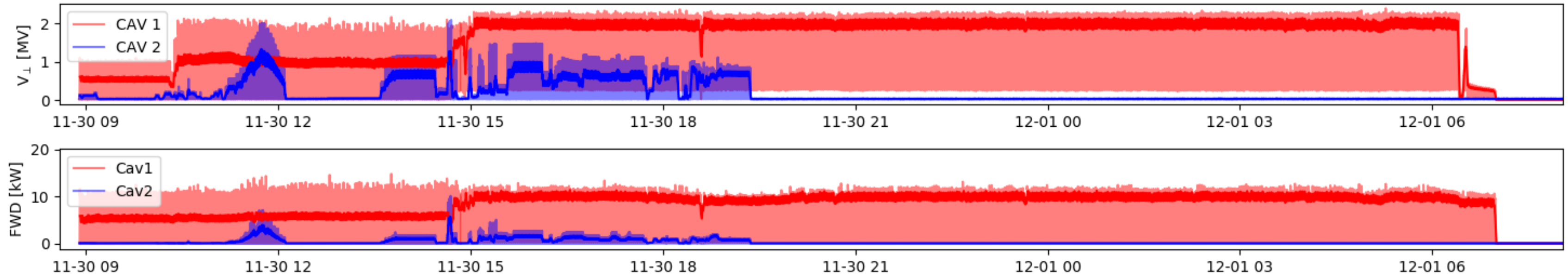
Oct 13, Stable Voltage CAV1/2 – 1.0 MV

- Many hours of stable operation with good correlation between RF and cryogenics
- We then also saw a few occasions with stable operation over many hours with sudden increase in cryo load and loss of RF conditions – not fully understood

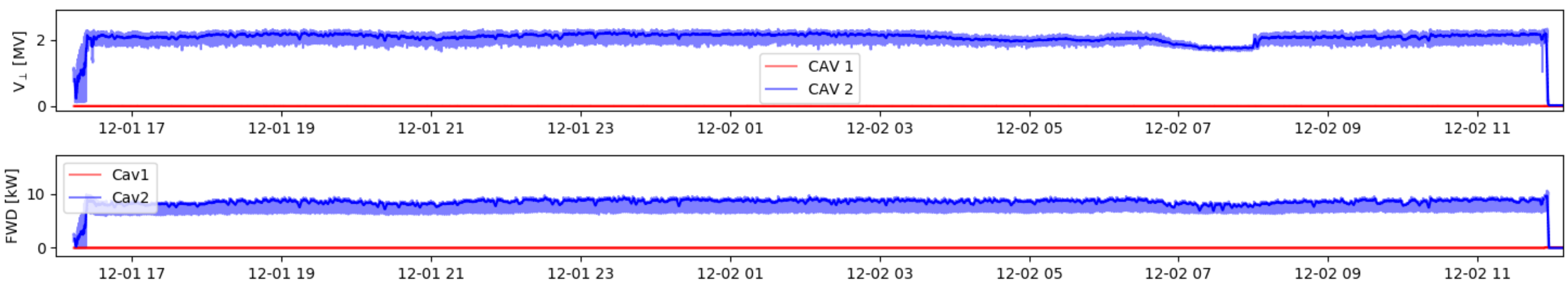


Crab Cavity Max Performance, Nov/Dec

Cavity 1 Voltage & RF Power (red)



Cavity 2 Voltage & RF Power (blue)

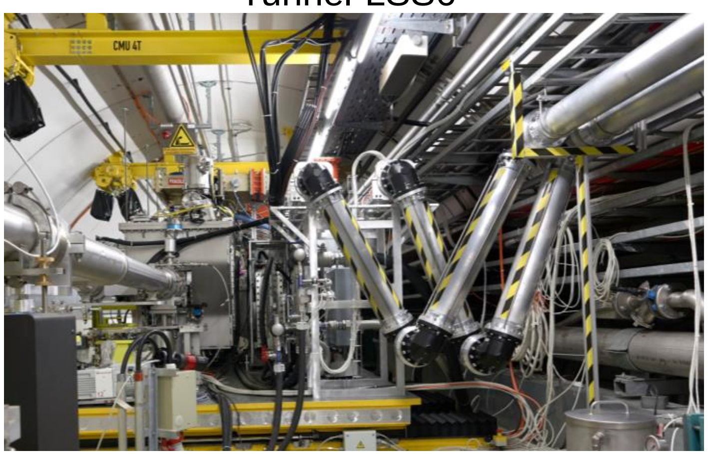


Note: After many hours of stable operation, we observed big thermal load and lost RF conditions, the trigger of such events is not fully understood

High Power RF

- Two 80 kW IOTs operational in SPS
  - Issues of linearity at very low power ($< 5\ \mathrm{kW}$) being addressed jointly with LLRF team
  - For series, SSPA spec with the required linearity
- RF chain validated during operation in SPS
  - Use of LHC-type circulators & loads are way oversized for crab needs, will be adapted for HL-LHC

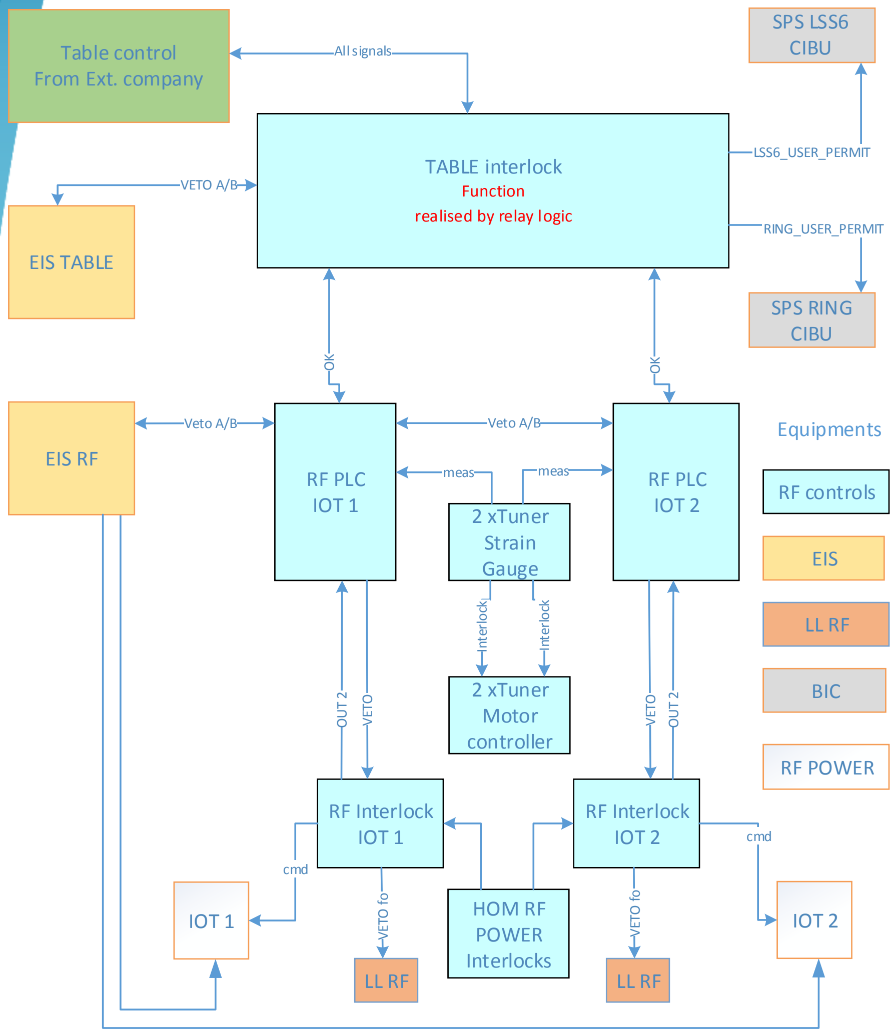
Tunnel-LSS6



Surface-BA6

E. Montesinos et al.

SPS-CC Interlocks and Automation



Main elements:

- One PLC + one fast interlock to control **each IOT / Cavity**
- One table interlock relay and PLC monitoring
- One dual RF power interlock for up to 8 HOM signals
- One dual Motor controller for tuner movement
- Dual strain gauge conditioner with interlocks

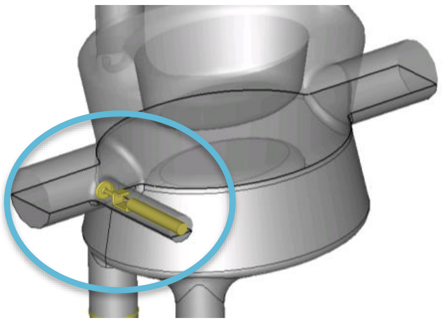
Main external connections:

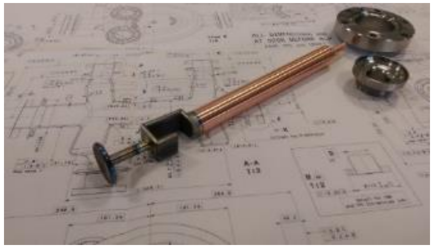
- Table control system with local and tunnel remote control possibility
- Cryogenic control interface for hardware Cryo OK signal
- Separate access system interface for RF controls and for table control
- Dual Beam interlock link for LSS6 and RING
- Low level RF (LLRF) VETO fibre link and extra contact for conditioning RF VETO

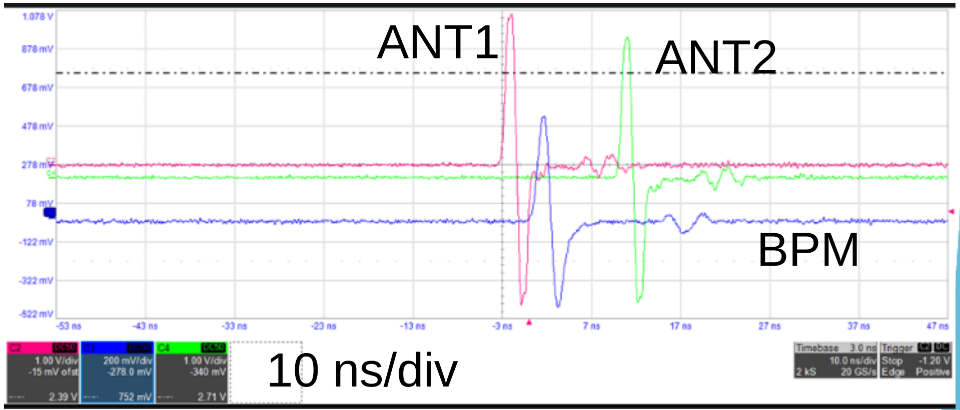
D. Glenat et al.

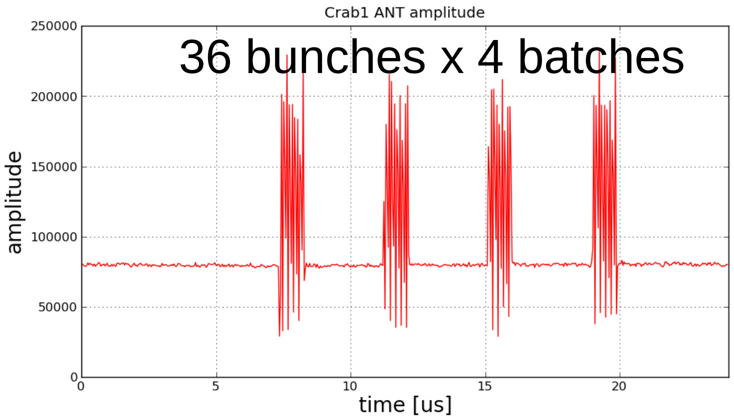
Direct Beam Coupling

- Due to the hybrid field ANT & HOM coupler design, we saw strong coupling to the beam passage on top of measuring cavity field variation

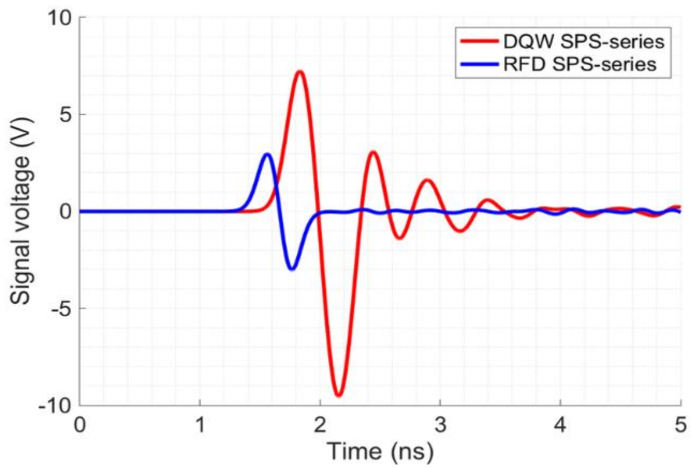


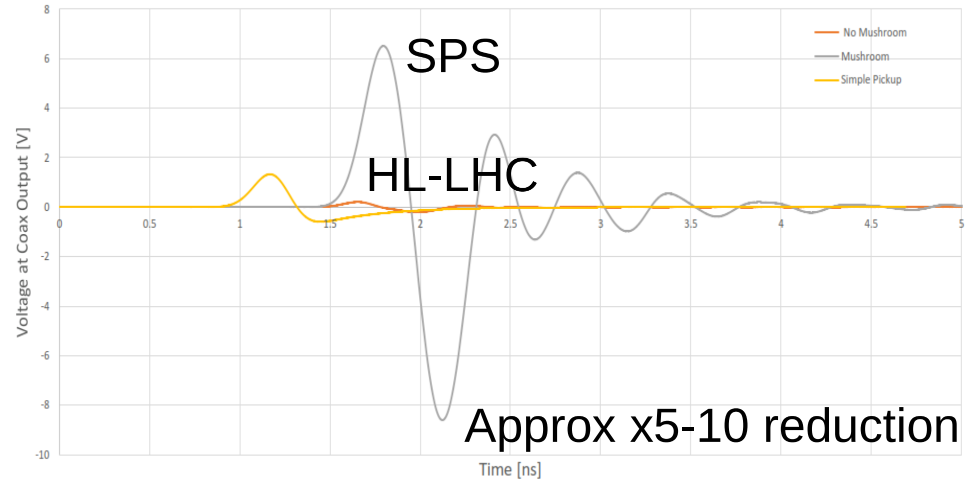




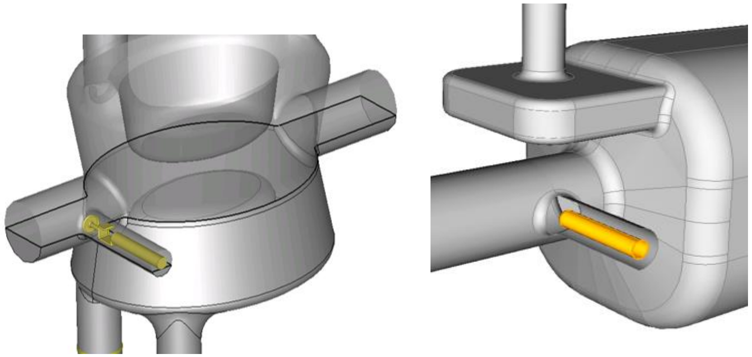


Direct Beam Coupling, Mitigation

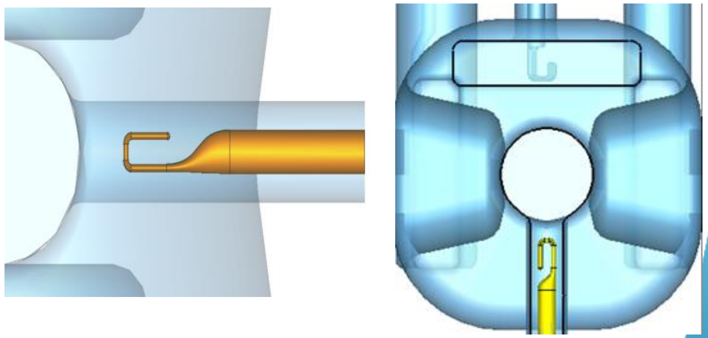




SPS Field ANT



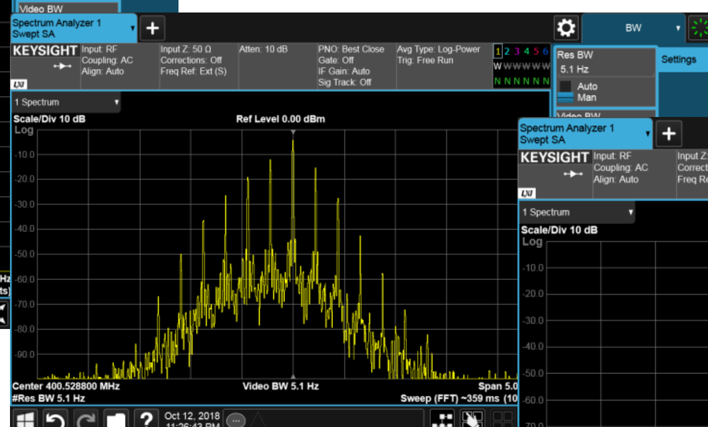
HL-LHC Field ANT

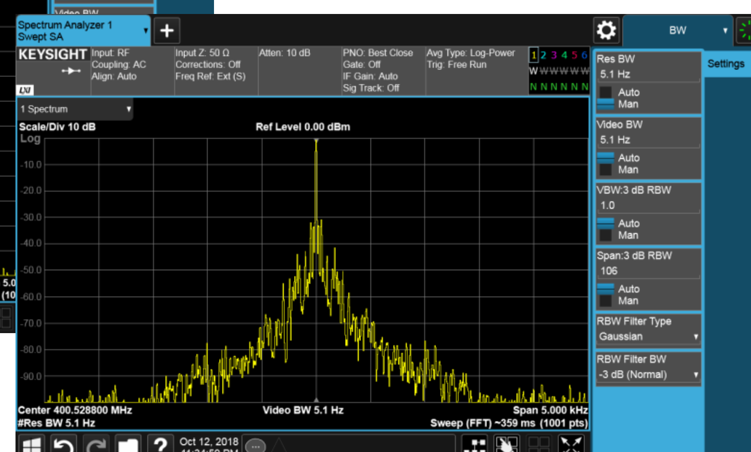


Electro-acoustic Instabilities > 1MV

- At 1MV, the LFD is ~ 400 Hz $(1/2$ the cavity BW)
- Self excited loop not implemented in early 2018, tested later in Nov.
- Cured by with tuning loop or with feedback. following the cavity tune with slow voltage ramp & tuning loop on.

Field Antenna Spectrum, manual tuning

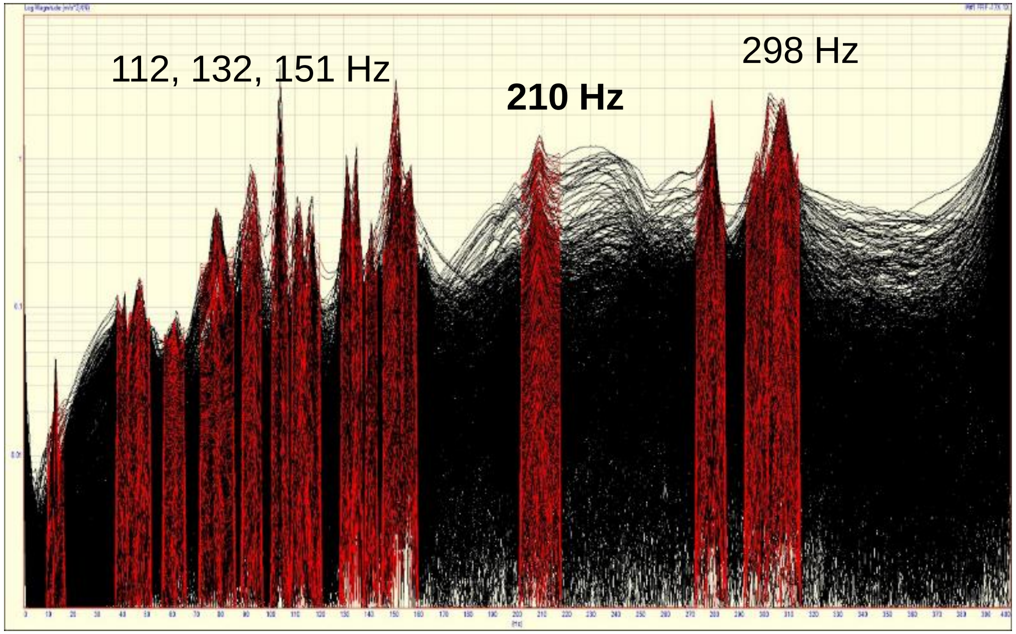




Modal Analysis of Bare Cavity

- Measurements on bare cavities with 5 tri-axial accelerometers & modal hammer

Measured Transfer Functions



Courtesy: L. Lacny, M. Guinchard, T. Jones, EDMS 1771639

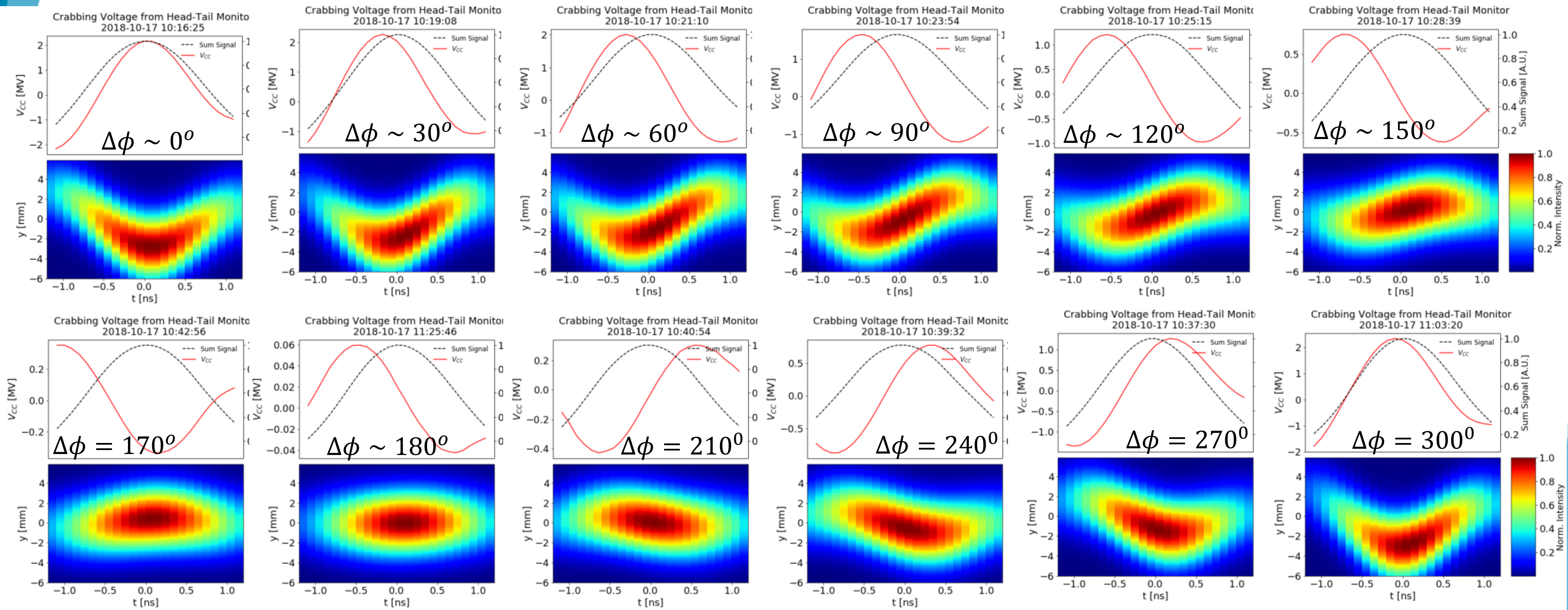
Final Comments

- SPS Crab Cavities
  - SPS experience was invaluable for both hardware and beam validation "almost" LHC like environment
  - Several operational aspects will be fine-tuned during 2021-23. Scrubbing will be needed before MDs
  - No unknown "fast failures" observed during SPS-2018 tests, have to probe the beam behaviour near quench fields ($> 2\ \mathrm{MV}$)

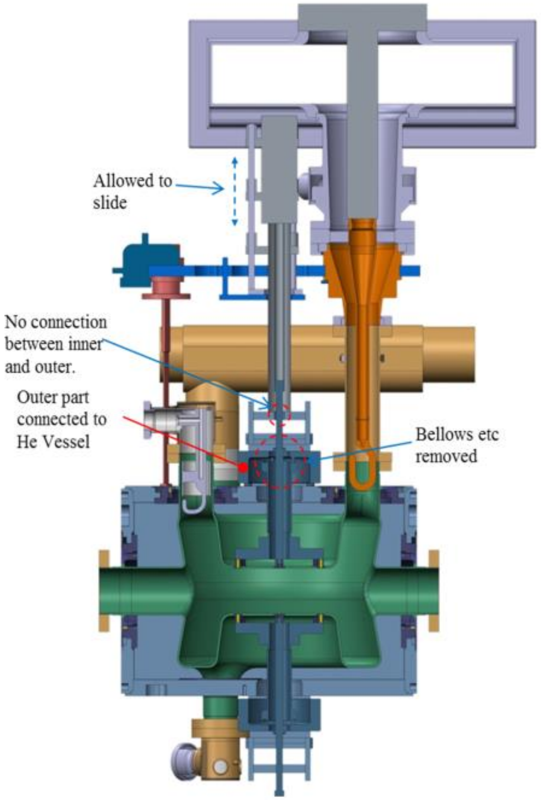
- Special thanks to our collaborations (UK & US) who played a critical part in the SPS success

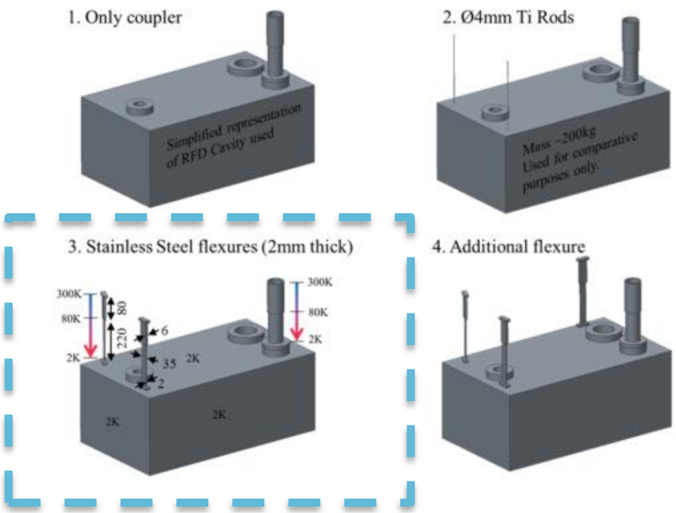
Backup

Transparency Tests

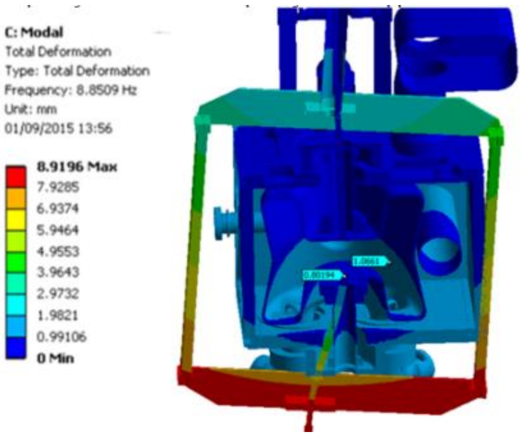


Dressed Cavity Modal Frequencies



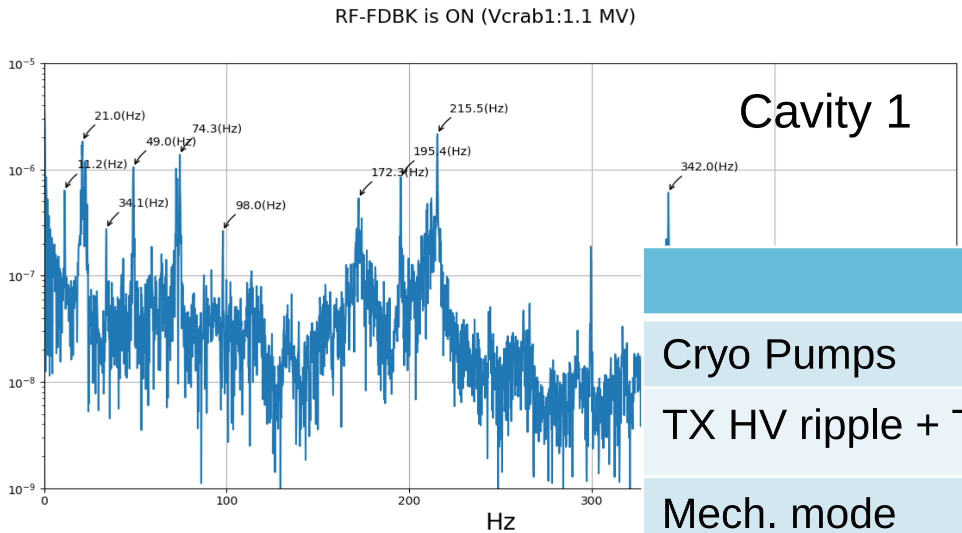


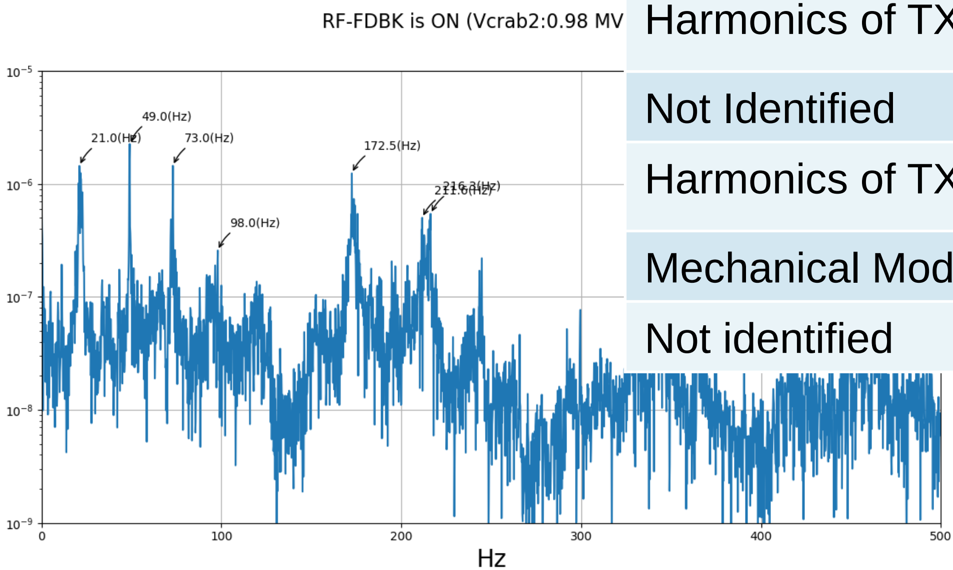
8.5 Hz, w/o Flexural Blades



Analysis	Max Deformation (mm)	Max von-Mises stress (MPa)	Mode 1 Frequency (Hz)	Mode 2 Frequency (Hz)	Mode 3 Frequency (Hz)	Mode 4 Frequency (Hz)
1	3.9	183	7.7	8.3	16.1	61.1
2	0.24	65.2	8.5	25.3	38.3	70.9
3	0.025	15.3	25.1	48.3	56.5	122
4	0.01	10.5	27.2	50.15	66.9	174

Microphonics, Feedback ON





	Cav 1 [Hz]	Cav 2 [Hz]
Cryo Pumps	20-30	20-30
TX HV ripple + Tuner mode	49	49
Mech. mode	74	73
Harmonics of TX ripple	98	98
Not Identified	171	172
Harmonics of TX ripple ?	195	
Mechanical Mode	210	212
Not identified	342	342

Courtesy: E. Yamakawa

Overview of 2K Operation