# HL-LHC Crab Cavities and SPS Tests

**R. Calaga on behalf HL-LHC WP4**

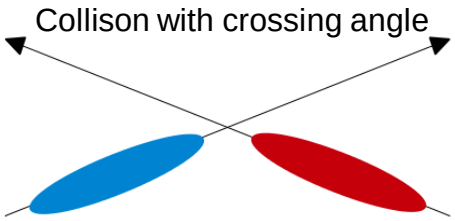
**CERN**

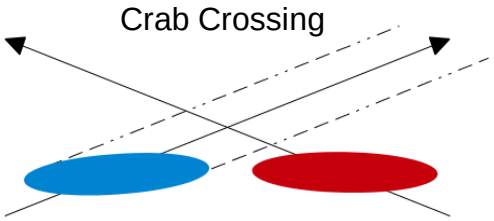
23 July 2019, EIC User Group Meeting, Paris
(Also presented at the recent EPS-HEP Meeting)

# HL-LHC Crab Cavity System

*Use 8+8 Superconducting compact RF crab cavities (ATLAS + CMS) to compensate the geometric angle of ~500 $\mu rad$*

*Recover ~70% of the Peak Luminosity – use levelling with $\beta^*$*

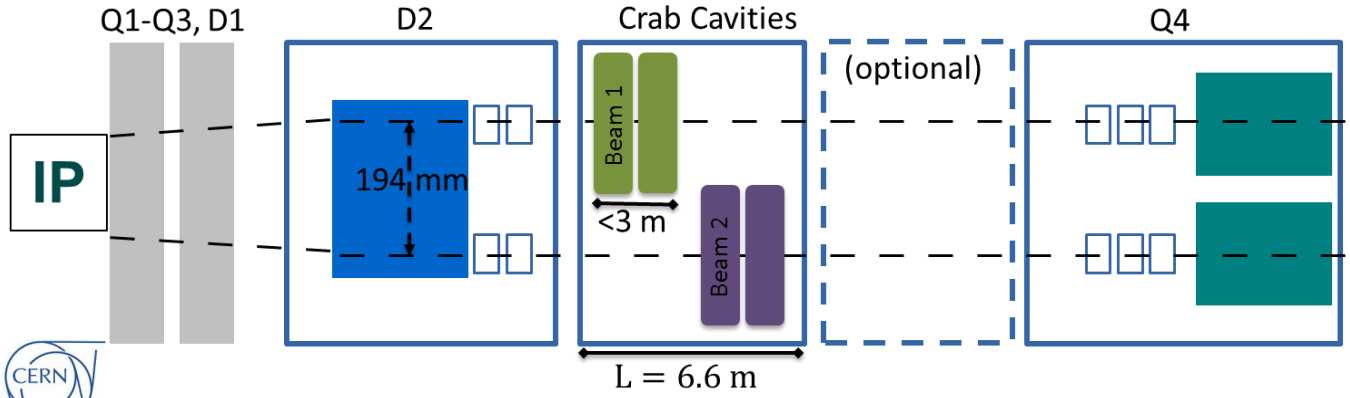



$$\Phi = \frac{\sigma_z}{\sigma_x}\left(\frac{\theta_c}{2}\right)$$

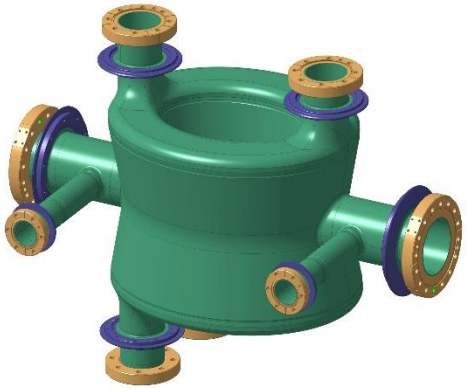
$7.55\ cm$

$\sim 7\ \mu m$

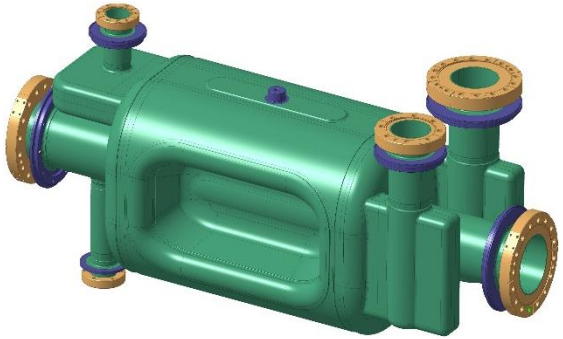


# Dressed Cavity Geometries

Double Quarter Wave



RF Dipole



$f_0 = 400$ MHz

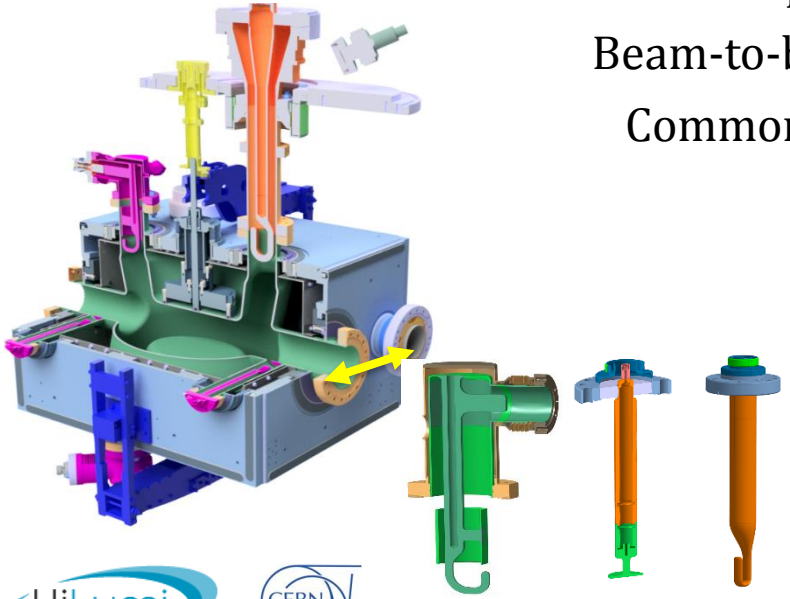
$V_T = 3.4$ MV/cavity

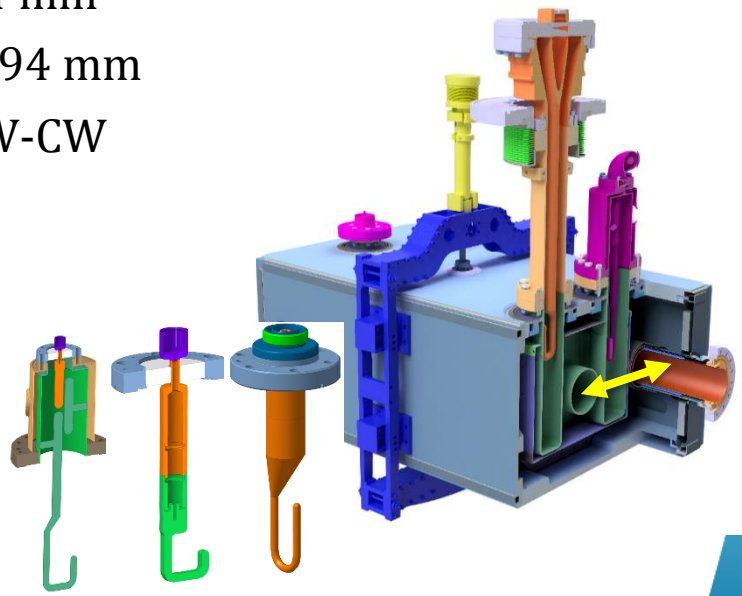
$(E_p, B_p < 40\ \mathrm{MV/m}, 70\ \mathrm{mT})$

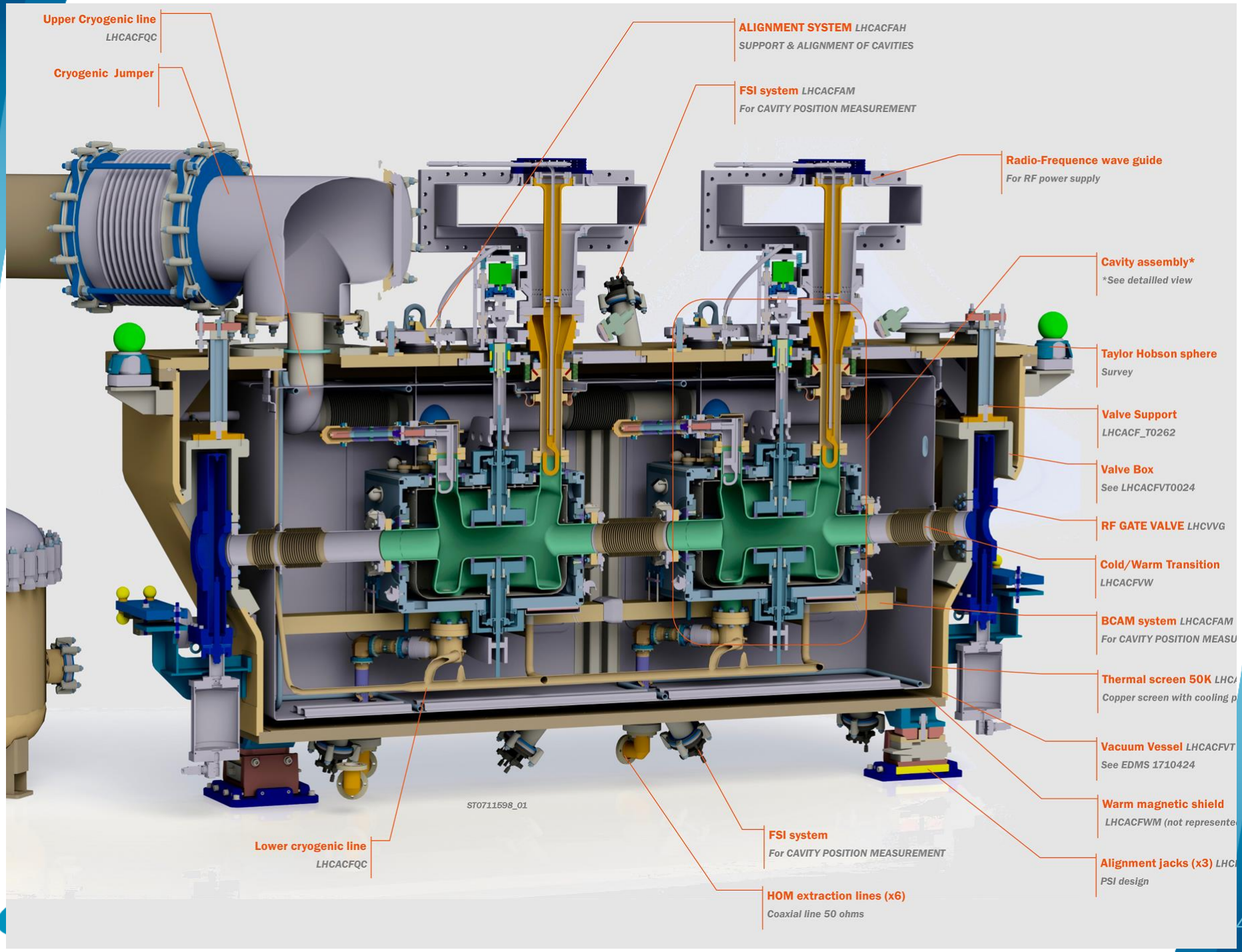
Beam aperture = 84 mm

Beam-to-beam dist = 194 mm

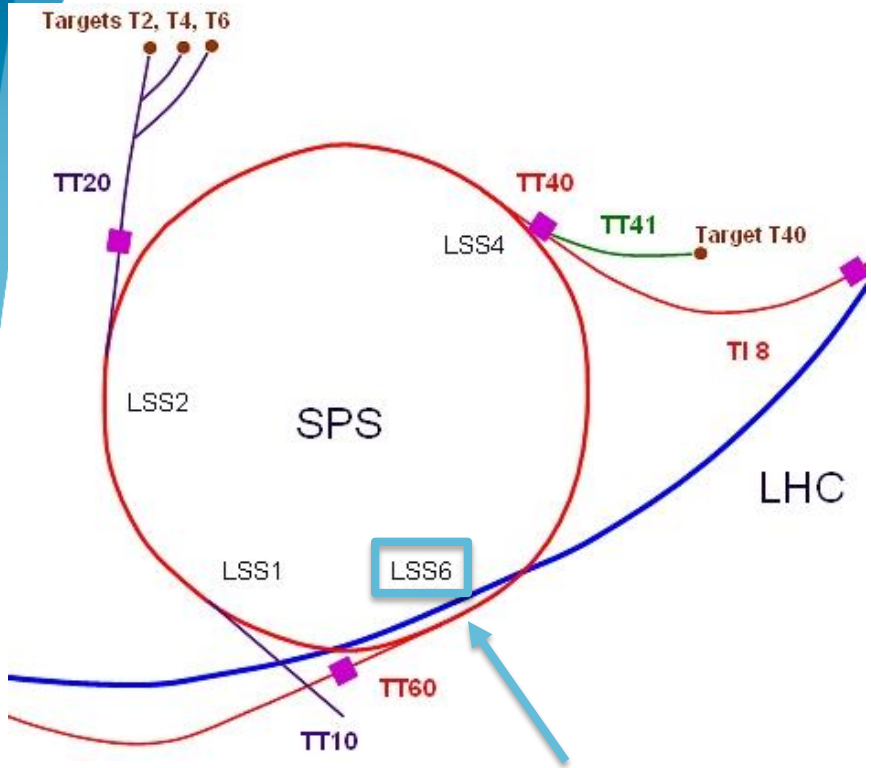
Common FPC = 40 kW-CW



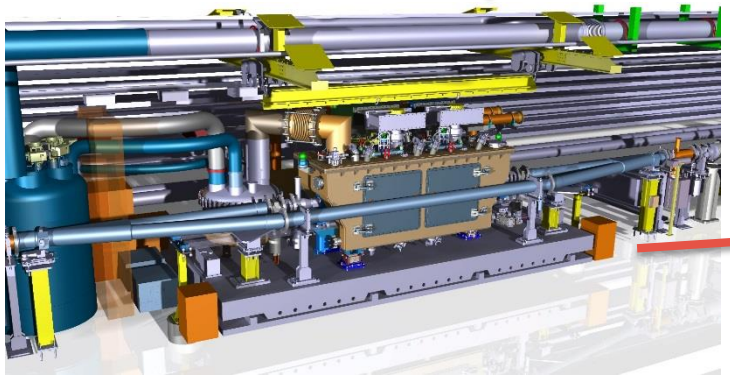


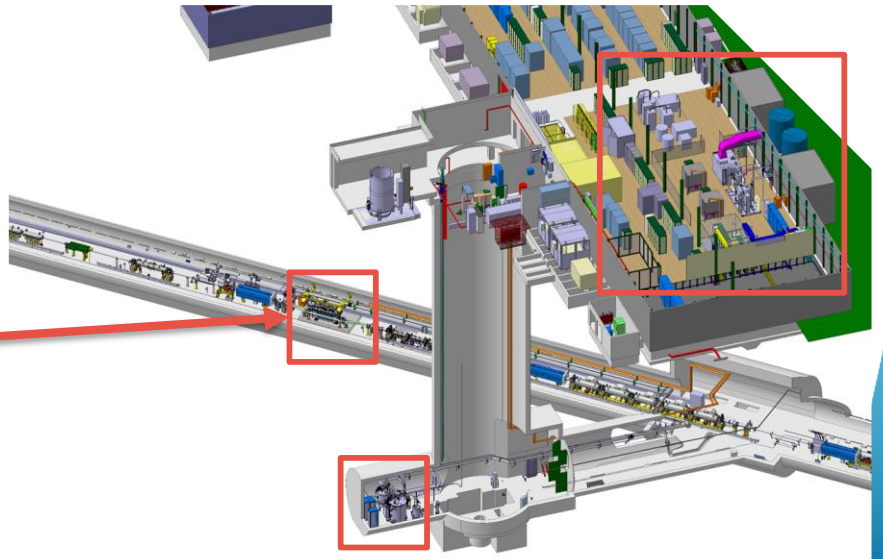

Upper Cryogenic line
LHCACFQC
Cryogenic Jumper
ALIGNMENT SYSTEM LHCACFAH
SUPPORT & ALIGNMENT OF CAVITIES
FSI system LHCACFAM
For CAVITY POSITION MEASUREMENT
Radio-Frequence wave guide
For RF power supply
Cavity assembly*
*See detailled view
Taylor Hobson sphere
Survey
Valve Support
LHCACF_T0262
Valve Box
See LHCACFVT0024
RF GATE VALVE LHCVVG
Cold/Warm Transition
LHCACFVW
BCAM system LHCACFAM
For CAVITY POSITION MEASU
Thermal screen 50K LHCA
Copper screen with cooling p
Vacuum Vessel LHCACFVT
See EDMS 1710424
Warm magnetic shield
LHCACFWM (not represente
Alignment jacks (x3) LHC
PSI design
ST0711598_01
Lower cryogenic line
LHCACFQC
FSI system
For CAVITY POSITION MEASUREMENT
HOM extraction lines (x6)
Coaxial line 50 ohms

# 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 |

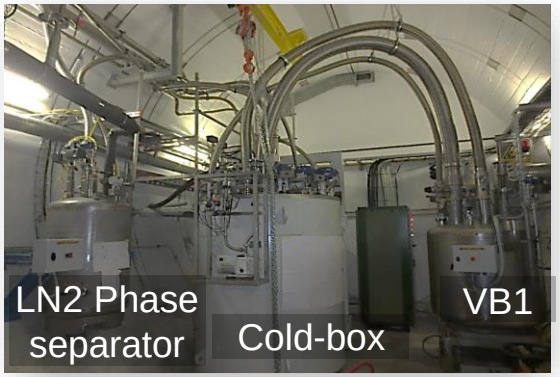




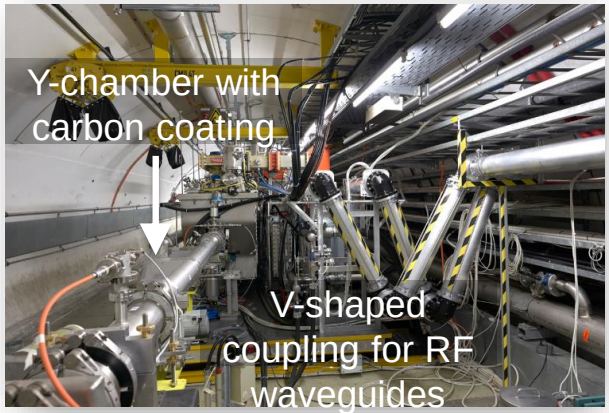
# SPS-LSS6 – Crab Cavity Module

# SPS-Crab Installation

- Massive installation of a new RF & Cryo plant in SPS machine during 2017/18



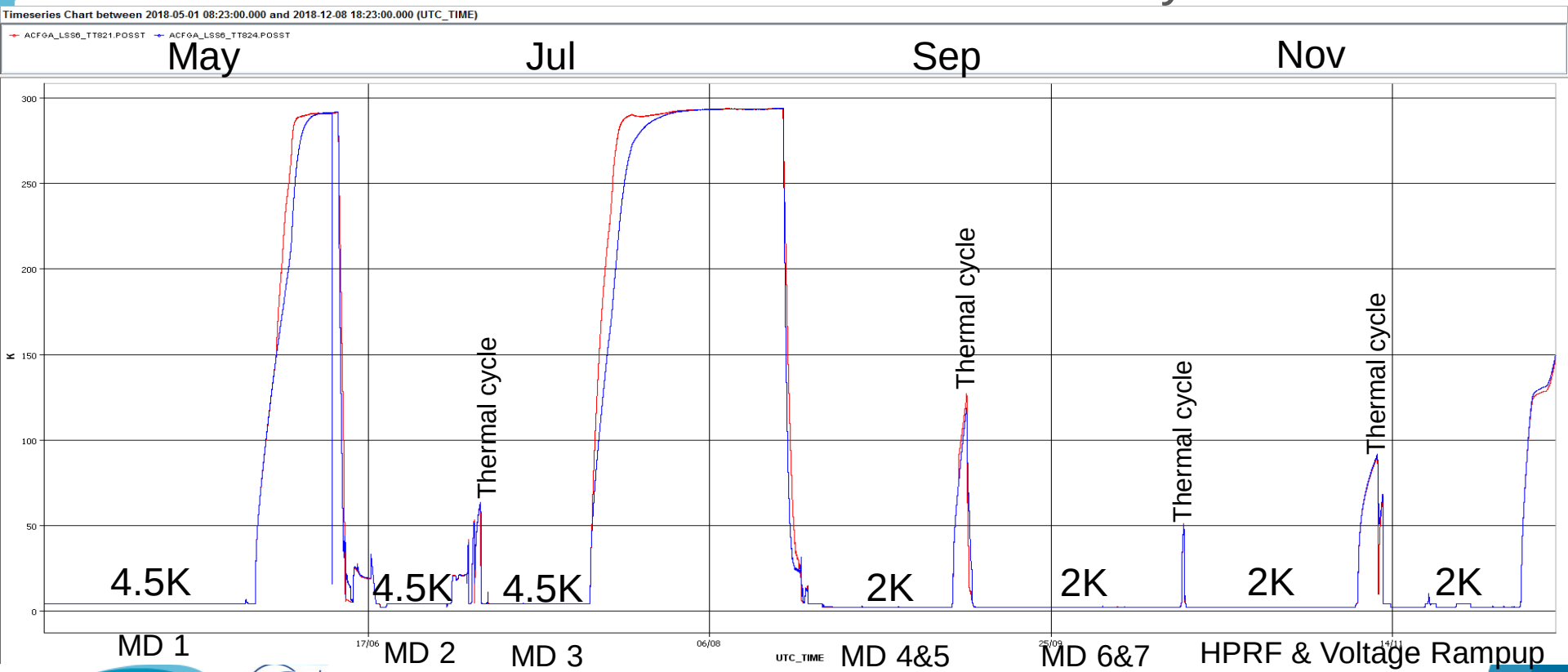

# Expected SPS Test Sequence

- 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

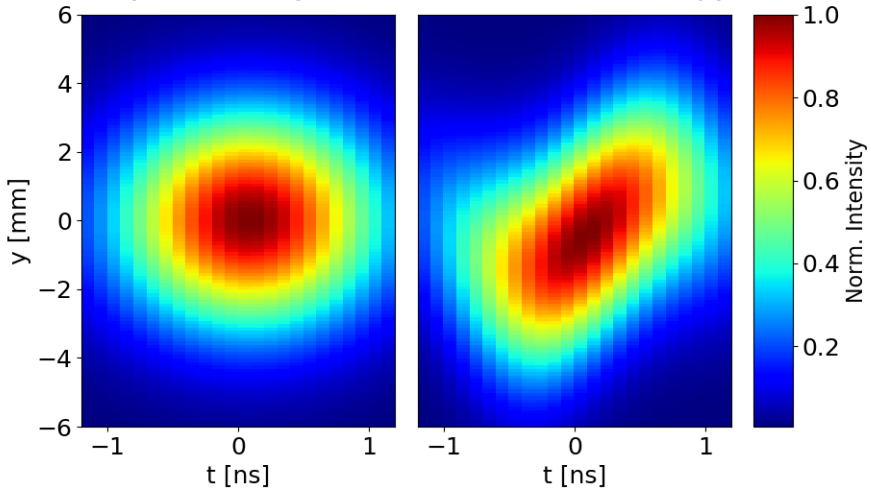
| MD# | | Cav1 | Cav2 [MV] | Temp [K] | Energy [GeV] |
|---|---|---|---|---|---|
| 1 | First crabbing, phase and voltage scan | 0.5 | 0 | 4.5 | 26 |
| 2 | 270 GeV ramp with single bunch | 1-2 | 0 | 4.5 | 26, 270 |
| 3 | Intensity ramp up | 1 | ~0.3 | 4.5 | 26 |
| 4 | 270 GeV coast setup | 1.0 | 0.5 | 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

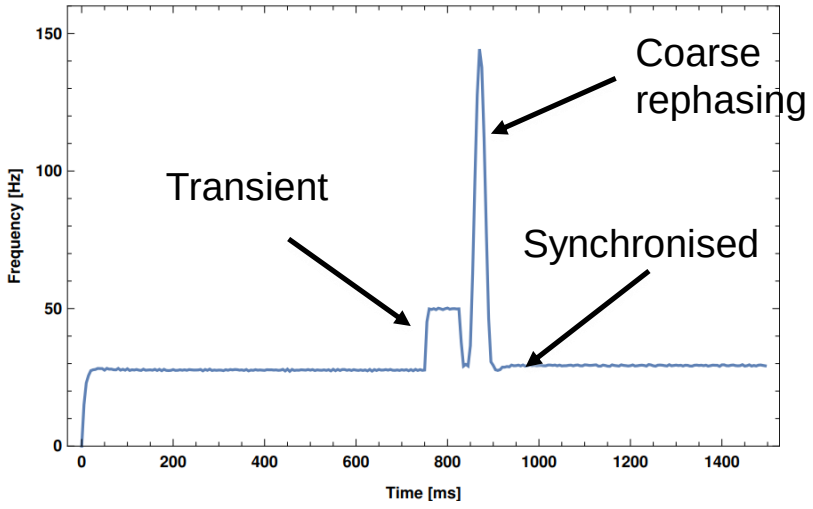
Beam measurements showed 10-20% larger voltage than RF measurements

L. Carver, T. Levens et al.

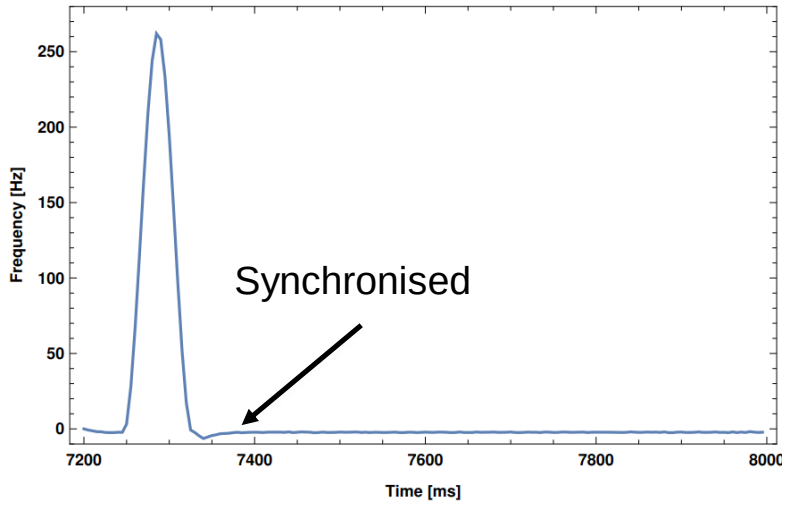
# How to synchronize Crab-RF ?

- 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

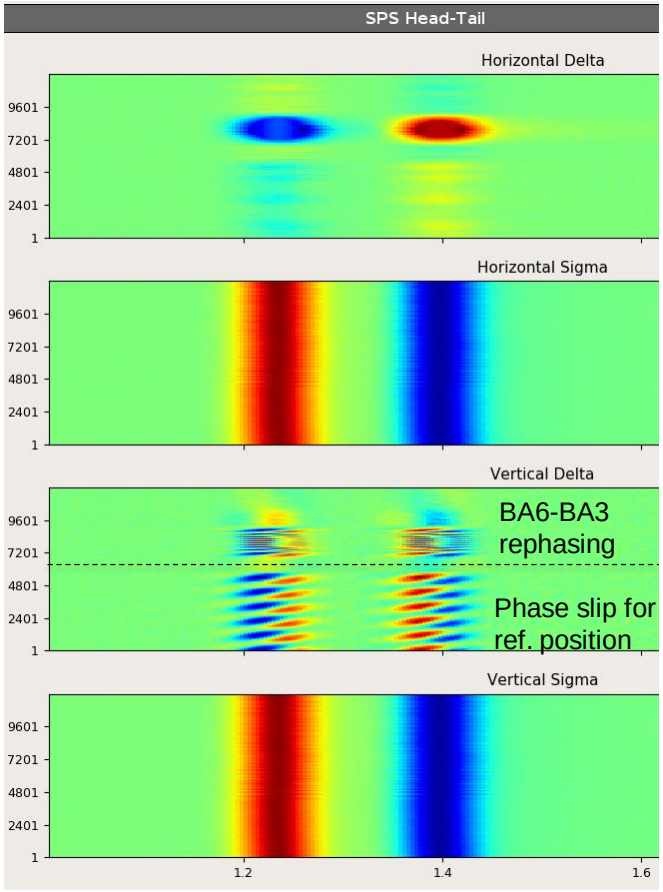


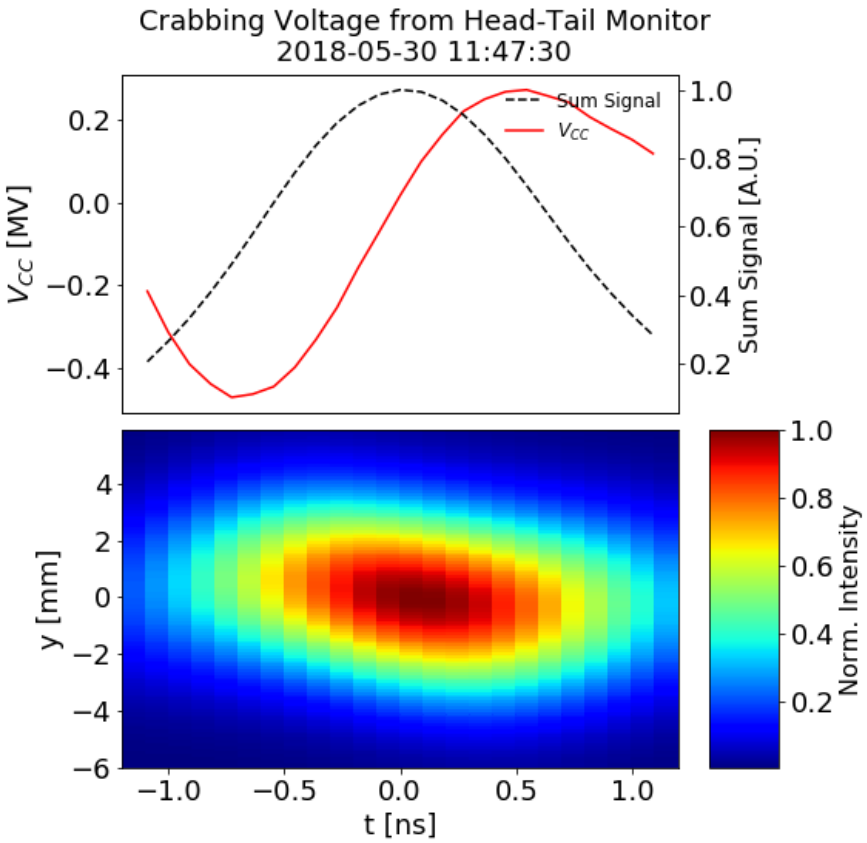

270GeV, Synchronized after ~7.4s
i.e. 0.2s after reaching flat top




T. Bohl et al.

# Reconstruction of Crabbing using HT

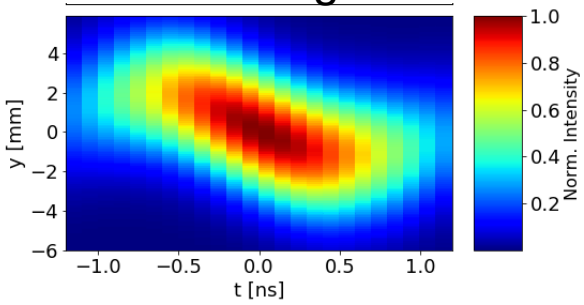



# of turns for ref position along the bunch ~ 2k turns
RF re-synchronization ~ 1s after injection

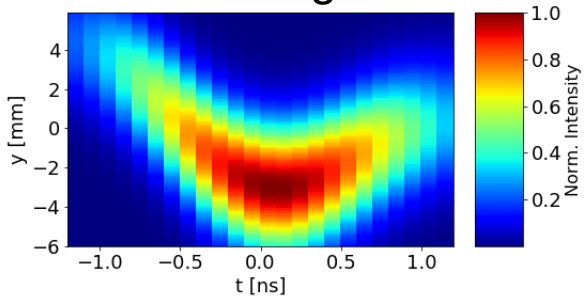
# Phase Scans & “Transparency”

0 Deg

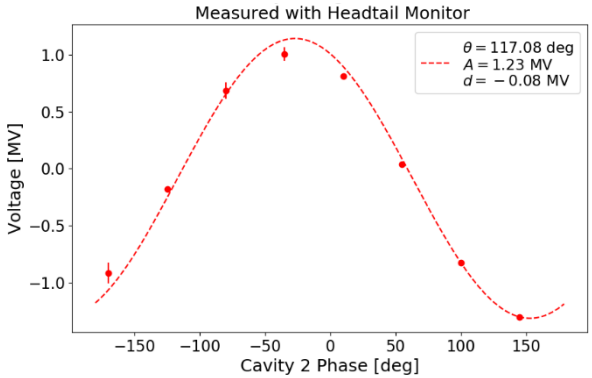



**RF phase scan w.r.t the beam phase with cavity 1**

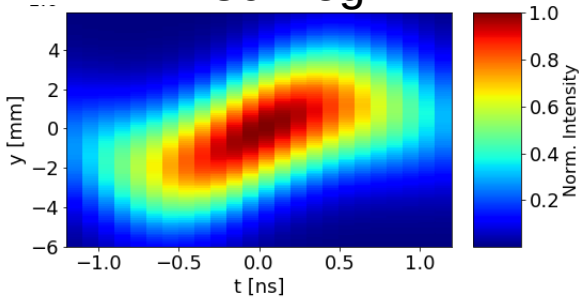
90 Deg




CAV2 Voltage/Phase

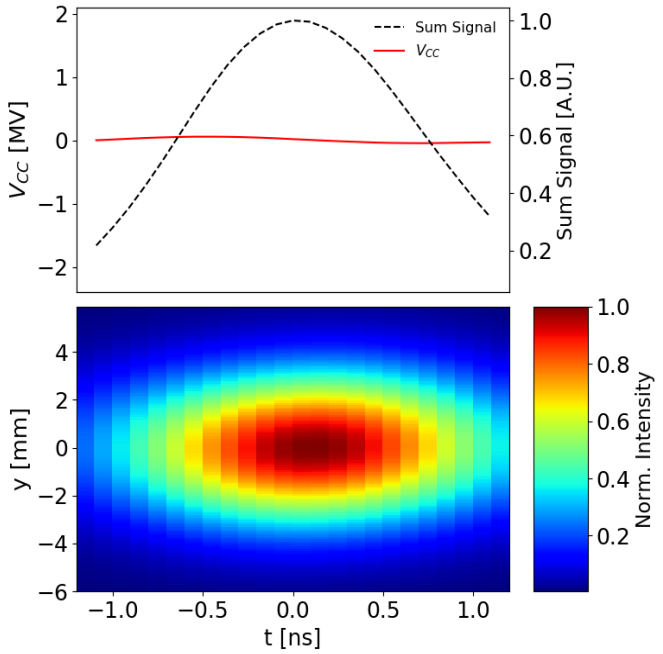



180 Deg

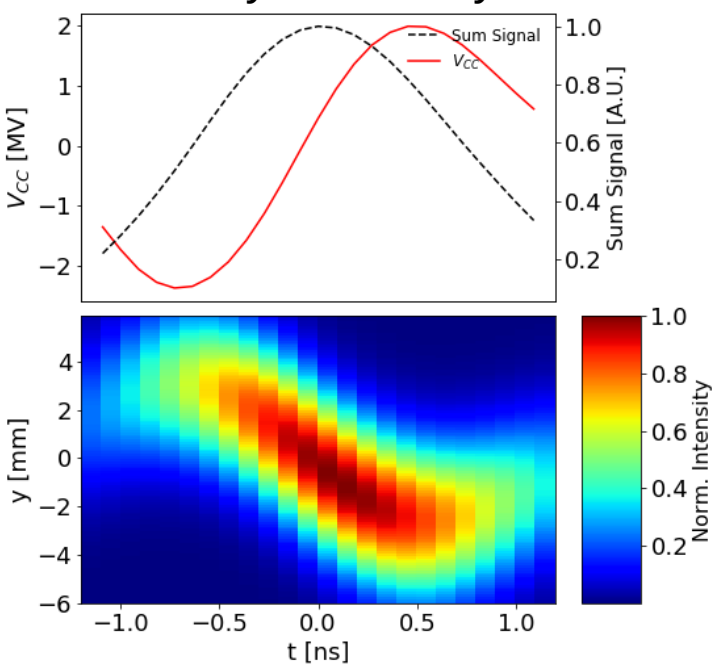


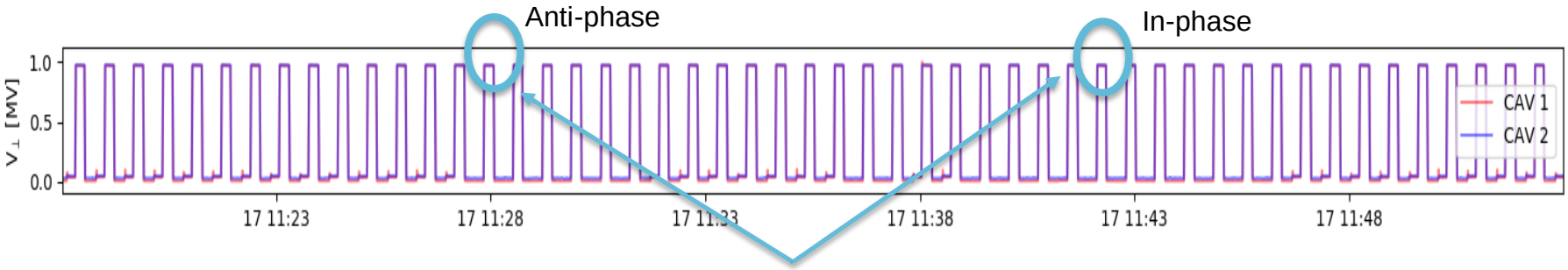
# Transparency: V=1MV in both cavities

Cavity 1 - Cavity 2




Cavity 1 + Cavity 2



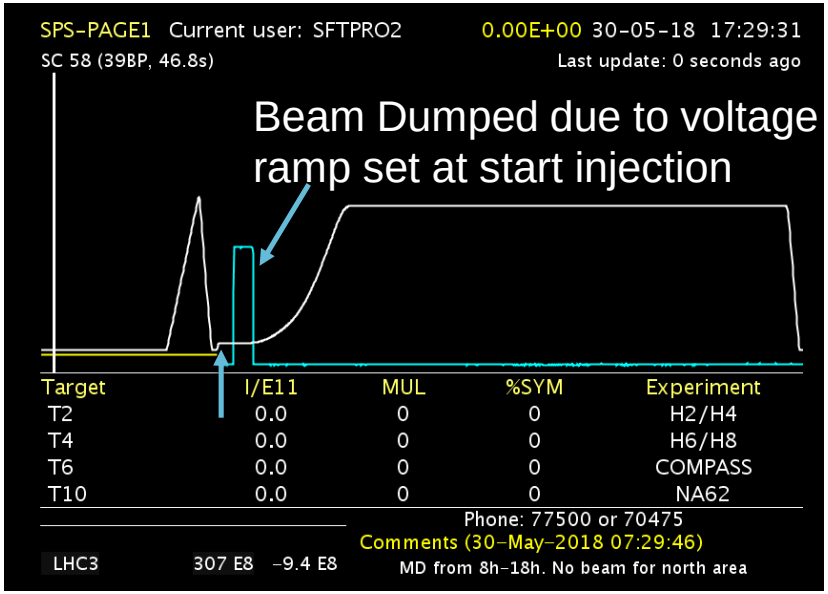



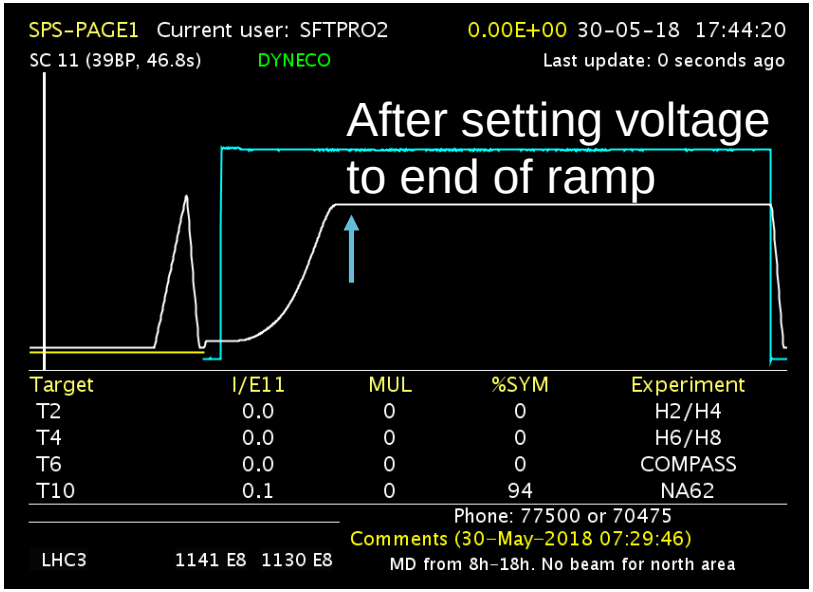

SPS MD cycle (~20 sec flattop)

# Energy Ramp to 270 GeV

- Due to large frequency swing during energy ramp, with cavities powered at fixed frequency, the beam is rapidly lost due to resonant excitation while crossing one of the betratron sidebands.
- With cavities off during the ramp the beam makes it through without losses. New operational scenario for HL-LHC

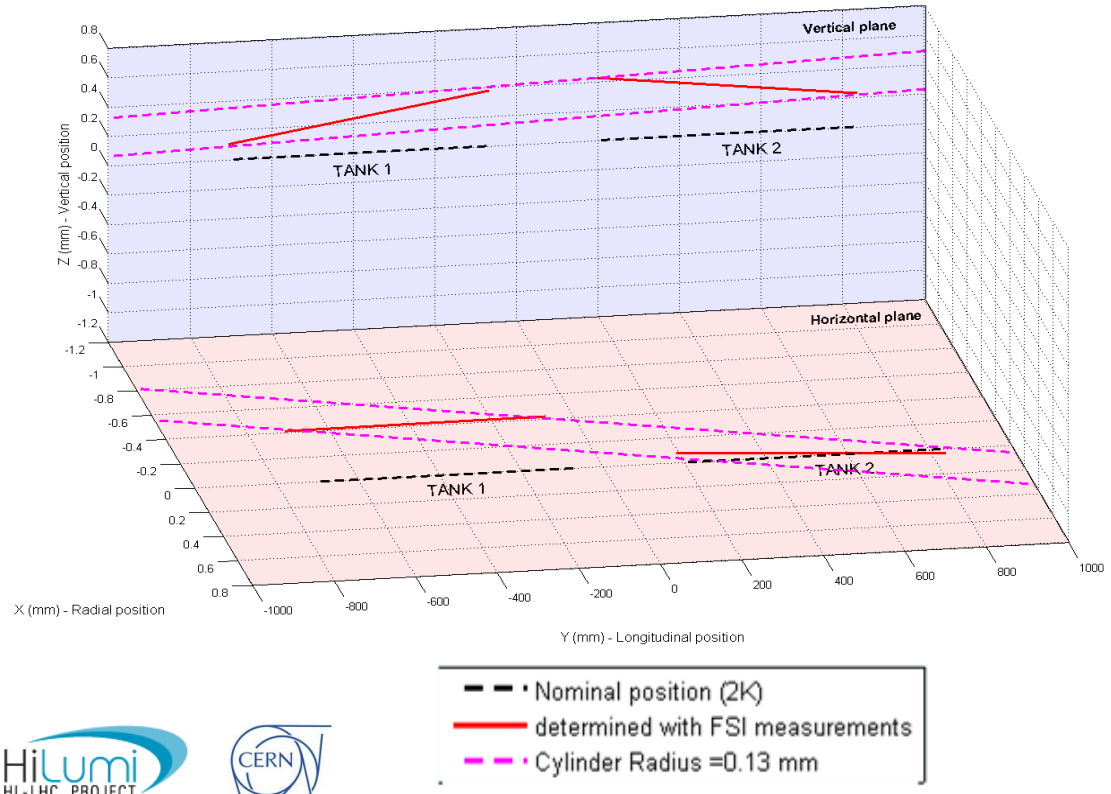
Cav1 ~1MV (400.787 MHZ), Cav2 off (400.528 MHz)

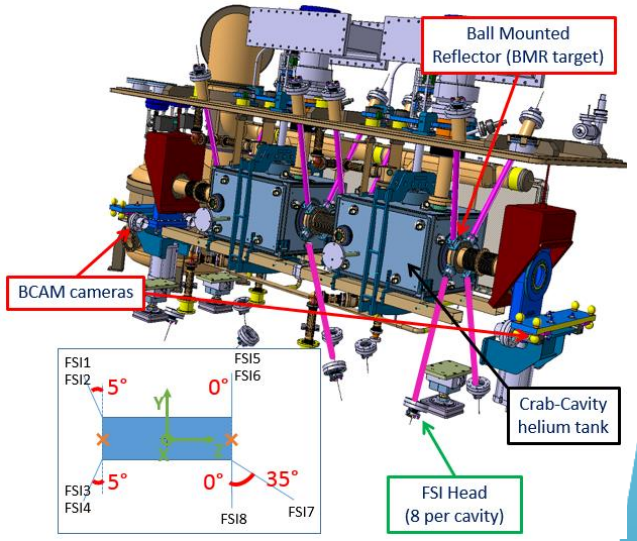


# Cavity Alignment

- Tight intra-cavity alignment tolerances transversely ($\pm 500$ μm at 2K) for HL-LHC
- Alignment reached w/o compensation is within a radius of 130 μm. FSI system validated and allows for continuous monitoring of cavity positions

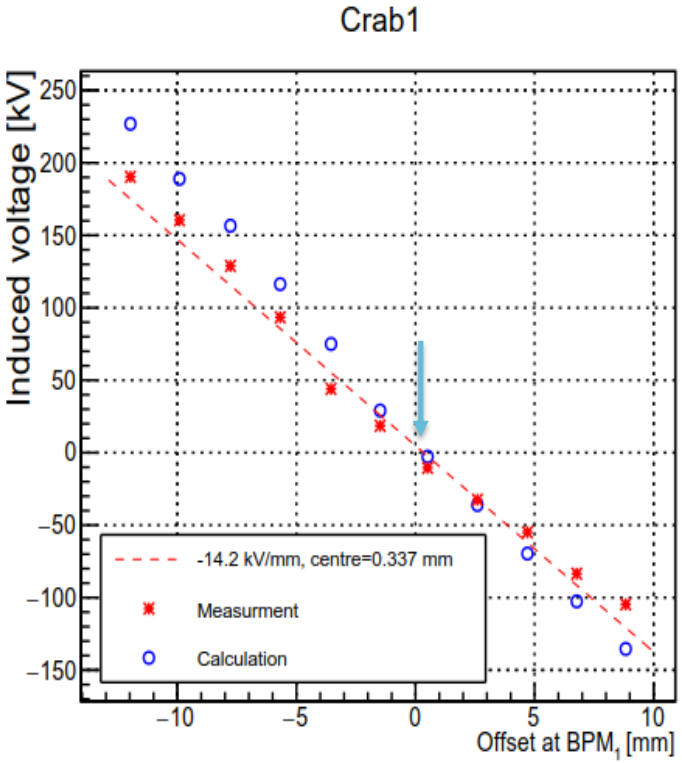


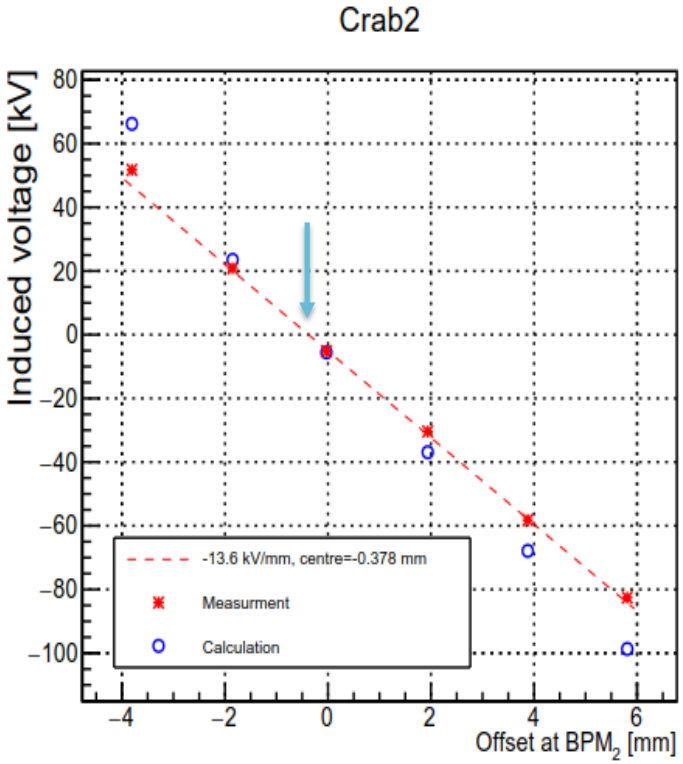




Courtesy: EN-ACE-SU/MME

# Beam Loading & Electrical Center

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

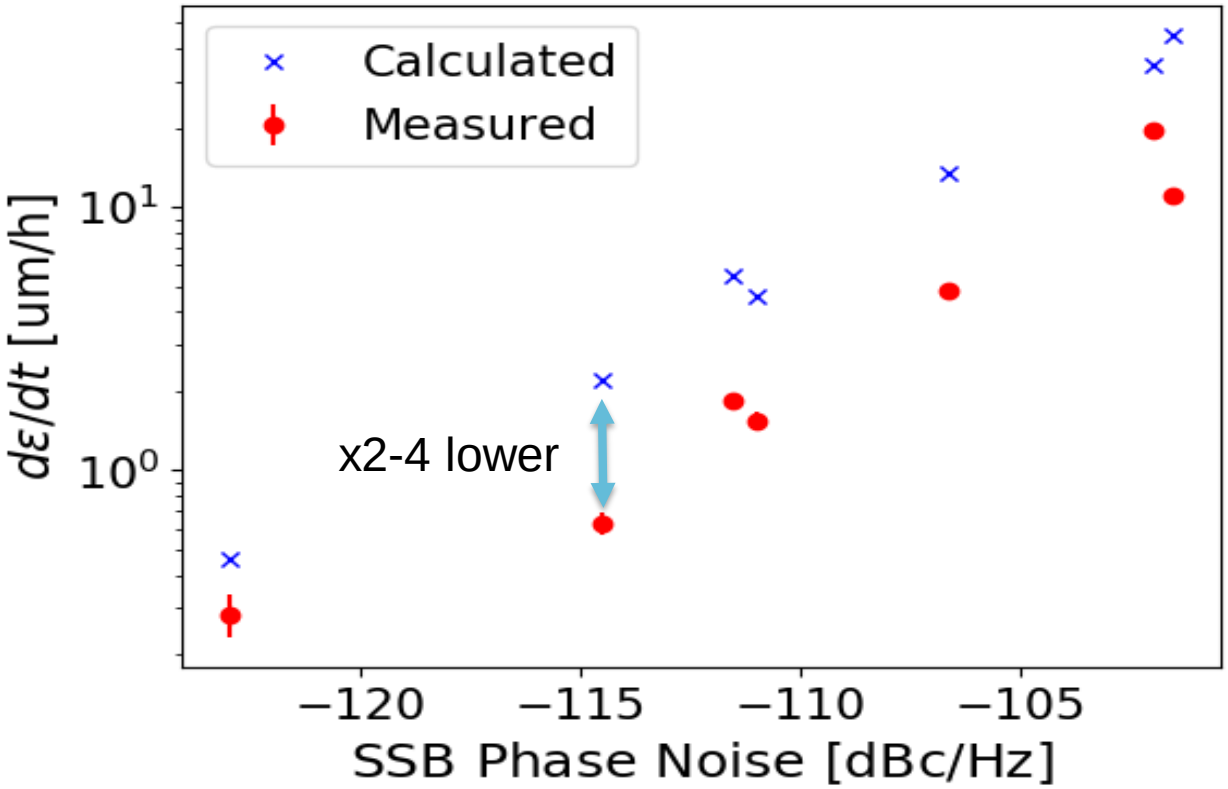



E. Yamakawa et al.

# Emittance Growth

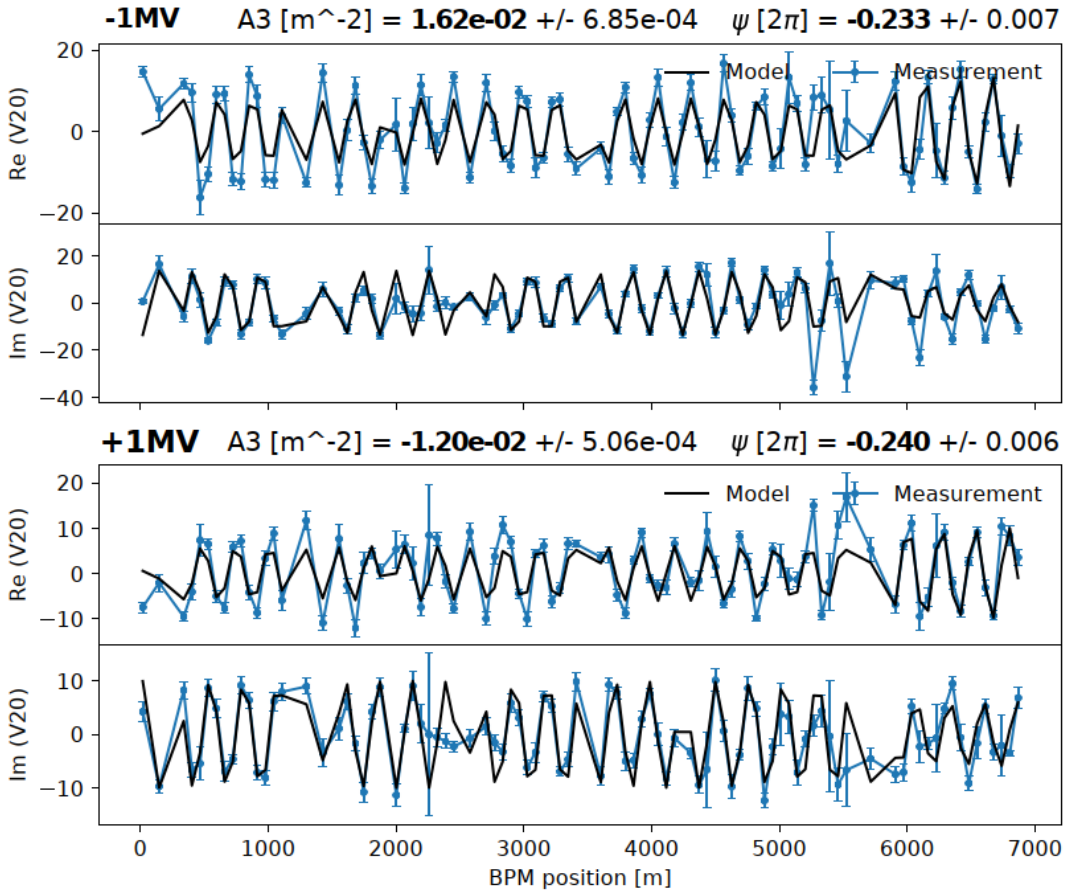
- SPS natural emittance growth at 270 GeV, $\leq 0.5\ \mu m/h$. HL-LHC needs to be below $0.05\ \mu m/h$
- CC expected growth with existing electronics (noisy!). Scaling with additional induced noise is qualitatively reproduced but more pessimistic than measured growth




P. Baudrenghien, L. Carver et al.

# RF Multipoles

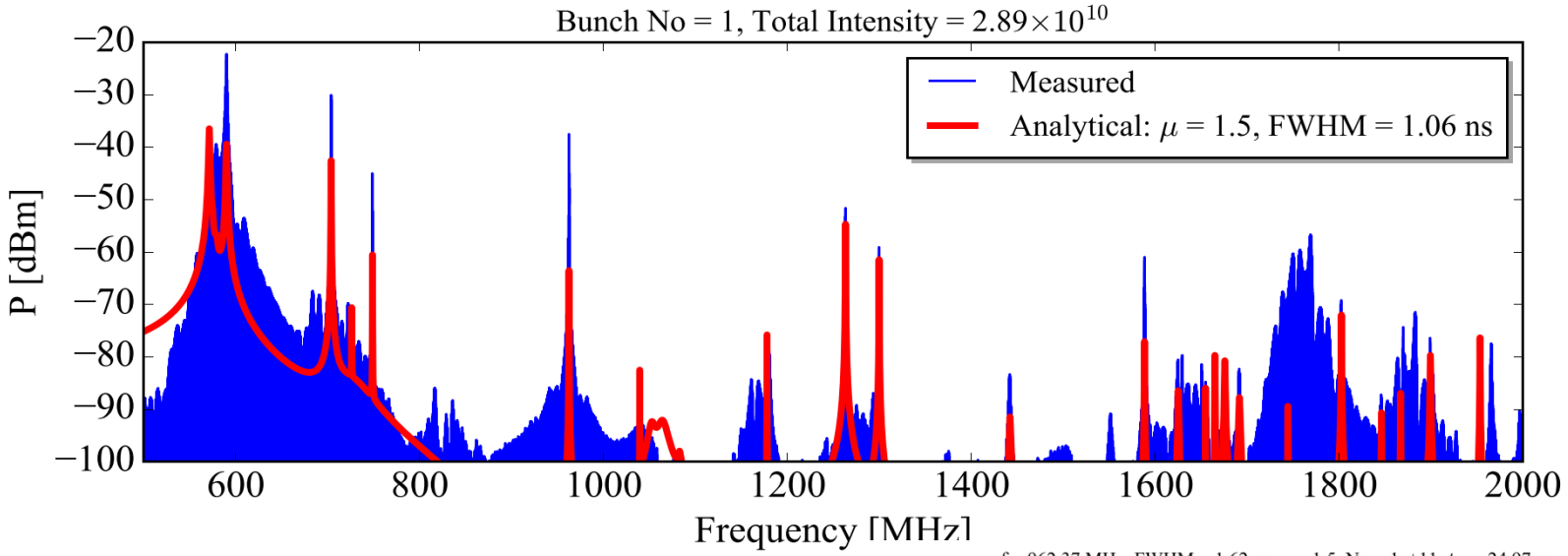
- Very promising results to measure for the first time RF multipoles with beam. But extracting the cavity multipoles from other machine elements still remains challenging



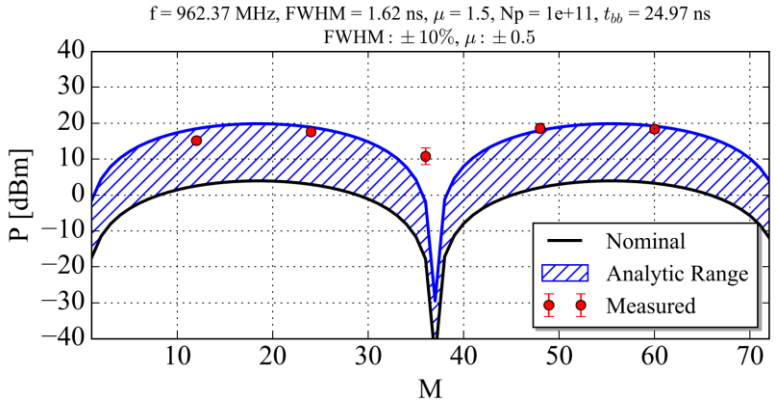

M. Carla et al.

# Higher Order Modes

- Integrated max HOM power measured $< 3$ W. More than 75% from $\sim 960$ 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

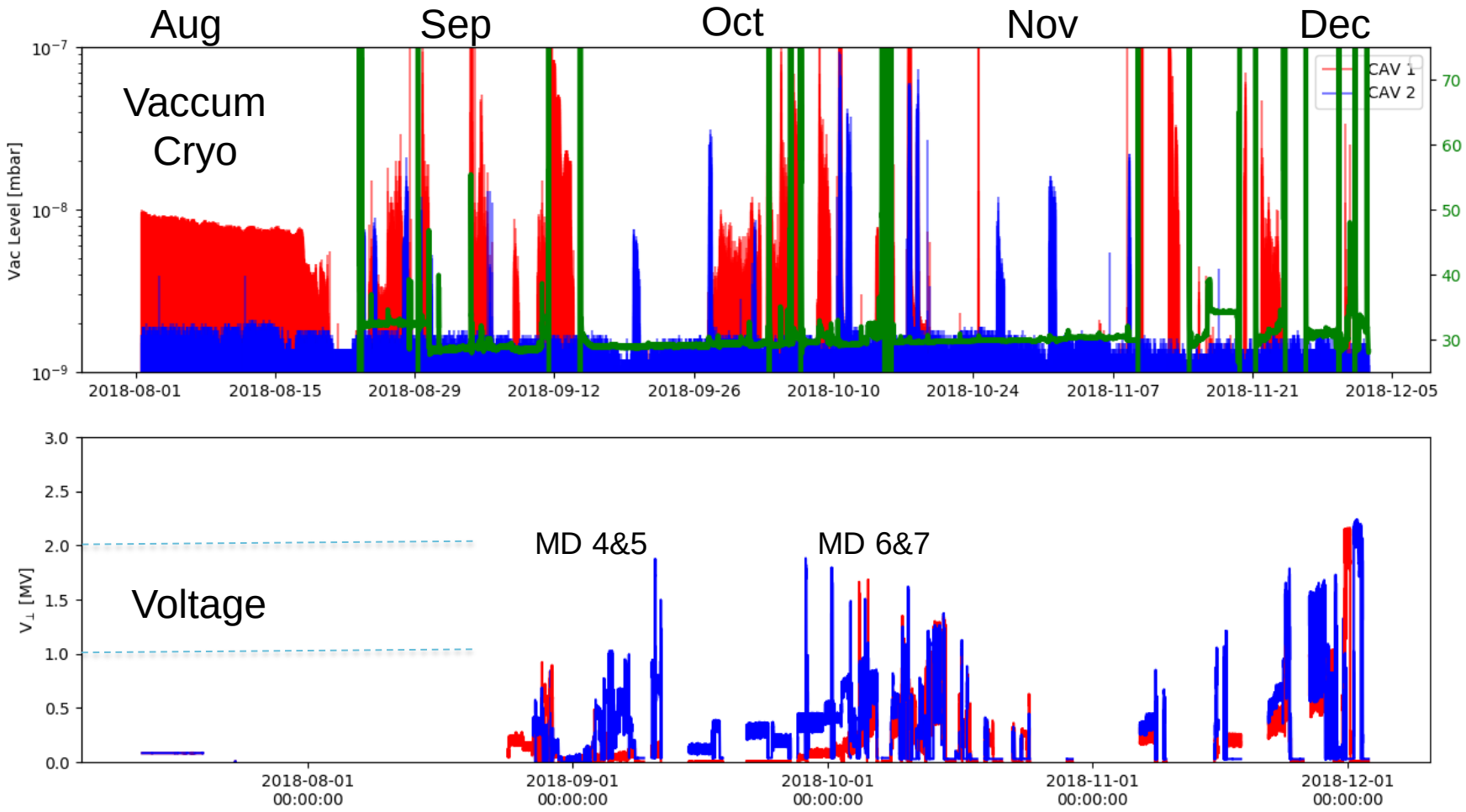
- MD6: 72 bunches at $2 \times 10^{10}$ p/b increased to $4 \times 36$ at $1 \times 10^{11}$p/b (1/2 the max intensity)
  - Limited by crab by-pass pressure rise $10^{-6}\mathrm{mb}$
  - With moderate voltage ($1\ \mathrm{MV}$), no beam induced failures or fast transients seen except for pressure rise
- MD7: $2 \times 60$ bunches at $1 \times 10^{11}$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

# Few Challenges Encountered

- Cavity voltage reach (3.4 MV nominal)
- 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
- Vacuum pressure rise in the bypass

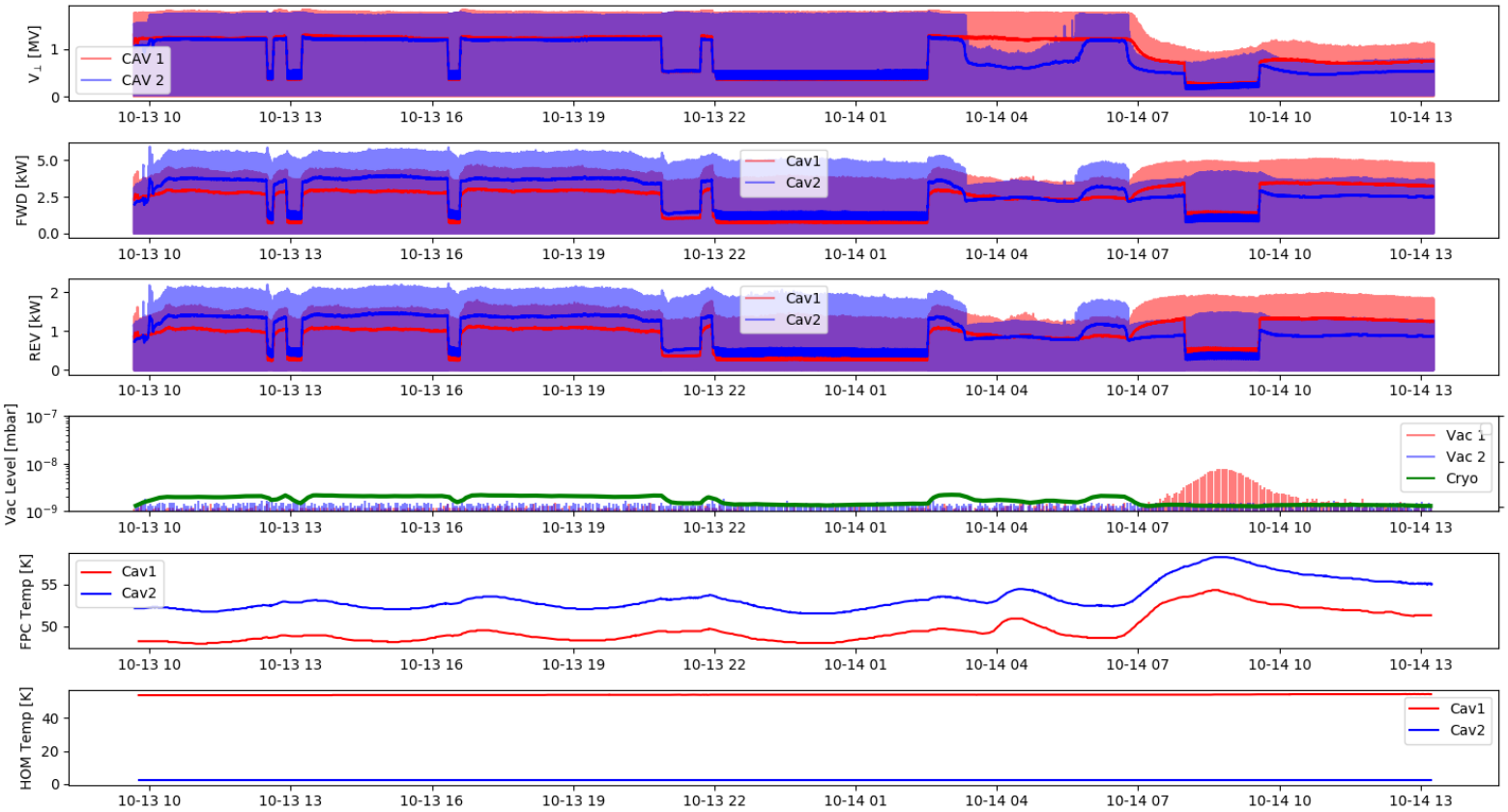
# Average Voltage Evolution (2K)

- Long RF conditioning period to get beyond 1 MV stable operation



# Oct 13, Stable Voltage CAV1/2 – 1.0 MV

- Many hours of stable operation with good correlation between RF and cryogenics. For most MDs 1.0 MV was used as safe operation
- Few occasions with stable operation over many hours with sudden increase in cryo load and loss of RF conditions – not fully understood




Voltage

RF power

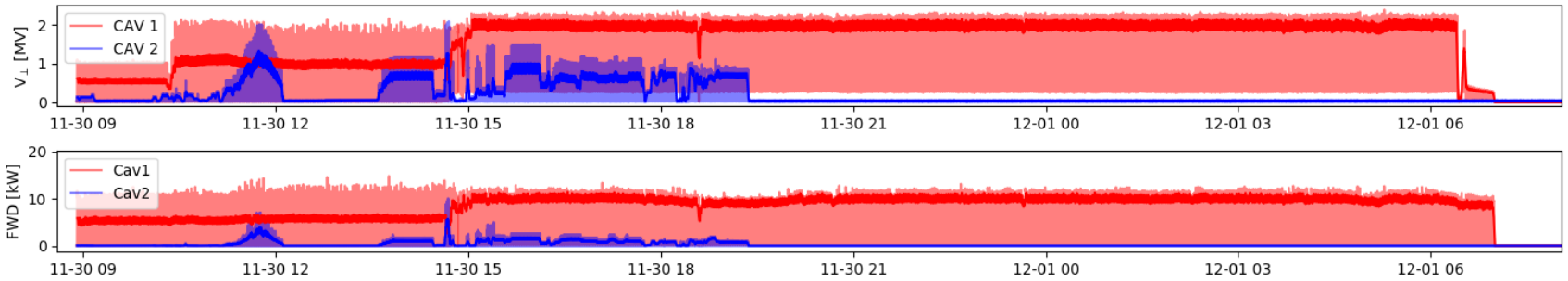
Vacuum
Cryo

Temperature
FPC

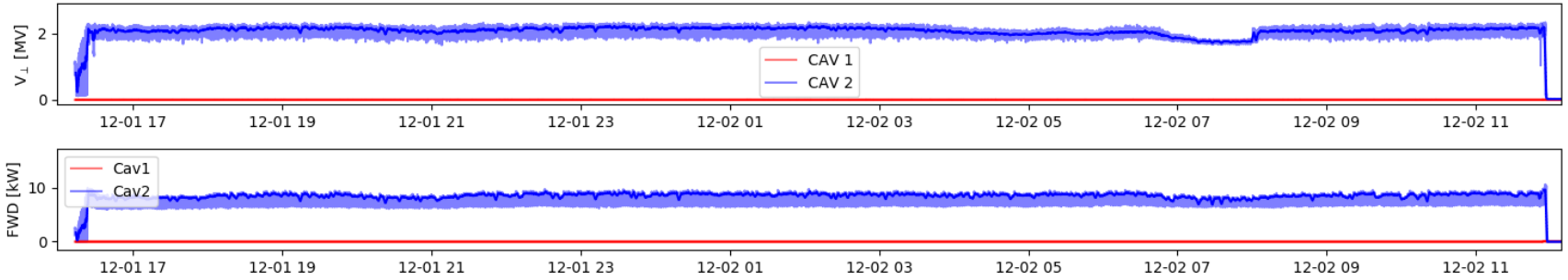
Temperature
HOMs

# Crab Cavity Max Performance, Nov/Dec

Cavity 1 Voltage & RF Power (red)




Cavity 2 Voltage & RF Power (blue)

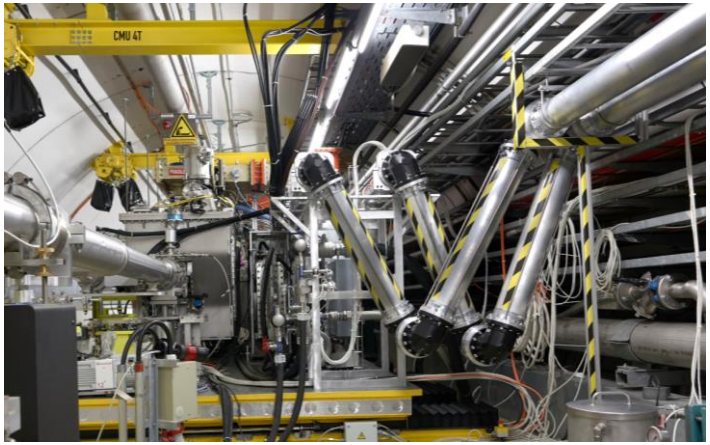



Note: After many hours of stable operation, we observed big thermal load and lost RF conditions, the trigger of such events is not fully understood

# High Power RF

- Two 80 kW IOTs operational in SPS
  - Issues of linearity at very low power ($< 5$ 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

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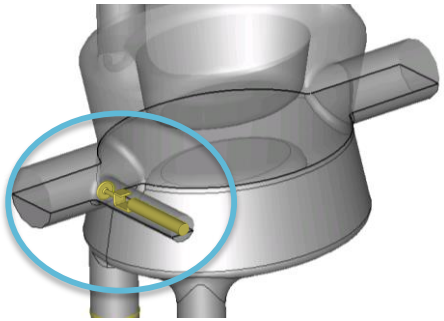
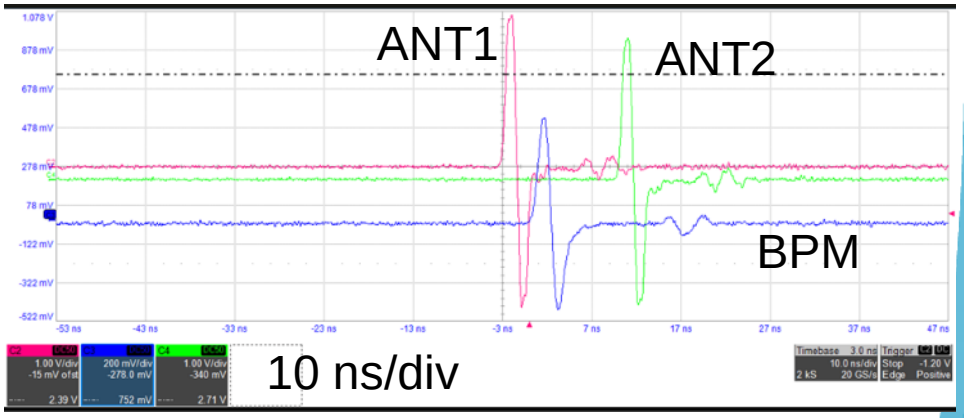
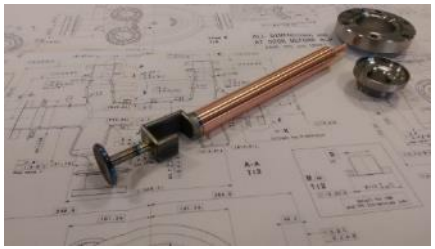
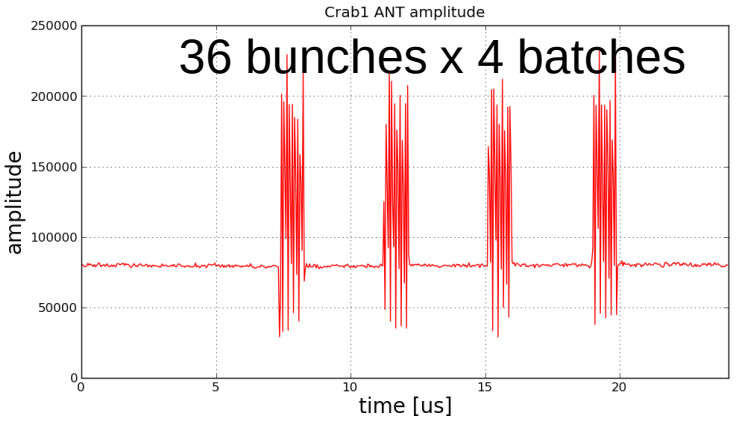
# Direct Beam Coupling

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



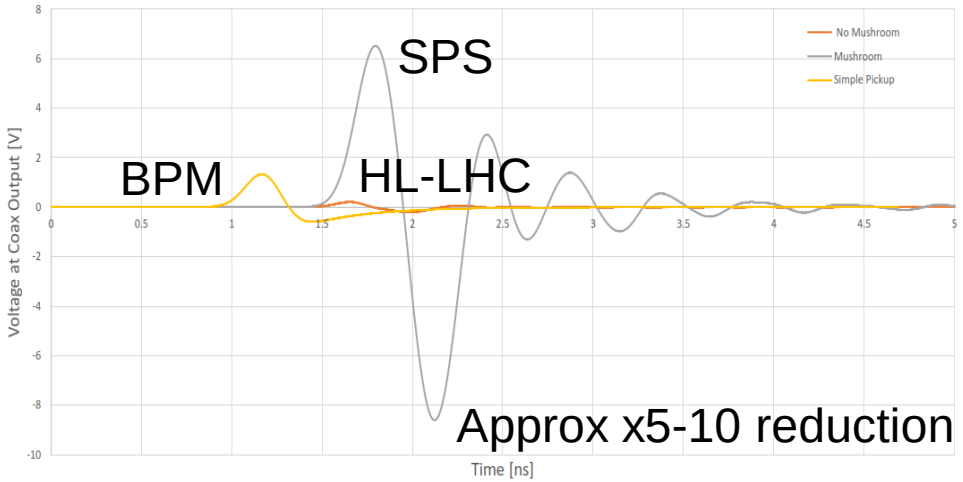


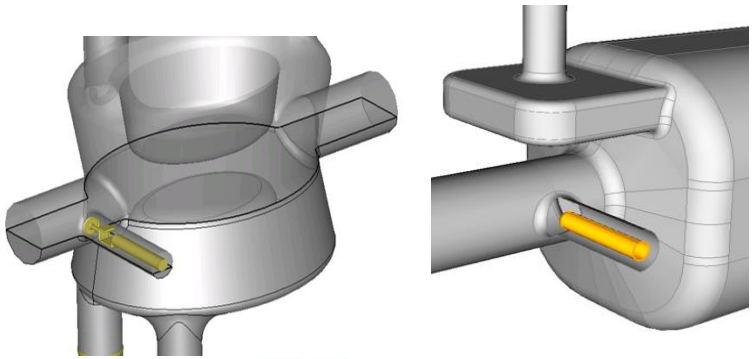


# Direct Beam Coupling & Mitigation

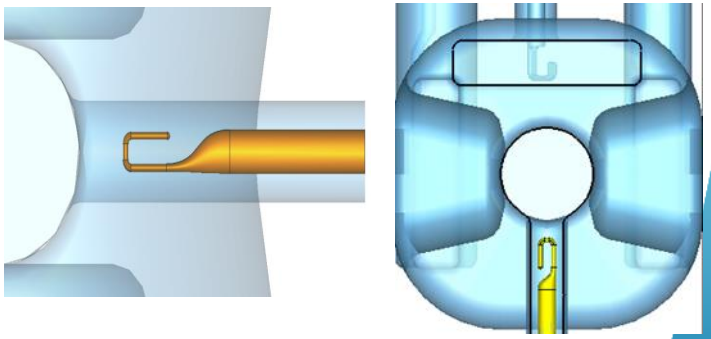
- Design change for field antenna adopted to minimize this effect by x10 for HL-LHC




**SPS** Field ANT

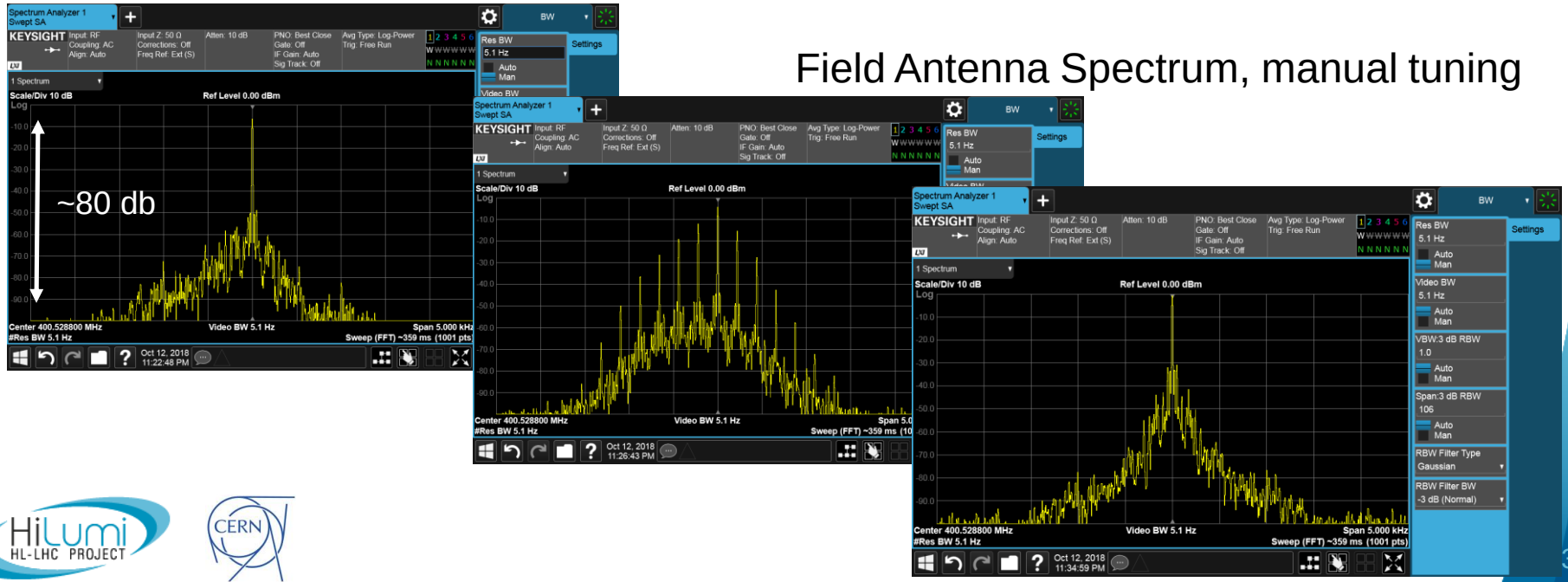


**HL-LHC** Field ANT



# Electro-acoustic Instabilities > 1MV

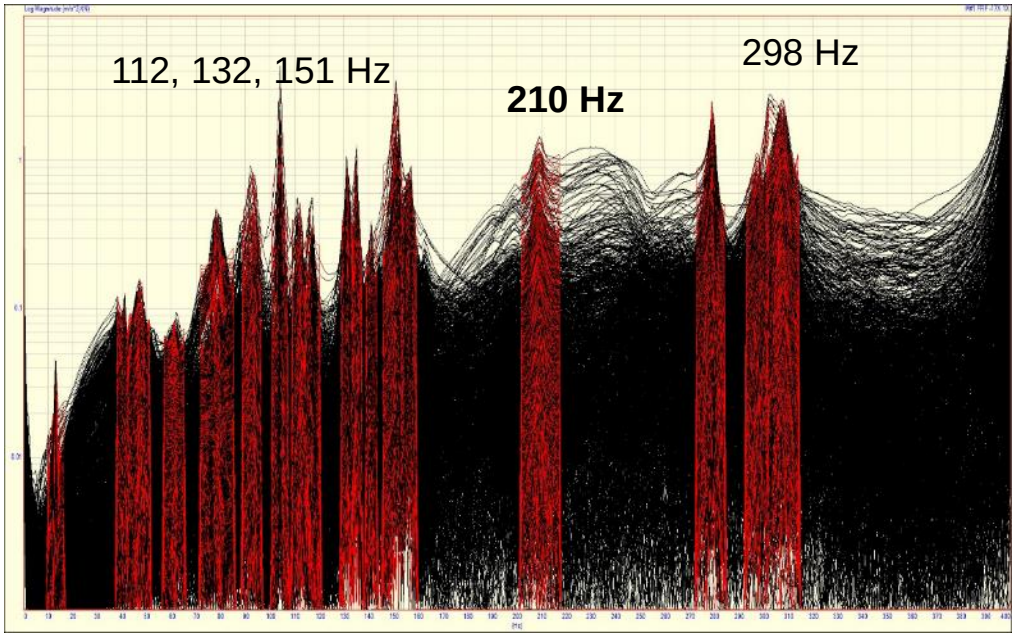
- At 1MV, the LFD is $\sim 400$ Hz (1/2 the cavity BW)
- Self excited loop not implemented in early 2018, tested later in Nov.
- Cured by with tuning loop  or with feedback. following the cavity tune with slow voltage ramp & tuning loop on.



# Modal Analysis of Bare Cavity

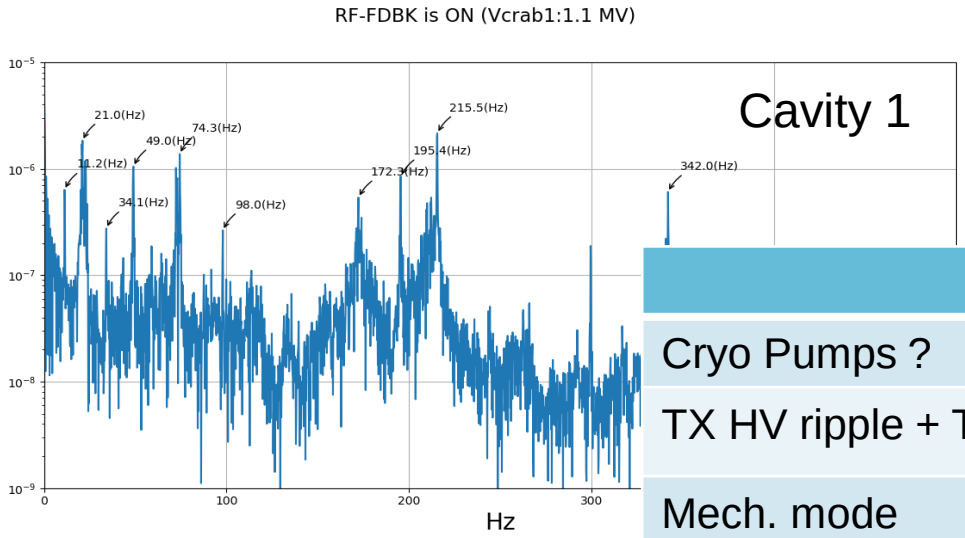
- Measurements on bare cavities with 5 tri-axial accelerometers & modal hammer

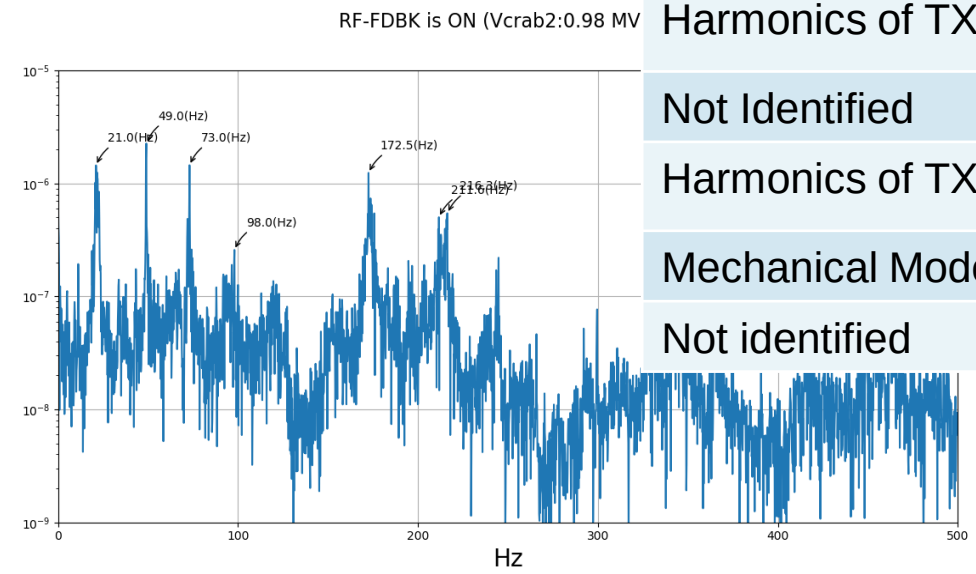
Measured Transfer Functions




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

# Microphonics



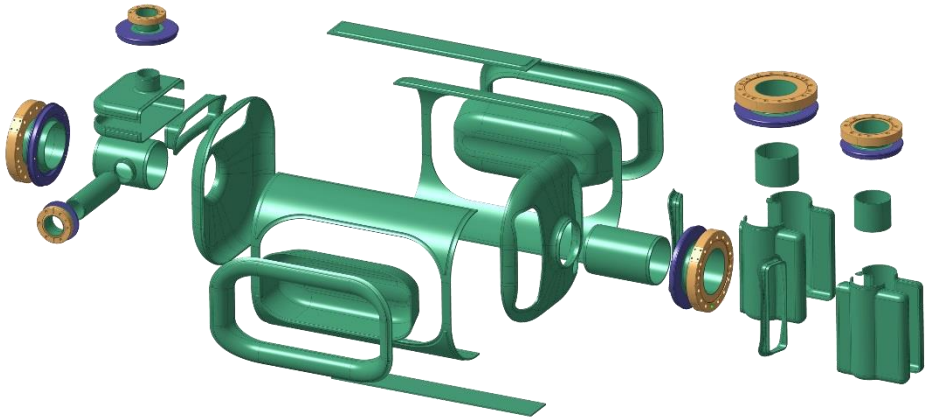

Due to small amplitude of detuning from microphonics, non-issue

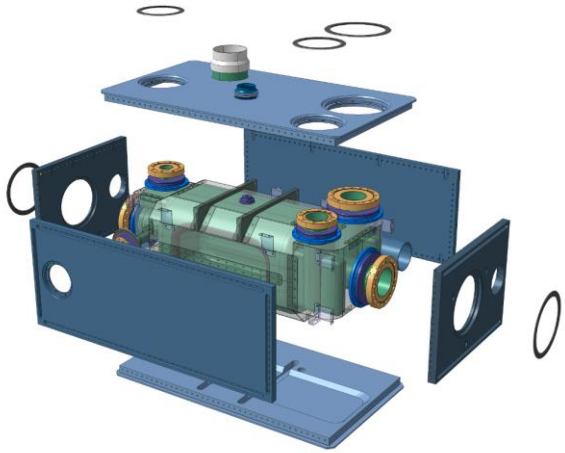
| | Cav 1 [Hz] | Cav 2 [Hz] |
|---|---|---|
| Cryo Pumps ? | 20-30 | 20-30 |
| TX HV ripple + Tuner mode | 49 | 49 |
| Mech. mode | 74 | 73 |
| Harmonics of TX ripple | 98 | 98 |
| Not Identified | 171 | 172 |
| Harmonics of TX ripple ? | 195 | |
| Mechanical Mode | 210 | 212 |
| Not identified | 342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

Courtesy: E. Yamakawa

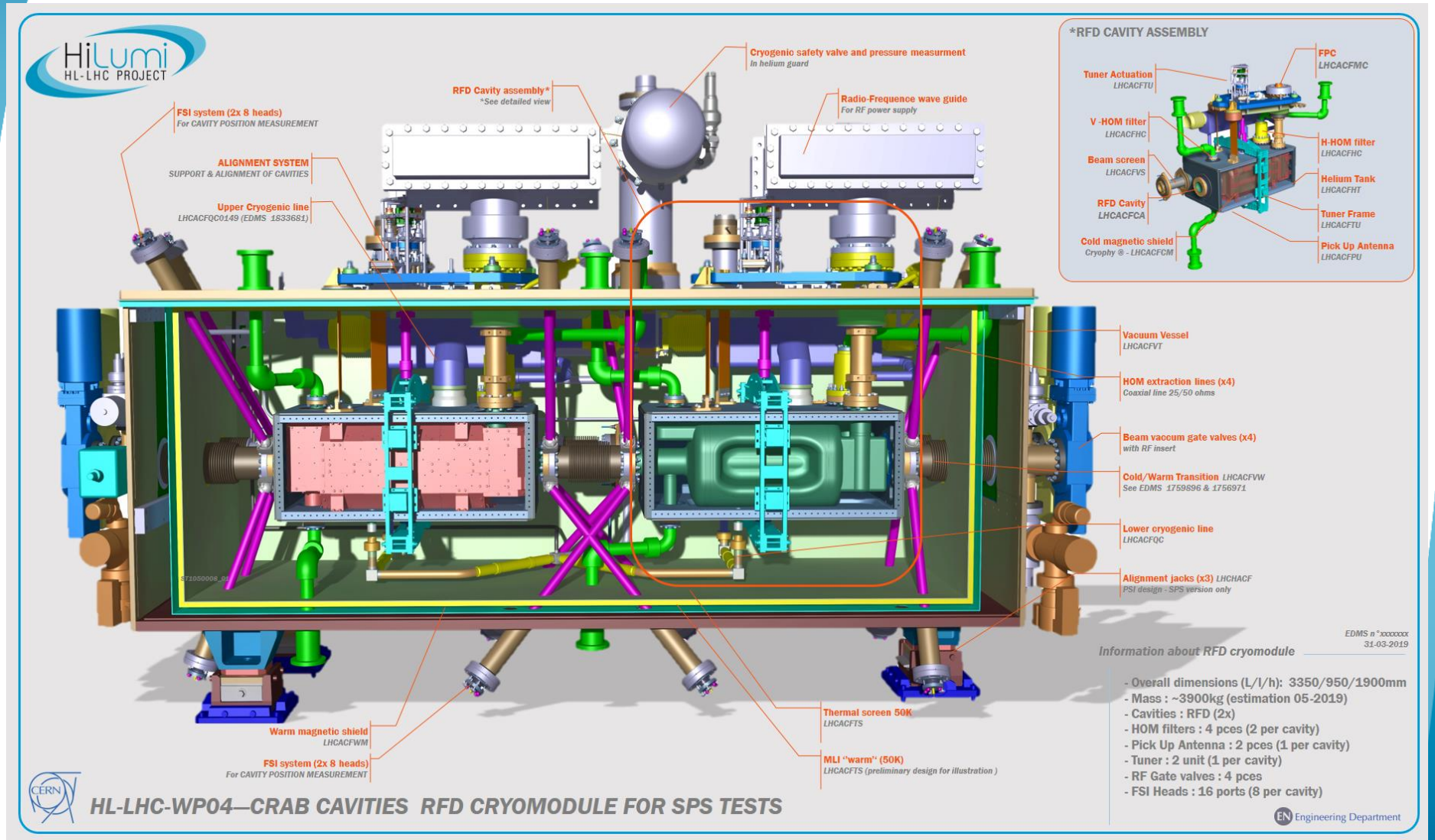
# RF Dipole Development

- The horizontal version (RFD) cavity fabrication in full swing at CERN for its installation in 2021-22
- The HL-LHC series production is launched with Canada/US/UK and industrial partners to produce a total of 10 modules by 2024-25





# RFD Cryomodule (CERN+UK)

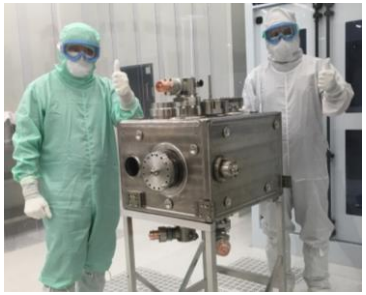
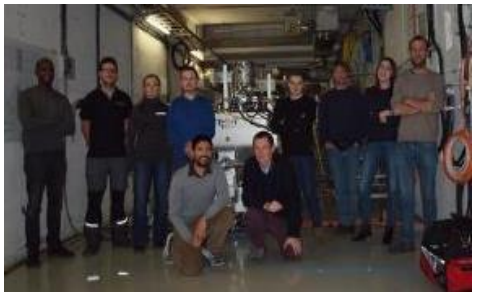
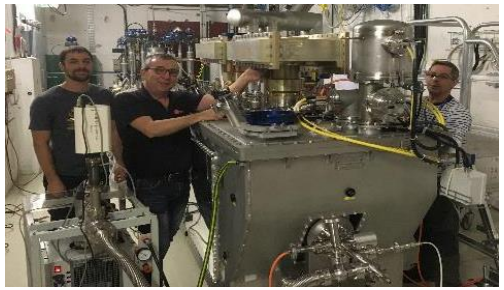



Cryostating in the UK

# Final Comments

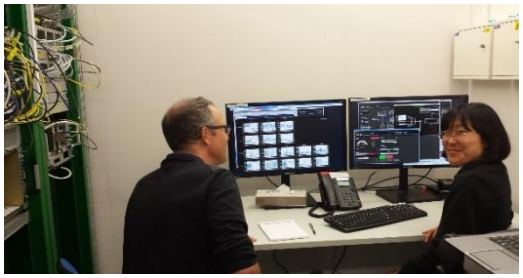
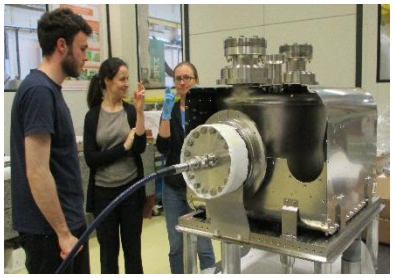
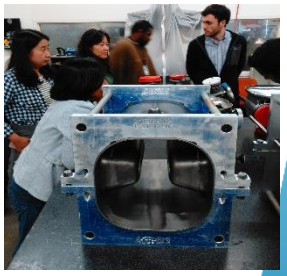
- SPS tests with Crab Cavities
  - SPS-DQW experience was invaluable for both hardware and beam validation “almost” LHC like environment
  - Several operational aspects will be fine-tuned during 2021-23. Scrubbing will be needed before MDs
  - The next prototype module (RFD) fabrication progressing well. Series for HL-LHC is now launched
- The SCRF infrastructure in SPS-LSS6 is unique can could serve for future studies (for ex: PBC)
- Special thanks to our collaborations (UK & US) who played a critical part in the SPS success

# Thank You !





https://videos.cern.ch/record/ (2631455, 2631454, 2630818)

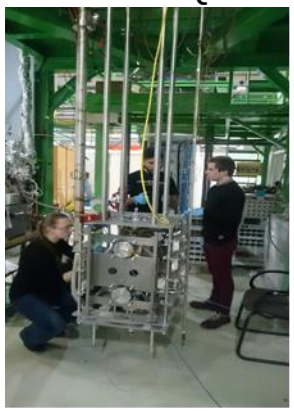
# Backup

# Vertical Cavity Tests (6 Cavities)

**Nominal Spec $V_{kick} = 3.4$ MV**

| | | DQW #1 (CERN) | DQW #2 (CERN) | DQW #1 (USLARP) | DQW #2 (USLARP) | RFD #1 (USLARP) | RFD #2 (USLARP) |
|---|---|---|---|---|---|---|---|
| Max Volt | [MV] | **5.04** | **4.8** | **5.8** | **5.3** | **5.0** | **5.75** |
| $E_p, B_p$ [MV/m, mT] | | 56, 109 | 54, 103 | 65, 125 | 59, 114 | 42, 73 | 56, 96 |
| $R_s$ min | [nΩ] | 10 | 10 | 9 | 9.5 | 11 | 7.6 |
| $R_s$, 3.4MV | [nΩ] | 15 | 18 | 15 | 17 | 13 | 8.2 |
| Max Volt with HOM | [MV] | **3.3*** | - | - | **4.7** | **-** | **5.5** |

CERN DQW



USLARP DQW & RFD

* Voltage limit for SPS-DQW with HOMs due to inadequate BCP of HOMs

# Summary of SPS-test Experience

- Bare cavity performance is +50% of the nominal voltage
  - In SM18 dressed cavities exhibited limit ~3MV, now understood
  - Performance of the SPS-test module limited to 1MV for machine developments, 2MV stable
- First crabbing of protons demonstrated. Main aspects such as transparency, beam loading, emittance growth, crab dispersion and other aspects studied – no show stopper
- Several hardware limitations: direct beam coupling, pondermotive instabilities, RF non-linearity at low power, RF/Cryo/Vacuum stability beyond 2MV..
- Consolidation of SPS test stand underway during LS2 with 2021 operation of DQW and 2022 RFD

# Ramp to 270 GeV

Vertical tune: $Q_y = 0.18$

RF Freq:

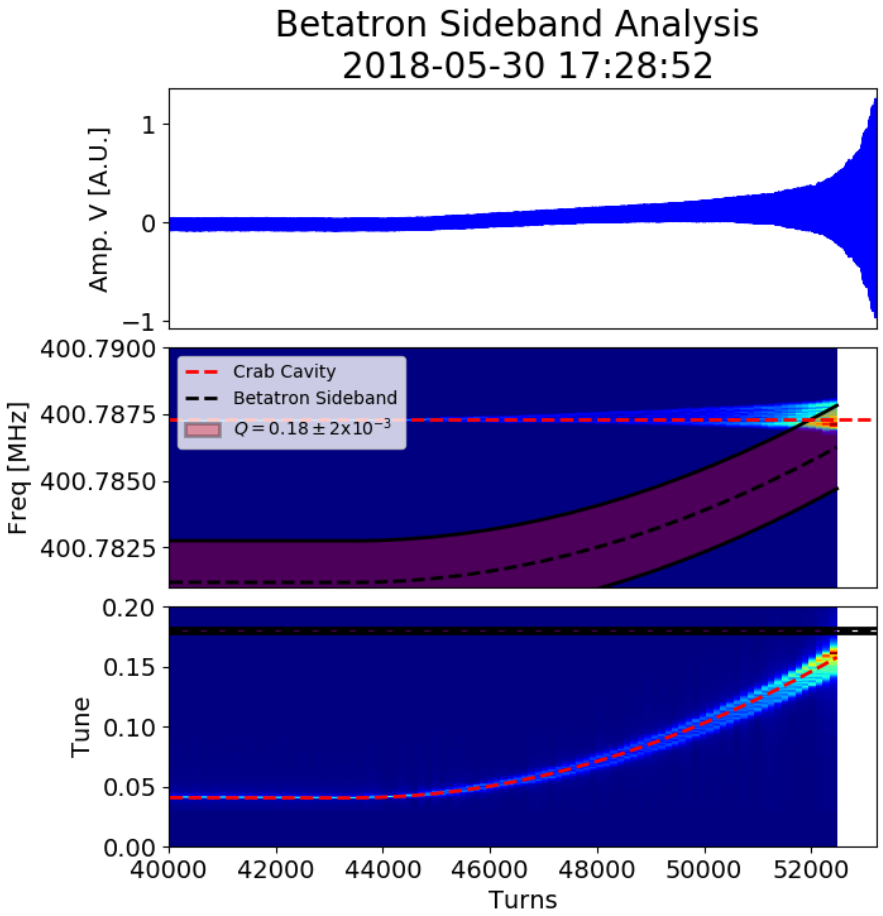
Cavity 1: 400.787 MHz (~1 MV)

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



# Transparency Tests