HL-LHC Crab Cavities and SPS Tests

R. Calaga on behalf HL-LHC WP4

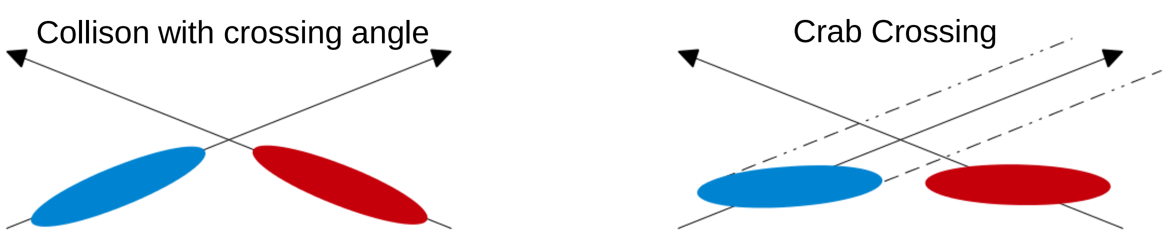
CERN

12 July 2019, EPS-HEP 2019, Ghent

HL-LHC Crab Cavity System

Use 8+8 Superconducting compact RF crab cavities (ATLAS + CMS) to compensate the geometric angle of ~500 μrad

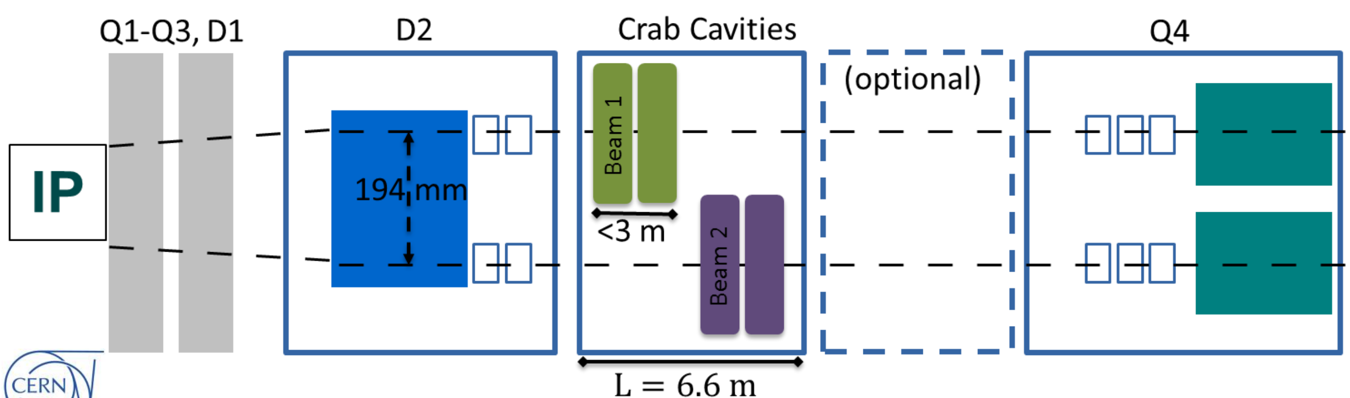
Recover ~70% of the Peak Luminosity – use levelling with β^*



$7.55\ cm$

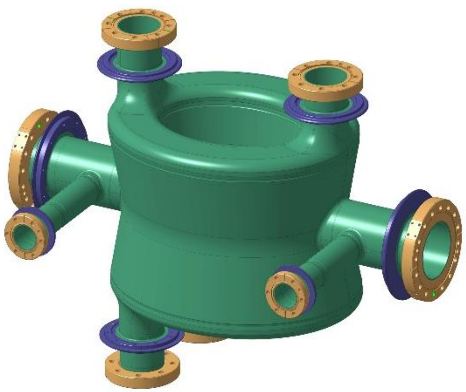
$$\Phi = \frac{\sigma_z}{\sigma_x}\left(\frac{\theta_c}{2}\right)$$

$\sim 7\ \mu m$

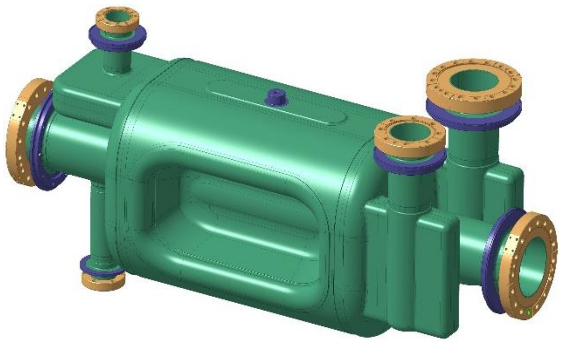


Dressed Cavity Geometries

Double Quarter Wave



RF Dipole



$$f_0 = 400\ \mathrm{MHz}$$

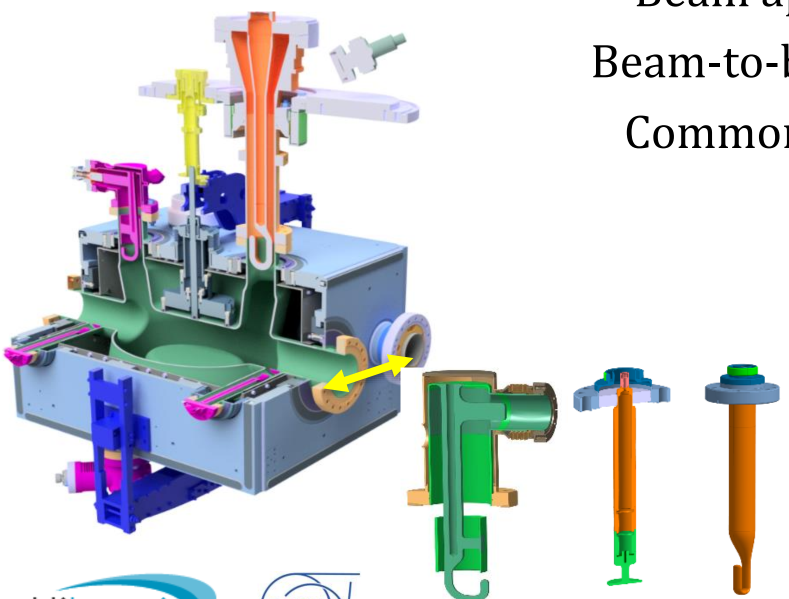
$$\mathrm{V_T} = 3.4\ \text{MV/cavity}$$

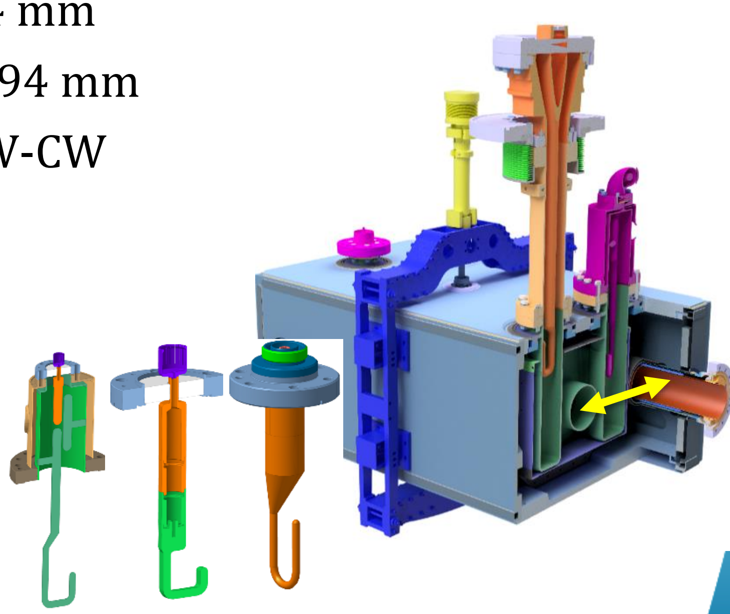
$$(\mathrm{E_p}, \mathrm{B_p} < 40\ \mathrm{MV/m}, 70\ \mathrm{mT})$$

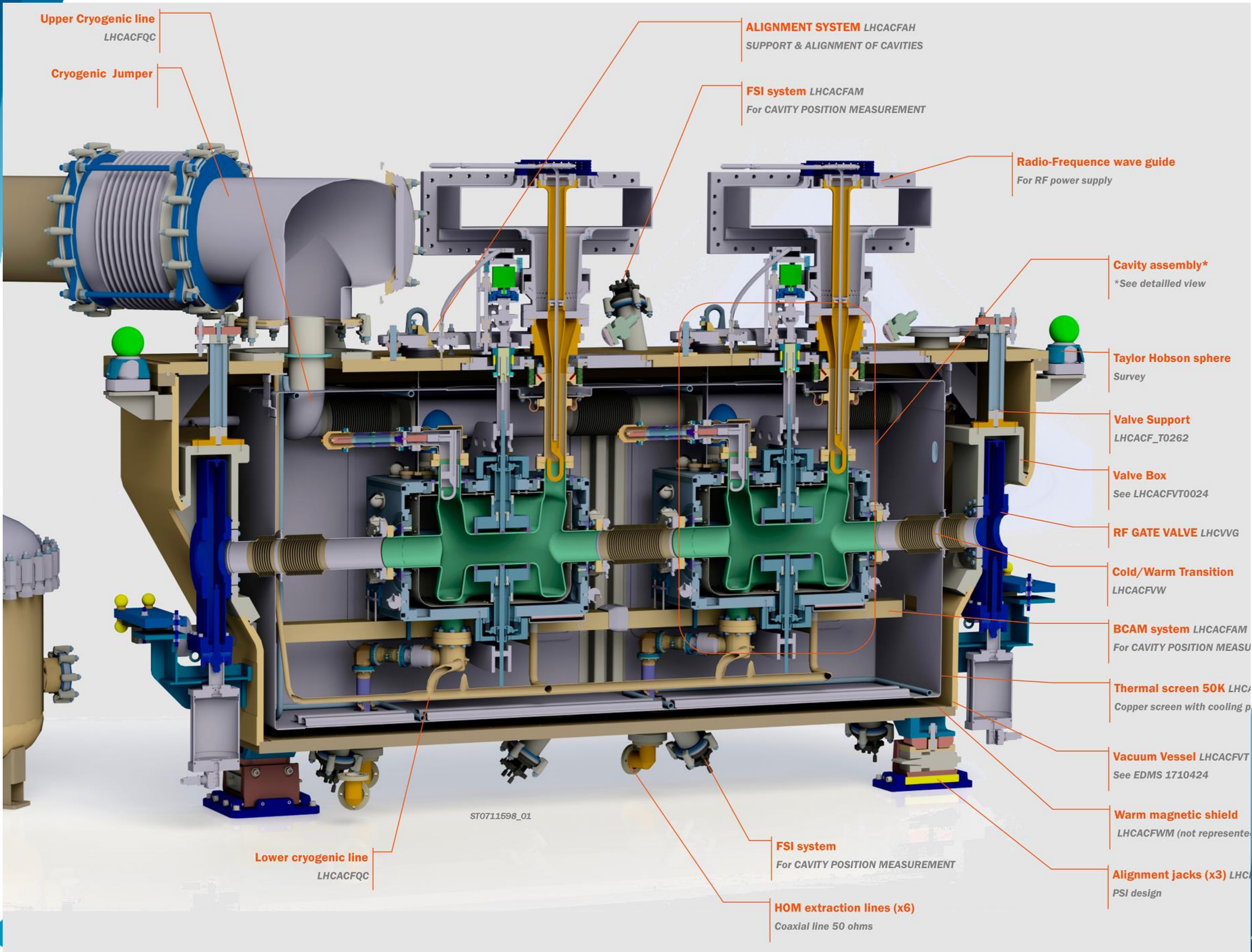
$$\text{Beam aperture} = 84\ \text{mm}$$

$$\text{Beam-to-beam dist} = 194\ \text{mm}$$

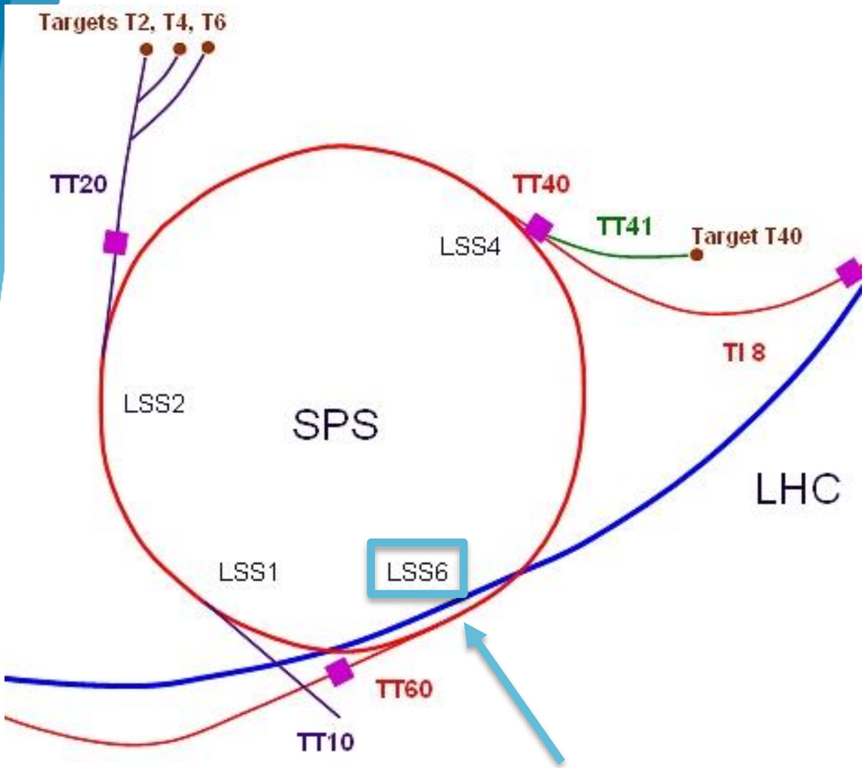
$$\text{Common FPC} = 40\ \text{kW-CW}$$



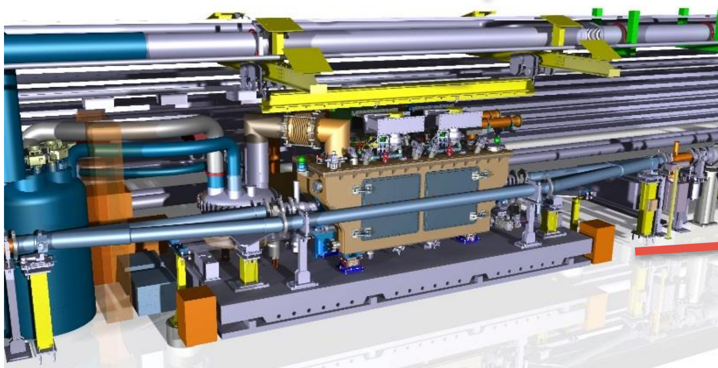


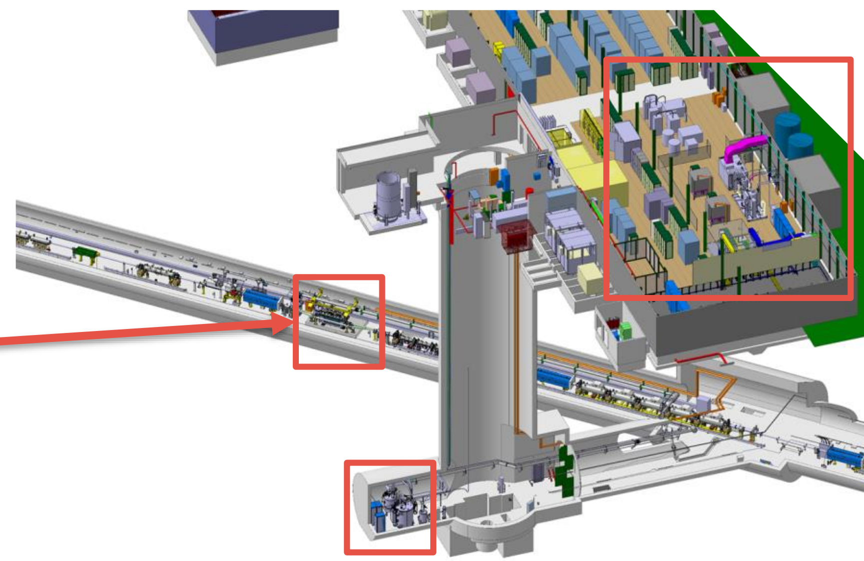

Upper Cryogenic line
LHCACFQC
Cryogenic Jumper
ALIGNMENT SYSTEM LHCACFAH
SUPPORT & ALIGNMENT OF CAVITIES
FSI system LHCACFAM
For CAVITY POSITION MEASUREMENT
Radio-Frequence wave guide
For RF power supply
Cavity assembly*
*See detailled view
Taylor Hobson sphere
Survey
Valve Support
LHCACF_T0262
Valve Box
See LHCACFVT0024
RF GATE VALVE LHCVVG
Cold/Warm Transition
LHCACFVW
BCAM system LHCACFAM
For CAVITY POSITION MEASU
Thermal screen 50K LHC
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

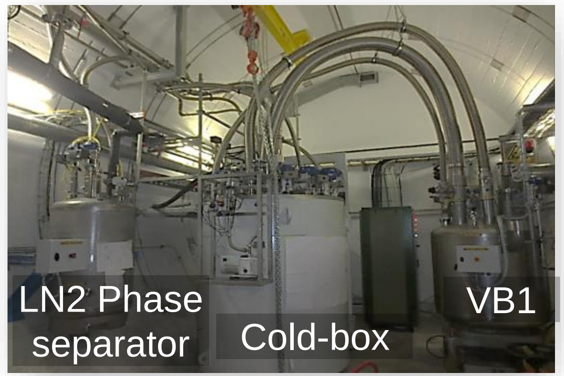


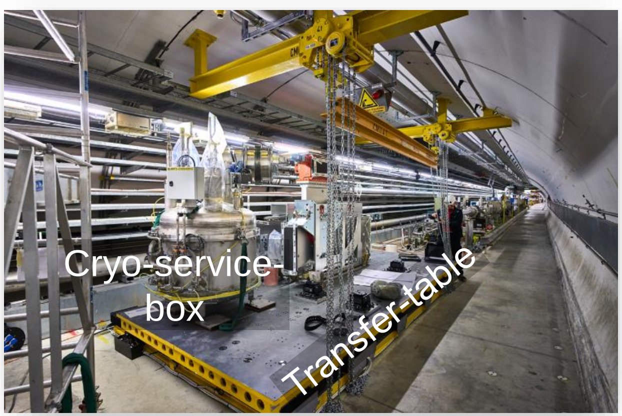


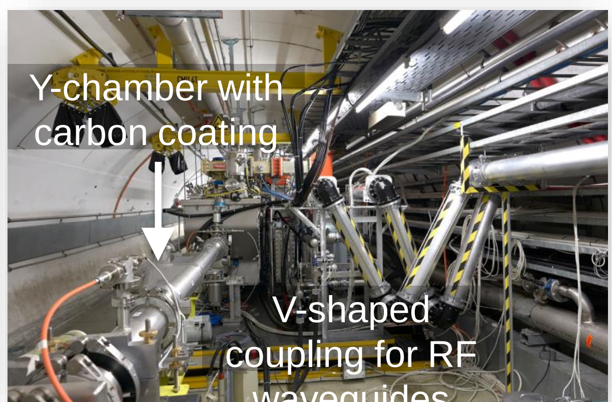
SPS-LSS6 – Crab Cavity Module

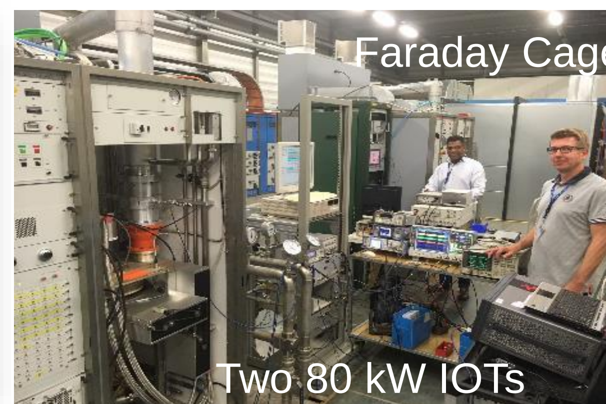
SPS-Crab Installation

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









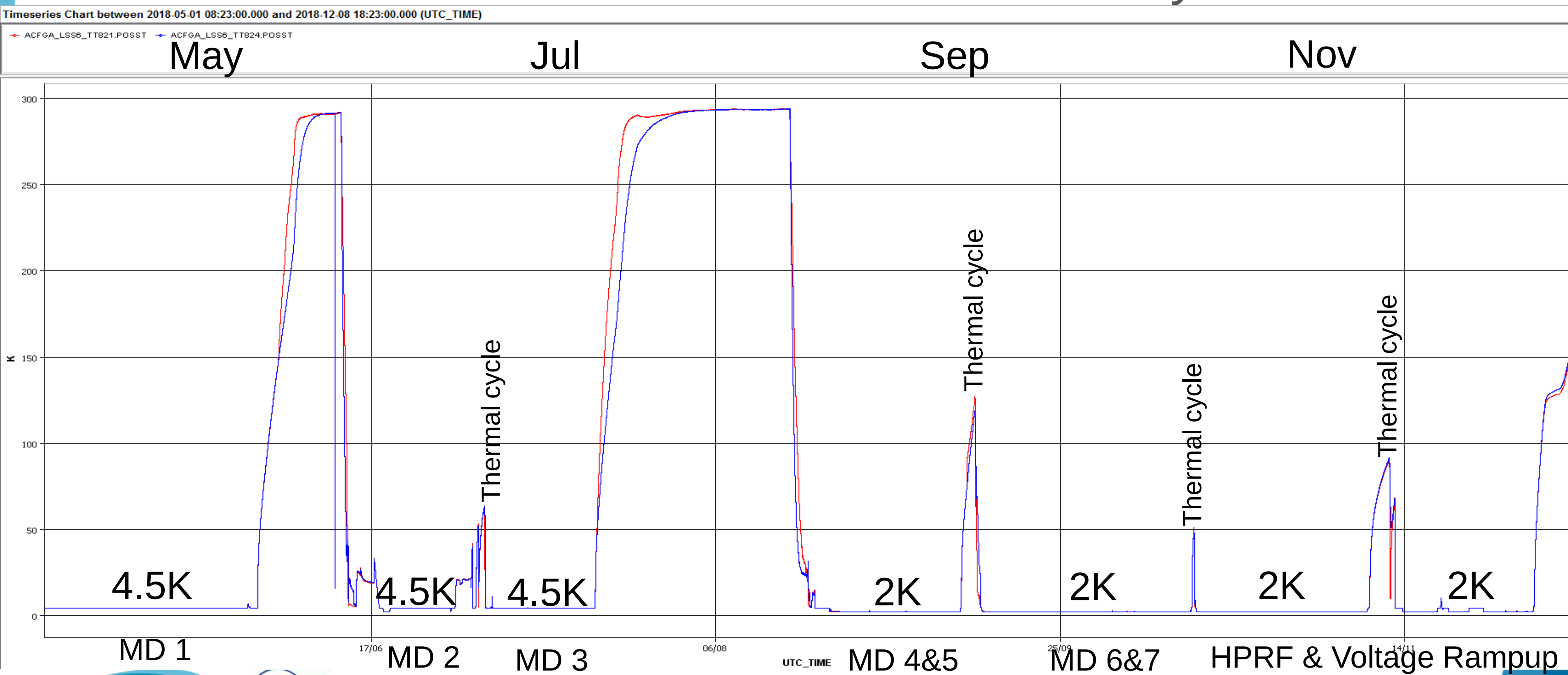
Expected SPS Test Sequence

- 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

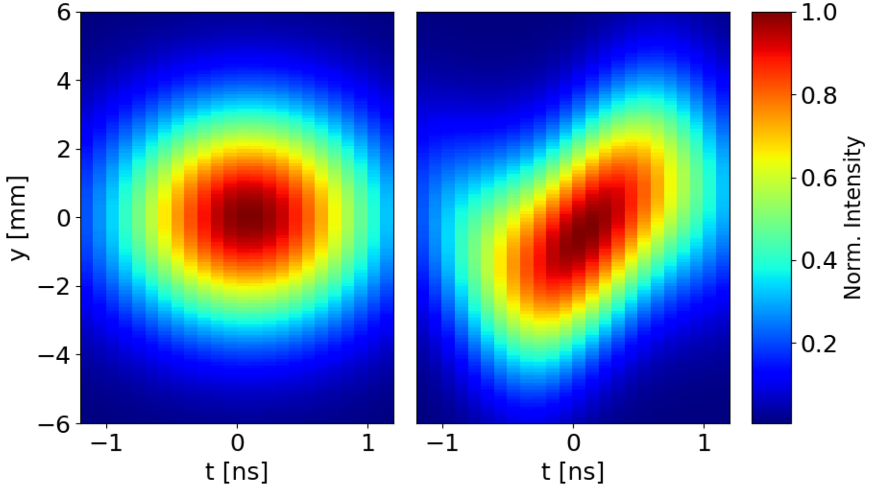
MD#		Cav1	Cav2 [MV]	Temp [K]	Energy [GeV]
1	First crabbing, phase and voltage scan	0.5	0	4.5	26
2	270 GeV ramp with single bunch	1-2	0	4.5	26, 270
3	Intensity ramp up	1	~0.3	4.5	26
4	270 GeV coast setup	1.0	0.5	2.0	270
5	Emittance growth at 270 GeV with induced noise	0	1.0	2.0	270
6	Intensity ramp up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

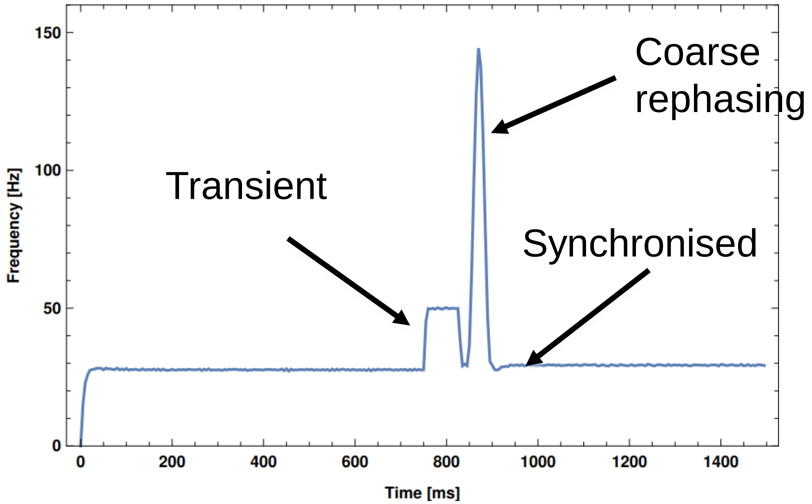
Beam measurements showed 10-20% larger voltage than RF measurements

L. Carver, T. Levens et al.

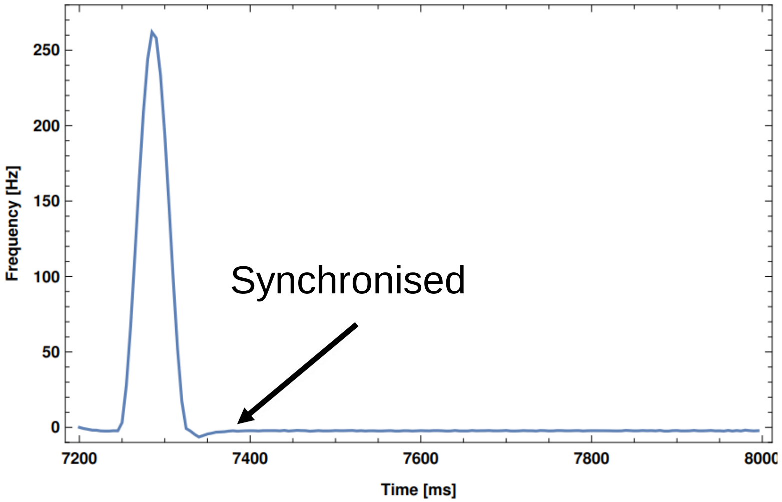
How to synchronize Crab-RF ?

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

26GeV rephasing
Synch after ~1s after injection

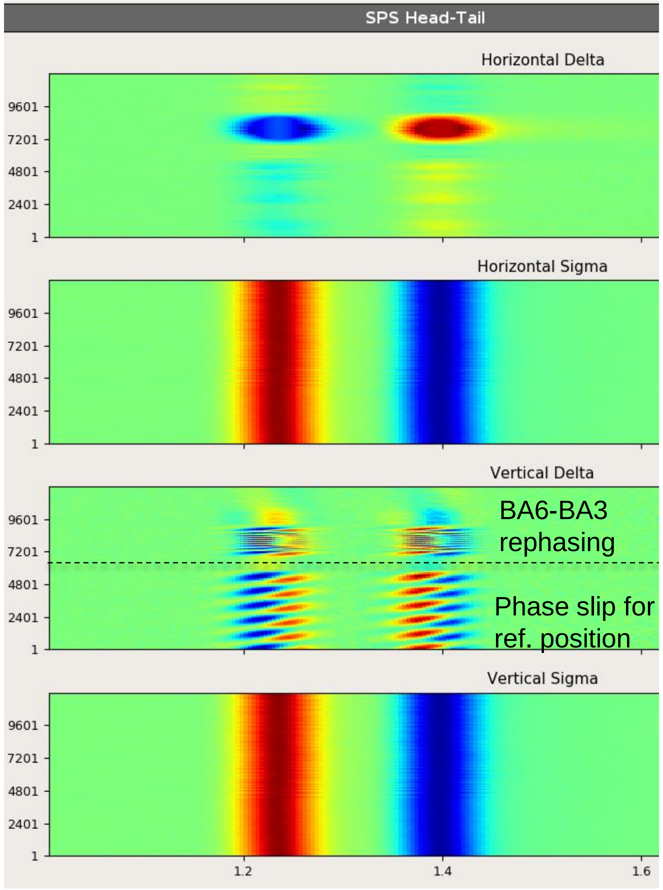


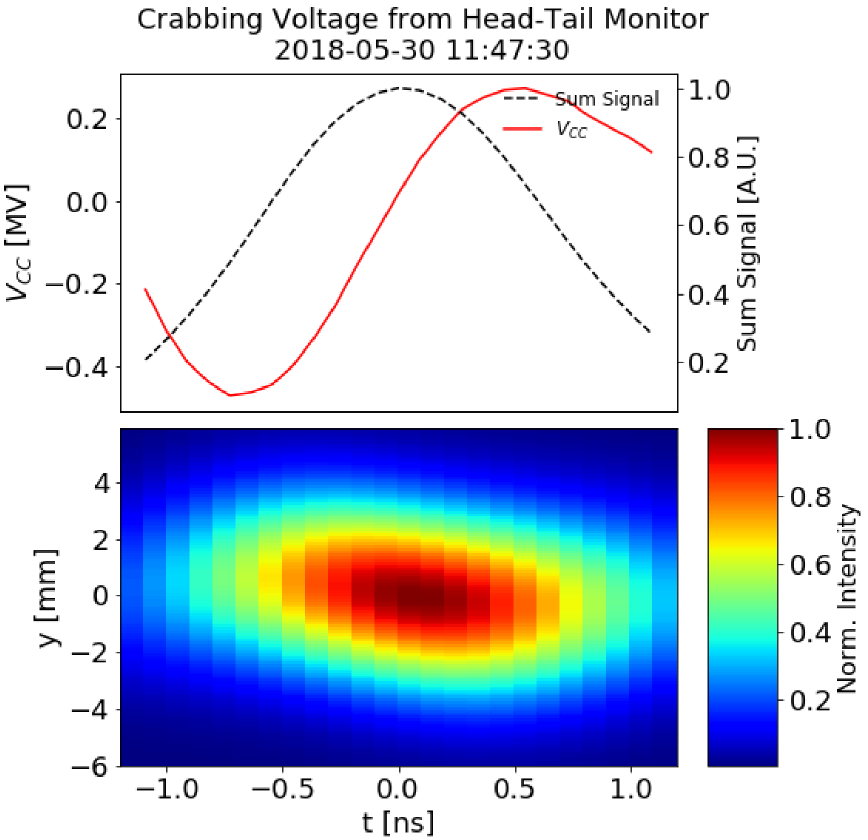
270GeV, Synchronized after ~7.4s
i.e. 0.2s after reaching flat top



T. Bohl et al.

Reconstruction of Crabbing using HT



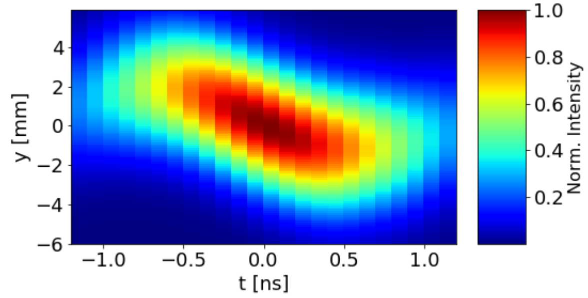


# of turns for ref position along the bunch ~ 2k turns
RF re-synchronization ~ 1s after injection

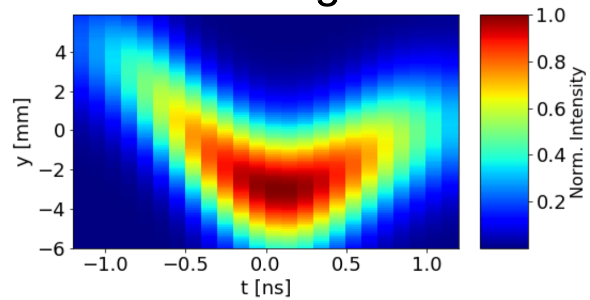
Phase Scans & "Transparency"

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

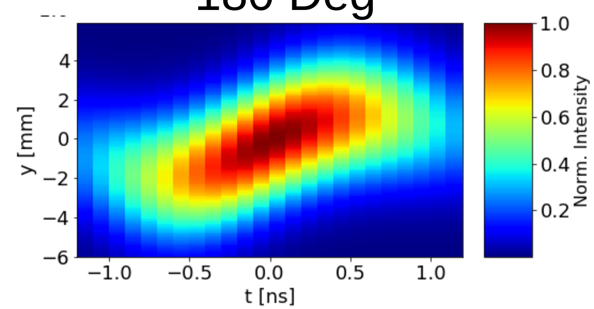
0 Deg



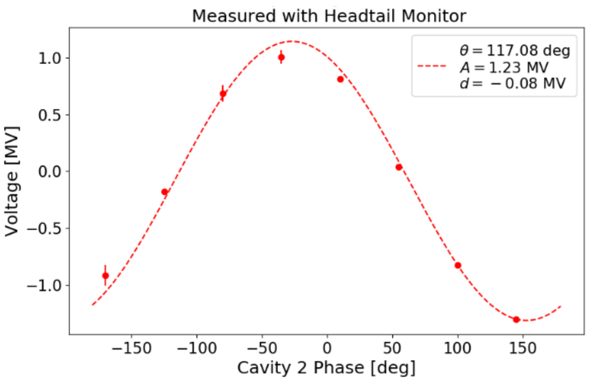
90 Deg



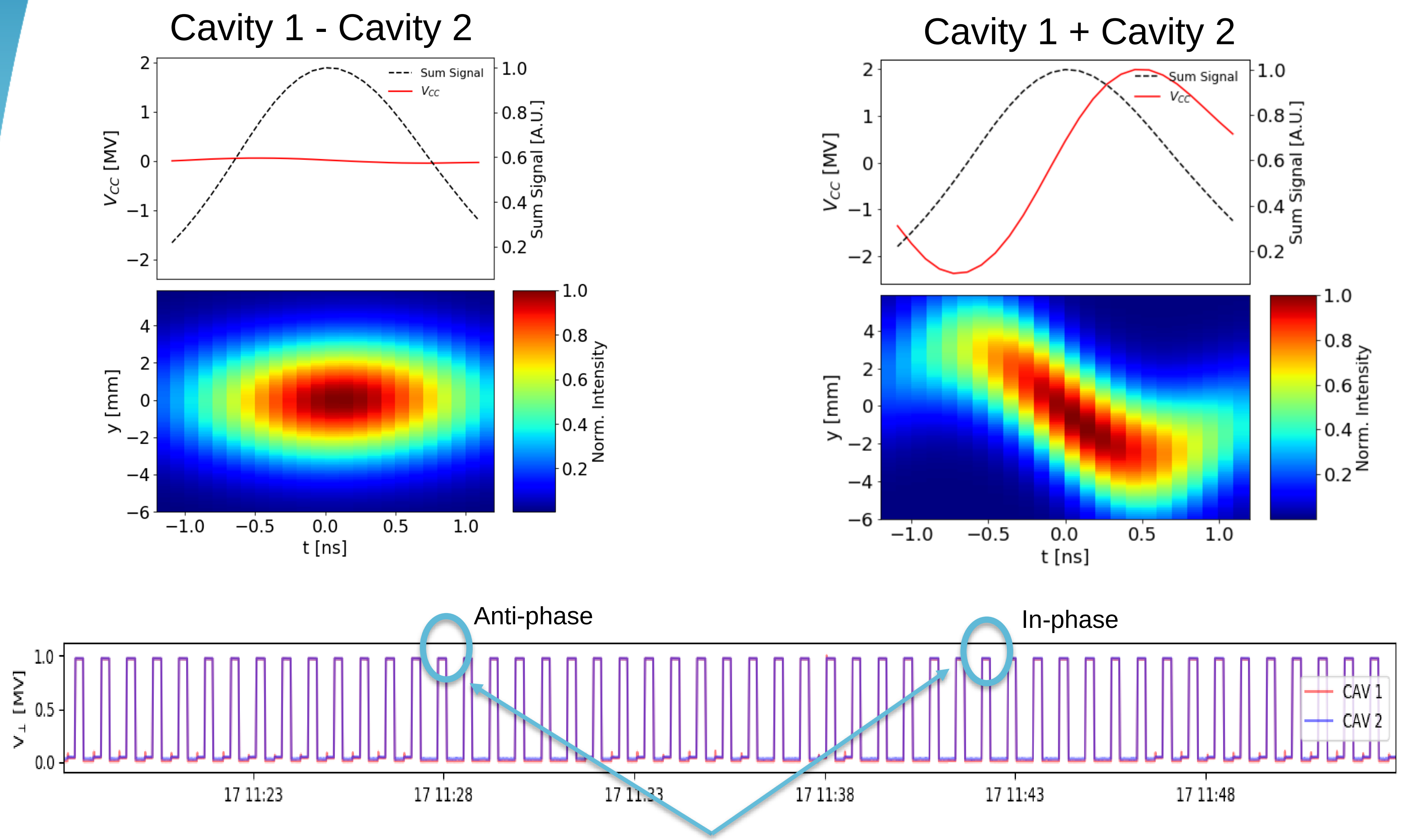
180 Deg



CAV2 Voltage/Phase



Transparency: V=1MV in both cavities

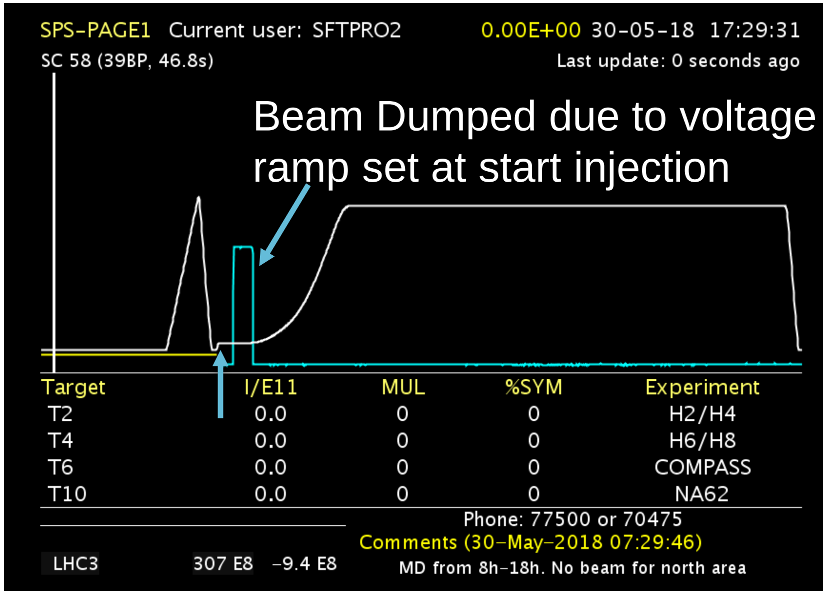


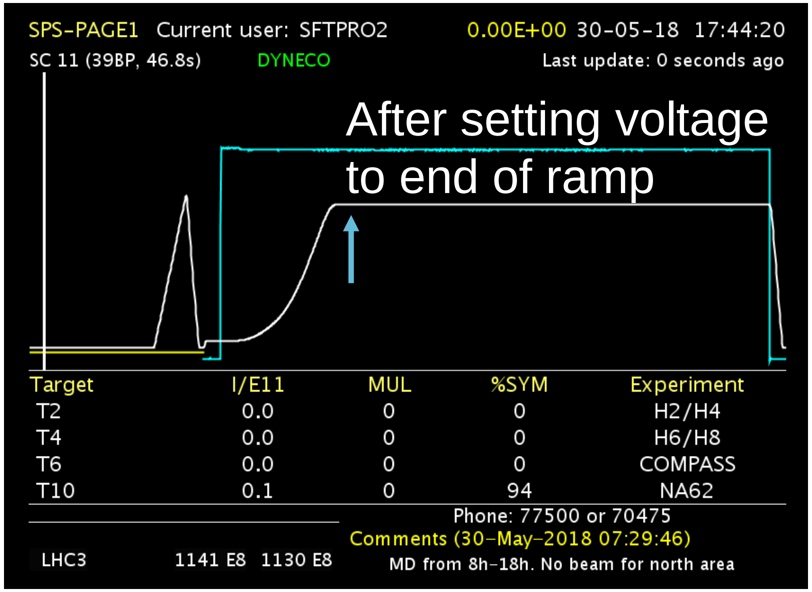
SPS MD cycle (~20 sec flattop)

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)





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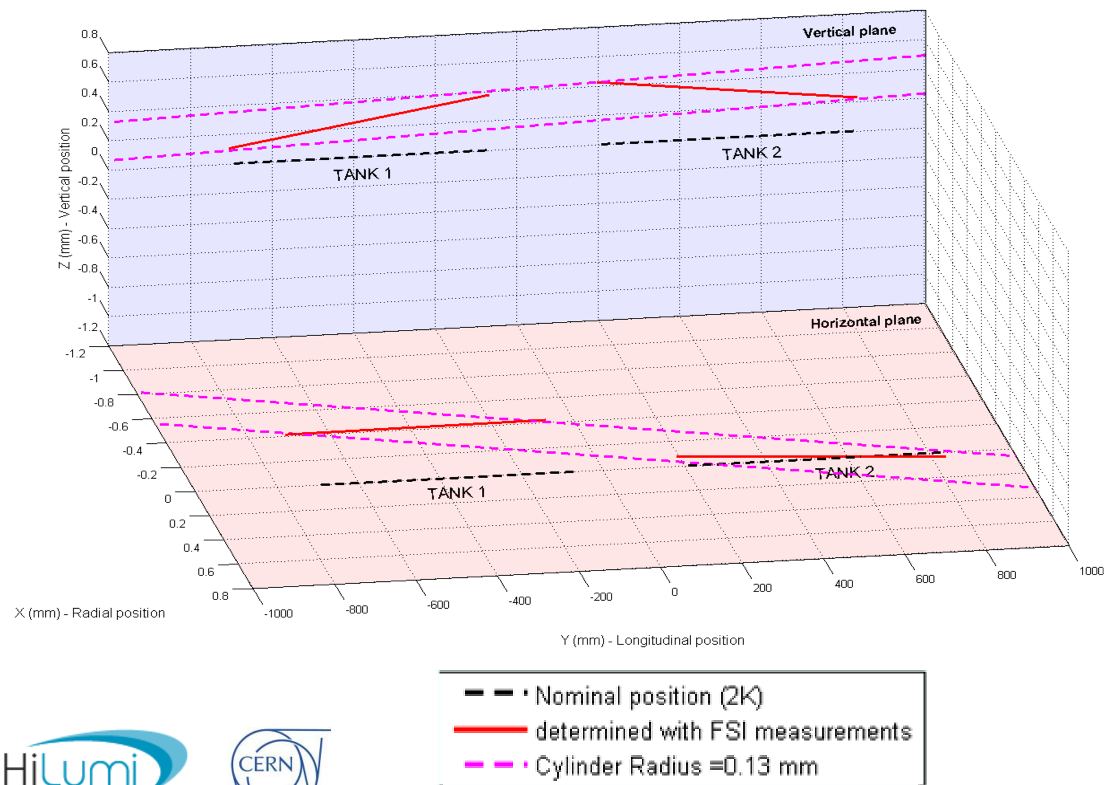
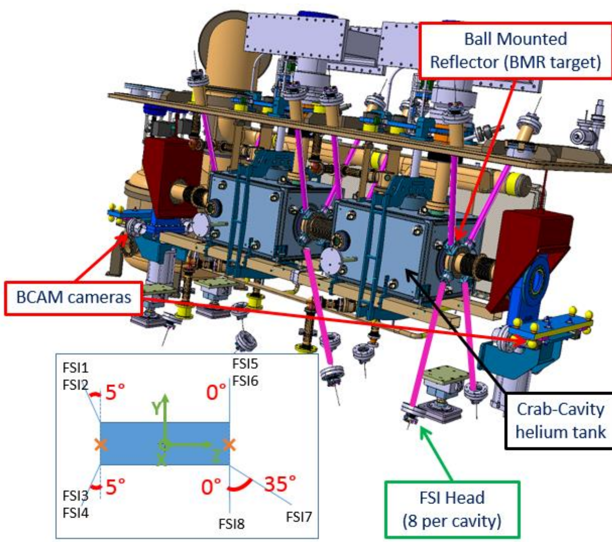
Cavity Alignment

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

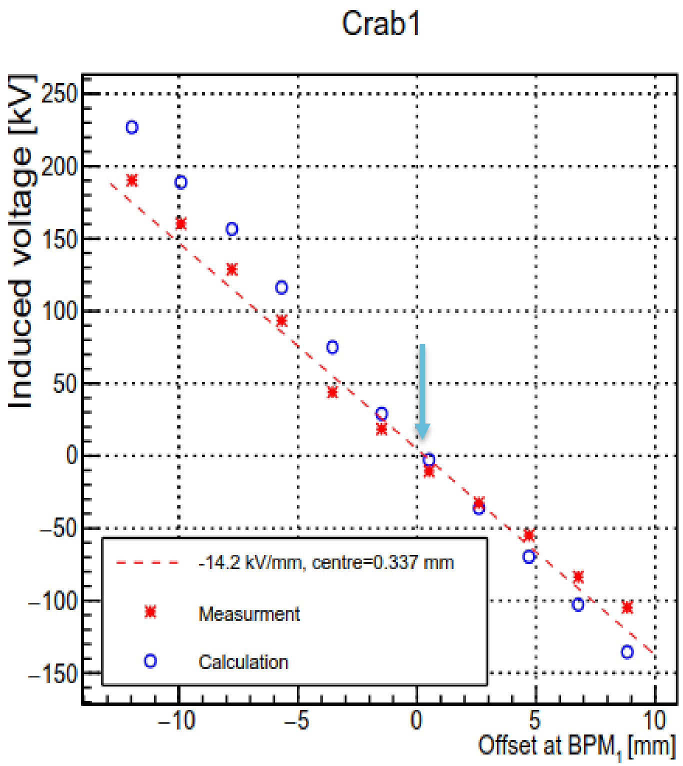


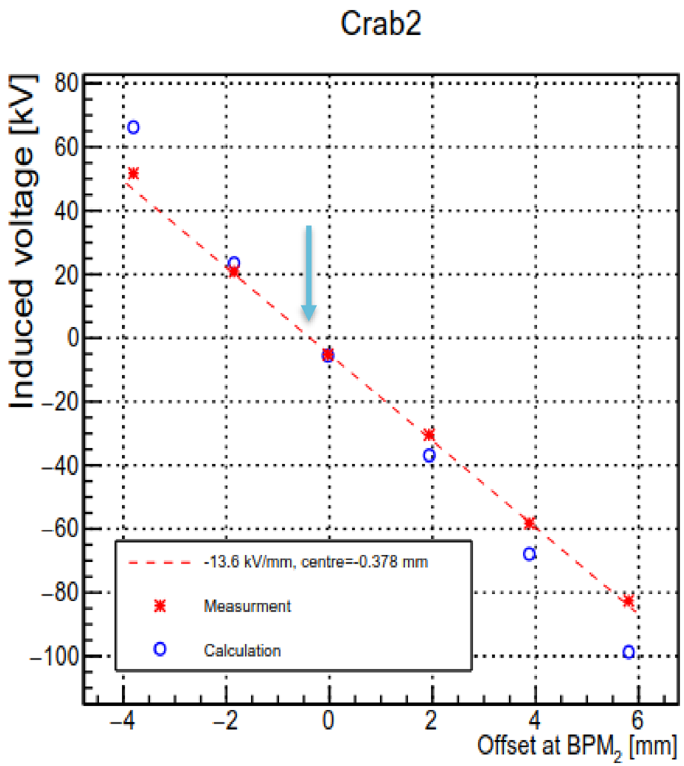


Courtesy: EN-ACE-SU/MME

Beam Loading & Electrical Center

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

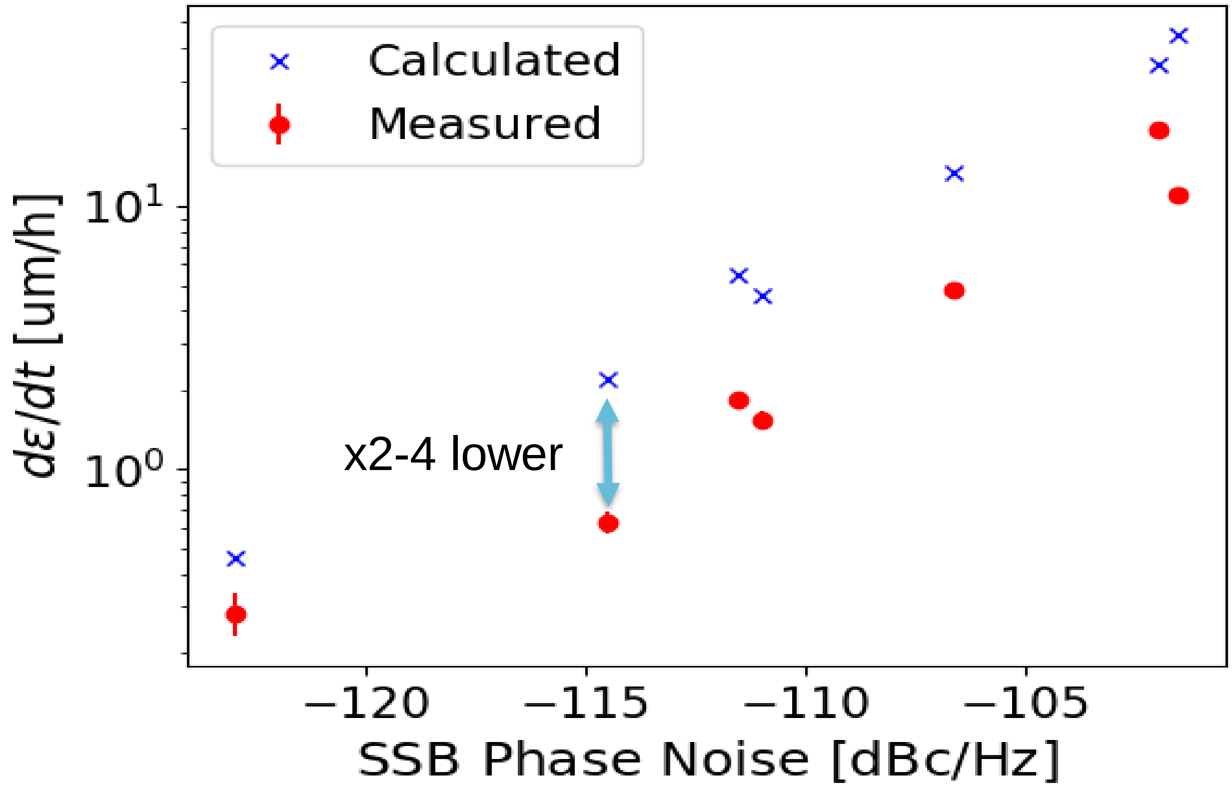




E. Yamakawa et al.

Emittance Growth

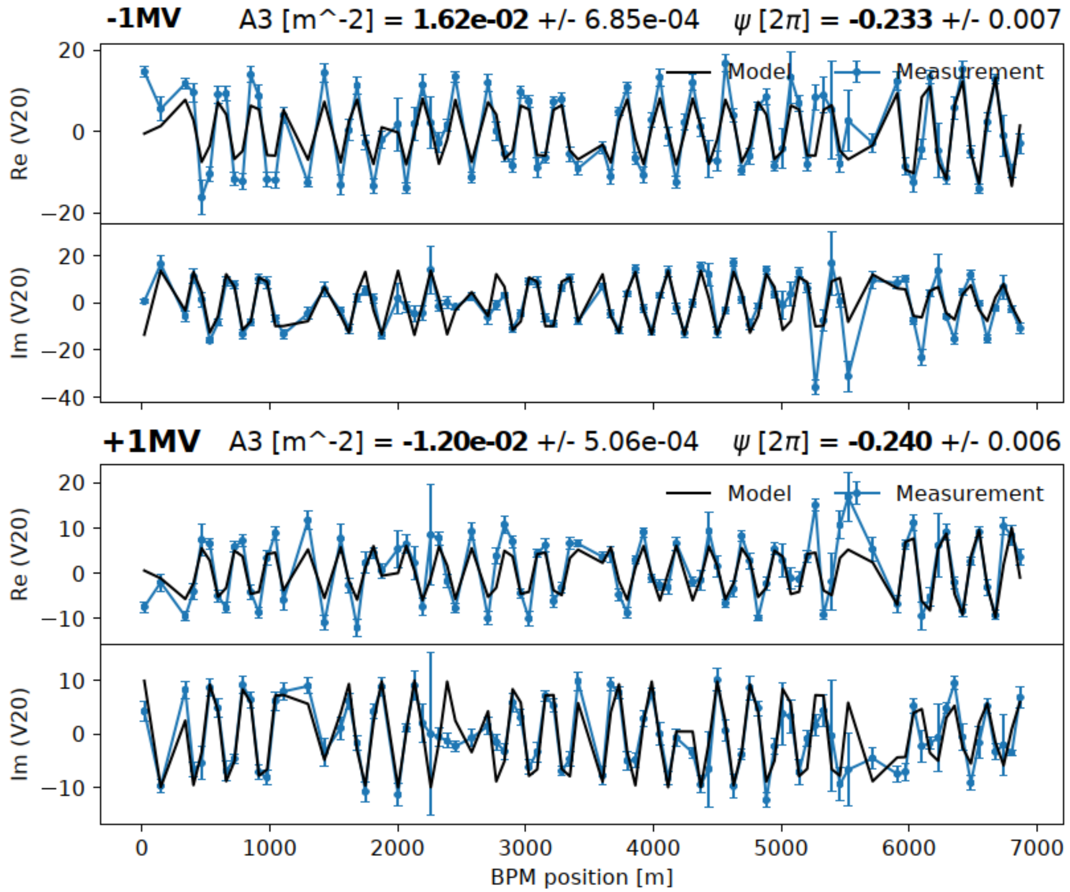
- SPS natural emittance growth at 270 GeV, $\leq 0.5\ \mu m/h$. HL-LHC needs to be below $0.05\ \mu m/h$
- CC expected growth with existing electronics (noisy!). Scaling with additional induced noise is qualitatively reproduced but more pessimistic than measured growth



P. Baudrenghien, L. Carver et al.

RF Multipoles

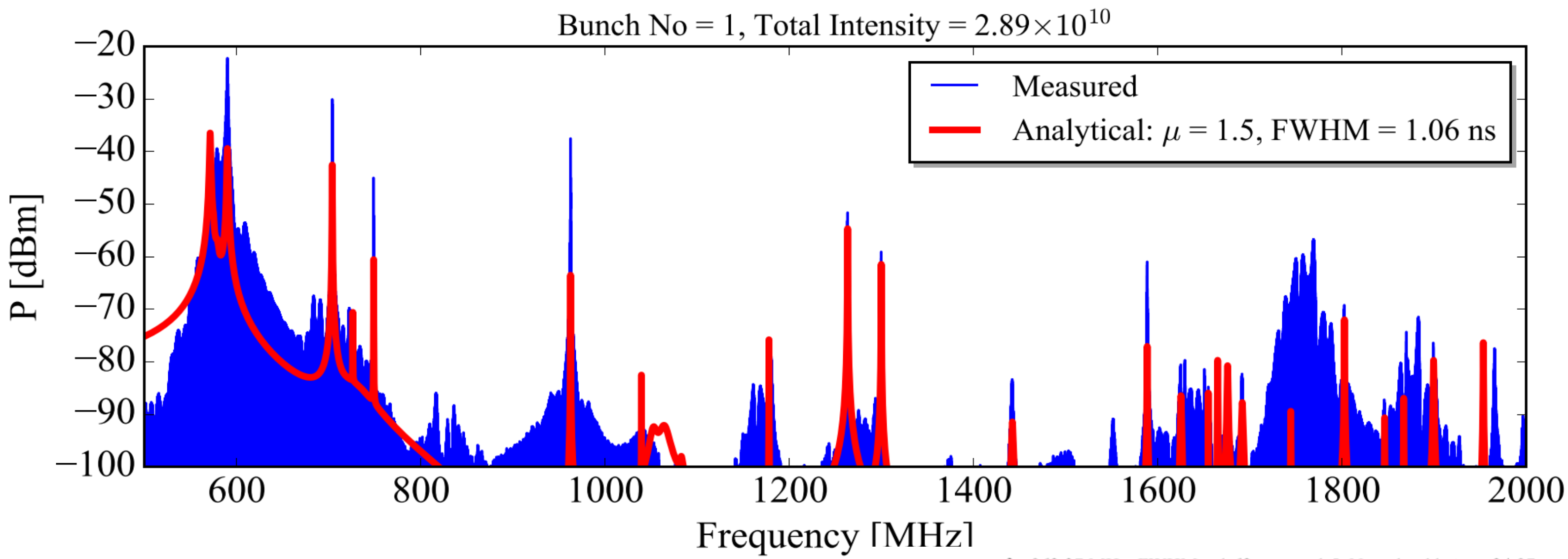
- Very promising results to measure for the first time RF multipoles with beam. But extracting the cavity multipoles from other machine elements still remains challenging



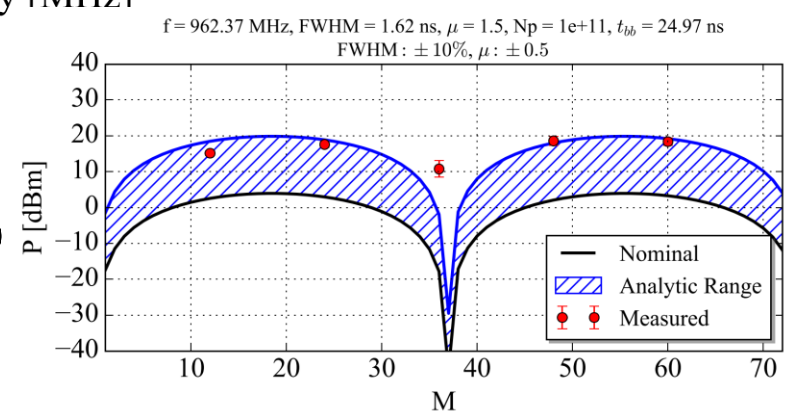
M. Carla et al.

Higher Order Modes

- Integrated max HOM power measured < 3 W. More than 75% from ~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 ($1\ \mathrm{MV}$), no beam induced failures or fast transients seen except for pressure rise

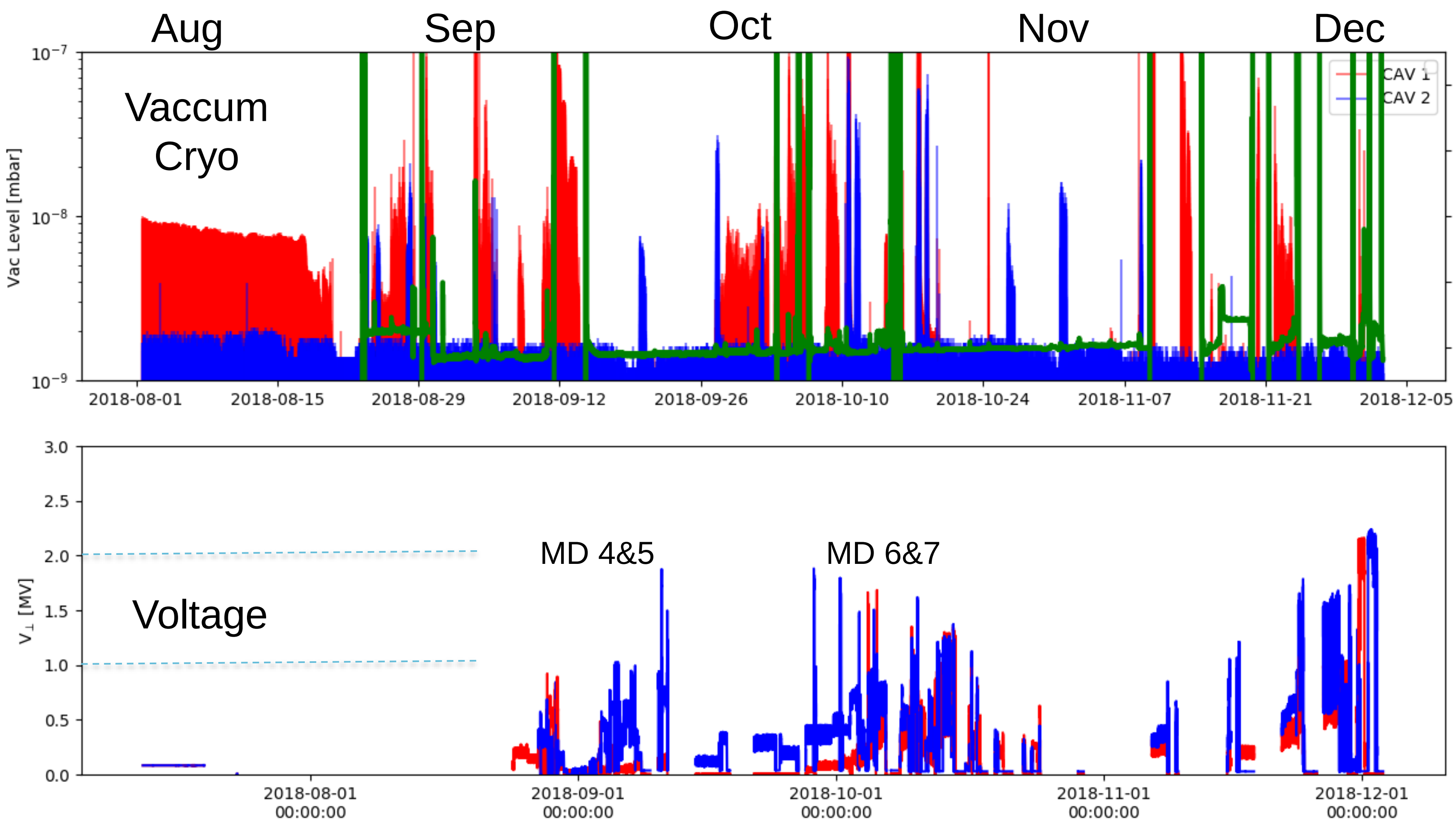
- MD7: 2×60 bunches at 1×10^{11}p/b
  - Also limited by vacuum pressure rise in by-pass
  - Cavities on/off at 1MV didn't make any difference on pressure dynamics
  - Ramp the multi-bunches to 270-400 GeV to reach closer to LHC like bunch lengths – longitudinally unstable beyond 12-bunches, required more setup time

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

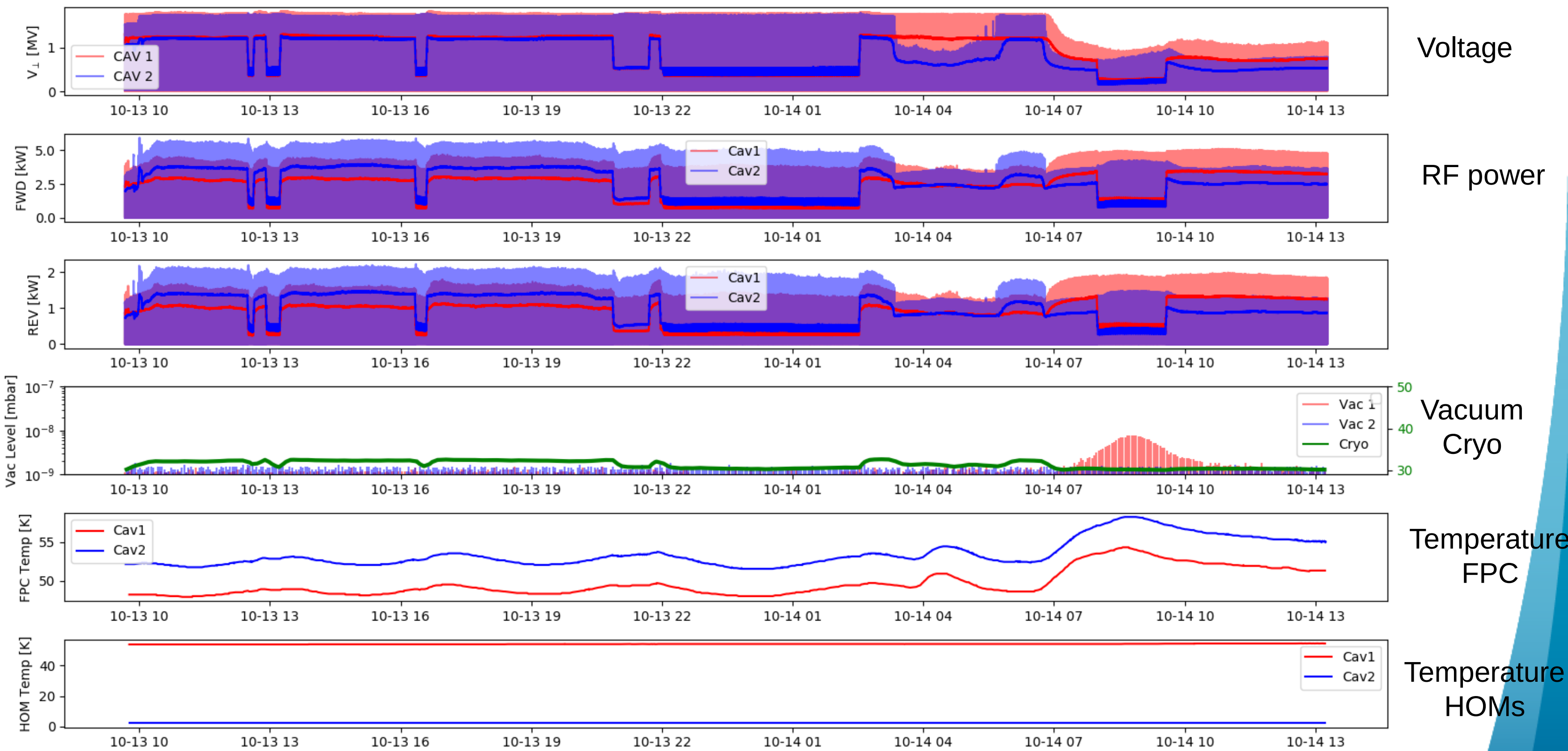
Average Voltage Evolution (2K)

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



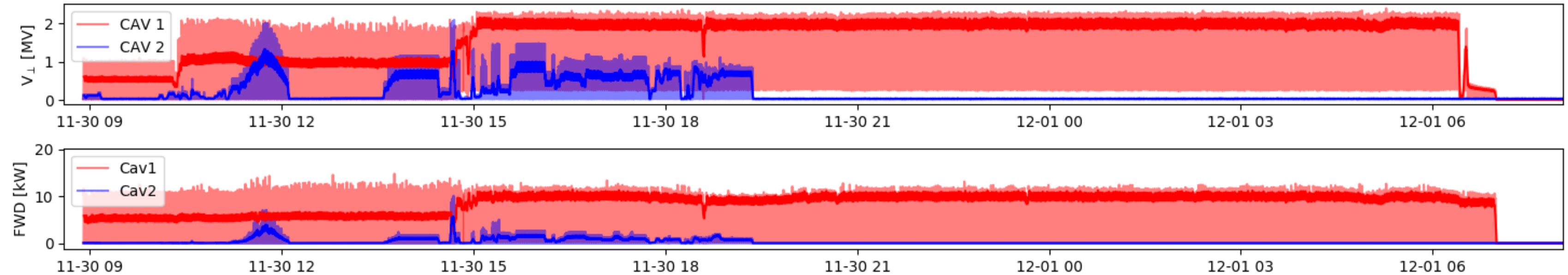
Oct 13, Stable Voltage CAV1/2 – 1.0 MV

- 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

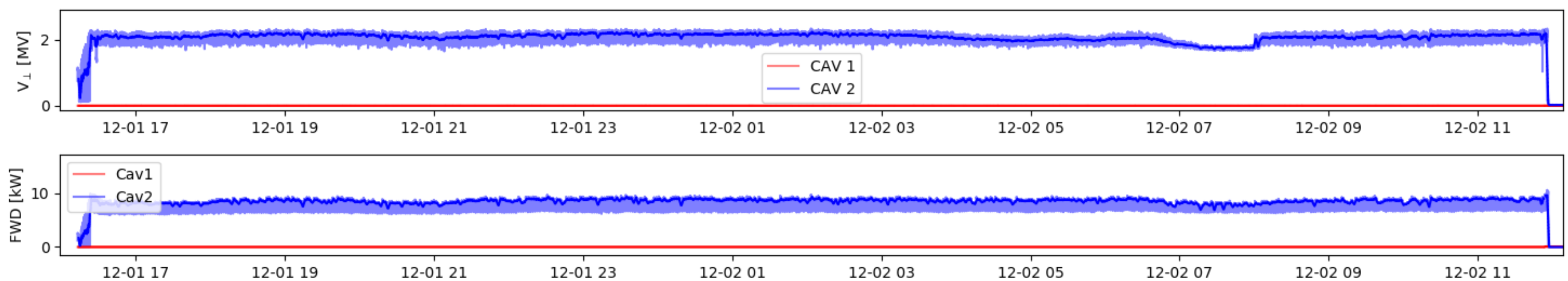


Crab Cavity Max Performance, Nov/Dec

Cavity 1 Voltage & RF Power (red)



Cavity 2 Voltage & RF Power (blue)

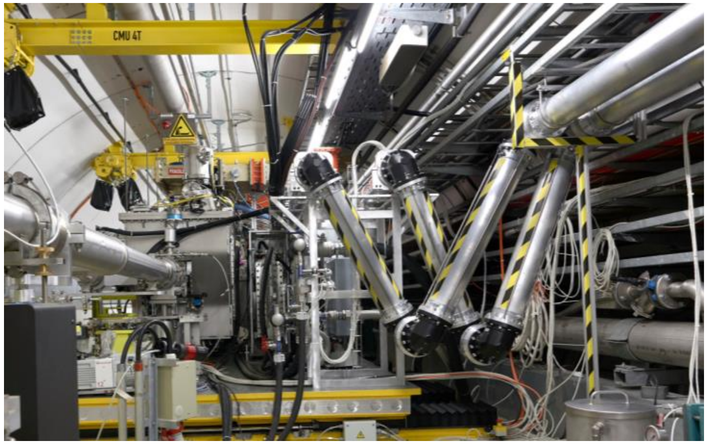


Note: After many hours of stable operation, we observed big thermal load and lost RF conditions, the trigger of such events is not fully understood

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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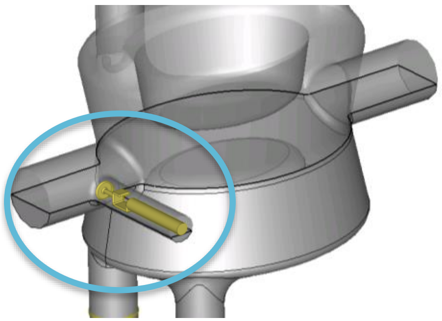
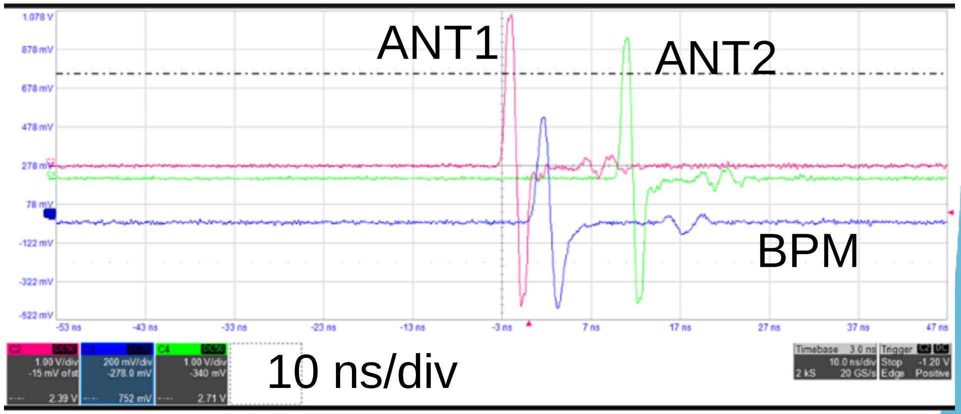
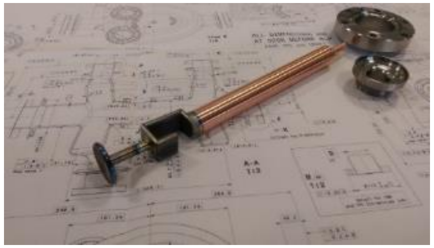
E. Montesinos et al.

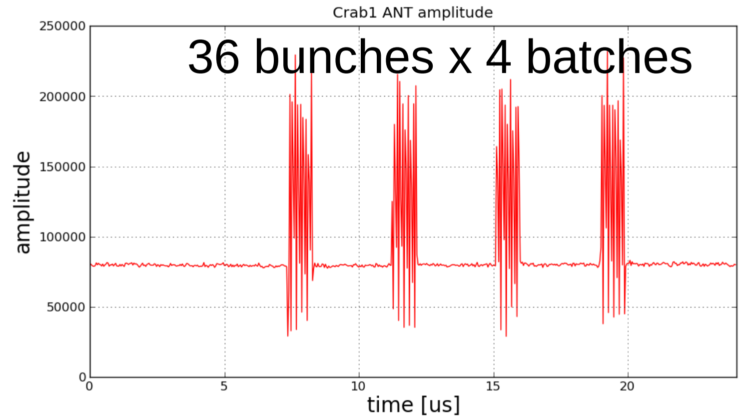
Direct Beam Coupling

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



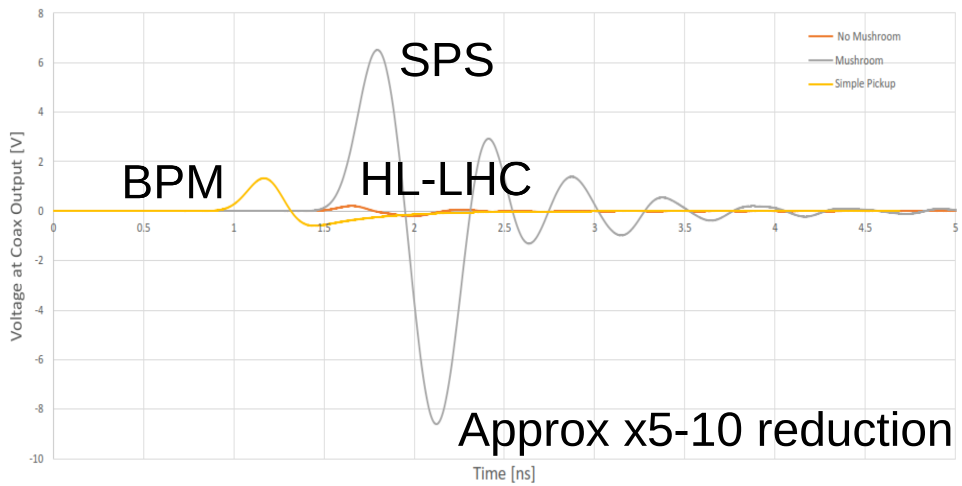




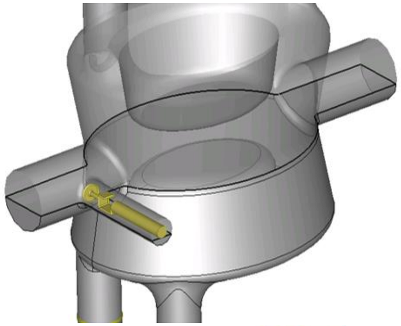
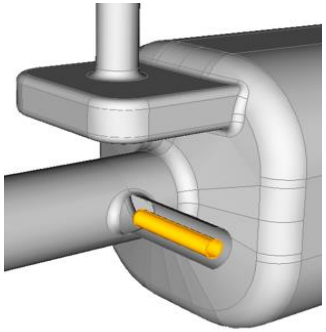


Direct Beam Coupling & Mitigation

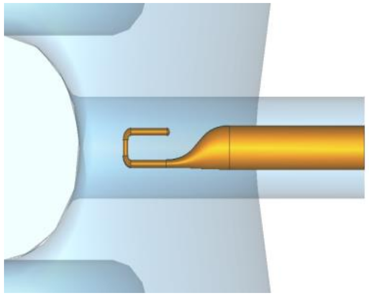
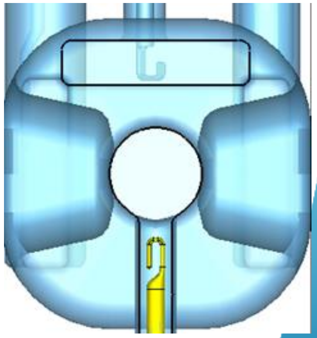
- Design change for field antenna adopted to minimize this effect by x10 for HL-LHC



SPS Field ANT

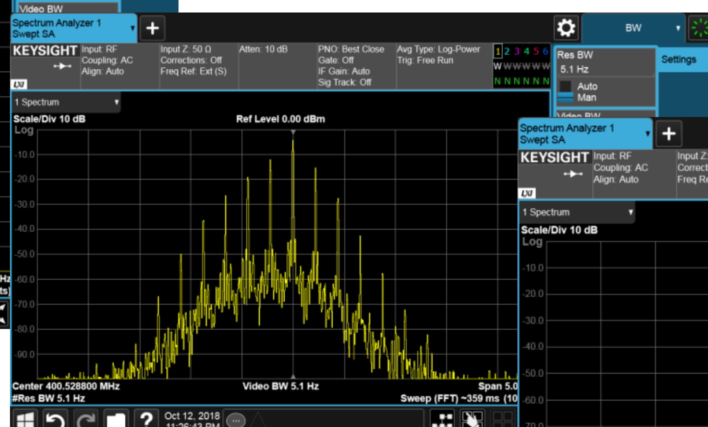



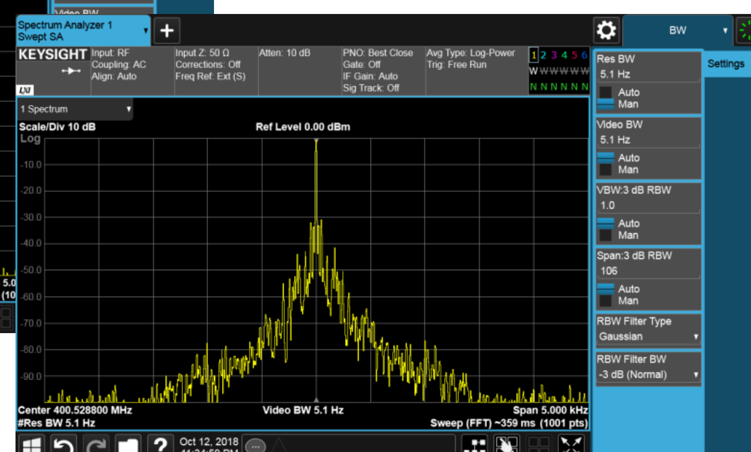
HL-LHC Field ANT

Electro-acoustic Instabilities > 1MV

- At 1MV, the LFD is $\sim 400\ \mathrm{Hz}$ $(1/2$ 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.



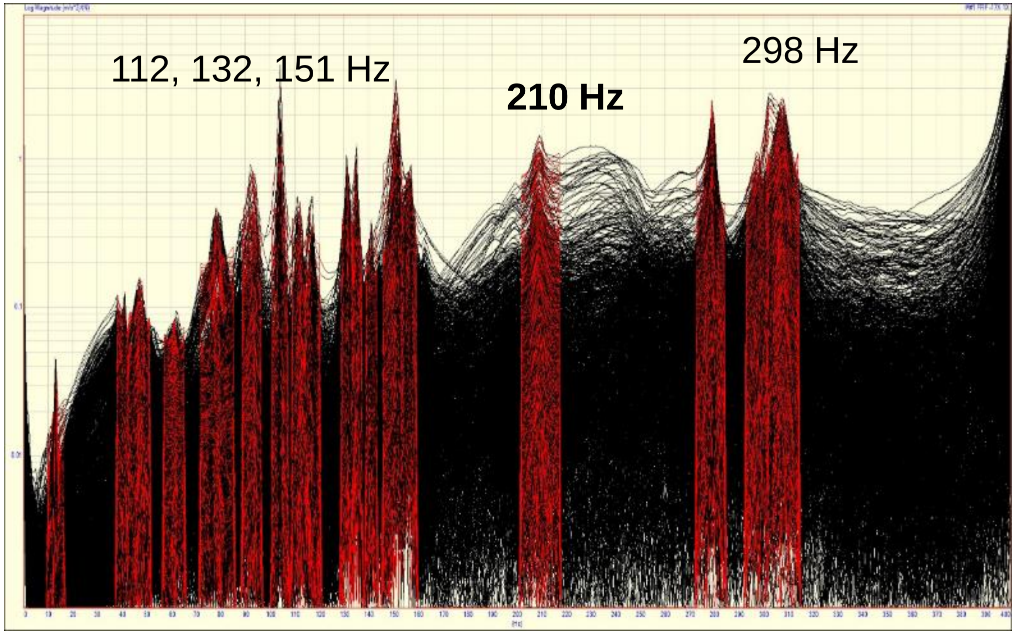


Field Antenna Spectrum, manual tuning

Modal Analysis of Bare Cavity

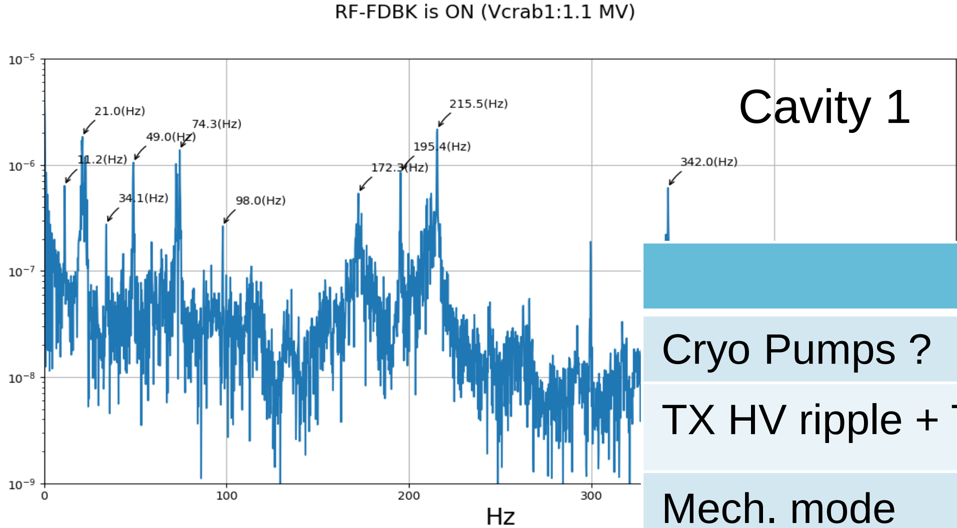
- Measurements on bare cavities with 5 tri-axial accelerometers & modal hammer

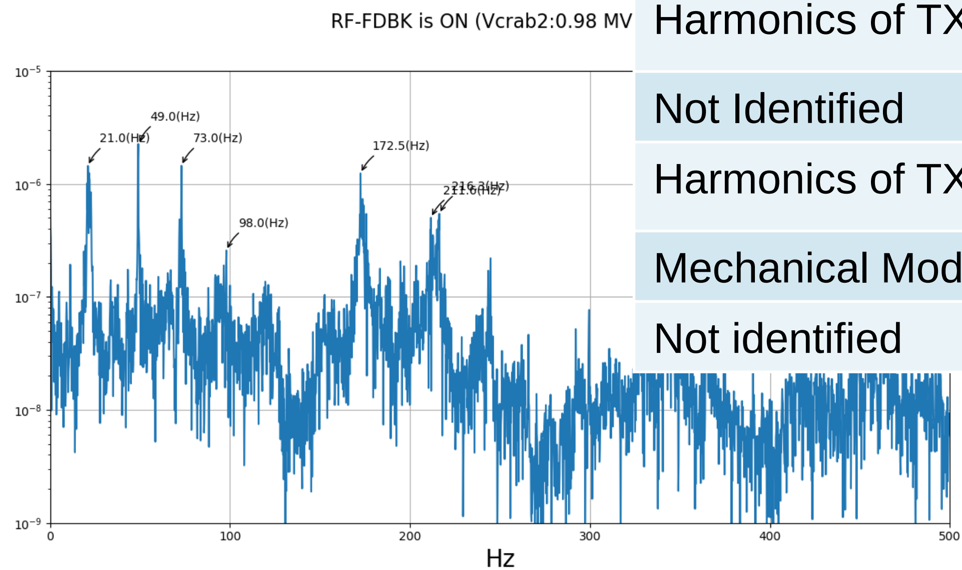
Measured Transfer Functions



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

Microphonics





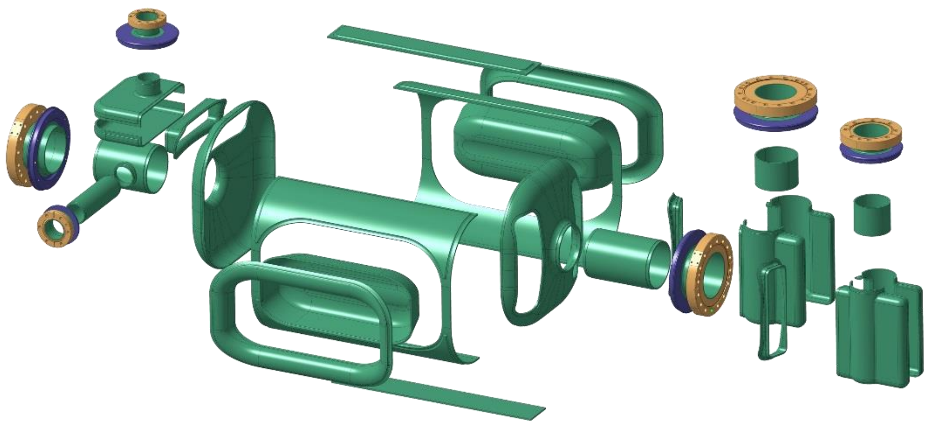
Due to small amplitude of detuning from microphonics, non-issue

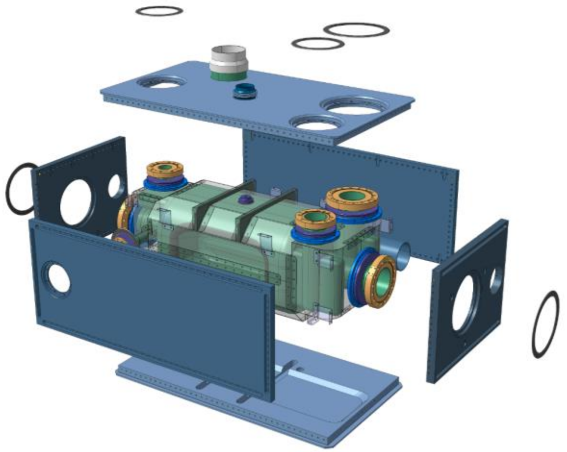
	Cav 1 [Hz]	Cav 2 [Hz]
Cryo Pumps ?	20-30	20-30
TX HV ripple + Tuner mode	49	49
Mech. mode	74	73
Harmonics of TX ripple	98	98
Not Identified	171	172
Harmonics of TX ripple ?	195	
Mechanical Mode	210	212
Not identified	342	342

Courtesy: E. Yamakawa

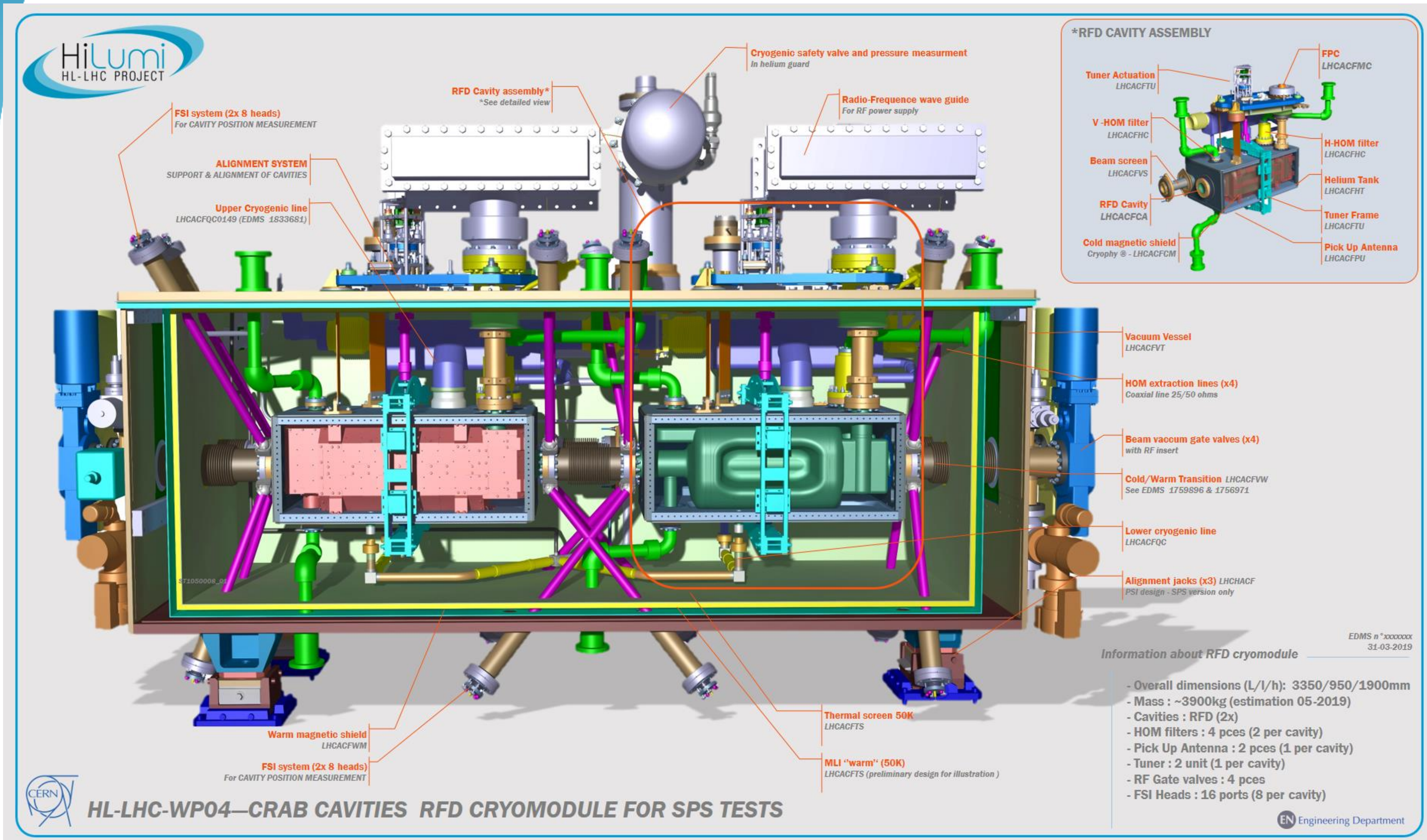
RF Dipole Development

- 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

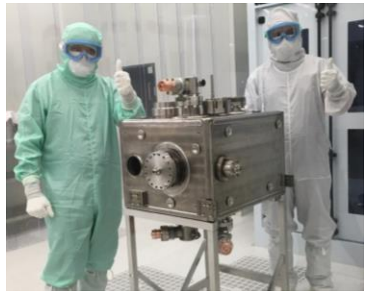
Final Comments

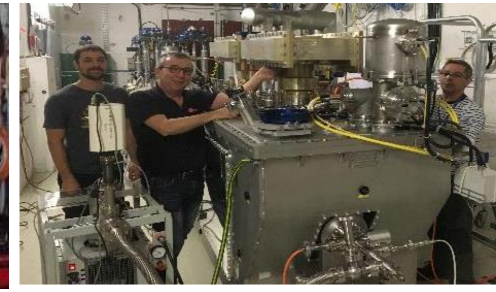
- SPS tests with Crab Cavities
  - SPS-DQW experience was invaluable for both hardware and beam validation "almost" LHC like environment
  - Several operational aspects will be fine-tuned during 2021-23. Scrubbing will be needed before MDs
  - The next prototype module (RFD) fabrication progressing well. Series for HL-LHC is now launched

- The SCRF infrastructure in SPS-LSS6 is unique can could serve for future studies (for ex: PBC)

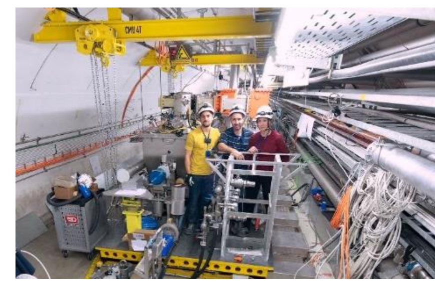
- Special thanks to our collaborations (UK & US) who played a critical part in the SPS success

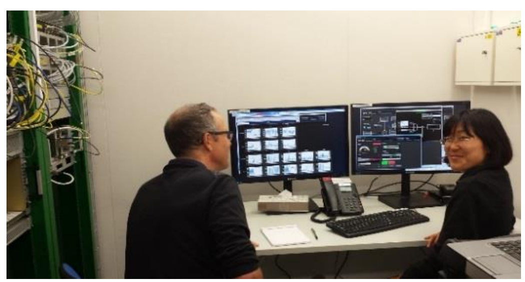
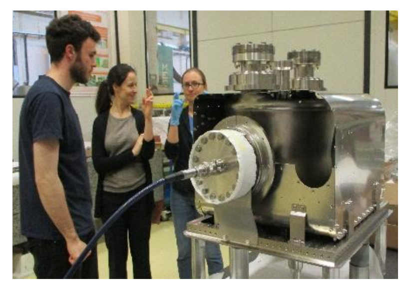
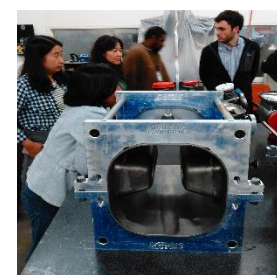
Thank You !





HiLumi HL-LHC PROJECT CERN

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

Backup

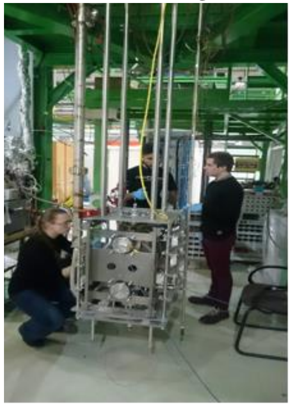
Vertical Cavity Tests (6 Cavities)

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**

* Voltage limit for SPS-DQW with HOMs due to <u>inadequate BCP</u> of HOMs

CERN DQW



USLARP DQW & RFD

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:

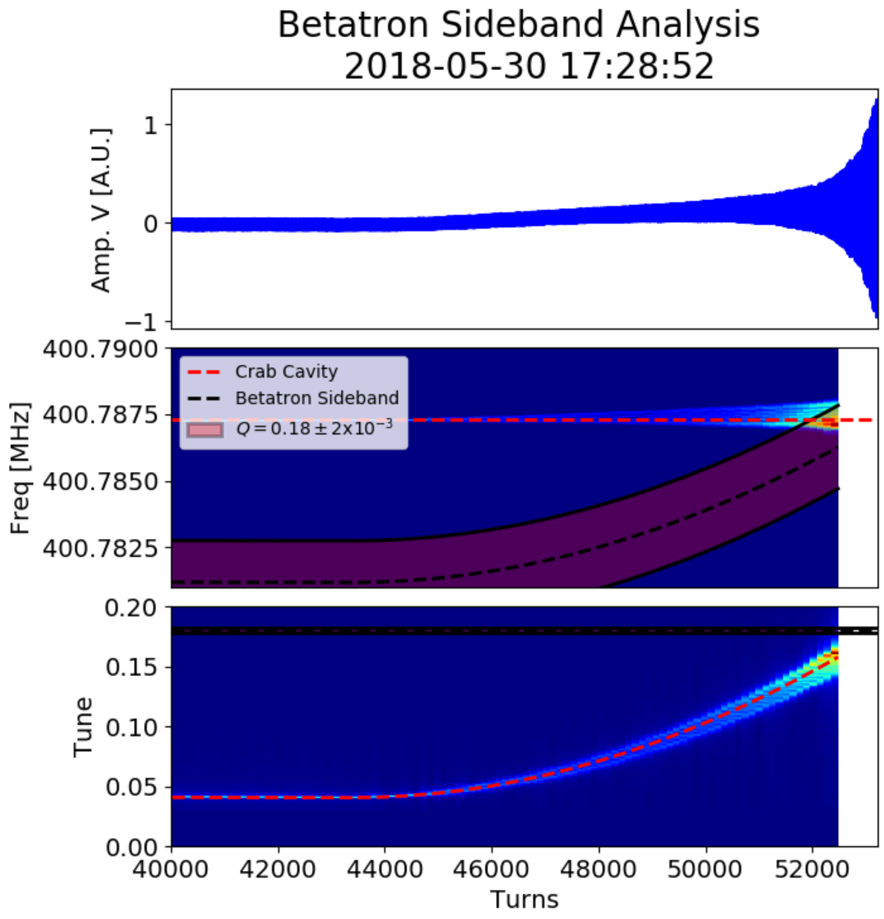
Cavity 1: 400.787 MHz (~1 MV)

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