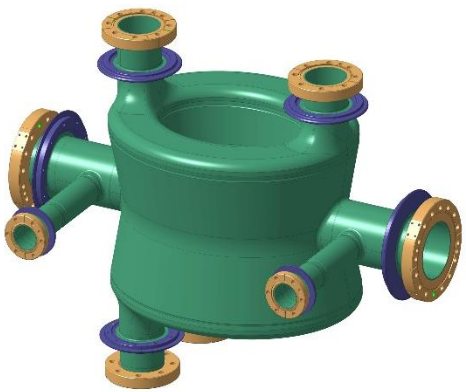
SPS Tests of Crab Cavities & Lessons Learned

HL-LHC WP4, CERN

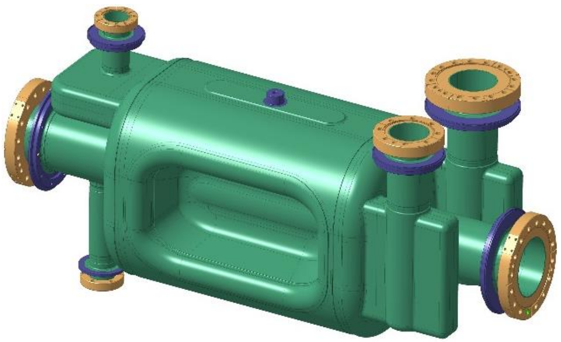
14 October 2019, HL-LHC Annual Meeting, FNAL

Dressed Cavity Geometries

Double Quarter Wave



RF Dipole



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

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

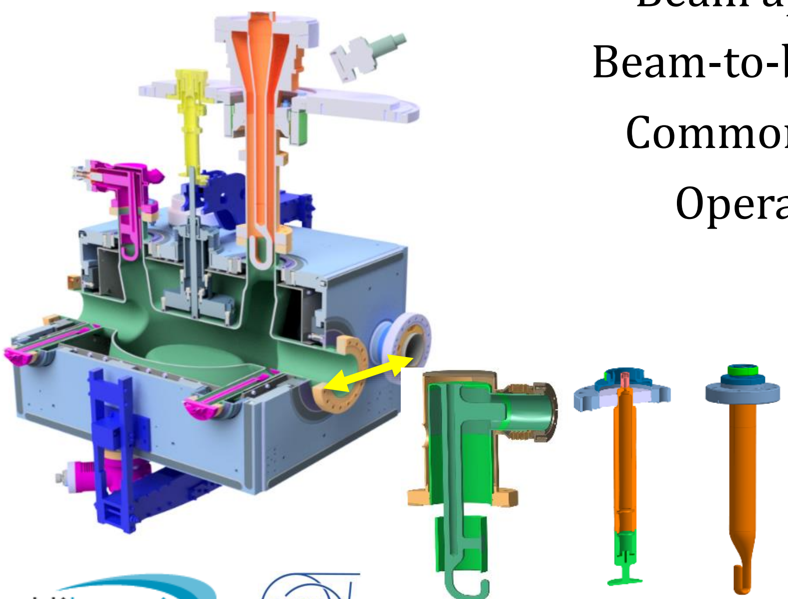
$$(E_p, B_p < 40 \text{ MV/m}, 70 \text{ mT})$$

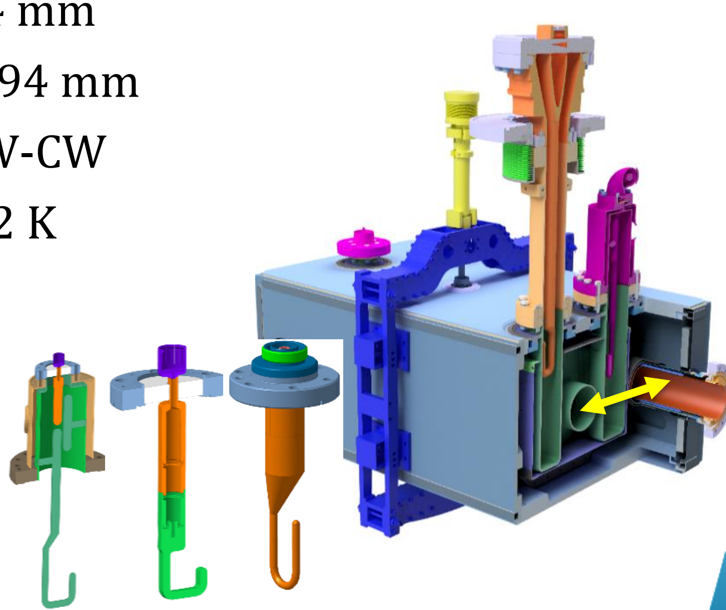
Beam aperture = 84 mm

Beam-to-beam dist = 194 mm

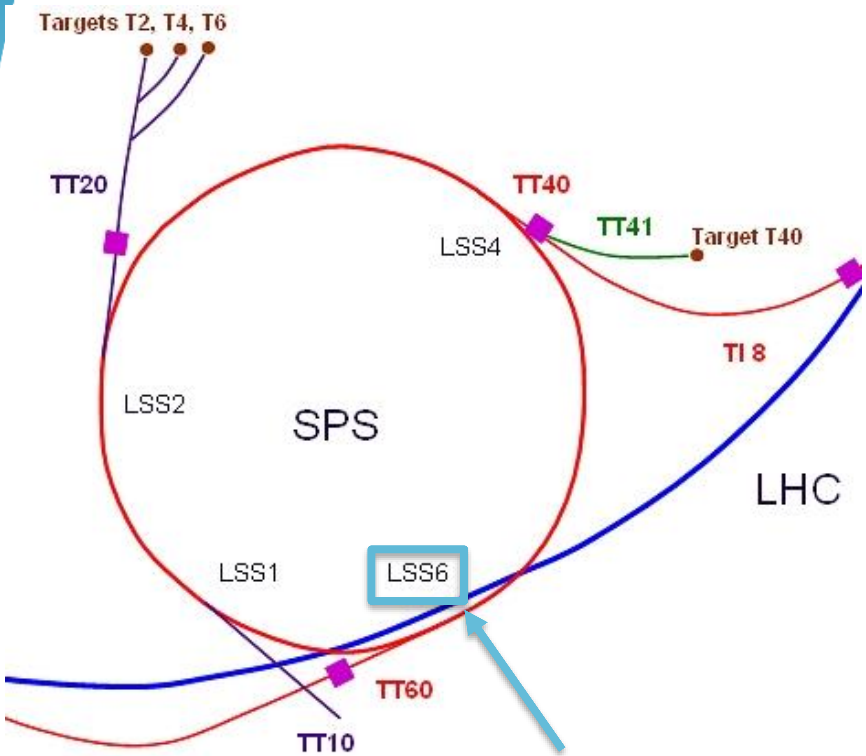
Common FPC = 40 kW-CW

Operating Temp = 2 K





Super Proton Synchrotron, SPS



LSS6-BA6 is the highest energy superconducting test facility in the world!

DQW cavities successfully installed & tested in 2018

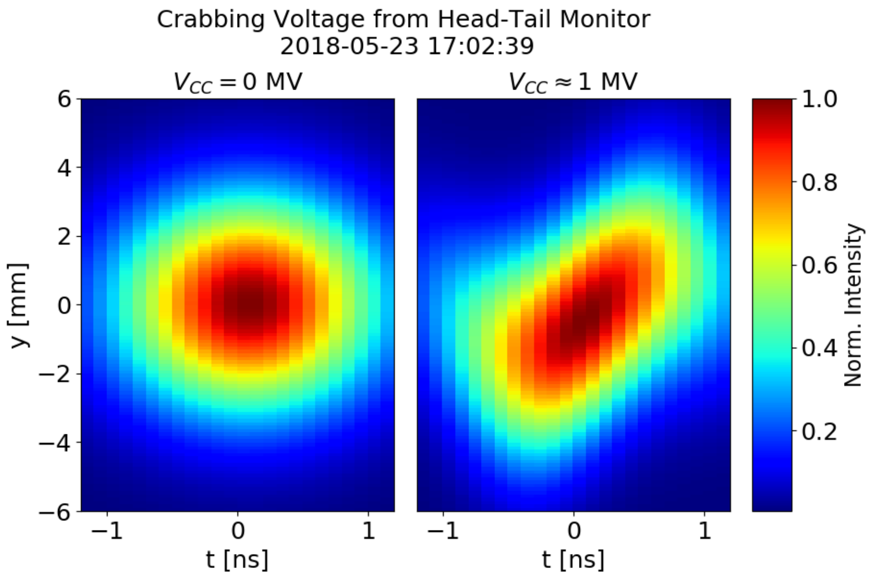
Circumference	7 km
Injection-Extraction energy	26-450 GeV
Main RF Frequency	200 MHz, TW
CC Operating Freq Range	400.528 – 400.788 MHz

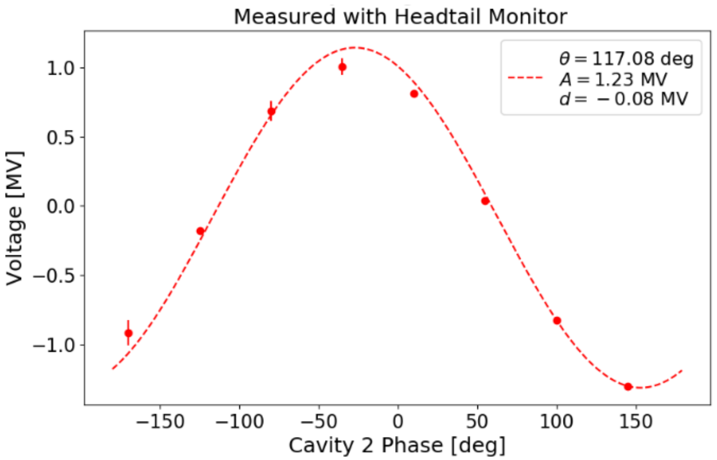
SPS-LSS6 – Crab Cavity Module

1: We can Crab Protons!

We can crab the proton beams of 3 ns, with predicted crabbing agrees with measured angles within 10%

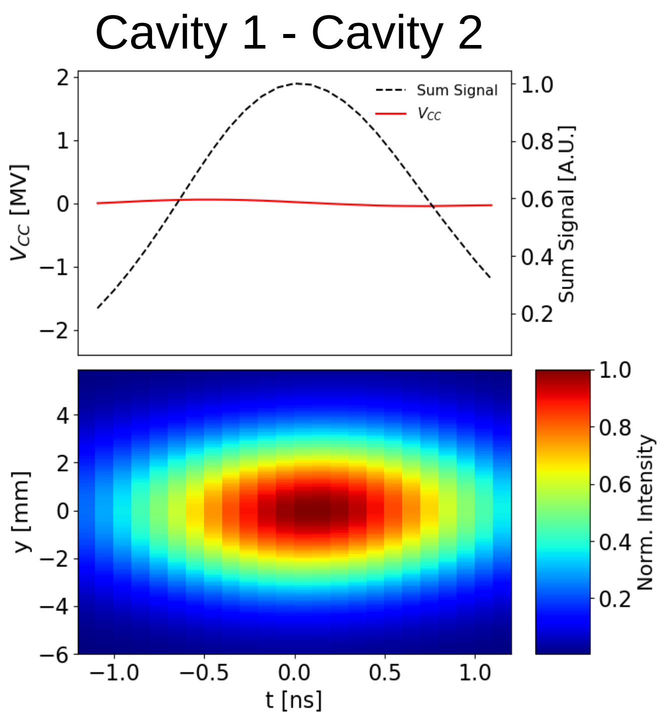
No noticeable effect on beam in variety of conditions including strong RF curvature

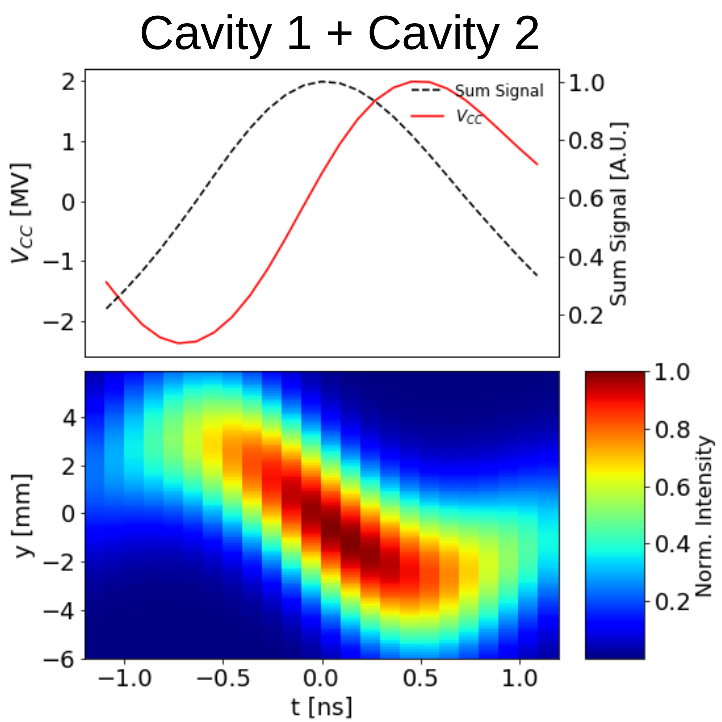




2: Transparency

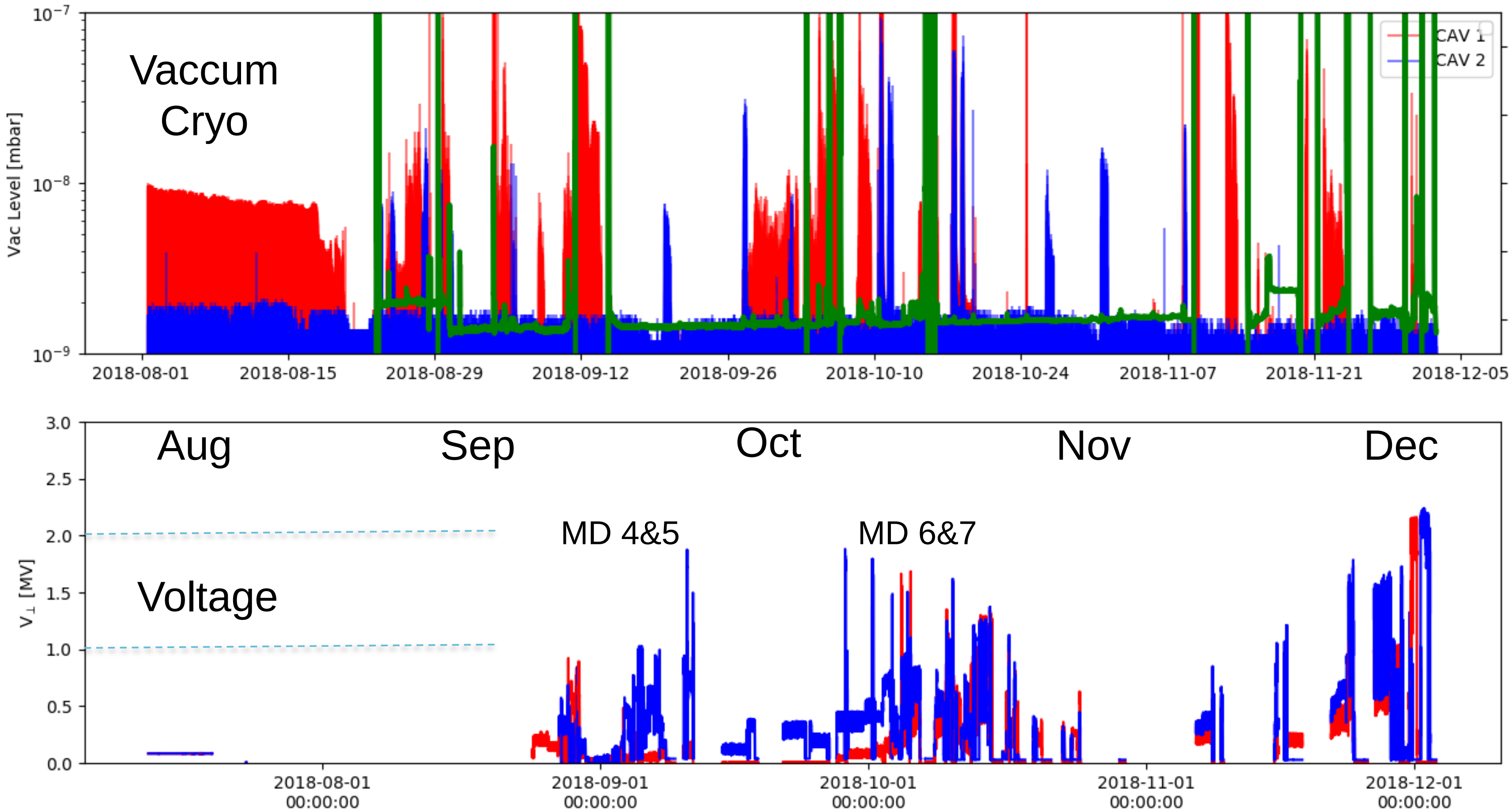
- We can regulate the intra-cavity phase in a precise and stable manner. In next run, we need to understand timescale of phase drifts





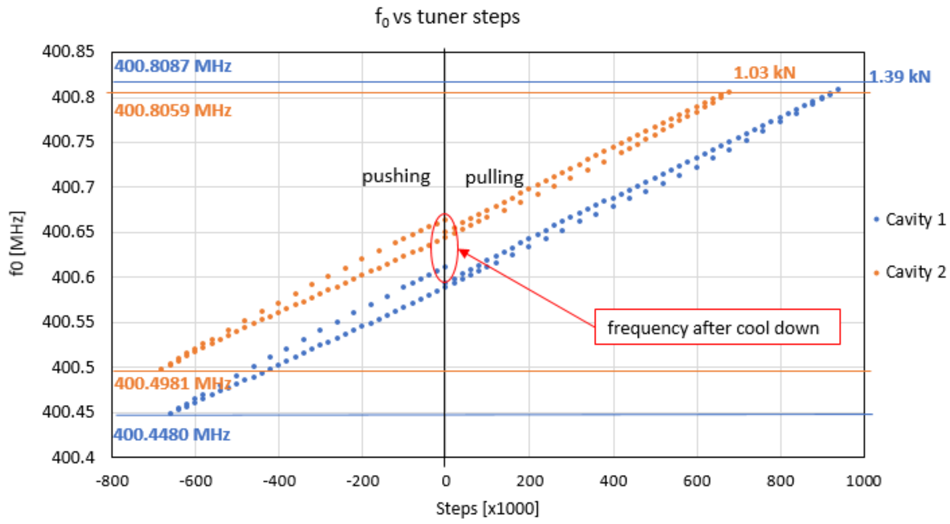
3: Voltage Ramp-Up

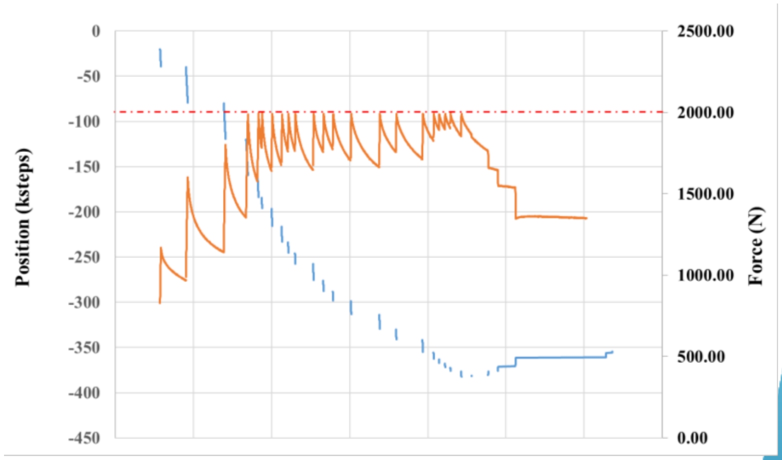
- Long RF conditioning to go beyond 1 MV stable operation. Maximum reached was 2.5 MV



4: Freq Tuning

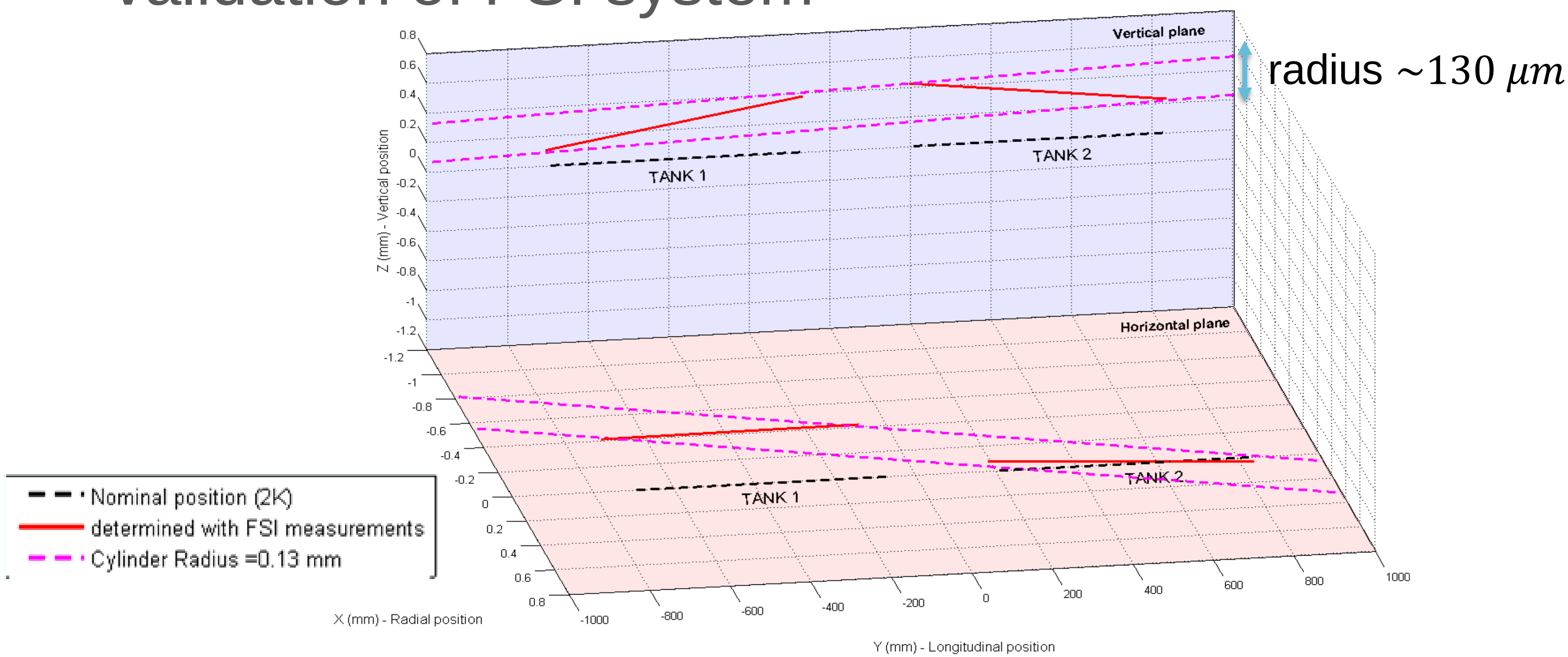
- Maximum range of $> 300\ \mathrm{kHz}$ achieved with resolution of few 10’s Hz (cavity BW 800 Hz)
- But observed sudden increase in stiffness and motor gear slippage towards end of 2018 – new mechanism warm part will be replaced in LS2





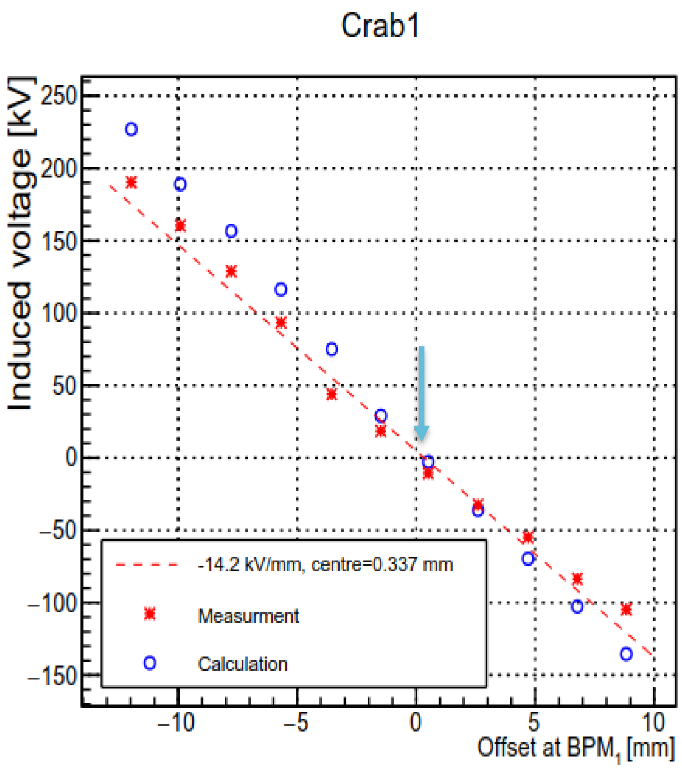
5: Alignment

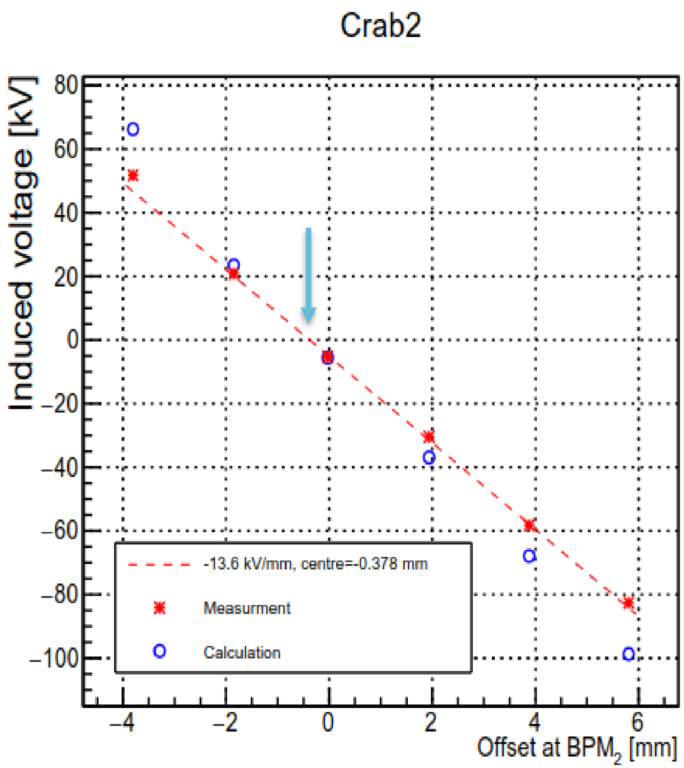
- Intra-cavity alignment tolerances $< 500\ \mu m$ in the transverse plane required.
- Achieved successfully during SPS test including validation of FSI system



Beam Loading & Electrical Center

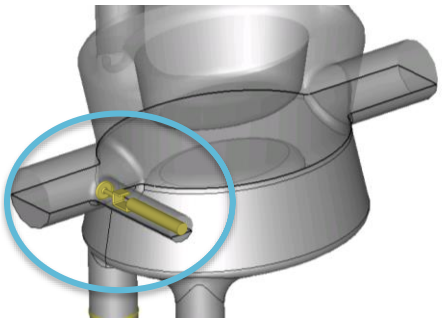
- Electrical center from beam induced voltage to validate mechanical alignment
- Test static re-alignment of $\sim 150\ \mu m$ in LS2 and re-measure with beam in 2021

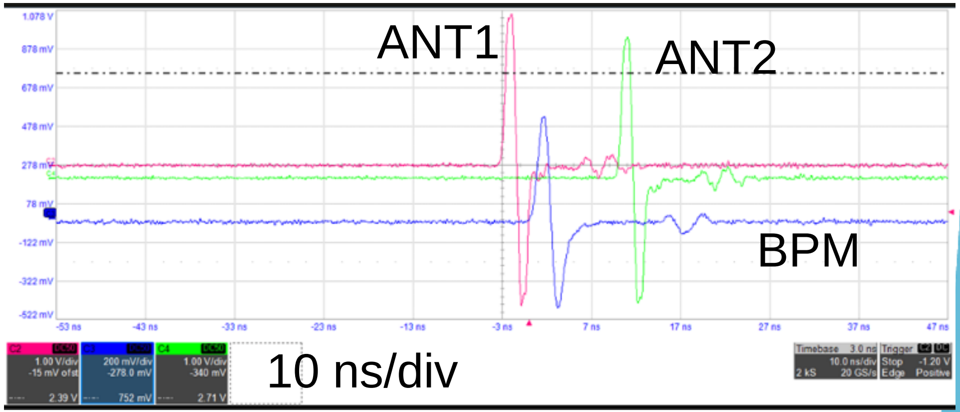


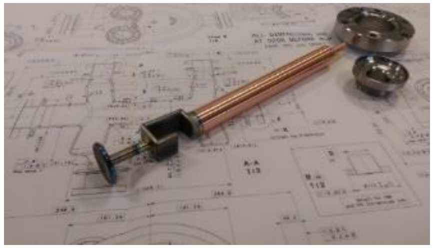


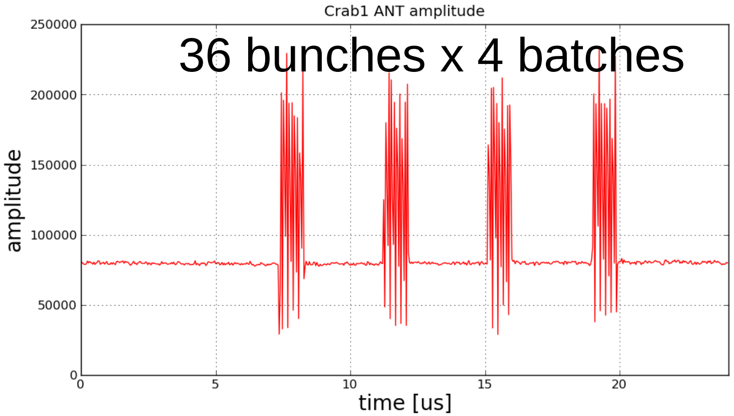
6: Field Antenna

- Strong coupling of the field antenna (like a BPM) to the beam passage instead of just measuring cavity field variation



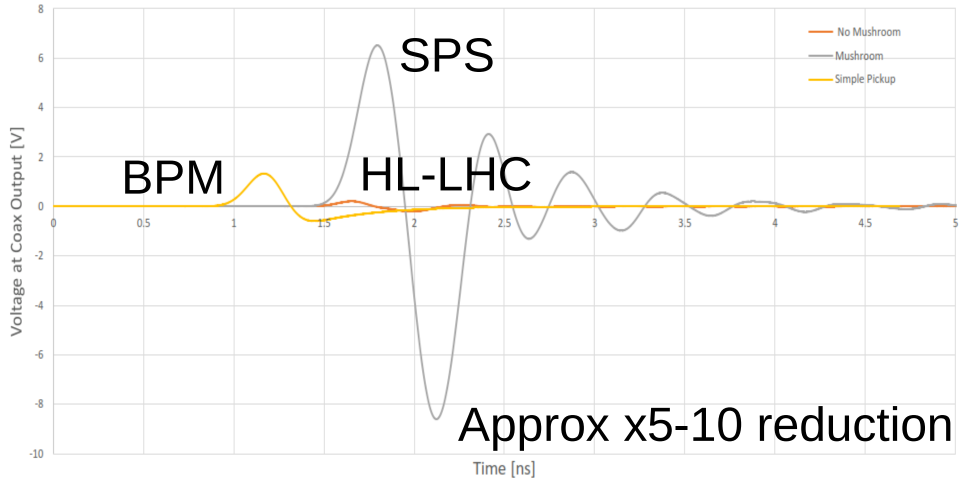




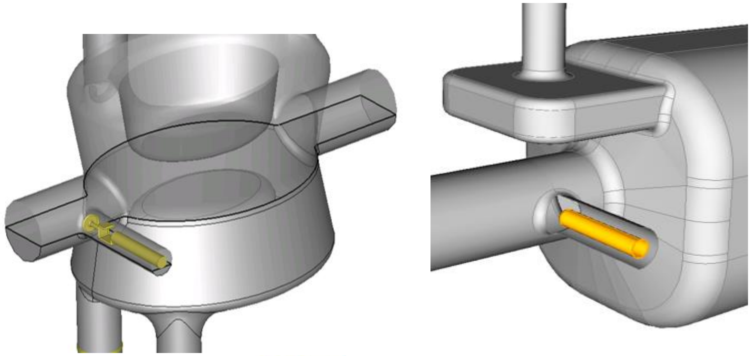


Direct Beam Coupling Mitigation

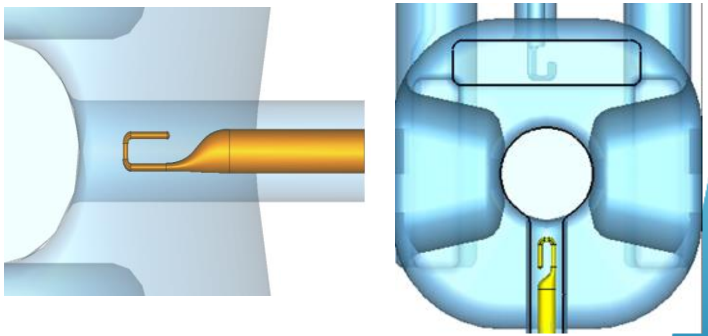
- Design change for field antenna adopted for HL-LHC to minimize this effect by approx. × 10



SPS Field ANT

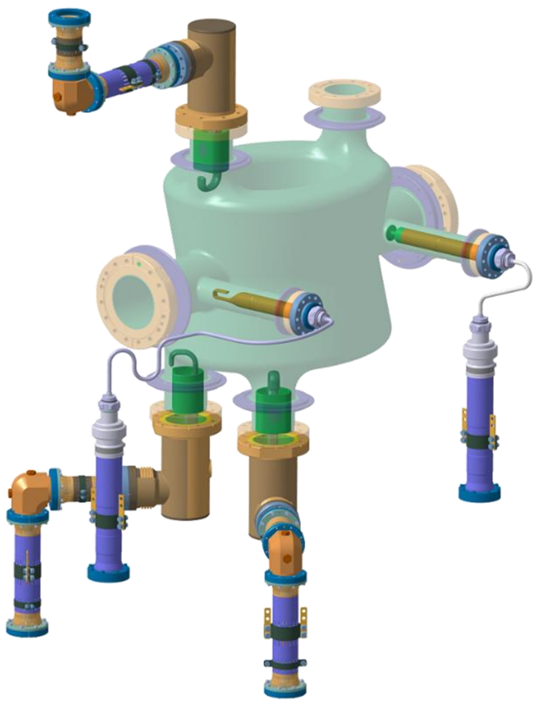


HL-LHC Field ANT

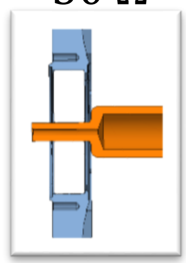


7: RF Feedthroughs

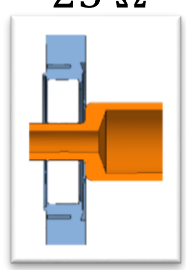
- Vacuum leaks at 2K experience during SPS solved with re-design for window brazing
- Feedthrough impedance used for SPS 38 Ω! Ideally 50 Ω, decision to go for 25 Ω for robustness & standardized feedthroughs for all couplers

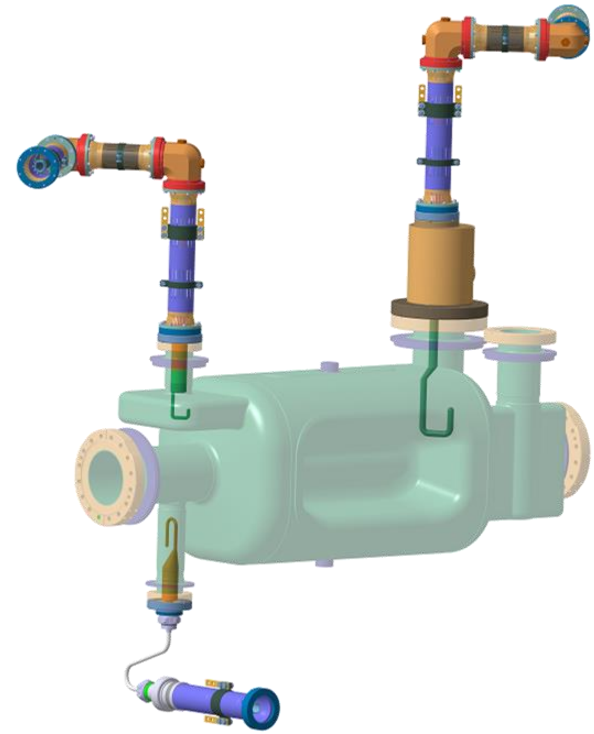


50 Ω



25 Ω

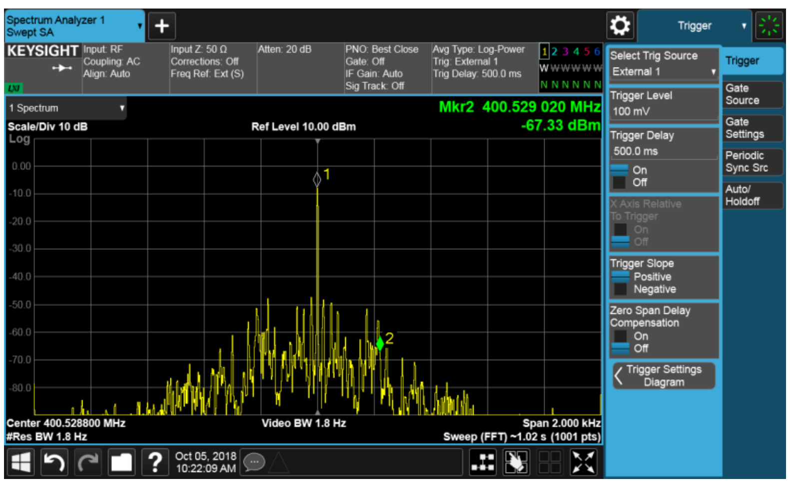




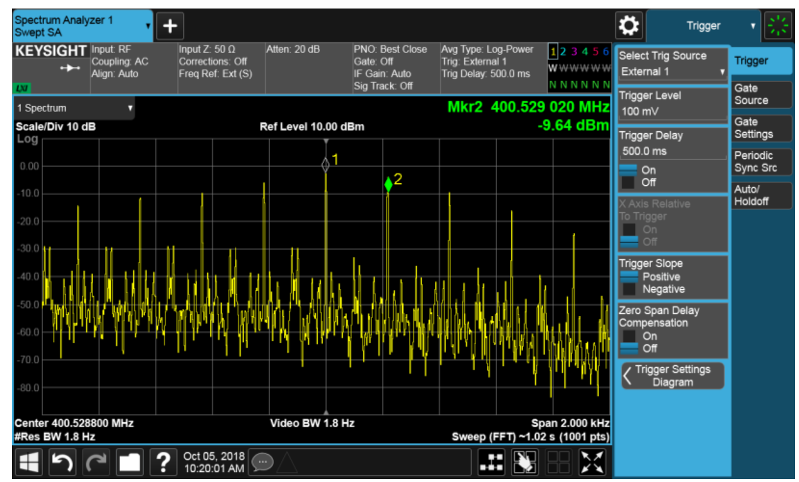
Electro-acoustic Instabilities > 1MV

- Electro-acoustic instabilities above 1 MV (LFD is ~400 Hz which is 1/2 the cavity BW)
- Self excited loop essential for setup. Now in place but not the case in 2018 MDs

800kV



1.9 MV

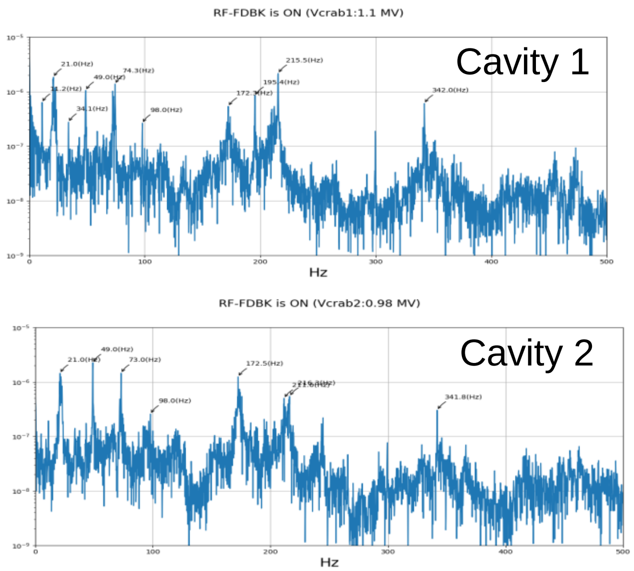


HiLumi HL-LHC PROJECT

CERN

9: Microphonics

- Microphonics, non-issue due small detuning & sufficient RF bandwidth
- Choice of bandwidth appropriate

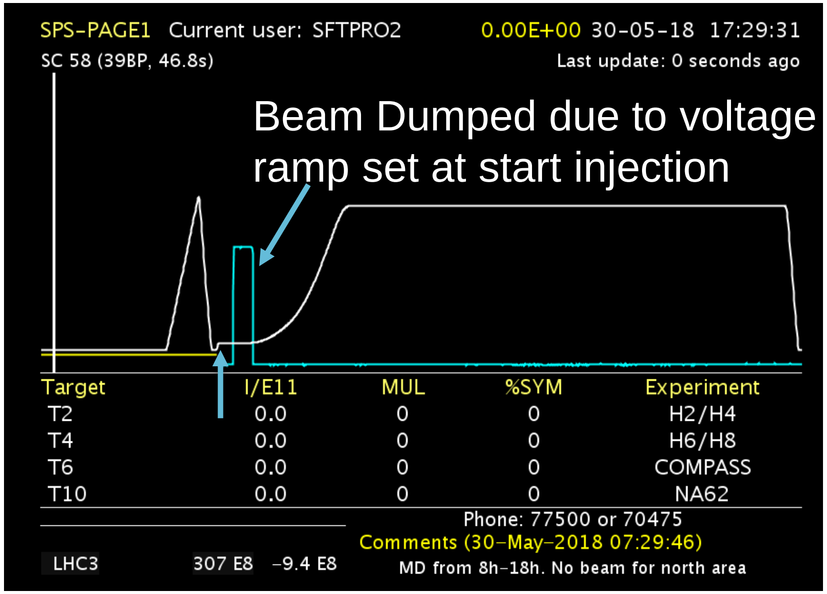


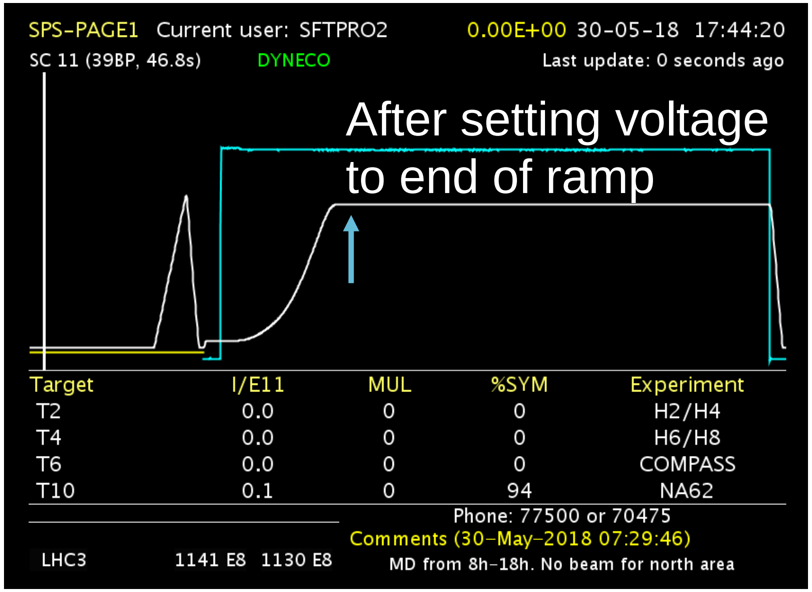
	Cav 1 [Hz]	Cav 2 [Hz]
Pumps ?	20-30	20-30
TX HV ripple + Tuner mode	49	49
Mech. mode	74	73
Harmonics of TX ripple	98	98
Not Identified	171	172
Harmonics of TX ripple ?	195	
Mechanical Mode	210	212
Not identified	342	342

10: Voltage Program, Ramp

- The easiest way (almost "brute force") was to run cavities off to circulate beam in the SPS
- Could be new operational scenario for HL-LHC where we turn on cavities at flattop. Easier than counter-phasing with low voltage, although the latter is baseline for HL-LHC

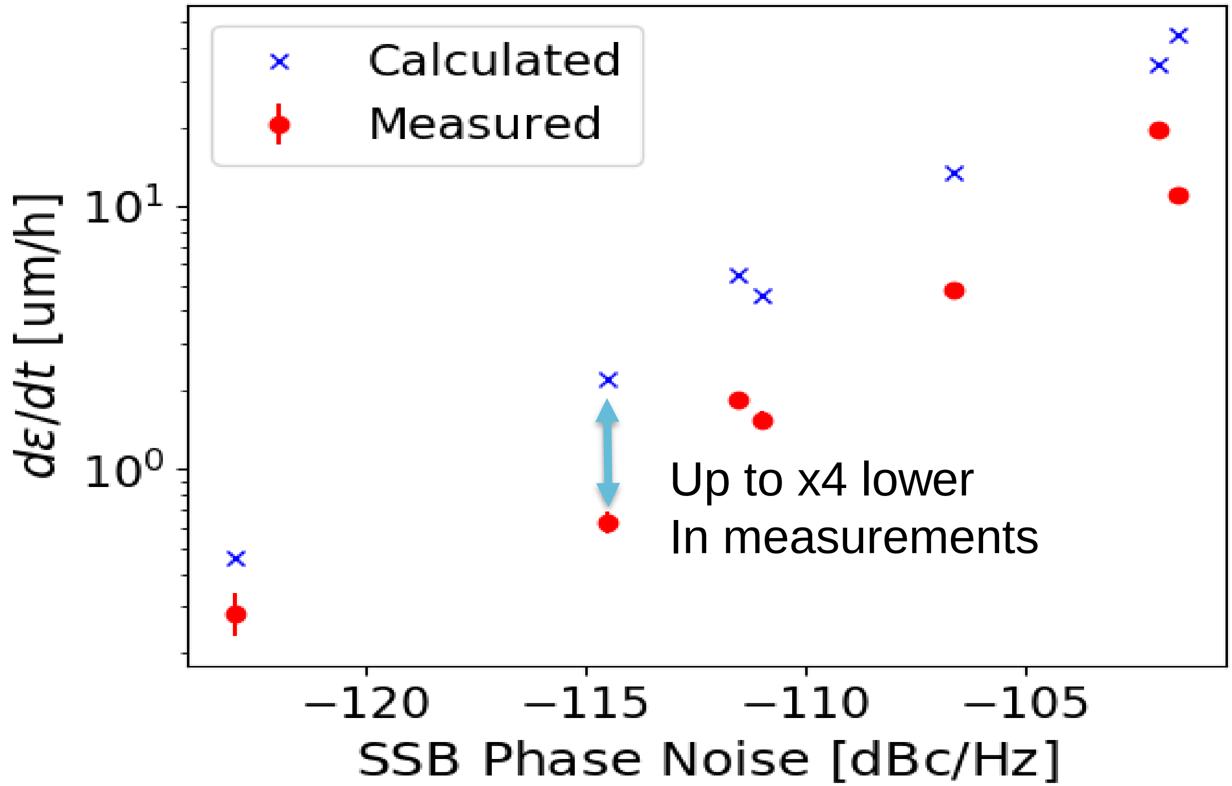
Cav1 ~1MV (400.787 MHZ), Cav2 off (400.528 MHz)





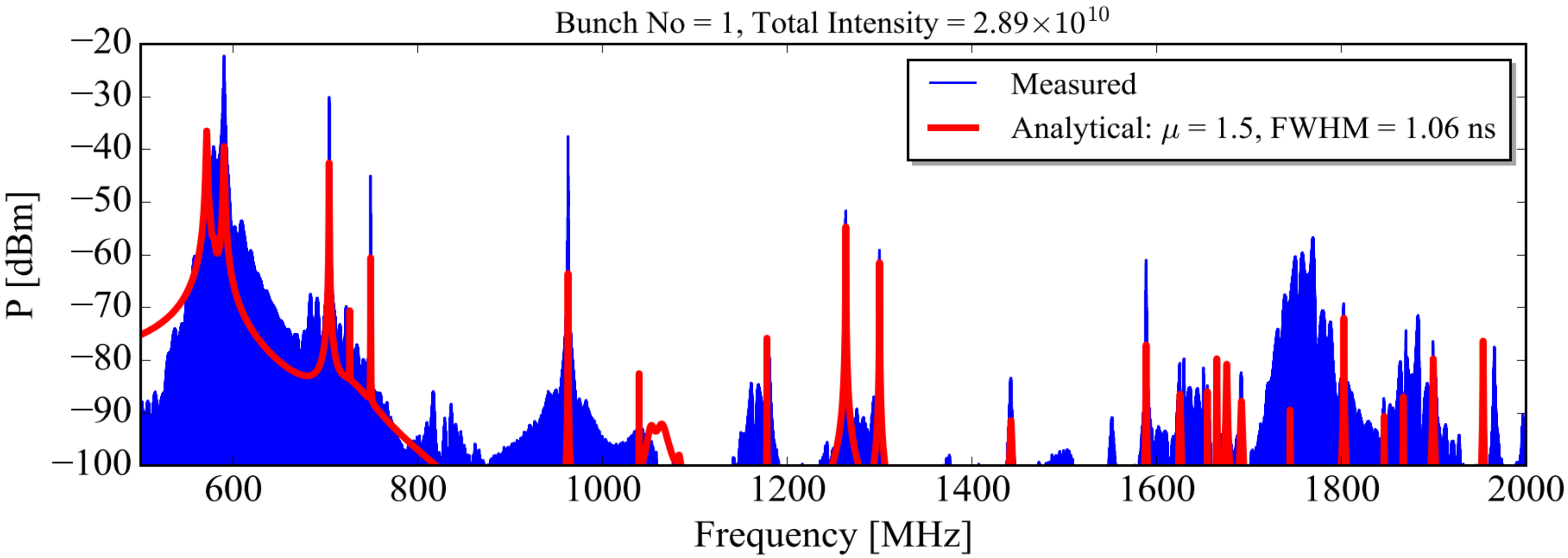
11: Emittance Growth

- Measured emittance growth is lower by ×2-4 compared to predicted values
- Not fully understood – appears like a systematic error, but positive outcome for HL-LHC

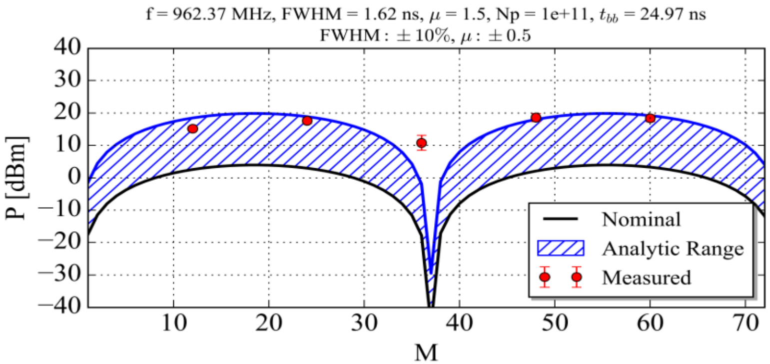


12: Impedance

- Integrated max HOM power measured < 3 W. More than 75% from ~960 MHz as expected
- Overall HOM power & scaling to the HL-LHC looks reasonable, some deviations related to lack of accurate beam profile

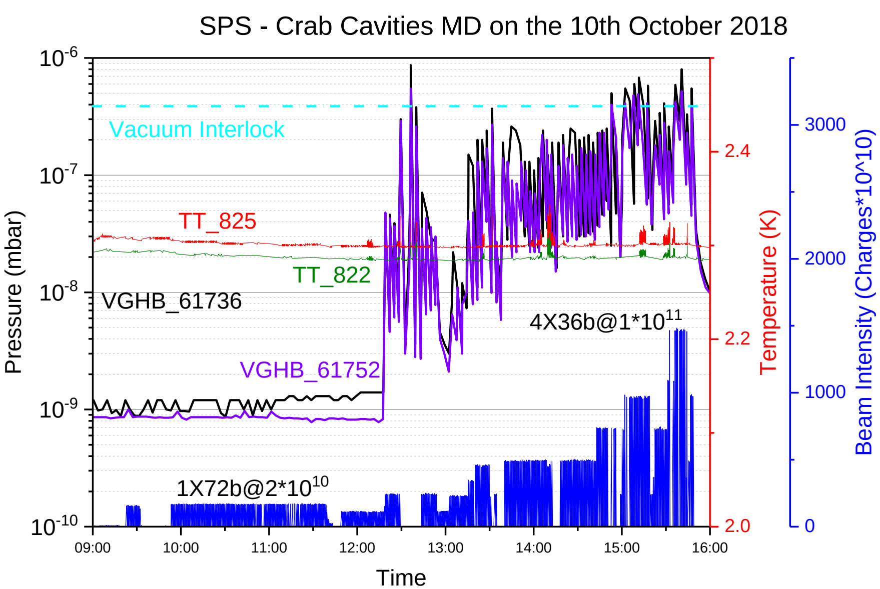


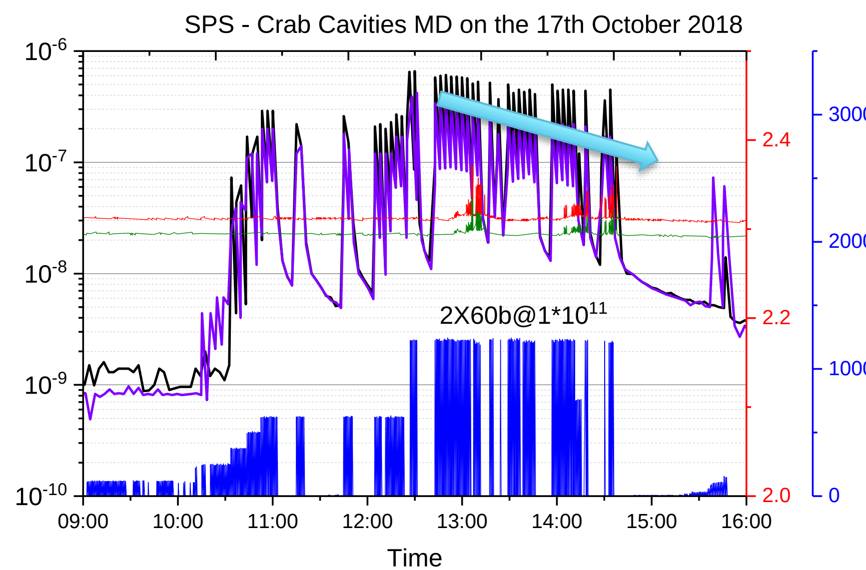
(including bunch length/distribution range)



12: Vacuum Dynamics

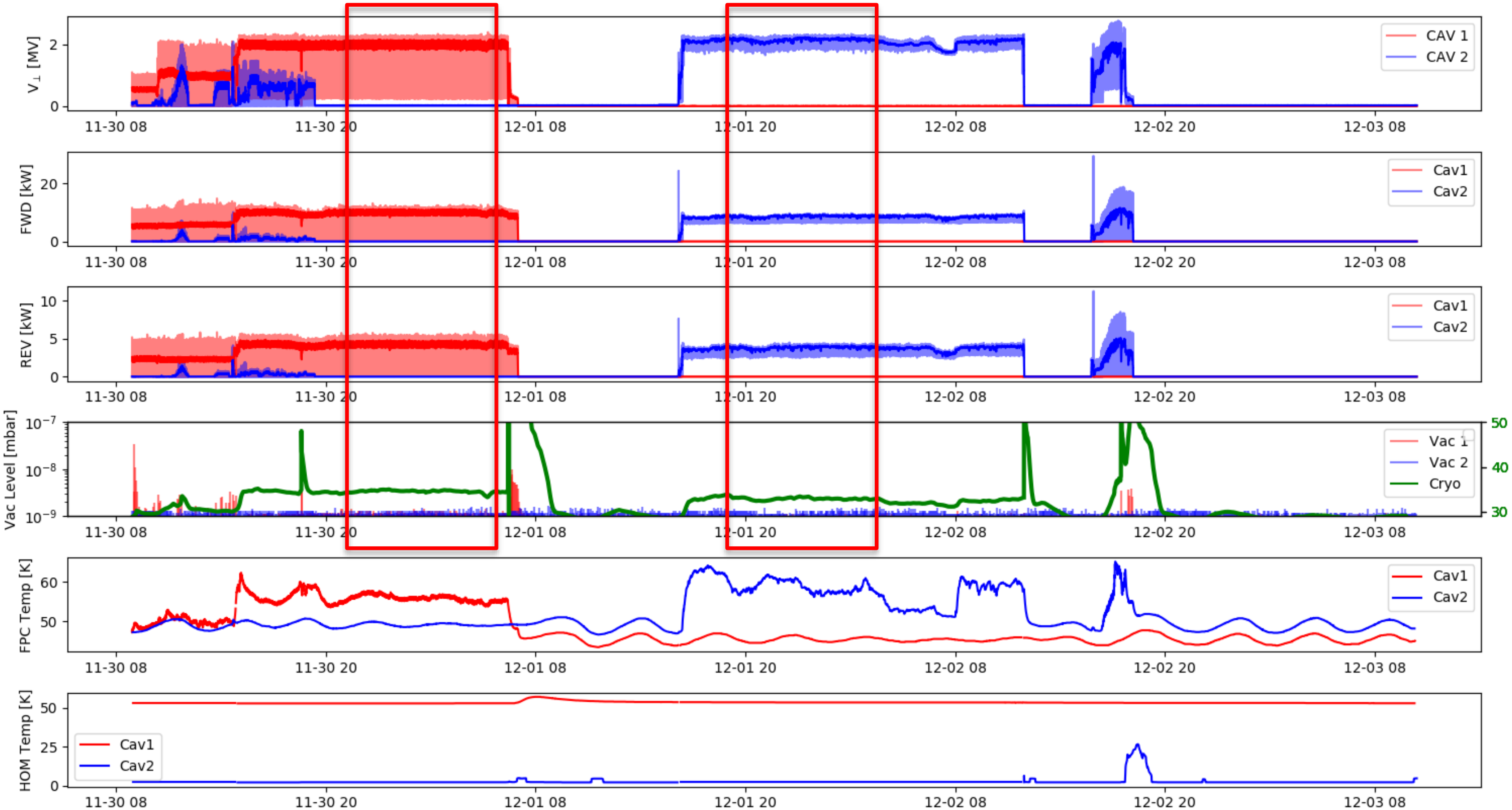
- High intensity limited by pressure rise in bypass (2×60 nominal bunches). No obvious problems with cavities or intensity related failure scenarios ($V = 1\text{MV}$)
- Scrubbing needed post LS2 to fill max current





13: Cryogenics

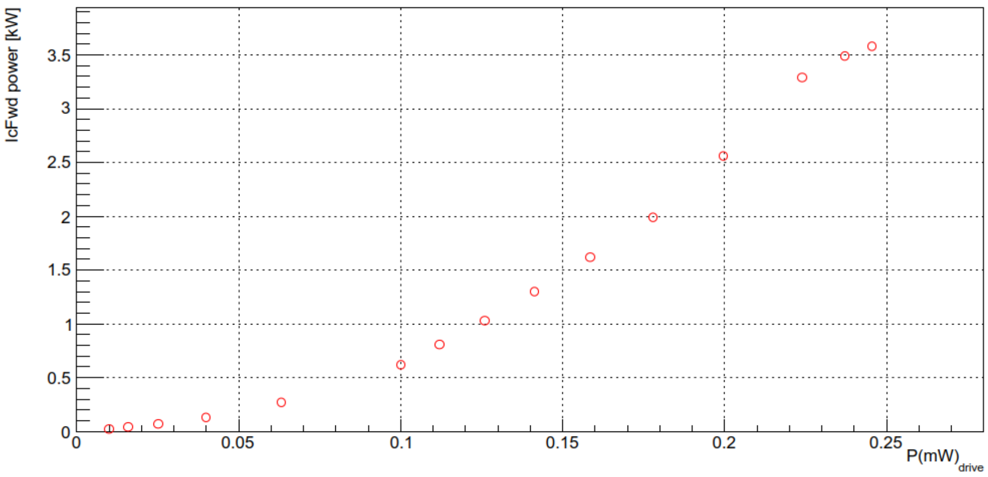
- Cav1 ~15 W & Cav2 ~8 W (at ~2.1 MV)
- Much higher than vertical tests (5 W). Better estimates needed post-LS2 after improved conditioning



14: RF Power

- Only notable issue with RF power was linearity at low power (< 5 kW). Added to specification for HL-LHC amplifiers (now SSPA)
- Rest of the RF chain validated

Surface-BA6



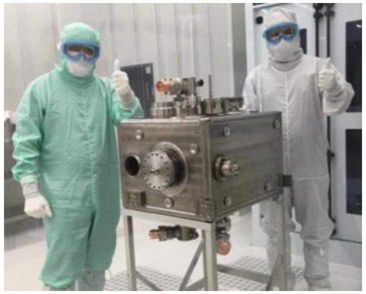
Final Comments

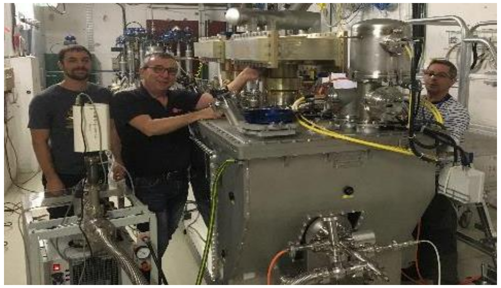
- SPS tests with Crab Cavities
  - SPS-DQW experience was invaluable for beam & hardware validation in an “almost” LHC like environment
  - Several operational aspects will be fine-tuned during 2021-24. Scrubbing needed before MDs
  - The next prototype module (RFD) fabrication on track for installation in 2021-22. Series for HL-LHC is now launched

- The SCRF infrastructure in SPS-LSS6 is unique can could serve for future SRF studies

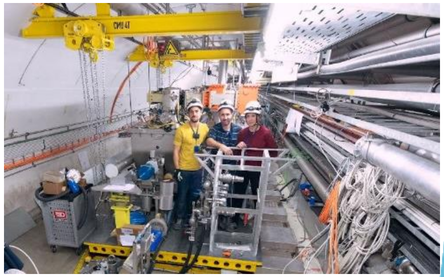
- Special thanks to our collaborations (UK & US) who played a critical part in the SPS success

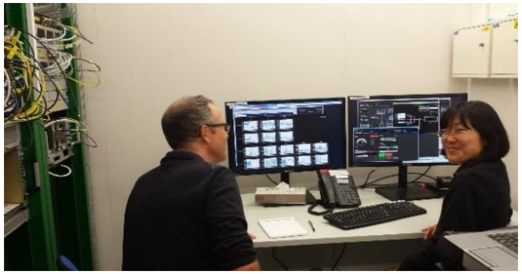
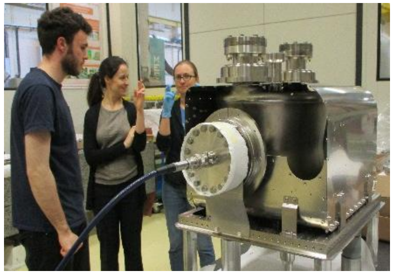
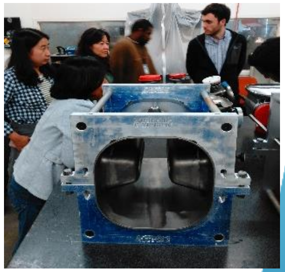
Thank You !







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