Crab Cavities

SPS MDs, Design Advancement, Plan for Production

HL-LHC WP4

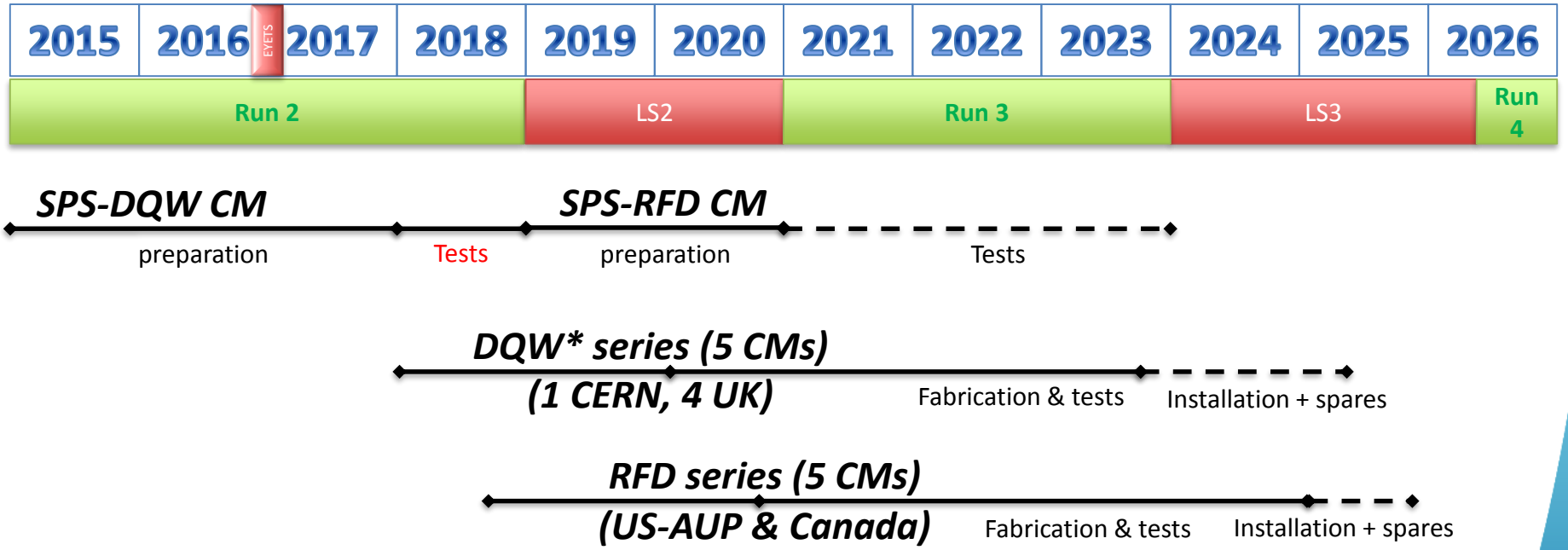
16 October 2018 - CERN

SPS-DQW!

WP04 Scope

16 SC compact crab cavities to partially compensate the geometric angle ($500\ \mu rad$) at ATLAS+CMS

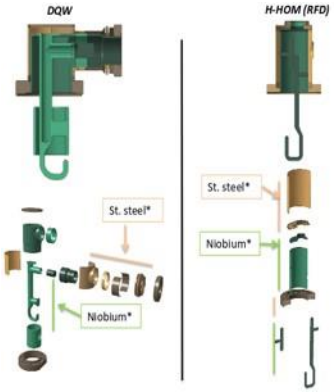
- *First protons through Crabs in SPS !*



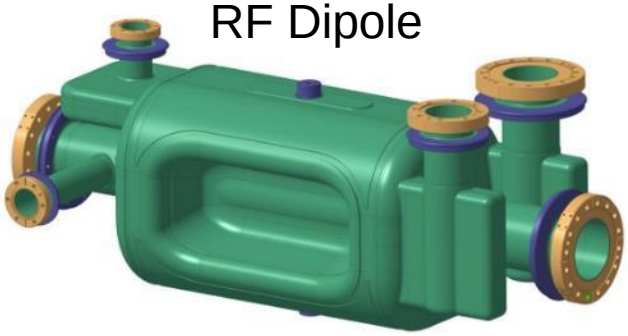
* Jacketed cavities produced by RI

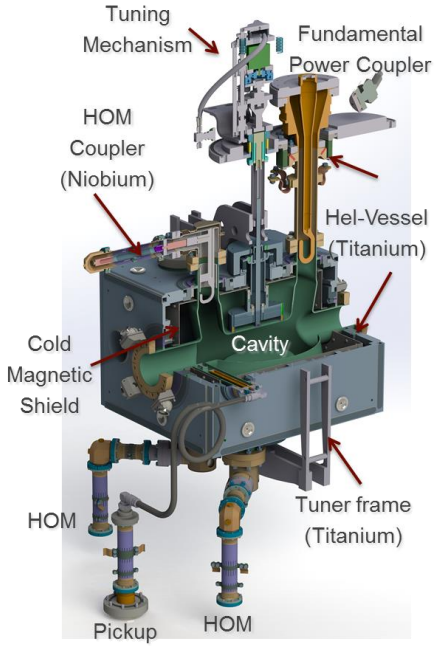
SPS Cavities 2K Volume

DQW



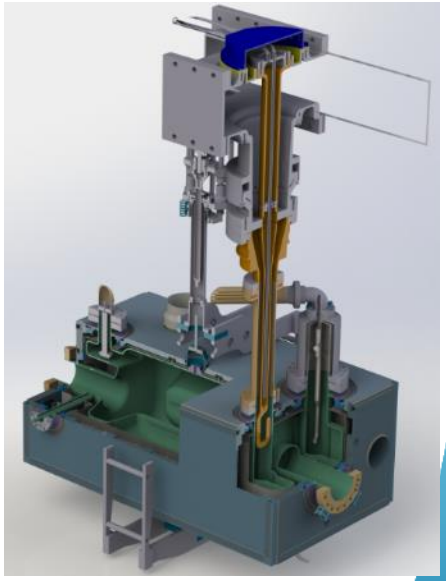
RF Dipole





- Main Mechanical interfaces:
  - He-vessel: New Bolted-welded concept
  - Tuner: Symmetric tuning, warm actuation
  - Three point support + alignment system

- Main RF interfaces
  - 1 FPC: Single ceramic coaxial line
  - 2-4 HOMs: Two stage filter, coaxial
  - 1 PU: Cu-Nb for field probe + HOM



WP4 Highlights, 2018

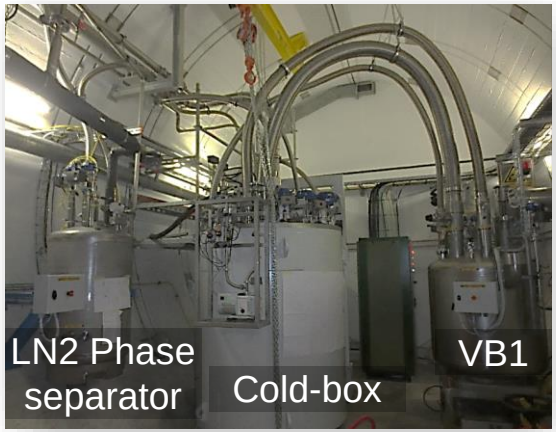
- DQW-SPS prototype demonstrates with first ever crabbing with protons
- DQW-HL-LHC jacketed cavities contract with RI signed & ongoing
- DQW-HL-LHC cryostating in final stages of negotiation for building 1 at CERN and 4 at UK

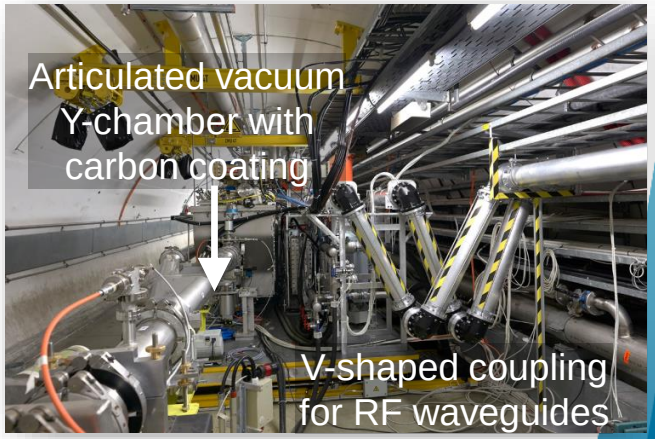
- RFD-SPS cavity fabrication started at CERN, cryostating to be performed at UK and the conceptual design in an advanced stage
- RFD-HL-LHC dressed cavities in-kind contribution from US-AUP with CD1 approval
- RFD-HL-LHC cryostating is approved to be an in-kind from Canada-TRIUMF

- Discussions ongoing with Novosibirsk for an in-kind contribution of high power RF amplifiers using solid state technology

SPS-BA6 Installation

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





What do we Validate ?

- Some critics ask, if it was necessary ?
- The over-arching reason was, can we “turn-off” crab cavities if they “don’t work”

- But, reality is somewhat different – during 2018, the **main** struggle was not with beam but getting the cavities, cryogenics and RF controls to function as intended

- In HL-LHC, we will have factor 8 times the same – hence the humbling experience of SPS is a lifesaver

Expected SPS Test Sequence

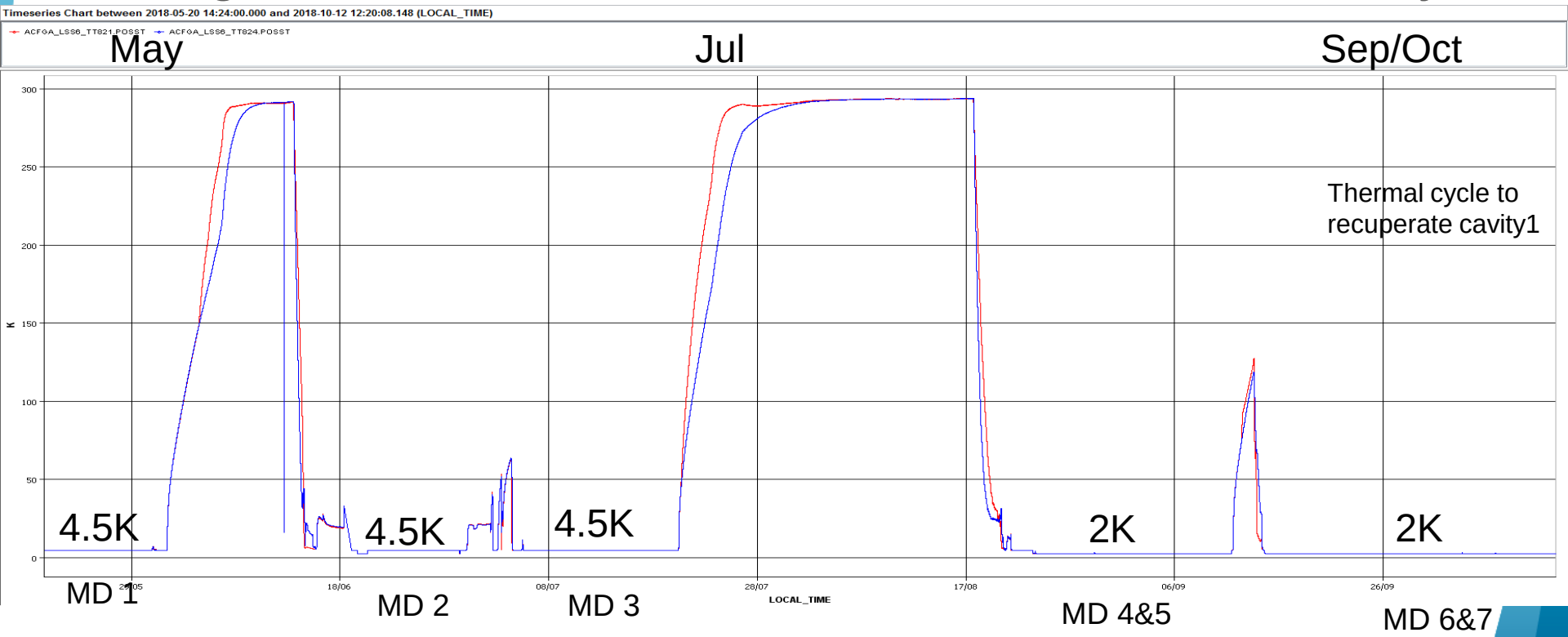
	What	When	MD slots
0	RF commissioning (no-beam)	Mar-Apr	~ 4 weeks
1	RF-beam synchronization	Apr-May	2-4 x 10h
2	Transparency to beam	Jun-Jul	2-4 x 10h
3	Performance & Stability	Aug-Sep	4 x 10h
4	High intensity RF operation	October	2 x 10h

- 4 main phases foreseen – 10 MDs requested
- 6 MDs have occurred. 1 MD tomorrow

- The only subject not yet quantitatively demonstrated is transparency (due to technical issues)

Cryogenic 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

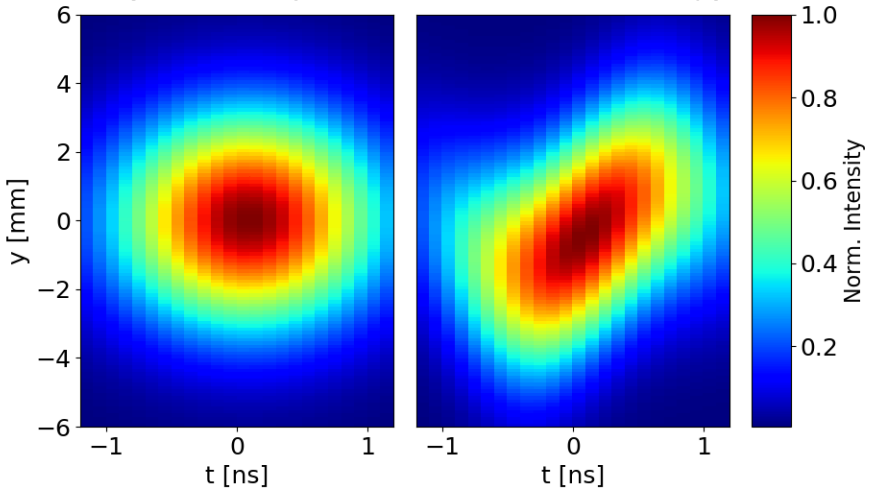
MD#		Cav1	Cav2 [MV]	Temp [K]	Energy [GeV]
1	First crabbing, phase and voltage scan	0.5	0	4.5	26
2	270 GeV ramp with single bunch	1-2	0	4.5	26, 270
3	Intensity ramp up	1	~0.3	4.5	26
4	270 GeV coast setup	1.0	0.5	2.0	270
5	Emittance growth at 270 GeV with induced noise	0	1.0	2.0	270
6	Intensity ramp up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

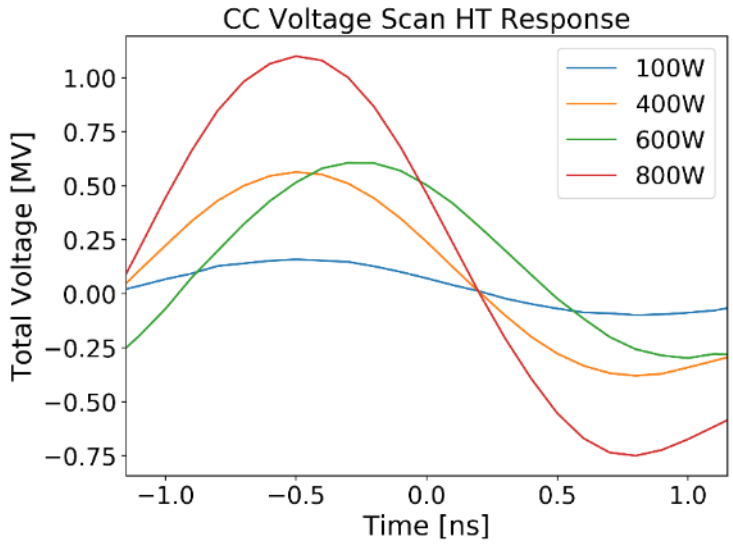
Protons meet Crabs

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)

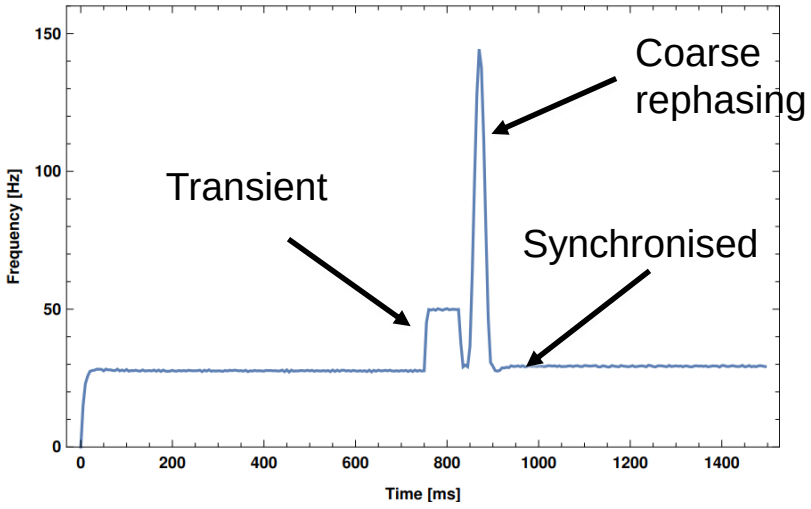




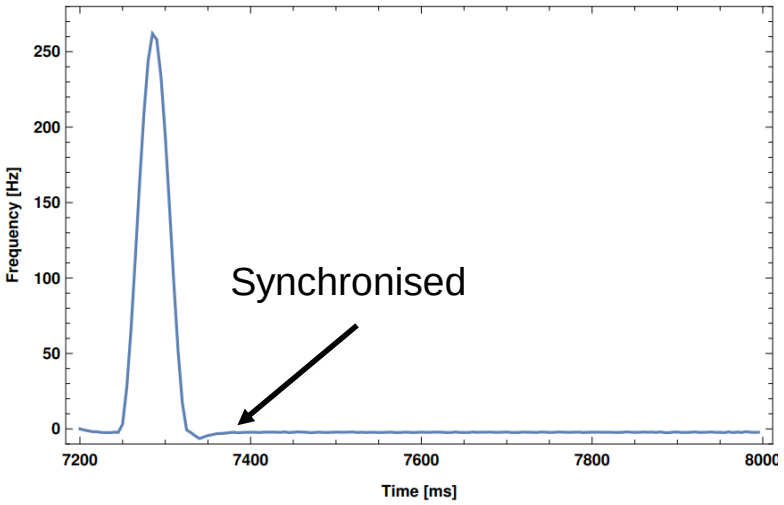
How to synchronize Crab-RF ?

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

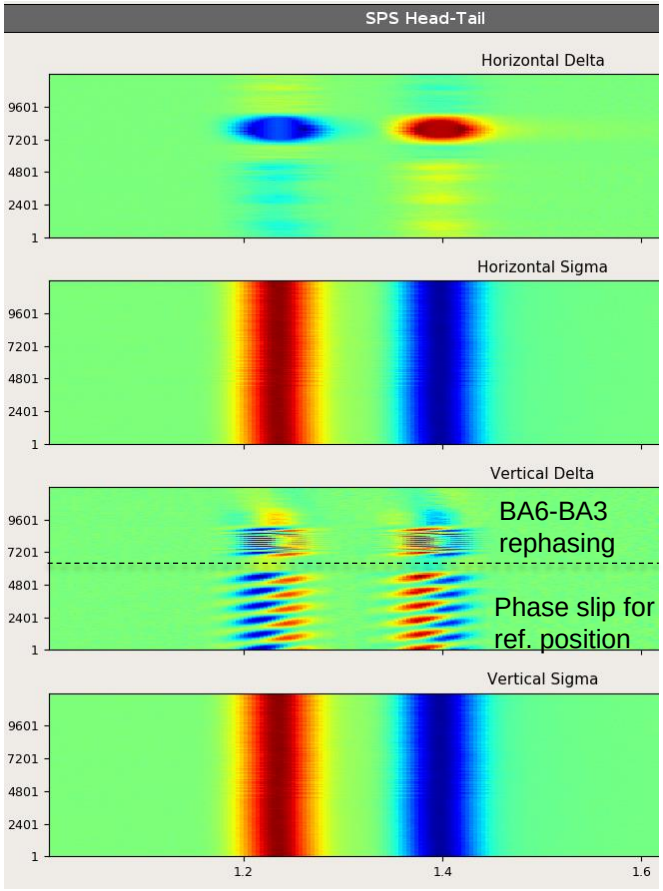
26GeV rephasing
Synch after ~1s after injection

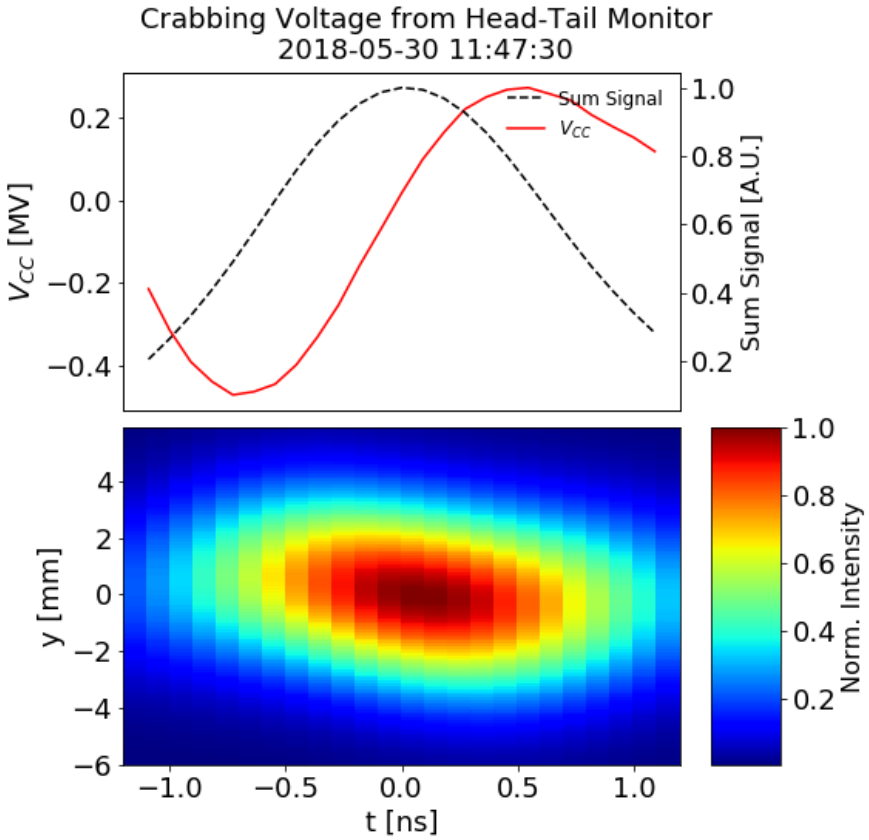


270GeV, Synchronized after ~7.4s
i.e. 0.2s after reaching flat top



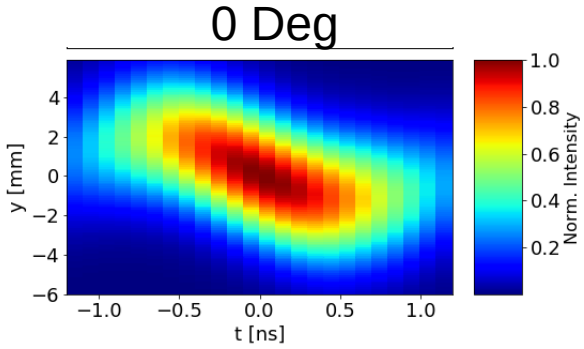
Reconstruction of Crabbing using HT



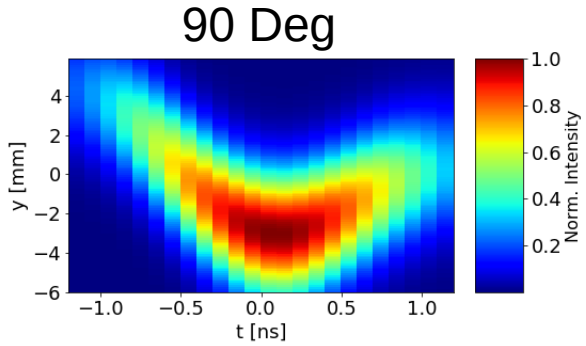


# of turns for ref position along the bunch ~ 2k turns
RF re-synchronization ~ 1s after injection

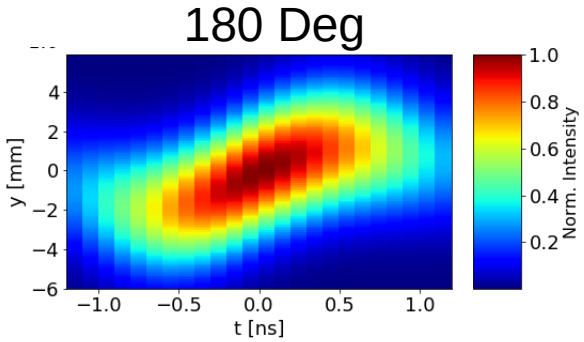
Phase Scans & “Transparency”



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

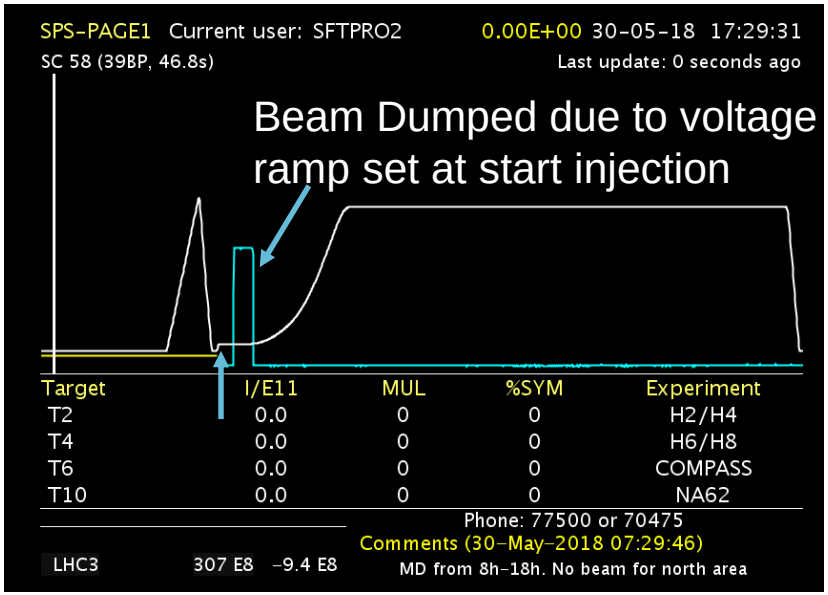


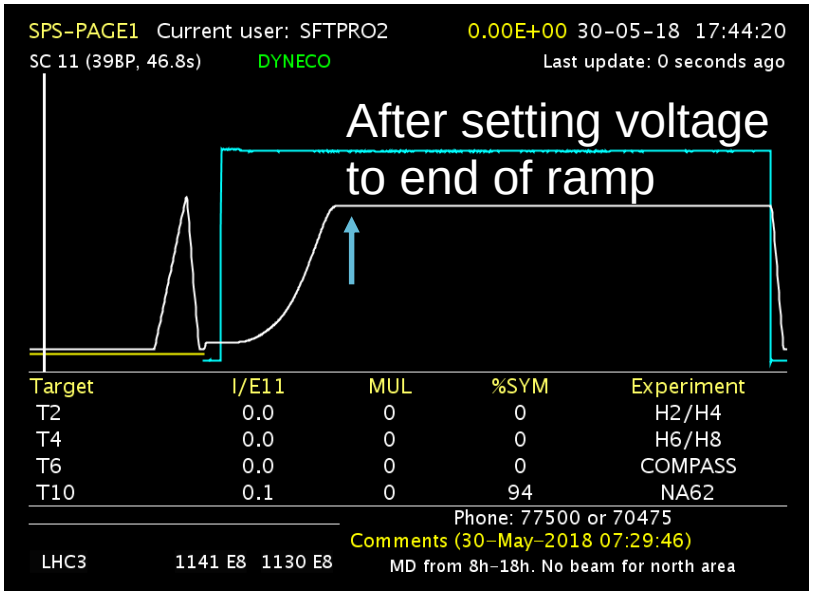
- Nominal bunch intensities easily reached at 26 GeV and 270 GeV.
- Cavity phase manipulation goes as expected.
- Intensities up to 72b*2e10 achieved with no issues.



270 GeV Ramp

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



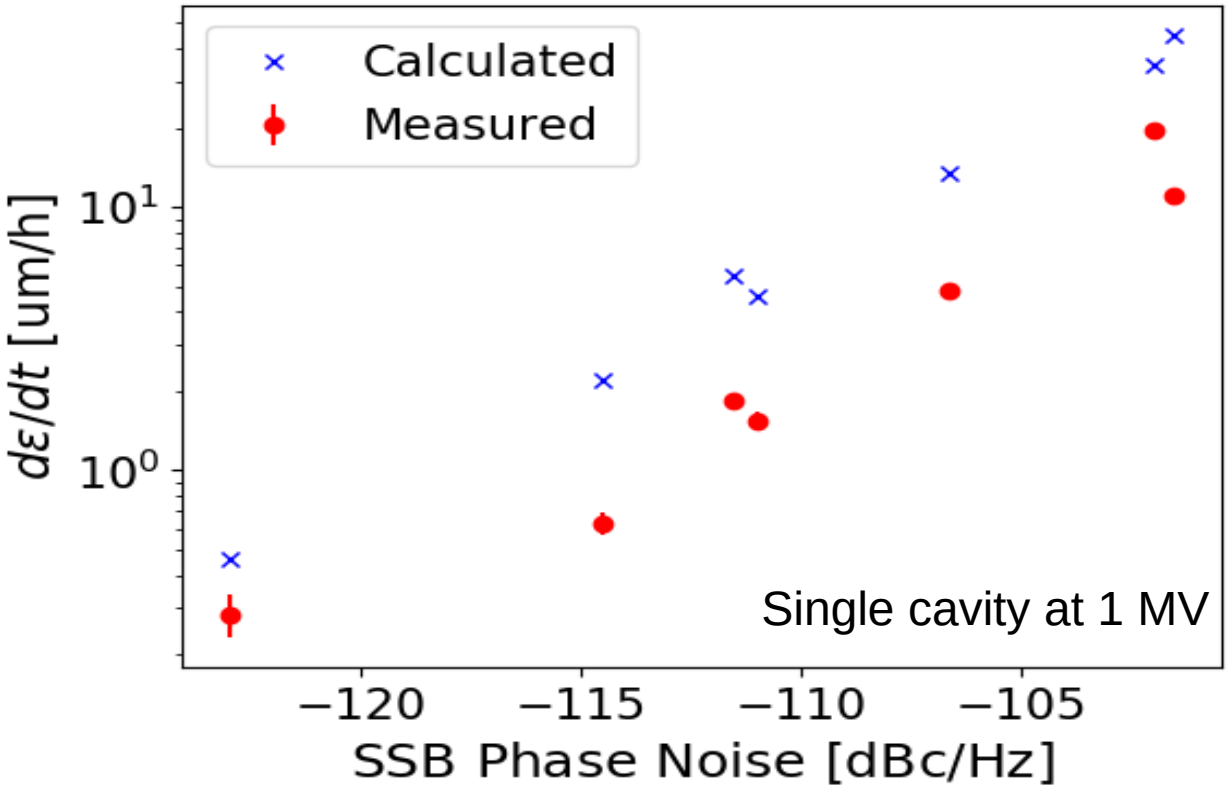


- With cavities powered during the ramp and without BA3-BA6 synchronisation, the beam is rapidly lost due to resonant excitation at the betratron frequency.
- With cavities off during the ramp the beam makes it through without losses.

Emittance Growth ?

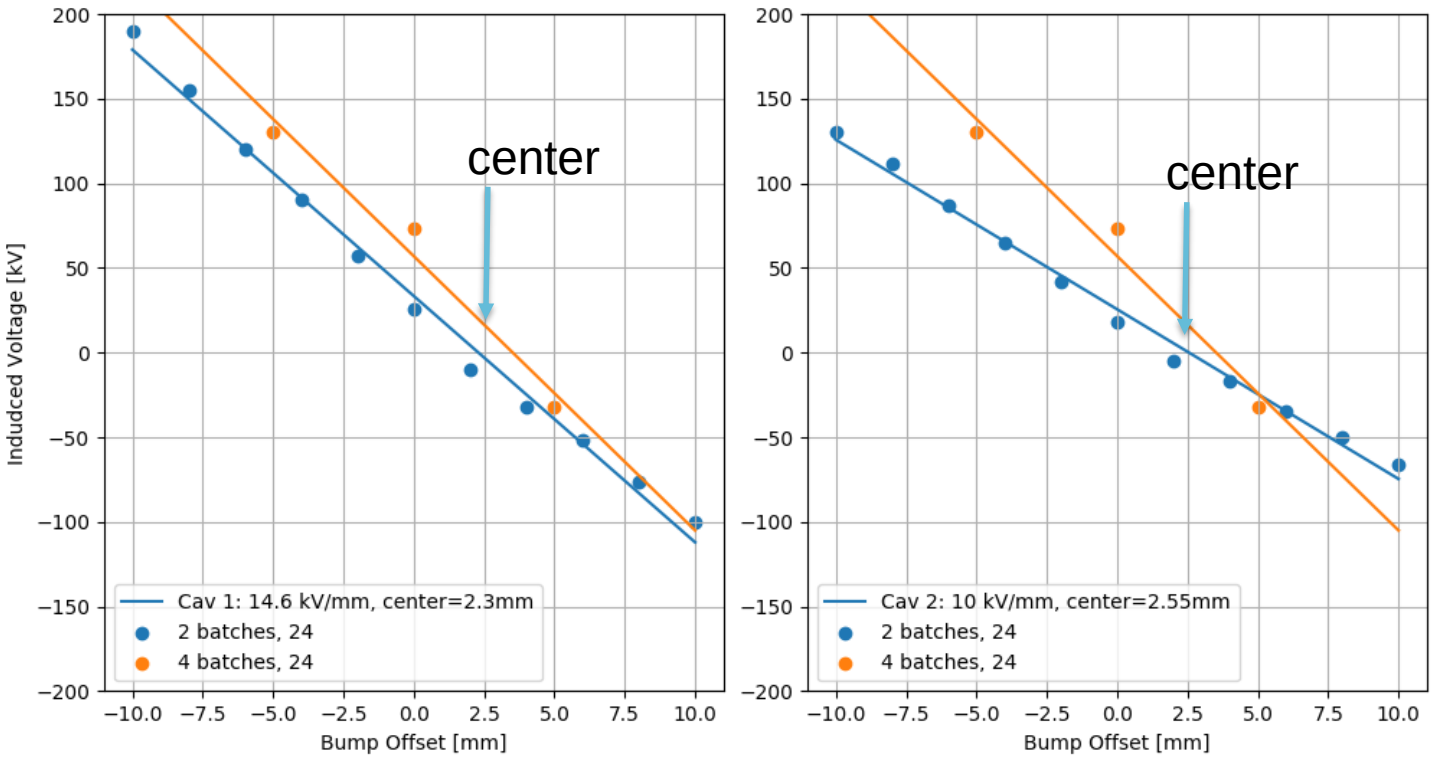
- SPS natural emittance growth at 270 GeV, $\leq 0.5\ \mu/\mathrm{hr}$
- Expected growth with existing electronics (noisy!)
  - Ph. noise up to $8\ \mu\mathrm{m/hr}$, amp noise: $1.4\ \mu\mathrm{m/hr}$ (σ_t: 2.0 ns)
  - HL-LHC we need to be below $0.05\ \mu\mathrm{m/h}$

See P. Baudrenghien talk



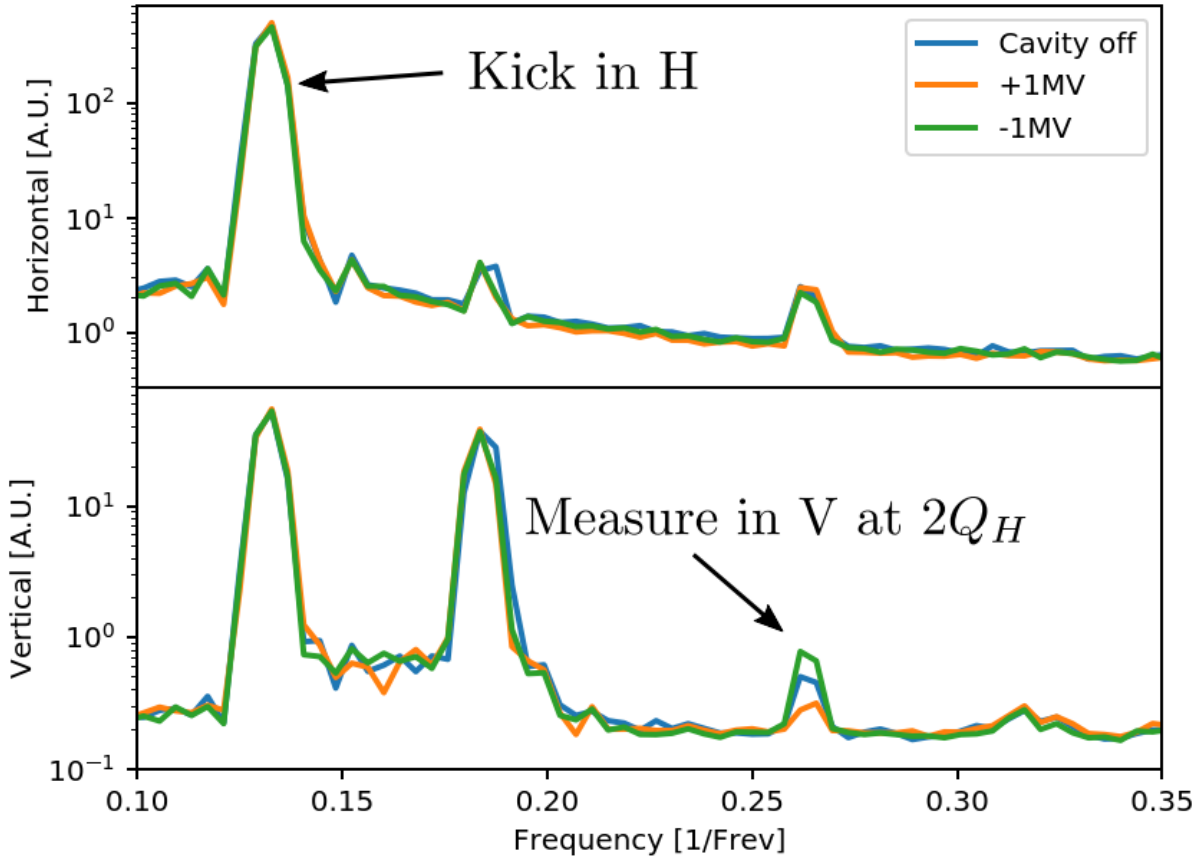
Beam Loading & Electrical Center

- Beam induced voltage from MD6 (prelim) → See E. Yamakawa's talk for more details



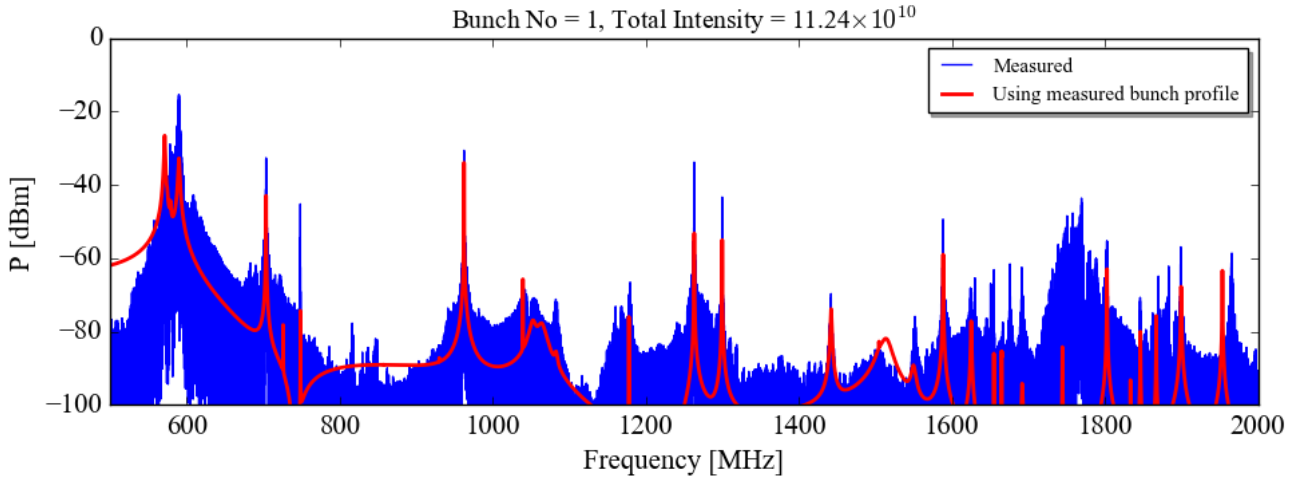
RF Multipoles, a3 Measurement

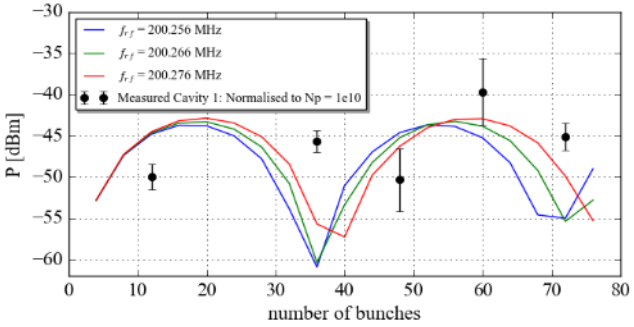
- Data analysis ongoing (M. Carla')… skew sextupole at $2Q_H$ clearly visible that is dependent on the cavity voltage



Higher Order Modes

- Peak HOM power measured from the most dangerous HOM (960 MHz) $\sim 100\ \mathrm{mW}$
- Some deviations from expected HOM power but overall HOM power & scaling to the LHC looks reasonable (see J. Mitchell's talk)

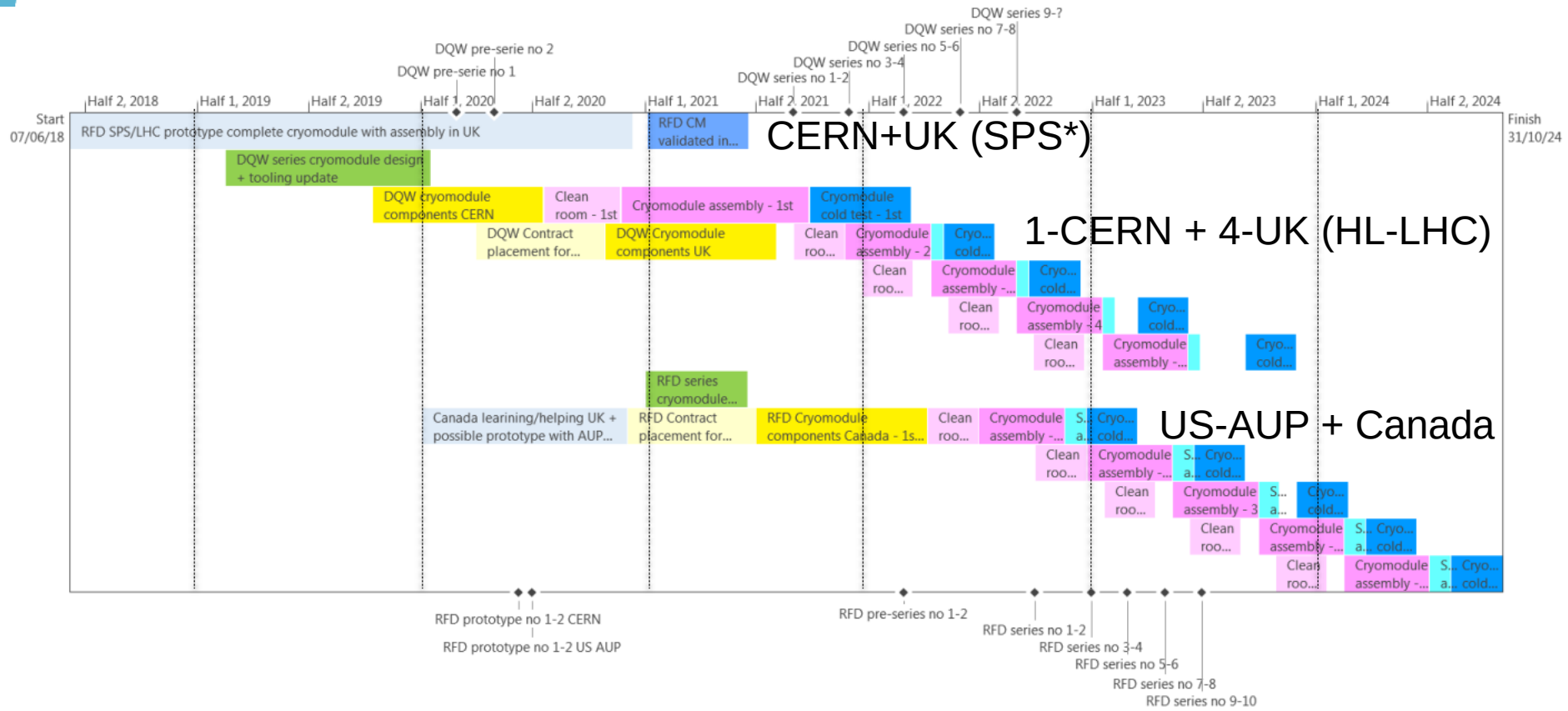




MD#6&7: High Intensity

- MD#6 → 36x4 batches, 1/2 the max intensity in SPS, limited by crab bypass pressure rise
  - With moderate voltage, no beam induced failures or fast transients seen except for pressure rise
- MD#7 → Try to push to 72x4 batches by partially conditioning the bypass in step
  - A quantitative transparency tests at 26 GeV with both cavities at 1-2 MV
  - Ramp the multi-bunches to 270-400 GeV to reach closer to LHC like bunch lengths

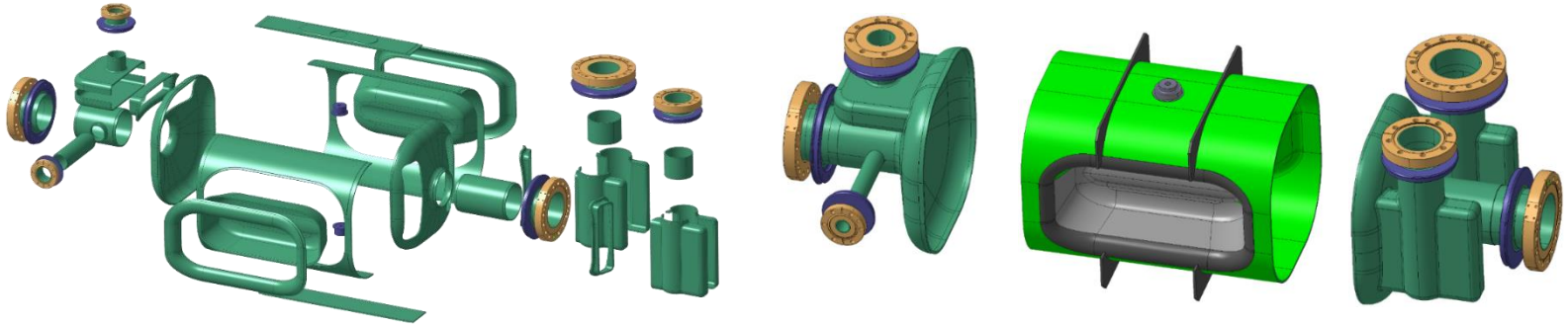
New WP4 Planning including collaborations, draft



* SPS-RFD beam tests delayed till 2021

CERN-RFD Fabrication

- CERN specification drawing in final stages of approval, shaping from Cu → Nb (see M. Garlasche)
- Good progress on the US-AUP side for series production in industry

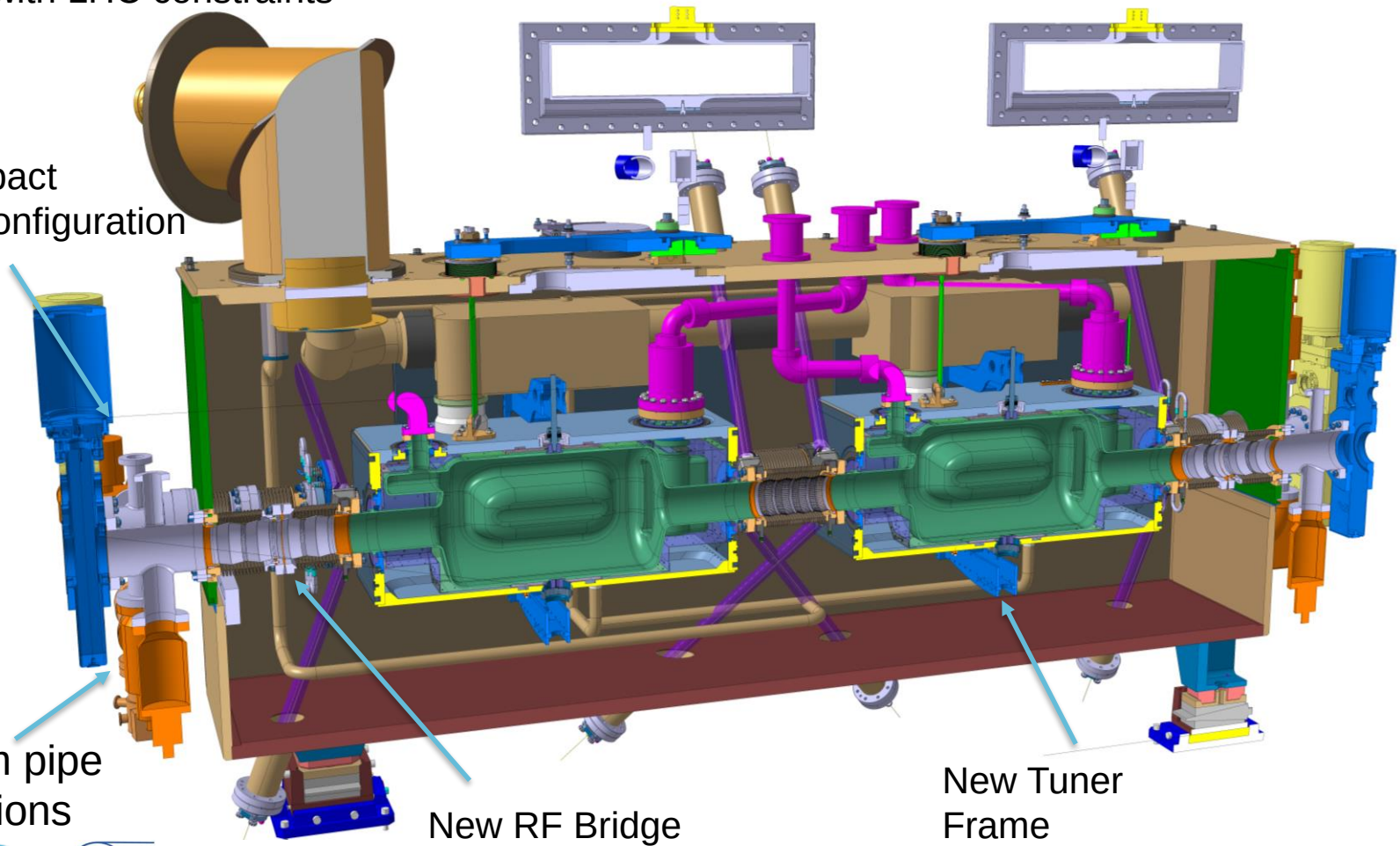


RFD (LHC-type) UK+CERN

Cryogenic update
with LHC constraints

Updated vacuum vessel assembly
from SPS (see T. Capelli's talk)

New compact
vacuum configuration



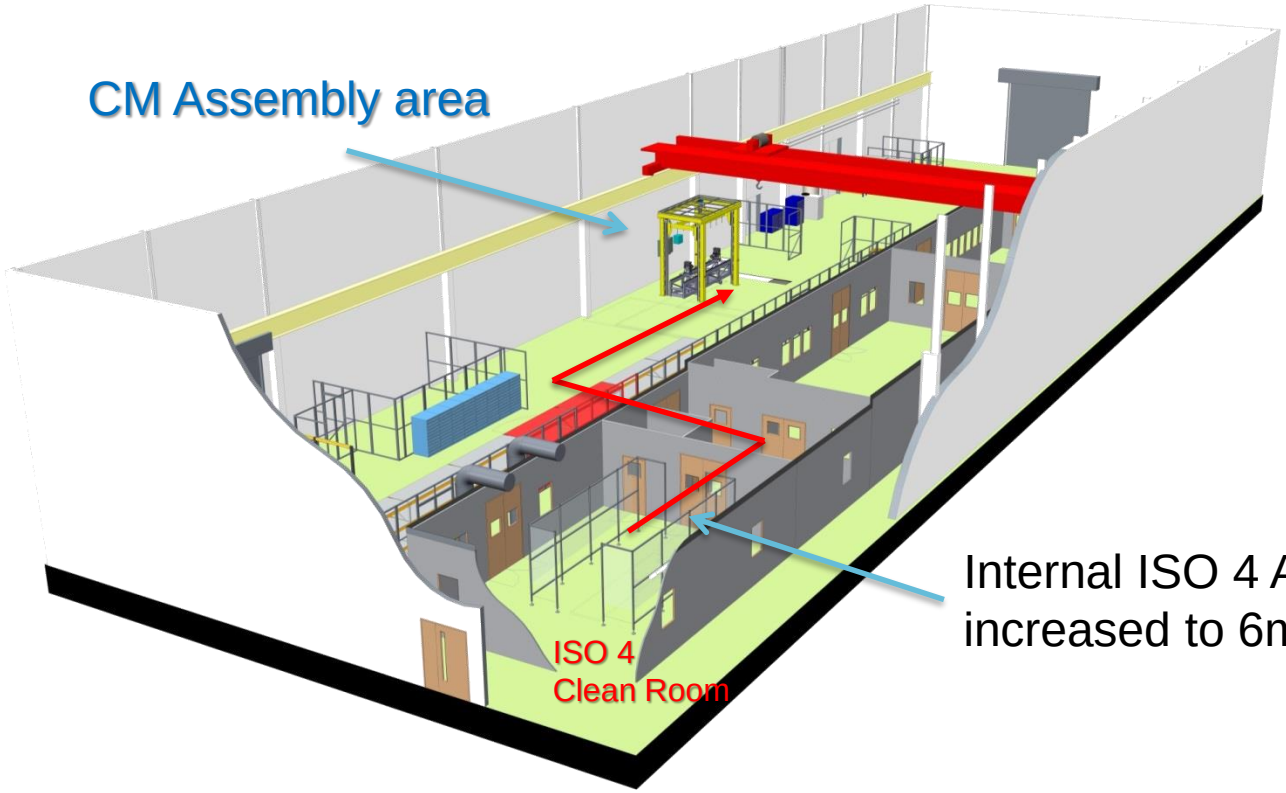
2nd beam pipe
& transitions

New RF Bridge

New Tuner
Frame

STFC Assembly of RFD Cryomodule

See E. Jordan's Talk



Internal ISO 4 Area increased to 6m long

High Power RF

- Two 80 kW IOTs operational in SPS (see E. Montesinos's talk)
  - Issues of linearity at very low power (< 5 kW) being addressed jointly with LLRF team
- Power couplers, HOMs and related transmissions lines also validated during operation in SPS
- For HL, discussions with Novosibirsk for SSPA prototype by 2020

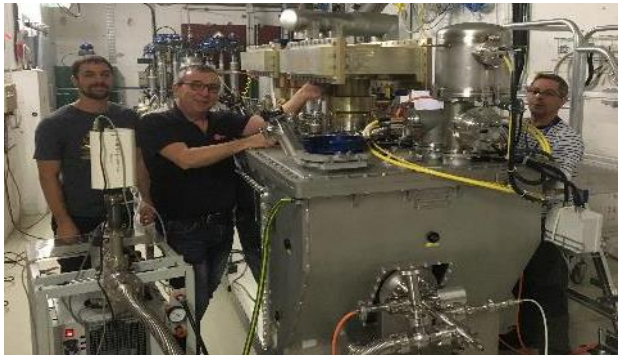
Final Comments

- SPS Crab Cavities
  - Despite many hurdles, a monumental effort was put in to conclude 2018 beam tests a success – it a humbling experience
  - Consolidation works in LS2 is needed to have test stand through Run3. RF-Dipole cavity fabrication started and we are looking forward towards a UK built cryostat

- HL-LHC Crab Cavities
  - RI-DQW pre-series started off well… RFD series cavities under US-AUP progressing well
  - Canada/UK series cryostating and Amplifiers from Russia (?) will be true international challenge

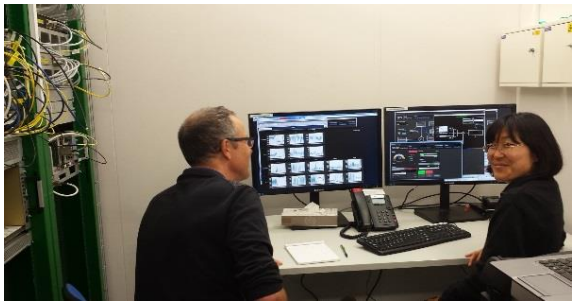
Thank You !











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

Backup

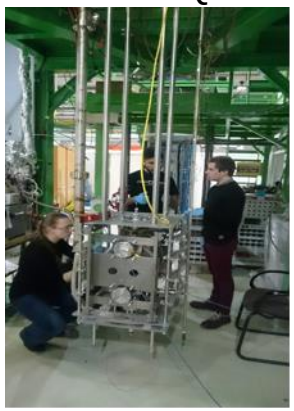
SPS Cavity Results (6 Cavities)

Nominal Spec $V_{kick} = 3.4$ MV, $R_s = 10\ n\Omega$

		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**	4.4	**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*	Not tested in VTA	Not tested in VTA	**4.7**	-	**4.8**

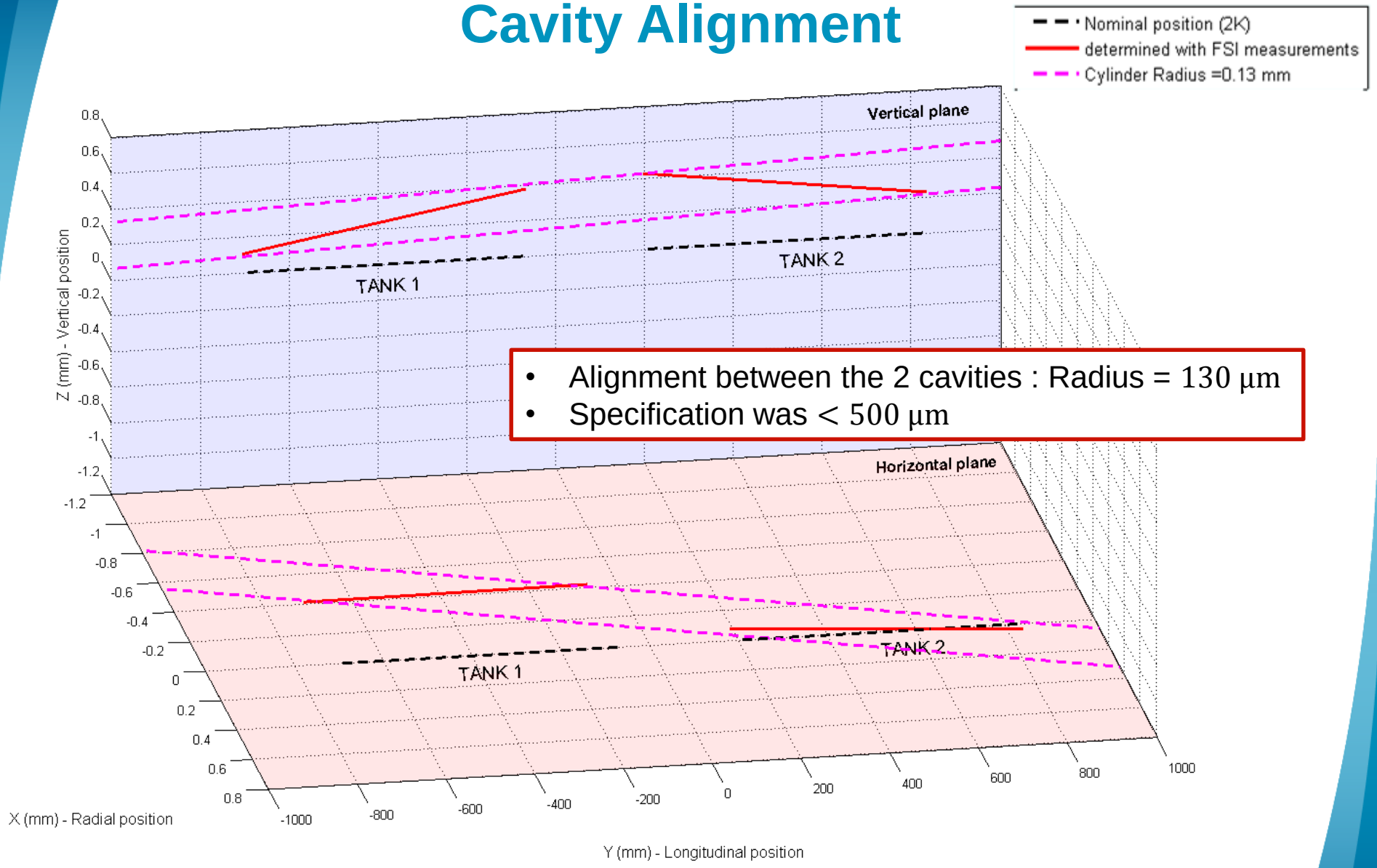
*Dressed cavity tests at CERN in VTA revealed feedthrough leaks during thermal cycling, a fix is being prepared

CERN DQW



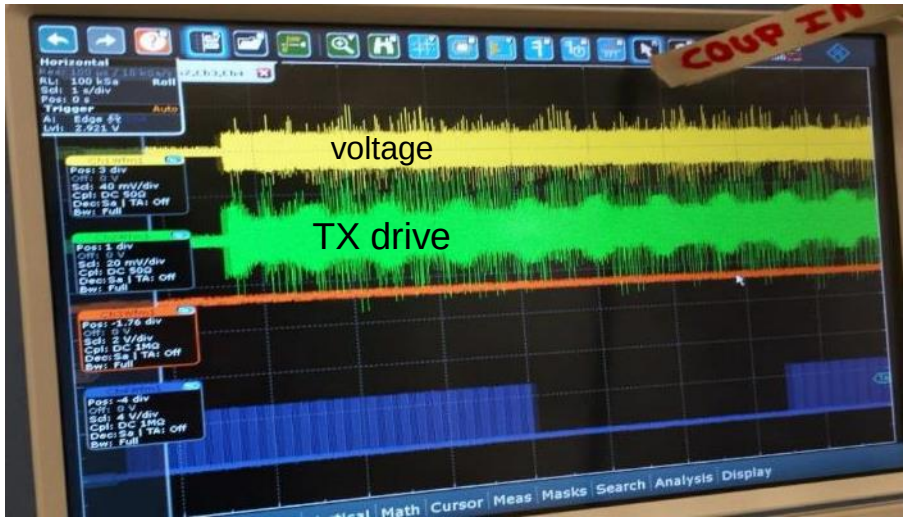
USLARP DQW & RFD

Cavity Alignment



- Alignment between the 2 cavities : Radius = 130 µm
- Specification was < 500 µm

RF Feedback & Beam Induced Signal



Input drive and voltage spikes at F_{rev}, due to direct beam coupling

Need to filter antenna signals better to suppress the direct beam induced signals

In parallel looking at alteration to cavity antenna to minimize effect

Ramp to 270 GeV

Vertical tune: $Q_y = 0.18$

RF Freq:

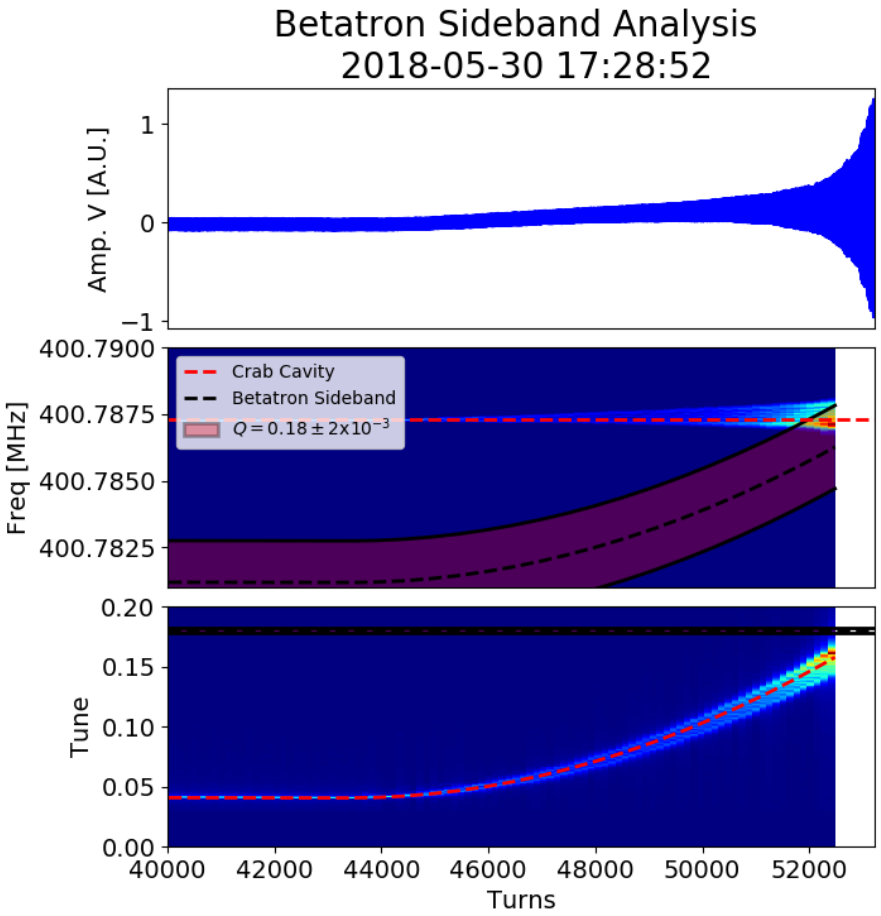
Cavity 1: 400.787 MHz (~1 MV)

Cavity 2: 400.528 MHz (almost zero)

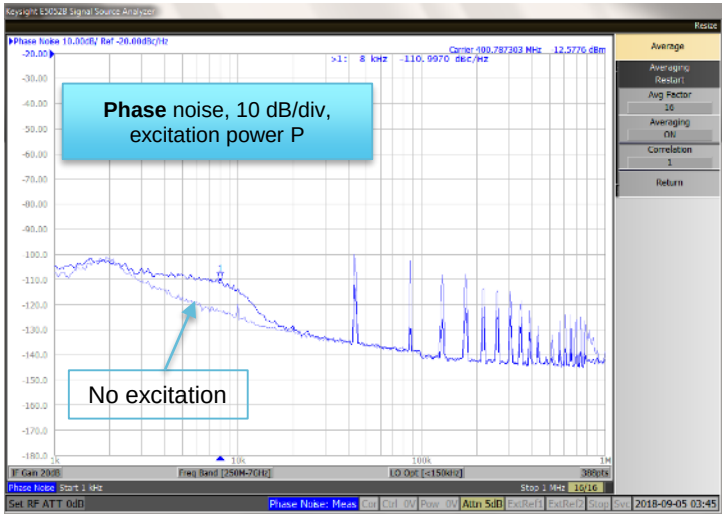
Resonant excitation observed as we cross the vertical tune (black dotted lines).

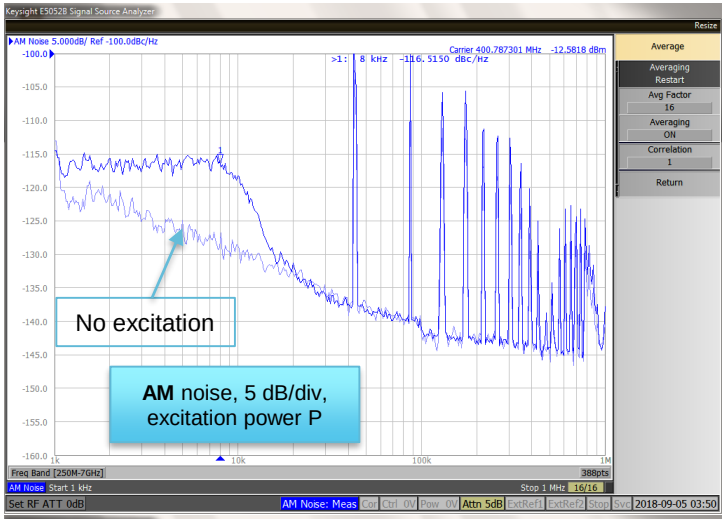
Kicking the beam at 270 GeV equivalent frequency , while sweeping the beam frequency from 26-270 GeV

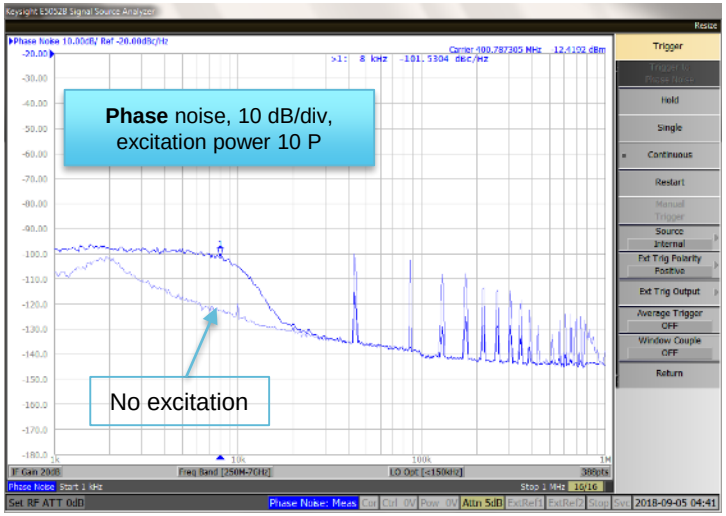
After setting the correct cycle start voltage to 270 GeV equivalent, beam circulated w/o any issue

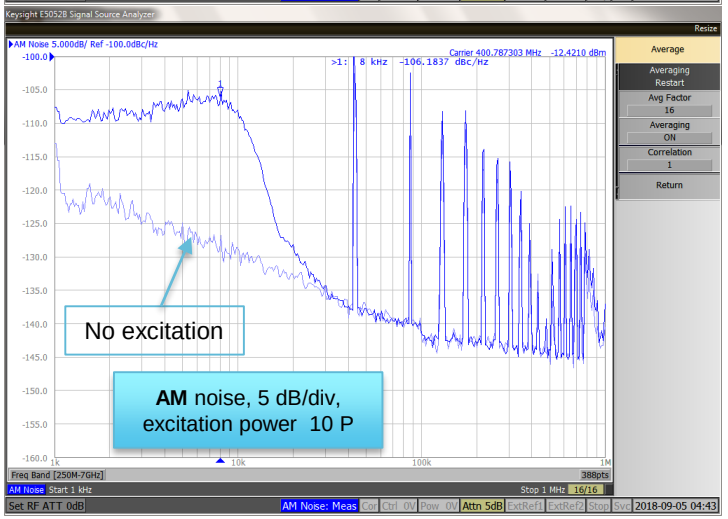


Noise spectra measured in Ant CC2









Left: Phase noise PSD. Right: AM PSD. 1 kHz – 1 MHz
Top: -10 dBm excitation, bottom: 0 dBm excitation (10 times more power)
Background trace shows PSD without noise injected. The marker is on the betatron line (8 kHz)
The frev lines are generated by the beam