First Crab Cavity testing on a hadron beam

Prof. G Burt, Lancaster University on behalf of the HL-LHC Crab cavity team (CERN, BNL, ODU, FNAL, LBNL, SLAC + UK team below)

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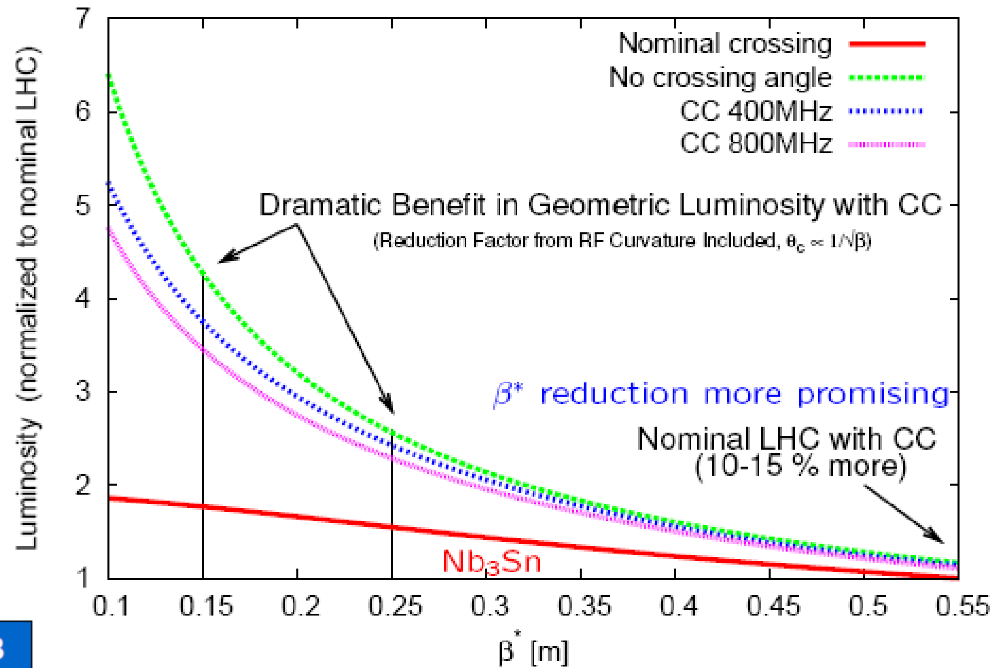
26th April 2019 – IoP PAB Group Meeting

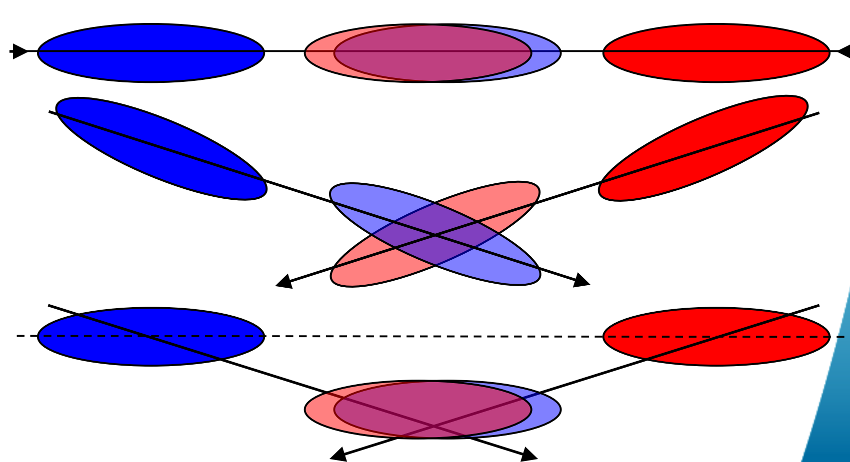
Luminosity increase

- Increasing the crossing angle decreases the long range effect but decreases geometric overlap
- Rotating the bunches with crab cavities before and after collision can reduce this effect

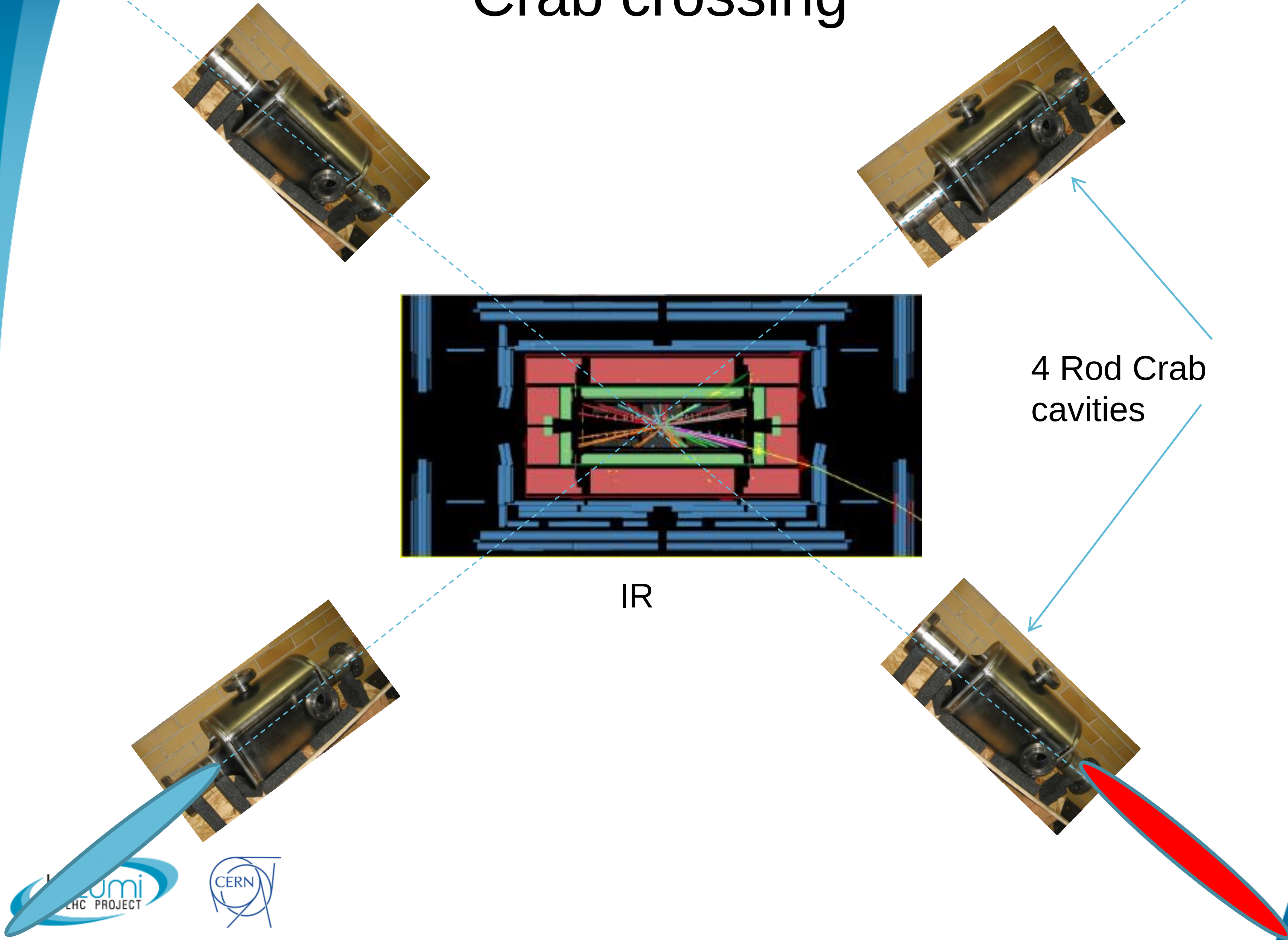
$$L \propto \frac{{N_b}^2}{\sigma^2} / R_{\Phi} F_{RF}$$

	2011	2012	after LS1	after LS3
Energy	3.5 TeV	4 TeV	7 TeV	7 TeV
β* [cm]	100	60	55	15
2ϕ [µrad]	260	313	247	473
$R_\Phi(\sigma_z = 7.55\text{cm})$	0.94	0.85	0.82	0.37
$R_\Phi(\sigma_z = 10.1\text{cm})$		0.76	0.74	0.28



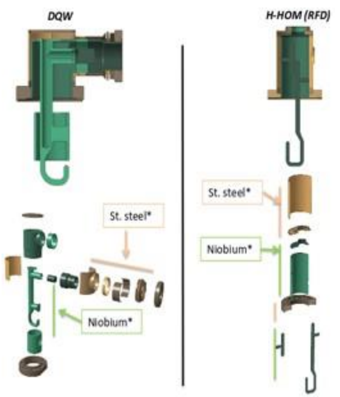


Crab crossing

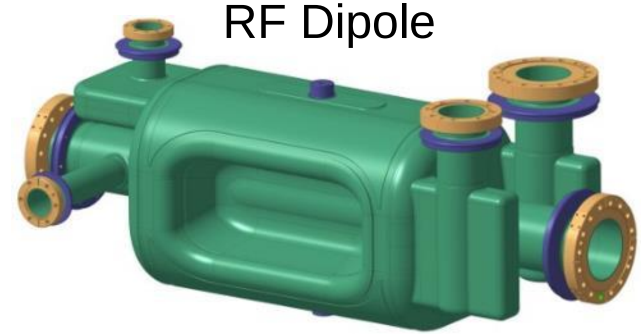


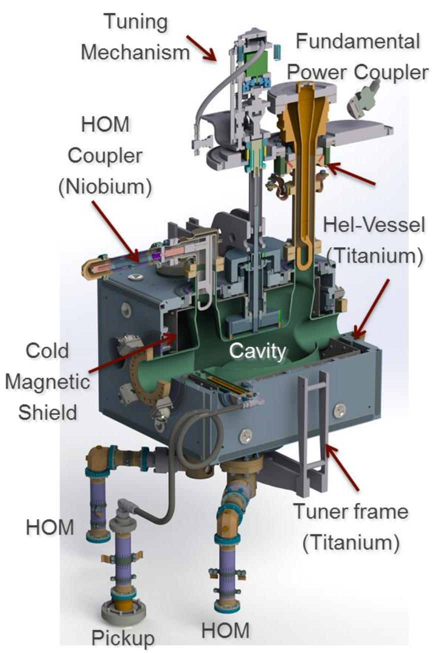
SPS Cavities

DQW



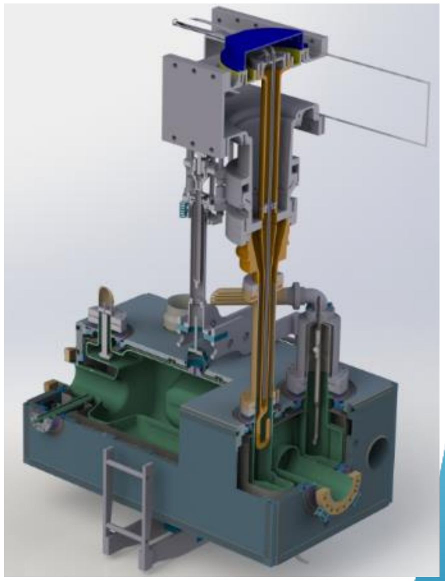
RF Dipole





- 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



What do we Validate in SPS?

- Demonstrate LLRF control of the cavity and find any issues
- Measure emittance growth from LLRF noise
- Measure and validate problems due to sextupole RF components to the crabbing field
- Measure the cavity impedance and power produced by monopole wakefields

- 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

SPS Crabs– HL-LHC-UK Contributions and leadership

- Cavity vertical testing – Lancaster
- HOM coupler design and measurements – Lancaster
- Warm & Cold magnetic shield design and manufacture – STFC & Lancaster
- Cavity supports and microphonics – STFC & Lancaster
- Thermal shield design – STFC
- LLRF measurements – Lancaster, Liverpool
- Impedance measurements – Lancaster, Liverpool
- Multipoles – Manchester and Liverpool
- Beam measurement and control - Liverpool

Lancaster University

Science & Technology Facilities Council

UNIVERSITY OF LIVERPOOL

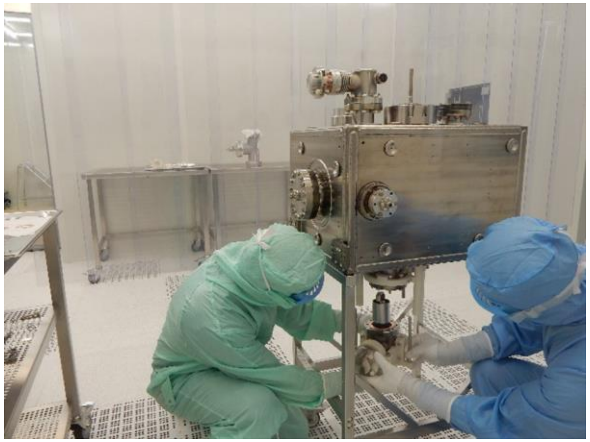
The Cockcroft Institute of Accelerator Science and Technology

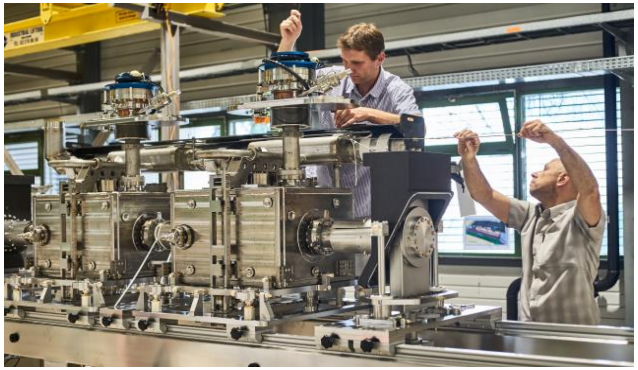
MANCHESTER 1824 The University of Manchester

CERN HL-LHC PROJECT

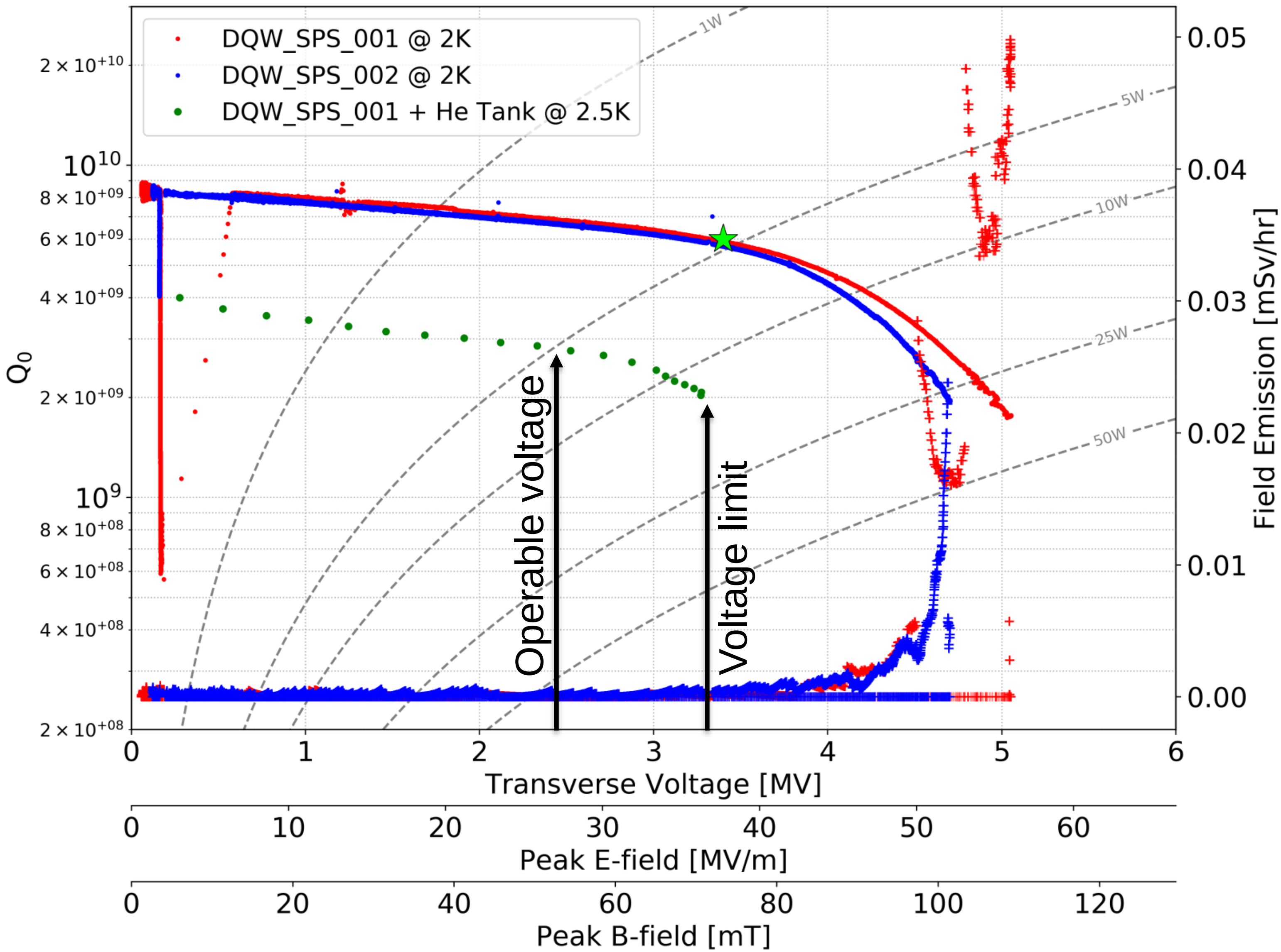
CERN

Cavity and Cryomodule production



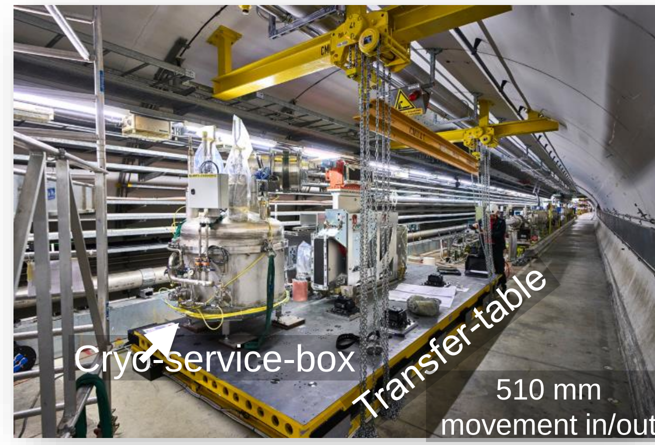


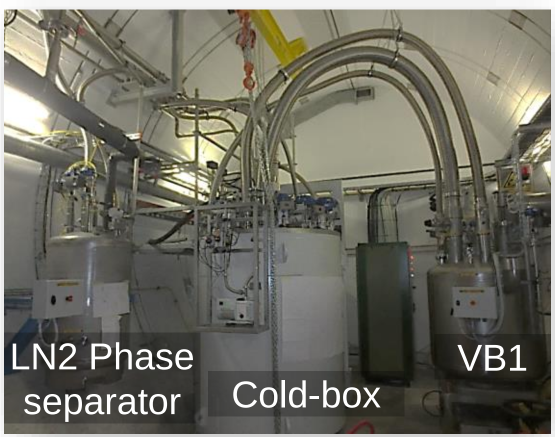
DQW + HOMs - CERN

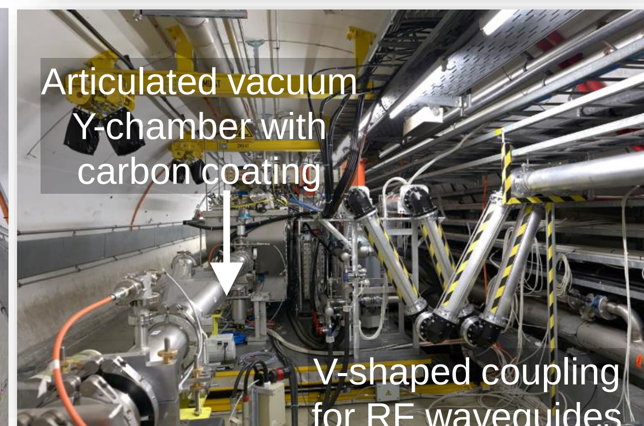


SPS-BA6 Installation

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







SPS-DQW!

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

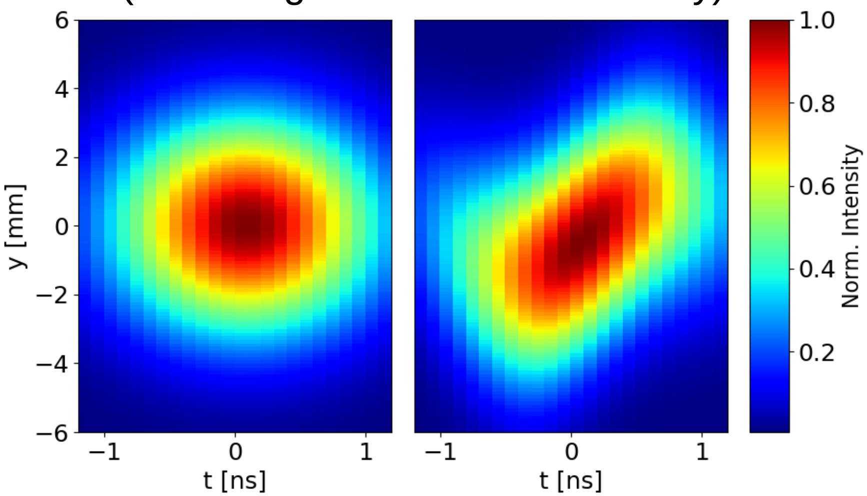
- 4 main phases foreseen – 10 MDs requested, in reality we got 7

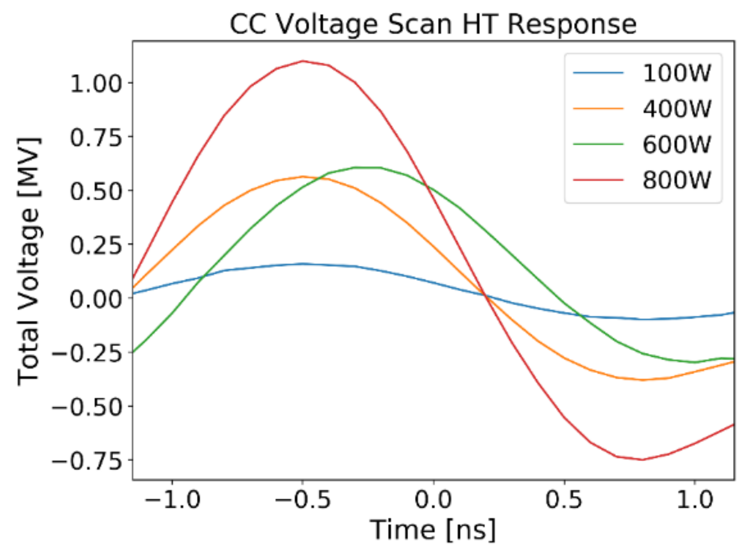
Protons meet Crabs

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

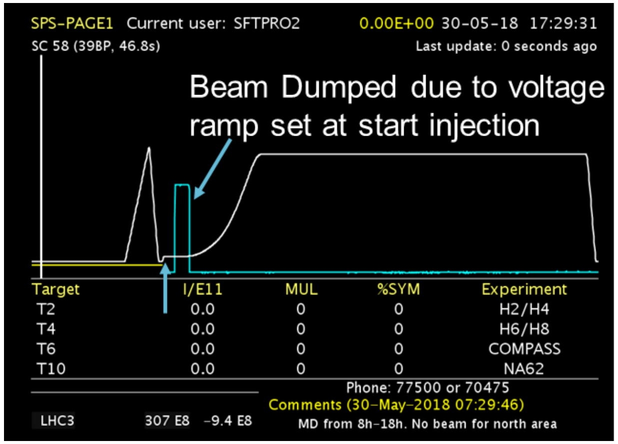
Single bunch
$0.2 - 0.8 \times 10^{11}$p/b

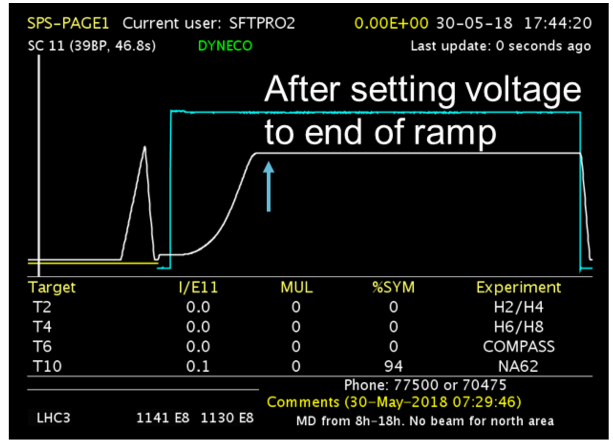
Crabbing reconstruction
(assuming Gaussian transversely)



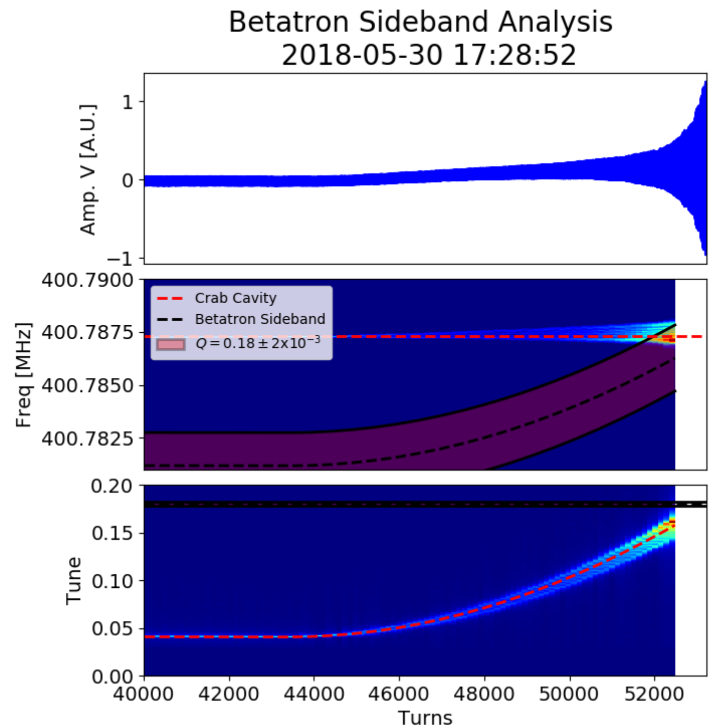


270 GeV Ramp





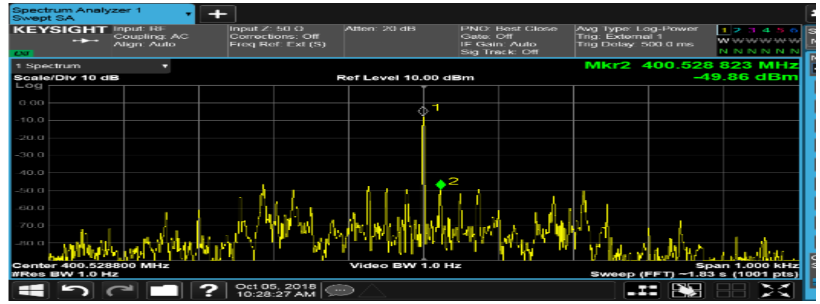
Cav1 ~1MV (400.787 MHZ), Cav2 off (400.528 MHz)



- 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.

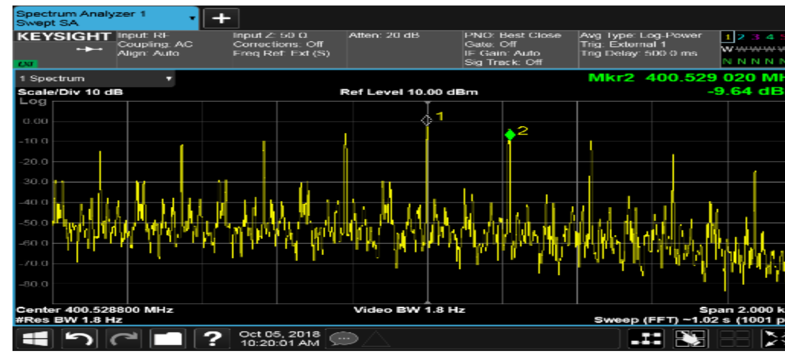
LLRF Issues

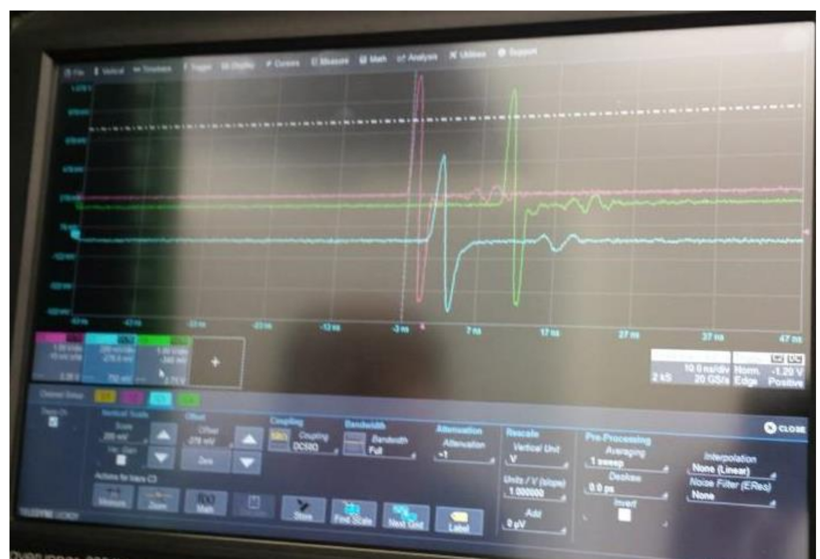
- The cavity is found to have a pondermotive instability where Lorentz force detuning (400 [Hz/MV^2) “pings” a mechanical resonance at 220 Hz, which causes the cavity field to oscillate further driving Lorentz force detuning at the mechanical resonance. Instability appears above 1 MV. In HL-LHC the tuner should be able to follow this resonance and hence will not be an issue.
- The IOTs were overspecified and we have found that when backed off their gain is highly nonlinear.
- The RF pick-ups were combined with a HOM coupler, however this coupled strongly to the beam at 400 MHz perturbing the measurements making feedback difficult



0.8 MV

1.9 MV





Head Tail Monitor

The Head-Tail Monitor gives two data sets

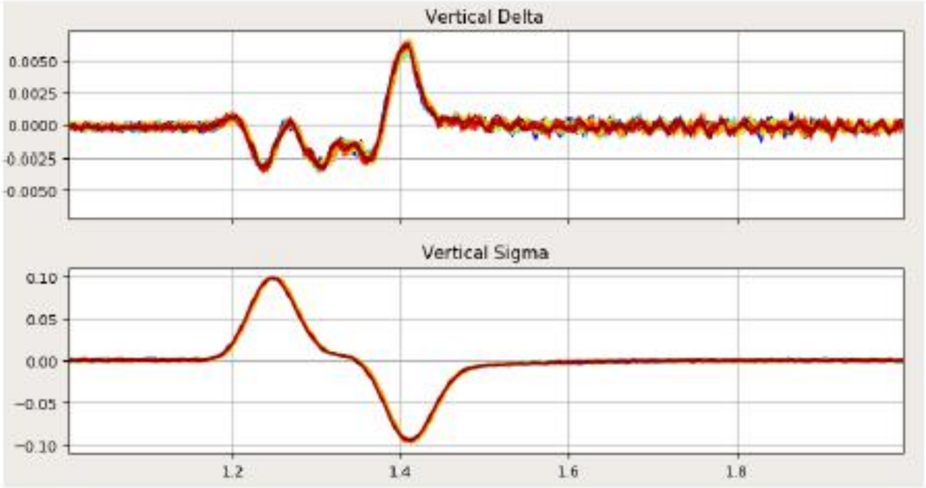
A sigma (or sum) signal which is the longitudinal line density for a given window (often 10,000 turns)

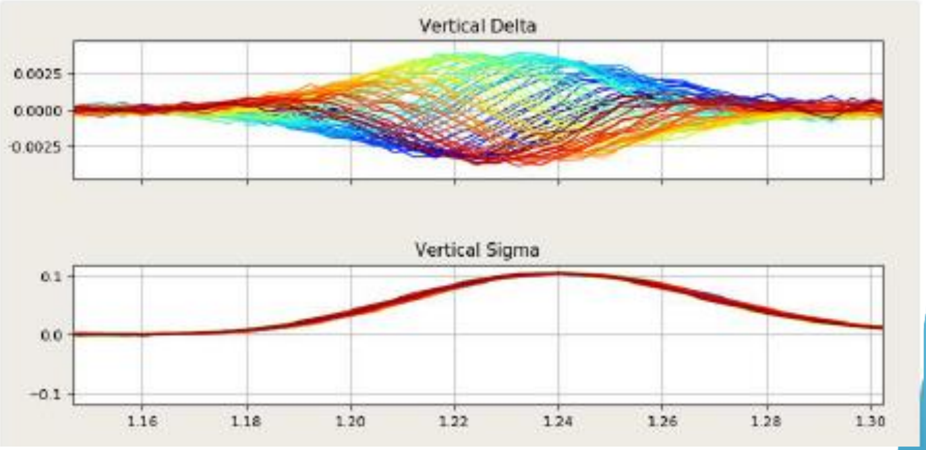
A delta (or difference) signal which is a measure of the transverse offset within the bunch

When synchronised with the main RF, the crab signal cannot be separated from he baseline as both appear static

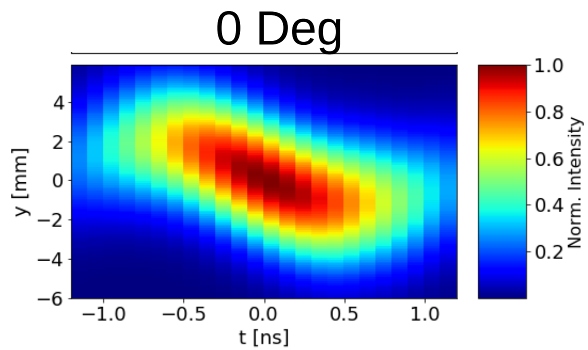
Step1: Calculate baseline from delta signal **before synchronisation**

Step2: Take delta signal acquisitions of interest and subtract baseline. Divide by the sum signal and apply normalisation factor to acquire intra bunch offset

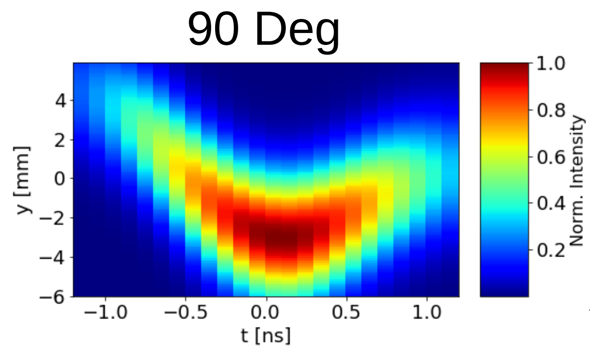


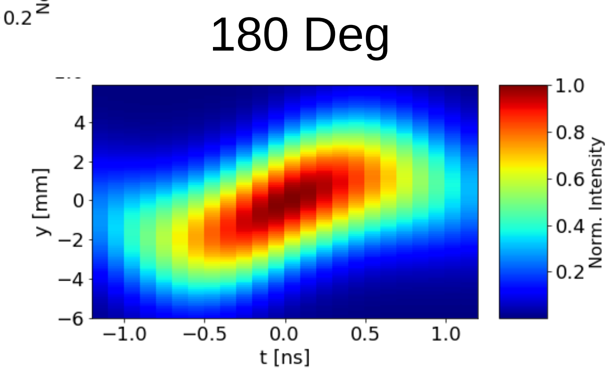


Phase Scans & “Transparency”



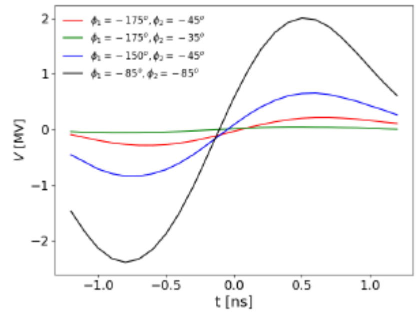
RF phase scan w.r.t the beam phase with cavity 1

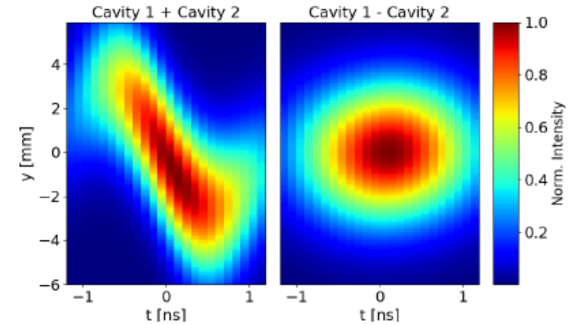




- Nominal bunch intensities easily reached at 26 GeV and 270 GeV.
- Cavity phase manipulation goes as expected.
- Intensities up to 72b*2e10 achieved with no issues.

- With two crab cavities we can have them in phase or anti-phase. When in antiphase the cavities are transparent to the beam (other than impedance)

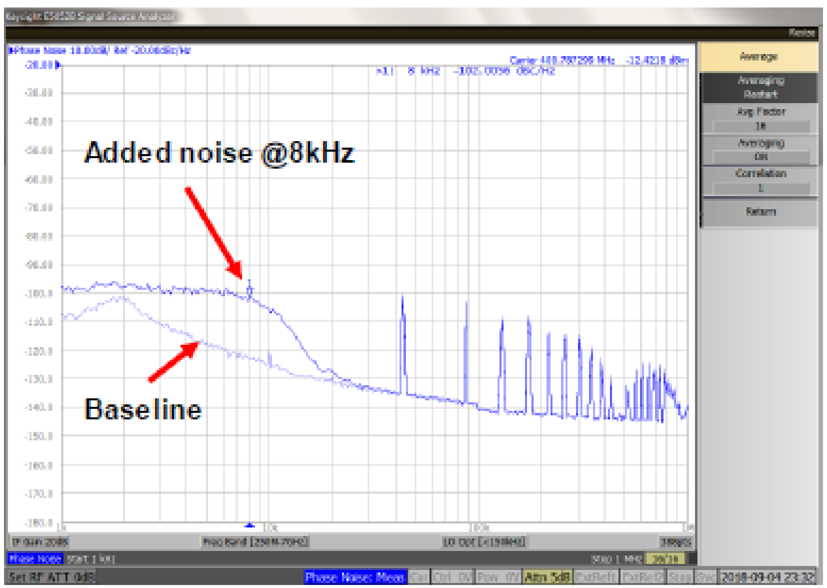




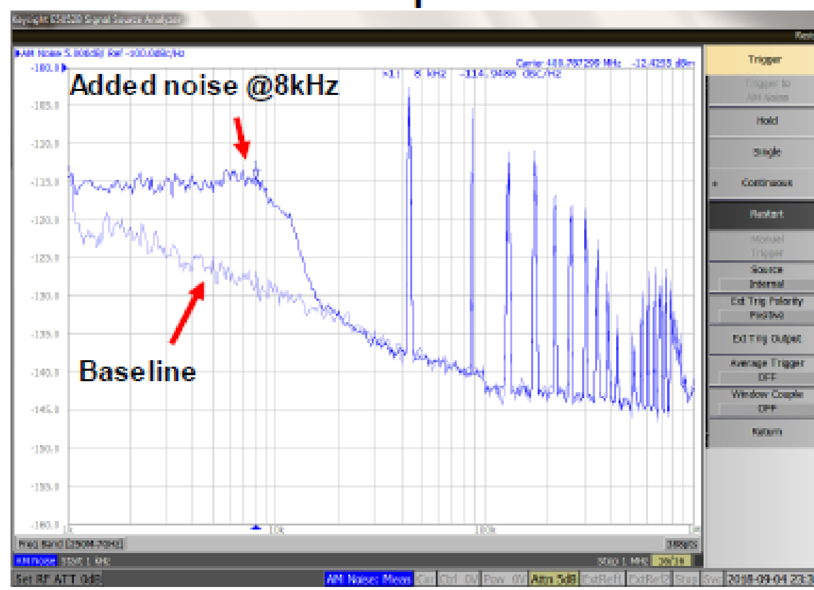
Injected Noise

- Emmittance growth due to LLRF noise is too small to see in the SPS so instead we inject amplified noise
- Added noise at DC to 10 kHz which excites at 8 kHz which is the first beatatron band

Phase

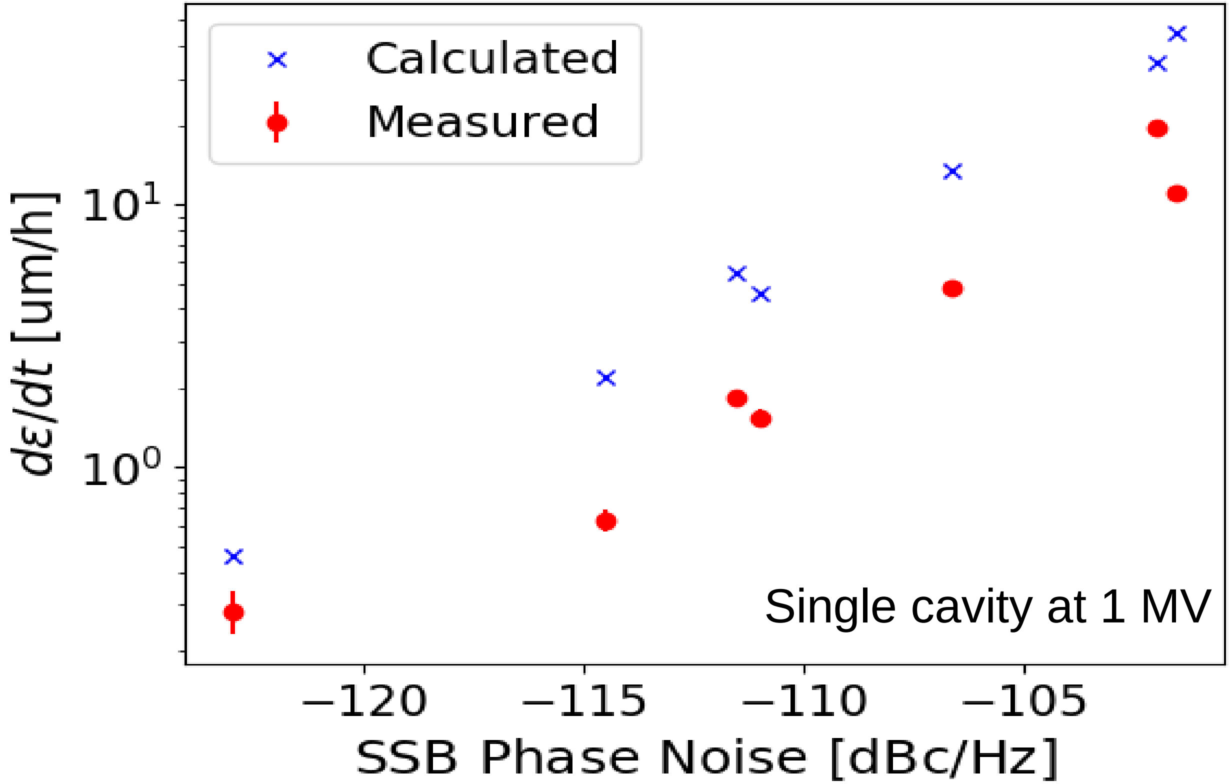


Amplitude

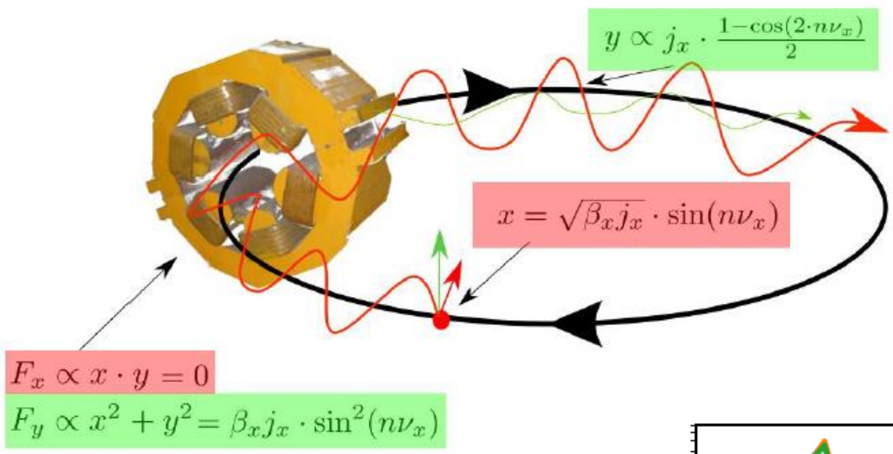


Emittance Growth

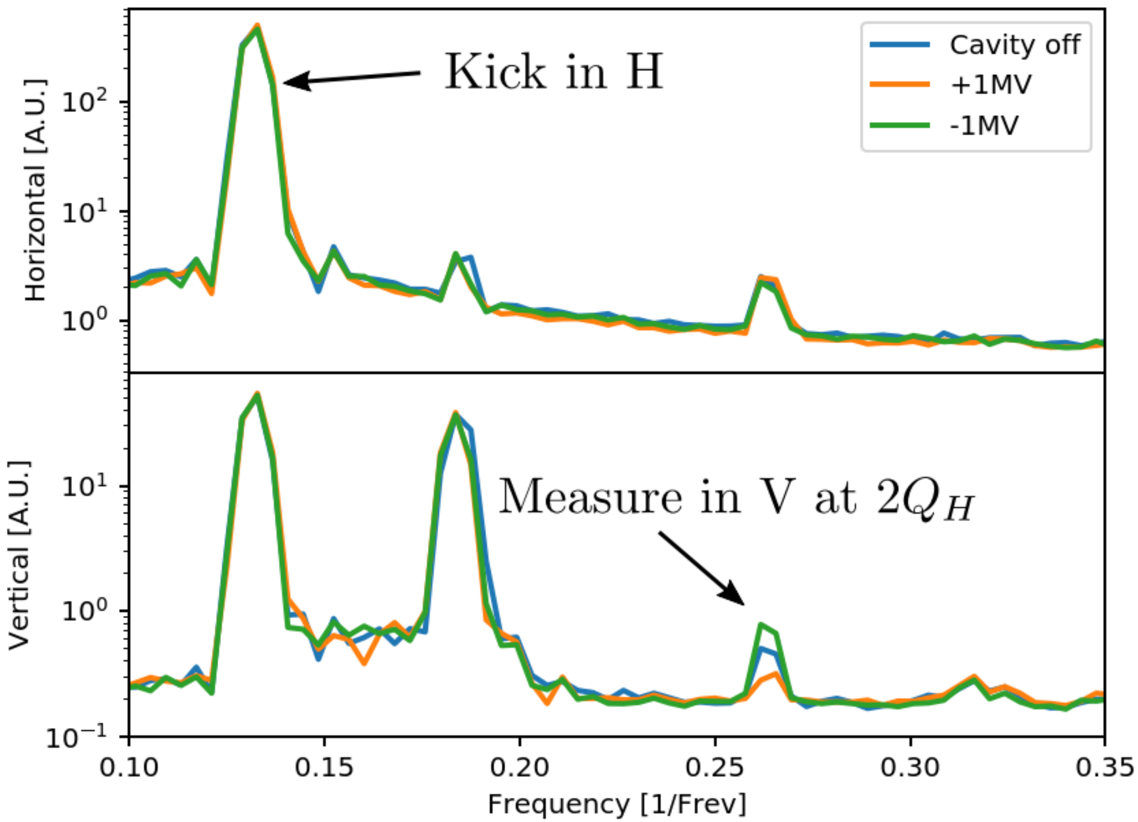
- SPS natural emittance growth at 270 GeV, $\leq 0.5\ \mu/\mathrm{hr}$
- Expected growth with existing electronics (noisy!)
  - Ph. noise up to $8\ \mu\mathrm{m/hr}$, amp noise: $1.4\ \mu\mathrm{m/hr}$ (σ_t: 2.0 ns)
  - **<u>HL-LHC we need to be below $\mathbf{0.05\ \mu m/h}$ more progress required</u>**
- Calculations overestimate by a factor of 2-4 which is thought to be due to beam losses or coupling between H and V planes



RF Multipoles, a3 Measurement

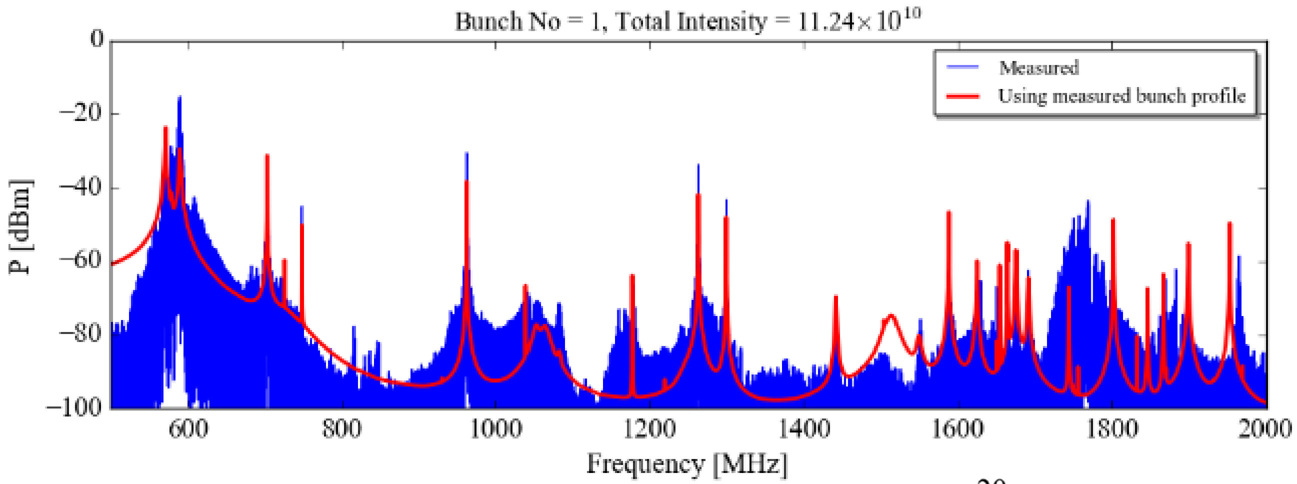


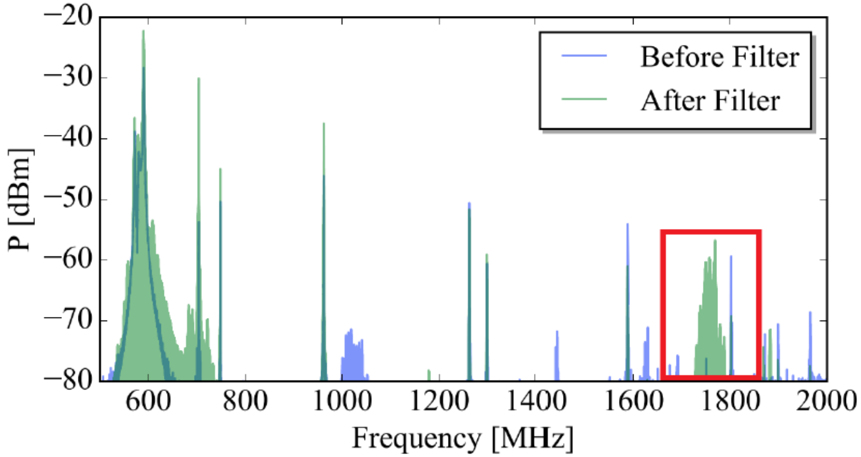
- Exite motion in H plane and skew sextupole couples this to the V plane.
- Skew sextupole at $2Q_H$ clearly visible that is dependent on the cavity voltage



Higher Order Modes

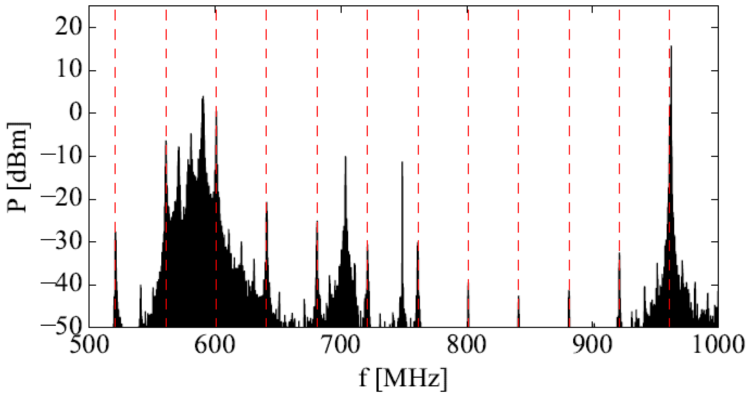
- Peak HOM power measured from the most dangerous HOM (960 MHz) ~100 mW
- Some deviations from expected HOM power but overall HOM power & scaling to the LHC looks reasonable
- Excess of wakefield power at 1.7 GHz is due to a missing multiplexer on the combined HOM coupler/pick-up. Will now be separated for HL-LHC

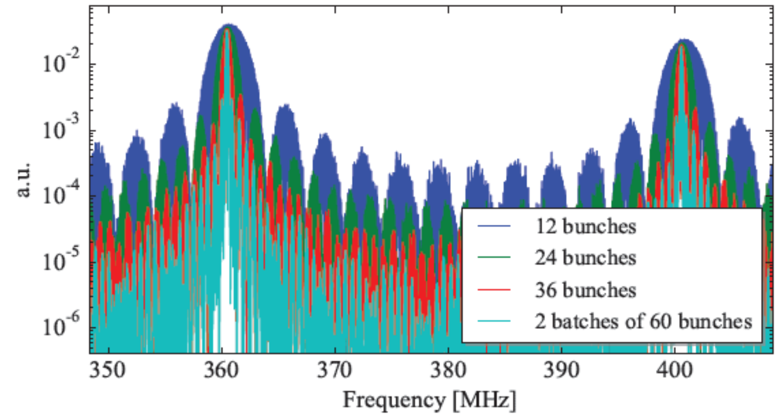


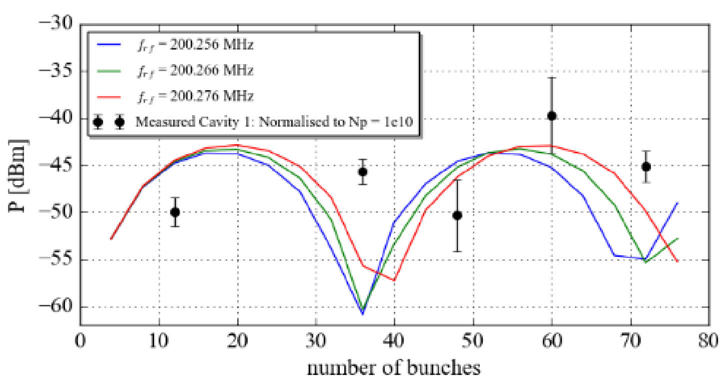


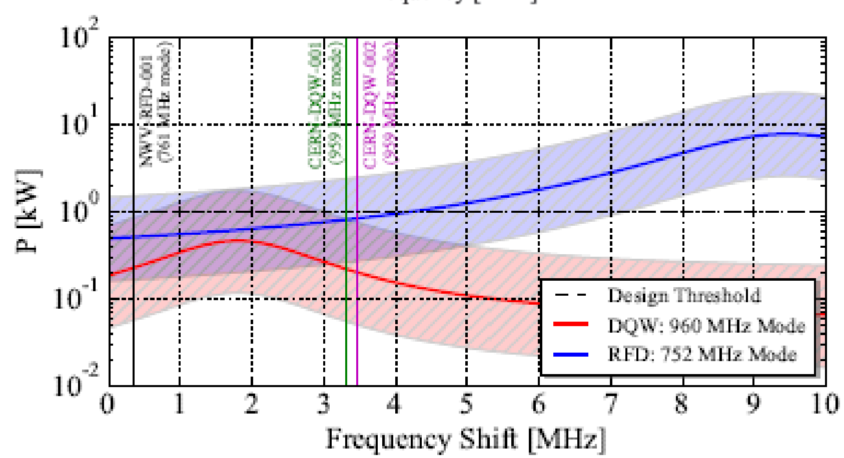
Higher Order Modes (Multibunch)

- For multibunch we get much higher powers at 960 MHz as its close to the 25 ns machine line
- Surprisingly changing the bunch spacing doesn't vary the power as expected, looks offset in frequency
- The SPS results have been used to calculate HL-LHC powers

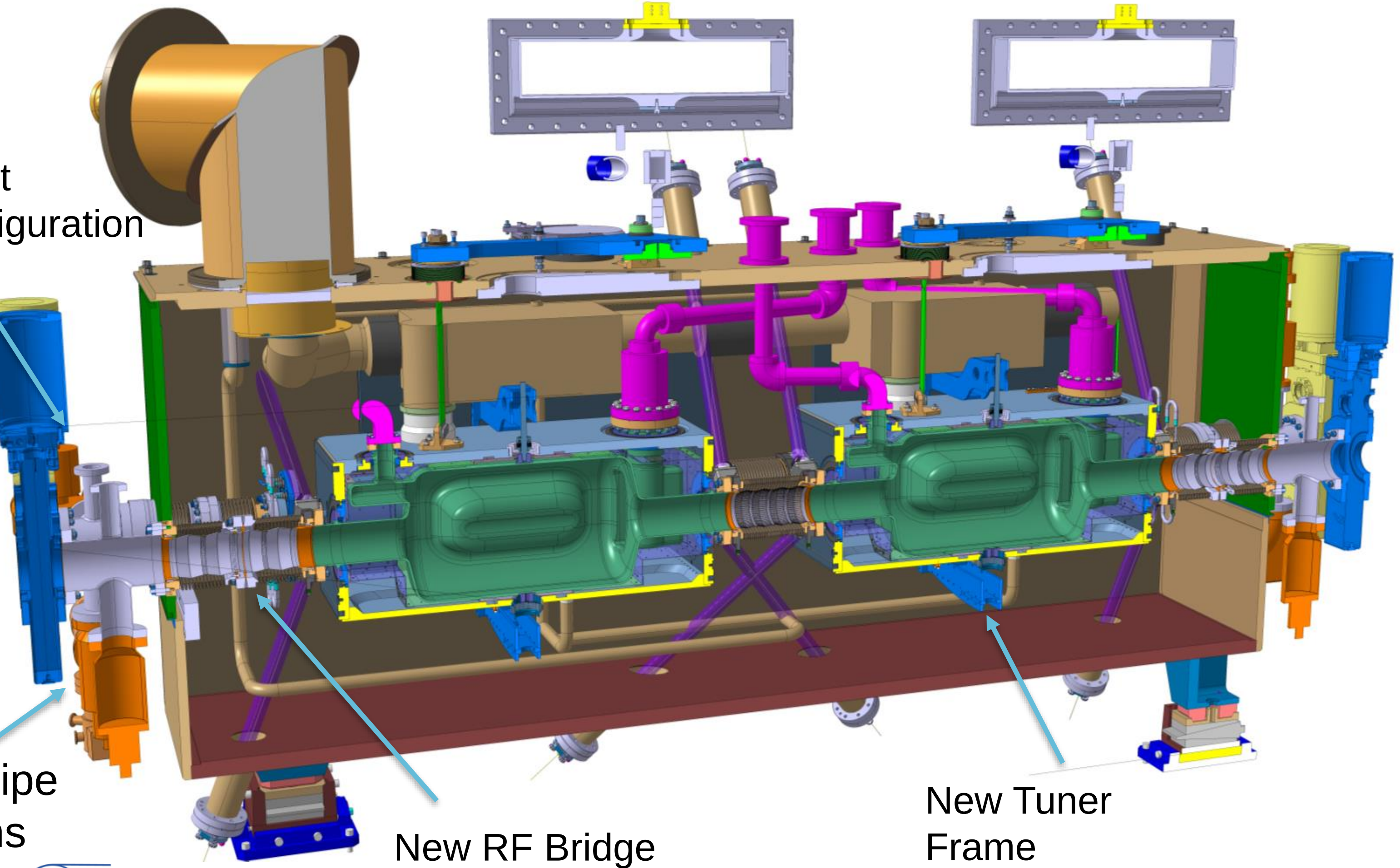




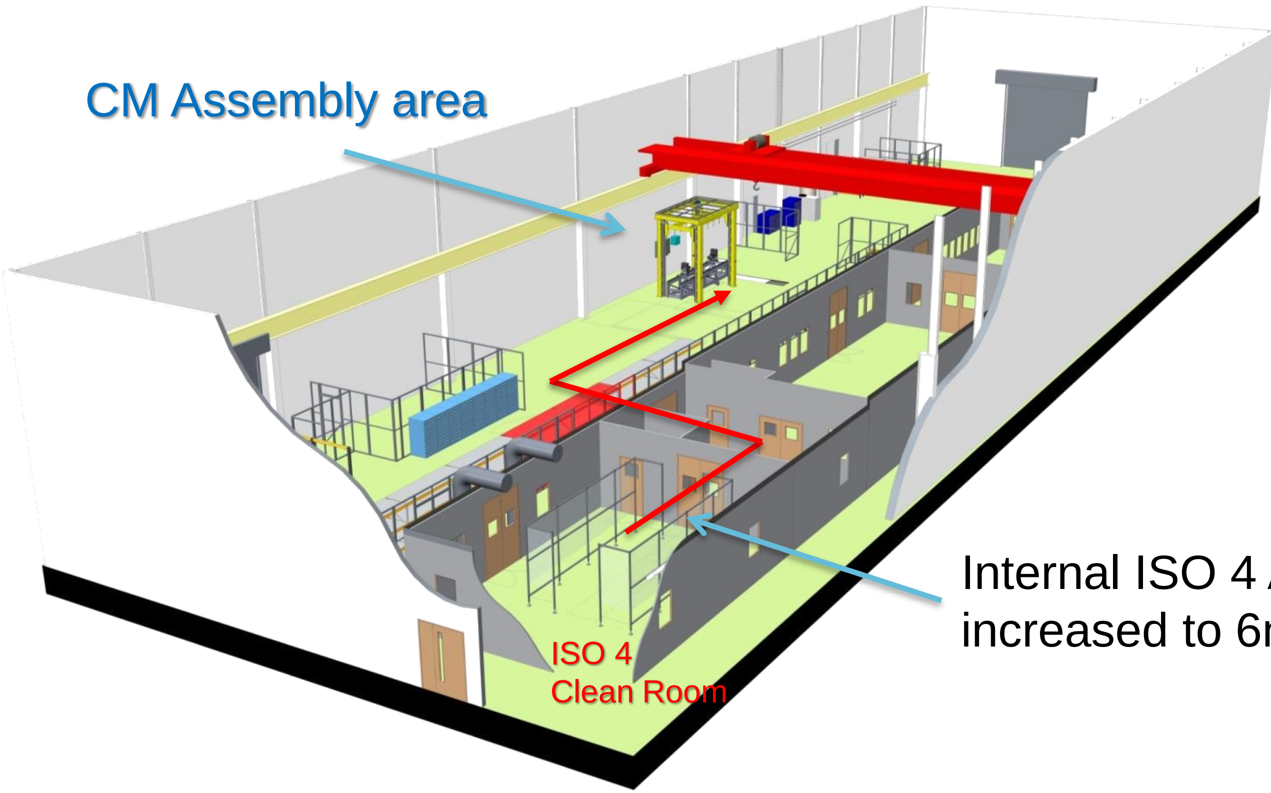




RFD (LHC-type) UK+CERN



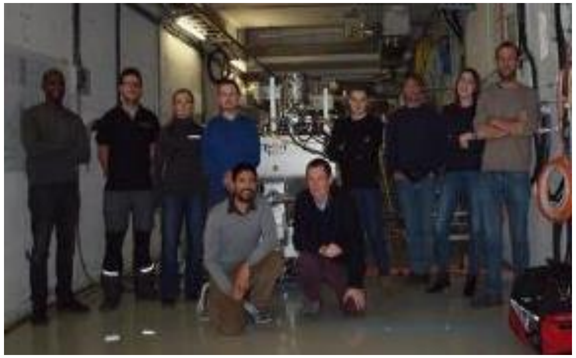
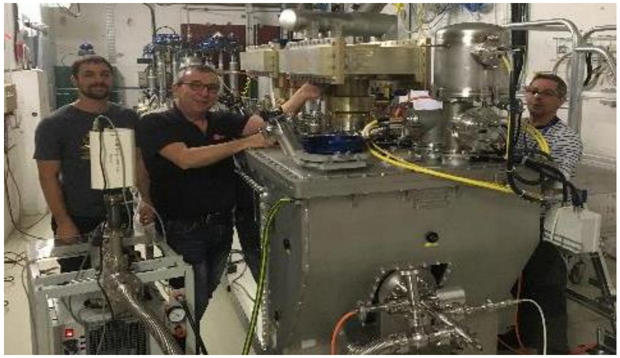
STFC Assembly of RFD Cryomodule



Final Comments

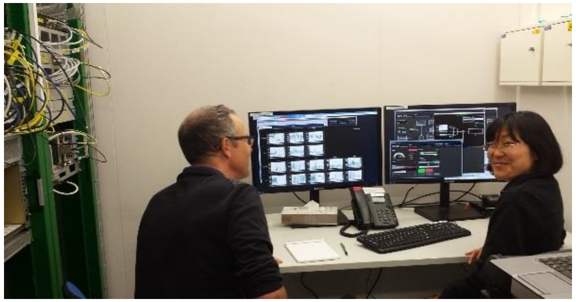
- SPS Crab Cavities
  - Despite many hurdles, a monumental effort was put in to conclude 2018 beam tests a success – it a humbling experience
  - UK led many of the key parts of the experiment
  - Consolidation works in LS2 is needed to have test stand through Run3. RF-Dipole cavity fabrication started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

Thank You !







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