Crab Cavity Tests of Hadron Beams in SPS

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On behalf of team of

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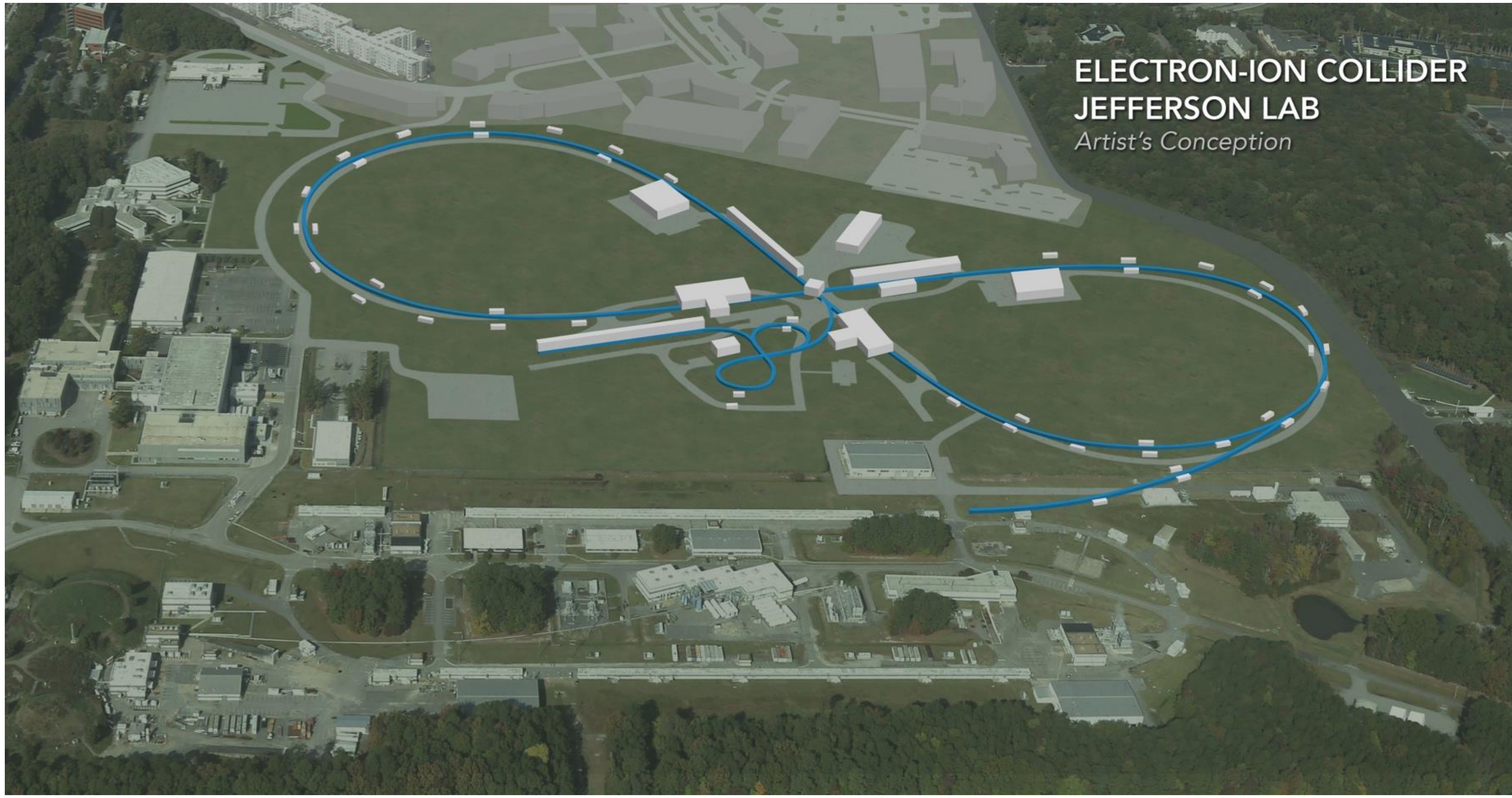


EIC Accelerator Collaboration Meeting

October 29 - November 1, 2018

Jefferson Lab

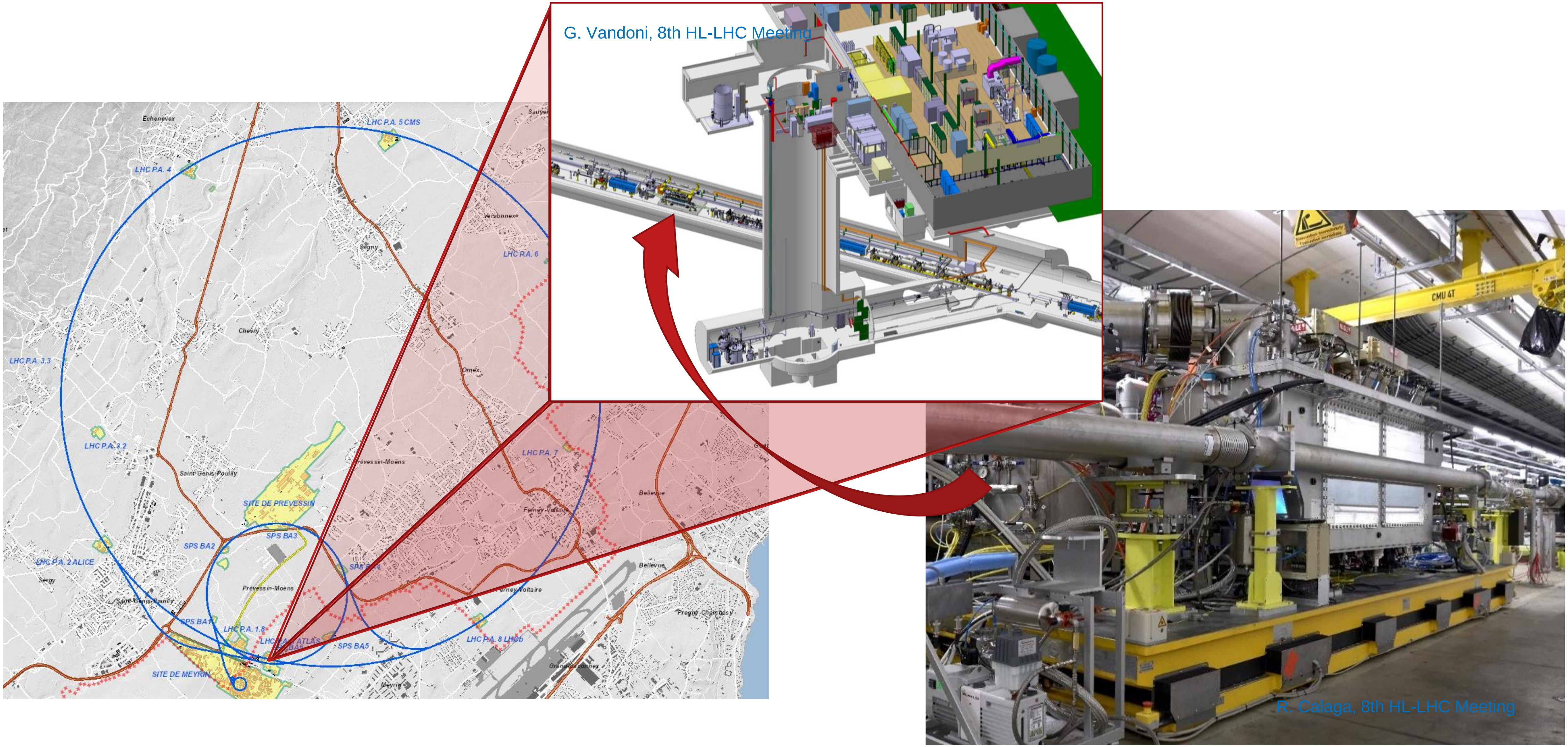
U.S. DEPARTMENT OF ENERGY | Office of Science

JSA

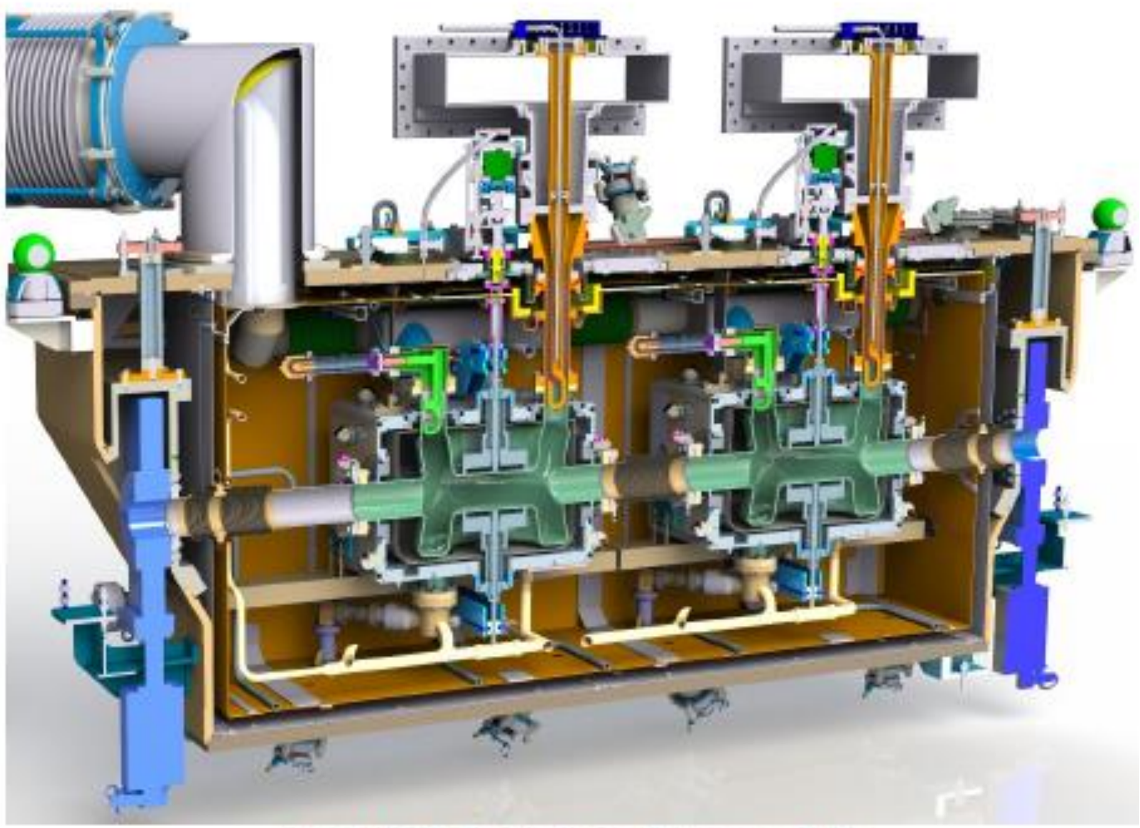
Acknowledgement

- DOE NP FOA funding makes it possible for this team to participate the proton beam test of crabbing system in SPS and learn comprehensive effect on beam and machine.
- CERN is providing excellent support with full access to the experiment and data.
- Team's prior DOE HEP US LARP collaboration experience is applicable and makes the work very efficient for EIC project.
- Most of slides are taken from HL-LHC collaboration meeting which happened at the end of crab cavity test (a week ago).
- Some of results are still preliminary as in-depth analysis is on-going.
- Special thanks to Silvia Verdú-Andrés at BNL for facilitating connections with CERN.

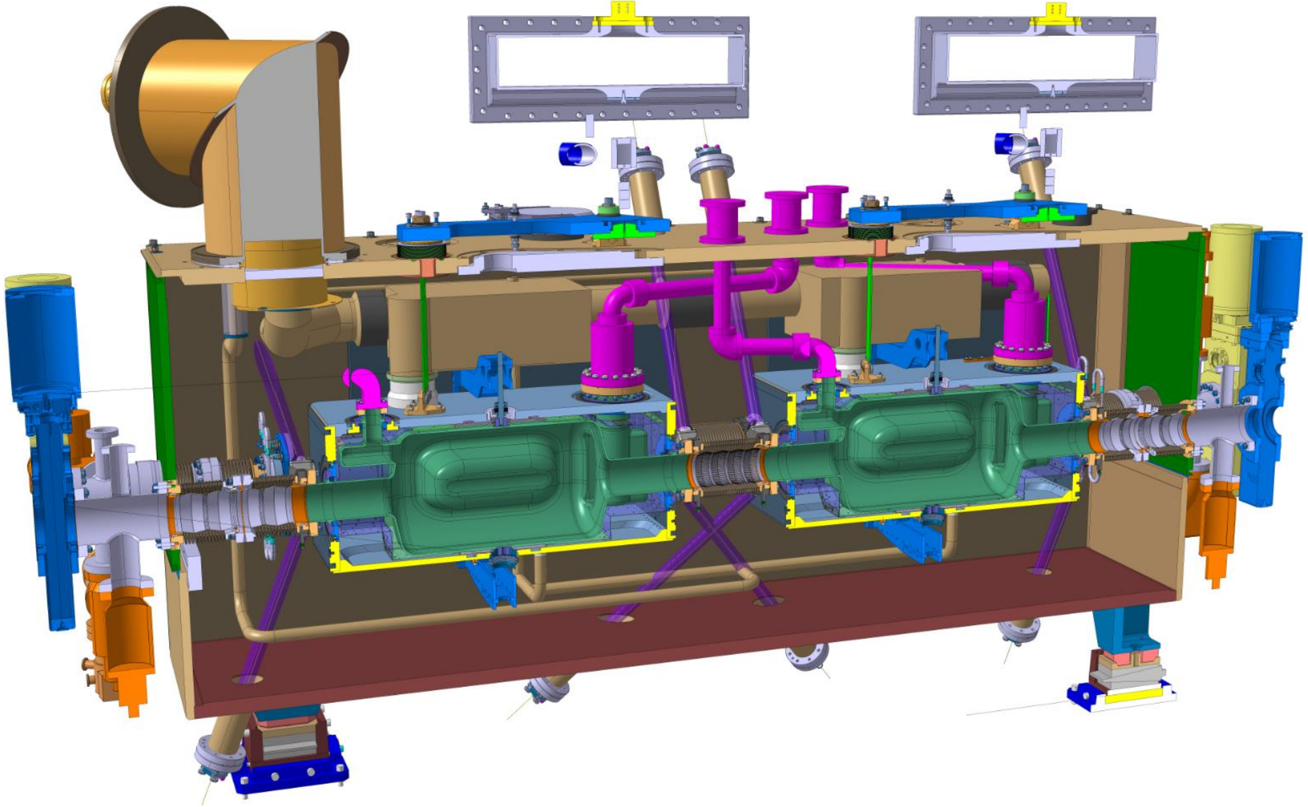
Crab Cavity Cryomodule in SPS



SPS Cryomodules



DQW Cryomodule
(Vertical crabbing)



RFD Cryomodule
(Horizontal crabbing)

Timeline and Highlights

- Cavity fabrication, cavity cold tests, cryomodule assembly, and CM cold test within 2 years (2016-2017).
- Cryomodule with two DQW cavities installed in SPS in January 2018.
- Challenges in many fronts; cryogenics, vacuum system, cabling, etc during test stand commissioning but overcome. Proton beam test carried on as scheduled.
- First ever proton beam crabbing on May 23, 2018.
- One of main SPS test goal “Transparency” proved on October 17, 2018.
  - Transparency = No crabbing with rf control of crab cavities.
- More tests (with or without beam) yet to come.
- No surprise so far regarding crab cavity effect on proton beam.

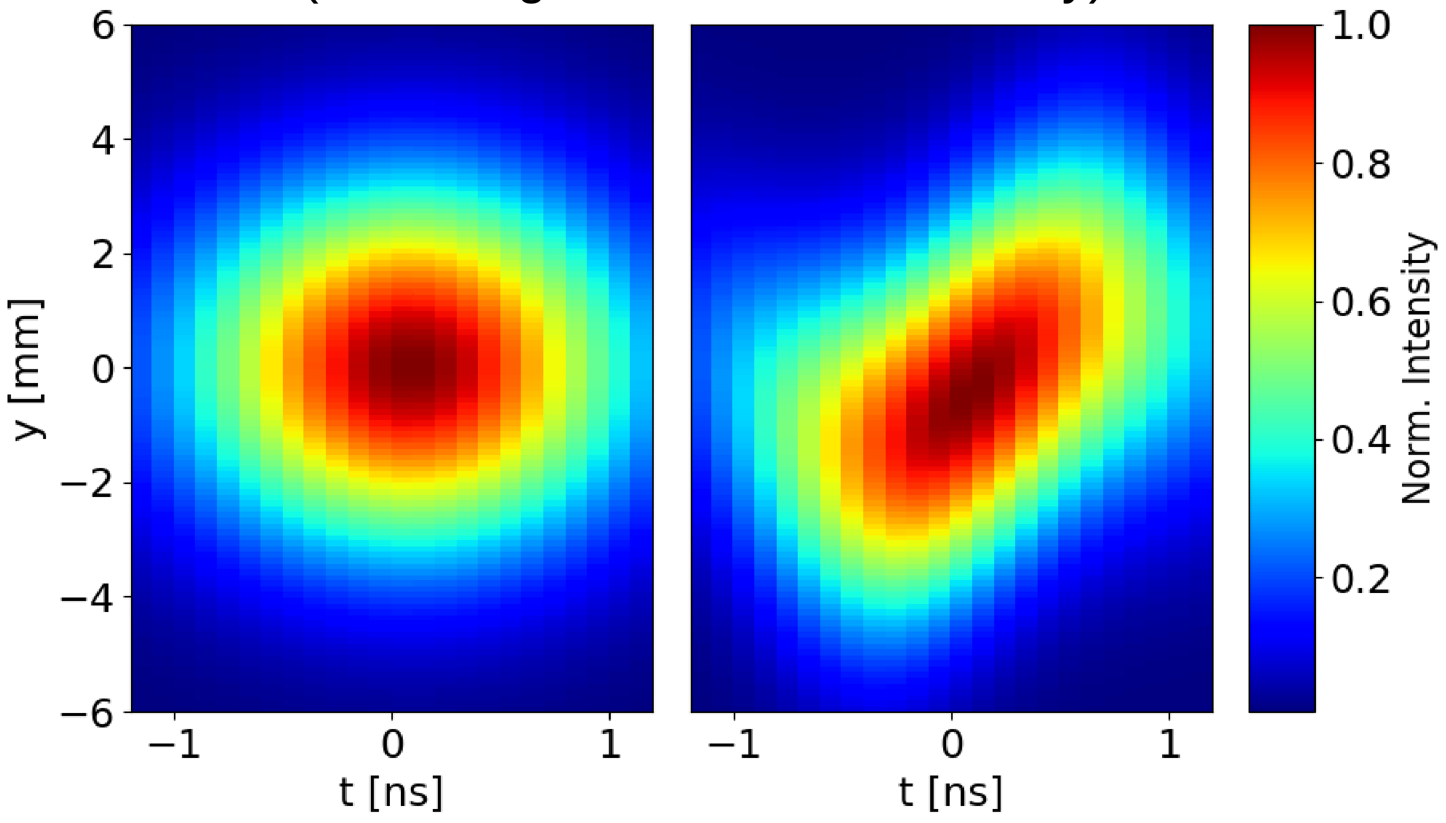
Machine Development Overview

MD#	Date	Tests	Cav1 [MV]	Cav2 [MV]	Temp [K]	Energy [GeV]
1	May 23	First crabbing, phase and voltage scan	0.5	0	4.5	26
2	May 30	270 GeV ramp with single bunch	1-2	0	4.5	26, 270
3	July 18	Intensity ramp up	1	~0.3	4.5	26
4	Aug 29	270 GeV coast setup	1.0	0.5	2.0	270
5	Sep 5	Emittance growth at 270 GeV with induced noise	0	1.0	2.0	270
6	Oct 10	Intensity ramp up to 4-batches	-	1.0-1.5	2.0	26
7	Oct 17	Intensity/Energy ramp up/Transparency	1.0	1.0	2.0	26, 270

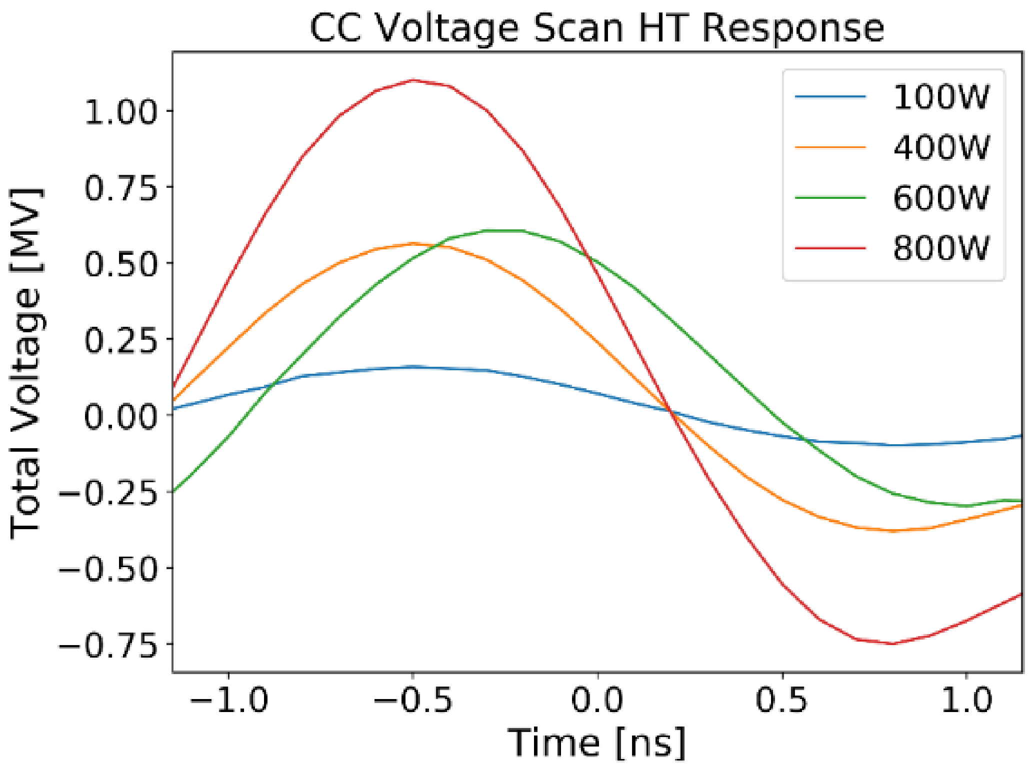
First Proton Beam Crabbing – MD#1

R. Calaga, 8th HL-LHC Meeting

Crabbing reconstruction
from Head-Tail monitor and wire scanners
(assuming Gaussian transversely)

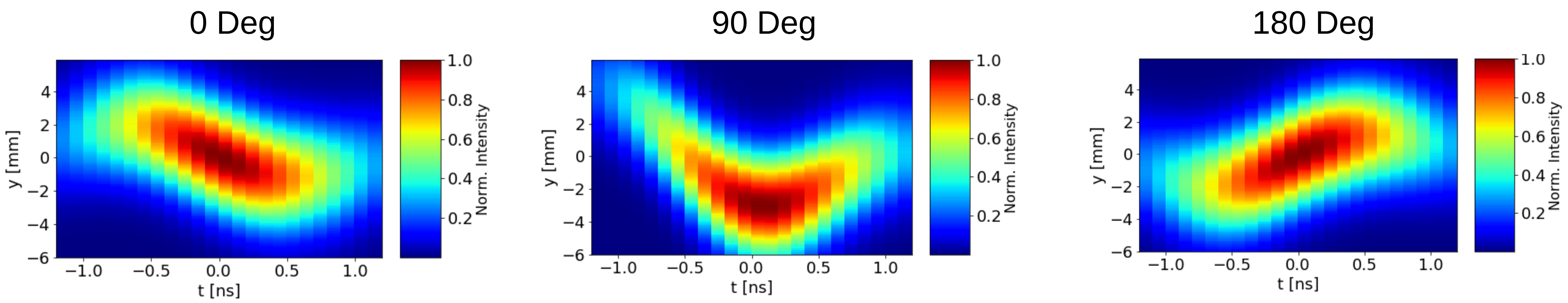


Single bunch
26 GeV
$0.2 - 0.8 \times 10^{11}$p/b
through Cavity 1



Phase Scans – MD#1

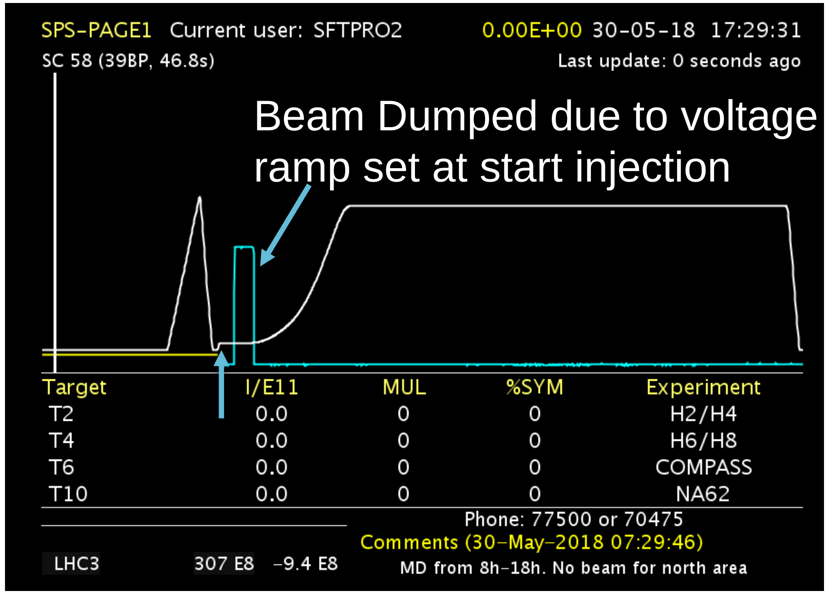
RF phase scan w.r.t the beam phase with cavity 1

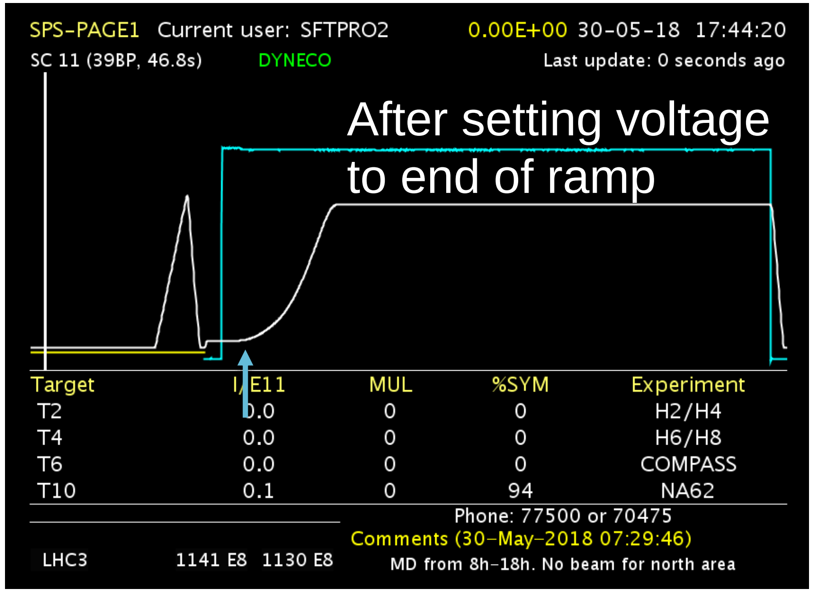


- Nominal bunch intensities easily reached at 26 GeV and 270 GeV.
- Cavity phase manipulation goes as expected.
- Intensities up to 72b*2e10 achieved with no issues.

Beam Energy Ramp – MD#2

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





After energy ramp to 270 GeV, beam intensity was also increased to 1.2e11.

- With cavities powered during the ramp and without BA3-BA6 synchronization, 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.

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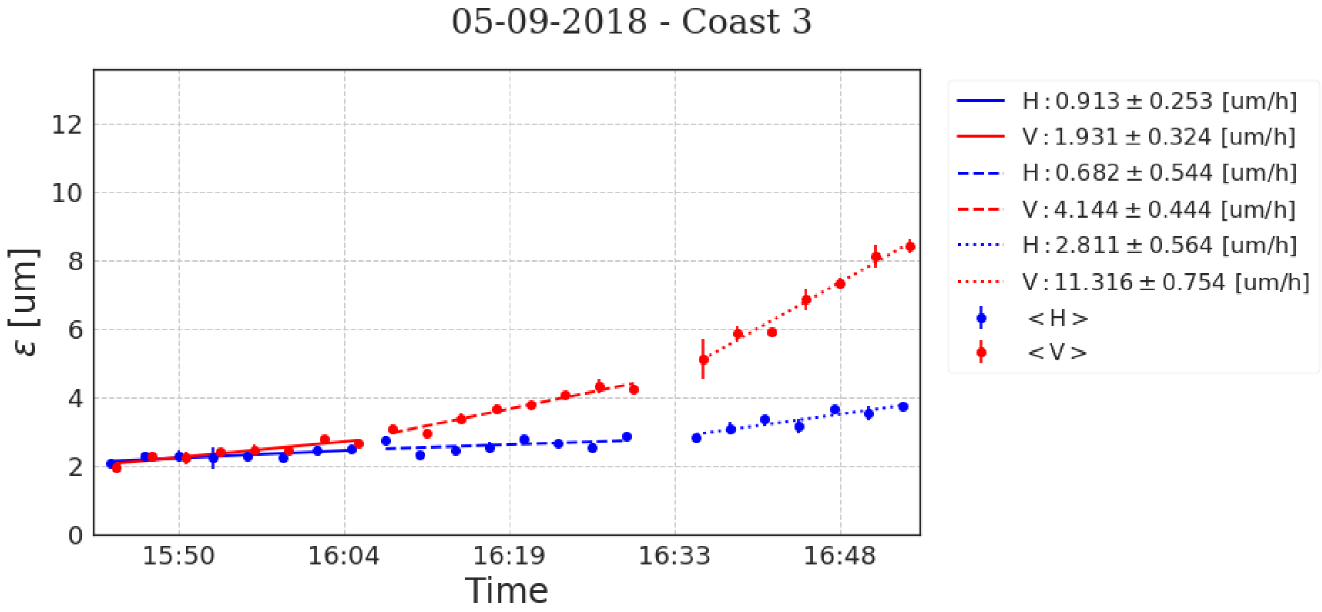
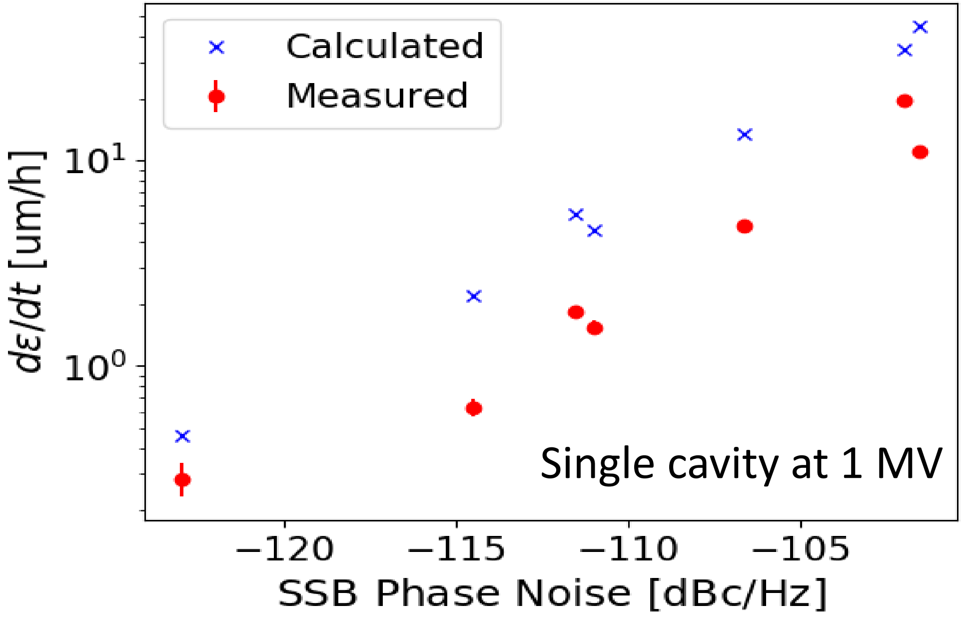
Emittance Growth – MD#5

- Emittance measurements with coast 270 GeV beams of different noise levels.
- The first measurements of emittance growth show a factor of 2 difference between calculated (higher) and measured
- 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 $0.05\ \mu\mathrm{m/h}$





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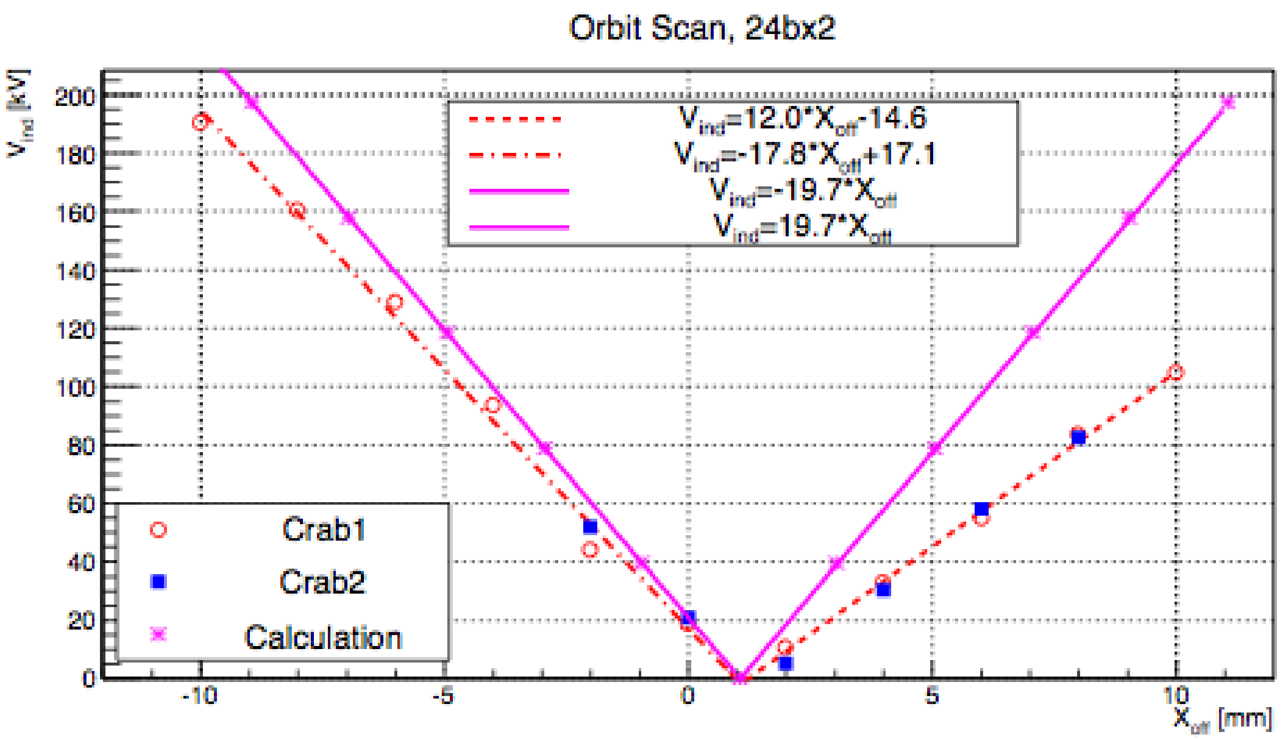
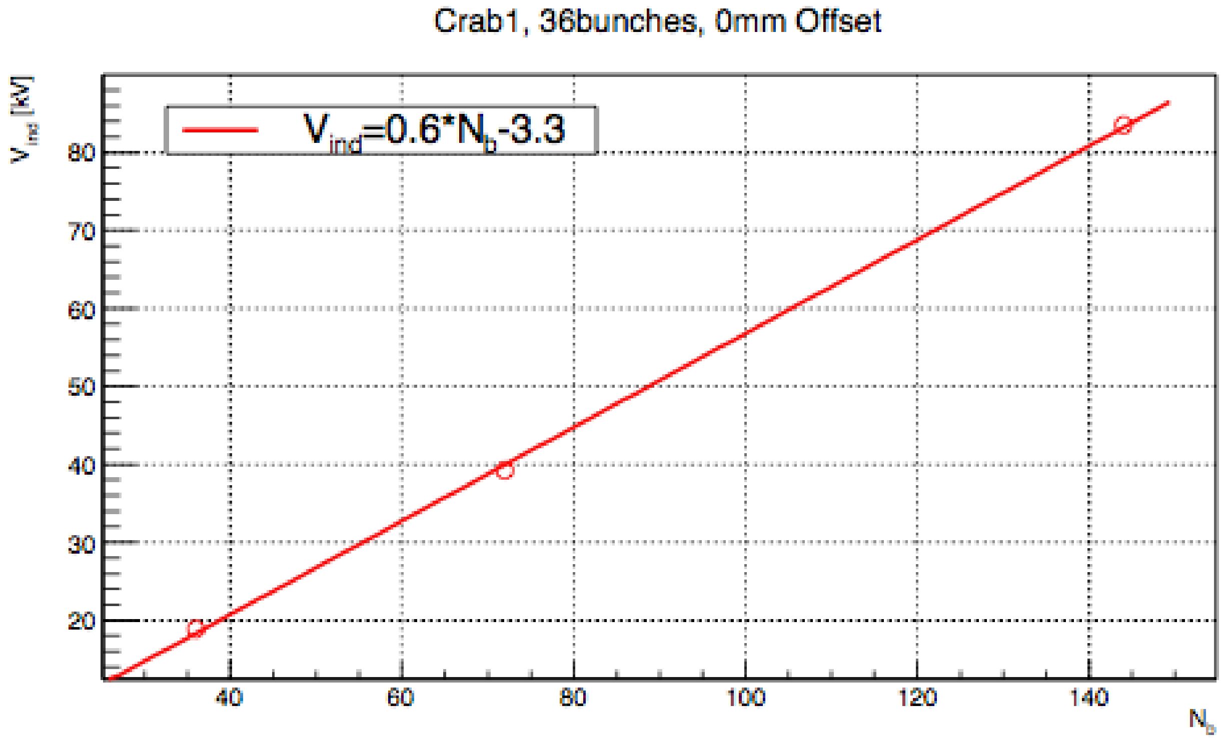
Beam Loading – MD#6

E. Yamakawa, 8th HL-LHC Meeting

- Beam trajectory is offset from the closed orbit in SPS-CCs locally : ±10 mm (measured by BPM)
- Electric center of cavities are +1.06 mm for both cavities.
- Asymmetry in measured data between negative and positive offsets need to be understood.

- 36bx1, 36bx2, 36bx4 at 0 mm, intensity scan
- Induced voltage is linearly increasing with beam intensity.





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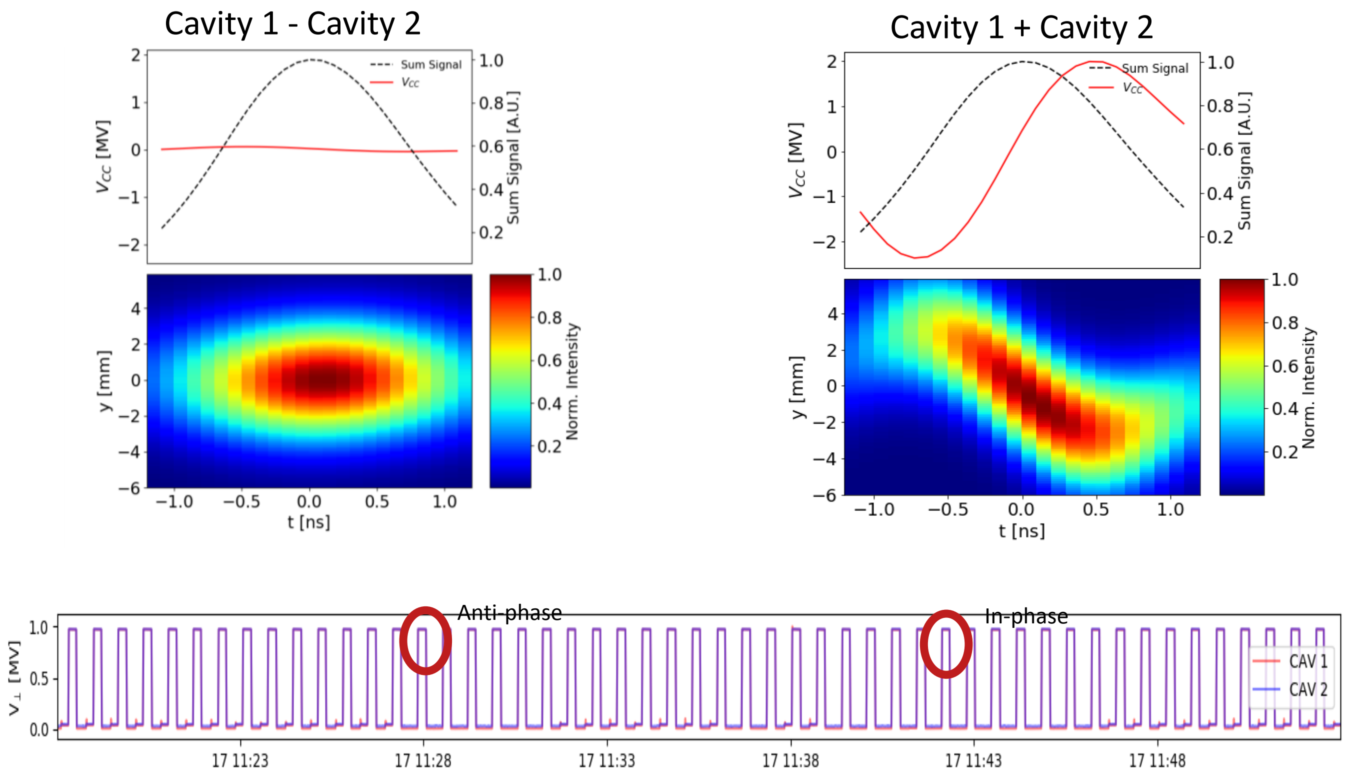
Crabbing Transparency – MD#7

- Both cavities at 1 MV.
- First aligned the phases of two cavities by making the biggest banana possible.
- Varied the phase of cavity 1 while keeping cavity 2 phase constant, scan through 360 degrees, and fine tuned the phases to correct it as best as possible.



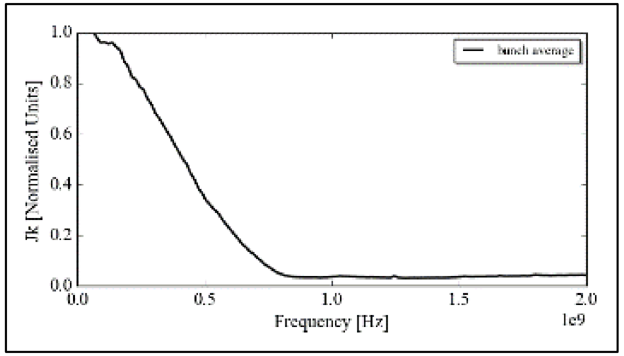
SPS MD cycle (~20 sec flattop)

Higher Order Modes

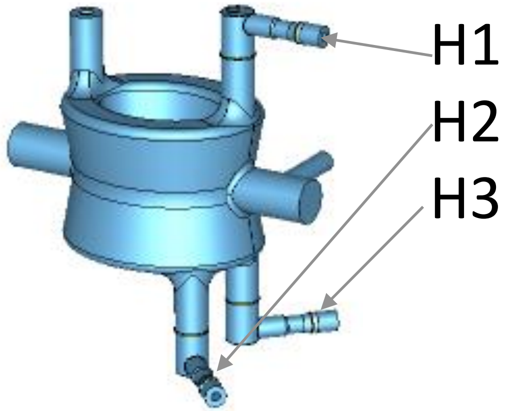
Measurement with beam (low # of bunches)
- Unforeseen power at 1.75 GHz – mismatch on pick-up (feed-back antenna). Solution found.
- Analytic under-represents – measured profile brings us closer – more analysis of this to come.
- Mode dependant coupling ratio – all power at 960 MHz (most detrimental mode) through top coupler

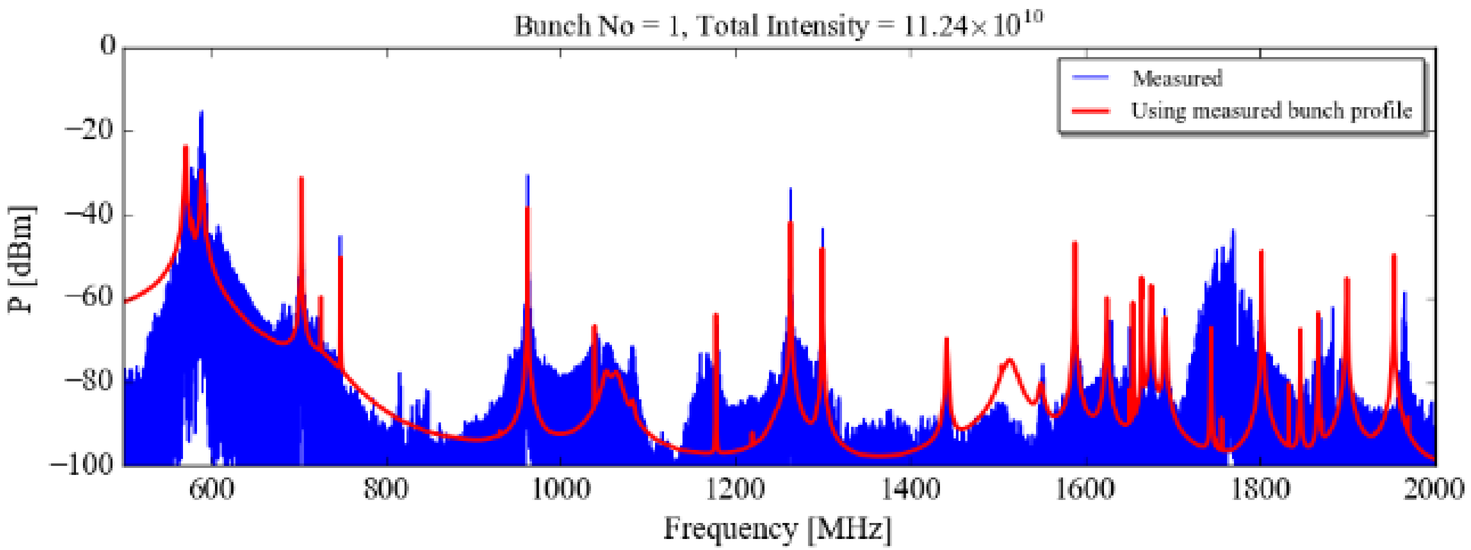
Measurement with multibunches (up to >70)
- Big deviation for 590 MHz mode – investigations into Q, R/Q and I(ω).

On-going work
- Longitudinal and transverse R/Q measurement
- Analysis of high intensity beam measurement



Measured bunch profile





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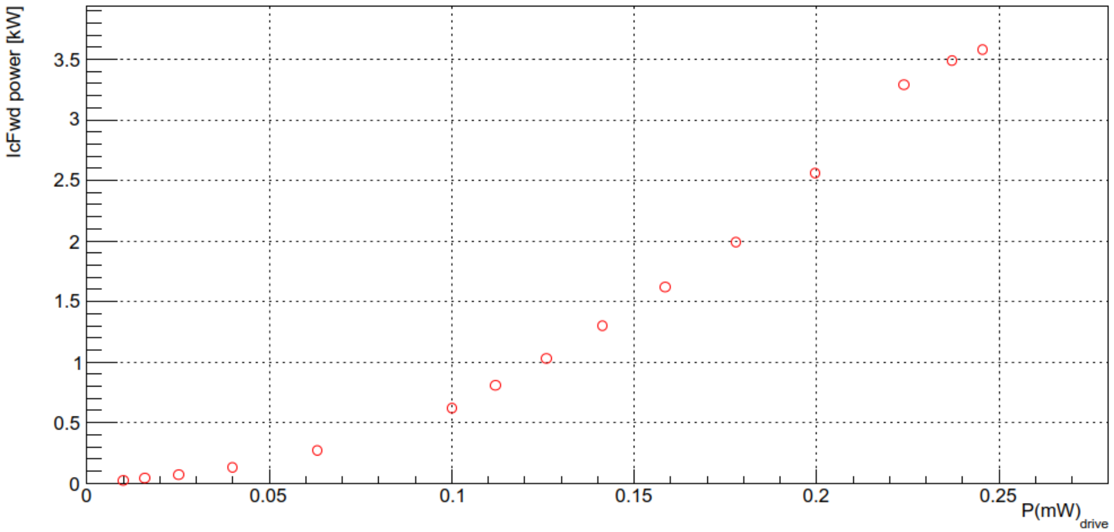
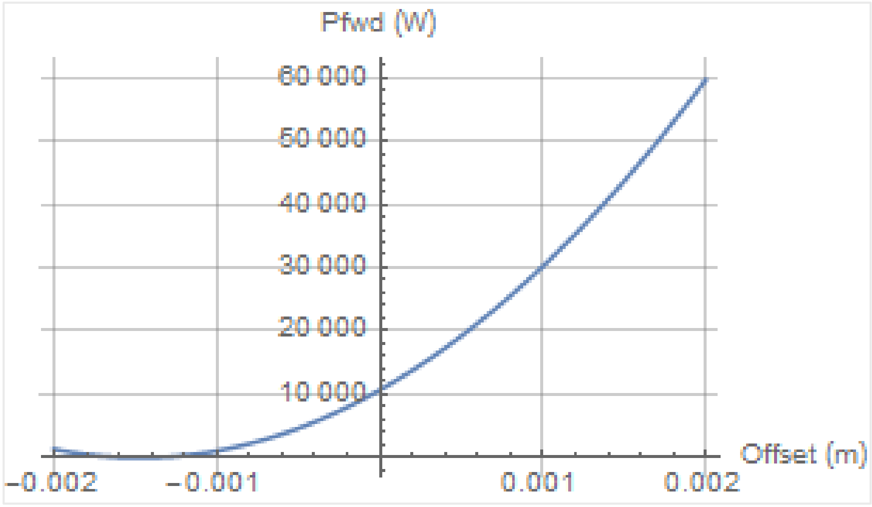
LLRF

- The power needed depends on the beam displacement. The HL-LHC system is designed to accept ±2 mm beam offset in the CC.
- In the SPS we have a 50 kW TX that has been used in the 0-5 kW range during the MDs
- We have observed very small gain at low drive level.
- In operation we will need the full dynamic range from 0 to 50 kW, including very low power
- The power needed depends mainly on the beam centering
- It is therefore important to have a system that can deal with a large range of TX power, including very low drive.



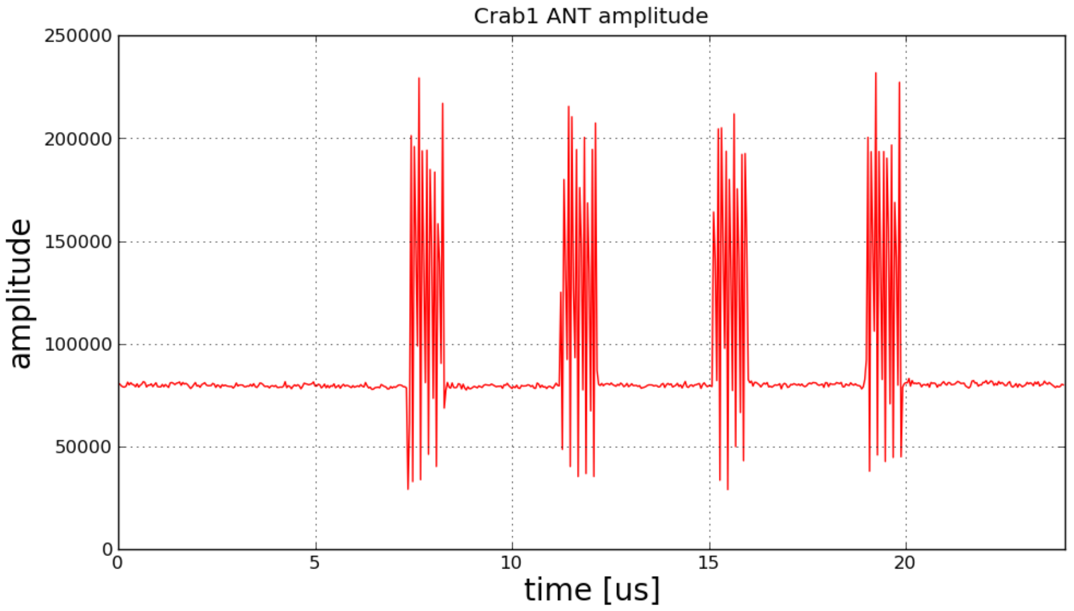
Amplifier output power (kW) vs. LLRF drive power (mW)



HL-LHC case

LLRF – Pick up

- Pick up antenna was found to have direct beam coupling.
  - Band pass filter used for SPS test
  - Solution found and modification underway for LHC



The ANT signal with batches with 4 batches of 36 bunches, nominal intensity. Cavity idling (Oct 12th, calibrated)

What Do (Should) We Learn from SPS Tests for EIC?

- How the actual data look compared to calculations and simulations?
- What are the limits of crab cavity performance in terms of design, current srf technology, HOM power, coupling between crab cavities, and in relation with overall machine components?
- Beam loading effects, optimal loaded Q of CC.
- Heat load, microphonics of the CC cryomodule.
- LLRF and beam instrumentation requirement to properly control and monitor CC.
- How can risk of hadron crabbing in EIC be reduced?

Our Plan

- Look in to the data collected during MDs and translate it to EIC cases.
- Participate SPS further MDs and collaboration meetings (expected spring 2019).
- RFD cryomodule work 2019-2020 and CM cold test scheduled in 2021.
- We hope our exercise mutually benefit EIC and HL-LHC at CERN.

Back Up

Bunch Spacing T_b	25 ns
available bunch number N_b	924
Bunch intensity N_p	1.0×10^{11}
RF frequency @ 26GeV f_{RF}	400.5288 MHz
Bunch length (4σ)	3.0 ns
Bunching factor F_b (@26GeV)	0.17
$I_{b,DC}$	0.64 A
R/Q (circuit-ohm)	210
Q_L	500,000
Time constant τ	397 us

Table 1: SPS-CCs parameters

Bunch Spacing T_b	25 ns
available bunch number N_b	3564
Bunch intensity N_p	2.3×10^{11}
RF frequency f_{RF}	400.789 MHz
Bunch length (4σ)	1.2 ns
Bunching factor F_b (@7TeV)	0.75
$I_{b,DC}$	1.47 A
CC voltage V_{cc}	3.4 MV
R/Q (circuit-ohm)	210
Q_L	500,000
Time constant τ	397 us

Table 2: HL-LHC parameters