Crab Cavity Operation in a Hadron Ring

Jean Delayen (ODU), Geoffrey Krafft (JLAB), Qiong Wu (BNL)

Project Description

- Crab cavities are necessary and were prioritized by the Electron Ion Collider Advisory Committee for Electron-Ion Colliders (EIC), and essential for all high luminosity colliders.
- Use of crab cavities in EICs such as eRHIC proposed by Brookhaven National Laboratory (BNL) and JLEIC proposed by the Thomas Jefferson National Accelerator Facility (JLAB) carries some risk, and the 2017 Report of the Community Review of EIC R&D for the Office of Nuclear Physics identified "Crab cavity operation in a hadron ring" as the **top R&D priority**. This proposal addresses directly that recommendation.

Row No.	Proponent	Concept / Proponent Identifier	Title of R&D Element	Panel Priority	Panel Sub-Priority
1	PANEL	ALL	Crab cavity operation in a hadron ring	High	A

- Scientists in our collaboration have been major contributors to the development of crabbing systems in the preceding LARP and on-going LHC HiLumi programs.
- By participating in the crab cavity project for the high luminosity upgrade of the Large Hadron Collider, especially the machine development experiments, we will have this non-repeatable opportunity for preliminary studies of the beam-cavity interaction.
- Output information from this proposal, such limitations from the crab cavity design will become useful input to the beam dynamics study for crab crossing scheme, such as partial tasks described in the proposal of 'Development and test of simulation tools for EIC beam-beam interaction'.

Budget Summary

	FY18 + FY19 (k$) *	Total (k$)
Funds Allocated	708 + 220	928
Actual Cost	273 + 73	346

* Red BNL and TJNAF Base
Black Funding directed to ODU

Deliverables and Schedule

	Y1Q1	Y1Q2	Y1Q3	Y1Q4	Y2Q1	Y2Q2	Y2Q3	Y2Q4	Status
Analysis of off-line room temperature and cryogenic tests									√
Routine remote communication with CERN									Ongoing
Remote preparation for test									√
Participation in rf beam synchronization									√ (Data Study)
Participation in transparency tests									√
Participation in emittance and stability measurements									√
Participation in high-intensity experiments									√
Analysis of test results									Ongoing
Benchmarking simulations with SPS data									Ongoing
Design experimental test of crab crossing in RHIC									Just started
Detailed analysis of SPS crab cavity with RHIC beam									Just started

Performed by:	**Full Collaboration**	**ODU/JLAB**	**BNL**

Some Project Specifics

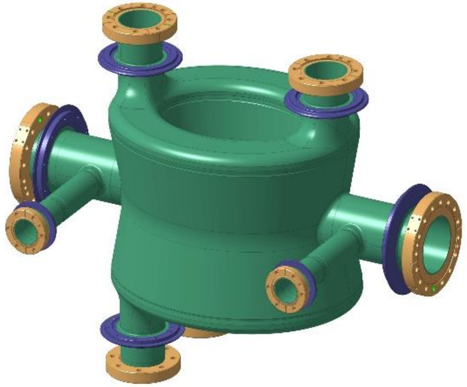
- Crab cavities for LHC, design and experiments
- Machine development periods at SPS
  - Major outcomes
  - Lesson learned and future plan
- Benefits to EIC crab cavity and beam dynamics study
- Documentation
- Future plan
- Summary

Crab Cavities for LHC

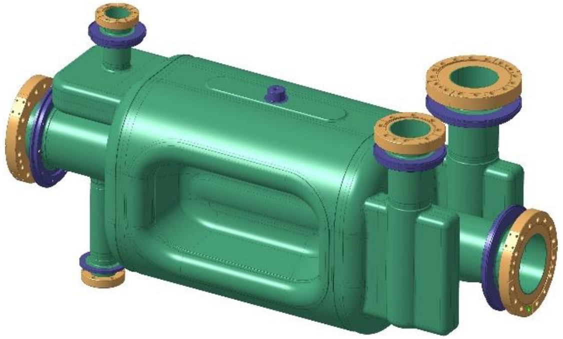
- Crab cavity for LHC program started in the US LHC Accelerator R&D Program (US LARP) in 2008, and continued in the US HL-LHC Accelerator Upgrade Project (AUP) into production mode.
- The LARP program fostered two successful designs of crab cavities (see next page) to the Hi-Lumi LHC program to recover a luminosity loss of 70% or more due to the crossing angle at the interaction region.
- The Hi-Lumi LHC requires a 400 MHz crab cavity to deliver a total of 12-13 MV per beam per side.
- Crabbing in both vertical and horizontal directions are required by different physics experiment sites.
- The EIC design at BNL requires 200 and 400 MHz crab cavities in horizontal crabbing. The EIC design at JLAB requires 476 and 952 MHz crab cavities in horizontal crabbing.
- Both EIC designs can benefit from the LHC crab cavity designs and the lessons learned from their performance in the tests conducted in the SPS at CERN.

Two Crab Cavity Designs Delivered by LARP

Double Quarter Wave (DQW)



RF Dipole (RFD)



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

$$\text{V}_\text{T} = 3.4\ \text{MV/cavity}$$

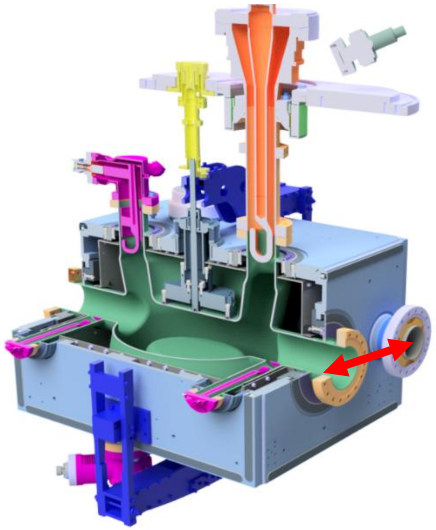
$$(\text{E}_\text{p}, \text{B}_\text{p} < 40\ \text{MV/m}, 70\ \text{mT})$$

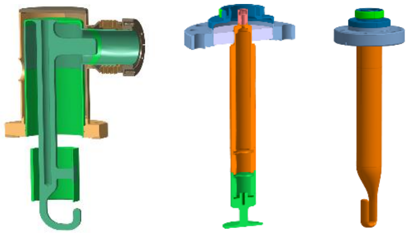
$$\text{Beam aperture} = 84\ \text{mm}$$

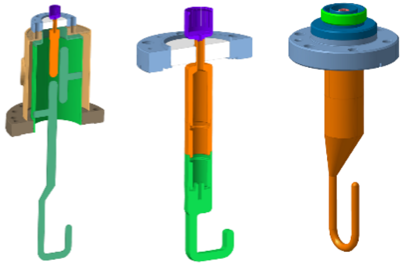
$$\text{Beam-to-beam dist} = 194\ \text{mm}$$

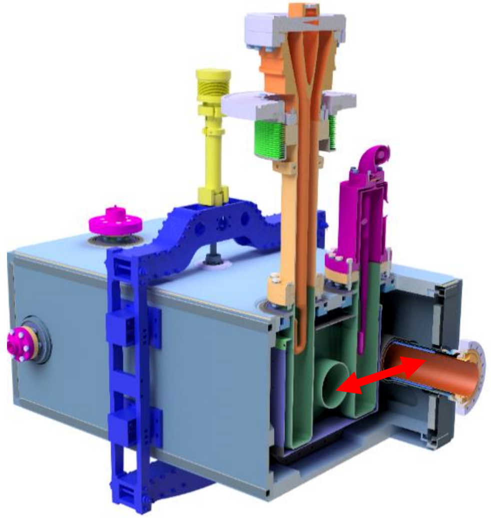
$$\text{Common FPC} = 40\ \text{kW-CW}$$

$$\text{Operating Temp} = 2\ \text{K}$$









Experience in the HL-LHC Prior to this FOA Program

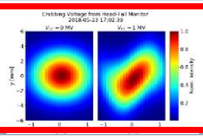
- Delivered DQW and RFD RF design
- Participated in fabrication of all LARP cavities
- Participated in the DQW cavity and HOM coupler production for SPS @ CERN
  - Fabrication
  - Trim tuning
  - Helium vessel and tuner assembly
- Participated in final design and fabrication of DQW and RFD cavities to be installed in the LHC
- Participated in tests
  - More than 30 vertical tests of DQW and RFD cavities and HOM couplers at JLAB
  - DQW cavity with HOM coupler and tuner vertical tests at CERN
  - Cryomodule test in SM18 at CERN
- Designed improvements from lessons learned
- Validated SPS prototype designs, with a goal to demonstrate ultimate SRF performance

Production at CERN for SPS–DQW Cryomodule

©M. Garlaschè, 7th HL-LHC Collaboration Meeting, Madrid, Nov 13-16, 2017

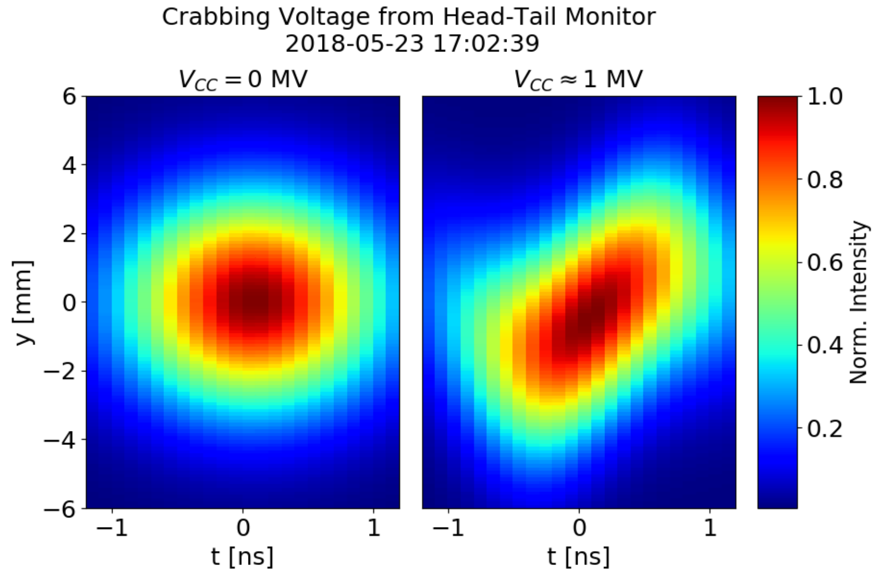
SPS-LSS6 – Crab Cavity Module in SPS Tunnel, January 2018

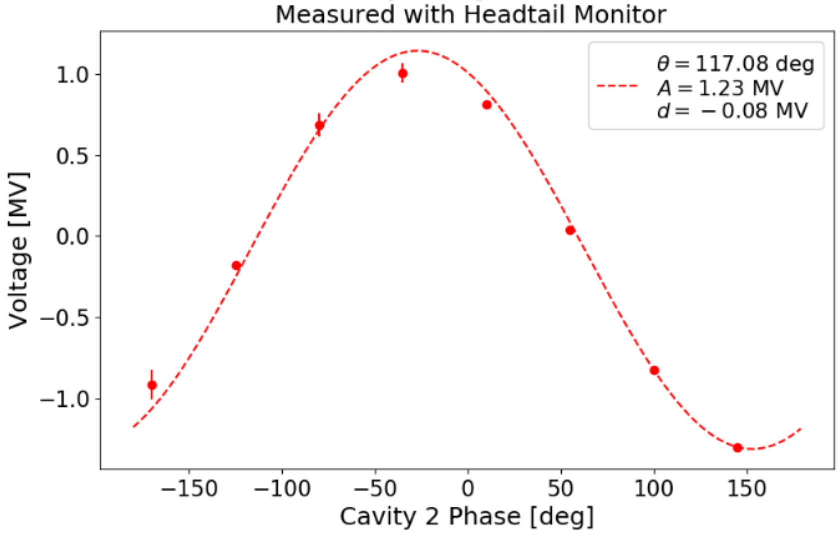
SPS Machine Development Periods at CERN in 2018

MD#	What	When	Major Results	FOA Covered Activity
0	RF commissioning (no-beam)	Mar-Apr	cavity conditioning, high level and low level RF commissioning, cryogenic commissioning,	N/A
1	First crabbing, phase and voltage scan	May 23	 First crab cavity meets proton; 180° phase and voltage scan	N/A
2	270 GeV ramp with single bunch	May 30	Cavity turn on strategy with small beam loss	N/A
3	Intensity ramp up	Jul 18	Higher order mode (HOM) spectrum agree well with simulation	N/A
4	270 GeV coast setup	Aug 29	Beam loading measurement, initial emittance growth coast setup	Participated in MD preparation and 10 hr beam test
5	Emittance growth at 270 GeV with induced noise	Sep 5	Emittance growth measured less than expected	Participated in emittance measurements, collected emittance data
6	Intensity ramp up to 4-batches	Oct 7	No beam induced failures with half the max intensity in SPS	Participated in MD preparation and 10 hr beam test
7	Intensity/Energy ramp up	Oct 17	Transparency test with both cavities; intensity built up close to LHC like bunch length @ 400 GeV	Participated in MD preparation and 2 hr beam test; Hi-Lumi collaboration meeting

Major Outcomes and Lessons Learned from SPS Tests

- First crabbing of hadron beam

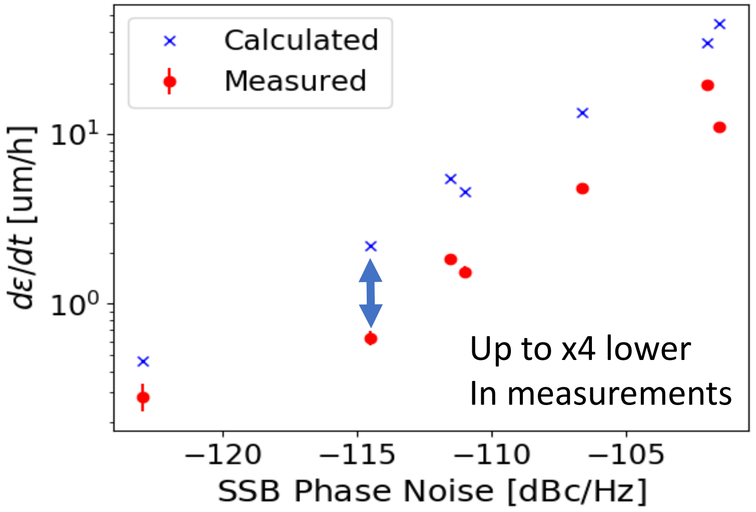


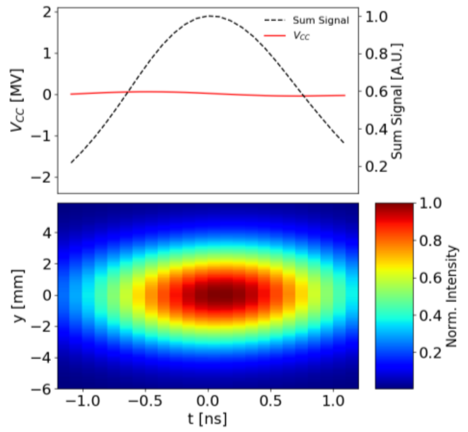


©R. Calaga, 9th HL-LHC Collaboration Meeting, Fermilab, Oct 14-16, 2019

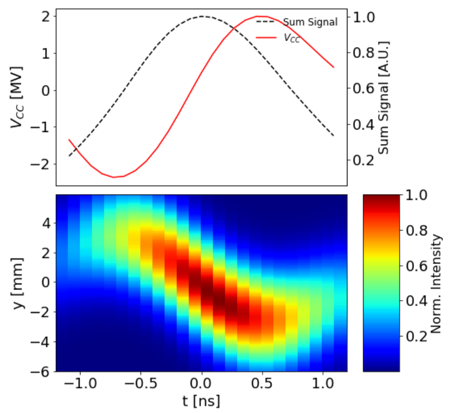
Major Outcomes and Lessons Learned from SPS Tests

- No unexpected phenomena were observed
  - Emittance growth within expectations
    - Although somewhat lower
    - Possibly a systematic error
    - Needs further analysis
- No noticeable effect of rf curvature
- Crabbing cavities could be made "transparent"





Cavity 1 - Cavity 2



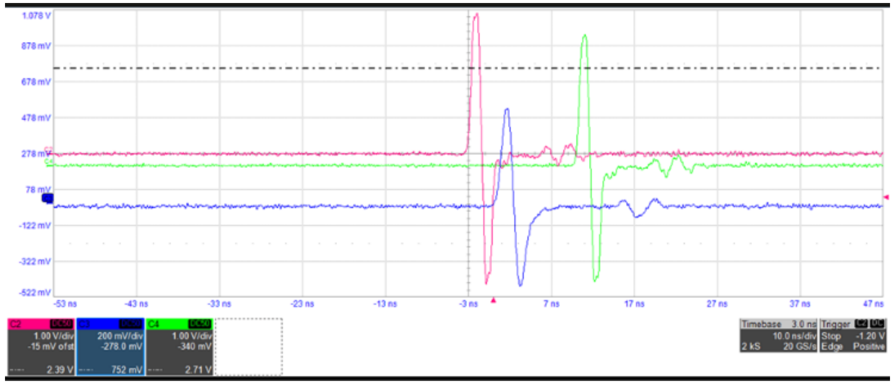
Cavity 1 + Cavity 2

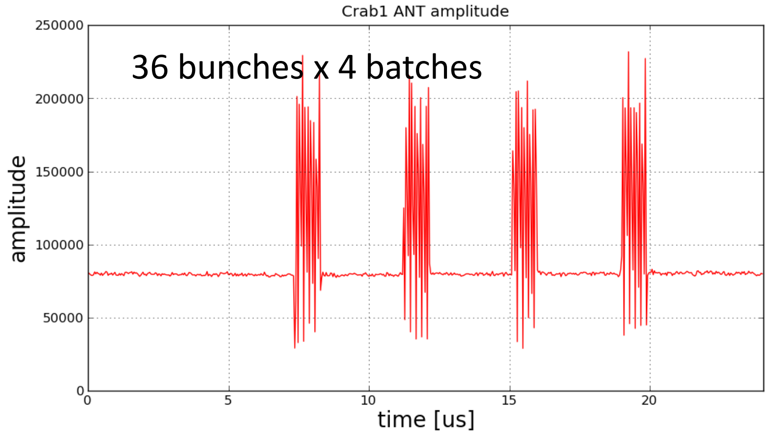
Calculation checked by FOA effort

©R. Calaga, 9th HL-LHC Collaboration Meeting, Fermilab, Oct 14-16, 2019

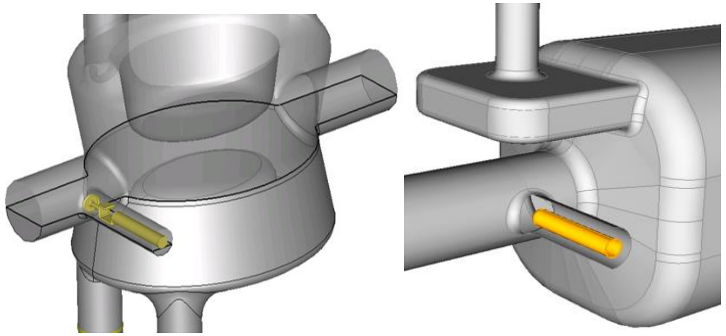
Major Outcomes and Lessons Learned from SPS Tests

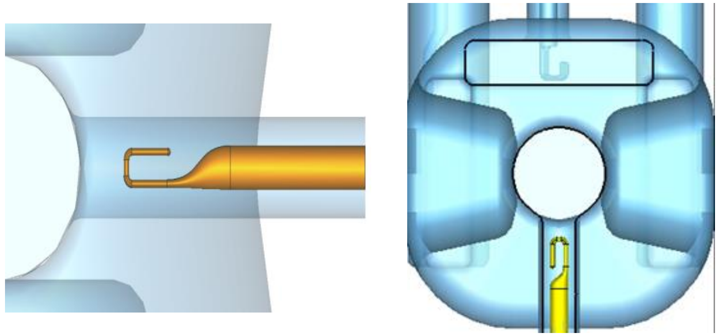
- Field antenna can sense each individual bunch and perturb field stability control





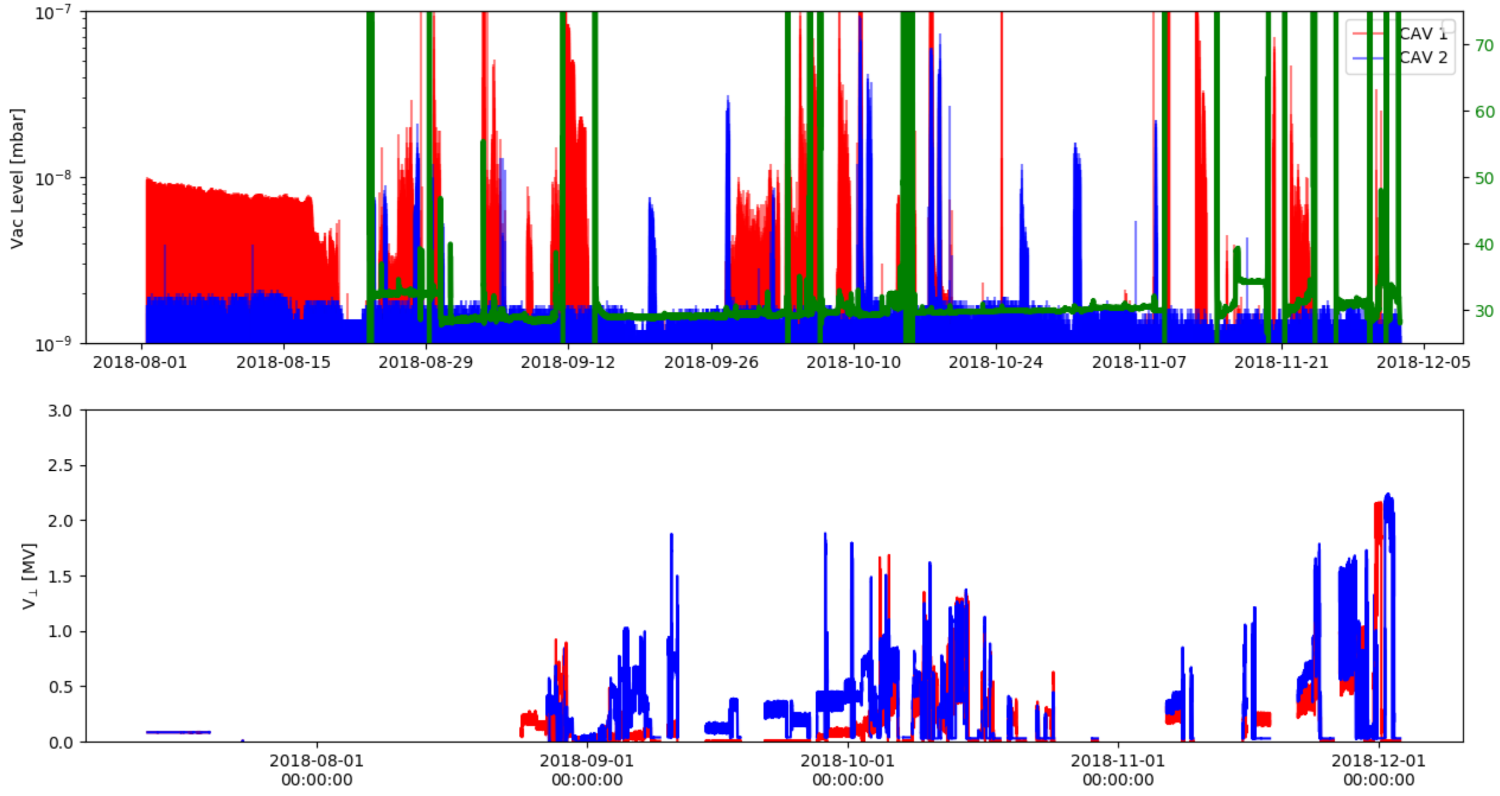
- Modified antenna designs are being implemented in following cavity designs for LHC and EIC





Major Outcomes and Lessons Learned from SPS Tests

- Voltage ramp up – Long RF conditioning to go beyond 1 MV stable operation
- Maximum reached was 2.5 MV in single cavity
- Planning to demonstrate operational voltage with RFD SPS test

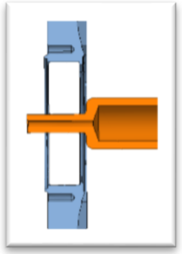


©R. Calaga, 9th HL-LHC Collaboration Meeting, Fermilab, Oct 14-16, 2019

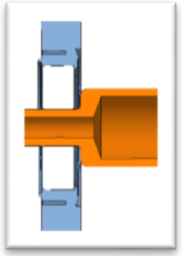
Major Outcomes and Lessons Learned from SPS Tests

- **RF Feedthroughs** – Vacuum leaks at 2 K
- Issue solved with redesign for window brazing
- Couplers for LHC changed from 50 Ω to 25 Ω – For robustness in transportation

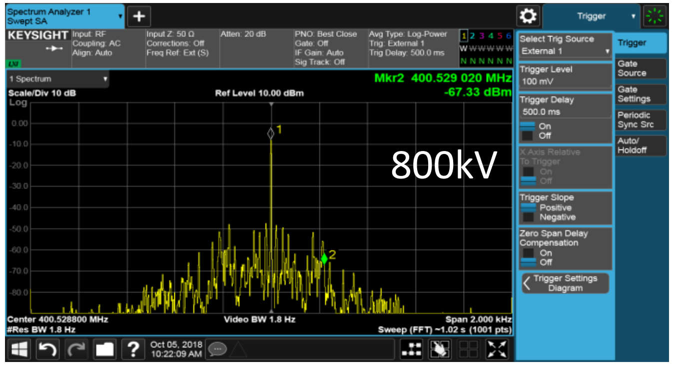
50 Ω

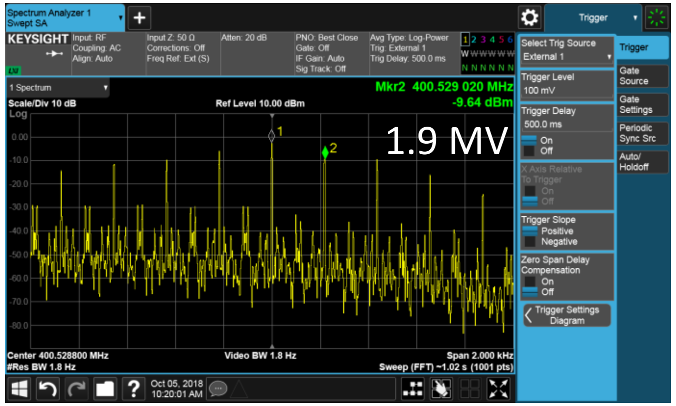


25 Ω

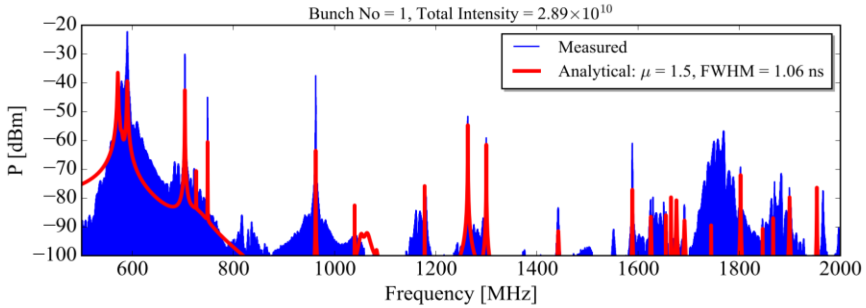


- Electro acoustic instabilities above 1 MV
- Self excited loop is required
- Microphonics not an issue





- **Impedance** - Integrated max HOM power measured < 3 W
- More than 75% from ~960 MHz as expected
- HOM spectrum study for both DQW and RFD cavities to minimize HOM power



©R. Calaga, 9th HL-LHC Collaboration Meeting, Fermilab, Oct 14-16, 2019

Lessons Learned – Additional Items

- Energy scan in the SPS ranges from 26 GeV to 270 GeV, which is very close to the proposed energy range for EIC. Machine protection and low level RF control requirements would be similar. We should follow closely in the development of these systems.
- Cavity fabrication and preparation should follow the same procedure that led to successful cavity operation, which include:
  - Trim tuning strategy
  - Chemistry treatment
  - The importance of prototype cavities
  - The importance of documentation for each step in multi-group collaboration work
- Cavity cryomodule installation in the tunnel, which include:
  - Cavity conditioning
  - Alignment (10 um level)
  - Cryogenic connection
  - Vacuum
- Cavity operation experience, which include:
  - Low level RF control with phase and voltage
  - Direct coupling of the passing bunches to pick-up antenna
  - Cavity beam loading measurements
  - Cavity HOM measurements
  - Heat load, expected and unexpected

Limitations of Previous SPS Tests

- Results are preliminary and still tentative due to the low (~1 MV) crabbing voltage in the cavities
- More definite answers will be obtained from further tests of DQW and RFD cryomodules at the SPS

Lessons to be Learned from Planned Future Tests

- Cavity-beam interaction at 3.4 MV in RFD cryomodule
- Crab cavity transparency to beam with crabbing and un-crabbing at 3.4 MV
- Minimizing heat load
- Crab cavity operation with ion beam
- Crab cavity operation with bunch length scanning
- Experience of cavity production and assembly over far away sites
- Collaboration between multiple groups

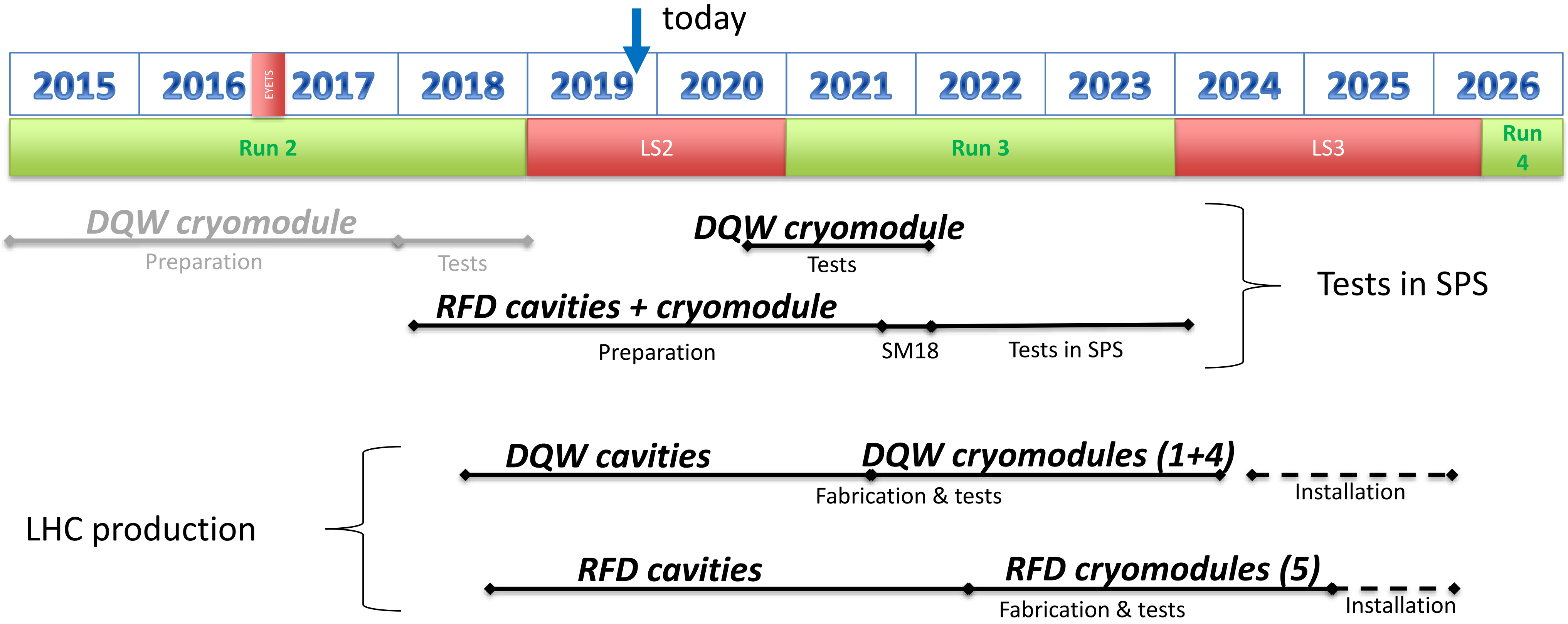
Crab Cavities & Cryomodules General Plans

©O. Capatina, 9th HL-LHC Collaboration Meeting, Fermilab, Oct 14-16, 2019

- 2 cryomodules for SPS tests
  - 1 cryomodule with 2 identical cavities (type «vertical» - DQW)
    - Tests in SPS in 2018 and 2021
  - 1 cryomodule with 2 identical cavities (type «horizontal» - RFD)
    - Tests in SPS in 2022

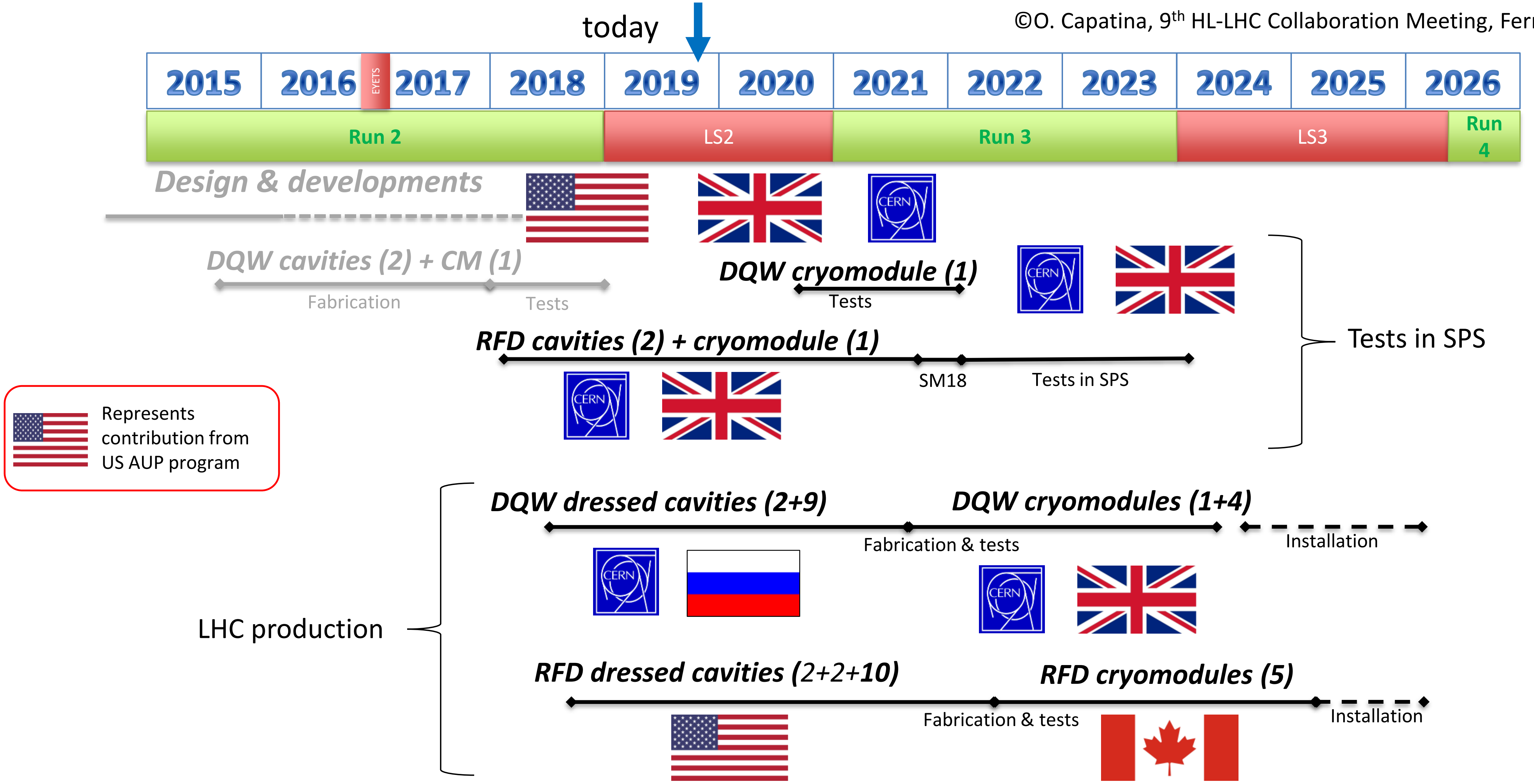
CERN is willing to cooperate in the schedule for future SPS tests with us

- 8 cryomodules (4 of each type) for installation in LHC during LS3 + 2 spares (1 of each type)



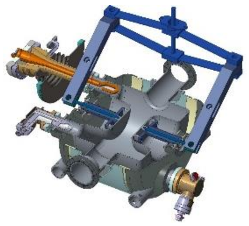
Crab Cavities & Cryomodules

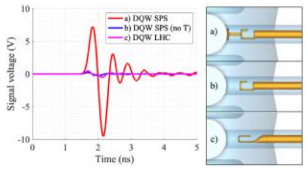
©O. Capatina, 9th HL-LHC Collaboration Meeting, Fermilab, Oct 14-16, 2019

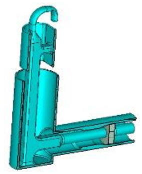


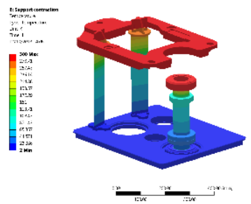
DQW Type Cavity Tasks Covered by this Proposal, Other than MD Participation:

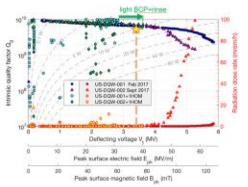
- EIC crab cavity study based on HL-LHC experience
- LHC crab cavity optimization based on SPS findings, including the pick-up coupler and beam pipe port length
- Discussion of cavity cold test at JLAB with HOM coupler installed
- Discussion of HOM coupler optimization with CERN based on prototype coupler fabrication and testings
- Discussion of thermal and mechanical numerical evaluations with CERN towards Hi-Lumi LHC
- Discussion of LHC crab cavity tuner design with CERN
- Summary of the DQW type crab cavity vertical tests
    - 5 superconducting cavities manufactured, and 17 vertical tests completed over 9 years
    - Fabrication, quality control, surface treatment, and testing sites included US company, US national lab/facility, and CERN
    - Multiple reports, include detail and summary, for all 5 cavities







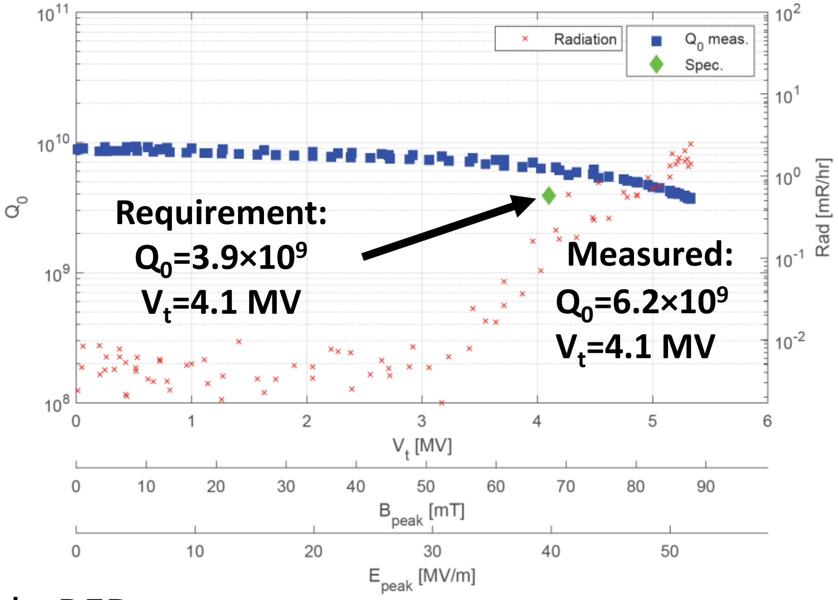




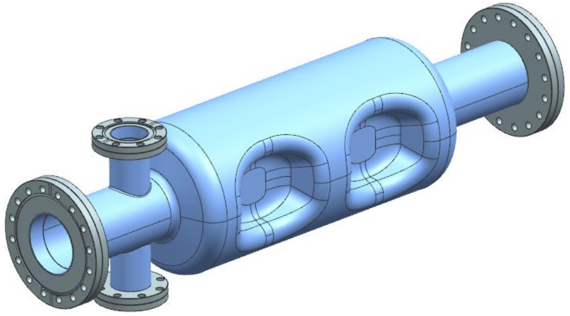
Development of RFD Cavity

©M. Garlaschè, 8th HL-LHC Collaboration Meeting, CERN, Oct 15-18, 2018

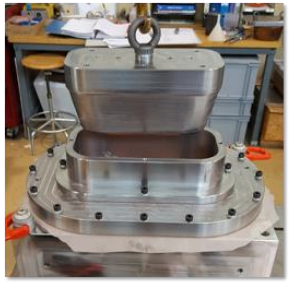
400 MHz prototype cavity for LHC with HOM couplers



952 MHz proof-of-principle RFD cavity for JLEIC



400 MHz prototype for SPS (CERN)



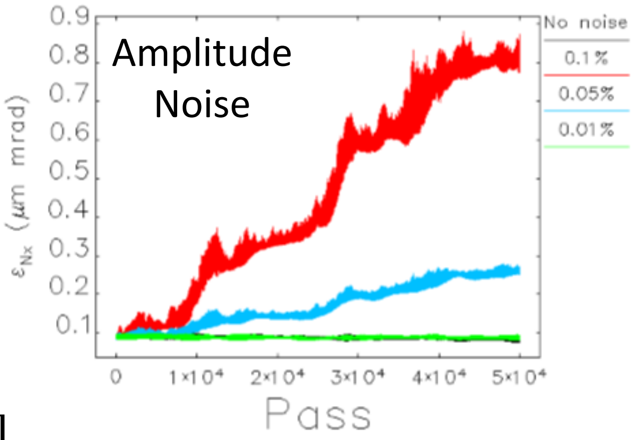
Beam Dynamics

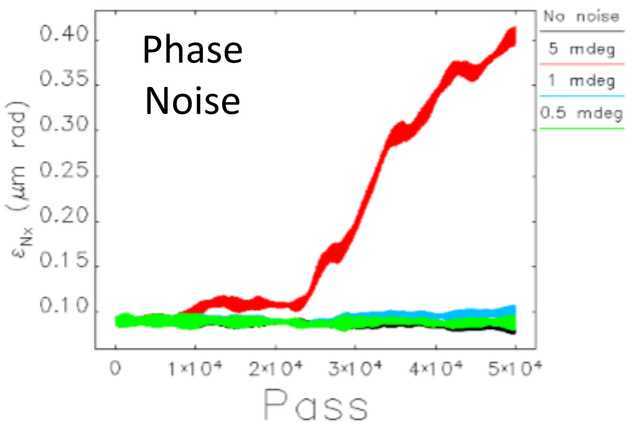
- Emittance scaling verification for JLEIC parameters

- Phase noise power needs to be many orders of magnitude lower at EIC than LHC

$$\frac{d\varepsilon_x}{dt} = \beta_{cc}\left(\frac{eV_0 f_c}{2E_b}\right)^2 C_{\Delta\phi}(\sigma_\phi)\sum_{k=-\infty}^{\infty} S_{\Delta\phi}[(k \pm \nu_b)f_c]$$

PhD Thesis – “Crab Cavity Requirements for the Jefferson Lab Electron-Ion Collider”, S. Sosa (ODU)





P. Baudrenghien and T. Mastoridis, “Transverse emittance growth due to rf noise in the high-luminosity LHC crab cavities”, PRAB **18**, 101001 (2015)

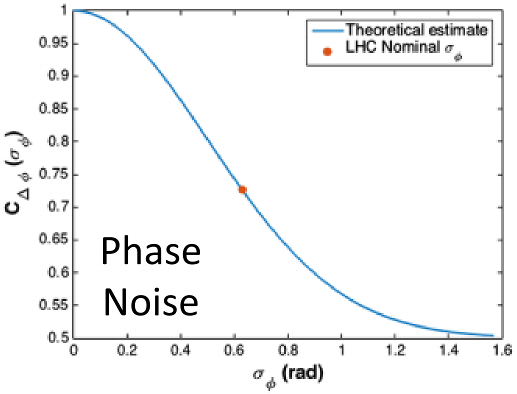


FIG. 3. Growth rate dependence on bunch length $C_{\Delta\phi}(\sigma_\phi)$, phase noise. The LHC nominal bunch length is shown for reference.

Comparison of some of the LHC and JLEIC crabbing parameters

	φ_{cr} (mrad)	β_{cc} (m)	V_0 (MV)	f_c (kHz)	E_b (GeV)
LHC	0.3	4,000	3	11.25	7,000
JLEIC	50	700	20.6	128.4	200

Documentation

- Reports and Thesis
  - BNL INTERNAL REPORT on Lessons from SPS beam test of a DQW cryomodule and implications for the EIC crab cavity system
  - Proof of Principle and Prototype Double Quarter Wave Crab Cavities Vertical Test Summary
  - Cryogenic RF Tests of US LARP DQW SPS-series Cavities
  - RFD LARP Crab Cavity VTS Summary
  - PhD Thesis – "Crab Cavity Requirements for the Jefferson Lab Electron-Ion Collider", S. Sosa (ODU)
- Workshops and Conference Proceedings
  - IPAC 2019
    - Cavity Design for the Updated eRHIC Crabbing System
    - Cryogenic RF Performance of Double Quarter Wave Cavities Equipped With HOM Filters
    - Design of a Proof-of-Principle Crabbing Cavity for the Jefferson Lab Electron-ion Collider
    - Analysis of Higher Order Multipoles of the 952.6 MHz Rf-Dipole Crabbing Cavity for the Jefferson Lab Electron-Ion Collider
  - SRF 2019
    - Design of LHC Crab Cavities Based on DQW Cryomodule Test Experience
    - An insight on the thermal and mechanical numerical evaluations for the high-luminosity LHC crab cavities
    - Status of the HL-LHC crab cavity tuner
    - Design of LHC crab cavities based on DQW cryomodule test experience
    - Overview of SRF Deflecting and Crabbing Cavities (Invited talk)
  - EIC Accelerator Collaborator Meeting 2019
    - Crab Cavity Developments for JLEIC

Plans for Next Year

- Crab cavity SPS & LHC series
  - Trim tuning strategy in production
  - HOM coupler surface treatment procedures

- Analysis of crabbing for EIC
  - Transient beam effects
  - Instabilities and collective effects
  - Impedance Workshop

- Beam loading calculation based on SPS experience
  - Analysis of HOM spectrum in crabbing cavities with lesson learned from SPS measurements
  - Machine protection analysis with crab cavity based on current EIC setups

- Prepare for next series of tests of the DQW and RFD cryomodules

Summary

- Scientists in our collaboration have been and remain major contributors to the development of crabbing systems in the preceding LARP and on-going LHC HiLumi programs
- Using cavities and cryomodules developed during those programs, these scientists participated in recent beams tests in the SPS at CERN
- These tests significantly advanced the LHC HiLumi upgrade program and have provided valuable hardware and experimental benchmarking results directly relevant to beam crabbing systems for EIC
- We are well integrated into the planning of future tests of SRF deflectors at CERN and are looking forward to the on-coming set of experiments