Overview of SRF Deflecting and Crabbing Cavities

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- ODU – J. Delayen, S. De Silva, …..
- JLAB – H.Park, N. Huque, E. Daly, T. Powers, …..
- SLAC – A. Ratti, Z. Li
- ANL – M. Kelly, …..
- TRIUMF – B. Laxdal, D. Storey, …..
- Niowave Inc. – T. Grimm, C. Boulware, J. Yancey

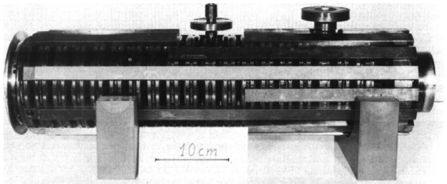
Outline

- Types of superconducting deflecting and crabbing cavities
- TM_{110} type cavities
- TEM-type and TE_{11}-like cavities
- Crabbing cavities for LHC high luminosity (HL-LHC) upgrade
- 1^{st} crabbing of proton beam at SPS
- Superconducting crabbing cavities for future electron-ion colliders
  - eRHIC
  - JLEIC

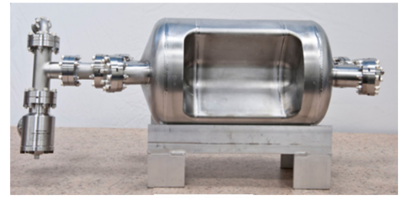
Timeline of SRF Deflecting/Crabbing Cavities

Deflecting Cavities

1970 — 2.865 GHz Karlsruhe/CERN Separator



2013 — 499 MHz JLab RF-Dipole Cavity



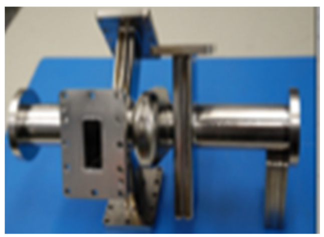
2014 — 650 MHz TRIUMF RF Separator

Crabbing Cavities

2007-2010

508.9 MHz KEK Crabbing Cavity

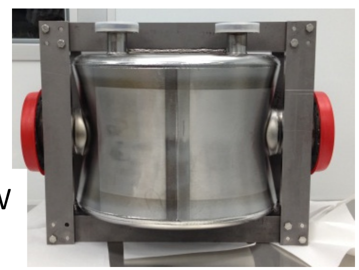
2007-2011



2.815 MHz SPX Crabbing Cavity

2010-2012

400 MHz 4-Rod Cavity



400 MHz DQW PoP Cavity

400 MHz RFD PoP Cavity

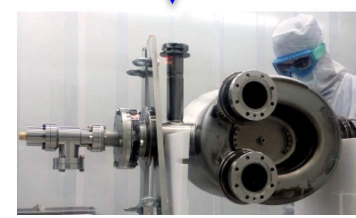
2013

750 MHz RF-Dipole Cavity

2014

2.815 MHz QMiR Crabbing Cavity

2015-2017



400 MHz DQW Prototype Cavity

400 MHz RFD Prototype Cavity

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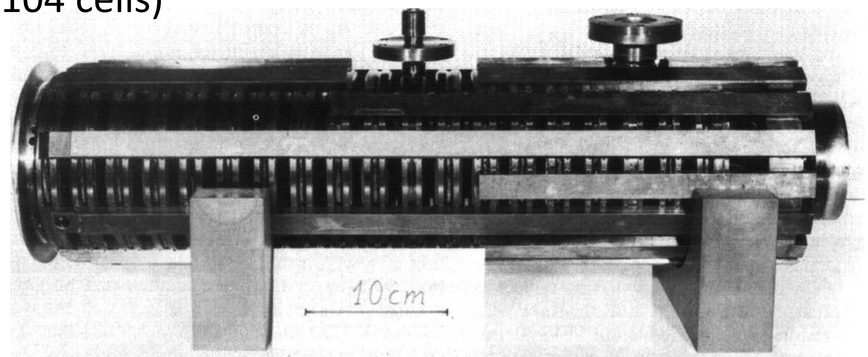
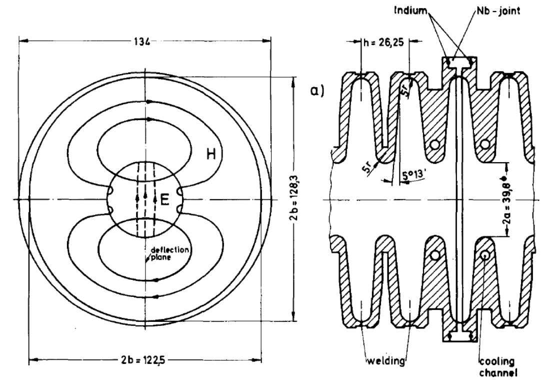
Some History

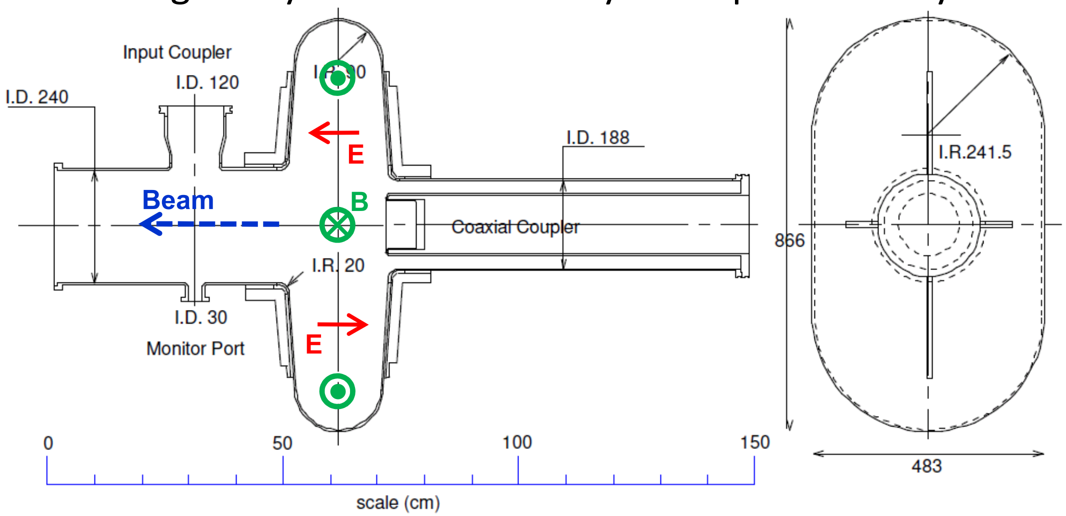
- 1st superconducting deflecting cavity
  - Deflecting cavity: 2.865 GHz Karlsruhe/CERN Separator (104 cells)





Designed 1970, operated 1977-1981
At IHEP since 1998

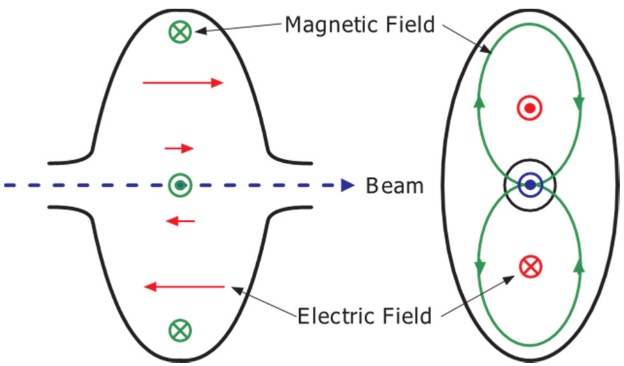
- 1st superconducting crabbing cavity
  - Crabbing cavity: 508.9 MHz cavity for SuperB Factory at KEK

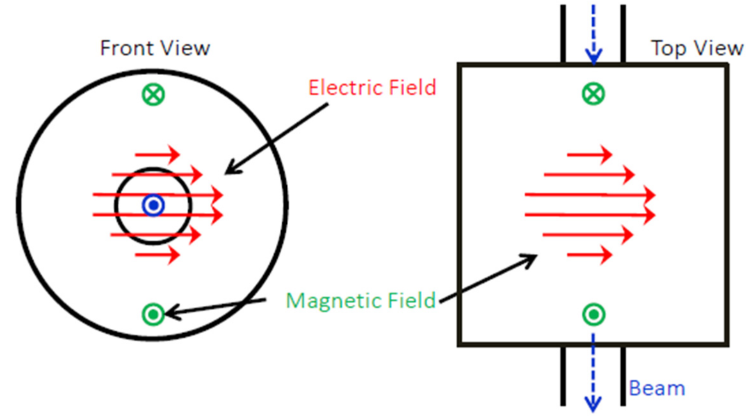


1st Crabbing of e beam –
Crab cavities operated from 2007-2010

- Lengler, *et. al.*, NIM 164 (1979)
- K. Hosoyama, *et. al.*, Crab Cavity for KEKB, SRF 1988

TM-Type to TEM-Type/TE-Like Cavities





- TM_{110}-type cavities: Contribution to the net deflection is mainly from transverse magnetic field
- Has lower order mode (TM_{010} mode)
- Squashed elliptical geometry: To separate the two polarizations of same frequency
- Large with respect to wavelength
  - Disadvantageous for low frequency
  - Advantageous for high frequency
  - Able to accommodate large apertures

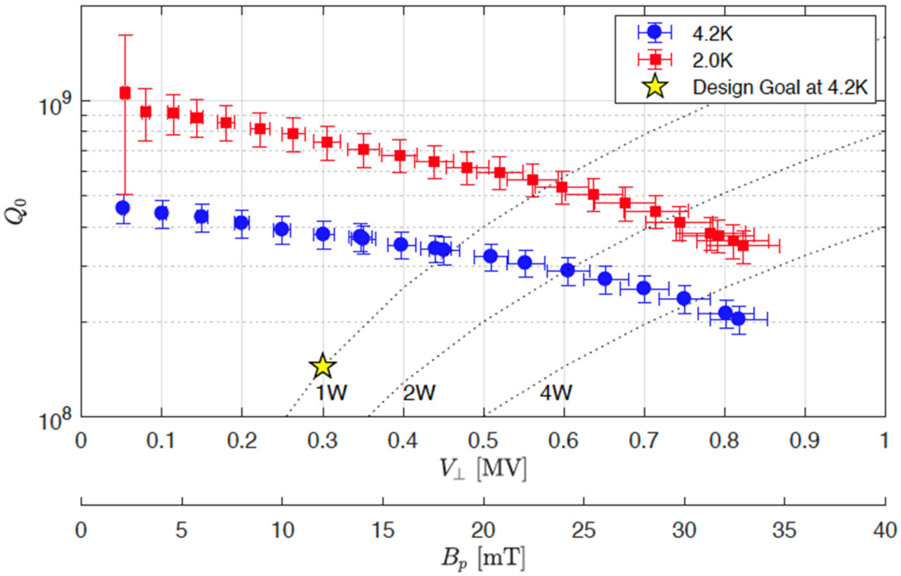
- TEM-type/ TE-like cavities: Contribution to the net deflection mostly by transverse electric field
- Cannot be a pure TE_{111} mode where the contribution from electric and magnetic fields cancel each other → Deformed shapes
- Compact designs
  - Favorable for low frequencies

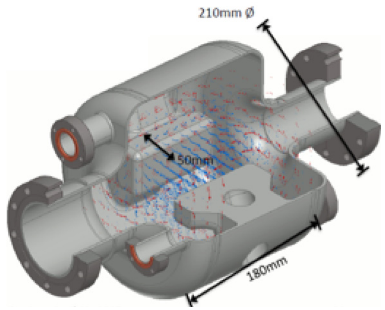
650 MHz TRIUMF RF-Separator

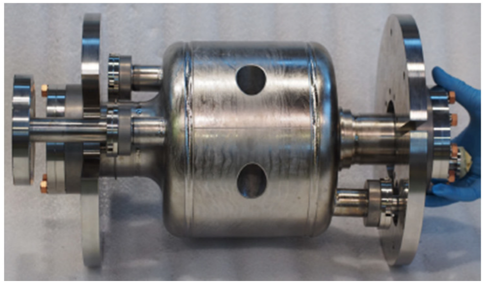
- RF separator for ARIEL e-Linac
  - To separate into two beams
- Transverse voltage specification: 0.3 MV
- Fabrication techniques followed:
  - Machined from bulk reactor grade Nb of RRR of 45 compared to usual RRR 300
  - Tungsten Inert Gas (TIG) welding (Developed as an alternative to electron beam welding)

Cavity performance parameters:

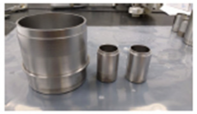
- Superconducting Niobium cavity at 4.2 K
- Resonant frequency: 650 MHz
- Deflecting voltage: 0.3 (0.6) MV
- Shunt impedance: 625 Ω
- Geometry factor: 99 Ω
- Peak electric field: 9.5 (19) MV/m
- Peak magnetic field: 12 (24) mT
- RF power dissipation: 0.35 (1.4) W







(b)



D. W. Storey, A Superconducting RF Deflecting Cavity for the ARIEL e-Linac Separator, PhD Dissertation, 2018

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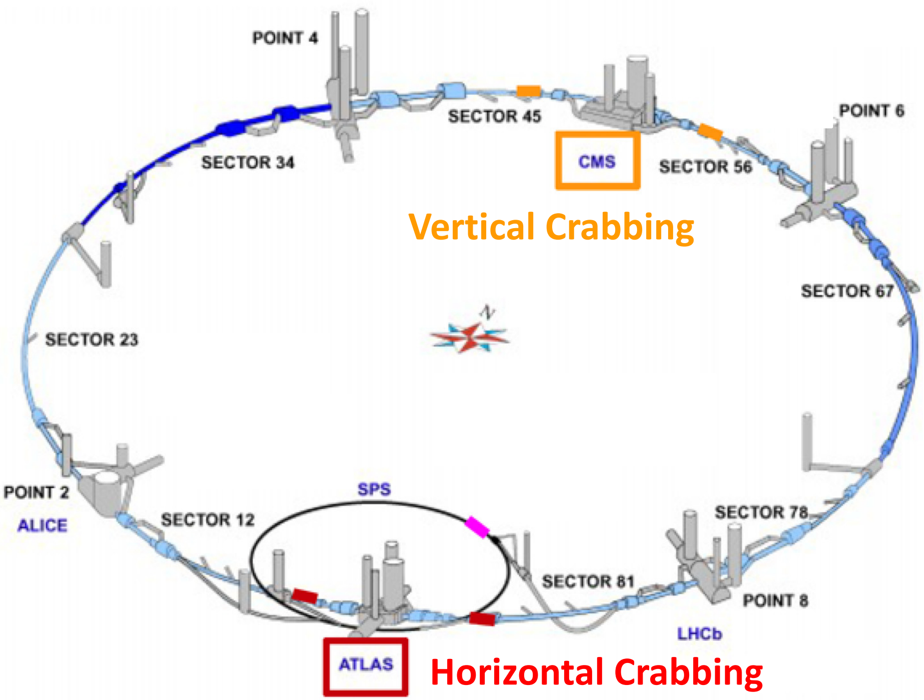
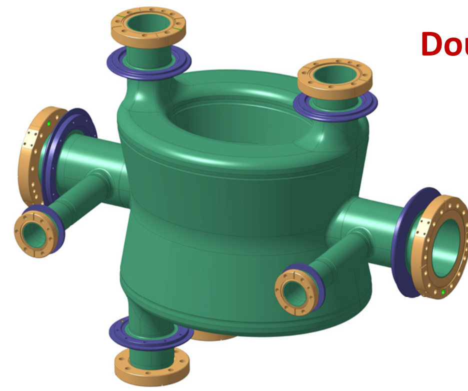
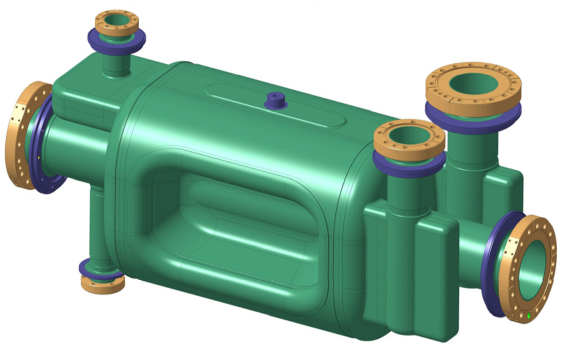
LHC High Luminosity Upgrade





Double Quarter Wave Crabbing Cavity



RF-Dipole Crabbing Cavity

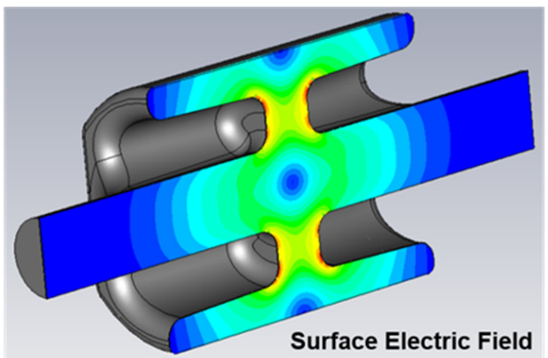
- Frequency $= 400.79$ MHz
- Aperture $=$ 84 mm
- Voltage $= 3.4$ MV /cavity (2 cavities /beam /IP side – 16 total)
- Operating temperature $=$ 2.0 K
- $Q_{ext} = 5 \times 10^5$, RF power to cavity $= 40$ kW (80 kW peak)
- Frequency tuning $= \pm 150$ kHz
- $P_{\text{static}} = 18$ W, $P_{\text{dyn}} \leq 30$ W (per module)

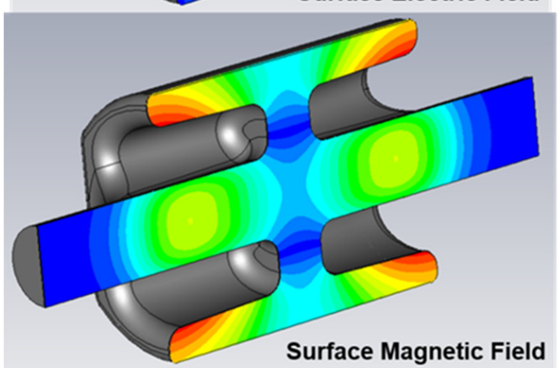
Proof-of-Principle Cavities for LHC HiLumi Upgrade

- Requires compact designs due to low operating frequency of 400 MHz
- TM_{110} squashed elliptical geometries are not applicable
- Solution: Designs operating in TEM or TE-like modes

4-Rod Cavity

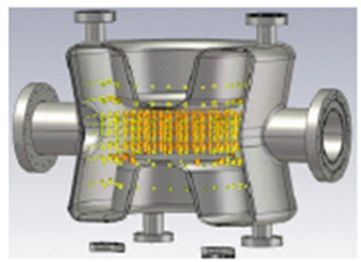
Operating in TEM mode



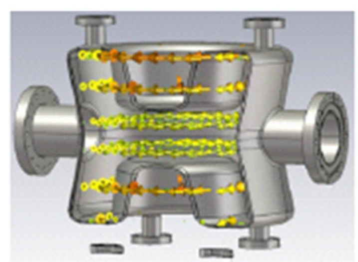


Double Quarter Wave Cavity

Operating in TE-like mode



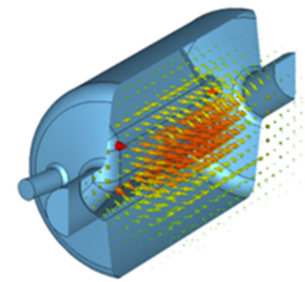
E Field



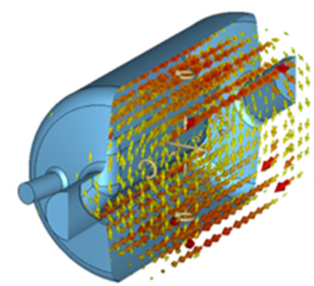
B Field

RF-Dipole Cavity

Operating in TE-like mode



E Field

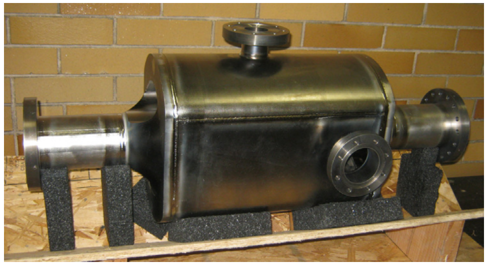


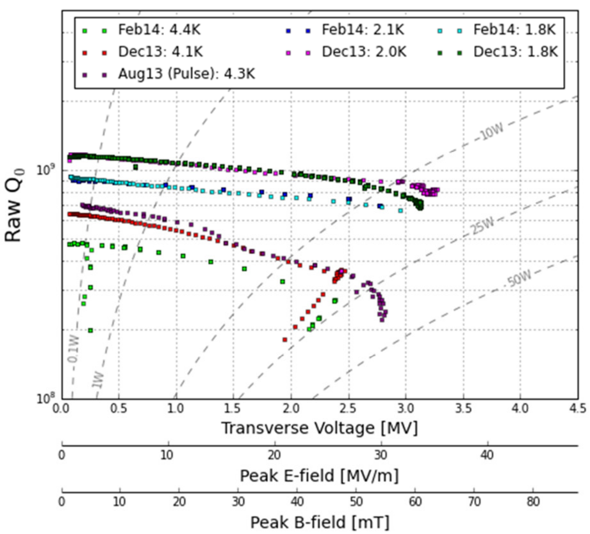
B Field

- B. Hall, *et*. al., Phys. Rev. Accel. Beams 20, 012001 (2017)
- B. Xiao, *et*. al., Phys. Rev. Accel. Beams 18, 041004 (2015)
- S.U. De Silva and J.R. Delayen, Phys. Rev. Accel. Beams 16, 082001 (2013)

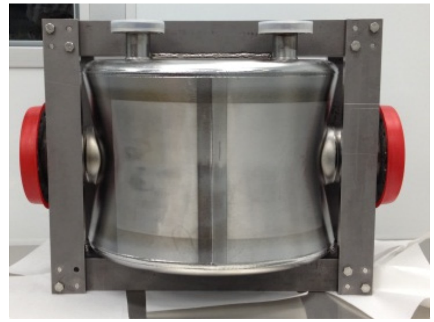
Proof-of-Principle Cavities for LHC HiLumi Upgrade

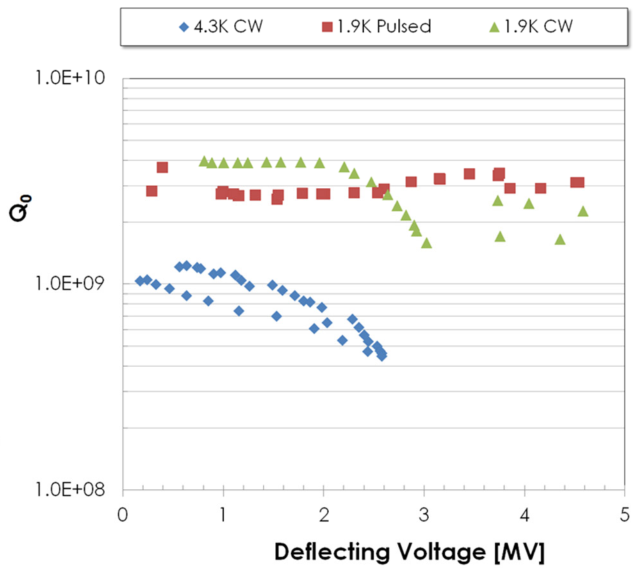
4-Rod Cavity



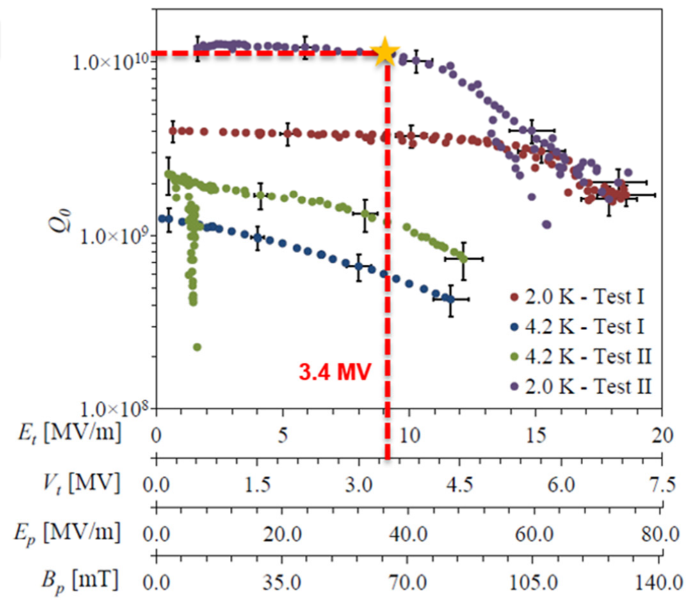


Double Quarter Wave Cavity





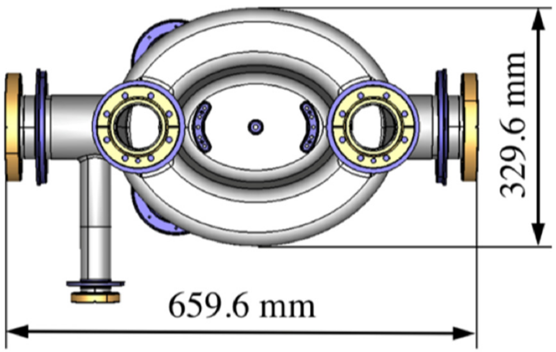
RF-Dipole Cavity

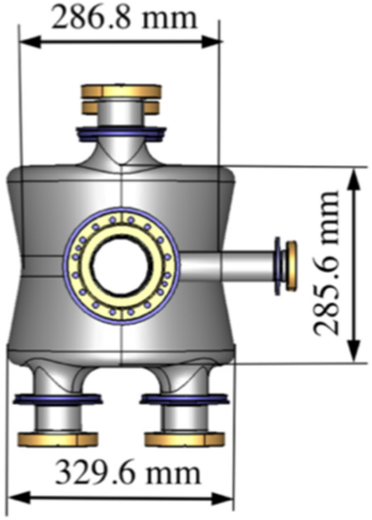


Proof-of-principle cavities successfully demonstrated the rf designs, fabrication, processing, and rf performance

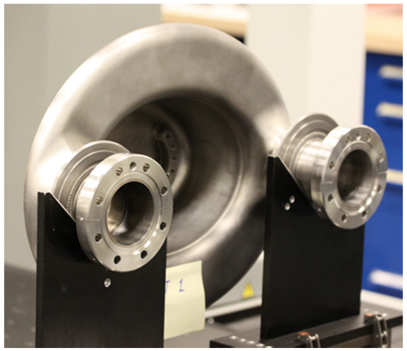
Double Quarter Wave (DQW) Crabbing Cavity

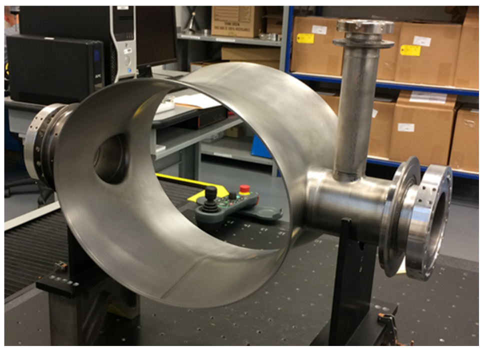
- Cavity design:
  - Operates in TE_{11}-like mode
  - No lower order modes
- DQW design for SPS

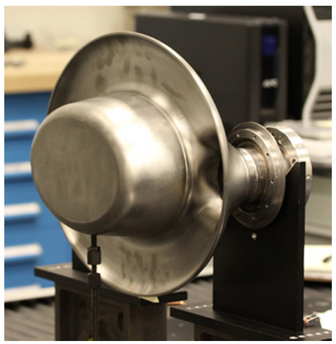




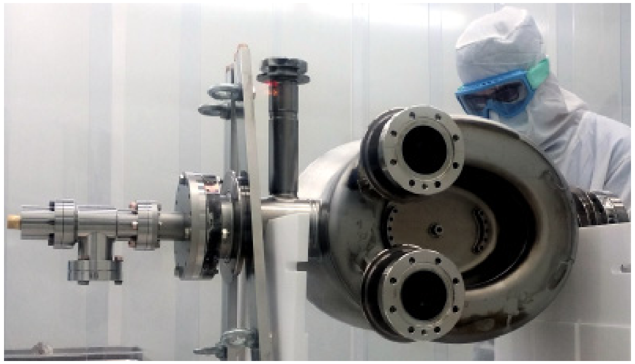
Frequency	**400.79**	**MHz**
LOM	None	MHz
Nearest HOM	567	MHz
V_T	3.4	MV
E_p	37.6	MV/m
B_p	72.8	mT
$[R/Q]_T$	429.3	Ω
G	87	Ω
$R_T R_S$	3.7×10^4	Ω^2







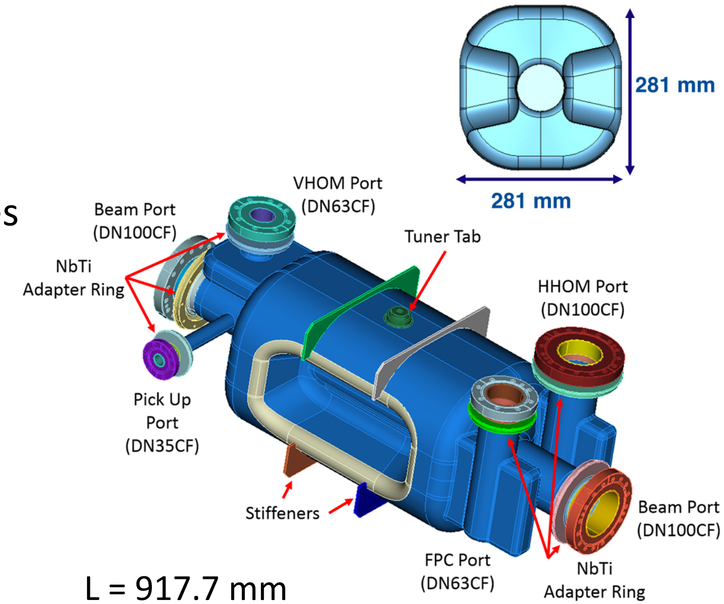
LARP Prototype DQW Cavity



CERN SPS DQW Cavity

RF-Dipole (RFD) Crabbing Cavity

- Cavity design:
  - Operates in TE_{11}-like mode
  - No lower order modes
- RFD prototype designed and fabricated under US-LHC Accelerator Research Program (LARP)

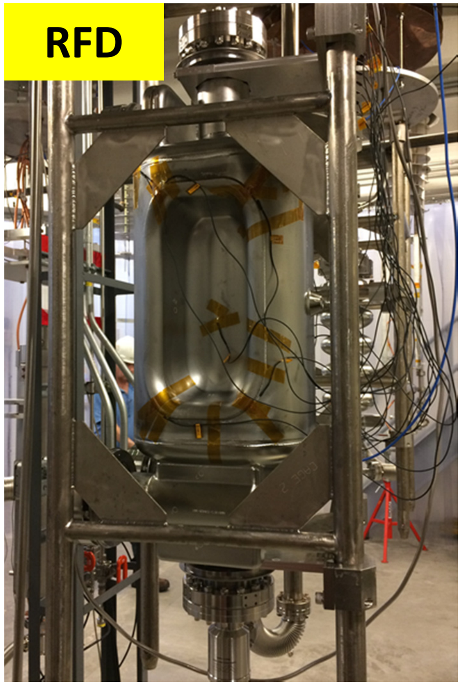


Frequency	**400.79**	**MHz**
LOM	None	MHz
Nearest HOM	633.5	MHz
V_T	3.4	MV
E_p	33	MV/m
B_p	56	mT
$[R/Q]_T$	429.7	Ω
G	106.7	Ω
$R_T R_S$	4.6×10^4	Ω^2

S.U. De Silva, *et. al.*, Fabrication, Processing and RF Test of RF-Dipole Prototype Crabbing Cavity for LHC High Luminosity Upgrade, IPAC 2017

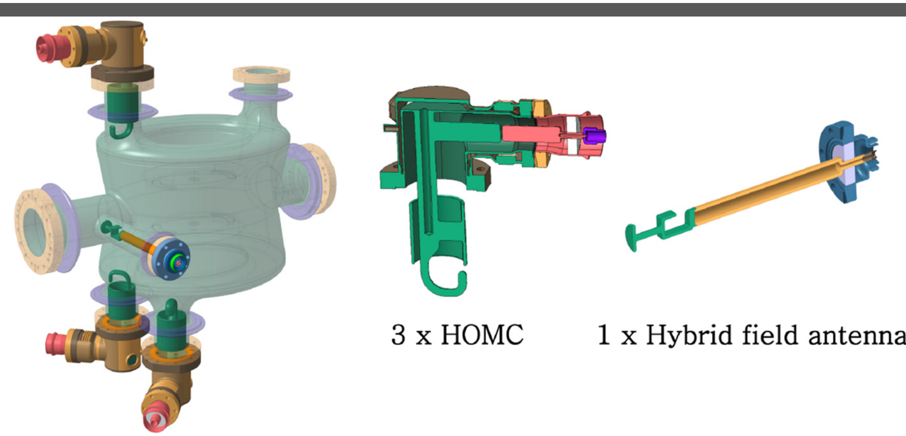
LARP Prototype Cavity Processing and Testing

- LARP prototype cavities: 2 each for both DQW and RFD
- Incoming inspection of sub-assemblies from Niowave Inc. (frequency measurement, dimensional measurement, weld inspection and etc.)
- Frequency trimming (RFDs only, DQWs were delivered after trimming)
- Final welding (3 subassemblies for each design)
- Bulk BCP
- Heat treatment → 600 C 10 hours
- Light BCP
- HPR
- Cleanroom assembly and leak check
- 120 C bake
- Test at 4K and 2K
- RF measurements of bare cavity and cavity with HOMs

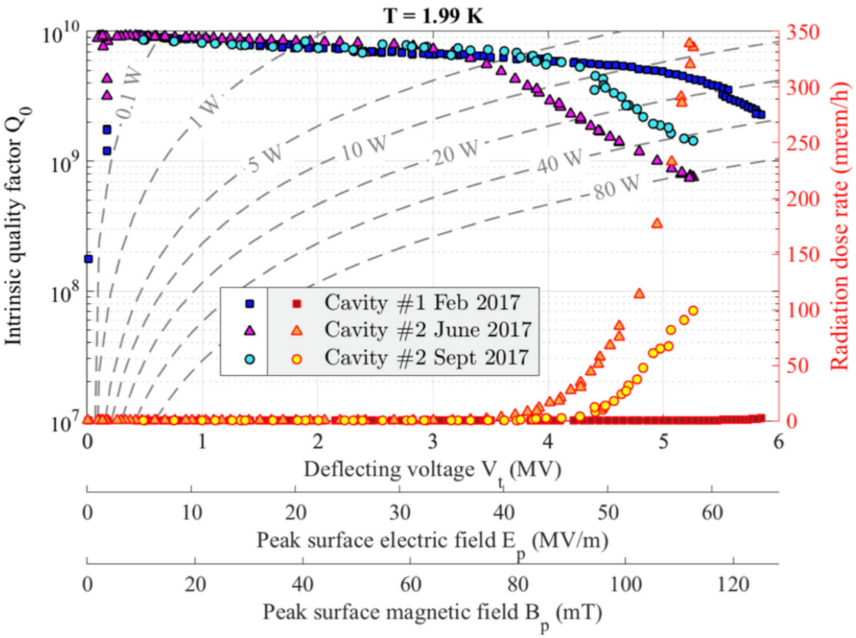


Cavity Performance of LARP DQW Cavity

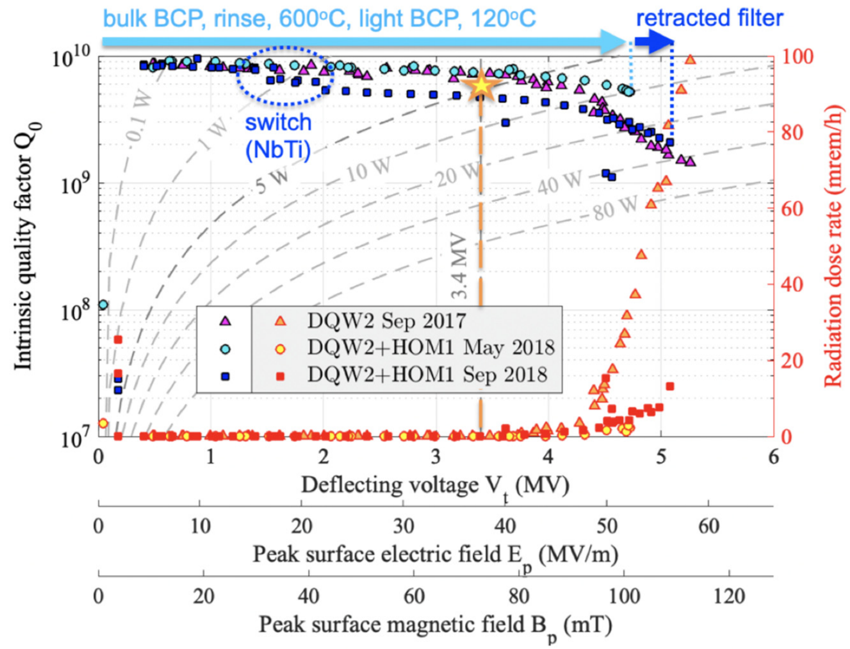
- Two cavities fabricated under US-LARP
- RF tests performed at JLab
- Bare cavity test of both cavities
  - Max V_t – 5.9 MV
- One of the cavities (DQW2) was tested with a single HOM coupler
  - Max V_t – 5.3 MV



Bare Cavity Test



Cavity Test with HOM Coupler

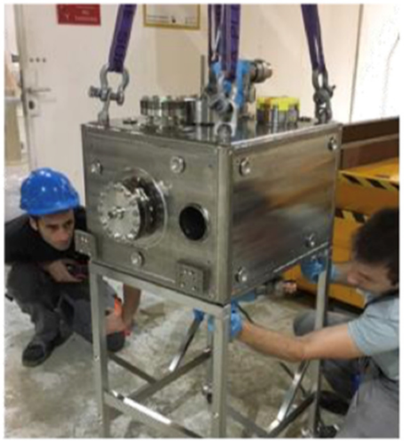


- S. Verdu-Andres, *et*. al., Phys. Rev. Accel. Beams 21, 082002 (2018)
- S. Verdu-Andres, *et. al*., Cryogenic RF Performance of Double-Quarter Wave Cavities Equipped with HOM Filters, IPAC 2019

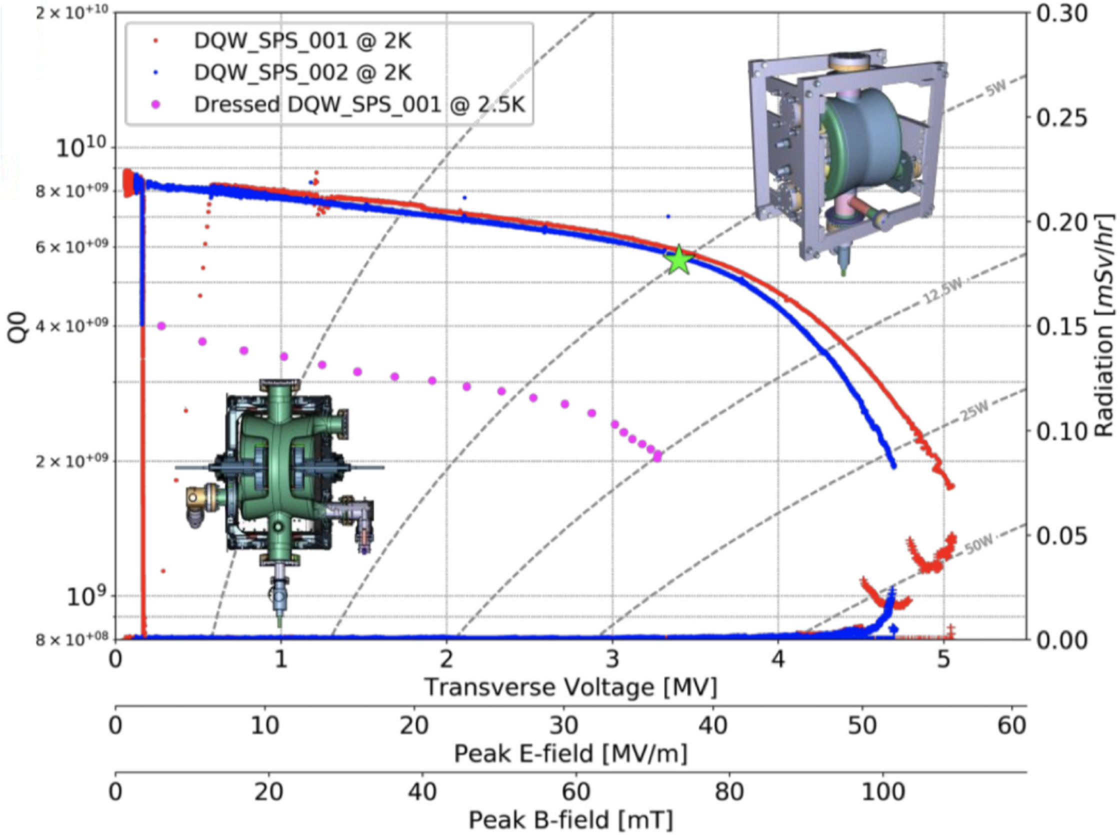
Cavity Performance of SPS Cavity

- RF Tests performed at CERN
- Multipacting barriers at low gradients observed and processed in both cavities
- Bare cavity test:
  - Dynamic load at nominal transverse voltage ≤ 5W
  - Minimum field emission onset > 3.6MV
  - Quench limit ≤ 4.8 MV
- Cavity test with He jacket: Test performed at 2.5 K

Bare Cavity



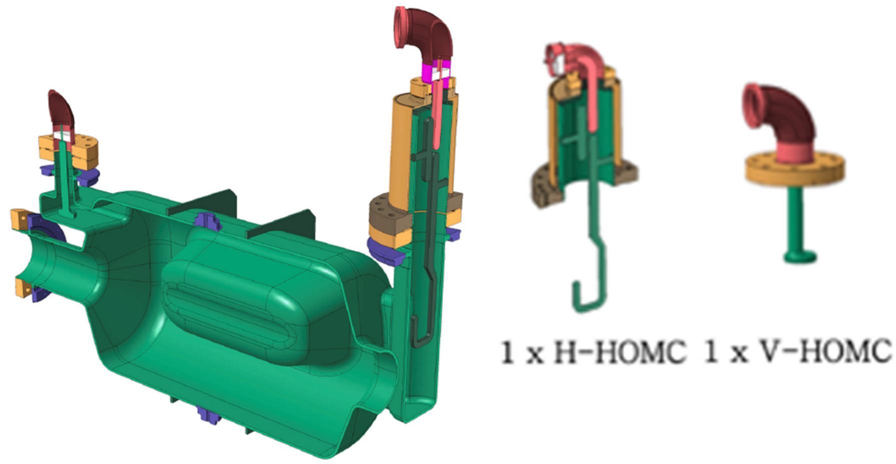
Cavity with He Jacket



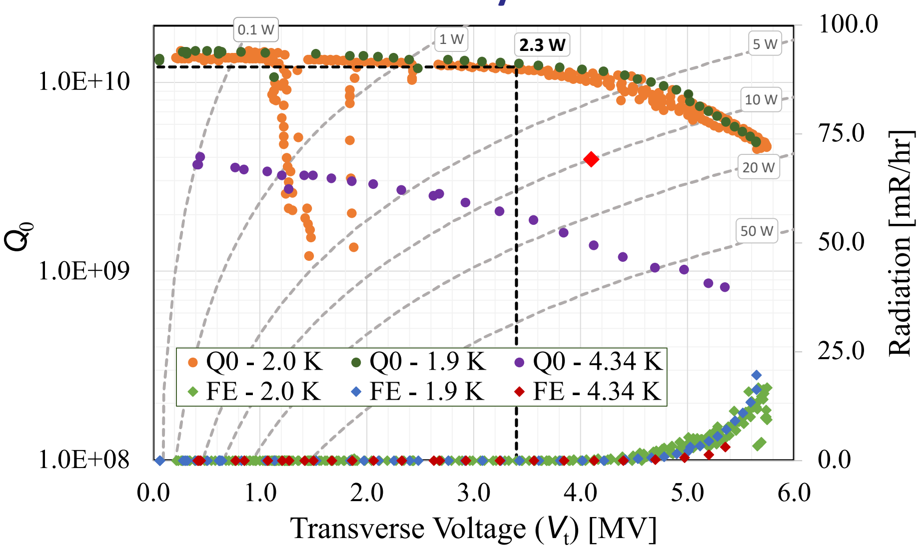
Cavity Performance of LARP RFD Cavity

- RF tests of bare cavity and cavity with both HHOM and VHOM couplers
- RF tests performed at JLab

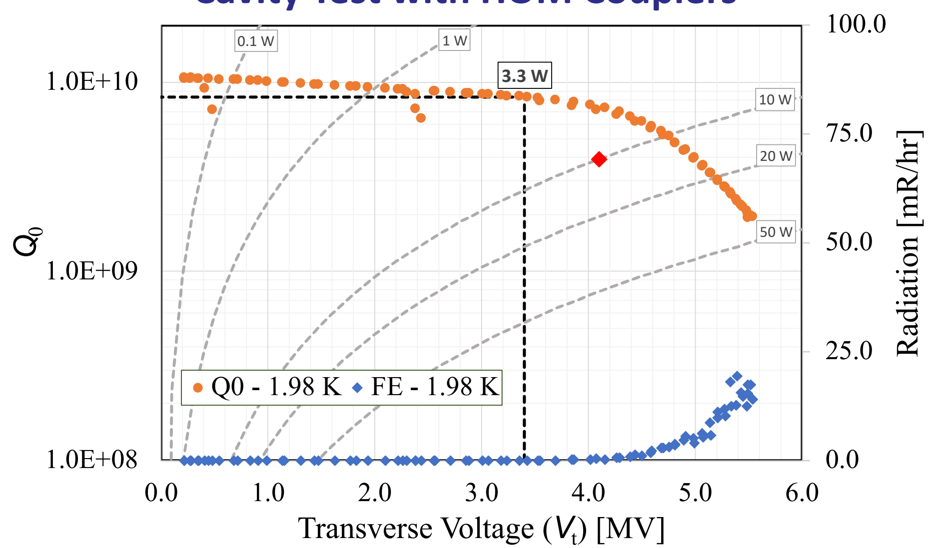
	Bare Cavity	Cavity with HOMs
Max V_T [MV]	5.75	5.54
Max E_P [MV/m]	56	54
Max B_P [mT]	95	91
P_{diss} [W] @ 3.4 MV	2.3	3.3



Bare Cavity Test



Cavity Test with HOM Couplers



S.U. De Silva, *et. al.*, Validation of LARP Prototype RF-Dipole Cavity Performance With Higher Order Mode Couplers, SRF 2019

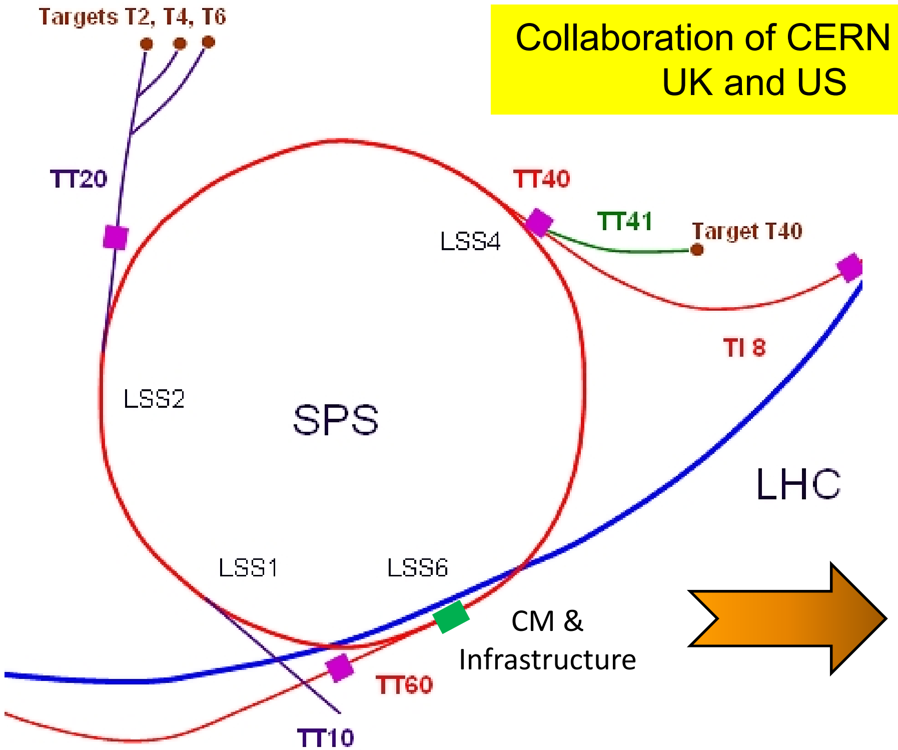
SPS Cryomodule Test

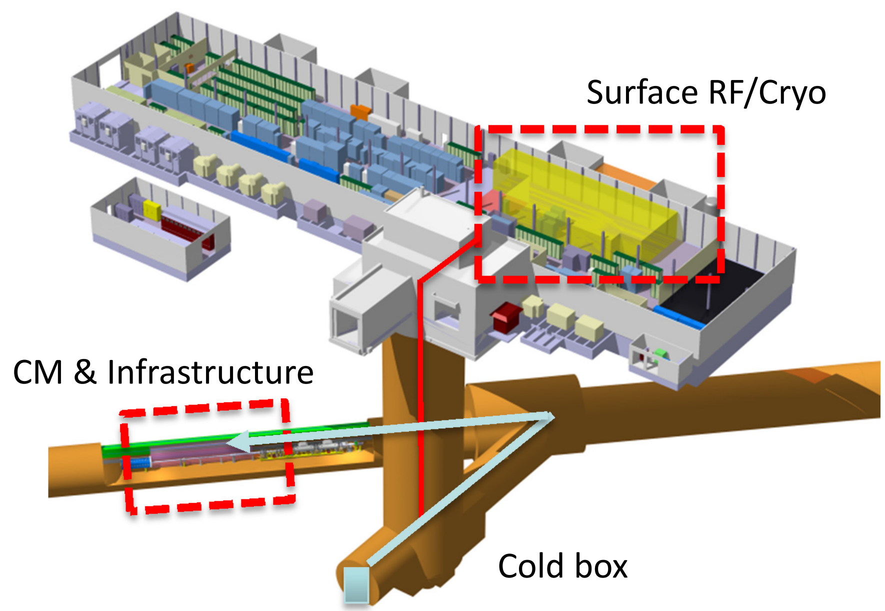
- Achieved 1st crabbing of a proton beam
- SPS cryomodule preparation and installation – 2016-2018
- Cryomodule installed at Long Straight Section (LSS) 6 at SPS with rf and cryogenic controls on the surface
- A dedicated liquid He line and refrigerator installed

SPS Machine Parameters

Circumference	**7 km**
Injection-Extraction energy	26-450 GeV
Main RF Frequency	200 MHz, TW
CC Frequency swing	400.528 – 400.788 MHz
CC bandwidth	800 Hz

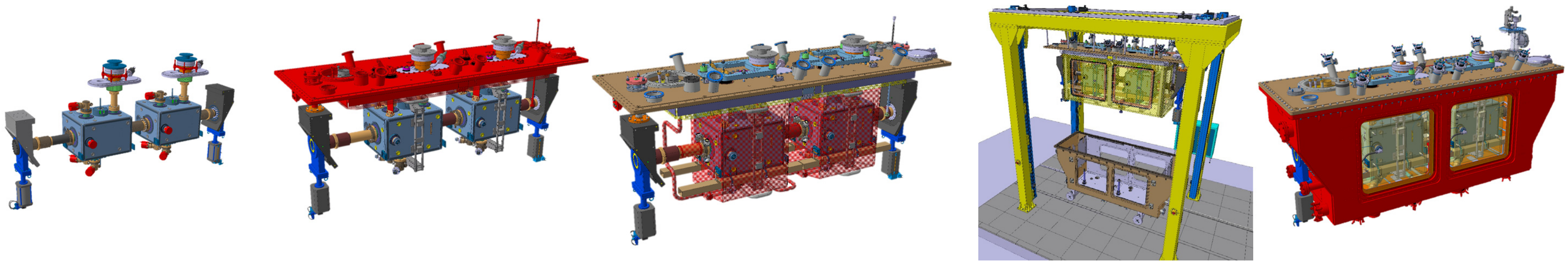
Collaboration of CERN WP4, UK and US

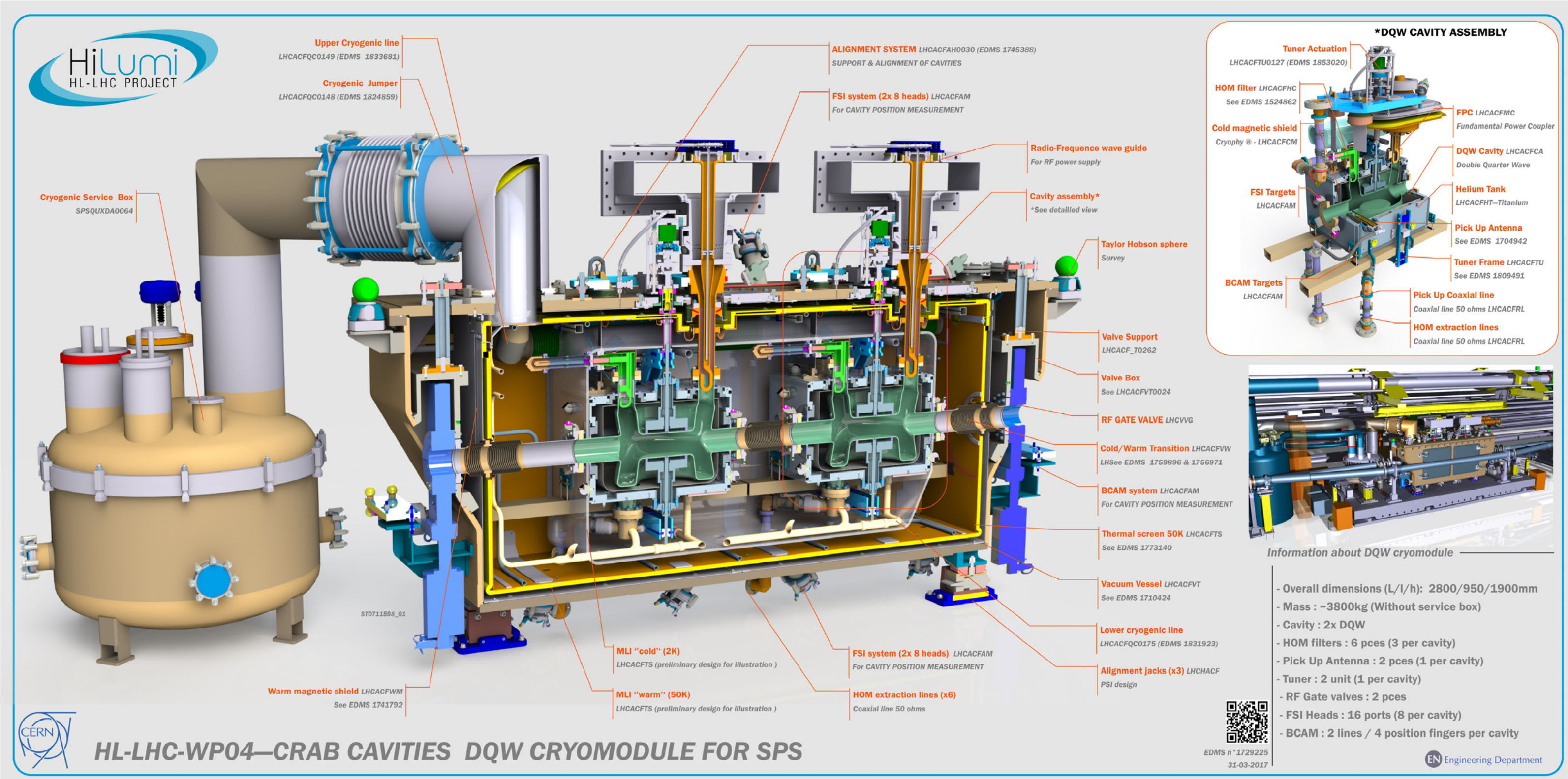




R. Calaga, SPS beam measurements & Operational Challenges, International Review of the Crab Cavity System Design and Production Plan for the HL-LHC, CERN, June 2019

DQW Cryomodule for SPS

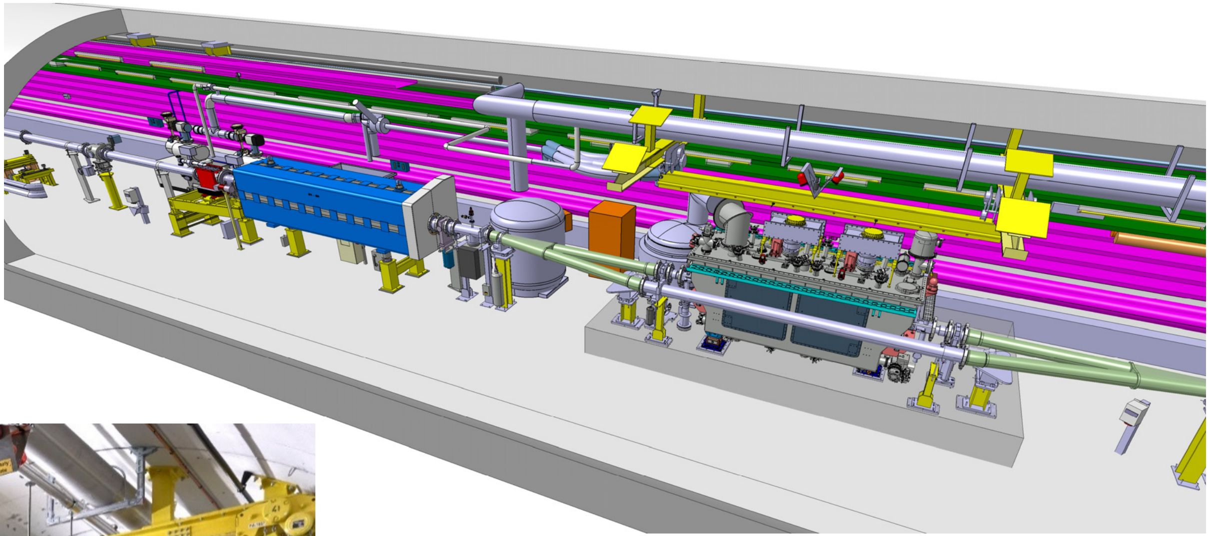


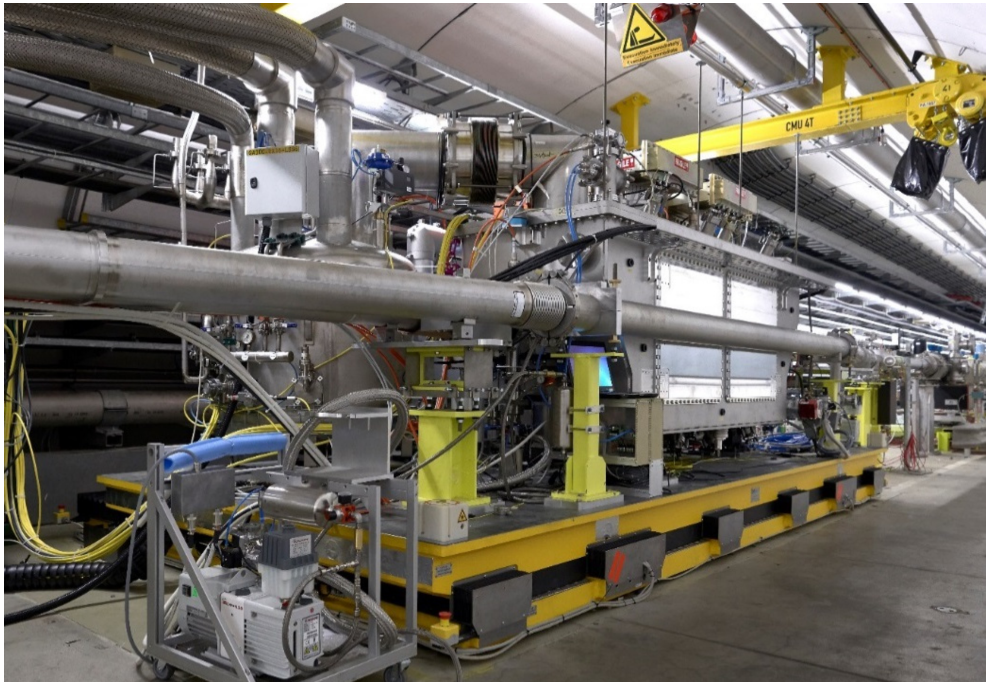


T. Capelli, RFD Cryomodule Design for SPS Tests, International Review of the Crab Cavity System Design and Production Plan for the HL-LHC, CERN, June 2019

SPS Cryomodule Installation

DQW Cryomodule on SPS





- DQW cryomodule was used only for test purposes
- Cryomodule set up in a moving table with mechanical bypass
  - To avoid issues with regular operation of SPS

SPS Test Sequence

- Planned for 10 machine development (MD) sessions to study 4 main phases of operation
  - RF-beam synchronization → Re-phasing of SPS RF to become synchronous with CC RF
  - Transparency to the beam
  - Performance and stability
  - High intensity rf operation
- First two slots were carried out for moving table and RF setup in-beam

MD#		Cav1 [MV]	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	-	1.0	2.0	26, 270, 400

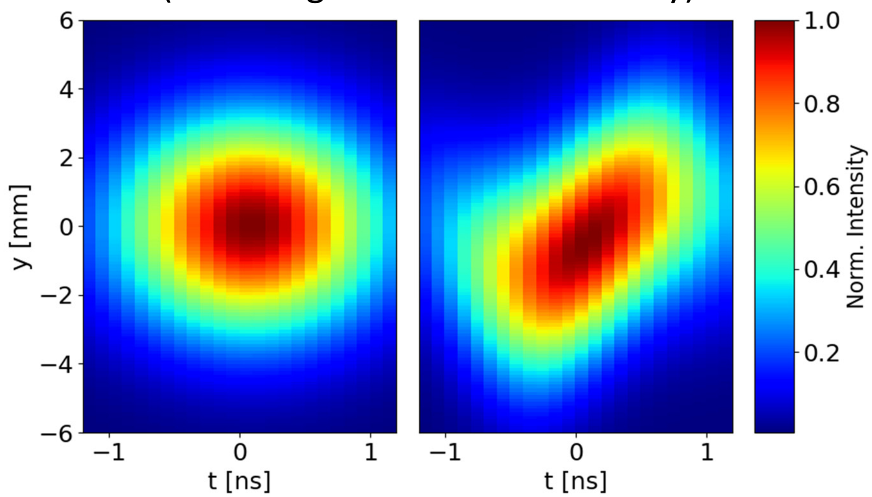
Crabbing of Proton Beams

1st successful demonstration of crabbing of proton beams at SPS

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)



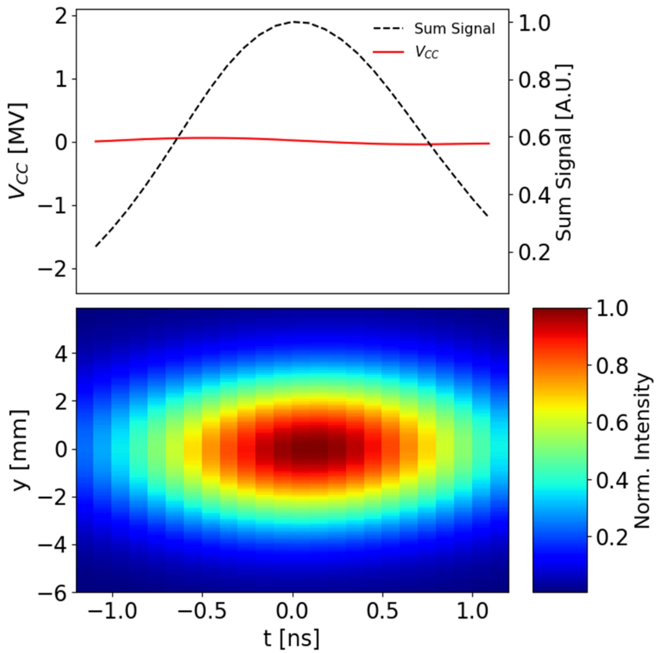
Head-tail monitor as main beam diagnostic

In general, beam measurements showed 10-20% larger voltage than RF signals

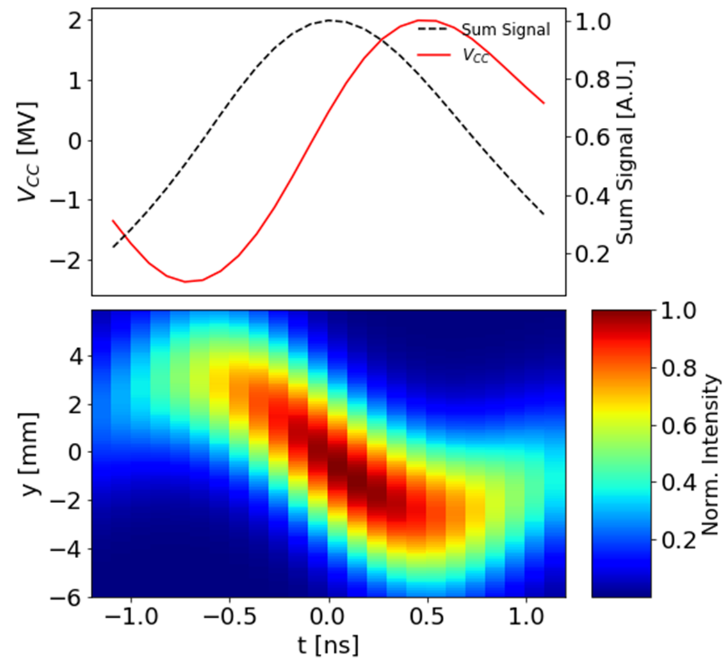
Transparency of Crabbing Cavities

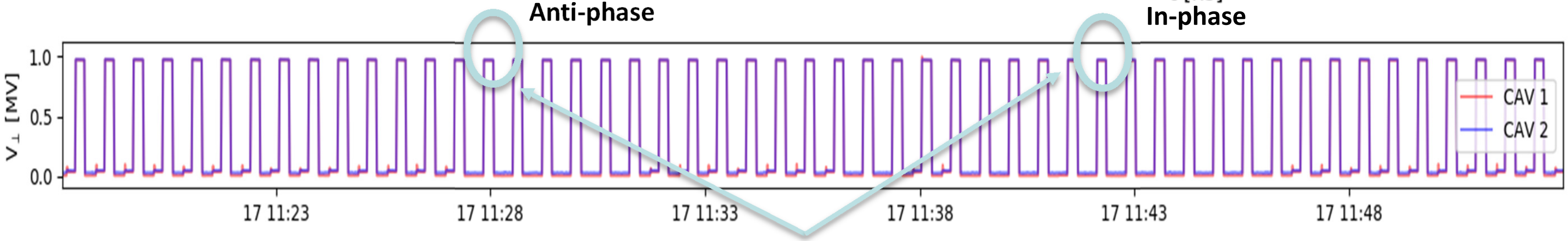
- Transparency of the cavities demonstrated at V_t = 1 MV

Cavity 1 - Cavity 2



Cavity 1 + Cavity 2

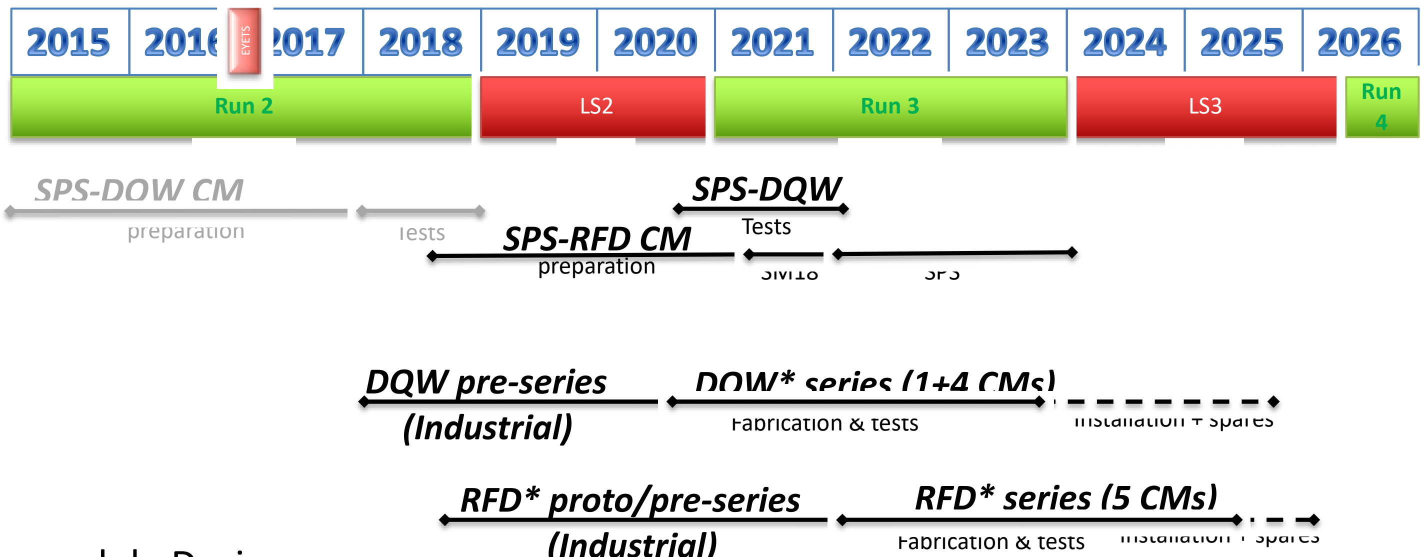




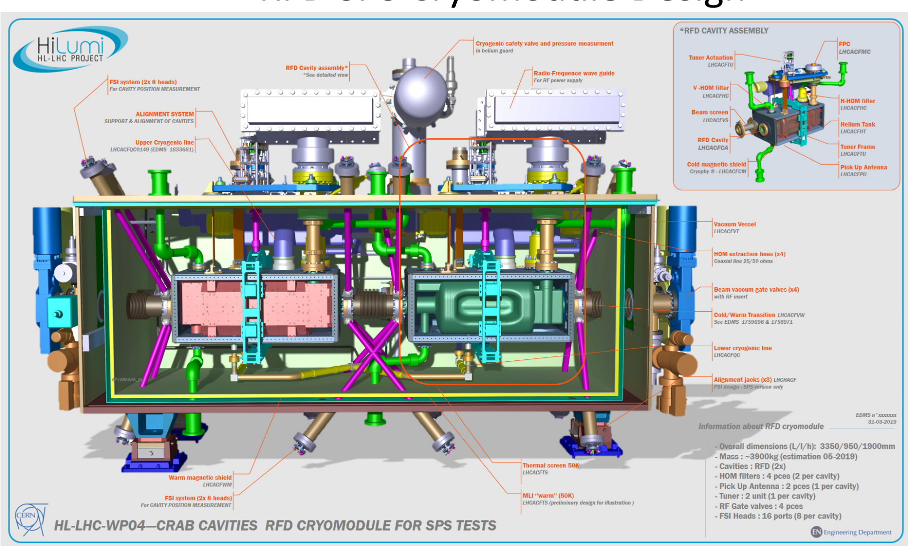
SPS MD cycle (~20 sec flattop)

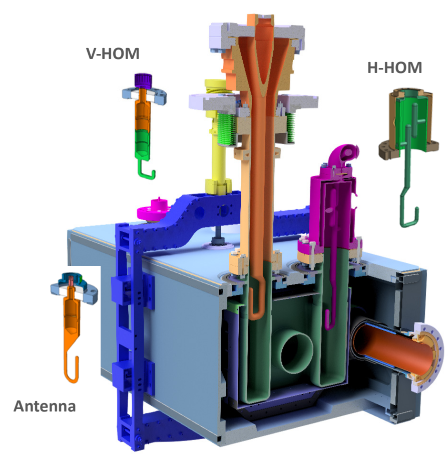
LHC Timeline

- Lessons learned implemented in SPS-RFD and in both DQW and RFD LHC cavities
- SPS-RFD test planned for 2022

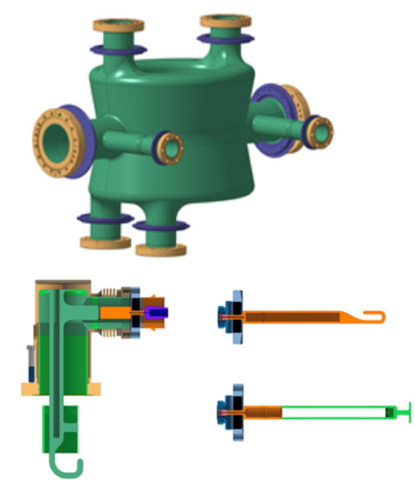


RFD SPS Cryomodule Design





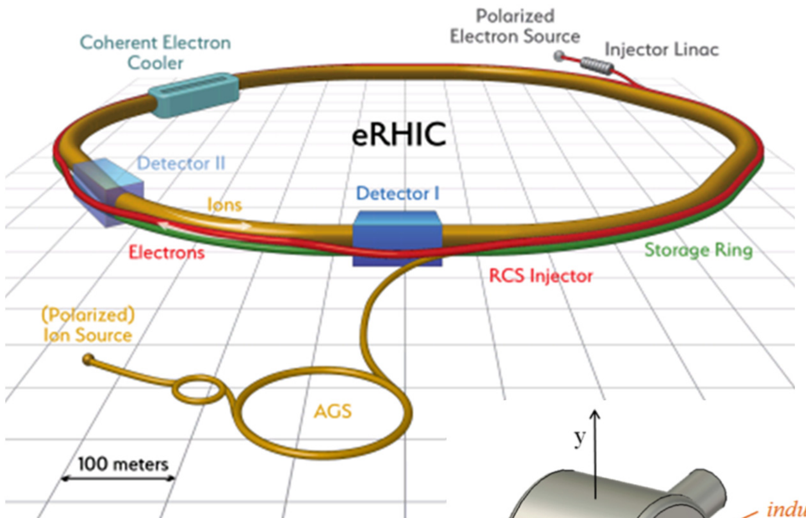
SPS RFD Cavity

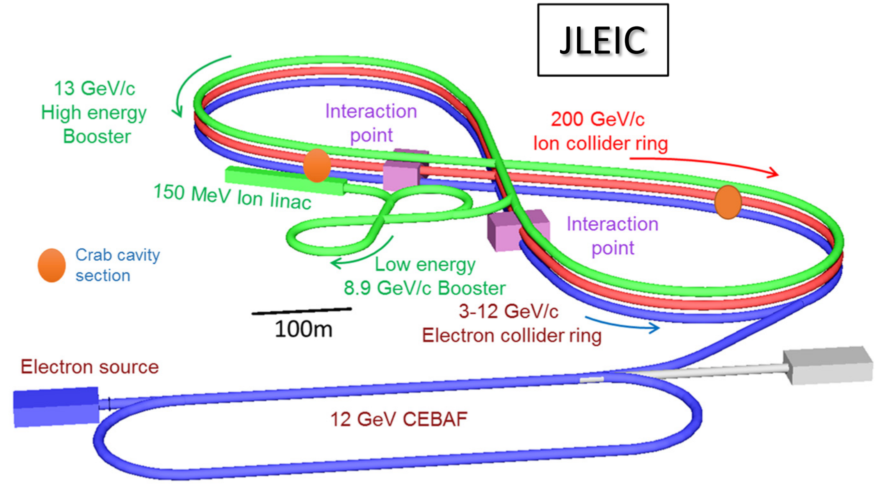


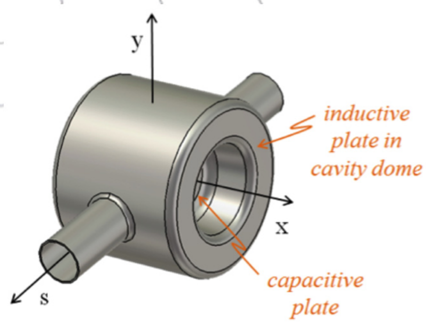
LHC DQW Cavity

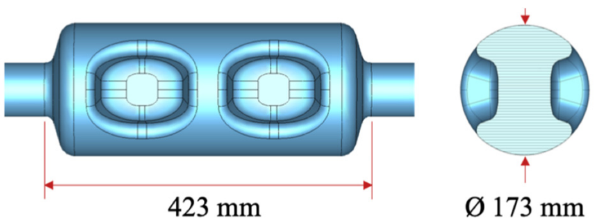
- T. Capelli, *et*. al., Design of Crab Cavity Cryomodule for HL-LHC, SRF 2019
- J. Mitchell, HOM Damping and SPS Measurements, International Review of the Crab Cavity System Design and Production Plan for the HL-LHC, CERN, June 2019

Future Electron-Ion Colliders



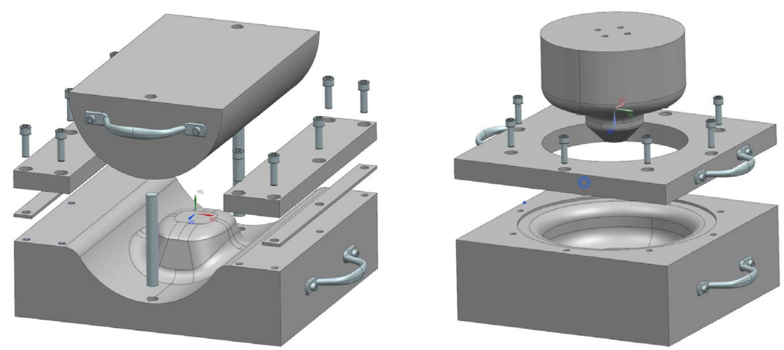






- V_t per cavity – 1.9 MV
- No. of cavities (e/p) – 3/12

Properties	eRHIC	JLEIC
Frequency [MHz]	338	952.6
Beam Energy (e/p) [GeV]	10/275	12/200
Crossing Angle	22	50
V_t per beam per side [MV]	4.0/13.0	4.2/21.5



- S. Verdu-Andres, *et. al.*, 338 MHz Crab Cavity Design for the eRHIC Hadron Beam, SRF 2017
- H. Park, *et. al.*, Design of a Proof-of-Principle Crabbing Cavity for the Jefferson Lab Electron-Ion Collider, IPAC 2019

Related Material at SRF 2019

- MOP099 – Design of Crab Cavity Cryomodule for HL-LHC, T. Capelli *et al*.
- TUP081 – Status of the HL-LHC Crab Cavity Tuner, K. Artoos *et al*.
- THP035 – Design of LHC Crab Cavities Based on DQW Cryomodule Beam Test Experience, S. Verdú-Andrés *et al*.
- THP036 – An Insight on the Thermal and Mechanical Numerical Evaluations for the High-Luminosity LHC Crab Cavities, E. Cano-Pleite *et al*.
- THP066 – Crab Cavity HOM Simulations and Measurements with Beam, J.A. Mitchell *et al*.
- THP069 – Validation of LARP Prototype RF-Dipole Cavity Performance With Higher Order Mode Couplers, S.U. De Silva *et al*.
- THP106 – An SRF Test Stand in High Intensity and High Energy Proton Beams, G. Vandoni *et al*.

Summary

- KEK crabbing cavity (1970) – First demonstration of successful implementation and operation of a superconducting crabbing cavity for an electron beam
- SPS cryomodule test (2018) – First demonstration of successful implementation and operation of a superconducting crabbing cavity for an proton beam
- Promising compact crabbing cavity designs
  - Concept has been successfully tested with Proof-of-Principle cavities
  - Improved prototype cavity designs for LHC High Luminosity Upgrade
  - Successful performance of prototype cavities
- Prototype engineering and testing at SPS ongoing and LHC
  - Continued test with DQW cryomodule at SPS
  - RFD cryomodule testing planned for 2022
  - LHC prototype cavity production for both DQW and RFD cavities have started
- Wider interest on new and compact deflecting/crabbing cavities due to recent applications of HL-LHC and future EICs