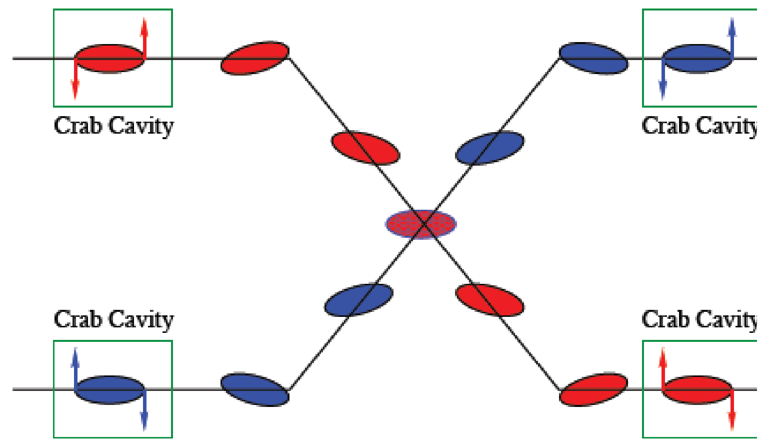
Crab Cavities Project

A. Ratti

LBNL

Outline

- Why Crabs
  - Motivation and boundaries
- Construction Project
  - Scope and Deliverables
  - Interfaces and Boundaries
  - Cost and Schedule
- System requirements and description
  - FNAL workshop
- Current status and LARP activity
  - PoP and Prototypes, integration
  - SPS test
- Next Steps and Planning
- Conclusions

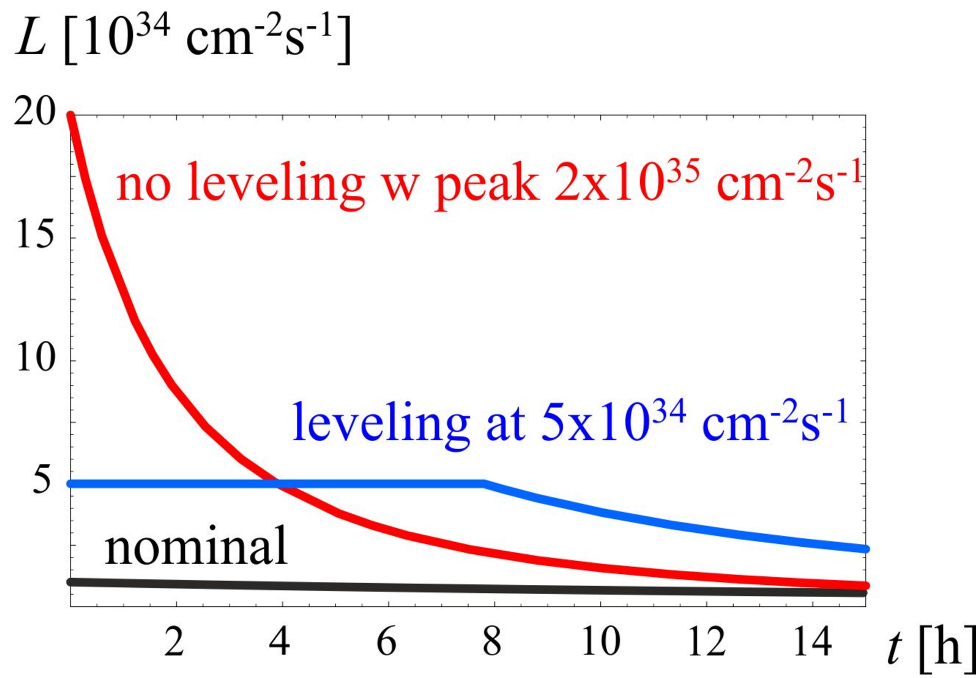


Why crabs?

- Substantial upgrade of integrated luminosity
  - Luminosity leveling, vertex density control
  - Effectiveness increases with larger crossing angles
  - Only known way to improve luminosity during the store
- Significant R&D on cavity technology for several years
  - Encouraging results are making this possible
  - Three designs under study in Europe and the US

Luminosity Levelling

- Luminosity decreases for proton burning (neglecting effects like emittance growth due to b-b, IBS, etc…)
- Total number of collisions ***∫Ldt*** in a run is limited by number of stored protons
- ⇒ store a lot of protons but keep instantaneous lumi «low» by detuning one (or more) parameter.
- ⇒keep the lumi constant by re-tuning the paramter(s) to compensate proton loss (and possibly any other effect).



System Requirements

- Voltage >= 10 MV (3.3MV/cavity)
  - SPS test 2 cavities/module
  - LHC 3 cavities/module
- Frequency = 400 MHz
- $Q_{ext} = 10^5 - 10^6$, R/Q ~300 W
- Cavity tuning/detuning ± 1.5-5.5kHz (or multiples of it)
- RF power source = 60 kW (< 18 kW nominal)
- Beam current ~ 0.5-1 A

LARP

Technical Specification

High Luminosity LHC

- Functional parameters
  - Including HOMs, Z…
- Enclosures (incl. materials…
- Cryogenics
- RF Power incl. couplers
- LLRF
- SPS Integration

Recently released by CERN

CERN-ACC-NOTE-2013-003

HiLumi LHC

FP7 High Luminosity Large Hadron Collider Design Study

Scientific / Technical Note

Functional Specifications of the LHC Prototype Crab Cavity System

Baudrenghien, P

et al

28 February 2013

High Luminosity LHC

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

This work is part of HiLumi LHC Work Package **4: Crab cavities**.

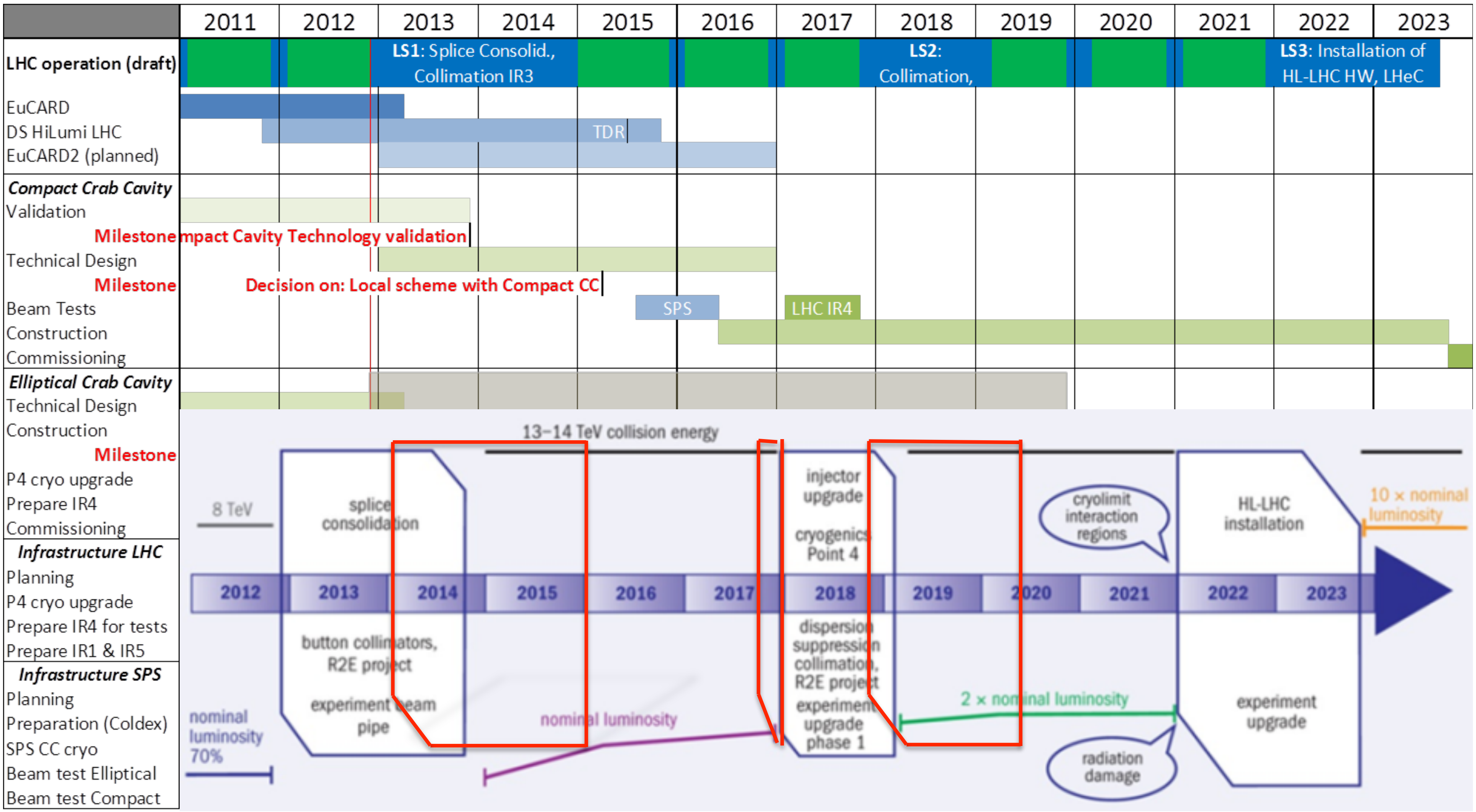
The electronic version of this HiLumi LHC Publication is available via the HiLumi LHC web site <http://hilumilhc.web.cern.ch> or on the CERN Document Server at the following URL: <http://cds.cern.ch/search?p=CERN-ACC-NOTE-2013-003>

CERN-ACC-NOTE-2013-003

Construction Project

- Crab cavities are included among the tasks selected in December 2012 as part of the construction project in support of the HL-LHC
- Feedback from DOE reminds that the effort on crab cavities should be carried through construction
  - Should not limit this contribution to the SPS test

Present overall planning (Dec 2012)



Scope of work

- LARP R&D
  - Deliver one cryomodule for testing in the SPS in ~2016/7 and possibly in Pt-4 in the LHC
    - 2 cavities, He vessels, tuners, HOM mode dampers
    - RF couplers provided by CERN
    - Cryogenics, RF power, local installation provided by CERN
- US Construction project
  - Deliver 10 cryomodules of 3 cavities each
    - Contain cavities, He vessels, tuners, HOM mode dampers
    - Cryogenics, RF power, local installation provided by CERN
    - 8 CM needed in pts 1 and 5, 2 spares

R&D Progress

- Engineering meeting at FNAL
  - Dec 2012
- Proof of Principle cavities testing
  - ODU/SLAC cavity tested
  - BNL cavity tests to start in 10 days
- Prototype cavities design
  - Underway at BNL and ODU
- Cryostat integration
  - Starting at FNAL
  - Supported by Niowave through a Phase II SBIR
- Modeling
  - EM design at SLAC
  - Beam beam studies at LBNL and FNAL

Detailed discussions Tuesday AM

Engineering Meeting @ FNAL

Dec 12-13, 2012

- Active discussions on all aspects of the project
  - From materials and processes
  - To cavity, couplers, tuner design
- Well attended
  - Highest attendance from CERN
  - Also LU, FNAL, ODU, BNL, LBNL
- Open collaboration
- Summary report available online

LHC Crab Cavity Engineering Meeting

Meeting Summary Report

S. Belomestnykh (BNL), R. Calaga (CERN), E. Jensen (CERN), A. Nassiri (ANL), T. Nicol (FNAL), V. Parma (CERN), T. Peterson (FNAL), A. Rowe (FNAL)

Abstract

The first crab cavity engineering meeting for the LHC luminosity upgrade project (HL-LHC)

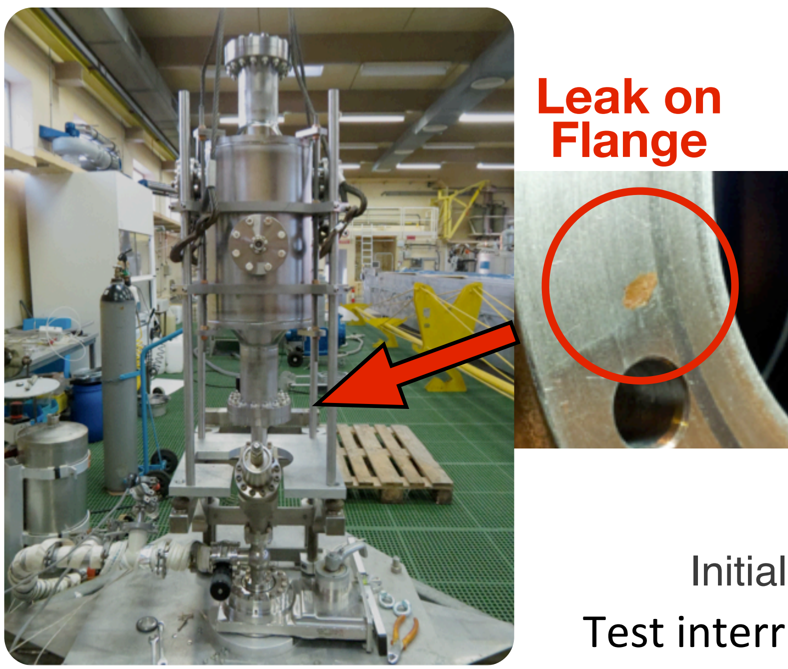
Engineering meeting summary

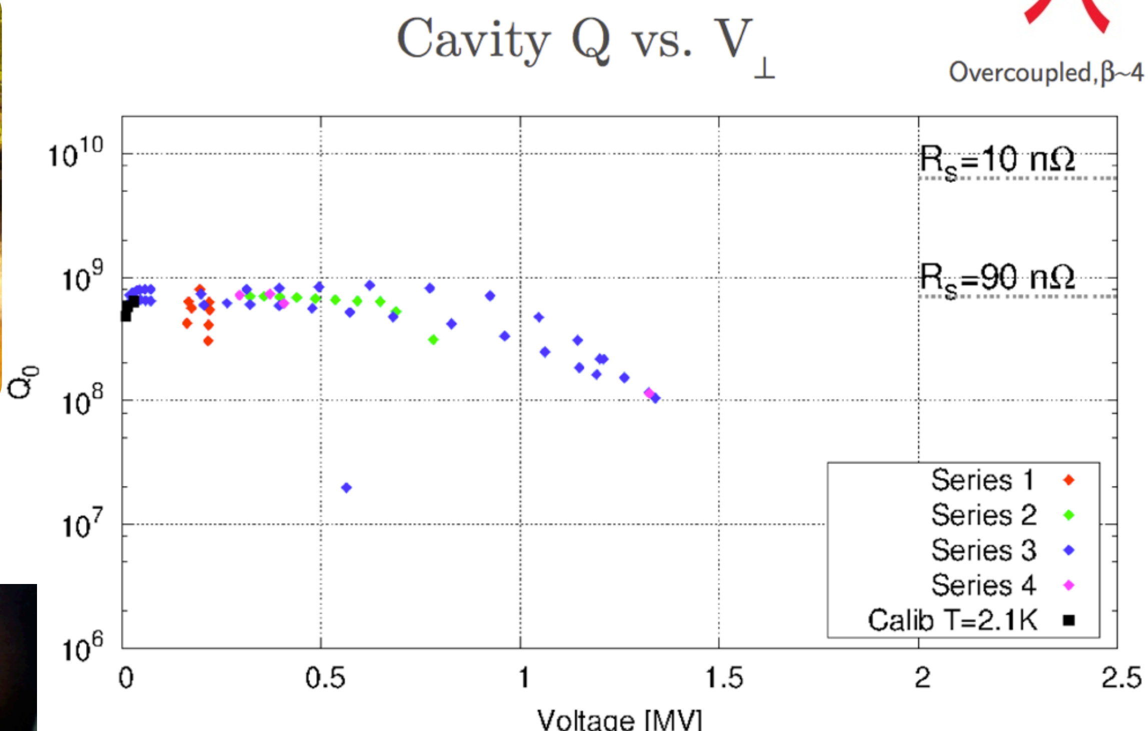
1 Executive Summary

Rama Calaga, Erk Jensen

1. Crab cavity tests with SPS beams are a mandatory validation step before any installation in the LHC. All RF, cryogenic, vacuum operation should be comprehensively tested with the SPS installation along with all relevant beam experiments to determine the effects on hadrons and machine protection.
2. A two-cavity cryomodule with identical cavities is seen as the best option for an SPS test of the crab cavity system.
3. All features compatible with and relevant for the final LHC system should be retained in the SPS cryomodule to the extent feasible. Therefore, the design of the SPS cryomodule can deviate to adapt to its environmental constraints.
4. All RF and cryogenic interfaces should be placed on the top with vertical mounting of the coupler and cryogenic feeds.
5. The choice of the power coupler dimensions and heat load limitations will be fixed as soon as possible.
6. The bypass beam standard beam pipe will be placed outside the cryostat vacuum by redesigning the Y-chamber for a larger separation. This allows for easier swapping of cryomodules and limits the risk of vacuum and cavity failures on SPS operation.
7. A dummy beam pipe at 194 mm like in the LHC should be foreseen and be placed in the liquid Helium volume if necessary. It can additionally be used to reinforce the cavity.
8. Tuning requirements from the beam of approximately 60 kHz with a resolution of 40-200 Hz depending on the cavity bandwidth should be foreseen. In addition, cavity specific frequency tuning to compensate Lorentz force detuning, cool-down and microphonics should be accounted for in the tuner design.

4-rod testing @ CERN





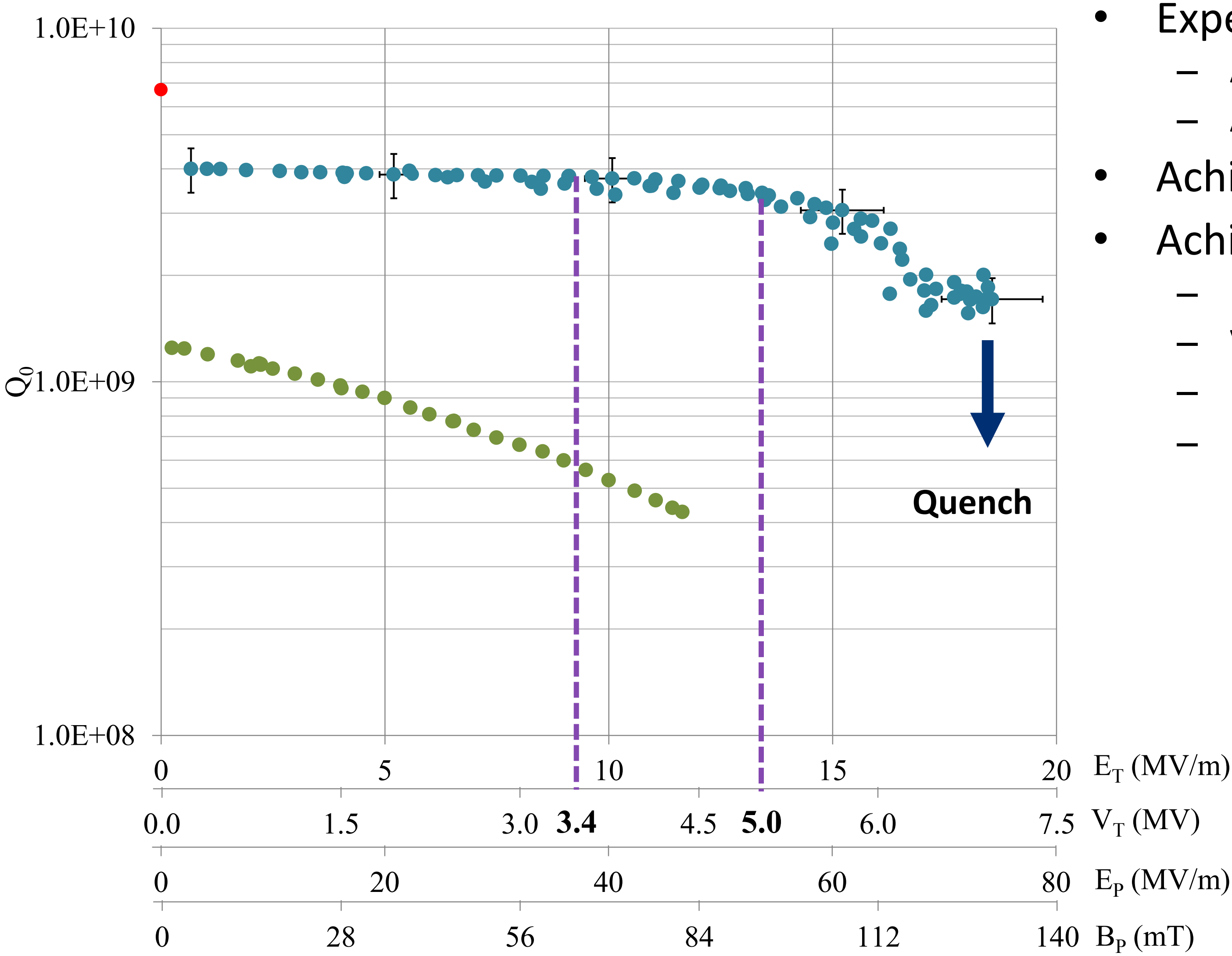
Note: Q_0 including flanges to be confirmed

SM18 tests in Nov 2012 on UK-4Rod Cavity

Initial measurements with compromised vacuum of 10^{-5} mbar

Test interrupted by SM18 shutdown resumes at the end of April

PoP RF Dipole 4.2 K and 2 K Test Results



- Expected $Q_0 = 6.7\times10^9$
  - At R_S = 22 nΩ
  - And R_{res} = 20 nΩ
- Achieved $Q_0 = 4.0\times10^9$
- Achieved fields
  - E_T = 18.6 MV/m
  - V_T = 7.0 MV
  - E_P = 75 MV/m
  - B_P = 131 mT

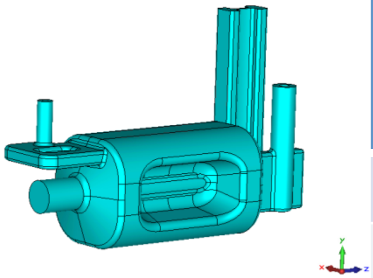
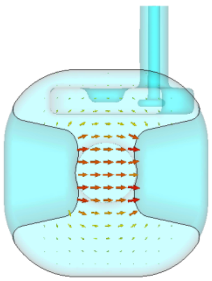
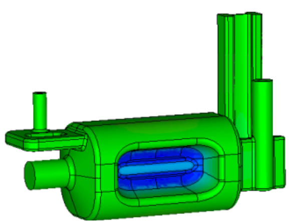
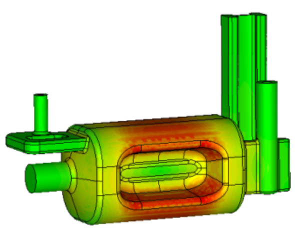
Jefferson Lab

Old Dominion University

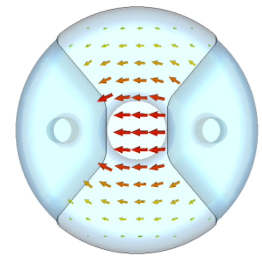
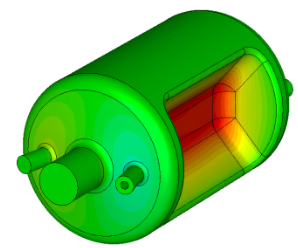
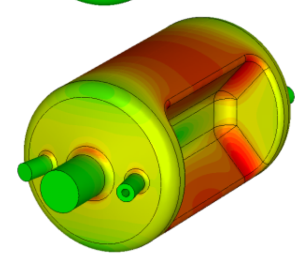
RF Dipole Proof-of-Principle Status

- Proof-of-Principle cavity achieved 7 MV deflecting voltage cw
- Residual surface resistance a little high (34 nΩ)
  - Possibly due to contaminated acid, not enough Nb removed
  - Consistent with losses in stainless steel flanges and copper probes in coupler ports
- Multipacting quickly processed and did not reoccur
- Proof-of-Principle cavity has achieved its purpose
- Ready to move on to the prototype cavity
- Reasonably confident that 10 MV can be achieved with 2 cavities

Prototype Design vs. Proof-of-Principle

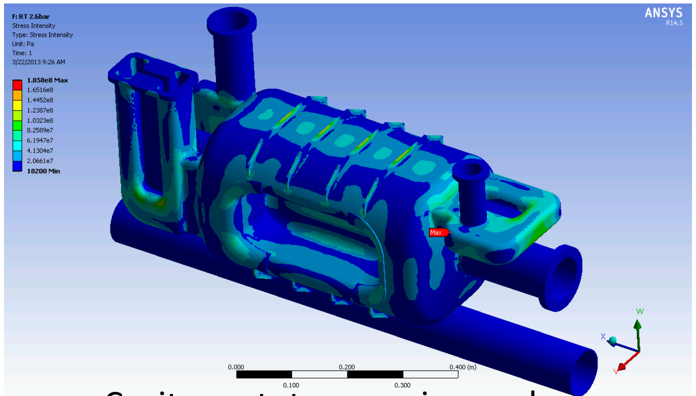





RF PARAMETERS	Prototype design	Proof-of-Principle	Units
Deflecting voltage (V_T^*)	0.375	0.375	MV
Peak electric field (E_P^*)	3.66	4.02	MV/m
Peak magnetic field (B_P^*)	6.14	7.06	mT
B_P^* / E_P^*	1.67	1.76	mT / (MV/m)
Stored Energy (U*)	0.13	0.195	J
Geometrical factor ($G = QR_S$)	106	141	Ω
$[R/Q]_T$	427.2	287	Ω
R_TR_S	4.54×10^4	4.04×10^4	Ω^2
At $E_T^* = 1$ MV/m			
At $V_T = 3.4$ MV			
Peak electric field (E_P)	33.2	36.5	MV/m
Peak magnetic field (B_P)	55.7	64.0	mT

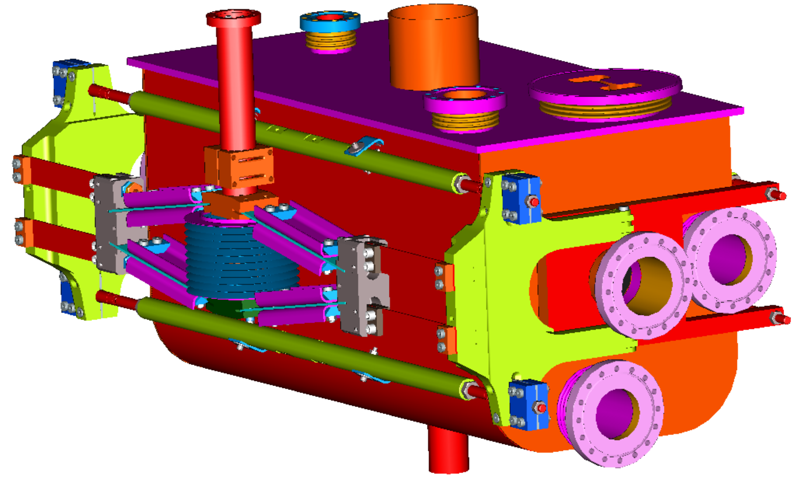





Prototype is superior to Proof-of-Principle across all parameters
Electromagnetic design is now frozen
Multipacting studies in waveguide couplers under way

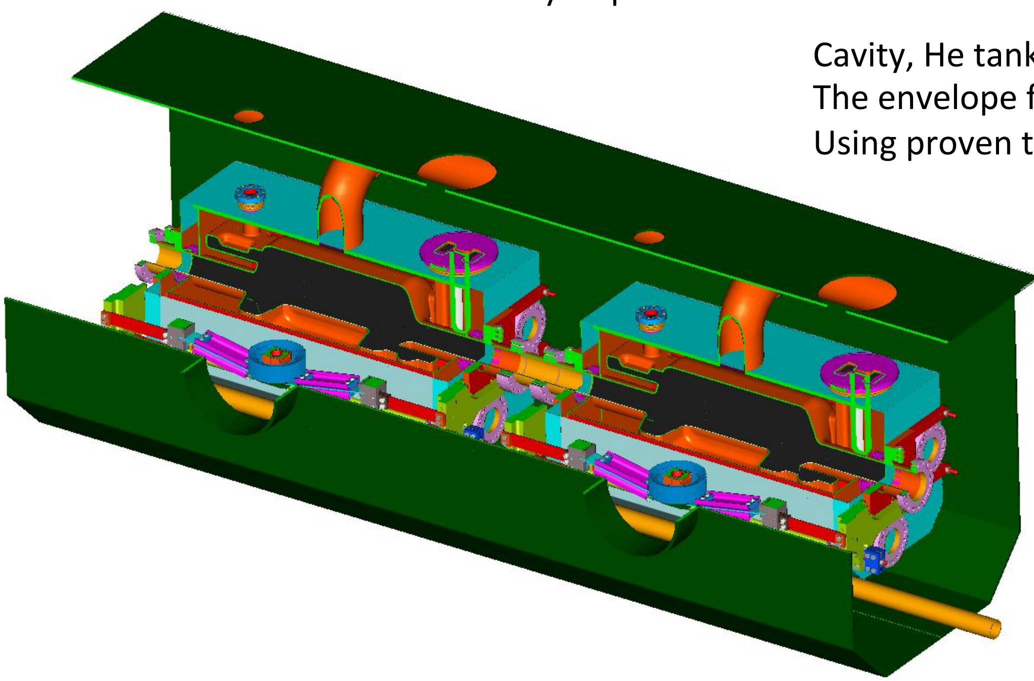
Prototype Cavity Engineering



Cavity prototype engineered
Mechanically stable
Meets SPS safety requirements

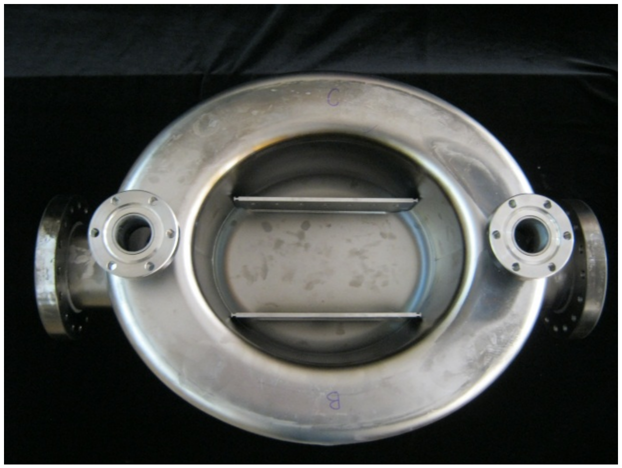


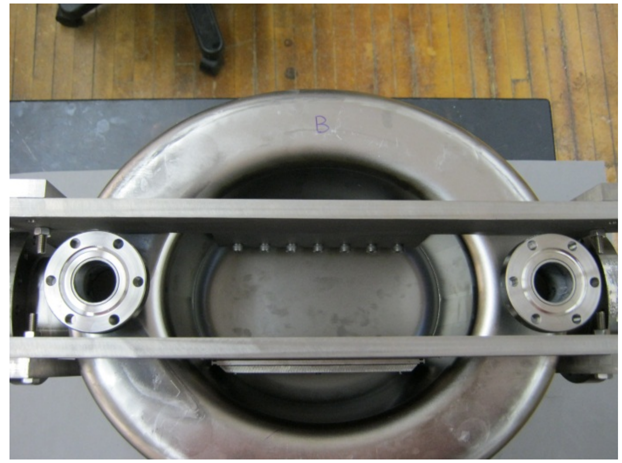
Cavity, He tank, and tuner assembly aiming for LHC installation
The envelope for SPS test can be significantly reduced
Using proven technology

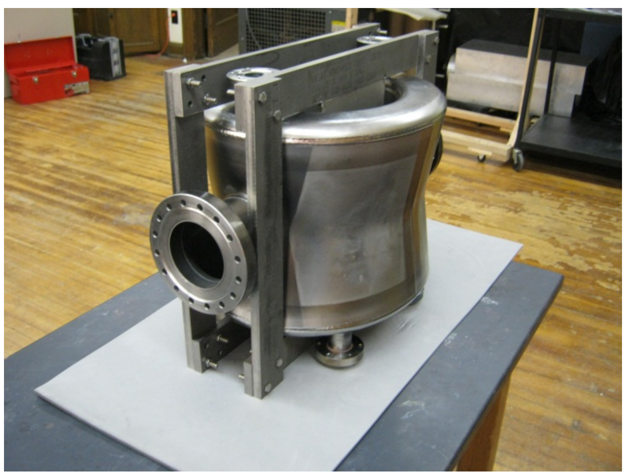


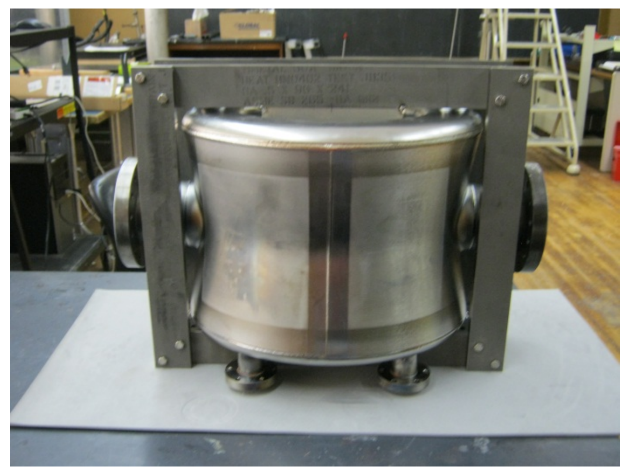
Cryostat concept
Moving forward to the real packaging for LHC
Simple modification for SPS test

Fabrication of the DQW PoP Cavity



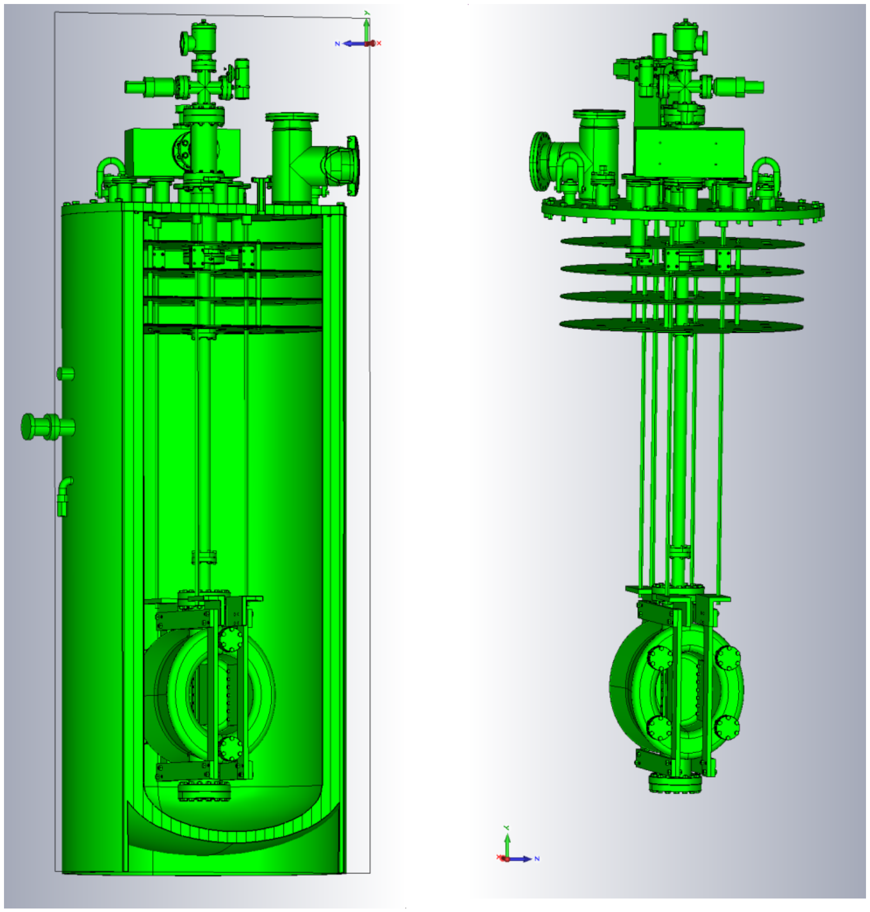




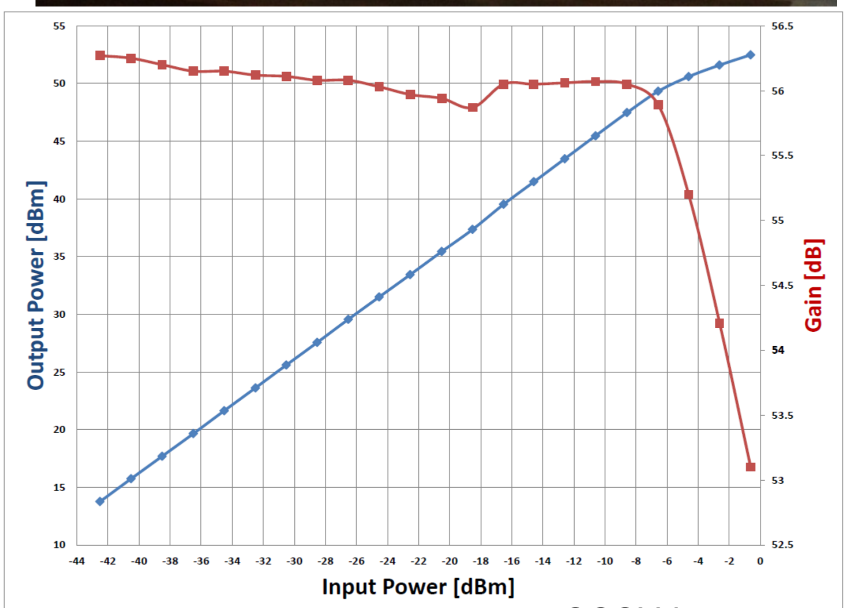


Courtesy of Niowave Inc.

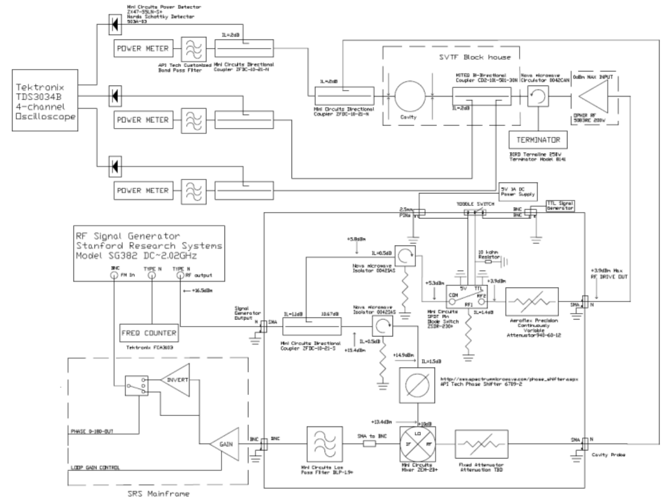
Vertical Test – Test Stand



Vertical Test – LLRF, Power Amplifier



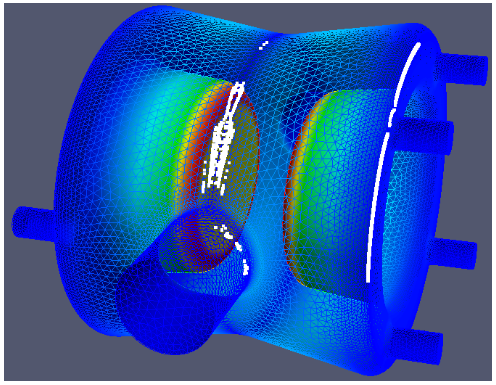
200W max power with 56±0.5dB gain

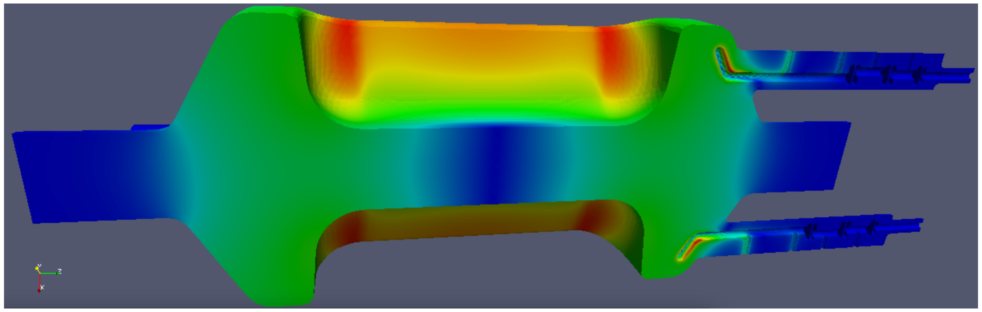


BROOKHAVEN NATIONAL LABORATORY

Modeling

- Supporting EM design of cavities and auxiliary systems
  - Multipacting analysis
  - Mode dampers coupling
    - And fundamental rejection





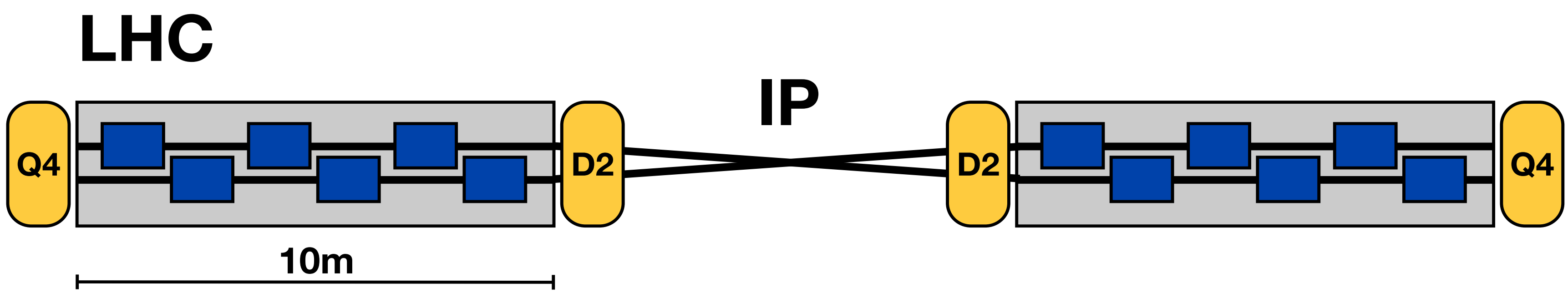
- Studies of three candidate designs

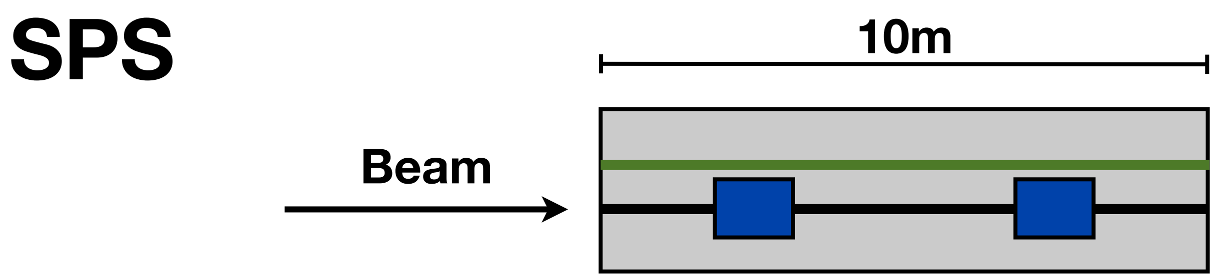
Path to the HL-LHC

- SPS Validation Tests
  - Crab concept with proton beams
  - Machine protection aspects
  - Beam measurements (noise, heat loads..)

- Essential to finalize LHC design
  - Final decision on crab cavity system only after SPS test

SPS vs. LHC





Organization

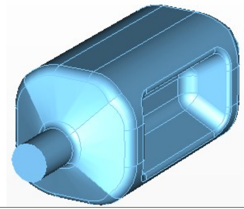
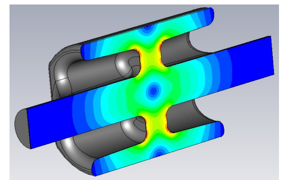
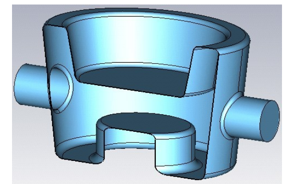
- CERN leads the global collaboration
  - Directly responsible for several tasks
    - RF power and controls, local installation, cryogenics, machine protection…
- US contributes well defined part of the project
  - Cavities and cryomodules
- Defined roles within LARP collaboration:
  - BNL, ODU – cavity development (tuners, mode dampers….)
  - FNAL - cryomodule design and integration
  - SLAC – EM modeling support
  - FNAL, LBNL - beam dynamics studies
  - Points of contacts defined at each lab

Conclusions

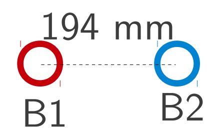
- Crab cavities have been selected as one of the activities in the construction project for the HL-LHC
- R&D program is making great progress
  - Very encouraging initial results
  - Detailed design of prototype cavities and integration of a system for SPS test
- CERN very actively involved
- Systems requirements document released
- FNAL takes ownership of the cryomodule design and integration
- US industry remains involved in a key role

Questions

Cavity Design Overview

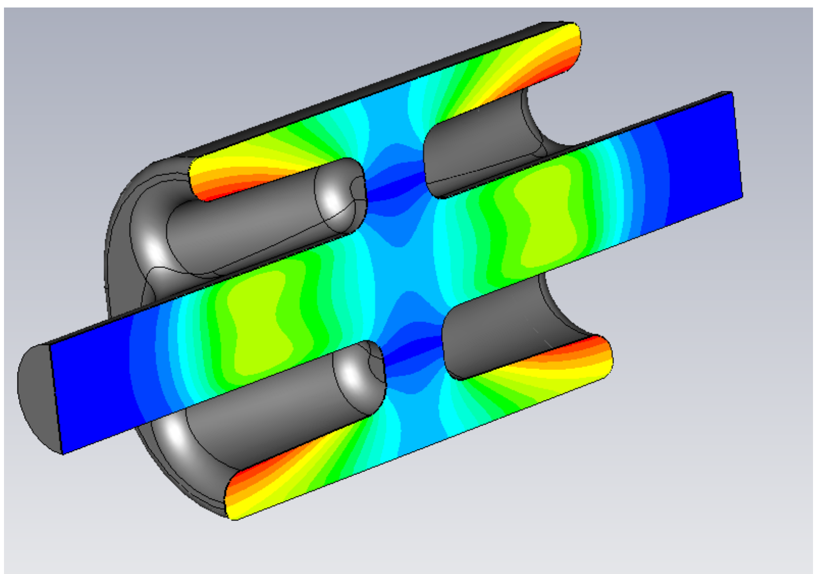
		Double Ridge (ODU-SLAC)	4-Rod (UK)	¼ Wave (BNL)	
Geometrical	Cavity Radius [mm]	**147.5**	**143/118**	**142.5/122**	
	Cavity length [mm]	597	500	330-405	
	Beam Pipe [mm]	84	84	84	
RF	Peak E-Field [MV/m]	33	32	43	$<$ 50 MV/m
	Peak B-Field [mT]	56	60.5	61	$<$ 80 mT
	R_T/Q [Ω]	287	915	345	
	Nearest Mode [MHz]	584	371-378	657	

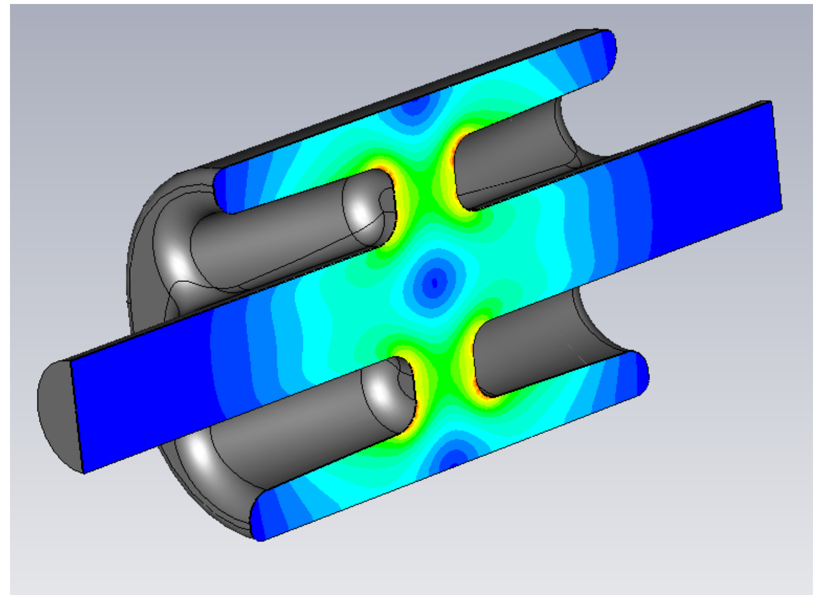


4 Rod - Cavity Shape

Cavity fitted LHC scenario (84 mm aperture compact transverse size) and has tolerable fields at the design gradient.

Removal of voltage variation.

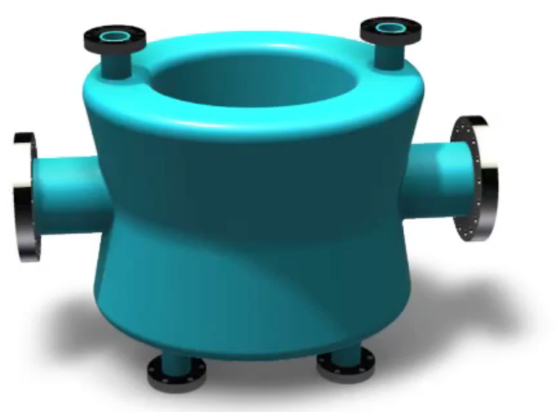


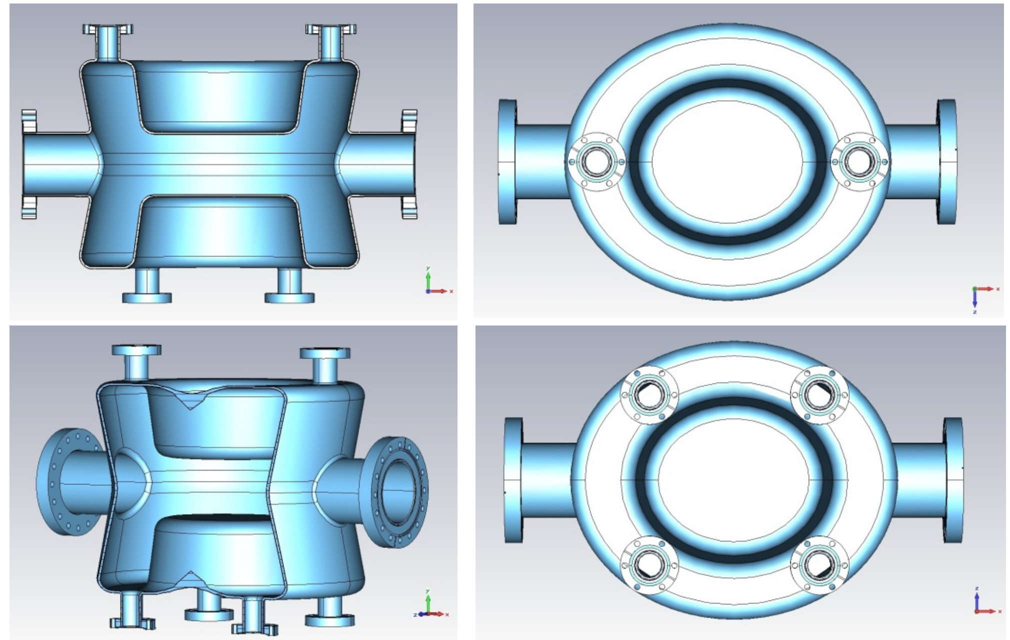


Emax @3MV	32.0 MV/m
Bmax @3MV	60.5 mT
Transverse R/Q	915 Ohms

$R_T/Q=(V(a)^2/wU)*(c/\omega a)^2$

Quarter Wave Cavity

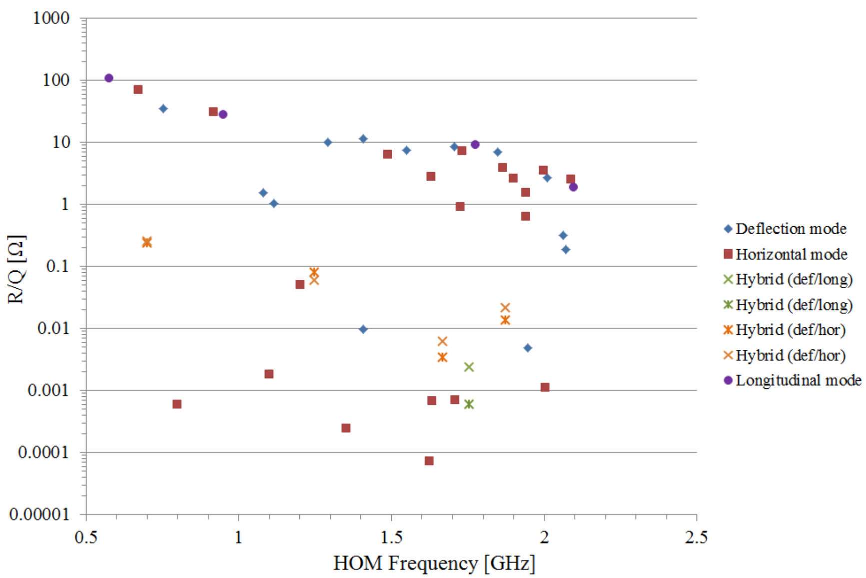


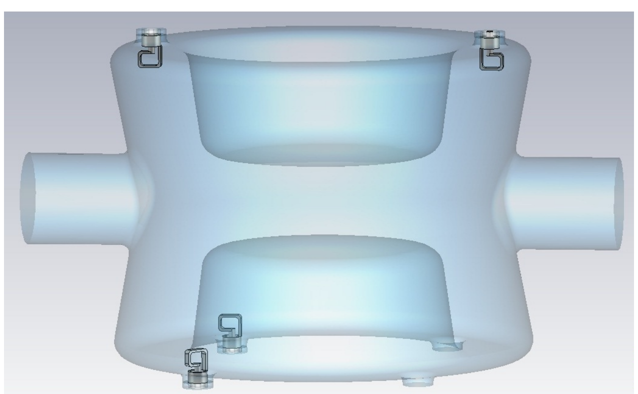


- Double quarter-wave resonator: Compact design at low frequencies; No Lower Order Modes and Same Order Modes, nearest Higher Order Mode is well separated from the fundamental mode → easier damping than in other designs; Very little parasitic acceleration (1.6 kV).
- 6 RF ports: 4 for HOM damping, 1 for FPC, and 1 for pickup.
- The cavity is developed as part of LARP and satisfies very strict space constrains near the LHC IPs.

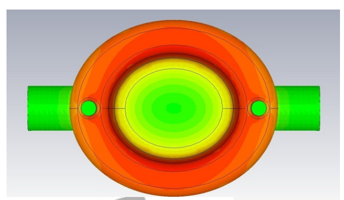
Crabbing (fund.) mode	1st HOM	Cavity length	Cavity width	Beam pipe diameter	Deflecting voltage
400 MHz	579 MHz	38.4 cm	14.2 cm	8.4 cm	3 MV

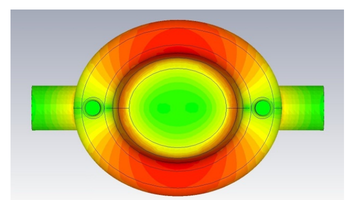
HOM damping

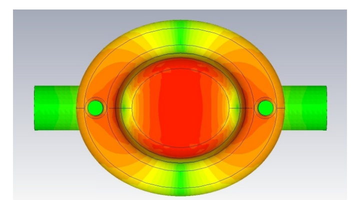




HOM frequency [GHz]	Mode Config.	R/Q [Ohm]	Qext
0.579	Longitudinal	108	1130
0.671	Horizontal	70.5	2340
0.700	Hybrid (y, z)	0.24/0.25	1140
0.752	Deflection	34.9	1750
0.800	Horizontal	6.02e-4	3160
0.917	Horizontal	30.9	2050
0.949	Longitudinal	28.1	3180
1.080	Deflection	1.54	1240
1.102	Horizontal	1.84e-3	1380
1.114	Deflection	1.06	1380
1.202	Horizontal	5.07e-2	7880
1.247	Hybrid (y, z)	8.0e-2/6.0e-2	1730
1.291	Deflection	10.0	926







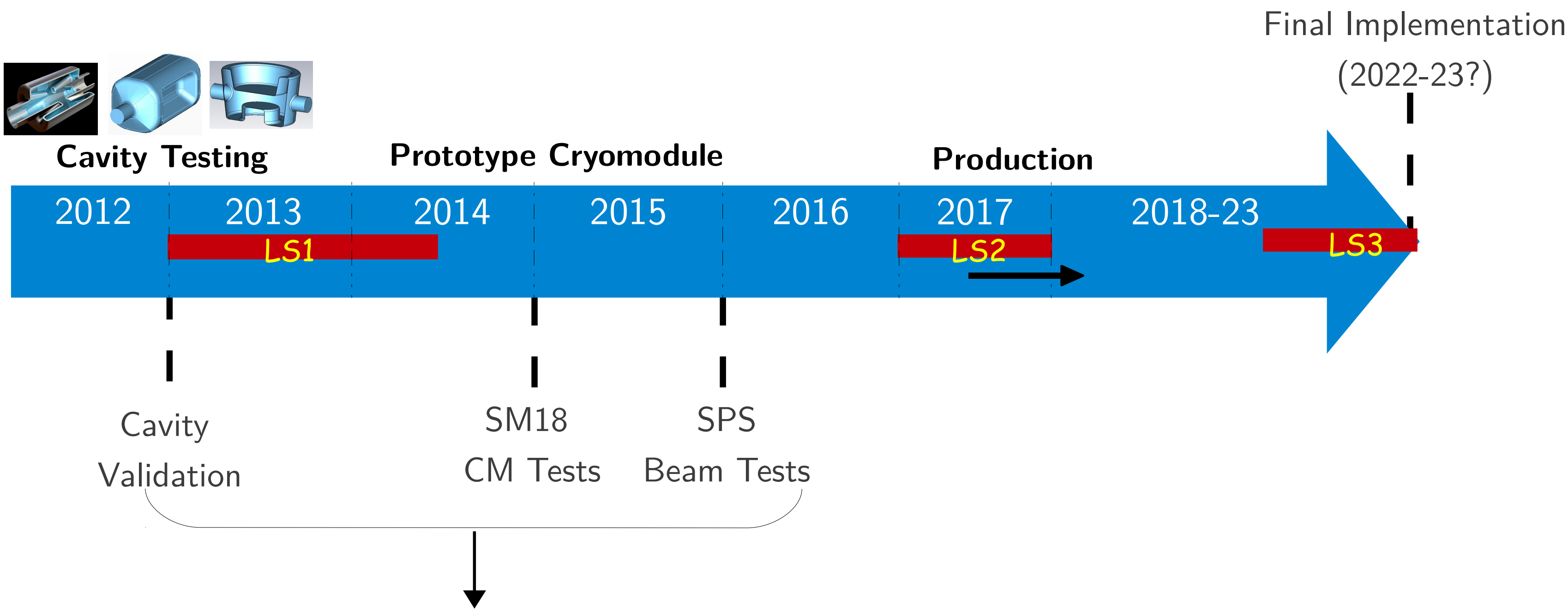
Cavity Development Summary

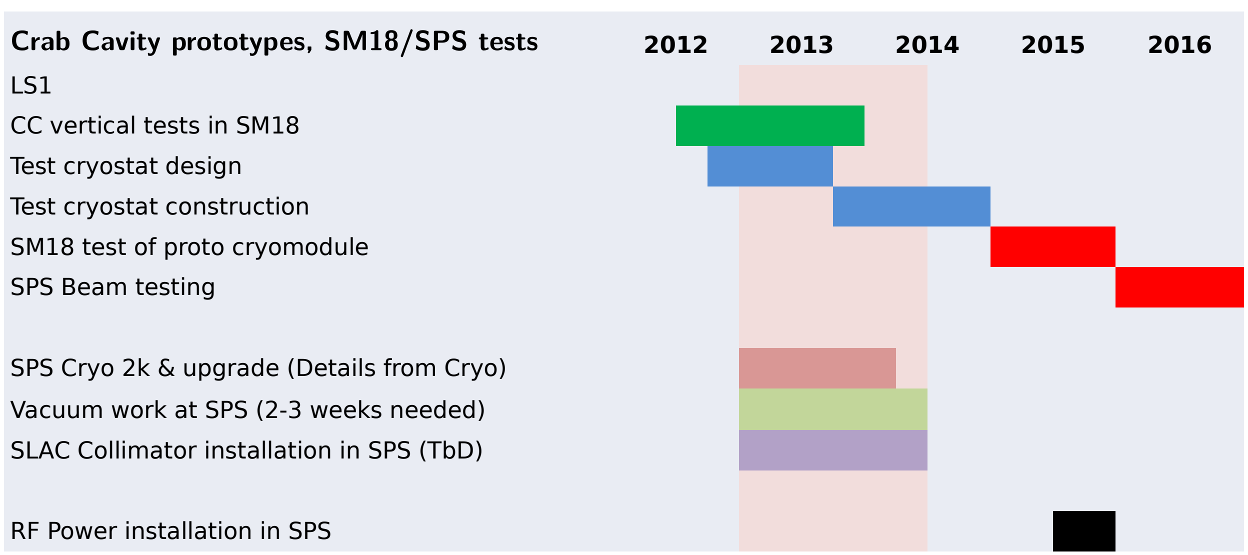
- All three candidate designs will go through comprehensive vertical testing in early 2013
- Starting integration into a cryomodule design for SPS test (and consistent with LHC implementation) with a meeting at FNAL on December 13-14, 2012
- Auxiliary systems designs (HOM dampers, tuners, diagnostics…) underway

Present Focus

- Demonstration cryomodule under development for a possible beam test in the SPS before LS2
  - Vertical tests of all three cavities
- Cross functional working group in place at CERN to develop feasibility for SPS test
  - Operations, RF, Vacuum, Cryogenics, Beam Dynamics, Machine Protection, Collimation, Instrumentation…
- Recommended as a result of CC-11

Timeline


Final Implementation
(2022-23?)
Cavity Testing
Prototype Cryomodule
Production
2012
2013
2014
2015
2016
2017
2018-23
LS1
LS2
LS3
Cavity
Validation
SM18
CM Tests
SPS
Beam Tests


Crab Cavity prototypes, SM18/SPS tests
2012
2013
2014
2015
2016
LS1
CC vertical tests in SM18
Test cryostat design
Test cryostat construction
SM18 test of proto cryomodule
SPS Beam testing
SPS Cryo 2k & upgrade (Details from Cryo)
Vacuum work at SPS (2-3 weeks needed)
SLAC Collimator installation in SPS (TbD)
RF Power installation in SPS