EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
CERN – ACCELERATORS AND TECHNOLOGY SECTOR

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LHC Crab Cavity Engineering Meeting

Meeting Summary Report

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Abstract

The first crab cavity engineering meeting for the LHC luminosity upgrade project (HL-LHC) was held from 13 to 14 December 2012 at Fermilad, Batavia, IL. The workshop was organized by a joint collaboration of CERN, HiLumi and US-LARP. The executive summary states the key conclusions from meeting and lists the required action items for the R&D, testing and final implementation of the crab scheme.

Geneva, Switzerland,
18 February 2013

LHC Crab Cavity Engineering Meeting

Workshop Summary, Edited by R. Calaga, E. Jensen

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.

2 INTRODUCTION

The first crab cavity engineering meeting for the LHC luminosity upgrade project (HL-LHC) was held from 13 to 14 December 2012 at Fermilab, Batavia, IL. The workshop was organized by a joint collaboration of CERN, HiLumi-LHC and US-LARP. Approximately 30 participants from several institutions from Europe and the Unites States participated in the workshop to discuss the present status of the crab cavity R&D and review the conceptual ideas of cryomodule and its constraints for an SPS. Future adaptation of such a cryomodule into the LHC was also discussed. The detailed participation list, scientific program along with the associated contributions are available at:

http://indico.cern.ch/conferenceDisplay.py?confId=136807

2.1 WORKSHOP CHARGE AND OBJECTIVES

The charge of the workshop was as follows:

1. Review fabrication challenges for the three compact cavities and the present test results
2. Review present conceptual ideas of the two-cavity cryostat including the tuning mechanisms, Helium vessel, shielding, thermal and mechanical analysis, RF system, controls, alignment, instrumentation and integration. Its future adaptation towards the final LHC system should be addressed.
3. Review the timeline for fabrication of the two cavity cryostat and respective systems for the SPS tests and the related prototyping effort.

3 SESSION SUMMARIES

Relevant notes from the sessions during the meeting are described in the following section.

3.1 FABRICATION TECHNIQUES, PRESENT STATUS & RESULTS

Convener: Tom Nicol (FNAL)

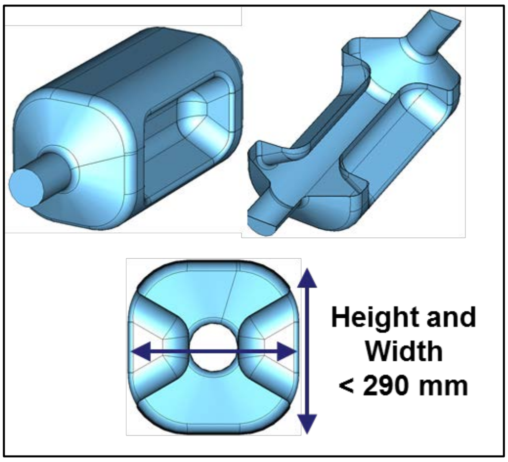
This opening session started with brief presentations by Bob Kephart and Giorgio Apollinari of Fermilab in which both expressed their own enthusiasm for the proposed project as well as Fermilab's interest in the collaboration. Fermilab has a long history working with CERN and many of the other contributing institutions and has much to offer in crab cavity design development.

Following this were presentations by Dr. Graeme Burt of Lancaster University, Subashini De Silva of Old Dominion University and Qiong Wu of Brookhaven National Lab which described the three crab cavity designs being developed for use in the LHC for its upgrade. All three designs accomplish the same goal of providing 400 MHz deflecting mode cavities for the planned LHC upgrade, but do so using substantially different geometries.

The cavity described by Graeme Burt is characterized as a “4-Rod” design given reentrant rod structures that penetrate the cavity geometry, two from each end. The figure below shows the prototype cavity as it’s readied for vertical testing.

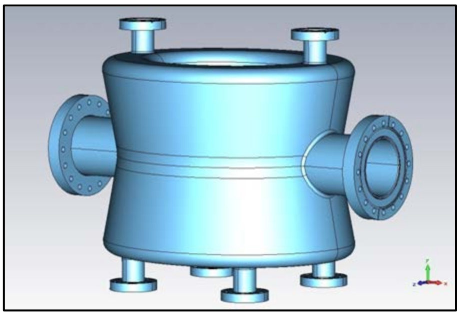
UK 4-Rod Cavity Prototype

The cavity design described by Subashini De Silva is characterized as an “RF-Dipole” and is of similar shape to the 4-rod geometry, but uses transverse pockets to produce the horizontal deflecting field. The cavity model is shown in the figure below.



Old Dominion RF-Dipole Cavity Design

The final design presented was from Brookhaven in which Qiong Wu described their “Double Quarter Wave” design shown below. One of the unique features of this design is the tapered mid-section of reducing the transverse size, accommodating the required close spacing of the beam tubes.

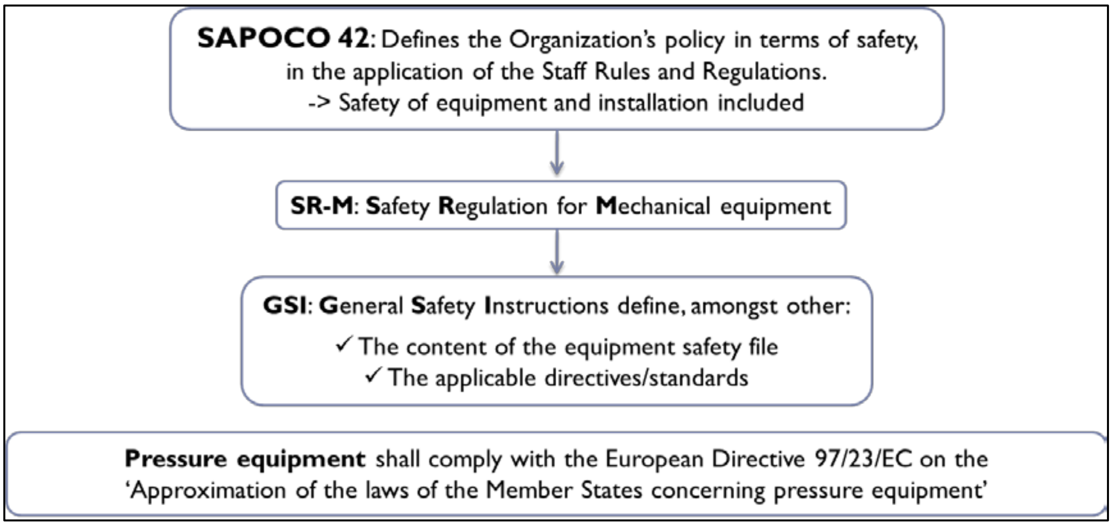


BNL's Double Quarter Wave Design

All of the designs presented offer challenges in HOM and input coupler design and integration, multipactoring suppression, cavity tuning, processing and cleaning, pressure sensitivity, pressure vessel code issues, and other physical constraints. Each institution is moving forward with design, analysis, simulation, prototyping, and testing with a near-term goal of integrating their design into a complete 2-cavity cryomodule.

The final presentation in this session was by Luis Alberty from CERN and described the pressure vessel code requirements and analysis results on simulations of each of the three prototype designs. His presentation provides an excellent backdrop for further and continued work in evaluating these kinds of structures. This subject promises to be one which will be studied at length over the next several years at SRF-related institutions worldwide on all types of cavity designs. Concerns about SRF materials, pressure sensitivity effects on cavity performance and tuning stability, and system and personnel safety are common to all projects and play key roles in this area of interest. The figure below is a brief overview of CERN's safety policy as it relates to pressure safety.

Preliminary analyses on these three designs show all to have stress related issues with their original designs with each responding differently to redesign, changing material thickness, incorporation of stiffeners, etc.



Short Introduction to CERN's Safety Policy

3.2 Helium Vessel & Tuners

Convener: Ali Nassiri

This session contained talks covering cryostat, helium vessel, and tuners for LHC crab cavities system. This session started with a presentation by Ofelia Capatina (CERN) on general specifications and general regulations related to the pressure safety equipment that are required to test LHC crab cavity system (including cavity, helium vessel and cryostat) both at SM18 (RF tests) and SPS beam tests. Second presentation was given by HyeKyoung Park (ODU/JLab) on the design of helium vessel and tuner for the proposed ODU-SLAC RF dipole cavity. This followed by a talk on helium vessel and tuner foe the BNL Quarter-Wave cavity which was presented by Binping Xiao (BNL). The final talk of this session was presented by Thomas Jones (STFC) who discussed helium vessel and tuner design of UK 4-rod crab cavity.

Ofelia Capatina gave a short summary of proposed cavity deign overview while taking into account integration specification of external dimension of the cavity as manufactured at room temperature. Currently, three (cavity) candidate designs are being pursued in parallel which will go through comprehensive vertical testing in 2013. Integration into a cryomodule design for SPS test, consistent with LHC implementation, has started. It was noted that the maximum radius external dimension which includes the wall thickness at room temperature should be less than 145 mm. Cavity tuning specifications (slow and fast) were presented and discussed without specific tuner design. Design of a "universal tuner" may not be possible, thus each cavity design may require its own tuner design. A summary of cavity operating frequencies and detuning is listed in table 1.

Table 1: Crab cavity operating frequencies and tuning range.

Parameter	Units	LHC	SPS		
Frequency	MHz	400.79	400.73	400.78	400.79
Δf	kHz	0	-58.2	-12.2	- 2.4
Bandwidth	Hz	400	400	400	400

Initial heat losses at 2K (saturated super fluid helium) including dynamic and static losses were discussed but detailed heat losses must be evaluated taking into account realistic cryomodule design and LHe distribution system. It is important to have a good and realistic estimate of losses especially for SPS tests. Some general parameters of the helium tank along with interfaces and standardization of interfaces for all cavities assemblies were presented. It is anticipated that the helium tank will operate with a helium pressure of about 30 mbar with pressure stability of 1 mbar. It was mentioned that cavity frequency sensitivity due to helium pressure fluctuation of about 200 Hz/mbar seems to be too large. In addition, cavity bandwidth of about 400 Hz implies that cavity frequency sensitivity to helium pressure fluctuation should be significantly lower. Discussions also centered on pressure vessel safety and specifically meeting CERN's safety policy and complying with the European Directive for pressure equipment 97/23/EC.

In the talk by HyeKyoung Park, we learned about the design of the helium vessel and tuner for the ODU-SLAC 400 MHz RF dipole cavity. She presented cryostat design consideration including space constraints, temperature (room and cryogenic) and external pressure to cavity. She also discussed safety code based on ASME Boiler and Pressure Vessel (BPV) Code allowable stress the lesser of 2/3 Yield or Tensile/3.5. She noted that recent test results of niobium samples (RRR>250) at JLab showed a wide variation at room temperature. ANSYS simulation results of cavity mechanical strength (warm and cold) were presented. In the warm case, with a 3-mm thick Nb the yield strength is ~ 69 MPa, as compared to BPV code allowable strength of 46 MPa. Simulations showed worst case during cool down. With 5 bar external pressure, modulus 123 GPa, Poisson's ratio of 0.38, density of 8.58 g/cm^3, yield strength is about 577 MPa (for 3-mm thickness), which is above the BPV code allowable strength of 385 MPa. HyeKyoung also presented some initial results on the cavity pressure sensitivity for a uniform 3-mm thick niobium with pressure sensitivity of about 235 Hz/Torr which produces the largest deformation on the top cavity surface where high magnetic field is observed. Simulations of Lorentz Force Detuning (LFD) indicate a total shift of -12.6 kHz at 3 MV of transverse deflecting voltage for a 3-mm uniform thickness niobium while the total frequency shift decreases to about -3.7kHz with 4-mm thick cavity wall. With a modified cavity model, 4mm uniform thickness, but with 3mm thick cavity top surface, the LFD under 2K nominal helium pressure results in 550 Hz total frequency shift. Several cryostat concepts were presented. She also presented four concepts for the cryostat design with cavity tuner which are shown in Figure 1.

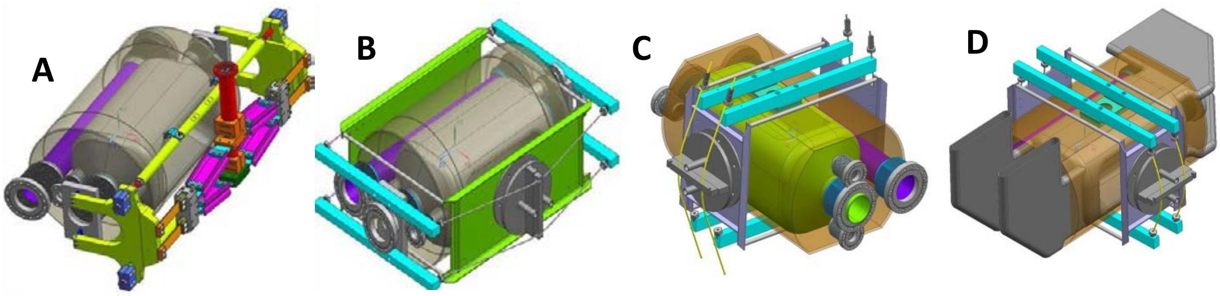


Figure 1: LHC crab cavity cryostat concept – A) JLab design, B) ANL design (helium pressure actuates bellows), C) ANL design (tuner deforms cavity outer surfaces), D) Waveguide

Binping Xiao presented a design of a compact cryostat for the BNL-proposed Double Quarter-Wave Crab Cavity (DQWCC). Simulation of the bare cavity under pressure shows a maximum stress of about 200 MPa for niobium thickness of 3 mm. A preliminary design of the helium vessel was presented that allows for adequate clearance for other beam lines in immediate vicinity. The tuner deign is a non-backlash threaded rod (or differential screw) which provides coarse tuning. A piezoelectric is incorporated in series with the threaded rod providing fine tuning. This design utilized the available space effectively to give more space for the couplers and make the implementation of the magnetic shielding easier. Simulation of tuner sensitivity shows roughly 1.93 MHz/mm with push/pull tuning. A push of 0.42 mm results in about 810 kHz change in frequency while a pull of 0.38 mm moves the cavity frequency off-resonance by about 733 kHz. The tuner design concept for the DQWCC is shown in figure 2. Magnetic shielding concept was presented to meet less than 1 μT field on the cavity surface. The overall approach of this design effort was to evaluate an integrated vessel/stiffer/tuner solution to provide a compact design of a double quarter-wave crabbing system.

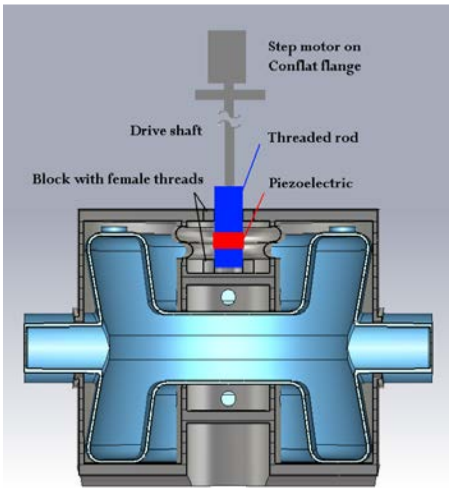


Figure 2: BNL DQWCC tuner design

The last talk of this session was presented by Thomas Jones on helium vessel and tuning for the UK 4-rod crab cavity. The helium vessel concept is a compact integrated design that provides adequate space for additional beam tube for the LHC installation. The helium vessel is made from Grade 5 titanium and stiffening ribs are provided to reduce environmental pressure changes. For this conceptual design, a modified Saclay-II tuner is envisioned (see figure 3). Frequency tuning of the cavity was studied in a simplified model which indicated a frequency shift per millimeter of transverse offset of 300 kHz/mm. With the current design the tuning range is 108 kHz and with tuning in both directions, the total rage of 216 kHz can be achieved. Using tuner on both sides could provide a total range of ±250 kHz.

Further work needs to be completed to improve the tuning range as well as limiting the force required by the tuners. Pressure vessel analysis was done. The maximum stress in niobium is about 60 MPa which is below the allowable 70 MPa calculated by yield stress. Results of the pressure vessel analysis done with the Daresbury Laboratory FEA model was in agreement within 5% error compared to the analysis done with the CERN model. The magnetic shielding consists of one layer of 2-mm thick μ-metal and one layer of 1-mm thick of Cryoperm. This shielding configuration gives 36x attenuation of the external magnetic field. With the earth magnetic field only, this gives less than 14 mG field at the cavity.

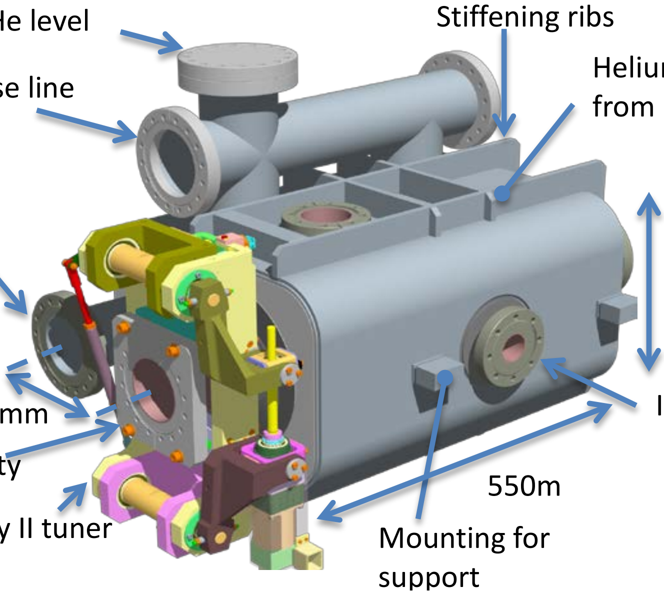


Figure 3: Daresbury Laboratory helium vessel conceptual

3.3 Couplers and Cryogenics

Convener: Sergey Belomestnykh (BNL)

There were three talks during this session:

- “RF power amplifiers (PA) & fundamental power couplers” by E. Montesinos
- “HOM and FPC couplers for LHC crab cavity” by Zenghai Li
- “Crab cavities – cryogenic circuit and heat loads” by K. Brodzinski

First, Eric Montesinos (CERN) gave an overview of the SPS RF power system. For the test of two prototype LHC cavities in SPS, it was specified that two 400-MHz, 60-kW, 1-MHz bandwidth RF power amplifiers would have to be prepared. During the LEP operation, four 352-MHz tetrode amplifiers were in service at SPS. Later on, one of them was modified to operate at 400 MHz. Maximum output power was 40 kW. This amplifier and one of the three remaining 352-MHz amplifiers (modified for 400-MHz operation) can be used for the test. They could reach 50 kW output, 10 kW short of specified 60 kW. Analysis of possible locations for tetrodes showed that the best solution is to install them close to the cavities with a very short waveguide run. The rest of the RF system will have to reside somewhere else: either ECX4 cavern or BA4 surface building.

After that, he presented an approach to the FPC development. A common FPC platform should be developed for all prototype crab cavities. As the FPC development is a lengthy process, Eric emphasized that we face a very tight schedule and that the coupler design shall be completed in February of 2013 to meet the cavity installation goal of December 2015. He presented two design options: with a cylindrical LHC-type RF window, and with a coaxial disk window *a la* SPS power load. Both designs have proven to be powerful and reliable. Whichever window will be chosen eventually, any of them can fit into a common FPC platform (SPL example). All three prototype cavities have small diameter (~40 mm) FPC ports, which are insufficient to support 60 kW RF power. During later discussion, it was decided that the cavities built for the SPS test will have FPC ports of 62 mm ID. The preferred orientation of the FPC is vertical, mounted on top of the cavity. The FPCs will be design to support DC biasing: they will end either with antennas or with hooks. To test the couplers, a self-supporting test box will be designed, and a test area will be refurbished.

Zenghail Li (SLAC) presented several design options of coaxial and waveguide HOM couplers. Unfortunately, in in the presentation he considered only one crab cavity design: SLAC-ODU RF dipole cavity. In the coaxial coupler option, straight antennas can be used for coupling to vertical and accelerating HOMs, and hook antennas are needed for coupling to horizontal modes. A 3-stage high-pass filter is proposed for rejecting the fundamental mode power. The filter design is quite long and there were concerns regarding clean assembly of such a structure. The waveguide type couplers, while efficient in extracting HOMs, are quite large and will greatly complicate the cryomodule design. Also, he considered coaxial and waveguide FPC options.

Krzysztof Brodzinski (CERN) presented options for cryogenic system in SPS BA4, and some analytical considerations for the cryostat design. The existing infrastructure includes a 4.5 K refrigerator TCF20. To run the crab cavities at 2 K, new hardware will have to be added, including a warm pump. This means that TCF20 cryoplant will be used in pure liquefaction mode with capacity of only 0.7 g/s. This would be a severe limitation on the crab cavity test in SPS. However, some old measurements indicate that the plant capacity might be 0.85 g/s or even 1.2 g/s. New measurements must be performed to confirm the cooling capability at 2 K. Then he proceeded to presenting the new cryo circuits to be added to the system and possible integration in SPS. Helium availability is another area of concern and Krzysztof suggested that LHe volume in a 2-cavity cryostat should be limited to 40 liters. Two options of the cryostat design were considered along with description of the cryostat instrumentation. His analysis of the heat loads indicates that 0.7 g/s could be a very difficult limit to meet. Other conclusions are: there should be one cryostat with two cavities rather than individual cryostats; and using LN_2 seems to be an obligation. He then presented his initial considerations for the cryostat operation, cost estimate for new 2 K specific equipment, and a schedule for the SPS cryogenics. The last few slides were devoted to further plans: testing at LHC IP4, and final implementation in LHC.

3.4 Cavity Cryostat Testing & Integration

Convener: Allan Rowe (Fermilab, TD/SRFDD)

<u>Session Summary and Comments</u>

An overview of cavity processing was presented that included an evaluation of processing recipe options. The general processing recipe appropriate for all resonator types was concluded to be the following:

Step	Process (post fabrication and inspection)	Technique
1	Damage layer removal – 120-150 um all RF surfaces, exterior BCP only if desired	1:1:2 BCP @ 12-15 deg C, flow optimized to promote sufficient material removal on all RF surfaces
2	US Cleaning + DI water rinse	60C DI water + mild detergent
3	RF tuning	
4	Hydrogen degasification	600C to 800C @ 1e-07 mbar — 600-650C required for CFFs
5	Light chemistry – 20-30 um	1:1:2 BCP @ 12 deg C
6	US Cleaning + DI water rinse	60C DI water + mild detergent
7	High Pressure Rinse	100 Bar pressure, ultra-pure water rinse, 100% surface coverage, ISO Class 4 or better
8	Clean drying and assembly	ISO Class 4 or better drying and assembly + slow evacuation

Damage layer removal via BCP is the only straight forward bulk material removal technique for any of the resonator geometries. Electropolishing or centrifugal barrel polishing fully fabricated structures would be difficult to implement and likely not worth the developmental effort. One may consider electropolishing sections of the resonator prior to final welding, but BCP will be necessary for final chemistry regardless. All geometries are amenable to flow-through BCP, however, achieving relatively uniform material on all RF surfaces may be difficult in all but the RF dipole geometry. Without proper flow optimization, removal ratios from low removal to high removal areas that are exposed to direct flow may range from 1:2 or 1:3 depending on how the BCP is exchanged within the resonator. BCP should be performed for a long enough duration to ensure sufficient removal (120 um or more) in the high magnetic field areas. Any post processing tuning technique should be able to compensate for differentials in material removal.

Hydrogen degasification can be successfully performed using the CERN high temperature furnace as described. The chosen temperature depends primarily on the construction of the resonator. If stainless steel conflat flanges are used, a lower temperature (600-650C) is required to prevent the knife edges from getting too soft.

High pressure rinsing (HPR) with ultra-pure water for field emission reduction is the most difficult process to properly implement with the non-axisymmetric resonator geometries. The goal for HPR cleaning should be to accomplish complete inner surface direct-spray rinsing regardless of the geometry. All areas that do not get rinsed can contribute to field emission as particles can migrate from low field to high field regions and become strong emitters. Shadowed regions, or areas where a direct high-pressure spray cannot reach, should be avoided if at all possible.

It appears that rinsing in multiple orientations and through multiple ports will be required for all structures with the RF dipole geometry the possible exception. The HPR process should be designed to limit the rinsing orientations and intermediate handling steps as each adjustment is an opportunity for contamination.

HOM couplers and other devices connected to the clean cavity must be just as cleanable and particle-free as the cavity itself. Of particular concern are the HOM couplers with their difficult to clean interior surfaces. Special cleaning techniques for these devices prior to clean assembly are likely required.

The cleanroom layout modifications in SM18 will provide sufficient space to accomplish the cleanroom cleaning and assembly tasks. Though cleanroom tooling and cavity manipulation was not discussed during this review, special consideration is required to maneuver and assemble the cavities to limit particulate contamination.

RF testing and cryogenic infrastructure modifications at SM18 were also presented. Cryogenic modifications, including transfer lines and new test dewars to support 2K operation are underway, however, a full operational schedule was not presented.

Project conflicts with other activities in SM18 are anticipated, especially for cryomodule testing. High-power testing capabilities are essential so full RF system integration in at least one RF bunker is required for the project.

Cavity performance diagnostics in development for the crab cavity program will be adapted from existing sources. If multiple resonator types will be vertically tested in SM18, the development of reliable second sound quench detection should receive priority since T-mapping systems are highly geometrically dependent. Quench detection in low-performing cavities can yield important insights into fabrication or processing errors. Therefore, in addition to second sound quench detection, local thermometry in suspected quench areas can be incorporated on repeated vertical tests.

Optical inspection with the Kyoto camera system will be useful in combination with second sound and local thermometry quench detection provided the quench is located in an area accessible to the camera. Alternative visual inspection techniques using high-quality borescopes or long distance microscopes and mirrors may prove to be valuable for quench locations out of reach of the Kyoto camera system.

A thorough summary of the APS SPX crab cavity prototype and Cryomodule under development at TJNL was presented. Topics of particular interest were the cavity alignment techniques, compact cryomodule design due to space limitations, and HOM designs. Though not discussed, APS SPX crab cavity cleanroom preparations require unique challenges due to the complicated waveguide HOMs. Techniques to overcome these challenges may be directly applicable to LHC crab cavity HOM cleaning.

3.5 CRYOSTAT CONCEPTS & ANCILLARY EQUIPMENT

Conveners: Vittorio Parma (CERN), Tom Peterson (Fermilab)

Alick Macpherson (CERN) – "Constraints on the 2016 Crab Cavities SPS Run"

Alick described the SPS location, SPS Pt 4, and various associated constraints for a crab cavity cryomodule test there. The topics described with some highlights from my notes are as follows:

- Cryogenics infrastructure (TCF-20 4.5 K liquefier) exists but can provide only limited cooling at 2 Kelvin after addition of 2 K pumping. 0.7 grams/sec in liquefaction mode so about 15 W maximum total heat load if all heat at 2 Kelvin, less when some capacity is distributed to the 4.5 K temperature level.
- A Mechanical Beam Bypass "Y-Chamber" for switching between two evacuated beam lines. The Y-Chamber system would allow cavities to be taken out of the beam line without breaking vacuum. Cryomodule must move with 340 mm motion using Y-chamber. 100 mm 2-K pumping line is main resistance to motion. Would need new Y-chamber for wider spacing. In detail, how to change out a cryomodule for tests of the 3 different cavity types is not resolved.
- An experimental cavern (ECX4) is close, provides a viable LLRF location, and is accessible during operation
- Beam line space available for crab Cavities + Instrumentation is quite limited. Alick provided dimensional details. SPS length available between double vacuum valves and BPMs = 3100 mm. Existing lateral spacing is 340 mm CL to beam line CL. Beam center to adjacent bypass pipe outer wall is 260 mm.
- If cavities on aisle side, need transport lane. Would like all couplers top and bottom due to lateral space constraints. Beam is 1200 mm above floor.
- A 3-D model of SPS space will be complete in January.
- 1 mm alignment constraint for cavities in SPS
- Crab Cavity space in SPS will not be free till 2015
- Limited access to SPS zone after SPS long shutdown
- Machine protection and response to failure modes are still under study

Sergey Belomestnykh (Brookhaven National Laboratory), John Skaritka (BNL) – "Thoughts on the Cryostat Concept"

Sergey described the BNL Quarter Wave cavity and provided a nice summary of what we need to know in order to do a cryostat design. Among items to know for a cryomodule design are:

- Heat budgets
- Number of penetrations
- Helium vessel and frequency tuner
- Fundamental power coupler and HOM couplers
- Magnetic shield requirements
- Cavity support and alignment requirements
- Cryostat space (size) limitations both in SPS and in LHC
- Shall we wait for the cavity design down-selection or start designing a "universal" cryostat?

Shrikant Pattalwar (CCLRC, Daresbury Laboratory) – "Cryostat Concepts, UK 4Rod Cavity"

Shrikant presented a top loading rectangular cryostat concept which provides a slim lateral profile, an advantage with the side-to-side physical constraints of the location in SPS, and relative ease of assembly / disassembly. It includes the use of invar with stainless steel incorporated into a triple-tube folded support to provide negligible net thermal contraction vertically for fixed cavity position. Shrikant also discussed the PED pressure code compliance issue. It would be an advantage in terms of reducing PED requirements if the maximum operating pressure could be kept at less than 0.5 bar gauge and liquid helium volume at less than 100 liters total for the cryomodule.

Dmitry Gorelov (Niowave Inc.) and Chase Boulware (Niowave Inc.) -- Cryostat Concept, ODU-SLAC RF Dipole

Chase presented the capabilities of Niowave in RF cavity development, fabrication, and testing. The cryostat concept is a cylindrical, all-welded vacuum vessel with either one or two cavities. The second beam tube would pass through the cryostat. For the DOE-HEP SBIR-funded cavity prototype shown in the conceptual design, the power input coupler comes out the head of the vacuum vessel below the beam tube.

General comments and discussion.

- Tuner access requirement? Many people favor tuner access for mechanical repair. We did not discuss it, but my comment is that, if the tuner includes a cold motor and cold mechanics, it would be nice to have access to the tuner without having to remove the cavities from the vacuum vessel.
- Space constraint in LHC for 2-4 cavities per CM? (Cavities on two beamlines, longitudinal constraint) Answer: YES, there are longitudinal spacing requirements, but we did not discuss any details. Focus was on the SPS tests.
- SPS 2 K pumping in tunnel? Location is not decided. Vibration must be considered so as not to create a microphonics problem.

- Wait for cavity design down-selection or start designing a “universal” cryostat? During this meeting we discussed having three cryostats, one for each cavity type. Preference would be no down-select before SPS test; but costs may constrain otherwise. A “universal” cryostat might not be practical due to different tuner port locations, etc. The answer might be neither of the above but for example begin the design for the first cavity which looks likely to be ready for test, if some leader in terms of schedule appears.
- First priority for planning SPS test cryostat is to get better heat load estimates and heat budget. We need thermal intercept plans, temperatures, etc., to see how it can fit into the cryogenic capacity constraints.
- We should consider a beam vacuum guard vacuum so cavities not cryopump the SPS beam line. Consider additional length which this adds within our limited space.
- The cryomodule for SPS is a difficult technical challenge even without space constraints or motion in SPS.
- We should do cold RF testing of the cryomodule on the surface before installation in the SPS beam line.

These notes are rather brief; the talks stand on their own and provide interesting information. The highlights of the meeting in terms of cryomodule design were the constraints described both physically in SPS and thermally given the existing TCF-20 liquefier as the cryo source. It was clear that not only will the integration of the cavity into the cryomodule be a challenge, but integration into SPS and close collaboration with CERN personnel for the SPS installation will be critical.

3.6 Fabrication, Schedule, SM18 Testing & Integration

Conveners: Erk Jensen, Rama Calaga

A revised planning of the HiLumi-LHC design study and the HL-LHC project was presented at the 2nd HiLumi-LHC Frascati meeting taking into account the extension of the Physics Run into 2013. In the new planning the crab cavities are to be installed in during the long shutdown 3 (LS3) foreseen for 2022-23. A significant amount of preparations are already taking place in the long shutdown 2 (LS2) in 2018. Therefore, it is mandatory that the crab cavity validation tests with beam take place in the SPS/BA4 region before LS2 as recommended by the advisory board for the LHC-CC11. It is therefore important to define the scope of the SPS tests while respecting the LHC constraints where feasible. Only if additional tests are mandatory at Point 4, tests in the LHC would be carried out following the SPS tests. However, it was already clear from the Frascati meeting that the transport of the cryogenic system from the SPS to Point 4 in the LHC is not practical and alternative solutions for Point 4 should be considered if the tests are judged necessary. Some preparations on RF, cryogenics and services are already planned to take place during LS1 in 2013-14. Imminent decisions for the overall crab cavity system should presently focus on the SPS tests taking into account the cryogenic, environmental (bypass), interface, safety and other remaining constraints. These constraints will be documented into a functional specifications for the crab cavity system and be frozen at the end of Jan 2013 to enable the respective engineering designs to progress based on these constraints.

News from 2nd HiLumi-LHC Frascati Meeting: A parallel session within the HiLumi-LHC workshop at Frascati was considered as a replacement of the annual crab cavity workshop series "LHC-CC12" in 2012. The contributions to the crab cavity WP4 session and the rest of the HiLumi-LHC activities can be found at this link. A brief reminder of the basic parameters for the crab cavity system was highlighted. Three cavities per IP side per beam should nominally provide a total deflecting kick of 10 MV which amounts to 3.3 MV/cavity at 400 MHz. These reference numbers were adopted after the input from SRF and optics constraints discussed at the LHC-CC11. It is now apparent that a total kick voltage of 11.8…13.4 MV per IP side per beam may be required using the updated optics scheme. If a strong constraint from the RF side requires the voltage to be reduced, a new scheme using an additional Q7+ magnet to adjust locally the optics functions at the location of the crab cavities to reduce the voltage to 8.2 MV. However, to progress on the R&D side, the nominal voltage of 10 MV is still assumed as a baseline until further cavity cold tests. These tests will indicate which total kick can be specified; new design parameters of either additional cavities or an additional magnet to offset for the cavity performance will be decided then. A further cost to benefit study will be required to finalize the ultimate option. Nevertheless, a 3-cavity system per IP side per beam is adapted as nominal to limit the probability of cavity trips and its impact on machine protection.

For the three potential candidates considered, common numerical tools are being used for comparative studies including HOMs, multipacting and n-pole errors. The HOM damping schemes presented have also made good progress with the use of newly designed coaxial high pass filters and hook-shaped couplers. Multipacting studies indicate that levels found in simulations at low field are "soft" and could be conditioned, while MP found at high fields have rather low impact energy to sustain multipacting. For the n-pole errors, detailed HFSS simulations have been performed for the most recent geometries and tracking studies using these field non-linearities have been carried out to study the impact on the long-term particle stability (dynamic aperture). Since all cavities now have *b3* as the first non-zero component, tolerances were given for *b3* based on its effect of feed-down to *b2* as a function of offset. Therefore, for the cavity with the largest *b3* component of approximately 4000 units, a 0.75mm offset is in the particle trajectory is given as a tolerance to maintain the dynamic aperture to the nominal level without crab cavities. The tolerances can be relaxed linearly with decreasing *b3*. For higher order components, tolerances will have to be specified in the future.

The SPS tests are considered as a mandatory step towards the crab cavity validation as LHC cannot be a test bed for such equipment. Several critical aspects of validation, commissioning, operation and machine protection will be verified during these SPS tests. In addition, possible beam measurements such as emittance growth, impedance, instabilities and appropriate feedback will be performed. Several beam experiments have already taken place in 2010-12 to verify the natural emittance growth in the SPS to differentiate it from the emittance growth induced by the crab cavities. However, the natural emittance growth is at least an order of magnitude higher than that expected for the crab cavities in the LHC. Therefore, a resonant external excitation at the betatron sidebands may be necessary to induce strong emittance growth, which can be later rescaled to LHC parameters.

The present schedule foresees preparation the SPS-BA4 region for cryogenic and RF system installations during LS1 and aims at installation of the cryomodule with two cavities in the 2015-16 Christmas break. For the cryogenic preparations, the existing TCF20 refrigerator will be checked for its liquefaction capacity before Jun 15, 2013. An upgrade from 4.5 K to 2 K will be performed in LS1 with an additional service module to the existing plant. At present a dynamic heat per cavity for a two cavity system is assumed to be 2.5 W. For the RF controls, it is assumed that an active feedback is key to reduce the impedance seen by the beam which is primarily depending on the loop gain. However, a tradeoff between a large feedback gain vs. noise should be taken in to account. In the LHC, the noise at the 1st betatron sideband is dominated by the TX noise and choosing a Tetrode/IOT as opposed to a Klystron will be advantageous to reduce the noise. Scaling from the Klystrons for the main RF cavities, a phase stability of 0.01° at 400 MHz seems feasible. For the LHC system, a strongly coupled LLRF system between the left and right cavities to regulate their set points at all times to ensure machine protection is considered baseline and under study. However, this requires a low loop delay and proximity of all RF systems to the cavities in a potentially high radiation area, which has to be foreseen. The cavity detuning will be necessary in the presence of feedback to make the cavity invisible during the injection and acceleration. This architecture and cavity operation with strong feedback will also be validated thoroughly in the SPS tests.

Machine protection simulations show that an ultrafast failure (less than 1-LHC turn) leading to an instantaneous phase change of 90° can lead to 1.7 σ of transverse offset and a total of 5 σ in case of failure of all 3 cavities with the same 90° phase change within one turn. A detailed analysis of the cavity field and phase behavior during a failure is under study to determine realistic failure scenarios and their impact. A better control of the transverse halo population could be an additional mitigation technique to avoid damage to the machine elements in case of rapid phase change. Instrumentation needs in addition to the present capability should be studied for fast detection of failures.

The HL-LHC overall project towards the luminosity upgrade and the HiLumi-LHC design study, which is subset co-financed by the EU, is now established and detailed web content exists to describe the various work packages and their roles and activities within this framework. The crab cavity is the work package 4 among the 14 other work packages within the HiLumi-LHC design study. Five official tasks within the WP4 were proposed in its initial form with several European institutes as beneficiaries and external partners from U.S. and Japan. Only task 4.4 relating to elliptical cavity development which was originally conceived as a backup solution is being revised to be removed as it might no longer be necessary. An intermediate activity report is now available and all future crab cavity activities will be coordinated and documented via this central web framework.

It was noted from the cryomodule sessions that a fixed design of the Helium vessel and tuner is necessary before advancing on the cryostat design. However, some advanced concepts for integration of the existing cavity, Helium vessel, tuner and cryogenics were already developed for the 4-rod cavity. It was accepted that CERN will provide the boundary conditions for the SPS cryomodule in the immediate future, which will be included in the functional specification document to be released end of Jan 2013. A master table for the three different cavities will be maintained to differentiate the design choices for the three cavities. It was concluded that the SPS cryomodule doesn't have to be identical to the final LHC cryomodule since many of the constraints of SPS and LHC machines are very different. Some of the basic design choices common to all three cavities for the SPS tests were already discussed at the workshop in detail.

- Test two identical cavities in one cryostat leading to three different cryomodules instead of a common test cryostat.
- Fundamental power coupler to allow for a top mounting configuration similar to that of the LHC.
- A bottom mounted coupler is possible, but not the preferred option,
- All cryogenic interfaces should also be on the top of the cryomodule.
- A 40 litre volume for available liquid Helium is recommended which can be extended up to 100 liters assuming an additional dewar supply which is to be foreseen.

Some open questions and comments relating to the Helium vessel and tuner:

> The total available space in the SPS and the final proposal for a 2nd beam pipe which is to be inside or outside the cryostat vacuum. This issue is now mitigated by providing a wider beam-to-beam spacing in the SPS bypass to allow for a beam pipe outside the cryostat vacuum. This also allows for swapping cryostats easily if multiple cryostats are to be tested in the SPS.
>
> Are tests at 4.5 K useful? As the nominal operating temperature is 2 K, it is highly desirable to test at 2 K. However, some useful tests will be performed at 4.5 K.
>
> Is there a dummy beam pipe at 194 mm for LHC compatibility? Further calculations of heat loads and integration of the tuners have to be performed to evaluate the necessity.

The required tuning range for SPS operation was discussed; a table was presented indicating that a range of approximately 60 kHz at different SPS energies would be appropriate. A minimum of 1.5 - 5.5 kHz of detuning (LHC) and a factor of 10 for the SPS for cavity transparency is required to place the cavity frequency away from the betatron sideband. Due to active feedback, a fast feedback is deemed not necessary during the detuning-retuning procedure. However, further studies have to be done to determine if a fast tuning system (beyond mechanical tuning) is required. It should also be noted that the Lorentz force detuning presented for the different cavities at the workshop were far larger (factor 10-50). Therefore, this frequency tuning, which is cavity specific, should be taken into account. A pressure stability of <1 bandwidth was specified and a resolution of the tuner should allow at least a factor 4 smaller (preferably factor 10) than the 400 Hz bandwidth. However, the bandwidth might be increased depending on available TX power which will be defined in the near future. Frequency changes due to fabrication, surface treatment, cool-down and other passive effects should be accounted for to define a final tuning strategy for each cavity.

The material choice for the Helium vessel is not imposed by CERN, however it was indicated that the use of titanium vessels lead to more complex interfaces and are presently not covered in the Harmonized European standards. Therefore, additional tests should be performed to define the standards. Due to almost negligible fields at the beam pipes, SS flanges are recommended; other flanges should also aim at SS to limit additional complexities from fabrication and seals. If a dummy beam pipe at 194 mm is present, it can be used as an additional reinforcement. The dummy beam pipe can reside in liquid Helium and thus can be inside the Helium vessel. The three Helium vessel and tuner concepts were outlined again under this point of view.

Fabrication of the different types of cryostat and their advantages and disadvantages should be reviewed. Challenges in the design choice, fabrication steps, integration along with feasibility of a two-cavity cryostat within the specified scheduled should be reviewed and mitigation should be discussed.

Cavity arrangement, support structure and the possibility for cavity alignment should be studied in detail. Some important points were already discussed in the previous contribution of beam-beam spacing and allowance for the dummy beam pipes for LHC compatibility. It was widely agreed that a two-cavity cryostat in the SPS seemed the best compromise from space, installations, cryogenics and minimum goals of the SPS tests. The support structure should be designed to be compatible with the final LHC system, which may include up to 3-6 cavities in a single module.

Taking into account the compressor suction pressure, control margin, relief pressure margin, pressure drop to relief and peak warm pressure, and a lower limit of 2.0 bar warm MAWP is practical for the ILC like modules. Maintaining lower peak pressures requires larger piping and shorter paths to the vents. Specifications on power per cm^2 for different parts of the cryomodule were given in case of a loss of vacuum to air. Several design features of the SRF equipment were described to outline the difficulty to define a precise pressure vessel code, which uniformly satisfies the safety regulations. In the U.S. a general requirement for a level of safety beyond the afforded ASME code is applied.

All major interfaces in the cryomodule were listed for requirement specifications including design considerations for cooling arrangement, pipe sizes, pressure stability, heat loads, alignment, support and other factors. Some general considerations for pipe sizes were outlined. Three examples of cryostat designs were shown (capture cavity, horizontal test cryostat and top-loading design). The top loading concept has some attractive features given the R&D nature of the SPS tests and the environmental constraints. This design approach is adopted by the 4-rod team, for which a cryomodule concept and cryogenic layout was developed and shown at this workshop.

For the overall schedule, it was mentioned that a design process for new cryostat or cryogenic box is typically 2 to 3 years. After a complete definition of requirements, details of associated components (e.g., tuner, input coupler) are known. With this information a conceptual design can take place within the first year. This leaves approximately 1 year engineering and design/drafting and another year for procurement and fabrication. Nevertheless this schedule is quite constrained. As an example, the schedule for the couplers was shown in detail. Tracing backwards in time from the time of installation in the SPS in 2015/16 Christmas shutdown, a material procurement and fabrication of all couplers should already be complete by the end of 2013. Therefore, all necessary specifications should be frozen within the first quarter of 2013 to keep the schedule.

Prior to the SPS tests, comprehensive tests of cavities, couplers and the assembled cryomodule will take place in the SM18 test facility at various time periods of the R&D. The final SPS cryomodule should first verify the compatibility from vacuum leaks, total heat load and RF performance before proceeding towards an installation into the tunnel. In addition compatibility of the cryogenic connections should already be foreseen in the SM18 test stand and test the movement of flexible conduits if necessary.

4 MEETING NOTES & COMMENTS

4.1 MEETING COMMENTS

Please see the executive summary for the highlight conclusions, action items are listed below

4.2 ACTION ITEMS AND OPEN ISSUES

1. A functional specification document for the crab cavities along with the first concepts for the cryogenic and RF system will be drafted and circulated among the collaboration by the end of Jan 2013.
2. A common coupler interface to the cavity with vertical mounting and dimensions will be finalized by Feb 2013 to proceed with the design and procurement of power coupler parts and test boxes.
3. A master table for the cryomodule general specifications to differentiate the three cavity design choices will be developed and maintained by CERN.