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Functional Specifications of the LHC Prototype Crab Cavity System

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Functional Specifications of the LHC Prototype Crab Cavity System

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Summary

This document outlines the functional specifications for LHC prototype crab cavities to be tested in the SPS, and describes a first look at the RF system, cryomodule and cryogenic aspects. These guidelines are prepared with input from experts at CERN and the HiLumi collaboration, including EuCARD and USLARP.

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1 Introduction

The LHC is now successfully operating for physics and progressing towards its design goals. It is the only energy frontier machine in high-energy particle physics for the foreseeable future. Maximum effort is now being put into to ensuring that machine and experiments operate optimally at their design performance in order to allow full exploitation of the physics potential of the LHC. However, already in 2006, a subsequent major luminosity upgrade (SLHC) was presented [1]. This focused on the need to achieve increased beam intensity and reduced beam sizes at interaction points (IPs) for higher luminosities. Increased beam intensities were to be achieved by upgrades of the injector chain and the reduction of the beam sizes by an upgrade of the inner triplets at the experimental interactions regions (IRs) 1 and 5 of LHC. This upgrade was primarily needed, as the existing triplets would have reached the end of their lifetime if LHC would operate at design parameters from 2007. The use of transverse deflecting cavities, known as crab cavities, was also proposed to correct the geometric effects of the wider crossing angles as a consequence of the reduced beam sizes with the IR upgrade. A number of collaborations have been put in place to study the performance of crab cavity schemes and to produce designs for such cavities. Excellent progress has already been made.

The present document describes the functional specifications for superconducting deflecting cavities and associated components foreseen for the LHC crab-crossing scheme, as requested by the LHC-CC11, in the executive summary [2]. General guidelines and requirements on the fabrication of the cavity and other equipment to comply with the CERN regulations are described with a focus on the prototype cavities foreseen to be tested in the SPS for a validation test prior to a full installation in the LHC.

Parameter	Unit	Nominal	Upgrade
Energy	[TeV]	7	
Protons/Bunch	[10^{11}]	1.15	1.7
Bunch Spacing	[ns]	50…25	
ε_n (x, y)	[μm]	2.5	3.75
σ_z (rms)	[cm]	7.55	
Bunch Length (4 σ)	[ns]	1.0	
Longitudinal Emittance	[eVs]	2.5	
β^* at IP1, IP5	[cm]	55	15
Betatron Tunes		{64.31, 59.32}	
Piwinski parameter: $\frac{\theta_c \, \sigma_z}{2\,\sigma^*} = \frac{\Delta_{in}\,\sigma_z}{2\,\beta^*}$		0.65	1.4…2.5
BB Parameter, ξ, per IP		0.003	0.005…0.008
Crossing-angle: θ_c	[μrad]	285	315…509
Accelerating RF	[MHz]	400	
Crab RF	[MHz]	-	400
Peak luminosity with crab cavity	10^{34} cm^{-2}s^{-1}	1.0	7…10
Pile up events per crossing		19	44…280

Table 1 General Parameter Table

2 Cavity Functional Specification

This section outlines general technical specifications, compatible with CERN regulations, to operate compact superconducting crab cavities in the SM18 test facility and SPS ring. It is foreseen that validation of the crab cavity system for deflection of high-energy beam in the LHC will require beam tests in the SPS involving two cavities in a horizontal cryostat. Further integration constraints from the LHC beam pipe separation impose a compactness constraint on any cavity design, as the overall cavity envelope is constrained to 145 mm (at 300K). Within this context, the cavity specifications are outlined in the following sub sections.

2.1 Frequency, Gradient & Quality Factor

At the LHC, the nominal cavity operating frequency is 400.790 MHz, which includes the complete set of couplers for input RF power, probes and HOM couplers. Note that as testing of bare cavities in a vertical test setup with low power (SM18) may not have the full set of couplers implemented, prototype cavities are to be tuned to this nominal frequency, taking into account the frequency changes from material removal during surface treatment and volume contraction during cool-down.

The nominal cavity gradient per cavity is 3.3 MV of integrated kick resulting in a total of 10MV in the LHC, with 3 cavities per beam per IP side [3]. Assuming a surface resistance of 10nΩ at 2K and a geometric factor of 100Ω, the cavity quality factor is estimated at $Q_0 = 1 \times 10^{10}$. Nominal operation with the beam on axis of the deflecting cavity should lead to minimal or zero beam loading. Therefore, only a small amount of RF power is required to sustain the field in the cavity without beam, which is determined by the external quality factor. The Q_{ext} will be adjusted so that the $(R/Q) \times Q_{ext}$ is constant for all three candidates, and is defined by the available RF power and beam loading tolerances.

Parameter	Units	Value
Frequency	MHz	400.790
Voltage /cavity	MV	3.3
Cavity β		1
Design Voltage	MV	3.0 (pushed=5.0)
R/Q	Ω	300-900
Q_0		$\geq 1\text{x}10^{10}$
Q_{ext}		$1\text{x}10^5$ - $1\text{x}10^6$

Table 2 Summary of Cavity Parameters

2.2 Operating Temperature

The operating temperature of 2K is chosen as a baseline for both the SPS tests and the final LHC installation [2]. This decision was based on the availability, global cryogenic and RF efficiency and the thermal margin available for machine protection aspects.

At a nominal voltage of 3.3 MV, Q_0 of $1\text{x}10^{10}$ and R/Q of 300Ω, the dynamic heat load due to the surface losses only is ~3.7 W/cavity at 2K. This leads to a manageable dynamic heat load of the final LHC system with 12 cavities per IR, even assuming a safety 50% safety factor on additional heat load.

As the BCS resistance at 400 MHz and 2K is ~1nΩ, cavity surface resistance is primarily dominated by the residual resistance contribution, and any improvement in surface treatment should lead to lower surface resistances and hence reduce the dynamic heat load proportionally.

For the SPS tests, we assume a two cavity cryostat, so the combined dynamic loss from the cavities will be ~6W at 2K. For a more detailed accounting of the heat loads from cavities, coupler interconnects and other elements of the cryostat, refer to section 4.2 in the cryogenics section.

2.3 RF Multipoles & Coupler Kicks & Limits

The crab cavity designs are such that, as a dipole mode cavity, they are not axially symmetric structures, and so potentially exhibit all higher order components at the operating frequency. To address these higher order components, the transverse kick for a particle traversing the cavity can be expressed a summation of its multipolar components (using the notation and formalism derived in Ref. [4]).

$$\Delta p_{\perp}(r,\phi)=\frac{1}{c}\int_{0}^{L}F_{\perp}\,dz=\sum_{n=1}^{\infty}\Delta p_{\perp}^{(n)}(r,\phi)$$

Transforming this into a magnetic kick for ultra-relativistic particles is useful to express in same units as magnetic multipoles with an essential difference being that RF multipoles are complex in nature.

$$B^{(n)}=\frac{1}{ec}F_{\perp}^{(n)}=\frac{nj}{\omega}E_{acc}^{(n)}$$

Using this formalism, the integrated strengths of the multipolar components for the three cavity shapes presented at LHC-CC11 were calculated [4], and the updated multi-pole values are given in Table 3. It is important to mention that the imaginary part of the kick of all multi-poles is negligible within the accuracy of the calculation hence their contribution to the crabbing is small.

	MBRC	Double Ridge	Quarter Wave	UK-4Rod
b_2	55	0	0	0
b_3	7510	4500	1070	1162
b_4	82700	0	0	0
b_5	2.9×10^{6}	0.4×10^{6}	-0.1×10^{6}	2.29×10^{6}
b_6	5.2×10^{7}	0	0	0
b_7	5.6×10^{8}	3×10^{8}	7×10^{6}	6.38×10^{8}

Table 3 Multipole components of the three cavity prototypes

Nevertheless, the multi-pole contribution to the tune, chromaticity and higher order aberrations to the beam are calculated with the absolute value of the multi-pole coefficient. Using the optical functions on the left and the right of the interaction regions and the largest values of the multipolar components up to b_3, a chromaticity modulation of about $8\text{x}10^{-2}$ is observed. For the largest value of b_3 (4500), long-term particle simulations indicate an orbit stability of approximately 500 μm to restrict the dynamic aperture change by less than 1σ. Therefore, a reduction of the b3 multipolar component by approximately a factor of 3 by appropriate cavity shaping is recommended to relax the orbit tolerance to >1mm. This orbit stability is compatible with the beam loading aspects (see RF power).

2.4 Impedance Budget & HOM Power

On resonance, the impedance of the fundamental deflecting mode is cancelled between the positive and negative sideband frequencies, which are symmetric around ω_{RF}. When the cavity is not operational, it is detuned, and the impedance of the fundamental deflecting modes will be damped by appropriate feedback (see LLRF).

Both narrow band and broadband impedance should be minimized throughout the entire energy cycle as LHC will accelerate and store beams of currents exceeding 1 Amp DC. Tolerances are set from impedance thresholds estimated from Ref. [6].

The longitudinal impedance has approximately a quadratic behaviour in the region of interest with the minimum threshold value at approximately 600 MHz. The total maximum allowed impedance from each HOM for all cavities, assuming that the HOM falls exactly on a beam harmonic is set at 2.4 MΩ. Assuming 12 cavities per beam (6 per IP), the longitudinal impedance cannot exceed 0.2 MΩ per cavity. For example, a mode with an R/Q of 100 Ω has to be damped well below a Q_{ext} of 2000. Adding a safety factor of 2, we recommend a Q_{ext} <1000. The Q_{ext} will have to be scaled with the appropriate R/Q’s for each mode in the 0-2 GHz range. Modes with frequencies above 2 GHz are expected to be Landau damped due to natural frequency spread and synchrotron oscillations.

In the transverse plane, the impedance threshold is set by the bunch-by-bunch feedback system with a damping time of τ_d= 60 ms [5]. Assuming the pessimistic case that the HOM frequency coincides with the beam harmonic, the maximum impedance is set at 2.7 MΩ/m at injection and 1.5 MΩ/m at top energy for a beam current of 1 A. Again, assuming 12 cavities per beam, the maximum allowed impedance per cavity is 0.225 MΩ/m at injection and 0.125 MΩ/m at top energy. Transverse impedance from each HOM in the 0-2 GHz range should not exceed this limit per cavity. Modes with frequencies above 2 GHz are expected to be Landau damped due to natural frequency spread, chromaticity and Landau octupoles.

2.5 Cavity Material

For cavity construction, the recommended material is high purity bulk Niobium with a Residual Resistivity Ratio (RRR) >300, and the cavity surface should be in a fully annealed condition. Material should conform to R04220-Type 5 as per ASTM B393-09e1 with additional and overriding requirements as specified in this document. Chemical composition for main impurities should be limited to the amounts listed in Table 4.

Element	Max Content wt%
Ta	0.050
W	0.007
Ti	0.005
Mo	0.005
All other metallic impurities, each	0.003
H_2, N_2, O_2, C	0.001

Table 4 Impurities tolerance for cavity material.

2.6 Cavity Tuner

Due to the tight transverse space constraints in the final LHC configuration, the tuning system should be adapted to fit within the specified transverse distances. Therefore, in both horizontal and vertical orientations, the tuner geometry should respect the LHC beam pipe spacing of 194mm and be compatible with any SPS envelope requirements. The tuning ranges specified do not include the warm-to-cold frequency change as it is cavity specific and should be accounted for in the design stage to arrive as close to the nominal frequency of 400.79 MHz. The cavity will be cooled by saturated superfluid helium at 2 K and about 20 mbar operating pressure. The expected pressure stability of the helium during operation is about 1 mbar. The cavity should be designed in order to minimise the sensitivity to pressure fluctuation, so that the induced detuning is significantly lower than the minimum cavity bandwidth.

The Lorentz detuning has also to be minimised by design, and compensation with tuner has to ensure safe operation within the minimum cavity bandwidth.

For beam tests in the SPS a slow mechanical tuner is required to bring the cavity on resonance in the energy range of the SPS (±60 kHz). In addition the tuner should allow for detuning or retuning of the cavity at a safe frequency, defined in terms of including cavity transparency and the suppression of the coupled bunch instabilities. Table below summarizes the potential energies at which SPS can be operated for crab cavity tests and their corresponding RF frequencies compared to that of the LHC operation.

Parameter	Unit	LHC	SPS		
Energy	GeV	450-7000	120	270	450
Frequency	MHz	400.79	400.73	400.78	400.79
ΔF_0	kHz	0	-58.2	12.2	-2.4
Bandwidth	kHz	0.4-4	0.4-4	0.4-4	0.4-4
Detuning	Hz	±5.5	±21.7		

Table 5 Detuning ranges for the LHC and SPS.

During the LHC beam injection, ramp and flattop, the cavity should be maintained as transparent as possible by means of detuning. A detuning frequency should be kept away from $Q.f_{rev}$ where Q is the betatraon tune to suppress coupled bunch instabilities in the crabbing mode for the growth rate to stay below the threshold set by the transverse damper (τ=60ms). The largest detuning expected is approximately ±5.5 kHz in the LHC and approximately ±21.7 kHz in the SPS. The detuning requires a resolution of at least ¼ of the final cavity bandwidth due to available power limits. Additional studies have to be carried out to verify if a tuning speed higher than the mechanical tuner is required if limitations arise from feedback and/or orbit control.

It should be noted that the cavity is to be either operated at the nominal constant voltage over an entire fill or with the possibility of varying the cavity voltages over the stable beams period of the fill (typical mean stable beams duration is ~12 hours). For the latter, the cavity-tuner design should account for the required frequency changes due to gradual Lorentz force detuning (approximately 0.5-1MHz) which can be well above the ±60kHz slow tuning range required for the SPS test in the some of the designs.

2.7 Cavity Welding and Coupler Flanges

Significant experience in welding complex shapes of bulk Niobium cavities already exists, and each cavity design should employ the appropriate fabrication sequence according to the shape and complexity of the resonator. Complex electron-beam welding at high surface field regions should be avoided, as this may negatively affect the cavity performance.

A general guideline, prior to the weld sequence, all parts should undergo an ultrasonic degreasing and chemical etching (or electro-polished) to remove at least a 20μm surface layer, and this should be followed by a rinse to remove any chemical residue. All welding should be performed with 100% penetration, and all welds must retain a smooth inner surface. Pressure of the electron-beam welding chamber should be maintained below $5\text{x}10^{-5}$ mbar, and Niobium vapour from welding should be evacuated. After the assembly, the cavity must be measured for dimensional and weight tolerances, and details of welding sequence and non-conformities provided to CERN.

Frequency measurement of the resonator should be carried out after the final weld step and appropriate adjustments be made to tune to the specified resonant frequency (preferably under vacuum). Bead pull measurements of the deflecting mode should be performed to confirm the symmetry of the field across the cavity and its deviation from the simulated field along the axis. Further higher order multipolar components will be measured at CERN with a dedicated 3D bead-pull setup.

The majority of the flanges should be manufactured in stainless steel and be joined to the niobium tubes by brazing. The flanges material to be used is type X2CrNiMoN17-13-3 (1.4429, AISI 316LN) stainless steel blanks for ultra-high vacuum applications requiring vacuum firing, procured according to CERN technical specification N° 1001-Ed.4-11.10.2006. CERN can provide this material if requested.

2.8 Chemical and Heat Treatment

Due to the complexity of the cavity geometries, only buffer chemical polishing is recommended. However, electro-polishing can be foreseen in future if necessary for improved performance. Acid treatment is performed to remove the cortical layer and defects from welding, machining, oxidation and other impurities on the surface layer. All chemical etching on the Niobium surface should be performed with an active flow of acid mixture. The mixture typically consists of HF (48%), HNO_3 (65%) and H_3PO_4 (85%) in volume ratio of 1:1:2 with the phosphoric acid as the buffer to stabilize the rate reaction. The bulk etching of the surface should remove approximately 15-20 μm, preferably using a rotational mechanism to ensure uniform removal of material. If a vertical setup is used, a rotation to tilt the cavity upside down could be foreseen during the surface treatment. To regulate material removal to ~1μm/min at a temperature $<10^0$C, a flow rate should be used, and the cavity should be cooled by external chiller spray on the surface to keep the temperature between $5\text{-}9^0$C. The BCP if possible should be performed in one complete go. All flanges will be covered with standard plastic (Viton) material and appropriate seals.

Heat treatments are performed typically for hydrogen degassing to avoid hydrogen disease. It is typically performed at 600-650 ^{0}C for greater than 24hrs, until equilibrium of the vacuum pressure is reached in the furnace. A Hydrogen concentration of 1ppm at a pressure of less than 10^{-7} mbar or smaller is a reasonable target. After heat treatment, a light chemistry to remove a thin layer of 15-20 μm should be performed to remove any impurities deposited on the surface.

2.9 High Pressure Water Rinse & Degreasing

A high-pressure water rinsing procedure is mandatory to remove any dust particles and impurities that could enhance the local surface fields and invoke field emission. It has been established that a high-pressure water rinse has shown to improve the high field Q-slope in several SRF cavities. All additional parts assembled into the cavity vacuum should be cleaned appropriately to ensure cleanliness of the cavity

2.10 Leak Tightness

A leak tightness check is to be done after all welds, surface treatments, and heat treatments to ensure the vacuum pressure to be better than 1 x 10^{-10} mbar can be maintained. For structural integrity during the cavity cool down cycle to 2K in a vertical test cryostat, the bare cavity under vacuum must withstand an external pressure greater than 2.1 bar. The CERN team will verify the mechanical stiffness of each design and recommend the appropriate mitigation technique to ensure safety of the cavity and the environment.

3 Specifications of Cavity Enclosures

3.1 Pressure Vessel Code

In the frame of SAPOCO 42 at CERN (defining the Organization’s policy in terms of safety), the safety regulations on mechanical equipment (SR-M) [7] applies, supported by the general safety instructions for standard pressure equipment (GIS-M2) [8]. In particular, the European directive 97/23/EC [9] provides the health and safety requirements for pressure equipment. According to which specific requirements apply, the pressure equipment is classified into four categories (I-IV) to define the limits of applicability. In each design, the determination of the category has to be carried out to appropriately place the pressure equipment and conform to those requirements.

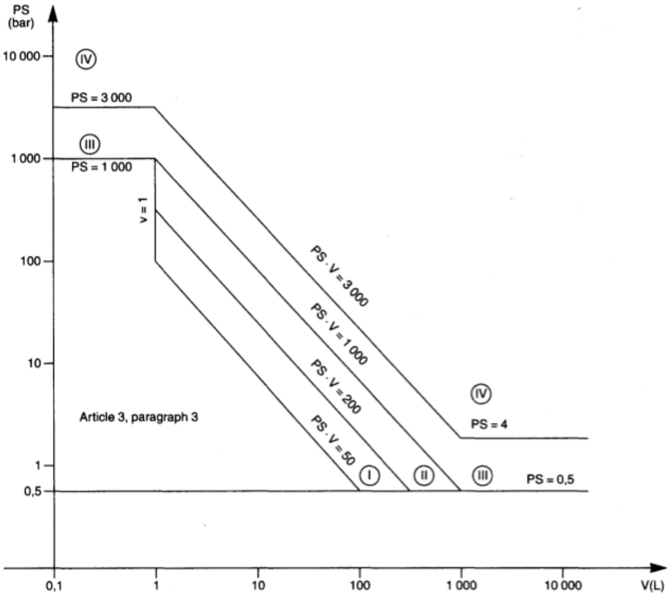


Figure 1 Assessment of risk category (European Directive 97/23/EC)

In a horizontal cryostat configuration, the pressure equipment will consist of several layers outside the cavity body. The first enclosing vessel is the Helium Tank maintained at 2K. This vessel will be shielded with additional copper thermal shields at 80K and any additional magnetic shields. The outer most steel shell structurally maintains the multi-layered shielding and the cavity with appropriate support structure and also separates the cryostat vacuum from the exterior.

The cavity, helium vessel and cryostat should be designed to withstand the maximum pressure taking into account the entire cooling cycle and the respective material properties. Appropriate relief valves on the cryostat and Helium vessel should be designed in case of a sudden pressure release to ensure the safe evacuation and maintain the integrity of the cryostat.

The pressure conditions for SM18 and SPS test environment are summarised in the table below:

Test environment	Safety valve set-point	Maximum allowable pressure (PS)	Test pressure (1.43xPS)
SM18 Test cryostat	1.5bar±0.15 *(abs)	1.5bar (abs)	2.1bar (abs)
SPS	1.8bar±0.15* (abs)	1.8bar (abs)	2.6 bar (abs)

Table 6 Pressure conditions for the SM18 and SPS test environment.

In particular, the cavities that will undergo SPS tests have to be designed for a maximum external pressure of 2.6 bar. The corresponding helium tank has to be designed for a maximum internal pressure of 2.6 bar.

All the cryo-module assembly: cavitie(s), helium tank(s), vacuum vessel have to be treated for the same risk category as the most critical one. From the figure above assessing the risk category, a pressure vessel has to be treated as risk category I if the (maximum allowable pressure * fluid volume) is greater than 50 bar * liters and smaller than 200 bar * liters. In particular, for a maximum allowable pressure of 1.8 bars, a helium tank enclosing a volume of 30 liters of helium has to be treated as risk category I.

3.2 Helium Tank

The baseline helium temperature used to cool the cavity is 2K at a pressure of about 20 mbar (saturated superfluid helium). The helium tank has to be designed accordingly. In particular, the helium tank has to be dimensioned correctly in order to extract the maximum heat load dissipated in the cavity, since the heat flux in superfluid helium depends on the bath temperature and on the helium channel dimension. As explained above, the helium tank for the SPS tests has to be designed for a maximum internal pressure of 2.6 bar.

The volume of helium to be contained by the helium tank should be minimised as much as possible due to limitations in cryogenic infrastructure for the SPS tests. Ideally the maximum volume should be 40 liters, however this value should not be a limitation for the design of the helium tank.

3.3 Static Magnetic Field Shielding

Degradation of the surface resistance of the superconductor (and hence the cavity Q) can occur due to trapped DC magnetic flux, and this can arise from stray fields in the vicinity of the cavity or from sources such as the earth's magnetic field. For any such external magnetic field, the contribution to the cavity surface resistance (assuming a RRR>250), is estimated to be

$$R_{mag} = 3[\mathrm{n\Omega}] < H_{ext}[\mu T] > \sqrt{f[GHz]}$$

Assuming a geometric factor of approximately 100, the R_{mag} has to be below 1-2nΩ to maintain the total surface resistance to below 10 nΩ. To achieve this magnetic shielding in the cryostat should reduce the external magnetic field on the outer surface of the cavity to below 1□T field to achieve the desired quality factor of Q = 1x10^{10}. For reference, the earth's magnetic field has a horizontal component of 20 μT and a vertical component of 44 □T.

Numerical simulations with shielding material for each cavity design should be carried out to determine the thickness and μ_r for the shielding material in order to achieve this specification. The presence of ports and any openings leading to leakage should be studied in detail. Simulations should include external stray field contributions from the LHC tunnel, separation dipole on the IP side of the cryostat, and the Q4 quadrupole on the non-IP side. It is recommended to evaluate the effect of shielding inside and outside the helium tank in terms of both effectiveness and compactness of in the transverse dimension. It is estimated that a shield internal to the helium tank made of cryoperm (μ_r=15000) will have to be at least of 1mm in thick, but for effective shielding a thickness of 3mm or larger maybe required.

3.4 Cavity Alignment

Severe alignment constrains result from the transverse and longitudinal alignment tolerances derived from LHC performance requirements. To summarize these constraints, based on performance issues, are divided into the following the categories:

1. Transverse rotation of the individual cavities inside the cryostat.
    a. Cavity rotation in the x-y plane introduces a parasitic crossing angle in the non-crossing plane, thereby counter acting the crossing angle compensation as well as giving non-closure of the crab bump in the crossing plane. To limit this, it is required that the transverse rotation tolerance be 0.3^0 per cavity.
2. Tilt of the cavity with respect to the longitudinal cryostat axis.
    a. Cavity tilt with respect to the cryostat axis should be less than 1 mrad.
3. Transverse displacement of cavities w.r.t each other inside a cryostat.
    a. Intra-cavity alignment in the transverse plane with respect to the cryostat axis should not exceed the 0.7 mm tolerance set by the multipolar effects.
4. Longitudinal displacement of cavities w.r.t each other inside a cryostat
    a. Longitudinal displacement of the cavities from their nominal position is not crucial as deviation can be compensated by adjustments of the individual cavity set point voltages to account for changes in the optical functions. However, this displacement should be minimized to limit the cavity voltage imbalance to less than 0.1% of the nominal voltage, which is approximately 1-2 cm. Thus the longitudinal displacement tolerance is set at of the cavities 10mm.

3.5 Temperature Mapping

For monitoring cavity temperature, thermal sensors can be mounted on the support structure, with placement likely to be on the lateral beam pipe region close to where the magnetic fields are maximal. Four such sensors should suffice, but some additional sensors if available could be placed on the cavity body for additional temperature measurements.

Second sound acoustic transducers may also be used for quench detection. Such sensors are already used in the SM18 setup, but temperature mapping system requires additional work, which is not foreseen at CERN at this time. Therefore, if these transducers are to be installed on an assembly, it is the cavity builders should assume responsibility for fabrication and integration of the temperature mapping flexible tapes.

4 Cryogenics for SPS BA4 test

For the cryogenic requirements of the crab cavities in the SPS, it is assumed that the crab cavities will be cooled with superfluid helium at 2K (using saturated helium bath solution), and that independent 80K circuits will be installed to minimize 2K heat loads where appropriate (i.e. couplers, cold-warm transition, thermal screens). It is also assumed that two cavities will be installed in one common cryostat (minimization of the heat load).

4.1 Cryogenic distribution

Cryogenic infrastructure in SPS BA4, having currently limited 4.5 K cooling capacity (being evaluated in 2013), will be modernized and modified to provide cooling power at level of 2 K. In the planned configuration the helium distribution between TCF20 cold box and the cryostat will consist of cryogenic transfer lines, liquid helium buffer tank and service module equipped with sub-cooling heat exchanger and expansion valve. The return line of 2 K helium gas will go from cryostat to service module to heater to then pumping unit, and then back to either the cold box or a He recovery line. The schematic layout of this infrastructure is presented in Figure 2.

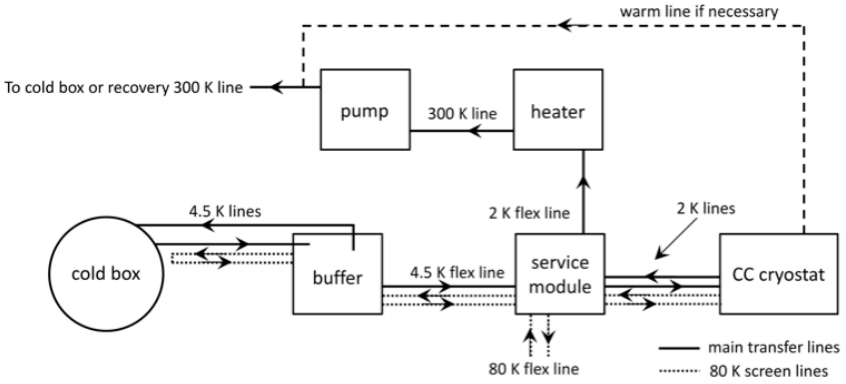


Figure 2 The layout of SPS underground cryogenic infrastructure for crab cavities testing

4.1.1 Buffer tank

The limited cold box capacity will be used to compensate static heat load of the system. To counter the dynamic heat load, a 200 litre buffer tank is included in the cryo line, and will be filled with 4.5 K liquid helium prior to operation of the cavities. The accumulated helium is then to be consumed to compensate cavities dynamic heat load during cavity operation. The capacity of the buffer will be calculated to cover about 8 hours of cryostat operation (2 cavities).

4.1.2 Service module

The cryogenic valve/interconnection box – called service module will be placed on a movable support table together with the crab cavity cryostat, and connected by rigid cryogenic transfer lines. The main components of this service module will be a sub-cooling heat exchanger and an expansion valve. All transfer lines from the service module to the buffer tank and the heater unit will be designed to accommodate the 500 mm movement of the support table, which is required when switching the cryostat in/out of the beam line. Transfer lines

All cryogenic transfer lines will be insulated with vacuum and thermally protected with actively cooled 80K screen. Low points should be avoided in the construction of the transfer lines. Flexibility of the lines (see flex lines indication in Figure 2) will be assured with typical elbow or omega shape.

4.1.3 Cryostat circuits

The cryostat interface will consist of four lines: 2K supply, 2K pumping, 80K inlet and 80K outlet (a warm recovery line can be added and connected with low pressure if necessary) lines, and the basic scheme of the cryostat circuits is presented in Figure 3. The transient operations (cool down/warm up) do not require additional piping or valves and for operation in the SPS, such a solution is compatible with expected transient duration.

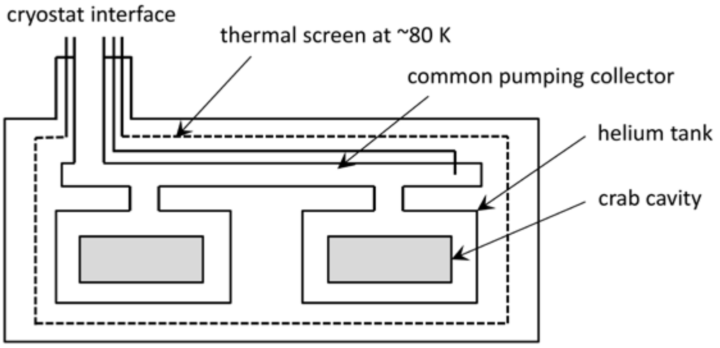


Figure 3 Crab cavities cryogenic circuits scheme

The helium tanks for two cavities will be separate but connected with a common pumping collector as presented in Figure 3. This constraint that the pumping collector is the only hydraulic link between the two helium tanks is required in an attempt to give cryogenic independence to the two cavities, so that under quench conditions the cavities are only indirectly coupled. The outlet of the 2K supply line in the pumping collector should be placed on the opposite side with relation to the pumping line outlet. The pumping collector will be used as a phase separator for both helium tanks.

HL per cryomodule		HL @2K [W]	HL @ 80K (TS)	Comment
Dynamic	Deflecting mode	5.0	-	Confirmed?
	Other Order Modes	TBD	TBD	
	RF Coupler	TBD	TBD	
	Beam Current	**0.5**		Tentative
Static	Radiation (cavity +Phase Sep. Cold surface + Thermal Shield	**0.2**	**6.8**	Rescaling from LHC o W/m2 @ cold mass o 1.7 W/m2 @ Thermal shield
	CWT	0.557(rad) + 0.892(cond) = 1.5W x 2 = **3.0**	0.625(rad) + 5.926 (cond) = 6.6W x 2 = **12.6**	1 heat intercept @ 80K in the middle
	Supporting System	**1.0**	**3.3**	6 tie rods/cavity
	RF Coupler	0.501(rad) + 0.853(cond) = 1.4W x 2 = **2.7**	0.587(rad) + 5.662 (cond) = 6.3W x2 = **12.6**	1heat intercept @ 80K in the middle
	Cables & Instrumentation	**1.0**	-	Tentative
	Other order modes	TBD	TBD	Design dependent
Totals		~**13.4** + TBD	~**34.9** +TBD	

Table 7 Summary of heat loaded on the Crab Cavities cryomodule for the SPS tests

The cavity couplers body will be thermalized at 80K in half of distance between 300K and 2K interfaces (not represented in Figure 2).

The cryogenic distribution interface for the cryostat will be provided from the top. The dimensions of the interface piping will be following:

- Pumping line ID=100 mm
- 2 K supply ID=10 mm (size imposed by service module J-T valve connections)
- 80 K supply/return ID=14 mm

Positioning of the interface layout is presented in section about the cryostat design.

4.2 Heat loads

The assumption for the heat loads is defined as the key values to be respected in relation to the limited cold box capacity. Table 7 presents calculated heat load values [10].

All the above heat load values will be multiplied by a 1.5 uncertainty factor to provide the overall heat load budget for the SPS cryomodule design. The heat load of the cryogenic distribution will be calculated, multiplied by factor of 1.3-1.5 and added to the cryostat heat load. The total load will have to be compatible with the refrigerator capacity.

In the case of missing TCF20 cold box capacity, increased capacity of the cryogenic supply devices (possible scenarios: installation of second TCF20 cold box, replacement of existing cold box by one with bigger capacity – to be studied) will have to be studied. Such situation would have a significant impact on planning and budget.

4.3 Instrumentation

The cryostat should be equipped with following instrumentation:

- Helium level measurement – each helium tank should be equipped with a level gauge, allowing for helium level measurement from the bottom through the phase separator (each gauge should allow for helium level regulation in the phase separator collector).

- Pressure measurement on the saturated helium bath is to be provided (PT x 1),

- Temperature measurement on each cavity helium tank is to be provided, installed on the bottom of each helium tank (suggested: CERNOX type transducer, TT x 2),

- Electrical heaters of 50 W are to be installed on each helium tank (EH x 2)

- Temperature measurement on 80 K line is to be provided (can be outside the cryostat, TT x 2 on inlet and outlet lines)

All sub atmospheric instrumentation/safety devices with ambient air interface will have to be equipped with appropriated helium guard.

4.4 Specific requirements for the cavity/helium tank/cryostat

4.4.1 Mechanical requirements

The combined cavity with helium tank assembly is to be designed to withstand pressure increase of ΔP of 2.6 bar without plastic deformation at ambient temperature. Safety devices should protect the cavity and the cryostat from such pressure rise situations.

Design pressure for the cryostat assembly should be based on installed safety devices according to their design rules; a cryostat equipped with a safety valve set at 1.8 bar and a rupture disc set at 2.2 bar)

- Both safety devices will be installed in the way to avoid potential projection of helium towards the passages or transport areas. Deflector installation is to be analyzed, but preliminary positions for the rupture disc and safety valve have been proposed on transfer line between the service module and cryostat – on the service module side.

4.4.2 Volume and layer of 2 K liquid helium

The minimum superfluid helium layer covering the cavity wall should not be thinner than 5 mm. The volume of helium in the helium tank should be rationally minimized, if possible below 30 litres of helium per cavity (60 litres in total including liquid helium in the phase separator collector).

4.4.3 Pumping collector and connection to the helium tank

The pumping collector should have a diameter of 100 mm (additional buffer volume for the cavities operation). The cross section of the connection between the pumping collector and the helium tank should have the same diameter/cross section as the pumping collector, and should have a length of at least 50mm.

During operation the phase separator collector will be filled with superfluid helium at about half of its volume.

5 RF Power and Couplers

For the RF power and fundamental power couplers CERN will provide:

1. Window Assembly: ceramic window, antenna and body with e-, light detector and vacuum flanges.
2. Outer Line with its inner copper coated
3. All in one RF & vacuum copper gaskets to be mounted on both sides of the Outer Line.

5.1 Power Coupler Parameters

It has been agreed during December 2012 FermiLab Engineering Meeting [11] that Antenna will be 27 mm diameter and DT 62 mm. Cavity flange and Outer Line cavity side flange will be DN63 Stainless Steel 316LN, with their inner diameter of 62 mm and outer diameter of 114 mm. Number of holes will be 8 x 8 mm.

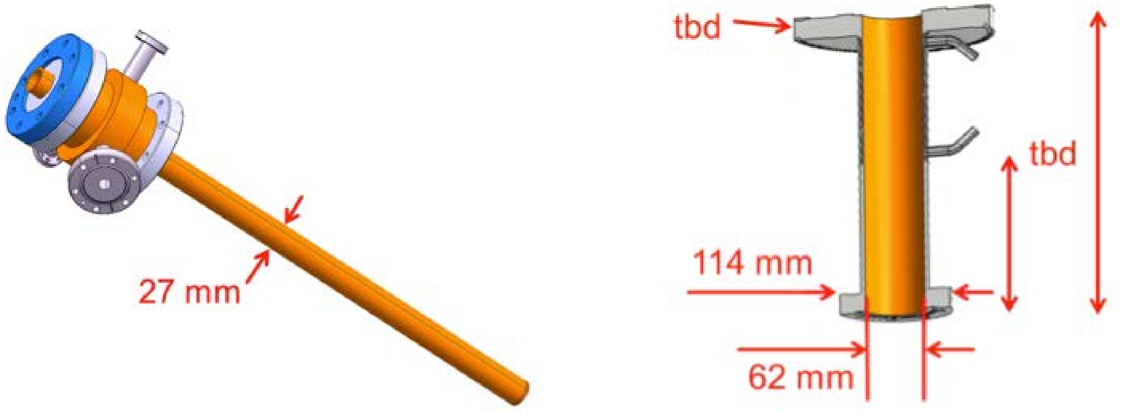


Figure 4 The fundamental power coupler; items to be provided by CERN (window assembly and Outer Line).

The Outer Line could be partially plain metal and partially a Double walled Tube (DT). The total length, as well as the air-side flange still has to be confirmed by Cryomodule team.

All cavity design teams are to confirm/provide the end shape of the antenna as well as the penetration distance of the antenna from the cavity flange reference plan.

Cavity	End shape	Distance between cavity flange plan toward end of the antenna
UK-4 Rod	R13.5 mm	To be provided
Double Ridge	R13.5 mm	To be provided
Quarter Wave	To be provided	To be provided

Table 8 Summary of the fundamental power coupler antenna details.

Coupler ports will have to be perpendicular to beam pipe, and the location of the port is to be confirmed by each cavity design team, but it is preferred that the port be on the top of cavity.

Further, the cavity vessel will have to be robust enough to stand couplers and waveguide items. Total weight of the window and Outer Line will approximately be 15 kg. Total weight including waveguide system will be close to 35 kg. This has to be very well addressed, especially if the orientation angle differs from being vertical.

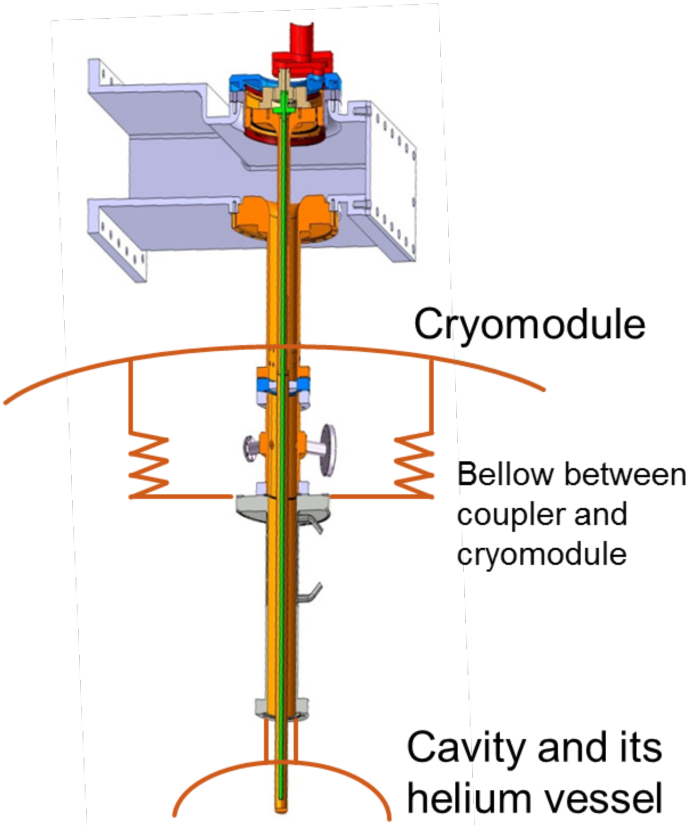


Figure 5 Cavity vessel will have to stand entire coupler weight

5.2 RF Power System and Ancillaries

For the SPS tests two independent 400-MHz, 40-80 kW RF power amplifiers will be prepared with a bandwidth of 1 MHz. During the LEP operation, four 352-MHz Tetrode amplifiers were in service at SPS. One of the four was later modified to operate at 400 MHz with a 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 potentially reach 50 kW output, and tests will be performed in 2013 to verify their maximum output power, efficiency and stability.

A short distance between the cavity and Tetrode amplifiers with a very short waveguide as shown in Figure 6 is a compact and preferred solution. A 2.5 kW solid state driver and high voltage power supplies along with other peripherals may reside either in the SPS ECX4 cavern or BA4 surface building and therefore shielded from radiation. Limitations from the round turn loop delay for cavity control should be taken into account for the fast feedback, which may become necessary in the LHC to ameliorate effects from fast RF failures.

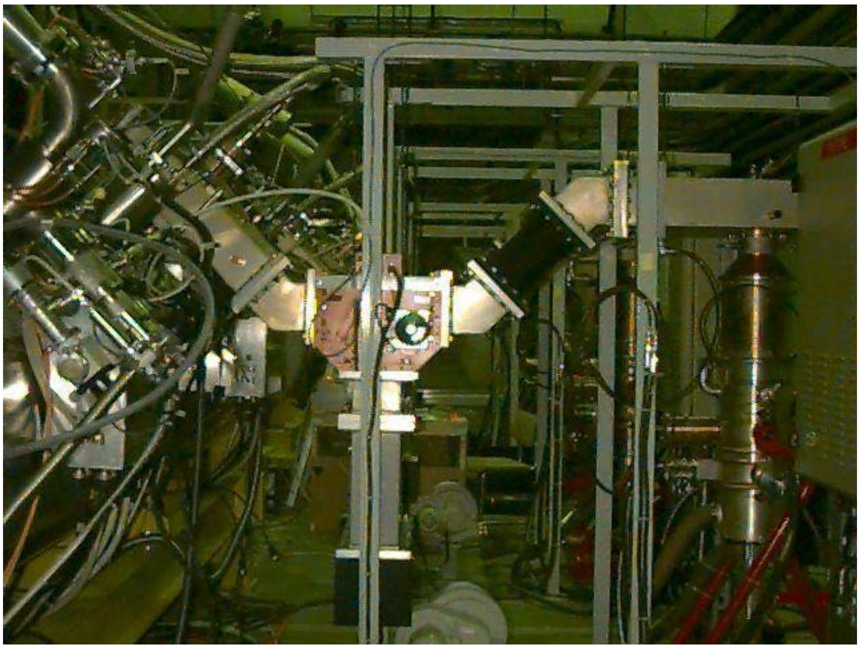


Figure 6 LHC main RF module test layout in the SPS circa 1996.

5.3 Pickup

A minimum of one pickup probe for each cavity is required with an appropriate coupling to fundamental deflecting mode of the cavity resulting in approximately 1W of output power at the cryostat. The number of HOM couplers is cavity specific to meet the impedance budget for a total of 12 cavities per beam (see impedance budget). A small amount of HOM output power (few watts) should be available for measurements for each coupler which will be used for impedance analysis during the SPS beam tests and potential safety interlocks in the final LHC.

6 LLRF Architecture for SPS & LHC

The LLRF must include the following functionalities

- A Tuning Control to keep the cavity on-tune during crabbing operation, and to keep the cavity parked at an optimal detuned position during filling, ramping and collisions without crabbing.

- A Cavity Field Control to keep the deflecting field at the exact demanded value. This system must allow for synchronized variations in several cavities (ramping of the crabbing field, counter-phasing between cavities). It must compensate for the transient beam loading caused by the modulated beam current (presence of gaps) to keep the field exact for all bunches. It must guarantee longitudinal stability (coupled-bunch oscillations) with the high beam current by effectively reducing the impedance of the cavity fundamental resonance [12]. The system must also reduce the noise in the cavity field (caused by electronics, transmitter noise, fluctuations in cryo pressure, mechanical vibrations) to minimize transverse emittance growth. Field control must be achieved during collisions with crabbing, but also during filling and ramping with zero crabbing field. Smooth transition between no-crabbing and crabbing must be realized.

- A system to synchronizes the phase of the RF kicks with the exact passage of the bunches. For each ring, the eight accelerating LHC cavities are driven from a single reference generated in a surface building above IP4 [3]. These two signals must be sent over phase-compensated links to IP1 (ATLAS) and IP5 (CMS). An alternative would be to re-generate the bunch phase from a local Pick-Up. The system must also cope with the planned modulation in bunch spacing (see below). For the SPS test, the 200 MHz reference must be sent from BA3 to LSS4 and multiplied to 400 MHz.

6.1 Coupled Bunch Instabilities

With accelerating cavities, in high beam current machines, the problem of (in)stability caused by the cavity impedance at the fundamental is now routinely cured by active feedback [12]. The amplifier driven by a feedback system feeds a current into the cavity, which attempts to cancel the beam current. The cavity impedance is then effectively reduced by the feedback gain. The limitation comes from the unavoidable delay in the loop. Above some gain level the delay will drive the feedback into electrical oscillations (not related to the beam). For a proportional feedback gain, the minimum effective impedance is

$$R_{\min} \approx \frac{R}{Q} \omega_0 T$$

where □ is the RF frequency in rad/s, *R/Q* the classic cavity parameter and *T* the loop delay (including TX group delay).

We propose to install the LLRF and TX in a cavern located close to the tunnel, so that the RF feedback delay is kept small (less than 1 □s). With this fi by 350 linear for a loaded Q of 1E6 [12].

6.2 Beam Loading and Choice of Loaded Q

In the crab cavities, the RF phase and the RF component of the beam current are in quadrature (0 degree stable phase, synchrotron convention). For a beam centered, there is no beam loading: the TX does not pass power to the beam. With a superconducting cavity (negligible loss) the needed power then decreases monotonically with the loaded Q. The situation is different for a beam circulating at an offset *x*.

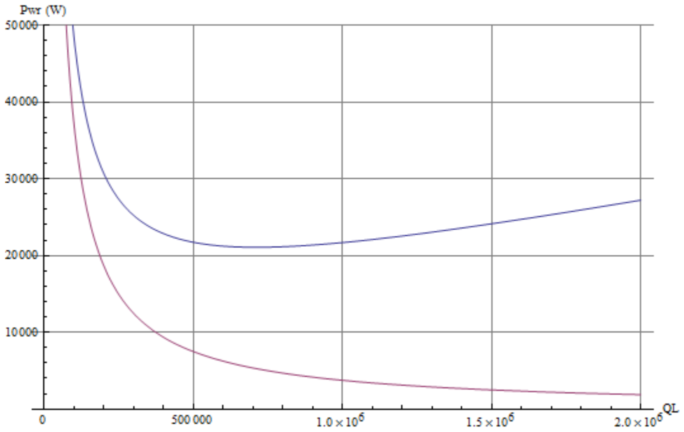
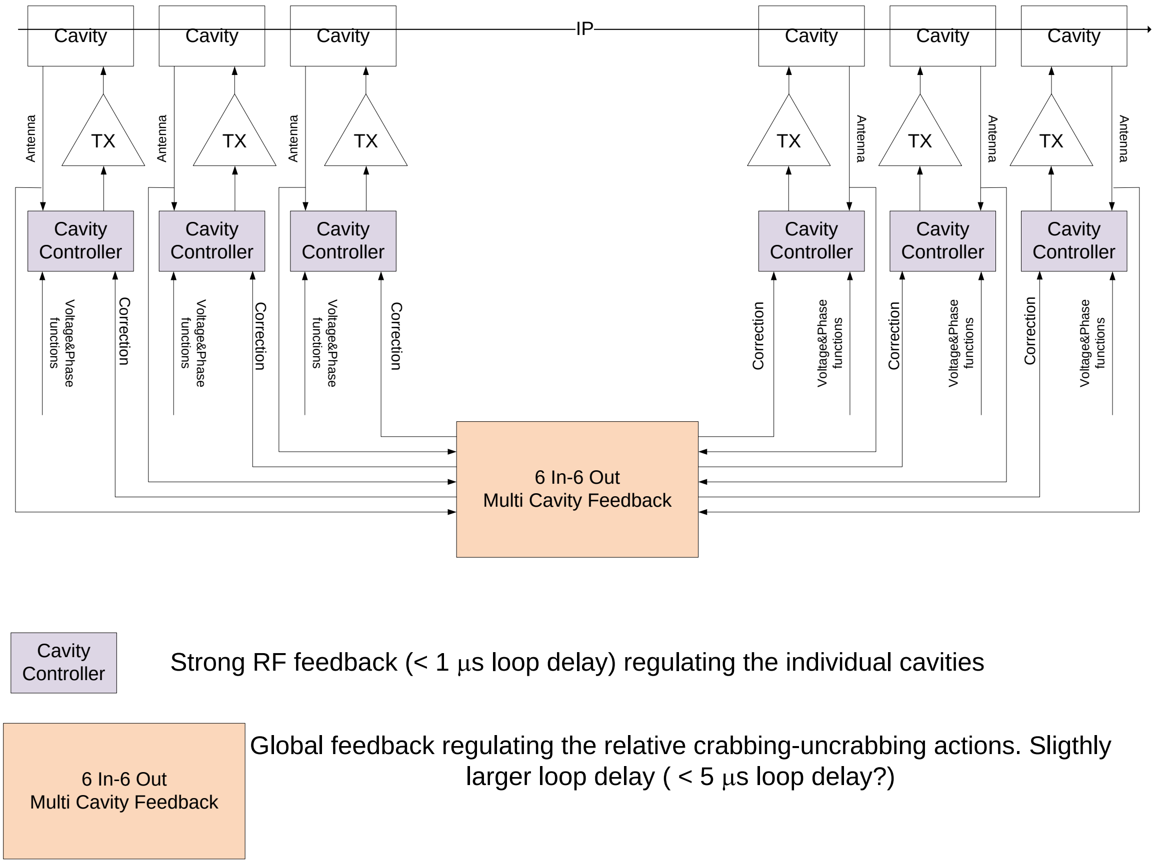


Figure 7 TX power vs cavity loaded Q for centred (red) and 1mm offset (blue) beams. R/Q = 300 MV RF, 1.1 A DC.

For a 1mm offset (tentative specification on the beam centering in the crab cavities), the power versus Q_L curve shows a broad minimum: from 3E5 to 1.5E6. The Cavity Field Control system will adjust the TX drive to keep the deflecting kick unaffected by the beam displacement. But the required TX power must be available. Selection of an optimal value in the above range comes from a compromise: a large Q_L reduces the field fluctuations created by the LLRF electronics and TX noise. But for tuning, a low Q_L is usually favourable as it relaxes the precision needed for the tuning mechanism. To minimize the power needed to compensate for fast tune variations it is also desirable to keep the cavity bandwidth larger than the frequency of the mechanical modes (low Q_L). Selection of the *optimal* Q_L will follow from the SPS tests.

6.3 Machine Protection

In case of the rapid change of the field in one cavity (quench or TX trip), the LHC Beam Dump System (LBDS) will dump the beam after a three turns maximum reaction time. The LLRF must help minimize the beam losses during these critical three turns. We propose to couple the six cavities of a given ring at a given IP in a 6-IN, 6-OUT feedback. Figure 2 shows the proposed architecture. Each cavity had its independent short delay controls loop (Cavity Controller represented in blue color and mentioned in the above sections). Per ring and IP, we add a central controller that receives measurements from all relevant cavities and that can make corrections to the drive of all individual TX (Multi Cavity Feedback represented in red). If the field starts changing in a cavity, the Multi Cavity feedback would adjust the field in the other cavities on both sides of the IP, so that the rotation quick remains closed during the critical three turns. This mechanism will be developed and tested in the SPS with two cavities.



Strong RF feedback (< 1 μs loop delay) regulating the individual cavities

Global feedback regulating the relative crabbing-uncrabbing actions. Sligthly larger loop delay (< 5 μs loop delay?)

Figure 8 Proposed LLRF architecture for one ring at one IP.

6.4 Phase Modulation Along the Beam

At present the spacing between LHC bunches is strictly constant along the ring. A large amount of RF power is used to fully compensate the transient beam loading caused by the 3 □s long abort gap and the smaller gaps required by the injection kicker. This scheme cannot be extended into the Hi-Lumi LHC era as it would require an RF power that is not available from the ACS system. The plan is to allow phase modulation of the ACS cavity field by the beam gaps while adjusting the voltage phase set point accordingly, bunch per bunch [12]. If the crab cavities are operated from the fixed RF frequency references, it will result in a 60 ps maximum displacement of a bunch center from the zero phase in the crabbing field. This may be acceptable given the 1 ns bunch length. If not, the LLRF must synchronize the bunch-by-bunch crabbing field with the actual phase modulation. The effect can be measured in the SPS test-stand and corrections can be tested if needed.

6.5 Operational Scenarios in the LHC

The crab cavities must cope with the various modes of the collider cycle: filling, ramping, physics.

- During filling, ramping or operation with transparent crab cavities, we detune the cavity but keep a small field requested for the active Tuning system. Parking the cavity half distance between two revolution frequency sidebands would be ideal for stability. As the kick is provided by a pair of cavities, counter-phasing can be used to make the small cavity field invisible to the beam. The RF feedback is used with the cavity detuned to provide stability and keep the Beam Induced Voltage zero if the beam is off-centred.

We can use the demanded TX power as a measurement of beam loading to guide the beam centring. We could also use the RF signal from another dipole mode, measured in the HOM couplers.

- On flat top
    - We reduce the detuning while keeping the voltage set point very small. The RF feedback keeps the cavity impedance small (beam stability) and compensates for the beam loading as the cavity moves to resonance.
    - Once the cavity detuning has been reduced to zero, we use the functions to synchronously change the voltage in all crab cavities as desired. Any levelling scheme is possible.

These RF manipulations will be first validated and commissioned in the SPS.

With a circulator between TX and cavity, the TX response is not affected by the cavity tune. This is very favourable for the proposed active compensation scheme, with a cavity being gently moved from parked position to tuned.

7 SPS Integration Constraints

In order to validate the crab cavities for the LHC, full beam tests in the SPS are prerequisite, and these tests have their own constraints in terms of integration and installation. However, these SPS-related constraints must place no additional constraints on on the LHC cavity design, and should fall within the shadow of the LHC design constraints, without compromising operational performance. As such, the operation of the cavity prototypes in the SPS must be at 2K, and the horizontal cavity envelope radius must be maintained at 145 mm. The integration constraints specific to the SPS installation are now detailed in the following sub-sections.

7.1 SPS Test Location

The requirement to run the cavities with an operating temperature of 2K implies they can only be installed at a location where cryogenics infrastructure is present. Given the limited capacity of the existing cryogenic infrastructure in the SPS, the only feasible location is at Point 4 of the SPS. Due to the limited cooling capacity and expected heat loads, the cavity installation should be as close as possible to the centre of the long straight section (i.e. centre of LSS4 of the SPS). The installation of the crab cavity cryomodules is foreseen in the area formally known as the COLDEX location in LSS4. This location is not only as close as possible to cryogenic infrastructure, but also has accessible integration space and the availability of a services alcove. A sketch of the area is given in Figure 9 and shows not only the cryomodule position, but also the general location of the supporting 2K cryogenics infrastructure and RF power amplifiers in the services alcove.

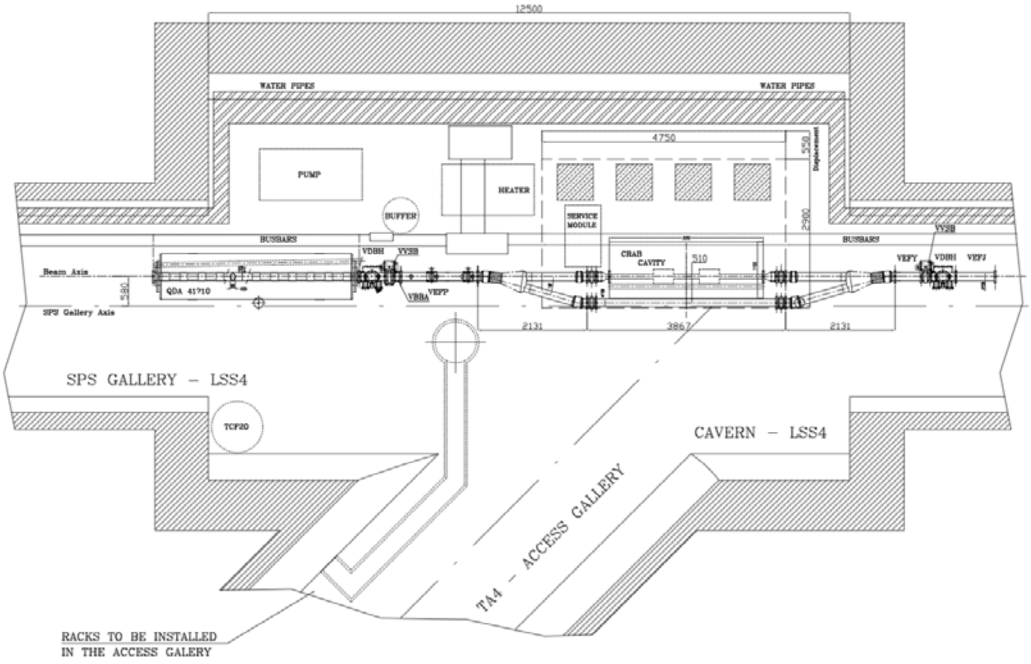


Figure 9 Crab Cavity Layout in LSS4 of the SPS

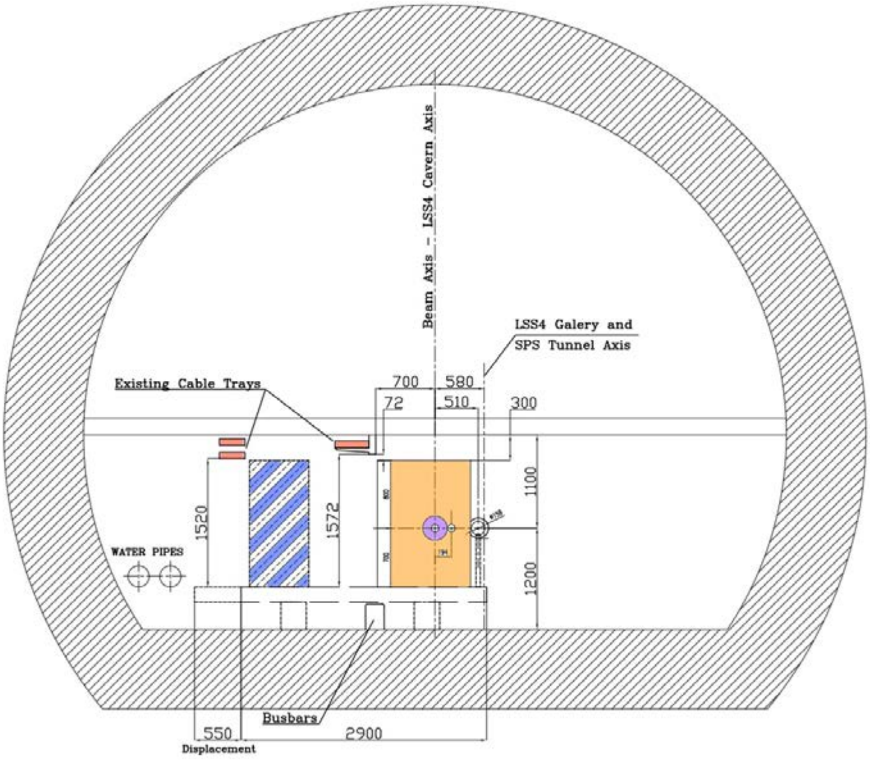


Figure 10 End on view of the crab cavity cryomodule envelope (yellow) and the RF power amplifiers (blue stripes).

7.2 BA4 Bypass & Integration

An essential requirement is that the prototype cavities not disrupt normal SPS operation when not in use. For this to be the case, the cavities have to either be shown to be invisible to the beam when not in operation, or they have to be physically removed from the beam line.

Until this transparency of the detuned cavities to the beam is validated, provision must be made to physically remove the cavities from the beam line when they are not being operated. Switching of cavities into or out of the beam line is to be achieved by installing the crab cavity cryomodule on a by-pass line that can be mechanically moved to in and out of beam positions. This by-pass line is implemented by means of a Y-chamber vacuum line as shown in Figure 11, and the mechanical movement is done by mounting Y-chamber, cryomodule, by-pass, RF power amplifiers and cryo service module on a support table that can be mechanically moved transverse to the beam direction in the horizontal plane. In order to integrate the cryomodule into the available space, the Y-chamber opening angle is set at 16 degrees, and the spacing between the two beam axes is 510 mm. With this spacing, and a standard bypass line of 159 mm outer diameter, the bypass line, when the cryomodule is in the in-beam position, does not impinge on the SPS transport lane, and so the installation is independent of normal SPS access considerations.

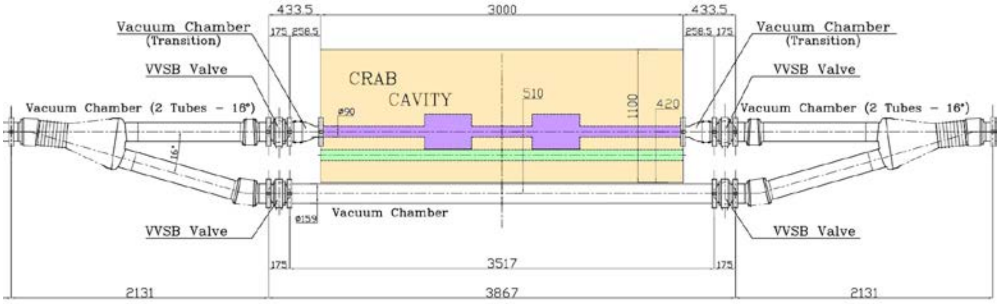


Figure 11 The crab cavity cryomodule enevlope, showing the envelope (yellow), the cavities (purple), and the dummy beam pipe (green).

7.3 Cryomodule Envelope

The available cryomodule envelope can then be extracted from the available space as shown in Figure 10 and Figure 11, and a summary of the cryomodule volume is given in table Table 9. Note that envelope defined for the cryomodule is the available integration volume and has to include not only the cryomodule itself but also the volume of the integrated service ports. For example the distance from cavity beam axis to top of extended cryomodule volume includes not only the cryomodule but also the space for the power coupler and cryogenic lines, which come in from the top.

Description	Distance [mm]
Cryomodule z-length	3000
Cavity axis to inner edge of cryomodule volume	420
Cavity axis to outer edge of cryomodule volume	680
Cavity axis to top of support table	700
Cavity axis to top of extended volume (cryomodule + couplers)	800
Cavity axis to SPS floor	1200
Diameter of bypass beam line	159
Diameter of cavity aperture	90

Table 9 Cryomodule integration envelope.

Based on cryomodule dimensions of taken from the UK-4Rod prototype design [14], the cryomodule envelope would be 1000mm wide by 1005mm high, with 570 mm from cavity axis to top of cryomodule. The exact size of the vertical envelope may differ between the cryomodules of different cavity types, but what must be respected is the vertical envelope defined by the support table and the top of the extended envelope for module plus couplers. Similarly, an envelope z-length of 3m is sufficient for encompassing a cryomodule with two of the longest of the 3 prototype cavity assemblies (this length is to be defined by the HOM couplers and tuning system).

Within this cryomodule envelope it is expected that the cryomodule will house two cavities, as well as a dummy LHC beam pipe with an axis-to-axis spacing of 194 mm. The cryomodule envelope is specified such that the dummy beam pipe can be mounted on the “inside” position (as shown in Figure 11), which is the case for the UK-4Rod cavity which has a power coupler port in the horizontal on the outer side of the cavity. For the other cavity types, the dummy beam pipe can be on either the inner or outer side of the cavities.

7.4 Support Infrastructure

At each end of the cryomodule, a standard vacuum valve is to be installed to protect the cavity conditioning during construction and installation phases. For protection of the cavity conditioning against leaks and over pressure situations and other such problems, fast vacuum valves are installed outside the Y-Chamber section similar to the COLDEX configuration.

The power coupler between RF amplifier/circulator and cryomodule must be rigid to avoid risk of coupler ceramic damage, independent of table movement; hence amplifier and circulator are to be fixed to the support table. Similarly, in order to maintain SPS operational availability while minimizing static heat loads on the cryogenics system, the connections between cryomodule and Cryo Service module must be rigid 80K shielded cryo-lines, and this requires the Cryo Service Module also be fixed to the support table. However this implies that an 80 K screen cryo line between the buffer tank and the Cryo Service module that permits a transverse movement of 510mm is required.

7.5 Positioning and Alignment Constraints

Placement of the cryomodule in the beam line will rely on fiduciary markers on the cryomodule, and the positional accuracy of these markers relative to the common cavity axis is taken as perfect. The alignment constrains on the cryomodule placement with respect to the nominal beam position map directly to constraints on the support table position, and are required to be 1/10th the performance based alignment budget of the cavities. This gives the following position accuracy constrains on the moveable table:

Positioning	Tolerance
Transverse Position accuracy	+/- 0.1 mm
Vertical position accuracy	+/- 0.1 mm
Longitudinal Position Accuracy	+/- 0.1 mm
Tilt resolution flatness resolution	+/- 100 urad

Table 10 Support table positioning tolerances

Movement of the support table from the in-beam to out-of-beam position has to be taken into account when ensuring reproducible positioning of the cavities in the in-beam position, and as such an adjustable movement range is defined as per Table 11.

Positioning	Tolerance
Vertical adjustment range	+/- 50mm
Transvers movement range	550 mm
Transverse tilt tolerance	+/- 1 degree
Longitudinal tilt tolerance	+/- 1 degree

Table 11 Support table adjustable movement range.

It is important to note that the specification constraints on cryogenic services such that the cryomodule is required to be operational at 2K in both the in-beam and out-of-beam position, and that the cryomodule module can be moved to either in-beam or out-of-beam position while cold. Also, due to limited integration space on the horizontal, it is expected that all services, wherever possible, access should the cryomodule from the top.

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