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Chapter 8

Radio Frequency systems

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1. Challenges for the existing LHC Accelerating System (ACS)

Superconducting cavities were introduced at CERN to boost the energy of the Large Electron Positron (LEP) collider and first prototypes of 4-cell 352 MHz cavities for LEP2 were produced in 1991. At that time and due to the relatively low frequency, copper cavities sputtered with a thin film of Niobium were shown to provide a reliable performance at the required gradients, and hence was an economical option compared to bulk Niobium. Other benefits include thermal stability due to the large copper substrate and insensitivity to stray magnetic fields. Hence, this technology was adopted to construct 288 cavities for LEP2. For the LHC, a proton machine with significantly lower synchrotron radiation losses per turn, the need for accelerating voltage is greatly reduced and therefore the LEP technology was adapted "as-is" without trying to push cavity performance. Furthermore the technology proved to be reliable and stable during LEP operation. The first LHC module with four single-cell 400.79 MHz cavities was successfully tested in 2000 and all four modules were installed and commissioned with beam by 2008 [Linnecar (2008)], in time for the LHC start-up.

LHC cavities Two cryomodules per beam are in operation (see Fig. 1). The cavities are connected with large aperture beam tubes (300 mm) to reduce the longitudinal impedance and thereby transient beam loading.

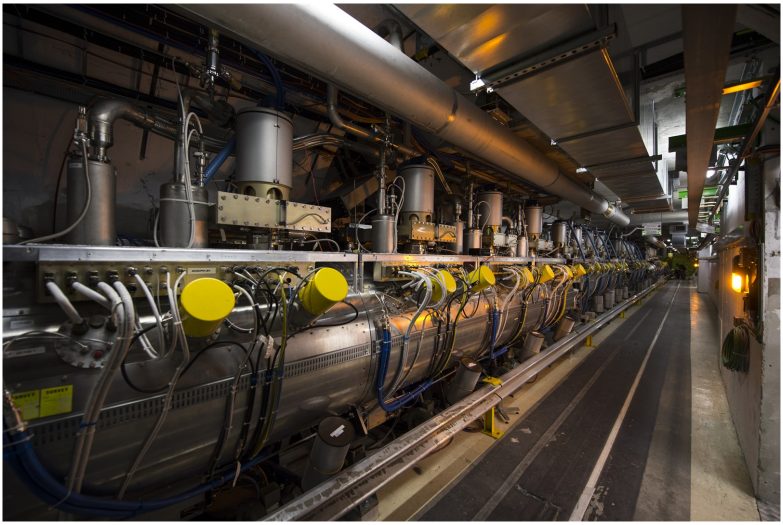

Fig. 1. ACS cryomodules in the LHC tunnel.

Table 1. LHC ACS cavity parameters.

RF frequency	400.79 MHz
Accelerating gradient	5.5 MV/m
Accelerating voltage	2 MV
Q_0	2×10^9
R/Q	$88.1\,\Omega$
Adjustable power coupler	$11000 < Q_{ex} < 200000$
Operating temperature	4.5 K
Tuning range	180 kHz

Two dipole mode couplers and two broadband couplers are mounted on the beam tubes adjacent to the cells to provide Higher Order Mode (HOM) damping [Haebel (1997)]. The main cavity parameters are summarised in Table 1.

RF powering & HL-LHC requirements Originally the LHC was designed for a maximum intensity of 1.15×10^{11} p/b. A full detuning scheme was proposed to cope with the transient beam loading effects during the energy ramp and collisions and was expected to enable the HL-LHC's intensity of 2.3×10^{11} p/b [Mastoridis (2017)]. With this scheme, the klystron power is independent of the beam current and maintained constant over one full turn at the expense of bunch-to-bunch phase modulation.

The cavities provide a voltage of up to 16 MV per beam. During Run I (2009–2012) and Run II (2015–2018) the voltage was adjusted to 6 MV at injection and to 12 MV at flat top, requiring between 80 and 120 kW per cavity. Each cavity is powered by a klystron with a maximum of 300 kW continuous wave (CW) forward power. Taking into account that the klystrons are operated today at $\approx 1.5\,dB$ below saturation (control margin) and that losses due to waveguides and reflections from circulators account for around 5–10%, the available klystron power at the cavity input is reduced to a maximum of around 200 kW.

During injection of the HL-LHC beams from the SPS into the LHC the half-detuning scheme is required to strictly preserve the bunch-to-bunch spacing. Recent studies [Timko (2018)] based on the operational experience during Run II and advanced beam dynamics simulations with CERN's BLOND code [BLOND (2022)] have concluded that 200 kW at the cavity input is likely too low to achieve a balance between reducing injection oscillations and keeping beam losses at acceptable limits. In the 2022 LHC Performance workshop [Chamonix (2022)] it was established that, using the half-detuning scheme, a minimum injection voltage of 7.8 MV is required, which translates to 265 kW at the cavity level. Additional margin may be needed as today's measurement of the klystron forward power has a 20% uncertainty and because the klystrons themselves have a $\approx 20\%$ spread in their power saturation values.

Means to increase RF performance The first measure to increase the power into the cavities is the replacement of the existing LHC klystrons with new high-efficiency plug-compatible klystrons. Their internal cavity structure, responsible for electron beam shaping and beam extraction, has been redesigned by CERN [Syratchev (2021)] and is presently under construction in European industry [Thales (2019)]. This modification is expected to increase the RF efficiency from 62% to 71%, raising the klystron forward power from 300 kW to 350 kW with the same input power. Plug-compatibility means that the existing high-voltage and modulator infrastructure can be used, limiting the needed investment. Automatic adjustment of the circulator settings to minimum reflection together with improved power measurements and optimised control algorithms is expected to reduce the present control margin from 1.5 dB to 1.0 dB below saturation, which means that 350 kW klystron forward power would result in 275 kW power in the cavities, just enough to cover the estimated minimum power of 265 kW needed.

Further measures to increase the available voltage can be: i) transient detuning of the cavities with ferro-electric fast reactive tuners (FE-FRT) [Shipman (2021)], currently under development at CERN, or; ii) the installation of additional cavities and RF power systems.

Along with any power increase a precise longitudinal impedance model of the LHC is needed to improve the simulations of injection, capture, ramp and flat top operation.

2. The HL-LHC Crab Cavities

For high luminosity operation of the LHC (HL-LHC), proton beams are squeezed to very small β^* at IP1 and IP5 (well below the nominal 55 cm). A non-zero crossing angle is required to control the effect of the large number of parasitic collisions. A crossing angle in combination with small β^* results in a geometric reduction of the luminosity by a factor of $R_\Phi = (1+\Phi^2)^{-1/2}$ due to imperfect overlap of the colliding bunches. Here, $\Phi = \frac{\sigma_z}{\sigma_x^*}\phi$ is referred to as the Piwinski angle and ϕ is the half crossing angle. In the HL-LHC, up to 70% of the peak luminosity is lost due to the geometric reduction factor, $R_\phi = 2.66$. The effect the crossing geometry is illustrated in Fig. 2 and compared to with the crab crossing scheme where the head and the tail of the bunches transported along different orbits maximize the overlap at the interaction point.

The HL-LHC upgrade will use a crab crossing scheme using superconducting crab cavities, also operating at 400.79 MHz, to compensate for geometric luminosity loss. The crab cavities placed on either side of the IP are used to generate a localized perturbation upstream of the IP where crabbing is required and compensates for it downstream, such that through the rest of the ring the bunches remain unperturbed. The local scheme requires up to 8 cavities per beam and per IP operating at 3.4 MV for a full compensation of the HL-LHC crossing angle. This scheme allows for the different crossing planes in IP1 and IP5 and exploits the large optical functions in this region to minimize the required voltage.

Fig. 2. Bunches colliding with a crossing angle without crab crossing (left); with the crab crossing (right).

Superconducting Crab Cavities In order to sustain the extremely high surface fields at a kick voltage of 3.4 MV per cavity for the HL-LHC in continuous wave (CW), superconducting technology is essential; space restrictions, voltage requirements, and impedance considerations strongly rule out a normal conducting option. The placement of the cavities in the interaction region requires unconventional cavities that are compact enough for the nominal beam pipe distance of 194 mm.

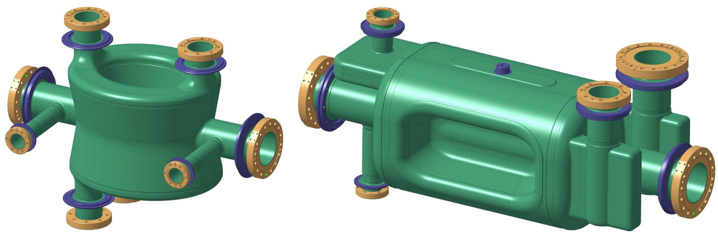

Fig. 3. Schematic view of the cavity with interfaces (left) DQW; (right) RFD.

Table 2. RF parameters for the DQW and RFD cavities.

quantity	unit	value
Frequency	MHz	400.79
Bunch length	ns	1.0-1.2 (4 σ)
Maximum cavity radius	mm	$\leq$ 145
Nominal kick voltage	MV	3.4
R/Q (linac convention)	Ω	430
Q_0		$\geq 10^{10}$
Q_{ext} (fixed coupling)		5×10^5
RF power	kW-CW	40 (80 peak, 1 ms)
LLRF loop delay	µs	≈ 1
Cavity detuning (if parked, optional)	kHz	≈ 1.0

As a result of an intense R&D within the FP7 HiLumi LHC, EuCARD and LARP programs and with other external collaborators, three compact designs at 400 MHz emerged as potential candidates of which two were retained after the prototyping phase [Verdu, Xiao (2015); De Silva (2013)]. The vertical crabbing is realized by the Double Quarter Wave (DQW) and the horizontal crabbing by the RF Dipole (RFD). The final design of the cavities including all external interfaces is shown in Fig. 3. The proposed designs are at least four times smaller in the plane of crossing compared to a conventional elliptical cavity with a ratio of the kick gradient to the peak surface fields lower by a factor of 2 or better. Table 2 summarises the main crab cavity parameters.

RF powering of Crab Cavities The longitudinal impedance of the operating mode of these cavities vanishes on axis, i.e. there is no beam loading for a centered beam; the RF generator does not exchange energy with the beam [Joachim (2011)]. For a beam circulating at an offset Δx, the beam-induced voltage is proportional to the offset and the average beam current. In deflecting cavities operated in the crabbing mode, kick voltage and beam current are in quadrature ($\phi_s = 0$, synchrotron convention). Restricting the unavoidable orbit offsets and drifts to a maximum of 1 mm, the required RF power is approximately $\leq$ 40 kW for an optimal Q_L of 5×10^5 This Q_L provides a good compromise between the required cavity bandwidth and the available RF power. For short excursions of the orbit, an input RF power of 80 kW up to 1 ms is feasible to cope with injection and other transients. An independent powering system for each cavity using Inductive Output Tubes (IOTs) at 400.79 MHz are used to produce the 40 kW CW power. This scheme allows for fast and independent control of the cavity set point voltage and phase to ensure accurate control of the closed orbit and the crossing angle in the multi-cavity scheme. Most importantly, fast control of the cavity fields will minimize the risk to the LHC during an abrupt failure of one of the cavities, ensuring machine protection before the beams can be safely extracted. For such fast and active feedback, a small loop delay between the RF system and the cavity is used for the RF infrastructure design.

RF Feedback and Controls for Crab Cavities The amplifier driven by a feedback system feeds a compensating current to cancel the beam current. The cavity impedance is then effectively reduced by the feedback gain with the round-turn-loop delay as the limiting factor. This delay is specified to be less than 1.5 µs for HL-LHC which allows a significant reduction of the cavity impedance seen by the beam. A rapid and unforeseen change of the field in one cavity should trigger the LHC Beam Dump System (LBDS) to extract the beam in a minimum time of three turns (270 µs). The RF controls should minimize the effect on the beam within the 3 turns to avoid abrupt displacements which can potentially damage the machine elements. Therefore, independent power systems of each cavity with a short delay cavity controller are used [Baudrenghien (2012)]. A central controller between the two systems across the IP makes the required corrections to adjust the cavity set points as necessary.

Beam operation with crab cavities The use of the crab cavities for HL-LHC also requires that during the injection, energy ramp or operation without crab cavities, the cavities remain transparent to the beam, known as "crabbing off". Since more than one cavity is used, counter-phasing (such that the relative cavity RF phase, $\phi_1 - \phi_2 = \pi$) reduces the effective kick voltage to zero while always keeping accurate control of the cavity field. This scheme is also most effective for beam stability. In the HL-LHC, a single frequency reference generated at the RF controls of the accelerating cavities at IP4 will be sent over phase-compensated links to the respective crab cavities at IP1 and IP5 to synchronize the crab cavities with the beam.

RF noise in the form of amplitude jitter in the crab cavity voltage introduces a residual crossing angle at the IP and a phase jitter results in a transverse offset at the IP. The long physics fills in the HL-LHC imply that amplitude or phase jitter of the crab cavity voltage leads to growth in the transverse phase space (emittance) and thereby reduces the luminosity [Calaga (2010); Baudrenghien (2012)]. This emittance growth is of particular concern with proton beams, which have very low synchrotron radiation damping. First performance estimates in HL-LHC with realistic crab cavity amplitude and phase noise yield about a 2% luminosity loss [Medina (2018)]. To achieve this extremely low level of the RF noise budget the noise floor of the RF controls has to be further reduced from the present state-of-the-art. A dedicated noise feedback system may be necessary to further reduce the impact on the luminosity loss [Baudrenghien (2019)]. This feedback system will work in conjunction with the existing transverse damping system to counter-act against the crab cavity RF noise.

Beam impedance For Higher Order Modes (HOMs) in HL-LHC, the total maximum allowed longitudinal impedance from each HOM, summing over all cavities in one beam, assuming the pessimistic case that the HOM falls exactly on a beam harmonic, is specified to be $\leq 200\,\mathrm{k\Omega}$ [HL-LHC TDR (2020); Shaposhnikova, Burov (2010)]. The same limit was imposed for higher frequencies although the allowed impedance has a quadratic behaviour. In the transverse plane, considering stability criteria for multi-bunches and assuming the pessimistic case, the maximum total transverse impedance in each plane is set to be $1\,\mathrm{M\Omega/m}$ [Biancacci (2014)]. The crab cavities equipped with HOM couplers were carefully designed to keep the impedance within tight tolerances, and the system remains close to the limits [Mitchell (2019)]. Modes with frequencies above 2 GHz are expected to be Landau-damped due to natural frequency spread in the respective planes. The beam power deposited in the longitudinal HOMs can become significant when the frequencies coincide with bunch harmonics. The HOM couplers are designed to accept up to 1 kW per coupler.

The crabbing field of the cavity geometries contain higher order components (described using multipoles) due to the lack of azimuthal symmetry. As the cavities are placed at locations with large beam size, the higher order components of the main deflecting mode can affect long-term particle stability. RF multipole components b_n of the RF deflecting field can be approximated and hence expressed in a similar fashion to magnets [Navarro (2013)].

SPS test facility The first proof of principle system with two superconducting DQW cavities was tested in the special test bench in the Super Proton Synchrotron (SPS) in 2018. The primary aim of these tests was to validate the technology with proton beams, demonstrate the ability to make the system transparent and establish a robust operational control of a multi-cavity system for the different modes of operation. A straight section (LSS6) of the SPS ring was equipped with a special bypass on a movable table and featuring Y-chambers with mechanical bellows that can be displaced horizontally (see Fig. 4). This allows for the crab cavity module to be placed out of the circulating beam during regular operation of the SPS and to be moved in only during dedicated machine development [Calaga (2018)].

A complete cryogenic system on the surface (SPS-BA6) and in the tunnel (SPS-LSS6) was installed to deliver 2 K helium for the test operation of the crab cavities. Two coaxial transmission lines are used to feed RF power of up to 40 kW from the amplifiers (IOTs) installed on the surface. Placement of the passive RF elements (circulators and RF loads) on the table was required to allow for the horizontal movement of the bypass remotely. All beam-pipes in this vacuum sector are coated with a thin film of amorphous carbon to reduce secondary electron yield and hence mitigate electron cloud effects.

A detailed campaign of dedicated experiments was carried out in the SPS with proton beams in 2018. Crabbing of the proton bunches was demonstrated (see Fig. 5) for the first time and several aspects related to the RF sychronization, cavity transparency, beam quality preservation,

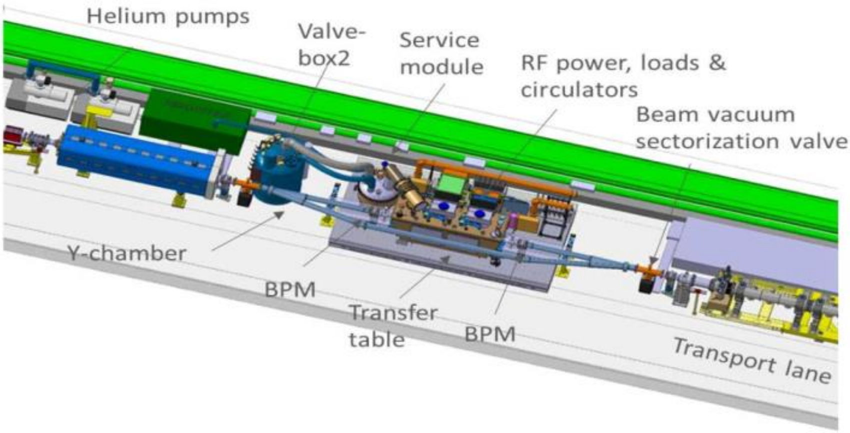

Fig. 4. SPS-LSS6 bypass for the installation of a 2-cavity crab cavity module for the first beam tests with protons [Calaga (2018)].

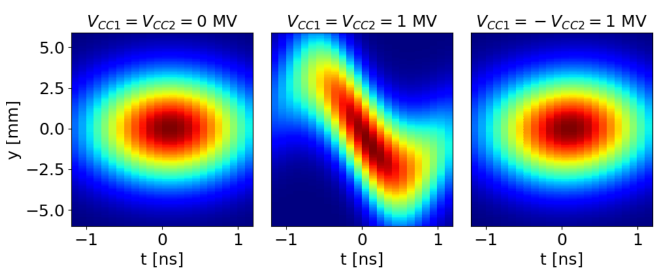

Fig. 5. Intra-bunch motion from three different cases measured with the HT monitor. Left: Crab cavities switched off (voltage = 0). Center: Synchronous crabbing with both cavities in phase corresponding to $V_{CC} \approx 2\,\mathrm{MV}$ total voltage ($V_{CC1} = V_{CC2} = 1\,\mathrm{MV}$). Right: Cavities in counter-phase, corresponding to residual $V_{CC} \approx 60\,\mathrm{kV}$ total voltage.

transverse emittance growth and intensity related effects were demonstrated [Calaga (2021)].

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