CONCEPTUAL SPECIFICATION

[BPTQR Crab Cavity RF Pick-up System]

[HL-LHC BPTQR - RF]

Equipment/system description

This conceptual specification concerns the beam pick-ups to be built within WP13 for the use with the crab cavity (CC) noise feedback and lowlevel RF systems (LLRF) [1] for Hi-Lumi LHC in point 1 and point 5 [2]. Three separate functionalities are to be covered [2]

- phasing of crab cavities with beam (functionality A)
- cancelling CC antenna direct beam coupling (functionality B) — should need arise
- CC amplitude and noise feedback (functionality C)

WP4 requests button pick-ups for functionality A and functionality B for which only the longitudinal signal is required. For functionality C, WP4 requests a short stripline in order to profit from the higher signal level available from a stripline. A summary of the analytical responses of the pickups agreed with WP13 pick-ups can be found in [3].

Layout Versions	LHC sectors concerned	CCD Drawings root names (drawing storage):
V X.X	S1-2, S2-3, S3-4, S4-5, S5-6, S6-7, S7-8, S8-1, Surface points	Text

TRACEABILITY

Project Engineer in charge of the equipment	WP Leader in charge of the equipment
N. Surname [Prepared by]	N. Surname [Checked by]

Committee/Verification Role	Decision	Date
TCC/ Performance and technical parameters	Rejected/Accepted	20YY-MM-DD
PO / Configuration, installation, interface parameters, cost and schedule	Rejected/Accepted	20YY-MM-DD
Final decision by PL	Rejected/Accepted/Accepted pending (integration studies, ?)	20YY-MM-DD

Distribution: N. Surname (DEP/GRP) *(in alphabetical order) can also include reference to committees*

Rev. No.	***Date***	***Description of Changes*** *(major changes only, minor changes in EDMS)*
X.0	20YY-MM-DD	Description of changes

1 CHOICE OF LOCATION AND PICK-UPS

1.1 Location

The selection of the locations directly upstream and downstream of the crab cavities [2] in IP1 and IP5, is motivated by the high beta functions available, proximity to the Faraday Cages that will house the electronics for the low-level control of the crab cavities and a favorable phase advance to observe crabbing induced by the cavities. With these sets of two locations per IP, a redundancy of two is achieved, albeit at a

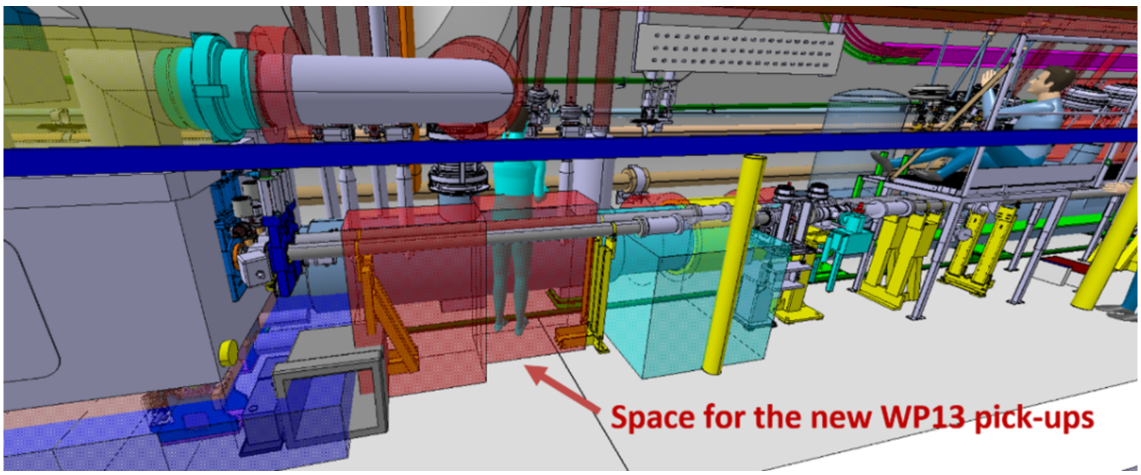

Figure 1: Installation location adjacent to crab cavities [2].

transverse phase advance close to π between the respective pick-ups. This is unfavorable for direct combination of the signals to adjust the feedback phase of the crab cavity noise feedback. Therefore, the baseline for the crab cavity noise feedback is to make use of the previous turn signals to compute the correction signal. The recourse to this scheme defines the limit of gain for stable operation of the noise feedback. Previous turn signals are also used to numerically remove static offset and static tilt before feeding back the processed signals to the crab cavity set point electronics. Static offset and static tilt are the result of equipment manufacturing as well as assembly tolerances, alignment tolerances, and beam closed orbit variations (including crabbing orbit) with respect to the equipment nominal axis orientation. The exact way to explore the redundancy of two pick-ups, i.e. one on each side of the IP, while maximizing the gain the noise feedback can be stably operated at, is subject to future study.

1.2 Choice of pick-up types

The selection of a stripline as baseline for the noise feedback is motivated by the higher signal level available leaving more possibilities in the analog signal conditioning for the chosen bunch-by-bunch processing decided by WP4. Contrary to the button pick-up with its exponential tail in the time domain response, the stripline, in absence of reflections at transitions and feed-throughs, and not considering the cabling transfer functions, has a time domain response *limited* in time. This characteristics removes a cause of interference in the measured average bunch position and head-tail position (tilt signal) for a particular bunch in single passage, from contributions of bunches close-by that can spoil the signal if the response of the pick-up were not time limited.

2 Number of pick-ups, location and cabling

2.1 List of individual pick-ups

Tables 1 and 2 summarize the individual pick-ups and and their location as well as the cables requested. The RF cable links to the Faraday cages need to have matched length and pairwise identical properties for the two sides of each of the pick-ups. Consideration shall be given to limit the number of connectors and patch cables needed. Where patch cables are used, they shall be equal in length for the two sides. Patch cable lengths shorter than half the bunch spacing (i.e. < 12.5 ns) limit the inter-bunch interference by multiple reflections. In general "as short as possible" or avoiding patch cables all together is the guideline. In case of need the high signal level from the stripline pick-up permits the installation of attenuators to reduce adverse effects of (mutltiple) reflections on the patch panel side of the installation. Responsibility of the cables connecting from the pick-up feedthroughs to the first patch panel shall be with WP13 who will employ SiO_2 dielectric cables that can withstand the foreseen bake-out.

Table 1: Pick-ups and locations for IP1 (horizontal crabbing) and cable type for connection to Faraday cage.

Type of pick-up	Beam/plane		location		cables	usage
Button	B1	V	IP1	left	$2\times$ 7/8"	phase loop (A)
Button	B1	V	IP1	right	$2\times$ 7/8"	phase loop (A)
Button	B1	H	IP1	left	$2\times$ 7/8"	functionality (B)
Button	B1	H	IP1	right	$2\times$ 7/8"	functionality (B)
stripline	B1	H	IP1	left	$2\times$ 7/8"	noise feedback (C)
stripline	B1	H	IP1	right	$2\times$ 7/8"	noise feedback (C)
Button	B2	V	IP1	left	$2\times$ 7/8"	phase loop (A)
Button	B2	V	IP1	right	$2\times$ 7/8"	phase loop (A)
Button	B2	H	IP1	left	$2\times$ 7/8"	functionality (B)
Button	B2	H	IP1	right	$2\times$ 7/8"	functionality (B)
stripline	B2	H	IP1	left	$2\times$ 7/8"	noise feedback (C)
stripline	B2	H	IP1	right	$2\times$ 7/8"	noise feedback (C)

Table 2: Pick-ups and locations for IP5 (vertical crabbing) and cable type for connection to Faraday cage.

Type of pick-up	Beam/plane		location		cables	usage
Button	B1	H	IP5	left	$2\times$ 7/8"	phase loop (A)
Button	B1	H	IP5	right	$2\times$ 7/8"	phase loop (A)
Button	B1	V	IP5	left	$2\times$ 7/8"	functionality (B)
Button	B1	V	IP5	right	$2\times$ 7/8"	functionality (B)
stripline	B1	V	IP5	left	$2\times$ 7/8"	noise feedback (C)
stripline	B1	V	IP5	right	$2\times$ 7/8"	noise feedback (C)
Button	B2	H	IP5	left	$2\times$ 7/8"	phase loop (A)
Button	B2	H	IP5	right	$2\times$ 7/8"	phase loop (A)
Button	B2	V	IP5	left	$2\times$ 7/8"	functionality (B)
Button	B2	V	IP5	right	$2\times$ 7/8"	functionality (B)
stripline	B2	V	IP5	left	$2\times$ 7/8"	noise feedback (C)
stripline	B2	V	IP5	right	$2\times$ 7/8"	noise feedback (C)

Samples of the used 7/8” cable shall be made available by EN/EL for qualification before contract placement. SiO2 cable and connectors are to be validated by WP4.

2.2 Grouping and total numbers

Buttons and striplines are grouped into one assembly denominated ”BPTQR” for each installation location. Each BPTQR assembly will feature pairs of buttons in *both* planes at identical longitudinal position and a stripline in the crabbing plane in *beam downstream* direction with respect to the buttons. Tables 3 and 4 show the disposition of the eight BPTQR assemblies required. An adequate number of spares needs to be provisioned (2 units) bringing the total number of units to be produced to ten units.

Table 3: Grouping and total numbers IP1

Pick-up assembly	Beam	location	cables 7/8”	cables 3/8”
BPTQR H(V) B1	B1	IP1 left	6	0
BPTQR H(V) B2	B2	IP1 left	6	0
BPTQR H(V) B1	B1	IP1 right	6	0
BPTQR H(V) B2	B2	IP1 right	6	0

Table 4: Grouping and total numbers IP5

Pick-up assembly	Beam	location	cables 7/8”	cables 3/8”
BPTQR V(H) B1	B1	IP5 left	6	0
BPTQR V(H) B2	B2	IP5 left	6	0
BPTQR V(H) B1	B1	IP5 right	6	0
BPTQR V(H) B2	B2	IP5 right	6	0

The 7/8” cables to be used need to be have undergone at factory a heat treatment process to reduced their electric length variation with temperature (original LHC RF specification called for 12 ppm/K at 20 degrees C with 2 ppm/K achieved according to manufacturer). A further reduction of variation with temperature, is achieved by taking similar paths with well controlled environment temperature. In order to reduce reflections the connector type to be used on the 7/8 ” cable side is specified to be ”7-16 male”. On the connections to the patch panel in the tunnel and on the pick-up side transition pieces are needed. The exact path is to be agreed with the integration work-package from tunnel patch panel to pick-up remains and can include patch panels in the tunnel under the ceiling.

3 Parameter tables for the two types of Pick-ups

3.1 Button pick-up

Table 5 summarizes the parameters of the button pick-up. Pairing of button pick-ups is easily achieved with high precision due to the simpler construction and series manufacturing established. Buttons are requested and will be used with their sum signal (common mode) for functionality A and functionality B as baseline.

3.2 Stripline pick-up

Table 6 summarizes the parameters of the stripline pick-up. An effective length of 120 mm and nominal impedance of 50 Ω is agreed with WP13 [6].

Table 5: Button pick-up parameters: Note that for bunch lengths not long compared to the button diameter a correction factor may need to be used for the transfer function in [3] (to be confirmed). Tolerances need to be met up to 1 GHz (t.b.c.)

Parameter	value		tolerance		comment
Pick-up diameter D_{PU}	81	mm			
Button head radius r_{b}	16.75	mm			
resonance free up to	> 3 or $5?$	GHz			no ringing within beam spectrum
Capacitance (per button) C_b	15	pF	± 0.5	pF	absolute value
pairing of buttons better than	± 0.1	pF			between sides
feedthrough impedance Z_{FT}	50	Ω	± 1.5	Ω	N-type (f) connector
matching cable side Z_{L}	50	Ω	± 1.5	Ω	N-type (m) connector

Striplines offer the possibility to chose their length so that the RF analog processing frequency band (assumed 400 MHz in baseline) can be close to the frequency the maximum power is available for a given bunch spacing and bunch length, considering cable losses. Their phase also varies linearly with frequency, an advantage for larger bandwidth processing and when observing in time domain. Striplines with non-uniform coupling [5] were not considered, as potential advantages do not outweigh any of the disadvantages, in particular their much more complex design.

Striplines have been used for many years successfully with the transverse feedback systems in LHC, however those have a short circuit at one end removing one possible perturbation from mismatch at signal generation, but introducing full reflection for signals returning from the analog signal conditioning electronics. The stripline proposed by WP13 for HL-LHC is matched to 50 Ω at both ends. As the length proposed for mechanical space constraint is shorter than half the total bunch length, good matching at the beam downstream end will be important. This is due to overlap of the signals that cannot be separated in time-domain. On the other hand it should be easier to build this shorter stripline with uniform impedance with strips well paired than for the case of a longer stripline. Using a stripline with external short circuit does not offer any advantage; in fact it is an advantage to have good matching on all ports.

Table 6: Stripline pick-up parameters. Tolerances are needed up to 2 GHz (?).

Parameter	value		tolerance		comment
Pick-up diameter D_{PU}	91	mm			
Stripline length l_{s}	120	mm			
Impedance of stripline Z_{s}	50	Ω	± 2.5	Ω	
pairing of strips better than	± 1.5	Ω			uniformity (active length)
feedthrough impedance Z_{FT}	50	Ω	± 1.5	Ω	N-type (f) connector
load matching Z_{L}	50	Ω	± 1.5	Ω	N-type (m) connector

4 Sensitivity and alignment

4.1 Required sensitivity for noise feedback

For the crab cavity noise feedback a very small turn-by-turn variation of the position and tilt due to crabbing, needs to be measured on top of a static value for position and tilt that does not change turn-by-turn. As the measurement is planned bunch-by-bunch (to also be compatible with single bunch operation) with the feedback bandwidth conveniently defined in the digital signal processing, a bunch-by-bunch sensitivity requirement is needed. For the electronics design the specification in terms of dynamic range is of primordial importance. This dynamic range needs to be specified both for the position measurement and the tilt measurement taking into account all deviations of the beam position and orientation of its trajectory with respect to the equipment center and orientation of its axis with respect to the beam trajectory.

The detection noise floor (noise) for the position measurement required and parameters relevant for the nominal operational mode with single bunch and with 25 ns bunch spacing are given in Table 7. With 25 ns bunch spacing the averaging possible over 144 bunch positions corresponding to the required feedback bandwidth of the noise feedback of 135 kHz relaxes the requirement [1]. For the tilt measurement parameters are given in Table 8.

The aim of these tables is to assign limits on the one hand to the alignments and mechanical tolerances, on the other hand to the operational margin for the actual beam trajectory, position and crabbing. With respect to the tolerances (alignment and mechanical) the request is that these are "2σ (?)", meaning they can be exceeded with a 5% probability.

Note that the pick-ups for both beams will be mounted on a common alignment table, the UAP ("universal alignment platform"). The pick-ups are to be mounted in fixed positions and orientations on this alignment platform before installation. During the assembly the pick-up axis is referenced from the individual pick-ups to the UAP mean axis. Any intentional or unintentional deviation of the beam trajectory from the nominal accelerator plane needs be absorbed in what is called "operational margin" in the tables 7 and 8. The fact that the UAP is chosen, which rigidly links the equipment for the two beams (no FRAS for these pick-ups), dictates to explicitly include this margin.

The alignment in the tunnel foreseen and correctable in all degrees of freedom on a yearly basis concerns the mean UAP. The individual beam pick-ups for beam 1 and beam 2 cannot be aligned post assembly with respect to the UAP mean reference. All remaining variations of the beam trajectory with change of optics and with operational margins need to be accommodated in the processing of the signals.

Tolerances refer to the beam local coordinate system (accelerator plane) which is inclined for LHC by $\simeq 1.41$ %. This inclination corresponds to an angle of $\simeq 14$ mrad. In point 1 and point 5 it is almost entirely a slope of the accelerator plane in beam direction (with no roll) and assumed covered by appropriately shimming or aligning at the locations, to be agreed between WP13 and WP15.

Note that the nominal operational figure of 400 μrad in table 8 for the tilt is based on a 30 μm bunch position at 7.5 cm from bunch center (1 σ) and is sensitive to the crab cavity voltage errors. For example an imbalance of crab voltage of 1 % (crab cavity voltage error) can lead to a $\simeq$ 30 % change of the residual crabbing (R. de Maria, 11.06.23, t.b.c.).

Table 7: Parameters for pick-up and position processing for noise feedback (single bunch and 25 ns bunch spacing), tolerances under revision. The quantity "dynamic range" is defined as $20\,\mathrm{dB}\log_{10}(\{value_{\mathrm{rms}}\}/\{range_{\mathrm{max,onesided}}\})$

Parameter	value		comment
mechanical alignment offsets (H/V)	± 0.5	mm	pick-up axis to UAP mean
mechanical alignment offsets (H/V)	± 1	mm	UAP yearly correction possible
beam orbit variation	± 1	mm	occurs dynamically in operation
acceptance of electrical centering	± 3	mm	dynamically during fill
electrical centering to better than	± 0.5	mm	as needed, responsibility WP4
single bunch position noise (SB)	0.32	μm	rms from simulations [1] t.b.c.
position dynamic range needed (SB)	63.9 (73.4)	dB	with (without) electric centering
position avg. noise (3.6 μs $\equiv 136$ kHz BW)	3.9	μm	relaxed rms per bunch for 25 spacing [1] t.b.c.
position dynamic range needed (25 ns)	42.2 (51.7	dB	with (without) electric centering

Table 8: Parameters for pick-up and tilt processing for noise feedback (single bunch and 25 ns bunch spacing), distribution of tolerances under revision. The quantity "dynamic range" is defined as $20\,\mathrm{dB}\log_{10}(\{value_{\mathrm{rms}}\}/\{range_{\mathrm{max,onesided}}\})$

Parameter	value		comment
alignment roll	$\pm 50?$	μrad	pick-up axis to UAP mean
alignment roll of UAP mean	$\pm 100?$	μrad	yearly correction; mixes H/V- plane
alignment $\perp$ CC-axis, pitch (IP1), yaw (IP5)	$\pm 50?$	μrad	pick-up axis to UAP mean
alignment $\perp$ CC-axis, pitch (IP1), yaw (IP5)	$\pm 100?$	μrad	UAP mean, yearly correction
operational margin, pitch (IP1), yaw (IP5)	$\pm 100?$	μrad	operational margin needed?
alignment CC-axis, yaw (IP1), pitch (IP5)	$\pm 50?$	μrad	pick-up axis to UAP mean
alignment CC-axis, yaw (IP1), pitch (IP5)	$\pm 100?$	μrad	UAP mean, yearly correction
operational margin, yaw (IP1), pitch (IP5)	$\pm 100?$	μrad	operational margin needed?
residual crabbing tilt (nominal)	400	μrad	best case, closed crabbing
residual crabbing tilt	10000	μrad	worst case (open crabbing bump)
single bunch tilt noise	8.3	μrad	rms from simulations [1] t.b.c.
tilt dynamic range needed (SB)	37.9 (61.6)	dB	closed case (worst open case)
averaged noise (3.6 μs $\equiv 136$ kHz BW)	100	μrad	relaxed rms per bunch for 25 ns spacing [1] t.b.c.
tilt dynamic range needed (25 ns)	16.3 (40.2)	dB	closed case (worst open case)

Leveraging on the collected experience gained for the LHC transverse feedback system and its stripline pick-up system, in how to achieve a high measurement precision and low fluctuation (noise) [4] is very important for the planned crab cavity noise feedback.

To note that a trade-off if button pick-ups were used for the noise feedback (functionality C), is that, while they can be better paired than striplines, experience with their possible inter-bunch interference they create still needs to be built up and can represent a significant disadvantage in the noise feedback, i.e. a source of additional measurement noise for the 25 ns bunch spacing case.

While the dynamic ranges expressed in dB required for position and tilt do not differ from one another too much, it must be noted that for the case of open crabbing the large tilt offset of 15 mrad cannot be compensated before digitization of the signals as is the case for a large average position offset. Performance estimations for the noise feedback for this extreme case in single bunch mode needs a full study of the scenarios.

5 Comment on parameters and tolerances

The parameter tables in section 3 and 4 define the chosen parameters for the pick-ups and the limits permitted to ensure the best possible quality of the signals for the needed function with the given constraints.

The exact impact of tolerances depends on the way the signal is processed after the pick-up. We assume a processing with down conversion from the RF harmonic at 400 MHz, validated by WP2 in simulation [7], with a bandwidth and sampling frequency sufficient to derive numerical values for the intra-bunch head-tail motion and average position using the schemes outlined in [4, 8, 9].

The digital per bunch data can subsequently be processed numerically to do averaging to achieve the required noise feedback bandwidth (nominally 135 kHz), adjust the feedback phase, and for removal of offsets (position and tilt), feeding a correction back to the crab cavity LLRF set-point.

If tolerances quoted are not met but stay invariant over time, there should in most cases be a way to remove their effect on the signal by using probe beams of known properties to determine suitable corrections. Discrepancies in the pairing is best observed in time domain with signals available for direct observation of the two sides in the Faraday Cage. For this reason the hybrid generating sum and difference shall be located in the Faraday cage and matched cables (7/8") with known, validated transfer functions used for all critical signals.

The pick-up location BPTQR is located next to the crab cavities on the side farther away from the IP with respect to the crab cavities. The cavities in normal operating mode are synchronised and adjusted to leave the minimum possible crabbing motion outside the IP region. In normal operation the pick-ups will see this non-closure part of crabbing plus any oscillation on top induced by noise in the crab cavity system, subject to the intended correction by the noise feedback. This non-closure part has been estimated and is given in the corresponding tables with a best case value and a worst case value (un-closed crabbing). The latter may occur in a machine development or commissioning scenario. Therefore two different operational modes must be considered

- crab cavity normal operation: a residual non-closure of crabbing is seen at pick-ups (that the noise feedback will have to ignore)
- crab cavity phasing mode: deliberate, larger non closure around ring for adjustments and studies, for example using only one crab cavity active or two crab cavities on one side of the IP only

5.1 Comments on Installation and alignment

All pick-ups considered are warm devices and must fit together with the planned head-tail monitor (not part of this specification) into the available space of 1150 mm on either side of the IR1 and IR5 on both beams close to the crab cavities at a high β function on both beams. The installation is proposed with only partial staggering with limited transverse space for feedthroughs cabling [2]. [update with new reference needed, 800 mm to 1150 mm].

Crab cavities have their dedicated remote controlled alignment system to guarantee a beam trajectory through the electrical center of the cavities. This is not the case for the string of pick-ups of 1150 mm with common support for which a manual mechanical realignment requires access. Such an access for realignment is only foreseen once a year, in particular to compensate for any systematic slow changes over time, such as the expected downward movement (0.5 mm/year).

Electrical centering of the signal before the hybrid used to extract sum and difference signal shall be provided by a system similar to the one conceptually described in [10].

5.2 Considerations for impact of tolerances

The functionality A is needed in normal crab operation (here called functionality A1), and for crab cavity phasing with deliberate crabbing around the ring (here called functionality A2); The beam phase measurement accuracy shall not depend on the presence of crabbing as it defines the absolute reference in time of when the beam passes with respect to the cavities. Therefore it seems the choice to have the dedicated button pick-up in the plane *perpendicular* to the crabbing is the optimum (not influenced by crabbing) for this functionality. Accurate average phase information of the beam is needed. The bandwidth required is low, typically averaging the bunch-by-bunch data over a machine turn is acceptable, easily achieved in the digital domain.

For functionality B the choice of plane as the plane of crabbing seems acceptable as the algorithm to subtract the beam generated component can be adaptive using beam on segments, and gaps (beam off segments) in the beam. Processing requires accurate amplitude information from the beam at the same bunch frequency harmonic as the signal treated by the cavity field probe uses, if the cancellation is done in the digital domain.

Functionality C for the crab cavity noise feedback requires to correctly disentangle amplitude perturbation from phase perturbation by measuring position and tilt and minimizing any cross-talk between these two measurements.

Between the center of the feedthroughs of the pick-ups for functionality B and functionality C there was a distance of 83.5 mm foreseen with full staggering [6] and more space is available longitudinally in the adopted option with 1150 mm. Perturbation of the transfer functions of button and stripline pick-up due to this proximity depends on which pick-up the beam encounters first and the quality of RF matching. Since the stripline pick-up signal is larger, the installation orientation shall be such that the beam first encounters the button pick-ups, for all planes and beams. WP13 agrees to quantify the effect of perturbation.

References

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