TUNE AND ORBIT FEEDBACKS

L. Ponce, J. Wenninger, K. Fuchsberger and S. Jackson, CERN, Geneva, Switzerland

Abstract

Major refactoring of the Tune and orbit Feedbacks systems has been performed during LS1 to improve stability and performance. The talk is presenting the changes implemented in the system with the testing Framework put in place. The main issues encountered during the beam commissioning are also reminded as well as the configuration used all along the LHC cycle. Finally, performance of the Orbit Feedback system is summarized through some orbit stability analysis.

NEW FEEDBACKS FOR 2015

Description of the systems

The tune measurement system is comprised of 4 independent acquisition systems:

- **On demand** used to perform measurement requiring changes in the acquisition chain settings or beam excitation,
- **Continuous GATED** and **Continuous High Sensitivity** used for nominal bunch intensity beam for tune feedback and continuous tune measurement,
- **Dev** system used for beam studies and as hot spare.

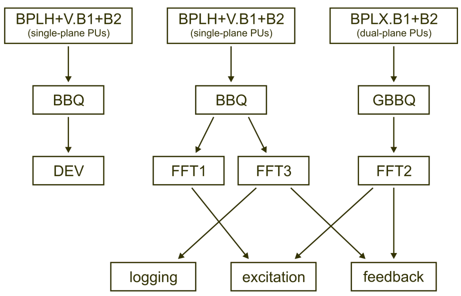


Figure 1: Tune measurement systems architecture.

In principle, the Tune Feedback System (QFB) can be configured to use any of the devices, but in practise, only the 2 CONTINUOUS devices (GATED and High Sensitivity) were used during 2015 as feedback functionality implies that acquisition settings are fixed

The Orbit Feedback (OFB) system is comprised of 2 different parts, implemented into 2 different software: the LHC Feedback Service Unit, so-called BFSU (formally OFSU) and the Orbit Feedback Controller, so called OFC.

Feedbacks after LS1

During Long Shutdown 1 (LS1), the Orbit Feedback system went through major re-factoring due to mandatory software migration and change of main developers.

The first important change concerned the Hardware. The old machines (4xCore, 32-bits running SLC5) have been replaced by new machines (24xCore with 64-bits processor) ported to SLC6. An extra timing receiver card has also been added to the OFC.

The BFSU class has been migrated from FESA2 to FESA3. More than 35000 lines of code have been ported mainly manually as the standard migration tools were not fully mature at the start of the process in July 2014. This represented a major effort of 3-4 months (without testing) for the BE/BI-SW team. As the code functionality and content were mostly unknown in advance, a systematic approach has been taken. The team had to understand, document and use JIRA for managing the changes resulting from the porting process. At least 1 issue was created for the porting of each action (now > 130 issues for BFSU porting alone) Code commits were (and still are) tagged with the issue number, this allows for automatic cross-referencing of issues and SVN commits.

Specific porting technicalities were encountered in the FESA2->FESA3 porting process: many issues with inherent 32-bit assumptions in the original code, handling of arrays changed from FESA2 to FESA3, many data-consistency issues with settings-properties setting acquisition-fields which used to be allowed in FESA2 but not in FESA3, etc...

The Controller (OFC) has also be ported to FESA3 with 2 main changes. Explicit types have been declared and the ROOT based logging has been replaced with standard logging system which allows to now use standard BE/CO tools for logging analysis.

In parallel of the porting, several changes have been made to improve stability. As a result from taking standard SLC version of ROOT, the code no longer needs to be built on operational hardware. Both Service Unit and Controller code have been cleaned-up: un-needed features (e.g BCT subscription/concentration) have been disabled from controller and several bugs and unchecked string manipulation have been identified and fixed. Most of the critical settings have been moved into LSA settings for less reliance on FESA persistency for settings. And finally, one of the major source of Ethernet overload was removed by balancing better the settings exchange between the Service Unit and the Controller over 10 seconds intervals and by reducing the size data structure.

Feedbacks Testing Framework

In parallel of code refactoring, a Testing Framework was put in place as a collaboration between BE-CO, BE-BI and BE-OP groups. The idea was to set-up a controlled testing outside operational environment to have less impact on operations and being able to test the systems before beam is back.

Different types of tests have been identified and then implemented to exercise the FESA mechanics, communication between the different components and the Control loop behavior.

The principle is to inject directly tests through UDP layer (Fig. 2), allowing a free choice of the language. Most of the tests have been implemented in JAVA, based on Junit test. This gives the advantages of a bigger community to write test, an easy interaction with the other parts of the control system and allow a first experience with JAVA real time behavior.

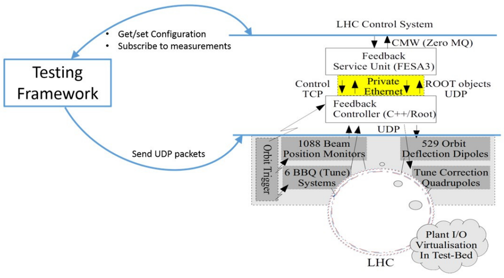


Figure 2: Testing Framework principle

Thanks to the TestBed Framework, functional tests of the Controller and the Service Unit software have been performed allowing to test new control algorithms and simulate non-ideal beam behavior. Various operational scenarios have also been tested: simulation of instrumentation faults, simulation of (intermittent) network faults, simulation of packet corruption, delays, jitters, etc... At the same time, stress tests and acceptance tests have been implemented and ran regularly.

The methodologies and the model put in place will be used by BE-BI group in 2016 when migrating other big projects to FESA3 (LHC BLM, Tune systems...).

OPERATIONAL USAGE OF THE FEEDBACKS

Interface with operation

Several properties are settable for operation, either via sequencer or via dedicated application (YASP). The main ones, already available during Run 1, are the On/Off command, loading of references (both for orbit and tune feedbacks) and setting of optics via the BFSU, dynamic change of the references via timing events.

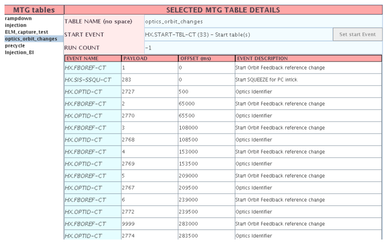
After LS1 re-factoring, new settings, which used to be experts settings only, have been exposed to operation. They are now stored in LSA and are trimmable either via sequencer or via YASP application, with the advantage of logging of all the changes. These settings are the gain of the different feedbacks, the number of Eigen values used for derivation of response matrix and the status of correctors/monitors.

Change of reference

During the ramp and squeeze, the reference orbit is changing because the amplitude and the shape of the bumps around the IPs are changing. The reference tunes are also changed from injection settings to collisions settings at flat top. Both changes are played over several seconds/minutes following the power converters functions and these changes have to be propagated to the references used by the feedbacks.

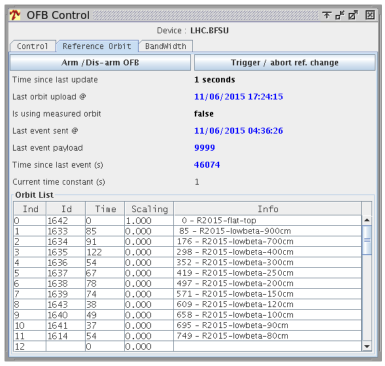
For the OFB, the settings (BPM readings/COD settings) of each reference are stored in LSA and sequencer tasks exist to load the reference and arm the feedbacks. To be noted that both Tune and Orbit feedbacks are not really playing a function as the power converters. Feedbacks controller fit a linear extrapolation between the actual settings and the requested settings over a time also set by the sequencer tasks and encoded in the timing event (called *timeConstant*).

The change of reference is triggered by specific timing events as long as the feedbacks stayed *armed* and the same timing event with a payload greater than 99 is used to *disarm*. All timing events needed to follow the change of references are generated before launching a given Beam Process in a dynamic timing table which is started at the same time as the Beam Process itself, Fig.3.



EVENT NAME	PAYLOAD	OFFSET (ms)	EVENT DESCRIPTION
HX.FBOREF-CT	1	0	Start Orbit Feedback reference change
HX.SIS-SSQU-CT	283	0	Start SQUEEZE for PC intlck
HX.OPTID-CT	2727	500	Optics Identifier
HX.FBOREF-CT	2	65000	Start Orbit Feedback reference change
HX.OPTID-CT	2770	65500	Optics Identifier
HX.FBOREF-CT	3	108000	Start Orbit Feedback reference change
HX.OPTID-CT	2768	108500	Optics Identifier
HX.FBOREF-CT	4	153000	Start Orbit Feedback reference change
HX.OPTID-CT	2769	153500	Optics Identifier
HX.FBOREF-CT	5	209000	Start Orbit Feedback reference change
HX.OPTID-CT	2767	209500	Optics Identifier
HX.FBOREF-CT	6	239000	Start Orbit Feedback reference change
HX.OPTID-CT	2772	239500	Optics Identifier
HX.FBOREF-CT	9999	283000	Start Orbit Feedback reference change
HX.OPTID-CT	2774	283500	Optics Identifier

Figure 3: Dynamic table table containing timing events to trigger optics and orbit reference changes.



Ind	Id	Time	Scaling	Info
0	1642	0	1.000	0 - R2015-flat-top
1	1633	85	0.000	85 - R2015-lowbeta-900cm
2	1634	91	0.000	176 - R2015-lowbeta-700cm
3	1635	122	0.000	298 - R2015-lowbeta-400cm
4	1636	54	0.000	352 - R2015-lowbeta-300cm
5	1637	67	0.000	419 - R2015-lowbeta-250cm
6	1638	78	0.000	497 - R2015-lowbeta-200cm
7	1639	74	0.000	571 - R2015-lowbeta-150cm
8	1643	38	0.000	609 - R2015-lowbeta-120cm
9	1640	49	0.000	658 - R2015-lowbeta-100cm
10	1641	37	0.000	695 - R2015-lowbeta-90cm
11	1614	54	0.000	749 - R2015-lowbeta-80cm
12		0	0.000	

Figure 4: List of orbit references used for the squeeze to 80 cm.

Both tune and orbit references are set on 2 different properties of the BFSU and the change is triggered by a dedicated timing event, introducing a critical dependence of the BFSU FESA class stability all along the beam cycle: as an example, 11 timing events are used in the squeeze to 80 cm, Fig.4.

Change of optics

The optics are used by the OFC to compute the SVD response matrix of the orbit feedback. In principle, this matrix should be recomputed for each matched point during the squeeze, but it is a quite lengthy process which can take between 1 and 2 minutes.

The dynamic change of optics during the squeeze also via timing event is implemented but was never deployed in nominal operation for different reasons. During Run 1, the number of optics loaded and calculated was reduced to avoid stability problem of the OFSU (former version of the BFSU): the process was not able to compute more that few optics. Moreover, the re-computation of the matrix with the feedback ON acting on the beam was never tested and then is raised the question of usage of the change of optics with a matrix re-computation time of the order of a minute comparable with the length of the segements. The last 2 points need more time with beam to test the stability and evaluate the use.

As a consequence, during 2015 operation, the matrix was recomputed only once before the start of the squeeze in a discrete mode: with orbit feedback OFF, the matrix is calculated with an intermediate optics (namely the 2.5 m optics for the squeeze to 80 cm) and the new references loaded before Feedback is switched ON again, the squeeze being played with the same response matrix.

Feedbacks settings along the cycle

Thanks to the new experts settings made available to operation during LS1, the usage of the different feedbacks along the cycle has been extended.

In preparation without beam, the optics are fetched for the whole cycle, a default response matrix is derived ignoring all BPM statuses and default settings of feedbacks response are loaded (*OFB Gain* = 1, *Eigen values* = 390-420 and *Radial loop Gain* = 0.5). The devices for the tune feedback are also set for pilot beam.

During injection the orbit feedback is manually switched ON to correct the orbit towards the reference, with pilot beams and/or physics beam. The tunes are corrected manually towards the references. The Tune devices are switched to the appropriate ones depending on the injected beam intensity (GATED devices for trains) as part of the sequence to prepare injection of physics beams.

During prepare ramp both Tune and Orbit feedbacks are switched ON via sequencer correcting to the injection references. The change of orbit reference is also loaded and OFB is armed.

During the ramp the tune references are kept constant, the orbit reference (crossing and separation) is changed at 2 TeV. The used settings are *OFB Gain* = 2, *Eigen values* = 390-420 and *Radial loop Gain* = 0.5. The OFB gain is increased to improve the correction efficiency during the snapback.

During the change of Tune, both Orbit and Tune feedbacks are kept ON. The orbit reference is constant and the tune references (and the fitter settings) are changed for physics settings linearly over the QCHANGE Beam Process length.

In preparation of the squeeze, the response matrix is calculated with the 2.5 m optics and the 11 orbit references are loaded, OFB is armed.

During the squeeze, the Tune feedback is kept ON with constant references. The Orbit feedback is also ON, changing orbit references at each matched point with a linear extrapolation between 2 segments to follow the change of separation and crossing bumps shape with the optics. The response settings are changed to *OFB Gain* = 1, *Eigen values* = 390-420 and *Radial loop Gain*= 0.5.

During the preparation of collisions, both feedbacks are switched OFF, but the change of orbit references is loaded and played to follow the collapsing of the separation bumps. Orbit is manually corrected using YASP application at the end of the collisions Beam Process towards the physics orbit reference.

In collisions, during th second part of 2015 run, the orbit feedback is ON with lower gain and Eigen values (*OFB Gain* = 0.2, *Eigen values* = 40-40 and *Radial loop Gain* = 0.02) to smoothly correct the orbit drift during STABLE BEAMS, in particular the drifts due to IP8 triplet movements. After optimization of the collisions (including leveling), the actual orbit is used as reference for the feedbacks.

The different settings of the feedbacks along the cycle are summarized in Table 1.

Mode	OFB State	OFB/ Radial Gain	Eigen values
Preparation	OFF	1 / 0.5	390-420
INJECTION	*ON*	1/ 0.5	390-420
RAMP	ON	2 / 0.5	390-420
QCHANGE	ON	1 / 0.5	390-420
SQUEEZE	ON	1 / 0.5	390-420
COLLISIONS	OFF	1 / 0.5	390-420
STABLE BEAM	*ON*	0.2 / 0.02	40-40

Table 1: Summary of the Orbit feedback state and settings for the different modes of operation in 2015. At injection, the OFB is manually switched on for a short time to correct towards injection orbit reference. In italic are the manual action.

MAIN ISSUES DURING 2015 OPERATION

After LS1, most of the stability problems that punctuated Run 1 operation have been fixed. We nevertheless had 3 beam dumps due to Tune Feedbacks in 2015, all due to tune signal quality problems and interference with the transverse dampers. We also experienced few teething problems with the orbit feedbacks (wrong reference or timing event not received), which did not generate any beam dumped.

Tune measurement quality

The performance of the tune feedback is highly depending on the tune signal quality and more specifically to a good signal to noise ratio. During 2015 operation, we still had 3 dumps because the tune feedback locked on a wrong tune peak (noise peak) value and the real tunes were pushed towards resonance leading to beam dumped triggered by high beam losses.

The saturation problem was solved by using different devices for the pilot and nominal bunch intensity beams. The switch between the devices is in the corresponding sequence and hardware settings of the devices have been adjusted for 2015 proton intensities. In addition of the intensity switch, the devices are also switched between GATED and Continuous HS for single bunch or trains beam structure. The problem of co-existence between tune measurement and transverse feedback effect (tune peak damped) was solved by using The GATED tune system: the tune measurement is gated on a limited number of bunches (the first 400) which also experience a reduced ADT gain (factor 100 below NOMINAL ADT gains). The window of the GATED device is now configurable from the tune viewer application, Fig. 5, as well as the value of the ADT gain (trimmable in LSA). These 2 options allowed an optimization during the intensity ramp-up so that the TUNE signal measurement improved allowing running with a good quality of the measurement and then the Tune feedback ON during the nominal physics production.

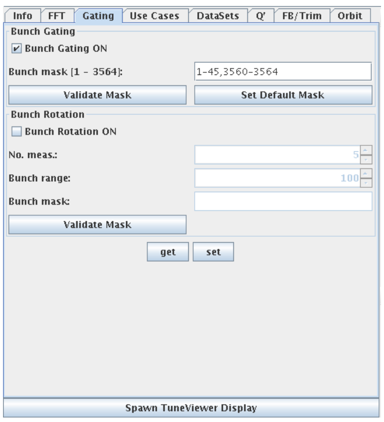


Figure 5: Settings of the GATED tune device measurement.

Operation with ions was more difficult as the GATED tune device system was not re-calibrated for ions intensity and then tune measurement was not very clean during ions run.

The co-existence of tune measurement in the vertical plane with the abort gap cleaning is still a problem and prevented the usage of the abort gap cleaning during the squeeze when tune feedback ON is needed.

Loss of timing event

At the beginning of the run, it was observed few times problem with the triggering of change of reference orbit, critical during the ramp as the crossing angles bump amplitude are changing. This was traced back to a configuration problem of the O/S of the BFSU in the processing of interrupts: 2 timing events, one to change the optics and one to change the orbit reference, were sent too close to each other and one of them was not treated.

Several mitigation were put in place in parallel to avoid critical situation with high intensity beams. First of all, the configuration of the BFSU machine has been corrected to handle properly the interrupts. At the same time, a delay of 500 ms was introduced in the timing table between the event to change the orbit and the event to change the optics, the timing for the optics ID change not being critical. After these changes, no more loss of timing event were observed, but the delay between the event has never been removed.

Wrong orbit references

Since Run 1, the reference orbits are stored in LSA with the optics tables. The change of reference is driven by sequencer using the TIMING USER associated to the Beam Process in the active hypercycle. The automation with the sequencer worked very well for the nominal operation, but during special run/Machine Development when cloning hypercycle, it happened 2 times that wrong orbit references were used because of re-use of the Beam process.

ORBIT FEEDBACKS PERFORMANCES

Systematic orbit errors

The orbit feedback performance was improved during 2015 compared to Run 1 thanks to an improved orbit measurement quality. The BPM rack cooling has been improved during LS1 to limit the orbit drift with temperature. The remaining affect after correction is smaller by a factor 5 to 10 compared to Run 1, Fig. 6.

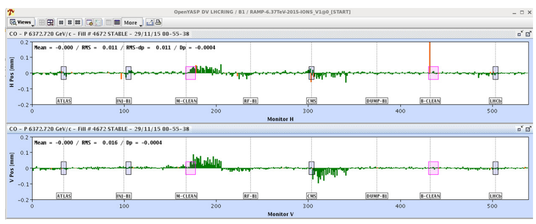


Figure 6: Effect of temperature on the orbit measurement: reference orbit is the orbit at the beginning of the STABLE BEAMS.

Some crates could still be improved around point 3,4 and 5, but the improved quality allowed to use the orbit feedbacks during physics.

Performance during the squeeze

Orbit correction during the squeeze is made with the Feedback combined with regular FeedForward of the corrections.

After LS1, orbit corrector functions are forced to follow a PLP segment. Trim and FeedForward is only possible in the matched points, allowing a smoother orbit in the squeeze without need to use the Feedback with High gain values.

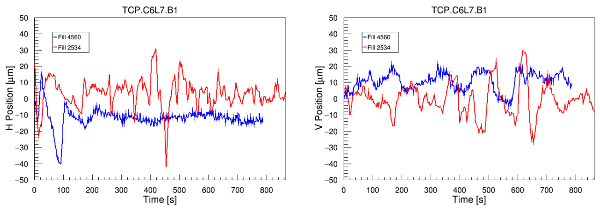


Figure 7: Orbit excursion during the squeeze in horizontal and vertical plane.

In Fig 7 are shown the orbit excursion in horizontal and vertical plane along the squeeze, in red the best orbit in 2012 after heavy FeedForward following a special high gain OFB pass through the squeeze and in blue an example of 2015 with a simple FeedForward in the matched point.

Some horizontal transients remains between the start of the squeeze and the first matched point at 85 s. Operating with a gain 2 times higher could bring down the orbit excursion below 20 μm, Fig 8, but the source of the perturbation still need to be analyzed.

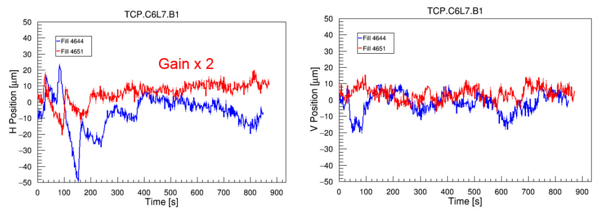


Figure 8: Orbit excursion during the squeeze with nominal gain in blue and with 2 times nominal gain in red.

Orbit Feedback during STABLE BEAMS

After LS1, orbit drift up to 0.2 mm rms has been observed with a period of 8 hours, see Fig.9. The drift period is in clear correlation with the IR8 triplet movement which has been present since the triplet cryostat is filled with Helium, Fig.10.

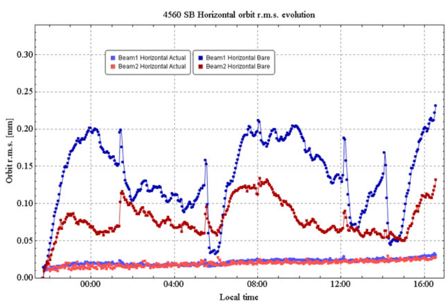


Figure 9: Orbit rms evolution during STABLE BEAMS.

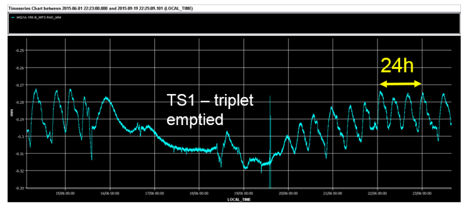


Figure 10: Wire Position System (WPS) measurement of the IR8 triplet over several days at the beginning of the run.

The cause of the triplet movement is not yet understood despite several tests made along the year [1]. To compensate the orbit drift, the Orbit Feedback was used during the STABLE BEAM period with gentle corrections (limited number of Eigen values and reduced gain) and excluding the interaction region to not interfere with the luminosity leveling.

Long-term orbit reproducibility

The evolution of the rms orbit excluding the areas close to IR1, IR2, IR5 and IR8 is an indicator of the long term reproducibility of the orbit, Fig. 11. It includes the BPM errors, ground motion, Orbit Feedbacks corrections, etc...

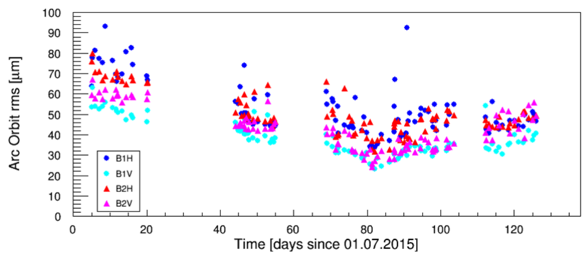


Figure 11: Arc orbit rms evolution for the 2 beams, 2 planes from fill to fill. Each point represent one fill and is taken after 5 min in STABLE BEAMS. The rms is calculated over healthy BPMs except IR1,2,5 and 8 bump region wrt orbit reference in the 25 ns period at day 85.

The orbit reproducibility is within 50 μm over 3 months. Long and short term (from fill to fill) reproducibility are very similar, slightly worse in the horizontal plane due to IR8 triplet movement.

CHANGES FOR 2016

No major change is planned to be implemented during the Year End Technical Stop for the operational feedbacks. Few ideas to improve the usability are nevertheless under study. The first one is the implementation of function for gains, to allow a more flexible operation. The Feedbacks gains could be pushed during the first 120 s of the ramp and the first segments of the squeeze where the largest orbit and tune perturbations are measured.

For the Tune Feedback, a factor 2 in the efficiency could be gained by changing the default acquisition settings, moving from 4000 turns at 4 Hz to 2000 turns at 8 Hz.

A re-factoring of the reference orbit construction and storage based on the knob concept is under development and could help for an easier management of the orbit references.

Several developments are also planned for the TestBed. The first one is to add more tests to increase the coverage of the use-case and code checks. Adding automatic builds to test at every change and additional reports should improve the code quality and efficiency of the tests. A more ambitious plan is to close the loop on the operational scenario tests to explore dynamic stability limits of the algorithm: capture the controller magnet corrections, recalculate (simulate) the beam reaction, send back the response to the BFSU.

SUMMARY

During LS1, the Orbit Feedback Systems went through a major re-factoring due to change of hardware and migration of the software version. Stability of the systems and operability have been improved a lot allowing a stable operation of the system during the year. More experts settings have been made available for standard operation allowing an easier setting-up and commissioning of the systems.

After few teething problems being solved at the very beginning of the year (software configuration for the Orbit Feedback and signal quality for the Tune feedback), nominal proton operation went smoothly with both Feedbacks systems used all along the cycle. We moved from a mode of operation with Feedbacks disabled during run 1 to a mode of operation with OFB switched ON during all the STABLE BEAMS period.

REFERENCES

[1] G. Ferlin, Cryogenic investigation plan for IT IR8 movement, at the LHC Machine Comittee 248^{th} meeting.