5th LHC Crab Cavity Workshop, LHC-CC11 Workshop Summary Report

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1 EXECUTIVE SUMMARY

Steve Myers, Paul Collier

1. The baseline scheme for HL-LHC remains as the local crab crossing scheme with 400 MHz superconducting cavities independent for each IP (IP1 and IP5).
2. A global option in point 4 is discarded for the final crab crossing scheme.
3. Detailed cavity specifications for compact cavities will be prepared by April 2012 based on an initial set of HL-LHC parameters.
4. Beam tests of the final compact design in both the SPS and the LHC are pre-requisites for a final installation in point 1 and 5. Prior to any installation, the cryomodule(s) will undergo a thorough RF and cryogenic tests in an SM18 like test stand to qualify for beam tests.
5. All pertinent RF and beam tests that can be performed before an LHC installation should be carried out in the SPS. To meet the present schedule, the target for the SPS tests is 2015 and no later than 2016. All beam studies prior to an SPS crab cavity installation to adequately prepare for the crab cavity tests are highly encouraged.
6. Important additional tests require a Point 4 setup with LHC beams. The LHC tests must be performed before LS2 to allow for the construction, preparation and installation of crab cavities in Point 1 and 5 in the final configuration.
7. The motivation, detailed objectives and requirements, both for the SPS and the LHC beam tests, will be defined\(^1\). The expected results, associated benefits and an overall planning (recommended also at LHC-CC10) should be outlined.
8. The precise location in the SPS should be reviewed again by a similar working group as the test setup with KEKB cavities. The requirements for RF, cryogenic, integration and instrumentation will be specified.
9. A temporary cryogenic system is required for the SPS crab cavity tests. 2K helium is the chosen solution. The cryogenics group will provide the information on the cooling capacity and additional infrastructure at BA4 in the SPS by the end of 2012.
10. The possibility to transport the temporary cryo system from the SPS to point 4 for an LHC test should be urgently studied. The associated time for this installation should be specified by the end of 2012.
11. Further studies for machine protection with crab cavities with realistic RF failure signals in conjunction with the upgraded collimation system are required. A working group should be formed soon to study all relevant machine protection issues and mitigation scenarios (redundancy, LLRF and other safety mechanisms).
12. Collaboration on SPS & P4 test cryostat development (& construction) is a priority. Joint design of a cryomodule will be set up, involving cavity designers, CERN and outside cryo experts.
13. Developments of low noise RF controls to reduce the RF noise at the betatron sidebands should be initiated. Integration of RF equipment and requirement due to high radiation area should be studied.

\(^1\) See chapter 5 for a preliminary motivation, objectives and planning of the SPS tests
2 INTRODUCTION

The 5th workshop on the crab cavities (LHC-CC11) for the LHC luminosity upgrade project (HL-LHC) was held from 14 to 15 November 2011 at CERN, Geneva, Switzerland. The workshop was organized by a joint collaboration of CERN, EUCARD, KEK and US-LARP. Approximately 52 participants from 3 continents and several institutions participated in the workshop to discuss the present status, future testing and implementation of the crab cavities in the SPS and the LHC. The detailed participation list, scientific program along with the associated contributions are available at:

http://indico.cern.ch/conferenceDisplay.py?confId=149614

2.1 WORKSHOP CHARGE AND OBJECTIVES

The charge of the workshop was as follows:

1. Technology status in view of the recent of the latest developments on compact cavities
2. Revised beam parameters and upgrade studies with crab crossing
3. SPS and LHC beam studies with crab cavities tests
3 SESSION SUMMARIES

Notes from the session summaries prepared by their respective conveners and additional material from the discussions during the workshop are detailed in this section.

3.1 LHC-CC STATUS & UPGRADE OVERVIEW

Jean-Pierre Koutchouk

Program of Session 1

The study of an LHC upgrade based on crab cavities on a relatively short time scale is a major challenge in machine design and RF technology. The goal of this first session is to review the justification of this strategy in the light of the LHC performance, of the LHC physics, and of other potential applications of crab cavities. Three talks cover:

• LHC performance and main limitations, by Mike Lamont/CERN,
• Highlights from the LHC physics, by Fabiola Gianotti/CERN,
• Project X and synergies with crab cavities, by Vyacheslav Yakovlev/FNAL, USA.

This summary attempts at underlining the salient aspects, summarizing discussions and drawing provisional conclusions in relations with the LHC upgrade.

LHC Performance and main Limitations, M. Lamont

The salient points

The LHC has shown outstanding performance in 2011, with 5.5 fb\(^{-1}\) accumulated. M. Lamont’s presentation analyses the reasons behind this success, and the issues that remain to overcome.

The beam characteristics from the injectors are better than planned: At 50 ns bunch spacing, the emittance is almost twice smaller than foreseen and the bunch charge approaches the “ultimate” LHC parameters. At 25 ns bunch spacing, the nominal charge is reached with an emittance 25% lower than planned.

Physics is carried out with a 50 ns spacing, while MD’s show encouraging signs of scrubbing for a 25 ns bunch spacing. In operational conditions, the peak event multiplicity averaged over the bunches are around 17 (20 nominal).

The beam optics is very close to the model and can be measured accurately using the rich functionality of the beam instrumentation. The dynamic aperture is larger than the collimator aperture thanks to an excellent magnetic field quality, complemented by non-linear corrections. Unexpectedly, the “ultimate” head-on beam-beam tune shift of 0.02 is easily reached. The long-range beam-beam effect appears qualitatively as expected. The machine mechanical aperture is better than expected, allowing a beta* of 1m at 3.5 TeV. The collimators efficiently protect the machine at 1/3 of the nominal beam power. The cumulative result is the beam and luminosity lifetimes larger than anticipated, and a peak luminosity that reaches 36% of the design luminosity, in spite of a two times lower energy.

The fastest turn-around time is about 2 hours, and the average run duration is 6 hours due to frequent beam aborts (the optimal would be around 15 hours).

The issues to overcome are all essentially external to the basic machine design:

• Fast and localized beam losses are observed, attributed to dust macroparticles falling into the beam. While the impact on 3.5 TeV running is marginal, this effect could become serious at 7 TeV.
• The vacuum show pressure rises in several areas, and their origin is not always understood.
• Unexpected beam induced heating is observed in collimators, injection kickers and beam screens, without consequences so far.
• Radiation to electronics (single events)

All issues that are understood give rise to improvement plans.

Highlights from the discussion

About the turn-around time (JPK): experience shows that it can approach 2 hours (3 hours was the estimated minimum). Some further decrease can be expected from combining ramp and squeeze. The increase in beam energy to 7TeV will necessarily increase the length of the ramp and ramp-down. For the calculation of the LHC upgrade performance, an average turn-around time of 3 hours appears as a realistic target.

About the run duration (JPK): the present average of 6 hours is rather close to the anticipated upgrade conditions, without luminosity levelling. The present LHC performance show that the detectors can efficiently cope with short duration runs.

Tentative conclusions for the HLLHC

The remarkable LHC performance shows that the machine has no unexpected limitations that would jeopardize an ambitious upgrade. On the contrary, the unexpected easiness in increasing the head-on beam-beam tune shift by a factor of two above nominal, and the absence of perturbations related to a transverse beam separation at the crossing points give high confidence that the nominal performance can be exceeded, and perhaps the “ultimate” performance as well. The basic hypotheses and strategies behind the luminosity Upgrade will need to be reassessed, to take into account the LHC experience, after they are extrapolated to the nominal energy of 7 TeV.

HighLights from the physics, F. Gianotti

The salient points

All LHC experiments perform extremely well, with efficiencies in excess of 90%. The average pile-up in ATLAS and CMS was 12 interactions per crossing over a fill towards the end of the proton run, but has reached peak values of 20, which is the LHC design value. The detectors are coping well. In a first phase, the goal has been to “rediscover” the SM and to accuracies similar to previous machines have been achieved in the measurements of several processes. In parallel searches for new physics are breaking new ground. A huge number of scenarios are investigated, searching for manifestations of new forces, new space dimensions, quark substrutures, supersymmetry, in particular as possible explanation for dark matter, etc. No new physics has been identified so far, but the integrated luminosity is 60 times below design goal and the energy two times lower, leaving scope for later discoveries. Yet, the SM Higgs is now very much constrained in possible mass (114 to 145 GeV). At the end of next year, it will be possible either to exclude the SM Higgs or to discover it at a 5σ confidence level.
Highlights from the discussion

**Still believe in SM Higgs?** (Mike L.): yes, still the most elegant mechanism for breaking of electro-weak symmetry.

**How much pile up is acceptable?** (Frank Z.): The detectors have seen up to 30-34 interactions per crossing and their maximum is possibly around 40. A target of 80 seems possible for the first phase of the detector upgrade scheduled in 2018, for data taking in 2019-2021. In a second phase, planned for implementation in 2022, the goal is to increase the maximum detector acceptance to 200².

**How fast to start data taking?** (JPK): in ATLAS, it takes only 5 minutes (ramp up voltage) for the detectors to become operational after stable beams have been declared.

**Is the background an issue?** (Lucio R.): no, the conditions are extremely clean; CMS suffers from some vacuum problems close to IP5.

**Detector lifetime?** (Rama C.): some changes are indeed already planned during LS1.

**If no SM Higgs, what can be the motivation for HLLHC?** (JPK): SM WW scattering cross section diverges at high energy and the SM Higgs is needed to remove the divergence. Without a SM Higgs, something strange in WW scattering is expected at 14 TeV. The HL-LHC would become even more necessary.

**Tentative conclusions for HLLHC**

Whatever the outcome of the Higgs search, the justification of the LHC luminosity upgrade is strong. The excellent behaviour of the detectors allows drawing initial hints for the upgrade scenarios: a reasonable target for the pile-up would be twice the expected capability of the present detectors which is 30-40. The goal for HLLHC would thus be to limit the pile-up below 200. Beyond this value, it does not seem possible to define yet inefficiency in using the luminosity that would depend on the channels. The switch-on of the detectors is so fast that it should not influence the optimization of the HLLHC run duration.

**Project X & Synergies with Crab cavities, V. Yakovlev**

**The salient points**

Project X is a multipurpose multi-megawatt proton source for neutrinos, muons, kaons and nuclear physics. After its first 3 GeV linac, the beams enter a switchyard, distributing the beams between a 3 GeV experimental area and the next acceleration stage of 8 GeV, followed by a 120 GeV circular accelerator. The 3 GeV beam oriented towards the 3 GeV experimental area is handled by a beam splitter distributing the beam to three channels (muons, kaons and nuclear physics). The beam splitter uses the RF phase of deflecting cavities to define three beams separated by [-2.5, 0, +2.5] mrad vertically. They enter then a three way Lambertson magnet which converts the vertical separation into an amplified horizontal separation of [-70, 0, +70] mrad. The feasibility study shows that:

- The deflecting cavities must be superconducting due to the high voltage and CW operation.
- The RF cavity aperture must be some 70 to 80 mm, similar to LHC.

² Information collected after the session
• The RF cavity voltage is 10 MV, about twice what is needed for the LHC.
• The RF frequency should be in the 400 MHz range,
• The amplitude and phase stability are much less demanding than in the LHC (4% and 0.5 deg.).

Several implementations have been considered, starting from elliptical KEK-like cavities to TEM rectangular parallel-bar cavities (J. Delayen, ODU) and variants that would be best fitted to the goal and to the existing processing facilities.

The synergies between the Project X deflecting cavities and the LHC crab cavities are significant.

Highlights from the discussion

**What about microphonics for the LHC CC?** (Frank Z.): They should not an issue due to wider bandwidth.

**What determines the low operating temperature?** (Philippe L.): RF losses not a great problem; 3.5 K operating temperature chosen for small helium fluctuations to minimize microphonics.

**Required phase stability?** (Chandra B. ): 1-2 degrees

**Planning, priorities for Project-X ?** (JPK) first priority is front end; middle of 2015 first experiment; deflecting crab cavity is not first priority;

**Cryomodule design?** (Ed C.): similar to what is planned to be built for 650 RF section, but contain only one cavity; would like to participate in cryomodule production for LHC crab cavities

Tentative conclusions for HLLHC

The synergies between the HLLHC crab cavities and Project X deflecting cavities are significant and advantage should be taken of them. The priorities of such cavities are different in the two projects, possibly leading to different timelines.

Global conclusion

The excellent performance of the LHC machine and detectors make a solid foundation for the LHC luminosity project. The weaker than anticipated beam-beam effect in LHC calls for a re-evaluation of some parameters of the upgrade scenarios. The best observed machine turn-around time is shorter than expected, and the average run duration of 6 hours close to what is expected from the luminosity lifetime for HLLHC. It is interesting to note that, in these conditions, the experiments still reach high efficiency in using the luminosity, above 90%. For a totally different purpose, Project X requires deflecting cavities, the parameters of which are unexpectedly close to HLLHC requirements. A collaboration between the parties would best take advantage of these synergies to face several of the superconducting crab cavity challenges.

Acknowledgements

Jean-Pierre thanked Rama Calaga and Frank Zimmermann for providing their notes taken during the discussions.
3.2 Technology Status & Challenges

Peter McIntosh

Ben Hall (Lancaster University) presented a new 4-rod geometry which was modified from the previous LHC-CC10 geometry to improve transverse field uniformity by reduction in rod cross section and outer geometry shape. An aluminum model cavity has been fabricated, which has coupler apertures incorporated to evaluate coaxial SOM, LOM and HOM coupler geometries. The structure is undergoing bead-pull tests at present with promising initial results. The first measurements have a minor frequency shift compared to simulations, most likely due to fabrication tolerances. Optimisation of the bead size and geometry is required to improve measurement resolution.

Mode damping simulations show all modes with R/Q <100 Ω. For a 3 MV deflecting voltage:

- $E_p = 32 \text{ MV/m}$ and $B_p = 60.5 \text{ mT}$ with $R/Q = 915 \Omega$ ($B_p/E_p = 1.89$)

Multipactor studies have been performed showing most dangerous 2-point multipacting in the beam-pipe @ 1.6 MV. Beampipe modifications (i.e. ridge) are being investigated to mitigate effect. LOM, HOM and FPC coupler studies are underway, with the HOM and FPC couplers requiring further optimisation. It was identified that beam-loading could cause an increase of coupling to the cavity operating dipole mode, increasing leakage power, which should be investigated further.

The fundamental benefits of the ridged cavity design were presented by Jean Delayen (ODU), which include supporting low frequencies, the cavity does not have a LOM component, making the mode damping process simpler, the nearest HOM is significantly separated by ~ 1.5 x fundamental, geometry provides a low surface field and high shunt impedance solution, with a good balance between $E_p$ and $B_p$. Four different crab/deflecting cavity developments were identified, which include:

- Jlab 12GeV upgrade deflecting (499 MHz)
- Project-X deflecting (365.6 MHz)
- LHC-CC crab (400 MHz)
- Electron-ion collider crab (750 MHz)

An evolution of an LHC-CC, 400 MHz design was presented which damps all modes with R/Q ~100 Ω. An optimised transverse field uniformity is identified with ~5 mm ridge extension into beam-pipe. Multipactor studies have been performed showing a 1-point, 1st order multipactor between 0.65 – 0.85 MV as the most dangerous. Pressure sensitivity studies have also been performed which have predicted a sensitivity of -212 Hz/Torr without cavity stiffeners. For a 3 MV deflecting voltage:

- $E_p = 30.6 \text{ MV/m}$ and $B_p = 56.7 \text{ mT}$ with $R/Q = 312 \Omega$ ($B_p/E_p = 1.85$ optimised)

At 5 MV deflecting voltage, the peak fields begin to breach the high surface field region and is not recommended to operate at this level. Power dissipation at 2 K = 2.25 W/cavity compared to 22.5 W/cavity at 4.5 K (for 3 MV) and at 5 MV, the power dissipation at 2 K = 6.25 W/cavity c.f. 62.5 W/cavity at 4.5 K. A more compact rectangular structure is also being investigated to reduce the footprint of the cavity at the expense of a slight increase in the peak electric field.
Rama Calaga (BNL) identified a number of Quarter Wave Resonator (QWR) structures which are being developed for high velocity (\(\beta=1\)) applications, which include:

- BNL 56 MHz Storage Ring
- BNL 12 MHz RF Gun
- Wisconsin 200 MHz RF Gun
- BNL 28 MHz Cavity
- eRHIC 181 MHz Crab Cavity

The first 200 MHz, QWR crab structure geometry for LHC was presented at LHC-CC10, which had a non-zero Vacc, which has been modified by adjusting top and bottom stubs for both a round QWR geometry and also an elliptical geometry, which at 400 MHz can provide both H and V orientation capability with respect to the impositions of the adjacent LHC beamline separation.

For a 3 MV deflecting voltage:

\[ E_p = 45.6 \text{ MV/m} \quad \text{and} \quad B_p = 96 \text{ mT} \quad \text{with} \quad R/Q_T = 313 \Omega \quad (B_p/E_p = 2.1) \]

This geometry still however has \(\sim9\%\) Vacc contribution and techniques for reducing this effect were identified, which include differential tapering of the upper stub side-wall which gives a reduced Vacc down to \(\sim5\%\). A transverse field uniformity of \(<1\%\) variation over \(\pm20\) mm is also predicted for this geometry. Preliminary multipacting analysis shows 1 and 2-point, low order effects @ low-medium \(E_p\) levels. HOM coaxial coupler development is underway based upon an existing 56 MHz cavity design solution.

Luca Ficcadenti (CERN) presented the development of classical elliptical and ‘squashed’ crab cavity geometry, with 2 different schemes for HOM damping investigated. The first utilises a single coaxial coupler to extract both H & V orientations of dipole modes, which is incorporated along with a Working Mode (WM) rejection coax which is used to reject the TE11 operating mode. With a \(Q_{ext} = 10^7\) for the WM coupler, up to 18 kW of fundamental mode leakage power is predicted, which is too excessive. By varying the WM coupler inner coax transverse position, the \(Q_{ext}\) can be increased further. Optimisation of the WM tuning ensures that all parasitic modes can be damped below specification limits; however WM coupler modification may degrade performance, which is to be investigated further. Multipactor studies have identified runaway trajectories in the direction of the small radius equatorial area, with more stable trajectories in the equatorial area. Options identified for rejecting leakage power from WM coaxial coupler include applying a resonant notch filter with power absorbed inside the cryostat, a KEK-type notch filter with power absorber outside the cryostat, or a SLAC type damper with 3 other order mode dampers which are appropriately orientated and coupled. The second damping scheme utilises a KEK \(\lambda/4\) notch filter which provides strong working mode rejection with an acceptable length coax of 30 cm.

Zenghai Li (SLAC) presented a horizontal & vertical ridged waveguide crab structure at 400 MHz which has been developed with a transverse dimension of \(250 \times 270\) mm. The cavity has 0.6% non-linear transverse field uniformity at \(\pm10\) mm and for a 3 MV deflecting voltage:

\[ E_p = 27 \text{ MV/m} \quad \text{and} \quad B_p = 56.4 \text{ mT} \quad \text{with} \quad R/Q_T = 330 \Omega \]

H & V waveguide damping has been investigated with the benefit that no notch filter is needed and the same structure can also be used as an input power coupler. A waveguide stub may be required to symmetrise field, which is to be investigated. The damping performance for this
optimised geometry exceeds specification damping requirements. The SCiDac ACE3P suite of simulations tools were described, identifying the following principal modules:

- Omega3P – eigenvalue
- S3P - S parameter
- T3P – beam and port excitation
- Track3P – MP and dark current
- Pic3P – full wave particle in cell
- TEM3P – thermal mechanical

The suite is fully parallelised, which increases computational speed significantly compared to serialised EM solvers. Common LHC-CC development now underway with ODU (see previous summary by J Delayen) using ACE3P as the structures proved to be very similar. Track3P has been used to assess stable and runaway multipacting properties. Omega3P has been used to determine eigenmodes and mode damping performance. Coaxial and waveguide coupler configurations are being investigated, properties of coaxial coupler geometries being more compact, need for high band-pass filter, central coax heating can become problematic which needs to be determined and the range of achievable Qext needs to be evaluated. With regards to waveguide couplers, properties include, low Qext with a more bulky geometry compared to coax, multipacting properties need to be determined and such configurations have larger static heat load. ACE3P can be used to evaluate all LHC-CC variants in an equivalent manner.
3.3 Prototyping Cavities & Cryomodules

Vittorio Parma

This session included two talks on compact cavity prototype manufacturing and was concluded by one talk on cryogenics in the SPS and LHC.

A 4-rod prototype cavity is being designed and manufactured by a collaborative effort involving the Cockroft Institute, STFC, JLAB, and TechX. The design of the cavity has undergone modifications in the rod shape as a result of trade-off in electric and magnetic field, but the design remains compatible with the LHC needs. The Cockroft Institute will be manufacturing a prototype in the framework of the EuCard program as a proof of the manufacturability of the concept. Vertical tests will be made to validate the performance. In order to avoid welds in critical locations, the end plates and rods will be wire cut out of a bulk Nb ingot, with the advantage of including special features like stiffeners from variable wall thickness, and potential performance advantage from large grain in the material. It was pointed out by the audience that cutting through bulk material could be critical for the leak tightness due to the risk of inclusions which normally rolling plates would reduce. Nevertheless nobody in the audience had relevant experience with this technology on niobium, so it was suggested to seek for relevant experience in other labs.

A material thickness of 4 mm was chosen, yielding a pressure sensitivity of below 100 Hz/Torr. Microphonics and vibration studies are still in progress but once again, the cutting process could allow obtaining variable thickness in the rods if needed.

The parallel bar design led by JLAB and ODU University is proposed in a number of variants suitable to different machine applications, with frequencies ranging between 365 MHz and 500 MHz one of which being the 400 MHz compact crab cavity proposed for the LHC. ODU and Niowave are now making a copper prototype in order to prove the manufacturability and make preliminary tests. The end plates are stamped, whereas the outer conductor forming is still in design. A challenging single stamping is being tried for the main body. Frequency measurements are made on the single components and are planned to be repeated at each step of assembly to understand the evolution of frequency. The prototype cavity is planned to be ready for testing by Spring 2012. A real LHC prototype is not planned at this stage due to funding limitations; it was stressed that an LHC prototype should be made consistently with a final LHC specification, which is presently still missing.

L.Tavian presented the issues from cryogenics. Testing of the prototype candidate compact crab cavities with beam remains a baseline choice, and should be done in the SPS first.

He explained that 4.5K seems to be the baseline design temperature so far, but he questions this choice, whose rationale should come from the cavity operational requirements (Rs, microphonics, tuning...) rather than from cryogenics infrastructure.

Presently, cavities are being tested down to 2 K; it is argued that the final selection of the operating temperature could be decided by laboratory testing, not requiring beam.
Testing in the SPS can be done by making use of an existing cryo plant, the TCF20, which operates at 4.5 K, but which could be upgraded to operate at 2K if needed (provided the expected liquefaction capacity is confirmed by tests).

Laurent pointed out that now that the global scheme in point 4 has been ruled out, one could still imagine testing the finally selected crab cavity prototype with the LHC beam in this location. The inconvenience from the cryogenics point of view is that this point operates at 4.5 K, and not at 2K. If this test is retained an overcapacity of ~170 w @ 4.5K per CC module should be foreseen. A decision should be taken rapidly because the upgrade of the P4 cryogenics is planned in the next long shutdown (2013-14). Another option triggered during the discussion, is the possibility of making use of the TCF20 in P4, upgraded for 2 K operation. This should be studied in more detail.

For the final installation of CC modules in LHC, Laurent underlined that from the point of view of cryogenic both 4.5K and 2K are possible options in IR 1 and 5, but from the electrical power consumption, operating at 2 K would be more efficient (~26 kW of electrical power per CC module at 2K as compared to ~43 kW per CC module at 4.5K).
3.4 BEAM STUDIES AND FUTURE TESTS

Gianluigi Arduini

The session included 5 talks: Prototype integration into SPS (E. Métral), Crab cavity integration into the LHC (S. Weisz), SPS Beam Studies (R. Calaga), SPS Emittance Growth Simulations (H. J. Kim) and LHC Beam-Beam MDs & Leveling Possibilities (W. Herr).

The study conducted by E. Métral et al. at the end of 2009 to determine the feasibility of installing a KEKB crab cavity in the SPS did not evidence any show-stopper. It is expected that the same should be true for the installation of a prototype LHC crab cavity for which the integration constraints might be less stringent due to its more compact size as compared to a KEKB crab cavity. The choice of LSS4 (at the position of COLDEX) may be no longer be optimum for the installation of a LHC crab cavity and the integration into the SPS should be reviewed in light of this question, taking into account the compatibility with other installations (e.g. electron lenses) that are being studied in the frame of the LHC injector and LHC High Luminosity upgrades. The issues related to radiation should be considered as the electronics for the LHC crab cavity might be radiation sensitive.

The test of a crab cavity in the SPS is certainly valuable, but the goal of the SPS experimental program and its significance for the evaluation of the performance in the LHC should be assessed together with the specifications for the SPS beam instrumentation.

The installation of the Crab Cavities in the LHC is certainly challenging in particular for the so-called “Local Scheme” in point 1 and point 5. This scheme is considered the baseline. Potential issues include the location of the RF equipment 150 meters away from the cavities and the tolerance to radiation given that the proposed position is close to the TAN. An early prototype installation in point 4 should be considered only for tests purposes. It was noted that that this could interfere with the installation of the capture (200 MHz) cavities or the harmonic (800 MHz) cavities although the installation of a crab cavity in LSS4 of the LHC would be only temporary.

The preliminary measurements conducted in the SPS have evidenced that a significant transverse blow-up occurs at 55, 120 and 270 GeV/c. This might be the result of an external excitation (at 600-700 Hz) observed in the SPS for various beams. The possibility that the transverse blow-up is due to the residual vacuum has been suggested, but this would not explain the observed dependence of the blow-up on chromaticity and RF voltage. The understanding of the origin of the observed transverse blow-up is mandatory in view of defining the experimental program in the SPS.
3.5 Beam Parameters & Layout

Massimo Giovannozzi

The session devoted to “Layout & Beam Parameters” of the LHC-CC11 workshop featured five talks reviewing the situation in terms of parameter space (F. Zimmermann), follow-ups from the previous LHC-CC10 workshop including a proposed non-linear model for the crab cavity (R. de Maria) and three talks on various aspects of crab cavity modelling (A. Grudiev and R. Appleby) and a first look at beam physics parameters impact of crab cavity field quality (J. Barranco).

The parameter space for the LHC upgrade has been reviewed in details, starting from the levelled peak luminosity of $5 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1}$ and a virtual luminosity of $10 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1}$, which are required to achieve the goal of 200-300 fb$^{-1}$ integrated luminosity/yr for a total integrated luminosity of 3000 fb$^{-1}$ by 2030. It is reminded the result presented by F. Zimmermann at Chamonix 2011 that the luminosity lifetime is proportional to the total beam current, which implies that a virtual luminosity of about $20 \times 10^{34} \, \text{cm}^{-2}\text{s}^{-1}$ is required to level for half of the effective beam lifetime. It is also reminded that various systems will need to be reviewed in details in order to assess whether they will stand the much increased total beam current. Independently on the bunch spacing the total beam current will be in excess of 1 A, with bunch intensities between $2 \times 10^{11} \, \text{p/b}$ and $3.5 \times 10^{11} \, \text{p/b}$ for 25 or 50 ns, respectively. Electron cloud effects and limitations have been reviewed including the new information from the recent scrubbing run in the LHC and the 25 ns tests. Options for the bunch rms length have been listed ranging from the current nominal value of 7.55 cm, to the extreme of long bunches of the order of 11.8 cm to the short bunches of 5 cm. This parameter is crucial for the impact on heating effects and IBS. It is clear that IBS should to be studied carefully as the growth rates will be much stronger than for the nominal machine. The importance of the beam distribution was discussed in details as it could be appropriately shaped in the longitudinal plane with many beneficial effects. Finally, the total crab cavity voltage as a function of crossing angle and optics parameters was reviewed. Unequal horizontal and vertical beta-functions at the IP (flat-optics) will be beneficial for reducing the crab cavity voltage required. In summary, it seems that a crab cavity at 400 MHz with 5 MV/beam/IP side seems a reasonable proposal, but a detailed review of the parameters used for the definition of the crab cavity parameters is certainly needed before issuing the specification document.

The second presentation focused on some follows-up from the last crab cavity workshop. At that time, the proposed location of the cavity was such that the crossing and separation schemes were generating a non-zero closed orbit. This is certainly an undesirable feature of the proposed layout, which was imposed by the constraint of maximizing the beta-functions at the location of the crab cavity in order to minimise the required voltage. A revised scheme was studied. It features the crab cavity on the non-IP side of the D2 separation dipole and the crossing and separation schemes closed at the IP-side of the D2. This requires very strong combined orbit correctors in the triplets (5 Tm) and strong two-in-one correctors at the entry of the D2 (8.5 Tm). This is certainly challenging from the technology point of view, but it has also a side effect in terms of a reduced aperture requirement for the D2 and also the Q4. During the
discussion it was proposed to absorb part of the effect of the orbit correctors in the D1 and D2 separation dipoles. Even if this could be possible for IR5, in which the crossing is in the horizontal plane, it does not seem feasible in IR1, due to the vertical crossing. The second action from the LHC-CC10 workshop has been the modelling of the non-linear field quality for the crab-cavity. In fact, as already showed by cavity designers last year, the transverse kick features non-linear effects and these should be tested in order to assess whether they might have a sizeable impact on the long-term beam stability (in terms of single-particle beam dynamics). It was shown that, under a number of assumptions, the integrated transverse kick can be developed in terms of time-dependent multipoles. These multipoles would be of normal and skew type, with different phases.

This fact was independently obtained from numerical simulations on the various designs for the crab cavities. It is worth mentioning that the issue of non-linear field quality for RF-cavities was already under consideration in the framework of the CLIC study. A clever definition of the mesh used for the numerical simulations of the field in the crab cavity allows extracting the fields at various azimuths, which is extremely convenient to extract the multipoles. The KEK cavity was used as sample device for this approach. The accuracy of the current numerical simulations is certainly enough for deriving quadrupolar and sextupolar multipoles, while the octupolar one is at the limit of the numerical resolution. Summary tables with the derived multipoles for several crab cavities were also presented, including comparisons with true magnetic multipoles. Even if the RF-multipoles are in general much smaller than the magnetic ones, still the time-dependence might turn out to be harmful. Hence, numerical simulations will be needed to assess the actual impact on the long-term dynamics of protons.

A complementary approach was presented, based on field fitting and subsequent representation via a dynamical map. The EMMA RF cavity was used as an example for the application of this technique. According to what was done in the past by D. Abell, four functions are enough to describe the field of a generic RF-device. These functions can be computed on a cylinder and then the vector potential can be derived, usually in the form of a series. The agreement between the numerical data and the fitted fields is very good. Then, from the vector potential the Hamiltonian can be derived and from it, using differential algebra techniques, maps can be obtained. This approach, when applied to a case for which the analytical solution is known, provides a solution in very good agreement with the analytical one. Using such an approach it should be possible to assess the impact of non-linearities in the crab cavity field on the key beam dynamical quantities. The only potential limitation is that these techniques are not particularly suited to long-term tracking. However, one could perform a cross-check of the RF-multipoles approach with this one, while the tracking could be performed with RF-multipoles, which are certainly more suited to fast tracking of many particles.

A first look at the impact of crab cavity non-linearity was presented. The time-dependence of the RF-multipoles was neglected in the study and only the total range of variation of selected beam dynamical quantities is evaluated. This is already a very important piece of information to start with. The quantities that have been considered are the tune shift (from $b_2$), amplitude detuning (from $b_4$), chromaticity variation (from $b_3$ and horizontal dispersion), coupling (from $b_3$
and vertical dispersion). The computations have been performed for IR5 and for Beam 1 and assuming a 400 MHz cavity with a total voltage of 10 MV. Various crab cavity designs have been considered. The tune shift can be as large at $1.4 \times 10^{-2}$ and is the main source of concern. The other quantities are much smaller and they can be neglected, at least at this level of the analysis. Detailed analysis of the aberrations using the MAPCLASS code was carried out pointing out that, in the static case, these aberrations seem to be harmless. Once more, it is worth stressing that the long-term analysis of the beam dynamics will provide the correct information on the target field quality of the crab cavities for the LHC.
3.6 Machine Protection

Jorg Wenniger

The strategy for machine protection of the LHC against failures induced by crab cavities depends
on the time scales of the failures, the frequency of failures and on the impact of the failures on
other machine components. From the point of view of machine protection (MP) failures may be
split into two main categories:

- Failures with time constants of many (> 20 or so) LHC turns (> 2 ms): in such cases
  beam surveillance, and in particular loss monitors, have sufficient time to detect
  abnormal conditions and trigger a beam dump. Such surveillance may come in
  addition to active interlocking of the concerned equipment, which typically reacts on
  times scale of some turns or some milliseconds. The execution of the beam dump
  itself can take up to 3 turns (until the last proton has left the accelerator), and a
  sufficient margin must be foreseen on interlock thresholds or reaction times to
  accommodate this inevitable delay.

- Failures occurring on the time scale of 1-3 turns: for such events active protection by
  beam observation is generally not possible (too slow), only active equipment
  surveillance may possibly trigger a dump in time (but the detection must occur a few
  turns before the failure brings the beams close to an aperture). The MP rule for such
  failures is to provide passive protection of the machine by collimators and absorbers.
  The protection devices must be designed to absorb the fraction of beam lost as a
  consequence of the failure without damage to machine components. Quenches as a
  consequence of failures may be tolerated as long as the frequency is not too high
  and the number of quenched magnets is limited.

For the LHC upgrade a local CC scheme involving one CC (or CC group) on either side of
each high luminosity IR is favored. The CC on the incoming beam side tilts the bunch such that it
collides without angle with the opposing beam. The CC on the outgoing beam side tilts the
bunch back. Outside the area delimited by the CC the bunch shape is not affected. As the CCs on
each side provide a ‘local tilt bump’, the simplest failure modes imply a non-closure of the tilt
bump: the head and tail deflections propagate into the ring and may typically hit the
collimators. Such failures may be induced by a voltage or phase error, due to RF trips, cavity
quenches, low level errors, operator errors etc.

Crab cavity failure modes and time scales have been discussed in the present and in last
year’s CC workshops (presentations by T. Baer and B. Yee). KEKB observations indicate failure
time scales of the order of one LHC turn (complete loss of RF voltage off on one CC). The time
scales depend on cavity Q values and on RF feedbacks, and may be even more complicated
when the effect of the beam is taken into account. The presently accepted typical time
constants are at the level of 1 millisecond, i.e. 10 LHC turns.

The effect of a CC on the beam depends on a number of parameters. If the CC is
designed to fully compensate the geometric loss of luminosity from the crossing angle, then it
effect on the beam is essentially inversely proportional to beta* (see T. Baer). Unfortunately the 
impact of the CC in case of failures is itself directly proportional to the usefulness of the CC for 
luminosity. For an ATS like optics with beta* in the range of 0.3 m or less, the last 1-2 sigma of 
the beam halo may be pushed unto the collimator jaws on the time scale of ~5 turns (see 
presentation by T. Baer). Assuming for HL-LHC beam halo population at the level of a few 
percent as measured in 2011, the amount of beam lost potentially over a few turns on the 
collimators may reach > 20 MJ. Those values must be compared to the tolerance for fast losses 
of up to 1 MJ of the present collimators (see R. Assmann). The situation is even worse if in the 
future during collisions the robust Carbon secondary collimators are retracted and replaced by 
impedance-friendly but also much less robust Copper collimators (see R. Assmann). To make 
such failures acceptable, the beam halo must be depleted by more than one order of magnitude 
as compared to today's observations (from percents to per mill of the total beam intensity). This 
may be achieved using hollow electron lenses (proposed LARP contribution, see T. Baer), 
provided it is complemented by monitoring of the beam halo population.
This session included five talks: (1) “Beam Stability in LHC with Crab Cavities” by Alexey Burov (FNAL), (2) “Nonlinear Response of Beam-Beam System and HL-LHC Crossing Angle” by Kazuhito Ohmi (KEK), (3) “Beam-Beam Simulations with Crab Cavities and Noise” by Stefan Paret (LBNL), (4) “Synchro-Betatron Effects” by Simon Mathieu White (BNL), and (5) “LLRF for Crab Cavities” by Philippe Baudrenghien (CERN).

1) “Beam Stability in LHC with Crab Cavities” by Alexey Burov (FNAL):

Alexey first reviewed his recent results on the loss of longitudinal Landau damping from a (constant) inductive impedance above transition (or constant space charge impedance below transition), to explain in particular the observations of the dancing bunches in the Tevatron, at both injection and top energy. These oscillations look like non-rigid (i.e. with changes in the longitudinal distribution, core and tails oscillating differently) dipolar longitudinal oscillations (i.e. with one node when several consecutive traces are superimposed). It is a single-bunch instability, which is damped by the longitudinal damper (with a bunch-by-bunch phase loop). This instability reappears when the feedback is OFF. According to the impedance model, this instability appears for a very small value of the synchrotron tune shift compared to the synchrotron frequency, i.e. only about 1-2%. In the classical theories (assuming the rigid-bunch approximation), the intensity threshold for the loss of Landau damping depends strongly on the bunch length, with the fifth power. Therefore it is very sensitive to the bunch length and that the longitudinal bunch distribution should be treated with great care, as the bunch length is not always clearly defined. Alexey used a general analysis starting from the Boltzmann-Jeans-Vlasov (BJV) equation and looking at the eigen-system of this equation. Note that Van Kampen already calculated this for infinite classical plasma, leading to the Van Kampen modes, i.e. a continuous spectrum with some discrete modes. As the sum of the growth rates of all the discrete modes is zero, it means that some of the discrete modes do not decay. This corresponds to the loss of Landau damping. Alexey summarized his results for three distributions: H-P (Hofmann & Pedersen) distribution, smooth (Sacherer's) distribution and the particular one of the Tevatron with seven coalesced bunches. For H-P, he found a threshold, which is about three times smaller than with the previous (Sacherer et al.) formalism. For the smooth Sacherer's distribution, he found a threshold, which is about one order of magnitude below (in the usual formalism it is only a factor of two to three below). For the particular case of the Tevatron, Alexey used the "exact" phase space distribution to recover the measured intensity threshold, which was about one order of magnitude below the smooth distribution. Based on this analysis, Alexey's recommendation to fight this instability is to smoothen (only) the core of the distribution, as it is extremely effective. It is worth mentioning that Alexey's findings are qualitatively in agreement with the previous theory (scalings etc.) but the numerical value is quite different and strongly depends on the evolution of the shape of the longitudinal profile through potential-well distortion, i.e. the rigid-bunch approximation is not sufficient.
Alexey then showed how a relatively small “Partial Water-Bagging” increases the threshold by a factor about twenty (without longitudinal emittance blow-up, which is the important feature). This flattening of the core of the longitudinal profile can be obtained by means of anomalous diffusion at resonance shaking, modulating the RF phase near the synchrotron frequency (detuning plus slowly change in amplitude). Nevertheless, possible issues arise: (i) this scheme is sensitive to the detuning from the maximal incoherent synchrotron frequency (the accuracy of the detuning should be at the level of few percents); (ii) the wake fields and beam loading will complicate the picture.

More recently, Alexey extended his results to narrow-band impedances and found that the result is quite close to the classical (Sacherer’s and Keil-Schnell’s) one even for a Partial Water-Bag distribution. Using the LHC Crab cavity (CC) ultimate parameters (as described in E. Shaposhnikova’s talk at LHC-CC10), Alexey found that the High-Order Mode (HOM) impedance should not exceed 0.6 MΩ per cavity (using 4 CC in total) at the synchrotron sidebands, with the sufficient condition that the quality factor is smaller than about 10⁴. As concerns the transverse limit, considering the minimum damping time of the transverse feedback which is 60 ms, the transverse HOM should not exceed 1.5 MΩ/m per cavity, with the sufficient condition that the quality factor is smaller than about 3 10³.

After the talks, there were some discussions about the sign of the chromaticity suggested by Alexey (i.e. negative above transition) to avoid all the higher-order head-tail modes. This possibility was already proposed in the past (as can be seen for instance in the LHC Design Report, Chapter 5), but remains to be tested (which should be done in a forthcoming machine development sessions). It was also mentioned that the quality factor for the operating mode should be decreased from about 10⁶ to a few 10³, which is certainly an issue. How can we reach this value? O. Bruning remarked that the computations should be redone with the HL-LHC parameters, which are more critical than the ones used in this talk. During the summary session, the detuning of the CC was discussed and Alexey mentioned that this is impossible for the Transverse Coupled-Bunch Instability (TCBI) as there are about 3000 coupled-bunch modes every about 11 kHz. Therefore, it was concluded that the CC can only be detuned for the fundamental mode (which is transverse for a CC) but not for the HOMs.

2) “Nonlinear response of beam-beam system and HL-LHC crossing angle” by Kazuhito Ohmi (KEK):

Kazuhito studied the case of a forced oscillation in a nonlinear system with the Duffing equation. This can explain for instance the Jump phenomenon observed in the presence of beam-beam. Measurements of luminosity degradation due to harmonic excitation with a CC phase noise were then reported. A strong luminosity loss was observed at 0.526 (with dipole oscillation) whereas as weak luminosity loss was observed at higher frequencies. A systematic study with strong-strong beam-beam simulations was then discussed, using a bunch-by-bunch feedback with a damping time of 100 turns. No x-y coupling was assumed and only the motion in the horizontal plane was studied at as the CC induces a horizontal excitation. The Jump phenomenon was recovered like in the Duffing system with a strong luminosity loss near 0.525.
It was found that the $\pi$ mode behaves similarly as the luminosity and that the $\sigma$ mode oscillation can appear but does not degrade the luminosity. In summary, the experiments performed on the CC noise in KEKB are well explained by the (reliable) strong-strong simulations.

Kazuhito then studied the case of the LHC and HL-LHC, trying to answer to two questions related to the luminosity lifetime: (i) is the effect of the crossing angle seen in LHC at 3.5 TeV? (ii) what are possible parameters for the HL-LHC? Weak-strong simulations have been used, as such slow luminosity decrement is difficult to be evaluated by 3D strong-strong simulations, because they are too heavy and unavoidable numerical noises are introduced. Depending on the choice of the crossing angle at IP8, luminosity degradation due to the crossing angle may be visible. Kazuhito’s simulations seem to indicate a broad minimum for the luminosity at a Piwinski angle of about 0.5, which is close to the nominal value. This indicates that there is some room for improvement for the HL-LHC. Furthermore, simulations revealed that above a beam-beam tune shift of about 0.02, the results are sensitive to noise and above about 0.03 they are sensitive to the Piwinski angle.

During the discussion, the actual noise in the LHC was asked but no answer was given. It was also emphasized that the transverse feedback was assumed to be noise-free. Only an offset in the (weak-strong) beam-beam simulations was considered. It was found that the noise level should be smaller than few $10^{-4}$ of the transverse rms beam size.

3) “Beam-Beam Simulations with Crab Cavities and Noise” by Stefan Paret (LBNL):

Stefan reminded first the main features of the simulation code he used (BeamBeam3D): strong-strong collision model, Lorentz boost, shifted Green’s function method, particle-domain decomposition for parallel computing, CC with noise and feedback system (FB) with noise. Note that there is no time delay for the second kick from the second CC and the only tune spread considered is the one from the beam-beam. The Beam Position Monitor (BPM) accuracy estimated at about 2 $\mu$m rms (which is maybe a bit pessimistic as it comes from the closed loop) and the FB gain at about 0.1, can lead to an erroneous kick of about 0.2 $\mu$m at the position of FB and a transverse offset at the IP of about 12 nm.

Using the nominal LHC values, Stefan benchmarked an analytical estimate of the transverse emittance growth with simulation. Using a Gaussian noise, simulations agree well with the analytical model and similar results are obtained with a noise from either the CC or the FB. Note that the simulations are unreliable for emittance growth rates below about 0.5 % per hour. Assuming a sinusoidal noise, the emittance growth varies strongly with the noise frequency and the growth rate is more than 50 times slower with the FB.

In summary, the main results are the following. A white CC noise of 4 nm yields 1 % per hour, which requires a phase stability of about 0.22 mrad. Is it achievable? With a white BPM noise of 2 $\mu$m, an emittance growth of about 7.7 % per hour is obtained. Is it acceptable?

4) “Synchro-Betatron Effects” by Simon Mathieu White (BNL):
Simon explained first the model he used in his BeamBeam3D simulation code (same code as the one used by Stefan): head-on interactions (with a self consistent 6D field calculations allowing for arbitrary distributions and crossing angle implemented “à la Hirata”), long-range interactions (lumped 4D beam-beam kick at +/- $\pi/2$ from the IP which underestimates the footprint area), CC (thin CC kick at +/- $\pi/2$ from the IP, only the local scheme was considered), transport done with a linear 6 x 6 transfer matrix (chromaticity kick available). The beam parameters used were those with 25 ns bunch spacing from O. Bruning’s talk in April 2011 (i.e. design with a peak luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$, and upgrade with a peak luminosity of 7.4 $10^{34}$ cm$^{-2}$s$^{-1}$ without CC and 2 $10^{35}$ cm$^{-2}$s$^{-1}$ with CC). The number of Long-Range (LR) interactions depends on the triplets and several options are considered. The main question to answer is: is the crossing angle set to have about 10 $\sigma$ separation for HL-LHC (corresponding to a full crossing angle of 475 $\mu$rad) still valid for the upgrade scenario?

Considering 21 LR interactions as a study case (IP1&5 only) and looking at the tune footprint, it is clearly seen that the latter is strongly distorted. The detrimental effects are clearly dominated by LR, which will lead to poor lifetimes. To reduce the effect of the LR interactions two possible mitigation measures are available: (i) increase the crossing angle, (i) increase the $\beta^*$. Increasing the crossing angle to 580 $\mu$rad (corresponding to a separation of about 12.2 $\sigma$) should be much better, still leading to a peak luminosity of about 6.2 $10^{34}$ cm$^{-2}$s$^{-1}$ (instead of the 7.4 $10^{34}$ cm$^{-2}$s$^{-1}$ without CC). But, is there enough aperture? Increasing the $\beta^*$ to 0.3 m (using the ATS optics) and using 410 $\mu$rad yields a peak luminosity of about 5.4 $10^{34}$ cm$^{-2}$s$^{-1}$, which requires leveling with CC. Therefore, in this case the aperture is lower, but the virtual luminosity is also lower. With CC, the compensation works better for larger $\beta^*$ and the values of the crossing angle considered clearly favor the 400 MHz cavities (instead of the 800 MHz).

Synchro-betatron effects were then studied to investigate if a CC can damp the sidebands excited by the crossing angle as it was predicted in the past with SIXTRACK simulations. The damping effect from the CC was clearly observed. The HL-LHC regime with a Piwinski angle of about 2-3 has not yet been probed in actual operation (at about 0.4) but design parameters (at about 0.7) should provide useful information. Synchro-betatron effects look similar for both cases studied: (i) synchrotron sidebands are excited by the crossing angle, (ii) under certain conditions they can damp the $\pi$-mode, (iii) removing the crossing angle with CC cancels these effects as well.

As concerns coherent modes, in the case of the LHC and for collisions in IP1 and IP5 only, two modes develop (without crossing angle): the 0 (or $\sigma$)-mode and the $\pi$-mode separated by the Yokoya factor times the beam-beam parameter. With a crossing angle the $\pi$-mode can disappear but the CC restores it.

In summary, CCs are required to reach the design goals for both scenarios considered (helping to recover clean footprints). The effect of LR interactions needs to be assessed to understand the limitations and experiments are required to understand the detrimental / beneficial effects of running with high synchro-betatron coupling. Simon concluded by mentioning that RHIC would like to contribute to HL-LHC with measurements to be performed in RHIC. A possible
collaboration has to be set up. Note that the effect on the transverse emittances was not yet studied in this analysis.

5) “LLRF for Crab Cavities” by Philippe Baudrenghien (CERN):

Philippe started by reminding us the LHC Low-Level RF (LLRF) architecture, mentioning that the two rings are perfectly independent. It is proposed to drive the CC from the RF reference and count on strong RF feedback to set the demanded field in the cavities. The integration of the CC with the existing RF system and LHC controls is considered to be simple, even with a bunch phase modulation scenario.

The RF feedback was then discussed in detail, reminding that the final bandwidth and beam loading performances depend on the loop delay (which should be tried to be as short as possible) and on the cavity geometry R/Q, but not on actual loaded Q value. A betatron comb filter can be used for instance to reduce the noise and the effective cavity impedance thereby improving the transverse stability (the filter is identical to the double peak comb filter used at PEPII on the accelerating cavities, for the reduction of the longitudinal impedance at the fundamental frequency). Note that the performance can probably be improved with a more sophisticated filter. For perfect closure of the orbit and to minimize the overall effect of one-cavity fault, the possibility of using coupled feedbacks was also looked at. With a simplified analysis (Linear Quadratic Regulator LQR, and no loop delay), it revealed the possibility to regulate on voltage difference (or voltage sum, or any linear combination). The distance between cavities will limit its potential (delays will limit the bandwidth of such coupled compensations). This still has to be studied in more detail.

In the LHC-CC10 workshop, Philippe presented the RF noise performances of the LHC and made some extrapolations for the CC. A phase noise of about 0.005° rms @400 MHz is to be expected, which can be reduced by FB and further more by a betatron comb filter.

The LHC is designed with an (almost) perfect beam loading compensation. With the 300 kW peak RF klystron power, we should be able to go up to nominal bunch intensity with the 25 ns bunch spacing (with the "half-detuning policy"), but not above. To reach 1.7E11 p / bunch with the existing klystron power, the voltage set-point will be modulated along the turn to minimize the power peaks required to compensate the transient beam loading.

An operational scenario was then proposed considering in particular the following boundary conditions: during filling, ramping and for physics with CC off, the cavities must be detuned; bringing the cavities from detuned to on-tune can only be done with an active RF feedback ON. With the proposed scenario, during filling, ramping or operation with transparent CC, we detune the cavity but keep a small field requested for the active tuning system. The RF feedback is used with the cavity detuned to keep the beam-induced voltage to zero if the beam is off-centered.

In summary, the integration of the CC with the existing RF system and LHC controls is straightforward. Benefiting from on-going developments in other systems (LHC longitudinal damper, Linac4 Cavity Controller, SPS 200 MHz and 800 MHz upgrade) the LLRF can further reduce the RF noise in the sensitive betatron bands, reduce the transverse impedance caused by
the cavity at the fundamental mode, and keep a good precision between the kicks affecting one beam (coupled cavities feedback). However the bandwidth of all these regulations will be fixed by the layout. For the main RF system of the LHC the loop delay is 650 ns only. A similar compact layout must be studied for the CC. Finally, the implications of the loaded Q on the LLRF still have to be looked at in detail.
4 ADVISORY BOARD MEETING AND COMMENTS

Steve Myers

4.1 PARTICIPANTS


4.2 MEETING COMMENTS

Please see the executive summary for the conclusions of the advisory board session. Other comments are noted in the minutes posted on the workshop website.

4.3 OPEN ISSUES AND ACTION ITEMS

4.3.1 MACHINE PROTECTION

Without special measures on the side of collimation (robustness), beam halo population and ultra-fast and highly reliable (SIL3-4) RF/cavity interlocking, the installation of CCs may represent an intolerable risk to the LHC machine.

In order to progress on the MP issues for CCs, the following actions must be pursued:

- **Reference scenarios must be defined for HL-LHC** in terms of beam intensity, beam optics (in particular beta* and crossing angles), collimation and CC operation. Such scenarios must be used as base for coherent simulations. At present the different actors do not work on a coherent set of machine configurations.

- **The robustness of collimators must be assessed** as precisely as possible, if possible with beam tests at Hiradmat (SPS) to avoid the inherent uncertainties of simulations.

- **Realistic reference failure scenarios must be defined for CCs** (RF trips, quenches, etc) and should be used as coherent input to all MP studies. Those scenarios should be confirmed by RF measurements (test benches) or beam tests (SPS, LHC).

- **The performance of hollow e-lens** to deplete the beam halo to sufficient level should be evaluated / confirmed. **Online monitoring of the beam halo population** must be developed in order to ensure low enough halo population in operation – interlocking the halo population must also be considered seriously.

- **Ultra-fast and highly reliable interlocking of CC** must be developed and tested.

- Finally **beam tests should be performed** to study in realistic conditions the modeling of failures, RF interlocks, etc on beams. Tests at the SPS may be performed earlier (Pt4 cryo) and may provide good test ground of CC versus MP, but could suffer from significantly less performing beam instrumentation as compared to the LHC. In case of SPS tests, the requirement in terms of instrumentation should be defined well in advance. Tests at the LHC are highly recommended as this will provide a more powerful
5  SPS Beam Tests

The addition of crab cavities to the LHC should ensure a robust functioning through the entire sequence of the LHC physics cycle. The cavities should have no effect on the LHC beam during the injection, energy ramp and beta-squeeze at top energy. RF structures yet to be realized will be used for the LHC crab crossing. Prototype tests with hadron beams are therefore a prerequisite to identify potential risks and allow devising appropriate mitigation techniques in order to ensure the safety of the accelerator. An essential milestone is to test a crab cavity in the SPS, in order to verify that crabbing can be achieved in a proton machine, that there are no major ‘showstoppers’: i.e. there are no severe operational constraints and to demonstrate that the important issue of machine protection and cavity transparency in LHC can be resolved. This should be done around 2015. A preliminary outline of the motivation, test objectives and requirements for the SPS tests with crab cavities are described in this section.

5.1 Preliminary Test Objectives

Beam studies in the SPS with crab cavities will study the effects of deflecting cavities on high energy proton beams as compared with the effects on electrons. As stated in the executive summary of this report, beam tests in the SPS and in the LHC are a pre-requisite for a final installation. Prior to a test installation of deflecting cavities in the SPS, studies with low intensity LHC beams in the SPS are being carried out to precisely determine the measurement conditions and hardware requirements for SPS experiments.

5.1.1 Optics Considerations

The proposed location, COLDEX, has a horizontal beta-function that is smaller than in the other parts of the machine. If the voltage of the cavity is insufficient for the proposed experiments, additional dedicated quadrupole power supplies (2…4) may be required to create local optics knobs to enhance the beta-functions near the location of the crab cavity. This will enable experiments to exploit the full energy range of the SPS (26-450 GeV). If LHC cavities (conventional or compact) become available with a larger kick voltage, this modification may not be necessary.

In addition, the precise location for the SPS tests will be reviewed in the light of the several compact designs now being prototyped. This will be studied by a working group to identify the best possible place for a test setup taking into account RF, cryogenic and other infrastructure. The transparency of the crab cavity to the regular SPS operation will be a vital consideration.

5.1.2 Impedance and Instabilities
Accurate knowledge of the impedance of the crab cavities and tolerances for higher order mode damping will be vital to understand the stability thresholds for nominal and ultimate beam currents and beyond in the LHC. Both bench measurements and beam tests in the SPS will enable a clear characterization of the cavity impedance and consequently the required damping to stay below the instability thresholds. SPS measurements using intensity dependent tune shifts and current dependent betatron phase advances were carried out for several years to determine the total machine impedance and to resolve the contributions of various elements. Additional measurements before the installation of the deflecting cavities will be performed to determine the added impedance from the deflecting cavities. New “localized” techniques maybe needed to increase the sensitivity of the measurements and to propose any required improvements to the presently installed measurement devices.

5.1.3 Long-Range Beam-Beam Effects

Two long-range beam-beam wires are installed in the SPS with which several long-range experiments have been carried out in the past years. These wires could potentially be used to induce an artificial long-range interaction in the presence of the crabbed bunches in order to study the combined effects in the presence of crab. A distance and current scan of the DC wires could be carried out at different energies with and without crab cavities. A working point scan will also be performed to investigate the sensitivity at different tunes. Other non-linearities like octupoles can also be introduced to enhance the effects if needed.

5.1.4 RF Noise, Stability and Controls

The effect of the RF noise on the beam emittance is a vital measurement for the final implementation of crab cavities in the LHC. A beam with good natural emittance and lifetime (and not only the usual beam current lifetime) is a requirement for such a measurement. Furthermore, the tilt from the crab cavity should be at least of the order of the horizontal beam size in order to observe the effect of the crab cavity. Therefore, beam parameters with a normalized rms emittance of ~2 μm and a beam momentum of 55 GeV/c would be ideal. Several experiments in the SPS studying the natural emittance lifetime in coast were already performed. These tests indicate a minimum energy of 120 GeV/c and intensities of 1x10^10 might provide a lower relative emittance growth of about 20%/hr in coast. However, at least a factor 4 smaller emittance growth is required from the introduction of crab cavities in the LHC so as to stay in the shadow of the present emittance growth rates in the LHC. Therefore, additional studies have to be performed to find a better working condition and instrumentation to reach a natural growth rate of about 1%/hr or lower in the SPS.

Tests first with single bunches and then with a few bunches will be performed to determine the emittance growth from crab cavities. This will be followed by experiments with a few batches to introduce RF transients and other high-current effects. A parametric scan of the RF noise amplitude and frequency is anticipated for a comprehensive study of the evolution of the beam size under varying conditions, so as to establish final tolerances for the construction of the LHC crab cavities. Some tests will be performed at different beam energies ranging from 55 to 450 GeV/c to study any relevant energy dependent effects.
5.1.5 Collimation

As efficient collimation is a vital issue, a planned 2nd collimator (from SLAC) is proposed to be installed in the SPS in 2011. The best location for the SLAC collimator was studied and a proposal from the crab cavity working group was made. It should be noted that both collimators in the SPS are in the horizontal plane which is also the anticipated plane of crabbing. In the proposition, the phase advances are chosen such that almost no crab effect is seen at the 1st (SLAC) collimator, whereas the full crab effect is seen at the second (CERN) collimator. This allows for dedicated collimation experiments to determine efficiency, beam losses and hierarchy of the collimator system is a pseudo primary-secondary configuration as in the LHC. However, to do so the vertical Ionization Profile Monitor needs to be moved to before the QD.517.

Machine protection issues due to fast voltage and phase failures will be extensively tested. The loss characteristics at the collimators and elsewhere in the ring will be thoroughly studied to determine the acceptable change in the cavity parameters in the LHC.

5.1.6 Operational Scenarios and Transparency

Some operational scenarios concerning single-beam issues envisioned in the LHC can be tested in the SPS. For the LHC, the cavities will be detuned and at “zero-voltage” (but with active feedback) to be invisible at injection and energy ramp. Therefore, accumulation of beam with “zero-voltage” in the SPS will be tested. Other issues related to beam loading and transient effects with and without RF feedback & slow orbit control will be attempted to study the stability and tolerances on the feedback systems.

Induced RF trips and its effects on the beam will be studied in detail to guarantee machine protection and to devise appropriate interlocks. Long term effects with crab cavities on coasting beams at various energies will also be tested.

5.2 Preliminary Planning & Resources

A preliminary planning presented at the workshop, taking into account the cavity prototyping, SPS beams test, LHC shutdowns and final implementation is shown below. A more detailed draft schedule describing each individual task is available and the overall planning will be revised according to the exact LHC operation schedule.
<table>
<thead>
<tr>
<th>Year</th>
<th>LHC Operation (draft)</th>
<th>LHC2 HiLumi LHC PDR TDR</th>
<th>EuCARD2 (planned)</th>
<th>Compact Crab Cavity</th>
<th>Elliptical Crab Cavity</th>
<th>Infrastructure LHC</th>
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**Compact Crab Cavity**
- **Validation**
- **Technical Design**
- **Construction**
- **Commissioning**
- **Milestone**: Impact Cavity Technology validation
- **Decision on**: Local scheme with Compact CC

**Elliptical Crab Cavity**
- **Technical Design**
- **Construction**
- **Milestone**: Decision on: Global scheme with Elliptical CC
- **P4 cryo upgrade**
- **Commissioning**
- **2 K or 4.5 K?**
- **possible**: if ell.

**Infrastructure LHC**
- **Planning**
- **Preparation (Coldex)**
- **SPS CC cryo**
- **Beam test Elliptical**
- **Beam test Compact**: D. Lohe, D. Tavian

**Infrastructure SPS**
- **Preparation**
- **SPS CC cryo**
- **Beam test Elliptical**
- **Beam test Compact**

**Timeline**
- LS1: Splice Console, Collimation IR1
- LS2: Collimation
- LS3: Installation of HL-LHC HW, LHC C

**Dates**
- LS1: 2011
- LS2: 2016
- LS3: 2022