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Summary of the 3rd LHC Crab Cavity Workshop (LHC-CC09)

Calaga, R (CERN) *et al*

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Summary of the 3rd LHC Crab Cavity Workshop (LHC-CC09)

Editors: R. Calaga, F. Zimmermann
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Introduction

The 3rd workshop on crab compensation for the LHC luminosity upgrade (LHC-CC09) was held September 16-18, 2008 at CERN, Geneva, Switzerland. The workshop was organized by joint collaboration of CERN, EUCARD, KEK and US-LARP. Approximately 35 (50) participants from 3 continents and several institutions participated (registered) to discuss the future strategy of implementing crab cavities in the LHC. The detailed participant list and the scientific program along with the associated contributions are available at:
http://indico.cern.ch/conferenceDisplay.py?confId=55309

Workshop objectives and structure

The charge of the workshop was as following:

1. Down-select a crab-cavity design from the proposed concepts and advance the cryomodule design
2. Review the beam simulation results and operational procedures for prototype tests
3. Establish a strategy for a full crab crossing scheme for the phase-II upgrade of the LHC

A scientific program committee of 17 members from 10 institutes around the world compiled a 2.5 day program spanning various subjects related to the design and implementations of crab cavities in the LHC. The program was split into 8 sessions with dedicated conveners. The session conveners prepared individual summaries which were presented to an advisory board chaired by S. Myers with representatives from most of the major collaborating institutes and representatives for ATLAS and CMS.

Key conclusions and R&D objectives

Key conclusions have been stated by S. Myers (Director of Accelerator and Technology, CERN) following the advisory board recommendations along with future R&D objectives for the LHC crab cavity program.

1. Following the success of KEKB, CERN must pursue the use of crab cavities for the LHC, since the potential luminosity increase is significant.
2. A final crab-cavity implementation for the LHC has not yet been settled. Both “local” and “global” crabbing schemes are still under consideration for the LHC upgrade phase II. Future R&D should focus on compact cavities which are suitable for both schemes.
3. One possible show-stopper has been highlighted: machine protection, which is critical for LHC. The effect of fast cavity changes needs to be looked at with high priority. Mitigation schemes such as raising the Q value of the cavity to ~10^6 (from ~10^5 at KEK) will be studied.
4. Another important issue is the impedance. Since the LHC revolution frequency changes during acceleration, the detuning of the cavity may be more difficult than was the case for KEKB, and other measures (like strong damping of the dipole mode) need to be examined.

5. High reliability of the crab cavities is essential; the trip rate should be low enough not to perturb LHC beam operation.
6. Validation cavity tests in the LHC itself are not deemed essential. It is considered plausible to install a new system in the LHC without having tested a prototype in the LHC beforehand. As in all new colliders, this has been done with many other components.
7. Demonstration experiments should focus on the differences between electrons and protons (e.g.- effect of crab-cavity noise with beam-beam tune spread; impedance; beam loading) and on reliability & machine protection which are critical for the LHC.
8. A beam test with a KEKB crab cavity in another proton machine is considered useful, meaningful and sufficient (for deciding on a full crab-cavity implementation in LHC) if it addresses the differences between protons and electrons.
9. Possible modifications of LHC Interaction Region 4 during the 2013/14 shutdown should be studied to evaluate the feasibility of installing and testing crab-cavity prototypes, and of accommodating a possible global crab-cavity scheme.
10. The timing of the crab-cavity implementation should be matched to the short and long-term goals and to the overall CERN schedule, and be in phase with the experiment upgrades.
11. **The crab-cavity infrastructure should be included in all other LHC upgrades scenarios.**
12. **Crab cavities can increase the LHC luminosity without an accompanying increase in beam intensity, thereby avoiding negative side effects associated with high intensity and high stored beam energy. This opinion has been endorsed by the general-purpose high-luminosity experiments.**

A working group has been established within CERN to study the feasibility of the KEK-B crab cavities in the SPS to test possible differences between electrons and protons in the presence of crab cavities. The working group is led by Elias Metral and has a mandate to conclude on the feasibility study by the end of 2009. The working group activities are documented at the following hyperlink: http://emetral.web.cern.ch/emetral/CCinS/CCinS.htm

The members of the working group constitute:

Rama Calaga (Crab cavity expert and possible measurements) - BNL&USLARP
Nicolas Delruelle (Cryogenics) - TE/CRG
Nicolas Gilbert (Space and integration) - EN/MEF
Elias Metral (Chairman, beam dynamics issues and SPS availability) - BE/ABP
Joachim Tuckmantel (Crab cavity expert and RF) - BE/RF
Frank Zimmermann (Crab cavity expert, measurements and linkman with KEK) - BE/ABP
Olivier Brunner (Klystrons and superconducting cavities) - BE/RF
Giovanna Vandoni (Vacuum) - TE/VSC
Jorg Wenninger (Machine protection) - BE/OP

The summaries prepared by the session conveners and additional material from the discussions during the workshop are presented in this document. The meeting minutes drafted by F. Zimmermann were substituted for summaries not provided by the conveners.

Summary, Session I: “Setting the scene”
Convenor: Jean-Pierre Koutchouk, CERN

Presentations

The summary and conclusions are based on the four presentations given:

- The crab crossing option for the LHC upgrade, by Frank Zimmermann, BE/CERN
- The views from the LHC experiments, by Marzio Nessi, ATLAS/PH/CERN
- The KEKB experience with crab crossing, by Yoshihiro Funakoshi, KEK
- Validity requirements and tests, by Oliver Bruening, CERN.

Summary & conclusions

Potential of the crab crossing option

A luminosity upgrade of the LHC is very challenging. Crab crossing allows a luminosity increase that is not purely built on a beam current increase and is therefore attractive. Its control over the crossing angle at the IP opens indeed two major possibilities:

- The capability of taking advantage of a beta* reduction, that would otherwise be quasi-neutralized by the required increase of the crossing angle,
- The capability of luminosity levelling by the crossing angle, that is superior to levelling by beta* modulation thanks to a simultaneous levelling of the beam-beam tune shift. If the bunch charge is not limited, the average luminosity is even increased.

Crab crossing involves two distinct challenges:

- Establish experimentally the feasibility from a beam dynamics and operational point of view. The RF noise level and the cross-talk with collimators and MP are potential issues.
- The technical feasibility of compact RF cavities compatible with a local crab crossing scheme at the required level of low noise and reliability.

Requirements from experimenters

The upgrade of the detectors is a major enterprise requiring about 10 years of preparation, 18 months of installation and a budget of some 250 MCHF per experiment. A LOI for Phase II is in work and planned for mid 2010. While a fraction of the detector upgrade is required for maintenance, the luminosity upgrade brings new major requirements in terms of granularity, background shielding, radiation resistance and activation. This is why operational luminosity leveling must be considered from the start. The experimenters support the crab crossing option as being a very elegant solution that fulfils this requirement. Coordination between experimenters and accelerator scientists becomes urgently needed to meet the challenging schedule and guaranty overall consistency of the objectives. Some decoupling of the luminosity upgrade from the completion of the complete sLHC project is needed.

Experience in KEKB

From the start, the global crab crossing scheme was observed to increase the specific luminosity. It took however two years before the peak luminosity could recover, and now exceed by over 15% the former records. At the origin of this phenomenon, a peculiar chromatic coupling was identified, that could be cured by skew sextupoles. The KEKB beam-beam tune shift has been increased from 0.056 without crab crossing to 0.09, while simulations predict as high as 0.15. The development of suitable crab cavities took 13 years. They were observed to be more stable than anticipated, with a trip rate decreasing to 1 and 0 per day for respectively the HER and LER. The phase noise is better than required. Peculiar coherent oscillations were observed that could be damped by an RF phase shift. The crab crossing operation will end at the end of this year.

Validation for LHC

Tests at the LHC raise several issues than need to be addressed carefully:

- The first installation window for crab cavities in IR4 appears to be 2014.
- Possible space conflicts with the 200 MHz cavities or dampers have to be dealt with.
- The compatibility with the physics program and machine safety has to be guaranteed.

A very precise experimental program needs to be defined with the potential of clear conclusions on the feasibility of the scheme.

Summary, Session II: Layout & Optics Scenarios
Convener: Yoshihiro Funakoshi, KEK

Riccardo de Maria presented **operational scenarios and optics design for an LHC test (phase-I).** A global crab cavity scheme was assumed. Motivations of the test are to show that crab cavities can be installed and operated safely in LHC, to find measurable proofs of a beneficial effect of the cavity on the luminosity and to test the luminosity leveling technique. During the injection and the ramp, the crab cavity should be transparent. The required crab-cavity voltage can be reduced by increasing beta function at the crab cavity (un-squeeze). Another way of reducing the crab voltage is to move the tune towards the integer, although this was presented not by this talk but another. **One of the points of the optics preparation is un-squeeze (anti-squeeze) in IR4.** The un-squeeze in IR4 is designed at 7 TeV. During the un-squeeze, the betatron phase advance between IP and the crab cavities changes by 0.05 unit. To compensate this shift, the arc optics should be perturbed from the nominal condition. The maximum value of the beta function in IR4 is three times higher than that at the crab cavities, which is not an efficient use of the aperture. A further optimization of the IR4 optics might be possible by (for example) installing bipolar power supplies for a few quads. With the above restriction and room for further optimizations, **the optics presented seems to fulfill the requirements for the global crab cavity test.**

Yipeng Sun presented results of the simulations on the beam dynamics issues in the crab cavity beam test (Phase I). **Simulation results on dynamic aperture, z-dependent beta beating, emittance growth during crab-cavity ramp, and degradation of collimation efficiency all look acceptable.** Second-order synchro-betatron resonances driven by the crossing angle could be suppressed by the crab cavities. The luminosity gain in the test can be as large as
25% for a single crab cavity (one beam only) and reduced beam emittance.

Rogelio Tomas presented results of the beam study at KEKB. **A beam-beam driven noise instability has been observed at KEKB.** The noise was artificially introduced to the cavity as a sinusoidal modulation of the crab phase. The instability occurred at some noise frequency between sigma and pi mode. The threshold of the instability was around 0.03 degrees of the modulation amplitude. With the modulation amplitude of 0.2 degrees, which corresponds to an amplitude of a few percent of the horizontal beam size (sigma_x), an abrupt luminosity reduction was observed. The phenomena can be excellently reproduced by beam-beam simulations. **Rogelio tried to extrapolate the threshold of the instability to the case of LHC, although the extrapolation does not seem to be straightforward due to the difference between the lepton and hadron colliders.** Also at KEKB, the “crab dispersion” was measured. The result agreed with the model prediction almost perfectly.

Yipeng Sun presented a possibility to make use of the crab cavity for off-momentum cleaning at LHC. If applicable, this would relax off-momentum optics constraints at the momentum collimators and **allow up to a factor two reduction in beta*,** down to 15 cm, at IP1 and 5. Also, it would enable very early cleaning for the off-bucket particles that have not yet reached the abort gap (good for background). A preliminary study by Yipeng Sun indicates that **the approach can indeed excite off-momentum particles to large transverse amplitudes**, however, so far only at higher RF frequencies (8 GHz and 2.4GHz). To realize off-momentum cleaning using the 800 MHz crab cavity, it will be needed to find proper resonance conditions fitting for this crab frequency.

Summary, Session III: Cavity Design
Convener: Jean Delayen (Jefferson Lab and Old Dominion University)

Session III on cavity design included the following talks

Impedance and Stability (Elena Shaposhnikova, CERN)
KEK R&D for LHC (Kota Nakanishi, KEK)
LARP R&D for LHC (Zenghai Li, SLAC)
UK R&D for LHC (Graeme Burt, Cockcroft Institute)
TEM Deflecting Cavity (Jean Delayen, Jefferson Lab and Old Dominion University)
Compact Cavities (Erk Jensen, CERN)

Impedance and Stability (Elena Shaposhnikova, CERN)

Impedance budgets are not yet fully defined.

The **longitudinal impedance** should be below 10 kOhm for two identical cavities and an LHC beam current of 2.4 A.

The **transverse impedance** should be below 0.4 MOhm/m under the same assumptions, to be multiplied with an additional beta function weighting factor.

KEK R&D for LHC (Kota Nakanishi, KEK)

KEK activities and crab-cavity infrastructures include a new electro-polishing system, a high-pressure rinsing, and a vertical cold test system for an 800-MHz LHC crab cavity.

An aluminum model cavity is planned, and multipacting calculations have been performed in collaboration with US-LARP.

The **KEK design of a pillbox-like compact crab cavity was presented**. Its RF properties have been calculated. This cavity design is the **most compact of all presented** at the workshop.

However the peak surface electric and magnetic fields are rather large and some of the HOM may be difficult to extract.

LARP R&D for LHC (Zenghai Li, SLAC)

A 2-cell 800-MHz cavity of elliptical shape had been chosen as the **US-LARP baseline**. It has been optimized at SLAC using impressive simulation tools, in particular with regard to couplers, damping of HOM, SOM and LOM, and multipacting.

A hard **multipacting barrier was removed** by a local change in geometry around the iris taking advantage of the dipole field configuration.

Cavity dimension sensitivity and tolerances have been analyzed, and significant progress is being made towards an engineering design, i.e. the cryostat integration treated by FNAL.

UK R&D for LHC (Graeme Burt, Cockcroft Institute)

The UK team has performed cavity optimization based on a non-dominated technique where optimal solutions lie on the **"Pareto front"** and sub-optimal solutions lie in front of it. The UK design, and two LARP designs are all close to the front. Multipactor studies may change the optimal solutions.

The **UK elliptical cavity is the only one not squashed**: it relies on the waveguide dampers to polarize the cavity. The UK non-squashed cavity is probably the easiest to design and manufacture, and it also has much looser tolerances on the couplers. Multipactor simulations need to be repeated and benchmarked for all the designs.

The UK also proposes a compact cavity, which is a **superconducting version of an existing CEBAF 2-rod separator normal-conducting cavity** (collaboration with H Wang at JLab). It has a 10 cm diameter beam pipe, and 40 cm diameter for both 400 and 800 MHz frequencies. 4-rod compact cavities could also meet the LHC requirement for a 400 MHz cavity. A full design is expected within 12 months. An optimized design has resulted in **low surface magnetic fields**, further optimization may be able to reduce the surface electric field.

TEM Deflecting Cavity (Jean Delayen, Jefferson Lab and Old Dominion University)

Designs for compact LHC crab cavities with **parallel bar geometry** have been presented from JLab and ODU for both 400 and 800 MHz.

These cavities have a 10 cm beam pipe diameter and **low surface electric and magnetic fields**. The deflecting mode is the lowest frequency mode which could simplify the extraction of unwanted modes. Higher order mode and multipacting studies are under way.

Development of these cavities for deflecting and crabbing applications is supported at present by DOE as part of collaboration with a small business (STTR Phase I)

Compact Cavities (Erk Jensen, CERN)

Erk Jensen advocated **concentrating the R&D effort on a local scheme and on compact cavities**, which fit the LHC constraints. The main reason is that for a significant luminosity gain in more than one IP, local crab cavities would be desired. The global scheme may profit from an enlarged beam separation near Point 4 (420 mm), while local crab cavities cannot rely on such luxury.

The **areas around Point 4** may eventually be used by other RF systems and will not remain available (ACN200 capture system/ADT upgrade?). The technological & beam dynamics issues which result from the choice of local compact crab cavities should be addressed. The R&D must be significant and requires good coordination.

Conclusion

There has been significant progress in optimization, simulation, and engineering of elliptical TM110 cavities. 400 MHz does not appear feasible with these cavities, and neither does a local option.

Several concepts for "compact" cavities have also emerged, which are attractive in terms of size, HOM properties, surface fields, and shunt impedance. **These compact cavities may enable 400 MHz and a local option**. Some support is available for the development for deflecting and crabbing applications. One question has not yet been answered, namely if 800 MHz is compatible with 4.6 K operation.

Summary, Session IV - Cryomodule Design
Convener: Paolo Pierini, INFN
Extracted from meeting minutes

Paolo Pierini summarized presentations by Slava Yakovlev and himself, as well as the subsequent discussions [adding some material from his later slides, not presented at the meeting].

Slava Yakovlev had discussed the cryostat and tuner compatibility, showing the conceptual layout of a module for Phase I, 800 MHz SLAC cavity. Paolo Pierini had discussed mechanical & thermal issues, with generic considerations on module design.

The conceptual design has advanced with respect to previous meeting, but only for a single cavity design, which is still “moving” and “conceptual”, far from fabrication stage. Still the couplers/tuners are not defined, and substantial work remains to be done. A definition of all ancillaries (couplers, tuners,...) is needed to finalize important details for module design (supporting, thermal management). No fundamental objections or showstoppers concerning the module feasibility have been found.

More specifically, the complex LHC crab cavity design and the beam line configuration pose very tight constraints for the cryostat design. An initial assessment of the LHC main RF cryostat points to a new design both from the RF and engineering point of view. An initial cryostat design for LHC crab cavities (the SLAC cavity design) was developed by FNAL. Strong geometrical constraints include limited space and asymmetric cavity position leading to complicated alignment. The cryostat design must respect constraints from both beam lines.

Challenges for the cryostat design include non-trivial He vessel concepts, multiple penetrations to the cavity from the outer world with the need for additional thermal intercepts, differential thermal contraction and thermal gradient, with mechanical constraint at the main coupler. Initial mass flow calculations were presented. It is easy to spoil 2 K advantage at 800 MHz if technological processes are not properly tuned to the geometrical complexity (e.g. bad surface). Test infrastructures will be needed at CERN.

In conclusion, substantial more work is needed towards the module; a heat load budget table must be established to verify the integration with LHC cryogenic; the cryostat will be complex in structural and thermal management due to the many coupler penetrations; analysis for static and transient conditions (cool down/warm-up) will be needed to assess the design; and a module test stand is definitely needed.

Summary, Session V: Crab Cavity Integration:
Convener: Edmond Ciapala, CERN
Extracted from meeting minutes

Ed Ciapala summarized the presentations of Olivier Brunner, Joachim Tückmantel, Bruno Vullierme, Mariusz Grecki, and Yoshihiro Funakoshi, as well as the subsequent discussions following their presentations.

It is not possible to free space in the IR4 ACN cavities region (power lines, RF couplers, access behind the ACN), leaving maximal 3 m longitudinally. Crab cavities could be powered by a 60-kW RF power station located in the UL's of Point 4. A detailed integration study would be needed. A rough cost estimate for IP4 infrastructure & RF power is 620 kCHF, not counting man power.

An RF transmitter of minimum power 5 kW is required for 200 micron beam offset from the center of the cavity. 60 kW is a better number. Transmitters are available: SPS 800-MHz new IOT based transmitters. The crab cavity transmitter could be added to the SPS order. RF noise is still considered not to be completely settled.

For the cryogenics installation two options were identified: (1) 2K system – replacing the existing service module with new design, requiring removal and reinstallation of adjacent ACS cryo-modules, with a cost above 1 MCHF and a total installation time of 10 weeks, (2) 4.5 K simple option, connecting the CC in parallel to the existing QRL extension for the ACS, with a cost of 150 kCHF and 1 week installation time. For option (2) the modified helium flow may be a concern for the ACS.

LLRF & feedbacks were reviewed. They are needed in view of beam loading, drive feedback, cavity dynamics, thermal, effects, microphonics, Lorentz detuning, noise sources. XFEL and FLASH pursue ATCA based hardware with a growing user community. The phase noise correction at FLASH achieves 0.01% amplitude stability and 0.01 degrees phase stability.

KEKB diagnostics of crabbing included streak camera images, and beam-beam deflection scans. Synchronous phase shifts along the bunch trains almost cancelled between the two rings. Almost no harmful effects were seen due to the crab cavities or the single crab cavity scheme (global crab cavity scheme) from the viewpoint of the beam dynamics, e.g. with regard to dynamic aperture, synchro-betatron resonances, bunch current dependent tune shift, loss parameter, bunch lengthening, and coupled bunch instability. The crab voltage is determined so as to maximize the luminosity in the real beam tuning situation at KEKB. Scanning techniques determine the optimum voltage, phase and the beam orbit centre. The phase errors of the crab cavities are much smaller than the allowed tolerances obtained from beam-beam simulations. In autumn of 2009, KEKB will operate for about 2 months. There is a possibility that this will be the final opportunity to operate the crab cavities at KEKB.

Summary, Session VI: Cryomodule Construction

Peter McIntosh (STFC)

This session comprised three talks dedicated to highlighting different aspects of cryomodule construction and testing. The session started with Ilan Ben-Zvi (BNL) who gave an overview of an approved phase-I SBIR proposal, comprising AES, BNL, LBNL and SLAC to develop the engineering design of an approved LHC-CC structure design. This 1-year design process would entail transfer of the physics design to a solid mechanical model and to perform initial thermal and structural analysis, culminating in a fabrication feasibility study. The success of the phase-I proposal could drive a subsequent 2-year phase-II application to build a complete LHC-CC superconducting structure at AES and to validate the structure at BNL's vertical test facility. Ilan described how the LHC-CC09 down-selection process could define the structure to be developed and from which the 3D mechanical solid models would be generated by AES. Fabrication techniques will be analyzed and appropriate engineering drawings generated following detailed stress and tolerance studies. Ilan urged the meeting to ensure that an immediate down-selection takes place to ensure a timely start for this funded SBIR activity. He commented that a design which is complex, but incorporates elements all of which have been done before, may be superior (for fabrication) to a design which appears simpler, but includes lots of "first of a kind" elements. All of the elements of the LARP cavity design meet these requirements, although the UK design has fewer elements with a novel on-cell damping scheme. Ilan then concluded by highlighting the fabrication and processing facilities which could be utilized for phase-II, which are now available at AES in Long Island, NY.

The second talk of the session was by Kota Nakanishi (KEK) who described the KEK-B crab cavity input coupler development and its subsequent conditioning to high power. He started by describing the KEKB-CC cavity processing recipe, which comprised barrel polishing, 100μm and 5μm electro-polishing, followed by annealing and high pressure rinsing. The vertical test verification of such a processed LER cavity showed an improved Q vs Epk response, reaching ~40 MV/m at 1e9. Kota then showed how the basic KEKB-CC coupler design was taken from the already proven and demonstrated main TM010 cavity design. The coupler preparation process includes pure water rinsing, plus additional 0_3 water rinsing. Drying each of the components with filtered nitrogen, before final assembly, which is then followed by an 80C bake as the coupler assembly utilizes indium seals. The high power conditioning of the input couplers took place on a test stand which utilized a conventional accelerating mode coupler with a T-stub transition. Manually conditioning both the KEKB-CC LER and HER couplers up to 250kW TW and 200kW SW, took only 8-16 hours. Verification of the coupler conditioning process was assured once integrated with the complete KEKB-CC and horizontal high power tests completed, which showed that both the operating Qo and deflecting gradients were not deteriorated following assembly into its respective cryostat.

The final presentation of this session was by Pierre Masen (CERN) who outlined the testing infrastructure at CERN's SM18 which comprises two horizontal, radiation-safe bunkers; the first being fed by a 300kW, 352MHz CW klystron and the second by a 300kW, 400MHz CW klystron. Pierre identified that at present, the de-mineralized water supply for these test stations is limited for simultaneous operation and there is limited cryogenics availability, with no 2K capability at all. Ageing ABB controls interface and instrumentation has hampered SM18 cryo-plant operation, since 2007 capacity has reduced to 22 g/s with ageing transfer line already consuming 8 g/s alone. Based upon integration experienced gained for the LHC accelerating mode cavities, a critical design aspect is the transport of the bare cavity from final processing through cryostat integration. The development of a suitable transport frame which can minimize induced shock during transit is seen as a priority. In addition to the described cryogenic plant restrictions, in order to test an appropriate LHC-CC, a suitable 800 MHz, and 60kW CW amplifier may be required to reside along with the existing 400MHz klystron. The 352MHz bunker is to be modified to operate in pulsed mode at 704MHz, to validate LINAC4 cryomodules, with such an improvement including 2K cryogenic capability. Pierre commented that the 400MHz test stand should remain in immediate availability as required to support continued LHC operation and therefore any LHC-CC test would have to share this testing infrastructure.

Summary, Session VII: Phase I Validation
Convener: Massimo Giovannozzi, CERN

Three talks were planned in this session, aimed at discussing the commissioning scenarios for a crab cavity in the LHC.

Andrew Butterworth presented the situation of the RF system proper. He reminded the key parameters of the LHC (sixteen superconducting cavities at 400 MHz) and SPS Landau cavities (two travelling wave 800 MHz cavities). The similarity with the proposed crab cavity parameters makes it possible to re-use the techniques, tools, and procedures developed for the commissioning of LHC and SPS systems in the case of the tests of the proposed crab cavities. As an example the conditioning (warm and cold) could be performed using the well-established procedures used for the SPS Landau system. The commissioning of the low level part would also profit from the embedded data acquisition system in the electronic cards: this system was quoted to have reduce the commissioning time from one month for the first cavity to about one day!

Jörg Wenninger reviewed the main concepts of the LHC machine protection system (MPS). The time between the detection of a failure and the firing of the dump kicker is of the order of three turns, implying that the machine safety has to be ensured during such a lapse of time. The time scale of the main failure scenarios ranges from a single turn (kicker failure) to ten turns (normal conducting magnet). Other failure scenarios will occur on a longer time scale. A crab cavity in the LHC might be source of concern for machine protection as it could produce single-turn failures. In fact, either the RF voltage or its phase could undergo drastic changes in just a single turn. These changes would have the effect of inducing non-controlled oscillations of the bunch along the s-axis. This, in turn, might lead to beam impact on the collimators without possibility of detecting such an event by the beam loss monitors. Even though this failure scenario should be analyzed in detail, e.g. evaluating the fraction of the beam intensity that would be lost on a collimator, and mitigation measures might be at hand (fail safe hardware for the crab cavity, change the Q-value to increase the reaction time) this situation should be carefully studied to exclude any show stopper.

Stefano Redaelli presented on behalf of Ralph Assmann the scenarios to perform beam tests in the LHC with the crab cavities. The assumed configuration foresees a single crab cavity aimed at restoring head-on collisions in IP5. These tests should address two key issues, namely whether the crab cavity can be operated so to avoid any disturbance to the proton beams, and quantify the impact on the machine luminosity. Two sets of beam parameters and luminosity increase have been worked out, based on nominal optics, i.e. β^* of 0.55 m, or the Phase I upgrade optics featuring □* of 0.25 m. It is advised not to change the emittance to a lower-than-nominal one, as this will have an impact on MPS and collimator settings. It is also stressed that a number of tests could be carried out even prior to installation of the cavity in the LHC ring. Indeed, the special optics in IR4 could be studied during dedicated machine sessions, considering also the impact of this special optics on the beam instrumentation installed in IR4. After having assessed the compatibility of the crab cavity with standard operation, it is proposed to check the impact on luminosity. Under the previous assumptions concerning the beam parameters to be used during these tests, it is clear that the luminosity change will be rather small, corresponding to about 4 %. This point is rather delicate, as even so luminosity can be measured to a great accuracy in lepton machines, the same does not hold for Hadron machines. During the discussion it was proposed to measure the beam-beam transfer function.

Summary, Session VIII: Phase II Strategy
Convener: Oliver Brüning, CERN

Session outline

Session 8 of the LHC-CC'09 workshop addressed the strategy for implementing Crab cavities in Phase 2 of the LHC. The session featured three half hour presentations with discussions that covered the following main topics:

- Installation options for crab cavities for Phase 2 of the LHC luminosity upgrade (presentation given by Rama Calaga from BNL).
- Installation issues in the high luminosity insertion regions (presentation given by Ranko Ostojic from CERN).
- Operational aspects for crab cavities in the Phase 2 luminosity upgrade of the LHC (presentation given by Stefano Redaelli from CERN).

Phase 2 Upgrade options and strategy:

Phase 2 of the LHC upgrade program aims at a 10-fold increase of the LHC luminosity with respect to the nominal operation. While all Phase 2 upgrade scenarios target for a peak luminosity of more than 10^{35} cm^{-2} sec^{-1}, in other words, more than 10 times of the nominal LHC peak performance with L = 10^{34} cm^{-2} sec^{-1}, the primary goal of the upgrade is a ten-fold increase of the integrated luminosity.

The electron cloud effect in the LHC does not allow a reduction of the nominal bunch spacing and therefore limits the total number of bunches to values close to or below the nominal number of 2808 bunches [VAL'06]. The operation with a 25ns bunch spacing implies approximately 30 parasitic beam-beam encounters per interaction region (IR), one every 3.5 meter, over the ca. 100 m long common vacuum section of the two beams between the D1 dipole magnets left and right from the interaction point (IP). Parasitic head-on beam-beam collisions are avoided with the help of a crossing angle of the two LHC beams at the IPs. Aiming for a minimum beam separation of approximately 10 sigma between the two LHC beams at the parasitic collision points implies that the crossing angle Φ_c is a function of the beam emittance e and the optical beta functions b at the IPs:

(1) $\Phi_c = sep[\sigma] \cdot \sqrt{\frac{\varepsilon}{\beta^*}}$

A detrimental side effect of the crossing angle is that it reduces the overlap length and increases the effective overlap cross-section of the two beams at the IP leading to a reduction in the peak luminosity given by the geometric luminosity reduction factor R:

(2) $R = \frac{1}{\sqrt{1+\Theta^2}}$

where □ is the so called Piwinski parameter:

(3) $\Theta = \sqrt{\frac{\Phi_c \sigma_s}{2\sigma_x}}$

Figure 1 shows the geometric reduction factor as a function of β^* assuming a constant beam emittance and bunch length and illustrates that reducing β^* to 25cm (half the nominal value) only results in an increase of the instantaneous luminosity by only a factor 1.4 instead of an increase by a factor 2 for head-non collisions.

$R(\beta^*)$

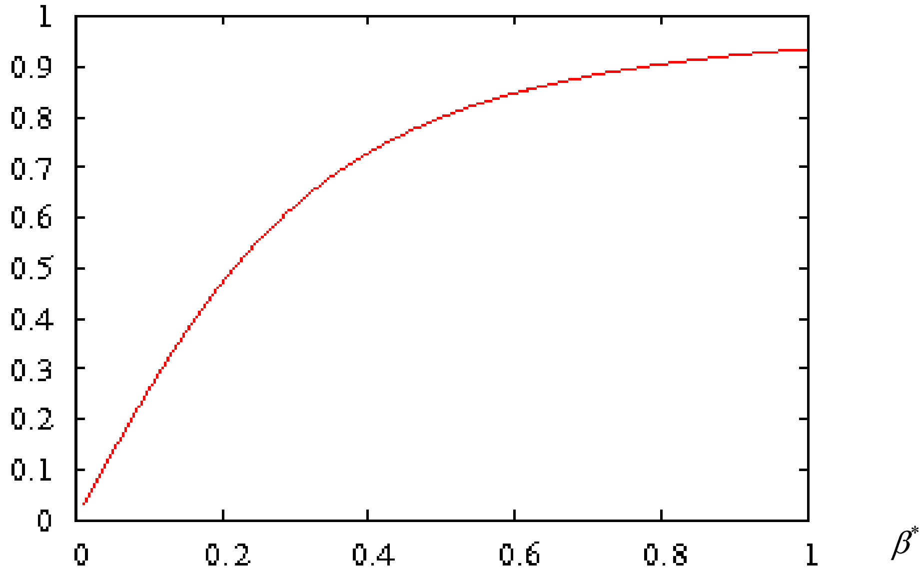

Figure 1: Geometric reduction factor R as a function of b* for constant transverse emittance and bunch length.

The instantaneous luminosity with crossing angle can be written as:

(4) $L = R \cdot \frac{f_{rev} \cdot n_b}{4\pi \cdot \beta^* \varepsilon} \cdot N_b^2$

where f_{rev} is the revolution frequency in the storage ring. With the maximum number of bunches being fixed by the electron cloud effect, the luminosity can only be increased by a variation of the number of particles per bunch (N_b), the beam emittance, the optical beta-function at the IP and the bunch length. All upgrade scenarios for the LHC assume that the LHC will be operated at the beam-beam limit. In this case, the peak luminosity is proportional to the maximum acceptable beam-beam tune shift parameter ($DQ_{b\text{-}b}$), the number of particles per bunch (N_b) and, assuming round beams at the Interaction (IP), inversely proportional to the optical beta function at IP [FZ]:

(5) $L \propto \Delta Q_{bb} \cdot \frac{N_b}{\beta^*}$

with

(6) $\Delta Q_{bb} \propto R(\beta^*, \varepsilon, \sigma_z) \cdot \frac{N_b}{\varepsilon}$

One can therefore identify four distinct strategies for increasing the instantaneous luminosity at the beam-beam limit:

I. Increase the bunch intensity N_b while keeping the beam brightness constant. This option requires a controlled emittance blow up at top energy (the nominal LHC beam size is at the aperture limit at injection energy).
II. Keep the beam emittance constant and increase the bunch intensity N_b proportional to 1/R.
III. Keep the number of particles per bunch N_b constant and reduce the beam emittance e proportional R. This approach requires a larger than nominal beam beam brightness at a smaller than nominal emittance.
IV. Minimize the geometric reduction factor at the IP and minimize β^*.

Strategies I) to III) require a significant injector complex upgrade beyond the current LINAC4 project that aims at a consolidation of the LHC operation with ultimate beam parameters. Strategy I) and II) imply larger than ultimate beam intensities and brightness and Strategy III) implies larger than nominal beam brightness at ultimate bunch intensities. All three strategies therefore imply more stringent conditions for the already challenging LHC machine protection and collimation systems. Furthermore, operation with higher than ultimate beam intensities also implies higher radiation levels for the whole LHC complex, implying potential further upgrades over the whole CERN accelerator complex.

Only strategy IV) is compatible with the ultimate performance of the already approved LHC and injector complex upgrades. A minimization of the geometric reduction factor at the IP can be done either with the help of Crab cavities or by shortening the bunch length. The later is quite expensive in terms of RF equipment (the longitudinal beam emittance cannot be reduced without increasing the IBS growth rates) [VAL06] and only the Crab cavity implementation provides an efficient method for avoiding the geometric luminosity reduction factor.

Four distinct upgrade scenarios are currently under discussion for the Phase 2 upgrade:

-The 'Full Crab Crossing' scheme (FCC) featuring Crab cavities that eliminate the effective crossing angle at the IP by tilting the LHC bunches in the longitudinal direction and thus avoiding a geometric luminosity reduction.

-The 'Early Separation' scheme (ES) featuring a crossing angle with more than 9 sigma beam separation in the common vacuum system of the two LHC beams where parasitic collision points exist and a dipole magnet, called D0 in the following, well inside the high luminosity detectors (ideally less than 3.5 meters away from the IP) that reduces the crossing angle around the collision point where no parasitic collisions can occur. If the Do dipole magnet cannot be placed in the central part of the detector, the scheme still requires a crossing angle that avoids parasitic head-on collisions in the region between the two D0 magnets left and right from the IP. In this scenario the peak performance would still benefit from a crab cavity installation. The Crab cavity requirements for the ES scheme are much relaxed with respect to the FCC scheme.

-The large Piwinski angle scheme (LPA) that compensates the large geometric luminosity loss factor with larger than ultimate bunch intensities.

-The low emitance scheme (LE) that compensates the geometric luminosity loss factor with larger than ultimate bunch brightness at ultimate bunch intensities.

Only the first two options, the FCC and ES schemes, rely on the use of Crab cavities. The LPA and SE schemes do both not require Crab cavities. However, only the FCC and ES schemes are compatible with ultimate beam parameters and thus with the existing LHC injector complex (including LINAC4).

Potential Crab Cavity Scenarios for the LHC upgrade

Rama Calaga highlighted in his presentation two different Crab cavity installation scenarios:

- A local installation of pairs of Crab cavities left and right of the IPs of the experimental insertions. This is currently the default option for the Crab cavity implementation of the Phase 2 IR upgrade.
- A global installation in IR4 using the currently reserved space for the 200 MHz captures cavities of the LHC. This scenario would lock the phase advance between IP1 and IP5 and is not compatible with a future installation of the 200 MHz capture cavitites.
- A global installation in IR4 plus somewhere else in the machine (requiring another insertion with dog-leg dipole magnets that increase the beam separation beyond the nominal beam separation of 194mm). This option would provide more flexibility for the phase advance between IP1 and IP5.

An installation of Crab cavities in IR4 has the advantage that the installation would benefit from already existing RF infrastructure (e.g. cryogenic connection, beam separation of 420mm with the help of special dog-leg dipole installations and RF power installations). The integration of Crab cavities in IR4 would therefore be easier than compared with a local installation. On the down side, the global scheme in IR4 implies also more complex beam dynamic issues (interface with the LHC collimation and machine protection systems) and requires higher cavity voltages as compared to a local scheme (due to the smaller optics beta-functions in IR4). Rama Calaga presents layout options for all both options, a local installation in IR1 and IR5 and a global installation in IR4 and discusses options for

increasing the installation space in IR4 by moving the dog-leg dipole magnets.
A local installation of Crab cavities in IR1 and IR5 implies a larger total number of cavities in the machine and the installation of dog-leg magnets that increase the beam separation in the insertions beyond the baseline separation of 194mm. This implementation would require a total of four additional dipole magnets for two dog-leg installations, one on each side of the IP. For the local installation the Crab cavities would be installed in regions with significant dispersion. The effect of the dispersion on the beam dynamics is estimated to be negligible but the discussions encouraged further studies on this aspect.
The detailed space requirements depend strongly on the final choice of the cavity technology. Two options are currently under discussion (see the discussions in Session 3 of this workshop for more details on cavity options):

- Elliptical cavity designs implying a cavity aperture of ca. 180mm which is incompatible with the nominal beam separation of 194mm once the cavity is placed inside a cryostat and implies a very demanding increase of the beam separation with the help of challenging dog-leg dipole magnets (for example 420mm as in IR4).
- Several compact cavity designs aiming at a cavity aperture of less than 150mm which could be compatible with the beam separation of 270mm requiring only a less demanding dog-leg magnet installation.

In view of the reduced space requirements and the attractiveness of a local Crab cavity installation, the discussions strongly supported further R&D work on compact Crab cavities.
Rama Calaga highlights that Crab cavities also provide an ideal mechanism for luminosity leveling and could therefore be potentially very interesting for any Phase 2 upgrade path.
In terms of required future studies, Rama Calaga highlights that a detailed Phase 2 lattice with Crab cavity installation and Phase 2 collimation system is still needed (including detailed specification of the crossing angle and the crossing scheme). Once a detailed lattice is available detailed dynamic aperture and cleaning inefficiency studies need to follow. Fr a global scheme one still needs to address the question if the phase advance constraints between IP1 and IP5 are compatible with the requirements for the off-momentum beta-beat correction.

IR installation issues for Crab Cavities in IR1 and IR5

Ranko Ostojic highlights the space and service requirements for Crab cavities and their related equipment und underlines that the galleries and caverns in the two main experimental insertions offer virtually no free space once the LHC Phase 1 IR upgrade has been implemented. Ranko Ostojic further underlines that the radiation conditions in the main experimental insertions will be very demanding and that any new equipment for the Crab cavities must be placed in well-protected areas. An installation of Crab cavities in IR1 and IR5 therefore not only requires the installation of additional cryogenic infrastructure but also the construction of new underground installation space with low radiation levels.
Ranko Ostojic further underlines that magnet requirements for the dog-leg installation in IR1 and IR5 are quite demanding (even for the reduced beam separation of 250mm with respect to IR4) and that the dipole magnet design for such an installation is far from trivial requiring on its own further R&D efforts.
The discussions concluded that any upgrade work in the main experimental insertions and IR4 should keep the needs for a future Crab cavity installation in mind and, where possible, implement already in the wake of other installation work implementations that could facilitate a Crab cavity installation in the future.

Operation Issues for a Phase 2 Operation with Crab Cavities

Stefano Redaelli proposed the development of detailed commissioning procedures as exist already, for example, for the operation with ions in the LHC. The preparation of such procedures well in advance of the actual cavity installation would highlight well in advance areas where the Crab cavity installation would impact on existing operation procedures, existing machine equipment (e.g. beam instrumentation equipment) and the machine protection system. Stefano Redaelli gave several examples of operation phases in the LHC that would probably be affected by the Crab cavity installation and would have to be newly commissioned once Crab cavities are installed in the machine.

As an alternative to the proposed Phase 1 installation of Crab cavities in IR4 for the demonstration of successful operation and luminosity improvement with Crab cavities in a Hadron storage ring, Stefano Redaelli proposes a negative test scenario, where the Crab cavities are used during operation without crossing angle with the aim of significantly reducing the luminosity without degrading the beam emittance and generating additional losses along the machine. Such a 'negative' test setup could deliver a stronger effect as compared to a positive test during the Phase 1 IR upgrade operation while still demonstrating the proper functionality of the Crab cavities and the compatibility of their RF equipment with the operation in a Hadron storage ring without generating additional constraints on the LHC collimation and machine protection systems.

The discussions supported the proposal of a 'negative' test set-up but also underlined, that a demonstration of a successful operation of Crab cavities during the Phase 1 IR upgrade operation should not be seen as a prerequisite for a later installation of a full system in the LHC. Alternative options for demonstrating the compatibility of Crab cavities with the operation in Hadron storage rings include detailed test on cavity test stands and the installation of Crab cavities in other Hadron storage rings than the LHC. As an example for alternative test storage rings the discussions mentioned the SPS, the PS and the Tevatron storage rings.

Discussions and Summary

Crab cavities are strictly speaking only required for one of the Phase 2 upgrade scenarios currently under study. However, this is the only Phase 2 upgrade scenario that I compatible with the approved upgrade projects and with the ultimate LHC beam parameters. An operation of the LHC with larger than ultimate beam intensities is far from obvious and implies larger radiation and machine protection issues in the LHC and its injector complex. This aspect alone justifies a further development of a Crab cavity installation scenario in the LHC.

The added bonus of luminosity leveling is another justification for studying a future Crab cavity installation in the LHC that would benefit all currently studied Phase 2 scenarios.

Compact Crab cavities are the prerequisite for a local installation of Crab cavities in IR1 and IR5. The R&D work related to the development of this new cavity design is therefore strongly supported.

A feasibility demonstration of the Crab cavity operation in the Phase 1 upgrade of the LHC with a local Crab cavity installation before 2014 does no longer to be a prerequisite for adopting Crab cavities for the Phase 2 upgrade plan. The overall functionality of Crab cavities has by now been successfully been demonstrated by the KEK-B operation and secondary worries about the detrimental effect of impedance and RF noise on the beam dynamics could in principle be studies on dedicated test stands and with installations in other Hadron storage rings. This observation eliminates the stringent previous requirements of a proof of principle of Crab cavity operation in the LHC prior to the implementation of the Phase 1 IR upgrade (e.g. 2014).

Summary of Session IX – Planning & Milestones, Down Selection: Convener: Paul Collier, CERN Extracted from meeting minutes

Paul Collier summarized the presentations of Edmond Ciapala, Roland Garoby, Akira Yamamoto, Eric Prebys, and Peter McIntosh, as well as the subsequent discussions (complemented by Frank Zimmermann).

An aggressive schedule would see first LHC beam tests with a prototype crab cavity in 2014. The cost for RF (excluding the cavities) and cryogenics are of order 4-6 MCHF for a CC phase I and 12 to 30 MCHF for phase II. Civil engineering will be the likely cost driver, but this cost could be incremental and contained, if its CV is part of an IR upgrade for LHC phase II. The cost for (new) separation magnets might already be higher. The total cost is of the order of one or two percent of the detectors upgrade cost.

Planning and impact on physics data taking is likely to be more important than cost of construction, implying that one should focus on being ready for Phase 2 of the LHC upgrade (2019?), and start a.s.a.p. the R & D for Phase-2 cavities.

KEK has a vigorous crab cavity program, the most experience, and the right infrastructure. But the KEK plans and possibilities are presently unclear due to the change of the Japanese government. The new government has not yet announced any budget for the coming year. Katsunobu Oide, the KEK Director of Accelerators, has raised no objection to transferring a KEKB crab cavity to CERN for beam tests in the SPS, provided the cavity can be appropriately modified (e.g. tuning range and speed) plus transported, and such beam tests will be pursued. The proposal can be discussed in greater detail at the CERN-KEK collaboration meeting in December.

Crab cavities (even just the US part) are too big to fit within LARP, but LARP can take a steering role in the US R&D. If crab cavities take off, they will have to get dedicated funding from the DOE. As LARP rotatable collimators and luminosity monitors ramp down, projects which are moving to take their place include, predominantly, R&D for PS2, and also E-cloud feedback in the SPS, while a "wait and see" attitude has been, and is, adopted towards crab cavities. LARP crab cavity support will probably stay in the range $300k-$600k/year. LARP will not continue to support efforts for a Phase I (IR4) test unless there is an unambiguous commitment from CERN to support such a test. US contributions are more than just US-LARP, however. Important SBIR and STTR projects have been approved by the US DOE at AES (at the moment for elliptical cavities, in collaboration with BNL) and JLAB (for compact cavities, with Jean Delayen as principal investigator), both aiming for the fabrication of crab-cavity prototypes.

The UK has considerable crab-cavity design capability. Work proceeds through the EUCARD FP7 LHC-CC work package. Funding and deliverables, UK LHC-CC qualification infrastructure and the EUCARD LHC-CC R&D Integration were described. The UK has led ILC-CC development through to system validation. Design synergies are clear for LHC-CC. The SRF infrastructure at CI is available for LHC-CC component and/or system verification. EUCARD LHC-CC design priorities have been identified. They require meshing with the global collaboration effort. Cavity down-selection process will define UK resource focus.

There emerged a strong objection to a phase I test in LHC since the location is not guaranteed, and the cavity likely different from phase 2. KEKB crab cavity tests in SPS could address numerous critical controversial issues and alleviate concerns. The ultimate goal is to install crab cavities in phase II, around the year 2019. To be ready on time, the R&D must start now. One would need to look at SPS test possibility, the needed klystron, needed cryogenics investment etc.

The crab-cavity phase I would have a total cost of ~10-15 MCHF, and a potential conflict with phase-I upgrade of LHC. The only possibility is to modify IR4. To pursue the R&D for LHC phase II one must understand the constraints. The focus will be put on compact designs which do not require doglegs.

Further discussion revealed various questions of risk – the risk of not being able to develop a compact cavity for phase 2 on time or of obtaining one not meeting the required performance, the risk to the machine (MPS), the risk to the physics program etc. A crab-cavity test stand at CERN is needed for phase 2. HOM damping and multipacting have not been studied for most, if not all, of the compact designs. Optics constraints, the impedance magnitude and bandwidth for active & passive damping schemes, etc. all need to be assessed in more detail. An updated parameter list for phase-2 upgrade scenarios should be established. Compatibility with high-energy physics operation is essential.

Paul Collier concluded that crab crossing is important possibility for the LHC and should be pursued. He recommended to eliminate Phase-I, and to focus on a compact cavity design, considering it vital to put THE final cavity into the beam. One could redefine phase I (in the LHC) with the objective to test the final design and equipment.

Ilan Ben-Zvi commented that one must have a real cavity test in LHC but not with the final design, as any crab cavity can address the crucial issues. The modification of IR4 during phase-I upgrade should be looked at with priority.

Philippe Lebrun asked if it would not be reasonable to work out a global scheme for phase 2. There is another bifurcation in the decision path, between local or global cavities as final goal. A first beam test in the LHC could be foreseen for 2014 at the very earliest.

Proposed ACTIONS:

1. Possible IR4 modifications for 2013/14 shutdown; revision of dogleg
2. Effect of crab cavity trip & machine protection; study failure modes
3. Requirements for local crab cavity designs (inner & outer aperture, impedance,...)
4. Impedance effects during acceleration and mitigation measures
5. LHC phase II IR1&5 layouts including crab cavities?
6. Noise tolerances with beam-beam, effect of dispersion at the crab cavity
7. Effect of IR dispersion at crab cavity
8. Study suitability of KEKB crab cavities for SPS beam experiment and, if positive, prepare such experiment
9. Develop and explore global crab cavity scenario for Phase II; compare with local scenario
10. Establish forum combining experimenters and accelerator people to discuss SLHC feasibility and options
11. Study of suitability of KEKB crab cavity, detuning range, impedance, transport issues, etc.
12. Demonstrate off-momentum cleaning with 800-MHz crab cavities in simulations

Appendix

Cavity Down-Selection Discussion
Peter McIntosh

1. **What are the design specifications for the LHC-CC?**
    1. Beam dynamics, impedance .. etc
    2. Space availability
2. **What are the fundamental goals for the Phase-I CC test?**
    1. Should not perturb LHC operation (demonstrate transparency)
    2. Feasibility of crab-crossing in LHC.
    3. With KEK-B now demonstrating Lumi increase:
        i. Impedance, noise, collimation and Lumi levelling are more important demonstrations.
3. **Do we have to demonstrate ~10% Lumi increase in Phase-I test?**
    1. Could use KEK-B CC in SPS for Phase-I test.
    2. Could then focus design effort on Phase-II (compact) CC design.
4. **EUCARD, US-LARP, SBIR (Ben-Zvi) and STTR (Delayen) funding available now:**
    1. Must focus effort/funding on a common strategy, driven by the down-selection process.
    2. Can't afford to wait!
5. **Need CERN clarification for:**
    1. Capture cavity utilisation □ impact on Phase-I tests
6. **Can compact CC go into LHC without a phase-I beam test on LHC?**
    1. If not then ph-I test in 2014 is a priority …. Looks extremely difficult!
7. **What verification tests can be performed elsewhere (SPS, Tevatron, KEK-B)?**
    1. Limited opportunity on KEK-B
    2. Tevatron closing in 2011
8. **Compact designs are not at the stage for down-selection:**
    1. Need a definite spec for this design (apertures, beamline spacing)
    2. Multipactor studies have not yet started.
    3. Must not forget beam dynamics issues.
    4. Timescales for possible tests of compact CC on LHC cannot match 2014 IR upgrade
9. **Consensus:**
    1. Phase II Lumi upgrade using CC's is priority.
    2. Test of final CC in LHC is fundamental requirement.
    3. The best R&D approach would be 2-yr design study for compact CC and 3-yr engineering/fabrication/RF test phase, ready for LHC beam test.
    4. Focus CC design on compact structure.
    5. Elliptical CC development put on hold.
    6. Determine dedicated location for CC installation for both **test** and final location.
    7. Preparation for such a test in LHC should be made during LHC IR ph-I upgrade.
    8. Explore opportunity for CC tests at SPS, Tevatron (costs etc)
        i. Determine benefits, Assess risks
        ii. NC prototype in SPS?!?