



High
Energy

High
Intensity

Hadron
Beams

Summary of CARE-HHH Mini-Workshop on LHC Crab Cavity Validation, 21 August 2008

R. Calaga, E. Ciapala, R. Garoby, T. Linnekar, R. Tomas,
and F. Zimmermann

Abstract

A global LHC crab-cavity collaboration is rapidly advancing the R&D of a complete crab cavity cryomodule and performing the associated beam dynamics simulations compatible with a prototype test in the phase 0/I upgrade with the aim of establishing a full crab crossing scheme for the phase II upgrade of the LHC. A one day CARE-HHH mini-workshop was held on August 21, 2008 at CERN to discuss crab crossing in the LHC phase 0/I & II upgrades and this reports summarizes the activities of the four sessions that took place during the workshop. The goals of this crab-cavity workshop were fourfold: (1) to discuss prospects of crab cavities in LHC upgrades (2) to review the status of the cryomodule development and beam dynamics, (3) to establish validity requirements for LHC crab cavities which need to be demonstrated prior to their installation into the LHC, and (4) to provide guidance & coordination for the global collaborators.

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WORKSHOP ON LHC CRAB CAVITY VALIDATION

August 21, 2008 – CERN

R. Calaga, E. Ciapala, R. Garoby, T. Linnekar, R. Tomas, F. Zimmermann

Introduction & Workshop Objectives

R. Calaga, R. Tomas, F. Zimmermann

A global LHC crab-cavity collaboration is rapidly advancing the R&D of a complete crab cavity cryomodule and performing the associated beam dynamics simulations compatible with a prototype test in the phase 0/I upgrade with the aim of establishing a full crab crossing scheme for the phase II upgrade of the LHC. A one day CARE-HHH mini-workshop was held on August 21, 2008 at CERN to discuss crab crossing in the LHC phase 0/I & II upgrades and this reports summarizes the activities of the four sessions that took place during the workshop. The goals of this crab-cavity workshop were fourfold: (1) to discuss prospects of crab cavities in LHC upgrades (2) to review the status of the cryomodule development and beam dynamics, (3) to **establish validity requirements** for LHC crab cavities which need to be demonstrated prior to their installation into the LHC, and (4) to provide guidance & coordination for the global collaborators. In total 28 registered participants attended the workshop: 16 from CERN, 4 from KEK, 2 from CI/DL, 2 from BNL, 2 from SLAC, 1 from FNAL, 1 from NIKHEF, and 1 from Oslo. There also was some additional US and KEK participation via WebEx (web phone). The workshop was structured in 4 sessions, each ending with 30-60 minutes of discussion.

The first session consisted of an overview of the LHC crab cavity R&D and integration issues. This was followed by a comprehensive overview of the KEK-B operational experience with crab cavities and LHC optics and collimation studies. The third session discussed the contributions from the various collaborators around the world and future directives for the R&D. The concluding fourth session focused on the pre-requisites prior to the installation of the crab cavities into the LHC and discussions thereafter. Some objectives were given to the session chairs as a guidance to steer the discussions and retrieve some conclusions that would be helpful for future R&D. The questions posed to the session chairs are listed below:

Session I

1. What more CERN input is needed and for which points should CERN-RF assume the lead (or major liaison) role
2. Is the phased upgrade plan effective and compatible with LHC requirements?
3. Is the R&D for the cryomodule adequate and feasible within the given time-line?
4. Feasible mode(s) of operation with crab cavities (for example: control of crossing angle).

Session II

1. What do we learn from KEK-B experience?
2. What results can be directly applicable to the LHC given the differences in beam sizes, energy, particles species etc... ?

3. CERN participation in KEK-B crab cavity experiments and input for LHC commissioning.
4. Are the crab optics compatible with LHC phased upgrade plan and what are the collimation concerns ?
5. Input from the magnets on the foreseen D1, D11, and D22. Are the assumptions for the CC aperture compatible with foreseen upgrades?
6. Priorities of simulations to be addressed in the near and far term.
7. Hardware contributions/deliverables from collaborating institutes (existing-KEK and future-US+KEK+UK). What hardware from CERN can complement the R&D effort ?

Session III

1. Guidance to the CC collaboration and R&D effort that may be helpful to address specific CERN concerns
2. How to provide periodic CERN input to R&D progress
3. If compact structures are available in the near future, will a local scheme be preferable for phase I and should it be pursued aggressively?
4. Time line for compact cavity development and testing
5. Can we test compact cavities elsewhere?
6. How can future projects like LHeC, eRHIC, B-Factories benefit from the crab R&D for LHC upgrade (for example: similar constraints on RF structures, etc..)?

Session IV

1. Is the 4 year development, fabrication and testing program sufficient (2009-2012)? Is 1 year of CERN acceptance tests be sufficient for installation (2012-2013)?
2. What does the LHC-CC team need to establish/validate in order to certify the crab cryomodule to be LHC ready
3. Can 2010 review at CERN initiate the fabrication and testing. Any external review required?
4. What are the needs and preferences from the experiments? Can they provide input for CC commissioning and luminosity increase & leveling?
5. What guidance can CERN provide to the associated funding agencies to boost the crab cavity R&D?
6. When can the collaborating institutes commit to a firm plan to fabricate the CCs and establish deliverables schedule? What form of a statement of interest from CERN in support of crab cavities is required by collaborating institutes?
7. What are the approximate beam commissioning time line and adequate measures for safe operation and beam transparency.

The answers to some of the above questions and discussions during the sessions are summarized by the respective session chairs.

Summary, Session I

F. Zimmermann

The first session set the **stage**, reviewed the **status**, and defined the **goals** for the workshop. After a brief opening with historical remarks by Frank Zimmermann, Rama Calaga presented an overview and status report of the LHC crab cavity scheme, and Joachim Tuckmantel discussed the LHC crab-cavity integration.

In his **opening**, Frank first recalled the motivation for LHC crab cavities. While they could gain no more than 20% peak luminosity for the nominal LHC, **in the various upgrade scenarios** they promise to **enhance the luminosity by factors of 2.5 to 5**. Historically, CERN was one of the first places in the world to develop superconducting deflecting “crab” cavities, together with Karlsruhe in the 1970s. Later, in 1988 Bob Palmer proposed crab cavities for linear colliders. Shortly thereafter Katsunobu Oide and Kaoru Yokoya discussed their use in storage-ring colliders. It took almost 20 years before they could, **for the first time, be installed in an operating collider, KEKB, in 2007**. It is noteworthy that the **Piwinski angle in KEKB is similar to that of the ultimate LHC**, and that the required **crab voltages are also comparable**.

Rama next presented the **overview and status of the LHC crab scheme**. He started with a chronology and a description of the global collaboration effort, including the points of contact inside and outside CERN. The potential luminosity gain was illustrated in graphical form as a function of the IP beta function. Background information is available at, and ideas can be shared via, the twiki page <https://twiki.cern.ch/twiki/bin/view/Main/LHCCrabCavities>. The approach adopted for the LHC crab cavities is one of a **phased upgrade**. Phase 0/1 could be in place around 2013. At the absolute minimum it will consist of one global crab cavity for one beam. Phase I.x would come slightly thereafter and comprise a modified IR to accommodate local crab cavities plus a change in the beam crossing scheme. Lastly, phase II would accompany a complete IR redesign for the year 2017 or beyond, with a larger beam separation. R&D efforts in 2007-08 culminated in the LHC-CC08 workshop at BNL early in 2008. These efforts established the basic “coordinates”, including a preliminary optics solutions & aperture estimates; they advanced the cavity-cryomodule development, also included beam-beam (K. Ohmi, Y. Morita) & impedance simulations, and last not least defined a task distribution plus a 5-year plan to get ready for beam testing. Rama displayed the optics for IR4 and IR5 highlighting possible locations for global and local crab cavities, respectively. Both **inner and outer aperture requirements** are issues: 84 mm is the minimum inner aperture, but more than 110 mm would be preferable. The outer size of local crab cavities should be no larger than about 200 mm, compared with 350 mm for the global cavities in IP4. Two conflicting requirements – proton bunch length and transverse beam separation – argue for a compromise RF frequency around 800 MHz. The proposed **baseline is a 2-cell squashed cavity at 800 MHz**, which would easily fit in the IR4 section, and with 2.5 MV crab voltage. **Couplers** are delicate, especially the ones **for the lower-order fundamental mode**. Important lessons can be drawn from the KEKB experience. Several improved coupler designs are being worked out at SLAC, CI, and KEKB. Warm tests are foreseen as the next step.

A collaboration of FNAL and CERN will attempt to adapt the existing “**CERN cryostat**” for housing a crab cavity. An important block of questions concerns **operational scenarios**, namely turning-on cavities with or without beam (KEK-B test), the **beam transparency at injection &**

ramp, the cavity de-tuning by several MHz (no overlap with 40 MHz bunch-repetition rate), the adiabatic **voltage ramping** of crab cavities, stable **orbit requirements**, which may be similar to those for the collimators (~200 μm , natural feedback), KEK-B experiments, understanding & solving the mysterious **drop in specific luminosity at high beam current in KEKB**, and to use KEK-B as a test bed for LHC crab cavities. Rama and Frank stressed that the LHC studies might help for understanding the KEK-B problem and vice versa. Akio Morita already performed simulations of adiabatic ramping, demonstrating that even fairly fast ramps (approximately 10 turns) do not lead to any significant emittance growth in the LHC. Also, the long filling time (~1ms) of a high Q superconducting cavities are therefore naturally adiabatic.

A task & coordination sheet summarized the **individual responsibilities of the various participating laboratories and organization**. The expected outcome of this workshop was that CERN and its collaborators establish and agree on a **5-year R&D plan**, with detailed work breakdown structure (WBS) to follow, and on a commitment for the 2013 goal. The FY09-12 funding will have an impact on the R&D pace. A strong support from LARP & EUCARD is expected. It was asked whether KEK would contribute to the cryomodule. Rapid progress in 2008-09 will bring us closer towards the preliminary CDR review. Further in the future, over the next 5 years, a **preliminary review** (2nd LHC-CC workshop) is foreseen **for mid-2009** in order to survey the technical design of cavity, couplers, cryostat, and controls, to discuss new simulation studies, operational scenarios and beam transparency, as well as to review the warm model fabrication with subsequent testing. A **comprehensive review** will take place **in 2010**. Following this the cryo-module fabrication and testing will go forward in 2010-12, involving hardware procurement, fabrication of components, assembly, and rigorous bench testing (RF & operational scenarios). LHC integration and commissioning is finally expected for 2012-13.

Joachim discussed the **LHC integration of a crab cavity**, covering the consensus reached at the BNL LHC-CC08 workshop, the cavity & cryostat requirements, external constraints, and conclusions. Crab cavities for the global option could be installed in the **staged ACN locations of LHC point 4**. He stressed that the crab cavities would need to make room when the ACN cavities are needed, with a pre-warning of 1 year. The ACN cavities may be required at higher LHC beam intensities prior to the injector upgrade. The transverse space available in IR4 would be adequate for 800-MHz cavities. The beam-beam distance in this region is 42 cm compared with a standard distance of 20 cm. Joachim stressed that the presence of crab cavities should **under no circumstances lower the integrated LHC luminosity**, with implications on **dynamic aperture, machine stops, vacuum, interlocks, and transparency**. Hardware, controls, ancillaries etc. should be prepared thoroughly so that the operation is worthwhile, plus the installation (and possible removal) should be swift. The crab cavities should not present a safety risk to personnel or material. He next presented a number of considerations on legal issues, electrical power, fire, radiation, material norms (e.g. for the choice of steel), vacuum flanges, and bake-out for the **cavity/cryostat system**. Joachim pointed out that **any tank full of LHe is a sort of bomb**. The vacuum tank needs to be equipped with a spring loaded "toilet lid valve" in case of rupture of interior vessels. An important constraint for the **main RF system** is that **before any work on or close to the cavities the liquid helium must be emptied**. Further thoughts addressed the liquid helium, the vacuum tank, compatibility of main RF and crab RF helium systems, transport conditions, and alignment aspects. Turning to the **RF** itself, radiation sensitivity is an issue, as are the need for a fast RF vector feedback, RF reference signal, high-power supply, RF transmitter, low-level RF, tune control, and interlock chain.

The **cryogenic system poses significant challenges, in particular if operation at 1.9 K is needed**. It will be difficult, if not impossible, to connect to the existing 1.9-K system. A much easier path would be to work at 4.5 K and to hook up to the main RF cryogenic line and provide for a standalone 2K pumping system if needed. This still requires a quench protection system, new lines for liquid and gaseous helium, regulations, and control connections. **Vacuum** requirements call for two RF compensated metal seal valves at the ends of the crab cavities. **Cooling and ventilation** aspects are also interesting. The crab cavities need water cooling at power levels of a few kW. **Remote control** will be important. Joachim's final, psychological advice to the crab cavities was to **be invisible if problems arise**.

Considering all the above aspects, Joachim concluded that **in the medium time range** (after having reached a reasonable luminosity and beam current not far from nominal) there is a **good chance for a not permanently installed TEST CRAB CAVITY in the area around Point 4**: at the location reserved for the (staged) ACN (or ADT-reserve..). The **additional hardware installation** is manageable, but it does not come for free (cryo-lines, RF high-power equipment, controls). **Apparent 'details'** have to be settled with **concerned LHC groups / persons** even before starting the construction of crab cavities (i.e. before signing any contract).

Following the questions injected by the organizers for session I, the **discussion** focused on the following points and questions:

- 1) Can we **decide the next questions by summer 2009**?
 - **choice of frequency - 400, 600 or 800 MHz?**
 - **shape of cavity - elliptical or compact?**
 - **operating temperature - 1.9 K or 4.5 K?** (800 MHz crab cavities at 4.5 K were not completely excluded)
 - must the **prototype be identical to final cavities**? No
- 2) Comments & other questions
 - Ranko Ostojic mentioned the availability of 1.9K near IP1 & IP5, but the issue of the pressure of 1 bar which may not be suitable for a superconducting cavity
 - Erk Jensen pointed out the use of the multiple harmonic systems (0.8 GHz + 1.0 GHz) to linearize the RF curvature. A similar scheme using 2nd harmonic system was initially studied by R. Calaga et al. in the 2006 LUMI06, CARE-HHH workshop in Valencia for the large crossing angle case where the effects of the curvature were more severe
 - **space in Point 4** may not be available (reserved for 200-MHz capture cavities)
 - can LHC continue **operation when the crab cavities are warm**?
 - can the tests be **decoupled** from each other and/or from LHC operation?
 - can there be meaningful tests in **other hadron colliders**? Would such tests elsewhere be conclusive? (e.g. in view of bunch length, collimation, collisions, ...)
 - possible tests in the **CERN AD** (proposal by Fritz Caspers) would be aimed at verifying the blow-up prediction

- what is the **purpose of the LHC prototype test? A go/no-go decision for US construction project** (Steve Peggs)!
- **benefits of the first test** must be made clear: demonstrating emittance growth, collimation, luminosity gain? Can we modify the beam conditions to enhance the effect for the test?!
- the LHC test **must show a measurable luminosity gain** (>10%) with intense beam, or **at least with the nominal LHC bunches or with beam conditions modified to enhance the effect of the test**
- **participation in beam tests at KEK**
- **cost of infrastructure**

Answers are expected by mid-2009.

Summary, Session II

Convenor: T. Linnecar

There were three talks in session II. The first two, by Kazuhito Ohmi and Yoshiyuki Morita, described experience with crab cavity operation in KEK, and the third, by Yipeng Sun, described some recent optics calculations for crab cavity use in LHC.

KEK has two crab cavities in operation, one in the HER and one in the LER. A “global” crabbing scheme is used, and full compensation of the bunch tilt can be obtained at the single crossing point where the Belle detector is situated. Simulation has predicted a luminosity gain of ~ 2 when the crabbing collision is used and under these conditions a maximum tune shift of ~ 0.15 can in theory be obtained. **The improved luminosity at low intensities, geometric increase, is fully demonstrated.** However as the beam intensities increase the beam-lifetime with crabbing degrades giving ~ 100 minutes for a tune shift of ~ 0.08 . Extensive machine studies and simulations are underway to understand this phenomenon and improve the lifetime in the very high beam-beam parameter regime. The talk by K. Ohmi described the hypotheses at present under consideration.

Simulations of the tuning process used in the machine to optimize the 12 parameter space (known) show that, unless very large initial errors are present, the luminosity peak should be found. However, the result is highly sensitive to initial conditions. Beam halo formation is a possible explanation for the poor life-time. Simulations suggest this is not so, but the simulation also fails to explain the observed asymmetry in lifetime with horizontal position. **The operation without crab cavities had asymmetry both with luminosity and lifetime but the operation with crab crossing in KEK-B shows asymmetry only in lifetime with horizontal offsets.** The tolerances predicted from simulations are very severe for horizontal offsets. In simulations, the correlation of the vertical beam size versus lifetime show better lifetime with smaller beam sizes. However, experimental observations suggest the opposite.

Two other effects under study are the effect of intra-beam scattering and the loss of dynamic aperture due to beam-beam acting dynamically on beta and emittance. Various beam measurement results suggest that lattice non-linearity can also be a good candidate for the luminosity reduction. High frequency noise leading to particle diffusion can also be important and it is shown that this effect increases with the beam-beam parameter. **Measurements of the coherent tune shifts with intensity show no big differences between operation with and without crab cavities suggesting no significant change in transverse reactive impedance.** It was also mentioned that very strong feedback for coupled bunch instabilities can cause degradation of luminosity and a gain of 2-3% was found to be optimum. **To gain full benefit from the crab cavities in KEK these issues must be solved.** In the LHC where the beam-beam parameter is significantly smaller they are perhaps less likely to be a problem though until a full understanding is reached this cannot be guaranteed. The **studies at KEK** in any case **give many insights that are useful for the design and operation of crab cavities in LHC.** Active participation in the operation of KEK with crab cavities by those directly concerned with the LHC upgrade would be highly beneficial. It is hopeful that this would also be helpful to KEK!

The crab structures in KEK-B consist of complex LOM/HOM couplers, stub supports, notch filters and ferrites in cryogenic environment. The hardware operation of the crab cavities in KEK

has been very successful. However, it was noted that the performance of the LER cavity has always been lower than that of the HER cavity. Orbit scans were performed to determine the magnetic center of the cavities and crab phase with respect to beam. The first high current trial caused high trip rate but after a warm up of the LER cavity to remove the condensed gas from the cavity walls, high beam currents in LER/HER, 1.7/1.35 A, have been stored without beam instability in the presence of the de-tuned passive cavities. **The cavities have been used actively to crab the beam with 1.5/1.8 MV at 1.62/0.95 A beam current.** Many RF parameters have been measured and Y. Morita described some of the most important. The RF noise has been measured and confirmed to be consistent with good lifetime values. The beam-pipe coaxial coupler is able to **tune the cavity by 30 kHz/mm**. The LER cavity tuner showed a strange hysteresis effect which was cured by a mechanical modification to remove jitter and backlash. It was noted that the piezo tuner was not functional several times. The induced LOM/HOM powers are within specification and the power, ~12 kW can be absorbed correctly. With asymmetric fill patterns large voltages in the LOM can be generated, leading to multipactor and vacuum trip.

There are **three issues of direct interest to LHC operation**. First, after ~1 year of operation the **crab trip rate** had lowered from 1.6/day to 1.4/day for the HER and 1.3/day to 0.7/day for the LER. To achieve these values the operational voltage of both cavities has been reduced, the cavities have been warmed up to de-pollute the cavity and **conditioning** is done whenever possible. In KEK the turn-around time after an abort is 0.5 hr, operationally acceptable; in LHC the turn-around time is much longer and this trip rate would be unacceptable. It is important to follow the trip-rate evolution in KEK. It was noted that a different coupler design may be needed for the LHC as the couplers are suspected to be the root cause of the trips. Second, **the maximum voltage obtainable in the LER has dropped from 1.5 to 1.27 MV**. The exact cause for this is unknown (surface damage?). Thirdly, **instability has been observed where the amplitude and phase of the two cavities oscillate coherently at 540 Hz**. This causes beam position oscillation and unstable collisions. A model has been proposed where the **beam-loading in one cavity can be coupled to that in the other by the beam-beam interaction**. An empirical solution has been found by shifting the crab phase by approximately 10 degrees, but it would be of interest to confirm the model via simulations. It has been proposed that the beta at the cavity could be lowered at constant crab angle, better for machine aperture, if the voltage is raised. This operation at lower temperatures, ~2.8 K will be tried. An important aspect of **switching the cavity on with beam is expected to be tested in KEK-B during the upcoming machine experiments**.

A wealth of experience in the design of the crab cavities, the cryostats and the associated RF systems has been **accumulated at KEK**. The LHC should take advantage of this wherever and whenever possible.

The final talk by Y. Sun addressed optics issues associated with global crabbing schemes. In KEK-B only a single crabbed beam is not ideal due to very high beam-beam parameter, but the LHC will benefit even from only crabbing one beam. A test with one single cavity acting on one beam only in the nominal scheme ($\beta^* = 55\text{cm}$) should give a gain in luminosity in one experiment of 5% while up to 5% might be lost in the other (depending on the betatron phase advance). This is a **marginal increase for a proof of principle experiment**. It was noted that **the test in the upgrade phase I ($\beta^* = 25\text{cm}$) yielding a significantly larger luminosity gain**

of up to 50% is more attractive. Some other ideas such as **increasing the crossing angle and/or decreasing the emittance aiding in a solid demonstration of luminosity gain with crab cavities will significantly boost the future upgrades with a full crab crossing scheme.** It was also noted that a **consistency and reliability test is crucial for the prototype tests.** Another scenario where the crab cavities are used at **medium or lower energies** to enhance the benefits needs investigation.

The **required crab cavity voltage could be reduced to 4.7 (9.3) MV if the beta function at the CC could be raised to 800 (208) m.** and this is being actively pursued. Optimizing the **overlapping of the bunches** for different voltages is now possible both via analytical calculations and simulations performed via GUINEA-PIG. Simulations suggest that the reduction in **dynamic aperture** for a global crabbing scheme is acceptable and confirm the expected increase in luminosity for the nominal and upgrade schemes. Preliminary results suggest that **losses** (loss map calculation) around the ring can be controlled and that collimation issues may not be too severe. The **hour glass effect** maybe different with and without crab crossing and **should be confirmed.**

Summary, Session III

Convenor: Edmond Ciapala

Prospects of Compact Crab Cavities for LHC
Peter McIntosh (CI)

The **motivation for crab cavities in LHC** was outlined; up to 3x (5x) increase in luminosity may be attainable. Between 3 and 7 MV deflecting voltage is needed. An overview of the necessary R&D for Phase 0 and 1 using elliptical cavities was given. With LHC bunch length of 7.55 cm, **800 MHz is just suitable, one module containing a two-cell BNL/SLAC elliptical cavity is required**. At 400 MHz, elliptical cavities are too large and alternative accelerating structures would be needed. This could be an option for Phase 2. A global crab scheme can be tested using the known design at 800 MHz. However **a local scheme with many cavities would require a new RF structure in order to fit into the tight IR regions**. In LHC IRs the spacing is only 20-25 cm.

For the **new structures** a short list of one or two designs needs to be made out of a number of proposals. **Six designs** were reviewed:

- FNAL mushroom cavity (N. Solyak)
- BNL offset TM₀₁₀ cavity (R. Calaga)
- SLAC spoke cavity (Z. Li)
- JLab rod cavity (H. Wang)
- SLAC half wave resonator (Z. Li)
- CI figure-8 cavity (G. Burt)

These designs exist only on paper and need to be further optimized and compared, looking at critical issues such as main and HOM coupler design, tuner design, fabrication processes and cryostat design. This is a longer term effort, but highly worthwhile if the requirements for a local scheme could be shown to be met. **Coordination is needed** to focus R&D for compact crab cavity design. **A decision on which of the structures to pursue must therefore be made soon**, ideally within one year. The following work would be on making and testing room temperature versions, moving on to a superconducting version and doing helium tests, construction of other components, and mounting in a cryostat for final tests. This is clearly a very long program of work, but could go on concurrently with elliptical cavity development for global test scheme, if resources were available.

Crab crossing concepts; some questions and remarks

F. Caspers, CERN.

The presumed need for perfect kick and return kick cancellation in crab schemes and risk of blow-up was questioned. Use of circular 1/2 ridged waveguide structure was proposed. Its suitability for SC technology would need study. The **use of an existing machine e.g. CERN-AD to do a test** was proposed. In this experiment the strip line kickers could be used to test the kick anti-kick principle and the associated emittance blowup. An **interesting proposal was the use of TM₀₁₀ cavities, operating at 200 MHz, providing simultaneously both longitudinal field and magnetic field for crabbing**. They could be fitted at LHC IP4 in the space reserved for the 200 MHz capture system.

Global Collaborations towards LHC Crab Cavity

J. P. Koutchouk, CERN.

Impetus has been gained due both to the recent **successful KEK cavity installation** and difficulties with other LHC upgrade proposals. Achieving the necessary **hardware reliability and robustness in operation** are important, as any overall loss of integrated luminosity obviously defeats the purpose of the crab scheme. Additionally machine study and commissioning time has to be reasonable, also the crab scheme must not preclude machine operation in non-crab mode. The obvious **advantage of luminosity leveling** is highly desired by the experiments. Therefore, the test of crab crossing is essential for future upgrades, especially to test the evolution of tail particles in the presence of imperfections.

CERN, KEK US-LARP, and FP7-EuCARD (Cockcroft institute and CERN) have all expressed interest in participating in the project. In particular, the UK FP7 proposal targets RF structure design as well as integration and system controls. It also specifies the relevant deliverables like warm model and related RF testing. It was noted that the ion program in the LHC and the LHeC (electron-proton) ring-ring collider proposal should also be considered with respect to crab crossing. As one of the outcomes, Jean-Pierre suggested **preparation of a comprehensive test scenario(s) for the prototype tests in the LHC which will be reviewed and certified by the several responsible CERN departments and management.**

Session 3, Discussion Issues:

- *Guidance to the CC collaboration and R&D effort that may be helpful to address specific CERN concerns.*

Specific CERN concerns on a crab scheme:

Full compliance of cavity and cryo systems **with CERN safety regulations** on mechanical design, cryogenics, cable types etc. is needed. A **full risk analysis** of the cryostat will be needed before installation. **Compatibility with existing infrastructures** is important to avoid time loss during installation and operation. The **crab system must be fully 'transparent' for beam operation** when not actually being used. The system needs to be fully operable by the control room. The **supply of 2K LHe to the system** is an important issue raised at this workshop. **Compatibility with requirements for other upgrade projects** (i.e. stronger inner triplets) should be looked at with cryogenics specialists.

- *How to provide periodic CERN input to R&D progress.*

A **CERN responsible should be designated in both CERN ABP and RF groups**, in addition to the overall CERN project manager.

- *If compact structures are available in the near future, will a local scheme be preferable for phase I and should it be pursued aggressively ?*

The **time scale for a local scheme** for phase one looks difficult.

- *Time line for compact cavity development and testing*

The **schedule for compact cavity selection, development and testing** would be of the order of five years at least. A tentative schedule can only be made once a design is validated.

- *Can we test compact cavities elsewhere ?*

and

6. How can future projects like LHeC, eRHIC, B-Factories benefit from the crab R&D for LHC upgrade (for example: similar constraints on RF structures, ...)?

Issues such as the testing of compact cavities in other machines and the benefits that could be available to other machines by upgrading with crab cavities remain to be explored in a future workshop.

Summary, Session IV

Convenor: Roland Garoby

The fourth session of the workshop was devoted to the analysis of the requirements to be satisfied by the Crab Cavity development and demonstration program. Three talks were given addressing issues concerning the RF equipment (T. Linnecar), the LHC exploitation (O. Bruning) and the CMS experiment (M. Nessi).

Inserting additional magnets close to the IP is a very difficult engineering challenge and it is likely to degrade the overall capability of the detector. This is why, among the three possible schemes envisaged today for increasing the LHC luminosity, **physicists strongly underline their preference for solutions using Crab Crossing**. The potential of easier luminosity leveling is also a highly appreciated bonus.

The validation test which will take place in 2012-2013 is the first step towards the implementation of any Crab Crossing scheme in the LHC. **Its goals must be precisely defined** and, while essential for demonstrating the principle of Crab Crossing in a hadrons' collider, **it shall have no detrimental effect on integrated luminosity in the ongoing experiments**. It is therefore mandatory to investigate all alternative options, like RHIC or the SPS. If LHC is confirmed as the only possible test-bed, very demanding requirements must be fulfilled:

- Hardware must be extensively tested before installation in the tunnel (need for a dedicated test stand),
- Installation and hardware commissioning must take place within the foreseen duration of the LHC shutdowns,
- Other upgrade options (e.g. implementation of the 200 MHz RF capture system) shall not be limited,
- LHC performance shall not be reduced, even if hardware fails (cavity trips, unavailability of the Crab Cavity system(s), ...).
- **A large enough effect on luminosity must be aimed at for the demonstration to be convincing. Setting the goal at ~+10% implies the installation of two crab cavities (global scheme with one cavity per ring)**. Not only the peak luminosity but also the integrated luminosity should be shown to benefit as expected.

An important concern to minimize time and effort for development is the specification, as soon as possible, of the basic parameters (frequency, geometry, operating temperature, ...) of the Crab Cavity system. As a matter of fact, **only 800 MHz elliptical cavities are presently advanced enough in design and test to be built and experimented on-time for the validation test**. The choice of that high frequency and the need to operate at high field in CW advocates for a low cooling temperature (2 K) which would have a large impact on the cost of the infrastructure. The possibility to operate at 4.5 K should therefore be analyzed very soon. To allow for a demonstration in 2012-2013 in the LHC, **a tentative schedule is proposed with a first milestone in April 2009 with answers to the requirements listed above (including the analysis of the use of another synchrotron as test-bed) and confirmation of the main hardware parameters. Validation of the detailed design could then proceed one year later (April 2010)**.

This schedule being very demanding, it is far from obvious that the equipment installed for the validation test will be matched to the needs of the final implementation of Crab Crossing in the LHC, and **it is cautious to advise the continuation of the R & D towards more compact**

cavities operating at lower frequency, aiming at the installation of an operational set-up in 2016-2017, simultaneously with Phase 2 of the IR upgrades.

The future operational Crab Cavity systems should therefore be directly designed for integration inside Phase 2 of the IR upgrades.