Summary of the first Crab Cavity Advisory Board Meeting on 18 September 2009

Present:

BEN-ZVI Ilan (BNL), BUTLER Joel (FNAL, CMS), DELAYEN Jean (JLAB), HOFFSTAETTER Georg (Cornell), JENSEN Erk (CERN), LEBRUN Philippe (CERN), NESSI Marzio (CERN, ATLAS), MYERS Steve (CERN, Chair), PREBYS Eric (FNAL, US-LARP), TSESMELIS Emmanuel (CERN), YAMAMOTO Akira (KEK) [*Advisory Board members*];

LEN L.K. (US-DOE) [*Guest*];

BRÜNING Oliver (CERN), CIAPALA Edmond (CERN), COLLIER Paul (CERN), FUNAKOSHI Yoshihiro (KEK), GIOVANNOZZI Massimo (CERN), KOUTCHOUK Jean-Pierre (CERN, EuCARD), McINTOSH Peter (STFC), PIERINI Paolo [*LHC-CC09 Session Conveners*];

CALAGA Rama (BNL, LARP), ZIMMERMANN Frank (CERN, EuCARD) [*LHC-CC09 Organizers*]

Excused:

CHATTOPADHYAY Swapan (Cockcroft Institute), RAUBENHEIMER Tor (SLAC), VIRDEE Jim (CERN, CMS) [*Advisory Board members*]

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Summary of Summaries
(**Steve Myers**)

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 focus** should be **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 ~106 (from ~105 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.**

Summary of Session I - Setting The Scene:

Jean-Pierre Koutchouk summarized the presentations of Frank Zimmermann, Marzio Nessi, Yoshihiro Funakoshi and Oliver Brüning, and the subsequent discussions.

For the upgrade the **crossing angle is bound to increase**, resulting in large luminosity loss due to the imperfect overlap of colliding bunches. **No beam dynamics show-stopper** has been found. **Luminosity leveling with the crossing angle** through crab cavities appears operationally simple and can increase the average luminosity. Crab cavities can be decoupled from other upgrade options.

The **upgrade of the experiments** is a major undertaking which must start now to be ready in 2018. The granularity of the detectors depends on the expected pileup. Luminosity leveling is very important for the experiments. The latter will support a full crab cavity solution. sLHC is presented as a block, involving several new machines, with possibilities of slippage in approval, planning and nominal performance. The scheduling and justification of the detector upgrade would benefit from some "**decoupling**". Given the presented complexity and ambition of the detector upgrade, a **forum joining detector and accelerator people** would be useful.

KEKB had long operated with 22 mrad crossing angle, without serious effect on synchro-betatron resonances. Since 2007 it operates with a **global CC scheme**. **Chromatic coupling**, specific to the CC optics (but not to the cavities), had reduced the performance until it was identified and corrected with skew sextupoles. A **beam-beam tune shift** of about 0.06 without CC's had been predicted to increase to 0.15 with CC. Presently the tune shift with crab cavities was about 0.09. The crab-cavity R&D had spanned 13 years. The crab cavities proved much more stable than anticipated. Still, on average there is one trip per day for HER, but 0 for the LER (from up to 25 in the beginning). The phase errors are much smaller than required. Puzzling coherent oscillations with beam-beam have been damped by an RF phase shift. The last opportunity for MD's with crab cavities may be this autumn. The brilliant success had required some time. The much improved trip rate of HER would still be problematic for SLHC.

Crab crossing is interesting for SLHC Phases I and II, and **compatible with ultimate beam parameters**. The original implementation plan encountered some issues, namely the proof of feasibility had been needed for 2010 (!) or 2014 (shutdown planning), but it would come too late. The MD time in LHC will be under heavy pressure. The crab cavities should **be transparent** when not used. CC's must be **compatible with machine protection and collimation** when used. It was debated whether crab cavities must not, or could, limit other upgrade options (200 MHz capture cavities or dampers). A test program must be able to provide clear conclusions on feasibility, benefits and absence of adverse effects for a LOCAL final system. A small anticipated increase of the luminosity by a global test scheme in LHC may not be a showstopper: the **beam-beam transfer function** measurement is indeed much more sensitive than luminosity counters.

In conclusion, the crab cavity option has a high potential in terms of performance and luminosity leveling. KEKB implementation demonstrates the feasibility and success for e- machines. It points as well to subtleties requiring time to be sorted out with so far lower performance than simulated, but all other upgrade options are facing similar challenges. The CC study is supported by the experimenters, who need as well a forum to discuss/decide on SLHC feasibility and options. The **planning for a feasibility test appears extremely tight in the present SLHC planning**. Whatever can be done not using LHC should be done, but the assessment of feasibility requires the LHC.

Summary of Session II – Layout & Design:

Yoshihiro Funakoshi summarized the presentations of Riccardo de Maria, Yipeng Sun (2), and Rogelio Tomas, and the subsequent discussions.

Operational scenarios and optics design for an **LHC test** (phase-I), with a **global crab cavity**, were presented, including anti-squeeze in IR4. During injection and ramp the crab cavity should be transparent. The required crab-cavity voltage can be reduced either by increase beta at the crab cavity (anti-squeeze) or by moving the tune towards the integer. The anti-squeeze in IR4 is designed for 7 TeV. It leaves the phase advance across the IR constant (no, or minimum, effect on global chromatic correction and tune). The **LHC optics can fulfill the requirements for a global crab cavity** (test). Impact on dynamic aperture, z-dependent beta beating, emittance growth during crab-cavity ramp, and degradation of collimation efficiency all look acceptable. Important synchrobetatron resonances driven by the crossing angle are suppressed. Luminosity gain in a test can be as large as 25% for a single crab cavity (on beam only) and a reduced emittance.

A **beam-beam driven noise instability** has been observed **at KEKB**. The instability occurs if noise is injected inside the continuum frequency spectrum of the beam, between sigma and pi mode, at phase modulation amplitudes larger than 0.03-0.2 degrees, leading to an abrupt luminosity loss for noise amplitudes, corresponding to a beam motion of 0.02 sigma at the IP, in excellent agreement with simulations. At KEKB, the measured "**crab dispersion**" and the model prediction are also in nearly perfect agreement.

The **use of crab cavities for off-momentum cleaning** has been proposed by Stephane Fartoukh. 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. 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 2.4 GHz).

Summary of Session III – Cavity Design:

Jean Delayen summarized presentations by Elena Shaposhnikova, Kota Nakanishi, Zenghai Li, Jean Delayen, and Erk Jensen, as well as the subsequent discussions.

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

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**. 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.

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 polarise 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 an improved modification of an existing CEBAF 2-rod separator 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.

Designs for compact LHC crab cavities with **parallel bar geometry ("toaster" shape)** have been presented from JLAB for both 400 and 800 MHz. A list of cavity properties has been presented. 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.

In **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 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.

Summary of Session IV - Cryomodule Design:

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 beamline 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 (cooldown/warmup) will be needed to assess the design; and a module test stand is definitely needed.

Summary of Session V - Crab Cavity Integration:

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

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 of Session VI – Cryomodule Construction:

Peter McIntosh summarized the presentations of Ilan Ben-Zvi, Kota Nakanishi, and Pierre Maesen, as well as the subsequent discussions on cavity down selection and cryo-module design.
For the prototype cavity fabrication there is an **SBIR**, whose collaborators are AES, BNL, LBL, and SLAC. The **Phase I – approved**! - is dedicated to a preliminary cavity design. **Phase II** will include a complete **mechanical design, the fabrication, and testing**. This would be a 2-year project, with a maximum funding of 750 k$. The plan for cavity engineering development by AES was detailed. **AES has substantial infrastructure for SRF cavity production** and is building up more.
Concerning the **down selection,** the most critical issue is to make a timely decision (now). 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. The UK design does look quite elegant as long as we can successfully get the irises in the cavity cells. The LARP design does have more bits and pieces, but taken separately we have done them all before. At this point the **LHC-CC strategy at CERN should drive the down select**.
The **cavity coupler treatment and tests for the KEKB crab cavities** were described, including fabrication process and conditioning, as well as the **preparation of the coupler**.
The possible **assembly and test of LHC crab cavities in SM18** have been examined. Transport is a critical issue, as is the bogie system needed for the cryomodule assembly in a cleanroom. There is limited cryogens availability for SC serial tests. The **cryoplant must be upgraded if 2-K operation is required for the LHC-CC tests**. The 400 MHz test stand must be kept in good shape over the LHC life time. The LHC-CC cryomodule tests would have to share the LHC horizontal test stand.

Crab cavities installed in Phase I should not perturb LHC operation ("transparency" to be demonstrated). The consensus of this session was to **focus the CC designs on the compact structures, and to put on hold elliptical CC development**.

Summary of Session VII – Phase I, Validation:

Massimo Giovannozzi summarized the presentations of Andrew Butterwoth, Jörg Wenninger, and Stefano Redaelli on behalf of Ralph Assmann, as well as the subsequent discussions.

Power system commissioning procedures will be well known if an already existing power source is used (SPS type 800 MHz). Controls and application software should be based on standard CERN controls infrastructure. LHC low-level electronics has built-in conditioning and diagnostics facilities, and is already well integrated into the control system. Powerful tools are being developed for **LLRF setting-up** which could equally be applied to the crab-cavity system. New automated tools using MATLAB (collaboration with SLAC) will save a lot of time. Typical conditioning time to full power and voltage for an LHC cavity was a few days to 1 week.

Between the detection of a failure and the firing of the LHC beam dump a delay of up to 3 turns can occur (270 microseconds). The shortest failure detection time is 40 microsecond (1/2 turn), from BLM system and experiment detectors. Possible crab-cavity failure modes include cavity trips, cavity phase changes or jumps, and "controlled" cavity voltage changes. In case of a crab cavity failure with a rapid 90 degrees phase shift, a betatron oscillation of 2-3 sigma amplitude is induced. It is feared that **relevant cavity failures can occur from one turn to the next**. If confirmed, this could make **protection against crab cavity failures** very difficult.

Installing a global crab cavity in IR4 was meant as a demonstration experiment with the goals to show that crab cavities do not disturb the beam, and that the predicted gain is really achieved. Some price is to be paid for a global scheme, namely a small degradation of the cleaning efficiency. Intensity should be minimized for beam tests, for which there are three categories: 1. Beam tests before installation of the IR4 crab cavity, 2. Beam tests after installation of the IR4 crab cavity, before squeeze and with low intensity, and 3. Beam tests with crab cavity in collision. Machine changes are a bigger worry than measuring the luminosity at the few % level.

In **conclusion**, the **RF can re-use major hardware/tools/procedures from the commissioning of other systems**. With regard to machine protection system, there is the **potential danger of single-turn CC failure**, which is to be addressed in detail. Data from KEKB CC trips might be useful in this regard. For safe beam tests, a systematic set of beam measurements is proposed. Luminosity measurement seems particularly challenging for hadron machines (extrapolation from Lepton machines not completely appropriate). Beam-beam transfer function measurements should help. A **list of key instruments/techniques required** is needed.

Summary of Session VIII – Phase II, Strategy:

Oliver Brüning summarized the presentations of Rama Calaga, Ranko Ostojic, and Stefano Redaelli, as well as the subsequent discussions.

Upgrade options at the beam-beam limit are 1) keep β^* and N/ε constant [requires controlled ε blow up at top energy], 2) keep ε constant and increase N with 1/R [LPA] – the options 1) and 2) imply larger than ultimate beam currents and brightness! 3) keep N constant and vary ε as R (referred to as small emittance scheme) which requires a smaller than nominal emittance, and 4) compensate R at IP and minimize β^* - this is compatible with ultimate beam parameters. The best strategy can only be known after gaining some operational experience. All options require larger triplet aperture and radiation hardness. **All but the last option require higher performance injector complex, leading to higher beam intensities, tighter collimation requirements, higher radiation levels and machine protection issues. The last option (4) requires crab cavities (it is the only option for Phase II upgrade with ultimate beam intensities).** Apart from the last arguments, the option CC 'only' offers the added value of **luminosity leveling**.

There are **three crab cavity scenarios for SLHC phase II**: global cavities in IR4, global cavities in IR4 and elsewhere in the ring, and local cavities. Local schemes have many advantages (e.g. rest of the ring is undisturbed, lower crab voltage, less impact on collimation), but require a larger number of cavities, and face the small beam-to-beam driving the quest for compact cavities. An extension of the IR4 dogleg might provide the space required for global crab cavities. A **moderate dogleg in the IRs of Point 1 and 5** could increase the available space so that many of the proposed compact cavity designs would fit. The maximum separation is within reach of conventional technology (for VV crossing). A draft IR optics with 25 cm beta* and two additional dogleg dipoles was presented. Luminosity leveling possibilities were illustrated.
Crab-cavity infrastructure requirements should be kept in mind for all other LHC upgrade projects. Local elliptical CC scheme implies larger dispersion at the cavity. Significant dispersion in crab cavities is claimed not to be an issue - machine tests? Compact crab cavities for local scheme eliminate need for dogleg insertion in IR1 and IR5 (if sufficiently compact), which motivates more support for compact CC R&D (even at the expense of CC development for a Phase-I CC tests).
The **goals and scope of the SLHC phase-I upgrade** were reviewed. Constraints include accessibility and maintenance: All electronics equipment for the triplets should be located in low-radiation areas. There are severe space constraints around IP1 and IP5 for any new equipment. New magnets must be similar in size to the LHC main dipole. Upgrade implementation will happen during the extended shutdown. Some parameters for the separation dipoles in the Phase-II crab-cavity draft optics are beyond the state of the art. Three of the four magnets should be weakened and lengthened.
Any new equipment in IR1 and IR5 (CC and separation dipoles) must conform in size with the **transport zone**.The phase-2 triplets will require **new cryogenic plants in IR1 and IR5**. Additional requirements from CC and separation dipoles need to be developed to optimize their design. It seems that additional tunnel alcoves in IR1 and IR5 for Phase-2 cryogenics and machine equipment (and moving power convertors from the RRs) are unavoidable.
The LHC beam **commissioning procedures** will need to be amended to include crab cavities. A number of steps are affected. A low-risk beam test with crab cavities could be performed with collisions at lower energy and/or using an anti-crab to decrease the luminosity at top energy without crossing. A detailed commissioning and operation planning was sketched, which will help in identifying potential conflicts with existing operation procedure, and in identifying beam instrumentation requirements and potential upgrades of the nominal LHC instrumentation The proposal to a low risk 'negative' demonstration of the CC functionality sounds promising and should be studied in more detail.
In conclusions, **crab cavities** are strictly speaking only required for one of the LHC Phase-2 upgrade options. But this is the **only option that provides Phase 2 performance levels with 'only' ultimate beam parameters**. Oliver Brüning recommends keeping this option alive until we know intensity limitations in the LHC. A justification based on luminosity leveling is not sufficient. The possibility of leveling is a nice side effect but can hardly justify the investment. The **support for compact crab-cavity R&D seems well justified**. A **dedicated test stand** may need to be developed. A phase 0 test in the LHC may not be strictly required in view of the **KEK results** (test in other machines?). The '**negative test'** proposal seems interesting.

Summary of Session IX – Planning & Milestones, Down Selection:

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 detector 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 programme 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.

The following comments have been received after the workshop.

Comments from Philippe Lebrun:

1. Given the number and variety of teams working on this topic (as well as the competition with other research topics in resource-limited programs, e.g. US-LARP or EuCARD), I believe it is very important that CERN makes **a clear statement on the importance of CC for the LHC lumi upgrade**, including the possibility (commitment?) of making beam tests in a proton machine.

2. The baseline scenario presented consisted of a validation test on a "global" scheme with CC at IP4, and a final "local" scheme with CCs at IP1 and IP5. Following the presentations and discussions in the workshop, it is not so clear that this is the way to go, since there seem to be difficult machine protection issues to solve, particularly with local schemes. Moreover, due to the limited beam separation, the "natural* place to put RF cavities in the LHC is IP4, and I guess one should aim at optimal use of this space (i.e. strictly reserving the 420 mm beam separation space for components with large transverse dimensions) rather than planning complex, costly and possibly risky beam separation schemes around the physics IPs. Consequently, one should also study the feasibility of **a global scheme for luminosity physics runs**, which would be installed in IP4 (or in a modified IP4), where the radial space would permit the use of elliptical SC RF cavities (which took some 20 years to develop). Studying the **consequences of cavity trips on machine protection** is of paramount importance for both local and global schemes. In parallel with this approach, and given i) the local scheme as present reference solution pending the study of a global scheme and ii) the long lead times in SC cavity development, one should also pursue the study of **"sub-compact" SC RF cavities, i.e. compatible with a beam separation of 194 mm.**

Comments and suggestions on the strategy for crab crossing in LHC from Jean-Pierre Koutchouk:

1) **Potential of crab crossing**:
   It does not seem arguable that crab crossing, if feasible, is a very interesting option for the luminosity upgrade that ought to be pursued vigorously.
2) **Where are the challenges?**
   There are two distinct series of challenges:
   - **Beam dynamics and operations**: crab crossing has never been tried in a **hadron collider** and only once in an electron collider, where it took two years to observe an improvement in performance, still rather modest. In the LHC, the challenge is much larger, relating to the absence of synchrotron damping with the resulting higher requirements on the RF noise level, and the subtle interactions of crab crossing with collimation.
   - As compared to KEKB, LHC requires **compact crab cavities**, ideally made compatible with the nominal LHC beam separation, with very low **noise level** and a **trip rate** much lower than achieved in the KEKB HER.
3) **Suggestions on how to face these challenges**
   - An **official statement by CERN on the high interest** of studying the feasibility of crab crossing is essential for the motivation and funding of collaborating institutes and LHC experimenters. This has been missing and is probably the **top priority** before any other scientific/technical consideration.
   - Obviously, the second priority would be to **clarify the possible show stopper** (incompatibility with machine protection) that came up in the workshop.
   - The **space requirement for a test global scheme in the LHC IR4** should be studied and resolved. If the former potential show-stopper issue can be solved, an implementation plan for releasing the required space should be the third priority at CERN. An increase of the length of IR4 is one possibility to be studied, possibly using the strength safety margin between “nominal” and “ultimate” implemented in the magnets.
   - Given the very tight schedule that requires the **development of sophisticated super-conducting cavities** significantly faster than achieved for LEP and KEKB, the **two main challenges** mentioned in section 2 should not be entangled, but be **addressed in parallel.**
   - For the beam dynamics challenge, the **installation of the KEKB crab cavity in the SPS is a useful first step, but cannot replace a test in the LHC**, as it will miss the key issue of operation compatibility with collimation. It will not allow the identification of side-effects of the type that plagued KEKB for two years.
   - Given the large number of partners interested, a strategy could be that the partners **best prepared for the implementation of elliptic cavities** with minimized technological unknowns **prepare a cavity for the test in IR4**, thereby **disentangling as much as possible the beam dynamics from the crab cavity issues**. This approach could have the advantage of testing as well the suitability of a global scheme as a simplified LHC upgrade.
   - With this “separation of variables”, the **other partners could concentrate on the most challenging design of crab cavities** compatible with the nominal beam spacing with the goal of suppressing the need for the great complication (if feasible) of local doglegs.
   - **Two feasibility reports** could be scheduled, corresponding to the two points of section 2.

Unofficial Comments from Rama Calaga:

1. Feasibility of SPS tests
a. KEK-B cavities (start with a table of parameters for both RF and beam)
b. 400 or 800 MHz LHC cavities in the SPS (place and environmental constraints)

2. Extension of IR4
Do we have any aperture limitations to extend the space by say 10-15 m ? Can we do it with current dipoles or which extra dipoles would be needed (assuming the nominal optics for now)?
Fallback option: Also find out what is the equipment in between the current dipole doglegs, this will give us constraints on space and hence transverse separation.

Unofficial Comment from Massimo Giovannozzi:

Three options for IR4 modifications

1) Rigid displacement of D3-D4 block
2) Move D3 towards D4
3) Installing crab cavities in the dogleg region

Start of a detailed assessment; details not included here.

Comments from Eric Prebys:

As requested, I'm writing to summarize my impressions and recommendations from the recent CC09 review at CERN. For reasons that will become apparent, we were not able to precisely address the charges of the review. Nevertheless, I feel that important decisions were made and the meeting was very beneficial overall.

I will divide my comments into "findings" and "recommendations". I will flag some of the latter as "action items", meaning that they should be given a fairly high near term priority, as they may significantly impact future plans.

Findings

1) The scientific case for the installation of crab cavities has gotten quite strong. Of the solutions proposed for Phase II, this is arguably the most attractive to the experiments, because it is less invasive than the early separation scheme, has less event multiplicity than the LPA scheme, and doesn't rely on the complete success of the SPL/PS2 program like the low emittance scheme. Italso provides a straightforward method to level the luminosity.
2) Recent results from KEK have unambiguously demonstrated the success of crab cavities as a method for increasing luminosity. This has significantly increased confidence in the technology; however, questions remain as to their effectiveness in a proton machine.
3) The cavity designs presented fall into two classes: "traditional" two cell elliptical cavities designed to operate at 800 MHz and "compact" cavities designed to operate at 400 MHz.
4) All of the elliptical designs are at a point where one could arguably do a down-select from among them, while the compact designs need more R&D before one could confidently make such a decision.
5) Around most of the ring, the beams are separated by 19 cm. This is too small to accommodate any of the designs, with the *possible* exception of a compact cavity designed for 800 MHz.

6) In IR4, a dogleg system increases the separation to 42 cm, which is enough to accommodate any of the designs. For this reason, a “Phase I” test has been proposed, in which one or two elliptical 800 MHz cavities are installed in this area during the shutdown for the Phase I luminosity upgrade – nominally in 2013. This would test the effect of the crab cavity on the proton beam, as well as allow us to study a global crabbing scheme, possibly increasing luminosity.
7) The IR4 region is currently reserved for the potential installation of 200 MHz capture cavities and transverse dampers during that same period.
8) A conceptual design exists to put doglegs in the design of the Phase II interaction insertions at IR1 and IR5, which will increase the beam separation to 27 cm – enough to allow at least some of the compact designs at 400 MHz. This would allow a completely local scheme in which the effect of the cavities is restricted to the region around the interaction point.
9) The infrastructure to support crab cavities at IR1 and IR5 will require a slight increase to the civil construction already necessary to support the overall Phase II upgrade in these areas.
10) Both the local and global schemes have implications for machine safety which have not been fully investigated.

Recommendations

1) CERN is encouraged to issue an unambiguous statement supporting the development of crab cavities as part of the Phase II luminosity upgrade, provided it is established that they can be operated without endangering the accelerator or detectors.
2) Work on the 800 MHz elliptical cavities and the Phase I test should be suspended and resources should be focused on the development of compact cavities for the Phase II upgrade.
3) The crab cavity group should develop a clear set of design criteria against which the designs will be evaluated.
4) **[action item]** The safety of the cavity should be investigated under both global and local scenarios. The consequences of cavity failure and phase shift should be considered and mitigation measures proposed.
5) **[action item]** An investigation should be made into the possibility of modifying IR4 to permanently accommodate crab cavities after the Phase I upgrade.
6) If the previously described modification is feasible, the option of a later test in that area, and perhaps even a global scheme based on elliptical cavities, should be reconsidered.
7) Crab cavity plans should be integrated into the overall Phase II upgrade plans, particular where civil construction is concerned.
8) **[action item]** The feasibility of a test involving the KEK crab cavity in the SPS, or possibly the Tevatron, should be investigated.
9) **[action item]** In spite of the fact that the Phase I test has been cancelled, a recommendation should be made with regard to the 800 MHz elliptical cavities, so that the labs which have been working on them have some guidance as to how to proceed. The format of the meeting did not really lend itself to an effective discussion of this issue, so perhaps a panel could be convened in the near future to address just the 800 MHz down selection. *This panel should not include people directly involved with any of the proposals.*

Comments from Emmanuel Tsesmelis:

As a general observation, the crab cavity solution minimizes the interference with the detectors and the experiments support such a solution.

Both ATLAS and CMS are planning a major upgrade of their Pixel detectors prior for the LHC Phase 1 upgrade. Details of this are being worked-out and should be co-ordinated with the shutdown required for the LHC machine upgrade.

Major modifications are required for the ATLAS LAr Forward Calorimeters prior to the LHC Phase II upgrade. This work would require a long shutdown of about 15 months to complete and should be co-ordinated with the shutdown required for the LHC machine upgrade.

Moreover, both ATLAS and CMS are planning a major upgrade of their Inner Tracking Detectors prior to the LHC Phase II upgrade. This will require a substantial shutdown of about 18 months for in situ installation and integration and should be co-ordinated with the shutdown required for the LHC machine upgrade.

The forward radiation shielding at Point 1 and Point 5 will need to be re-designed given the new large-aperture inner triplets. This includes a new TAS absorber. Background to the detector muon spectrometers resulting from the new radiation shielding in this region will need to be carefully calculated and controlled. To this end, liaison between the machine groups and the experiments is mandatory to ensure an effective design of this interface region.

A new all-beryllium experimental beampipe will be requested by the experiments prior to going to Phase II. The design of such a beampipe has already started in TE Department and should continue there with close links to the experiments.

There is a need to develop a plan for the evolution of both integrated and instantaneous luminosities. These two parameters need to be optimized. The number of pile-up events in the detectors is dominated by the instantaneous luminosity while the radiation dose to the detectors is dominated by the integrated luminosity. It would be of interest to study the attained integrated luminosity by running at an instantaneous luminosity of less than 10^{35} cm^{-2} s^{-1} and with luminosity leveling. A peak luminosity of 10^{35} cm^{-2} s^{-1} will complicate the construction of the upgraded detectors. Luminosity leveling at around 4 10^{34} cm-2 s-1 might be a good option if it can deliver 300-400 fb^{-1} per year.

In order to continue the deliberations between the machine groups and the experiments, a joint forum to discuss issues at the interface for the LHC upgrade should be set up. In addition to discussing technical solutions, the schedules and operation plans should also be reviewed.

Proposed ACTIONS:

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

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Reported by **Frank Zimmermann**