Abstract
200 MHz capture cavities and feedback system upgrades are presented, with criteria for identifying upgrade needs and lead-times for taking decisions on the upgrades options and for preparing Crab cavity installations in IR4.

200 MHZ RF IN LHC – BACKGROUND & HISTORY
200 MHz systems have been planned from an early stage in LHC [1]. An original proposal was for a longitudinal feedback system (ADL). It made use of four cavities per beam, with a total voltage of 225 kV. For ultimate beam intensity a total of 250 kW was needed, allowing use of a single 60kW tetrode amplifier per cavity. The ADL was later considered unnecessary as the natural spread in synchrotron frequency inside the bunch was considered sufficient to damp single bunch instabilities. The estimated cost was 5.2 MCHF. Before the SPS impedance reduction program the emittance of the extracted LHC bunch exceeded 1.0 eVs; this could not be fully captured in the ACS 400 MHz LHC RF system. Two solutions were envisaged. Firstly a passive 400 MHz single-cavity SC RF system in the SPS, operating in a detuned mode such that the bunch would be shortened by variation in cavity impedance across its length [2]. A prototype was installed and tested in the SPS but was found to be difficult to handle operationally.

The second solution was to install a low-frequency 200 MHz capture system in the LHC (ACN). This proposal [3] dates from 1998. The purpose was to improve capture, and minimize losses for large emittance beams from SPS with large injection errors. These were estimated at up to 1eVs and ±50 MeV and ±15° respectively. The system comprises four normal conducting cavities per beam, with 3 MV total per beam, requiring 240 kW per cavity at ultimate LHC beam intensity. This cost was 13.9 MCHF, considerably more than the original ADL. With the 2001 budget crises and the need to save on LHC construction costs, a proposal was made to initially install only half of the ACS and half of the ACN, which would be adequate up to half-nominal intensity. However completion of the very successful impedance reduction program in the SPS resulted in 0.6 eVs emittance being obtained up to nominal intensity, and even above. The decision was therefore taken to install all the ACS, and postpone 200MHz ACN till later, once it would be found necessary.

ACN 200 MHZ RF CAVITIES IN LHC
The design is based on the SPS 200 MHz Standing Wave Cavities (SWC) used in the SPS to accelerate leptons during the LEP era. The nominal frequency is 200.210 MHz. The main design constraints were reduced diameter due to 420 mm beam separation, and keeping HOM frequencies away from multiples of the 40 MHz bunch frequency. This resulted in slightly higher shunt impedance and lower Q than for the SPS SWC. With R/Q 192 Ω and Qo of 30,000 the power dissipated in the cavity at nominal field of 0.75 MV is 49 kW. The design called for special cooling channels to evacuate the high power. For optimum operation the coupler Qext was taken as 5000, giving an impedance of 960 kΩ. With a maximum of 1 MV for nominal 0.58 mA beam current the RF power needed is around 250 kW; this allows handling of the expected injection transients [4]. Simulation of capture [5] confirms that emittances of up to 1 eVs can be handled.

The cavity has four Higher Order Mode (HOM) couplers, a high average power main coupler, a piston tuner and two passive damper loops (to be brought in after capture or in coast)

Figure 1: 200MHz ACN Cavity
Eight bare cavities were built by Ettore Zanon, Italy. All had been RF tested at low power and accepted by the end of 2003 [6]. They are presently in storage under dry nitrogen. They have not yet been fitted with the auxiliary components and have not seen any RF power.

ACN AUXILIARY CAVITY COMPONENTS
The (HOM) couplers, tuner (200 kHz range), and the two fundamental mode dampers were recuperated from the SPS SWC cavities and refurbished. The HOM couplers may need tuning for the 50/75 ns bunch spacings in LHC. A new power coupler, based on the new SPS TWC one is proposed. A low power version has been built to validate the geometry. To handle the high power the new design needs a special capacitive coupling loop
without DC contact and separate water cooling of the body, inner coaxial line and the coupling loop.

The low power tests have proven feasibility of the design but it needs to be finalized and a prototype tested. For this, and for final production, a 200 MHz 500 kW test stand is planned in BB3 where the diacrode tests for SPS upgrade are to be based.

**ACN 200 MHZ POWER PLANT**

The RF drive chain is as in the PS and SPS 200 MHz tetrode power systems. The final amplifier design is based on RS2058 tetrodes as for the original SPS SWC200. There are 25 remaining amplifiers from SPS and 30 more would be needed. The final amplifier combiner arrangement is as in the SPS TWC200 power plant.

![Figure 2: ACN Power Layout – Tetrode Option.](image)

A circulator prevents reflected power going back to the final stage. A prototype circulator has already been obtained. The power loads are the same as SPS 200, but need to be constructed. New Power Converters will be needed as the old SPS ones have been used to repair other systems or are needed for spares.

An interesting development would be the use of diacrod es instead if tetrodes. A single diacrode could replace the four tetrodes in the output stage. A layout is shown in Figure 3. Diacrod es are not yet generally available, but a diacrode study will start in 2010 for the SPS200 TWC upgrade and in the context of TIARA as collaboration with the Muon Initial Cooling Experiment (MICE). The diacrode approach eliminates the complex combiners arrangement and has operational advantages. With less power devices it promises reduced maintenance. On the other hand the redundancy of a multi device system is lost. The diacrode itself is more expensive, being designed for a higher power level. The diacrode also needs a completely new power converter, since 35 kV is required instead of the 12 kV for a tetrode.

![Figure 3: ACN Power Layout – Diacrode Option.](image)

**ACN LOW LEVEL RF AND CONTROLS**

Each cavity will need a cavity loops and tuning control system. This will be of almost the same complexity as the ACS SC cavities. There will be no need for the ‘Polar Loops’ of the ACS which are needed to remove klystron ripple, but similar RF feedbacks, tuner control, longitudinal damper, function generators and remote control facilities will all be required. Incorporation of the ACN into the beam control system of SR4 would be relatively straightforward.

**ACN INTEGRATION AT IR4**

The cavities would be installed in the reserved space between the dampers and the synchrotron light monitors,
the four Beam 1 cavities on the left hand side of IR4 and the four for beam 2 on the right. Figure 4 shows the layout on the left hand side. The power amplifiers are installed in the UL44/46 tunnels. Feedback electronics are installed close to the power system, in shielded units, since there is no space in UX45 for additional Faraday cages. Incorporation of the ACN into the beam control system of SR4 would be relatively straightforward. Equipment controls would be located in UX45 and SR4.

COST ESTIMATES

Table 1 shows overall cost, assuming the baseline tetrode power option. Recovered material including tetrodes constitutes a part of the total. A rough estimate for the additional cost with the diacrode option is around 750 kCHF, which would make an estimated total cost for this option of just over 14 MCHF.

<table>
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<th>Item</th>
<th>For LHC</th>
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<th>Buy Tot.</th>
<th>kCHF Unit</th>
<th>kCHF Total</th>
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</tr>
<tr>
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<td></td>
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<tr>
<td>Other tetrodes</td>
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<td></td>
<td></td>
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Table 1: ACN Costing (Tetrode Option)

ACN INSTALLATION PLANNING

Figure 5 shows a tentative overall planning of the various activities needed to prepare and install the ACN system. It includes preparation of cavities and RF components, construction of a test stand, prototyping (for the diacrode option), construction of power amplifiers, then installation of all equipment in the LHC. The installation work in the machine is scheduled across three normal end-of-year shutdowns. This would need to be modified for the recently proposed two-year LHC operation cycle. The overall time needed is just over four years from the time of making the decision to install.

ADT UPGRADE NEEDS

In case of lack of kick strength, due for example to large injection oscillations, the options would be:

1) To push system to its limits, +40% could be feasible in pulsed mode, but reliability may be compromised
2) Increase the beta functions at kickers; this would need to be studied.
3) Install additional kickers in IR4. Space is reserved to install one extra kicker module per plane per beam, bringing this from two to three, giving an extra 50% in kick strength. This would cost around 4 MCHF.

In case of large instability growth rates due to large impedance at higher frequency, e.g. from collimators, the present 20 MHz bandwidth could be increased with new amplifiers and new matched strip line kickers. If significantly more bandwidth were needed, e.g. for electron cloud or TMCI, a completely new dedicated high-frequency system could be installed in the reserved space, complementing the existing systems. This is part of ongoing SPS studies on ecloud and feedback systems. Completely new signal processing electronics, kickers and power amplifiers would be needed, requiring special developments and certainly incurring long lead times.

CRYOGENICS UPGRADES IN IR4

Cryo upgrade needs have recently been presented [7]. An upgrade is definitely needed for the Phase 2 10x luminosity upgrade, to supply the inner triplet at IR5. It is not considered needed for the IR upgrade Phase 1 (2x in luminosity), unless there are larger dynamic losses than presently expected, due e.g. to electron cloud. The performance of the cryogenics will be monitored with increasing beam intensity during the 2010 run. For nominal RF, running with gradients approaching 8 MV/m, the RF load is 270 W to 430 W/sector. At the limit, pushing for higher gradients (50% more) on the SC cavities is still within the allowed capacity. However IR4 is critical, supplying RF and magnets. The layout of an upgrade is still needs study, as does its integration in UX45. It would take two years to prepare the upgrade, and several months to install and to commission. It may be possible to gain knowledge of electron cloud heat load (extrapolation) by the end of 2012.

Nevertheless it can also be noted that independent cryo in IR4 would be a major operational advantage for RF.

Cryb cavity requirements are still expected to be within the present IR4 cryo capacity. Only simple modifications to the QRL RF service module and the RF extension are needed to connect the crab cavity. [8] See below.

ACN REVIEW

Ultimate intensity could be captured successfully directly in the ACS 400 MHz, if SPS emittance can be kept to 0.6 eVs. This is being pursued in an SPS 200 MHz TWC upgrade proposal [9]. It would reduce beam loading, giving higher voltage hence shorter bunches. From 2009 experience, LHC injection seems stable. It appears that LHC injection phase errors...
Figure 5: Tentative Planning for ACN Fabrication and Installation

Vary slowly and can be tracked and corrected pulse-to-pulse. Tests are planned in 2010.

The ACN system is technically feasible. Bare cavities plus tuners and major components are available but much remains to be done, notably on power couplers and the high power system. The system would certainly be costly to construct and maintain; it would be two new additional and substantial high power RF systems in LHC, with the increased operational complexity. The system needs to either remain on continuously with feedback, or passively damped after injection. There is also increased impedance. Finally beam still needs to be transferred to the 400 MHz RF system at end of filling; if there is there is any dilution in 200 MHz bucket over a prolonged LHC filling time, lossy transfer and ghost bunches could result on the transfer into the 400 MHz bucket.

Furthermore, like ACS, good performance will not be easily achieved above ultimate, due to beam loading and RF power limitations in the presence of transients.

With present beam experience, however it is not possible to discount the need for the ACN. Work must therefore continue to prepare for an eventual installation in a defined time, once the need is confirmed. Beam behaviour in will be analysed in 2010 and 2011 to help get to a final decision.

CRAB CAVITY IN IR4

After the LHC-CC09, 3rd LHC Crab Cavity Workshop strongly renewed interest was focused on this option to increase LHC luminosity. The outcome of the workshop was that a new design of compact SC crab cavity would be the best long-term option. The first test would nevertheless be with a global scheme in IR4. It was established however that this could not be installed in time to fit the current Phase 1 upgrade, planned for 2015, and would have to be at a later date. Installation would be in either of the reserved spaces for ACN or additional ADT. [10] The cryo upgrade proposed [8] is relatively straightforward and could be installed during a shutdown of only a few weeks.

800 MHZ IN LHC

Higher harmonic Landau cavities have frequently been installed in high energy proton machines, e.g. ISR, SPS, and RHIC, making dramatic improvements in longitudinal stability. They can be used in bunch lengthening or shortening mode, depending on their phasing with respect to the main RF system. A higher harmonic cavity introduces a spread in synchrotron frequency inside the bunch. Bunch stability thresholds depend on both energy spread and synchrotron frequency spread; a harmonic cavity is a preferred alternative to emittance blow up in presence of instabilities. In LHC there is the possibility of bunch instabilities from impedances at frequencies outside the range of cavity feedbacks. These may pose limitations as we go to higher intensities.
A study has been done on a 1.2 GHz higher harmonic system [11] with three SC cavities per beam, providing ~3 MV total. An 800 MHz system, with relaxed requirements on HOM coupler and power coupler design, has also been considered. This would need extensive studies and R&D on cavities, couplers and HOM couplers. The time scale would certainly be beyond 2014/15. Time and effort must be invested in a preliminary study.

CONCLUSIONS

The baseline planned upgrades in IR4 have been presented, i.e. ACN installation, possible ADT upgrades and Cryogenics upgrade. Crab cavity installation in IR4 depends on a decision to free either the spare ADT or ACN space reservations. The 200 MHz upgrade in SPS emerges as having a significant potential benefit for LHC, and may well be higher priority than the ACN. The SPS RF upgrade proposal will be further elaborated to confirm this. The higher harmonic system for LHC must also be studied and a conceptual design proposal made.

Cryogenics upgrade may not be strictly necessary for the Phase 1 IR upgrade, but it would bring significant advantages for RF operation and will ultimately be needed in any case for Phase 2. The proposal and layout must be studied.

Work on all the proposed upgrades will need to continue, up to the point where beam experience allows final priorities to be set. Beam performance will be closely followed during the long 2010/2011 running period.

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REFERENCES