Status of the LHCb upgrade

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1 Introduction

With the Letter of Intent (LoI) for the LHCb upgrade [1], submitted in March 2011, the collaboration declared its interest in upgrading the detector to 40 MHz readout with a highly flexible software-based trigger. Following recommendation by the LHCC to proceed to the Technical Design Reports (TDRs), a Framework TDR for the LHCb upgrade [2] has been submitted in May 2012 and was endorsed by the committee in September. In its November 2012 session, the CERN Research Board approved the upgrade of LHCb to be part of the long-term exploitation of the LHC.

The physics programme of the LHCb upgrade has also been endorsed in the draft of the updated European Strategy for Particle Physics. It provides improvement in sensitivity of more than an order of magnitude for most key flavour physics observables compared to what has been achieved by LHCb to date. This will provide the most thorough survey of potential effects of physics beyond the Standard Model, in particular with several observables that have tiny theoretical uncertainty, such as the unitarity triangle angle γ, and CP violation effects in oscillations of neutral charm and beauty mesons, and rare B meson decays to dimuons.

The LHCb sub-systems are progressing well with R&D and are currently undergoing several reviews with the aim to decide among the various technological options. Following the completion of the R&D phase, the remaining choices of baseline technology will be made in time for the sub-system TDRs, scheduled for the second half of 2013. Future subsystem MoUs will be submitted, once the corresponding TDRs will have completed their approval process. The overall timescale sees installation of the upgraded experiment in the second long shutdown (LS2) of the LHC in 2018, to be ready for data taking in 2019.

In the following we give an update on the R&D activities and the status of the various technological options for the tracking and particle identification detectors. We further review the status of track reconstruction and data processing, as well as the progress in preparing for the LHCb upgrade in terms of interaction with the LHC machine groups, infrastructure, schedule and funding.

2 Tracking system upgrade

2.1 Vertex Locator upgrade

The VELO R&D effort has progressed toward the technology review and choice. A VELO upgrade workshop to kick-off preparation of the technology decision was held in December 2012 with participation of the tracking, physics and trigger working groups. The R&D effort is concentrating on a few crucial items: the module-zero development with a realistic cooling solution (for both the pixel and microstrip options), the development of sensors and ASICs, of a thin RF box based on the milling method, and the performance evaluation of realistic detector options by full simulation of the LHCb upgrade detector.

Following discussions with LHC experts, the baseline aperture of the VELO RF box was set to 3.5 mm (inner radius), see Section 6.1. A new approach for milling the upgrade RF box was explored in which first the outside of the box is milled, then the box is sucked against an outer mould and the inside shape is milled out. A small scale demonstrator box was manufactured. Vacuum and metrology measurements are underway. In addition, methods for thinning after fabrication are now being investigated.

Prototyping for high thermal conductivity PocoFoam modules with integrated cooling pipe is well underway with mockups available and thermal simulations producing first results. A large number of microchannel devices were received, with both hydrophilic and hydrophobic bonding processes. Individual tests demonstrated resistance to about 300 bar. A soldering technique with nano-foils for the connectors of the cooling capillaries is under investigation. The mechanical strength appears to be sufficient, while other properties (e.g. leak tightness) are yet to be investigated.

The pixel and microstrip module conceptual designs and module zero constructions are advancing. Prototype microstrip sensors received last year were tested and showed excellent signal-to-noise (S/N) performance. Test-beam and irradiation studies were also made of pixel sensors. The Timepix3 pixel chip (on which the eventual Velopix chip will be based) was submitted end of March for an engineering run production. Progress on the microstrip ASIC is reported in Section 2.5 below.

The full simulation of the upgrade VELO was put in place and new tools developed to facilitate easy modifications of the VELO geometry, applicable for both the L- and U-shaped foils. The compact detector geometry for both the pixel and strip sensor options were implemented and the ensuing improvement on the impact parameter resolution will be assessed. Detailed module designs were implemented in the LHCb central databases. Pattern recognition is in place for both pixel and strip solutions. For the upcoming technology review, the central simulation production will focus on four basic configurations of the VELO: pixel versus microstrip, each with a microchannel- or PocoFoam-based cooling option.

Important milestones will have to be met in the next six months. Most importantly, a technology review will be held in May to address cooling and pixel/strip technology choices. Following this, a decision on the VELO technologies will be taken by the collaboration during summer. In view of this review, a reliable design of the pixel sensors to resist high voltage under non-uniform irradiation conditions must be developed. An important collaboration effort on simulation is being deployed to extract detector and physics performance parameters for the review. The full-size box and milling precision will be addressed, with complete metrological measurements and vacuum tests. R&D to further thin down locally the RF box surface will continue. Orbital welding of integrated cooling pipes will be addressed on full module mockups, and long term temperature and pressure cycling tests of microchannel devices will be carried out. Concerning the pixel ASIC, the focus will be on readout tests with the Timepix3, and on design of the Velopix.

2.2 Trigger Tracker upgrade

The main achievements of the past six months were the development of a detailed simulation of a realistic detector geometry, identification of the major optimization parameters (segmentation, inner radius, magnetic field), progress in the mechanical design and definition of the main electronics work packages. Two competitive solutions in terms of material minimization were identified. The first is based on the "stave concept" described in the LoI [1], with active cooling embedded in a carbon foam support structure hosting hybrid circuits providing the electrical connectivity of the silicon front-end electronics elements to the back-end electronics. The second is based on a support structure based on carbon-fibre "roves" designed to provide mechanical stability supporting flex-rigid hybrid circuits. The major R&D item in the second approach is the design of an effective cooling system for the innermost portion of the detector that preserves the overall extremely low mass. Construction of a thermomechanical module for studying cooling strategies has been started.

The following activities will be the focus of effort in the coming months. On mechanical issues, the choice of the inner radius will be made, based upon detector simulation results. The thickness and segmentation of sensor tiles for the baseline design will be defined. The results from thermomechanical mockup tests of sub-assemblies will be evaluated and used to finalize the detector design (full plane). On the electronics front, the digital part of the FE specifications (processing block) and the design of the data flow architecture will be developed. The power distribution scheme (low mass cables, DC-DC converters, power supplies) will be defined. The signal integrity with the proposed data distribution scheme (low mass cables, transition to optical at detector periphery) will be validated. Progress on sensor design is also expected: choices of sensor technology, thickness and segmentation will be made, as well as the design of the sensors for the inner sector. In view of the upgrade trigger tracker conceptual design review which will take place in the autumn, several system integration and production aspects will be explored (definition of the QA methodology, testing jigs, etc).

2.3 Tracker upgrade

Considerable progress has been made on the two proposed solutions, one with straw tubes at the sides and a long-fibre Central Tracker (CT) in the middle, the other with an

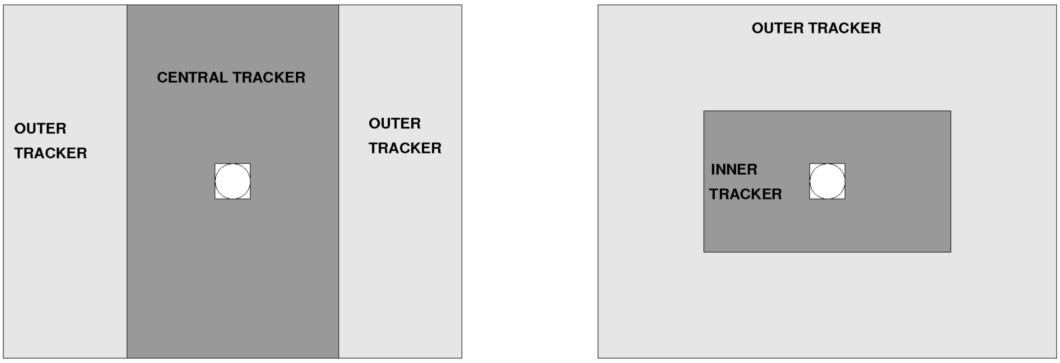

Figure 1: Schematic layouts of the two options being studied for the upgrade of the LHCb tracking stations (not to scale). Left: OT straw tubes (light shaded area) with scintillating-fibre CT (dark shaded area). Right: OT straw tubes (light shaded area) with IT made of microstrip silicon sensors (dark shaded area). The central hole is for the beam pipe.

enlarged silicon Inner Tracker (IT), as depicted in Fig. 1.

2.3.1 Inner Tracker option

In order to better match the requirements of the Outer Tracker (OT), the enlarged silicon micro-strip Inner Tracker (IT) evolved to a more rectangular design, see Fig. 1, containing Si-modules with up to three sensors being daisy-chained together. Tests to bump-bond large Si-sensors together, rather than use conventional wire bonding, show that the adherence of the bumps is not sufficient, causing shorts in the connections. Hence, the more conventional wire-bonding or tape-automated bonding will be adopted. Prototype modules with two and three sensors daisy-chained with wire-bonding have been produced. Their performance has been tested with a source and yield a S/N with the present Beetle chip larger than the required 10:1. A light mechanical support for the IT ladders has been designed, and the construction of two prototype mechanical ladders is well under way. Simulations show that in regions with the highest OT hit density the occupancy is reduced by more than a factor two due to a combination of shorter straws, and the very low mass IT design.

2.3.2 Central Tracker option

Several studies of the scintillating fibre tracker option have been performed, with an emphasis on the radiation hardness aspects. Performance of the light propagation in fibres and of the light collection with the silicon photomultipliers (SiPM) have been studied for various radiation doses. Detailed simulations of the radiation in the LHCb upgrade detector, of the photon propagation in the fibres, the light collection in the SiPMs, and GEANT simulations of the proposed detector have been performed. The results of these studies were used to predict the detector behaviour after LHCb will have collected 50 fb^{-1}

of data. The conclusions of these R&D studies have been the main subject of a major review, held in February 2013 with internal and external reviewers, and the conclusions were that the detector technology is viable in the LHCb upgrade environment. Finally, solutions have been proposed for the fibre module construction, the readout electronics, and for cooling the SiPM to low temperatures (-50 °C).

The next goals are the production of a full detector module prototype, and to define a complete front-end electronics solution for the proposed detector. These will be reviewed later this year, and will be the basis for the choice of technology and the Technical Design Report.

2.4 Outer Tracker upgrade

The effort on the Outer Tracker (OT) upgrade has focused on the developments of the 40 MHz readout electronics, in particular the study of radiation tolerance of several FPGA types that are being considered for the FE digital signal processing. The OT upgrade electronics architecture and replacement strategy were successfully reviewed in March (the first of a series of electronics review in the LHCb upgrade). The reviewers' report is expected in April 2013.

2.5 Silicon strip ASIC (SALT chip)

The development of the silicon **S**trip **A**SIC for the **L**HCb **T**racker upgrade (the SALT chip) has continued. This chip will be used for the TT upgrade detector and for the (still optional) VELO microstrip and large IT sensors. Tests of the first submitted block (the 6-bit ADC) are ongoing, while a second block (the first version of the FE block) was simulated, designed and submitted in February 2013. A third submission with at least 8 channels, comprising both FE and ADC, will be submitted in the first half of 2013. The collaboration is also working on the emulation framework for the on-chip digital processing which includes high-level modelling (using the Gaudi framework), low-level modelling using HDL machine language and finally FPGA emulation. A first version of the Gaudi- and HDL-based emulation is ready. Work is ongoing on defining a new set of interfaces and data flow for each processing algorithm. The design work on both the hardware and software parts of the SALT project will be continued.

3 Track reconstruction

Track reconstruction for the upgrade was one of the main topics discussed at an LHCb High Level Trigger (HLT) workshop in January. A major concern is to guarantee a fast turn around to test the impact of new geometries and alternative pattern recognition strategies on the HLT performance for the upgrade. To this aim, it was decided to write a trigger emulation which runs at the end of the LHCb reconstruction program, known as Brunel.

Since February we have the first Monte Carlo (MC) test data available that include simulation of all upgrade tracking detectors, allowing to test the whole sequence and the interplay of the various detector systems. All pattern recognition strategies of the current experiment have been adapted to the upgrade geometry, which includes tracking for the VELO-pixel as well as the VELO-strip option, forward tracking (through the fibre tracker starting from VELO tracks), seeding (stand-alone algorithm in the tracker stations), upstream tracking (VELO + trigger tracker), and downstream tracking (combination of forward tracking and upstream tracking especially to reconstruct long-lived particles). All algorithms run with very high efficiency ($> 92\%$ long-track reconstruction efficiency for tracks with momentum lager than 5 GeV) with acceptable time consumption. Initial checks of performance as function of number of primary vertices and occupancy show a robust behaviour. The focus of the next months will be to test the robustness under more realistic and harsher conditions, e.g. lower hit efficiency due to potential ageing effects, cross-talk, more noise hits in the detectors, realistic simulation of gaps at module boundaries and realistic description of the material budget. In view of the performance of the tracking with respect to the trigger, a careful validation of the impact parameter resolution of the various VELO options and of the efficiency and timing of the upstream algorithm is required.

The next step, before a large Monte Carlo production of physics samples will be launched, is to put the so-called compact VELO geometry in place. For both the pixel and the strip options a detector geometry that extends closer to the beam pipe is being investigated, and the VELO pattern recognition needs to be adapted to these modified designs. The aim is to pass simulation data to the physics group by mid-April, in time to get feed-back on the two different detector layouts, as well as on the two different cooling options (PocoFoam and microchannel) for the VELO workshop in May.

4 Particle identification

4.1 RICH system

The key decision for the hadron-identification system of the LHCb upgrade concerns the future of RICH-1. A solution is sought which will deliver an excellent and robust performance at the highest luminosities under consideration, for which the occupancy in the innermost region of the photodetector plane of the existing detector will approach high levels. The choices are between (i) retaining the optics of the current detector, (ii) increasing the focal length of the focusing mirrors in order to reduce occupancy, and (iii) removing RICH-1 entirely and re-building RICH-2 as a two-radiator system. Simulation and engineering studies are at an advanced stage, and a final decision will be taken in June.

The choice of photodetector does not depend on the above decision, but will also be taken in June. A leading candidate is a commercially available multianode PMT (MaPMT). Tests are ongoing to evaluate the performance of the MaPMT and characterise its response to magnetic fields, and engineering studies are underway to design the photodetector mountings. In parallel, work is proceeding on the front-end read-out electronics. Two possibilities are under consideration, the CLARO-CMOS, a dedicated chip being developed in Italy, and the already available Maroc-3. The decision on the front-end electronics will be taken in August, and a design review of the full electronics readout chain is scheduled for the autumn. The RICH system upgrade TDR will appear in December.

4.2 Calorimeter system

The existing electromagnetic and hadronic calorimeters will remain, but the Scintillating Pad Detector and Preshower will be removed, as they are considered inessential for the most important calorimeter-based physics topics of the upgrade, such as radiative penguin studies, and are not required for the trigger.

The principal challenge lies in the front-end electronics, which must read out at 40 MHz, and cope with the five-fold reduction in gain that will be applied to the PMTs. Maintaining the noise level of the analogue components under these requirements is a demanding task, and two solutions are being considered and prototyped, one ASIC based and the other making use of discrete components. Work is at an advanced stage, benefitting both from laboratory and test-beam studies. A decision between the two options, and on many of the other key questions in the calorimeter upgrade, will be taken in the summer.

Finally, studies are continuing to understand better the response of the calorimeter to radiation during high luminosity running. These studies are focused on test modules that have been irradiated in the LHC tunnel itself, and another module that has been exposed in the PS IRRAD facility. The results will establish whether and when any of the modules in the centre of the inner region of the calorimeter will need replacing. Sufficient spares exist should replacement prove necessary.

4.3 Muon system

Only minimal requirements will be need for the muon system readout to comply with the new DAQ and trigger schemes, so the most urgent task is the design of new off-detector electronics, where work is now commencing.

Data taken at high luminosity at the end of the 2012 run are being analysed, together with Monte Carlo, to understand better the performance of the muon system at upgrade luminosities, with particular attention being paid to the high-rate inner regions of M2 and M3. Preliminary indications and earlier studies suggest that the detectors will behave well, certainly in the initial years of operation, but ageing and rate considerations may motivate the installation of new detectors and accompanying front-end electronics in these places at a later stage. Possible technologies include triple-GEMs and high-granularity MWPCs. The muon system TDR is scheduled for December this year.

5 Data processing

The task of the data processing concerns the transport of the data from the output of the FE electronics up to their reconstruction. It encompasses data acquisition, trigger and computing.

5.1 Data acquisition

The readout architecture has been reviewed in December 2012. The reviewers gave positive feedback and identified no showstoppers. They provided recommendations related to the obsolescence of the LLT and the Muon FE electronics, buffering in the readout board, robustness of the data transmission, organization of the firmware developments and the use of copper links between the readout board and the network switches. Appropriate actions have already been taken on the Muon FE electronics, as mentioned in Section 4.3. Detailed reviews of the sub-detector readout architectures will follow and are scheduled before the sub-detector TDR submissions. The first one took place in March for OT.

Several scenarios for the implementation of the readout architecture are under study. In one of them, the readout electronics is close to the network switches in a building located on the surface. This solution simplifies the power distribution, cooling and eases the maintenance, but requires 400 m optical links between the FE electronics and the TELL40. A long distance optical link test was performed at CERN end-2012. Preliminary results are very encouraging but several technical issues have to be resolved to go all the way up to the surface. They are mainly related to the cost of the high quality OM4 fibres and to their installation.

Prototyping the readout board is progressing well. A first version of the AMC40 daughter and ATCA mother boards have been produced. The current set of results demonstrates the viability of the readout board using large FPGA, crossbar and ATCA technologies. Characterization of all serial link paths, hardware IP blocks as well as the validation of the TFC distribution are foreseen for this autumn. A second version of the AMC40 board is in preparation improving the buffering capabilities by a large factor.

Technologies and market surveys are conducted in order to determine the cost-effective solution for a large multi-Terabit/s network. In parallel, dedicated R&D are pursued using commercial components. They are focused on the direct connection of the TELL40 to a CPU using PCI Express links and the use of 10 Gbps copper cables between the TELL40 and the switches.

5.2 Trigger

To mitigate the risk of the obsolescence of the low-level trigger (LLT) electronics, studies are going on to migrate the Calorimeters and the Muon algorithms in the readout board. They show that the readout board design is well suited to house the LLT. More studies have to be pursued in order to evaluate the required manpower to develop firmware and to commission this upgrade implementation of the LLT. The latter has also some advantages allowing the computation of new global variables like the number of electromagnetic clusters above threshold. Monte-Carlo data will be generated soon to study the performance of the LLT running in the upgrade conditions.

Concerning the high-level trigger (HLT), a workshop took place end of January to study the post-LS1 and upgrade setups. The limitation of the output trigger rate at 20 kHz in the upgrade condition is a very strong requirement, given the increase in cross-section and luminosity. Several possibilities will be studied and where possible, already be deployed after the LS1 shutdown:

1. split the two stages of the HLT, HLT1 and HLT2, in order to run these two codes independently. This enables the deferral to disk of the HLT1 output, and delaying the HLT2 processing until after relevant calibrations (such as for the RICH) become available. This in turn allows a more aggressive rate reduction in HLT2 utilizing for example the particle identification information of the RICH;

2. split data in several output streams, and *park* some of them in order to delay or omit further offline reconstruction for a subset of the data;

3. perform some analyses on trigger information only, therefore reducing or eliminating the need for certain streams to be reconstructed offline;

4. optimize the code through improved vectorization where possible, and through continued profiling;

5. use of co-processors like GPUs or dedicated LLT track track triggers to reduce the CPU load.

The work on an *Upgrade Physics and Trigger* document has started. A first draft is expected for the end of April.

5.3 Computing

The computing covers several domains: the workload management system, the framework, the simulation, the reconstruction applications, as well as the daily operation for data reconstruction and stripping. Some of these software and applications will run in a very demanding context in the event filter farm.

At present, simulation studies are essential for the technological choices to be made for the TDRs and to evaluate their impact on physics reach as well as to prepare the data processing applications. A dedicated geometry database has been set up to allow for the many options to be studied for each sub-detector starting from the description of the current detector. The core libraries have been extended to support the new technologies as well as the simulation, digitization and reconstruction applications. Extensive work is expected in the next months on improving further the simulation frameworks and on the tracking and particle ID with the upgrade detectors. Samples of key physics channels with various sub-detectors combinations will be produced centrally for the trigger and physics performance studies that are planned.

The computing is in the phase of reviewing the existing tools, practices and requirements. Two major reviews have been organized. The first one on the *DIRAC & computing infrastructure* will be finalized in April 2013, the second one on the *Computing model* will be finalized in May 2013. Documents will be widely distributed and discussions are foreseen during the coming LHCb Software and Analysis weeks.

In parallel, a working group has been setup to federate all the R&D on GPU technology and to evaluate its possibilities. Tools are also in place to measure software performance and to observe the software optimization process.

6 Preparation for the LHCb upgrade

6.1 Interactions with LHC machine groups

In the past months two issues have been addressed in the discussions with the LHC machine groups: the possibility to reduce the inner radius of the RF-shield in the VELO with respect to the present radius in order to improve the impact parameter resolution, and the question whether a Target Absorber for Secondaries (TAS) and Neutrals (TAN) is needed in IP8 in order to protect the triplet quadrupole magnets and other machine elements.

Regarding the inner radius of the RF-shield in the VELO, three issues had to be considered with the machine groups:

- the required aperture for the beam, taking into account the β^* range, the crossing angle, the emittance of the beam and the bunch charges;
- RF effects, taking into account the transverse and longitudinal impedance, the heat dissipation and pick-up;
- the dynamic vacuum, taking into account synchrotron radiation and electron-cloud feedback on the ion instability.

All three issues have been carefully assessed and no showstopper was found. The proposed new LHCb VELO aperture of 3.5 mm instead of 5.5 mm has therefore been approved by the LMC.

Detailed FLUKA simulations have been carried out by the machine groups to estimate the energy deposition around IP8 at $2 \times 10^{33}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ luminosity. They showed that a TAS is only effective as protection for the first quadrupole magnet and that a luminosity of $2 \times 10^{33}\,\mathrm{cm}^{-1}\mathrm{s}^{-1}$ is fully compatible without installation of a nominal TAS. However, in order to reduce the heat load on the quadrupole magnet Q1 and the dipole magnet D2, a minimal absorber integrated into the small compensator magnet and a minimal TAN have been recommended by the LMC, since they could be prepared without a major effort.

These and other related issues will be further discussed with the relevant machine groups and by the HL-LHC Coordination group.

6.2 Infrastructure

Although the new infrastructure for the upgrade depends very much on the decision of new detectors to be installed in 2018, LHCb has started to study the possibility of installing services in the long shutdown (LS1). The aim is to prepare the installation of optical fibres between the underground and the surface area. These fibres will exchange the data from the sub-detector to the common readout boards. At present, LHCb is evaluating the costs of the fibres, support structure and their installation. It is envisaged to mount the support structure before LHC will re-start in 2015, while the installation of optical fibres can proceed during any longer technical stop before LS2. Wherever possible, consolidation work for the present detector will consider modification for the future LHCb upgrade. The preparation work for the new buildings housing the upgraded computer farm, storage and assembly hall and the control room are progressing well.

6.3 Schedule

Most of the Technical Design Reports (TDRs) for sub-systems of the LHCb upgrade will be issued at the end of 2013. A document with milestones for each project up to the TDR has been prepared. These milestones will be closely monitored and discussed during regular upgrade meetings. All milestones set up to March 2013 have been achieved. The steep rise in number of milestones is just ahead. Several reviews on electronics and detector technology for the upgrade have been carried out successfully. The very important decisions on the detector technology for the Tracker, Vertex Locator and RICH are schedule for summer 2013. With the present LHC long term planning, the installation of the LHCb upgrade is still scheduled for 2018/19 and will require 18 months.

6.4 Funding

The Memorandum of Understanding (MoU) for the Common Project items [3] has been submitted to the RRB in April 2012. This document includes a detailed cost breakdown for the Common Projects of the LHCb upgrade, as well as an estimate for the total upgrade cost of order 57 MCHF.

Following submission of this MoU, the collaboration has been asked to provide some preliminary information on the expected funding situation. Table 1 summarizes the total CORE funding, including the Common Projects, that is requested to each country for the LHCb upgrade. Following first contacts with the funding agencies some encouraging feedback has already been received concerning at least 70% of the requested funds. A detailed cost sharing among institutes will be defined when submitting the individual sub-system TDRs towards the end of 2013, together with the relevant Addenda to the MoU.

Country	CORE request [MCHF]
Brasil	1.56
CERN	8.00
China*	
France IN2P3	6.20
Germany BMBF	2.88
Germany MPG*	
Great Britain	11.40
Ireland	0.50
Italy INFN	7.80
Netherlands	3.60
Poland	1.25
Romania	0.90
Russia	5.00
Spain	1.64
Switzerland	5.00
Ukraine*	
United States	4.95
Total	60.67

Table 1: Total CORE funding (including Common Projects) in MCHF being requested to each country for the LHCb upgrade. An exchange rate of 1 EUR = 1.2 CHF has been assumed. Countries marked by * are still in the process of finalizing their request.

References

[1] LHCb collaboration, *Letter of Intent for the LHCb Upgrade*, CERN-LHCC-2011-001, LHCC-I-018.

[2] LHCb collaboration, *Framework Technical Design Report for the LHCb Upgrade*, CERN-LHCC-2012-007.

[3] LHCb collaboration, *Addendum No. 01 to the Memorandum of Understanding for Collaboration in the Construction of the LHCb Detector. The Upgrade of the LHCb Detector: Common Project items*, CERN-RRB-2012-119A.