High Energy

High Intensity

Hadron Beams

Final Report of the HHH Network

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Final Report of CARE-HHH Network

Introduction and Executive Summary

The CARE-HHH network gave birth to, and developed, many key ideas, concepts, strategies and technologies which have subsequently become integral components of the official upgrade plans for the CERN accelerator complex and of the GSI/FAIR project.

The innovations coming from HHH include detailed scenarios for the upgrade of the LHC and its injectors; the design of novel large-aperture, high-field or rapid-cycling superconducting (s.c.) dipole and quadrupole magnets; the identification of various bottlenecks in intensity or aperture, and the development of pertinent mitigation schemes, including a variety of remedies for the beam-beam interaction, for the electron-cloud effects, and for existing limitations on the collimation cleaning efficiency possibly overcome using crystals; advanced optics solutions for interaction regions and booster synchrotrons; and an improved understanding of high-intensity beam dynamics.

HHH established and strengthened pan-European and international collaborations, e.g., with European universities, with previously unconnected European organizations such as the European Fusion Development Agreement (EFDA) and the European Space Agency (ESA), as well as with overseas partners like US-LARP and KEK. Several open-access databases and web references were produced to the benefit of the worldwide accelerator community. An intense dissemination effort through publications and presentations was supported throughout the 5-year programme.

Impact on European Research Landscape

HHH established a detailed roadmap for the European high-energy high-intensity hadron-beam facilities, formulating needed or desirable upgrade steps over the next decade, and initiating pertinent technical developments. In addition HHH made a further impact on the European research landscape via the launch of long-term activities, through new collaborations, and by the strategic involvement of European industry.

Significant ideas and concepts which originated in the frame of HHH include:

- the phasing of the LHC luminosity upgrade (“phase 1” and “phase 2”);
- an LHC “phase-1” interaction-region (IR) upgrade using larger-aperture NbTi magnets;
- the upgrade of the LHC injector complex involving higher energy and/or higher-intensity storage rings, as will be realized with Linac4, the SPL, PS2 and the upgraded SPS, with the goals of increasing beam intensity and reducing the effective LHC turnaround time;
- novel electron-cloud mitigation techniques such as carbon coating, black metals, mechanically or magnetically rough surfaces, enamel-based clearing electrodes, and wide-band beam feedback, most of which were qualified in beam tests at the SPS and PS, to suppress any electron-cloud build up for the SPS upgrade, PS2, and FAIR;
- the identification of several schemes for increasing the LHC luminosity by a factor of ten above nominal, and the development of four example scenarios for this LHC high-luminosity upgrade (“phase 2”), namely: “large Piwinski angle”, “early separation”, “full crab crossing”, and “low emittance”, each with its own distinct merits and challenges;
- the concept of LHC “luminosity leveling” to reduce the maximum event pile-up in the detector while providing a high integrated luminosity;

- the demonstration that, at the contemplated much higher luminosity, the new NbTi or Nb_3Sn interaction-region quadrupoles can efficiently be shielded against increased energy debris from the collision points, and that Nb_3Sn gains a factor 1.3-1.4 w.r.t. NbTi;
- the advancement of crystal collimation for higher-intensity operation and the qualification of novel and multiple crystals with SPS beams;
- the potential gains from crab cavities at an upgraded LHC, a staged crab-cavity implementation consisting of validation, a single global prototype, and, finally, compact local cavities, as well as the establishment of a worldwide LHC crab-cavity collaboration;
- several refined schemes for LHC long-range beam-beam compensators, e.g. ones based on high-temperature superconductor or cold copper, and RF wire devices;
- the possible benefits from LHC "crab-waist" sextupoles including their use for long-range collisions and at collimators;
- pioneering contacts with European industries, e.g. enamel producers in Germany, beam instrumentation companies, manufacturers of s.c. cables and magnets, software developers for RF devices, as well as with other communities, e.g. ESA/ESTEC, the LHC experiments, SNS, EUROTeV, EPFL Lausanne, etc.;
- the design and optimization of high-field or fast cycling s.c. magnets, and particularly for FAIR the development, first proposed inside HHH, of a pulsed s.c. dipole with curved shape, which led to the procurement of a prototype from INFN; and
- improved hadron-beam diagnostics with several industrial spin-off products.

HHH guided and stimulated this progress by organizing numerous workshops, topical meetings, as well as targeted scientific exchanges, in which many of these ideas came to the surface. The pure networking activities were complemented by an intense dissemination effort in the form of publications and presentations.

Workshops and Collaboration Dynamics

HHH was organized in three work packages: Advancements in Accelerator Magnet Technologies (AMT), Novel Methods for Accelerator Beam Instrumentation (ABI), and Accelerator Physics and synchrotron Design (APD). Each work package organized its own series of workshops. At least one workshop was held per work package per year. In addition, a number of topical mini-workshops were organized to make progress on specific issues, and several joint workshops on topics of common interest were co-organized with European or international partners. In total 39 primary HHH workshops were organized, 8 of which by AMT, 6 by ABI, and 17 by APD. The remaining 8 were co-organized by APD together with other institutions

The workshop participants came from numerous European laboratories (CEA, CERN, CI, CIEMAT, DESY, EFDA, ENEA, FZJ, GSI, IFJ-Krakow, INFN, IN2P3, ITEP-Moscow, JINR-Dubna, PSI, RAL, STFC,…), from European organizations (e.g. ESA), from European universities (in France, Germany, Italy, Spain, Switzerland, UK, etc.), from international organizations (e.g. IFMIF), from the US-LARP (BNL, LBNL, FNAL, SLAC), from other US laboratories (JLAB, NHMFL, ORNL), from US universities (e.g. Cornell, MIT, Texas A&M), from Asia (IHEP in China, KEK in Japan), and from European industry (Alstom, Accell, NBB, Bruker BioSpin, Outokumpu, Ansaldo, Eisenwerke Düker, AUROSAT, Bergoz, Globes Electronics, Kyocera, Wendel Email, Siemens). The number of participants varied between a minimum of 15 and a maximum of around 200. The workshops assumed a key role in determining the HHH collaboration dynamics.

In the frame of the AMT work package, 8 workshops were held on superconducting magnets and cables, and on applications of s.c. magnets to high-energy accelerators. Numerous industrial companies were involved in the AMT events. Many of the workshop topics were aligned with the superconductor development activities in the CARE-NED activity progressing in parallel. The early AMT workshops reviewed the capabilities of European industries and laboratories, and defined the needs and development directions for high-field and large-aperture as well as for fast-ramping s.c. magnets. Three workshops addressed the particular aspect of heat generation - by beam loss, by collision debris, or by the ramping of the magnet - as well as improved insulation and cooling schemes. The outcome of these workshops has been taken into account in the magnet design for the LHC interaction-region upgrade and in the fast-cycling pulsed magnet designs proposed for FAIR, the PS2 and an eventual SPS2. Other, later and larger AMT workshops considered the magnet requirements imposed by the beam optics solutions and by the interaction-region layouts developed within the APD work package, as well as magnet-specific issues like design and costing tools, novel design concepts, and magnet optimization. One special AMT workshop looked at the proposal to install an s.c. injector ring based on transmission-line magnets in the LHC tunnel. This proposal was rejected as a result of the workshop discussion. In summary, the AMT workshops have generated a strong European and international R&D community capable to develop the next generation of s.c. accelerator magnets, and to support both FAIR and the various phases of the CERN upgrades.

The ABI work package organized one workshop per year. The workshops were loosely connected, each time addressing a different type of beam diagnostics or beam control. Taken together they provided a complete survey of hadron beam instrumentation: trajectory and beam position measurements using digital techniques; DC current transformers and beam-lifetime evaluations; remote diagnostics and maintenance of beam instrumentation devices; simulation of BPM front-end electronics and special mechanical designs, Schottky, tune and chromaticity diagnostics (with real-time feedback); and transverse and longitudinal emittance measurements in hadron (pre-)accelerators. Numerous inter-laboratory collaborations and partnerships with industry resulted from this activity.

APD organized one major workshop per year, strongly involving the four LHC experiments, and other CERN non-accelerator departments, like TS, in addition to the participating institutes listed above. The APD workshops covered future hadron colliders (LHC upgrade scenarios) and rapidly cycling high-intensity synchrotrons (CERN injector complex upgrade and FAIR design), including closely related themes, e.g. high-intensity beam-dynamics issues, optics solutions for the upgraded LHC interaction region and for booster synchrotrons, machine protection, collimation, energy deposition, accelerator-physics simulation code web repository, and simulation code benchmarking efforts. The first APD workshop in 2004 brought the entire community together. Its primary focus was the review of upgrade issues and of inherited upgrade scenarios. The workshop endorsed a staged upgrade scenario, distinguishing an initial “phase 1” with changes only in the LHC interaction region, and a subsequent “phase 2” with major hardware modifications. Various joint activities were triggered at this workshop, e.g. the CERN-GSI collaboration on incoherent electron-cloud effects. A secondary goal was surveying the state-of-the-art in hadron-beam dynamics simulations, aided by an expert panel discussion. This first workshop already eliminated the so-called superbunch scheme for the LHC in view of unacceptable event pile up. The following workshop considered some revised upgrade scenarios with less pile up, especially a derivate of the former superbunch scheme - the large-Piwinski angle upgrade scenario with initially 75-ns bunch spacing. For the first time IR upgrade solutions were presented which reached β^* values of 0.25 m using large-aperture NbTi quadrupoles rather than Nb_3Sn. At this workshop also the idea of an “early-separation scheme” with further reduced β^* values, below 0.25 m, was first proposed. Large-angle crab-cavities were abandoned. The third workshop rejected the so-called dipole-first schemes, but added the novel concept of slim s.c. magnets (dipole or quadrupoles) embedded deep inside the detector, and it brought up the idea of small-angle crab crossing. Options with 12.5-ns bunch spacing were shown to lead to unacceptable heat load and were subsequently abandoned. Two new LHC upgrade scenarios were constructed that compromise between arc heat load and detector pile-up, one with 25-ns spacing, the smallest possible β^* and early beam separation, the other with 50-ns spacing, longer flat bunches, β^* of 0.25 m, and a large Piwinski angle. The fourth workshop in 2007 focused on the CERN injector upgrade, and on the production of the beams required for various LHC upgrade scenarios by the new injector complex, as well as on the possibility of luminosity leveling to reduce the peak pile up. Bolstered by KEKB progress, “full crab crossing” became a third option for the LHC upgrade. For PS2, arguments were invoked in favor of either conventional magnets or fast cycling s.c./superferric magnets. The last workshop, in 2008, synthesized the results of 5 years of HHH networking activity. It established 4 different scenarios for the LHC high-luminosity upgrade. The fourth, new scenario makes use of the low-emittance higher-brightness beam available from the SPL and PS2.

In addition to these primary workshops, APD organized a number of mini-workshops and working meetings. One mini-workshop, organized jointly with CARE-ELAN and EUROTeV in 2007, was devoted to technological consequences of electron-cloud effects. This workshop launched collaborative efforts for the development of novel coatings (black metals, carbon) and enamel-based clearing electrodes in view of the SPS upgrade and PS2. A follow-up workshop, in 2008, reviewed the achievements, and it fostered a pertinent collaboration with the European Space Agency and its partners on coatings and computer modeling. At this workshop also another electron-cloud remedy based on a static spatially modulated weak magnetic field was discussed. Further two mini-workshops advanced the idea of LHC crab cavities. The first of these, arranged jointly with the US-LARP and BNL, established a global collaboration on LHC crab cavities. The second crab-cavity mini-workshop discussed the validation requirements prior to installing a crab cavity in the LHC. Another three mini-workshops looked at the LHC interaction region upgrades, including the related magnet development in Europe and the US, or at beam-beam effects and beam-beam compensation, respectively. An HHH-APD networking support for crystal channeling, reflection and collimation, provided a forum of discussion to which many associated institutes in Russia and US, such as IHEP, PNPI, JINR and FNAL, have contributed. APD organized no less than 5 mini-workshops on crystal collimation in hadron colliders, to prepare, conduct and analyze a series of experiments with SPS proton and ion beams, and some complementary experiments at FNAL. As part of the crystal activity, the international conferences “Channeling’06” and “Channeling’08” were co-organized and sponsored by HHH. HHH-APD also supported participation in beam experiments on crystals or beam-beam compensation studies at the SPS, the FNAL Tevatron, and BNL RHIC. In addition, HHH-APD organized two CERN-GSI bilateral working meetings on “collective effects – theory and

experiments", which allowed an exchange of ideas and approaches in high-intensity beam dynamics, encouraged a common planning of future experiments and simulations at GSI and CERN, and, overall, fostered a much closer collaboration between the CERN upgrade study groups and the GSI FAIR design team.
In addition to workshops, exchanges of key scientists between member laboratories or associated institutes, over typical periods of 1 to 4 weeks, helped to make progress on crucial issues, for example energy deposition, high-field magnet design, crystal modeling, beam-beam interaction, or electron-cloud simulations.

Dissemination and Outreach

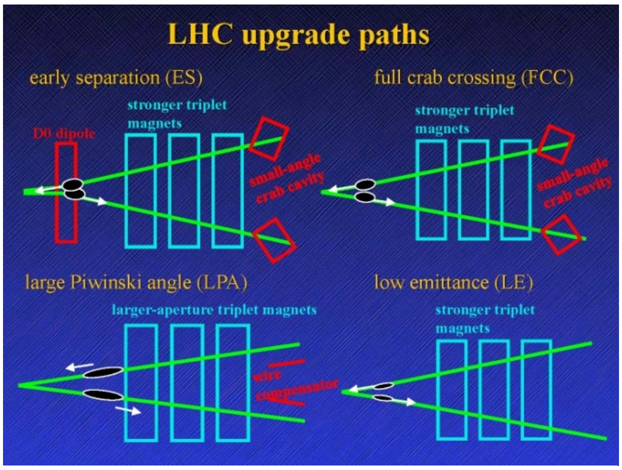
In total HHH generated 156 documents reflecting presentations or publications delivered outside the previously mentioned workshops, plus (so far) 31 proceedings of workshops organized within HHH. The HHH documents include 8 CARE Reports, 69 CARE-Conference papers, 14 CARE Notes, 9 CARE journal articles, and 4 CARE theses. HHH also supported 44 scientist exchanges, as well as (partly) 15 master and PhD students. Also a total of 9 summer students were trained and contributed to HHH activities. Another important component of the HHH dissemination effort was the development and extension of the superconductor database and the accelerator-physics simulation codes web repository, as well as the maintenance and development of HHH web sites, plus several other web-based repositories. Presentations and discussions by HHH speakers at various experiment workshops and university seminars, as well as the reciprocal participation of the LHC experiments in HHH events, provided a valuable link to the particle-physics community, which aligned the accelerator upgrade plans with the detector requirements and with the upgrade plans of the experiments. In addition, many new contacts were established to communities outside particle physics, e.g. ORNL/SNS, and outside accelerator physics, e.g. the European Space Agency, on topics of common research interest.

Deliverables

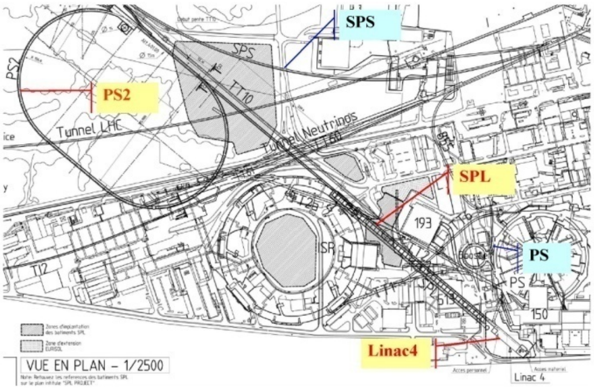
The primary deliverables of HHH are a "web database for s.c. cables and magnets" which includes data from the LHC, Tevatron, RHIC and ITER, along with automatic tools for generating and importing these data from different projects, and the "accelerator-physics simulation codes web repository" containing no fewer than 53 programs. Another two deliverables were the generation and the continuous updating of the HHH and HHH-APD web sites. In addition, an LHC-upgrade IR optics and layout web repository, a booster synchrotron (PS2) optics web repository, and a structured list of intensity limits for the LHC and its injectors were also created, and represented important milestones. The last HHH deliverable is this final report.

Conclusions

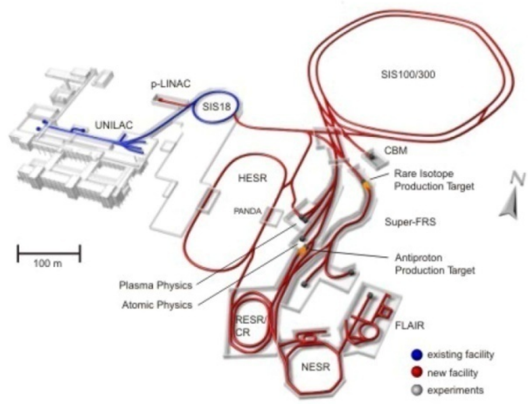
After 5 years of intense HHH networking activity, the LHC luminosity upgrade has assumed a realistic shape. Meanwhile concrete efforts are underway for implementing the first upgrade phase around 2012/13. Hitherto considered baseline upgrade scenarios (e.g. 12.5-ns spacing, or superbunches) had to be completely abandoned. In their place, HHH has put 4 alternative scenarios, all with comparable luminosity - 10 times above nominal - , with similar event pile up rates, and with acceptable arc heat loads. HHH networking has also introduced the concepts of luminosity leveling and of a phased upgrade, both highly appreciated by the experiments. At the same time the CERN injector complex upgrade, first proposed in the frame of HHH, was advanced dramatically. HHH networking has also initiated an important fast-pulse s.c. magnet design for FAIR, as well as a collaboration on electron-cloud mitigation for the SPS upgrade which resulted in an impressive set of “solutions”, that promise to fully eliminate the occurrence of an electron cloud in future accelerators. Strong support by HHH has also pushed forward the development and manipulation of crystals for collimation applications, which may overcome one of the most important intensity limitations of the LHC.

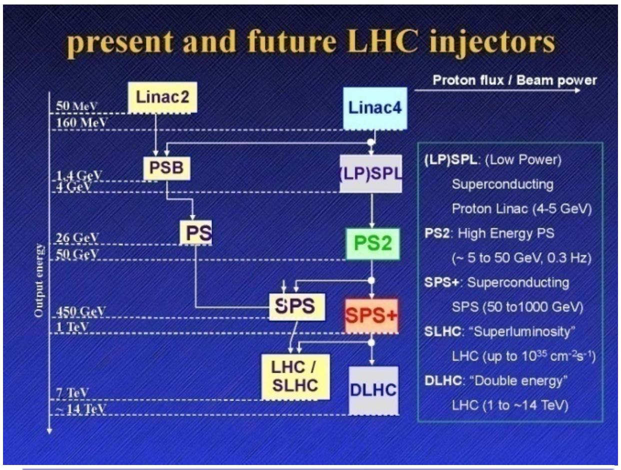


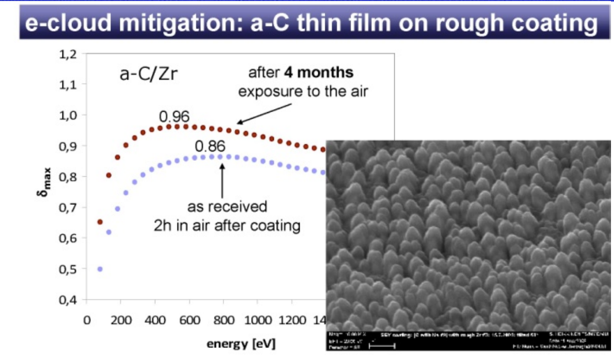
layout of the new LHC injectors

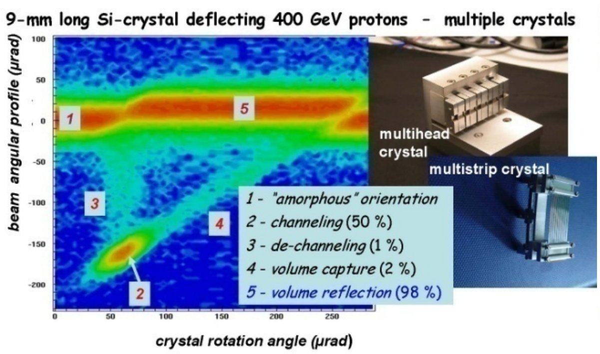


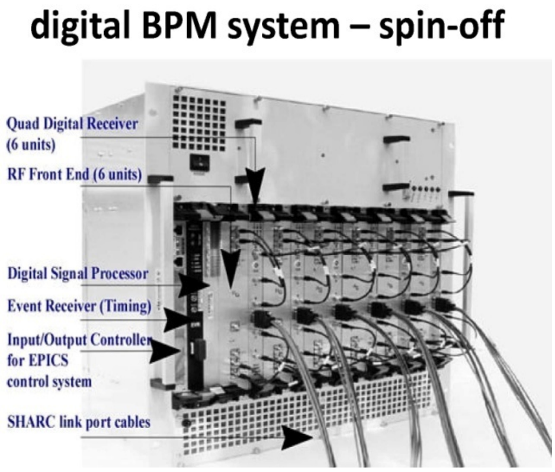
Facility for Antiproton and Ion Research

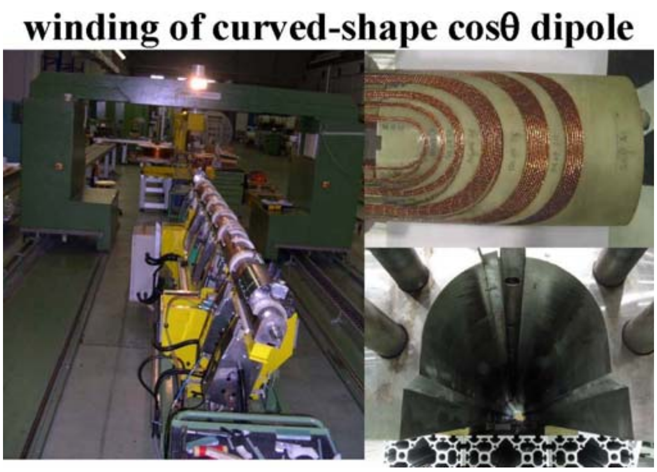



present and future LHC injectors
Proton flux / Beam power
Linac2
Linac4
50 MeV
160 MeV
1.4 GeV
4 GeV
26 GeV
50 GeV
450 GeV
1 TeV
7 TeV
~ 14 TeV
Output energy
PSB
(LP)SPL
PS
PS2
SPS
SPS+
LHC / SLHC
DLHC
(LP)SPL: (Low Power) Superconducting Proton Linac (4-5 GeV)
PS2: High Energy PS (~ 5 to 50 GeV, 0.3 Hz)
SPS+: Superconducting SPS (50 to1000 GeV)
SLHC: "Superluminosity" LHC (up to 10³⁵ cm⁻²s⁻¹)
DLHC: "Double energy" LHC (1 to ~14 TeV)


e-cloud mitigation: a-C thin film on rough coating
a-C/Zr
after 4 months exposure to the air
0.96
0.86
as received
2h in air after coating
δmax
energy [eV]


9-mm long Si-crystal deflecting 400 GeV protons - multiple crystals
beam angular profile (μrad)
crystal rotation angle (μrad)
multihead crystal
multistrip crystal
1 - "amorphous" orientation
2 - channeling (50 %)
3 - de-channeling (1 %)
4 - volume capture (2 %)
5 - volume reflection (98 %)


digital BPM system – spin-off
Quad Digital Receiver (6 units)
RF Front End (6 units)
Digital Signal Processor
Event Receiver (Timing)
Input/Output Controller for EPICS control system
SHARC link port cables


winding of curved-shape cosθ dipole