PPAP Roadmap Input: FCC-hh

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Background

The ESPPU concludes that "*Europe, together with its international partners, should investigate the technical and financial feasibility of a future proton–proton collider at CERN with a centre-of-mass energy of at least 100 TeV"*. It is clear that such a machine could not be technically delivered today, and that significant studies and R&D are needed over an extended period. We wish to argue that, since this is recognised as a key route to the asymptotic future of energy-frontier physics, the UK should engage meaningfully with the long-term programme, reaping the benefits of R&D investment for nearer-term projects, and building links with UK industrial and academic engineering expertise. If it is realised, FCC-hh will be the largest science project in human history, and the UK should begin to identify its contribution.

The accelerator and detector R&D roadmaps resulting from ESPPU will aim to provide evidence to the next update exercise in five to seven years, which sets a natural time scale for work. Moreover, we should be mindful of a potential scenario where ILC begins construction within that period. We need to be in a position where, as a community, we could seriously consider the option of constructing a new hadron collider at CERN on a relatively short time scale – the 2040s – rather than pursuing two e+e- machines simultaneously

Physics case

The physics case for a high energy hadron collider has motivations from Higgs / electroweak physics, QCD, and searches. The "guaranteed" highlight of the programme is a precise measurement of the Higgs (triple) self-coupling, projected to be measured to 5%, and unobtainable at this level via any other route. Furthermore FCChh offers the only opportunity to

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constrain the quartic Higgs self-coupling at any level. In parallel, the reach of direct searches will be extended by an order of magnitude compared to LHC. Although there is no guarantee of new physics, an order of magnitude step further above the electroweak symmetry-breaking scale and towards the GUT scale is highly significant, and may represent the last achievable step for the programme of direct collider experiments at the energy frontier. FCC-hh will also be ideally placed to rapidly follow up on any new observations at an ILC operating in high-energy mode. If no physics beyond the Standard Model were revealed at FCC-hh, this would imply a very high degree of fine-tuning, which is in itself a major new insight into the nature of the universe.

The technical feasibility case for FCC-hh requires an extension of current preliminary physics studies, in order to fully understand the experimental environment and how requirements on sensitivity and precision will drive innovation in trigger, detector and reconstruction technologies. This in turn requires investment in phenomenological calculations – sensitivities to new physics signals, QCD background estimations, Monte Carlo event generators and evolution of parton distribution functions – which is an area of major UK strength. Sensitivity studies, dependent on the use of advanced analysis techniques developed for the LHC, can draw upon established expertise in the experimental community. Detector design studies, likewise, will draw directly on current HL-LHC work and expertise. Contributions to FCC-hh studies are therefore largely not in conflict with ongoing UK work on LHC, but rather represent a continuum of activity, in a similar way to the direct path from Tevatron to LHC to HL-LHC.

Short term R&D and Impact

Detector

UK physicists have already made important contributions to the FCC-hh Conceptual Design Report, in our key strength areas of tracking detectors, calorimetry and trigger / DAQ. The CDR studies indicate that the construction of an FCC-hh detector will be exceptionally challenging, and require technology far beyond the current state-of-the-art. Developments here are likely to require fundamental enabling R&D in order to achieve leaps forward, rather than the incremental work required for future e+e- machines. Pushing the envelope in this way, without the requirement for an immediate move to detector construction, could form an important component of an overall STFC ‘blue skies R&D’ platform. Examples of required technologies include: highly integrated low-mass and radiation-tolerant detector systems; substantially increased on-detector data processing and intelligence; development of new thin superconducting magnet technologies; and entirely new methods of controlling, powering and gathering data from billions of detector channels. We note that we are potentially less than twenty years from the start of FCC-hh detector construction; fundamental R&D towards LHC detectors began at a similar distance in time from the startup of that machine. Early, albeit limited, investment towards an overwhelming instrumentation challenge will allow the widest possible range of approaches to be investigated in a cost-effective way, and pathfinder demonstrators to be delivered with benefits for other intermediate science projects.

Accelerator

The basic enabling technology for FCC-hh is high-field superconducting magnets; the key cost driver is civil and heavy electrical engineering. In each case, a step change in cost-performance is required. The UK has industrial strengths in all these areas, which was largely unused in the LHC programme, and is currently only peripherally engaged in future projects. FCC-hh represents an opportunity to re-engage UK industry in a ‘grand challenge’ global project, with enough time in hand to build a new working relationship. Although time scales are long, they are no longer than successfully delivered programmes in the aerospace, defence and transport sectors; we need to learn to work with engineering contractors in a similar mode.

The ESPPU comments, "*The particle physics community should ramp up its R&D effort focused on advanced accelerator technologies, in particular that for high-field superconducting magnets, including high-temperature superconductors*”. It is not clear whether, even after an extended R&D and industrialisation programme, conventional superconducting dipoles can deliver the necessary cost-performance-reliability tradeoff. We propose that the UK now consider how best to place itself to address this fundamental problem. We have world-leading industrial capability in superconducting magnets for medicine and instrumentation, but we do not have a track record in large-scale production of dipole magnets for accelerators. Work here needs to proceed first via an evaluation exercise, in engagement with the European R&D programme, and involving the efforts of national labs, the community, and experts in HTS technology from industry and academia. This should include examination of the potential wider applications of new magnet technology.

In parallel, the FCC-hh opportunity in areas of existing UK technological strength should be investigated. These range from a continuation and expansion of the successful and intellectually challenging UK work on machine elements for and simulation of HL-LHC, to exploration of the opportunities for new and cost-effective civil engineering approaches for accelerator construction. These aspects will be essential if we are to approach *juste retour* for the UK in any new CERN accelerator project, whilst also maintaining our leadership in important areas of accelerator science.

These evaluation efforts could initially proceed at modest scale, but would require a clear focus in establishing a longer-term forward path for UK machine contributions, full engagement with the wider European R&D agenda, and a well-defined pathway towards wider investment if and when the scientific and technical case is made.

Resources

Quantification of resources for a long-term project without an agreed design is challenging. We present here an aggressive ‘straw person’ scenario based on a direct move to FCC-hh detailed design phase after the next ESPPU.

- 2021 – 2023: Evaluation studies of machine technology challenges and opportunities, first phase of an advanced detector R&D programme, preliminary physics studies (5FTE, £0.5M capital)
- 2024 – 2027: First phase of HTS magnet programme and machine studies, demonstrator phase of detector R&D programme, detailed physics studies in parallel with LHC LS3 (10FTE, £5M capital)
- 2027: Next update of ESPPU; ‘go decision’ on detailed design studies for FCC-hh
- 2028 – 2032: Detailed design studies for machine; HTS magnet demonstrator programme; detector design phase towards updated CDR (20FTE, £20M capital)
- 2033: Approval of FCC-hh construction
- 2033 – 2036: Civil construction; industrial magnet pre-series; final detector prototyping phase (50FTE, £20M capital plus direct machine contribution)
- 2036 – 2044: Machine and detector construction, (including software engineering); ramp-up of physics preparations post-LHC, including development of required theory codes and tools (60-80FTE; £100M capital plus direct machine contribution).
- 2044 – 2047: Commissioning
- 2048: Start of physics

Assuming a total machine cost of 20GCHF, a CERN baseline contribution of 500MCHF per year (cash within existing budget plus loans), a 50% non-member-state contribution, and the existing distribution of member state size, the total bill to the UK over the period 2033 – 2044 would be around £375M at 2020 rates, or £35M per year (roughly equivalent to peak STFC capital spend on PPAN science in the current programme) Total additional costs up to the commissioning phase for R&D and detector work would be around £150M capital plus £100M staff costs.

The scale of these costs indicate that FCC-hh will not be ‘business as usual’. The need to push strongly for cost optimisation in magnets and civil engineering, probably requiring entirely novel approaches, is clear. Also clear is the necessity to ensure industrial return and wider benefits from this substantial investment. Put bluntly, the money invested should return to the UK economy, either directly or indirectly. Our proposal is that the UK begin to address these considerations, as part of an extended pre-approval phase FCC-hh, as soon as possible. The necessary step-change in capability and international relationships will only be achieved through early R&D investment.