Conceptual Design

Baseline Parameters

The key parameters for the FCC-hh conceptual design need to be defined and it needs to be established that one can expect to meet these parameters with reasonable risk with a technical design.

A first set of target values for the key FCC-hh baseline parameters have been identified. Detailed studies have to be performed to optimize these parameters in order to reduce the risk, power consumption or cost as well as to increase the performance. This R&D programme will contain analytic and numerical studies, hardware developments including prototyping and experimental verification.

Examples of key issues are:

- The high synchrotron radiation power emitted by the beam and the related issues such as cooling and beam pipe design.
- The high energy stored in the beam and the resulting machine protection issues.
- The high radiation emitted by the beam in the interaction points but potentially also elsewhere.
- The magnet aperture is a most important cost driver, therefore an aggressive target value of 40mm has been chosen. This however has strong implications on the design of the beam pipe region, in particular the cooling and vacuum system and on the beam stability. The feasibility of the target aperture needs to be established in a close collaboration by many different experts.

For the baseline definition the following questions must be addressed:

- *Explore whether additional design drivers and critical issues exist that need to be integrated into the baseline parameter definition.*
- *Verify that the target parameters appear achievable based on the existing studies.*
    - *Which beam pipe radius is required and what is the magnet aperture?*
    - *Can 80% of the ring be filled with bunches?*
- *Choose several parameters*
    - *Which beam-beam separation and mitigation techniques are necessary?*
    - *RF voltage*
- *Explore the possibility to improve the design parameters to reduce the risk, power consumption or cost or to increase the performance.*
    - *Can the beam charge be reduced to minimize synchrotron radiation load and machine protection/ radiation issues?*
        - *This requires a reduction of the beta-functions at the collision point or an increase in beam-beam tuneshift*
        - *A fast turn-round is also important to maintain high average luminosity*

Layout

The layout needs to respect a diversity of constraints as well as optimize the machine performance and cost. Considerations arise from site constraints, beam performances optimization, machine protection issues, radiation effects and many more.

Specific question concerning the global layout

- *What is the overall layout of the tunnel, e.g. racetrack vs. LHC-type or something in between?*
    - *How are the experiments distributed? E.g. in the same straight section for local chromaticity correction? Or at opposite points of the collider?*
- *Do we need one or two beam dumps/extractions?*
- *How does the injection layout look like? In particular, how does it constrain the collider layout and integration into the site?*
- *Do we need short cuts between different parts of the tunnel for feedback or other purposes?*

In collaboration with the infrastructure team and probably after the baseline definition:

- Which is the tunnel diameter? Which are the tunnel diameters?
- Where are shafts located?
- Is a single tunnel or a double tunnel better?
- The maximum acceptable sector length and design of the connection between sectors (cryogenics, magnets, …)

For the layout definition an evaluation of the design requirements and a first lattice design is essential for all relevant parts of the machine. In particular:

- *Arcs*
- *Collimation*
- *Experiment insertions*
- *Extraction and injection*
- *Other lines (RF, reserve experiments, short straight section bends for racetrack)*
- *Integration of the lattices and verification of the performance of the combined system including intensity and loss related limitations*

Injection requirements

The definition of the injection parameters includes the injection energy, the sequence in which the injection is performed, which also defines the time at which the collider is operated at injection energy, and the total time required between two luminosity runs. Also the injection layout needs to be integrated into the overall layout.

The acceptable injection parameters strongly depend on the collider ring design. Of particular importance are the lowest field at which the collider magnets can be operated with acceptable field quality as well as the beam stability at injection. The injection sequence will depend on the injector design and on the amount of beam that one can safely transfer in a single shot. The issues require close interaction with the overall design.

The main questions that need to be answered for the baseline design are

- *From where and in which sequence will the beam be injected?*
- *What are the beam energy, emittance and other key parameters?*

This requires addressing:

- *The lowest energy accessible with the magnets (and power supply).*
    - *A first estimate of the potential field quality*
    - *A first estimate of the impact on dynamic aperture*
    - *A first assessment of mitigation techniques*
    - *A first estimate on the allowed speed of the ramp*
- *The beam stability at injection:*
    - *Collective effects, i.e. impedances etc.*
    - *The mitigation methods, e.g. feedback*
- *The injection sequence*
    - *How many bunches can be injected at one time?*
    - *What is the space between injection batches?*
- For specific magnet designs more detailed studies will have to be performed of:
    - Magnet field quality at injection
    - The resulting dynamic aperture
    - Mitigation techniques
    - The ramping effects

Physics requirements

Currently the physics requirements are specified via, energy, luminosity, time structure, pile-up per bunch crossing and L^*.

- *Review the specifications for completeness and identify potential issues, if any.*
- *Alternative parameter sets need to be investigated.*

HE-LHC

Based on the work for the high-energy collider, the option to use high field magnets in the LHC tunnel should also be investigated.

- The use of high field magnets in the LHC tunnel needs to be explored.

Staging scenarios

Potential staging scenarios need to be identified and investigated. This will largely be addressed once a baseline has been defined

- The potential to stage the project needs to be explored.

Arc design and beam pipe

The design of the beam pipe in the arcs strongly impacts the beam performance and the inner aperture of the main dipoles, which are a most important cost driver. A number of design options should be explored in a strong collaboration between the magnet, vacuum, cryogenics and beam dynamics experts.
The beam pipe design is critical for the cost and one should have a good guess for the baseline definition to guide the magnet work.

Magnets

The arc dipoles of FCC-hh are the main design and cost driver. The target fields are challenging: 16T for magnets using Nb_3Sn and 20T for magnets that also use high temperature superconductors. The performance will have to be proven with models. It is important that each region develops at least one model to provide the necessary redundancy and also to start to develop the capability of each region to provide these magnets.
It is important to understand the dependence of the magnet cost on strength, aperture and field quality in order to cost optimize the overall design. The required safety margin in strength needs to be carefully evaluated. The field quality is also critical at injection energy and during the ramp.
In addition, there is likely the need to develop some very high performing magnets for the experimental insertions. These can drive the insertion design, which in turn can impact the overall design and parameters.

- *Are the target fields for the arc dipoles good goals?*
- *What is a good target value for the quadrupole field gradient in the arcs?*
- *What is the dependence of the magnet cost on the aperture?*
- *Which injection field can we assume and how fast can we ramp?*
- *Which other magnets are design drivers?*
- *Which research and development needs to be done?*
- What is the magnet field quality at injection and at full field?
- What are realistic designs for the special magnets that will be needed for the experimental insertions?

Vacuum

The beam screen has to provide good vacuum and sufficiently small impedance for the beam as well as to efficiently remove the high synchrotron radiation heat load (up to 44W/m/beam, a total of around 5MW) and to shield the magnets. In particular it has to cope with a strong variation of the heat load during the ramp. At the same time the space used for the screen has to be minimized to limit the magnet aperture, which is one of the main cost drivers.
The generation of electron clouds from synchrotron radiation and free electrons needs to be suppressed. The system also needs to deal with pressure burst and ions. Additional challenges are the large size of the system and the high radiation environment. So-called UFOs (Unidentified Falling Objects), which are probably caused by dust particles, have impacted the LHC operation and one needs to find methods to avoid them in FCC.

Experimental verification of the performance of the technical components is key. An example is the measurement of the secondary electron emission yield of the beam screen surface, in particular if a high temperature superconductor coating is applied. Experiments with beam are also important and could be carried out in a positron ring such as CESR-TA.

- *Which distance between beam screen and magnet aperture do we need?*
- *Which transparency do we need for the beam screen?*
- *How can we operate the beam screen with the large variation in heat load?*
- *Which vacuum quality can we expect?*
- *Which HTS coatings can be considered?*
- *What can we do to mitigate a potential electron cloud problem?*
- *How many electrons do we produce with the synchrotron radiation?*
- *Which other vacuum issues are key to the FCC-hh design?*
- *Which research and development programme is required?*

Beam Physics

Lattice design, integration and tolerances

A complete design of the FCC-hh lattice is the basis for a credible CDR. A core team with strong links to the hardware and systems design teams is essential to develop the lattices, manage version control, and make reliable performance predictions. The optimization of the lattice is critical for cost and performance, early considerations have to be given to the constraints arising from the FCC-ee design -- while the requirements of the lattice are different for the two machines, the geometry of the tunnel as determined by the bend centers must accommodate both. Cell lengths, dispersion suppressors, utility straight sections (RF, etc.) must be optimized, and reduced-beta insertion optics at the interaction regions could reduce the required beam intensities, aiding the challenges of machine protection and synchrotron radiation. Also, the high power from collision debris and subsequent magnet protection must be studied with the experimental groups. Tolerance studies of alignment, dynamic aperture (at injection and at full energy), etc., must be performed in collaboration with the collective effects team.

- *A first design of all lattices is essential to be able to define the baseline layout.*
- *The lattices need to be integrated to verify that they function together.*

Experiment insertions

The design of the experimental insertions is important and challenging. A pushed small beta-function will allow improving the ratio of luminosity to circulating beam current, the latter causing machine protection challenges and strong synchrotron radiation. The insertion design has to also be consistent with the needs of the experiments and be able to cope with challenges such as the high power of protons coming from the interaction point.

- *How could a first experimental insertion design look like based on reasonable target performances of the components?*
- *Which is the minimum beta-function that can reasonably be achieved?*
- *How much space do we need for the experimental insertion to allow for further improvements?*
- *Which technology issues need to be addressed?*
- *How does the ion operation constrain the design?*

Collimation system

A concept for the collimation needs to be developed and the optics designed accordingly.

The collimation system is more demanding than even in LHC. For example, the higher beam energy likely demands a better cleaning efficiency not to tighten the required quench limits for the superconducting magnets. However tight constraints exist, since for example the collimators are one of the main impedances for the colliding beam and since they are a part of the machine protection scheme.

An improved overall design strategy is essential. This includes the functional and optics design as well as the collimator design.

The development of improved collimators is instrumental, e.g. the use of new materials, improvements in radiation hardness, the use of hollow electron lenses or crystals. Simulations of the collimation system performance will be crucial to evaluate and optimize the system design, as will be an evaluation of the impact of the losses on the machine components.

- *How can a collimation concept look like?*
- *Where do we place collimators?*
- *Which optics is required? How much space do we expect to need?*
- *Which efficiency is required?*
- *What are the primary beam losses that we can expect?*
- *Which technological solutions need to be developed?*

To design the collimation system simulation studies of the beam loss, the scattering of the protons on the collimators and the propagation of the scattered protons to further collimation stages are required.

Extraction and injection

Important challenges for the injection and extraction lines are the machine protection and the minimization of losses. In order to prevent damage the beam will most likely have to be injected in short pulses. These need to be short enough that they cannot damage the machine in case of a misfired kicker.

The required number of beam dumps needs to be established.

- *How many beam dumps do we need?*
- *Which options exist for the injection layout?*
- *How much space is required?*
- *What is the injection sequence?*
- *Which technological challenges need to be addressed?*

Collective effects

The collective effects---such as beam-beam and impedance effects, electron cloud and intra-beam scattering---are design drivers at collision energy as well as at the injection of the beam into the collider ring.

Impedance

Impedance effects at injection will have a strong impact on the minimum aperture and hence on the cost of the main dipoles. At full energy, they will also put severe constraints on the design of the collimation and feedback systems.

A reliable prediction of the impedance effects on the beam requires:

- A careful estimate of the impedance of the relevant beam line components, which necessitates specialized theoretical tools and experimental verification.
- Studies of the impact of these impedances on the beam, which necessitates theoretical tools and benchmarking.
- Conceptual and optimization design of mitigation methods, in particular feedback systems, and their integration in the performance prediction studies.

This team will have to approve all components that are seen by the beam.

- *What is the impedance of different beam pipe designs and of other components (RF etc.)?*
    - *Including required thickness of copper coating, impact of HTS coating, photon stops etc.*
    - *Impact of beam screen transparency and other impedance sources*
    - *Kickers, RF system, …*
- *How do the impedances affect the beam at injection?*
- *Mitigation techniques*
    - *Which RF voltage is required for beam stability?*
    - *Which feedback at which speed is required?*
    - *Alternative feedback system designs*
- *What are the impedance constraints at collision energy?*
    - *In particular the collimators and the impact on the collimation system design*

Electron cloud effects

Electron cloud effects can render the beam unstable and lead to very high heat loads in the beam pipe. Detailed theoretical and experimental studies are essential. This work needs to be performed in close collaboration with the vacuum system design team as well as the other design teams.

- *Which secondary emission yields, photon yields and reflectivities are acceptable for the different beam pipe designs and beam parameters?*
- *Which mitigation techniques can be envisaged to achieve these?*

Beam-beam effects and beam parameter evolution

Head-on and parasitic beam-beam collisions can lead to emittance growth and beam loss. The increased length of the interaction region and the potentially reduced distance between bunches will lead to a substantially larger number of parasitic crossing than for example in the LHC. Due to the radiation damping if the proton beam, the head-on beam-beam effect will increase significantly during the luminosity run, if no countermeasures are taken. The natural evolution of the beam parameters in presence of damping, beam-beam effects and intra-beam scattering need to be studied. The required methods to control the beam parameters need to be devised. For example, the reduction of the longitudinal emittance will lead to a bunch shortening, which could lead to the loss of Landau damping in the machine and makes it difficult for the experiments to separate background and physics events.

Theoretical studies are required to predict the importance of these effects and the necessary instrumentation and countermeasures need to be devised. These include the use of a larger crossing angle together with so-called crab cavities to avoid the luminosity loss and the use of wires or electron lenses to cure the beam-beam effects. Emittance, chromaticity and tune measurements that can be parasitically applied during the luminosity run are important instrumentation examples.

Together with the lattice integration team, dynamic aperture studies need to be performed.

- *Head-on collisions*
    - *What is the acceptable beam-beam tuneshift for the different parameter sets?*

        - *Can we live with larger tuneshift like a lepton ring?*
            - *Can we just wait for an equilibrium? What would the equilibrium be?*
            - *How do we best control the luminosity? How does the selected method impact the beam?*
            - *The beams will probably tend to become flat. What are the consequences?*
        - *Which experiments should be carried out?*
- *Parasitic crossings*
    - *Which beam separation is required to avoid significant parasitic beam-beam effects for the different parameter sets?*
    - *Exploration of mitigation techniques*
        - *Parameter choice*
        - *Crab cavities*
        - *Wires*
        - *Electron lenses*
        - *…*
- Two-beam stability
    - *First considerations*
    - Additional impact of impedances
- Dynamic aperture with beam-beam

Integrated operation concept

- *How to evolve the beam parameters during collision*
- *Required instrumentation*
- *How can we control the emittance?*
    - *Noise into feedback, kickers, small beam-beam offsets, …*
    - *Need to measure emittance parasitically in lumi-run*
- *How can we control the luminosity?*
- *Fast turn-around*
- *How can we put together an integrated tool to understand the beam evolution with time?*

RF systems and feedback

The RF system is critical for the longitudinal beam stability and also impacts the transverse. In addition, fast feedback is required to suppress beam instabilities. During the operation, the beam emittances are damped in the longitudinal and transverse planes. It will be necessary to control them with a heater system. In particular a decrease of the longitudinal emittance could lead to a bunch shortening, which makes the separation of physics events from the background events more difficult in the detectors. The needs for transverse emittance control remain to be studied within the parameter evolution activity.
Whether crab cavities will be needed in FCC-hh, remains to be studied.

- *RF system conceptual design*
    - *Definition of RF frequency and voltage*
    - Significant power to the beam
    - RF provides an impedance
    - Impedance effects depend on RF
- Longitudinal feedback and emittance control
- *Transverse feedback*

    - *Speed is critical for beam stability, in particular at injection*
- Potentially emittance control
- Potentially crab cavities

Ion operation

Poses some constraints on the interaction region design. Some improvement of the injectors appears possible.

- *How does the ion operation constrain the interaction region design?*
- *How could the injector chain be improved to increase the ion luminosity?*
- *Which challenges need to be addressed?*

Beam Stored Energy Issues

The stored beam energy at injection and at full energy will be very high in FCC-hh. With the current baseline parameters one finds more than 8 GJ per beam at collision energy. The handling of the beam and its losses is critical.

Machine protection

Machine protection design is a key aspect of the machine feasibility.

- *Beam dump concept*
    - *Beam dump insertion length, optics and lattice magnet requirements*
    - *Do we need one or two?*
    - *Design of dump line*
    - *Painting of beam*
    - *Protection against asynchronous kicker firing*
- *Magnet protection and sector length*
- *Magnet quench due to losses, important input for the collimation*
- Radiation and availability considerations
    - E.g. redundancy, majority voting
- *Hydrodynamic tunneling*
- *Identification of key machine protection issues*
- *Development of a machine protection concept*

Radiation

High levels of radiation will exist in some locations in FCC-hh. An obvious example is the 100kW of hadronic power produced due to beam burn-off in each of the two interaction points. It is therefore necessary to determine the expected secondary beam losses and the corresponding energy deposition as well as the resulting radiation dose different parts of the machine. The impact of the radiation on the technology choices need to be assessed and mitigation techniques such as shielding and radiation hard components need to be developed.

- Estimate the impact of beam loss on the collimators, injection septa, interaction region and other key components
- Estimate the radiation due to beam losses, beam burn-off and synchrotron radiation; establish dose rate map.
- Estimate the impact on the key components
- Develop a shielding strategy
- Contribute to the radiation and availability considerations
- Radiation robust design concepts
    - e.g. optical systems
- *In particular radiation constraints and shielding needs for the experiment insertions provide important input for the optics design and technology choice and are needed for the baseline design.*

Other Technical Systems

Beam instrumentation and diagnostic

- *Identify key parameters for the design and critical issues and components*

Anticipated issues

- Parasitic emittance measurement is critical for emittance control during luminosity run
- High resolution BPMs

Beam transfer elements

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Already known issues:

- *Fast injection kickers will be required to maximize the fraction of the collider ring with beam*
- *The impedance of the kickers is likely important*

Collimation system and absorbers

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Anticipated issues:

- The collimation system design most likely is strongly constrained by the collimator hardware. Identification of robust collimator materials is thus critical.

Control system

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Dump and stoppers

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Already identified issues:

- *An estimate of beam dump dimensions and energy handling capability ae important for the layout decision.*

Element support and alignment

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Machine detector interface systems

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Cryogenics system

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Know issues:

- *Control of operation with strongly varying heat load and potentially constrained temperature windows.*
- *Minimisation of space needed between beam screen and magnet aperture to provide sufficient shielding and cooling*

Machine protection system components

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Normal magnets

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Power converters

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Quench protection and stored energy management

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Know issues:

- *The acceptable sector length*

Superconducting magnets and cryostats

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Proximity cryogenics for superconducting magnets and RF

- *Identify key parameters for the design and critical issues and components*
- Address the key issues

Know issues:

- *Control of operation with strongly varying heat load and potentially constrained temperature windows.*
- *Minimisation of space needed between beam screen and magnet aperture to provide sufficient shielding and cooling*

Shielding

- *Identify key parameters for the design and critical issues and components*
- Address the key issues