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Cryogenic Studies for the Proposed CERN Large Hadron Electron Collider (LHeC)

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Abstract

The LHeC (Large Hadron electron Collider) is a proposed future colliding beam facility for lepton-nucleon scattering particle physics at CERN. A new 60 GeV electron accelerator will be added to the existing 27 km circumference 7 TeV LHC for collisions of electrons with protons and heavy ions. Two basic design options are being pursued. The first is a circular accelerator housed in the existing LHC tunnel which is referred to as the "Ring-Ring" version. Low field normal conducting magnets guide the particle beam while superconducting (SC) RF cavities cooled to 2 K are installed at two opposite locations at the LHC tunnel to accelerate the beams. For this version in addition a 10 GeV re-circulating SC injector will be installed. In total four refrigerators with cooling capacities between 1.2 kW and 3 kW @ 4.5 K are needed. The second option, referred to as the "Linac-Ring" version consists of a race-track re-circulating energy-recovery type machine with two 1 km long straight acceleration sections. The 944 high field 2 K SC cavities dissipate 30 kW at CW operation. Eight 10 kW @ 4.5 K refrigerators are proposed. The particle detector contains a combined SC solenoid and dipole forming the cold mass and an independent liquid argon calorimeter. Cooling is done with two individual small sized cryoplants; a 4.5 K helium, and a 87 K liquid nitrogen plant.

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ABSTRACT

The LHeC (Large Hadron electron Collider) is a proposed future colliding beam facility for lepton-nucleon scattering particle physics at CERN. A new 60 GeV electron accelerator will be added to the existing 27 km circumference 7 TeV LHC for collisions of electrons with protons and heavy ions. Two basic design options are being pursued. The first is a circular accelerator housed in the existing LHC tunnel which is referred to as the “Ring-Ring” version. Low field normal conducting magnets guide the particle beam while superconducting (SC) RF cavities cooled to 2 K are installed at two opposite locations at the LHC tunnel to accelerate the beams. For this version in addition a 10 GeV re-circulating SC injector will be installed. In total four refrigerators with cooling capacities between 1.2 kW and 3 kW @ 4.5 K are needed. The second option, referred to as the “Linac-Ring” version consists of a race-track re-circulating energy-recovery type machine with two 1 km long straight acceleration sections. The 944 high field 2 K SC cavities dissipate 30 kW at CW operation. Eight 10 kW @ 4.5 K refrigerators are proposed. The particle detector contains a combined SC solenoid and dipole forming the cold mass and an independent liquid argon calorimeter. Cooling is done with two individual small sized cryoplants; a 4.5 K helium, and a 87 K liquid nitrogen plant.

KEYWORDS: LHC

INTRODUCTION

Particle Physics has approached new phenomena at the energy frontier with complementary devices for ee, ep and pp scattering, as LEP, HERA and the TeVatron for exploring the physics at the Fermi scale of order 100 GeV. With the LHC the investigation of the TeV energy scale has now begun. Owing to its high energy, intense hadron beams, the LHC provides the unique opportunity to be complemented by an electron-proton and electron-ion scattering complex, the Large Hadron Electron Collider (LHeC), with which the physics of deep inelastic lepton-hadron scattering, following HERA, can be moved to the new energy frontier.

The default design, soon to be published, is for a 60 GeV electron beam and a hundred times higher ep luminosity, as compared to HERA. This permits to solve many outstanding questions, as to the coupling constants or the non-linear behaviour of the gluon density, in strong and electroweak interactions. The LHeC will be a crucial complement for the unfolding and understanding of new phenomena at the TeV scale should these appear at the LHC. Preliminary studies of the physics case and systems requirements for the LHeC are presently ongoing and a conceptual design report will be issued in 2011 for approval and preparation of the next project phase. The electron beam of 60 GeV nominal design energy will be added to the present 7 TeV proton collider by a new recirculating energy recovery linac (ERL) or by an electron ring machine to be installed in the existing LHC tunnel. The version with the electron machine in the LHC tunnel is referred to as the “Ring-Ring option (RR)” and requires an additional 10 GeV SC injector. The ERL combined with the LHC is referred to as the “Linac-Ring option (LR)”. Collision for both options, RR or LR, will take place at a LHC interaction point where a dedicated cryogenic detector will be installed as shown in FIGURE 1. This paper gives an account of the preliminary studies of the cryogenic systems requirements, for the Ring-Ring and the Linac-Ring option and, the detector cryogenics.

RING-RING VERSION

The Ring-Ring version uses in large part existing infrastructure and (limited) free space in the 27 km circumference LHC tunnel in which the new main lepton accelerator will be installed. The particles are injected into the LHC tunnel at 10 GeV with a re-circulating superconducting high field pulsed injector which will be described later. Final particle energies in the Ring accelerator at LHC reach 60 GeV. Normal conducting low field magnets guide and focus the electron or positron beams on their trajectory with the exception of the three insertion magnets at each side of the detector which will be SC to reach the high focusing field required. Acceleration of the particles is exclusively done with SC cavities housed in cryomodules. They will be placed at two opposite locations at the existing LHC ring; at point 1 (corresponds to the location of the LHC ATLAS detector) and, at point 5 (corresponds to the location of the LHC CMS detector). While at point 5 a continuous straight section can be built in a bypass parallel to the CMS cavern, at ATLAS two straight sections are conceived on each side of the detector cavern with a connecting particle beam pipe crossing the detector hall. Thus cryomodules are installed at three separate locations at the LHC tunnel requiring three independent cryo-systems for their cooling. The cryomodules of 10 m length contain each eight 0.42 m long 2-cell cavities. The frequency is 721.42 MHz and the acceleration field 11.9 MV/m corresponding to 5 MV per cavity. In total 14 cryomodules are required from which eight are installed in the 164 m long CMS bypass and, respectively three on each side of the ATLAS detector in the 42 m long caverns. Distance between the modules is 3 m.

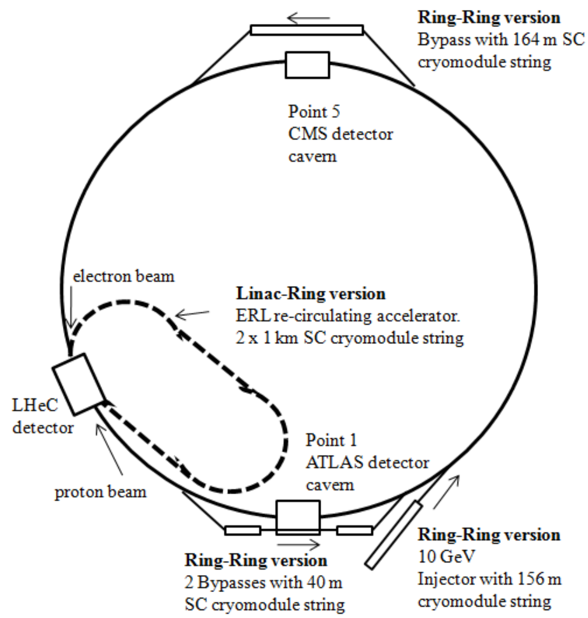

FIGURE 1. Simplified lay-out of the CERN LHC area with the two versions “Ring-Ring” and Linac-Ring” as extension of the 27 km LHC to an electron/proton/heavy ion collider LHeC. (not to scale).

Cooling requirements

The cavities operating at superfluid helium temperatures of 2 K dissipate an estimated 4 W per cavity at 5 MV. The cryomodule has three temperature levels; a 2 K bath containing the cavities, a 5-8 K combined thermal shield and heat intercept for couplers and other equipment and, a 40-80 K thermal shield. In TABLE 1 the thermal loss estimates are listed. With state of the art efficiencies of modern cryoplants reaching 1/COP values of 1000 W/W at 2 K, 250 W/W at 5 K and 20 W/W at 40 – 80 K minimum plant powers are estimated. To the equivalent cooling power at 4.5 K we add a 50 % contingency for the distribution system with transfer lines which run in parallel to the cryomodules. In TABLE 2 the equivalent cooling powers of the three cryoplants are given.

TABLE 1. Thermal loss estimate of cryomodules operating at 2 K. In brackets the values with ultimate thermal losses (50 % contingency) which are taken into account for cryoplant sizing.

Temperature (K)	**2**	**5-8**	**40-80**
One cryomodule			
Static loss (W)	5	15	100
Dynamic loss (W)	32	15	80
Sum (W)	37	30	180
8 modules (CMS site) (W)	296 (444)	240 (360)	1440 (2160)
3 modules (ATLAS left) (W)	111 (166)	90 (135)	720 (1080)
3 modules (ATLAS right) (W)	111 (166)	90 (135)	720 (1080)

TABLE 2. Cryoplant equivalent cooling powers.

Site	Plant power @ 4.5 K (kW)
CMS site	3.0
ATLAS left	1.2
ATLAS right	1.2

At CMS a dedicated 3 kW @ 4.2 K cryoplant is needed. Comparatively modest cooling powers suggest to specify a single compact refrigerator cold box in contrast to split versions as proposed in this paper for the Linac-Ring version described below. The split version is based on LHC technology with a combined surface and underground cold box. It will be installed directly in the underground cavern at proximity to the cryomodules string requiring only warm high and low pressure links with the compressor stations on surface. For the 2 K temperature level two cold compressors with a total compression ratio of 10 are proposed followed by warm compressors to compress the gas to ambient pressure.

At the two ATLAS sites two options are conceivable; the first consists of connecting to the LHC QRL transfer lines and their terminal feedboxes (for inner triplets cooling) at vicinity with a "parasitic" use of excessive cooling power of the LHC cryoplants. The feasibility of this option and potential (negative) impacts have to be studied in more detail which is beyond the scope of this paper. The second option is to install and use two dedicated cryoplants comparable to the one proposed for the CMS site, however, with reduced capacity. Also in this case the cold box will be installed at proximity to the cryomodule strings. The two refrigerators are of the same design principle as for CMS, except for their size and capacity which is much smaller.

10 GeV Injector for the Ring-Ring version

The injector is a three-pass recirculating pulsed 10 Hz machine providing leptons at injection energies to the LHeC Ring machine of 10 GeV. FIGURE 2 shows its basic principle. Cryomodules of the XFEL (ILC) type with 1.3 GHz superconducting cavities are proposed which allow the application of already existing technology requiring little adaptation for LHeC. A 156 m long string will be composed of in total 12 cryomodules each 12.2 m long. Cryogen distribution is done within the volume of the cryostats. Bath cooling is provided with 2 K superfluid helium at saturation conditions. Adopted from XFEL the common pump line of 300 mm runs within the cryomodules envelope to collect vapor of all individual cavity baths. Hence, no external transfer line is required which simplifies the overall design. The suction pressure of 30 mbar is provided by cold compressors in the cold box and subsequent ambient compressors at distance. Two more temperature levels of 5-8 K and 40-80 K are used for intercepts and thermal shielding.

The operation of the injector at LHeC is in part comparable to XFEL, this during the injection and loading phase of leptons into the LHeC ring. During all the other operation phases of a complete LHeC cycle (ramping to final particle energies in the LHC/LHeC tunnel and subsequent physics runs) the injector machine is "idle". Only static heat losses of the cryomodules and the cryogenic infrastructure have to be intercepted during this time period being large compared to the short injection phase. Principly a reduced power cryogenic system

TABLE 3. Thermal loss estimate of the 144 m long string made of 12 XFEL type cryo-modules. In brackets values with 50 % contingency.

Temperature (K)	**2**	**5-8**	**40-80**
Static loss (W)	5	15	100
Dynamic loss (W)	8	3	40
Sum (W)	11	18	140
Sum 12 modules (W)	132 (198)	216 (324)	1680 (2520)

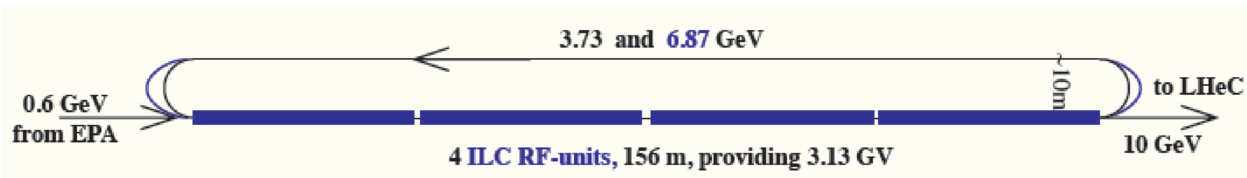

FIGURE 2. Principle of the 10 GeV re-circulating Injector with high gradient pulsed SC cavities (23 MV/m) and 12 cryomodules of the ILC/XFEL type operating at 2 K.

operating with an "economizer", i.e. a large liquid helium storage filled during low demands which boosts the cryomodules during the injection phases could be conceived. However, a simpler approach is the design for constant maximum cooling power when active, and, during idle periods, internal electric heaters in the 2 K bath are switched on. This principle is adopted for this study. A compact single refrigerator cold box providing temperatures from 300 K to 2 K will be installed in a protected area at vicinity to the extraction region of the cryomodule string while the compressor set is at surface. For the estimation of power consumption and cooling performances we shall use the experience gained at DESY during XFEL cryomodules tests. With a final energy of 10 GeV and three pass operation the acceleration field adopted is 23 MV/m. At DESY power consumption measurements have been made on cryomodules for an acceleration field of 23.8 MV/m and 10 Hz operation. Our estimates as shown in the TABLE 3 are based on these recent data. With 1/COP values as used in above section and a 50 % margin for additional thermal losses we estimate the required cooling power of the plant to 2 kW @ 4.5 K.

LINAC-RING VERSION

The ERL (Energy Recovery Linac) is of the racetrack type with two 1 km long straight sections for the six pass lepton acceleration using SC cavities and, two arcs of 1 km radius with normal conducting magnets for re-circulation. FIGURE 3 shows the basic cryogenic lay-out. Its underground location is under study by civil engineering. One option foresees the accelerator outside with respect to the existing LHC tunnel, the other inside (FIGURE 1 shows the version "inside"). The latter is favored as more existing CERN surface areas can be used. Eight 721 MHz SC 5-cell cavities of length 1.04 m long will be housed in 14 m long cryomodules. Bath cooling of the cavities is done with slightly subcooled saturated superfluid helium at 2 K. Heat intercept and thermal shielding is at 5-8 K and 40-80 K. The Cryomodule design will be based on previous work and studies of both existing SC linear accelerators and, such being under construction and planned ones. Among these are CEBAF, ILC, XFEL, SPL, e-RHIC. For this study adapted

TESLA/XFEL type cryomodules are proposed similar to the ones modified and tested in CW mode for BESSY [3]. The parameters of the 944 SC cavities to be used are given in the table below. Due to continous CW operation the dissipated heat per cavity will be 32 W which is a very high load. Appropriate adapted design of the high supply flow and return pump flow lines have to be done and, equally important is the sectorisation of the cryomodules which need more detailed studies. All pipe runs are inside the cryostat strings for this preliminary design. The 1 km long straight sections are sub-divided in four strings with 250 m length each. An individual string is supplied by a dedicated cryoplant providing cooling at all temperature levels. The refrigerator cold boxes will be of the split type as explored and implemented at LHC with a surface cold box close to the compressor set producing temperature levels between 300 K and 4.5 K and, an underground cold box providing the 2 K at corresponding 30 mbar saturation suction pressure with cold compressors. The final location of the ERL will dictate civil engineering constraints and the "ideal" symmetric configuration of placement of the refrigerator will have to be reviewed accordingly. The final distribution of cryogenic equipment can, hence, deviate from this proposal. The total cooling power of the ERL with 944 cavities of 32 W each amounts to 30 kW @ 2 K based on the parameters given in TABLE 4. These figures are state of the art. Studies are ongoing and improved quality factors are expected in the future with reduced thermal load. Promising data is reaching us from BNL.

For the calculation of the cooling performances of the refrigerators only the largely dominating dynamic thermal loads of the cavities are taken into account dwarfing all other thermal losses of the cryomodules becoming negligible in a first order approach. Recent developments and industrial design of large scale refrigerator systems as for LHC [2] indicate the feasibility of a 1/COP of 700 W/W for 2 K plants. Hence, with this figure the total electric grid power amounts to 21 MW. The total equivalent refrigerator power at 4.5 K is estimated to 84 kW. This corresponds to about ½ of the installed cooling power at LHC. In case contingencies are taken into account, which is an engineering design requirement, the cooling capacity would approach LHC. For this preliminary study contingencies are omitted, this also in view of expected future improved cavity performances. Eight cryoplants with 10 kW @ 4.5 K are proposed for ERL. This consists of an engineering challenge, however, the technology is in large part available today. Further development of cold compressors and detailed industrial engineering design of refrigerator cold boxes will be needed.

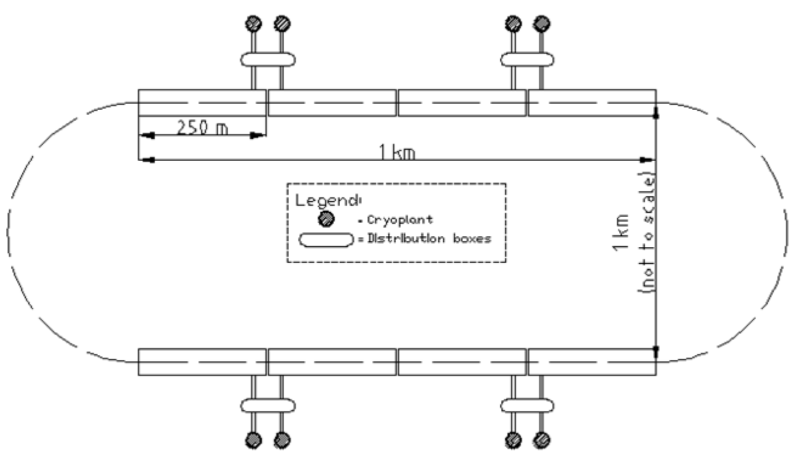

FIGURE 3. Basic lay-out of the 6 pass ERL with two 1 km long SC acceleration sections with a 10 GeV linac each. Eight 3.8 kW @ 2 K cryoplants. Configuration that each pant supplies a cryomodule string of 250 m length. (figure not to scale).

TABLE 4. Parameters and cooling requirements of the ERL (Linac-Ring version).

Parameter	**Value**
Two linacs	length 1 km
linac passes	6 times
Final energy	60 GeV
5-cell cavities	length 1.04 m
Number	944
Cavities/ cryomodule	8
Number cryomodules	118
Length cryomodule	14 m
RF frequency	721.42 MHz
Voltage per cavity	21.2 MV
R/Q	285 Ω
Cavity Q_0	2.5 10^{10}
Operation	CW
Bath cooling	2 K
Cooling power/cav.	32 W @ 2 K
Total cooling power	30 kW @ 2 K

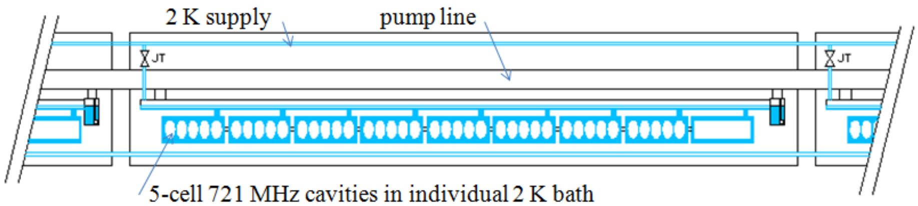

FIGURE 4. Lay-out proposal of the 14 m long cryomodules with eight 5-cell 721 MHz cavities operated at 2 K. Supply pipes and the 30 mbar pump line is within cryostat envelope. Principle similar to TESLA/XFEL and BESSY.

PARTICLE DETECTOR

The Hadron/Lepton collisions will take place in one single dedicated particle detector designed for high precision tracking and particle calorimetry which will be installed at the LHC point 2 underground cavern where currently the ALICE detector is used for heavy ion collisions at LHC.

The magnet system of the LHeC detector comprises a thin superconducting solenoid for particle detection as well as a set of dipoles to bring the electron beam in and allow for a low angle collision mode with the proton beam. The solenoid provides a field of 3.5 T in a free bore of 1.8 m and has an axial length of 5.7 m. The two saddle type dipoles extend the common cold mass length on each side of the solenoid to 9.5 m. The stored energy is about 70 MJ and the total cold mass 14 tons. Aluminum stabilized NbTi Rutherford cables will be used. Cooling is done by forced flow two-phase helium in cooling pipes attached to the Al-alloy coil support cylinder. Electric powering is under study with options of series powering of all magnets with one pair of 10 kA current leads (CL) or with two separate sets at different currents. In both cases low loss HTC conductor will be used at the low temperature level of the CL to minimize power consumption. They are housed in a cryostat installed at distance in a non-radiation environment which contains a larger amount of helium sufficient for safe ramp down in case of refrigerator failure. Redundant centrifugal pumps provide for circulation of the slightly subcooled liquid helium to the magnets. The two-phase return flow is brought to a phase separator in the cryostat. A superconducting link connects the current leads to the magnets and is housed in the common helium transfer line. The refrigerator is at proximity to the cryostat and the compressor set is installed on surface. The expected modest thermal losses of the magnet system of some 60 W @ 4.5 K, low loss current leads and, the estimated overall systems losses suggest a small sized standard refrigerator in the class of 300 to 400 W @ 4.5 K. FIGURE 5 (right) shows a simplified flow scheme of the cryogenic system proposed.

A liquid Argon calorimeter is envisioned as part of an EMC. It can be installed in a separate cryostat or share the cryostat with the solenoid. In the latter case the systems compactness is increased and the inner thermal shield can be omitted. The calorimeter will have an overall 18 m^3 volume from which approximately 12 m^3 will be slightly subcooled liquid argon. Cooling is done with two-phase liquid nitrogen in longitudinal pipe runs and its circulation is provided by two redundant small sized liquid nitrogen pumps. The liquid nitrogen is supplied from a surface standard dewar to an intermediate cryostat which serves also as the phase separator. For the liquid argon filling a line connects from the surface to an intermediate dewar from which it is transferred to the LAr cryostat in the detector. This dewar also serves as emergency volume in case of vacuum loss or leak problems to which the liquid argon can be transferred from the cryostat. FIGURE 5 (left) indicates the functional principle.

The cooling principles of both cryogenic systems proposed in this paper are based on previous design and experience from the much more complex ATLAS detector cryogenics.

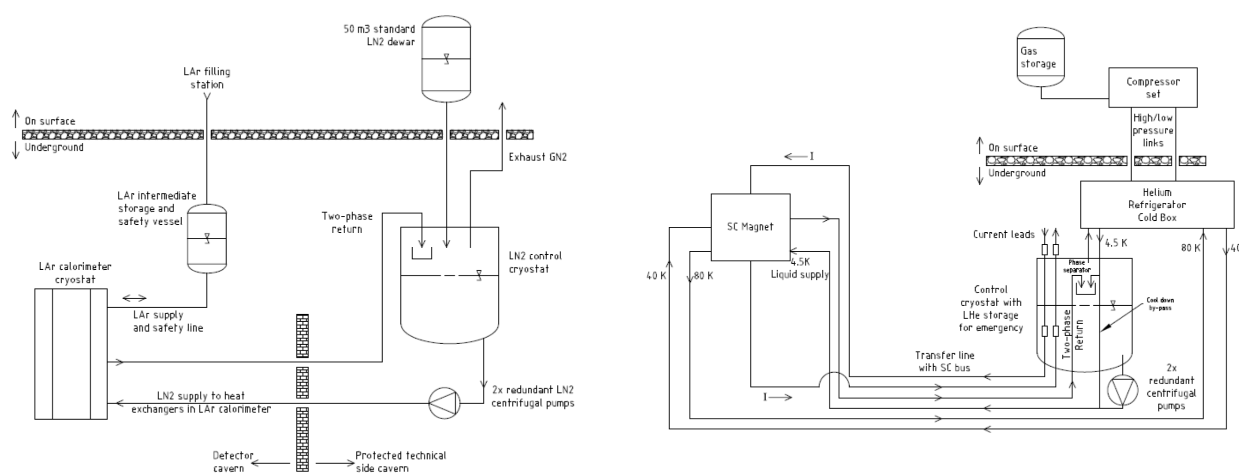

FIGURE 5. Basic cryogenic flow scheme for the cooling of the liquid argon calorimeter of the detector and of the SC magnets of the detector.

CONCLUSION

LHeC offers Lepton and Hadron physics beyond HERA with unprecedented energies. At CERN studies of the physics case and the technological requirements to design and build such new facility are being pursued and a CDR will be published end of 2011 for review. The striking advantage of an extension from LHC to a LHeC lies apart from the new physics in the comparatively small investment cost, the possibility of quasi undisturbed continuation of LHC hadron physics and the fact that the technologies are largely already at hand today. This applies also to the cryogenic part. No so-called "show-stoppers" could be detected during the studies. The cryogenics of the detector technologies developed and implemented at the ATLAS experiment can be used in a "down-scaled" way. For the accelerator cryogenics the two options Ring-Ring and Linac-Ring differ strongly in principle and investment. While for the RR four medium sized 2 K refrigerators are required only for the cryomodules of the injector and the three LHC tunnel bypasses, the LR option with two 1 km long CW operated 2 K SC cavities is extremely demanding. The total installed cryogenic power will likely exceed 100 kW @ 4.5 K equivalent, approaching values of the LHC. However, these estimates are only based on currently proved data. The development of high Q SC cavities is being pursued in several laboratories and new encouraging results are on the horizon which seem to indicate improved quality with positive impact for cryogenics.

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