PRELIMINARY STUDY OF USING "PIPETRON"-TYPE MAGNETS FOR A PRE-ACCELERATOR FOR THE LHC

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Abstract

One of the luminosity limitations of the LHC is the rather low injection energy (0.45 TeV) with respect to the collision energy (7 TeV). The magnetic multipoles in the main dipoles at low field and their dynamic behaviour are considered to limit the achievable bunch intensity and emittance. We report on a preliminary study to increase the injection energy to 1.5 TeV using a two-beam pre-accelerator (LER) in the LHC tunnel. The LER is based on "Pipetron" magnets *as originally proposed for the VLHC. The aim of the study is to assess the feasibility and to identify the critical processes or systems that need to be investigated and developed to render such a machine possible

MOTIVATION

A primary goal for the LER (Low Energy Ring) injector accelerator is to inject 1.5 TeV proton beams into the LHC, instead of the current injection scheme with 0.45 TeV beams from the SPS. At this new energy the field harmonics [1] of the LHC magnets are sufficiently satisfactory to prevent the luminosity losses, which are expected when applying the transfer of the 0.45 TeV SPS beams. In the long term, the LER injector accelerator would greatly facilitate the implementation of a machine, which doubles the LHC energy (DLHC).

BASIC LAYOUT

We examined installation of the LER accelerator inside the LHC tunnel (Fig. 1), 1.35 m above the LHC. LER would accept 0.45 TeV proton beams from the SPS through the existing TI2 and TI8 transfer lines, and then accelerate the two beams to 1.5 TeV. The LER accelerator would be based on two-in-one super-ferric, combined-function magnets (Fig. 2). These magnets were originally proposed for the VLHC Stage 1, a p-p collider in the US for which prototypes were recently successfully tested at Fermilab [2-3].

Boundary Conditions

In order to minimize the potential impact of the LER implementation process on the ongoing LHC physics program, the following LER design and construction criteria have been adopted:

- The LER accelerator will be installed in the LHC tunnel during regular LHC shutdowns.
- No new tunnel digging will be required.
- The current SPS-LHC beam injection scheme will remain intact and will be used "as-is" to inject beams into the LER ring. A reversal to the standard SPS-LHC injection will remain possible.
- The LER accelerator components will be designed and fabricated using as much as possible known technologies.

It is expected that the design and construction of the LER would take 5-6 years.

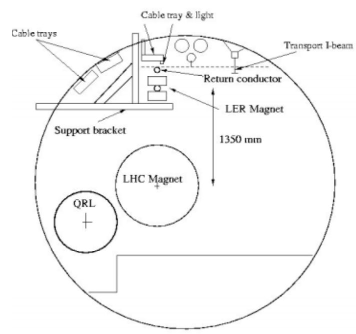

Figure 1: Position of the LER ring above the LHC magnets in the 3.8 m diameter tunnel.

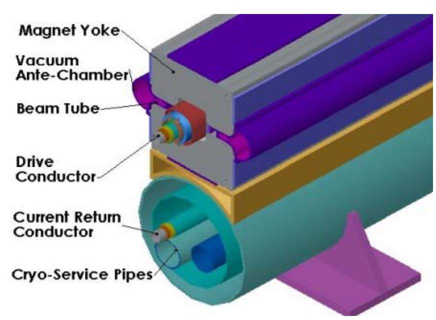

Figure 2: The original VLHC pipetron magnet in the VLHC configuration with the return conductor and cryo-service pipes below the magnet.

LER Beam Handling

In the new LHC beam injection scheme, the proton bunch stacking and the formation of the full intensity beam is performed in the LER ring. The beam passes through the LHC beam-pipe in several of LER/LHC straight sections. This means that in some straight sections the LER and the LHC accelerators share the same beam pipe. This scheme is being proposed to eliminate costly and time consuming digging of new bypass tunnels around the ATLAS and CMS detectors. Injection is using the existing LHC channels. In the straight sections 2, 3, 7 and 8, the two beams remain in independent LER beam pipes. The experiments in points 2 and 8 are supposed to be inactive during the runs with

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LER. In Fig. 3 the beam trajectory is schematically depicted.

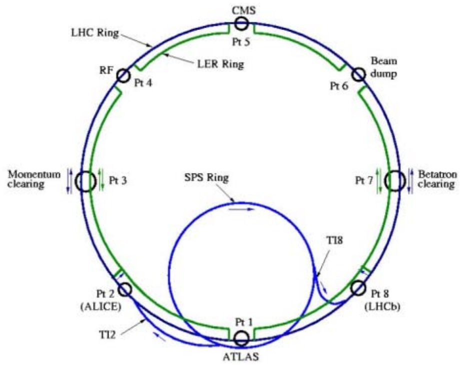

Figure 3: Layout of the two accelerator rings with common beam pipe in 4 straight sections.

After stacking of the clock-wise and the counter-clock wise turning beams and acceleration to top energy, the beams are passed from LER into the full LHC ring using one of the bypass lines in the common straight sections in a single transfer mode. For this single transfer, only one set of the LER transfer line magnets need to be ramped down. The ramping down has to be done in a time period determined by the time interval between the tail and the head of the beam train (~ 87 μs).

LER LATTICE

A preliminary design of the LER optics [4] used the VLHC combined function magnets in order to replicate the LHC optics and match the LHC footprint. The dispersion suppressers were modelled on the ones of the Main Injector at Fermilab with 66 % of the magnet length and 75 % of the LER arc cell length. A list of arc and dispersion suppression cells for LER that allow to exactly reproduce the LHC lattice is shown in Table 1.

At the LER top energy field of 1.595 T, the required magnet current is 55 kA, which is considerably lower than the current originally requested for the VLHC (89 kA for 1.966 T). The required LER gradient corresponds to ± 3 %, as opposed to ± 4 % for the VLHC. The lower field and gradient further improve the quality of the main arc magnets, as the operation is further away from the saturation region (around 1.9 T), or may allow for a larger magnet gap.

Table 1: Arc and dispersion suppressor magnets

Cell Type	Cell Length (m)	Magnet Type	Magnet Length (m)	Number per cell	B (T)	dB/dx (T/m)
Arc	107	GF/GD	12	8	1.595	4.858
Suppressor	80	GSF/GSD	8	8	1.595	10.112

The VLHC magnet gap is 20 mm. The preliminary LER lattice design [4] suggests that a 20 mm gap may be sufficient, but more detailed lattice simulations, including a beam impedance and a beam instability study [5], are needed to reach a more binding conclusion.

LER-LHC BEAM TRANSFER

Beam transfer from the LER ring into the LHC ring is the most challenging task of the LER proposal. The vertical separation of the LER and LHC rings can be made to be 135 cm. This means that the 1.5 TeV beam needs to be bent down (or up) out of the LER (or LHC) ring, transported, and then bent into the LHC (or LER) ring over a vertical distance of 135 cm. About half of this distance, 67.5 cm, is needed to clear any LHC magnets. The LER-LHC transfer line magnets must use only the magnet free sections between D1 and Q5 in the LHC. The proposed design assumes that the beam transfer is made using 4 bends, each with a bending power of 168 Tm (Fig. 4).

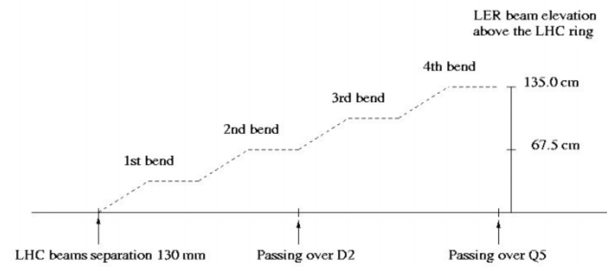

Figure 4: Beam transfer LER-LHC, 4 bends are used to get clear of the LHC magnets.

Once the LER beam has cleared these magnets it will not be difficult to transfer the beam into the LER ring. The operation of clearing the LHC magnets must take place necessarily within the available free space of the straight sections so the transfer line magnets can reside at the LHC ring level. A preliminary LER lattice design [4] was made to produce the footprint as close as possible to that of the LHC to preserve the best possible beam quality in the LER ring and in the LER-LHC beam transfer operation. The VLHC and LHC magnets have a horizontal beam separation of 150 mm and 194 mm, respectively. The beam transfer is done in both horizontal and vertical planes. The preliminary layout of the LHC-LER beam transfer is shown in Fig. 5. The LHC-LER transfer line study [4] indicates that it is necessity to increase the separation between the clock-wise and counter clock-wise beams as early as possible in order to preserve a high quality beam optics in the LHC-LER transfer line. For that reason the D1 dipole has been split into two dipoles (D1A and D1B, each of ~ 8 m length, and ~ 8 T field). This gives a beam separation of ~ 130 mm at the exit of D1B. Both magnets could be made using Nb_3Sn technology as presently pursued by the NED collaboration [6]. D1B could also be made as a longer 4 T field magnet based on NbTi. The first vertical bend is arranged using three sets of magnets. The first set consists of fast pulsing pairs of single bore magnets which, when turned off, allow the beam to pass into the LHC ring. A beam drift space after the first set of magnets is created to allow for the LER and LHC beam pipe separation. The second set consists of pairs of normal-conducting magnets, which can be placed just above the LHC beam pipe. The third set consists of two-bore, high-field superconducting magnets to complete the first bend. The 2nd, 3rd and 4th bends consists of two-bore, high-field superconducting magnets. In the horizontal plane the clock-wise and the counter-clock LHC beams have no separation at D1, but they are separated by 194 mm at D2. The first magnet pair of the first vertical bend section is placed at a location that the clock-wise and counter-clock beams are separated by ~130 mm, more than enough to allow for operating these magnets with a good magnetic field quality. A short, horizontal dipole is placed in front of the second vertical magnet set to produce the 150 mm beam separation for LER. A 20 m long drift space after the V7 magnet string is intended for LER quadrupoles.

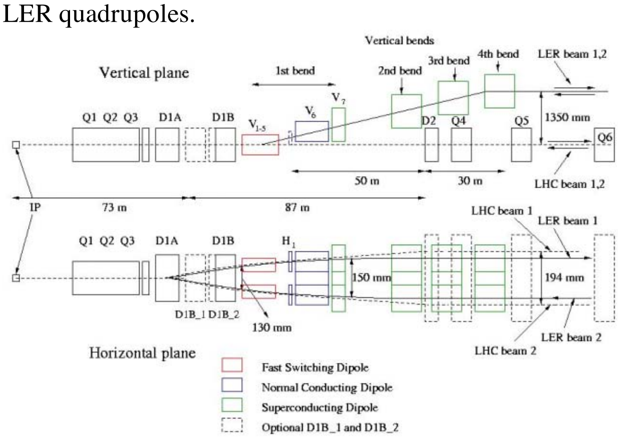

Figure 5: A preliminary arrangement of the LER-LHC transfer line magnets.

In order to understand the choice and arrangement of the magnets in the first bend we must look at the timing sequence of the SPS-LER-LHC beam transfer scheme. This is indicated schematically in Fig. 6.

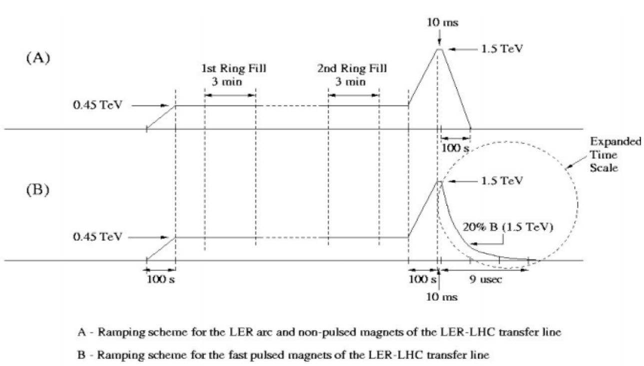

Figure 6: Timing scheme for the LER-LHC beam transfer.

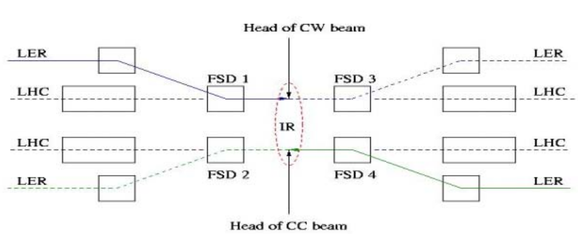

Figure 7: Timing relation between the neighbouring fast switching dipoles.

When the SPS is ready for beam transfer, all LER magnets, including those in the transfer lines, are ramped to the required fields for the 0.45 TeV beam. A ramping time of 100 s is characteristic of the main arc LER magnets. The stacking of the first SPS beam begins and it lasts for about 3 minutes. Then the stacking of the 2nd SPS beam begins and lasts for about 3 minutes as well. As soon as the stacking of the second beam is completed, the LER magnets ramp to 1.5 TeV, again in 100 s. The 1.5 TeV beams may circulate for ~ 10 ms to stabilize, and then the Fast Switching Dipoles of the LER-LHC transfer line are turned off, forcing the beams to circulate from then on in the LHC rings only. In particular, as shown in Fig. 7, the FSD1 and SD4 magnets must stay on for the duration of the beam train (~ 87 μs) after FSD2 and FSD3 were turned off. All FSDs of the first bend will have to be turned off during the passing of the ~ 3 μs long beam gap. Work is ongoing [7] into the design of a magnet with a single cos θ−shaped conductor with flux containing cores using thin Fe3%Si laminations. Such a magnet can have an inductance of ~ 1 μH for a length of ~ 1 m. The conductors should be made out of 99.999 % pure OFHC copper and operate at temperatures below 20 K. Part of the powering circuit will also be located at low temperatures. A minimal distance of 130 mm between the bore centres of the FSD magnet pair is sufficient to suppress possible cross-talk of their magnetic flux.

CONCLUSIONS

A preliminary layout for the lattice and the beam transfers has been found. The new D1 magnets as well as the fast switching dipoles of the LHC-LER transfer line can be made using known technologies. However, the challenge should be underlined of having a totally reliable operation of fast switches to avoid irreversible damage. More studies are needed on the beam stability and the impedance to prove the viability of the LER concept. In such a case, also the safer and more expensive solution, based on bypass tunnels around the detectors, will be investigated.

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