OPTICS OF A 1.5 TEV INJECTOR FOR THE LHC*

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Abstract

A concept is being developed to install a second, low energy ring (LER) above the LHC to accelerate protons from 450 GeV to 1.5 TeV prior to injection into the LHC. The arc and dispersion suppresser optics of the LHC would be replicated in the LER using combined function 'transmission line' magnets originally proposed for the VLHC. To avoid costly civil construction, in the straight sections housing detectors at least, the LER and LHC must share beampipes and some magnets through the detector portion of the straights. Creating the appropriate optics for these LER-LHC transition regions is very challenging: In addition to matching to the nominal LHC lattice functions at these locations the changes in altitude of 1.35 m separating the LER and LHC must be performed achromatically to avoid emittance blowup arising from vertical dispersion when the beams are transferred to the LHC.

INTRODUCTION

The large sextupole component of the LHC magnets' fields at the low energy end of their dynamic range is expected to eventually become a limiting factor in achievable luminosity. One possible path being considered for avoiding this difficulty as part of a luminosity upgrade includes rebuilding the SPS injector with high−field magnets – increasing the beam energy from the current 450 GeV up to 1 TeV for transfer to the LHC. The major drawback to this solution, however, is that the high energy physics (HEP) program would lie dormant during the entire time required to install a new machine in the SPS tunnel.

An alternative possibility that's been recently suggested would be to install a second ring of high quality magnets above the LHC, which would accept the 450 GeV SPS beams and accelerate them to 1.5 TeV for injection into the LHC. The attraction to this approach is that the LER magnets could be installed during routine LHC shutdowns and would not disrupt the HEP program.

A thorough discussion of the low-energy ring (LER) concept and details of the main ring magnets is available elsewhere in these proceedings [1]. In the present note only those aspects of LER implementation that impact the optical design are considered.

LATTICE

For the LER option to make any sense as an alternative to rebuilding the SPS, the project can not involve any major civil construction. This constraint automatically dictates that the LER must replicate the LHC footprint, but more significantly, it also determines that the LER and LHC must share common beampipes, at the very least, through the IR1 and IR5 high luminosity detectors.

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It is currently envisioned that injection from the SPS would continue to occur at IR2 and IR8, with the beams being immediately transferred to the LER for acceleration, but the details of these transactions have not yet been addressed. It would also be desirable to have the LER utilize facilities located in other LHC straights – such as the RF (IR4) and beam abort (IR6) – although it is not obvious that this will be possible. It *is* clear, however, that with the LER 1.35 m above the LHC at the ends of each straight, the momentum and betatron scraping insertions at IR3 and IR7 can *not* be accessed by the LER because the primary collimators are located at the extreme u/s and d/s ends of the insertions.

Arc and Dispersion Suppresser Cells

The main body of the LER lattice is constructed using combined function 'transmission-line' magnets originally designed for the low field VLHC ring [2]. There are several factors that recommend use of these magnets, including; their small (26 x 24 cm) physical cross-section which allows them to fit easily in the tunnel space above the LHC, and; their excellent field quality at the lower strengths appropriate for the LER application eliminates the need for further R&D development [3].

The arc and dispersion suppresser cells are designed to replicate both the LHC optics and machine footprint. The optics and corresponding magnet parameters are shown in Fig. 1, and Table 1.

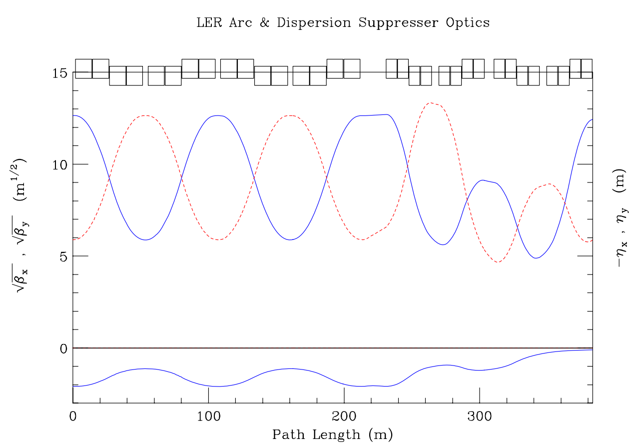

Figure 1: Optics in the arc cells and transition through a dispersion suppresser unit. (Dashed lines are vertical values; solid lines, horizontal).With 90^o of phase advance per cell, $\beta(max) = 160$ m, and $\eta(max) = 2.09$ m.

The dispersion suppresser cells have 2/3 of the bend and approximately 3/4 the length of arc cells. It can be seen in Fig. 1 that the β-match across the dispersion suppresser is not perfect. This is an indirect consequence of duplicating the LHC footprint – bend centers in the LHC suppressers are irregularly spaced, which, for the gradient magnets used in the LER also translates into irregularly spaced focusing centers. The β-wave is small though, and could be easily corrected with trim quadrupoles.

Table 1: Magnet parameters at 1.5 TeV in the standard arc and dispersion suppresser cells.

Cell	L_{cell} (m)	L_{mag} (m)	# / cell	B (T)	B' (T/m)
Arc	106.9	12.0	8	1.595	±4.969
D.S.	80.2	8.0	8	1.595	±10.11

IR1 & IR5 High Luminosity Insertions

The LER is situated 1.35 m above the LHC throughout the main ring arcs. Formidable challenges arise in trying to design a transfer line that can drop the beam from this altitude to that of the LHC, pass the beam through the detector, and then transport it up to the arc elevation again by the end of the straight section. The difficulties arise from the need to keep clear of the LHC IR magnets, and the paucity of free space available to perform these manipulations. The elevation changes must also be accomplished achromatically to avoid residual vertical dispersion at the IP when matching to the LHC injection optics. In addition, the horizontal beam-beam separation is 150 mm in the main LER gradient magnets – compared to 194 mm in the LHC – contributing the further complication that the LER and LHC can not share identical beam separation/recombination schemes.

These constraints are closely intertwined, and the beamline design must consider all issues simultaneously. For example, the achromatic optical condition partially impacts the options available for the vertical bending scheme, and *vice versa*. On the other hand, the vertical bending that initially separates the LER beampipe from the LHC also determines the point where it becomes possible to install horizontal LER magnets to flatten the beam trajectories at 150 mm separation. In subsequents section the design descriptions attempt to de-couple these issues as much as possible.

Horizontal Separation of the LER & LHC Beams

At a minimum, the LER and LHC must share common magnets through the detector, triplets, and first separation dipoles(s) D1. In the baseline LHC design beam separation/recombination spans 104.1 m each side of the triplets. Of this, 23.9 m is consumed by the weak (1.27 T @ 7 TeV/c) 6 x 3.4 m D1 dipoles, and 9.45 m by D2 – leaving a drift space of just 70.75 m. Divergence of the beams exiting D1 is so gradual (1.11 mm/m) that LER transfer magnets could not be installed until the beams were, at most, just 37.6 m from the face of D2, which is much too late to clear D2 vertically and the downstream LHC quadrupoles.

No LER beamline solution has been found that would leave the current D1-D2 configuration intact. A conceptual separation scheme has been devised which fulfills both the LER and LHC separation requirements, but the large-bore, high field dipoles will require new Nb_3Sn technology [4]. Relevant magnet properties, path lengths, and beam separation in this approach are provided by Table 2.

Table 2: Horizontal beam separation and parameters of the horizontal separation–recombination dipoles seen by the LER and LHC beams at 1.5 TeV. Also listed are the beam path length (S), and altitude of the beams (vertical separation of the LER beams begins at the exit of D2A).

Type	L_{mag} (m)	B (T)	S (m)	Alt. (mm)	Sep'n (mm)
LER & LHC Common Dipoles					
D1	8.96	1.70	8.96	0	27
D2A	7.70	1.70	29.13	0	130
LER Only					
$D2B_{LER}$	1.00	2.14	52.63	75	150
LHC Only					
$D2B_{LHC}$	1.26	1.70	104.10	0	194

The weak baseline D1 dipoles are replaced by a single, strong magnet to separate the beams rapidly. This is followed 12.5 m later by an opposing strong dipole (D2A) that removes most of the horizontal beam divergence. At the exit of D2A the beam separation is sufficient to install vertical LER separation magnets. When these vertical bends are energized enough clearance between the LER and LHC is created 23 m downstream to install a short dipole (D2BLER) to fix LER beam separation at 150 mm. When the LER vertical bends are turned off, the LHC beams continue to diverge from D2A until reaching 194 mm separation, where a short, strong D2BLHC cancels the residual horizontal divergence. This scheme fits in exactly the same space as the baseline D1–D2 configuration.

Vertical Separation of the LER from the LHC

The 135 cm elevation change from the LHC to LER altitude is divided into two stages. First, the beam is raised to 67.5 cm and leveled off across the D2B dipole and Q5 magnets in the LHC. Another pair of vertical bend sets complete the transition to 135 m and level the beams off by the end of the straight section. (The decision to break the elevation change into two steps simplifies the optical design needed to cancel vertical dispersion).

The magnet parameters of the first set of vertical bends are summarized in Table 2. The initial magnets, labeled V1 – V5, enclose beampipes common to both the LHC and LER. Energizing these magnets determines whether the circulating beams will move up to the LER or get transferred into the LHC. These are pulsed magnets which must be able to turn off in 3 μsec – the gap length between the head and tail of the LHC bunch train. Work is progressing well on the design of these magnets [5], which will be single cosθ-shaped copper conductors operating near 90 kA. The D2BLER dipole is 4 m downstream of the last V5 magnet. This is immediately followed by 6 more of the single conductor vertical dipoles, and then 3 short, high–field, superconducting dipoles. The other 3 bend centers completing the vertical transition all consist of 7 short, 8 T magnets.

Table 3: Magnet parameters, including apertures, of the first set of vertical bends at 1.5 TeV separating the LER and LHC beams.

Type	#	L_{mag}(m)	B (T)	w (mm)	h (mm)
Fast Pulsed Dipoles					
V1	5	1.10	1.667	40	40
V2	4	1.00	1.503	40	50
V3	3	1.00	1.370	40	60
V4	2	1.00	1.255	40	70
V5	2	0.95	1.158	40	80
Normal Conducting					
D2B	1	1.00	2.14	30	30
V6	6	2.00	2.00	30	30
Superconducting					
V7	3	1.50	±8.00	30	30

LER Optics in the IR1 & IR5 Insertions

It is clear from the earlier discussions that the vertical and horizontal beam manipulations are the dominant factors driving the LER insertion design. Developing an optical solution is fairly straightforward by comparison.

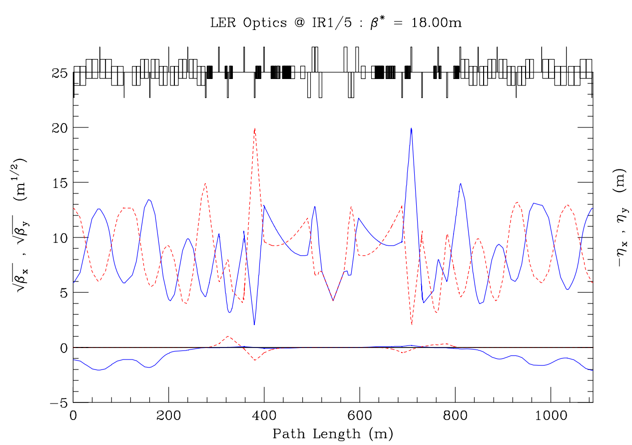

Figure 2: The high luminosity straights IR1 & IR5 with injection optics: β* = 18 m, and β(max)= 400 m.

LER lattice functions are illustrated in Fig. 2, extending through the dispersion suppresser plus first full arc cell each side of the straight. The optics are matched to the LHC injection β* of 18.0 m, with zero dispersion at the IP in both planes. Although the maximum β of 400 m is somewhat larger than the 300 m of the LHC injection optics, it should be possible to reduce this value in future design iterations. The corresponding quadrupole parameters are listed in Table 4. There are 2 more quadrupoles each side of the IP than there are in the LHC – a consequence of the additional LER constraints of cancelling vertical dispersion and its derivative. Quadrupole #9 in the LER is directly above the LHC Q7 at the end of the straight.

Table 4: Quadrupole parameters at 1.5 TeV in the LER insertions IR1 & IR5 for beam #1 and β* = 18 m. The triplet quadrupoles are common to the LER & LHC. Magnets 1-10T are powered exactly anti-symmetrically.

Straight Section Quads			
Quad #	L_{mag} (m)	B' (T/m)	
		u/s	d/s
1	6.30	-40.847	40.847
2a &2b	5.50	40.847	-40.847
3	6.30	-40.847	40.847
4	2.0	131.09	-131.09
5	2.0	-157.03	157.03
6	2.0	198.65	-198.65
7	2.0	-143.52	143.52
8	2.0	159.34	-159.34
9	2.0	-66.78	66.74
Dispersion Suppresser Trim Quads			
10T	1.0	37.58	-37.58
11T	1.0	-32.13	23.05
12T	1.0	8.07	-7.91

SUMMARY

A preliminary design of a 1.5 TeV LHC injector constructs the ring lattice from transmission-line gradient magnets. A solution for IR1 & IR5 matching LHC injection optics has also been found. It requires re-design of the LHC separation scheme, and relies on new pulsed dipoles for vertical separation between the LER and LHC.

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