

# INJECTION AND DUMP SYSTEMS FOR A 13.5 TeV HADRON SYNCHROTRON HE-LHC

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## Abstract

One option for a future circular collider at CERN is to build a 13.5 TeV hadron synchrotron, or High Energy LHC (HE-LHC) in the LHC tunnel. Injection and dump systems will have to be upgraded to cope with the higher beam rigidity and increased damage potential of the beam. The required modifications of the beam transfer hardware are highlighted in view of technology advancements in the field of kicker switch technology. An optimised straight section optics is shown.

## INTRODUCTION

For HE-LHC two injection energy options are considered, 450 GeV and 1.3 TeV. The flattop energy is 13.5 TeV. The beam parameters refer to the 25 ns HL-LHC beams with  $2.2 \cdot 10^{11}$  particles per bunch in a normalised rms emittance of  $2.5 \mu\text{m}$  [1].

## INJECTION

In case of a 450 GeV injector, the injection system and transfer lines can be the same as for LHC. Only the injection region optics would require rematching if the HE-LHC side experiments differ in size and optics from the present ones. For an injection energy of 1.3 TeV, the beam rigidity increases by a factor 2.9 compared to LHC. There are several options: increasing proportionally the insertion space for septa and kicker and limit the  $\beta^*$  of the experiment, or introducing new hardware concepts such as superconducting septa, beam passage through a quadrupole cryostat, and kickers terminated in a short circuit together with a higher rate of rise of current. Superconducting septa seem unavoidable for 1.3 TeV injection: the transfer line would need dipole fields of 6 T using the existing TI 2 and TI 8 tunnels. The septum angle can be significantly reduced by passing the

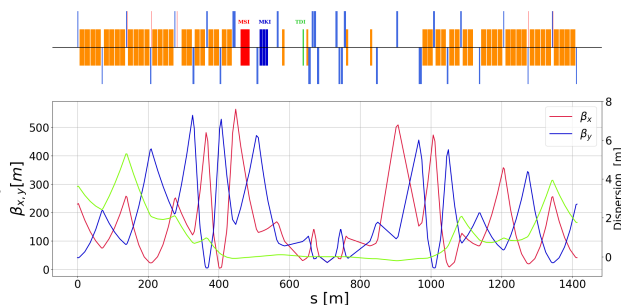


Figure 1: Optics of the long straight section in Injection Point (IP) 2 housing injection of B1 (septum in red, kicker in blue, injection dump in green) and a side experiment.

Table 1: Injection Kicker Parameters

		LHC	HE-LHC	
Inj. energy	GeV	450	1300	1300
Rigidity	T-m	1503	4339	4339
Required Bdl	T-m	1.20	3.47	3.47
Rise time	$\mu\text{s}$	1.0	1.0	<b>1.5</b>
Gap width/height	mm	54/54	40/40	40/40
Gap field	T	0.11	0.215	0.215
dI/dt	kA/ $\mu\text{s}$	4.7	6.8	4.6
Current	kA	4.7	6.8	6.8
Voltage	kV	47.3	<b>68.5</b>	45.7
# magnets		4	6	6
Install. length	m	15.3	22.6	22.6

beam through a hole in the cryostat of the upstream matching quadrupole. For the injection kickers, the space between the straight section quadrupoles is increased to install 6 instead of 4 modules. With this optics, shown in Fig. 1, where the injection planes are swapped with respect to the LHC system, a  $\beta^*$  of around 10 m can be reached. Assuming a field rise time of  $1 \mu\text{s}$  the kicker system PFN would need to be charged to almost 70 kV; relaxing the rise time to  $1.5 \mu\text{s}$  decreases the voltage to 46 kV, similar to the present system. The current would be slightly increased compared to LHC but remains a reasonable value of 6.8 kA, see Table 1. Increasing the field rise time to  $1.5 \mu\text{s}$  impacts the overall filling of the machine. In particular since, due to the damage limit of transfer line collimators and the injection dump, only batches of 100-150 bunches can be injected at once (energy deposition similar to HL-LHC), which requires shorter rise times than present to reach the same fill factor [2]. One could envisage to minimize the impact on the high-luminosity experiments, at the expense of the  $\beta^*$  reach at the side experiment, by further increasing the space for the injection systems. With increased magnetic length the rise time can be lowered, thus the total number of bunches in the machine can be increased. It has to be kept in mind that the experimental cavern constrains the location of the side experiment: however, one could envisage to shorten the presently available space for the experiments and shift the triplet between injection and experiment into the cavern to gain more space for the injection system.

## EXTRACTION

The beam dump system concept for HE-LHC is based on that of the present LHC, which uses a sequence of (i) extract, (ii) dilute and (iii) absorb, to abort the  $\sim 700$  MJ beam in a loss-free way [3]. The present dump system comprises laminated steel pulsed extraction kicker magnets, DC powered laminated steel Lambertson septum magnets, laminated

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steel pulsed dilution kicker magnets and a 7.7 m long, 0.7 m diameter graded graphite beam dump block, surrounded by steel and concrete shielding. The extraction and dilution kickers use the same solid-state fast high current thyristor switch technology. The dump kickers have alumina vacuum chambers with a few  $\mu\text{m}$  of Ti coating for reducing the beam coupling impedance. The system is completed by beam instrumentation and dedicated passive protection devices to intercept beam in case of a kicker error.

For HE-LHC it is assumed that the existing tunnel and caverns are reused, which implies similar extraction trajectories, both horizontally and vertically, and therefore similar kicker and septum angles. With this in mind, the sweep radius is limited to  $\sim 300$  mm, to avoid significant extra civil engineering to enlarge the existing LHC dump caverns. The total length of the beamline from extraction kicker to dump block is about 975 m. The dump systems for Beam 1 and Beam 2 are located symmetrically around P6 of the LHC and use the full straight section, with a special optics to provide the long drift distance needed between kicker and septum, and from the septum to the next machine quadrupole, to allow the beam to be extracted past the cryostat. For the present layout, there are only two stand-alone matching quadrupoles each side of the IP (Q4 and Q5) which are not in the continuous cryostat. This overall concept is retained for HE-LHC. The main changes are the extra  $\int B\text{-dl}$  required for the kicker and septum elements, and the increased beam energy to be absorbed in the dump block and protection devices. The optics function and phase advances between kicker and protection devices are kept at a level very similar to LHC, while the drift space between the matching quadrupoles is increased by 7 m to allow for a longer extraction kicker system, see Fig. 2. The increased space requires shifting the dilution kickers for the other beam further downstream. The implication for the subsystems are presented below.

### Extraction Kickers

For the extraction kickers the same deflection as for LHC is assumed to clear the first thin normal conducting (NC) septum blade. To cope with the higher beam rigidity, it is envisaged to increase the installed magnetic length, and both the peak current and the rate of the current rise. In case of a higher injection energy, the kicker gap can be decreased.

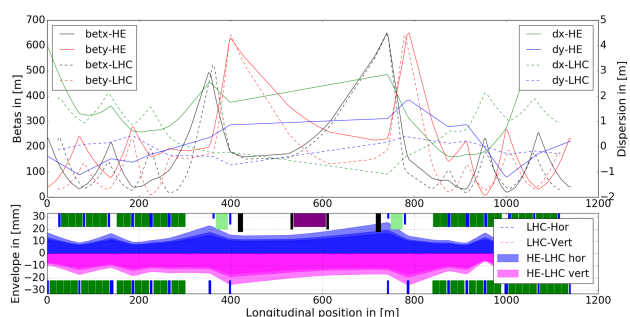


Figure 2: Optics and beam envelopes of the Long Straight Section (LSS) housing the extraction systems for both beams.

Table 2: Extraction Kicker Parameters

Parameter	Unit	LHC	HE-LHC	HE-LHC
Inj. energy	GeV	450	1300	450
Rigidity	T·m	23337	45034	45034
Required B·dl	T·m	6.30	12.16	12.16
Rise time	$\mu\text{s}$	3.0	3.0	3.0
Gap width/height	mm	72/72	72/54	72/72
Gap field	T	0.323	0.492	0.492
dI/dt	kA/ $\mu\text{s}$	6.2	7.0	9.4
Current	kA	18.5	21.1	28.2
Voltage	kV	29.7	23.9	23.9
# magnets		13.7 <sup>1</sup>	33	33
Installed length	m	25.6	32.5	32.5

Table 2 shows the main kicker parameters for the HE-LHC options with 450 GeV and 1.3 TeV injection energies, respectively. As comparison the present LHC extraction kicker parameters are listed. The module length is reduced to decrease the magnet inductance and hence the required capacitor voltage compared to the LHC kickers. However, the peak current of 28 kA needed to reach the higher gap field of 0.5 T is demanding for the HE-LHC option with 450 GeV injection energy. In case of 1.3 TeV injection energy, the gap can be reduced and a peak current only slightly higher than the present system is required. Both HE-LHC options rely strongly on the increased system length from 26 m to 33 m. The rise time is assumed to be the same as for the present system, however, in case of swept beam the energy deposition would exceed the damage limit of the extraction protection absorbers by a factor 2-3. Decreasing the rise time of the kickers from 3 to 2  $\mu\text{s}$  would increase the bunch separation which is more effective than increasing the spot size itself. In this case the rate of the current rise would increase from 9.4 to 14 kA/ $\mu\text{s}$  and the capacitor voltage from 24 to 36 kV, which significantly affects the design of switches and electrical contacts, the switch dynamic range and related switching speed, and the probability for kicker erratics due to high voltage breakdown. The bunch separation on the absorbers and consequently the rise time of the kickers needs still to be defined.

### Extraction Septa

Extraction of the beam is vertically above the continuous cryostat. The HE-LHC layout would keep the same entrance location, but only use two (B+C) of the present three normally conducting Lambertson septum versions. The deflection angle of 2.4 mrad needs to be maintained, which requires a  $\int B\text{-dl}$  of 108 T·m. With the field increased to the maximum possible values a total of 70 T·m is available. The remaining deflection would be provided by either an additional seven 1.24 T MSDC units occupying an additional  $\sim 35$  m, or by two new 4 T, 4.8 m long superconducting septa [4] occupying an additional  $\sim 11$  m. The superconducting (SC) version has the advantage of keeping the kick centre closer to the original location at the centre of LSS6, which

<sup>1</sup> 15 modules are installed to correctly extract with one unit missing

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reduces the vertical trajectory difference with respect to the reference. The latter is assumed as the baseline: the parameters for the two options are compared in Table 3. For the SC septum the details of the integration and susceptibility to beamloss need to be addressed in detail - the SC septum will need to be located adjacent to the present TCDS septum protection device, or another 10 m downstream, which changes the kick centre and moves the vertical offset another ~25 mm downwards - this could pose a problem for the extracted beam passage past the Q4 cryostat.

Table 3: Options for HE-LHC Extraction Septa

Parameter	Unit	Baseline	Option
New units		2	6
New septum type		SC	NC
New septum field	T	4.0	1.24
Total $\int B \cdot dl$	T·m	108	108
Additional total length	m	35	11
$\Delta_S$ Kick centre	m	13.9	18.1
$\Delta_v$ Trajectory	mm	-33.3	-43.5

## DUMP LINE AND DILUTION

The dilution system is already a challenge for HL-LHC at 7 TeV, where the peak dose in the dump absorber is around 3 kJ/g for a regular sweep, and goes up to around 5 kJ/g for the assumed worst case failure of 50% missing horizontal dilution [5]. For the HE-LHC dump absorber, the most suitable material would presently be a solid graphite core with  $\sim 1 \text{ g/cm}^3$  density. The limit in deposited peak energy density fixes the dilution sweep length, which is a factor 2-3 longer than the present LHC sweep length. The dilution kicker parameters are calculated based on the given dump line geometry and reasonable hardware limits of 25 kA and 30 kV. Assuming the present kicker dimensions and inductance per unit length, the length and number of modules are varied to reach the target kick, sweep length, voltage and current. The resulting dilution kicker characteristics are shown in Table 4. The HE-LHC dilution system requires a total installed length of 42 m with 38 modules, compared to 20 m system length and 10 modules for LHC. The beam offset at the exit of the vertical dilution kickers results in a tight aperture. The parameters shown in Table 4 result in a 2.6 turn beam pattern spiral with a maximum radius

Table 4: Parameters of the HE-LHC Dilution Kickers

Parameter	Unit	DiluterV	DiluterH
Required kick	mrاد	0.329	0.318
Required B·dl	T·m	14.82	14.32
# modules		24	14
System length	m	24	18
Gap width/height	mm	66/36	58/32
Field	T	0.88	1.02
Current	kA	23.2	26.1
Voltage	kV	28.6	28.9
Frequency	kHz	44.4	44.4
H/V offset at exit	mm	10.6/4.1	2.4/0

of  $\sim 200$  mm on the dump absorber. The corresponding frequency of 44 kHz (14 kHz for LHC) and the field of  $\sim 1$  T require a careful consideration of the magnetic material used. Due to its high saturation field of up to 2 T, steel laminations of FeSi type were chosen for the present LHC extraction and dilution kicker yokes. For frequencies in the range of 50-100 kHz the magnetic permeability of these materials strongly decreases which would increase the reluctance of the yoke. However, for large aperture magnets, as specified here, and the frequency of  $\sim 44$  kHz, the reluctance of the yoke is still negligible compared to that of the aperture. The challenging aperture requirements, due to the beam offset in the vertical dilution kickers, could be overcome by increasing the oscillation frequency. In this case nanocrystalline steel, with its potentially higher permeability at these frequencies, would need to be studied as yoke material. As studied for the FCC-hh dilution pattern, the beam deflection tolerances in the dump line are surprisingly tight due to neighbouring bunches or branches starting to overlap and exceeding the energy deposition limits on the dump absorber [6]. Hence, the required field tolerance and consequently, the permeability of the magnetic material has to be carefully evaluated. A focusing structure in the dump line could alter the beam spot size on the dump and relax the dilution requirements. Due to the given geometry of the extraction, integration of quadrupoles upstream of the dilution kickers seems, however, to be excluded. It is assumed that the dilution kickers are excited with a damped sinusoidal waveform, implying that the sweep spiral would go inwards. In case of an asynchronous beam dump the swept beam would cross inner turns. This failure scenario was intensively studied for FCC-hh and resulted in acceptable levels of energy deposition on the absorber block [5]. In case of HE-LHC the bunch and spiral spacings of the sweep pattern are different with respect to FCC-hh, as are the rise times of the extraction and dilution kickers which means that this scenario needs to be studied for HE-LHC.

## CONCLUSIONS

HE-LHC injection and extraction concepts with optimised straight section optics and feasible kicker and septum parameters are presented. In case of 1.3 TeV injection energy, the luminosity reach of the experiments is impacted by shorter injection batches due to absorber limits and, depending on the size and  $\beta^*$  reach of the side experiments, due to the injection kicker rise time. Both, the absorber limits for injection and extraction protection and the shortest possible rise time remain to be studied; therefore significant changes to the overall system parameters and consequently to the luminosity reach are still possible. For the extraction systems, the higher injection energy option renders a more relaxed kicker system due to the smaller magnet aperture. The septa baseline for both injection at 1.3 TeV and extraction requires superconducting technology. The dilution system is challenging due to its large aperture and high oscillation frequency which might require research in magnetic materials.

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