Chapter 11

Beam injection

11.1 Overview

Injection into the LHC is performed in the combined experimental and injection insertions in Points 2 and 8. The transfer line TI 2 brings the beam to within ∼150 m left of Point 2 for injection into Ring 1, and TI 8 delivers the beam ∼160 m right of Point 8 for injection into Ring 2 [59].

A schematic layout of the injection region at Point 8 is given in figure 11.1. In both insertions, the beam approaches the LHC from outside and below the machine plane. The beam is directed by a series of dipoles in the injection line, already located in the LHC tunnel, towards a series of five Lambertson-type septum magnets, which deflect the beam horizontally by 12 mrad under the outer ring. A series of four MKI kicker magnets deflects the beam vertically by 0.85 mrad onto the closed orbit. The vertically defocusing quadrupole Q5, between the MSI and the MKI, provides, through its kick enhancement, about one quarter of the required total vertical deflection. To facilitate the setting up of the injection with pilot bunches and to protect the LHC in case of malfunction of the injection kickers, an injection beam stopper, TDI, is placed 15 m upstream of the superconducting recombination dipole D1, supplemented by an additional shielding element, TCDD, 3 m upstream of D1. The protection against injection errors is further complemented by two collimators, TCLI, near the superconducting quadrupole Q6 on the other side of the insertion.

The geometrical layout and arrangement of MSI, MKI and TDI/TCDD is virtually identical for both injection regions. However, despite being based on the same design criteria, the optics varies between Point 2 and Point 8 due to the displaced IP in Point 8. The precision of the injected

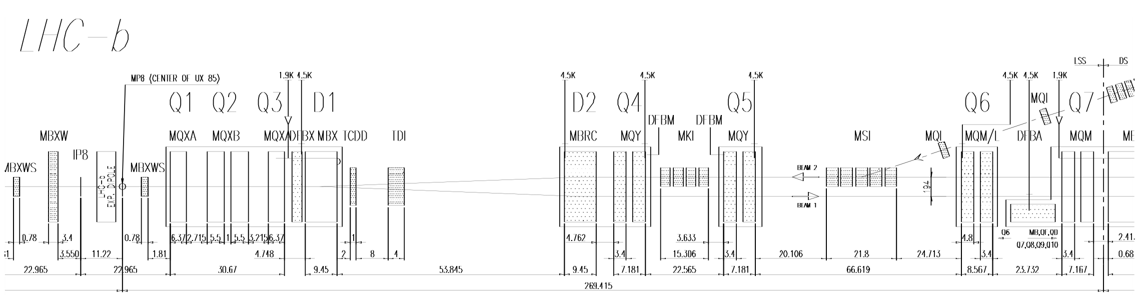

Figure 11.1: Schematic layout of the injection region right of IP8 (distances in m).

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Table 11.1: Main parameters of the injection septum magnets.

	MSIA	**MSIB**	
Septum core length	4000	4000	mm
Coil core length	3650	3650	mm
Core width	734	734	mm
Core height	529	529	mm
Gap height	25	25	mm
Septum thickness	6	15.5	mm
Number of coil turns	16	24	-
Number of coil layers	4	6	-
Number of turns per layer	4	4	-
Electrical coil resistance at 20 °C	10.9	16.4	mΩ
Inductance	10.2	23.7	mH
Dissipated power	10.6	15.9	kW
Water flow per coil	7.9	11.8	l/min
Coil pressure drop	5	5	bar
Design current	950	950	A
Nominal magnetic field in the gap	0.76	1.13	T
Magnet weight	9800	9900	kg

beam's position with respect to the LHC closed orbit is specified to be less than $\pm 1.5\sigma$, including SPS closed orbit errors at extraction, ripple and drifts of power supplies, and injection kicker ripple. Further parameters can be found in the descriptions of the individual components.

11.2 Injection septa

Five septum magnets (MSI), of two different types (MSIA and MSIB), deflect the incoming beam horizontally by 12 mrad under the outer ring. For injection into Ring 1, the septa are located in RA23 between Q6 and Q5, and similarly for Ring 2 in RA87. The MSIA and MSIB magnets differ in the septum thickness (the distance of the holes for the circulating beams from the pole face) and the coil configuration, and, consequently, the field in the gap. In the beam direction, there are three MSIB magnets followed by two MSIA magnets and, including the inter-magnet gaps, the whole system stretches over 21.8 m. The main parameters of the injection septum magnets are given in table 11.1.

The magnets were designed and built by a collaboration between CERN and the Institute for High Energy Physics (IHEP), Protvino, Russia. See figures 11.2 and 11.3 for views of the magnets. The 1.0 mm thick steel laminations have a 10 μm thick Fe_3O_4 layer as electrical insulation. The magnet yokes are an all-welded construction and are assembled from different half cores, the so-called septum core and the coil core. The septum core contains circular holes for the circulating beams, thus avoiding the need for the careful alignment of the usually wedge-shaped septum blades used in classical Lambertson magnets. The septum core is longer than the coil core to reduce the

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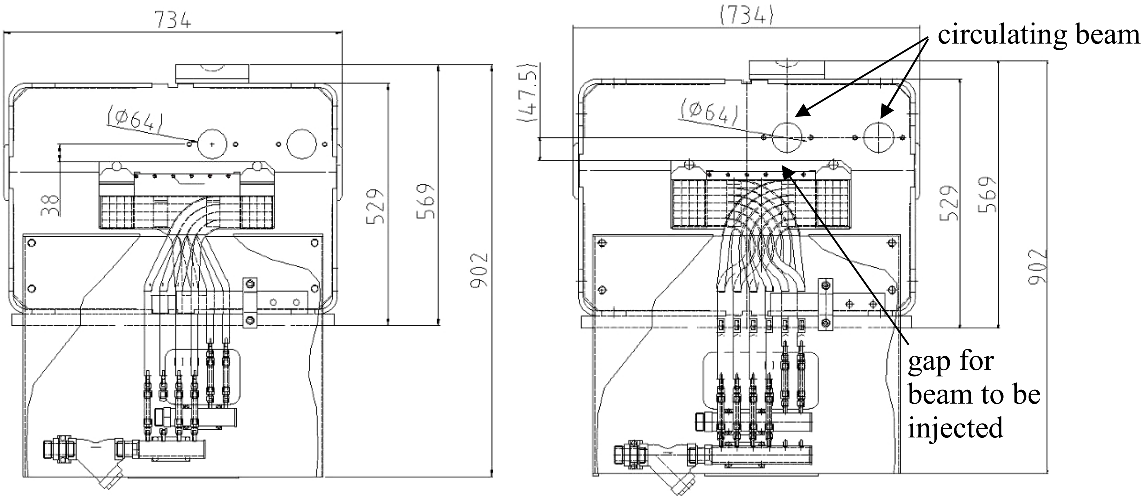

Figure 11.2: MSIA (left) and MSIB (right) connection front face view (dimensions in mm).

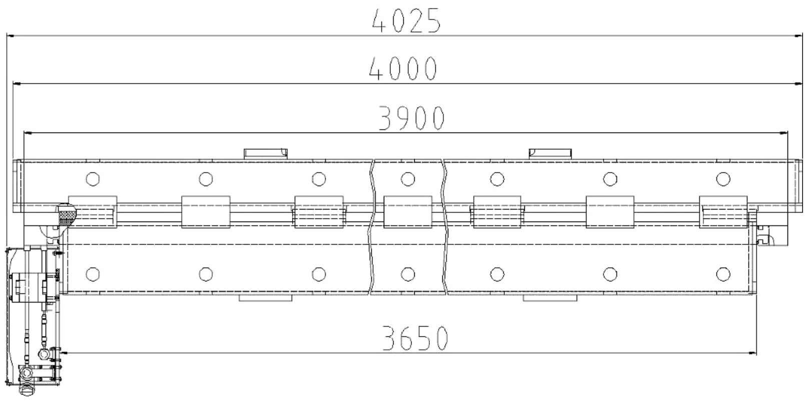

Figure 11.3: MSI side view (dimensions in mm).

stray field extending from the field gap to the circulating beam holes. The coil core holds the single pancake coil. The coils are made from a 15 mm wide OFHC square copper conductor, with a circular cooling hole of $\approx$ 4.5 mm diameter, insulated with glass fibre tape, and impregnated using a radiation resistant resin. Each coil water outlet carries a thermo-switch, to prevent overheating of the coil by switching off the MSI power converter, through the magnet surveillance system, in the event of a failure in the cooling circuit. The trip temperature on the switch is 65°C.

11.3 Injection kickers

The injection kicker system (MKI) comprises four fast pulsed magnets per injection. The magnets are housed in a separate vacuum tank containing both beam pipes, which has been recovered from the LEP separators. For injection into Ring 1, the magnets are located in RA23, and for Ring 2 injection, in RA87. The pulse generators and part of the power and control electronics are located

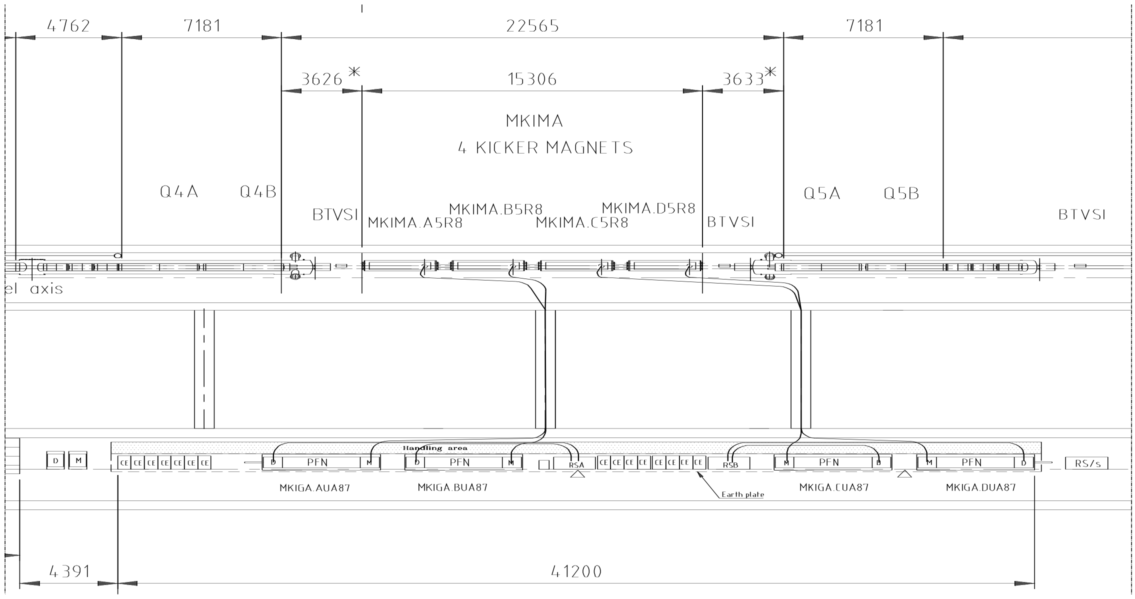

Figure 11.4: Injection kicker layout right of Point 8 (plan view) (distances in mm).

in the adjacent underground galleries: UA23 for Point 2 and UA87 for Point 8. The transmission cables pass through two existing holes previously used for wave-guides. Figure 11.4 shows the layout (plan view) around the LHC injection kickers in Point 8.

The beam to be injected approaches the kicker system from below at an angle of 0.85 mrad, requiring a total integrated dipole field of 1.2 Tm for deflection onto the central machine orbit. To limit the emittance blow-up at injection, reflections and flat top ripple of the field pulse must stay below $\pm$ 0.5%, which is a very stringent requirement. The pulse repetition time, imposed by the SPS acceleration cycle is 18 s in the case of 3-train extraction. The LHC will be filled with 12 batches of 5.84 μs or 7.86 μs duration, to be deposited successively on the machine circumference, with 11 gaps of 0.94 μs in between them to allow for the injection kicker rise time. One final gap of 3.0 μs allows for the fall time of the injection kickers and allows also for the rise time of the beam dumping kickers. The main parameters are summarised in table 11.2.

Figure 11.5 shows the schematic circuit diagram of the injection kickers. Each magnet is powered by a separate pulse-forming network (PFN). Two PFNs are charged simultaneously from one resonant charging power supply (RCPS). To be able to vary the pulse duration, a main switch (MS) and a dump switch (DS) are needed, one at either end of the PFN. A carefully matched high-bandwidth system is necessary to fulfil the stringent pulse response requirements. The system is therefore composed of a multi-cell PFN and a multi-cell travelling wave kicker magnet, connected by a matched transmission line, and terminated by a matched resistor. To achieve the required kick strength, a low characteristic impedance of 5 Ω was chosen.

The design voltage is 60 kV, as in most SPS kicker installations, allowing the use of several proven components such as transmission lines, connectors, and termination resistors. The voltage on the magnet is half of the PFN voltage. Allowing for overshoot, the design voltage of the magnet is 35 kV.

Table 11.2: Main MKI system parameters.

Item	Value	Unit
Number of magnets per system	4	-
System deflection angle (4 magnets)	0.85	mrad
$\int$ B dl	0.325	Tm
Magnet beam aperture (diameter)	38	mm
Characteristic impedance	5	Ω
Operating charging voltage (PFN)	54	kV
Field flat top ripple	$< \pm 0.5$	%
Field flat top duration	up to 7.86	μs
Field rise time 0.5%–99.5%	0.9	μs
Field fall time 99.5%–0.5%	3.0	μs
Yoke length	2.650	m
Magnet length (mechanical)	3.400	m

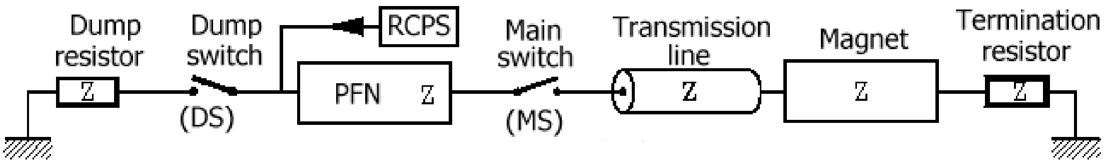

Figure 11.5: Schematic circuit diagram.

Each kicker magnet consists of a series of 33 cells, which is a compromise between bandwidth and cost. Figure 11.6 shows a cross section of one magnet cell, with matching capacitors mounted between a high voltage and a ground plate. The plates are spaced by three ceramic-metal insulators, which together form an independent cell assembly. To achieve a characteristic impedance of 5 Ω within the space constraint of the 540 mm diameter tanks, two 210 mm diameter ceramic plate capacitors with contoured rims have been used, leading to a nominal self-inductance and capacitance per cell of 101 nH and 4.04 nF, respectively, including the plate end effect.

In order to reduce beam impedance while allowing a fast field rise time, the beam passes through a ceramic pipe with silver stripes on its inner wall. The stripes provide a path for the image current and screen the ferrite yoke against beam induced heating. The stripes are connected to the standard vacuum chambers of the machine directly at one end, and via a decoupling capacitor of 300 pF at the other, using the ceramic pipe itself as dielectric. The pipe is made from a 3 m long extruded ceramic tube with a wall thickness of 4 mm.

The ferrite cores are made from high permeability, high resistivity NiZn, 8C11 grade, and have a C-configuration to allow earthing of the coaxial HV cable input connection and the output connection to the terminating resistor [60]. In addition to their magnetic properties, which are specially adapted to this application, they exhibit very good vacuum performance after appropriate treatment. In order to obtain a fully bakeable design, the conductors are made from stainless steel. The shape of the ground conductor has been optimised to provide a homogeneous field without requiring shims on the ferrites.

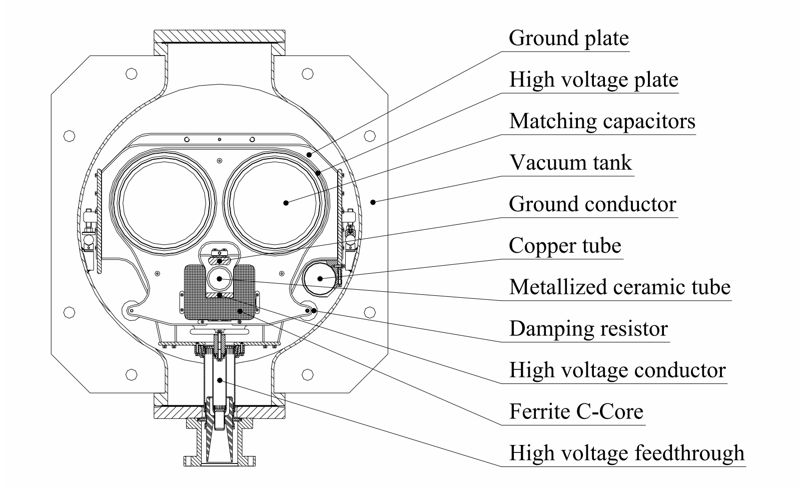

Figure 11.6: MKI magnet cross section.

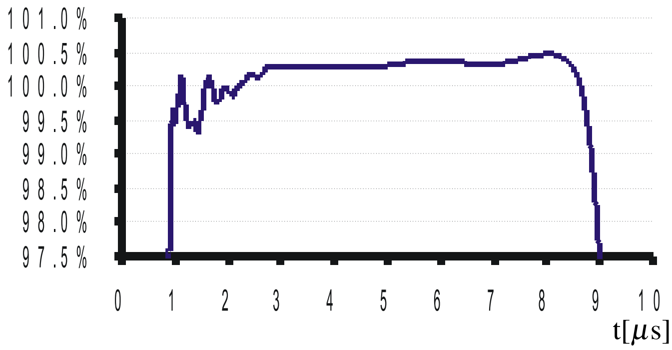

Figure 11.7: MKI prototype current pulse shape (top part of scale).

PFN type generators are used to produce rectangular pulses with very low ripple. The top part of the current pulse in the prototype magnet is shown in figure 11.7. Main and dump switches have been designed for minimum size and easy maintenance. They use three-gap thyratrons of types CX 2003 and CX 2503, installed in independent tanks, with isolating transformers for heaters, reservoirs, and grid biasing. These switches are mounted directly onto the PFN to save space and cost, as in the SPS injection kicker installation [61].

The pulse is transmitted from the PFNs to the magnets through 10 35 m long parallel RG220 type coaxial cables of 50 Ω impedance. The conductors are drawn from electrolytic copper, and low density polyethylene of high purity is used as dielectric. The cable can be exposed to an integrated radiation dose of at least 10^6 Gy. Cable ends are terminated by moulded high voltage connectors, as already in use in the SPS.

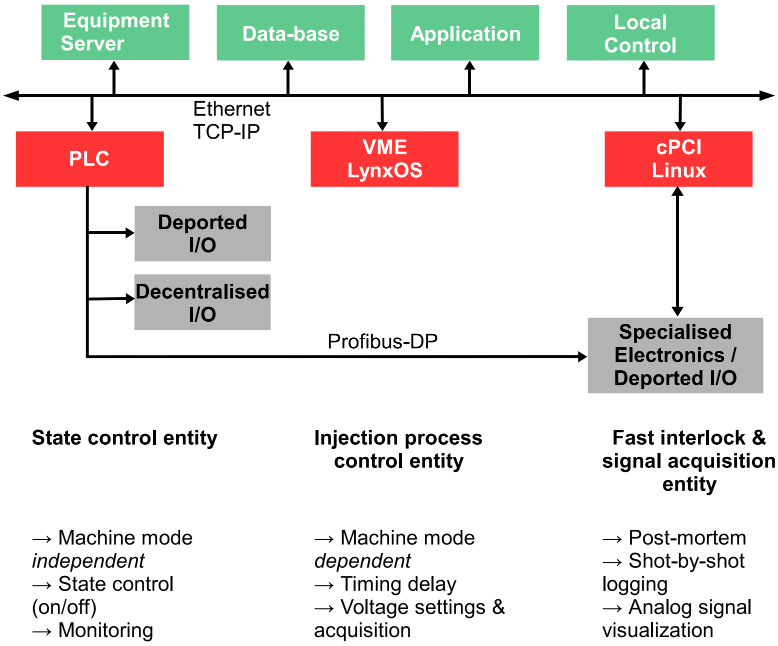

Figure 11.8: MKI control system architecture.

11.4 Control system

The kicker control system, schematically shown in figure 11.8, comprises three independent entities: one for the control of the equipment state (ON, OFF, STANDBY…), one for the control of the injection process (timing system and operational setting management), and one for the control of the fast signal acquisition and interlock logic (protection of the equipment and of the machine), each implemented in an appropriate technology.

The injection process is composed of two consecutive stages which are repeated for each injection. The first a slow stage is divided into two phases: a 1’000 ms long charging phase of the primary capacitor bank, followed by a 2 ms long resonant charging phase for charging the PFNs with a pulse-to-pulse reproducibility of 0.1%. The second, fast stage, of 10 μs duration, is for synchronisation of the timing system with the circulating beam and the ‘to-be-injected’ beams, triggering of the thyratron switches, discharging of the PFNs, and generation of the magnetic pulse.

11.5 Beam instrumentation

The beam instrumentation around the injection systems is a direct continuation of the transfer line systems in TI 2 and TI 8. The functional specifications for the transfer lines have therefore been used in the design choices for these systems. A schematic overview of the instrumentation in the injection region is given in figure 11.9. The transfer line beam position monitors (BPMI) allow steering of the beam up to the entry of the septum magnets. The BPMs around the injection elements are standard ring BPMs installed on the superconducting quadrupoles. Luminescent screens (BTVI) using the optical transition radiation effect (OTR) are used to determine the transverse

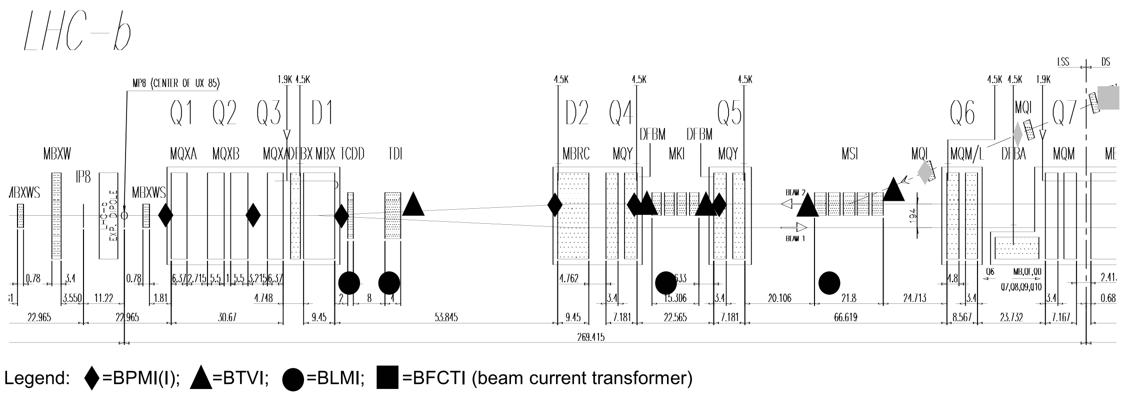

Figure 11.9: Schematic view of injection related instrumentation (case of injection near Point 8) (distances in mm).

beam sizes and centre of gravity upstream and downstream of the major injection elements, and to provide complementary position information during the setting up and steering of the injection. Standard SPS type beam-loss monitors (BLMI) are used to localise the losses linked to the injection process. The installed instruments can cope with the full variety of LHC beams. For proton operation, the intensity varies from a single pilot bunch, namely 5×10^9 protons, to 4 batches of 72 bunches with up to 1.7×10^{11} protons per bunch.