CHAPTER 3

PROTON LINAC FOR LHC INJECTION

3.1 LINAC REQUIREMENTS

Linac2 has been the primary source of protons for the CERN accelerator complex for the last 25 years and over the past few years the machine performance has been steadily improved in anticipation of the demands that will be made on it in the LHC era [1]. The nominal LHC requirement will be for a beam of 180 mA in 30 μs at the entrance of the PSB, i.e. 20% higher proton current from the Linac2 than the design value of 150 mA and inside the same emittances. Fig. 3.1 shows the increase of the Linac2 operational current and of the high intensity test current delivered to the PSB over recent years, with the corresponding steps taken. A description of these improvements is presented in the following paragraphs.

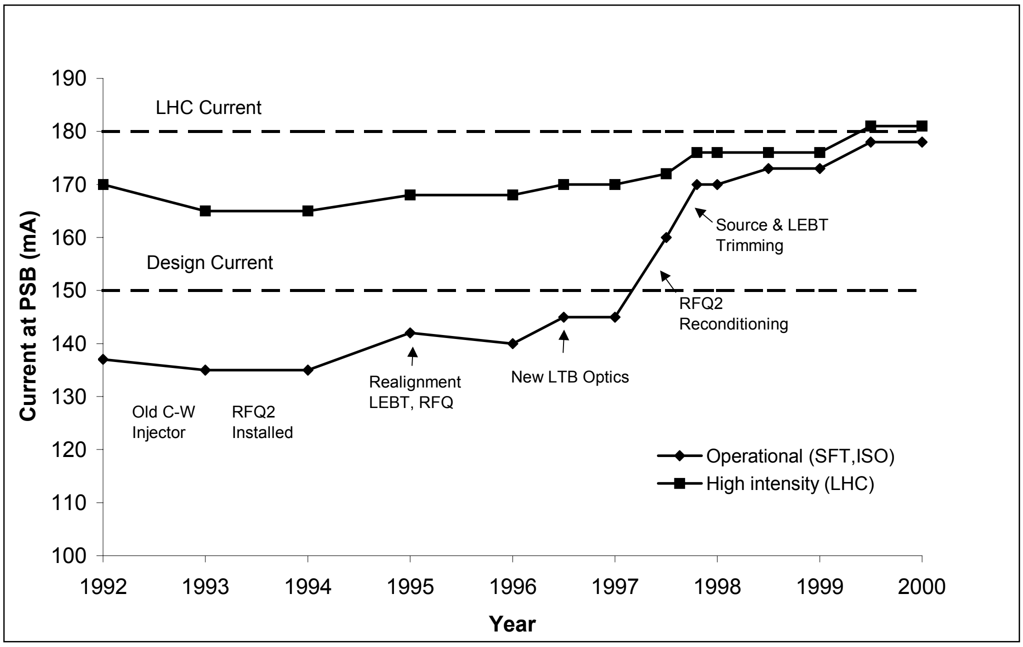

Figure 3.1: Evolution of Linac2 operational and high intensity beam current measured at PSB entry.

3.2 PROTON SOURCE OPTIMISATION

The total beam from the Linac2 duoplasmatron source is around 350 mA with a hydrogen consumption of about 4 ml/min. The gauge pressure of approximately 3.5×10^{-5} mbar in the source housing falls to the mid 10^{-7} level in the RFQ. With this relatively high pressure in the beam transport section between source and RFQ neutralisation is very high, making the effective focusing strength of the solenoids in the line highly dependent on the gas flow from the source. Once this process was understood, gains in intensity of around 10% were obtained by iterative re-optimisation of source parameters and solenoid focusing strengths.

3.3 REPLACEMENT OF THE COCKROFT-WALTON INJECTOR BY RFQ2

The main intensity bottlenecks in the original layout of Linac2 were the space charge limited 750 keV Cockroft-Walton injector with its long transfer line to the linac. In 1993 they were replaced by a new 90 kV platform and a 750 keV RFQ (RFQ2) designed for 200 mA current with compact (<1 m long) beam matching lines. After the RFQ installation, the linac was immediately able to provide 135 mA for the normal operation and a beam of 165 mA with standard emittances for high intensity studies [2].

A first increase in the RFQ2 current was obtained in 1995 with a careful realignment of the system. After a complete set of source emittance measurements, the source was re-aligned on the measured beam axis instead of the mechanical axis and then the solenoids between the source and the RFQ were also aligned on their magnetic axes [3]. After this, the RFQ could be properly aligned and its transmission increased by about 5% .The number of RF sparks (induced by ions hitting the electrodes) was also reduced.

The next step towards higher RFQ current was a slow re-conditioning of the RFQ cavity during operation at the linac. In order to accelerate a space charge dominated beam of 200 mA, the RFQ was designed for a high electrode voltage, 178 kV, resulting in a peak surface electric field of more than twice the Kilpatrick limit [4]. The operation at this high field level was initially plagued by a high RF sparking rate and the RFQ could only operate reliably up to 92% of the design level which resulted in a 10% reduction in beam transmission. The origin of the breakdowns was finally traced to back-streaming oil vapours from a defective drag pump in the RFQ vacuum system that enhanced field emission from the electrodes and finally started the breakdowns. After replacement of the pump, steady operation at high field level in the following years slowly eliminated the hydrocarbon from the electrodes and the RFQ was reconditioned in small steps from 92% up to 100% of the nominal level during normal operation [5]. As a result, the current delivered by the linac increased from 145 to 160 mA.

3.4 LINAC RF IMPROVEMENTS

Allowing for 5% beam losses in the transfer line, 180 mA at the PSB entry correspond to 190 mA out of the linac. Adding up the beam power corresponding to this current, the copper power and a margin for phase and amplitude control, tuning precision and amplifier balancing, about 2.7 MW per Linac2 final RF amplifier will be needed, i.e. 10% more than their design power. An upgrade programme has been gradually applied to the RF chains to increase their output power. In fact, the final amplifier tubes (TH170R), rated at 2.5 MW for a duty cycle greater than that used at Linac2, can deliver more provided that enough drive power is available. For this, an additional amplifier stage was added in the Tank 1 chain, which suffers the heaviest beam loading and modern 4.5 kW solid state amplifiers replaced ageing tube pre-amplifiers in all chains. These more reliable semi-conductor amplifiers also contribute to a decrease in the linac fault rate. Great attention has also been given to the correct adjustment of the feedback loops, which have not only to compensate for an increased beam loading but also have to stabilise amplifiers that are often working in the non-linear region close to saturation.

3.5 BUNCH SHAPE MEASUREMENTS AND OPTIMISATION OF THE LINAC SETTINGS

Particular care was given to minimising the losses inside the linac tanks. This required a complete set of measurements for the re-optimisation of the working point (phase and amplitude setting) for the three linac tanks. These measurements were performed using the longitudinal emittance measurement line and the new bunch shape monitors that give the bunch density distributions in the three geometrical planes and their variations along the beam pulse [6]. Some careful optimisation of the quadrupole setting was also necessary. An example of a measurement is shown in Fig. 3.2.

3.6 BEAM TRANSPORT TO THE PSB

The 80 m long high current beam line between the Linac2 and PSB uses 20 quadrupoles, 2 bending magnets, 8 steering magnets and a debuncher cavity together with eight position pick-ups and two emittance measurement lines. This line has been simulated and re-optimised for the high current beam. The beam is strongly space charge dominated at the beginning of the line and becomes emittance dominated after about 50 metres. The focusing of the line was modified to provide a “quasi” FODO system with constant phase advance per focusing period, an arrangement that turned out to be the most convenient for optimising transmission and beam qualities whilst minimising the sensitivity to steering by the stray field of the PS.

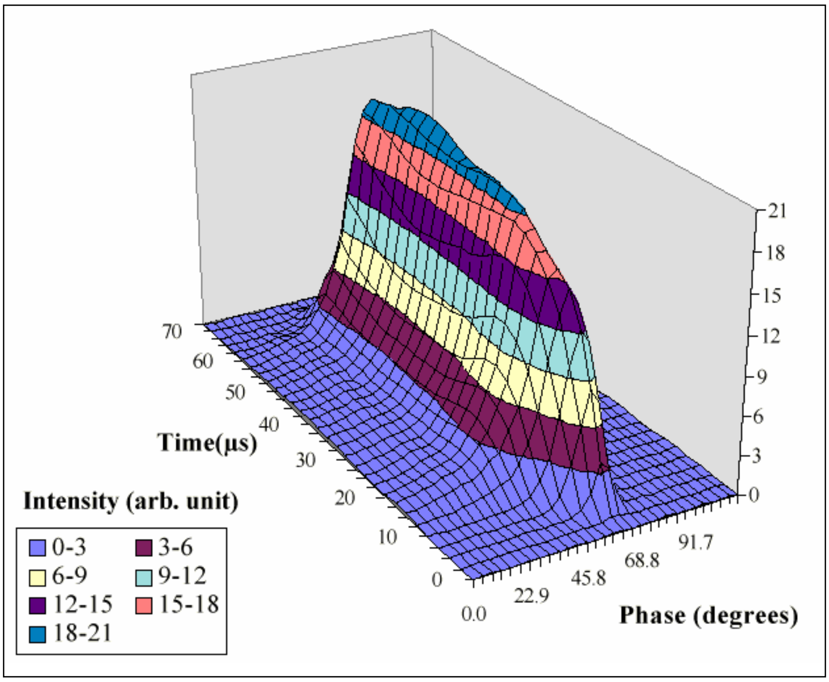

Figure 3.2: Bunch shape evolution along the beam pulse as measured by the Bunch Shape Monitor.

3.7 LINAC2 PERFORMANCE

The result of the installation of the new injector and of many improvements to the source, RF, optics and diagnostics of Linac2 and its transfer lines was the achievement of test currents up to 183 mA and the improvement of the operational current (for SPS and ISOLDE) up to 178 mA. This makes Linac2 the highest intensity ion linear accelerator in the world (peak current). No limitations are observed in the pulse length, making it possible for the linac to produce high intensity beams up to 120 µs long. The transverse emittances at high intensity are about the same (i.e. within measurement accuracy) as at low intensity (140 mA). A summary of Linac2 beam parameters at 180 mA current is given in Tab. 3.1, while Tab. 3.2 shows the measured beam currents and transmissions for the different elements of the Linac2 accelerator. The losses, mainly concentrated in the RFQ and the first tank of the Linac, are due to space charge effects, as predicted by beam dynamics simulations.

Table 3.1: Characteristics of LHC proton beam from Linac2.

Parameter	**LHC Specification**	**Achieved**	
Current during pulse	180	182	mA
Pulse length	30	>100	µs
Transverse norm. rms emittance	1.2	1.2	µm
Momentum spread (± 2σ)	± 0.15%	± 0.15%	

Table 3.2: Output beam current and transmission at high intensity for the different elements of Linac2.

	Output Current	**Transmission**
Source	360 mA (p^+,H_2^+)	
RFQ	204 mA	~ 86%
Linac tank 1	194 mA	95%
Linac tanks 2 and 3	190 mA	98%
Transfer line to PSB	180 mA	95%

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