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PRESENT PERFORMANCE OF THE CERN PROTON LINAC

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Abstract

The original 1973 design specification of the CERN 50 MeV Proton Linac was for a 150 mA beam but this intensity was rarely used. Preliminary tests for the high brightness beam required for LHC indicated that 170 mA could be produced for short pulses (30 μs). Since then further optimisation has enabled the 170 mA to be delivered reliably, within the nominal emittances and dispersion, in long pulses (120 μs) to the user, the PS Booster (PSB), about 80 m downstream of the linac. The improvements will be described along with the steps envisaged to attain a goal of more than 180 mA.

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The original 1973 design specification of the CERN 50 MeV Proton Linac was for a 150 mA beam but this intensity was rarely used. Preliminary tests for the high brightness beam required for LHC indicated that 170 mA could be produced for short pulses (30 μs). Since then further optimisation has enabled the 170 mA to be delivered reliably, within the nominal emittances and dispersion, in long pulses (120 μs) to the user, the PS Booster (PSB), about 80 m downstream of the linac. The improvements will be described along with the steps envisaged to attain a goal of more than 180 mA.

1 INTRODUCTION

Linac2 has now been the primary source of protons for the CERN accelerator complex for the last 20 years [1]. In spite of its age, the machine performance has been steadily improved over the past few years in anticipation of the demands that will be made on it in the LHC era. Table 1 indicates the evolution of the beam intensity delivered to the PS Booster (PSB) over recent years. Figure 1 shows the layout of the linac and PSB injection lines.

In the early years, there was no particular demand for high intensities from the linac as, usually, more than sufficient protons could be supplied to the users, and high intensity beams were only produced as an academic exercise or to supply special test beams. It was generally felt that 150 mA out of tank 3 of the linac was a limit defined by the RF power available. However, the anticipated requirements of LHC started investigations into the possibilities of accelerating higher currents. By limiting the beam pulse length to around 30 μs, it proved possible to accelerate around 170 mA. However, existing high intensity users required a beam pulse length of the order of 120 μs. The measures taken to attain the present performance for a long beam will now be described.

Table 1. Evolution of operational beam intensity at transformer TR60 in Linac2 since 1992.

Date	Event	mA
up to1992	C-W injector operation	140
1993	RFQ2 installed	135
1994	Typical operation	135
1995	Realignment RFQ+LEBT	142
1996/I	Annual startup	140
1996/II	New high energy optic	145
1997/I	Annual startup	145
1997/II	New setting RFQ	160
1977/III	Source + LEBT adjustment	170
1998/I	Annual startup (reduced)	158
1998/II	Stable operation	173

2 INSTALLATION OF RFQ2

The high beam brightness required by the LHC requires some modifications to its injectors, and in particular an increase in the linac peak current. The consequent reduction in the number of turns needed in PSB injection leads to a smaller emittance at the end of the process. A major step towards a higher linac current was the replacement in 1993 of the old 750 kV Cockroft-Walton and Low Energy Beam Transport (LEBT) by a new 90 kV platform, a 750 keV RFQ (RFQ2) with compact (<1m long) beam transport lines between source and RFQ, and RFQ and linac [2]. After two months of installation work and one month of setting-up, the linac was able to provide 135 mA for the normal operation and 165 mA for high intensity studies.

3 RFQ2 ALIGNMENT

Whilst the RFQ was still on the test stand, it was found that the beam at its output was mis-steered. After installation on Linac2, the high-energy end of the RFQ had to be positioned off axis to get a good transmission through the linac. On

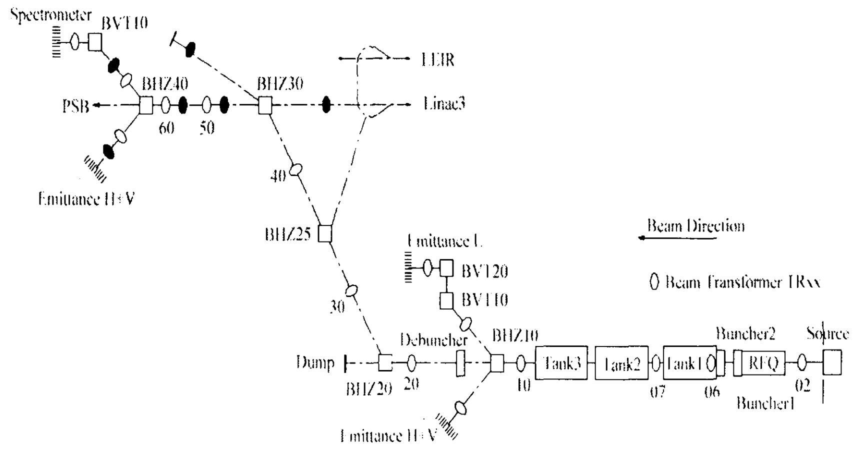

Figure 1: Schematic layout of Linac2 and its transfer lines.

the stand, the beam emittance measured directly behind the source showed that the beam was off axis in position and angle. Although the source anode hole had been centred to better than 0.1 mm, it was not perpendicular to the beam axis. This same error was also found on Linac2 and corrected [3].

The line between the source and the RFQ contains two solenoids. Due to coupling, a beam passing through a solenoid off axis in, say, the horizontal plane can cause errors in beam position and angle in both transverse planes at the output. Originally, the solenoids had been aligned on their mechanical, not on their magnetic axes. Moving the solenoids whilst checking the beam centre (position and angle in both transverse planes) enabled the beam to be brought onto axis into the RFQ. As a result the overall performance of the RFQ improved with a reduction of RF breakdowns, which were often induced by ions hitting the electrodes, and the RFQ could be realigned mechanically to the theoretical axis.

4 RFQ2 CONDITIONING

The RFQ was designed to accelerate a space charge dominated beam of 200 mA. For this reason the design vane voltage had to be relatively high (178 kV) [4] which corresponds to surface electric fields of more than 2 times Kilpatrick on a large fraction of the electrodes and locally as high as 2.5. Conditioning on the test bench was only partially successful; only about 95% of the nominal voltage was attained before heavy sparking started. Once installed at the linac, the RFQ was operated at 92% of the design voltage to avoid excessive breakdowns that would have perturbed the whole CERN proton acceleration chain. This resulted in a 10% reduction in beam transmission.

It turned out that a defective drag pump in the RFQ vacuum system used to pump the large amount of hydrogen coming from the source, was backstreaming oil vapours into the cavity. The hydrocarbon deposit on the vane surface enhanced field emission (dark current) that finally resulted in RF breakdown.

Steady operation at high field level in the following years slowly eliminated the hydrocarbon from the electrodes. Figure 2 shows Fowler-Nordheim, ($ln(I/V^{2.5})$ vs. $1/V$), plots of dark current, derived from the excess power going to the electrons [5], as function of vane voltage at different moments of the RFQ2 history. The derived field enhancement factor β is a figure of merit for electrode roughness and cleanliness. Between 1993 and 1997 the dark current in the RFQ (operating at 92% of the nominal level) went down from about 70 mA to virtually zero. A comparison of the beta-factors deduced from Figure 2 shows that the cavity after delivery from the workshop (1990) was already somewhat polluted (β=220), while at the installation at the linac (1993) pollution was extremely high (β=920), It went down drastically (β=67 in 1997) after removing the source of pollution and slow RF conditioning. The present value is reasonable for the standard of surface finish used in the RFQ.

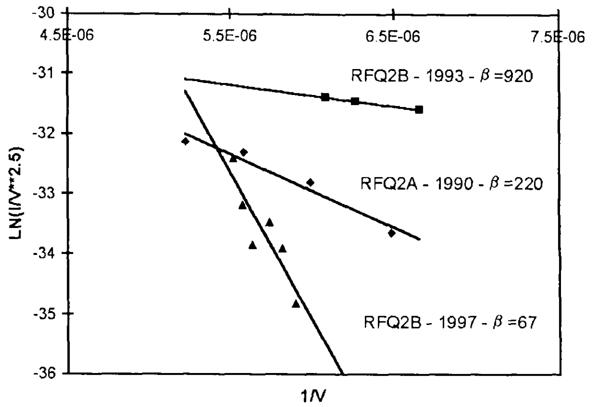

Figure 2: Fowler-Nordheim plots for the RFQs.

Following the discovery of the reduced β, the RFQ was reconditioned from 92% up to 100% of the nominal level during normal operation. The level was increased in small steps, taking care to limit the breakdowns so as not to perturb the users. As a result, the current delivered by the linac went up from 145 to 160 mA.

5 RF IMPROVEMENTS

The RF power needed for the design current of 150mA (cavity plus beam loading) is about 2.1 MW for each of the 5 final amplifiers, well within the capabilities (2.5MW) of the amplifiers [6]. For LHC, allowing for 5% beam losses, the 180 mA at the PSB correspond to 190 mA in the linac. For this, the final amplifiers will have to provide about 2.5 MW. With a 10% margin for phase and amplitude control, tuning precision and amplifier balancing, at least 2.7 MW per final amplifier will be needed

Some upgrades were gradually applied to the RF chains to increase their output power. The final amplifier tubes (TH170R) are rated for 2.5 MW power at a duty cycle greater than that used at Linac2, but they can deliver more power provided that enough drive power is available. Initially an additional amplifier stage was added in the Tank 1 chain which experiences the heaviest beam loading. Then modern 4.5 kW solid state amplifiers were installed in all the chains to replace aging tube units which generally had a lower power output. These more reliable transistor amplifiers have also contributed to a decrease in the linac fault rate.

Great attention was also given to the correct adjustment of the feedback loops which have not only to compensate for an increased beam loading but also have to stabilize amplifiers which are often working in the non-linear region close to saturation.

6 HIGH ENERGY OPTICS

The 80 metre 50 MeV proton beam line from the linac to the PSB is composed of 20 quadrupoles, 2 bending magnets, 8 steering magnets, and a debuncher cavity and is also equipped with eight position pick-ups and two emittance measurement lines. The optics of the line has been studied and optimised for the high current.

The space charge force varies considerably along this line as the beam comes out of the linac with a very marked longitudinal microstructure that is gradually lost. 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 has been set-up in such a way so as to provide a "quasi" FODO system with constant phase advance per focusing period: this arrangement turned out to be the most convenient for optimising transmission and beam qualities, and minimising the sensitivity to steering. This last parameter is particularly critical, as the stray field of the PS machine penetrates the transfer line and sensitivity to steering has been considerably reduced with this configuration. Figure 3 shows the measured beam centre displacement before and after the change.

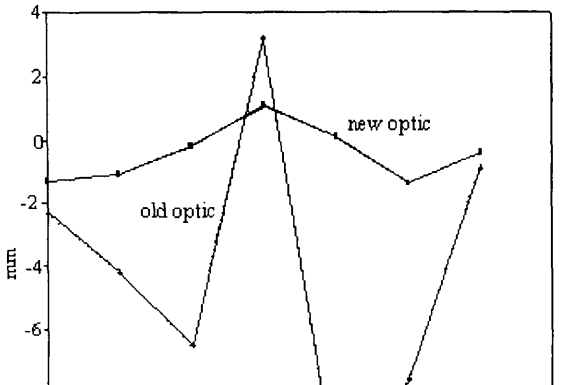

Figure 3: Measured beam centre displacement for 0.25 mrad variation in steering after the linac.

7 SOURCE OPTIMISATION

Normally, the total beam out of the duoplasmatron source is around 275 mA with a hydrogen consumption of about 7 std.ml/min. This results in a N_2 equivalent pressure of approximately $3.5*10^{-5}$ mbar in the preinjector housing falling to the high 10^{-7}s in the RFQ. With this relatively high pressure in the LEBT, neutralisation is very high. Thus, the effective focusing of the solenoids is highly dependent on the gas flow from the source. Gains in intensity of around 10% were obtained by iterative re-optimisation of source parameters and solenoid focusing strengths. Naturally, as source parameters and the injector vacuum quality change with time, this optimisation process must be repeated at regular intervals.

8 LINAC OPTIMISATION

In parallel to these major changes to the linac, a major long term effort was initiated to reduce the losses in the machine and transfer lines. A consequence of the new optics, and its inherent stability against perturbations, was that it became much simpler to control losses in the high energy transport line. Equally it is also easier to optimise both transverse and longitudinal parameters in the linac itself. Computer programmes are being developed to try to optimise the linac on-line using hill climbing techniques to find the optimum combinations of these parameters.

9 THE FUTURE

During one short study period in 1997, a peak current of 176 mA in 120 μs was passed to the PSB. This demonstrated that there is still potential for further improvements in intensity. The goal is to try to pass the 180 mA barrier in the near future. However, it is also known that there are serious bottlenecks at the beginning of the linac that will require ingenuity to overcome . It is also appreciated that this higher performance will place new demands on the linac with attendant consequences on reliability.

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