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A HIGH INTENSITY PROTON RFQ**

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This paper covers the RFQ2 installation and running-in at the linac, the simulations and measurements to determine the new parameter set-up for Linac 2, the measurements of beam intensity and quality at the output of the linac and how they compare with beam dynamics simulations. The first operating experience of Linac 2 with its new injector is also described.

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During the 1993 CERN shut-down the 750 kV Cockcroft-Walton pre-injector of Linac 2 (including its low energy beam transport) was replaced by the high intensity RFQ2 and its associated proton source, 90 kV pre-injector and beam transport elements. A higher current and a better matching to the linac were required for the production of a high brightness beam for the Proton Synchrotron Booster, the next accelerator in the injection chain of the future Large Hadron Collider.

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Introduction

The CERN Large Hadron Collider (LHC) will be supplied with protons from the injector chain Linac 2 - PS Booster - PS - SPS. In order to achieve the required beam brightness at the end of this accelerator chain, the 50 MeV Linac 2 is required to provide the PS Booster with a beam of 180 mA with a normalised rms emittance of $1.2 \mu\text{m}$ (LHC definition, $(\beta_r\gamma)\sigma^2/\beta$) [1]. While this emittance is of the same order of magnitude of usual Linac 2 emittances, the current required is significantly higher than its design value of 150 mA. The main current limitation being due to the presence of particles out of the bucket after bunching in the old pre-injector, so to achieve the required linac current a high intensity RFQ was needed. These considerations gave a boost to the RFQ2 project which had started on a test basis as early as 1988 and led to the design, construction and installation of the RFQ2A system on a test bench. During the tests, it delivered currents higher than its design value of 200 mA, indicating that the goal of 180 mA out of the linac was attainable [2]. The installation of the RFQ2 on the front-end of Linac 2 was scheduled for the January-February 1993 shut-down, with the aim of reliably providing the Booster with the standard production intensity of 130 mA from the start-up in March, and with the high intensity beam during the tests of the PS complex as LHC injector, scheduled for 12 days at the end of December 1993.

The RFQ2

The RFQ2 complex includes a duoplasmatron proton source, a 90 kV pre-accelerating column, a Low Energy Beam Transport to the RFQ, the 202.56 MHz RFQ2, and a matching

section to the linac (four quadrupoles and two bunching cavities), where the beam is injected at 750 keV [3]. The RFQ2 has been designed for a beam current of 200 mA and, in order to compensate for the high space charge within a compact (1.8m) structure, a design peak electric field of 35 MV/m (2.5 times the Kilpatrick limit) has been necessary. This field can be reached only under very good vacuum conditions, as shown by RFQ2A which, whilst on the test stand, suffered a pollution from oil coming from the vacuum system. This considerably reduced its voltage holding capability and forced a careful cleaning of the RFQ [4]. After cleaning, the RFQ2A reached again the nominal field but with a higher breakdown rate and reduced reliability.

This, considering the high reliability demanded from a machine that is the only proton injector of CERN (usual down times at Linac 2 are of the order of 2% of the scheduled beam time), resulted in the decision to build another RFQ, RFQ2B, for installation on Linac 2 and to be equipped from the beginning with a vacuum system based mainly on oil-free units. The RFQ2B is basically identical to the RFQ2A, so that the latter, intended to be permanently installed at the RFQ test stand, could be used as a spare in case of problems. Only a different design of the vane undercuts was adopted for 2B, in order to ease tuning and field adjustment. The RFQ2B was built during 1992 and tested with beam at the end of that year; beam parameters were consistent with those which had been measured for the RFQ2A.

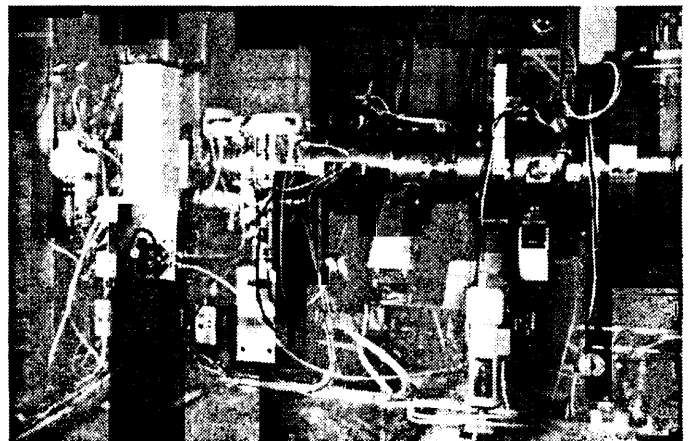


Fig. 1 the new Linac 2 injector. From left, the Faraday cage, the RFQ2 and the input of Tank 1

RFQ Installation

A view of the new Linac 2 injector is shown in Fig.1. The dismantling of the old 750 kV column and LEBT and the installation of the RFQ2 complex with its beam

commissioning at the Linac had to be compressed into the standard two and a half month shut-down of the PS complex. To speed-up the programme, the complete RFQ2 assembly (source, LEBT and RFQ plus ancillary equipment like vacuum pumps) was transported from the test stand to the Linac 2 area as a unit on its single support thus maintaining the alignment and reducing the installation time. After two weeks of beam tests, the linac was able to deliver the production beam to the Booster as scheduled [5].

Matching to Linac 2 and Linac Optimisation

The running-in process was backed up by extensive beam dynamics simulations carried out with the programs PARMULT and PARMILA [6]. The emittance and current values measured at the source were used as input beam parameters for an "end-to-end" simulation of the RFQ-matching line-Linac 2 complex. Thus a global optimization of the parameters was achieved. In the linac, a value of 60 degrees for the zero current phase advance per focusing period was found to be the choice that guaranteed a good transmission together with minimum transverse and longitudinal emittance growth. The focusing law was changed according to the higher space charge. After some iterations of empirical optimization for all the parameters (giving slight deviations from the theoretical values for some quadrupoles and some RF parameters), a current of 150 mA at the output of the linac was obtained.

The phases of the two bunching cavities in the matching section between RFQ and the Linac had been set to values determined at the test stand from energy measurements. Recently, they have been verified using a more accurate method [7] based on the comparison between the beam loading observed in the buncher RF feedback system at different RF phases and the effect of a purely reactive loading (a detuning of the cavity), and slightly changed. At the start-up, the relative phases of the three Linac 2 tanks were kept as they were before the RFQ installation, and the phase of the RFQ and two bunchers, connected to the same phase shifter, was adjusted until the correct beam intensity and energy out of the linac were obtained. Later, in the frame of a general re-optimisation of Linac 2 settings after the RFQ installation, some development sessions (MD's) were devoted to check the tank amplitudes and phases with the method of the tank characteristics [8]. The 10 MeV beam out of Tank 1 has been transported through unpowered and detuned Tanks 2 and 3 up to the longitudinal emittance measurement line at the end of the linac. The beam arrived completely debunched, but nevertheless the mean energy could be measured and plotted as function of tank phase, for different amplitudes. The comparison between measured curves and theoretical single particle simulations gives, with good precision, the nominal amplitude and phase. This same procedure was then repeated for the other tanks where transport is easier and accuracy higher. As an example, in Fig.2 are shown the measured and theoretical characteristic curves of Tank 2.

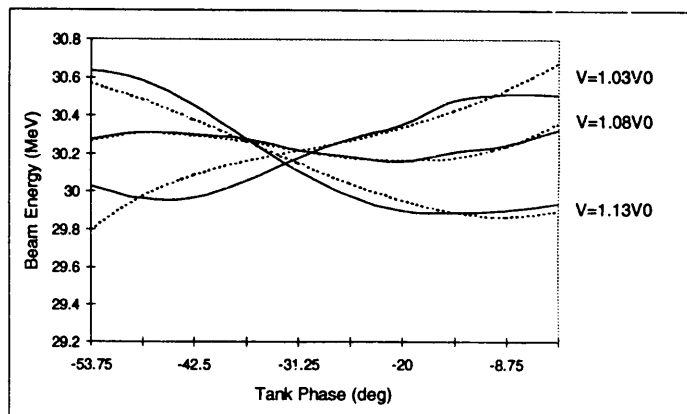


Fig. 2 Measured (continuous) and theoretical (dotted) characteristic curves of Tank 2 for three different tank levels

Linac 2 High Current Performance

From the start-up in March 1993, the Linac 2 could easily provide the PS Booster with the standard intensity of 130 mA and with a high intensity beam of 150 mA. The optimisation of the Linac parameter space is done at high intensity, a then the source arc current reduced to decrease the number of protons until the normal operation current of 130 mA out of the linac is obtained. In parallel with normal operation, a study was going on in order to improve the high current performance up to the specified 180 mA. In particular, two problems were limiting the Linac 2 maximum current; firstly the RFQ2 showed a high sparking rate when operating at its nominal RF level, and secondly, the transmission through the Linac was lower than foreseen by beam tracking codes (87% instead of 95%). The sparking problems in the RFQ required operation at a voltage 5% lower than nominal during all the 1993 run. This maintained the sparking rate at a level acceptable for the PS Booster (at this voltage level, an average of 0.1% of the pulses were lost) whilst ensuring at the same time an RFQ transmission of 75%, largely sufficient for the standard Linac 2 operation. During the December 1993 LHC injection tests, a higher RFQ voltage, but still 1% lower than nominal, could be maintained only by pulse to pulse modulation of the RFQ level, i.e. by keeping it high only the two out of 12 high intensity cycles required by the Booster. In this way, the number of pulses lost due to the RFQ during the tests was kept below 1%. Currents obtained during the LHC tests are shown in Table 1; for a current of 170 mA out of the linac, about 160 mA were delivered to the Booster, at the end of the long transfer line.

The 1994 shut-down was used for a thorough investigation of the RFQ2 system to find out the reasons for the high spark rate. In particular, the turbo vacuum system was completely revised after detecting a loss of oil from the 5 cc. reservoir of the drag pump in the forevacuum system (this system is permanently in operation to pump out the hydrogen coming from the source), which could have led to oil diffusing into the RFQ. Some leaks were also detected and repaired. After these interventions, a sharp decrease in the RFQ spark rate has been observed. During 1994 the RFQ level could be

increased, up to its nominal value, and during some high intensity MD's, a voltage 5% higher than nominal could be used resulting in a current of 220 mA out of the RFQ and of 190 mA out of Linac 2 (see Table 1). Fig.3 shows the measured Linac 2 currents as function of RFQ level.

TABLE 1
Measured beam currents at Linac 2 transformers

Transformer	Transformer position	Current (mA)	
		Tests 1993	MDs 1994
TRA02 (*)	after source	340	350
TRA06	after RFQ	193	220
TRA07	after Tank 1	175	195
TRA10	end of linac	170	190

(*): note that TRA02 measures heavier ions as well as the protons

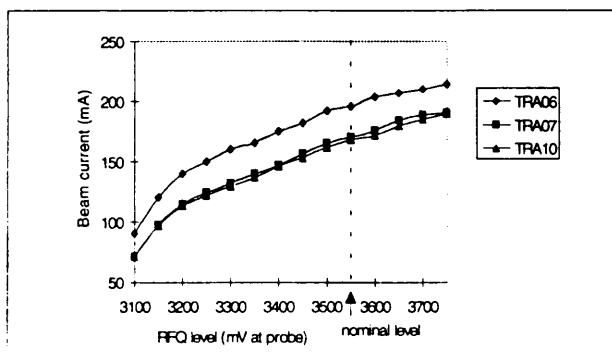


Fig. 3 Linac 2 currents as function of RFQ level

The improvement in Linac 2 current has been obtained by pushing the RFQ to higher field, while beam transmission through the linac remains around 87%. An analysis of beam alignment (measure of the transverse emittance centre as function of linac quadrupole levels) shows that the beam is oscillating horizontally inside the linac, with an amplitude of few millimeters. Improving the beam alignment could increase the already satisfactory transmission and reduce the emittance growth. Thus an improved mechanical movement system is being prepared so that the complete RFQ2 assembly can be mechanically displaced more freely and precisely with respect to the linac, in order to optimise empirically the injection trajectory (severe space constraints forbid the installation of steerers). Equally studies are foreseen to understand the origin of this beam misalignment, which is not due to bad alignment of the RFQ elements.

The Linac 2 RF system, designed for a maximum power of 2.5 MW on the final stages, has delivered during the 1994 MD's up to 10% more power for some of the stages, with only minor modifications and careful tuning of all RF chains. Some additional investment will be necessary in the future to make it able to deliver the higher power on a routine basis.

As far as beam quality is concerned, an emittance growth of 15% in the transverse planes is measured in the linac; the emittances are well inside the requirements for the LHC beam. The longitudinal emittance remains as it was before the installation of the RFQ, i.e. still a factor 2.7 higher than the computed value. Table 2 reports a comparison between

calculated and measured horizontal emittance parameters after the linac, and Fig.4 the measured transverse emittances.

TABLE 2 Emittance parameters for the horizontal plane

	alpha	beta (mm)	Emittance (63%) (mm-mrad)
Calculated	-0.67	20.26	7.69
Measured	-1.5	17.8	8.3

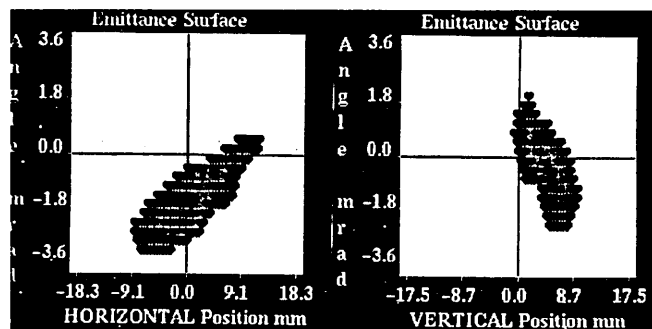


Fig. 4 Measured Linac 2 Horizontal and Vertical Emittances

Conclusions

The installation of the RFQ2 at the front end of Linac 2 has been successful; the linac reliably delivers its production beam. For the high intensity operation, 170 mA out of the linac was obtained in 1993, while in 1994, after solving some vacuum problems in the RFQ, the current could be increased up to 190 mA.

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