DESIGN OF A CHOPPER LINE FOR THE CERN SPL

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Abstract

The SPL (Superconducting Proton Linac), a 2.2 GeV linac for high-intensity applications under study at CERN, requires a fast chopping at low energy of the H^- beam. The most stringent demands on the chopper come from the operation of a Neutrino Factory, which requires 44 MHz bunch frequency in the accumulator ring and in the muon bunch rotation. This imposes a chopper structure with fast rise and fall times, below 2 ns, to remove 3 consecutive 352 MHz bunches out of every 8.

An improved design of the standard travelling-wave chopper structure has been analysed and tested on a prototype. Additional effort has gone into the design of a pulse generator or power amplifier capable of providing the required rise and fall times. Since short rise times and high chopper voltages are conflicting requirements, the maximum voltage has been limited to 500 V per plate. A prototype driver has been built and tested.

A very compact beam line design is proposed, which is still compatible with the low chopper voltage. The line houses the chopper structure and the dump, provides the separation between chopped and unchopped beam, and matches both from the RFQ and to a DTL. Effects of space charge and of varying beam parameters are analysed. In particular, the influence of the beam energy at the chopper on the line components is discussed in detail. A diagnostic line designed to perform the measurements necessary to validate this set-up is also described.

1 INTRODUCTION

The Superconducting proton Linac (SPL) study [1] at CERN aims at the design of a 2.2 GeV, 4 MW beam power H^- linac that would re-use most of the 352 MHz RF equipment of the decommissioned LEP collider. The main applications for this machine would be the generation, via the CERN Proton Synchrotron, of a high-brightness beam for the LHC and the delivery, via an accumulator-compressor ring system, of a high-power beam for secondary particle production.

The main physics communities interested in high-intensity beams at CERN are concerned with neutrinos and with radioactive ion beams. They would both largely benefit from an extension of the CERN proton production complex towards a higher beam power. In particular, neutrino physicists have ambitious plans for both a neutrino superbeam produced in the conventional way by the 4 MW proton beam, and also later a Neutrino Factory complex, an intense source of neutrinos produced by the decay of previously cooled and accelerated muons [2].

Recently, the construction of only the room-temperature part of the SPL, up to 120 MeV beam energy, has been proposed as a means to increase in an intermediate stage the proton flux from the CERN injector complex [3], by rising the injection energy into the PS Booster (PSB), presently at 50 MeV.

All of these applications require chopping at low energy of the linac beam, to minimise longitudinal capture losses in the rings. The development of an appropriate chopper and chopper line are therefore considered as a high-priority activity for the SPL study, and are now integrated into a common programme with CEA and IN2P3 in France for the construction and testing of an SPL front-end configuration [4].

The most demanding design parameters of the CERN chopper come from the Neutrino Factory [2]. For this case, a relatively high 44 MHz RF frequency is required for the accumulator, to efficiently rotate and re-accelerate the muon bunches produced on the target. Therefore, only 8 linac bunches fall into an accumulator period, and out of these 3 have be eliminated by the chopper, leaving only 5 linac bunches in each accumulator bucket. The resulting 3/8 chopper-on duty cycle is quite demanding for the chopper and its pulser, imposing the use of a fast chopper, whose rise and fall times stay between the 352 MHz bunches. Because short rise times and high chopper voltages are conflicting requirements, the maximum voltage has been limited to 500 V per plate. This increases the required chopper length for a given deflection and therefore forces consideration of deflector plates that could be placed inside quadrupoles.

The chopper energy of 3 MeV has been preferred to lower energies for the lower space charge and for leaving the choice of the following RF structure open between RFQ and DTL [4]. The only concern at this energy is activation due to losses in the RFQ and in the line, the threshold for Copper activation being at 2.16 MeV. The main parameters of the SPL chopper are summarised in Table 1.

Table 1: Parameters of the SPL chopper

Energy	3 MeV
Bunch Frequency	352 MHz
Rise-fall time	< 2 ns
Chopper voltage	± 500 V
Maximum chopper frequency	44 MHz
Chopping factor (max.)	40 %
Repetition rate	1-50 Hz
Beam pulse duration (max.)	2.8 ms
Bunch current (max.)	40 mA

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2 CHOPPER AND PULSER DESIGN AND PROTOTYPES

The proposed SPL chopper structure [5] consists of a pair of deflecting plates with a meander type delay printed on alumina, without separating ridges. Tests carried out on prototypes (double 100 Ω meander on 3 mm alumina, Figure 1) show good agreement with numerical simulations in terms of attenuation and dispersion. The printed meander on alumina has very good vacuum properties, easy implementation and good radiation resistance and heat transfer (water cooled metal ground plane). The 100 Ω characteristic impedance permits a meander width below 25 mm for β=0.08 and thus economy on driver power, and the possibility to install the deflectors inside quadrupoles. The field coverage factor is such that the actual voltage seen by the beam is 400 V.

An UHV prototype at 50 Ω is now in preparation, with dimensions such as to fit inside existing CERN quadrupoles. This prototype will be water-cooled, to withstand the voltage of 500 V with an average current of 3 A per plate.

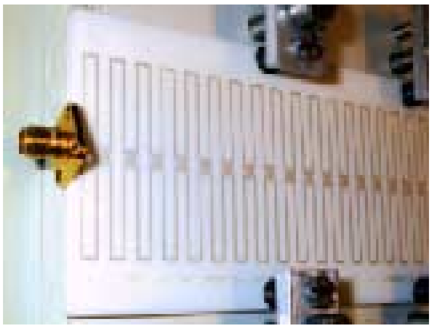


Figure 1: Chopper prototype, double 100 Ω layout (Z_0=50 Ω)

A prototype of the 500 V chopper pulse amplifier has been partially realised and tests are in progress [6]. It is based on the idea of generating the low and high frequency components of the required spectrum (DC to above 200 MHz) with two different generators. The sum of the two signals is obtained using the meander type deflecting structures virtual ground planes as low frequency deflectors. Measurements of the high frequency generator prototype (Figures 2 and 3), which is the most critical component, show rising and falling fronts of ~2.5 ns with maximum amplitude of 475 V.

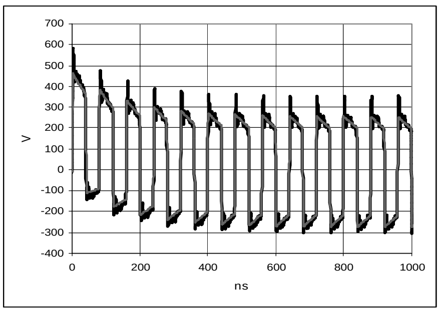


Figure 2: Measured and computed output signal.

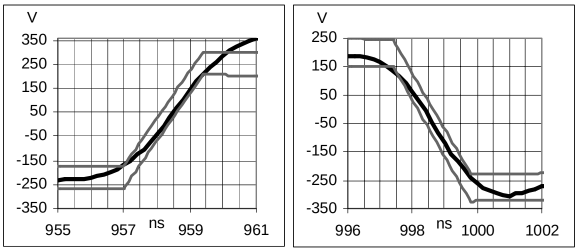


Figure 3: Rising and falling fronts

Although these numbers do not comply with specifications yet, they still demonstrate the effectiveness of the chosen layout and possibilities of substantial improvements have been identified.

3 DESIGN OF THE CHOPPER LINE

The chopper line is situated between the first stage of acceleration (RFQ at 352 MHz) and the second stage (RFQ or DTL at 352 MHz). The line has been designed for 40 mA bunch current, but higher currents are in fact possible, as will be discussed later. In order to maintain the FODO focussing structure and therefore limit the emittance growth we have designed the chopper section as a FODO with 90 degrees phase advance for the centre of the beam and an acceptance 1.7 times the nominal RFQ output emittance. This resulted in a 1.6 m long FODO period with two 450 mm quadrupoles, one of which houses the 700 mm chopper structure, actually split into two sections 300 and 400 mm long. Due to the limit on the chopper plate voltage the FODO period housing the chopper is longer than the FODO in the accelerating structure and thus a matching section between a fast phase advance and a slow one must be envisaged. In our baseline case the ratio between the focusing period length of the accelerators and of the chopper is around 10. An adiabatic matcher would require several periods, while a compromise has been found with a 2 period matcher. In the matchers and in the chopper an RF cavity (150 kV maximum effective voltage) keeps the beam bunched and provides the longitudinal matching. A sketch of the line is shown in Figure 4. Its overall length, from RFQ exit to DTL input, is 3.7 m.

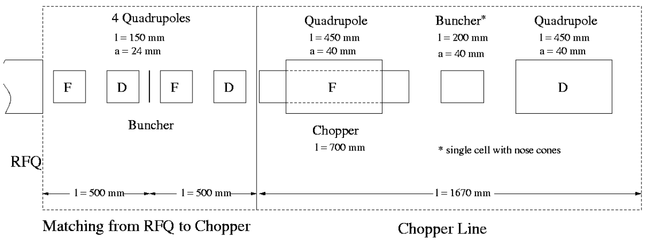


Figure 4: The chopper line with matchers from and to the acceleration stages.

Multiparticle computations [7] prove a) that the line provides a clean separation for the baseline beam (Figure 5); b) that the line can be used successfully up to 100 mA at 3 MeV; and c) that the line can match and chop a beam with an energy as low as 2.3 MeV.

Notwithstanding the efforts of minimising the emittance growth with a careful matching we find a 17% transverse emittance growth for a 3 MeV beam. No longitudinal emittance growth has been found after a 10'000 particle run.

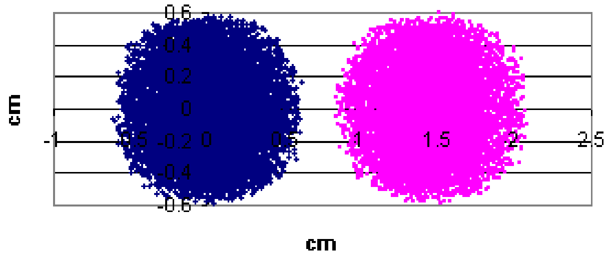
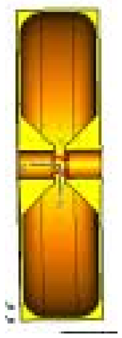


Figure 5: Separation between chopped (right) and unchopped beam at the plane of the dump.

4 THE BUNCHING CAVITIES

The line includes three bunching (bunch rotating) cavities at 352 MHz. The buncher design aims at a minimum length on the beam line and a sufficiently high shunt impedance to keep the peak RF power well below 50 kW, the maximum power that can be delivered by a set of tetrode amplifiers recovered from the LEP inventory. A standard pillbox design with nose cones was preferred over two other possible designs, one with quadrupoles inside half drift tubes and the other being a quarter-wavelength cavity [8]. Figure 6 shows a cross-section of the resonator, as generated by the 3-D RF simulation code Microwave Studio (CST Darmstadt) and summarises the main cavity parameters.



Inner diameter:	520 mm
Inner wall distance	110 mm
Beam aperture	40 mm
Gap distance	10 mm
Shunt impedance	750 kΩ
Transit time factor	0.43
Quality factor	21264

Figure 6: Cross-section and parameters of the buncher cavity

5 CONSTRUCTION AND TESTING

It is planned to build the chopper line at CERN in 2004/05, making use of existing equipment, such as the quadrupoles, recuperated from old transfer lines, and the RF amplifiers for the bunchers. The study of an appropriate beam stop for the chopped beam has just started, and it will largely profit from the development done for the SNS beam stop [9].

Beam tests with protons from a 3 MeV re-configuration of the IPHI RFQ [10] are planned in collaboration with CEA and IN2P3 at Saclay starting from mid-2005 [4]. The foreseen test assembly is shown in Figure 7. The chopper line (without the downstream matching section) will be installed after the RFQ, and a diagnostic line will allow measuring beam parameters. In a second stage, a second accelerating section up to 5 MeV, made of an RFQ or a DTL, could be added to the test stand.

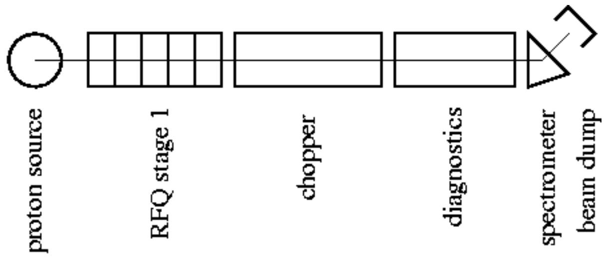


Figure 7: Layout of the chopper line test stand

The initial interest of the IPHI project being for high beam currents, up to the 100 mA that can be delivered by the source, it is foreseen to test the line to the maximum possible current. Another requirement would be to increase the duty cycle up to CW. However, the bunchers will not be used in this mode because of heat dissipation.

Beam diagnostics are being developed to verify the beam parameters of the set-up at both 3 MeV and 5 MeV. A particular problem for the instrumentation is the high power of the continuous beam, which excludes the insertion of material in the beam path. The parameters to be measured are beam current, emittance, beam position and profiles, energy and energy spread. Specific time-resolved instrumentation will also be developed to characterise the performance of the chopper.

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