OPTIMAL DESIGN OF A HIGH CURRENT MEBT WITH CHOPPER

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Abstract

Many existing and proposed projects require a certain temporal structure imposed on the beam pulse, e.g creating gaps for low-loss extraction from a circular accelerator. Usually this is achieved using chopper systems. In order to reduce the average beam power on the chopper target and simplify kicker requirements, the chopper system is located in a lower energy part of the accelerator, typically in the medium energy transport line (MEBT) between the RFQ and the linac. Many of the MEBT layouts proposed and in use, look very much alike and try to achieve a compromise between the two opposing requirements of providing strong transverse focusing and sufficiently long empty drifts for the kickers. As a result, both requirements are not fully satisfied leading to space charge induced emittance increase and very challenging technical specifications for the kicker and its power supply. These difficulties quickly increase with the beam current. We propose a different MEBT layout, which does not compromise the quality of beam transport and allows space for a kicker with any reasonable parameters. A generic design of a 5.5 m long MEBT transporting 100 mA with emittance increase of less than 5% is shown as an example.

INTRODUCTION

The low energy part of many existing and proposed high current hadron linear accelerators have similar structure: an ion source, a low energy transport line (LEBT), an RFQ, a medium energy transport line (MEBT), and injection into a main linac. Often a certain temporal structure of the beam pulse is required. A typical example is dividing the beam into single-turn segments for low-loss extraction from a circular accelerator. This can be achieved by using a chopper, which consists of a kicker, deflecting the unwanted part of the beam pulse off the axis, and a target, absorbing the deflected beam. It is advantageous to place the chopper at as low energy as possible because it is easier to deflect the beam and to manage the beam power on the target. The beam energy in a MEBT usually, in the range from 2 to 5 MeV, is sufficiently low for a feasible chopper design. Unfortunately, it is also low enough that beam space charge forces have a significant effect on the beam dynamics, which can result in the emittance increase. The design of many MEBTs with a chopper is a compromise between preserving the quality of the beam, efficiency, and cost of the chopper. We will show below that it is possible to decouple the requirements of high quality beam transport from requirements for efficient chopping, thus making it possible to have both fully optimized.

OPTIMAL BEAM TRANSPORT

In order to minimize emittance growth in a transport line due to space charge effect at least two conditions have to be fulfilled [1]: provide strong transverse focusing and avoid abrupt changes of the focusing strength. A simple periodic FODO structure can provide high quality transport for a long distance if envelope stability criteria are met, namely the zero current phase advance per period should be less than 90º. A general layout of such a structure is shown in Fig.1. We used this structure in all subsequent numerical simulations for transporting a 2.5 MeV beam with 100 mA peak current bunched at 402.5 MHz. It is convenient to choose the phase advance per unit length in the FODO to be the same as in the beginning of the linac. In this case there is no need for an additional matching section at the MEBT end. We used the Spallation Neutron Source DTL phase advance per cell in the example MEBT. It is impossible, in practical cases, to make a similar smooth transition from a RFQ to a MEBT because of, generally, very strong transverse focusing in a RFQ. In order to reduce emittance growth associated with this transition we put a matching section consisting of four quadrupoles in the beginning of the MEBT. The rest of the channel in the example FODO MEBT uses identical 7 cm long quadrupoles with 40 T/m gradient placed with 7 cm drifts between them. Providing the longitudinal focusing is the most technically challenging task. We use 402.5 MHz cavities with 100 kV gap voltages in the example. Evolution of the transverse emittance along the FODO channel is shown in Fig. 2. There is an abrupt jump in the beginning caused by a sudden change in focusing strength from the RFQ to the MEBT. Emittance increase is negligible in the rest of the MEBT; therefore one can design a FODO MEBT with as many periods as needed to achieve the required chopping efficiency, as will be discussed below, without a significant increase of the beam emittance.

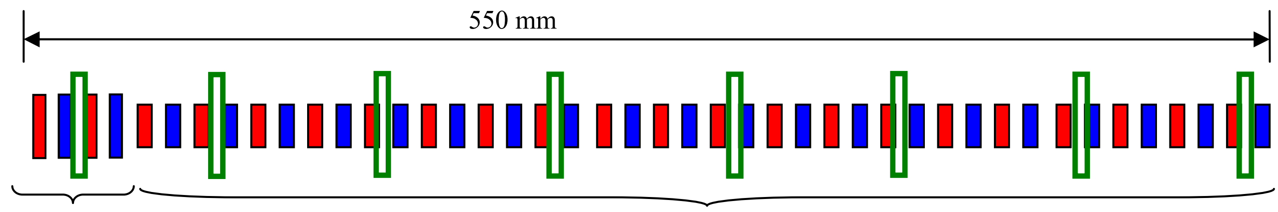

Figure 1: FODO channel structure. Blue and red rectangles represent focusing and defocusing quadrupole magnets respectively; green rectangles represent buncher cavities.

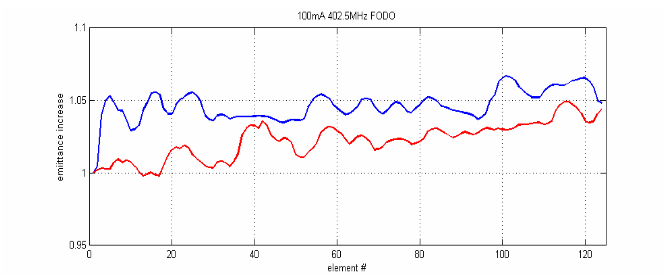

Figure 2: Transverse emittance increase along the FODO channel. Blue – horizontal; Red – vertical.

OPTIMAL CHOPPER

In order to be effective a chopper has to separate chopped and unchopped slices of beam by a distance large compared to the beam transverse size. We define chopping efficiency as $R = \frac{d}{\sigma}$, where d and σ are the separation and beam size on the target respectively. The beam displacement in case of a lumped kick is

$$d = \sqrt{\beta_1 \beta_2} \sin(\Psi_{12}) \cdot \alpha , \tag{1}$$

where β_1 and β_2 are beta functions at the kicker and the target locations respectively; Ψ_{12} is the betatron phase advance between the kicker and the target; α is the deflection angle of the kicker.

Substituting $\sigma = \sqrt{\beta_2 \varepsilon}$, where ε is beam emittance, we have

$$R = \sqrt{\frac{\beta_1}{\varepsilon}} \sin(\Psi_{12}) \cdot \alpha . \tag{2}$$

A simple estimation of the kicker deflection is $\alpha = k \frac{V \cdot L}{\Delta}$, where k is a numeric coefficient, V is the kicker voltage, and Δ is the gap between the kicker plates.

The kicker aperture should allow beam to pass through without significant losses therefore $\Delta = a\sigma = a\sqrt{\beta_1 \varepsilon}$, where $a \approx 5 - 10$ is a numerical coefficient of the designer's choice, depending on the safety margin required. After substituting this to (2) we have for the chopping efficiency:

$$R = \frac{k}{a} \cdot \sin(\Psi_{12}) \cdot \frac{V \cdot L}{\varepsilon} \tag{3}$$

For maximizing R the transport channel between the chopper and the target should be tuned for $\Psi_{12} \approx 90^\circ$; then

$$R \approx \frac{k}{a} \cdot \frac{V \cdot L}{\varepsilon} , \tag{4}$$

and, at a first glance, it does not depend on the transport properties at all. But in the case of a long kicker the betatron phase changes along its length as $\int \frac{ds}{\beta}$, therefore only part of the kicker of length $L \approx \beta_1$ is effective, resulting in

$$R \approx \frac{k}{a} \cdot \frac{V \cdot \beta_1}{\varepsilon} .$$

This relation shows the main contradiction between quality of the beam transport, which requires strong focusing, and hence small β_1, and effective chopping, which requires β_1 being large. The root cause is the betatron phase variation along the kicker. We propose to eliminate it by dividing one long chopper into several shorter ones, each of them placed with optimal phase advance from the target. Equation (4) is valid for each kicker and their kicks will add up if $\Psi_{12} \approx (2k+1) \cdot 90^\circ$ for every kicker. In the case of a FODO structure with 90° phase advance per cell the kickers should be placed in every other cell with the polarity of the every other kicker reversed as shown schematically in Fig.3. The spaces without kickers can be used for buncher cavities and diagnostics. Chopping in both planes allows for better utilization of the available space. The fact that ion velocity is significantly less than the speed of light allows connecting kickers by external delay lines and exciting them from a single power supply without sacrificing the kick rise time [2].

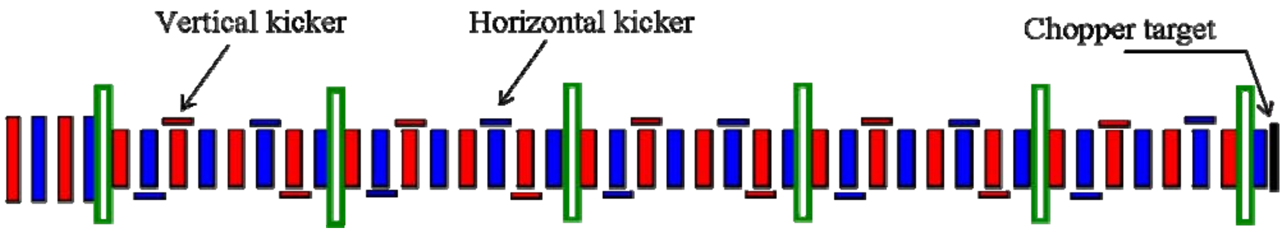

Figure 3: Schematic view of FODO transport channel with the distributed chopper. Blue and red rectangles represent focusing and defocusing quadrupole magnets respectively; green rectangles represent buncher cavities.

PRACTICAL CONSIDERATIONS

The proposed structure of the MEBT with a distributed chopper might look complicated compared to a traditional one with a long chopper. But, in addition to better beam quality, there are a number of advantages, which should be considered.

1. All elements of the FODO channel are identical. Permanent magnets can be used, which allows for a compact design with all elements inside a single vacuum chamber.
2. Stronger transverse focusing results in smaller beam size, which, in turn, allows for smaller aperture of the magnets, kickers and RF cavities. Smaller aperture is very beneficial, especially for the kicker and RF cavity design.
3. Multiple kickers allow for very flexible design of the kicker power supply. Some of them can be used as quasi-electrostatic devices with relatively slow rise time but large duty factor, and the rest of them can be used as high speed matched strip lines. This eliminates the need for combining high voltage, wide bandwidth, and large duty-factor requirements into a single power supply.
4. The chopped part of the beam is deflected gradually along the MEBT. By placing annular masks in front of each kicker, a distributed chopper target is created, which reduces the power load on the final target and serves as a beam collimator simultaneously.
5. The length of the MEBT can be made as long as needed to provide the required chopping efficiency with the available power supply for the kicker. The main cost factor is the number of buncher cavities, but it may well be offset by the reduced RF power requirements due to reduced aperture.
6. Better beam quality at the MEBT exit allows for smaller apertures in the downstream linac, which potentially can be a huge cost saving factor.

CONCLUSIONS

We propose to use a smooth and strong as possible beam transport channel as a foundation of a high current MEBT. Short chopper kickers are distributed along the MEBT in accordance with favorable betatron phase advance to the target. This approach allows to preserve the beam emittance and to provide enough space to accommodate the required integral kicker length. We presented an example of a 5.5 m long FODO channel transporting 100 mA with 5% emittance increase, and allowing for 1m of integral kicker space in each plane. The additional advantages are small aperture of the beam elements and flexibility of combining kickers with different characteristics.

ACKNOWLEDGEMENT

ORNL/SNS is managed by UT-Battelle, LLC, for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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