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DYNAMICS OF BUNCHES PARTIALLY CHOPPED WITH THE MEBT CHOPPER IN THE ESS LINAC

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Abstract

The front-end of a hadron linac typically has a transient time during turning on and off and bunches in the head and tail of a pulse from this period likely have wrong parameters and a risk to cause beam losses. A risk of losses must be avoided as possible in a high power machine so these bunches are removed with deflectors called *choppers* in the ESS Linac. From experiences of other machines, a rise time of a chopper as fast as one RF period (2.84 ns for ESS) is challenging to achieve and not necessarily needed with no ring to inject like ESS, and hence a 10 ns rise time is planned for a chopper in the medium energy beam transport of ESS. This, however, means that several bunches receive intermediate deflections and may propagate with large trajectory excursions. This paper studies dynamics of such *partially chopped* bunches in detail to ensure no significant loss is caused by them.

INTRODUCTION

The European Spallation Source (ESS) is a neutron source planned in Lund, Sweden based on a proton linac with a 2 GeV beam energy, 62.5 mA peak current, 352.21 MHz bunch frequency, 2.86 ms pulse length, and 14 Hz repetition rate, producing an unprecedented 5 MW beam power. For such a high power linac, minimization of beam losses is one of the most important and difficult challenges. Figure 1 shows the layout of ESS Linac [1]. The beam produced in the ion source (IS) is first accelerated with room temperature structures, a radio frequency quadrupole (RFQ) and drift tube linac (DTL), and then accelerated in three superconducting (SC) sections, consisting of spoke, medium-β, and high-β cavities. The linac also includes low, medium, and high energy beam transports (LEBT, MEBT, and HEBT) for characterizations and manipulations of the beam.

A conventional microwave discharge ion source used in the ESS Linac typically has a rise and fall time of tens of µs [2] and the bunches in the head and tail of a pulse, generated in this period, are likely to have wrong parameters related to the space-charge force. Though it is hard to predict behaviors of these bunches and they may or may not cause losses, it is better to remove them to avoid a risk of losses as possible. Modern hadron machines such as SNS Linac, J-PARC Linac, CERN Linac4, and RAL FETS use a system so-called *chopper*, which deflects and removes bunches together with a dedicated beam dump to manipulate the pulse structure for the ring injection [3]. Such a system can be also used for ESS to remove above mentioned bunches and the plan is to have two choppers: a slower chopper in the LEBT with a rise time of 2-3 µs removes most of these bunches

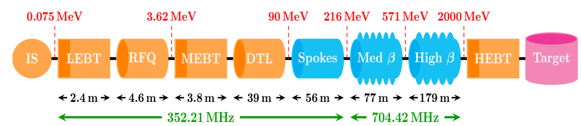

Figure 1: Schematic layout of the ESS Linac. Blue (orange) color indicates room (superconducting) temperature.

and a faster chopper in the MEBT with a rise time of 10 ns removes the remaining bunches in the 2-3 µs part.

The 10 ns rise time of the MEBT chopper is a balance between the required engineering effort and the ideal of beam dynamics. The difficulty to achieve a fast rise time lies in the switch. Fast switches on the order of 10 ns are commercially available and some are tested for a chopper of the RAL FETS [4]. On the other hand, experiences of the above mentioned machines proved that a rise time as fast as one RF period (2.84 ns for ESS) could be an engineering challenge to achieve and could require more space in the lattice. The 10 ns rise time means that several bunches receive intermediate deflections and may propagate in the linac with large trajectory excursions. Although the SNS Linac and J-PARC Linac have a similar situation and they are having no issue [5,6], these *partially chopped bunches* are still of concern to cause losses. Therefore, the intent of this paper is to study dynamics of these bunches in detail and to ensure that they cause no significant loss and the 10 ns rise time is fast enough. ESS also uses the often quoted 1 W/m as the limit of allowed losses but it is ideal to keep an order of magnitude or so margin during the operation. Hence, it is desired that the losses due to the partially chopped bunches are limited to the level of 10^{-3} W/m or at most 10^{-2} W/m to leave a room for the bulk of the pulse. It is also desired to have losses as small as possible in the SC sections since SC structures are generally more sensitive to losses than normal temperature structures.

PARTIALLY CHOPPED BUNCH

Prior to studying the losses, this section gives a brief description of the MEBT chopper of ESS and discusses basic properties of the partially chopped bunches. The top part of Fig. 2 shows a schematic layout of the MEBT lattice, where blue boxes above (below) the central line are focusing (defocusing) quadrupoles, green boxes are buncher cavities, and red lines and triangles are the chopper and its dump. As seen in the figure, the chopper and its dump are located after the first quadrupole triplet. Hardware of the chopper is planned be similar to that of the CERN Linac4 [7]; an electric deflector with a 20 mm gap and 40 cm length is surrounded with a large aperture quadrupole. However, due to the differences

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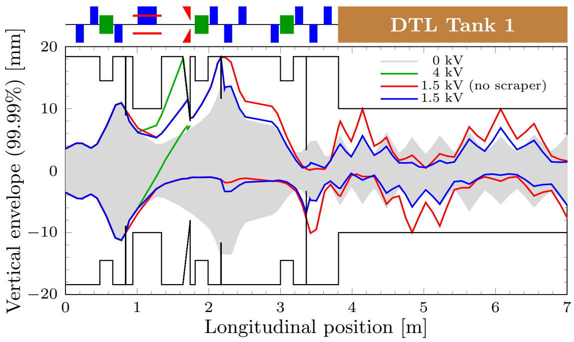

Figure 2: MEBT lattice schematic (top), aperture (black), and vertical envelopes of a partially chopped bunch (1.5 kV).

in the beam energy (3.62 MeV for ESS), deflection angle, rise time, and aperture, details will be different. With the maximum voltage of 4 kV, the chopper deflects a bunch by 14.6 mm at the end of the dump, which is 60 cm away from the center of the chopper plates (~24 mrad deflection). Because the rise and fall of a chopper for the RAL FETS, which has similar parameters as the MEBT chopper of ESS, are almost linear [4], a perfectly linear rise and fall is assumed as an approximation in the simulations of the next section.

The main part of Fig. 2 shows vertical envelopes (enclosing 99.99% of particles) in the MEBT and the beginning of the DTL, calculated with TraceWin code [8], for the case of 1.5 kV, together with the cases of 0 and 4 kV as references. The black lines represent the aperture and the tight apertures located at 0.84, 2.17, and 3.36 m represent three scrapers. The 1.5 kV is selected as a representative since the voltages around this value is worst in terms of losses as seen in the next section. Looking at the no scraper case, only a fraction of a bunch hits the dump and the rest touches the aperture of the DTL and cause losses due to the large trajectory excursion. For the case with the scrapers, the second and third scrapers intercept some particles, which otherwise enter the DTL, and significantly reduce the reach of the outermost particle, improving the efficiency of the chopper.

Figure 3 shows the relation between the voltage and efficiency of the chopper, where the efficiency is defined as one minus the transmission rate at the end of the MEBT. For the case with no scraper, the chopper is effectively on above ~3 kV and off below ~1 kV and so only the bunches under this range of ~2 kV are of concern. The efficiency improves with scrapers but the voltage range of concern remains ~2 kV. Since the chopper voltage changes by ~1.1 kV in one RF period[1], there are only one or at most two bunches under such a voltage range. One or two potentially ill-behaved bunches may look insignificant but even a loss of a single bunch from each pulse could produce a power loss up to 5 W in the ESS Linac. Therefore, behaviors of these one or two bunches and losses caused by them, if any, are studied in detail in the next section.

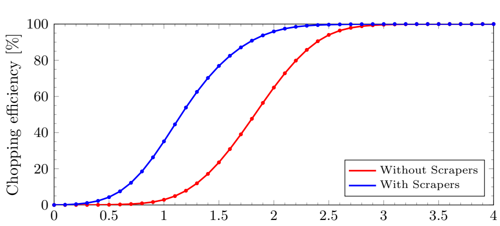

Figure 3: Chopper efficiency vs. voltage.

BEAM LOSS

As a first step, to see the trend of the losses caused by the partially chopped bunches, tracking simulations are performed with TraceWin code for voltages from 0 to 4 kV in a step of 100 V. About one million particles from a RFQ simulation are tracked from the beginning of the MEBT entrance to the end of the SC sections. In the simulations, the space-charge force is calculated 25 times in every [(relativistic-β) × (wavelength)] with 3D PICNIC routine [9] of a 10×10×10 mesh size. The top and middle rows of Fig. 4 show losses due a single bunch in unit of W/m (multiplied with 14 Hz to include the effect of the repetition rate) for only selected six cases due to the space limitation. The longitudinal position extends only over the DTL and the section of spoke cavities since no loss is observed in the following sections. Four conclusions are drawn from these simulations: i) without scrapers, losses occur in the range of ~1-2.5 kV, ii) without the scrapers, the worst case is around 1.5 kV and causes the peak loss on the order of 10^{-3} W/m, iii) practically no loss in the SC sections due to that the SC sections have much larger apertures than the DTL, iv) the scrapers not only improve the efficiency but also suppress the losses to a practically negligible level for all the voltages.

The last row of Fig. 4 shows the total losses, assuming the perfectly linear rise or fall, for the 10 ns rise, 10 ns fall, and 100 ns rise. For all three cases, the voltage is assumed to begin to rise or fall in synchronization with a bunch. Namely, for the 10 ns rise, the voltages are 0, 1.14, 2.27, 3.41 kV; for the 10 ns fall, 4, 2.86, 1.73, 0.59 kV; and, for the 100 ns rise, 0, 0.11, 0.23, $\cdots$, 3.97 kV. For the cases of the 10 ns rise and fall, the losses may be reduced by adjusting the timing to start the rise and fall with respect to a bunch. However, neither the exact rise time nor waveform are not known yet so such a detailed optimization is not performed at this stage. For the cases of the 10 ns rise and fall, the total loss is dominated with one or two bunches in the range of 1-2.5 kV and hence should not exceed the level of 10^{-3} W/m. This is confirmed with the figures of the left and middle. On the other hand, because these losses are caused by the trajectory excursion and the phase advance of the trajectory excursion is independent of the chopper voltage, the losses of the different voltages occur at the same locations and could accumulate and the peak loss for the 100 ns rise case reaches to the order of 10^{-2} W/m. This indicates that the rise time should not relax too much from the 10 ns to keep the losses within the 10^{-3} W/m level.

[1] (4 kV)×[(352.21 MHz)×(10 ns)]$^{-1}$ ~ 1.1 kV.

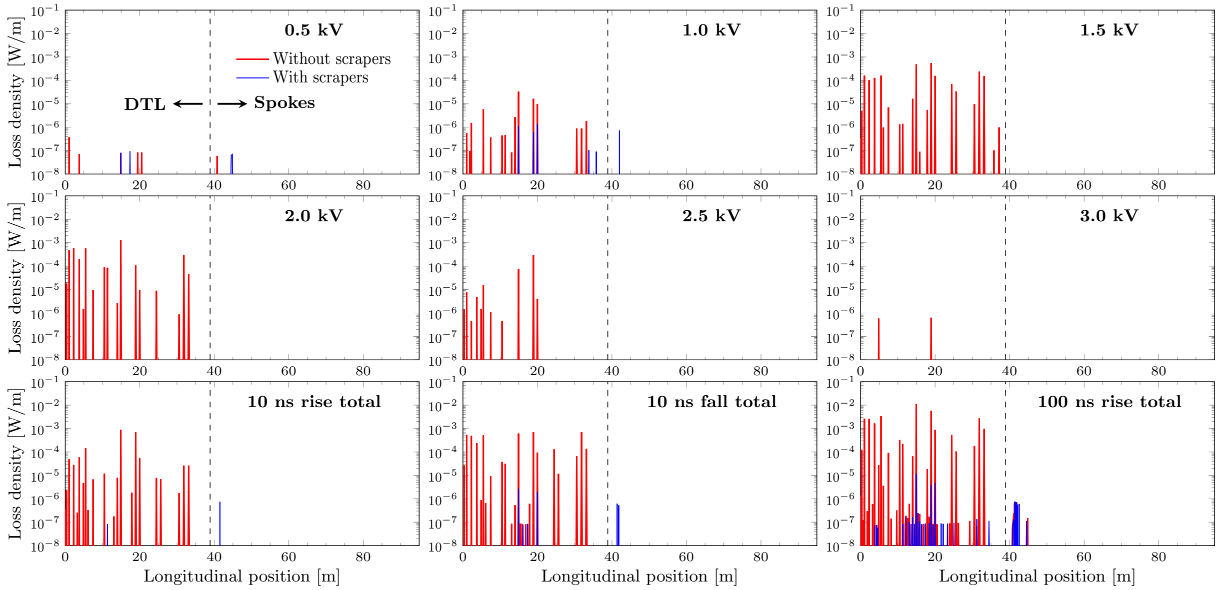

Figure 4: Losses due to one partially chopped bunch for various chopper voltages (top and middle). The total losses during the 10 ns rise, 10 ns fall, and 100 ns rise (bottom).

The above simulations are done with the perfect lattice but the losses could be enhanced with various lattice errors. To see the impact of lattice errors, the tracking simulation is repeated with lattice errors for the 1.5 kV case with no scraper to observe the worse case. In the simulation, so-called the *tolerance values* [10] are used as errors and, in addition, the trajectory excursion due to the lattice errors are left out (otherwise the trajectory excursion due to the chopper is also canceled). These conditions of errors also represent fairly pessimistic cases. The top of Fig. 5 shows the losses in the DTL and SC sections. The *Average* shows the average loss over all one thousand random seeds and the *99% confidence level* shows the worst losses after excluding the worst 1% cases. Comparing these two results, the SC sections have losses only in the worst 1% cases, indicating practically no loss in the SC sections. The bottom of Fig. 5 is the same as the top but the the DTL part is magnified. For the average case, the peak loss approaches to 10^{-2} W/m, which is an order of magnitude larger than the case with no error. Though this result is based on very pessimistic conditions, it indicates a very bad trajectory in the DTL could increase the losses to this level even for the 10 ns rise time and hence importance of a good trajectory correction.

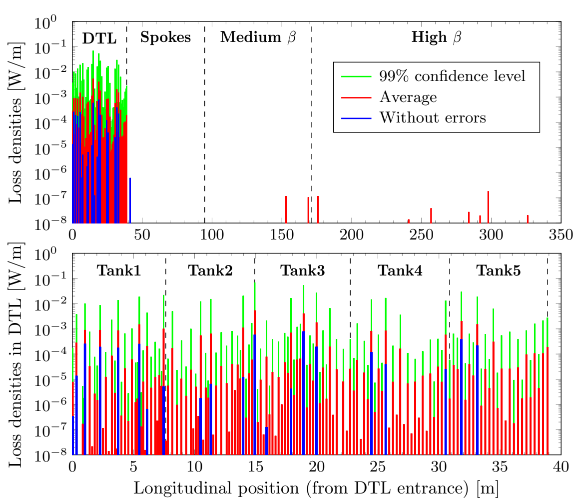

Figure 5: Losses due to one partially chopped bunch with lattice errors for the 1.5 kV case .

CONCLUSIONS

Dynamics of bunches partially chopped with the MEBT chopper is studied for the ESS Linac. It is shown that practically no loss occurs in the SC sections and the planned 10 ns chopped rise time is reasonable in terms of the losses in the DTL. It is also shown that the MEBT scrapers improve the chopper efficiency and also largely suppress the losses due to the partially chopped bunches.

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