LONGITUDINAL BUNCH PROFILE MONITORING AT THE ESS LINAC

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Abstract

The European Spallation Source (ESS), which is currently under construction, will be a neutron source based on 5 MW, 2 GeV proton linac. This high intensity linac will among other beam instrumentation require longitudinal bunch profile monitors. These shall be used during the commissioning phase and start-up periods for beam dynamics optimization and beam loss reduction. The paper focuses on the preliminary studies concerning the longitudinal bunch profile monitoring at the ESS linac.

INTRODUCTION

The European Spallation Source (ESS) is a material science facility, which is currently being built in Lund, Sweden and will provide neutron beams for neutron-based researches [1]. The neutron production will be based on bombardment of a tungsten target with a proton beam of 5 MW average power. A linear accelerator (linac) [2] will be used to accelerate protons up to 2 GeV and transport them towards the target. The ESS linac will create a pulsed beam with an average pulse current of 62.5 mA, pulse duration of 2.86 ms and repetition rate of 14 Hz. The beam will be bunched at 352.21 MHz frequency in the first and 704.42 MHz in the ending part of the linac.

It is essential to have a linac equipped with a certain set of beam instrumentation during the commissioning phase and start-up periods of a linac in order to tune it for optimal beam transmission and minimal beam losses during the operation periods. An example of such an instrument is a Longitudinal Bunch Profile Monitor (LBM), which provides information about an average time structure of a bunch. This paper summarizes the current status and plans regarding the LBM system at the ESS linac.

LBM LAYOUT AT THE ESS LINAC

Four LBM devices are currently planned to be installed in the ESS linac. Their anticipated positions along the linac are marked on Fig. 1. The one-sided RMS longitudinal bunch size is expected to shrink from ~150 ps to 3 ps during the acceleration process. The intrinsic limit for the LBM methods that are based on detection of the bunch electric field at the beam pipe boundary can be estimated [3] as

$$\Delta t = \frac{R_{bp}}{\sqrt{2}v\gamma}, \tag{1}$$

where $\Delta d = v/\Delta t$ represents the RMS value of the longitudinal charge distribution on the inner wall of the beam pipe with radius R_{bp}, which is produced by a charged particle moving with speed v. Due to the rather low Lorentz factors γ of the ESS beam the one-sided RMS bunch lengths will be far below this limit (see Fig.2). Therefore the available options to measure the bunch profiles are rather limited. The most common device used for measuring the longitudinal bunch profile in proton machines like ESS is one called Bunch Shape Monitor (BSM) proposed by A. Feschenko [4]. A typical phase resolution of this device is ~1 ^{o} [5], which is accurate enough only for one of the 4 planned LBM devices at the ESS linac[1], namely LBM1 located in the MEBT section. However it has been recently proposed by A. Feschenko that a resolution of 0.5 ^{o} or less could be achieved with a modernized version of the RF deflector, which should provide more symmetric electro-magnetic fields with less fringing fields at the edges [6]. As this is accurate enough for both LBM1 and LBM2 device, ESS aims for both to be a Feschenko's BSM with proposed modernized RF deflector. Depending on how well the modernized BSM resolution can be improved the LBM3 could potentially also be a BSM device. However the expected bunch lengths at the LBM4 location will be to short to be resolved even with the modernized BSM. Therefore LBM4, and potentially LBM3 as well, require development of a new device type. Additional argument for new development in the case of LBM3 follows from the study of the space charge effect on the performance of a BSM, which is the subject of the following section.

BSM AND SPACE CHARGE EFFECT

Feschenko's BSM is based on collecting the low energy Secondary Electrons (SEs) emitted from a thin wire target placed in the beam. The time structure of the primary bunch is transformed into spatial distribution of SEs through a RF modulation generated by a RF deflector. High negative voltage potential is applied to the wire to accelerate the SEs towards the RF deflector with a set of slits and an electron detector at the exit.

There are several contributions to the resolution of a BSM [5, 6]. Some can in principle be controlled by the design (e.g. contributions due to non zero wire size, due to defocusing, focusing and dispersive properties of RF deflector, etc), while others represent a natural limit and are a consequence of either the space charge (SC) of the primary bunch or the physical process of SE emission (time, velocity and direction spread of emitted SEs). The most worrying intrinsic limitations to the resolution are the time delay of SE emission and the SC effect due to the primary bunch. Here the latter is discussed for the case of the ESS linac.

The electromagnetic field of the analyzed beam disturbs the trajectory of the SEs on their way towards the RF deflector.

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[1] The quoted phase resolution was determined at the linac frequency of 352.21 MHz, thus 1^{o} corresponds to ~8 ps.

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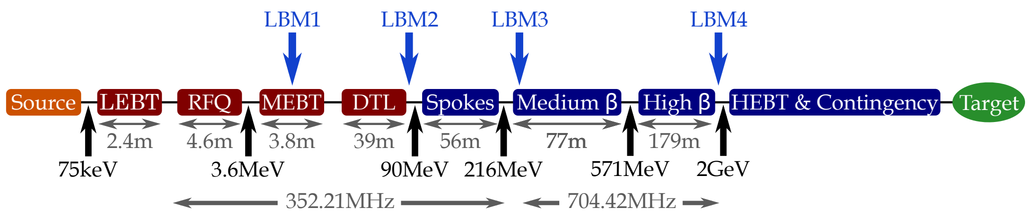

Figure 1: ESS linac and LBM layout.

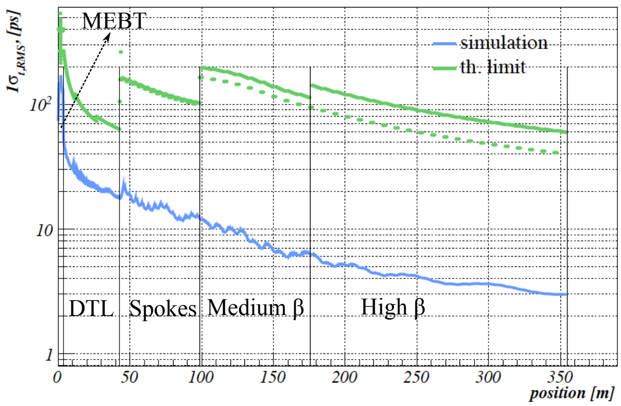

Figure 2: Expected one-sided RMS bunch lengths at the ESS linac (blue) and intrinsic limit on the one-side RMS length due to the spatial spread of charge field (green).

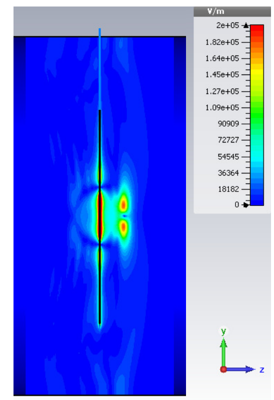

Figure 3: Calculated bunch electric field for conditions expected at LBM4 location.

This results in distortion of the measured longitudinal profile. The effect has been studied for the case of the ESS linac with a simulation, which was divided into two steps:

- Calculation of the electric field.
  The dynamic electric field of the moving bunch passing the wire and the static field of the wire under potential were calculated separately with the use of the CST studio suit software [7]. The Particle-in-Cell (PIC) solver was used for calculation of the bunch and Electrostatic solver for the wire field. The electric field components in the region of the interest were extracted into binary files for next simulation step. An example of a calculated bunch electric field is shown on Figure 3.
- Tracking of the SEs.
  This was performed with a custom made C++ shared library, which can be loaded in ROOT framework [8]. The library provides objects for running the tracking simulation and the analysis of the results.

In the results presented here, a wire under potential of −10 kV and of radius 0.1 mm was considered. The proton bunch is assumed to have a 3D Gaussian distribution of charge with equal RMS size in both vertical and horizontal planes, $\sigma_x^{RMS} = \sigma_y^{RMS}$, which was taken to be equal to the average value of the corresponding ESS parameters. In order to limit the focus of the study only to the influence of the SC, the SEs were emitted with zero initial velocity, no time delay, at a fixed point on the wire closest to the RF deflector and in the fixed direction of smallest distance to the deflector. Each emitted SE's contribution to the measured profile was weighted depending on the fraction of the protons hitting the wire in the time step before the SE's creation.

An example of simulation result is presented on Fig. 4, which shows the SE time distribution expected at the beam pipe boundary. It can be seen that the primary bunch SC non-linearly distorts the measured distribution, resulting in a non-symmetric shape.

The simulation has been performed for LBM1 at two

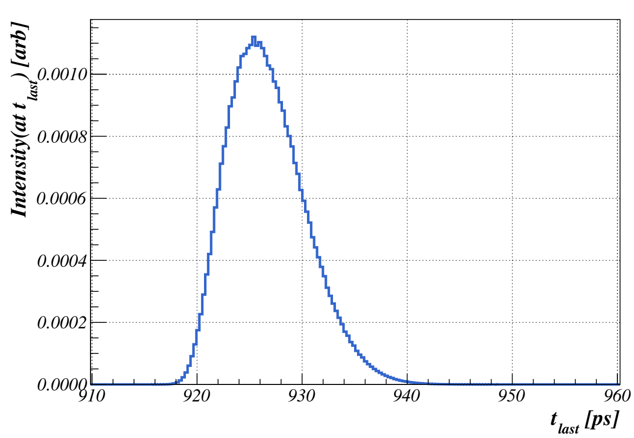

Figure 4: Time distribution of the SEs at the beam pipe boundary for conditions expected at LBM4 location.

different positions inside the MEBT (beam pipe radius R_{bp}=15 mm), beginning and middle, as well as at planned locations of LBM3 (R_{bp}=50 mm) and LBM4 for four different wire positions along the direction of the smallest distance to the deflector. The results are presented on Fig. 5 and marked with full circles. In order to asses how the SC effect changes with bunch density, the simulation for LBM4 was performed with different bunch lengths, while the rest of the conditions were kept as expected at the ESS linac (marked with blue color on Fig. 5. The top plot on Fig. 5 shows the normalized difference in the RMS value of the SE time distributions expected at the beam pipe boundary:

$$\Delta^{\mathrm{RMS}} = \frac{\sigma^{\mathrm{RMS}}_{z,sc} - \sigma^{\mathrm{RMS}}_{z,0}}{\sigma^{\mathrm{RMS}}_{z,0}}. \quad (2)$$

where $\sigma^{\mathrm{RMS}}_{z,sc}$ and $\sigma^{\mathrm{RMS}}_{z,0}$ respectively represent the RMS value for simulation with and without SC included. Similarly the bottom plot shows the normalized difference for the mean value of the SE time distribution at the beam pipe boundary:

$$\Delta^{\mathrm{mean}} = \frac{t^{\mathrm{RMS}}_{z,sc} - t^{\mathrm{RMS}}_{z,0}}{\sigma^{\mathrm{RMS}}_{z,0}}. \quad (3)$$

where $t^{\mathrm{mean}}_{z,sc}$ and $t^{\mathrm{mean}}_{z,0}$ respectively stand for the mean value of SE arrival time for simulation with and without SC included. Here the differences are compared to the true one-sided RMS length of the bunch in units of time in order to quantify the degree of distortion for the expected SE time distribution. As there are other sources that degrade the BSM resolution, the contribution due to the SC is desired to be as minimal as possible. From the Fig. 5 it follows that the SC contribution can be neglected only in the case of LBM1, while a new device type should be considered for the case of both LBM3 and LBM4. This is discussed in the following section.

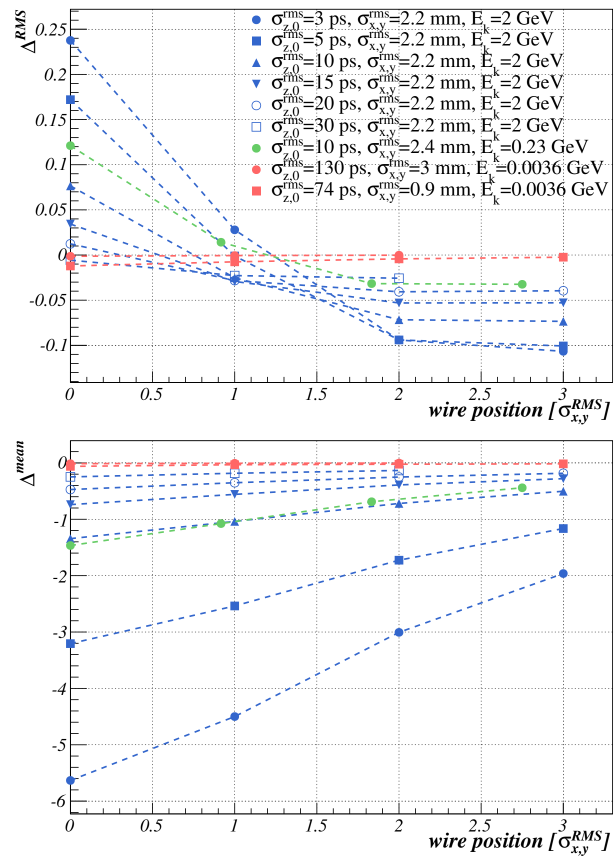

Figure 5: Expected normalized difference in RMS (top) and mean (bottom) of the SE time distributions at the beam pipe boundary as a function of wire position in units of one-sided RMS beam transverse size $\sigma^{RMS}_{x,y}$.

ALTERNATIVES

For the case of LBM3 and LBM4 an alternative based on Cherenkov or transition radiation together with a streak camera is currently being studied. The primary motivation for focusing on photons as the secondary particles is to avoid the SC effects. Additionally both Cherenkov and transition radiation interactions are considered to occur fast in contrast to SE emission, where it was experimentally shown, that an the emission time delay does not exceed (4±2) ps [9]. Due to the rather low beam energy at the LBM3 location, there is a concern regarding a sufficient photon yield from transition or Cherenkov radiation. Therefore it is additionally planed to use the new method proposed in [10] for this location, either as a supplementary option or as a back-up solution.

SUMMARY

There are four LBM devices planned to be installed at the ESS linac. The two devices located in the lower energy part of the linac are aimed to be a Feschenko's BSM with a modernized deflector. The bunch shape measurements in the end parts of the linac will be challenging due to very short bunches expected in these sections, where one-sided RMS bunch lengths of down to ~3 ps are expected. A standard solution with sub-picosecond resolution does not exist for proton machines like ESS, thus a research and development effort has to be performed for the case of the two devices located in the high energy parts of the ESS linac.

REFERENCES

[1] "ESS: Technical Design Report", ESS-2013-001

[2] M. Eshraqi et al., "The ESS linac", MOXAP07, IPAC2014, Dresden, Germany (2014).

[3] R.E. Shafer, AIP Conf. Proc. 212, 26 (1990).

[4] A.V. Feschenko, AIP Conf. Proc. 281, 185 (1992).

[5] A.V. Feschenko, Topical workshop on bunch shape measurements, ESS, Lund, Sweden, February 2013.

[6] N.E. Vinogradov et al, NIMA, 526, 206 (2004).

[7] `ttps://www.cst.com`

[8] `http://root.cern.ch/drupal/`

[9] A.V. Feschenko, FRXOR01, RUPAC2012, Saint-Petersburg, Russia (2012).

[10] A. Shishlo, A. Aleksandrov, Phys. Rev. Spec. Topics - Acc. and Beams, 16, 062801 (2013).

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