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CONCEPT OF A BEAM DIAGNOSTICS SYSTEM FOR THE MULTI-TURN ERL OPERATION AT THE S-DALINAC*

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Abstract

The S-DALINAC is a thrice-recirculating electron accelerator operating in cw-mode at a frequency of 3 GHz. It is possible to operate the accelerator as an Energy-Recovery LINAC, due to the implementation of a path-length adjustment system capable of a 360° phase shift. The multi-turn ERL operation has been demonstrated in 2021. While operating the accelerator in this mode, there are two sets of bunches, the still-to-be accelerated and the already decelerated beam. Effectively, they act as a 6 GHz beam with largely different absolute longitudinal coordinates in the same beamline. For this mode, a non-destructive, sensitive beam diagnostics system is necessary in order to measure the position of both beams simultaneously. The status of a 6 GHz resonant cavity beam position monitor (cBPM) will be given together with the results of a wire scanner measurement of the multi-turn ERL beam.

INTRODUCTION

The Superconducting Darmstadt Linear Accelerator (S-DALINAC) is a thrice-recirculating linear electron accelerator operating in cw-mode at a frequency of 2.997 GHz [1]. It has been upgraded in 2016 by the installation of a third recirculation beamline. A path-length adjustment system included in the newly built beamline allows the change of the path-length by up to 100 mm corresponding to a phase shift of 360° in beam phase [2]. It is therefore possible to operate the S-DALINAC as an Energy-Recovery-Linac (ERL) by shifting the beam phase by 180° which was first demonstrated in 2017 [3]. A floorplan of the S-DALINAC is shown in Fig. 1.

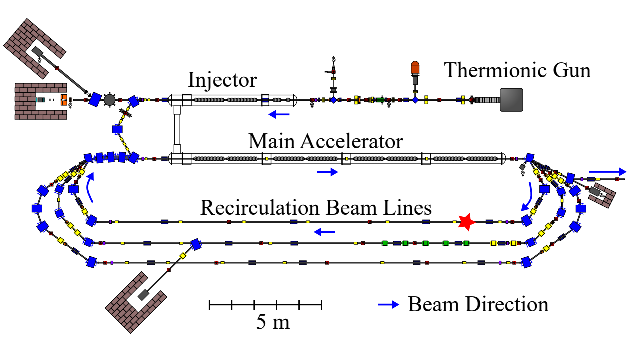

Figure 1: Floorplan of the S-DALINAC. The red star marks the position of the wire scanner and the planned cavity beam position monitor.

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In 2021, the multi-turn ERL operation was demonstrated at the S-DALINAC [4,5]. During this operational mode, the beam was accelerated twice and subsequently decelerated twice again. In this mode, the once accelerated beam and the once decelerated beam share the same beamline (first recirculation) but do not necessarily have the same orbit in this beamline. Therefore, a beam position measurement capable of determining the positions of both beams simultaneously is required. In addition, a beam phase and current measurement is desired. The measurement has to be non-destructive as it would otherwise interrupt the ERL mode. A particular challenge is the operation at low beam currents of 100 nA, which corresponds to bunch charges of about 30 aC, while the beam is tuned. As conventional pick-ups are not suitable for these low bunch charges, two solutions are pursued:

1. A resonant cavity beam position monitor (cBPM) operated at 6 GHz.
2. A wire scanner measurement.

6 GHz RESONANT CAVITY BEAM POSITION MONITOR

In ERL mode, the beam has an effective bunch repetition frequency of 5.995 GHz in the first recirculation beamline. The first concept is a position measurement using a resonant cavity BPM with its TM_{110} mode at the doubled fundamental frequency of nearly 6 GHz. The TM_{110} mode is the so called dipole mode. It can be used for position measurement as the field strength depends linearly on the beam current and the transverse offset to the cavity center for small offsets. In order to distinguish between a change of the beams position and its current, a non-destructive current measurement is necessary.

Design and Construction

The required cavity radius R_{res} for a simple pillbox cavity without beampipes can be calculated to

$$R_{\mathrm{res}}^{110} = \frac{c_0 \cdot a_{mn}}{2\pi \cdot f_{\mathrm{res}}} \approx 30.5\,\mathrm{mm}, \quad (1)$$

where $f_{\mathrm{res}} = 6\,\mathrm{GHz}$ is the resonance frequency, c_0 is the speed of light and a_{mn} is the nth zero of the Bessel function of mth order [6]. However, simulations using CST Microwave Studio [7] have been carried out in order to determine the geometrical parameters of the cBPM. The monitor has been designed with two separate cavity cells, one for the horizontal and one for the vertical position measurement. To ensure the excitation of the TM_{110} mode along the desired axis, mode separators were included. Two capacitive antennas

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will be used for the out coupling of each position signal. A sectional view of the designed monitor can be seen in Fig. 2. The resulting geometrical parameters are summarized in Table 1. Aluminum was chosen as the material for the monitor and the separate pieces have been constructed by the in-house mechanical workshop.

Table 1: Resulting Geometrical Parameters of the Cavity Beam Position Monitor

cavity cell diameter	57.4 mm
cavity cell length	18.2 mm
distance between cells	40 mm
beam pipe diameter	25 mm

Read-Out Electronics

The proposed read-out electronics consist of a 180 degree hybrid coupler where the difference signal of both antennas of one cavity cell is used and amplified. The signal will then be processed by an in-house developed rf-board. The processing consists of an amplitude detection and base band IQ-demodulation by mixing the monitor signal with the frequency doubled signal from the local oscillator.

Measurement Procedure

A resonant cavity at 6 GHz will not be able to measure the beam position from bunch to bunch. The measured position will be the averaged position of both beams over the sampling time of the read-out electronics. Several steps are required to determine the positions of both beams independently:

- At first, the cBPM must be calibrated. In order to do so, the beam is blocked before the second deceleration, so that only the position of the once accelerated beam is measured.
- The block is removed and both beams are measured giving the averaged position signal.
- The position of the once decelerated beam must then be calculated from both previously determined positions, the once accelerated beam and the averaged signal.

As long as only the decelerated beam is moved, e.g. by a corrector magnet, the calibration still holds and the position of the second beam is measured correctly. If the first beam is re-tuned, the calibration procedure has to be repeated. However, if the first beam moves unintentionally, this measurement method will give incorrect results.

WIRE SCANNER MEASUREMENT

An alternative position measurement is a wire scanner measurement where a wire is driven horizontally and vertically through the beam and the secondary particle emission is measured by a scintillating detector outside of the beampipe. Since the count rate is proportional to the beam intensity, the beam profile can be measured and with a calibrated wire scanner drive, the beam position can be determined as well. A wire scanner has been constructed and installed into the beamline. During the multi-turn ERL operation in 2021, several beam position measurements of the once accelerated beam and the once decelerated beam could be carried out. The measurement procedure is similar to the 6 GHz monitor measurement: At first, the position of the once accelerated beam was measured while blocking the once decelerated beam. The corresponding plot can be seen in Fig. 3 a), where the number of counts per position step is shown over the vertical beam position. The peak is clearly visible at a beam position of 2.3 mm. After this measurement, both beams were measured together which gives a sum signal of two Gaussians. The corresponding plot is shown in Fig. 3 b), where the peak of the once accelerated beam is still clearly visible. Additionally, a second peak is visible at a beam position of −5.4 mm which must correspond to the once decelerated beam. If both peaks were not well separated, then the position of the once decelerated beam would have to be calculated from the two previous measurements.

The wire scanner has to be re-calibrated if the once accelerated beam moves, as this measurement procedure is similar to the measurement with the cBPM. Furthermore, the time for one measurement is in the order of several seconds which makes the wire scanner measurement not suitable for beam tuning, but it will serve as a good method for comparing the results of the cBPM measurements. It is also noticeable that the background increased in the second measurement which indicates beam loss of the once decelerated beam.

CONCLUSION AND OUTLOOK

For the multi-turn ERL operation at the S-DALINAC, a measurement system capable of measuring the beam position of the once accelerated and once decelerated beam in the same beamline simultaneously is required. The status of a 6 GHz resonant cavity beam position monitor has been given together with the results of a wire scanner measurement of the multi-turn ERL beam.

For the 6 GHz monitor the geometrical parameters have been determined by simulations and after the technical drawings were made, the monitor has been constructed by the in-house mechanical workshop. The necessary rf-board for the read-out electronics is in development by the in-house electrical workshop. While this monitor provides a measurement for the multi-turn ERL mode, frequent calibrations would be needed since it can not be determined if the once accelerated beam moves unintentionally. As a next step, the unloaded quality factor will be determined and the coupling will be set. In addition, a testing bench has been developed and constructed for in-depth testing of the monitor's performance.

The alternative is a wire scanner measurement which has been conducted during the multi-turn ERL operation in 2021. The measurements show the functionality of the wire scanner with two beams in the same beamline. Similar to the 6 GHz monitor, frequent calibrations would be needed and the measurement time of several seconds makes this measurement inconvenient for beam tuning. Additionally,

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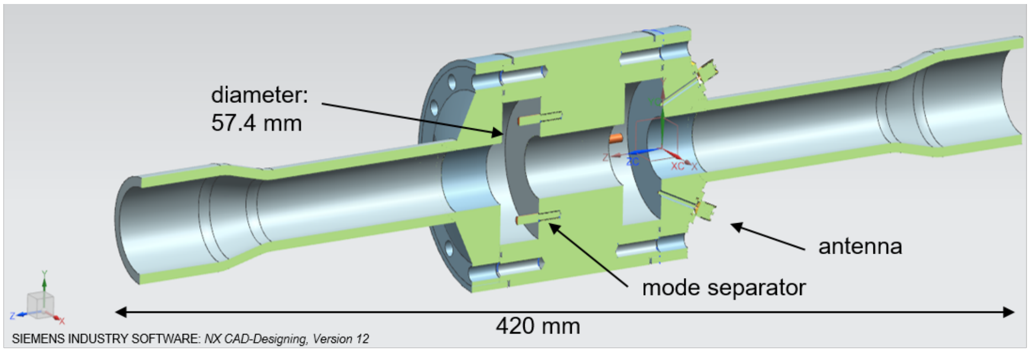

Figure 2: A sectional view of the designed cavity beam position monitor.

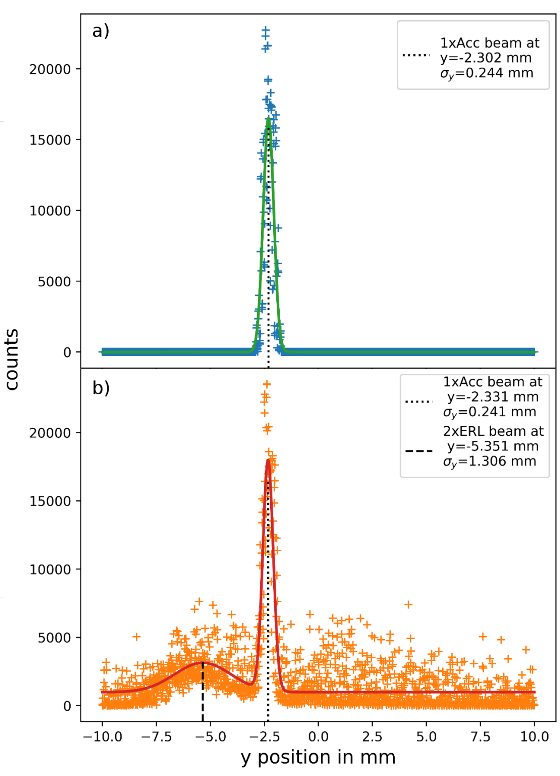

Figure 3: Measurement of the counts per position step as a function of the vertical beam position. a) Measurement the once accelerated beam, while the once decelerated beam was blocked. b) Measurement with the once accelerated and the once decelerated beam in the same beamline.

it is planned to use the wire scanner together with very fast LGAD detectors [8]. This would allow a bunch-to-bunch measurement in the multi-turn ERL mode.

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