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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 linear electron accelerator operating in cw-mode at a frequency of 3 GHz. A path-length adjustment system in the second recirculation beam line allows to shift the beam phase by 360° and thus to operate in ERL mode. For the multi-turn ERL operation, the beam will be accelerated twice and subsequently decelerated twice again (not demonstrated yet). For this mode, it is necessary to develop a nondestructive beam diagnostics system in order to measure the beam position, phase and beam current of both, the accelerated and the decelerated beam, simultaneously in the same beamline. The conceptional study of a 6 GHz resonant cavity beam position monitor will be presented together with alternative solutions.

INTRODUCTION

The Superconducting Darmstadt Linear Accelerator (S-DALINAC) is a thrice-recirculating linear electron accelerator operating in cw-mode at a frequency of 3 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 an increase of the path length by up to 100 mm corresponding to a phase shift of 360° in beam phase. It is therefore possible to operate the S-DALINAC as an Energy-Recovery-Linac (ERL) by shifting the beam phase by 180° which was demonstrated in 2017 [2]. A floorplan of the S-DALINAC is shown in Fig. 1.

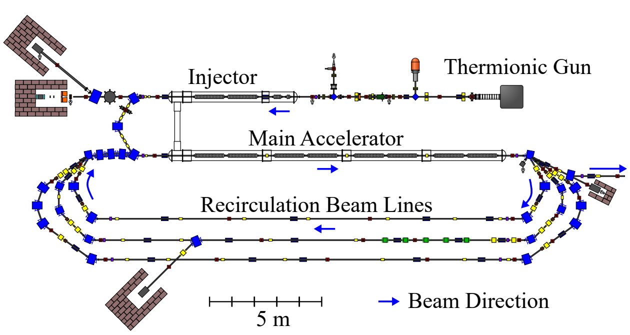

Figure 1: Floorplan of the S-DALINAC

For the upcoming multi-turn ERL operation, the beam will be accelerated twice and subsequently decelerated twice again. In this mode, the once accelerated beam and the once decelerated beam will 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 beam positions of both beams simultaneously is required. In addition, a beam phase and current measurement is desired. The measurement has to be nondestructive as it would otherwise interrupt the ERL mode. A particular challenge will be 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 pickups are not suitable for these low bunch charges, the following solutions are under investigation:

1. A resonant cavity beam position monitor (BPM) operated at 6 GHz.
2. A resonant cavity beam position monitor operated at 3 GHz together with a pulsed beam of about 1.7 MHz.
3. A wire scanner measurement.

6 GHZ RESONANT CAVITY BEAM POSITION MONITOR

In ERL mode, the beam has an effective bunch repetition frequency of 6 GHz in the first recirculation beamline. The first concept is a position measurement using a resonant cavity BPM with its TM_{110} mode at a frequency of 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 nondestructive current measurement is necessary. When the beam crosses the cavity center the signal will show a phase shift of 180°. Therefore, a beam phase measurement is required whereby the BPM can be calibrated to the transverse side. Both measurements can be conducted using another type of cavity located close to the cavity BPM. This type of cavity is routinely used at the S-DALINAC [3] and its TM_{010} mode is excited independent of the beams transverse position.

Electromagnetic Conception

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

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

where $f_{res} = 6\,\text{GHz}$ 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. The beampipe at the S-DALINAC has a radius of 17.5 mm which leads to a decrease of the resonance frequency which in turn has to be compensated by

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decreasing the cavity radius. However, simulations using CST Microwave Studio [4] showed that the beampipe radius must be decreased in order to excite the dipole mode at the required frequency. The shunt impedance R_s can be seen as a measure of how well the mode is excited. It is the proportionality constant between the beam current squared and the power induced in the cavity:

$$R_s = \frac{P}{I^2}. \quad (2)$$

Figure 2 shows the shunt impedance R_s over the x-position for different beampipe radii. The mode excitation starts at 14 mm and increases for smaller radii. As previous beam times and simulations have shown, the acceptance in the machine is of crucial importance for ERL operation [5]. Therefore, it was decided to use a radius of 12.5 mm for the beampipe openings of the cavity BPM. This leads to a cavity radius of $R_{res} = 28.7$ mm. In order to determine the cavity length l_{cav}, the shunt impedance has been simulated with varying cavity lengths. The associated plot can be seen in Fig. 3. The quadratic function fit gives a maximum shunt impedance at $l_{cav} = 19.0$ mm.

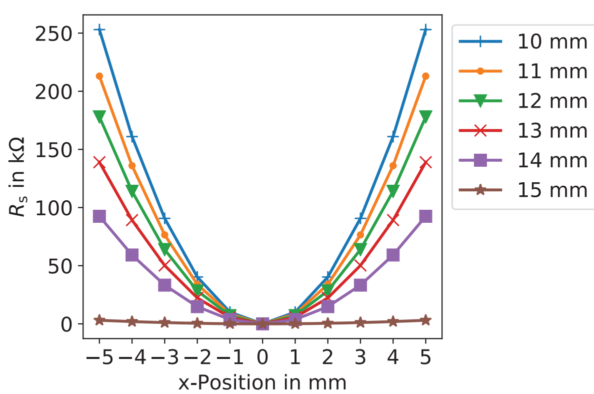

Figure 2: Shunt impedance R_s over the x-position for different beampipe radii. The mode excitation starts at 14 mm.

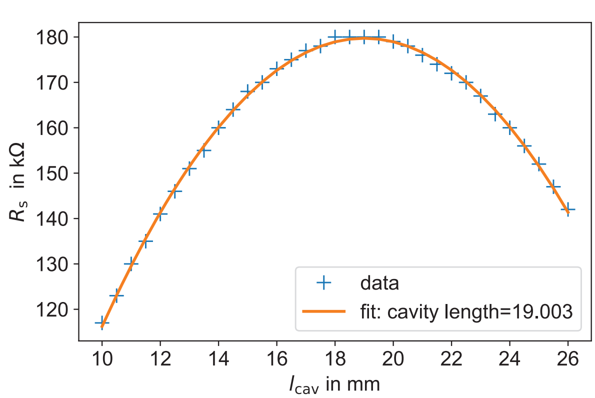

Figure 3: Shunt impedance R_s over the cavity length l_{cav}. A fit gives a maximum at $l_{cav} = 19.0$ mm.

As mentioned above, the measurement system must additionally consist of a beam phase and current measurement. It is planned to use another resonant cavity with a TM_{020} mode excitation. This mode possesses the same features as the TM_{010} mode but the radius can be larger so that it won't be necessary to decrease the beampipe radius. The cavity radius and length were determined in the same way as for the TM_{110} cavity. The resulting parameters for both cavities are summarized in Table 1.

Table 1: Resulting parameters for the position and the phase and current monitors.

	Phase / Current Monitor	**Position Monitor**
Mode	TM_{020}	TM_{110}
R_{res}	46.1 mm	28.7 mm
l_{cav}	19.3 mm	19.0 mm

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 one microsecond which is the sampling time of the electronics. Several steps are required to determine the positions of both beams independently:

- At first, the measurement 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 respectively.

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 moved, the calibration procedure has to be repeated. However, if the first beam moves unintentionally, this measurement method will give incorrect results.

3 GHZ RESONANT CAVITY BEAM POSITION MONITOR + PULSED BEAM

The second idea for the beam position measurement is to use the already existing cavity BPMs for the non-ERL mode. At the S-DALINAC there are a total of 6 cavity BPMs, one at the beginning and one at the end of each straight recirculation beamline. These cavities have been developed in 1996 [6] and are currently not fully in operation. A picture of one of This type of cavity can be seen in Fig. 4. It consists of a TM_{010} cavity for beam phase and current measurements and a TM_{110} cavity for the position measurement. It is designed for the regular bunch frequency of 3 GHz what makes it unusable in normal ERL operation since the signals of the

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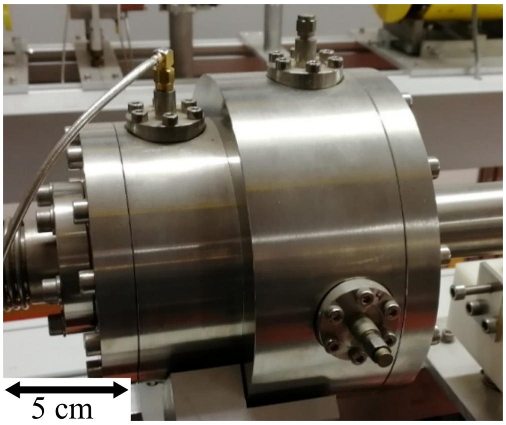

Figure 4: Cavity BPM at the S-DALINAC. It consists of a smaller TM_{010} cavity for beam phase and current measurement and a larger TM_{110} for the position measurement.

effective 6 GHz beam would cancel out each other. If a beam pulsing is applied such that there is only a single bunch train in the machine, the position of the once accelerated and the once decelerated beam could be measured successively. The bunch train must be long enough for the cavities to get excited but shorter than 300 ns. This is the time the bunch train needs from the cavity BPM through the second acceleration, the second recirculation, the first deceleration and back to the cavity BPM. The beam pulsing must be applied such that the gap between macro pulses is larger than the length of the bunch trains (duty cycle less than 50 %), so that there will be no overlap of bunches in the monitor.

A test measurement from 1999 [6] was performed with a beam pulsing of 10 MHz. In this test, a decay time of

$$\tau = \frac{Q_L}{2\pi \cdot f} = 27\,\text{ns} \tag{3}$$

was measured which shows that the monitors meet the required time resolution of 300 ns. Using this type of cavity BPM in combination with a pulsed beam could help with beam tuning but would not be usable in normal ERL operation.

WIRE SCANNER MEASUREMENT

The third concept 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 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. However, the measurement time will be of the order of several seconds which makes it inconvenient for beam tuning. The measurement procedure is similar to the 6 GHz monitor measurement: At first, the current and position of the once accelerated beam are measured while blocking the once decelerated beam. After that, both beams are measured together which gives a sum signal of two Gaussians. The position and current of the once decelerated beam has to be calculated from the two previous measurements. Information on the beam phase cannot be determined by this method.

CONCLUSION

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. Three concepts for such a measurement system have been presented: A 6 GHz resonant cavity beam position monitor, a 3 GHz resonant cavity beam position monitor together with a pulsed beam operation and a wire scanner measurement. All three options are worked on in parallel. The optimal measurement for position, phase and current will then be chosen for further operation.

For the 6 GHz monitor the cavity radius and length have been determined by simulations to $R_{res} = 28.7$ mm and $l_{cav} = 19$ mm respectively. While this monitor provides a measurement for the normal ERL mode, frequent calibrations would be needed since it can not be determined if the once accelerated beam moves unintentionally. For this monitor refinement of the simulations will be done including the addition of a coupling antenna and the material.

As an alternative to the 6 GHz monitor, the already existing 3 GHz monitors could be used. They only have to be calibrated once, however they are not suitable without a pulsed beam. Since the position measurement of the 3 GHz monitor system has not been in operation for many years, it is planned to make one of the monitors ready to use again for the upcoming beam time. For a test measurement, the preparations are ongoing.

The second alternative is a wire scanner measurement. 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. The construction of the wire scanner has to be finished for the upcoming beam time and the read out electronics have to be tested.

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