BEAM-BASED ALIGNMENT OF SRF CAVITIES IN AN ELECTRON INJECTOR LINAC*

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Abstract

Proper alignment of accelerating cavities is an important issue concerning beam quality of linear rf-accelerators. In particular, SRF cavities of injector linacs using high accelerating gradients on low-velocity electron beams can deteriorate the beam quality significantly when not aligned sufficiently. On the other hand, knowing the exact position of every cavity after several cool-down cycles of a cryomodule can be difficult depending on the particular module design. We will report on operational experience on the SC injector of the Darmstadt superconducting recirculating linac and ERL (S-DALINAC) showing unwanted effects on beam dynamics and beam quality due to cavity misalignment, such as transverse beam deflections by changing accelerating phases and a growth of transverse emittance. These effects could already be observed at small beam currents of a few nA, so space-charge effects were eliminated to be the reason for these observations. In this work we will report on the possibility to realign SRF cavities after cool-down by measuring the transverse deflection of the beam and compare results with beam dynamics simulations.

INTRODUCTION

Proper alignment of beamline-components is crucial to achieve and sustain highest beam quality in accelerators. In this work we focus on beam quality degradation induced by a misalignment of an SRF acceleration cavity. It is well known that accelerating cavities do not only transfer energy to the beam but also focus the beam slightly when operated on the accelerating phase or defocus on the decelerating phase [1, 2]. For ultra-relativistic electron beams on axis of a rotationally symmetric cavity transport matrices are known and the motion is well understood [1, 2]. A slight growth of the transverse emittance dependent on the bunch length must be expected. It can be neglected for most applications except for low beam momentum and high accelerating fields like present for example in rf guns or injector linacs [2,3]. Typically, the electrons are assumed to pass the accelerating cavities on axis which is true in the case of perfectly aligned cavities, only. Investigations on alignment restrictions for high energy lepton colliders which aim for smallest emittances in the nm scale showed relaxed constraints on accelerating cavities compared to

the quadrupole magnets of the accelerator for high energy beams [4]. Nevertheless, in the injection section of a linac the beam still has low momentum and thus low rigidity. Misaligned injector cavities can, therefore, be an issue for beam quality. The focusing effect of rf cavities induces a kick on the particles when they do not pass the cavity on axis. Furthermore, this kick is phase dependent. Different particles of the bunch receive different transverse kicks due to their individual longitudinal position. This mixes the longitudinal and transverse phase spaces and can result in an emittance growth [5]. When the bunch length is not short or when longitudinal tails exist, these phase-dependent kicks can also produce transverse halo like recently reported from cERL [6]. On the other hand, perfect *a priori* alignment of SRF cavities within a cryomodule or SRF linac can be quite challenging. Sometimes thermal stress slightly shifts the cavities positions during several cold-warm cycles and not every module allows correction of single cavities or even checking and manipulating the alignment from outside the vacuum vessel in cold condition. For that reason, we present a method for beam-based alignment [4] of an SRF cavity which can be applied even at very low beam currents. The method has been demonstrated in experiments at the superconducting Darmstadt linear electron accelerator S-DALINAC.

S-DALINAC

Simulations and measurements presented here are concerning the SRF capture cavity of the injector of the superconducting recirculating electron linac and ERL (S-DALINAC) at Darmstadt. This accelerator is fully operating since 1991 [7] and has recently been upgraded with an additional recirculating beamline allowing single- and multi-turn ERL operation [8]. It operates at a frequency of 3 GHz and uses eleven superconducting cavities designed for particles moving with the speed of light (β=1) with a design gradient of 5 MV/m for acceleration. The SRF injector linac consists of a 5-cell and two 20-cell niobium cavities to reach a maximum energy of 10 MeV. The total beam energy of the accelerator after four passes of the electron beam through the main linac is 130 MeV.

The cryomodules of the S-DALINAC have been designed and built in the 1980's [9]. The injector consists of one short module housing a 5-cell capture cavity and of one standard module housing two 20-cell cavities. The accelerating cavities and their frequency tuners are mounted on the same rigid bench inside the helium vessel so relative alignment in between the two single cavities of
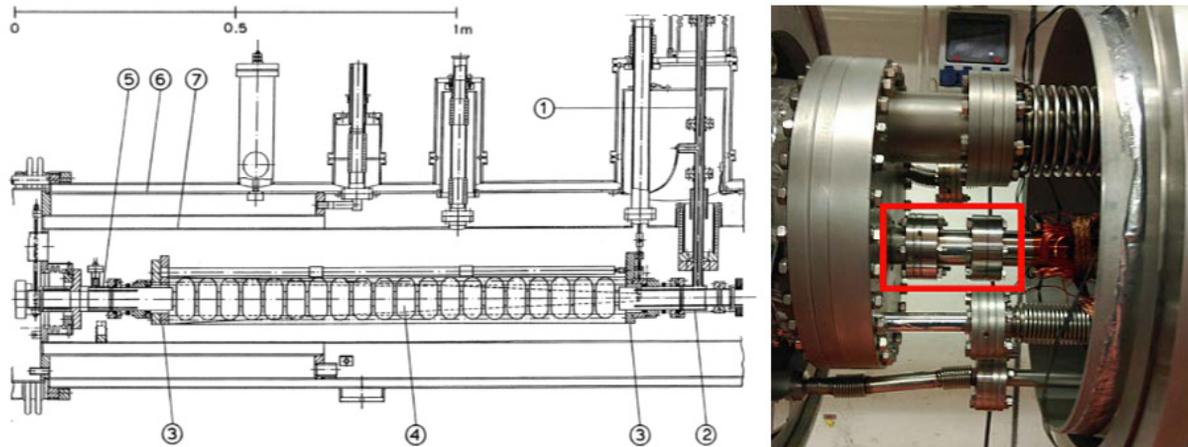
Figure 1: Technical drawing of one half S-DALINAC cryomodule (left picture) [9]. The cavities (3), the couplers (2,5) and the frequency tuners (4) are sitting inside the helium vessel (7) on an aluminium bench. The helium vessel is hanging on the 80 K shield (6) by steel rods. The 500 W rf power is coupled in by a coaxial line (1). On the right picture the interconnection in between two modules is shown [11]. The big bellow of the helium gas return line is relatively stiff and can induce stress in between helium vessels from different modules. The beam tube is located in the red box.

one module is no issue. On the other hand, the complete helium vessel is not solidly fixed inside the module but hanging on thin steel rods from the 80 K shield for reduction of heat leakage. Furthermore, the cavity position inside the cryomodule is not accessible from the outside anymore after closing the vacuum tank and the interconnections between the cryomodules. So thermal stress during cool-down or warm-up cycles can slightly shift the helium vessel and thus the cavity alignment in between the different modules. Recently severe periodic pressure fluctuations in the helium vessel as well as in the insulation vacuum of the cryomodules could be observed and fixed. But these fluctuations probably have had an influence on the cavities' positions. Figure 1 shows an overview of the cavity's mounting inside the module and of the interconnection in between two modules. As cavity alignment cannot be remeasured after cool-down by traditional techniques, we use unwanted steering and defocusing of the beam induced by the rf cavities as diagnostics for cavity misalignment which can then be cured by properly adapting the position of the entire cryomodule. This strategy has been proven successful for the second module of the injector linac in the past [5]. Our method for beam-based alignment of rf cavities will be outlined below.

ELECTRON BEAM OBSERVATIONS

Unwanted effects on the electron beam have been observed while operating the injector of the S-DALINAC: The first one was a transverse deflection of the electron beam when changing the accelerating phase of the 5-cell capture cavity. Tuning the rf phase by 8 degrees, the beam was steered completely over the first 3 cm diameter scintillating screen placed after the injector cryostat at ~5.3 m from the cavity position (see Fig. 2). This steering made beam commissioning and operation quite challenging. The tuning range of the correction magnets in front of the injector cryostat and in between the two

cryomodules was not big enough to find a setting without beam deflection. The second observation was a defocusing and a rotation of the beam on the same screen at the optimum accelerating phase. The last observation was an increase in both transverse emittances by a factor of 1.5 to 2 with respect to the expected values [12]. This increase was not an issue for beam operation as acceptance limits of the subsequent accelerator parts haven't been exceeded. But it gives a hint on the actual beam quality degradation in the injector linac. As beam currents in the S-DALINAC injector never exceed 100 µA in cw operation (33.3 fC corresponding bunch charge) [10] space charge has almost no effect on the S-DALINAC electron beam [5] and could only explain an emittance growth of about 1%. The beam current in recirculating operation of the S-DALINAC for electron scattering experiments is typically even lower and amounts to about 1-2 µA.

Measurements on Electron Beam

In order to quantify the misalignment of the first cryomodule, measurements of the emittance of the electron beam exiting the injector linac and of beam deflection that was induced by changing the rf phase of the 5-cell capture cavity have been done. These measurements were performed at a very low cw beam current (100 nA, 0.03 fC bunch charge) allowing the constant use of scintillating screens. The results of these measurements can be seen in Fig. 2 and Table 1. The steering of the beam by changing rf phases has been determined to 3.2±0.1 mm/deg in horizontal and 1.9±0.1 mm/deg in vertical direction. These values have been used for an estimate of the cavities' displacement as described in the next section. After realignment of the entire cryomodule, the same measurements have been carried out again. As it can be seen in Fig. 2 the steering of the beam could be almost eliminated (less than 0.2 mm/deg) and transverse emittances could be reduced significantly (see Table 1).
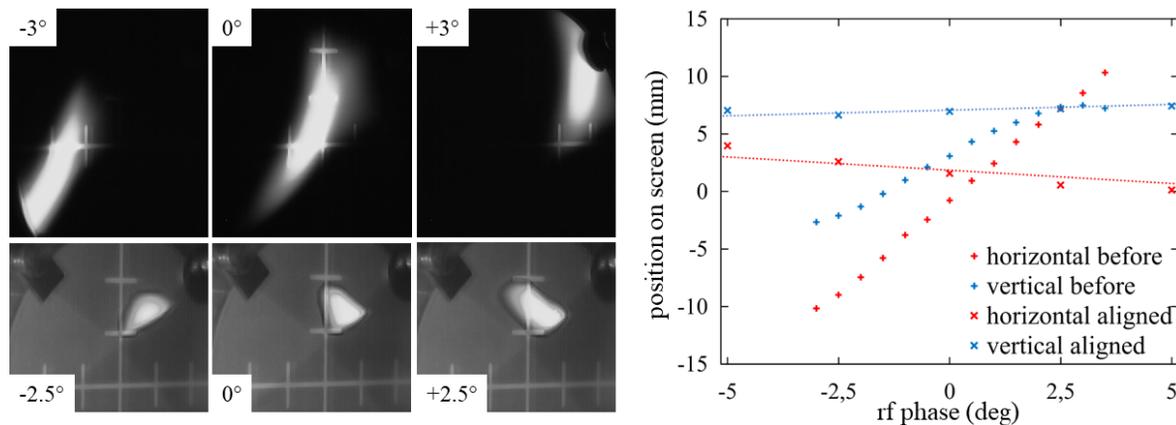
Figure 2: Deflection of the beam on a scintillating BeO screen 5.3 m downstream when changing the rf phase of the 5-cell capture cavity with respect to the optimum (0°). The tics on the target cross axis are 5 mm apart. Before correction (upper series) the beam is steered over the complete target. Proper focusing was impossible. After correction (lower series) the beam is much less steered and focused much better at the optimum rf phase. A total change of rf phase of more than 20 deg was possible without losing the beam on the screen.

Table 1: Measured and simulated normalized transverse rms-emittance before and after alignment.

		ε_{nx} [π μm]	ε_{ny} [π μm]
before alignment	simulated	0.54	0.31
	measured	1.3 ± 0.1	0.4 ± 0.02
after alignment	simulated	0.43	0.24
	measured	0.84 ± 0.05	0.15 ± 0.05

SIMULATIONS

Dedicated simulations of the corresponding beam dynamics in the injector have been conducted. The tracking program "General Particle Tracer" [13] was used. Space charge has been switched off for saving simulation time and the rf fields in the cavity have been approximated by an extrapolation from a MAFIA simulated field map along the axis [14, 15] to a cylindrically symmetric field map [16]:

$$E_z(r,z) = E_z(z)\cos(\omega t + \phi)$$

$$E_r(r,z) = -\frac{1}{2} r E'_z(z)\cos(\omega t + \phi)$$

$$B_\phi(r,z) = \frac{r\omega}{2c^2} E_z(z)\sin(\omega t + \phi)$$

This approximation is valid close to the beam axis, only. Simulation of space charge effects and more realistic field maps in 3D would be needed as input for quantitative understanding of real particle movement or any collective effects inside the cavity. But for the alignment purposes presented here a reduced simulation sufficed and speedy simulations have been our main goal. Beam measurements, subsequent simulations and corrections followed by a second series of beam measurements took ~3 hours, only. First, the beam through the cold injector was simulated without any misalignment to obtain the best estimate for transverse emittance. Then, the simulated 5-cell cavity has been displaced off axis by different amounts for simulating a displaced but yet not rotated cavity axis. Then the rf phase has been varied in the same range applied to the beam in the measurements and the steering with respect to phase changes at the position of the scintillating screen has been evaluated. This has been repeated until good agreement to measurements could be achieved. The best simulation run was corresponding to a displacement of the first cavity axis of 6±0.5 mm in horizontal and 4±0.5 mm in vertical direction with respect to the subsequent 20-cell cavities. This misalignment was corrected by correspondingly adjusting the position of the cryomodule housing the SRF 5-cell cavity. The series of measurements performed after that repositioning verify the successful alignment.

Emittance simulated under the misalignment condition was increased in both directions as observed in the beam measurements before (see Table 1). The change in measured emittance turned out slightly larger than expected from simulations. This can be explained by the simple field-map approximation and by not taking into account tilt angles between cavity axis and the reference orbit. Such angle offsets will be investigated in future and may explain, in addition, observed beam rotation.

CONCLUSION

In summary simulations could reproduce the steering effects and transverse emittance increase when taking cavity misalignment into account. It was possible to quantify and correct the cavity offset. The presented method allows checking and realigning positions of SRF cavities in a convenient amount of maintenance time, even when exact positions are not accessible in cooled down condition. The beam quality could be increased significantly proven by the measurements afterwards. In future we plan to check misalignment in cavity rotation angles as well and to pursue additional measurements on the main linac evaluating recent results from machine alignment [11].

REFERENCES

[1] J. Rosenzweig, L. Serafini, "Transverse particle motion in radio-frequency linear accelerators", *Phys. Rev.* E **49** (1994) p. 1599–1602.

[2] L. Serafini, J. Rosenzweig, "Envelope Analysis of Intense Relativistic Quasilaminar Beams in RF Photoinjectors: A Theory of Emittance Compensation", *Phys. Rev.* E **55** (1997) p. 7565–7590.

[3] K. Floettmann, "RF-induced Beam Dynamics in RF Guns and Accelerating Cavities", *Phys. Rev. STAB* **18** (2015) 064801. DOI: 10.1103/PhysRevSTAB.18.064801

[4] P. Tenenbaum *et al.*, "Beam Based Alignment of the TESLA Main Linac", Proc. of EPAC'02, Paris, France Jun. 2002, pp. 515-517.

[5] F. Hug *et al.*, "Beam Based Alignment Simulations and Measurements at the S-DALINAC", Proc. of PAC'09, Vancouver, BC, Canada, May 2009, pp. 3841-3843.

[6] O. Tanaka *et al.*, "New Halo Formation Mechanism at the KEK Compact Energy Recovery Linac", *Phys. Rev. Accel. Beams* **21** (2018) 024202. DOI: 10.1103/PhysRevAccelBeams.21.024202

[7] A. Richter, "Operational Experience at the S-DALINAC", Proc. EPAC 1996, Sitges (Barcelona), Spain, Jun. 1996, pp. 110-114.

[8] M. Arnold *et al.*, "Construction and Status of the Thrice Recirculating S-DALINAC", Proc. of IPAC'17, Copenhagen, Denmark, May 2017, pp. 1384-1387, doi:10.18429/JACoW-IPAC2017-TUPAB030

[9] V. Aab *et al.*, "The Superconducting 130 MeV Electron Accelerator at Darmstadt", Proc. of SRF'87, Argonne, IL, USA, Sep. 1987, pp. 127-140.

[10] T. Kürzeder *et al.*, "New Injector Cryostat Module Based on 3 GHz SRF Cavities for the S-DALINAC", AIP Conference Proceedings **1434** (2012) pp. 961-968. DOI: 10.1063/1.4707013

[11] M. Lösler et al., "Hochpräzise Erfassung von Strahlführungselementen des Elektronenlinearbeschleunigers S-DALINAC", zfv **6/2015** (2015) pp. 346-356. DOI: 10.12902/zfv-0090-2015

[12] P. Dijkstal *et al.*, "Automated Transverse Beam Emittance Measurement Using a Slow Wire Scanner at the S-DALINAC", Proc. of IPAC'15, Richmond, VA, USA May 2015, pp. 817-819.

[13] General Particle Tracer, Version 2.6 http://www.pulsar.nl/gpt

[14] M. Brunken *et al.*, "Latest Developments from the S-DALINAC and its Free-Electron-Laser", Proc. of LINAC'98, Chicago, IL, USA, Aug. 1998, pp. 403-405.

[15] T. Weiland., "Time Domain Electromagnetic Field Computation with Finite Difference Methods", Int. Jour. Num. Modeling **9** (1996) pp. 295-319. DOI:10.1002/(SICI)1099-1204(199607)9:4<295::AID-JNM240>3.0.CO;2-8

[16] "map1D_TM", in General Particle Tracer, User Manual.