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DESIGN OF A MULTI-CELL SRF REDUCED-BETA CAVITY FOR THE ACCELERATION OF LOW ENERGY ELECTRON BEAMS

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Abstract

A recent upgrade of the superconducting Darmstadt linear accelerator (S-DALINAC) allowed the operation in the energy recovery linac (ERL) regime. The ERL mode provides significant benefits for free electron laser (FEL) experiments. At the same time, it imposes strict requirements for the quality of the accelerated beams. Presently, an increased longitudinal energy spread is observed at the S-DALINAC due to the mismatch in phase in the first accelerating structure, which is a superconducting radio-frequency (SRF) 5-cell $\beta = 1$ cavity. In this work we discuss an alternative design for accelerating low-energy electron beams using an SRF multi-cell cavity with a constant geometric β.

INTRODUCTION

Historically, the S-DALINAC is the third superconducting particle accelerator in the world [1]. Recently, the accelerator has been commissioned for ERL operation [2]. High currents available at ERLs prove beneficial for driving FELs or other radiation sources, and, hence, investigating ERL beam dynamics at the S-DALINAC is expected to provide insight into FEL operation in multiturn ERLs. Historically, the S-DALINAC has been the driver of the first German FEL [3].

There are several projects aimed at improving the performance of the S-DALINAC. This work deals with finding a solution for the problem of the significantly increased energy spread of the beam that has been observed at the S-DALINAC. The increased energy spread originates from the capture section which is a part of the injector linac.

Two electron guns are available at the S-DALINAC: a spin polarised gun (SPG) and a thermionic gun (TG), which produce electron beams with initial energies of 200 keV (after upgrade [4]) and 250 keV, respectively. The purpose of the injector linac is to accelerate these low-energy electron beams. Presently, it consists of a 3 GHz 5-cell SRF $\beta = 1$ cavity and two 3 GHz 20-cell SRF $\beta = 1$ cavities. Initially, in addition to the 5-cell structure a 2-cell cavity with a reduced value of geometric β has been implemented in order to preaccelerate the beam. Figure 1 shows the cooling cryostat (red) which hosts the 2-cell and the 5-cell cavity and the RF power input system (green). Nowadays, the 2-cell cavity is permanently out of operation and cannot be replaced without a new cryostat. This situation necessitates to accelerate electron beams with relative velocities β of 0.69 in the 5-cell $\beta = 1$ cavity. A significant mismatch in phase results in an inefficient acceleration (see Fig. 2) and an increased energy spread of 27 keV for the output beam.

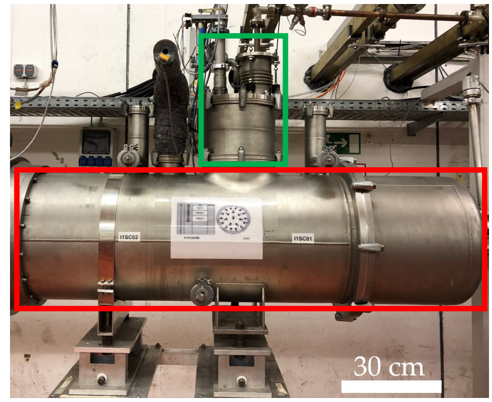

Figure 1: Cryostat.

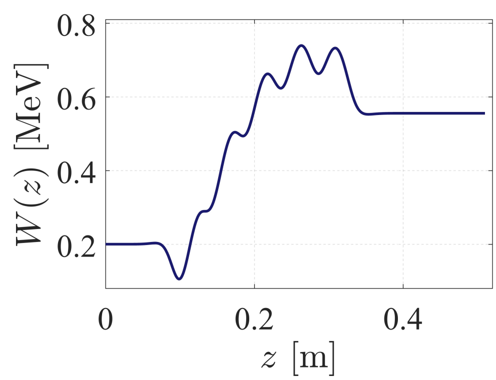

Figure 2: Energy gain of the beam in the 5-cell cavity.

UPGRADE OF THE CAPTURE SECTION

In order to reduce the energy spread of the beam at the S-DALINAC, the 5-cell cavity must be replaced with a new cavity. The new cavity must be capable of accelerating the electron beam up to an energy of at least 1 MeV while keeping the energy spread minimal. Other important requirements for the new structure are mechanical reliability and minimal investment costs.

The most commonly used methods for the acceleration of low energy electron beams are normal conducting β-graded cavities and SRF 1-cell or 2-cell independently driven structures. At the S-DALINAC spatial restrictions exclude a possibility of implementation of a normal conducting cavity for the injector linac. The implementation of independently driven SRF cavities would require a new cryostat, thereby failing to satisfy the minimal investment-cost requirement.

Hence, a cavity that can be operated with the existing cooling cryostat and the existing RF input power system was developed. As result of a quantitative and qualitative analysis, a 6-cell reduced-β cavity has been designed and will replace the 5-cell cavity [5]. The 6-cell cavity is now

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being manufactured. In the next chapters we discuss the RF design, beam-dynamics, mechanical characteristics and current state of production of the 6-cell cavity.

RF DESIGN

The cell shape of the 6-cell cavity is based on the 1.3 GHz TESLA cavity type, dimensions of which have been scaled such that the resonant frequency of the fundamental mode is 3 GHz. The cell shape was additionally optimised in order to match a reduced value of geometric beta ($\beta < 1$). The choice of the geometric beta and the number of cells for the 6-cell $\beta = 0.86$ cavity has been discussed in [6]. The RF design and optimisation has been carried out in CST MWS® [7]. The RF parameters of the 6-cell $\beta = 0.86$ cavity (see Fig. 3) are collected in Table 1.

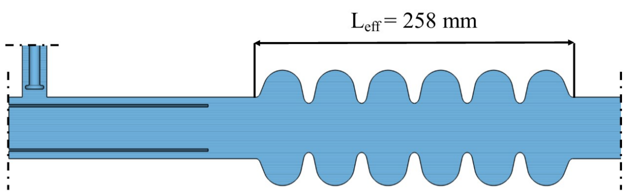

Figure 3: Layout of the 3 GHz 6-cell $\beta = 0.86$ cavity.

Table 1: RF Parameters of the 6-cell Cavity

Parameter	Value
Mode	TM_{010}
Frequency	2.997 GHz
Operation regime	CW
Operation temperature	2 K
Accelerating gradient	4.8 MV/m
R-over-Q	308 Ω

The 6-cell cavity is planned to be operated at a moderate accelerating gradient of 4.8 MV/m. This allowed to make design decisions in favour of the mechanical rigidity of the cavity. In particular, the iris radius was increased in order to increase the longitudinal rigidity of the structure despite the disadvantageous effect on the R-over-Q value.

Analytic calculations have shown that approximately 100 W of the forward RF power from the generator is required in order to operate the 6-cell cavity at the specified accelerating gradient. The existing RF amplifier at the S-DALINAC can deliver up to 500 W of RF power. In addition, numerical calculations in CST MWS® have shown that the 6-cell cavity is fully compatible with the existing RF input power coupler. The coupling coefficient between the generator and the cavity can be adjusted over a wide range.

BEAM DYNAMICS

The 6-cell cavity is capable of accelerating electron beams injected from the TG and the SPG up to energies of up to 1.5 MeV with a minimised energy spread growth. Figure 4 illustrates results of the particle tracking simulation in ASTRA [8] for the 200 keV and the 250 keV beam in the 6-cell cavity.

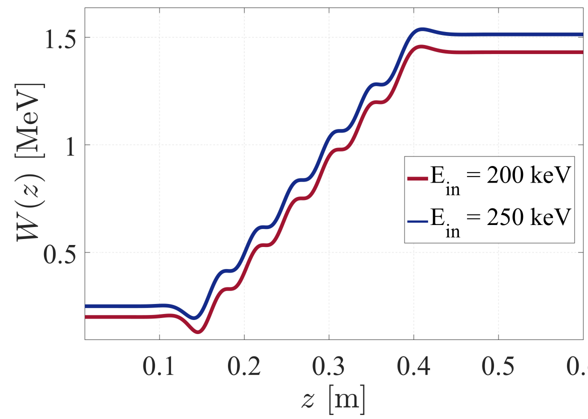

Figure 4: Energy gain of the beam in the 6-cell cavity.

Figure 5 shows the longitudinal phase space of the output beam from the 6-cell cavity injected from the SPG. The resulting bunch tail is due to the constant length of the cavity cells. However, the tail is located beyond 95% of the distribution of particles. Thus, its effect is negligible in our case. The energy spread could be further reduced by shortening the length of the left end-cell and by increasing the length of the right end-cell. The obtained results for the 6-cell cavity indicate an eight-times-lower energy spread and three-times-higher energy gain of the beam in comparison to the 5-cell $\beta = 1$ cavity for the same electric field on axis of the cavity of 10 MV/m .

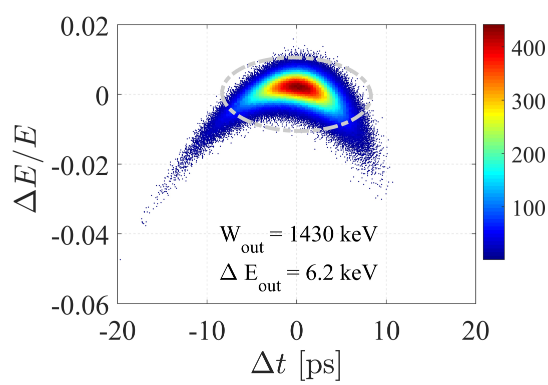

Figure 5: Longitudinal phase space of the output beam (grey dashed ellipsoid enclosing 95 % of particles in the distribution).

In order to minimise the energy spread of the accelerated low energy electron beams in a multi-cell cavity with cells of constant length, bunches must be short compared to the full RF cycle. In case of the S-DALINAC the bunch length is expected to be 5 ps, while the full RF cycle of the 6-cell cavity is 333 ps. An increase of the input bunch length will lead to an increase of the energy spread of the output beam. In order to effectively control the bunch length at the entrance of the 6-cell cavity a beam diagnostic tool is under development and will be used for the commissioning of the 6-cell cavity [9].

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MECHANICAL CHARACTERISTICS

The mechanical stability of the 6-cell cavity was one of the priorities during the optimisation of its geometry. A mechanical model of the 6-cell cavity with a wall thickness of 2.5 mm has been studied and optimised using finite element analysis in ANSYS [10]. A smooth transition from the end-cells to the drift tubes allowed to increase the longitudinal rigidity K of the cavity by 1 kN/mm. The key mechanical parameters of the 6-cell cavity are collected in Table 2.

Table 2: Mechanical Characteristics of the 6-cell Cavity

Parameter	Value
Material	Nb
Wall thickness, mm	2.5
K, kN/mm	5.6
df/dl, kHz/µm	2.1
df/dp, Hz/mbar	26

From the experimental data it is known that the average pressure fluctuations in the cryostat of the capture section during operation is approximately 1.5 mbar. Thus, a frequency detuning of 39 Hz is expected, which can be easily compensated by the tuning system. The existing tuning system now implemented for tuning the existing 5-cell cavity will be used for the 6-cell cavity as well. To enable that, the existing tuner frame and piezo tuners will be modified.

CAVITY MANUFACTURING

The production of the new 6-cell cavity has started end of 2018. Prior to the manufacturing of the single components, the expected cool-down and BCP frequency shifts of the cavity were estimated in order to correct the inner dimensions accordingly for the mechanical processing. The half-cells were then deep-drawn from 2.8 mm thick niobium sheets (RRR=300). After that, the dumbbells and endgroups were welded from the single components. Currently, these parts are trimmed in order to reach the desired target frequencies which correspond to the correct resonance frequency of the cavity after assembly. Target frequencies and trimming sensitivities df/dl were obtained through CST simulations taking into account the increased half-cell length of the components compared to the assembled cavity which is necessary for the preparation of the welds. After finishing the trimming of the components, the cavity will be welded and a first BCP will we conducted. Afterwards, a tuning and cold test is planned at the S-DALINAC vertical test cryostat [11] to verify the cool-down and BCP frequency shifts. The final amount of material to be removed through the second BCP treatment can then be determined from the measurements to ensure that the correct operational frequency will be achieved. Expected cavity delivery is end of 2019. Final field-flatness tuning, heat treatment and HPR are planned before the cavity could be ready for installation around spring 2020.

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CONCLUSION

The need for a non-standard method for the acceleration of the low-energy electron beam is motivated by limitations in space and investment costs at the S-DALINAC. In absence of practical constraints the suggested method can be improved further on by optimising the lengths of the first cell and the last cell of the cavity. The implementation of the 6-cell cavity at the injector of the S-DALINAC will improve the overall beam quality. The cavity is expected to be delivered to the S-DALINAC facility in end of 2019.

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