UPGRADE OF THE CAPTURE SECTION OF THE S-DALINAC INJECTOR*

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Abstract

In order to reduce the energy spread of the recirculated beam, the injector of the S-DALINAC needs to be optimized, because the non-isochronous recirculation cannot correct for errors originating from the injector linac. For the S-DALINAC, spatial restrictions suggest the use of superconducting radio frequency (SRF) technology for the capture section. In this work, we consider various SRF cavities with an operating frequency of 3 GHz for a possible upgrade of the capture section of the S-DALINAC. The first results of the RF and beam-dynamics (BD) simulations for the proposed options are presented in this work.

INTRODUCTION

The S-DALINAC is a superconducting linear electron accelerator with three recirculation beam lines. It operates at a frequency of 3 GHz in the continuous wave (CW) regime [1]. The maximal output energy is 130 MeV and the beam current is up to 20 µA. The electron beam is either produced in a thermionic gun or in a spin polarized electron gun (SPG) with energies of 250 and 100 keV respectively. It is mandatory to use the SPG for future experiments.

Before entering the main accelerator, the electron beam goes through the superconducting (SC) injector linac. It consists of the capture section followed up by two 20 cell SRF $\beta=1$ cavities with an accelerating gradient of 3-5 MV/m at 3 GHz; TM_{010}; π – mode; T=2 K. At the moment the capture section consists of a 5 cell SRF $\beta=1$ cavity (see Fig. 1).

Figure 1: Photo of the capture section of the S-DALINAC injector (the 5 cell SRF $\beta=1$ cavity in the tuner frame).

The required minimal output energy from the capture section at the S-DALINAC is 1 MeV. The 5 cell cavity is capable of providing the necessary energy to the beam with an input energy of 250 keV (thermionic gun). The situation changes for the 100 keV (SPG) beam. It is not possible to reach the necessary acceleration. In both cases

a significant energy spread growth is observed. In this regard, the capture section of the S-DALINAC needs to be re-designed to be able to use the SPG. The following critera were defined for a new accelerating structure:

- Operating frequency 3 GHz (TM_{010}; π– mode)
- Acceleration of an electron beam from the
- energies of 100-250 keV to at least 1 MeV
- Flat top peak electric field on the central axis of the cavity $E_0 < 10$ MV/m
- No increase of the energy spread of the beam
- Fitting inside the present cryostat
- Compatible with the present input coupler
- Minimal investment cost
- Reliable in operation (mechanical model)

After an analysis of a number of accelerating cavities we ended up with three main candidates for the upgrade. In the following sections we discuss the design and selection process. For RF computations we use the CST MWS software [2] while for BD simulations the ASTRA code [3] was chosen. Space charge was not taken into account in this stage of the computations due to the low current of the beam.

CHOICE OF A CAVITY TYPE

It is a common practice to use normal conducting (NC) β-graded accelerating structures for capture sections in electron linacs [4, 5]. In case of the S-DALINAC we have a very limited longitudinal space in general and for the capture section in particular, i.e., ~270 mm for the effective length of the accelerating structure. As a consequence, we need an SRF cavity for the upgrade to reach the necessary energy gain in the limited space in the CW regime at 3 GHz.

Basic Shape

A number of SRF cavity types are available nowadays (spoke, quarter-wave, elliptical etc.). At a frequency of 3 GHz corresponding to the wavelength λ=10 cm the elliptical shape is the only reasonable choice because of the transverse size of SRF cavities at this frequency [6]. One of the brightest representatives of elliptical SRF structures is the TESLA cavity [7]. As an example, for the European XFEL project 816 TESLA cavities were manufactured and tested with excellent results [8]. Taking into account the large experience in manufacturing and operation procedures, we decided to use the TESLA shape as an anchor model and modify it for our needs. It is worth to mention that the operating value of E_{acc} in our case will be 4-5 times lower than the typical values that are used for TESLA structures (~25 MV/m).

Layout

We considered three options for the upgrade, shown in Fig. 2, from left to right: a five cell β-graded cavity (β=0.55; 0.78; 0.86 0.91; 0.93), two independently driven cells (β=0.75) and a five cell reduced-β cavity (β=0.75).

Figure 2: Side view of the proposed layouts (CAD models).

The setup with two independently driven accelerating cells allows to tune the RF phase separately for each cell. Thus this structure is flexible to changes of the working parameters (e.g. the input energy of the beam, the accelerating gradient). On the other hand such layout requires a new cryostat and an additional RF amplifier. In order to reach 1 MeV with only two cells it is necessary to have an accelerating gradient of ~15-20 MV/m which is a rather expensive solution in our case.

We carried out RF and BD simulations to compare the performance of the other two cavities. The resonant frequency was tuned to 3 GHz and a field flatness (FF) of 99 % was achieved for each considered cavity. It is worth noting that tuning of the FF of the reduced-β cavity was done by optimizing the geometry of the half end-cells. For the β-graded cavity that was not sufficient and 34 geometric parameters in total were optimized to achieve an evenly distributed electric field strength on the central axis of the cavity. As a result the dependence between the output energy of the beam and the peak electric field on axis was obtained for the β-graded, the reduced-β cavity and the current setup (E_{in}=100 keV) (see Fig. 3).
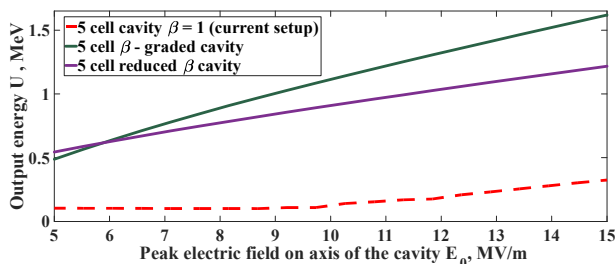

Figure 3: Output energy of the beam vs peak electric field on the central axis of the cavity.

In heavy ion accelerators β-graded SRF sections are a state-of-the-art widely used technique [9, 10]. β-grading in a single elliptical SRF multi-cell cavity works in simulations. However in real life it seems to be very problematic to guarantee a mechanically stable structure during operation due to the individual geometry of each cell. The main concern is to maintain the necessary FF at cold temperature. The FF is one of the key parameters of multi-cell SRF cavities affecting the accelerating voltage, the peak surface fields and the coupling.

It is not possible to accelerate the 100 keV beam using the current setup. Implementing a β-graded elliptical cavity is in our case not recommended because of failing stability during operation. The reduced-β cavity is capable

of providing 1 MeV to the 100 keV beam after an additional optimization of the structure (number of cells, value of geometric beta etc.). The main advantage of the reduced-β cavity over the β-graded cavity is the much less complicated geometry. Further computations have shown that it is possible to achieve not only the necessary energy gain but also a decrease of the energy spread.

REDUCED-BETA CAVITY

At this point of our work it was confirmed that the SPG will be upgraded so that the injection energy will go up from 100 keV to 200 keV [11]. In that regard we want to design a reduced-β cavity for the input energy of 200 keV with a possibility to accelerate the 100 keV beam.

Number of Cells and Geometric β

The available length for the capture cavity is ~270 mm. This means that the current cryostat is able to host a cavity with a number of cells up to 6.

The performance of a five and a six cell reduced-β cavities was studied. We carried out computations for various peak electric field values on axis to make a choice of the optimal value of geometric β for further energy acceptance studies (E_{in}=200 keV) (see Fig. 4).
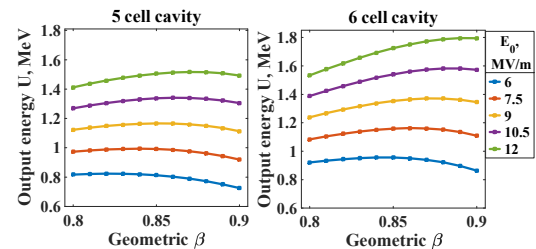

Figure 4: Energy gain vs geometric beta.

An N+1 cell cavity can be operated with a lower value of E_0 compared to an N cell cavity to achieve the same energy gain. In this way the 6 cell cavity is favored, however, the mechanical model must be evaluated carefully in future. The optimal value of the geometric β will depend on the operating value of E_0.

Energy Acceptance

Another important question is the energy acceptance of the cavity. The estimated energy acceptance of the 5 cell β=0.85 cavity and the 6 cell β=0.86 cavity is shown in Fig. 5.
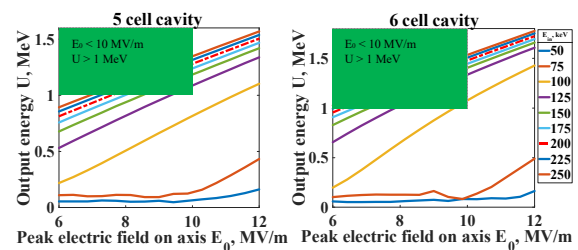

Figure 5: Output energy of the beam vs peak electric field on axis for various values of the input energy of the beam E_{in}.

07 Accelerator Technology

T07 Superconducting RF

Both cavities are capable to accelerate the 200 keV beam to the necessary energy. However the six cell cavity is also capable to accelerate the 100 keV beam, which is a significant advantage over the 5 cell cavity. The green area in Fig. 5 covers the required parameters: E_p<10 MV/m, U > 1 MeV.

CURRENT STATUS

The 6 cell β=0.86 cavity (see Fig. 6) is now being optimized in order to minimize RF losses and to have an efficient acceleration at the same time.
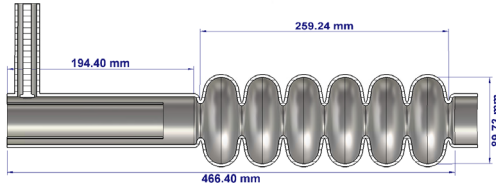

Figure 6: Side view of the 6 cell reduced-β cavity and the coupler of the current setup of the capture section.

The operating value of E_0 will be in the range from 6.5 to 10 MV/m. The current RF parameters of the fundamental mode at the E_0 of 10 MV/m are collected in Table 1.

Table 1: RF Parameters of the 6 Cell Reduced-β Cavity

Parameter	Value
f, GHz	3
β	0.86
K_c, %	2.52
E_0, MV/m	10
E_{acc}, MV/m	5
$R/Q_{\parallel}$, Ohm	453
E_{peak}/E_{acc}	2.6
B_{peak}/E_{acc}, Oe/MV/m	52.35

Depending on the specifications of the Niobium (Nb) we will evaluate the necessary input power for the required accelerating gradient and optimize the geometry of the central cells for these parameters (including geometric beta). Our main goal in RF optimization is to minimize the ratios of E_p/E_{acc} and B_p/E_{acc}. With respect to the effective length of the 6 cell reduced-β cavity which we define as the distance from left end iris to right end iris, the minimally required accelerating gradient is 4 MV/m.

The plots below (see Fig. 7) present the comparison of the energy gain and the energy spread growth of the proposed cavity and current setup (E_0=10 MV/m; E_{in}=200 keV; 5 ps (rms) single bunch).
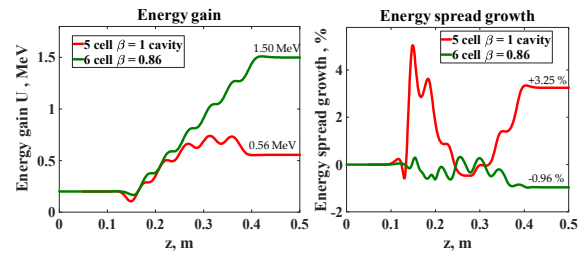

Figure 7: Comparison of energy gain and energy spread growth between the 6 cell β=0.86 cavity and the current setup 5 cell cavity.

The proposed cavity has an energy gain exceeding the one in the current setup by 167 % for the same peak electric field on axis. The energy spread in the proposed cavity is reduced while in the current setup it grows by 3.25 %.

CONCLUSION AND OUTLOOK

Three options were considered for the upgrade of the S-DALINAC capture section. Preliminary calculations indicate that the reduced-β cavity has more advantages than the other structures. The RF optimization of the 6 cell reduced-β cavity is still in progress. The proposed cavity accomplishes the following goal: the output energy is more than 1 MeV, the energy spread is reduced and the cavity fits into the present cryostat. The next step is to proceed with further RF optimization. After that we plan to investigate a mechanical model of the cavity (microphonics, vacuum pressure etc).

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