BEAM DYNAMICS CALCULATIONS AND MAGNET DESIGN FOR FUTURE MEASUREMENTS OF TRANSVERSE BEAM BREAK-UP AT THE S-DALINAC*

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Abstract

The superconducting electron accelerator S-DALINAC at TU Darmstadt produces c.w. electron beams of up to 90 MeV. The S-DALINAC consists of a SC 14-MeV injector linac, a SC main linac and two recirculation paths. Currently a third recirculation is in its final design phase and will be constructed end 2014 in order to achieve an energy of 130 MeV in future. The main linac houses eight 20-cell SRF cavities operating at 3 GHz and 2 K. Due to the occurance of transverse beam break-up, the highest stable beam current obtained so far amounts to 5 µA only, which is below the design beam current of 20 µA but sufficient for the nuclear physics experiments carried out in Darmstadt since 1991 [1]. In this work we will present beam-dynamics calculations and newly designed magnets for planned experiments at the S-DALINAC in order to benchmark different strategies of increasing the threshold current for beam break-up.

INTRODUCTION

The Superconducting DArmstadt LINear Accelerator (S-DALINAC) is delivering electron beams for nuclear- and astrophysical experiments at the University of Darmstadt since 1987 [2]. It has been designed for producing beams of either unpolarized or polarized electrons [3] up to energies of 1 to 130 MeV with beam currents from several pA up to 60 µA in single pass mode or 20 µA in recirculating mode using up to two recirculation beamlines. Due to the limited cooling power of the cryo plant in conjuction with a too low quality factor of the superconducting cavities the total beam energy in c.w. mode is limited to 90 MeV currently [4]. In order to reach the design energy of 130 MeV in future an additional third recirculation will be operational in spring 2015 [5]. The current layout of the S-DALINAC is shown in Fig. 1.

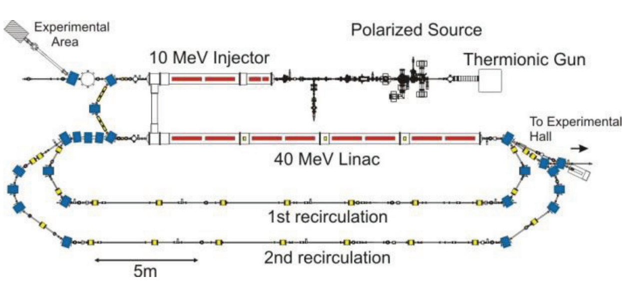

Figure 1: Floor plan of the S-DALINAC.

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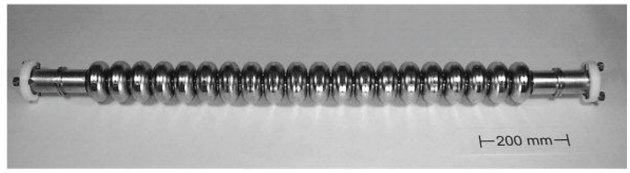

Figure 2: S-DALINAC 20 cell cavity. .

For acceleration of the beam ten 20 cell superconducting elliptical cavities (see Fig. 2) with a quality factor of $Q_0 \approx 10^9$ and a maximum accelerating gradient of 5 MV/m are used while the operation frequency of the cavities is 3 GHz. By recirculating the beam up to two times, later three times, the maximum energy of 130 MeV can be achieved. In the adjacent experimental hall this beam can be used for several experiments such as electron scattering in two electron spectrometers or experiments with tagged photons. For these experiments an energy spread (rms) of $1\cdot10^{-4}$ as well as a very low γ-ray background are required.

OPERATIONAL EXPERIENCE

The S-DALINAC is the first superconducting and recirculating cw accelerator for electrons which has been put into operation in Europe [2]. The injector has been constructed in 1987 while the complete accelerator started operation in 1991 and has been used for experiments in nuclear, astro- and radiation physics since then. A great success has been the observation of a first infrared laser beam at the free electron laser (FEL) in 1996 [6]. For achieving an FEL operation the peak current of the electron beam needed to be increased to 2.7 A at a pulse length of some ps and an operation frequency of 600 MHz [4]. Originally it was thought of operating the S-DALINAC as an ERL as well when using the FEL but the challenges of operating this first European FEL had been high enough even without trying the ERL mode.

BBU AT THE S-DALINAC

One reason for this has been the occurance of instabilities due to the high peak current of the electron bunches – a first observation of transverse beam break up (BBU) at the S-DALINAC. This BBU occurs at a relative low threshold current of some µA due to the design of the 20-cell accelerating cavities which have not been optimized for suppressing any higher order modes (HOMs).

The occurance of beam break up also limits the

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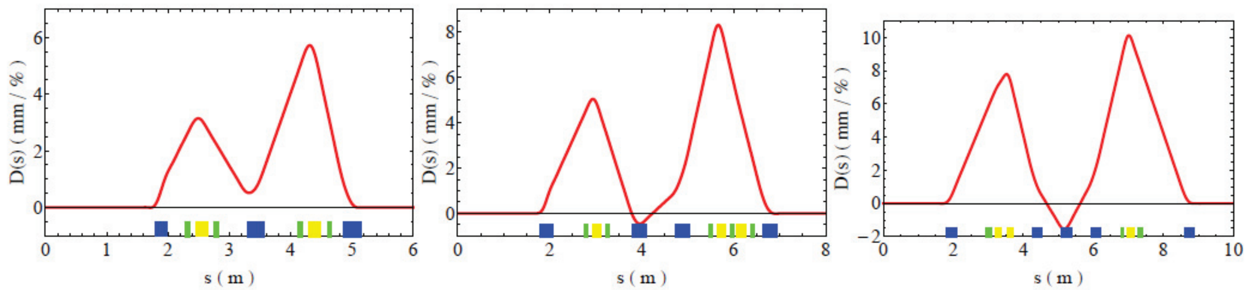

Figure 3: Transverse dispersion of the electron beam in the recirculation arcs of the S-DALINAC in the first, second and third recirculation (from left to right side). Dipole magnets are marked blue and quadrupoles yellow. The green areas mark possible positions for additional sextupole magnets which will be placed at positions with as high dispersion as possible..

maximum achievable beam current in recirculating operation of the S-DALINAC. While the design currents in single pass mode can be obtained easily, the current in recirculating mode is limited. The operational experience obtained during many years of beam time for nuclear physics showed a maximum of up to some µA only, operating the S-DALINAC in the twice recirculating mode. The highest stable current achieved so far in a long term experiment accounts for 5 µA [1], which is well below the design value of 20 µA but convenient for the experiments carried out. On the other hand this quite low threshold current gives an opportunity of investigating transverse beam break up in a recirculating linac experimentally.

BBU SUPPRESSION

Transverse BBU can occur when a travelling electron beam with a rather high peak current excites higher order dipole modes (HOMs) in the accelerating cavities. These HOMs can either disturb the following bunches or, in a recirculating design as used in ERLs, even the same bunch at its subsequent passes through the linac. Early observations of this phenomenon have been reported from the very first SRF linacs at threshold currents of a few µA [7,8]. In the last years high effort has been made to raise the BBU threshold currents. This is mainly done by designing accelerating cavities with a strong damping of HOMs but can also be achieved by matching the transverse beam optics [9,10] of the beam transport system. A very interesting approach of avoiding transverse BBU has been presented in [11,12]. The author proposes to keep the natural chromaticity in a large scale recirculating linac (eRHIC at BNL) instead of correcting for it. If the product of chromaticity ϕ in the recirculation arcs and the energy spread σ_δ of the beam gets large enough the electrons "forget" the kick of any dipole modes while passing the recirculations and each linac sees a fresh electron beam [11]. The relation to be fulfilled is given below:

$$|\phi\sigma_\delta|>>1 \qquad (1)$$

This concept of avoiding BBU has been investigated in simulations only so far. For that reason we propose experiments at the S-DALINAC for testing this strategy of avoiding BBU taking advantage of the low threshold current of this recirculating linac mentioned above.

BEAM DYNAMICS SIMULATIONS

In order to test the hypothesis that a given amount of chromaticity can decrease BBU, the natural chromaticity of the S-DALINAC has been calculated first. It accounts for $\phi = 137$. In combination with an energy spread of the S-DALINAC of $\sigma_\delta < 10^{-3}$ this value is far too low to match the condition given in eq. (1). So additional sextupoles for the S-DALINAC recirculation arcs are needed in order to increase the chromaticity and test the proposition of [11,12]. These sextupoles will be installed in the recirculation arcs of the S-DALINAC at positions with a high amount of transverse dispersion in order to have the biggest effect on the chromaticity. Figure 3 shows the dispersive tracks in the three recirculations of the S-DALINAC and possible positions of sextupoles taking into account the space needed for these additional beamline components as well. Using these sextupoles the chromaticity can be increased by two orders of magnitude to $\phi = 15000$, which would be high enough to satisfy the condition given in eq. (1).

In addition the non-isochronous recirculation scheme used at the S-DALINAC can be used to increase this value even further. In the non-isochronous recirculation scheme the electrons are accelerated on edge of the accelerating field and perform a half integer number of betatron oscillations in longitudinal phase space in order to stabilize the beam against rf jitters [13,14]. At the S-DALINAC this could be used to decrease the energy spread significantly [15]. Figure 4 shows the longitudinal phase space for the S-DALINAC case. During acceleration the energy spread is increased to values far above 10^{-3}. This can be used to increase the dispersion in the arcs and thus the chromaticity even further.

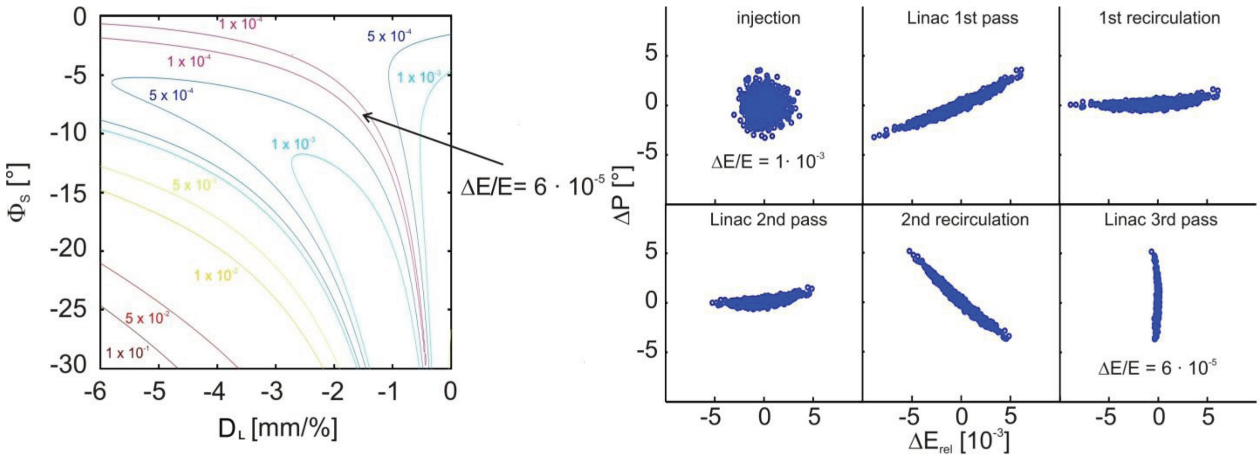

Figure 4: Hillplot of the resulting energy spread at extraction for different sets of longitudinal dispersion and synchrotron phase (left) [15]. Beside the isochronous point exist areas of reduced energy spread. On the right side a bunch of 5000 particles has been tracked through the linac using the optimized parameters. The particles perform a half oscillation in longitudinal phase space ending up on a reduced energy spread. During acceleration the energy spread is above 10^{-3} due to the on edge acceleration. This can be used to achieve a high dispersion in the arcs and a high chromaticity as well.

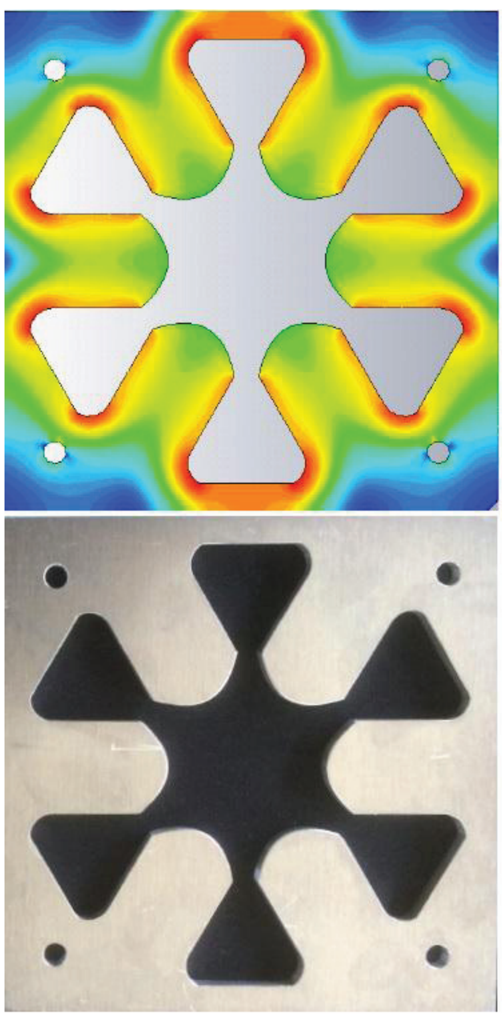

Figure 5: Simulated fields in the yoke (top) and photograph of a sheet (bottom) of the new sextupole. The sheets have a size of 20 cm x 20 cm.

MAGNET DESIGN AND CONSTRUCTION

The new sextupoles will be constructed as laminated magnets from 1 mm sheets made of mu-metal. The geometric length of the yoke amounts 7.5 cm. We will use coils with 45 windings each and an exciting current of up to 7 A. Figure 5 shows a simulation of the magnetic fields inside the yoke at the maximum current of 7 A and a photograph of a sheet. A prototype has been constructed by now and is undergoing magnetic measurements currently. As soon as these sextupoles are installed at the S-DALINAC first experiments on the influence of chromaticity on transverse BBU will take place.

SUMMARY AND OUTLOOK

The S-DALINAC is a superconducting, recirculating electron linac suffering from transverse beam break up at very low threshold currents of some μA. This fact provides a unique opportunity for testing different strategies of avoiding BBU experimentally.

As soon as the newly designed sextupoles are installed systematic experiments on the influence of chromaticity on transverse BBU for different numbers of linac passes will be carried out.

In addition to the experiments with electron beam, simulations of the HOM spectra of the used cavities as well as beam dynamics simulations will be carried out in order to refer the experimental results to theory.

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