INVESTIGATIONS ON TRANSVERSE BEAM BREAK UP USING A RECIRCULATED ELECTRON BEAM*

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Abstract

The recirculating superconducting accelerator S-DALINAC provides electron beams of up to 130 MeV for nuclear physics experiments at the University of Darmstadt since 1991. It consists of a 10 MeV injector and a 40 MeV main linac and reaches its final design energy using up to two recirculation paths. The superconducting main linac houses eight 20-cell SRF cavities operated at 3 GHz and 2 K. The very low threshold current of only a few µA for the occurrence of beam break up in addition with the recirculating linac design gives a unique opportunity to the ERL community for testing different strategies of avoiding beam break up experimentally at this accelerator and to benchmark beam dynamics simulations concerning this topic. To minimize the impact of HOMs on the recirculating electron bunches we will place skew quadrupole and sextupole magnets in our accelerator and test their effect on the threshold current. We will report on the status of beam dynamics simulations concerning their use in the accelerator and present actual calculations for the positioning of the skew quadrupoles. An outlook on the future activities at the S-DALINAC will be given.

INTRODUCTION

Transverse beam break up (BBU) is one of the main problems of modern superconducting energy recovery linacs. A theory of BBU instability in ERLs was shown in [1]. It occurs when an electron bunch travelling through an accelerating cavity excites higher order dipole modes (HOM) in it. These HOMs can have a large quality factor and thus a long lifetime in superconducting cavities. The bunch will be deflected by the electro-magnetic field of the mode. In a recirculating design this gets even worse as the same bunch can be deflected by the same HOM in the same direction. Thereby the maximum beam current which can be transported and accelerated is limited in every recirculating linac. This limit is called the BBU threshold current. For ERLs worldwide which are planned or already under constructions this is a crucial parameter as they yield for beam currents of 10-100 mA and above.

On the contrary in early SRF linacs only a few µA of beam current were possible because of BBU [2,3]. Also the S-DALINAC [4] is limited in its beam current when operated in recirculating mode. The highest stable current achieved so far in a long term experiment accounts for 5 µA [5], which was well below the design value of 20 µA but convenient for the experiments carried out. The low threshold currents at the S-DALINAC allow to carry out experiments on transverse beam break up without the risk of damaging the accelerator.

S-DALINAC

The Superconducting Darmstadt LINear Accelerator (S-DALINAC) provides electron beams for nuclear- and astrophysical experiments at the University of Darmstadt. It consists of a superconducting 10 MeV injector and a 40 MeV linac. With two recirculation beam lines the main linac can be used up to 3 times. As electron sources a thermionic and a photo gun, which can also produce polarized electrons [6], can be chosen. This layout was originally designed to provide beam energies of up to 130 MeV and beam currents of either 60 µA in single pass mode or 20 µA when recirculated twice. But as mentioned above, the design beam current in recirculating operation could not be achieved so far.

For acceleration of the beam twelve 20-cell SRF cavities are used on an operation frequency of 3 GHz. These cavities have been produced in the 1990s and have never been optimized with regard to HOM suppression. Furthermore no HOM couplers can be used as most HOMs are trapped within the middle cells of these long 20-cell cavities.

In August 2015 the installation of an additional recirculation beam line will begin and is scheduled to be finished in January 2016 [7]. A floor plan of the S-DALINAC is shown in Fig. 1. In the current setup with only two recirculations the power dissipated by the cavities to the helium bath was too high when used at maximum gradient as the quality factor of the cavities is smaller than originally planned [8]. The upgrade is done in order to reach the design energy of 130 MeV in c.w.-operation with a smaller accelerating gradient per cavity

BBU SUPPRESSION

Many efforts have been made and are still going on to raise the BBU threshold currents. There are two strategies to address the problem. As a basis, cavities of ERLs are designed to damp the higher order modes. Also HOM couplers will be used. The second approach is matching the optics of the beam transport system. We are planning to increase the low threshold current of the S-DALINAC by manipulating the beam optics in the recirculation loops.

Variation of the Transverse Phase Advance

In [9] it is proposed to match the transverse phase advance in an ERL in a way that a negative feedback of the HOM excitation is provided which can increase the

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ISBN 978-3-95450-183-0

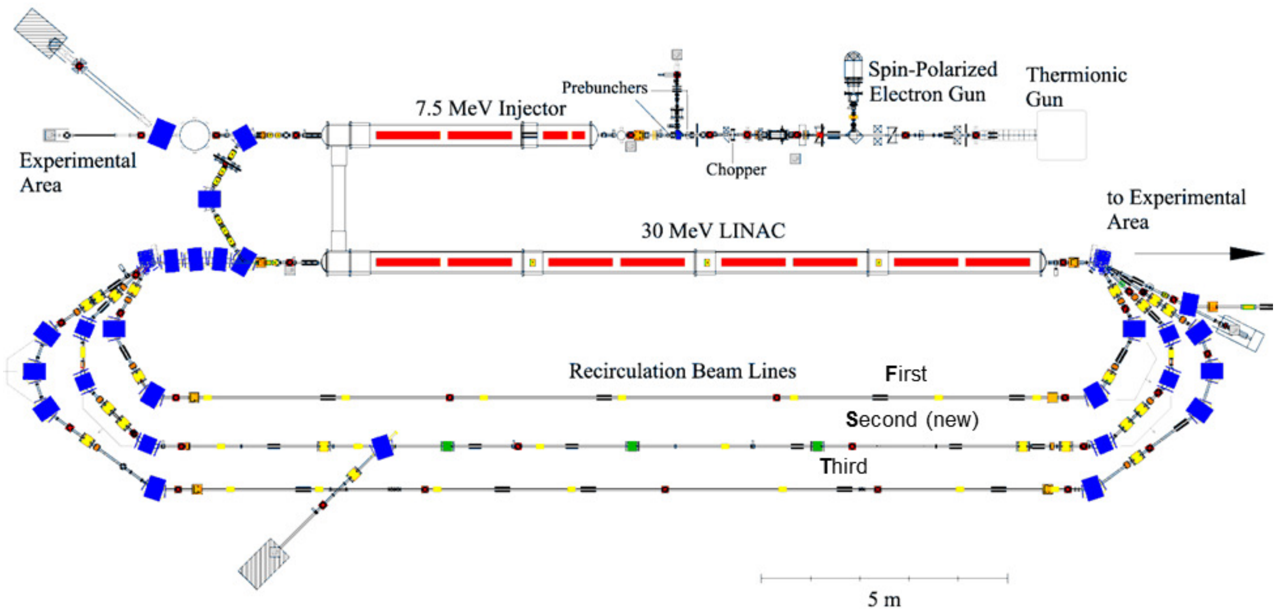

Figure 1: Floor plan of the S-DALINAC with planned upgrade. Skew quadrupole magnets are shown in green in the strait section of the new (Second) recirculation. Sextupoles will be positioned in the arcs (shown in orange)

threshold current. In addition simulations in [9] show that a coupling of the x and y planes of transverse motion could increase the threshold current even further.

We will test these approaches and try to reach for higher currents when running the S-DALINAC as a single or three times recirculating linac in 2016. The exchange of the complete phase space will be done in the second recirculation path. Therefore three skew quadrupole magnets need to be implemented in our FODO lattice. In order to achieve the exchange of vertical and horizontal phase spaces a 4x4 rotation matrix is needed.

Such a matrix can be calculated analytically like in [10]. For our case we chose a lattice, which fits best into our regular lattice. The three skew quadrupoles are distributed in a way that between half of their distance to each other respectively one conventional quadrupole (first focussing, second defocussing) will be positioned (SFSDS).

The positions of the skew quadrupoles are marked green in Fig.1. The analytical solution (thin lens approximation) for such a system [10] provides the refractive power for the skew quadrupoles of $\delta_s = 1/s\sqrt{2}$ and for the conventional quadrupoles of $\delta_{F/D} = \pm\sqrt{2}/s$. With a beam energy of 68.85 MeV and a drift of $s = 1.981$ m between each magnet's focal plane the gradients easily can be calculated to $G_s = 0.4184$ T/m and $G_{F/D} = \pm 1.4206$ T/m then. Finally a numerical optimization using the *elegant* code [11] has been carried out in order to find the exact values for the 5 magnets of the rotation system (see Table 1).

Table 1: Optimized Quadrupole Gradients for the Phase Space Rotation System

Focussing/Defocussing Quadrupoles	±1.082 T/m
Skew Quadrupole 1&3	0.4408 T/m
Skew Quadrupole 2	0.4347 T/m

The skew magnets have been manufactured already and are currently undergoing tests in the first recirculation of the S-DALINAC (see Fig. 2). They will be used for first experiments on BBU in summer 2015 and then be relocated to their optimized positions during installation of the new recirculation beamline.

Figure 2: Three skew quadrupole magnets in the first recirculation of the S-DALINAC. They will be relocated in the second loop in the described SFSDS lattice above.

Variation of Chromaticity

In [12] it is shown that a recirculation beam line with high enough chromaticity ξ let electrons "forget" the kick obtained by any dipole mode. The condition which has to be fulfilled for that behaviour is also given in [12]:

$$|\Delta E/E \cdot \xi| >> 1 \quad (1)$$

With its typical energy spread ΔE/E of about 10^{-3} to 10^{-4} the natural chromaticity of <100 in the recirculation beam lines is not big enough to test this theory with the S-DALINAC. Therefore two sextupole magnets will be installed in each arc of a recirculation at positions of high dispersion in order to increase ξ. In total there will be 12 sextupoles (four per recirculation beam line).

ISBN 978-3-95450-183-0

The magnets were constructed from 1 mm sheets of mu-metal (see Fig. 3). The magnets with 35 windings per coil were tested in continuous operation showing no significant heating operated with 7 A. At that current the field gradient was determined to be 109 T/m^2 (see also Fig. 3). While the geometric length of the yoke amounts 7.5 cm the magnetic length was found to be 9 cm.

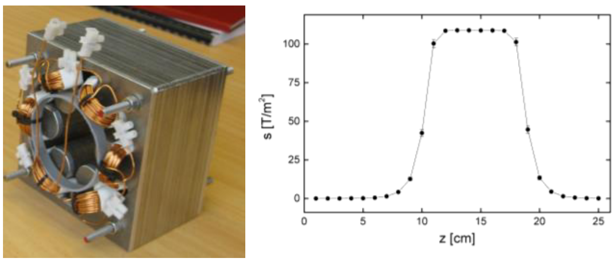

Figure 3: Photo of a sextupole magnet and results of a field gradient measurement on it.

So far simulations of the beam dynamics with the *elegant*-code [11] showed, that the sextupole magnets can increase the chromaticity per turn to values of 1000 and higher, when one uses a larger energy spread of $2.5 \cdot 10^{-3}$. Fulfilling the condition in [12] is thereby possible but nevertheless one has to watch carefully the emittance growth caused by such a setting [13,14]. In Figure 4 the envelope of the first recirculation beam line is shown with and without using the sextupole magnets in it.

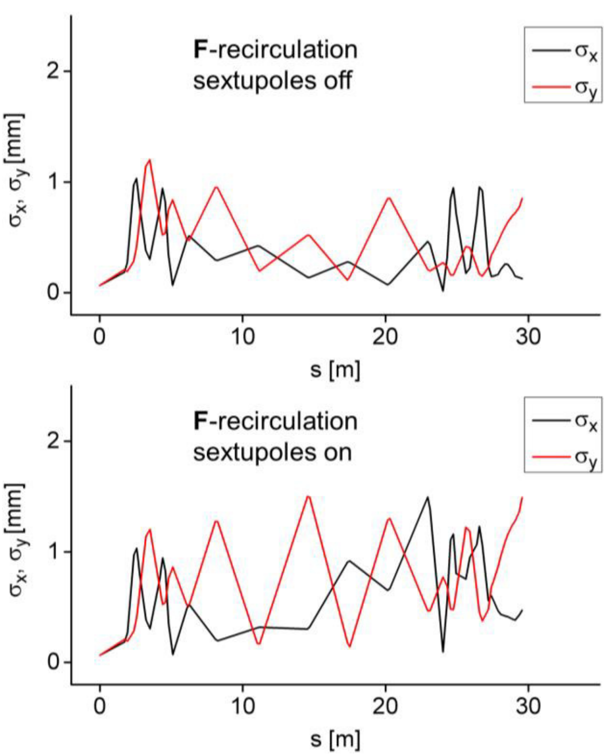

Figure 4: Beam envelope in x and y direction of the first recirculation beam line with sexupoles switched off and on (E = 38 MeV and $\Delta E/E = 2.5 \cdot 10^{-3}$).

The quadrupole magnets were set in a way, that they compensate already for negative effects caused by the sextupoles, while we tried to reach the needed chromaticities. In the shown example we got ξ_x and ξ_y of about 1000 but the emittance increased by a factor of 20 for ε_x and a factor 12 for ε_y. A proper beam transport gets challenging with an emittance growth like that. So far we think of testing the effect of chromaticity to the BBU threshold current by only recirculating once and then dump the beam or recirculate many times but only activate the sexupoles in a specific turn finding a setting which also provides a proper beam transport.

FUTURE ACTIVITIES

After testing the strategies for BBU suppression with the 3 times recirculated electron beam, we plan to commission the S-DALINAC as a single and double turn ERL. The major preparations for this are already done. Within the arcs of the new beamline, dipole magnets can be moved by stepper motors on their table in order to allow a change of the pathlength by about 10 cm. This represents a complete rf-wavelength and will allow to change the mode of operation from an accelerating multi-turn linac to an ERL. The separation magnet together with its vacuum chamber were designed and built to allow the extraction of a decelerated beam at injection energy (see Fig. 5). In future it will be possible to either steer the beam directly after the first linac pass into the second recirculation beamline and decelerate it afterwards or to use the main linac twice by bringing the beam first in the F-recirculation before performing the 180° phase shift in

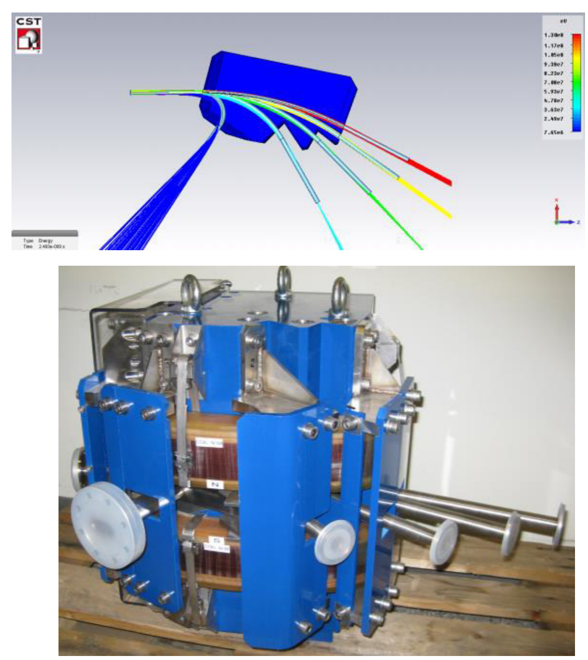

Figure 5: Separation magnet for the S-DALINAC upgrade providing possibility to extract the electron beam at injection energy for ERL mode. A picture taken from CST [15] simulation and a photo of the recently delivered magnet with vacuum chamber are shown.

ISBN 978-3-95450-183-0

the second recirculation and decelerate the beam twice before extraction at injection energy. The use of the third recirculation will not be possible in ERL-mode. A schematic of a possible ERL setting is shown in Fig. 6.

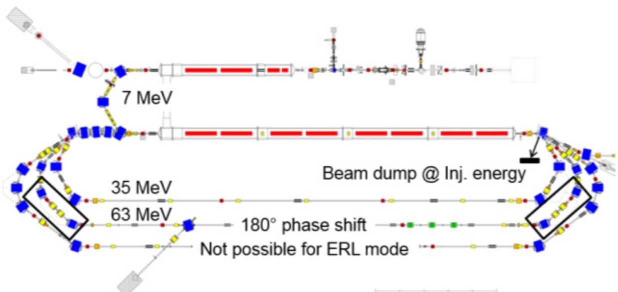

Figure 6: Possible energy configuration for the S-DALINAC in ERL operation. The dipole magnets inside the rectangles will be moveable to allow the necessary shift of the pathlength.

So far, there is no ERL operation for users planned. It will be used for research in accelerator physics, e.g. further tests on BBU, LLRF control, diagnostics and other ERL related questions. Junior accelerator scientists will have the opportunity to work and learn with this machine running in ERL mode. The ongoing research program on basic questions in nuclear structure physics will strongly benefit from the operation of the S-DALINAC in the upcoming triple-recirculation scheme.

SUMMARY AND OUTLOOK

The S-DALINAC is a recirculating linac were BBU occurs already at a few µA. Strategies of increasing the threshold current by manipulating the beam optics in the recirculation loops can be tested. After the upgrade of the S-DALINAC with a third recirculation beam line we plan to check the influence of chromaticity by using sextupole magnets. The variation of the transverse phase advance will be investigated as well. Skew quadrupoles can be used to perform a complete phase space exchange. In the future those devices can be used as well when we will operate the S-DALINAC as a single or double turn ERL.

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ISBN 978-3-95450-183-0