MEASUREMENTS OF THE BEAM BREAK-UP THRESHOLD CURRENT AT THE RECIRCULATING ELECTRON ACCELERATOR S-DALINAC*

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Abstract

Linear accelerators, in particular those using a recirculating design and superconducting cavities, have to deal with the problem of Beam Break-Up (BBU). This instability can limit the maximum beam current in such accelerators. Knowing the effectiveness of prevention strategies is of great interest especially for future accelerators like energy recovery linacs (ERL) which aim for high beam currents. One option is to optimize the cavities and higher order mode couplers of those machines. In addition one may adapt the beam line lattice for further suppressing BBU. The superconducting recirculating accelerator S-DALINAC at the Technische Universität Darmstadt provides electron beams in c.w. for nuclear physics experiments since 1991. As the SRF components were never optimized for higher order mode suppression the S-DALINAC suffers from BBU at relatively low beam currents of a few µA. While those currents are sufficient for most nuclear physics experiments we can investigate BBU with respect to the beam optics. Measurements were done and different BBU limits were found for different energy settings of the accelerator. First tests were carried out to increase the maximum beam current by varying the beam optics in the first recirculation loop.

INTRODUCTION

The S-DALINAC is a recirculating superconducting linear accelerator located at the Technische Universität Darmstadt. It provides electron beams in c.w. for nuclear physics experiments since 1991 [1]. It consists of a 10 MeV injector and a 40 MeV main linac, both superconducting using 3 GHz elliptical niobium cavities. The linac houses eight 20 cell cavities for the main acceleration, while the injector cryo-module uses beside two of those cavities an additional two cell and five cell structure for pre-acceleration. So far two recirculation beam lines allowed to use the main linac up to three times. Currently a third recirculation is under construction allowing an additional linac pass in future [2]. Figure 1 shows a drawing of the S-DALINAC and Fig. 2 a photograph of one of its cavities. The design beam current in the recirculating mode at 130 MeV beam energy was 20 µA. Early estimations [3] during the design phase of the S-DALINAC predicted no transverse beam break-up (BBU) within the design parameters of beam energy and current, but nevertheless operation experience showed that instabilities occurred, which could be related to BBU. Therefore the S-DALINAC can be used to investigate the behavior of BBU as it shows up at low beam current which ensures that we can do so without the risk of damaging the accelerator.

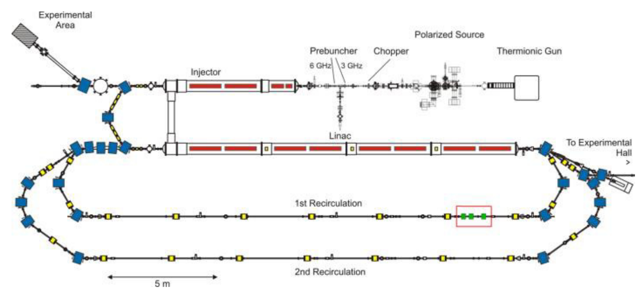

Figure 1: Floorplan of the S-DALINAC with two recirculation beam lines. Three skew quadrupole magnets (green) were installed in the first recirculation line in order to mix the transverse phase space advance.

Figure 2: Picture a of S-DALINAC 20 cell cavity.

BEAM BREAK-UP

When electron bunches travel through an accelerating structure they can excite higher order modes (HOM) in it. Especially in superconducting cavities these modes can have a large quality factor and thus a long lifetime. Such HOMs, for example dipole modes, deflect the beam in transversal direction and the bunches start to oscillate around the design orbit. In case of a recirculating accelerator design the bunches may re-enter the cavity with that offset and the same HOM can be excited even more and thus the deflection becomes even larger. If the deflection becomes too large the beam will be lost and one talks about beam break-up.

Early superconducting accelerators [3,4] have observed this phenomenon and also Energy Recovery Linacs (ERL), were the electron beams also re-enters the same linac to deaccelerate the electrons and gain back their energy, suffer from it [5]. As the excitation of a HOM becomes larger if the bunch charge is larger, BBU limits the maximum beam current in recirculating linac and ERLs. A formula, taken and modified from [6], shows the threshold beam current for a single turn ERL with one HOM:

$$I_{th} = -\frac{2 p_b c}{e\left(\frac{R}{Q}\right) Q \frac{\omega}{c} T_{12} sin(\omega t_r)} \quad , \qquad (1)$$

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where p_b is the momentum of the electron at the cavity, e is the elementary charge, $(R/Q)Q$ is the shunt impedance and ω the angular frequency of the HOM, T_{12} is the element of the recirculation transport matrix, while t_r is the travel time of the electrons through the recirculation loop. The number of passes through the accelerating cavities decreases the maximum beam current even more. A theory of BBU instabilities in multi-turn ERLs can be looked up in [6]. For conventional recirculating accelerators and microtrons a description can be found in [4].

To increase the maximum beam current in such accelerators there are two main approaches. The first addresses the minimization of the HOM excitation which can be done by optimization of the cavity design and RF power couplers, as well as the damping of the HOMs with HOM-couplers. The second strategy is to match the beam optics of the recirculation loops represented by the transport matrix element T_{12} in Eq. (1). As the S-DALINAC suffers from BBU at relatively low beam currents, changes in the beam optics can be realized and their impact on the threshold current can be tested.

BBU-LIMITS AT THE S-DALINAC

Operational experience of the last decades showed, that the design beam current could not be reached for different reasons, one is BBU. As the small beam currents of a few μA were sufficient for the nuclear physics experiments further investigations were not undertaken. In 2015 during the preparation of the beam for experiments we searched for the maximum beam current that could be reached. Tests were performed at two different energy settings of the S-DALINAC.

First BBU was observed as we tried to turn up the beam current in a set-up were the main accelerator was used three times with an energy gain per linac pass of 23.2 MeV, while the injection energy was 5.8 MeV. At 7.5 μA the beam was lost. We repeated this several times and every time the beam was lost at the same beam current value no matter if the current was turned up slowly or fast. In previous test, the electron beam only passed the main linac twice and was lost at about 10.7 μA. That event however was not because of BBU but due to problems with the RF amplifiers. When we lost the beam due to BBU our RF system [7] showed regular behaviour before the beam was lost and so did our beam loss monitor system [8].

As the theory predicts lower threshold currents at lower injector energies [4], we used the same beam optics settings and scaled it down to 3.5 MeV injector energy (and 14 MeV energy gain per linac pass). This time BBU was found at a beam current of 5 μA, which meant a reduction of injector energy by 40% resulted in a 33% lower threshold current. Figure 3 shows the beam current measured at a Faraday cup during this experiment. When BBU occurred less than 50% of the initial beam current was measured at the cup. After such an event the output current was decreased for machine protection and the beam was instantly stable again.

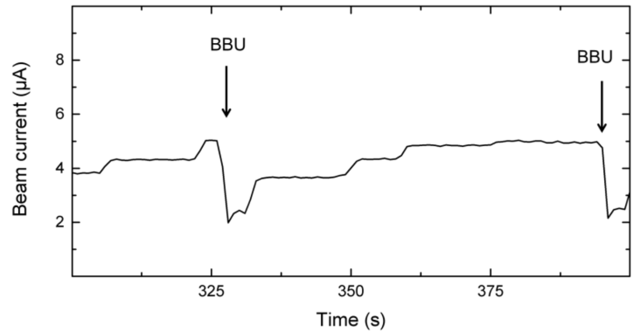

Figure 3: Beam current measured at a Faraday cup after the electrons were twice recirculated (three linac passes) with injection energy of 3.5 MeV. Turning up the current the beam was lost due to BBU at 5 μA.

Mixing of the ransverse hase pace dvance

One possibility to increase the BBU threshold current in a recirculating linac is the mixing of the transverse phase space advance. As for example described in [4] one could reflect a beam displacement from the x to the y plane, which means a reduction of the corresponding transport matrix element from Eq. (1) down to zero ($T_{12} \rightarrow 0$).

For the measurement the same energy setting as before was used at the S-DALINAC, but additionally three skew quadrupole magnets in the first recirculation beam line [9] were powered to couple the x and the y plane of motion of the electrons. The position of the skews is shown in Fig. 1. In this set-up turning the dispersion plane of the beam by approx. 45° without having beam losses was possible. Although this was not a complete rotation of the beam, an increase of the beam current compared to the setting before (at the same beam energy) was now possible. This time BBU occurred just at 8.2 μA instead of 5 μA. This means that the change in the beam optics resulted in an increase of the threshold current by more than 60%. In Fig. 4 the drop of the beam current measured on the Faraday cup can be seen as BBU occurred during these tests.

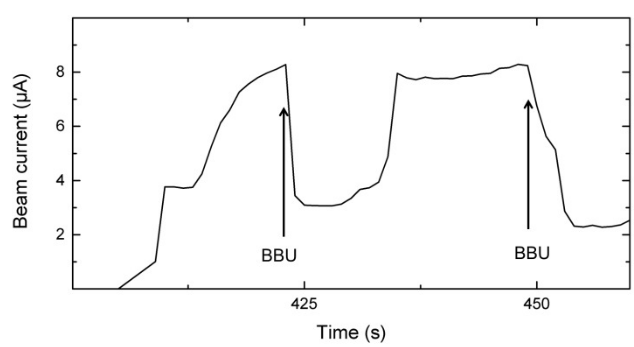

Figure 4: Beam current measured at a Faraday cup after the electrons were twice recirculated (three linac passes) with injection energy of 3.5 MeV. Skew quadrupoles in the first recirculation loop were used to mix the transvers space advance which resulted in an increased threshold current of 8.2 μA.

Summary

To summarize, the results of all four measurements can be seen in Table 1. As expected the BBU threshold current was higher for higher injection energies and less recirculations. The highest beam current was possible recirculating the beam only once, but as described before the limit was not BBU in that case. In a last test we were able to show that it is possible to increase the threshold current by using the beam optics (skew quadrupoles) at the S-DALINAC.

Table 1: BBU Test Experiments at Different Energy and Recirculation Settings at the S-DALINAC

Experiment. No.	1	2	3	4
E_{inj} (MeV)	5.8	5.8	3.5	3.5
E_{linac} (MeV)	23.2	23.2	14	14
Linac passes	2	3	3	3
Skews used	no	no	no	yes
I_{max} (μA)	10.7	7.5	5	8.2
BBU observed	no	yes	yes	yes

CONCLUSION

During the design phase of the S-DALINAC estimation of its BBU-Limit were presented in [3]. The worst case prediction was a threshold current of 24 μA at the maximum energy of 130 MeV, which means 10 MeV injector energy. Scaled down with the injector energies of our experiments this limits are still higher than the threshold currents we observed during the measurements. For a better overview the numbers are summarized in Table 2. One reason that the measured threshold currents were lower than estimations from the worst case scenario might be the change in the beam line layout from the time the estimations were made and the lattice today. The lattice used during the tests was implemented some years ago [10]. It was done to ensure a good acceptance and stability, but perhaps it has lowered the BBU limits. For a complete analysis further beam optics studies have to be done. Also more measurements and simulations of higher order modes in our 20 cell cavities are necessary.

Table 2: Comparisons of BBU Threshold Currents from Worst Case Estimation (presented in [3]) and Experiments with a Twice Recirculated Beam at the S-DALINAC at Different Energy Settings

E_{inj} (MeV)	3.5	5.8	10
E_{linac} (MeV)	14	23.2	40
Estimated I_{th} (μA)	8.4	13.9	24
Measured I_{th} (μA)	5	7.5	-

OUTLOOK

Just a few months after the last tests on BBU in 2015 were realized, a major upgrade and maintenance at the S-DALINAC started. This includes beside a new electron scraper system [11] the installation of an additional recirculation beam line [2] positioned between the two existing ones. Within the arcs of the new beam line, dipole magnets will be movable by stepper motors in order to allow a change of path length by 10 cm (see Fig. 5). This represents one complete RF-wavelength and will allow to change the mode of operation from an accelerating multi-turn linac to a single- or double-turn ERL. In addition another two skew quadrupoles were added to the beam reflection system presented in [9]. In the future it will be possible to use a reflector consisting out of five quadrupole magnets within the new recirculating beam line. This will allow for a much easier adjustment of the beam, while doing a full reflection of the x and y planes of transverse motion in order to find new BBU limits with higher threshold currents. The position of the skew quadrupoles can be also seen in Fig. 5. Further investigations on BBU using the S-DALINAC as a conventional linac with three recirculations and in its ERL modes are planned.

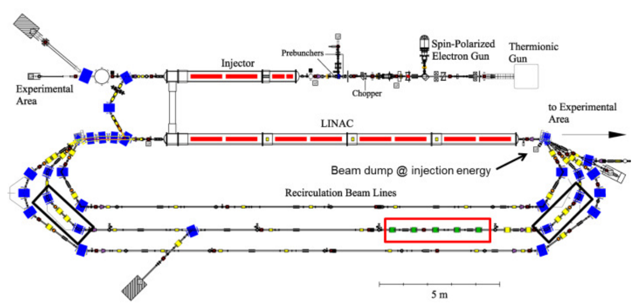

Figure 5: Floorplan of the S-DALINAC in 2016. A third recirculation loop has been installed between the two existing ones [2]. The dipole magnets inside the black rectangles will be movable to allow the necessary shift of the path length in order to run the accelerator as a single- or double-turn ERL. Five skew quadrupole magnets were installed (red box) to mix the transverse phase space advance.

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