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

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Abstract

Beam break-up (BBU) instability is an important limitation to the beam current which can be accelerated in a superconducting linac. In particular recirculating machines and Energy Recovery Linacs (ERLs) have to deal with that problem. Therefore, it is important to find strategies for increasing the threshold currents of these machines. At the recirculating superconducting accelerator S-DALINAC at the Technische Universität Darmstadt BBU was observed in different recirculation schemes. As expected the threshold current increased for a higher beam momentum. But also an improvement by mixing the transverse phase space advance with three skew quadrupole magnets was measured. Furthermore measurements in a new ERL scheme at the S-DALINAC are planned for the future.

INTRODUCTION

In recirculating linear accelerators transverse beam break-up BBU can be a crucial limitation of the maximum beam current [1,2]. Also Energy Recovery Linacs (ERL), as a special type of recirculating machines, have to deal with that limitation [3]. BBU occurs when electron bunches travelling through an accelerating cavity excite a higher order dipole mode (HOM) in it. These modes can have a large quality factor and thus a long lifetime in superconducting cavities. The electro-magnetic field of such a mode deflects the beam and then the bunches start to oscillate around the design orbit of a recirculation loop. When they re-enter the cavity with that offset the same HOM can be excited even more and thus the deflection becomes larger. As the excitation strength of the HOM also depends on the bunch charge the beam current is limited. The formula, taken and modified from [4], shows the maximum beam current for an ERL with one HOM and one recirculation:

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

where p_b is the momentum of the 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. A theory of BBU instabilities in multiturn ERLs can be looked up in [4]. Similar to conventional recirculating accelerators [2] the threshold current is further decreased with the growing numbers of turns.

Despite early estimations [1] during the design phase of the S-DALINAC, which predicted no BBU within the design parameter of beam current (20 µA), BBU was observed below that value. We decided to take this as an opportunity to measure the threshold currents at different accelerator settings and test beam line modifications to raise the BBU limit.

S-DALINAC

The recirculating superconducting Darmstadt Linear Accelerator S-DALINAC at the Technische Universität Darmstadt provides electron beams in c.w. for nuclear physics experiments since 1991 [5]. It consists of a 10 MeV injector and a 40 MeV main linac. For acceleration twelve elliptical SRF cavities are used at an operation frequency of 3 GHz. The injector cryo-module houses a two cell and a five cell cavity for pre-acceleration and two 20 cell cavities for the main acceleration. The linac houses also eight 20 cell cavities. Two recirculating beam lines allowed to use the main linac up to three times. The design beam current in the recirculated mode at 130 MeV was 20 µA.

In August 2015 the installation of an additional recirculation beam line [6] and other modifications [7] at the S-DALINAC started. The upgrade will also allow for operating the accelerator as a single- or double-turn ERL in future. Benefitting from the practical experience gained during measurements of BBU in the conventional recirculation mode we are confident to do more investigations on that topic, in particular on BBU in a single- or double-turn ERL once the new recirculating scheme has been commissioned in autumn 2016.

BBU SUPPRESSION

The strategies to minimize the effect of BBU in recirculating and energy recovery accelerators can be divided into two main categories: the optimization of the accelerating structures including the rf system and HOM couplers and the matching of the beam optics of the recirculation lines represented by T_{12} in Eq. (1). As we are not able to change the cavity parameters at the S-DALINAC we tested modifications of our recirculation loops beam optics. Skew quadrupole magnets can be used for varying the transverse phase space advance [2], e.g. reflect a beam displacement from the x to the y plane. Using this measure it is possible to increase the threshold current by reducing the corresponding transport matrix element down to zero ($T_{12} \rightarrow 0$). The 4×4 transport matrix describing a

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reflection about a plane at 45° to the horizontal axis takes the following form [3]:

$$\begin{bmatrix} 0 & M \\ M & 0 \end{bmatrix} \quad (2)$$

An infinite increase of the threshold current however is not realistic as one can see from a two dimensional theory [8] and from the fact, that there will be more than one HOM in a real accelerator. Certainly, beam rotation or beam reflection can reduce the positive feedback on the HOMs and thus can increase the threshold current.

BBU MEASUREMENTS

In the following section measurements of the BBU threshold current at the S-DALINAC are presented. A drawing of the accelerator as it was used in 2015, before the on-going upgrade, is shown in Fig. 1.

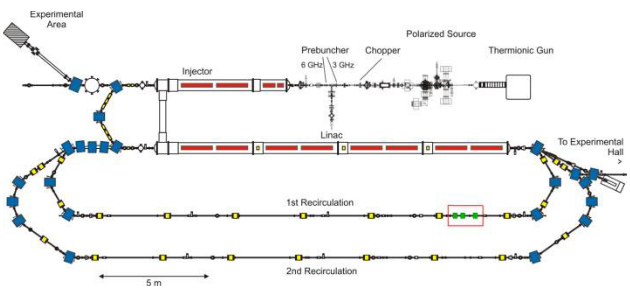

Figure 1: Floorplan of the S-DALINAC during the measurements in 2015. Three skew quadrupole magnets were installed in the first recirculation line in order to mix the transverse phase space advance.

To find the BBU threshold currents at different energy and recirculation settings we recirculated the beam one or two times. The beam current was dumped and measured on a Faraday cup in the extraction beam line. Two energy setups were tested which can be seen in Table 1.

In a first test, with injector energy of 5.8 MeV and once recirculating, no BBU could be observed. We lost the beam at 10.7 µA due to problems with our rf amplifiers. After fixing that issue, it was decided to add another linac pass, as we were not completely sure, if we would observe BBU at all. When turning up the current to 7.5 µA the beam was suddenly lost. This time the beam did not become unstable as before, our rf system [9] showed a regular behaviour as well as our beam loss monitor system [10].

As we were sure, that we repeatedly observed a BBU event at a certain threshold current, we used the beam optics settings again, scaled it down to a lower injector and linac energy and tested again. In this third experiment BBU occurred already at 5 µA of beam current, which was expected, as the threshold current scales with the injector energy [2]. In Fig. 2 a part of the measurements of the experiments 3 and 4 with lower injector energy is shown. It did not matter if we turned up the output beam current of the electron gun slow or fast, the beam was always lost at the same current value in a way that less than 50% was measured on the Faraday cup after the last linac pass. After such an event the output current was decreased for machine protection and the beam was instantly stable again. Using three skew quadrupole magnets in the first recirculation beam line we managed to turn the dispersion plane approx. 45°. Using only three quadrupoles [11] a complete reflection of the beam was not possible. Nevertheless their use resulted in an increase of the threshold current by more than 60%.

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

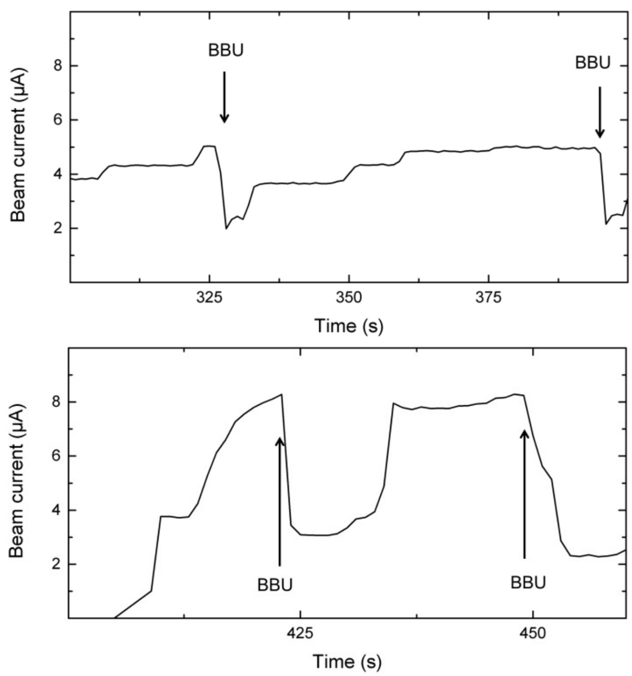

Figure 2: Beam current transported through the recirculating accelerator measured on a Faraday cup for two different recirculating settings and same beam energies. The upper picture shows the beam loss due to BBU in low energy setting (experiments no. 3 from Table 1) and conventional recirculation mode. The lower picture illustrates an increased threshold current when skew quadrupoles were used.

Several estimates for the BBU threshold current of the S-DALINAC were presented in [1]. In a worst case scenario for the maximum injection energy of 10 MeV, 24 µA have been calculated. Scaled down to the beam energies we used in our experiments this estimate was

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pretty good. One reason why the threshold currents were still lower than the worst case scenario predicted, might be that the layout of the recirculation beam optics during the design phase of the S-DALINAC was different from the lattice used during this experiments. The actual beam optics were implemented to ensure a good acceptance and stability [12] of the beam, but they might have worsened BBU.

A complete analysis of the experimental data is still in progress. For a better understanding we started a measurement of our HOM spectra as well as simulations with CST microwave studio [13]. A preliminary plot of the quality factors (without any coupling) of the HOMs in our 20 cell cavites is presented in Fig. 3. A photograph of a 20 cell S-DALINAC cavity is shown in Fig. 4.

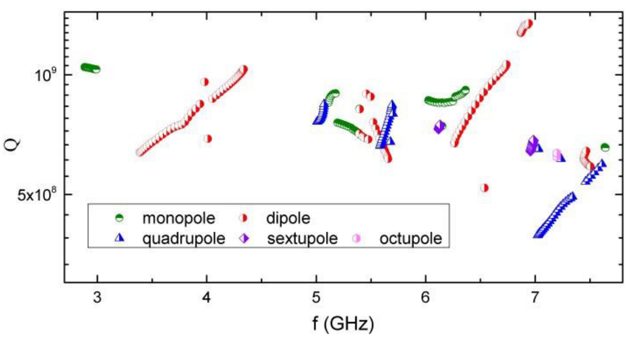

Figure 3: Preliminary simulation results for the quality factors of 300 HOMs in a S-DALINAC 20 cell cavity.

Figure 4: Picture a of S-DALINAC 20 cell cavity.

UPCOMING EXPERIMENTS

As mentioned before the S-DALINAC has been upgraded with another recirculation beam line during the last months. It has been 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. With the operational experience of BBU at the S-DALINAC as a conventional linac we plan to do further investigations on BBU in that ERL scheme.

In addition we were able to add another two skew quadrupoles to the beam reflection system presented in [11]. So in future we are using 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, as described by Eq. (2).

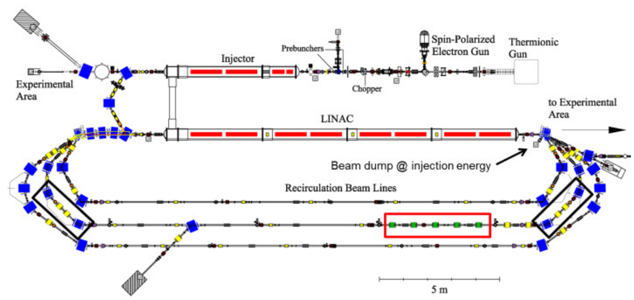

Figure 5: Floorplan of the S-DALINAC after installation of an additional recirculation loop [6]. The dipole magnets inside the black rectangles will be movable to allow the necessary shift of the path length in order to run the accelerator as a single- or double-turn ERL. Five skew quadrupole magnets were installed (red box) to mix the transverse phase space advance.

CONCLUSION

BBU was observed at a few µA at the S-DALINAC which was operated as a recirculating linac. The threshold current was depending on the injector energy. A first test with skew quadrupole magnets for mixing the transverse phase space advance was performed and resulted in a rise of the BBU threshold current. The analysis of the results is still in progress. In future the S-DALINAC can be operated in an ERL scheme and it is planned to do further investigations on BBU in this operation mode.

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