UPCOMING MEASUREMENTS OF TRANSVERSE BEAM BREAK UP AT THE SUPERCONDUCTING RECIRCULATING ELECTRON ACCELERATOR S-DALINAC*

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Abstract

The 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 energy using up to two recirculation paths. The superconducting main linac houses eight 20-cell SRF cavities operated at 3 GHz and 2 K. Due to transverse beam break up the design beam current of 20 µA could not be reached in recirculating operation mode yet, the highest stable beam current obtained so far accounts for 5 µA, which is sufficient for the nuclear physics experiments carried out at Darmstadt [1].

On the other hand the very low threshold current for the occurance 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 and to benchmark beam dynamics simulations concerning this topic. We will report on upcoming experiments which will be carried out at the S-DALINAC for that purpose.

INTRODUCTION

The Superconducting DArmstadt LINear Accelerator (S-DALINAC) is operating since 1987 as a source for nuclear- and astrophysical experiments at the university of Darmstadt [2]. It is designed for producing beams of either unpolarized or polarized electrons [3] up to energies of 1 up to 130 MeV with beam currents from several pA up to 60 µA in single pass mode or 20 µA in recirculating mode using two recirculations. The layout of the S-DALINAC is shown in Fig. 1.

For acceleration of the beam ten 20 cell superconducting elliptical cavities (see fig. 2) with a quality factor of $Q_0 \approx 10^9$ are used. The operation frequency of the cavities is 3 GHz while the maximum accelerating gradient of each cavity accounts for 5 MV/m. As the main linac consists of 8 standard 20-cell cavities it can provide an energy gain of 40 MeV. By recirculating the beam up to two times the maximum energy of 130 MeV can be achieved. In the adjacent experimental hall this beam can be used for different experiments such as electron scattering in two electron spectrometers or experiments with tagged photons. For these experiments an energy spread (rms) of $1 \cdot 10^{-4}$ as well as a very low γ-ray background are required.

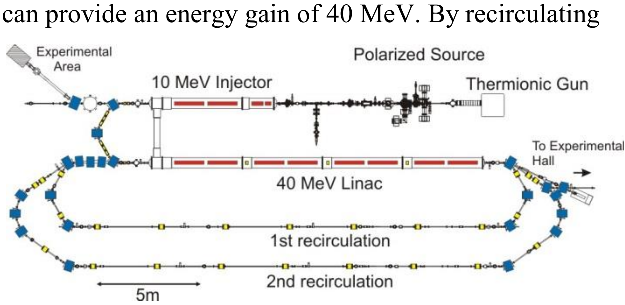

Figure 1: Floor plan of the S-DALINAC.

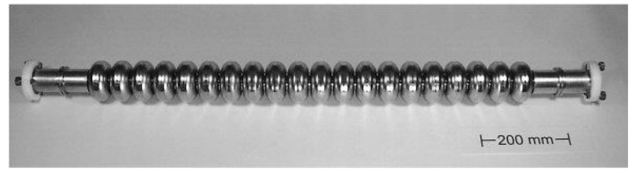

Figure 2: S-DALINAC 20 cell cavity.

OPERATIONAL EXPERIENCE

The S-DALINAC is the first superconducting and recirculating cw accelerator for electrons which has been put into operation in Europe [2]. After setting up the injector in 1987 the complete accelerator started operation in 1991 and has been used for experiments in nuclear, astro- and radiation physics since then. In 1996 a first infrared laser beam at the free electron laser (FEL) could be observed [4]. For the FEL operation the peak current of the electron beam was up to 2.7 A at a pulse length of some ps and an operation frequency of 600 MHz [4]. Originally it was planned to operate the S-DALINAC as an ERL as well when using the FEL but the challenges of operating this first European FEL had been big enough even without trying the ERL mode. One reason has been the occurance of instabilities due to the high peak current of the electron bunches – a first observation of transverse beam break up at the S-DALINAC which occurs at a relative low threshold current of some µA due to the design of the 20-cell accelerating cavities which haven't been optimized for suppressing any higher order modes (HOMs).

The beam break up also limits the maximum achievable beam current in recirculating operation of the S-DALINAC. Operational experience obtained during many years of beam time for nuclear physics showed that a stable operation in the twice recirculating mode is possible only up to some µA. The highest stable current achieved so far accounts for 5 µA [1], which is well below the design value of 20 µA but adequate for the experiments carried out. On the other hand this low threshold current gives an opportunity of investigating transverse beam break up experimentally.

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PROPOSED EXPERIMENTS

Transverse beam break up (BBU) occurs when an accelerated beam with a high peak current excites higher order dipole modes in the accelerating cavities. These modes can 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 has been observed in the very first SRF linacs at threshold currents of a few µA [5,6]. Much effort has been made to raise the BBU threshold currents mainly by designing accelerating cavities with strong damping of HOMs but also by matching the transverse beam optics [7,8] or even using the chromaticity of the beam transport system [9]. The latter two have been investigated in simulations only so far. For that reason we propose experiments at the S-DALINAC for testing strategies of avoiding transverse beam break up taking advantage of the low threshold current of this recirculating linac mentioned above.

Variation of the transverse phase advance

Matching the transverse phase advance in a recirculating linac in a way that a negative feedback of the HOM excitation is provided can increase the threshold current significantly [8]. Figure 3 shows simulation results for the threshold current using different cavities and transverse phase advance in the recirculation for a once recirculating ERL [8]. It can be seen that the threshold current increases for certain amount of phase advance in the recirculation path.

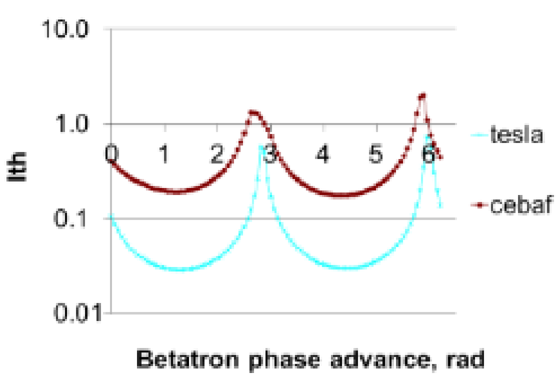

Figure 3: BBU threshold currents for two different types of accelerating cavities and different amount of betatron phase advance [8].

As the recirculation lattice of the S-DALINAC allows for an easy variation of transverse optics, such a relation should be measured as well when changing the transverse betatron phase advance of the recirculations. In order to make the results comparable with simulations the HOM spectrum of the S-DALINAC 20-cell cavities need to be derived first by carrying out simulations with CST microwave studio.

An opportunity to increase the threshold current even further can be a coupling of x and y planes of transverse motion as it has been presented in [8] as well. In such a scheme solenoids or skew quadrupoles are used to mix the horizontal and vertical plane of transverse motion.

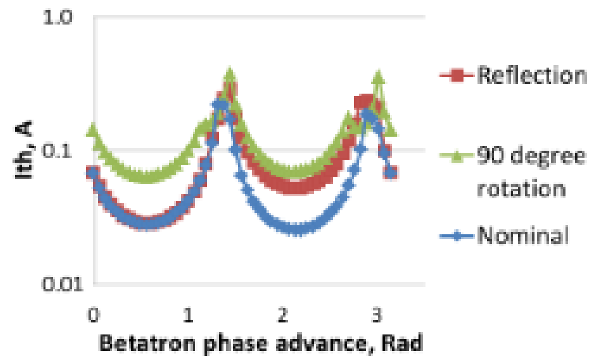

Figure 4: BBU threshold currents for different amount of betatron phase advance and coupled motion of x and y planes in tranverse phase space using reflectors (skew quadrupoles) or solenoids [8].

In order to test this topic at the S-DALINAC additional skew quadrupoles and solenoids need to be installed in the straight sections of the recirculation paths. These magnets are under design at the moment at will be installed within one of the next shutdown periods.

Variation of chromaticity

An interesting approach of avoiding transverse beam break up has been presented in [9]. The author proposes to keep natural chromaticity in a large scale recirculating linac (eRHIC at BNL) instead of correcting for it. If the product of chromaticity in the recirculation arcs and energy spread of the beam gets large enough

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

the electrons "forget" the kick of any dipole modes while passing the recirculations and each linac sees a fresh electron beam [9].

In order to test this hypothesis additional sextupoles for the S-DALINAC recirculation arcs are currently under design as the natural chromaticity of the S-DALINAC doesn't account for large enough values to satisfy the condition in formula (1). As soon as these sextupoles are installed first experiments on the influence of chromaticity on transverse beam break up will be carried out.

Variation of bunch length

As derived in [10] the strength of excitation of HOMs in cavities is dependent of the bunch length σ_b like:

$$P \propto e^{-\sigma b} \qquad (2)$$

This means that a bunch will excite HOMs stronger as it gets shorter, while longer bunches lead to weaker excitations. Usually in linacs acceleration is performed on

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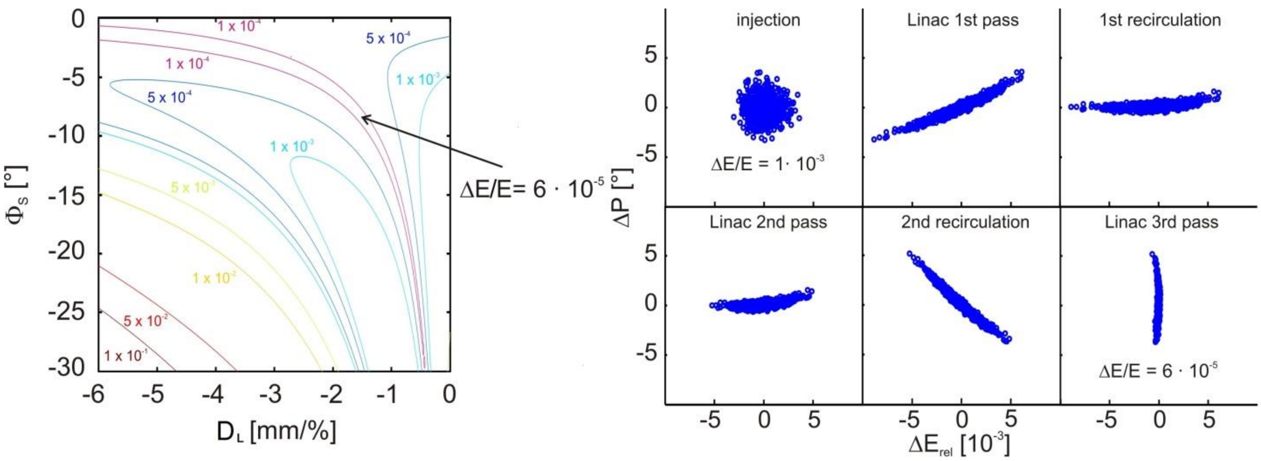

Figure 5: Hillplot of the resulting energy spread at extraction for different sets of longitudinal dispersion and synchrotron phase (left) in a twice recirculating linac [13]. Beside the isochronous point with acceleration on crest of the rf field exist areas of reduced energy spread. The minimum has been determined to D_L = -1.5 mm/% and Φ_S = -9.5° On the right side a bunch of 5000 particle has been tracked through the linac using the optimized parameters. The particles perform a half oscillation in longitudinal phase space ending up on a significant reduced energy spread. During acceleration the bunch length is enlarged which leads to weaker excitation of HOMs. This will be investigated within this project concerning its influence on BBU thresholds..

crest of the rf field using short bunches in order to achieve a low energy spread of the beam. In recirculating linacs like ERLs the recirculations have to be isochronous then in order to keep the bunch length short.

As an alternative one can use acceleration on edge of the rf field with non-isochronous recirculation paths like it is common in microtrons for stabilizing the beam against losses. But also for few turn accelerators the concept of non-isochronous recirculation can be of advantage like proposed in [11,12] and shown experimentally at the S-DALINAC in [13]. Using this acceleration scheme the longitudinal phase advance during the acceleration process has to add up to a half-integer number of synchrotron oscillations in order to get an optimized energy spread of the beam at extraction [11]. Figure 5 shows simulations performed for the S-DALINAC showing the optimized longitudinal working point and the propagation of longitudinal phase space during acceleration.

For suppressing beam break up this concept provides an opportunity to accelerate the beam on longer bunch lengths and hence weaker excitations of HOMs while the resulting energy spread keeps low. Within the planned experiments at the S-DALINAC it will be investigated if this leads to an increase of the BBU threshold current as it is expected.

Currently additional beam dynamics simulations in longitudinal phase space are in process in order to find settings with different bunch lengths during acceleration and similar energy spread at the end of acceleration process. In a next step systematic measurements will be performed using the accelerator settings achieved within these simulations.

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 provides a unique opportunity to the ERL community in testing different strategies of avoiding beam break up experimentally.

The proposed experiments at the S-DALINAC accelerator will be started as soon as possible. Currently different magnets like solenoids and sextupoles are under design and will be integrated into the beam line within one of the next shutdown periods.

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.

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