

# OPERATIONAL FINDINGS AND UPGRADE PLANS ON THE SUPERCONDUCTING ELECTRON ACCELERATOR S-DALINAC\*

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## Abstract

The S-DALINAC is a superconducting recirculating electron accelerator with a final energy of 130 MeV. It operates in cw at 3 GHz. It accelerates beams of either unpolarized or polarized electrons and is used as a source for nuclear- and astrophysical experiments at the university of Darmstadt since 1987 [1,2]. The layout of the S-DALINAC is shown in Fig. 1.

We will report on the operational findings, recent modifications and on the future upgrade plans: First results from the new digital rf control system, the injector current upgrade and the improved longitudinal working point will be presented. In addition, an overview of the future plans, namely installing an additional recirculation path and two scraper systems will be given.

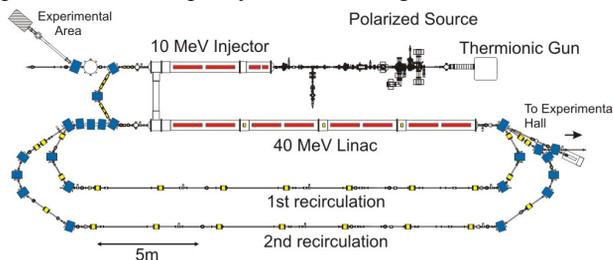


Figure 1: Floor plan of the S-DALINAC.

## DIGITAL RF CONTROL SYSTEM

In the old RF control system at the S-DALINAC the 3 GHz probe signals of the 12 superconducting cavities have been converted down into base band by a four quadrant vector demodulator, which gives the I and Q vectors of each cavity (in the rotating coordinate system of the reference oscillator). These rf control loops were used for 20 years to ensure constant acceleration of the electrons and to provide a small energy spread of the beam, which turned out to be no better than  $\pm 10^{-3}$ . During the last years, a new digital RF control system was developed and finally put into operation in the end of 2010. [3]

In principle, the concept of the old system was kept: the rf signals, again, are converted down to the base band which allows splitting the hardware into a frequency dependent rf board containing the I/Q (de)modulator and a frequency independent (digital) FPGA board processing the signals. The current revision of the FPGA board evolved from prototypes described before. In addition to the existing 3 GHz rf boards a new 6 GHz board has been developed and successfully tested with the new 2f buncher cavity newly installed for the polarized electron source.

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For the high Q superconducting cavities a Self-Excited Loop (SEL) algorithm is used whereas for the copper cavities the much simpler Generator Driven Resonator (GDR) algorithm was found to be sufficient. So far, many different algorithms have been implemented and tested on a real cavity, some of them can be switched during runtime. So far, the following results have been achieved:

The GDR algorithm has been tested with different copper cavities. Typical values achieved with the new 3 GHz chopper cavity are a phase error of  $0.076^\circ$  rms and a relative error in magnitude of  $1.37 \cdot 10^{-4}$  rms. These errors are within the specifications. The SEL algorithm was tested with a cavity operated in the cryo-module of the S-DALINAC. The phase error measured was  $0.22^\circ$  rms being below the target specification of  $0.7^\circ$  rms. (Fig. 2) On the contrary the total amplitude error of  $6.6 \cdot 10^{-4}$  rms is still above the desired  $8 \cdot 10^{-5}$  rms but still an improvement compared to the performance of the old analogue system. Nevertheless, these were just first results measured recently. Investigation and improvements will go on.

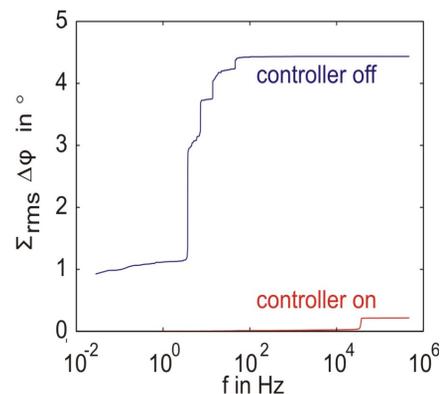


Figure 2: Integrated amplitude spectra of the phase error of the SEL. The phase controller is deactivated (blue, free run) or activated (red).

## INJECTOR CURRENT UPGRADE

The increase in energy and intensity up to 14 MeV and 200  $\mu$ A, needed for upcoming nuclear physics experiments with bremsstrahlung, required a major modification of the injector accelerator. [4] In order to facilitate the higher power transfer of up to 2 kW to the electron beam the old coaxial RF input couplers, being designed for a maximum power of 500 W, had to be replaced by new waveguide couplers. Moreover, a new cryostat module was designed (Fig 3). Once installed the present injector module will serve as a spare module for the main linac which will reduce the turnaround time for future maintenance work dramatically.

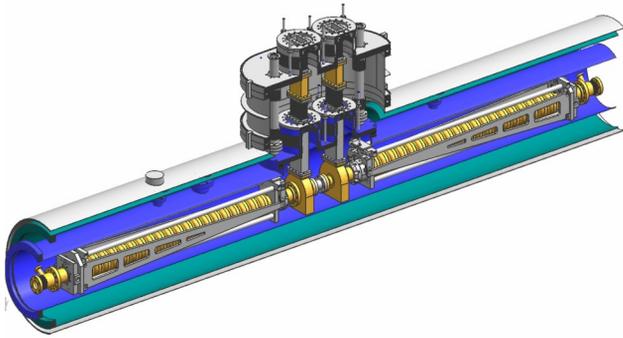


Figure 3: New designed injector module for the S-DALINAC.

## NEW LONGITUDINAL WORKING POINT

Numerical beam dynamics simulations suggested that a different longitudinal working point of the S-DALINAC could lead to a reduced energy spread of the electron beam [5,6]. It has been shown that the effects of amplitude and phase jitter of the accelerating cavities in the linac on the beam energy can be reduced by the choice of an off-crest synchronous phase together with a non-isochronous beam transport system. In the past, two major objectives could be identified to ensure a proper tuning of the machine routinely. One was to modify each recirculation paths to provide a longitudinal dispersion and to allow easy access to this rather complicated beam-line property and second the set-up of a diagnostic system to measure the longitudinal dispersion. Both objectives have been successfully addressed within the last year.

The reconfigurations of the recirculation paths (in particular the lattice of the arcs has been reviewed) are completed: Both recirculations now provide a longitudinal dispersion  $D_L$  of -1.5 mm/% while the value of  $D_L$  can be adjusted easily by retuning the quadrupoles in the arcs.

To measure the longitudinal dispersion a prototype system was installed in the first recirculation arc, using an rf monitor (originally designed for non-destructive beam intensity measurements) located at the beginning of the straight section behind the last dipole. As the passing beam excites an oscillation inside the monitor, the longitudinal dispersion can be determined by measuring the phase shift of this oscillation as a function of the energy of the electron beam. Therefore, the monitor signal is mixed with the local oscillator frequency of the rf control system to down-convert it into the base band, leading to I/Q values describing the relative phase of the rf monitor. To determine  $D_L$  the magnetic field of the dipoles in the arc have been set to different values changing the energy of the reference trajectory. For every dipole setting the I/Q-values (plotted in fig. 4 top) have been measured, giving directly the phase variation. To determine  $D_L$  it is necessary to calculate the path length difference  $dl$  of the electrons on trajectories representing different beam energies using the relation:

$$\tan \varphi = \frac{I}{Q} \rightarrow \frac{d\varphi}{dl} = 3.6 \frac{\text{deg}}{\text{mm}} \rightarrow D_L = \frac{dl}{dE}$$

For the complete measurement, the arc has been tuned to a different longitudinal dispersion by changing the quadrupole gradients and the longitudinal dispersion was measured as described above. Figure 4 bottom gives the obtained values of  $D_L$  as a function of the quadrupole gradient and a linear fit of the data (agreeing perfectly with the expected parameters obtained with the simulation). Moreover one can conclude that  $D_L$  can be changed over a large interval within the arcs without beam losses including the envisaged value of  $D_L = -1.5$  mm/%.

The diagnostic set-up as well as the modification in the accelerator lattice has proven to be adequate. While the reconfiguration of the recirculation arcs has been finished, the longitudinal dispersion diagnostics system (LDDS) has to be installed through-out the whole machine which will be the task within the next months. Once the system is complete, a demonstration experiment with a non-isochronous recirculated beam has to be performed. To do so the machine will be tuned to different longitudinal working points while measuring the yielded energy spread by electron scattering in a spectrometer to confirm the simulations according to the new longitudinal working point. In a last step the non-isochronous recirculation scheme will start its regular operation.

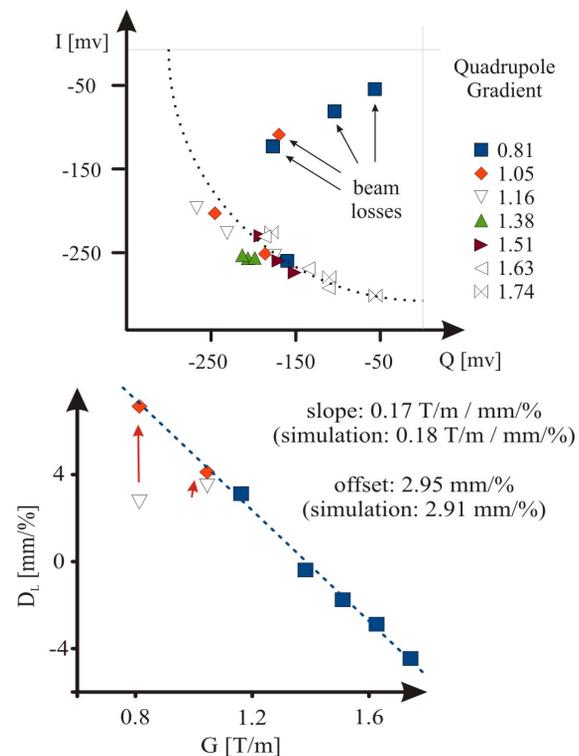


Figure 4: Measured I/Q values of the beam for different dipole and quadrupole settings (top) and resulting longitudinal dispersion (bottom) of the first recirculation. The red arrows mark the correction of beam losses which appeared only at very low quadrupole gradients in the arc.

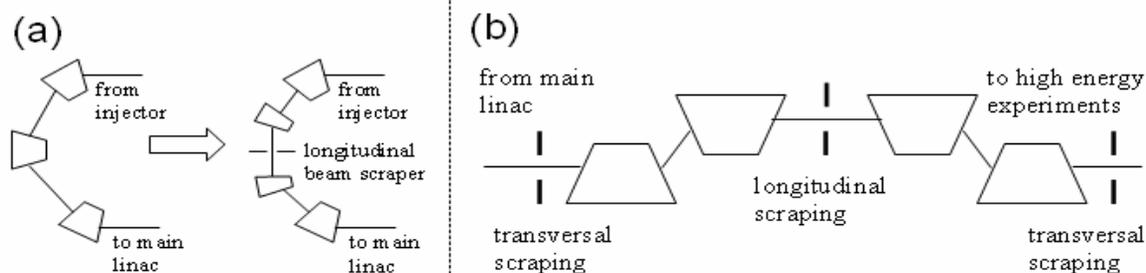


Figure 5: Left: Proposed modification of the injector bending section to implement a scraper removing the low energy tail of the beam. The proposed installation in the extraction beam line is shown on the right.

## ADDITIONAL RECIRCULATION

So far, the final energy of the S-DALINAC has been restored to 80 MeV in cw mode by partially improving the quality factor of the superconducting cavities. [7] In the end one can estimate that a final energy of 90 to 95 MeV might be reachable which compared to the design energy of the accelerator is still much too low. Therefore, the installation of a third recirculation to boost the accelerator energy is envisaged, allowing to use the energy gain of the main linac another time, which would lead roughly to 120 MeV. A preliminary design study was undertaken, focusing mainly on two different options. One, currently being favoured is to build the new recirculation in between the two existing ones.

A considerable advantage of this layout is that most of the existing beam-line and magnets can be used again (even so the energy of the beam changes). Beside the 4 new bending magnets to form the additional recirculation path, only the separation and combining magnets at the beginning and the end of the recirculations have to be replaced.

## BEAM SCRAPER SYSTEMS

If not optimized electron accelerators usually generate  $\gamma$ -ray background from bremsstrahlung processes on beam-line components which often prevents sensitive detection of photons from the reactions. The background is produced by beam losses coming from some beam halo which is generated during acceleration and reinjection of the recirculated beam.

We plan the installation of beam scrapers at two different locations: Beam dynamic simulations show that the electron beam behind the injector has some low energy tail which cannot be avoided even when the accelerator is tuned optimally. This longitudinal tail is still within the acceptance to get accelerated in the main linac and finally transported to the experimental areas. Providing a clean halo-free beam requires longitudinal shaping of the beam behind the injector, i.e. inside the 180° bending arc. A suitable system and the necessary modifications are shown in Fig. 5 (a): the innermost dipole magnet has to be replaced by two half-size magnets. In between energy defining slits have to be installed.

The injector arc scraper system will remove the low energy tail of the beam injected into the main linac. After three passes through the linac (housing 8 independently controlled accelerating cavities) a transversal scraping, combined with an additional longitudinal collimation will ensure the highest beam quality by removing any beam halo. The system proposed is shown in Fig. 5 (b). In addition, the longitudinal scraping can further reduce the energy spread of the beam at the cost of beam current. As the dispersion is maximized in this section, a more efficient energy collimation compared to the existing system can be assured.

## SUMMARY AND OUTLOOK

We reported on the ongoing upgrades for the S-DALINAC. So far the digital rf control system is operational and will be further improved during operation. The work on the injector upgrade and the new longitudinal working point will be finished within this year.

For the future upgrades detailed magnet and beam dynamics studies are in progress. The new scraper systems and the third recirculation are planned to be operational till 2013.

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