

PHASE AND ENERGY STABILIZATION SYSTEM AT THE S-DALINAC

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Abstract

The Superconducting Darmstadt Linear Accelerator S-DALINAC is a recirculating electron accelerator with a design energy of 130 MeV operating in cw. Before entering the 30 MeV main accelerator the low energetic electron beam passes both a normal-conducting injector beamline preparing the beam's 3 GHz time structure as well as a superconducting 10 MeV injector beamline for preacceleration. Since the superconducting injector accelerates on-crest while the main accelerator accelerates off-crest the beam phase is crucial for the efficiency of the acceleration process and the minimization of the energy spread. Due to thermal drifts of the normal-conducting injector cavities this injection phase varies by about 0.2 degree over a timescale of an hour. In order to compensate for these drifts, a high level phase controller has been implemented. Additionally a low energy scraper system has been installed between the injector and main linac in order to lock both the phase and the energy spread at the linac entrance.

MOTIVATION

The S-DALINAC (see Fig. 1) is a recirculating electron accelerator providing electron beams with energies up to 130 MeV in cw operation. It provides beam currents between several nA and 60 μ A for nuclear structure and astrophysical experiments since 1987 [1]. The electron beam can be produced by two alternatively usable sources. The thermionic electron gun produces an unpolarized beam while the S-DALINAC Polarized Injector [2] creates polarized electron beams by illuminating a GaAs cathode with a laser beam. After beam preparation in the n.c. injector beamline including chopper and prebuncher cavities the electron bunches enter the s.c. 10 MeV injector. There the electrons are preaccelerated on-crest by niobium cavities working at a resonance frequency of 3 GHz. Leaving the s.c. injector the electron beam can either be used for nuclear resonance fluorescence experiments at the Darmstadt High Intensity Photon Setup DHIPS [3] or it can be guided to the main accelerator by a 180°-arc. The main accelerator can be used up to four times using the three recirculations in order to reach the design energy of 130 MeV. It has been shown that the energy spread can be reduced significantly from 120 keV to 30 keV by using a non-isochronous recirculating mode [4]. Theoretically this mode reproduces the same energy spread as before the first injection to the main linac. This depends heavily on the correct injection phase since a mismatch of 2° can increase the relative energy spread from $8 \cdot 10^{-5}$ to $3 \cdot 10^{-4}$. Experience shows that the beam phase behind the s.c. injector drifts

and oscillates on a timescale of several hours. An example measurement of these dynamics without compensation can be seen in Fig. 2. The reason for these phase shifts still is not fully understood. One possible explanation are instabilities of the high voltage supply of the source, that already have been observed. Another possibility is a thermal drift of the n.c. beam preparation cavities. To compensate for these drifts a high-level phase controller has been developed. This controller now locks the exit phase of the s.c. injector. To decrease the energy spread even further an additional low energy scraper system has been installed. This system can eliminate the beam halo and it can prevent any energetically mismatched electrons leaving the s.c. injector. Furthermore it can reduce the energy spread of the beam arbitrarily but reduces the intensity simultaneously.

PHASE CONTROLLER

To adjust the phase behind the s.c. injector it has to be changed before entering it. The following three devices have a significant influence on the exit phase, that has been measured by a rf monitor.

Chopper The Chopper forces the continuous electron beam of the electron gun on a cone-shaped trajectory that wanders over an aperture converting the continuous beam into a bunched one. This obviously defines the reference phase for every adjacent rf device.

Prebuncher The buncher cavity introduces a velocity gradient within every electron bunch by decelerating the early electrons and accelerating the late ones while leaving the reference particle's velocity unchanged. This focuses the bunch longitudinally after a defined distance. By shifting the buncher's phase an overall acceleration or deceleration can be introduced that changes the travel time to the injector entrance and therefore the entrance phase.

s.c. 2-cell cavity The 2-cell cavity is used to preaccelerate the low-energy electrons for the not sufficiently β -graded cavities of the injector. Although it is operated on-crest, it can be used similarly to the buncher to adjust the exit phase using time-of-flight effects.

The results shown in Fig. 3 motivate the use of the buncher for beam phase adjustments since it is the most efficient and linear device that has been tested.

Implementation

Hardware The low-level control system of the rf cavities is implemented on an in-house developed board [5]

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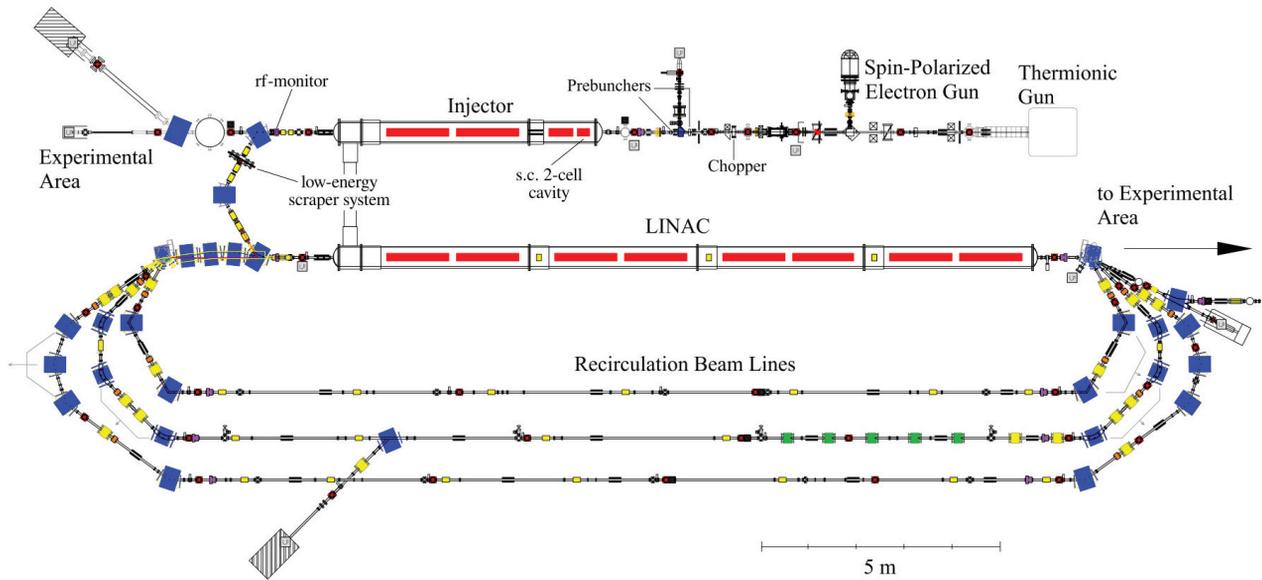


Figure 1: floorplan of the S-DALINAC showing the n.c. cavities and the low energy scraper system

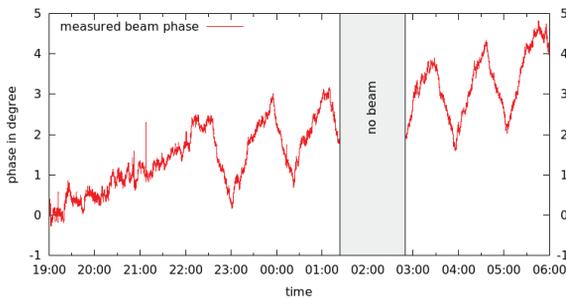


Figure 2: Measured beam phase behind the s.c. injector with visible phase drifts and oscillations

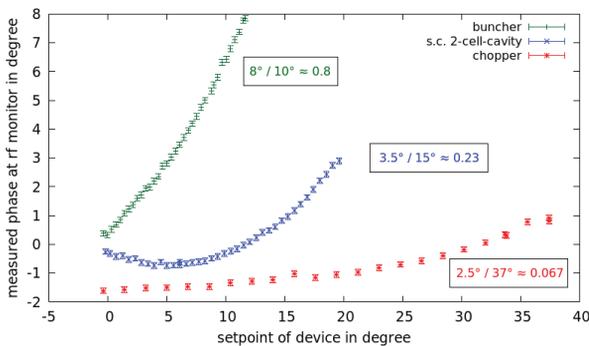


Figure 3: Measurement of the influence on the beam phase behind the s.c. injector

using a Xilinx Spartan-6 FPGA module. The probe signal of the cavity is mixed down to the base band and fed to the controller board, where it is analyzed digitally. The FPGA-Module uses integral and proportional control algorithms to adjust the amplitude and phase. The adjusted signal is converted to the 3 GHz band and fed to the cavities as a new

input signal. Additionally the board provides slower process data with a sample rate of up to ten samples per second over CAN-bus.

Software The process data provided by the low level control board is read and managed by a PC acting as a EPICS-Input-Output-Controller (IOC) [6], that converts the data to a human readable format. The new developed phase control algorithm is implemented as software control-loop on this IOC.

Algorithm The injector phase controller reads the phase of rf monitor behind the s.c. injector and compares it with a desired exit phase. The difference to the desired phase is fed to the actual control loop that consists of a parallel proportional and integral controller as shown in Fig. 4. Most of the phase compensation is achieved by the proportional controller with its proportional gain of 0.1 while the weak integral controller with its time constant over over 1 s only compensates for the remaining offset that the proportional controller leaves systematically.

First Results of the Phase Controller

Measured result from first tests of the phase controller are shown in Fig. 5. The control algorithm has been activated and monitored over several hours. Comparing Fig. 5 with with Fig. 2, it is clearly visible that the whole dynamic of the measured phase is shifted to the phase setpoint of the controlled buncher phase leaving the measured phase constant. To quantify the improvement, the measured phase behind the injector has been monitored over 2.5 hours. With the control algorithm being deactivated the standard deviation has been 0.15° and decreased to 0.02° with activated controller.

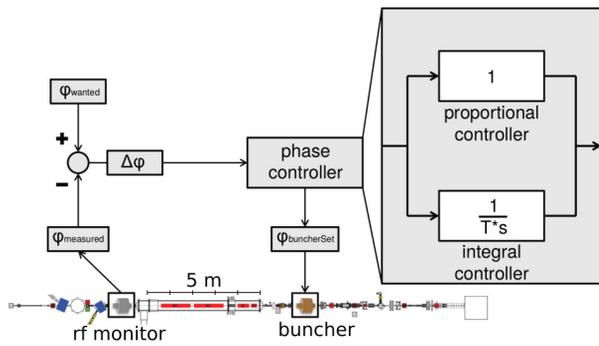


Figure 4: Schematic view of the injector phase controller algorithm

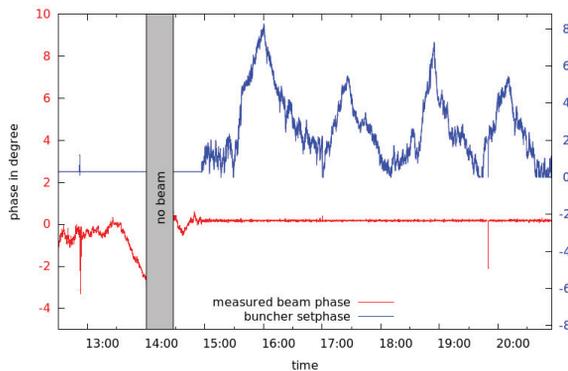


Figure 5: Comparison of the measured beam phase behind the s.c. injector and the controlled setphase of the n.c. pre-buncher

LOW ENERGY SCRAPER SYSTEM

Electron scraper systems stop parts of the electron beam by using blocks made out of materials with a high stopping power. This principle can be used to remove any halo and to define the energy spread, if the scraper blocks are placed at a position where the beam is expanded by dispersion.

Material

Materials that can be used as scraper brackets need to be suitable for high vacuum conditions, need to have a high stopping power for electrons, and need to provide a high heat conductivity. The stopping power determines the minimal thickness of the brackets to definitely stop the electrons. A good heat conductivity guarantees a good heat distribution and an efficient heat transfer to the cooling water, since the low energy scraper brackets of the S-DALINAC need to withstand a beam power of up to 200 W. Additionally it would be desirable to use a material that can be machined by the in-house workshop. Therefore copper was picked because it is best in both, thermal conductivity and electron stopping power.

Bracket Geometry

To optimize the geometry of the scraper brackets several simulations have been done using GEANT4 [7]. Figure 6

shows a schematic of the used geometry. Using a realistic beam profile the chamfer angle α and length L have been optimized. The chamfer angle turned out to be very important for a smooth temperature distribution and showed an optimum at 3° . The length of the parallel section L can increase the energy spread if chosen too long while introducing temperature hotspots if chosen too short. An optimum has been found at $L = 20$ mm. The necessary cooling power

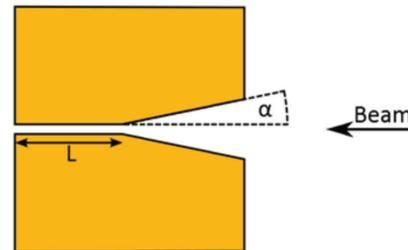


Figure 6: Schematic of the scraper brackets geometry

has been derived using CST MATHYS STUDIO 2013 [8]. With a worst-case scenario and a suitable water cooling the maximum temperature was simulated to 338 K what seems reasonable.

Beam Dynamics

To create an energy defining scraper system, a position had to be chosen where the beam is expanded by dispersion. Inside the 180° -arc between injector and main linac it was possible to shift some quadrupoles and to gain some space for a system with an overall length of up to 200 mm. The beam dynamics were changed in such way that the arc stays achromatic and isochronous. The new beam dynamics calculation done using XBEAM [9] is shown in Fig. 7. At the scraper's position the dispersion is a constant in the horizontal component and is set up with a value of 4 mm/%.

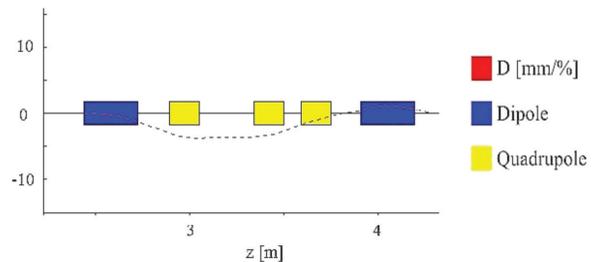


Figure 7: XBEAM simulation of the beam line showing a constant dispersion at the scraper's position

Construction

Due to the limited space in beam direction, the scraper chamber containing the scraper brackets as well as a light emitting BeO-target behind the brackets had to be designed very short. The BeO-target is used to check the beam position, size and shape and has to be movable. Additionally

the brackets have to be mounted electrically isolated to be able to measure the individual charge deposition. This is foreseen to be used as an additional diagnostic parameter. A sectional view of the final design is shown in Fig. 8. The

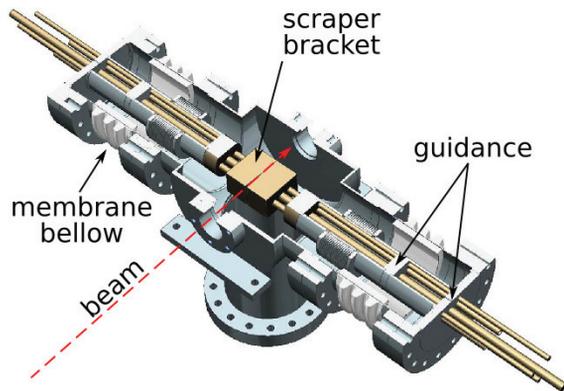


Figure 8: 3D-CAD model showing the sectional view of the scraper system

scraper brackets are guided using three brass bars and two cooling water pipes made out of copper. The membrane bellows allow a stroke of 30 mm. The precise motion of the brackets is done using a self-developed articulated jack with a stepper motor at the end of each side which can be seen in Fig. 9. The smallest step size is calculated to be less than 0.1 mm.

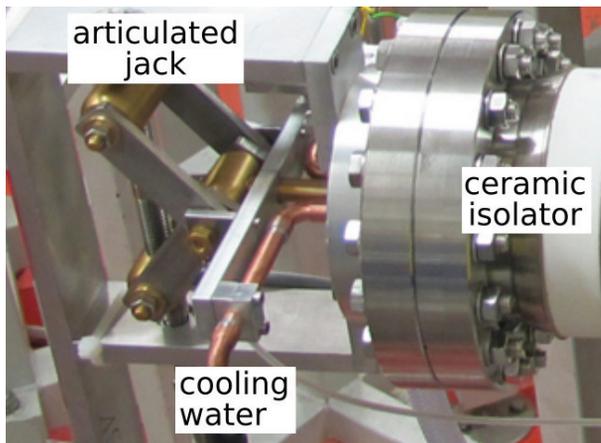


Figure 9: Articulated jack driven by a step motor for exact positioning

Commissioning

A first test of the scraper system has been done with a 140 nA electron beam at an energy of 5.8 MeV behind the s.c. injector. The beam has passed the following main linac only once to avoid an increase of the energy spread due to the recirculation. At a final energy of 24.6 MeV the energy spread and beam current have been measured using a spectrometer with a thin Au-foil target of 1.0 mg/cm². The result are shown in Fig. 10. It can easily be seen, that the energy spread could be reduced from 15 keV to less than 10 keV.

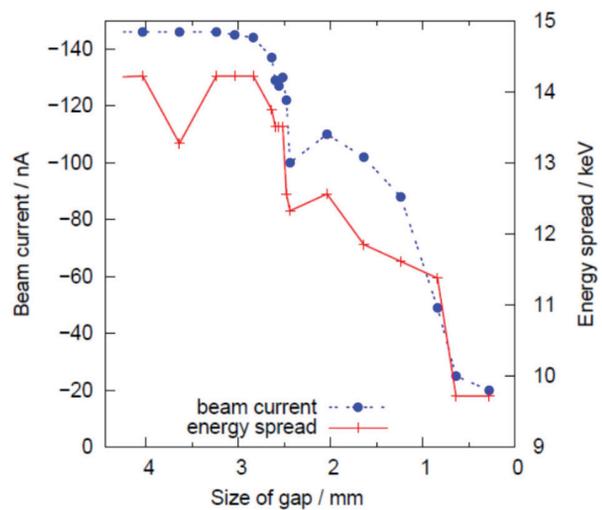


Figure 10: First commissioning by measuring the change of energy spread using scattering at a thin Au-foil (1.0 mg/cm²). The beam energy has been 24.6 MeV in single-pass mode.

As expected one can also see the decrease of the beam current since the energy spread is decreased using a destructive method by stopping parts of the beam. The fluctuations of the curve can be explained by the energy and phase variations that have already been described in the phase controller section. During this scraper measurement the injector phase controller was not yet implemented.

CONCLUSION AND OUTLOOK

Both the injector phase controller as well as the low energy scraper system have been tested individually and showed a very satisfying performance. The phase controller reduced the phase variations by a factor of 7.5 in respect to a 2.5 hour standard deviation, while the scraper system successfully showed the intended decrease of the energy spread. The influence of the phase controller on the actual energy spread at the experiment still has to be investigated and both system need to be tested synchronously to see the overall effect on the beam stability. This will be done during upcoming beamtimes.

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