LATEST DEVELOPMENTS FROM THE S-DALINAC AND ITS FREE-ELECTRON-LASER*

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Abstract

The FEL at the superconducting electron accelerator S-DALINAC has been operated at wavelengths between 6.6 and 7.8 µm corresponding to electron beam energies between 31.5 and 29.6 MeV respectively. In house developments like active stabilization of the optical cavity's length based on a laser interferometer and a fast 10 channel online-spectrometer for the near infrared laser radiation were incorporated and used for investigation of the properties of the FEL itself. In addition a simple focusing system produced power densities of 10^8 W/cm^2 and enabled us to perform first ablation experiments from different tissues. To optimize the complicated bunching process, the low energy part of the S-DALINAC was carefully studied by tracking calculations in order to achieve bunch length < 3 ps corresponding to peak currents > 1.5 A, necessary to operate the FEL reliably in the saturated regime. For operation at higher energies using two recirculations of the electron beam, longitudinal tracking simulations show that off crest acceleration together with nonisochronous recirculation introduce longitudinal stability resulting in significant improvement in energy spread.

1 S-DALINAC

The S-DALINAC operating since 1991 is a recirculating electron linac using superconducting (sc) accelerating cavities allowing for a continuous wave (cw) electron beam [1]. The machine provides beam to serve a variety of nuclear and radiation physics experiments and is since 1996 also used as a driver of a Free-Electron-Laser in the mid infrared wavelength region. A layout of the accelerator and the FEL is shown in Fig.1.

The electron beam is generated by a thermionic cathode, on a high voltage terminal providing a 250 kV electrostatic preacceleration. The beam gets its time structure in a chopper/prebuncher section at room temperature (see Sec. 3.) and is then accelerated up to 10 MeV in the sc injector linac consisting of a 2-cell (β=0.85) and a 5-cell (β=1) capture cavity and two 20-cell (β=1) accelerating cavities. Each of them is made of bulk niobium and operates at 2 K in a liquid helium bath at a

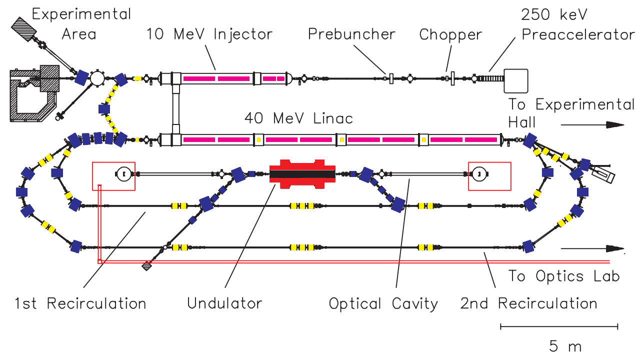

Figure 1. Layout of the S-DALINAC and its Free-Electron-Laser

resonant frequency of 3 GHz. Behind the injector the beam can be used in a low energy experimental area or bent 180° by a magnetic arc to be injected into the 40 MeV main linac consisting of eight 20-cell cavities. For nuclear physics experiments with electron energies up to 130 MeV the beam can be recirculated twice passing through dedicated beam transport systems.

The FEL is driven by transporting the beam from the first recirculation into the undulator through a magnetic bypass system. The infrared radiation generated and amplified in the 80 periods hybrid undulator is accumulated in a 15 m long optical cavity formed by two dielectric mirrors. For experiments part of the stimulated radiation is coupled through the downstream mirror and guided through an evacuated transfer to an optical laboratory.

Since its commissioning the S-DALINAC delivered some 16000 hours of beam time for experiments covering a wide range of beam parameters. Energies ranging from 2.5 MeV up to 120 MeV and currents from a few nA to 50 µA could be realized in a 3 GHz mode. The FEL is driven in a 10 MHz cw mode using a subharmonic injection scheme leading to peak currents of about 2 A at energies between 30 and 38 MeV.

2 FREE-ELECTRON-LASER

The FEL at Darmstadt benefits from the superconducting drive linac enabling time structures of the laser ranging from 100 µs long macro pulses to 10 MHz cw operation. The FEL has been operated so far at wavelength between 6.6 and 7.8 µm corresponding to electron energies between 31.5 and 29.6 MeV respectively. The wavelength could be tuned continuously in this range determined by the bandwidth of the dielectric

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mirrors by changing either the magnetic gap of the undulator or the electron energy. During the commissioning [4] of the FEL using an electron beam with an energy of 30.4 MeV and a measured bunch length of 3 ps corresponding to a peak current > 1.5 A, we were able to extract an average cw laser power of 3 W at a wavelength of 7.4 µm through a mirror with 99 % reflectivity. The net gain of the arrangement was measured to 3-5 %.

The laser output power turned out to be very sensitive to length variations of the optical cavity in the micrometer range. These perturbations are caused by vibrations on the optical tables due to cryogenic pumps and the heavy machinery of the helium liquifier as well as long time drifts caused by air pressure and room temperature changes. Therefore it was essential to develop an active feedback system to stabilize the length of the optical cavity. A commercial michelson interferometer (HP 5527A Laser Position Transducer) measures the length variations and generates a drive signal for the piezo transducers holding the mirrors. The control parameters can be software adjusted. The remaining length variation due to vibrations was measured to be a gaussian distribution with 232 nm FWHM, as shown in Fig.2., while the long time drifts were eliminated completely. Without feedback the position error is about 500 nm FWHM with drifts of 20 µm within 24 hours preventing stable laser operation.

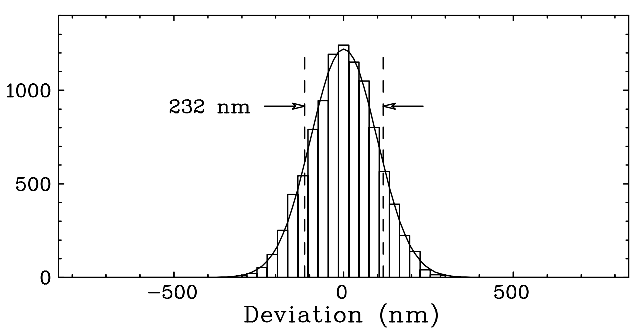

Figure 2. Length variation of the optical cavity with interferometric feedback active.

In order to control and optimize the laser performance an online- spectrometer was developed with a typical Czerny Turner setup for the spectral splitting and a ten element pyroelectric strip detector. The detector output is monitored online on a LED display or connected to ADC's for further analysis. The resolution of this device is 20 nm per element. Drifts and changes in the electron beam steering through the undulator leading mostly to longer wavelengths could be easily corrected with this device. The laser beam stabilized and monitored in such an way could be used for first ablation experiments on different tissues performed in cooperation with J. F. Bille and his group from the university of Heidelberg. The laser beam was focused by a single CaF_2 lens with a focal length of 350 mm to a spot size of 160 µm providing a power density of some 10^8 W/cm^2. The resulting ablation depths were measured with a scanning electron microscope and the ablation mechanism was described by an analytical model. It turned out that the ablation was due to thermal interaction. The measured ablation depths could be explained by a model assuming the tissue as water, being heated and vaporized by the radiation pulses. Ablation sufficient for medical purposes demands at least a 10^3 times higher power density in order to avoid too much thermal damage for nearby tissue. We are sure to reach this goal by means of more sophisticated focusing optics and by optimizing the optical transfer system. The use of regenerative amplifiers for the laser beam is also envisaged to reach even higher power densities in the future.

3 TRACKING CALCULATIONS OF THE INJECTOR LINAC

The quality of the laser output depends on the parameters of the electron beam entering the undulator, especially the longitudinal properties energy spread and bunch length are critical for the shape of the spectrum and the output power. These properties are almost fixed after the injector, therefore the beam dynamics in the low energy part of the accelerator was studied intensively by tracking calculations. For driving the FEL the thermionic cathode is pulsed with a repetition rate of 10 MHz. Pulses with a duration of 1 ns are extracted from the gun at 250 keV. The subharmonic chopper/prebuncher section working at the 5th subharmonic cuts out 370 ps corresponding to a charge of 6 pC and compresses these bunches to a length of 5 ps at the entrance of the capture cavity. For FEL operation we so far used only the 5-cell capture cavity followed by two 20-cell standard accelerating cavities.

The tracking simulations of this part of the machine are performed using the code GPT [5] including space charge forces and electromagnetic fields of the rf-resonators calculated by MAFIA [6]. The simulations are performed to find an optimized parameter set for the injector as well as to compare empirically found parameter sets and measured beam properties with the simulation results. The gauging relation between the tracking code parameters and the machine parameters like rf-phases and amplitudes were determined from separate calibration measurements. The nice agreement between measured beam properties from a previous FEL beam time and the simulation results confirmed this calibration method. Searching for an optimized setting with respect to bunch length and energy spread revealed an enormous sensitivity concerning the choice of rf-phases and amplitudes for the first two accelerating cavities due to non relativistic behavior in this section. In contrast to the common feeling (accelerate as fast as possible) the simulations suggested to reduce the field amplitude of the first 20-cell cavity. Since the longitudinal phase space is found to be correlated at the exit of the injector we can benefit from magnetic bunching in the 180° bending arc towards the main linac. According to the tracking results a bunch length of 2 ps (FWHM) with sufficient energy spread of ± 33 keV (rms) at an energy of 8 MeV can be achieved at the entrance of the main linac as shown in Fig.3. below.

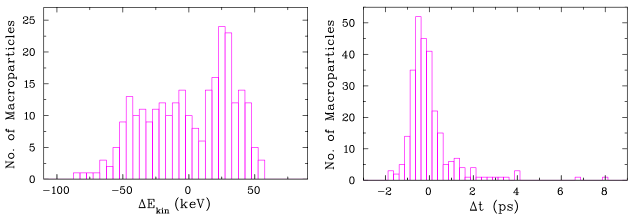

Figure 3. Distributions of particle energy and arrival time at the main linac for an optimized injector setting.

For the next beam time it is envisaged to verify this calculated parameter set hopefully leading to an increased small signal gain and higher peak power of the laser because of the shorter electron bunch. The simulations also showed that even at a quite modest bunch charge of 6 pC space charge effects influence the beam dynamics in our injector.

4 NONISOCHRONOUS RECIRCULATION

The principle of phase focusing is well known and used in circular machines like synchrotrons and microtrons. Recirculating linacs with only a few separate recirculations however, like the S-DALINAC, are usually operated with an isochronous beam transport system and on crest acceleration. The energy spread is then determined by the bunch length and the stability of the rf field in the accelerating cavities. But as pointed out by [7] the choice of an off crest synchronous phase together with a nonisochronous beam transport system offers a welcome longitudinal stability, thus reducing the effects of amplitude and phase jitter in the linac.

We simulated the situation at the S-DALINAC with two recirculations and 3 passes through the linac by simple tracking of the longitudinal phase space. We assumed a relativistic electron beam coming out of the injector uniformly distributed in longitudinal phase space with an energy spread of ± 0.1 % and a bunch length of 2° with respect to the rf-period. The eight cavities of the main linac are assumed to have an uncorrelated field amplitude jitter of 10^{-3} and a phase jitter of ± 1°. The longitudinal phase space distribution was calculated at the exit of the linac after 3 passes as a function of the synchronous phase ϕ_s and the longitudinal dispersion of the recirculating beam transport system. The simulations showed that at a working point of $\phi_s = -9.7°$ and $r_{56} = 5.3° / \%$ we can gain a factor of four in energy spread compared to isochronous recirculation. The remaining energy spread is mainly caused by the injected beam, while the contribution of amplitude and phase jitter in the linac becomes almost negligible. In Fig.4. the tracking calculations are summarized in a two parameter plot of the resulting energy spread. These concepts, highly relevant for improving the beam quality for nuclear physics experiments, could be verified already qualitatively and will be measured quantitatively soon.

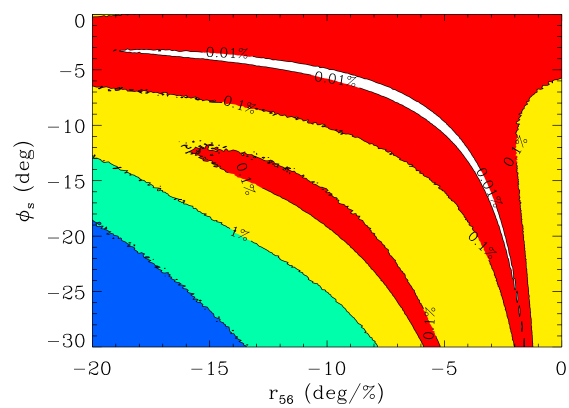

Figure 4 Energy spread after three linac passes as function of the synchronous phase ϕ_s and the r_{56}-matrix element of the recirculating beam transport system.

5 CONCLUSION

The successful operation of the FEL at the S-DALINAC has opened a wide new field of research possibilities. Therefore from now on besides the nuclear and radiation physics activities, both, user oriented experiments with the infrared light from the laser as well as investigations of basic FEL properties will be carried out. Improvement of the accelerator itself is focused on a better understanding and an optimization of its low energy part. To assure that the influence of space charge effects is taken into account correctly, we have already started to investigate the pulsed emission in the gun and electrostatic preacceleration using the time dependent Particle in Cell module of the MAFIA code.

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