

# THE DARMSTADT FEL USING THE SUPERCONDUCTING CW ACCELERATOR S-DALINAC \*

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## Abstract

The free electron laser (FEL) at Darmstadt driven by the superconducting (sc) electron accelerator S-DALINAC performed its first lasing in December 1996. Since then it operated at wavelengths between 6.6 and 7.8  $\mu\text{m}$  corresponding to electron beam energies between 29.6 and 31.5 MeV in two run time periods. By varying the electron beam energy and the gap width of the 80 period hybrid undulator the photon wavelength could be tuned continuously through the range mentioned above, which corresponds to the acceptance of the two dielectric mirrors, forming the 15 m long optical cavity. The potential of sc accelerator technology in providing high quality electron beams had to be fully exploited to ensure sufficient amplification for saturated laser operation despite of the limited peak current (2.7 A) from the S-DALINAC. Therefore a full set of beam diagnostics using transition radiation had to be developed to measure and to maintain all relevant beam parameters like pulse length, energy spread and transverse emittance. However the application of sc accelerator technology enables the special feature of this project, in particular the widely variable macro pulse structure ranging from a few microseconds to true cw operation. Historically the Darmstadt FEL is after Stanford the second installation using a sc driver accelerator and the first FEL providing a cw photon beam.

## 1 Introduction

The first FEL went into operation already in 1977 at Stanford[1] proving the principle of a free electron laser suggested by Madey. In the meantime more than 30 FEL experiments went into operation driven by conventional electron accelerators in the following 20 years. The Darmstadt FEL driven by the S-DALINAC is in fact the second FEL using superconducting accelerator technology and the first FEL in Germany.

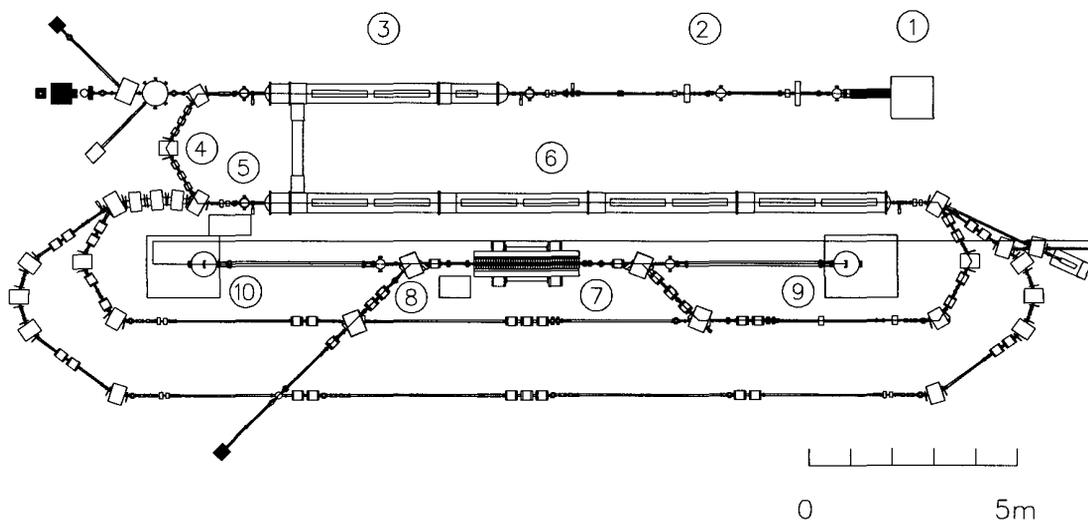
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There is a growing demand for intense photon beams with well defined parameters from different communities like e.g. solid state physics, medicine, material science and biology. Besides synchrotron light sources an FEL provides such photon beams and it is therefore worthwhile to mention that there will be a number of FEL projects using superconducting drivers in the near future (for a recent review see [2]). We believe that the connection of FEL and superconductivity will be very fruitful because of the potential of sc accelerator technology in beam quality and time structure flexibility, leading to desirable photon beam features for the users. The Darmstadt FEL is in this spirit the first FEL delivering a continuous photon beam.

## 2 Commissioning of the FEL

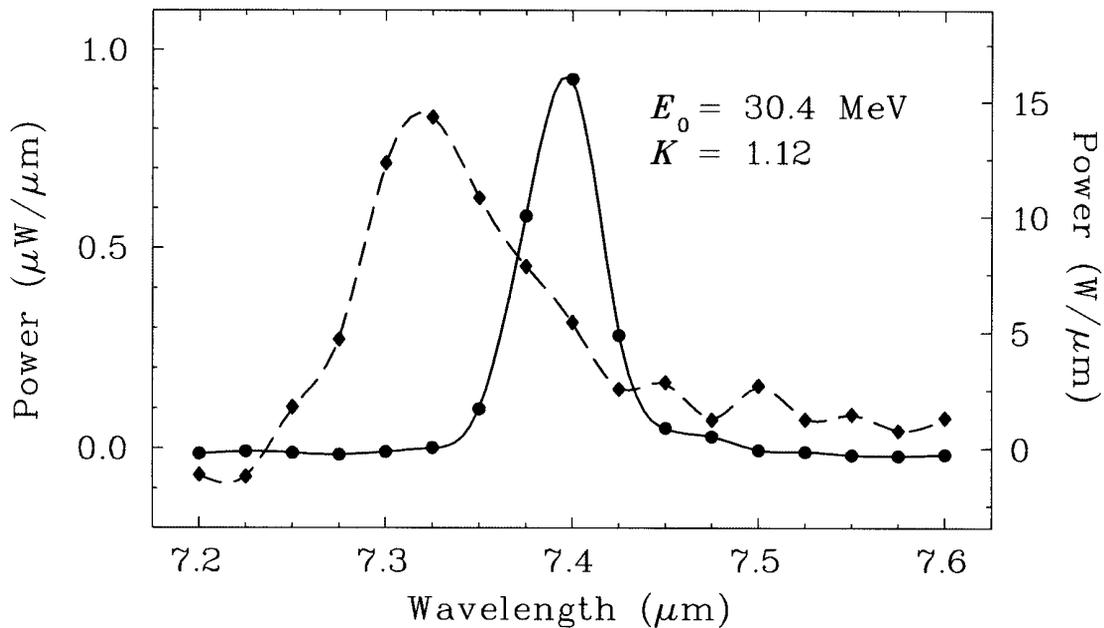
The superconducting Darmstadt linear electron accelerator [3] was originally designed to serve for nuclear physics experiments. A feasibility study [4] during the construction phase of the accelerator however showed that the machine with small modifications only could be used as a driver for an FEL in the near infrared wavelength range. Figure 1 shows the layout of the S-DALINAC and its FEL. The electron beam is generated by a thermionic cathode (1), electrostatically preaccelerated to 250 keV and gets its time structure by a chopper/prebuncher section (2) at room temperature. The beam is then accelerated up to 10 MeV in the superconducting injector linac (3), consisting of a 2-cell ( $\beta=0.85$ ) and a 5-cell ( $\beta=1$ ) capture cavity as well as two 20-cell ( $\beta=1$ ) bulk niobium cavities working at 3 GHz. For injection into the main linac (6), providing an accelerating voltage of up to 40 MV with eight 20-cell cavities, the beam has to pass an 180° arc (4) with a variable longitudinal dispersion of  $\pm 10$  mm/%. After the main linac the beam can



**Figure 1:** Layout of the S-DALINAC and its FEL. Positions (1)–(10) are explained in the Text.

be recirculated twice to reach energies up to 130 MeV for nuclear physics experiments. Alternatively an injection from the first recirculation into the undulator (7) via a magnetic bypass system is possible. The FEL experiment (for a detailed description see [5]) consists of the hybrid undulator with 80 periods formed by cobalt-samarium permanent magnets and vanadium permendur pole pieces and the 15 m long optical cavity formed by two dielectric mirrors (9,10). For beam diagnostics two dedicated stations were set up in front of the main linac (5) and behind the undulator (8) to measure the bunch length using coherent transition radiation (CTR) and the energy spread using optical transition radiation (OTR).

After this brief description of the overall set up of the FEL experiment we would like to focus on two major developments of the last years which led to laser operation, a new arrangement of the optical cavity and a full set of beam diagnostics using transition radiation [6] to determine all longitudinal and transverse beam parameters. The optical cavity is formed by two spherical mirrors characterized by their radii of curvature which determine the shape of the resulting optical mode. For our present optical cavity we chose mirrors with a reflectivity of 99.8 % and a radius of curvature of 8.5 m. This configuration is rather tolerant with respect to tilt errors and has a total loss of 0.9 % only for one round trip of the optical pulse, including diffraction losses. In order to get enough amplification for saturated laser operation a very high beam quality was necessary. The most critical parameter was the limited peak current of 2.7 A, thus it was necessary to measure and optimize the bunch length of 2-3 ps. To generate the high charge electron bunches suitable for lasing operation we started with 1 ns long pulses from the gun at a repetition rate of 10 MHz. These pulses were shaped by a 600 MHz subharmonic chopper/prebuncher system. Detailed beam dynamics studies of the injection linac using a tracking code proposed to benefit from a strong correlation between energy and phase of the beam at the exit of the injector. The following 180° arc could be used to compress the bunch further magnetically with a nonisochronous setting of the magnets. This resulted in a 3 ps long electron bunch with a peak current of > 1.5 A measured with an autocorrelation technique and a Michelson interferometer using the coherent mm-wavelength transition radiation [7]. This sophisticated but inexpensive bunch length monitor turned out to be extremely useful to optimize the injector parameters for short bunches. In a dispersive section behind the main linac we used optical transition radiation to check the energy spread. Once satisfied with the longitudinal phase space we measured the transverse emittance again via OTR by a quadrupole scan in the straight section in front of the bypass to the undulator. The beam parameters obtained were used to calculate the optimal matching conditions at the entrance of the undulator. A beam diagnostics station behind the undulator to measure again bunch length and energy spread allowed a last



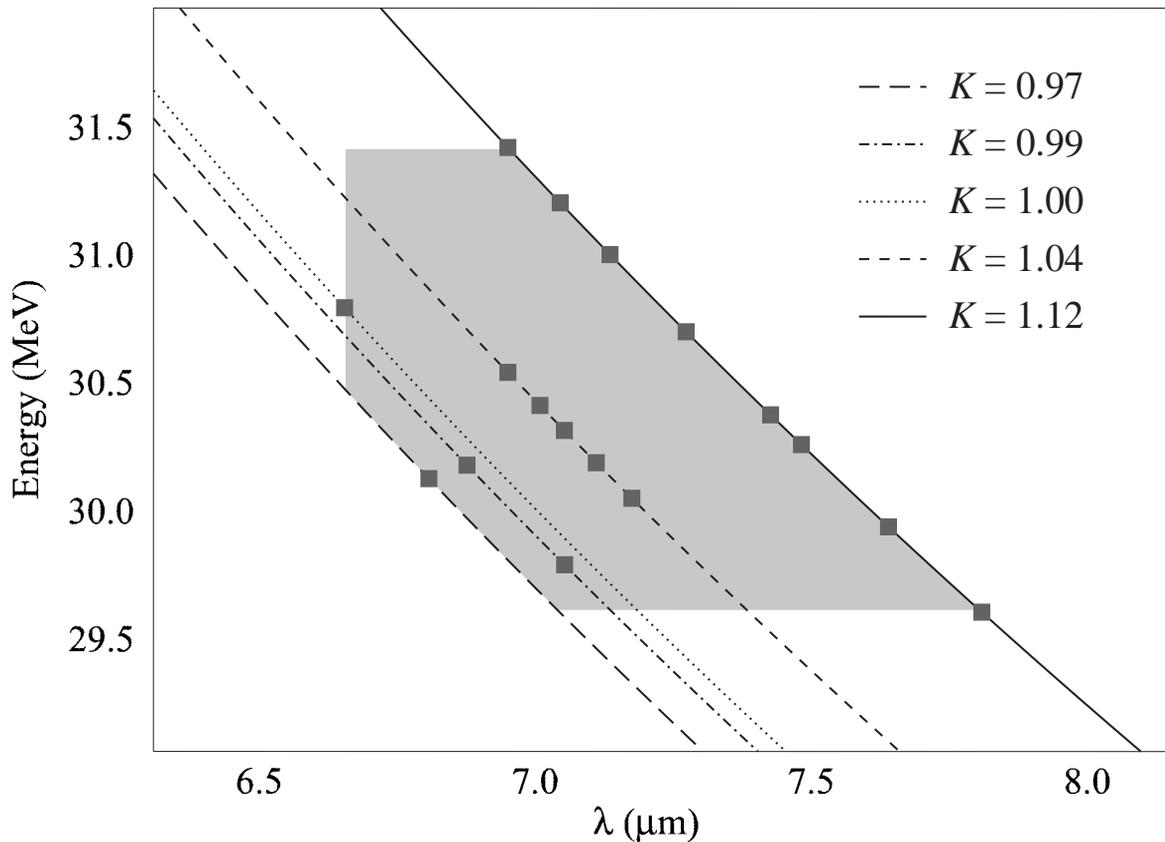
**Figure 2:** Spontaneous emission spectrum (diamonds and left axis) and lasing spectrum (dots and right axis) of the free electron laser.

check of the beam quality through the undulator. Using the described set up procedure for the electron beam we were able to drive the FEL into saturation reliably once the current length of the optical cavity was found. Further optimization could be achieved by observing the spontaneous or the laser spectrum respectively. Figure 2 in this sense can be seen as a summary of this section: With a beam energy of 30.4 MeV and an undulator parameter  $K = 1.12$  corresponding to a laser wavelength  $\lambda_s = \lambda_u / 2\gamma^2 \cdot (1 + K^2/2)$  of  $\lambda_s = 7.4 \mu\text{m}$  we were able to increase the power of the spontaneous emission by a factor of  $10^7$ . The net gain was measured to be 3-5 % after some optimization and the quality factor of the optical cavity was  $Q > 100$ .

### 3 Results

During two beam time periods since the first lasing in December 1996 we gained enough operating experience to measure most of the parameters of the laser. First experiments using the infrared photon beam including ablation studies on different tissues were performed.

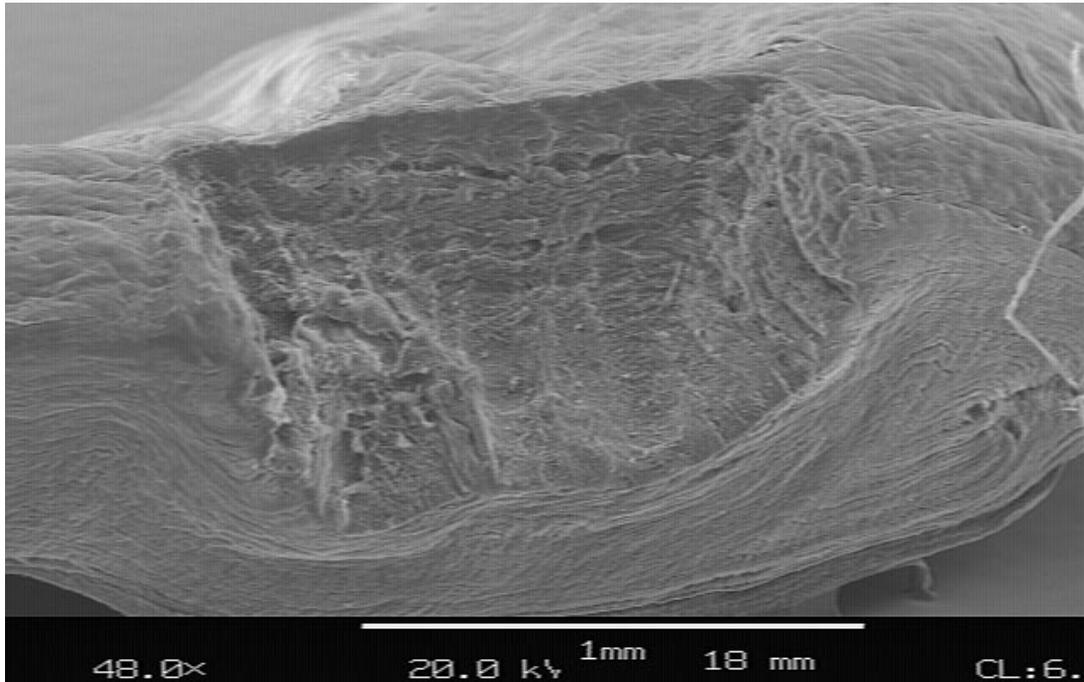
One of the outstanding features of an FEL is its tuneable lasing wavelength by variation of the electron energy or the undulator field. As shown in Fig. 3 we were able to tune the wavelength continuously between 6.5 and 7.8  $\mu\text{m}$  (corresponding to the bandwidth of the dielectric mirror set used) by varying the electron energy by  $\pm 1$  MeV and the undulator gap respectively the peak magnetic field in the undulator. In order to perform experiments



**Figure 3:** Tuneability as a function of  $E_0$  and undulator parameter  $K$ . Each square represents a measured lasing spectrum.

with the laser beam it was necessary to stabilize the length of the optical cavity. This was achieved using a laser interferometric feedback system. The stabilized cavity length was found to be within a gaussian distribution with 150 nm FWHM. Using feedback, the laser operation became stable enough to perform first experiments such as laser ablation of different tissues in cooperation with J. F. Bille and his group from the University of Heidelberg. For these investigations the laser beam was focused by a single  $\text{CaF}_2$  lens with 350 mm focal length. The spot size was measured to be 160  $\mu\text{m}$  corresponding to a power density of some  $10^8 \text{ W/cm}^2$ . As an example Fig. 4 shows a scanning electron microscope image of laser ablation of bovine cornea tissue.

Finally, we were able to demonstrate laser operation in a very wide range of time structures starting from makropulses of a few hundred  $\mu\text{s}$  to true 10 MHz cw operation, which is possible due to the superconducting driver linac. The Darmstadt FEL will not become a dedicated user facility, but in the future we will perform experiments which require the special features of our FEL in parallel with the ongoing nuclear physics program of our lab. In particular it is planned to continue basic studies how to use the laser for medical purposes and to investigate the features of tapered undulators.



**Figure 4:** Scanning electron microscope image of bovine cornea tissue after laser ablation with the FEL. The ablation depth was  $400\ \mu\text{m}$ .

## 4 Acknowledgement

We are very grateful for many stimulating discussions with H. A. Schwettman and T. I. Smith. We like to thank K. Gerstner and T. Tschudi for their help during the development of an accurate absolute length measurement system for the optical cavity.

## 5 Literature

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