Latest of the Superconducting Darmstadt Electron Accelerator S-DALINAC *)

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I. Introduction

Reports on the status of the Superconducting Darmstadt Linear Accelerator S-DALINAC have been given regularly and its design and layout is described in contributions to the preceding workshops on rf superconductivity [1]. Therefore, we will focus on the progress which has been achieved since the most recent report [2] published in the late summer of last year.

In Sect. II we give a short summary of the design parameters and describe the layout of the S-DALINAC. The status is presented and report on first experiments which used the electron beam accelerated by the S-DALINAC is given.

Section III deals with the operational experience and with recent developments. We write about skill at operating cavity tuners and rf control and present data for all presently installed superconducting cavities. In order to handle the two recirculating beam transport systems of the accelerator successfully a system for adjusting the path length had to be installed. We also report on this.

Section IV introduces the Free-Electron Laser (FEL) project at the S-DALINAC. Therefore, we describe the FEL experiment and the necessary accelerator modifications. Experiments just started after the conference yielded to first spontaneous emission.

Finally Sect. V contains a short outlook how we intend to improve the operation of the S-DALINAC and how we proceed with the experimental program.

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II. The Accelerator and its Present Status

The S-DALINAC has gone into operation at the end of 1990 when for the first time an electron beam was recirculated and reaccelerated twice and a maximum energy of 75 MeV was obtained. A photograph of the accelerator taken from the side where the beam is extracted to the experimental area is given in Fig. 1a, whereas the general layout is shown in Fig. 1b.

In the upper right part of Fig. 1 the 270 keV injection can be seen where a dc electron beam produced by the electron gun is electrostatically preaccelerated and chopped as well as bunched in order to get the micro structure needed for acceleration in the rf linac. This section is followed by the superconducting injection linac formed by a short cryomodule, housing the 5-cell capture section, and a standard cryomodule containing two 20-cell acceleration cavities. An isochronous 180° beam transport system allows the beam from the injector to enter the main linac (center of Fig. 1) at energies up to 10 MeV. The superconducting main linac consists of four cryomodules, containing two 20-cell cavities each. The foreground of the photograph shows the two 180° bends of the recirculating beamlines. Their straight sections lead to the two corresponding bends (in the rear of the photograph and left portion of Fig. 1b), where the recirculated beams are reinjected into the main linac via a four magnet chicane. Extraction of the beam to the experimental area is performed in the lower right corner of Fig. 1a. For the FEL project, the present beam transport system of the accelerator is extended by a bypass of the first recirculation shown in the center of the layout. The straight section of this bypass includes the undulator and passes into the optical resonator with its mirror chamber at each end. An optical beam transport system, which can be seen in Fig. 1a just above the optical resonator, extracts the laser beam to an experimental area outside the accelerator hall.

Table 1: Design parameters of the S-DALINAC.

Beam Energy / MeV	$10-130$
Energy Spread / keV	± 13
CW Current / μA	≥ 20
Operating Frequency / MHz	2997
Number of Structures (1 m)	10
Capture Section (0.25 m)	1

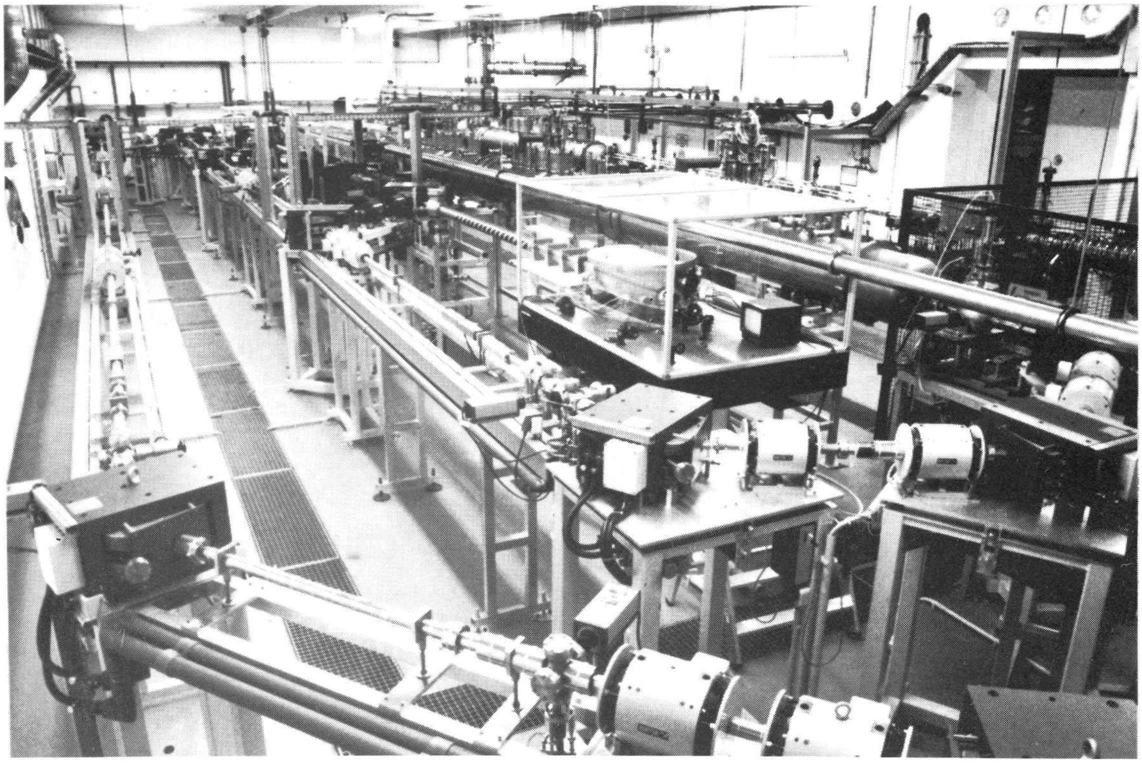

Fig. 1a *View of the main linac, the recirculation beam lines and the FEL.*

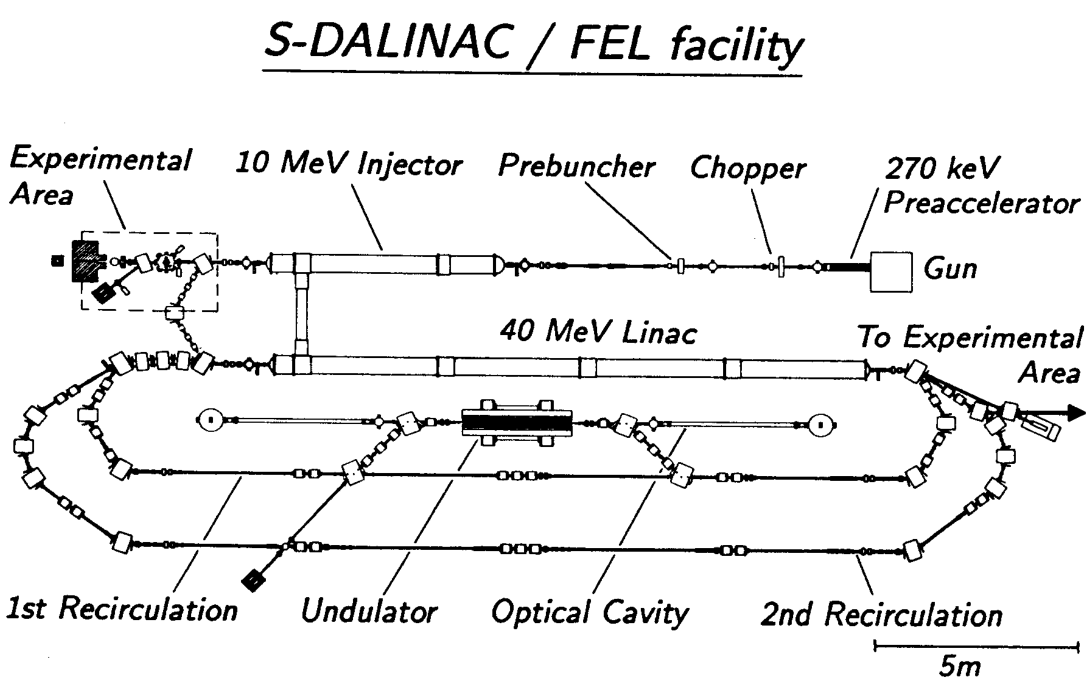

Fig. 1b *Genaral layout of the S-DALINAC.*

The design parameters of the S-DALINAC, which are summarized in Tab. 1 above, result mostly from the requirement, that the accelerator will be mainly used for inelastic electron scattering coincidence experiments. The FEL operation has slightly different requirements which are given in Sect. IV below.

Since its completion at the end of 1990 the accelerator has produced many hours of beam time which could be used during accelerator test runs and also for different nuclear and atomic physics experiments. Table 2 gives a summary of beam utilization listed according to the different experiments, which are the production of channeling radiation at low energies [3], nuclear resonance fluorescence experiments (γ,γ') also at energies below 10 MeV [4], and at high energies (30 - 86 MeV) first elastic (e,e) and inelastic (e,e') electron scattering experiments which were used to calibrate a new spectrometer (QCLAM). The beam time at high energies also includes channeling radiation experiments at 65 and 72.5 MeV which were carried out in a collaboration with the MPI Munich. The maximum energy obtained in an accelerator test run was 104 MeV, where the accelerator was operated with 50% duty factor (limited by the refrigeration power of 100 W) at a pulse duration of about one second. The achieved energy of 104 MeV is not limited by the cavities' field gradient (see Sect. III below) but only by the Helium refrigerator. Single pass operation for FEL experiments at about 30 MeV just starts (see Sect. IV).

Table 2: Beam utilization at the S-DALINAC.

Experiment	Energy / MeV	Current / μA	Time / h
Channeling Radiation	3.0 - 7.7	0.001 - 30	420
Nuclear Resonance Fluorescence	2.5 - 8.5	20 - 40	1150
High Energy Experiments	30 - 86	0.1 - 1	126
Accelerator Test and Development	5.0 - 104	1.0 - 20	1900
			$\Sigma = 3596$

III. Operational Experience and Developments

During many hours of beam time for atomic and nuclear physics experiments, as mentioned above, we gained precious experience in operating mechanical frequency tuners [5] for the superconducting cavities and in operating the microprocessor controlled rf system [6]. All eleven cavities as well as the normalconducting chopper/prebuncher system can now be operated reliably, especially since the magnetostrictive fine and the motor driven coarse tuners are part of the computer controlled rf system. The average tuning range turned out to be 1.5 kHz (fine tuner) and 1 MHz (coarse tuner) respectively, the average resolution is better than 1 Hz / 10 Hz. A more detailed description of the rf system and a comparison with other accelerators systems is given at this workshop [7].

The present installation contains quite different superconducting cavities made from niobium of different purity ranging from RRR = 30 to RRR = 280. Table 3 below list the accoding performance data.

Table 3: Accelerating fields of superconducting cavities measured with electron beam.

# Cells	RRR		E_{acc} / MVm^{-1}
5	30	HTTT	7.0
20	30		3.0
20	100		6.3
20	280		6.5
20	280		7.2
20	280		4.4
20	30		3.6
20	280		4.6
20	100		5.4
20	280		10.1
20	280		>3.4

$\langle E_{acc} \rangle = 5.6$

The average accelerating field measured with electron beam amounts to 5.6 MV/m which is well above the designed accelerating gradient of 5 MV/m. The at first listed 5-cell cavity, made from RRR = 30 niobium, is high temperature titanium treated [8] at the University at Wuppertal. As capture section, this 25 cm long, $\beta = 1$ cavity accelerates the injected 270 keV beam (see above) to an energy of about 1.8 MeV. For the 20-cell cavities the two remaining RRR = 30 cavities yield only 3.3 MV/m, whereas the two still installed RRR = 100 cavities together with six new cavities fabricated from RRR = 280 niobium give an average accelerating gradient of 6 MV/m. To avoid the severe degradation in Q_0 after an always possible intermediate warm up, which was observed for our prototype RRR = 280 cavity as well as for different cavities in other laboratories [9,10], all six high RRR cavities were fired at 750° for several hours in the UHV furnace at Wuppertal prior to installation in the accelerator cryostat. Since at least two warm up periods did not affect the performance of any of the temperature treated RRR = 280 cavities we conclude that also for 3 GHz 20-cell cavities gradients higher than 5 MV/m are possible. Although gradients of 10.1 MV/m measured with electron beam (see Tab. 3) are remarkable, at present such results are rather exceptional. For a reliable operation of superconducting cavities, as mentioned above, one also has to consider a reduction in the accelerating field of at least 10%. Here detuning due to radiation pressure and ponderomotive effects [7] are not taken into account.

In order to recirculate the beam from the main linac and to reaccelerate it another time two requirements have to be fulfilled: i) the energy of the recirculated beam has to be five times the energy of the injector beam because the last magnet of the chicane is identical with the last magnet of the 180° bend for the beam from the injector and ii) the phase of the recirculated beam has to match the phase of the injector beam. First attempts to accelerate the electron beam twice [2] or even to pass the main linac three times, followed by the calculation of the phase slippage which the injector beam undergoes in the first main linac cavities, led to the construction of a system for adjusting the path length of the recirculating beam transport systems. The phase slippage too strongly depends on the injector beam energy which means that keeping the recirculation length unchanged is impossible. Therefore single magnets or groups of beam transport devices are mounted on linear bearings which are driven by computer controlled synchron motors (see Fig. 2). In the first recirculation the first 180° bend is used to change the path length. Here the mid dipole together with the third quadrupole is movable in the direction of the incoming beam, whereas the last dipole together with the fourth quadrupole is

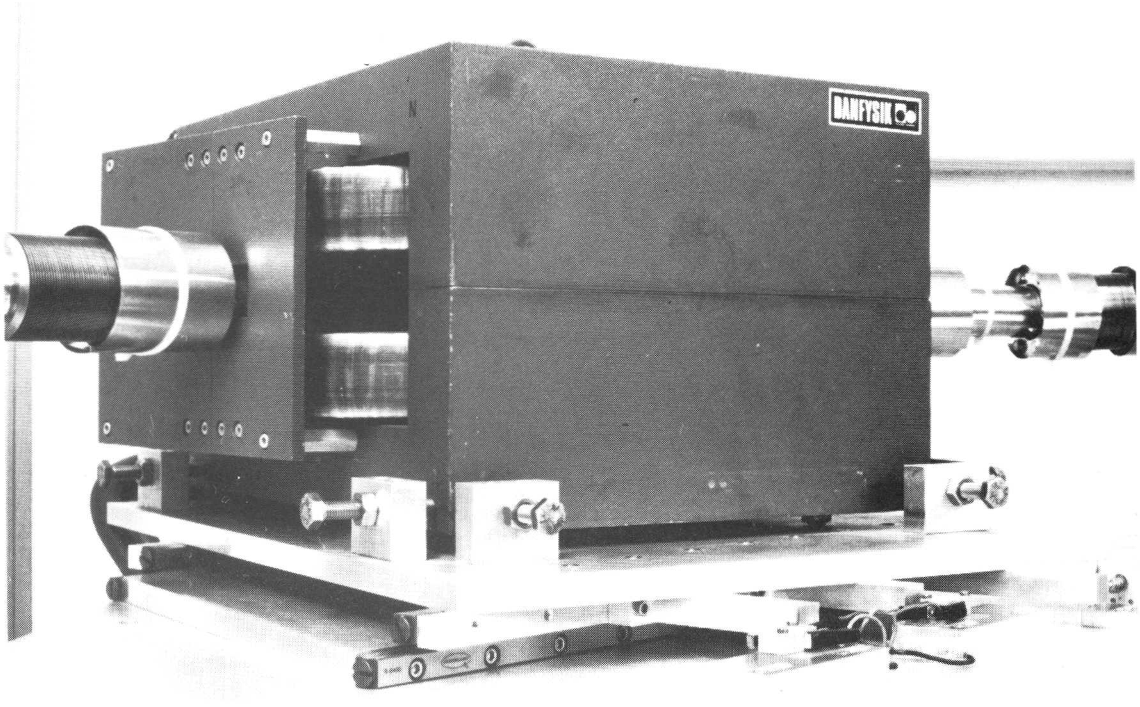

Fig. 2 *View of one movable dipole as it is used for the path length adjustment of the recirculations.*

movable parallel to the straight section of the recirculation (see also the general layout, Fig. 1b). Both groups are synchronously moved under the constraint to have the third and fourth quadrupole on a common axis. For the second recirculation the situation is even simpler. There, in the second bend, the three mid dipoles are used; the first and third dipole are movable in the direction of the incoming and outgoing beam respectively, whereas the second is again movable parallel to the straight section of the recirculation. For both recirculations a change in the path length of more than 180° with respect to the accelerator frequency of 3 GHz is possible. TRANSPORT [11] calculations showed that only a slight change in the setting of the quadrupoles is required. Without a path length adjustment the successful operation of the S-DALINAC as a recirculating machine would not have been possible.

IV. The Free-Electron Laser Project at the S-DALINAC

While completing the accelerator with its recirculations a free-electron laser in the near-infrared region was set up [12,13]. Utilization of the electron beam accelerated in single pass operation yields laser wavelengths between 6 and 2.5 μm corresponding to electron beam energies of 35 to 50 MeV . The modifications of the configuration of the accelerator, as it is used for nuclear physics experiments, which are necessary for the operation of the FEL have been carried out.

A modified high current injector consisting of a pulsed electron gun (I > 27 mA, $\epsilon_n = 1\ \pi \cdot$ mm$\cdot$ mrad) and a subharmonic 600 MHz chopper / prebuncher system has been designed, tested separately and installed at the linac [13]. Every 300^{th} rf bucket can be filled with an electron bunch at a peak current of nearly 3 A. Beside the FEL mode of operation the electron gun can also produce a dc beam for atomic and nuclear physics experiments.

The beam transport system for the FEL has been designed as an isochronous bypass to the straight section of the first recirculation and consists of four 45° bending magnets and eight quadrupole magnets. After its installation at the end of 1990 the system is operative and already used to deliver electron beam for spontaneous emission experiments.

The undulator, which has been built by Spectra Technology Inc., Bellevue, USA, was delivered and installed in January this year. It has been built as a hybrid system with wedged poles and magnets in order to increase the magnetic field on the electron beam axis. The period length amounts to 32 mm and the device consists of 80 central periods with the nominal field amplitude and 2.5 periods of reduced field strength at both ends to compensate for end field effects. At a minimum gap of 15.3 mm a magnetic field amplitude of 0.42 T could be measured thus exceeding the design goal by 5 %. All the magnetic specifications could be fulfilled. The absolute field homogeneity amounts to 0.46 %, the maximum steering errors could be measured to be 50 G·cm and the flatness of the electron trajectory is 120 μm at an electron energy of 50 MeV.

The nearly concentric symmetrical optical cavity, having a length of 15 m and a Rayleigh range of 1.02 m, is installed as well as the optical transfer line which is used to extract the laser beam from the accelerator hall to an optical experiment setup. All cavity components are installed inside the vacuum. The dielectric cavity mirrors on a CaF_2-substrate with a reflectivity of 99.5 % and 99.9 % respectively, will be mounted onto translation stages which are driven by a combination of dc motors and piezoelectric actuators inside two mirror chambers (see again Fig. 1a). The cavity length and mirror alignment will be monitored continuously and will be actively stabilized by means of an interferometer and an alignment laser / quadrant detector system [14].

Table 4: **Parameters of the Darmstadt FEL.**

Electron beam		
	Energy / MeV	35 - 50
	Normalized emittance / πmmmrad	2.2
	Energy spread / keV	±13
	Peak current / A	2.7
	Micropulse length / ps	1.9
	Mode of operation	cw
Undulator magnet		
	Period / cm	3.2
	Gap / mm	15 - 25
	Peak field / kGauss	4.2 - 1.5
	K	1.26 - 0.4
	Number of central periods	80
	Total magnetic length / m	2.72
Optical cavity		
	Length / m	15.0
	Rayleigh range / m	1.02
	Waist diameter (@5 μm) / mm	2.8
	Mirror radius of curvature / m	7.64
FEL-Properties		
	Wavelength / μm	6 - 2.5
	Small signal gain / %	16 - 14
	Peak power / kW	100 - 300
	Pulse length / ps	1.9
	Repetition rate / MHz	10
	Mode of operation	continuous

With the completely installed FEL setup, whose main parameters and aimed properties are summarized in Tab. 4 above, first experiments in detecting spontaneous radiation were carried out. The electron beam could be transported through the undulator at minimum gap with beam enveloppes similiar to TRANSPORT [11] results. In October this year first spontaneous emission could be observed at an electron energy of slightly less than 30 MeV and a beam current of 5 μA during pulses of 4 μs length. Extensive measurements will be carried out within the next weeks.

V. Outlook

Beside further developments, as there are the test of a new rf-coupler prototype and the design of a superconducting 2-cell capture cavity, we are going to proceed in atomic and nuclear physics experiments as well as in FEL experiments. We still intend to optimize the operation aiming for reliability and a better reproducibility. Investigation into accurate Q measurements should help us to localize rf-losses which are presently the limit for the maximum beam energy. In 1992 the remaining low RRR cavities will be replaced by RRR = 280 cavities. Beside this in collaboration with Cornell and Wuppertal the test of a TESLA prototype 9-cell cavity at 3 GHz is planned.

Acknowledgement

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