THE SUPERCONDUCTING 130 MeV CW-ELECTRON ACCELERATOR AT DARMSTADT*)

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I. Introduction and Present Status

Reports on the status of the Superconducting Darmstadt Linear Accelerator (S-DALINAC) have been given regularly. Therefore, we will focus on the progress which has been achieved since the most recent reports [1,2] in late summer last year. Also this paper will not cover the Free-Electron Laser (FEL) project for which the accelerator will serve as a driver. The status of the FEL project is described in a seperate contribution [3].
The design parameters of the S-DALINAC are summarized in Tab.1 below.

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

Most of the figures quoted above like energy, energy spread, and cw operation are requirements resulting from the fact, that the accelerator (besides being a driver for the FEL) will be used for inelastic electron scattering coincidence experiments.

The installation of the accelerator could be completed in January of this year. This is documented by Fig.1, a photograph of the accelerator taken from the side where the beam is extracted to the experimental area. In the upper right part of the picture the low energy injector (at room temperature) consisting of the electron gun, operated at a potential of -270 kV, and a chopper-prebuncher-section can be seen. It is followed by the superconducting injector linac formed by a short cryomodule, housing the 5-cell capture section, and a standard cryomodule containing two 20-cell accelerating cavities. An isochronous beam transport system (180° bend) allows the beam from the injector to enter the main linac (center of Fig.1) which consists of four cryomodules, containing two 20-cell cavities each. The foreground of the photograph is dominated by the two 180° bends of the recirculating beamlines. Their straight sections (left portion of Fig.1) lead to two identical 180° bends (in the rear of the photograph), 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.1. The magnets sitting to the right of the straight section of the first recirculation form the beam handling system of the FEL project. They will be installed during the next shutdown this summer.

In Sect.II we mainly present results from accelerator tests, whereas in Sect.III the performance of the superconducting accelerating cavities is discussed in detail. Developments, which had become necessary to improve the operation of the accelerator, are covered by Sect.IV while Sect.V gives an outlook on our activities planned for the near future.

II. Accelerator Tests and Utilization of Beam

In order to operate the eleven superconducting cavities of the completely installed S-DALINAC, the new microprocessor controlled rf system [4] had to be put into operation. The system was tested succesfully with the injector linac during a running period of several weeks last fall. It turned out, that -with a simple modification- also amplitude and phase of the normal conducting chopper- and prebuncher cavities could be controlled. The entire system (twelve rf channels) became operational in January of this year and has been operated without major problems since then.

In order to recirculate the beam from the main linac and to accelerate it correctly two requirements have to be observed: 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 for reinjection is identical with the last magnet of the 180° bend for the beam from the injector

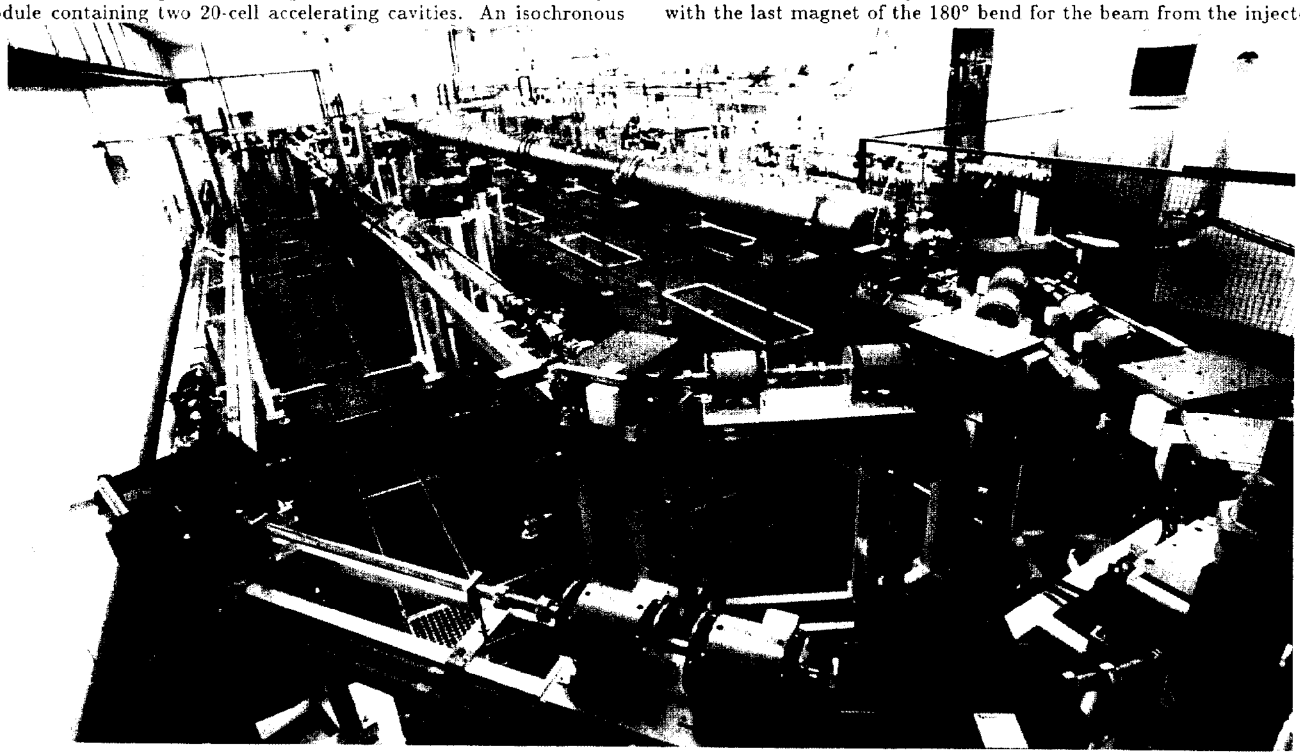

Fig. 1 *View of the S-DALINAC as seen from the extraction side*

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and ii) the phase of the recirculated beam has to match the phase of the beam from the injector. The energies of the injector beam as well as of the recirculated beam are easily determined from settings of the dipole magnets in the respective bends whereas for the measurement of the relative phases rf current monitors in front of and behind the main linac in conjunction with a pulsed beam are used. Beam pulses with a width of 70 ns (the round trip time in the first recirculation amounts to 135 ns) at a repetition rate of 1 kHz allow to distinguish between signals in the rf monitors induced by the injector beam or the recirculated beam respectively.

For reasons, which are explained in Sect.III, the energy gain of the main linac amounted to 16 MeV only. This forced us to operate the injector at 4 MeV in order to obtain the above mentioned energy ratio. A phase lag of 10° of the 20 MeV recirculated beam with respect to the injector beam could be measured at the position of the rf monitor in front of the main linac. Taking into account the not yet completely relativistic beam energies, this means, that the path length of the first recirculation has to be increased by 2 cm. We are presently continuing these measurements and investigating to which extent the chicane will tolerate a deviation from the energy ratio of five to one.

During the course of these measurements, two quadrupoles were installed between the injector linac and the isochronous 180° bend. This doublet together with a diagnostic station installed in the straight beamline behind the injector allows to determine the horizontal and vertical emittance of the injector beam as well as the orientation of the respective transverse phase space ellipses. These beam properties were measured extensively at beam energies between 4 and 6.5 MeV and their dependence on the focussing of the 270 keV beam from the room temperature injection into the superconducting capture section was studied. It turned out, that the normalized emittance is always between 1 and 3 π mm mrad in the horizontal as well as in the vertical direction; no significant dependence on the beam energy was found. Best results were always obtained, when the 270 keV beam was focussed in such a way, that it had a waist at the entrance of the 5-cell capture section.

We also found that the orientation of the phase space ellipses do not agree with the predictions of simulation calculations. The additional quadrupole doublet behind the injector linac is therefore used to optimize the beam transport through the isochronous 180° bend, which by itself is not very tolerant with respect to different orientations of the phase space ellipses.

As usual, the accelerator has not only been used for beam tests but also (mostly during nighttime and over the weekends) for the investigation of channeling radiation [5] and nuclear resonance fluorescence, two experiments installed in the direct beamline behind the injector linac.

III. Performance of the Superconducting Cavities

The present installation contains quite different cavities: most of them have been fabricated from RRR = 30 niobium, some from RRR = 100 material. The cavity made from RRR = 280 niobium is the prototype of a series of six new cavities, which have been fabricated in the meantime. The most important properties of the cavities are summarized in Tab.3 below, where the order is the same as in the accelerator, starting with the capture section (top row) and ending with the last cavity of the main linac (bottom row).

Table 3 Performance of the superconducting cavities

# Cells	RRR	E_{acc} / MVm^{-1}	Energy Gain / MeV	Remarks
5	100	5.5	0.95	New Coarse Tuner
20	30	3.0	1.6	
20	100	6.3	5.7	
20	30	2.4	2.3	
20	30	-	-	$Q_L < 4 \cdot 10^6$
20	30	4.5	4.3	
20	30	2.0	1.9	
20	30	(1.4)	-	} inoperative
20	100	(3.4)	3.4	} Coarse Tuners
20	280	6.6	(2.5)	New Coarse Tuner
20	30	3.6	3.1	H.T. Titanium Treatment

A few remarks have to be added: The fourth cavity from the top and the one in the bottom line were fabricated from RRR = 30 niobium. Recently, they have been postpurified by high temperature titanium treatment [7] by the group of H. Piel at the University at Wuppertal. The first one of these cavities showed such a low Q value immediately after cooldown, that it was impossible to measure its maximum accelerating gradient because of the tremendous dissipation of rf power into the liquid helium. The second cavity (bottom row) achieved a maximum gradient of 3.6 MV/m quite well in agreement with a value of 3.9 MV/m determined in a first test at Wuppertal, in particular since all the accelerating gradients given in Tab.3 have been derived from the energy gain of an accelerated electron beam. The two figures in parenthesis in the third column of Tab.3 indicate, that these two cavities could not be tuned to the correct operating frequency due to inoperative mechanical tuners (the problem of tuners is discussed in Sect.IV below). The average accelerating gradient of the present installation therefore amounts to 3.9 MV/m.

There are several reasons, why the energy gain of the accelerator is not just the sum of the maximum gradients of all the cavities: i) In most cases one has to keep the gradient below its limit by about 10% in order to achieve a stable and reliable operation of the accelerator. ii) Particularly at the front end of the injector linac the phase lag of the low energy beam with respect to the phase velocity of the cavities (β = 1) has a substantial influence on the energy gain obtainable. Corresponding figures, again derived from the energy gain of the beam during a stable long term operation, are therefore quoted seperately in Tab.3. The value of 2.5 MeV for the cavity in the penultimate row has been put into parenthesis, because it is due to a not yet understood Q degradation of this cavity, which occured during an intermediate warmup of the accelerator to 130 K caused by a shutdown of the refrigerator. As can be seen from the figures in the fourth column of Tab.3, the single pass energy of the accelerator presently amounts to 23.5 MeV.

IV. Developments

The common goal of all the developments described below is to obtain cavities, which operate reliably at the design gradient of 5 MV/m. One promising way to achieve this seems to be the postpurification of cavities made from rather low RRR material by high temperature titanium treatment from the outside, a method, which does not require a subsequent chemical polishing of the cavity inside, which would change its operating frequency. Using this method, very good results have been obtaind in laboratory tests at Wuppertal [6] and at Cornell [7].

A second way is to use cavities fabricated from high RRR material. We have ordered six such cavities and a prototype is installed in the accelerator since January. It achieved a gradient of 6.6 MV/m and was operated reliably for about two weeks at gradients between 3.5 and 5 MV/m before the not yet understood degradation of its Q value occured. Since similiar effects have been observed in other laboratories also [8], the possibility cannot be excluded, that cavities made from high RRR material (or postpurified ones) are particularly sensitive to this phenomenon. It is quite obvious, that the cause of the Q degradation has to be determined and a cure has to be found.

Besides the properties of the cavities themselves the performance of the equipment directly associated with the cavities inside the cryostat is extremely important. In the past we had many occasions, when a cavity could not be used, because its mechanical tuner had become inoperative after a very short time of operation. We therefore developed a new mechanical coarse and fine tuner. A prototype of this device mounted around the 5-cell capture section is shown in Fig.2. The tuner consists of a mainframe formed by the two inner plates fixed to each other by four titanium rods. The left cutoff tube of

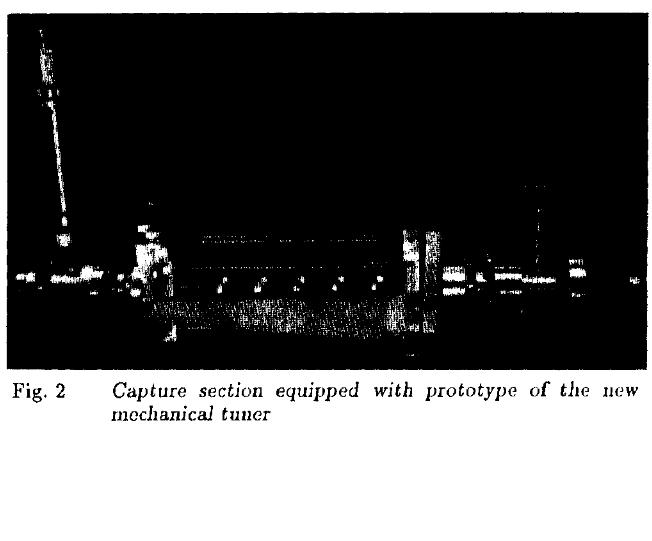

Fig. 2 *Capture section equipped with prototype of the new mechanical tuner*

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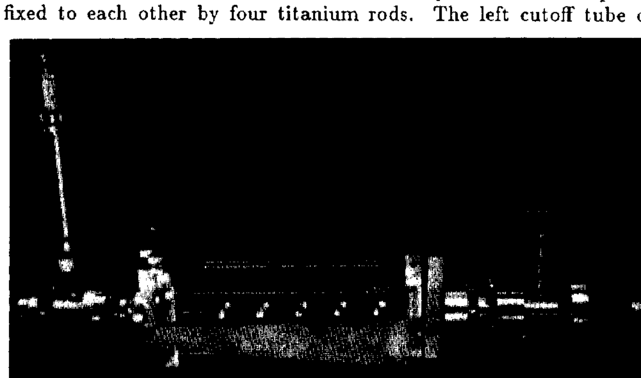

Fig. 2 *Capture section equipped with prototype of the new mechanical tuner*

the cavity (the rf input coupler is already mounted to it in Fig.2) is fixed to the left plate and the cells of the cavity rest on the lower two of the titanium rods. The right cutoff tube of the cavity (the rf output coupler is already attached) is fixed to a cylindrical part, which is pushed against a movable plate by the spring action of the cavity. Two stainless steel cylinders allow angular movements between the plate and the cylindrical piece. The plate in its upper part pushes against a magnetostrictive rod, a design that has been developed some two years ago and has been used succesfully since then. The lower part of the moving plate is connected to a lever on each side, which reduces the spring force of the cavity by a factor of ten. A vertically moving part to the left of the mainframe, guided by two linear ball bearings and actuated by a special screw and nut drive in the center, is connected to the levers and moves them up and down providing a tuning range of 1 MHz, while the magnetostrictive rod allows fine tuning over a range of 4 kHz. The driving shaft of the screw (resting on top of the tuner) connects the device to a motor and reduction gear outside the cryostat via a rotary feedthrough.

In the present installation, the 5-cell capture section and the prototype of the new 20-cell cavities are equipped with these tuners. Both of them operated extremely well since January, even though they had to be used several times per day.

Similiar considerations like in the case of the mechanical tuners led to the development of new rf input- and output couplers. The new design basically consists of a concentric tube inside the cutoff tube of the cavity, forming a coaxial line with an impedance of 21 Ohms, which is shorted at the end pointing away from the cavity. The 50 Ohms 7/8" coaxial input line is connected radially to this device via a $\lambda/4$ impedance transformer at a distance of $\lambda/4$ from the shorted end. Calculations using the computer code URMEL [9] have been performed to predict the external Q of this device as a function of the distance between the open end of the center tube and the iris of the first cell of the cavity. It is expected, that an external Q of $3 \cdot 10^7$ will be obtained with this distance being as comfortable as 80 mm. The calculations indicate also, that the coupling is performed through the TM_{01} mode of the cutoff tube only, which means, that the electron beam sees no transverse electrical field at all while entering or leaving the cavity. The coupler is mechanically very rigid, promising a good reproducibility of the external Q. Two prototypes have been built and are presently investigated at room temperature. Next steps will be the calculation of the coupling to cavity modes other than the fundamental TM_{010} passband and measurements using a variable coupling between the 7/8" input line and the coaxial line of the coupler.

In connection with the fabrication of the six new cavities a new method for the tuning of the field flatness has been developed. Following the ideas of ref.[10], a comparison was made between the Eigenfrequencies of the fundamental passband calculated with URMEL and via a lumped circuit model. Deviations in the center of the passband are due to the fact, that the simple lumped circuit model takes into account the coupling between neighbouring cells only, whereas an analysis of URMEL calculations shows, that in our cavities, which have a cell to cell coupling of 4.2%, coupling to the cells following the direct neigbours still amounts to $7 \cdot 10^{-1}$, decreasing by approximately a factor of 50 from cell to cell when looking at even more distant cells.

We therefore developed a tuning method, which works as follows: In a first step the field profile of the π-mode is determined by a bead pull measurement. Then the most evident deviations from the ideal field profile are tuned to such an extent, that the phase of each cell can be expected to be correct. In a second step the frequencies and field profiles of all 20 modes of the fundamental passband are measured and from these data the complete matrix describing the Eigenvalue problem is calculated. This means, that coupling from each cell to any other cell is taken into account. Then in a numerical procedure the Eigenfrequencies of the individual cells are varied in such a way, that i) the desired frequency for the π-mode and ii) a flat field profile for the π-mode are achieved. The results of this calculation are the necessary corrections for the Eigenfrequency of each cell and mode frequencies as well as field profiles for each step of the correction procedure. This allows a quick check during the final tuning procedure by measuring the mode frequencies any time a cell has been tuned.

The result of this procedure is best demonstated by Fig.3, where in the upper part a field profile (π-mode) of a cavity as it comes out of production is shown. In the center of Fig.3 this profile is shown as it looks after the first tuning step has been performed. The bottom part of the figure shows the final result after the numerical analysis and the final tuning have been performed. It should be noted that always the field profiles of the neighbouring modes $17\pi/20$, $18\pi/20$, and $19\pi/20$ are checked also.

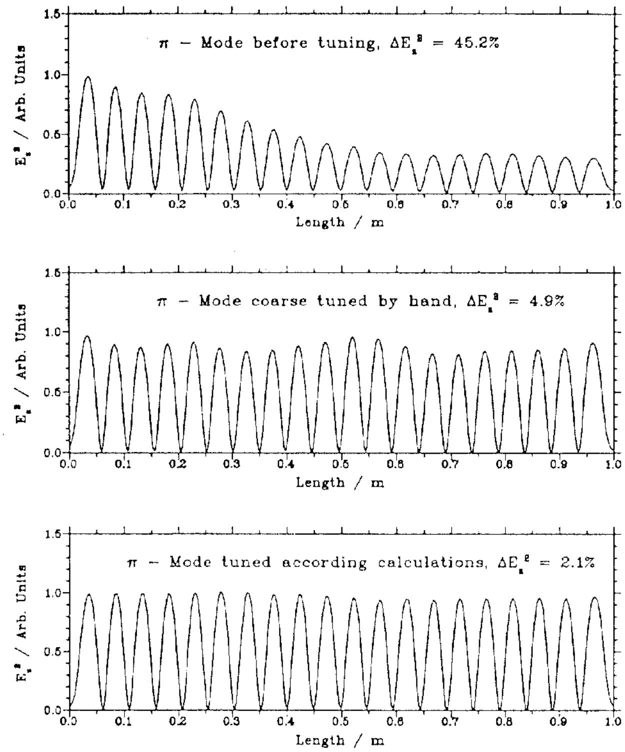

Fig. 3 *Field profiles of the π-mode in a 20-cell cavity before (top), during (middle) and after (bottom) tuning for field flatness*

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The accelerator is the result of a very fruitful collaboration with H. Piel and his group from the physics department of the University at Wuppertal. The still continuing help of H. Heinrichs, R. Röth and J. Pouryamout, particularly in connection with the high temperature titanium treatment of existing cavities is greatfully acknowledged. We are much indebted to H. Lengeler for fruitful discussions and his contionus support. Stimulating discussions with B. Aune, I. Ben-Zvi, J. Delayen, T. Grundey, E. Haebel, A. Mosnier, D. Proch, J. Sekutowicz, A. Schwettman, K. Shepard and T. Weiland have been very helpful in the course of the project. We are very grateful for the tremendous help provided by the technical staff at the S-DALINAC and the mechanical and electronics workshops.

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