# THE DARMSTADT SUPERCONDUCTING LINAC *)

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## Abstract

Since the superconducting injector of the accelerator produced a first beam in August 87 the first half of the main linac (two cryogenic modules containing four superconducting structures) has been installed. Four channels of the newly developed rf control system have been built and successfully tested with the main linac, three defective tuners have however prevented a beam test using all of the installed structures simultaneously. The beam from the injector linac was used routinely for atomic and nuclear physics experiments during the course of this year.

## I. Introduction

Status reports on the 130 MeV superconducting electron accelerator presently under construction at the Nuclear Physics Institute of the Technische Hochschule Darmstadt have been presented when the injector produced its first beam [ 1 ] and after the installation of the first two structures of the main linac [ 2 ]. Therefore only the main design parameters of the accelerator (see Tab. I) are recalled here and a short description of its layout is given in Sect. II.

Table I: Design parameters of the accelerator

| | | |
|---|---|---|
| Beam energy / MeV | | 10 - 130 |
| Energy spread / keV | | ±13 |
| cw current / μA | | ≥ 20 |
| Operating frequency / MHz | | 2997 |
| Number of structures | 1.00 m long | 10 |
| Capture section | 0.25 m long | 1 |

Main emphasis is laid on the experience which could be gained in operating the three superconducting accelerating structures of the injector (see Sect. III) and the first four (out of eight) structures of the main linac (covered in Sect. IV) which were operated using newly developed rf control circuits. Results from acceleration tests and experiments using the beam from the superconducting injector linac are given in Sect. V while Sect. VI contains a summary of the performance of the accelerating structures and their associated equipment (like tuners, couplers, etc.). Finally in Sect. VII we give an outlook on how we will proceed in the completion of the accelerator and on current and future improvements and developments.

*) Work supported by the Deutsche Forschungsgemeinschaft, and by the Bundesministerium für Forschung und Technologie (contract number 06DA454).

## II. Present Status

A schematic layout of the accelerator is shown in Fig. 1. The electron gun is followed by a 250 kV electrostatic preacceleration and the room temperature part of the injection where preformation of the bunches is accomplished. The superconducting injector linac uses a 5-cell capture section (0,25 m long) and two 20-cell accelerating structures (1 m long) to produce a 10 MeV beam. The main linac containing eight 20-cell structures increases the energy by 40 MeV and two beam transport systems each consisting of two isochronous 180 $^{\circ}$ bends (like the injection into the main linac) and a straight section allow for two recirculations of the beam, increasing the energy to a maximum of 130 MeV.

Extraction of the beam to the experimental facilities for electron scattering is indicated in the extreme right portion of Fig. 1. The upper left portion shows two experimental set ups, an apparatus for the investigation of channeling radiation and a facility for nuclear resonance fluorescence measurements (see Sect. V) in the straight beam line behind the injector linac.

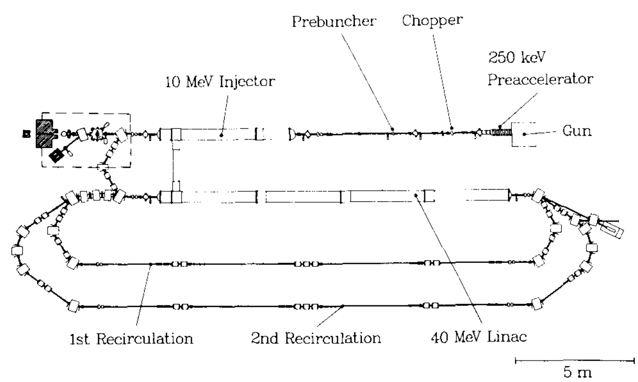


Fig. 1 *Layout of the superconducting 130 MeV accelerator*

The present status of installation is as follows : The room temperature part of the injector is in operation since some two years now. The beam transport systems for the injection and the two recirculations including the beamline and associated vacuum components are installed and ready for use. The superconducting injector linac is fully equipped with accelerating structures and has produced a first beam in August 87. The first two of the four cryogenic modules of the main linac are installed and equipped with four 20-cell structures. An 8 m long beam line containing two observation stations (one behind the second cryogenic module and one right in front of the bends into the recirculations) as well as a quadrupole dublett replaces presently the third and fourth cryogenic module. The photograph of Fig. 2 shows the present configuration. The accelerator is viewed from the extraction side; the beam line most to the

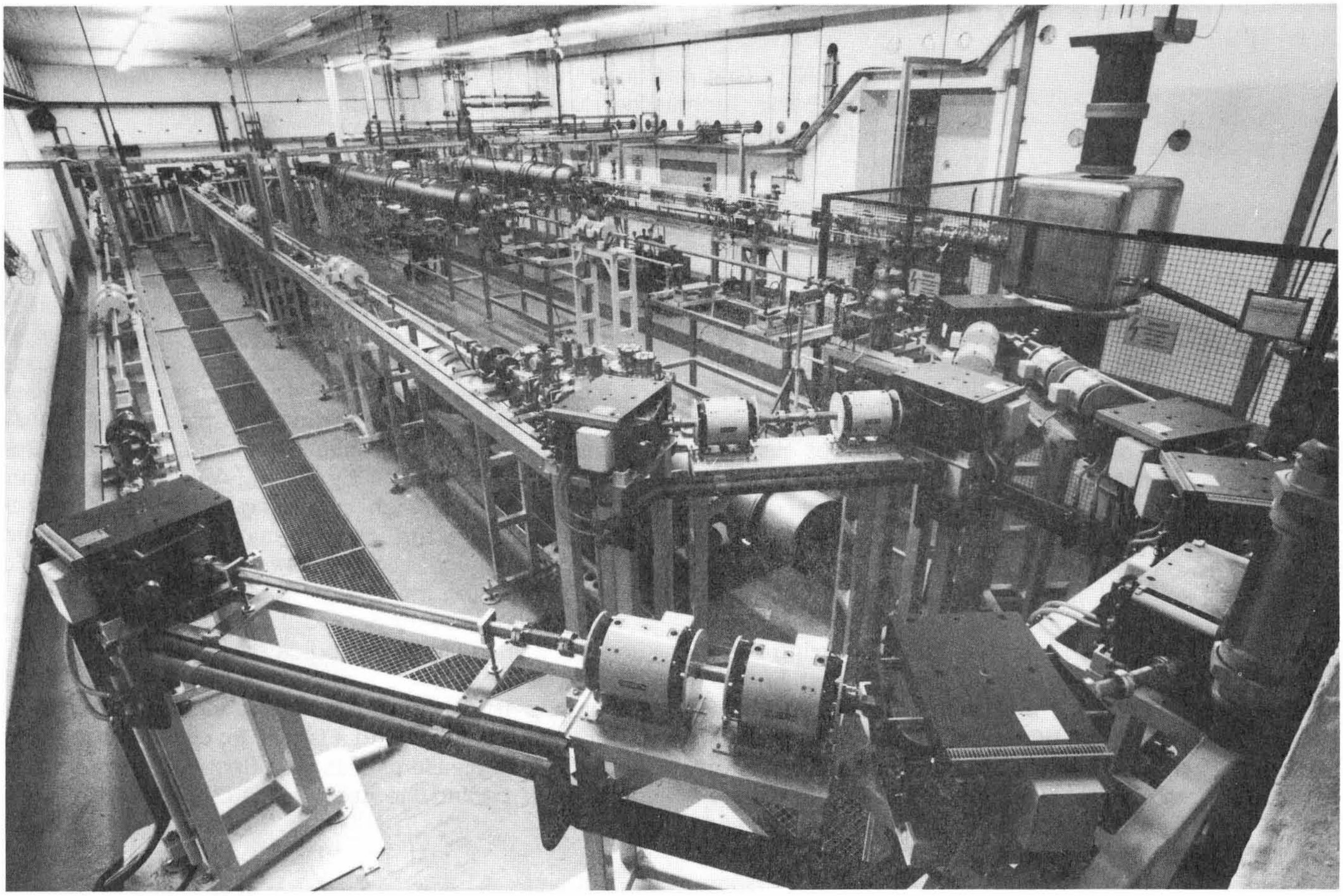

Fig. 2 *View of the accelerator as seen from the extraction side*

right consists of the electron gun (foreground) followed by the room temperature part of the injection and the cryostat of the injector linac. The first two cryogenic modules of the main linac and the 8 m long beam line mentioned above return the beam to the two recirculations (left portion of Fig. 2).

All rf transmitters (twelve klystrons, 500 W each) are installed and four channels of the rf control electronics (described in Sect. IV) have been built and tested after using two prototypes to phaselock the structures of the main linac to these of the injector. The 2 K / 100 W helium refrigerator and cryogenic components have been working very satisfactorily for some 10 000 hours of 2 K operation but some shortcomings of the four stage roots pump (necessary for operation at 2 K) have still prevented a power and final acceptance test.

## III. Injector

The injector linac contains three superconducting structures, a 5-cell capture section which is necessary since the incoming beam has a velocity equal to $\beta = 0.74$ but all accelerating structures have a phase velocity equal to $\beta = 1$, and two "standard" 1 m long 20-cell structures for further acceleration of the beam. Each structure is powered by its own individual klystron, therefore amplitude and phase control are performed at low rf power levels.

Nevertheless, to achieve phaselocked operation of several superconducting accelerating structures turned out to be the most time consuming task in the course of the construction of the accelerator. Careful investigations showed that mechanical vibrations, caused by the heavy machinery of the helium refrigerator (compressor and roots pumps) which are located close to the accelerator, are transmitted through the cryogenic transfer line into the cryostat and cause variations of the resonant frequencies of the superconducting structures. The sensitivity is extremely high, a change in length of 1 µm of a 1 m long 20-cell structure results in a frequency shift of 500 Hz, and thus even a strongly overcoupled structure with a loaded quality factor of $Q_L \approx 3 \cdot 10^7$ will show phase variations of $\pm 0.45^{\circ}$ if its length is oscillating by as little as one nm! The original attempt to control the resonant frequency of the structures mechanically by fast piezoelectric translators failed because of the mechanical resonances of the structures in the frequency range of 200 - 400 Hz, a fact that limits the use of the piezoelectric feed back control circuit to very low frequencies.

Therefore, in order to achieve the design value for the energy spread of the accelerated beam (see Tab. 1), an rf control system had to be developed that keeps phase variations (between any of the structures and the reference oscillator) below $1^{\circ}$ and stabilizes the amplitude of the accelerating field to $1 \cdot 10^{-4}$. A first successful operation of the three structures in the injector linac was obtained using a concept very similar to the one described in [3] except that in our system the amplitude is controlled by a PIN attenuator and phase stabilization is achieved using a combination of a $0^{\circ}$ power divider, two double balanced mixers (DBM), and a $90^{\circ}$ hybrid acting as a power combiner. These modifications were necessary since a complex phasor modulator (CPM), the central control element used in the system of ref. [3], is not available for an operating frequency of 3 GHz. This concept is still used to operate the injector linac which in the meantime has produced not only beam for tests but also about 500 hours of beamtime for experiments (see Sect. V).

## IV. Main Linac and RF Control System

The main linac consists of four cryogenic modules, each of them housing two 1 m long 20-cell accelerating structures. After a first successful period of operation of the superconducting injector in fall of 87 the first module of the main linac was installed in December 87. During the following months the two structures contained in this module were predominantly used for the development and test of our new rf control circuits (see this Sect. below). However, at the end of this testing period an 8 MeV beam from the injector was transported through the injection bend into the main linac and accelerated to 12 MeV by the two structures of the first module.

In June 88 the second cryogenic module, containing another two structures, was added. Simultaneously the development and construction of rf conrol circuits was continued, in the meantime four complete channels have been tested extensively and are working satisfactorily. We were however not able to perform an acceleration test using all of the installed structures since two of the mechanical coarse tuners operating at 2 K failed. Nevertheless another beam test was performed in which a 4.8 MeV beam from the injector was accelerated to 10.2 MeV using the first and third structure of the main linac. In the meantime an attempt to repair the defective tuners was only partially successful and another warm up of the accelerator has become necessary.

The principle of rf control for the structures of the main linac is different from the one still used for the injector linac. It seemed disadvantageous to use this concept for all twelve rf channels required for the operation of the complete accelerator where computer control of the system is a necessity since digitally controlled phase shifters and attenuators are very expensive at 3 GHz.

Thus, we decided to use the principle of ref. [4] where a minimum of rf elements is used and where all control functions are performed at low frequencies. Operation of the system can be deduced from Fig. 3 which shows a simplified block diagram. The accelerating structure (cavity) driven by the klystron is part of a self excited loop. A monitor signal from the structure is downconverted in an rf vector demodulator (bottom left of Fig. 3). The two output signals from the demodulator represent orthogonal components of a vector describing the field of the accelerating structure in the frame of the reference oscillator, thus containing complete information about amplitude and phase. These signals travel through the low frequency (IF) part of the control circuitry (right portion of Fig. 3) before they are upconverted in frequency by an rf vector modulator (top left of Fig. 3). The output of this modulator is amplified by the klystron, closing the self excited loop.

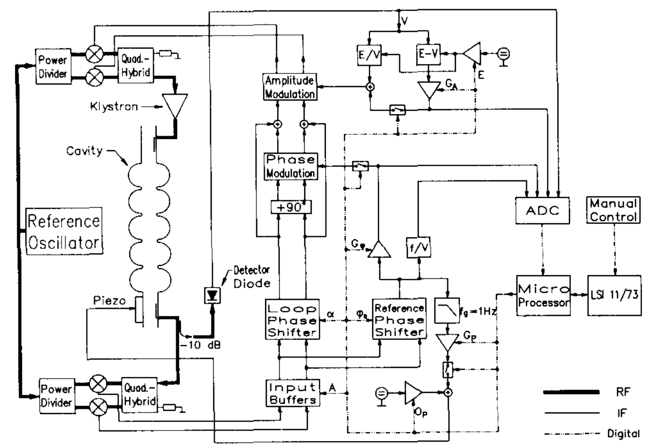


Fig. 3 *Simplified block diagram of the rf control circuit*

In the IF section the signals pass through variable gain input buffer amplifiers, a rotational matrix acting as a loop phase shifter, a phase controller which is a low frequency CPM, and analog multipliers used for amplitude control. The amplitude error signal is derived by comparing an internal reference E (top right of Fig. 3) with a signal obtained from a Schottky-detector diode. In this circuit the limiting function E/V is always active while the actual feedback control with gain $G_A$ is switchable. The phase error signal is obtained by passing the signals from the input buffers through another rotational matrix, the reference phase shifter. It is then amplified ($G_\varphi$) and can be switched to the phase modulator to obtain phase control. The low frequency components of the output from the reference phase shifter are used (bottom right of Fig. 3) to correct slow frequency shifts of the accelerating structures through the piezoelectric translators.

The single board microcomputer used to control the rf channels is a development of our laboratory based on an MC 68020 processor. Through an analog data acquisition (ADC) it is able to keep track of the most important analog signals in the IF section (some of them indicated in Fig. 3). Not shown in Fig. 3 is an analog bus which allows to switch nine analog signals to cable drivers from where they are transmitted to an oscilloscope in the control room.

The consequent separation of microwave and low frequency components in this concept led to a very space and cost effective solution: All rf parts except for a small external 20 dBm amplifier could be integrated onto a single stripline printed circuit board taking only one slot of a NIM crate. By using new LSI circuits also the IF section could be realized on a single board in a VME Bus crate which also contains the microcomputer and the analog bus drivers.

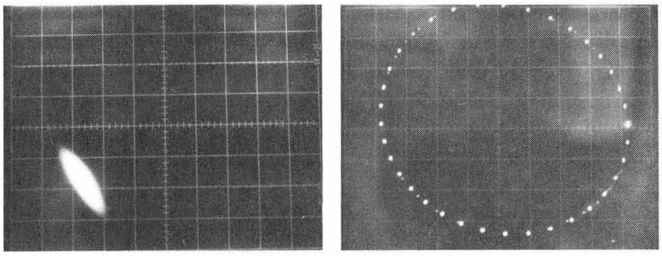

Fig. 4 *Output signals of the rf vector demodulator (left) in polar coordinates. The reference phase is stepped in increments of 10°. Input signals to the rf vector modulator (right) for a single setting of the reference phase, same presentation.*

Four channels of this control circuitry have been tested successfully establishing phaselocked operation between the accelerating structures of the main linac and the injector or a reference oscillator respectively. The left photograph of Fig. 4 shows a polar presentation of the output signals from the rf vector demodulator on an oscilloscope, the dots representing the tip of the rf field vector in the frame of the reference oscillator. For this picture the reference phase has been stepped in increments of 10° at a speed of 30 ms/step. Traces between the 10° steps in some portions of the picture are due to overshoot in the feedback control caused by nonlinearities still present in the rf vector modulator. They are however caused by the stepping of the reference phase and disappear when a steady state is controlled. In that case only a single spot is visible and a change of the reference phase by 1° can be distinguished clearly. For such a steady state condition the right photograph of Fig. 4 shows the output signals from the IF section in the same polar presentation, giving an impression of how much correction in the radial (amplitude control) as well as in the tangential (phase control) direction is needed to keep the field in the structure stable in amplitude and phase.

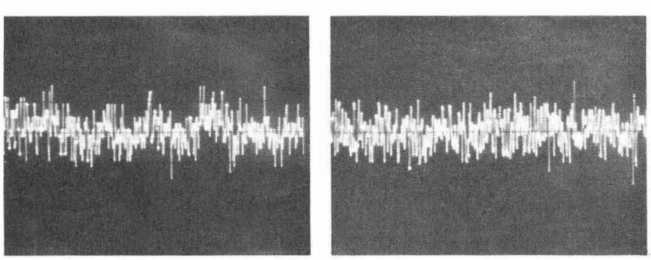

Fig. 5 *Phase error signal in time presentation (left). Sensitivities are 1 mV/div corresponding to 0.2 °/div vertically and 5 ms/div horizontally. AC components of amplitude signal from the Schottky-detector diode (right). Sensitivities are 2 mV/div vertically and 5 ms/div horizontally. The DC level amounts to 1400 mV.*

The two photographs in Fig. 5 display a phase error signal (left) as obtained from an independent DBM and the amplitude signal (right) from the Schottky-detector diode in time representation. The signals show that phase variations amount to less than $\pm 0.3^\circ$ and that the amplitude was controlled to within $\pm\ 3 \cdot 10^{-3}$. It should be noted that most of the "noise" dominating the signal in Fig. 5 is due to pickup from the power supplies of the klystrons at present limiting the performance of the feedback control circuits, a situation which certainly can be improved in the near future.

## V. Beam Tests and Experiments

A first beam test with the injector linac [1] produced a beam of 6.8 MeV from which accelerating fields of 6 MV/m for the capture section (#1), 3.2 MV/m for the first (#2), and 2.5 MV/m for the second (#3) 20-cell structure could be inferred. The limiting effects were electron loading for the two structures (#1 and #3) fabricated from niobium of medium purity (RRR ≈ 100) and a thermal quench for #2 which is made out of reactor grade niobium. Several attempts of helium processing raised the maximum field of #3 to 4.2 MV/m still limited by electron loading but did not affect the fields of #1 and #2. This however raised the maximum beam energy of the injector linac to 8.5 MeV. It seems that further improvement can only be achieved by either replacing or at least cleaning the structures by an ultrasound treatment and rinsing them with ultrapure water.

The first two structures (#4 and #5) of the main linac both fabricated from reactor grade niobium showed after their installation fields of 3 MV/m and 1 MV/m, respectively. Extensive helium processing did not affect these numbers, but #4 showed frequency instabilities which prevented a phaselocked operation at fields in excess of 1 MV/m.

When two prototypes of the new rf control circuits had become operational they were used to control the fields of structures #4 and #5 and to obtain phaselocked operation with the three structures of the injector linac. An 8 MeV beam from the injector was transported around the 180° isochronous bend and through the first module of the main linac. Behind this module a viewscreen and a thick target for bremsstrahl production had been installed. The beam diameter could be kept within a few millimeters in front of and behind the module without any intermediate focusing. A NaJ detector was used to measure bremsstrahl spectra at 0°. An endpoint energy of 8 MeV was obtained from the injector beam with no field in structures #4 and #5. Adding #5 and #4 to the acceleration process increased the endpoint energy to 9.2 and 10 MeV respectively, indicating a field of about 1 MV/m for both structures. As mentioned above the field in structure #4 could be increased if the phase control circuit was switched off, a condition, which of course produces a beam with a huge energy spread.

Despite the rather disappointing fields of structures #4 and #5 they were left installed and the second cryogenic module of the main linac containing structures #6 and #7 was added in June 87. Soon after cool down for the following test period the mechanical tuners of structures # 1, # 2, and # 7 became inoperational. Therefore a beam test was performed using structures # 1 and # 2 of the injector together with # 4 and # 6 of the main linac. The beam was transported down the 8 m long beam line behind the main linac and the first dipole magnet of the recirculation bend was used to deflect it into a faraday cup installed in the extraction of the accelerator (see right portion of Fig. 1). The excitation of the dipole magnet allowed determination of the beam energies from which the accelerating fields of the individual structures (given in Sect. VI) were inferred. Again the quality of the beam was very satisfactory; energy, intensity, and position were stable and its diameter was less than 2 mm before entering the dipole magnet.

During the course of 87 the beam from the superconducting injector was used quite extensively (mostly during night hours) for the two experiments installed at the end of the straight beam line (see Fig. 1, top left). A summary of beam energies, currents, and time used for these experiments is given in Tab. 2.

Table 2: Experimental use of the injector linac

| Experiment | Energy / MeV | Current / µA | Time / h |
|---|---|---|---|
| Channeling Radiation | 3.0 - 7.7 | 0.001 | 140 |
| Nucl. Resonance Fluorescence | 2.5 - 8.5 | 30 | 390 |

The channeling radiation experiment [5] required rather low currents on the order of 1 nA but the best beam quality obtainable since the Si(Li) detector was positioned at 0° behind the crystal target and the electron beam from the accelerator was neither deflected by a beam transport system nor collimated before hitting the target. Measurements of the intensity of the channeling radiation as a function of the tilt angle between the crystal orientation and the beam axis resulted in a distribution with a width of 0.43° in good agreement with the expected acceptance angle of the crystal indicating that there is no significant contribution from the beam divergence.

The nuclear resonance fluorescence experiment is a very important supplement to the electron scattering experiments still performed at Darmstadt using the 26 year old 60 MeV low duty factor accelerator DALINAC. It requires high currents and long running time compared with the channeling radiation experiment because of the small cross sections involved. Most of the time 30 µA were used and without any focusing elements behind the injector linac the spot size at the exit window (about 5 m downstream the beam line) was only 4 - 5 mm in diameter. It should be noted that both experiments take full advantage of the cw beam since they are limited by the counting rates in the respective detectors. A spectrum of channeling radiation with good statistics e.g. can be measured in 4 minutes, whereas it would take some 60 hours with a beam of 0.1 % duty factor.

## VI. Experience with Superconducting Structures

The accelerating structures of the injector linac are installed since August 86, the structures of the main linac # 4 and # 5 since December 87, # 6 and # 7 since June 88; structure # 7 has been replaced by # 7a in September 88 because of a defective rf window at its input coupler. The accelerating fields achieved with these structures are summarized in Tab. 3 where two figures are given for each structure, the first (labeled "exp") is derived from the energy of an accelerated beam, the second (labeled "rf") is derived from rf measurements. All of the fields are very disappointing compared with modern standards but one has to recall the fact that these cavities have been fabricated some 4 years ago, most of them from reactor grade (RRR ≈ 30) niobium. It is apparent that the two samples which are made from niobium of higher purity (RRR ≈ 100) clearly show the highest accelerating fields. We have therefore ordered another two structures which are presently being manufactured from high purity material (RRR ≈ 280) to find out whether our design value of 5 MV/m can nowadays be reached in a "standard" fabrication process.

Table 3: Fields of superconducting structures

| # | Type | Location | RRR | $E_{acc}$ / MV/m (exp) | (rf) |
|---|---|---|---|---|---|
| 1 | 5 cell | Injector | 100 | 5.5 | 6.0 |
| 2 | 20 cell | Injector | 30 | 2.9 | 3.2 |
| 3 | 20 cell | Injector | 100 | 4.4 | 5.4 |
| 4 | 20 cell | Linac | 30 | 2.7 | 4.9 |
| 5 | 20 cell | Linac | 30 | 1.0 | 1.2 |
| 6 | 20 cell | Linac | 30 | 2.7 | 5.3 |
| 7 | 20 cell | Linac | 30 | ? | 1.1 |
| 7a | 20 cell | Linac | 30 | ? | 2.5 |

The discrepancy between the figures derived from beam energies and the ones from rf measurements are mainly due to two reasons: (i) For the rf measurements the structures were powered to a field level as high as possible, just before a quench occured. It is however in general not possible to operate a structure for several hours in a phaselocked condition at this high field level. (ii) The rf measurements were performed on the cavities as they are installed in the accelerator with a strongly overcoupled input which reduces the accuracy of the measurements.

Our operational experience with the equipment directly connected to the cavity can be summarized as follows: After some problems with prototypes the rf windows of the input couplers seem to be rather reliable. The ones installed in the injector have been cycled from 300 K to 2 K and back for several times without problems. The only exception is the window of structure # 7 which developed a leak after its first cool down. The piezoelectric translators used for fine tuning of the structures have a rather poor performance in helium atmosphere at 2 K. The change in length per tuning voltage (40 μm / kV at 300 K) is reduced to 5 μm/kV and their breakdown voltage (1.7 kV in air at 300 K) is reduced to 200 - 300 V. This results in a typical tuning range of only 500 Hz for a 20-cell structure. Therefore we built magnetostrictive devices of the same dimensions as the piezos ($\phi$ = 25 mm and L = 70 mm) and tested them with structures # 1 and # 6. They give a tuning range of 2 kHz and 750 Hz for the respective structures with very modest drive current ($\leq$1 A) through their superconducting coils. Their response is nonlinear and shows a hysteresis but they can be used in the rf control system since their action is limited to very low frequencies anyway because of the mechanical resonances of the structures.

The mechanical coarse tuners become very unreliable after a short period of operation. We have therefore started the development of a different type of mechanical tuner which will be combined with long (L $\geq$ 700 mm) magnetostrictive translators. The range of the mechanical tuner is determined by the accuracy and reliability of the predicted frequency change of a structure when it is installed and cooled down for the first time. From installation of structures # 2 through # 5 we derived a figure of 5.66 MHz ± 0.31 MHz but structures # 6 and # 7 changed their frequencies only by 5.21 MHz and 5.22 MHz respectively and for structure # 7a a change of as little as 4.45 MHz was observed. It should be noted that a temperature cycling from 2 K to 300 K and back leaving the structures mounted inside the cryostat changes the operating frequencies by less than 100 kHz indicating that some irreversible length change of the structures occurs during their first cool down. We therefore need a mechanical coarse tuner with a range of at least 1 MHz capable of giving increments as small as 50 Hz.

## VII. Outlook

Presently the accelerator is warmed up to room temperature and the defective mechanical tuners will be repaired. Despite of the disappointing fields we will leave all of the structures installed and rather run another test period hopefully being able to accelerate a beam by all seven structures and to produce more beam time for experiments behind the injector. Towards the end of this year we will install the third cryogenic module and hope to complete the accelerator (installation of the fourth module) after a test period in spring 89. Averaging the accelerating fields given in Tab. 3 results in a figure of 2.9 MV/m which should enable us to recirculate the beam and deliver it to the experimental area for tests of the new spectrometer (which will be delivered in December 88) and its detector system. As soon as the structures fabricated from the high purity niobium will be ready for installation they will replace those with the lowest accelerating fields. In a longer course we also consider to replace the other structures to finally achieve the design energy of 130 MeV.

Parallel to the accelerator development a study [ 6 ] has been performed investigating the possible operation of a Free Electron Laser (FEL) in a bypass of the first recirculation. The very promising results of this study and its proposed realization [ 7 ] have led to funding of the project just recently.

## Acknowledgement

The accelerator is the result of a very fruitful collaboration with H. Piel and his group from the physics department of the University of Wuppertal. The still continuing help of H. Heinrichs and in particular of J. Pouryamout is gratefully acknowledged. Construction of the accelerator would have been impossible without the enormous efforts of the scientific staff and the many students at our laboratory involved in the project; we therefore feel obliged to V. Aab, K. Alrutz-Ziemssen, D. Flasche, V. Huck, K.D. Hummel, M. Knirsch, F. Lindqvist, W. Lotz, T. Rietdorf, U. Schaaf, S. Simrock, E. Spamer, A. Stiller, O. Titze, W. Voigt, H. Weise, and W. Ziegler. We are much indebted to I. Ben-Zvi for his essential help and to H. Lengeler and E. Haebel for their continuous support by fruitful discussions and help with equipment. Stimulating discussions with B. Aune, J. Delayen, B. Elschner, T. Grundey, D. Proch, K. Shepard and A. Schwettman 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 DALINAC and the mechanical and electronics workshops of the institutions at Wuppertal and Darmstadt.

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