DEVELOPMENT AND TEST OF A NEW CRYOSTAT MODULE FOR THE INJECTOR OF THE S-DALINAC*

T. Kürzeder[#], J. Conrad, F. Hug, N. Pietralla, A. Richter, S. Sievers,
Institut für Kernphysik, TU Darmstadt, Darmstadt, Germany
R.G. Eichhorn, Cornell University, CLASSE, Ithaca, NY 14853, USA

Abstract

The present injector of the superconducting Darmstadt electron linear accelerator S-DALINAC provides an electron beam of up to 10 MeV kinetic energy and up to 60 μA current in continuous wave operation. A new cryostat module has been constructed to replace the actual one in order to provide higher beam energies of up to 14 MeV and currents of up to 250 μA for nuclear resonance fluorescence experiments at the Darmstadt High Intensity Photon Setup (DHIPS). As before two 20-cell superconducting microwave cavities will be operated at an acceleration frequency of 3 GHz in a liquid helium bath at 2 K. For the injector upgrade two new elliptical 20-cell niobium cavities were manufactured and in addition a third spare one. The rf power is transferred to the cavities by newly developed waveguide-transition line and input couplers. The module was assembled for a first test and cooled down to 4 and 2 K outside the accelerator. This test was successful and confirmed the rf properties of the newly designed waveguide power couplers.

INTRODUCTION

The superconducting Darmstadt electron linear accelerator S-DALINAC [1] is a recirculating linac, operating twelve superconducting niobium cavities at a frequency of 2.997 GHz. The main acceleration is done by ten 20 cell elliptical cavities operated in liquid helium at 2 K with a design accelerating gradient of 5 MV/m. These one meter long cavities are paired in five identical cryostat modules. One module is part of the injector cryostat of the S-DALINAC, while the other four are connected and form the main linac. The layout of the machine is shown in Fig. 1. Recently, a new electron source for polarized electrons [2] has been added, while it is still possible to use the thermionic source instead. After a normal conducting chopper/prebuncher section the beam is accelerated in the injector cryostat to energies up to 10 MeV. Behind this section the first experimental area (DHIPS) [3] is located. Alternatively, the beam can be bent into the main linac with two recirculation paths. With an energy gain of 40 MeV per pass the maximum design energy of 130 MeV can be used for experiments in the adjacent hall.

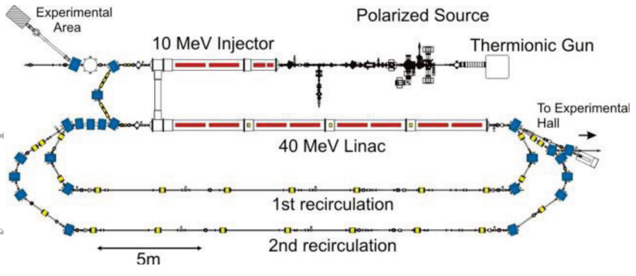

Figure 1: Floor plan of the S-DALINAC.

The injector upgrade project [4] aims at a beam energy and current increase from 10 MeV with 60 μA up to 14 MeV and up to 250 μA to be used at DHIPS. While the main linac will not be upgraded the higher intensities cannot be used for an operation with recirculated beams. The plan was to replace the current standard module in the injector by a new one which is capable to increase the described parameters.

Over the last years an upgraded injector cryostat module has been developed with several new components and special parts. Finally, in 2011 the cryostat vessels were built and the last components were ready for assembly in spring 2012.

CONSTRUCTION OF THE MODULE

The standard S-DALINAC module houses one power coupler for each of the two cavities. These couplers and their coaxial 7/8” (21 mm diameter) transition line are limited to rf power of up to 500 W. New power couplers were developed [5] to guarantee the needed 2000 W rf power. As a result, the coupler had to be based on a waveguide transition line (WR-284, inner cross section $72\times34\ \text{mm}^2$) for which the standard module did not provide sufficient space.

As the new module has to fit spatially into the existing injector cryostat the concept was based on the standard S-DALINAC modules. Nevertheless, the middle section (so called tower section), had to be completely redesigned. As one can see from the Fig. 2 this section has now the shape of a stadium to provide enough space to house and mount the new rectangular waveguide transition lines and power couplers. In Fig. 3 it is shown

Figure 2: Photo of the new cryostat module. The stadium shaped tower section in the middle houses the WR-284 transition lines.

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[#] kuerzeder@ikp.tu-darmstadt.de

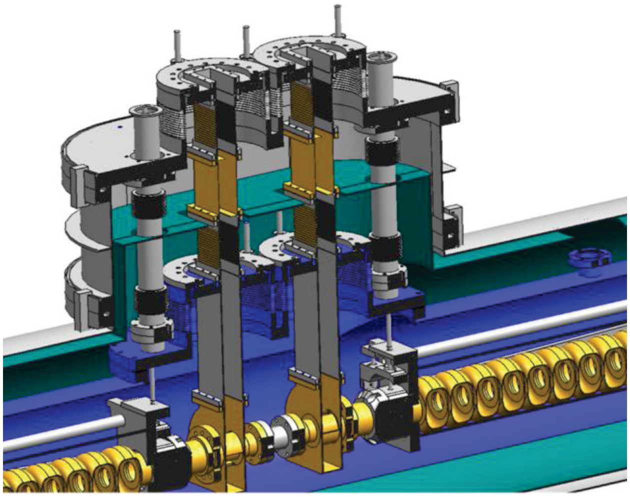

Figure 3: Tower section of the cryostat module showing the waveguide transition lines with its flexible bellows. The helium vessel is shown in blue housing the power couplers and cavities. The LN_2-shield is shown in green.

that each rigid waveguide is connected to the power coupler inside the helium vessel. The necessary flexibility within the space of the insulating vacuum is guaranteed by two rectangular waveguide bellows made of stainless steel and copper plating on the inner side. Additional, circular bellows on top of the helium and vacuum vessel provide even more degrees of freedom during the assembly. To protect the waveguide transition lines from the strong vacuum forces these bellows are supported and fixed in their position after sealing the corresponding vessel.

An insulating vacuum between the helium and the outer vessel is in the range of 10^{-5} mbar, and an 80 K shielding using liquid nitrogen reduces the heat transfer to the cold mass due to convection and heat radiation. In addition to that, helium tank and nitrogen shield are both wrapped with multilayer insulation.

As the design accelerating gradient of the standard cavities is only 5 MV/m it was decided to build three new cavities and to use two of them in the new module. This measure should guarantee that the needed gradients of up to 7 MV/m can be reached with acceptable heat transfer to the liquid helium. More details on the construction of those cavities and other parts of the module can be found in [6].

TESTS AT 4 AND 2 K

The module was developed to be operated as part of the injector cryostat. For a first test we built a special set up, to cool down the module outside the accelerator in order not to disturb its operation and beam times. Normally, the front and the end of the module are connected to the neighbouring cryostats. For the test those ends were wrapped with multilayer insulation but were not shielded by the 80 K interception. In order to create an insulating vacuum in the order of 10^{-3} mbar special end caps were used to seal the vacuum vessel.

As we did not have any possibility to connect and cool down the module with our helium refrigerator it was filled from a 250 l dewar. In addition, the filling of the nitrogen shielding had to be done manually. Nevertheless we were able to use one of the pump units of the S-DALINAC to reduce the pressure inside the helium space to 35 mbar in order to achieve the 2 K operation temperature.

Frequency Shift

During the whole cool down it was necessary to verify the shift in the resonance frequency, especially of the π-mode which is used for acceleration of the beam. Therefore the frequencies of the π-mode and the 19/20 π-mode and the temperature were recorded during the whole process. Figure 4 shows the shift to higher frequencies of the π- and its neighbouring 19/20 π-mode when cooling down the cryostat module. It was found, that the frequency increases by about 4.5 MHz for an evacuated cavity cooled down from 300 to 2 K. This means when tuning a vented cavity at room temperature one has to aim for a frequency 5.4 MHz below the operation frequency.

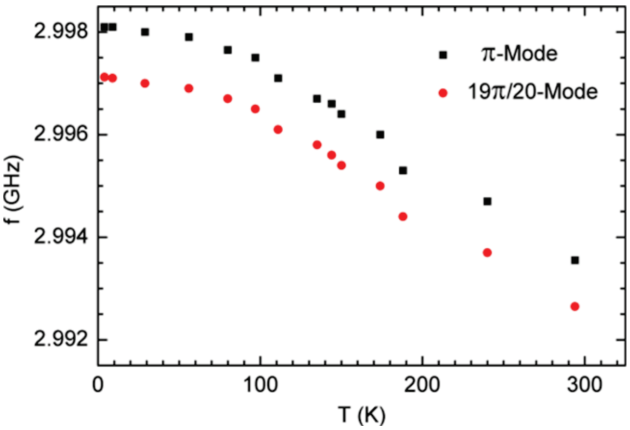

Figure 4: Shift of the resonance frequencies of the π- and 19/20 π-mode due to change in temperature.

External Quality Factor

The measurements of the external quality factor of the input and output couplers were done once the cavity and couplers were completely covered with liquid helium at 4 K. A vector network analyzer was used to measure the complete scattering matrix (S_{11}, S_{12}, S_{21}, S_{22}). For an isolated resonance of a cavity with two couplers the elements of the scattering matrix are described by

$$S_{ji} = \delta_{ji} + i\frac{\sqrt{\Gamma_j \Gamma_i}}{f - f_0 - i\,\Gamma/2} \qquad (1)$$

$$\text{with } \Gamma = \Gamma_1 + \Gamma_2 + \Gamma_\Omega .$$

Thereby f_0 is the resonance frequency, Γ_1, Γ_2 and Γ_Ω are the partial widths which describe the loss of energy due to two couplers to the cavity and ohmic losses, respectively.

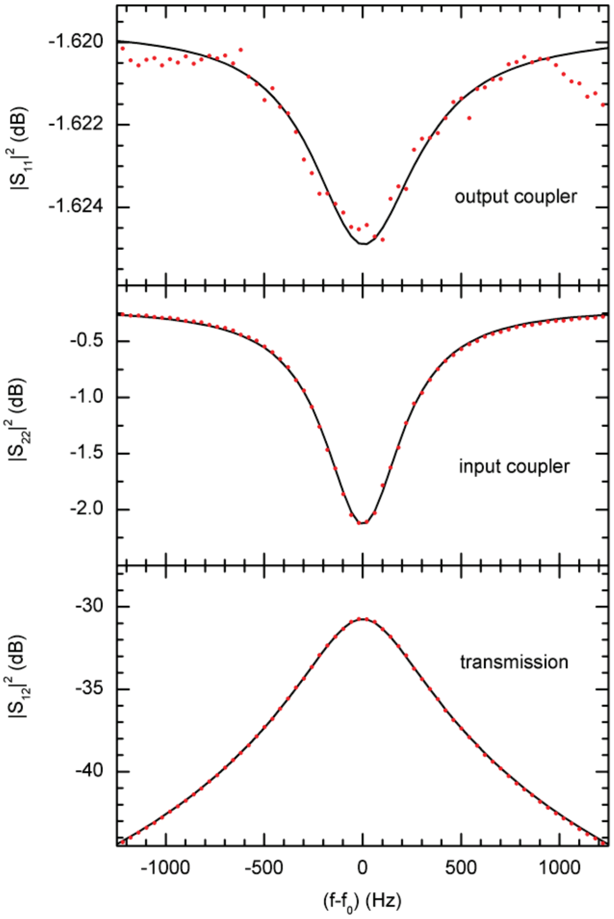

Figure 5: Frequency spectra in reflection and transmission measured on a cavity at 4 K in the new cryostat module. Fits of eq. (1) (black lines) to the measured data (red dots) of the scattering matrix elements are shown.

Those parameters have been found from a fit to the measured data (Fig. 5). The quality factor is related by

$$Q_{ext,i} = \frac{\Gamma_i}{f_0} \tag{2}$$

to the corresponding partial width. The quality factor of the input coupler was found to be $6.25 \cdot 10^6$ with a relative error of ±1.5%. This value is very close to the quality factor of $5 \cdot 10^6$ for which the coupler was designed [5] in order to accelerate an electron beam of 100-250 µA. For the output coupler, which has not changed in design, an external quality factor of $1.55 \cdot 10^{10}$ with a relative error of ±15% was found, showing also a good agreement with the design value. In operation, the output coupler is used to provide a probe signal for the rf control system of the S-DALINAC. Both quality factors were also measured at 2 K which was demanding as the pumping units required to do so caused heavy vibrations. Extensive averaging led to similar results as at 4 K.

Cryogenic Losses

The static heat transfer into the liquid helium (with no rf applied) was estimated by determination of the rate by which the helium evaporated. With knowledge of the density and evaporation enthalpy of helium at a given temperature one can calculate the thermal power loss by measuring the evaporated volume per time:

$$P = \Delta H(T) \cdot \rho(T) \cdot \frac{\Delta V}{\Delta t} \tag{3}$$

At temperatures of 2 and 4 K the thermal losses were determined to lie between 5 and 6 W. This is in good agreement with the estimates which were made during the design phase of this project. We are optimistic that after implementation in the accelerator the static losses will be 1 or 2 W lower, because of the better insulation compared to the test setup. Anyway, with 4 W static losses of the actual S-DALINAC cryostat modules an addition of 1-2 W by exchanging the injector module to the overall static losses would not have a big impact as the cryo-plant of the S-DALINAC provides 100-120 W cooling power at 2 K.

OUTLOOK

Currently, the cryostat module is prepared to be swapped into the injector section of the S-DALINAC which is scheduled for the next shutdown of the accelerator. Once in place, the removed injector module will be used as a spare component for the main accelerator, as the cryostat modules are identical. This will reduce maintenance periods in the future.

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