INJECTOR UPGRADE FOR THE SUPERCONDUCTING ELECTRON ACCELERATOR S-DALINAC

T. Kuerzeder[1], J. Conrad[1], R. Eichhorn[1], J.D. Fuerst[3], B. Bravo Garcia[1], H.-D. Graef[1], C. Liebig[1], W.F.O. Mueller[2], A. Richter[1], F. Schlander[1], S. Sievers[1], and T. Weiland[2]

[1]Institut für Kernphysik, TU Darmstadt
Darmstadt, 64289, Germany

[2]Institut für Theorie Elektromagnetischer Felder, TU Darmstadt
Darmstadt, 64289, Germany

[3]Argonne National Laboratory
Argonne, Illinois, 60439, USA

ABSTRACT

Since 1991 the superconducting Darmstadt linear accelerator S-DALINAC provides an electron beam of up to 130 MeV for nuclear and astrophysical experiments. The accelerator consists of an injector and four main linac cryostats, where the superconducting cavities are operated in a liquid helium bath at 2 K. Currently, the injector delivers beams of up to 10 MeV with a current of up to 60 µA. The upgrade aims to increase both parameters, the energy to 14 MeV and the current to 150 µA. Due to an increase in the required RF power to 2 kW the old coaxial RF input couplers, being designed for a maximum power of 500 W, have to be replaced by new waveguide couplers. Consequently, modifications to the cryostat-module had become necessary. We review the design principles, the necessary changes in RF components (i.e. couplers, transition line, stub tuner), the production of the SRF cavities and the new magnetic shielding. A report on the status will be given.

KEYWORDS: Cryostat design, SRF cavity, power couplers, RF
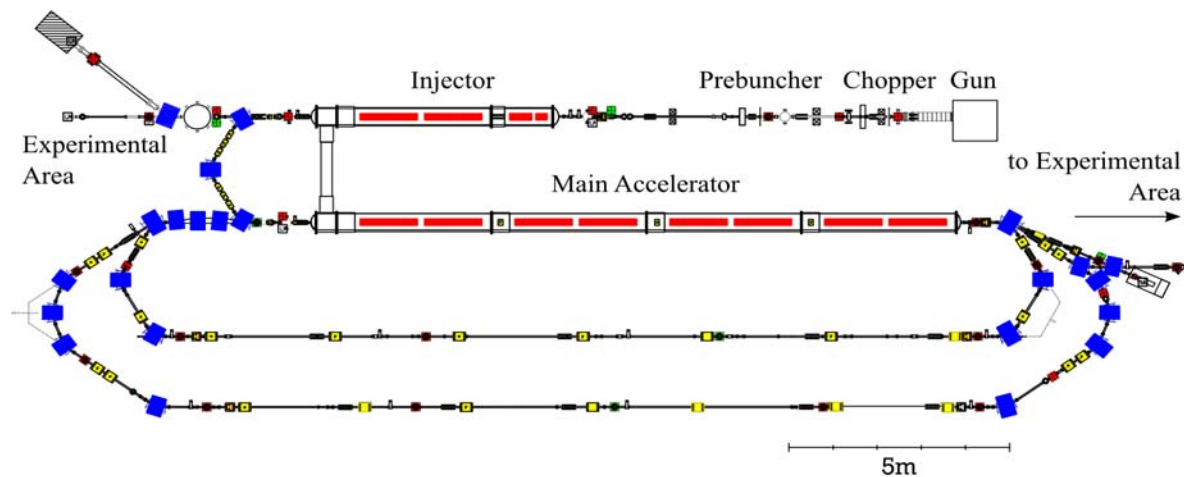
FIGURE 1. Floor plan of the S-DALINAC. The injector linac consists of one cryo-module with two 20 cell cavities, while the main linac uses 4 of those modules. The accelerating voltage of the main linac can accelerate the beam three times, when the beam is brought back to its entrance via two recirculation paths.

INTRODUCTION

The superconducting Darmstadt electron linear accelerator S-DALINAC [1] is a recirculating linac, using twelve superconducting niobium cavities at a frequency of 2.9975 GHz. It was first put into operation in 1987. Running at a temperature of 2 K the main acceleration is done by ten 20 cell elliptical cavities with a design accelerating gradient of 5 MV/m. The first pair of those cavities is used in the injector section of the machine. Behind this section, the beam can be used in the first experimental area where typically nuclear physics experiments at a maximum energy of 10 MeV are located. Alternatively, the beam can be bent into the main linac. With its two recirculations and an energy gain of 40 MeV per pass the maximum design energy of the S-DALINAC is 130 MeV. Electron beams with energies between 15 and 130 MeV can be used for several experiments in the adjacent experimental hall. The layout of the machine without that hall is shown in FIGURE 1.

The S-DALINAC uses cryostat-modules with two cavities per module. Each cavity has an RF input coupler, which is capable of a maximum power of 500 W. Assuming a 5 MV/m gradient and some RF overhead power needed for the control of the cavities the beam current is limited to 60 µA for the injector and 20 µA for the main linac (when recirculating twice), which might be higher for lower beam energies.

NEW POWER COUPLER

The first step to reach the envisaged beam energies and current was to design a new RF power coupler, which is capable of 2 kW instead of the actual 500 W coax-to-coax coupler [2]. Consequently, a waveguide-to-coax coupler design [3] was chosen. Like the old couplers, the transverse fields on the beam axis had to be minimized. This can be achieved by coupling to an intermediate coupling tube, which further on couples to the cavity. Moreover, two diaphragms reduce even more the excitations of transverse electromagnetic fields inside the beam tube, now to less than -40 dB. This is essential at low beam energies especially at the injector linac.
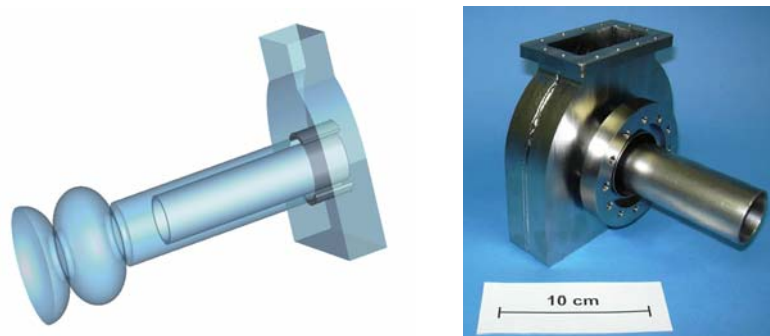
FIGURE 2. The design and the finally fabricated waveguide-to-coax coupler for the injector upgrade. The RF enters via the waveguide part and passes the diaphragms before it couples to the intermediate coupling tube, which enters the cavity via its cut-off tube (as indicated on the left).
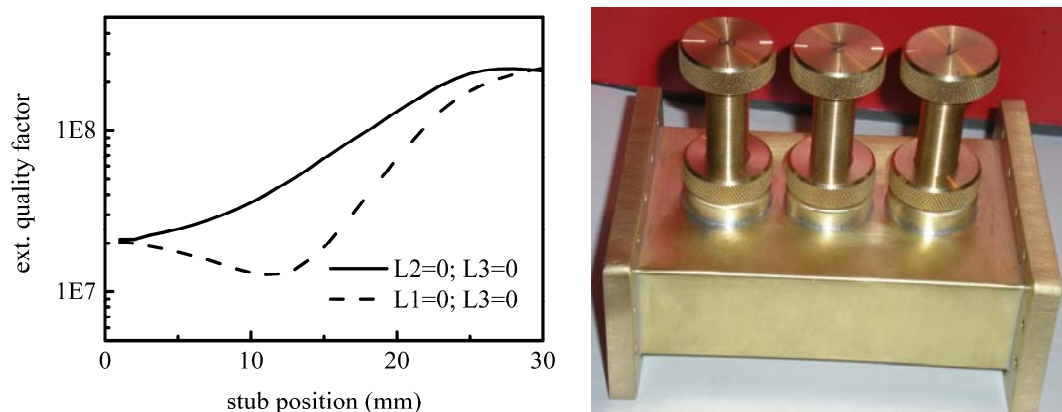
FIGURE 3. Left: External quality factor as a function of different stub positions, measured at a superconducting cavity installed in the main linac. In this example 2 stubs were driven out (position 0) while the third was continuously moved into the waveguide. Right: Picture of a prototype triple stub tuner for a WR-284 waveguide.

For clarification, FIGURE 2 shows how the coupling from waveguide to coax was realized. The cut-off tube and the first cell of a S-DALINAC cavity is also shown. The coupler was made out of bulk niobium, the fabrication including the EB-welding was done by FZ Juelich. The removal of the damage layer and the surface treatment will be the same as described in the SRF cavities section, even so less critical. As the coupler is a non-resonant device, the fields are much lower and thus the surface quality requirements are less stringent. This is also true for the coupler shape, as the transmission parameters depend only weakly on the apertures. Removing 100 μm will not have a measurable effect.

Stub Tuner

The length of the coax tube of the coupler is adjusted to provide an external quality factor Q_{ex} of $5 \cdot 10^6$ which is the optimum for accelerator operation at beam currents from 150 to 250 μA. To change the external Q for different modes of operation, a triple stub tuner has been designed. After simulations and offline tests, a first prototype has been tested on a superconducting cavity in our existing linac. FIGURE 3 shows how the stub tuner is able to change the Q_{ex} of the system. As expected, it was possible to decrease and increase the external quality factor. There are several different combinations in stub positions resulting in the same quality factor, but frequency pulling can be minimized by an optimal combination. With the relatively low quality factor of the new power coupler,

without stub tuner, one now is still able to achieve higher Q_{ex} being important for small beam currents or for diagnostic reasons.


CRYOSTAT DESIGN

In order to replace the existing cryostat module without changing the whole accelerator it was decided to keep the old module design, namely the length and the diameter of the cryo-vessel. The changes required to house the modified RF feedthroughs are in the so-called tower section: The new RF power couplers need a WR-284 waveguide transition (cross section 72×34 mm^2) instead of the smaller 21 mm circular transition line of the current coax-to-coax couplers.

In FIGURE 4, a simplified 3-D view of the design is shown, hiding some smaller lines for liquid nitrogen, helium and some other details like supports for the cavities, the magnetic shielding and the MLI. Mounted on a movable carriage the cavities together with their frequency tuners as well as their input and output RF couplers are inserted into the helium vessel from the side. The cavities are operated at 2 K so the internal pressure of the helium vessel is 35 mbar during operation, while the beam line vacuum is about 10^{-8} mbar. Between the helium vessel and the outer housing, a cylinder of aluminum is located as a thermal shield. It is cooled down to 77 K by liquid nitrogen. Together with the insulating vacuum of 10^{-5} mbar in this section and some 20 layers of MLI, a minimum heat transfer is ensured.

The challenge of the new design was to accommodate the already mentioned bigger rectangular waveguide transition line, while keeping all sections leak tight and still mountable. Also, besides the changes in geometry, the vacuum forces on the new couplers had to be compensated. While the old coax-to-coax coupler is supported by a shell of stainless steel, the connection between the new coupler and the transition line had to be
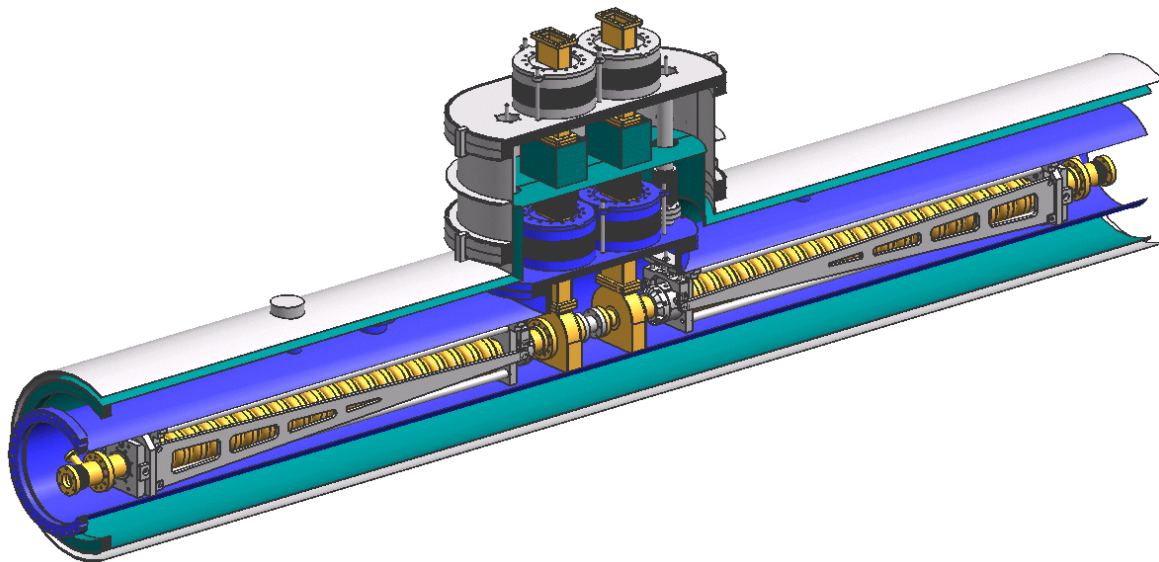
FIGURE 4. 3-D Design of the new injector module. Inside the helium vessel RF input and output couplers, together with the 20 cell cavities and their frequency tuners are shown. These inner parts are surrounded by a thermal shielding, cooled with liquid nitrogen, made out of aluminum. The outer pressure vessel will be stainless. In the center, the waveguides and their transitions through the different vacuum/ pressure stages in the so-called tower section are shown. For a better view the carriage which supports the tuners, the beam line, several lines for nitrogen and helium, the magnetic shielding and the MLI are not shown.

designed force-free.
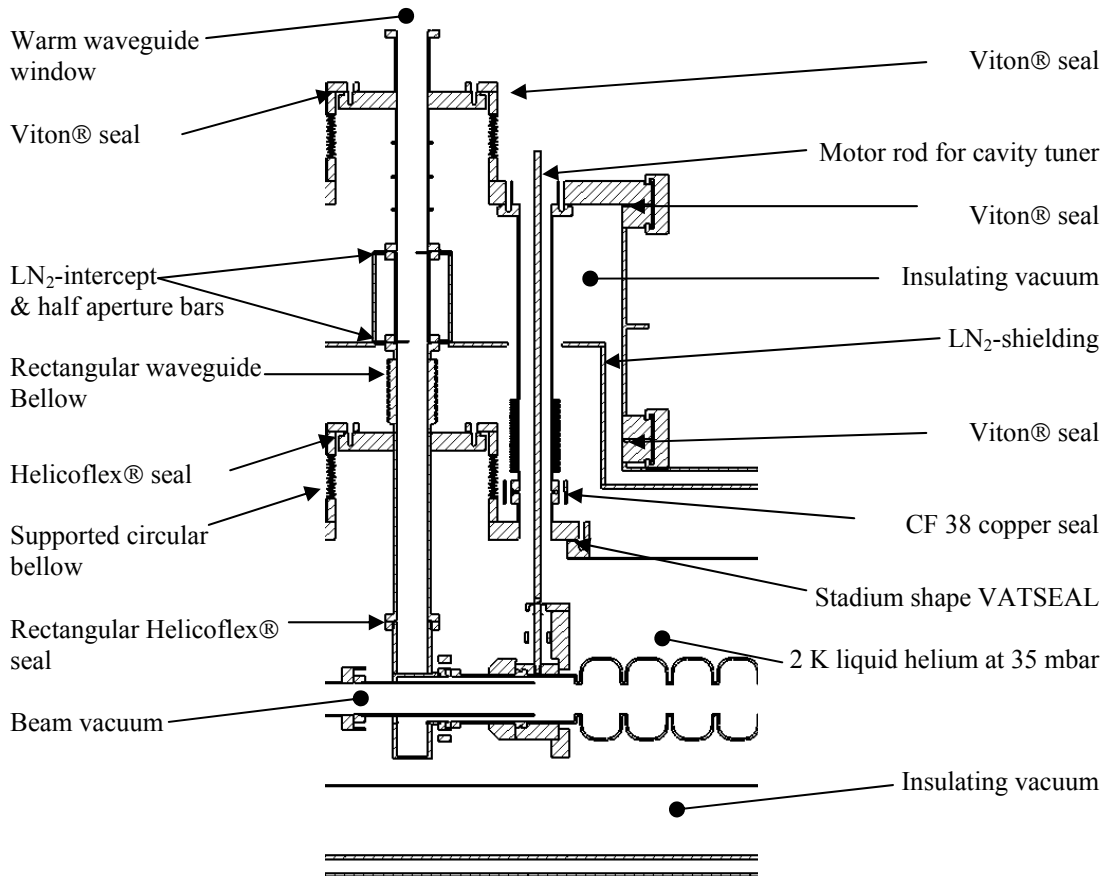
FIGURE 5. 2-D cross-section of the tower section. The waveguide transition line is shown from the helium vessel at 2 K to ambient (at the top flange). The different pressure stages and the position of seals and other elements are shown.

To ensure this, the waveguide connected to the coupler has a circular flange to attach to an adequate counterpart of the helium vessel. This counterpart holds a bellow to compensate small uncertainties in height and angle. For offsets in horizontal directions oversized holes are planned. By fixing this bellow in its position during assembling, forces on the power coupler can be reduced while pumping the vacuum. The fixing will be done by 3 threaded rods for each bellow.

Outside the helium vessel, a rectangular waveguide bellow is intended to compensate the misalignment in position and angle in the transmission line. Further up, a thermal intercept to the liquid nitrogen-shield will keep the static heat losses below 0.4 W. Small bars inside the following waveguide are planned to minimize the transfer from thermal radiation down to the input coupler. The adjacent waveguide transition lines and connections are designed to keep the static heat transfer from the warm into the nitrogen below 5 W per transition line. The beam-line vacuum will be sealed by a warm waveguide pressure window installed outside the cryo-vessel. The overall heat losses in the helium will be below 4 W (which is comparable with the old-design cryo-modules). The estimated dynamic heat loss in the waveguide transition lines due to RF operation is below 200 mW.

FIGURE 5 shows the so-called tower of the module as a cross-section. The different pressure stages and the positions of the seals can be seen. The big rectangular opening of the helium vessel will be sealed with a special VATSEAL® gasket. A tube going from the helium vessel through all vacuum stages holds the motor rod of the cavity frequency tuner. The motor itself will be located at ambient outside the cryo-module. This arrangement was
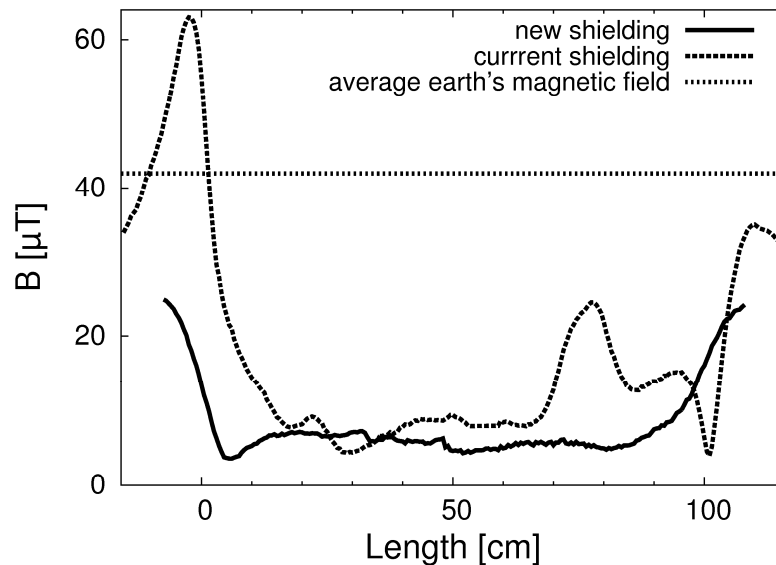
FIGURE 6. The absolute magnetic flux strength a the cavity location for the old magnetic shielding setup and a new one are compared to the average earth magnetic field 42 µT in the laboratory. The cavity is placed between 0 and 100 cm, thus the average magnetic field strength in that region is 13.8 µT for the old setup and 6.3 µT for the new setup.

not changed compared to the current modules as it proved to work reliably. Additional CF 38 standard flanges are intended for a feedthrough of electric cables through the different pressure stages. Those are needed for several temperature sensors, a heat load inside the helium vessel, as well as for the magneto-restrictive Nickel rod (surrounded by a superconducting solenoid) which is used for the frequency fine tuning of the cavities.

Magnetic Shielding

Shielding the superconducting cavities against the earth's magnetic field is necessary to minimize their RF surface resistance, thus improving the quality factor of the cavities. Due to the complex geometry of the frequency tuner, an optimal magnetic shielding is hard to design. By now different design options are still under investigation. One idea is to add an additional layer of 0.2 mm CRYOPERM®, another is to test piezoelectric actuators [4] and replace our actual magneto restrictive elements in the cavity tuner. FIGURE 6 shows those improvements in the actual shielding by adding more layers of CRYOPERM®. The up-to-date tests showed an average magnetic flux strength of 6.3 µT is possible. Although that means an improvement by a factor of 2, compared to the old setup, reaching the design quality factor of a cavity requires a field less than 3 µT. Therefore, further efforts will be required.

SRF CAVITIES

The superconducting cavities of the S-DALINAC were built almost 20 years ago for a design gradient of 5 MV/m. It was shown during operation that fields of 6 MV/m and higher are possible [5]. Unfortunately, the design value of the quality factor of $3 \cdot 10^9$ has never been reached [6], which sometimes confines the enduring accelerator operation with high beam energies because of limited refrigerating capacity. Improving the quality factor is an ongoing project at the S-DALINAC using different techniques for preparation of the

TABLE 1. Frequencies of the π-Mode for a 20 cell S-DALINAC cavity at 2 K and at ambient (before and after chemical surface etching). To fully remove the damage layer, a chemical etching of 150 μm is planned for the new cavities (was 50 μm for the old cavities). To compensate for this, the shape was modified by 0.1 mm resulting in a different frequency before the treatment.

Cavity	π-Mode
at 2 K	2.99752 GHz
at 300 K	2.992 GHz
before chemistry (1989)	2.9935 GHz
before chemistry (2009)	2.996 GHz

TABLE 2. Frequencies of the new dumb-bell shape from simulation and measurement. A copper dumb-bell was used for the measurement while a good electric contact was ensured by strongly clamping copper plates against its openings.

Dumbbell frequency	0-mode	π-mode
simulated	2.8899 GHz	2.99681 GHz
measured	2.89147 GHz	2.99523 GHz
expected		2.996 GHz

cavities [7]. For the injector upgrade project it was decided to order 3 new cavities from industry, using state-of-the-art technologies in order to get perfect cavity with quality factors closer to the physical limit.

Unlike the first series where single cells were built and measured before being welded to a full 20 cell cavity, dumb-bells will be produced this time, being the common way to fabricate multi-cell cavities today. One advantage of this modified procedure is that the π-mode of a dumb-bell is (to first order) equivalent to the π-mode of the cavity. Thus it is easy to check the frequency and correct shape errors before the final EB-welding. The deep-drawing, the EB-welding, and the coarse chemical etching of the inner surface will be done by RI company (former named Accel), while all frequency measurements and adjustments will be done by us. The last production steps, like frequency and field flatness tuning and the final chemical treatment will also be done in-house.

The first step in the cavity production was to refine the cavity shape by adding 0.1 mm to the thickness. This was done in order to compensate for a stronger chemical etching after the production. This etching is required to remove the damage layer- an approximately 100 μm thick layer of material on the inner surface having very poor RF properties.

Estimating the new frequency for the π-mode was done by extrapolating cavity data from chemical treatments at the S-DALINAC. It was found that taking 40 μm off the surface material lowers the π-mode frequency by 1 MHz. Thus the frequency is expected to be 2.996 GHz before all chemical treatments. This result was verified by measurements on a copper dumb-bell with the new shape as well as simulations with CST Microwave Studio [8]. TABLE 1 shows the different frequencies of the π-mode depending on temperature and production status, while in TABLE 2 the result of simulation and measurements at the new dumb-bell can be seen. Currently, a setup for frequency measurements of the niobium dumb-bells is under development. First tests showed that a good electric contact between the dumb-bell and two copper plates can be achieved without deforming the resonator as long as the pressure is imposed near the equator.

The frequency increase by trimming the dumb-bells has been calculated to be approximately 12.6 MHz/mm for the π-mode. After trimming all dumb-bells and welding the cavity, the frequency can be decreased by compressing all or one single cells or increased by stretching them. During the whole production process the elongation of the dumb-bells and the cavity length has to be controlled. A complete 20 cell cavity should end up with the right frequency and a length of 1 m. A few millimeters deviation are acceptable (for example to compensate the frequency shift due to the mounting of the coupler) and will not have an effect on the acceleration performance.

STATUS

At the moment the dumb-bells for the cavities are produced and the following tests and production steps are clarified. A final chemical treatment on the new power couplers has been done and they are ready for assembly. Except some smaller parts, the design of the cryo-module is finished. Currently, we are in contact with some vendors for the last missing components. Challenges like the improvement of the magnetic shielding are still a matter of ongoing research. The Q-Tuner prototype showed satisfactory results so a final design, eventually with a remote control, can be made.

ACKNOWLEDGMENTS

REFERENCES

1. Richter, A., "Operational Experience at the S-DALINAC," in *EPAC'96*, Sitges, 1996, pp. 110-114.
2. Auerhammer, J., Eichhorn, R., Genz, H., Graef, H.-D., Hahn, R., Hampel, T., Hofmann, C., Horn, J., Luettge, C., Richter, A., Rietdorf, T., Ruehl, K., Schardt, P., Schlott, V., Spamer, E., Stascheck, A., Stiller, A., Thomas, F., Titze, O., Toepper, J., Wesp, T., Weise, H., Wiencken, M. and Winkler, T., "Progress and Status of the S-DALINAC," in *SRF'93*, Newport News, 1993, pp. 1203-1211.
3. Kunze, M., Mueller, W.F.O., Weiland, T., Brunken, M., Graef, H.-D. and Richter, A., "Electromagnetic Design of new RF Power Couplers for the S-DALINAC," in *LINAC'04*, Luebeck, 2004, pp. 736-738.
4. Sahu, B., Chowdhury, G., Ghosh, S., Kanjilal, D., Mathuria, D., Mehta, R., Pandey, A., Patra, P., Rai, A. and Roy, A., "Use of Piezo Actuator to Frequency and Phase Lock a Superconducting Quarter Wave Resonator," in *LINAC'08*, Vancouver, 2008, in press.
5. Auerhammer, J., Genz, H., Graef, H.-D., Huck, V., Luettge, C., Richter, A., Rietdorf, T., Schardt, P., Spamer, E., Ruehl, K., Stascheck, A., Thomas, F., Titze, O., Toepper, J. and Weise, H., "Latest of the Superconducting Darmstadt Electron Accelerator S-DALINAC," in *SRF'91*, Hamburg, 1991, pp. 110-120.
6. Araz, A., Brunken, M., Gopych, M., Graef, H.-D., Hasper, J., Hertling, M., Platz, M., Richter, A., Watzlawik, S., Kunze, H., Mueller, W., Setzer, S., Weiland, T., Bayer, W. and Laier, U., "Recent Results and Developments from the S-DALINAC," in *SRF'05*, Ithaca, 2005.
7. Eichhorn, R., Araz, A., Brunken, M., Conrad, J., Graef, H.-D., Hertling, M., Hug, F., Konrad, M., Kuerzeder, T., Platz, M., Richter, A., Sievers, S. and Weilbach, T., "Results from a 850°C Heat Treatment and Operational Findings from the 3 GHz SRF Cavities at the S-DALINAC," in *SRF'07*, Beijing, 2007.
8. Computer Simulation Technology: www.cst.com