RECENT RESULTS AND DEVELOPMENTS FROM THE S–DALINAC*

A. Araz, M. Brunken, M. Gopych†, H.-D. Gräf, J. Hasper, M. Hertling,
M. Platz, A. Richter, S. Watzlawik, Institut für Kernphysik, TU Darmstadt, Germany
H. Kunze, W. Müller, S. Setzer, T. Weiland, TEMF, TU Darmstadt, Germany
W. Bayer, U. Laier, Gesellschaft für Schwerionenforschung, Germany

Abstract

Field emission accompanied by the emission of light has already been studied in a 20 cell superconducting niobium 3 GHz cavity of the S-DALINAC [1]. The investigations were extended to cavities of the S-DALINAC injector, where the location and intensity of light emitters as well as the spectral distribution of the emitted light were investigated. We conclude that the light emitters are dust particles heated by the RF field inside the cavity. Measured bremsstrahlung spectra of dark current electrons can be reproduced using GEANT4 [2] simulations. The maximum electron energies determined from these spectra are compared with results obtained by numerical simulations of electron trajectories. The emission of characteristic X-rays from niobium could be measured with a special semiconductor detector installed inside the beam vacuum tube downstream of the injector. The intensity of the X-rays as a function of the accelerating field is well described by a Fowler-Nordheim relation with a field enhancement factor of $\beta = 340 \pm 40$.

Furthermore the first results of high temperature treatment (850°C) applied to the 5-cell capture cavity of the S-DALINAC in a high vacuum furnace at Darmstadt are presented. The intention of the procedure was to remove residual hydrogen from the cavity niobium. Residual gas analysis during the heat treatment showed that the cavity was rather strongly contaminated.

For the injector linac new RF input couplers have been designed aiming at a minimal transverse kick. The couplers presently under construction will be able to handle several kW of power.

The most significant improvement of the infrastructure concerned the 2K helium refrigerator. There, the original piston compressor was replaced by an air cooled screw compressor, and four pumping modules operating in parallel were installed for the 2K operation, superseding the former five stage roots pump.

ACCELERATOR

The superconducting Darmstadt electron linear accelerator S–DALINAC was put into operation in 1987. It uses twelve superconducting niobium cavities cooled to 2 K and operated in the π-mode at the frequency of a 2.9975 GHz with an average accelerating field of 5 MV/m. A standard cavity consists of 20 cells. The design energy of the accelerator is 130 MeV [3]. The layout of the S–DALINAC is shown in Fig. 1.

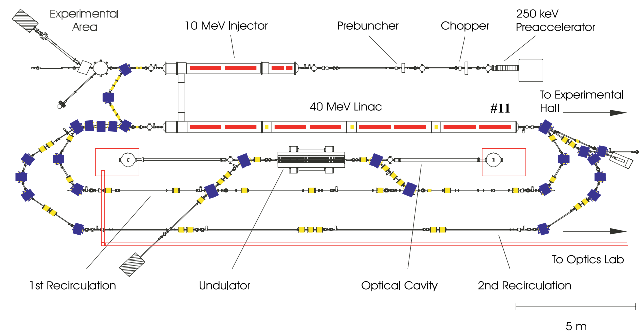

Figure 1: Layout of the S–DALINAC

X-RAY AND FIELD EMISSION AT THE INJECTOR OF THE S-DALINAC

During channeling radiation experiments behind the injector of the S-DALINAC high emission rates of characteristic X-rays have been measured by the X-ray detector system AXAS^{MCA} with no electron beam passing through the injector cavities only with rf power on. It was found that the emitted X-rays are characteristic for niobium. The measured X-ray spectrum is given in Fig. 2. Since only the accelerating cavities are made of niobium they are the only candidates to emit these X-rays. This points at field

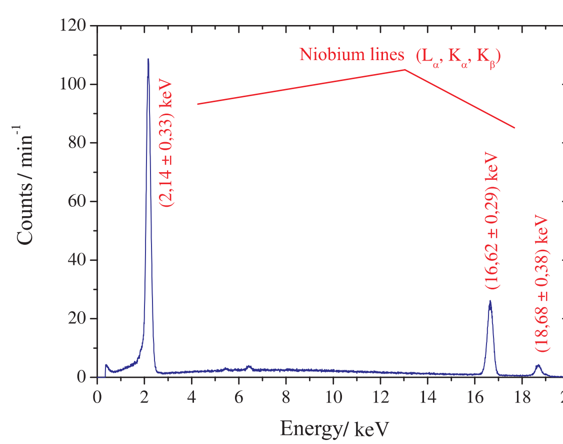

Figure 2: X-ray spectrum emitted by cavity #2 at E_{acc} = 5.4 MV/m

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† Corresponding author : gopych@ikp.tu-darmstadt.de

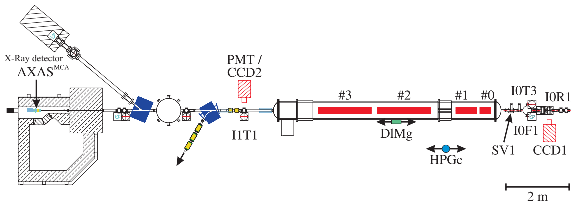

Figure 3: Overview of the S–DALINAC injector with the positions of experimental set-ups for investigation of field emission

emission in these cavities. By impact ionization field emitted electrons can cause emission of characteristic X-rays. Therefore additional measurements were performed to investigate field emission in the cavities. Figure 3 shows an overview of the experimental set-ups. The X-ray emission has been observed in two injector cavities, namely #1 and #2. A number of X-ray spectra at different accelerating gradients has been taken. The intensity of characteristic niobium lines allowed us to estimate the dark current strength in the cavities. From plotted Fowler-Nordheim curves the field enhancement factors β were found to be equal to 255 and 340 for #1 and #2 respectively.

With two mirrors installed in the beam vacuum system at the positions of the cameras CCD1 and CCD2 light emission from cavities #1 and #2 was detected as well. The same phenomenon had been already observed in a cavity of the main linac [1]. In opposite to the main linac cavity there was only a single location of light emitting spots inside each of the investigated cavities. By means of a set-up of optical longpass filters and a photomultiplier (PMT in Fig. 3) measurements of optical spectra of light emitted from the spots were performed for both cavities. The optical filters covered a wavelength range from 515 to 850 nm. The resulting optical spectrum for the cavity #1 at $E_{acc} = 4.3$ MeV is shown as a histogram in Fig. 4. The spectral power density showed that the light emitting spots

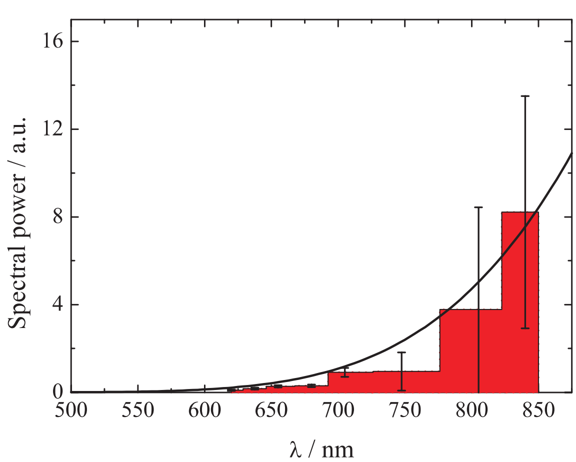

Figure 4: Spectrum of light emitted from the light spots inside cavity #1 at $E_{acc} = 4.3$ MeV. The solid line shows the Planck curve for 1200 K.

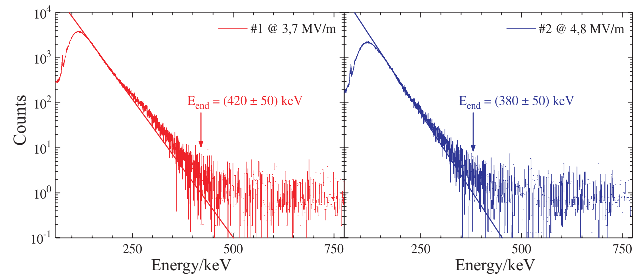

Figure 5: Background corrected bremsstrahlung spectra at $E_{acc} = 3.7$ MeV for cavity #1 (left) and at $E_{acc} = 4.8$ MeV for cavity #2 (right).

are black hole body radiators with a temperature of some 1200 K.

The field emitted electrons are accelerated in the cavity over a certain distance before being stopped in the cavity wall producing bremsstrahlung. This was measured with a high purity gearmanium (HPGe) detector (see Fig. 3). The detector was moved along the injector to determine the region where the maximum bremsstrahlung is emitted. Two measured bremsstrahlung spectra for cavities #1 and #2 with deduced end point energies are given in Fig. 5. Positions of maximum bremsstrahlung intensity along the injector agreed with the locations of light spots within measurement accuracy. This result and relatively high electron energies determined from the bremsstrahlung spectra let us assume that the light emitting spots could simultaneously be the dark current emitters. It was attempted to reproduce these bremsstrahlung spectra using GEANT4 [2], a toolkit for the simulation of passage of particles through matter. The simulation geometry consisted of a flat niobium target bombarded by electrons from a point source placed in a

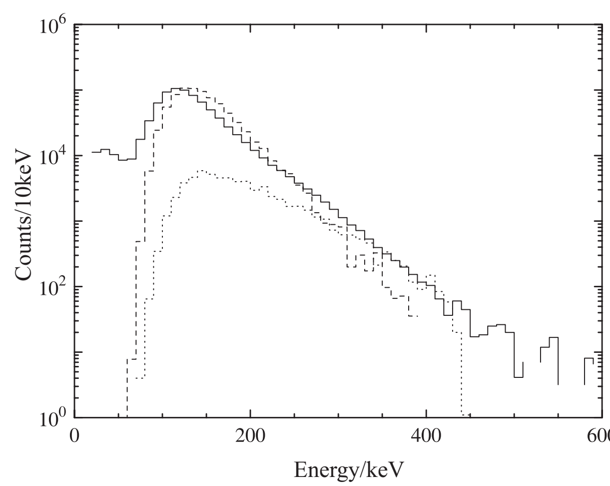

Figure 6: Comparison of a measured bremsstrahlung spectrum from cavity #1 at $E_{acc} = 3.7$ MeV (solid line) with two simulated ones for exponential electron energy distribution (dashed line) and for monoenergetic electrons with an energy of 450 keV (dotted line).

closed volume. Bremsstrahlung production cross sections for Nb were calculated for energies from 50 to 600 keV in steps of 25 keV. One result of GEANT4 simulation is that the electron energies seem to be exponentially distributed. Figure 6 shows resulting simulated spectra in comparison with a measured one.

The observed light can be emitted by glowing dust particles. They can be heated either by impacting dark current electrons or by adsorbed rf energy. The entire dark current from the X-ray data amounts to $8.7 \leq I_e \leq 284$ nA for #1 ($E_{acc} = 4.1$ MV/m) and $46 \leq I_e \leq 1470$ nA for #2 ($E_{acc} = 5.4$ MV/m)). From a simple model with 50 silicon dust particles with a radius of 50 μm each at a thermal equilibrium of 1200 K a minimum dark current of 1500 nA is required. Thus it seems to be unlikely that the dust particles are heated in this way. On the other hand dielectric loses in the particle can be estimated following [4] to amount to $0.73 \leq P_{loss} \leq 7.3$ mW for #1 ($E_{acc} = 4.1$ MV/m) and $1.27 \leq P_{loss} \leq 12.7$ mW for #2 ($E_{acc} = 5.4$ MV/m) respectively. This corresponds to thermal equilibrium temperatures between 800 and 1630 K. Consequently the dielectric losses are enough to heat the dust particles up to the temperature of 1200 K.

HIGH TEMPERATURE TREATMENTS

The high temperature vacuum firing has proven to be an inherent part of the surface preparation of superconducting cavities. This procedure is applied to stress anneal the niobium and to remove hydrogen from the material inoculating cavities against the “Q disease” during their operation [5]. The S-DALINAC niobium cavities were heat treated at 750°C after their commissioning as well. However recent studies have shown that the niobium is still contaminated by hydrogen increasing the homogenous part of the surface resistance. This required a renewed treatment of the cavities at high temperatures. Therefore a high temperature vacuum furnace allowing temperatures up to 1400°C and beyond was put into operation at Darmstadt in December 2004. Its construction and basic parameters are described in [6].

The first cavity fired in the vacuum furnace was the 5-cell capture cavity of the S-DALINAC. The performance of this cavity during the last operation period was strongly limited by field emission and its quality factor ($1.9{\cdot}10^8$) was significantly lower than the average one of all cavities amounting to $7.3{\cdot}10^8$. First this cavity was etched using a gentle chemical polishing followed by rinsing with ultra-pure water and drying in a nitrogen atmosphere. Afterwards the cavity was vertically installed in the furnace mounted in a support frame to prevent distortion under its own weight. The installation was performed under laminar flow conditions. The whole procedure of firing lasted 8 days including 60 hours at the target temperature of 850°C and at a vacuum of $\leq 1 \cdot 10^{-6}$ mbar maintained by an ion getter pump with high effective pumping speed for H_2. The cavity temperature during the heat treatment was measured through

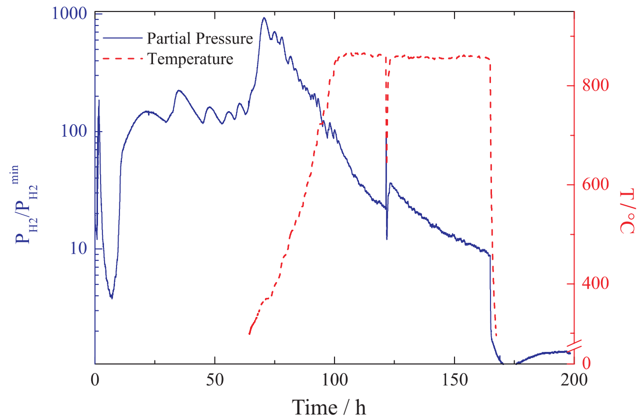

Figure 7: Development of the relative partial pressure of the molekular hydrogen (solid line) and the temperature (dashed line) during furnace operation.

a viewing port by means of an infrared pyrometer with a 300 to 1400°C range. The residual gas in the furnace was analysed using a mass spectrometer. The development of the relative partial pressure of molecular hydrogen and the cavity temperature as a function of time are shown in Fig. 7. Because of strong outgassing of the cavity the temperature was slowly increased and reached 850°C some 100 hours after the beginning of the heat process. One can see that the maximum concentration of H_2 was already observed at 370°C and then declined with increasing cavity temperature. This behavior indicates that most of the hydrogen has been removed from the cavity niobium.

The fired 5-cell cavity was reinstalled in the accelerator cryostat and was thoroughly tested at 2 K. The unloaded quality factor Q_0 has improved distinctly and amounts to $8.5{\cdot}10^8$. Fig. 8 shows the development of the 5-cell cavity

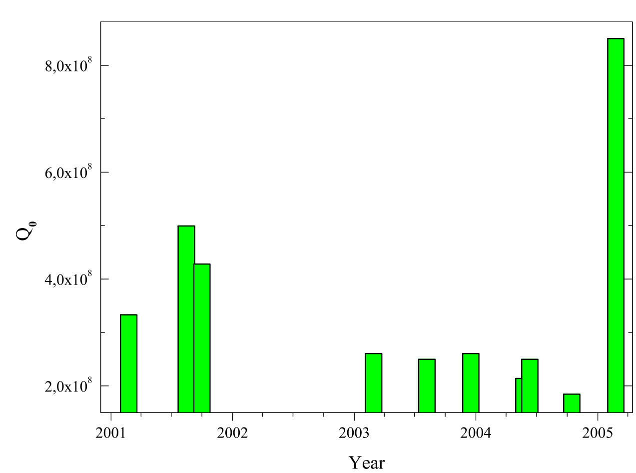

Figure 8: Comparison of the measured unloaded quality factor Q_0 of the 5-cell cavity for the last four years. The last bar represents Q_0 after the heat treatment.

quality factor for the last four years. Besides this increase of Q_0, no field emission has been found in the cavity at field gradients up to 6.5 MV/m. In view of this successful heat treatment it is planned to fire gradually all the cavities used in the accelerator.

NEW RF POWER COUPLERS

Since its comissioning improvements and modifications have been added to the S-DALINAC according to the demand of the experiments planned. Presently future nuclear physics experiments at the injector of the S-DALINAC need electron energies up to 14 MeV and a cw beam current of 150 to 250 μA. To achieve these parameters about 2 kW of rf power must be transferred to the electron beam. Since the present coax-coax input power couplers with variable coupling are limited to some 500 W, the S-DALINAC injector upgrade requires new more powerful ones. The new couplers should be as compact as possible and should keep the emitance growth of the electron beam small. Taking into account these conditions two versions of waveguide power couplers a single-waveguide-coax and a twin-waveguide-coax coupler were proposed and thoroughly studied [7, 8]. The single-waveguide-coax coupler design was finally chosen for the upgrade. The geometry of the coupler with its parameters is shown in Fig. 9. The asymmetric diaphragms with $\varphi_1 = 55°$ and $\varphi_2 = 47.9°$ are optimized for minimum transverse electromagnetic field components on the beam axis.

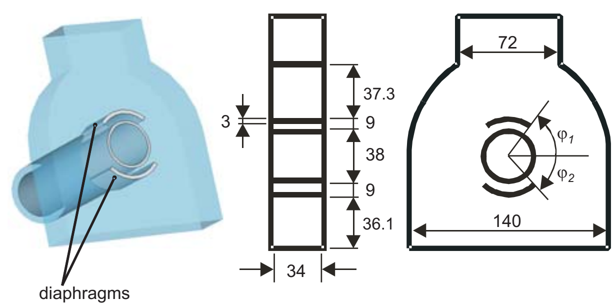

Figure 9: The geometry of the single-waveguide-coax coupler (unit of length is mm).

IMPROVEMENT OF THE INFRASTRUCTURE

During the last two years the infrastructure concerning the 2K helium refrigerator has been considerably improved. The original piston compressor was replaced by a new air cooled screw compressor KAESER ESD 351. This model is characterized by economical power consumption, low noise emission and low servicing effort. The ESD 351 can produce a maximum pressure of 14.6 bar at an intake pressure of 1.08 bar. Its mass flow rate is 60 g/s in comparison to 43 g/s for the piston compressor.

The previous pump system (necessary for 2 K operation) consisted of a five stage roots pump with a mass flow rate of 5 g/s and maintained a helium vapour pressure of 35 mbar inside the accelerator cryostats. It has been replaced by a system based on four RUTA RA7001FU/K/SV1200/G pump modules made by Leybold with a mass flow rate from 0,75 to 2 g/s helium at 12 mbar each. These modules are connected in parallel in contrast to the former pump system where the roots pumps were connected in series. This means that the system is vary redundant and rather fail-safe. The roots pumps of the new pump system are frequency controlled and can keep the cryostat pressure constant within 0.1 mbar in a range from 25 to 45 mbar.

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