FIELD EMISSION RELATED PHENOMENA IN A 3 GHz 20 CELL CAVITY OF THE S–DALINAC*

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Abstract

Investigations of field emission accompanied by emission of light in a superconducting niobium rf cavity of the S-DALINAC [1] have been carried out by analysis of both, bremsstrahlung and optical spectra. The spectral power density of the observed light spots could be interpreted as black body radiation emitted at a temperature of some 1500 K. From bremsstrahlung spectra measured at accelerating gradients from 6 to 7 MV/m the maximum energies gained by dark current electrons that were accelerated and able to leave the cavity were determined. In order to localize a possible position of an emission site, trajectories of dark current electrons in the cavity were numerically simulated by a code based on the Leap-Frog method. The simulations have shown that the observed electron energies cannot be gained in a cavity with an ideal field flatness. Best agreement has resulted for a strongly deteriorated field profile with an end cell detuned by 5.4 MHz. Experimental evidence for this hypothesis is deduced from a comparison of the present eigenfrequencies of this particular cavity with both, the present eigenfrequencies of other S–DALINAC cavities and the eigenfrequencies of the respective cavities after their initial tuning for field flatness in the π-mode.

INTRODUCTION

The S–DALINAC was designed to accelerate electrons up to 130 MeV using twelve superconducting cavities cooled down to 2 K. The standard accelerating structure operated at the frequency of 2.9975 GHz is made of niobium with a residual resistivity ratio of $RRR \approx 280$ and it consists of 20 cells. The design value for the electric field strength of 5 MV/m was achieved by almost all cavities and could be exceeded in most cases. The injector contains a two-cell capture cavity ($\beta = 0.85$), followed by a 5-cell cavity ($\beta = 1.0$) and two standard structures. This enables a maximum electron energy of 10 MeV. The energy gain in the main linac consisting of eight 20-cell cavities amounts to 40 MeV. Two recirculating beam lines allow the electron beam to pass through the main linac three times. The layout of the S–DALINAC is shown in Fig. 1.

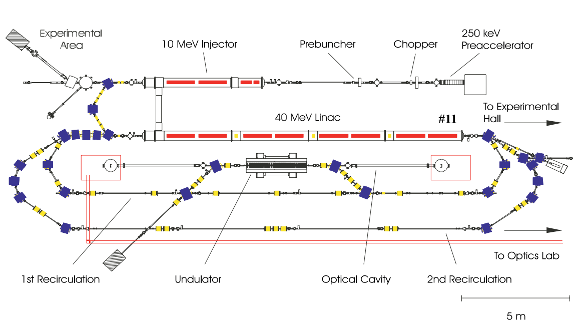

Figure 1: Layout of the S–DALINAC

Field emission observed in the last cavity of the main linac (#11 in Fig. 1) was accompanied by emission of light from bright spots inside the cavity. A number of diagnostic measurements (optical and bremsstrahlung) on this cavity have been performed to investigate this phenomena in oder to avoid this problem during the operation of the accelerator in the future. For the measurements the cavity remained installed in the accelerator cryostat and was powered by its 500 W klystron. In the following the results of the measurements and numerical simulations aiming on an explanation of the experimental data are presented.

OPTICAL MEASUREMENTS

The experimental set up is given in Fig. 2. First, the light spots inside the cavity were registered by a CCD camera placed at a viewport ((3) in Fig. 2) for optical measurements in the straight beam line. The spots were located on

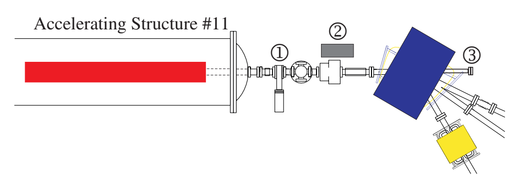

Figure 2: Experimental set up downstream of the main linac. The figures denote: (1) view screen, (2) BGO detector, (3) viewport for optical measurements.

the irises of the cavity and remained stable during the observation. At an accelerating field of $E_{acc} = 7.6$ MV/m three groups of spots could be identified varying the focal plane of the CCD camera. The first group lay in the middle, the second group close to the end of the cavity and the third one was even outside the cavity in the cutoff tube. An optical spectrum of the emitted light was taken using a photomultiplier (Hamamatsu R1457) together with a set of optical filters. The high pass filters covered a wavelength range of 600-850 nm in steps of 15 to 70 nm. The resulting spectrum corrected for the wave length dependent ef-

* Supported by the DFG (FOR 272/2-1, GRK 410/2 and SFB 634)

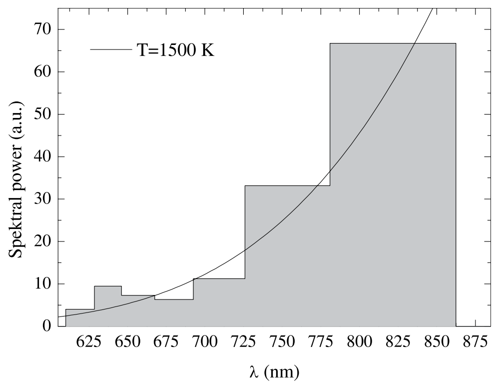

Figure 3: Spectral distribution of the radiation emitted by the light spots.

ficiency is displayed in Fig. 3. The power spectral density rises permanently starting at 600 nm and shows similarity to those of the black body radiation. This can be fitted by a spectral distribution corresponding to a black body temperature of 1500 K. Thus the observed light emission very likely results from small particles, thermally insulated from the surface of the cavity and heated by the rf-field or by field emission electrons.

BREMSSTRAHLUNG MEASUREMENTS

Electrons emitted from the surface of a cavity loaded by field emission are accelerated by the electric field. Most of them hit the cavity surface near their own emission sites. But a small part of the electrons with favorable starting conditions can gain a significant energy and perhaps can even leave the cavity. These electrons form undesired dark current in accelerators. Knowing their energies one can try to identify the starting cell by means of numerical simulations. In oder to determine the energy of these electrons they were directed onto a view screen behind the cavity ((1) in Fig. 2) and were scattered into the wall of the beam line. Produced bremsstrahlung was taken by a BGO detector ((2) in Fig. 2) positioned above the beam line. The end point energy of the bremsstrahlung spectrum corresponds to the maximum energy of the incident electrons. Bremsstrahlung spectra were measured for accelerating fields E_{acc} of 6.84, 6.66, 6.48 and 6.12 MV/m. The results of the measurements are summarized in Fig. 4. End point energies were deduced from these spectra by means of exponential fits shown in Fig. 4 as white solid lines. The obtained electron energies are 3.75, 3.4, 3.05 and 2.3 MeV corresponding to decreasing accelerating fields with an experimental accuracy of 100 keV.

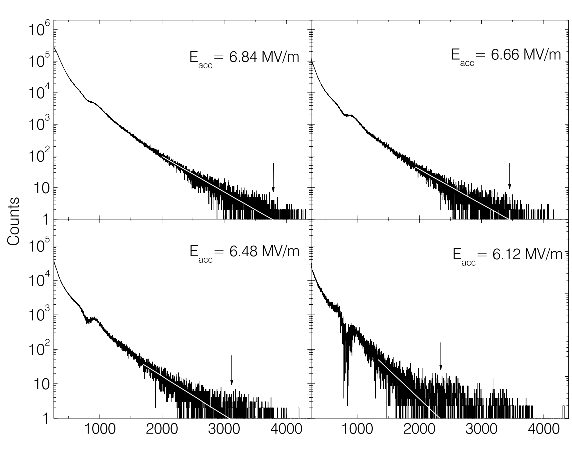

Figure 4: Bremsstrahlung spectra measured with a BGO detector for different accelerating gradients.

SIMULATION

The maximum electron energies at the end of the cavity determined from bremsstrahlung spectra amount to about half of the energy gained by a regularly accelerated electron. This fact suggests that the emission site is localized in the middle of the cavity. In oder to check the assumption the behavior of dark current electrons was numerically simulated by a tracking code written especially for the simulation of particle trajectories inside the accelerating structure. The program is based on numerical integration of the relativistic equation of motion in electromagnetic fields using the Leap-Frog method [2]. An initial field distribution in the cavity is calculated using the MAFIA eigenmode solver [3]. Because of the rotational symmetry of the considered cavity the eigenmode simulation is performed in an r-z plane. Calculation of the trajectory is terminated when the electron hits the cavity wall. Space charge effects and the secondary emission process itself are not taken into account in the simulation program.

At first a flat field distribution (i.e. field amplitudes of the accelerating π-mode have equal magnitude but opposite sign in neighboring cells) was assumed. Electrons were started from the surface of the 10th iris with a zero velocity in a phase interval from -30° to 30° and scanning the entire region of an iris, where field emission occurs most likely. These simulations have shown, that there were no electrons which could be properly accelerated through the cavity. Numerical calculations repeated for other irises provided the same result.

After initial fabrication all accelerating structures were tuned for flat field profiles. The operating π-mode, however, is extremely sensitive to perturbation of single cells (particularly the end cells) of multicell structures. During a regular cavity test performed after a shutdown period it was found that the power transmitted through the particular cavity was smaller than the average of the other ones by 20 dB. Assuming that the average transmitted power corresponds to a structure with a flat field profile then the field amplitudes in the first and 20th cell for the cavity under investigation should differ in this case by a factor of 10. This difference can be obtained as a result of a detuning of either the first or the last cell of the cavity by 5 MHz. As an

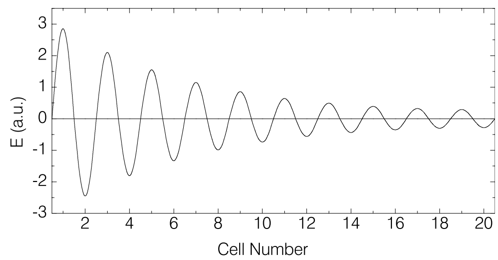

Figure 5: Field profile of a 20 cell S–DALINAC structure with the first cell detuned by 5 MHz.

example the field profile of a 20 cell S–DALINAC structure with the first cell detuned by 5 MHz calculated from a simple lumped circuit model is shown in Fig. 5.

If the assumption of such a field profile is correct, trajectory simulations for this cavity should be able to reproduce the energies obtained from the bremsstrahlung spectra. Therefore the same simulations have been carried out for a cavity with a detuned first cell. Electrons are started from the iris between the first and the second cell because of the high electric field in this region. The field profile was obtained from the flat field distribution calculated with MAFIA scaled with the respective corrections from the lumped circuit model. Simulations for an accelerating structure with the first cell detuned by 5.4 MHz have succeeded in reproducing the experimental energies most suitably. A comparison of experimentally observed and corresponding calculated energies is given in Tab. 1. The excellent agreement shows, that under the hypothesis of a detuned end cell (causing a non-flat field profile) the observed dark current energies can be explained.

Table 1: Comparison of the energies obtained experimentally with the calculated ones .

E_{acc} (MV/m)	E_{kin} (MeV) Experiment	E_{kin} (MeV) Simulation
6.12	2.3 ± 0.1	2.16 ± 0.08
6.48	3.05 ± 0.1	3.1 ± 0.05
6.66	3.4 ± 0.1	3.45 ± 0.05
6.84	3.75 ± 0.1	3.8 ± 0.05

A possibility to verify these assumption without severe interruption of the accelerator operation lies in a measurement of the dispersion curve of the accelerating TM010 passband. These frequency measurements where performed on several of our cavities including the last cavity of the main linac using a vector network analyser. We used a simple analytical model to compare the measured frequencies with the assumption of a detuned cavity. This model describes each cell of the cavity by a lumped circuit. Coupling is introduced only between neighbouring cells by a coupling capacitor. A one parameter fit to the measured frequencies was performed varying the cell coupling factor, of a field flat cavity within this model. The fitted cell coupling factors varies between 0.034 and 0.036 compared to a design value of 0.04. This may be due to initial fabrication inaccuracy of the 1.2 m long slim 3 GHz cavities used at the S-DALINAC. The measured and the calculated frequencies where in good agreement, except for the case of the last cavity of the main linac, where the measured frequencies could not be described by our model with the one parameter fit described above. We detuned the first cell in our simple model by +5.8 MHz and varied the cell coupling factor to fit the measured data. Figure 6 shows the difference between the calculated and the measured frequencies

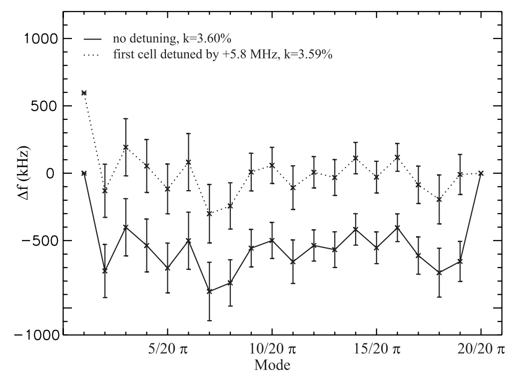

Figure 6: Difference between the measured passband frequencies and the calculated frequencies in case of a flat field profile (solid line) and in case of a perturbed field profile resulting from a detuned edge cell (dashed line).

of the last linac cavity in case of the assumption of a flat field profile and of a field profile resulting from a detuned end cell. The measured frequencies are in good agreement with the calculated frequencies in the latter case. This supports the underlying postulate of the tracking simulations to reproduce the bremsstrahlungs measurements performed at the last main linac cavity. It is planned to remove this cavity from the accelerator and to measure its field profile during the next shutdown period of S–DALINAC. If the assumption of a detuned end cell turns out to be true, it would be retuned before the cavity goes through the final preparation cycle for reinstallation.

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