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OPERATING EXPERIENCE WITH SC RESONATORS AT THE S-DALINAC*

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The recirculating electron accelerator S-DALINAC provides beams for a wide variety of nuclear and radiation physics experiments and since December 1996 it is also successfully used to drive a free electron laser (FEL) in the mid infrared wavelength region. The sc cavities of the S-DALINAC operate at 2997 MHz and therefore at a temperature of 2 K. Up to now the S-DALINAC has provided some 16000 h of beamtime for experiments. Guided by operational experience numerous developments concerning equipment directly associated with the superconducting (sc) cavities like tuners, rf couplers, etc., were performed. The operational principle and performance of the respective parts is discussed. Manufacturing of the sc cavities themselves, tuning for field flatness of the π-mode, and treatment prior to installation as well as treatment after degradation is presented together with a summary of the current cavity and accelerator performance.

Keywords: Superconductivity; Radiofrequency; Cavities

1 INTRODUCTION

In 1987 the sc injector of the S-DALINAC became operational and in January 1991 a first electron beam which had been accelerated three times in the main linac (using two recirculating beam transport systems) was produced. During installation, commissioning and the

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following years of operation of the accelerator regular reports on its status were given at the respective conferences. For a most recent overview see Ref. [1] and for further details, references therein. In this article we will try to summarize briefly our experience in operating a small sc electron accelerator having been developed and being used in the environment of a university for research in low energy nuclear and radiation physics.

In Section 2 we will give a brief description of the accelerator itself and of the different experimental areas using the electron beam. Fabrication of the sc cavities, treatment prior to their installation in the accelerator and after degradation as well as the current cavity performance are described in Section 3 whereas Section 4 covers the development of several components necessary for reliable operation of the sc cavities themselves. In Section 5 we will summarize the performance of the accelerator and draw conclusions from our operational experience.

2 ACCELERATOR AND EXPERIMENTAL AREAS

The S-DALINAC provides electron beam for several experimental areas. A layout of the entire facility is presented in Figure 1. The hall to the left houses the accelerator itself (described below) and two experimental areas. At energies below 10 MeV an area (1) allows

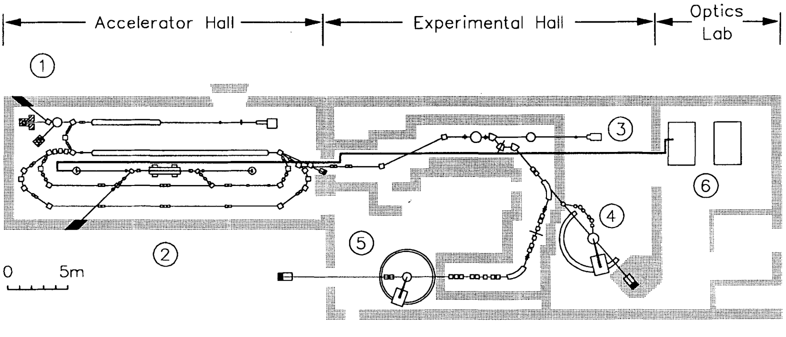

FIGURE 1 Layout of the S-DALINAC facility. Encircled numbers denote experimental areas and are referred to in the text.

for nuclear resonance fluorescence experiments and for production and investigation of channeling radiation and parametric X-rays (PXR). In the same hall the FEL (2) which was successfully operated in December 1996 for the first time[2,3] is installed. Its beam is transported to the optics lab (6) for experimental use. In the experimental hall the electron beam at energies above 25 MeV can be used for radiation physics (3) or for nuclear physics investigations using the electron spectrometers in locations (4,5).

An enlarged layout of the accelerator is presented in Figure 2. The electron beam is produced by a thermionic gun (1) and electrostatically accelerated to 250 keV. Its time structure, necessary for rf acceleration at a frequency of 3 GHz, is prepared at room temperature in area (2) before it enters the sc injector linac (3) which contains a 2-cell and a 5-cell capture cavity and two 20-cell cavities, and provides beam energies up to 10 MeV. Then the beam is bent (4) by 180° and after passing a diagnostics station (5) injected into the main linac (6) which contains eight 20-cell cavities and provides an energy gain of up to 40 MeV.

For further acceleration the beam can be recirculated twice by means of the two beam lines in the lower part of figure, before it is extracted to the experimental hall. In the center of the Figure 2 alongside the main linac, the installation of the FEL, containing the undulator (7), diagnostics stations (8), and two optical tables (9,10) carrying the mirror chambers of the optical cavity, is located.

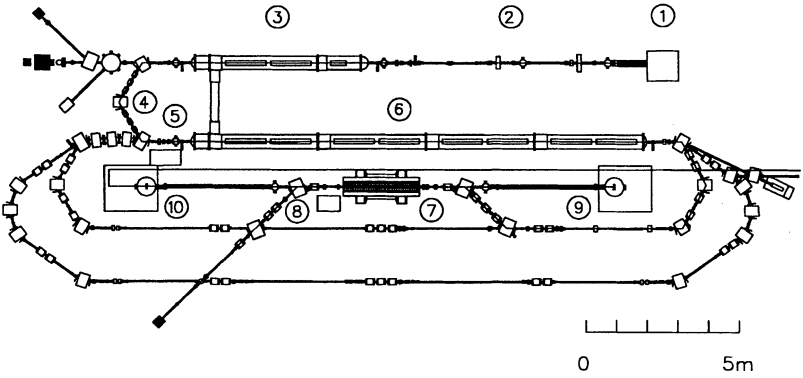

FIGURE 2 Layout of the accelerator. Encircled numbers denote main components and are referred to in the text.

3 SC CAVITIES

Except for the 2-cell and 5-cell capture cavities housed in the injector linac the S-DALINAC uses 20-cell cavities operating at 3 GHz for acceleration of the electron beam. The decision for this rather high frequency and the large number of cells per unit was the result of economic considerations: at 3 GHz the diameter of the cells at the equator amounts to some 92 mm and consequently the accelerator cryostat has an outside diameter of 500 mm only, which allows a fairly inexpensive realization. Simultaneously the large number of cells per unit reduces the number of rather expensive auxiliary equipment like frequency tuners and rf couplers. The risk of exciting higher order modes (HOM) at high Q values is minimized by selecting a very low cut-off frequency of 3.5 GHz for the end tubes of the cavity. This allows all HOMs (except for the very lowest electric dipole mode) to propagate to the rf couplers where they can be damped. Also the excitation of HOMs is very weak because of the fairly low beam current ($\leq 60\,\mu$A for a single-pass beam and $\leq 20\,\mu$A for a three-pass beam) of the S-DALINAC.

A photograph of a 20-cell cavity is shown in Figure 3. Fabrication and preparation of the cavities was performed in a close interaction

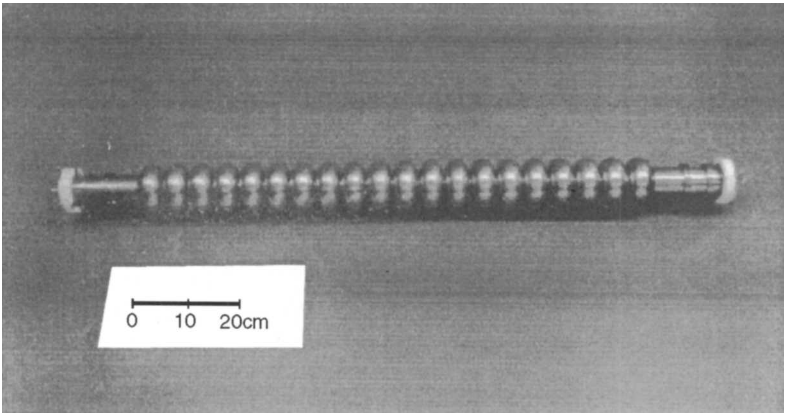

FIGURE 3 Photograph of a 20-cell cavity operating at 3 GHz. The cavity consists of 18 identical center cells and two end cells which compensate the influence of the attached beam tubes.

between industry and our institution. The cavity cells are made from 2 mm thick niobium sheet material with a nominal RRR of 280. In a first step half cells were formed by deep drawing and machining of the rims. Next two half cells were electron beam welded at the equator to form a cell, which then was tuned to a predetermined frequency by inside chemical polishing. The order in which 18 center cells and two end cells should be welded together to form a 20-cell cavity was determined from field profile measurements of 20 individual cells, only stacked together.

After electron beam welding at the irises between the individual cells and adding the beam tubes to both ends, the interior of the 20-cell cavity was chemically polished again. Final tuning of the cavity to a predetermined frequency and field flatness of the accelerating mode (π-mode) was achieved by introducing small radial deformations in three equally spaced locations along the equator of individual cells. For this purpose a special algorithm had been developed, based on the assumption that these deformations changed only the eigenfrequencies of the cells, but not the cell to cell coupling strengths. This proved to be the case so that the algorithm provided a prediction of eigenfrequencies and field profiles for each intermediate step of the tuning procedure. Finally, for the π-mode, a nonuniformity of the accelerating field in the individual cells of less than 2% was achieved. The final step of the manufacturing process and the preparation of the cavities consisted of a final inside chemical polishing (for cleaning and to tune the cavity to the desired operating frequency of the accelerator) and outgassing of hydrogen (several hours at 750°C) in a UHV furnace. It is worthwhile noticing that the cavities were not tested at low temperature in an external cryostat prior to their installation and operation in the accelerator.

If the performance of a cavity has degraded due to a contamination of its surface (caused e.g. by a vacuum failure) cleaning and chemically polishing the affected surface are recommended methods to cure the degradation. However, since the chemical treatment affects the eigenfrequency of the cavity, care has to be taken to remove as little material from the cavity surface as possible. This can be achieved if chemical polishing is applied under very well controlled conditions, as it is the case for the excellent infrastructure of the Tesla Test Facility (TTF) at DESY.[4] There, two 20-cell cavities were cleaned using ultrasonic agitation in demineralized water, followed by chemical polishing at a constant temperature of 10°C and a final rinsing with ultrapure water. A thickness of only one micron was removed from the surface changing the eigenfrequency of the π-mode by as little as 20 kHz. Both cavities fully recovered from the observed degradation. For several other cavities we successfully used a different cleaning method which can be applied in the modest infrastructure of our own institution. After ultrasonic cleaning, the inner surface of the cavities was first oxidized using nitric acid and then rinsed with water. In a second step the oxide was removed by hydrofluoric acid before the cavity was finally rinsed with highly demineralized water. Recently we have added a system for high pressure (10 MPa) rinsing of the cavities but results from this treatment are not yet available.

The current performance of the ten 20-cell cavities installed in the S-DALINAC is as follows: they reach accelerating gradients of 5–10 MV/m, averaging 6.7 MV/m. This is far below figures which are reached presently for sc cavities intended for linear colliders, but exceeds our design gradient of 5 MV/m in all cases. Disappointing is the fact, that the unloaded Q values of the ten cavities yield an average of 7.7×10^8 only, well below 3×10^9 which we have aimed at. We will return to this subject in Section 5.

4 ASSOCIATED EQUIPMENT

Almost as important as the cavity performance is the reliable and reproducible operation of equipment closely associated with the cavity itself. These parts quite often operate at low temperatures and either in helium atmosphere or in vacuum. Therefore it is usually not possible to obtain complete devices commercially, they rather have to be developed for their usually very special application. At the S-DALINAC two very typical devices of this type are in routine use now, but first had to be designed and then tested following guidelines from earlier operational experience: frequency tuners and rf couplers for the sc cavities. They will be briefly described in the following.

Tuning of the cavity eigenfrequency to the accelerator frequency is performed by elastically stretching the cavity in axial direction. The sensitivity of this method is $\Delta f/\Delta l = 500\,\mathrm{kHz/mm}$. It has to be compared with the loaded bandwidth of the cavity which in our case amounts to 100 Hz at an operating frequency of $f = 3$ GHz. Control of the cavity eigenfrequency to within 1 Hz requires that the cavity length ($l = 1$ m) needs to be controlled to within 2 nm. Therefore we decided to use a combination of a motor driven coarse tuner and a magnetostrictive fine tuner, operating at a temperature of 2 K and in a helium atmosphere of some 32 mbar. Two guidelines were followed for the design: all parts inside the cryostat should move slowly and the number of parts sliding on each other had to be minimized (rolling was preferred). The prototype of the construction has been discussed earlier.[5] It proved to work reliably and with the necessary accuracy, and since several years the ten 20-cell cavities and the 5-cell capture cavity of the S-DALINAC are equipped with these tuners which, for a 20-cell cavity, provide a range of 1 MHz for the coarse tuner and 1 kHz for the magnetostrictive fine tuner, respectively, with a resolution of better than 1 Hz.

The most important requirements for the rf couplers were: (a) mechanical rigidity to avoid variation of the coupling strength due to vibrations and (b) externally variable coupling strength for the input coupler whereas the probe coupler should have a fixed but well predictable coupling strength. Furthermore, the couplers had to fit into the existing modules of the cryostat and in particular the input coupler had to match the existing 7/8in coaxial rf input line of the cryostat. The operational principle of the couplers and a measurement from a prototype have already been discussed,[6] therefore we only recall the basic idea: coupling of e.g. the rf input line and the sc cavity is performed in two steps through an intermediate, strongly reentrant cylindrical resonator. The axis of this resonator coincides with the cavity axis (and thus also with the beam axis) allowing the beam to pass through its hollow center conductor. The coaxial rf input line is radially attached to this resonator and the distance between the center conductor of this line and the center conductor of the resonator determines the coupling strength. This distance can be varied from outside the cryostat. On the other hand the power transfer from the resonator to the sc cavity is determined by the distance between the end of the hollow center conductor of the resonator and the iris opening of the first cell of the cavity. This distance was optimized during the design and is fixed. A series of warm prototypes and one partly superconducting prototype showed that the coaxial resonator of the input coupler had to be built from niobium to achieve reliable operation. Because of their weak coupling strength and the low power flow the probe couplers are fabricated from stainless steel. Since 1994 all sc cavities of the S-DALINAC (except the 2-cell capture cavity) are equipped with these couplers and it has turned out that in particular the variable input coupler is very useful to optimize the performance of the sc cavities according to the strongly different beam loading conditions, the S-DALINAC has to cover.

5 SUMMARY

The S-DALINAC has to cover a very wide range of beam energies and currents according to the demands of the different experiments (see Section 2). Table I contains a summary of typical beam parameters for the individual experiments. The upper four rows of Table I show that electron energies from as low as 2.5 MeV up to 120 MeV and beam currents from below 1 nA up to 50 μA have been used in the 3 GHz cw mode of the accelerator where every rf bucket is loaded with an electron bunch and no macrostructure is superimposed on the continuous beam. For the FEL a peak current much higher than it can be produced in this mode is absolutely essential. Therefore, using a subharmonic injection scheme, only every 300th rf bucket is loaded with an electron bunch, which in turn carries 300 times the charge of a "normal" bunch. The operation is still continuous at a bunch repetition frequency of 10 MHz. The lowest row of Table I shows typical figures for a 3 GHz cw beam which has been recirculated two times.

TABLE I

Experiment	*Energy* (MeV)	*Current* (μA)	*Mode*	*Time* (h)
Nuclear resonance fluorescence	2.5–10	20–50	3 GHz cw	3900
LE-channeling, PXR	3–10	0.001–30	3 GHz cw	2100
HE-channeling, PXR	30–85	1	3 GHz cw	800
Electron Scattering	30–120[a]	0.5–5	3 GHz cw	6600
FEL	30–38	$2.7\ \mathrm{A_{peak}}$	10 MHz	2900
Resolution: $\Delta E_{\mathrm{FWHM}} = 50$ keV at $E_0 = 85$ MeV, $\Delta E/E_0 = \pm 3 \times 10^{-4}$				$\sum$16300

[a] At a duty factor of 33%.

The last column of Table I shows how much beamtime has been used by each type of experiment since commissioning of the accelerator.

The fact that the maximum beam energy produced by the S-DALINAC is still somewhat below the design figure of 130 MeV is due to the still modest unloaded Q values of the sc cavities quoted in Section 3 above. If all cavities are operated at 5 MV/m or above their average value of 7.7×10^8 leads to an rf power dissipation exceeding the capacity of the closed cycle helium refrigerator, which amounts to 100 W at 2 K only. Besides the experimental program we are therefore still investigating possible reasons for this phenomenon in order to find a cure. Present studies concentrate (despite the outgassing procedure described in Section 3 above) on hydrogen content of the cavity material and on the possibility of insufficient magnetic shielding of the cavities, which cannot be excluded a priori because of the complicated geometry inside the helium vessel of the cryostat.

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