RESULTS FROM THE S-DALINAC – ONE YEAR OF OPERATIONAL EXPERIENCE FROM A SUPERCONDUCTING ELECTRON ACCELERATOR *)

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Abstract

Since August 1991 the superconducting cw-electron accelerator S-DALINAC at Darmstadt produced single and multi pass beam which is used for different experiments. At energies below 10 MeV investigation of channeling radiation production and nuclear resonance fluorescence experiments are performed. Single pass operation yielding beam energies up to 40 MeV has been used for tests of the Free Electron Laser (FEL) beamline and for the investigation of spontaneous emission from the undulator mainly. Two and three pass operation at higher energies produces beam for electron scattering experiments, (e,e') and (e,e'x), as well as for the production of channeling radiation. True cw operation allows for energies up to 84 MeV limited by the capacity (100 W at 2 K) of the He-refrigerator. At higher energies the duty factor has to be reduced (e.g. d = 50% at 104 MeV), pulse length is on the order of seconds. The successful operation of the entire accelerator was the result of several developments. (i) Six accelerating cavities fabricated from RRR = 280 niobium raised the average field gradient to 6 MV/m. (ii) The control systems for gun, rf, cavity tuners, and the beam transport system including beam diagnostics have been integrated into a reliable remote control of the S-DALINAC. (iii) Computer controlled path length adjustments for the two recirculating beamlines were installed for optimization of the reinjection phase.

Introduction and Present Status

Since the last Linac Conference in 1990 the S-DALINAC has achieved remarkable progress. The accelerator has gone into operation at the end of 1990 when for the first time an electron beam was recirculated and reaccelerated twice and a maximum energy of 75 MeV was obtained. Since then the amount of beam time for different atomic, nuclear physics and free-electron laser physics experiments has kept increasing and the maximum energy, achieved in August '91, raised to 104 MeV [1]. Table 1 below gives the design parameters of the accelerator.

The S-DALINAC consists of a 270 keV injection beam line where the dc electron beam produced by a thermionic electron gun is electrostatically preaccelerated and chopped as well as bunched in order to get the micro structure needed for acceleration in the rf linac. Here a 3 GHz continuous wave structure can be produced as well as a subharmonic micro structure as it is used for FEL operation (see below).This section is followed by the superconducting injection linac formed by a short cryomodule, housing the 5-cell capture section, and a standard cryomodule containing two 20-cell acceleration cavities. An isochronous 180° beam transport system allows the beam from the injector to enter the main linac at energies up to 10 MeV. The superconducting main linac consists of four cryomodules, containing two 20-cell cavities each. The recirculating beamlines consist of two 180° bends formed by separate dipole magnets and four quadrupoles each, connected by straight sections containing seven quadrupoles. Reinjection of both recirculated beams into the main linac is performed via a four magnet chicane. Extraction of the beam to the experimental area is possible after each pass through the linac.

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TABLE I
Design parameters of the S-DALINAC

Beam Energy / MeV	10 – 130
Energy Spread / keV	±13
CW Current / μA	≥ 20
Operating Frequency / MHz	2997
Number of Structures (1 m)	10
Capture Section (0.25 m)	1

For the FEL project [2], the present beam transport system of the accelerator is extended by a bypass to the first recirculation. The straight section of this bypass includes the undulator and passes into the 15 m long optical resonator with its mirror chambers at each end. An optical beam transport system extracts the laser beam to an experimental area outside the accelerator hall.

Operational Experience an Developments

During the beam time for atomic and nuclear physics experiments we gained valuable experience in operating the superconducting cavities and its frequency tuners [3]. Eleven cavities as well as the normalconducting chopper/prebuncher system can now be operated reliably, especially since the magnetostrictive fine and motor driven coarse tuners are part of the computer controlled rf system (see below). A detailed description of the rf system and a comparison with other accelerators' systems is given in [4]. During the last two months the energy spread of the beam could be reduced by a factor of two to $\Delta E/E \leq 10^{-3}$ by improving the performance of the amplitude control circuits. A further reduction of the energy spread seems to be possible by carefully optimizing the individual channels of the rf control system.

The present installation contains quite different superconducting cavities made from niobium of different purity ranging from RRR = 30 to RRR = 280. The according performance data are given in [1]. The average accelerating field measured with electron beam amounts to 6 MV/m which is well above the designed accelerating gradient of 5 MV/m. The highest gradient measured by the energy gain of the electron beam amounts to 10 MV/m and is remarkable for 20-cell cavities, since at present such results are rather exceptional. For a reliable operation of superconducting cavities one has to consider a reduction in the accelerating field of at least 10%. Here detuning due to Lorentz forces (electromagnetic surface forces) and ponderomotive effects [4] are not taken into account.

In order to recirculate the beam from the main linac and to reaccelerate it another time two requirements have to be fulfilled: i) the energy of the recirculated beam has to be five times the energy of the injector beam because the last magnet of the chicane is identical with the last magnet of the 180° bend for the beam from the injector and ii) the phase of the recirculated beam has to match the phase of the injector beam. First attempts to accelerate the electron beam twice [5] or even three times, followed by the calculation of the phase slippage which the injector beam undergoes in the first main linac cavities, led to the construction of a system for adjusting the path length of the recirculating beam transport systems. The phase slippage too strongly depends on the injector beam energy which means that keeping the recirculation length unchanged is impossible. Therefore single magnets or groups of beam transport devices are mounted on linear bearings which are driven by computer controlled synchron motors. For both recirculations a change in the path length of more than 180° with respect to the accelerator frequency of 3 GHz is possible. TRANSPORT [6] calculations showed that only slight changes in the settings of the quadrupoles are required. Without a path length adjustment the successful operation of the S-DALINAC as a recirculating machine would not have been possible.

While commissioning the accelerator control of all beam transport devices and all beam diagnostics as well as of the electron gun was carried out by a local computer system. Since then a much more reliable system has been developed which includes the rf cavity-control and allows for a quite comfortable remote control of the S-DALINAC. Figure 1 gives the functional diagram.

The controller for more than 150 power supplies for dipole and quadrupole magnets and for steering coils, a multichannel ADC, a control unit for eight Faraday cups, and the selection of view screens used for beam diagnostics and the corresponding TV cameras is handled by an LSI 11/73. Hardware adapted programs interface between the different devices and a common data block which can be controlled by local software or using Ethernet from the remote control room. There two workstations build a graphical user interface and two groups of four knobs each can be assigned to any beam transport device.

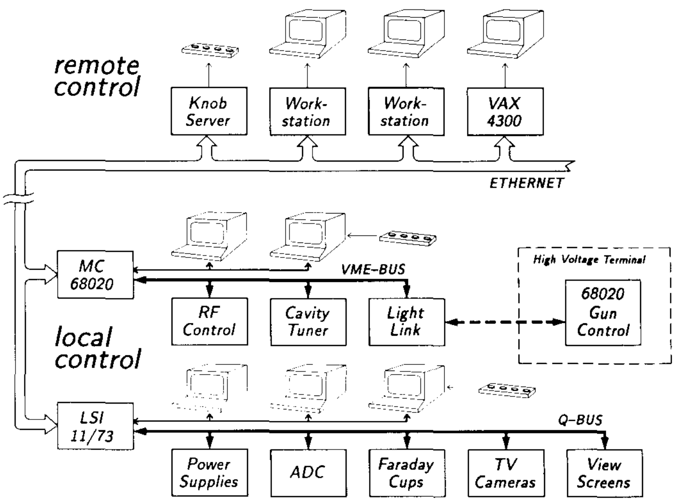

Fig. 1 S-DALINAC control system

The rf-control system, in detail described in [7], consists of a 68020 microprocessor board build in house which is directly connected to 12 rf-control channels of the accelerating cavities and the driver for their tuners via VME-bus. The same microprocessor board acts as an interface to the electron gun control in the high voltage terminal. The connection is realized by a light link. Again either local software allows for operating the rf-system and the electron gun or remote control is possible using a more comfortable user interface, including another group of four knobs assignable to all relevant parameters of the rf-control circuits. For program development and long time storage of machine settings the remote control is part of the laboratory computer cluster.

Utilization of Beam

Since its completion the accelerator has produced many hours of beam time for accelerator test runs but mainly for different nuclear and atomic physics experiments.

At energies below 10 MeV the production of channeling radiation [8] and nuclear resonance fluorescence experiments (γ, γ') [9] are carried out behind the injection linac. Since summer 1991 a high energy beam (30 - 86 MeV) was delivered for first elastic (e,e) and inelastic (e,e') electron scattering experiments which were used to calibrate a new spectrometer (QCLAM). Subsequent to the calibration first coincidence measurements (e,e'p) could be carried out. At energies between 65 and 72.5 MeV the production of channeling radiation as a function of the crystal temperature was studied in a collaboration with the MPI Munich. For the first time the polarization of channeling radiation was measured in a scattering experiment.

Single pass operation for FEL experiments at about 30 MeV also started. We could study the production of synchrotron radiation i.e. spontaneous emission, the whole experimental setup was tested, and the optics including a 50 m long transfer line for the produced near-infrared light were aligned. The next FEL run scheduled for this fall will be used for the commissioning of the subharmonic injection (see below) and to examine the spectral distribution of the spontaneous emission during first lasing experiments.

The maximum energy obtained in an accelerator test run was 104 MeV. Here the accelerator was operated with 50% duty factor (limited by the refrigeration power of 100 W) at a pulse duration of about one second. The achieved energy of 104 MeV is not limited by the cavities' field gradient (see above) but only by the Helium refrigerator.

Further Developments

While completing the accelerator with its recirculations a free-electron laser in the near-infrared region was set up; details are reported in [2] and [10] includes a status report. Utilization of the electron beam accelerated in single pass operation yields laser wavelengths between 6 and 2.5 μm corresponding to electron beam energies of 35 to 50 MeV. The modifications of the accelerator, necessary for the operation of the FEL have been carried out. A modified high current injector consisting of a pulsed electron gun and a subharmonic 600 MHz chopper / prebuncher system has been designed, tested separately and installed at the linac [2].

The subharmonic 600 MHz system uses a frequency generator, phase locked to the accelerator's frequency standard, as a reference for two rf-control circuits (chopper and prebuncher). The principle function is identical to the circuits of the superconducting cavities [7].

For FEL operation the electron gun is pulsed with the 300th subharmonic ($\hat{=}$ 10 MHz) which together with an additional macro structure on the produced electron beam and together with the 600 MHz chopper yields a quite flexible system. While in cw nuclear physics operation electrons are accelerated in every rf period with a beam current of 20 μA ($\approx$3.6 mA peak current), in cw FEL operation only every 300th rf-bucked is filled corresponding to electron peak currents of 2.7 A.

Inbetween there exists a wide variety in time structure only limited in the combination of peak current and macro pulse length with respect to the acceptable energy spread. Limits are set by the time constants of the rf-control circuits and of the superconducting cavities themselves. Using the 600 MHz chopper as well as the 3 GHz chopper at the same time, another feature enlarges the variety: every 5th rf-bucket can be filled or two out of five rf-periods can be used for acceleration.

The increased bunch charge in cw FEL operation gives the opportunity to investigate the excitation and propagation of higher order modes (HOM) as it is interesting with respect to future linear colliders. With its 5 pC per bunch and 100 ns time spacing the induced rf-power per cavity will be about 0.1 % of that in a linear collider cavity. A first estimate yields rf-power in the order of a few mW which allows for measuring the spectral distribution up to about 20 GHz. The propagation of HOM power can also be investigated using the rf-couplers of all superconducting cavities. Because of the possible macro structure the HOM external quality factor can be measured by changing the beam duty factor. Thus the S-DALINAC operated in the FEL mode seems to be a highly suitable tool with respect to accelerator development and some aspects of linear collider studies.

Outlook

Presently six 20-cell cavities, fabricated from RRR=280 niobium, are in the process of their final preparation. They will replace cavities with low Q and therefore we expect (due to lower losses) cw operation at energies above 84 MeV after the next shutdown period. Also the development of a new superconducting rf input coupler (a prototype will be installed and tested this fall) will help to reduce the load on the He refrigerator, allowing to operate the cavities at higher gradients.

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