Development of a Superconducting RF Photo Gun

For all electron accelerators the quality of the injected beam is of crucial importance for the operation of the whole facility. Driven by this need a worldwide research effort is directed towards the development and improvement of electron injectors. RF photoinjectors claim a central part in this field as they are able to produce very high quality electron beams.

Special requirements arise from the operation of high-average-power free-electron lasers and energy recovery linacs. To overcome the serious challenges which the huge RF power requirements and the corresponding cooling efforts present to a normal-conducting design an RF photoinjector with a superconducting cavity would be the natural choice for CW operation. Several approaches have been made, but for the first time a superconducting RF photo gun was successfully put into operation during the year 2002 in Rossendorf. This one is based on a half-cell resonator designed in collaboration with the Budker Institute of Nuclear Physics in Novosibirsk.

The ongoing effort in Rossendorf is now directed to develop a superconducting RF photoinjector for ELBE. In collaboration with the Max Born Institute, Berlin and BESSY, Berlin a 3-1/2 cell photoinjector is planned. This design is targeted to deliver a 77 pC, 1 mA CW beam corresponding to the ELBE specifications but also to allow tests with up to 1 nC bunch charge.
First operation of a superconducting RF-gun

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For the first time, a superconducting RF gun where a photo cathode is inside a superconducting cavity has been working stably over a period of seven weeks.

The cavity of the RF gun is a TESLA type [1] half cell closed by a shallow cone with a centred hole in which the cathode is situated. A detailed description of the cavity has been published in [2]. An overview of the gun is shown in Fig. 1. The gun cavity, together with the cathode support, the RF coupler and a part of the beam tube are installed in the He vessel of the cryostat.

![Image](image_url)

**Fig. 1:** Cryostat of the SRF gun with preparation chamber.

The cathode can be moved by means of a manipulator from the preparation chamber into the cavity. Through a port at the beginning of the beam line laser light is guided to the cathode.

In the preparation chamber Cs₂Te layers are deposited onto the cathodes. In the chamber the pressure was 10⁻¹⁰ mbar, but during the heating of evaporators it increased to 10⁻⁶ mbar. For that reason the quantum efficiency of the cathodes was not better than 0.25%.

The laser consists of an oscillator which works in the additive pulse modelocking (APM) mode. The oscillator supplies a pulse frequency of 26 MHz. After amplification and conversion UV laser pulses with 263 nm wavelength and 5 ps (FWHM) length are obtained. A jitter σ=2 ps (peak-peak) was measured with a stable reference signal from the RF oscillator.

Beam line diagnostics include steereers, view screens, solenoids, a pepper pot mask for measuring the transverse emittance, and a dipole magnet for measuring energy and energy spread. The beam current can be measured by an insulated beam dump at the end of the line.

Fig. 2 shows the measurement of the quality factor of the cavity in dependence on the field strength. The values are from direct RF measurement and from a comparison of measured electron energy with simulation.

The maximum field strength of 22 MV/m near the cathode is limited by field emission. The insignificant difference of Q values with and without cathode shows the good performance of the four stage coaxial RF filter.

![Image](image_url)

**Fig. 2:** Determination of the maximum field strength from RF and energy measurements.

Fig. 3 presents the cathode emission and accelerated (dump) current together with the corresponding electron energy as a function of the laser phase. For a phase window of 60° we obtain complete transmission and the energy reaches its maximal value at φ=0°. These properties are determined by the geometry of the cavity and the field amplitude.

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Fig. 3: Transmission of the electron beam and the dependence of the energy from the laser phase.

At a temperature of 4.2 K we could not see any changes of the quality factor $Q = 2.5 \times 10^8$ of the cavity during the whole period of operation. The field emission of the cavity, which is the reason for the limitation of the field strength, is caused by the difficult clean room handling of the big intrinsic parts of the cryostat. But nevertheless a field strength of 22 MV/m and an electron energy of 900 keV have been obtained.

The maximum bunch charge was 20 pC, which corresponds to an average current of 520 µA in the cw-mode. It is limited by average power and repetition rate of the laser and by the small quantum efficiency of the photo cathode.

Due to the long drift space after the gun and the arrangement of optical elements, we could measure the transverse emittance for bunch charges between 1 and 4 pC only. In agreement with PARMELA calculation we have measured normalized rms-values between 1 and 2.5 mm mrad.

[1] A. Aune et al., DESY 00-031, Hamburg 2000
RF System and Measurements at the Superconducting RF Gun

H. BÜTTIG, R. SCHURG, A. TRIBENDIS

The Superconducting RF Gun (SRF GUN) was put into operation successfully in 2002 [1]. During a seven week period several experiments had been done to study the performance of the system itself and to measure beam parameters. The RF system was designed to provide flexibility, e.g. to measure the cavity performance and to operate the gun with beam. A modified self exciting RF system was chosen in which the SC cavity determines the frequency because the built-in cavity tuner could not be used.

The general outline of the RF system is shown in Fig. 1. The generator operates in a phased locked loop (PLL) and its frequency is controlled by the eigenfrequency of the TM_{010}-mode of the cavity. A self exciting circuit oscillates under the condition that the total gain in the loop amounts to one and that the total phase shift along the loop is an integer multiple of 2\pi. In principle one doesn’t need a generator to operate a self exciting loop. In our case the error signal of the PLL drives the automatic frequency control (AFC) of the generator and closes the loop.

![Fig. 1: General Outline of a self-exciting (AFC) RF-system.](image)

In the phase detector (a high-level mixer was used) the phases of the cavity probe signal and the RF output signal of the generator are compared. If the amplitudes of the two input signals are kept constant the filtered dc output signal of a mixer depends only on the frequency- and phase difference of its two input signals. If the frequency and phase of the generator signal match the cavity TM_{010}-resonant frequency and zero phase, the system locks in, indicated by zero output voltage of the phase detector. The phase shifter in the LO-path of the mixer controls the working point of the system. Care must be taken when tuning this phase shifter because of two working points with opposite phase settings. Only one setting is stable and provides "lock-in" and tracking.

![Fig. 2: Block diagram of the RF-system.](image)

The block diagram of the RF-system used is shown in Fig. 2. Its "core" is the self exciting frequency loop described above. The output signal of the generator (SMT-Rohde & Schwarz) is distributed into three signals, one to synchronize the laser system, one to control the self exciting frequency loop (AFC) and one to drive the RF amplifier providing the cavity gradient and the beam power. Several tests had been done to ensure that the internal PLL system of the laser locks to the signal of the self exciting RF system, which is frequency- and phase modulated by microphones. The PLL of the laser is remote controllable. Gradient- and phase control of the SHF Gun are performed by individual control loops. The controller board used was designed for the ELBE RF-system and is described in [2]. Two RF-amplifiers were planned, a 150 W solid-state amplifier (SSB-Electronic GmbH) to study the cavity performance without beam and a 5 kW klystron amplifier to operate the cavity with beam. The VKL7811 klystron provides 10 kW RF-saturated power at 1300 MHz, its 3-dB bandwidth is 3.5 MHz. The TM_{010}-eigenfrequency of the GUN was lower. Detuning was possible by carefully adjusting the cavity-plungers of the klystron while increasing the power step by step. The body-current has to be monitored permanently during the procedure and was kept below 40 mA. Because the input cavity and the output cavity of the klystron are not tunable, the output power of the detuned klystron is limited to about 5 kW.

Measurements had been done to test the setup itself and to verify the measurements done at DESY using the vertical test stand [3]. The setup used is given in Fig. 2, the procedure used is described in [4] and [5].

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Cavity parameters:
- TM010-eigenfrequency: 1297.234 MHz @ 4.2K
  1294.545 MHz @ 4.2K.
- Characteristic Impedance $R/Q = 120.5 \, \Omega$
- Transit time factor TTF= 0.7525
- Coupling $\beta = 1$
- Length of the accelerating gap: 0.0738 m
- DESY: $Q_0 @ 4.2 \, K = 2.3 \times 10^8$ [2]
- DESY: $Q_0 @ 1.8 \, K = 1.5 \times 10^{10}$ [2]

Because of the manual helium filling using a dewar most of the experiments were performed at 4.2 K. Two tests had been done using pump-down technique to achieve a helium temperature of 2.5 K. The unloaded quality factor $Q_0$ is increased by a factor of three when changing the helium temperature from 4.2 K to 2.5 K.

The gradient against the incident RF power is shown in Fig. 5. The maximum incident RF power was limited by field emission without photo cathode as well as with photo cathode inserted. Because the photo cathode represents a certain load the maximum gradient is reached at higher RF power levels. In both cases field emission limits operation at the same gradient.

![Fig. 5: Gradient vers. incident RF-power (field emission limited).](image)

During all experiments the flow of the helium return gas was measured. In Fig. 6 the helium flow rate is plotted against the gradient $E_{\text{peak}}$. The helium flow represents the dissipated power ($P_{\text{diss}} \sim E^2$).

![Fig. 6: Helium gas flow vers. gradient, without beam.](image)

In 2002 the project for a cw-mode photo injector with superconducting cavity has been continued. With the test-stand containing a half-cell cavity the operation of a superconducting rf gun was demonstrated successfully. In the following the results of the beam parameter measurements will be presented. These results were obtained during two operation period in March and June 2002. A description of the gun design is published elsewhere [1], and further information on the various subsystems are given in some other contributions of this annual report.

For the beam parameter measurements a diagnostic beam line was installed. Its layout is shown in Fig. 1. At the beam line the following elements were arranged: two solenoids for focusing, three steerer sets for adjustment, four movable Chromox view screens, a pepper-pot mask for transverse emittance measurement, a 30° spectrometer magnet, a kicker cavity planned for pulse length determination, and a beam dump with current measurement. The essential drawback of the measurement set-up was the position of the first solenoid. Although it was as close as possible to the cryostat vessel, the distance between it and the cavity was too long. Due to a strong increase of the beam divergence from the gun for higher bunch charges, the beam envelope at the solenoid was too large for a proper focusing and the beam was partly lost.

The UV laser delivered pulses up to 40 nJ with a micropulse frequency of 26 MHz. This corresponds to a bunch charge of 25 pC for a photo cathode with a quantum efficiency of 0.3%. Lower bunch charges were produced by reducing the laser power with a polarization filter. The macropulsing of the electron beam, necessary in the case of inserted view screens, was done by pulsing the pump diodes of the laser amplifiers. The Measurements were carried out with an rf input power between 40 and 100 W (without beam) corresponding to peak field strengths $E_{x,\text{max}}$ between 18 and 22 MV/m.

**Fig. 1**: Schematic of the diagnostic beam line at the superconducting rf photoelectron gun.
Fig. 2 presents the variation of the laser pulse. The emission current at the cathode, the accelerated beam current (dump current) and the beam energy are shown. The cathode current could be measured since the photo cathode is electrically insulated with respect to the cavity. The measurement was done at 39 W rf power (18 MV/m peak field strength) and approximately 2 pC. An operation window was found between about 0° and 50° where the rf field extracts the electrons and their energies are high enough that they can pass through the beam line.

![Graph showing cathode beam current, accelerated beam current and beam energy as a function of laser phase for 2 pC bunch charge and 18 MV/m peak field strength (40 W rf power).](image)

**Fig. 2:** Cathode beam current, accelerated beam current and beam energy as a function of laser phase for 2 pC bunch charge and 18 MV/m peak field strength (40 W rf power).

The beam energy in dependence on the rf power is presented in Fig. 3. In this measurement the laser phase was 10°, i.e. the electron energy had nearly its maximum value. From the vertical spot size of the electron beam on the view screen behind the spectrometer magnet the energy width could be determined.

![Graph showing beam energy as a function of rf power.](image)

**Fig. 3:** Beam energy as a function of applied rf power.

![Graph showing energy spread as a function of laser phase and PARMELA simulation with 10 ps and 20 ps laser pulse length for 1.5 pC bunch charge and 18 MV/m peak field strength.](image)

**Fig. 4:** Measured energy spread as a function of laser phase and PARMELA simulation with 10 ps and 20 ps laser pulse length for 1.5 pC bunch charge and 18 MV/m peak field strength.

The result of ΔE/E as a function of the laser phase at 40 W rf power and 2 pC bunch charge are shown in Fig. 4. Additionally, the figure shows two curves for different laser pulse lengths obtained from PARMELA calculations. The measured energy width could be caused by a laser pulse with an effective length of 20 ps which includes the jitter in the phase synchronization.

Cs$_2$Te Photo Cathodes for the Superconducting RF Photoelectron Gun

D. Janssen, P. Michel, P. Evtyushenko, T. Quast, J. Teichert

The Rossendorf superconducting rf (SRF) photoelectron gun [1] uses caesium telluride photo cathodes. The advantages of this material are a high quantum efficiency, long life-time and ruggedness against bad vacuum. Cs$_2$Te is a semiconductor with a band width of about ...eV. Therefore it requires UV laser light for electron production. The laser has a 26 MHz Nd:YLF oscillator (1053 nm) with additive pulse mode looking, diode-pumped amplifiers, and twofold frequency doubling. It produces pulses at 263 nm with 5 ps length and 40 nJ maximum energy. The Cs$_2$Te photo layer is on the top surface of a gold-coated copper cylinder with 10 mm diameter and 15 mm length. This cylinder itself is part of a complicated cathode assembly, about 220 mm long, which can be moved inside vacuum from the preparation chamber into the resonator cavity, and can be mounted there by means of a thread.

The deposition of the Cs$_2$Te layers on the gold-coated cathode surface was done in the cathode preparation chamber by subsequent Te and Cs evaporation. The chamber had an ion pump and a titanium sublimation pump. The vacuum pressure was 10$^{-10}$ mbar. In the chamber there were four evaporators for tellurium and caesium (caesium chromate), a quartz oscillator to measure evaporation rate and layer thickness and a cathode heating. The evaporator in use could be moved in front of the cathode by a manipulator. Tungsten coils around the evaporators heated them and their temperatures could be measured. An aperture in front of the cathode defined the size and position of the Cs$_2$Te spot. It was also used as an electron collector. For that purpose a high voltage could be applied.

The aim was to produce an about 20 nm thick spot of Cs$_2$Te with 5 mm diameter central to the cathode surface. Before deposition the cathode was heated to a temperature of 120°C. The deposition was started with the tellurium. The temperature of the evaporator was successively increased until Te evaporation happened. The evaporation was stopped if the desired thickness of 10 nm was reached. After that the Cs evaporation was performed in the same way. During Cs deposition the layer was illuminated with the laser beam and the photo current was monitored. The Cs evaporation was performed until the photo current saturated. We found that in the following few minutes the photo current dropped down to about 60 % of its former value.

The main problem during the evaporation process was the rapid increase of the vacuum pressure up to about 10$^{-7}$ mbar. To prevent a further degradation, it was necessary to increase the evaporator temperatures very slowly. We think that the bad vacuum was the reason for the low quantum efficiency of less than 1% of the produced photo cathodes. Furthermore, the reproducibility of the evaporation process and the mechanical position accuracy were unsatisfactory.

The quantum efficiency of the prepared photo cathodes were measured in the preparation chamber and inside the photo gun where the insulated cathode allow to apply a high voltage or the rf field of the cavity could be used. Fig. 1 shows the result of a quantum efficiency measurement in the preparation chamber with a slightly defocused laser spot.

During the use of the photo cathode in the SRF gun we observed that the photo current fluctuated with the laser spot position on the cathode. This inhomogeneity is also visible in the photograph of the cathode after use in Fig. 2.

More systematic studies of the photo emission homogeneity were performed by scanning the focused laser beam across the cathode. These measurements were done in the preparation chamber and with the cathode in the cavity with dc bias or rf field. Thereby a virtual cathode was used to get the laser beam position on the cathode. (After the movable mirror a part of laser beam was directed onto a florescence screen with a coordinate mesh.) Fig. 3 presents homogeneity measurements carried out in the preparation chamber. The circular distribution agrees with the Cs$_2$Te spot diameter of 5 mm but a region with high quantum efficiency was found on one side. The photo current distributions of the cathode measured in the gun cavity with dc bias and applied rf field are shown in Fig. 4. The different fields influences the distributions but in both cases a high quantum efficiency at the lower left part of the cathode is visible.

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**Fig. 1:** Photo current versus bias voltage of the aperture measured in the preparation chamber.

**Fig. 2:**...

**Fig. 3:**...

**Fig. 4:**...

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**Fig. 2:** Photograph of a gold-coated cathode with deposited CsTe layer.

**Fig. 3:** Photo current distribution measured in the preparation chamber.

**Fig. 4:** Photo current distribution of the cathode measured inside the gun cavity with applied dc bias (above) and rf field (below).

Superconducting RF gun drive laser diagnostic system

P. Evtushenko, T. Quast

During the experiments with the Rossendorf superconducting RF gun [1] we have found that a diagnostic of the drive laser parameters is a very important issue for the gun operation. The drive laser diagnostic system is shown in the Fig. 1.

Position and size of the laser spot on the photocathode have a strong influence on the electron beam transport in the gun cavity. Hence it is necessary to online monitor and control both parameters. Position of the laser spot on the cathode was adjusted with a remote controlled mirror holder driven by piezo motors. A quartz plate was inserted behind the mirror to reflect a part of the laser light to a reference screen with a mesh. The reference screen is placed at the same distance from the adjustable mirror as the photocathode, hence the laser spot on the reference screen has the same size and is moved by the same distance like the spot on the cathode. The position on the reference screen was monitored by a video camera.

The bunch charge was changed by controlling the laser micropulse power. Therefore a λ/2 plate at the entrance of the amplifier could be remotely rotated. To monitor the laser power during the gun operation a reflection from a quartz wedge was given on a UV diode. The diode was calibrated with the help of thermopile type powermeter.

The drive laser obviously must be synchronized to the RF system of the gun. Since it was not possible to stabilize the SRF cavity frequency to a stable master oscillator the cavity frequency was defined as a reference frequency. So the laser was synchronized to the cavity frequency. The laser oscillator works with repetition rate 26 MHz. To ensure a high accuracy the phase detection was performed at 1.3 GHz, comparing the master oscillator with the 50th harmonic of the laser repetition frequency.

The phase detector with an PID controller adjust the oscillator cavity length via a piezo element. The phase detector signal represents the phase jitter of the laser with respect to the reference. In our experiments the jitter was 12 ps peak-peak. The laser jitter with respect to a stable reference is about of 2 ps.

The drive laser for the SRF gun in Rossendorf, was developed at the Max-Born-Institute in Berlin in the group of Ingo Will [2].

Fig. 1: The optical diagnostic at the SRF gun.

Fig. 2: The phase detector signal: laser is not synchronized (upper), laser is synchronized to the cavity frequency (lower).

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Cavity field calculations for the ELBE superconducting electron gun

K. Möller

In February 2002 for the first time ever at the ELBE facility an electron beam was obtained from a superconducting photoelectron RF gun (SGUN). Based on the experience gained in the prototype experiments now work is being conducted for an improved design and a final version of a superconducting electron gun. One important aspect of these activities are extensive simulation calculations. For this purpose additionally to existing codes two new computer codes have been developed. This was considered to be worthwhile since in view of the high total costs of a development of a superconducting gun it is of importance to have several independent checks of the design concept. Furthermore with source codes which are known in all detail one is highly flexible with respect to any desired modification. The first code (SGUN_FIELD) calculates the cavity fields (electric and magnetic) and the resonance frequency for a given cavity contour and a given field mode. In the second code (SGUN_MOTION) the motion of electron bunches in the cavity is calculated [1].

![Fig. 1 1.3 GHz fundamental mode in a spheric cavity cell.](image1)

![Fig. 2 Electric field in the 1/2-cell SGUN prototype cavity.](image2)

![Fig. 3 1/2-cell SGUN cavity with part of the attached beam line.](image3)

The SGUN_FIELD code is based on the MAXWELLian equations which are solved in cylinder coordinates imposing the usual boundary condition of vanishing tangential electric field components on the cavity surface. By defining a mesh within the cavity the partial differential equations are converted into a system of homogeneous algebraic equations. These equations are solved by an iteration method. Finally one ends up with the values of the electric field vector in the mesh points. The magnetic field is obtained by once again applying the MAXWELLian equations. Quite a lot of effort has been made to check the numerics of the SGUN_FIELD code. To this end among numerous tests the code was also applied to a spheric cavity (Fig. 1). In this case the solution can be derived in analytical form. Inserting the analytical solution into the numerical equations it turned out that the analytical solution solves these equations with high accuracy. In Figs. 2,3 results are shown for 1/2-cell cavity $TM_{010}$-mode fields.

[1] this report, p. 57
Simulation calculations of electron motion in the ELBE superconducting electron gun

K. Möller

The motion of electron bunches in cavity fields, obtained e.g. from SGUN_FIELD [1], is calculated by means of the newly developed code SGUN_MOTION. The kind of results yielded by SGUN_MOTION can be seen by looking at the examples shown in Figs. 1, 2. Here the electron motion was calculated for the 1/2-cell cavity which was used at the ELBE superconducting gun prototype experiments. In Figs. 1, 2 the coordinate system has been chosen such (cf. [1]) that the cavity beam axis ranges from \( \overline{z_{le}} = -17.03 \) mm to \( \overline{z_{right}} = +53.63 \) mm with the maximum of the cavity contour at \( z = 0 \). At the cathode in the cavity \( z = z_{le} \) a bunch of cylindrical shape is generated by a 3-dimensional random number generator. The electrons of the bunch undergo interactions due to the electric and magnetic cavity fields as well as to the interelectron forces as soon as they emerge from the surface of the cathode. In the figures (upper lines) the time evolution of the bunches is shown with the current positions on the beam axis of the cavity displayed as snapshots in time intervals of 40 ps. As shown in the figures simultaneously with looking at the spatial behaviour of the bunches also a set of derived quantities is calculated and displayed such as the kinetic energy, the velocity and the transverse normalized rms emittance. Also calculated (but not shown here) are the transverse and the longitudinal particle momenta, the transverse velocity, the longitudinal emittance, the transverse and longitudinal phase space distributions and the current rf-phase. The main parameters of the example presented here are given in figure caption of Fig. 1. Fig. 2 represents the same calculation as Fig. 1 but with the interaction between the electrons switched off. From the comparison of Fig. 1 and Fig. 2 one can infer that the existence of the interelectron forces (space charge) leads to an increase of the bunch radius by about a factor 3 whereas in the absence of space charge (Fig. 2) the bunch radius even slightly decreases. This latter fact is due to the off-axis radial cavity field which results in a focusing effect. Furthermore one can conclude that the observed normalized emittance growth almost completely originates from space charge effects. It should be mentioned that in the given test example the initial velocity distribution of the electrons was set equal to zero (resulting in zero normalized emittance at start). In first test calculations the SGUN_MOTION code has revealed good performance up to 1nC bunch charge. A good agreement was obtained between the results for 1100 and 11000 bunch particles respectively. After further checks and comparison of the results with other electron transport codes the SGUN_MOTION code will be used for detailed systematic calculations to contribute to the search for an optimum design of a superconducting RF photogun.

Fig. 1 Electron bunch motion in the 1/2-cell SGUN cavity with space charge interaction switched "on". The main parameters are: average field gradient: 20 MV/m, RF phase at bunch start: 45.8°, bunch length: 10 ps, bunch charge: 20 pC.

Fig. 2 Electron bunch motion in the 1/2-cell SGUN cavity with space charge interaction switched "off". The parameters are the same as in Fig 1.

[1] this report, p. 56
Feasibility study of an industrial 1.3 GHz 100 kW table top accelerator

Ch. Schneider

At the Forschungszentrum Rossendorf (FZR) the build-up of the superconducting (sc) 1.3 GHz accelerator ELBE is still in progress. Furthermore, a new sc photo injector (SRF gun) [1] is under development, which should accelerate electrons up to 10 MeV at 1.3 GHz frequency. Since the applications of electron accelerators also for industrial purposes are steadily increasing one can speculate about transferring the above named state of the art technology to industrial electron accelerators. At the FZR a feasibility study of such a table top electron accelerator (TTEA) has been performed to investigate its technical limits and marketability.

The use of electron accelerators is more and more interesting for applications where the destructive potential of the electrons are used like sterilization of medical waste and medical products, food irradiation or decontamination of sewage. For these processes a high power is required to achieve a high product throughput in a plant. The aim is therefore to use beam powers of around 100 kW or more. The energy of such electron accelerators should be kept below the threshold of the photo nuclear reaction ($\gamma$,n). For that reason the design values are 10 MeV electron energy and at least a mean beam current of 10 mA.

There are two machines on the market, which could serve for comparison because they are leader in beam power and efficiency. One is the IMPELA [2], a normal conducting linear accelerator driven in pulsed technique at 1.3 GHz with special designed cavities for cooling purpose. This machine has a beam power of 50 kW at 10 MeV beam energy. The market leader is the Rhodotron [3], equipped with a large half-wavelength coaxial cavity operated at 107.5 MHz. The beam is re-circulated through the cavity several times. The version TT300 of the Rhodotron provides a power of 150 kW at 10 MeV.

The central device in the concept of the TTEA is a sc cavity with implemented photo cathode, like the SRF gun, see Fig. 1. The cavity is made of 6 standard TESLA cells and a special 1/2 niobium cell. In the rear of the 1/2 cell is an opening for the photo cathode with following coaxial filter. The photo layer of the cathode is made of Cs$_2$Te therefore an UV-Laser with 0.26 µm wavelength is necessary for electron emission. For 10 mA beam current and cathode quantum efficiencies between 2 and 10% a design laser power of 6 W is required. The cavity and the cathode support are housed in a cryostat. A helium plant performs the liquid helium supply and the shield cooling of the cryostat. A small helium liquefier in the category of about 10 l/h is sufficient here. The beam is guided through a 90° bended beamline, scanned by a raster system and extracted through a window, comparable to similar irradiation plants. The RF is produced by e.g. a 130 kW klystron and coupled to the cavity by a high power coupler.

![Fig. 1: Major components of the 1.3 GHz sc table top electron accelerator driven by a photo gun.](image)

First results of operating the sc photo gun (SRF) at a Helium bath temperature of 4 K are described in [1]. For the evaluation of the technical feasibility of the entire concept the different components can be separated in three groups. Components that are technically approved and in similar implementations available on the market, need only adaptation and commissioning. These are the liquid helium plant, the cryostat, the beam extraction system, the RF generation and RF control. The second group belongs to up till now not realized components but from likewise designs, literature or expertise their proper performance could be expected. These are the laser system, the RF power coupling, the 6 and 1/2 cells cavity and the quantum efficiency of the Cs$_2$Te cathode between 2 and 10%. The last group are components or functionalities that are not approved until now. These are the operation of the cavity cathode system at 1.8 K and the quality loss of the niobium cavity due to surface contamination from the cathode material at long time laser power operation.

From the viewpoint of efficiency the super conducting technology has its main advantages for high gradients and cw beams due to the low RF loss in the sc cavity walls. Since the production of cold helium is a very inefficient process the overall efficiency must be taken into account. In Tab. 1 the main contributions to the total efficiency for the TTEA are specified. The efficiency of the cavity with the cryogenics included is around 50% at 100 kW beam power. The total efficiency of beam power to mains power amounts to around 20%. Since the RF power loss in the cavity walls depends not on the beam current, a high beam
power is also achievable with normal conducting cavities operated in pulsed mode with very high beam current. The IMPELA accelerator e.g. is operated with a duty factor of 5% for a mean beam power of 50 kW. Taking into account efficiencies for klystron and its power supply the same as for the TTEA one ends up with a total efficiency for the IMPELA with around 15% at 50 kW beam power [2]. The concept of the Rhodotron has two major advantages. One is using a low gradient due to accelerating the beam several times through the cavity and therefore producing low RF loss in the cavity walls. The second is using a low RF frequency of 107.5 MHz generated very efficiently by a tetrode amplifier. The total efficiency of the Rhodotron amounts to around 40% at 100 kW [3].

The marketability of irradiation plants are dominated to around 40% by the capital costs of the accelerator [4]. The operating costs of such plants are very comparable but may slightly differ due to e.g. the time period of the maintenance intervals and mains power costs. Comparing the capital costs between the different concepts some additional items for the TTEA must be considered, these are the helium plant, the laser system and the cryostat. These further costs amount totally to around 1.5 million €. The extra systems Helium plant and laser worsen also the ease of maintenance because they enhance the complexity of the complete machine.

From the feasibility study the following conclusions can be drawn. The TTEA seems to be technical practicable except for some outstanding tests of the SRF gun concept for long term operation at high beam current and of course difficulties which could arise from actually not realized components like the laser system or the high power coupler. There are industrial accelerators on the market with comparable or slightly better parameters but simpler in design and therefore easier to maintain in an industrial surrounding. The main advantages of the SRF concept, which are excellent beam parameters like emittance, bunch length or energy spread are from minor importance for industrial applications.

![Table: Total efficiency of the table-top accelerator.](image)

<table>
<thead>
<tr>
<th>Mains power subsystems</th>
<th>Power or efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mains power Helium plant</td>
<td>106 kW</td>
</tr>
<tr>
<td>Beam power (100kW) + RF loss of the cavity and power coupler</td>
<td>100.3 kW</td>
</tr>
<tr>
<td>Sum</td>
<td>206.3 kW</td>
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<td>Efficiency of beam power (100kW)</td>
<td>48.5 %</td>
</tr>
<tr>
<td>Mains power klystron power supply</td>
<td>400 kW</td>
</tr>
<tr>
<td>+ Mains power helium plant</td>
<td>506 kW</td>
</tr>
<tr>
<td>Total efficiency: mains power to beam power</td>
<td>19.8 %</td>
</tr>
</tbody>
</table>

Fig. 2: Total efficiency of the table-top accelerator.

[1] this report, p. 47