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PHIN

Report on the Development of a Radio-Frequency Photo Electron Source with Superconducting Niobium Cavity (SRF Gun Realization)

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Abstract

The report describes the realization of a superconducting RF photo electron source which will be installed at the ELBE superconducting electron linac.

1. Introduction

In the research center Dresden-Rossendorf (FZD) a superconducting RF photo-injector (SRF gun) with a 3 ½-cell niobium cavity has been developed for installation at the ELBE superconducting electron accelerator. This SRF gun will allow for continuous wave operation with a final electron energy of 9.5 MeV and with an average current of up to 1 mA. The goal of this project is to build a fully functioning superconducting photo-injector which will be used in routine operation at ELBE in future. Beside the significant beam quality improvement expected for the ELBE accelerator, the operation at ELBE will allow long term studies of important issues of SRF injectors like low-temperature operation and lifetime of photocathodes, or cavity quality degradation. Because of its attractiveness, the capability for the future applications in modern accelerator projects will be demonstrated.

Therefore the SRF gun will operate in three modes: the standard ELBE FEL mode with 77 pC and 13 MHz pulse repetition, the high charge mode for neutron physics at ELBE and ERL studies (1 nC, 0.5 MHz), and the BESSY FEL mode (2.5 nC, 1 kHz). In Tab. 1 the gun parameters of these operation modes are presented. The ELBE mode is determined by the two existing far infrared FELs, requiring 13 MHz bunch repetition rate, as well as the maximum average current of the ELBE accelerator of 1 mA. For this mode the new gun will improve the beam quality essentially in comparison to the existing thermionic injector. The high charge mode is impossible with the existing ELBE injector, but it is essential for neutron physics experiments where time-of-flight measurements require more than 1 µs pulse spacing without significant average current reduction. At the same time, 1 nC is a typical bunch charge for new FEL projects and state-of-the-art normal-conducting RF photo injectors (e.g. the X-FEL at DESY). Thus 1 nC is interesting for beam parameter measurements in a comparable study. For the soft X-ray BESSY FEL project, a bunch charge of 2.5 nC is envisaged and the SRF gun will be evaluated with respect to that future application.

Table 1: Gun design parameters and expected beam values of the planned operation modes.

	ELBE mode	**high charge mode**	**BESSY-FEL**
RF frequency	1.3 GHz		
beam energy	9.5 MeV		
operation	CW		
drive laser	262 nm		
photocathode	Cs_2Te		
quantum efficiency	≥1 %		≥2.5 %
average current	1 mA	≤0.5 mA	2.5 µA
pulse length	5 ps	20 ps	50 ps
repetition rate	13 MHz	≤500 kHz	1 kHz
bunch charge	77 pC	1 nC	2.5 nC
transverse emittance	1.5 µm	2.5 µm	3.0 µm

The development of the SRF gun was launched in 2004 with the start of the CARE/PHIN project. During the three year until now all components of the SRF gun have been designed, fabricated in the laboratory workshops, or delivered by companies. Besides the SRF gun itself, a sophisticated diagnostic beamline is under construction, which will allow the measurement of all significant beam parameters as current, energy, energy spread, transverse emittance, and bunch length. The SRF gun also required some investment in the infrastructure. A photocathode preparation laboratory was built. This lab and the room for the driver laser were equipped with clean-room technique. Test benches for rf measurement and warm tuning of the niobium cavity, for the check of the cathode cooling system, and for measurements of the cavity tuners were built. Finally, the existing thermionic injector at ELBE was displaced and modified in order to obtain the space for the installation of the new SRF photoinjector.

The SRF photo injector consists of the following main components:

- helium cryostat,
- niobium cavity,
- main power coupler,
- cavity tuning system,
- photocathode,
- photocathode support and cooling system,
- photocathode transfer system.
- UV driver laser,
- UV laser beam line,
- helium pipeline,
- liquid nitrogen pipeline.

A three-dimensional computer model of the SRF gun cryostat with cathode transfer system is presented in Fig. 1. In the following sections a short description of the design, parameters and realization status is given.

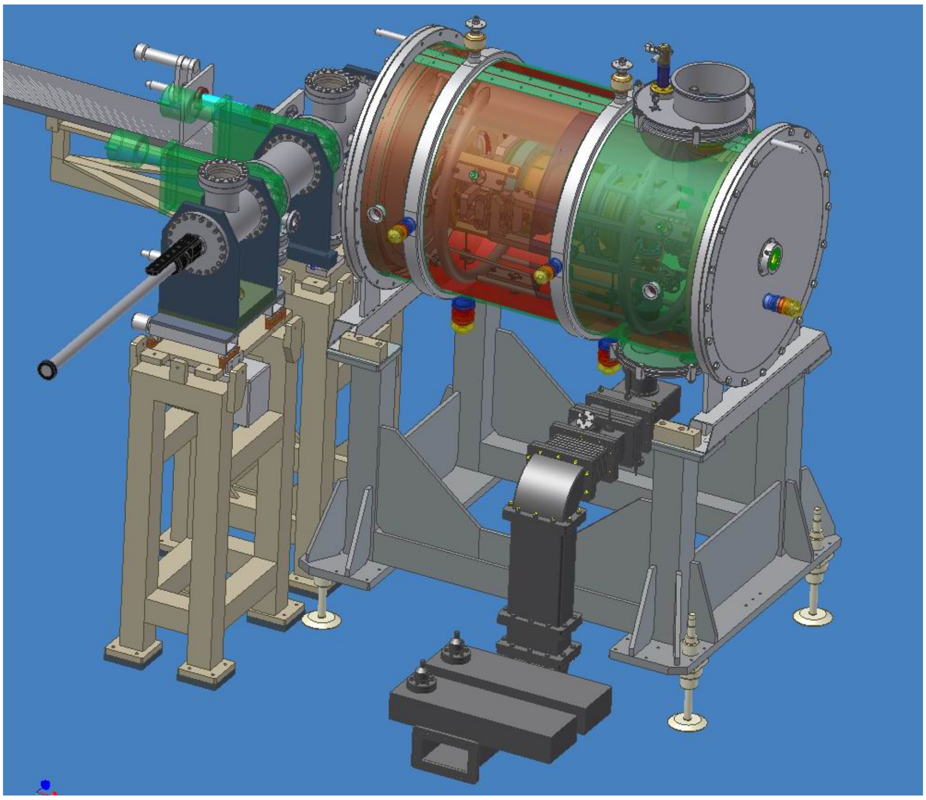

Figure 1: three-dimensional design model of the SRF gun

2. Helium Cryostat

The SRF gun cryomodule contains the 3½ cell niobium cavity which consists of a half-cell with the normal-conducting cathode in it and three acceleration cells with TESLA shape. The cavity must be cooled with liquid super-fluid helium. Thus the helium temperature is between 1.8 and 2.0 K, which corresponds to He gas pressures between 20 and 35 mbar. The envisaged acceleration gradient of this cavity is 18.8 MV/m which corresponds to a maximum axial peak field of 50 MV/m in the TESLA cells. The geometry constant is 240 Ω and R/Q is 165 Ω. For $Q_0 = 1\text{x}10^{10}$ and the gradient mentioned above a RF power dissipation of 26 W is expected.

Fig. 2 shows a section view of the SRF gun cryomodule. The stainless steel vacuum vessel has a cylindrical shape with 1.3 m length and 0.75 m diameter. The vessel has flat plates on both sides and is designed as short as possible in order to get a minimum length of the transfer rod for cathode exchange, and on the beam line side it is planned to install a solenoid magnet for emittance compensation as close as possible. The He port and the N_2 port are on top of the vessel on the right hand side. From the port the He flows through a heater pot and the two-phase supply tube into the chimney of the He tank. For the cooling of the thermal shield, liquid nitrogen is used. The 70 K shield consists of a cylindrical Al sheet welded to two circular tubes filled with N_2. The liquid N_2 tank in the upper part of the module must be refilled approximately every five hours by means of the liquid nitrogen pipeline. The liquid N_2 is also used for the cooling of the photo cathode stem.

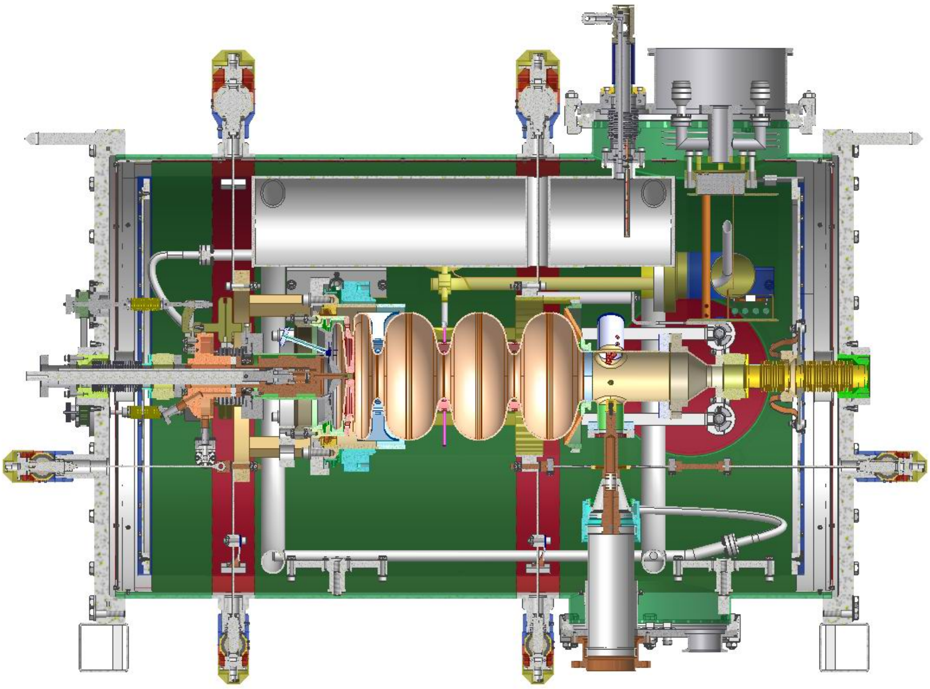

Figure 2: Sectional drawing of the SRF gun cryostat.

The cavity is passively protected against ambient magnetic fields by means of a μ-metal shield, placed between the 80 K shield and the vacuum vessel. The He tank is made of titanium. Three stainless steel bellows are integrated for the two tuning systems and for the manually tuned choke filter cell. The ten thin titanium spokes support the He tank and allow the adjustment of the cavity position. The spokes terminate in micrometer drives and vibration dampers attached to the vacuum vessel. From outside it is also possible to move the cathode support and cooling system which allows the adjustment of the photo cathode with respect to the cavity. For that reason, three rotation feed-throughs exist in the backside plate of the vacuum vessel. Fig. 3 shows the design of that system.

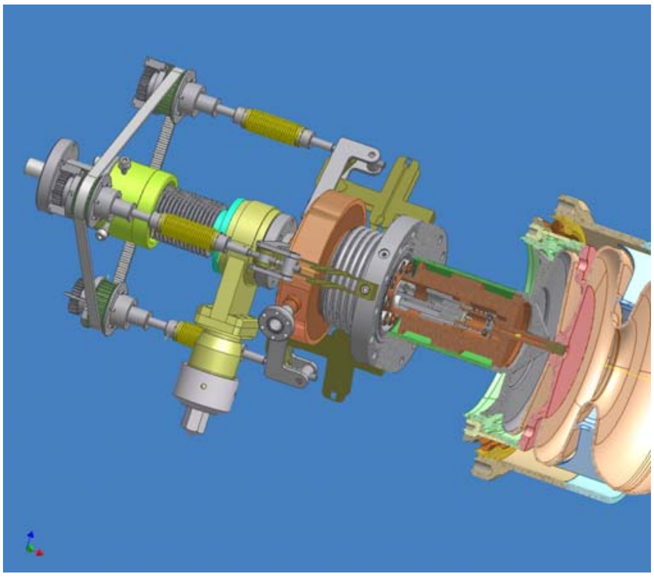

Fig. 3: Design of the cathode cooling system with motor-driven alignment. The wheels with the gear belt are outside the vacuum vessel.

A photograph of the cryostat vessel with opened side covers is presented in Fig. 4. The view shows the beamline side. The pot above the beamline tube is part of the He system and contains the heater. Below the beamline the power coupler is visible. The two horizontal spindles above and below the beamline tube belong to the cavity tuners.

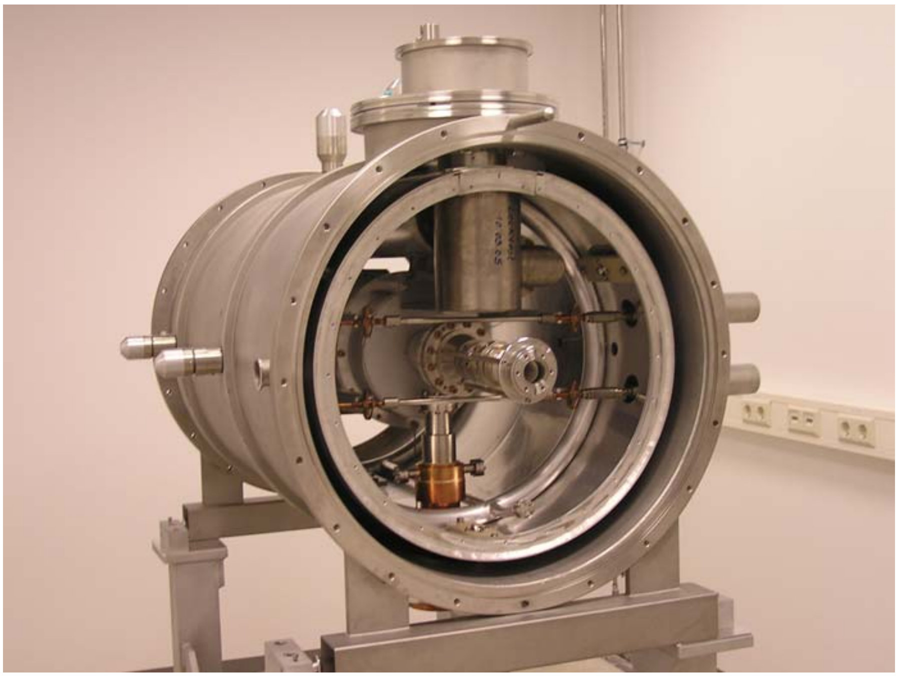

Fig. 4: Photograph of the cryostat vessel during assembly.

The photograph in Fig. 5 shows a view to the photocathode side. In the center is the tube for the cathode insertion. The copper body is the liquid nitrogen reservoir for cathode cooling. The three bellows belong to the cathode alignment system and will be connected to feed-throughs in the vacuum vessel (see Fig. 3).

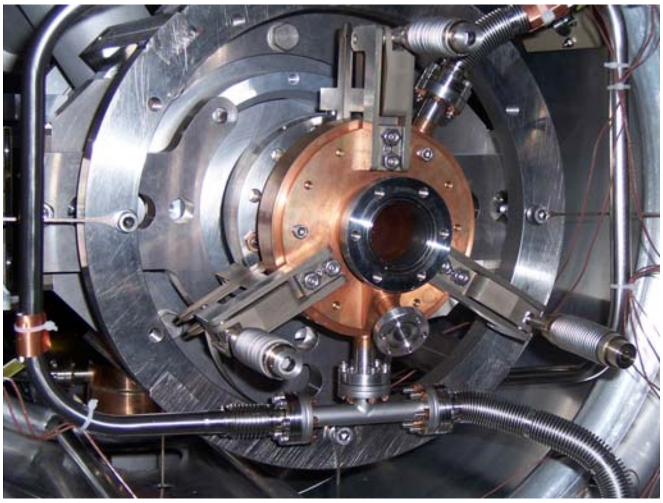

Fig. 5 View to the photocathode side of the SRF gun cryostat.

Figure 6 shows the helium and nitrogen port of the cryostat. The photo was taken in November during the vacuum and N_2 cooling tests, when the cryostat was not connected to the He pipeline.

Fig. 6: View to the He and N_2 ports.

In the cryostat several diagnostic components are installed. The liquid Helium levels can be measured in the cavity tank and the He heater pot. A sensor exists for the He gas pressure measurement. Sensors were installed in order to obtain the liquid nitrogen level in the tank for the thermal shield and the cathode cooling. The photocathode is electrically insulated. Thus the photo emission current can be measured. All together 14 temperature sensors have been installed which will allow measurements at critical points of the Nb cavity (e.g. HOM coupler temperatures), at the main power coupler, the thermal shield, and to get the photocathode temperature during operation. The Fig. 7 shows the RhFe temperature sensors installed at the HOM couplers and beam tubes of the cavity. To analyze cavity vibrations, acceleration sensors have been installed at the two end tube of the cavity. The diagnostics at the main power coupler consists of light, temperature and vacuum monitors. Here the aim is to prevent any damage of the windows by arc discharges.

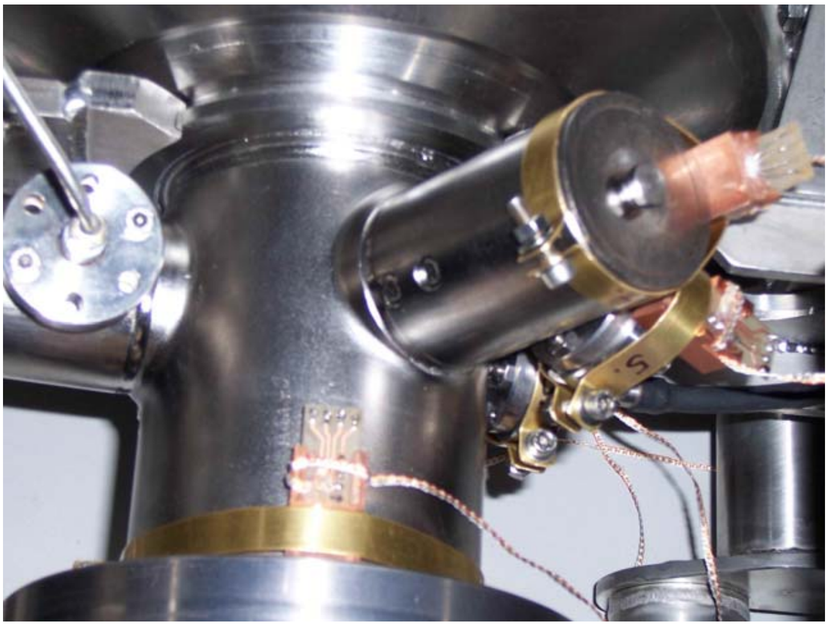

Fig. 7: Photograph of the cavity beam tube with installed temperature sensors.

3. Niobium Cavity

The niobium cavity of the new SRF gun has 3.5 cells. The back wall of the half-cell has a slightly conical shape and has a centered hole for the photocathode. The photocathode itself is normal conducting and cooled with liquid nitrogen. A circular vacuum gap ensures thermal insulation between cavity and photocathode. Therefore the heat produced in the cathode does not burden the helium bath. On the other hand the coaxial line formed by this geometry causes rf power losses of the cavity. An additional choke filter attached to the coaxial line, also made of superconducting niobium, prevents this effect. The three full cells have TESLA shapes with exception of the TESLA cell adjacent to the gun half-cell, where the left cup has been shortened in order to obtain a better phase matching of the electron bunch. The design of the gun half-cell is the result of a combined rf field and beam-dynamical numerical optimization process and taking into consideration the constructional and technological constrains for superconducting cavities. The main optimization conditions were, that the electric and magnetic surface field strengths in the gun half-cell do not exceed the corresponding values in the TESLA cell (0.11 T and 52 MV/m), and that the electric field in front of the cathode has its maximum at the launching phase. The contour shape of the cavity obtained from the numerical optimization is shown in Fig. 8. The corresponding parameter values are given in Table 2.

Fig. 8: Contour shape of the SRF gun cavity.

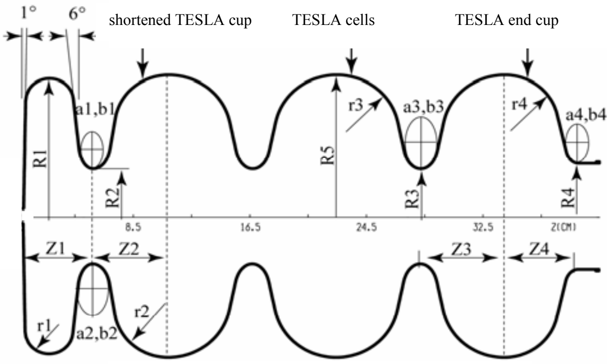

Table 2: Cavity shape parameters, all lengths in mm

cell	**shape parameter**	**name**	**value**
gun half-cell	back wall angle		1°
	Cathode hole diameter	d_0	12
	Length	Z_1	37.7
	Equator radius	R_1	102.5
	iris radius	R_2	35
	Circular arc radius	r_1	11.44
	ellipse horizontal half axis	a_1	9
	ellipse vertical half axis	b_1	16
shortened TESLA midcup	Length	Z_2	52
	Equator radius	R_5	103.3
	iris radius	R_2	35
	Circular arc radius	r_2	37.12
	ellipse horizontal half axis	a_2	12
	ellipse vertical half axis	b_2	19
TESLA midcup	Length	Z_3	57.7
	Equator radius	R_5	103.3
	iris radius	R_3	35
	Circular arc radius	r_3	42
	ellipse horizontal half axis	a_3	12
	ellipse vertical half axis	b_3	19
TESLA endcup	Length	Z_4	56
	Equator radius	R_5	103.3
	iris radius	R_4	39
	Circular arc radius	r_4	40.3
	ellipse horizontal half axis	a_4	10
	ellipse vertical half axis	b_4	13.5

The calculated acceleration field profile, as well as the magnetic and electric surface fields are shown in the Fig. 9.

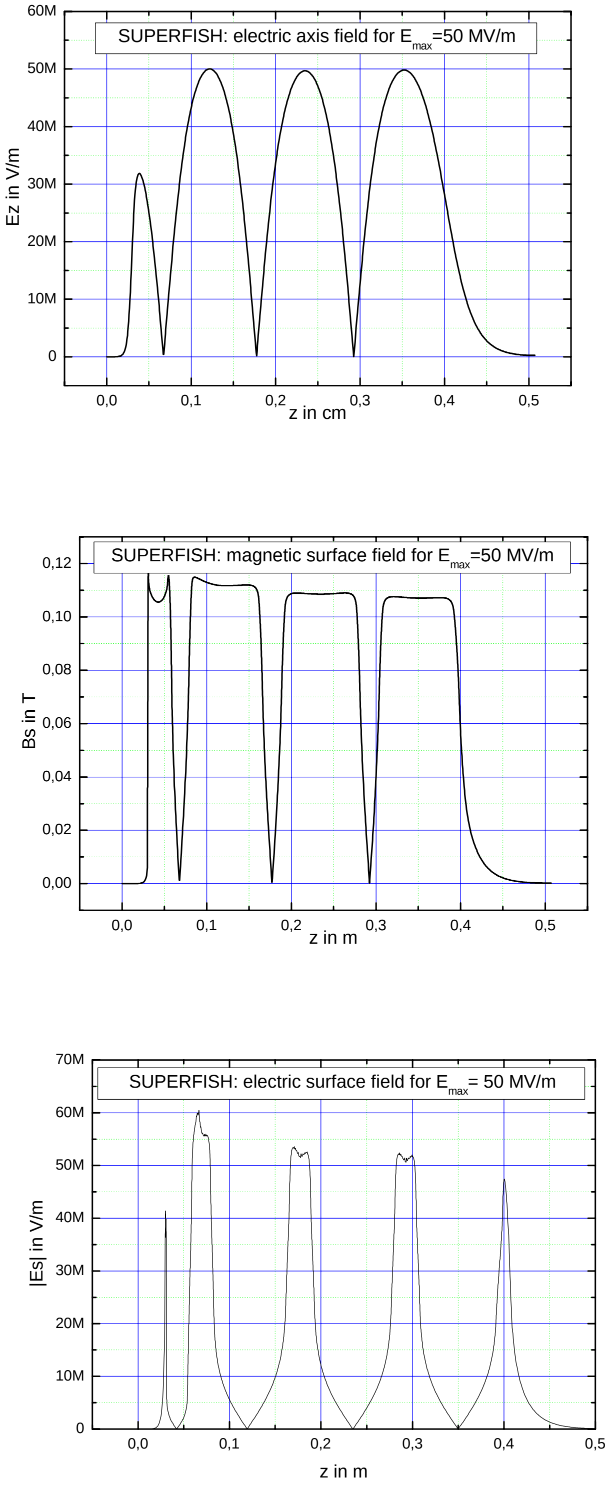

Fig. 9: Distributions of the axial electric acceleration field, of the magnetic surface field, and of the electric surface field for the SRF gun cavity.

Starting from the computer optimized geometrical shape of the cavity, the design drawings were made at FZD. The design of the choke filter was taken from the Rossendorf half-cell gun. The arrangement for the rf power coupler, the design of the two higher-order mode couplers and the pick-up were adopted from the TESLA cavity. The production of two cavities with niobium of grade RRR 300 and 40 respectively was performed by the company ACCEL. The cheaper RRR 40 cavity was produced for technological tests and rf measurements. The RRR 300 cavity is used in the SRF gun. A photograph of the RRR 300 cavity is shown in Fig. 10. A summary of the cavity properties is given in Tab. 3.

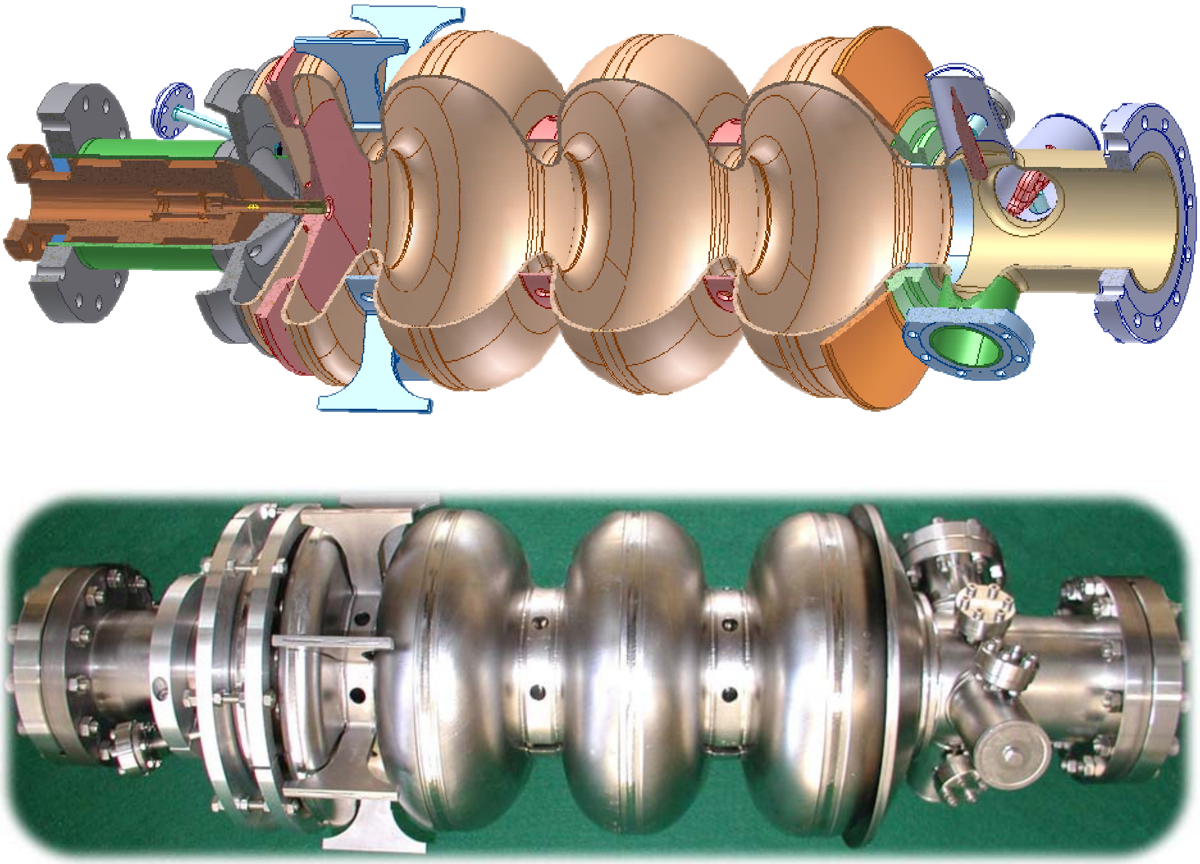

Fig. 10: Cut view and photograph of the 3½ cell cavity (Nb RRR 300) for the SRF gun.

After delivery the so-called “warm tuning” was carried out. This process is necessary since the fabricated cavity does not have the right frequency and the field profile is shown in Fig. 9. The shape of the SRF gun cavity, especially of the half-cell does not allow the use of existing tuning machines for TESLA cavities. Therefore a new cavity tuning machine with integrated bead pull measuring was built at FZD (see below). The following treatments were BCP and baking, a second warm tuning, BCP and HPR, and measuring in the vertical test bench. All these treatments were performed at DESY and ACCEL. A detailed description of these treatments and the corresponding measurements will be published in the report deliverable 2006/14 “SC RF gun test”.

Table 3: SRF gun cavity parameters

3 ½ cell cavity	

frequency	1.3 GHz
rf power	10 kW
total length	80 cm
cell diameter	207 mm
material	cells: Nb RRR 300
	other parts: Nb RRR 40
	flanges: NbTi
cell shapes	3 TESLA cells
	Cathode half-cell with 12 mm hole
Beam tube	flange for main power coupler
	2 HOM couplers (TESLA type)
	Pick-up antenna
Cathode side	Choke filter
	Pick-up antenna
	tube for photocathode support
tuners	half-cell tuner
	TESLA cells tuner

4. Main Power Coupler and Cavity Tuning System

The 1.3 GHz main power coupler is completely adopted from the ELBE accelerator module. It is designed for 10 kW input power and CW operation. The coupler has a ceramics window (alumina) at 77 K and a warm window in the wave guide. The Fig. 11 shows the 1.3 GHz coupler during conditioning in the test bench and Fig. 12 presents a photograph with the coupler in the cryomodule.

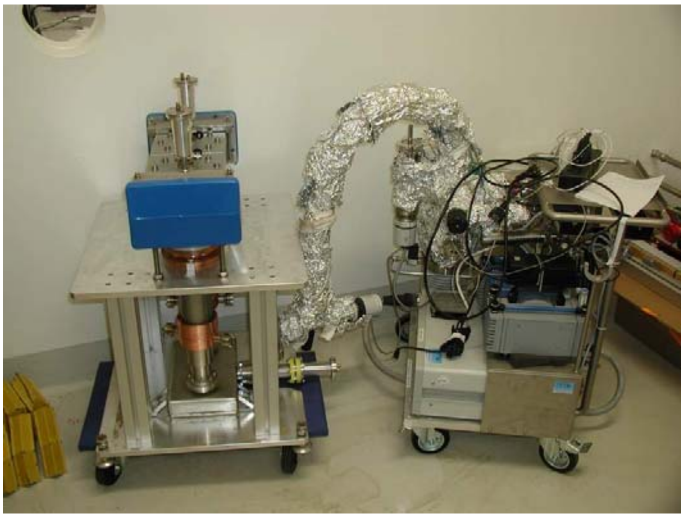

Fig. 11: Conditioning of the 10 kW main power coupler

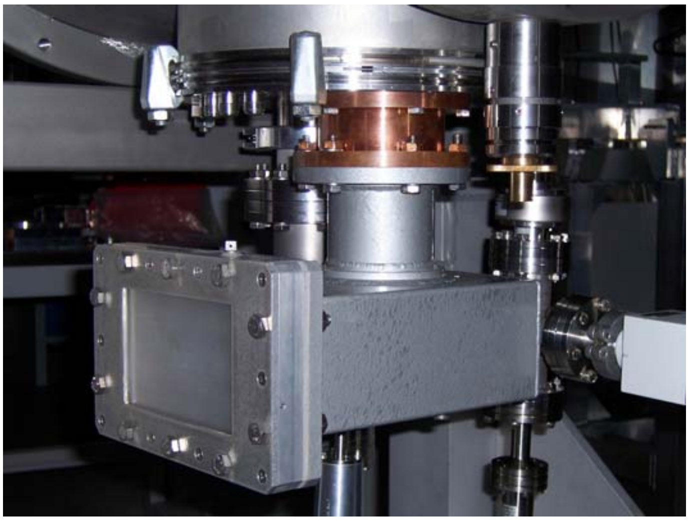

Fig. 12: Photograph of the power coupler in the cryostat

For the SRF gun cavity a frequency tuning is needed for the choke filter, the half-cell and the three TESLA cells. The bandwidth of choke filter is comparably large. Therefore a tuning during assembling in the warm stage is sufficient. For the accelerating cells tuning is required during operation. The half-cell on one hand and the three TESLA cells on the other differ essentially in their mechanical properties, especially in their stiffness. Therefore it was decided to use two separate tuning systems, one for the half-cell and one for the three TESLA cells in common. The basic design is adopted from the dual spindle-lever tuning system of the ELBE cryomodule. But the two tuners for the SRF gun cavity have required a sophisticated mechanical design due to many mechanical and cryogenic constraints and the insufficient clearance at the cathode side of the cavity and the He tank. At the end, the ELBE tuner design was modified essentially.

The tuner mechanism consists of a spindle with partly left-hand thread and right-hand thread and two levers. Via the threads and the lever system the rotational motion is transformed into a longitudinal motion performing the length variation of the half-cell and the TESLA cells, respectively. The use of two levers ensures that no axial force is present on the spindle. The bearing point of the leverage system has no rotational parts. It consists of two flexible links as it is shown in Fig. 13. The advantage is the lack of any hysteresis due to friction effects and bearing clearance. The third flexible link is connected with a moving bolt which transfers the force to the parts of the He tank joint to the end plates of the half-cell or the TESLA cells. To allow the movement the He tank has two bellows.

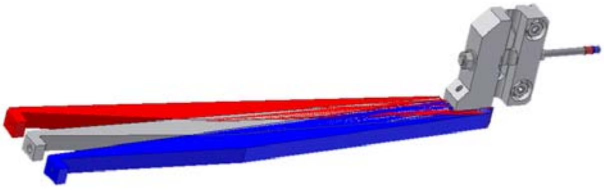

Fig. 13: Lever and flexible link of the tuner

The step motor driving the tuner spindle is outside the vacuum vessel. The fixed point is between the half-cell and the first full cell where the star-like arranged plates of the cavity are welded with the He tank. The motor motion is transmitted by rotation feed-throughs and a two-stage bellows coupling (the 70 K point is in between) to the spindle of the tuning system. The bellows compensate the shrinking offset and reduce the heat conduction. Both tuning systems have the same design. They differ in the lever lengths and the connection to the cavity only. A 3D design picture with tuners and cavity shows Fig. 14.

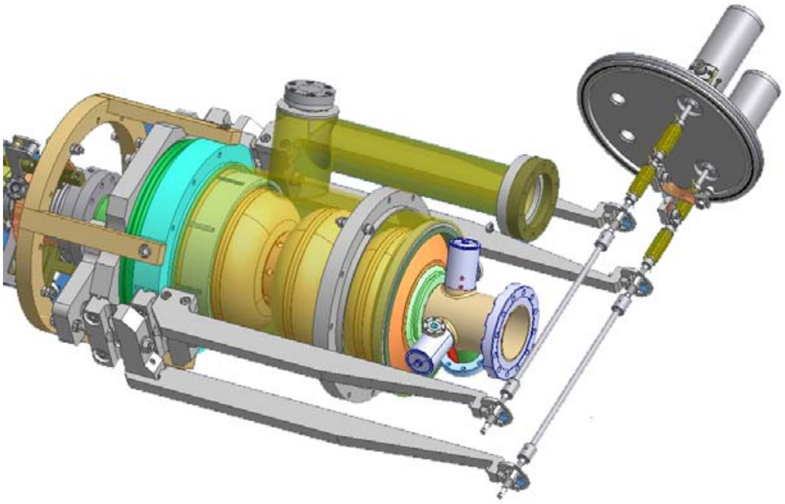

Fig. 14: The two tuners of the SRF gun cavity. The upper lever pair tunes the TESLA cells and the lower lever pair the half-cell.

For operating tests and parameter measurements a test bench for the designed tuning system was built up. A summary of the parameters of the tuning system are given in Table 4.

Table 4: Parameters of the SRF gun tuners.

	half-cell tuner	TESLA cell tuner
lever length	630.6 mm	570.2 mm
Leverage	50.4	44.2
lever range	33 mm 3.0°	30 mm 3.0°
tuning range	0.7 mm 204 kHz	0.7 mm 404 kHz
cavity frequency constants Δf/dL	178 kHz/mm	283 kHz/mm
mechanical drive step	0.70 nm/step	0.62 nm/step
frequency drive step	0.23 Hz/step	0.28 Hz/step
mechanical resolution	3 nm	
frequency resolution	1 Hz	
position of step-motors	warm, outside	

5. Photocathode and Transfer System

The SRF photo gun uses a normal conducting photocathode. The photoemission layer consists of caesium telluride. The design of the photocathode stem is shown in Fig. 15 and a photograph of a photocathode is presented in Fig. 16. A bayonet fixing attaches the photocathode to the support system. In Fig. 15 the ring and the spring belong to the bayonet fixing. The thermal contact to the cooling system is realized by the cone of the copper stem. The cylindrical part, which ends in the half-cell boring, has a diameter of 10 mm.

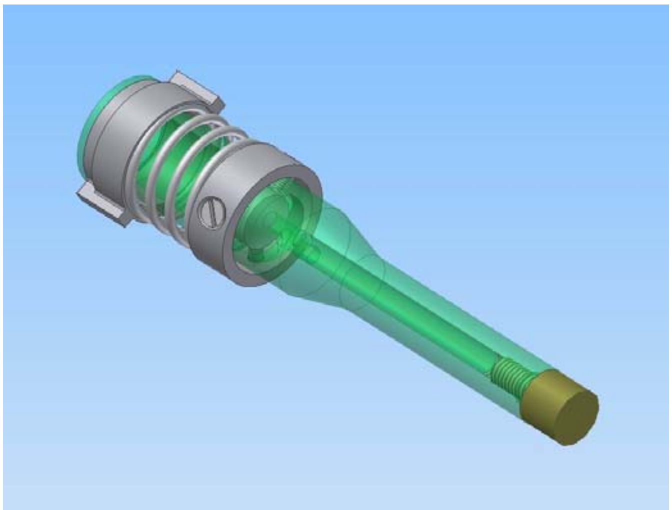

Fig. 15: Design of the photocathode

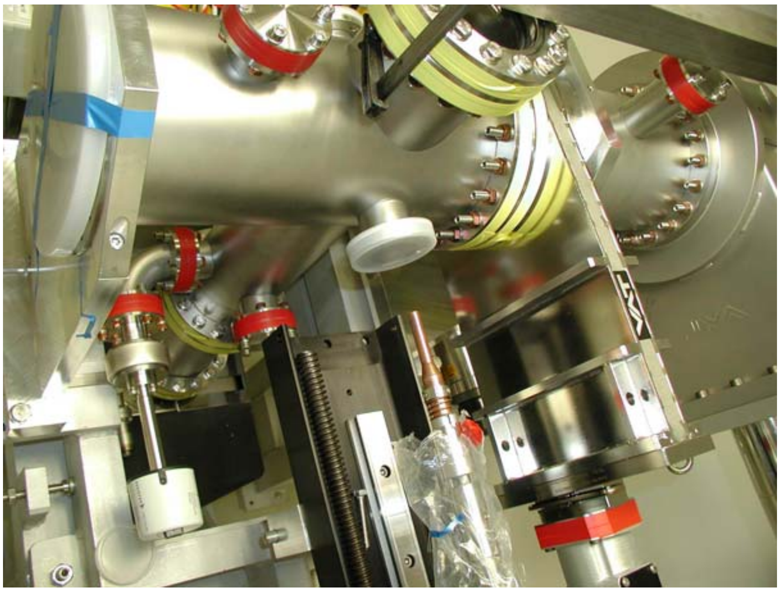

Fig. 16: Photograph of the cathode transfer system during adjustment

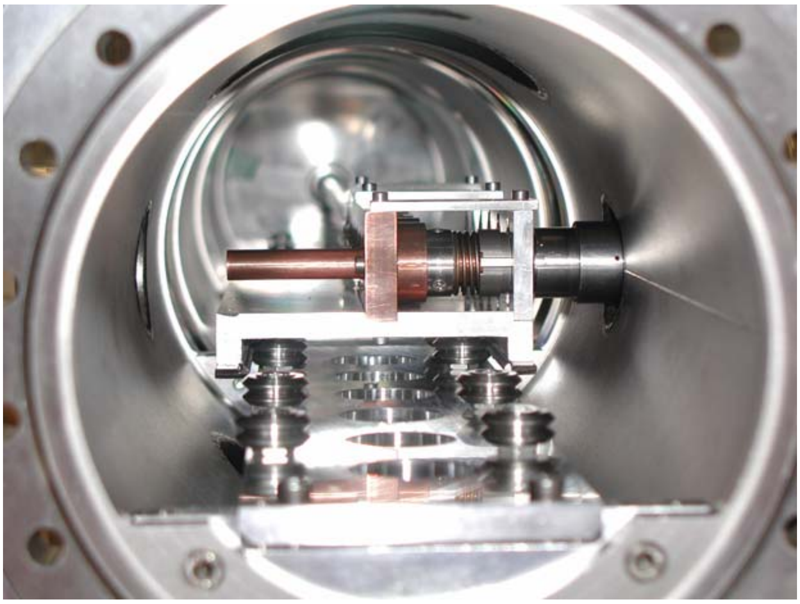

Fig. 17: Photograph of a photo cathode being in the carrier of the transfer system and connected to the transfer rod

Photo cathodes with Cs_2Te emission layers have life times between a week and several months depending on the fabrication quality of the layer and the operation conditions. The Cs_2Te layer is highly sensitive to oxygen and water vapour. Thus the photo cathodes must be transported and stored in ultra high vacuum. For that reason a photo cathode transfer system was designed allowing the transport of cathodes from the preparation system to the SRF gun, the storage of six cathodes in a carrier and the exchange of cathodes between the storage chamber and the SRF gun. Two of these systems were built as shown in Fig. 18. One system is connected to the SRF gun and the other to the cathode preparation chamber. The system attached to the photo cathode preparation chamber is presented in Fig. 19.

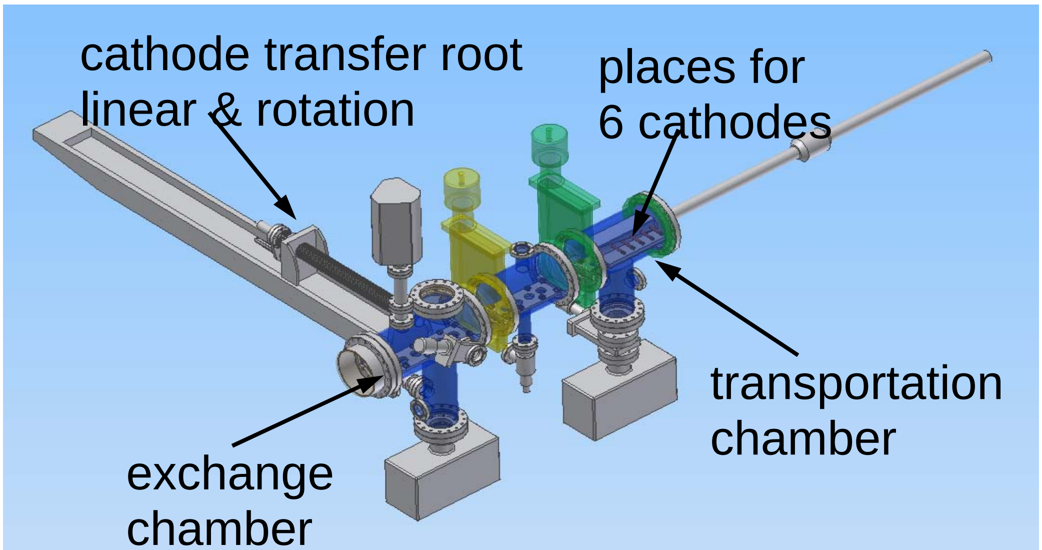

Fig. 18: Design of the photo cathode transfer system

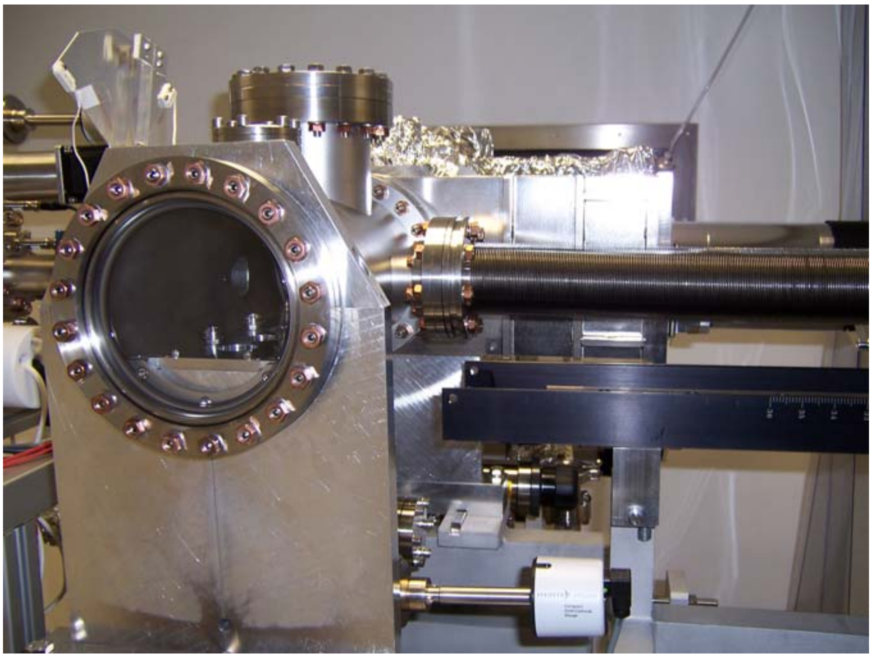

Fig. 19: Photograph of the cathode transfer system in the photo cathode preparation lab

8. Driver Laser and Laser Beam Line

Within a national collaboration project, the Max-Born-Institut Berlin (MBI) is developing the driver laser system. The Cs_2Te photo cathodes require a UV laser beam. The SRF gun will be operated in three different modes. The corresponding laser parameters are given in Table 5. These different parameters for the ELBE mode and the other two modes require different solutions for the driver laser. Thus two channels of the driver laser are designed. Within the project the laser channel for the high-charge mode (and BESSY mode) has been built. This channel has a 13 MHz oscillator at 1053 nm, a 500 kHz pulse picker, a regenerative amplifier, and a conversion stage to the UV. A challenge for both channels is the comparably low energy per laser pulse on one hand and the high average power, CW operation of the laser on the other hand. For this combination the conversion into UV is very difficult. The second channel of the driver laser with the 13 MHz pulse frequency (ELBE mode) is under development at MBI und will be delivered in autumn 2007.

Table 5: Driver laser parameters for the three SRF gun operation modes

	ELBE mode	High-charge Mode	BESSY mode
wave length	262 nm		
pulse frequency	13 MHz	0.5 MHz	1 kHz
bunch charge	77 pC	1 nC	2.5 nC
pulse length	5 ps	20 ps	50 ps
laser power	0.8 W	1 W	1 mW
pulse energy	60 nJ	1 µJ	1 µJ
temporal profile	Gaussian		
lateral profile	flat top		

The FZD is responsible for the laser beam line set-up which transports the laser beam from the laser room to the photo cathode of the SRF gun in the ELBE accelerator hall. The design of the laser beam line is finished. The mechanical components are delivered and fabricated. Most of the mechanical components are already installed. The remaining work will be carried out in winter shut-down of ELBE in December 06 – January 07. Fig. 20 shows the CAD design of the laser beam line.

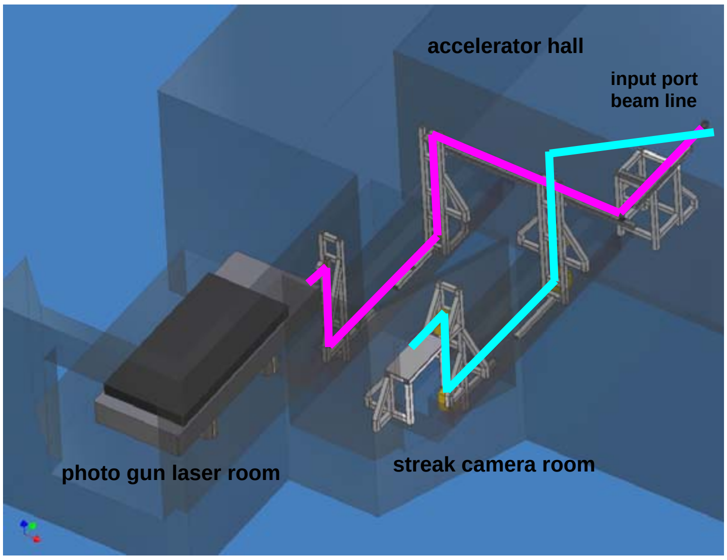

Fig. 20: Design of the driver laser beam line. The figure also contains the Cherenkov radiation beam line for bunch length measurement with a streak camera.

7. Test Benches

For the functional test and parameter measurements several test benches were built and operated:

- photo cathode cooling system test bench,
- tuner test bench,
- bead pull apparatus for field profile measuring,
- warm tuning machine,
- coupler test stand for rf power coupler conditioning.

Except for the coupler test bench, all the other test benches were designed and built within the SRF photo gun project.

8. Infrastructure

The most important issue was the installation of the helium pipe line which connects the SRF gun to the ELBE helium refrigerator. For this connection it was also necessary to replace the helium pipe to first ELBE cryomodule and to build a new valve box. These installations were carried out during the winter shut-down of ELBE in December 2005 and January 2006. Later in 2006 the liquid nitrogen pipeline was installed. In the Figures 21 and 22 are photographs of the new He pipeline and valve box. In the summer shut-down 2006, the currently used thermionic injector of ELBE was modified and components moved in order to obtain the space for the installation of the new SRF photo injector. For the rf power connection the waveguide has been installed. One of the 10 kW spare klystrons of the ELBE accelerator can be used. The laser room was reconstructed and clean room techniques were installed. A new hutch for the streak camera of the bunch length measurement system was built.

Fig. 21: Photograph of the new helium pipeline in the accelerator hall for the SRF gun

Fig. 22: Photograph of the valve box with part of helium pipeline for the SRF gun

8. Future work

The niobium cavity for the SRF gun has been ready for more than one year. During this time the cavity has been treated (buffered chemical polishing and high pressure rinsing) several times and three measurements in the vertical test stand at DESY have been carried out with insufficient results. It turned out that the envisaged acceleration gradient will only be obtained if the high pressure rinsing system is modified according to the needs of the geometry of the 3 ½ cell cavity. Therefore a contract with the company ACCEL was placed for modification of their HPR system. This modification will be finished till end 2006. In January the next treatment (BCP and HPR with the modified system) and the measurement in the vertical test stand will be performed. Then the helium tank welding can be finished in February 2007 and the cavity will be at Rossendorf for assembly in the cryostat begin March 2007. Since the time is very short and substantial, complicated assembling work in the clean room has to be carried out, there is a high risk for the installation of SRF gun within the next ELBE shut-down end of March 2007. Then the next date for installation is the summer shut-down June/July 2007. It is intended to set-up the diagnostic beam line for the SRF gun in the summer shut-down. For both dates of possible installation of the gun, the available time till end of the PHIN project in December 2007 will be sufficient for test operation and beam parameter measurements of the SRF gun.

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