A PROPOSED SUPERCONDUCTING PHOTOEMISSION SOURCE OF HIGH BRIGHTNESS

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ABSTRACT: We describe the design of an electron injector for the production of a microbunched electron beam with high brightness, low energy spread, and potentially high beam power. A photoemission cathode is placed in the high electric field region of a superconducting niobium cavity resonator. The cathode material consists of a thin layer of alkali antimonide evaporated onto a niobium substrate. It will be illuminated with short laser pulses phase-locked to the rf electric field. In addition, we describe an UHV chamber for photocathode preparation and lifetime experiments.

1. INTRODUCTION

The special properties of photoemission qualify this type of electron emission for future high brightness electron injectors [5]: The desired time structure of the electron beam can be directly realized by appropriate modulation of the incident light; chopper and buncher facilities are not necessary. The delay between photon incidence and electron emission is negligible and normally dominated by the transit time inside the absorption layer. Ultra-short electron bunches can be produced for special applications. In addition, photoemission can deliver much higher current densities than thermoemission, at very low transversal electron energy. A beam brigtness of 10^{11} A/(m·rad)^2 seems to be possible. To prevent emission growth due to space charge the electrons must be accelerated to a relativistic velocity immediately after emission. Photoemission sources using electrostatic or normalconducting rf acceleration structures have already been developed in several laboratories [1, 3, 4]. Moreover, an electron beam with partial spin polarization can be generated.

A superconducting rf cavity resonator can be driven continuously with a field strength, which forces normalconducting cavities to be pulsed at low duty factor, leading to a continuous microbunched electron beam. In addition, the shape of superconducting structures can be optimized with respect to minimal emittance of the beam; shaping according to maximum shunt impedance is not necessary. The cryogenic environment of the superconducting cavity will help to achieve the special vacuum conditions necessary for long-term operation of high quantum efficiency photoemission layers.

2. THE PHOTOCATHODE PREPARATION CHAMBER

For introductory investigations on photoemission layers with high quantum efficiency we have built a special ultrahigh vacuum chamber (Fig. 1), very similar to the chamber built at SLAC [7]. Cesium antimonide Cs_3Sb is a material of fairly high quantum efficiency (about 4% at 532 nm), which is known to have a relatively low sensitivity to residual gases. We will investigate it first because it is easy to evaporate. Composed alkali antimonides like Na_2KSb:Cs have considerable higher quantum efficiency, but require much more effort in preparation. Gallium arsenide GaAs has also very high quantum efficiency, but its optical absorption is lower, and the absorption layer is typically thicker. This is a disadvantage when aspired to achieve ultra-short pulses. All these substances are extremely sensitive against active gases; their long-term operation requires an extraordinary high vacuum. The pressure in our chamber is at present $1.5 * 10^{-10}$ mbar with about 88% H_2, 10% CO, and 2% of CH_4, Ar, and He. The partial pressures of active gases like O_2, N_2 and CO_2 were clearly below 10^{-12} mbar. These conditions are sufficient for cathode preparation. The chamber is actively pumped by an ion getter pump. Pressure and gas composition are controlled by an extractor-type ionization gauge and a quadrupole mass spectrometer.

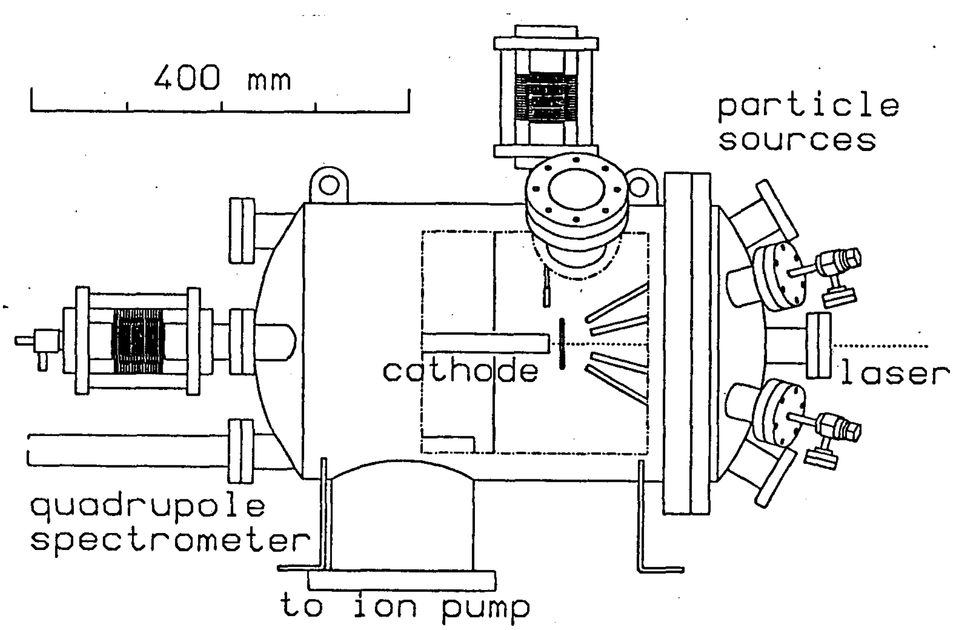

Figure 1: The Photocathode Preparation Chamber

The preparation chamber has three alkali metal sources for cesium, sodium, and potassium besides a simple antimony source. The cathode substrate can be heated to 600°C, necessary for surface cleaning and preparation of photocathodes. For temperature dependence measurements of quantum efficiencies the cathode temperature can be varied between this value and 77 K by cooling with liquid nitrogen. Quantum efficiency measurements are made with a green He-Ne laser ($\lambda = 543$ nm) of 0.5 mW light power. The cathode can be retracted and replaced by a quartz microbalance to evaluate the evaporation rates. Two gas leak valves serve to give certain amounts of active gases directly onto the cathode: On one hand, a small amount of nitrogen fluoride or oxygen is known to increase the quantum efficiency. On the other hand, greater amounts of residual active gases are believed to be the main reason for degradation of photoemissive layers in actively pumped systems. Therefore it will be of great importance to know the influences of various residual gas components exactly.

3. THE SUPERCONDUCTING PHOTOEMISSION SOURCE

The design of the whole system is presented in Fig. 2: Heart of the photoemission source is the superconducting cavity resonator, housing in its center the photoemission layer. This layer is placed at the top of a stem with niobium tip; it can be retracted into a preparation chamber at the back side of the cavity without breaking the vacuum. This preparation chamber is a smaller counterpart to the stand-alone chamber described above. Vacuum requirements are the same, but much less instrumentation will be required. The emitted and accelerated electrons pass the beam tube at the front side and enter a beam analysis system. This system is just under construction and will be presented later.

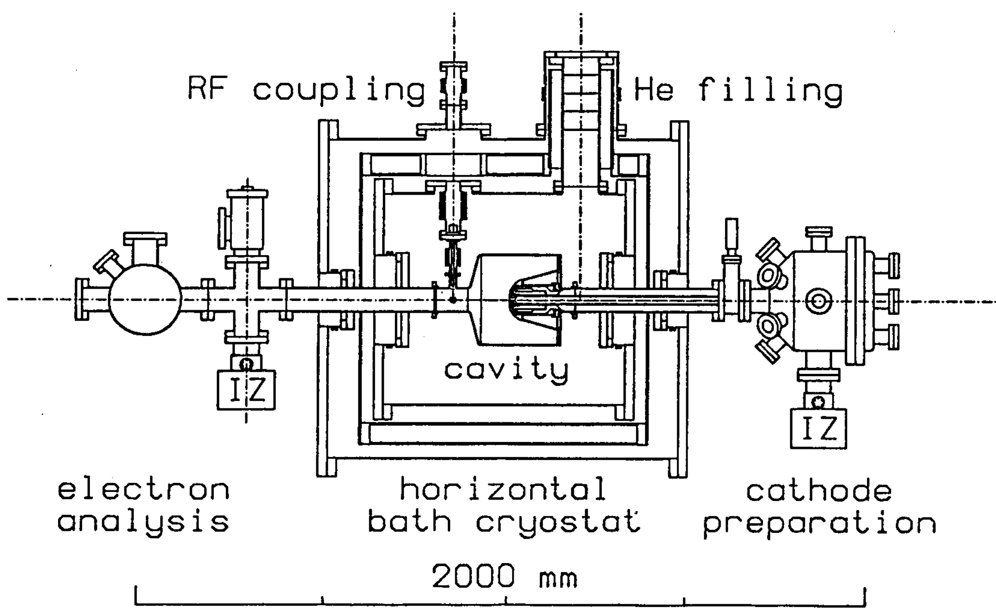

Figure 2: The Superconducting Photoemission Source

The beam tube will also be used as optical pathway for the incident light pulses. A frequency-doubled Nd:YLF-laser ($\lambda = 527$ nm) is a convenient light source. By mode-locking one can produce very short pulses down to about 35 ps. Further decrease down to about 10 ps is possible with a pulse compressor. The laser must be phase-locked to the rf field to emit the electrons at the optimal phase angle. With a 500 MHz cavity the operation of the laser at the fourth subharmonic will provide a reasonable repetition rate. Depending on the laser configuration installed various operation modes of the electron source can be obtained. Table 1 contains the beam parameters for constant microbunch modes with short (*1) and ultra-short (*2) pulses. In addition, it contains a burst mode (*3) with increased light intensity and low duty factor. The values are based on an average laser power of 1 W and an acceleration voltage of 2 MV.

The superconducting cavity is made from niobium with a critical temperature of 9.2 K. It will be operated at 4.2 K in a liquid helium bath. Because the cavity has to be connected to external facilities at front and back side we will use a horizontal bath cryostat. The rf power is transferred into the cavity via a side-tube coupler with variable coupling strength. A preliminary coupler is designed for 500 W maximum rf power, restricting the average beam current to 250 μA. In a final version the coupler shall be adapted to a 25 kW tetrode amplifier, thus allowing an average beam current of 12.5 mA at 2 MV accelerating voltage.

Table 1: Conceptual beam parameters for various operation modes

Mode type	1. short bunches	2. ultrashort	3. burst mode
Laser pulse length	70 ps	10 ps	70 ps
Pulse repetition rate	125 MHz	125 MHz	100 Hz
Bunch charge	160 pC	150 pC	14 nC
Peak beam current	2.3 A	15 A	200 A
Average beam current	20 mA	19 mA	1.4 μA

Due to the helium-cooled walls the vacuum inside the cavity will be exceptionally good, and all residual pressures except He and H_2 will be extraordinary low - a very advantageous fact for the lifetime of our photocathode layer. Nevertheless, the cathode layer will be faced to surfaces at room temperature during preparation and even in operation position. Therefore a very good vacuum already at room temperature is required for the whole UHV system.

4. CAVITY DESIGN AND BEAM DYNAMICS

The main advantage of a superconducting cavity is its extremely low surface resistance resulting in a resonance quality factor of typically 10^9. Due to this fact the field strength is not limited by global heat-up of the wall, but by local impurities of the surface which at a certain field level cause superconductivity to break down. Using advanced surface preparation techniques and niobium of high thermal conductivity, peak surface magnetic fields of 80 kA/m (according to an acceleration voltage of 2 MV) can be achieved confidentially [6, 8]. Therefore, the cavity shape needs not be optimized for maximum shunt impedance, but can be designed for optimal beam dynamics. This has been done by running the particle-in-cell computer code TBCI-SF using the fields calculated by URMEL-T computer code [2]. The final cavity design, tuned to 500 MHz basic frequency, is shown in Fig. 3. The reentrant shape places the photocathode into a region of very high electric and low magnetic field. The results of particle motion simulation have also been used to define the optimal emission phase: Defining electric field maximum at 0°, the emittance of the beam has a minimum for emission at -60°. Further results of these calculations are shown in Table 2.

Table 2: Results of particle motion simulation

Bunch charge (10 ps bunch)	78.5 pC	78.5 pC	2.51 nC	2.51 nC
Peak acceleration field	25.0 MV/m	37.5 MV/m	25.0 MV/m	37.5 MV/m
Beam divergence	33 mrad	31 mrad	48 mrad	39 mrad
Bunch radius	7.3 mm	7.1 mm	9.0 mm	8.1 mm
Kinetic energy of electrons	1.87 MeV	2.77 MeV	1.87 MeV	2.75 MeV
Energy spread	17 keV	33 keV	60 keV	62 keV
Final bunch length	2.33 mm	2.47 mm	3.00 mm	2.83 mm

In the basic mode, the geometry factor of the $1\,cm^2$ cathode surface (390 MΩ) is extremely high compared to the geometry factor of the whole cavity (90 Ω), thus rf losses at the cathode are negligible, even if the cathode is semiconducting. Beyond that, the thin layer should become superconducting, too, by proximity effect.

The substrate for the cathode layer must have the facility to be retracted to the preparation chamber and therefore must not be fixed to the cavity. The resulting coaxial structure couples to the cavity field with a coupling quality factor of about 10^7. To decrease power transmission a superconducting band rejection filter is included in this coaxial line, increasing the coupling quality factor to at least 10^{10}. This rejection filter has been experimentally designed using a copper model. Tuning to the cavity resonance will be done during operation by shifting the cathode stem back or forth a few tenths of a millimeter. The residual rf power running down the coaxial line will be used for a monitor output.

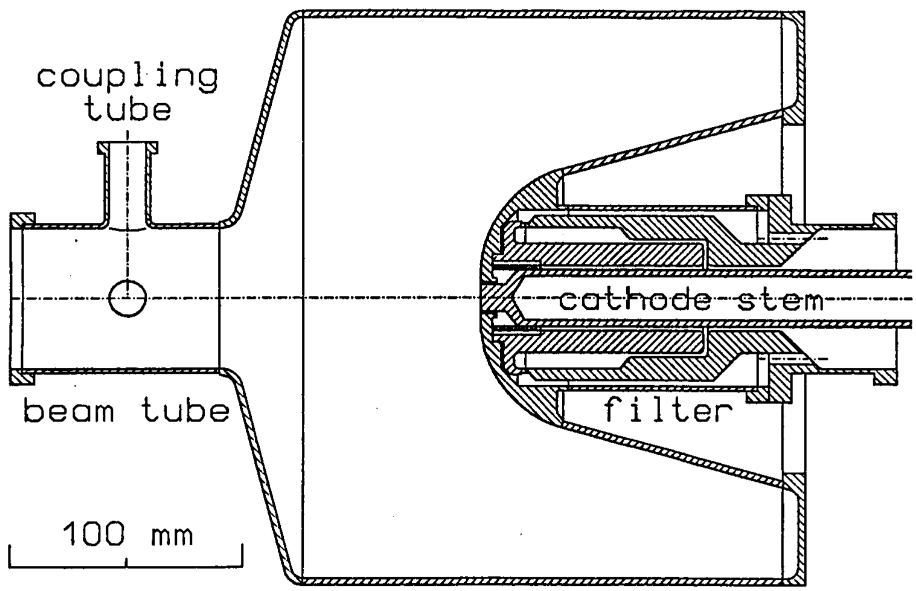

Figure 3: The Superconducting Reentrant Cavity Resonator

5. APPLICATIONS FOR BASIC RESEARCH

These special features qualify our superconducting cavity for fundamental experiments on electron emission, including photoemission, field emission, and photo-assisted field emission, besides its application as electron injector. The emitting surface can be prepared in a convenient vacuum chamber and transferred into the cavity without breaking the vacuum. Especially, rf field emission from impurities of the superconductor surface is a matter of great interest, because this effect frequently limits the fields achievable in superconducting cavities.

If the cavity is excited in a higher order mode with higher magnetic fields at the cathode it is eventually possible to measure the surface resistance of the semiconductor layers with sufficient accuracy to explore the proximity effect.

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