Photocathodes Inside Superconducting Cavities

An experimental approach to a superconducting photoemission source of high brightness

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Abstract: The combination of photoemission as electron source and superconducting accelerator technology should result in an injector which can deliver an extremely bright electron beam (like normalconducting photoelectron injectors) in continuous operation. But the mutual interactions of both technologies are unknown and must be investigated experimentally. Here we describe the experiments which we perform to examine these interactions and present some preliminary results. In addition, we propose a possible design for a prototype "Superconducting Photoemission Source" together with some numerical simulation results.

Advantages of Superconductivity and Photoemission in Electron Sources

A high–brightness electron beam is an essential requirement in several future accelerator projects, like linear colliders (TESLA) and UV–FEL's. Therefore several improvements on electron injectors have been presented in recent years:[1] Photocathodes provide a considerably higher current density than conventional thermionic cathodes, while under typical conditions the kinetic energy of the electrons is the same.[2] But their main advantage is the possibility to modulate them within times as short as 1 ps.[3] This enables to replace the conventional dc acceleration gap by an rf acceleration cavity [4] without energy spread. It can provide its high field level over a large distance and immediately accelerate the electrons to relativistic energies, strongly reducing space-charge induced emittance growth. In addition, no chopper or prebuncher system is required. This type of photoemission RF gun has been developed at several accelerator labs[5] and is already used in some progressive machines.[6] But none of those projects has ever used a superconducting cavity for acceleration. It is inferior in pulsed operation, but in continuous operation it can provide much higher field levels than normalconducting cavities. Therefore a superconducting high brightness gun should be of special interest in combination with a superconducting accelerator. The reduction of rf power consumption is only of minor importance in a few-cell device, but the negligible rf losses allow to optimize the cavity geometry for minimum beam emittance without regarding its shunt impedance.

Material	ΔE [eV]	λ_0 [nm]
Cs_3Sb	1.95	640
K_2CsSb	1.8	700
$Na_2KSb:Cs$	1.4	890
GaAs:Cs,O	1.35	930

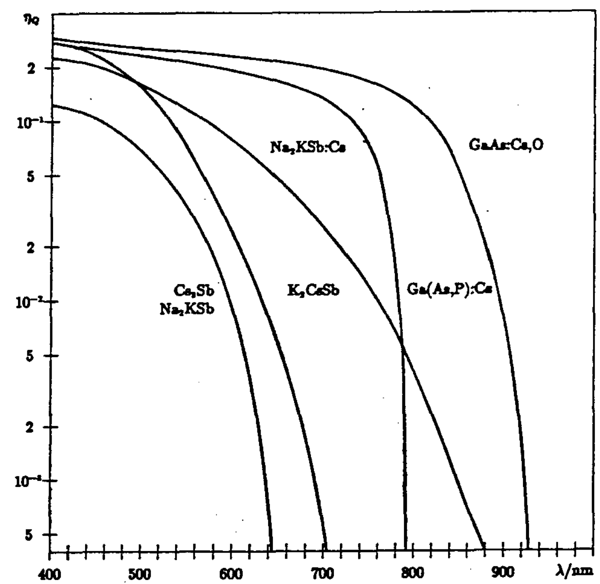

Figure 1: Spectral Quantum Efficiency of Semiconductor Photocathodes

Various photoemissive materials can be used for photoelectron sources:[7, 8] Conventional metals like stainless steel (or niobium) are very rugged, but their work function is high (typically above 4 eV) and their quantum efficiency (defined as emitted electrons per incident photon) is low (typically below 10^{-4}) – most of the photons just heat the cathode. Thus metallic cathodes can be used in superconducting cavities only for low average current applications. The cathodes of our choice are semiconductors with low electron affinity, especially alkali antimonides containing cesium. They show extremely high quantum efficiency (above 10%), low work function (about 2 eV) and a steep rise of quantum efficiency just above the threshold energy (Figure 1). But due to their chemical activity, they have to be maintained in ultrahigh vacuum systems, and their lifetime during operation is severely limited: They react with residual active gases, they are destroyed by backaccelerated residual gas ions, and their cesium can desorb by ion, electron, or laser excitation. In normalconducting systems they have to be frequently replaced, and special care has to be attended to the vacuum system. But the cryogenic environment of the superconducting cavity should strongly suppress all destruction mechanisms and make them operating more stable. On the other hand both superconducting cavities and semiconductor photoemitters are extremely surface sensitive, and various interactions can be imagined: Photocathode material on the superconducting surface could cause field emission or normalconducting spots and thermal breakdown. The high field level at the cathode could cause uncontrolled field emission [9] or rf losses. How strong these effects are and how they can be overcome is simply unknown and must be cleared by experiments.

Experiments about Photocathodes in Superconducting Cavities

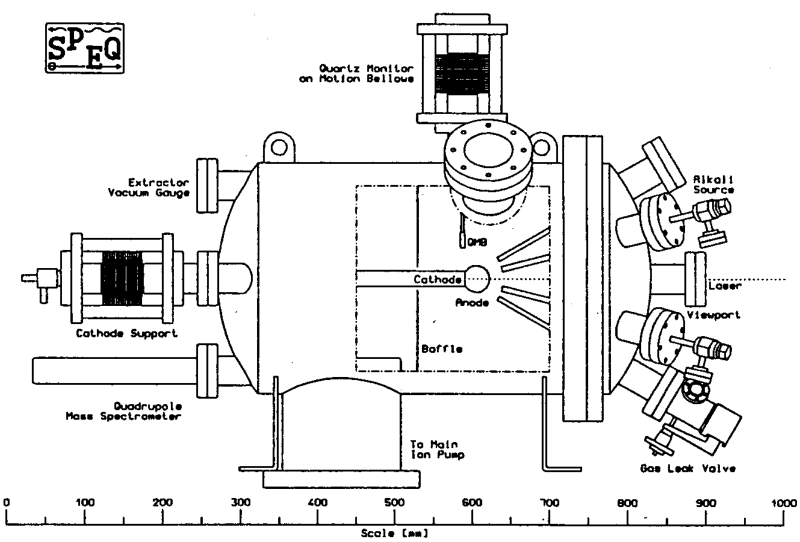

Figure 2: Independent Photocathode Preparation Chamber

In advance we built a system to study the preparation of antimonide photocathode layers on metallic substrates. Although this topic has already been investigated twenty years ago, little information is available and everyone working on this area has to gain his own experience. Our experiment consists of a preparation chamber with evaporation sources, evaporation rate monitor, quantum efficiency measurement equipment, and vacuum maintenance and control systems (Figure 2). Its basic pressure is regularly below 10^{-10} mbar after bakeout. The cathodes are evaporated on a heatable niobium substrate. Our intentions are: (1) to gain experience on photocathodes and to develop the necessary devices, (2) to define a good preparation process first for Cs_3Sb, later for K_2CsSb, and (3) to investigate the reactions of photocathodes with various active gases. Small amounts of O_2 or H_2O are known to increase the quantum efficiency, larger amounts of all active gases should destroy the cathode performance. In the latest period of measurement, we could reproducibly prepare Cs_3Sb–layers with quantum efficiencies of $(2.3 \pm 0.2)\%$, where a thickness of 10 $\mu g/cm^2$ Sb (corresponding to about 100 nm

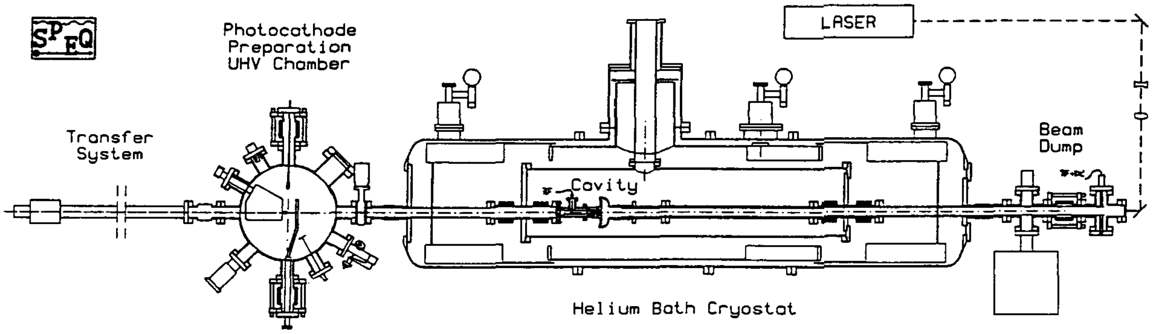

Figure 3: Experimental Setup with 2.8-GHz Half Cell Cavity

Cs_3Sb) proved to be a good value. In the future these experiments will accompany and complement our main activities; the experience gained here has already proved to be extremely important for designing.

Our main experiment consists of a superconducting cavity containing a photocathode (Figure 3). Both the performance of the superconducting cavity (maximum field and quality factor) and the quantum efficiency of the photocathode shall be measured in various operational states. The beam is simply dumped in a faraday cup; a measurement of beam emittance is not intended. This experiment is actually in erection; we schedule the first complete cold test being performed before the end of this year.

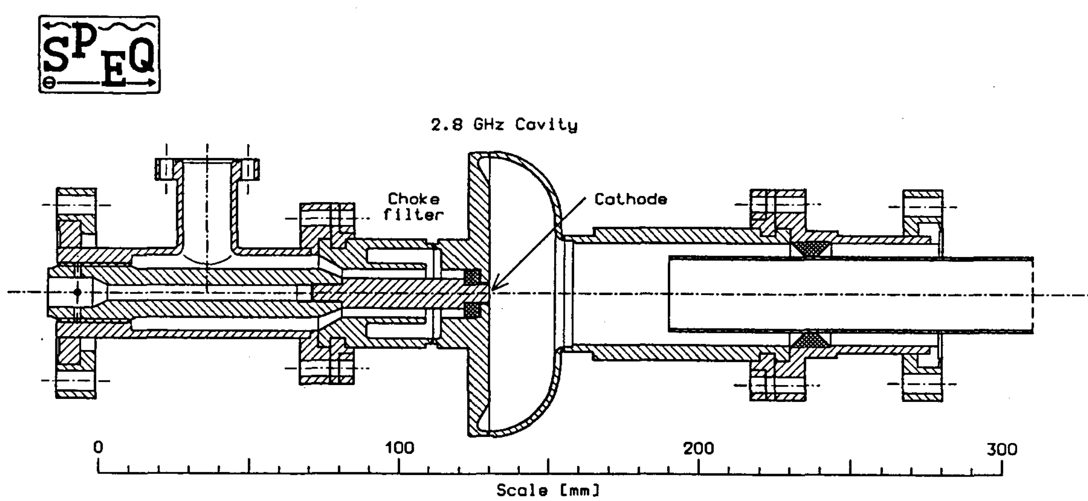

Figure 4: Superconducting 2.8 GHz Half Cell Cavity

The cavity is shaped as half a 3 GHz spherical cell closed with a plate (Figure 4), its basic frequency is 2.828 GHz. The photocathode has a diameter of 6 mm and is located in the center of the plate, the acceleration distance along the axis is about 25 mm. The electric field at the cathode is only a factor 1.2 lower than the peak surface electric field (at the iris). The resistivity of the Cs_3Sb semiconductor is in the

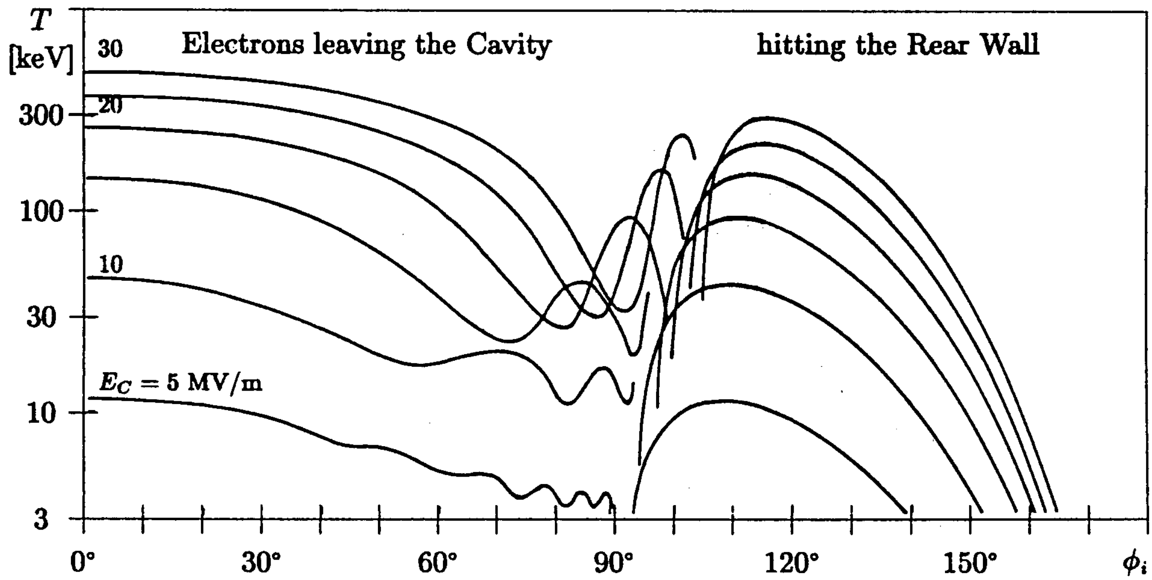

Figure 5: Numerical simulation: Energy distribution of accelerated electrons

order of 0.05 $\Omega\cdot$m already at room temperature, thus the thin layer is transparent for microwaves. In addition its resistive losses are scarcely measurable because the magnetic field at the cathode is low and its geometry factor is 1.2 MΩ compared to 140 Ω for the whole cavity. The ratio of peak surface magnetic field (near the equator) to E_C is 1.9 mT/(MV/m). The beam tube at the opposite side of the cavity contains an inner tube which serves as variable rf input coupler and collects at the same time the emitted electrons as faraday cup. Through the hole of the inner tube the cathode can be observed directly and illuminated with laser light. Particle dynamics simulations show that already at cathode fields of 5 MV/m the whole beam enters the tube without hitting the cavity walls. Typically, all electrons emitted between 0° and 90° rf phase leave the cavity, the second value rising slowly with cathode field, the rest (up to 180° rf phase) is backaccelerated and hits the rear plate (Figure 5). The beam energy of both parts steeply rises with cathode field. Because we're not interested in a high quality beam, we can in principle operate our experiment with a cw laser. In fact, we'll use a cw HeNe–laser ($\lambda = 543$nm, $P = 0.5$mW) in the beginning, resulting in an average current of about 1 μA. But the large fraction of electrons hitting the cathode ($P_C = 16$mW at $E_C = 10$MV/m) could cause serious problems in cathode lifetime which will not occur if a pulsed laser is used.

The photocathode layer is evaporated on the niobium top of a movable stem on the cavity axis. The stem is beared in a sapphire ring which provides electrical insulation and good thermal contact to the cavity. The coaxial line formed by the stem and its surrounding vacuum tube is blocked by a choke resonator to reduce rf losses. Normal-conducting tests with the setup showed that the filter increases the external quality factor from 5×10^4 to at least 10^{10} if properly tuned to the cavity. Rough tuning has been done by etching the choke groove; fine tuning during operation can be done by moving the cathode stem, changing the cavity frequency. The filter is located directly behind the cavity and is superconducting, too, to avoid heat production. Both are produced from high purity (RRR=250) niobium (to enable good cavity performances at least without photocathode) and welded together. Due to its complicated shape, chemical etching of the assembly is difficult to control. Thus a bakeout procedure (at 800°C or at 1300°C with Ti envelope) is intended as final preparation. The whole setup is mounted inside a horizontal bath cryostat to give access to both sides. Operation temperature will be 4.2 K (expected $Q_0 = 4 \times 10^7$) or 1.8 K. A diagnostic system around the cavity (temperature or γ–ray mapping) is not yet planned, but could be mounted easily because the cavity is rotary symmetric.

Of course photocathodes are not prepared inside the cavity, but in a preparation chamber outside the cryostat. This chamber is similar (but smaller) to the chamber described above, connected to the cavity with a vacuum tube. For a preparation the cathode stem is retracted into the preparation chamber, then the photocathode components (antimony and alkali metal) are evaporated onto its top, finally the stem is inserted into the cavity again. Old layers can be removed from the substrate by heating the stem. The whole process can be done while the cavity remains cold, even without switching off the cavity rf.

Design Proposal for a Prototype Superconducting Photoemission Source

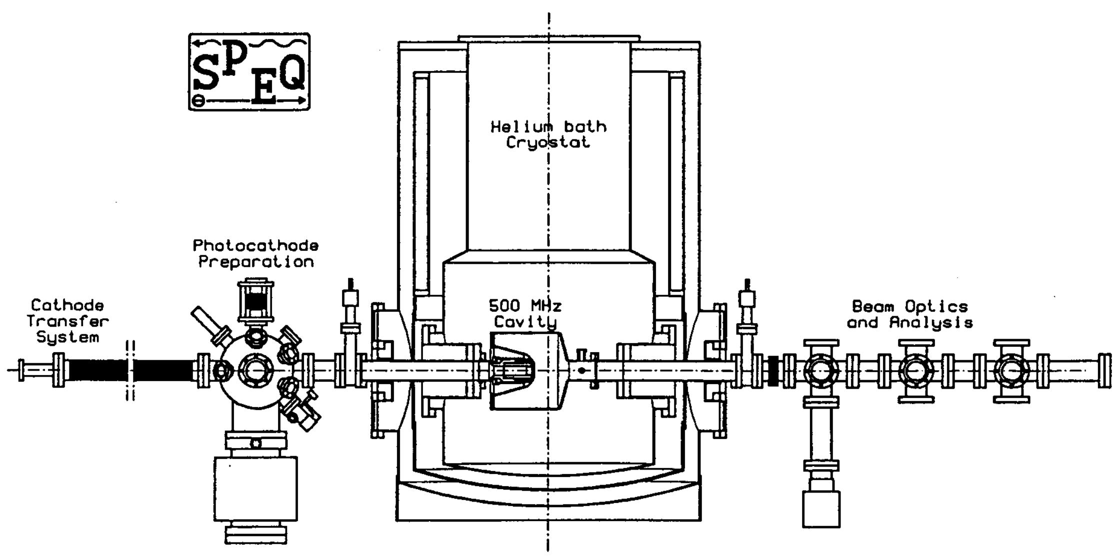

Figure 6: Setup of Prototype Electron Source with 500 MHz Cavity

In completion to our experimental activities we developed a possible design for a prototype of a superconducting photoemission source (Figure 6).[10] In many topics it resembles the 3 GHz experiment, but because a bright beam shall be generated much more care has been given to cavity shape, beam optics, and laser type.

Cavity Material	High RRR Nb	
Frequency	500	MHz
Peak Surface E/E_C	1.1	
Peak Surface B/E_C	2.4	$\frac{\mathrm{mT}}{\mathrm{MV/m}}$
G factor Cavity	90	Ω
G factor Cathode	390	MΩ
Q_0 at 4.2 K	10^9	
Acc. Distance	10	cm

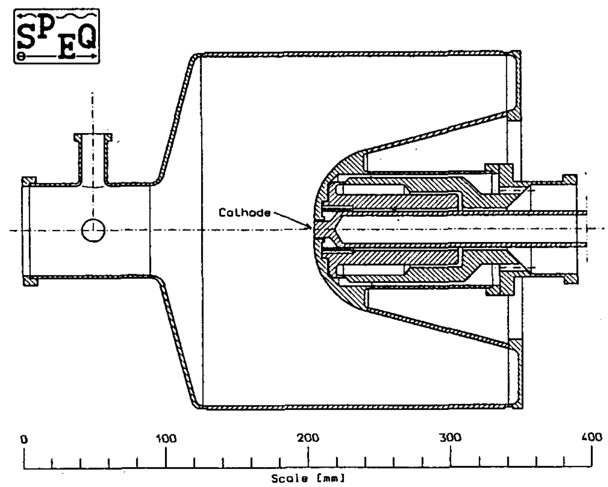

Figure 7: Superconducting 500 MHz Cavity for Prototype Source

The cavity is of reentrant type with smoothed edges and a resonance frequency of 500 MHz (Figure 7): The low frequency is advantageous resulting in low energy spread even for longer electron pulses and in a long acceleration distance. This cavity shape has been optimized with respect to beam emittance using particle dynamics calculations with TBCI–SF code. Recent considerations let us assume that a suitably shaped second cell would further increase the brightness, compensatig emittance growth due to nonlinear rf forces and increasing the beam energy.[11] An alkali antimonide photocathode is located on top of the nose cone, resulting in an acceleraton distance of about 10 cm. The peak surface electric field, located at the nose edge, is only a factor 1.1 higher than the cathode field. The ratio between peak magnetic field (at the nose base) and cathode field is 2.4 mT/(MV/m), thus cathode fields up to 32 MV/m seem reasonable. The material of the cavity can be high RRR niobium as well as niobium sputtered on copper. The cathode has an area of 1 cm^2, its geometry factor is 390 MΩ compared to 90Ω for the whole cavity. Mounting on a movable stem and preparation in an external chamber is similar to the 3 GHz system, only the filter has been designed more cautiously. The present shape has been tested on a copper model to increase the external quality factor from 5×10^6 to at least 10^{11}. Here moving the stem changes the filter frequency much more than the cavity frequency.

The following requirements are imposed to the laser: (1) Its photon energy must exceed the work function of the photocathode (2 eV) to achieve high quantum yield, but not too far to keep the transverse energy low, (2) the laser must be pulsed with a pulse length of 50 ps (corresponding to 9° rf phase) or shorter, synchronized to the rf signal, and (3) the laser pulse energy should be in the order of 10 nJ with a repetition rate as high as possibe. A mode–locked, frequency–doubled Nd:YAG–laser fits in this pattern, the only component not being commercially availabe is the synchronization. Pulse energies of 8 nJ with a repetition rate up to 100 MHz can be achieved. For enhanced requirements optical amplifiers and pulse compressors are available.

Start Conditions				
Cathode Electric Field	E_C	16		MV/m
Microbunch Charge	Q_b	160		pC
Transverse Kinetic Energy	$\langle T_\perp^i \rangle$	0.2		eV
Pulse Shape		**Uniform**	**Gaussian**	
Laser Pulse length		$t = 70$	$2\sigma_t = 70$	ps
Laser Spot Size		$r = 5$	$2\sigma_r = 5$	mm
Optimal Injection Phase	ϕ_0	$-25°$	$-38°$	
Final conditions				
Average Kinetic Energy	$\langle T^f \rangle$	802.4	795.5	keV
RMS Energy Spread	ΔT^f	±20.9	±35.8	keV
RMS Longitudinal Emittance	ϵ_n^L	15.8	117	mm · mrad
RMS Beam Radius	r	10.0	8.2	mm
RMS Beam Divergence	θ	33.2	31.4	mrad
RMS Transversal Emittance	ϵ_n^T	1.8	2.4	mm · mrad
Peak Current	$\hat{I}$	2.3	1.55	A
Peak Normalized Brightness	$\hat{B}_n$	7.2	2.7	$10^{10} \frac{A}{m^2 rad^2}$

Table 1: Results of Numerical Simulation for the 500 MHz Cavity

A number of particle dynamics calculations have been performed for this setup;[12] the resuts are given in Table 1. Starting with a bunch charge of 160 nC and a (moderate) cathode field of 16 MV/m we already get a peak brightness of 2.7×10^{10} A/(m^{2}rad^2). Because about 60% of the beam emittance is space–charge induced, the brightness can be considerably increased by a higher cathode field. A two–cell cavity should even be capable of producing a continuous beam with a brightness above 10^{11} A/(m^{2}rad^2).

Conclusions

We believe that photoemission inside a superconducting acceleration cavity is a very promising concept for future high–brightness electron injectors. Our hope is that this concept will be realized as soon as we have proved its feasibility.

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