

LOW EMITTANCE POLARIZED ELECTRON SOURCE BASED ON SUPERCONDUCTING RF GUN*

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Abstract

Continuous effort has been paid in last decades for a better polarized electron source for the high energy physics experiments. The DC guns with GaAs type photocathodes have been successfully operated in several laboratories, but the beam emittance is regrettably very poor. Although rf gun has been considered for the generation of the polarized electron beams with low emittance, the limit on vacuum is still an open question for the currently designed RF guns. In this paper a new proposal is reported: polarized SRF gun, i.e. superconducting rf gun with polarized photocathode. The polarized SRF gun would eliminate this vacuum barrier because of its low working temperature. Some questions including the cathode response time and the electron back bombardment are discussed in some detail, and the beam dynamics simulation gives positive forecast of the future application of polarized SRF gun.

INTRODUCTION

Some high energy physics experiment instruments, such as colliders (ILC, ELIC, eRHIC...), require highly polarized electron beams with high average current and very low transverse emittance.

DC polarized guns with GaAs-type photocathodes have been realized in JLab, SLC, Bates/MIT, Mainz and Bonn. Because all of these dc guns run in the range of 100kV to 350kV voltage, the longitudinal emittance of the polarized beam is rather poor, and the transverse emittance is increased during the extra bunching system between the gun and the main accelerator.

Several proposals about polarized electron source based on rf gun have been reported by BINP and SLAC [1, 2]. Because rf guns can produce the lowest emittance beam among the serving electron sources, they are predicted to be potentially good polarized electron sources for e+e-colliders. But because the currently designed rf guns cannot achieve the ultra high vacuum required by NEA (negative electron affinity) GaAs-type cathode, i.e. better than 10^{-10} mbar in operation, the cathode lifetime can only last several rf pulses. On the other hand, serious electron back bombardment to the cathode is another obvious reason for the short life time of the cathode and also the large dark current.

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Polarized superconducting rf gun, i.e., Rossendorf SRF gun with a GaAs-type photocathode, should produce a low emittance short-bunch polarized electron beam like polarized rf gun. Because of its low operation temperature, polarized SRF gun provides the best vacuum environment for sensitive NEA GaAs-type photocathode and then eliminates easily the vacuum barrier which hinders the realization of polarized rf gun.

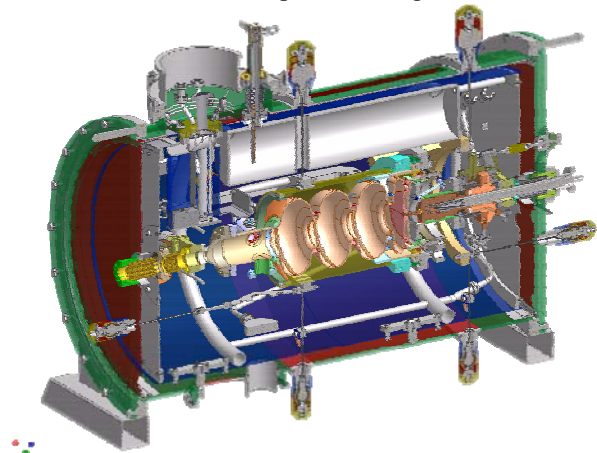


Figure 1: section view of Rossendorf SRF gun.

FEASIBILITY ANALYSIS

Since polarized SRF gun is a new proposal, there are several questions should be cleared before it is accepted and detailed studied. These questions come from two aspects: the gun and the cathode. SRF gun with Cs_2Te cathode is a newly approved technology [3], and recently a new SRF gun with $3+1/2$ cell cavity is on the way to provide beam for the ELBE superconducting linac (see Figure 1)[4]. This design will be used in the first version of polarized SRF gun. For most of the polarized electron sources, NEA GaAs-type semiconductors are the best candidates of electron emitter. In our proposal the GaAs-type photocathode with the superlattice structure and the heavily p-doped surface will be employed, which has the polarization more than 80%, and quantum efficiency (Q.E.) better than 1.0% [5]. This kind of photocathode has no so-called surface charge limit (SCL) phenomena, because the superlattice structure photocathode has increased tunnelling probability not only of the electrons in the conduction band into vacuum but also that of holes in the valence band to the surface (see figure 2). Thus there are no electrons trapped in the band-bending region which cannot be recombined by the holes and prevents the electrons in the later portion of the single pulse from escaping to the vacuum.

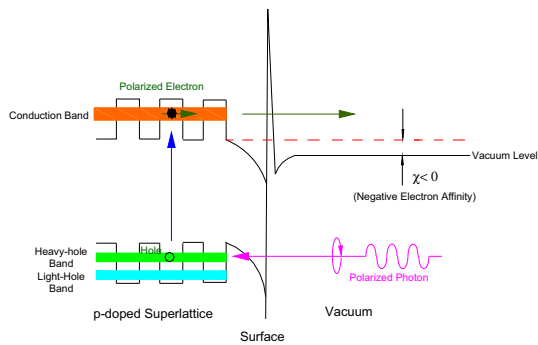


Figure 2: polarized electrons emitted from NEA surface of a semiconductor with superlattice structure [5].

Temporal response of cathode

The temporal response of photocathodes is very important for the application of SRF gun. For 1.3GHz SRF gun, a pulse less than 10 degree rf phase can be accelerated efficiently. The cathode response time depends on the thickness of emission layer. If the working layer of NEA photocathode is thicker, Q.E. is larger but the response time is longer. The electron bunch coming out from bulk GaAs has a long tail of more than 100ps, which will lead to large energy spread and then unendurable large longitudinal emittance. In the serious case some electrons in the tail will travel back to the cathode, e.g. electron back bombardment, which will damage the cathode. However, the response time of the electron pulse out from 200nm GaAs is found as short as ~2ps [6]. The ps response time makes the efficient acceleration in the SRF gun possible. There is no publication about the response time of superlattice photocathode, but it can be derived that when the working layer is thinner than 200nm, the temporal response of the cathode is also in the ps region.

Electron back bombardment

Electron back bombardment is one of the main reasons for the short life time of cathodes and the large dark current in the polarized rf guns. For the SRF gun design, this problem doesn't exist any more. At first, the superconducting cavity has the form with big iris diameter, which reduces the possibility of the electron back bombardment. Secondly, the cathode in the SRF gun is isolated to the cavity thermally and electrically, so the cathode can be loaded up to -5kV bias voltage, which restrains the electron back bombarding onto the cathode surface. Thirdly, in the rf guns the peak field on the cathode surface can be as high as 50~100 MV/m, and the large surface field is responsible for the dark current and secondary electron emission. However, due to the limit of maximum surface field on the wall of superconducting cavity, the peak field in the cathode range is only ~20MV/m. So there is less danger of field emission, and then less possibility of electron back bombardment.

Contamination from the cathode to the cavity

In the dc gun and rf gun cases, the contamination of the cathode is most critical topic, but in our proposal, it has to be considered reversely: does the cathode material pollute the superconducting cavity around the photocathode? Because for the superconducting cavity, the contamination of particles on the wall will lead to decline of the cavity quality and even induce the cavity to quench. Although there was no obvious slide-down of the cavity during the operation in the test of the half gun cavity with Cs₂Te cathode [3], it is still difficult to conclude that there will be undoubtedly safe to employ GaAs-type semiconductor in the superconducting cavity. One reason is that the first test lasted only several weeks, and the long term experiment is needed to answer this question. The other reason is that the different semiconductor materials may have different effect on the around area.

Thermal emittance

The lower limit of the normalized transverse emittance that can be provided by the injector is determined by the "thermal" emittance of the given cathode material. If the source is required to provide the beam with less than 1μm normalized transverse emittance, the initial thermal emittance becomes a large part in the final value. According to the former reports, the thermal emittance of Cu photocathodes has been measured as 0.6 μm per 1mm radius spot [7]; for Cs₂Te photocathodes the estimation of the thermal emittance by Klaus Floettmann is 0.43 μm per 1mm radius spot [8]. Because polarized electrons from NEA GaAs-type originate from near the bottom of the conduction band where they arrive at the surface fully thermalized, the thermal energy at the cathode surface should correspond to the crystal lattice temperature, which corresponds to $\epsilon_{n,rms}=0.1$ μm per 1mm radius spot for room temperature, and 0.06 μm per 1mm radius spot when the cathode is cooled down to 100K [9].

For the SRF gun, the cathode is cooled down to 77K by liquid Nitrogen, thus the GaAs-type photocathode has a lower thermal emittance than that in dc and rf guns. It can be even predicted that the polarized SRF gun with GaAs-type cathode has lower transverse emittance than the current SRF gun with Cs₂Te photocathode.

BEAM DYNAMICS SIMULATION

Some beam dynamics simulation has been done with the ASTRA code [10]. In order to obtain high average current required by colliders and the other nuclear physics instruments with the polarized SRF gun, one choice is to adopt high repetition rate and moderate bunch charge. The other is to use moderate repetition rate and high bunch charge. For example, if the gun produces 77pC/bunch @ 13MHz, which corresponds to 1 mA current, and 0.77nC/bunch @130MHz is 100mA. Here the simulation focuses on two choices of bunch charge: 77pC and 0.77nC.

In this simulation two emittance compensation schemes have been considered. One is to use a solenoid at the exit

of the SRF gun. This solenoid focuses the relativistic 9.0MeV electron bunch at 1.1 m distance from the photo cathode. The second scheme is to retract cathode surface few millimeters from the half cell back wall [11], which forms a weak focusing field near the cathode surface, and has obvious efficiency in the case of large bunch radius.

Table 1 gives the optimized result of Astra simulation. The large number of variables and constraints in the simulation under consideration, including the initial beam distributions at the photocathode, the cathode surface position, the phases of time dependent fields, and the solenoid field. But the geometry and the field strength of the gun are fixed as the currently design of 3+1/2 cell cavity, in which the maximum field is 50MV/m. The image charge effect near the cathode area and the thermal emittance of the photocathode have been involved in the simulation. The $\epsilon_{x,rms}$ is the minimum normalized transverse emittance, and the $\epsilon_{z,rms}$ and the energy spread are the data at the position of 6 m down from the cathode.

Table 1: Optimized simulation result

Bunch charge	0.77nC	77pC
Bunch length	Plateau, 20 ps	Plateau, 10 ps
Rising time	4 ps	2 ps
Spot size σ_x	Radial, 1.3 mm	Radial, 0.5 mm
$\epsilon_{x,rms}$	1.4 μm	0.3 μm
$\epsilon_{z,rms}$	37 $\pi\text{keV mm}$	6.3 $\pi\text{keV mm}$
Energy spread	60 keV	34 keV

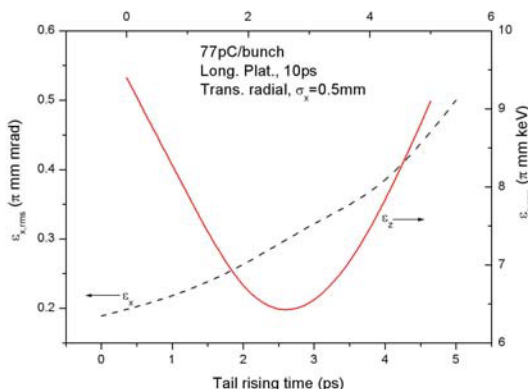
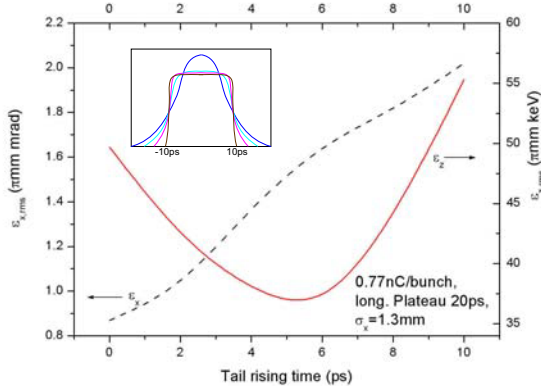


Figure 3: The sensitivity of transverse emittance (dash) and longitudinal emittance (solid curve) to the longitudinal profile for 0.77 nC/ bunch (top) and 77 pC/bunch (bottom), respectively.

The proper shape of the laser pulse illuminating the cathode is very important for getting the minimum emittance. The radial transverse distribution is adopted in our simulation, because it is believed to reduce the nonlinear effect in the centre of the electron bunch, and it can be realized from the laser shaping technology [12]. The longitudinal shape of the bunch is described as plateau with head and tail, which have the same value in the simulation. If the rising time is equal to half of the bunch length, this bunch can be treated as Gaussian shape. The sensitivity of emittance to the tail can be found in figure 3. When the tail-rising-time increases, the transverse emittance rises because of the increasing of the space charge force in the centre of the bunch. However, the longitudinal emittance decreases at first and then increases because of the large area occupied in the rf phase of accelerating field by the bunch.

CONCLUSION

The prospects for operating the Rossendorf SRF gun with a NEA GaAs-type photocathode have been discussed. The polarized SRF gun will be a new application for the Superconducting RF technology in the field of high energy physics and nuclear physics. The high accelerating field in the gun and the best vacuum environment would make SRF polarized gun a competitive candidate for the sources of the electron linear collider projects. The more dedicated theoretical simulation and the experimental study about the polarized SRF gun are needed in order to realize this kind of new polarized electron source.

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