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Polarized Electrons from High-Gradient Guns*

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INTRODUCTION. The emittance of a photoinjector depends on the extraction field at the cathode. High fields rapidly accelerate the electron beam to relativistic energies thus minimizing the effects of space charge (SC). If the field is too low, the SC must be kept low by increasing the beam dimensions until an adequate rf or magnetic bunching system can be employed. DC-biased guns with extraction fields of up to 10 MV/m at the cathode have been successfully operated for producing non-polarized electron beams [1,2]. However, if polarized electrons are to be produced, the extraction fields must generally be lowered to keep the dark current, which will otherwise quickly spoil the quantum efficiency (QE) at the band-gap edge, below ~20 nA. Thus polarized beams from dc-biased guns are usually extracted with large spatial and temporal dimensions and then bunched in separate rf cavities before and during acceleration. The bunching process typically increases the beam emittance by at least an order of magnitude.

Polarized RF Photoinjectors. The basic components of an rf photoinjector, illustrated in Fig. 1, consist of an rf gun with a photocathode, a laser and optical system producing the desired pulse structure, an rf source, and a timing and synchronization system. If a GaAs photocathode is used, it must be activated before insertion under vacuum into the already rf-processed cavity.

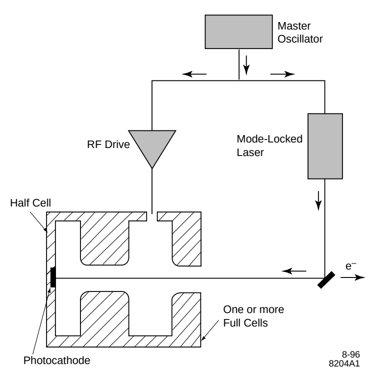

Figure 1. Principal components of an rf photoinjector.

Assuming that a polarized rf-gun could be successfully produced and operated, what would be its advantages compared to a polarized dc-gun plus rf compressor? The principal advantage is that an rf photoinjector produces an inherently lower beam emittance. For an FEL this advantage is crucial. For a high-energy collider this emittance is still not low enough to eliminate the electron damping ring (DR), but it will certainly simplify both the DR and the intervening beam transport system. Bunch shaping is

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much more feasible and can be used to further reduce the beam emittance. Since the transmission will be higher, the charge to be extracted can be reduced by up to a factor of two, mitigating the restrictions of the cathode charge limit [3]. The QE will also be higher (Schottky effect), reducing the demands on the source laser system. Finally, beam-loading compensation is somewhat more effective and more straightforward for an rf gun.

REVIEW OF R&D PROGRESS. Up to the present there has not been a successful demonstration of photoemission from an activated GaAs cathode using an rf gun. However there has been experimental progress.

Dark currents on the order of 1 nC/(μs of rf after filling cavity) are typical for conventionally cleaned S-band guns operating at ~130 MV/m [4], which would result in >100 nA average dark current at 180 Hz. At KEK it has been demonstrated that the dark currents from a Cu cavity that has been specially cleaned with high-pressure, ultra-pure water (UPW) and then assembled in a Class 100 clean room can be reduced to ~130 (~13) pC/(μs of rf) at 130 (90) MV/m [5].

A complete GaAs test requires an rf gun equipped with a load-lock and an associated activation chamber. A relatively high-power pulsed laser tuned to a wavelength between 750 and 850 nm is also required although initial tests can use a pulsed laser system operating at shorter wavelength such as a doubled Nd:YAG or YLF. There are at present only two guns being used. Testing of GaAs cathodes has been underway at CERN since 1995 [6]. The 1.5-cell S-band gun for the CTF drive beam is based on the BNL design. The gun and following booster section, which have been manufactured and assembled under clean room conditions [7], normally exhibits relatively low dark current. Since the gun was designed to be used with a Cs_2Te photocathode, it was already equipped with a separate activation chamber with a Cs source and a transporter for moving the cathode into the gun through a load-lock. For the initial tests, no attempt was made to activate the GaAs. The GaAs crystal, cut from a bulk-grown wafer with dopant density of $5x10^{18}$ cm^{-3}, was simply glued to an inset in the face of a detachable Mo nose for the rf plug using In as the glue. After chemical cleaning and a mild bake, the rf plug was inserted into the gun. Given the high dopant density, it is not surprising that the resonant frequency of the cavity was found to be unaffected. After vigorous processing of the first sample, a field at the cathode of ~90 MV/m was achieved, but the cathode plug was later found to be seriously damaged as a result of the rf processing. At the maximum field, no dark current was detected, however from the light visible on a screen, an upper limit of 60 pC/(μs of rf) was estimated. For an S-band gun operating with a 2-μs rf pulse at 180 Hz, this limit corresponds to an average current of ~10 nA, well within the criterion mentioned earlier. A second sample, not activated but with a thin layer of Cs, was processed more gently to 60 MV/m without visible damage and again without detectable dark current.

At INP, Novosibirsk, a prototype S-band polarized rf gun has been constructed for the injector of the VEPP-5 complex [8]. A cross section of this gun (base pressure without rf was <10^{-11} Torr) is shown in Fig. 2. In the initial test the lifetime of a positive electron affinity (PEA) GaAs cathode (QE~0.05% at HeNe wavelength) was measured to be about 0.5 h. During the test, dark current for a field of 60 MV/m was observed to be about 2 orders of magnitude larger than for a clean cathode [9]. Recently a negative electron affinity (NEA) GaAs cathode was tested at INP. Beginning with a QE of 1% (HeNe wavelength) and a cathode field of ~20 MV/m, the dark current was very high, resulting in a drop of the QE by an order of magnitude within a matter of a few rf pulses at 0.5 Hz. Data for each pulse was analyzed. It was found that the dark current for a given field was proportional to the QE. Fowler-Nordheim plots of the QE-normalized data suggest possible anomalous dark current behavior for the NEA cathode. This behavior will be checked in future experiments with the Faraday cup moved further away from the cathode [10].

Although the INP results are disturbing, there is actually no fundamental reason that an NEA semiconductor should field emit since there are essentially no free conduction band electrons when optical excitation is absent unless the external field is large enough to create an inversion layer at the surface. An inversion layer begins when the bands at the surface are bent downward to at least mid-gap. Since the behavior of highly-doped p-GaAs is similar to a metal, the additional bending necessary can be estimated from the usual Schottky-effect analysis. Assuming band bending of ~0.5 eV at low field, a weak inversion layer should begin at an external field of ~50 MV/m although rapid accumulation of free electrons would require significantly higher fields [11]!

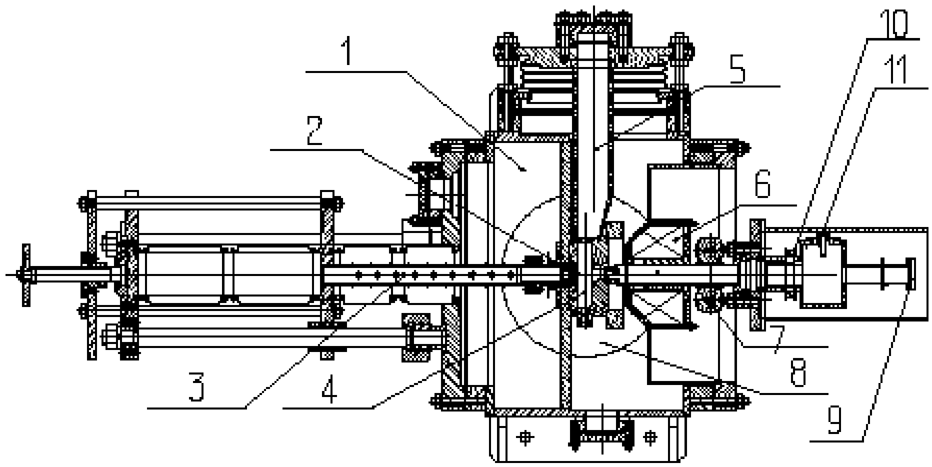

Figure 2. Cross section of the INP prototype polarized rf gun showing: 1) activation chamber, 2) photocathode assembly, 3) manipulator, 4) accelerating cavity, 5) waveguide, 6) focusing lens, 7) transverse corrector, 8) working chamber, 9) vacuum window for laser beam, 10) ceramic insulator, and 11) cavity for measuring bunch length. (From Aleksandrov et al., ref. 9.)

Recent measurements at Mainz of the electron photoemission time from a thin (epilayer of 150 nm), strained-layer GaAsP crystal indicate an emission time of no more than ~10 ps for the lowest charge (~0.5 fC) measured [12]. The measurements were made using a dc gun biased at 100 kV. The crystal was illuminated by a 100-fs laser tuned to the polarization peak, which was at 836 nm. The laser spot diameter at the cathode was ~0.6 mm. The resolution of the rf analyzer was ~1 ps at 2.45 GHz. An observed increase of bunch duration with charge was attributed to an external space charge effect, but more recently the Novosibirsk-Legnaro group has shown that this effect is internal to the gun and is a current limitation not attributable to a gun space-charge effect [13]. In fact the limit may be the same cathode charge limit described in ref. 3. The limit for the Mainz measurement, ~20 mA cm^{-2}, is only about a factor of ten below the limit found for the SLC source under similar conditions after scaling for differences in QE, epilayer thickness, and extraction field [14].

There is increasing evidence that the effect of the cathode charge limit can be greatly reduced by using a very high dopant density at the surface of the GaAs [15].

HIGH-GRADIENT PULSED GUNS. Recently, very low emittances have been reported using a Cu cathode with extremely-fast, pulsed extraction fields on the order of several GV/m and illuminated by synchronized short laser pulses [16]. The beam-emittance associated with such guns should be limited by the thermal emittance, which would be significantly lower for an NEA GaAs cathode than for Cu [17]. Dark currents for copper cathodes with anode spacings on the order of 1-mm have been found acceptable [18]. The problems for an NEA GaAs cathode include not only the possibility of high dark current as for the rf gun (although for the pulsed gun there is no backward accelerating voltage), but also a possibly severe cathode charge limit because of the extremely high current densities. The advantages for a polarized electron source in addition to lower emittance include possibly higher polarization due to field-assisted emission [19] and for the same reason higher QE.

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[14] The current limit found for the Novosibirsk-Legnaro source was ~25 A cm^{-2}. The higher value can be attributed to excitation with much higher-energy laser pulses (524 nm), which, it should be pointed out, cannot be used for a high-polarization cathode.

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[18] T. Srinivasan-Rao et al., "Dark Current Measurements At Field Gradients Above 1 GV/m," to be published in Proc. of the *Advanced Accelerator Concepts Eight Workshop*, Baltimore, MD, July 5-11, 1998.

[19] Extremely high fields may also result in a lower polarization due to Stark broadening of the energy levels.