A 500 kV PHOTOEMISSION ELECTRON GUN FOR THE CEBAF FEL*

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Abstract

The proposed FELs at CEBAF require an electron source delivering 120 pC bunches at a repetition rate of 7.485 MHz, corresponding to an average current of 0.9 mA. To meet this requirement we will employ a 500 kV DC photoemission electron gun to produce nominal 100 psec bunches of modest peak current. The subsequent injector system will bunch and accelerate this beam, producing 60 A, 2 psec bunches for the FELs. The photoemission gun will use a negative electron affinity GaAs photocathode, which provides good quantum efficiency and an adequate temporal response. The optical beam will be provided by a frequency doubled Nd:YLF laser system, actively mode locked to a subharmonic of the fundamental accelerator frequency. The principal technical difficulties associated with an electron source of this type involve the operating lifetime of the photocathode, and the operation of a high voltage gun in the presence of the alkali metals necessary to produce the photocathode. Various design aspects of the CEBAF gun will be presented, along with evidence that the technical problems can be successfully handled.

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Introduction

The baseline designs for each of the two proposed CEBAF FELs [1] require 120 pC electron bunches at a 7.485 MHz repetition rate. The IRFEL will use 60 A, 2 psec bunches, while the UVFEL will use 120 A, 1 psec bunches. The 60 A bunches will be obtained by RF bunching the beam from a photoemission electron gun, while the 120 A bunches will be produced by magnetic compression of the 60 A bunches. Thus, the electron gun itself must deliver a 7.485 MHz train of 120 pC pulses suitable for subsequent bunching. Simulations by Liger *et al.*, [2] indicate that electron bunches of 100 psec duration, 500 kV energy, 10 mm- mrad normalized emittance, and several mm diameter at the gun anode can be bunched to meet all the requirements for the FELs. The high bunch repetition rate requires that the electron gun be operated CW, which in turn rules out the possibility of using a normal conducting RF gun, since the accelerating gradients practical in normal conducting CW structures are too low to support the required cathode current density. Superconducting RF guns have been proposed as a way around this limitation, and a demonstration project is underway [3, 4], but it is premature to incorporate a gun of this type into the plans for an FEL to be constructed in the near term. Consequently, a DC high voltage gun is required.

A thermionic emission cathode could certainly be used in the present application. However, the shortest duration pulses obtainable from gridded thermionic emitters are so long that a sub-harmonic bunching system would be required in our application. Given the relative ease of varying the pulse duration and emitting area from a photoemission cathode, the higher beam brightness available from photocathodes, and the modest current and current density requirements of the present application, a photoemission gun was judged to be the best choice.

The photocathode for this gun must have a reasonable quantum efficiency and operating wavelength. The choices are between positive electron affinity alkali antimonide cathodes, and negative electron affinity semiconductor photocathodes. Both types of cathodes have been employed in practical photoemission electron guns, and both have demonstrated performance characteristics beyond what is required for this gun [5, 6]. We have chosen to use a GaAs negative electron affinity photocathode, based on the high quantum efficiencies typical of this cathode, and our experience in using them.

The principal technical difficulties associated with the use of either of the above cathodes in electron guns involve the operating lifetime of the cathode, and the operation of metallic surfaces in the gun at high DC field strengths in the presence of the alkali metals necessary to form the photocathodes. Bare metal photocathodes are often suggested as a way to avoid these problems, but cannot be employed for a CW gun of this type. Bare metals at best have high work functions and low quantum efficiencies, which in the present application would produce high thermal loading on the emitting area, and which would require CW ultraviolet lasers substantially beyond the present state-of-the-art. In the following discussion we will present evidence that good quantum efficiency, negative electron affinity GaAs photocathodes should perform well in our application.

Gun Design

The mechanical design for the gun is similar to that of a 400 kV gun constructed at SLAC by the author and others several years ago [7], and is shown schematically in Figure 1. This design is developed around a large ceramic insulator commercially available from Litton. These insulators are conservatively rated for 200 kV operation in air. Two of these ceramics will be stacked, and the assembly operated in a low pressure SF_6 tank for 500 kV operation. The ceramics are coated on their interior surface with a high resistivity material to prevent charge buildup on the ceramic produced by the low levels of field emission from the various metallic surfaces in the gun.

The electrostatic design of the gun is done with the program POISSON. The anode and cathode surfaces are flat and parallel to produce a high degree of electric field uniformity over the emitting area. The cathode field necessary to support the delivery of the design charge is, of course, dependent upon the illuminated area on the photocathode. It will be possible in practice to vary the cathode field strength between 6 and 10 MV/m by changing the anode-cathode spacing. POISSON calculations of the field strengths in the gun for these two cases are shown in Figure 2 [8]. This range of field strengths is well suited to the delivery of 120 pC in 100 psec from an emitting area ranging between 3 and 5 mm diameter.

The gun will operate very much in a "transient" regime, in that the bunch duration is substantially less than the time necessary for the bunch to traverse the anode-cathode gap. It will be necessary to do detailed studies with a time dependent code, such as MASK, to determine optimum values for the emitting area and pulse duration. However, our requirements for bunch charge and duration are so modest, compared with what has already been achieved with photoemission guns, that we foresee no difficulty in meeting our design values. For example, Oettinger *et al.*, [9] have reported current and emittance values for 100 psec pulses emitted from cesium antimonide photocathodes which exceed our requirements.

The vacuum design of the gun will emphasize good ultra-high vacuum practice and high voltage performance. All electrodes will be manufactured from vacuum melt stainless steel, and will be polished with diamond pastes. Vacuum pumping will be with a combination of conventional ion pumps and non-evaporable getters. Based upon previous experience with such photocathode systems, we anticipate achieving operating vacua of below 10^{-10} mbar. The gun beamline to the buncher will be isolated by a single segment of the three segment differential pumping system developed at CEBAF to isolate the superconducting RF cavities from the conventional beamline vacuum. This single segment differential pump, which is based on the use of non-evaporable getter elements, provides a measured factor of 30 pressure reduction for active gases.

Cathode Selection

Alkali antimonide or negative affinity semiconductor photocathodes could be used equally well in this gun. Our choice of the GaAs negative affinity cathode is based upon our experience with it. A common reason for choosing alkali antimonide cathodes is the faster temporal response they provide. The GaAs cathode, however, is quite adequate for 100 psec pulses [10]. The formation, gas poisoning, and charge delivery capability of GaAs photocathodes has been investigated in a series of experiments conducted at SLAC [7]. These experiments were executed in actively pumped vacuum chambers specifically designed for the particular measurements. For example, Figure 3 shows an experimental setup used to study charge delivery from these cathodes.

Activation of the GaAs surface to negative electron affinity with Cs and NF_3 was compared to the more conventional process using Cs and O_2. It was found that cathodes activated with NF_3 were approximately an order of magnitude less sensitive to poisoning by typical residual gases than those activated with O_2. In addition, the quantum efficiency of cathodes prepared with NF_3 was superior to that of the O_2 cathodes. Studies by a group at Mainz [11] have also demonstrated the superior performance of NF_3 in the preparation of high quantum efficiency GaAs photocathodes. In general, quantum efficiencies exceeding 5% can be reproducibly prepared using this method on substrate quality GaAs samples. Often the quantum efficiency is significantly better than this value.

During these experiments, GaAs photocathodes with lifetimes under continuous low level illumination of 10^4 hours or greater were prepared. Equally significantly, using the apparatus of Figure 3, 1000 coulombs from a good quantum efficiency cathode, at an average current of 10 mA and a beam voltage of 9.5 kV, was delivered to the water cooled beam dump without destroying the cathode. The excellent vacuum conditions in these test chambers was essential to the good performance of these cathodes. Other groups have noted similarly good performance from GaAs photocathodes when proper attention is paid to the vacuum conditions [12]. Cathode performance at this level would imply operation of the CEBAF FELs for a period of two weeks before stopping for photocathode reactivation. The maximum number of photocathode reactivations possible is not known with any certainty, and is no doubt dependent upon cathode material, gun vacuum, and cathode history. In practice, GaAs photocathodes can typically be reactivated a dozen or more times.

Laser System

We will use a frequency doubled CW Nd:YLF laser, actively mode locked to the 40th subharmonic of the 1497 MHz fundamental frequency of the accelerator. This will produce an optical pulse train at 74.85 MHz. Nine of every ten optical pulses will simply be discarded with the aid of an electro-optic shutter, producing the required 7.485 MHz pulse train. At the 527 nm laser wavelength, a 1/2% quantum efficiency photocathode will deliver 2.13 mA per watt of optical power. Our 0.9 mA average current requirement, coupled with our use of only 1/10 of the laser power available, leads to a requirement for 4.23 W of laser power for operation with a 1/2% quantum efficiency cathode. Commercial systems delivering this level of CW mode locked power in the green are available. Consequently, it is possible to plan on the successful operation of this gun with a cathode quantum efficiency about an order of magnitude below the typically obtained values.

High Voltage Issues

High voltage holdoff in electron guns containing cesiated photocathodes is an important issue. We have had mixed experience in this area. In all guns we have constructed to date, the GaAs cathode has been activated by directing a flow of cesium vapor directly at the GaAs wafer in its operating location in the cathode electrode. Consequently, the cesium also impinges on some fraction of the cathode electrode, lowering its work function as well. The high DC field levels and the low work function electrode surface create an obvious risk of high voltage breakdown. Such breakdowns cause gas bursts, which in turn can destroy the photocathode quantum efficiency. Though we have operated photocathode guns with fields strengths on nearby electrode surfaces as high as 13.9 MV/m, we have also had breakdown problems in other guns with fields as low as 4-5 MV/m.

Several avenues are available to reduce the high voltage breakdown problem. We will operate the gun with as low a field strength as permissible to meet our design parameters. As indicated in Figure 2, reducing the cathode field to 6 MV/m will keep the fields in the cathode area reasonably low, as compared to the 10 MV/m case. It is well known that coating electrodes reduces prebreakdown emission phenomena until quite high field strengths are reached. This method has not yet been tried with cesiated electrode surfaces, but is an obvious candidate to reduce the problem, particularly given the modest field levels required in this gun. It is also possible to devise a cesium source to illuminate only the cathode area to be activated. Perhaps the most obvious solution is to fabricate the photocathode outside the gun electrode structure, and transfer it under ultra-high vacuum into its operating location. This is the solution used in several RF photocathode guns, but is more complicated in our case, since our cathode operates at 500 kV. While this solution is essentially certain to work, we will not attempt it initially due to its added complexity.

Summary

We will build a 500 kV DC electron gun with a negative electron affinity GaAs photocathode to meet the design requirements of our proposed FELs. Our experience with these cathodes indicates they should meet our design requirements and offer the advantages of high quantum efficiency and long operating life. The parameters for the laser to illuminate the cathode are well within what is commercially available. The major technical issue involves the operation of the gun at high DC electric field strengths without breakdown. A number of ways of dealing with this problem are available, and will be pursued in order of increasing complexity.

References

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Figure Captions

Figure 1. Mechanical Design of the 500 kV Photoemission Gun

Figure 2. Poisson Calculations for the Anode-Cathode Area of the Gun

a.) Cathode Field = 10 MV/m

b.) Cathode Field = 6 MV/m

Figure 3. Experimental Setup to Study Total Charge Delivery from GaAs Photocathodes

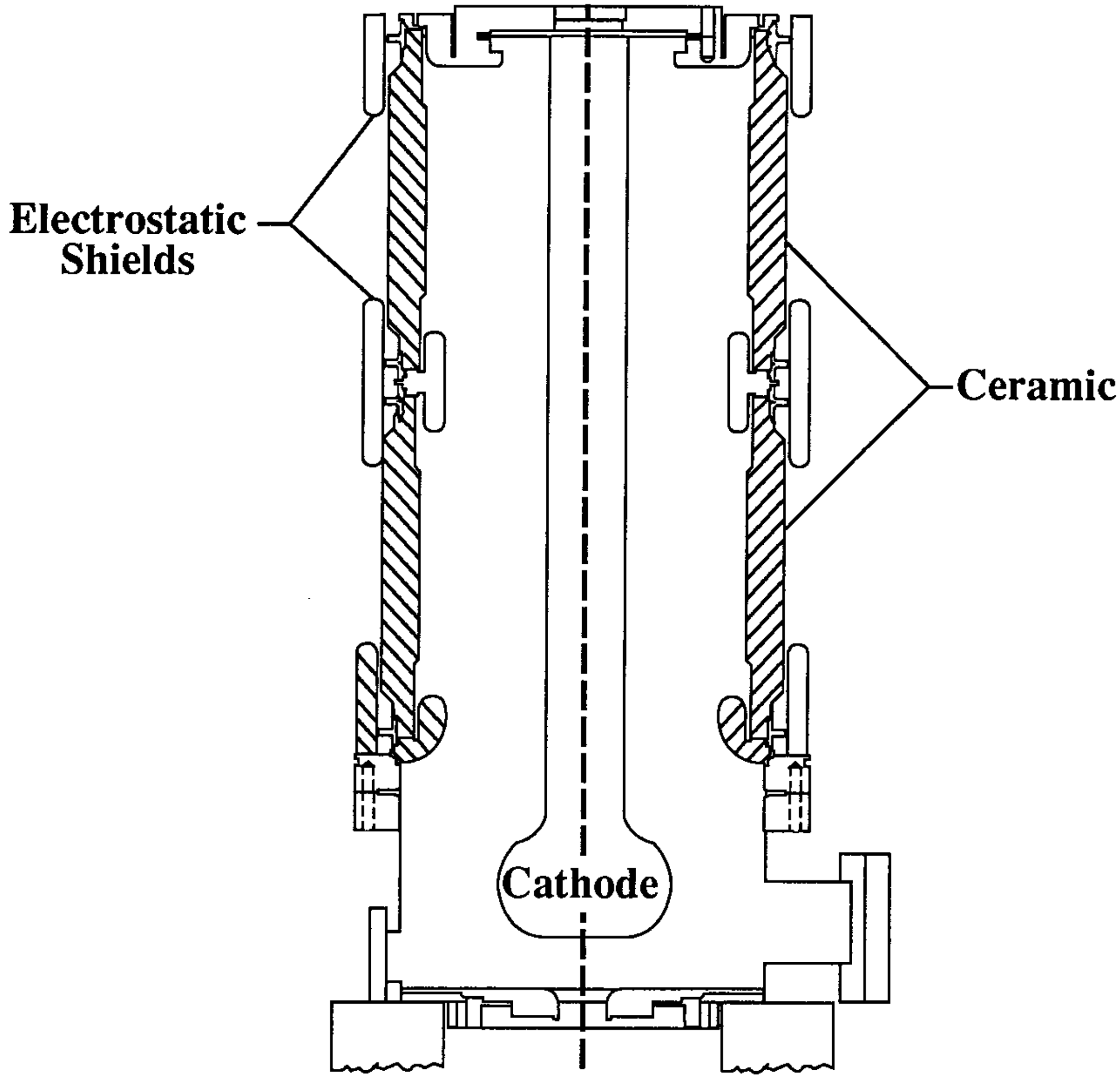


Figure 1

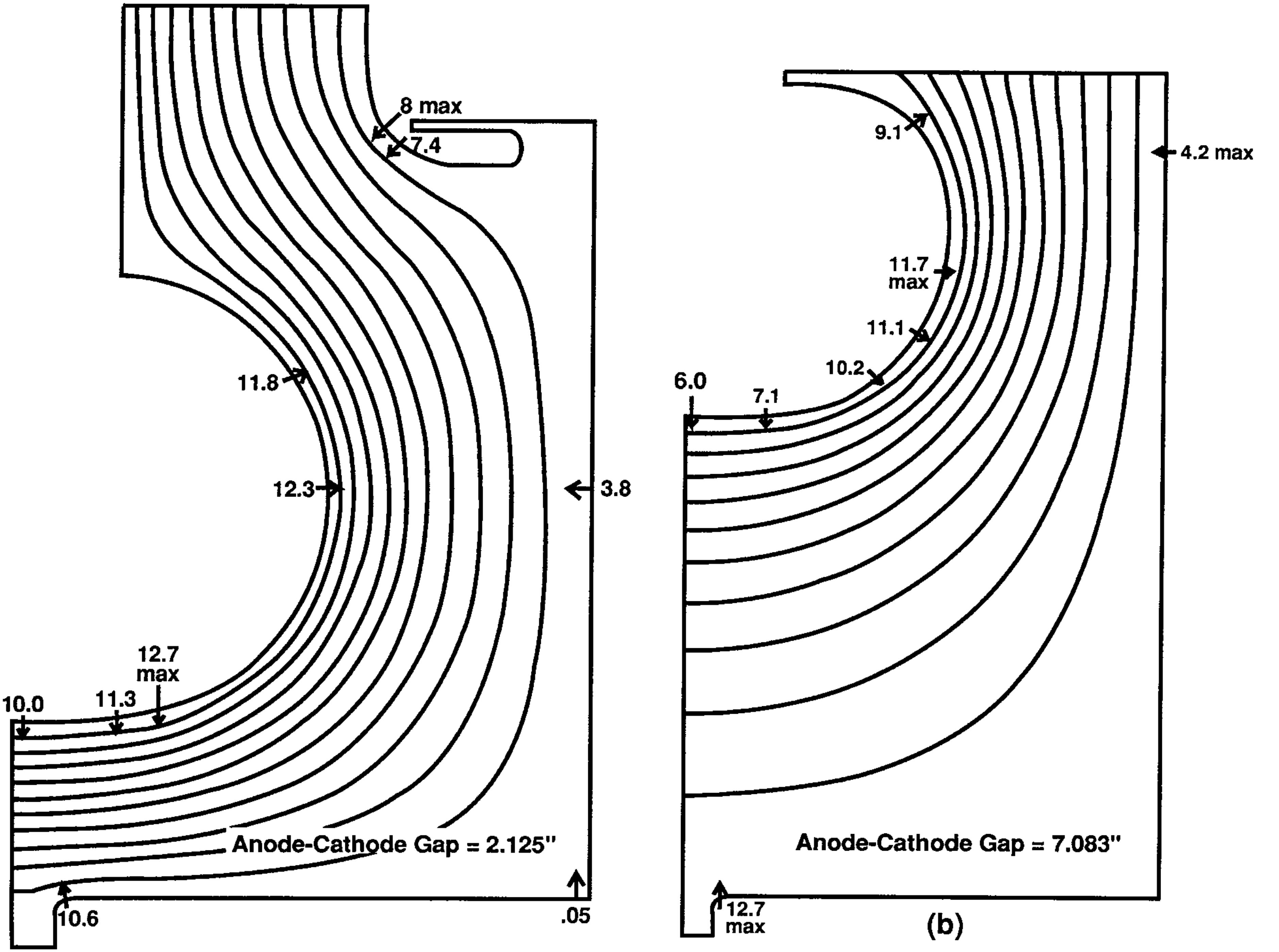
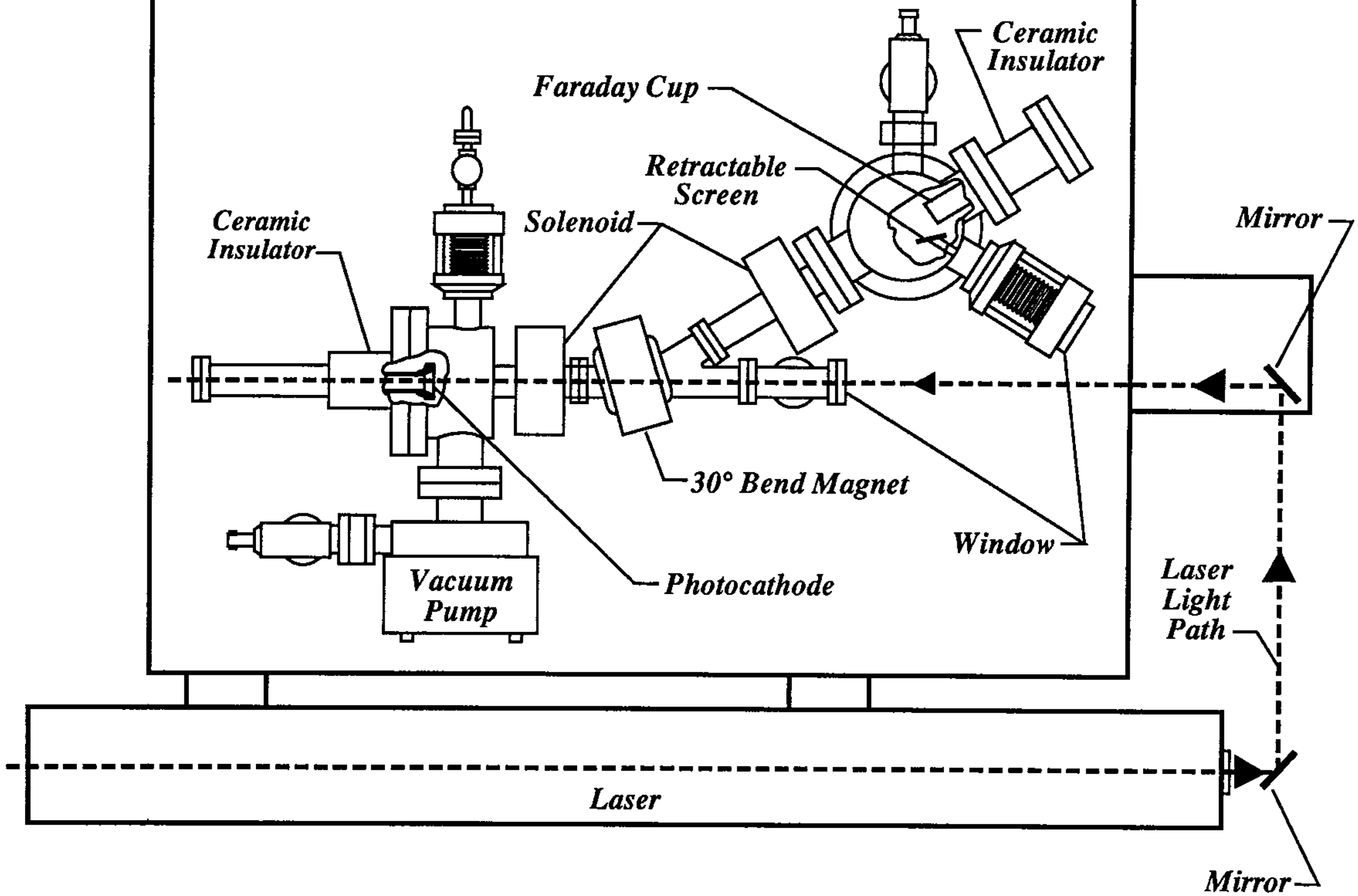

8 max
7.4
11.8
12.3
3.8
12.7
max
10.0
11.3
10.6
.05
Anode-Cathode Gap = 2.125"
9.1
4.2 max
11.7
max
11.1
10.2
6.0
7.1
Anode-Cathode Gap = 7.083"
12.7
max
(b)

Figure 2

fig 3


Ceramic Insulator
Faraday Cup
Retractable Screen
Ceramic Insulator
Solenoid
Mirror
30° Bend Magnet
Window
Vacuum Pump
Photocathode
Laser Light Path
Laser
Mirror