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Polarized Electrons at Jefferson Laboratory

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Abstract. The CEBAF accelerator at Jefferson laboratory can deliver CW electron beams to three experimental halls simultaneously. A large fraction of the approved scientific program at the lab requires polarized electron beams. Many of these experiments, both polarized and unpolarized, require high average beam current as well. Since all electrons delivered to the experimental halls originate from the same cathode, delivery of polarized beam to a single hall requires using the polarized source to deliver beam to all experiments in simultaneous operation. The polarized source effort at Jefferson Lab is directed at obtaining very long polarized source operational lifetimes at high average current and beam polarization; at developing the capability to deliver all electrons leaving the polarized source to the experimental halls; and at delivering polarized beam to multiple experimental halls simultaneously. Initial operational experience with the polarized source will be presented.

INTRODUCTION

At Jefferson Lab, polarized electrons are presently delivered by a 100 kV GaAs photoemission electron gun of quite conventional design (1). This gun has no load lock system. Polarization orientation at the injector is accomplished with a Mainz style "zee" spin manipulator (2). An identical gun is used in an off line laboratory for photocathode development studies and polarization measurements. Several smaller ultrahigh vacuum chambers are used to address specific issues, such as photocathode cleaning and activation techniques, reduction of field emission from electrode structures, etc.

Approximately 50% of the approved scientific program at the lab requires polarized electron beams. Many of these experiments require ~ 80% beam polarization, and most of the experiments not explicitly requiring high polarization would use it if available. Many experiments, whether requiring polarized beam or not, require average beam currents of 100 μA or greater. Some experiments which do not require polarized beam desire to operate from a photoemission electron

gun, because of the ability to deliver non-standard beam time structures by modulating the laser illuminating the cathode.

In the present CEBAF injector, all electrons must originate from the same cathode. Thus, when delivering polarized beam to one experiment, beam delivery to other simultaneous experiments is an additional load on the polarized source. This point is important, since the general experience with photoemission polarized electron sources is that the operational lifetime of the photocathode is strongly correlated with the total charge delivered, rather than simply the clock hours the cathode is used.

Finally, the specifications on the beam spot size and energy spread delivered to the experimental halls translate into very demanding beam quality specifications in the injector. The injector includes an emittance filter and a sophisticated three-beam chopping and bunching system designed to meet these requirements. The three beam chopping system also provides independent current control for the beams to the three experimental halls. For a typical DC beam from the thermionic electron gun, only a few percent of the electrons leaving the cathode reach the experimental halls. Such large beam losses are very undesirable when polarized beam is being delivered.

As a result of the above realities, the polarized source program at Jefferson laboratory is directed toward achieving long photocathode operational lifetimes from the existing gun; to delivering polarized beam to more than one experimental hall simultaneously; and longer term, to developing a "best technology" photoemission polarized source. In developing this latter source, we will examine all of the issues which are believed to affect photocathode operational lifetime, and incorporate the best practical solutions to these issues.

OPERATIONAL LIFETIME

By operational lifetime, we mean the time during which a photocathode can deliver the required beam conditions, not simply some decay constant. This operational lifetime is the convolution of a number of effects, such as:

- initial cathode quantum efficiency
- static vacuum in the vicinity of the cathode (pressure and composition)
- vacuum degradation during operation with beam
- available laser power
- useful photocathode area
- electron losses from the photocathode to the experimental target

Some of these issues are intimately connected with the requirements for a particular polarized source. For example, if a very small emittance must be delivered, only a small area of the photocathode may be illuminated. Thus to effectively use a large cathode area, it is necessary to either move the laser spot at the cathode and correct the electron beam steering downstream, or move the cathode itself. We address several of these issues in the following sections.

Initial Quantum Efficiency

Cleaning the surface of the semiconductor to be activated as a photoemitter is a very important step in obtaining a high initial quantum efficiency. For the best results, it is necessary to prepare an atomically clean semiconductor surface. Bulk GaAs can be successfully cleaned by wet chemistry and in-vacuum heat treatment. Unfortunately, the very thin layers which provide the highest polarizations cannot be cleaned with wet chemistry, since these processes remove too much material. It is also very difficult to clean semiconductors which contain, for example, aluminum or silicon.

Atomic hydrogen has been demonstrated to remove difficult contaminants on many III-V, II-VI, and elemental semiconductors, such as carbon on GaAs, oxygen on silicon, etc. (3). No chemical cleaning is required prior to the use of atomic hydrogen. The process does not remove material from the bulk semiconductor, so it is very suitable for use with the very thin materials which give high polarization. In the case of GaAs, atomic hydrogen exposure passivates the surface. This allows us to clean a GaAs wafer in one system, and transfer it through air into our electron guns, without loss of the benefit of the cleaning. This is a real advantage when a non-load-locked gun is used. We have been routinely using this process for a year, and have prepared high quantum efficiency photocathodes in three different guns using this process.

Figure 1 shows a view of the system we constructed to evaluate atomic hydrogen cleaning. In this ultrahigh vacuum system, we can clean a semiconductor as well as activate it and measure its lifetime at low average current. We typically operate with a hydrogen pressure of ~30 mtorr in the pyrex dissociation chamber. The RF discharge operates at about 100 MHz, with 40 W of forward power. The sample to be cleaned is held at ~300 C during the cleaning. The time necessary to clean a sample is clearly dependent upon the geometry, and we have not established a minimum time required. For our relatively poor geometry, cleaning times of 30 to 45 minutes are adequate. It is clear that these times could be shortened with improved geometry. During the cleaning, hydrogen in the main chamber is pumped by a combination of a non-evaporable getter and an ion pump. Once the hydrogen flow is stopped, the chamber pressure quickly recovers to $\sim 10^{-10}$ torr.

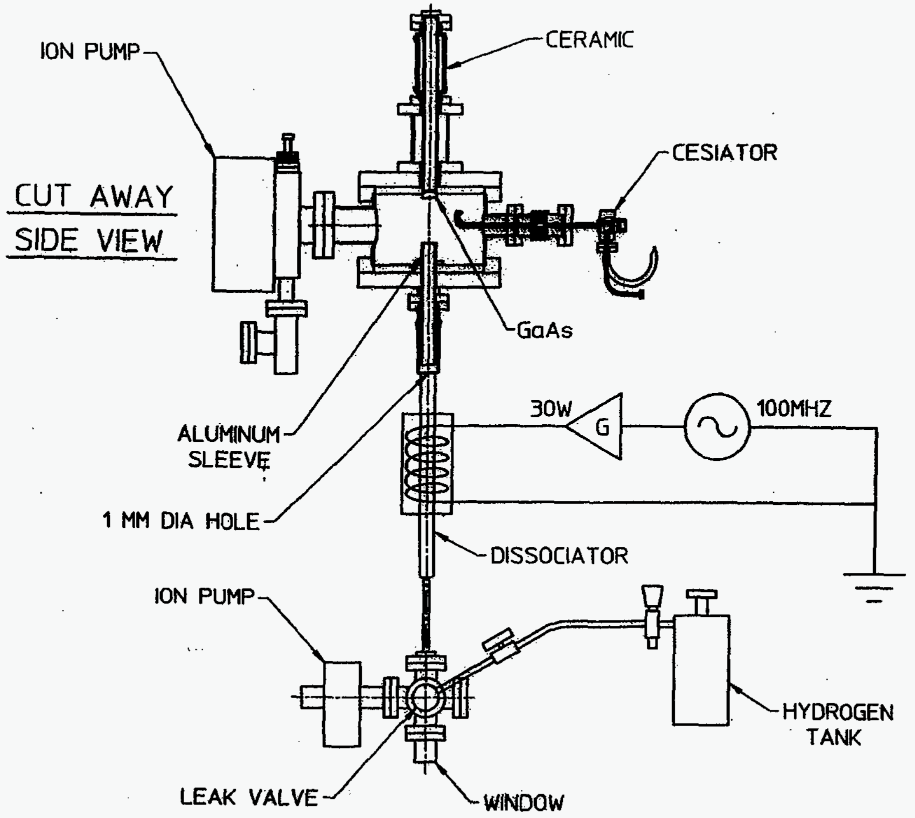

FIGURE 1. Schematic view of the ultrahigh vacuum test system constructed to evaluate atomic hydrogen cleaning and activation of GaAs photocathodes.

Following the cleaning step, the cathode is heated above 450 C to remove the hydrogen.

A typical result for quantum efficiency versus wavelength for an atomic hydrogen cleaned bulk GaAs wafer is shown in Figure 2. The dopant density of this sample was 3.3 x $10^{18}/cm^3$, and the sample was only degreased prior to introduction into vacuum. We routinely achieve quantum efficiencies above 10% at 780 nm, and above 6% at 862 nm.

We have also constructed a small "roll-around" atomic hydrogen cleaning system. This system is not baked. GaAs wafers are cleaned in this system, and then transferred to one of our electron guns. Even though the samples have been transferred through air, we obtain very high quantum efficiencies on these cathodes as well. Finally, we have adapted an atomic hydrogen source to be

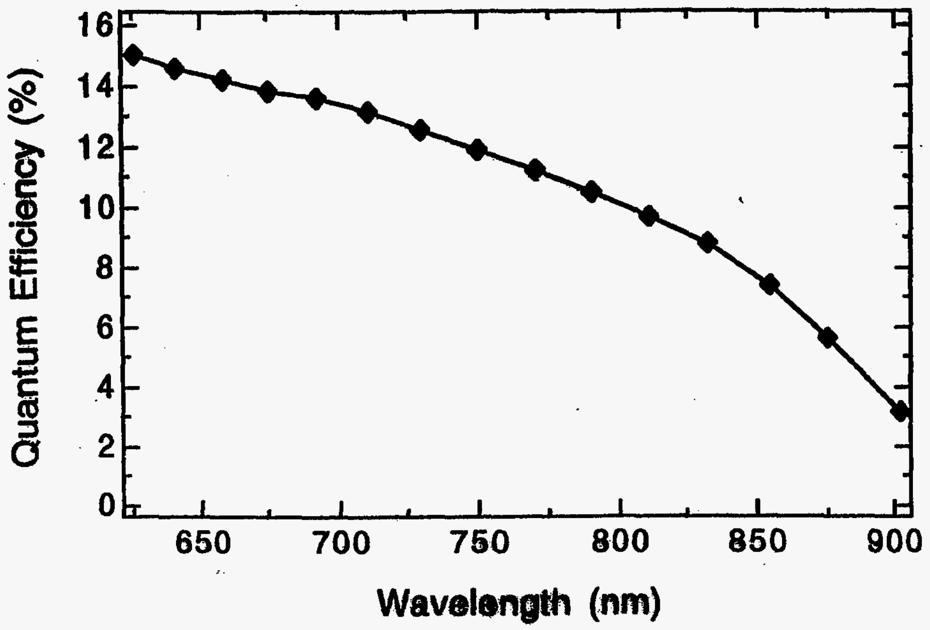

FIGURE 2. Typical Quantum Efficiency of a GaAs photocathode prepared after atomic hydrogen cleaning.

mountable directly on our non-load-locked guns. Given the success we have experienced with this process, we will incorporate it into the "best technology" gun we are developing.

Vacuum Improvements

The vacuum environment in the vicinity of the photocathode is a very important factor in its operational life. Certain gases, such as water and carbon dioxide, degrade the quantum efficiency when present at extremely low partial pressures. Even in vacuum chambers where these chemically active gases are not present in significant amounts, any residual gas in the vicinity of the cathode may be ionized by the emitted electrons, and damage the photocathode by backbombardment. Accordingly, steps to improve the vacuum environment in any region which can communicate, vacuum-wise, with the photocathode can be expected to improve the cathode lifetime.

In the polarized sources developed to date, ion pumps and NEG pumps are employed. These pumps are normally mounted downstream of the anode aperture, and as a result, the effective pumping speed at the cathode is reduced.

We are examining a number of potential pumping schemes for use in our "best technology" gun project. In the meantime, we are making a significant change in the pumping arrangement on our existing gun. We are adding a large diameter cylindrical chamber on the cathode side of the anode chamber. This chamber contains an array of NEG pump modules which will have an initial pumping speed for active gases over 2000 L/sec. A wire mesh cylinder provides a grounded surface radially inside the NEG array. The open fraction of the wire mesh is so large that it does not represent a significant conductance restriction.

Small amounts of electron beam loss in the vicinity of the cathode can result in desorbed gases which reach the cathode. Specular reflections of the incident laser beam from the GaAs surface and the surfaces of the optical input window provide a potential source for such electron beam loss. We have replaced our input window with one AR coated for our operational wavelengths. This change should reduce electron beam losses from this origin by close to an order of magnitude. These two improvements to our present vacuum system are planned for testing in September, 1997.

Improved Laser Power

Our present laser is a semiconductor diode oscillator-amplifier (4). The oscillator is RF gain switched at either 499 Mhz or 1497 Mhz, providing a train of short duration (60 to 80 ps FWHM) optical pulses locked to either the fundamental RF frequency of the accelerator, or the frequency of the bunch train delivered to one of the three halls. The purpose of this gain switching is to provide electron pulses which are short enough to pass through our chopping system without beam loss. In addition to the RF structure provided by gain switching, temporal control of the amplifier current allows us to produce the complex macropulse structure used during accelerator tuning.

Over the past year, the output power of this laser has been increased from 100 mW to 360 mW. These output powers can be obtained at either RF frequency. The ultimate power limitation on a system of this type arises from damage to the output facet of the amplifier. The manufacturer has indicated that we should be able to operate up to about 600 mW from our present amplifier, and we have demonstrated 500 mW in the laboratory. By chosing the proper diodes, the laser is operable over a broad wavelength region of interest. At the present time, we have systems operating at ~780 nm and ~862 nm. With a 1% quantum efficiency photocathode, 500 mW will deliver 3.15 mA at 780 nm, and 3.47 mA at 862 nm.

In January 1998, we will install a laser system which incorporates three separate 499 MHz lasers, each illuminating the same spot on the photocathode. This will allow us to have independent control over the current to each of the three experimental halls, eliminating the beam losses which would otherwise be experienced when the halls operate with different beam current. Much more information on lasers of this type is presented in the talk of Matt Poelker at this workshop.

Electron Losses from Photocathode to Target

Loss free transport of the beam from the photocathode to experimental target is an essential element in achieving the maximum operational lifetime from a photocathode. To obtain loss free transport through a complex injector such as ours, it is necessary to have an accurate model of the system, incorporating all of the physical phenomena present. Such a model allows us to develop a full set of initial settings for the beamline elements, and by iterating between measurement and model, provides guidance toward the final injector setup.

Our model is based on an in-house version of PARMELA developed by Hongxiu Liu (5). His model incorporates measured fields for all magnetic elements, calculated fields for all RF elements, and accurately includes the effects of space

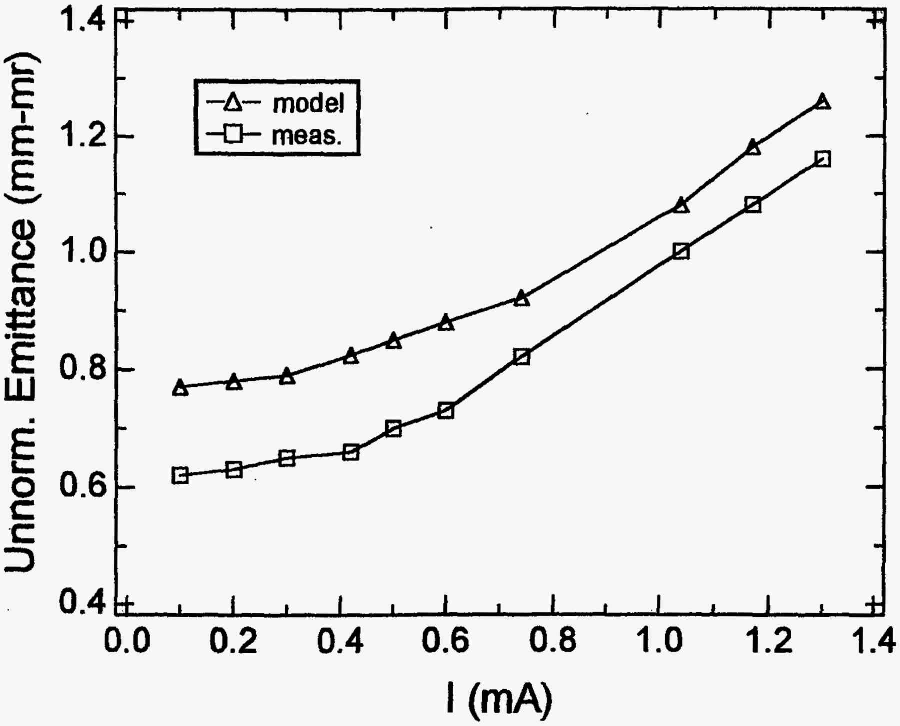

FIGURE 3. Comparison of modelled and measured emittance growth through the "zee" spin manipulator, as a function of the DC beam current.

charge. He has managed to incorporate such elements as double-focussing electrostatic bends and Wien filters, both of which are astigmatic, into his code. An example of the quality of the results he has obtained is shown in Figure 3. Several years ago the emittance of the beam transmitted through the "zee" spin manipulator was measured to grow at unexpectedly low average beam currents. We suspected that this growth was a result of space charge effects at the very small beam waists produced by the short focal lengths (10 cm) of the electrostatic bends, but were not able to calculate this. As demonstrated in Figure 3, the present code has convincingly captured this effect.

Calculations based on this model indicate that although we use a short pulse laser and operate with very low microbunch charge, space charge is sufficient to cause unacceptable bunch lengthening from the cathode to the apertures of the chopping system. A pre-buncher has been added to the system to counteract this bunch lengthing, and code is being applied to determine the best way to set this prebuncher up. The model indicates that we should be able to deliver at least 100 μA to an experimental hall from the polarized source by a combination of:

- careful attention to the transverse optics
- replacement of the "zee" spin manipulator with a Wien filter plus solenoid
- careful optimization of the pre-buncher field

These changes are planned for installation in January 1998.

THE BEST TECHNOLOGY GUN PROJECT

With the changes to our existing polarized source indicated above, we believe that we will have done as well as we can based on the use of the present gun. It is clearly desirable to incorporate a load-lock onto the polarized gun. In planning to do that, our ideas enlarged to attempt to incorporate the best technology which might be applied to all of the identified problem areas of photoemission polarized electron guns. Our reasons for enlarging the scope of the work stemmed from the observation that essentially all of the polarized gun designs built to date have been developed as variants of the original gun built at SLAC (6). That gun was essentially a thermionic gun design modified to incorporate the GaAs photocathode. Variations to this design, often clever, have been made to address one or another of the real or perceived problems in operating a GaAs gun. We have decided to move a step back, and attempt to examine the best possible technologies for achieving the desirable features of a photoemission gun, to the extent that these are known. In particular, we will examine:

- the choice of materials for vacuum system construction
- pumping methods to provide the lowest practical ultimate pressure

- electrode materials and treatments which will minimize field emission
- charge drainage over the inner surface of the primary insulator (7)
- load lock schemes for cathode introduction and activation
- incorporation of high sensitivity, field emission based vacuum diagnostics
- incorporation of atomic hydrogen cleaning

No doubt additional issues will arise as we become more deeply involved with this project. We do not have a rigid time scale for this work. Instead, we anticipate that the changes to the existing source scheduled for January 1998 will provide us enough operational flexibility to give us time to complete the new gun work without short-changing it. It is our intention to test all sufficiently novel aspects of the new gun in a meaningful way before incorporating them into the final design. We anticipate that this project will require about 18 months. Our intention is to install two of these guns at the injector, and operate from each in alternation.

SIMULTANEOUS BEAM POLARIZATION TO MULTIPLE EXPERIMENTAL HALLS

The beam delivered by the CEBAF accelerator is recirculated up to five times through a pair of equal energy linear accelerators, and then deflected through either 0 degrees, or + or - 37.5 degrees to reach the three experimental halls. As a consequence, there is considerable precession between the injector and any experimental hall. Exactly longitudinal polarization is available in all three halls at integral multiples of 2.115 GeV. However, there are over 400 possible energy combinations between 2 and 6 GeV which provide simultaneous longitudinal polarization in any two halls (8). Thus, it is practical to plan for simultaneous operation of two experimental halls with polarized beam.

In general, the delivery of longitudinal polarization to even one experimental hall requires that the polarization be oriented correctly leaving the injector to arrive longitudinal at the experimental hall. To verify this orientation, as well as measure the polarization accurately, we have developed a Mott polarimeter operating at 5 MeV (9). After this location in the accelerator, the only elements which can precess the spin are the beamline dipoles, and their effect is accurately calculable. The maximum analyzing power of gold at this energy is 0.52, and the device is operable with high average beam currents (~10 μA), permitting accurate polarization measurements to be made rapidly.

It appears possible to make an accurate determination of the beam energy by measuring the net precession between the injector and the experimental halls. To do this, the polarization is swept in the plane of the accelerator at the injector.

The 5 MeV Mott polarimeter is used to verify that the polarization is in the plane of the accelerator, and to measure the projection of the polarization in this plane. Mfller polarimeters in the experimental halls measure the projection of the polarization as well. The net precession from the injector to the experimental hall is thus determined. This precession depends only on the geometry of the accelerator and the energy gains through the two linacs. It appears possible to measure the energy with an absolute precision of about 10^{-4} by this technique.

INITIAL OPERATING EXPERIENCE

The polarized source was pressed into operation unexpectedly in February 1997, when a machine protection element of the thermionic gun failed. It was operated for 5 weeks, delivering typical currents of 30 μA CW. The highest current reached briefly was 140 μA. Cathode operational lifetimes during this run were reasonable.

The source was scheduled for operation for physics from mid-July through the first week of August, 1997. Polarized beam was delivered to two experimental halls simultaneously. Hall A conducted polarization transfer measurements from ^{16}O, while Hall C studied helicity correlated effects in preparation for parity violation measurements. Helicity correlated effects were also studied in the Hall A beamline on a parasitic basis. The source delivered 50 to 70 μA CW to Hall A, and 10 to 15 μA CW to Hall C. The transmission from the photocathode to the experimental halls was ~70%, demonstrating that we are already achieving some fraction of the anticipated gain from the use of the pre-buncher. For the duration of these runs, we delivered over 8600 μA-hours to the experimental users, and over 12,500 μA-hours from the photocathode. During all this operation, the photocathode lifetime was exceptionally poor. We had known beam scraping in the early portion of the beam transport system from the gun, but were not able to eliminate it, and we believe that this was the origin of the poor cathode lifetime. Studies will be conducted later this fall in an attempt to diagnose and hopefully eliminate this problem.

Despite these difficulties, the experimenters were able to accomplish some significant measurements. The Hall A experiment employed a focal plane polarimeter to measure recoil proton polarization, and completed a series of measurements on ^{16}O, using a water target. In addition, they were able to demonstrate from measurements on hydrogen that we will be able to do a very good job measuring G_{Ep} using this technique (10). The groups studying helicity correlated effects have concluded that the beam quality is close to good enough for parity violation measurements to proceed. Helicity correlated position asymmetries were at the 20 nm level, and helicity correlated beam energy variations were at the level of 10^{-8}. The helicity correlated intensity asymmetries were typically 10 to 20 ppm, and were strongly correlated with the correct optical alignment of the Pockels cell used to reverse the beam polarization. By imaging the exit of the Pockels cell onto the photocathode (which was not the case for the above measurements) and employing previously developed feedback stabilization, the experimenters believe they will have a system adequate for their planned measurements (11). A full "dress rehearsal" of a parity violation measurement is planned for this coming December, with the complete experiment to follow in April 1998.

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