Faraday Cup Beam Dumps
for the UCLA PBPL

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May 16, 1994

Abstract

Two identical Faraday cups have been designed and built to stop a 20 MeV, 1 nC electron pulse beam, accelerated at the UCLA Particle Beam Physics Laboratory (PBPL). The dumps were also designed to serve as charge measuring diagnostics. Each device is a simple design using a carbon graphite core, Delrin insulation, vacuum tubing components, and lead brick shielding. The graphite core stops the beam while producing manageable secondary radiation sources. The overall design considerations and final solutions are summarized.

*Work supported by the UCLA Physics Department.
Introduction

An electron linear accelerator and beam line are currently under construction at the UCLA Center for Advanced Accelerators (CAA). A UV laser (266 nm wavelength, \( E_{UV} = \frac{hc}{\lambda} = 4.67 \text{ eV} \)) will liberate \( \approx 1 \) nC bunches of electrons, 4 ps long, from a copper photo-cathode (work function=4.5 eV). The pulses can be produced at a repetition rate of 5 Hz, corresponding to an average beam current of \( 5 \times 10^{-9} \) A. These electron bunches will be initially accelerated to 4.5 MeV by an RF gun containing the photo-cathode, the beam will then pass through a Plane-wave Transformer (PWT) linac and accelerate to energies near 20 MeV\(^1\) with a corresponding average power of 0.1 W.

The 20 MeV electron bunches will be directed through several proposed research experiments. One such experiment is an Infrared Free Electron Laser (IR FEL). Another experiment to be driven by the accelerator is a Plasma Wake-field Accelerator (PWFA)\(^2\).

Two identical Faraday cups will be used to stop the energetic electron beam and measure the captured charge after it has passed through bend dipole magnets at two separate locations along the beam line.

The beam line configuration is presented in Appendix A\(^3\).

Overall Design Considerations

This simple Faraday cup design needed to meet four basic requirements. One was to stop the electron beam while producing a minimal amount of secondary radiation. Another was to be installed and operate in a high vacuum. The third requirement was to be properly shielded in order to meet all safety demands. And the final requirement was to measure the total charge of each beam pulse and remain electrically insulated from the rest of the beam line. The overall design of the Faraday cups, minus the shielding, is presented in Figure 1.
A solid carbon graphite core is used to stop the electron beam pulses. Graphite was chosen due to its low cost and low atomic number relating to negligible neutron emission and lower x-ray yields at the energies at which this accelerator operates.

Delrin is used to mount the core snugly inside the vacuum nipple and provide electrical insulation. It is low cost and easily machined. In addition, Delrin will only outgas small quantities of moisture and free formaldehyde under vacuum and remains mechanically sound up to 0.6 megarads of direct particle radiation exposure.

Each Faraday cup will attach at the end of a beam transport line which is maintained at a high vacuum. The principle vacuum hardware used for one Faraday cup (see Figure 1) is presented in Table 1. Additional vacuum hardware not listed was also required. The end cap was modified to install a hermetically sealed BNC feed through connector (see Figure 1) for measuring the voltage from the graphite core.
Table 1
Faraday Cup Vacuum Hardware

<table>
<thead>
<tr>
<th>Fig.1 Reference</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>4 5/8” to 2 3/4” adapter flange</td>
</tr>
<tr>
<td>B</td>
<td>4 5/8” flange nipple with 3” O.D. tube</td>
</tr>
<tr>
<td>C</td>
<td>4 5/8” blank non-rotatable notap flange (end cap)</td>
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</table>

To protect against harmful radiation, lead brick shielding is used around each Faraday cup in addition to the concrete shielding provided by the bunker walls.

The total collected charge after each electron pulse will be obtained by measuring the voltage, or potential difference, between the graphite core and the grounded conducting walls of the vacuum nipple, and multiplying by the known capacitance of this system.

Carbon Graphite Core Design

In order to determine the basic design dimensions of the carbon graphite core for each Faraday cup, the electron range, rms Coulomb scattering, secondary electron emission, back-scattering of primary electrons, and beam spread following exit from the bend dipoles are considered. The Faraday cups are beam line components; therefore, a solid cylindrical core to be inserted in vacuum hardware was an obvious geometry. The basic core design is presented in Figure 2.
Electron Range

The electron range was used to determine the longitudinal dimension of the graphite core. The electron range is the stopping distance of an electron penetrating a material, as a function of the incident electron energy and type of material. A plot of electron range versus incident electron energy for various materials is presented in Figure 3. This plot is based upon the continuous-slowing-down approximation (CSDA) range, which determines the path length of a moving electron if its energy loss rate along the path is always equal to the mean rate for its energy. In addition, the CSDA takes into account energy loss by bremsstrahlung and by collisions with atomic electrons. Thus the electron range is the total path length. An electron range of approximately 10 g cm$^{-2}$, corresponding to 5.7 cm (2.25 in.), was extrapolated from Figure 3 for electrons with 20 MeV incident energy penetrating carbon graphite (ρ=1.75 g cm$^{-3}$).
A common measure of the straight-line penetration distance is the practical range $R_p$. This stopping distance is relatively insensitive to beam geometry and accurate to about 2% over an energy range extending to approximately 30 MeV\textsuperscript{10}. For low-Z materials\textsuperscript{11}

$$R_p = \left( \frac{A}{\rho Z} \right) (0.285E_0 - 0.137),$$

where $E_0$ is the incident electron energy in MeV, $A$ is the atomic weight and $Z$ is the atomic number of the material, and $R_p$ is in cm. Thus for 20 MeV electrons penetrating carbon graphite ($A=12.01, Z=6$), $R_p$ was calculated to be 6.4 cm (2.5 in.).

A relationship between the practical range and the CSDA range is given by\textsuperscript{12}

$$R_p = R_{\text{CSDA}} \left[ 0.51 \left( \frac{Zm_e}{E_0} + 0.69 \right) \right]^{-1},$$
where $m_e$ is the electron rest mass (0.511 MeV). Using the previous result for $R_p$ and solving equation (2) for $R_{\text{CSDA}}$, a value of 5.7 cm (2.2 in.) was obtained. This value is in excellent agreement with the value of 2.25 in. extrapolated from Figure 3.

A straight-line practical range $R_p$, plus an additional 20% safety factor, yielded a longitudinal (in-line) dimension of 3.0 in. (see Figure 2).

**Coulomb Scattering**

Coulomb scattering was used to calculate the radial dimension of the cylindrical graphite core. The rms Coulomb scattering contribution to angular divergence $\theta_{\text{scat}}$ of a high energy electron traveling a path length $s$ through a material is given by

$$\theta_{\text{scat}} = \frac{\pi}{\sqrt{2pc\beta}} \sqrt{\frac{s}{X_0}},$$

where $\theta_{\text{scat}}$ is in radians, $pc$ is in MeV, $\beta=v/c$, and $X_0$ is the radiation length of the material. From a tabulated value of 42.7 g cm$^{-2}$ for carbon, the radiation length of graphite ($\rho=1.75$ g cm$^{-3}$) is $X_0=9.6$ in. Thus for $pc=20$ MeV, $\beta=1$, and using the practical range $R_p=2.5$ in. for the path length $s$, $\theta_{\text{scat}}$ was calculated to be 0.38 radians ($21.7^\circ$).

The radial dimension of the carbon graphite cores must have a minimum value given by

$$R_{\text{min}} = R_p \sin(\theta_{\text{scat}}).$$

Thus using the previous results for $R_p$ and $\theta_{\text{scat}}$ in equation (4), a value of $R_{\text{min}}$ equal to 0.9 in. was obtained. An additional factor of 50% was added to this result to protect against beam divergence prior to contact with the core, which would result in penetration off the central axis. Therefore, a final radius of $R=1.38$ in. (see Figure 2) is used.

With the basic cylindrical dimensions calculated, the next step was to determine the dimensions and geometry for an aperture in the graphite cores as presented in Figure 4.
Secondary Electron Emission

When high energy charged particles strike the surface of a solid, scattered secondary electrons are emitted by the solid, a phenomenon known as secondary electron emission\textsuperscript{15}. Since this type of emission follows a cosine distribution about the normal to the surface, a coned shaped aperture (see Figure 4) was necessary in order to redirect the secondary electrons back into the Faraday cup graphite core.

Primary Electron Back-scattering

A small percentage of the incident electrons will be elastically scattered backwards upon near direct and direct impact with the heavy nuclei of the core material. As determined by Starke\textsuperscript{16}, electrons back-scattered by a graphite collector accounted for less than 3% of the initial energy in a 2.3 MeV beam. Therefore, at higher energies the relativistic kinematics make it highly unfavorable for back-scattering to occur. Only the considerably small fraction of electrons with scattering angle of 180° will actually scatter backwards. The majority will be projected in a forward cone due to relativistic effects\textsuperscript{17}.

\textbf{Figure 4.} Cross section of the carbon graphite core aperture design.
Spread of the Incident Beam

To determine the core aperture diameter (see Figure 4), it was necessary to calculate the total beam spread upon impact with the graphite core. A bend dipole magnet is placed in the beam line 0.5 m prior to each Faraday cup. The dipole bends the beam in a 45° arc; therefore, an initial spread in the beam will be increased due to the geometry of the curved trajectory through the bend dipole.

As a first order approximation, a zero width beam with an energy spread $\Delta E/E \equiv 2\%$ at the bend dipole entrance was assumed. For charged particle acceleration in a dipole field,

$$E = pc = 0.3cBr ,$$

where $E$ is in MeV, $B$ is the magnetic field strength in teslas, and $r$ is the arc radius in millimeters. Thus the change in radius $\Delta r$ is proportional to the change in energy $\Delta E$ for a constant magnetic field according to

$$\frac{\Delta r}{r} = \frac{\Delta E}{E} \equiv 2\% .$$
Referring to Figure 5, as electrons with energies $E \pm 1/2\Delta E$ enter the dipole magnet at point A, they will curve with radii in the range $r \pm 1/2\Delta r$. For $r = 670\,mm$, equation (6) was solved to obtain $r_{\text{min}} = 660\,mm$ and $r_{\text{max}} = 680\,mm$. Using these results and the law of sines, the small angles $\theta_{\text{min}}$ and $\theta_{\text{max}}$ were calculated to be $0.41^\circ$ and $0.40^\circ$ respectively. From these results and the properties of triangles, the following relations were determined:

$$\alpha = \frac{\theta_{\text{min}} + \theta_{\text{max}}}{2}, \quad (7)$$

$$\beta = 67.5^\circ - \frac{\theta_{\text{max}}}{2}, \quad (8)$$

$$\gamma = 45^\circ + \theta_{\text{min}}, \quad \text{and} \quad (9)$$
Finally, the spread of the beam as it exits the dipole magnet was given by the law of sines,

\[ d = l_{\text{min}} \sin \alpha \sin \beta \].

(10)

Thus, solving equations (7) through (10) and substituting into (11), \( d = 3.9 \text{mm} \) was obtained.

Upon exiting the dipole, the beam will continue spreading as it propagates a distance of 0.5 m away from the dipole. The electrons will travel in straight lines offset a maximum of \( \theta_{\text{min}} \) or \( \theta_{\text{max}} \) from the normal to the magnet edge depending on their energy and thus their radius of curvature. Therefore, the additional contributions to the total spread were

\[ D_{\text{min}} = (0.5m) \tan(\theta_{\text{min}}) \], and

(12)

\[ D_{\text{max}} = (0.5m) \tan(\theta_{\text{max}}) \].

(13)

Finally, the total beam spread was \( D = d + D_{\text{min}} + D_{\text{max}} = 11.0 \text{mm} \) (0.4 in.). The actual aperture diameter of 1.0 in. (see Figure 4) was more than a factor of two greater than this result to account for the initial zero width beam approximation.

**Beam Energy Loss in Carbon Graphite**

The methods of beam energy loss for 20 MeV electrons in carbon graphite played important roles in the further refinement of this design. Specifically, it was necessary to know in what proportions the initial energy was divided. Most of the energy was transferred to the graphite core by ionization which appears in the form of heat. The remainder was emitted from the core as external bremsstrahlung radiation\(^{18}\).
The fractional radiation yield, or bremsstrahlung efficiency, for electrons stopped in a material of atomic number \( Z \) is\(^{19} \)

\[
\frac{E_{\text{rad}}}{E_0} = \frac{Z E_0}{1600 + Z E_0},
\]

(14)

where \( E_0 \) is the initial kinetic electron energy in MeV. For an electron beam with \( E_0 = 20 \) MeV brought to rest in carbon graphite \((Z=6)\), \( E_{\text{rad}} \) was calculated to be 1.4 MeV.

The radiation yield for various materials\(^{20} \) is plotted in Figure 6. Reading off the plot, the percent yield for 20 MeV in carbon is approximately 7\%, or 1.4 MeV which matched the previously calculated result. Therefore, the remaining 93\% of the initial energy was converted to heat by ionization within the core.

![Figure 6. The percent radiation yield of various materials versus incident electron energy.](image)

**Delrin Insulation Design**

The carbon graphite core for each Faraday cup had to be installed in vacuum tubing while remaining insulated from that same tubing. In order to properly insulate the graphite core in each Faraday cup, two Delrin rings of 0.5 in. width mount the core inside the vacuum flange nipple. These rings were cut in half and placed in mating grooves machined 0.5 in. in from each end of the core. The 2.75 in. diameter core and two sets of
insulator rings slide snugly into the 2.87 in. (I.D.) vacuum nipple. The insulator ring dimensions and installation detail are presented in Figure 7.

![Diagram of insulator dimensions and core installation](image)

**Figure 7.** (a) The Delrin insulator ring dimensions. (b) The graphite core installation using the Delrin rings.

**Vacuum Issues**

Since the Faraday cups are beam line components, they will be in a high vacuum environment during operation of the accelerator. Therefore, how the design affects the vacuum was considered.

**Virtual Leaks**

Due to the snug fit of the core and insulators in the vacuum flange nipple, a virtual leak will be created behind the core and between the two insulator rings. To insure proper pump down of the entire beam line system, modifications to the graphite core and Delrin insulators were required. These modifications were based on localized effective pumping speeds necessary to maintain the vacuum in the afore mentioned regions.

The effective pumping speed $S_{\text{eff}}$ is the rate at which a volume, separated from the actual pump by a system of conducting elements (pipeline, tubing, apertures, etc.), will be pumped out and is given by

$$
\frac{1}{S_{\text{eff}}} = \frac{1}{S} + \frac{1}{C},
$$

(15)
where \( S \) is the speed of the pump, \( C \) is the total flow conductance of the system of conducting elements, and all variables are in liters \( s^{-1} \). In the molecular flow region, which is dominant at high and ultra-high vacuum\(^{23} \), the flow conductance is independent of pressure and dependent on the geometry of the conducting pipelines. For a long, narrow tube (\( d < 0.1L \)) in molecular flow\(^{24} \)

\[
C = 12.1 \frac{d^3}{L}, \tag{16}
\]

where \( d \) is the diameter and \( L \) is the length of the tube, in cm. For a system of conducting elements in parallel connection, the total flow conductance is\(^{25} \)

\[
C = C_1 + C_2 + C_3 + \cdots . \tag{17}
\]

Therefore, drilling holes through the graphite cores and creating gaps between each pair of Delrin semi-rings were considered simple solutions to the virtual leak problem. Once the dimensions to these modifications were chosen, it was necessary to compute the effective pumping speeds to make sure adequate vacuum was obtained.

Solving equations (16) and (17) for 4 identical conducting tubes through each core with \( d = 0.6cm \) (0.25 in.) and \( L = 10cm \) (4 in.), the total flow conductance of this system was calculated to be 1.2 liters \( s^{-1} \). The UCLA beam line has pumps with speeds around 20 liters \( s^{-1} \), thus, plugging \( S \) and \( C \) into equation (15), the effective pumping speed was 1.2 liters \( s^{-1} \). Though this result was much less than the actual pumping speed, the maximum volume behind the graphite core was only 0.3 liter. Thus the effective pumping speed for this region was quite sufficient.

The region between each pair of Delrin semi-rings has a volume of 0.04 liter. Each semi-ring was cut so that a gap of 0.25 in. was created where each matching pair met before. A rough approximation of the total flow conductance per pair was calculated by considering each gap as a group of 4 tubes in parallel with diameters equal to the thickness of the rings and length equal to the width of the rings. Therefore, a pair of semi-rings has two gaps approximated by a total of eight conducting tubes with a total
flow conductance of 0.3 liter s\(^{-1}\). This in turn gave an effective pumping speed of 0.3 liter s\(^{-1}\), which was needed for this very small region. In addition, the second pair of rings has the same modification so that the resulting conductance should factor out some of the initial approximations in this case.

The modifications to the graphite core and to the Delrin semi-ring designs are illustrated in Figure 8.

**Figure 8.** Modifications to the graphite core and to the Delrin semi-ring designs.

**Carbon Graphite Outgassing**

Another vacuum consideration is the outgassing of the carbon graphite core. Presented in Figure 9 are the relative total outgassing rates for various grades of graphite including AXF-5Q\(^{26}\). This grade of graphite has very similar properties to the PGCS-3 (\(\rho=1.75 \text{ g cm}^{-3}\)) grade used for the cores\(^{27}\).
As illustrated in Figure 9, a 0.4 g sample of AXF-5Q\textsuperscript{28} reaches a peak in outgassing rate around 350°C. The peak for each Faraday cup core (mass=650 g) will therefore be three orders of magnitude greater in approximately the same temperature range. To insure minimum contamination to the vacuum in the beam line during bake-out (T\textless; 200°C), the procedure below was followed:

1. Ultrasonically cleaned the cores.
2. Baked cores for a minimum of 12 hours at 400°C in a high vacuum.
3. Let cores cool to room temperature while remaining in vacuum.
4. Removed cores from vacuum and immediately sealed them in airtight containers.
5. Installed cores in vacuum flange nipples and installed Faraday cups as close to beam line bake-out time as possible.

Heating of the cores by ionization could also cause outgassing if the temperature rise is great enough. During operation of the linac, the average power of the beam incident on the graphite cores is 0.1 watt. The temperature rise per beam pulse in the graphite is\textsuperscript{29}
\[ \Delta T = \frac{N_e \Delta E}{\rho V C_p} \]  \hspace{1cm} (18)

where \( N_e \) is the number of electrons per pulse \((6.2 \times 10^9)\), \( C_p \) is the specific heat of graphite \(^{30} \) \((0.17 \text{ cal g}^{-1} \text{ K}^{-1} \text{ at } 20^\circ \text{C})\), and \( \rho V \) equals the mass of the core. In equation (18), \( \Delta E \) is the energy deposited in the core by ionization. At 20 MeV, 93\% of the beam energy will be dissipated by ionization in graphite; therefore, \( \Delta E = 18.6 \text{ MeV} \) \((7.2 \times 10^{-13} \text{ cal})\). Substituting this result into equation (18) and \( \Delta T \) is calculated to be \(4.1 \times 10^{-5} \text{ K}\). Thus the temperature rise per pulse is unmeasurable, consistent with negligible heating from a 0.1 W beam.

**Shielding Considerations**

At medium energies, liberated neutrons and bremsstrahlung photons are possible hazards associated with stopping an electron beam. The yields of these sources of secondary radiation and associated equivalent-dose rates were calculated, and the shielding criteria were studied in order to determine the requisite amount of shielding for each Faraday cup.

**Neutrons**

The threshold energy for neutron yield in carbon is 18.7 MeV, thus virtually zero neutrons are liberated at 20 MeV\(^{31} \). Therefore, the shielding required for bremsstrahlung emission will be quite ample for any neutrons emitted during operation of the linac.

**Bremsstrahlung**

When considering the shielding design, bremsstrahlung radiation possesses the greatest potential hazard\(^{32} \). The radiation emanating from the carbon graphite cores was considered 'thick-target' bremsstrahlung\(^{33} \).

The equivalent absorbed dose rate \( H \) is the amount of direct exposure to radiation produced by mechanisms common to the operation of an accelerator at some given initial energy. For the forward \((0^\circ)\) direction at 1 meter from the source, as a function of
incident electron beam average power in kW and energy in MeV, $H$ is given by the rule of thumb\textsuperscript{34}

$$H \approx 2000 E_0^2,$$

where $H$ is in units of rem (a measure of exposure) h\textsuperscript{-1} kW\textsuperscript{-1} m\textsuperscript{2}. This equation is for electrons ($E_0 < 20$ MeV) incident on high-Z materials. For the 10\textsuperscript{-4} kW, 20 MeV beam, equation (19) gives $H = 80$ rem h\textsuperscript{-1} m\textsuperscript{2}.

The absorbed dose rate as described above is plotted\textsuperscript{35} in Figure 10, for both the forward ($0^\circ$) and the sideward ($90^\circ$) directions. In this case the unit of measure of exposure was the rad which is equivalent to the rem.

![Graph showing absorbed dose rate](image)

**Figure 10.** Absorbed dose rate at 1 meter from the source per unit incident average electron beam power versus incident electron energy for thick-target bremsstrahlung from a high-Z target.

From Figure 10, values of $H_{fwd} = 60$ rad h\textsuperscript{-1} m\textsuperscript{2} and $H_{side} = 1$ rad h\textsuperscript{-1} m\textsuperscript{2} were obtained. The higher forward equivalent absorbed dose rate of 80 rem h\textsuperscript{-1} m\textsuperscript{2} was used to provide an additional safety factor.
Shielding Criteria

The parameters used to determine shielding requirements were the accelerator workload, the orientation (or use) factor, the occupancy factor, the maximum average allowed dose-equivalent rate, and the necessary barrier attenuation factor.

The workload $W$ of an accelerator is equal to the dose-equivalent rate multiplied by a 40 hour work week. Therefore, $W_{\text{fwd}} = 3200 \text{ rem wk}^{-1} \text{ m}^2$ and $W_{\text{side}} = 40 \text{ rem wk}^{-1} \text{ m}^2$ were calculated.

The orientation factor $U$ for primary and secondary barriers in an accelerator facility, has a maximum safety value of unity.

The occupancy factor $T$, accounts for the average time per 40 hour work week that areas to be shielded are occupied. The value $T=1$ is used for the work areas and control rooms.

For areas accessed by the general public, the maximum average acceptable dose-equivalent rate of $H_M = 0.01 \text{ rem wk}^{-1}$ was required.

The necessary barrier attenuation factor $B$, corresponds to the thickness of a given material which will attenuate the radiation to the desired acceptance level. For bremsstrahlung photons the attenuation factor is

$$B = \frac{H_M d^2}{WUT} = \frac{H_M d^2}{H} \quad \text{E} \leq 100 \text{ MeV}$$

(20)

where $U$ and $T$ are unity and $d$ is the distance to the occupied areas in meters. The UCLA PBPL has a minimum distance of 3 meters from the Faraday cups to the occupied areas outside the concrete bunker walls. Therefore, for $d = 3 \text{ m}$ the necessary attenuation factors of $B_{\text{fwd}} = 2.8 \times 10^{-5}$ and $B_{\text{side}} = 2.3 \times 10^{-3}$ were calculated.

The necessary attenuation factor $B$ of thick-target bremsstrahlung versus shielding thickness is plotted in Figure 11 for concrete (a) and for lead (b).
Figure 11. Necessary attenuation factor B as a function of incident electron beam energy versus shielding thickness, for thick-target bremsstrahlung from a high-Z target.

The total attenuation factor provided by shielding of different materials within distance \(d\) is simply \(^{42}\)

\[
B = \prod B_{\text{material}}
\]

From Figure 11a, the attenuation provided by the concrete bunker walls (90 cm thickness) was approximately \(10^{-2}\). Therefore, the remaining \(2.8 \times 10^{-3}\) (0°) and 0.23 (90°) attenuation factors were provided by lead shielding of 18 cm (7.1 in.) and 7 cm (2.8 in.) respective thicknesses as determined by Figure 11b. The actual lead shielding configurations around each Faraday cup were provided using 2"x4"x8" lead bricks.
Charge Measurement

The charge $Q_0$ of each electron beam pulse collected in the graphite cores will be determined by measuring the voltage between the vacuum flange nipple wall and the core, and is given by

$$Q_0 = V_0C.$$  \hfill (22)

This voltage signal will be an exponentially decaying step function

$$V = V_0e^{-\frac{t}{RC}},$$  \hfill (23)

where the resistance $R$ and capacitance $C$ of the system are measured directly with an impedance meter. The voltage signal will be sent through the BNC connector to an oscilloscope to determine parameters such as the RC time. Once calibrated, the signal will be sent to a charge sensitive analog to digital converter (ADC) which will calculate the charge per pulse by integrating the signal. The capacitance can be measured independently, and if the resistance is large, the voltage will be constant for the short pulse length.

Conclusion

The two identical Faraday cups have been constructed and are currently ready to be installed in the UCLA PBPL beam line. Each Faraday cup has been designed with a solid carbon graphite core that will stop the electron beam while producing bremsstrahlung radiation. These emissions will be attenuated to required safe limits by localized lead shielding and the concrete bunker walls. In addition, each Faraday cup has been designed to be used as a charge measuring beam diagnostic.

Acknowledgments

This paper fulfills the completion requirement for the Physics 199 course I took with Professor James Rosenzweig whom I would like to thank for the opportunity. I would
also like to thank Gil Travish for helping me organize my ideas and proof reading my drafts, not to mention showing me the many ins and outs of Microsoft Word.
APPENDIX A

UCLA PBPL Beam Line Configuration
IR FEL Beamline

RF Photocathode Gun
- Solenoid
- Mirror "Box"
- Cube: Slits, Screen
- Cross: Screen, Alignment mirror, Pump
- Quad Quadruplet: BPMs, Steering, Screen
- Bend Dipole
- PWT Linac
- Pulse Length Monitor: Ceramic Break
- Quad Triplet: BPMs, Steering
- Energy Monitor
- Beam Dump
- 20 l/s
- 70 cm
- 74.2 cm
- 100 cm
- (19.5")
- 591.9 cm
- Isolated for ICT

Legend:
- Bellows
- Gate Valve
- Quadrupole
- Steering magnet
- 6-way diagnostic cross
- Beam Position Monitor

UCLA Particle Beam Physics Laboratory
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