

Radium EDM Experiment High Voltage System: Hazard Mitigation & Operating Procedures

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Contents

1	Introduction	2
2	Description of Hazards & Controls	3
2.1	Electrical: Batteries and Battery Banks	3
2.2	Electrical: High Voltage DC	4
2.3	High Pressure & High Vacuum	8
2.4	Radiological: Production of X-Rays	9
3	Procedure for Engaging the Ra EDM HV System	14
4	Procedure for Disengaging the Ra EDM HV System	15
5	Checklist	16

1 Introduction

The Radium EDM experiment requires an electric field (E -field) with a magnitude and sign that can be changed frequently during the course of a measurement. This E -field is produced within a 2 mm gap between a pair of copper electrodes located inside of an ultrahigh vacuum system. A computer-controlled high voltage (HV) system is used to control & monitor the voltage & current supplied to the electrodes. The HV system is composed of a single HV supply and associated control & monitoring circuitry. The experimental design goal for the Ra EDM experiment is to produce a minimum E -field of 100 kV/cm, which implies that we must supply a minimum potential difference of 20 kV across the 2 mm gap.

For the last two years, one electrode has been energized with one HV supply and the other electrode has been held at ground. Because the experiment is very sensitive to small asymmetries of the E -field as it is flipped, the two electrodes will be energized with opposite polarities of 10 kV from two different HV supplies. This should help suppress any asymmetry from forming between the two electrodes. Since the HV supplies can output up to 30 kV, the maximum potential difference that is now possible is 60 kV. Although this is double the value before, the hazards and mitigation are not different.

This document has been revised to include this modification and to include a procedure transferring the HV control system between electrode systems, see Sec. (6). The HV control system consists of the HV power supplies, control/monitor electronics, and shielded HV cables. An electrode system consists of a standard ultra high vacuum system, HV vacuum feedthroughs, and HV electrodes. We plan on having at least two different electrode systems that will be powered by a single HV control system. The HV control

system can power only one electrode system at a time. No new hazards are associated with transferring the HV control system between the electrode systems.

The highest possible voltage, current, and stored energy of this HV system are 60 kVDC, 0.3 mA, & 864 kJ. The main hazards associated with this equipment are electrical, high pressure & vacuum, and radiological. Personnel are prevented from coming into contact with energized electrical equipment by physical barriers, which are interlocked to the power of the HV supplies, see Sec. (2.2). The high vacuum systems are composed of unmodified, commercially-available components and result in a pressure differential of 14.7 psi relative to atmosphere. The ventilation provided in each lab, F-130 & H-126, significantly mitigates the hazard posed by the failure of the high pressure component of the system, see Sec. (2.3). The minimum equivalent thickness of glass that surrounds the electrodes significantly shields the personnel from low energy x-rays, which may be generated when the electrodes partially discharge, see Sec. (2.4).

The rest of this document contains procedures for engaging & disengaging the HV supplies, see Secs. (3) & (4), a checklist corresponding to these procedures, see Sec. (5), and a catalog of physical reference data relevant to this hazard analysis, see Sec. (A).

2 Description of Hazards & Controls

2.1 Electrical: Batteries and Battery Banks

The system contains four unmodified, commercially-available 12 VDC batteries that provide 10 A · hr. Two batteries power each optically-coupled signal monitoring circuit, which draw less than 10 mA from each battery. In the case of a short, then all of the energy ($2 \times (12 \text{ VDC}) \times (10 \text{ A} \cdot \text{hr}) = 864 \text{ kJ}$) from a pair of batteries would be released in a short period of time. This hazard is mitigated by covering the battery leads with insulating material such as electrical tape.

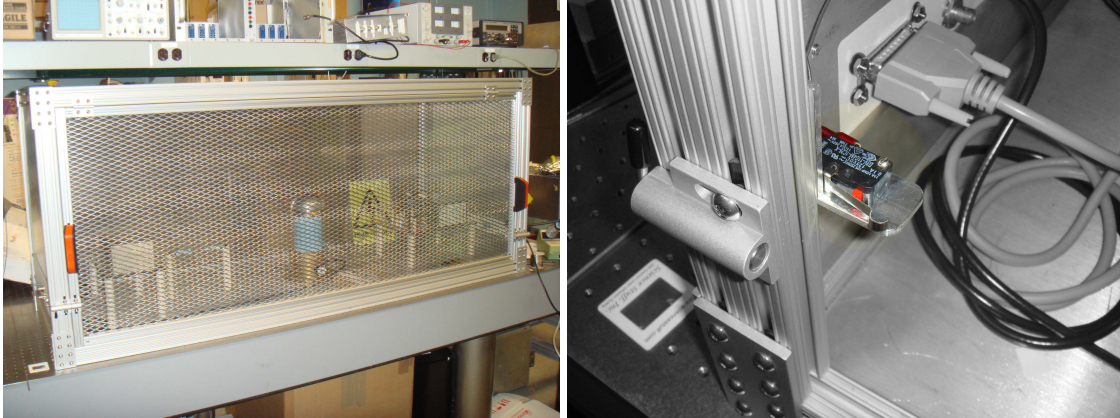


Figure 1: Picture of HV Box. When the door is closed (left), two microswitches (right), on either side of the door frame, are closed allowing the HV supplies to be engaged.

2.2 Electrical: High Voltage DC

The HV supplies are unmodified, commercially-available OEM devices produced by Spellman HV. Each is powered by a 24 VDC supply, draws less than 1 A, and can output up to 30 kVDC & 0.3 mA. The high voltage dividers (nominal 1000:1) are unmodified, commercially-available device that outputs a voltage monitoring signal, which has a maximum value of 30 VDC. All of the low voltage circuits are protected by transient voltage suppressor diodes.

The main hazard in this section is the accidental exposure of personnel to (1) a large potential difference and (2) an electrical discharge due to a breakdown of some insulating material. The primary engineering control used to mitigate these hazards are interlocked, physical barriers. These microswitch interlocks are tested at least once per year. Specifically, the HV supplies, high voltage divider(s), and optically-coupled signal monitoring circuits are all housed inside of a box made of aluminum, see left half of Fig. (1). This HV Box, which is referenced to ground, is a physical barrier between the personnel and any connections that are “hot” (i.e. at high voltage). To open the box, one has to unlatch a bulky, hinged door and lift it up. In doing so, two microswitches, on either side of the door frame, are opened, which trips the interlock, and consequently, the power from the 24 VDC supply to the HV supplies is interrupted, see right half of Fig. (1).

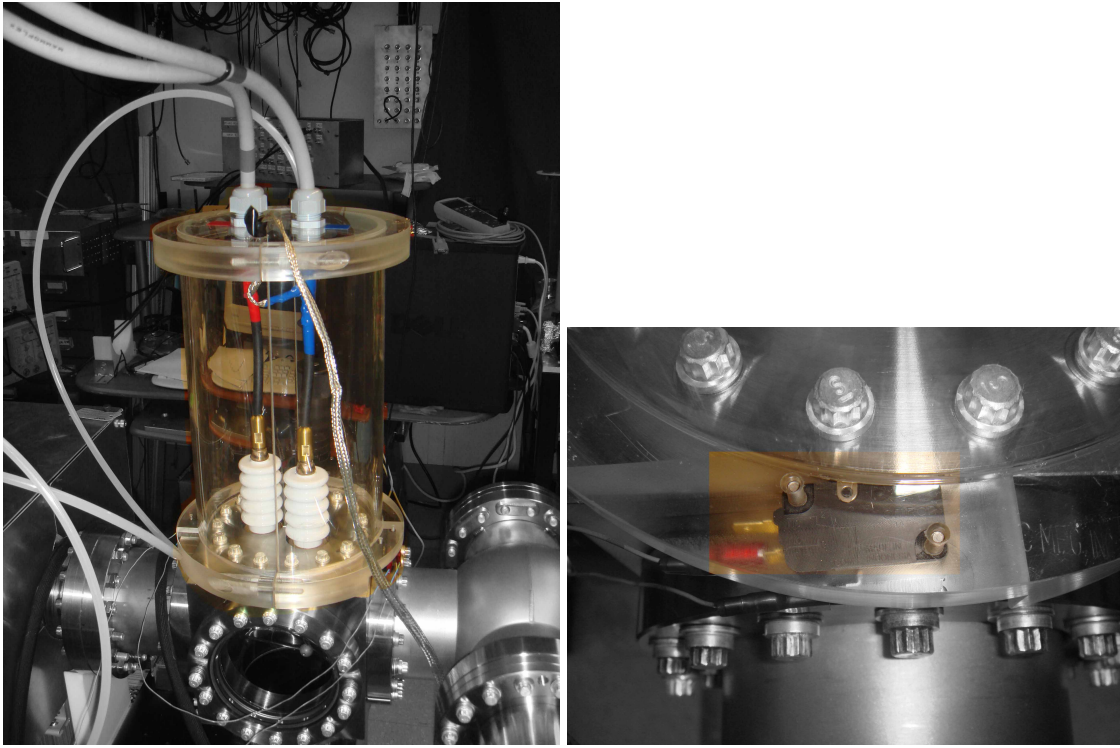


Figure 2: Picture of Clamshell. This picture illustrates how the clamshell (left) looks when installed to the double high voltage feedthrough flange. One of the two microswitches (right) is connected to the wires at the bottom of the clamshell. Feedthroughs and an ultra high vacuum system similar to the ones depicted in this photograph will be used for the tests described in this document.

The high voltage signals are transmitted out of the box via two separate shielded HV cables, each of which has a rating of 30 kVDC. This cable is an unmodified, commercially available product designed specifically for HV applications. It is connected to the electrodes via ultrahigh vacuum ceramic electrical feedthroughs, which have a rating of 30 kVDC. The parts of the HV cable and feedthroughs that are exposed (i.e. unshielded) are enclosed within a clamshell cover, see Fig. (2). The clamshell includes a microswitch, which interrupts the power from the 24 VDC to the HV supplies when the clamshell is opened & removed from the feedthrough flange.

Both the box and the clamshell are physical barriers that prevent accidental contact to any of the “hot” electrical components while the HV supplies is engaged. In addition, they are equipped with microswitches that interrupt the connection between the 24 VDC supply and the HV supplies when either the box or the clamshell is opened. It takes several seconds to open the box or the clamshell and access the potentially “hot” electrical components inside. On the other hand, the characteristic discharge time $\tau = RC$ can be estimated by the equivalent resistance to ground R and the equivalent capacitance C . The specification sheet indicates that the energy stored in a single HV supply is $U = 0.2$ J at 30 kV and the discharge time with no load is $\tau = 100$ ms. This implies that the internal capacitance is $C = 2U/V^2 = 444$ pF and the internal resistance to ground is $R = \tau/C = 225$ M Ω . Since the HV power supply is connected a series of resistors totalling 200 M Ω , the equivalent resistance to ground is $R \approx 100$ M Ω . The capacitance of the cable is about $C/\ell \approx 60$ pF/ft and the cable length is $x \leq 100$ ft, For the maximum length of cable, the total capacitance including the power supply is about 1 nF. Therefore, the stored energy and discharge time for one electrode/HV supply circuit are 0.5 J and 110 ms. This indicates that, at a maximum, it should take about 0.7 seconds to discharge from 30 kVDC to under 50 VDC, which is shorter than the time it would take to access the “hot” electrical components. Since there are two independent electrode/HV supply circuits, the total energy stored in the high voltage part of the apparatus is about 1 J. As an

additional administrative control, the procedure to disengage the HV supplies requires the personnel to wait 30 seconds after shutting off both the HV supplies & the 24 VDC supply.

As a secondary measure to mitigate the hazard posed to personnel from electrical discharges, we have minimized the possibility of breakdown by the various insulating media in the HV system. This is accomplished in the following five ways: appropriate insulation, avoidance of sharp edges, good housekeeping, limiting the control voltage, and adequate clearance. First, the HV system contains unmodified, commercially-available electrical components that are designed for at least 30 kVDC. For example, the wire that transmits the HV out of the HV supply is insulated with XLPE (cross-linked polyethylene) and is rated to 40 kVDC. Second, any uninsulated “hot” conducting components or joints are constructed without any excessively sharp points. For example, joints between the HV rated current-limiting resistors are connected such that the sharp ends of the leads are not exposed. Third, we have procedures in place to keep all of the “hot” components dry and dirt-free. Fourth, the control voltages to the power supplies are limited to half their maximum value which limits the high voltage output of the supplies. This means that at the highest control voltage setting, there will be no more than a 30 kV difference between the two supplies.

Lastly, the breakdown voltage of air, about 75 kV per inch for dry air, is used to determine the clearances between “hot” components and grounded components. Day-to-day variations in the atmospheric conditions (most notably humidity) could potentially reduce the dielectric strength of air by up to a factor of 2. It is for this reason that the clearance requirements generally quoted in the HV safety literature ranges from 1 inch per 5 kV to 1 inch per to 10 kV. Inside the box, which is exposed to “room” air, all of the unshielded “hot” electrical components are at least 4 inches away from the grounding plane. The two HV supplies are separated by more than 12 inches. At 20 kV (30 kV), this provides a safety margin of 7.5 (5) for humid air and 15 (10) for dry air.

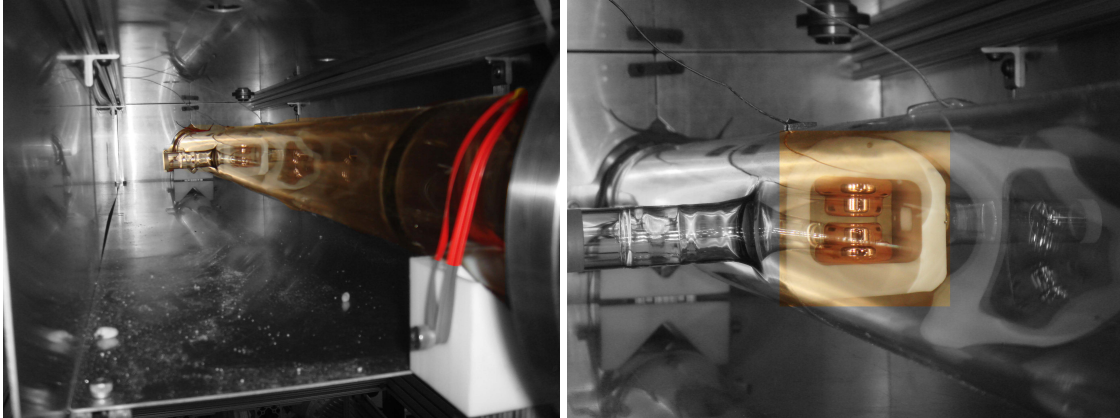


Figure 3: Picture of Copper Electrodes Inside of a Borosilicate Glass Tube.

The same argument holds when the two feedthroughs are exposed to “room” air and mounted on separate flanges. On the other hand, the two feedthroughs may also be mounted on the same flange, with a separation of 1.5 inches. In this case, dry air must be circulated through the clamshell covering the feedthrough. At 20 kV (30 kV), the dry air provides a safety margin of 5.6 (3.7). Even if there were an electrical discharge between the adjacent feedthroughs, the personnel would be protected by the clamshell cover.

The worst case scenario is for a short to occur between the two electrodes. In this case, the full current 0.3 mA would run through the high voltage circuit inside the box. There is no interlock to shut off the HV power supplies in this scenario because the risk of this happening is very low. Even so, this would not constitute a safety hazard since there are physical barriers in place to prevent anyone from coming into contact with this current while hot.

2.3 High Pressure & High Vacuum

The electrodes are held under vacuum inside of a standard ultrahigh vacuum system. For the upcoming series of measurements, at least two different vacuum system configurations will be used. In the initial configuration, the electrodes will be under vacuum inside of a long glass tube, see Fig. (3). Regardless of the exact configuration, in every case,

the vacuum systems are composed of commercially-available components and result in a pressure differential of 14.7 psi relative to atmosphere.

The high voltage dividers are unmodified, commercially available devices that are pressurized to 8 psig of SF₆ gas. This device is pressurized by the manufacturer and is designed to handle this pressure. SF₆ gas is stable, inert, non-toxic, and non-flammable. It is used to prevent the moisture in the air from entering the housing of the high voltage divider, which would degrade the long term (months) performance of the device. In the short term (days), a leak does not significantly degrade the performance or safety of the high voltage divider. The operating procedures include recording the pressure of the HV divider. If the pressure falls out of the manufacturer's operating range (2 to 10 psig), then the HV supplies will not be engaged. The main hazard associated with an SF₆ leak is the displacement of oxygen in the air. A release of the entire volume of SF₆ contained inside the high voltage divider, about 4 liter · atm, would, for example, displace only about 30 ppm of the air in the room F-130 (18 ft × 24 ft × 10 ft), which is not an asphyxiation hazard (i.e. the Oxygen Deficiency Hazard (ODH) "Fatality Factor" F_i is zero).

SF₆ is used inside the high voltage divider because it has a factor of 3 higher dielectric strength than dry air. In the very unlikely event of a discharge inside the high voltage divider, only about 1% (by volume) of the SF₆ gas may be decomposed into toxic vapors notably HF and S₂F₁₀. If the discharge were to result in a complete release of the gas into the room, then the toxic gases would displace a total of 0.6 ppm of the air in the room. This is below both OSHA and NIOSH exposure limits. Finally, both hazards posed by the release of the gas is mitigated by the fact that the air in the lab, rooms F-130 & H-126, is cycled through at least once per hour by the ventilation system.

2.4 Radiological: Production of X-Rays

The only radiological hazard that may be present is the production of x-rays when there is an electrical discharge between two components at different potentials. Discharges in air

are not expected to produce x-rays since the electrons are not accelerated to high enough energies between collisions with air molecules. However, x-rays may be produced when a short burst of electrons strikes one of the two copper electrodes, while under vacuum. The characteristic x-ray peaks for copper ($Z = 29$) occur near energies of 1, 8 & 9 keV, which we'll show are easily absorbed by the glass and/or stainless steel walls of the vacuum system. The greater potential hazard is the high energy portion of the continuous bremsstrahlung spectrum, which can be estimated by Kramer's formula:

$$\frac{d^2N_\gamma}{dtdu} = \left[\frac{I_{\max}}{e} \right] \left[\frac{2\alpha}{3\sqrt{3}\ell} \right] \left[\frac{eV_0}{m_e c^2} \right] \left[\frac{2Z(1-u)}{u} \right] \quad (1)$$

where N_γ is the maximum number of x-rays with energy E produced, $u = E/E_0$ is the relative energy of the x-rays, $E_0 = eV_0$, V_0 is the potential between the electrodes, e is the elementary charge, I_{\max} is the peak charging current, α is the fine structure constant, $\ell \approx 6$ for a "thick" target, m_e is the electron mass, c is the speed of light, and Z is the atomic number of the target. At x-ray energies much smaller than the mass of the electron, it is safe to assume that the angular distribution is nearly isotropic.

The amount of x-rays that can reach the personnel depends on the type & thickness of the shielding between the electrodes and the personnel. At the very least, the x-rays must penetrate an equivalent thickness of 5 mm of borosilicate glass, which has an attenuation length that varies dramatically with x-ray energy, see Fig. (6). After passing through the glass (i.e. just at the outer surface of the glass), the x-ray power spectrum, as shown in Fig. (4), is given by:

$$\frac{dP}{du} = \left[\frac{d^2N_\gamma}{dtdu} \right] uE \exp\left(-\frac{\Delta t}{t_0(E)}\right) \quad (2)$$

where P is the x-ray energy per unit time per unit relative energy, $\Delta t \approx 5$ mm is the minimum thickness of the glass, and $t_0(E)$ is the x-ray energy attenuation length. Finally,

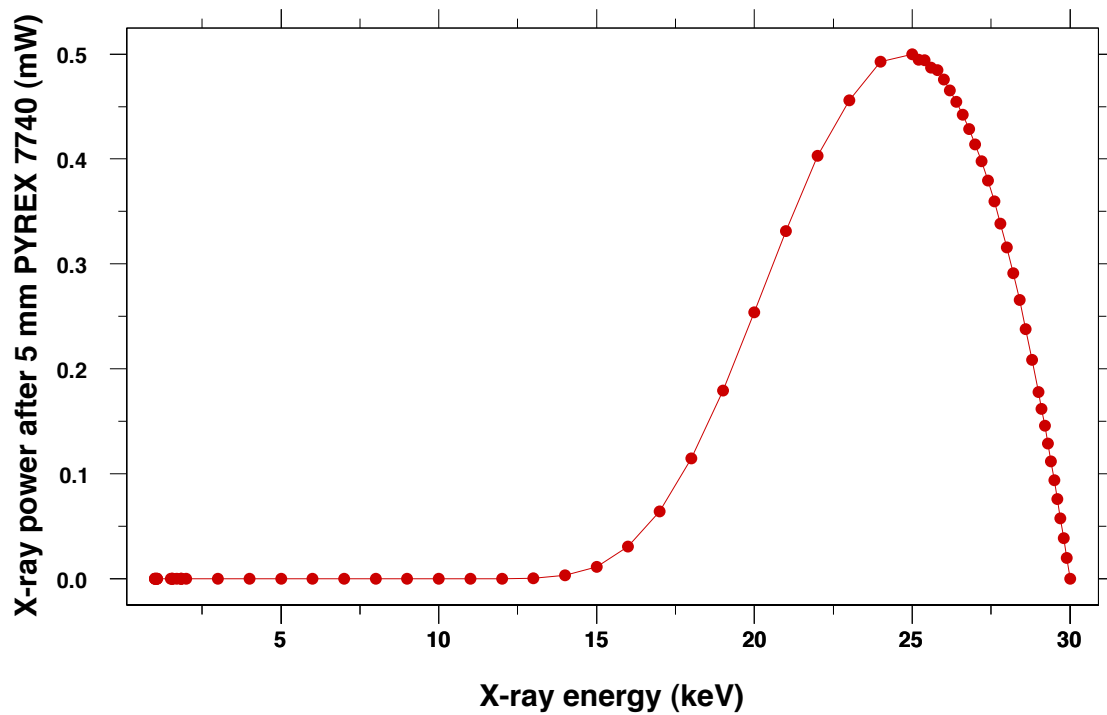


Figure 4: Maximum X-ray Power Spectrum After Passing Through 5 mm of Pyrex 7740 at $V_0 = 30$ kV. The peak at roughly 25 keV occurs because higher energy x-rays are less likely to be produced but are more likely to penetrate the glass.

to estimate the upper limit on the absorbed dose, we'll use the following formula:

$$\text{estimated dose} \leq \langle P \rangle \left[\left(\frac{I_{\text{dis}}}{I_{\text{max}}} \right) t_d r_d \right] \left[\frac{\Omega}{4\pi} \right] \left[\frac{f_T}{m_T} \right] [w_R w_T] \quad (3)$$

where $\langle P \rangle = \int_0^1 (dP/du) du$ is the average x-ray power, $I_{\text{dis}}/I_{\text{max}}$ is the discharge current relative to the maximum peak charging current, t_d is the average duration of a discharge, r_d is the number of discharges per hour, Ω is the solid angle covered by the personnel, f_T is the fraction of x-rays absorbed by the tissue, m_T is the mass of the tissue, w_R is the radiation weighting factor (i.e. quality factor), and w_T is the tissue weighting factor.

First, the highest power of x-rays occurs for the high voltage and current that corresponds to the maximum allowed control voltage ($V_0 = (+15 - -15)$ kV & $I_{\text{max}} = 0.3$ mA). Second, based on our most recent experience with the HV system with one HV supply, we'll assume that there are no more than 1 discharges per hour ($r_d \leq 1$) lasting no more than 1 second each ($t_d \leq 1$) with a discharge current of no more than 1% of the maximum HV supply current ($I_{\text{dis}}/I_{\text{max}} \leq 0.01$). These discharges occur only while the electrodes are being "conditioned" and do not occur after the electrodes have been conditioned. Third, we'll make the very conservative assumptions that any x-ray emitted towards the half of the room ($\Omega = 2\pi$) where the personnel are located is completely absorbed ($f_T = 1$). Fourth, we'll assume a tissue weighting factor of $w_T = 0.2$ and a total mass of $m_T = 50$ kg. Finally, by noting that $w_R = 1$, we estimate that the dose rate at the outer surface of the vacuum system surrounding the electrodes is no more than $0.3 \mu\text{rem/hr}$. In the event that the control voltage limiter fails and the electrodes are exposed to 60 kV and 0.6 mA, then, under these conditions, the dose would be less than 0.1 mrem/hr .

This estimate should be considered very conservative because, depending on the location of the discharge on the electrode and the exact configuration of the vacuum system, a substantial fraction of the x-rays will be completely absorbed by either the copper electrodes themselves or the stainless steel vacuum hardware. Both of these metals have

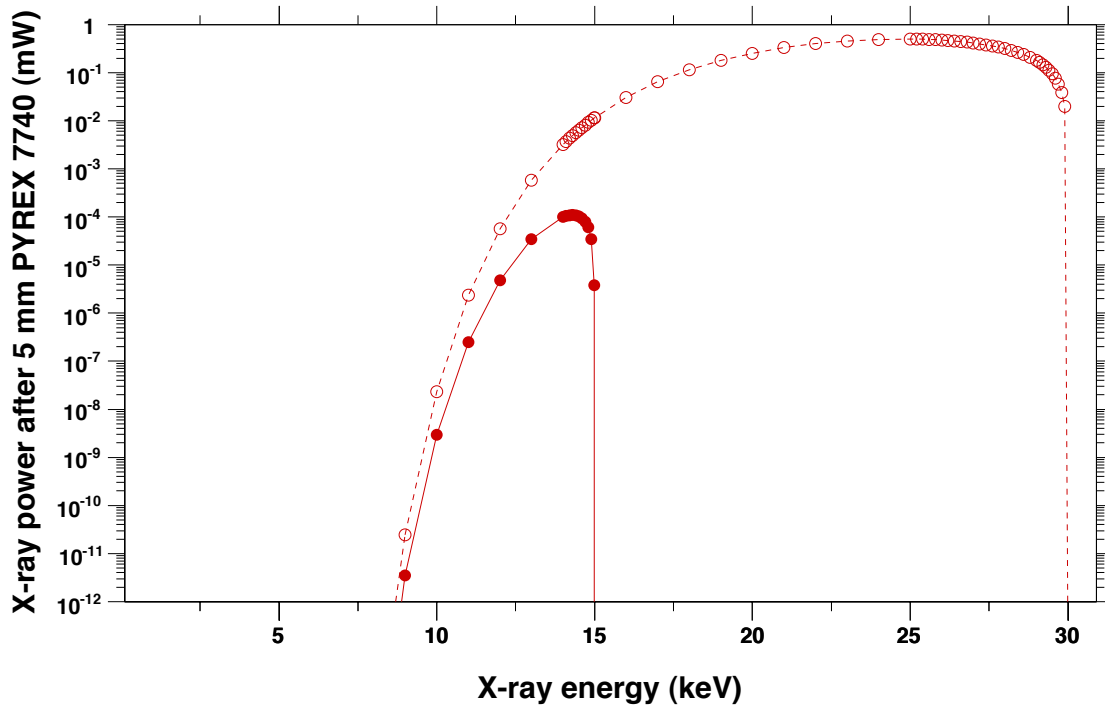


Figure 5: Maximum X-ray Power Spectrum After Passing Through 5 mm of Pyrex 7740 at $V_0 = 15$ & 30 kV. The closed (open) dots and solid (dashed) line corresponds to the spectrum for $V_0 = 15$ kV ($V_0 = 30$ kV). The x-ray power for $V_0 = 15$ kV is at least four orders of magnitude smaller than that for $V_0 = 30$ kV. The x-ray power for $V_0 = 20$ kV is at least two orders of magnitude smaller than that for $V_0 = 30$ kV.

attenuation lengths that are at least a factor of 20 shorter than glass, see Fig. (7). Under normal operating conditions, the potential difference between the two electrodes will be 20 kV. We have put hardware limits on the control voltage that limits each HV supply output to 15 kV. Finally, several electrical components would have to fail for $V_0 \geq 30$ kV.

3 Procedure for Engaging the Ra EDM HV System

1. No fewer than two people must be present *while* the HV system is being engaged.
2. Before turning on the HV supplies, ensure the following conditions are met (i.e. record them on the checklist and paste into the logbook).
 - Insure that both the 24 VDC supply and the Master Key on the HV Interface Box are OFF.
 - Record the reading on the vacuum gauge. It should be no higher than 9.0×10^{-6} Torr.
 - Record the reading on the pressure gauge on the high voltage divider. It should be no lower than 2 psi.
 - Clear the area of any tools, dust, and debris.
 - If necessary, turn on dry air flow.
 - Make sure the HV box is securely closed & that the clamshells are securely mounted to the the vacuum HV feedthroughs.
 - Inspect all grounding connections.
 - Once the inspection has been completed, insure that both the local & remote control voltages are 0 VDC.
3. Turn on the 24 VDC supply.
4. Turn the Master Key to the HV Interface Box. The HV supplies are now engaged and should be outputting 0 VDC.
5. Set desired high voltage using the local or remote control.

4 Procedure for Disengaging the Ra EDM HV System

1. No fewer than two people must be present *while* the HV system is being disengaged.
2. Ramp the control voltage to 0 VDC.
3. Wait until the monitor signals indicate that the HV supplies are effectively at zero output.
4. Turn OFF the Master Key to the HV Interface Box.
5. Turn OFF the 24 VDC supply.
6. Wait an additional 30 seconds for internal capacitance to discharge before moving to the next step. Verify complete discharge by the monitor signals & grounding stick.
7. Insure that the vacuum chamber and HV Box are properly grounded.
8. The HV system is now safe for maintenance.

5 Checklist

The following table should be filled out every time the HV supplies are engaged/disengaged.

names:	engaging	disengaging
date & time		
name		
24 VDC supply & Master Key status?	off / ON	off / ON
vacuum gauge (Torr)		
high voltage divider pressure (psi)		
area clear?	yes / NO	yes / NO
dry air flow	on / OFF	on / OFF
HV Box and Clamshell status?	on / OFF	on / OFF
ground connections good?	yes / NO	yes / NO
control voltages set to 0 VDC?	yes / NO	yes / NO

6 Procedure for Transferring the HV Control System Between Electrode Systems

1. No fewer than two people must be present throughout the entire procedure.
2. Disengage the Ra EDM HV System following Sec. (4) and document using the Checklist in Sec. (5).
3. Disconnect the HV cables from the first electrode system.
4. Check operation of the interlock system of the second electrode system following "Procedure for Testing the HV System Interlocks."
5. Properly ground the second electrode system.
6. Connect the HV cables to the second electrode system.
7. Insure that both the HV and ground connections are secure and clean.
8. The HV system is now ready to be engaged.

A Physical Properties of Relevant Materials

Material	Composition pct. by weight	Density g/cm ³	Dielec. Str. kV/in
Dry Air	N ₂ = 0.756, O ₂ = 0.231, Ar = 0.012	0.0012	75
Sulfur Hexafluoride	SF ₆ = 1	0.0062	225
Ceramic	Al ₂ O ₃ = 1	3.7	200
Corning 7056	see Tab. (2)	2.29	
Pyrex 7740	see Tab. (2)	2.23	335
Macor	see Tab. (2)	2.52	5206
Plexiglas	C ₅ O ₂ H ₈ = 1	1.19	450–990
Fused Silica	SiO ₂ = 1	2.20	635–1016
Aluminum	Al = 1	2.70	N/A
Copper	Cu = 1	8.94	N/A
μ -Metal	see Tab. (3)	8.74	N/A
Stainless Steel 304	see Tab. (3)	8.00	N/A

Table 1: Composition, Density, and Dielectric Strength of Relevant Materials.

	Ceramic (Alumina)	Corning 7056	Pyrex 7740	Macor	Fused Silica (Quartz)
SiO ₂	-	0.68	0.806	0.46	1.0
B ₂ O ₃	-	0.18	0.130	0.07	-
Na ₂ O	-	0.01	0.040	-	-
Al ₂ O ₃	1.0	0.03	0.023	0.16	-
K ₂ O	-	0.09	-	0.10	-
Li ₂ O	-	0.01	-	-	-
MgO	-	-	-	0.17	-
F	-	-	-	0.04	-

Table 2: Composition by Pct. Wgt. of the Relevant Glass & Glass-Like Materials

	μ -Metal	Stainless Steel 304
Ni	0.8000	0.0950
Fe	0.1493	0.7013
Mo	0.0420	-
Mn	0.0050	0.0100
Si	0.0035	0.0050
C	0.0002	0.0008
Cr	-	0.1875
P	-	0.0002
S	-	0.0002

Table 3: Composition by Pct. Wgt. of the Relevant Metals

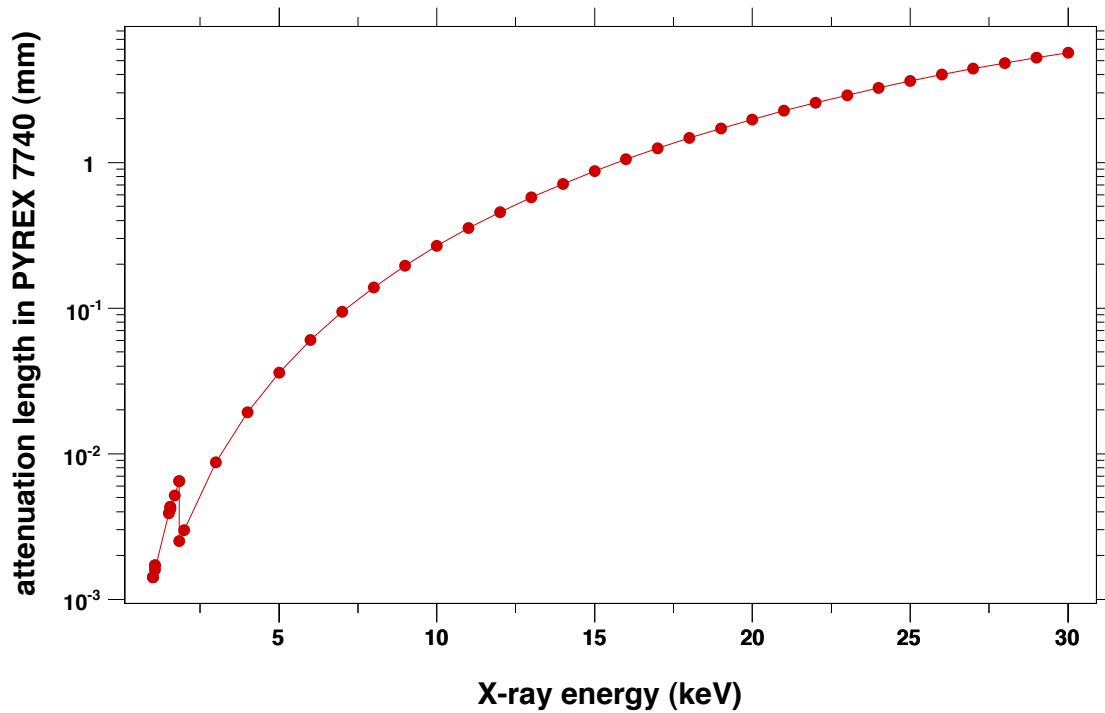


Figure 6: Attenuation of X-rays Passing Through Pyrex 7740 Glass. This glass is a typical borosilicate glass used for ultra high vacuum applications.

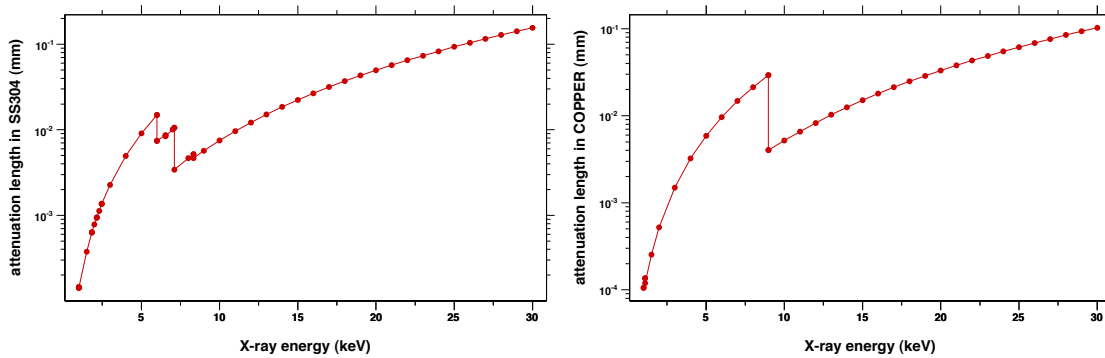


Figure 7: Attenuation of X-rays Passing Through Copper & Stainless Steel 304.

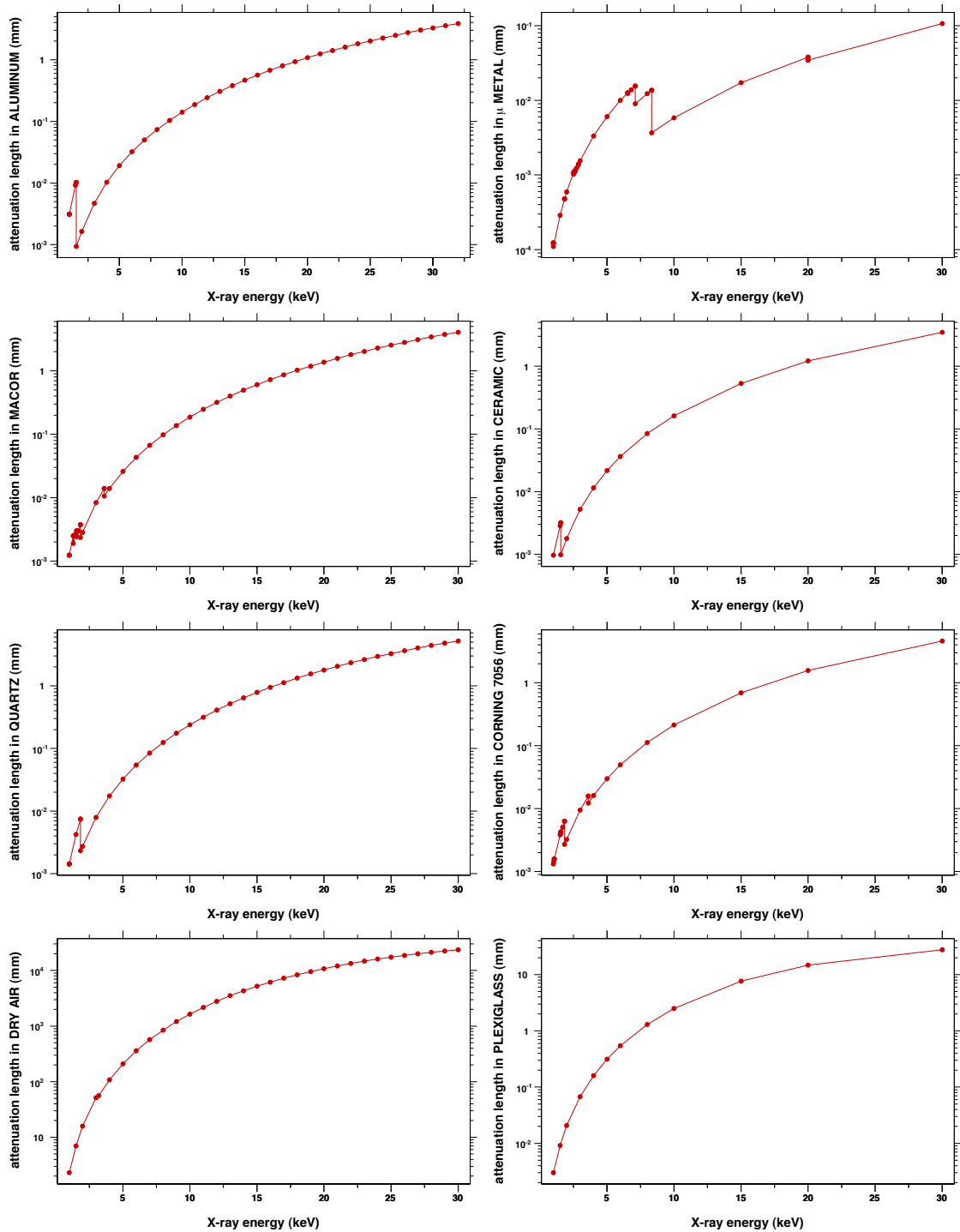


Figure 8: Attenuation of X-rays Passing Through Various Metals, Ceramics, Glasses, Dry Air, and Plexiglas.