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Title

Use of a 600 kV NHVG Electron Beam Accelerator for Wire Insulation Crosslinking

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1 Introduction to the Nested High Voltage Electron Beam Accelerator

This application describes the use of Applied Energetics' proprietary "Nested" High Voltage Generator (NHVG) technology in electron beam cross-linking applications. The NHVG operates based on the principle of voltage addition. It consists of a large number of voltage sources in series, each insulated from the adjacent source using both solid and oil insulation. The conductors separating the insulating region are arrayed in “Faraday Cages.” This arrangement leads to extremely reliable insulation, and to smaller, lower cost accelerators. This device produces electron beams with ease, precision, and with a modest size.

In this application we outline a system designed to produce a 600 kV electron beam at up to 40 mA to cross-link plastic wire insulation.

The system is shown in Figure 1, and has the following properties:

- 600 kV electron beam
- 40 mA current capability
- Electron beam scanning system
- Electron beam window
- Shielding for the wire handling fixture

This system does not require the use of pressurized "greenhouse" gases such as SF_6.

The NHVG e-beam system is available with and without the wire handling system. It is also available with sealed shielding for operation with gases other than air such as helium, nitrogen, and mixtures with controlled amounts of oxygen.

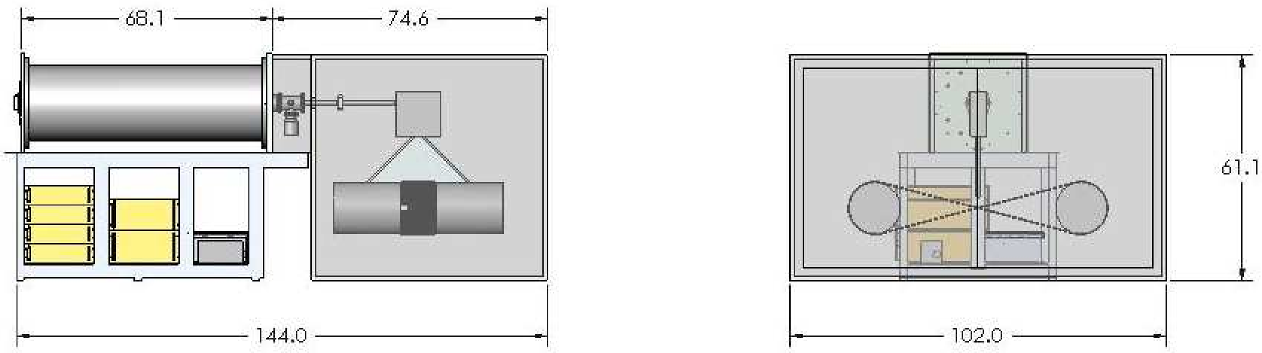

Figure 1a. Accelerator side view (left) and front view (right). The left view shows the cylindrical accelerator with control and power electronics underneath. The right view is a face view of the accelerator and side view of the capstan assembly.

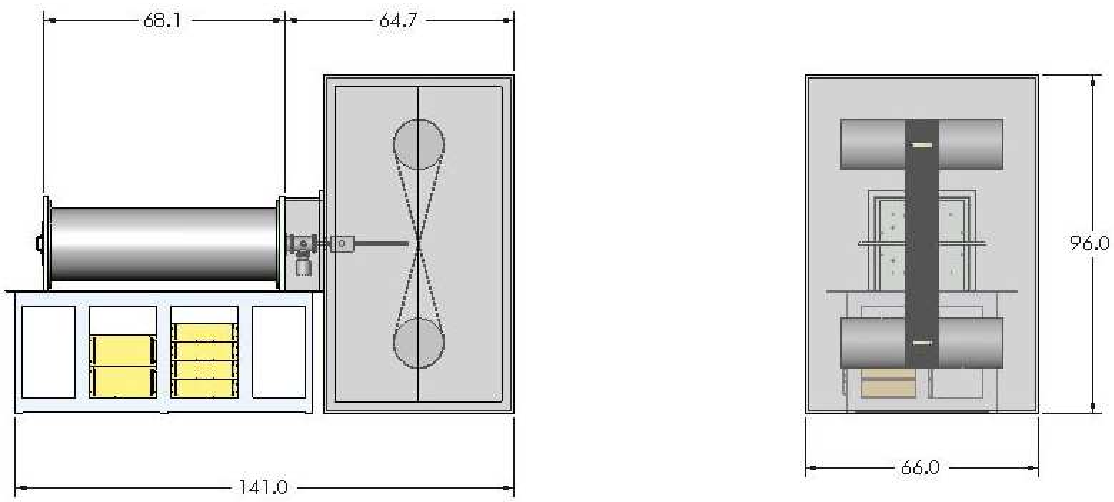

Figure 1b. An alternate variant on the size and positioning of the wire and capstan assembly.

2 Wire Insulation Crosslinking Requirements

The basic parameters of an accelerator are its voltage and current. The voltage determines the depth of penetration. The current determines the rate of irradiation. The 600kV, 40mA accelerator design is based on providing an average dose of 150 kGy to the wire. The irradiation crosslinkable polyethylene insulation in this example ranges in thickness from 0.25 to 0.76 mm, and is assumed to have a density of 1.4 g/cm^3. The "window" will be made from 12 µm thick titanium.

The insulation thickness and the wire handling details set the voltage of the machine. The current is set by the dose and the wire speed requirements. Other important variables are the window support design (and the current density), the distance from the scanner foil to the wire, and the speed of the processing system.

2.1 Wire Parameters

Table 1, Examples of stranded AWG wire processing parameters

Wire Size	Outside Diameter	Wall Thickness	E-beam voltage
(AWG)	(inches)	(inches)	(kV)
22	0.047	0.010	400
20	0.073	0.015	450
18	0.078	0.015	450
16	0.091	0.015	450
14	0.137	0.030	600
12	0.153	0.030	600
10	0.177	0.030	600

The most efficient use of the electron beam occurs when the following statements are true:

- The energy deposited in the copper wire is minimized
- The energy deposited in the gas between the beam scan horn and the wire is minimized
- The wires are as close together as possible

Effect of the Capstan

If a variety of wires are used on a single capstan, the use of the beam will be driven by the spacing required for the largest wire. Multiple capstan drums can be provided to increase processing speed for smaller wires.

Wire Twisting and Scanning

When the beam is directed towards the wire, the beam impinges on the wire from the front, and the dose makes the type of contours shown in Figure 2. We design capstans so that the wire is irradiated from both sides. With a certain amount of wire twisting, which occurs in almost all cases, the dose is very uniform.

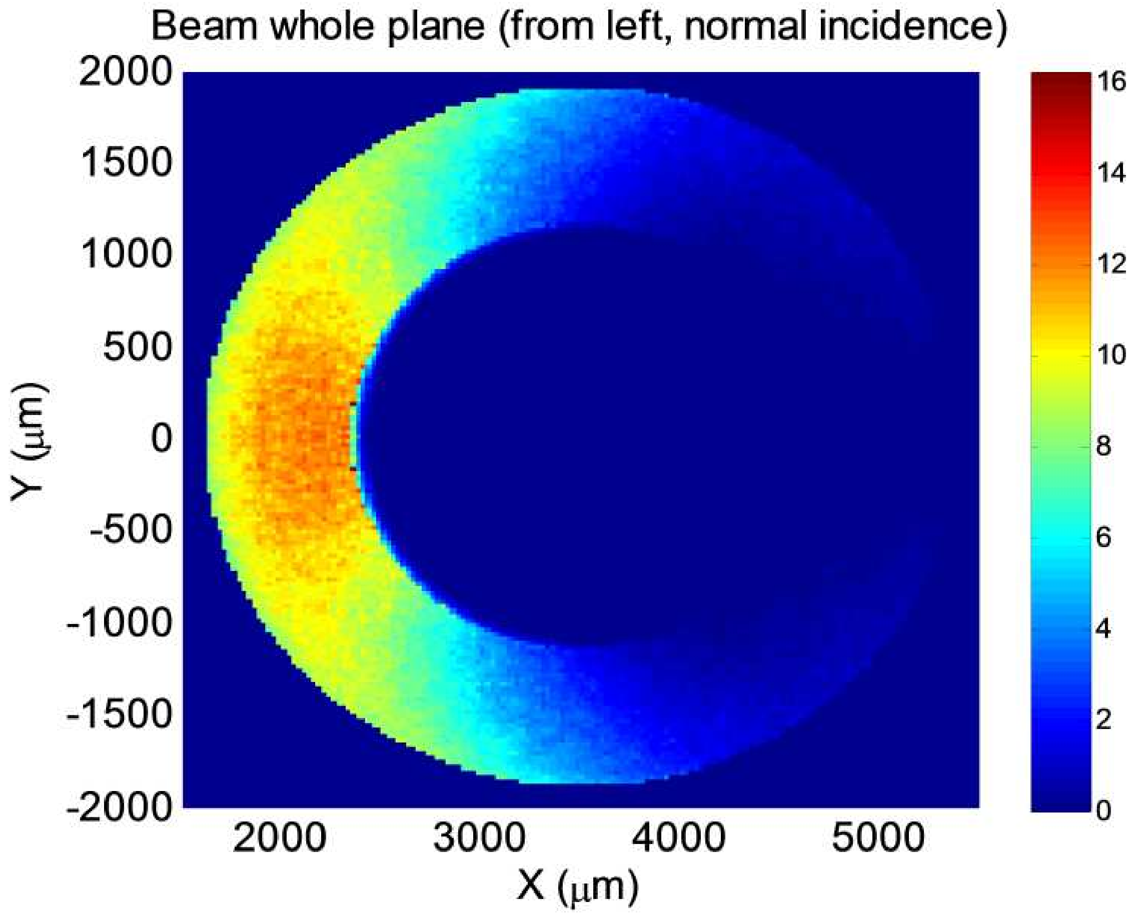

Figure 2a. Monte Carlo simulation of a planar electron beam impinging on flame retardant plastic coated #10 copper wire. The central circle is the copper. The region between the two circles is the plastic.

If there is no wire twist or variable scanning there will be a region of reduced dose at the 6 o'clock and 12 o'clock positions in the drawing (see Figure 2b). This reduction in dose is eliminated in two ways. The wire naturally twists as it goes through the wire handling fixture, and the beam is scanned with electron angles of up to 30° from the normal.

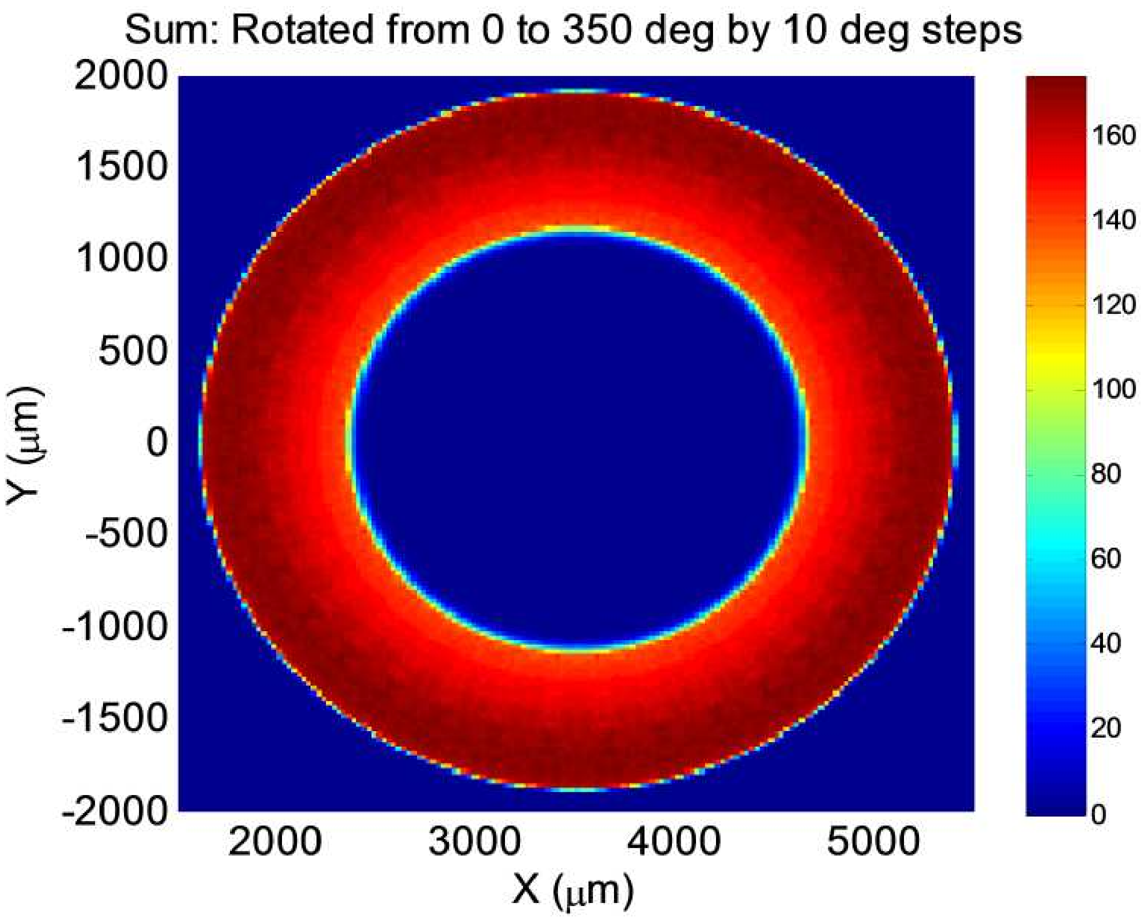

Figure 2b. Irradiated dose contours without twist from two sides at the figure-eight capstan cross-over point.

2.2 Optimizing the Wire Presentation to the Beam for Dose Uniformity and Power Reduction

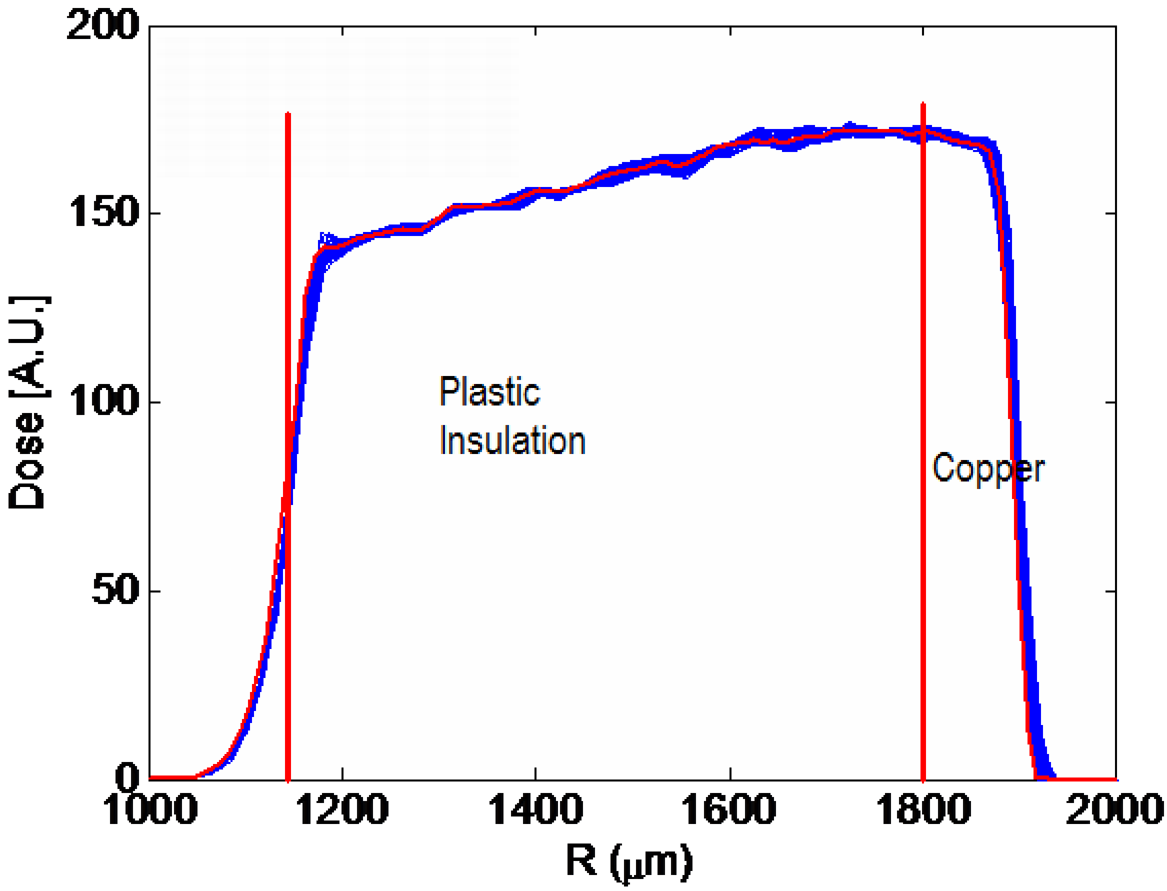

Figure 3. Monte Carlo simulations of dose as a function of radius for the case where the wire twists at least 30 degrees in the handling fixture. With azimuthal asymmetries removed, the best uniformity is achieved at 600 to 620 kV for 0.76 mm (0.03 inch) of insulation.

2.3 Calculations of Current Required

Assumption 1 - the transmission through the window is 67 %. The window struts will obscure approximately 20 % of the beam and backscatter will reduce the beam current another 20 %.

Assumption 2 - the energy fraction in the plastic can be taken from the Monte Carlo Calculations as 30 to 60% between 380 to 600 kV. We will use 45% as the fraction achieved at 400kV and 60% for greater than 550kV.

Assumption 3 – a large wire capstan will have slots which are 1.50 times farther apart than the wire diameter so 1/3 of the beam will miss the wire.

Assumption 4 - the scan width will be 2 feet (0.6 meters).

Assumption 5 – the maximum capstan wire processing rate is 5000 ft/min.

Assumption 6 – the density of irradiation crosslinkable polyethylene is 1.4 g/cm3.

Case 1: 10AWG, 0.18 inch diameter wire

The net effective plastic mass on the 10 AWG wire is 3.8 g/ft (12.5 g/m). Using the NHVG at 600kV and 40mA and a dose rate of 150 J/g requires 570 J/ft. At 24 kW the net power through the foil is 16 kW, the net power applied to the wire is 11 kW, and the net power in plastic is 6.6 kW. At 570 J/f this corresponds to 11.6 ft/second or 700 ft/minute.

Case 2: 16AWG, 0.092 inch diameter wire

This wire would use the medium wire size capstan with the net effective plastic mass on the 16 AWG wire is 0.98 g/ft (3.2 g/m). Using the NHVG at 450kV and 50mA and a dose rate of 150 J/g the net power in the plastic is then 4.5 kW for a net 147 J/ft. This corresponds to 31 ft/sec or 1860 feet per minute.

A logical approach for the processing of the variety of wire sizes is to have a longer scanner of 3 feet wide. The scan can be controlled to put more or less current on one capstan side or the other.

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3 System Design

The basic design is from our design for the 600 kV Ion Implantation NHVG, and from a recent 300 kV device built for plastic film processing. The 300 kV unit uses 43 kV per section, leading to a requirement for 14 sections for the 600 kV unit.

The power drive section of the NHVG consists of high frequency switching primary coils and high frequency secondaries in each power supply. The core unit is 1.5 meters (5 ft) long, with a typical diameter of 0.41 meters (16 inch) and a flange width of 0.47 meters, (18.5 inch). The complete length is approximately 12 feet or 3.6 meters long including the pumping, the scanner, and the wire handling fixture. The vacuum pump is a turbo-molecular pump. The oil reservoir is above the unit and the oil tank is below the unit. The orientation of the unit is horizontal.

A standard equipment rack is built into the table supporting the NHVG. The table structure will hold the NHVG with the wire handling equipment bolted to the floor.

3.1 Electron Gun Design

We use a LaB_6 emitter electron gun with an estimated life of 2 years in continuous operation. The electron beam diameter is dependent on the settings of the focus lens, the current setting and the internal geometric focus settings. The beam is designed to exit the accelerator at a diameter of about 2 cm.

The beam current is controlled by an external switching power supply without internal active components. The electron gun is thermally controlled with a "Wehnelt" electrode biased by current to limit the presence of unwanted more divergent electrons.

3.2 Beam Optics and Scanning Design

The scanner will be either horizontal or vertical depending on how the system fits best into existing plant space. The sketches of Figure 1 are two concepts of many possibilities. The scan is designed for a length of 36" (90 cm) and a beam diameter of 3 to 6 cm for a total window area of up to 540 cm^2.

At 540 cm^2, 20 kW, and 40 mA we will have 0.08 - 0.16 mA/cm^2 fluences which are compatible standard practice in the electron beam industry.

3.3 Control System

The NHVG control system will be designed to be compatible with the customer's common factory protocols. Because we have a high voltage system, all controls are fiber optic coupled or carefully buffered in order to reduce or eliminate problems with transients. No electrical signals are directly connected to the computer without intermediate components. The system is designed to remember "recipes" which consist of a set of voltage, current, scan width and scan rate. The inputs and outputs available in the system are listed below as well.

The current and voltage are controlled by feedback via a processor using the "End Cell" values as inputs.

Operator Settings: Recipe or Voltage, Current, Scan width and rate.

Diagnostic Measurements	Purpose	Format
Measured “end cell” voltage	Indicates total Voltage	Analog Reading
Measured “end cell” current	Measures total Current	Analog Reading
Scan OK	Measures Scanner dB/dt	Digital Indicator
Vacuum OK	Indicates pressure < 5e-6 Torr	Digital Indicator
Vacuum Gauge	Vacuum measurement	Analog Reading
Rough Pump Gauge	Vacuum Pressure < 1e-2 Torr	Digital Indicator
Cathode current setting	Controls the Beam Current	Analog Setting
Supply voltage	Controls the Main voltage	Analog Setting
Stray Radiation	Monitor/shut down	Digital Indicator
Stray Radiation 2	Redundant alarm	Shuts Down Beam
Interlock	Shuts down for safety faults	Digital Indicator
		Shuts Down Beam

The 120VAC control system power is delivered separate from the main 208 VAC input power so that consistent continuous monitoring is provided when the main 208 VAC power is off.

The system external interface will be "customized" to meet customer requirements. It can be integrated with customer control software.

3.4 Physical Setup and Radiation Shield

The physical setup of the machine is as shown in Figure 1. Radiation shielding is provided with the accelerator. The largest part of the radiation shield is the "box" around the Capstan wire presentation fixture. All accelerator systems are shown except the user interface/control which may be located elsewhere for remote operation. Various panels around the accelerator have been removed in the figure for clarity of understanding.

There is a "hole" in the shield through which the beam enters the scanner. This radiation is primarily backward directed towards the cathode and vacuum column of the accelerator.

In normal operation, the shielding is designed to eliminate stray radiation. In case of a fault or unusual occurrence, the system will be shut down by fault mode radiation detectors. Shielding panels may be added on the front side area of the accelerator depending on the measured radiation survey.

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3.5 Stray Radiation

X-rays are produced in case of beam scattering from the electrodes, with a contribution from the X-ray flux through the unit electron beam hole. Scattering is normally minimal unless a malfunction occurs. An approved radiation alarm will be interlocked into the system along with an analog radiation detector. The system as supplied will comply with state and federal limits radiation production for industrial equipment.

3.6 NHVG Ancillary Components

The NHVG ancillary components include the vacuum pump, scanning system, oil de-bubbling system, and oil storage. These are included in the main accelerator "Table" assembly. These components will consist of (specifically):

- Electrically actuated valves for control of the oil pumping system
- A built-in oil reservoir (the oil required is approximately 60 to 80 liters)
- A small roughing pump to remove bubbles from the oil
- An oil cooling system

3.7 System Requirements

The 600kV NHVG Accelerator has the following requirements (approximate):

Approximate "footprint"	12 ft long by 7 ft wide
Service Access	1.5 ft in back, 3 ft in front
3φ Power Required	208 VAC, 90 A service for 25 kW or 480 VAC, 40 A service
Safety	Dual Radiation alarms and Emergency Stops
Ozone	Vault should be kept at Nitrogen positive pressure if ozone production is to be avoided.
Floor loading	The weight of the radiation shield assembly is approximately 30 tons.

3.8 Maintenance

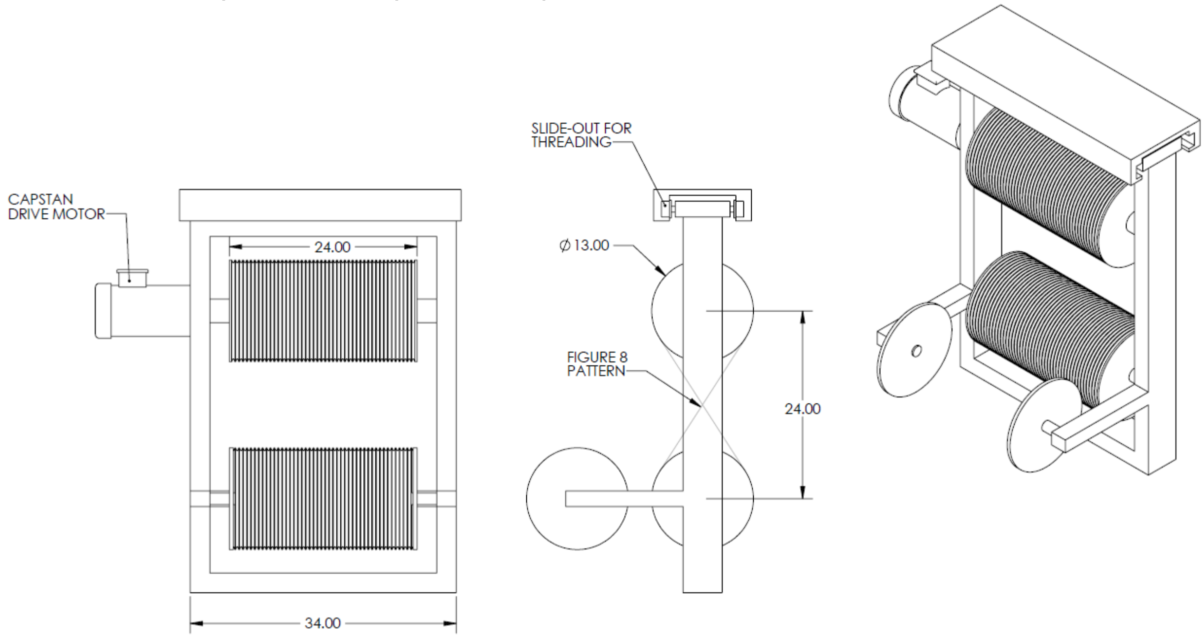
The following routine maintenance should be performed at the specified intervals and only require 1 day every 6 months:

1. Every six months replace window foil
2. Every 12 months replace the following:
   a. Cathode
   b. Insulating oil in machine (about 50 gallons estimated cost $300)
   c. Oil in mechanical vacuum pump
   d. Check status of turbo-molecular pump lubrication

The annual maintenance estimated material costs are $6000/yr.

3.9 Optional Capstan

The optional Capstan assembly is shown in the figure below. It is a figure 8 type with a direct drive for operation at up to 5000 fpm



4 Company Background

Applied Energetics was founded with the goal of using commercial, entrepreneurial approaches to facilitate the rapid development of new technology and systems for Department of Defense and security applications. In particular, we recognized the potential of laser guided energy as a new and important directed energy weapons' technology. LGE and its related counter-IED, ultrashort pulse laser, and high voltage technologies form the basis of our business and our technical capabilities.

For eight years, Applied Energetics has been developing LGE and our "Banshee" direct discharge counter-IED technologies. AE currently has active customer funded programs in and several (classified) pending patent applications in the area of laser guided electrical discharges for defense and lightning suppression.

In support of DoD efforts to develop a capability to place electrical energy on remote targets, Applied Energetics developed Laser Guided Energy™ (LGE™) technology in which ultrashort laser pulses are used to create Laser Induced Plasma Channels (LIPC®) which guide electrical discharges.

While our core technology is the use of USP lasers for the guiding of electrical energy as a weapon, AE's ability to utilize "spin-off" technologies from our development programs to address urgent needs for U.S. Government applications has been demonstrated. A successful example of this strategy is the development and fielding of a high voltage Counter-IED technology for the U.S. Marine Corps. The high voltage technologies developed for our core LGE technology have been applied to commercial projects.

4.1 Facilities

Applied Energetics has invested significant company resources to create a unique and dedicated test facility to quantify system operational parameters and requirements and to fully develop Applied Energetics' proprietary Laser LIPC technology for specific U.S. Government customer applications. AE has developed a unique and regularly demonstrated capability to produce laser guided [electrical] discharges over significant distances in an instrumented laboratory environment. This facility is specially equipped for the study of optical filamentation and guided electrical discharges. This unique optical and laser complex includes a fully-instrumented electrical discharge chamber and existing ultrashort pulse lasers. High current experiments are also regularly performed where the discharge connects to instrumented targets. Few laboratories worldwide have capabilities that approach the facilities at Applied Energetics for the generation and study of optical filaments.

AE's facility is currently equipped with an instrumented, enclosed, indoor, laser test range that can be configured for experiments up to 90 feet in length. Currently three terawatt-class, filament, CPA laser systems are configured for generating filaments in this range:

- AE's Single Pulse, Terawatt Ultrashort Pulse Laser system, and
- Two Burst-Mode, Terawatt, Ultrashort Pulse Laser systems developed under U.S. Government contracts.

AE's facility includes a complete machine shop and metal fabrication capability, custom electronics design, fabrication, assembly and test, and precision assembly and test areas for optical, mechanical, and electrical sub-systems and components. We have approximately 18,000 square feet of open floor space dedicated to the terawatt ultrashort pulse experimental test-beds and prototype assembly and testing.

4.2 High Voltage Facilities

Applied Energetics has in-house a number of high voltage assets including fully instrumented high voltage test center, a variety of high voltage measurement tools, a 300 kV accelerator which can be configured for either electron or ion beam creation, and a variety of custom in-house pulse generators.