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HIGH BRIGHTNESS CATHODES FOR MICROFOCUS X-RAY GENERATORS

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13. ABSTRACT *(Maximum 200 words)*

Nondestructive inspection techniques such as Computed Tomography (CT) and Backscatter Imaging Tomography (BIT) have advanced to the point where detectors and image processors have reached a plateau in performance. Further improvement in the inspection techniques must come from better X-ray sources.

Microfocus X-ray sources offer this improved performance due to their small X-ray spot size, which is generally on the order of tens of microns. The small spot approximates a point source, which reduces geometric distortions of the image. The sources currently available, however, frequently do not meet industrial user maintenance and ease-of-use standards, especially with regard to beam stability and electron emitter lifetime. By using new emitter materials, careful electron gun design, and proper high-vacuum construction techniques, we have developed a high-energy (360 keV), low-maintenance microfocus X-ray source with the improved performance required to meet these demands.

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1. INTRODUCTION.

X-rays are generated by the interaction of an accelerated electron beam with a block of solid matter. Thus, any X-ray system will consist of an electron source or gun, a beam accelerating and focusing system, and a target. The operational characteristics of an X-ray machine are determined by the method used to produce the electron beam and the acceleration system. In this project we have designed and built a microfocus system offering improved performance in three key areas: higher X-ray flux, higher X-ray energy, and lower maintenance.

Microfocus sources are ideal for non-destructive test methods requiring precise X-ray imaging, as they offer a small X-ray spot size (The term "microfocus" generally is applied to machines with a spot size of tens of microns). Yet they have seen only limited use due to several practical limitations with present equipment. These limitations are:

- High maintenance requirements.
- Low X-ray flux.
- Poor beam stability.

We have addressed each of these problems in the design of our new instrument.

Maintenance of the X-ray source consists chiefly of periodic replacement of both the electron emitter and the beam target. The traditional electron emitter consists of a heated length of tungsten or tantalum wire, which requires frequent skillful replacement. We have employed a lanthanum hexaboride (LaB_6) emitter, which not only lasts longer but also is easier to replace. We have also significantly improved the vacuum inside the apparatus to increase emitter lifetime.

Insufficient X-ray flux is caused by low-brightness emitters, by poor electron gun and accelerator design, and by insufficient beam energy. The LaB_6 emitter has improved the brightness. To improve the acceleration and focusing of the beam, we have employed a high-precision electron gun design (similar to that used in electron microscopes) and carefully modeled the spreading and focusing of the electron beam in its passage through the system. To further improve X-ray flux, we have increased the electron beam energy by using a double-ended design, in which the cathode is set at a negative high voltage and the anode at a positive high voltage. The design goal was a maximum energy of 500 keV, but reliability concerns led us to reduce this to 360 keV.

Beam stability is controlled by the same parameters outlined above. Beam voltage stability is determined by the closely-regulated high-voltage power supplies. Beam current is made very stable by our use of a self-biased triode electron gun. The self-biasing applies negative feedback to the gun to eliminate drifting due to fluctuations in emitter temperature, resulting in very stable electron current throughout the adjustment range. In addition, we have designed the control electronics of the system to be as robust and simple as possible, requiring the smallest possible number of necessary user adjustments

Performance specifications of the L&W Micronfocus 360 are listed in the following table.

Table 1.
Performance Specifications
Micronfocus™ 360.

Parameter	Specification
Usable beam voltage:	150 – 360 kV
Voltage stability:	± 0.1%
Beam current:	Up to 1.0 mA, 17-step adjustment.
Beam stability:	± 0.003 mA
Min. spot size:	60 microns FWHM, continuously tunable
Target style:	Transmission or 45° reflection
Target cooling:	Circulating insulating fluid.
Emitter style:	Demountable.
Emitter material:	LaB6 crystal.
Emitter lifetime:	1500 hours projected.
Beam optics:	Single pair X–Y centering coils, single gap lens focusing coil
Voltage source:	Dual external HV supplies. connected via cables.
Vacuum pumps:	Dual ion pumps, rough-pumped by turbomolecular pump
Internal vacuum level:	0.1 microTorr

2. PROJECT BACKGROUND.

In the Phase I portion of this project we investigated the operational requirements and design options for an electron gun intended for use in a microfocus X-ray system. We found that long life and mechanical stability were the two main requirements. We compared the standard X-ray tube electron source, the tungsten wire filament, with other options including field emission, Schottky and LaB_6 emitters, concluding that field emission and Schottky emitters are not viable source selections. The LaB_6 emitter was determined to have the best combination of physical and electrical characteristics for use as an electron source in our application. We discuss this in detail below.

In Phase II of this project we investigated the various options for electron gun design, tube current control, beam focusing and positioning and high voltage generation and application. The quality of the output X-ray radiation depends on all areas of the tube and high voltage design. While currently available microfocus sources do work, their use of obsolete technology and general "black art" design cries out for improvement. No one single design facet will accomplish this; rather, we employed a careful scientific design approach, using currently available e-gun and vacuum technology to attack all aspects of the design problem.

3. SYSTEM DESIGN.

The system will produce X-rays of energy up to 360 keV. A double-ended design is used; an overall view is shown in Figure 1. High voltage is generated by two power supplies and applied to the cathode and anode by large high-voltage cables and insulating sockets. The cathode chamber contains the electron gun and is maintained at a potential of up to −180 kV. Electrons are emitted from the gun and accelerated toward the target. Midway through the machine, magnetic coils are used for focusing and X – Y steering of the beam onto the target. The anode target is in turn maintained at a potential of up to +180 kV and cooled by circulating insulating oil. X-rays are emitted from the target in a direction perpendicular to the electron beam. The focusing system produces a X-ray spot size of 60 microns or less.

3.1. Electron Emitter.

The electron emitter is the very heart of the system; its selection had an effect on almost all other design decisions. Electrons are produced by heating the emitter material so that its electrons absorb enough energy to leave the material. Eventually, due to this heating, the emitter will wear out and require replacement. Long emitter lifetime is obviously an important design goal. Ease of replacement is also a goal, not only to minimize the downtime but also to ensure that gun performance is consistent from one run to the next.

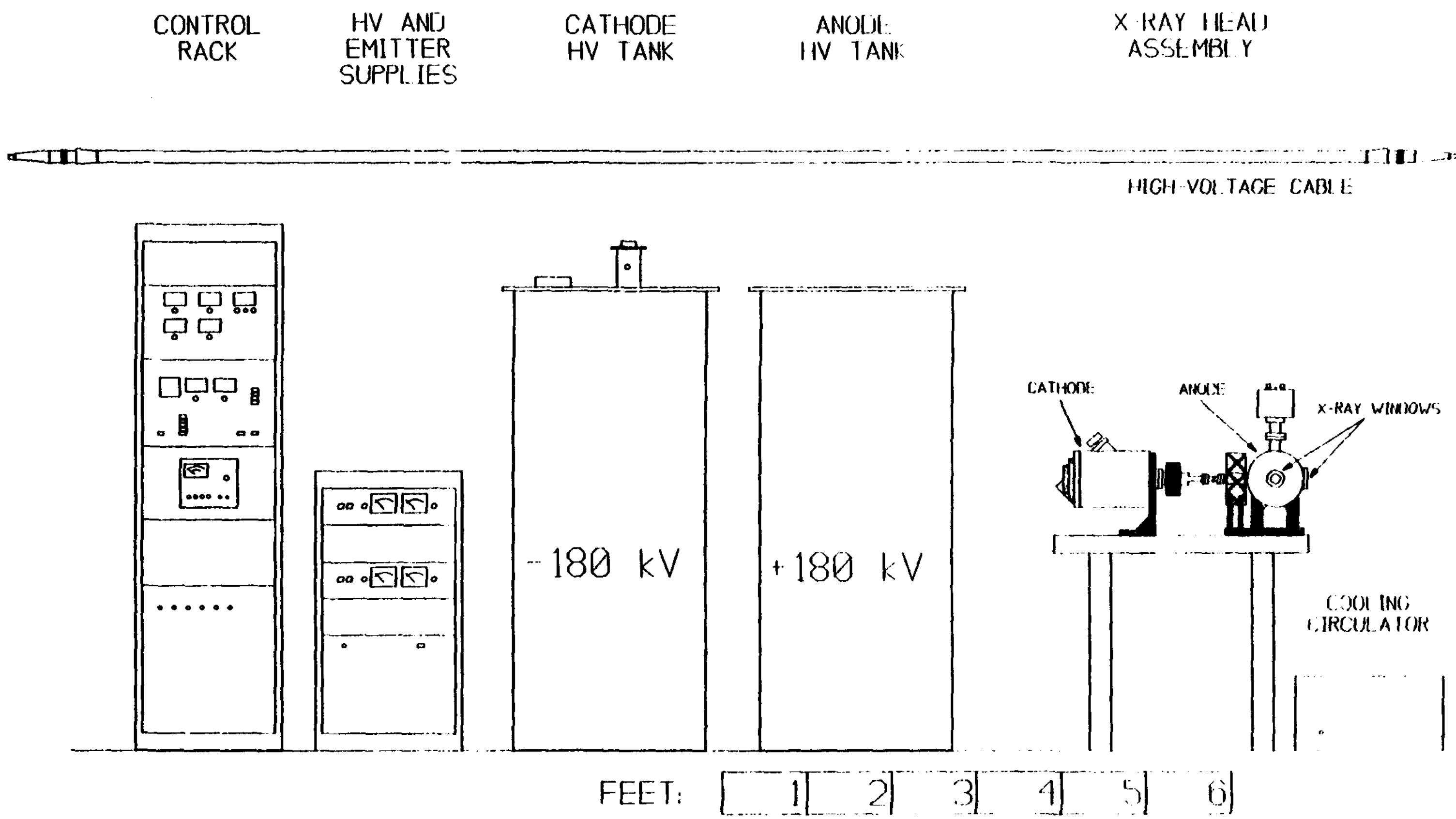

Figure 1. Overall view of the instrument

Existing X-ray microfocus tube designs frequently employ a tungsten wire or ribbon filament as an emitter. The apparent simplicity of this arrangement is deceptive. Not only is the filament is comparatively short-lived, but a new filament must usually be made by the operator by bending wire or ribbon to a precise shape. This process is difficult to control and frequently results in inconsistent operation of the X-ray source when filaments are changed. Better performance is realized by using longer-lived emitters mounted in a tightly controlled manner.

As mentioned previously, in Phase I we compared several design options for the electron source, finding that LaB_6 was the best choice. Parameters for comparison are lifetime, brightness, mechanical stability and uniform depletion. Emitter lifetime and brightness are strongly linked; increasing the operating temperature of an emitter naturally raises not only its electron emission but also the evaporation rate of the emitter material. As the evaporation depends sensitively on temperature, small increases in temperature — as little as 100 °C — can decrease emitter lifetime by a factor of three or four.

While one can acheive the desired current of about 1 mA with a tungsten filament, this would result in a very short lifetime. Typical filament lifetimes in microfocus sources are tens of hours, with 150 hours possible if great care is taken in filament construction. The LaB_6 emitter is more efficient in terms of electrons emitted per amount of material evaporated, and thus lives longer. We use a commercially available emitter for which its manufacturer estimates a lifetime in excess of 1500 hours under our operating conditions.

A further advantage of the commercial LaB_6 emitter is ease of installation. In order to maintain beam optical characteristics, distances between the emitter and other parts of the electron gun must be reproducible to fractions of a millimeter. This is difficult to achieve if a new emitter must be constructed for each installation. The emitter used offers plug-in convenience and may be obtained in a standard mount from several different suppliers.

The depletion of the emitter is fairly well known and predictable. Since the emitter surface is flat it continues to erode in a flat plane. By designing the electron gun properly we are able to make the X-ray spot size insensitive to depletion of the emitter. Thus the beam characteristics remain constant as the emitter wears out.

One disadvantage of the LaB_6 emitter, however, is maintaining a sufficiently low system pressure. The emitter manufacturer specifies a maximum pressure of 10^{-6} Torr for proper operation, and states that further reduction of system pressure will increase lifetime more. As existing microfocus units do not maintain this low pressure, it would not be possible to simply retrofit a unit using a tungsten filament with a LaB_6 emitter. We have, however, applied our experience with high-vacuum systems to reduce system pressure to the low 10^{-7} Torr range. This is discussed further in section 3.2.

In actual use, the emitter performed as advertised by the manufacturer. When a new one is installed, a little time (an hour or two) is required to gradually heat the emitter and outgas it. After that, the emitter does not appear to require any "warmup" or other special treatment; the electron beam reaches full strength a few seconds after the emitter is switched on. Although a air inrush to the system while the emitter is switched on will destroy it, exposure to the air when the emitter is cool does not appear to degrade the emitter. We recommend, though, that standard high-vacuum practices be followed when performing maintenance. For example, the vacuum system should be backfilled with a dry non-reactive gas such as nitrogen.

3.2. Vacuum System.

Literature provided by the emitter manufacturer emphatically states that it is necessary to maintain system pressure at high-vacuum levels to use the emitter properly. As stated above, the emitter gradually wears out due to evaporation. At sufficiently high pressures, though, emitter erosion is accelerated by reaction with background contaminants, chiefly water. Above 10^{-6} Torr, this accelerated erosion rate is more than 10 times higher than the evaporation rate and is unacceptably high. As pressure is reduced through the 10^{-7} Torr range, the erosion rate drops sharply, and in the low 10^{-8} Torr range, contaminant-assisted erosion is insignificant. A system pressure in the low 10^{-7} Torr range is thus desirable.

This placed significant constraints on system construction. Materials with low "outgassing" rates, or those which minimize contaminant emission from their surfaces, must be used. The vacuum chambers are made of type 304 stainless steel. The high voltage insulators are made of the machinable ceramic Macor, rather than plastics such as Delrin, which tend to outgas too much. All parts are thoroughly cleaned before installation.

Seals must also be of high quality. In general, soft metal gaskets should be used instead of elastomer O-rings. Metal gaskets are used on all demountable flanges except under the electron gun and target, where elastomer O-rings are used. The Macor high-voltage sockets are permanently fastened to their flanges using high-grade vacuum-compatible epoxy.

The high-vacuum pump is also crucial. Diffusion pumps would contaminate the system with pump fluid. Turbomolecular pumps are frequently employed in other units, but require a backing mechanical pump. These can cause problems in the event of a power failures or similar event. Moreover, turbopumps require periodic maintenance of their bearings, resulting in system downtime. We use dual ion pumps, which are designed to operate optimally in this pressure range and which are almost maintenance-free.

Since ion pumps do not, however, start working at atmospheric pressure, an external pumping cart is provided for initial pump-down of the system. An oil-sealed mechanical vacuum pump is inadequate, as it not only would take a long time to reach the low pressure required for starting the ion pump (below 10^{-4} Torr) but also would cause problems due to backstreaming of oil vapor into the system. Sorption pumps are frequently used in this capacity, but require liquid nitrogen, which may not be available to the NDT user. We thus used a turbomolecular pump backed by a mechanical pump. These pumps, along with a controller and vacuum gauge, are mounted on a wheeled hand truck and connected to the system via a flexible stainless steel hose. With this the user can quickly pump the system down after closing the chamber and then remove the pumping cart. Since the turbopump is used only occasionally, its lifetime should be long enough.

Base system pressure is then about 1×10^{-7} Torr, rising to 4×10^{-7} Torr when the gun is on. At this pressure, evaporation and erosion of the emitter are roughly equal, and the emitter lifetime is estimated to be 1500 hours.

3.3. Electron Beam Optics.

Precise generation and focusing of the electron beam is clearly vital to true microfocus X-ray generation. We have made extensive use of available scientific software to model the electric fields and electron trajectories inside the apparatus. From these we were able to develop an electron gun with optics far superior to any microfocus X-ray generator previously developed.

The gun has three electrodes. The cathode is, of course, the LaB_6 emitter. The anode is far away with a potential of up to 360 kV relative to the cathode. In between the two, mounted on the cathode socket assembly, is an intermediate electrode used for tuning the beam, referred to as the bias electrode or Wehnelt electrode. This is a modified version of a triode design frequently used in electron microscopes.

We have determined that actual geometry of the Wehnelt electrode is not all that critical. Rather, the important parameter is the distance between the emitter and the Wehnelt electrode's aperture. With this distance properly set, a small negative voltage is applied to the Wehnelt to repel electrons. The beam then experiences a crossover near the Wehnelt, diverges, and becomes practically parallel by the time it reaches the anode plate. This was tested with computer modelling and practical tests. A sample computer simulation is shown in Figure 2. Operation of the Wehnelt electrode is further discussed in Section 4.3.

The involved design of the electron gun makes the downstream focusing and deflection system much simpler than in previous microfocus systems. The beam emitted from the gun is almost parallel, and the mechanical design is such that the emitter is always pointing down the exact center of the beamline. Between the cathode and anode vacuum chambers there is a drift pipe which connects the two. Around the drift tube are beam focusing and deflection coils to control the spot size and assure that the beam hits the anode target.

In actual use, final alignment of the cathode and anode chambers is made by physically moving the anode chamber with respect to the cathode — some movement is allowed by flex in the drift pipe. The chambers are then clamped in place. The beam is then steered to the target with the steering and focus coils. Once the system is aligned, it is not necessary to re-align the system unless the target is removed for some reason. Indeed, from day to day only minute adjustments in the steering are necessary; the beam generally strikes the same spot on the target when the machine is turned on.

Actual spot size was measured during test runs by projecting the spot through a 0.003" slit on the distant screen of an image intensifier tube. The beam profile was observed on an oscilloscope. Measurement of the full width at half-maximum of the resulting peak showed the spot size to be $60 \pm 15\ \mu$, independent of both beam energy and current. That this small spot was achieved with a single lens is, we believe, testament to the usefulness of the gun design in this application. Of course, at higher beam currents, the focusing must be deliberately detuned to increase the spot size and avoid damaging the target. We generally kept the power density at the target below 2 W/cm of radius, which caused no target damage.

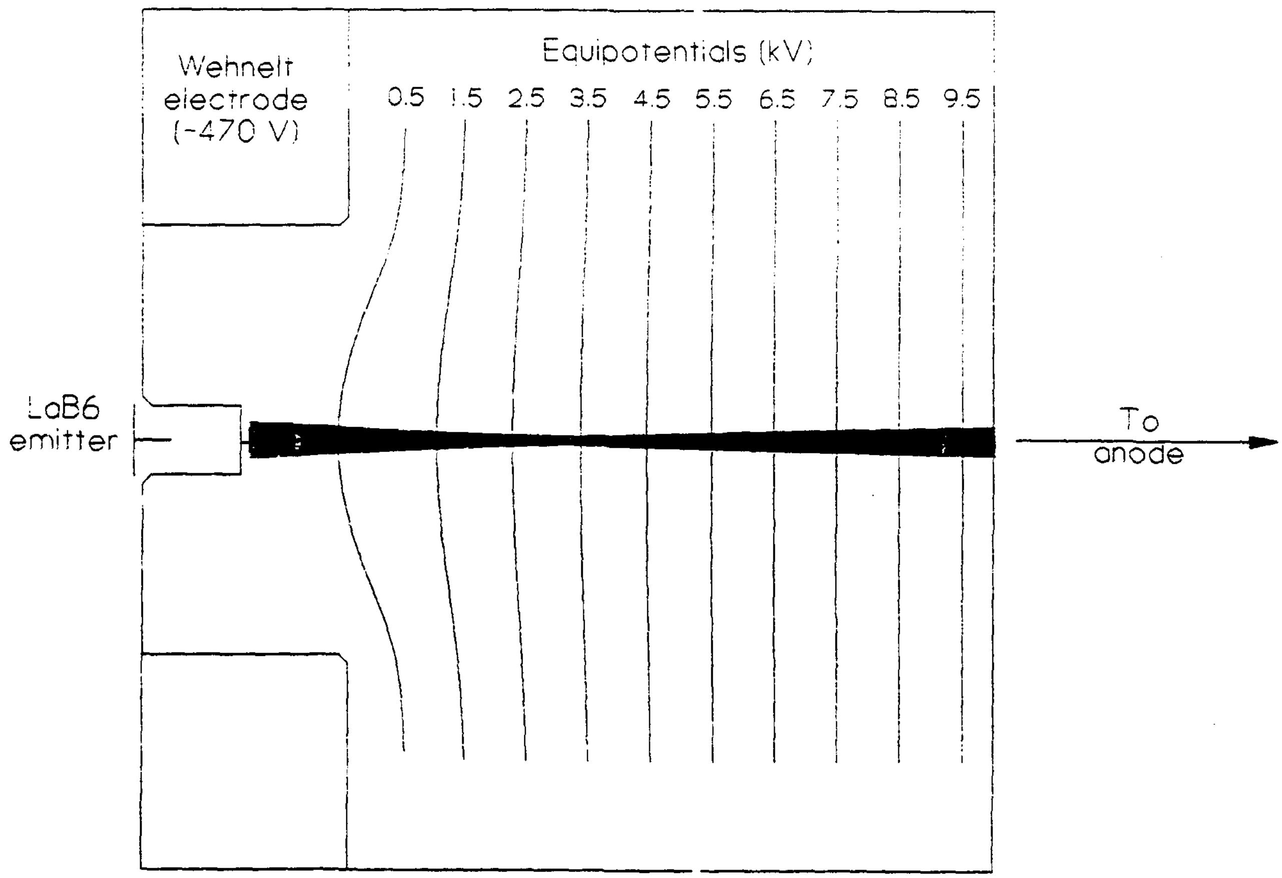

Figure 2.
Electron trajectory simulation.

3.4. High Voltage Application.

Existing microfocus systems operate at voltages lower than 200 kV. While high-voltage power supplies with output of 300 kV are readily commercially available, application of such a high voltage to the X-ray head is no small task. The cables, plugs, and sockets required are physically large, and care must be taken with the materials used in construction. While these items are commercially available, our instrument has additional requirements of ultra-high-vacuum capability and as small a size as possible. This eliminated some candidates for the design.

The electron gun is mounted on the end of the high-voltage socket, which is integral with the tubehead. The anode is mounted on another socket in the other vacuum chamber. Both sockets are constructed of Macor, a machinable ceramic. The gun end of the cathode and the target on the anode have rounded shields to reduce electric field stress and stray electron emission. The cathode assembly is shown in Figure 3.

To keep costs and design time down, we adapted an existing 210-kV cable and plug design to the system (recall that each end runs at 180 kV). The cable and plug assemblies are a standard design used in other X-ray instruments. The standard plug is made of natural rubber and sealed into its socket with silicone insulating grease. For reasons of reliability, we have deliberately de-rated the high voltage connections and recommend that they be operated only at 180 kV per end. The machine will operate at higher voltages, but reliability will be compromised.

Our original design goal was for 500 keV total beam energy — 250 kV on each end — as analysis of the socket and plug design had indicated that this might be possible by using different plug and insulator materials (The prototype has ±300 kV supplies for this reason.). This proved not to be the case. Indeed, we believe the 210-kV rating to be somewhat optimistic for this application. For best reliability, then, we have de-rated the system to ±180 kV.

The high-voltage system also deals with stray X-ray emission, a problem in many X-ray sources. This stray radiation is caused by field emission of electrons from the high voltage components to the grounded tubehead. Any sharp points, even microscopic ones, in the surface of high-voltage electrodes cause field emission, as the electric field lines converge about the sharp point, producing a local field far higher than the macroscopic field. The field-emitted beams collide with the chamber walls, producing uncontrolled X-ray emission. The extreme case of a field-emitted beam is, of course, a high-voltage discharge.

Conventional X-ray tubes are mounted in a "ray-proof" housing which reduces radiation in all directions except the primary beam. Microfocus radiography sometimes requires the user to wrap lead around the tubehead to prevent the stray radiation affecting the film. Although the X-ray conversion efficiency is low for type 304 stainless steel, the material of which the head is constructed, at 180 kV there can still be significant amounts of stray radiation.

Our solution to this was to design a system which reduced the electric fields that cause the emissions. The electron gun is mounted on a rounded shield piece, which prevents electron emission from sharp edges in the vacuum seals and socket termination. The shield's surface was highly polished and all possible emission points removed. The shield

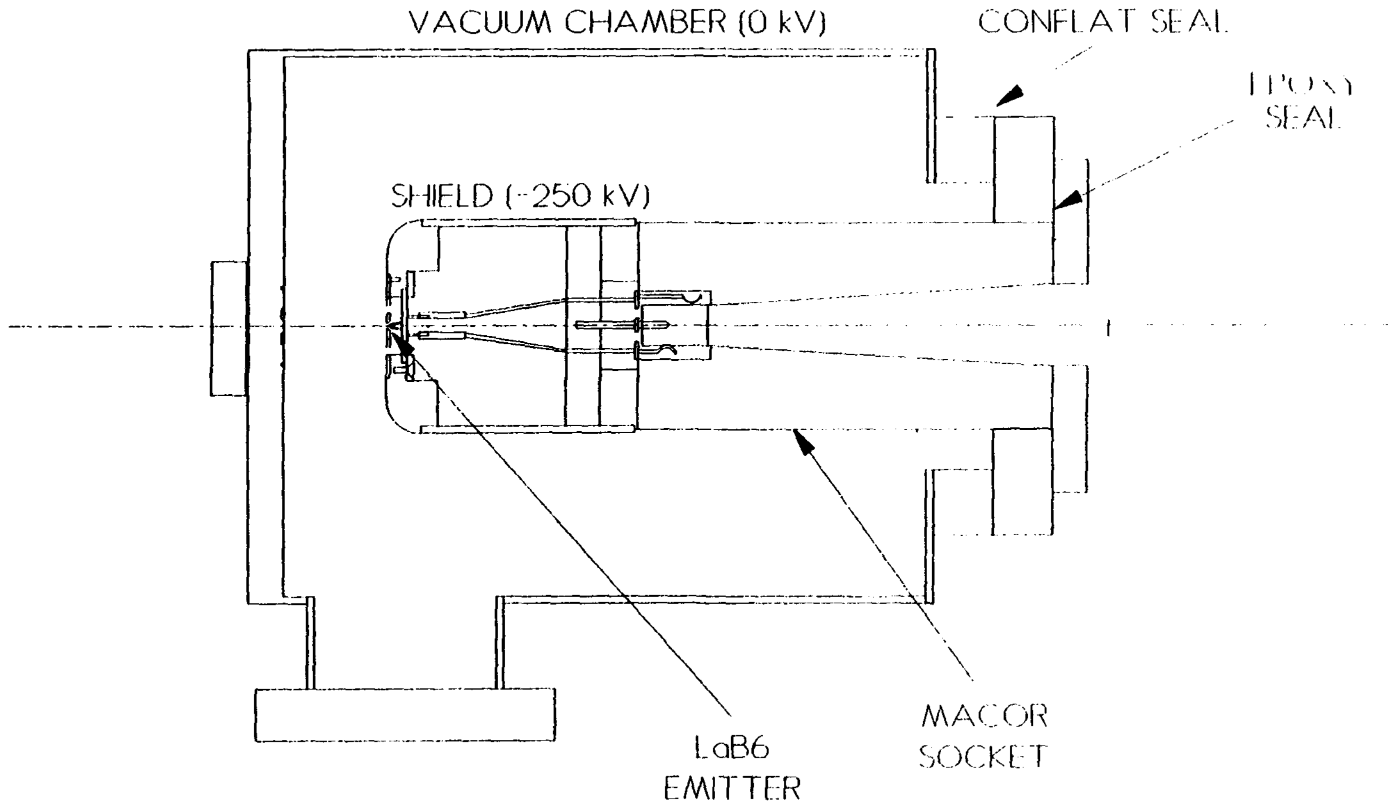

Figure 3. Cathode assembly

also increases the high-voltage standoff capabilities of the insulator by decreasing leakage along the surface of the insulator.

Even the most careful design and smoothest manufacture will not, however, completely eliminate field emission. The last step must be performed with the system assembled, and is referred to as "conditioning." After evacuation of the system, the high voltage is gradually increased with the electron emitter off. The user will observe small discharges as the voltage is increased. Voltage is raised to the point where small discharges occur and then left constant. After a time, the discharges will have tapered off, and the voltage can be raised again.

Conditioning in this manner removes remaining sharp points. Each discharge damages the point where the discharge occurs, until eventually the point is completely blasted away and a smooth surface left behind.

In actual use, about one day is required for conditioning after the system has been open. This must be performed carefully, as transients occurring during the discharges place considerable stress on the plug/socket assembly; this is one reason why we de-rated the high-voltage plugs. After that, when the system is next turned on for use at the beginning of the day, voltage can be increased smoothly over a period of a few minutes while watching for discharges. During the work day, the high voltage can be abruptly turned on and off as the user requires.

3.5. Target Cooling.

The anode tubehead contains the target with cooling. The system has been designed to provide either a reflected or transmitted X-ray beam. One of the most difficult requirements of the anode is the cooling of the target.

Since the machine has +180kV on the anode, it is not as easy to cool the target as in end-grounded systems. We inject cooling silicone fluid up through a tunnel in the Macor and back down the inside of the socket, around the plug. The oil serves a dual use of cooling the target and insulating the high voltage cable. A small peristaltic pump is used to circulate the coolant, and flow sensors have been employed to shut the system down if coolant flow is interrupted.

In bench tests, this system was found to keep the target at about 130 °C under simulated use conditions. In actual use, no heat-related damage to the target was observed.

4. ELECTRONICS.

4.1. High Voltage Generation.

While L&W Research does design and construct its own high-voltage supplies, we elected here for cost and time reasons to use two commercial supplies, one positive and one negative. The prototype unit has high frequency Cockroft-Walton ±300 kV supplies, but commercial units would be provided with ±200 kV supplies. The high voltage generators in this system were installed in two separate oil tanks at L&W.

The supplies consist of a rack-mounted control unit connected to a separate multiplier circuit chain or "stack." The stack is immersed in oil in a tank; this provides a grounded shield about the stack and allows the unit to operate in closer quarters then if it were in air. The primary concern regarding the design of the high voltage tanks was to insure there was adequate spacing between the high voltage stack and the side walls. Each tank must withstand not only a constant 180kV dc but also 360kV transients if (when) there is a high-voltage spark in the X-ray head. An extra resistance was placed in series with the high voltage stack to act as a current limit during transient conditions. Oil dielectric strength was kept well within the design specification of 300 kV/inch. The tanks were initially filled directly from the oil drums with no processing, but the oil quality was later improved while in the high voltage tanks by circulating it through a 5-micron oil filter with water separation properties.

The high voltage system is thus easy to maintain and repair. Neither vacuum processing of the oil nor vacuum filling of the tanks is required. The system is modular, with the entire high voltage stack in one assembly and the electron gun supply in another. The beam current control electronics, discussed below, can be accessed from the top of the tank without removal of the rest of the HV system.

4.2. Beam Current.

The electron source requires an isolated supply to power the emitter. This supply must provide a current-regulated output controllable from a low-voltage area and be isolated to at least twice the rated supply voltage.

There are several ways to provide power for the emitter supply. Isolation transformers are frequently used, but are impractical in our application, the emitter supply is instead powered by a generator driven via an insulated shaft by a motor located on the top of the tank. The generator is immersed in the oil, so a brushless design was chosen. The drive motor is a basic DC motor powered from the control rack. The whole assembly was built on a separate deck, removable from the tank.

The LaB_6 emitter needs a constant-current supply for proper operation. The primary problem here was developing electronics that were able to withstand the normal transient voltages that occur in a X-ray tube. A simple resistive voltage divider system is used. This uses no electronics except for passive devices such as resistors and diodes.

To set the desired elecron emission of 1 mA, emitter heating current is set at about 1.8 to 1.9 A. As the electron gun is operated in a saturated mode, whereby electron emission is regulated by the Wehnelt aperture (see below) and the gun is partially space-charge limited, the simple supply works well. Emitter current is adjusted with a separate insulated rod which goes to the top of the tank. The emitter does not need constant tweaking, so this was left as a manual factory adjustment.

4.3. Beam Current Control.

In a X-ray tube the electron beam current, typically referred to just as "mA," can be controlled using two methods: varying the emitter temperature or voltage-biasing the emitter.

In most conventional X-ray tubes, beam current is adjusted by varying the current passed through the tungsten filament. This changes the filament temperature and hence controls the thermionically-emitted electron current. Typically some type of electronic feedback is used which monitors beam current and adjusts filament temperature. We see from above that this method is not suitable for our design. As mentioned in Section 3.3, we employ a second method, voltage biasing, by placing a third electrode close to the emitter to which is applied a small negative voltage. This is the Wehnelt or bias electrode. The electric field from this electrode can restrict emission from the emitter surface up to the point of shutting it off completely, independently of the emitter temperature.

There are actually two types of voltage biasing: direct and self biasing. In direct biasing a separate voltage supply is used to provide the negative potential. The tube current is measured in the current chain and an external circuit determines the required bias voltage which then must be adjusted to compensate for any changes. In self-biasing the emitter supply is isolated and a resistance is placed in the current path between the Wehnelt electrode and emitter potential. Beam current flowing through this resistance will develop a potential which will vary with tube current, creating a negative feedback effect which stabilizes the beam. Beam current is adjusted by changing resistor value. The self-biasing method is much simpler and requires very little external circuitry.

We found in early stages that it is difficult to employ a potentiometer as an adjustable bias control, because bias resistor values not only are quite large but also cover a large range. We thus use discrete resistors to control bias, mounted on a 17-position rotary switch.

4.4. Control Electronics.

In line with the design philosophy of the rest of the instrument, the control electronics was kept as simple as possible. There are three separate modules in the control rack: the beam control, X-ray control, and vacuum modules.

The beam control module contains circuit boards for control of the magnetic focus and X—Y deflection coils. Although only one of each of these is used, the module was designed to accommodate two focus and two X—Y boards. The coil power supplies are both linear, current regulated, voltage controlled supplies. All the boards provide feedback by way of front panel mount LED meters to assist in proper beam tuning.

The control module has the interlocks and beam control. The interlock uses a simple relay logic design to shut down the beam unless the temperature and vacuum level are correct, coolant is flowing, and the door to the X-ray room is closed (this last is a safety precaution). Electrical power application is controlled by a key switch to prevent unauthorized machine operation. The control module allows for timed exposures as well as manual on/off operation.

The vacuum module contains the ion pump control and power supply. Again in the interest of saving time and money, a commercial ion pump control unit was used. The unit is equipped with external outputs to provide a vacuum interlock for our control system, and is used to drive a 20 liter/sec diode ion pump. This is a rugged system with proven reliability.

In the late phase of testing, we found that a second ion pump was necessary. For this pump, we made our own controller, consisting mainly of a high-voltage power pack and current meter.

5. CONCLUSIONS.

L&W Research recognizes the NDT user's need for a robust, reliable, simple instrument. For that reason, at every stage in the design process, we have made use of the best off-the-shelf high technology available, designing our own parts when none were available.

The project goals were to improve beam flux, beam energy, reliability, and ease of use and maintenance. We find that the LaB_6 emitter and the self-biasing gun, both used here for the first time in a microfocus unit, have worked well, improving reliability and ease of use. We plan to continue using them in future designs.

We have successfully improved beam energy, but not as much as we would have liked. The prototype unit works well at 360 keV, but operation above that energy is less than reliable. The major problem lies in the high-voltage terminations. While there are other designs available, we believe that the double-ended design, with external power supplies, has reached its limit here. Further increases in beam energy will probably require a different approach, with the X-ray tube integral to the power supply.

Field testing of the prototype unit will be performed at Wright Laboratory, where the instrument will be installed in a new computerized-tomography system. This will allow the NDT community to evaluate the worth of high-energy microfocus sources. In the meantime, L&W Research will be applying the technology developed in this project to microfocus sources with even higher beam energies.

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