Invited Paper

Electron Guns for Terahertz Vacuum Electron Sources

R. Lawrence Ives *, George Collins, Michael Read, George Miram, David Marsden
Calabazas Creek Research Inc., 690 Port Drive, San Mateo, CA 94404 USA
* Email: RLI@Calcreek.com

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Abstract: Advanced techniques are allowing fabrication of high frequency RF circuits to high precision. Dimensional tolerances of a few microns are routinely achieved, allowing precise fabrication at frequencies approaching, and sometimes exceeding, 1 *THz*. Fabrication is usually performed by computer-controlled machines, often without human intervention. A more challenging task, however, is fabrication and assembly of electron guns operating at thousands of volts and temperatures often exceeding 1000 ℃. Electron gun assembly, especially for thermionic guns, is still primarily a manual process. Because the electron gun operates at a high negative potential, it is necessary to electrically isolate the gun from the RF circuit, requiring one or more bonding processes, which usually include brazing or welding. A further complication is integrating the electron gun and circuit with a magnetic field providing beam confinement. Precise alignment is required to achieve adequate beam transmission. Again, this alignment is typically a manual procedure. This publication identifies the issues associated with the design, fabrication, assembly, and integration of high voltage thermionic electron guns with Terahertz RF circuit and describes simplification provided by the latest generation of high current density cathodes.

Keywords: Cathodes, Reservoir cathodes, Electron guns, Electron beams, RF sources, Terahertz

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1. Introduction

Numerous methods exist for precise fabrication of RF circuits, including LIGA, deep reactive ion etching (DRIE), micro electro-discharge-machining (EDM), laser ablation, and micro-milling. These methods achieve dimensional tolerances in the range of microns to submicrons. Consequently, source designers are building electron device circuits capable of providing RF power well into the millimeter and lower THz frequency ranges. A number or techniques and processes from the semiconductor industry are being applied to fabrication of metal or metal plated circuits for traveling wave tubes and backward wave oscillators, including wafer technology to produce multiple circuits in parallel [1].

These high tolerance precision circuits are fabricated using computerized machining and processing equipment. The result is a single component built to precise dimensions, often with multiple copies extracted from a single wafer. Literally hundreds of such circuits have been fabricated.

The circuit, however, is only one component of an RF source. Before the circuit can function, it must interact with a high voltage, high quality, electron beam. Generation and propagation of this electron beam can be much more challenging than fabrication of the circuit.

An ideal source for a THz electron beam would be a micro-fabricated field emission array. Research is in progress on Spindt-type field emitters and carbon nanotube arrays. These devices are also fabricated to high precision using computer controlled machines and processes. Small arrays have produced significant levels of current in laboratory experiments; however, implementation into actual RF sources has been problematic. The structures are quite fragile and often fail from arcing or ion bombardment. There are currently no commercial RF sources using electron beams from field emitter arrays.

All successful vacuum electron RF devices to date use thermionic cathodes as the electron source. Based on technology many decades old, they continue to be the only readily available, reliable source of electron beams. Though the basic design is well established, recent advances in fabrication techniques, materials, and capabilities are renewing interest in thermionic cathodes. Dramatic performance improvements directly impact implementation into the new generation of high frequency RF sources. This paper will describe these performance improvements and how they affect the design, fabrication, and operation of high power THz RF sources.

2. Cathode advances

A new generation of cathodes is available with significantly improved performance over conventional cathodes. These include controlled porosity reservoir (CPR) cathodes and scandate cathodes. The most important characteristic for gun designers is the increase in emission current density. With conventional cathodes, emission current densities are typically limited to 10 A/cm^2 or less for useful lifetimes. Operation of these cathodes at higher current densities dramatically reduces lifetime. Either the porous tungsten structure cannot provide the barium required or the barium is rapidly depleted from increased evaporation. CPR cathodes overcome this problem by providing a large reservoir of barium near the emission surface to compensate for the increased evaporation. Scandate cathodes provide a significantly lower work function and thereby allow higher current densities at lower temperatures than CPR or conventional cathodes. It is the ability of these new cathodes to operate at high current density that greatly facilitates fabrication and assembly of high frequency RF sources.

2.1 CPR cathodes

Reservoir cathodes provide increased lifetime by placing a large supply of barium calcium aluminate near the emission surface [2]. Measurements at the Cathode Life Test Facility in Crane, Indiana demonstrated both the increased lifetime and uniformity of emission over time. Unfortunately, the cost for reservoir cathodes was unacceptably high until Calabazas Creek Research, Inc. (CCR) developed the sintered tungsten wire approach in 2004 [3]. This technique provided a structurally robust material with a regular array of pores for barium diffusion to the emission surface. The basic configuration is shown in Figure 1.

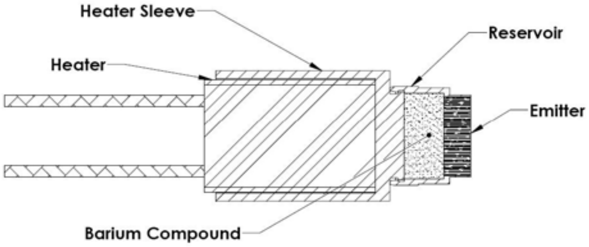

Fig. 1 Configuration of a reservoir cathode.

The emitter cap material is obtained by winding 20 *micron* diameter tungsten wire on a metal spool and sintering. The resultant material is essentially solid tungsten with a regular array of pores corresponding to the gaps between the wires. Figure 2 shows a cross section of sintered wire material. The cathode emitter can be designed for a specific operating current density by calculating the operating temperature and determining the resultant monolayer evaporation rate of barium from the surface. The thickness of the cap controls the barium diffusion rate from the reservoir according to Knudsen Flow. One can then provide sufficient barium to the surface to match the monolayer evaporation rate.

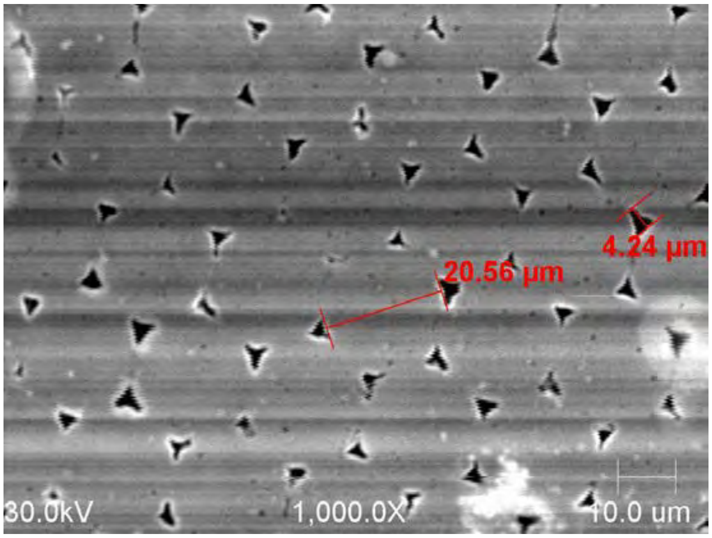

Fig. 2 Cross section of sintered tungsten wire used for cathode emitter caps

One advantage of this approach is the simplicity, which results in low cost. Typical emitter cap thicknesses are 0.035-0.120 *inches*, depending on the current density. The sintering process provides sufficient material for many cathodes. The wire is also used for electro discharge machining (EDM) and filament wire. Consequently, it is produced in large quantities at low cost. Cathode fabrication does not require expensive equipment, impregnation, or complicated machining processes. CPR cathodes are commercially available for a wide variety of applications [4].

One disadvantage with CPR cathodes is the increased operating temperature. While the increased lifetime can be compensated by the increased supply of barium, the higher heater power and thermomechanical issues limit the maximum practical current density. Most current applications operate at current densities of 40 A/cm^2 or less.

2.2 Scandate cathodes

Scandate cathodes provide high current densities by reducing the work function of the emission surface. Scientists began investigating scandate cathodes more than thirty years ago [5,6]. Significant progress was not achieved, however, until Chinese developers, and later researchers at the University of California – Davis, made significant advances in understanding the operation and developing fabrication and assembly processes.

The precise emission mechanism for scandate cathodes is still unclear. Currently there are two primary competing models. The Ca-Sc-O monolayer model was suggested by Hasker [5] based on observations in Auger electron spectra. Raju and Maloney proposed the semiconductor model, which claims the increased emission is caused by penetration of the electric field into the surface layer [7]. Yiman et al. considered several models to explain the patchy surface emission observed in previous scandate cathodes [8]. Using experimental data and analyzing with various models, they concluded that the best correlation occurred when one considered the impact of external fields on a semiconductor layer proposed by Wright et al. for oxide cathodes [9]. Further investigations using Auger Electron Spectroscopy and measurements made by others [10,11,12], concluded that scandate cathodes possess a Ba-doped Ba-Sc-O complex approximately 100 *nm* thick that acts like a semiconductor, leading to the observed electron emission behavior.

Researchers at UC-Davis focused on improvements in the materials and fabrication of scandate cathodes [13]. Sc_2O_3- added tungsten powders prepared by a sol-gel method were reduced to nanometer size using dry hydrogen at high temperature. These were die-pressed, sintered, and impregnated with barium calcium aluminates. The material was then formed into cathodes following additional processing to remove water and decompose any barium hydroxide and carbonate in the pores. The composition was confirmed using X-ray diffraction and scanning electron microscopy. The cathodes produced space charged limited current densities of 40 A/cm^2 at $850^o\ C_{br}$ and 170 A/cm^2 at $1050^o\ C_{br}$. Life testing is in progress, with no degradation in emission following 10,680 *hours* of operation.

3. Mechanical issues for high frequency electron beam devices

The RF circuit defines the characteristics of the electron beam in any vacuum electronics source. Designers begin with the required operating and performance requirements, then design circuits providing the required RF power, assuming an ideal electron beams with the correct current, size, and voltage. Depending on the particular design code, it may be practical to determine circuit performance including variations in beam size, quality (ripple), velocity spread, and current density. One can then define performance characteristics for the electron beam that will allow the RF circuit to provide the RF power required by the user. This becomes the starting point for the electron gun designer.

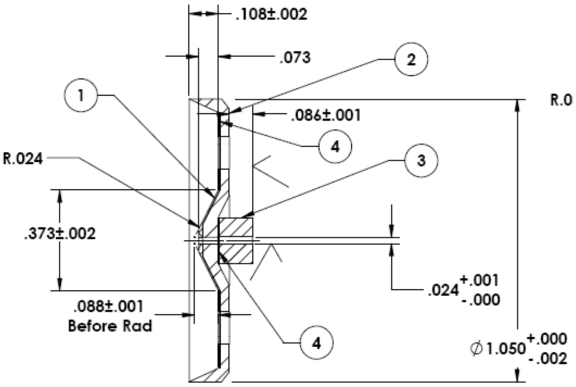

Fig. 3 Anode assembly for a 100 *GHz* Backward Wave Oscillator. The dimensions are in inches.

For lower frequency RF sources, for example in S-Band or X-Band, machining tolerances can be on the order of ten thousands of an inch (0.25 *mm*) without significantly impacting performance. These tolerances are easily achieved by a skilled machinist and computer numerically controlled (CNC) equipment. At frequencies above 100 *GHz*, however, the equivalent tolerance is less than one thousandth of an inch (25 *microns*), and achieving such precision becomes much more challenging. Fig. 3 shows a machining callout of an anode assembly for a 100 *GHz* backward wave oscillator (BWO).

While this is difficult, it is well within capabilities of typical machine shops and not particularly challenging. The required dimensions are programmed into a CNC lathe or milling machine, and the computer does the rest. The real challenge arises when parts or assemblies must be manually bonded together to high accuracy. Fig. 4 shows the relative spacing between the face of a cathode and the associated focus electrode for the 100 *GHz* BWO electron gun. This assembly is achieved by laser welding the focus electrode to the cathode assembly. In this case, the technician is responsible for appropriately mounting or fixturing the parts in a laser welder and bonding the assembly components. This is inherently a non-symmetrical process, where heat is applied at one location on a weld joint. The asymmetrical heating results in thermal shifting of the parts that impacts the final orientation. Consequently, achieving the spacing to a tolerance of 0.0002 *inches* (5 *microns*) is not reliably achievable. In fact, even measuring the distance of the cathode face from an angled edge is problematic. For this particular assembly, the bond was temporarily performed and measured several times before settling on what appeared to be the best configuration that could be achieved.

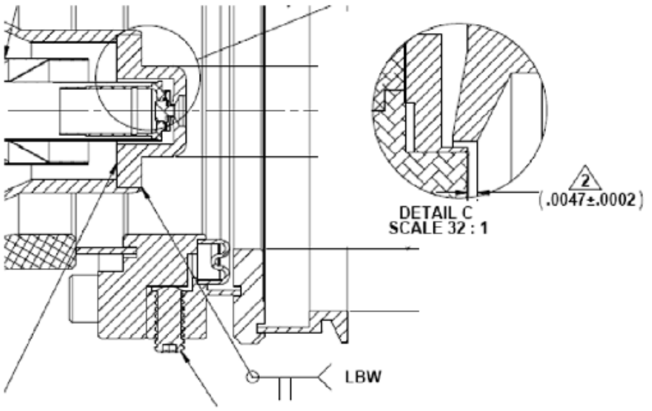

Fig. 4 Drawing showing laser beam weld of focus electrode and required dimensional precision

The problem can become more difficult the greater the distance of the bonding surface from the required dimension. A particularly difficult bond is the electron gun to the circuit. Not only is this bond radially located relatively far from the centerline of the device, it is also a blind bond. The cathode region cannot be accessed to determine the alignment of the cathode with the anode and beam tunnel after the weld. Of particular concern is concentricity, as this is usually a tungsten inert gas (TIG) weld. Some distortion of the bond joint always occurs with the localized application of the extreme heat required to melt metal. Techniques are available to minimize relative motion of the bonded assemblies, but one can never be sure what is actually achieved.

Another issue is axial and radial alignment with the magnetic field that guides the electron beam through the RF circuit. In this case, the components are often completely different devices which are mechanically connected using fasteners, such as screws or bolts. Fortunately, one often has the freedom to shift the relative position of these components while the device is operating. This allows, for example, correctly aligning the axial magnetic field with the electron beam by monitoring the collector or body current. Axially aligning the electric and magnetic fields is more difficult, as this impacts the beam quality. This cannot be easily monitored, except perhaps by monitoring the RF output, which, after all, is the ultimate diagnostic. Still, axially shifting the tube can be cumbersome and time consuming.

Note that the tolerances and dimensions described above were for a 100 *GHz* RF source. This is still in the millimeter-wave regime. Devices in the THz frequency range are much more difficult, as the dimensions and tolerances scale with wavelength. It soon becomes clear that conventional fabrication and assembly processes may not be adequate for THz RF sources.

CCR is addressing several alignment issues by mounting the electron gun directly to the anode and circuit, independent of the vacuum envelope. Fig. 5 shows a model of this technique applied to the 100 *GHz* BWO. This technique allows verification of the alignment of the beam tunnel with the cathode before the tube is sealed. Once the anode, beam tunnel, and circuit are secured to the electron gun, no subsequent assembly or bonding processes impact this alignment. This does, however, require a flexible connection of the output window to the tube envelope. This is accomplished by welding the window sleeve to a bellows at the collector end of the tube and has the additional advantage of allowing a complete low power test of the RF beam line by connecting this assembly to a Network Analyzer. Consequently, both the electron beam line alignment and the RF beam line are fully verified prior to sealing the tube.

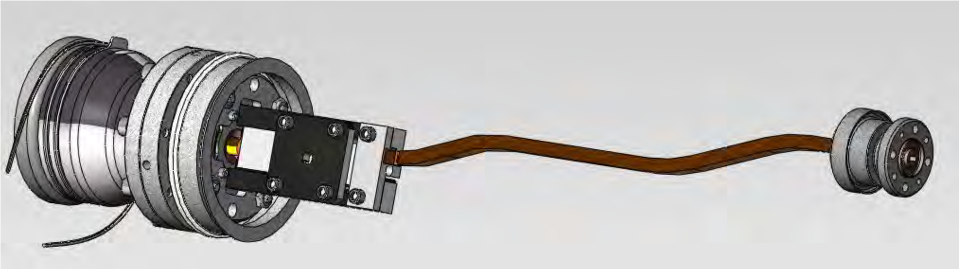

Fig. 5 Electron beam line for 100 *GHz* BWO

Fig. 6 shows application of this technique to a 650 *GHz* BWO. The electron gun is mounted to the RF circuit with standoffs and an insulator. A special fixture locates alignment pins to precisely position the cathode to the RF circuit. Once the cathode is securely mounted, flexible leads for the heater and accelerating voltage are connected to a high voltage feedthrough. This insures that the cathode is correctly aligned with the RF circuit, regardless of subsequent assembly operations to seal the tube.

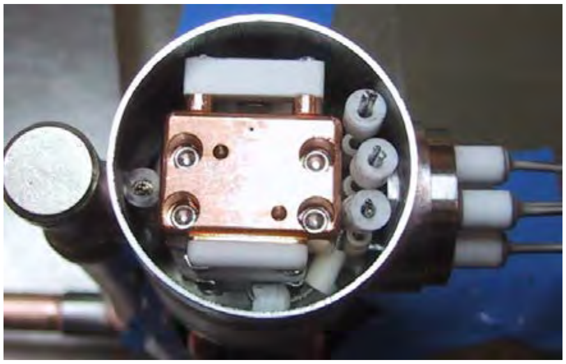

Fig. 6 Top view of a 650 *GHz* BWO showing the electron gun mounted to the RF circuit

4. Beam compression and magnetic field issues

Conventional cathodes are typically limited to emission current densities of less than 10 A/cm^2. Most devices requiring long life time are limited to 5 A/cm^2 or less. Most high power RF devices, however, require current densities from 30 A/cm^2 to more than 100 A/cm^2. This requires compression of the electron beam in the gun. In Brillouin focused devices, the magnetic field is shielded from the cathode and imposed after the electron beam achieves maximum electrostatic compression. This requires precisely matching iron structures and the magnetic field with the electrical and dimensional characteristics of the electron beam. This can typically be achieved to relatively high precision; however, the match between the beam characteristics and the magnetic field confinement is lost as the electron beam is bunched by the RF circuit. For high power devices, confined flow is usually employed to use magnetic field strengths significantly higher than for Brillouin focusing. This requires penetration of the magnetic field into the cathode – anode region and precise matching of the electric fields of the gun with the magnetic field profile. This becomes a much more challenging assembly issue. Even a slight axial mismatch between the electric field generated inside the tube to the magnetic field outside can cause major issues with beam quality and transmission.

While reducing the compression for confined flow guns significantly reduces beam quality issues, any compression at all requires precise axial alignment of the electric and magnetic fields. Fig. 7 shows a relatively low compression electron gun with the axial magnetic field slightly displaced from the optimum location. This results in reduced beam quality and potential degradation in the performance of the RF source.

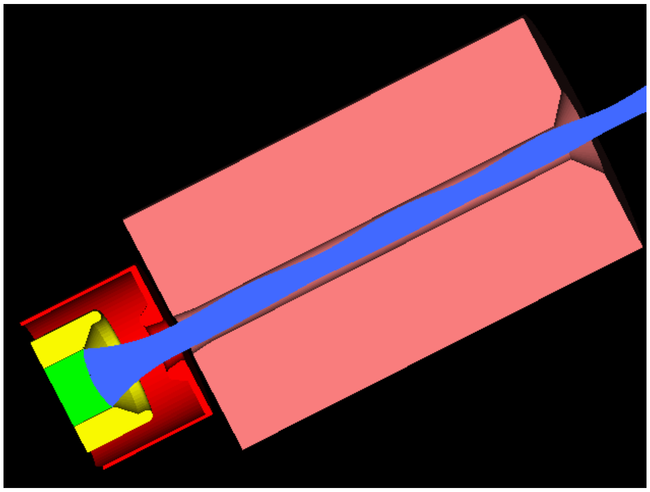

Fig. 7 Effect of mismatched electrostatic and magnetic field profiles in a confined flow electron gun. The magnetic field was translated 1/10 of the cathode radius upward, resulting in an asymmetric beam which nearly intercepts the anode.

High current density cathodes, such as those described in Section 2, can significantly reduce the severity of this problem. Fig. 8 compares the beam performance of an electron gun using cathodes with different current emission densities. As is readily apparent, the quality of the low compression beam is dramatically improved. This requires, however, an emission current density of 30 A/cm^2, which is beyond the acceptable limit for conventional cathodes. CPR or scandate cathodes, however, can easily meet this requirement.

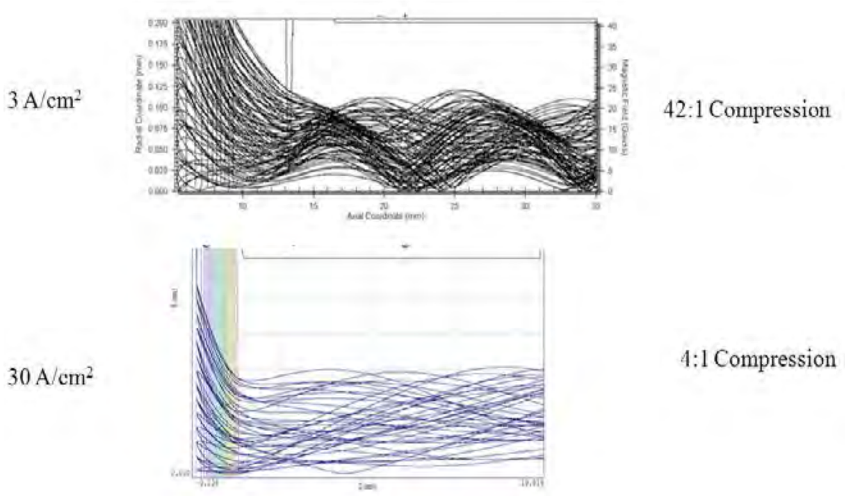

Fig. 8 Simulation of an electron gun for a 100 GHz, Brillouin focused backward wave oscillator

The ideal solution is to incorporate a zero compression electron gun. In this case the beam current density required in the circuit is provided directly from the cathode. Translational alignment of the electric and magnetic field becomes a non-issue, as the magnetic field becomes completely flat through the entire gun region.

This becomes particularly advantageous for multiple beam devices using confined flow. In existing devices with beam compression, complex iron structures shape the magnetic field profiles around the individual cathodes. This increases mechanical complexity, cost, and risk. It also significantly increases the time to design the gun. Figure 9 shows two beam trajectories for a 15-beam X-Band klystron using CPR cathodes at 31 A/cm^2 with no beam compression. The electron gun design required a few hours and there are no iron structures inside the klystron to shape the magnetic field. The entire electron gun resides inside a solenoid providing a flat magnetic field from the electron gun to the collector. No axial alignment of the fields is required, significantly simplifying installation and operation, as well as reducing cost.

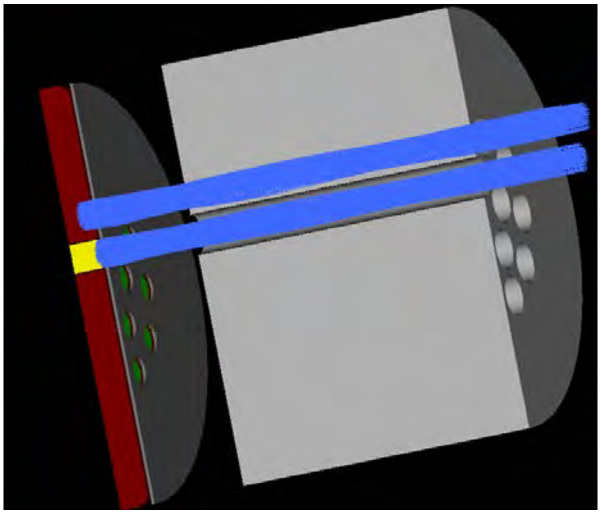

Fig. 9 Simulation of two of 15 beam in an X-Band klystron with no beam compression

Zero compression electron guns also do not usually require a complex focus electrode. Since these are not Pierce-type guns, the focus electrode can be a simple flat plate coplanar with the cathode. Not only does this reduce electric field gradients on the focus electrode, but it greatly simplifies assembly, since alignment of the focus electrode to the cathode is no longer as critical. This also becomes necessary, as higher electric fields at the cathode are required to achieve the higher emission current densities.

5. Summary

Traditional assembly processes are not directly applicable to assembly and implementation of electron guns in sub-millimeter and THz relevant electron beam devices. The high precision required eliminates many of the bonding processes and procedures used in lower frequency devices. Designs must provide for verification of alignment that is not impacted by subsequent procedures or processes. Alternatively, it is necessary to implement techniques to achieve alignment external to the vacuum envelope.

Alignment can be facilitated and beam performance improved using high current density cathodes that reduce or eliminate beam compression. CPR and scandate cathodes provide both high current density operation and long life. It is anticipated that these will become the cathodes of choice for high frequency RF sources.

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