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HIGH-CURRENT-DENSITY, HIGH BRIGHTNESS CATHODES FOR FREE ELECTRON LASER APPLICATIONS - A REVIEW

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M.C. Green

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For The Accelerator Group
Lawrence Livermore National Laboratory
Livermore, CA 94550

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1.0 Introduction

The recent advances in the devices known as free-electron laser, or FELS, have aroused the interest of the Strategic Defense Initiative because of the perception of their possible applicability to the area of ballistic missile defense.

The output radiation from a FEL resembles that from a true laser in that it has a narrow sharply peaked spectral distribution coupled with high phase coherence. However the combination of very high demonstrated conversion efficiency[1] together with the potential to transfer prodigious peak and mean powers to the radiation field sets FELS apart from ordinary lasers.

Relativistic electron beams with high current densities and low electron energy spreads are a prerequisite for successful operation of FELS. If high radiation powers and good interaction efficiency are required, high currents in addition to high current densities are a necessity.[2] These requirements become more and more stringent the shorter the radiation wavelength.[3]

High mean power levels imply high pulse repetition rates and FELS that address high duty cycle applications place particularly severe demands upon the present ability of electron accelerators to provide the necessary combination of high beam brightness and high peak and average beam current.

The electron source and injector are critical technologies in this area and cathodes with an intrinsic brightness capability of $> 2 \times 10^{11}$ A/(m^2 rad^2) at beam currents of several kiloamps are required for a number of presently planned devices.

2.0 Brightness and Emittance of Electron Beams and Cathodes

Brightness and emittance are two parameters used to measure the quality of an electron beam in terms of laminarity and energy spread. Brightness is the easier concept to grasp intuitively. It is defined as the beam current per unit cross-sectional area per unit solid angle,[4] with units of Amps/(meters)^2 steradians.

Emittance is a less obvious but in some respects more rigorous measure of the disorder of an electron beam in terms of the distribution of positions and momenta of the electrons. Unfortunately a great deal of confusion has occurred because authors in differing disciplines have used different definitions of emittance. This distressing situation has reached the point where the major laboratories working on high power FELS all use their own definitions of emittance. This renders comparison of data between the groups needlessly difficult.

In part this arises from the relatively non-intuitive nature of emittance as a measurement parameter. An extremely useful monograph has been written and circulated by Samuel Penner of the National Bureau of Standards (Appendix 1) which attempts to clarify the situation and proposes a common working convention for emittance and for the related quantity brightness.

A beam of particles may be regarded as distributed in a six dimensional phase space about an arbitrarily selected reference particle. Each particle will have coordinates x, x', y, y', ℓ, δE where x and y are space coordinates orthogonal to each other and to the local direction s of the reference particle. $x' = \frac{dx}{ds}$, $y' = \frac{dy}{ds}$, ℓ is the distance along s from the reference particle and δE is the energy difference between the particle and the reference particle.

This gives rise to an overall distribution function for the particles in a beam $f_6(x, x', y, y', \ell, \delta E)$. It is often desirable to characterize the distribution of particles by the separate transverse or longitudinal components of emittance and the three two-dimensional phase space distributions associated with f_6 are obtained by integrating over the other four dimensions.

The most commonly used definition for a two-dimensional emittance E is that $E = 1/\pi$ times the area in phase space (e.g. x, x') occupied by the particles in the beam. It is often useful to normalize this quantity by dividing the transverse momentum by mc where m is the particle rest mass and c is the velocity of light in vacuo.

This can be done by introducing a factor $\beta\gamma$ such that normalized emittance $E_N = \beta\gamma E$. βc is the velocity and γmc^2 the total energy of the reference particle.

The units of emittance are meter·radians. Unfortunately, as Penner points out, the factor $1/\pi$ is sometimes omitted from the definition of two-dimensional emittance. When the latter definition is used the factor π may or may not be written explicitly. Thus for example

$$E_x = 2 \times 10^{-6} \text{ meter radians} \qquad \text{(a)}$$

or $$E_x = 2\pi \times 10^{-6} \text{ meter radians} \qquad \text{(b)}$$

or $$E_x = 6.28 \times 10^{-6} \text{ meter radians} \qquad \text{(c)}$$

may all represent the same actual emittance, there being no way to distinguish (a) from (c) unless an explicit definition is provided.

At present the major laboratories working in this area all use normalized emittance but otherwise differ in their standard definitions. Penner reports that Lawrence Livermore uses (a), Los Alamos uses (b) and Boeing Aerospace uses (c). This situation coupled with the minor confusion generated by some results being expressed in centimeter radians as opposed to meter radians means that great caution must be employed when comparing emittance data from different sources.

A similar situation exists with respect to brightness (which may or may not be normalized by incorporating a $(\gamma\beta)^2$ term). Brightness may be defined as

$$B = \pi^2 i / V_4$$

where V_4 is the volume in four dimensional phase space occupied by the current i. The units of brightness are meters^2 radians^2. The volume V_4 has an associated factor of π^2 which, as with emittance, may or may not be explicitly included, thus introducing a potential order of magnitude uncertainty into the comparison of the results of different workers!

Brightness scales with current density which should therefore be explicitly stated when considering the "intrinsic brightness" of a cathode.

3.0 General Requirements for Cathodes in High Brightness Electron Guns

The first and most important requirement for a cathode for a high brightness electron injector is a low and uniform surface work function. This is a prerequisite for the cathode to be able to furnish a copious supply of electrons by thermionic or photoemission with a reasonable input of energy. (Cathodes based upon emission from a plasma cloud constitute a special case since the plasma, which has effectively zero work function, may be generated by voltage breakdown of a high work function material. However for other reasons which will be discussed in detail later in this review such cathodes are best suited to moderate brightness, high current, low pulse repetition rate applications.)

For high power FEL applications the following general criteria must be met by candidate cathodes. The cathode should be capable of a total emitted current of several kiloamps. (A present application requires 3 kA at 3 MeV from the electron gun). This requires that the cathode structure can be fabricated with a physically large diameter, possibly as large as 20 cm diameter depending upon the current density employed.

The cathode must be capable of supporting fully space-charged-limited emission current densities of several tens of A/cm^2. Current densities of $\geq 10^2$ A/cm^2 may be desirable for research purposes within the constraints set by the need to support the extraction field gradients required for these emission densities. It should be noted that the problem of voltage breakdown becomes more severe as the size of high voltage high current electron guns is increased.

In this context the cathode and its surrounding electrode surface should be able to support a voltage gradient of $\geq$ 120 kV/cm with pulse widths of 50-100 nsec. No degradation in emission quality, pulse droop etc. should be experienced over this time scale with pulse repetition rates of up to 5 KHz.

The intrinsic cathode brightness should be high, of the order of 2×10^{11} $A/meter^2$ $radian^2$ or better.

$$\text{Cathode brightness } B = \frac{1}{\pi^2} \frac{I}{R^2 \left(\frac{kT}{mc^2}\right)}$$

where I = current and R = cathode radius. The kT term in the denominator implies that the electron temperature in the cathode should be as low as possible to minimize the energy spread of the emitted electrons.

It must be possible to fabricate the cathode to precise dimensional tolerances which must be maintained under operating conditions. The Pierce gun configuration currently employed

for many high brightness linear electron beam sources requires a concave spherical cathode emitting surface. In a 3 MeV 3 kA injector this would be of radius 25-100 cm for focussing purposes. The electrode and cathode spacings must be precisely maintained in the gun in order to minimize spherical and other optical aberations which degrade brightness.

At high current densities the cathode surface must be capable of being manufactured with a very smooth finish (roughness $\approx$ 0.1 μm) to prevent "punch through" of the space charge cloud above the cathode surface leading to localized areas of temperature limited emission. Electrons from these regions would experience little or no space charge smoothing with a resulting drastic increase in energy spread.[5,6,7]

Finally a practical cathode should ideally be capable of operating in a moderate vacuum (10^{-6}-10^{7} torr) rather than an ultra high vacuum environment, should have an operating lifetime of hundreds of hours or more and if possible be reusable after air exposure if the injector system is dismantled for servicing or modification.

4.0 Candidate Cathode Types

A considerable number of different cathode types based on a variety of different emission mechanisms have been suggested, and in some cases tested, as potential high brightness high current electron sources for use in FELs.

The following general types of cathodes which encompass all the realistic emission sources for high current FELs will be reviewed in more detail. These are plasma and field emission cathodes, oxide cathodes, lanthanum hexaboride, laser driven thermionic and photocathodes and impregnated tungsten dispenser cathodes.

5.1. Plasma and Field Emission Cathodes

When an intense electric field is applied across the gap between two conductors in vacuum a current of electrons is drawn from local regions of the cathode. This current is observed to flow at electric field strengths 100-1000 times smaller than is consistent with the basic theories of field and Schottky enhanced field emission applied to the electrode as a whole. For sufficiently high field strengths the heat generated at these points of local breakdown vaporizes and ionizes material from the cathode resulting in the formation of local plasma flares. These plasma flares have surfaces of essentially zero work function from which macroscopic currents may be drawn. Energy from the hot plasma couples to the cathode surface heating it further. In time more and more regions of the cathode are "turned on" until the plasma surface covers the entire surface of the cathode. At this point the current drawn from the cathode is generally described by the space charge limited flow from the entire cathode area.

With further passage of time the plasma surface expands rapidly towards the anode reducing the space charge limited impedance of the gap (or in the case of an electron gun increasing the microperveance) until the gap is completely shorted by the plasma. In typical intense beam diodes with electric fields at breakdown of $\sim$ 1 MV/cm, initial turn-on occurs in a few ns, complete plasma formation requires 5-20 ns and the plasma expands with velocities of 2-3 cm/μs, (this is the so-called closure rate).

The area of explosive emission cathode plasmas in relativistic electron beam diodes has been well reviewed by Hinshelwood[8] in a 1985 report.

This type of plasma cathode is generally referred to as a field emission cathode because of the assumed mode of initial voltage breakdown from field emission sites or whiskers on the surface. However a strong minority opinion holds that plasma generation is initiated by explosive dielectric breakdown of surface dielectric inclusions due to charging.[9,10,11,12]

This type of cathode has the advantages of cheapness, simplicity, and tolerance of poor vacuum. These cathodes can be fabricated in large diameters. Multi-kiloamp currents can routinely be drawn.

However the intrinsic brightness of this cathode type is at best moderate. The electron source is a plasma cloud with an electron temperature in the region 1-10 eV. This introduces a large electron energy spread in the emitted electrons.

The plasma cloud with its multiple initiation points constitutes a temporally varying, spatially non-uniform source. As the plasma expands the effective spacing of the gun electrodes changes drastically. There is in addition temporal uncertainty

in the pulse risetime arising from the delay associated with the initial breakdown.

A variety of techniques have been devised to improve the breakdown characteristics of the cathode surface and particularly the spatial uniformity of the plasma cloud. An ingenious method, although now of historical interest only, was the use of "spark board" cathodes" at LLNL[13] where a printed circuit was patterned with a large number of annular electrode pairs and breakdown was initiated almost simultaneously at a large number of different sites by applying a voltage pulse to these electrodes to initiate lateral dielectric breakdown across the surface of the board.

More recently good results have been obtained with "felt" cathodes where many microfibers provide a large number of sites for either field emission or dielectric breakdown.

However at best these cathodes are capable of brightnesses in the 10^8-10^9 A/m^2 rad^2 region[14] and brightness does not remain constant during the pulse.[15,16]

A further limitation of these cathodes is the need to allow the plasma cloud to clear from the cathode to anode gap before the device can be pulsed again. This severely limits the pulse repetition frequency. Typically rates of the order of a few Hz are employed.

In addition the total number of pulses which can be drawn from a plasma or field emission cathode is limited to a few thousand pulses before the breakdown characteristics become too degraded by destruction of the initiation sites many of which are vaporized with each pulse.

This cathode is not therefore a candidate choice for high brightness high p.r.f. high duty cycle applications.

5.2 True Field Emission Cathodes

It should be noted in passing that extremely high brightness electron sources can be made from individual field emission tips where electric field enhancement at a very small radius refractory metal emitter tip can generate local emission current densities of 10^6-10^7 A/cm^2. The small tip radius results in a total tip current limited to the microamp range by ohmic heating of tip material. Such cathodes are used as very high brightness electron sources in electron microscopes.

Recently microcircuit fabrication techniques have been used to construct planar arrays of many thousands of closely spaced field emission tips aligned with apertures in a gate electrode which serves as the extractor electrode to draw field emission from the tips.[17]

These field emission arrays show promise for the future of being able to provide low energy spread electron sources operating at tens or hundreds of A/cm^2 and switchable with fast rise and fall times with a voltage swing on the gate electrode of the order of 250 V.[18]

However the manufacture of large area field emission cathodes is still some years in the future. Currently small area arrays of 10^4 tips can be made and although high current densities can be obtained total currents are still in the milliamp region. The problem of fabricating these cathodes with curved surfaces together with difficulties arising from sensitivity to voltage transients causing tip failure remain to be solved.[19]

5.3 Oxide Cathodes

Oxide cathodes have been known for more than fifty years. They are still probably the standard thermionic electron source in research r.f. linacs and for some years in the 1950s and 60s they were the workhorse cathode of the microwave tube industry. They are still manufactured in enormous numbers for cathode ray tubes in oscilloscopes, displays, monitors and domestic television receivers.

The oxide cathode consists of a metal (usually nickel) sheet curved into the desired electrode shape for the cathode and coated with a thin layer of barium strontium calcium carbonate. A resistance heater is provided to raise the cathode temperature to 800-1000°C.

When heated in vacuo the "triple carbonate" loses carbon dioxide which is pumped away and generates a layer of mixed oxides of barium strontium and calcium. Slight reduction of the barium oxide occurs, sometimes enhanced by "promoters" alloyed into the nickel base which abstract oxygen. This generates a small excess of metallic barium in the oxide layer which as a result becomes a low work function semiconductor electron emitter.[20]

The work function of the oxide layer activated by excess barium is low enough (~1.7 eV) to provide pulsed thermionic emission current densities of up to 50 A/cm^2 at readily attainable cathode temperature. The oxide cathode is cheap to manufacture, commercially available and can be fabricated in large diameters.

Unfortunately the intrinsic brightness of the oxide cathode falls rapidly with increasing current density. This arises because the thickness of the oxide emitting layer is of the order of .005 inches and the activated oxide has significant ohmic impedance. This limits the d.c. emission density of the oxide cathode to approximately 0.5 A/cm^2. Above this current density resistive heating causes thermal destruction of the oxide layer. At higher current densities this can be prevented by progressively reducing the pulse width and duty cycle. However at current densities of tens of A/cm^2 a substantial voltage gradient exists across the oxide layer. This gives rise to voltage variations from point to point across the cathode surface which imposes an equivalent energy spread on the emitted electrons thus degrading the cathode brightness.

5.4 Lanthanum Hexaboride Cathodes

Lanthanum hexaboride is an interesting material in that it has been found to behave as a moderately low work function bulk emitter. The low volatility of LaB_6 permits it to be heated in vacuo to 1750°-2000°K. At 1900°K the evaporation rate is of the order of 10^{-8} gms/cm^2/sec and an emission current density of 8-10 A/cm^2 can be drawn.[21] At higher temperatures current densities of several tens of A/cm^2 can be obtained. These high temperatures are necessary because the work function of even the lowest work function crystal plane (the (310) plane)[22] of LaB_6 has been measured at 2.50 eV.

Polycrystalline LaB_6 material has some problems of stability and reduced brightness due to the spread of work functions (2.5-3.2 eV) between the different exposed crystal planes and the growth of some planes at the expense of others during cathode operation.[23] Single crystals can be grown and are commercially available in diameters of 3-5 mm.[24,25] Impressive brightness figures have been obtained from pointed single crystal LaB_6 emitters in the thermionic triode electron guns used in electron microscopes.[26]

Brightness values as high as 1-2 x 10^{11} A/m^{2}rad^2 at emission current densities of 40-50 A/cm^2 have been reported[27] for small LaB_6 single crystal emitter tips operating at about 2070°K. At this temperature cathode life is very short, however at lower current densities lifetimes of more than 1000 hours have been obtained with operating temperatures of 1800-1900°K. Several groups report[28,29,30] brightness figures of 0.8-1.0 x $10^{1?}$ A/m^2 rad^2 under these conditions. It should however be noted that electron microscope guns typically deliver beam currents of much less than a microamp, a very different operating regime from the kiloamp requirements of high power F.E.L.s.

The high required operating temperatures present problems in using LaB_6 since at elevated temperature it is highly reactive chemically towards almost all support materials. The least incompatible materials are carbon and rhenium. Heater power (and life) also present engineering problems at these temperatures.

LaB_6 as a bulk emitter is capable of emitting electrons under conditions of intense ion bombardment. Destruction of the surface simply exposes more material although generally with perturbed stoichiometry which somewhat increases the work function. For this reason large polycrystalline LaB_6 cathodes have been used in high power gas discharge based lasers and in ion sources. In the latter case ion plus electron current densities can be very high.

The largest LaB_6 cathodes reported in the unclassified lierature have probably been fabricated by Leung at Lawrence Berkeley. He reports that simple bar type large area LaB_6 emitters tend to fracture in operation due to a combination of the high co-efficient of thermal expansion, the high required

operating temperature and the brittle ceramic like mechanical characteristics of LaB_6.[31] However Leung has successfully fabricated and operated a massive tapered LaB_6 filament 10 cms long and varying in width from 0.5 to 1 cm, cut from a LaB_6 plate in the form of a double hairpin zig-zag to accommodate the stresses due to thermal expansion.[32]

He has also successfully fabricated and operated a thin walled cylindrical LaB_6 cathode 1.1 cms in diameter and 3.5 cms long with an emitting area of 13 cm^2 in an ion source.[33] This latter cathode operated at 2000°K, with a combined ion and electron emission current density of 100 A/cm^2 under a high pressure of cesium vapor. Brightness is not a meaningful quality in this regime but it is noteworthy that such a large LaB_6 cathode can be fabricated, and adequately mechanically supported at operating temperature in a practical device.

Notwithstanding their high current density capability it is clear that LaB_6 cathodes are not optimum as high brightness emitters in very large electron guns. There are three reasons for this. First LaB_6 emitters over $\sim$ 0.7 cm in diameter presently have to be made from polycrystalline material. Even if large single crystals were available the concave cathode surface in a Pierce gun would expose several different crystal planes with a substantial spread of work functions. Second, at 2000°K the electron energy spread is of the order of 0.2 eV, approximately double that of alternative thermionic emitters capable of operating closer to 1000°K. Third, due to the high required operating temperature coupled with the brittle nature of LaB_6, thermal expansion stresses present severe problems for large area cathodes.

Leung has successfully fabricated a 5 cm diameter planar disk LaB_6 cathode which could potentially be ground into a concave spherical shape suitable for a Pierce gun. However he considers that for diameters larger than this would be necessary to cut spiral or zig-zag channels completely through the material in order to divide it into the equivalent of thin strips to accommodate stresses due to thermal expansion.[34] Such channels would not be desirable in a Pierce gun cathode as they would perturb the extraction field at the surface. Field penetration into the grooves would introduce an unacceptable amount of translaminarity into the emitted electron trajectories with a serious sacrifice of brightness.

5.5 Laser Driven Thermionic Cathodes

A novel approach to the problem of generating short pulses of high current cathode emission with high intrinsic brightness has been pursued by Oettinger and co-workers.[35] By rapidly heating the surface of either a smooth cesiated tungsten plate or an actual B-type impregnated porous tungsten dispenser cathode with a Q-switched Nd:glass laser they were able to generate pulses of space-charge limited thermionic emission at several tens of A/cm^2 over a time scale shorter than that of the thermal desorbtion of the activator layer (Cs or Ba) from the irradiated cathode surface.

This technique seems unlikely to lead to a FEL cathode capable of operating at high pulse repetition frequency since some hundreds of nanoseconds after the onset of the thermionic emission a second current pulse was observed due to plasma formation via thermal desorption of cesium or barium atoms from the cathode surface. Probably because these plasmas were largely composed of heavy metal ions their closure velocities were relatively low, (0.17-0.4 cm/μsec for Cs).

This experiment is of value however because of the insight it gives into the desorption behavior of cesium under intense laser irradiation, which is directly relevant to laser driven photocathodes. It also raises the possibility of switching the beam in synchrony with the incident laser pulse, in this case by rapid thermal cycling of the cathode surface.

In cathodes where work function reduction is accomplished by the presence of a polarized layer of an alkali or alkaline earth metal chemisorbed to the surface of a higher work function metal the lowest surface work function is obtained with a sorbed layer of cesium (or cesium and oxygen). Cesiated tungsten can have a work function as low as 1.6 eV rather than the 4.5 eV average of clean tungsten. Due to the smaller atomic radius and lower polarizability of barium a barium/oxygen coating on tungsten only lowers the work function to around 2.0 - 2.1 eV. Notwithstanding this, in conventional thermionic emission it is possible to draw much higher current densities from a barium activated tungsten surface than from its cesium activated counterpart. This is because the cesium is relatively weakly bound with an activation energy for desorbtion of 2.05 eV as opposed to 3.5 eV for barium. Hence the barium coated surface can be heated to a higher temperature than the cesiated surface before the activating metal desorbs. This temperature differential is more than sufficient to compensate for the difference in work function, due to the exponential dependence of emission current density upon temperature.

5.6 Laser Driven Photocathodes

Some electron accelerators used to drive FELs require trains of very short ($\lesssim$ 50 ps) current pulses with very high repetition rates (many MHz) and with high peak brightness. (See Section 6.0). Photocathodes illuminated by intense light pulses from a mode locked laser are potentially capable of filling this need.

The process of photoelectric emission from a conductor into the vacuum involves the following three steps:

(i) absorption of incident photons and transfer of their energy to the electrons (excitation of photoelectrons).

(ii) movement of the photoelectrons from the excitation site to the photocathode-vacuum interface.

(iii) escape of the electrons through the interface into the vacuum.

For making an efficient photocathode, the highest possible efficiency is required for each of the three stages. In an ideal photocathode each incident photon should excite an emitted electron to provide a quantum yield of 100%. In reality the quantum yield never exceeds 50% and more typically ranges from $\sim$ 10% down to $< 10^{-4}$% for some metals.[36]

5.6.1 Pure Metal Photocathodes

Metals are characterized by high optical reflectivity which prevents the penetration of the majority of the incident photons. Photoelectrons generated in metals are particularly susceptible to transport losses because of the high probability of collision with free electrons. Finally the work functions of most metals are high, reaching 4-5 eV in some cases.

Notwithstanding these unfavorable attributes and the resulting extremely low quantum yields clean metal surfaces are very robust. They can absorb high incident laser powers and can operate with little or no degradation in vacua as poor as 10^{-5} torr.

Current densities of up to 170 A/cm^2 have been claimed by Sherman et al. for a magnesium photocathode illuminated by 2 picosecond pulses of 313 nm uv light from a frequency doubled dye laser illuminating an area of 0.05 cm^2 with peak power of $> 10^7$ watts.[37] Peculiar effects were experienced due to the short pulse width, which was shorter than the electron transit time. A very low extraction field gradient of 0.5-2 kV/cm was reportedly used by these workers.

In experiments by workers from Los Alamos and the Naval Postgraduate School where an ArF excimer laser was used to illuminate a 3 cm^2 copper photocathode with 15-30 nsec pulses of 193 nm uv light at 2-3 Hz. 70 A/cm^2 space-charge limited emission was obtained with an extraction field gradient of 100 kV/cm.[38] The current pulse closely matched the temporal profile

of the laser pulse. A peak laser power density of 4×10^6 watts/cm^2 was employed corresponding to 100 mJ/cm^2 per pulse.

In terms of potential FEL applications the low quantum yield of pure metal photocathodes sets unacceptable limits on the attainable pulse repetition rate except for short pulse trains. Thus at a 5 kHz p.r.f. with a 50 nanosecond pulse width (which is one of the specific applications requirements against which cathodes are being judged in this review) the copper photocathode surface described above would rapidly exceed the melting point of the material even if state of the art cooling techniques analogous to those used for the copper electron collectors of high power microwave tubes were employed. A multikilowatt average output power laser would also be required.

5.6.2 Negative Electron Affinity Photocathodes

The proportion of the incident laser power dissipated as heat in the photocathode surface is a function of the reflectivity and quantum yield. The highest available quantum yield photocathodes are fabricated from heavily p-type doped semiconductors activated by a monolayer of cesium and oxygen[39] (or fluorine). Monocrystalline p-type GaAs of other p-type III-V compound in the form of semiconductor wafers or epitaxial layers are typically used and such cathodes can exhibit quantum yields of tens of percent.

These structures have very long photoelectron mean free paths and hence escape depths of the order of 1 μm. Band bending at the surface by the cesium dipole layer reduces the surface barrier to zero or more usually to a negative value. These photocathodes therefore possess negative electron affinity (NEA) and are known as NEA emitters.

Single crystal (100) GaAs cesiated NEA cathodes have been investigated for use in the lasertron by Sinclair[40] and by Springer and co-workers at Los Alamos for use in FELs.[41] Sinclair has extracted emission current densities of up to 180 A/cm^2 using light pulses from a mode locked Nd:YAG laser.[42]

These cathodes are essentially cold emitters. Hence the thermal contribution to the electron energy spread is small.

However the features of these cathodes which give rise to the very high attainable quantum yields result in engineering tradeoffs which cast in question the suitability of these cathodes for use in practical high average power devices.

Firstly the large escape depth of the active layer of these cathodes gives rise to an intrinsic emission-time uncertainty. This has been measured to be in the range from 8 to 71 picoseconds for active layers between 50 nm and 2 μm in thickness.[43]

Second, defect-free single crystal III-V substrate material is not yet available commercially with the quality consistently

high enough to reproducibly fabricate high quantum yield cathodes. Quantum yield variations of .1-9% from wafer to wafer are typical. Large point to point quantum yield variations on individual wafers make the fabrication of large area cathodes particularly difficult.

Third, and perhaps most serious, the negative electron affinity of these cathodes derives from the presence of a sorbed monolayer of cesium and oxygen. Cesium is exceedingly reactive chemically towards electronegative species. It therefore vigorously getters a variety of residual gases in tne vacuum environment of the cathode. This process destroys the dipole structure of the Cs/O(F) surface layer which is vital to the NEA effect. In addition cesium is rather weakly bound to the cathode surface and tends to desorb slowly even at room temperature.

Since there is only a monolayer of cesium available at the cathode surface this type of photocathode shows steady degradation even in an ultrahigh vacuum environment (>30% performance loss after 20 hours at 10^{-10}-10^{-11} torr) unless the surface is periodically reformed from an external cesium source. NEA cathodes are thus extremely fragile and require a working vacuum environment in the $< 10^{-10}$ torr range plus the provision of a cesium channel and O_2 or NF_3 sources for cesium replenishment and reactivation.

The gettering of residual gases is probably the dominant degradation mechanism in NEA photocathodes, however cesium desorbtion might take over at high pulse repetition rates where more average energy would be dissipated in the photocathode surface. The high conversion efficiency of these cathodes reduces the proportion of the input energy lost as heat however.

Cesiated III-V semiconductor NEA cathodes as presently fabricated have very smooth surfaces. They are planar not curved (they are based on single crystal wafers obtained from suppliers to the microwave and high speed microcircuit industry). However it should be noted that at sufficiently high emission current densities a planar cathode could in principle be used in a high brightness electron gun with zero initial electrostatic convergence.

Their voltage hold-off characteristics are not yet well known. However the inevitable presence of a small partial pressure of cesium is a cause for concern here because of the reduction in the work function of the other electrodes in the gun due to adsorbed cesium which increases the magnitude of field emission currents flowing from incipient breakdown sites. The very narrow effective pulse widths which would be employed in r.f. linac applications of these cathodes tend to somewhat delay the onset of voltage breakdown problems as a general rule. However. it is likely that the maximum voltage gradient that could be supported would be reduced in a cavity containing a cesiated NEA emitter.

5.6.3 Cesium Antimonide Photocathode

Compounds composed of alkali metals and antimony form semiconductors with good photoemissive properties. The multialkali Cs-Na-K-Sb system discovered by Sommer[44] (the S-20 photocathode) is widely used commercially in photomultipliers etc. Recently the earlier binary composition Cs_3Sb (the S-11 photocathode) has been investigated as a potential electron source for use in r.f. linacs.[45]

Cesium antimonide photocathodes are positive electron affinity photoemitters. The material has a photoelectron escape depth of a few nanometers.[46] The quantum yield of Cs_3Sb photocathodes is therefore substantially lower than that of the NEA III-V photocathodes, being in the range 1-3%, however the shallower escape depth of Cs_3Sb essentially eliminates the emission time jitter of the NEA emitter. The quasi-bulk emitter structure of the Cs_3Sb material renders it somewhat less sensitive to ambient vacuum conditions.

The spectral response of Cs_3Sb extends from λ = 640 nm (1.98 eV photons) to λ < 320 nm (> 3.8 eV photons). This material can therefore be used with a frequency doubled Nd:YAG laser (λ = 532 nm) which can be Q-switched to generate short intense light pulses or modelocked to deliver trains of very short pulses at very high pulse repetition frequency.

P. Oettinger and co-workers[47] have developed prototype laser driven Cs_3Sb photocathodes in this country. They have achieved peak current densities of up to 200 A/cm^2 from a 1 cm^2 photocathode irradiated with single 50 nanosecond pulses from a Nd:glass Q-switched laser. The energy spread for Cs_3Sb photoelectrons generated by 532 nm irradiation is approximately 0.2 eV,[48] which sets a minimum value to the transverse energy spread of the beam. Recently Oettinger has measured a normalized brightness of 10^{11} A/m^2 rad^2 at 80 A/cm^2 from a Cs_3Sb cathode.[49]

Investigators at the University of Tokyo[50] have also obtained promising results, generating a train of 35 picosecond pulses with a peak current density of 75 A/cm^2 and a pulse repetition frequency of 2884 MHz by irradiating a 1.33 cm^2 Cs_3Sb photocathode. (The high p.r.f. was obtained by etalon upconverting a modelocked Nd:YAG pulse frequency of 169.6 MHz).

Springer and co-workers at Los Alamos have tested Cs_3Sb photoemitters in an r.f. accelerating cavity capable of generating a peak surface field of 60 MV/meter at 1300 MHz. They report an average normalized beam brightness of 4.2 ($\pm$ 20%) x 10^{10} A/m^2 rad^2 with extraction currents of 100-150 Amps and a best brightness value of 9 x 10^{10} A/m^2 rad^2 with a peak current of 100 Amps, corresponding to a calculated current density of 600 A/cm^2 based on the area of the photocathode illuminated by the laser beam.[51]

This is a noteworthy result, particularly as the electrons were accelerated to 1.1 MeV in the cavity before the beam brightness measurement was made. The current pulses were about 55 picoseconds in length, generated by a train of 53 picosecond 532 nm light pulses from a frequency doubled Nd:YAG laser cavity modelocked at 108.33 MHz. A Pockels cell gated the laser output to give bursts of 108.33 MHz pulses with a maximum length of 20 μs at an overall 1-Hz repetition rate.

Cesium antimonide photocathodes are fabricated in situ by evaporating alternating layers of Cs and Sb onto a substrate (typically nickel plated copper) held initially at 130-150°C. There is some trial and error involved in this procedure and it is usual to illuminate the cathode surface with low intensity white light and monitor the photo current while adjusting the deposit composition for maximum quantum yield. A vacuum of better than 10^{-9} (preferably 10^{-10}) torr is necessary for this procedure.

For experiments in which high extraction fields will be applied to Cs_3Sb photocathodes the cathodes have typically been fabricated in a separate UHV preparation chamber and then moved under UHV conditions through a sample transfer line into the main experimental chamber or electron gun. The whole system including the experimental chamber must be bakeable as a unit to 200-250°C in order to achieve the low background pressure required.

A separate preparation chamber is used to form the Cs_3Sb layer, partly to minimize the amount of cesium deposited upon high voltage insulators and electrode surfaces in the experimental chamber which would otherwise exacerbate the problems of high voltage breakdown. Unfortunately this procedure of transference from the cesium evaporation chamber is known to produce cathodes which are as a rule rather unstable with time and in operation, generally exhibiting a continuing reduction in quantum yield.[52] This is because of the strong tendency of cesium to desorb from the cathode. At room temperature the rate of loss of cesium from a cesium antimonide photocathode which is in an "alkali-metal-free" vacuum environment has been found to be of the order of 5×10^4 atoms/cm^2/sec.[53] However if a Cs_3Sb photocathode degrades to too great an extent it can be reformed in vacuo after returning it to the preparation chamber, by first heating the substrate to 400°C, which evaporates all the cesium and antimony and erases the cathode and then cooling to 130-150°C whereupon a new cathode can be constructed on the cleaned substrate.

Cs_3Sb photocathodes represent a different set of engineering compromises from the negative-electron-affinity cesiated III-V semiconductor photoemitters. They are somewhat less sensitive to the vacuum environment (although still requiring pressures below 10^{-9} torr), suffer much less pulse broadening due to photo emission time jitter and are considerably easier to fabricate. They can be made on curved substrates and they can generate

impressive emission current densities with low electron energy spread.

The engineering tradeoff for these advantages is the relatively low quantum yield. The preparation conditions described above routinely result in quantum yields of 1-2% for a 1 cm^2 Cs_3Sb cathode. (Uniformity of quantum yield from point to point over larger area cathodes is still a problem.)

The quantum energy of frequency doubled Nd:YAG laser light at 532 nm is 2.3 eV. The incident peak laser power required to generate a photocurrent of I amperes is

$$P = 2.3\ I/(\text{quantum yield}).$$

For a nominal quantum yield of 1% a current density of 100 A/cm^2 requires a peak incident power density of 2.3×10^4 watts/cm^2.

The phase angle constraints of r.f. linacs limit the width of the electron bunches to approximately 3^o. This implies a maximum duty cycle of ~1%. Running at this duty cycle with a peak current density of 100 A/cm^2 a Cs_3Sb photocathode would receive an average incident laser power density of the order of 2.3×10^2 watts/cm^2. Of this, 1% would be removed as photoelectrons and approximately 30% would be reflected leaving 160 watts/cm^2 to be dissipated in the photocathode surface.

Heating of the Cs_3Sb surface to quite moderate temperatures leads to rapid evaporation of cesium with resulting reduction in quantum yield and the danger that a cesium plasma cloud will form leading to uncontrolled electrical breakdown in the gun. The upper operating temperature limit for a Cs_3Sb photocathode is probably 100-120°C. A highly conductive well-cooled substrate will be required to avoid exceeding this if the average power input is increased from its present low levels.

5.7 Impregnated Porous Tungsten Dispenser Cathodes

Impregnated tungsten matrix dispenser cathodes were developed in the 1950s[54] to serve the needs of the microwave tube industry which was suffering from engineering constraints imposed by the current density limitations of the oxide cathode. In the context of this review the key features of the dispenser cathode are that it uses barium rather than cesium as an activator for the emitting surface and that in operation it continuously regenerates the work function reducing layer by dispensing a supply of barium atoms which diffuse from the underlying matrix via millions of micropores opening onto the emitting surface. These pores might, in photocathode terms, be considered analogous to millions of minute cesium channels with their orifices actually in contact with the cathode surface.

The strong binding of barium to certain high work function metal surfaces means that a dispenser cathode can be heated to elevated temperature in vacuum (1000°-1100°C at which temperature cesium would rapidly be lost) without excessive desorption of the activator layer.[55] Such barium as does evaporate is immediately replaced by dispensation from the matrix in a continuous dynamic equilibrium. At these temperatures high current densities can be drawn from advanced dispenser cathodes.

The superior performance and reliability of the dispenser cathode has made it the standard cathode for the microwave tube industry. Ninety percent of the hundreds of millions of dollars worth of microwave tubes shipped in the USA each year contain dispenser cathodes. Large numbers of dispenser cathodes are also used in argon and krypton ion lasers (where they operate under conditions of intense ion bombardment) and in the xenon arc flash lamps used to pump Nd:YAG and Nd:glass laser rods. In flashlamps combined ion and electron current densities at the cathode can reach tens of thousands of A/cm^2. However brightness is not a meaningful parameter under these circumstances which differ substantially from those pertaining to electron emission in vacuum.

The military importance of microwave tubes has prompted all three Services to allocate funding to dispenser cathode development. During the past seven years much effort has been devoted to the study of the operating mechanisms of dispenser cathodes and their detailed physics.

Areas such as matrix and impregnant chemistry,[56,57] barium transport,[58,59] matrix materials,[60] emission enhancing metals and alloys,[61-65] the micro structure of the barium/oxygen activator layer,[66-72] the poisoning effects of residual gases,[73-76] the achievable lifetimes at various current densities etc.[77-79] have been investigated in depth. As a result of the understanding gained it has become possible to design improved cathodes on the basis of engineering knowledge rather than empiricism. Parameters may be controlled and tailored for specific operating requirements e.g. ultra long life at moderate current density for a downlink transmitting tube in an earth satellite or maximum ion

bombardment resistance during high current density c.w. operation in a travelling wave tube used for electronic warfare.

The impregnated tungsten dispenser cathode was first reported by Levi[80] in 1953 and was a natural derivative of the so-called L-cathode developed earlier by Lemmens and co-workers.[81] The L-cathode was capable of c.w. cathode current densities at least an order of magnitude higher than an oxide cathode, although at the rather high temperature of 1250°C, with a life of some 2000 hours. Originally the impregnated cathode, containing a barium oxide/alumina melt, gave roughly a factor of five lower current density than the L-cathode; however Levi[82] found that by adding calcium oxide to the impregnant the current density capability could be made comparable to that of the L-cathode. This embodiment constituted the Philips B-type cathode with an impregnant mix of 5 BaO:3 CaO:2 Al_2O_3.

The basis of the emitter of the typical impregnated cathode today is essentially unchanged from Levi's development. It consists of an indirectly heated porous tungsten matrix fabricated from 4-5 μ average grain size powder, which is isostatically pressed and sintered to give an overall porosity of around 20% with good pore interconnectivity. The tungsten pellet is impregnated with a melt of mixed calcined BaO-CaO-Al_2O_3 drawn into the pores by capillary action in an atmosphere of dry hydrogen. After activation in vacuum (10^{-6} torr or better) at 1150°C_B, the cathode is capable of 2 A/cm^2 at 1050°C_B, and ongoing life tests in excess of 70,000 hours exist at this current density.

Tungsten is an excellent material for formulating the framework of the bulk cathode matrix, due to its chemical reactivity and high temperature dimensional stability. However, it is now known that tungsten is not the optimum material for the actual emissive surface. For high-current-density operation the cathode surface must be modified to improve the binding of the barium oxygen dipole layer.

The simple concept of modeling the dispenser cathode as a two component system, these components being the activator generating "chemical factory" of the bulk matrix and the activator binding cathode emitting surface with its chemisorbed barium/oxygen dipole layer, has proved to be the key to improving dispenser cathode performance.[83] The two components considered in isolation can be separately optimized for their specific functions.

The basic tungten matrix dispenser cathode is limited to 2-4 A/cm^2 fully-space-charge-limited emission at acceptable operating temperatures. This is due to the imperfect binding of the barium/oxygen electric double layer to tungsten and to large local variations in the work function caused by differing activation of the various crystal planes of the individual tungsten grains exposed at the surface.

In the 1960s work in Europe focussed on the formation of superior emitting surfaces by sputtercoating tungsten dispenser cathodes with other metals. Rhenium, osmium and iridium surface layers were found by Zalm[84] to activate to a lower, more uniform work function than tungsten giving higher current density capability.

More recently improved understanding of the operating mechanism of dispenser cathode has led to an order of magnitude increase in emission performance.

Two factors were instrumental in this performance breakthrough:

1. Understanding and control of the effect of the sputtered surface film microstructure and composition upon work function.
2. The development of subsurface diffusion barriers to stabilize the sputtered surface film at the temperatures required for emission current densities of 100 A/cm^2 and above.

The primary requirement for dispenser cathode operation at very high current density is a uniform surface work function well below 2 eV. This permits cathode operation at temperatures low enough to prevent material limitations and barium evaporation rates from impacting excessively upon cathode operating life.

A substantial work function reduction can be achieved by employing alloy sputtercoatings with controlled composition rather than pure platinum group metals.

It has been found that variations in the ratio of osmium to tungsten in the surface coating of a cathode have a marked influence upon the surface work function achieved. For binary alloys the optimum composition lies in the range 50-60% osmium. A cathode with this coating composition is capable of providing nine or ten times the fully-space-charge-limited current density obtainable from an uncoated tungsten matrix dispenser cathode at the same temperature.

Ternary alloy coating compositions have been utilized to achieve very low work function dispenser cathodes with only a very small variation in work function from point to point across the emitting surface.

Surface uniformity becomes critically important at high current density because of the small spacing between the potential minimum and the cathode surface.[85]

At current densities between 10 and 100 A/cm^2 the space charge cloud above the cathode surface becomes comparable in thickness to the diameter of the surface pores. At 100 A/cm^2, the potential minimum spacing is of the same order as the micro roughness of the as machined surface.

Any surface discontinuities or patches of different work function must have lateral dimensions smaller than the potential

minimum spacing to avoid delaying the onset of fully-space-charge-limited emission.

This is difficult to achieve without careful control of the coating microstructure. A typical commercially-coated M-type dispenser cathode displays a highly variable coating grain structure and surface topography with visible pores, stress cracks, and local lack of adhesion. As a result of rapid diffusion of tungsten through cracks and along coating grain boundaries areas of the surface form patches of osmium tungsten alloy with an excessively high tungsten content which raises the local work function.

The coating microstructure can be considerably improved through critical control of the sputtering parameters. These include argon pressure, deposition rate, electrode voltages, substrate temperature, surface pretreatment, etc. By this means, a nearly ideal coating microstructure can be achieved with a very fine-grained film, with minimal residual stress and uniform alloy composition. Under the correct conditions, the sputtered film will form smooth permeable caps over the matrix pore mouths, thus minimizing the space charge cloud perturbation by surface discontinuities.

High resolution scanning Auger microscopy has shown no detectable composition variations on a lateral scale of 350 Angstroms for microporous coatings deposited under optimized conditions. Substantial preferential orientation of the crystallites in the sputtered film can be obtained, which further narrows the spread of work functions on the activated surface.

Techniques have been developed to stabilize the optimized surface composition and microstructure against changes resulting from alloying with the ulk matrix. These methods employ the introduction of a diffusion barrier layer into the matrix surface grains by enriching them with osmium or iridium by chemical and thermal pretreatment of the matrix before impregnation.[86]

Coatings fabricated with optimized surface coatings and subsurface diffusion barriers have been emission tested at $\geq$ 100 A/cm^2.[87]

Fully-space-charge-limited emission at 50 A/cm^2 was obtained at 1090$^{\circ}C_B$. The full space-charge limitation point at 100 A/cm^2 loading was attained at 1145$^{\circ}C_B$ with a 2 μsec pulse width. At these temperatures the thermal energy spread of the electrons is calculated to be less than 0.15 eV. Extremely sharp transitions between fully-space-charge-limited emission and temperature-limited emission were obtained even at 100 A/cm^2. This reflects the high degree of composition uniformity and the narrowness of the work function distribution of the crystallographically-ordered surface layer. In combination with the spacecharge smoothing of the electron velocities and spatial distribution which occurs during fully-space-charge-limited operation these

performance parameters are the key to the high intrinsic brightness potential of the alloy coated dispenser cathode.

The dispenser cathode's emissive layer is a chemisorbed electric double layer of barium and oxygen with an atomic monolayer order of thickness. This barium-oxygen atomic dipole layer has no measurable resistive impedance in series with that of the bulk matrix.

Therefore, extremely high current densities may be drawn from dispenser cathodes in good vacuum without activator layer destruction by ohmic effects. The lack of resistive heating in the cathode surface layer means that the dispenser cathode can be run at a high average duty cycle. Indeed, experimental experience has shown that under these conditions electron cooling (the so-called Nottingham effect) rather than ohmic heating in the matrix controls the cathode surface temperature.

The upper limits of dispenser cathode emission current density capability have not yet been explored. It seems likely that voltage breakdown[88] and electron cooling effects[89] will set limits rather than problems intrinsic to the cathode emissive surface. The 120 kV/cm operating field gradient criterion for this review is already routinely exceeded in microwave tube electron guns using dispenser cathodes with multimicrosecond pulse widths.

6.0 Choice of Best Performing Cathode Types

Two cathode types stand out from among those reviewed as having the most potential suitability for use in accelerators for FELs. These are the Cs_3Sb photocathode and the alloy coated impregnated tungsten dispenser cathode.

It is likely that due to the differing requirements of electron accelerators in terms of pulse width and pulse repetition frequency, each of these cathode types may be best suited to a specific variety of accelerator in application.

R.f. linacs require short pulses of current (a few tens of picoseconds in width) injected at a very high pulse repetition frequency. This arises because of the small phase angle of the r.f. field over which electrons can be accelerated without drastic loss of brightness.

These pulse widths and pulse repetition frequencies exceed the capabilities of grid switching techniques, which in any case tend to increase the spread of transverse momenta of the electrons as a result of grid lensing effects. Because of this it has been the usual practice to pulse a thermionic (oxide) cathode source at a subharmonic of the main linac frequency to generate relatively long pulses of current. These pulses are then temporally compressed in a klystron-like pre-buncher before being injected into the linac proper. Unfortunately this pulse width compression is obtained via velocity modulation and is therefore at the expense of an increased spread in longitudinal energy of the electrons.

The ability to "switch" a photocathode with picosecond current rise times in synchrony with the incident illumination and to generate intense pulses of photoemission current with an electron energy spread of the order of 0.2 eV makes them very attractive for use in conjunction with r.f. linacs. The availability of cavity mode-locked Nd:YAG lasers able to generate high peak power picosecond light pulses at the required p.r.f. renders the application of Cs_3Sb photocathodes as electron sources for high power linacs potentially feasible. Very impressive current density and brightness figures have been obtained at the 1 MeV level with short pulse trains from a Cs_3Sb photocathode in an r.f. cavity.

There are however a number of unknowns with respect to the use of Cs_3Sb photocathodes as high current density electron sources in full scale linacs operating at high average beam power. The primary area for concern is the need for an ultra high vacuum environment (better than 10^{-9} torr). This is difficult to achieve in such a situation.

The second potential problem area is the desorbtion of cesium from the cathode surface which takes place slowly even at room temperature. This will limit the cathode lifetime and means that the cathode must be kept very cool ($< 100\text{-}120^{\circ}C$) in

operation or it will simply evaporate. This will become increasingly difficult as the mean photon flux incident on the cathode is increased with increasing average power in the device.

Finally the desorbed cesium will coat metal electrode surfaces and insulators in the injector region and lead to an increased probability of high voltage breakdown. Multipactor generated secondary electron avalanches could also be a problem in an r.f. cavity due to the reduced surface work functions.

The alloy coated tungsten matrix dispenser cathode does not have the optical switchability of a photocathode, however it does have a number of performance advantages which render it the best candidate for operation in longer pulse width applications (tens of nanoseconds or greater) which would be better addressed by induction linacs.

The dispenser cathode is a well understood system based on a mature technology. Dispenser cathodes are manufactured in large numbers for linear beam microwave tubes and small commercial linacs for cancer therapy.

Dispenser cathodes are extremely robust. Their vacuum requirements are 2-3 orders of magnitude less stringent than those of photocathodes. This enormously eases the operating difficulties in large scale high power electron beam systems. Because of their internal barium generation and dispensation system dispenser cathodes are resistant to poisoning by residual gases and to some extent self repairing in use. With appropriate precautions they can be brought up to atmospheric pressure and reused after storage in dry nitrogen if it is necessary to demount them from the vacuum system of the injector while it is modified or repaired.

Dispenser cathodes can be made in large sizes, 17.5 cm dia cathodes are commercially obtainable. Sizes up to 25 cm dia could be made with minor modifications to existing fabrication equipment. They have excellent dimensional stability and can be machined to complex shapes and be highly polished.

Pulse width and duty cycle capabilities comfortably exceed the criteria for this review. 100 A/cm^2 fully-space-charge-limited emission current density has been demonstrated with 2 microsecond pulses. Duty cycle limitations are a function of electron cooling effects. However a 5% duty cycle at 100 A/cm^2 should be achievable with standard cathode heating techniques.

Barium evaporation rates from dispenser cathodes are low (10^{-9}-10^{-10} $gms/cm^2/sec$ at normal operating temperature) and the work function reduction caused by barium adsorbed onto adjacent electrode surfaces is less severe than with cesium. If required, electrode surface coatings which are extremely resistant to barium adsorbtion have been developed in the microwave tube industry.

Finally high brightness operation with 50 nanosecond pulses at kilohertz repetition rates has been demonstrated at 700 amps beam current using 3 1/2" diameter alloy coated tungsten dispenser cathodes in a full scale induction linac injector test stand at LLNL. The beam brightness of 1.3×10^{10} A/(m^2 rad_2) was measured after post acceleration to 1.5 MeV through several accelerator stages without emittance filtering.

7.0 Conclusions

The results of this review lead to the conclusion that Cs_3Sb photocathodes and alloy coated tungsten matrix dispenser cathodes have shown the best performance potential to date for high current density, high p.r.f., high brightness applications.

It is probable that the former cathode type would be more suitable for generating picosecond pulses with very high prf in an r.f. linac while the latter would be more suitable for the requirements of an induction linac with pulse widths of tens of nanoseconds and prfs of several kHz.

Cs_3Sb photocathodes are at a relatively early stage of development with respect to high current density high power applications, however short pulse current densities of hundreds of A/cm_2 have been drawn with excellent beam brightness under U.H.V. conditions. Their optical "switchability" makes possible the generation of short intense current pulses via Q-switched or mode locked laser irradiation.

Alloy coated dispenser cathodes are a more mature technology due to their widespread use in microwave tubes and medical accelerators. They can furnish fully-space-charge-limited current densities of > 100 A/cm_2. They do not possess the optical switchability of photocathodes, however they are thermally robust and can operate satisfactorily at pressures 2-3 orders of magnitude higher than those required by photocathodes. Very good beam brightness has been demonstrated in a full scale induction linac injector test stand using commercially obtained advanced alloy coated dispenser cathodes.

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Appendix A

DRAFT MONOGRAPH CIRCULATED BY S. PENNER

A Proposed Convention for Emittance and Related Quantities

Samuel Penner
National Bureau of Standards
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I. Introduction

The emittance of a particle beam is a measure of its disorder. A real beam contains particles with a distribution of energies, positions and transverse momenta. It is sometimes desirable to characterize the distribution of particles by just two numbers, the transverse and longitudinal emittance. A great deal of confusion has occurred because authors from various disciplines have used different definitions of emittance. A related quantity, beam brightness, has an even greater range of possible definitions. In this paper we compare a number of commonly used definitions of emittance and brightness, and suggest some standard definitions.

A beam of particles is distributed in a six-dimensional phase space about an arbitrarily-chosen reference particle. The distribution function is $f_6(x,x',y,y',\ell,\delta E)$ where x, y are the two space coordinates orthogonal to each other and to the local direction, s, of the reference particle. $x' = \frac{dx}{ds}$, $y' = \frac{dy}{ds}$, ℓ is the distance along s from some particle to the reference particle*, and δE is the energy difference between any particle and the reference particle. The three two-dimensional phase space distributions associated with f_6 are obtained by integrating over the other four dimensions, e.g.,

$$f_x(x,x') = \int_{y,y',\ell,\delta E} f_6(x,x',y,y',\ell,\delta E)\, dy\, dy'\, d\ell\, d(\delta E) \qquad (1)$$

and similarly for f_y and f_E.

The most commonly used definition of a two dimensional emittance is $\frac{1}{\pi}$ times the area in phase space occupied by the particles in the beam[1]. Sometimes the factor $\frac{1}{\pi}$ is omitted from the definition; when the latter definition is used the factor π may or may not be written explicitly. Thus for example

$$\varepsilon_x = 2 \times 10^{-6} \text{ meter radians} \qquad (a)$$

$$\varepsilon_x = 2\pi \times 10^{-6} \text{ m-rad} \qquad (b)$$

$$\varepsilon_x = 6.28 \times 10^{-6} \text{ m-rad} \qquad (c)$$

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*Alternatively, one could use time or phase instead of ℓ for the longitudinal coordinate.

1. J. D. Lawson "The Physics of Charged Particle Beams," Clarendon Press, Oxford, 1977, page 178.

may all represent the same actual emittance. There is no way to distinguish (a) from (c) unless an explicit definition is given. Each of these ways of defining emittance has its proponents.[2] Personally, I prefer (a) because it is the definition used by Lawson in a standard reference work[1], and because it is the same definition used in circular accelerator theory, where a matched beam radius is simply given by $x = \sqrt{\varepsilon\beta}$, where β is the Courant-Snyder β-function[3].

A more fundamental problem occurs because in a real beam the distribution of particles in phase space is not uniform, nor is the distribution necessarily bounded by a smooth surface. The two most common ways of specifying emittance are the "envelope" or "edge" emittance and the RMS emittance.

The envelope emittance in a two-dimensional phase space is usually obtained from the smallest ellipse which can be circumscribed about the (x,x') coordinates of all the particles in the beam. There are two problems with this commonly used definition. First, the bounding ellipse will have a larger area than the actual particle distribution, and second the measurement of the location of all the particles implies a perfect measurement apparatus. To illustrate the first problem, consider a zero emittance beam, one in which $x' = ax$ for all particles. If the beam is transported through a system with spherical aberrations such that $x' = ax + bx^3$, the phase space area of the beam remains zero, but the area of the smallest circumscribed ellipse becomes non-zero. To illustrate the second problem, consider a beam with a gaussian spatial distribution, and a measurement system with some measurement noise. The apparent size of the beam will depend on the details of how the measurement data is reduced. Sometimes one specifies the emittance in terms of the area of a contour in phase space which contains a given fraction (e.g., 90% or 99%) of the particles, or in terms of a contour where the particle density in phase space is a specified fraction of the central density. The possibilities are endless.

The RMS emittance concept removes all of the ambiguities inherent in the use of the envelope emittance, but introduces some new ones. The two dimensional RMS emittance is given by

$$\varepsilon_{RMS} = \left[\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2\right]^{1/2} , \qquad (2)$$

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2. My present understanding is that Livermore uses (a) (per Don Prosnitz), Boeing uses (c) (per John Adamski), and Los Alamos uses (b) (per Jerry Watson).

3. E. D. Courant and H. S. Snyder, Ann. Phys. 3, 1(1958).

where < > indicates the average for all the particles in the beam of the enclosed quantity.[4] Unfortunately, there is a second commonly used definition of ε_{RMS}, given by Lapostelle[5]. Lapostolle's emittance, which we shall designate ε_p, is related to ε_{RMS} by $\varepsilon_p = 4\varepsilon_{RMS}$. Lapostolle's emittance is equal to the envelope emittance of the Kapchinsky-Vladimirsky (K-V) distribution[6]. It is also equal to the "2σ" emittance of a gaussian beam,

$$\varepsilon(2\sigma) = 4\sigma_x\sigma_{x'} \quad . \tag{3}$$

where $\sigma_x = \langle x^2 \rangle^{1/2}$ and $\sigma_{x'} = \langle x'^2 \rangle^{1/2}$ are the RMS size and divergence of a gaussian distribution.

The concept of normalized emittance is an especially useful one because the concepts of statistical mechanics are valid in phase spaces where the coordinates are configuration coordinates and their conjugate momenta. It follows from Liousville's theorem that particle densities in normalized phase space are invariant and thus normalized emittances are preserved by linear transformations. The transverse momentum associated with x is $p_x = P\frac{dx}{ds}$, where P is the momentum of the reference particle (along s by definition). It is conventional to divide by mc where m is the particle rest mass and c the speed of light to obtain the normalized transverse momentum

$$\frac{p_x}{mc} = \beta\gamma\frac{dx}{ds} \quad . \tag{4}$$

We therefore define normalized transverse emittance as

$$\varepsilon_N \equiv \beta\gamma\varepsilon \quad . \tag{5}$$

In eq(5), ε can be any of the forms of (unnormalized) emittance discussed above, and ε_N is the corresponding normalized quantity. βc is the velocity and γmc^2 the total energy of the reference particle. Under acceleration, in the absence of nonlinear process, ε_N (of whichever form) is constant. For relativistic electron beams, the factor β (≈1) is often omitted. The units of normalized and unnormalized emittance are the same, e.g., meter-radians, mm-mrad, etc. Occasionally one will see normalized emittance for an electron beam quoted in units of "m_0c-cm", or the like. When this abomination is encountered, interpret it as radian-cm. (Note, however, that cm is <u>not</u> a preferred unit.)

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4. F. J. Sacherer, IEEE Trans. on Nucl. Sci. <u>NS-18</u> (1971) p. 1105.

5. P. M. Lapostolle, <u>op.cit.</u>, p. 1101.

6. I. M. Kapchinsky and V. V. Vladimirsky, Proc. Int. Conf. on High Energy Accelerators, CERN, Geneva (1959) p. 274.

Brightness is defined as the beam current per unit crosssectional area per unit solid angle,[7] i.e.

$$dB = \frac{dI}{dA\,d\Omega} \quad . \tag{6}$$

We use the symbol dB to emphasize that brightness is a differential quantity. Standard practice in the FEL field is to give some average value for the entire beam. Unfortunately, the averaging process is seldom, if ever, defined. A "reasonable" averaging process is to define

$$B = \frac{I}{\int dA\,d\Omega} \tag{7}$$

where I is the current. The integral is taken over the total four dimensional phase volume occupied by I. For any distribution in which the particles are confined to a volume limited by

$$\frac{x^2}{a^2} + \left(\frac{ax'}{\epsilon_x}\right)^2 + \frac{y^2}{b^2} + \left(\frac{by'}{\epsilon_y}\right)^2 \leq 1 \quad , \tag{8}$$

$$\int dA\,d\Omega = \frac{\pi^2}{2}\,\epsilon_x\epsilon_y \quad , \tag{9}$$

thus for any such distribution (which includes the K-V distribution),

$$B = \frac{2I}{\pi^2\epsilon_x\epsilon_y} \quad . \tag{10}$$

Note that the definition (7) is not useful for a distribution function with infinite tails (such as a gaussian), since I would be finite but $\int dA\,d\Omega$ is not.

In section II of this paper, we propose a standard convention for reporting emittance and brightness. In section III we give the relationship between the definitions used at several accelerator laboratories and our proposed standards. In section IV we discuss the concepts of admittance and emittance filters. Finally, in section V, we describe and compare some commonly used distribution functions.

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7. Reference 1, page 182.

II. Proposed Conventions

Emittance, ε_N, (without any qualifying adjectives, arguments, or other subscripts) is $\frac{1}{\pi}$ times the total area of the beam in a two dimensional normalized transverse phase space. The units of emittance are meter-radians (m-rad), or any power of 10^3 thereof such as millimeter-milliradians (mm-mrad). Specifically, units of centimeters should not be used. If the beam is not cylindrically symmetric about the reference particle, two emittances should be stated, ε_{Nx} and ε_{Ny}.

Unnormalized emittance, $\varepsilon = \varepsilon_N/\beta\gamma$ should be quoted in the same units as ε_N, and with x and y subscripts if necessary.

Root-mean-square-emittance, ε_{RMS}. The Sacherer definition, equation (2) will be used.

$$\varepsilon_{RMS} = [\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2]^{1/2} \quad , \tag{2}$$

The normalized RMS emittance is $\varepsilon_{NRMS} = \beta\gamma\varepsilon_{RMS}$.

Brightness, B. Equation (10) should be used. It must be made clear whether peak or average brightness is meant. The units of brightness are $(\text{meters})^2$ steradians, or any power of 10^6 thereof. We recommend that emittance and current be stated explicitly since brightness is often a misleading quantity.

Normalized brightness $B_N = B/(\beta\gamma)^2$

III. Crosswalk to other definitions

It is our understanding that the three laboratories (BAC, LANL, and LLNL) all use normalized emittance and brightness. Beyond that, they all go their separate ways. The LLNL convention for emittance agrees with our proposed standard. LANL uses π times our standard but writes the factor π explicitly. BAC agrees with LANL but performs the numerical multiplication by π. Both LLNL and BAC use a definition of brightness which is π^2 times our standard, equation (10). In my opinion there is no reasonable justification for this. LANL uses a definition of brightness that is 1/2 of our standard, apparently because they did not recognize that the volume of the four dimensional unit sphere is $\pi^2/2$. The following table gives factors by which numbers quoted by the various laboratories should be multiplied to convert to our proposed standard definitions.

Table I	LLNL	BAC	LANL
emittance	1	$\frac{1}{\pi}$	$\frac{1}{\pi}$
brightness	$\frac{1}{\pi^2}$	$\frac{1}{\pi^2}$	2

IV. Admittance and Emittance Filters

Admittance is a measure of the maximum emittance that can be transmitted through a beam transport system containing limiting apertures. (Warning: The obscenity "emittance acceptance" should never be used.) The simplest example of an emittance filter is a transport system described by the transfer matrix

$$R = \begin{bmatrix} \cos\mu & \beta\sin\mu \\ -\frac{1}{\beta}\sin\mu & \cos\mu \end{bmatrix} , \qquad (11)$$

where β is a constant and μ is a linear function of distance along the axis of the system. If the system is cylindrically symmetric, has a beam pipe of radius r, and a length L such that $\mu(L) > \pi$, the admittance of the filter is

$$A = \frac{r^2}{\beta} , \qquad (12)$$

and the maximum (normalized) emittance that can be transmitted is $\epsilon_{N\max} = \beta\gamma A$. If r is expressed in millimeters and β in meters, the units of A and $\epsilon_{N\max}$ are mm mrad.

If a beam with emittance much larger than $\epsilon_{N\max}$ is transmitted through an emittance filter, it will emerge with emittance $\epsilon_{N\max}$ (and much reduced current). If, thereafter, the beam is not distorted (e.g., by non-linear space charge effects, beam breakup, geometrical or chromatic abberations,) it will have emittance $\epsilon_{N\max}$ thereafter, and a distribution function similar to K-V distribution.

V. Typical Distribution Functions

In this section we describe three commonly-used distribution functions and compare their properties. In this section we will use unnormalized coordinates and emittances.

The K-V distribution is a uniform distribution of particles on the surface of a four-dimensional hyperellipsoid. For convenience, we place the principle axes along the x,x',y, and y' directions. The property of the K-V which makes it useful is that all two dimensional projections, e.g.

$$f(x,x') = \int dy dy' f(x,x',y,y') \tag{13}$$

are uniformly populated ellipses. Thus the space charge forces in a K-V distribution are linear functions of x and y inside the beam.

The "water-bag" distribution is a uniform population of particles in the volume of a four dimensional hyperellipsoid. We have seen beams from several electron linacs which look very much like "water-bag" distributions. I do not know the origin of this distribution. I would appreciate a reference to its originator.

The gaussian distribution is commonly used in high energy physics accelerator calculations. A beam which has "lived" in a storage ring for many revolutions will have a gaussian-like distribution.

The following table lists the properties of these three distributions. $f(x,x',y,y')$ is the four dimensional distribution function, normalized so that

$$\int f(x,x',y,y')\, dx dx' dy dy' = 1 \quad . \tag{14}$$

$f(x,x')$ is the two dimensional distribution function, given by equation (13). The one dimensional distribution function is

$$f(x) = \int f(x,x') dx' \quad . \tag{15}$$

The one and two dimensional distribution functions in other variables can be obtained by inspection. For the K-V and water-bag distribution, a and b are the semi-axes of the distribution in x and y and ε_x, ε_y are the corresponding (envelope) emittances. We have defined

$$r^2 = \frac{x^2}{a^2} + \frac{a^2 x'^2}{\varepsilon_x^2} + \frac{y^2}{b^2} + \frac{b^2 y'^2}{\varepsilon_y^2} \quad , \tag{16}$$

$$\rho^2 = \frac{x^2}{a^2} + \frac{a^2 x'^2}{\varepsilon_x^2} \quad , \tag{17}$$

and $dV = dx dx' dy dy'$. When a distribution function is given for a specified region, e.g., $\rho^2 < 1$, it is understood to be zero outside that region. The integrals over 2σ regions extend from -2σ to +2σ in each variable integrated.

Table II. Summary of Distribution Functions

	K-V	water-bag	gaussian
$f(x,x',y,y')$	$\frac{1}{\pi^2\epsilon_x\epsilon_y}\,\delta(r^2-1)$	$\frac{2}{\pi^2\epsilon_x\epsilon_y}$, $r^2<1$	$\prod_{i=1}^{4}\frac{1}{\sqrt{2\pi}\,\sigma_i}\,e^{-\frac{1}{2}(x_i/\sigma_i)^2}$
$f(x,x')$	$\frac{1}{\pi\epsilon_x}$, $\rho^2<1$	$\frac{2}{\pi\epsilon_x}(1-\rho^2)$, $\rho^2<1$	$\frac{1}{2\pi\epsilon_{RMS}}\cdot e^{-\frac{1}{2}[(x/\sigma_x)^2+(x'/\sigma_{x'})^2]}$
$f(x)$	$\frac{2}{\pi a^2}(a^2-x^2)^{\frac{1}{2}}$, $\lvert x\rvert<a$	$\frac{8}{3\pi a^4}(a^2-x^2)^{3/2}$, $\lvert x\rvert<a$	$\frac{1}{\sqrt{2\pi}\,\sigma_x}\cdot e^{-\frac{1}{2}(x/\sigma_x)^2}$
$\langle x^2\rangle^{\frac{1}{2}}$	$a/2$	$a/\sqrt{6}$	σ_x
ϵ_{RMS}	$\epsilon/4$	$\epsilon/6$	$\sigma_x\sigma_{x'}$
$\int_{2\sigma} f(x,x',y,y')dV$	1	0.444	0.830
$\int_{2\sigma} f(x,x')dxdx'$	1	0.889	0.911
$\int_{2\sigma} f(x)dx$	1	0.975	0.955

END

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