Field Variation and other factors of Heater Design in Dispenser Cathodes

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Introduction:

Cathode designs from Vacuum Electron Device (VED) original equipment manufacturers (OEMs) frequently come with the drawing note, "Non inductive potted heater " or "Heater wire to be . . . wound in a noninductive configuration." Such requirements are generally qualitative and create a paradox whereby the cathode designer must select between manufacturability and inductiveness. No ohmic heater is completely non-inductive.

By their nature, heater coils with an internal current create stray magnetic fields. When using an ac power supply, the variation in these stray magnetic fields at or near the emitting surface serves to periodically deflect emitted electrons, thus imparting undesirable signals – "ripple" – on the electron beam. The magnetic field by the emitting surface of the cathode can be critical, with the field at the cathode cylinder a secondary consideration. With the creation of a suitable model, the field at various points along the cathode is calculable. Less frequently, direct measurements are made.

Spectra-Mat uses nine "typical" heater styles in its cathodes: (1) single coil; (2) single coil-center return; (3) stacked coil; (4) bifilar with a crossover; (5) bifilar with a hairpin; (6) single coil toroid; (7) center return toroid; (8) bifilar toroid; and (9) coiled-coil crossover heater. Each has some advantages and disadvantages in construction and use. Figure 1, below shows various configurations. There are many other configurations possible, including spiral or "pancake" and split toroids.

Figure 1. Various Heaters Found in Potted Cathodes

Analyses:

To form a complete picture of the field variations determined by the heater geometry, a model of each heater was created in Field Precision's *Magnum* FEA code.

The model consisted of a heater can, assumed to be molybdenum, with a planar tungsten emitter. The field calculation was made 2 mm above the top surface. The tungsten emitter was assumed to be 1 mm (.040") with a .25 mm (.010") gap between the top of the heater and bottom of the emitter. A separate calculation at the edge of the cathode assumes a measurement at the cathode edge. See Figure 2.

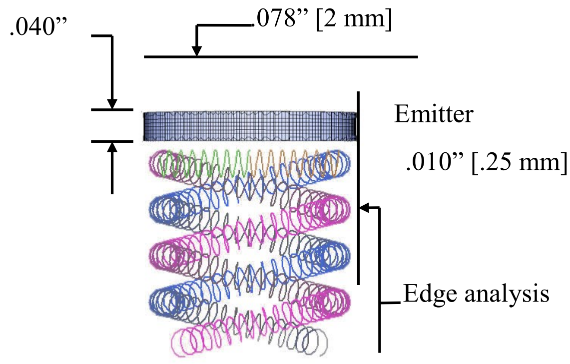

Figure 2: Emission surface to heater spacing (Coiled-coil heater shown)

Assumptions concerning the models are as follows:

- Constant wire length
- "Zero" diameter wire
- Constant current
- Planar emitting surface
- Constant.heater outer diameter
- Tungsten, molybdenum, alumina not paramagnetic.

No estimate of wire or cathode temperature was calculated. Current input for each model was 2.0 A.

Figure 3 displays typical output. The bifilar hairpin model under the emitter creates a large field at the wire surface, the (–1.27) mm line on the chart. This is in the potting, at the intersection of the wire and the potting, away from the emitting surface. There is a spike and trough where the heater loops back onto itself.

The five lines of Figure 3 represent different measurement points. The two lines at (1.27 mm) and (.063 mm) are inside the cathode potting. As we proceed further away from the wire, at the emitting surface and then above the emitting surface, the field sums to a more consistent level.

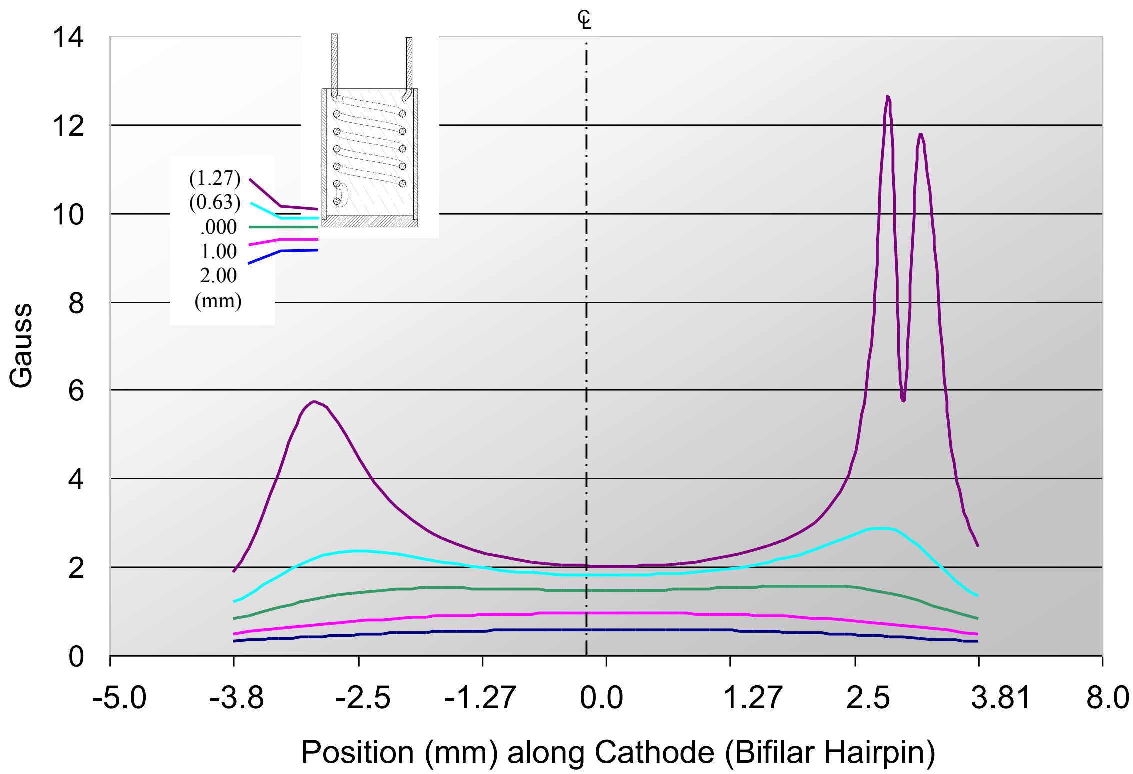

Figure 3: Field from bifilar hairpin heater

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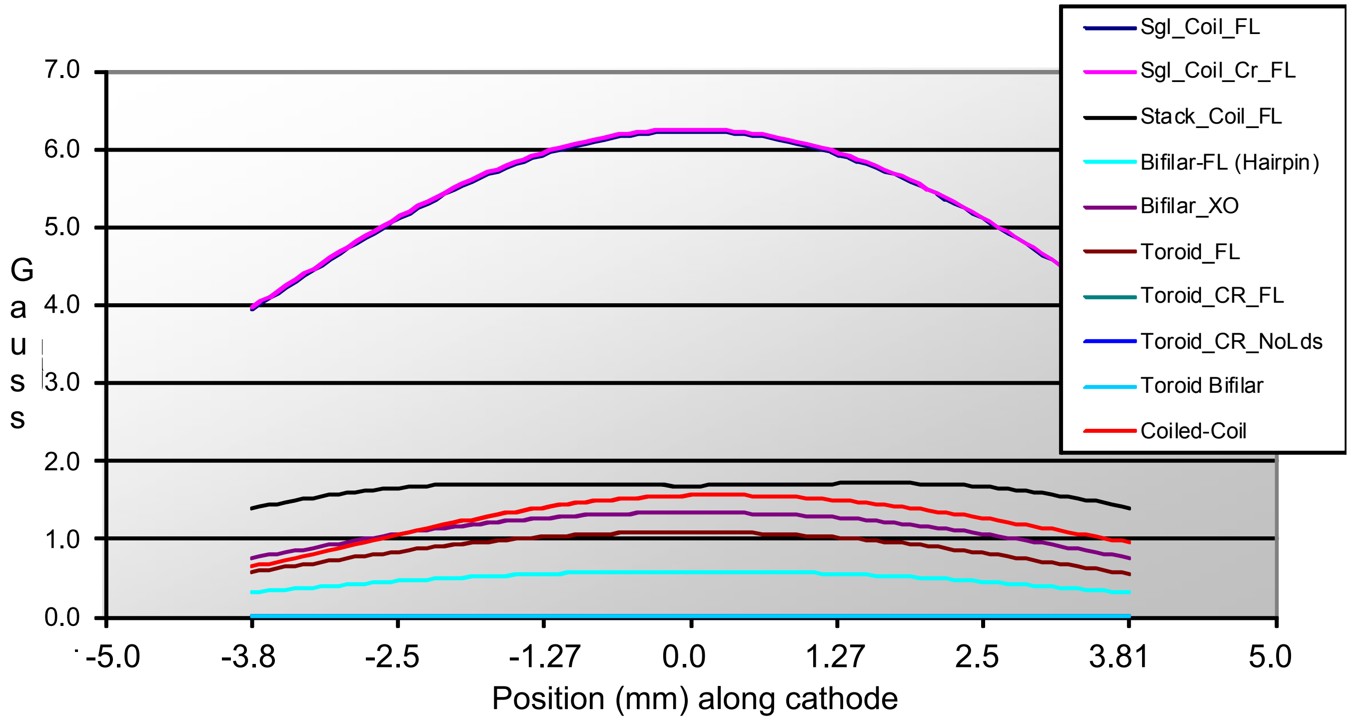

Figure 4: Field of all heaters

At 2 mm away from the emission surface we have a relatively flat field of approximately .5 gauss.

A comparison to a measured test part was performed. At the center of a Ø.7.62 mm diameter cathode heater with a coiled-coil heater potted in the back cavity, at a measurement distance of 2 mm (approximately), the measured field is 1.5 gauss. Our calculated value for the same geometry is 1.7 gauss. The values, while not perfectly aligned, are similar enough to allow an expectation that the comparisons of the study are generally representative of the heater types.

Figure 4 shows all of the fields for the heaters, measured at 2 mm away from the emission surface. Note that in Figure 4, the three lowest field heaters are barely visible, as they are orders of magnitude lower in field than the heaters with the highest field.

As the study is intended for a representative, qualitative review, not absolutes, a more useful representation is to choose one heater and compare the remaining units using that as a baseline. From that chart, relative values can be quickly ascertained to aid the designer. To create the comparison chart the toroid heater was chosen as the baseline heater, as it was roughly in the middle of the group. A straight toroid such as the unit shown in Figure 5

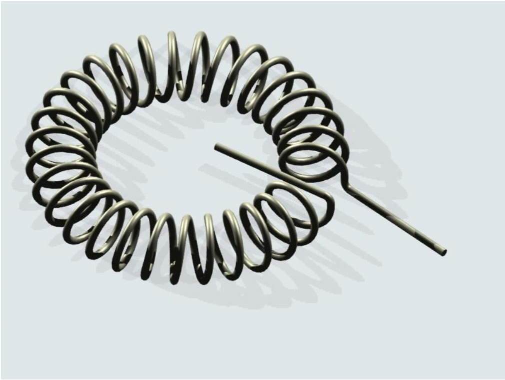

Figure 5: Toroid heater

has an moderate field — unlike the bifilars or the center return units, there is no wire specifically arranged to counterbalance the field in the primary coil.

Figure 6, then, is the same data as Figure 4, but plotted as a ratio of the field of one specific heater over the field of the toroid. To amplify the differences, the ratio is plotted on a log scale. We see immediately that the center return toroid and the bifilar toroid are (roughly) two orders of magnitude lower than our baseline toroid, and that the single coils, even with a center return, are six-fold higher in magnetic

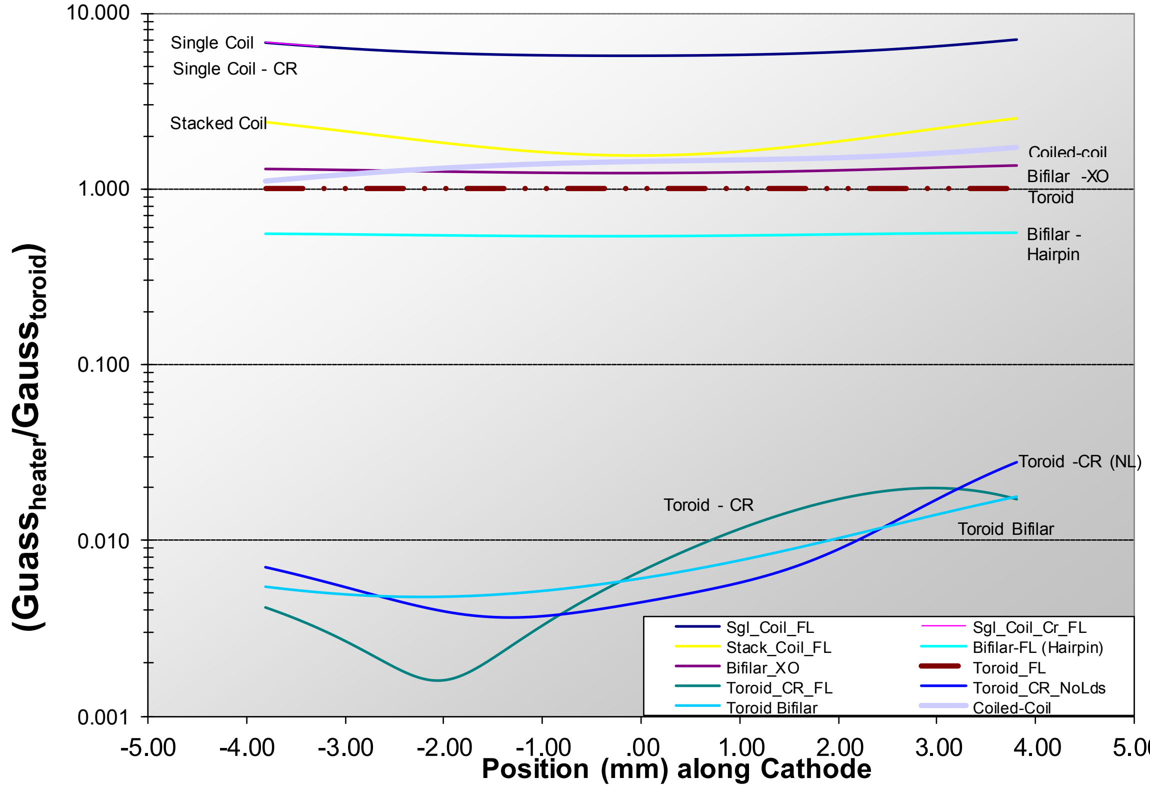

Figure 6: Relative fields normalized against to the toroid heater.

field than our baseline toroid.

A similar exercise along the edge provides the field at the molybdenum body edge. This data is presented in Figure 8. The peaks and valleys indicate the position of the coils (versus the gaps between the coils) inside the cathode.

The differences between the highest and lowest field are not as magnified along the edge of the cathode in Figure 8 as compared to Figure 6, above the (planar) emitter. Starting above the emitter down to 7.0 mm below the emitting surface, the fields decrease for the toroids but not for the heaters with individual coils parallel to the measurement line.

Case study and discussion:

We recognize an important factor: all other things equal — same potting cavity, same emitter, same body — total power to get to a specific temperature should be constant.[1]

The data and graphs provide an interesting visual to estimate which heater would provide the lowest induced magnetic field at the surface and diameter of a cathode. The assumptions are not realistic in actual designs, notably the assumption that wire length would stay the same when going from one heater to another. For this reason, the analysis is more qualitative than quantitative. Let us examine a sample case. We have a working cathode design with a stacked coil heater, and are requested to decrease the ripple. The stacked coil is relatively "cool" design made from Ø.227 mm (.009") W-3%Re. The outer diameter is a maximum of Ø5.3 mm. Total wire length is 307.4 mm.

We begin this exercise by examining a toroid design. A toroid will typically use a smaller wire diameter and less wire overall for the same temperature in a cathode with identical exterior geometry, as the toroid has significant space restriction when compared to a helical heater.

We find in our study that a center return toroid — the "best" choice — will be cumbersome, as the wire diameter is not conducive to a center return loop. To

1. In reality, 'all other things' are rarely equal. Minute variations can create havoc when meeting specifications of ±1—2% at 1000°C. For example, absolute position within a cathode, molybdenum body emissivity, tungsten emissivity, potting density, total wire surface area and the physical connection point have been demonstrated within Spectra-Mat to play a role in cathode temperature. This ignores the effect of the variation in W-3%Re wire, which alone can create up to 3% cold resistance fluctuations.

effectively create a toroid, we would need a Ø.5 mm primary coil inner diameter with a Ø.228 mm wire.

This gives a maximum, perfect spacing between the center return and coil of only 0.14 mm. Guaranteeing potting between the center return and coil would be difficult if not impossible to maintain.

We make an assumption about the heater primary diameter, based on the existing design. We would end up with a toroid with a primary diameter of 1.0 mm.

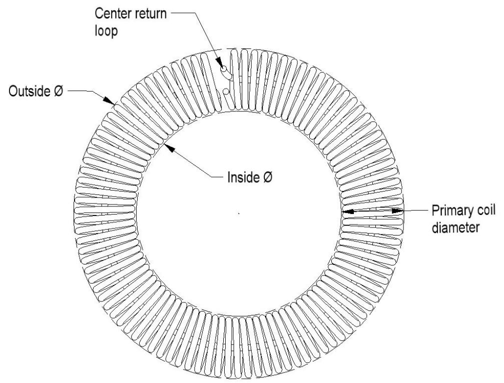

Figure 7: Toroid, Center return

The inside coil diameter becomes Ø3.3 mm. Each turn is approximately $D_{primary} \times \pi$. For 307.4 mm of wire, we end up with a requirement of ~ 100 turns.

Can this fit into the available space? We calculate a circumference of at least 100 x (wire diameter). As we've restricted ourselves to the same wire diameter as the starting design, and we need some spacing between each turn. Assume at least .10 mm spacing coil to coil. We end up with 100 x (.228 + .102), or 3.3 mm. The circumference of the ID is Ø3.30* π or 10.37 mm. The longer, stacked coil heater when configured as a toroid quickly runs out of cathode body volume. We find we must change wire diameter and length. The length will get much shorter, to about 1/3 of the original heater, and the wire diameter drops to about .58 of the original, to keep all other parameters equal.

Thus begins a series of calculations to maximize heater wire in a cavity while maintaining a specific resistance. In the case study, it was determined that cutting the ripple approximately in half would be sufficient. This was more readily achieved by creating a coiled-coil version, maintaining the same wire diameter and approximate length.

We see, then, that other factors might better determine when a particular coil is used. Some generalizations follow:

- Longest life will be from the most wire of the largest diameter. Stacked coils and coiled-coils tend to the largest amount of wire inside a given volume.
- Straight coils are simplest to make and very inexpensive. If there are no special constraints, start with a straight coil.
- Bifilar straight coils are more difficult than a single coil, but still easier than most other heaters to manufacture.
- Toroids will generally run hotter than the longer coils, as they tend to smaller wire diameters and less wire.
- Toroids should always be used in fast warmup devices, as they represent (including the alumina and molybdenum body) the least thermal mass.
- Bifilar and center return toroids are most susceptible to electrolysis, if the heater is run DC.
- For the cathode designer, a grounded lead is better than two leads from the heater, to minimize electrolysis failures.
- AC filament power is preferred to DC.
- If DC is used, the next higher assembly should be designed to insure the hottest part of the heater is negative with respect to the cathode body.
- Bifilar cathodes are more difficult to pot with alumina, as the coil-to-coil spacing tends to collapse.
- Bifilar toroids can be devastatingly difficult to pot.
- Center return toroids should have ample space between the return lead and the coil.
- Center return heater (toroids or straight coils) should always be grounded by the coil, not the center return. This consistency allows the user to apply correct polarity to heater.
- Center return through toroids is much hotter, over 100°C , than the surrounding coil.

A summary table is presented as Figure 9, with consideration of various heater styles and manufacturability.

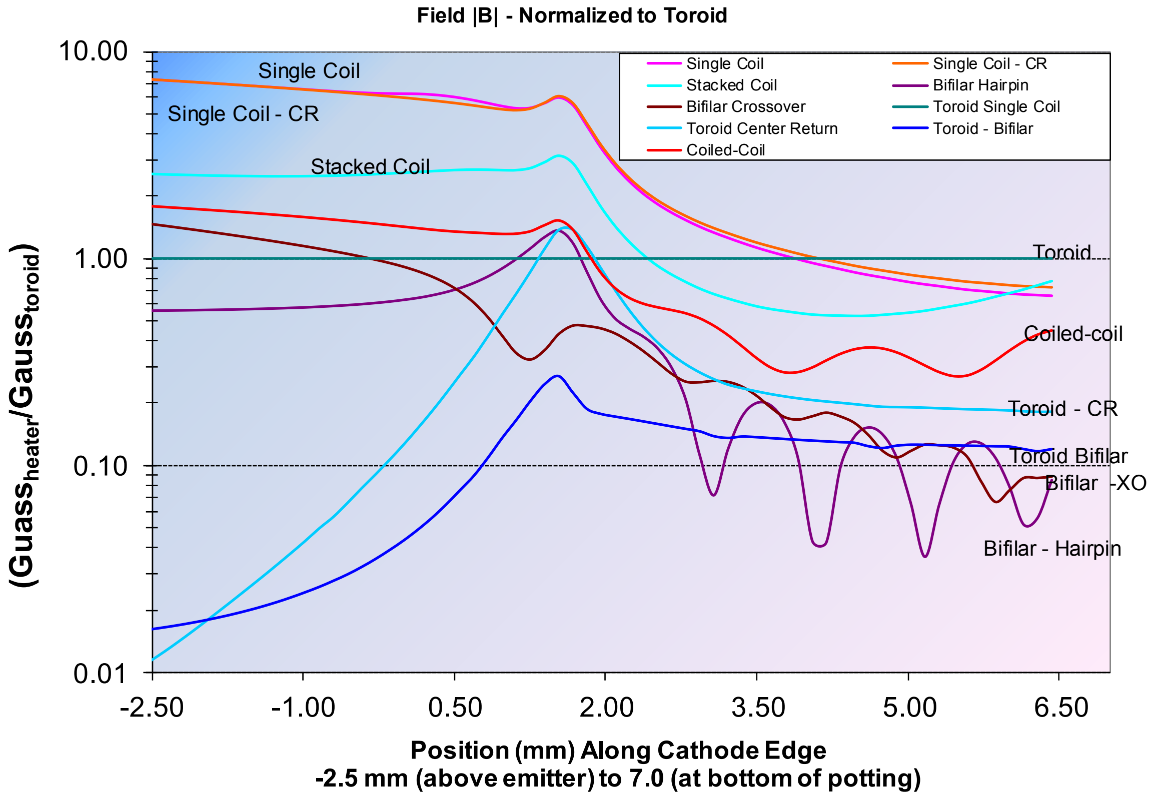

Figure 8. Fields along the edge of cathode.

Heater Style	Fields (Relative |B|) Along Ø	Edge Line	Manufacturability	Jigging	Potting	Turn-to-Turn Potential	Size	Relative Wire Temperature	Comments
Single Coil	6.1	3.0	E	S	E	L	L	C	Simple; special case heater only Heat away from Emitter
Single Coil - Cent. Ret.	6.1	3.0	E-M	S-M	E	M	L	C	Practical if fields aren't a concern. Center return too far away to balance field.
Bifilar - Crossover	1.3	.40	M	M	M	H	L	C	Better field along the emitter (Crossover dominates) Collapses onto itself
Bifilar - Hairpin	.55	.41	M-D	M-C	M	H	L	C	Better Fields along the emitter; hollow center. Collapses; Failures at hairpin during manufacturing
Stacked Coil	1.9	1.5	E-M	C	M	H	C	M	Can tune temperature & (theoretically) field. Hollow Center. Short package.
Toroid - Single Coil	1.0	1.0	E	M	M	M	C	M-H	Hollow Center for all toroids. Wire in toroids runs hotter. Easiest toroid, with some field gains.
Toroid - Cent. Ret.	.009	.34	M-D	M-C	D	H	C	H	Limit on small sizes. Low fields except at leads Center return is hotter than rest of coil. Difficult to pot.
Toroid - Bifilar	.007	.12	D	M	D	H	C	M	Best fields (leads excepted). Limits on small sizes. Difficult to pot.
Coiled-Coil	1.4	.80	D	C	D	L	C	H	Turn-to-turn internal reflection increases wire temperature. Requires wire winding machines. Can be inexpensive in qty

Manufacturability: (Easy, Moderate, Difficult) Turn-to-Turn Potential (Low, Medium, High)
Jigging (Simple, Moderate, Complex) Size (Compact, Long)
Potting (Easy, Moderate, Difficult) Rel Wire Temp: (Cool, Mid, Hot)

Figure 9. Comparison of Heaters

Reference:

Portions of this were presented at IVEC 2006 under presentation 14-2, *An Examination of Magnetic Fields from Cathodes, (*Paff, J.E., IVEC April 2006. IEEE 1-4244-0108-9/06)

While no data was taken from either of the following, these two memorandum contain similar studies and were invaluable for understanding and review

C. Schwartz and J. Ward presented measured data on a hairpin bifilar heater, a coil-bifilar coil (similar to the coiled coil, but with a hairpin turn instead of a crossover), a bifilar coiled-coil "Magnetic Field Measurement of Various Cathode Heaters." (Tube Division Memorandum, Varian Associates, 26-Apr-1961). Mr. Schwarts and Mr. Ward present off axis data as well as centerline data, and data along the hairpin. Their data and what is presented here agree substantially in at least one factor, obvious but nonetheless useful to note: the hairpin or crossover always represents an unbalanced field.

C.S. Quan presented similar calculated information in "Heater Filament Design for Minimum Cathode Flux", Hughes Aircraft Company, 10-May-1978. Mr. Quan evaluated four variations of toroids, a pancake filament in two layers, and a bifilar helix filament. The study presented here and in Mr. Quan's are in agreement that a center return toroid or a bifilar toroid are lowest in field.