Proposal for a Room-Temperature Thermionic Converter

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1. Introduction

This paper describes a proposed thermionic converter that extracts ambient heat from the environment and converts this into electrical energy. It makes use of existing vacuum electron emission technology for thermionic refrigeration, but whereas that technology pumps heat from the cathode to the anode in the form of a hot electron stream, this device converts that stream into useful electrical power.

2. History and Prior Art

The proposed device is best described as a form of *magnetic triode*. A magnetic triode is a vacuum tube having three electrodes, but whereas in the conventional triode the control electrode (grid) is placed between the cathode and anode, in the magnetic triode it is placed to one side to act as an electron accelerator, and the presence of a crossed magnetic field causes the electrons emitted from the cathode to follow a curved path to then reach the anode. The control electrode is driven positive to draw electrons from the cathode but the curved trajectory prevents the electrons from reaching this positive electrode. As a signal amplification device the magnetic triode does not offer any advantage over the conventional triode, and is more costly and complex, hence has not found use. However when used as a thermionic converter it does offer significant advantages.

N.B. In the literature there is some confusion regarding the terminology, some writers refer to the positive control electrode as an anode (and the collecting electrode as a second cathode) while others refer to the control electrode as a grid (but it does not have a grid-like form). We will use the convention that the emitting electrode is the *cathode*, the electron collecting electrode is the *anode* while the control electrode is the *accelerator*.

In 1956 George N. Hatsopolous wrote a thesis [1] on a device he called a *Thermo-Electron Engine* which developed from a simple magnetic triode into a more complex version having multiple cathodes and anodes. His thesis contains the results of measurements on experimental models which show that

(a) the crossed magnetic field reduced the current flowing from cathode to accelerator to negligible proportions. This type of cut-off is known in other crossed field devices such as magnetrons as *Hull cut-off*.
(b) the magnetic field diverted the electrons from the cathode to be adsorbed into the anode and to then flow in an external resistor connected between cathode and anode. Thus the anode was at a small *negative* potential wrt cathode.
(c) The electrical power delivered to the load resistor was in excess of the electrical power supplied to the accelerator.

Thus, considered as a classical triode amplifier, the device provided power amplification from accelerator electrode to anode, but unlike the classical triode no DC power was supplied to the anode. The output power came from the power supplied to heating the cathode, hence acting like a thermionic converter. Although in the experimental models the cathodes were heated by electrical filaments, when used as a thermionic converter the cathodes would be heated from an external source of high temperature heat.

In 1965 US patent 3,202,844 [2] was granted to James E. Hatch for an *Energy Conversion Apparatus*. No reference is made to Hatsopolous' earlier work. A magnetic triode thermionic converter is described where the crossed magnetic field magnitude is non-uniform; it is claimed that this reduces the probability of electron collisions. As in the Hatsopolous device, heat energy supplied to the cathode was converted into electrical energy.

At the time of these inventions vacuum tubes almost invariably used hot cathodes, which supplied electrons by thermal emission. Although so called *cold cathodes* were known, these could not compete with the current densities available from hot cathodes so little thought was given for using cold cathodes for thermionic conversion. The invention of the *Spind-tipped* cathode, where high current densities can be achieved by field emission from a cold cathode surface covered in nano-tips, opened up the possibility of extracting heat at room temperature. Recently Wu and Ang [3] have considered the feasibility of low temperature refrigeration and show that the use of a crossed magnetic field can beneficially ensure that only electrons above the Fermi energy are extracted from the cathode, thus cooling the cathode by the Inverse Nottingham effect. Their device would be a *magnetic diode* supplied with DC, pumping heat from cathode to anode, hence acting as a heat pump.

3. Proposed Scheme

The basic scheme is outlined in Figure 1 which shows a vacuum tube of rather unusual configuration. The device is a magnetic triode, using a Spindt-tipped cold cathode where electrons are delivered by field emission, the electric field being supplied by the accelerator electrode. Electrons are diverted by the crossed magnetic field to escape from the high electric-field region to reach the anode which is in a low electric field region.

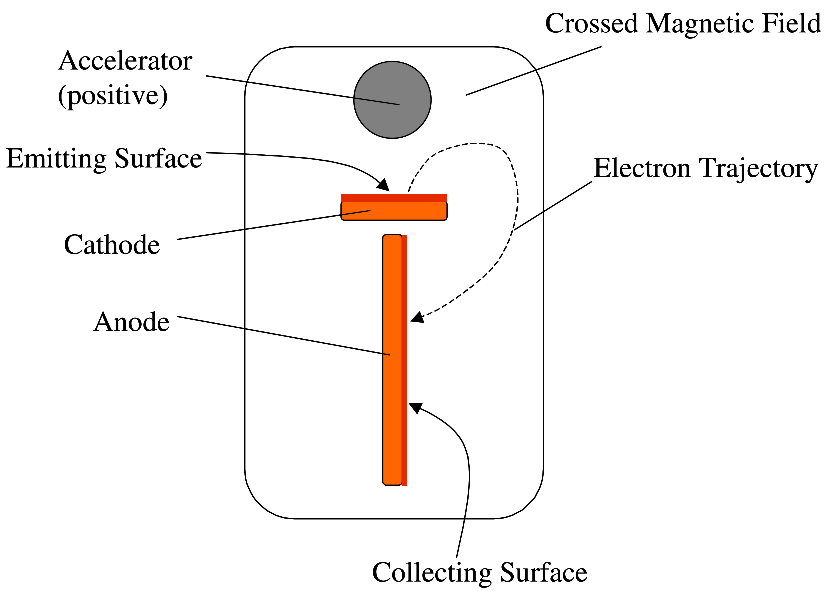

Figure 1. Proposed Vacuum Tube

The cathode emitting surface faces an accelerating electrode, this electrode being at a high positive potential with respect to the cathode. A crossed magnetic field is present with amplitude beyond the Hull cut-off value so that emitted electrons cannot reach this electrode. This magnetic field is centered on the accelerator, and has diminishing value at increasing radial distance from it (the permanent magnet and tapered pole pieces to achieve this are shown in Figure 2). Electrons leaving the cathode follow trajectories with local curvature dependent on their velocity and the local B field value. Low velocity electrons near the cathode surface have small cyclotron radii hence return to the cathode. Higher velocity electrons leave the vicinity of the cathode to follow a trajectory as illustrated in Figure 1. These electrons are collected by the anode to then flow in an external load connected between cathode and anode.

Since no current flows in the accelerator circuit, power is not drawn from the high voltage supply. The crossed magnetic field at the cathode surface produces a filtering effect with respect to electron energy so that only electrons with energies above the Fermi level get stripped away, hence cooling the cathode via the Inverse Nottingham effect (see [3]). The higher velocity electrons carry that extracted heat energy away, to deposit that energy at the anode. The unusual positioning of cathode and anode is designed to ensure that this extracted energy is not deposited as heat (as in thermionic refrigerators), but is delivered in the form of an electrical power flow to the external load.

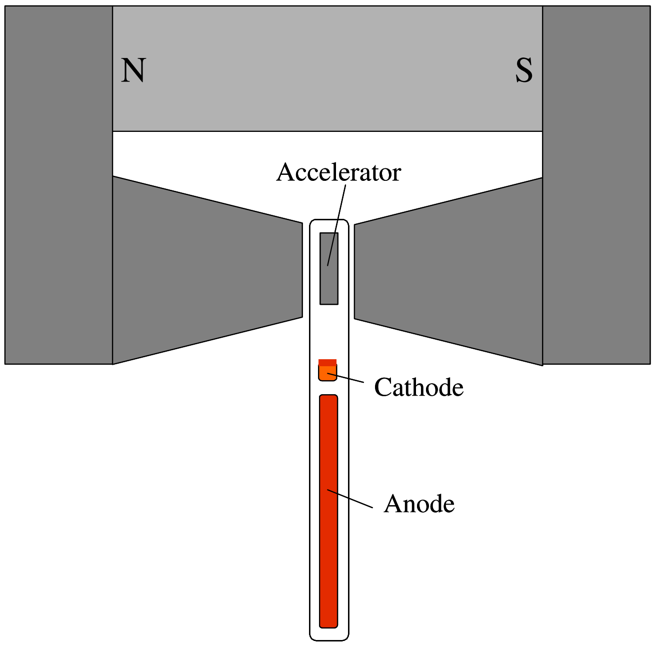

Figure 2. Magnetic Configuration

4. Discussion

At first sight it appears that this system is some form of perpetuum mobile, hence is prohibited by the laws of physics. No power is supplied, but magically the system pumps heat from the cathode and dumps it into an electrical load. Can this really happen? Fortunately there have been recent experiments to support this idea, researchers Xin Yong Fu and Zi Tao Fu at Shanghai Jiao Tong University have performed an experiment using two identical electrodes side-by-side [4]. With no magnetic field present, although electrons thermally emitted from one electrode can reach the other, by symmetry the reverse reaction is true and no detectable current flows. However when a magnetic field was applied current flow from one electrode to the other was observed. This present scheme obtains the same effect, but whereas the Fu[2] device produced only tiny current from the thermal emissions, this new device uses field-enhanced emission to produce significantly greater current hence power levels. It may also be noted that, had the Hatsopolous triode used a cold cathode, it too would have created electrical energy, albeit smaller than that measured by him.

Field emission occurs because of the high electric field at the cathode emitting surface, due to the high positive potential on the accelerating electrode. To minimize backward emission from the anode, this is placed in a position where the cathode acts to screen the positive accelerator electrode. Figure 3 shows the electric equi-potential contours for the arrangement. It can be seen that the screening effect is quite considerable, the electric field at the surface of the anode is at most one tenth of that at the cathode surface, hence is below the level required for onset of emission. Thus field emission from the anode is virtually eliminated, and current can only flow one way from cathode to anode.

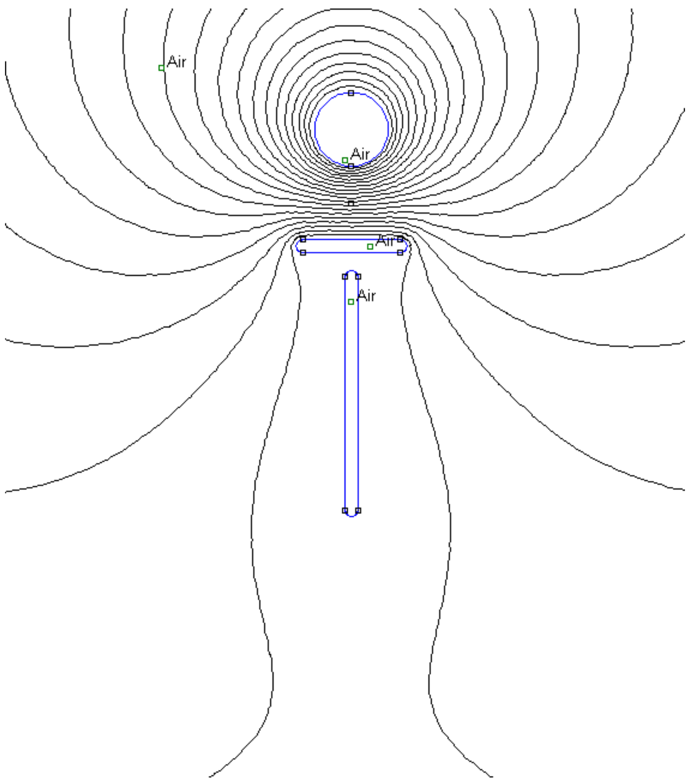

Figure 3. Equi-potential Contours

The average Fermi energy for thermal electrons is about 0.025 eV, hence the output voltage on the anode will be very small in the order of -0.025V. Anode potential is therefore very close to zero (cathode potential) so electrons that reach the anode will not gain any energy from the electric field, any energy they do gain as they approach the accelerator electrode is lost as they travel away from it. However the anode *is* slightly negative with respect to cathode, so these electrons will lose energy and be absorbed into the anode at less energy than when emitted from the cathode. Thus

Nottingham effect anode heating will be less than cathode cooling (see later section on further improvements for this consideration), and the difference energy goes into the electrical load.

5. Output Voltage and Impedance

As already stated, the output voltage of any room temperature thermionic converter will be very low, hence the load resistor will also be of low value. For a DC device this is a serious disadvantage (if one had an everlasting battery that produced useful power (say 10W) at a potential of only 0.025V, that is a current of 400A into a load resistor of 62.5μΩ, it would be very difficult to utilize that device!). One solution to this problem is to use the converter in pulsed mode, where its output can be converted to a useable voltage and impedance by simple transformer action. Using two converters in push-pull feeding a center-tapped primary is the obvious way to go, as shown in Figure 4. Here the tubes are driven by high voltage pulses applied to the accelerator electrodes. An alternative scheme could used tubes with control grids adjacent to the cathodes, then the accelerator electrodes would be at constant HV DC potential and the control grids would perform the switching action (as in cathode ray tubes).

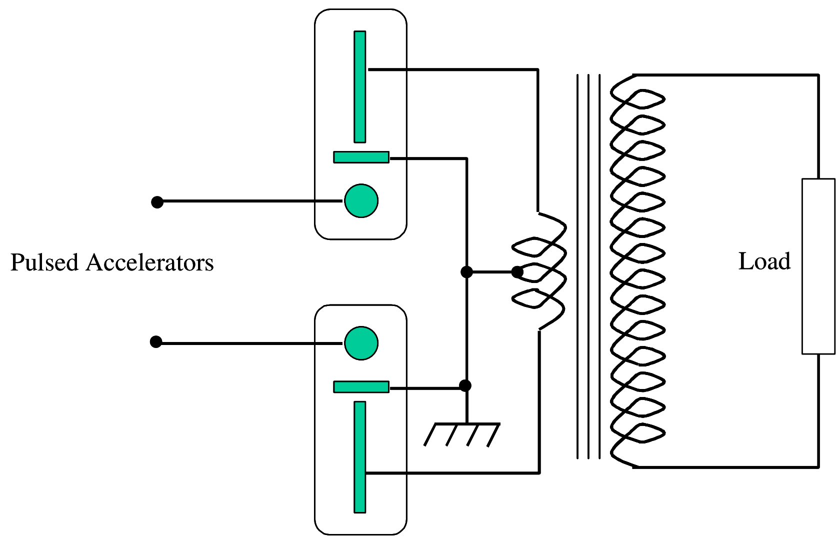

Figure 4. Push-Pull Circuit

6. Further Energy Considerations

Electrons leaving the cathode region will have a range of energies, hence those with higher velocity will follow a path having less curvature than the lower velocity ones and will impact the anode at greater distance from the cathode, Figure 5. This velocity filtering effect is well known and, by segmenting the anode, offers a further improvement to reduce anode heating from the high-energy electrons.

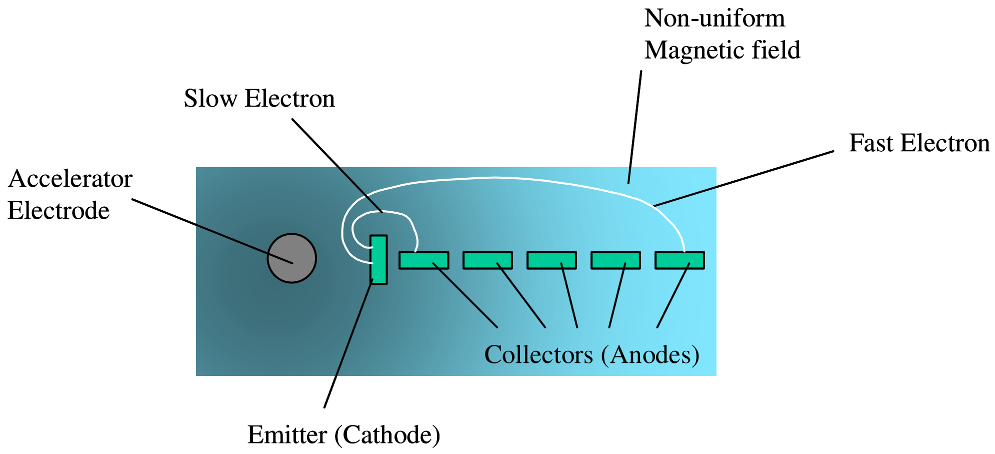

Figure 5. Velocity Filtering

By connecting adjacent anode segments to adjacent turns on the transformer primary, transformer action ensures that there is an increasing negative potential on successive segments. Thus higher energy electrons have to cross a higher negative potential barrier before reaching the anode segment. This arrangement ensures that all electrons reach the anode circuit close to Fermi energy. The final circuit is shown at Figure 6.

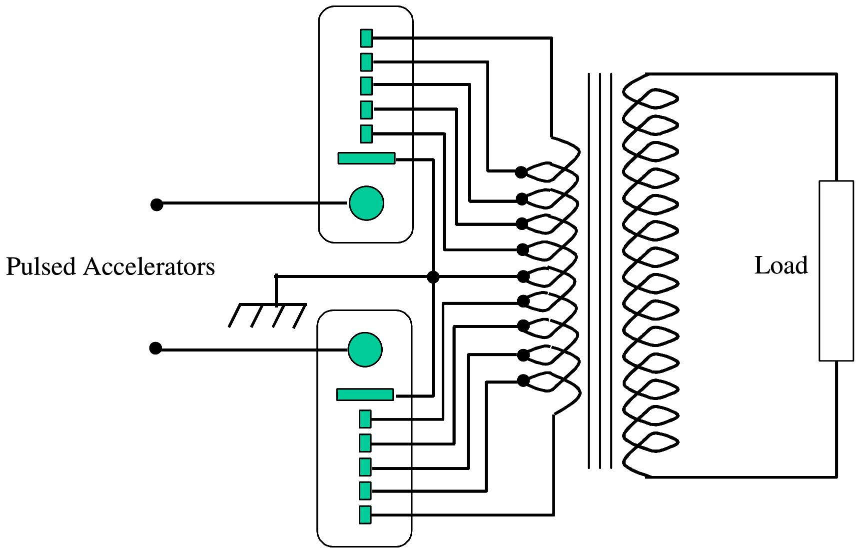

Figure 6. Final Circuit

7. Nano-scale Device

As described the magnetic triode is a macro-scale device. It may be more beneficial to create an array of smaller scale devices, perhaps even nano-scale. If so the electrical connections could wire the devices in series (so as to increase the output voltage) parallel (to increase current) ladder networks. Then the transformer action is not required and useful DC power could be produced.

8. References

[1] G. N. Hatopolous, “The Thermo –Electron Engine”, Thesis. M.I.T. May 1956

[2] USPO Patent 3,202,844, “Energy Conversion Apparatus”, patented Aug. 24 1965, Inventor James E. Hatch.

[3]. L. Wu and L. K. Ang, “Low temperature refrigeration by electron emission in a crossed-field gap”, Applied Physics Letters 89, 133503, 2006.

[4] Xin Yong Fu and Zi Tao Fu, “Realization of Maxwell’s Hypothesis”, Shanghai Jiao Tong University.