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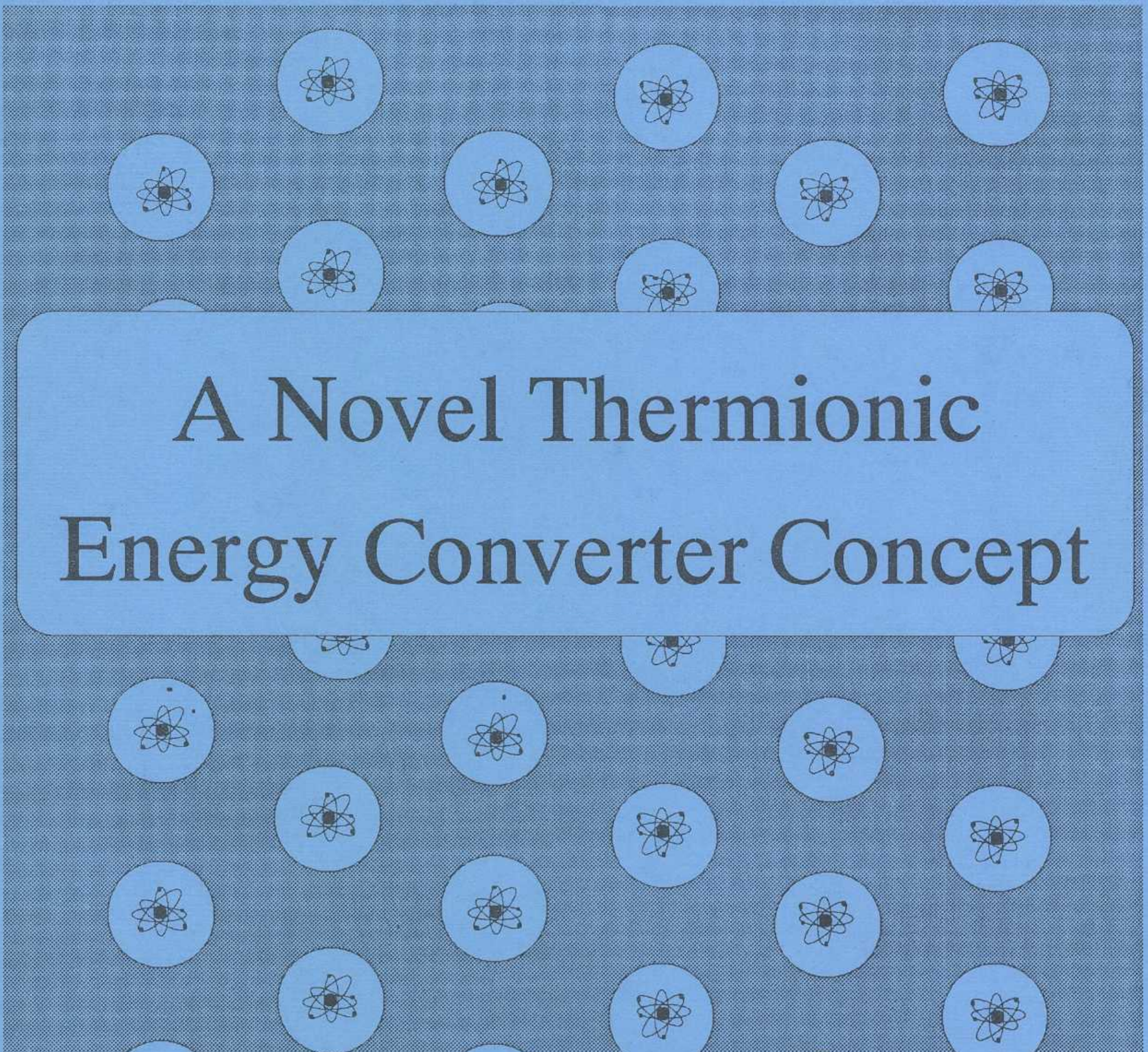

A Novel Thermionic Energy Converter Concept

Robert Svensson

A NOVEL THERMIONIC ENERGY CONVERTER CONCEPT

by

Robert Svensson

Akademisk avhandling
Som för avläggande av filosofie doktorsexamen i miljövetenskap med inriktning mot fysikalisk kemi vid Göteborgs Universitet försvaras vid offentlig disputation torsdagen den 26 maj 1994 kl. 10.15 i föreläsningssal KD, Kemihuset, Chalmers Tekniska Högskola och Göteborgs Universitet.

Opponent är Dr. Ir. Lodewijk Wolff, Energy Conversion Systems B.V.,
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Avhandlingen försvaras på engelska.

Department of Physical Chemistry
University of Göteborg 1994

Abstract

A thermionic energy converters (TEC) is a heat engine without macroscopic moving parts which converts heat directly to electricity. It may be described as a heat engine in which electrons evaporate from one electrode, the emitter, at a high temperature and condense on another electrode, the collector, at a lower temperature. The efficiency of TECs is limited by the need of power for the ion producing agent and the potential drop on the collector surface, the collector work function. The losses in the interelectrode gap (IG) are relatively high, and the electron current and output voltage are limited by collisional effects, plasma voltage drop and the work function of the collector electrode.

The efficiency of a TEC today is 5 - 10 %. TECs might be very interesting in for example environmental friendly hybride cars. Another very interesting application is cogeneration of heat and electricity in small boilers for local power production, for which purpose TEC technology is very suitable.

TECs with an efficiency of 30 - 40 % are possible with a new technology incorporating condensed highly excited states of Cs, so called Rydberg Matter (RM). RM has metallic properties and a very low density, which gives a very low work function. Using low work function matter in the collector decreases the internal losses in the TEC. RM has also properties which decrease the losses in the IG by means of decreasing the effective IG distance to be considerably smaller than the mechanical electrode distance.

The research TEC used in the experiments presented in this thesis is an "open" type of TEC suitable for study of various plasma and surface phenomena. When the collector surface in the TEC was covered with a thin layer of carbon, an unusually high collector back current appeared, several magnitudes higher than the back current from a "normal" TEC collector electrode. It was found that the *I-V* characteristic in the back current region was linear and that no current saturation was reached during the experiments. The resistivity of the back current plasma was very low and the current was unidirectional.

Calculations showed that the effective work function of the collector surface under these circumstances is very low, lower than any yet known electron emitting surface. Due to the very low work function and the low resistive properties in the (IG), it is possible to design a TEC with an increased efficiency. In the TEC an internal voltage loss figure, V_B , of 1.64 eV has been reached. A V_B value as high as 1.9 - 2.1 eV is generally considered as very good.

A NOVEL THERMIONIC ENERGY CONVERTER CONCEPT

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List of papers

This thesis is a summary of the following papers:

I. R. Svensson, B. Lönn and L. Holmlid, **"Apparatus for efficient atomic level studies of alkali plasmas using sampling, probing and spectroscopic methods".**
To be submitted to J. Sci. Instrum.

II. R. Svensson, L. Holmlid and L. Lundgren, **"A semiconducting low pressure, low temperature plasma of cesium with unidirectional conduction".**
J. Appl. Phys. 70 (1991) 1489 - 1492.

III. R. Svensson and L. Holmlid, **"Very low work function surfaces from condensed excited states: Rydberg matter of cesium".**
Surface Sci. 269/270 (1992) 695-699.

IV. L. Holmlid and R. Svensson, **"Collector for Thermionic Energy Converters".** Swedish Patent No 9102263-2. (International application No.: PCT/SE92/00530).

V. B. E. R. Olsson, R. Svensson and J. Davidsson, **"Spectroscopic Investigation of the Interelectrode Region in an Open Caesium Plasma Diode".**
Submitted to J. Phys. B.

VI. R. Svensson and L. Holmlid, **"Temperature studies and plasma probing of a Rydberg matter collector in a Thermionic Energy Converter".**
Proceedings 27th Intersociety Energy Conversion Engineering Conference, (IECEC 1992, San Diego, CA), Society of Automotive Engineers, Warrendale 1992, Vol. 3, p. 537-542.

VII. R. Svensson, L. Holmlid and L. Lundgren, **"Field ionization of Rydberg atoms in a thermionic converter".**
Proceedings Thermionic Energy Conversion, Specialist Conference, (eds. L. R. Wolff, W. B. Veltkamp, J. M. W. M. Schoonen and H. A. M. Hendriksen), Eindhoven University of Technology, Eindhoven, 1990, p. 63 - 66.

Fig. 8. The emitter assembly with a mounted 20 mm long, 5 mm high and 0.5 mm thick Mo emitter foil. The round part is the interface between the vacuum chamber and the air. One of the two studs for an extra electrode can be seen behind the emitter.

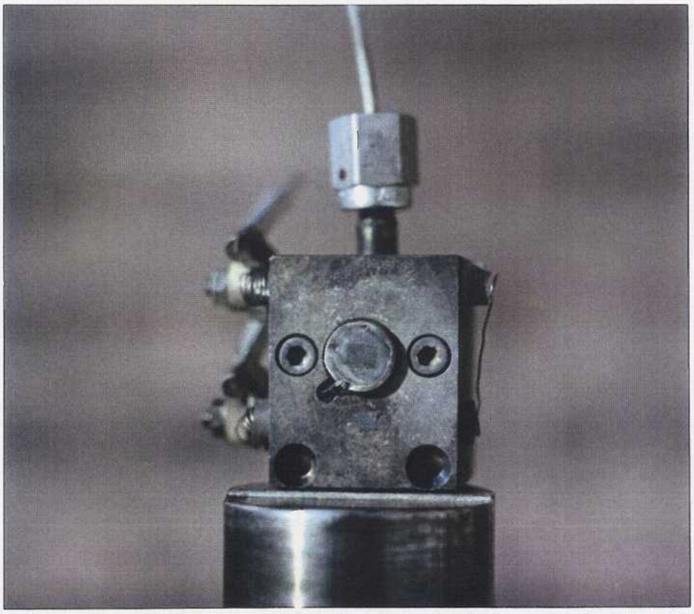

Fig. 9. The collector assembly with a 400 hole collector foil mounted with a TC attached to the rim of the collector. The heater spiral is attached to the square block around the collector. The cesium valve control rod can be seen on the top of the assembly. The round part below is the Cs container.

VIII. R. Svensson, L. Holmlid and E. Kennel, **"Experiments with different collector hole matrices in a Thermionic Energy Converter".** Proceedings Thermionic Energy Conversion Specialist Conference 1993 (eds. L. Holmlid and R.Svensson), Göteborgs Universitet and Chalmers University of Technology, Göteborg. 1993, p. 93-95.

IX. R. Svensson and L. Holmlid, **"Experiment with a diamond covered Mo emitter in a thermionic energy converter".** Proceedings 28th Intersociety Energy Conversion Engineering Conference, (IECEC 1993, Atlanta, GA), American Chemical Society, Washington 1993, Vol.1, p. 1063-1067.

X. R. Svensson, L Holmlid and Y. Olefjord, **"ESCA (XPS) analysis of TEC emitter and collector surfaces used to generate Rydberg matter of Cs".** Proceedings Thermionic Energy Conversion Specialist Conference 1993 (eds. L. Holmlid and R. Svensson), Göteborgs Universitet and Chalmers University of Technology, Göteborg 1993, p. 143-148.

XI. R. Svensson, K. Engvall, L. Holmlid, J. Braun and L. Lundgren, **"High emissivity electrodes for MHD channels".** Proceedings Eleventh International Conference on Magnetohydrodynamic Electrical Power Generation, Beijing, 1992. International Academic Publishers, Beijing, Vol. 1, p. 248-252.

1. Introduction to TEC concept

1.1. The TEC. A general description

The vacuum TEC functions by the well known principle of thermal electron emission from a metal surface. The emission saturation current density is a function of the emitter electrode temperature and is given by the Richardson-Dushman (R-D) equation,

$$I_s = AT_E^2 \exp(-e(W_E/kT_E)), \qquad (1)$$

where $A = 4\pi m\, k^2 e/h^3 = 120\ A/\mathrm{cm}^2\mathrm{K}^2$, W_E is the work function of the emitter electrode in eV, T_E is the absolute emitter temperature, e is the unit charge, k is Boltzmann's constant and I_s is the saturation current density in A/cm².

A TEC is a heat engine without macroscopic moving parts. It may be described as a heat engine in which electrons evaporate at a high temperature and condense at a lower temperature. The condensation energy can be drawn out of the system as electrical energy. The TEC is usually built up with two metal electrodes in a casing: one very hot electrode, the emitter, which emits electrons, and one

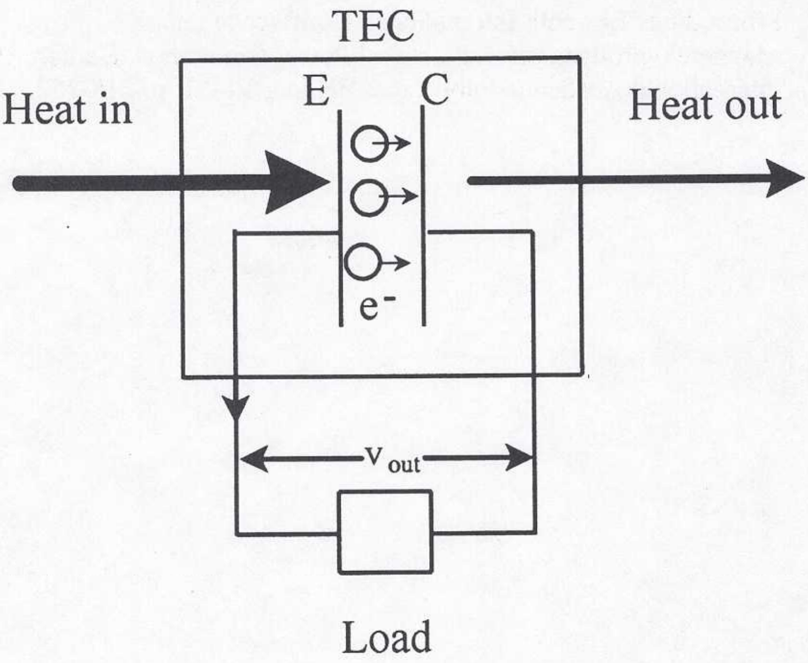

Fig. 1. Schematic drawing of a TEC. The load is a resistive load or a voltage converter, E is the emitter electrode, C is the collector electrode and V_{out} is the output voltage from the TEC.

moderately hot, the collector, which receives the electrons. The electrons pass back to the emitter through an electrical load, where electrical energy is drawn out. See fig. 1.

The simplest device working on the TEC principle is the so called vacuum TEC, where the interelectrode gap (IG) is empty (vacuum).

If the emitter work function is higher than the sum of the collector work function and the output voltage (V_{out}), the electric current is constant and independent of the output voltage. This is represented by (a) in fig. 2. and eq. 1. All electrons from the emitter reach the collector. From the point at which the emitter work function is equal to or lower than the sum of the collector work function and the output voltage, the current decreases. Only electrons represented by the Boltzmann tail, the curve (b) in fig. 2 have enough kinetic energy to pass the retarding potential and reach the collector. The curve represented by (b) satisfies the equation

$$I_E = AT_E^2 \exp(-e(W_C + V_{out})/kT_E) \qquad (2)$$

where T_E is the emitter temperature, W_C is the collector work function, k is Boltzmann's constant and A is a constant. since the electrons must overcome the potential $V_{out}+W_C$ to reach the collector.

An efficient and useful vacuum converter is difficult to realize, since the interelectrode distance must be very small to prevent space charge limiting of the current. Outside the emitter surface, there are electrons whose negative charge prevents further electrons from the emitter to enter the IG. In principle the collector

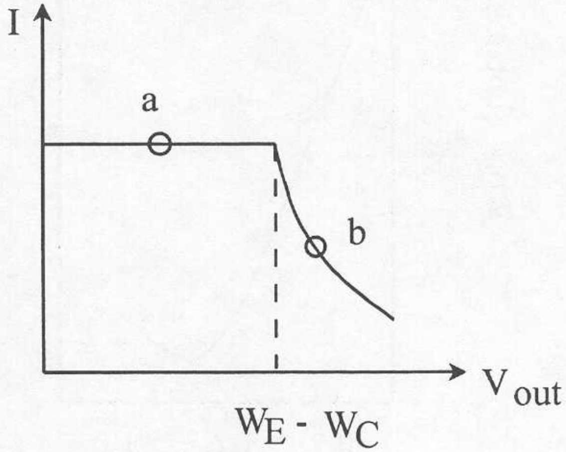

Fig. 2. The I-V characteristic of the vacuum TEC. W_E is the emitter work function, W_C is the collector work function and V_{out} is the output voltage. The point "a" is the constant current region, and "b" is the so called Boltzmann line.

surface should be placed in the region where the negative space charge cloud would be located. This means that there must be a gap of approximately 10 μm between the emitter and the collector. It is very difficult to keep this distance constant while the converter is temperature cycled, since the thermal expansion short circuits the electrodes. A closed-space TEC concept, where this problem is dealt with has been proposed [1].

1.2. Work function and cesiated metal surfaces

The adsorption of atoms or molecules on a metal surface results in changes of the electron work function. If for example cesium atoms adsorb on the metal surface, the work function decreases. The decrease in work function is dependent on the degree of coverage, Θ, of the adsorbing cesium atoms which is expressed in atom layers. The decrease in work function for e.g. a W electrode surface is an almost linear function of the coverage from zero to approximately Θ = 0.5. The minimum at the work function is found at around Θ = 0.7 for the example in fig. 3 where the work function vs. the degree of coverage of cesium on a W surface is

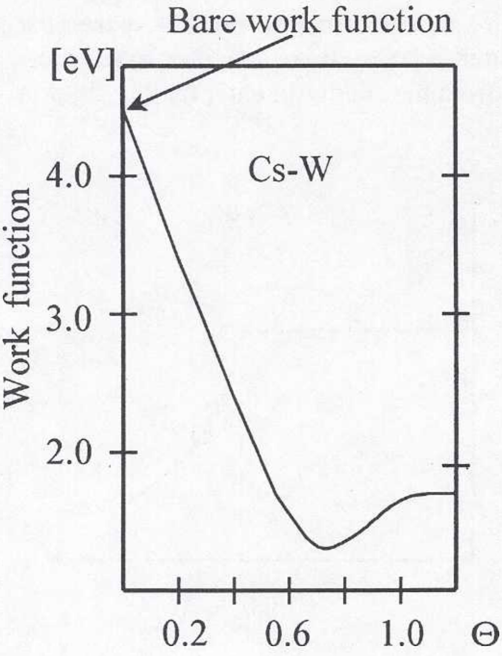

Fig. 3. An example how the work function of a metal surface is altered when covered with an alkali metal. This case shows the work function of a W surface as a function of the surface coverage of Cs. Θ is the cesium coverage expressed in atom layers.

shown [2]. When the coverage exceeds 0.7 atom layers, the work function of the surface starts to increase. With a few atom layers of cesium on the surface, the work function is approximately that of pure cesium which is around 1.81 eV [2,3]. The coverage is influenced only by the surface temperature and the cesium pressure. Since the work function is a function of the coverage, the work function can be expressed in terms of surface temperature and cesium pressure

$$W = \mathrm{f}(T, p) \tag{3}$$

where W is the work function of the bare metal surface, p is the cesium pressure and T is the surface temperature [2]. Fig. 3 shows the work function variation of a W surface as a function of the surface coverage of cesium.

Cesiated electrode surfaces are used in TECs, in the so called vapor TECs. The vapor TEC has cesium vapor at a low pressure in the IG which influences the work function of the electrode surfaces due to surface adsorption of Cs atoms. The cesium coverage and hence the electrode surface work function is a function of the cesium vapor pressure and the electrode temperatures.

It is important to make a TEC where the difference between the emitter work function and the collector work function is as large as possible, since this relation influences the efficiency and the output voltage of the TEC. The emitter work function of a vapor TEC is of the order of 2.5 - 3.5 eV, and the collector work function is in the order of 1.5 - 2 eV. These figures are very approximate, since the work functions are strongly dependent of the desired operational temperatures for the TEC, desired output voltage and the Cs pressure.

Seen from the standpoint of acquiring a high output voltage the emitter work function should be high in comparison to the collector work function. A high emitter work function is not difficult to use, but this has to be paid for with a corresponding decrease in the emitted electron current or an input temperature increase. Thus, it is of greater interest to decrease the collector work function in order to get a high output voltage. Thus, the energy losses the electrons are subjected to when entering the collector surface and falling down to the Fermi level is decreased. At a first glance, a work function close to zero should be ideal, but this would also give a tremendous electron back emission which to a large part would cancel out the emitter current. However, a low collector work function and a suitable low collector temperature, in order to keep the back emission down, would give a highly efficient TEC.

1.3. Material properties influencing the work function

The work function, strictly speaking, is a bulk property. It depends on the energy distribution of the electrons in the volume of the materials. The work function differs, for the same substance, depending on the crystal orientation of the emitting surface. An example for Mo is given below [3]:

Crystal face	Work function (eV)
(110)	5.00
(112)	4.55
(111)	4.10
(001)	4.40

Different crystal faces have different density of ion cores, and in the above example the crystal face (110) shows the highest density of ion cores and the face (111) shows the lowest density of ion cores in the surface. Generally it can be shown that the lower density of ion cores in the surface (and hence in the bulk) the lower the work function of the material, which is described by the so called uniform-positive background model. Investigations of these properties of some metals have been performed by Lang and Kohn [4].

To obtain a low work function surface, except for the previously discussed method of an adlayer of e.g. pure cesium, oxygen has been introduced into the IG of experimental TECs. It is well known that metal oxide surfaces have low work functions. The oxidized surface has a larger distance between the atoms than that of the pure metal surface, which reduces the work function. Oxide cathodes have been used for many decades in for example low and medium power electron tubes with moderate acceleration voltages. The thorium oxide cathode in vacuum gives a high electron current at a relatively low temperature, 950 - 1100 K [5].

1.4. Description of the vapor TEC

In order to eliminate the space charge and be able to use a larger IG, one usually introduces ions in the TEC. In the vapor filled TECs the gap between the electrodes is filled with an alkali vapor. In these TECs the negative space charge is more or less neutralized by positive ions produced by ionization of the alkali vapor atoms. The presence of the alkali also influences the work function of the electrode surfaces according to the previous discussion. Cesium is mostly used since it's ionization potential is the lowest of all stable elements, 3.87 eV. The only practical type of converter at present is the cesium diode TEC.

The TEC is either a two-electrode type, i.e. a diode, or a three-electrode type, i.e. a triode. There are two main types of vapor TECs, the low pressure TEC and the high pressure TEC. In the low pressure TEC there is no gas discharge and the ionization is maintained only by surface ionization [3,6]. In the high pressure TEC the ionization is mainly maintained by a gas discharge. In the latter a fraction of the voltage drop across the electrodes is used for maintaining the gas discharge. The high pressure TEC is the most common type, since this type allows a higher output current due to more efficient ionization. Fig. 4 shows an electron energy diagram for a common vapor TEC [2].

However, the ion production obtained with this method has to be paid for with

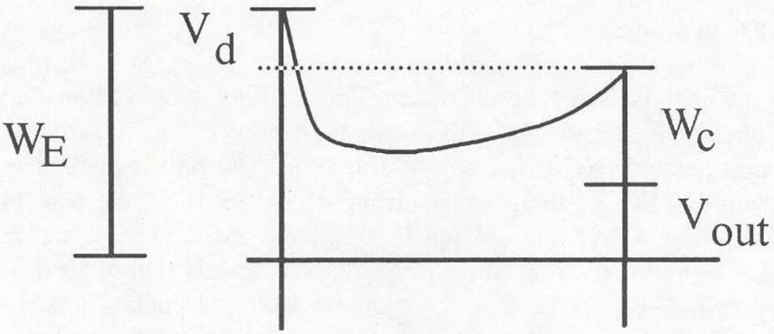

Fig. 4. An electron energy diagram for a high pressure vapor TEC. The minimum is due to the ionization of the Cs vapor, which is at it's maximum approximately in the middle of the IG. The positive ions give the electrons emerging from the emitter an accelerating force out into the IG. W_E is the emitter work function, V_d the arc drop, W_C the collector work function and V_{out} the output voltage.

a fraction of the total voltage over the TEC, why the output voltage always will be lower than that for the ideal vacuum TEC. The operating point in the I - V diagram is chosen where the product $I_{out} \times V_{out} = P_{out}$ is maximum. Fig. 5 shows an I - V diagram for a high pressure vapor TEC.

The quantity V_B is often used in the TEC literature for the internal losses in the TEC. V_B is defined as the sum of the collector work function (W_C) and the voltage drop used for ionization, the arc drop, (V_d). For more information about TEC basics, see refs. [2,7]

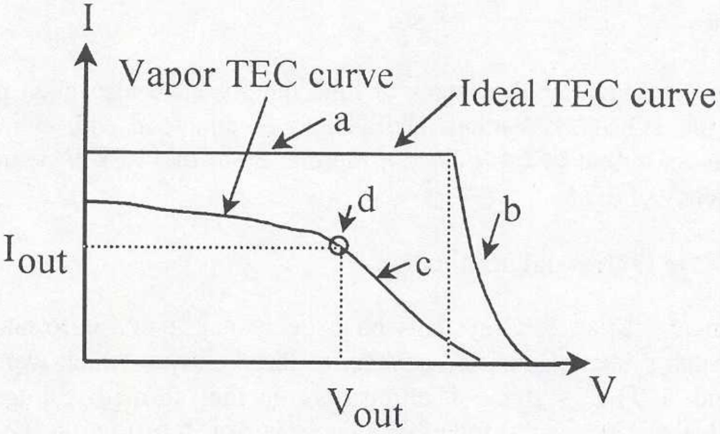

Fig. 5. An I - V characteristic for the high pressure vapor TEC. Curve part "a" and "b" represents an ideal TEC curve, curve "c" represents a real TEC. Point "d" is the operating point for the real TEC. The operating point is chosen where the output power is maximum.

1.5. The TEC in space

There are mainly two types of space TEC technologies: radioisotope heated TECs and nuclear fission heated TECs. For high power density requirements the nuclear fission reactor TEC is the only usable type. The power of planned nuclear fission powered TEC systems range from 10 kWe (kW electric power) to approximately 250 kWe. The planned American space TECs are commonly constructed as cylindrical units, which size is approximately that of an IEC standard R20 battery cell. The nuclear fuel, for example UO_2 , is packed inside the cells, why the emitter electrode is the inner one, and the collector is the outer part of the cylinder. The cells are connected in series in order to give the desired output voltage, and the TEC groups are then connected in parallel. The TEC system low voltage and several hundred amperes are fed to a power conditioner consisting of a power MOS transistor switched transformer system, which after rectifying, delivers the desired voltages to the space craft systems. The life-time is between 7 and 10 years.

The space TEC's emitter temperature and power input is regulated by means of controlling the fission rate i.e. with the aid of control drums made of for example BeO. One problem with TEC systems in space is to get rid of the waste heat from the collectors of the TECs. The most common way is to lead the heat via heatpipes with liquid metal to large radiators on the outside of the power unit. Some typical space nuclear power reactor data on a 10 kWe space reactor are [8]:

Emitter temperature	1700 K
Collector temperature	880 K
Current density	2.5 A/cm^2
Efficiency	5.56 %

High power space TEC systems of high quality have also been produced in Russia, like the TOPAZ II system. The TOPAZ is equipped with cylindrical TEC cells, and has an output of 6 kW_e and a thermal input of 115 kW, which gives an overall efficiency of 5.2 %.

1.6. The TEC in terrestrial applications

Experimental solar TEC systems have been in use in California, USA, for some time. Such systems consisted of a series large mirrors which were placed on stands around a TEC system. The mirrors together formed a huge parabolic reflector with the TEC in the focus. With this mirror construction it was easy to obtain the high emitter temperatures which the TEC system required to function. However, the existing TEC concept is not very interesting for solar applications, since the silicon cell and recently invented photochemical cells have a very good efficiency and use the visible light directly without converting it to heat. If it is possible to increase the efficiency and drastically decrease the emitter and collector temperatures of TECs, they might be able to compete with the solar cells.

However, the TEC is very interesting for electricity generation in combustion power plants. For large power plants TECs can be of interest for a so called "topping stage", which means that electricity is generated in a temperature interval above the normal steam cycle. Special chemically resistant TECs which can stand the corrosive combustion gases are developed in Holland [9] and the USA [2]. Fig. 6 shows a Dutch workhorse prototype TEC for use in combustion heated power systems [9,12]. Recent research has shown that the best way to transfer the heat from the combustion to the TEC is by means of radiation from a body which is heated by the hot combustion gases [10]. Very interesting research on TECs for

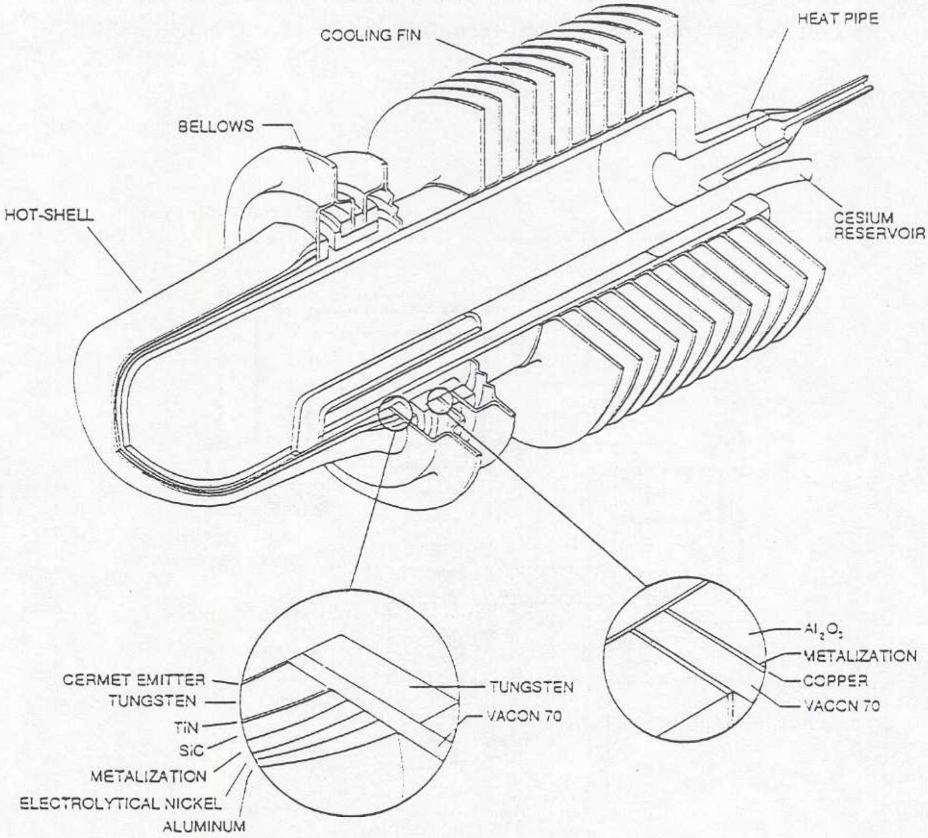

Fig 6. A Dutch prototype TEC for terrestrial power production [9]. The dome to the left consists of the TEC electrodes, where the emitter is the outer dome, and the collector is the inner dome. The cooling fins dissipate the collector waste heat.

cogeneration of electricity in small scale applications is taking place in Holland and Russia, where TEC systems with a power around a few hundred watts are developed for use in gas central heating systems [11].

2. Research TECs

2.1. Traditional closed research TECs

Most TEC experiments have been performed in closed research TECs. The emitter heating systems are mostly electric or electron gun based. In a closed research TEC the electrodes cannot easily be interchanged. In the worst cases the entire construction must be disassembled by means of breaking welded joints or with other destructive methods get access to the electrodes of the converter. On most research TECs only the IG distance, emitter temperature and the cesium vapor pressure can be varied. Most closed research TECs have planar electrodes. Fig. 7

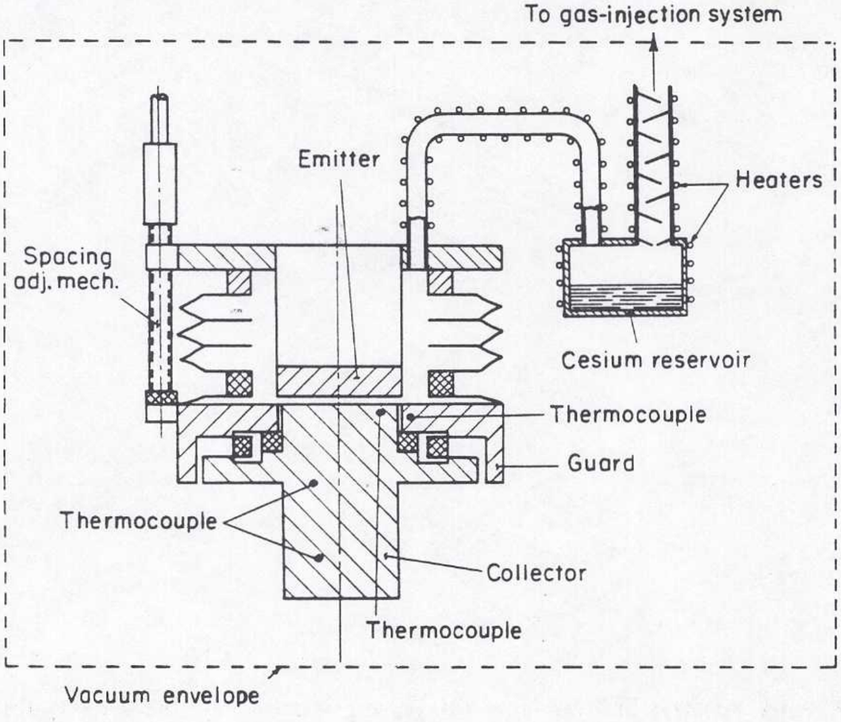

Fig. 7. A closed research TEC. The screw to the left is a part of the electrode distance adjustment mechanism [2].

shows a closed research TEC [2].

2.2. The open research TEC

In order to enhance the possibilities to examine the plasma properties and the electrode surfaces during the experiments, the "open" TEC was developed [13]. This TEC has no closely surrounding walls which can interfere with the plasma, since the electrode system is located in a vacuum chamber where the walls are far away from the plasma and the electrodes.

The alkali vapor is supplied to the IG through tiny holes in the collector surface. The emitter is a metal foil which is fastened in a holder which also serves as electric lead for the heating current which heats the foil. The plasma is "free" in the sense, that the electrodes and the plasma are easily accessible for probing and characterization inside the vacuum chamber. The plasma is only limited by the plane parallel to the electrode surfaces. The electrodes and the plasma are ocularly observable through windows in the vacuum chamber.

Most converters have the electrodes integrated with the walls of the TEC enclosure.

The advantages of the open design can be summarized as follows:

1. No interference with the walls.
2. The electrodes can easily be exchanged.
3. The electrode surfaces can easily be prepared, e.g. by carbonizing.
4. Plasma and electrode surface analysis is possible.
5. Various additives can easily be used.
6. Creep current phenomena on electrode holders is minimized, since they are far away from the plasma region.
7. The IG can easily be altered.

The open converter concept has of course some drawbacks:

1. The open TEC consumes alkali metal at a high rate. Some alkali metals, e.g. cesium, are expensive.
2. Long time continuous experiments cannot be performed, e.g. lifetime tests cannot be done.
3. The electrode area has to be small in order to limit the alkali consumption.
4. The alkali pressure in the IG is not very easy to estimate exactly.

However, the open TEC is only designed for research purposes why these drawbacks generally can be accepted, and the open concept is not intended to be a model for a commercial design. The open research TEC is described in detail in paper I and to some extent also in section 6.

Fig. 8 shows a photograph of the emitter assembly with a mounted Mo emitter foil.

Fig. 9 shows a photograph of the collector assembly with a collector hole foil with a thermocouple spot welded to the rim of the collector.

3. The role of the TEC in various energy systems. Environmental effects

There are many advantages with a TEC power generation system, e.g.:

- Environmentally advantages due to an easier control of emissions, compared to e.g. an internal combustion engine (ICE).
- A long system life due to a minimum of moving parts.
- Low total service costs.
- Good economy also in small energy systems.
- Low noise, very important for domestic applications.
- No lubrication systems. Thus, no leak or waste problems with lubrication oils.
- Possibility to chose the most environmentally suitable fuel. Probably easier and cheaper to change from one kind of fuel to another in a TEC system than in an ICE.
- Less soot particle emissions than from a Diesel engine.

3.1. The TEC as an electric generator in small boilers

One very attractive terrestrial application is to make a small home furnace where heat and electricity can be coproduced. Using this technology, the electricity is more or less "free". The power producing unit is independent of the commercial power grid. The heating system fans, gas valves or oil pumps are also operative when the power grid is down, and there might also be a considerable amount of electricity left for other purposes. The surplus electricity can for example be used for a freezer, which is operative also when the power grid is down. Only the gas or oil supply sets the runtime for the TEC power system. A Dutch TEC concept is under development in cooperation with a Russian research institute. This system, which is a natural gas powered boiler, is designed to deliver 500 W electric power [14,11].

Such cogeneration systems can also be very important for the industry, where there is use for process heat as well as for electricity. A very important feature is that critical parts of a production line can be kept running also when the commercial power grid is down. Such systems can be very important in remote areas, but also in more dense populated areas where gas or oil fueled boilers are used anyhow. The idea of cogeneration of heat and electricity is very interesting, since society will be less vulnerable during a power failure situation. If a high efficient TEC is used, the power figure of 500 W can be increased to 1500 - 2000 W for the same amout of heat used.

3.2. The TEC as a topping stage in a combustion power plant

In a combustion power plant with TECs, it is possible to generate some amount of electricity at a high temperature, and use the output heat from the TEC collector to generate steam for a steam turbine cycle [15]. The output heat can also be used for preheating the combustion air for the burners. The emitter can function at relatively high temperatures, from 1350 to 1850 K. If energy at these temperatures can be used for energy conversion, the Carnot efficiency of the power plant is increased since a wider temperature interval of the process is used for the production of electricity. This is referred to as a "topping cycle". A schematic picture of a topping cycle is shown in fig. 10.

If for example a combustion power plant has an efficiency of 45% and the TEC power unit has an efficiency of 7 % the entire power system will then acquire an overall efficiency of

$$E_{\text{tot}} = E_{\text{TEC}} + (1 - E_{\text{TEC}})E_{\text{com.}} = 0.07 + (1-0.07)0.45 = 0.48. \qquad (4)$$

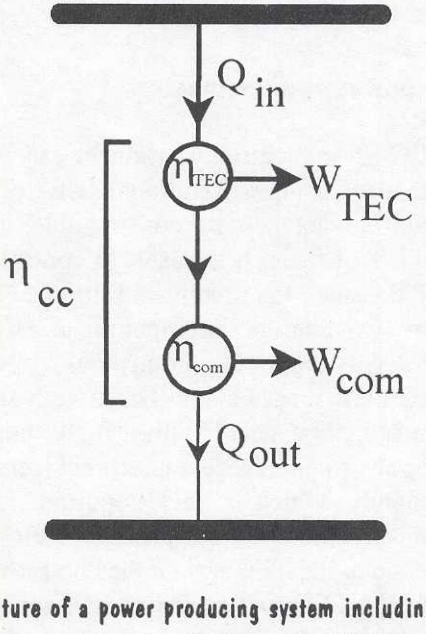

Fig. 10. A schematic picture of a power producing system including a TEC topping cycle. Q_{in} is the input heat in the system, η_{TEC} is the TEC unit efficiency, W_{TEC} is the output work (electricity) from the TEC unit, η_{com} is the efficiency of the combustion powered system without a TEC (e.g. a steam turbine), W_{com} is the output work (electricity) from the turbine, Q_{out} is the waste heat from the turbine stage and η_{cc} is the combined cycle efficiency.

where E_{tot} is the total efficiency, E_{TEC} is the TEC efficiency and E_{com} is the efficiency of the combustion power plant without TECs.

The net efficiency gain is thus 3%. This value is calculated with a traditional TEC included in the system. If the TEC efficiency could be increased to, for example 30 %, the overall efficiency in the same power plant increases to

$$E_{tot} = E_{TEC} + (1 - E_{TEC})\, E_{com} = 0.30 + (1-0.30)0.45 = 0.62. \qquad (5)$$

The increase in net efficiency between the use of traditional TECs and high efficiency TECs will then be

0.62 - 0.48 = 0.14 or 14 %.

The power plant will deliver 17 % more electricity for the same amount of used fuel, compared to a plant without any TEC stage, which means that large amounts of fuel can be saved, and the emission of polluting gases is reduced .

A combined cycle power plant including a gas turbine as a topping cycle, and a steam turbine in the "bottom" have today an estimated total efficiency of 58 % [16].

3.3. The TEC for mobile power applications

A high efficiency TEC as an electricity producer can be an attractive power source in hybrid cars, instead of using a traditional ICE connected to an electric generator. The environmental advantages are considerable, since the TEC system can be powered with a number of fuels. It is easier to control the emissions from a TEC burner than from an ICE, since the combustion in the TEC system is external and continuous. An already existing good competitor to TEC systems is a hybrid car power unit developed by Volvo and other companies in Sweden. The electricity generation unit is an electric permanent magnet based high speed generator driven by a gas turbine without a reduction gear. With a high enough efficiency on the TEC system, a TEC based power unit can be a good replacement. The TEC system can be made to operate silently, which is very important for operation in dense populated areas. The maintenance for a TEC is probably much less than for a rotary or reciprocating machinery, since the TEC system has no moving parts except for a fuel pump and a burner fan. The TEC system has no lubrication system, which is an advantage from environmental pollution point of view as well as from maintenance view.

3.4. Environmental aspects. A comparison between TEC and an ICE

An ICE is often limited to use a few specific fuels suitable for a specific type of engine. For example, while a Diesel engine has a rather limited number of suitable fuels, a TEC system can be fueled with a number of fuels, since the combustion is external and rather system undependent. Possible fuels for a TEC system are for example:

- Conventional Diesel oil.
- Vegetable fuel oils.
- Ethanol.
- Methanol.
- LPG (Liquid Petrol Gas).
- Hydrogen.
- Natural gas.

If for example ethanol is used instead of a petroleum fuel in a power producing system, following advantages can be mentioned:

- Less volatile, i.e. less environmental impact in connection with handling and distribution.
- Less environmental toxicity in connection with for example a fuel leak into the environment. -Alcohol is faster degraded in the environment.
- Negligible amounts of aromates in the exhaust gases.
- Less ground ozone problems than with petroleum based fuels in sensitive areas [17].

A disadvantage with alcohol is higher emissions of formaldehyd (HCHO). However, HCHO is rather easily degraded in the troposphere in a reaction chain involving photochemical reactions.

Since alcohol fuels probably are produced from biomass, the final products water and carbon dioxide are returned into the natural environmental circulation.

4. Rydberg states and Rydberg matter

The work with the new TEC concept was primarily aimed to increase the efficiency of the TEC by means of the development of a new collector which has a very low work function. Cesiated metal surfaces have a work function around 1.2 - 1.4 eV as best, and with an oxide surface, it is possible to obtain a work function of 1.2 eV. In order to make a TEC with a very high efficiency, a work function of 0.4 - 0.7 eV is desirable. Since the IG distance is an efficiency limiting factor, it is also desirable to reduce it. The desired low work function collector as well as the desired small IG distance can be realized with a new type of matter, consisting of condensed highly excited states (Rydberg states) of cesium, so called Rydberg matter of Cs (RM). The question is, whether RM exists or not. A Russian group at

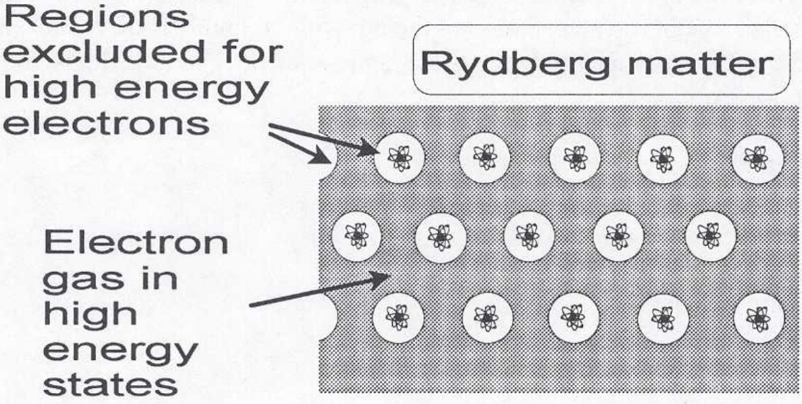

Fig. 11. Simplified schematic picture of RM.

the Kurchatov Institute in Moscow has given a theoretical description of RM [18,19]. They predict the existence of a condensed state where excited electrons interact and form an electron gas between the ion cores. This electron gas gives the condensed matter almost metallic properties. The electrons occupy the space between the positive core ions in a way similar to ordinary chemical bonding and they behave as electrons in an ordinary metal. Fig. 11 shows a simplified picture of RM.

RM has metallic properties and a very low density, and hence a relatively large distance between the ion cores, which gives the desired low work function. It is also partially filling the IG, why the actual electrode distance decreases. The RM in the TEC is under continuous production and decay, why a traditional "wear out" discussion of the RM is not valid. The conductivity of RM is somewhere in the range of that of the semiconductors or carbon.

Rydberg states are electronic states of atoms or molecules with their outermost electron excited to a very high energy level, i.e. large values of the principal quantum number n. The energy levels are given by a simple formula similar to that valid for the hydrogen atom. Rydberg states are thus called hydrogenic. The energy levels are given by

$$E = - C_1 E_H/n^2 , \qquad (6)$$

where E_H is the ionization energy for the hydrogen atom, equal to 13.6 eV and C_1 in a constant for each element. Rydberg states are created in the interaction with hot surfaces, and several experiments which prove the formation of Rydberg states have been performed, see for example refs. [20,21].

The Rydberg states are easily field ionizable, since the Rydberg electron is loosely bound. An external electric field can easily distort the Coulomb field from the core ion, so the electron can leave the atom. The electric field strength limit for this process is given by

$$E_{lim.} = 3.2 \times 10^{8} / n^{4} \text{ (V/cm)} \qquad (7)$$

The time required for this process to take place is not well known, but it is probably of the same order as the radiative life-time. For $n = 40$ this means that a field strength of 120 V/cm is enough to give ionization. The size of the Rydberg states increase rapidly with n. The orbit radius for high l numbers is given by the equation

$$r = C_2 \, a_0 \, n^2, \qquad (8)$$

where C_2 is a constant and a_0 is the radius for the ground state hydrogen atom, 0.53 Å. This means that, for example, at $n = 40$ the radius is 1700 Å. As the size of the electron orbit increases with n, the electron binding energy decreases. The size as well as the lower binding energy contribute to the extremely high polarizability of Rydberg states, which increases as n^7 [22]. In general, the dispersion part of the attraction forces between atoms and molecules depends on the product of the polarizabilities of the interacting particles. This means that the attractive forces between Rydberg states respectively between Rydberg states and ground state atoms or molecules become very large. As a consequence, the collision cross sections also become very large. Since large collision cross sections and attractive forces lead to rapid condensation, the same may be valid for a gas of Rydberg states.The resistivity of the RM consisting of condensed highly excited Cs atoms ranges from 7×10^{-3} to 2×10^{-7} Ohm m for an excitation level of $n = 20$ to $n = 10$ respectively. The resistivity is increases with excitation level, n. The resistivity of RM is comparable to semimetals as Ge, C and Si which has a resistivity of 46×10^{-2}, 1.4×10^{-5}, and 1×10^{-7} ohm m respectively [18,19].

The work function of cesium RM is estimated by Manykin et. al. to be in the range of 0.1 - 0.8 eV when the principal quantum number n ranges between $n = 20$ to $n = 6$ [23].

The Cs atoms interact with a carbon layer [32] which is applied on the collector surface where they are transferred into a highly excited state with a high n quantum number. The excited states of Cs condense on the collector surface and form RM.

There are also strong evidences that IR radiation reexcites the RM which has the effect that the lifetime of the RM is drastically increased in the TEC.

5. Review of the paper

The unifying theme of the papers included in this thesis is new phenomena in a TEC IG which can lead to the design of a highly efficient TEC.

Paper I describes the research apparatus which was used for the TEC experiments. It was also used for a wide range of more general plasma and electrode material investigations presented in the thesis.

It was discovered that when a thin layer of carbon was applied on the collector electrode surface, an entirely new behavior of the TEC and the properties of the IG appeared. When a voltage was applied over the TEC, with the positive terminal to the emitter and with the collector grounded, a very high collector back current appeared, even at relatively low collector temperatures. The high current is supposed to occur due to RM in the IG.

In **paper II** experiments and characterization of the high back current are presented. A large number of runs was performed, where it was discovered that that the resistivity in the IG to some extent was dependent on the voltage which initiated the back current. The high back current was unidirectional. The differential resistivity in the IG was very low, down to 0.01 Ohm m. The low resistivity remained almost unaltered when the interelectrode distance was varied between 0.4 mm and 8 mm. The resistivity results indicate that there is a metallic matter in the IG, which supports the theory that RM is present in the IG.

Paper III presents more experiments concerning the high current phenomena. The work function for the collector was estimated to be less than 0.7 eV, and there were no indication of a current saturation in the fourth quadrant. The emphasis of this work was on the work function of the RM which probably is in direct contact with the collector.

Paper IV is the patent on the new low work function collector.

In order to characterize the IG, extensive optical spectrometric measurements in the infrared and in the visual region were performed. These experiments have clearly showed that there is a great difference in the degree of electron excitation in the normal plasma and in the plasma when the high collector back current is present. The analysis of the spectra has been performed by Bo Olsson and Jan Davidsson, and is presented in **paper V.**

In **paper VI** plasma probing experiments are presented. They showed that the potential gradient in the IG was very small compared to that of a "normal" cesium plasma, i.e. the plasma created by the electron current from the emitter when the collector is positive. This paper also presents temperature gradient studies of the collector surface. The temperature gradient in the collector surface is much smaller in the case of the high back current than in that of a normal plasma. The experiments also showed that the properties of the IG and the region close to the collector are almost metallic, which indicates the existence of RM in the IG. The collector also had a very low work function.

Paper VII presents measurements on excited states in the IG and collector work function calculations.

It was of interest to find out whether the collector hole matrix design affected the formation of the low work function properties of the collector or not. Several experiments were performed with various collector hole matrices. The general properties of the low work function collector were unaltered. The results are reported in **paper VIII**.

In **paper IX** experiments with a diamond covered emitter are reported. The intention with the diamond emitter experiments was to investigate whether an infrared radiating and electrically insulating emitter surface influenced the properties of the low work function collector. The results of these experiments support the assumption that IR radiation enhances the production of RM.

In order to investigate possible material residues in the electrodes, ESCA analysis of the electrode surfaces have been performed. The analysis, which is reported in **paper X**, showed that very small residues from the surrounding electrode support materials existed, and that traces of oxygen and carbon were present. The contents of cesium and carbon in the surface layers of the electrodes, especially the collector, were high, which was expected.

Paper XI describes a possible application of the low work function surface technology in MHD channel electrodes. The experiments were performed with a three-electrode setup where the high emissivity electrode was formed by RM on a metal mesh electrode.

6. Results

6.1. Experimental apparatus

The experiments presented in this thesis have been performed in a research TEC which is presented in detail in paper I. It consists basically of two metal electrodes and an alkali metal container. One electrode is hot, the emitter electrode, and one electrode is colder, the collector electrode. A cesium plasma is confined between the two electrodes. The cesium vapor effuses to the IG through tiny holes in the collector foil, see fig. 12. Thermionically emitted electrons from the emitter travel through the plasma, reach the collector, and pass through an electronic control system back to the emitter.

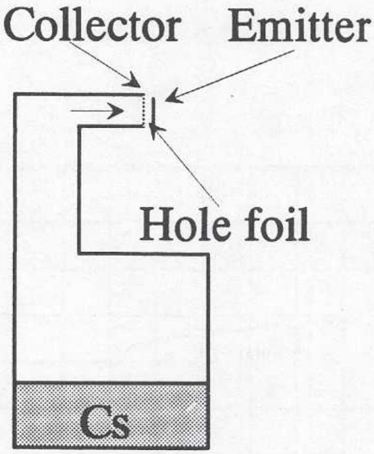

Fig. 12. Schematic drawing of the experimental TEC.

The TEC has an "open" architecture which means that the electrodes are placed in a vacuum chamber, very large in comparison to the dimensions of the electrodes [24,25]. This design permits various probing and analyzing experiments to be performed on the plasma and the electrodes. The emitter electrode is a band foil, and the collector is a circular metal foil with a hole matrix. Fig. 12 shows a schematic figure of the cesium source and the electrodes.

The electrodes in the apparatus can easily be interchanged, since they are only attached with screws to the electrode holders. The experiments presented here have been performed with a Mo emitter, 20 mm long, 5 mm high and 0.5 mm thick. The collector foil was made of Ni, 0.2 mm thick with 400 laser bored holes with a diameter of 0.1 mm distributed over an area of 0.16 mm^2. The interelectrode distance (*d*) can easily be varied from a few tenth of a mm to approximately 7 mm. The emitter temperature T_E can be varied from 400 K to approximately 2000 K, the collector temperature T_C is regulated, and can be varied from 330 K to approximately 850 K. The cesium container temperature T_u can be varied from 325 K to approximately 800 K.

The container has a capacity of 18 cm^3 of alkali metal, which permits, for cesium, an uninterrupted run-time of 12 hours. In practice 5 or 10 gram glass ampoules with cesium are used, which give a run-time of 2 - 4 hours. The apparatus has also a voltage sweep system for plasma control. The apparatus is also very well suited for various general alkali metal plasma experiments, to which various substances can be added.

6.2. Measurements on excited states in the IG

Experiments with Mo emitters and Ni and Ta collectors in the TEC have been

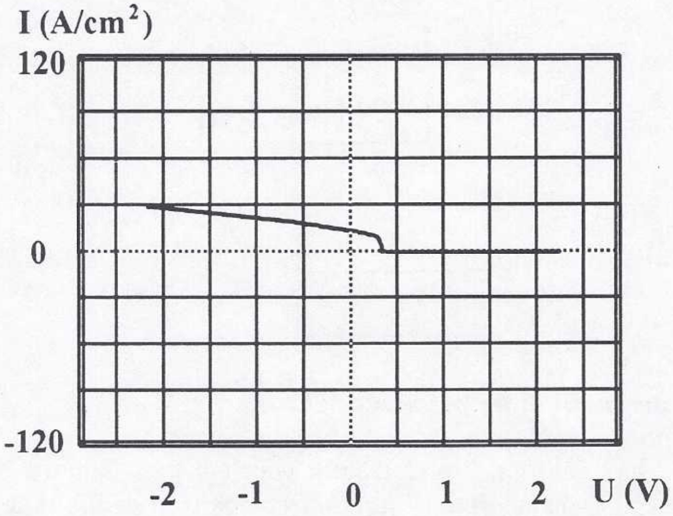

Fig. 13. The Cs vapor TEC *I* - *V* characteristic for a clean Ni collector and a Mo emitter. The V_B value is between 1.9 and 2.1 eV.

performed. The results from the experiments with the collector materials were virtually the same, but the erosion rate of the Ta collector foil was considerably

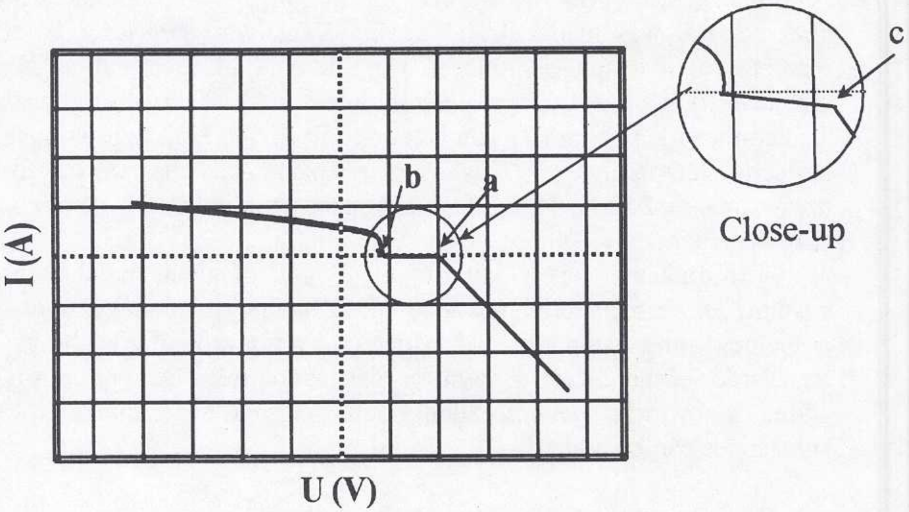

Fig. 14. An *I* - *V* characteristic with carbonized collector surface. Voltage and current values are deliberately omitted in the figure since many different values were used.

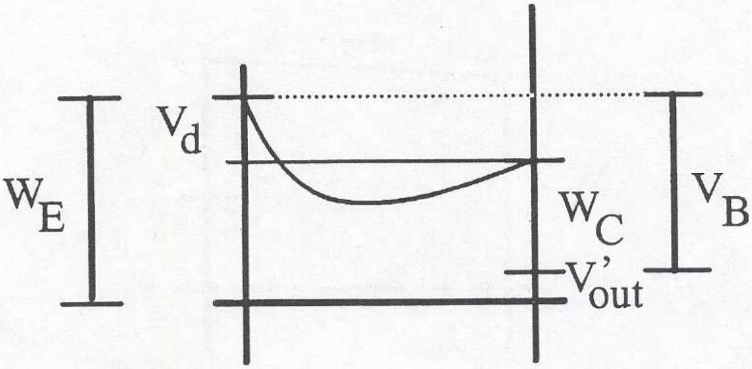

Fig. 15. The potential diagram for ordinary TEC conditions. W_E is the emitter work function, W_C is the collector work function, V_B is the barrier index, V_d is the arc drop and V'_{out} is the output voltage.

higher than that of the Ni collector foil. Fig. 13 shows a rather typical TEC I - V characteristics where T_E is 1400 K, T_C is 670 K, T_u is 570 K, d is 0.4 mm and V_B is around 1.9 - 2.1 eV.

An experimental series with the collector surface covered with carbon was performed. The collector surface was covered prior to the experiments with a thin layer colloidal graphite dissolved in water. The TEC parameters were approximately the same as in the experiment with a clean metal collector surface from which the above depicted I-V characteristics was taken. After approximately half an hour runtime with a carbonized collector, the TEC showed an entirely new behavior. The emitter current in the first and second quadrant showed the same characteristics as in the experiment from fig. 13, but the collector back current was considerably higher, see fig. 14. These high back current properties of the TEC were detected in a wide interval of emitter and collector temperatures. T_E was varied from 900 to 1700 K, and T_C was varied from 500 K to 770 K. The electron energy diagram for an ordinary TEC situation in the apparatus with an arc drop, V_d, is shown in fig.15.

It was of great interest to find the W_C value, since the current was high and T_C was relatively low. This could be done with the use of the so called back voltage factor or barrier index, V_B, together with data from the I - V characteristics of a number of runs. V_B is defined as the sum of W_C and the voltage drop, V_d, across the IG:

$$V_B = W_C + V_d \qquad (9)$$

It is possible to calculate V_B directly from the I - V curves with the equation [25]

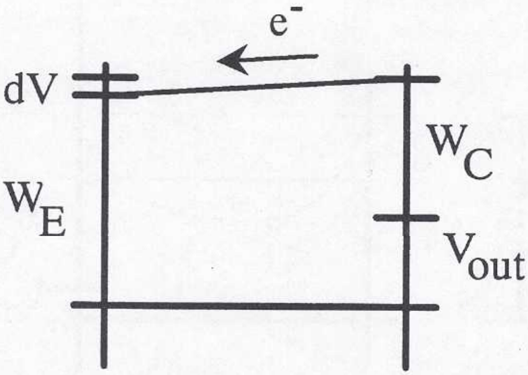

Fig. 16. The potential diagram for the TEC with Rydberg states in the IG. W_E is the emitter work function, W_C is the collector work function, V_{out} is the output voltage and dV is a small voltage across the IG.

$$V_B = - V_{out} - (kT_E /e) \ln(i/AT_E^2), \tag{10}$$

where V_{out} is the output voltage, T_E the emitter temperature, i the current density, and the constant A is equal to 120 A cm $^{-2}$K $^{-2}$.

The diagram shows the situation (point "b" in fig. 14.) where the current goes to zero in the first quadrant. An electron energy diagram with Rydberg states in the IG is shown in fig. 16, where the high back current starts in the fourth quadrant, point "a" in fig. 14.

From the energy diagrams in fig. 15 resp. fig. 16 the equations

$$V_{out} = W_E - W_C + dV \tag{11}$$

$$V'_{out} = W_E - V_B \tag{12}$$

respectively can be derived. Eqs. (10) and (11) give

$$V_B = (V_{out} - V'_{out}) + W_C - dV \tag{13}$$

From eq. 13 W_C can be derived when $V_{out} - V'_{out}$ goes to zero. dV is assumed to be small in comparison to W_C due to the low ionization potential of the Rydberg states. $V_{out} - V'_{out}$ is directly accessible from the run data in fig. 14 where point "a" is denoted V_{out} and point "b" is denoted V'_{out} . $V_{out} - V'_{out}$ can be plotted against V_B .

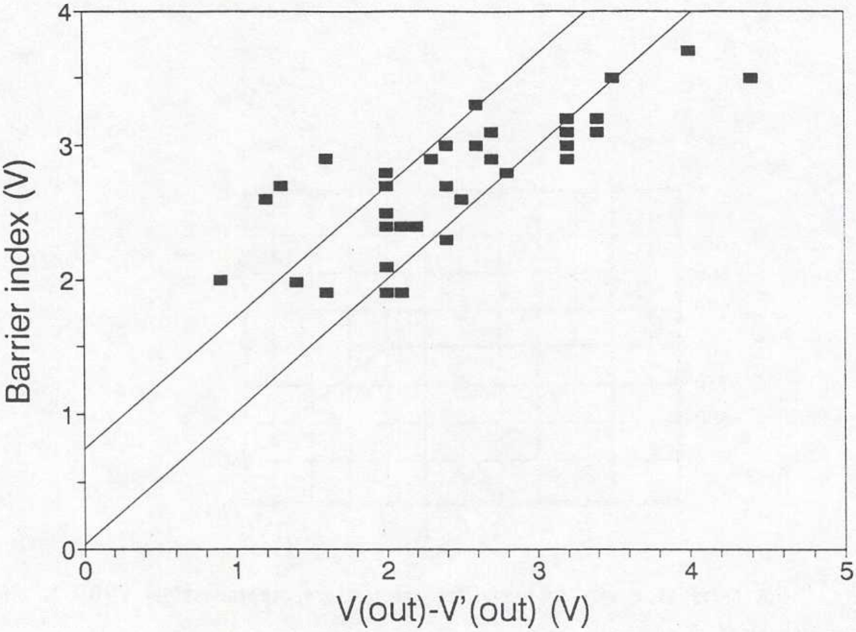

Fig. 17. V_B for a large number of runs plotted against V_{out} - V'_{out}. The collector work function value can be read where the lines intercepts the Y axis. The collector work function value lies in an interval between 0.1 and 0.7 eV.

Such a plot is shown in fig. 17. If the lines in the plot are extrapolated to the vertical axis a collector work function of 0.6 - 1.5 eV can be derived, see eq. 13 and fig. 17.

For example a Rydberg state with an *n* quantum number of 40 have a diameter of 0.17 μm and a binding energy of 9 meV. This means that it only requires 12 V/m to ionize it which easily can be reached in the IG [26,22]. The point where the Rydberg state field ionization current appears (point "a" in fig. 14.) should in the first approximation correspond to zero field strength in the IG. However, there must exist a certain low field strength before the ionization takes place, corresponding to a total voltage over the IG of d*V*. However, d*V* is probably rather low due to the high excitation level of the Cs atoms, as depicted in fig. 16. An interesting phenomenon is the curve part showed in the close-up figure in fig. 14. The slope before point "c" is probably a current limiting due to a double layer on the RM. In point "c" the double layer is broken down, and the RM surface is "clean" and gives full electron emission.

For more information about excited states in a TEC, see ref. [29].

6.3. Resistivity and work function measurements

The very high collector back current observed with carbon on the collector requires some discussion. In order to obtain a high thermionic electron emission from a metal electrode and a current through the IG, the requirements are:

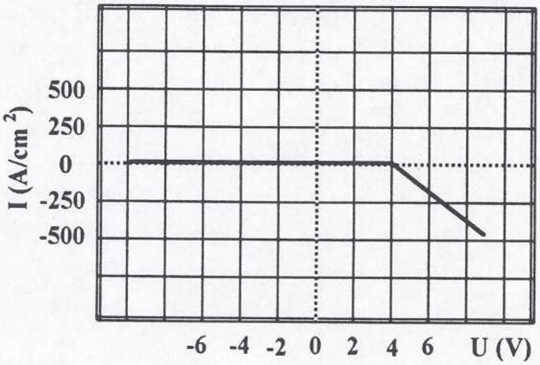

Fig. 18. An *I* - *V* curve at a very high emitter temperature, approximately 2900 K. The collector was carbonized.

1) a low work function of the electrode surface, and
2) conditions which in one or another way eliminate the current limiting space charge outside the electron emitting electrode surface and
3) conditions which decrease collisional losses which in a normal plasma limit the current considerably.

The work function value deduced in the previous section fulfills note 1), but if the high current was supposed to occur in a normal plasma, notes 2) and 3) would still not be fulfilled and hence, the current could not reach the values indicated in the experiments in section 6.2. Several experimental studies were performed within a large emitter temperature interval, in order to investigate the high current and the unidirectional properties of the current. The properties of the high current can be seen in the pictures in the previous section.

The collector temperature in these experiments was kept in a narrow interval, but for most of the experiments T_C was kept at 670 K and T_u was kept at 570 K.

Some of the experiments were run with very high emitter temperatures where it clearly could be seen that the current in the IG was unidirectional. Fig. 18 shows a curve where T_E is 2900 K. At this temperature the alkali coverage on the emitter foil surface is very low due to low surface adsorption why the work function is relatively high, and hence the emitter current is relatively low. However, T_C is kept at 670 K why the parameters of the collector surface are the same except for possible heating of the center of the collector by the increased incident IR radiation from the emitter.

The input power to the emitter foil, except for the power emerging from the emitter heater circuitry, can be described by the equation

$$P_{\mathrm{E}} = (U_{\mathrm{acc.}} + W_{\mathrm{E}})I \tag{14}$$

where $U_{\mathrm{acc.}}$ is the actual accelerating voltage between the electrode surfaces, I is the current through the IG and W_{E} is the emitter work function. For example, P_{E} is 48 W at $I = 6$ A, $U_{\mathrm{acc}} = 3$ V and $W_{\mathrm{E}} = 4$ eV. The actual accelerating voltage between the electrode surfaces is not the voltage measured across the terminals on the apparatus, due to work function differences of the electrodes. The rather high input power to the emitter heats the foil considerably. The collector work function measurements were performed where the back current was maximum. The maximum current was transformed into current density, which together with the measured surface temperature was inserted into the Richardson equation which gave a work function value of 0.6 eV. It was not possible to measure the saturation current, since the emitter foil melted down before reaching that point. The highest current density which could be reached was 500 A/cm^2 . Even if the surface has a work function of 0.6 eV, this is not enough to fulfill the requirements for the transportation of such a high electron current through the IG. The space charge limiting effect and the collisional losses in the IG would still limit the current.

The possibilities that a high density of ions in the IG might cancel the space charge effect can be ruled out since calculations have shown that even if all the cesium in the IG was ionized, it is not sufficient to neutralize the very high electron density.

The linear behavior of the I - V characteristics and the fact that the resistivity and the magnitude of the current stay virtually unaffected when the interelectrode distance is altered, from approximately 1 mm to more than 5 mm, cannot be explained within the traditional plasma theory. As a comparison, the emitter saturation current, i.e. in a normal plasma situation, decreases strongly when the IG is increased.

These results can be explained within the hypothesis that the IG is partially filled with excited matter of the type predicted on theoretical grounds by Manykin et al. [19]. We refer to this matter as Rydberg Matter (RM). The RM is predicted to have metallic properties which is in agreement with the observed linear behavior of the I - V characteristics in fig. 18. The absence of collisional losses can also be explained within the RM theory under the assumption that the electron transport is like that of an ordinary metal or semimetal, and also since the density of the ion cores in RM is very low compared to an ordinary metal. The RM is supposed to be in direct contact with the collector. The existence of RM in the IG explains the phenomena, if the RM is supposed to fill the IG in a way that there is only a very small gap between the RM and the emitter foil, where a normal plasma can exist. If this space is only 5 - 10 μm wide the space charge limiting of the electron current is removed. A limited number of experiments with the TEC showed I - V curves where the characteristics were rather similar to those from an ideal vacuum TEC where the IG must have a distance of not more than 5 - 10 μm in order to cancel the space charge.

The characteristic properties of these experiments were the more or less horizontal emitter current curve crossing the current axis and entering the first quadrant which is rather similar to that of an ideal vacuum TEC. See fig. 4 in paper IV. A characteristic was recorded where the V_B value was 1.64 eV which probably is the best value ever recorded for a TEC. These observations also support the theory that most of the IG is filled with the metallic-like RM which makes the TEC act as an ideal vacuum device, even with a very large IG.

The current limiting factor in the gap is probably not the resistance in the plasma in the gap between the RM and the emitter. The condensed matter probably extends close enough to the emitter surface to form a thin, almost ideal vacuum-like gap with very high field strength and low losses for the electron current. During the experiments, a current saturation was never reached. Fig. 19 shows the electron potential diagram for the above described situation.

The resistivity of the IG was between 0.02 and 0.16 Ohm m. Manykin et. al. [19] have calculated the resistivity for condensed highly excited states of Cs to $7x10^{-3}$ Ohm m for an excitation level of $n = 20$. Excited states of Cs formed at hot surfaces with a quantum number n between 10 and 30 have been investigated. The diameters of these range from 0.01 to 0.1 μm, and they have an ionization potential of 10 - 100 meV [21,31]. A condensed phase of these states have approximately the same distance between the atom cores as a gas at a pressure of 0.01 to 10 mbar.

The pressure in the IG is in the right order for the formation of this condensed state. Thus, the measured resistivities in the IG correspond to the theoretically

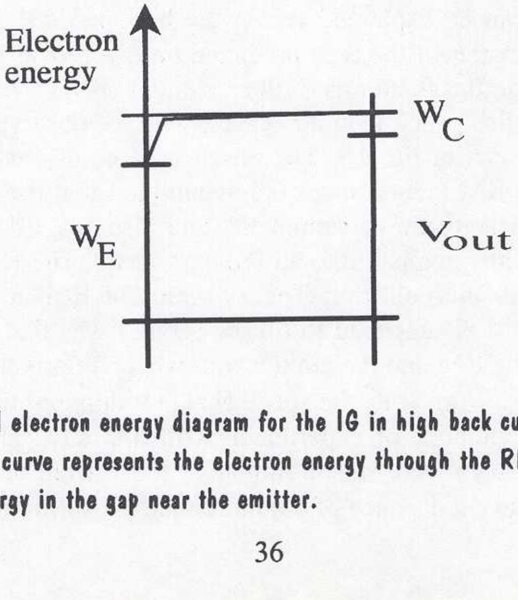

Fig.19. The simplified electron energy diagram for the IG in high back current mode. The almost horizontal part of the curve represents the electron energy through the RM, and the steep, short slope the electron energy in the gap near the emitter.

calculated *n* numbers [19]. Deviations from the theoretical values are to be expected since the conditions in the IG are not ideal.

The work function value of the RM is probably much less than the measured value of 0.6 - 0.7 eV. A value of 0.1 - 0.4 eV might be possible for the IG. These values correspond to an *n* quantum number of $n = 13$ to $n = 20$ [23].

6.4. Voltage probing of the IG

In order to investigate the potential distribution of the IG, experiments with a Langmuir probe were performed. The Langmuir probe consisted of a 0.1 mm thick tungsten wire whose tip was inserted in the plasma and which could be moved from the collector surface to the emitter surface perpendicular to the electrode plane. The apparatus was run in normal plasma mode (P mode) and also in the mode which exhibits the high collector back current, Rydberg current mode (RC mode). The interelectrode distance was relatively large, approximately 7 mm, in these experiments to have a wide enough space for the probe movements. The experiments have been performed with a few different electrode voltages and currents. See the potential diagram in fig. 20.

The potential function could not be measured very close to the surfaces, since the probe tip was thicker than possible electrode surface sheaths. However, the aim with this experiment was to investigate the properties of the bulk of the IG, and for that purpose the probe tip was small enough.

Several potential measurements were performed in RC mode as well as in P mode. The potential distribution in P mode had a higher gradient than in RC mode.

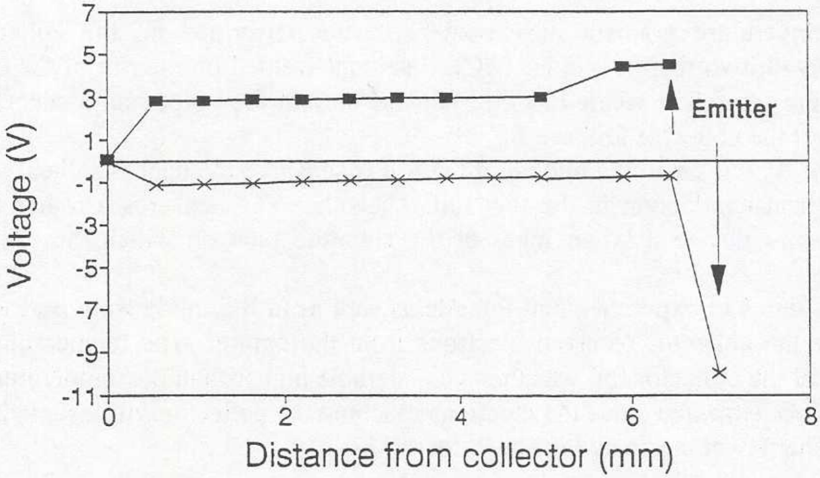

Fig. 20. A potential diagram over the IG in RC mode and P mode. The upper curve is from RC mode measurements, and the lower curve is from P mode measurements. The collector was grounded.

However, it must be emphasized that the IG in these experiments was considerably wider than that of a normal TEC and a field was applied to the emitter which accelerated the electrons to the collector (plasma mode, or P mode) why no exact comparisons with normal TEC conditions can be made. The potential gradient in RC mode was only a few mV per mm. The small gradient in RC mode shows that the conduction in the IG is very high compared to that in P mode. The results from the P mode measurements with a relatively high potential gradient are expected. The high conductivity supports the theory that the IG is filled with RM with metallic properties. The RM acts as a low resistive metal bridge for the current through the main part of the IG. These results are in agreement with the experimental results in sections 6.2. and 6.3. The rather high constant voltage in RC mode is probably due to differences in work function of the probe and the RM surrounding the probe.

Using the experimental results from the voltage probing the resistivity of the RM is in the range of 10^{-5} - 10^{-4} Ohm m. This value is somewhat lower than those given in sections 6.3 and 6.4 since these results include resistivity in possible sheaths and electrodes. This value is calculated from a measured voltage difference in the middle of the IG excluding the regions close to the electrodes. It corresponds to a quantum number of approximately $n = 10$ which then corresponds to a work function of 0.5 eV for the RM. However, due to the non-ideal conditions in the IG, these values must not be considered very accurate. The homogeneity and the area of the RM on which the measurements were done are very uncertain variables, which influence the resistivity calculations.

6.5. Collector surface temperature distribution measurements

Temperature gradient measurements were performed on the collector foil surface with two thermocouples (TC), one spot welded on the rim of the collector foil where the foil is welded to the stainless cesium feed pipe and a second to the middle of the collector foil, see fig. 21.

The TC closer to the middle of the foil is sensitive to changes in heat flow due to low heat conduction in the thin foil. The other TC measures a rather constant temperature due to a larger mass of the stainless pipe on which the foil is spot welded.

A series of experiments in P mode as well as in RC mode were performed. In P mode the collector received electrons from the emitter. The temperature in the middle of the collector foil was then considerable higher than the temperature of the rim. This is expected since the electrons reaching the collector will lose their energy there. The power dissipated is equal to

$$P_C = (W_C + U_{acc})I \qquad (15)$$

where P_C is the dissipated power in the collector foil. W_C is the collector work function, I is the current and U_{acc} is the accelerating voltage between the

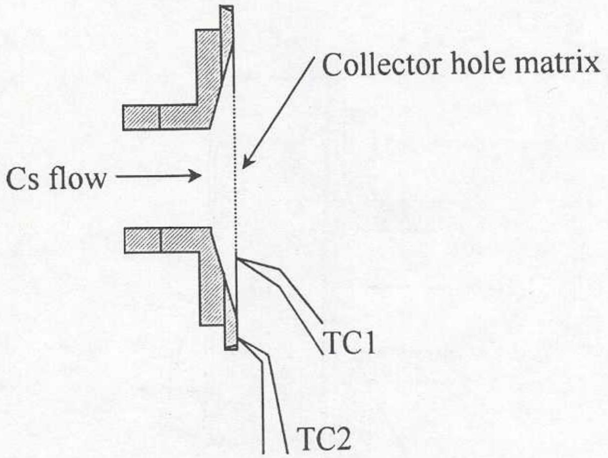

Fig.21. The TC arrangement on the collector surface. TC1 is called the "inner TC" and TC2 is called the "outer TC" in the text.

electrodes. The result can also be seen as a test that the TC configuration works. However, it must here be noted that the entire measured electron current *from* the emitter to the collector probably does not reach only the collector foil. Some portion of the electron current is picked up by the collector support surfaces around the collector. The percentage of the electrons hitting the collector support is not very easy to estimate, since the emitter electron emission density is a function of the cesium coverage along the emitter. Actual values of total dissipated power are from 15 to 40 W. However, the electrons do not have an energy corresponding to the entire accelerating voltage when entering the collector, due to velocity losses in the plasma. A total loss free energy transport fulfilling eq. 15 would give larger temperature differences than detected in the collector foil.

When the RC mode was used, the temperature difference between the TCs was much smaller in almost all experiments and sometimes close to zero. The temperature difference in P mode varied between 20 K to 60 K, where the higher temperature was read on the TC closer to the middle of the foil. The temperature difference in RC mode varied between zero and 20 K. In this case zero means that the difference in reading was less than a K. Most of the measurements gave a temperature difference of around 5 K where the higher temperature was read from the outer TC. These differences were not very dependent on the current in the IG, which was kept between 25 to 35 A cm^{-2}. However, in some runs the inner TC showed a slightly higher temperature, which probably was due to IR radiation from the emitter.

The small difference in temperature readings between the two TCs, when the

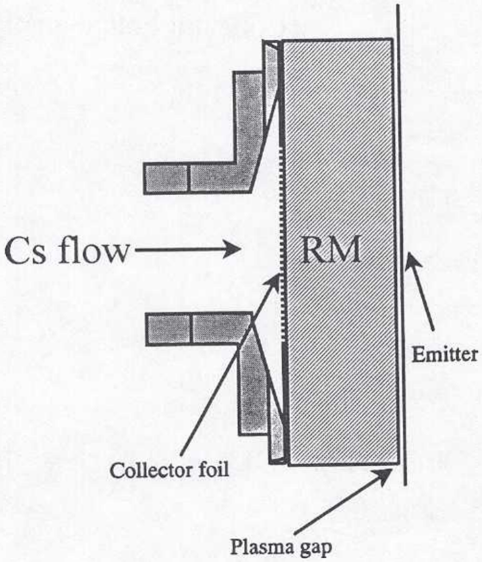

Fig. 22. A simplified schematic picture of the RM covered collector surface. The "brick" of metallic-like RM acts as a heat equalizer over the surface.

apparatus was run in RC mode, indicates that the RM is in direct contact with the collector surface. The electrons from the collector Ni metal surface are in thermal equilibrium with the RM why there is almost no electron energy jump between the collector surface and the RM, hence the low cooling effect of the foil. The low cooling effect is also due to a very low work function of the RM layer. The results of the temperature measurements are thus in agreement with the assumption that the RM is in contact with the collector foil, which was stated in the sections 6.3 and 6.4. The results show that there is very little radial heat transfer through the collector foil. This conclusion is based on the fact that the temperature difference between the two TCs approached zero when the IG distance was increased.

A heating effect of the collector might from a classical point of view be due to impinging ions, but it is not very probable that there is any appreciable ion current to the collector since the RM probably should be heavily disturbed. There is a very small possibility that there is a significant production of ions in the very narrow gap close to the emitter foil due to the small amount of Cs there. The spectroscopic measurements (sec. 6.10) do not indicate any ions in the IG in RC mode. Fig. 22 shows a simplified picture of the RM covered collector surface.

6.6. Experiments with different collector hole matrices

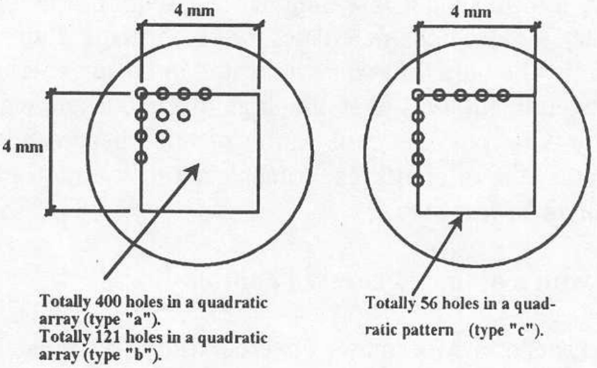

Fig. 23. The collector hole matrices. The matrices are made from 0.2 mm thick Ni foil.

All the reported experiments with the apparatus described in this thesis have been performed with collector hole matrices which consisted of 400 laser bored holes with a diameter of 0.1 mm arranged in a quadratic pattern with the area of 4x4 mm^2. In order to investigate if some of the reported anomalous phenomena in the apparatus might be influenced by the collector hole matrix design, a series of experiments with different hole structures was performed. Three types of hole matrices were used. The 400 hole matrix will here be referred to as the "standard" matrix. The other matrices used in these experiments was one with 121 holes in a quadratic pattern and one with 56 holes forming a square, see fig. 23. The hole diameter was the same for all the matrices. The experimental series started with an experiment with the standard matrix where emitter temperature, collector temperature, IG distance and cesium pressure were set to approximately the same values as in previous experiments where the apparatus was optimized for investigation of the high back current. This will be referred to as "the reference experiment". The reference experiment gave the expected results, which means that the high back current appeared with a carbonized collector only. The experiments with the new matrices were at first carried out with the same apparatus parameters as in the reference experiment. When the experimental series started the emitter saturation current was very low, even after an hour or more. This was due to the low cesium vapor pressure in the IG because of the fewer holes in the collector matrix. The Cs pressure was subsequently increased in order to have the same Cs vapor pressure in the IG as in the reference experiments.

A series of experiments with non-carbonized surfaces were performed showing no back current. The matrices were then carbonized, and the high back current appeared. The magnitude of the current and the resistivity of the IG showed the same properties as for the reference experiment. The experiments showed that the RM density and the distribution on the collector surface was rather similar to that of the reference experiment. Since the matrices all had fewer holes than the standard matrix it could be expected that a lower back current should be registered, if the RM distribution on the collector surface is dependent on the number of holes or hole edges in the foil. In such a case a higher resistivity of the IG should also be expected. However, the RC characteristics were virtually the same as in the reference experiment. The only difference indicated in these experiments compared to the reference experiment was that the high back current was unstable and appeared irregularly. One possible explanation of this phenomenon is that due to the fewer holes than in the reference experiment, the distribution of the RM to the collector surface might be less stable.

6.7. Experiments with a diamond covered emitter

In these experiments a Mo emitter covered with a diamond layer was used. Prior to the experiments the surface resistance was measured. The resistance between a probe at the diamond surface and the Mo substrate was 85 kohm. During the experiments the collector was grounded, and voltages from zero to 350 V and IG distances between 0.5 to 5 mm were used, which gave a field strengths between 3.5 MV/m and 70 kV/m. The standard type of collector was used.

After the experiments the diamond emitter (DE) was taken out from the system, and the surface resistance was measured. With an electronic resistance meter and a pair of Pt wires approximately 0.2 mm thick with smooth ends, the surface resistance with respect to the Mo substrate was measured. The resistance had increased considerably compared to that of the DE before the experiments. The resistance before the experiments was 85 k Ohm to the substrate, and after the experiments it was 350 - 700 k Ohm. However, the very narrow plasma streak source's resistance to the substrate could not be detected with this method.

Prior to the experiments with the diamond emitter (DE) an experiment with an

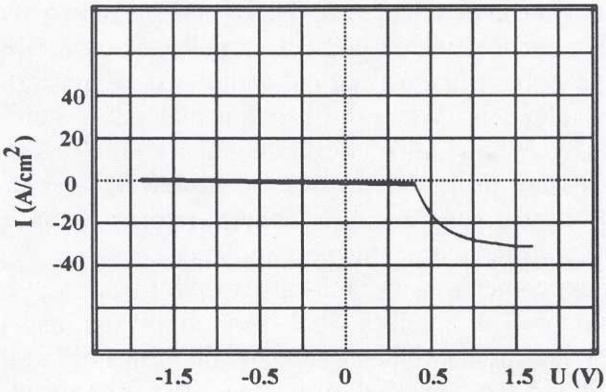

Fig. 24. The back current characteristic in the DE experiments. The emitter current in quadrant two was in the mA range.

emitter of pure Mo metal was performed. T_E was 1200 K, T_E 670 K, and P_{Cs} was approximately 0.5 - 1 mbar. The results of this experiment were similar to those reported in sec. 6.3 and 6.4. This is referred to as "the reference experiment".

The experimental series started with emission tests of the DE in a vacuum. The electron emitting properties of the DE were examined when it was cold as well as hot. The DE did not show any electron emitting properties when cold. The parameters of the apparatus were then set to those in the reference experiment. In the beginning no significant current in any direction was detected. After 30 minutes and with $T_E = 1200$ K a high back current appeared, see fig. 24.

The back current was less than 35 A/cm^2 . There was a limiting effect in the current not seen in the reference experiment. The emitter temperature could be varied in a wide interval, from 850 K to 1450 K without remarkable changes in the back current. If T_E was decreased below 800 K the high back current disappeared. This is consistent with the reference experiment.

An emitter current in the mA region was detected which probably emerged from the ends of the DE which were bare metal. Three hours after start I_E increased slowly and a few plasma streaks appeared as sharp "needles" between the electrodes. The measured current, temperature and an estimated emitting area where the needles emerged from gave a work function for the DE of less than 1.5 eV for the spots. This value is in the low end for being only a cesiated Mo surface, why the emission probably is caused by some yet unknown phenomena. Due to the very low Cs vapor pressure around the bare ends of the DE, their contribution to the emission was negligible. This estimation was also based on the fact that the current was very low before the plasma streaks appeared and that the current was a function of the number of visible plasma streaks. Seen from another standpoint this observation gives an experimental evidence for the previously assumed low Cs pressure around the emitter ends outside the circular collector structure.

Thus, the high back current phenomena appeared also with an emitter which was originally mainly an isolator. The IR radiation from the surface probably enhanced the RM production on the collector. The current cannot enter the emitter foil in the middle since that part is an isolator, why the RC probably flowed to the bare ends. However, on the bare ends the Cs pressure is low, why the RM density is low which probably is the explanation of the limited size of the RC.

6.8. ESCA analysis of the electrodes

Surface analysis was performed with the ESCA (Electron Spectroscopy for chemical Analysis) analysis method on a few used emitter and collector surfaces. The collector surfaces had all been carbonized prior to the TEC experiments and had been used in several runs, each one lasting for 2 hours, prior to their removal from the apparatus and transport to the ESCA analysis facility. The region that was analyzed had a diameter of 0.8 mm. This study was performed mainly for three reasons:

- to verify the existence of C on the electrode surfaces,
- to see to what extent the Cs diffused into the bulk of the electrodes,
- to investigate whether other materials in the system might have contaminated the electrodes.

Spectra were taken on the surface layer as well as at a depth of 1000 Å down in the material. Only the surfaces which had faced the IG were analyzed. In some cases, a probably oxidized spot on the upper layer of the collector surface was scratched clean.

In the emitter, the amount of Cs was largest on the surface while the content of Mo was much smaller. Also the oxygen content is large. This means that the surface layer consists mainly of Cs and its oxides. At 1000 Å depth Mo dominates the spectrum, but Cs is still present. The Cs signal was only 25 % of that on the surface. The Cs content at this depth is approximately 10 - 20 atomic %. Oxygen was also present at this depth and the ratio between Cs and O peaks was the same as on the surface, why oxidization of the surface during transport to the ESCA facility is not probable. There was also a notable carbon content on the emitter surface. There were indications that the carbon might also exist chemically bound as carbides on the surface.

The spectrum of the collector shows that the surface layer consists mainly of Cs and O as in the case of the emitter. However, the amount of C is larger than for the emitter. After etching to 1000 Å depth the spectrum becomes less complex with Ni dominating. Some oxygen is left but virtually no C. However, small amounts of Mo are observed which are probably due to Mo erosion and migration from the emitter.

It is of interest to note that substantial quantities of C are found on the electrode surfaces. The C layer is crucial for the RM production on the collector.

6.9. Three-electrode experiments

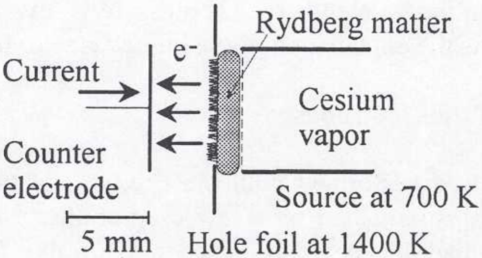

Fig. 25. A schematic drawing of the three-electrode setup. The emitter is a Mo foil, The hole foil is a 0.2 mm thick Pt foil with many holes and the collector is the "standard" collector matrix.

A new device has been constructed which is designed to form and retain a layer of RM on a metal mesh. The construction is showed in Fig. 25. Between the collector and the emitter in the TEC a third electrode was introduced. This electrode is a Pt mesh with many laser machined holes giving an open area fraction of about 20 %.

The condensing Rydberg states of Cs diffuse out into the space between the collector and the Pt mesh, here called the "hole foil". Some of the RM extends out through the holes in the foil, where the RM in the holes gives a very low work function surface, and a high current can flow from the hole foil to the emitter. The work function of the surface of the hole foil is between 1.2 and 1.4 eV.

Experiments were performed which gave current densities of 10 A/cm^2. A sweep voltage was applied between the hole foil and the emitter. When the emitter was negative an electron emission current was detected which was similar to that of 2-electrode experiments described in sections 6.3 and 6.4. When the hole foil was negative with respect to the emitter a considerably higher current, compared to that of the emitter, was measured. The *I* - *V* characteristics recorded in this mode were rather similar to those from previously described 2-electrode experiments in RC mode. The *I* - *V* characteristics support the assumption that RM penetrates the holes in the hole foil and gives a low work function surface on the other side of the hole foil. Fig. 26 shows an *I* - *V* characteristic for the emitter - hole emitter circuit.

The production of RM was monitored by means of a voltage across the

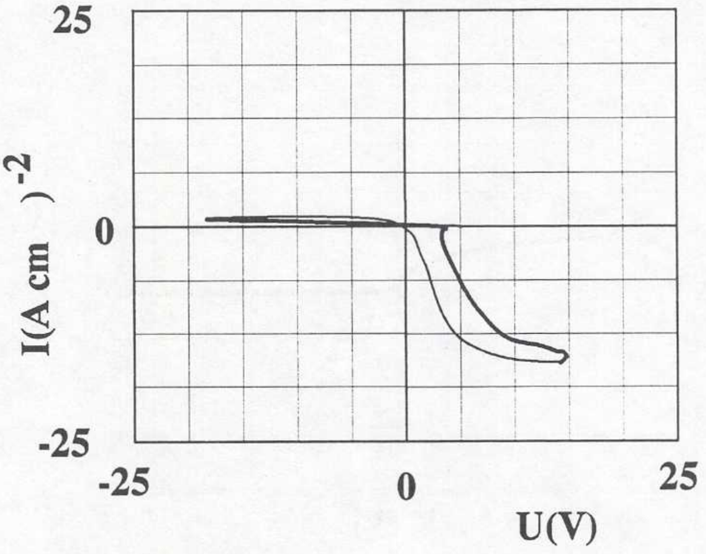

Fig. 26. An *I* -*V* characteristic for the emitter - hole emitter circuit. In the second quadrant the emitter electron current to the hole emitter is represented, and in the fourth quadrant the hole emitter electron current to the emitter is represented.

collector and the hole foil. However, the current measured in the space between the hole foil and the IR emitter was lower than that from a 2-electrode RC experiment, and a clear current saturation was detected. A possible explanation is that the RM cannot establish a direct contact with the hole foil due to the high temperature of the hole foil, which means that there is a plasma gap at it's surface. It is also possible that the main part of the gap between the hole foil and the emitter is not filled with RM, but with a normal plasma. The hole foil had to be kept at a rather high temperature probably in order to emit the necessary IR radiation for the RM production on the collector surface. A decrease in hole foil temperature gave the result that the RM in the space between the collector and the hole foil vanished, which is consistent with the observations in the two-electrode experiments where the emitter takes the place of the hole foil. More investigations are necessary on this subject.

6.10. Spectroscopic investigations of the IG

Spectroscopic measurements were performed on the IG of the TEC. The study, which is presented in paper V, includes runs in normal plasma mode (P mode) as well as in Rydberg current mode (RC) mode, see fig. 27. The solid curve shows the normal and expected behavior in P mode, where the emitter foil emits electrons. The dotted line represents the RC mode, where the electrons are emitted from the colder collector electrode.

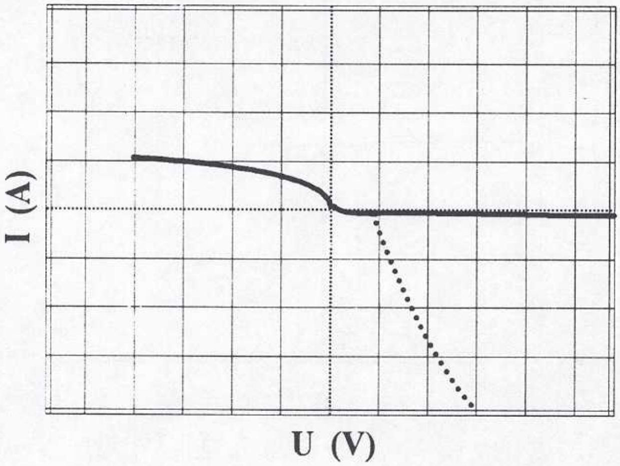

Fig. 27. An *I* - *V* characteristic when an AC voltage is applied over the IG. The solid line shows the behavior in P mode, and the dotted line the behavior in RC mode when the collector is the electron emitting electrode. The TEC is not optimized for delivering output power.

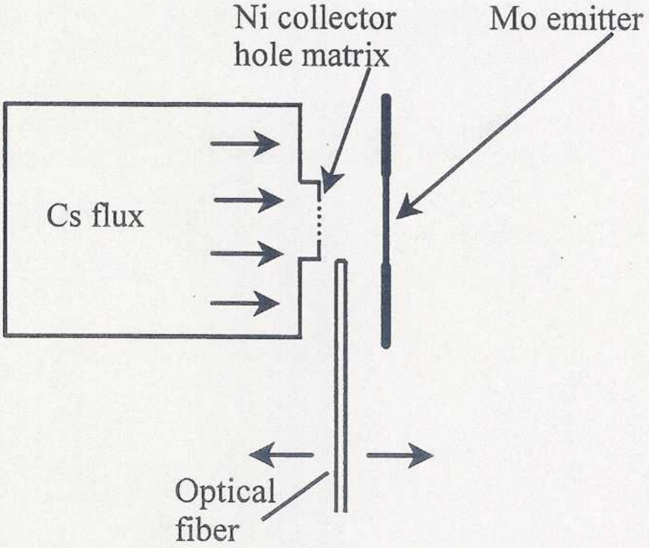

Fig. 28. The optical fiber and the electrode setup. The electrode setup is similar to that in sections 6.2 and 6.3. The optical fiber can be moved along the IG.

The emission spectra in the two modes were analyzed and compared. The apparatus setup is similar to that described in sections 6.2 and 6.3 The objective for these experiments was to investigate possible differences in the plasma between the two modes. Fig. 28 shows a schematic picture of the setup of the optical fiber and the electrodes. The spectroscopic experiments were performed with the ambition to

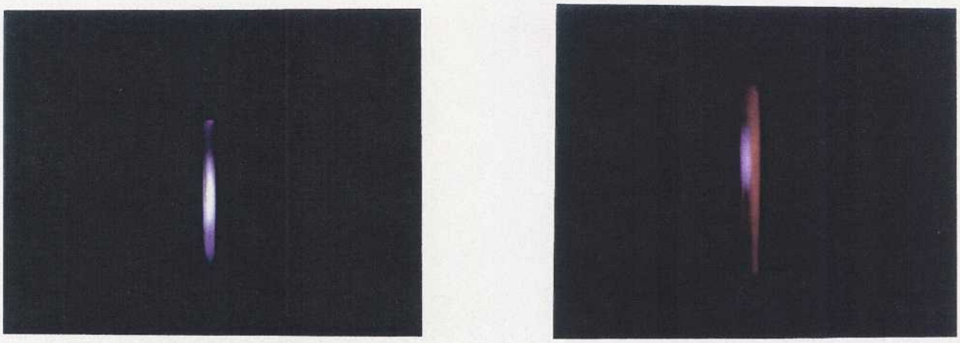

Fig. 29. These pictures are taken from the roof top window on the apparatus. The left picture shows the IG and the electrodes in P mode, and the right picture shows the IG and the electrodes in RC mode. The total power input in P mode is 17.5 W and in RC mode 26.5 W.

keep similar currents through and voltages across the electrode gap in P mode as well as in RC mode. It is somewhat difficult to know the exact voltage between the electrodes, since the work function of the electrodes is not accurately known. It should be borne in mind that the effective potential drop over the electrode space is different from the applied voltage due to the difference in electrode work function, and this potential drop depends also on the direction of the external voltage applied to the electrodes. Thus, several spectra were taken with different voltages over the electrodes and different currents through the IG. However, it was found that the spectral characteristics were only to a small extent dependent on the voltage across the IG.

The results of the spectroscopic experiments is that the degree of electron excitation is considerable lower in RC mode than in P mode, which might indicate that the density of free electrons is lower. This could actually be seen with the bare eye, see fig. 29. Why there should be a considerably lower density of free electrons in RC mode than in P mode is not easily explained within conventional plasma physics. The excitation temperature of the highly excited states near the hot foil actually is much higher than near the collector. These observations and the fact that the intensity differs between the two modes in general indicate that the conduction mechanism in RC mode differs considerably from that in P mode.

In P mode ions were seen at an applied voltage of approximately 6 V. No ions were observed in RC mode. Due to the very high conductivity in RC mode, the same applied acceleration voltage was probably never reached. The absence of ions *might* be due to the difference in applied voltage. This discussion is included in ref. [31] but not in the article (paper V). Experiments in which this limitation is canceled are planned. The low density of free electrons in the electrode gap and the lower light intensity in RC mode support the theory that the electrode space is partially filled with RM, which has metallic properties and carries the electron current.

High electron excitation temperatures, around 1000 - 1300 K, exist near the emitter. This observation is consistent with the theory that there exists a small gap between the emitter and the RM, where a normal plasma can exist. The rest of the IG is filled with RM. This agrees with the picture that RM decays near the hot emitter. Probably this gap between the emitter and the RM is thin enough to act more or less like a vacuum gap with virtually no space charge limitation for the electrons. This might be a partial explanation of the high current discussed in sections 6.3 and 6.4.

7. Conclusions and future research

7.1. Conclusions

When experiments with the TEC were performed with clean metal surfaces, the collector back current was in the order of milliamps per cm^2 which is considered as normal back currents in a TEC. The high back current reported in sections 6.2 and 6.3 appeared only when the collector surface was carbonized. Other experiments performed in our group have clearly indicated the existence of highly excited cesium states when cesium vapor interacts with carbon foils or carbonized metal surfaces.

The phenomena in the TEC cannot be explained within the traditional plasma theory. The current is too high with respect to space charge limiting, too linear in the measured ranges and the high current indicates an electrode work function which is far lower than that of any known cesiated metal electrode surface. The theory that a condensed form of highly excited cesium atoms, Rydberg Matter (RM), exists in the IG gives an explanation for these phenomena. The voltage probing results also indicate that a low resistive material exists in the IG in agreement with the RM theory. The temperature studies of the collector surface indicate that the RM equalizes the temperature of the foil in the same manner as a metal layer would do. The low heat flow also indicates a very low work function of the RM. Emission spectroscopy indicates much lower free electron density in the RC mode than in a normal plasma, which supports the RM theory.

Ocular observations and photographs show that the light intensity in the IG is much lower in RC mode than in plasma mode with the same, or with even higher, electrical power input. These observations also support the RM theory.

7.2. Future research

In the experiments reported in this Thesis a saturation point of the high back current was normally not reached due to limitations in the power systems and overheating of the electrodes. It is of great interest to find out if and where a current saturation can be found as the emitter saturation current in a normal plasma. A saturation point can give the effective work function of the RM surface, and perhaps also give information about the narrow plasma gap at the emitter foil.

Rapid pulsing of the TEC is interesting for finding methods for controlling the RM on the collector for use in high efficiency TECs. Pulsing experiments of traditional TECs have been performed by other groups [27]. More work is also planned in order to investigate the RM density as a function of variables like current and voltage over the IG. A TEC prototype with RM collector is planned in the near future.

In order to gain a deeper knowledge about the inner structure of the RM diffraction experiments are planned. A good method might be to use neutrons with an energy of approximately 3 meV which probably give less perturbation of the RM than for example high energy photons.

More experiments in the high back current mode are planned, e.g. long-time runs. The run-time with the presented set-up was limited by the cesium supply which gave a run-time of approximately 2 hours with the used cesium ampoules. The low resistivity in the back current mode and the probably extremely high saturation current level makes it very interesting to use the RM device in a high-temperature switch, like the "Tacitron" [28]. Such switches are useful in for example nuclear powered satellite systems where semiconductor devices cannot survive because of high temperatures and high radioactive radiation levels from e.g. an on-board nuclear power system.

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