“Re-establishment and optimization of the heating unit of a tungsten cathode for the production of alkali plasma in a Q-machine”

Master Thesis

In order to obtain the academic degree
„Master of Science in Engineering“

Degree program:
„Engineering, Environment & Biotechnology“
Management Center Innsbruck

MSc Supervisor: **Ing. Ronald Stärz**
Management Center Innsbruck
Mechatronics- Mechanical Engineering
Austria

Tutor 1: **ao. Univ.-Prof. Dr. Roman Schrittwieser**
Leopold-Franzens-University Innsbruck
Institute for Ion Physics and Applied Physics
Austria

Tutor 2: **Robert L. Merlino, Ph.D., Professor**
University of Iowa
Experimental Plasma Physics
U.S.A.

Author: **Patrick Hofreiter, BSc**

Matriculation number: **0810352006**

Iowa City, June 2010

DECLARATION IN LIEU OF OATH

I hereby declare, under oath, that this master thesis has been my independent work and has not been aided with any prohibited means.

I declare, to the best of my knowledge and belief, that all passages taken from published and unpublished sources or documents have been reproduced whether as original, slightly changed or in thought, have been mentioned as such at the corresponding places of the thesis, by citation, where the extent of the original quotes is indicated.

The paper has not been submitted for evaluation to another examination authority or has been published in this form or another.

Iowa City, 30.06.2010 ______________________________

Contents

1 Abstract

The Institute of Ion Physics and Applied Physics at the University of Innsbruck (Austria) and the Department of Physics and Astronomy from the University of Iowa (U.S.A.) produce alkali plasma for research by using a Q-machine.

A Q-machine consists - among other things - of a heating source which is used to heat up a tungsten or tantalum plate, during high vacuum to about 2000K.

Due to bridging of a cooling water unit, during handling the heating source of the Q-machine in Innsbruck, the heating source and the water cooling coil has been damaged. Therefore a defect analysis as well as problem handling measures was necessary. The damaged heating source and the cooling water unit had been repaired and a description of the commissioning procedure was provided which should protect the machine from further damages. Furthermore it was necessary to rebuild the vacuum system of the Q-machine because it was out of commission for approximately three years. Accordingly, it was possible to re-commission the Iowa Q-machine to reach an operating condition which allowed a contactless temperature measurement at the hot plate by using a pyrometer.

Similar to the Q-machine in Innsbruck, the Q-machine in Iowa City was not in working order for the last three years. In this case the defects of the machine, especially of the high vacuum system had been analyzed and eliminated, so that the re-commissioning of the Q-machine was possible. Consequently an operating condition could be reached which allowed the contactless temperature measurement at the hot plate in order to obtain its temperature profile. Therefore it was possible to compare the actual temperatures with an ideal recommended temperature profile for plasma production in a Q-machine.

The results of this comparison show that there is still room for improvement for the heating unit in Innsbruck as well as in Iowa City to obtain a more uniform temperature profile at the hot plates surface. Furthermore the heating units of the Q-machines in Innsbruck and Iowa City had been compared with other heating systems and possible optimizations were suggested.

The fundamentals, the approach and the results of the research are documented in this master thesis.

2 Kurzfassung

Das Institut für Ionenphysik und Angewandte Physik der Universität Innsbruck (Österreich) und das Institut für Physik und Astronomie der University of Iowa (U.S.A.) erzeugen mit Hilfe einer Q-Maschine Plasma für Forschungszwecke.

Eine Q-Maschine besteht neben einigen anderen Bauteilen aus einer Heizeinheit, welche für gewöhnlich dazu dient, eine Wolfram oder Tantal Platte innerhalb eines Hochvakuums auf eine Temperatur von 2000K aufzuheizen.

Die Heizeinheit und eine Wasserkühleinheit der Q-Maschine in Innsbruck wurden auf Grund einer Überbrückung dieser Kühleinheit während des Betriebes der Maschine schwer beschädigt. Infolge dessen war es notwendig, eine Fehleranalyse durchzuführen um im Anschluss die jeweiligen Defekte beheben zu können. Zusätzlich wurde eine Bedienungsanleitung verfasst, um weitere Beschädigungen an der Q-Maschine zu verhindern. Die Q-Maschine war einige Jahre außer Betrieb und das Vakuumsystem musste wieder hergestellt werden. Somit konnte ein Betriebszustand der Q-Maschine erreicht werden, welcher eine kontaktlose Temperaturmessung mit einem Pyrometer an der heißen Platte erlaubte.

Die Q-Maschine in Iowa City war ebenfalls drei Jahre außer Betrieb. Es musste auch für diese Maschine eine Fehleranalyse durchgeführt werden, wobei die Probleme hauptsächlich im Vakuumsystem lagen. Im Anschluss wurden die Fehler behoben und es konnte auch für diese Maschine ein Betriebszustand erreicht werden, welcher ebenfalls eine kontaktlose Temperaturmessung der heißen Platte erlaubte, um ein Temperaturprofil erstellen zu können.

Somit konnten die ermittelten Temperaturen mit jenem idealen Temperaturprofil verglichen werden, welches für die Plasma Produktion beim Einsatz einer Q-Maschine empfohlen wird.

Die Ergebnisse dieses Vergleichs zeigen schlussendlich, dass ein Optimierungspotential sowohl bei der Heizeinheit in Innsbruck, als auch bei jener in Iowa City vorliegt. Zusätzlich wurden die Heizeinheiten von der Q-Maschine in Innsbruck und in Iowa City mit anderen Heizeinheiten verglichen, um Optimierungsmöglichkeiten bestimmen zu können.

3 Acknowledgments

It is a pleasure to thank those who made this master thesis possible.

I would like to thank my supervisor Ing. Ronald Stärz, ao. Univ. -Prof. Dr. Roman Schrittwieser and Robert L. Merlino, Ph.D., Professor for the encouragement and the guidance which allowed me to complete this master thesis in Austria and in the United States of America.

Furthermore I would like to thank both Experimental Plasma Physics Groups in Innsbruck and in Iowa City for their technical assistance from the initial to the final level of the experiments.

For financial support, I would like to thank the Austrian Marshall Plan Foundation.

Finally, I offer my regards and blessings to my family and my girlfriend Theresa who encouraged me during my studies.

4 Preface

The idea of the Q-machine was born in the late 1950-ies by the plasma physicist Harry Dreicer from the Los Alamos Laboratory in New Mexico. The first Q-machine was built by Nathan Rynn and Nicola D'Angelo in 1960 in the Princeton Plasma Physics Laboratory, New Jersey. [1]

After the great scientific success of the first Q-machine by N. Rynn, N. D'Angelo and later also Bob Motley (who even wrote a book about Q-machines) many world-wide Q-machines were constructed. [1]

Around the 1960-ies Prof. Ferdinand Cap of the Innsbruck Theoretical Physics Institute built a Q-machine in Innsbruck. [1]

Towards the end of the 1970-ies, the first boom was over. Many of the Q-machines were dismantled or given to developing countries. At the beginning of the 1980-ies there were fewer Q-machines on earth than finger on the hands: Risø, Irvine, California (two), Sendai (two), Durban, South Africa, Innsbruck. [1]

In the middle of the 1980-ies an unexpected renaissance of the Q-machines started and for a while new Q-machines were built. N. D'Angelo and Robert Merlino built a Q-machine in Iowa City. [1]

This master thesis deals with the re-establishment and optimization of the heating unit of the Q-machine in Innsbruck as well as the one in Iowa City.

5 Basics

5.1 Plasma [2]

In order to get a conception of plasma, examples from our natural environment are very helpful. Frequently used visible examples of plasma are lightnings, the sun with its sunspots as a hot plasma ball and the auroras. Another, perhaps the biggest example of plasma is our universe. More than 99,99% of the visible matter of the universe is in the plasma state.

For the real understanding of plasma the mentioned visualizations are not enough, therefore a definition of plasma is necessary. Following are two definitions mentioned to distinguish the concept of plasma.

5.1.1 The simple Definition of Plasma [2]

Plasma is a matter in the gaseous state which is electrically excited and whose properties are essentially determined by free charge carriers.

For obtaining plasma there are usually three components necessary. Following each of those components is described.

I. Electrically neutral gas

   The gas particles which can either be in their ground state or in an excited state. For example: atoms, molecules, clusters, aerosols, et cetera

II. Electrically charged particles

   Cations can be singly or multiply charged, whereas anions are usually only singly charged (but possibly in various excited states). Existing dust particles in plasma are usually negatively charged.

   Examples: anions, cations, molecular ions [e.g. C_{60}^{-}], dust particles, electrons

III. Electromagnetic quanta (photons)

There are some different possibilities how plasma can be produced but the most common is by an electrical discharge in a gas. Plasma can also be obtained by a sudden or gradual heating up of a gas until a high temperature of several 1000 K. Furthermore plasma can be created by surface effects, laser irradiation or chemical reactions. The mentioned methods for producing plasma should only give a short overview. The relevant effects for the plasma production in the Q-machine such as the contact ionization and the thermionic emission will be discussed later.

5.1.2 The strict Mathematical Definition of Plasma [2]

$$\sum q_+ n_+ = \sum q_- n_- \qquad (1.1)$$

n_+, n_- characterize the particle density with the number of particles per unit volume and q_+, q_- describe the charge number as well as the charge state. Equation (1.1) shows that plasma is electrically neutral and this corresponds to a charge density of zero. This means that neither inside nor outside the plasma are space charges and therefore also no electric field.

The quasi neutral condition of plasma

$$\left|\sum q_+ n_+ - \sum q_- n_-\right| << \sum q_+ n_+ \qquad (1.2)$$

shows that by creation of a space charge, small deviations from the quasi neutrality take place. The deviations of the quasi neutrality lead to a strong electric field which tries to re-establish the quasi neutrality.

Based on the presence of free charge carriers, plasma could be influenced with electric and magnetic fields. Consequently this property leads to variable applicability of plasma.

Plasma in technology is used for many different areas. Some examples like plasma welding, -cutting, -etching and -coating show a wide variety application possibility of plasma.

5.2 The Principle of a Q-machine and its Main Components

A Q-machine is used for the production of quiescent alkali plasma. The abbreviation Q-machine stands for “Quiescent Plasma Machine”, based on its producible quiescent plasma. By using a standard Q-machine plasma with plasma densities up to $10^{11} cm^{-3}$ can be obtained. [3]

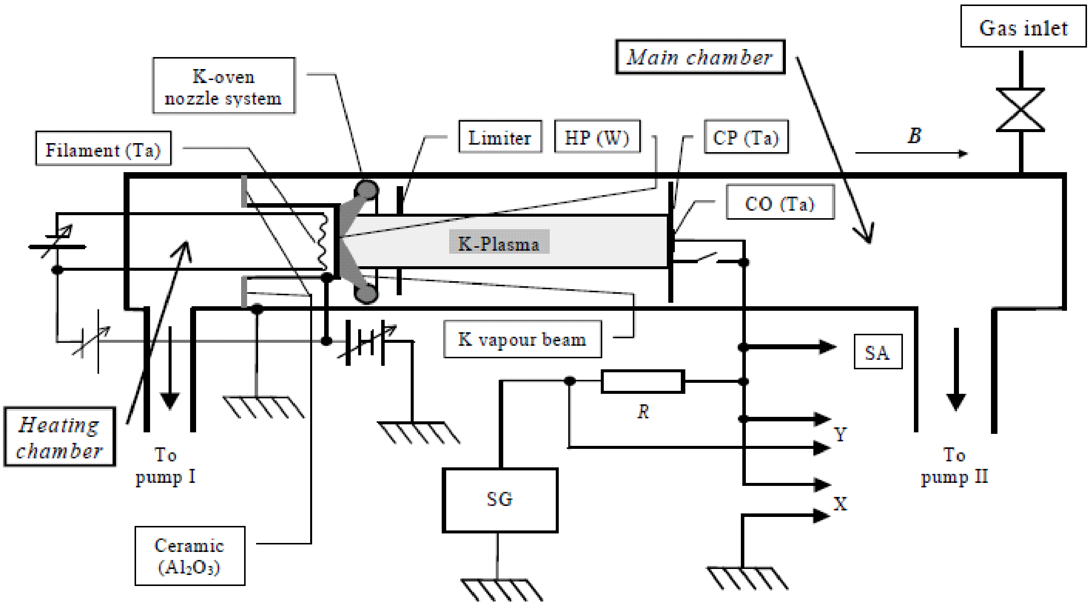


Figure 1: Schematic of the Q-machine in Innsbruck [1]

HP (W)	Hot Plate (tungsten)
CP (Ta)	Cold Plate (tantalum)
CO (Ta)	Circular collector and a concentric ring
SA	Spectral analyzer, X,Y-XY-recorder
SG	Signal Generator

Table 1: List of abbreviations to Figure 1 [1]

The following description of the Q-machines principle is based on the configuration of the Q-machine in Innsbruck. The Figure 1 above shows the schematic of the Q-machine in Innsbruck and should help for visualizing the following description.

Basically the Q-machine has two separated vacuum chambers. The main chamber and the so called heating chamber which is evacuated separately, so that the pressure in the main chamber can be raised by inlet of a gas [1]. Therefore, both chambers have a separate vacuum pumping circuit. The low pressure of approximately 5*10^-6mbar can be reached in each case with a rough pump for the fore vacuum and a diffusion pump for the ultimate vacuum.

A filament is placed in the heating chamber and is necessary for heating up the hot plate per electron bombardment from its back side to a temperature of approximately 2000K. The diameter of the hot plate has a typically dimension between 3 and 6 cm. Furthermore it is made of tungsten and has a thickness of 3mm [4]. The thickness of the hot plate has an influence on its temperature profile and usually it is advantageous to make the hot plate thicker to obtain a more homogenous temperature profile. After a lot of experiments and many heating hours of the tungsten plate its surface shows visible different ranges which have obviously different orientations of the crystal lattice. Consequently these ranges on the hot plates surface have different values of the work function and this influence both effects which take place on the hot plate but these effects will be discussed later. [1]

The main chamber is enclosed within a magnetic coil to confine the plasma column in its diameter between the hot plate and the cold plate. The magnetic field of the Q-machine in Innsbruck reaches up to $B \cong 0{,}32T$ but there were and there are other Q-machines with magnetic fields up to $0{,}7T$. [1]

A potassium oven nozzle system in the main chamber is placed next to the hot plate and is necessary to create a potassium vapour beam directed to the hot plates surface. [1]

Under these conditions two common effects take place on the hot plate the thermionic emission ("Richardson emission") and the contact ionization ("Langmuir-Saha effect"). Furthermore plasma can be obtained with plasma density up to $10^{11} cm^{-3}$ [3]. The mentioned effects will be discussed under the following point 5.3.

5.2.1 Essential Effects in the Q-machine

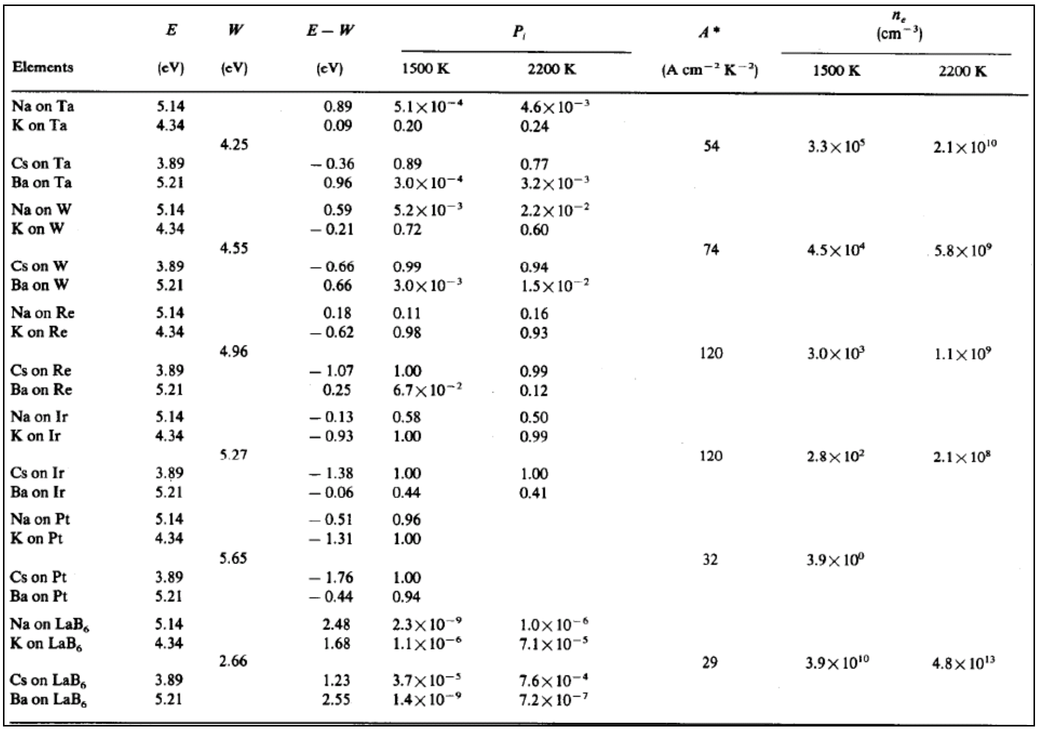
The plasma source of the Q-machine is composed of a refractory metal plate which is heated up above 2000K. This high surface temperature is necessary to emit thermionic electrons as well as ions by a bombardment with alkali atoms of the hot metal plate. Consequently in the presence of thermionic electrons and ions, plasma can be produced. The effects which take place at the hot metal plate during atom bombardment are the thermionic emission of electrons (“Richardson emission”) and the surface or contact ionization (“Langmuir-Saha effect”). [3]

The phenomenon of contact ionization (“Langmuir-Saha effect”) describes that an atom or molecule with a low ionization energy V_i by interacting with a hot metallic surface, with a high work function W_M, will be ionized with a high probability. The ionization probability depends on the difference V_i - W_M and in addition on the metal temperature. By using this ionization method single ionized positive ions can be obtained. [3]

The hot plate is usually made of the basic elements tungsten (W_W=4,55 eV) or tantalum (W_{Ta}=4,25 eV) but it is also possible to choose another elements [5]. The properties of the element for the hot plate influence the plasma production dramatically [6]. Based on the requirements of contact ionization it is necessary to choose an element with a high work function W_M to obtain a high ionization probability. The work function describes the minimum energy which an electron from the interior of the metal needs to leave the metal [7]. Furthermore it must have a high melting point since it has to be heated up until high temperatures to facilitate thermionic emission [5]. The “Richardson emission” describes even the thermionic emission of electrons from a hot metallic surface. If the temperature of the hot plate is to low (~900℃) only ions can b e produced and it emits no thermionic electrons, furthermore it is not possible to obtain plasma [3]. Of course rhenium (W_{Re}=4,96 eV) would have ideal properties with its high work function as well as with its high melting point to fulfill the requirements to get a high ionization probability but it has one big disadvantage, it is very expensive [8].

There are also specific requirements to the element which is used for the atom bombardment of the hot plate. Based on the phenomenon of contact ionization for obtaining single ionized positive ions it is necessary to choose an element with a low ionization energy. The lowest ionization energies of the elements have the alkaline metals cesium ($V_{i,Vs}$=3,89 eV), rubidium ($V_{i,Rb}$=4,18 eV), potassium ($V_{i,K}$=4,34 eV) and sodium ($V_{i,Na}$=5,14 eV), but also lithium ($V_{i,Li}$=5,39 eV), barium ($V_{i,Ba}$=5,21 eV), strontium ($V_{i,Sr}$=5,70 eV) and a few lanthanides can be ionized in this way [5].

Only for certain element combinations is the ionization probability high enough. By the combination of the element cesium on tungsten for example, the ionization probability at a metal temperature of 2200 K will reach a value of 0,94, for cesium on tantalum 0,77 and for potassium on tungsten 0,60 [5]. The mentioned ionization probabilities are some examples chosen from the following table.



	E	W	$E-W$	P_i		A^*	n_e (cm^{-3})	
Elements	(eV)	(eV)	(eV)	1500 K	2200 K	($\mathrm{A\,cm^{-2}\,K^{-2}}$)	1500 K	2200 K
Na on Ta	5.14	4.25	0.89	5.1×10^{-4}	4.6×10^{-3}	54	3.3×10^{5}	2.1×10^{10}
K on Ta	4.34		0.09	0.20	0.24			
Cs on Ta	3.89		− 0.36	0.89	0.77			
Ba on Ta	5.21		0.96	3.0×10^{-4}	3.2×10^{-3}			
Na on W	5.14	4.55	0.59	5.2×10^{-3}	2.2×10^{-2}	74	4.5×10^{4}	5.8×10^{9}
K on W	4.34		− 0.21	0.72	0.60			
Cs on W	3.89		− 0.66	0.99	0.94			
Ba on W	5.21		0.66	3.0×10^{-3}	1.5×10^{-2}			
Na on Re	5.14	4.96	0.18	0.11	0.16	120	3.0×10^{3}	1.1×10^{9}
K on Re	4.34		− 0.62	0.98	0.93			
Cs on Re	3.89		− 1.07	1.00	0.99			
Ba on Re	5.21		0.25	6.7×10^{-2}	0.12			
Na on Ir	5.14	5.27	− 0.13	0.58	0.50	120	2.8×10^{2}	2.1×10^{8}
K on Ir	4.34		− 0.93	1.00	0.99			
Cs on Ir	3.89		− 1.38	1.00	1.00			
Ba on Ir	5.21		− 0.06	0.44	0.41			
Na on Pt	5.14	5.65	− 0.51	0.96		32	3.9×10^{0}	
K on Pt	4.34		− 1.31	1.00				
Cs on Pt	3.89		− 1.76	1.00				
Ba on Pt	5.21		− 0.44	0.94				
Na on LaB_6	5.14	2.66	2.48	2.3×10^{-9}	1.0×10^{-6}	29	3.9×10^{10}	4.8×10^{13}
K on LaB_6	4.34		1.68	1.1×10^{-6}	7.1×10^{-5}			
Cs on LaB_6	3.89		1.23	3.7×10^{-5}	7.6×10^{-4}			
Ba on LaB_6	5.21		2.55	1.4×10^{-9}	7.2×10^{-7}			

Table 2: Properties of some usable elements for the hot plate material and for the oven filling [9]

E	ionization potentials
W	work functions
P_i	ionization probabilities (for 1500K and 2200K)
A	effective Richardson constants
n_e	emitted electron densities (for 1500K and 2200K)

Table 3: List of abbreviations to Table 2 [9]

6 Contactless Temperature Measurement with a Pyrometer

For contactless temperature measurements pyrometers are very common. The following description of the measurement principle explains the possible usage of a pyrometer.

6.1 Electromagnetic Spectrum

Every form of matter which has a higher temperature than the absolute zero Kelvin (-273,15°C) emits electromagnetic radiation. Based on the objects temperature an internal mechanical movement of the molecules takes place. Furthermore the movement represents charge displacement and electromagnetic radiation (photon particles) will be emitted [10]. The higher the temperature of colored bodies the higher the radiation frequencies are, which will be emitted. The frequency of infrared or visible light can be very high for example 10^{12}Hz and that is why for the characterization of the electromagnetic spectrum the wavelength (λ) is used (see Figure 2). The wavelength can be characterized with the propagation velocity of light (c) and the frequency (f). [11]

$$\lambda = \frac{c}{f} \qquad (2.1)\ [11]$$

The propagation velocity of light in vacuum or air is approximately 3×10^8 m/s. The light velocity for light diaphanous mediums like water will be a little bit smaller than in vacuum or air. [11]

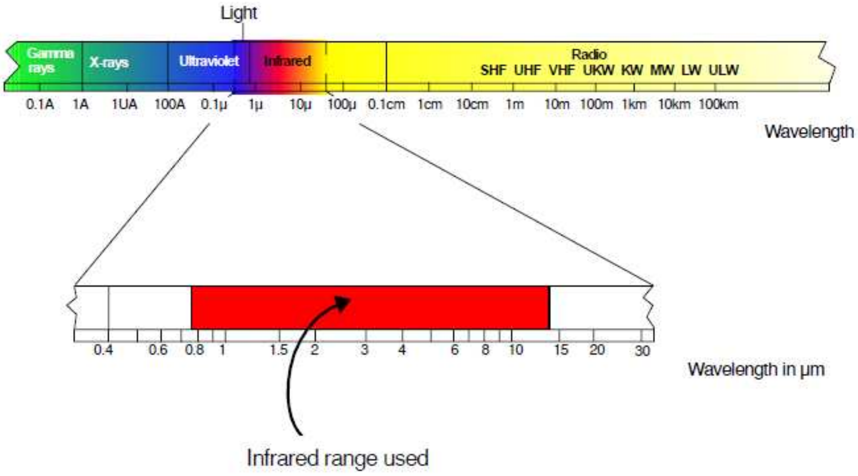


Figure 2: The electromagnetic spectrum, with the red marked effective measurement range of the company Raytek`s IR thermometer [10].

The following figure (Figure 3) shows the radiation characteristics of objects which absorb the impinged light completely in relation to their temperature. These objects have a black color and that is why they are called “blackbodies” (Figure 6). In the ideal case blackbodies do not reflect or transmit light. [11]

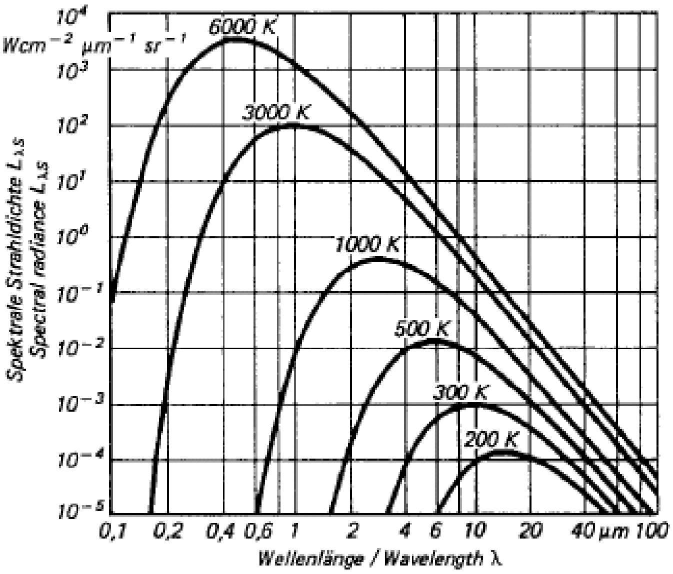


Figure 3: Radiation characteristics of a blackbody in relation to its temperature [11].

Figure 3 shows that for every temperature of a blackbody a wide spectrum of wavelengths will be radiated. Furthermore it shows that the increasing of the body temperature leads to a lower wavelength which will be radiated with the maximal intensity (“Wien Displacement Law”). [11]

Based on this attitude it is possible to obtain the temperature by interpreting the radiated spectrum. Typically the complete intensity at the collected wavelength range has to be measured and the ideal case would be between zero and ∞. The result corresponds with the integral of the curves in Figure 3. [11]

The following figure (Figure 4) shows the interrelationship between the measured overall intensity and the temperature of the body. It shows that the intensity of a body radiation is in the best case proportional to the fourth power of its temperature (Stefan Boltzmann Law of blackbodies). [11]

$$P = \varepsilon \sigma A T^4 \qquad (2.2)\ [12]$$

P	Total Radiant Power	$[W]$
A	Radiating Surface Area	$[m^2]$
T	Temperature	$[K]$
ε	Emissivity	[dimensionless], for Blackbodies $\varepsilon = 1$
σ	Boltzmann Constant	$5{,}67033 \times 10^{-8} W / m^2 \times K^4$

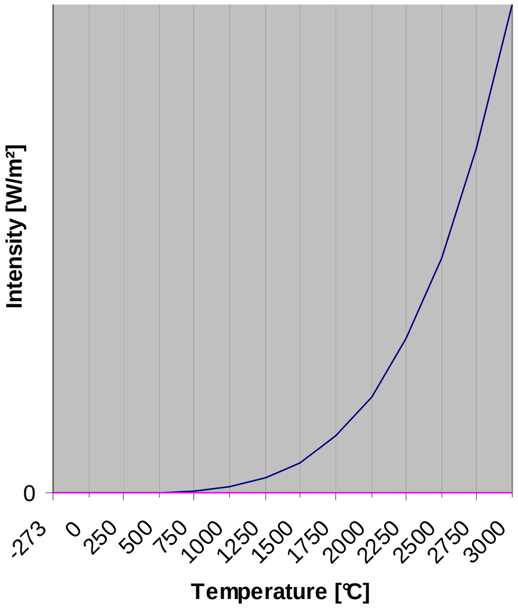


Figure 4: Interrelationship between intensity and the temperature of a body [11]

Furthermore the graph in Figure 4 shows that the doubling of the body temperature results in a 16 times higher intensity.

The following figure (Figure 5) shows the possible radiations from a body and furthermore visualizes possible radiation absorption of the body. These radiations together with the absorption property of the body are the factors which determine the overall emission. The sum of emissions is composed of absorption (A), reflection (R) and transmission (T) and is equal to one [10].

$$A + R + T = 1 \qquad (2.3)$$

If a device under test is a matter of solid bodies no transmission in the infrared range will take place (T=0). [10]

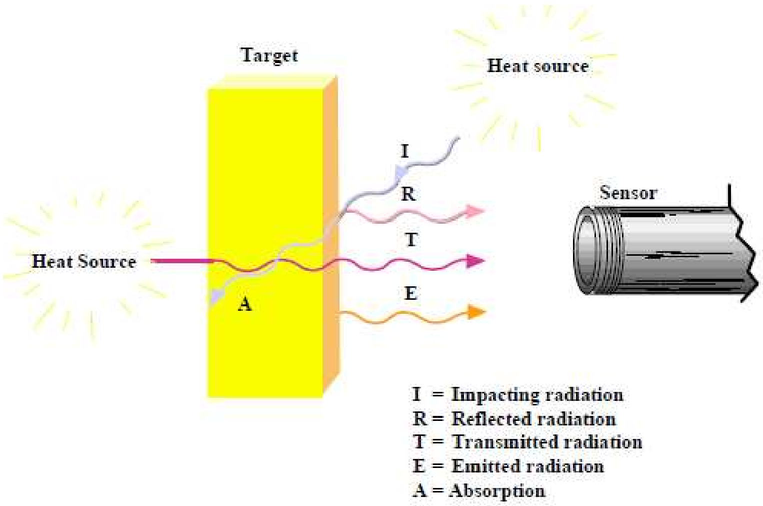


Figure 5: Visualization of the factors of influence on the overall emission of a body [10].

The Kirchhoff´s Law describes that the total amount of energy at all wavelengths which are absorbed by a body versus the emitted amount of this body must be the same, otherwise the temperature will change [12]. Consequently the result for absorption and emission is:

$$A \Leftrightarrow E = 1 - R \qquad (2.4)$$ [10]

6.2 Emissivity

The mentioned interrelationship between intensity and wavelength (frequency) at a certain temperature is only effective for blackbodies. Every gray or non-gray body has a more complicated radiation characteristic than blackbodies because of their reflecting and transmitting properties of light. Consequently only blackbodies have a radiation curve which can be easily associated with the temperature like it is shown in Figure 4. Real bodies deviate from this curve and therefore a deviation ratio to the blackbody has to be considered.

The emissivity (ε) represents the deviation ratio between the real emissive power of a form of matter and that of a blackbody at the same temperature. Consequently the deviation of “colored objects” from the blackbodies radiation characteristics can be compensated. [11]

The emissivity can have a maximum of one and a minimum of zero whereas bodies with a constant emissivity less than one are called gray bodies (Figure 6). The reason for this name is that a body considered in a spectral range with a constant emissivity, appear mostly gray. Furthermore bodies for which the emissivity dependents also on temperature and on wavelength are called non-gray bodies (glass, metals and plastic films). [10]

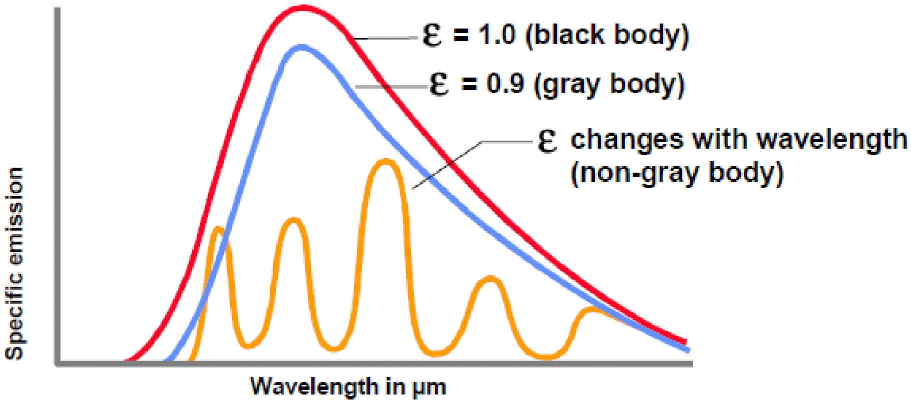


Figure 6: Specific emission at different emissivities

For noncontact temperature measurements it is necessary to know the emissivity of the device under test for a specific wavelength range [11].

There are several different possibilities to obtain the emissivity. Many frequently used materials are listed in tables with their corresponding emissivity. Furthermore the wavelength range can also be found in these emissivity tables. [10]

Following are listed more methods to obtain the emissivity:

- Comparison measurement with a contact thermometer (e.g. thermocouple) [11]
- Partial blackening of the surface of a sample body which has the same material than the device under test → comparison measurement with the blank surface of the sample body [11]
- Creation of a black body by drilling a hole in a sample body which consists of the same material as the device under test → comparison of the measurement with the blank surface of the sample body [11]
- Spectrometer analysis [11]

If the emissivity of the device under test is known, the pyrometer has to be fed with this parameter to obtain the actual temperature of the body. One must pay attention to pyrometers which do not have the possibility to feed it with the emissivity. These pyrometers measure only an apparent temperature of the body. Therefore a calculation by using among other things this apparent temperature, the wavelength and the emissivity of the body has to be done to obtain its actual temperature. The basis for this calculation represents the Planck´s Radiation Law.

$$I_{\lambda} = \frac{2\pi hc^2}{\lambda^5}\left[\frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}\right] \qquad (2.5)\ [12]$$

c	Velocity of Light	$[\frac{m}{s}]$
λ	Wavelength	$[m]$
T	Apparent Temperature	$[K\ ]$
π	Circle Constant	$3{,}14159$
h	Planck`s Constant	$6{,}6260755 \cdot 10^{-34}\, J \cdot s$
k_B	Boltzmann´s Constant	$1{,}3806504 \cdot 10^{-23}\, \frac{J}{K}$
I_{λ}	Spectral Irradiance	$[J \cdot s^{-1} \cdot m^{-2} \cdot sr^{-1} \cdot m^{-1}]$

The Planck`s Radiation Law describes the spectral irradiance and its interrelationship with the wavelength which a blackbody radiates at a specific temperature [12].

The calculated value for the spectral irradiance from equation (2.5) has to be divided by the emissivity (ε = [dimensionless]) of the body, hence the actual spectral irradiance can be obtained. Afterwards equation (2.5) has to be rewritten and calculated with the actual spectral irradiance to determine the actual temperature of the body. [12]

Based on the emissivity characteristics of most materials it is generally possible to allocate them qualitatively into three groups.

- **Metals** (e.g. tungsten, tantalum, etc.)
  One problematic property of metal bodies with surfaces without discoloration is that they reflect the radiation from other close hot objects. Another problem of metallic objects is that their emissivity will change after a certain time period because of oxidizing or pollution. Consequently the emissivity can be heavily dependent on the temperature and the wavelength (Figure 7). [11]

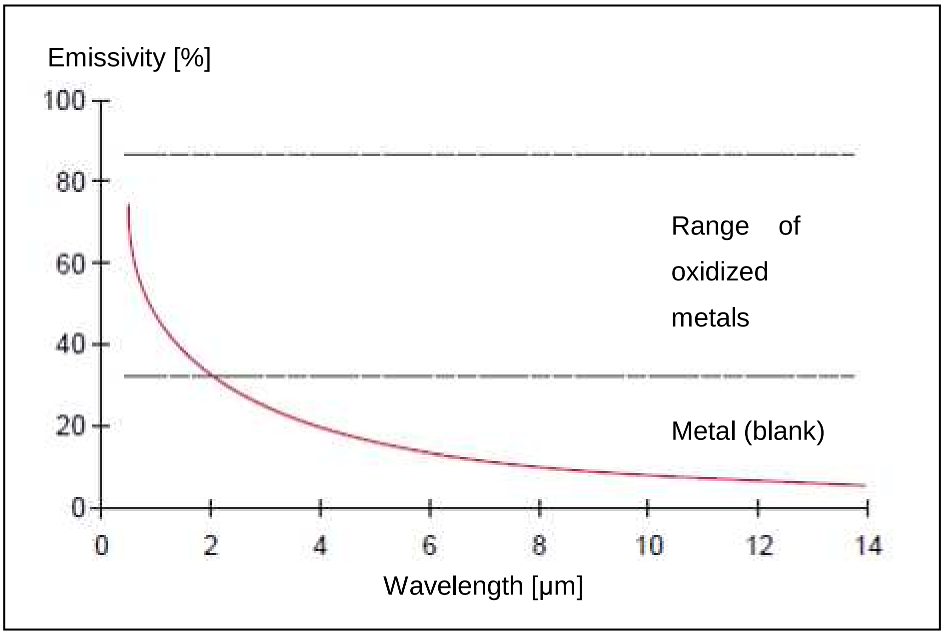


Figure 7: Emissivity of metals (from German to English translated diagram) [13]

- **Non-metals**

  Based on the emissivity can be organic matters (wood, comestible, paper, etc.) as well as ceramics and chamottes attached to the group of non-metals (Figure 8). [11]

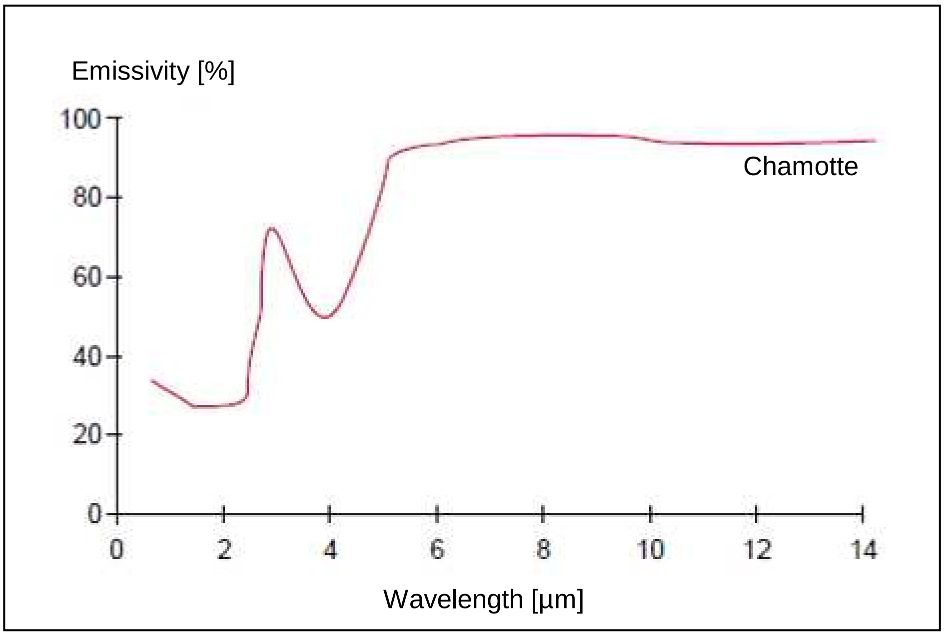


Figure 8: Emissivity of non-metals (from German to English translated diagram) [13]

- **Radiation permeable materials**

  For example glass, quartz, water, plastic foil as well as hot gases and flames belong to radiation permeable matters but they are not permeable for every range of wavelength. [11]

6.3 General Assembly and Functionality of a Pyrometer

A general assembly of a pyrometer and its components are visualized in Figure 9.

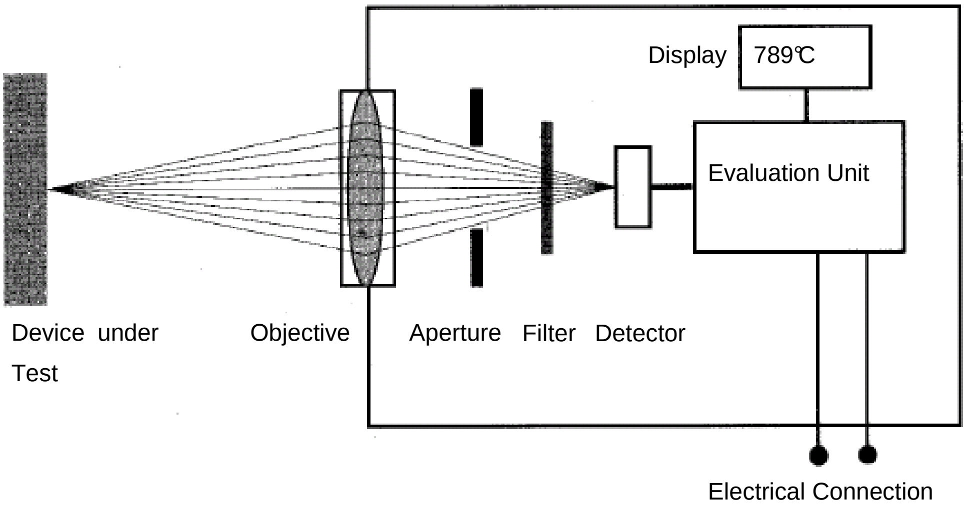


Figure 9: Generally assembling of a pyrometer [11]

The radiation of the device under test is collected by the objective of the pyrometer. Behind the objective the aperture is placed which is necessary to gate out disturbing boundary rays. Afterwards, the infrared rays which pass the aperture and the filter will be detected and dissipated into an electric signal by the detector. In a final step the evaluation unit linearizes the electric signal and converts it into a standardized output signal. If it is a matter of pyrometer which considers the emissivity of the device under test the temperature can be read off directly from the display otherwise the described calculation in chapter 6.2 has to be done. [11]

7 Q-machine in Innsbruck

7.1 Defect Analysis and Problem Handling – Innsbruck

The Q-machine in Innsbruck was off duty for several years (Figure 10). In the past the tungsten cylinder and the water cooling coil had been damaged caused by bridging the interlock of the cooling water unit. That is why the commissioning of the Q-machine was not possible and a defect analysis and repair of damaged components had to be done to allow its commissioning again. Probably the overheating was also the reason for the damaged heating unit which did not have a filament anymore. It is likely that the original filament of the heating unit burned out since it was not found. Consequently, it was also necessary to rebuild the filament to re-establish the heating unit and allow its commissioning. The following mentioned corrective measures were taken and an operating condition for the temperature measurement at the hot plate could be reached. Therefore it is possible to compare the heating unit in Innsbruck with other heating units.

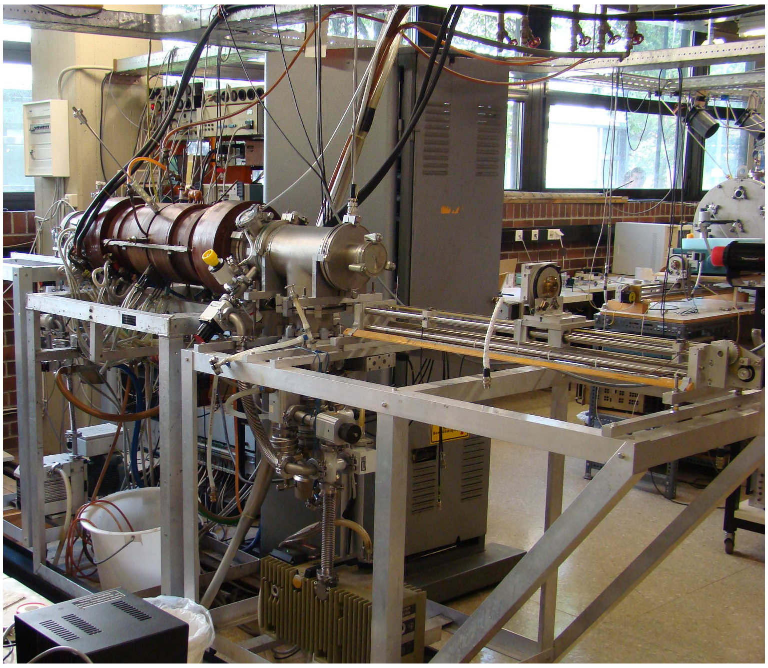


Figure 10: Q-Machine in Innsbruck

7.1.1 Hot Plate (Tungsten)

The material of the hot plate in the Q-machine in Innsbruck is tungsten (W_W=4,55 eV) and it is composed in fact of a tube and a plate. Based on the dimension of the hot plate it is also called tungsten cylinder. The external diameter of the hot plate is 60mm, its thickness is 3mm and the whole cylinder is 180mm high (Figure 11).

The cylinder wall is usually thinner than the hot plate to minimize the heat flow from the hot plate. Consequently it will be easier to obtain a more homogeneous temperature profile on the hot plate [1].

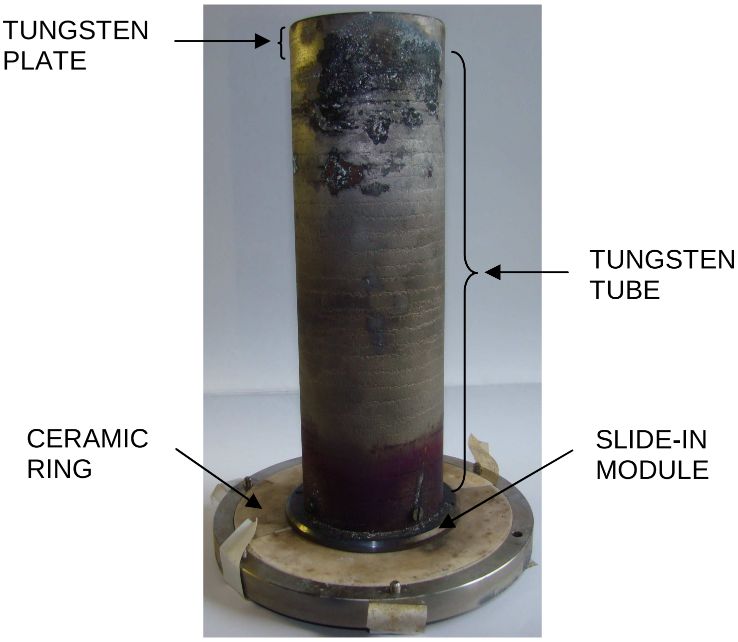


Figure 11: Hot plate (tungsten)

Figure 11 shows the hot plate with its fixing devises after the mentioned cooling water breakdown. The following Figure 12 will be needed to understand how the damage on the hot plate, its cooling coil and the heating source could have happened. The filament and the heat shield in Figure 12 had been added by the author.

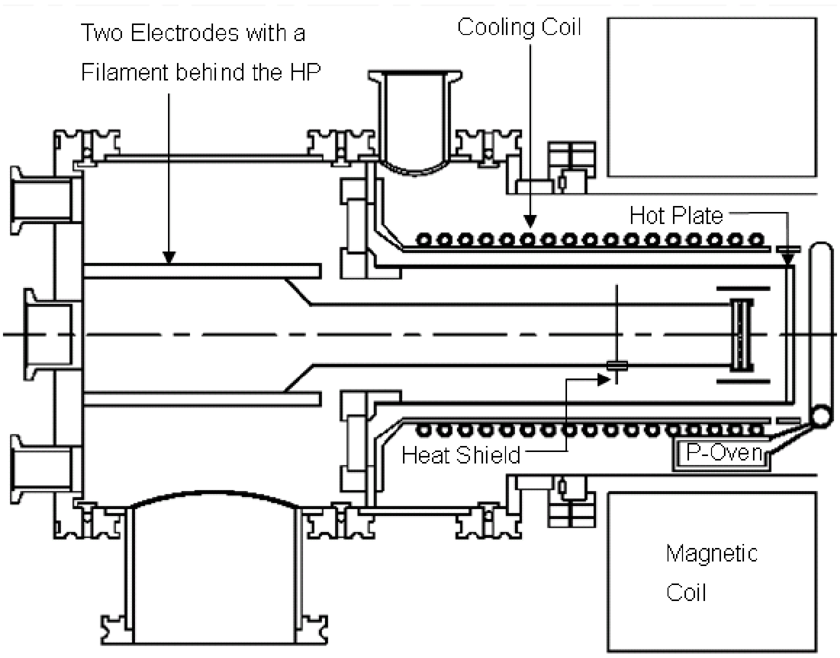


Figure 12: Schematic of the hot plate with its cooling coil, the heating source and the potassium oven [4]

As already mentioned in section 5.2 “The Principle of a Q-machine and its Main Components” a filament is placed on the back side of the hot plate which heats up the plate until a temperature of approximately 2000K. The cooling water breakdown during the heating up period of the hot plate led to an overheating of the tungsten cylinder with its slide in module and the cooling coil. The results of the overheating for the slide in module and the tungsten cylinder with a wall thickness of 0,5mm were that the cylinder has visible discolorations and crack formations. Based on the thermal expansion of the slide-in module and the high cylinder temperature the crack formations on the tungsten cylinder took place.

One indicator for this explanatory statement is that the positions of all the crack formations at the cylinder are at bore holes, closely to the slide in module. The picture above in Figure 13 shows the discoloration as well as some crack formations of the tungsten cylinder. The shown crack formation between the two bore holes arose from a screw which pressed on the face side of the cylinder during the overheating.

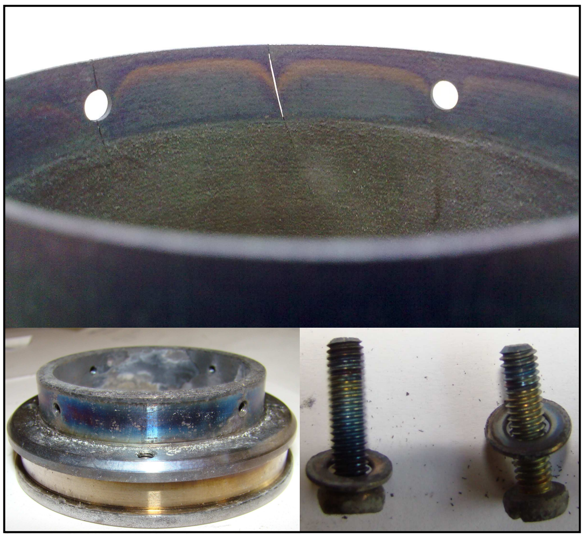


Figure 13: Overheating based discolorations and crack formations of the tungsten cylinder and its attachments

Another indicator that the damages happened by the thermal expansion of the slide in module is that the ceramic ring cracked also two times and these cracks had bigger breaking points closely to the slide in module than on the outer boundary of the ceramic ring (Figure 14). [14]

Figure 14: Bonded crack formations of the ceramic ring

Anyway it was necessary to change all the screws which where also overheated to guaranty a fixed position of the hot plate (Figure 13). Furthermore the ceramic ring had to be bonded (Figure 14) and all components had to be cleaned until they where useable again. The cleanness of the components is required to protect the vacuum pumps from pollution as well as to avoid outgassing sources within the machine.

By using the description in section 7.2 “Commissioning – Innsbruck” false settings during operating should be prevented and furthermore an overheating of the Q-machine should not take place again.

7.1.2 Water Cooling Coil of the Hot Plate

Further damages as the result of overheating occurred at the water cooling coil of the hot plate (Figure 12). Originally the cooper cooling coil at the region of the hot plate was brazed on a cooper cylinder and at distant regions soft soldered. The brazed regions of the cooling coil were not damaged by overheating but the soft solder did not resist the overheating and the soldered connection disconnected. Figure 15 shows a strong pollution of the hot plates cooling unit and the potassium oven as well as the described damage of the cooling coil.

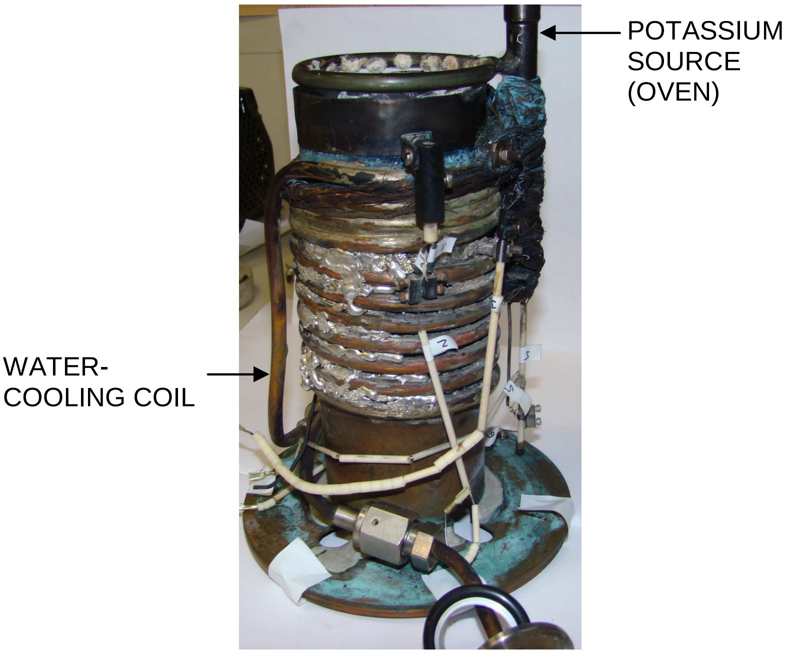


Figure 15: Water cooling coil of the hot plate with the potassium oven

The damage shown in Figure 15 had to be repaired to obtain a big contact area between the copper coil and the cylinder to dissipate the heat from the cylinder as much as possible. Therefore the needless soft solder had to be substituted with copper wires which were also soft soldered afterwards to fill up the cavities between the wires. Consequently, a big contact area of the copper coil could be reached with this simple and cheap method to recover the required cooling effect of the hot plate cylinder. Figure 16 shows the cleaned and repaired cooling unit with the hot plate in its assembled position.

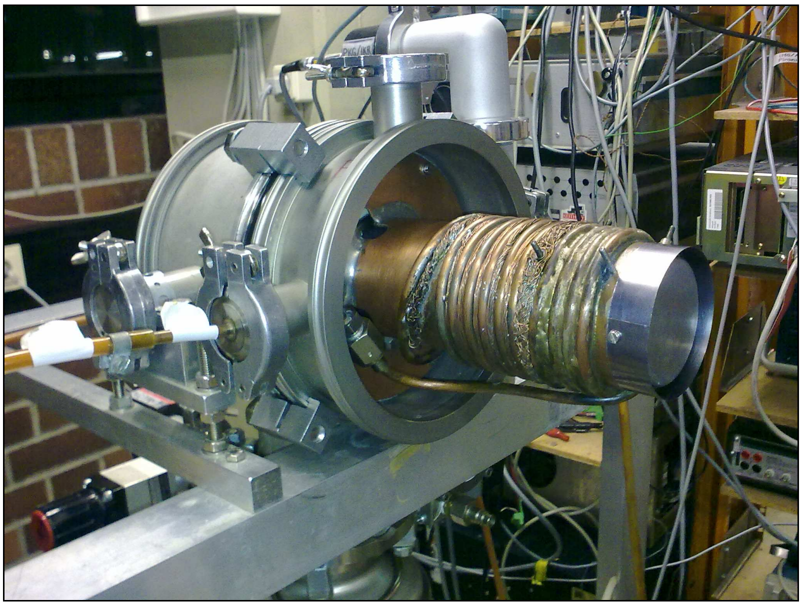


Figure 16: Assembled position of the hot plate and its cooling unit

7.1.3 Heating Unit

As mentioned before in section 5.2 “The Principle of a Q-machine and its Main Components” there is a filament in the Q-machine in Innsbruck in use to heat up the hot plate. Therefore one low voltage power supply is necessary which supplies a current of approximately 40A and a few volts to heat up the filament and provide the thermionic electrons for heating the hot plate. A high voltage power supply provides a voltage of approximately 2 kV between the filament and the grounded hot plate (Figure 17).

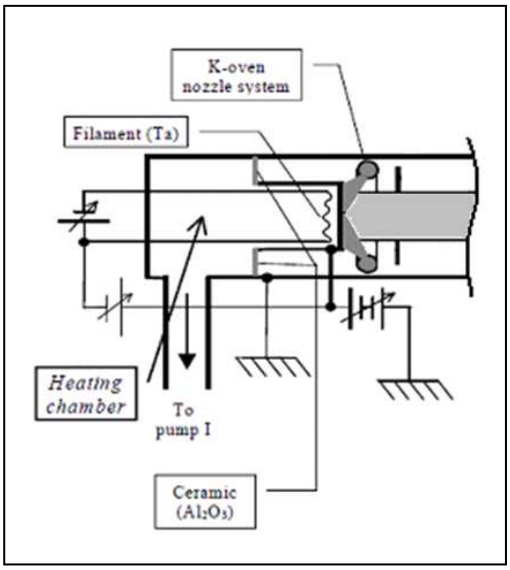


Figure 17: Connection scheme of the heating unit

The hot plate represents the ground of this electrical assembly and therefore the filaments electrical potential is -2 kV. This -2 kV potential accelerates the electrons from the filament toward the back of the hot plate [8]. The electron current to heat the hot plate is about 1 A and therefore an overall power of approximately 2 kW of both power supplies together will be needed to heat up the hot plate to the required temperature of about 2000 K.

The original power supplies technology of the heating unit is out of date and many of the electrical connections are corroded. Furthermore the cage of the power supplies does not safely isolate all the electrical assemblies therefore they have been replaced with new power supplies to protect the operator as well as the Q-machine for possible accidents. For the electrical connections of the high voltage and the low voltage power supply with the electrodes of the filament and the hot plate the schematic diagram shown in Figure 17 was considered.

7.1.3.1 Filament

As mentioned before in chapter 7.2 was it necessary to rebuild a filament for the heating unit. The following Figure 18 shows the filament which was used for the experiments to obtain the mentioned reference values in section 7.2.7 which helps for the commissioning of the Q-machine in Innsbruck.

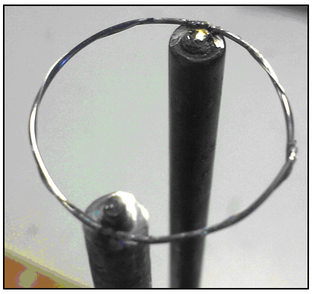


Figure 18: Tantalum filament with a tungsten wire reinforcement

The filament was made of a 0,5mm thick tantalum wire reinforced by a 0,15mm thick tungsten wire spot welded to a ring with an outside diameter of 21mm (Figure 18). The filament should be positioned with a distance of 7mm behind the hot plate. Based on this filament dimension and position the mentioned reference values in section 7.2.7 will be effective. The author attempted to use a filament distance of 4mm to the hot plate but very fast switching operations like sparkovers took place.

The small diameter of the filament was chosen on the recommendation of Mr. Patrick Winkler and Prof. Roman Schrittwieser to prevent the filament from damages. The filament will be strained by the Lorentz force $I \times B$ which represents in this case a force density per length unit. For example, by using a magnetic field with $B = 0{,}2T$ and a heating current $I_h = 50A$, force values up to $10\frac{N}{m}$ can be reached. [1]

7.1.3.2 Tantalum Heat Shield

It is shown in Figure 12 that it was necessary to place a heat shield behind the filament. Furthermore the radiated heat and the emitted waste particles from the filament can be enclosed between the heat shield and the hot plate as much as possible. Accordingly the leakage of radiated heat can be minimized and a larger amount of emitted waste particles will be condensed on the walls of the hot plate cylinder.

The heat shield is made of a tantalum disc with a thickness of 0,3 mm which has one tight fitted bore hole to fix the shield on one electrode of the filament. Another bore hole of the heat shield for the second electrode with a ceramic bushing between them is necessary to reach a floating position of the heat shield. For the commissioning experiments of the heating unit, the heat shield was positioned 76 mm behind the hot plate.

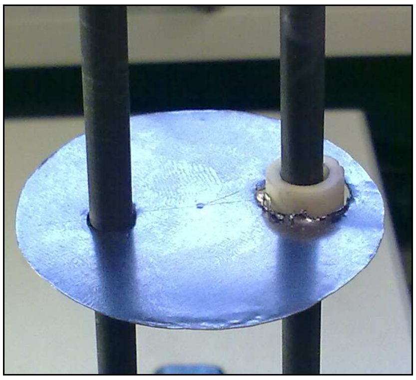


Figure 19: Tantalum heat shield

Another heat shield which was positioned on the cooper cylinder of the hot plates cooling unit to minimize the radiated heat flow from the hot plate has been damaged during the repair of the cooling unit. Therefore it was necessary to restore the heat shield which should help to maintain the temperature at the hot plates boundary as high as possible. Figure 16 shows the arrangement of the heat shield compared to the position of the hot plate.

7.1.4 Vacuum System

The defects of the Q-machine`s vacuum system in Iowa City were more fatal than those of the vacuum system in Innsbruck. That is the reason why the defects and their problem handling referring to the vacuum system are only discussed in chapter 8.1 “Defect Analysis and Problem Handling - Iowa City” to avoid iterations.

7.2 Commissioning – Innsbruck

The following commissioning instruction of the Q-machine in Innsbruck is necessary to reach an operating condition, which allows a contactless measurement of the hot plates temperature by using a pyrometer. That is the reason why it is not necessary to produce plasma for this measurement and why the last steps to produce plasma are not mentioned in this description. The commissioning procedure for plasma production is the same as described, but the heating of the potassium oven is not mentioned.

As already mentioned in “7.1 Defect Analysis and Problem Handling – Innsbruck” has the tungsten cylinder and the water cooling coil been damaged in the past caused by bridging of the cooling water unit. Based on this worst experience, false settings during operating should be prevented by using this description. Consequently the commissioning for the operator will be easier, and the Q-machine with its measurement equipment will be prevented from damages.

The following schematic shows the most important components of the Q-machine its gauges and nearly all the valves. This figure helps for visualization of the mentioned settings in this chapter.

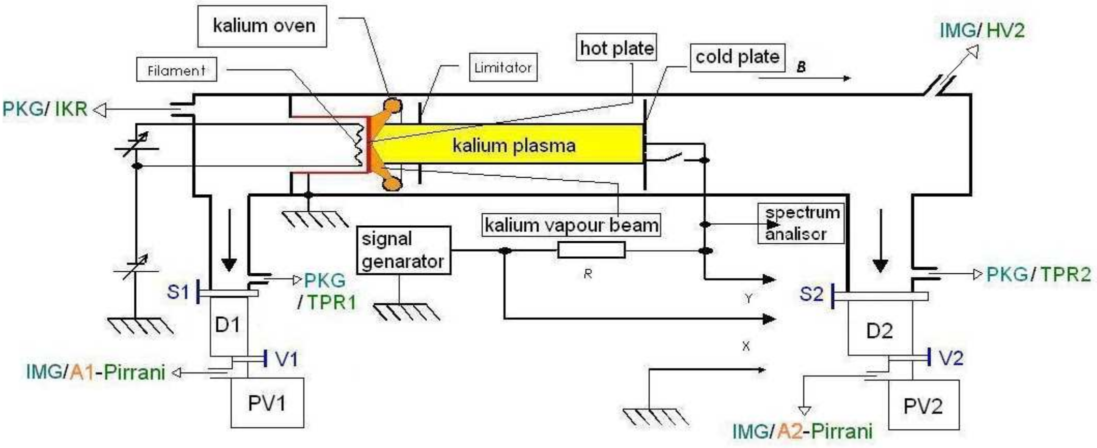


Figure 20: Components and measuring equipment of the Q-machine in Innsbruck

D1, D2	diffusion pumps
PV1, PV2	rough pumps
PKG, IMG	vacuummeters
Pirrani, TPR1, TPR2, IKR, HV2	gauges
S1, V1, S2, V2	valves

Table 4: Abbreviations to Figure 20

7.2.1 Water Cooling Systems

At the beginning of the commissioning it is necessary to open the following water faucets above the Q-machine to prevent the machine from overheating.

- D1/D2 (cooling water for the diffusion pumps),
- Cylinder (cooling water for the walls of the main chamber),
- HP (cooling water for the hot plate)
- and the faucet for the cooling system of the magnetic field above the DP-machine

Check the tightness of the water tubes and the faucets. If the fuse of the control panel is switched on the lights KW-D1, KW-D2 and KW HP at the control panel must shine (Figure 21).

7.2.2 Operating Starting Position of the Q-machine

Be sure that the following settings are correct:

- the fuse for the control panel labeled as vacuum security system is switched off
- the valves VA and VB of the by-passes are open
- the valve between the rough pump at the hot plate chamber and the valve V1 is open
- the valve between the rough pump at the main chamber and the valve V2 is open

- the valves V1 and V2 between the rough pumps and the diffusion pumps have to be closed
- check optical if the valve S1 between the hot plate chamber and the diffusion pump D1 is close
- check optical if the valve S2 between the main chamber 2 and the diffusion pump D2 is close

7.2.3 Rough Pumps

If the previous conditions are fulfilled the rough pumps PV1 and PV2 can be switched on at the same time. If the Q-machine was opened or the rough pumps were not used for a longer time the gas ballast valve of the pumps should be switched on for a few minutes. Thereby existing condensates can be removed from the system.

The pressure of the hot plate chamber can be measured with the gauge TR 211 labeled as PKG/TPR1. On the other side the pressure of the main chamber can be measured with the gauge TR211 labeled as PKG/TPR2.

If a pressure about $2\times10^{-2}\,mbar$ $(1{,}5\times10^{-2}\,torr)$ is reached the valves of the by-passes should be closed. After that the pressure has to be monitored for 15 minutes. If the pressure increases in the mentioned period of time over $1\times10^{-1}\,mbar$ $(7{,}5\times10^{-2}\,torr)$ the diffusion pumps will not have enough time to get heated up. If the chambers are tight enough the air has to be pumped out of the hot plate chamber and the main chamber again to a pressure of $2\times10^{-2}\,mbar$ $(1{,}5\times10^{-2}\,torr)$.

7.2.4 Control Panel

Most of the valves for the diffusion pumps and the security system can be activated at the control panel. Furthermore the control panel shows the status of the magnetic field, the cooling water flows and the charging circuit of the power supply (Figure 21).

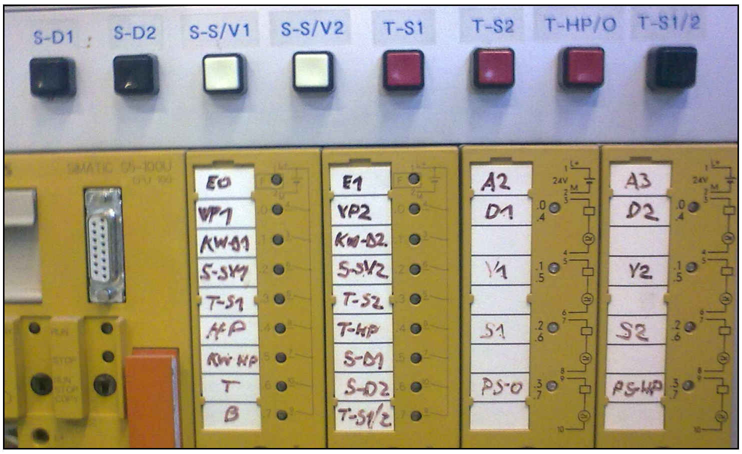


Figure 21: Control panel

Pay attention because the power supplies are not connected with the control panel at the moment.

The following table on page Table 5 describes the settings of the Q-machine by using the control panel.

Labeling Lights	Light ON/OFF	Status/Button
KW-D1 and KW-D2	ON	There is a water flow for cooling the diffusion pump (the faucet D1/ D2 is open).
KW-HP	ON	The water flow for cooling the HP exists.
		Buttons: S-S/V1 and S-S/V2
S-S/V1 and S-S/V2	OFF	The security system is switched ON.
V1 and V2	OFF	The valves V1 and V2 between the rough pumps and the diffusion pumps are closed.
S-S/V1 and S-S/V2 V1 and V2	ON ON	The security system is switched OFF and the valves V1 and V2 are open.
		Buttons: S-D1 and S-D2
S-D1 and S-D2	ON	The buttons S-D1 and S-D2 for switching on the diffusion pumps are pressed.
D1 and D2	ON	The diffusion pumps are running.
		Buttons: OPEN → T-S1 and T-S2 CLOSE simultaneously→ TS1/2
T-S1 and T-S2	ON	The buttons for open the upper valves S1 and S2 of the diffusion pumps are pressed.
S1 and S2	ON	The valves S1 and S2 are open.
B	ON	The magnetic field is switched ON.
		Button: T-HP/O
T-HP/O	ON	Opens the charging circuit of the power Supply
PS-HP	ON	There is a current through the power supply connected to the HP

Table 5: Description of the Q-machines settings by using the control panel

7.2.5 Diffusion Pumps

Switch on the water cooling system for the diffusion pumps D1 and D2 by using the faucet D1/D2 above the Q-machine.

After reaching the mentioned pressure under point 3 of around $2\times10^{-2} mbar$ ($1{,}5\times10^{-2} torr$) close the by-passes by using the valves VA, VB and switch on the fuse of the vacuum security system. The valves V1 and V2 will open and close alternately. Close the security system by using the buttons S-S/V1 and S-S/V2. The security system is off and the valves V1, V2 are open when the lights at the cubicle S-S/V1, S-S/V2 are on.

If the pressure of the diffusion pumps foreline decreases below $1\times10^{-1} mbar$ ($7{,}5\times10^{-2} torr$), switch on the diffusion pumps D1, D2 by using the buttons S-D1 and S-D2. The period of time for heating up the D2 diffusion pump is 12 minutes and for the D1 diffusion pump 10 minutes. If the pressure in the main chamber and in the diffusion pumps foreline does not increase above $1\times10^{-1} mbar$ ($7{,}5\times10^{-2} torr$) during this period, the valves S1 and S2 can be opened.

When the pressure decreases below $1\times10^{-2} mbar$ ($7{,}5\times10^{-3} torr$) the hot cathode ionization gauge (IMR 310) labeled as IMG/HV2 can be switched on at the ion gauge control unit IMG 300. The cold cathode ionization gauge (PR 26) labeled as (PKG/IKR) will switch on and off automatically if you use the button T2-P automatic at the ion gauge control unit (CM330). The high vacuum ionization gauge IMR 310 measures the pressure at the hot plate chamber and the gauge PR 26 the pressure in the main chamber.

Be careful if the pressure increases above $1\times10^{-2} mbar$ the hot cathode ionization gauge (IMR 310) has to be switched off quickly.

7.2.6 Magnetic Coil

Switch on the water cooling system for the magnetic coil by using the faucet above the DP-machine. Next, switch on the magnetic field by using the key at the power supply unit. Activate every button under the key from the top down. Next, increase the armature voltage slowly. The needles of the analog display for the armature voltage and for the current should increase equally. The maximum safe current for the magnets is approximately 100A when cooled by water at line pressure. In order to operate the magnets at currents greater than 100A, a booster pump must be employed to increase the water flow. If the current increases over 100A the magnetic coils will get very hot and a higher pressure of the cooling water will be needed to avoid the evaporation of the water and consequently an overheating of the magnetic coils. If the water pressure is higher the fluid is able to dissipate more heat flow of the magnetic coils. For increasing the water pressure the pump of the magnetic coils water cooling system has to be switched on. Afterwards it is possible to increase the current over 100A.

7.2.7 Reference Values for a secure Heating up Period of the Hot Plate

The listed reference values in the following tables (Table 7 and Table 8) should help for choosing the right settings of the power supply and the current source to heat up the hot plate with the filament. The position as well as the dimensions of the filament and the heat shield which were used for the experiments to obtain the following reference values were already described in section 7.1.3 “Heating Unit”.

HVPS	High Voltage Power Supply
LVPS	Low Voltage Power Supply

Table 6: Abbreviations to Table 7 and Table 8

Reference		1	2	3
Time [hh:mm]		11:47	11:55	11:59
HVPS	Accelerating Voltage [V]	2500	2500	2500
	Current Flow [mA]	230	480	500
	Power [W]	620	1230	1300
LVPS	Filament Current [A]	33	33	33,2
	Voltage [V]	3,1	3,2	3,2
	Filament Power [W]	102,3	105,6	106,24
PR26-Pressure [mbar]		1,50E-06	1,50E-06	1,E-05
IMG-Pressure [mbar]		3,20E-05	3,20E-05	4,E-05
Boundary Area Temperature [°C]		1315	1630	1690

Table 7: Reference values for the power supplies at an accelerating voltage of 2,5kV

Reference		1	2	3	4	5	6	7	8	9
Time [hh:mm]		13:35	13:37	-	13:40	13:42	-	13:58	-	14:10
HVPS	Accelerating Voltage [V]	1500	1500	1500	1500	1500	1500	1500	1500	1500
	Current Flow [mA]	-	30	140	260	400	510	690	790	1090
	Power [W]	-	60	230	410	610	780	1060	1190	1600
LVPS	Filament Current [A]	20	30	33	34	35	36	37,5	37,5	39,5
	Voltage [V]	1,3	2,3	2,7	2,9	3,1	3,3	3,6	3,6	3,9
	Filament Power [W]	26	69	89,1	98,6	108,5	118,8	135	135	154,05
PR26-Pressure [mbar]		-	2,E-06	1,E-05	9,E-06	6,E-06	5,E-06	6,E-06	6,E-06	9,E-06
IMG-Pressure [mbar]		-	6,E-06	6,E-06	7,E-06	8,E-06	8,E-06	1,E-05	6,E-05	1,E-05
HP Boundary Temperature [°C]		-	-	HP glows	1108	1200	1380	1535	1596	1752
HP Center Temperature [°C]		-	-	-	-	1335	1430	1610	1680	1850

Table 8: Reference values for the power supplies at an accelerating voltage of 1,5kV

The following Figure 22: Reachable Temperature of the Hot Plate with a certain Power for an Accelerating Voltage of 1,5kV and 2,5kV [15]” visualizes the results of Table 7 and Table 8.

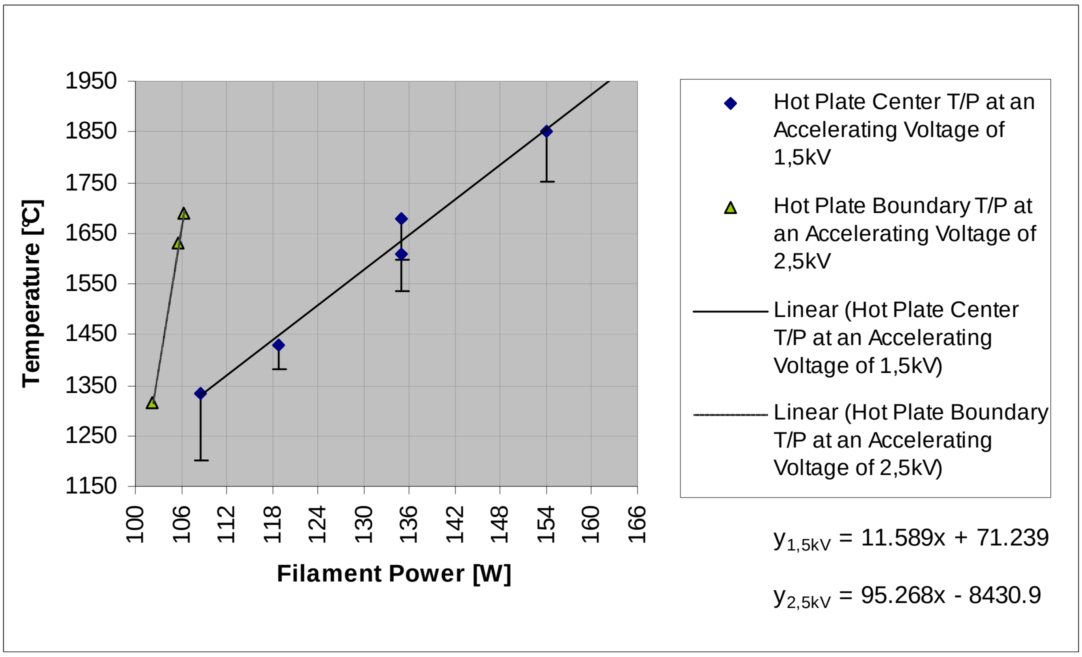


Figure 22: Reachable Temperature of the Hot Plate with a certain Power for an Accelerating Voltage of 1,5kV and 2,5kV [15]

Figure 22 shows two graphs which describe the hot plate temperature at an accelerating voltage of 1,5kV and 2,5kV by changing the filament power. The measuring points of the graph for the 1,5kV accelerating voltage show the hottest places nearly the center of the hot plate. The reason why the hottest spots were not at the center of the hot plate will be discussed later in section 9.1.1 on page 43.

The lines under the hottest points of the graph for the 1,5kV accelerating voltage describe the temperature from the center until the boundary of the glowing profile on the hot plate.

The measuring points of the other graph show only the temperatures at the boundary of the glowing profile for different filament power settings.

The temperature of the hot plate can be read off directly from the pyrometer at the end of the Q-machine. The pyrometer needs a 15 minutes heating period after the settings can be changed to the two color method 2C. In the meantime the hot plate can be focused with the pyrometer. An operating temperature for the plasma production in a Q-machine of minimum 1727℃ (2000K) is recommended [3].

7.2.8 Heating up the Hot Plate

The Q-machine in its actual situation should not be commissioned. Before commissioning a risk analysis is necessary. Electrical connections as well as protective grounding are not conforming to standards. Additionally it is not possible to switch off the Q-machine central and emergency stops are absent [15]. The troubleshooting started already and if all the faults are eliminated the Q-machine can be commissioned by using the following description.

Switch on the water cooling system for the hot plate by using the faucet HP above the Q-machine.

The recommended period of time for heating up the hot plate is approximately half an hour. The pressure at the beginning of the heating up process should be below $6\times10^{-6} mbar$ ($4{,}5\times10^{-6} torr$) and pressures higher than $5\times10^{-5} mbar$ ($4{,}13\times10^{-5} torr$) mbar should be avoided. If the pressure is getting too high some discharges between the filament and the hot plate will take place. The hot plate pressure should be continuously monitored as the power supplies are adjusted to higher power levels.

Switch on the low voltage power supply and the high voltage power supply. Open the charging circuit of power by using the control panel. Next set the low voltage power supply to a current of 20A. A voltage of 1,3A should be observed. Wait about five minutes to heat up the hot plate chamber. If the chamber has been at atmosphere recently some outgassing will take place during this heating up period. Because of the outgassing the pressure in the chambers will rise a little bit. If the pressure settles down after about these five minutes set the accelerating voltage of the high voltage power supply to 1500V. Next, increase the filament current stepwise to 30A and wait again until the pressure settles down. With these settings a current flow between the filament and the hot plate takes place and should reach approximately 33A. The hot plate will start to glow.

Further settings should be compared with the reference values of Table 7 and Table 8. Additional the graphs in Figure 22 should help to find the right accelerating voltage and filament power for heating up the hot plate. The left graph in the diagram demonstrates with its highest measuring point the limit for the reachable temperature at an accelerating voltage of 2,5kV. By increasing the filament power at this point fast switching operations for the settings of the power supplies take place [15]. The graph on the right hand shows that a high filament power is necessary to reach an operating temperature of approximately 1750℃.

7.3 Turn off the Q-machine

For turning off the Q-machine the high voltage- and than the low voltage power supply need to be turned off. After that, turn off slowly the magnetic coils armature voltage to zero so that the needle of the analogical display decreases equal to the needle of the currents analogical display. Accordingly, slowly deactivate every button under the key from bottom up and after that turn off the power with the key.

Before turning off the diffusion pumps the hot cathode ionization gauge (IMR 310) labeled as IMG/HV2 must be switched off and the cold cathode ionization gauge (PR 26) labeled as (PKG/IKR) will switch off automatically. Afterward the valves S1, S2 can be closed. Than switch off the diffusion pumps and for closing the valves V1, V2 use the faucet of the security system. If the diffusion pumps are not hot anymore the water pump of the magnetic coils cooling system can be switched off and all water faucets can be closed. Lastly switch off the two rough pumps.

8 Q-machine in Iowa City

The principle of a Q-machine was already described in chapter 5 by using the machine in Innsbruck as an example. The Q-machine in Iowa City works on the same principle but its construction is different (Figure 23).

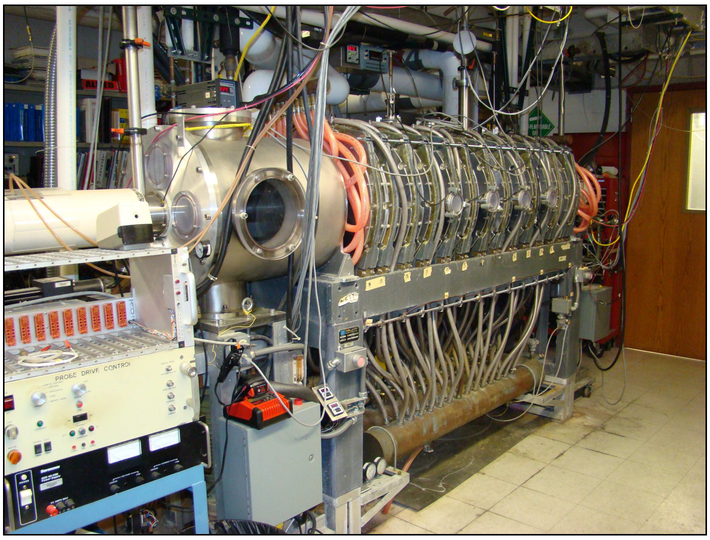


Figure 23: Q-Machine in Iowa City

The main focus of attention in this master thesis dedicates to the heating unit of the machine but there are also some other mentionable differences. This machine features another hot plate assembly with an oven and that means that it is possible to use this machine double ended (Figure 24).

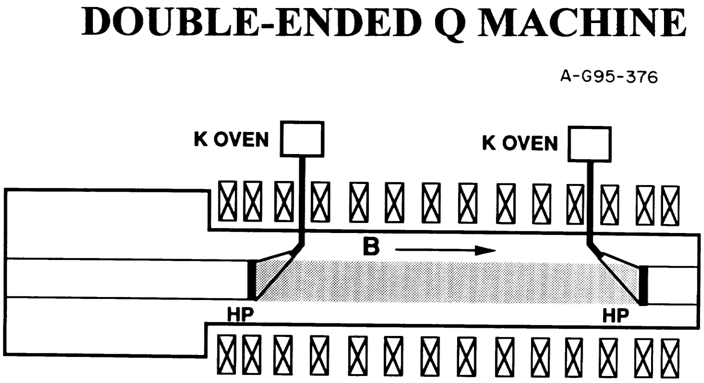


Figure 24: Schematic of the double ended Q-machine in Iowa City

The usually operating condition of this machine is double ended and it provides a plasma column 60 mm in diameter and 1400 mm in length. The plasma column is confined also by an axial magnetic field which has a setting range up to 7 kG. The cooling of the magnets occurs by a self-contained system, which consists of a cooling tower with the cooling solvent ethylene glycol. The glycol is used to cool deionized water in a secondary heat exchanger, which then circulates through the magnet coils. Furthermore it is mentionable that the hot plate is made of tantalum (W_{Ta}=4,25 eV) and the atomic beam oven is usually loaded with a mixture of cesium chloride and calcium. Based on these different used materials compared with the Q-machine in Innsbruck, there occurs another condition for the production of plasma. The influence on the effects in the Q-machine of the chosen materials for the hot plate and the loading of the atomic beam oven were already discussed in section 5.2.1.

8.1 Defect Analysis and Problem Handling - Iowa City

The Q-machine in Iowa City was not also working for a time period of a few years but compared with the Q-machine in Innsbruck it was basically in a better condition because no operating mistakes with the result of overheating, for example took place. Anyway, the Q-machine in Iowa City had also some defects which were time consuming to eliminate. The target for the Q-machine in Iowa City was to reach an operating condition by using one hot plate which allows temperature measurements on this hot plate like at the Q-machine in Innsbruck. This target could be reached and additionally plasma can be produced again. Therefore it is possible by using the results for the hot plate temperature to make a comparison between the heating-unit of the machine in Iowa City with other heating systems. As mentioned before had the Q-machine in Iowa City also some defects but not the same like the machine in Innsbruck. It was necessary to change some pressure gauges but the main problem was to re-establish the vacuum system.

8.1.1 Vacuum System

The vacuum system in Iowa City has basically the same assembling than the system in Innsbruck. Both chambers have a separately pumping circuit and each is connected with a rough pump whereas a diffusion pump is interconnected between this rough pump and the chamber. Additional exists for each circuit a bypass which connects the rough pump directly with the respective chamber. Furthermore it is possible to evacuate the chamber and the diffusion pump with its closed high vacuum valve which separates the connection between the pump and the chamber. This evacuation procedure is necessary to create a fore vacuum which is required by the diffusion pump. Therefore an operating condition can be reached which enables to switch on the diffusion pump. After a required heating up period from the manufacturer the diffusion pump can be connected with the chamber if the valve of the bypass is closed and the diffusion pump will start to evacuate the chamber. The described assembling and the schematic commissioning procedure of the vacuum system should only give a short overview. That is why it is necessary to read for the real commissioning the manual of the respective pumps manufacturer.

Before it was allowed to commission the vacuum system in Iowa City without problems the system has had to be re-established. At the beginning of the re-establishment of the vacuum system it was necessary to minimize possible defects.

First of all the visible contamination inside the Q-machines assemblies, the chamber walls as well as their inspection glasses have had to be cleaned. Only the metallic surfaces were cleaned with alcohol and the polycarbonate inspection glasses with water. The cleaning procedure was necessary to reduce the effect of outgassing inside the machine but it facilitated also the loading of the atomic beam oven with the already mentioned cesium, calcium mixture.

Additional possible sources of error were visible brittle O-ring gaskets which have had to be changed with new ones and greased with vacuum paste to prevent them from brittleness.

Moreover another visible inspection of the rough pumps and the diffusion pumps oil quality and its fill level showed which pumps required a cleaning and an oil change. Consequently the respective pumps have had to be rebuilt and cleaned with alcohol and afterwards filled with adequate oils to the fill level which is required by the manufacturer manual.

After those mentioned visible inspections and the problem handling of the respective, possible sources of error the commissioning of the vacuum system showed that the evacuation of the chamber needed a long time period. The pressure in the chamber decreased very slowly and the required pressure during a non heated hot plate of approximately $1 \times 10^{-6} torr$ could not be reached. Of course, the chamber was open and therefore the impact of outgassing was a reason for this long evacuation period but the reachable end pressure evidenced to another problem. Consequently a helium-leak-detector has had to be connected with the Q-machine to search for leaks and it detected a leak which was easy to fix by changing of a brittle O-ring gasket. Afterwards, the reachable end pressure was nearly the same as before but the laboratory engineer Mr. Mike Miller found another discrepancy of the vacuum system. Based on his experience in the past with this vacuum system he has known that the pressure difference before and after the diffusion pump was too small. Furthermore he thought that the reason for the worse reachable end pressure must be a defect of the diffusion pump. Consequently, another leak check with the helium leak detector showed that his guess was correct. At the bottom of the diffusion pump a leak was detectable and the rebuilding of the diffusion pump visualized a crack at the diffusion pumps bottom. That is the reason why the diffusion pump has been changed by another one and therefore it is possible to reach the required end pressure. Furthermore the basis for the commissioning of the heating system was established to make some temperature measurements at the hot plate.

8.2 Commissioning - Iowa City

The commissioning procedure of the Q-machine in Iowa City compared with the described commissioning procedure of the Q-machine in Innsbruck in section 7.2 is basically nearly the same. Furthermore no operating mistakes happened in the past and a laboratory engineer who is well versed with this machine shows every new operator the exactly commissioning procedure with the most important reference values for the power supplies. Based on these reasons it was decided not to describe the commissioning in this section.

9 Comparison of the Heating Units

The procedure from the re-establishment of operating until the commissioning of the Q-machine by using the machines from Innsbruck and Iowa City as examples was already described in the previous chapters. Therefore the operating conditions of the heating unit can be reached to make some temperature measurements at the hot plate which allow a comparison between the heating units. Furthermore it is possible to collect some optimization proposals for the heating unit. The target of this optimization is to reach a uniform temperature profile at the hot plate. That means that in the ideal case the temperature profile looks like how it is shown in Figure 25 [4].

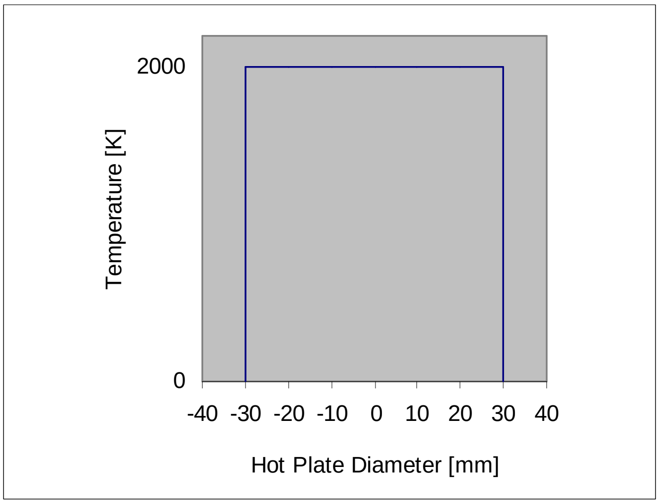


Figure 25: Ideal temperature profile of a hot plate with a diameter of 60mm

As already mentioned in section 5.2 has a hot plate typical a diameter of 30 to 60mm and in the real case by using common heating units the temperature profile decreases at the hot plates edges. In the sections 5.2 and 7.1.1 it was also mentioned that it is important to make the hot plate thicker than its cylinder wall to obtain a more homogenous temperature profile. The reason is that thinner cylinder walls minimize the heat flow from the hot plate [1].

Therefore the construction of the hot plate as well as the used method for heating it, are main factors of influence to change the temperature profile at the hot plate. There exist at least three different methods for heating the hot plate [16].

- One method to heat the hot plate can be realized by using a heat radiation cathode which has to be placed behind the hot plate [16].

- Another method is to heat the hot plate by directly passing current trough the hot plate [16].

- The third method is to use a filament positioned behind the hot plate to heat it up by electron bombardment [16].

It does not matter which heating method will be used, in any case it is very important to heat the hot plate as uniformly as possible. By using a filament to heat the hot plate it is not so easy to obtain a uniformly temperature profile because of the magnetic field which will also force the heating electrons to follow the magnetic field lines. Therefore the electron bombardment and consequently the heating takes only on those parts of the hot plate place where the magnetic field lines occur. Hence the heating filament has a rather sophisticated shape. After some time of operating the whole hot plate will be heated by heat conduction [1].

9.1 Heating Unit with a Single Filament and Tantalum Heat Shields - Innsbruck

As already mentioned is in the heating unit of the Q-machine in Innsbruck a single filament in use which is placed between the heat shield and the hot plate. The electrical connection of the heating unit and the hot plate allows the heating of the hot plate with the filament per electron bombardment to a temperature of approximately 2000K.

The construction and the electrical connection of the heating unit with its filament and heat shield as well as the construction of the hot plate and its water cooling coil were already described in section 7.1 which starts on page 17.

Furthermore the commissioning of the heating unit with the described filament and reference values for the settings of the power supplies by using this filament, were also already described in section 7.2.7 and 7.2.8.

Accordingly, detailed technical information can be found in the mentioned sections above and therefore it was decided not to describe those details of the heating unit again.

9.1.1 Position of the Heat Shields and the Filament during the Temperature Measurements

The following description explains a further advantage of the heat shield which is installed behind the filament and its position. Furthermore it explains the orientation of the filament in comparison to the hot plate during its temperature measurements. The second heat shield is already described in section 7.1.3.2 on page 24.

Another advantage of the heat shield disc as the mentioned in section 7.1.3.2 “Tantalum Heat Shield” is that it protects the filament from stresses in the heating unit in Innsbruck. The electrodes are only fixed on one end at the blind flange of the Q-machine and on the other end of the electrodes has to be spot welded the filament (Figure 27). If there is no heat shield in use, the electrodes will be more flexible, depending on their thinness as well as their length between their fixing point and the filament. The heat shield facilitates a fixed position of both electrodes and therefore it is possible to spot weld the filament with reduced stresses. Consequently the filament will be more protected from cracks by using this heat shield in the Q-machine in Innsbruck. Primarily commissioning experiments tried by the author have shown on one hand that the spot welded seams between the filament and the electrodes without a heat shield are sometimes not strong enough to bear the stresses from the electrodes.

On the other hand the experiments have also shown that the position of the heat shield along the electrodes should not be changed if the filament has already been spot welded on the electrodes. The changing of the heat shields position causes stresses at the spot welded seams of the filament and the electrodes. Those stresses at the spot welded seams can be followed by their cracks. Therefore the position of the heat shield 76 mm behind the hot plate was chosen before spot welding of the filament. This position of the heat shield and the position of the filament with 7mm behind the hot plate were already mentioned in section 7.1.3.1 and 7.1.3.2.

Furthermore it was already mentioned in section 7.2.7 on page 32 that the reason why the hottest spot was not at the center of the hot plate during the temperature measurements at the hot plate will be discussed in this section.

Normally it is very important to align the center of the filament with the center of the hot plate to heat it uniformly. If the center of the filament is displaced that means also that the filament is not parallel to the surface of the hot plate. Furthermore the distance of the filament to the hot plate will not be on every point the same. Consequently, a higher current will flow where there is a smaller distance between the filament and the hot plate and those regions will reach higher temperatures [17].

During the experiment the filament in the Q-machine in Innsbruck was displaced approximately 10mm as it is shown in Figure 26.

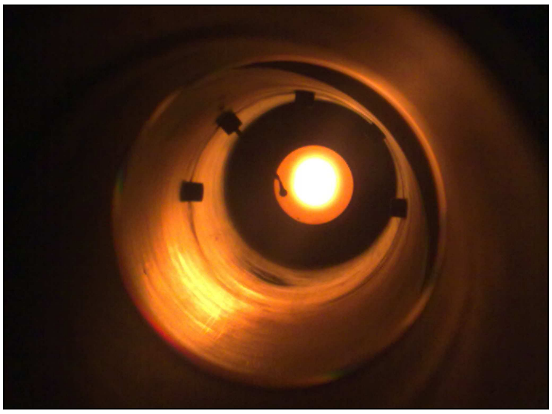


Figure 26: Hot spot of the Hot plate

The displacement of the filament probably happens during the difficult connecting of the heating unit with the female chamber.

The filament and a heat shield are positioned on two long electrodes and have to be slide in into the cylinder of the hot plate (Figure 27).

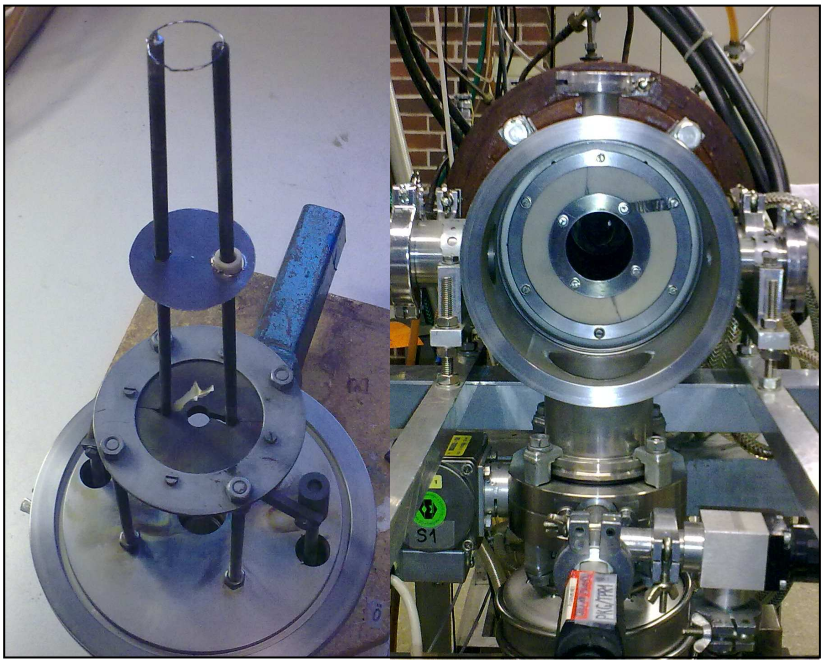


Figure 27: Filament and heat shield positioned on two electrodes and the female hot plate chamber

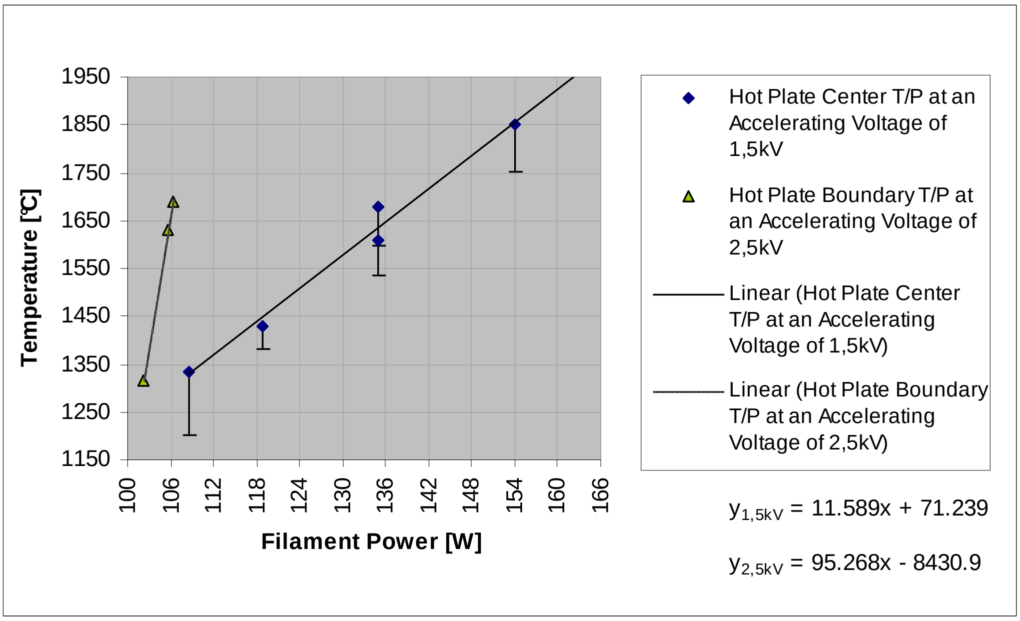
The difficulty lies in the small distance of 13mm between the heat shield and the inner wall of the cylinder and additionally it is not possible to see the position of this heavy construction. Probably a contact between the heat shield and the inner wall of the hot plate cylinder displaced the filament.

9.1.2 Temperature Measurements at the Hot Plate

The target of this experiment was to heat only a small part of the hot plate to a temperature of approximately 2000K and to find the correct settings of the new power supplies to get reference values for further experiments. Anyway it was also important to make some temperature measurements at the hot plate to obtain a raw heating profile of the single ring filament.

The temperature at the hot plate was measured contactless by using a pyrometer. This pyrometer also allowed the temperature value to be read directly from a display.

The settings of the Q-machine during the experiment are shown as a list of reference values for further experiments in section 7.2.7 in Table 7 and Table 8. Furthermore the measured temperature values from the center of the hot plate and from its boundaries over the particular filament power were visualized in a diagram which is shown Figure 22 on page 34. Nevertheless this diagram was already described but following it will be discussed a little bit more and therefore it has to be mentioned again (Figure 28).



$y_{1,5kV} = 11.589x + 71.239$

$y_{2,5kV} = 95.268x - 8430.9$

Figure 28: Reachable Temperature of the Hot Plate with a certain Power for an Accelerating Voltage of 1,5kV and 2,5kV [15]

Of course by using the filament with the already described dimensions in section 7.1.3.1 it is not possible to heat the whole hot plate homogenous depending on the diameter (21 mm) of the filament and the diameter of the hot plate with 60 mm.

Nevertheless the obtained temperature values for the hot spot at the hot plate show that the temperature difference between the hot spots center and the boundaries are less than 100℃ (see Figure 28, 1,5kV curve). Only the first temperature measurement points show a higher difference between the center and the boundaries of 135℃. The temperature differences between the center and the boundaries of the hot spot increased at higher filament power. The reason why the first temperature difference at 108,5 W was higher could be that the heating up period of the hot plate had not been finished when temperature measurement was made.

The small differences of the measured temperatures show, that the single filament ring works very well to heat the hot plate, but to be sure that the temperature profile of the hot plate will be homogenous it would be necessary to make more temperature measurements along the hot plate to obtain a precise temperature profile. Furthermore it would be recommended to use a filament ring with a larger diameter to make it possible to heat the whole hot plate.

9.2 Heating Unit with a Spiral Filament and Ceramic Shield – Iowa City

The heating unit of the Q-machine in Iowa City works basically the same way as the Q-machine in Innsbruck but the filament structure which is discussed in section 9.2.1 is different. Furthermore the dimension as well as the material of the hot plate is also different than the used one in Innsbruck. The hot plate is made of tantalum and has a diameter of 63,5 mm and a thickness of 5,1mm. Furthermore the hot plate cylinder with its attachment is welded to one assembly. The cylinder wall is also thinner than the hot plate to minimize the heat flow from the hot plate. Consequently it will be easier to obtain a more homogeneous temperature profile on the hot plate [1]. The main focus of attention in this master thesis dedicates to the heating unit of the Q-machine but it is also mentionable that the atomic beam oven of the Q-machine in Iowa City is made of an injector (see Figure 29). Therefore this oven has a simple construction compared than the atomic beam oven in Innsbruck which was already shown in Figure 15 on page 21, since the oven in Innsbruck consists of a complex ring system with little bore holes.

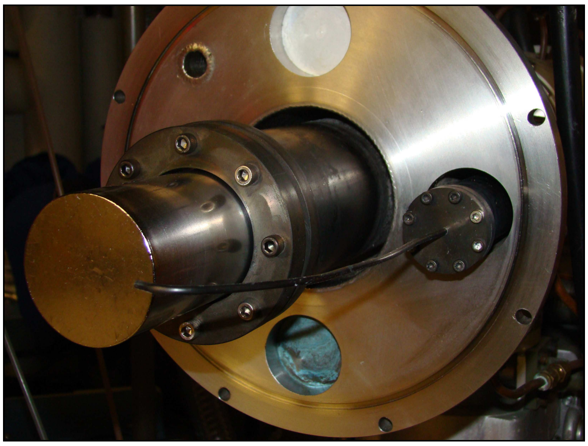


Figure 29: Hot plate (tantalum) with the atomic beam oven

9.2.1 Dimension as well as the Position of the Heating Shield and the Filament during the Temperature Measurements

Compared to the filament of the heating unit in Innsbruck the filament of the heating unit in Iowa City already has the correct diameter to heat the whole hot plate. The filament is made of a 1,0 mm diameter thick tantalum wire which is wound to a spiral to allow a uniformly distributed electron bombardment of the hot plate as much as possible (see Figure 30). Furthermore the filament is fixed with tantalum hooks on a bifid ceramic disc which has also the function as a heat shield. Those are reasons why it is not necessary to spot weld the filament and consequently it will be rugged against cracks which due to the Lorentz force which was described in section 7.1.3.1. The ceramic disc has to be split to protect itself as well as the filament from crack formations which could arise due to thermal expansion.

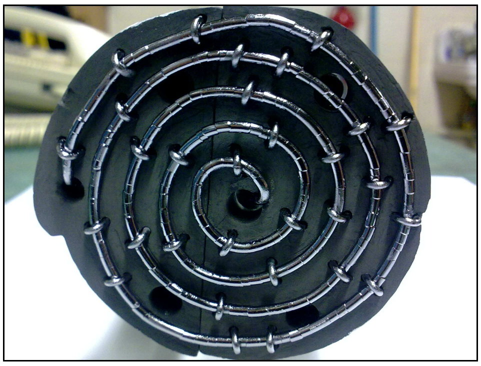


Figure 30: Tantalum filament

The electrodes of the heating unit are very rugged constructed and have a length with about 600 mm which conforms approximately three times the length of the electrodes in Innsbruck (see Figure 31). The disc with the biggest dimension which is shown on the left side in Figure 31 near the center of the picture makes an arrangement of the filament in the center behind the hot plate possible and has also the function as a heat shield. Therefore the filament will be positioned parallel to the hot plate how it is recommended in section 9.1.1. In addition to the heat shield on which the filament is fixed, the heating unit consists of another one which is positioned approximately 140 mm behind the filament.

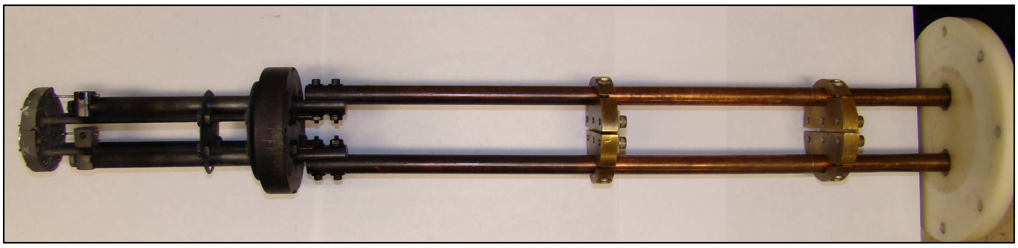


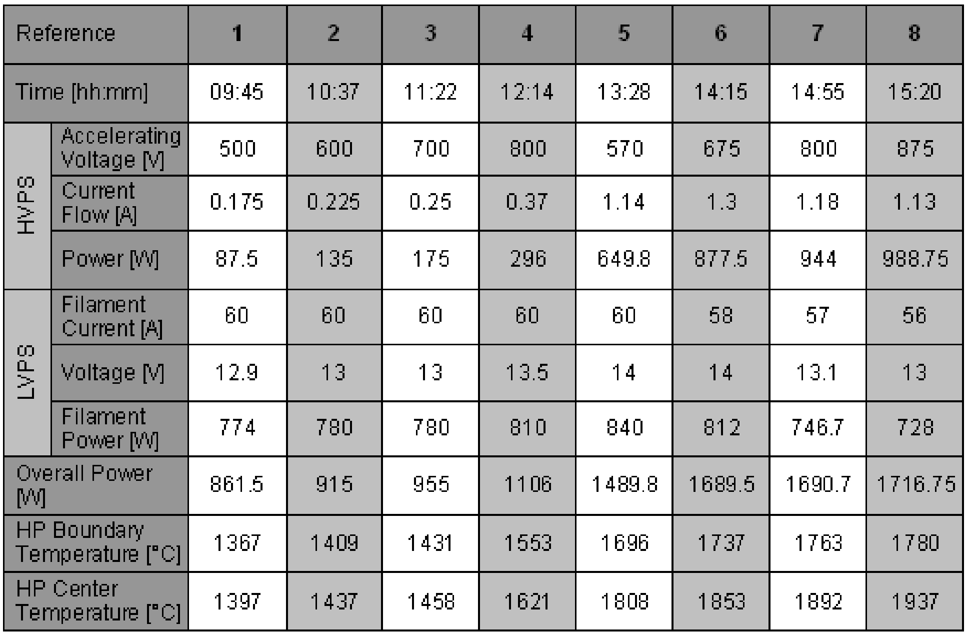
Figure 31: Filament with its heat shield and the electrodes

The distance between the filament to the hot plate during the temperature measurement experiments was 3,2 mm and the heating unit worked very well by using this mentioned distance. As mentioned in section 7.1.3.1 on page 23, the Q-machine in Innsbruck, which uses a distance of 4 mm, was subject to fast switching operations and sparkovers. Nevertheless these fast switching operations are probably the result of a displacement of the filament which causes a smaller distance between the filament and the hot plate and consequently sparkovers will take place.

9.2.2 Temperature Measurements at the Hot Plate

The contactless temperature measurement at the hot plate was possible by using a pyrometer. This pyrometer has been calibrated by using a black body radiator to allow a good temperature measurement. After the temperature measurement with the pyrometer it was necessary to calculate the real temperature of the hot plate as it was described in section 6.2. Therefore the emissivity of the hot plates material (tantalum) has been considered to obtain the actual temperature. The value for the emissivity of tantalum has been chosen from a table and is 0,49 [18].

The listed reference values in the following table (Table 9) shows the settings of the power supplies as well as the corresponding, obtainable temperature of the hot plate. These reference values should help for choosing the right settings of the power supply and the current source to heat up the hot plate with the filament described in section 9.2.1.



Reference		1	2	3	4	5	6	7	8
Time [hh:mm]		09:45	10:37	11:22	12:14	13:28	14:15	14:55	15:20
HVPS	Accelerating Voltage [V]	500	600	700	800	570	675	800	875
	Current Flow [A]	0.175	0.225	0.25	0.37	1.14	1.3	1.18	1.13
	Power [W]	87.5	135	175	296	649.8	877.5	944	988.75
LVPS	Filament Current [A]	60	60	60	60	60	58	57	56
	Voltage [V]	12.9	13	13	13.5	14	14	13.1	13
	Filament Power [W]	774	780	780	810	840	812	746.7	728
Overall Power [W]		861.5	915	955	1106	1489.8	1689.5	1690.7	1716.75
HP Boundary Temperature [°C]		1367	1409	1431	1553	1696	1737	1763	1780
HP Center Temperature [°C]		1397	1437	1458	1621	1808	1853	1892	1937

Table 9: Reference values for the power supplies of the heating unit

The pressures during the temperature measurement experiments were constant. The pressure in the main chamber was $1\times10^{-6} torr$ and in the hot plate chamber $5{,}4\times10^{-6} torr$. Furthermore the magnetic coils were set to 300 A and therefore the magnetic field B was 1,9kG.

The results for the actual hot plate temperatures depending on the settings for the overall power are shown in the figure below.

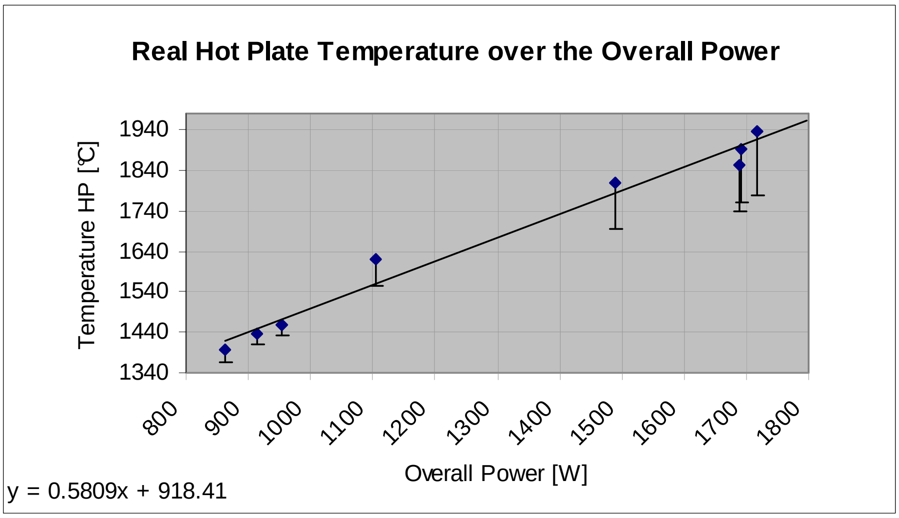


Figure 32: Hot plate temperature over the overall power

Figure 32 shows the hottest places in the center of the hot plate and the lines under the hottest spots describe the temperature at the boundary of the hot plate. Furthermore it shows that the temperature difference between the center and the boundary of the hot plate increases by increasing the overall power. The temperature measurements at higher center temperatures than 2000K (1726,85 ℃) were necessary to heat also the boundary regions of the hot plate up to the recommended temperature of 2000 K [3]. Therefore the diagram shows also which overall power will be necessary to allow ionization at the boundary of the hot plate.

9.2.3 Temperature Profile of the Hot Plate

The settings for the power supplies which were used for the highest measured temperature in section 9.2.2 were also used to obtain a temperature profile of the hot plate by using a digital camera. Therefore it was necessary to calibrate the camera with the pyrometer. The camera was fixed at the end of the Q-machine to guarantee for every picture the same distance to the hot plate (Figure 33).

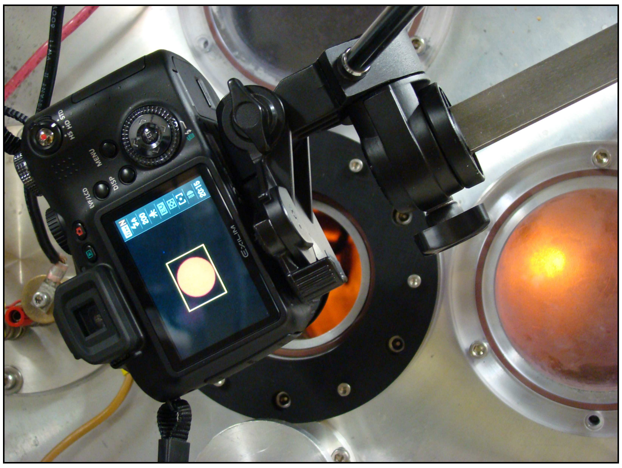


Figure 33: Fixed position of the digital camera

Additionally it was important to use for every picture the same settings to avoid a change of the gray value which was already calibrated. The camera was provided with a filter for a wavelength of 680nm and the inspection glass, made of borosilicate was permeable for a wavelength range of 0,3µm until 2,6 µm [19]. Furthermore it was possible to obtain certain gray values for several points from the hot plates picture by using the software ImageJ. Consequently it was possible to allocate the gray values specific temperatures. Nevertheless it was also necessary to calculate the real temperature of the hot plate as it was described in section 6.2. Therefore the emissivity of the hot plates material (tantalum) has been considered again to obtain the actual temperature.

The following figures (Figure 34 and Figure 35) show the temperature profile of the hot plate in its horizontal- and vertical-Axis. The shown arrangement between temperature profile and the dimension of the hot plate in the following figures can be insignificantly displaced. The reason for this insignificant displacement is that the temperature profile has been obtained by using a picture which was not exactly focused.

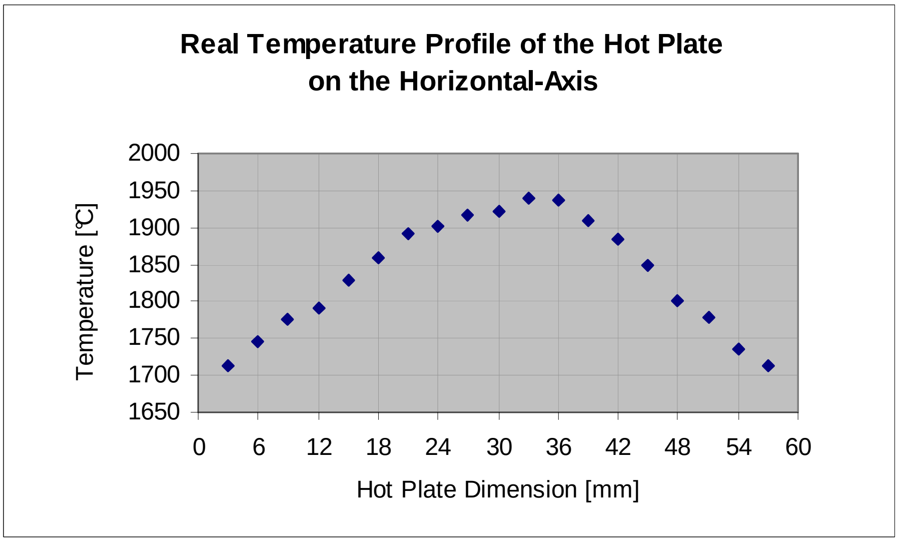


Figure 34: Temperature profile of the hot plate on the horizontal-axis

Both figures (Figure 34 and Figure 35) show a temperature difference between the center and the boundary of the hot plate of approximately 250℃.

The temperature measurement with the pyrometer which is visualized in Figure 32 shows at the same overall power (1716 W) a temperature difference of 157℃.

The reason why the results are different is probably that the used pyrometer allows a big measurement error because of its principle of operation. By using this pyrometer it is necessary to compare optically the color of the glowing hot plate with the color strip of the pyrometer. Therefore it happens sometimes that measurement errors take place because of the difficulty to compare the glowing hot plate color with the correct color on the color strip.

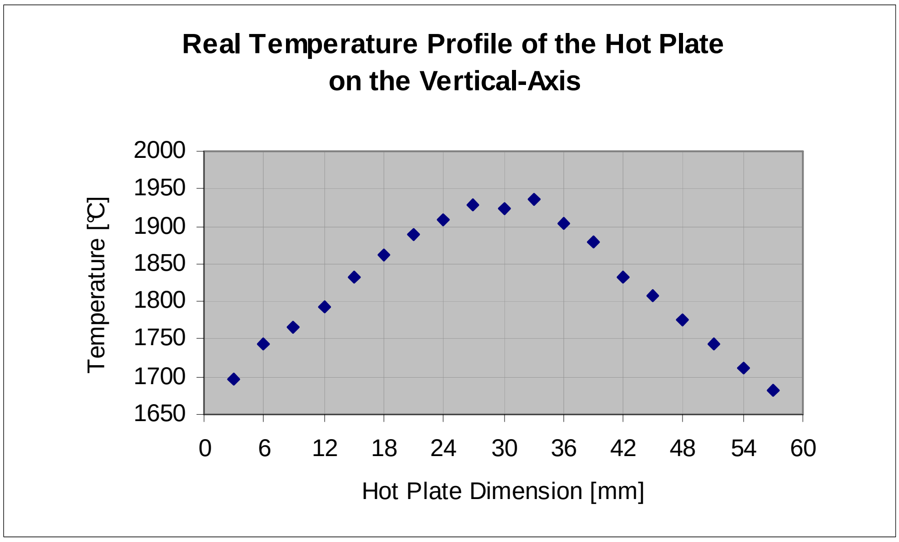


Figure 35: Temperature profile of the hot plate on the vertical-axis

Basically the figures (Figure 34 and Figure 35) show a nearly constant decrease of the temperature from the center of the hot plate to its boundary. The real temperature profiles compared with the ideal temperature profile (Figure 25) of the hot plate shows that there is still room for improvement.

9.3 Heating Unit with a Molybdenum Cathode and LaB_6 filled Grooves – Irvine, California

The Physics Department in Irvine (California) developed in the middle of the seventies the following method to heat a hot tungsten plate with a diameter of 50 mm and a thickness of 6,3 mm [20]. The wall thickness of the hot plate cylinder of 0,5 mm has been chosen thinner than the hot plates thickness in order to minimize the heat flow from the hot plate.

The hot plate is heated by electrons from LaB_6 which emits very strongly and is pressed in its powdered form into the grooves of a circular molybdenum plate (see Figure 36) [1], [20]. This cathode is positioned behind the hot plate and has to be heated up by a single filament [1].

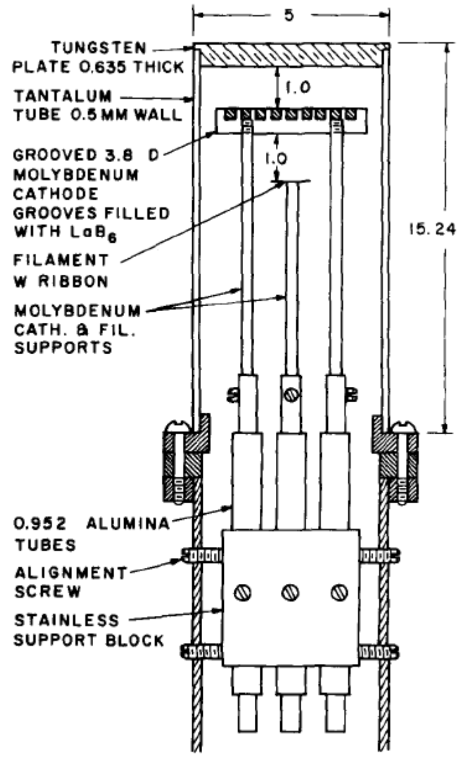


Figure 36: Schematic of electron bombardment ionizer (dimensions in cm) [1]

The single filament, connected with a power supply heats the cathode from its back side per electron bombardment. If the cathode is hot enough the LaB_6 emits electrons by itself and the actual heating power supply for the hot plate can be switched on [1]. Therefore the hot plate will be heated by the bombardment of the LaB_6 emitting electrons because of the negative bias with respect to the hot plate [20]. If the hot plate is hot enough and glows white, the filament can be switched off since then the LaB_6 will be heated by the heat radiation from the hot plate. The LaB_6 surface will be emissive if its temperature does not decrease below approximately 1200℃ [20].

The described heating method allows an enormous advantage for the temperature distribution on the hot plate how it is shown in Figure 37 [1].

The unit of the temperature values in Figure 37 is Kelvin and the temperature measurement has been taken with a L & N pyrometer. The emissivity of tungsten as well as the reflection of the vacuum window has been considered [20].

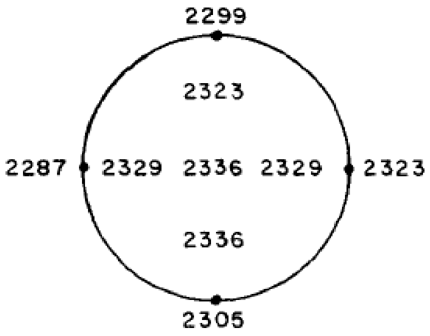


Figure 37: LaB6 cathode heated hot plate with its temperature distribution [20]

As mentioned above is in this heating unit also a filament in use but it is only for the start of the heating process necessary. This filament heats the molybdenum cathode with its LaB_6 filled grooves nonuniformly. Nevertheless if the main heating is done on the hot plate, this will smooth out the temperature of the cathode by heat radiation. Consequently the intensity of the electron emission of the LaB_6 and eventually also the temperature of the hot plate will be rather homogeneous and radial symmetric [1].

To protect this heating system from an unstable operation it is necessary to use an electronic regulation of the electric power. This electronic regulation prevents the higher electron emission from the LaB_6 to a stronger heating of the hot plate which produces also more heat radiation to heat the molybdenum cathode with the LaB_6 and the system will become unstable [1].

Figure 37 shows that this heating method allows a very small temperature difference between the boundary and the center of the hot plate of approximately 50K. Therefore this heating unit represents an improvement for the Q-machine in Innsbruck as well as for the Q-machine in Iowa City.

9.4 Heating Unit with a rotating Cathode System and improved Heat Shield – Sendai, Japan

The Graduate School of Engineering of the Tohoku University introduced in 2001 a Q-machine source with a rotating cathode system and a limiter-type heat shield [16].

Basically this heating unit also used a filament which is wound similar to the filament in Iowa City (see (1) Figure 38), and its diameter is 52 mm. Nevertheless the filament is coupled on a rotating assembly behind the hot plate and not fixed like the filament in Innsbruck or Iowa City. The hot tungsten plate has a diameter of 60 mm and is a component of the fixed part (8). [16]

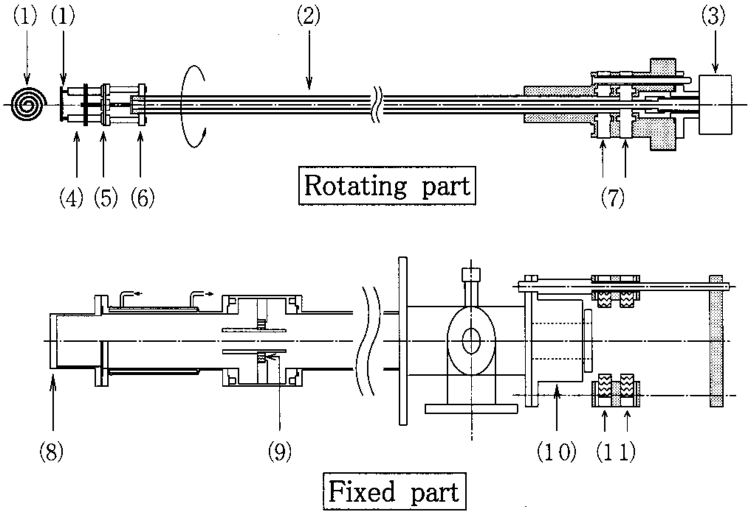


Figure 38: Fixed part and rotating part of the improved Q-machine source [16]

This method with the rotating cathode allows convertibility of the inevitable spatial non uniformities of heating power from a filament cathode into temporal fluctuations with sufficient frequency. Therefore the azimuthal asymmetry of the heating power will be averaged over one cycle and thus, the thermal inertia of the hot plate material serves to dump the fluctuation on the average (see Figure 39). [16]

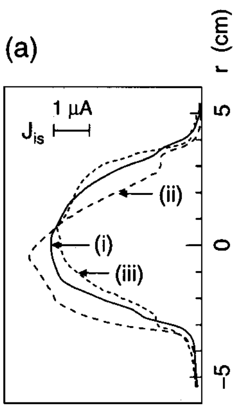


Figure 39: “Radial J_{is} (ion saturation current of the probe) profiles at f_{HP}= 200 rpm (i) and f_{HP}= 0 rpm (ii) and (iii), respectively” [16]

The ion saturation current J_{is} can be measured by using the Langmuir probe measurement method. Furthermore the measured J_{is} profile of the biased probe allows the estimation of the temperature distribution on the hot plates surface. The proportional interrelationship between the J_{is} and the plasma density which is determined by the temperature of the hot plate makes this estimation of the temperature distribution possible. [16]

Figure 39 shows that the increasing of the rotating parts rotation speed leads to a more symmetrical J_{is} profile (i) due to the averaging effect. Therefore the temperature distribution on the hot plates surface will also be more symmetrical. [16]

A further improvement could be reached by using heat shields which surround the hot plate. The schematic arrangements of the heat shields relative to the hot plate are shown in Figure 40 and the resulting temperature distributions are shown in Figure 41. [16]

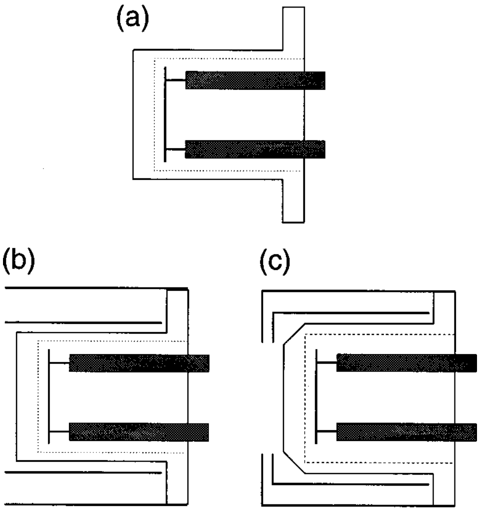


Figure 40: “Side views of the hot plate with (a) no heat shield; (b) the cylinder-type heat shield; (c) the limiter-type heat shield” [16]

The cylinder-type heat shield which is shown in Figure 40 (b) has double coaxial cylinders and covers the extremity of the hot plate. Nevertheless the result for the J_{is} profile which is shown in Figure 41 (b) makes it visible that the decrease of the hot plates temperature at its boundary cannot be completely prevented. [16]

The limiter-type heat shield which is shown in Figure 41 (c) has brims to shade the edge of the hot plate. Furthermore a new hot plate type of construction with a side shape which is trapezoidal allows an electron bombardment from the backside of the whole hot plates surface region.

The result for the J_{is} profile which is shown in Figure 41 (c) makes it visible, that the limiter-type heat shield in combination with the rotating cathode produces a flatter temperature profile of the hot plate with a sharper temperature difference at the edges. [16]

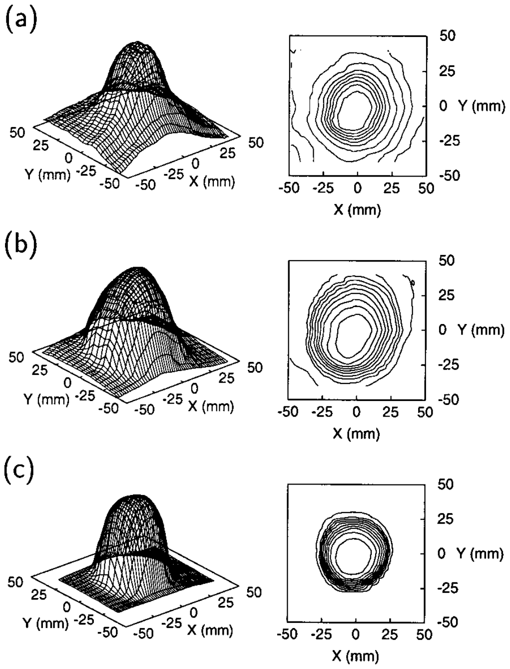


Figure 41: "Bird`s-eye and contour views of Jis at fHP= 200rpm with (a) no heat shield; (b) the cylinder-type heat shield; (c) the limiter-type heat shield" [16]

The results of this heating unit and the heat shield described above show that they present a potential optimization for the heating source of the Q-machine in Innsbruck as well as for the Q-machine in Iowa City.

10 Perspective

As already mentioned, the described “Heating Unit with a Molybdenum Cathode and LaB6 filled Grooves – Irvine, California as well as the “Heating Unit with a rotating Cathode System and improved Heat Shield – Sendai, Japan represent an improvement for the heating unit in Innsbruck and in Iowa City (see 9.3 and 9.4).

Nevertheless, the rotating cathode system has a very complex construction, therefore it would be difficult to build it and probably would it be very expensive. Furthermore it is difficult to have a moveable component in a vacuum chamber and to guarantee in the meantime the air tightness of the system.

The improved heat shield type of construction described in section 9.4 would be also a good optimization possibility to increase the boundary temperature of the hot plate but it would be associated with a new construction of the hot plate which leads also to a cost-intensive optimization.

As mentioned before the heating unit with LaB_6 would also be a good possibility to obtain a better temperature profile of the hot plate and it would be easier to rebuild the present system. Nevertheless, a complete substitute of the heating unit would be mostly cost-intensive.

The best further procedure to obtain a more uniform temperature profile of the hot plate for the heating unit in Iowa City would probably be to add a heat shield which surrounds the hot plate. Some temperature measurements at the hot plate should be made afterwards which should help to find further, necessary procedures.

For the heating unit in Innsbruck it is recommended to try further experiments with a filament with another type of construction and probably different positions of the heat shield behind the filament. The filaments diameter is generally smaller than the diameter of the hot plate and that is why it is not possible to bombard the edges of the hot plate. That is the reason why the filaments diameter should be chosen as big as possible to allow an electron bombardment which covers nearly the whole region of the hot plates surface from its backside. Furthermore, it is necessary to find the best settings for the power supplies of the heating unit with the new filament. By using those settings of the power supplies it is recommended that more temperature measurements at the hot plate be made to obtain a temperature profile of its whole surface. Consequently it would be possible to revaluate the quality of the temperature profile at the hot plate and further procedures can be defined.

11 References

[1] Schrittwieser, R., *ao. Univ.-Prof. Dr.*, Script: Ion and Plasma Physics – Plasma Physics Part, Version of 11.05.2009, 7th Chapter, 1-11.

[2] Schrittwieser, R., *ao. Univ.-Prof. Dr.*, Script: Ion and Plasma Physics – Plasma Physics Part, Version of 02.03.2009, 1st Chapter, 7-8, 21-24.

[3] Motley, R.W., Q-machines, Academic Press, INC. New York, 1975, 14, Table 2-2,161.

[4] Winkler, P., Institute for Ion Physics and Applied Physics, University of Innsbruck, Verbal Communication in the laboratory on 22.06.2009.

[5] Avram, C., Doctoral Thesis: An Investigation of Energy Storage Processes in Double Layers, 1998, 89-92.

[6] Schrittwieser, R., *ao. Univ.-Prof. Dr.*, Script: Plasmaphysik, Version of 14.07.2009, 6th Chapter, 11.

[7] Schrittwieser, R., *ao. Univ.-Prof. Dr.*, Script: Ion and Plasma Physics – Plasma Physics Part, Version of 10.03.2009, 3rd Chapter, 8.

[8] Schrittwieser, R., *ao. Univ.-Prof. Dr.*, Script: Skriptum zum Laborpraktikum, Version of 03.11.1992, 28.

[9] Schrittwieser, R., *ao. Univ.-Prof. Dr.*, Koslover, R.,K., Rynn, N., Department of Physics, University of California, American Institute of Physics, J. Appl. Phys. 58 (1), 1985, 599.

[10] Gruner, K.-D., (2007), Principles of Noncontact Temperature Measurement, Raytek GmbH, http://support.fluke.com/raytek-sales/Download/Asset/9250315_ENG_A_W.PDF, (20100703), 6-14.

[11] Stärz, R., *Ing.*, Management Center Innsbruck, Mechatronik Maschinenbau, Script: Messtechnik Sensorik, 2010, 67-75.

[12] Hecht, E., Optics, Adelphi University, Third Edition, Addison Wesley Longman, Inc., 1998, 576.

[13] Online on the Internet: Infrapoint Messtechnik GmbH, Temperaturmesstechnik Hauptkatalog (2007/2008), http://main.infrapoint.com/main/images/stories/pdf/de_kat_ohne_preis_web.pdf, 2nd Edition; (20100703), p.4.

[14] Mehlmann, F., *Mag*., Institute for Ion Physics and Applied Physics in Innsbruck, Verbal Communication in the laboratory on 22.07.2009.

[15] Maszl, C., *Dipl-Ing.*, Institute for Ion Physics and Applied Physics in Innsbruck, Verbal Communication in the laboratory on 12.02.2010.

[16] Kaneko, T., Ishida, H., Hatakeyama, R., Sato, N., Graduated School of Engineering, Tohoku University, An improved Q-machine source with a rotating cathode system, American Institute of Physics, Rev. Sci. Instrum., Vol. 72, No. 10, October 2001, 3854-3858.

[17] Merlino, R. L., *Ph.D., Professor*, Department for Physics and Astronomy, University of Iowa, Verbal Communication in the laboratory on 22.06.2010.

[18] Weast, R. C., *Ph.D*., Astle, M. J., *Ph.D*., Beyer, W. H., *Ph.D*., CRC Handbook of Chemistry and Physics, CRC Press., Inc., 66th Edition, 1985-1986, E-392.

[19] Online on the Internet: Material Properties Overview, http://www.cvimellesgriot.com/products/Documents/TechnicalGuide/Material_Properties_Overview.pdf, (20100704)

[20] Laul, V., Rynn, N., Böhmer, H., Physics Department, University of California, Improved mehtod for heating large tungsten cathodes, Rev. Sci. Instrum., Vol. 48, No. 11, November 1977, 1499, 1500.

12 List of Figures

13 List of Tables