On the interaction of coil and plasma at a Radio-Frequency Ion-Thruster (RIT)

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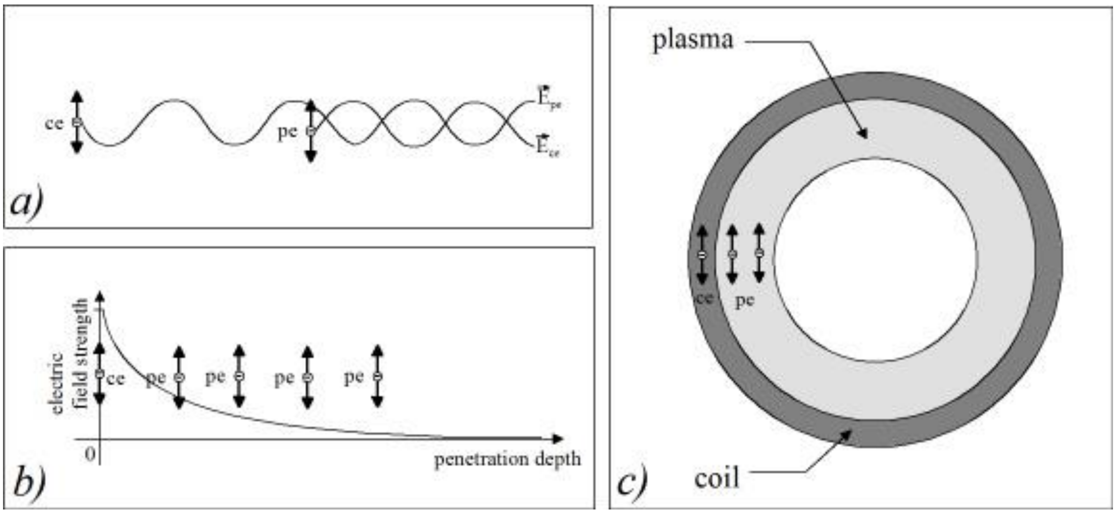
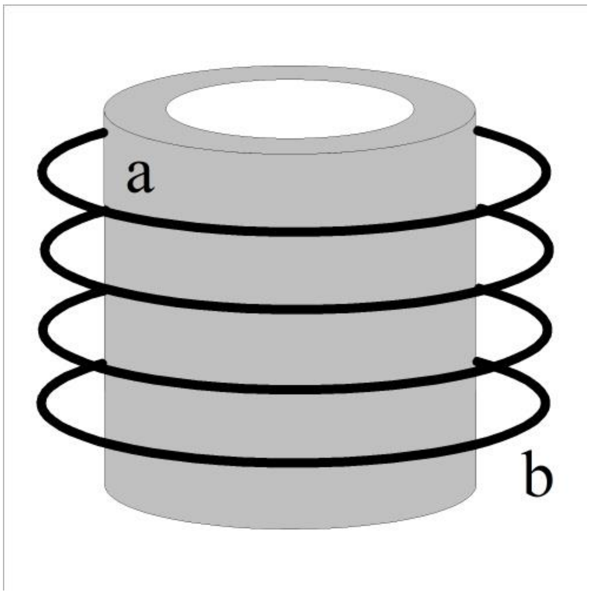
Abstract: The electric space-propulsion (EP) bases on the mechanism of ionizing the propellant. The now charged propellant can be influenced by external electric and magnetic fields; with the objective to generate thrust. The ionizing technique differs with the kind of EP. The Radio-Frequency Ion-Thruster (RIT) uses electric eddy-fields for ionization; the eddy-fields accelerate electrons, which transfer their additional kinetic energy to the neutral propellant-particles via collision. If the transferred energy is high enough, the particles are ionized in this way. Origin of the eddy-fields is a coil that surrounds the region of ionization. The interaction of coil and plasma is the core-mechanism of a RIT. This interaction and its effect on the coil behavior are discussed in the following paper.

The first principles of the following view are charges, electric fields that originate from these charges and the strict mutuality of force; charges as source of electric flied and charges under effect of electric fields. One remarkable effect is the limited penetration depth of the electric eddy-fields into the plasma. Origins of the penetrating fields are free electrons in the coil-material that are alternating accelerated again by an external applied electric field. The electric field generated by free coil-electrons plus the movement of these electrons effect the eddy-fields inside the plasma. The external field that accelerates the coil-electrons is sine-shaped, what means that the oscillation of the free coil-electrons is sine-shaped, too. Hence, the fields penetrating the plasma can also be considered as sine-shaped, see figure 1a. The free electrons of the plasma are alternating accelerated by the penetrating electric fields. Under this conditions (origin of electric field plus oscillating movement) the plasma-electrons themselves are now sender of oscillating electric fields. But because of the inertial behavior of the plasma-electrons the oscillating fields generated by the coil-electrons and the oscillating fields generated by the plasma-electrons are not in phase. Hence, they partially compensate each other. The more free electrons in the plasma are accelerated by the penetrating field the more this field is weakened, see figure 1b. This occurs until a point is reached, where plasma-electrons remain uninfluenced by the penetrating field. From this point the penetrating field can be assumed as completely compensated. The length to this point is the limited penetration depth. With the radial symmetry of the ionization area (respectively plasma area) the result is a hollow-cylinder-shaped zone of directed (oscillating) electron current inside the plasma, near to the surrounding coil. In the center of the plasma area the charges remain in undirected movement (figure 1c).



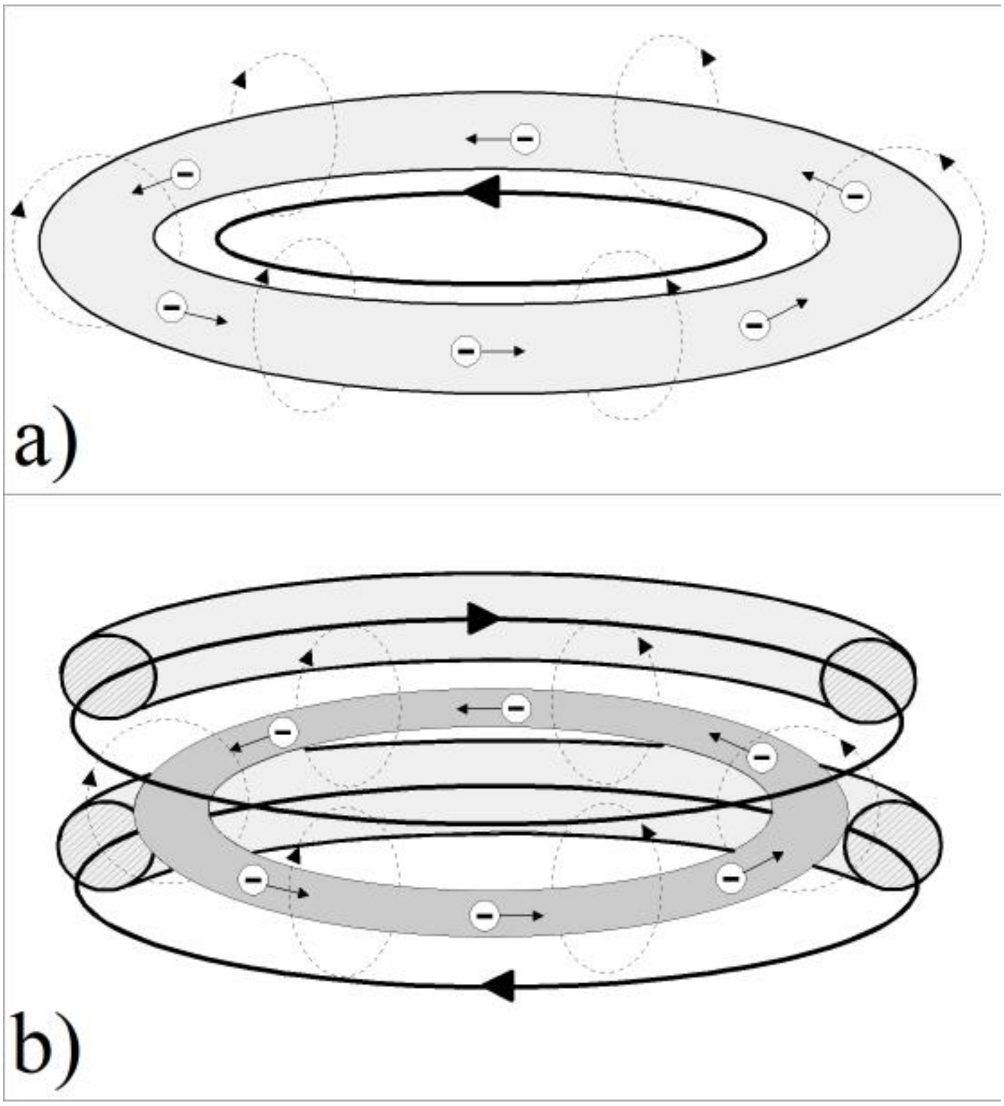
1Scheme for limited penetration depth.(a)Field of electrons in plasma(pe) compensates field of coil electrons(ce). (b)Compensation effect increases with penetration depth. (c)Top-view of coil-plasma arrangement. Field penetration into the plasma(light grey).

This hollow cylinder of plasma (plasma sheath) with a directed current of electrons can again be assumed as a coil (figure 2); a coil with one winding. According to Faradays law [1] of induced voltages basing on time-alternating magnetic fluxes the directed electron current of the plasma sheath induces a voltage in the surrounding coil that is opposed to the external voltage that is applied to the coil.



2Model of plasma coil interaction. The coil (a) surrounds the plasma. The limited penetration depth effects a hollow-cylinder shaped sheath, where the penetrating field from the coil causes an electron current inside the plasma.

As one can see in figure 3; the electron current in the coil generates a time-depending alternating magnetic field that induces an electric field in the internal space (figure 3a). This electric field accelerates the free electrons in the plasma inside the internal space. The resulting current inside the plasma generates a time-depending alternating magnetic field that induces an electric field in the coil-windings; which is opposed to the external applied field (figure 3b).



3Mutual induction of coil and plasma. (a) The surrounding coil (light grey) generates an eddy-field in the inner space that accelerates the plasma electrons. (b) The current of plasma electrons (darker grey) induces an eddy-field inside the coil that is opposed to the field applied to the coil.

The system of coil and plasma of a RIT can be characterized by the values of external to the coil applied voltage and current. The resistivity R as quotient of voltage and current provides a characteristic value of the behavior of the free electrons inside the coil. Since the electrons of the plasma influence the electrons inside the coil, the resistivity with and without plasma is different.

$$R_{with\,plasma} \neq R_{without\,plasma}$$

As mentioned above the field induced in the coil by the free plasma electrons is opposed to the field applied external to the coil. It can be assumed as: The applied field accelerates the coil electrons and the induced field decelerates the coil electrons; the induced field increases the resistivity of the free electrons inside the coil. Hence, the resistivity without plasma is smaller than the resistivity with plasma.

$$R_{with\ plasma} > R_{without\ plasma}$$

According to the law of Ohm the resistivity is the ratio of applied voltage U to resulting current I. To generate a given current a higher voltage is necessary with plasma than without plasma.

$$R_{with\ plasma} \cdot I = U_{with\ plasma} > U_{without\ plasma} = R_{without\ plasma} \cdot I$$

This means, in the presence of plasma an additional voltage U´ is necessary to effect the given current I.

$$U_{with\ plasma} = U_{without\ plasma} + U'$$

The voltage without plasma can be determined via the resistivity without plasma. This offers the advantage that the equation only depends on a constant (resistivity) and the experimental investigatable value of given current. The resistivity without plasma can be detected by taking the I-U-characteristic without the presence of plasma. For example of such a characteristic see figures 4-7.

$$U_{without\ plasma} = R_{without\ plasma} \cdot I$$

The additional voltage U´ that is necessary to cause a given current I in presence of the plasma bases on the inductive effect of the electron current inside the plasma. The electrons of the plasma generate an induction voltage inside the coil that has to be compensated by a plus of voltage to achieve a given current.

$$U' = -U_{ind}$$

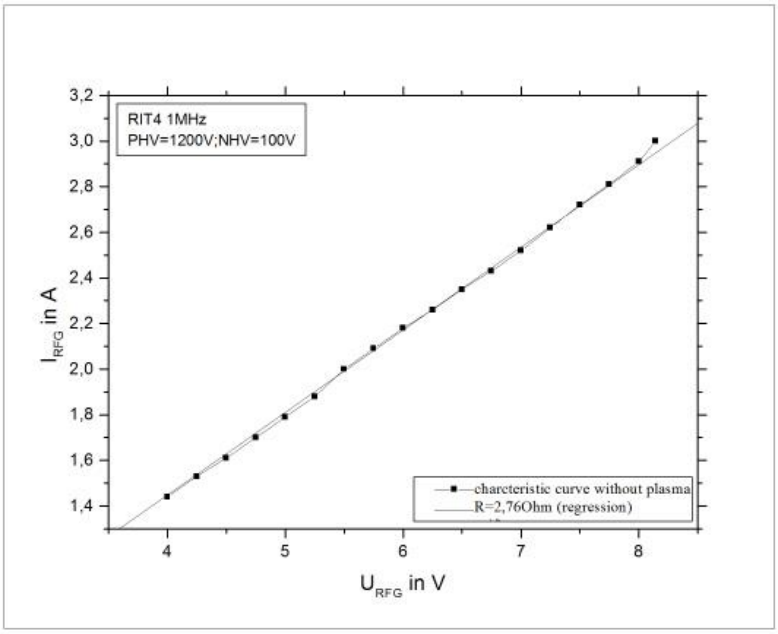
The voltage that is applied to the coil of a working RIT depends on the electric characteristic of the coil (without plasma) and the voltage that is induced by the electron current inside the plasma.

$$U_{with\ plasma} = R_{without\ plasma} \cdot I - U_{ind}$$

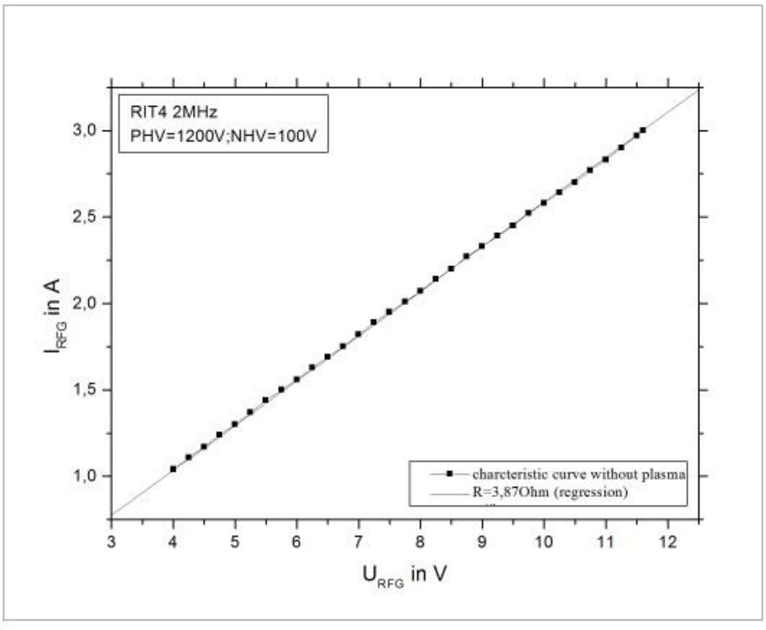
Since the characteristic of the coil is a constant, the measured applied voltage to the coil depends on the characteristic of the plasma that determines the behavior of the electron movement that is responsible for induction.

This consideration results in a mechanism for modelling the coil-plasma interaction. By the laws of induction the effect of the coil on the plasma is determined. Hence, the strength of the eddy-field accelerating the plasma electrons is known. Coincidentally, one is able to determine the effect of the current of plasma electrons on the coil; this is the additional U_{ind} that occurs inside the coil. This inductive voltage U_{ind} depends on the value of plasma electron current. Now the accelerating field and the resulting current are given. With this boundary condition the dynamic of the plasma electrons basing on the plasma structure can be modeled. Since the electrons are only able to follow the alternation of the eddy-field, while the heavier ions remain in rest, the Drude-model would be a sufficient base for the plasma structure; see [2]. The Drude-model is well known in the metal-physics: free electrons are moveable in front of a background of static positive charges.

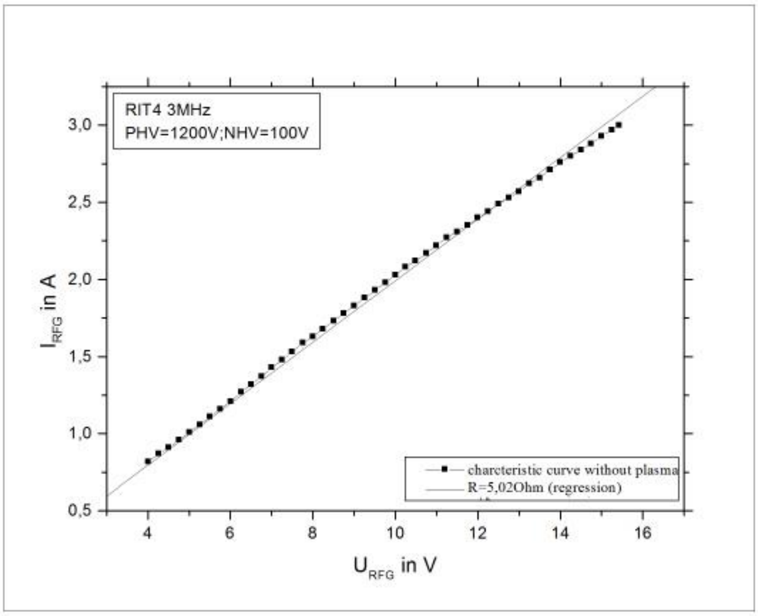
At least, the resistivity of the coil without plasma has to be determined. The taking of the U-I characteristic curve of the coil without plasma will deliver this information. In [3] this measurement was made for RIT-4 at three different frequencies (1MHz, 2MHz, 3MHz). For taking the U-I characteristic curve voltage and current applied to the radio-frequency generator (RFG) was measured. By linear regression the frequency-depending resistivity was calculated.



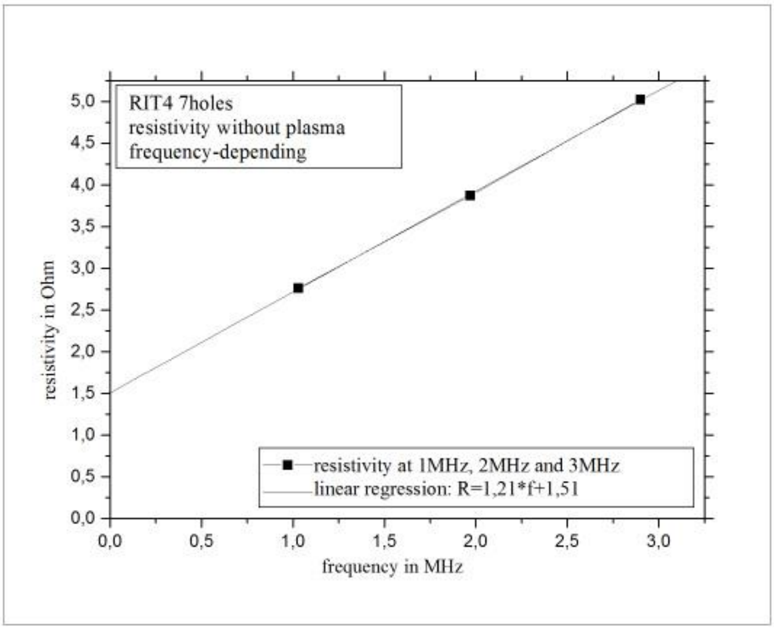
4Charateristic curve and resistivity regression for 1MHz.



5**Characteristic curve and resistivity regression for 2MHz.**



6Characteristic curve and resistivity regression at 3MHz.



7Plot of frequency-dependence of resistivity without plasma.

References:

[1] W.Greiner: Theoretische Physik Band 3: Klassische Elektrodynamik; Auflage 5, Verlag Harri Deutsch Frankfurt; 1991

[2] N.W.Ashcroft, N.D.Mermin: Festkörperphysik; Oldenbourg VerlagMünchen Wien; 2001

[3] D.Kirmse: "Zur Physik der Radiofrequenz-Ionentriebwerke am Beispiel der elektrischen Charakterisierung von RIT-2 und RIT-4"; Dissertation; Giessen 2012