An Approach for Thrust and Losses in Inertial Electrostatic Confinement Devices for Electric Propulsion Applications

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Abstract: Inertial Electrostatic Confinement in non-fusion mode is investigated for space propulsion applications. As part of this research, the Saha equation has been applied in this model to obtain the partition of particles. In addition, this study presents an assessment of loss mechanism modeling, including ionization, Bremsstrahlung, particle-grid collision, and excitation losses. Moreover, a thrust model for the jet extraction out of an IEC device is presented. Solution approaches are presented for a conical jet profile neglecting collisions and an approximated profile with an exponential function including collisions as electron impact ionization and ion-ion collisions.

Nomenclature

ΔE_{kj}	=	energy difference between *j* and *k* excitation stage
Φ_{well}	=	grid potential difference
$\eta_{e,i}$	=	transparency coefficient of grid
λ_k	=	wavelength at excitation stage *k*
γ	=	heat capacitance ratio
υ	=	collision frequency
A_{jk}	=	Einstein coefficient
c_s	=	sound speed
E_i	=	ionization energy
h	=	Plank constant
I_{sp}	=	specific impulse
k_B	=	Boltzmann constant
k_{ion}	=	ionization rate coefficient
n_{core}	=	particle density of plasma core
n_g	=	particle density around cathode
n_i	=	particle density of ions
n_i	=	particle density of electrons
P_{brems}	=	Bremsstrahlung loss

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P_{exc}	=	excitation power loss
P_{ion}	=	ionization power loss
P_{jet}	=	power of jet
r_A	=	radius of anode
r_C	=	radius of cathode
r_c	=	radius of core
$r_{ed,in}$	=	radius of inner edge region
$r_{ed,out}$	=	radius of outer edge region
r_g	=	radius of cathode
r_{jet}	=	radius of the cross-section of jet
S_{brems}	=	Bremsstrahlung radiation constant
T_e	=	electron temperature
U	=	partition function
u	=	velocity profile along jet exhaust direction
x_s	=	position of sonic point
Z_i	=	ion charge state
Z_{eff}	=	effective charge
IEC	=	Inertial Electrostatic Confinement
IRS	=	Institut für Raumfahrtsysteme

I. Introduction

Research on Inertial Electrostatic Confinement (IEC) is going on since the 1950ies, but intensive studies for applications as neutron source is existing in the USA[1,2,3] and Japan[4,5] since 1990. Plasma phenomena as jet extractions from the plasma confinement were only investigated with secondary interest[6]. In 2011, IRS started a project with the purpose to understand the jet extraction from IEC devices and evaluate the applicability for space propulsion systems. As part of these studies, experiments regarding discharge phenomena, discharge conditions, setup scaling, and dependencies on propellants (Ar, He, N_2) were conducted.[7] Moreover, optical emission spectroscopy investigations were performed receiving information about the plasma species composition.[8] A numerical study has been performed with the ESA Advanced Concepts Team to investigate physical effects leading to a jet extraction[9]. In order to evaluate on a theoretical/analytical base of whether this jet extraction is applicable for space propulsion applications, two approaches exist. The first one is calculating the thrust by a model reflecting the physical effects leading to a jet extraction. This requires an understanding of the underlying phenomena. The second approach, which is in the focus of this paper, assesses all possible losses and the required input power. Having that, an estimation of the residual input power inherited by the ions gives a maximum of the power left for thrust generation. In cooperation with Gradel sàrl, having a profound expertise in neutron source development, the loss mechanisms of the IEC in fusion and non-fusion operation have been assessed and an approach of a thrust model has been introduced.[10]

The paper is structured as follows: Chapter II gives an introduction to the inertial electrostatic confinement theory and the jet extraction mechanism. Before heading into the discussion of loss mechanism, the access of the particles partition and distribution is introduced in Chapter III. The losses such as ionization, Bremsstrahlung, particles-grid collisions, and excitation are presented in chapter IV. Moreover, the calculation algorithm for the losses estimation is descried. In Chapter V, a 1-D thrust model will be briefly introduced.[10] In the end, a summary of the models introduced for losses and thrust and respective outlooks are presented in chapter VI.

II. Inertial Electrostatic Confinement Principle

The simplest setup of an IEC device consists of two spherical, concentric electrodes, the outer being the anode and the inner being the cathode (Figure 1Figure 1). Having a potential difference between the inner and outer grids, a glow discharge ignites between the electrodes creating charge carriers. The ions get accelerated into the center of the negatively biased inner cathode grid; electrons are directed to the grounded anode. If the ion acceleration is sufficiently high fusion processes might occur. Otherwise the ions get accelerated to the other side of the cathode where they leave the inside and get accelerated back again. In that way they tend to oscillate through the system until they get lost by collisions. The confinement mechanism and fusion processes have been investigated extensively for commercial neutron source applications. Thereby different operation modes have been identified, being the Star Mode relevant for fusion applications[11], the Jet Mode (see Fig.2(a)), and the Spray Mode (see Fig. 2(b)) for space propulsion applications.

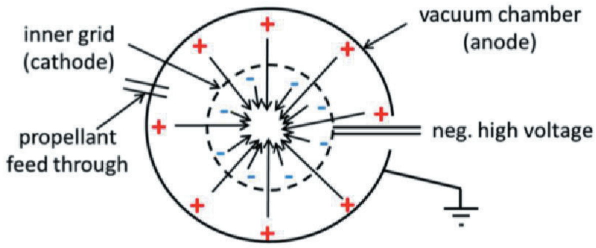


Figure 1: Schematic of an IEC device

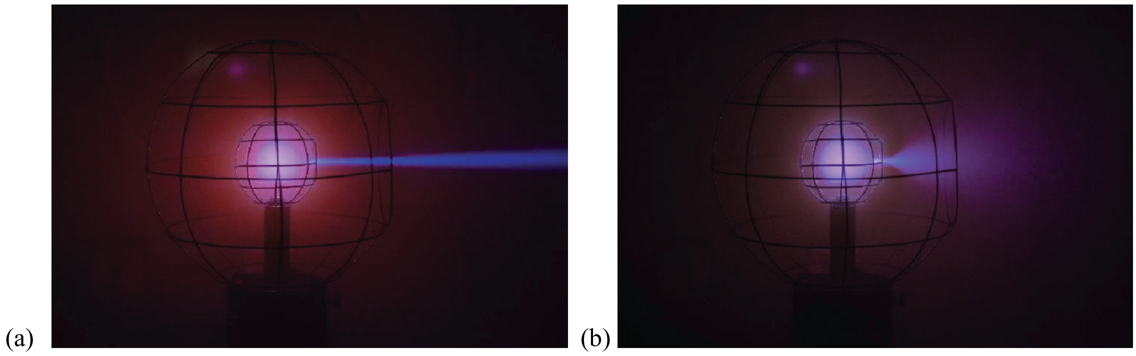


Figure 2. IEC in Jet Mode (a) and Spray Mode (b)

There are several theories how this jet extraction could be established but none is yet adequately confirmed by measurements. The general consensus is that the jet extracted from the confinement is an electron triggered mechanism. Looking at the potential field lines generated only by the externally applied field, the cathode inside is field-free in absence of particles [9] However, the grid structure provokes that field lines can reach into the inside of the cathode at the grid openings. Although only ions get accelerated into the cathode center due to the negative cathode voltage, they in turn collide with the grid or with other particles and electrons are generated. These are trapped inside the cathode due to the high negative potential at the grid and a virtual anode in the center that is created by the oscillating ions. If the grid openings are large and the electric field high enough the field lines reach the trapped electrons where they encounter a less negative potential. If their thermal energy is high enough electrons are able to leave the cathode. Due to the curved shape of the field lines like a collecting lens the electrons get accelerated on a constricted beam path. On their way out they in turn ionize background gas.

But so far this doesn't explain how highly energetic ions from the cathode center can leave the system via this jet extraction. In simulations of Ref. 9 with a Particle-In-Cell tool an electron jet could be reproduced. But an ion jet forming within the cathode could be produced only indicating a formation outside the cathode. However, preliminary experiments show the possibility of ions extracted from the cathode center. [12] A very general assumption made here is that the electrons drag ions with them, but electrons are usually much faster than ions and much lighter. If electrons leave the cathode center through one of the grid openings, the abundance of negative charge carriers between virtual anode and cathode grid leads to a strong electrostatic force that pushes ions at the edge of this virtual anode in the direction of the leaving electrons. A balance establishes as soon as enough ions have left.

III. Distribution of Ionization State

Before calculating the loss in IEC, the distribution of particles and ionization state should be determined at first. The distribution of ionization states in a plasma could be solved by using Saha equations. The Saha equation describes the equilibrium between impact ionization and recombination.[13] For a plasma in a local thermodynamic equilibrium (LTE), ion, atom and electron densities are linked to the temperature by the Saha equation:

$$\frac{n_{i+1} \cdot n_e}{n_i} = \frac{2U_{i+1}}{U_i}\left(\frac{2\pi m_e k_B T_e}{h^2}\right)^{3/2} \exp\left(-\frac{E_i}{k_B T_e}\right) \quad (1)$$

where n_e is the electron density, k_B is the Boltzmann constant ,T_e is the electron temperature, h is Plank constant, E_i is the ionization energy of an i-fold ion, and U_i the respective partition function that can be calculated using:

$$U_i = g_{i,0} + g_{i,1} e^{-\frac{E_{i,1}}{k_B T_e}} + g_{i,2} e^{-\frac{E_{i,2}}{k_B T_e}} + \cdots \tag{2}$$

For a maximum number of ionization levels n, a system of n Saha equations needs to be solved. In IRS, an analytical solution and numerical solution have been developed and verified.[14] The numerical solution is a useful tool to obtain the precise density of particles in a large temperature span. However, the calculation time and resource for numerical solution is large. For analytical solution, although the result could be compared with the online data base NIST to make sure the accuracy, it could not be solved without given an electron density. For both strategies the electron temperature T_e and the ionization energies E_i need to be determined.

IV. Losses in IEC Devices

As stated above one of the approaches followed in the analyses of IEC space propulsion applications is the assessment of loss mechanisms in IEC devices in non-fusion mode. Nevertheless, theoretical approximations about the influence of loss mechanisms in IEC neutron sources have been done by several researchers and are the starting point, although any losses through a jet extraction are not considered. Losses of the confinement can be divided into design-dependent and design-independent losses. For verification purposes loss mechanisms occurring in fusion mode were computed and then compared to the work of Ref. 15 followed by simulations in non-fusion mode with argon that will be presented. Table. 1 shows the different loss mechanisms that will be considered, grey highlighted columns are already implemented into a simulation tool and verified. The other mechanisms still have to be implemented and verified.

Table 1 Loss mechanism in IEC devices[10]

Design-dependent losses	**Design-independent losses**
Ion-grid collision	Bremsstrahlung losses
Electron-grid collision	Excitation losses
Ionization (plasma source)	Charge exchange
…	…

The following paragraph will show the different theories for the presented loss mechanisms in more detail.

A. Ionization

Ionization of the working gas is mandatory for an IEC device to function. Consequently, at least one-folded ionized particles are required. Higher ionization grades do not harm the device's functionality but are not necessary either. The power used to ionize the working gas is not available for propulsion purposes and is therefore treated as loss.

To ionize a particle, a bound electron needs to be removed from the atom. In order to achieve this, an ionization energy E_i must be transferred to an electron. In addition, the information about the number of ionized particles in a given timespan (n_i) is required in order to calculate the power used for ionizing the working gas. The number can be obtained by the Saha equation which was introduced in the last section. Lastly, the rate coefficient for ionization ($k_{ion,i}$)[16] should be included in the calculation. All in all, the power loss for ionization could be generalized in the following Eq. (3).

$$P_{ion,i} = k_{ion,i} \cdot n_i \cdot E_i \tag{3}$$

B. Bremsstrahlung Loss

This type of radiation occurs when a charged particle (typically an electron) is deflected by another charged particle (typically an ion). During this encounter the electron emits Bremsstrahlung and loses some of its kinetic energy. In order to determine Bremsstrahlung losses (P_{Brems}), the equation in Ref. 15 has been simplified and applied:[17]

$$\frac{P_{brems}}{\mathrm{V}} = S_{brems} {n_e}^2 \sqrt{\frac{k_B T_e}{e}} Z_{eff} \tag{4}$$

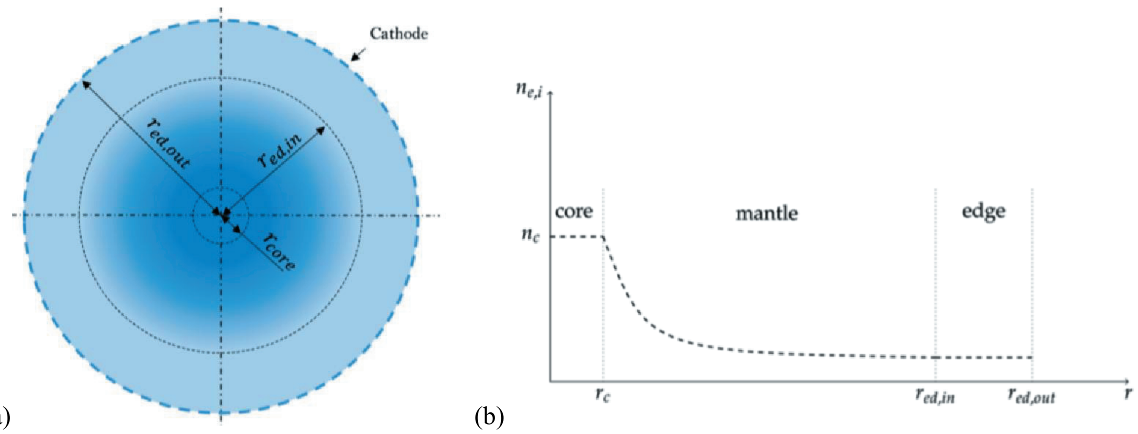
where V is the volume enclosed by cathode sphere, S_{brems} is the radiation constant for Bremsstrahlung, and e is the elementary charge. The effective charge (Z_{eff}) could be presented in following equation:

$$Z_{eff} = \sum_i \frac{z_i^2 n_i}{n_i} \tag{5}$$

C. Particle-Grid Collision

Considering particle-grid collisions, a division of the plasma regions within the cathode is necessary. If a spherical grid setup is chosen, for verification of the results on the one hand and calculating the losses for the IRS IEC setup on the other hand, the following assumptions based on Ref. 15 can be used. Assuming a single potential well is created within the cathode the plasma can be divided into three regions: core, mantle, and edge. The core is defined as $0 < r < r_{core}$, where r is the radius and r_{core} is the core radius, the mantle region as $r_{core} < r < r_{ed,in}$, and the edge region as $r_{ed,in} < r < r_{ed,out}$, where at $r_{ed,out}$ equals the cathode radius (see Eq (6) and Fig. 3(a)). The plasma densities of both species, electrons and ions, are assumed to stay constant in the core region, then drop of with r^{-2} up to $r_{ed,in}$ and then remain constant again, see Fig. 3(b)

$$n_{e,i} = \begin{cases} (n_{core})_{e,i}, & if\, 0 < r < r_c \\ (n_{core})_{e,i}\,(r_c/r)^2\,, & if\, r_c < r < r_{ed,in} \\ (n_{core})\;(r_c/r_{ed,in})^2, & if\, r_{ed,in} < r < r_{ed,out} \end{cases} \tag{6}$$



(a) (b)

Figure. 3 a) Schematic of plasma region in a spherical IEC cathode; b) Theoretical density characteristic in a single potential well

An expression for the power lost due to electron-grid and ion-grid collision is given in Ref. 15

$$P_{g,e,i} = (1 - \eta_{e,i}) 4\pi r_g{}^2 n_{g,e,i} v_{e,i} E_{g,e,i} \tag{7}$$

With

$$v_{e,i} = \sqrt{\frac{2E_{g,e,i}}{m_{e,i}}} \tag{8}$$

where the index e denotes electrons and index i ions. The transparency $\eta_{e,i}$ describes the fraction of permeable cathode sphere surface. A reasonable assumption for this parameter is $\eta_{e,i} = 0.99$ because the so-called multi-channeling can lift the transparency to such high values. Additionally, it is assumed to be the same value for ions and electrons. The grid radius is $r_g = r_{ed,out}$, the grid density $n_{g,e,i}$ is the respective particle density at the cathode, given by Eq. 6. Moreover, $n_{core,e} = n_{core,i}$ is implied, as well as electrons and ions possessing the same energy when colliding with the grid, defined as , $E_{g,e} = E_{g,i} = e \cdot \Phi_{well}$, with Φ_{well} being the grid potential difference. The Eq. (7) does not depend on temperature and does only differ for electrons and ions in mass. Due to the higher ion mass, their velocity is much lower than the electron velocity and consequently ion-grid power losses are always less than electron-grid power losses using this expression.

D. Excitation

If energy lower than the ionization energy of a particle is transferred to one of its bound electrons, said electron can be excited to a higher energy state. In contrast to the ionization process, the electron remains bound to the atom. Each element has its own unique energy levels which can be populated by electrons. Other than the ground state, there are unstable levels that are called excited states. After a given lifetime, the electron falls back to a lower excited state and excess energy is freed as a photon. There are various possible transitions depending on the species and excited state of the particle.

The wavelength-dependent power loss can be calculated referring to Ref. 18 as

$$\frac{P_{exc}(\lambda_k)}{V} = \Delta E_{kj} A_{kj}\, n_{i,k} \tag{9}$$

where ΔE_{kj} is the energy difference between j and k excitation stage for one atom, A_{kj} is Einstein coefficient which represents the probability of an atom decay from excited state k to state j per second, and $n_{i,k}$ is the particle density of an i-fold ionized atom in the k-th excitation level.

The ΔE_{kj} could be obtained by Eq. (10). The A_{kj} could be calculated by knowing the wavelength and involved energy level. The $n_{i,k}$ could be calculated based on the assumption of Boltzmann distribution, which is shown in Eq. (11)

$$\Delta E_{kj} = \frac{h \cdot c_0}{\lambda_k} \tag{10}$$

$$n_{i,k} = n_i \frac{g_{i,k}}{U_i} \exp\left(-\frac{E_{i,k}}{k_B T_e}\right) \tag{11}$$

In these formula, c_0 is the light speed, $g_{i,k}$ is the degeneracy factor of the k-th excitation level of an i-fold ion and $E_{i,k}$ the respective excitation energy. The partition function (U_i) of an i-fold ion can be calculated by using Eq. (2).

E. Algorithm

The goal for the calculation algorithm is to estimate the operating status of IEC by some known criteria (e.g. IEC geometry, chamber pressure, input power, and applied potential). The main idea is to find the point of the energy equilibrium between the input power and output power (i.e. power losses and power of jet P_{jet}). While the losses are calculated by using the equations provided in last chapter, both input and jet power need to be given. Fig. 4 shows the working principle of the used algorithm.

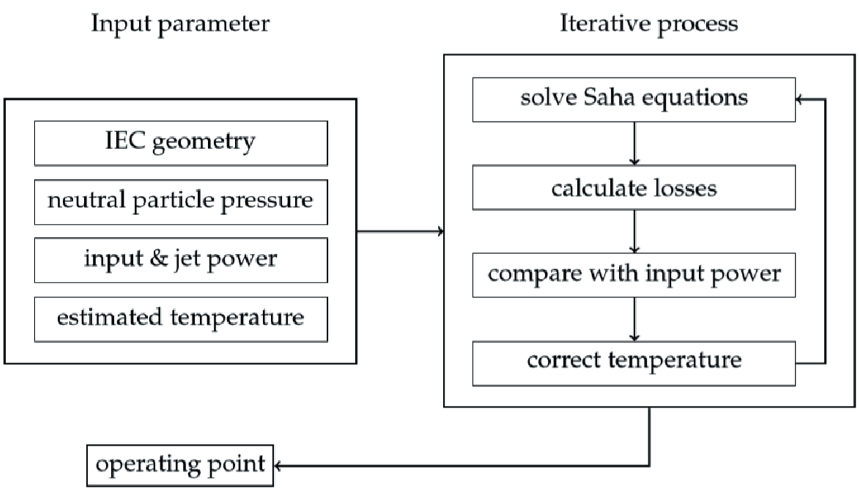


Figure. 4 Working principle of the computation algorithm[14]

Upon the calculation is initiated, an estimated temperature serves as a starting point from which the operating status is determined in an iterative process. In the iteration processes, Saha equations are solved as a first step in order to obtain the fractions of the different particle density. With the fraction of particle densities in different excited states, the losses can be calculated, respectively. Following that, these losses, together with the jet power, are compared with the input power.

The algorithm used to correct the temperature is dependent on which solution technique is used to solve the Saha equations. With the numerical solver, the temperature is adapted in a very simple way by utilizing the proportional correlation between temperature and losses. If the combined output power (P_{jet} and P_{loss}) is greater than the input power P_{in}, the temperature is increased, and vice versa. In order to reach an equilibrium, the increment needs to be adapted as well. Every time the difference in input and output power switches its sign, the temperature increment is halved.

On the other hand, the temperature adaption is slightly more complex for the analytical method. For this approach, an electron density must be provided in advance as well as a quasi-neutral plasma is assumed. In low temperature regions, where the Saha equations predict that the plasma is mostly composed of neutral particles, the given electron density can only be achieved by very high heavy particle densities. With these densities rising, the excitation losses rise as well and the simple proportional correlation between temperature and losses is not given anymore. Instead, the correlation is more complicated and the operation point needs to be found with a different approach. To solve this, the temperature correction is made by comparing the losses of the current iteration with the ones of the last iteration. In case of a smaller deviation from the input losses, the sign of the temperature correction stays the same as before. Otherwise, the sign is changed and the temperature increment is halved.

The iterative process for both algorithms is canceled after a good congruence or a maximum number of iterations is reached. While an operating point is found for any given input parameters when using the numeric solver, the analytic solver may not find a proper operating point. This is due to the same reasons that made it necessary to use a different algorithm to find the operation point. The losses get higher for both high temperatures and low temperatures because of the coupling of heavy particle densities and excitation losses. Thus, a minimum in the losses exists that may be higher than the given input power. In order to achieve convergence, the input power needs to be higher or the electron density needs to be corrected downwards.

V. Thrust Modeling

The thrust modeling approach is a direct method of assessing the thrust, apart from an experimental measurement, while the losses calculation is the indirect approach and only gives an upper limit of the power left for thrust generation. As in a neutral gas nozzle plasma can accelerate when the cross sectional area of the plasma increases, accelerating it from subsonic to supersonic velocity. In chapter II the hypotheses for jet extraction in an IEC device was already depicted. Lacking a fundamental understanding of physical phenomena, but having a bunch of indicators, the jet extraction was modeled as a plasma expansion by area expansion starting with a preliminary model with simplifying assumptions.

A 1-dimensional thrust model implementing plasma acceleration by plasma expansion was derived. The assumptions made for this thrust model are: A quasi-neutral plasma with single positively charged ions in steady state, the electron can be neglected and only the ion mass is considered in the plasma flow, without consideration of recombination, isotropic in the plasma beam, the electrons are assumed to be nearly isothermal. Combining the continuity and momentum equation, the velocity in the region of area expansion can be assessed. Eq. (12) is the derivation of continuity and momentum equation.

$$\frac{du(x)}{dx} = \frac{m_i u(x)^2 (v_i + \omega) + k_B T_e \left(\omega - u(x) \frac{dA(x)}{dx} \frac{1}{A(x)} \right)}{k_B T_e - m_i u(x)^2} \tag{12}$$

This differential equation becomes singular if the denominator becomes zero: $k_B T_e - m_i u(x)^2 = 0$. Solved for $u(x)$ at exactly the point for ion sound velocity with an adiabatic index of γ =1 and charge state of $\underline{Z_i}$ =1. In addition, if the nominator becomes also zero at the ion sound velocity, the singularity at x_s can be solved. Both of derivation for $u(x)$ *and* $u'(x)$ at x_s are shown in Eq. (13) and Eq. (14):

$$u(x_s) = c_s = \sqrt{\gamma Z_i \frac{k_B T_e}{m_i}} \tag{13}$$

$$u'(x_s) = \frac{1}{4} \left[\sqrt{8 c_s^2 \frac{d}{dx} \left[\frac{dA(x_s)}{dx} \frac{1}{A(x_s)} \right] + v_i^2} - v_i \right] \tag{14}$$

With Eq. (13) and Eq. (14), the plasma velocity can be determined by integrating Eq. (12) in both directions starting from the sonic point. The relevant velocity for propulsion applications is the velocity at the anode grid. Therefore it is reasonable to integrate from the sonic point, which should be somewhere between cathode and anode, to the anode grid which is the jet exhaust. This differential equation has to be solved numerically.

Two kinds of jet profiles have been discussed in Ref. 10: both of them are the conical jet without particle collision and approximated jet contour with particle collision. The equations of the radius for both profiles are shown in following equation:

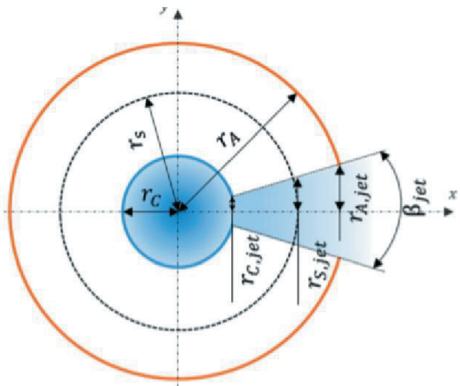


Figure 5. Schematic for the dimensions of a IEC jet.

$$r_{jet,conical}(x) = tan\left(\frac{\beta_{jet}}{2}\right)(x - r_C) + r_{C,jet} \tag{15}$$

$$r_{jet,approx}(x) = a + be^{cx} \tag{16}$$

where *a*, *b*, *c* are constants with $0 < a < 1$, $0 < b < 1$, $0 < c$. The comparison of the radius and exhaust velocity in two kinds of jet assumption are showed below. A detail derivation for the thrust model could be founded in Ref. 10.

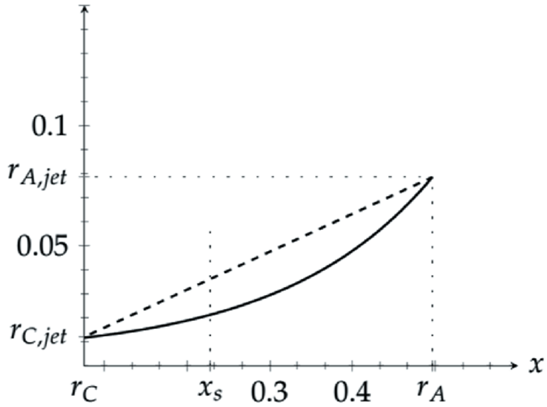


Figure 6. Jet radius of approximated jet profile (solid) and conical jet profile

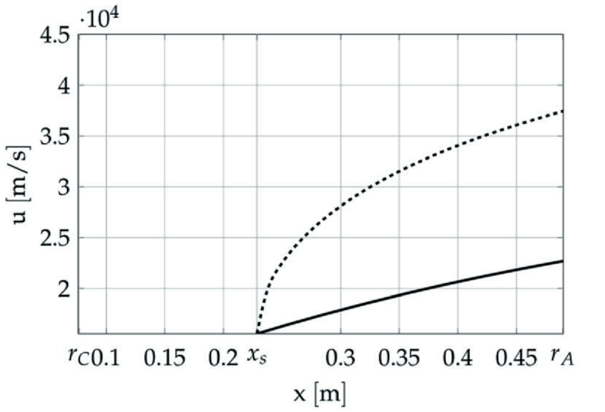


Figure 7. Velocity as a function of the jet path (conical, no collisions - dashed; approximated, incl. collisions - solid)

VI. Conclusion and Outlook

In the course of this paper, a design tool for non-fusion IEC devices for electric propulsion applications has been described. Depending on the requirement, the Saha equation can be solved by either analytical method or numerical method. Four loss mechanisms of an IEC device in non-fusion mode were examined: there are ionization, bremsstrahlung, particles-grid collisions, and excitation. The calculation algorithm for IEC devices in jet mode was introduced. The operating status of IEC could be obtained by inputting the known parameters, such as geometry of grid, pressure of neutral particle, and input power, as well as the estimated values, such as jet power and electron temperature. In the iteration processes, the electron temperature will be corrected in iteration loop by comparing net value of the input power with the sum of jet power and losses. The calculated operating point could further be applied into the thrust model to access the performance of IEC devices for electric propulsion purpose. The detail of the model was described in Ref. 10

For further improvement of the design model for IEC devices, a wide range of issues need to be addressed. First of all, the implemented grid losses need to be reworked in order to achieve a better congruency with reality. The approach used up to now mixes two different phenomena. On the one hand, the ion density is calculated by using the plasma core's density. On the other hand the energy and ion velocity is the one gained in the electric field from the applied potential between anode and cathode. To improve the calculation, these two parts need to be separated. A formula needs to be derived that addresses the losses from ions hitting the cathode from inside of the plasma core. Furthermore, a way to calculate the ion density resulting from glow discharge at the anode needs to be found for use in the formula examined in this paper.

Additionally, the loss model could be extended to cover further losses like the upscattering and jet losses. Upscattering occurs when a particle gains enough energy, i.e. through collisions with others, to leave the confining potential well. Although, it is assumed that this loss mechanism has minor influence on the total losses in low temperature regions, it should be considered in order to reflect the reality as good as possible. A further loss mechanism that could be implemented is the charge exchange between ion and neutron. Fast ions and neutral particles can collide in the device, thus exchanging their kinetic energy. A part of kinetic energy is lost since neutral particles cannot be affected by the electric field of the IEC device.

Furthermore, in order to reach a better understanding of the processes in an IEC device, a multi-temperature model could be applied to the calculations. In the present version, the LTE assumption is applied. However, modifications of the grid losses calculation will require a deeper knowledge about ion temperatures since the inside plasma-grid collision losses are mainly affected by the kinetic energy of ions.

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