Advanced Plasma (Propulsion) Concepts at IRS

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ABSTRACT

Several advanced plasma propulsion designs have been developed and characterized at IRS in the past years. Among them are the hybrid thruster TIHTUS, the steady state applied field thrusters AF MPD ZT1 and ZT2 and advanced iMPD designs. These concepts show promising potential for future missions. The paper will discuss the designs and their operational features.

In addition, more advanced systems are under investigation, among others fusion systems and magnetic sail systems. These systems are not likely to see in-flight testing within the next years, but they offer opportunities for investigation potentially applicable to terrestrial designs.

KEYWORDS: Plasma systems, advanced space propulsion, plasma modeling and simulations

Introduction

To this day, mankind has only limited access to its solar system and space flight to the closest planets has remained a technical challenge. This arises from the limited technical abilities especially in the field of propulsion, which is intuitively known for launchers. Even when it comes to interplanetary transfer, present day's propulsion systems' characteristically low performance restricts missions by forcing prohibitively long voyage durations.

In general, there are two ways to overcome this arduousness: Improving the propulsive characteristics of existing systems, and considering new approaches.

The engineering objective in advancing existing mass ejection propulsion systems can be identified performing analyses and optimization, such as proposed in [1]. These considerations show, that there's an overall benefit in raising the specific impulse, but also that this has to be tuned with the acceleration of the system, its masses and last but not least both its efficiency and its mass specific power. The latter is also the driver in the conception of more advanced mass ejection space propulsion.

Other space propulsion concepts not ejecting mass such as magnetospheric sail (M2P2) have to be studied differently.

This contribution concentrates recent efforts and results in advancing space propulsion at the Institute of Space Systems (IRS): In the first part, recent results on MPDs and a presentation of the hybrid thruster TIHTUS are given. The second part of the contribution looks out to more advanced concepts based on fusion and M2P2.

1. Steady state applied field MPD

The applied-field MPD (AF-MPD) thruster is a propulsion concept with high specific impulse and relatively high thrust density compared to other common electric propulsion systems such as ion and arc jet thrusters. The AF-MPD thruster can be operated in a very wide power range up to some MW power levels. AF-MPD thrusters use four acceleration mechanisms: expansion through nozzle; interaction between self-induced magnetic field and discharge current; interaction of discharge current and applied magnetic field; interaction of induced hall current and applied magnetic field.

Based on DLR's AF-MPD X16 thruster a laboratory AF-MPD ZT1 has been built up for a power level of 12 kW to investigate the optimization of thrust and efficiency. The AF-MPD ZT1 was successfully operated in steady-state mode at discharge power range of 5 – 6 kW (fig.1 and fig.2).

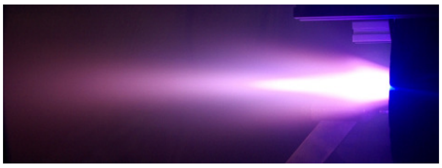

Figure 1: Plume of the AF-MPD ZT1 thruster in steady-state operation with 5.4 kW (Argon)

For future work, this data has to be extended in order to establish an improvement of scaling model [2].

To provide a better experimental data for comparing with the SAMSA Code [3], a new active water cooled configuration of the thruster was designed for steady-state operation of the SX1 thruster at a power level of 12 kW (fig.3). Involved in ESA and EU (HIPER) programs in cooperation with Alta, IRS is aiming for the development of high power electric propulsion systems.

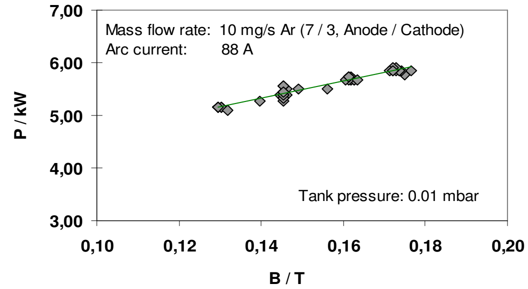

Figure 2: Experimental results of AF-MPD ZT1

In the framework of these programs, a 100 kW AF-MPD thruster is to be developed and tested within 2011 [2]. Primarily designed for this project, AF-MPD ZT2 was improved to the SX3 (fig.4) configuration to guaranty a steady-state operation at a power level of 100 kW.

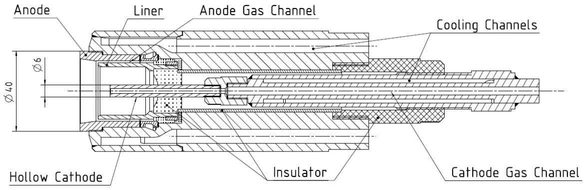

Figure 3: Sectional view of new AF-MPD SX1 thruster (Improved AF-MPD ZT1)

This design is currently being manufactured. The followed experimental investigation of the SX3 thruster will round up the data of SX1 thruster with respect to thrust, efficiency and scaling behaviour of AF-MPD thrusters.

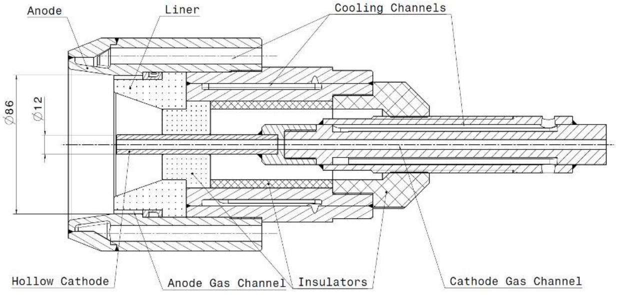

Figure 4: Sectional view of new 100 kW AF-MPD SX3 thruster (redesigned AF-MPD ZT2) [2]

2. Advanced Water-fed PPT

Pulsed Plasma Thrusters (PPT) have been investigated for several decades leading to successful space application, recently on FalconSatIII [4]. They offer a robust and low cost design, high c_e, low power consumption and easy thrust control. The common design uses a block of PTFE (Teflon™) as propellant. However, possible benefits of using liquid propellants have been pointed out [5-7].

The self regulated ablation from a solid block of Teflon™ limits the thruster performance. Only a fraction of the ablated mass per pulse is properly ionized and accelerated. The rest evaporates at relatively low velocities [8], also known as late time ablation. The use of a pre-determined liquid mass can improve acceleration and performance. A thruster without late time ablation would provide insight into efficiency margins of the PPT technology. Further, a liquid system avoids depositions of carbon and fluoride residues on surfaces altogether. Also the use of waste liquids and combined operation with other liquid propulsion systems are feasible.

In competition with other propulsion systems, any pulsed liquid system design needs to stay as close to the simplicity of a solid propellant PPT as possible, lest the feasibility degrades in terms of cost, reliability, size and performance. The complexity of handling liquid propellant and the increase in system mass must be minimized. A possible approach is to literally stick to the block, meaning to renew the area of the surface layer for ablation after each pulse, with the liquid being fed self regulated. This is realized similar to a candle using a wick to draw fuel.

Fig. 5 shows a schematic overview of the respective system components, with arrows pointing downstream.

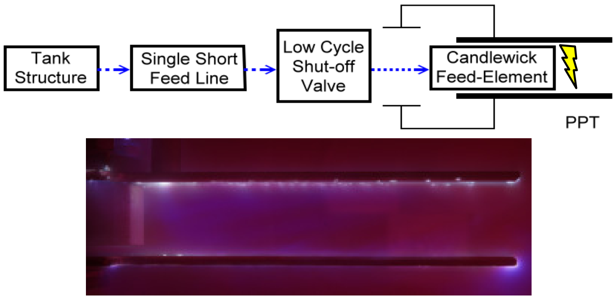

Figure 5: Schematic Setup of Liquid PPT (upper) and photo during operation at IRS (lower)

The liquid (purified water) is fed to the wick-element by means of the pressure gradient between tank and ambient space. It will saturate the wick. The tank is commonly heavy due to high pressure storage. However, the wick soaks up with the liquid and the PPT operation does only require mass flow rates in the µg-range. This allows for utilization of a very lightweight tank, shaped with regard to both volume and satellite demands. The short tubing and a singular shut-off valve have a low system mass. The valve prevents unwanted feeding during launch and PPT idle times. It is the only moving part of the system. Exposed to a space environment, a layer of ice is created on the wick-surface between the two PPT electrodes. PPT operation with liquid feeding is considered similar to PTFE feeding. After initiation of the pulse, a discharge arc forms between the electrodes, ablating propellant similar to its PTFE-pendant. After a pulse, no late time ablation can occur. To avoid ablation of the wick, ceramic materials are considered. The small system size suggests application on mini-satellites, prolonging orbital lifetime. This is supported by recent ESA studies and an increasing interest in cheap technology demonstration.

First steps towards a liquid PPT design are made at IRS. An experimental laboratory model has been set up for testing of handling, feeding and pulsed operation with purified water. The feasibility has been successfully demonstrated inside an IRS test facility. The thruster performed flawless. The analysis of results and design are subject to further research. The pulsed operation inside the vacuum chamber is shown in the lower half of fig. 5.

3. Hybrid Thruster TIHTUS

A hybrid plasma thruster is under experimental [9-11] and numerical [12] investigation. TIHTUS (Thermal-Inductive Heated Thruster of Stuttgart University) is two-staged and consists of an arcjet as the first stage and an inductively heated plasma generator (IPG) as the second stage [13]. A photo of the device in operation is shown in fig. 7 together with a schematic. The plasma plume down-stream the arcjet of the 100 kW class, called HIPARC and developed by IRS with NASA, has high temperature and velocity at the core and lower energies in the surrounding flow. To increase the energy in the plasma flow, the second stage inductively couples energy into the colder region of the plasma near the wall due to the skin effect. This not only augments both specific impulse and thrust but also flattens the radial profile of the plasma flow which may be interesting for plasma technology processes. Further, between the two stages, an additional mass flow can be added. This may be erosive gases, which would destroy the first stage cathode. With the current technology demonstrator, a thrust level of about 2N is reached at a total power of 50kW and a mass flow of 300mg/s [9].

For a better understanding of the physics and for a comparison of the experimental results, numerical investigations of the thruster are ongoing. After the validation of the numerical code, optimization of thrust and efficiency can be performed.

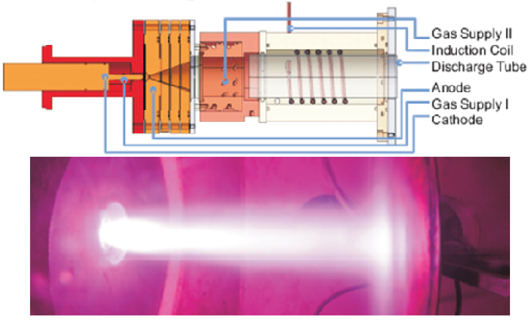

Figure 7: Schematic of TIHTUS (upper) and photo in operation (lower) [11]

There are several interesting options for optimization. Some necessary experiments like changes in geometry are rather expensive both in money and time. This effort is intended to be reduced by numerical simulations.

For the numerical simulation of TIHTUS, the program system SINA (Sequential Iterative Non-equilibrium Algorithm) will be used and improved. SINA was developed in order to numerically simulate the complex thermal and chemical phenomena in the DC plasma wind tunnel facilities at the IRS that are used for the testing of heat shield materials [14]. It can also be applied on axi-symmetric plasma sources or thrusters with an electric arc. SINA consists of three different semi-implicit and explicit independent solvers (Navier-Stokes solver, Chemistry / Vibrational / Electron energy (CVE) solver, discharge solver) which are loosely coupled (fig. 8).

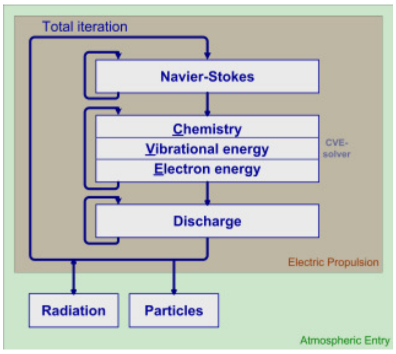

Figure 8: Structure of the code SINA for TIHTUS

4. Magnetically Confined Fusion Propulsion

One option to shorten interplanetary travel times consists in replacing lengthy conventional transfers such as Hohmann's or gravity assist maneuvers by a transfer made up of two continuous burns and estimated by

$$D = \frac{c_e^{\,2}}{F} M_d \left(\frac{1}{\sqrt{\varepsilon}} - 1 \right)^2 \qquad (1)$$

for its voyage distance D and by

$$\tau = \frac{c_e}{F} M_d \left(\frac{1}{\varepsilon} - 1 \right) \qquad (2)$$

for its duration τ [15]. In these equations, F designates the thrust, c_e the exhaust velocity, M_d the vessel dry mass and ε the ratio of dry to initial mass. From Tsiolkovsky's equation one concludes that high c_e improves ε for a maneuver described by its velocity increment Δv. Assuming a given Δv and a limitation of the mass specific power

$$\alpha = \frac{P}{m} = \frac{\frac{1}{2} F c_e}{m} = \frac{1}{2} a c_e \qquad (3)$$

with the absolute power P and characteristic mass m, one obtains that raising c_e for a given value reduces the acceleration a. Hence, it has a detrimental effect on the duration to build up Δv and consequently on the mission duration. However, if it was possible to raise α considerably, for example by using fusion, it would be possible to reap the benefits of high c_e and high thrust at the same time. Therefore, nuclear fusion seems not only to be an alternative to terrestrial energy provision [16], but also to be a very attractive one for space propulsion [17-20].

Both Magnetically Confined Fusion Propulsion (MCFP) plasma and systems have been investigated at IRS [20-23]. MCFP is a thermal propulsion concept. The power is provided by the excessively hot magnetically confined fusion plasma. The propellant may consist in fusion products – the so called ash – but it is also thinkable to aliment the system with an additional coolant heated by the plasma and ultimately ejected as propellant [20, 23].

The propulsion system relies on the fusion plasma whose operation is defined by the fusion criterion yielded by an energy and particle balance from which the characteristic triple product $n_i \tau_E T_i$ made up of the first species' ions' particle density n_i, the energy confinement time τ_E and the ions' temperature T_i can be calculated [21].

The thermal power of the products in so called ash drives (AD) is assumed to be expanded with the exhaust velocity

$$c_{e,ash} = \mathrm{c}_0 \left[1 - \left(\frac{\frac{3}{2} k_\mathrm{B} T_i \tilde{\tau}_{Ea} \Psi}{c_0{}^2 m_{pyr}} + 1 \right)^{-2} \right]^{\frac{1}{2}} \cdot \qquad (4)$$

In this equation, c_0 is the speed of light, m_{pyr} the product mass yield per reaction, Ψ the product particle multiple and $\tilde{\tau}_{Ea}$ the ratio of ash to energy confinement time. The Boltzmann constant is noted k_B. The thrust calculates from

$$F_{ash} = m_{pyr} R_{ik} c_{e,ash} \qquad (5)$$

using the reaction rate R_{ik}. The thrust efficiency η_{TH} can be approximated by the ratio of product to reactant density.

In working gas drives (WGD), the power losses of the plasma are partly recovered by the coolant/propellant (c/p$^{\mathrm{ant}}$). These parts sum up to P_{Twg}. The exhaust velocity is

$$c_{e,wg} = \mathrm{c}_0 \left[1 - \left(\frac{P_{T,wg}}{c_0{}^2 \frac{dm_{wg}}{dt}} + 1 \right)^{-2} \right]^{\frac{1}{2}} \cdot \qquad (6)$$

The mass flow of the injected c/p$^{\mathrm{ant}}$ is noted dm_o/dt and needs to assure the necessary cooling of the system.

Both system concepts call for subsystems such as the reactors hardware, i.e. the first wall, a blanket which has to be porous in case of WGDs magnets assuring the plasma confinement and a cryo system providing operational temperatures of the magnets. Moreover, there have shields to protect the vessel against harmful radiation and there have to be radiators since the spatial vacuum eliminates waste heat disposal by convection and conduction leaving radiation the only resort. Note that the recovery of waste heat for propulsive means in WGD will lead to a considerably diminished radiator size compared to AD and therefore better propulsion system mass M_P.

Hydrogen is destined to be used as c/p$^{\mathrm{ant}}$ for its excellent caloric and propulsive properties. As for the fusion fuel, in general four reactant couplings are considered: D-T, the "classic" fusion reaction considered for terrestrial power generation, and the three advanced couples D-³He, p-^{11}B and ³He-³He. The major advantage the advanced couples promise, are a considerable reduction in neutron radiation and hence lightweight shields. However, investigations at IRS [21] showed that only D-³He is worthwhile as a fuel. Typical propulsive data is documented in table 1.

System	T_i / keV	B / T	P / W	c_e / m/s	F / N	η_{TH} / %	M_P / kg	ε / %	τ / d
D-T - AD	22	3	3.0 e 6	2.2 e 6	2.8	1	4.8 e 5	99.94	2700
D-T - WGD	22	3	5.3 e 8	6.0 e 3	1.8 e 5	94	4.6 e 5	3.43	220
D-³He - AD	90	14	7.8 e 7	5.1 e 6	30.7	4	1.7 e 5	99.85	477
D-³He - WGD	90	14	1.9 e 9	1.8 e 5	2.0 e 4	91	1.0 e 5	35.69	20
p-^{11}B - AD	165	106	5.1 e 10	6.0 e 6	1.7 e 4	26	1.0 e 7	99.62	160
p-^{11}B - WGD	165	106	1.8 e 11	2.8 e 4	1.3 e 7	93	3.2 e 6	18.42	80

Table 1: Propulsive characteristics of MCFP systems (generic system, 10m³ of plasma, B magnetic containment) - ³He-³He systems do not ignite.

5. Inertial Electrostatic Confinement: Status

The most common fusion based setups, TOKAMAK based reactors as ITER or inertial confinement fusion as in NIF, require huge, heavy and complex structures. A more applicable solution due to their simplicity of setup is Inertial Electrostatic Confinement (IEC). This technology offers high energy density in small and light reactors, however no breakeven is expected. But due to the design simplicity and scalability, development was still pursued and research done over decades aimed to increase the fusion rates as much as possible.

The simplest setup was thought up in [29]: A spherical, concentric and strong negatively biased grid is placed in a grounded, evacuated, spherical chamber (Figure 10).

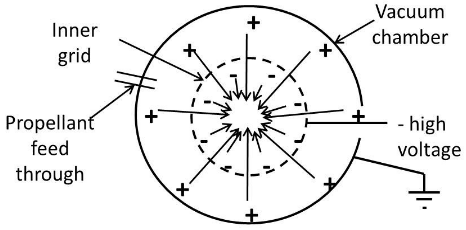

Figure 10: scheme IEC device

The grid is the cathode, the chamber wall the anode. The chamber is flooded with fuel. Ions are generated glow discharge and then accelerated to the grid center as a point of stable equilibrium. While the majority of ions do not take part in fusion processes, occasional events may occur if the ions' energy is sufficient.

The reason for starting this venture at IRS is that it is believed IEC to be one of the most promising concepts for the next generation of electric propulsion with high specific impulses. That means an IEC setup can also be operated in ranges where no fusion processes occur. Ions will be accelerated into the center of the cathode grid and will be trapped there until a hole in the potential surface of the cathode grid allows them to escape [26, 30, 31]. These thrusters can be compared to conventional ion thrusters. But it also seems promising technology for Isp's in the range of e.g. the DS4G [32] or higher. Since it is feasible to accelerate ions to an energy that is enough to allow for particles to fuse, it may also be possible to use the high kinetic energy of ions to generate thrust instead.

Moreover the extracted ion beam is a reference case for PICLAS, a code in development at IRS, IAG (both University of Stuttgart) and IHM (Forschungszentrum Karlsruhe). PICLAS aims at simulating highly rarefied plasmas as in PPT, by joining Particle-In-Cell (PIC) with DSMC and Fokker-Planck [33].

If a plasma beam with very high ion velocities can be extracted, a third interesting aspect is the potential application for simulation of high energetic radiation. IRS is co-operating with Baylor University in developing a facility for environmental simulation of complex dusty using an inductively heated plasma generator [34]. The IEC test stand is likely to provide ions with energies in the range of natural plasmas and hitherto only insufficiently simulated.

A two-grid-system test stand will be built at IRS in order to understand the basics of confinement and plasma beam extraction. A grid design study has been conducted in order to obtain the most adequate setup for a test campaign that is supposed to deliver knowledge about the confinement process within the cathode grid and certain operation conditions e.g. the star mode. In a second test sequence a plasma beam extraction shall be established and examined with Langmuir probes and LIF measurements in order to obtain information about electron and ion properties.

6. Mini-magnetospheric plasma propulsion system

Mini-magnetospheric plasma propulsion (M2P2) is a concept with low demand of propellant. This is a consequence of using solar wind to create thrust. The idea is based on the magnetic sail concept [35]: Coils generate a magnetic field around a space craft. Charged solar wind particles interact with the field according to the Lorentz force

$$\vec{F}_{Lor} = q\vec{v} \times \vec{B} \qquad (7)$$

where q is the particle charge, $\vec{v}$ is the particle velocity and $\vec{B}$ the coil produced magnetic induction. Thus, the charged particles are deflected and produce a momentum transfer to the magnetosphere and finally to the space craft. This final momentum transfer depends on the magnitude of the interaction cross section between the magnetic field and the particles. The biggest problem of this concept is that a coil with a very large diameter of several km and a current of several kA are essential to produce a non-negligible momentum transfer to the magnetosphere.

It was therefore proposed to inject plasma into the field [35], causing an inflation of the magnetic bubble (fig. 11), explainable with the MHD induction eq. (10).

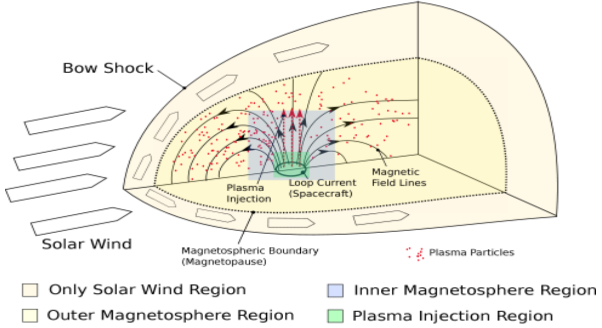

Figure 11: Schematics of the magnetic sail with plasma injection and enlarged magnetosphere

The MHD induction equation

$$\frac{\partial \vec{B}}{\partial t} - \nabla \times \left(\vec{v} \times \vec{B}\right) = \frac{1}{\sigma \mu_0} \Delta \vec{B} \qquad (8)$$

(σ: electric conductivity, μ_0 magnetic constant) is valid in the vicinity of the plasma source, this means the consequence according equation (10) is a change in $\vec{B}$ resulting in the discussed enlargement of the magnetosphere. Thus, the proportionality changes from $B \propto 1/r^3$ (r: distance) to $B \propto 1/r^k \mid k < 3$ with the decrease parameter k.

According to recent theoretical studies the enlarged magnetosphere measures 20 [36] to 80 km [37]. This huge diameter is the problem for experiments of M2P2. Only limited experimental research focuses on the change of a magnetic field after the injection of the plasma [38, 39]. Thus, numerical simulation is essential for M2P2 studies.

There are currently two main concepts for simulating the M2P2 system. The first is an MHD approach used in [36], the second proposed in [37] is a hybrid one joining MHD and kinetic equations. Results in thrust and size differ of six orders of magnitude between the two approaches making statements about an eventual practical use of M2P2 extremely difficult. The reason for the differences are the different spatial scales of the underlying model spanning from a few centimeters up to approximately 50 km, which is a great numerical difficulty. On one hand the MHD approach is not valid for all required scales on the other hand the coupling in a hybrid approach is difficult and the kinetic approach is a great computational effort.

Despite the latter we want to discuss the application of a fully kinetic approach to obtain data on M2P2. The fundamental equation is the gas kinetic Boltzmann equation:

$$\left(\frac{\partial}{\partial t} + \vec{v}\frac{\partial}{\partial \vec{x}} + \frac{\vec{F}}{m}\frac{\partial}{\partial \vec{v}}\right) f\left(\vec{x},\vec{v},t\right) = \left.\frac{\partial f\left(\vec{x},\vec{v},t\right)}{\partial t}\right|_{coll} \qquad (9)$$

Here, $f\left(\vec{x},\vec{v},t\right)$ is the single particle distribution function at location $\vec{x}$, at time t, with velocity $\vec{v}$. Furthermore, $\vec{F}$ is an external force and m is the mass of the particles. The term on the right-hand side is called the collision term to describe the collision effects between particles. This term causes the great mathematical effort in solving the Boltzmann equation [36]. For M2P2, the equation can be divided into two parts. The first part is the non-collisional long term interactions, they are describing the plasma behaviour dominated by collective plasma phenomena and neglecting the coulomb collisions, described mathematically by the Vlasov equation. A widely used approach for solving it is the PIC method. The second part is the collisional long range interactions, the Coulomb collisions which cannot be neglected for small spatial scales, i.e. at the plasma injection region. In such a case one has to solve the Fokker-Planck equation. An example for a highly efficient method for solving it was developed in [40].

In [41], solvers and numerical requirements for the fully kinetic approach currently studied at the IRS are discussed.

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