Future thruster application: combination of numerical simulation of ECR zone and plasma X-ray Bremsstrahlung measurement of the SWISSCASE ECR ion source

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Abstract

We present the combination of the numerical 3D magnetic field simulation of SWISSCASE, the new 10 GHz ECR ion source at the University of Bern in Switzerland, and the experimental X-ray Bremsstrahlung measurement of the same ion source, to determine the hot electron and the total electron number densities of its ECR plasma. The results, which are in excellent agreement with literature, demonstrate the quality of the numerical simulation, the X-ray Bremsstrahlung measurement and the method of combination to calculate these particle densities. The revealed key parameters of the ECR plasma such as geometry, particle densities and Bremsstrahlung emission, may enable the development of a microwave ECR plasma model, yet to be defined, which can be integrated into a Finite Difference Time Domain (FDTD) simulation to reproduce realistic microwave-plasma interaction. The presented method of 3D magnetic field modeling, X-ray Bremsstrahlung measurement and the subsequent determination of the electron densities is not limited to the SWISSCASE ion source but can further be used for detailed investigation and optimization of current and future electric propulsion concepts.

Nomenclature

ω_{MW} = microwave angular frequency, Hz
B = magnetic field density, T
m_e = electron mass, kg
e = electron charge, C
n_{ehot} = hot electron number density, 1/m^3
n_e = total electron number density, 1/m^3
n_z = particle density of ion charge state z, 1/m^3
Φ = plasma potential, V
V = volume, m^3
T = temperature, eV

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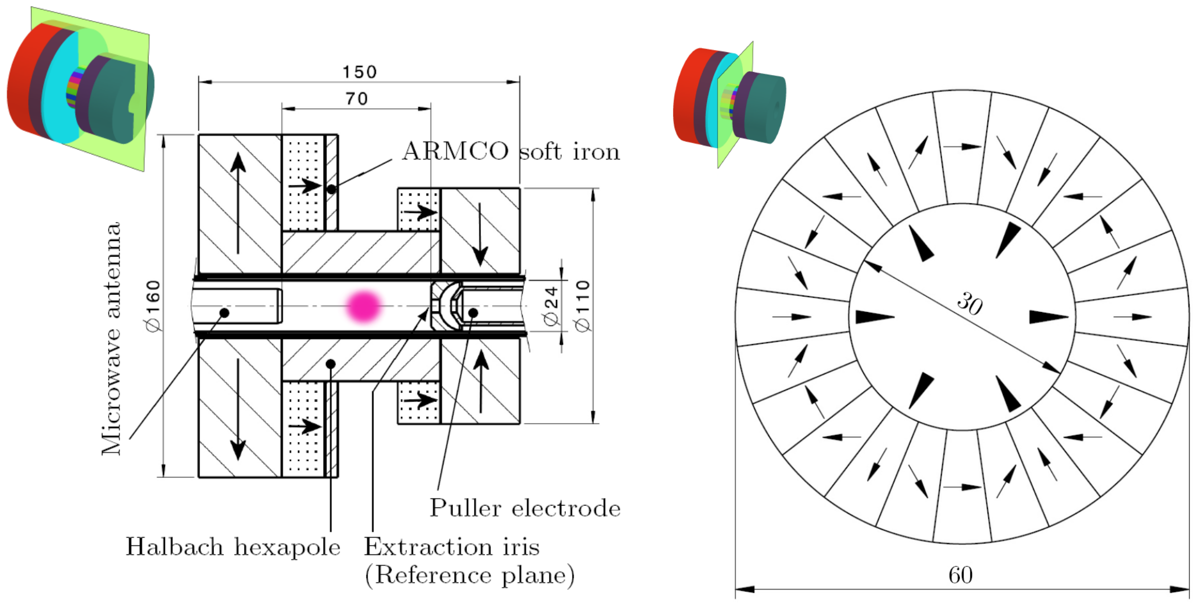

(a) (b)

Figure 1: (a) Cross sections of the SWISSCASE permanent magnet confinement (Pink: ECR plasma) along the main axis and (b) detail of the Halbach hexapole confinement perpendicular to the main axis. Arrows in the permanent magnetic material indicate the direction of magnetization. All measures in mm.

$f_{f/c}$ = hot electron fraction
A = area, m^2
r_m = magnetic confinement mirror ratio
r_{pl} = ECR zone radius, m
t = time, s
E = energy, eV or J

Introduction

Inside an ECR ion thruster, the ECR plasma is an active microwave element. Therefore, detailed knowledge about the locality of the ECR zone is required to precisely model the microwave situation inside such a thruster. In addition, knowledge of the magnetic field is required for the ion optical simulation of Hall, DC, Ion and MPD thrusters to ensure thruster efficiency and to minimize sputtering of electrodes and acceleration grids.

We demonstrate the precision of the 3D simulation of SWISSCASE, the ***S****olar* ***W****ind* ***I****on* ***S****ource* ***S****imulator for the* ***CA****libration of* ***S****pace* ***E****xperiments*, a new 10 GHz min-B ECR ion source, installed at the University of Bern in Switzerland. The obtained precision in the simulation of complex 3D magnetic fields can be used not only for the design of ion sources but also for the design of electric propulsion systems. Generally the determination of the hot electron density inside an ECR plasma by probes is hindered and limited by multiple plasma-probe-interaction effects. We present the determination of the electron density inside SWISSCASE using the numerical simulation of its confinement in combination with an X-ray Bremsstrahlung measurement of SWISSCASE. Comparing the results with the cut-off limited electron density demonstrates the usability of the numerical simulation and the method of the electron density calculation.

1 The simulated particle confinement and Bremsstrahlung

The magnetic plasma confinement of SWISSCASE is formed by permanent magnets and will be used to produce ions for the calibration of mass spectrometers such as ROSINA[6] flown aboard the space-craft ROSETTA and PLASTIC[7] flown aboard the space-craft STEREO.

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[6] **R**osetta **O**rbiter **S**pectrometer for **I**on and **N**eutral **A**nalysis

[7] **PLA**sma and **S**upra-**T**hermal **I**on **C**omposition investigation

Two cross sections of the simulated particle confinement of SWISSCASE are shown in Fig.1. Using Opera3D by *Vectorfields*, a comprehensive FEM simulation of the magnetic confinement field, the plasma potential as well as ion and electron trajectories of the complex Halbach hexapole [14] responsible for the radial particle confinement was performed [4]. Fig.2 shows the simulated magnetic field along the main axis of SWISSCASE and compares it to the measured value.

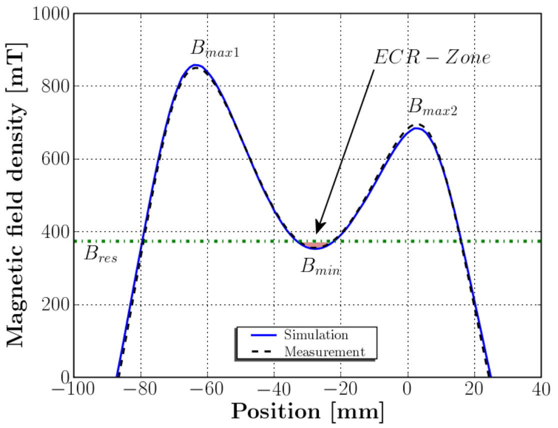


Figure 2: SWISSCASE: Comparison of measured and simulated magnetic field on the main axis of SWISSCASE. The maximum relative error at the ECR zone is below 1%. In the 3D model, the ECR zone represents a volume enclosed by an iso surface of constant magnetic field, which fulfills the ECR criteria (see Eq.2).

Eq.2 allows to determine the magnetic field which qualifies for the ECR mechanism [1].

$$B_{ECR} = \frac{\omega_{MW} \cdot m_e}{e} \tag{1}$$

All units are in mks, with B_{ECR} as the magnetic field required for resonance, ω_{MW} the incident microwave angular frequency, m_e the electron mass and e as its charge. For SWISSCASE the required magnetic field is 388.7 mT. We used this value to select the elements in the FEM simulation result to represent the ECR zone and to precisely determine its geometry and locality. Fig.3a and 3b show a section view of the 3D magnetic simulation result. We can identify the iso-contour line which is qualified for the ECR mechanism by its magnetic field value of 388 mT. To further help visualizing the 3D structure of the ECR zone, Fig.4 shows a 3D view of the simulated SWISSCASE ECR zone with section cut.

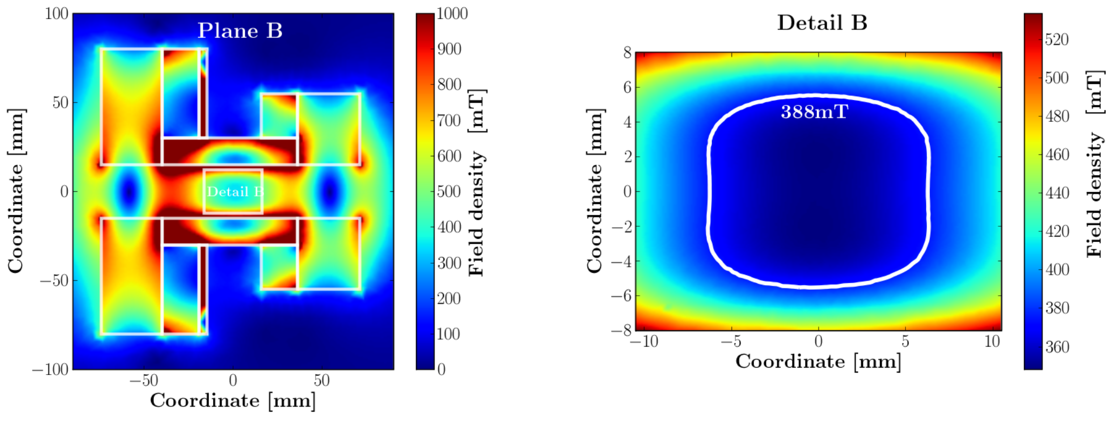
The simulation resulted in precise geometrical data about the ECR zone of SWISSCASE. Table 1 gives a summary of its geometrical properties which we used for all further calculations of the Bremsstrahlung radiation power density and the electron number densities.

ECR zone diameter	12	mm
ECR zone length	13	mm
ECR zone volume	980	mm^3
ECR zone surface area	478	mm^2

Table 1: Summary of geometrical properties of the SWISSCASE ECR zone.

2 The X-ray measurement

The SWISSCASE ECR plasma features at least two electron fractions, one with a low temperature, in thermodynamic equilibrium with the bulk plasma and another one, a hot fraction, with a higher temperature [4], which dominates the ionization process. The hot electron fraction produces a Bremsstrahlung spectrum by collisions with ions and neutrals. We used this Bremsstrahlung spectrum to determine the temperature of the hot electron population. Fig.6 shows a cross section of the X-ray measurement setup which is used to produce the following Bremsstrahlung spectra.



(a) (b)

Figure 3: (a) Magnetic field in section view of the SWISSCASE FEM simulation result and (b) detailed view of the center part of (a). The ECR zone is visualized by a white iso-contour line of 388 mT.

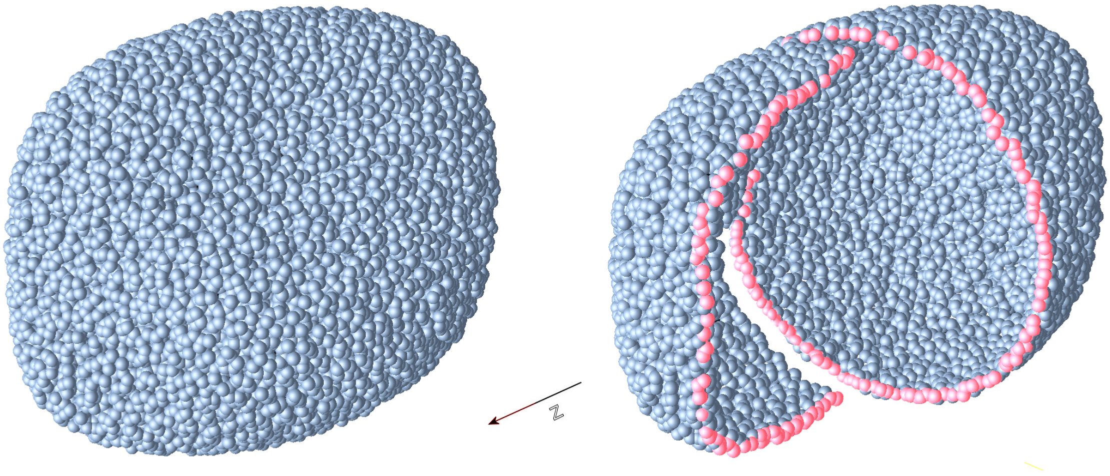


Figure 4: The ECR zone of SWISSCASE: Isosurface of a constant magnetic field (left image) and cut-away seen from the negative z-direction (image to the right). Each ball represents one element of the FEM simulation qualified by the ECR criteria $B = \omega\, m_e/e = 388.7$ mT. The balls at the cutting faces are colored red for better visualization. The diameter of the structure measures 12 mm, its length in z-direction is 13 mm.

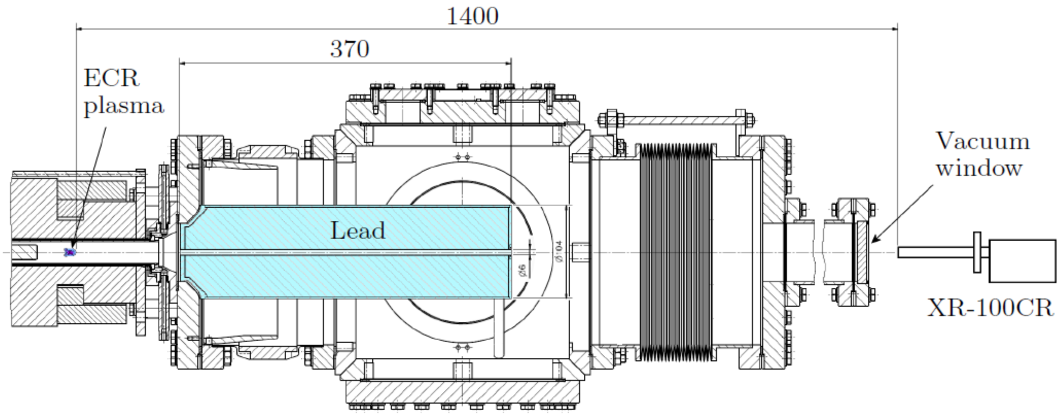


Figure 5: Setup of the presented X-ray Bremsstrahlung measurement. In light blue, a lead collimator is shown which inhibits secondary X-ray emission from electrons and ions hitting the facility walls.

Assuming a Maxwellian kinetic energy distribution for the hot electrons, the intensity of the emitted Bremsstrahlung as a function of the photon energy E_{photon} can be written as [8, 9, 10]:

$$I(E_{photon}) = I_0 \cdot \exp\left(-\frac{E_{photon}}{T_{ehot}}\right) \tag{2}$$

With $I(E_{photon})$ the intensity of the incident photons, I_0 the maximum photon intensity at the minimal photon energy in the exponential decay spectrum and T_{ehot} the hot electron temperature. This rationale shows that an X-ray Bremsstrahlung spectrum obtained from the hot electron population should feature an exponential decay with increasing photon energy.

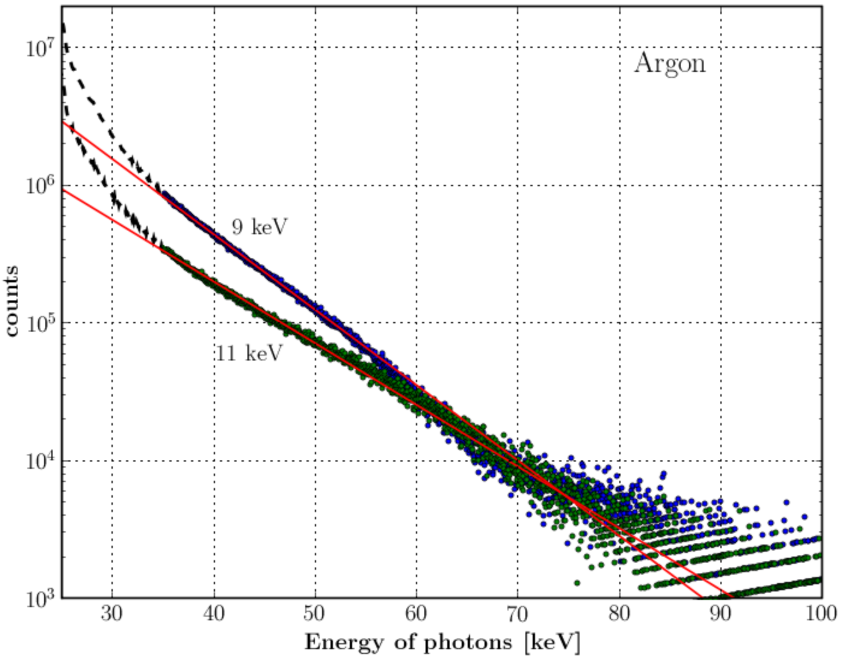


Figure 6: Bremsstrahlung spectrum of two different SWISSCASE argon ECR plasmas. One is obtained at a feed gas pressure of $1.8 \cdot 10^4$ mbar, shown in blue. The other is obtained at a feed gas pressure of $5 \cdot 10^5$ mbar, shown in green.The excitation microwave frequency was 10.88 GHz and the microwave input power was 95 W for both spectra. Two exponential decay functions (red lines) represent electron temperatures of 9 keV for the data in blue and 11 keV for the data in green respectively.

Fig.6 shows two spectra obtained from two different SWISSCASE ECR plasmas[5]. The exponential decay fit of 9 keV corresponds to a plasma X-ray measurement with a neutral gas pressure of $1.8 \cdot 10^4$ mbar. Another plasma X-ray measurement with a neutral gas pressure of $5 \cdot 10^5$ mbar can be fit with a 11 keV exponential decay for photon energies larger than 35 keV. This finding is in excellent agreement with the fact that the 9 keV plasma features more overall Bremsstrahlung emissions and a slightly lower mean charge state at more overall ion current in the extracted ion beam compared to the 11 keV plasma of SWISSCASE. In the following we will use the 9 keV hot electron temperature to calculate the hot electron number density, because this plasma represents the very well characterized standard working condition of SWISSCASE. In contrast, the 11 keV ECR argon plasma is inferior in ion beam performance for all useful charge state up to Ar^{12+}.

3 The hot electron density in the SWISSCASE ECR zone

We use a semi empirical approach by Huba et al. 2007, [3] to determine the Bremsstrahlung power density of the SWISSCASE hot electron population (Eq.3):

$$P_{Br}/V = 1.69 \cdot 10^{-38} \cdot n_{ehot} \cdot \sqrt{T_e} \cdot n_1 \cdot \sum_{i=1}^{z_{max}} z^2 n_z \tag{3}$$

All units are in mks except T_e in eV , with P_{Br}/V the Bremsstrahlung power density, n_{ehot} the electron density, T_e the hot electron temperature, n_1 the particle density of charge state one, z the charge state of ion species and n_z the ion density of charge state z. The numerical simulation of the magnetic field is used to determine the ECR zone volume V.

P_{Br}/V can also be expressed by the integration of the measured X-ray photons incident on the X-ray detector of our measurement (Eq.4):

$$P_{Br}/V = K_G \cdot \frac{1}{t_{obs}} \cdot \frac{1}{V_{plasma}} \cdot \int_0^\infty I(E_{photon}) \cdot dE_{photon} \tag{4}$$

with K_G as a geometrical factor, extrapolating the Bremsstrahlung radiation incident on the detector to the total Bremsstrahlung radiated by the ECR plasma. Assuming an isotropic Bremsstrahlung radiation pattern of the ECR plasma, K_G can be represented by Eq.5:

$$K_G = \frac{4\,\pi\,L^2_{plasma-det}}{A_{det}} \tag{5}$$

All units are in mks, $P_{Br}/V\ I(E_{photon})$ is the Bremsstrahlung emission power density of the plasma under investigation, $L_{plasma-det}$ is the distance from the plasma center to the detector, A_{det} is the active detector surface, t_{obs} is the time of observation, V_{plasma} is the plasma volume and $I(E_{photon})$ is the measured photon intensity count rate which is corrected by the detector efficiency and the X-ray transmission loss of the vacuum window used in the experimental setup. Furthermore, we can assume quasi charge neutrality of the ECR plasma (Eq.6):

$$n_{ehot} = n_1 \cdot f_{h/e} \cdot \sum_{z=1}^{z_{max}} z \cdot \frac{n_z}{n_1} \tag{6}$$

All units are in mks, with $f_{h/e} = n_{ehot}/n_e$ as the hot electron fraction, z_{max} the maximum charge state of interest in the plasma under investigation and z the charge of the respective ion counted in electron charges. From Eq.3, Eq.4 and Eq.6 we derive Eq.7:

$$n^2_{ehot} = K_G \cdot \frac{I_0 \cdot e \cdot \sqrt{T_e}}{t_{obs} \cdot V} \cdot \frac{10^{38}}{1.69} \cdot f_{h/e} \cdot K_I \tag{7}$$

with K_I as a plasma parameter ratio represented by Eq.8:

$$K_I = \frac{\sum_{z=0}^{z_{max}} z \cdot \frac{n_z}{n_1}}{\sum_{z=0}^{z_{max}} z^2 \cdot \frac{n_z}{n_1}} \tag{8}$$

In order to determine K_I the ion charge state distribution inside the plasma under investigation is necessary. The ion charge state distribution inside the SWISSCASE ECR plasma is accessible by the charge state distribution of the extracted ion beam, corrected by an extraction function. The extraction function considers that higher charged ions feature a higher charge-to-mass ratio and are better confined by both, the magnetic and the electrostatic confinement[1, 2, 5, 7, 11], provided by the hot, well confined, ECR electrons. The extraction correction function is given by Eq.9[2]:

$$n_z \sim I_z \cdot \sqrt{\frac{m_i}{e \cdot T_e}} \cdot \frac{r_m}{r^2_{pl}} \cdot \exp\left(-\frac{z \cdot \Phi}{T_i}\right) \tag{9}$$

with n_z the particle density of ion charge state z, m_i the ion mass, T_e the cold electron temperature, r_m the mirror ratio of the magnetic confinement, r_{pl} the plasma radius, Φ the plasma potential and T_i the ion temperature. From Eq.9 it is clear that higher charged ions are confined exponentially better than lower charged ions. This leads to a lower mean charge state in the extracted ion beam than in the ECR plasma under investigation. Table 2 gives

Charge state	Ion beam absolute I_z in μA	Ion beam relative I_z/I_1	ECR plasma relative n_z/n_1
Ar^{1+}	2.73	1.0	1.0
Ar^{2+}	15.8	5.79	$1.57 \cdot 10^1$
Ar^{3+}	12.4	4.54	$3.36 \cdot 10^1$
Ar^{4+}	10.1	3.7	$7.43 \cdot 10^1$
Ar^{5+}	8.33	3.05	$1.67 \cdot 10^2$
Ar^{6+}	6.01	2.2	$3.27 \cdot 10^2$
Ar^{7+}	3.24	1.19	$4.79 \cdot 10^2$
Ar^{8+}	1.75	$6.41 \cdot 10^{-1}$	$7.03 \cdot 10^2$
Ar^{9+}	$8.0 \cdot 10^{-2}$	$2.93 \cdot 10^{-2}$	$8.74 \cdot 10^1$
Ar^{10+}	$1.6 \cdot 10^{-2}$	$5.86 \cdot 10^{-3}$	$4.75 \cdot 10^1$
Ar^{11+}	$1.0 \cdot 10^{-3}$	$3.66 \cdot 10^{-4}$	8.07
Ar^{12+}	$3.0 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$	$6.58 \cdot 10^{-1}$

Table 2: Summary of the extracted and the actual charge state distribution in a SWISSCASE argon ECR plasma with a hot electron temperature of 9 keV.

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From Table 2 we can see that the mean charge state in the plasma is higher than in the extracted ion beam, as it is expected from the better confinement of the highly charged ion species. With this charge state distribution we can calculate the plasma parameter ratio K_I and consequently the hot electron temperature by Eq.7. Table 3 gives a summary of the calculation parameters and the resulting electron densities for the 9 keV plasma.

Parameter	Value
Neutral pressure	$1.8 \cdot 10^{-4}$ mbars
X-ray photon count rate I_0	34.72 cts/s
Plasma Bremsstrahlung total power	$2.47 \cdot 10^{-7}$ W
Plasma Bremsstrahlung power density	0.252 W/m^3
Geometry factor K_G (Eq.5)	$4.93 \cdot 10^6$
Plasma parameter ratio K_I (Eq.8, Table 2)	0.137
Hot electron density	$4.64 \cdot 10^{16}\ 1/m^3$
Hot electron fraction (estimation, see section discussion)	10 %
Total electron density	$4.64 \cdot 10^{17}\ 1/m^3$
Cut-off density	$1.46 \cdot 10^{18}\ 1/m^3$

Table 3: Summary and comparison of plasma parameters for a 9 keV SWISSCASE ECR plasma.

4 Discussion

The parameter $f_{h/e}$, the fraction of the hot electron number density relative to the total electron number density inside an ECR plasma, is subject of investigation in ECR research and is very difficult to access experimentally and is expected to vary depending on experimental conditions. Literature values range from $f_{h/e} = 4 \cdot 10^{-5}$ (Golubev et al., 2000, 37.5 GHz, T_{ehot} = 710 keV)[12] through $f_{h/e} = 0.1$ (Girard et al., 1994, 10 GHz to 18 GHz, T_{ehot} = 80 keV)[9] up to $f_{h/e} = 0.5$ (Petty et al., 1991, 10.5 GHz, T_{ehot} = 300 keV)[13].

In the presented calculation method, $f_{h/e}$ is the only parameter which comes with such a large literature range. The hot electron ratio has significant influence on the resulting hot electron and total electron number density as shown in Fig.7, fixing a1ll other calculation input parameters to the values shown in Table 3. Fig.7 shows, that the hot electron and the total electron number number density depend on the hot electron fraction in inverse manner leading to a decreasing total electron number density and an increasing hot electron number density with an increasing hot electron fraction. The total electron number density exceeds the critical cut-off density for a hot electron fraction lower than 1 %. Since we did not observe any significant noise neither in the extracted SWISSCASE ion beam nor in the reflected microwave power, we can exclude an unstable, noisy and over-dense plasma[2]. Hence, the hot electron fraction in the SWISSCASE ECR plasma is higher than 1 %. This

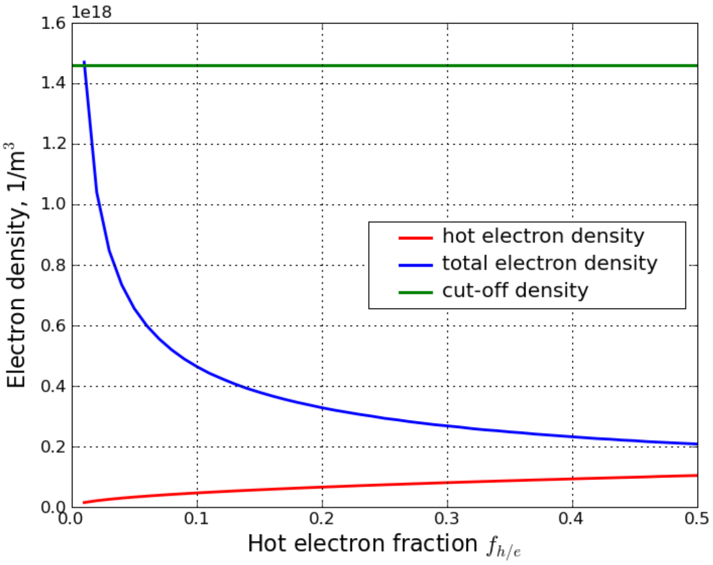

Figure 7: The resulting hot electron (in red) and total total electron number density (in blue) as a function of the hot electron fraction $f_{h/e}$ from 0.01 to 0.5 with all remaining input parameters fixed to the values shown in Table 3. For comparison, the critical cut-off electron density for an excitation frequency of 10.88 GHz is shown in green.

represents another anchor point for $f_{h/e}$ in current ECR research excluding very low electron fractions below 1 % for SWISSCASE. Regarding the high argon charge states, which SWISSCASE is able to produce, we chose a hot electron fraction of 10 % which is well within the literature value range [2, 6] for a 10 GHz ECR ion source.

5 Conclusion

The results of the numeric SWISSCASE ECR zone simulation and the X-ray Bremsstrahlung measurement of the same ion source can be combined to obtain values for hot electron and total electron number densities which are in excellent agreement with literature. Furthermore the presented method to calculate these electron densities reveals further constraints for the value of the hot electron fraction versus the total electron number density, a value hardly accessible by experiment and not yet conclusive in literature. The presented set of plasma parameters is self consistent. If a reliable value for the hot electron fraction $f_{h/e}$ is available for the ECR plasma of interest, the resulting electron density can be used for the development of a microwave-ECR-plasma model for the integration into a Finite Difference Time Domain microwave simulation.

Acknowledgements

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