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ABSTRACT

The Plasma Ion Mass Spectrometer (PIMS) is the first device able of measuring the absolute flux of ions in each charge state present in the edge plasma of tokamaks. Ion-optical simulations with the ion-trajectory code SIMION 7 are carried out to improve the characteristics of this *in-situ* measuring device. Critical properties like mass resolution and transmission of the PIMS are calculated and optimized for a range of plasma parameters, i.e. different ion temperatures T_i and sheath voltages V_s. Also the influence of small magnetic field misalignments is investigated.

1. INTRODUCTION

Until the development of the Plasma Ion Mass Spectrometer (PIMS) there was no device available for measuring the absolute flux of ions in each charge state present in the edge plasma of tokamaks (magnetic fusion devices). Besides the knowledge of the local density in the edge region the PIMS can give an indication of the average ion temperature of the impurities [1,2,3]. The charge state distribution and absolute flux of impurities is dependent on the location and magnitude of the impurity sources and the transport of impurity ions within the Scrape-Off Layer (SOL) and on closed flux surfaces.

Spectroscopic observations of hydrogenic isotopes usually comprising the main plasma species are useful and somewhat easier to perform, but cannot yield the fuel ion T_i directly since the hydrogenic fuel ions do not emit photons. Instead assumptions or modeling are required to determine the degree of ion-neutral coupling.

In contrast, the Plasma Ion Mass Spectrometer (PIMS) offers an alternative approach that can access the plasma impurity ions as well as hydrogenic species and their velocity distribution directly. The benefit of mass spectrometry compared to spectroscopic methods is that a full evaluation of species in the plasma edge can be achieved by this *in-situ* measurement at a very precisely defined point in space [1,2,3]. These measurements are very relevant for next step magnetic fusion experiments such as ITER [4] since the production and screening of impurities in current tokamaks is still not well understood and ITER will need a low plasma impurity content to reach its fusion energy goals. Accurate PIMS measurements in JET will provide an excellent benchmark for the edge plasma simulation codes and thus improve our predictions for ITER.

2. JET PIMS GEOMETRY

The PIMS is a trochoidal mass spectrometer that uses the magnetic field for the confinement of the plasma as its B-field. Thus only electrostatic voltages have to be applied [5]. The dimensions of the active components of the JET PIMS are $4.35 \times 8.5 \times 18.5$ mm, the focal length is 5.45mm. Due to the space restrictions the number of collectors has been restricted to two. The entrance slit is 30μm x 2mm and made out of a single piece of TZM alloy to maximize its power handling characteristics. Figure 1 presents the geometry of the final PIMS design as realized in the ion optics calculations with the ion trajectory program SIMION 7 [6] for realistic electric and magnetic fields. The ratio of ions hitting the collectors to the number of ions launched into the entrance slit is defined as transmission.

There are two distinct sections to the device: the source section where ions that are traveling parallel to the magnetic field enter through an aperture slit and then pass into an electric field region which pulls them towards the defining slit; and an analyzer region where the image of the defining slit is focused onto two gold collector wires. The number of particles reaching the collector regions at a given magnetic field strength is a function of the ion temperature and the sheath voltage along with the electric field across the device.

3. DESIGN OPTIMIZATION BY SIMULATION CALCULATIONS

The classical PIMS, its original design specifications and simulation results have already been described in detail in [5]. Schematically it comprises of the same components as the final version, but without drift tube and another barrier insulator design.

3.1. DRIFT TUBE PIMS

The 'Drift Tube PIMS' does not change the internal electrode assembly of the classical PIMS. The new feature in this design is the addition of an approximately 5mm long drift region after the entrance slit. There are two reasons motivating this change:

1) Due to the high heat flux towards the entrance slit plate a TZM shielding plate in front of the fragile electrode assembly is required for protection.
2) The dimension of that drift tube provides an additional parameter in optimizing the ion flux towards the analyzing region of the PIMS. By varying the width in the order of the gyromagnetic radius of the different ion species components with awkward starting angles will impinge on the walls of the drift tube. This has two positive effects:
   a) These particles – which are anyway very unlikely to reach the collector region – cannot contribute to the eventual build up of space charge due to deposition of charged particles on the barrier insulator. That is a major step forward for the long-term performance of the PIMS. But due to restrictions in the computer codes used, i.e. these time dependent space charge effects cannot be accurately simulated; the only effect seen in the transmission pattern in the presented calculations is a slight decrease due to the additional loss of some incoming particles.
   b) Those ions with awkward starting angles are filtered out. Beam broadening is decreased and the resolution is consequently enhanced.

Simulations show that the high M/Z ratio ions C^{2+} and C^{+} have an increased transmission. This can be explained by the fact that the electric field penetrates into the drift tube cavity and positive ions are already accelerated at an earlier stage towards the defining slit. This is of significance for the low charge ions since due to their large gyro-magnetic radius the distance parallel to the magnetic field lines did not allow for a whole cycloidal orbit without that early stage of acceleration driving them towards the defining slit and analyzer region, respectively.

3.2. FINAL PIMS GEOMETRY

The final geometry of the PIMS (Figure 1) was evaluated in varying the width and the position of the barrier insulator. The barrier insulator plays a very crucial role in the optimizing procedure [7].

On the one hand it is an essential constructional element preventing ions from passing directly to the collector region; on the other hand it causes problems in both, simulation and practical utilization. There are mainly two reasons for this:

1) The barrier insulator is placed in line with the applied electric field inside the PIMS, i.e. perpendicular to the electric field plates. This causes inhomogeneities of the electric field in both, the defining slit region and the analyzer section. To minimize the disturbing field effects it is obviously advantageous to fabricate the barrier insulator as thin as possible (0.1mm) to optimize the distance between defining slit and barrier insulator as well as between barrier insulator and the ion passing section in the collector plate situated in the analyzer region. By modeling of various possible positions of the barrier insulator a maximization of the transmission and resolution characteristics has been determined.
2) A far more undefined problem is the issue of space charge building up on the barrier insulator. In contrast to calculations [1], proving the negligible effect of space charge within the ion beam itself, this matter is much more complicated due to the uncertainty in how quickly any accumulated charge will leak away. Furthermore quantification is extremely difficult and current simulation software is not able to accurately model these perturbations.

3.2.1. Transmission Characteristics

Our base case assumption is an ion temperature T_i = 50eV and sheath voltage V_s = 100V. Figure 2 compares the maximum transmission characteristics for all three designs versus charge state for the base case. All the results presented here are for the most common toroidal magnetic field at the probe of 2.3T, corresponding to B = 2.5T in the plasma centre. One can clearly see that a major improvement has been reached for all mass/charge ratios.

Also the mass resolution is greatly enhanced compared to previous designs. This is due to the more homogeneous E-field in the analyzer region achieved by optimizing properties associated to the barrier insulator.

3.2.2. Misalignment with the magnetic field

Also the effects of magnetic field misalignments in x- and y-direction, respectively, show improvements (for x-direction shown in Figure 3) compared to the classical PIMS design. Both the transmission is enhanced and the triangular shapes are more accurate and narrower, with an improvement in the full width at half maximum to peak height ratio of approximately a factor of 3.

3.2.3. Effect of ion temperature and sheath potential on transmission

Maybe the most important improvement in developing the final PIMS geometry is the greatly enhanced feature of the relative insensitivity of the transmission characteristics as functions of ion temperature at the fixed sheath voltage of 100V. Figure 4 shows the behavior of all charge states of carbon at various ion temperatures. One should note that due to EDGE 2D calculation one expects the lower charge states having lower ion temperatures, therefore in the final design also a small fraction of these high M/Z ratio ions can be detected. Not such an impressive improvement can be deduced from Fig.5 presenting the transmission for all carbon charge states at different sheath voltages. The idea for improvement of that feature– especially for low charge state carbon impurities – would be a shift or extension of the collectors parallel to the magnetic field to the rear of the PIMS; but this is not possible due to space restrictions. Nevertheless it can be stated that also Fig. 5 represents acceptable transmission behavior for measurements under different electron temperatures and thus varying sheath potential.

CONCLUSION

With SIMION 7 we have computed the transmission characteristics of the two recent PIMS designs and explored the effects of varying ion temperatures, sheath voltages and magnetic field misalignments. Finally a design comprising good characteristics for a range of plasma characteristics has been developed. In recent experimental campaigns charge state distributions have been obtained with good agreement to the presented predictions.

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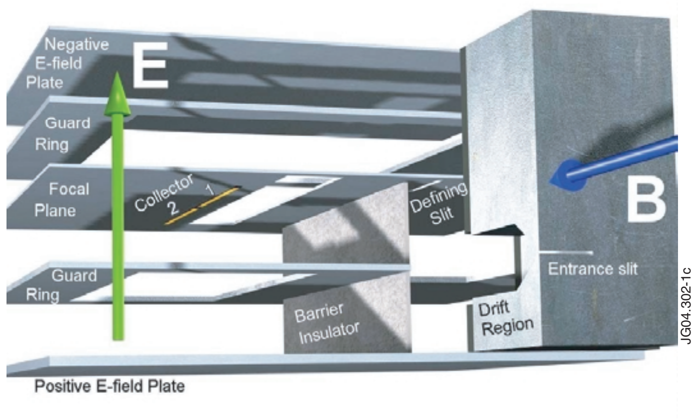

Figure 1: Geometry of the final PIMS probe as realized in the ion optical calculations.

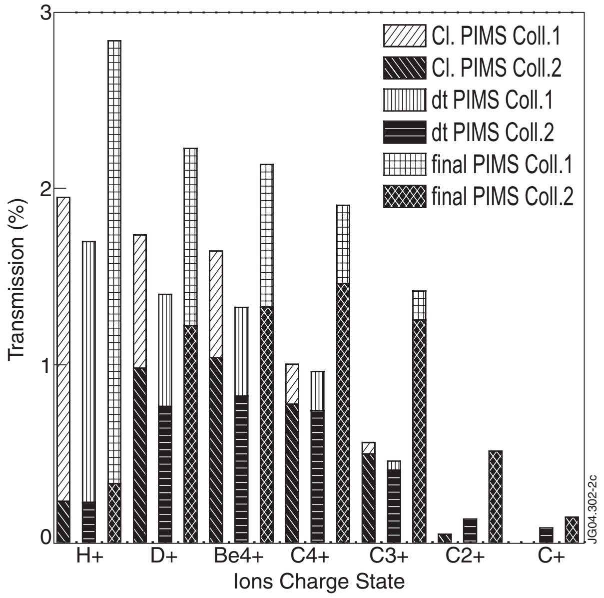

Figure 2: Peak transmission for different charge states of carbon, hydrogen and Be^{4+} for the base case.

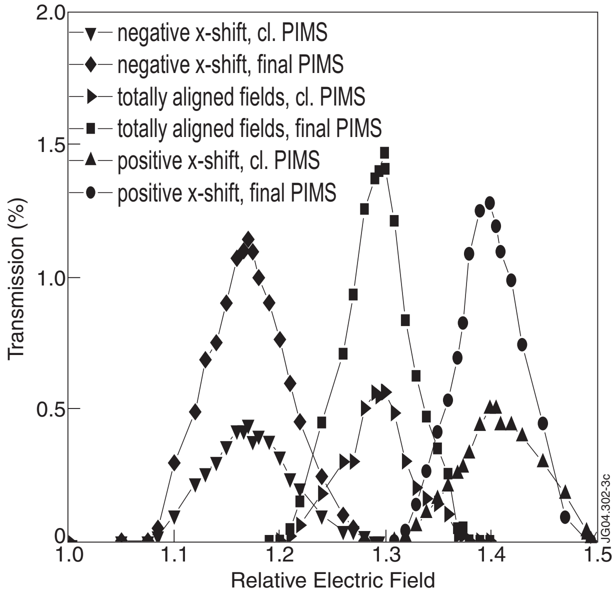

Figure 3: Effect of magnetic field misalignments in x-direction.

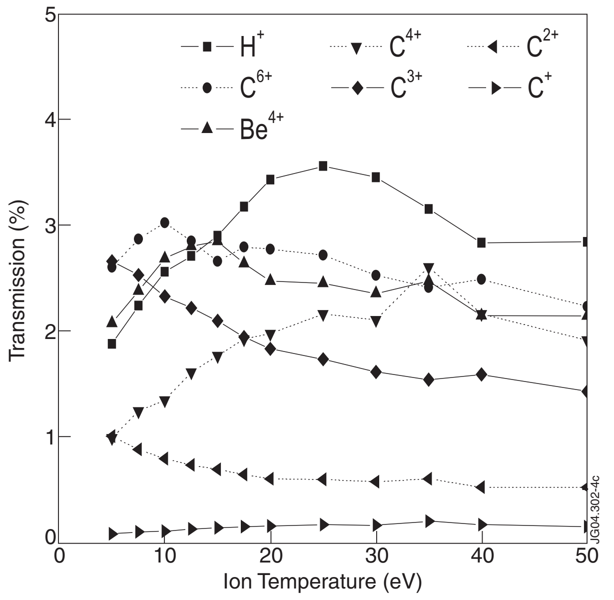

Figure 4: Behavior of all charge states of carbon at various ion temperatures at a fixed sheath voltage of 100V.

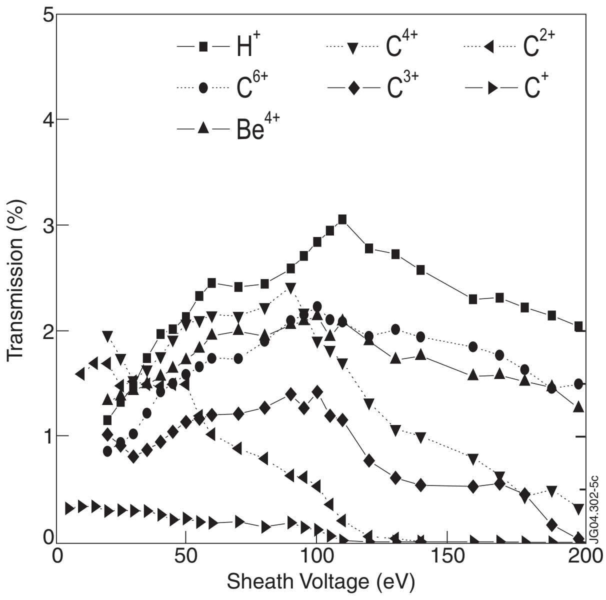

Figure 5: Transmission for all carbon charge states at different sheath voltages at fixed Ti = 50eV.