3D SIMULATION STUDIES AND OPTIMIZATION OF MAGNETIC HOLES OF HTS-ECRIS FOR IMPROVING THE EXTRACTION EFFICIENCY AND INTENSITIES OF HIGHLY CHARGED IONS

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Abstract

3D simulation studies using RADIA code have been performed to optimise the magnetic holes in the high temperature superconducting electron cyclotron resonance (HTS-ECRIS) ion source for improving the extraction efficiency and intensities of highly charged ions. The magnetic field improvements using simple techniques like optimisation of iron regions is found to be economical. The extraction efficiency can be increased three-fold in the case of a hexapole magnet depending on the level of the uniformity of the fields in the high and low regions. This technique further minimises localized heating of the plasma chamber walls which can improve the vacuum conditions in an ECR ion source. For superconducting sources where the x-ray heat load poses severe problems during operation, such a reduction of heating load is of great significance. The typical triangular pattern of the plasma impact observed on the plasma electrode of HTS ECRIS at various tuning conditions are reproduced by the simulations. Details of the simulations and experimental results will be presented.

INTRODUCTION

Today, ECR ion sources are being utilized as high current injectors for various accelerator projects around the world due to its simplicity, robustness, wide mass range of ions with excellent beam intensities and long lifetime as compared to other ion sources [1]. The backbone of this kind of source is based on a minimum B magnetic configuration where the electrons are confined to increase the probability of stripping ions to higher charge states. The design of this kind of magnetic configuration is based on well known ECR scaling laws. This study was undertaken to improve the extraction efficiency and especially the intensities of the highly charged ions. Earlier, experiments have shown that the optimum plasma electrode position inside the plasma chamber is not the same for the extraction of low, medium and highly charged ions. It was observed for the RIKEN [2] and JYFL ECR ion sources [3] that the intensities of highly charged ions increased as the plasma electrode was moved further away from the ECR zone. On the other hand, the intensities of medium charged ions, increased as the plasma electrode was moved closer to the ECR zone. Normally the extraction field, B_{ext}, should be slightly lower than the last closed magnetic surface, B_{last}, for the efficient production of highly charged ions [4]. A closer look led us to investigate further the magnetic configuration of the source at the extraction side. The magnetic field region at extraction (towards the exit of the hexapole) where the highly charged ions are extracted shows that there exist three weaker field regions (due to the use of a hexapole) where the plasma can still escape rather than being extracted. This is due to the radial component of the solenoid field which only partially cancels the radial field produced by the hexapole especially at the ends of the hexapole. It is expected that by further optimizing these weaker field regions, much higher intensities of highly charged ions can be extracted. Since no detailed work is available in the literature, except for a brief mention [5], it was important to perform 3D calculations of the combined magnetic field using the computer code RADIA [6]. Localized heating of the plasma chamber walls could be reduced which in turn would improve the vacuum conditions in the ECR ion source. For superconducting sources, the x-ray heat load which poses severe problems during operation and localised heating in the superconducting coils (quenches) can be further minimized.

MAGNETIC STRUCTURE OF AN ECRIS

In ECR ion source, combined magnetic field consisting of an axial and radial components generated by solenoid and a multipole magnet respectively is used. This kind of open magnetic field configuration is found necessary for good plasma confinement, stability and also for ease of extraction of the ions [1]. For efficient operation, the combined magnetic field structure should follow the well known ECR scaling laws ; the last closed surface should be at least twice that of the resonance field, B_{ecr}, within the plasma chamber, where B_{ecr} is the field required for the electron cyclotron resonance condition. In addition, the periphery of the plasma should be far away from the walls of the chamber to reduce the probability of melting of the plasma chamber. For a typical magnetic field configuration in conventional ECR ion sources, a triangular shape at both extremes is evident on the plasma electrode at extraction side and on the bias electrode if the electrode is in the form of a disc at injection side. The radial losses have a pattern on the plasma chamber wall which is symmetric corresponding to the orientation of the multipole, where the plasma impacts are oriented on the pole directions of the multipole. For the case of a multipole where order of the multipole, n =3 (sextupole) ,

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the plasma has a three fold symmetry, similarly, if n =4 (octupole) , the symmetry is 4 fold. For most of the ECR ion sources, the multipole has been optimised for n = 3 for optimum performance. Generally, the magnetic structure is chosen so that the field confines the plasma in all possible directions as much as possible and losses to the walls of the plasma chamber are minimised.

3D SIMULATIONS OF THE MAGNETIC STRUCTURE OF HTS-ECR PKDELIS

During operations with the 18 GHz HTS-ECR PKDELIS ion source [7], it has been observed that the plasma impact on the electrode shows a triangular structure typical of ECR sources, but the extent of the losses inside the triangular pattern varies with different sources depending on the magnetic field configurations and tuning conditions. This is a normal observation found in ECR sources where a plasma electrode is used for defining the beam size during the extraction of the beam. In addition, the six loss areas can also be found on the inner chamber wall of these sources.

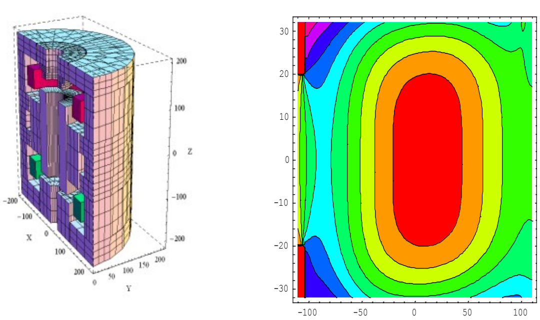

Figure 1: Magnetic structure built using RADIA

It means that most of the plasma was being lost to the electrode (diameter of plasma electrode 32 mm) than what was actually going through the extraction hole (hole diameter 12 mm). The plasma electrode positioned at the peak value of the extraction magnetic field (z = +82.5 mm), was not the correct position for extraction of high intensities of highly charged ions. This position was suitable for extraction of high intensities of low and medium charged ions. As pointed out by D.Hitz,[4] the best position to extract high intensities of highly charged ions is to place the plasma electrode at the position of B_{last}. By performing a 3D magnetic field simulation, the triangular structure was reproduced and matched well with the observed pattern. A model that was built to simulate the structure is shown in figure 1. The magnetic configuration clearly showed that the leaking plasma was going through the weaker regions of the magnetic field instead of being extracted through the plasma electrode where the field is relatively higher at positions close to the edge of the hexapole. This was supported by the model that close to the extraction area or the edge of the hexapole magnet, three weakest points of the total magnetic field existed. This is also true in the injection side and could also be improved by optimising these regions. For example, some sources have shown more plasma impacts on the injection side as compared to the extraction side of the source.

RESULTS AND DISCUSSION

We investigated by moving the electrode away from the ECR zone [7] which resulted in extracting higher intensities of highly charged ions of argon (figure 2, without the use of mixing gas, 150 μA of Ar^{11+}).

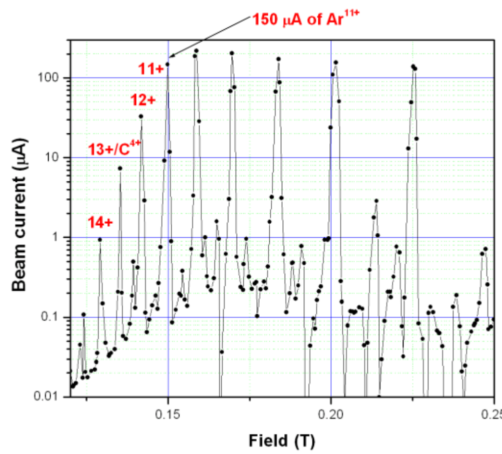

Figure 2: Charge state distribution optimised on Ar^{11+}

In addition, the shift in the charge state distribution (CSD) for argon (CSD peak at Ar^{10+}) was clearly seen at lower levels of RF power (400 W of absorbed power from 18 GHz klystron) than the case at higher levels of RF power (500W from 14.5 GHz TWT amplifier), where the charge state distribution peaked at Ar^{8+} using oxygen mixing gas, ~ 25 μA of Ar^{11+}), at position z = + 82.5 mm [8,9]. The best position was at z = +98 mm slightly inside the hexapole [7]. In this case, the field of the three magnetic holes should be higher than the field at the plasma electrode so that the plasma could be more efficiently extracted. This can be further improved by field shaping using iron material. The other possible solution could be to increase the length of the hexapole which may turn out to be more expensive; Three options effectively were looked into to see the improvement in optimising the field of the magnetic holes ; all simulations have been performed corresponding to the beam tuning conditions when the source was optimised for Ar^{11+} (injection coil current 120 A, extraction coil current 80 A); they are as follows ;

i) effect of incorporating iron ring close to the edge of the hexapole

The effect of incorporating iron rings close to the edge of the hexapole were simulated. The inner and outer diameters were chosen appropiately as 35 mm and 74.5 mm and the closest distance from the edge of the hexapole was 1 mm. Four rings of thickness 5, 10,15 and 20 mm were simulated at z = +98 mm.

ii) effect of incorporating iron ring further away from the edge of the hexapole

The effect of incorporating iron rings further away from the edge of the hexapole was simulated using inner diameters of 41mm, 54.8 mm and 69.5 mm and keeping the outer diameter fixed at 86.8 mm. The closest distance from the edge of the hexapole was 5 mm. Rings of varying thickness were simulated. at z = +98 mm. Figure 3 shows the correction after integrating all the iron rings.

iii) effect of increasing the length of the hexapole at the extraction side

The effect of increasing the length of the hexapole towards the extraction side in small incremental steps was simulated at z = +98 mm. It was found that the length of the hexapole should be made considerably longer (L=225 mm) to optimize the weakest magnetic field regions (shown in figure 4.) and the cost implications show that it is more economical to tune the magnetic field using iron as in cases (i) and (ii)

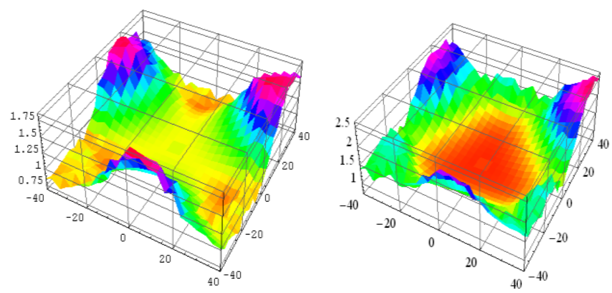

Figure 3: (left) View of three magnetic holes at z =+98 mm, before optimization (Right) optimized at z=+98 mm using iron rings integrated with the hexapole

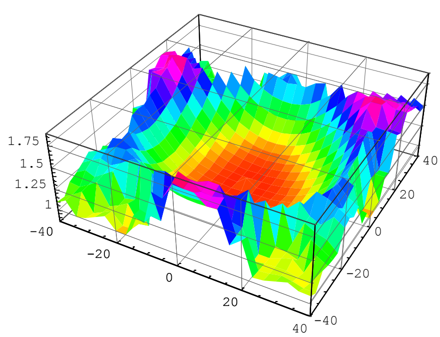

Figure 4: After optimization at z=+98 mm, using an extended hexapole of length 225 mm.

SUMMARY AND CONCLUSION

All the methods described to optimize the field in the weaker regions show definite improvements. It is expected that the efficiency of extracting the ions from the plasma should scale three-fold according to the uniformity in the fields. In principle, much higher intensities of highly charged ions can be extracted depending on the levels of the magnetic field. It is left to the designer to decide which is more advantageous and thereby optimize the best performance to cost ratio. In summary, the 3D simulations show that further improvements in the tuning of the magnetic field can be done for improvement of the extraction conditions in a typical ECR ion source. Besides, localized heating of the plasma chamber walls could be reduced which can further improve the vacuum conditions in an ECR ion source. The lifetime of synthetic high voltage insulators used between the plasma chamber and the cryostat can be increased further. For superconducting sources, the x-ray heat load which poses severe problems during operation and the localised heating in the superconducting coils can be further minimized.

ACKNOWLEDGEMENTS

One of the authors (G.R) would like to thank Department of Science & Technology (DST) for the help and support.

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