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Design of a compact electron cyclotron resonance ion source for medium charge state light ions[a)]

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At the Australian Nuclear Science and Technology Organization we are developing a new isotope ratio mass spectrometer based on the measurement of multiple charge state ions. We have carried out a review of our existing ECR ion source and identified a number of design flaws. For the new instrument, we are producing a new ECR source and have refined the design, in particular by using 3D simulations to improve the magnetic confinement field and by a combination of simulations and experiments to improve the design of the microwave coupling. © *2012 American Institute of Physics*. [doi:10.1063/1.3669789]

I. INTRODUCTION

At the Australian Nuclear Science and Technology Organization (ANSTO) we have shown the effective application of a small volume ECR ion source for the efficient consumption of sample gases to produce multiple charge state ions for the measurement of isotopic ratios.[1,2] Our existing 7 GHz permanent magnet source[3] has proven to have weaknesses, as detailed in the following review, both in its magnetic field configuration and in its microwave coupling. Thus, a redesign process was undertaken to produce a higher performance ion source to be incorporated into an isotopic ratio mass spectrometer instrument which ANSTO is currently building. This paper outlines the limitations of the existing ion source and describes the development of new designs for the new source, including improved magnetic confinement and microwave coupling.

II. CURRENT ION SOURCE DRAWBACKS

A. Magnet array

Our existing ECR ion source, developed for mass spectrometry experiments, was designed for efficient utilisation of sample material, and decomposition of molecules by generation of high charge state ions. Against these criteria our original design functions correctly and enabled satisfactory measurement of isotopic ratios such as ^{16}O:^{17}O and ^{16}O:^{18}O. However, during operation output currents have been below those that would be expected. Sample retention and memory effects are evident in the ion source due, we believe, to strong wall recycling effects enhanced by the presence of parasitic loss zones. These occur as weaknesses in the confinement field where it is less than that of the extraction point (see Fig. 1). These loss zones allow ions to be lost to the surface as opposed to being extracted as beam, and may cause enhanced wall recycling in the ion source adding to the memory effect of the system. Defects in the magnetic field have only been able to be examined after recently acquiring the 3D electromagnetic modeling package, LORENTZ (Integrated Engineering Software, http://www.integratedsoft.com). Previously, field designs were done with 2D software and the loss zones were not apparent in the results.

B. Microwave coupling

In our existing source, the plasma chamber is made of quartz, with a stainless steel cooling jacket between the quartz bottle and the magnet array. Microwaves are fed in parallel to the axis, somewhat off centre, to accommodate the gas injection tube, with an abrupt transition from the rectangular waveguide to the cylindrical chamber. The RF cavity is defined by the internal diameter of the cooling jacket and terminated by the extraction electrode. The diameter of this cavity is 53.6 mm, and the wavelength of the microwave at 7.0 GHz is 42.9 mm. This limits the number of modes which can exist in the RF cavity. The small diameter of the cavity is required to maintain a small volume for the purpose efficient sample consumption and pump out rates, as well as to minimise the amount of magnetic material required.

III. REVISED ECRIS DESIGN

A. Magnet array

The magnetic field configuration of the existing source falls well short of the optimal field values for ECR ion sources, as described by the empirical scaling laws.[4,5] Table I lists the key values for the magnetic configuration of the existing ion source, where B_{ECR}, B_{rad}, B_{ext}, B_{min}, and B_{inj} refer, respectively, to the fields at the ECR zone, at the radius of the plasma chamber, at the extraction point, at the minimum in the source centre and at the injection maximum. In redesigning this source, the aim has been to achieve the target values determined by the scaling laws, while maintaining

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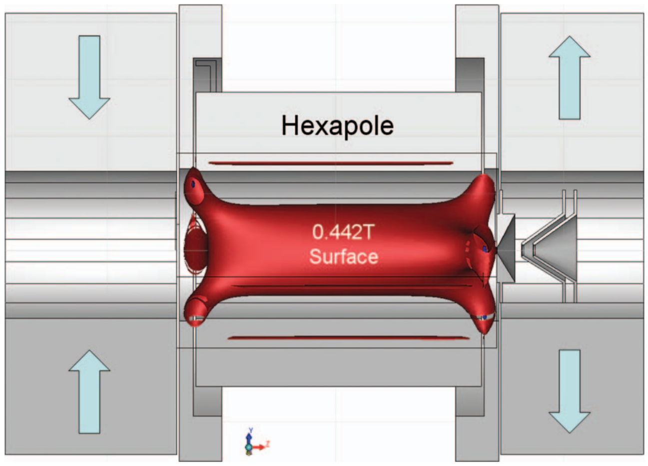

FIG. 1. (Color online) Existing ANSTO ECRIS: iso-surface plot of the magnetic field surface where it equals that at the extraction point (value of 0.442 T). The 3 "fingers" at each end correspond to loss zones.

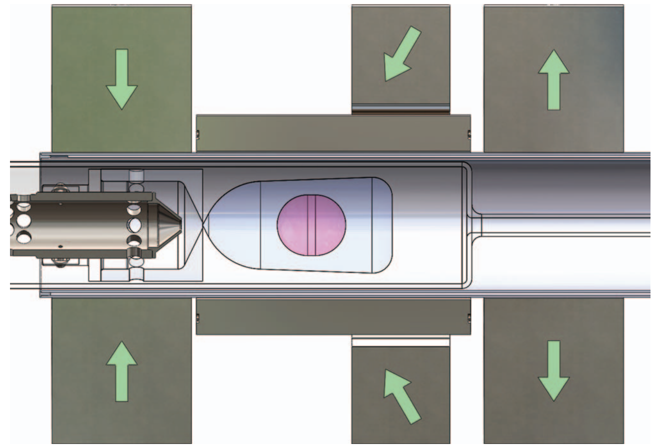

FIG. 2. (Color online) Revised ECR ion source design. The central ball shows the approximate surface shape of the ECR zone; the next surface is the approximate shape of the surface with field equal to the extraction field value.

the low volume aspect of our ion source which is important for our application. To achieve this we have adopted a three ring axial field design (Fig. 2), and an offset Halbach array hexapole.[6]

The three-ring structure was used so as to reduce the length of the source, with the "mid ring" providing a strengthening of the injection field maximum, and a reduction to the minimum. This is illustrated in Fig. 3, where the contributions of each ring to the axial field are plotted. The two front and rear rings are dimensionally the same, with opposite field directions. The permanent magnet material to be used is NdFeB grade N45SH.

Both the field direction of the mid ring and the spacing between the rings were optimized through an iterative process. This resulted in the arrangement shown in Fig. 2, with the field direction of the mid ring inclined at 60° to the axis. As shown in Fig. 2, in comparison to Fig. 1, the extraction field surface is now closed, and tapers to the extraction point. It is hoped that this will increase beam output, and decrease the strength of the wall recycling effect.

The offset Halbach array is understood to have less anti-parallel fields than the traditional design, and to have a slightly higher performance.[6] The thickness of magnetic material has been reduced to 14.5 mm, compared to 30 mm in the existing source. This was due to the larger than required radial field in the original design.

Table I shows how this structure compares to the original design, and against the target values. Optimization calculations have been carried out based on those discussed by Sun *et al.* in Ref. 7 which indicate that we are not wasting magnetic material to achieve our desired values. Note, however, that the optimum injection field is difficult to achieve with permanent magnets without introducing iron plugs in the rear of the source, which we are unable to accommodate.

TABLE I. Magnetic field configuration parameters for ECRIS at 7 GHz. The target values are based on empirical scaling laws (Refs. 4 and 5).

	B_{ECR} (T)	B_{rad} (T)	B_{ext} (T)	B_{min} (T)	B_{inj} (T)
Existing ECRIS	0.25	0.89	0.44	0.22	0.49
Target values	0.25	0.50	0.45	0.20	1.00
New ECRIS	0.25	0.56	0.46	0.20	0.76

B. Microwave coupling

The original design of the ECR ion source utilised a 100 W 7.0 GHz microwave generator. It was found that there was difficulty igniting the plasma and hence concern about the coupling of the microwave field to the plasma. An investigation of the system was carried out. LORENTZ plots showed magnetic field directions associated with the skin which forms the ECR zone surface are mostly parallel with the cylindrical cavity axis. It is assumed that for the most effective coupling to the electrons through the electron cyclotron resonance, the microwave |E| field should be perpendicular to the magnetic field lines. The TE_{01} cylindrical waveguide (cavity) mode produces a circumferentially symmetric electric field distribution, with no radial (or axial since it is TE) electric field component. With a cavity diameter of 53.6 mm, the length of the cavity can be adjusted for resonance at 7.0 GHz. The

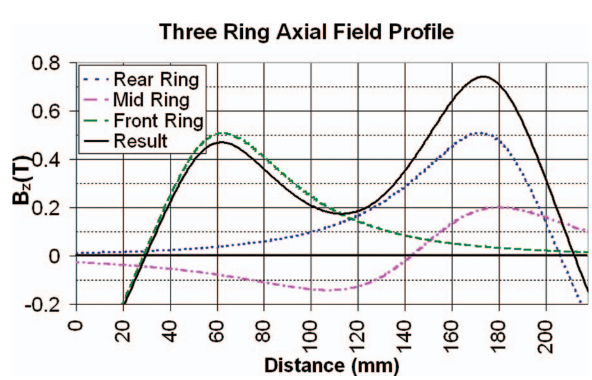

FIG. 3. (Color online) Axial magnetic field plots for the revised three-ring source structure. Each ring's axial field profile is summed to generate the resulting combined field profile.

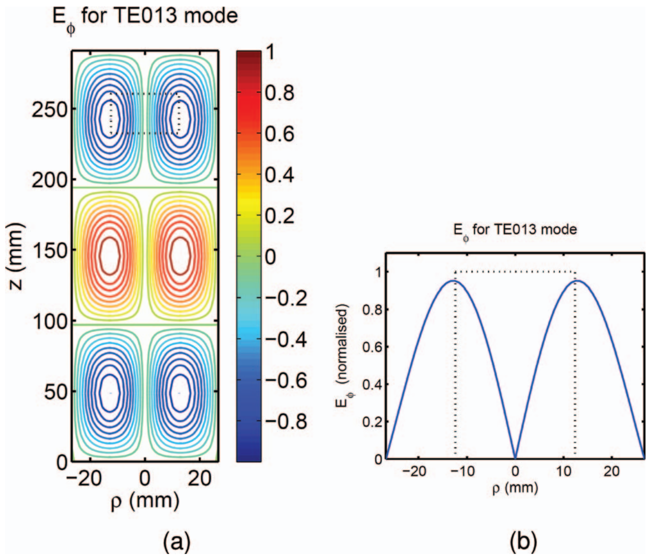

FIG. 4. (Color online) (a) TE_{013} mode in a cylindrical cavity of diameter 53.6 mm fed by 7 GHz microwaves, showing the E_{φ} field contours. (b) The dotted box shows the approximate location of the ECR zone in the centre of the source.

cavity length in the revised design was chosen to be three modes in length (291 mm), as illustrated in Fig. 4(a). The variation of the electric field in the radial direction is illustrated in Fig. 4(b), showing a minimum on axis and a maximum near the edge of the ECR zone. It is anticipated that if the cavity is resonant then the |E| field can build to a suitable value to enable the discharge within the plasma chamber to ignite the source.

The launching of the microwaves into the cavity was changed from an axial arrangement to a radial configuration. This was done to assist the excitation of the TE_{01} mode. In Fig. 5 it is evident that the TE_{10} mode, which is the dominant mode in the rectangular waveguide, will excite both the TE_{11} and TE_{01} modes in a cylinder, when launched radially with the long edge of the waveguide parallel to the cylinder axis.

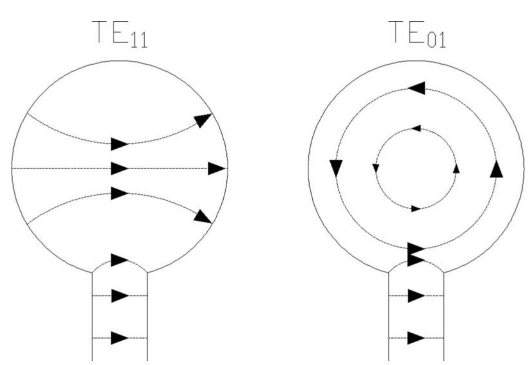

FIG. 5. The E field directions at the coupling of a rectangular waveguide (TE_{10} mode) to a cylindrical waveguide,[8] showing the excitation of TE_{01} and TE_{11} modes in the cylinder.

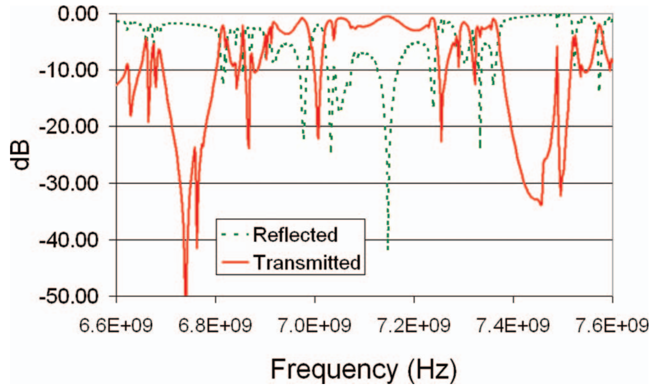

FIG. 6. (Color online) Transmitted and reflected power for a rectangular waveguide feeding into a cylindrical cavity. See text for details.

The desired TE_{01} mode has cylindrical symmetry and a mode filter can be used to suppress the undesired TE_{11} mode. In this case the mode filter has conductive surfaces perpendicular to the desired TE_{01} E fields, and was implemented using an 8 segment radial array of 100 × 15 mm flat plates supported by low density foam inserted into the cavity.

To verify our design ideas, test cavities, and a 2-port cylindrical waveguide section with the same diameter as the cavities, were manufactured and studied using a network analyzer (Agilent Technologies model E5071C). Figure 6 shows the transmission and reflection results obtained between 6.6 and 7.6 GHz for a cylindrical waveguide with the correct diameter. The cut-off frequency f_c for the TE_{01} mode is 6.83 GHz. The TE_{11} mode, which has much lower f_c, is suppressed by the mode filter. Reasonable matching is achieved where transmission is high, indicating effective coupling from the rectangular waveguide feed to the TE_{01} mode in the cylindrical waveguide. Similar performance is expected for the cavity. We confirmed that the TE_{01} mode is excited dominantly in this range with transmission tests, by observing that the transmission was insensitive to the angle between the input and output waveguide couplings. Tests were also carried out by inserting pieces to emulate the cavity formed with the plasma electrode and with the quartz tube.

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