第 31 卷 增刊 I 高 能 物 理 与 核 物 理 Vol. 31, Supp. I
2007 年 7 月 HIGH ENERGY PHYSICS AND NUCLEAR PHYSICS Jul., 2007

Modified Multipole Structure for Electron Cyclotron Resonance Ion Sources

P. Suominen[1)] T. Ropponen H. Koivisto

(Department of Physics, University of Jyväskylä (JYFL), P.O. Box 35, FI-40014, Jyväskylä, Finland)

Abstract Experiments have shown that especially the radial magnetic field component plays a crucial role in the production of highly charged ions with Electron Cyclotron Resonance Ion Sources (ECRIS). However, in several room temperature operating ECRISs the radial magnetic field strength is below the optimum value, mainly due to the limits in permanent magnet technology. Remarkable radial magnetic field improvement can be reached with a relatively simple and cost-effective idea called Modified MultiPole Structure (MMPS). The MMPS differs strongly from the former structures because here the magnetic field is increased only locally without affecting the plasma size. The idea was studied experimentally with a new MMPS plasma chamber prototype, which was designed and constructed for the JYFL 6.4GHz ECRIS. The new chamber is versatile and made it possible to perform several new types of measurements. These showed that the MMPS is especially applicable to increase very high charge-state ion production. Typically the ion current increases more than a factor of 2 in the case of highly charged ions such as Ar^{16+}.

Key words ECR, MMPS, ARC-ECRIS

1 Introduction

Highly-charged heavy-ion beams are usually produced with Electron Cyclotron Resonance Ion Sources[1] (ECRIS) where the microwave heated plasma is confined in a strong magnetic field. The magnetic field is divided into an axial part (produced by solenoid magnets) and to a radial part (produced by a multipole magnet). The importance of the magnetic field configuration has been studied with fully superconducting ECRIS. It was found (see for example Ref. [2]) that the radial magnetic field strength is especially important in the production of very high charge-state ion beams.

Permanent magnet hexapoles are often too weak in ECRISs operating frequencies of over 14GHz. A new method to strengthen the hexapole called Modified MultiPole Structure[3, 4] (MMPS) has been developed at JYFL. Unlike with the conventional multipole the magnetic field is increased only locally at the magnetic poles (i.e. where the plasma leaks radially towards the plasma chamber walls). Consequently, it had to be studied how this affects to the properties of the plasma and the production of highly-charged heavy-ions. This paper summarizes the effects of the MMPS.

2 Modified multipole structure (MMPS)

The principle of the MMPS idea is to decrease the loss-cone of the electron by increasing the radial magnetic field strength (B_r) using a material which has high permeability and saturation magnetic field values. An example, where a small cross-section iron block is added to a Halbach[5] and Offset-Halbach[6]

Received 20 April 2007

1) E-mail: pekka.a.suominen@phys.jyu.fi

type hexapoles, is shown in Fig. 1. Magnetic field of 2T is induced inside the “iron pole”. Because the normal component of the magnetic field is continuous over the boundary between two media, the same magnetic field strength is reached at the inner surface of the plasma chamber wall.

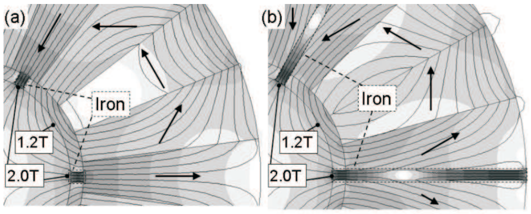


Fig. 1. An idea of the MMPS applied in (a) Halbach and (b) Offset-Halbach hexapoles.

In an ideal hexapole the radial magnetic field strength increases with r^2 from symmetry axis towards the plasma chamber wall. Fig. 2 shows an example where the 0.23T resonance radius (for 6.4GHz) decreases from 47mm to 35mm if the hexapole strength is increased from 0.5T to 0.9T. In the MMPS the magnetic field increases much more steeply in the vicinity of the iron (close to r^{20}) and the magnetic field boost does not affect the plasma volume or shape. The effect of the iron pole in the azimuthal direction (at the plasma chamber wall) is also local (see Fig. 3), only a few millimeters wide depending on the shape and the size of the iron pole.

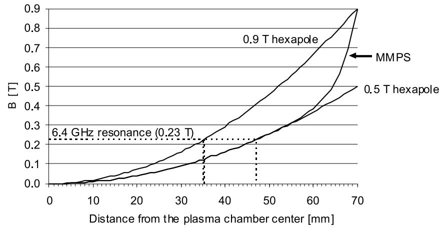
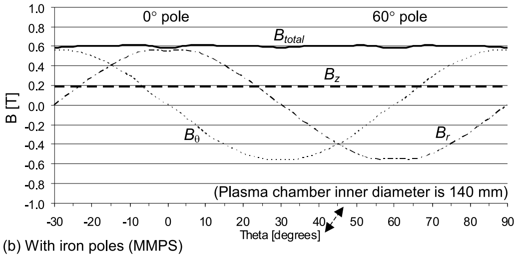


Fig. 2. Comparison between the typical hexapole and a MMPS-hexapole.

The solenoidal magnetic field also strongly affects to the iron poles and has to be taken into account in the MMPS design. Consequently, realistic 3D magnetic field simulations are necessary. Fig. 4 shows that with careful optimization the positive effect of the iron poles is very clear along the plasma chamber wall and the shape of the magnetic field is maintained.

(a) Without iron poles



(b) With iron poles (MMPS)

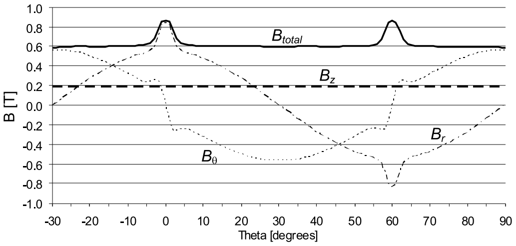


Fig. 3. Magnetic field at the plasma chamber wall (a) without iron poles (z=0mm) and (b) with the iron poles (MMPS).

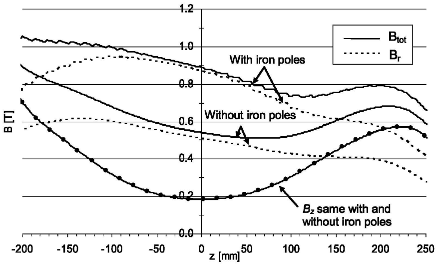


Fig. 4. Effect of the iron pole on the different magnetic field components at the plasma chamber wall (r=70mm) at the magnetic pole.

In this work a MMPS-hexapole was constructed (see Fig. 5), but nothing limits the use of the MMPS technique in other order multipoles (quadrupole, octupole or some higher order multipole). It should also be studied if the MMPS could be used in other plasma ion sources than an ECRIS or other applications where charged particles have to be confined in the magnetic field. In the ECRIS the MMPS idea can possibly be used in the following cases:

1) An existing hexapole is upgraded. In some cases it is relatively easy and cost effective to just add the iron parts needed into the existing structure.

2) A completely new hexapole is being built in order to reach the maximum performance; for example in an 18—28GHz ECRIS. In this case it would be necessary to build a Halbach-type hexapole as strong as is possible, i.e. about 1.3—1.5T. With the MMPS the radial magnetic field can be then locally boosted to over 2T.

3) A very cost effective hexapole is needed. For an ECRIS a hexapole with radial mirror ratio of about 1.2 to 1.5 could be built and apply the MMPS to increase the radial mirror ratio to over 2.

2.1 Experiments with the MMPS plasma chamber

Measurements were performed using the JYFL 6.4GHz ECRIS with a new MMPS plasma chamber (Fig. 5). The design and the features of the new chamber are presented in detail in Ref. [7].

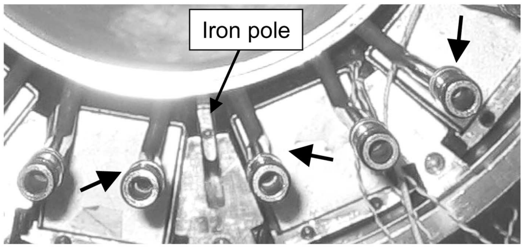


Fig. 5. The JYFL-MMPS plasma chamber prototype.

Figure 6 shows two aluminum liners, which were used during a one-week contaminating MIVOC-run. The upper part (a) shows the flux without the MMPS boost and lower part (b) the case with the full MMPS boost. Although the MMPS boost is narrow it clearly reduces the plasma impact areas. The dark area in the figure is formed when carbon ions escape from the plasma and remain on the liner surface. The figure shows that not only the electron flux but also the ion flux is changed by the MMPS.

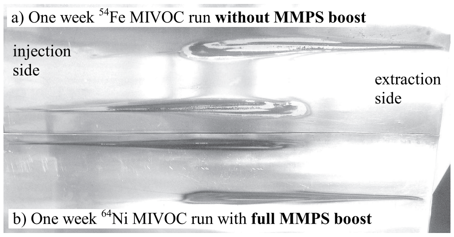


Fig. 6. Plasma flux pattern on liner (a) without and (b) with the MMPS.

Figure 7 shows that the plasma potential stays almost constant as a function of the MMPS boost. This is because the increased radial magnetic field reflects more electrons back to the plasma (decreased X-ray count, see more details from Ref. [4]). In addition, due to the quasi-neutrality of plasma, also more ions are “reflected” back to the plasma (decreased ion flux towards the plasma chamber walls, see Fig. 6). The increased ion density can also be seen from the increased intensity of the extracted ion beam. In addition the plasma potential is mainly formed by low energy electrons, whose movement is dominated by collisions[8, 9], not by the magnetic field. Therefore the MMPS effect on the plasma potential is not so significant and the plasma potential remains almost unchanged. It has been found[8, 9] that the plasma potential is low when the ECRIS has a good performance and is well conditioned. This can be seen from Fig. 7 where the ECRIS was not well conditioned in the case of the measurements performed with Ar^{9+} ions.

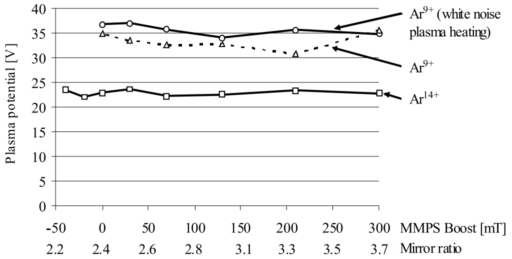


Fig. 7. Plasma potential as a function of the MMPS[4].

In the MMPS measurements using 6.4GHz microwaves[10] the highest ion currents were usually obtained with a relatively high radial mirror ratio of 2.8 — 3.3. This is in good agreement with the measurements performed using the SC-ECRIS (6.4GHz) at MSU, where the optimized radial mirror ratio was measured to be about 2.9[11]. When applying the MMPS the pressure seems to drop by 5% — 10%, i.e. there are fewer neutrals in the plasma chamber. Because the gas feed was kept constant this indicates that the MMPS increases the total ionization efficiency. Also the total ionic current (high voltage power supply current) increases by 5% — 10% with the MMPS boost. Calculations have shown that the MMPS slightly increases both the average ion charge-state of the plasma and the number of extracted particles.

In the measurements with 6.4GHz microwaves the radial mirror ratio was 2.2 — 3.6, which is considered to be sufficient for efficient ECRIS operation (see Refs. [2] and [4]). Measurements were also performed with 10.75GHz microwaves in order to study the effect of the MMPS when radial mirror ratio is low (1.4 — 2.2). In both cases the MMPS has the strongest effect on the highest charge-states. In Fig. 8 the "Relative intensity" is the ion beam current with the MMPS divided by the ion beam current without the MMPS (i.e. 100% corresponds the case where MMPS does not affect to the ion current). Detailed data can be found from Ref. [4]. Very interesting phenomenon is that the relative ion beam intensity increases almost linearly as a function of the ion charge-state. A solid explanation for this has not been found yet. However, the result is excellent because the highest charge-state ions are always the most difficult to produce. The intensity of low charge-state ions decreases when the MMPS is applied.

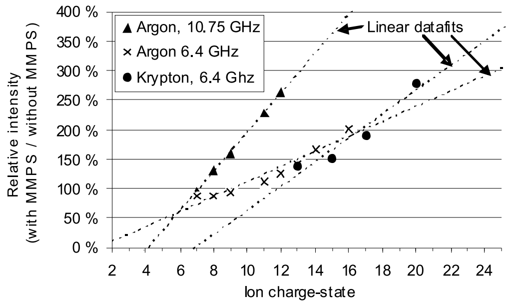


Fig. 8. Effect of the MMPS as a function of charge-state.

At 10.75GHz the radial mirror ratio was increased from 1.4 to 2.2 by the MMPS. Corresponding mirror ratio increase can be obtained using MMPS for example in a 28GHz ECRIS with a permanent magnet hexapole (see for example Ref. [12]). According to the results shown in Fig. 8 the intensity of Ar^{16+} ion beam can increase by a factor of 3 when the MMPS is used.

3 ARC-ECRIS

New ECRIS-concept named as ARC-ECRIS has been designed, built and preliminary tested at JYFL. The new concept includes only two electric magnets to form minimum-B structure. These magnets are "twisted" in arc-like form as shown in Fig. 9(b). The idea is somewhat similar than in magnetic fusion plasma experiments like MFTF-B[13] and Baseball[14] (Lawrence Livermore National Laboratory, USA) and GAMMA10[15] (University of Tsukuba, Japan). These experiments focused to heat only light ions (hydrogen and helium) up to fusion temperatures. Several experiments were cancelled as the ions could not be heated enough. In addition problems occur because of highly-charged "impurity" ions[16]. Consequently, it looks promising to use such a magnetic field configuration in an ion source for the production of highly-charged heavy-ions (where low ion energies are preferred because of the better beam emittance).

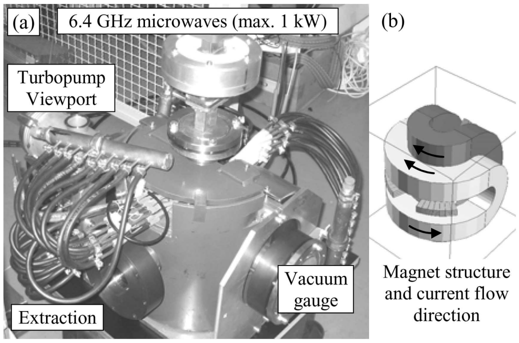


Fig. 9. (a) Photograph and (b) magnet structure of the first ARC-ECRIS prototype.

Preliminary tests with the ARC-ECRIS prototype showed that multiply charged ions can be produced with such device. The spectrum shown in Fig. 10 is only to have an idea about the charge-state distribution. This is because 80% — 90% of the beam hits the puller electrode. Consequently, the extraction system has to be improved. Detailed paper of the ARC-ECRIS design and the measurements will be published later.

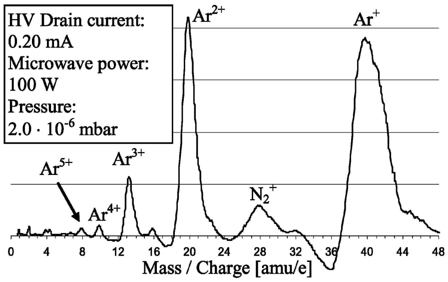


Fig. 10. An example spectrum of argon plasma.

4 Acknowledgments

This work has been supported by the EU 6th program "Integrating Infrastructure Initiative –

Transnational Access", Contract Number: 506065 (EURONS) and by the Academy of Finland under the Finnish Centre of Excellence Program 2000—2005, (Project No. 44875, Nuclear and Condensed Matter Physics Program at JYFL)

References

1 Geller R. Electron Cyclotron Resonance Ion Sources and ECR Plasmas (Institute of Physics Publishing, London, 1996)

2 Gammino S, Ciavola G, Celona L et al. Rev. Sci. Instrum., 2001, **72**: 4090

3 Koivisto H, Suominen P, Tarvainen O et al. Rev. Sci. Instrum., 2004, **75**: 1479

4 Suominen P. PhD thesis, JYFL research report No. 6/2006, <http://www.phys.jyu.fi/theses/pekka_suominen.pdf>

5 Halbach K. Nucl. Instrum. Methods, 1980, **196**: 1

6 Suominen P, Tarvainen O, Koivisto H et al. Rev. Sci. Instr., 2004, **75**: 59

7 Suominen P, Tarvainen O, Frondelius P et al. AIP Conference Proceedings, 2005, **749**: 171

8 Drentje A G. Rev. Sci. Instr., 2003, **74**: 2631

9 Tarvainen O. PhD thesis, JYFL research report No. 8/2005, < http://www.phys.jyu.fi/theses/olli_tarvainen.pdf>

10 Suominen P, Tarvainen O, Koivisto H. Rev. Sci. Instr., 2006, **77**: 03A332

11 Antaya T A, Gammino S. Rev. Sci. Instr., 1994, **65**: 1723

12 Thuillier T, Koivisto H, Lamy T et al. Rev. Sci. Instr., 2006, **77**: 03A323

13 Porter G D, Rensink M. J. V. Sci. Technol., 1985, **A3**: 1157

14 <http://www.llnl.gov/timeline/70s.html>

15 Inutake M et al. Phys. Rev. Lett., 1985, **55**: 939

16 Ikeda K et al. Rev. Sci. Instr., 1999, **70**: 332