Recent Progress in High Frequency Electron Cyclotron Resonance Ion Sources

D. Hitz[1)]

(Commissariat à l'Energie Atomique, Département de Recherche Fondamentale sur la Matière Condensée,
Service des Basses Températures, 17 Rue des Martyrs, 38054 Grenoble Cedex 9, France)

Abstract As they are first optimized for their ion losses, ECRISs are always under a fundamental compromise: having high losses and strong confinement at the same time. To help ECR ion source developers in the design or improvement of existing machines, general comments are presented in a review article being soon published. In this 160 pages contribution, fundamental aspects of ECRISs are presented, with a discussion of electron temperature and confinement and ion confinement. Then, as microwaves play a key role in these machines, a chapter presents major guidelines for microwave launching and coupling to ECR plasma. Moreover, once ECR plasma is created, understanding this plasma is important in ion sourcery; and a section is dedicated to plasma diagnostics with an emphasis on the determination of electron and ion density and temperature by vacuum ultraviolet (VUV) spectroscopy. Another chapter deals with the role of magnetic confinement and presents updated scaling laws. Next chapter presents different types of ECRISs designed according to the main parameters previously described. Finally, some industrial applications of ECRISs and ECR plasmas in general are presented like ion implantation and photon lithography. Some hints taken from this review article are presented in the following article.

Key words ECR plasmas, ECR ion sources, EUV lithography

1 Introduction

Since their discovery, ECRISs have shown spectacular improvements in terms of extracted ion currents and charge states, owing to a better understanding of the relevant plasma physics and to a lot of technological developments. For example, xenon ions up to Xe^{13+} were observed in 1973[1]; the 5μA level shifted from Xe^{17+} with Triplemafios[2] up to Xe^{35+} with GTS.

In this article, after a brief state of the art, the accent is put on one weak point of most ECRISs, i.e. microwave coupling and rf power level. A last chapter presents a possible application of ECR technology in microchips industry. The paper presented here is a small fraction of a general description of various ECRISs with their pros and cons (from all-permanent magnet up to fully superconducting devices). This general state of the art is presented in a review article indicated below. Possible ways to optimize ECRIS are also proposed.

2 State of the art of ECRIS

Up to now, considerable work has been done in ECR plasma understanding through plasma diagnostics and plasma modeling. ECRIS performances also improved thanks to a better definition of scaling laws governing the magnetic configuration of this type of device. In addition, other mechanisms like gas mixing, polarized disk, plasma chamber wall material, etc. powerfully contribute to source efficiency.

Received 20 April 2007

1) E-mail: denis.hitz@cea.fr

It is now generally admitted that an ECRIS powered at the highest microwave frequency compatible with magnetic scaling laws would give the largest beam intensities, provided that it is equipped with a well adapted extraction system. Generally speaking, all-permanent magnet ECRIS will run between 2.45GHz and 14GHz, while using a variable frequency generator to get a good rf tuning with the plasma chamber cavity and to compensate for the lack of magnetic field adjustment. Even though it is possible to move the permanent magnets for an online source tuning, use of a variable frequency is by far much easier. Furthermore, variable frequency transmitters provide a large bandwidth leading to a wider resonance zone. This is favorable as energy exchange between electrons and microwaves takes place in this region.

On the other hand, ECRISs, that use a combination of permanent magnets and coils (room temperature or superconducting), generally run between 14GHz and 24GHz, with an optimum around 18GHz.

Table 1. Main characteristics of superconducting materials.

material	critical temperature T_c	irreversible field /T	current density, $J_c/(A/mm^2)$
(LTS) NbTi	10K	12T (4.2K)	4 10^3 (5T, 4.2K)
(LTS) Nb_3Sn	18K	7T (4.2K)	10^4 (5T, 4.2K)
(LTS) MgB_2	39K	15T (4.2K)	10^4 (5T, 4.2K)
(HTS) $YBa_2Cu_3O_{7-x}$	95K	$>$100T (20K)	10^6 (77K)
(HTS) $Bi_2Sr_2CaCu_2O_{8-x}$ called Bi2212	96K	$>$100T (20K)	10^3 (20T, 20K)
(HTS) $Bi_2Sr_2Ca_2Cu_3O_{10-x}$ called Bi2223	111K	$\approx$100T (20K)	500 (77K)

Finally, fully superconducting ECRISs are suitable for frequencies above 18GHz. Thanks to the huge progress done in superconducting wire technology, it is now possible to think in ECRISs powered at frequencies above 50GHz while having a magnetic configuration compatible with the magnetic scaling laws. Low Temperature Superconducting (LTS) wire Nb_3Sn utilized either at 4.2K or 1.8K seems to be the best candidate for the next source generation. Table 1 gives main characteristics of various superconducting wires LTS and High Temperature Superconducting (HTS). This table shows how attractive are BISCCO wires, nevertheless they are made of sintered powder with crystalline defects and grain boundaries that are obstacle to high currents.

3 Microwave coupling and power

3.1 Microwave coupling

This parameter seems to be now one of the weakest points of an ECRIS. Most today sources use basic rf couplings through coaxial or rectangular waveguides. Even if the first technique allows a compact source and contributed to the success of Caprice, diamagnetism studies showed its poor efficiency. Rectangular waveguides are preferred even for a compact machine: it is still possible to reduce the small side of the waveguide as proved in[3]. On the other hand, it is easy to get a good tuning between the multimode cavity (the plasma chamber) and the waveguide without plasma, but things are completely different with plasma. Between 10GHz and 18GHz, WR90, WR75 and WR62 rectangular waveguides usually work well, however, tuning between those waveguides and the plasma chamber are hopefully supposed to be good since the plasma chamber is large enough to be considered as a multimode cavity. Actually, such an empirical rf coupling works well for a reasonable level of power as one can obtain some mA of O^{6+} or Ar^{8+} with less than 1kW. Moreover, experiments were performed with Caprice equipped with a special corrugated aluminum plasma chamber. The purpose of these groves was firstly to get a better microwave coupling[4] and also to enhance the plasma chamber surface and then to increase the number of secondary electrons. As compared with a cylindrical aluminum plasma chamber, a gain of 20% in intensity was obtained.

On the other hand, large sources now require a lot of rf power: more than 3kW at 18GHz and up to 10kW for frequencies above 28GHz. And then, it is absolutely necessary to optimize the level of rf power. This optimization already starts from the transmitter: for example, VSWR rises with waveguide temperature and oversized and/or watercooled waveguides are recommended.

At 28GHz, for example, output mode from the gyrotron is generally TE_{02} mode. Neither TE_{02} nor TE_{01} has a homogeneous rf power distribution and it is difficult to imagine a good energy transfer to the electrons. Launching TE_{11} or HE_{11} mode close to the source axis would certainly be more efficient (see Fig. 1).

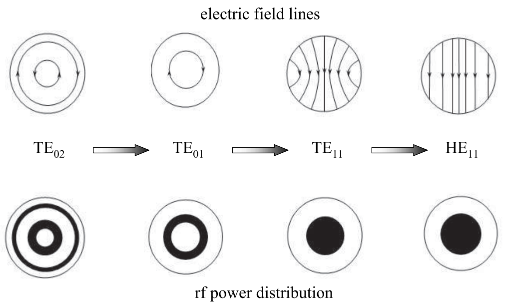

Fig. 1. Conversion process from TE_{02} into HE_{11} mode.

Fig. 2. shows two coupling possibilities at 28GHz: TE_{01} as done with SERSE 28GHz and VENUS 28GHz and TE_{11}. Use of this latter mode would certainly be "power saving".

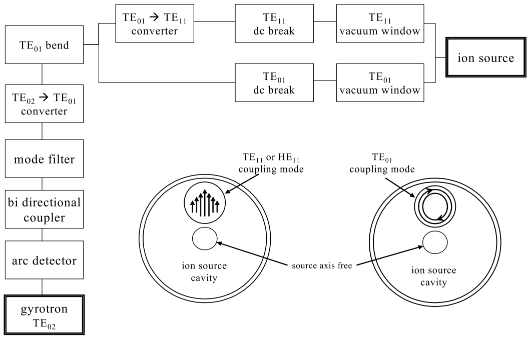

Fig. 2. Shows two coupling possibilities at 28GHz: TE_{01} as done with SERSE 28GHz and VENUS 28GHz and TE_{11}. Use of this latter mode would certainly be "power saving".

3.2 Microwave power

Once the microwave coupling is optimized, arises the problem of rf power level. Previous experiments with different superconducting ECRISs show how dangerous it is to run the source with several kW of rf power either in cw or pulsed mode. Of course, plasma chamber cooling must be in accordance with the rf power level, keeping in mind that all power goes to the chamber wall through the well known thin star impacts.

Plasma chamber size is also a key point: it is now well known that large plasma chambers, enabling long ion lifetime, are better to deliver very high charge states. However, they require large quantity of rf power. Fig. 3 presents the rf power evolution per volume unit for different types of ECRIS. Despite its small size, an all-permanent magnet source reaches its saturation at about 1.5kW per liter. But, since its plasma chamber size is about 1/2 l, the rf power remains rather low and no microwave coupling problems are encountered. However, when the plasma chamber size increases as for GTS, more rf power is needed. For example, 1.5kW are necessary to obtain 1.5mA at 14GHz. Things become problematic above 2kW because plasma chamber and waveguides cooling is more difficult to achieve for long term operations. Fig. 3 also shows that, even if several kW are launched into large superconducting ECRISs, intensities do not saturate either at 18GHz or at 28GHz.

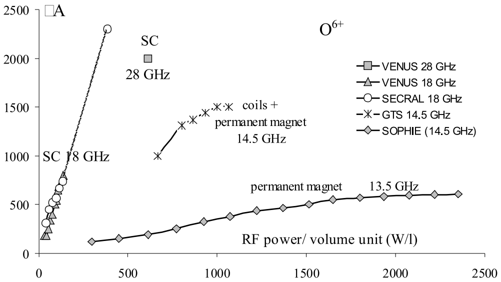

Fig. 3. O^{6+} intensity evolution versus rf power per volume unit for four different ECRISs (SC stands for superconducting). Data are taken from [5] for SECRAL, [6] for VENUS, [7] for GTS and [3] for all-permanent magnet.

For these large devices, an optimization of the rf power intensity has to be investigated. Even if the use of TE_{11} or HE_{11} mode at 28GHz would certainly reduce the optimum rf power intensity, several kW would still be needed to get large beam intensities and very high charge states. For the case of O^{6+}, SECRAL, with a TE_{10} mode microwave transmission at 18GHz and a smaller plasma chamber volume, has a better efficiency than SERSE or VENUS at 28GHz with TE_{01} mode.

If one considers a typical ECRIS equipped with an hexapolar magnetic configuration, magnetic field lines are such that they present a three branch star shape at each end of the plasma chamber. As electrons and consequently ions follow these field lines, there is some space in the plasma chamber without almost any particles. A simple solution to be “power saving” is to avoid the microwaves going into this space. This could be achieved by simple grids or by some metallic pieces of course well cooled. In other words, an optimized plasma chamber would no longer be simply cylindrical, but must correspond to the shape of the magnetic field lines. Moreover, if corrugated, such a star shape plasma chamber could still serve as a multimode cavity; anyhow, the use of a movable biased disk would efficiently work as a piston. Finally, it is hard to take benefit of a broad bad frequency with a gyrotron, as with a TWT. For example, the tube utilized for SERSE 28GHz is at 27.962GHz, which correspond to a resonance field at 0.9986T. And the use of several gyrotrons having slightly different frequencies is costly not conceivable. The only solution is to tune the magnetic gradient around the resonance with coils or iron plugs.

4 Industrial applications

It is commonly known that ECRIS can advantageously been used in ion implantation, however the use of an ECR plasma as a light source still remain confidential despite experiments performed at LBL and CEA. For example, Extreme UV lithography needs powerful photon source able to deliver more than 100W at 13.5nm. In addition, source lifetime must be several months and it must not produce any debris that could pollute the wafer. Up to now, gas discharge plasma (GDP) and laser produce plasmas (LPP) are best candidates, but their major drawbacks are their lifetime and the debris they produce. ECR plasma could be an alternative as it has several advantages: it works in CW during months and doesn’t produce any debris. However, 100W of photon power corresponds to 6.7×10^{18} photons, while the electron density of high frequency ECRISs is about $10^{13}\mathrm{e}^-/\mathrm{cm}^3$. This means that an ion must undergo a lot of excitation/deexcitation processes during its lifetime. Preliminary experiment showed that an all-permanent magnet ECRIS can produce 6×10^{15} photons[8]. Therefore a possible powerful ECR photon source could be a small plasma spot at 37GHz surrounded by another plasma at 50GHz. This second plasma would provide the electrons that are necessary for the excitation processes. In addition, as compared with GDP or LPP, an ECR plasma has the capability to use at the same time several elements of the periodic table known to give photons at 13.5nm (O^{6+}, Xe^{10+}, $\mathrm{Sn}^{8+..10+}$). And then the photon source plasma could advantageously be a mixture of various elements, metallic or not. Already utilized in today EUV source, a mirror system Wolters type would be installed inside the plasma chamber to take photons emitted by the 50GHz plasma and focus them in the so-called intermediate focus. Some other tricks useful for an efficient photon source are also presented in Refs. [9—12].

5 Conclusion

Powerful ECRISs not only require optimized magnetic configuration but also optimized plasma chamber for the use of minimum rf power as possible. For more details, a complete review of recent progress in ECRIS could be found in:

Advances in Imaging and Electron Physics, Volume 144. Edited by Peter Hawkes, Elesevier Science, ISSN 1076-5670/05.

6 Acknowledgments

This review could not have been written without the outstanding work done during tens of years by the worldwide ECRIS community, to which I give my warmest thanks for the real pleasure I had to work with in this domain.

References

1 Apard P, Bliman S, Geller R et al. Physics Letters, 1973, **A44**: 432—434

2 Bliman S, Dousson S, Fremion L et al. Nucl. Instrum. Methods, 1978, **148**: 213—216

3 Hitz D, Delaunay M, Girard A et al. An All-Permanent Magnet ECR Ion Source for the ORNL MIRF Upgrade Project. Proceedings of the 16th ECRIS Workshop, AIP Conference Proceedings, 2005, **49**: 123—126

4 Melin G, Nguyen T K, Farchi A. RF Waves and RF Coupling Systems in ECR Ion Source. Proceedings of 12th ECRIS Workshop, 1995. 105—109

5 ZHAO H W, SUN L T, ZHANG X Z et al. Rev. Sci. Instrum., 2006, **77**: 03A333

6 Lyneis C M, Leitner D, Abbott S R et al. Rev. Sci. Instrum., 2004, **75**: 1389—1393

7 Hitz D, Cormier D, Mathonnet J M et al. Grenoble Test Source (GTS): a Multipurpose Room Temperature ECRIS. Proceedings of the 15th ECRIS Workshop, 2002. 53—55

8 Hitz D, Delaunay M, Quesnel E et al. All-Permanent Magnet ECR Plasma for EUV Light. 3rd International Symposium on EUV Light, Miyazaki, Japan (2004)

9 Hitz D, Cormier D. Device for Controlling the Electronic Temperature in an ECR Plasma. Patent #WO2005/046296

10 Delaunay M, Hitz D. Photon Source Comprising an Electron Cyclotron Resonance Multicharged Ion Plasma Source. Patent #FR0550724

11 Hitz D, Delaunay M. Photon Source Comprising an ECR Source with Pressure Gradient, Patent # FR0551256

12 Hitz D, Delaunay M, Vannuffel C et al. Photon Source Comprising an ECR Source Equipped with Mirrors. Patent # FR0503421