A 2.45-GHz electron cyclotron resonance multi-mA Li^+ ion gun for fusion plasma diagnostics

D. Wutte, M. Leitner, and HP. Winter
Institut für Allgemeine Physik, Technische Universität Wien, Wiedner Hauptstr. 8-10, A-1040 Wien, Austria

(Presented on 31 August 1993)

For the purpose of neutral-lithium beam tokamak–plasma diagnostics we have developed a compact, high current (several tens of mA/cm^2) 2.45-GHz electron cyclotron resonance (ECR) Li^+ plasma ion source in coaxial geometry, coupled to a helium-buffered lithium feeding system working according to the heat pipe principle. The accel–decel-type ion extraction system features either seven holes or one single aperture. First experimental results for the extractable Li^+ and He^+ ions in both cw and pulsed-mode operations are presented.

I. INTRODUCTION

For the successful development of future thermonuclear fusion reactors, a detailed knowledge of plasma–wall interaction and impurity transport processes in the outermost regions of magnetically confined hot plasmas is of foremost interest. Injection of a beam of fast (10–100 keV) neutral lithium atoms into the tokamak edge plasma has been shown to provide a wide range of diagnostic information,[1] by analyzing the line radiation following collisions of the Li atoms with the plasma particles.[2–5] For high-resolution measurements, neutral beam-equivalent currents of several mA/cm^2 are needed.

ECR ion sources are excellent candidates to produce ion beams to be neutralized for the above-mentioned purposes, because of their reliability and extended lifetimes even with reactive feeding gases or vapors.[6] This led us to develop a compact 2.45-GHz ECR ion source (10-cm long, discharge plasma tube diameter 23 mm) in coaxial geometry.[7] As its follow-up, we have now constructed and operated a 2.45-GHz ECR Li^+ ion source with Li vapor as the working medium, to produce the required high Li^+ ion current densities. The Li vapor is introduced into the ECR plasma region from a He-buffered heat-pipe-like feeding system. In this way, the source can also serve as a He^+ ion gun, considering the recent interest in slow as well as fast neutral helium beams for tokamak plasma diagnostics.[8,9]

In the present contribution we describe the construction of the new Li^+ source, in particular its lithium vapor feeding system. First results are presented for the achievable Li^+ and He^+ ion beam currents when operating the ECR discharge either in the pulsed or cw mode.

II. ION SOURCE CONSTRUCTION

A. ECR plasma discharge

A schematic view of the present ion source discharge geometry, featuring a 2.45-GHz ECR plasma within a simple magnetic mirror field, is shown in Fig. 1.

Variable microwave power is fed from a 2.45-GHz magnetron via a Teflon vacuum window, which insulates the microwave line from the discharge chamber and permits one to bias the latter at extraction voltages of up to 30 keV. A 90° rectangular-to-coaxial wave guide transition protects the vacuum window from Li-vapor deposition (see below).

The magnetron can be operated in both the cw and pulsed modes, producing up to 1-kW power in the cw mode. The plasma tube (inner diameter 35 mm) and the microwave antenna (diameter 8 mm, tip diameter 6 mm, cf. Ref. 7) are made of stainless steel. Since 2.45-GHz microwave cannot be transported in this discharge vessel geometry, the antenna tip had to be placed next to the first ECR point where the magnetic field strength reaches 87.5 mT.

The axial magnetic mirror field is produced by two water-cooled solenoids completely encased by iron yokes. This allows one to reach a magnetic mirror ratio of up to 4, if the distance between the solenoids is appropriately enlarged (cf. Fig. 2). Such a relatively high magnetic mirror ratio provides good axial plasma confinement and makes it possible to couple up to 1-kW microwave power into the plasma. In this way, rather dense plasmas can be generated, which are well suited for the production of the desired intense ion beams.

The ion extraction is of the accel–decel type, featuring either seven 2-mm-diam apertures or one single 5.3-mm diam hole, in both cases offering a total free plasma area of 22 mm^2. Distances between extraction aperture and accel electrode, and between accel and decel electrodes are 4.5 and 3 mm, respectively. With the decel electrode grounded and the accel electrode biased negative with typically -200 V, the plasma discharge vessel could be set at a positive voltage: U_{extr} of $\leqslant 10$ kV.

B. Lithium feeding system

The lithium feeding system schematically shown in Fig. 3, is directly coupled to the plasma chamber. It works according to the heat pipe principle, in a similar way as widely utilized for alkali vapor spectroscopic measurements[10] and charge-exchange cells.[11] Its design is based on a heat conductive element devised by Grover *et al.*[12] Three heater systems keep the required temperature gradient and assure that the temperature of the whole plasma tube exceeds 200 °C (Li melting point 186 °C),

 0034-6748/94/65(4)/1094/3/$6.00

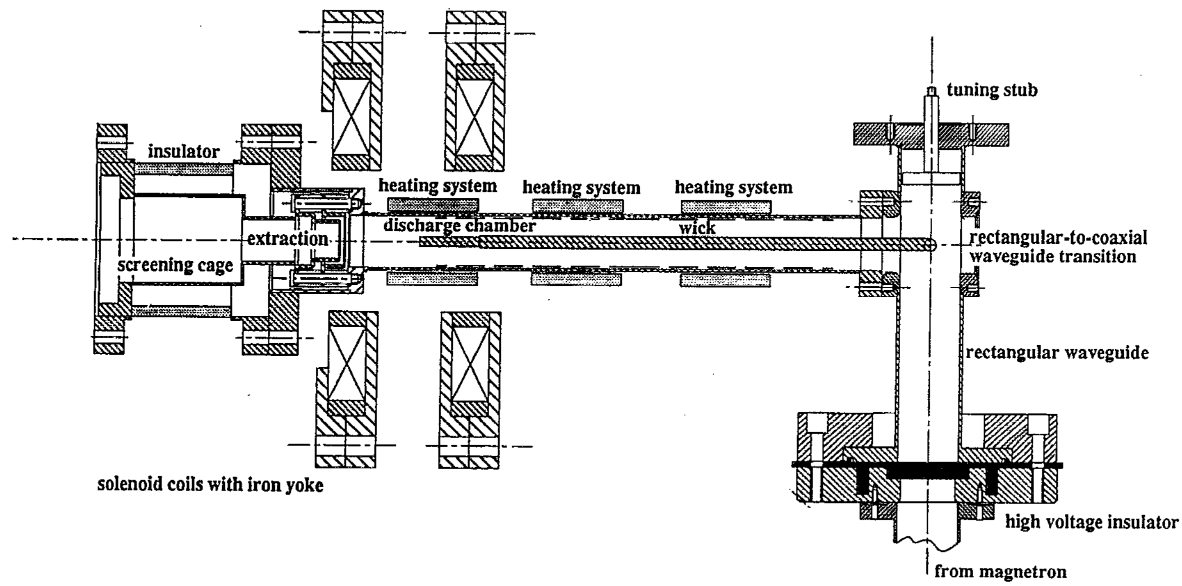

FIG. 1. Schematic drawing of the ECR ion source discharge vessel situated within the magnetic mirror field and coupled to the lithium vapor heat pipe and the microwave inlet.

such that the metal vapor condenses at any point of the tube in the liquid phase.

Three layers of a stainless-steel mesh line the inner wall of the tube until close to the first ECR point. This "wick" is saturated with lithium and thus serves as a lithium reservoir. As buffer gas we used helium to determine the total pressure in the discharge vessel in the order of 10^{-3} mbar (the residual gas pressure in the vacuum jar is about 10^{-6} mbar during discharge operation). There is a pressure drop between the hot zone in the plasma region, where the temperature rises above 500 °C, and the extremities of the tube ($T \approx 200$ °C). Li vapor lost from the plasma will flow toward the cooler parts of the tube and condense as liquid at the mesh. For continuous operation it is necessary for the liquid to return steadily toward the plasma region. As is common for heat pipes, this is achieved by capillary forces. There is always a depletion of liquid in the hot zone due to evaporation, whereas in the cooler parts the liquid lithium will accumulate. With a suitably chosen wick the capillary forces can always overcome the viscous retarding forces, thus ensuring a steady influx of the liquid into the plasma region, controlled by the temperature of the hot zone and the total pressure in the discharge vessel. Lack of the working liquid would cause the mesh to "dry up" and thus stop the influx of Li vapor.

There are two possibilities for loss of lithium vapor or liquid, a desired one due to the extraction of Li^+ ions, and another one by the flux of Li atoms from the hot zone through the ports of the discharge tube. The latter loss, which has to be kept as small as possible, is proportional to the squared ratio of the radius to the length of the discharge tube.[11] Since our tube is 30-cm long, this Li loss remained in the order of 1% only. Under steady-state conditions the metal thus circulates in a quasiclosed cycle, and it is well feasible to control the lithium flux into the plasma as well as the respective lithium partial pressure, by just

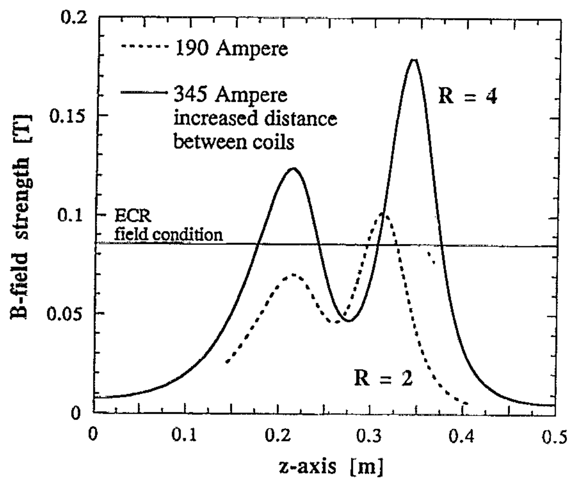

FIG. 2. Course of axial magnetic field strength in the ECR discharge region, for two different distances and settings of the magnetic coil current.

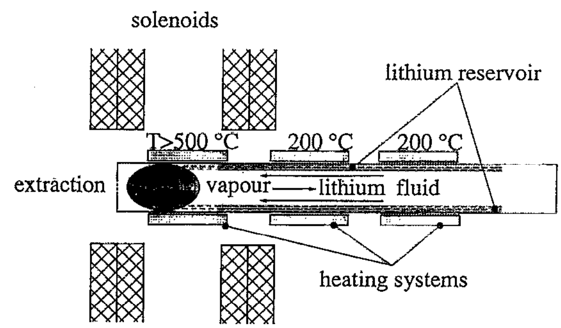

FIG. 3. Commonly chosen temperatures of the heat pipe heating systems.

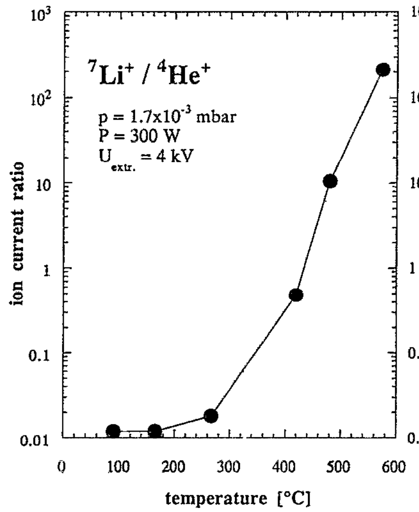

FIG. 4. Ratio of extracted ion currents (after magnetic sector field analyzer, He pressure fixed) of $^7Li^+$ and $^4He^+$, respectively, vs central heat pipe temperature.

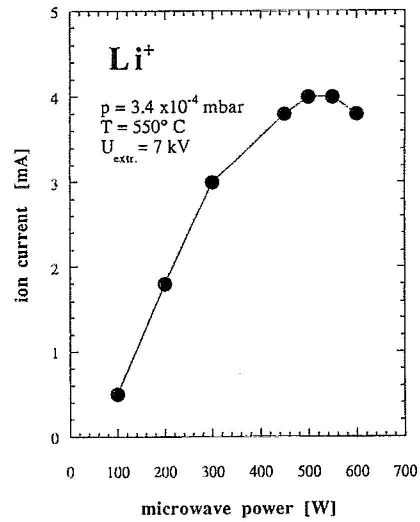

FIG. 5. Course of total extracted Li^+ ion current vs microwave power coupled into the ECR discharge (operating heat pipe, He pressure fixed, extraction voltage 7 kV).

varying the temperature of the first heater and the He gas pressure. To assure thermal steady-state conditions of the "heat pipe" oven for different microwave power input, pulsing of the discharge has proven necessary, in which way a stable beam production for many hours could be achieved. Figure 4 shows the ratio between extracted Li^+ and He^+ ion currents vs the temperature of the first heater. Whereas with steady-state heat pipe operation the fraction of He^+ ions in the extracted beam remains smaller than 1%, the situation becomes just opposite with the heaters switched off. In this way it is very easy to change the composition of the extracted ion beams, which feature is of considerable interest for their prospective application for fusion plasma diagnostics.

III. FIRST OPERATING EXPERIENCE

With the discharge tube inner diameter being comparably small (35 mm, see above), microwaves launched into the plasma can only be absorbed in the first ECR zone next to the antenna tip. Consequently, the source had to be operated at relatively high neutral gas/vapor pressure, i.e., plasmas could only the generated above 5×10^{-4} mbar, and the most convenient working pressure is about 10^{-3} mbar. The imposed high magnetic mirror ratio serves for a good axial plasma confinement and permits coupling of up to 1-kW microwave power into the discharge, to produce quite dense plasmas suitable for extraction of correspondingly strong ion beams. With the present extraction area of 22 mm^2, ion current densities of up to 30 mA/cm^2 at 4–6-kV extraction voltage could be reached so far. However, running the discharge at elevated microwave power necessitates pulsed operation and/or forced cooling of both the plasma tube and the antenna tip, to avoid their excessive thermal loading. At least for pulsed operation the extraction system with seven holes provided considerably higher ion beam quality than the single aperture extraction, because of which the former was exclusively used for obtaining data shown in Fig. 5, which has been measured with a shielded Faraday cup (entrance aperture 40-mm diameter) about 40 cm downstream of the ion extraction aperture. Further investigations including extracted ion beam emittance measurements will be made in the near future.

ACKNOWLEDGMENTS

This work has been supported by the Kommission zur Koordination der Kernfusionsforschung at the Austrian Academy of Sciences. Thanks are due to Mssrs. W. Beck and H. Schmidt for skillful construction of parts of the ECR ion source.

[1] E. Wolfrum, F. Aumayr, D. Wutte, HP. Winter, E. Hintz, D. Rusbüldt, and R. P. Schorn, Rev. Sci. Instrum. **64**, 2285 (1993).

[2] K. McCormick and the ASDEX team, Rev. Sci. Instrum. **56**, 1063 (1985).

[3] F. Aumayr, R. P. Schorn, M. Pöckl, J. Schweinzer, E. Wolfrum, K. McCormick, E. Hintz, and HP. Winter, J. Nucl. Mater. **196–198**, 928 (1992); J. Schweinzer, E. Wolfrum, F. Aumayr, M. Pöckl, HP. Winter, R. P. Schorn, E. Hintz, and A. Unterreiter, Plasma Phys. Controlled Fusion **34**, 1173 (1992).

[4] R. P. Schorn, E. Hintz, D. Rusbüldt, F. Aumayr, M. Schneider, E. Unterreiter, and HP. Winter, Appl. Phys. B **52**, 71 (1991).

[5] R. P. Schorn, E. Wolfrum, F. Aumayr, E. Hintz, D. Rusbüldt, and HP. Winter, Nucl. Fusion **32**, 351 (1992).

[6] R. Geller, P. Ludwig, and G. Melin, Rev. Sci. Instrum. **63**, 2795 (1992).

[7] S. Fiedler and HP. Winter, Rev. Sci. Instrum. **63**, 2532 (1992).

[8] N. Brenning, J. Quant. Spectrosc. Radiat. Transfer **24**, 293 (1980).

[9] A. Pospieszczyk, F. Aumayr, H. L. Bay, E. Hintz, P. Leismann, Y. T. Lie, G. G. Ross, D. Rusbüldt, R. P. Schorn, B. Schweer, and HP. Winter, J. Nucl. Mater. **162–164**, 574 (1989).

[10] C. R. Vidal and J. Cooper, J. Appl. Phys. **40**, 3370 (1969).

[11] M. Bacal and W. Reichelt, Rev. Sci. Instrum. **45**, 76 (1974).

[12] G. M. Grover, T. P. Cotter, and G. F. Erickson, J. Appl. Phys. **35**, 1990 (1964).