NUKLEONIKA 2003;48(Supplement 2):S99–S104

PROCEEDINGS

The TSL 6.4 GHz ECR ion source – status, improvements and measurements

Daniel van Rooyen,
Dan Wessman

Abstract The TSL 6.4 GHz ECR ion source performs reliably and is well optimized for the various ion species that are routinely provided for experiments. Beam intensities are comparable with other similar sources but at the lower end of the spectrum. We are thus investigating a number of methods of improvement. The development of a micro-oven for low melting point materials was successfully concluded. Further development is needed to improve the consumption rate in order to enable more effective use of expensive isotopes. Measurements with operation of the source in the after-glow mode were successful but the pulse to pulse reproducibility should be further improved. Although the maximum gain compared to the CW mode is satisfactory, accomplishing a higher factor would be even more advantageous for beams delivered to CELSIUS. A systematic study of various parameters was started in order to find optimal operating conditions running in the after-glow mode.

Key words ECR • ion source • after-glow mode

Introduction

The TSL 6.4 GHz ECR ion source was constructed in a collaboration between TSL and JYFL (Jyväskylä) as a copy of the Michigan RT 6.4 GHz. The first beams were extracted in November 1990. Subsequently, a similar ECRIS was constructed for installation at JYFL. ECR beams are vertically injected into the cyclotron, which is a single pole machine with three sectors for vertical focussing. The maximum average field is 1.75 T at a maximum useful radius of 1.2 m. The bending limit is given by $K = 192\ Q^2/A$ MeV; the focussing limit (protons) of 100 MeV is circumvented by using frequency modulation up to 180 MeV. Refer to Refs. [3, 7] for more detailed descriptions of the characteristics of the cyclotron.

The ECRIS is routinely used for a number of periodically recurring experiments in various fields: physics (fusion reactions, CHICSI experiments in the CELSIUS storage ring); bio-medical research (DNA double-stranded break repair etc.); ion track micro-technology (nano-wires and GMR based magnetic field sensors). Beams most often extracted are: B, N, O, Ne, Mg, Ar, Xe.

Status and performance of the TSL ECR ion source

Considering the long and extensive use of the TSL ECR ion source, near optimal tuning conditions were established for the different ion species. It should be noted that the source operation proved to be very reliable and beam-time is very seldom lost due to breakdowns or insufficient intensity. In a comparison of similar sources, it is clear that the per-

D. van Rooyen✉, D. Wessman
The Svedberg Laboratory,
Uppsala University,
P.O. Box 533, S-751 21 Uppsala, Sweden,
Tel.: +46 18/ 471 3445, Fax: +46 18/ 471 3833,
e-mail: daniel.vanrooyen@tsl.uu.se

Received: 26 November 2002, Accepted: 20 May 2003

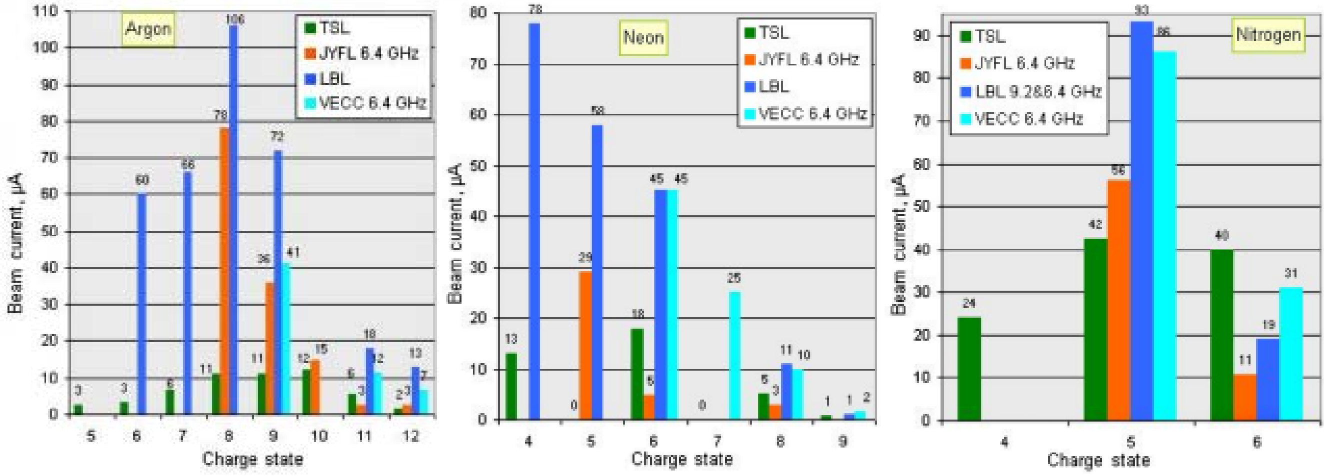

Fig. 1. Comparison of the performance of the TSL 6.4 GHz ECR with various other similar ECR's. (The data for the JYFL 6.4 GHz reflects the status before the magnetic field upgrade.)

formance of our source is comparable, but at the lower end of the spectrum (Fig. 1). In the recent two years it was again attempted to verify the nature of the difference between the JYFL and TSL ECR ion sources. Due to the many factors playing a role in the performance of an ECR – of which is not the least the previous ion history, even repeating previous performances are not always trivial. Nevertheless we are seriously embarking on (1) a study of possible explanations of these differences and (2) various actions that can be taken to improve its performance.

New beams

User interest was expressed for a sulphur [13] beam, which was satisfactorily developed but not accelerated. The developed (and accelerated) silicon beam was satisfactory with the intensity comparing reasonably well with reports from other laboratories. Beam currents were as in the Table 1.

Fe beam development using the MIVOC (**M**etal **I**ons from **V**olatile **O**rganic **C**ompounds) [1] method resulted in stable beams but with beam currents only on the verge of usable intensities. Beam intensities of up to a factor 2 higher could not be kept stable for reasonably long periods.

Instead of implementing the micro-oven it is thus as yet not an option to rather use the MIVOC method for metallic beams of (relative) expensive isotopes.

Development of micro-oven

A micro-oven for low melting point solids was developed during 2000, with a first run with Mg^{25} and Mg^{26} in September 2000, and the oven further improved for a next run in February 2001. Details of the oven are shown in Figs. 2 and 3. A primary condition in the design was the essentiality to be able to refill the oven without disturbing the ECRIS vacuum. Although the oven is now functioning well, further optimization is necessary. Due to the limited space available with access via the radial ports (Fig. 4), the volume of the oven is severely restricted with the implication that the maximum mass is limited to ca. 230 mg Mg – thus limiting runs to ca. 90 hours before refilling is needed.

Consumption rate and ionization efficiency measurements were routinely done. Ionization efficiency is defined as, for example, the summed beam current for all Mg ions relative to the mass of Mg metal consumed.

Depending on the beam intensity needed, and thus the degree of heating, the consumption rate (Mg) is varying between 2.5 and 4.5 mg/h. The ionization efficiency of ca. 0.7% compares well with figures reported [2].

For the moment we are content with the oven performance as it is as yet not foreseen that beams from solids will become a strong component of our beam spectrum. Even though $Mg^{25,26}$ is not so extremely expensive, it would be advantageous to prevent loosing large percentages of the material on colder inner surfaces. A heated inner structure

Table 1. Analyzed silicon, sulphur and iron beam intensities from the TSL 6.4 GHz ECR ion source.

ECRIS	Laboratory	Data source	Beam currents (eμA)							
				Silicon			Sulphur		Iron	
			Q	5+	7+	3+	5+	7+	11+	13+
JYFL, 6.4 GHz	Jyväskylä, Finland	Web (before upgrade)		26.5	10.2	–	–	36.5	2.5	5.6
LBL, 9.2&6.4 GHz	Berkeley, USA	[5]		72	–	10	20	63	5	–
NAC, 10.1 GHz	Faure, South Africa	NAC beam records		10.4	–	–	–	–	0.9	3.2
TSL, 6.4 GHz	Uppsala, Sweden	TSL beam records		14	6	–	–	22.8	1.5	1.6*
HIL UW, 10 GHz	Warsaw, Poland	[10]		–	–	–	50	60	–	–

*Fe intensities of 2.5 to 3 μA could not be kept stable for longer periods than several hours.

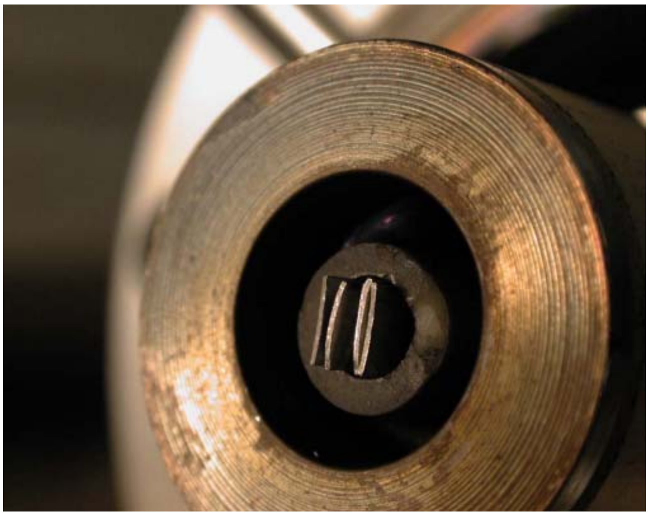

Fig. 2. Close-up of oven tip (26 mm outside diameter).

Fig. 3. Detail of micro-oven.

Fig. 4. TSL ECR ion source indicating radial port where micro-oven is positioned.

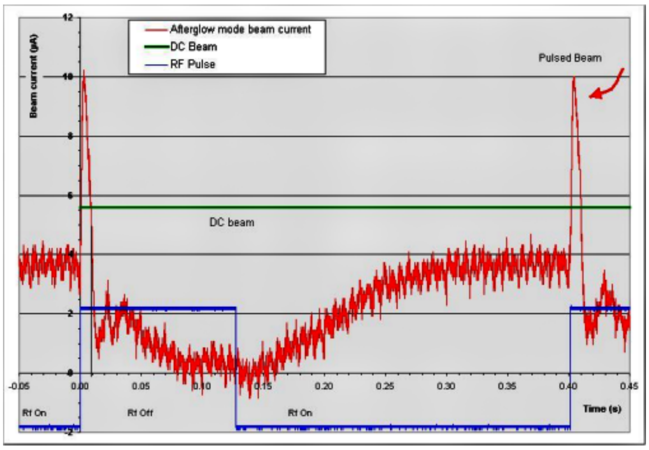

Fig. 5. Ar^{11+} beam current measurement with the ECRIS operated in the after-glow mode.

concentric with the plasma chamber inner surface would be worthwhile to be developed. Increasing the volume in a new micro-oven design will also be a high priority. With even better optimization of the various source parameters it is believed that both the consumption rate and ionization efficiency could be further improved. As time allows we will thus proceed with these mentioned improvements.

Operation in pulsed mode

More often, at TSL as elsewhere, it is essential to have the maximum possible average beam available to users – which thus necessitates the use of DC ECR beams. This is not the case, for example, when heavy ions are produced for acceleration in CELSIUS.

At various laboratories it has been established that pulsing of the microwave power leads to a factor of 2 to 3 increase in the extracted beam intensity measured immediately after cut-off of the RF pulse. For high charge states increase factors of up to 10 were also reported [6].

Previous measurements with the TSL ECRIS operated in the so-called after-glow mode extracting lighter ions were not very encouraging due to plasma instabilities.

Ar^{11+} is of specific interest for acceleration in CELSIUS and running the ECRIS in pulsed mode optimized for this (heavier) ion was further investigated. With re-tuning of several of the source parameters, a stable condition of the plasma could be accomplished. The after-glow peak of 10 μA was repetitive with time and is thus an increase almost by a factor of 2 compared to the DC beam (Fig. 5). For this relative low charge state this result was very satisfactory. For this test measurement the relevant parameters are pre-sented in Table 2.

Conclusions from a preliminary systematic study are:

- increasing the pulsing frequency does not lead to a significant increase in beam intensity and leads to the plasma being more susceptible to instabilities;
- the RF_{on} pulse should be sufficiently long for the plasma to stabilize;
- tuning is simpler if the RF_{off} pulse is sufficiently long for the plasma to completely die away – but there seems to be an advantage in building up the plasma before it completely quenches.

Table 2. Typical parameters for operation in the pulsed mode (after-glow mode).

Klystron off (ms)	Klystron on (ms)	Pulsing frequency (Hz)	Length of after-glow beam pulse (ms)
128	273	3	10

Improvements and measurements

Biased disk

A small change to enable increased voltage deliverable to the biased disk led to an intensity increase of ca. 20% for higher charge states, i.e. Xe^{27+}, which made acceleration of these beams more comfortable.

History effects of Si and B

It could not statistically be indicated sufficiently well enough that a run with Si, and thus creating a SiO_2 layer on the plasma chamber inner surface, has a positive effect on subsequent beam intensities. One may conclude that the cold electron effect of the SiO_2 is not noticeable when superimposed on the effect of the biased disk. A positive effect that was indeed clear is that optimal tuned conditions for subsequent beams are reached with more ease.

Contrary to measurements performed at other laboratories (private communication – J. Ärje, JYFL, Jyväskylä), a run with B seems to have a negative effect on subsequent beams. A possible explanation is that our observance applies only to high Q beams (for example: $^{129}Xe^{27+}$) where very high vacuum is essential and that B, using the MIVOC method with decaborane $H_{14}B_{10}$, is still outgassing from the inlet lines.

Magnetic field upgrade

The SC-ECRIS at NSCL/MSU is a very well performing 6.4 GHz ECR ion source. From a study of the magnetic field characteristics of the SC-ECRIS at NSCL/MSU it was concluded [9] that the magnetic field of the RT 6.4 GHz ECR's can be adapted and the magnitude increased to such an extent to resemble the configuration of the SC-ECRIS (Fig. 6).

During 2001 the magnetic field configuration of the JYFL 6.4 GHz ECRIS was adapted to incorporate these calculations with very positive results as shown in Fig. 7.

In collaboration with JYFL, a similar reconstruction of the TSL ECRIS is scheduled to start in November 2002. Currently the 9 axial coils are symmetrically positioned in 3 groups of 3 each at injection, centre and extraction. A new yoke will be manufactured and the 9 coils regrouped in only an injection set (5 coils) and extraction group (4 coils). The new yoke will completely surround each set of coils enabling a further enhancement of the magnetic field. Additionally, the fields at the injection and extraction region will be strengthened by respectively adding a plug of high quality magnetic steel at injection and two rings in the vicinity of the plasma electrode. The strength of the hexapole magnetic field will also be increased. This will be accomplished by adding a cylinder of magnetic steel closely surrounding the plasma chamber.

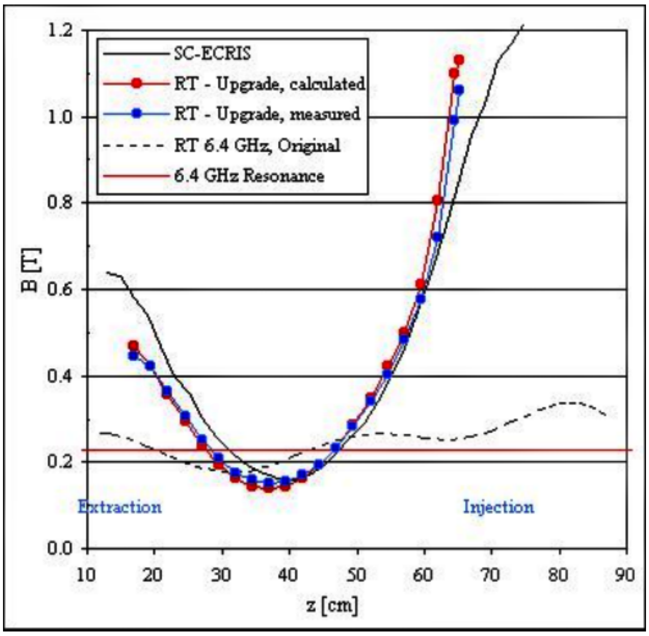

Fig. 6. Comparison of axial magnetic field before and after upgrade of coil configuration with reference to the SC-ECRIS magnetic field. (Figure courtesy of Hannu Koivisto, JYFL.)

With completion of the last scheduled run with heavy ions at the end of December 2002, we start with the disassembly of the ECR ion source. Towards the end of January 2003 the coil modifications should be completed and all yoke components on site and ready for assembly. During February the new yoke and coils will be assembled and all services connected. The final stage of positioning the plasma chamber and the injection assembly (extra iron plug, biased disk, gasfeeds) will be completed such that pumping vacuum can start at the beginning of March. We allow for ca. two

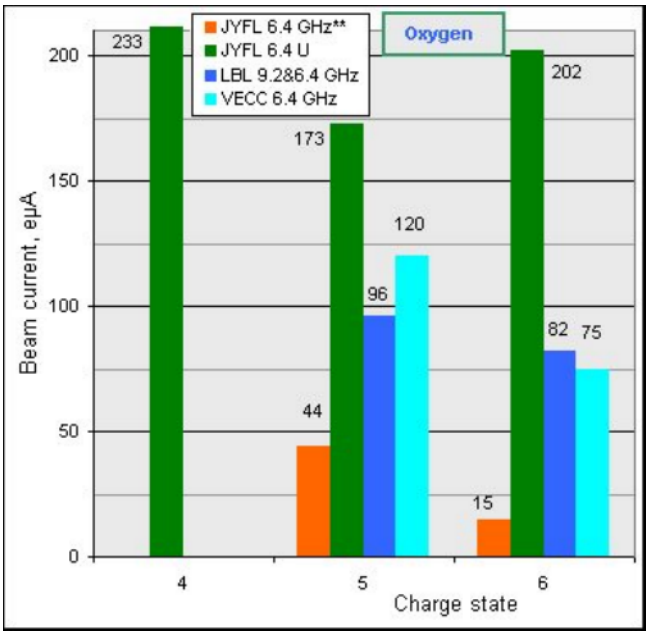

Fig. 7. Improvement in beam intensities for the Jyväskylä 6.4 GHz ECR ion source after adaptation of the magnetic field configuration. (Figure courtesy of Hannu Koivisto, JYFL.)

weeks of pumping and outgassing which then provides a final 3 weeks for testing before the first experiments with heavy ions from the ECR ion source are scheduled for the beginning of April 2003.

All drawings are now finalized and we have received the first quotations for those yoke components whose dimensions are too large to be manufactured internally. The first of the necessary new components involved in the upgrade have also been manufactured and machining will continue dependent on available workshop time.

Future prospects

Apart from the magnetic field upgrade, further future prospects are:

Improving plasma characteristics

VECC, Calcutta reports [12] the very positive effect of plating the inner surface of the plasma chamber with Al and thereby increasing beam intensities with up to a factor of 2. This confirms the established belief that provision of secondary cold electrons (in this case from the oxidised Al) to the ECR plasma has a significant effect stabilizing the plasma, resulting also in significantly higher beam intensities extracted.

Using a biased disk positioned axially at injection is an alternative source of cold electrons, although new results seems to indicate that the effect of the biased disk is rather related to optimisation of the plasma potential or improved extraction conditions. Similar to the detailed study of various effects and operational modes of biased disks at RIKEN (Japan) [8] and ATOMKI (Hungary) [4], it should thus also be experimentally established what the optimal operational mode for the TSL ECR ion source is.

Improving MIVOC beams

The MIVOC method is known as a very convenient technique to produce metallic ions, especially as the use of an oven or any other heating or sputtering is avoided. The method does, on the other hand, require exact procedures and careful tuning of the source. Understanding of the MIVOC method and the related tuning of the ECRIS have been improved and valuable experience has been gained. It is believed that we can still further improve on reached intensities. Furthermore, this knowledge can now be extended to other elements (Ni, Co, Cu, Ge and also I_2).

Optimization of the extraction system

On a longer term it would be worthwhile to study the extraction system and verify whether possibilities exist to improve the current system. Additionally, the injection beam-line should be re-evaluated and the possibility of an updated emittance system investigated.

New inflector

To improve the acceptance and transmission of beams from the ECRIS into/through the cyclotron, a new inflector was designed [11]. The relevant parameters (e.g. *k*' which is related to the direction of the electric field) are chosen to minimize the inflector fringe field. The electrode spacing at entrance, d_0, is 8 mm and the width of the electrode is 16 mm, thus improving the aspect ratio from 1 to 2. The off-centre distance between the centre of the cyclotron and the centre of the trajectory at the inflector exit was chosen as 11.7 mm. Calculations for the ion trajectories for 3 reference ions were done. These calculations indicated that the inflector exit parameters and the energy gain is sufficient to clear all the central region components. Construction of the inflector is nearly completed and the first tests are scheduled for October 2002.

Conclusion

The source is performing well and in a stable and dependable fashion. Extracted beam intensities can be improved. First tests for the operation of the ECRIS in the after-glow mode gave positive results. We have, with reference to various aspects, embarked on a programme to improve our ECRIS. In addition, we expect that the development and further optimization of the new inflector will improve intensities available from the cyclotron.

References

1. Ärje J, Leinonen H, Seppälä R *et al.* (1999) Status report of the JYFL-ECR ion sources. In: Proc of the 14th ECRIS Workshop, 3–6 May 1999, CERN, Geneva, Switzerland, pp 116–119
2. Barué C, Been T, Dupuis M *et al.* (1999) Metallic ion developments at GANIL. In: Proc of the 14th ECRIS Workshop, 3–6 May 1999, CERN, Geneva, Switzerland, pp 111–115
3. Berglund M (1993) Studies of axial injection in the Gustav Werner Cyclotron. UPTEC 93 104E. Institute of Technology, Uppsala University
4. Biri S, Nakagawa T, Kidera M *et al.* (1999) Highly charged ion production using an electrode in biased and floating modes. In: Proc of the 14th ECRIS Workshop, 3–6 May 1999, CERN, Geneva, Switzerland, pp 81–85
5. Brown IG (ed.) (1989) The physics of ion sources. Wiley, New York
6. Geller R (1996) Electron cyclotron resonance ion sources and ECR plasmas. IOP, Bristol
7. Hedblom K, Berglund M (1993) Beam optics calculations for the axial hole in the Gustav Werner Cyclotron. TSL-Note 93-04. Uppsala University
8. Kidera M, Higurashi Y, Nakagawa T *et al.* (1999) Effect of biased electrode to high energetic electrons in plasma of RIKEN 18 GHz ECRIS. In: Proc of the 14th ECRIS Workshop, 3–6 May 1999, CERN, Geneva, Switzerland, pp 86–89
9. Koivisto H, Heikkinen P, Ärje J *et al.* (2001) Development work with the JYFL ECR ion sources. In: Proc of the 16th Int Conf on Cyclotrons and their Applications held at NSCL/MSU, 13–17 May 2001, East Lansing, USA. AIP 600:255–257

10. Sudlitz K, Kulczycka E (1999) 10 GHz ECRIS for Warsaw Cyclotron. In: Proc of the 14th ECRIS Workshop, 3–6 May 1999, CERN, Geneva, Switzerland, pp 205–207
11. Toprek D, Reistad D, Lundström B *et al.* (2002) Design of the central region in the Gustav Werner Cyclotron at the Uppsala University. Nucl Instrum Meth Phys Res A 486:539–544
12. VECC Progress report (2000) VECC, Calcutta, India
13. Zyromski KE, Loveland W, Souliotis GA *et al*. (2001) Fusion enhancement in the ^{32,38}S + ^{181}Ta reaction. Phys Rev C 63:024615