The 18 GHz upgrade of the CERN ECR4 ion source

C.E. Hill, D. Küchler
CERN, Geneva, Switzerland

Abstract

The existing Electron Cyclotron Resonance Ion Source ECR4 at Linac3 is the main option as source of highly charged heavy ions for the heavy ions programme of the LHC. But in the current configuration the number of particles extracted from the source is limited and not sufficient to meet the needs of the injector scheme [1, 2].

One possible solution is the upgrade of the source from the present 14.5 GHz to 18 GHz. The physics background, technical problems and solutions and additional options to gain particles are described in the present paper.
1 Introduction

Since 1994 the Electron Cyclotron Resonance Ion Source ECR4 has been delivering highly charged heavy ions for the SPS fixed target physics. Currents up to 100 eµA of Pb$^{27+}$ could be extracted from the source (at 20 kV extraction voltage).

In [1, 2] it is mentioned that the source should deliver 100 to 300 eµA of Pb$^{27+}$ at a repetition rate of up to 10 Hz, 200 µs pulse length to fill LEIR. With the present source it is impossible to reach this current. One may run with only 100 eµA, but there is no margin of security and one has to rely on all the assumptions made for the other machines in the accelerator chain. It is therefore necessary to replace the existing source by a new one. Today there exist either physically or in the design stage several sources able to deliver the necessary beam — PHOENIX [3], GyroSERSE [4], GTS [5] or PECRIS V [6], but these will be very expensive and/or consume manpower resources.

Another (and cheaper) possibility would be to upgrade the existing source from the present 14.5 GHz to 18 GHz. Based on the well known, and extensively tested scaling laws (see Section 2), one can expect a gain of 54 %, i.e. a current of 154 eµA, only due to this measure. Additional measures in the source and linac operation may lead to an even higher current (see Section 4). The technical details of the upgrade are described in Section 3. Additional options are described in [7].

2 The physics background and the scaling laws

Geller [8] proposed that there is relation between the ion current $I_q$ for a certain charge state $q$ and the frequency $\omega$ of the microwave injected into the source

$$I_q \sim \omega^2$$

Source upgrades and a lot of experiments have proved this scaling up to a frequency of 28 GHz in the cw mode operation of the source [5, 9] (Figure 1). It seems it is also valid for the afterglow mode (the mode presently used with the ECR4). But the phenomenon of the afterglow is not as extensively studied as cw operation. Thus the scaling may not work for all cases. Another effect of the frequency upgrade will be a change in the plasma volume. It has been shown that the ion currents $I_q$ scale for the cw mode with the length of the resonance zone $L$ [5].

$$I_q \sim L$$

Due to the unknown real magnetic structure for an optimised afterglow from the upgraded source one cannot give an enhancement factor for the bigger volume at the present status of the study. In [5] the length changed from 11.5 cm to 16 cm, which gave a gain in ion current of 39 %.

The structure of the magnetic field is important for an high intensity ion beam. The frequency upgrade will have consequences also for this. The electron cyclotron resonance frequency $\omega_{ce}$ is related to the resonant magnetic field $B_{res}$ via

$$\omega_{ce} = \frac{eB_{res}}{m_e}$$

e is the electron charge and $m_e$ the electron mass. For the present frequency of 14.5 GHz the resonant magnetic field is 0.52 T, for the frequency of 18 GHz one will get 0.65 T.

The present fields for an optimised afterglow are:

1) Some experience suggests that the ideas and results of the cw operation cannot be transfered to the afterglow mode (e.g. biased disk [10]).
– axial magnetic field at injection side: $B_{\text{inj}} = 1.16 \text{ T}$,
– axial magnetic field at extraction side: $B_{\text{ext}} = 0.84 \text{ T}$,
– radial magnetic field $B_{\text{rad}} = 0.85 \text{ T}$ (edge piece) . . . $1.0 \text{ T}$ (middle piece) [12]
  (due to special shape of ECR4 hexapole),
– axial magnetic field at minimum: $B_{\text{min}} \approx 0.4 \ldots 0.5 \text{ T}$.

The fields suggested by the rules published by Hitz et al. [13] cannot all be reached:
– the last closed surface $B_{\text{last}} = 2 \cdot B_{\text{res}}$,
– $B_{\text{inj}} = 4 \cdot B_{\text{res}}$,
– $B_{\text{ext}} = B_{\text{rad}}$,
– $0.30 < B_{\text{min}} / B_{\text{rad}} < 0.45$,
– $B_{\text{rad}} = 2.2 \cdot B_{\text{res}}$.

But one should try at least to keep the axial mirror ratio. That would mean increasing the fields
to $B_{\text{inj}} = 1.44 \text{ T}$ and $B_{\text{ext}} = 1.04 \text{ T}$ (assuming that the afterglow would have its optimum with
the same mirror ratios at the higher frequency).

The radial field cannot be modified keeping the existing hexapole.
The emittance of the source has to be within the acceptance of the LEBT, also after the upgrade.
The Design Report [14] gives for the source a horizontal/vertical emittance of $< 120\pi \text{ mm-mrad}$
(measured in a test stand) and a horizontal/vertical acceptance of the LEBT of $200\pi \text{ mm-mrad}$.
The energy spread is unknown.
Measurements of emittances for such an upgrade are not known but one can expect an emittance
increase of 15-20 % [15]. This should be still inside the acceptance of the LEBT.

3 The 18 GHz upgrade – technical aspects

The required microwave generator is commercially available. E.g. the French company SAIREM
offers a complete system with following specifications (offer 10277, 8 October 2002):

2) Assuming a rough estimation (based on measurements done during the commissioning of the source [11]):
  1 A in the coil gives $10^{-3} \text{ T}$. 

Figure 1: Extracted intensities of xenon ions for SERSE at different frequencies and for other
ECRIS [9].
single cabinet housing power supply and RF circuit,
- RF power 2 kW (model GKP 20 KP),
- power stability $< 10^{-3}$,
- power control from 0 to 100 %,
- reflected power protection,
- waveguide WR62,
- remote controllable,
- price: 99,700 Euro (without additional options).

Due to the fact that it is the same waveguide as the present system the generator may be easily installed replacing the present system. But the microwave injection into the source may give problems as reported from a similar upgrade of the CAESAR source [16].

The present injection system uses a waveguide from the generator to the source and a coaxial system to bring the power into the plasma chamber (see Figure 2). For 18 GHz and the coaxial system it was difficult to tune the CAESAR source and the coupling was very poor. In the new design (see Figure 3) the waveguide is prolonged up to the plasma chamber, the coaxial system is removed and the microwave injection works better.

![Figure 2: The present design of the CERN ECR4 with the coaxial microwave injection.](image)

The same changes have to be done for the ECR4. This concerns a redesign of the plasma chamber, the cooling of the plasma chamber, the insert for oven and gas and the connection for the waveguide. Especially the redesign of the plasma chamber may be a tricky job. The ECR4 is very compact and the joints between several parts are very difficult. However, an analysis with network analysers should guide the design of any necessary modifications.

Designing and building all the new parts will take at least 6 months. Then the source has to be assembled and the behaviour of the microwave injection and the source as whole has to be studied. This will take 3 months. Then long term stability tests would be necessary; another 3 months. All together from the design stage to the full characterisation of the new source will take of the order of 12 months.
But the redesign has also one advantage. The opening for the oven can be bigger, so it may be possible to use the oven designed at GSI. This oven is bigger, i.e. it can contain more material, which would prolong the time the source can run without intervention. There exists a high temperature version of the oven (up to 2000 °C), which may increase the number of available elements from the source.

As stated in Section 2 the axial magnetic field has to be increased. The present power supplies for the source solenoids are capable of delivering currents up to 1250 A. This is sufficient for the extraction side, but for the injection side one will need a power supply capable to delivering up to 1500 A (at least but some margin would be desirable). The question is, can the present supply be upgraded or another existing supply used. This has to be studied.

D. Hitz [15] reported problems upgrading a source to a higher frequency, changing the axial fields but keeping the radial field. This may lead to source instabilities, a worse emittance and hot spots destroying the plasma chamber. Careful running-in of the source may avoid some of the problems. To see the effect on the emittance one should measure it before and after the upgrade. If it is necessary one may think about additional measures in the extraction system (a three electrode configuration instead of the present two electrode configuration) and the LEBT to partially compensate the worsened emittance.

Due to the fact that not only the partial current of Pb\(^{27+}\) will gain from the modifications but also the total current of the extracted beam will rise, an improvement of the radiation shielding around the extraction region will be necessary.

The rest of the source (extraction system, the high voltage, the main insulation and the cooling system) can be used as is. There are no changes necessary but small improvements may be possible.

4 Additional options to gain current

Based on experiences from the operation of Linac3 one can deduce that there are some bottlenecks in the beam transport. Especially the LEBT and the MEBT are suspicious (see Figure 4). Experiments to analyse these parts of the machine are planned for 2003. Beam simulations of the whole machine are under way. The measurement of the emittance of the source would give an important input for the simulations and the understanding of the problems especially in the LEBT. One can expect from these optimisations to gain some percent of beam at the end of the linac.

The ion source operates in the afterglow. At the moment the source delivers 100 e/µA in an interval of 650 µs. For the injection into LEIR only 200 µs are necessary. As shown in Figure 5
it is possible, to some extent, to shorten the pulse whilst gaining in ion current. However the pulse-to-pulse and the long term stability suffer from the shorter pulse. Additional tests are needed to find the right source settings for the shorter pulses. The total gain from this method one can expect is 5-10%.

5 Conclusions
The upgrade to 18 GHz is a solution to increase the output of the present ECR4 ion source. With the additional measures mentioned in Section 4 one can expect to meet the needs of the injection scheme.
But the effort to regain an operational source is not negligible. This is why it would be necessary to start as soon as possible with the design of the source upgrade to meet the schedule of delivering the final ion beam to the LHC in Spring 2008.
Figure 5: Behaviour of the afterglow concerning pulse length and intensity. For the first five measurements the current of the injection solenoid was increased systematically. And for the last measurement additionally the gas flow was increased and the extraction solenoid reduced.
References