LHC will accelerate not only protons but also heavy ions, as lead. The ions will be produced by an ECR ion source. It is required that the ion source should deliver 100 – 300 µA of Pb$^{77+}$ [1]. The present ECR4 ion source is not able to deliver such a current without modifications.

An idea of how to increase the current from a source point of view was to use the so called scaling laws. According to the scaling laws the current from the source is proportional to the excitation frequency squared. If the frequency is changed from the present 14.5 GHz to 18 GHz, the current would increase with a factor 1.5. Since the source is designed for 14.5 GHz, the injection system might need to be redesigned to fit to 18 GHz. Further, the power supplies for the mirror coils most likely has to be changed since we need a higher field in the plasma chamber. A more complete description of the 18 GHz upgrade of the CERN ECR4 ion source is found in an article by C.E. Hill and D. Kuchler [2].

A guide in the design work of the upgrade to 18GHz is simulations. This report is a short summary of the results of an attempt to simulate the situation if 18 GHz is injected into ECR4. S-parameters and the electric field distribution are calculated for both 14.5 GHz and 18 GHz.
1. Introduction

The transmission of microwaves through the injection system in the ECR4 ion source is calculated. The aim is to understand if an upgrade from 14.5 GHz to 18 GHz is possible.

The simulations are performed with the program Microwave Studio 4.3 from CST. In this program a transient solver (time domain) is used to calculate the S-parameters. The solver calculates the development of fields through time at discrete locations and at discrete time samples. It calculates the transmission of energy between various ports and/or open space of the investigated structure. The program can give information on for example the electromagnetic field distribution in the structure at a specific frequency or the field behavior far away (farfield calculations).

The injection system from the transmitter to the plasma chamber consists of rectangular waveguides, a coupler region and a coaxial line leading to the plasma chamber, see Figure 1.

![Figure 1: The injection system of the RF into the ECR4 ion source.](image1)

To the left in Figure 1 a part of the plasma chamber is drawn, in the middle there is the coaxial part and to the right the coupling chamber is sketched. On top of the coupling chamber, the first part of the rectangular waveguide is visible. It starts with a quartz window (vacuum seal) and then there is the HV break. The HV break is not shown in this figure but in Figure 2.

![Figure 2: The HV break of the ECR4 ion source. Two waveguide ends, a teflon sheet and the epoxy plates which hold the waveguides together.](image2)
There are three different important parts in the injection system which has to be considered in the calculations:

- The high-voltage (HV) break
- The coupling chamber
- The end of the coaxial line, i.e. the transition between coaxial line and plasma chamber.

Even if we in the following will consider the different parts separately, the correct result is only obtained if the simulation is done including the whole structure. Another thing to keep in mind is that the simulations are done without any plasma which of course will change the behavior of the RF.

2. The HV break.

The HV break is simply two waveguide-ends separated by a thin teflon sheet, see Figure 2. The waveguides and the teflon are held together with two pieces of glass fiber reinforced epoxy, which are screwed together.

The transmission through this part should in general be quite good. However, some of the microwave power will leak out through the separation of the waveguides where the teflon sheet is positioned. Since we inject as much as 1.3 kW rf power into the source, even a small leakage could be dangerous.

Only the fundamental mode of the waveguide, TE_{01}, is stimulated at port 1 in the calculations and the same mode is recorded at port 2. If any other mode is present (for example reflections from the other parts of the injection system) they are not included in this calculation. The ports are perfectly matched, all power at port 2 is absorbed.

**Results:**

*S-parameters:

In Figure 3 the transmission coefficient, S2.1, versus frequency is shown. At 14.5 GHz the transmission coefficient is 0.84 and at 18 GHz it is 0.97. If the system is perfectly matched, the percent of the injected power which are transmitted are given by the transmission coefficient according to,

$$|\text{transmission coefficient}|^2 = \frac{P_{\text{trans}}}{P_{\text{inj}}}.$$

From this relation we have that 70% of the injected power is transmitted in the 14.5 GHz case and 94% in the 18 GHz case. If all the power lost in the system in the 14.5 GHz case (30%) is radiated, this means that 12 mW/cm² could be detected at 0.5 m and 3 mW/cm² at 1m.

(Note that only one mode is recorded at the exit port.)

![Figure 3: The transmission coefficient S2.1 for the HV break.](image-url)
The power which is not transmitted is either reflected, lost through heating of the dissipated material (teflon and epoxy) or radiated.

**Farfield calculations:**
In the same simulation, the farfield was calculated. The total efficiency and the radiation efficiency were calculated for 14.5 and 18 GHz, respectively.
In the case of 14.5 GHz the total efficiency is 0.257, which means that 25.7% of the stimulated power leaks out through the high voltage break. The radiation efficiency is 0.996 which means that 99.6% of the power lost is radiated, the rest is lost in the dissipative material.
In the case of 18 GHz the total efficiency is 0.0508 and the radiation efficiency is 0.991.

**Conclusion:**
Around 30% of the injected power is lost in the high voltage break at 14.5 GHz, according to the simulations. The radiation may therefore be too big. Measurements have to be performed to confirm the simulations. In the 18 GHz case the radiation is much less, only around 6%.
One solution to the radiation problem is to use a choke flange on one of the waveguide ends. The groove in the flange will prevent the microwaves to leak out. Such choke flanges are commercially available.
A simulation of exactly the same structure as above but with a groove in the lower waveguide results in almost no power loss in the HV break even for 14.5 GHz. S2,1 is in this case 0.995 for 14.5 GHz and 0.985 for 18 GHz which means that 99% and 97% is transmitted, respectively. The farfield calculations results in a total efficiency of 0.007 and 0.001 and a radiation efficiency of 0.995 and 0.999 for 14.5 GHz and 18 GHz, respectively.

### 3. The coupling chamber

The coupling chamber is very large compared to the wavelength of the RF. The field distribution therefore becomes very complicated inside the chamber. The simulations give the transmission and reflection coefficients and the electric field distribution for 14.5 GHz and 18 GHz, respectively. The TE\(_{01}\) mode is excited at the top of the small rectangular waveguide in Figure 4, port 1, and then the S-parameters are calculated, defining port 2 as is shown in Figure 4. In total 10 different modes are included at the exit port.

![Figure 4: The coupling chamber](image)
**Results:**

*S-parameters:*
The reflection coefficient, $S_{1,1}$, parameter is presented in Figure 5.

![S-Parameter Magnitude](image)

Figure 5: The reflection coefficient versus frequency. TE$_{01}$ is excited at port 1 and detected at port 1.

At 14.5 GHz the reflection coefficient is 0.97, which means that 94% of the power is reflected. At 18 GHz the reflection coefficient is 0.39, i.e. 15% of the power is reflected. Note that this is only for mode TE$_{01}$.

The transmission coefficient is $S_{2,1}$ and in the frequency range 12 – 19 GHz for mode 1-10 is presented in Figure 6.
Figure 6: The transmission coefficients, S2,1, for the coupling chamber. TE₀₁ is excited at port 1 and 10 different modes are included at port 2.

From Figure 6 we get the following table:

<table>
<thead>
<tr>
<th>Mode</th>
<th>14.5 GHz</th>
<th>18 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>S2(1,1)</td>
<td>0.06093</td>
<td>0.04672</td>
</tr>
<tr>
<td>S2(2,1)</td>
<td>0.02701</td>
<td>0.08555</td>
</tr>
<tr>
<td>S2(3,1)</td>
<td>0.1666</td>
<td>0.06331</td>
</tr>
<tr>
<td>S2(4,1)</td>
<td>0.1474</td>
<td>0.4064</td>
</tr>
<tr>
<td>S2(5,1)</td>
<td>0.1248</td>
<td>0.2955</td>
</tr>
<tr>
<td>S2(6,1)</td>
<td>0</td>
<td>0.4062</td>
</tr>
<tr>
<td>S2(7,1)</td>
<td>0</td>
<td>0.2353</td>
</tr>
<tr>
<td>S2(8,1)</td>
<td>0</td>
<td>0.5579</td>
</tr>
<tr>
<td>S2(9,1)</td>
<td>0</td>
<td>0.1743</td>
</tr>
<tr>
<td>S2(10,1)</td>
<td>0</td>
<td>0.2124</td>
</tr>
</tbody>
</table>

The cutoff frequency for mode 6-10 at port 2 is higher than 14.5 GHz.

In Figure 7 the electric field distribution at shown in the x-, y- and z-direction. In all figures (a, b and c) the cutting plane and the phase is the same. The field is shown with a logarithmic scale.

Figure 7a: E-field at 14.5 GHz in the x-direction.

Figure 7b: E-field at 14.5 GHz in the y-direction.
It is not clear what these results mean. Obviously the source would not work if 94% of the power is reflected at the entrance to the coupling chamber. Maybe the assumption that it is a TE$_{01}$ mode which is most favorable mode in order to transmit power into the structure, is wrong. Further, we do not know how many modes which should be included at port 2. Maybe we miss the most important one when we only include 10.
4. The end of the coaxial line, i.e. the transition between coaxial line and plasma chamber.

If the transmission of the 18 GHz microwave is bad, there are two things to change in the design of the injection system which could help:

- the diameter of the inner coaxial conductor
- the length of the inner conductor (i.e. the antenna length in the plasma chamber).

Unfortunately this is very difficult to simulate separately, without including the whole structure, since we do not know the mode structure in the coaxial line.

5. Discussion and Conclusion

In this report, the different important parts of the RF injection system of ECR4 ion source are discussed and attempts to simulate the various parts are presented.

However, separate simulations of the different parts do not give correct results. Instead, one has to make a single simulation of the whole structure. This is due to the fact that so little is know of the mode structure inside the chambers. Another unknown parameter is the mode which is the most favorable to excite in the initial rectangular waveguide since we do not know the mode conversation of the system. Therefore one has to, not only simulate the whole structure, but also include many modes as excitation modes.

To make a simulation which includes the whole injection system and allows many modes to be exited at port 1 (and many modes included at port 2) was impossible with the computer capacity available. Another problem was that the plasma is not possible to include in the calculations and a plasma will of course considerably change the behavior of the RF inside the injection system.

The only thing to conclude from these simulations is that it is of importance to measure the radiation from the HV break.

Hopefully in the future we know more about this type of ECR ion sources so that we can simplify the problem and we will have more powerful computers so we more easily can perform the simulations.

References