DESIGN OF THE INJECTION INTO THE 800 MeV/amu HIGH POWER CYCLOTRON*

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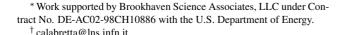
Abstract

We present the design of the injection into a separated sector cyclotron (SSC) aimed at the production of a high power beam of 800MeV/amu molecular H_2^+ for ADS-Reactor applications. To work out the beam line parameters and beam dynamics simulations, including the first accelerated turns, we used the ray-tracing code Zgoubi and the OPERA magnetic field map of the cyclotron sector. We simulated the injection path of the H_2^+ and evaluated radial injection scheme in order to evaluate the parameters so derived. The paper details and discusses various aspects of that design study and its outcomes.

INTRODUCTION

The present paper addresses an attempt to find an appropriate injection design for our SSC: the cyclotron complex consists of an injector cyclotron accelerating H_2^+ molecules from 50 KeV/amu up to 60 MeV/amu. The beam is then injected to our 6-sector cyclotron by means of electrostatic and magnetic elements, and accelerated up to 800 MeV/amu. In order to do so, 6 RF cavities, 4 single-gap and 2 double-gap are used, which are PSI-like. A plot of the OPERA magnetic field map in the median plane, for one sector is shown in Fig. 1. There are many considerations that explain the magnetic field shape [1]:

- The azimuthal variations show that the field is decreasing in the central region which ensures more focusing of the beam.
- The superconducting coils of each sector, which are wound around the hills, and the iron of the sector, produce the magnetic field that has to follow the $\gamma(r)$ law in order to keep the isochronicity, where γ stands for the Lorentz factor.
- The isofield lines show that one edge of the sector has spiral shape while the other is quite straight: even though it is better to have spiral edges to increase the vertical focusing, the design of the magnet becomes problematic when it comes to using superconducting coils, because of the expansion radial force exerted from the inner region of the coil towards the outer radii. A superconducting magnet with a convex shape of the coil would be very difficult to build.
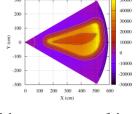
Figure 1: Plot of the z-component of the magnetic field in the median plane for one sector, with the isofield lines.

BEAM DYNAMICS AT INJECTION

Orbits at various energies from injection to nearby extraction are shown in Fig. 2. These orbits were obtained by Zgoubi [2] . It can be easily seen that the distance between consecutive turns (that have the same step size in energy) decreases quickly. In fact, the transverse separation of the turns is very important to consider in our design because it has to be maximized in order to allow clean injection. The step width per turn can be described by the formula [3]:

$$\frac{dR}{dn_t} = \frac{U_t}{m_0 c^2} \frac{R}{(\gamma^2 - 1)\gamma} \qquad (1)$$

where U_t denotes the energy gain per turn. However, this assumes that the condition of isochronicity is perfectly satisfied. It can be deduced from Eq. 1 that both the energy gain per turn and the injection radius should be made as big as possible in order to increase the step width per turn at injection as well. The transverse separation of the turns as a function of the kinetic energy is shown in Fig. 3.

The first orbit suitable for acceleration is the first closed orbit shown in Fig. 2. This orbit is very important to study in order to match the injected beam properly. Paraxial rays were generated around this orbit in order to compute the transfer matrix of the sector. From that, the betatron functions of the sector ensuring the 6-fold symmetry were computed. The beam envelope of the entire cyclotron was then obtained by multi-turn tracking of a set of particles generated around the eigen ellipse. Both axial and radial beam envelopes are shown in Fig. 4 and 5 respectively. All the results obtained here assume a H_2^+ beam energy of 60 MeV/amu and a normalized emittance of 13.5 π mm.mrad.

INJECTION LINE

The injection system needs to transport the beam from a point outside the cyclotron ring to the first orbit suitable for
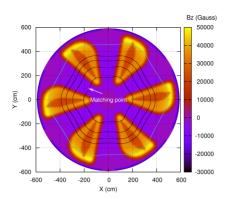
Figure 2: Plot of the closed orbits: the first closed orbit at injection which corresponds to an energy of 60 MeV/amu is shown in black, the next ones, still in black, correspond to a constant step size of energy of 80MeV/amu with respect to each other. The blue one however shows the closed orbit near the extraction, at 700 MeV/amu. The point marked with a pink color is the matching point inside the first closed orbit that will be used to match the beam properly.
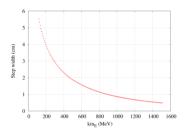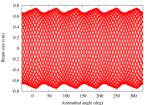

Figure 3: Plot of the transverse separation of the turns as a function of the kinetic energy: this result was obtained from tracking by searching for the closed orbits assuming a constant energy gain per turn of 4 MeV/amu.

acceleration. The main constraints of the design are:

- The beam has to match the equilibrium orbit at a reference azimuth that in our simulations is $\theta = 150°$. This position is referred to as the matching point (see Fig. 2): the beam machine functions (betatron functions) as well as the beam coordinates have to be matched at this point.
- The beam envelope has to be kept small along the injection trajectory: in our case, the maximum beam

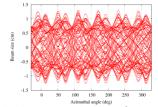Figure 4: Axial beam envelope vs θ along the 1st closed orbit.

Figure 5: Radial beam envelope vs θ along the 1st closed orbit.

size allowed in both the vertical and horizontal plane is 4 cm in the region where 150 cm $<$R$<$ 500 cm.

An easy and straightforward solution to the injection problem is to track backwards ($\equiv$ clockwise) starting from the matching point. So the field map had to be flipped. Then, to insert the injection elements, the magnetic field was recalculated by adding the equivalent magnetic field to, either electrostatic or magnetic devices. The solution obtained is shown in Fig. 6.
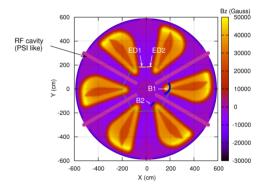

Figure 6: Layout of the injection system for the Superconducting Ring Cyclotron.

NB: The effect of the two RF cavities along the injection trajectory was neglected in the current study.
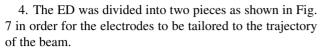
Electrostatic Deflectors (ED): Design Considerations

According to a design study of the RF cavities [4], it was shown that the voltage at injection should not exceed 500 kV for each single gap cavity instead of 1 MV. This implies that the step width was even smaller at injection. Taking this into account, as well as the radial dispersion of the beam, it was found that we have $\approx$ 1 cm available space (in the radial direction) at the location of the matching point. The choice then was to place an electrostatic deflection channel at this location. In fact, there are many reasons that explain this choice:

1. The small step size which is of about 1 cm here;

2. The neighbouring turns would not be affected by such a thin electrode while a magnetic element would need much more material to be placed between the turns;

3. Avoid arcing problems by placing the septum in the free space between two magnets: for each material, there is a critical magnetic field beyond which the spark damage is severe [5]. The upper limit here is 60 kV/cm inside the drift.

4. The ED was divided into two pieces as shown in Fig. 7 in order for the electrodes to be tailored to the trajectory of the beam.
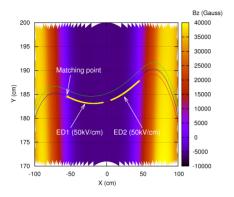

Figure 7: Plot of the beam trajectory inside the eletrostatic deflectors (red curve): the blue curve shows the first closed orbit (that has to be matched) while the green one represents the first accelerated orbit at the location of the septum.

Magnetic Channels (MC)

The choice then was to use two magnetic channels B1 and B2: B1 was placed inside the gap of the main magnet for two reasons:

1. It was preferred to avoid the RF cavity which will occupy most of the space inside the drift.

2. While tracking backwards, it was noticed that we gain at least 1 cm more at this location.

The next step was to focus the beam properly. For that, a gradient was applied to magnet B2. Figure 8 and Fig. 9 show the axial and radial beam envelope respectively. A conservative value of 0.68 kG/cm was found which ensures that the beam size does not exceed 4cm inside the pole gap.
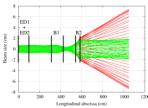

Figure 8: Axial beam envelope vs the longitudinal abscissa along the injection trajectory: the green and red curves show the result when a 0.68 kG/cm or 0 kG/cm gradient is applied to the magnet B2, respectively. The difference between the two envelopes is observed after dipole magnet B2.
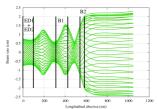

Figure 9: Radial beam envelope vs the longitudinal abscissa along the injection trajectory: there is almost no change in the beam envelope before and after applying the gradient to the dipole B2. However, the beam size exceeds 4 cm outside the pole gap which is fine especially that the radial inter-turn separation at the location of B2 is not limiting any more.

The specifications for the magnetic and electrostatic elements required are summarized in Table 1. It is important

Table 1: Magnetic and Electrostatic Elements Required for the Proposed SRC Injection System

Element Label	Type	Strength	Effective Length
ED1	Electrostatic septum	50 kV/cm	0.55 m
ED2	Electrostatic septum	50 kV/cm	0.39 m
B1	Magnetic septum	9 kG	1.13 m
B2	Magnetic channel	18 kG	0.42 m

to point out that the solution proposed has the merit to avoid us using quadrupoles inside the cyclotron ring to focus the beam.

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