SIMULATION OF TWO BEAMS EXTRACTION FROM SUPERCONDUCTING CYCLOTRON C400

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Abstract

Superconducting cyclotron C400 [1] dedicated for acceleration of the $^{12}C^{+6}$ and $^{2}H^{+}$ ions up to energy 400 MeV/nucleon is being under development at IBA (Belgium). Extraction of the carbon ions by means of electrostatic deflector (E=140 kV/cm) and protons by the help of $^{2}H^{+}$ ions stripping were studied. These beams precise alignment at ~3 m from the cyclotron just before an energy degrader was studied as well. Number of elements in the separate extraction lines, their geometrical location, length, and value of the dipole and quadrupole component of the magnetic field inside them were determined by the help of ions tracking. Possibility of two beams extraction using partly the same extraction line was also undertaken. Extraction of ions by separate lines and their subsequent alignment to one direction using the bending magnets was found as more suitable variant.

STUDY OF THE BEAM EXTRACTION POSSIBILITY IN PRINCIPAL

Carbon beam

Average magnetic field in C400 cyclotron is of about 3.6 Tesla at the final radii. Due to decreasing gap (from some centimetres in the centre to 12mm at the extraction radii) of the magnetic system the isochronous field expands very close to the pole edge and just outside the pole there is an essential filed drop. In such magnetic field (see Fig. 1) rapid beam extraction by means of the electrostatic deflector seems as more effective. This possibility was studied in the preliminary beam extraction simulations.

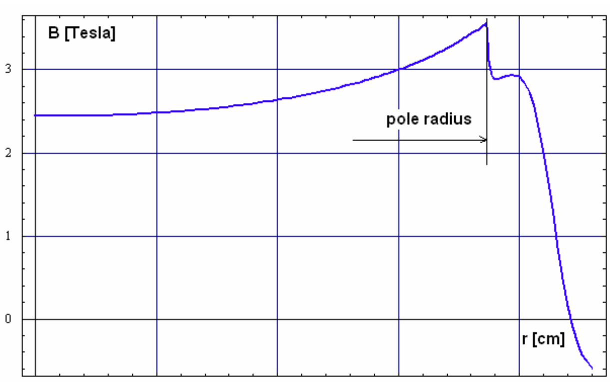

Figure 1: Average magnetic field of C400 cyclotron.

It is possible to extract beam by means of one electrostatic deflector (which is located in valley between sectors) with 140 kV/cm field strength inside.

A number of simulations concerning an improvement of the magnetic field focusing properties and optimization of the deflector position and septum thickness were carried out in order to reduce the beam losses before and during the extraction. Simulations show that the acceleration and the extraction of $^{12}C^{6+}$ along spirals seems as more preferable (smaller field strength in deflector is required and less particles are lost in the deflector).

Finally, septum of the deflector (septum thickness – 0.3mm and deflector aperture – 3mm) was located on radius 180.2cm for this tracking. Under these conditions the total losses just before extraction are 31.6% (28.1% - septum losses and 3.5% - axial losses). We consider the ion to be lost in axial direction if its axial coordinate exceeds 6mm from median plane of the cyclotron. Beam portraits at the deflector entrance are presented in Fig. 2.

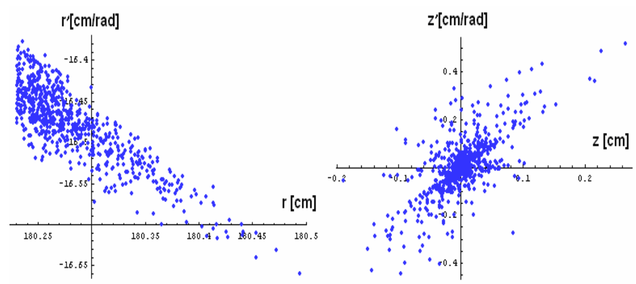

Figure 2: Beam portraits at the deflector entrance.

Transverse beam emittances at the deflector entrance are: $\varepsilon_r \approx 0.25\pi$ mm•mrad, $\varepsilon_z \approx 0.8\pi$ mm•mrad, beam average energy W ≈400.7 MeV/amu, energy spread is of about ±0.1%.

Proton beam

Extraction of the protons supposed to be done by means of the stripping foil. Main purpose of the preliminary computations was a definition of the minimal values of the protons energy which could be provided by the 1-turn and 2-turn schemes of extraction.

It was found that 320 MeV is the minimal attainable energy of protons which can be extracted during 1-turn after the stripping foil and 260 MeV is the minimal energy of protons for 2-turn extraction. The last variant was chosen as optimal one because of the energy of the 2-turn extracted protons is essentially closer to the usually used energy for the proton beam treatment.

A set of computations was carried out to optimize the extracted protons trajectory (to avoid a penetration of the protons beam into a cryostat during 1st turn of extraction). Optimal position of the stripping foil was found: R=160cm, φ=53° (see Fig. 3).

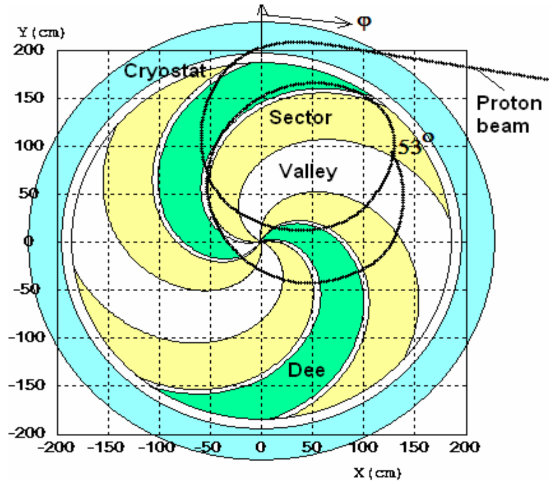

Figure 3: Extraction trajectory of the 260 MeV proton beam.

OPTIMIZATION OF THE EXTRACTION OPTICS

Modelling of action of the different focusing elements in both carbon and proton extraction systems was carried out to avoid the beams large divergence during the extraction. Necessity of precise two beams alignment at ~3 m from the cyclotron just before an energy degrader providing the ~1-2mm beam spot at this point for the both beams was taken into account.

During these simulations attempt to use partly the same extraction channel for the both beams was done. The results showed that in this case it was impossible to provide the acceptable beam spots before the degrader and the beams had also rather large transverse size (sometimes up to 6-8cm) during the extraction. Therefore, the extraction of the carbon and proton beams by the separate channels and further their alignment by the help of the bending magnets outside the cyclotron was chosen as the acceptable variant (see Fig. 4).

In these simulations the passive magnetic elements (correctors) are supposed to be used inside the cyclotron and the active current elements (quadrupole lenses and bending magnets) – to be used outside the yoke. Results of these calculations are presented below.

Carbon beam

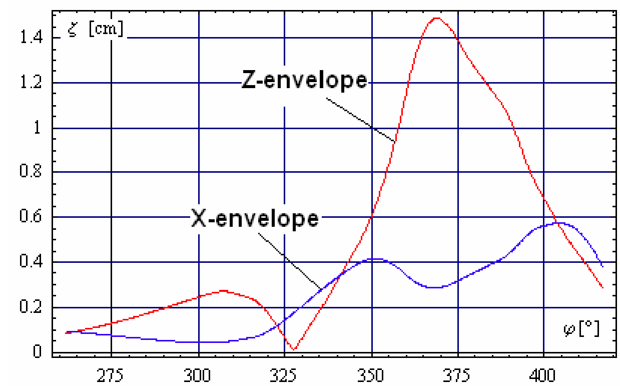

Figure 5: Carbon beam RMS envelopes inside the cyclotron.

Carbon beam size inside the cyclotron is not larger than 3cm (see Fig. 5). It is possible to provide such transverse beam size using the magnetic elements with quadrupole component of the magnetic field for the beam focusing. The required component is not more than 23 T/m.

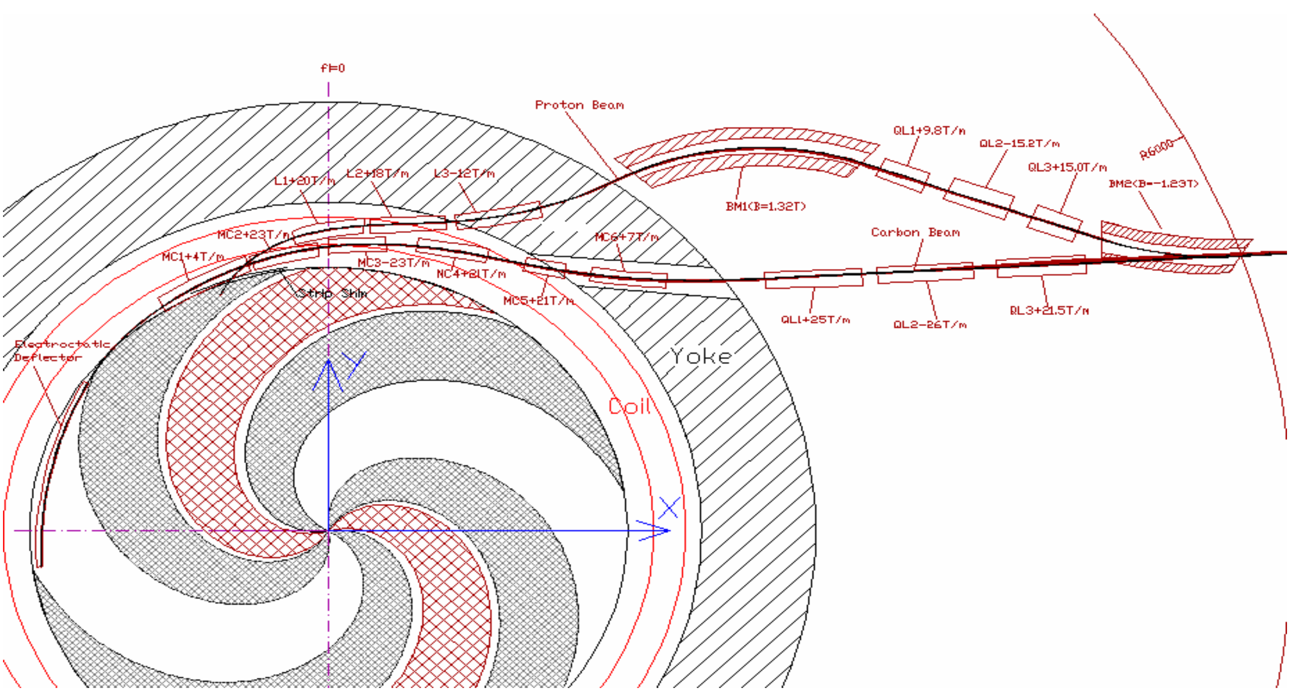

Figure 4: Plan view of the carbon and proton extracted beams and of the elements of extraction lines (proton beam is shown from the pole edge.

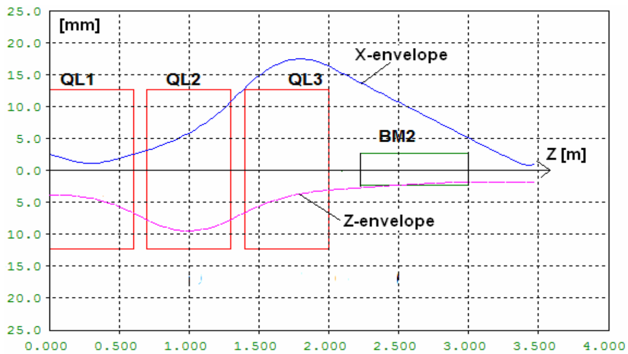

Figure 6: RMS carbon beam envelopes outside the cyclotron. Z is a length of the beam way from the entrance into the first lens QL1.

Use of the quadrupole lenses triplet (with gradients not more than 26 T/m) provides the carbon beam spot size in front of the energy degrader ~3mm (see Figs. 6, 7).

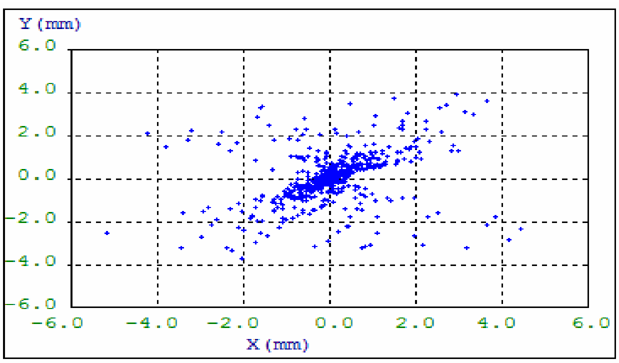

Figure 7: Carbon beam portrait on transverse plane just before the energy degrader.

Beam emittances at this point are equal to: ε_x=9.6π mm•mrad, ε_y=4.8π mm•mrad. The emittances of the carbon beam have an essential growth during the extraction inside the cyclotron (see Fig. 8). This growth occurs mainly due to the nonlinearities of the edge magnetic field in azimuth range (360-380)°. Use of the elements with sextupole component of the magnetic field in order to avoid such growth will be studied in the near future.

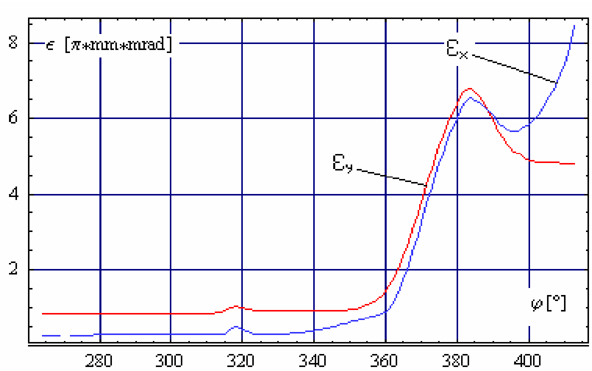

Figure 8: RMS emittances of the carbon beam during the extraction in the cyclotron (final point of computation is located at exit from the return yoke)

Proton beam

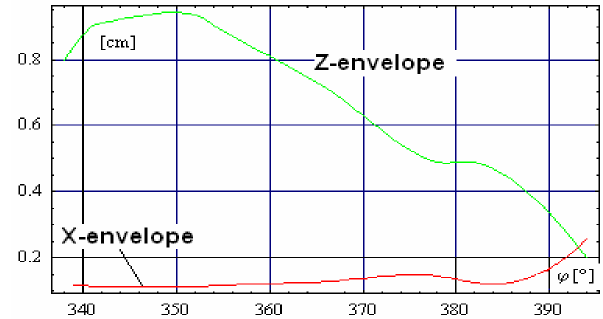

Figure 9: RMS proton beam envelopes inside the cyclotron.

Proton beam size inside the cyclotron is not larger than 2cm (see Fig. 9). It is possible to provide such beam size using the correctors with not more than 20 T/m gradients inside them.

Two bending magnets with magnetic field ~1.3 Tesla and a triplet of the quadrupole lenses (with gradients not more than 16 T/m) were used to align proton beam to carbon one and to focus proton beam before entrance to the energy degrader (see Fig. 10). Edge focusing of the bending magnets was also used in this case.

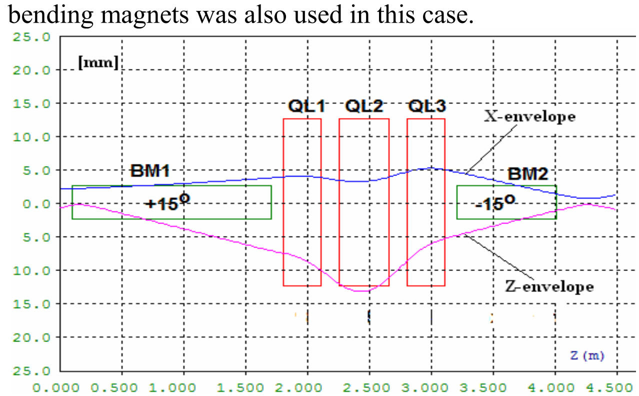

Figure 10: Proton beam RMS envelopes outside the cyclotron. Z is a length of the beam way from the entrance into the first Bending Magnet.

Proton beam emittances before energy degrader are equal to ε_x=4.5π mm•mrad, ε_y=3.2π mm•mrad.

CONCLUSIONS

Possibility of the extraction of the carbon ions by means of electrostatic deflector (E=140 kV/cm) and protons by the help of $^2H^+$ ions stripping was approved by the simulations.

Parameters of the extraction systems for both beams which provide the beams focusing and alignment to each other were determined as well.

REFERENCES

[1] G.Karamysheva et al., “IBA C400 Cyclotron Project for Hadrontherapy”, this conference.