Report of the Design and Development of Compact High-Temperature Superconducting Skeleton Cyclotron (HTS-SC)

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A compact high-temperature superconducting skeleton cyclotron (HTS-SC) was proposed to produce a high intensity H^+ beam for accelerator-based multi-port Boron Neutron Capture Therapy (AB-mBNCT) system [1] and the production of medical radioisotopes (RI). HTS-SC is a unique air-core cyclotron to avoid any residual magnetization as well as iron saturation that usually occurs around 2 T. Besides, the linear relationship between coil current and the magnetic field strength also provides an easy calibration of the magnetic field to accelerate different species of ions for multiple purposes. In addition, high-temperature superconducting (HTS) coils were used to ensure a stable operation with an elevated cooling condition in a hospital environment.

HTS-SC is a compact K-80 cyclotron with a small extraction radius of 40 cm for a 50 MeV H^+. It consists of a series combination of circular high-temperature superconducting (HTS) coils, acting as the main coil (MC) and trim coils (TC), stray-field shield coils (SSC), harmonic coils (HC), and 3 sector coils with a maximum spiral angle of 40°. The isochronism of the magnetic field was determined by various static orbit analysis. The latest magnetic field distribution for the acceleration of H^+ is shown in Figure 1.

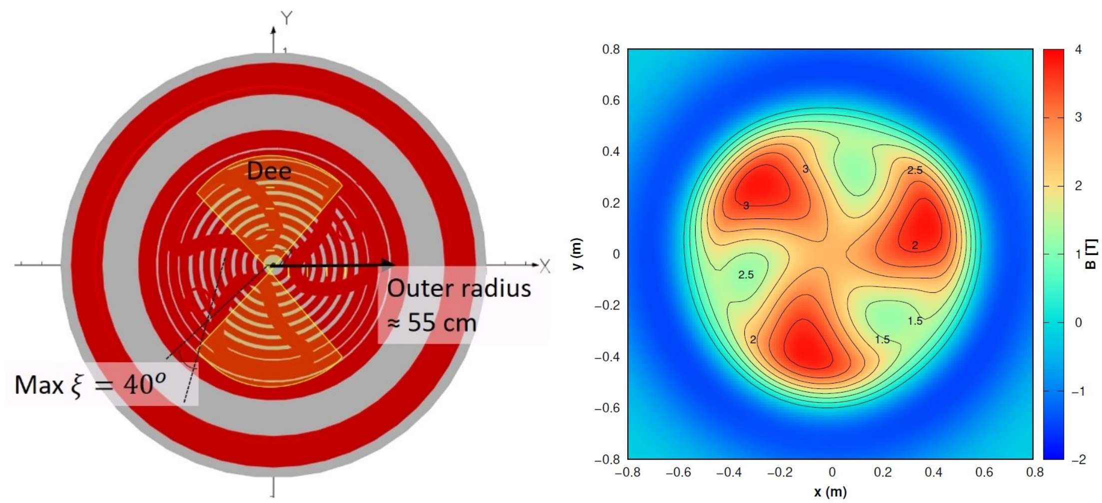

Figure 1: Top view of HTS-SC and the corresponding magnetic field distribution at median plane.

As a high-intensity beam is the key requirement for this machine, suppression of the space charge (SC) effect to achieve a satisfactory beam quality have been challenging in this work. Therefore, extensive beam dynamics were performed using particle-in-cell (PIC) codes such as SNOP [2] and OPAL [3]. Special attention were given at injection and extraction, where the eigenelipse and beam condition varied and beam loss was usually severe. In the central region, a spiral inflector with a high bending number, k=1.6 was adopted. The beam emittance and injection energy are maximized during injection to minimize the SC effect. Overall, a satisfactory beam transmission of more than 20% is achieved for a 10 mA beam. Upon passing the injection phase, the transmitted particles were accelerated smoothly without excessive beam loss until extraction. Electrostatic extraction was adopted in this work to prevent excessive particle loss due to Lorentz stripping under a high magnetic field. Precessional extraction (PE) was adopted in order to increase the turn-separation by a pair of harmonic coils, with its amplitude carefully optimized to maximize the extraction efficiency. As a result, PE was able to achieve a maximum extraction efficiency of almost 100% for a low-intensity beam and $> 80\%$ for a monoenergetic 1 mA beam. If the energy gain per turn was further increased from 80 to 100 kV, the maximum extraction efficiency of 1 mA beam can be further enhanced to $> 90\%$ using multi-turn extraction. On top of this, a preliminary design of the extraction beamline using gradient correctors was also investigated to ensure a complete extraction from the main field. Finally, this work concluded the feasibility of HTS-SC to inject, accelerate and extract high-intensity H^+ beam for AB-mBNCT and RI production.

References

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