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# OPERATION WITH THE LAPECR3 ION SOURCE FOR CANCER THERAPY ACCELERATORS*

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*Abstract*

An all-permanent magnet electron cyclotron resonance ion source-LAPECR3 (Lanzhou All Permanent magnet Electron Cyclotron Resonance ion source No.3) had been developed as the $C^{5+}$ ion beam injector of Heavy Ion Medical Machine (HIMM) accelerator facility since 2009 in China. The first HIMM demo facility was built in Wuwei city in 2015, which had been officially licensed to treat patients in early 2020. The facility has been proven to be very effective, and more than 1400 patients have been treated so far. In order to prevent ion source failure, each facility employs two identical LAPECR3 ion sources. At present, there are eight HIMM facilities are under construction or in operation, and more than 16 LAPECR3 ion sources were built. In order to improve the performance of the ion source for long term operation, some techniques were employed to optimize source performance and to avoid the damage of key equipment. This paper will introduce the operation status of LAPECR ion sources at these HIMM facilities and present the latest results of carbon beam production.

## INTRODUCTION

Carbon ion radiotherapy, with its unique Bragg peak, good Relative Biological Effect (RBE) and higher Liner Energy Transfer (LET), is considered to be one of the best tumour treatment methods and has developed rapidly in recent 30 years. Since the heavy ion medical accelerator in Chiba (HIMAC) at the National Institute of Radiological Sciences (NIRS) was constructed as the first medical dedicated heavy ion accelerator in 1994[1], many countries began to developed their own medical accelerator as a high-tech medical instrument. Researchers at Institute of Modern Physics (IMP) in China started carbon irradiation research since 1996. The first medical carbon ion irradiation accelerator in China, which was named Heavy Ion Medical Machine (HIMM), was constructed in Wuwei city in 2015[2]. The schematic layout ot HIMM facility as showed in Fig. 1. Since the first HIMM facility was officially permitted to clinical treatment in March 2020, more than 1400 patients have received carbon ion radiotherapy.

So far, there are 8 HIMM facilities either in operation or under construction in China, and more than 16 LAPECR3 ion sources were built. These facilities are distributed in Wuwei, Lanzhou, Putian, Wuhan, Hangzhou, Nanjing, Changchun and Jinan separately.

Although the first demonstration facility in Wuwei city has achieved remarkable results in the past 7 years, there were some problems which affected the routine operation of the accelerator. For example, the carbon contamination leads the instability of the beam, short the lifetime of the ion source. In the early operation of HIMM facility, the performance of the ion source has degraded significantly after one mouth operation. The beam intensity and the beam stability were decreased. Besides, the insulator ceramics of the ion source could damage sometimes and the ion sources could not sustain any more. In order to solve the problems, continuous work had been carried out. This paper will illustrate the operation status of LAPECR ion sources in the HIMM facilities and present the latest results of carbon beam production.

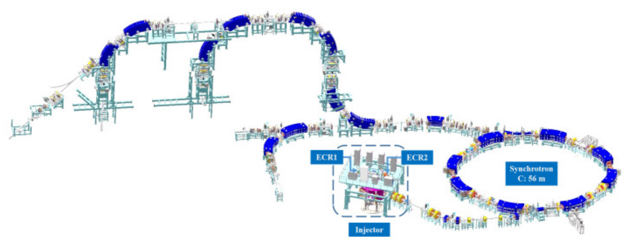


Figure 1: Schematic layout of HIMM facility.

## LAPECR3

According to the requirements of ion source applications, the LAPECR series ion sources were developed successfully at IMP [3], including the LAPECR1 ion source for light ion application, the LAPECR2 for atomic physics research and the LAPECR3 ion source which was dedicate designed for carbon irradiation. Table 1 presents the key parameters of these ion sources. The LAPECR series ion sources were designed to operate at 14.5 GHz, and the magnetic field was generated from permanent magnet to lower the power consumption and easy to maintain. The LAPECR3 ion source features as compact size and high performance, the requirements of the ion source are to produce intense carbon beams with better beam emittance, such like more than 100 eμA of $C^{5+}$ and more than 300 eμA of $C^{4+}$. So, an iron plug was adopted in injection side of the LAPECR3 ion source to enhance the injection field. To optimize the microwave coupling, a movable bias disc was designed with adjusting distance of ±5 mm. Moreover, a movable extraction puller electrode, which consists of a Mo head and a stainless-steel base, was employed to optimize the beam extraction. It is necessary to use a bigger ceramic to improve the gas flow conductance at the extraction region. Besides, the plasma chamber was made from stainless-steel with good water cooling, which allowed

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maximum power feeding of 650 W. Microwave was directly feed into plasma chamber with WR62 wave guide. Figure 2 gives the structure of the LAPECR3 ion source.

Table 1: Key Parameters of LAPECR Series Ion Sources

| Species | LAP-ECR1 | LAP-ECR2 | LAP-ECR3 |
|---|---|---|---|
| RF | 14.5 | 14.5 | 14.5 |
| $B_{inj}$ | 1.4 | 1.25 | 1.8 |
| $B_{min}$ | 0.35 | 0.42 | 0.4 |
| $B_{ext}$ | 0.7 | 1.07 | 0.9 |
| $B_{rad}$ | 0.9 | 1.2 | 1.14 |
| $L_{mirror}$ | 78 | 255 | 170 |
| $L_{ecr}$ | 46 | 100 | 64 |
| $D_{chamber}$ | 40 | 67 | 50 |
| Dimension | Φ202*210 | Φ650*560 | Φ450*380 |
| Application | Light ions | Multiple ions | Carbon therapy |

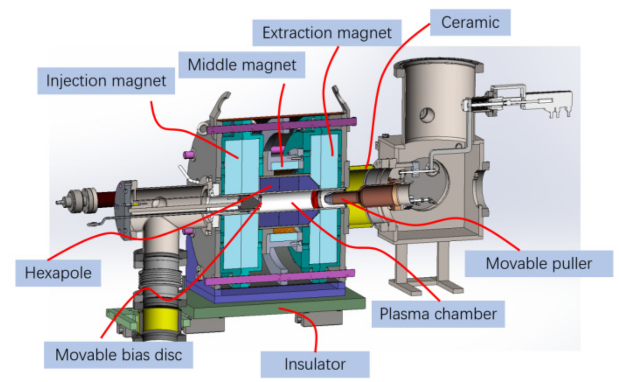


Figure 2: Structure of the LAPECR3 ion source.

There are totally 16 LAPECR3 ion sources was built to employed in 8 HIMM facilities so far, and the new ion source was upgrade from the old version according to the experience of operation.

## OPERATION STATUS

The first HIMM facility has been used to treat patient for about 4 years. There were many failures were found in the early operation, including the shutdown of the microwave generator and high voltage supply, also frequent discharges in the extraction area were found. The failure was finally verified to be caused mainly by two reasons. Firstly, some equipment of the ion source system is easy to be affected by the others. For example, due to the interference caused by the other equipment, sometime the microwave signal interrupt abrupt resulting in the microwave amplifier fault. Another is the imperfect interlock between the high voltage power source and the vacuum gauge, which lead to occasional shut-down of the high voltage power supply.

Some methods were taken to avoid these malfunctions. An improved microwave signal generator has been employed to resist electromagnetic interference. And a time delay has been adopted to judge the reality of interlock signal. The recent operation status of the ion source indicates that the main problems of the equipment has been resolved.

In addition, the clear gas $CH_4$ was fed to the plasma chamber as working gas to enhance the stability of the plasma, which also reduced the pollution of the chamber significantly and consequently increase the operation time of the ion source. Since the employment of methods above, LAPECR3 ion source could remain stable operation for 3 months and no malfunction occurred.

Moreover, with the help of a signal generator to modulate the time structure of microwave, the LAPECR3 ion source has successfully tested with afterglow mode, which was hoped to decrease the duty cycle of the ion source operation while with comparable or even higher output ion current and hence reducing the carbon pollution in the plasma chamber. The test results as shown in Fig. 3, the maximum peak current of $C^{5+}$ reached to 180 eμA while the beam current of 24 eμA at the steady stage. The pulse repetition rate was set to 10 Hz with the duty cycle of 50% for the microwave. The result demonstrates the possibility of the afterglow mode applied in the routine operation of LAPECR3.

In order to extend the lifetime of the ion sources in HIMM facility, the afterglow mode operation was adopted in 2021 year in HIMM-WUWEI, the lifetime of the ion source was extended significantly. Now, the maintenance interval of the ion source exceeds 200 days, and the LAPECR3 ion sources could supply ion beam for more than 8500 hours per year.

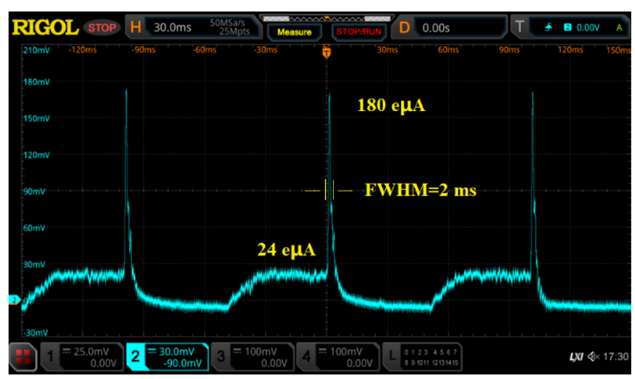


Figure 3: Afterglow mode test on $C^{5+}$ ion beam.

## LATEST RESUTLS

In 2023, China 's 2nd generation carbon ion radiotherapy accelerator start to designs, which requiring the ion source to provide more than 1 emA of $C^{4+}$ ion beam for accelerator injection. In order to meet the requirements of the new facility, the production of intense current $C^{4+}$ ion beam was systematically studied on a dedicated test bench.

In order to improve the extraction current of the ion source, a high extraction voltage needs to be applied. Figure 4 shows the dependence of the extraction high voltage and the extraction gap on $C^{4+}$ beam current. It can be seen that $C^{4+}$ beam current increases with the extraction voltage improving; In addition, the extraction beam intensity can also be well adjusted by changing the extraction electrode gap. Finally, more than1 emA of $C^{4+}$ ion beam was obtained at 32 kV extraction voltage and a 26 mm extraction gap.

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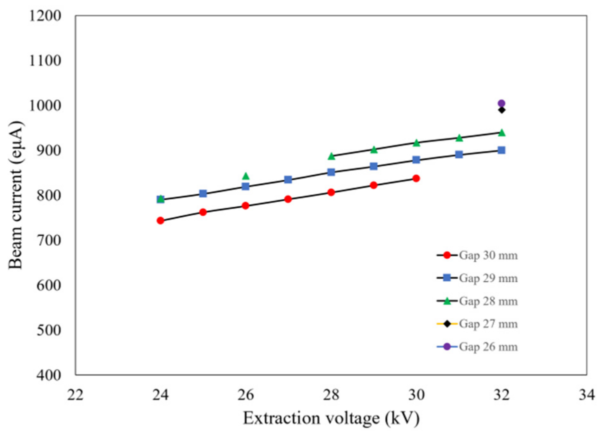


Figure 4: $C^{4+}$ beam current versus extraction high voltage with different extraction gap.

With the purpose of investigating the impact of the extraction high voltage on the beam emittance, the $C^{4+}$ beam emittance versus the extraction high voltage has been measured as shown in Fig. 5. Easy to see that with the in-crease of the extraction voltage, the emittance of the $C^{4+}$ beam does not growth, which indicates that the high voltage extraction mode is beneficial to the beam transportation.

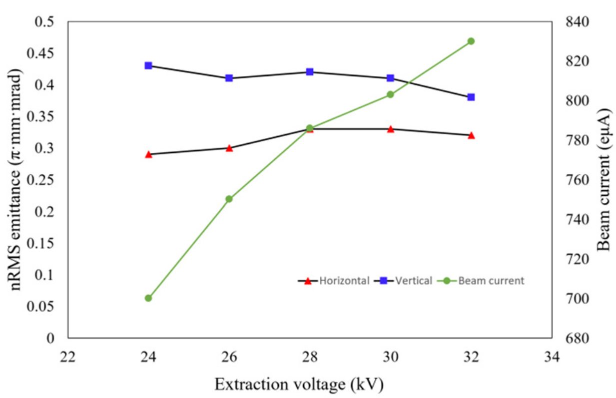


Figure 5: $C^{4+}$ beam emittance versus extraction high voltage.

The beam emittance go against the requirement of the ion source in the 2nd generation carbon therapy accelerator, works should be carried out to reduce the growth of the beam emittance. It is better to use a higher performance ion source to supply such intense carbon beam, a hybrid superconducting ion source should be a good candidate. There will be enough space to design a highly efficient beam extraction system for intense carbon beam, it could be expected that the beam emittance could be limited to an optimal value.

## CONCLUSION

Based on the 10 years development of the LAPECR3 ion source, the lifetime and the performance of the ion source has improved significantly. Continuous work should be carried out to reduce the carbon contamination and to im prove the beam stability.

## ACKNOWLEDGEMENT

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