RECENT PROGRESS OF A CW 4-ROD RFQ FOR THE SSC-LINAC*

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Abstract

The SSC-LINAC is under design and construction as a linear injector for the Separated-Sector Cyclotron (SSC) of the Heavy Ion Research Facility at Lanzhou (HIRFL). The continuous-wave (CW) 4-rod radio-frequency quadrupole (RFQ) of the SSC-LINAC has important progress in past years. In the autumn of 2016, the cavity has been operated with 35 kW on CW mode in automatic RF controlled mode during RF power commissioning, which is needed to accelerate $^{238}U^{34+}$ beams. The beam transmission efficiency, transverse emittance and energy spread has been obtained in beam commissioning. In this paper, the results of experiments will be presented and discussed in detail.

INTRODUCTION

To achieve excellent performance in nuclear and atomic physics, the Heavy Ion Research Facility in Lanzhou (HIRFL) was upgraded with a multifunctional Cooler Storage Ring (CSR) at the end of 2007 [1]. As the only injector of the HIRFL, the Sector Focusing Cyclotron (SFC) is needed to provide ion beams for the Separated Sector Cyclotron (SSC) and the CSR. The SSC has to be shut down when the SFC provides the beams to the CSR, which results in the low utilization of the HIRFL. Furthermore, several new experiment such as the Super Heavy Elements (SHE) and precise mass measurement experiments have a higher beam current requirement, which cannot be satisfied by the SFC. To solve these problems, a room-temperature heavy ion linac called SSC-LINAC was proposed as a new injector of the SSC to replace the SFC [2], as shown in Fig. 1. The SSC-LINAC mainly consists of a superconducting high-charge-state electron cyclotron resonance (ECR) ion source, a low energy beam transport (LEBT) system, a CW 4-rod RFQ, a medium energy beam transport (MEBT) system, three IH-DTLs and a high energy beam transport (HEBT) section [3].

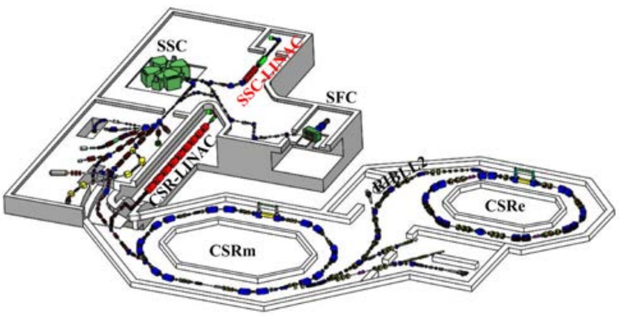

Figure 1: Layout of the HIRFL with the SSC-LINAC.

As a critical component of the SSC-LINAC, the RFQ is required to accelerate intense beams and operate in CW mode, which was the greatest challenge. In beam dynamics, a quasi-equipartitioning design strategy was applied to control the emittance growth and beam losses caused by intense beams [4]. The main parameters of the RFQ are listed in Table 1. The thermal analysis and cooling design have been done carefully by the CST [5] code. A bottom plate, 12 stems and 4 mini-vanes are all cooled by deionized water to ensure security and reliability of the CW mode operation [6].

Table 1: Main Parameters of the SSC-LINAC RFQ [4]

Parameters	US Letter Paper
Frequency	53.667 MHz
Ratio of Charge to Mass	1/3~1/7
Beam Current	0.5 pmA
Duty Factor	100%
Input Energy	3.728 keV/u
Output Energy	143 keV/u
Inter-Vane Voltage	70 kV
Vane Length	2.508
Transmission efficiency	94.1%

The SSC-LINAC has important progress in past years. The cavity was delivered to the Institute of Modern Physics (IMP) in the first season of 2013. The RF performance measurement, including the frequency, quality factor Q_0 and the electric field distribution, was finished in 2014. Then, the commissioning with high RF power and ion beams has been finished. In this paper, the RF power and beam commissioning are reported. The experimental setup for the RFQ test is depicted in Fig. 2.

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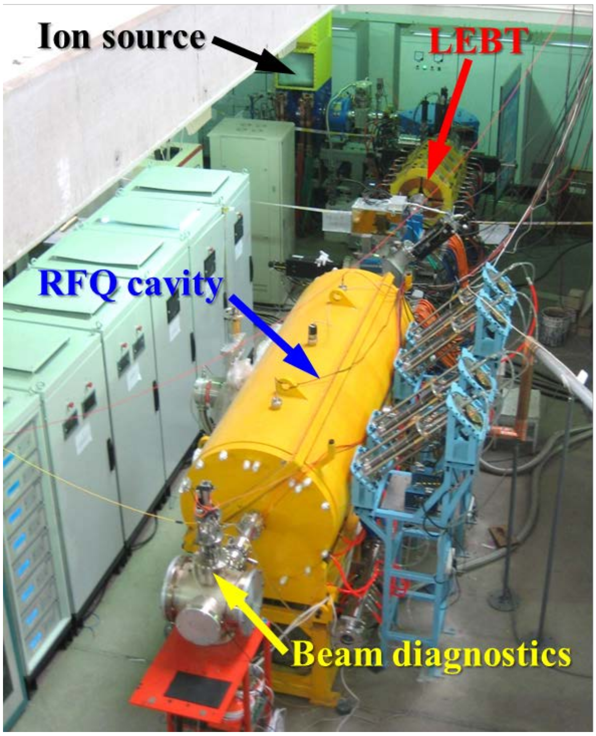

Figure 2: Overview of the RFQ test area.

RF POWER COMMISSIONING

The main goal of the SSC-LINAC RFQ high power commissioning is the demonstration of RF features and stable operation of the 4-rod RFQ in automatic RF controlled mode.

The commissioning began from pulse mode with a 5%. duty factor. The amplitude of the pulse power of the cavity and the pulse length rise gradually without any serious sparking and vacuum troubles. In the first season of 2015, the cavity has been operated with 35 kW on CW mode with the vacuum under 5.0×10^{-5} Pa. According to the experimental results of the bremsstrahlung spectrum [7] emitted from the electrodes, a 35-kW power is needed to generate a 70-kV inter-vane voltage for accelerating beams with the ratio of charge to mass of 1/7 such as $^{238}U^{34+}$.

The frequency shift and water temperature are monitored during the high-power test on CW mode. As shown in Fig. 3, the temperature of the output cooling water raised gradually when the RF power increased. The RFQ cavity operated on 35-kW CW mode with the maximum temperature increment of 7.0°C. The temperature of the inlet water had a temperature fluctuation as shown in the blue curve of Fig. 3, because the cooling water comes from an air-cooling system. Figure 4 shows that the resonance frequency decreased linearly with the RF power of the cavity during the CW mode operation. A linear fitting method was used to analyse the relationship between the resonance frequency and RF power. The fitted rate of the frequency shift is -2.58 kHz/kW. The shift will be tuned by automatic RF controlling system with four plungers, so that the RFQ can operate with a stable resonance frequency.

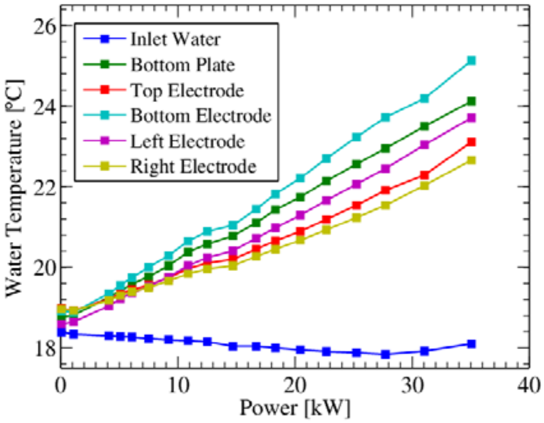

Figure 3: Temperature of the deionized water at the water outlet port except the inlet water.

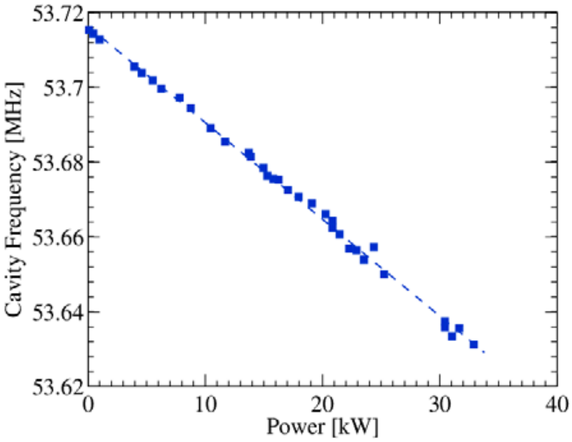

Figure 4: Frequency shift caused by the increasement of the RF power without tuning during CW operation.

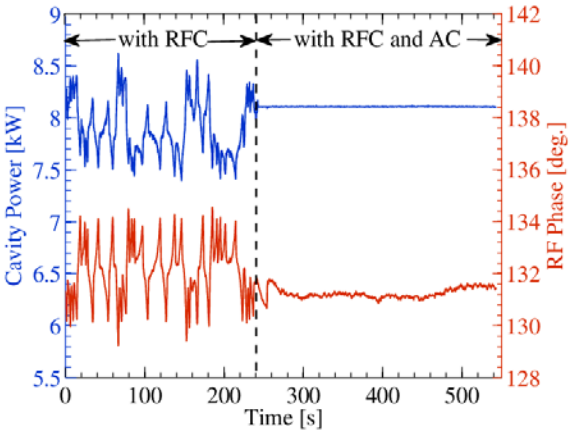

Figure 5: RF power of the cavity and RF phase during CW operation in automatic RF controlled mode.

The automatic RF controlling system consists of an automatic resonant frequency controlling (RFC) system and an automatic RF amplitude controlling (AC) system. The operation in automatic RF controlled mode was begun in 2014. The 4-rod RFQ was operated successfully with the

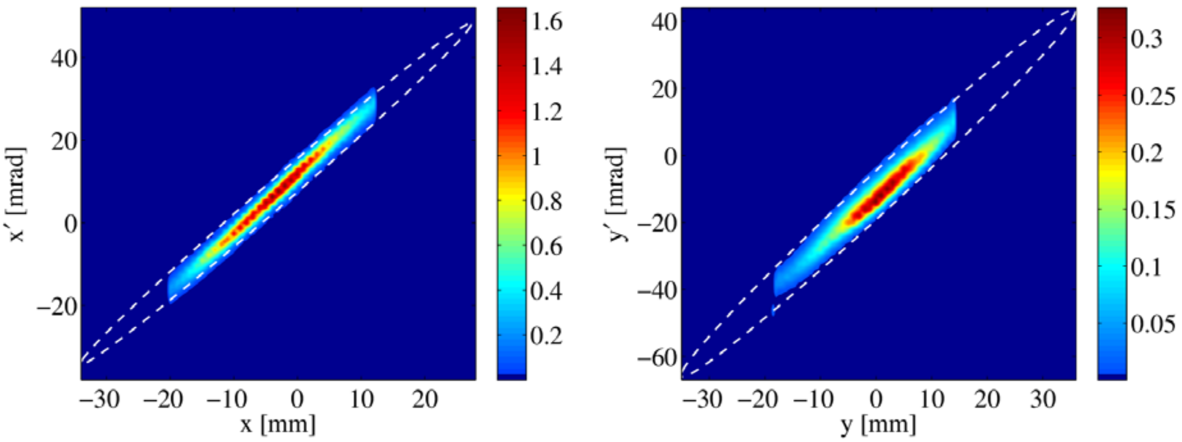

Figure 6: The horizontal (left) and vertical (right) phase space projection measured at the exit of RFQ. The color temperature map is the measured projection, and the white dashed line is the theoretical ellipse.

automatic RF controlling system in March 2016.Then, a 35-kW CW commissioning was finished in the autumn of 2016. Figure 5 represents the variation of RF power and phase with an 8-kW power. The power shift range of ±0.6 kW was achieved with the operation of the RFC system only. When the RFC and AC system were all operated, the RFQ operated stably with a power fluctuation of ± 4.2 W.

BEAM COMMISSIONING

After the RF power commissioning, the beam commissioning with the beam transmission efficiency, transverse emittance and energy spread measurement was performed on CW mode.

The transmission efficiency of 94% was measured by two faraday cups at the upstream and downstream of the RFQ, respectively. The beam energy of 142.78 keV/u was obtained by the time of flight (TOF) method. Both the transmission and beam energy satisfy the injection requirement of the downstream DTL.

The output transverse phase space projection for $^{16}O^{5+}$ beams were measured by two slit-wire type emittance scanners at the diagnostics station downstream of the RFQ. Figure 6 shows a preliminary measurement result. The measured normalized RMS emittance in the horizontal and vertical plane after RFQ are 0.23 πmm·mrad and 0.35 πmm·mrad, respectively. Because of large beam transverse envelopes due to have no quadrupoles at the RFQ exit, some beams cannot be accepted by emittance scanners, as shown in the color temperature map of Fig. 6. While, compared with the theoretical ellipse (see the dashed line in Fig. 6) there is still a good coincidence.

In the measurement of energy spread, combined beams with $^{12}C^{3+}$ and $^{16}O^{4+}$ ions were used for the reason of the calibration of the energy spread detector. Figure 7 represents the energy spectrum of $^{12}C^{3+}$ and $^{16}O^{4+}$. The measured full width at half maximum (FWHM) of the energy spread is approximately 7.5%.

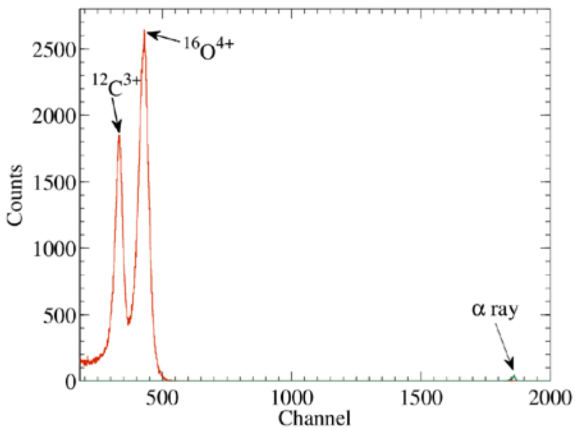

Figure 7: The energy spectrum of combined beams.

CONCLUSION

The RF power and beam commissioning of the SSC-LINAC have been finished at the IMP. The RF power commissioning demonstrated that the 4-rod RFQ for SSC-LINAC operated stably in automatic RF controlled mode with a 35-kW CW power. In the beam commissioning, the normalized RMS horizontal emittance of 0.23 πmm·mrad, vertical emittance of 0.35 πmm·mrad and FWHM value of the energy spread of 7.5% were obtained at exit of the RFQ. The results of commissioning can meet the requirement of the SSC-LINAC project.

In the near future, the accurate measurement of the emittance will be performed with a triplet at the RFQ exit, and the beam tests with a higher charge-to-mass ratio such as $^{238}U^{34+}$ are desired.

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