A TWO-METER LONG RFQ FOR THE DIRECT PLASMA INJECTION SCHEME AT IMP*

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Abstract

A RFQ has been designed and built for research of direct plasma injection scheme (DPIS), which can provide high current and highly charged beams. Because of the strong space charge forces of beam from laser ion source, the beam dynamics design of the RFQ was carried out with the RFQ design code LINACSrfq which gives control over all RFQ parameters, including the space charge physics. Another feature of the RFQ is its high energy gain in two-meter long which will be described in detail. Construction of the RFQ cavity and a 100 MHz/250 kW amplifier has been completed. A laser ion source is being tested. The assembling of the whole system including the ion source, the RFQ, the beam analyzing and diagnostic system is being done. Preliminary test results will be presented.

INTRODUCTION

Laser ion source (LIS) can produce many kinds of ion beams by laser light hitting solid targets, and it is the source of high intensity (up to ~100 mA C^{4+}), short pulse length (~10 μs), and desirable pulse repetition rate (~1-10 Hz), which well meets the requirement of single-turn and single-pulse injection of synchrotrons[1]. Usually, there is a low energy beam transport (LEBT) line between ion source and RFQ for beam transmission and emittance match, but there is always strong space charge effect due to the low energy and highly charged states of the beam. To eliminate the space charge effect in LEBT and to improve the emittance match a new acceleration scheme, direct plasma injection scheme (DPIS), was proposed by M. Okamura through a RIKEN-CNS-TIT collaboration, in which LIS and RFQ are connected together directly without LEBT [2]. As a R&D program which is dedicated to researches of a compact carbon ion cancer therapy machine and intense heavy ion beam injection for Cooler-Storage-Ring of the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR)[3], Institute of Modern Physics (IMP) have studied the DPIS since 2007. A two-meter long 4-rod RFQ designed for $^{12}C^{6+}$ has been built and tested, and a new LIS is being tested. Design and tests of the RFQ will be presented in this paper, and a RF amplifier designed for the RFQ will be introduced, too.

BEAM DYNAMICS DESIGN

Beam dynamics design of the RFQ was performed with LINACSrfq code [4]. The code has three distinct characteristics: First, it requires an equipartitioned condition at the end-of-shaper (EOS). When the beam is equipartitioned, there is no free energy in the degrees of freedom that could drive emittance growth. This strategy for having an equilibrium beam is very effective, especially for high current beams. Second, users can choose between a matched-only design strategy or an equipartitioning design strategy (or other strategies) for the main acceleration section of RFQ. The matched-only design strategy was finally adopted for the IMP RFQ design after comparing the two design strategies against the primary goal of achieving maximum energy within an RFQ length of 2 meters [5]; Third, the rules designed for synchronous phase, aperture and modulation parameter in the main acceleration section can be varied easily by changing the coefficients in them to meet design goals.

One requirement of the IMP RFQ is that its output energy should be as high as possible which was unknown at the beginning, and it was finally determined through many runs of LINACSrfq and comparisons. Beam dynamics design results are listed in Table 1 and plotted in Fig. 1-2 respectively.

Table 1: Main Parameters of IMP RFQ

Ion	$^{12}C^{6+}$
Frequency [MHz]	100
Input/output energy [MeV]	0.36 / 7.12
Current [mA]	20
Voltage [MV]	0.12
Minimum aperture [cm]	0.707
Modulation parameter	1-2.1
Synchronous phase	-90° to -20°
Transmission efficiency [%]	94.84
Electrode length [m]	2.0
Number of cells	100
Input trans. norm. RMS emittance [πmm mrad]	0.2
Output trans. norm. RMS emittance [πmm mrad]	0.3479

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From Fig. 1 we see that, to get as high energy gain as possible the synchronous phase Φ_s was pushed very hard from -90° to -20° in just 2 meters. This resulted in some beam synchrotron oscillation, which could cause beam loss and emittance growth. Fortunately a large minimum aperture a of 0.707 cm has ensured the high transmission efficiency. Although a larger output emittance was not avoided, the design requirements are still met. In addition, bigger longitudinal zero-current phase advance per period σ_{0l} leads to shorter RFQ length, but it should not exceed the transverse zero-current phase advance σ_{0t} in order to avoid a serious resonance. Therefore the rule of modulation parameter was tuned to make σ_{0l} approach σ_{0t} but not exceed, as shown in Fig. 2.

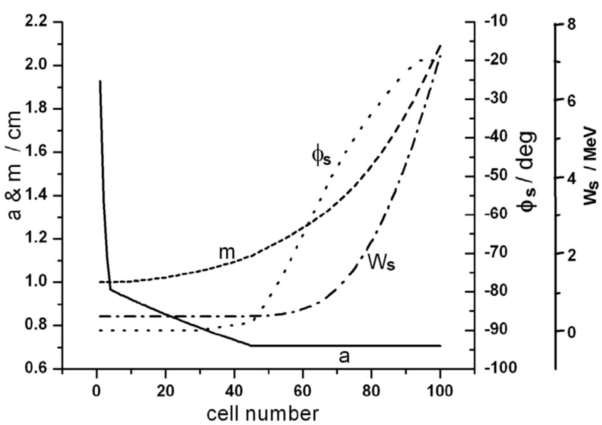

Figure 1: Plot of main parameters of IMP RFQ.

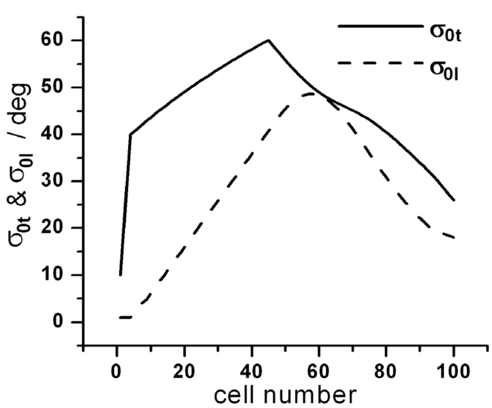

Figure 2: Plot of σ_{0t} and σ_{0l}.

The influences of changes of the input beam parameters, which are Twiss parameters α and β, transverse emittance, energy and current, on transmission efficiency of accelerated particles were investigated, and results are shown in Fig. 3-5.

Figure 3 shows that there are two small islands where the transmission efficiency is bigger than 94.67%, and the transmission efficiency is bigger than 92.2% in a large range of input α and β when the transverse emittance is matched. Figure 4 shows the relationship between transmission efficiency and input transverse emittance, from which we can see that the transmission efficiency is more than 90.0% as long as the input emittance is less than three times the matched value (0.0187 πcmrad in real). The influences of changes of input energy and current on transmission efficiency are shown in Fig. 5, which indicates that the transmission efficiency will be above 90% when the input energy is between 0.96 and 1.04 times the design value and the input current is between 0.5 and 2.5 times the design value.

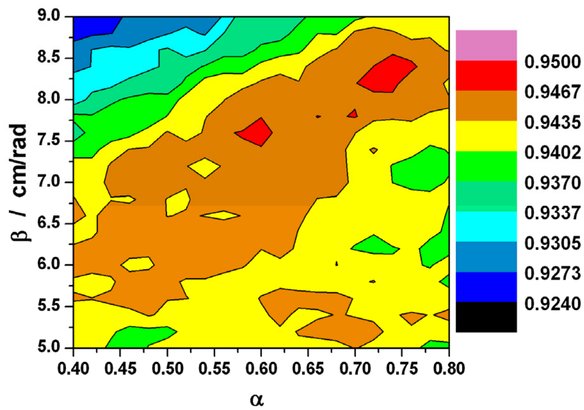

Figure 3: Transmission efficiency with different input α and β.

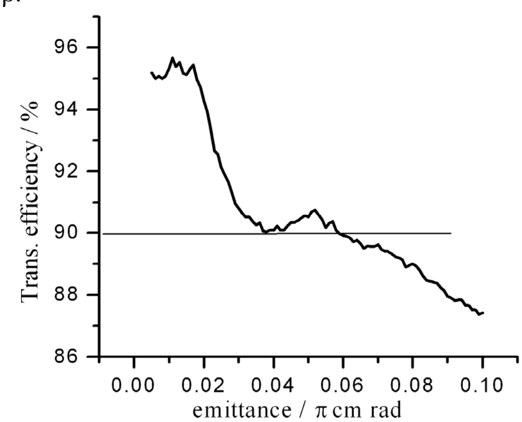

Figure 4: Transmission efficiency with different input emittance (in real).

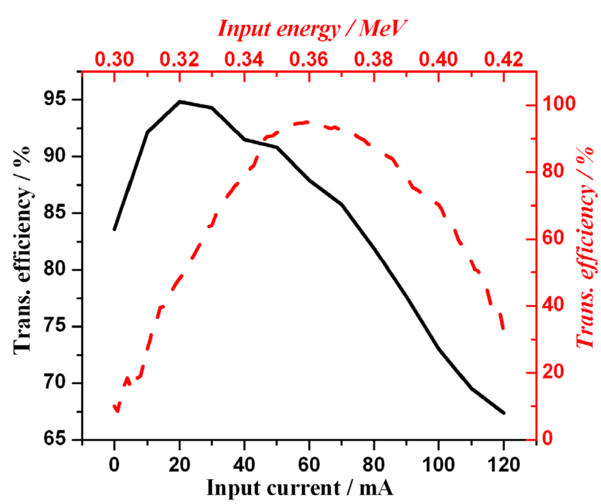

Figure 5: Transmission efficiency with different input current and energy.

According to the design results the RFQ is stable with respect to changes of the input beam parameters, and it can well accept and accelerate the input beams from LIS which has a high intensity and whose profile can change dynamically [6].

COLD MODE TEST OF RFQ CAVITY

The 4-rod RFQ cavity (as shown in Fig. 6) was designed, built and tuned by Neue Technologien GmbH & Co. KG (NTG) and IAP at Frankfurt, Germany, and shipped to IMP at April, 2010. But cold mode test and conditioning of the RFQ was carried out at a late time, June, due to the repair of coupler which was damaged during transportation. The contents of cold mode test are Q_0, shunt impedance and voltage distribution. For Q_0 the test is referred to '3 dB' method, however tests of shunt impedance and voltage distribution are based on perturbation principle, in which a small value of capacitor (e.g. 1 pF) is required. All the tests were carried out with a vector network analyzer, and the results are Q_0 being 4400 and shunt impedance being 84.3 kΩ (defined by $R=V_p^2/P$, where R is shunt impedance, V_p inter electrode peak voltage and P power loss in cavity) respectively. Voltage distribution was measured by placing the 1 pF capacitor on the 13 RF resonating cells along beam transfer direction, and result is shown in Fig. 7.

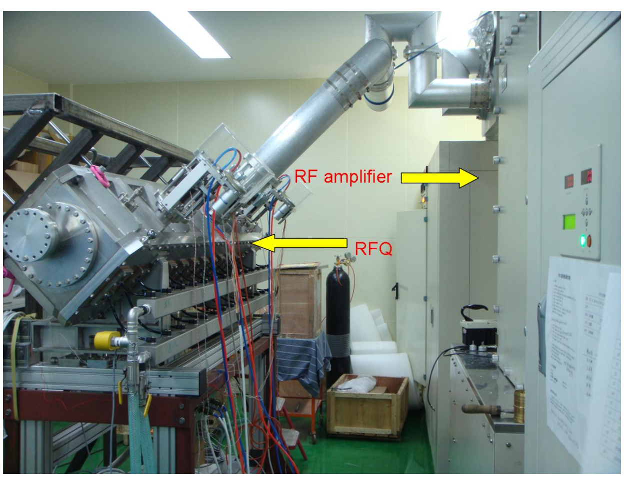

Figure 6: Plot of IMP RFQ and RF power supply.

CONDITIONING OF RFQ

Conditioning is done to clean the RFQ inner surface where may exist gas or other substances that affect beam transmission. Conditioning of IMP RFQ was done by applying a 250 kW pulsed RF power amplifier, whose maximum duty cycle is 5% and maximum pulse width is 500 μs. One function of the amplifier is that it can calculate the power fed into RFQ by sampling small amount of the power through directional coupler and then displays the value automatically.

IMP RFQ conditioning started at a very low power level, typically 10 W, and in CW mode with a CW low power amplifier, for which the 250 kW amplifier was substituted after reaching 200 W. The high power amplifier also started at a low power level (15 kW) with a duty cycle of 0.05%, and after 96 hours reached 180 kW which is needed to generate 120 kV voltage in RFQ, then the power had been kept for 12 hours to ensure conditioning is successful.

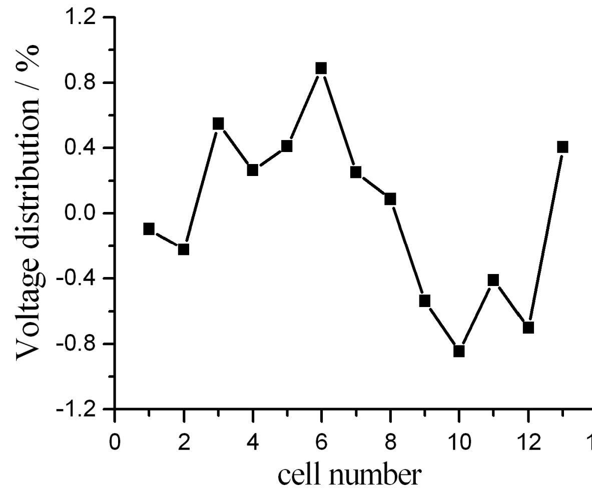

Figure 7: Voltage distribution of IMP RFQ.

CONCLUSION

A RFQ has been deigned and built for the DPIS at IMP, and according to the beam dynamics design results the RFQ is stable with respect to changes of input beam parameters, indicating it can well accept and accelerate beams from LIS. On arrival of the RFQ at IMP cold mode test and conditioning were implemented, and results show that the performance of the RFQ can meet the requirements of DPIS. At the same time a new LIS is being built which is supposed to be completed at the end of October, and at that time DPIS can finally be realized at IMP.

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