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DESIGN VALIDATION OF HIGH CURRENT INJECTOR FACILITY AT IUAC DELHI

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Abstract

High Current Injector (HCI) is an upcoming heavy ion accelerator facility at Inter University Accelerator Centre (IUAC), New Delhi, INDIA and it will serve as an alternative injector to the existing Superconducting Linear accelerator(SC-Linac). HCI is designed to achieve the maximum energy gain of 1.8 MeV/u for the ions, including the Noble gasses and metallic ions, having $A/q \leq 6$. It consists of an 18 GHz high temperature superconducting electron cyclotron resonance ion source, multi-harmonic buncher, Radio Frequency Quadrupole (RFQ), spiral buncher and six interdigital H-mode Drift Tube Linac (IH DTL) cavities operating at 97 Mhz resonant frequency. The RFQ accelerates the ions from 8keV/u to 180keV/u energy and the six DTL cavities are used to achieve the maximum energy gain of 1.8 MeV/u. Recently, the bunched beam of N^{5+} was successfully accelerated through RFQ and six IH-DTL cavities and we achieved the designed energy goal, which is an important milestone of this project. These results validated the design parameters of all RF cavities, accelerating to achieve the designed energy goal of 1.8MeV/u. Here, present status and future plans of the project shall be presented.

INTRODUCTION

HCI was envisaged to meet the requirement of higher beam intensity (tens of eμA) and provide almost all the ions from the periodic table including the Nobel and metallic ions to the existing beam time user [1-3]. Higher beam current intensity endorse the scientist to probe the low cross-section reactions processes. There is another possibility to produce the higher charge state from HCI and allowing higher energetic charged particle beams for the injection into SC-Linac. This project has been started early in 2005-06 including the design of a compact HCI building, beam optics, layout, prototyping of its major beam line components, indigenous development of RF cavities and their control systems. In this context, the low level RF and beam test of the individual RF components, installed in the beam line, have been carried out to check their performances and functionalities time to time. The commissioning of HCI up to first achromatic bending magnet was completed in the mid of 2019-20 in Beam Hall III at IUAC Delhi and it was kept ready for the beam acceleration and design validation of its energy gain. A control room was also established to keep an eye on all the parameters of individual system during the first beam test. After the installation of all beam line components up to the first achromatic analyser bending magnet, N^{5+} (A/q=2.8) beam was successfully accelerated and the first major milestone of this project was achieved in the year of 2021 in spite of having Covid-19 pandemic spread worldwide. In order to validate the designed energy gain from each of the RF cavities, N^{5+} beam was accelerated through all individual cavities one by one and the output energy gain was verified by applying the required analysing magnetic field. In this paper, the HCI design goals, major components, layout, beam test results, cavities performances during test, present status and future projections shall be discussed.

HCI DESIGN GOALS AND MAJOR COMPONENTS

HCI consists of mainly an 18 Ghz High Temperature Superconducting Electron Cyclotron Resonance Ion Source (HTSC-ECRIS), Multi-harmonic Buncher (MHB), 48.5 Mhz Radio Frequency Quadrupole (RFQ), 48.5 Mhz Spiral Buncher and six interdigital H-mode Drift Tube Linear Accelerator (IH-DTL) cavities operating at 97 Mhz resonant frequency along with the other beam line components like dipole and quadrupole magnets and associated beam diagnostic devices [4]. The final design plan and its 3D layout based on the calculated beam optics is shown in Fig. 1 and its major components are discussed here.

HTSC-ECR Ion Source

18 Ghz HTSC-ECRIS is one of its own kind of ion source covering almost all the ions from the periodic table up to U^{238}. It was developed with the collaboration of PANTECHNIK, France and IUAC Delhi, INDIA and known as a PKDELIS [5]. It produces the large amounts of highly charged positive ions and currents higher than those available from the existing Pelletron accelerator at IUAC. In the ECRIS, the plasma potential plays an important role in the optimization of longitudinal focussing and transportation of the beam through the HCI beam line.

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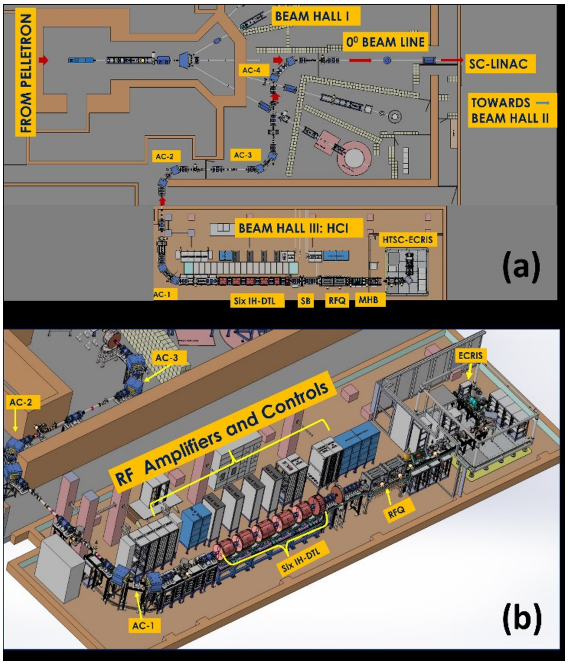

Figure 1: Schematics of (a)HCI design and (b) 3D layout.

High Voltage Deck and Beam Transport

The ion source, along with an analysing magnet, quadrupole lenses and steerers have been placed on a 200 kV high voltage deck. The source can be operated up to 30 kV extraction as per the requirement. By optimising the high voltage, analyser magnetic field (on deck) and accelerating columns parameters, the required beam energy (8keV/u) of the desired species can be obtained at the RFQ entrance.

Multi-Harmonic Buncher

The beam from the source is a continuous (DC) beam and any conventional RF accelerator may not be able to adiabatically bunch and accelerate the beam efficiently. MHB, operating at the fundamental frequency 12.125 MHz with its two higher harmonics (24.25 and 36.375 MHz), is used to bunch the DC beam up to 2 ns (FWHM) [6]. The bunched beam is focussed at RFQ entrance for further beam acceleration.

Radio Frequency Quadrupole

RFQ plays a significant role in the HCI for the double action namely beam acceleration and transverse focussing [7]. Here, the bunching is not done so efficiently by RFQ, then we have placed an external buncher (MHB) to reduce the length of the RFQ. The operational frequency of RFQ is 48.5 Mhz and it is designed to accelerate the ions from 8keV/u to 180keV/u energy and installed downstream to MHB. Bunching action of MHB increases the transmission efficiency of the RFQ by providing the bunched beam about 2ns (FWHM) at the RFQ input. 2.5 meter long RFQ consists of four-modulated rods having 70kV inter-vane voltage. It was found that the frequency is very sensitive to room temperature variations but could be controlled by regulating the flow of cooling water. A 120kW, 48.5Mhz (M/s. QEI Corp., USA) Tetrode vacuum tube based RF amplifier is used for powering the cavity. The RFQ cavity is already powered up to 40kW. At present, a new coupler is designed, fabricated and installed into the cavity to handle power up to 100kW.

Spiral Buncher

The spiral buncher installed upstream to first DTL cavity, is designed to further bunch the beam up to 1ns (FWHM) and match the longitudinal input parameters required at the entrance of first DTL accelerator. The spiral type open-ended quarter-wave $\lambda/4$ resonator is opted for bunching due to its high shunt impedance, mechanical and vibrational stability [8, 9]. It's frequency is 48.5 Mhz and was preferred due to having a larger longitudinal acceptance. SB requires maximum 1kW RF power to generate the desired gap voltage 80kV. To minimise the longitudinal beam emittance growth further in HEBT, two more SBs shall be installed during the commissioning of HCI beam line to SC-Linac.

Drift Tube Linear Accelerator

Finally, the time focussed beam coming out from the spiral buncher enters into six numbers of normal temperature IH-DTL cavities following the KONUS beam optics for further beam acceleration. DTLs are operational at 97 Mhz frequency and designed to accelerate the beam from 180keV/u to 1.8MeV/u [10]. The transverse focussing is performed using miniature quadrupole triplets installed externally between two consecutive DTL cavities whereas the longitudinal focussing is maintained by using the inbuilt integrated bunching section (first three RF gaps) in the DTL2-5 cavities. DTL cavities are operating in CW mode and such cavities are characterized by a high capacitive load contribution of the accelerating electrodes that provide the longitudinal electric field components for the beam acceleration. To minimize the electric capacitance of IH-DTLs, KONUS beam dynamics was adopted in design. The electrical design and simulation of DTL cavities has been done using CST Microwave Studio whereas the beam dynamics and generation of the drift tube geometry was carried out using the LANA code. The various characteristic parameters of the RFQ and DTL cavities are given in Table 1.

COMPACT BEAM DIAGNOSTIC SYSTEM

Transverse Beam Diagnostics

A compact beam diagnostics along with the conven-tional Faraday cup and beam profile monitors, were indigenously fabricated and installed to measure the current and profiles at the entrance of each of the DTL cavities to keep minimum space between DTL cavities and to avoid beam losses [11].

Longitudinal Beam Diagnostics

The beam needs to be focussed in time before the injection into the RFQ and DTL cavities. This task is performed using a multi harmonic buncher (MHB) and spiral

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Table 1: RF Cavity Parameters for HCI

Cavity Paramters	RFQ	DTL1	DTL2	DTL3	DTL4	DTL5	DTL6
Frequency (Mhz)	48.5	97	97	97	97	97	97
Cavity Length(m)	2.5	0.39	0.69	0.90	0.94	0.92	0.82
No. of RF Gaps	42	11	13	13	11	11	9
Designed E. Gain (MeV/u)	0.18	0.32	0.55	0.85	1.15	1.46	1.8
RF Power for $A/q \leq 6(inkW)$	80	5	11	18	18	24	25
RF Power for A/q=2.8(in kW)	17	1.1	2.4	3.9	3.9	5.3	5.5
Energy Gain for $(N^{5+})(MeV)$	2.5	4.5	7.7	11.9	16.1	20.4	25.2
Analysing Mag. Field $(N^{5+})(G)$	1906	2683	3517	4373	5086	5731	6364
E. Gain Validation	Validated	Validated	Validated	Validated	Validated	Validated	Validated

buncher.This was measured using Fast Faraday Cups (FFC) installed in HCI. One coaxial type FFC is installed downstream to RFQ whereas other stripline FFC is placed just before the first DTL cavity to measure the bunch length of accelerated beam. The bunch length at the entrance of first DTL was measured to be 1.6 ns during first (N^{5+}) beam test but the beam tuning optimization is underway for the further improvement.

BEAM TEST RESULTS AND DESIGN VALIDATION

The first beam test was planned in HCI for the acceleration of N^{5+} beam having A/q 2.8. The ariel view of HCI accelerator facility can be seen in Fig. 2. There were various RF power levels required for each of the cavity to achieve the designed acceleration voltages and energy gains. Since, high power RF conditioning of the RFQ and six DTL cavities were completed for this test in the early of 2021 and the cavities were kept ready for the beam acceleration. Maximum RF power required for RFQ and six DTL cavities to get the design energy gain for N^{5+} were calculated and shown in Table1.

Figure 2: Arial-view of HCI in Beam Hall-III.

HCI heavy ion beam accelerator facility was extensively tested with N^{5+} (A/q=2.8) beam in CW mode with all subsystems operational. The capability of RFQ and six numbers of multi-gap IH-DTL RF structures to accelerate N^{5+} beam are tested and verified as per the design value of energy gain. The energy gain by each of the RF cavities were analysed and verified one by one. The transmission efficiency for the accelerated N^{5+} beam by RFQ was found to be more than 90% whereas it was found from 75% to 90% for the DTL cavities. In order to increase the transmission efficiency by each of the RF cavities and analysed beam current intensity, we followed the iterative process of optimization of transverse and longitudinal beam tuning during the operation. We found that the phase and amplitude tuning of all RF cavities (MHB, RFQ, SB and DTLs) surely improves the beam transmission at the output. Though, the intensity of N^{5+} beam after the first achromatic bend was achieved with more than 150 enA in the first full beam line test but the beam tuning optimization is underway for further improvement in the beam transmission. The final output beam energy (1.8MeV/u) was confirmed by the analyzer magnetic field which was found very close to the theoretical calculation.

CONCLUSION

We found that N^{5+} beam was successfully accelerated through all RF cavities and we crossed an important milestone of this project after achieving the designed goal of 1.8MeV/u energy gain. The results validated the design features of all individual RF cavities and subsystems including the control system.

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