Table 1: Energy and RF parameters measured during acceleration of N^{5+} beam

	RFQ	DTL#1	DTL#2	DTL#3	DTL#4	DTL#5	DTL#6
Measured E (MeV)	**0.504**	**4.48**	**7.7**	**11.9**	**16.1**	**20.4**	**25.2**
RF Power (kW	**20**	**1.29**	**2.37**	**4.55**	**3.8**	**5.5**	**5.6**
Pick up from Cavity (mV)	**44.7**	**43**	**31**	**40.1**	**32.6**	**37.2**	**37.2**
Achromat B-field (G)	**1906**	**2683**	**3417**	**4277**	**4986**	**5631**	**6264**
Designed Energy (keV/A)	**180**	**320**	**550**	**850**	**1150**	**1460**	**1800**

(B) Testing of ceramic based high power RF coupler

To test the beam of higher A/q, the RFQ power coupler has been modified from the existing coupler which uses commercial CF35 feedthrough as an RF window with a custom-made coupler. The newly designed RF coupler (Figure 11) uses a specially designed 20 mm thick alumina of 100 mm diameter as an RF window. The ceramic is brazed with inner conductor and outer jacket that is made of ETP copper. The outer copper jacket is further brazed with SS304 ring that is finally welded with the CF150 stainless steel flange that attached to the RFQ chamber. Its water-cooled inductive loop can withstand up to 120kW power in CW operation at 48.5MHz. The coupling factor of the RF coupler insertion and rotation inside the coupling cell have been analysed using CST Microwave Studio for different effective loop areas. The shape of the loop has been adopted in order to increase the coupling coefficient. The loop is made of two concentric copper pipes one with a diameter of 12mm and the other of 6mm. The loop has several bends which were introduced in order to optimize the coupling coefficient. One end of the inductive loop is then brazed to the central conductor of the feedthrough and the other end is brazed on the rotatable CF150 flange of the coupling cell of the coupled RFQ cavity. Inside the loop and the feedthrough, water flowing at maximum 10 litres/min is used for the cooling of the loop surface as well as ceramic. After the leak test of the coupler, it has been installed in the RFQ chamber. The RFQ cavity has been conditioned up to 40 kW with the newly installed RF coupler. Conditioning of the cavity above 40kW is in progress.

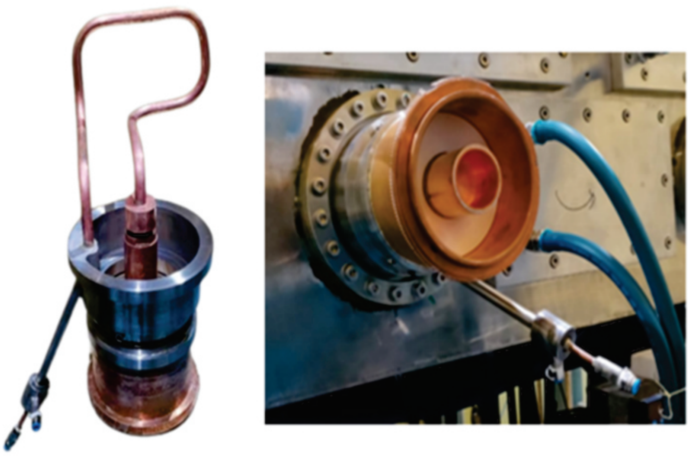

Figure 11: Photograph showing the Ceramic based high power RFQ coupler.

2.1.5 Spiral buncher (SB)

R V Hariwal, Sugam Kumar, R Ahuja, Parmanand Singh, Y Mathur, V V V Satyanarayana, S Venkataramanan, C P Safvan and R Mehta

In this academic year, the beam bunching was successfully carried out for N^{5+} beam using SB placed downstream to RFQ. We have measured about 6.3ns bunch length when the SB was OFF and the bunch quality improved by four times to 1.6ns after switching SB ON. The power required was about 350-400 watts for the N^{5+} beam test. The SB is conditioned to 1.2 kW and is ready for higher A/q beam test.

In additional to the first spiral buncher, two more spiral bunchers of similar type are required in the HEBT section of HCI. The procurement process of both these bunchers is already completed and the fabrication of them is expected to finish by the middle of this year. Copper plating of the bunchers will be performed at the Centre for Electrochemical Research Institutes (under CSIR, Govt. of India), Tamil Nadu. The 3D design of the spiral buncher is shown in Figure 12.

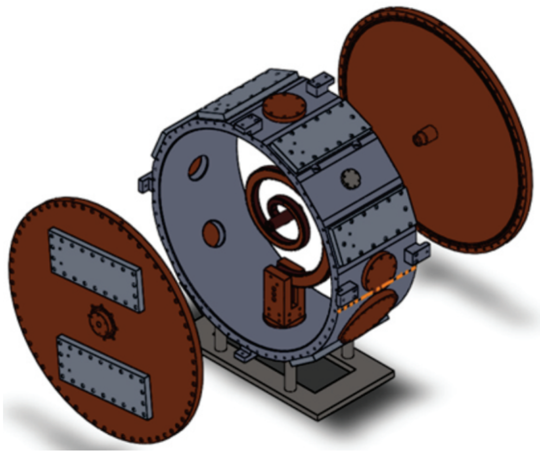

Figure 12: 3D model of spiral buncher.

2.1.6 Drift tube linear accelerators and associated diagnostics

Rajesh V Hariwal, C P Safvan, Sugam Kumar, Rajeev Ahuja, T Varughese, VVV Satyanarayana, Chandra Pal, Parmanand Singh, Yaduvansh Mathur, Deepak K Munda, Ashok Kothari, Ruby Shanthi, S Venkataramanan, P Barua, Kundan Singh and R Mehta

(A) DTL: Present status

The design validation and the capability of heavy ion beam acceleration and energy gain through all six DTL cavities have been checked and verified for N^{5+} beam having mass to charge ratio 2.8. The beam current and profiles have been measured using the compact beam diagnostics system embedded at the entrance of each DTL cavity. The heavy ion (N^{5+}) beam acceleration through the six DTL cavities in continuous wave (CW) mode and the present status are discussed below.

(B) High power RF conditioning of DTL cavities for N^{5+} beam

The beam tuning was planned in HCI accelerator facility for the acceleration of N^{5+} beam having A/q ~2.8. There were various RF power levels required for each of the cavity to achieve the designed acceleration voltages and energy gains. Last year, only three DTL cavities were tested for the beam acceleration. This year, high power RF conditioning of all the DTL cavities were completed and the cavities were kept ready for the beam acceleration of N^{5+} beam. The required RF power for DTL 1 to 6 cavities to get the design energy gain for N^{5+} are 1.1 kW, 2.4 kW, 3.9 kW, 3.9 kW, 5.3 kW and 5.5 kW respectively and are shown in Figure 13**.** Most of the cavities were left running for day and night to make them ready for the beam acceleration. The temperature and water flow rate were monitored continuously during the high-power conditioning to avoid any amplifier breakdown.

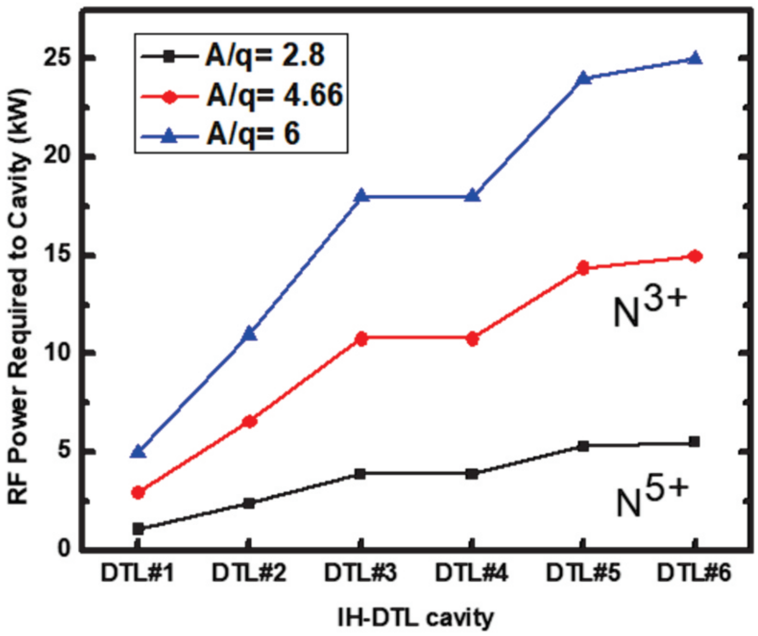

Figure 13: RF power requirement of IH-DTL cavities for designed energy gain for different A/q.

(C) N^{5+} Beam acceleration and successful design validation

HCI facility was extensively tested with N^{5+} (A/q=2.8) beam in CW mode with all subsystems operational. The capability of all 97 MHz multigap interdigital H-mode (IH) DTL structure to accelerate the heavy ion beam like N^{5+} was tested and verified as per the design value of energy gain. The energy gain by each of the DTL cavities was analysed and verified one by one. The energy gain from DTL 1st to 6th cavity was measured to be 0.32 MeV/u, 0.55 MeV/u, 0.85 MeV/u, 1.15 MeV/u, 1.46 MeV/u and 1.8MeV/u respectively which match very well with the designed value of DTL cavities. The transmission efficiency for the accelerated N^{5+} beam by the six DTL cavities were observed between 75% to 90%. It was approximately 90% for DTL 1st, 2nd, 4th, 5th and 6th cavities, whereas it was found around 75 % for the 3rd DTL cavity and needs more optimization of transverse and longitudinal parameters to increase the transmission efficiency during beam tuning. This will be taken up in future.

(D) DTL high power conditioning for N^{3+} (A/q =4.67) beam

After the successful design validation and energy gain through the six cavities for N^{5+} beam, it was decided to increase the A/q value from 2.8 (N^{5+}) to 4.66 (N^{3+}). The cavities require more power to provide the required acceleration. Some of the cavities are ready for the acceleration and others are under high power conditioning. Further, it was planned to do the conditioning of all the cavities at full power, which is going on. The present status of the cavities is tabulated in Table 2.

Table 2: The present status of DTL cavities.

Cavity	**DTL #1**	**DTL #2**	**DTL #3**	**DTL #4**	**DTL #5**	**DTL #6**
RF Power Required for A/q=6	5 kW	11 kW	18 kW	18 kW	24 kW	25 kW
Designed Energy Gain	0.32 MeV/u	0.55 MeV/u	0.85 MeV/u	1.15 MeV/u	1.46 MeV/u	1.8 MeV/u
RF Power Required for A/q = 2.8 (calculated for N^{5+} beam)	1.1 kW	2.4 kW	3.9 kW	3.9 kW	5.3 kW	5.5 kW
Analysing Mag. Field of Achromatic Bend (Cal. for N^{5+} beam)	2683 G	3517 G	4373 G	5086 G	5731 G	6364 G
Status of DTL cavities (for A/q =2.8)	**Energy gain Validated**	**Energy gain Validated**	**Energy gain Validated**	**Energy gain Validated**	**Energy gain Validated**	**Energy gain Validated**
RF Power Required for A/q = 4.66 (calculated for N^{3+} beam)	3 kW	6.6 kW	10.8 kW	10.8 kW	14.4 kW	15 kW
Energy Gain for N^{3+} Beam	4.48 MeV	7.7 MeV	11.9 MeV	16.1 MeV	20.44 MeV	25.2 MeV
Analysing Mag. Field of Achromatic Bend (Cal. for N^{3+} beam)	4472 G	5863 G	7288 G	8478 G	9552 G	10606 G
Present Status of DTL cavities for N^{3+} Beam (A/q =4.66)	**Ready for beam Test**	**Ready for beam Test**	**Conditioning Underway**	**Conditioning Underway**	**Conditioning Underway**	**Ready for Test**
High Power Conditioning Present Status	6 kW	9 kW	10 kW	10 kW	11 kW	24 kW

(E) Bunch length measurement at the entrance of first DTL

There was a requirement of longitudinal beam diagnostics to measure the bunch length at the entrance of the first DTL cavity along with beam current and profiles. It would give the time structure information of the incident beam at the DTL entrance and it was possible by installing a Strip-line Fast Faraday Cup (SFFC) developed in BARC, Mumbai India. A compact diagnostic box setup consisting of the wide bandwidth strip-line fast Faraday cup (SFFC) has been installed at the entrance of the first DTL cavity for the bunch length measurements downstream to 48.5 MHz RFQ and spiral buncher (SB). The time structure of the beam was measured using the SFFC by switching the SB OFF and ON. The results provide the information of the bunching capacity and effectiveness of the MHB and spiral buncher. The test was successfully performed with N^{5+} beam and the bunch length (FWHM) were measured to be about 1.6 ns after putting ON the MHB and SB#1. Further, optimization of the tuning parameters is going on to improve the beam quality. The SFFC set-up installed in HCI and the measurement results are shown in Figure 14.

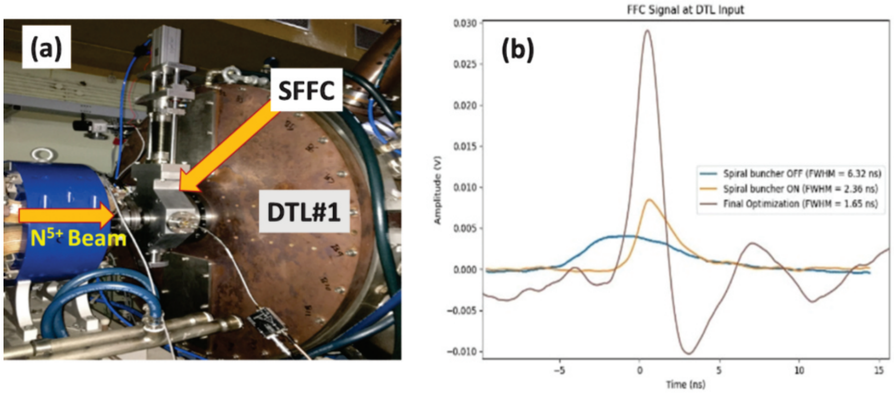

Figure 14 (a) Setup for bunch length measurement and, (b) Measurement results.

(F) Other developments: SEM grid BPM development for HCI

An indigenously designed SEM grid BPM for high current injector facility was proposed this year. This device will be a non-disruptive type and beam profile could be measured anytime without disturbing the beam. This was thought to make the transverse beam parameter measurement faster and making the beam tuning process convenient from an operational point of view. There were some minor design modifications done in the Faraday Cup of DTL#2. It was found that the LEMO connector, which was used for the suppressor voltage, burned out after the successful test due to its inability to handle the -380 VDC supply voltage. This was repaired and the LEMO connector was replaced with a BNC connector. There was also a diffusion leak found in the FC set up which was also repaired. The FC flange assembly was changed with the spare one and the FC was installed back in the compact diagnostic box. Leak testing was done successfully and now the cavity is fine and ready for the high-power conditioning and power test.

2.1.7 Conclusion

This academic year was the most challenging and fruitful year for HCI. A major milestone was achieved by getting the designed energy gain from the RF cavities. The measurements and optimization of transverse and longitudinal beam parameters were also carried out during the test which have validated the mechanical and electrical design parameters of the cavities.

2.2. STATUS OF THE COMMISSIONING AND TESTING OF COMPACT THz RADIATION FACILITY BASED ON FREE ELECTRON LASER

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[2]Bhabha Atomic Research Center, Mumbai, India
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2.2.1 Introduction

The compact, pre-bunched Free Electron Laser facility named as Delhi Light Source (DLS) is in advanced stage of commissioning at IUAC [1, 2]. This year electron beam of energy of ~ 1.3 MeV produced by a photocathode based normal conducting RF gun operating at 2860 MHz has been demonstrated. As per the design of DLS, the electron beam with energy ~4-8 MeV will be produced from the electron gun and will be injected into the compact undulator to produce THz radiation in the frequency range of 0.18 to 3.0 THz. The entire accelerator facility is being installed inside an operational class 10000 clean room. The experimental facilities to utilize THz radiation and electron beam will be also accommodated in the same clean room.

2.2.2 Progress of various subsystems of DLS

The progress of the various activities related to setting up the compact FEL are listed in the following sub-sections:

2.2.2.1 High power RF conditioning of the electron gun and production of electron beam

In the last year's Annual Report (2020-21), the scheme of RF conditioning of the photo cathode based electron gun and the demonstration of the first signature of electron beam in the form of 'Dark Current' had been reported. The electron gun, a 2.6 cell copper cavity operating at 2860 MHz frequency, could not be conditioned beyond a forward power of ~ 800 kW as the proposed vacuum based circulator could not be installed after the Klystron due to some technical issues. The interlock system to monitor the reflected power didn't allow the RF system to increase the forward power beyond 800 kW. After producing the dark current, substantial effort was dedicated in the current academic year to shoot the laser pulse from a commercial Nd-YAG laser system and to strike the Copper photocathode placed at the entrance of the cavity. In order to ensure the incidence of UV laser pulse on the photocathode without reflection from anywhere on the cavity surface, the positioning of the laser beam along with laser power was mapped, and the co-ordinates were recorded with the help of a YAG screen installed permanently at the entrance of the cavity as shown in figure 1(a) [3]. The RF Gun was conditioned with a maximum pulse width of 4 s up to 800kW with 50 Hz repetition rate by minimizing the reflected power [4]. The produced electron beam from the photo cathode has been viewed on the YAG screen installed with a camera and is also recorded on Oscilloscope using a beam catcher. The photograph of the detection of the electron beam is shown in figure 1(b).

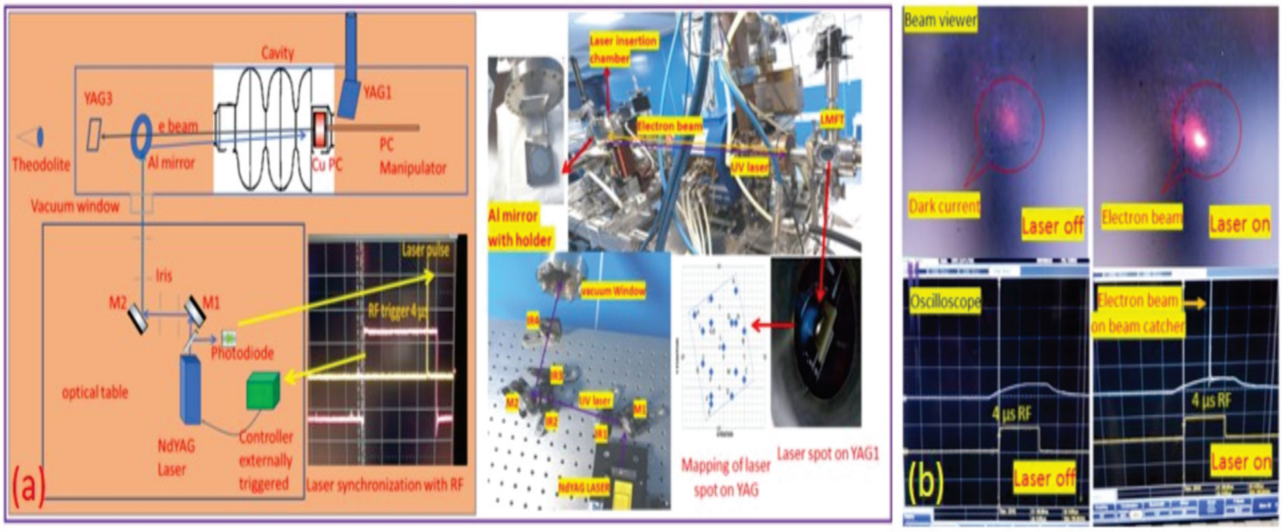

Figure 1. (a) The positioning of laser beam and transport mechanism, (b) Photograph of produced electron beam.

2.2.2.2 Analysis and Simulation studies of dark current and detected electron beam

ASTRA simulation code is used to perform the calculation related to the production of dark current and the laser beam induced electron beam from the copper photocathode. The simulation of dark current showed that the electrons, originated from the ring boundary of the photocathode plug, will be able to exit from the cavity with the appropriate solenoid field (figure 2(a)). In the calculation related to the production of photo-electrons, the forward RF power (650 kW) incident on the electron gun is used to calculate the e-gun's accelerating field (26 MV/m). Though, 1 ns width of the laser pulse covers three RF cycles, only one cycle is considered in order to make the calculation simple and it is shown that the electron ejected out between 0 to 70 degree (total ~ 70 ps), out of 360 degree of a RF cycle, will have sufficient energy to exit the e-gun and that makes the FWHM of the electron bunch as ~ 40 ps. The total number of electrons that come out from the copper photocathode with a Quantum Efficiency ~10^{-5} with the laser energy of ~5 J is calculated to be ~0.6 pC. Therefore the input parameters for ASTRA calculation are: total charge: 0.6 pC, bunch length: 40 ps and phase angle: 70/2 = 35 degree. The calculation shows that the energy of the electron beam is ~1.3 MeV (maximum) extended to a very low value for an optimum magnetic field of the solenoid to focus the beam on the YAG with a current of 21 Amps. During the experimental observation by performing the solenoid scan [5], it has been found that the beam focusing somewhat optimizes around 21 Amps but get deteriorated beyond 22 Amps (figure 2(b)).