2. ACCELERATOR AUGMENTATION

2.1 HIGH CURRENT INJECTOR

The High Current Injector (HCI) Project will accelerate the ion beam from ECR source using normal temperature Radio-Frequency Quadrupole (RFQ), IH type Drift Tube Linac (DTL) and superconducting low beta cavity module to match the input velocity at our existing superconducting linear accelerator. The following sections describe the annual progress of various components.

2.1.1 High Temperature Superconducting ECRIS, PKDELIS and Low Energy Beam Transport (LEBT)

G. Rodrigues, P.S.Lakshmy, Y. Mathur, Kedar Mal, Sarvesh Kumar, R.K.Gujar, U. K. Rao

18 GHz HTS ECR ion source operation, developments and maintenance

The 18 GHz HTS ECR ion source of HCI has been continuously in operation for various beam acceleration tests through the downstream RFQ and DTL cavities. Different charge states of Ne, N_2, O_2, etc. were developed, extracted and transported for beam tests. Ar and Kr beams have been developed to study the charge state distributions (CSD). HTS ECRIS has been operated with 1.7 kW Klystron and 200 W TWT amplifier as well. The performance of the ion source with the TWT amplifier coupled at lower power levels were found very satisfactory and different charge states of Ar beam have been extracted. A new gas line using a metal hose has been fabricated for utilising the gas mixing technique. The 30 kV platform has been modified to install the micro oven power supply for metal beam development.

The operation of the klystron amplifier using a signal generator due to the failure of the 18 GHz oscillator lead indirectly to a degraded performance of the ion source since the rf coupling was not good. It is believed that the rf coupling has weakened probably due to the dc bias tube sitting inside the plasma chamber which apparently was not sitting co-axially inside the chamber. This is being presently looked into detail. A leaking 'high current feedthrough' made of 'styecast' material at the injection side cryostat was recently replaced with a newly designed feedthrough consisting of a metal to ceramic bonding. The injection side cryostat was opened up completely and the faulty feedthroughs were first de-soldered meticulously; the new metal to ceramic bonded feedthroughs were carefully assembled and soldered back ; new '40 layer' aluminium-mylar sheets were finally wrapped around the cold head assembly to replace with the old material. Fig.1 shows different stages of feedthrough installation process.

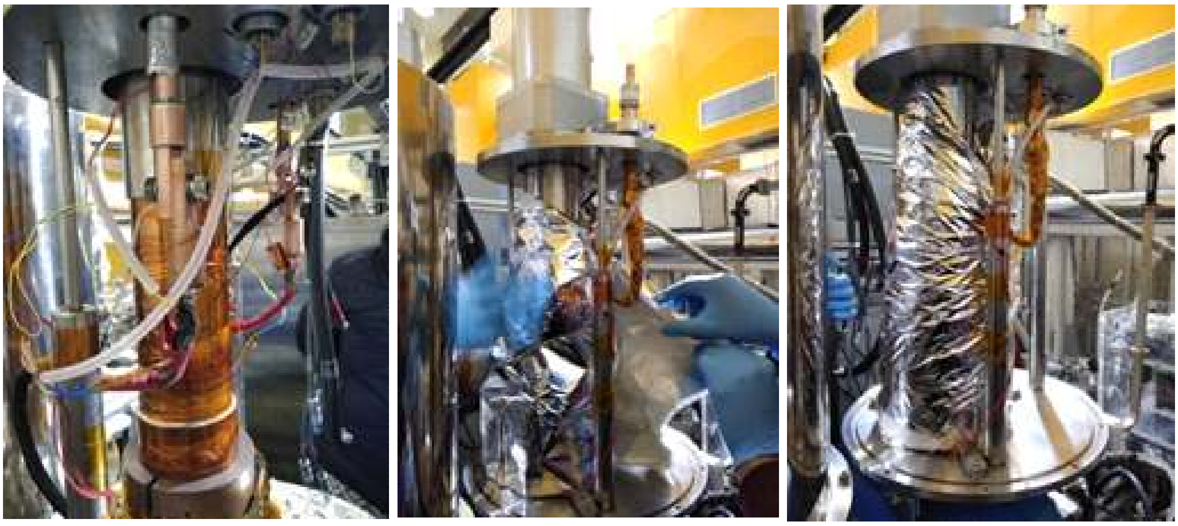


Fig.1 'High current feedthroughs' and 'aluminium-mylar' layers installation

2.1.2 Beam Tests

G.Rodrigues, P.Barua, A.Kothari, Chandrapal Shakya, S.Venkatarmanan, Rajesh Kumar, S.K.Suman, V.V.V.Satyanarayana, Parmananda Singha, Y.Mathur, U.K.Rao, Abhijit SarkarR.Ahuja, T.Varghese, R.V.Hariwal, Sanjay Kedia, Sugam Kumar, Mukesh Kumar, Prem Kumar,Kundan Singh, Deepak Kumar Munda, Kedar Mal, P.S.Lakshmy, Sarvesh Kumar, U.G.Naik,A.J.Malyadri, Raj Kumar, Rajeev Mehta, C.P.Safvan, B.P.Ajith Kumar

(a) Beam acceleration tests through LEBT and MEBT

A maximum DC beam transmission of 25% and 36% transmission (N^{5+}) for bunched beam were achieved through RFQ and the energy measurements were carried out using a temporarily installed beam line consisting of 45° bending magnet and quadrupole magnets with diagnostic devices as shown in Fig.2.

Fig.2 Beamline using 45° bending magnet for energy measurement

Beam acceleration tests were carried out through RFQ, DTL #1 and DTL#2 cavities after installation of all the six DTL cavities, miniature quadrupoles between the DTL cavities, quadrupoles, steerers, achromat #1 and diagnostic devices as per the beam optical design of HCI. A spiral buncher is also located at the entrance of the DTL#1. Beam tests have been carried out in a stepwise manner to carry out the energy gain measurement from RFQ, DTL #1 and DTL#2. All the beam tests have been carried out using N^{5+} beam. Beamline was tested initially to check for the beamline misalignment using DC beam at energy 8 keV/amu. The boosted energy achieved from RFQ, DTL#1 and DTL#2 are 180keV/amu, 317keV/amu and 550 keV/amu respectively. The transmission has been optimized for DC as well as bunched beams at the exit of achromat#1. A part view of the commissioned HCI beam line upto achromat #1 is shown in Fig.3.

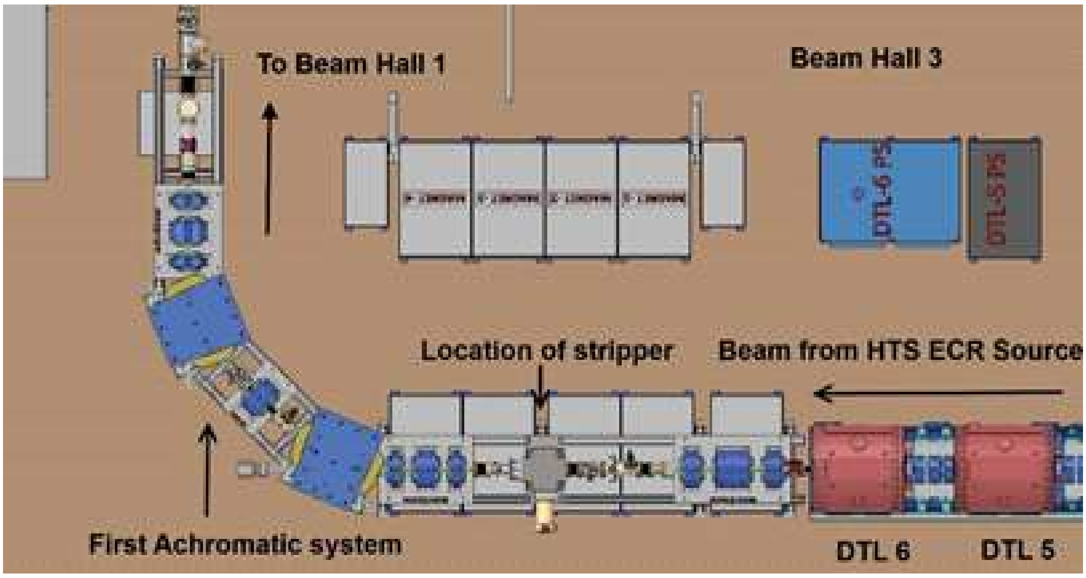


Fig.3 Part view of HCI beamline upto achromat#1

2.1.3 DC and bunched beam, transmission studies through the RFQ

G.Rodrigues, P.Barua, A.Kothari, Chandrapal Shakya, S.Venkatarmanan, Rajesh Kumar, S.K.Suman, V.V.V.Satyanarayana, Parmananda Singha, Y.Mathur, U.K.Rao, Abhijit Sarkar, R.Ahuja, T.Varghese, R.V.Hariwal, Sanjay Kedia, Sugam Kumar, Mukesh Kumar, Prem Kumar,Kundan Singh, Deepak Kumar Munda, Kedar Mal, P.S.Lakshmy, Sarvesh Kumar, U.G.Naik, A.J.Malyadri, Raj Kumar, Rajeev Mehta, C.P.Safvan, B.P.Ajith Kumar

Transmission studies of bunched beam through the RFQ cavity is of utmost importance because it is the first accelerator in the HCI which will determine the accelerated beam intensities to the downstream cavity, DTL. In the case of DC beams, in this case, N^{5+} was accelerated through the RFQ, and the maximum transmission was measured to be 24 %. In the case of bunched beam, the MHB was optimised and the transmission was measured to be 36%. The transport parameter settings for the DC beam before the entrance of the RFQ were also maintained in the bunched beam tests, with slight tuning of the transport parameters in the MEBT section to optimise the transmission. It should be noted that, the lack of a visual diagnostic close to the entrance of the RFQ may be one of the reasons for the poor beam tuning and the resulting transmission. Further work is underway to install a visual diagnostic as close as possible to the RFQ and to further improve the transmission.

The accelerator chain of the HCI facility includes 48.5MHz 4-rod RFQ, operating in cw mode, to accelerate ion beam of A/q of 6 from 8keV/u to 180keV/u. Last year an interim beam test was completed with the RFQ and six DTL tanks. The RFQ was operated in cw mode at 19kW power for the beam of N^{5+} (A/q=2.8) which has been accelerated successfully with two DTL tanks powered and other used as drift. The test facility includes 90° achromat bending magnet and Faraday cup along with the BPM installed at the end of the diagnostic chamber for the energy, current and beam profile measurement. Beam current was optimised as a function of RFQ vane voltage and RF phase for bunched beam from multi-harmonic buncher.

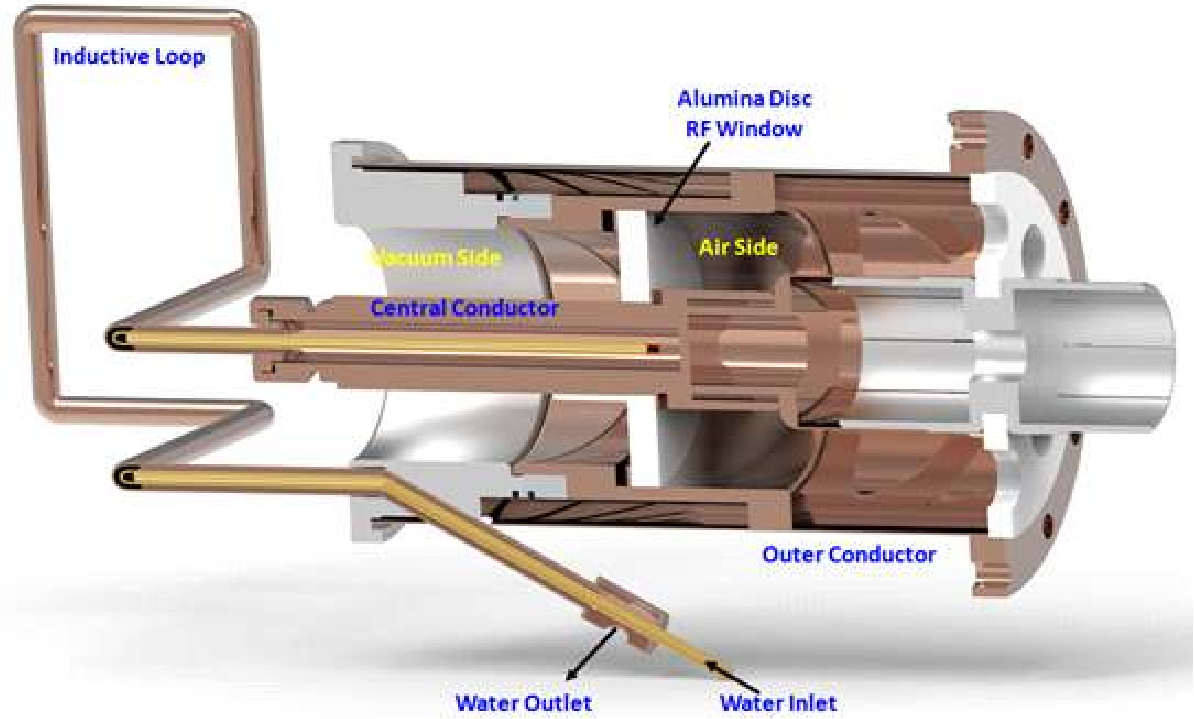


Figure 4: CAD assembly of the rotatable water-cooled L-shaped rf power coupler. An alumina ceramic brazed with inner and outer conductor is used as an RF-window

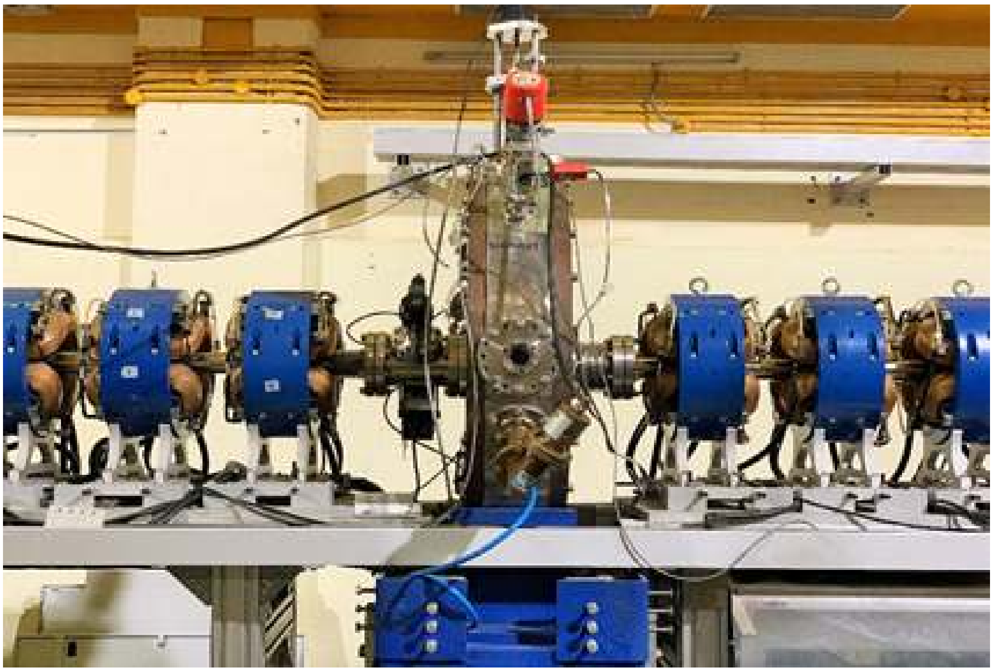
To test the beam of higher A/q, rfq power coupler has been modified from existing coupler which uses commercial CF35 feedthrough as a rf window with custom made coupler shown in figure 4. The newly designed RF coupler uses specially designed 20mm thick alumina of 100mm diameter as an RF window. Its water-cooled 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 analyzed in 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 of with diameter 12mm and other of 6mm. The loop has several bends which were introduced in order to optimize the coupling coefficient. The one end of the inductive loop is then brazed to the central conductor of the feedthrough and another 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, 2 liters/min is used for the cooling of the loop surface as well as ceramic.

2.1.4 Spiral Buncher Cavities : Design and Tests

Sanjay Kedia, Rajeev Mehta, V.V.V.Satyanarayana, Parmananda Singha, Y.Mathur, R.Ahuja, T.Varghese, R.V.Hariwal, Kundan Singh, B.P.Ajith Kumar

The three 48.5 MHz spiral buncher (SB) cavities have been designed and developed for the High Current Injector

(HCI) accelerator to match the input Twiss parameters at the entrance of superconducting super buncher (SSB) cavity by providing the longitudinal beam phase matching between Radio Frequency Quadrupole (RFQ) and SSB. The location of three spiral bunchers has been fixed in such a way that ion beam can be transported from RFQ to SSB with negligible growth in longitudinal beam emittance within the framework of first-order linear beam optics. The medium energy beam transport (MEBT) section and high energy beam transport (HEBT) section includes one and two spiral buncher cavities, respectively. The MEBT cavity has been designed, developed, installed, and beam tested in HCI. The preliminary beam testing of MEBT cavity has been carried out by measuring the effect in current when the buncher cavity was powered since capacitive pickup was not installed to measure the buncher width. It was observed that the ion current had become almost double when the buncher cavity was powered and optimized for required power level, as shown in Table. The installation of capacitive pickup is underway to measure the bunch width at the entrance of DTL-1.



The commissioning of the MEBT spiral buncher cavity.

Table: The beam test result of MEBT spiral buncher cavity

Ion Beam	Before Spiral	After Spiral	Comments
Ne^{+8}	2.3 nA	4.3 nA	(Old Beamline) Current became almost double when the spiral buncher kept on
	2.1 nA	4.4 nA	
Ion Beam	**After RFQ**	**After DTL**	**Comments**
N^{+5}	1300 nA	460 nA	(New Beamline) Transmission has been increased by a factor of ~two by tuning the spiral buncher.
	1500 nA	650 nA	

The two HEBT spiral buncher cavities have been designed to provide the longitudinal beam matching between DTL and superconducting super buncher of the LINAC. The electrical and mechanical design of HEBT spiral buncher cavities has been prepared in Computer Simulated Technology Microwave Studio (CST-MWS) and SolidWorks, respectively. The drift tube thickness of HEBT bunchers was done to get the uniform electric field profile along the beam direction while $\beta\lambda/2$ was kept constant during the refinement. The HEBT bunchers require ~2 kW of input power to produce ~160 kV across two RF gaps. The simulated quality factor and shunt impedance for two identical HEBT SB cavities are ~8300 and ~13.5 MΩ, respectively. The cylindrical type chamber was fabricated of copper-plated mild-steel (MS) while other components including end plates, spiral, stem, and flanges were fabricated of pure OFHC copper due to excellent electrical as well as thermal conductivity. The cavity frequency can be easily coarse tuned by varying the length of spiral, and it can be further fine-tuned to ±200 kHz by varying the diameter of drift tubes and stem, in both the directions even after fabrication. The electrical and mechanical design in CST-MWS and SolidWorks has been presented in the figures below.

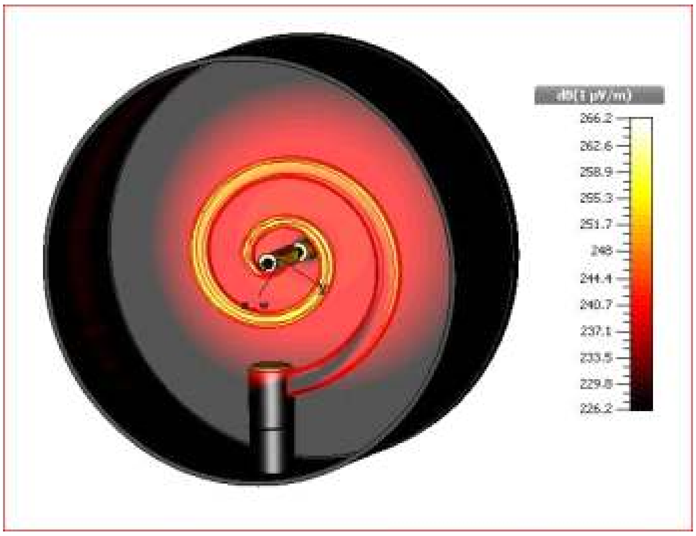


Fig. Electrical design of HEBT spiral buncher cavities in CST-MWS.

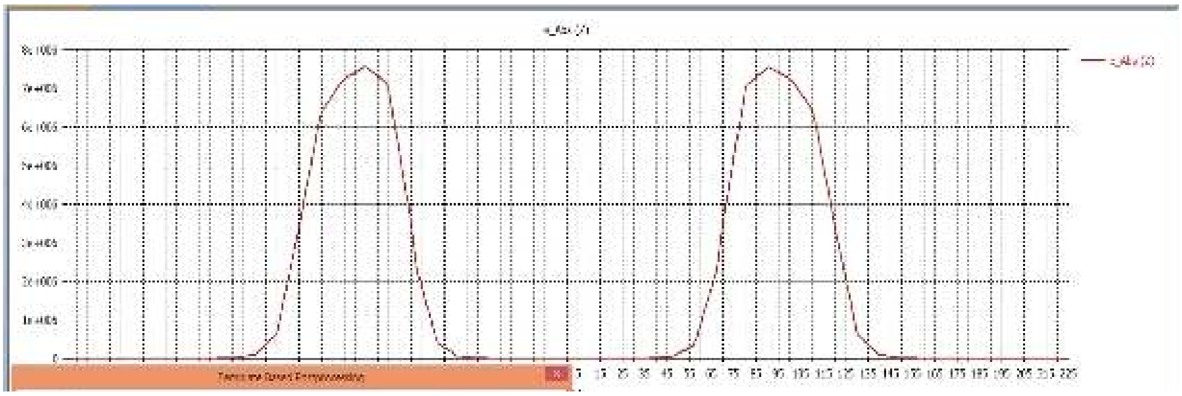


Fig. Electric field profile in CST-MWS.

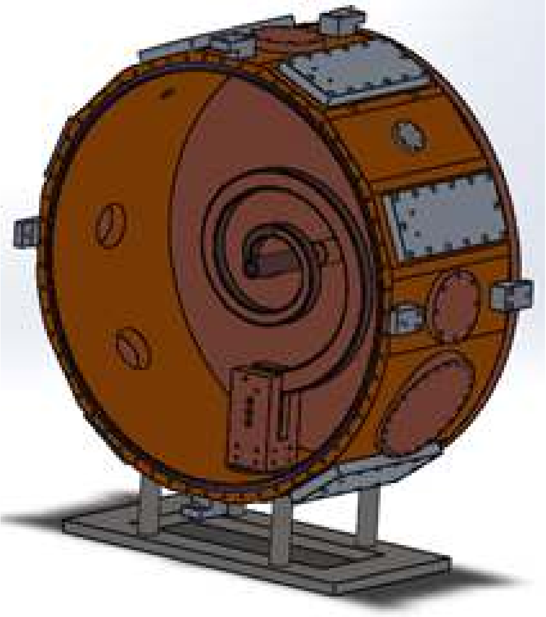


Fig. Mechanical design of HEBT spiral buncher cavities in solid works.

2.1.5 Development of Compact Beam Diagnostic System (CBDS) for High Current Injector (HCI)

R.V.Hariwal, T.Varghese, R.Ahuja, P.Barua, A.Kothari, Chandrapal Shakya, Kundan Singh, Deepak Kumar Munda, B.P.Ajith Kumar

The state-of-art design and successful beam test results of the prototype Compact Beam Diagnostic System (CBDS) in HCI, have proved the possibility of successful indigenous development of CBDS for MEBT section where the space limitation is the most challenging task in HCI. This year, we have completed the design, fabrication of six sets of CBDS, assembly and installation at the entrance of DTL cavities and online test with N5+ beam in HCI. The fabrication of all components have been done indigenously. CBDS comprises compact diagnostic box (CDB), Faraday cup (FC) and beam profile monitor (BPM). CDB is made of Al 6063T material and its length is 70 mm along the beam direction. The operation, communication/interface, programming and data acquisition of CBDS are tested offline in the laboratory with the help of a test bench before the final installation in HCI. We have also developed indigenously a CBDS controller using IDX 7505 for the purpose of BPM. The FCs at the entrance of DTL2-DTL6 have been used to measure the beam current more than 500 nA and BPMs provided the beam profiles at the entrance of DTL2 and DTL4 cavities during recent beam run in HCI. This beam test has validated the complete design and operation of CBDS. CBDS Controllers for DTL3, DTL5 and DTL6 are now ready and they will be tested in coming HCI beam run. We would like to acknowledge Mr Rajeev Mehta, Mr Rajeev Ahuja, Dr. C P safvan, Mr R N Dutt, Mr Ashish Sharma, Vacuum lab and workshop officers for their technical support.

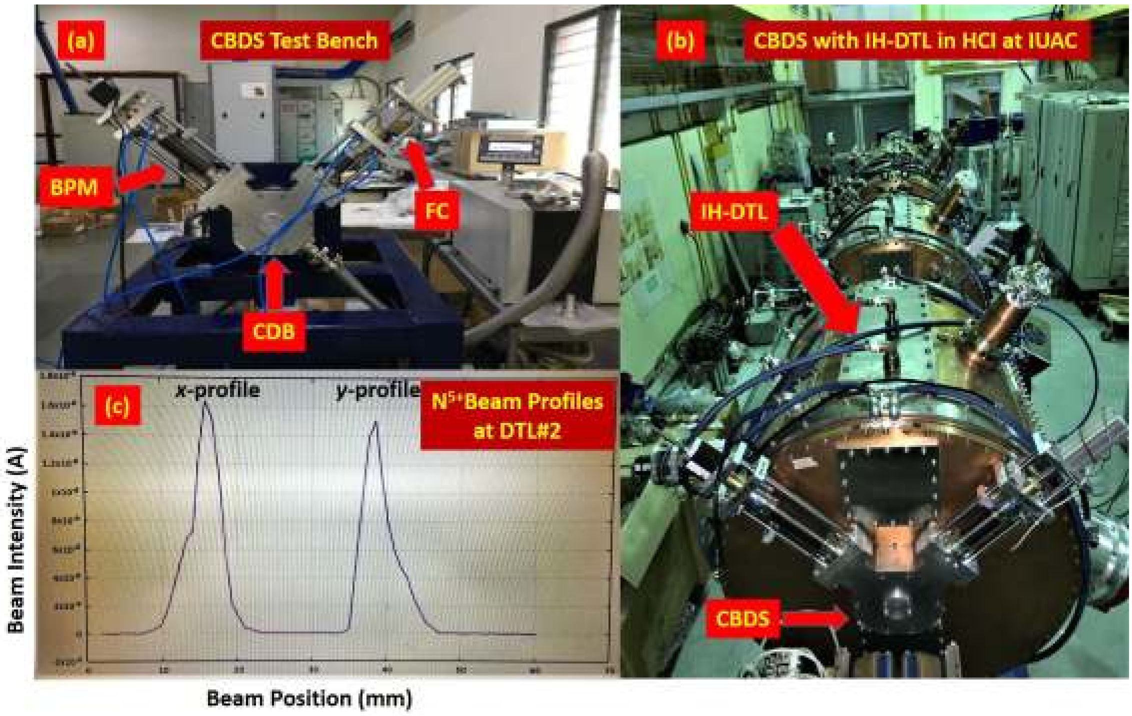


Figure: (a) CBDS offline test bench (b) CBDS installation at the entrance of DTL cavities in HCI and (c) beam profile at the entrance of DTL2 during beam test run in HCI.

2.2 COMMISSIONING OF A COMPACT FREE ELECTRON LASER FACILITY TO PRODUCE INTENSE TH$_z$ RADIATION

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[4]Variable Energy Cyclotron Center, Kolkata, India
[5]Brookhaven National Laboratory,USA
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[7]High Energy Accelerator Research Organization, KEK, Tsukuba, Japan
[8]Diamond Light Source Ltd, Diamond House, Didcot,Oxfordshire, UK

2.2.1 Introduction:

A compact pre-bunched Free Electron Laser (FEL) facility named Delhi Light Source (DLS) [1] is at the stage of commissioning at IUAC. The light source being developed at IUAC is based on the principle of pre-bunched Free Electron Laser where a low emittance electron beam in the energy range of 4 – 8 MeV will be injected into a compact undulator to produce the THz radiation in the frequency range of 0.18 to 3.0 THz. The electron beam and THz radiation propagating together through the undulator will be separated just at its exit and will be transported in separate beam lines equipped with dedicated set of experimental facilities for electrons and THz radiation. The commissioning status of the major subsystem is described below.

2.2.2 Development of Various Subsystems of DLS:

The developments in the major areas of the compact FEL are discussed in the following sections:

2.2.2.1 The electron gun and the high power RF system

The copper cavity as the electron gun along with the copper photocathode was fabricated and tested in the past. Recently the cavity was installed in the beam line and aligned with respect to the reference points along with the solenoid magnet. The high power RF system consisting of Klystron, Modulator, waveguide etc. are installed and tested with load. The final test of the complete system with the load is being carried out and after successful testing, the high power RF conditioning of the copper cavity will be started.

The high power RF device along with Low Level RF (LLRF) associated with other controls and accessories will energise the 2.6 cell RF gun. The temperature of the cavity will be controlled by a dedicated chiller with a temperature accuracy of ± 0.05°C. A dedicated IQ based LLRF control for frequency tracking and for phase/amplitude control is worked out and will be tested shortly. Various safety interlock modules are getting ready and some of them are being installed in the high power RF system. An EPICS based distributed and heterogeneous control system is under development to interface various beam line components along with MODBUS TCP based Klystron Modulator. The high power RF system along with waveguide installed at IUAC are shown in figure 1.

Figure 1. High Power RF system along with waveguide was installed at IUAC

2.2.2.2 Fiber Laser system to produce electron beam from photocathode

The laser system for the DLS project was decided to be Ytterbium (Yb) doped fiber laser system which is being developed at KEK, Japan. Semiconductor Optical Amplifier (SOA) is used to reduce the repetition rate from 130 to 5 MHz to avoid laser pulse loading. Then after stretching and amplification through the PCF fiber (pre amplifier), it is to be passed through the pulse picker to pick up the pulses in the ~ 3 - 4 microsecond RF window with a typical repetition rate of 6.25 or 12.5 Hz. At this stage, a multi-bunch structure with 15-20 laser pulses and a separation of 200 ns are generated at a repetition rate of 6.25 or 12.5 Hz. These laser pulses will be amplified by two burst amplifiers to increase the pulse energy. The splitting mechanism to split a single laser pulse in to 2, 4, 8 or 16 has to be incorporated either after or before the amplification stage. The train of micropulses after conversion from IR to UV will be incident on the photocathode (Copper or Cs_2Te) by using telescope system to produce the train of multi-microbunches of electrons. With 0.1 μJ/pulse, we can produce a maximum of 200 pC charge from Cs_2Te photocathode. The average current can go upto ~18nA for 6pC charge/mircobunch for 15x16 multi-microbunch structure with 12.5 Hz rep rate.

All the stages of Oscillator, Pre-Amplifiers, Amplifiers-1, 2 have been developed and tested (figure-2). Currently the work on the pulse compressor is going on. Once it is tested successfully, the work on the fourth harmonic generation from IR to UV followed by the splitting of a single pulse in to 16 (max) will be started. It is expected that the complete system will be tested in May-June 2020 and then the system will be shipped to IUAC for its installation in the beam line.

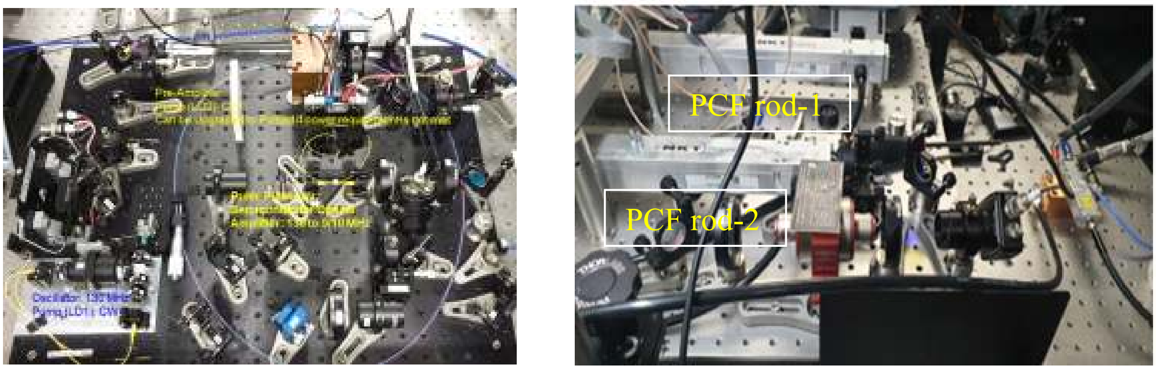

Figure 2. Oscillator, Pulse picker, Pre-amplifier (left) and two Amplifiers (PCF rod) (right) were tested

2.2.2.3 Electron beam transport and electromagnets

The electron beam and the THz radiation propagate together throughout the complete length of the beam pipe inside Undulator. At the exit of undulator, the electron beam, separated from the THz radiation, will be transported by an achromatic system consisting of two dipoles, five quadrupole and a few steering magnets to deliver the beam at the experimental stations (the extreme left in figure - 3). The first dipole bending magnet will be placed ~ 0.4 m downstream from the undulator exit and the separation between the beam line of THz and electron beam is designed to be kept at 2 m. After the second achromatic bend, the beam will be focused at three different experimental stations before being transferred to the beam dump. To transport the beam efficiently, as per the transverse beam optics calculation, it is required to install total six quadrupoles, five steering and two dipole magnets. All the magnets were designed and produced by BARC, Mumbai (figure 3) and most of them were already shipped to IUAC. The power supplies of the magnets are being designed and developed at IUAC.

Figure 3. Schematic of e-beam transport line after undulator and the various electromagnets developed by BARC

2.2.2.4 Undulator

The undulator for the Delhi Light Source (U50-DLS) was designed in the past using the code RADIA with 30 periods (50 mm period length) and with a variable gap of 16 to 45 mm corresponding to the peak magnetic field of 0.6 to 0.1 T respectively.

During the procurement process, an offer was received from HZB, Germany to accept one of their spare undulator which was available in good condition. It was found out that this spare undulator has got similar parameters to the one designed for DLS. Recent magnetic field measurement on the HZB's undulator reveals that the device is fully operational and is in excellent condition. Currently the Undulator has been shipped from HZB to DESY, Germany to accomplish a few refurbishment jobs followed by a final measurement of the magnetic fields which are going to be done in presence of IUAC's personnel. It is expected that after the successful measurement of the magnetic fields, the undulator will be shipped to IUAC by April 2020.

2.2.2.5 Progress of the Photocathode Deposition System

To prepare the semiconductor photocathode at IUAC, a deposition system consisting of four independent vacuum chambers (base vacuum ~ 10^{-11}mbar) was designed at IUAC where the photocathode plug will be transferred from the first to fourth chamber to perform the operations viz. (a) surface cleaning, (b) deposition with semiconductor material (c) Storage of the freshly deposited plug and (d) insertion of the plug into the electron gun. Collaboration was established between IUAC and Brookhaven National Laboratory, USA to fabricate and test the complete system. The final stage of integration and the testing is being done with the active participation of IUAC personnel and it is expected to produce the first Cs_2Te photocathode thin film by the first quarter of 2020. The design and the image of the integrated system are shown in figure 4.

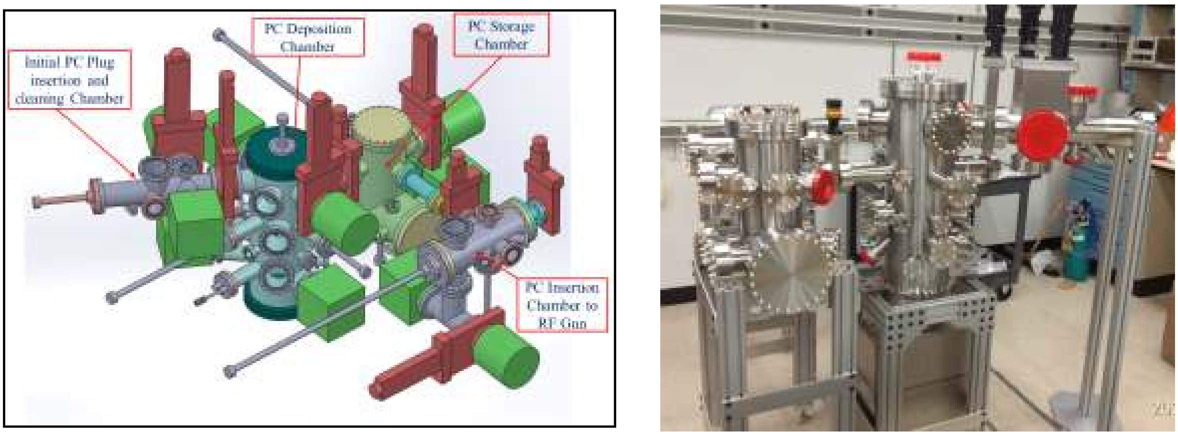

Figure 4. The schematic of the Photocathode Deposition Mechanism with the image of the deposition systems

2.2.2.6 Beam line commissioning

The 3-D beam line design for the compact THz facility of IUAC has been completed upto the Undulator (Figure-5). The remaining design of the beam line upto the electron beam dump is currently in progress. At present, the beam line components including the insertion chamber, the electron gun, beam position monitor, Laser reflection chamber, etc. are installed in the beam line (Figure-5). Various electromagnets, Faraday Cups, View screens equipped with Gigabit CMOS camera with indigenously developed trigger compatible software based on EPICS to measure the transverse profile of the beam are to be installed soon. A device named THz Extraction Chamber currently under designing stage will be installed at the exit of the Undulator. In this chamber, the electron beam and the THz radiation after propagating through the undulator will be separated out by Titanium foil which will reflect the THz radiation at 45 degree and will let the electron pass through the foil. Then the electron will be transported up to the experimental stations dedicated for electron beam and the reflected THz radiation from Titanium foil will be analysed first by measuring its power and frequency and then will be transported to three different experimental stations for doing experiments with THz.

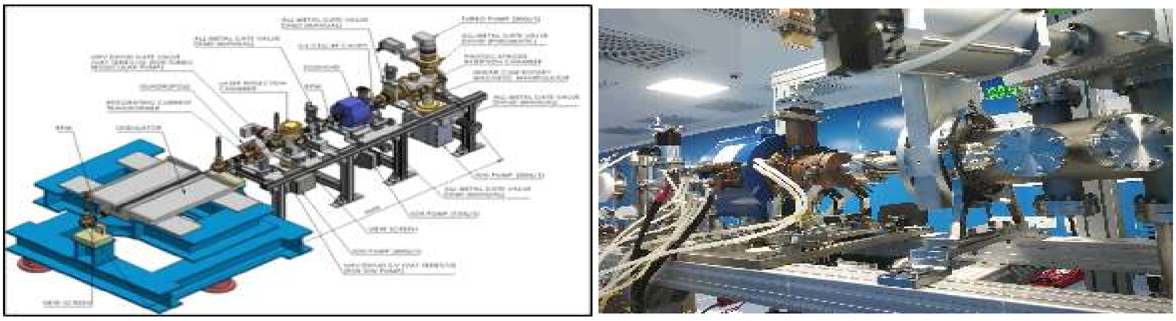

Figure 5. 3-D beam line drawing upto the undulator with installed components upto the Laser reflection chamber

2.2.3 Conclusion

The compact Free Electron Laser facility of IUAC is at the commissioning stage at IUAC. The important components of the facility e.g. the RF cavity, Copper photocathode, High Power RF device, the fibre laser system, solenoid magnet, Undulator, various beam line components etc. are either installed or will be installed in next few months. It is expected that the electron beam and the THz radiation will be demonstrated by the second and third quarter of 2020 respectively.

[1] S.Ghosh, et. Al. Nuclear Instruments and Methods in Physics Research – B 402, (2017), page 358-363.