2 ACCELERATOR AUGMENTATION

2.1 HIGH CURRENT INJECTOR

2.1.1 18 GHz HTS ECR Ion Source & Low Energy Beam Transport Section

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(A) Performance of 18 GHz HTS ECR ion source and related maintenance activities

In the last academic year, the ion source was operated mainly for extracting different metal beams. Gaseous beams of neon and nitrogen were tuned for beam tests for the newly installed achromat 2 (HEBT section of HCI) and for beam bunching tests. Heating was observed in one of the flexible waveguide sections that led to breaking of the outer insulation of the flexible waveguide during high RF power ~1.3 kW operation of the source for metal beam development. The transmission line was re-routed and all the flexible waveguides were replaced with rigid lines. Helium pressure drop was observed in the extraction side cryocooler during source operation. The low pressure dropped to 35 psi in running condition. Helium pressure was monitored in OFF condition before recharging helium. There was no further pressure drop observed in OFF condition. Cryocooler was recharged using helium gas of purity 99.9999% to the recommended value of static pressure of 220 psi using a vacuum manifold connected as shown in figure 1. The operation of the extraction cryocooler was restored to normal working conditions.

Figure 1: View of the vacuum manifold connected to extraction side cyocooler.

(B) Metal beam development

Micro-oven was installed at the injection side of the source after successfully extracting copper beam using the sputtering technique in the last academic year. A 60 V, 5A power supply was installed on the 30 kV platform and powered by a 3 kV isolation transformer to operate the sputtering unit. The remote control operation of the micro-oven was also tested. Temperature calibration of the micro-oven was carried out before applying voltage to the loaded material. Efforts were put forth to extract Al beam by using the micro-oven. Al wire of thickness 1 mm was used and the oven voltage was increased up to 5.5 V which corresponds to a temperature higher than the melting point of aluminium. However, no signature of aluminium beam was observed, most probably due to low vapour pressure available at that temperature. Ag and Pb beams have been developed successfully using micro-oven. A wire of diameter 2 mm and length 30 mm was placed inside the micro oven. A U-shaped molybdenum wire was inserted at the front end of the oven to lock the crucible inside the oven and to prevent it from falling out in the chamber.

Various charge states of Ag were tuned using O_2 as mixing gas. Figure 2(b) shows the beam profiles of Ag isotopes. In Figure 3(a), a charge state distribution (CSD) spectrum of Ag plasma with O_2 as the mixing gas is shown after optimizing for $^{107}Ag^{19+}$ and successfully extracting more than 5 eμA of a beam of $A/q \leq 6$. The spectrum clearly shows two isotopes of Ag, i.e. ^{107}Ag and ^{109}Ag, getting populated. Similarly, the tuning of various charge states of Pb was also carried out with O_2 as mixing gas. Figure 3(b) shows a CSD of Pb plasma with O_2 after optimization of ion source parameters for Pb^{33+}. The maximum intensity of Pb^{33+} was only ~ 400 enA which has an A/q ratio higher than 6. Due to the low beam intensities of Pb beams, the image slits were opened 10 mm wide during the Pb beam run and the isotopes of Pb (204, 206, 207, and 208) could not be separated due to this reason. The nitrogen gas present in the ion source, which is also seen in the CSD, may be the cause of the low beam intensities of Pb beams. Later, a leak was found in the gas line itself and the same was corrected. Pb beam development will be continued aiming to achieve higher intensities of beams of A/q $\leq$ 6.

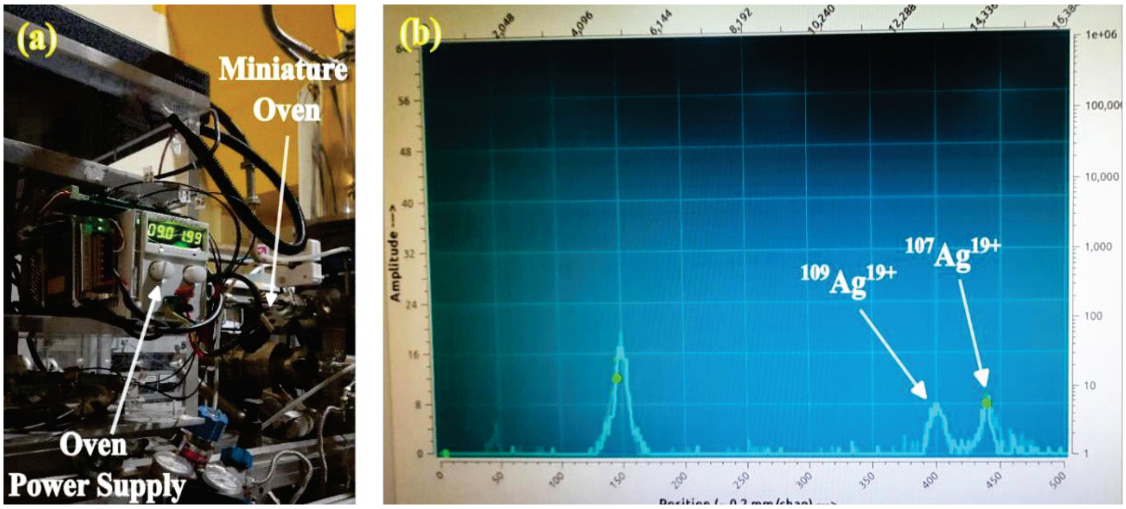

Figure 2 : (a) Micro-oven coupled at the injection side of the ECR source (b) Beam profile depicting the isotopes of Ag.

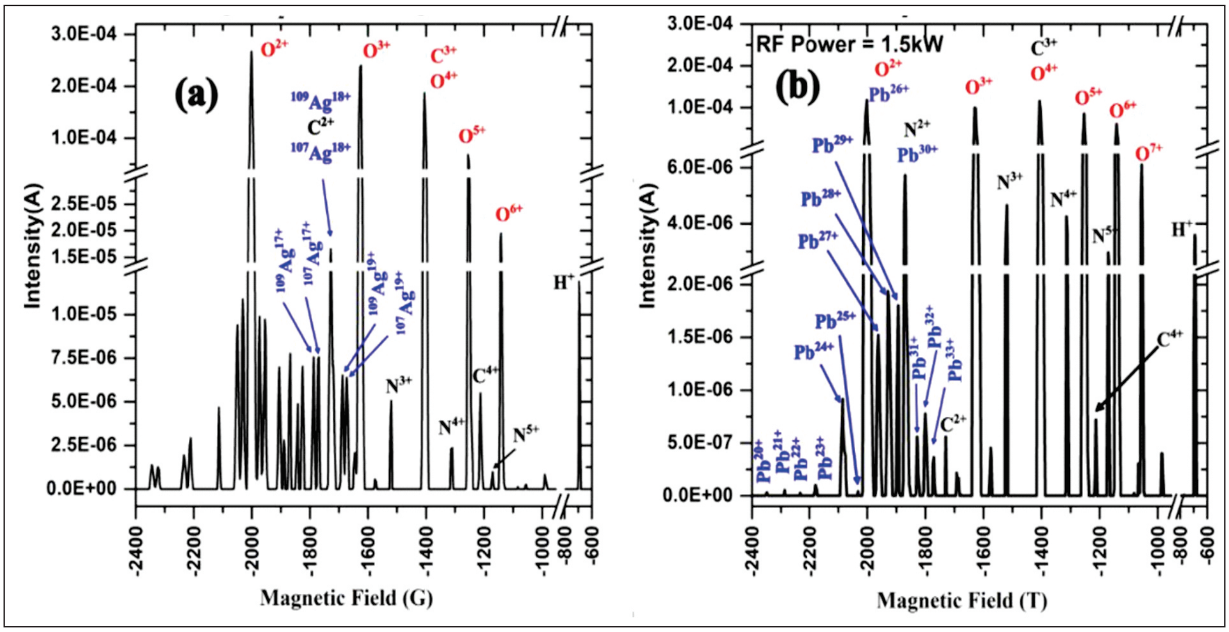

Figure 3: Charge state distribution spectra of (a) Ag and (b) Pb using O_2 as mixing gas.

(c) Preliminary bremsstrahlung measurements

A multi-channel analyser based data acquisition system for measuring Bremsstrahlung spectrum from ECR plasma was installed in the high voltage area and tested (figure 4.). A NaI scintillation detector having an in-built preamplifier was used for recording the spectra. An indigenously developed spectroscopy amplifier was used to amplify the preamplifier signal. A voltage of 800V from a 3 kV NIM based power supply was used to bias the detector. The detector was placed at the 0° port of the analyser magnet of the LEBT section. The energy calibration was carried out using ^{152}Eu and ^{133}Ba sources in the range of 121 keV to 1.1 MeV. The bremsstrahlung spectra were recorded from Ag plasma with O_2 as supporting gas, for different mirror ratios and bias voltages and by keeping all other source parameters constant during the measurement. The mirror ratios were calculated for different coil current settings during the tuning, using POISSON/SUPERFISH codes.

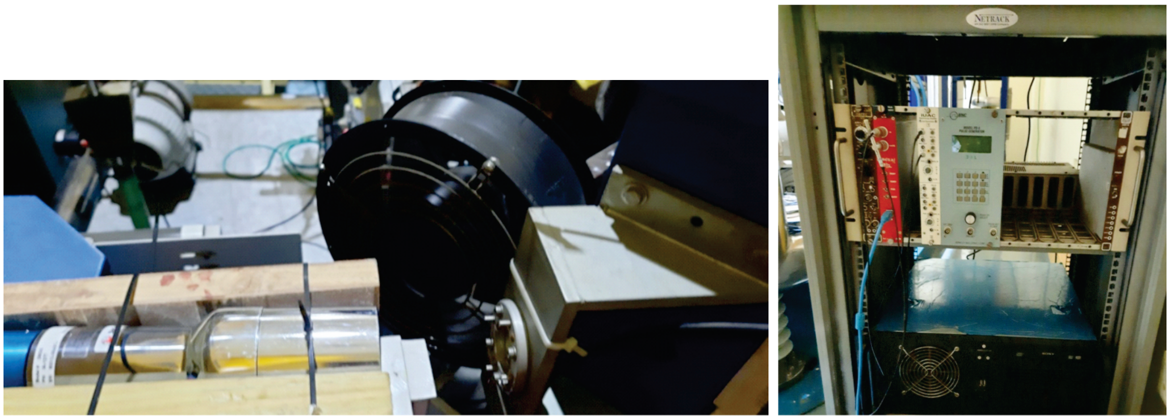

Figure 4. (Left) View of the NaI detector mounted close to the 0° port of analysing magnet and (Right) data acquisition system installed close to the 200 kV high voltage platform.

(D) Beam Tests

HCI beam test was carried out in the newly installed HEBT section up to the 2nd achromat. N^{6+} (A/q = 2.33) beam of initial energy 8 keV/u and intensity of 6.5 eμA was accelerated through the RFQ and all the 6 DTL cavities. The initial energy was gained only through the source extraction voltage. High voltage platform was not floated during this beam test. The beam was bunched using MHB and spiral buncher. The optimized bunch width measured at the Fast Faraday Cup was around 4.8 ns and corresponds to a maximum transmission through RFQ. The final energy of the beam after acceleration through RFQ and the DTL cavities was measured to be 1.8 MeV/u. Beam through RFQ and each DTL cavity was analysed in sequence using first achromatic magnet to achieve the correct energy. Longitudinal and transverse tuning were done in iteration for each of the cavities for optimising maximum transmission. Beam was transported successfully up to the Faraday cup installed after the second achromat magnet. A beam intensity of 280 enA was achieved at the last Faraday cup of the HEBT section. Beam transmission from achromat 1 to achromat 2 was 100 %.

(E) Preventive Maintenance Schedule & Breakdown Maintenance of High Voltage Power Supplies

The group performs yearly scheduled preventive maintenance of every instrument to preserve its life, performance and to ensure breakdown-free operation during the year-long continuous operation of the system.

- In ion source area, all high voltage power supplies (HVPS), deck HVPS (200kV), extractor & focus HVPS were cleaned. All the loose connections were checked and the supplies were operated through remote control. Besides these, all bleeder resistor networks were cleaned and covered with acrylic sheet.
- All power supplies were operated in local and remote modes, with and without load. Finally, all high voltage power supplies were made in working order.
- Installation of oven power supply (60 V/5 A) and the signals in the fiber optical communication system related to the oven power supply were changed.

- Repair of HCI Deck HVPS (200 kV/ 5 mA) :

Deck HVPS was not working due to faulty remote module. This power supply was checked in the lab with an alternate extension cable (the cable was made in the lab). Some signals were not coming from PWM and op-amp ICs. Finally, the faulty ICs were changed. The deck HVPS is working fine.

- Repair of Oven Power Supply (60 V/5 A) :

Oven power supply was faulty due to shorting of the ion source. The power supply was found in shutdown mode and some electronic components were also found faulty. The faulty components were changed and the oven power supply is working fine.

2.1.2 RFQ & DTL Accelerators

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Beam acceleration test has been carried out by injecting an N^{6+} beam of energy 8 keV/u into the RFQ as well as through all six DTL cavities. To maximize the beam intensities just after the DTL cavities, the phase and amplitude of all cavities (MHB, RFQ, SB and DTL's) were optimized. With an input beam intensity of 6.5 eμA at the entrance of the RFQ, the final beam intensity of N^{6+} achieved through DTL-6 was 382 enA at the required energy 1.8 MeV/u. The beam energy has been confirmed through the Achromat-1 (magnetic field of 5203 Gauss) and Achromat-2 (magnetic field of 5589 Gauss). The various beam and RF parameters of RFQ , SB and DTL's are listed in the table 1 below.

Table 1. Energy and RF parameters measured during acceleration of N^{6+} beam.

	RFQ	SB	DTL#1	DTL#2	DTL#3	DTL#4	DTL#5	DTL#6
Measured E (MeV)	0.504	NA	4.48	7.7	11.9	16.1	20.4	25.2
RF Power (kW)	12	0.3	0.9	1.76	5	3.7	6.0	5.3
Pick up (mV)	33	107	39	20	30	30.4	30.6	28.8
Designed E (MeV/u)	0.18	NA	0.32	0.55	0.85	1.15	1.46	1.8

2.1.3 Drift Tube Linear Accelerators and associated Beam Diagnostic Devices

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(A) Present status of DTL cavities and Diagnostics:

Last year, N^{5+} (A/q= 2.8) ion beam was successfully accelerated through all the six DTL cavities and beam current was analysed and measured in the Faraday Cup (FC-04-2) kept after the Achromat bending magnet ACH#1 in the HCI beam hall#3. In this academic year, the beam line was extended from BH#3 to BH#1 and it was planned to accelerate N^{6+} (A/q= 2.3) beam and transport upstream to ACH#2 in beam hall#1. All the cavities were kept ready for the N^{6+}beam acceleration. Some small modifications were also carried out in the cavities during the maintenance period, like addition of Turbo pump adapters, slight rotation of power couplers to optimize the coupling coefficients, cleaning the cavity entrance and exit plates, etc. The low-level RF characterizations of each of the DTL cavities and SB#1 were carried out to ensure the maximum acceleration efficiency and better cavity performance. The RF parameters of the cavities are presented in table 2.

Table 2: The RF characteristics of DTL cavities.

Cavity	SB#1	DTL #1	DTL #2	DTL #3	DTL #4	DTL #5	DTL #6
Resonant Frequency (MHZ)	48.500780	96.995190	96.988811	97.000440	97.000601	97.000190	96.999180
S11 parameter (-dB)	24	35	31	38	35	49	33
Quality Factor (unloaded)	2138	8223	11318	12103	14849	12771	14654
Quality Factor (loaded)	1050	4620	6180	6800	7900	7366	7900
Coupling Coefficient (RF drive coupler)	1.037	0.78	0.83	0.89	0.88	0.85	0.86
Vacuum Achieved (Torr)	1.5×10^{-7}	1.4×10^{-7}	4.6×10^{-7}	2.8×10^{-7}	3.1×10^{-7}	4.5×10^{-7}	1.8×10^{-7}
Maximum RF Power required for A/q=6	1 kW	5kW	11 kW	18kW	18 kW	24 kW	25 kW

In order to check and validate the performance of the cavities with time, they were kept operational all the time and run under high power conditioning mode. All the DTL cavities are running smoothly since 2019. DTL#1 has been tested to a maximum RF power of 6 kW which is more than the required power (5 kW) for A/q = 6. It was observed during conditioning that the vacuum in DTL#2 and DTL#6 started deteriorating. The vacuum leaks were detected through DTL-TP (Turbo Pump) joints. The issues were resolved after replacing the O-rings but this time, copper adapters were also added to the cavities before the TP to change the RF path and to avoid any malfunction of TP controllers due to high power radiation. During the frequency tuning, the motor was found stuck in DTL#4 due to damaged copper-beryllium fingers and it was not possible to minimise the reflection during high-power conditioning. This issue was resolved just by removing the finger by de-soldering them from the tuner rod and now it is working fine. We faced some difficulties in the high-power conditioning of DTL#6 cavity also due to the higher reflections of more than 12 kW. At 11.5kW drive power the reflection was observed to be 1 kW. After sometime, the reflected power improved to 550 watts at 20 kW input power. After 10 days of conditioning, it was found that the reflection increased to 8 kW at 21 kW forward power. The temperature of the flexi solid line was also found very high; 83-88 °C. It was then decided to change the flexi lines to solid coaxial transmission lines to avoid such heating which may change the line impedance and hence lead to the higher reflection. The DTL#6 cavity was opened and some black spots and burned surfaces were found on the top ridge. The cavity was cleaned properly and closed to resume the conditioning again. This year the high-power RF conditioning of DTL#2, DTL#3, DTL#4, DTL#5 and DTL#6 were done up to 10 kW, 14 kW, 8 kW, 8 kW and 10 kW RF power respectively. The cavities were kept ready for the required beam acceleration.

All the beam diagnostic components are regularly used and working fine. They were tested during the N^{6+} beam acceleration also. For the beam test, all the connections were made from BH#3 to the main control room for remote operation. Now the Compact Beam Diagnostic System (CBDS) can be controlled and operated from the main control room.

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

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2.2.1 INTRODUCTION:

The compact, pre-bunched Free Electron Laser facility named as Delhi Light Source (DLS) is being commissioned at IUAC [1,2]. Last year, the production of electron beam of energy of ~ 1.3 MeV by a photocathode based normal conducting RF gun operating at 2860 MHz had been reported. This year, after the installation of the high-power RF source with Circulator, RF conditioning of the gun could be performed at higher power and production of electron beam up to 4.5 MeV was demonstrated. The energy and charge of the produced electron beam was measured using Dipole magnet and ICT respectively. An experimental chamber is being installed in the electron beam line to perform a simple experiment with the electron beam. In near future, the electron from the electron gun will be injected into the compact undulator to produce THz radiation.

2.2.2 PROGRESS OF VARIOUS SUBSYSTEMS OF DLS:

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

2.2.2.1 Commissioning status of the beam line

Last academic year, the complete 3-D designing of the entire beam line along with its commissioning status up to the entrance of the Undulator along with the Solenoid magnet, Beam Position Monitor (BPM), Integrated Current Transformer (ICT) and beam viewer was reported. This year, the Undulator was placed in its actual position in the FEL beam line and it was aligned within a fraction of a mm using Theodolite and the Taylor Hobson alignment tool. The vacuum chamber, for transporting the beam through the Undulator, was also aligned and installed in the beam line. The BPM along with ICT is being installed before and after the vacuum chamber of the Undulator to measure the beam current before and after the undulator.

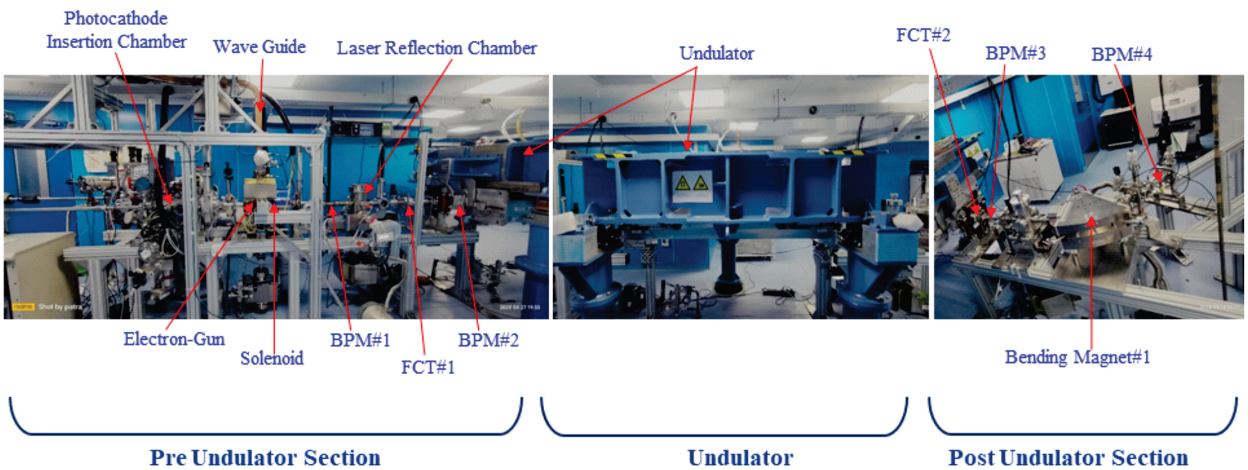

Figure 1. The complete beam line for pre and post Undulator sections along with the first Dipole magnet and the last BPM (BPM#4).

Two Dipole magnets along with their vacuum chambers were received from BARC. One of them got installed at the exit of the undulator after the Terahertz extraction chamber in the sixty degree (60°) bending line of the dipole and is being used for the measurement of energy of the produced electron beam. The straight section of zero-degree line is kept ready for the installation of the experimental chamber to conduct the first experiment using the electron beam. The photograph of the installed beam line along with the bending magnet is shown in figure 1.

2.2.2.2. Final Commissioning of the High- power RF System

In the last year's Annual Report, it was reported that the conditioning of the electron gun, a 2.6 cell 2860 MHz copper cavity, was limited up to the forward power of ~ 800 kW as the proposed vacuum based circulator could not be installed after the Klystron due to some technical issues. This year, in place of the vacuum-based Circulator, a SF_6 Gas based Isolator was installed in the waveguide system [3]. In order to accommodate the new isolator, necessary design changes were made in the RF delivery system. One Wave Guide (WG) pump section with ion pump was removed and the RF window before this WG pump section is now used to separate the vacuum part and the SF_6 part. At the output of the isolator, a Groove to Groove flange adapter and additional new RF window was installed. This RF window has a CPR284F flange at the input side which is pressurized manually with SF_6 using the filling nipple and the needle valve. Manual filling ensures that only very tiny amounts of SF_6 can leak from the WG and not from the filling system or SF_6 bottle. Necessary interlocks for arc sensing and SF6 gas monitoring was incorporated. After installation of the Circulator, the RF conditioning of the photocathode gun could be carried out at higher RF power level.

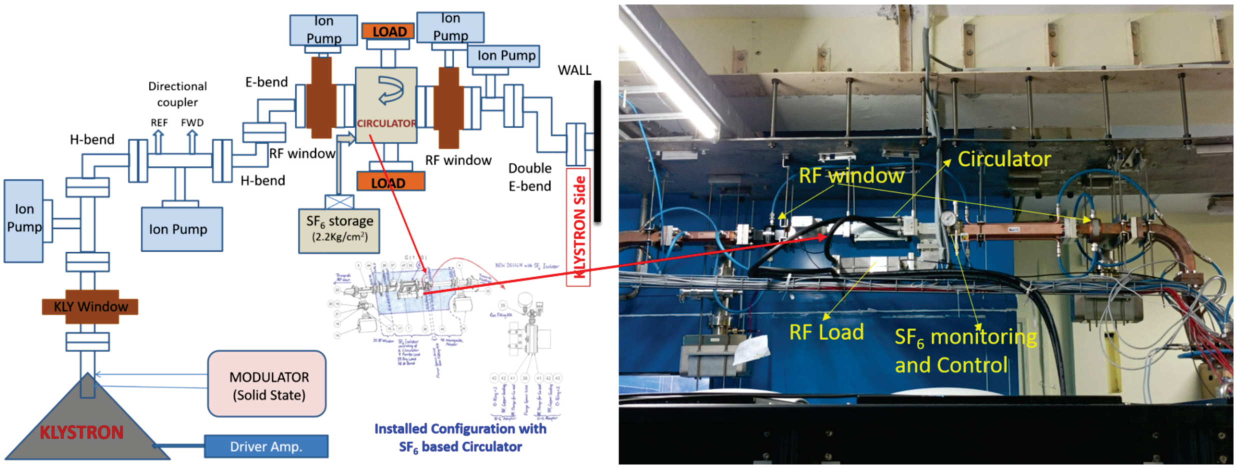

Figure 2. Installation of SF_6 gas-based Isolator for protection against reflected power.

2.2.2.3 RF conditioning of Photocathode Gun and production of high energy electron beam

The production of electron beam was already demonstrated last year by striking a nano second UV laser beam on the Cu photocathode, but the energy of the produced beam was ~1 MeV due to limitations in the high-power RF system to condition the cavity beyond 800 kW. After installation of the SF_6 based isolator, rigorous RF conditioning of the RF photo cathode gun was continued in 24 7 mode. The gun was tuned to 2860 MHz resonance frequency by precisely setting up the temperature of the water chiller to 35 °C with an accuracy of 0.05 °C. The load matching was done by optimizing the position of the photocathode plug using the vacuum manipulator at the entrance of the gun. The VSWR interlock conditions were always maintained well within the specified limit of the Klystron by continuously tracking the frequency of the Gun with the master oscillator frequency to minimize the reflected power during conditioning. The high-power conditioning was started with a low pulse duration of 1.2 µs up to 10 MW of RF forward power initially supplied at 10Hz repetition rate and then pulse duration was increased in steps up to the desired 4 s pulse duration. The dark current was monitored during RF conditioning using a commercial faraday cup compatible for continuous dc beam operation and a lock-in amplifier. The Electric field generated in the RF gun as well as the energy of the electron beam at the given forward power level was estimated. In order to calibrate the Electric field generated in the Cavity, the Energy measurement of the photo electron beam generated at different RF forward power levels was carried out.

2.2.2.4 Measurement of Energy and charge of the produced electron beam

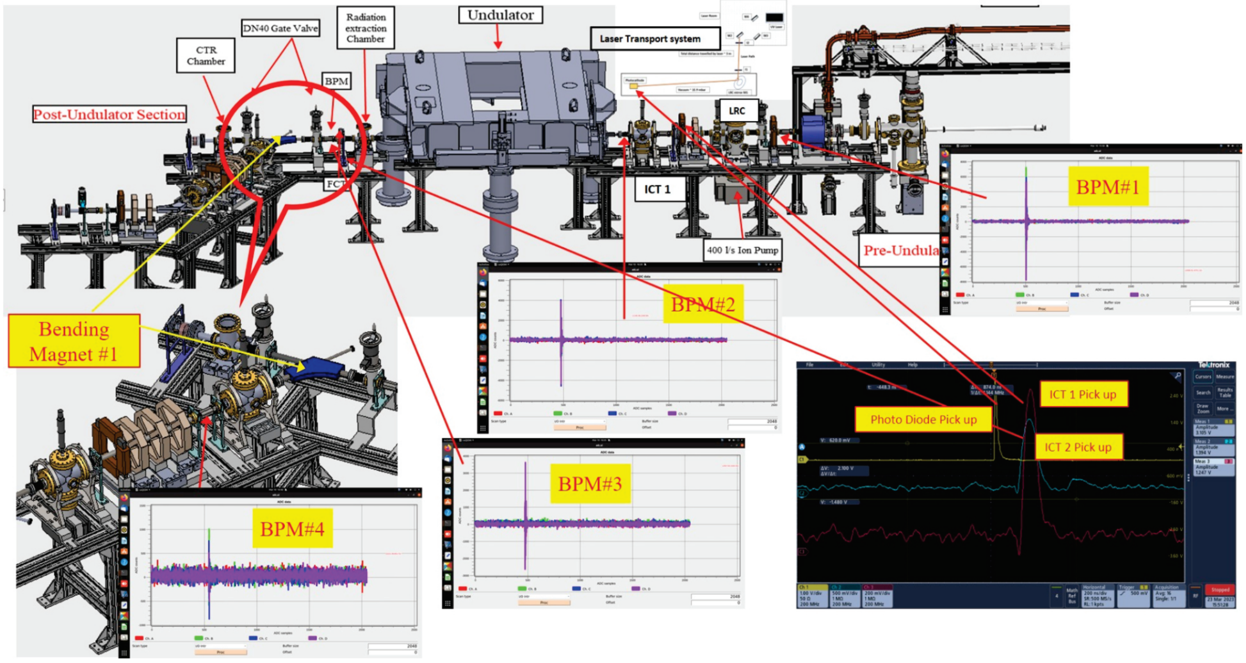

Figure 3. The complete beam line for pre and post Undulator section along with modifications for laser viewer.

In order to produce electrons from the copper photocathode, UV laser having wavelength range 266 nm was made to incident on the cathode. As the distance to be travelled by the laser from the laser room is approximately 3 meter, with about half the distance in air and half the distance in vacuum, a simple method was developed to transport the laser beam accurately on the center of the photocathode. A theodolite was placed in the laser room where one can see the reflection of the photocathode from the mirror placed in the Laser Reflection Chamber (LRC) (figure 3). Two irises were placed along the line to define the path and the nanosecond UV laser was transported through that path. Four BPMs were installed at different locations in the beam line to see the position of laser induced electron beam. The laser incident spot on the copper photocathode was varied to keep the position of the electron beam at the center of both the BPMs after optimization of the magnetic field of the solenoid. The Beam line steerers and the Kicker coil of the undulator were used to keep the position centered in the post undulator BPM at the entrance of the dipole magnet. The charge of the electron beam was measured using the ICT installed along with the BPM. The magnetic field in the dipole was varied to transport the electron beam through the 60 degree line and signals were obtained in the BPM installed in the same line after the dipole. As there was no energy slit installed at the exit of the first dipole magnet, the magnetic field required to keep the electron at the center of the last BPM(#4) was used to measure the energy of the electron beam. The electric charge before and after the undulator was measured using the pick-up signal from the ICT on an oscilloscope. The signals of various BPMs along with the ICT signal during beam Energy measurement are shown in figure 3. The measured beam energy values at different RF power levels along with the charges are listed in Table 1.

Table 1. Measured values of electron beam parameters

Input Power of RF gun (MW)	Acc. Field of RF gun (MV/m)	Mag. Field (BM#1) (Gauss)	Measured Energy of e-beam (MeV)	Measured charge of e-beam (pC)
3	56.5	480	3.4	0.44
3.5	61	510	3.8	0.59
4	65	550	4.5	0.81

2.2.2.5 Status of the Photocathode Deposition System

The production of electron beam was already demonstrated by striking the laser beam on the Cu photocathode. It is being planned subsequently to enhance the electron beam production using Cs_2Te photocathode. For this semiconductor photocathode, a cathode deposition system had been designed at IUAC in the past and subsequently fabricated at Brookhaven National Laboratory (BNL), USA. Last year, the installation of the entire photocathode deposition system near the electron gun inside the clean room (shown in figure 4(a)) was reported. This year, the alignment of the magnetic manipulators and cathode plug transfer from one manipulator to the other was carried out in air. The entire system was leak checked at a leak rate of ~5x10^{-12} mbar l/s and found to be leak tight. The temperature calibration of the cathode plug inside the deposition chamber was performed and the results are shown in figure-4(b). The calibration of the quartz crystal monitor for thickness measurement of the cathode film will be conducted shortly, and subsequently the actual deposition will be started on Molybdenum substrate.

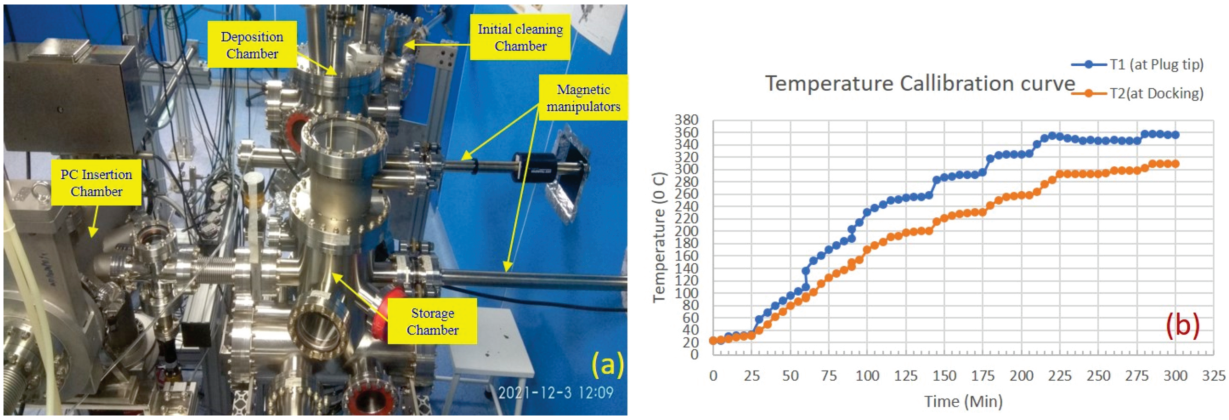

Figure 4. (a) Photograph of the photocathode deposition system installed at IUAC
(b) Temperature calibration of the photocathode plug.

2.2.2.6 Status of the development of the Fibre Laser system

A state-of-the-art Fiber Laser system is being developed as a collaborative project between IUAC and High Energy Accelerator Research Organization (KEK), Japan. The laser system, which is at the final stage of development, is expected to produce ultra-short laser pulses with energy 1.5 Joule with a pulse width of 500 femto-seconds. The frequency of the Oscillator of the fiber laser system is 130 MHz, which after down-conversion will produce laser pulse at a repetition rate of 5–10 MHz. There will be a provision to split a single laser pulse into 2, 4, 8 and 16 pulses. However, the energy per pulse after splitting will be reduced compared to the initial energy of 1.5 Joule.

Being a state of the art and futuristic device, many technical challenges are being faced to meet the specifications of the device. Three young personnel of IUAC had received hands on training at RRCAT, Indore and will be working on the IUAC's fiber laser system at KEK, Japan during next few months. It is expected that the final testing of the complete fiber laser system will be accomplished at KEK Japan by the autumn of '2023 and subsequently it will be shipped to IUAC and installed by the end of '2023.

2.3 CONCLUSION

The commissioning of the compact Free Electron Laser at IUAC for the production of THz beam is in its final phase. The RF conditioning of the electron gun has been accomplished up to 5 MW of peak RF power for the desired 4 s duration. Production of 4.5 MeV electron beam from the RF photo cathode gun using a nano-second UV laser has been kept ready for user experiments. High power RF conditioning is being continued up to a power of 5 MW and 10 MW at 4 s and 1.2 s pulse width respectively. The femto second fiber laser system is also in the final stage of development and is expected to be commissioned at IUAC by the end of 2023. It is expected that the first signature of THz radiation can be demonstrated within a year.

References:

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

[2] S. Ghosh, et. al. Proceeding of National Laser conference, IIT Kharagpur, December 2023

[3] B.K. Sahu, et. al, Proceeding of Indian Particle Accelerator Conference, (InPAC2023), Paper ID-382.