

भापअ केंद्र –टीआईएफआर पेलेट्रॉन सुविधा

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अतिचालक लीनॉक एवं संबद्ध विकास

वी.नानल^{1,*}, ए.श्रीवास्तव^{2,3}, आर.पलित¹ और जे.ए.गोरे²

¹डीएनएपी, टाटा मूलभूत अनुसंधान संस्थान, मुंबई-४००००५, भारत

²नाभिकीय भौतिकी प्रभाग, भाभा परमाणु अनुसंधान केंद्र, ट्रॉम्बे, मुंबई-४०००८५, भारत

³होमी भाभा राष्ट्रीय संस्थान, अनुशक्ति नगर, मुंबई-४०००९४, भारत



एक क्रायोस्टेट के अंदर चार चौथाई तरंग अनुनादकों का संयोजन।

सारांश

भाभा परमाणु अनुसंधान केंद्र और टाटा मूलभूत अनुसंधान संस्थान के बीच एक सहयोगी परियोजना के रूप में स्थापित पेलेट्रॉन लीनॉक सुविधा, भारत में भारी-आयन त्वरक-आधारित अनुसंधान के लिए एक मुख्य केंद्र रहा है। 14 MV पेलेट्रॉन त्वरक का दिसंबर 1988 में कमीशन किया गया और त्वरित किरणपुंजों की संवृद्धि हेतु स्वदेशी रूप से विकसित अतिचालक लीनॉक अभिवर्धक के साथ संवर्धन किया गया। लीनॉक अभिवर्धक की प्रावस्था I को 2002 में शुरू किया गया और दूसरी प्रावस्था II पूरी होने के बाद, यह सुविधा नवंबर 2007 में उपयोगकर्ताओं को समर्पित की गई। यह देश का प्रथम अतिचालक त्वरक है और अतिचालक लीनॉक का विकास भारत में त्वरक प्रौद्योगिकी में एक प्रमुख मील का पत्थर है। लीनॉक अभिवर्धक के अधिकांश महत्वपूर्ण घटकों को स्वदेशी रूप से अभिकल्पित और विकसित किया गया है। नाभिकीय, परमाणु, संघनित पदार्थ, जैव-पर्यावरणीय भौतिकी एवं अनुप्रयोगों में सीमांत अनुसंधान को आगे बढ़ाने के लिए इस केंद्र में विभिन्न प्रकार की अत्याधुनिक प्रयोगात्मक सुविधाएं विकसित की गई हैं। यह सुविधा वैज्ञानिक रूप से उपयोगी है और इसके महत्वपूर्ण रोचक परिणाम सामने आए हैं। यह लेख लीनॉक के विकास, संबंधित उपकरण और कुछ अनुप्रयोग-अभिविन्यासित कार्यक्रमों की एक झलक प्रदान करता है।

BARC-TIFR Pelletron Facility

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Superconducting LINAC and Associated Developments

V. Nanal^{1,*}, A. Shrivastava^{2,3}, R. Palit¹ and J. A. Gore²

¹DNAP, Tata Institute of Fundamental Research, Mumbai-400005, INDIA

²Nuclear Physics Division, Bhabha Atomic Research Centre, Trombay, Mumbai-400085, INDIA

³Homi Bhabha National Institute, Anushakti Nagar, Mumbai – 400094, India



Assembly of four quarter wave resonators inside a cryostat.

ABSTRACT

The Pelletron Linac Facility, set up as a collaborative project between the Bhabha Atomic Research Centre and the Tata Institute of Fundamental Research, has been a major centre for heavy-ion accelerator-based research in India. The 14 MV Pelletron accelerator was commissioned in December 1988 and was augmented with the indigenously developed superconducting Linac booster to enhance the energy of the accelerated beams. The phase I of linac booster was commissioned in 2002, and after the completion of phase II, the facility was dedicated to users in November 2007. This is the first superconducting accelerator in the country, and the development of the superconducting Linac is a major milestone in the accelerator technology in India. Most of the critical components of the Linac booster have been designed and developed indigenously. A variety of state-of-the-art experimental facilities have been developed at this centre to pursue frontier research in nuclear, atomic, condensed matter, bio-environmental physics and applications. The facility is scientifically productive and has led to significant interesting results. This article gives a glimpse of the developments of the Linac, associated instrumentation and some application-oriented programmes.

KEYWORDS: Superconducting LINAC, Pelletron accelerator, Pelletron

*Author for Correspondence: V. Nanal
E-mail: nanal@tifr.res.in

Introduction

The Pelletron Linac Facility (PLF), set up as a collaborative project between the Bhabha Atomic Research Centre (BARC) and the Tata Institute of Fundamental Research (TIFR), has been a major centre for heavy ion accelerator-based research in India [1]. The Pelletron accelerator (procured from NEC, USA) was formally inaugurated on 30th December 1988 and marked an important milestone in nuclear physics research in India. The facility was augmented with the indigenously developed superconducting linac booster to enhance the energy of the accelerated beams [2]. The phase I (Superbuncher +3 Modules) of the Linac booster was commissioned in 2002 and after the completion of phase II (4 Modules), the facility was dedicated to users on 28th November 2007. This is the first superconducting accelerator in the country. *Development of the superconducting Linac is a significant milestone in the accelerator technology in India. Most of the critical components of the Linac booster have been designed and developed indigenously.*

A variety of state-of-the-art experimental facilities have been developed at this centre to pursue frontier research in nuclear, atomic, condensed matter, bio-environmental physics and applications. The facility is scientifically productive, with ~75% uptime, and serves the experimental community comprising scientists and students from BARC, TIFR, research centres, and universities within India and abroad. Till date more than 350 users from about 50 institutions (including Universities, IITs) have carried out the research at this facility. About 165 Ph.D. theses and about 825 publications (including 40 Letters) in international refereed journals have resulted from the research activities at the PLF. More details about the facility, programs and publications can be found at the PLF webpage <https://www.tifr.res.in/pell/>

The linac booster consists of seven liquid helium cryostat modules, each housing four lead-coated (2 μ m) copper quarter wave resonators (See Figure 1). The cavities are designed to operate at 150 MHz with an optimum acceptance at a velocity corresponding to $\beta=0.1$. In order to maintain a stable phase and amplitude of the electric field in the cavity, the RF controller cards based on a self-excited loop (SEL) with phase and amplitude feedback have been developed indigenously. The cryogenic system for the LINAC has been designed for a typical power dissipation of 6 W in each resonator. The LINAC Phase I (superbuncher + 3 modules) and Phase II (4 modules) are connected by an achromatic, isochronous mid-bend magnet system (QD-MD-QD-QDMD-QD). A compact longitudinal phase space is essential for acceptance in Phase II after the mid-bend and for optimization of the beam quality at target position.

The heart of the cryogenic system for the heavy-ion superconducting linac booster is a custom-built liquid helium refrigerator, the Linde TCF50S. The refrigerator is designed with a dual JT (Joule-Thomson valve) at the final cooling stage, which allows simultaneous connections to the module cryostats and to a liquid helium storage dewar (1000 Litre). The two-phase helium at 4.5 K produced at the JT stage in the refrigerator is delivered to the cryostats through a cryogenic distribution system. The phase separation is achieved in the individual cryostats and the cold (4.5 K) helium gas is returned,

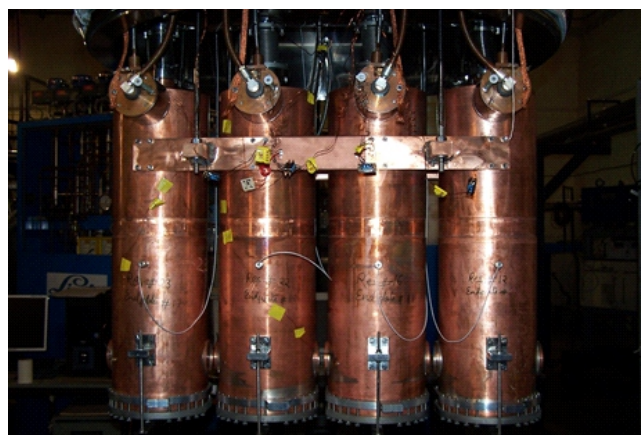


Fig.1: Assembly of four quarter wave resonators inside a cryostat.

by the distribution system, back to the helium refrigerator. The cryogenic distribution system is designed to deliver both liquid helium and liquid nitrogen to the cryostats.

The performance of QWR is found to be excellent with an average energy gain of 0.4 MV/q per cavity corresponding to 80% of the design value ($Q \sim 1-2 \times 10^8$, an average accelerating field of 2-2.5 MV/m). Beam transmission from the entry to the exit of the LINAC is found to be 80% and the beam timing (FWHM) of ~ 600 ps is measured at the target position. For acceleration of different beams, an algorithm for RF power and phase settings of the individual resonators has been devised. The Linac is routinely operated for experiments using beams of ^{12}C to ^{35}Cl . Due to growing interest in studying light ion induced reactions at higher energies, we have also accelerated ^7Li ($E < 10$ MeV/A) and $^{10,11}\text{B}$ ($E < 8$ MeV/A) beams through Linac. The terminal gas stripper is routinely used for Silicon and heavier beam operations with LINAC.

Recent Developments at Linac

Various sub-systems of the LINAC are continuously being improved to facilitate ease of operations and improve the reliability.

The refrigeration plant has been upgraded to enhance the refrigeration capacity to ~450 Watts at 4.5K without LN2 pre-cool, from the original capacity of ~300 Watts. This completely eliminates the use of liquid Nitrogen for plant pre-cooling, which helps to reduce operational costs and more importantly improves the stability of operations. The entire plant upgrade was successfully completed at site. A 400 KVA UPS has been installed for the main Helium Compressor to minimize failures due to power fluctuations. Improvements have been made to the helium recovery system for minimizing helium losses.

While setting the beam acceleration through Linac, the phases of cavities are independently set for appropriate acceleration of the bunched beams injected from the Pelletron. In order to improve the reliability and accuracy of the RF phase settings, a high-precision phase measurement unit has been developed based on the AD8302 phase detector chip. In order to obtain a complete range of 360°, two chips are required to

generate the phase angle along with the quadrant information. The phase difference between the master oscillator and the cavity pickup is processed in two detector chips operating 90° out of phase. The outputs are processed to obtain the absolute phase angle and the quadrant information. This is then displayed in the range $\pm 180^\circ$ or $0-360^\circ$.

Detailed phase stability measurements of the RF subsystem consisting of various RF devices, which operate at different sub-harmonic of the Linac clock, have been carried out. It was observed that temperature instabilities, ground loops and poor RF/EMI shielding due to aging effects were responsible for the phase jitter and drifts. The long-term drifts and phase noise in the RF control of the LE buncher system have been minimized to a level better than 50 ps.

The control systems for cryogenic distribution, coupler, tuners, and beam line slits have been indigenously developed and installed. Most of the instrumentation systems are controlled/monitored through silicon lab-based microcontrollers and are designed with a user friendly interface. The status of vacuum and beam line valves (open/close) can be viewed from the control room via LabView interface. A simple scintillator detector system, consisting of CsI crystal developed at BARC, coupled to a commercial PMT, is being set up to monitor the radiation levels around the cryostat and to enable the requisite access restriction for safety of personnel. A PIC18F4520 microcontroller based remote display unit for neutron area monitors is developed. The search & secure system has been upgraded to sequential mode to comply with safety requirements.

EPICS (Experimental Physics and Industrial Control System), an open-source toolset widely used for accelerator control, is being implemented to upgrade the Java-based distributed control system of the Linac. The EPICS-based control system has been developed and installed for the beam transport modules, including dipole, quadrupole, steerer magnets, and beam diagnostic devices (Faraday cup and Beam Profile Monitor controllers). The Input/Output Controller (IOC) for the beam control system is built on the EPICS Base 7 platform, running on Linux with the Asyn module and stream device protocol over IP. The front-end GUI is developed using Phoebe CSS. Additionally, we have developed a standalone slit control system and a remote-controlled stepper motor controller for the tuner and coupler system. The integration of these systems, along with the Beam Transport control system, into a unified GUI is currently in progress.

The Target lab, which is extensively used to prepare specialised self supporting targets for in-beam experiments, with natural and isotopically enriched materials, and stripper carbon foils for the accelerator. A new 4-pocket electron gun setup and a new rolling machine have been installed. Resistive evaporation setup has been refurbished. A dedicated thickness monitor setup to measure alpha energy-loss using standard alpha source has been set up.

For heat treatment of low-beta Nb cavities, a custom-designed, bottom loading, high-vacuum-high-temperature furnace to operate at a maximum of 1200°C has been installed at TIFR. The design was optimized to provide a vertical hot zone of 600 mm diameter and 1000 mm high with a load capacity of

100 kg. The heat shields were optimized to achieve the maximum operating temperature at a modest power of less than 20kW.

ELOG, a web based application, is set up for operation and maintenance record keeping. This also includes inventory, major fault log and is completely shareable.

Beam Scanner and Variable Pulse Width Chopper

We have developed a simple method of beam scanning using an X-Y magnetic steerer in the beamline. A triangular waveform is applied to control the excitation current in the steerer for scanning the beam simultaneously in both horizontal (X) and vertical (Y) planes. A programme generates a raster pattern governed by a presettable number of X sweeps for each Y sweep. The scan area, step size and scanning speed are adjustable parameters. The dwell time at each of X-Y position was adjusted considering the time constant arising due to the inductance of the steerer. Typically, a beam scan on a $\sim 10 \times 10 \text{ mm}^2$ is achieved in ~ 5 sec. The scanner has been successfully employed for uniform irradiation of GaAs substrate for photoconductive THz applications using ^{12}C beam

Lifetime measurements in gamma spectroscopy are a crucial tool in nuclear physics. To measure the lifetimes in the intermediate range of milliseconds to minutes, a novel beam chopper based on beamline steerer magnet is developed. The beam is swept away on a nearby Tantalum slit, in the desired time window by controlling the high-current power supply of the steerer magnet using a square wave. The system is powered by an ARM Cortex-M3 32-bit RISC processor, part of the ARM® Cortex™-M3 family. It features a graphic touch-screen LCD and is fully programmable through a user-friendly menu. Both the voltage levels (to control the degree of beam deflection) and the timing at each voltage level (to control the beam on/off duration) can be programmed. The beam deflection can occur either horizontally or vertically using the X or Y steerer power supply. The beam chopper was successfully tested with a 45 MeV ^{12}C beam decay spectroscopy of ^{139}Ce (half-life $\sim$ ms).

Experimental Programmes

There are a total of seven beam lines housed in two separate caves-hall 1 and 2 (See Figures 2 and 3). Experiments are performed in both halls with beams from Linac as well as from Pelletron. In addition, beams from Pelletron are available in the cascade hall (5 beam lines) and proton/neutron irradiation setup at 6 m. The research activities at the facility span a variety of problems in nuclear, atomic, condensed matter physics and interdisciplinary areas. The research work in nuclear physics, which is the main thrust of this facility, covers areas of nuclear structure studies at high angular momentum and excitation energies; and the heavy ion reaction dynamics-elastic, inelastic, transfer, fusion and fission reactions. In addition, studies pertaining to nuclear data generation relevant to nuclear reactors as well as IAEA coordinated research programs on advanced nuclear reactors, nuclear astrophysics, and elemental analysis using PIGE (Particle Induced Gamma Emission) are carried out. Application-oriented programs like radioisotopes production, radiation damage studies (space-bound devices, yield improvement in wheat & rice seeds), secondary neutron



Fig.2: Experimental area User Hall 1 where both Pelletron and LINAC beams are located.

production for cross section measurements, radiation dosimetry studies, ion irradiation in semiconductor crystals for photoconductive THz emitters, Accelerator Mass Spectrometry, production of track-etch membranes etc., are also pursued. Many new experimental activities have been initiated in the recent past by different user groups.

Major experimental facilities include:

- Clover Detector Array for discrete gamma ray spectroscopy with auxiliary detectors
- 150 cm diameter Scattering Chamber, with two independently rotatable arms permitting detector rotation and target ladder adjustment from remote without beam interruption using Programmable Logic Controller, for charged particle spectroscopy and fission studies
- $\text{BaF}_2/\text{LaBr}_3$ array for high energy gamma ray studies with BGO/Nal(Tl) multiplicity filter
- Charged Particle Array based on Si pad (ΔE) and CsI(E) detectors
- Neutron Detectors Array of 18 Liquid Scintillation detectors and Annular parallel plate avalanche counter having 12 segments with angular coverage from 5° to 11° , for Time of Flight Technique based compound nucleus residue tagging
- MWPC and Si-strip detectors for angular distribution measurements of particles
- 7.0 Tesla superconducting magnet for hyperfine interaction studies
- Irradiation setup and Low background offline counting facility
- Electron spectrometer, X-ray detector setups, recoil-ion spectrometer, atomic-hydrogen source and a multiple target holder assembly for atomic physics studies with gas and foil targets
- High current proton (upto 24 MeV, ~ 200 nA) and neutron irradiation (through (p,n) reaction on Li, Be targets) facility

A Momentum Achromat for light Rare Ion Experiments (MARIE) is under development. A VME based DAQ and

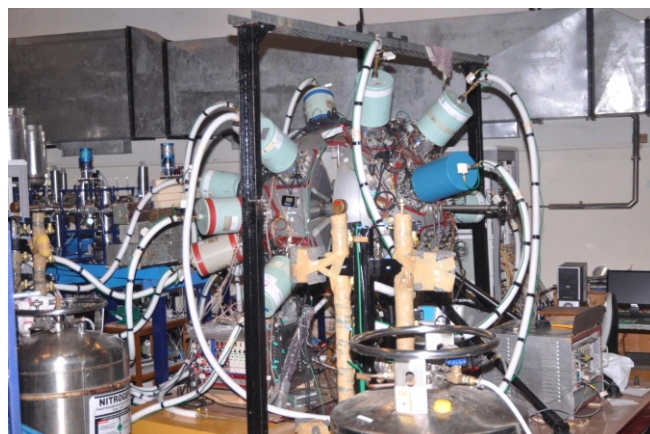


Fig.3: Picture of the Indian National Gamma Array with the Compton suppressed clover detectors in user Hall 2 at PLF.

advanced digital DAQ with analysis programs are developed in-house. In addition, Indian National Gamma Array (INGA) was installed at PLF [3], a new readout scheme based on the Digital Signal Processing (DSP) technique. The INGA, consisting of a 24 Clover HPGGe detector array with a total photo-peak detection efficiency of $\sim 5\%$, is a powerful "femtoscope" for the study of the structure of atomic nuclei at high spins (see Fig. 3). More than 50 experiments have been successfully completed. A versatile low-temperature high-magnetic-field setup is used for an on-line time differential perturbed angular distribution (TDPAD) technique to study different problems in solid state physics [4] as well as for measurements of nuclear g-factors, an essential ingredient for understanding nuclear structure at high excitation energies. The R&D efforts in instrumentation in the laboratory have also led to various international collaborations, including those with major upcoming RIB facilities such as FAIR and SPIRAL2.

Interdisciplinary Research Programmes

Demand for production and separation of clinically important radionuclides from non-reactor source has grown in recent years. The research work at PLF has resulted in development of innovative techniques on methods for separation of no-carrier-added radionuclides using benign chemicals and chemical pathways following the mandate of Green Chemistry [5].

Prof. Prabhu's group have demonstrated continuous wave (CW) terahertz generation from antennas fabricated on ^{12}C -irradiated semi-insulating (SI) GaAs substrates [6]. The dark current drawn by the antennas fabricated on irradiated substrates is up to 4 orders of magnitude lower compared to antennas fabricated on un-irradiated substrates, while the photocurrents decrease by only orders of magnitude. This can be attributed to the strong reduction of the carrier lifetime by about 2.5 orders of magnitude. Reduced thermal heating allows for higher bias voltages to the irradiated antenna devices resulting in higher CW terahertz power, just slightly lower than that of low-temperature grown GaAs (LT GaAs) at similar excitation conditions.

The radiation damage studies for space devices/components are also routinely performed at PLF, TIFR.

Shanmugam *et al.* [7] had studied the Silicon Drift Detector (SDD), intended to be used in Chandrayaan-2 instruments, with an aim to understand and quantify spectroscopic performance degradation due to irradiation. The expected end-of-life (EOL) 10MeV equivalent proton fluence was modeled using SPENVIS simulation software. The Silicon Drift Detector was irradiated with 10 MeV protons for the doses up to 24 krad in logarithmic steps and measured the energy resolution and the leakage current at each dose and it was shown that the energy resolution degradation was acceptable for the cumulative proton dose of ~11 krad, which was within acceptable limits.

Future Plans

To increase the mass acceptance of the heavy-ion superconducting Linac, it was decided to replace the lead plated Cu cavities ($\beta=0.1$) by low beta ($\beta=0.07$) bulk-Niobium (Nb) cavities, in the first linac module. This together with high-voltage upgrade of the Pelletron will lead to significant increase in overall performance.

The Nb QWR design has been finalised and two SS prototypes (one at CDM-BARC and one at CWK-TIFR) have been fabricated. For the design qualification, resonant frequency measurement and field mapping using the bead-pull method was done. A precision bead-pull test setup has been developed at TIFR, employing a 6 mm diameter teflon bead for this purpose. Changes in electric field and resonant frequency were measured in two ways - i) frequency modulation technique with a high-precision signal generator and a 500 MHz digital oscilloscope, and ii) measurement of the electric field from the phase shifts using a Vector Network Analyzer. The comparison with simulations is then used to optimize and finalise the Nb QWR dimensions. Efforts are underway for the development of digital LLRF control for the superconducting cavities and solid state amplifiers.

Upgradation of the various experimental facilities is an ongoing process. The development of heavier ion beams, such as ^{40}Ca , ^{48}Ti , ^{56}Fe , and ^{58}Ni , has been initiated. Additionally, efforts to develop special beams of isotopes like ^3He , ^{10}Be , and ^{14}C due to their significant scientific interest are underway.

Acknowledgments

The BARC-TIFR Pelletron Linac Facility is an unique and exceptional facility. Right from the inception to continued productive operations, it has been a great teamwork of generations of scientists, technicians, and support staff. We are thankful to all those who have been instrumental in shaping the facility. We gratefully acknowledge the PLF staff, users, DNAP (TIFR), NPD(BARC) and various other sections of TIFR and BARC, for their constant support.

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