उच्च तीव्रता प्रोटॉन त्वरक

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LEHIPA के लिए उच्च शक्ति वाली रेडियो आवृत्ति प्रणालियां

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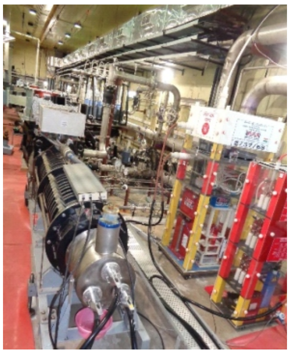

क्लाइस्ट्रॉन एच.पी.आर.एफ. प्रणाली

सारांश

निम्न ऊर्जा उच्च तीव्रता प्रोटॉन त्वरक (एल.ई.एच.आई.पी.ए) को स्वदेशी रूप से निर्मित किया गया है और प्रोटॉन किरण के त्वरण को 20 MeV की ऊर्जा स्तर तक बढ़ाया गया है। इस तीन त्वरक गुहाओं के सोपानी संचालन द्वार प्राप्त किया गया है; रेडियो आवृत्ति चतुर्द्ध्रुवी (आर.एफ.क्यू) और दो चरण अपवाह नालिका रैख़ित त्वरक (ड्रिफ्ट ट्यूब लिनक्स - डी.टी.एल) को तीन क्लाइस्ट्रॉन आधारित उच्च शक्ति 352 MHz प्रणालीयो द्वारा, प्रत्येक 1 मेगावाट प्रणाली से संचालित किया गया है। पूर्ण रूप से परीक्षित किए गए रेडियो आवृत्ति (आर.एफ.) और डीसी घटकों और/या उप प्रणालियों, शक्ति आपूर्ति, मापन और नैदानिकी अंतर्बद्ध और सुरक्षा प्रणालि को एकीकृत, परीक्षण किया गया और एक समेकित उच्च शक्ति रेडियो आवृत्ति (एच.पी.आर.एफ) प्रणाली के रूप में स्थापित किया गया है। 10 किलोवाट का एक ठोस अवस्था शक्ति प्रवर्धक विकसित किया गया है बंचर गुहिका को शक्ति प्रदान करता है।

High Intensity Proton Accelerator

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High Power Radio Frequency Systems for LEHIPA

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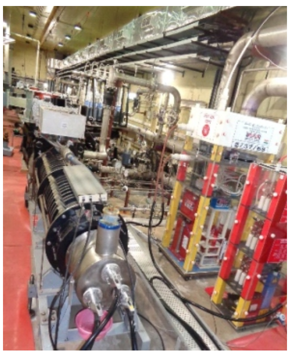

Klystron HPRF system

ABSTRACT

The Low Energy High Intensity Proton Accelerator (LEHIPA) has been indigenously built and proton beam has been accelerated to an energy of 20 MeV. This has been achieved by driving a cascade of three accelerator cavities; Radio frequency quadrupoles (RFQ) and two stages of Drift Tube Linacs (DTL) i.e. 10 MeV DTL and 20 MeV DTL by each of the three klystron based high power 1 MW at 352 MHz systems. The thoroughly tested radio frequency (RF) and DC components and/or sub systems, power supplies, measurement and diagnostics, interlock and protection systems were integrated, tested and commissioned as a consolidated high power RF (HPRF) system. The RF power from klystron RF system is transmitted through high power rectangular waveguide WR2300 systems towards accelerating cavity. A solid-state power amplifier of 10 kW has been developed and powers the buncher cavity.

KEYWORDS: *Accelerator, Buncher, Interlock and protection, RF, Klystron, LEHIPA, Proton, Waveguide*

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Introduction

High energy proton accelerators have applications in the areas of scientific, medical etc. BARC is embarked upon the development of high energy proton accelerator for its ambitious program of Accelerator Driven Sub-critical reactor (ADS). In ADS [1], proton beam from proton accelerator is coupled to a sub critical reactor, which can be operated in sub-critical mode and have inherent safety features. As a front end of a high energy proton accelerator development, LEHIPA has been developed and commissioned at BARC and accelerated the proton beam up to 20 MeV. LEHIPA has three accelerator cavities viz., 3 MeV Radio frequency quadrupole (RFQ), 10 MeV and 20 MeV Drift Tube Linacs (DTL) that are powered by each of Klystron based high power radio frequency (HPRF) system. The article describes details of klystron based HPRF system, its wave guide (WG) based transmission system and a solid state amplifier (SSA) for buncher cavity.

Klystron Based MW Level HPRF Systems

Radio frequency (RF) particle accelerators use RF fields in the accelerator cavities for particle acceleration, which is generated by RF power. The HPRF system is an important critical system that generates electric field across the cavity for beam acceleration.

LEHIPA (20 MeV) - a front end of ADS, uses three 352 MHz, 1 MW klystron (TH2089) based HPRF systems [2] to power its three accelerating sections viz. 3 MeV RFQ, 10 MeV DTL and 20 MeV DTL. These three accelerating sections are coupled in series via their respective beam transport lines viz. low energy beam transport (LEBT) between ion source and RFQ, and medium energy beam transport (MEBT) between RFQ and 10 MeV DTL. The MEBT section includes a buncher cavity, which is powered by a 10 kW solid state RF power amplifier. The three klystron RF systems have been successfully designed, developed, tested and then, integrated with RFQ and both the DTLs to accelerate the proton beam to 20 MeV energy.

HPRF systems are complex and comprise of a variety of sub-systems. These systems incorporate high voltage and high current subsystems in addition to RF Power components, measurement & diagnostics and interlock & protection sub systems. All these except klystron and circulator are indigenous including high efficiency & compact-bias supplies, waveguide components with reduced insertion losses, fast protection system against arcing & other fault conditions [2]. Mitigation of RF radiated & conducted emission [3] and proper thermal management has ensured the reliable operation of HPRF system.

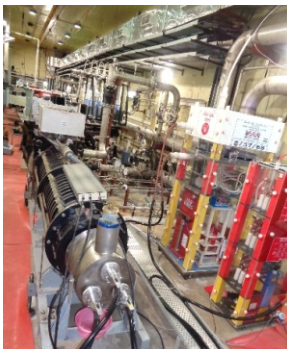

Fig.1: Klystron HPRF system.

Fig.2: Klystron HPRF with WG line.

Each of the 1 MW at 352 MHz RF system (Fig.1 & 2) comprises of 1 MW klystron, RF components like harmonic filter, directional coupler, circulator, RF loads, interlock and protection system (Fig.3), eight low voltage (LV) and high voltage (HV) bias supplies, wave-guide window, and WR2300 wave-guide components, like straight sections, magic tees, bends etc. Except klystron and circulator, all the sub systems and components of 1 MW RF system [4] are indigenously developed by Micro, Small & Medium Enterprises(MSME) i.e local industries based on BARC design. Fast acting Interlock and Protection system (IPS) (Fig.3) [5] is used for safe and reliable operation of high power RF system. All the bias supplies of the HPRF system are controlled by IPS, which have to function satisfactorily in RF interference (RFI) environment. Each RF system is cooled by low conductivity water (LCW) having total inventory of almost 2000 lpm per system

HPRF systems of LEHIPA are physically spread over three floors or levels of the building. In its basement, there are klystron gallery and Linac gallery housed in two parallel tunnels. Linac gallery houses three accelerating cavities. Klystron gallery (Fig.1 and 2) houses the major RF components like klystron, circulator, RF Load (Fig.4), Harmonic filter etc. handling 1 MW RF power [6]. It also houses major part of HV sub-systems of all the three HPRF systems. RF power from each of the three HPRF systems is coupled to each of the (resp.) three accelerating sections via a long wave-guide WR 2300 based transmission line. The mezzanine floor accommodates IPS and LV bias supplies (Fig.3) of the three HPRF systems. The regulated high voltage power supply (RHVPS) (100 kV, 25 A) is used for biasing cathode of each klystron and is physically located on the ground floor. Each of the three HPRF systems that is spread over large area, is expected to operate and perform at design parameters while overcoming on-field challenges.

Table 1: Parameters of Klystron HPRF system.

Parameter	Klystrons HPRF System		
	I	II	III
Frequency	352.21 MHz	352.21 MHz	352.21 MHz
RF Power	750 kW	830 kW	850 kW
Gain	41 dB	39 dB	40.2 dB
Efficiency	60 %	54.8 %	57.4 %
2nd & 3rd Harmonics	-25 dBc & -30 dBc	-25 dBc & -30 dBc	-25 dBc & -30 dBc

Fig.3: Interlock and protections systems and LV supplies.

Fig.4: Circulator (1 MW) and 0.8 MW RF Load.

HPRF system may cause radiated emissions (RE) and conducted emissions (CE). Hence its constituent components and sub systems that are spread over large space may get exposed to conducted and radiated emissions. So, electromagnetic compatibility (EMC) of IPS and other subsystems has been ensured. The techniques of filtering, glavanic isolation, effective grounding topology, shielding, EM suppression practices have been followed to achieve EMC. By integrating the multi-disciplinary sub-systems/components and techniques in the domains of RF, HV, high current, low level signal instrumentation, RFI suppression, vacuum, thermal management etc., each of the three 1 MW klystron-based HPRF systems has been designed, developed and tested independently on RF load. Each HPRF system then, separately integrated and tested with 3 MeV RFQ, 10 MeV DTL and 20 MeV DTL sections. Using these RF power systems LEHIPA has been successfully tested and proton beam accelerated to 20 MeV energy.

Indigenous Waveguide Transmission Systems

The three independent WR2300 based waveguide (WG) systems [7] have been designed, developed and commissioned for three accelerating sections for 20 MeV accelerator [4]. One WG line is for RFQ and one each for 10 and 20 MeV DTL. These WG systems constituting various types of waveguide components, like, straight sections, tapers, directional couplers, 30 and 45-degree bends, phase shifters, water-based WG RF loads, windows etc. and having both half height and full height structures, have been designed and developed using local MSME parties and commissioned with the respective accelerating cavities.

Waveguide system* for 3 MeV *RFQ

The RFQ required more than 600 kW RF power at 352 MHz to be coupled across its two ports for proton acceleration from 50 keV to 3 MeV energy. RF power from HPRF system is divided in two parts and coupled to each of the two ports of 3 MeV RFQ. The waveguide transmission line (Fig.5) involves various components like E-plane and H-plane bends to rotate the polarisation, Magic Tee to divide and generate two RF power outputs with equal amplitude and phase, water cooled RF loads at various locations to dissipate the unwanted and unbalanced reflected power from RFQ, directional couplers to measure the RF power in both forward and reverse modes at various locations across WG line, RF windows to transmit RF power while simultaneously providing isolation between air and vacuum inside the RFQ. All these waveguide components were designed with stringent specifications at 352 MHz and were fabricated with local Indian industries. These were characterised for their RF performance parameters, and then installed and commissioned with RFQ for 3 MeV operation.

Waveguide system for 10 MeV DTL-1

The 10 MeV DTL-1 accelerator section required a total RF power of ~800 kW at 352 MHz and has four coupling ports for coupling the RF power. Hence, the RF power from HPRF system has been split into 1: 4 by two successive stages of 1:2 power dividers i.e., using a two-stage binary divider into two sets of in-phase and anti-phase vectors. The anti-phase vectors are

Fig.5: Waveguide transmission line from Klystron HPRF to 3 MeV RFQ.

Fig.6: Installed and commissioned waveguide systems of 10 MeV DTL.

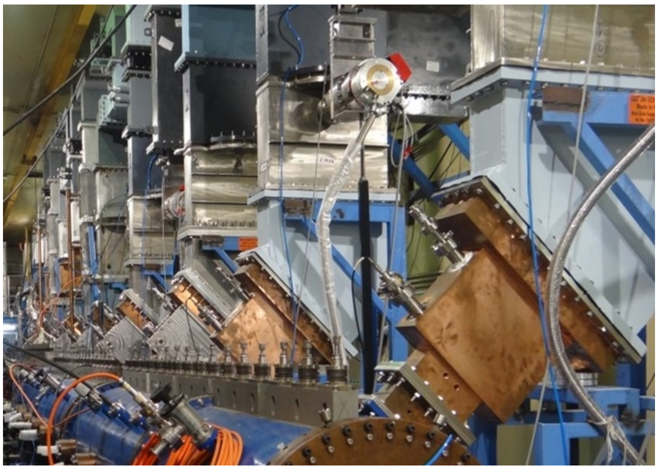

Fig.7: Installed and commissioned waveguide systems of 20 MeV.

Fig.8: SSA (10 kW at 352.21 MHz) (in klystron gallary) for Buncher cavity (on the left) and its coaxial transmission line in Linac gallary(on the right).

again rotated using an additional path length of waveguides to feed in phase power into four ports of DTL-1. Each waveguide line (Fig.6) has directional couplers at various locations to measure both forward and reflected power for diagnostics and in some cases for protection against faults. A total of eight directional couplers are used in the system. The water-based WG RF loads located at the centre of magic tees are used to dissipate the unbalanced reflected power from the DTL side.

Waveguide system for 20 MeV DTL -2

Almost similar waveguide system (Fig.7) with similar layout as that of 10 MeV DTL -1 has been tested, installed and commissioned for 20 MeV DTL-2 accelerator. All the three waveguide systems for 3 MeV RFQ, 10 MeV DTL-1, 20 MeV DTL-2 have been commissioned with their respective accelerator section.

Solid-state RF power amplifier for buncher cavity

LEHIPA uses buncher cavity between RFQ and 10 MeV DTL to bunch the incoming protons from RFQ using RF power from a solid-state RF power amplifier. Indigenous 10 kW, 352.21 MHz Solid-State Amplifier (SSA) [8] (Fig.8), housed in the klystron gallary, has been designed and developed along with coaxial transmission line for coupling the RF power to the buncher cavity of MEBT (Fig.8).

This SSA has been designed using the solid-state transistor technology. It consists of 16 power amplifier modules, two 8-way power combiners, a two-way combiner, a two-way divider, two 8-way dividers, pre-driver, driver modules, DC power supplies, sensors, and an interlock and protection system. The output of the RF power amplifier is coupled to the buncher cavity using 3-1/8”, 50 Ohm coaxial transmission system. This transmission system incorporates directional couplers for power measurement, bends for rotation of wave front, and straight sections. All these are made in rigid 3-1/8 inch transmission line. The salient technical specifications of SSA are given in Table 2.

The RF power waveform during testing and after coupling to Buncher cavity are shown in Fig.9. The RF power waveforms of 3 MeV RFQ and 10 MeV DTL during proton beam acceleration are shown in Fig.10.

Table 2: Salient technical specifications of SSA

Sr. No.	Parameters	Values
1.	Centre Frequency	352 MHz
2.	Bandwidth (3 dB)	>30 MHz
3.	Max. power output	12 kW
4.	Harmonics	<-25 dBC
5.	Coolant	water
6.	Output Connector	3-1/8” EIA Flange
7.	Efficiency	>60% both pulse and CW
8.	Power gain	>70 dB

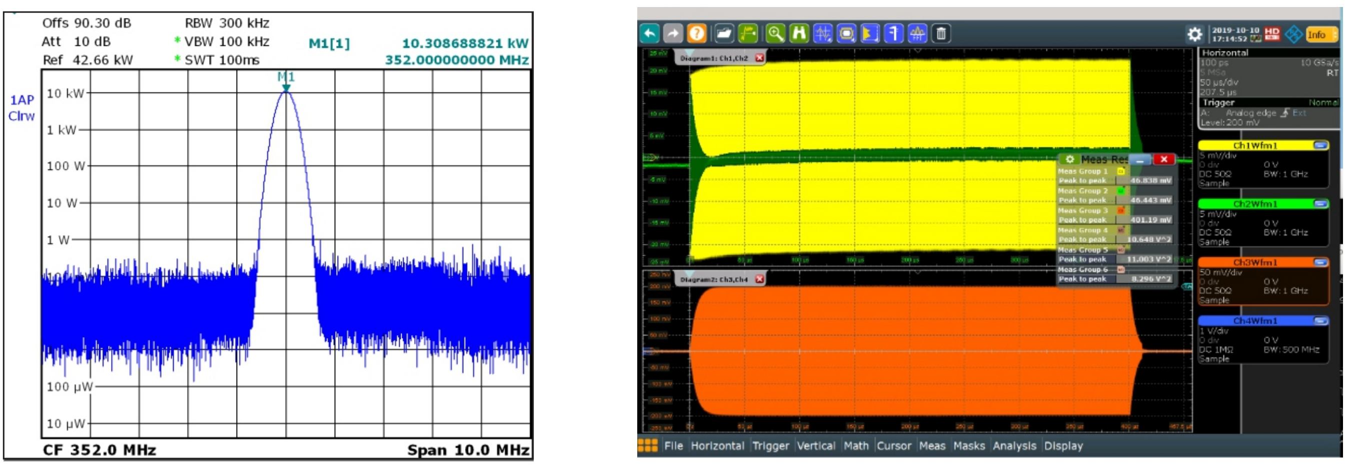

Fig.9: RF Power Waveform of SSA and RF waveforms recorded after RF amplifier was integrated with buncher.

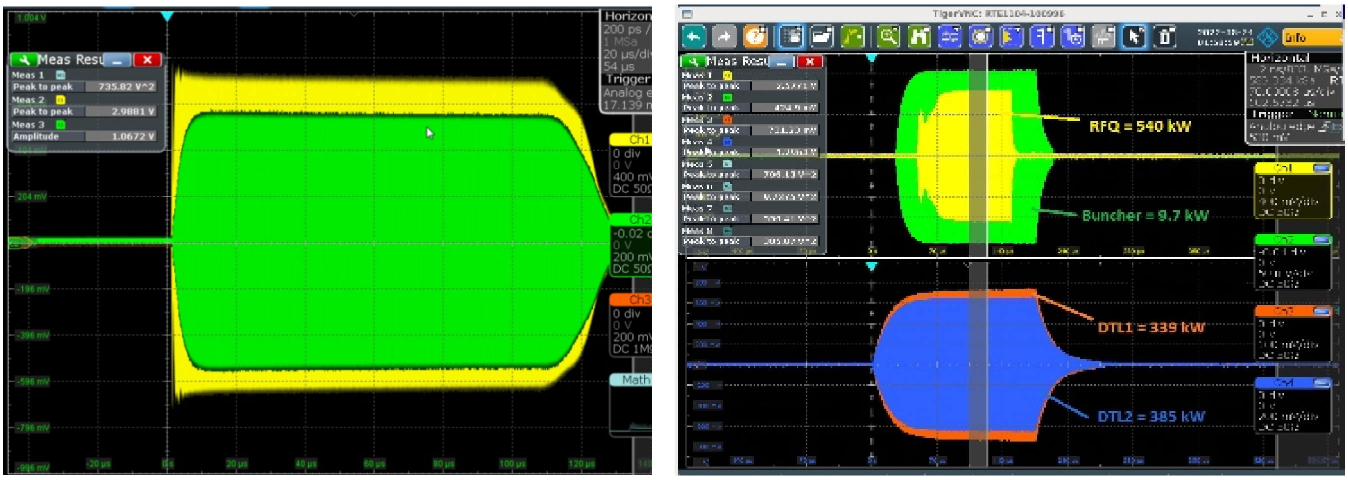

Fig.10: RF Power Waveforms across 3 MeV RFQ and 10 MeV DTL.

Conclusions

In LEHIPA, three klystron based HPRF systems along with WG transmission lines have been successfully operating with 3 MeV RFQ, 10 MeV DTL1, 20 MeV DTL2 respectively for 20 MeV proton beam acceleration. RF power waveforms recorded across 3 MeV RFQ & 10 MeV DTL operation are shown in Fig.10. All these RF systems have been locally designed, tested and commissioned.

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