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लेहिपा और मेहिपा हेतु ठोस अवस्था शक्ति प्रवर्धक तथा निर्वात इलेक्ट्रॉनिक उपकरणों का स्वदेशी अभिकल्पन एवं विकास

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एकीकृत प्रोटोटाइप – आईओटी एवं 64:1 पावर कॉम्बाइनर

सारांश

भापअ केंद्र ने त्वरकों के लिए स्वदेशी रूप से अभिकल्पित ठोस अवस्था शक्ति प्रवर्धक (एसएसपीए)तैयार एवं विकसित किया है। फर्मीलैब के पीआईपी-II अंतःक्षेपण परीक्षण (पीआईपी2आईटी) सुविधा में नौ 7 kW SSPAs का कमीशनन किया गया। एसएसपीए के 25 kW, 50 kW और 300 kW का एक समूह मेहिपा और लेहिपा हेतु विकास के अधीन है। ये एसएसपीए क्रमशः लेहिपा और मेहिपा के आरएफ त्वरकों के अति-चालकता और कमरे के तापमान वाले गुहिकाओं को शक्ति प्रदान करते हैं। इन उच्च लाभ एवं उच्च दक्षता वाले एसएसपीए की महत्वपूर्ण उप-प्रणालियाँ हैंः 2 kW शक्ति प्रवर्धक (पीए) मॉड्यूल, मॉड्यूलर एवं हॉट स्वैपेबल डीसी विद्युत आपूर्ति, विद्युत विभाजक एवं संयोजक, एसी विद्युत वितरण प्रणाली, अंतर्बंध संरक्षण एवं निगरानी प्रणाली (आईपीएमएस) और आवासीय उप-प्रणालियों के लिए एक संहत एवं स्थिर यांत्रिक संरचना। वैकल्पिक रूप से उच्च दक्षता (एचई) प्रेरक उत्पादन नली (आईओटी) और एचई 400 kW क्लाइस्ट्रॉन का अभिकल्पन एवं विकास आरंभ किया गया है। इस लेख में, भापअ केंद्र में इन अभिकल्पन एवं विकास प्रयासों का विवरण दिया गया है।

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Indigenous Design and Development of Solid State Power Amplifiers and Vacuum Electronic Devices for LEHIPA and MEHIPA

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Integrated prototype IOT and 64:1 power combiner

ABSTRACT

BARC has indigenously designed and developed Solid State Power Amplifiers (SSPA) for accelerators. Nine 7 kW SSPAs were commissioned at Fermilab's PIP-II Injector Test (PIP2IT) facility. A family of SSPAs 25 kW, 50 kW, and 300 kW are under development for MEHIPA and LEHIPA. These SSPAs power the super-conducting and room temperature cavities of RF accelerators of LEHIPA and MEHIPA respectively. The important subsystems of these high gain and high efficiency SSPAs are: 2 kW power amplifier (PA) module, modular and hot swappable DC power supplies, power divider and combiner, AC power distribution system, interlock protection and monitoring system (IPMS) and a compact & stable mechanical structure for housing the subsystems. Alternatively design and development of high efficiency (HE) inductive output tube (IOT) and high Efficiency 400 kW klystron has been initiated. This article gives details of these design and development efforts at BARC.

KEYWORDS: *IOT, Klystron, Radio Frequency, solid state Power amplifiers, IPMS*

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Introduction

Bhabha Atomic Research Centre has envisaged development of an Accelerator Driven subcritical reactor System (ADS). A 1 GeV high-intensity proton accelerator is being developed in a phased manner for the Indian ADS program. These are Low Energy High Intensity Proton Accelerator (LEHIPA), Medium Energy High Intensity Proton Accelerator (MEHIPA) and High Energy High Intensity Proton Accelerator (HEHIPA). As envisioned in the Amrit kaal document [1] of DAE, all the accelerators of the 1 GeV proton linac shall be powered by Solid State Power Amplifiers (SSPA) [2,3,4,5] in radio frequency (RF) range. As a part of roadmap for indigenous RF power technology development, research and development (R&D) of RF power devices and /or systems is focused on three distinct technologies viz., inductive output tube (IOT), high efficiency klystron and solid state power amplifier (SSPA) in ultra-high frequency (UHF) range.

In modern RF accelerators worldwide, a gradual shift towards solid state power amplifier (SSPA) technologies has been observed. This is attributed to the advantages offered by solid state RF over conventional vacuum tubes such as a) use of low voltage DC power supplies (DCPS), b) low power circulators, c) increased efficiency d) increased MTBF, e) simple on and off sequence, f) modularity and redundancy, and g) graceful degradation of RF power. As a complimentary technology development, design and development of kW level high efficiency (HE) inductive output tube (IOT) and HE klystrons has started.

SSPA System Architecture

Fig.1 shows the modular architecture and the interconnections of all sub-systems of SSPA. A Low Power RF amplifier (LPRF) amplifies a 325/352 MHz input signal. An *n*-way input divider splits it equally. This 1/*n* output is fed to each identical 2 kW PA modules. These amplified outputs are combined by an *n*:1 power combiner and measured by a directional coupler. The value of *n* scales with the SSPA rating. It is 14, 28, and 160 for the 25, 50 and 300 kW SSPAs respectively.

SSPA System: 25 kW @ 325 Mhz

In 25 kW SSPA, a LPRF system amplifies 325 MHz signal input from signal generator. The amplified power is split equally by a 14-way divider and fed to each identical 2 kW power amplifier (PA) module. A 14:1 power combiner combines these amplified outputs. An output directional coupler measures the forward and reflected power output. A circulator rated at 28 kW protects the SSPA system against RF reflection from the SC cavities. The amplifier can operate in both pulse and CW mode. Power factor is greater than 0.9 and THD is below 30%. Table 1 lists its principal RF specifications.

SSPA System: 50 kW @ 325 Mhz

A 50 kW, 325 MHz SSPA is RF power amplifier designed using 28 power modules, which are combined using a 28-way cavity combiner. An external signal is amplified by a LPRF system rated at 600 W. This RF power drives the 28 modules rated at 2 kW each. The combined power output is taken on EIA 6-1/8” line. A CW directional coupler rated at >60 kW is used to measure and have circulator for protection of SSPA against the reflected power. The main specifications of the 50 kW SSPA are shown in Table 1.

SSPA system: 300 kW at 325/352 MHz

The configuration of the 300 kW SSPA is shown in Fig.1. A small signal input is amplified to a power level of 3 to 4 kW at 325/352 MHz by a LPRF system. The LPRF output is divided in to 160 outputs each rated at 18 to 25 W by a 160-way power divider. It drives each PA module rated at 2 kW, 352 MHz and biased by a respective DCPS. The outputs of such 160 power modules (PA) biased by 160 numbers of DC power supplies (DCPS), are combined by a 160-way power combiner to produce the net RF power output of 300 kW. The main

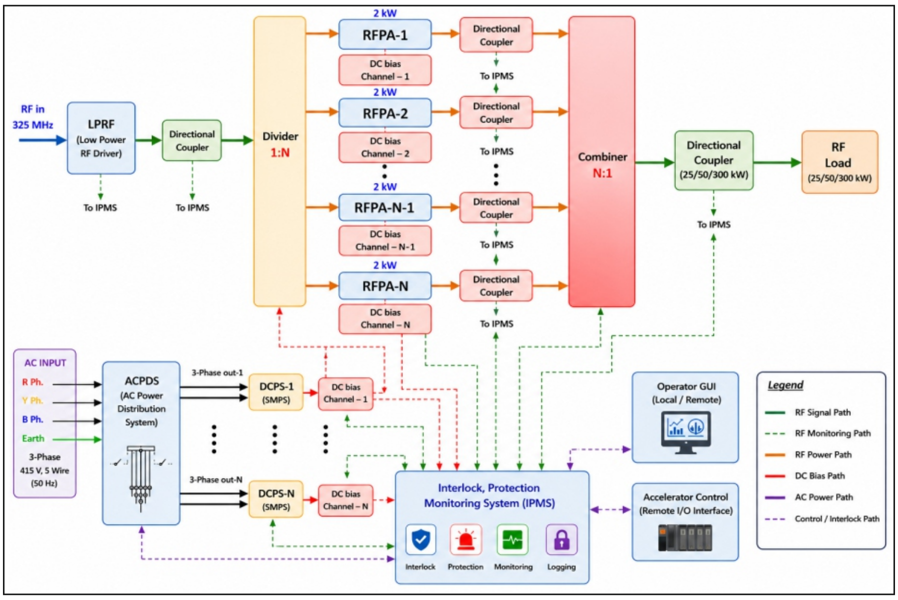

Fig.1: Modular architectural block diagram of SSPA systems.

Table 1: Technical Parameters of designed SSPAs.

Sr. No.	Parameters	25 kW SSPA	50 kW SSPA	300 kW SSPA
1.	Centre frequency	325 MHz	325 MHz	352;325 MHz
2.	Mode of operation	Pulse&CW	Pulse&CW	Pulse; pulse&CW
3.	RF output power @ 1dB compression	≥ 25 kW	≥ 50 kW	≥ 300 kW
4.	Bandwidth @ 3 dB	≥ 4 MHz	≥ 4 MHz	≥ 4 MHz
5.	Power gain	≥ 68 dB	≥ 71 dB	≥ 71 dB
6.	Gain variation (30%–90% output power)	≤ 2 dB	≤ 2 dB	≤ 2 dB
7.	Phase variation over power band	≤ 15^{o}	≤ 15^{o}	≤ 15^{o}
8.	Harmonic power (half & full power)	Better than –25 dBc	Better than –25 dBc	Better than –25 dBc
9.	Spurious power (half & full power)	Better than –50 dBc	Better than –50 dBc	Better than –50 dBc
10.	VSWR handling (half to full power)	≤ 1.4	≤ 1.4	≤ 1.4
11.	AC to RF efficiency at peak power	≥ 45 %	≥ 42 %	≥ 42 %

technical specifications of the 300 kW SSPA are shown in Table 1. SSPA rated at 300 kW, 325 MHz is designed to operate in both pulse and CW mode whereas 300 kW, 352 MHz amplifier is designed to operate at 10% duty factor with pulse length of 50 us to 2 ms only.

Description of Sub-systems of SSPAs

AC Power Distribution System

AC Power Distribution System (ACPDS) implements the distribution, routing and monitoring of AC mains power from high power transformer to the resp. DC power supplies (DCPS). It distributes the incoming 3-ϕ main power line into multiple 1-ϕ lines to power DCPS modules.

DC Power Supply (DCPS) with hot swapping scheme

The DC biasing system (Fig.2) of the SSPA uses multiple high-efficiency Switched Mode Power Supply (SMPS) units as DCPS (Fig.2) powered through the ACPDS. It operates from a 415 V, 3-phase AC supply and integrates protection and monitoring through the IPMS. These supplies are optimized for stable output under dynamic load conditions. They use a compact water-cooled design with high power density and efficient thermal management suitable for high-channel-count SSPA systems. Remote ON/OFF control, enable/disable functions and health-status monitoring are provided for integration with the central IPMS system.

Stable Mechanical Structure

A stable mechanical structure shall house SSPA sub-systems viz., LPRF, power divider and combiner, ACPDS, DCPS, PA modules, cables, water cooling hardware and circuit.

Low Power Radio Frequency (LPRF) system

A LPRF system is the front-end RF amplifier stage of the all the SSPAs. It feeds required power at 325/352 MHz to the input of the 1: *n* -way power divider. LPRF have a limited no. of

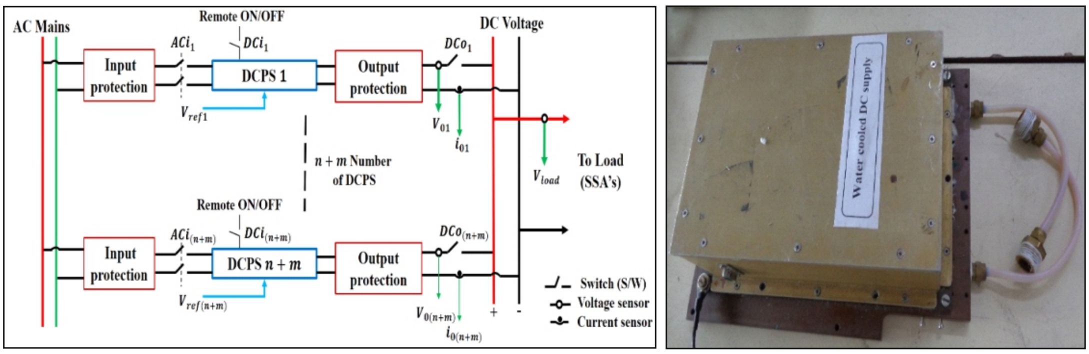

Fig.2: DC power supply system architecture with hot swapping scheme and tested DCPS.

Table 2: LPRF Specifications.

Sr. No.	Parameters	Values
1.	Power rating (peak)	≥3 kW
2.	Gain @ 3 kW peak power	57 dB
3.	3 dB bandwidth	7 MHz
4.	Harmonics	<-30 dBc
5.	Input VSWR	≤1.2

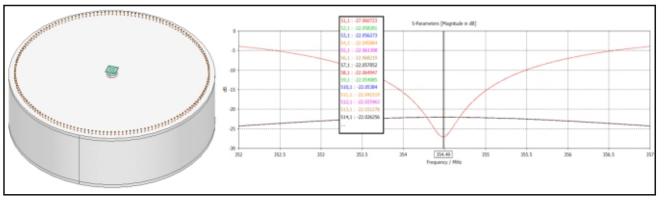

Fig.3: Fabrication model of divider and its Transmission and return loss.

series of amplifiers along with protections. Table 2 lists the salient specifications of LPRF for 300 kW SSPA. The LPRF for 25 and 50 kW SSPAs are scaled down version of LPRF used in 300 kW SSPA.

Power divider

All the SSPA systems use either a cavity divider or planar PCB based power divider. Power divider derives respective number of RF power outputs to drive the PA modules. A 160-way RF power divider has been designed and simulated for the 300 kW, 352 MHz SSPA. It consists of a cylindrical cavity, 160 numbers of RF outputs on SMA connectors and a 1 -5/8" RF input. Fig.3 shows the fabrication model of the 1:160-way divider and its simulation results.

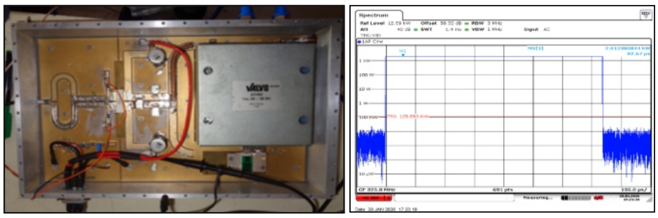

Fig.4: Developed 2 kW PA module and its measured power waveform.

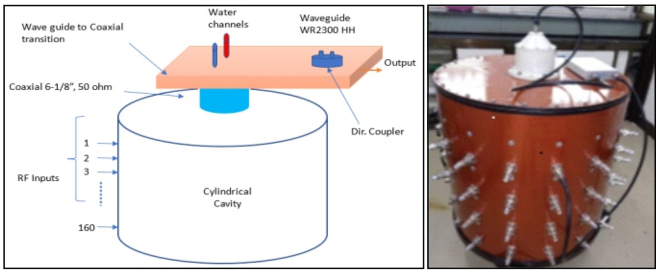

Fig.5: Sketch of 160-way combiner and fabricated 64 way cavity combiner.

PA Module

The Power Amplifier (PA) module is the fundamental building block of all the SSPA systems mentioned above. Each PA module is capable of delivering approximately 2 kW RF output power at 325/352 MHz. Since the reliability of the PA module is critical for the overall performance of the SSPA system, the design utilizes high-reliability RF components with Mean Time Between Failures (MTBF) greater than 200,000 hours. The developed RF PA module and its test results shown in Fig.4.

Power combiner

The power combiner [5] is a multi-input and single output device used to combine the output from multiple PA modules.

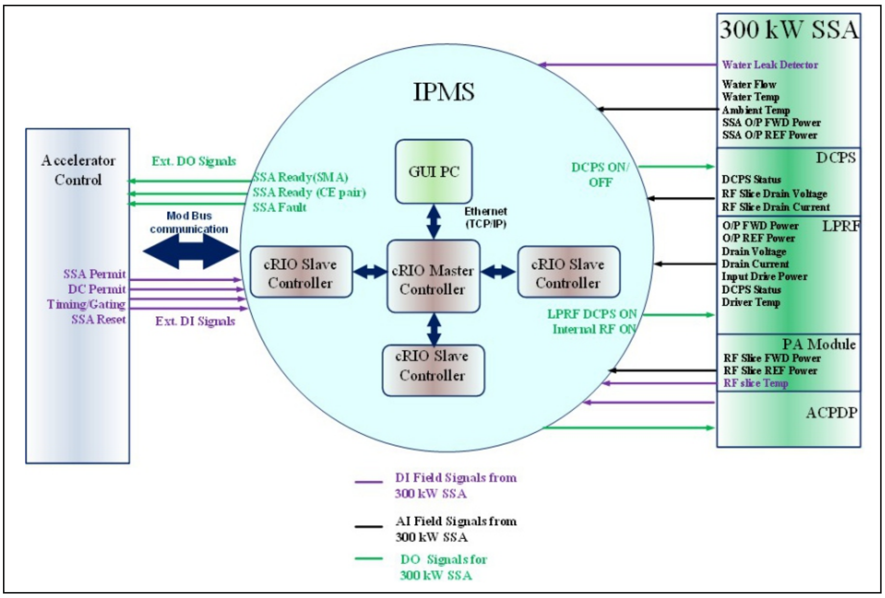

Fig.6: Scheme of IPMS.

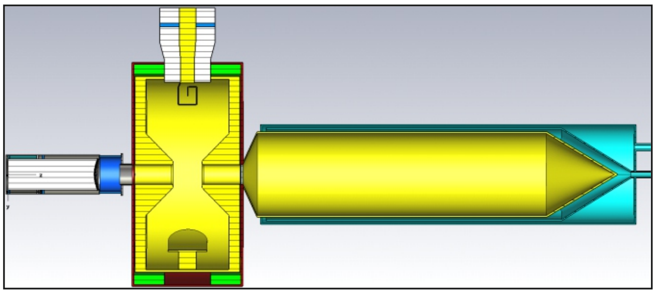

Fig.7: Integrated model of IOT.

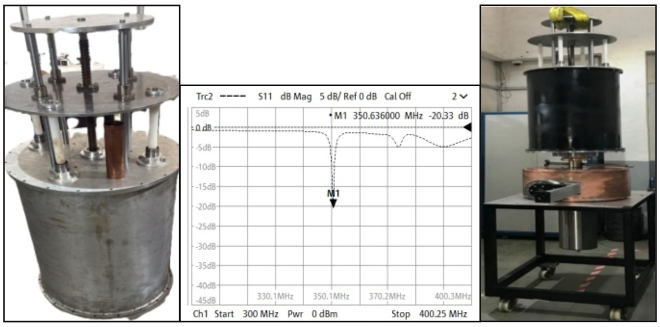

Fig.8: Input Cavity of IOT and its input matching graph and integrated prototype IOT.

Fig.5 shows the 160-way cavity type power combiner comprising of a cylindrical cavity, 160 numbers of RF inputs, a coaxial to waveguide transition, an output WR2300 half-height waveguide (CW case) etc. For CW operation, it has provision for water-cooling. All the SSPAs use the similar type of power combiner with scaled number of inputs.

Interlock, Protection and Monitoring system (IPMS)

IPMS is used for the safe and reliable operation of SSPA. It protects the SSPA in case certain parameters of signals exceed the specified trip limit. The IPMS can accept the commands from Local GUI display as well as the Remote-control system. Main functions of IPMS are a) To ensure interlock among internal/External signals, b) Sequential ON/OFF of various subsystems of SSPA, c) Acquiring and processing of signals d) Data logging and real time display e) Trip generation and protection of SSPA system f) Trip annunciation to the operator in case of abnormal signal conditions g) Calibration and setting of trip parameters h) Protect the SSPA against faulty operating conditions i) Communication of SSPA parameters to remote system. Fig.6 shows the scheme of the IPMS system.

HE Inductive Output Tube

Efficiency of high power RF system is mainly governed by its power generation device. High efficiency (HE) vacuum electronic devices (VEDs) operating in UHF range (300 MHz to 3 GHz) are specialized vacuum tubes intended for generation of high RF power with high efficiency. The simulated design of one such inductive output tube (IOT) is shown in Fig 7.

IOT design at 325 MHZ

An IOT [6] has been simulated and designed for operation at 325 MHz,100 kW and at an efficiency of approximately 70%. The design simulation of all the sub-components of the IOT, viz. the gridded electron gun, drift space, the input and output cavities, the magnetic circuit, and water cooled collector are completed. The input cavity (3 λ/4) is a TM^{01} mode coaxial cavity, while the output cavity (λ/4) is a TM^{01} mode re-entrant cavity.

The magnetic circuit is designed to provide a brillouin focusing to the electron beam. The simulation of the integrated model (Fig.7), along with studies on the effect of the output gap and the R/Q of the output cavity on the efficiency and output power level is completed.

Prototype IOT development

Based on the design, a prototype IOT (Fig.8) was developed. Its input cavity with insulator arrangements for electron gun was fabricated. It has variable input tuner for tuning the cavity. Its variable input coupler matches the cavity impedance to 50-ohm. The fabricated input cavity and its RF characterisation is shown in Fig.8. Its further optimization is in progress. The fabricated output cavity has variable tuner for achieving the resonance at 325 MHz and an output loop coupler for extracting RF power via output Teflon window. The integrated IOT assembled together and RF characterised with both input and output cavities and water cooled collector with stainless steel water jacket is shown in Fig.8. Design of electron gun has been initiated.

High Efficiency Klystron at 352 Mhz

Though vacuum devices excel in high power, achieving high efficiency in smaller and compact footprint remains a primary research challenge. HE klystron [7] with efficiency

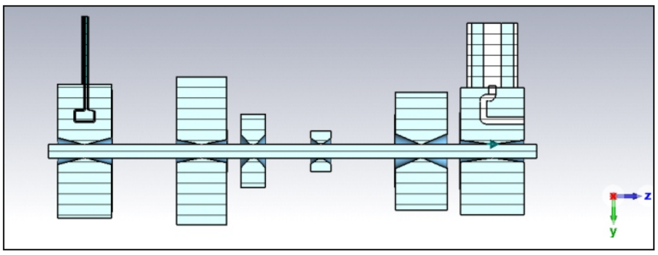

Fig.9: Simulated model of HE klystron at 352 MHz.

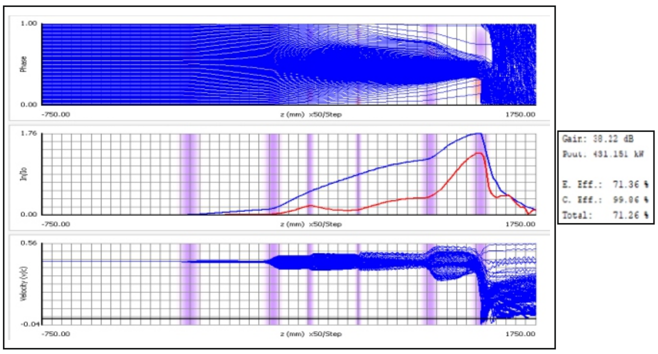

Fig.10: Initial 1-D Model 352 MHz Klystron Design-simulation and its parameters.

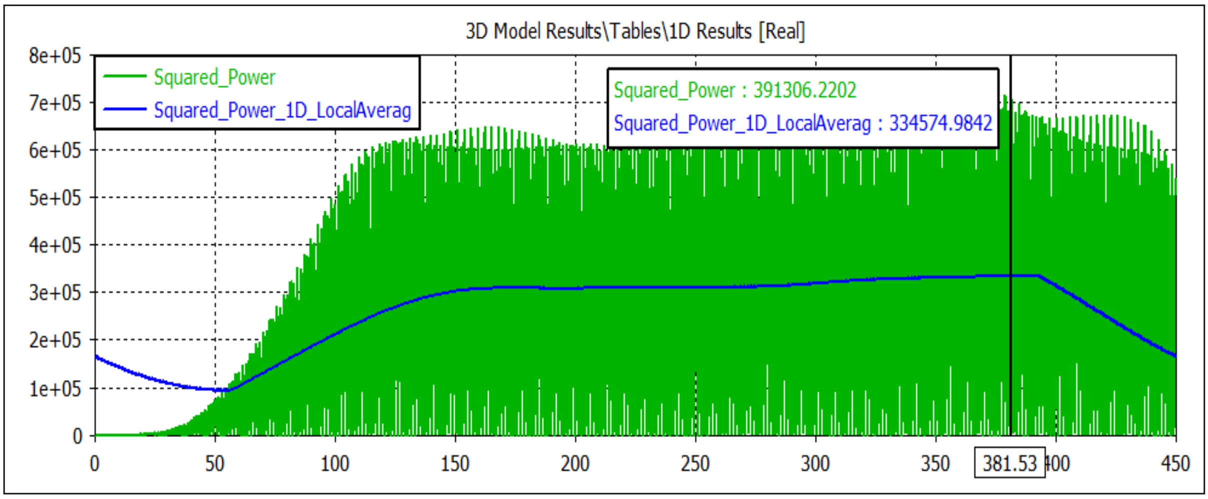

Fig.11: RF power Output received from simulation of HE UHF klystron at 352 MHz.

more than 75% is strongest candidate among all. This technology development initiated is HE, vertically mounted klystron of RF power 400 kW at 352 MHz. The initial simulated model is shown in Fig.9. Figure 10 gives 1D model of HE klystron, its initial beam parameters and efficiency achieved via simulation. RF power obtained from simulated HE klystron is shown in Fig.11. Further design is in progress.

Management of electron scattering, secondary electron emission in insulators, cavities and collector remains crucial, as they degrade their performance.

Conclusion

IOT has been successfully designed and its prototype has been developed except electron gun. HE UHF klystron design has been initiated. BARC has developed solid-state amplifiers for indigenous accelerator programs. SSPA development [2, 3, 4, 5] progress is well continuing. Major subsystems of 352/325 MHz and 25 kW, 50 kW 300 kW SSPAs have been designed and their development is underway. All these technologies are completely indigenous and are in line with the Atmanirbhar Bharat mission.

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