ठोस-अवस्था प्रवर्धक

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स्वदेशी 325 MHz ठोस अवस्था शक्ति प्रवर्धक

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त्वरक नियंत्रण प्रभाग, भाभा परमाणु अनुसंधान केंद्र (भापअ केंद्र), ट्रांबे-400085, भारत

फेर्मीलैब में पीआईपी2आईटी के एसएसआर के साथ आठ एसएसआर1 युग्मित किए गए
(photo) फोटो: फेर्मीलैब, यूएसए के सौजन्य से

सारांश

भारतीय संस्थानों और फर्मीलाब के बीच विज्ञान और प्रौद्योगिकी सहयोग के समझौते के तहत, भाभा परमाणु अनुसंधान केंद्र ने स्वदेशी रूप से 325 मेगाहर्ट्ज पर 7 किलोवाट और 20 किलोवाट ठोस अवस्था प्रवर्धक शक्ति प्रणाली डिजाइन / परिकल्पित और विकसित किया हैं। इन रेडियो आवृत्ति शक्ति प्रवर्धक में उच्च रेडियो आवृत्ति प्रदर्शन सूचकांक हैं जैसे, एसी / प्रत्यावर्ती धारा से रेडियो आवृत्ति निपुणता 50% से अधिक, शक्ति लाभ >60 डीबी, लाभ और चरण स्थिरता क्रमशः 0.02 डीबी/सी और 1 डिग्री/सी से बेहतर आदि। आठ ऐसे 7 किलोवाट प्रवर्धकको फर्मीलाब, यूए.स.ए. और एक भाभा परमाणु अनुसंधान में तैनात किया गया है। 20 किलोवाट ठोस अवस्था प्रवर्धक शक्ति प्रणाली को डिजाइन / परिकल्पित और विकसित किया गया है। दोनों ठोस अवस्था प्रवर्धक शक्ति प्रणालीयों ने त्वरक में विशेषज्ञों की अंतरराष्ट्रीय टीम द्वारा आयोजित कठोर अंतिम डिजाइन समीक्षाओं को सफलतापूर्वक पूरा कर लिया है।

Solid-state Amplifier

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Indigenous 325 MHz Solid State Power Amplifiers

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Eight SSAs coupled to SSR1 of PIP2IT @Fermilab (Photo Courtesy of Fermilab, USA).

ABSTRACT

Under the agreement of science and technology co-operation between Indian Institutions and Fermilab, BARC has indigenously designed and developed 7 kW and 20 kW solid-state amplifier power systems at 325 MHz. These RF power amplifiers have high RF performance indices like AC to RF efficiencies greater than 50%, power gain >60 dB, gain and phase stabilities better than 0.02 dB/^{0}C and 1 degree/^{0}C respectively etc. Eight such 7 kW amplifiers have been deployed at Fermilab, USA and one at BARC. The 20 kW SSA has been designed and developed. Both the solid state amplifiers have successfully completed the rigorous final design reviews conducted by international team of experts in accelerator.

KEYWORDS: *Accelerator, Amplifier, Efficiency, Fermilab, FNAL, Interlock, PIPII, Proton, RF, SSA*

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Introduction

The Department of Atomic Energy (DAE) has envisaged setting up High Intensity Superconducting Proton Accelerator (HISPA) for the Indian Accelerator Driven Sub-critical reactor System (IADS). Accelerator programs of the Department planned in the coming decades needs many critical technologies. Solid State Amplifier (SSA) i.e. radio frequency (RF) power systems are one of them and fall under custom designed high technology systems.

The Science and Technology Cooperation agreement was signed between Department of Atomic Energy (DAE), India and Department of Energy (DOE), USA. Due to the commonality of Indian interests with the Proton Improvement Plan II (PIP-II) project in the domain of accelerators technology, an Indian Institutions and Fermilab Collaboration (IIFC) was formalized. The Proton Improvement Plan II (PIP-II) of Fermi National Accelerator Laboratory (FNAL), USA involves up-gradation of its accelerator complex to support a broad physics research program as well as to power the world's most intense beam of high-energy neutrinos for the Deep Underground Neutrino Experiment (DUNE) [1].

The PIP-II design requires two levels of RF power at 325 MHz for their single spoke resonator (SSR) section with Beta = 0.22 for SSR1 & Beta = 0.47 for SSR2 of the LINAC. RF power of 7 kW at 325 MHz for the SSR1 and 20 kW at 325 MHz for SSR2 cavities is generated by solid state amplifiers (SSA). Under IIFC, Bhabha Atomic Research Centre (BARC) has the responsibility to provide 325 MHz SSAs for SSR1 and SSR2 cryomodules having superconducting cavities.

BARC has designed and developed state-of-the-art 325 MHz, 7 kW and 20 kW SSA power systems. Both these indigenous SSAs have successfully completed final design reviews (FDR) conducted by a team of experts from international accelerator laboratories like CERN, GANIL, SLAC, Fermi lab and DAE .

The SSAs use advance and new high power laterally diffused metal oxide semiconductor field effect transistor (LDMOSFET) devices. Using latest and innovative technologies, SSA's delivering 100s of kilo-watt (kW) power can be realized. The advantages of solid-state amplifiers over tube based RF power systems are multiplicity i.e. modularity, low voltage operation, graceful degradation among the others. Both 7 kW and 20 kW SSAs will also be used in Indian accelerator program like Medium Energy High Intensity Proton Accelerator (MEHIPA).

Table 1: RF performance parameters of nine 7 kW SSAs at PIP2IT.

Sr. No.	Parameters	Values
1.	Frequency (MHZ)	325
2.	RF Output Power (kW Typical)	7
3.	DC to RF Efficiency @ 7 kW (%)	61.6 to 66.35
4.	AC to RF Efficiency @ 7 kW (%)	51.4 to 54.9 %
5.	2nd Harmonics (dBc)	(-) 32.57 to (-) 43.37
6.	3rd Harmonics (dBc)	(-) 48.4 to (-) 71.37
7.	Environmental Standard	IEC 60068
8.	EMI / EMC Standard	CISPER 11 & IEC61204-3, EUT Under controlled electromagnetic category

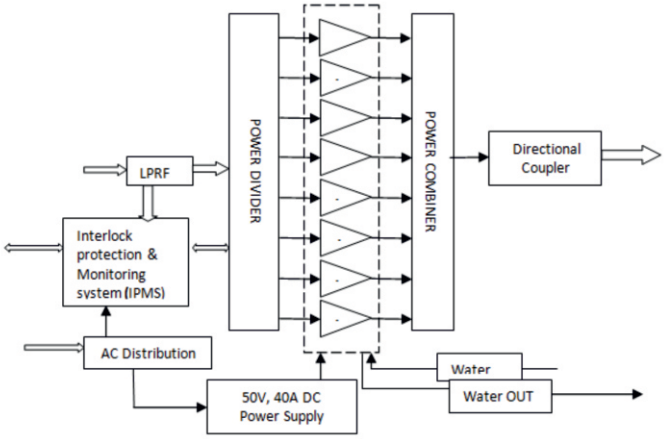

Fig.1: Modular architecture of 325 MHz, 7 kW SSA.

SSA 7 kW at 325 MHz

The SSR1 cavities, with β= 0.22, are powered by 7 kW 325 MHz RF power in the PIP II Injector Test (PIP2IT) facility - the technology demonstration part of PIP II. BARC has designed and developed state-of-the-art 325 MHz, 7 kW SSA power systems. Nine numbers of such 7 kW SSA power systems were produced by Electronic Corporation of India (ECIL) and have been deployed at PIP2IT facility Fermilab, USA. Eight SSAs have coupled the RF power to superconducting cavities (SC) of SSR1 cryomodule. The PIP2IT has successfully accelerated ionized hydrogen up to 17 MeV through one SSR1 cryomodule. One number of 325 MHz, 7 kW SSA is deployed at IADD of BARC.

These high power SSAs are designed using a modular topology wherein power output from multiple power amplifier (PA) modules are combined to achieve overall high-power output. The modular architecture of the 325 MHz, 7 kW level SSA with its sub-systems has been shown in Fig.1. It comprises of major sub-systems viz., a low power RF (LPRF) driver section, input power divider (1:8), eight power amplifier (PA) modules of 1 kW power rating each, a power combiner (8:1), eight direct current (DC) bias power supplies to power eight PA modules, an interlock protection and monitoring system (IPMS), an AC power distribution panel (PDP) and an output directional coupler. RF power from LPRF driver is split into eight in-phase power signals of equal amplitude by an input divider (1:8) and coupled to eight PA modules of 1 kW power each. An 8:1 power combiner, combines the amplified output power from eight PA

Fig.2: Power waveform in CW mode.

Fig.3: EIGHT SSAs coupled to SSR1 of PIP2IT @Fermilab (Photo Courtesy of Fermilab, USA).

modules to achieve 7 kW RF power at SSA output.

Table 1 lists some of the tested performance parameters of the nine SSAs. Fig.2 shows the RF power waveform in continuous wave (CW) mode of operation. The sub-systems of the SSAs have been subjected to stringent qualification tests as per international standards for improved and reliable performance during accelerator operation. The 7 kW SSA is capable of producing 5.37 kW power in the event of 1 PA module fail condition, thereby assuring availability of rated RF power for SSR1 cryomodule operation without interruption in beam acceleration for PIP-II operation. The 7 kW SSA can operate in both continuous wave (CW) and pulse mode. The salient features of the SSA include high AC to RF efficiency, high power gain, compactness, low harmonics, graceful degradation of power & easy maintenance. Fig.3 shows eight 7 kW SSAs [4] coupled to SSR1 cryomodule at PIP2IT facility of Fermilab, USA.

SSA 20 kW at 325 MHz

An efficient and compact 325 MHz, 20 kW SSA has been designed and developed by BARC, which will be useful to power SC SSR2 cavities.

Architecture of 20 kW SSA at 325 MHz capable of CW operation is shown in the block diagram in Fig.4. The major sub-systems of 20 kW SSA include a low power RF (LPRF) driver section, 1:24 input power divider, twenty-four power amplifier

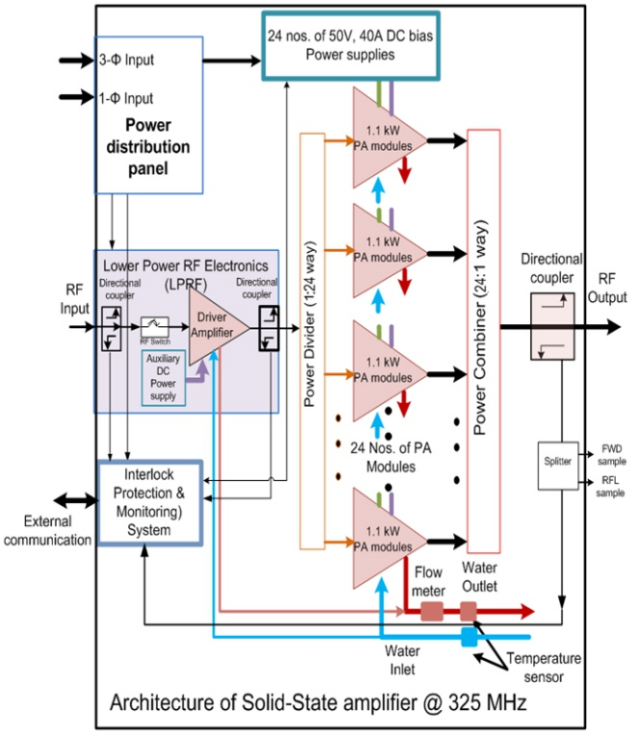

Fig.4: Modular architecture of 325 MHz, 20 kW SSA.

Fig.5: SSA 325 MHz, 20 kW.

Table 2: Important tested performance parameters or specifications of 20 kW SSA.

Important tested Specifications 20 kW SSA	
Description	**Specification**
Frequency	325 MHz
RF Output Power	20 kW Typical
1dB Bandwidth (Mhz)	7 MHz (Min.)
Power Gain	>85 dB (Min.)
Group Delay	<200 ns
Gain magnitude over 30% to 90% dynamic range	≤ 2 dB
Phase of the amplifier gain from 30% to 90% dynamic range	≤ 15^{0}
AC to RF Efficiency (at 17.1KW) (min)	>45%
AC to RF Efficiency (at 10.75KW) (min)	>40%
All Harmonics	<-25dBc
Spurious	<-60 dBc
VSWR handling (half power to full)	≤ 1.4
Power factor and THD	>0.9 and < 28%

(PA) modules of 1 kW power each, a 24:1 power combiner, twenty-four DC bias power supplies to bias the PA modules, an interlock protection and monitoring system (IPMS), AC power distribution panel (PDP) and an output directional coupler. RF power from LPRF driver is split into in-phase power signals of equal amplitude by the 24:1 input divider and fed to the twenty-four PA modules. The amplified output power from twenty-four PA modules is combined via 24:1 power combiner to achieve 20 kW RF power at SSA output.

In addition to complying with other stringent performance requirements, the amplifier has capability to deliver 17.1 kW under two failed PA modules condition. This fulfils the RF power availability of 17.1 kW using 24 modules with two PA module redundancy for PIP-II operation.

The important performance parameters of 20 kW SSA, which are experimentally verified, are listed in Table 2. The 325 MHz, 20 kW SSA designed, developed and successfully tested and is shown in Fig.5. The mean time between failure (MTBF) and mean time to replace (MTTR) calculations for these SSAs have been carried out. Based on these calculations, availability [5] of RF power from SSA has been estimated. Both these SSA have availability of of 99.995%. All the efforts of indigenous design, development, engineering, qualification and testing of the amplifiers have demonstrated excellent performance for critical parameters. These parameters include wall plug efficiency i.e. AC power to RF efficiency, overall gain, gain magnitude and phase variation, group delay, harmonic content and spurious outputs. These amplifiers will be used for Indian Accelerator Programs.

Conclusions

The technology of solid-state RF power amplifiers at 325 MHz for superconducting accelerators have been developed successfully. Eight RF power stations have been installed and commissioned at Fermilab's PIP2IT facility in the USA and proton beam has been accelerated to 17 MeV energy. The technology development of 20 kW SSA at 325 MHz is ready for deployment. Both these 7 and 20 kW SSAs have displayed excellent performance parameters including 'Availability', which are paramount for successful accelerator operation. This technology augmented with power combiner of higher ratings can be scaled up to 100's of kW of power regime.

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