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DEVELOPMENT AND OPERATION OF PIP-II INJECTOR TEST, SSR1 CRYOMODULE, 325 MHz AMPLIFIERS

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Abstract

The PIP-II Injector Test (PIP2IT) [1] has successfully accelerated ionized hydrogen up to 17 MeV through a superconducting, single spoke resonator (SSR1) Cryomodule at Fermi National Accelerator Laboratory (FNAL). Each of the SSR1 cavities is tuned to 325MHz and requires up to 6 kW of RF power to accelerate 2mA of ionized hydrogen at the design gradients. RF power amplifiers, specialized for SRF cavity beam operations, were designed by Bhabha Atomic Research Center (BARC) and constructed in a collaboration between the BARC in Mumbai, India and the Electronics Corporation of India Limited (ECIL) in Hyderabad, India. The RF amplifiers meet the specifications and requirements mutually approved between BARC and FNAL. They operate at 325 MHz with a linear power output of 7 kW in both CW and pulse mode. The amplifiers are compatible with the FNAL accelerator personnel safety system and the cavity protection interlocks. Access to controls and internal diagnostic instrumentation are compatible with EPICS control standards. This paper gives details about RF power amplifier development within the Department of Atomic Energy (DAE), India and the operational details with PIP2IT at FNAL.

INTRODUCTION

Charged particle accelerators were developed for pursuing research in frontier areas of physics. Their scope and usefulness has been extended to a variety of applications like food industry, health care, agriculture, environment, archaeology industry, national security, and waste management.

Advance technology development in cryogenic and super conducting RF (SCRF) resonating cavities has led to a new era in modern RF accelerators. SCRF cavities have reduced the RF power requirement by orders of magnitude for achieving the same accelerating potentials.

High power radio frequency (HPRF) system is one of the most important and critical technologies in an SCRF accelerator. HPRF needs to demonstrate of high performance amplifiers to achieve higher power levels with improved efficiency. The cost of such amplifiers is comparable to vacuum tube based amplifiers. Hence, the solid-state RF power amplifiers have become increasingly suitable for the super conducting accelerator applications.

These RF systems are developed using innovative designs / techniques with their experimental validation, application of stringent qualification standards during their development, and earlier operational experience with accelerators.

State-of-art solid state radio frequency power amplifiers (RFPAs), designed and developed by Bhabha Atomic Research Centre (BARC) and productionized at ECIL, are now a part of Fermilab's beam facility in USA.

INTERNATIONAL COLLABORATION

The Science and Technology (S&T) Cooperation agreement was signed between Department of Atomic Energy (DAE), India and Department of Energy (DOE), USA. Radio Frequency Power is one among the sixteen technologies listed under Technical Cooperation. Due to the similar interests in accelerator technology, a collaboration named as Indian Institutes and Fermilab Collaboration (IIFC) has been established to design and develop the superconducting radio frequency accelerators for both the Indian and Fermilab programs.

Fermilab is upgrading its accelerator complex to deliver high intensity neutrino beams as well as to provide beams for a broad range of experiments.

The 800 MeV, 2 mA Superconducting (SC) linear accelerator (LINAC) named PIP-II [2] is being developed at Fermilab. In the PIP II Injector Test (PIP2IT) - a technology demonstration part of PIP II, single spoke resonator (SSR1) cavities with β 0.22 utilizes 325 MHz RF power. Under IIFC, BARC has designed and developed the solid-state RF power amplifier at 325 MHz for its proton accelerator [3] and for Fermilab, USA.

DEVELOPMENT OF RF POWER SYSTEMS FOR SUPER CONDUCTING SPOKE RESONATORS OF PROTON ACCELERATORS

High power RF (HPRF) systems provide power to normal conducting (NC) or superconducting LINAC for beam acceleration. HPRF systems must be reliable, rugged, with

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high availability, easy maintainability and should be highly controllable [4]. For large, linear accelerators, the capital and operating cost of the RF system dominates the capital and running cost of the accelerator. So, HPRF systems must be compact and provide high electrical efficiency 'η', which in turn reduces the economic impact.

The rapid advancements in high efficiency Laterally Diffused Metal Oxide Semiconductor (LDMOS) technology in VHF/UHF band have pushed the power output of solid-state RF devices to higher scale. The solid-state RF power amplifiers (SSRFPA) have many advantages like simple start-up procedure, no warm-up time, low voltage operation, and graceful degradation of power.

SOLID-STATE RF AMPLIFIERS AT 7 kW, 325 MHz

For the superconducting accelerator program, BARC has successfully, indigenously designed, developed and tested high efficiency and compact 7 kW solid state RF systems at 325 MHz.

These solid-state RF systems 7 kW at 325 MHz have been developed as per mutually accepted functional requirement specification (FRS) [5] and technical requirement specifications (TRS) [6]. These were tested as per a very detailed acceptance plan, both at individual sub system level and total amplifier.

The major sub systems of this 325 MHz, 7 kW RF power amplifier (RFPA) (Fig. 1) are, a low power RF (LPRF) driver, an input 1:8 power divider, eight 1 kW power amplifier (PA) modules, an output 8:1 power combiner, eight DC power supplies, an interlock and protection measurement system (IPMS), AC power distribution panel (PDP) and an output directional coupler. RF power for input LPRF driver power is split into eight parts by a 1:8 input divider and each 1/8th part is given to 1 kW PA module. The output power from these eight, water cooled PA modules is combined via an 8:1 power combiner to get 7 kW RF power, which is measured by an output directional coupler. Due to its modular nature, it can still deliver partial output power to accelerator even though few of its power modules are down or by reconfiguring the specific number of its modules for the desired power output.

Based on this technology of 7 kW, 325 MHz RF amplifier [7], the mass production of the same was done at Electronic Corporation of India Ltd. (ECIL), Hyderabad while following the international qualification standards.

They have salient features as high AC to RF efficiency, high power gain, compactness, low harmonics, good modularity, use of lower voltages, higher currents, relatively low load resistances and low maintenance, and can operate in both CW and pulse mode.

Qualification Standardization in RF Amplifiers

Application and validation of stringent qualifications tests of individual subsystems of an RF system is an important and critical aspect of the development. It improves RF system performance for accelerator operation. The subsystems of 7 kW RF amplifier (Fig. 2) have been tested

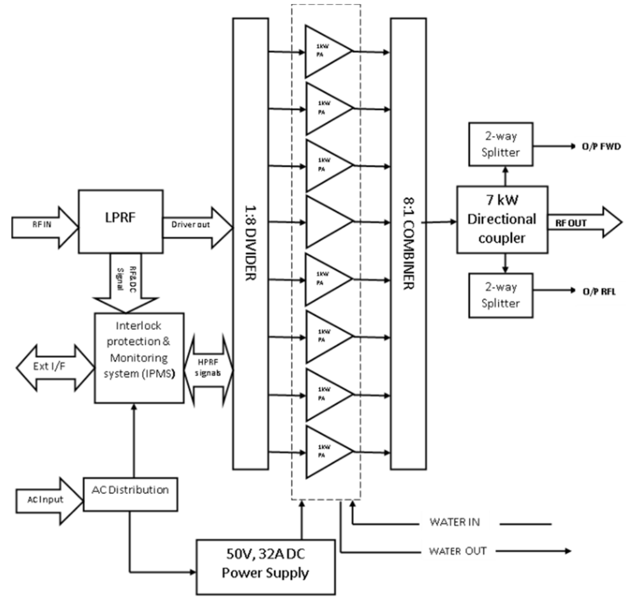

Figure 1. Architecture of 7 kW, 325 MHz RF power amplifier.

successfully the various qualification tests like, radiated emission (RE) & conducted emission (CE) test (CISPR 11), low & high temperature (IEC-60068-2-1&2), Shock (IEC-60068-2-27), Transport Vibration (IEC-60068-2-64), Humidity test (IEC-60068-2-78). Figure 2 shows 1 kW power amplifier modules undergoing EMI testing at ECIL.

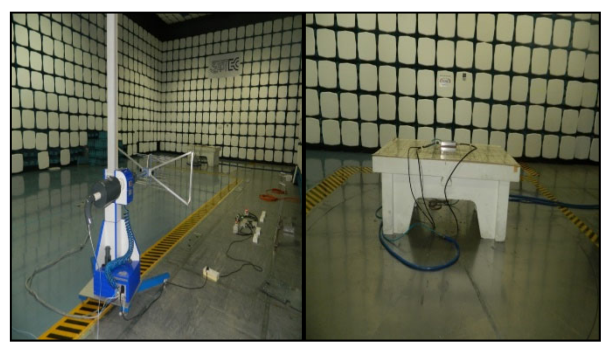

Figure 2: Qualification EMI testing of RF power modules.

The RF power waveforms obtained under CW and pulse mode of operation are shown in Fig. 3 and Fig. 4, respectively, and the RF power amplifier is shown in Fig. 5.

Figure 3: RF power (7 kW) waveforms in CW mode

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Figure 4: RF power (7 kW) waveforms in pulse mode.

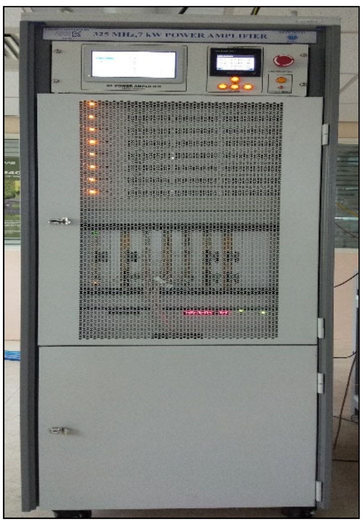

Figure 5: Solid state RF amplifier 325 MHz, 7 kW amplifier at ECIL.

Table 1 lists the tested specifications of these RF power amplifiers.

Critical amplifier-parameters like gain magnitude and phase variation in 10 dB dynamic range (in 10% to 100% of full rated power), group delay, harmonic content, and spurious outputs affect the quality of RF power and hence, the quality of accelerator beam to which it is coupled. Tables 1 and 2 shows that RFPAs have performed very well in these critical parameters. AC to RF efficiency of RFPA determines the utilized Mains AC power and unutilized power is heat dissipated to air and water, thus giving effective utilization of Mains AC power. These RFPAs have achieved good AC to RF efficiency of > 50 %. Figures 6, 7, and 8 show RF output power, AC to RF conversion efficiency and gain of eleven RFPAs, respectively.

Performance range of the parameters in the form of minimum to maximum recorded for these nine RFPAs during its detailed testing is listed in Table 2.

Table 1: Tested Parameters of RFPA

Description	Specification
Frequency	325 MHz
RF Output Power	7 kW Typical
1dB Bandwidth (MHz)	7 MHz, minimum(±3MHz)
Power Gain	62-64 dB Typical
Group Delay	< 100ns
Phase of the amplifier gain over 10 dB dynamic range	< 15 °
Temperature coefficient of gain (28± 2°C)	≤ 0.04dB/°C
Temperature coefficient of phase (28± 2°C)	≤ 1 degree/°C
AC to RF Efficiency (at 7KW)	~ 53 to 54 %
All Harmonics	<-25dBc
Spurious	<-60 dBc
Connectors	
RF in	N(F)
RF Out	3 1/8” flange
AC power input to the rack of 7KW amplifier unit	3Ø,4-wire (Delta) 480/440, 60/50Hz, 1Ø-110V,60Hz
Environmental Standard	Applicable as per IEC60068
EM/EMC Standard	Applicable as per CISPR 11 & IEC61204-3, EUT Under controlled electromagnetic environment category

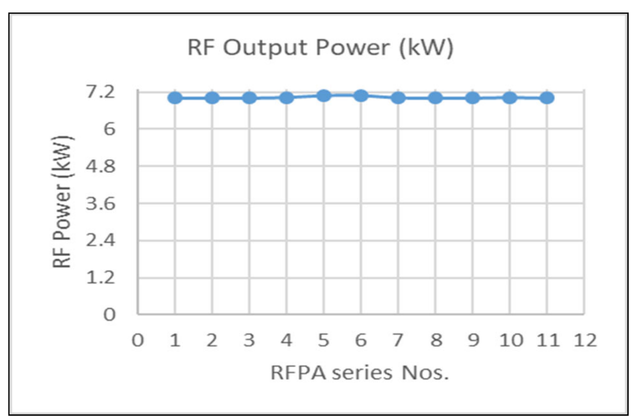

Figure 6: RF power of eleven RFPAs.

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Table 2: Performance Range of the Parameters of Nine RFPAs

	Specifications	Parameter Range for nine RF amplifiers
1	Frequency (MHz)	325
2	O/P RF Power(W)	7000.0
3	Efficiency DC-RF (%)	61.6 to 66.35
4	Efficiency AC-RF (%)	51.4 to 54.9
5	Gain(dB)	62.9 - 64.15
6	Group Delay(ns)	77.35 to 90.39 nS
7	1dB BW(MHz)	26.65 (avg)
8	2nd Harmonic(dBc)	(-)32.57 to (-) 43.37
9	3rd Harmonic(dBc)	(-) 48.4 to (-)71.37
10	Environmental Standard	IEC60068
11	EM/EMC Standard	CISPR 11 & IEC61204-3, EUT Under controlled electromagnetic environment category

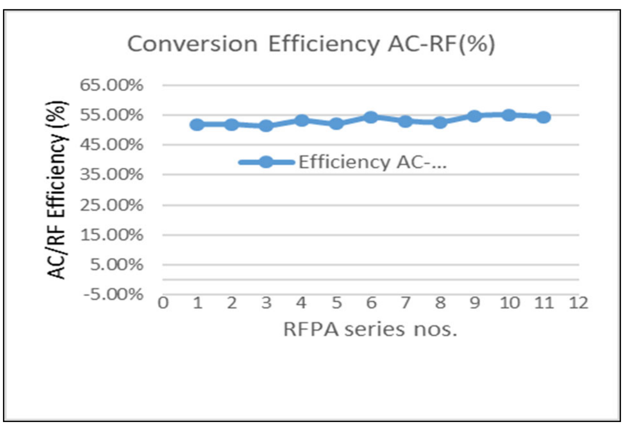

Figure 7: AC to RF conversion efficency of eleven RFPAs.

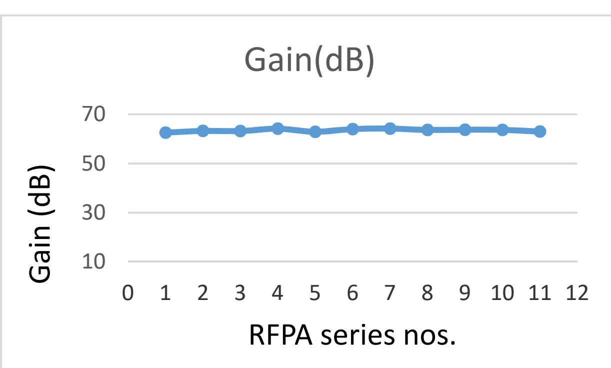

Figure 8: Gain of eleven RFPAs.

PIP2IT OPERATION

PIP2IT comprises of two major sections. The first consists of room-temperature technology and includes a radiofrequency quadrupole. The second section based on superconducting radiofrequency technology, consists of two cryomodules which houses cold, superconducting structures that accelerate the beam, known as cavities. The second cryomodule, a type known as SSR1, was designed and built by Fermilab.

Nine 325 MHz, 7 kW RFPAs were delivered to Fermilab. Eight RFPAs (Fig. 9) were integrated with eight cavities of single spoke resonator 1 (SSR1) cryomodule of PIP2IT beam facility.

Figure 9: Eight RFPA systems commissioned & coupled to SSR1 @ Fermilab.

PIP2IT at the U.S. Department of Energy's Fermilab accelerated proton beam through part of its new superconducting section for the first time at nearly perfect transmission in October 2020 with power coupled from first RF power amplifier.

Thereafter a total of eight RF amplifiers were coupled to low-energy portion of the PIP-II linac, housed in the PIP2IT facility. They were operated for over 300 hours. The amplifiers provided the power to successfully accelerate 2 milliamps of particles through eight SSR1 cavities to a beam energy of up to 17 MeV. The PIP2IT configuration required a peak power level of 4 kW from the amplifiers to accelerate the full beam intensity.

Figure 10 graph shows the amplifier RF power drive to eight cavities of SSR1 (Fig. 11) though actual RF power in the cavity will be slightly less because of insertion losses in the transmission line and minor amount of reflected power.

CONCLUSION

HPRF systems are critical to any NC / SC accelerator because of their multi-disciplinary nature, complexity involved, their cost of development as well as operating cost, their efficiency and their impact on accelerator down time. Indigenous HPRF systems based solid-state devices have been successfully designed and developed at BARC and productionized at ECIL after facing and overcoming various challenges. These systems have been coupled to SSR1 of PIP2IT at Fermilab and 2 milliamps of particles have been accelerated to 17 MeV energy.

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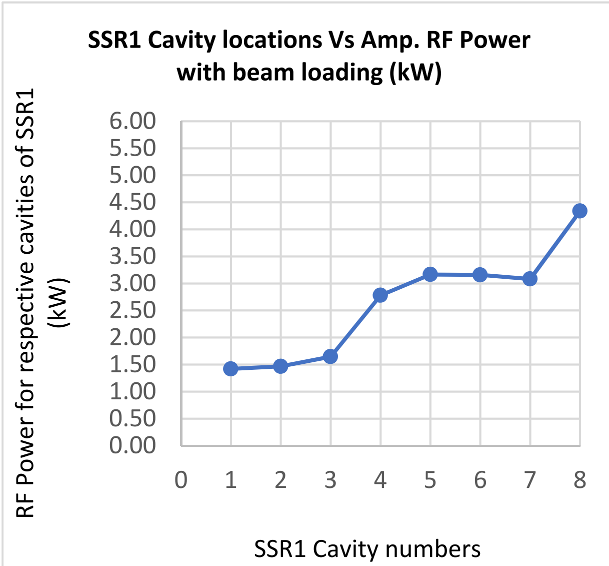

Figure 10: RF power coupled to cavities of SSR1.

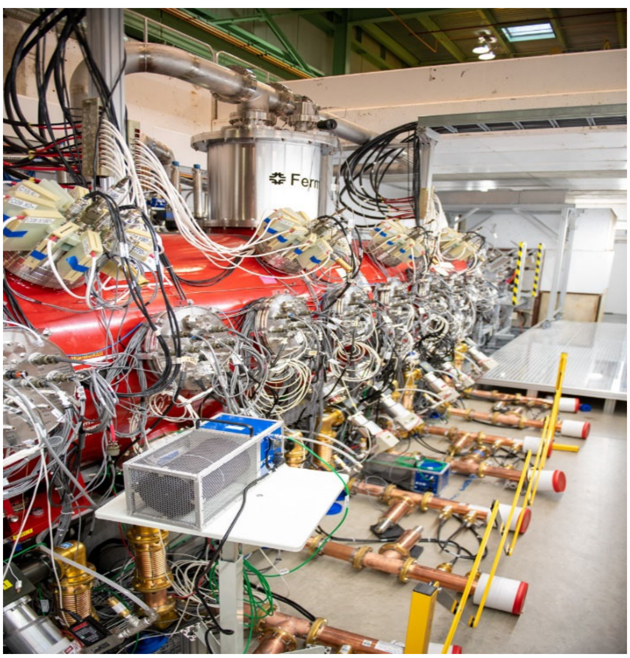

Figure 11: SSR1 cryomodule before RF distribution connection.

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REFERENCES

[1] https://pip2.fnal.gov/how-it-works/pip2it/

[2] https://indico.fnal.gov/event/9939/material/2/0

[3] Manjiri Pande et al, Invited talk, “RF power for 325 MHz superconducting cavities”, Workshop on ‘Technology development for superconducting cavities’, at RRCAT, Indore, India, July 2017.

[4] Manjiri Pande *et al.*, Invited talk, “Development of 325 MHz solid-state RF amplifiers for superconducting spoke resonators of high intensity proton accelerators”, presented at *Asian Federation for Accelerator and Detectors (AFAD) 2019*, at IUAC, New Delhi, India, February 2019.

[5] J.K. Mishra, et al, “Functional Requirement Specifications for 7kW, 325 MHz Solid State RF Power Amplifier System”, Fermilab Engineering Document ED0003408, at FNAL, Batavia, IL, USA, co-listed DAE Document DAE 103, DAE, Government of India, Anushakti Bhayan, Mumbai 400 001, India, June 2017.

[6] J.K. Mishra, et al, “Technical Requirement Specifications for 7kW, 325 MHz Solid State RF Power Amplifier System”, Fermilab Engineering Document ED0004290, at FNAL, Batavia, IL, USA, , co-listed DAE Document DAE 104, DAE, Government of India, Anushakti Bhayan, Mumbai 400 001, India, August 2017.

[7] J.K. Mishra *et al.*, “High efficiency RF amplifier development over wide dynamic range for accelerator application”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 868, pp. 48-52, 2017. https://doi.org/10.1016/j.nima.2017.05.023