ठोस-अवस्था प्रवर्धक

6

त्वरकों के लिए यूएचएफ में kW और MW स्तर की ठोस-अवस्था प्रवर्धक प्रणालियाँ

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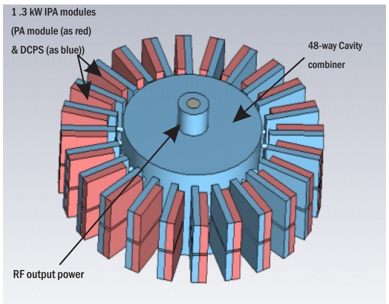

50 kW, 325 MHz SSA HPRF सेक्शन की व्यवस्था

सारांश

ठोस अवस्था प्रवर्धक (एसएसए) तकनीक अत्यन्त प्रमापीय, रेडियो आवृत्ति (आरएफ) सामर्थ्य विस्तार योग्य, कम वोल्टता पर प्रचालित, और आकर्षक निम्नीकरण जैसी सुविधा प्रदान करती है। ये विशेषताएं इसे सामान्य तथा अतिचालक गुहिकाओं पर आधारित त्वरकों के लिए उपयुक्त बनाती है। भापअ केंद्र ने स्वयं और अपने सहयोगात्मक कार्यक्रमों के लिए एसएसए तकनीक के विकास पर सफलतापूर्वक कार्य किया है। एसएसए प्रौद्योगिकी के विकास की इन गतिविधियों के परिणाम स्वरूप विभिन्न रेडियो आवृत्तियों पर कुछ वाट से लेकर 20 किलोवाट तक उच्च शक्ति प्रवर्धकों का विकास किया गया है। मासफेट और सर्कुलेटर जैसे घटकों के अतिरिक्त, इस एसएसए तकनीक का विकास पूर्णतः स्वदेशी है। अभिकल्पन और एकीकरण की मौलिक पद्धतियों की मदद से, एसएसए की कुल सामर्थ्य, सामर्थ्य घनत्व, प्रतिवाट लागत, उपलब्धता आदि जैसे मापदंडों में सुधार किया जा सकता है। भापअ केंद्र , पऊवि ने अपना महत्वाकांक्षी, स्वदेशी रेडियो आवृत्ति (आरएफ) त्वरक कार्यक्रम शुरू किया है, जो किरणपुंज त्वरण के लिए रेडियो आवृत्ति (आरएफ) सामर्थ्य की मदद से गुहिकाओं में विद्युतचुम्बकीय क्षेत्र स्थापित करता है। इसलिए, एक नई अनुसन्धान और विकास गतिविधि के रूप में, आरएफ शक्ति की घरेलू आवश्यकताओं को पूरा करने के लिए किलोवाट एवं मेगावाट स्तर के एसएसए तंत्रों की सकंल्पना की गई है। मध्यम ऊर्जा, उच्च तीव्रता वाले प्रोटॉन त्वरक (मेहिपा) के लिए 325 मेगाहर्टज पर 50 किलोवाट के और रेडियो आवृत्ति चतुर्ध्रुव (आर एफ क्यू) या बहाव नलिका लिनैक (डी टी एल) के लिए 325 मेगाहर्टज पर 280 किलोवाट के स्वदेशी एसएसए विकास की सकंल्पनात्मक अभिकल्पन योजना को अंतिम रूप दिया गया है। अनुसन्धान और विकास के प्रयासों के इसी क्रम में, सामान्य प्रचालक आधारित त्वरक के लिए 352/325 मेगाहर्टज पर 1 मेगावाट के एसएसए की भी सकंल्पना की गई है। इन सभी स्वदेशी एसएसए तंत्रों की वैचारिक अभिकल्पन योजनाओं की चर्चा को इस लेख के माध्यम से प्रस्तुत किया गया है।

Solid-state Amplifier

6

Solid-State Amplifier Systems of kW and MW level at UHF for Accelerators

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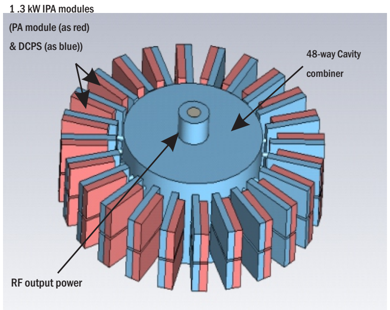

Arrangement of HPRF section of 50 kW, 325 MHZ SSA

ABSTRACT

Solid state amplifier (SSA) technology is highly modular, scalable in radio frequency (RF) power, has low voltage operation and offers graceful degradation. These features make it technology of choice for both normal and superconducting cavity based accelerators. BARC has worked successfully on SSA technology for its own program and for collaboration program. These development activities on SSA technology have led to the development of high power amplifiers starting from few watts to 20 kW at different frequencies. This SSA technology is indigenous except for basic components like MOSFET, circulator etc. With the help of innovative design and integration methodologies, the SSA parameters such as overall power rating, power density, cost/W, availability etc. can be improved. BARC, DAE has launched its ambitious domestic radio frequency (RF) accelerators program, which uses RF power at various levels to set up RF field in RF cavities for beam acceleration. So, as a new research and development activity, SSA systems in kW and MW level is conceptualized to cater to this domestic RF power need. Conceptual design scheme of indigenous 50 kW SSA at 325 MHz for medium energy high intensity proton accelerator (MEHIPA) and 280 kW SSAs for radio frequency quadrupole (RFQ) or Drift Tube LINAC (DTL), at 352/325 MHz is finalized. In continuation of same R&D efforts, a 1 MW SSA at 352/325 MHz for normal conducting accelerator has also been conceptualized. The conceptual design schemes of all these indigenous SSAs are discussed and presented in this article.

KEYWORDS: *ADS, AC to RF efficiency, MTBF, Particle Accelerator, Power divider and combiner, Solid State*

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Introduction

Application areas of accelerators include basic sciences, energy, medical, and security systems. Accelerator development in a country is one of its defining parameter to measure technological advancement. Radio frequency (RF) linear accelerator (LINAC) for accelerator driven sub critical system (ADS) is being developed at Bhabha Atomic Research Centre (BARC) as a multi-phase program. One of the major research and development (R&D) activity involves development of high power RF (HPRF) systems for Indian accelerator program and DAE's international collaborations. Worldwide, international laboratories including ANL [1][2], BARC [3][4][5], RRCAT are pursuing HPRF systems based on SSA technology among other options. With innovative ideas and advance design techniques, BARC has designed and developed high power solid state amplifier (SSA) systems with acclaimed performance specifications for accelerator application. This article presents conceptual design scheme (CDS) of SSA inclusive of its architecture, innovative integration and layout schemes for three SSAs of RF power levels 50 kW, 280 kW and 1 MW having features like high efficiency, compactness and ruggedness.

The guiding factors of CDS of SSA

Theme of this CDS is based on four I's i.e. ideas, innovate, implement and indigenise for self-reliance in high power SSA technology. In SSA, with the help of these four I's, four C's can be achieved i.e. comprehensive design, cost effectiveness, compactness and competitive performance.

The important features of SSAs designed and developed at BARC are high efficiency performance (~54 to 55% wall plug efficiency), compact design (approximately 13.7 kW/m^3 power density), cost effective implementation, compliance to international standards (EMI/EMC and vibration standards) [5] and, reliable operation. Efforts are made to constantly improve SSA performance parameters by innovative design efforts. SSA R&D for the RF accelerators presented in this article will highlight these efforts, which incorporate innovative design methodologies, new ideas of system integration and implement them to achieve better performance.

Conceptual Design of kW/MW SSAs

Medium energy high intensity proton accelerator (MEHIPA) phase 1 is an accelerator program to develop a 40 MeV proton accelerator. It has normal conducting section up to 10 MeV incorporating RFQ and DTL and superconducting accelerator sections above 10 MeV incorporating Single Spoke Resonator (SSR)).

As per LEHIPA measurement data, RF power requirement for DTLs at 3-11 MeV and 11-20 MeV is around 800 kW (4 ports, 200 kW) each, and around 560 kW (2 ports, 280 kW) for 3 MeV RFQ. These RF power measurements are inclusive of insertion losses across the RF power system and reflected power from accelerator.

The maximum RF power requirement of superconducting SSR cavities of MEHIPA with adequate margin is about 50 kW. Hence, a SSA of 50 kW at 325 MHz is designed. Conceptual designs of 50 kW SSA for SSR cavities, 280 kW and/or 1 MW SSAs for RFQ/DTLs are presented in this article. Depending on accelerator power requirements, the output power of SSAs can be scaled up to 500 kW and 1 MW by combining multiple 280 kW SSA blocks. These SSAs can be built for both 325 MHz and 352 MHz with minor modifications in IPA module and Power combiner/dividers.

The main sub-systems of these SSAs are, a low power RF (LPRF) driver, power amplifier (PA) modules, direct current (DC) bias power supplies, power divider, power combiner, interlock protection and monitoring system (IPMS), AC power distribution arrangement and a number of directional couplers. The first basic SSA tower uses a modular topology where power output from multiple power amplifier (PA) modules are combined via power combiner to achieve overall high-power output.

The preliminary design of major sub systems of these SSAs inclusive of innovative ideas and integration methodologies to meet 4 C's is discussed below.

- *Integrated PA (IPA) module*: The number of interconnecting cables increases with the number of PA modules and DC power supplies (DCPS). This results in increase in complexity of cable routing, requirement of more space, increase in cable losses, system noise etc. A design innovation by integrating PA module, DC PS and its protection circuit, known as Integrated PA (IPA) module on a single heat sink and with direct interface between them resolves most of the issues. It reduces number of DC cables, noise, uses single heat sink and single protection circuit for both PA module and DCPS, ensuring high level of integration with power combiner. This effectively reduces size and cost, increases efficiency, increases availability due to increased mean time between failure (MTBF) and reduced mean time to repair (MTTR).

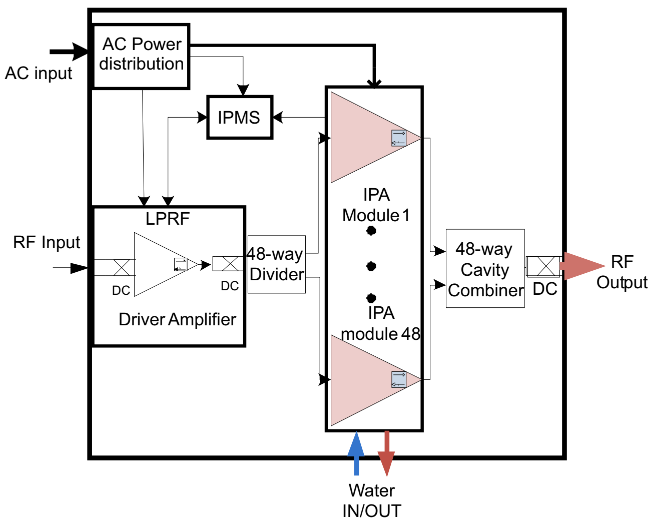

Fig.1: Architecture of 50 kW SSA at 325 MHz for MEHIPA-phase 1.

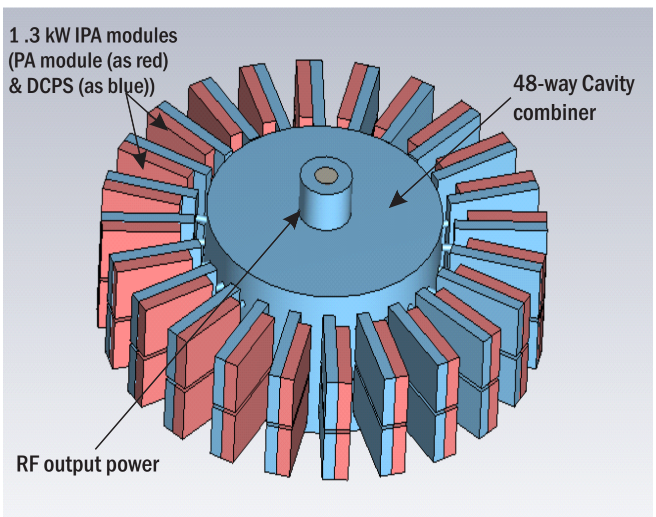

Fig.3: Arrangement of HPRF section of 50 kW, 325 MHZ SSA.

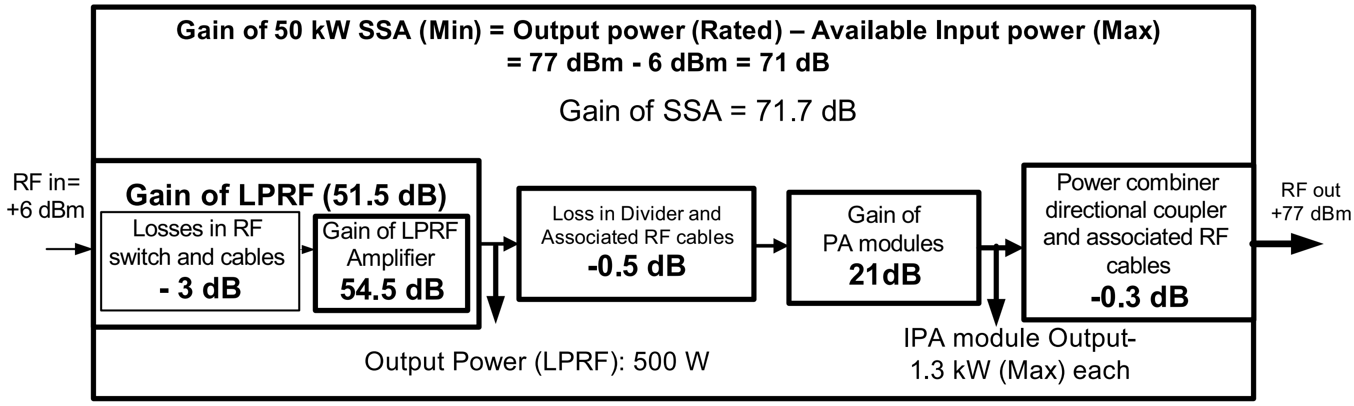

Fig.2: SSA Gain budget for 50 kW, 325 MHZ SSA.

- *Cables-less high power interfaces*: Innovative interface design of IPA modules and their direct mounting on cavity combiner enables the cable-less high power RF interface. It further improves compactness, and reduces cost, improves efficiency and eases maintenance.
- *Modular IPMS*: Modular and distributed IPMS design implementation helps simpler design, easy diagnosis, less cabling, less noise and easy maintenance with improved reliability.
- *Power combining methodology*: Overall design concept for power combining methodology for these three SSAs is same except for levels of combining. In 50 kW SSA, single stage cavity combiner based power combining is used. The 280 kW SSA design uses two stages of power combining and 1 MW SSA design uses four stages of high power combining. Architectural details and salient features of these SSAs are presented in this section.

Design of 50 kW SSA at 325 MHz for MEHIPA

Architecture of the proposed design of 50 kW, 325 MHz SSA for SSR cavities is shown in Fig.1. The 50 kW SSA integrates all 48 IPA modules, each rated for 1.3 kW RF power, by directly mounting on a single cavity combiner. This cavity combiner and IPA arrangement achieves higher level of IPA module integration with lower combining losses and linear combining. Other sub systems of SSA like LPRF, AC-PDP, IPMS will be housed in a separate cabinet, and will be located very near to SSA installation.

SSA design involves estimation of SSA gain requirements and gain budget for various sub-systems. Gain budget of the 50 kW SSA at 325 MHz (assuming +6 dBm (maximum) input from low level RF (LLRF)) and its sub-systems is shown in Fig.2. Fig.3 shows the arrangement of high power RF components. The power density of the complete 50 kW SSA is estimated at around 13.6 kW/ m^3.

Wall plug efficiency of the SSA is estimated at 53% (min.) based on conservative efficiency values for sub-systems like integrated PA module 58% (min.), and efficiency of cavity combiner around 95% (min.). Some of the critical specifications for this SSA are given in Table 1.

Conceptual design of 280 kW SSA

To meet the requirements of RFQ and DTLs, innovative design adopted for 50 kW has been extended for 280 kW SSAs at 352 MHz for LEHIPA and 325 MHz for MEHIPA. In this SSA, maximum possible input ports on the cavity combiner were estimated based on the dimensions of cavity combiner and IPA module. Redundancy of IPA module has also been considered to increase SSA reliability. Cylindrical cavity combiner operating in TM_{010} mode at 325 MHz/352 MHz has its resonance frequency related to its radius. The Radius of cylindrical combiner cavity for resonance frequency of 352 MHz/325 MHz is approximately 350 mm. Cavity dimensions and IPA module size dictates the maximum input ports feasible on the cavity combiner. For these frequencies and dimensions of IPA module, maximum 128 nos. of IPA

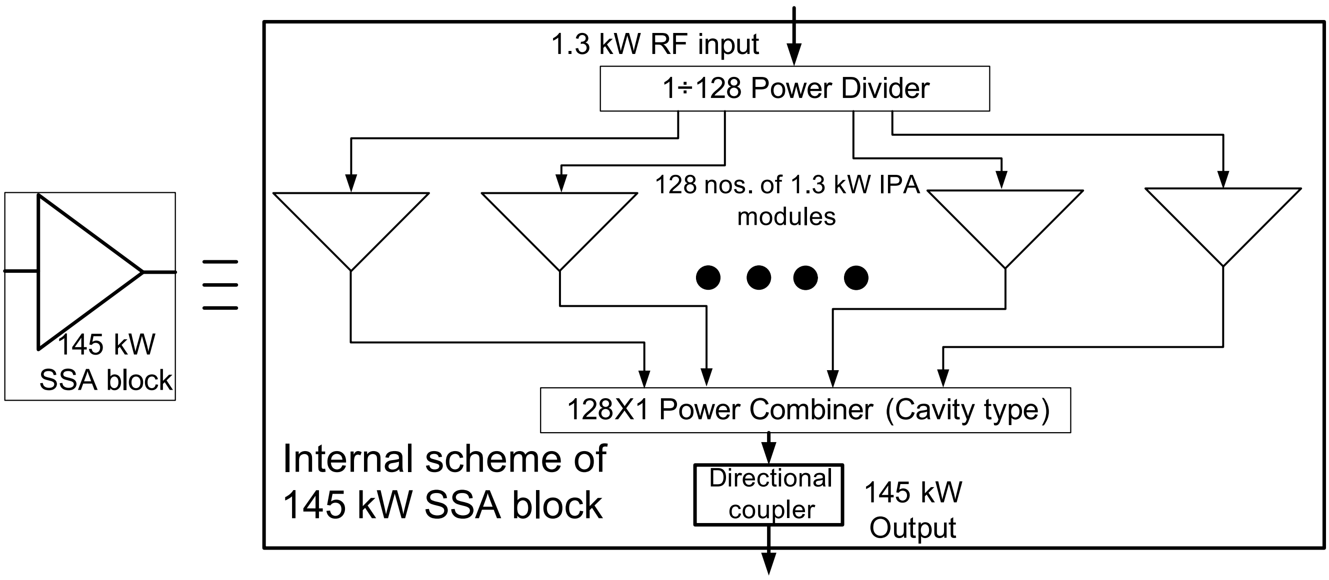

Fig.4: Internal Scheme of 145 kW SSA block.

modules can be integrated with the cavity combiner. With IPA module rating at 1.3 kW, power of each SSA block or tower is 145 kW and offers redundancy of about 15 IPA modules for nominal power of 140 kW. Internal RF Scheme of 145 kW SSA tower is shown in Fig.4.

145 kW SSA blocks comprises of a 128-way power divider, outputs of which feeds to 128 nos. of 1.3 kW IPA modules. Output from these IPA modules is combined using a 128-way cavity combiner. 128 IPA modules are assembled directly on the 128-way cavity combiner with cable-less RF interface and hose-less water interface for compact and efficient assembly. This scheme reduces footprint size and cost of the implementation by saving inventory of RF cables and water circuit.

LPRF (Driver) unit that feeds RF power to 128-way divider of this SSA block comprises of 1.3 kW IPA module. AC power distribution sub-system distributes and manages AC power flow for reliable and safe operation of the SSA block. IPMS unit is designed as distributed topology to provide functions like interlock, protection and monitoring of various parameters and keep amplifier operational under normal operating conditions and helps during diagnosis of failures.

Combining of two such SSA blocks is estimated to deliver 280 kW output which is sufficient to directly feed each ports of DTL/RFQ. Output port of 145 kW SSA block is 8 - 3/16", 50-ohm flange. The two-way power combiner for combining these two SSA towers will be coaxial line to waveguide type combiner, whose output will be available on waveguide WR2300 HH port. Some of the critical specifications of the 280 kW SSA are listed in Table 1.

Conceptual design scheme of 1 MW SSA

The present R&D efforts for 1 MW SSA at 352 MHz are aimed to provide overall scheme and mitigate the challenges involved in its design and implementation to achieve compact, cost effective, high efficiency and high availability. The design is aimed at enabling self-reliance and 'Make in India' to reduce import dependence. The architecture cum concept scheme (Fig.5) of 1 MW SSA consists of three stages namely the input

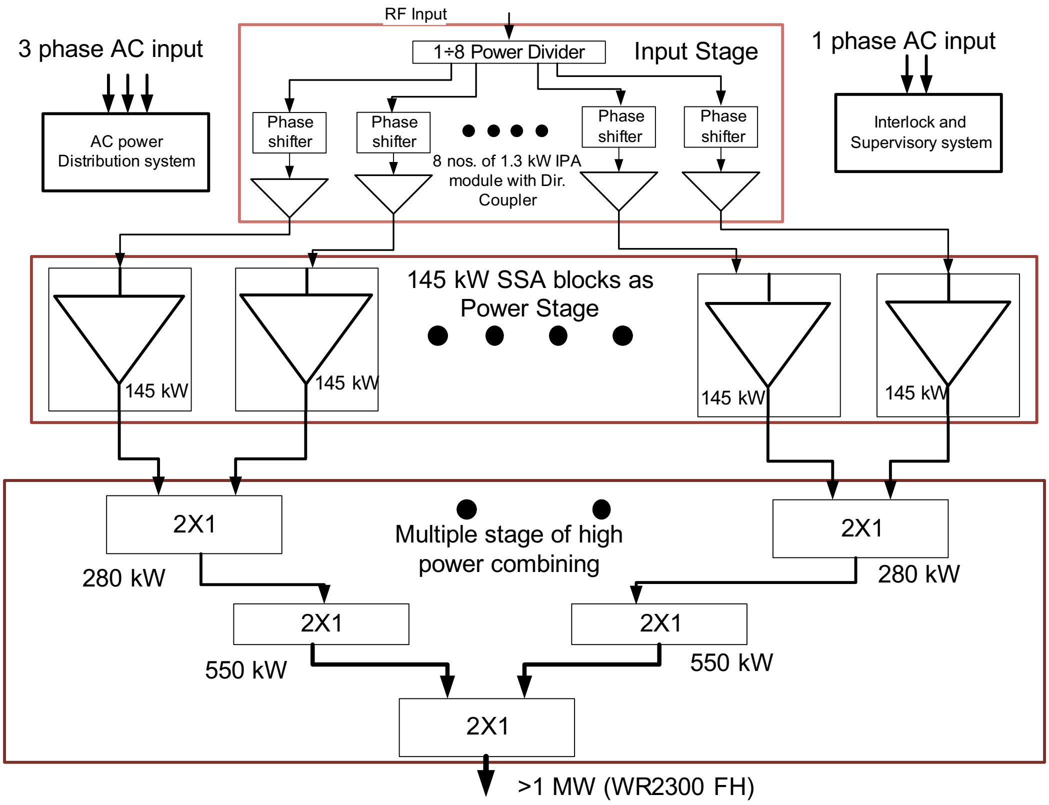

Fig.5: General Block Diagram Super Power 1 MW, 352 MHz SSA System.

Table 1: Critical specifications of SSAs 352/325 MHz SSA.

Sr. No	SSA specification	Parameter values for 1 MW	Parameter values for 280 kW	Parameter values for 50 kW
1	Guaranteed Output power at 352/325 MHz	1 MW (CW and pulse)	280 kW (CW and pulse)	50 kW (CW and pulse)
2	Bandwidth (-3 dB)	= 4 MHz	= 4 MHz	= 4 MHz
3	Power gain requirement	= 84 dB	= 78.5 dB	= 71 dB
4	Harmonics*	< -25 dBc	< -25 dBc	< -25 dBc
5	Spurious*	< -55 dBc	< -55 dBc	< -55 dBc
6	AC to RF Efficiency$	~ 40% (@1 MW)	~ 42% (@280 kW)	~ 50% (@50 kW)
7	Smallest amplification unit (Basic building block)	1.3 kW IPA module	1.3 kW IPA module	1.3 kW IPA module
8	Smallest integrated amplification sub-system	~145 kW SSA block, 8 nos.	~145 kW SSA block, 2 nos.	50 kW SSA block, 1 no.
9	Output connector and VSWR	WR2300 FH/HH, <1.4	WR2300 HH, <1.4	6 1/8" EIA, <1.4
10	Input connector and VSWR	SMA (F), <1.2	SMA (F), <1.2	SMA (F), <1.2
11	System cooling	Water cooled	Water cooled	Water cooled

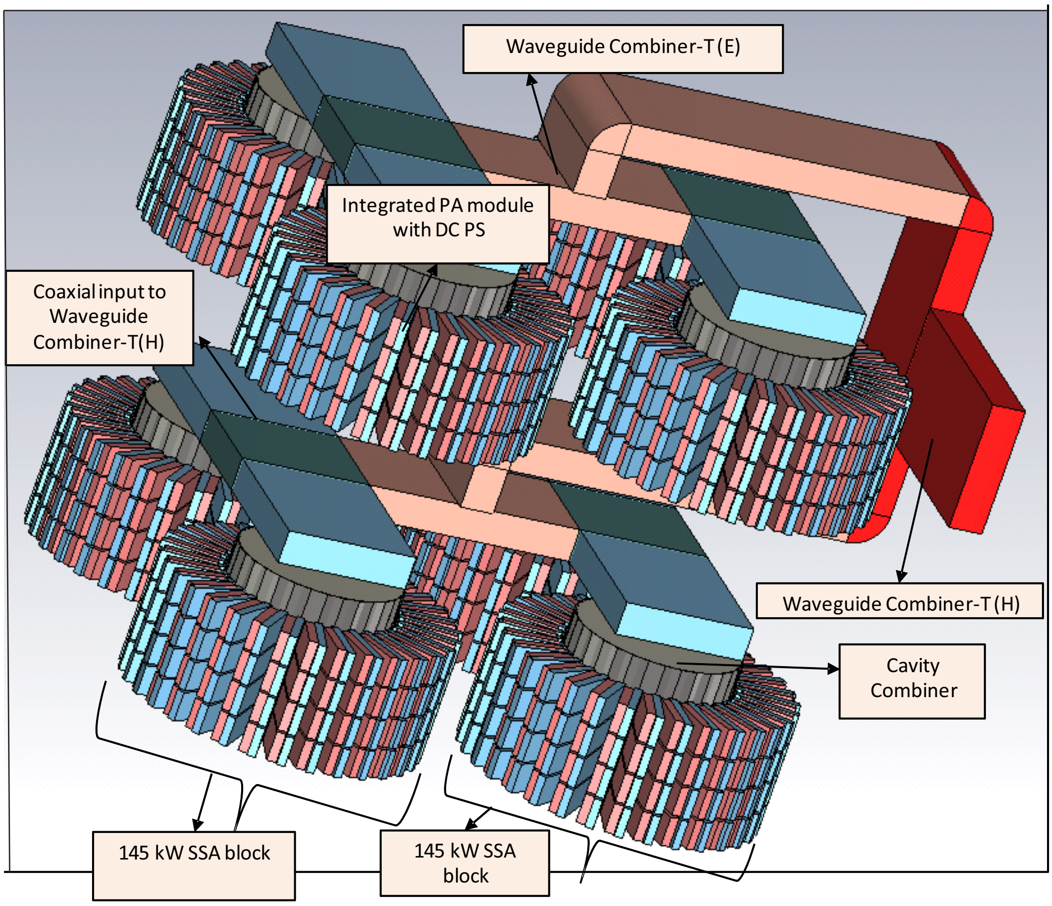

Fig.6: : Physical arrangement scheme of 1MW segment of 1 MW SSA.

stage, the power stage and high power combining stage. It uses 145 kW SSA tower as the main building block as shown in Fig.5. This scheme, has following salient features.

■ The 'Input stage' consists of an eight (8) - way power divider that feeds the input RF power via phase shifter (to provide flexibility in phase matching) to eight (8) numbers of 1.3 kW IPA modules. Output from these modules is fed to 145 kW SSA block.

■ Power stage comprises of eight nos. of 145 kW SSA blocks.

■ Multi-stage high power combining: As described in previous section, two 145 kW SSA towers are combined to deliver 280 kW maximum power per port of normal conducting accelerating cavity. However, if 500 kW or 1 MW output power is needed. If power required per port is less that 145 kW, SSA blocks will have more redundancy and availability, it can be delivered by power combining as shown in Fig.5. Availability of RF Power at 145 kW, 280 kW, 500 kW and 1 MW level provides flexibility to the accelerator facility.

■ Modular protection and monitoring at IPA module level simplifies overall interlock, protection and monitoring system (IPMS).

Some of the critical requirements cum design specifications of this scheme of 1 MW SSA that can be achieved are listed in Table 1.

Physical arrangement scheme of eight nos. of 145 kW SSA blocks of is shown in Fig. 6 as cylindrical towers. To achieve output power of 1 MW, further combining is done using waveguide-based network. The design, development and deployment experience of various waveguide components for LEHIPA reduces risk in these designs.

*Harmonics and spurious levels of 1.1 kW PA module (on which IPA modules of 1.3 kW are based) is -30 dBc and -60 dBc. These values are standard acceptable range for accelerator RF systems.

$The AC to RF efficiency is based on measured AC to DC efficiency of DCPS, measured DC to RF efficiency of PA modules, combining loss calculations based on gain magnitude and phase spread.

Conclusion

BARC has focused on the design and development of state of the art high power SSAs for Indian accelerator program. Innovative design techniques and integration topologies adopted to develop these SSA are aimed to achieve high efficiency, compact and cost effective SSAs with reliable operation. Objectives further include enabling self-reliance and indigenous manufacturing of high end SSAs technology via Indian industries. This further accomplishes 'Made in India objectives of Govt. of India and provides critical import substitute. Main features of these high power SSA design are high power density from 12 kW/m^3 for 50 kW up to 15 kW/ m^3 for 280 kW and 1 MW and low cost per watt.

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