ERL2024, Sep 24, 2024

Challenges and breakthroughs in recent RF Solid State PA design by Radial Combiner design with Initiatives for SDGs

Presented by Riichiro Kobana
R&K Company Limited

Abstract

R&K, an independent company, has achieved production of 2.3 million 1.9GHz microwave power amplifiers for mobile-comm's-base-stations and then also supplies wideband power amplifiers for automobile EMC testing for domestic automobile industries. Then 16 years ago, we started designing and producing some hundreds kW RF SSA for accelerator applications as alternatives to Klystron / tube.

The measure characteristics of SSA is a possibility to design a band in a very wide frequency range available from few MHz to 14 GHz, and its upgradability of max-power in few kW to few MW design even after system completed. Recently, SSA is being recognized the significant advantages over vacuum tubes in terms of size, low power consumption, higher efficiency, low cost, and adaptive power design. In addition to these, we have learnt that SSA has very low phase noise and low envelope noise that cannot be achieved with vacuum tubes.

All these advantages are transforming SSAs into the first-chosen RF power source even for particle accelerators. There is no doubt that all these improved performances of SSA will minimize overall resource utilization, and well match with sustainable industry and society.

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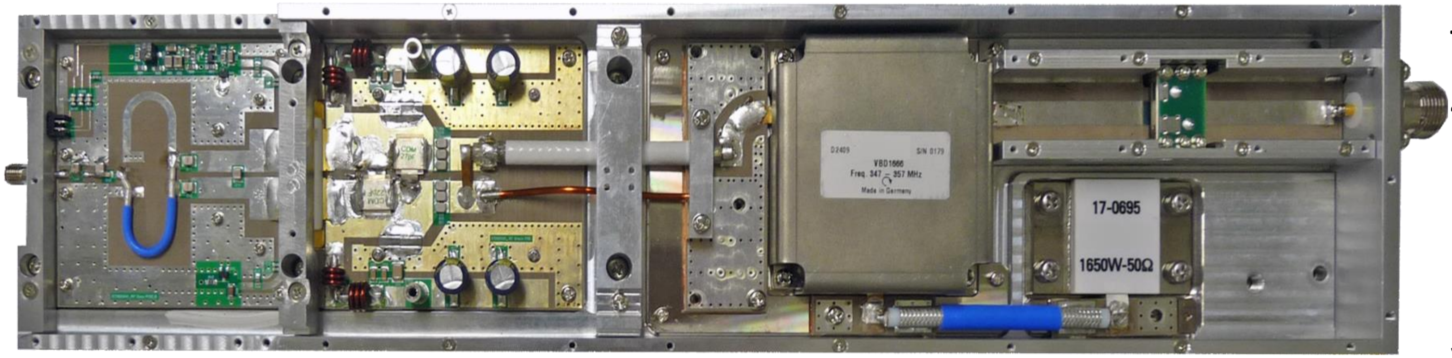
SSA RF Module

352MHz > 1kW･CW･PA Module

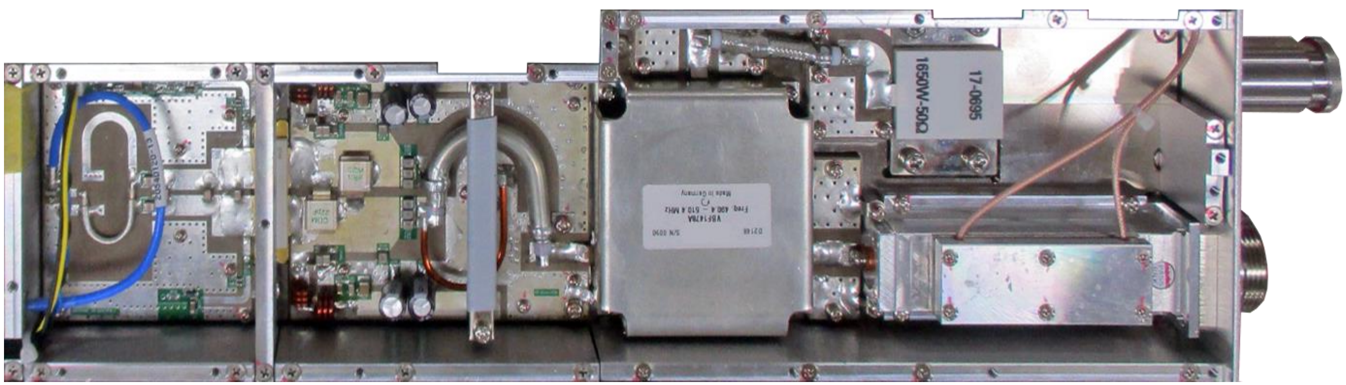


Final SSA Module “ SIZE-A”.

Typ. size for VHF SSA Module
400(L) x 92(W) x 30(H)mm,

G>+23dB, P-1dB>800W, and
Psat>1.2kW at class AB biasing
Efficiency DC-RF >76% @+50V
with output Circulator protect.

500MHz > 1kW･CW･PA Module



Final SSA Module “ SIZE-B”.

Typ. size for UHF SSA Module
350(L) x 88(W) x 33(H)mm,

G>+22dB, P-1dB>750W, and
Psat>1kW at class AB biasing
Efficiency DC-RF >72% @+50V
with output Circulator protect.

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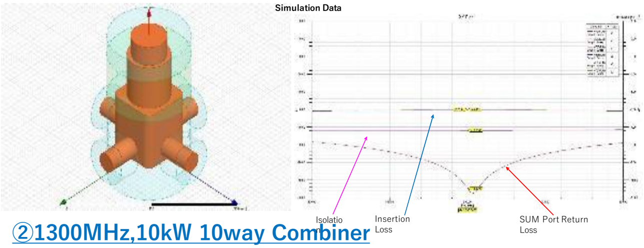
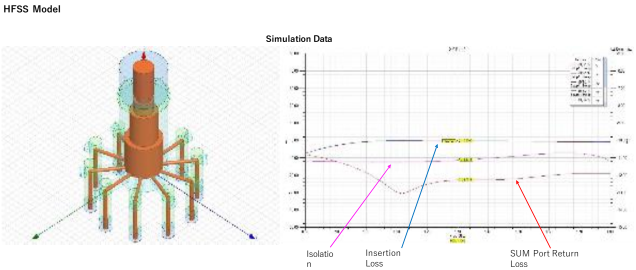
Various kind of design for very high power Radial Combiners

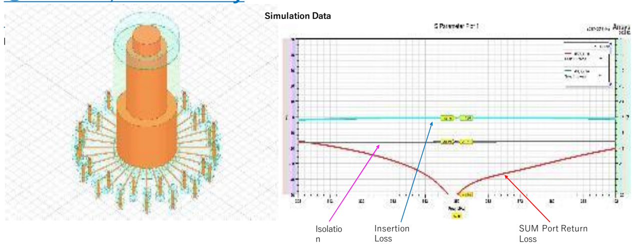
①500MHz,350kW(Pulse) 4way



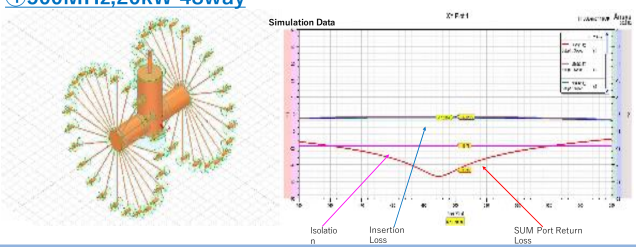
②1300MHz,10kW 10way Combiner



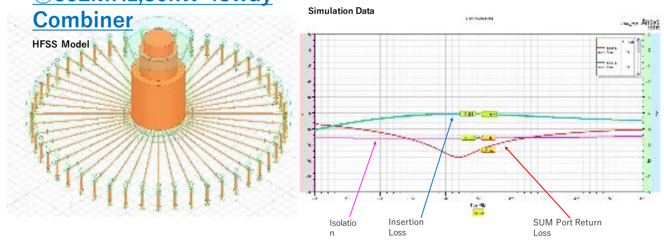
③352MHz,80kW 32way



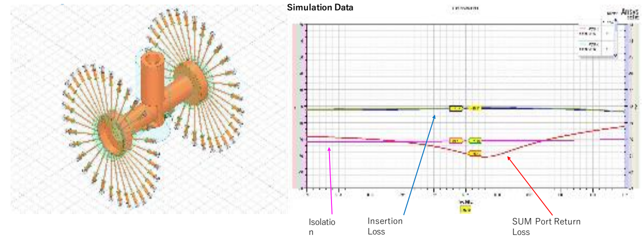
④500MHz,20kW 48way



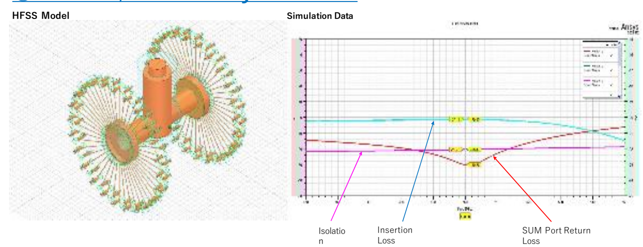
⑤352MHz,80kW 48way Combiner



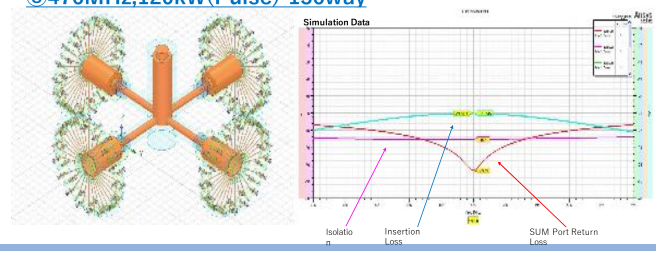
⑥972MHz,240kW(Pulse) 64way



⑦500MHz,70kW 96way Combiner



⑧476MHz,120kW(Pulse) 136way



※ Low power consumption,
※ high efficiency
※ low cost,

are all realized with following rugged radial power combiner circuits by HFSS and COMSOL simulation design.

- ◎ Odd, Even, and Prime ports design are all available.
- ◎ Max power is only limited up to the connector design.
- ◎ Isolation to adjacent ports are achieved by the number of branches.
- ◎ Max. insertion loss is only -0.05dB to -0.15dB max. with very broadband.
- ◎ RF Power Combiner using cavity resonators have high Q and low loss, but this method has a very low Q, so the temperature characteristics are very stable and the loss is relatively low.
  In particular, most RF losses are caused by coax-cables, so the power combining method of the future will likely shift "coax with waveguide cascaded combiners".

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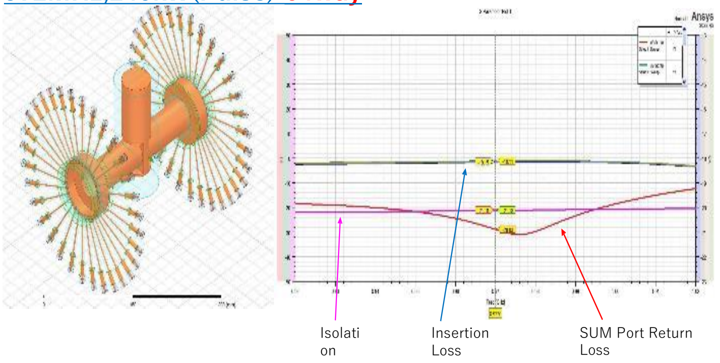
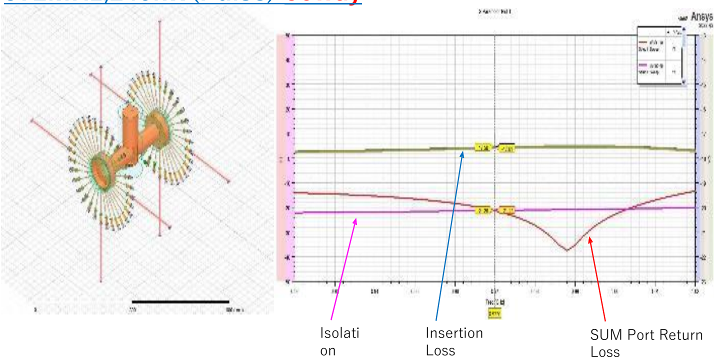
Single structure, but Multiple ports RF Power Combiner
972MHz > 240kW, Pulse RF, 64/60/56/48way design

Adaptive Power Amplifier Design

972MHz,240kW(Pulse) 64way



972MHz,240kW(Pulse) 56way

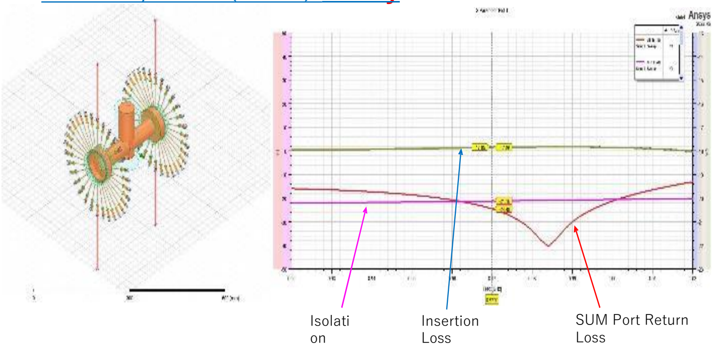


The fixed combiner device, but various branches make the Adaptive Functions.

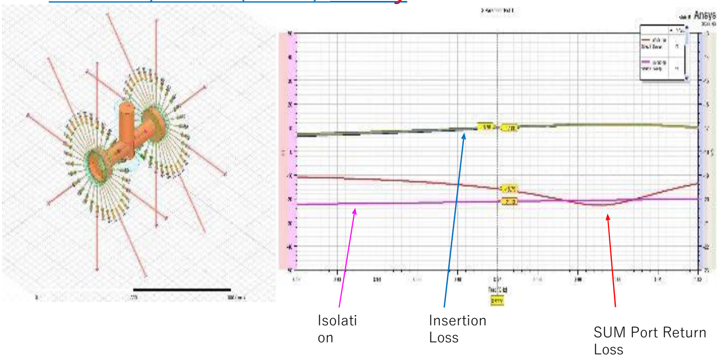
With quarter wave "Short" Can change 64way, 60way, 56way, 48way Radial Power Combiner Functions.

Start with a small budget and scale to your maximum possible potential.

972MHz,240kW(Pulse) 60way



972MHz,240kW(Pulse) 48way



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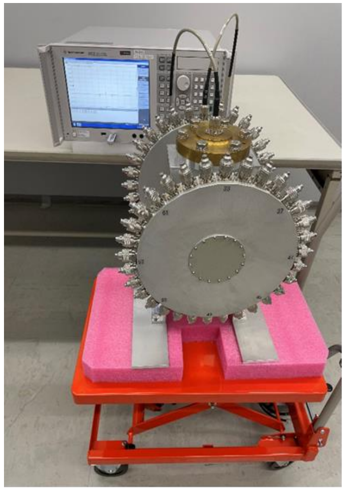
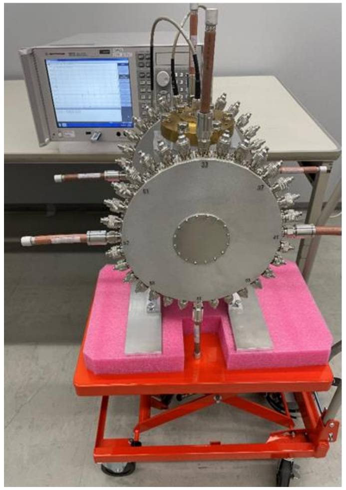
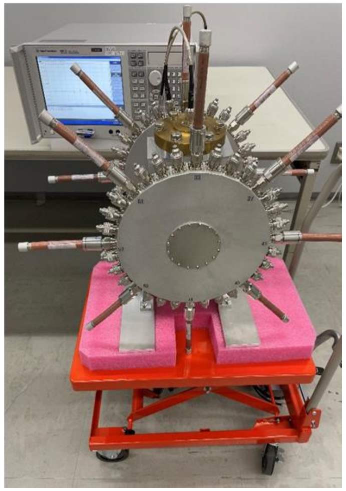
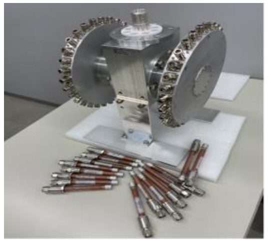
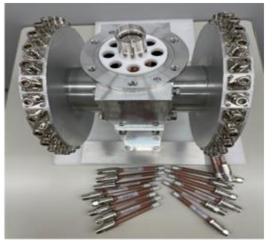
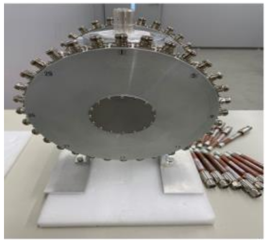
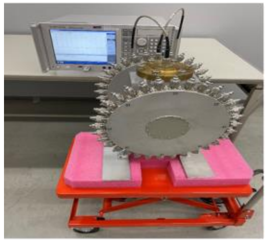
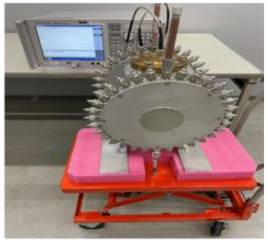
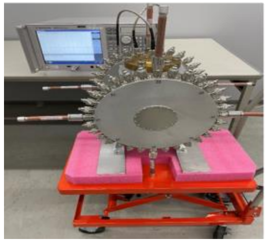
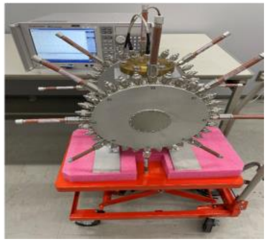


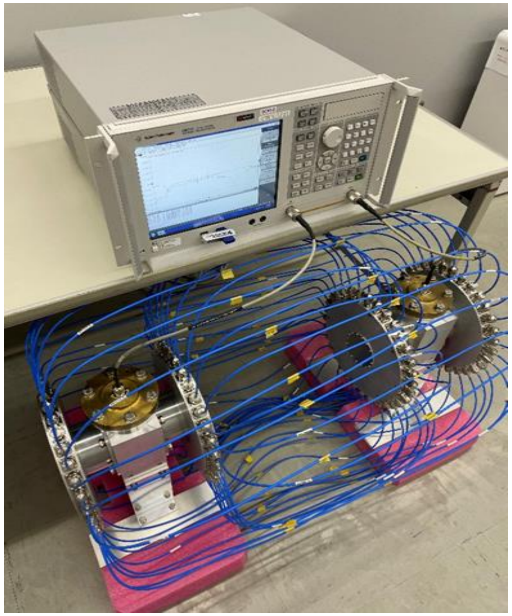






Adaptive
64 way Combiner
and
Quadrature Short

64/60/56/48 way

----Measurement----



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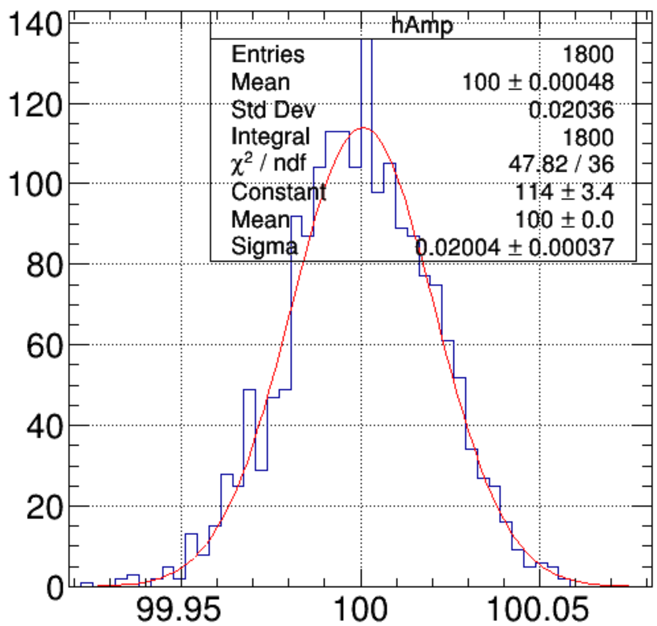
R&K 476MHz SSA for SACLA - pulse by pulse stability

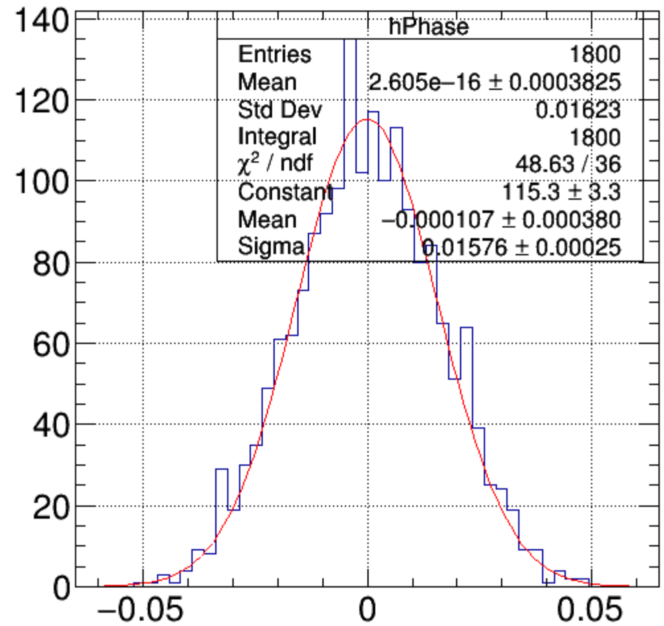
Stability (short term)

- RF-out @ 100kW @476MHz
  0.020% , 0.016deg (sigma)

I would like to express my sincere gratitude to the RIKEN team for giving us the opportunity to collect "phase and level stability data under free-running conditions of RF over 100kW".
For a long time, cost, reliability, and power efficiency came first, and it has been difficult for us to obtain such fulfilling stability data.
Conventional vacuum tube amplifiers always have an electron transit time, and they are extremely sensitive to the thermal noise. They are noise source.
However, as shown here, solid-state amplifier is now possible to achieve this level of stability even without locking the signal by LLRF.



Level vector stability σ A/A [%]



Phase vector stability σ phase [deg]

JASRI/RIKEN Eito Iwai, 2024, Private Communication

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So far, we have covered the important aspects of the SDGs, such as SSA size, low power consumption, high efficiency, low cost, adaptive combiner design, very low phase noise and low envelope noise.

However, we will now move on to the most important topic of latest RF GaN products, where we will discuss the most important aspects of the SDGs, such as the outlook for GaN RF-Device power efficiency for the near future.

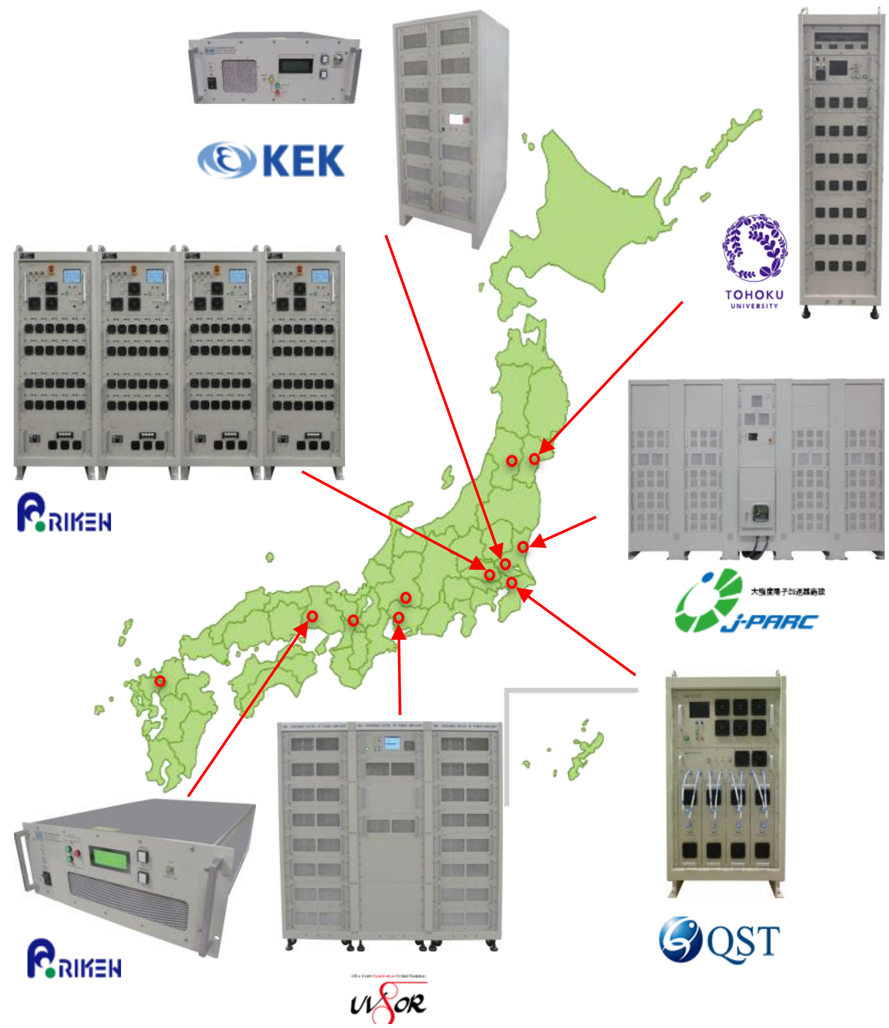
In the 1300 MHz band, the current LD-MOS efficiency is 58% for DC-RF, but R&K has already achieved a DC-RF efficiency of 70% with GaN device.

Also, in the 1500 MHz band, the current LD-MOS efficiency is 49% for DC-RF, but R&K has already achieved a DC-RF efficiency of 70% with GaN device.

Regretably, I am very sorry to say that as a result of discussions with the manufacturer, due to the NDA agreement, we are unable to disclose the detailed timeline of the semiconductor devices at this time. We are very sorry, but we will make an announcement at a later date, so I appreciate your understanding.

Delivery Record of R&K SSPA for National Laboratories in Japan

Customer	Prefecture	Frequency (MHz)	Power (kW)	Mode	Qty	Delivery
Tohoku Univ.	Miyagi	500	15	CW	1	Mar. 2019
		9000	1	Pulse	1	Mar. 2021
QST	Miyagi	2856/5712	0.8/0.8	Pulse	1/20	Mar.2021~
Yamagata Univ.	Yamagata	200	150	Pulse	1	Mar. 2015
KEK	Ibaraki	114/571	12/10	Pulse	2/2	Mar. 2017~
		1300	8/16	CW	2/1	Mar. 2013~
		2856	0.6	Pulse	51	Mar. 2014~
		5200	1	Pulse	1	In Production
		11424	0.5	Pulse	2	Mar. 2011~
		0.01~254	0.5	CW	18	Mar. 2010~
J-PARC	Ibaraki	324	30/120	Pulse	2/1	Dec. 2013~
		0.01~254	0.5	CW	9	Aug. 2012~
		0.1~100	3	CW	5	Mar. 2012~
RIKEN	Saitama	74	4.5	CW	1	Apr. 2018
		200/500	200/300	Pulse	1/1	Mar. 2014~
		0.5~15	1/3	CW	1/1	Mar. 2021~
QST	Chiba	100	30	Pulse	1	Jan. 2013
		10000	0.8	Pulse	1	May. 2015
		14000	1	Pulse	1	Feb. 2022
Tokyo Tech	Tokyo	200	150/250	Pulse	1/1	Jul.2020
TMU	Tokyo	2450	1	Pulse	1	Dec.2023
NIFS	Gifu	0.009~250	0.7	CW	1	Dec. 2017
UVSOR	Aichi	90.115	5/20	CW	1/1	Apr. 2015~
Kyoto Univ.	Kyoto	2856	0.4	Pulse	6	Mar. 2021
		6000	0.2	Pulse	1	Jul. 2018
RIKEN	Hyogo	2856/5712	0.8/0.8	Pulse	2/11	Mar. 2019~
SPring-8	Hyogo	2856	1.2	Pulse	1	Jan. 2012
		0.01~254	0.25/0.5	CW	6/3	Mar.2009~
SAGA-LS	Saga	0.009~100	0.1	CW	1	Aug. 2013



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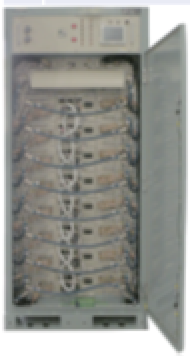
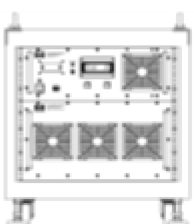
Recent Delivery Record of R&K SSPA (Narrowband) for SLAC

R&K → SLAC NATIONAL ACCELERATOR LABORATORY → Fermilab, Jefferson Lab

№	Frequency	Power	Project	Total Qty	Status	Qty Delivered to SLAC	Delivery	Qty Delivered to Fermilab	Delivery	Qty Delivered to JLAB	Delivery
①	185.7MHz	60kW CW	LCLS-II	2	Delivered	2	Dec. 2017				
②	185.7MHz	6kW CW	LCLS-II-HE	1	Delivered	1	Dec. 2022				
③	199.6MHz	3kW CW	LCLS-II	1	Delivered	1	Sep. 2017				
④	358.54MHz	64kW Pulse	SPEAR3	1	Delivered	1	Jun. 2016				
⑤	475MHz	500W CW	1MeV	1	Delivered	1	Apr. 2023				
⑥	476MHz	100W CW	LCLS-II	3	Delivered	3	May 2021				
⑦	1.3GHz	80W CW	LCLS-II	7	Delivered	2 5	Oct. 2017 Aug.2018				
⑧	1.3GHz	3.8kW CW	LCLS-II	278	Delivered	262	Jan.'16 ~ Aug.'18	8	Jan.~ Nov.'16	8	Jan.~ May '16
⑨	1.3GHz	4.6kW CW	LCLS-II	3	Delivered	1 2	Apr. 2018 Dec. 2018				
⑩	1.3GHz	7kW CW	LCLS-II-HE	25 179	Delivered In Production	2 7	Sep. 2020 Dec. 2020	8	Sep. 2020	8	Dec. 2020
⑪	3.9GHz	900W CW	LCLS-II	18	Delivered	8 2	Aug. 2018 Nov. 2019	8	Oct. 2018		
⑫	11.424GHz	500W Pulse	LCLS-II	3	Delivered	1 2	Aug. 2017 Mar. 2021				


185.7MHz 60kW CW

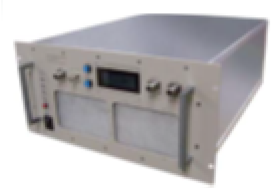

199.6MHz 3kW CW


358.54MHz 64kW Pulse


1.3GHz 3.8kW/4.6kW CW


1.3GHz 7kW CW


3.9GHz 900W CW (2 SSAs in 1 Rack)


11.424GHz 500W Pulse

① 185.7MHz 60kW CW SSPAs
These SSPAs were purchased by LBNL and delivered to SLAC.

BERKELEY LAB

As of Mar. 21, 2024

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Recent Delivery Record of R&K SSPA for Overseas National Laboratories

R&K

< Alphabetical Order >

Laboratory	Country	Frequency (MHz)	Power (kW)	Mode	Qty.	Delivery
Argonne	USA	352	2 200 160	CW CW CW	16 1 12	Jul. 2019 Aug. 2022 In production
		117.3	10	CW	1	Jan. 2020
		850~1200	0.5	CW	5	May 2021
Brookhaven	USA	0.009~254	0.5	CW	8	Feb. 2019~
CERN	Switz.	5~1000	0.25	CW	3	Nov. 2015
		5~1200	0.3~0.5	CW	2	Jan. 2019
CLS	Canada	0.009~250	0.1	CW	5	Oct. 2018
DESY	Germany	1300	8	CW	1	In production
Fermilab	USA	0.01~225	2.5	CW	2	Jan. 2021
		325	7	Pulse	1	Jul. 2022
LBNL	USA	185.7	60	CW	2	Dec. 2017
		0.009~250	0.2	CW	2 4	Oct. 2019 Oct. 2021
		500	60	CW	2	Nov. 2023
Los Alamos	USA	201.25	20	Pulse	3	Dec. 2018~
Notre Dame	USA	476	10	Pulse	1	Jan. 2016
		2856	0.3	Pulse	2	Oct. 2015~
RAL/STFC	UK	0.5~30	3	CW	14	Aug. 2017~
		1.8~4	100	Pulse	1	Jan. 2020
		202.5	4.5 10	Pulse Pulse	1 5	Jul. 2022 Jul. 2023
SLAC*	USA	1300	3.8 4.6 7	CW CW CW	278 3 204	Jan. 2016~ Apr. 2018~ Sep. 2020~
		0.009~254	0.5	CW	2 2	Aug. 2018 Jul. 2020
		0.009~320	1	CW	2	Sep. 2021
TRIUMF	Canada	650~2800	0.3	CW	1	Mar. 2019

*See “Recent Delivery Status of R&K SSPA for SLAC”
for more comprehensive delivery record including the other models.

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RF/Microwave Power Amplifiers and Components

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