Achievements and Prospects of Solid-State RF Power Amplifier towards Green Accelerator.

Technology fusion of mobile communication, broadcasting devices, and accelerators.
Guide to low-cost, high reliability solution.

October 29, 2019

Presented by Riichiro Kobana

R&K COMPANY LIMITED - President

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1. Evolution of Transistor

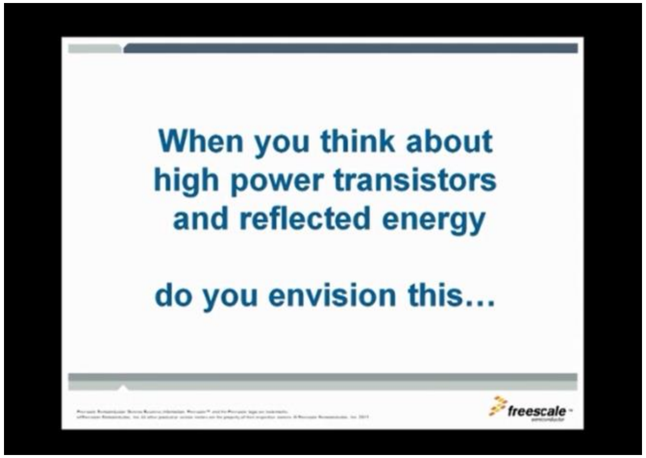
2. R&K Technical Capability and Strength

3. Architectural Change of SSA and Innovation

4. Evolution and Completion of Modern Green SSA Application

5. R&K Recent Delivery Status

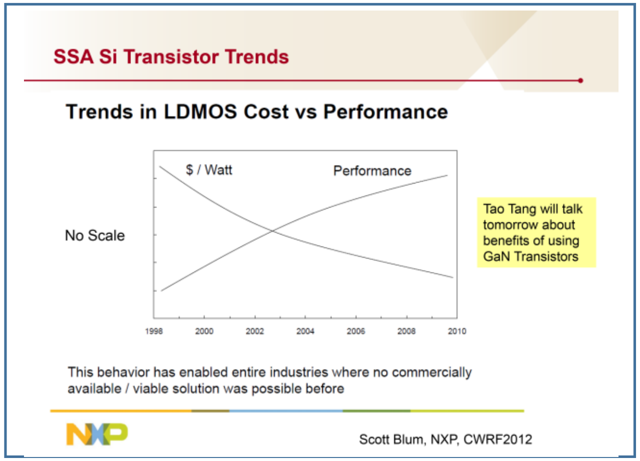
1. Innovation of Transistors



When you think about high power transistors and reflected energy

do you envision this…

Freescale introduced LDMOS on April 13, 2011. The video shows high ruggedness of LDMOS on fully reflected circuit.



SSA Si Transistor Trends

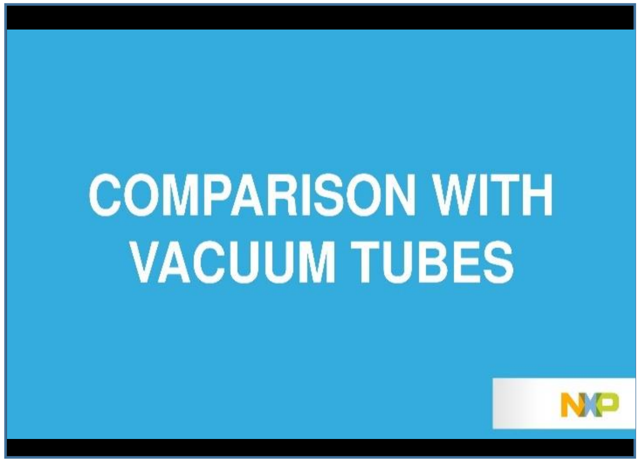
Trends in LDMOS Cost vs Performance

Tao Tang will talk tomorrow about benefits of using GaN Transistors

This behavior has enabled entire industries where no commercially available / viable solution was possible before

Scott Blum, NXP, CWRF2012

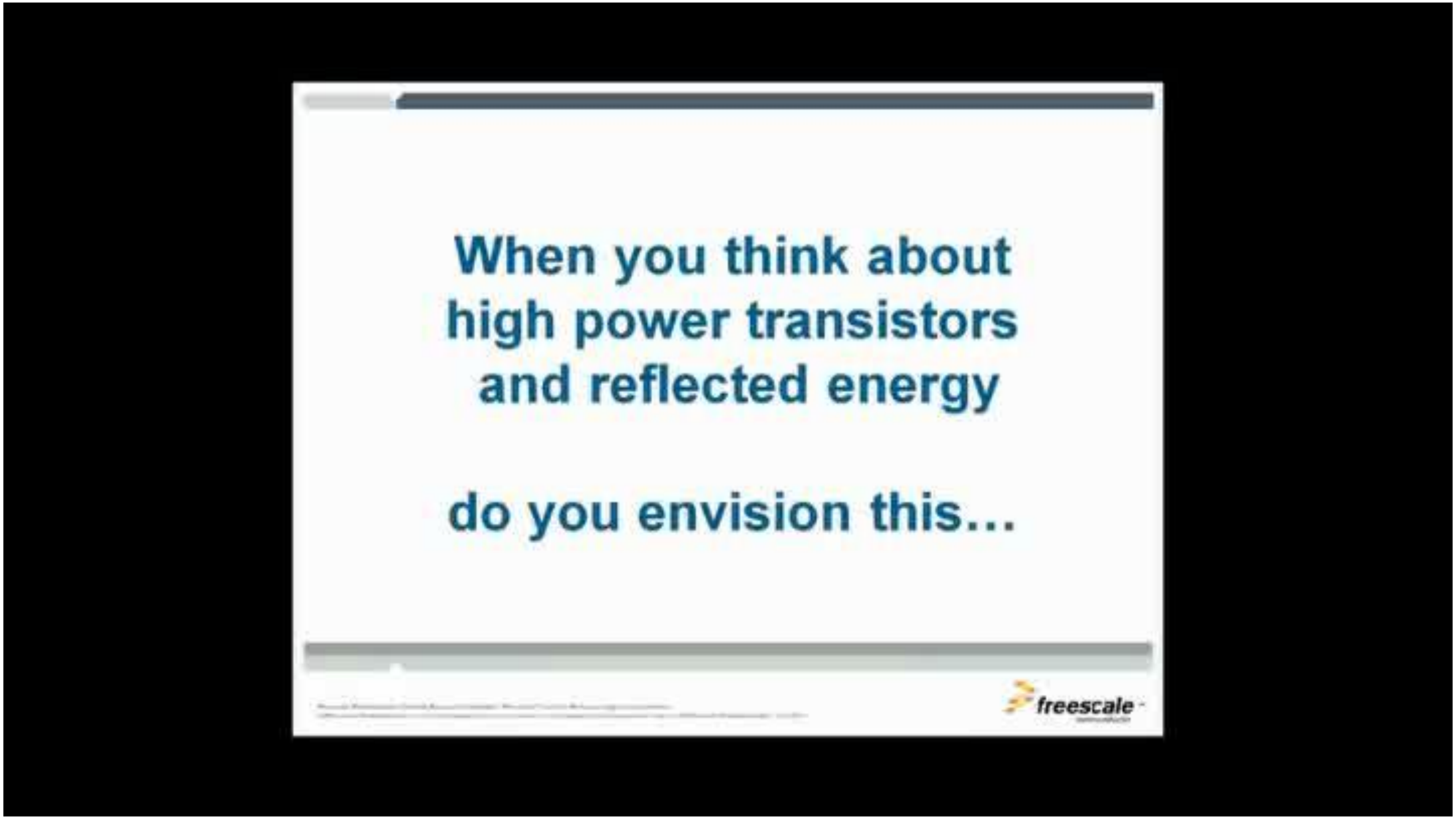
NXP document in 2012. The chart describes “Cost per Watt” trends in LDMOS Cost versus Performance.



COMPARISON WITH VACUUM TUBES

NXP document released in June 2017, describing the major advantages of solid-state amplifier compared to vacuum tube amplifier.

1-A. Innovation of Transistors



When you think about
high power transistors
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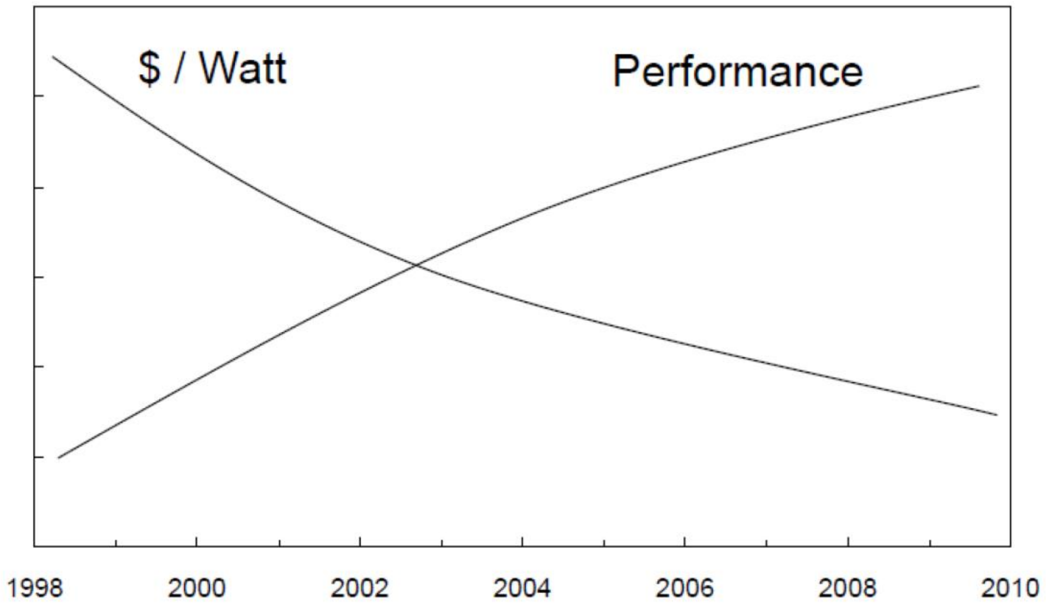
SSA Si Transistor Trends

Trends in LDMOS Cost vs Performance

No Scale



Tao Tang will talk tomorrow about benefits of using GaN Transistors

This behavior has enabled entire industries where no commercially available / viable solution was possible before

2. R&K Technical Capability and Strength

Mass Production Experience (SSA for PHS Base Station)

1995: R&K started designing and developing SSA for mobile communication base station

↓

2000: Accumulated sales of SSA: 20 thousand units

↓

2002: Move into new premise.

Accumulated sales of SSA: 1 million units.

↓

2003: Accumulated sale of SSA: 1.2 million units

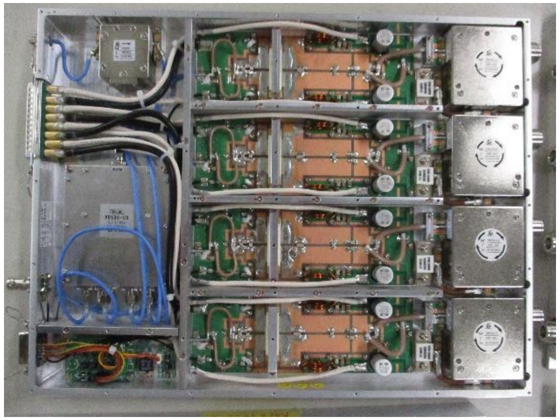
↓

2004: Built 2nd Factory Building

Total 2.3million SSAs shipped!

*This shipment record was introduced on 50th year anniversary edition of Microwave Journal magazine

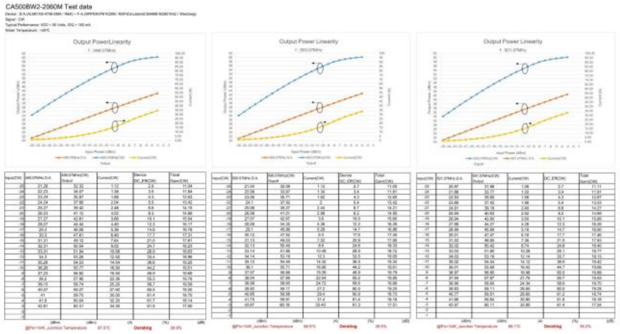
2. R&K Technical Capability and Strength



RF “4-Parallel” Module (4.4kW) Inner Photo.
4 solid-state amplifier pallets are equipped in parallel within the module.

12 pcs of RF “4-Parallel” modules (50kW) and 6 pcs of heatsinks are inserted into the rack.

Rack photo with installed modules.
Amplifier system can operate after relocating modules. (cold-swap)



CA500BW2-2060M Test data

Characteristic of single transistor at 2MHz band, 500MHz, 1kW, power supply efficiency 61%

広帯域製品

・200MHz～1000MHz 4kW 16合成器

・1000MHz～2500MHz 2kW 16合成器

・2000MHz～6000MHz 100W 8合成器

狭帯域製品

・509MHz±3MHz 20kW 64合成器

・1275MHz±100MHz 600W 8合成器

・5712MHz±20MHz 100W 8合成器

R&K社では、高周波大電力増幅器の電力合成器に、超低損失で、しかも奇数合成や偶数合成での大電力合成が可能な『ラジアルコンバイナー』を採用することによりオールソリッドステートで、数kW～100kWの出力を実現します。
現時点での最大/最小の周波数帯域幅比は最大5倍です。
特に内部吸収抵抗を備えた製品が特徴でもあります。
現在、更なる広帯域化、大電力化を目指して、開発を進めています。

For CA200BW0.4-7282RP

200MHz±0.2MHz
POWER: 150kW/Pulse
36WAY-Combiner
INPUT: N
OUTPUT: 3-1/8 EIA

For CA1300BW10-6369R

1300MHz±5MHz
POWER: 8kW/CW
14WAY-Combiner
INPUT: 7/16 EIA
OUTPUT: 3-1/8 EIA

Power combining at final stage amplifier unit.
Initial spec performance secured even with 7% transistor failure

GE
Critical Power

GP100 6 kW True Three Phase Rectifier

Applications

Advanced Features

Use Scenarios

Features

Electrical Specifications

Input

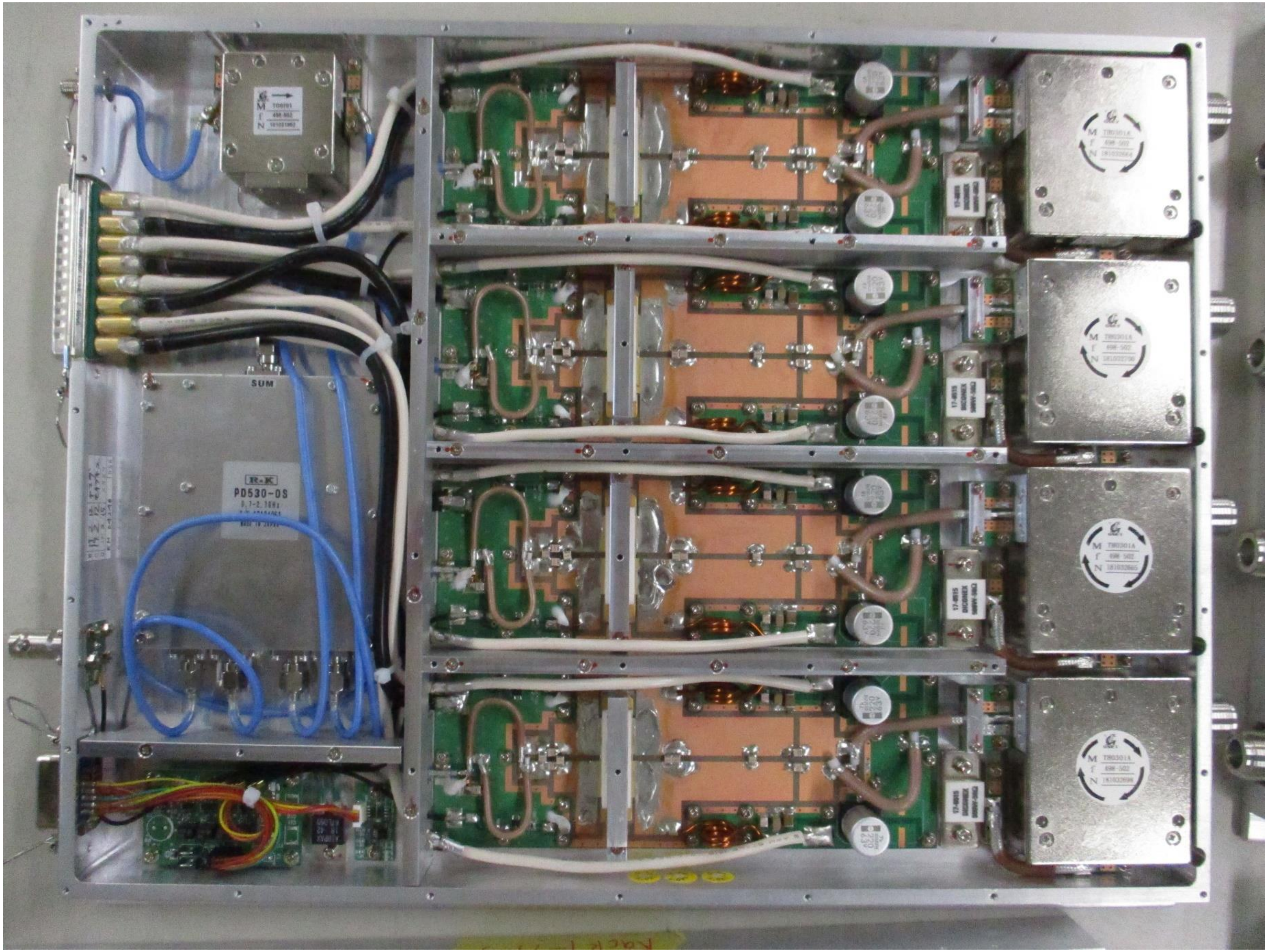
Output -52VDC Main

Environmental, Compliance & Physical

Ordering Options

Achieve switching power supply efficiency ≥ 96%.
Resonant switching power supply is hot-swappable.

2-A. R&K Technical Capability and Strength

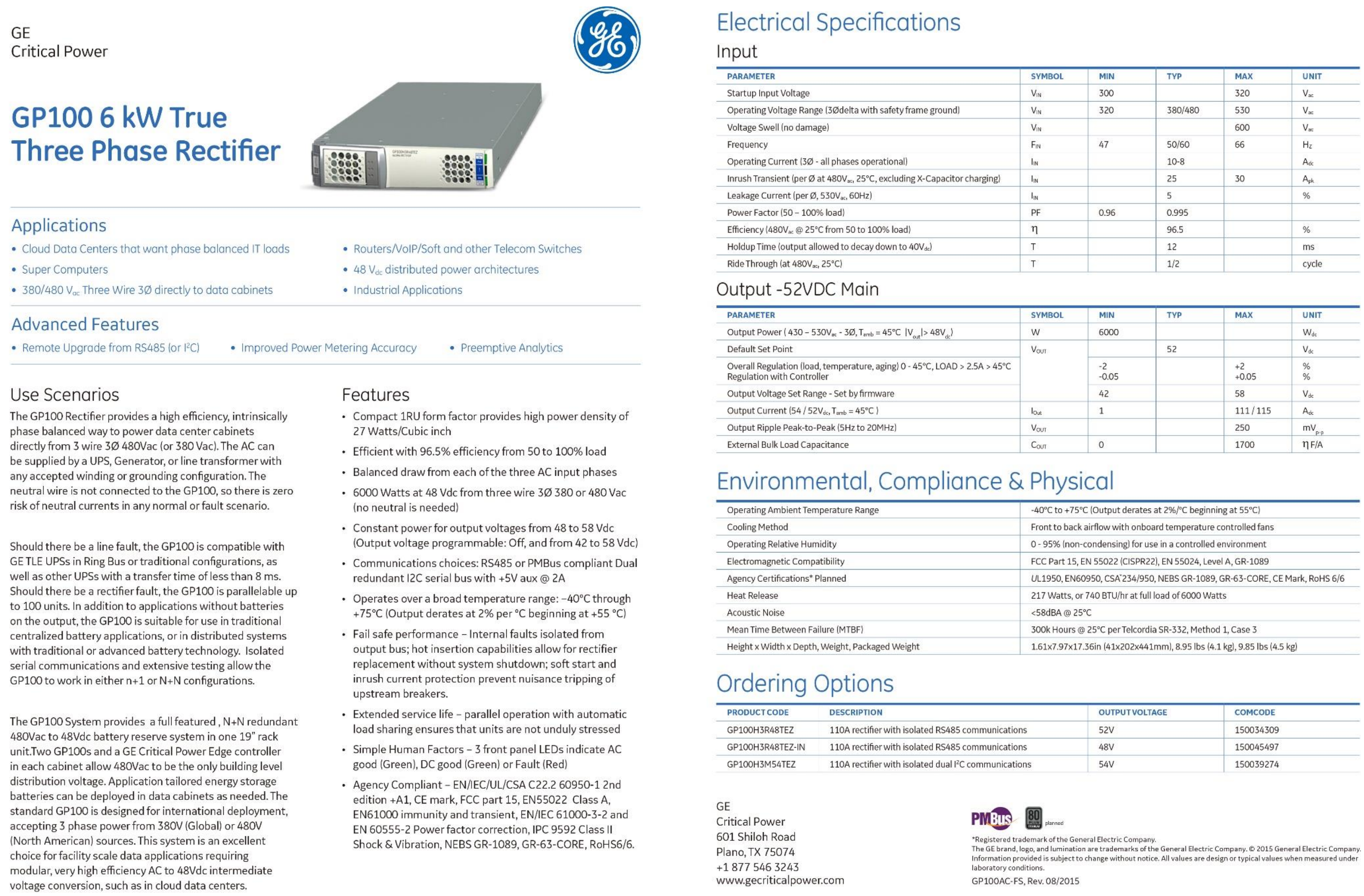


2-B. R&K Technical Capability and Strength

2-C. R&K Technical Capability and Strength

500MHz, 300kW/Pulse

2-F. R&K Technical Capability and Strength



GE
Critical Power

GP100 6 kW True Three Phase Rectifier

Applications

- Cloud Data Centers that want phase balanced IT loads
- Super Computers
- 380/480 V_{ac} Three Wire 3Ø directly to data cabinets
- Routers/VoIP/Soft and other Telecom Switches
- 48 V_{dc} distributed power architectures
- Industrial Applications

Advanced Features

- Remote Upgrade from RS485 (or I²C)
- Improved Power Metering Accuracy
- Preemptive Analytics

Use Scenarios

The GP100 Rectifier provides a high efficiency, intrinsically phase balanced way to power data center cabinets directly from 3 wire 3Ø 480Vac (or 380 Vac). The AC can be supplied by a UPS, Generator, or line transformer with any accepted winding or grounding configuration. The neutral wire is not connected to the GP100, so there is zero risk of neutral currents in any normal or fault scenario.

Should there be a line fault, the GP100 is compatible with GE TLE UPSs in Ring Bus or traditional configurations, as well as other UPSs with a transfer time of less than 8 ms. Should there be a rectifier fault, the GP100 is parallelable up to 100 units. In addition to applications without batteries on the output, the GP100 is suitable for use in traditional centralized battery applications, or in distributed systems with traditional or advanced battery technology. Isolated serial communications and extensive testing allow the GP100 to work in either n+1 or N+N configurations.

The GP100 System provides a full featured , N+N redundant 480Vac to 48Vdc battery reserve system in one 19" rack unit.Two GP100s and a GE Critical Power Edge controller in each cabinet allow 480Vac to be the only building level distribution voltage. Application tailored energy storage batteries can be deployed in data cabinets as needed. The standard GP100 is designed for international deployment, accepting 3 phase power from 380V (Global) or 480V (North American) sources. This system is an excellent choice for facility scale data applications requiring modular, very high efficiency AC to 48Vdc intermediate voltage conversion, such as in cloud data centers.

Features

- Compact 1RU form factor provides high power density of 27 Watts/Cubic inch
- Efficient with 96.5% efficiency from 50 to 100% load
- Balanced draw from each of the three AC input phases
- 6000 Watts at 48 Vdc from three wire 3Ø 380 or 480 Vac (no neutral is needed)
- Constant power for output voltages from 48 to 58 Vdc (Output voltage programmable: Off, and from 42 to 58 Vdc)
- Communications choices: RS485 or PMBus compliant Dual redundant I2C serial bus with +5V aux @ 2A
- Operates over a broad temperature range: −40°C through +75°C (Output derates at 2% per °C beginning at +55 °C)
- Fail safe performance – Internal faults isolated from output bus; hot insertion capabilities allow for rectifier replacement without system shutdown; soft start and inrush current protection prevent nuisance tripping of upstream breakers.
- Extended service life – parallel operation with automatic load sharing ensures that units are not unduly stressed
- Simple Human Factors – 3 front panel LEDs indicate AC good (Green), DC good (Green) or Fault (Red)
- Agency Compliant – EN/IEC/UL/CSA C22.2 60950-1 2nd edition +A1, CE mark, FCC part 15, EN55022 Class A, EN61000 immunity and transient, EN/IEC 61000-3-2 and EN 60555-2 Power factor correction, IPC 9592 Class II Shock & Vibration, NEBS GR-1089, GR-63-CORE, RoHS6/6.

Electrical Specifications

Input

PARAMETER	SYMBOL	MIN	TYP	MAX	UNIT
Startup Input Voltage	V_{IN}	300		320	V_{ac}
Operating Voltage Range (3Ødelta with safety frame ground)	V_{IN}	320	380/480	530	V_{ac}
Voltage Swell (no damage)	V_{IN}			600	V_{ac}
Frequency	F_{IN}	47	50/60	66	Hz
Operating Current (3Ø - all phases operational)	I_{IN}		10-8		A_{dc}
Inrush Transient (per Ø at 480V_{ac}, 25°C, excluding X-Capacitor charging)	I_{IN}		25	30	A_{pk}
Leakage Current (per Ø, 530V_{ac}, 60Hz)	I_{IN}		5		%
Power Factor (50 – 100% load)	PF	0.96	0.995		
Efficiency (480V_{ac} @ 25°C from 50 to 100% load)	η		96.5		%
Holdup Time (output allowed to decay down to 40V_{dc})	T		12		ms
Ride Through (at 480V_{ac}, 25°C)	T		1/2		cycle

Output -52VDC Main

PARAMETER	SYMBOL	MIN	TYP	MAX	UNIT
Output Power (430 – 530V_{ac} - 3Ø, T_{amb} = 45°C $\lvert V_{out}\rvert$> 48V_{dc})	W	6000			W_{dc}
Default Set Point	V_{OUT}		52		V_{dc}
Overall Regulation (load, temperature, aging) 0 - 45°C, LOAD > 2.5A > 45°C Regulation with Controller		-2 -0.05		+2 +0.05	% %
Output Voltage Set Range - Set by firmware		42		58	V_{dc}
Output Current (54 / 52V_{dc}, T_{amb} = 45°C)	I_{Out}	1		111 / 115	A_{dc}
Output Ripple Peak-to-Peak (5Hz to 20MHz)	V_{OUT}			250	mV_{p-p}
External Bulk Load Capacitance	C_{OUT}	0		1700	η F/A

Environmental, Compliance & Physical

Operating Ambient Temperature Range	-40°C to +75°C (Output derates at 2%/°C beginning at 55°C)
Cooling Method	Front to back airflow with onboard temperature controlled fans
Operating Relative Humidity	0 - 95% (non-condensing) for use in a controlled environment
Electromagnetic Compatibility	FCC Part 15, EN 55022 (CISPR22), EN 55024, Level A, GR-1089
Agency Certifications* Planned	UL1950, EN60950, CSA˙234/950, NEBS GR-1089, GR-63-CORE, CE Mark, RoHS 6/6
Heat Release	217 Watts, or 740 BTU/hr at full load of 6000 Watts
Acoustic Noise	<58dBA @ 25°C
Mean Time Between Failure (MTBF)	300k Hours @ 25°C per Telcordia SR-332, Method 1, Case 3
Height x Width x Depth, Weight, Packaged Weight	1.61x7.97x17.36in (41x202x441mm), 8.95 lbs (4.1 kg), 9.85 lbs (4.5 kg)

Ordering Options

PRODUCT CODE	DESCRIPTION	OUTPUT VOLTAGE	COMCODE
GP100H3R48TEZ	110A rectifier with isolated RS485 communications	52V	150034309
GP100H3R48TEZ-IN	110A rectifier with isolated RS485 communications	48V	150045497
GP100H3M54TEZ	110A rectifier with isolated dual I²C communications	54V	150039274

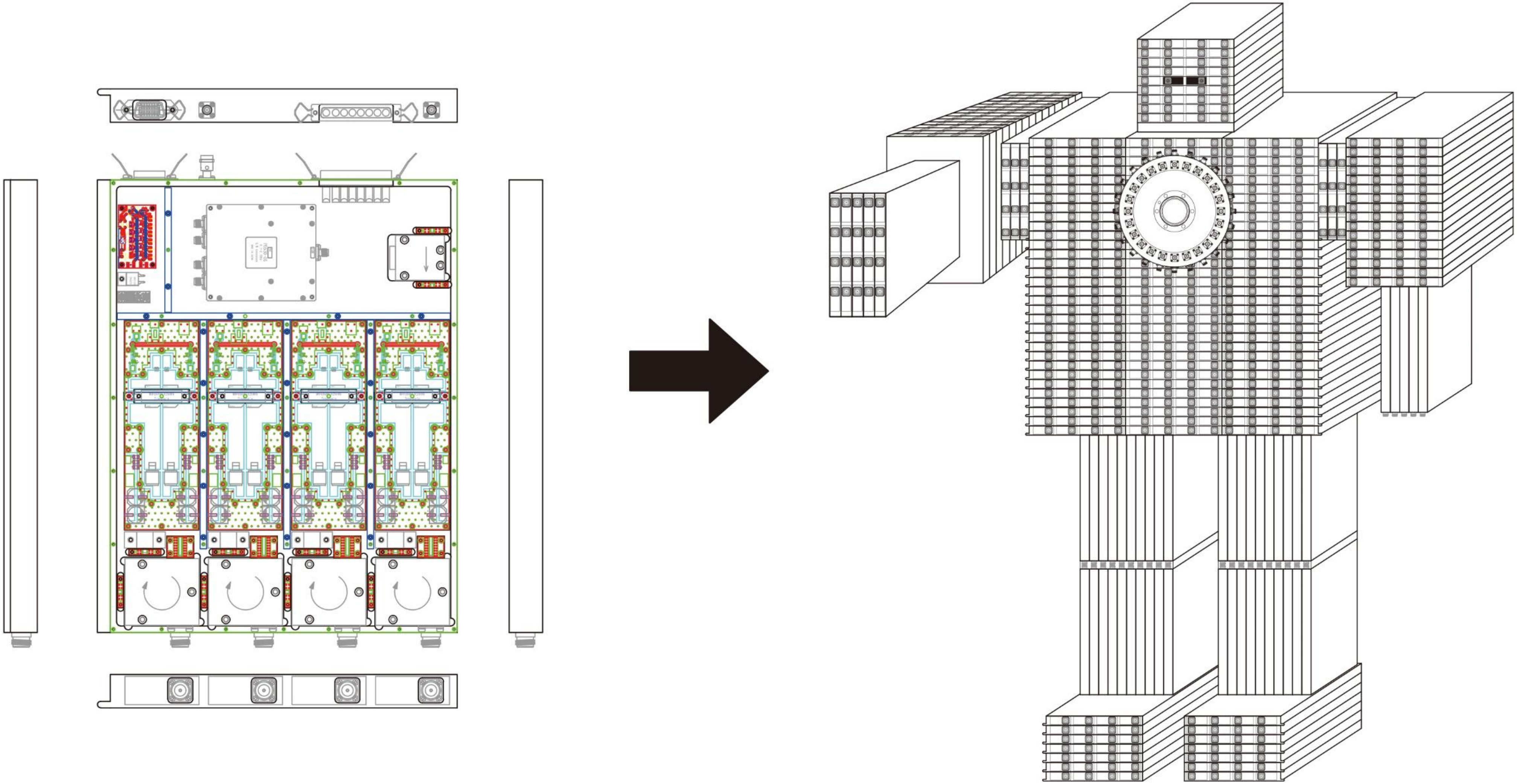
GE
Critical Power
601 Shiloh Road
Plano, TX 75074
+1 877 546 3243
www.gecriticalpower.com

planned

*Registered trademark of the General Electric Company.

GP100AC-FS, Rev. 08/2015

2-G. R&K Technical Capability and Strength

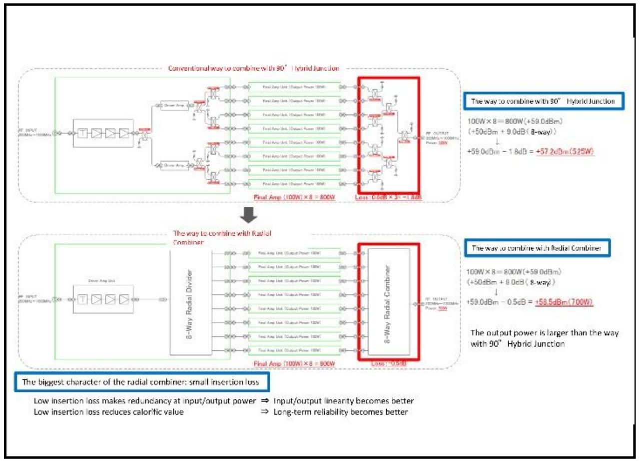


2-H. R&K Technical Capability and Strength

1.3GHz ≥ 3.8kW

1.3GHz ≥ 7kW

3. Architectural Change of SSA and Innovation



The way to combine with 90° Hybrid Junction

100W × 8 = 800W(+59.0dBm)
(+50dBm + 9.0dB (8-way))
↓
+59.0dBm − 1.8dB = +57.2dBm(525W)

The way to combine with Radial Combiner

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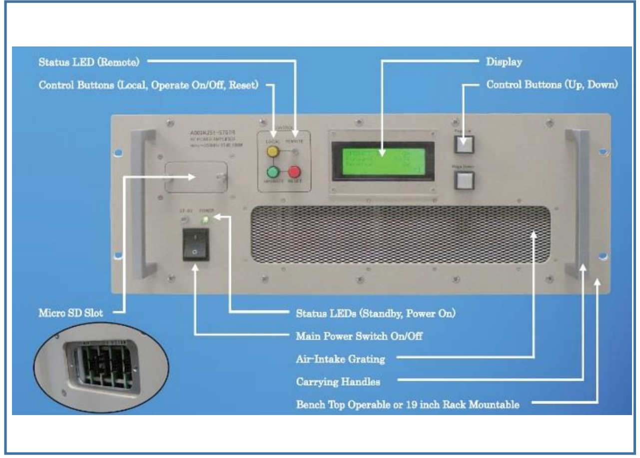
The output power is larger than the way with 90° Hybrid Junction

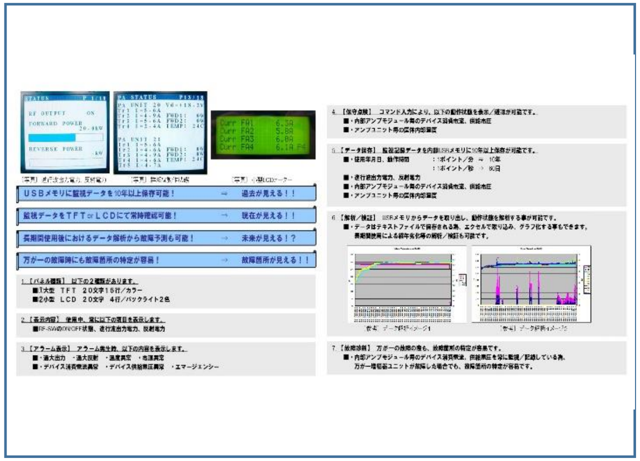
The biggest character of the radial combiner: small insertion loss

Low insertion loss makes redundancy at input/output power ⇒ Input/output linearity becomes better
Low insertion loss reduces calorific value ⇒ Long-term reliability becomes better

Conventional 2-way Combining vs
Single-Stage Combining by Radial Combiner



Status Monitoring and SD Card Recording
External Output via Modbus Communication



USBメモリに監視データを10年以上保存可能！ ⇒ 過去が見える！！

監視データをTFT or LCDにて常時確認可能！ → 現在が見える！！

長期間使用後におけるデータ解析から故障予測も可能！ → 未来が見える！？

万が一の故障時にも故障箇所の特定が容易！ → 故障箇所が見える！！

1.【パネル種類】 以下の2種類があります。
■①大型 TFT 20文字15行／カラー
■②小型 LCD 20文字 4行／バックライト2色

2.【表示内容】 使用中、常に以下の項目を表示します。
■RF-SWのON/OFF状態、進行波出力電力、反射電力

3.【アラーム表示】 アラーム発生時、以下の内容を表示します。
■・過大出力 ・過大反射 ・温度異常 ・電圧異常
■・デバイス消費電流異常 ・デバイス供給電圧異常 ・エマージェンシー

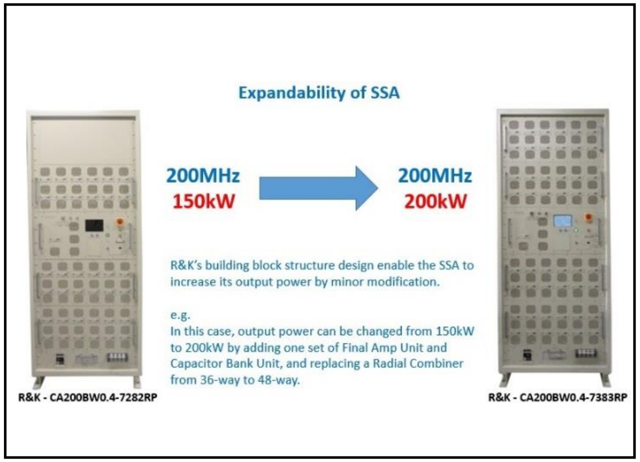
4.【保守点検】 コマンド入力により、以下の動作状態を表示／確認が可能です。
■・内部アンプモジュール毎のデバイス消費電流、供給電圧
■・アンプユニット毎の筐体内部温度

5.【データ保存】 監視記録データを内部USBメモリに10年以上保存が可能です。
■・使用年月日、動作時間 ：1ポイント／分 ⇒ 10年
：1ポイント／秒 → 80日
■・進行波出力電力、反射電力
■・内部アンプモジュール毎のデバイス消費電流、供給電圧
■・アンプユニット毎の筐体内部温度

6.【解析／検証】 USBメモリからデータを取り出し、動作状態を解析する事が可能です。
■・データはテキストファイルで保存される為、エクセルで取り込み、グラフ化する事もできます。
長期間使用による経年劣化等の解析／検証も可能です。

7.【故障診断】 万が一の故障の際も、故障箇所の特定が容易です。
■・内部アンプモジュール毎のデバイス消費電流、供給電圧を常に監視／記録している為、
万が一増幅器ユニットが故障した場合でも、故障箇所の特定が容易です。

Status Monitoring and SD Card Recording
Long-term Data Recording by 1sec by 1min.



Expandability of SSA

200MHz 150kW → 200MHz 200kW

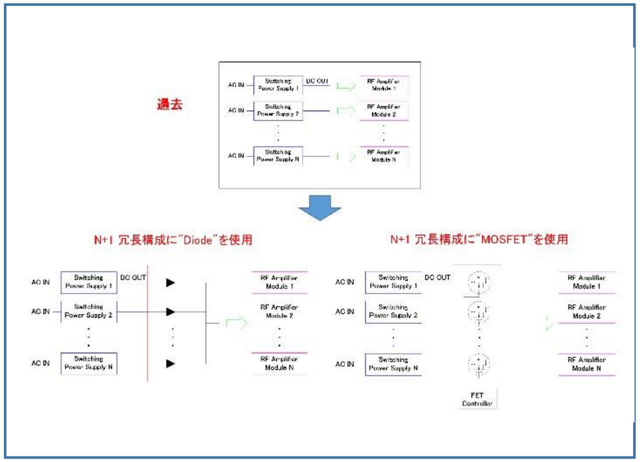
R&K's building block structure design enable the SSA to increase its output power by minor modification.

e.g.
In this case, output power can be changed from 150kW to 200kW by adding one set of Final Amp Unit and Capacitor Bank Unit, and replacing a Radial Combiner from 36-way to 48-way.

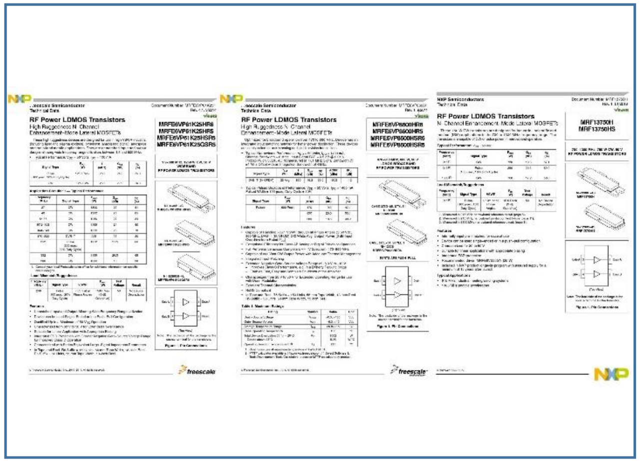
R&K - CA200BW0.4-7282RP

R&K - CA200BW0.4-7383RP

Output Power Expandability by
Building Block Structure



High Available Power Supply

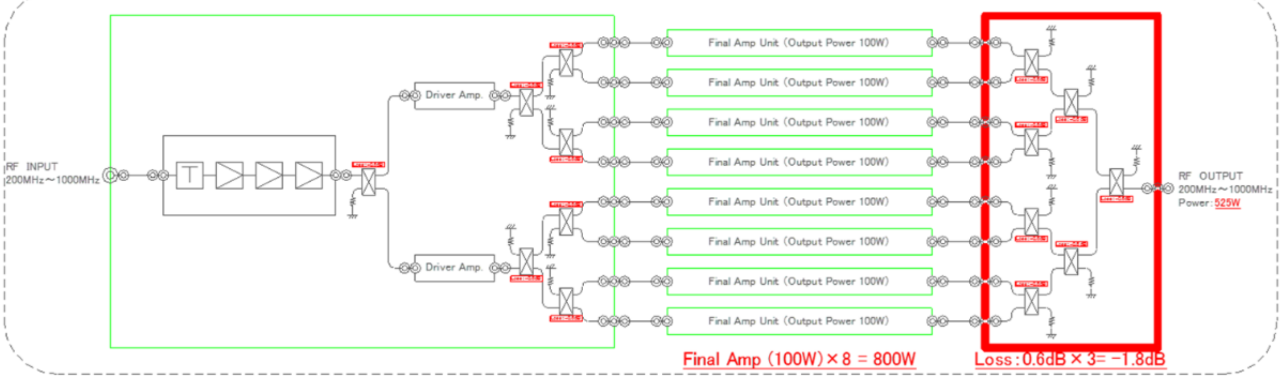


Low Cost LDMOS available in Market
High VSWR Handling/Broadband Lineup

3-A. Architectural Change of SSA and Innovation

Single-Stage Combining by Radial Combiner

Conventional way to combine with 90° Hybrid Junction



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(+50dBm + 9.0dB(8-way))
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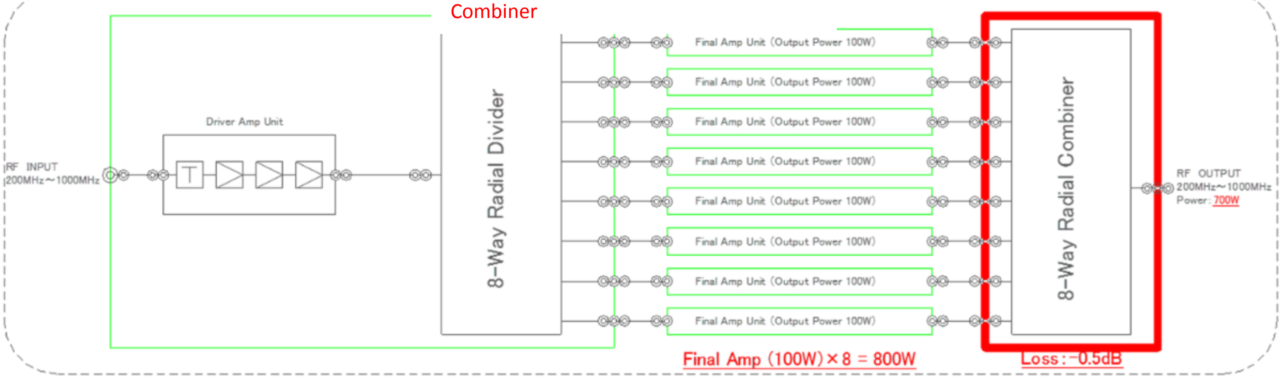
The way to combine with Radial Combiner



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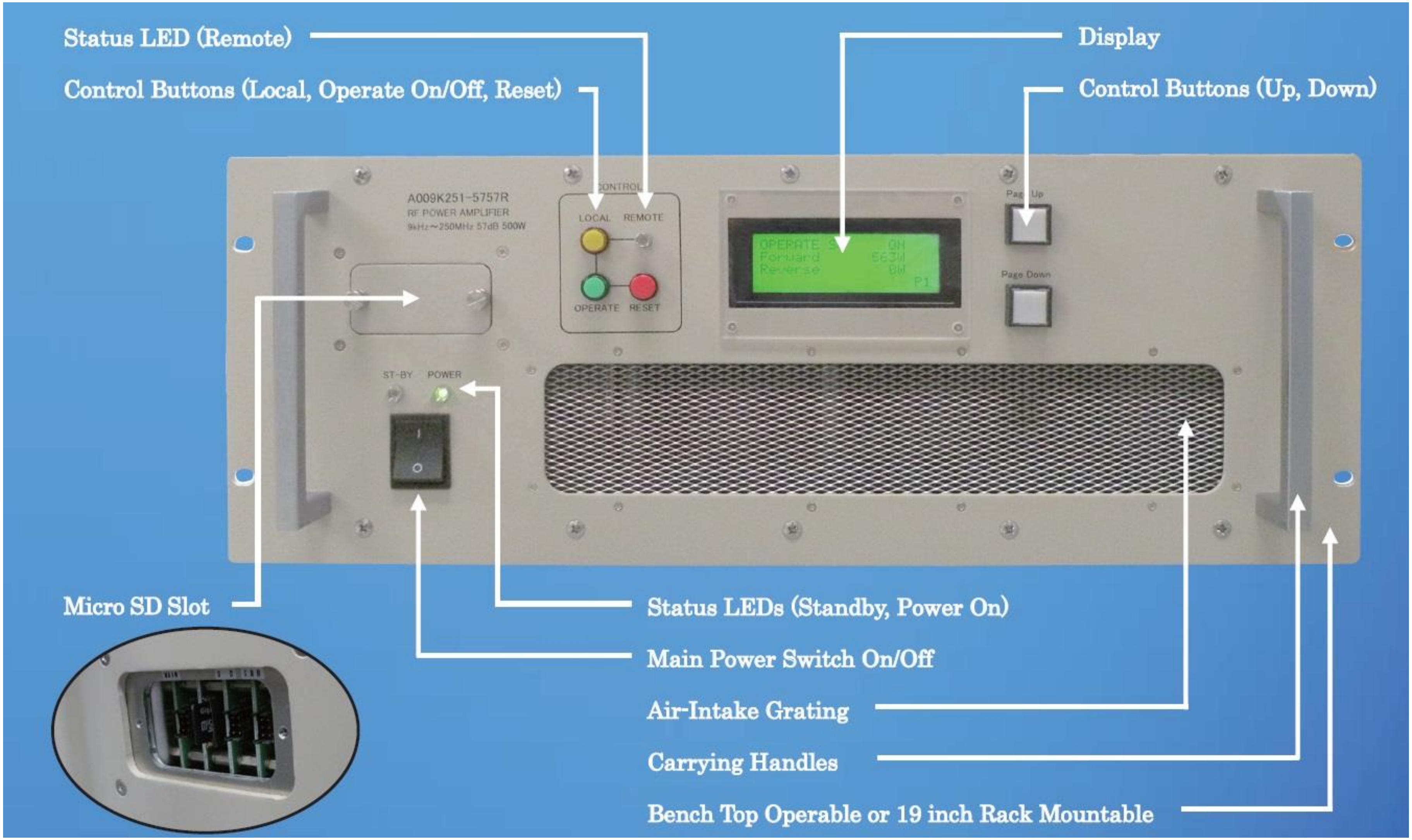
The biggest feature of the radial combiner: small insertion loss

Low insertion loss enhances redundancy at input/output power ⇒ Input/output linearity becomes better
Low insertion loss reduces calorific value ⇒ Long-term reliability becomes better

3-B. Architectural Change of SSA and Innovation

Multi Monitoring System



Status LED (Remote)

Control Buttons (Local, Operate On/Off, Reset)

Display

Control Buttons (Up, Down)

Micro SD Slot

Status LEDs (Standby, Power On)

Main Power Switch On/Off

Air-Intake Grating

Carrying Handles

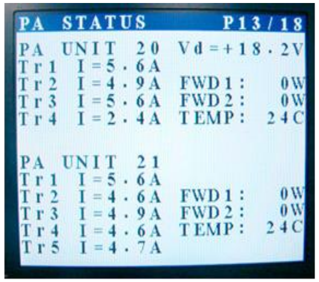
Bench Top Operable or 19 inch Rack Mountable

3-C. Architectural Change of SSA and Innovation

Multi Monitoring System

```
STATUS                P 1/18
RF OUTPUT          ON
FORWARD POWER
                20.0kW
REVERSE POWER
                   - kW
```

［写真］ 進行波出力電力、反射電力



```
PA STATUS          P13/18
PA UNIT 20  Vd=+18.2V
Tr1  I=5.6A
Tr2  I=4.9A  FWD1:   0W
Tr3  I=5.6A  FWD2:   0W
Tr4  I=2.4A  TEMP:  24C

PA UNIT 21
Tr1  I=5.6A
Tr2  I=4.6A  FWD1:   0W
Tr3  I=4.9A  FWD2:   0W
Tr4  I=4.6A  TEMP:  24C
Tr5  I=4.7A
```

［写真］ 詳細な動作状態

```
Curr FA1    6.3A
Curr FA2    5.8A
Curr FA3    6.0A
Curr FA4    6.1A P4
```

［写真］ 小型LCDメーター

ＵＳＢメモリに監視データを10年以上保存可能！　⇒　過去が見える！！

監視データをＴＦＴ or ＬＣＤにて常時確認可能！　⇒　現在が見える！！

長期間使用後におけるデータ解析から故障予測も可能！　⇒　未来が見える！？

万が一の故障時にも故障箇所の特定が容易！　⇒　故障箇所が見える！！

1. 【パネル種類】　以下の２種類があります。
   - ■①大型　ＴＦＴ　２０文字１５行／カラー
   - ■②小型　ＬＣＤ　２０文字　４行／バックライト２色

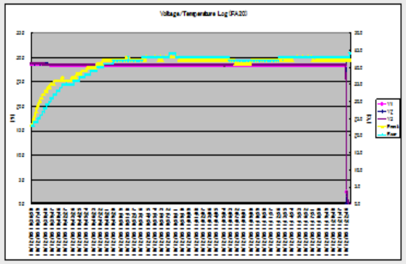
2. 【表示内容】　使用中、常に以下の項目を表示します。
   - ■RF-SWのON/OFF状態、進行波出力電力、反射電力

3. 【アラーム表示】　アラーム発生時、以下の内容を表示します。
   - ■・過大出力　・過大反射　・温度異常　・電源異常
   - ■・デバイス消費電流異常　・デバイス供給電圧異常　・エマージェンシー

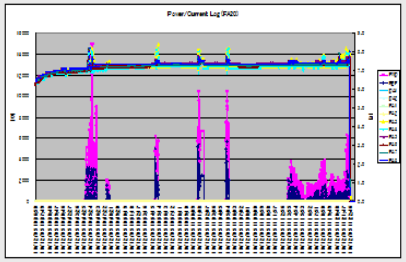
4. 【保守点検】　コマンド入力により、以下の動作状態を表示／確認が可能です。
   - ■・内部アンプモジュール毎のデバイス消費電流、供給電圧
   - ■・アンプユニット毎の筐体内部温度

5. 【データ保存】　監視記録データを内部USBメモリに10年以上保存が可能です。
   - ■・使用年月日、動作時間　：1ポイント／分　⇒　10年
     　：1ポイント／秒　⇒　60日
   - ■・進行波出力電力、反射電力
   - ■・内部アンプモジュール毎のデバイス消費電流、供給電圧
   - ■・アンプユニット毎の筐体内部温度

6. 【解析／検証】　USBメモリからデータを取り出し、動作状態を解析する事が可能です。
   - ■・データはテキストファイルで保存される為、エクセルで取り込み、グラフ化する事もできます。
     長期間使用による経年劣化等の解析／検証も可能です。



［参考］ データ解析イメージ1



［参考］ データ解析イメージ2

7. 【故障診断】　万が一の故障の際も、故障箇所の特定が容易です。
   - ■・内部アンプモジュール毎のデバイス消費電流、供給電圧を常に監視／記録している為、
     万が一増幅器ユニットが故障した場合でも、故障箇所の特定が容易です。

3-D. Architectural Change of SSA and Innovation

Expandability of SSA

R&K - CA200BW0.4-7282RP

200MHz
150kW

→

200MHz
200kW

R&K's SSA can expand its output power by Building Block Construction that is expandable system hardware architecture designed to add final amplifier units and capacitor bank units later when more output power is required for test or application at the user.

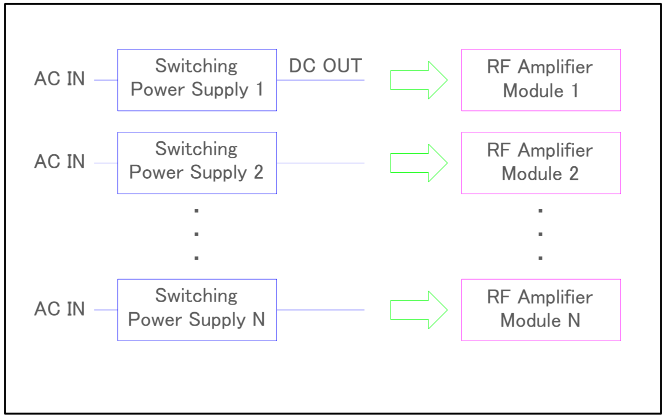
e.g.
In this case, output power can increase from 150kW to 200kW by adding one set of Final Amp Unit and Capacitor Bank Unit, and replacing a Radial Combiner from 36-way to 48-way.

R&K - CA200BW0.4-7383RP

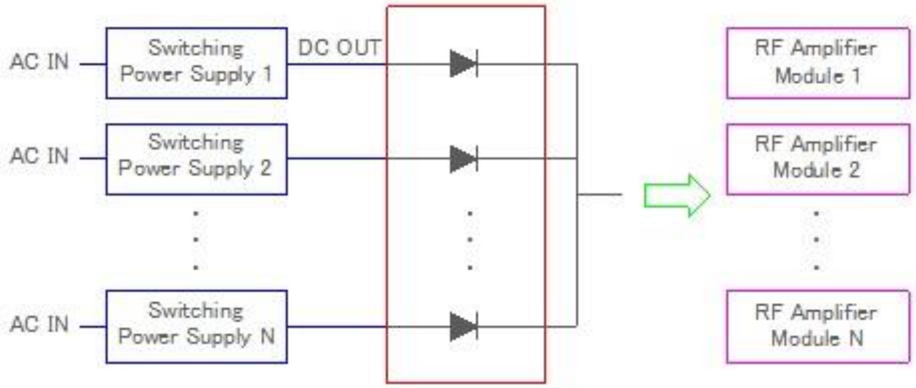
3-E. Architectural Change of SSA and Innovation

HAPS
(High Availability Power Supply)

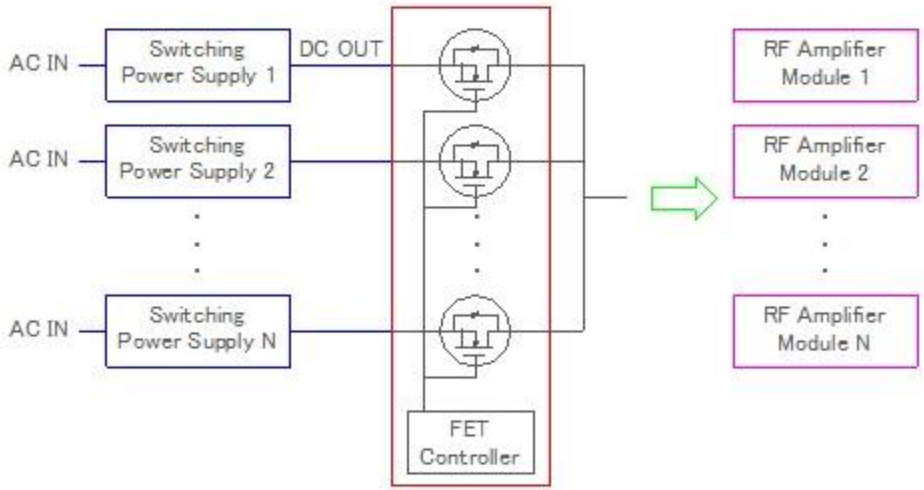
Previously..



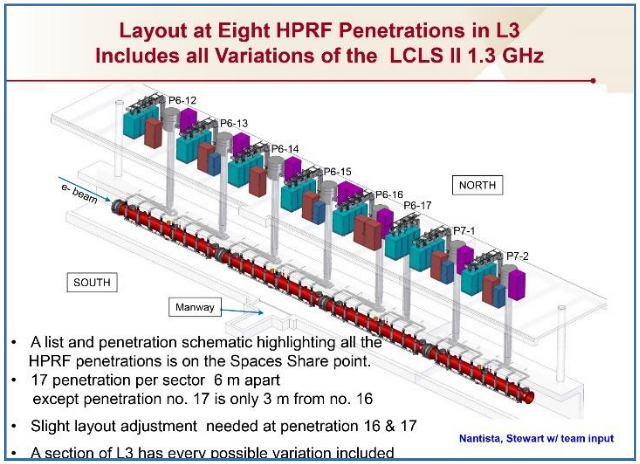
Use “Diode” for N+1 Redundancy



Use “MOSFET” for N+1 Redundancy



4. Evolution and Completion of Modern Green SSA Application



Layout at Eight HPRF Penetrations in L3
Includes all Variations of the LCLS II 1.3 GHz

- A list and penetration schematic highlighting all the HPRF penetrations is on the Spaces Share point.
- 17 penetration per sector 6 m apart except penetration no. 17 is only 3 m from no. 16
- Slight layout adjustment needed at penetration 16 & 17
- A section of L3 has every possible variation included

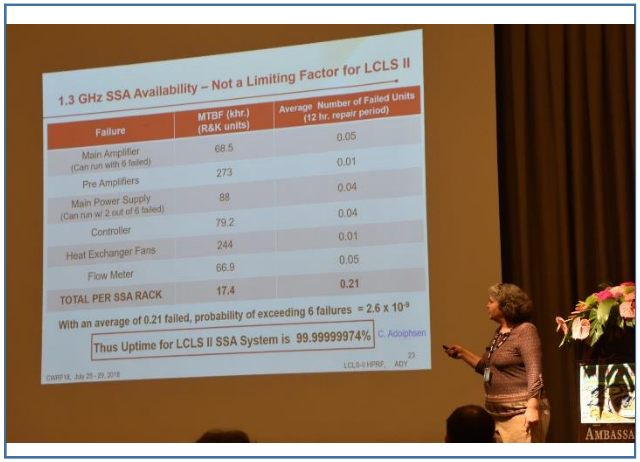
Nantista, Stewart w/ team input

Trends for SSSC Architecture
Highly reliable SSA accelerates this trend.

R&K 7 1.3 GHz SSAs at R&K Prior to Shipment

- 6 of these were shipped to FNAL and JLAB (3 each) in Januarry, 2016 for Cyro Cavity Tests.
- 1 of these was left at R&K for 2.5 months for long term tests
  - Continuous running for 2 months.
  - PA Module Swap tests from SSA to SSA show remarkable compatability – important for operations when swapping w/spares
- 4 more delivered to FNAL and 5 more to JLAB in April 2016 for full complement to test one Cryo Module with 8 Cavities. (Note FNAL already had one SSA capable of 3.8 KW output.)

1300MHz ≥ 3.8kW CW-SSA
1st Shipment for SSSC Architecture System



1.3 GHz SSA Availability – Not a Limiting Factor for LCLS II

Failure	MTBF (khr.) (R&K units)	Average Number of Failed Units (12 hr. repair period)
Main Amplifier (Can run with 6 failed)	68.5	0.05
Pre Amplifiers	273	0.01
Main Power Supply (Can run w/ 2 out of 6 failed)	88	0.04
Controller	79.2	0.04
Heat Exchanger Fans	244	0.01
Flow Meter	66.9	0.05
TOTAL PER SSA RACK	**17.4**	**0.21**

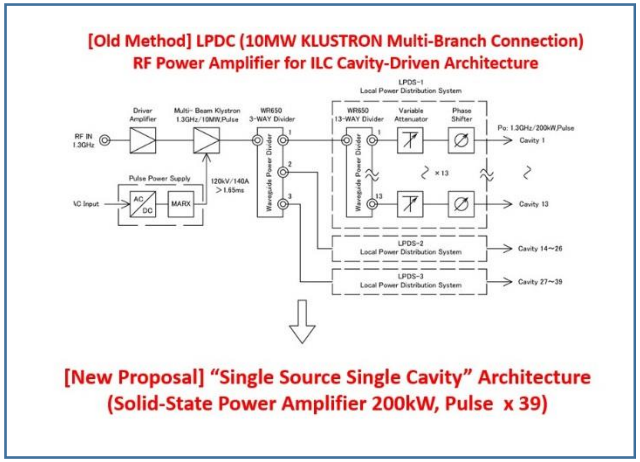
With an average of 0.21 failed, probability of exceeding 6 failures = 2.6×10^{-9}

Thus Uptime for LCLS II SSA System is 99.99999974%

C. Adolphsen

CWRF18, July 25 - 29, 2018 LCLS-II HPRF, ADY 23

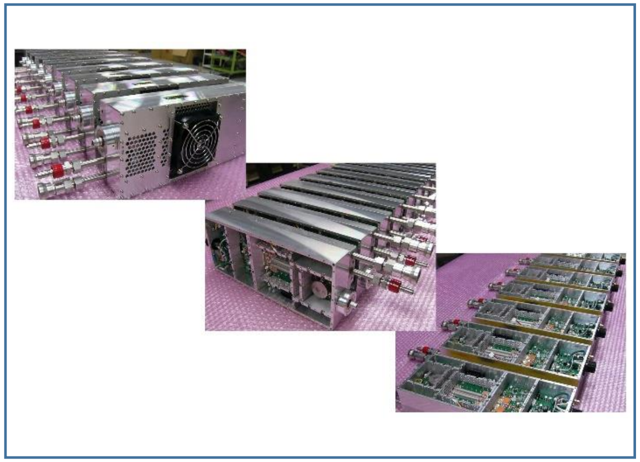
Presentation in CWRF 2018 Taiwan
Performance Review and Evaluation



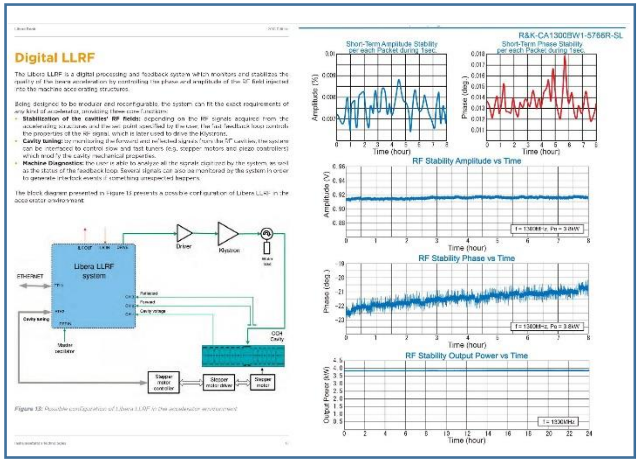
[Old Method] LPDC (10MW KLUSTRON Multi-Branch Connection)
RF Power Amplifier for ILC Cavity-Driven Architecture

[New Proposal] "Single Source Single Cavity" Architecture
(Solid-State Power Amplifier 200kW, Pulse x 39)

10MW-MBK and LPDS-39 Distribution
MARX-Mod, LPDS, Circulator, Dummy



Cost Reduction by Standardized Design
And Volume Production



Digital LLRF

The Libera LLRF is a digital processing and feedback system which monitors and stabilizes the quality of the beam acceleration by controlling the phase and amplitude of the RF field injected into the machine accelerating structures.

Being designed to be modular and reconfigurable, the system can fit the exact requirements of any kind of accelerator, providing three core functions:

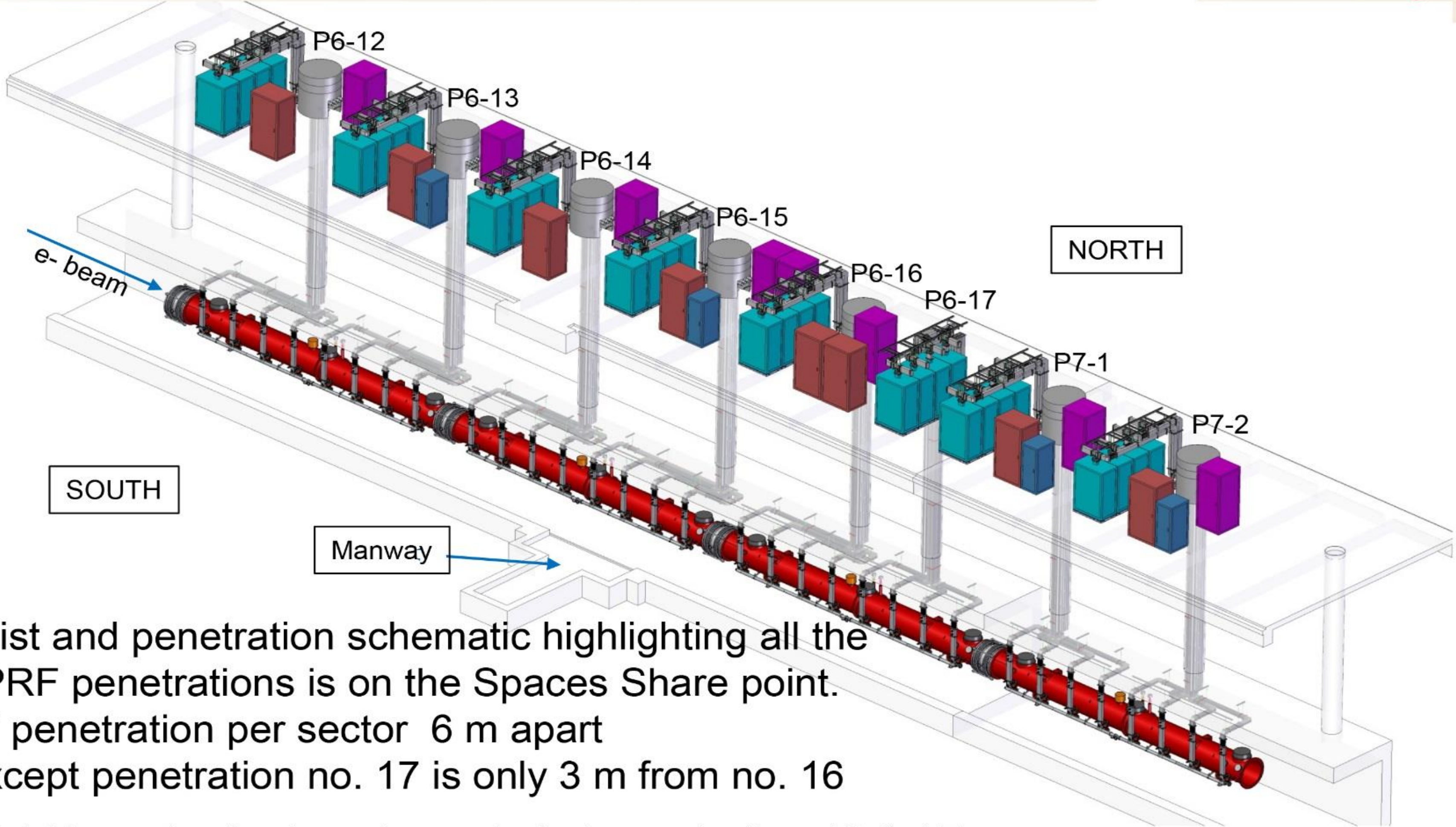
- **Stabilization of the cavities' RF fields:** depending on the RF signals acquired from the accelerating structures and the set point specified by the user, the fast feedback loop controls the properties of the RF signal, which is later used to drive the Klystrons.
- **Cavity tuning:** by monitoring the forward and reflected signals from the RF cavities, the system can be interfaced to control slow and fast tuners (e.g. stepper motors and piezo controllers) which modify the cavity mechanical properties.
- **Machine Diagnostics:** the user is able to analyze all the signals digitized by the system, as well as the status of the feedback loop. Several signals can also be monitored by the system in order to generate interlock events if something unexpected happens.

The block diagram presented in Figure 13 presents a possible configuration of Libera LLRF in the accelerator environment.

Figure 13: Possible configuration of Libera LLRF in the accelerator environment

Highly-Stabilized SSSC Architecture
Full Auto-control and Performance Stability

Layout at Eight HPRF Penetrations in L3 Includes all Variations of the LCLS II 1.3 GHz



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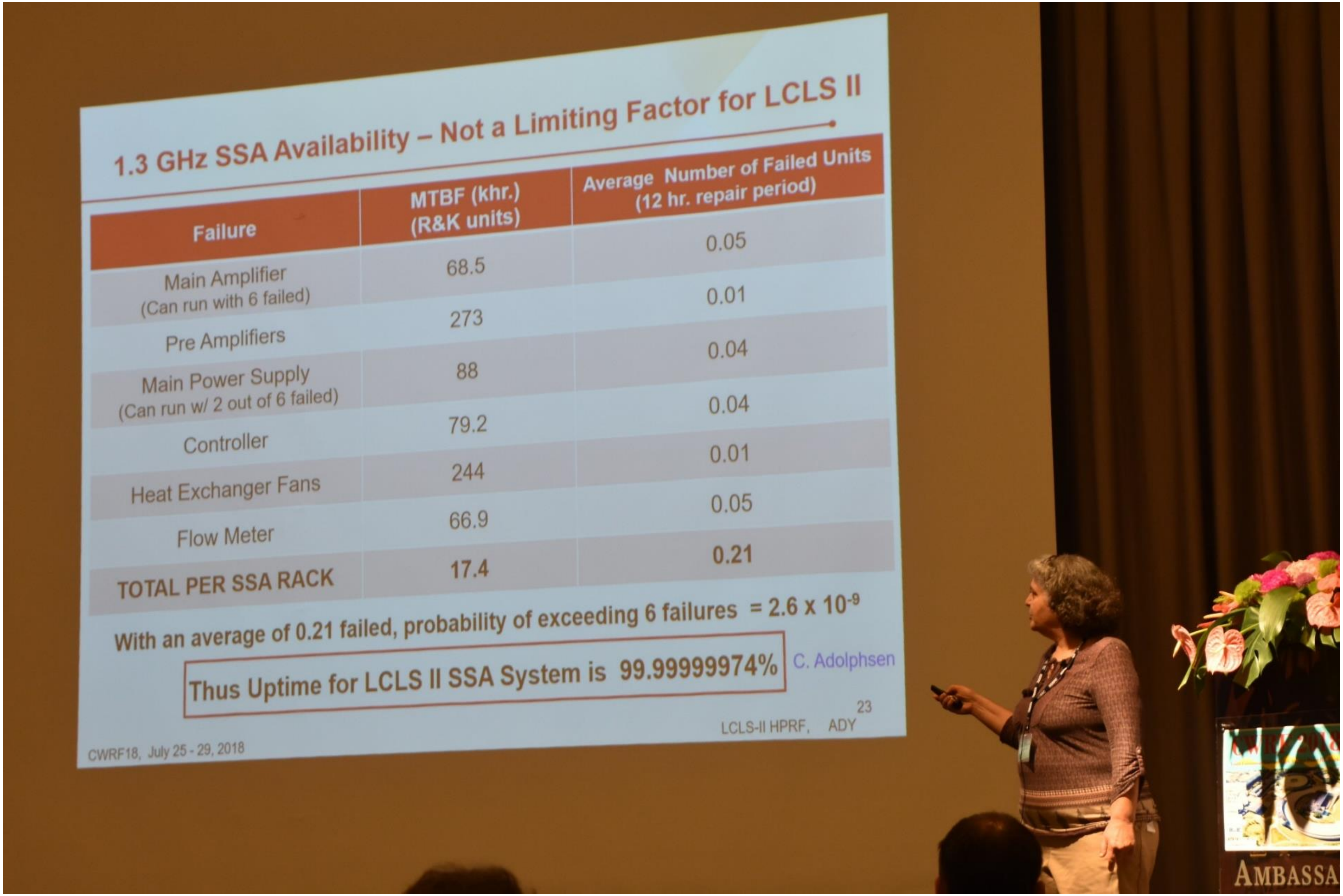
4-A. Evolution and Completion of Modern Green SSA Application

[New Proposal] Single Source Single Cavity (SSSC) Architecture



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C. Adolphsen

CWRF18, July 25 - 29, 2018

LCLS-II HPRF, ADY 23

4-B. Evolution and Completion of Modern Green SSA Application

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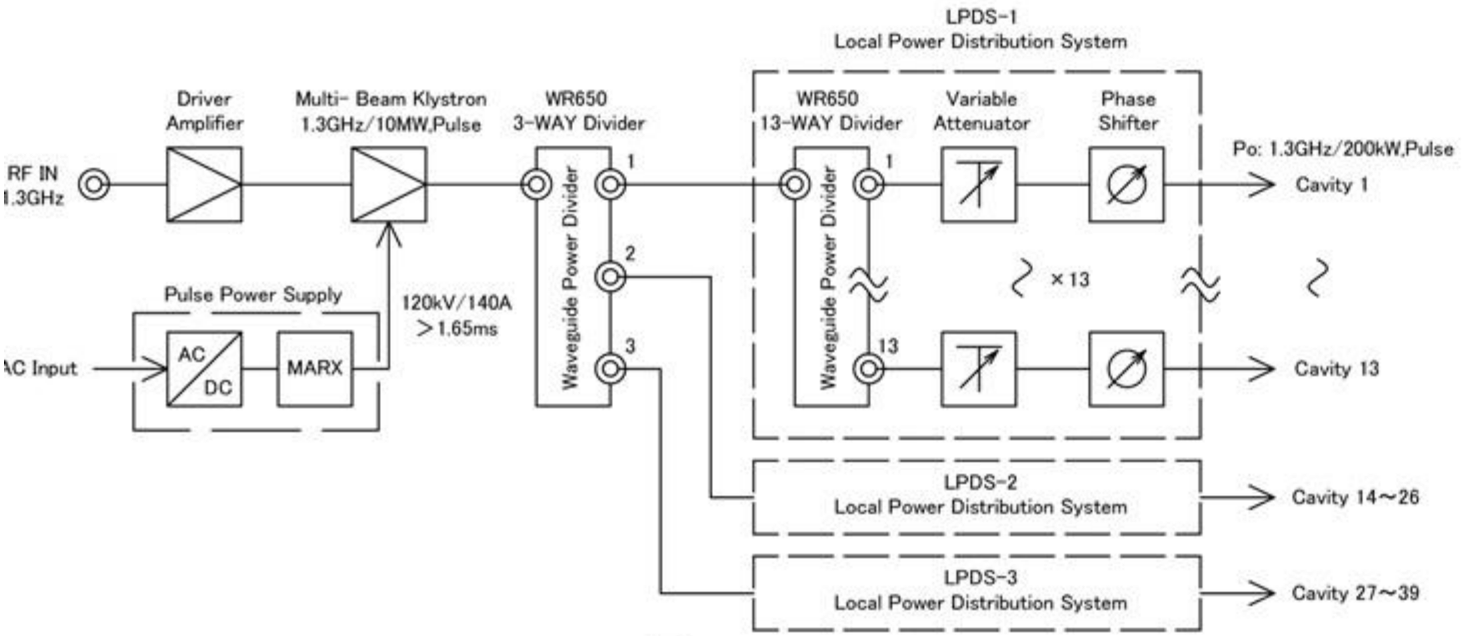
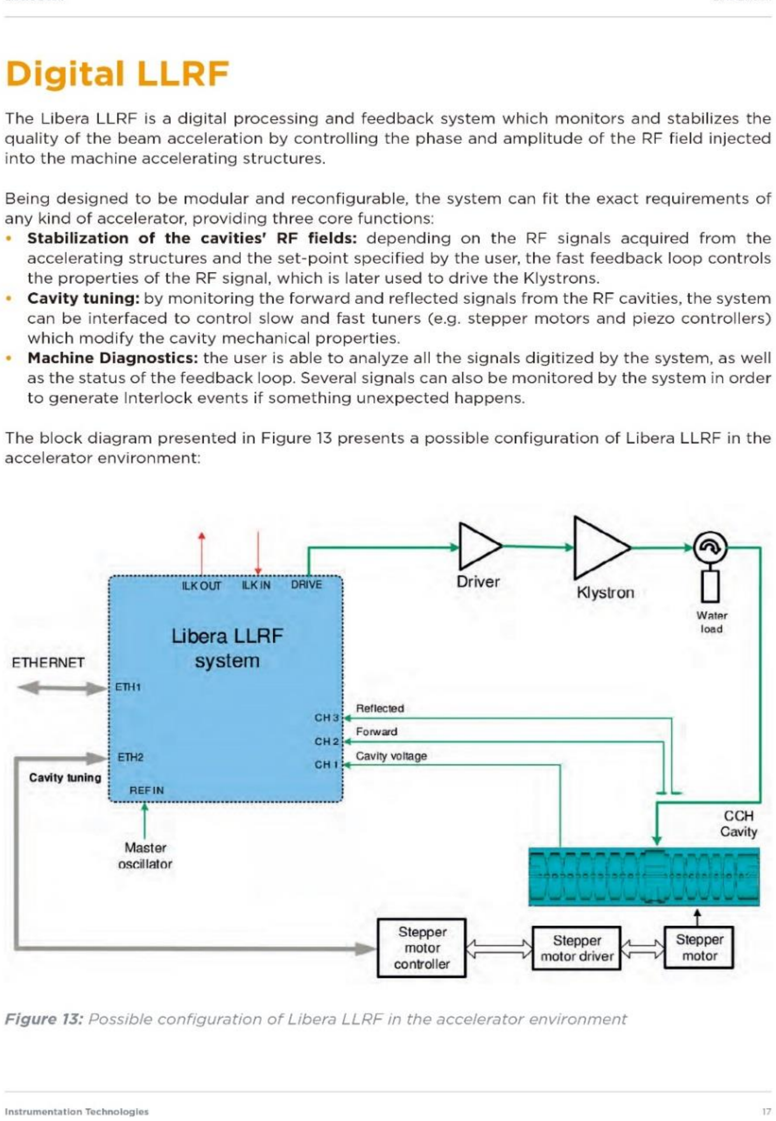
RF Power Amplifier for ILC Cavity-Driven Architecture



[New Proposal] "Single Source Single Cavity" Architecture
(Solid-State Power Amplifier 200kW, Pulse x 39)

4-D. Evolution and Completion of Modern Green SSA Application

Ultra-high Stability of
Single Source Single Cavity Structure



Libera Book

2018 Edition

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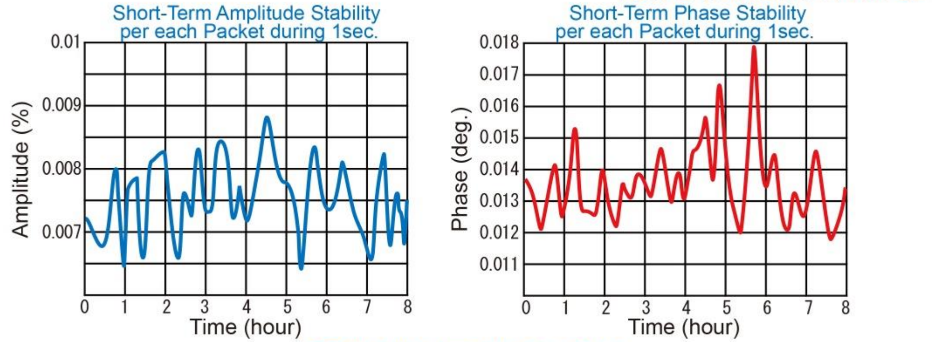
The block diagram presented in Figure 13 presents a possible configuration of Libera LLRF in the accelerator environment:

Figure 13: Possible configuration of Libera LLRF in the accelerator environment

Instrumentation Technologies

17

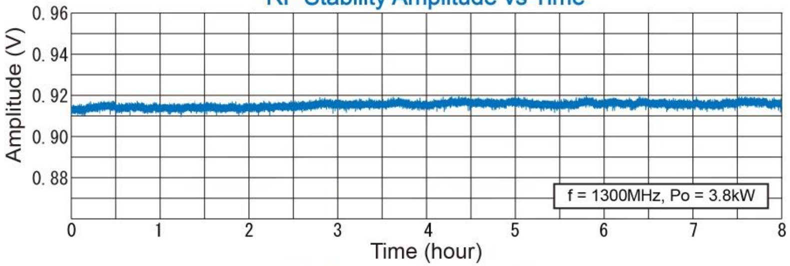
R&K-CA1300BW1-5766R-SL



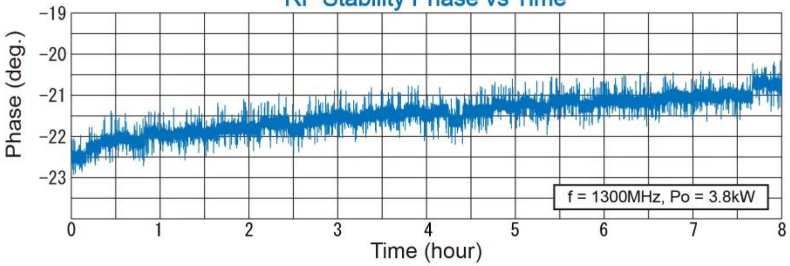
Short-Term Amplitude Stability per each Packet during 1sec.

Short-Term Phase Stability per each Packet during 1sec.

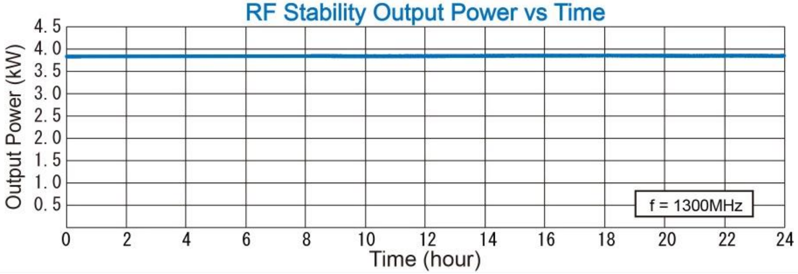
RF Stability Amplitude vs Time



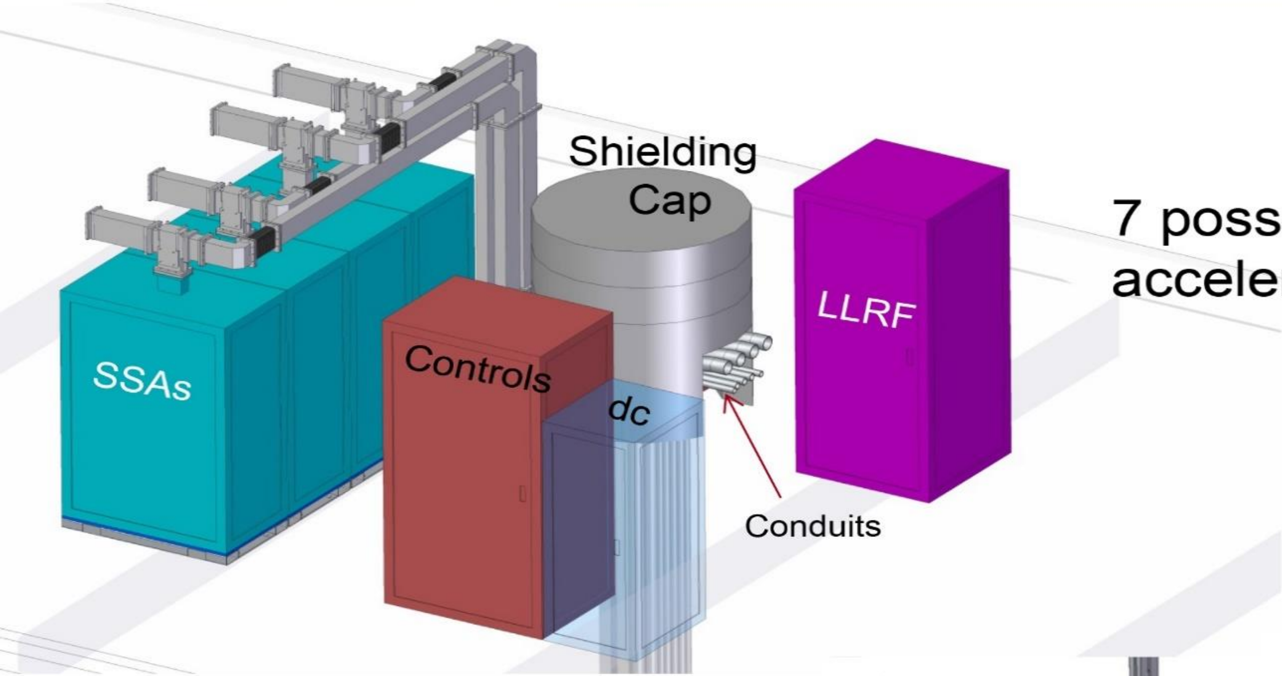
RF Stability Phase vs Time



RF Stability Output Power vs Time



Basic Layout at a typical LCLS-II 1.3 GHz HPRF Penetration Installation Level Waveguide Layout 80% Complete

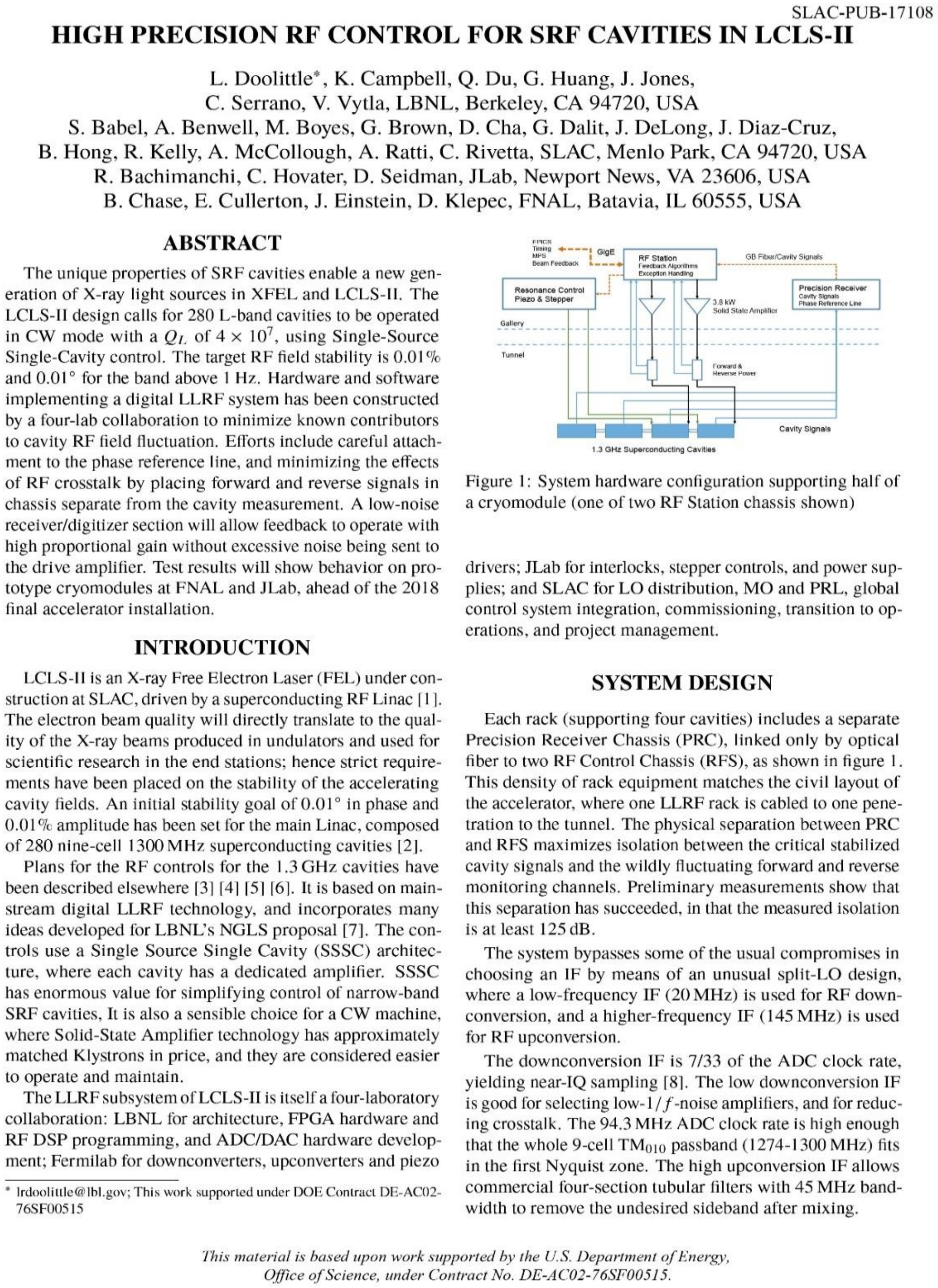


7 possible variations at the accelerator housing ceiling.

Nantista, Stewart w/ team input

WG routs in the tunnel optimized for proximity of penetration to the Cryomodule.

[New Proposal] Single Source Single Cavity (SSSC) Architecture



SLAC-PUB-17108

HIGH PRECISION RF CONTROL FOR SRF CAVITIES IN LCLS-II

L. Doolittle*, K. Campbell, Q. Du, G. Huang, J. Jones,
C. Serrano, V. Vytla, LBNL, Berkeley, CA 94720, USA
S. Babel, A. Benwell, M. Boyes, G. Brown, D. Cha, G. Dalit, J. DeLong, J. Diaz-Cruz,
B. Hong, R. Kelly, A. McCollough, A. Ratti, C. Rivetta, SLAC, Menlo Park, CA 94720, USA
R. Bachimanchi, C. Hovater, D. Seidman, JLab, Newport News, VA 23606, USA
B. Chase, E. Cullerton, J. Einstein, D. Klepec, FNAL, Batavia, IL 60555, USA

ABSTRACT

The unique properties of SRF cavities enable a new generation of X-ray light sources in XFEL and LCLS-II. The LCLS-II design calls for 280 L-band cavities to be operated in CW mode with a Q_L of 4×10^7, using Single-Source Single-Cavity control. The target RF field stability is 0.01% and 0.01° for the band above 1 Hz. Hardware and software implementing a digital LLRF system has been constructed by a four-lab collaboration to minimize known contributors to cavity RF field fluctuation. Efforts include careful attachment to the phase reference line, and minimizing the effects of RF crosstalk by placing forward and reverse signals in chassis separate from the cavity measurement. A low-noise receiver/digitizer section will allow feedback to operate with high proportional gain without excessive noise being sent to the drive amplifier. Test results will show behavior on prototype cryomodules at FNAL and JLab, ahead of the 2018 final accelerator installation.

INTRODUCTION

LCLS-II is an X-ray Free Electron Laser (FEL) under construction at SLAC, driven by a superconducting RF Linac [1]. The electron beam quality will directly translate to the quality of the X-ray beams produced in undulators and used for scientific research in the end stations; hence strict requirements have been placed on the stability of the accelerating cavity fields. An initial stability goal of 0.01° in phase and 0.01% amplitude has been set for the main Linac, composed of 280 nine-cell 1300 MHz superconducting cavities [2].

Plans for the RF controls for the 1.3 GHz cavities have been described elsewhere [3] [4] [5] [6]. It is based on mainstream digital LLRF technology, and incorporates many ideas developed for LBNL's NGLS proposal [7]. The controls use a Single Source Single Cavity (SSSC) architecture, where each cavity has a dedicated amplifier. SSSC has enormous value for simplifying control of narrow-band SRF cavities, It is also a sensible choice for a CW machine, where Solid-State Amplifier technology has approximately matched Klystrons in price, and they are considered easier to operate and maintain.

The LLRF subsystem of LCLS-II is itself a four-laboratory collaboration: LBNL for architecture, FPGA hardware and RF DSP programming, and ADC/DAC hardware development; Fermilab for downconverters, upconverters and piezo drivers; JLab for interlocks, stepper controls, and power supplies; and SLAC for LO distribution, MO and PRL, global control system integration, commissioning, transition to operations, and project management.

Figure 1: System hardware configuration supporting half of a cryomodule (one of two RF Station chassis shown)

SYSTEM DESIGN

Each rack (supporting four cavities) includes a separate Precision Receiver Chassis (PRC), linked only by optical fiber to two RF Control Chassis (RFS), as shown in figure 1. This density of rack equipment matches the civil layout of the accelerator, where one LLRF rack is cabled to one penetration to the tunnel. The physical separation between PRC and RFS maximizes isolation between the critical stabilized cavity signals and the wildly fluctuating forward and reverse monitoring channels. Preliminary measurements show that this separation has succeeded, in that the measured isolation is at least 125 dB.

The system bypasses some of the usual compromises in choosing an IF by means of an unusual split-LO design, where a low-frequency IF (20 MHz) is used for RF downconversion, and a higher-frequency IF (145 MHz) is used for RF upconversion.

The downconversion IF is 7/33 of the ADC clock rate, yielding near-IQ sampling [8]. The low downconversion IF is good for selecting low-$1/f$-noise amplifiers, and for reducing crosstalk. The 94.3 MHz ADC clock rate is high enough that the whole 9-cell TM_{010} passband (1274-1300 MHz) fits in the first Nyquist zone. The high upconversion IF allows commercial four-section tubular filters with 45 MHz bandwidth to remove the undesired sideband after mixing.

---

* lrdoolittle@lbl.gov; This work supported under DOE Contract DE-AC02-76SF00515

This material is based upon work supported by the U.S. Department of Energy,
Office of Science, under Contract No. DE-AC02-76SF00515.

4-E. Evolution and Completion of Modern Green SSA Application

[Old Method] LPDS (10MW KLYSTRON Multi-Branch Connection)

Proceedings of the 13th Annual Meeting of Particle Accelerator Society of Japan
August 8-10, 2016, Chiba, Japan

PASJ2016 MOP038

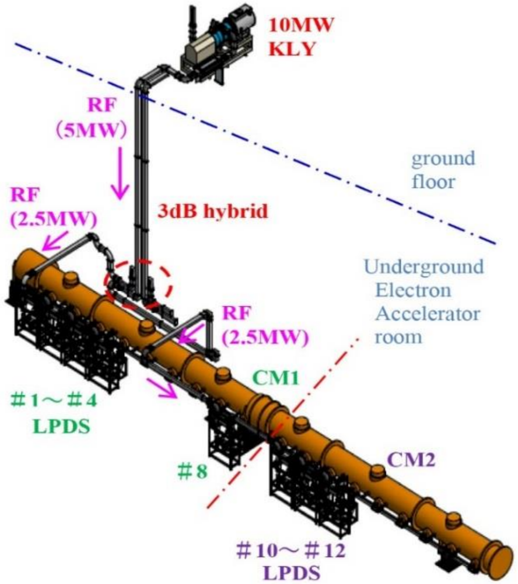


Figure 7: LPDS The small unit.

Table 1: Process of Operation and the Required Time (LPDS The Small Unit)

作業工程	必要人数／所要時間
①アルミ枠設置床へ墨入れ (1 台目のみ)	1 人 ／ 3 時間
②アルミ枠固定	1 人 ／ 1 時間
③導波管サポート材取付け	1 人 ／ 4 時間
④サーキュレータ組込	2 人 ／ 3 時間
⑤ハイブリッツド組込	2 人 ／ 2 時間
⑥フェーズシフター組込	2 人 ／ 2 時間
⑦ダミーロード組込	2 人 ／ 1 時間
⑧導波管の最終接続	2 人 ／ 3 時間
⑨RF 入力試験	1 人 ／10 時間
LPDS 小ユニット 1 台 合計	1～2 人 ／26 時間
LPDS 小ユニット 10 台 合計	1～2 人／260 時間

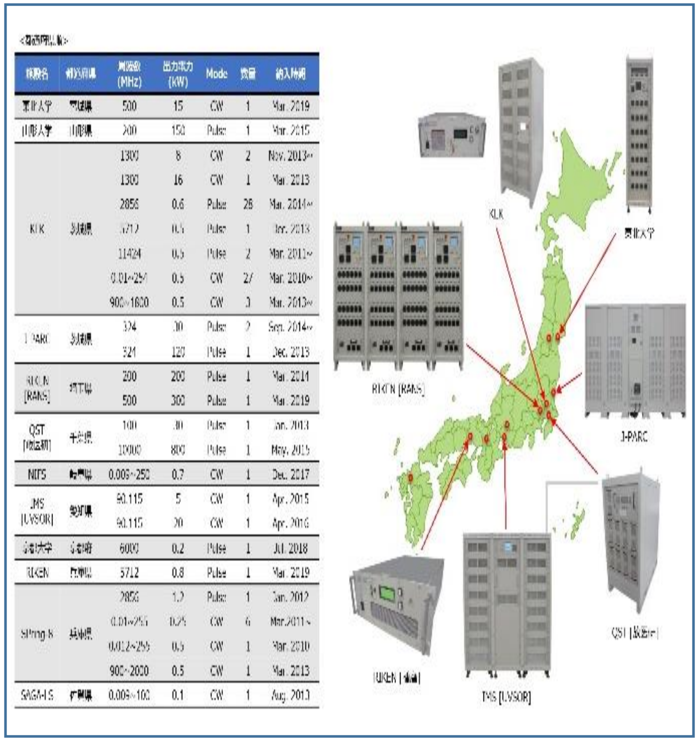
Source:
Proceedings of the 13th Annual Meeting of Particle Accelerator Society of Japan, "STATUS OF RF POWER DISTRIBUTION SYSTEM CONSTRUCTION FOR ILC IN STF"
Authors:
Norihiko Hanaka, Kazuya Ishimoto, Naoto Numata, Kazuhiko Yasu, Mitsuo Akemoto, Dai Arakawa,
Masato Egi, Hiroaki Katagiri, Tateru Takenaka, Hiromitsu Nakajima, Shigeki Fukuda, Hideki Matsushita,
Toshihiro Matsumoto, Takako Miura, Shinichiro Michizono

Unlike "Single Source Single Cavity" architecture, LPDS (Multi-distributing system for high power klystron power amplifier) consists of power splitter, variable attenuator, phase shifter, isolator, dummy load, and so on. They are combination of passive microwave components, but the structure relies heavily on the mechanical durability.

↓

Extremely complicated mechanical system. In order to achieve long term reliability for phase and power accuracy with 39-way distribution, adjustment by highly skilled and experienced technicians is absolutely necessary. The system is not suitable for simple, highly accurate, and automated operation.

5. R&K Recent Delivery Status



<国内納入実績>

機関名	都道府県	周波数 (MHz)	出力電力 (kW)	Mode	数量	納入時期
東北大学	宮城県	500	15	CW	1	Mar. 2019
山形大学	山形県	200	150	Pulse	1	Mar. 2015
KEK	茨城県	1300	8	CW	2	Nov. 2013~
		1300	16	CW	1	Mar. 2013
		2856	0.6	Pulse	28	Mar. 2014~
		5712	0.5	Pulse	1	Jan. 2013
		11424	0.5	Pulse	2	Mar. 2011~
		0.01~254	0.5	CW	27	Mar. 2010~
		900~1600	0.5	CW	3	Mar. 2013~
J-PARC	茨城県	324	30	Pulse	2	Sep. 2014~
		324	120	Pulse	1	Dec. 2013
RIKEN [RANS]	埼玉県	200	200	Pulse	1	Mar. 2014
		500	300	Pulse	1	Mar. 2019
QST [放医研]	千葉県	100	30	Pulse	1	Jan. 2013
		10000	800	Pulse	1	May. 2015
NIFS	岐阜県	0.009~250	0.7	CW	1	Dec. 2017
IMS [UVSOR]	愛知県	90.115	5	CW	1	Apr. 2015
		90.115	20	CW	1	Apr. 2016
京都大学	京都府	6000	0.2	Pulse	1	Jul. 2018
RIKEN	兵庫県	5712	0.8	Pulse	1	Mar. 2019
SPring-8	兵庫県	2856	1.2	Pulse	1	Jan. 2012
		0.01~255	0.25	CW	6	Mar.2011~
		0.012~255	0.5	CW	1	Mar. 2010
		900~2000	0.5	CW	1	Mar. 2013
SAGA-LS	佐賀県	0.009~100	0.1	CW	1	Aug. 2013

For Domestic Market

№	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	199.6MHz	3kW CW	LCLS-Ⅱ	1	Delivered	1	Sep. 2017				
③	358.54MHz	64kW Pulse	SPEAR3	1	Delivered	1	Jun. 2016				
④	1.3GHz	80W CW	LCLS-Ⅱ	12	Delivered	2 5	Oct. 2017 Aug.2018				
⑤	1.3GHz	3.8kW CW	LCLS-Ⅱ	278	Delivered	262	Jan. 2016 ~ Aug. 2018	3 4 1	Jan. 2016 May 2016 Nov. 2016	3 5	Jan. 2016 May 2016
⑥	1.3GHz	4.6kW CW	LCLS-Ⅱ	3	Delivered	1 2	Feb. 2018 Dec. 2018				
⑦	3.9GHz	900W CW	LCLS-Ⅱ	16	Delivered	8	Aug. 2018	8 (Scheduled)	T.B.D.		
⑧	11.424GHz	500W Pulse	LCLS-Ⅱ	1	Delivered	1	Aug. 2017				

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

For SLAC related Projects

< Alphabetical Order >

Laboratory	Country	Frequency (MHz)	Power (kW)	Mode	Qty.	Delivery
Argonne	USA	352	2	CW	16	Jul. 2019
		117.3	10	CW	1	In Production
Brookhaven	USA	0.009~254	0.5	CW	2	Feb. 2019
CERN	Swiz	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
LBNL	USA	185.7	60	CW	2	Dec. 2017
Los Alamos	USA	201.25	20	Pulse	1	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	13	Aug. 2017~
		1.8~4	100	Pulse	1	In Production
SLAC*	USA	1300	3.8	CW	278	Jan. 2016~
TRIUMF	Canada	650~2000	0.3	CW	1	Mar. 2019

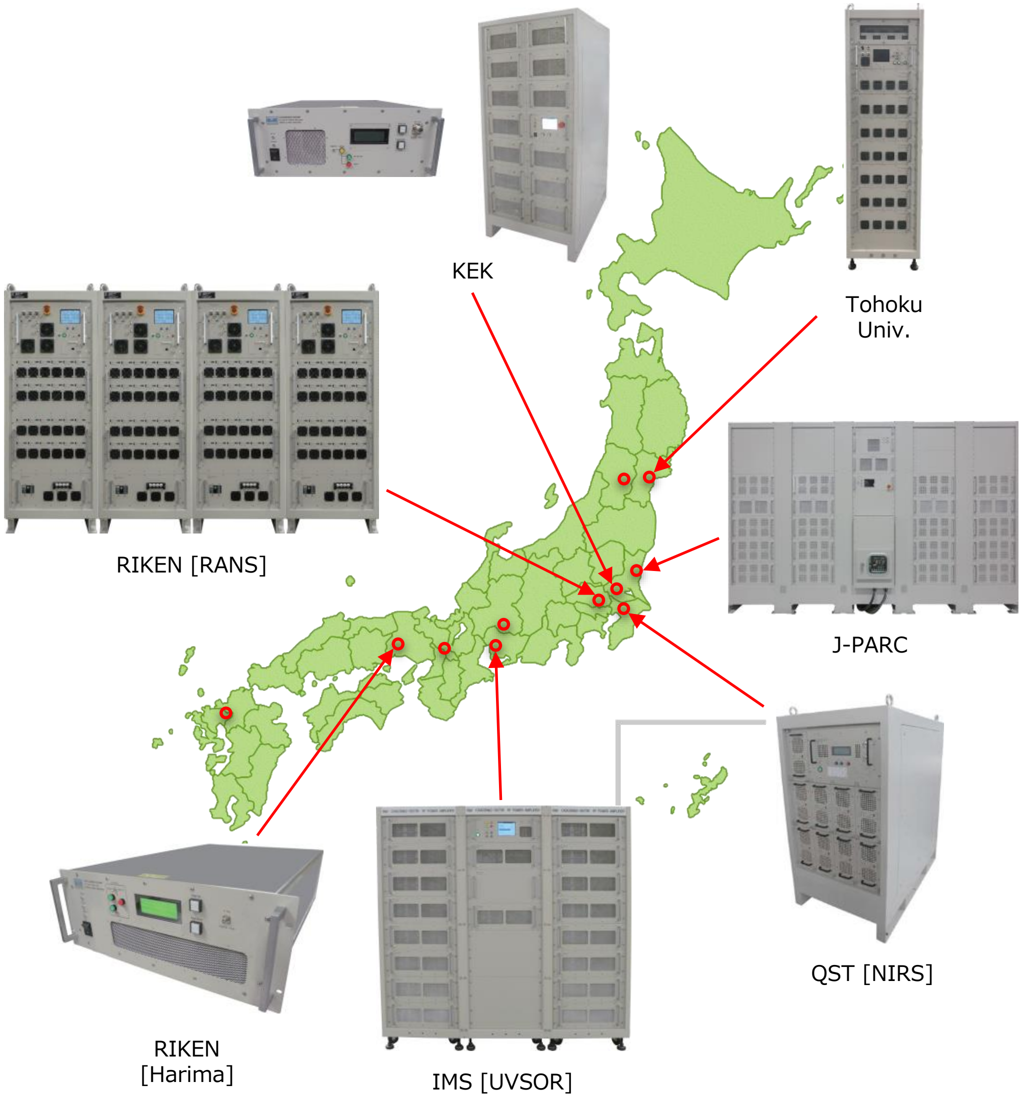
*See 'Recent Delivery Status of R&K SSPA for SLAC' for more comprehensive delivery record including the other models.

For European/USA Market

5-A. R&K Recent Delivery Status

<Listed by Prefecture>

Institution	Prefecture	Frequency (MHz)	Output Power (kW)	Mode	Qty.	Delivery Date
Tohoku Univ.	Miyagi	500	15	CW	1	Mar. 2019
Yamagata Univ.	Yamagata	200	150	Pulse	1	Mar. 2015
KEK	Ibaraki	1300	8	CW	2	Nov. 2013~
		1300	16	CW	1	Mar. 2013
		2856	0.6	Pulse	28	Mar. 2014~
		5712	0.5	Pulse	1	Dec. 2013
		11424	0.5	Pulse	2	Mar. 2011~
		0.01~254	0.5	CW	27	Mar. 2010~
		900~1800	0.5	CW	3	Mar. 2013~
J-PARC	Ibaraki	324	30	Pulse	2	Sep. 2014~
		324	120	Pulse	1	Dec. 2013
RIKEN [RANS]	Saitama	200	200	Pulse	1	Mar. 2014
		500	300	Pulse	1	Mar. 2019
QST [NIRS]	Chiba	100	30	Pulse	1	Jan. 2013
		10000	800	Pulse	1	May. 2015
NIFS	Gifu	0.009~250	0.7	CW	1	Dec. 2017
IMS [UVSOR]	Aichi	90.115	5	CW	1	Apr. 2015
		90.115	20	CW	1	Apr. 2016
Kyoto Univ.	Kyoto	6000	0.2	Pulse	1	Jul. 2018
RIKEN	Hyogo	5712	0.8	Pulse	1	Mar. 2019
SPring-8	Hyogo	2856	1.2	Pulse	1	Jan. 2012
		0.01~255	0.25	CW	6	Mar.2011~
		0.012~255	0.5	CW	1	Mar. 2010
		900~2000	0.5	CW	1	Mar. 2013
SAGA-LS	Saga	0.009~100	0.1	CW	1	Aug. 2013

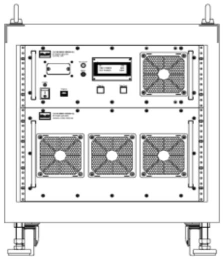


5-B. R&K Recent Delivery Status

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	199.6MHz	3kW CW	LCLS-Ⅱ	1	Delivered	1	Sep. 2017				
③	358.54MHz	64kW Pulse	SPEAR3	1	Delivered	1	Jun. 2016				
④	1.3GHz	80W CW	LCLS-Ⅱ	7	Delivered	2 5	Oct. 2017 Aug.2018				
⑤	1.3GHz	3.8kW CW	LCLS-Ⅱ	278	Delivered	262	Jan. 2016 ~ Aug. 2018	3 4 1	Jan. 2016 May 2016 Nov. 2016	3 5	Jan. 2016 May 2016
⑥	1.3GHz	4.6kW CW	LCLS-Ⅱ	3	Delivered	1 2	Apr. 2018 Dec. 2018				
⑦	3.9GHz	900W CW	LCLS-Ⅱ	16	Delivered	8	Aug. 2018	8 (Scheduled)	T.B.D.		
⑧	11.424GHz	500W Pulse	LCLS-Ⅱ	1	Delivered	1	Aug. 2017				

185.7MHz
60kW CW

199.6MHz
3kW CW



358.54MHz
64kW Pulse

1.3GHz
3.8kW/4.6kW CW

3.9GHz
900W CW
(2 SSAs in Rack)

11.424GHz
500W Pulse

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

BERKELEY LAB

5-C. R&K Recent Delivery Status

< Alphabetical Order >

Laboratory	Country	Frequency (MHz)	Power (kW)	Mode	Qty.	Delivery
Argonne	USA	352	2	CW	16	Jul. 2019
		117.3	10	CW	1	In Production
Brookhaven	USA	0.009~254	0.5	CW	2	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
LBNL	USA	185.7	60	CW	2	Dec. 2017
Los Alamos	USA	201.25	20	Pulse	2	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	13	Aug. 2017~
		1.8~4	100	Pulse	1	In Production
SLAC*	USA	1300	3.8	CW	278	Jan. 2016~
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.

R&K

R&K Company Limited

RF/Microwave Power Amplifiers and Components

www.rk-microwave.com

Q&A - 1

1. The cooling water temperature (of the current vacuum tube design) is +50degC.

If the amplifier is 200kW and efficiency is 50%, consumption power is 3% of 400kW, 12kW/unit.
If RF conditions are same, average heat generation is stable.
Our preliminary calculation of heat generation of solid-state power amplifier is 6kW (12kW－6kW).
For quantity 39 units, it’s going to be 234kW.

If we calculate accurately, however, heat generation at 55% efficiency is 3% of 363,636kW, consumption power is 10.9kW/unit.
The heat generation of this semiconductor is 10.91kW-6kW=4.91kW.
For quantity 39 units, it’s going to be 191.49kW.

Q&A - 2

2. ***The footprint of power amplifier unit only needs to be within (W)100cm x (D)100cm x (H)70cm.***

It would be possible to have power supply unit (3% of 200kW SSA with efficiency 50% is 1kW, power supply module is going to be 2~3 pcs/set) built-in the power amplifier if we further reconsider high-voltage power Supply, Marx modulator, and all waveguide components like circulator.

Measures against radiation is also possible.

Q&A - 3

3. AC-RF power supply final efficiency of 10MW klystron is about 40%, according to the comments from Prof. Yoshioka.
(Klystron itself is 65%, so I thought that more than 50% was possible…)

The efficiency of GaN transistor is 75%, AC power supply efficiency is 95%, total loss of all combiners is 1dB.
The calculation is 0.75 x 0.95 x 0.794328= 0.5659587, we can target 56% of AC to RF efficiency that is impossible for Klystron to achieve.
Substantial cost reduction is possible by using GaN transistor of higher power like 1500W device.
1500W GaN transistors are just put on the market as of today, but some others additionally may come on to the market in 2020.