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STATE ATOMIC ENERGY CORPORATION ROSATOM

Next Generation High Power Solid-State RF Sources

SC NIITFA, Moscow

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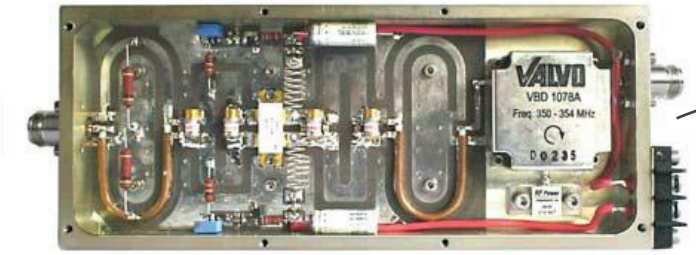
RuPAC 2016, S. Petersburg 21-25 Nov. 2016

Summary

- 3G SSPA technology
- 72 MHz CW Amplifier
- 352 MHz pulsed Amplifier

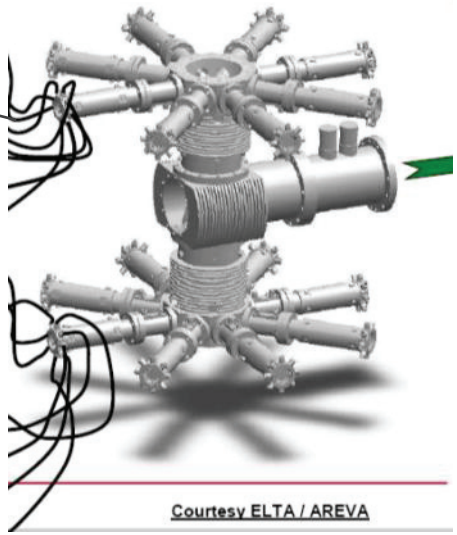
Solid-State RF
State-of-the-art

RF module

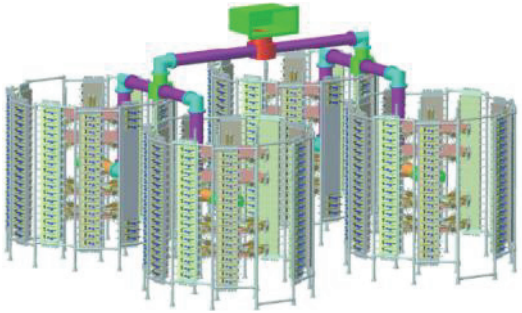


- Standard 300-600 W RF boards with one transistor – copies from evaluation boards
- Tuned by hand matching circuits
- Circulators (lose 5% to 7% efficiency)

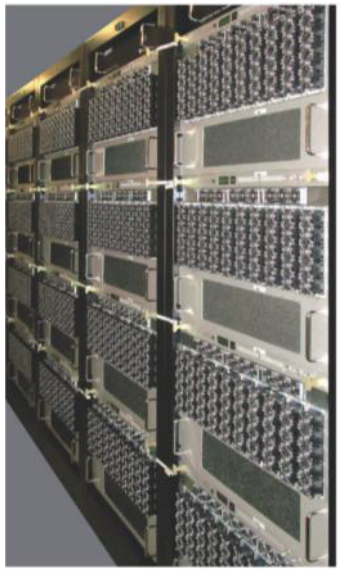
Power combiner



- Cascading architecture with >100 inputs
- Lose ~ 0.5% efficiency @ each cascade
- Impedance between cascades tuned “by hand”
- Broken modules drop efficiency significantly

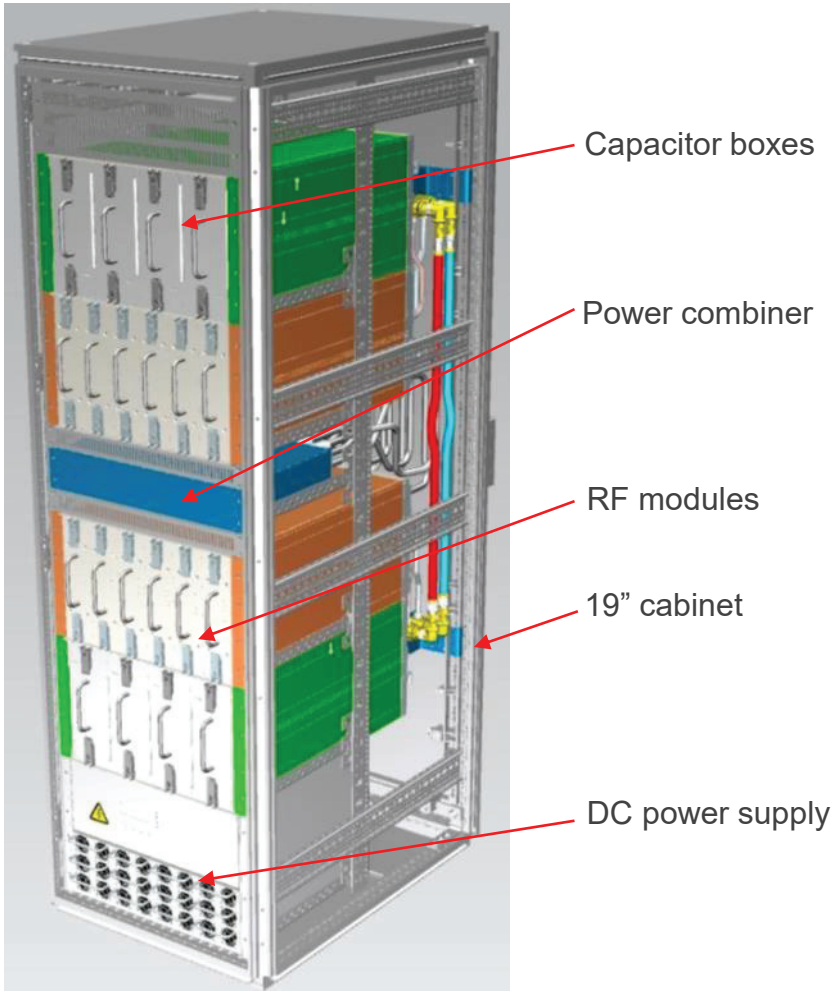


- Bulky system
- Hardly scalable
- Complete redesign for new frequency
- Wall plug efficiency ≈ tubes
- Complex maintenance
- High cost



DELTA-SIGMA INC. DRWP transmitter
250 kW at 49.25 MHz

SSMG*
Unified system architecture



Corresponds customers demands towards lower TCO**

- High efficiency (>55%)
- Low MTTR (< 5 min), high MTBF (>100.000 h)
- Compact (Average RF power >25 kW/m^2)
- Cost effective
- Turnkey

System approach

- Unified architecture for various applications, frequencies, powers (up to 1.3 GHz, 3 MW)
- High modularity and scalability
- Reduced costs and development efforts
- Use off-the-shelf components as much as possible
- No handmade parts/tuning
- All components fit into standard 19“ cabinet

Custom designed components

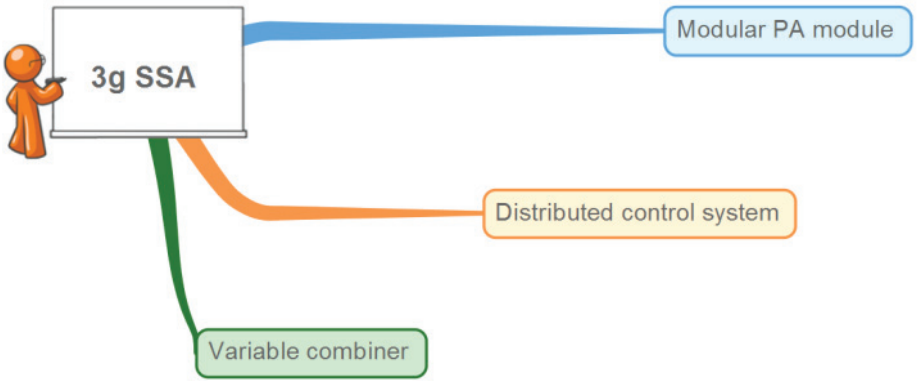
- RF power modules
- Power combiner
- Control system

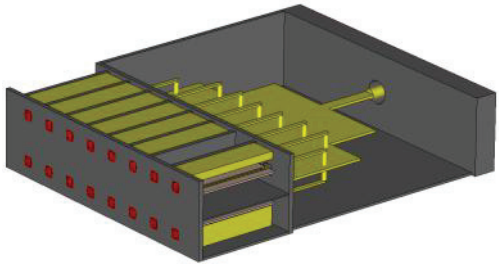
Standard components

- DC power supply
- 19” cabinet
- Auxiliaries, e.g. industrial computer, cooling

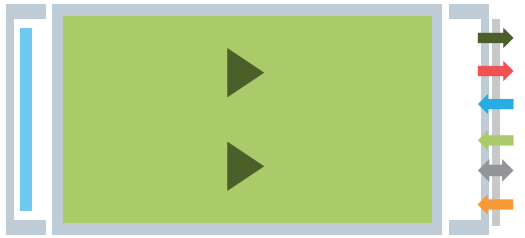
* SSMG = Solid State Microwave Generator * TCO = Total Cost of Ownership

3G SSA Key Features

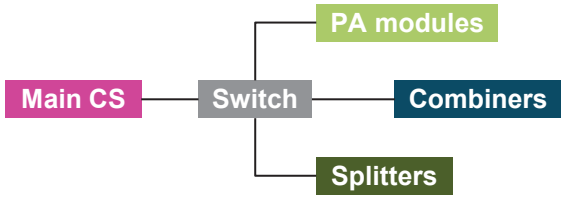




- Operation with arbitrary number of powered up modules in arbitrary arrangement from installed in the system
- De-energized system protection from RF power coming to the output



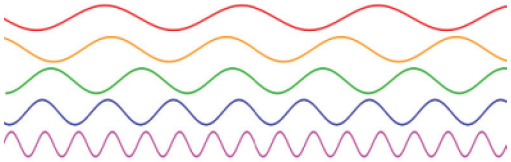
- Universal mechanical design for wide frequency ranges from 50 to 1300 MHz and all regimes from short pulses to CW
- Use of unified components for different projects



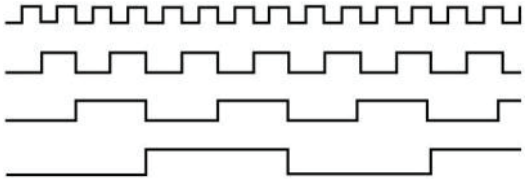
- Minimum number of cables:
  - Use of Ethernet connections for units communication
  - P2P communication between units
  - Use of PoE to provide electrical power for units controllers

3G SSA Key Features
Modular Power Amplifier Module

Universal mechanical design for wide frequency ranges from 50 to 1300 MHz (down to 10 MHz with fractional changes)

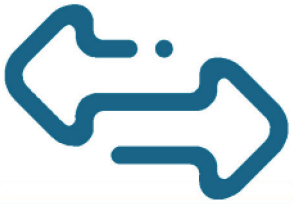


Universal mechanical design for all regimes from short pulses to CW

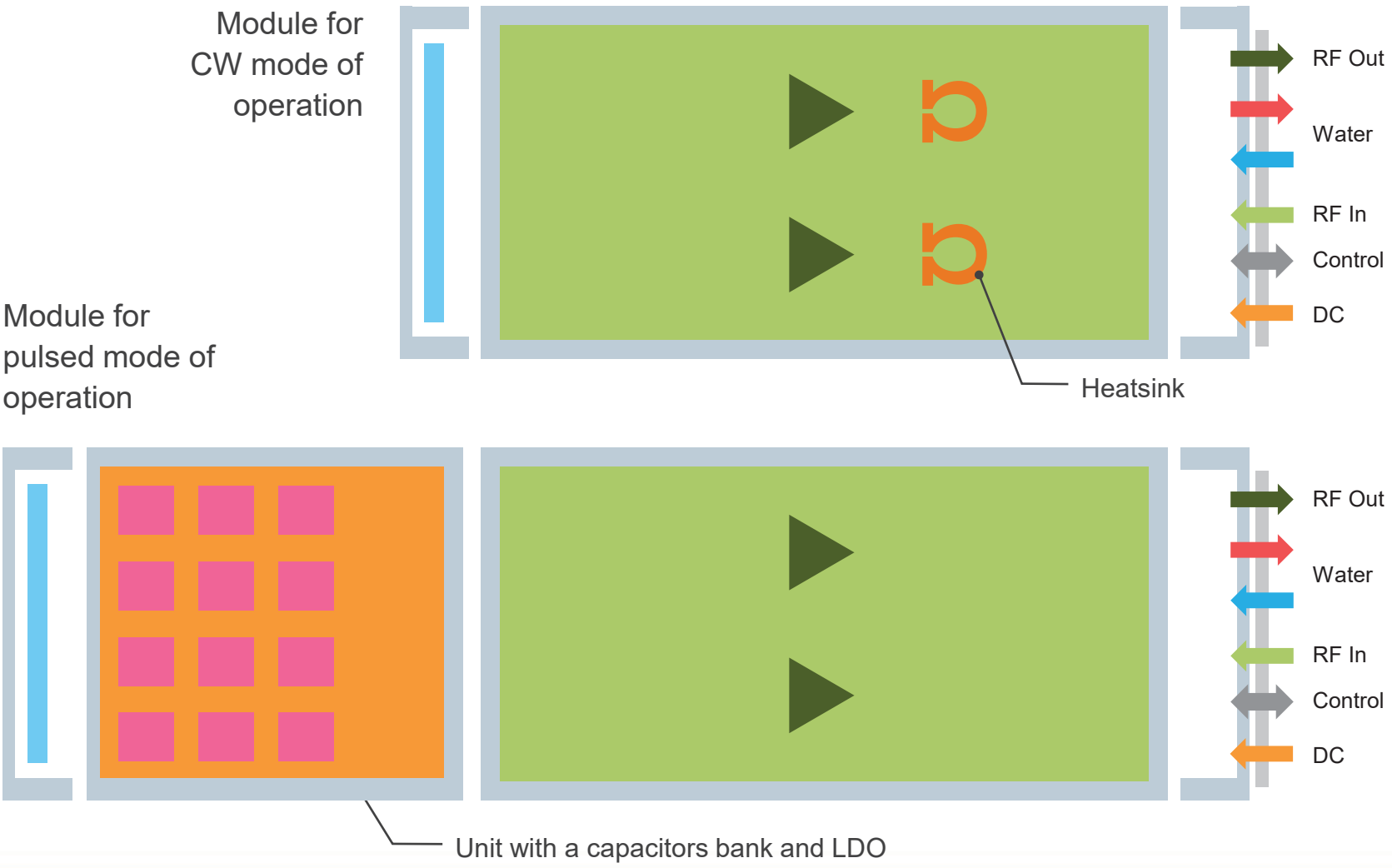


Modules in module – decompose the module into functionally-mechanically “independent” building blocks. Specified task – specified set of the building blocks with the minimum unique ones

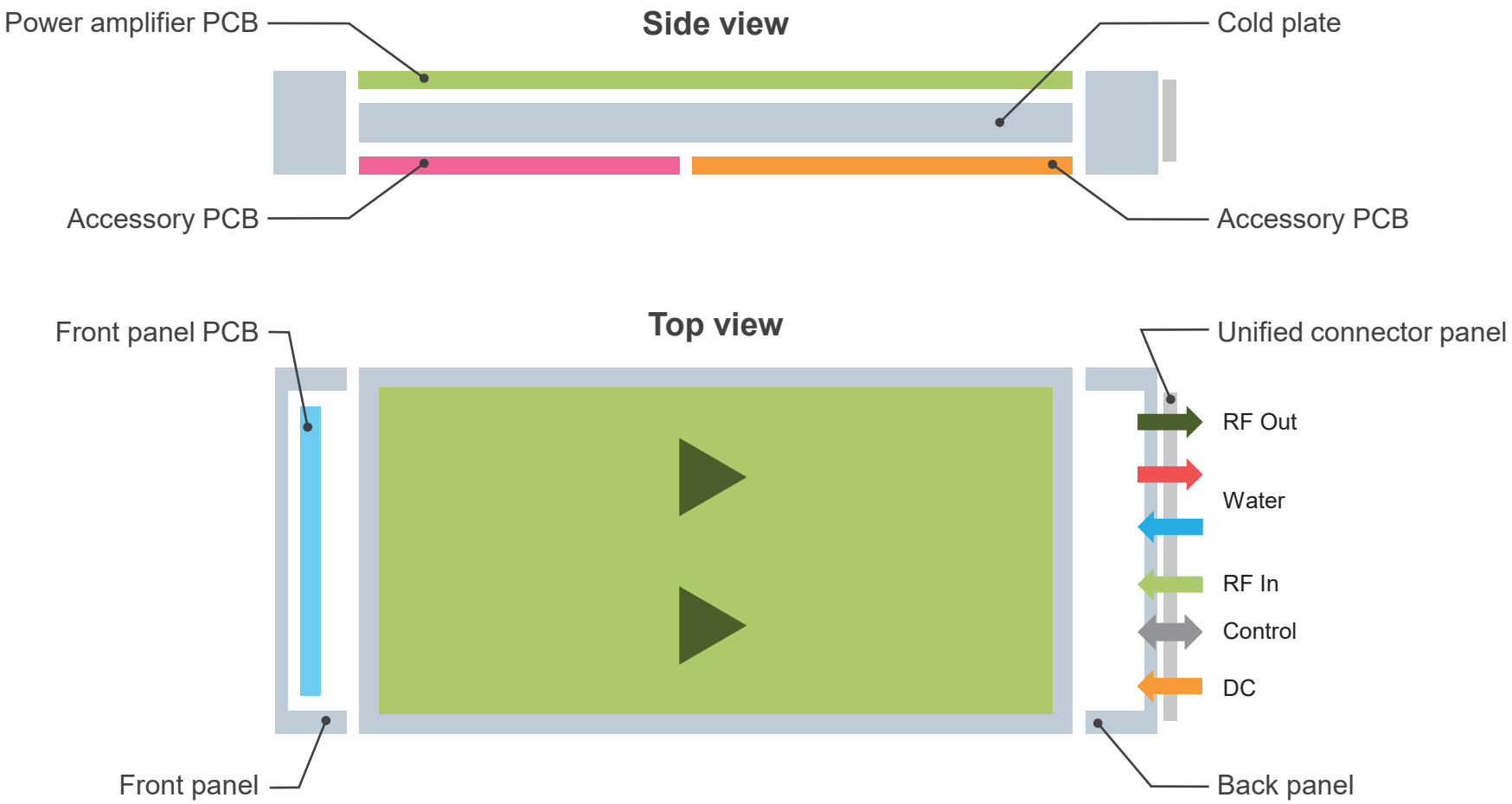
Hot-swap feature



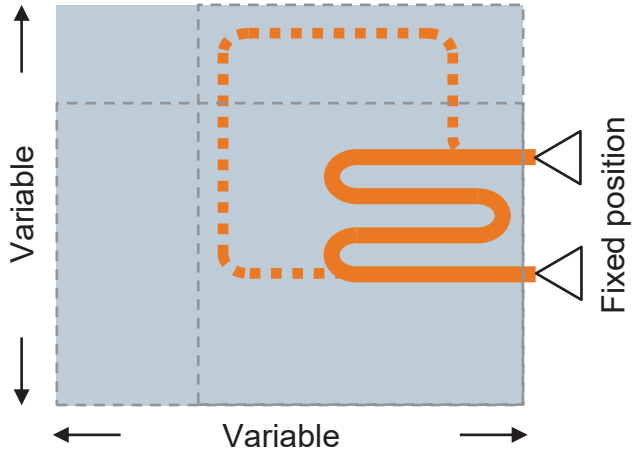
Modular Power Amplifier Module
CW and Pulsed Mode Design Example



Modular Power Amplifier Module

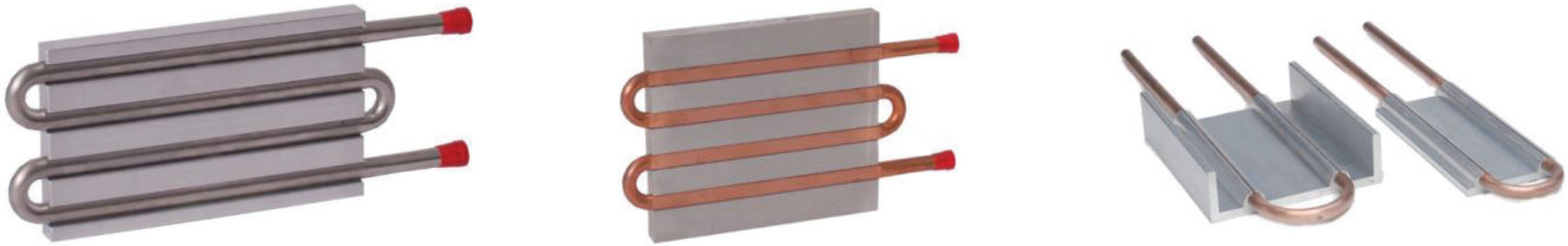


Modular Power Amplifier Module
Cold Plate



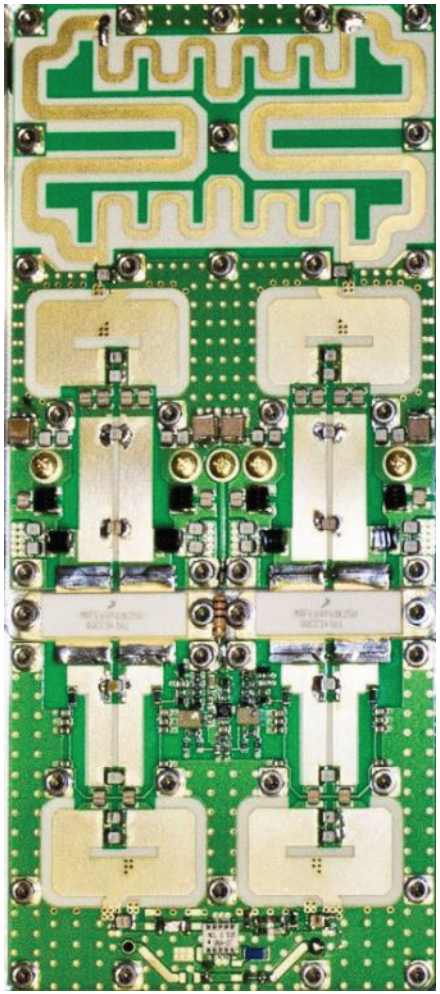
Design concerns

- Aluminum plate with press-in copper or stainless steel pipes
- Pipes (Ø6 or Ø8) inlet/outlet at fixed position to allow connection to “unified connector panel”
- Cold plates of different depth/height for different applications (frequency, mode) – ideally a predefined set of several cold plates
- Manufacturing can be outsourced



Copper and stainless steel press-in pipes

Modular Power Amplifier Module
Power Amplifier PCB



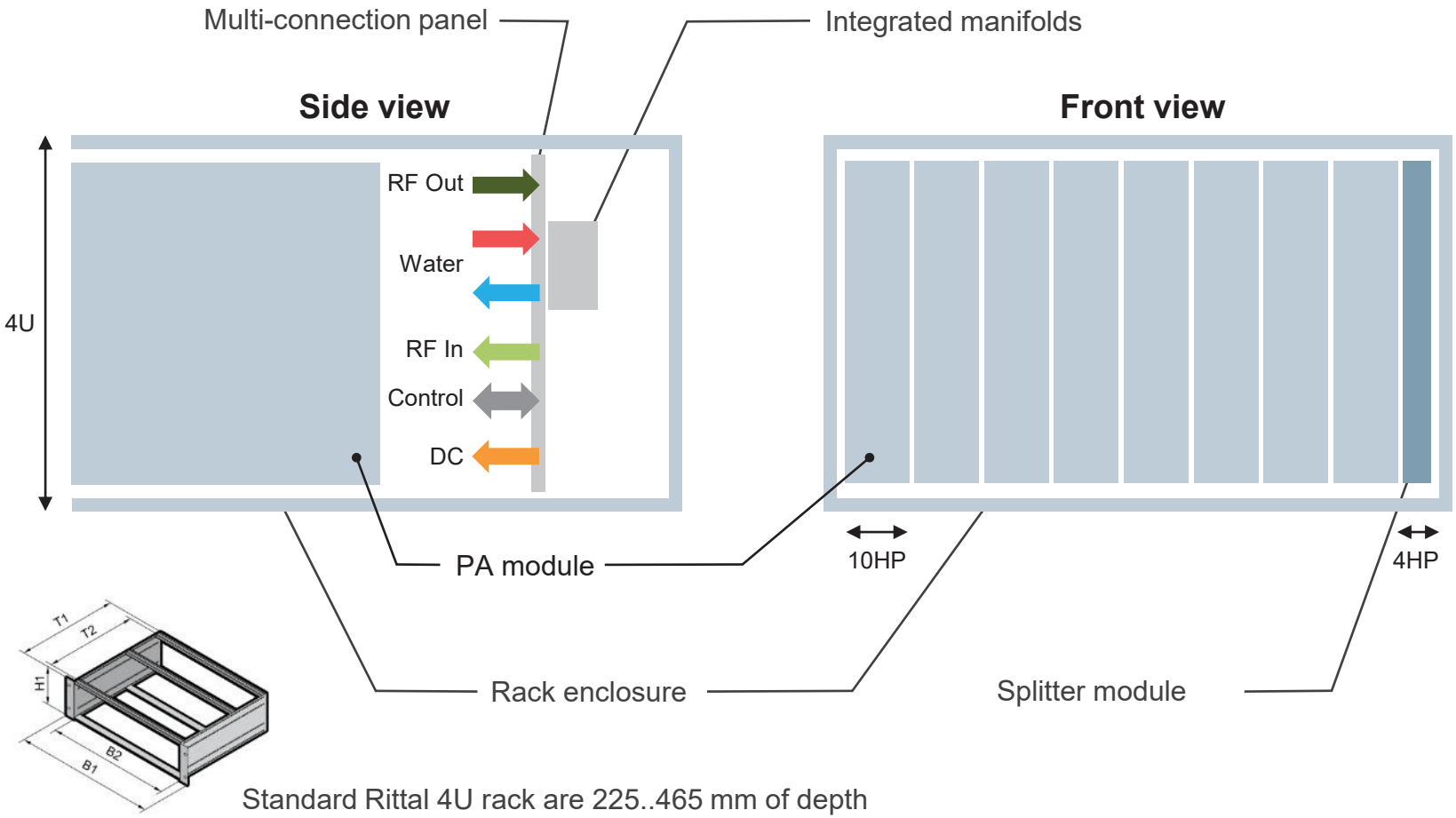
2 LDMOS PA design advantages

- Quite high output RF power
  (2x MRFE6VP61K25H: 2.6 kW @ 50 MHz, 2 kW @ 500 MHz)
- No significant changes in design with change of operation mode
  - Use of standard RF connectors at modes of operation up to CW
    (7-16 connector: 7.5 kW @ 50 MHz, 1.5 kW @ 1.3 GHz)
  - Use of standard DC connectors for currents up to 100 A
    (2.5 kW RF / 50% / 50 V = 100 A)
- Same module height (4U) for different frequencies of operation
  (mechanical design and accessory PCBs can be unified)
- System MTBF decreased just twice with module removal from operation in case of a single transistor failure
- Simplified power electronic PCBs development (e.g. LDO, DC/DC converter) because of moderate DC supply currents required
- Test of an assembled PAM is possible without preliminary components tests (simpler module → less rejection rate → simpler maintenance)

2 LDMOS PA design disadvantage

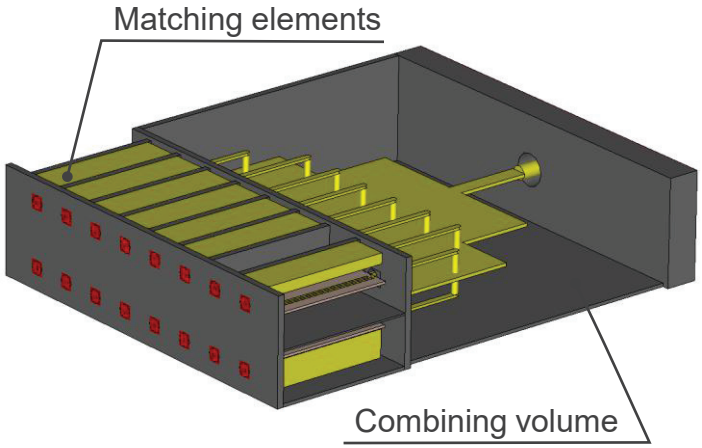
- More PA modules required for pulsed mode machine

Modular Power Amplifier Module
Rack Design



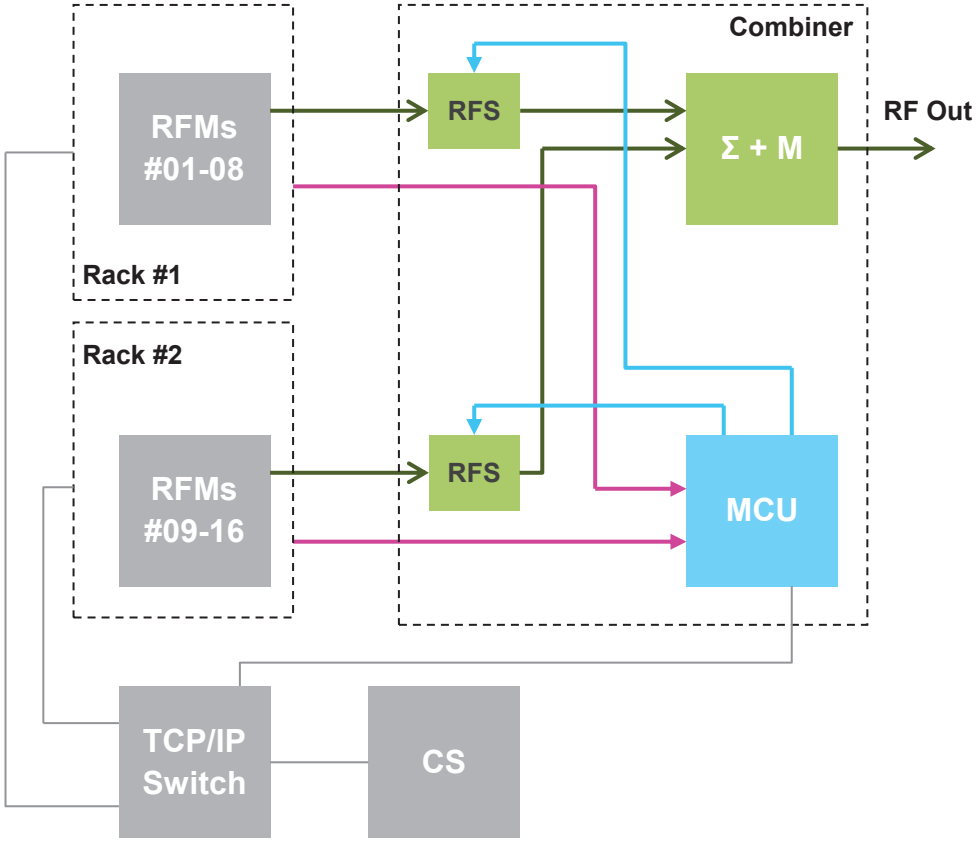
Standard Rittal 4U rack are 225..465 mm of depth

Variable RF Power Combiner



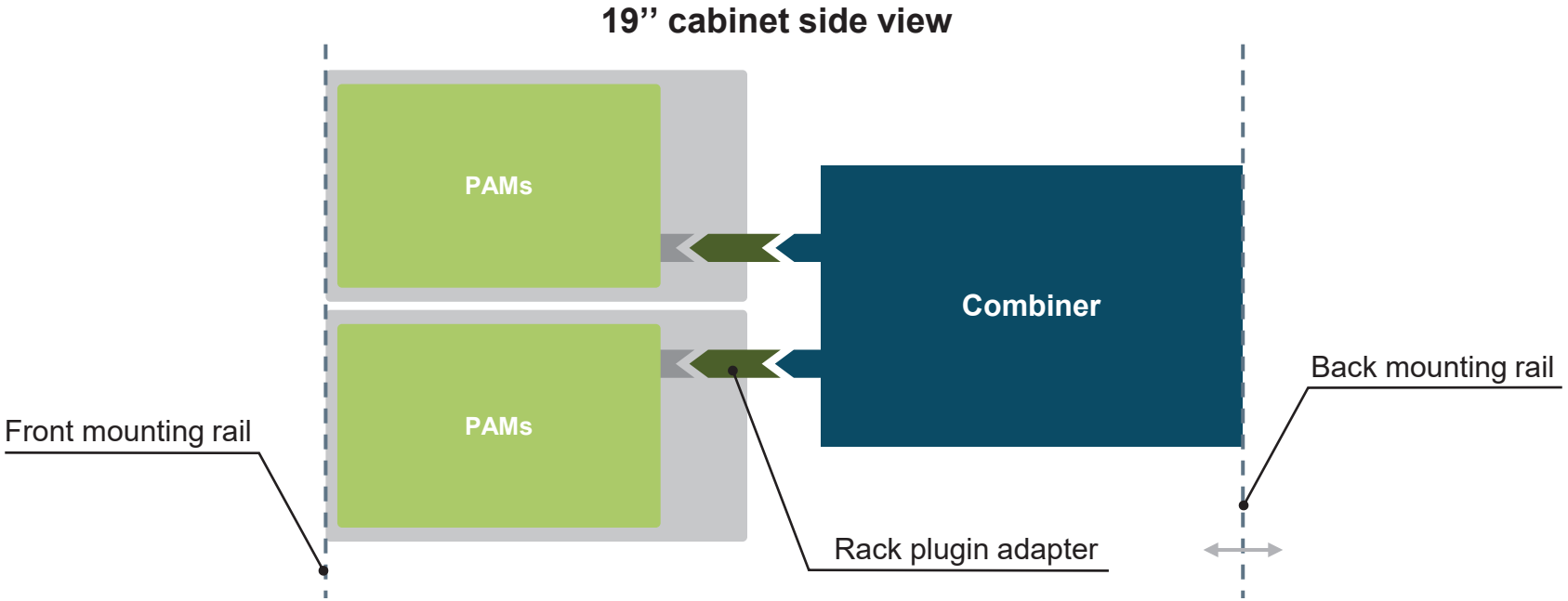
- Matching elements based on RF switches (RFS) with linear actuator
- Operation with arbitrary number of powered up modules in arbitrary arrangement from installed in the system
  - Operation at **maximum efficiency at nominal** power level with de-energized redundant (or failed) PA modules
  - Operation at **maximum efficiency at lower power** levels with appropriate number of de-energized PA modules
- De-energized system withstand at least full nominal RF power coming to the output
- Completely automated combiner test and tuning stand – no manual tuning or externally connected tuning devices required

Variable Combiner Operation



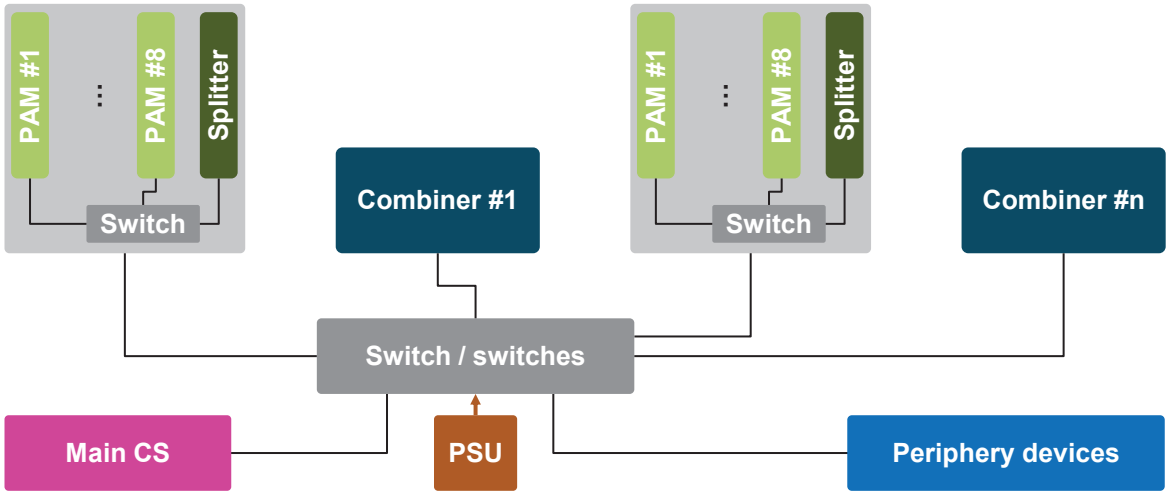
- **De-energized system**
  - All RFS in home positions because of pullback spring (short condition at the combiners loops)
- **Normal operation**
  - All RFS in “50 Ohm matching” positions
- **Module failure / hot-swap** (up to 8 modules)
  - Interlock enables (pink line)
  - Control signal from MCU to home position run for appropriate RFS
  - Control signal from MCU for “-1 module matching” for other RFS

PA Modules and Combiner Arrangement



- Plugin connectors between PA racks and combiner allow easy assembling and service (additional analysis required to check possibility of direct PAM to combiner connection w/o adapter)
- Standard 19'' cabinet rails for PA racks and combiner mounting and fixation provide enough precision without costly custom designed alignment devices
- Back mounting rail can be positioned individually for developed project combiner dimensions
- Instead of plugin connectors the regular connectors can be used for more convenient combiner placement and connection with RF cables

Distributed Control System



- Ethernet connections with star topology for units communication simplified interconnections infrastructure
- Power over Ethernet (PoE) technology allow to provide electrical power for units controllers with use of standard TCP/IP PoE switches
- P2P communication between units allowed
- Almost infinite scalability and expandability with auxiliary/periphery devices

72 MHz Generator (1st Approach of Modular Design)

Control System
RF Module #1
RF Module #2
RF Module #3
RF Module #4
8:1 Combiner
RF Module #5
RF Module #6
RF Module #7
RF Module #8
Power Distribution Module
Water Manifolds

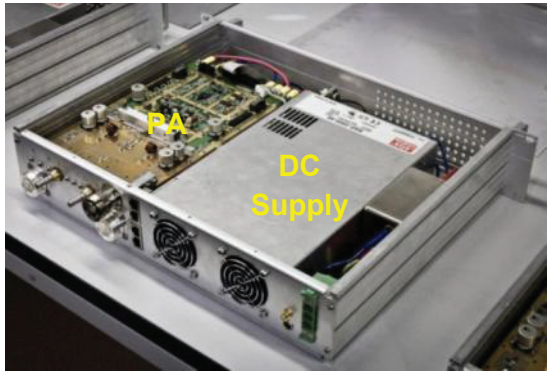
Features

- Modular design
- System assembled in 19" cabinet (26U occupied)
- RF module consists of PA, DC power supply, ~~and circulator~~
- RF combiner with build-in directional coupler
- Front panel free of wires and connectors
- Most of cables and hoses placed behind side panels
- Quick-plug water connectors with shut-off used

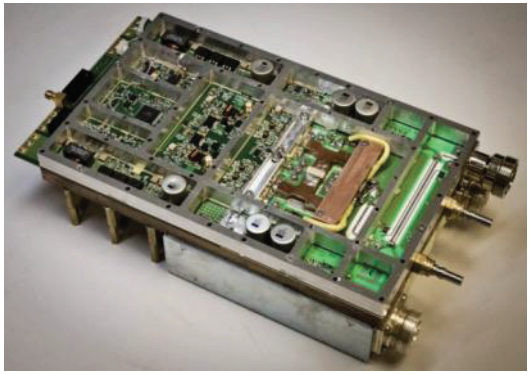
Achieved results

- Frequency of 72 – 73 MHz
- Output RF power of **12 kW** in **pulse mode**
- Output RF power of **10 kW CW**
- Measured overall efficiency > 55% at 10 kW
- Operations **without circulators**

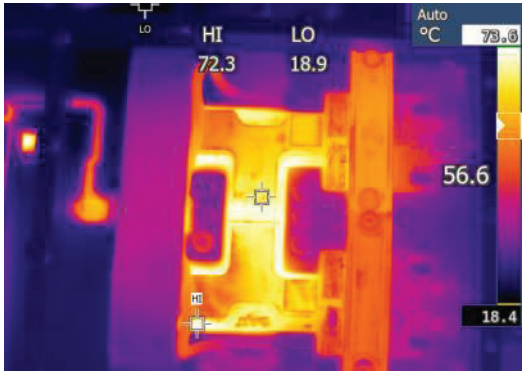
72 MHz Generator
2 kW CW RF Module



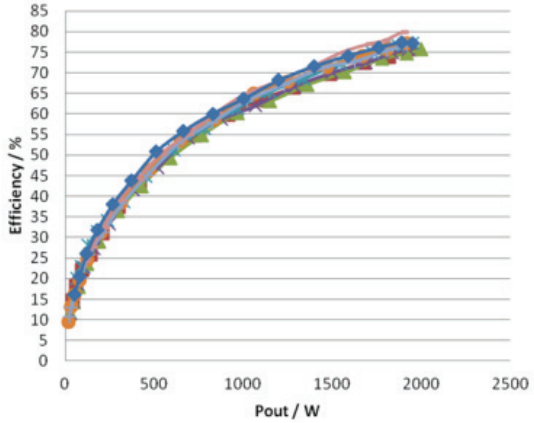
RF Module



PA with installed Ω-shaped heatsink



IR picture of output transformer
at 2 kW CW of output power



RF Modules PAE dependence on RF power

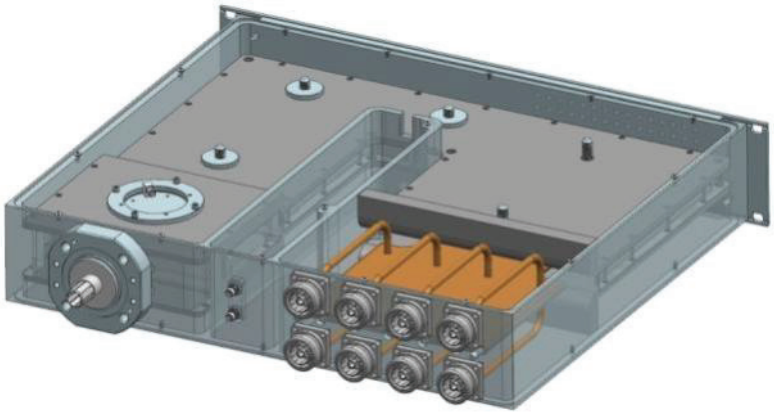
Design advantage

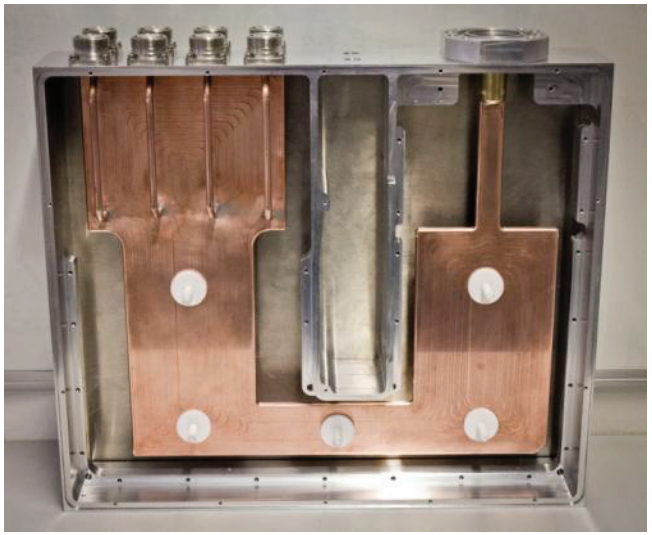
- RF module can be used as an independent RF amplifier
- Operation w/ and w/o circulator possible

Design drawback

- In case of small changes in PA (e.g. output part optimization) a change of the whole module required
- Difficult to maintain in case of transistor failure

72 MHz Generator
8-way RF Power Combiner





Design advantage

- Compact 2U design
- RF inputs and output at the back panel
- Build-in bi-directional coupler

Design “drawback” point

- Does not isolate single port – the whole combiner operation depends on impedance of a single input (as opposed to Wilkinson, Gysel, and hybrid types of combiner)
    - But such isolation can be provided externally by RF switch

72 MHz Generator
Web interface

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Control panel

Power control

Start | Stop

Power status

AC | Button | Relay

System status

Active

Status IL

Power Amplifiers' DC

ON | OFF

RF Enable

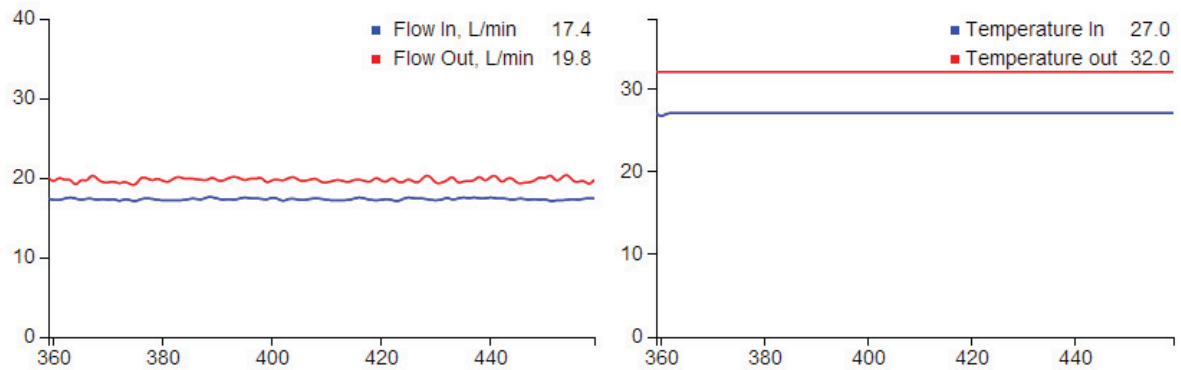
ON | OFF

Readings

Frequency	72.5000MHz
Power	10.016 kW
Forward	17504
Reflected	728

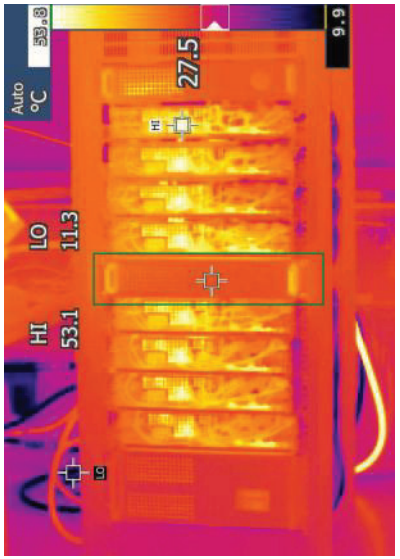
Module	Input dBm	Forward W	Reflected W	Voltage V	Current 1 A	Current 2 A	Temp. ℃	PAMs DC
#1	14.7	1491	15	51.8	18	20	40	ON OFF
#2	13.1	1135	6	51.2	20	19	39	ON OFF
#3	14.6	1162	20	53.4	19	18	40	ON OFF
#4	14.7	1562	48	51.8	22	19	40	ON OFF
#5	15.7	1169	538	52.7	20	19	45	ON OFF
#6	14.5	301	15	51.5	21	19	41	ON OFF
#7	14.7	1375	39	51.1	21	20	40	ON OFF
#8	14.2	629	20	52.7	20	18	42	ON OFF

Water flow statistic

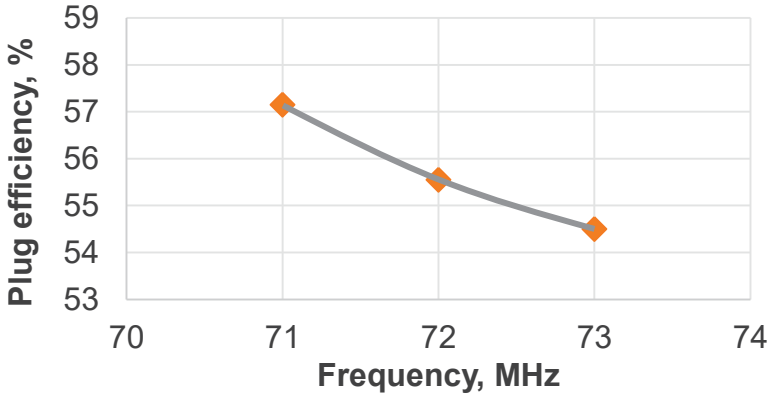


72 MHz Generator
High power tests

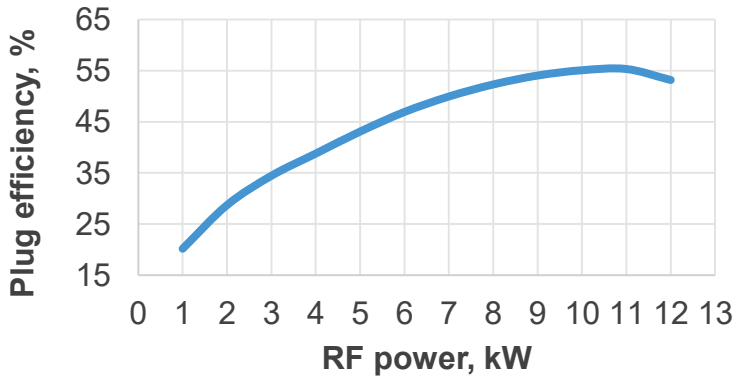
- Tests performed at ITEP test stand
- Test duration: 4 runs X 3 hours CW
- Cooling water t° 28°C
- Output power > 10 kW
- Wall plug efficiency 55%
- Spurious (±650 kHz) -59 dBc
- Power combiner t°<40°C, no breakdowns @ 12 kW



IR picture at 8 kW CW

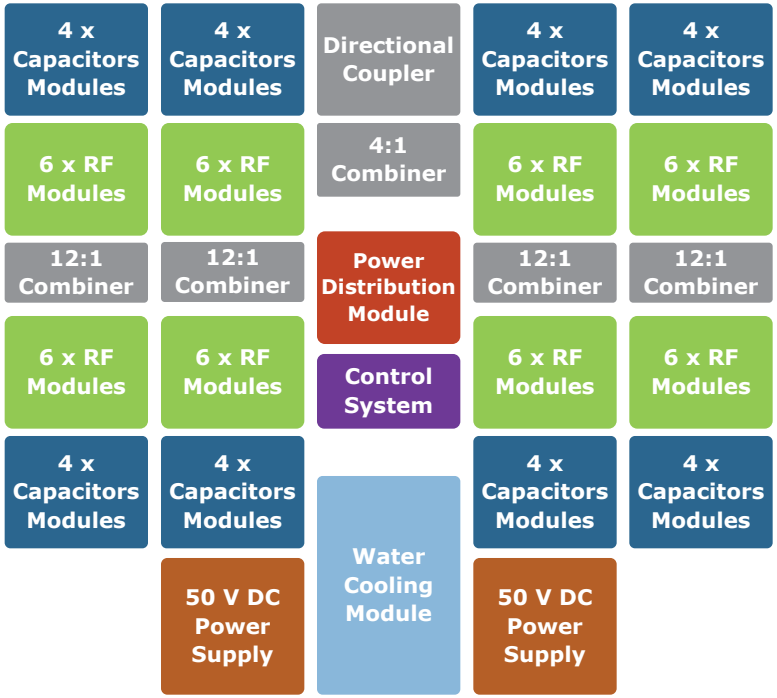


Total efficiency at 10 kW CW



RF output power at 72.5 MHz

352 MHz Amplifier for ESS Spokes



Modules arrangement in cabinets

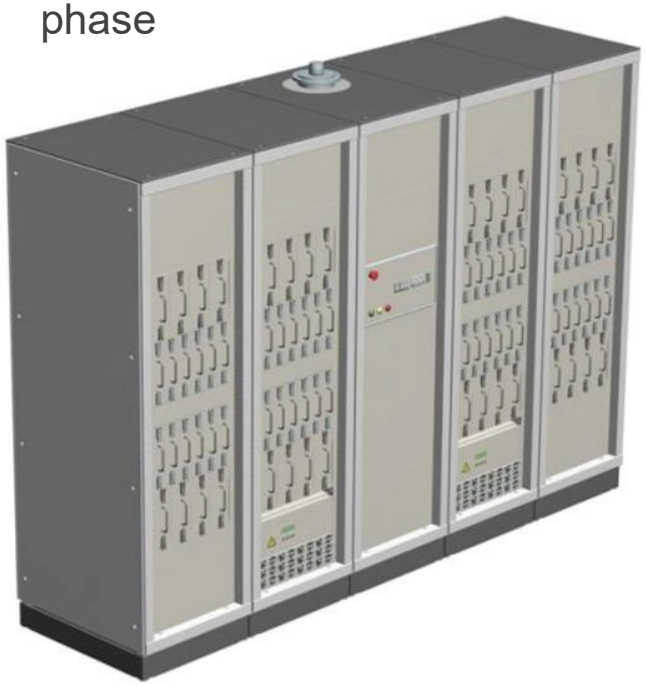
352.21 MHz, 400 kW

3.5 ms pulse

14 Hz repetition rate

5% d.c.

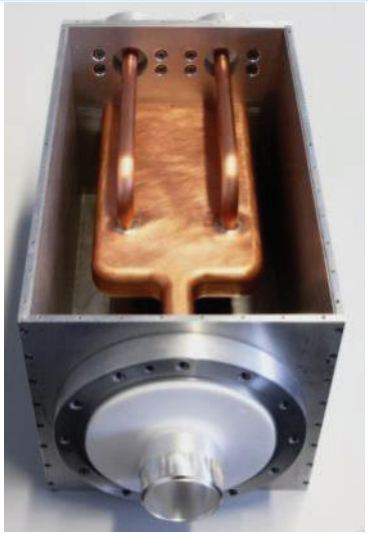
Withstands full reflection at any phase



352 MHz system external view

High RF Power Components

12:1 power combiners



4:1 power combiner

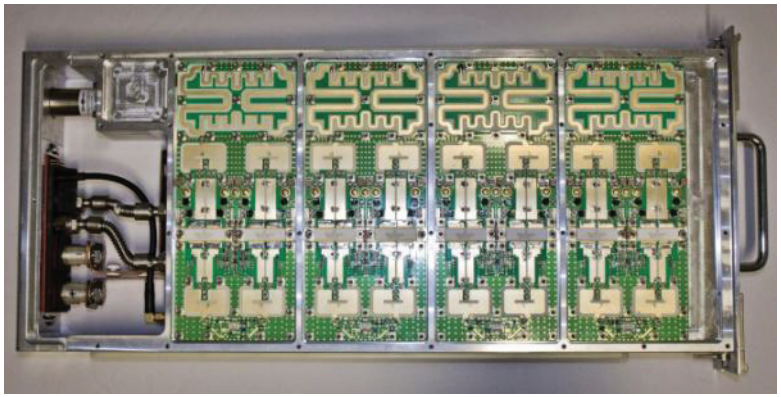
Bi-directional coupler

Development status

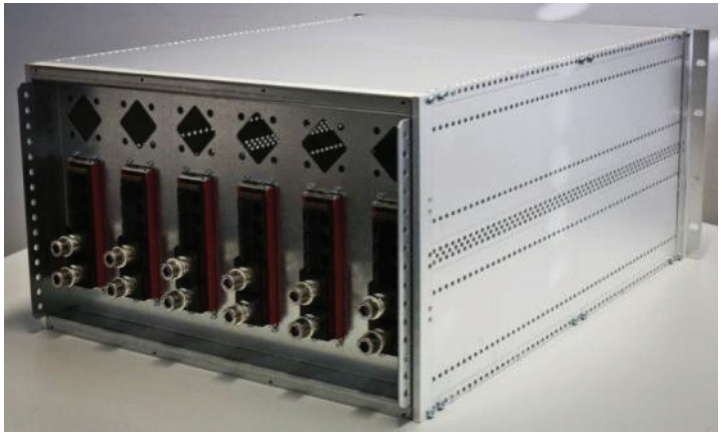
- 4x 12:1 RF power combiners manufactured, measured, and tuned
- 4:1 RF power combiner manufactured, measured, and tuned. Losses are less than 1%
- Bi-directional coupler manufactured, measured, and tuned
- All coaxial waveguide components are delivered and assembled

RF Modules

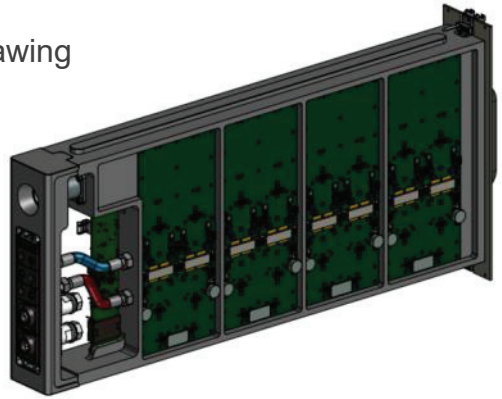
6x RF Modules dock-station
(front and back view)



RF Module test assembly with 4x 2 kW PA units



RF Module drawing



Design advantage

- Module can be changed by simple slide in because of plugin connectors use

352MHz RF Module
Series prototype

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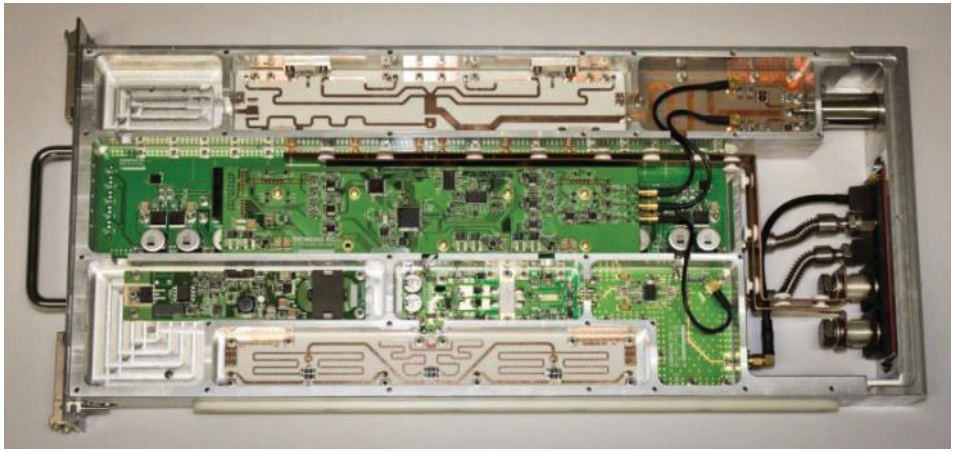
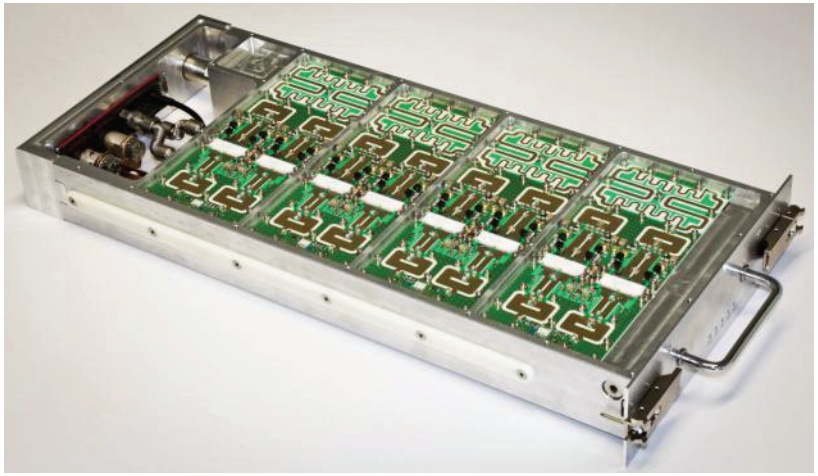
- 4 x2 transistor pallets
- Input/output splitter/combiner
- DC distribution
- MCU, power detectors
- RF switches inside the module





352MHz RF Module
Series prototype tests

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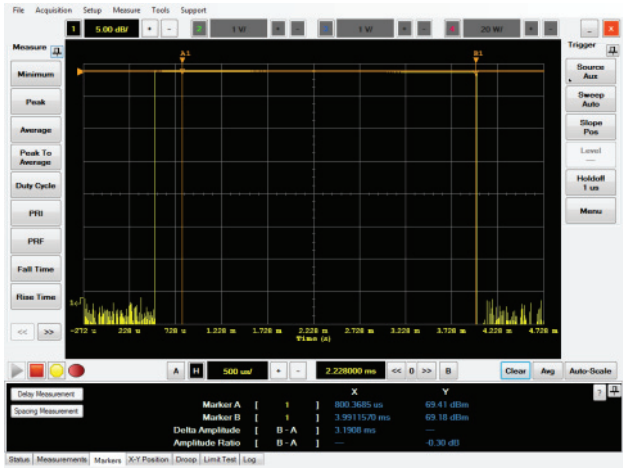
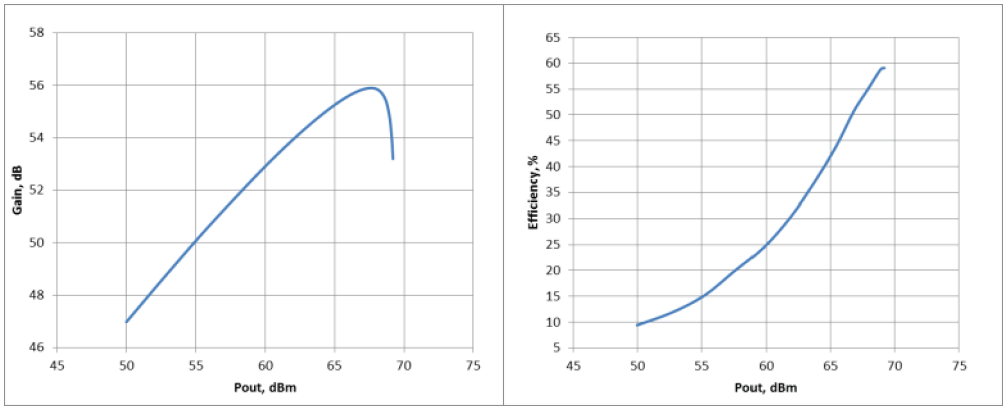
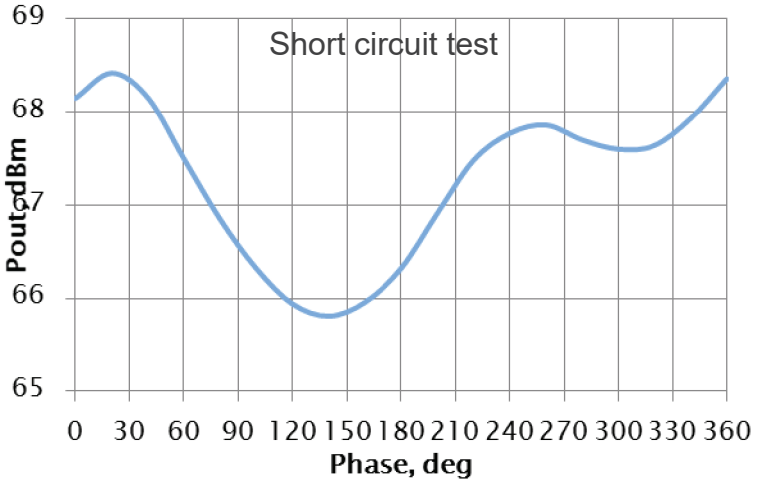
3.5 ms pulse shape at 8 kW

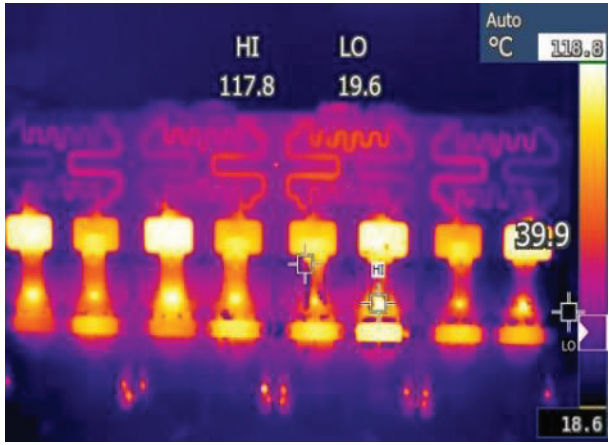


Gain and PAE dependence on Pout



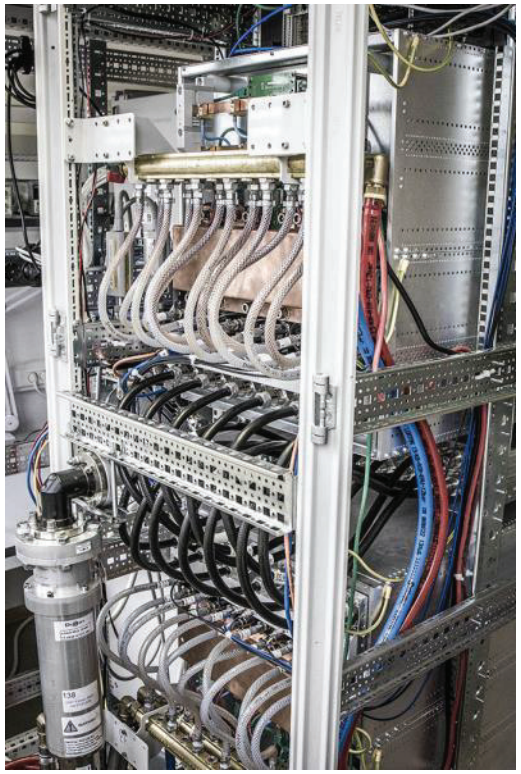


Heat dissipation at full reflection with “worst” phase



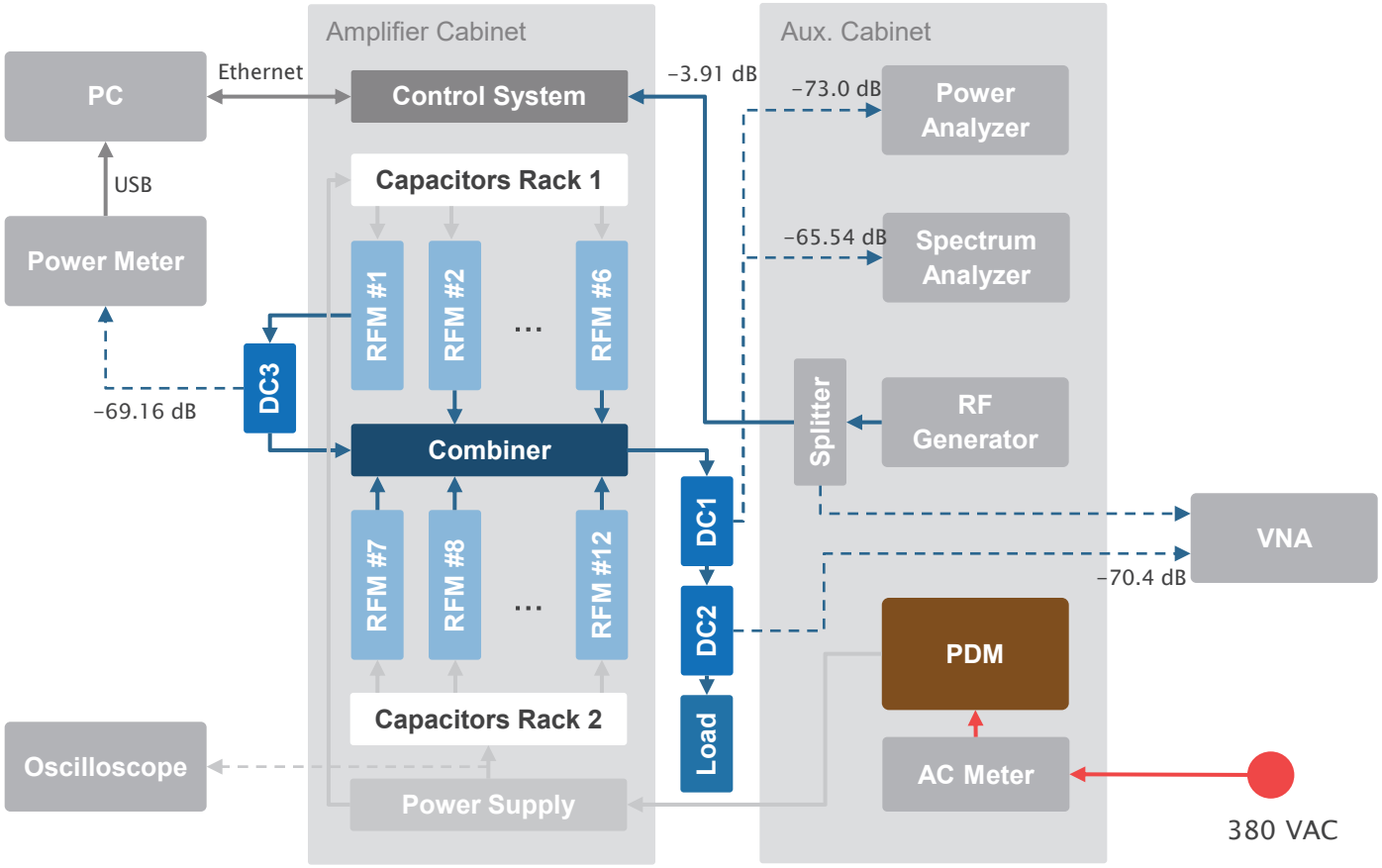
Assembled System Under Test Stand

Front view of the amplifier cabinet and aux. cabinet with measurement equipment

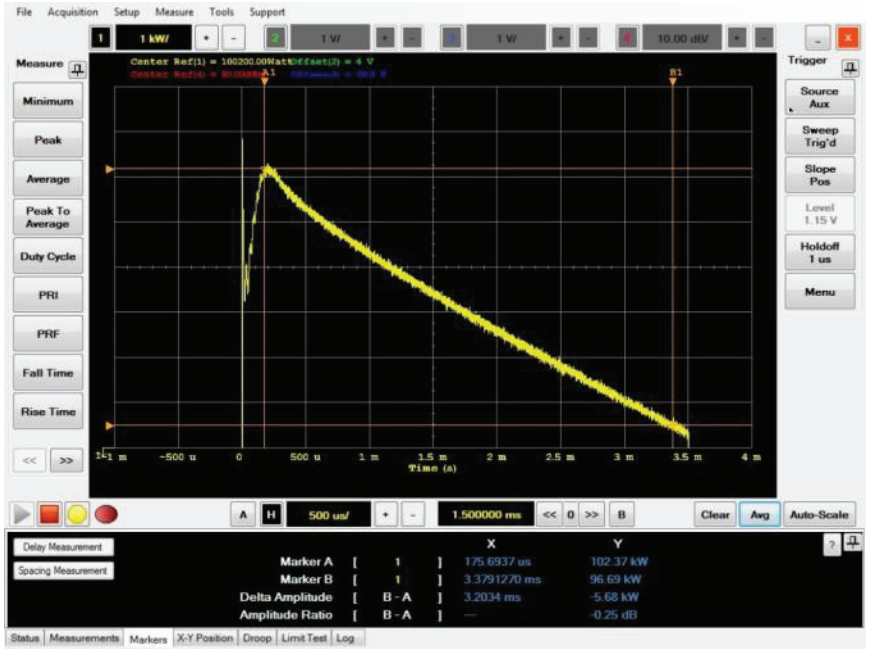


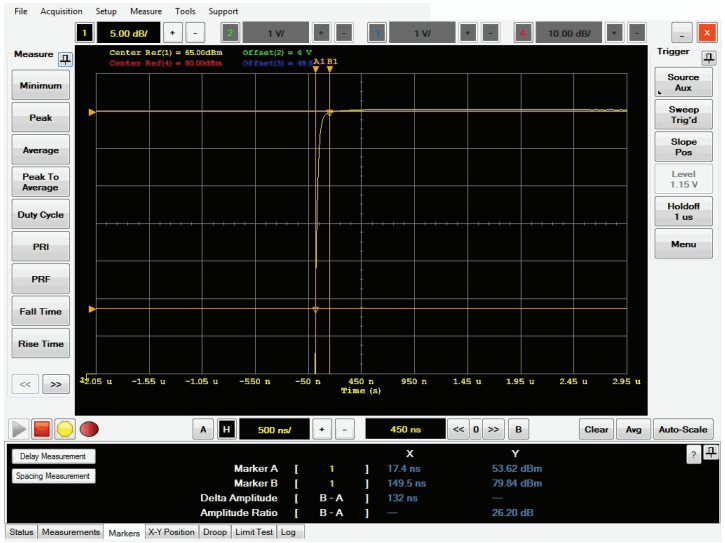
Back view of the amplifier cabinet with connected dummy load

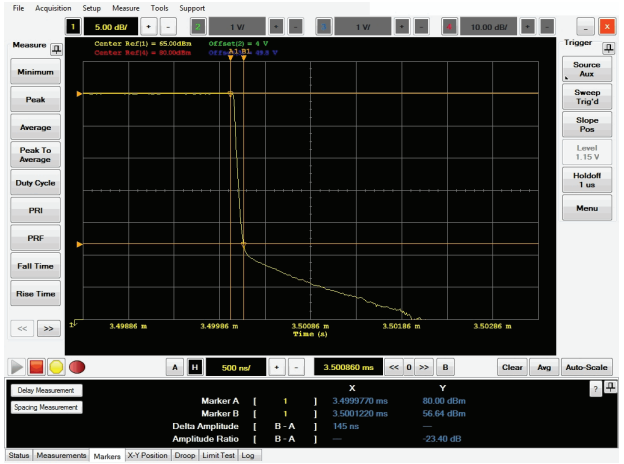
Test Stand Arrangement and Connections



Test Results. Pulse Shape



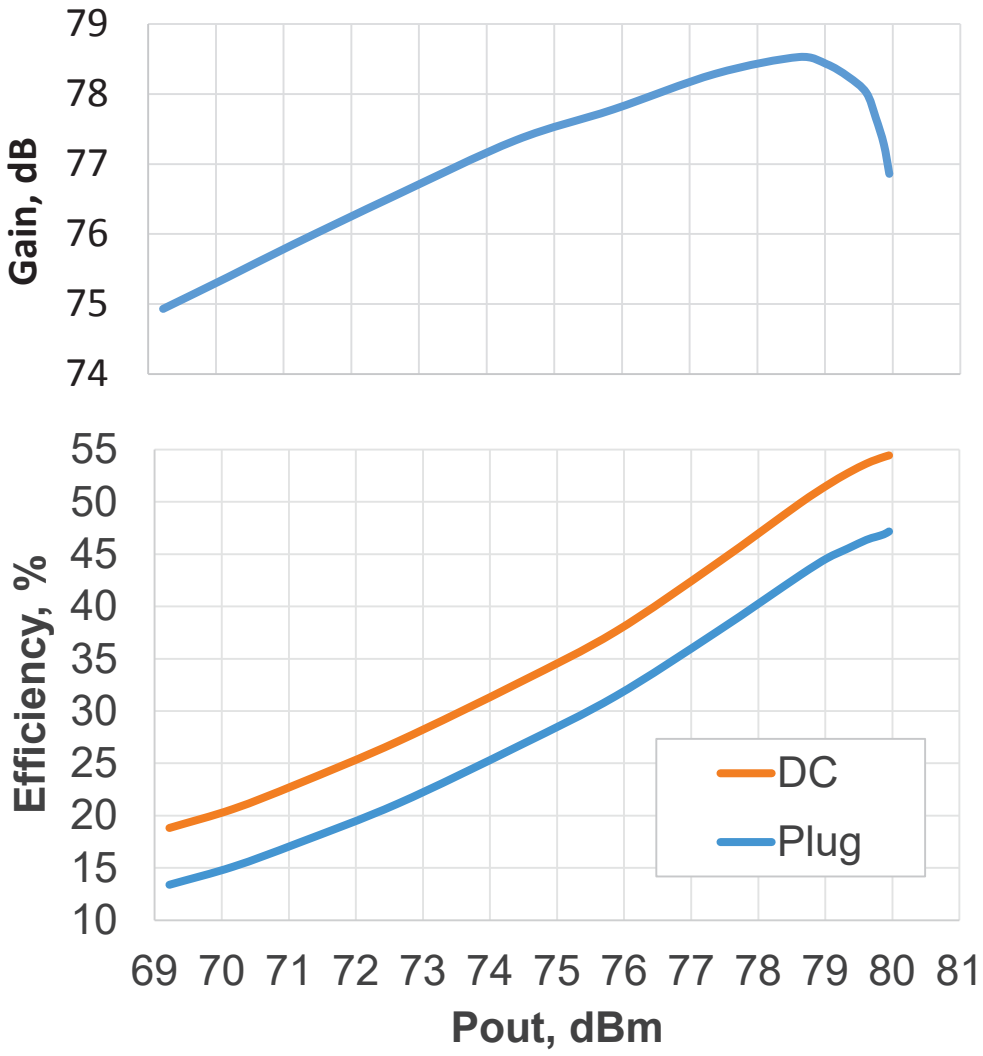




Rise time is 100 ns*
Fall time is 36 ns*
Pulse flat top drop during pulse is ~5%

* Measured within 10-90% boundaries
** Pulse leading edge overshot and falling edge trailing tail are caused by RF generator behavior

Test Results. Gain and Efficiency



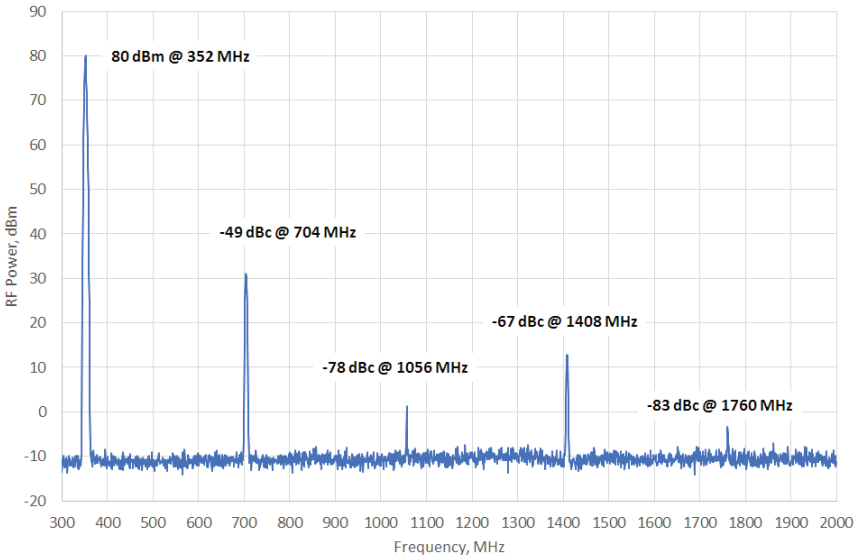
RF amplifier gain is better than **75 dB** for 10-100 kW output RF power range

RF amplifier plug efficiency at 100 kW output RF power is **47%** (DC efficiency is 55%)

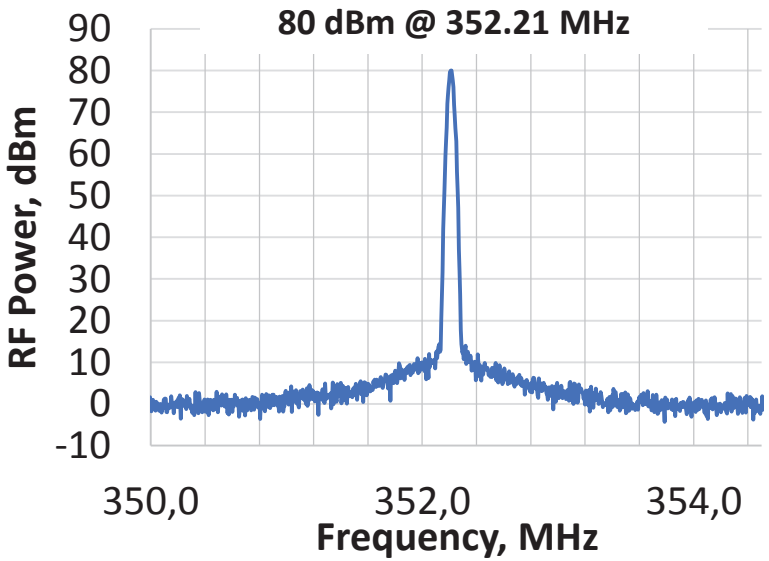
Plug efficiency value include continuous power consumption (~**700 W**) for supporting subsystems like control system (~100 W), power supply unit (~350 W), and measurement detectors (~250 W)

Test Results. Spectrum

RF amplifier spectrum at 100 kW

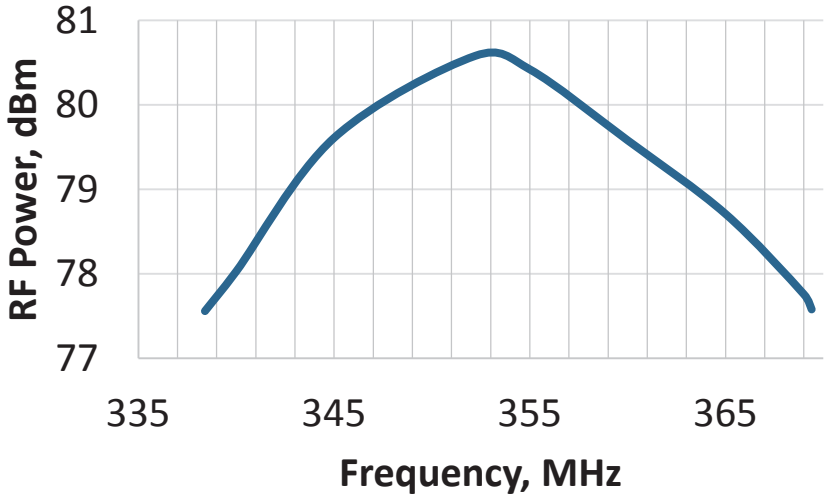


Harmonics are better than -49 dBc

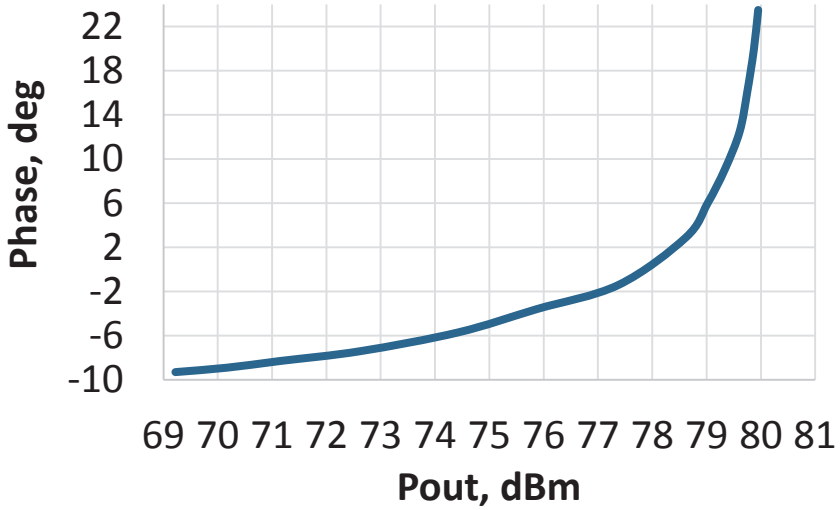


Spurious are better than -65 dBc

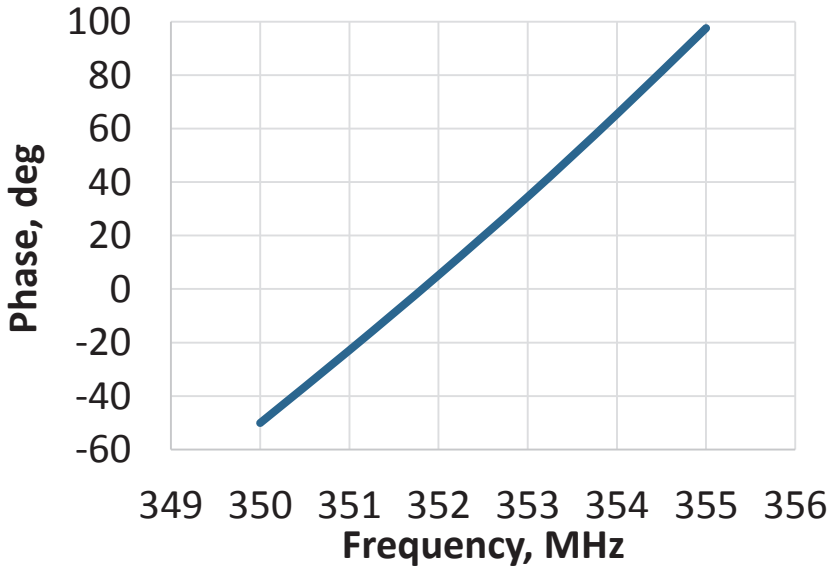
Test Results. Output Power and Phase Dependencies



-3dB bandwidth is ±15.5 MHz



Phase dependencies on output RF power and frequency



Conclusion

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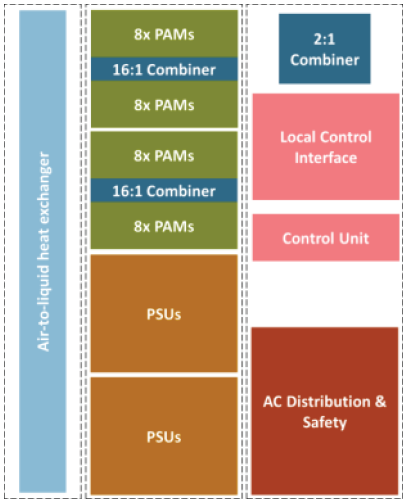
Achieved results

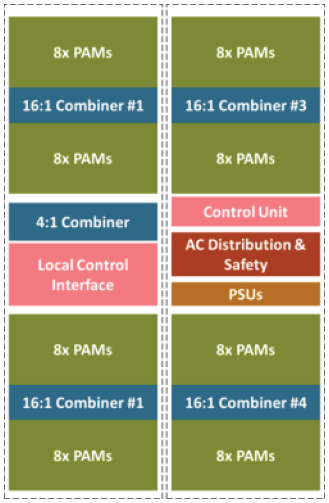
- Output power up to 104 kW (3.5 ms pulse, 5% duty cycle)
- Plug efficiency of 47% at 100 kW of RF power
- Harmonics are less than -49 dBc
- Spurious are less than -65 dBc
- -3dB bandwidth is ±15.5 MHz
- Pulse rise time is 100 ns, fall time is 36 ns
- Pulse drop during 3.5 ms pulse is about 5%
- Operation without circulators

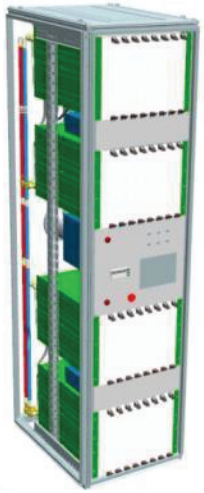
3G SSPA Design examples

60 kW
186 MHz
CW



250 kW
202 MHz
pulsed





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THANK YOU FOR ATTENTION!