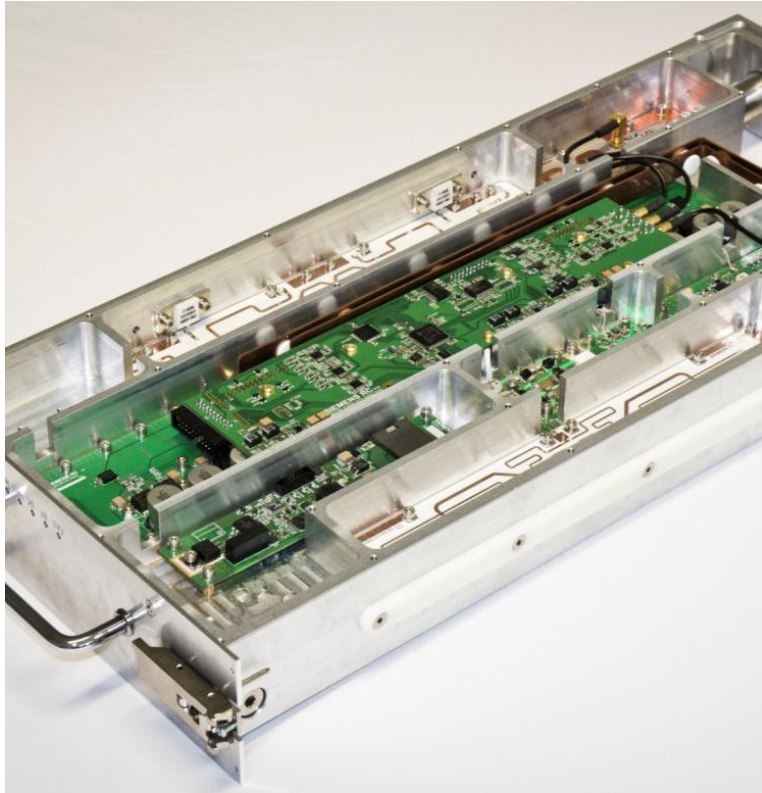


100 kW Very Compact Pulsed Solid-state RF Amplifier

Development and tests

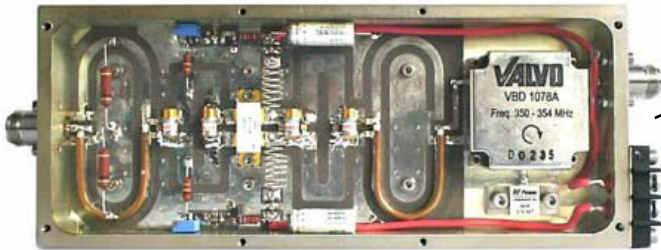
Summary



- SSPA technology
- 352 MHz Amplifier design
- 352 MHz Amplifier test results

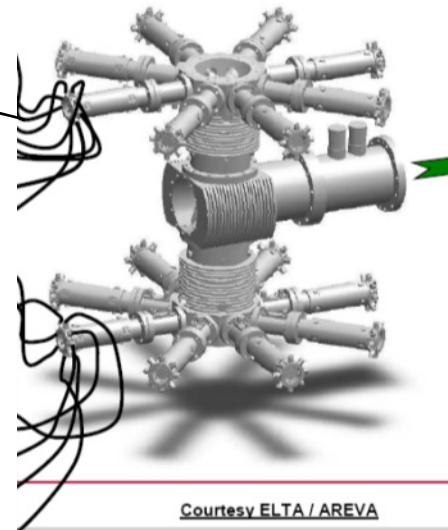
Solid-State RF State-of-the-art

RF module



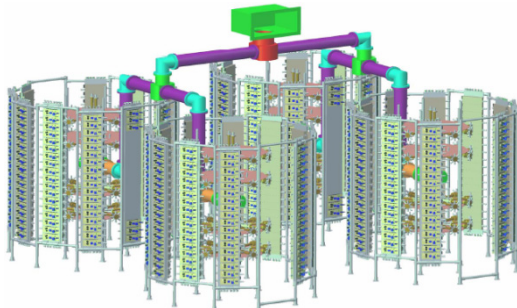
- Standard 300-600 W RF boards with one transistor – copies from evaluation boards
- Tuned by hand matching circuits
- Circulators (lose 5% to 7% efficiency)

Power combiner



Courtesy ELTA / AREVA

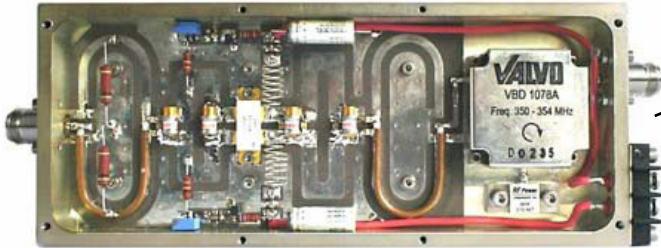
- Cascading architecture with >100 inputs
- Lose ~ 0.5% efficiency @ each cascade
- Impedance between cascades tuned “by hand”
- Broken modules drop efficiency significantly



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

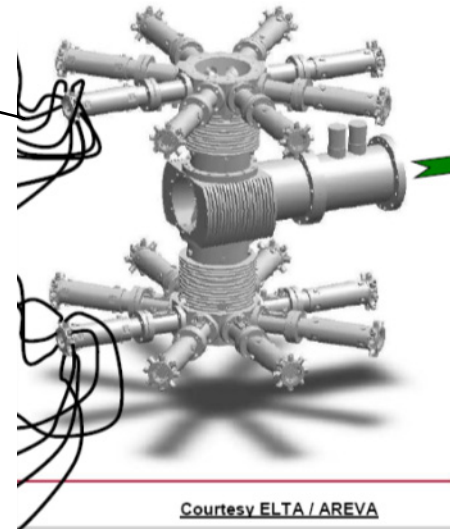
Solid-State RF State-of-the-art

RF module



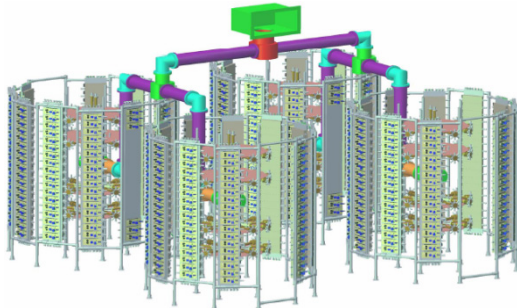
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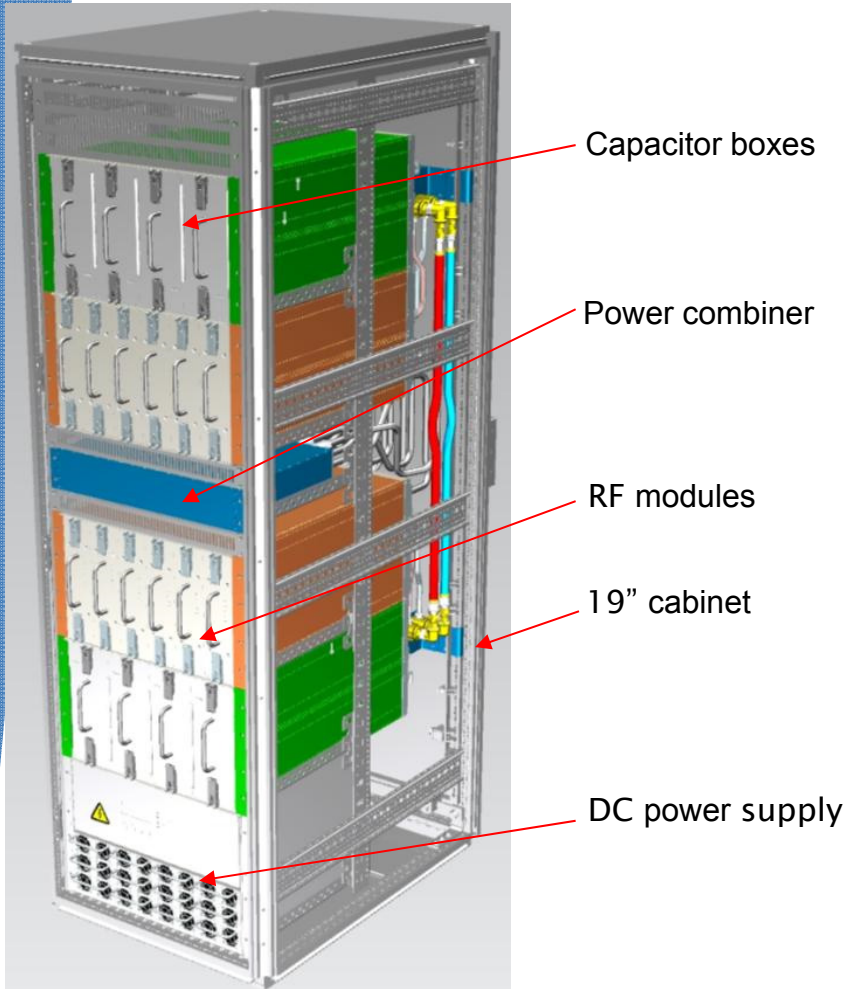
Courtesy ELTA / AREVA

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- High cost

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/m²)
- Cost effective
- Turnkey
- Highly scalable for power, frequency, Pulse and CW applications

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

352 MHz Amplifier for ESS Spokes

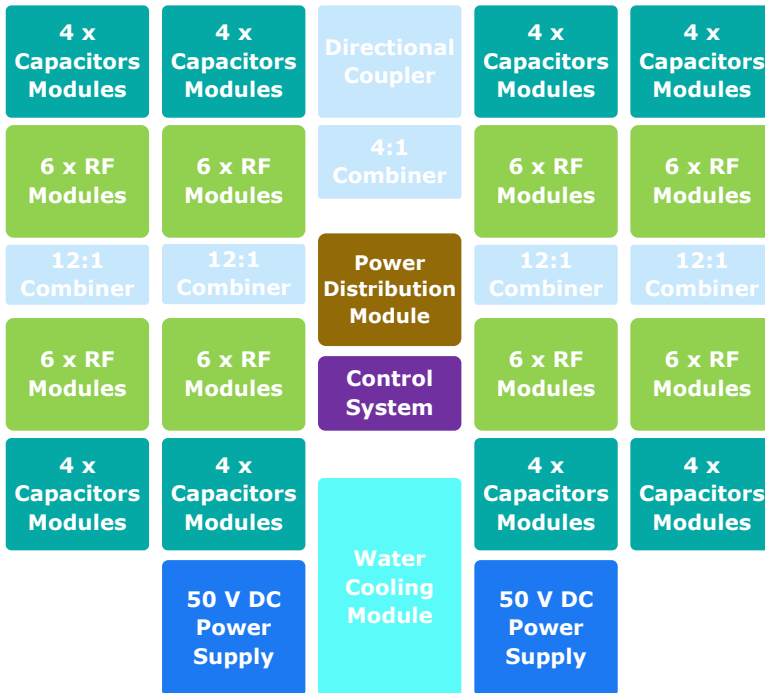
352.21 MHz, 400 kW

3.5 ms pulse

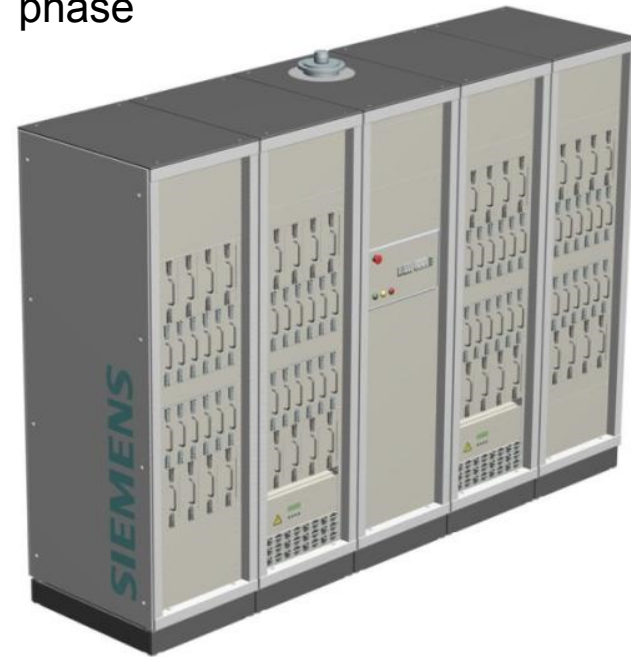
14 Hz repetition rate

5% d.c.

Withstands full reflection at any phase



Modules arrangement in cabinets



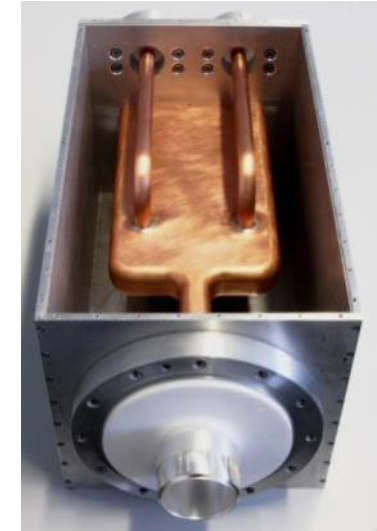
352 MHz system external view



High RF Power Components



12:1 power combiners



4:1 power combiner



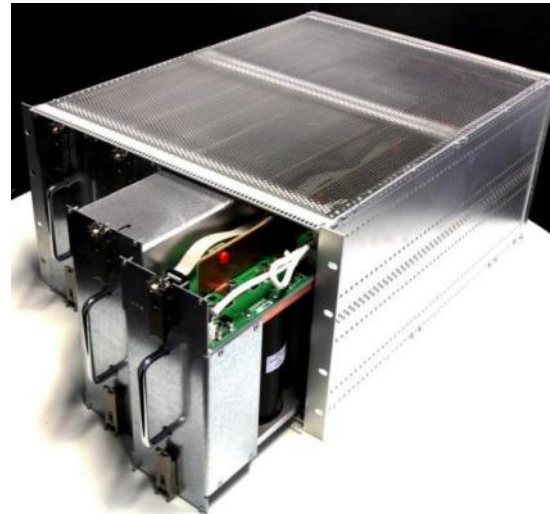
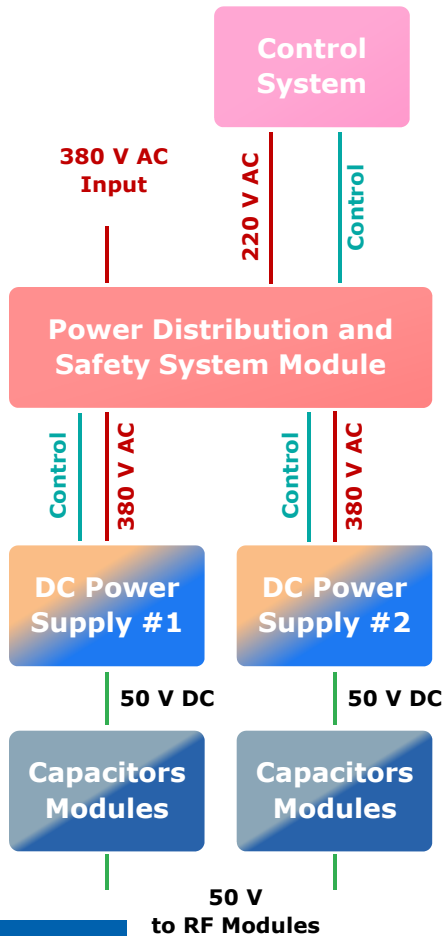
Bi-directional coupler

Development status

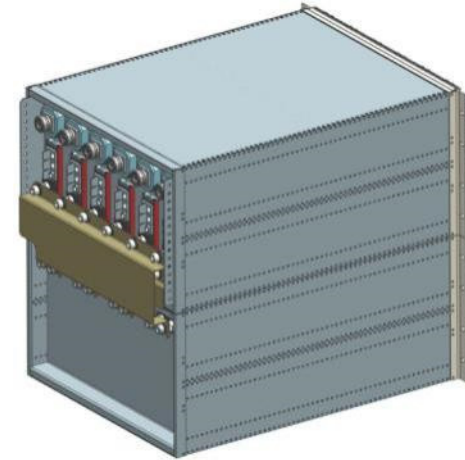
- 4x 12:1 RF power combiners manufactured, measured, and tuned
- 4:1 RF power combiner manufactured, measured, and tuned. Losses are less than 1%
- Bi-directional coupler manufactured, measured, and tuned
- All coaxial waveguide components are delivered and assembled

Power Supply System

Power supply system connections



4x Capacitors Modules Box



C bus connection between capacitors and RF modules

Development status

- 8x boxes with dock-stations delivered and assembled with quick-connectors
- Capacitors Modules assembled and tested at nominal power
- Power Distribution Module assembled

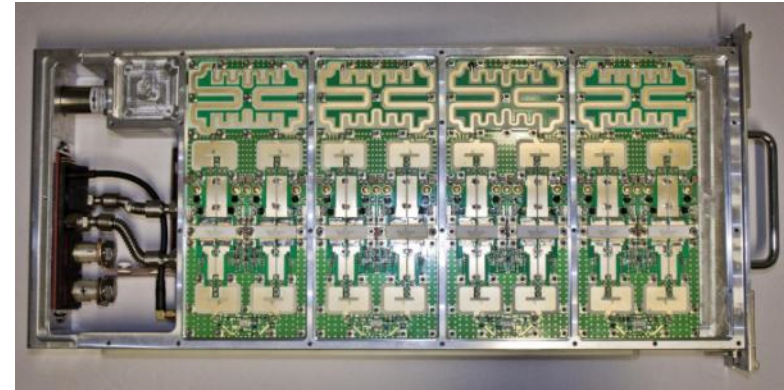
Design advantage

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

RF Modules

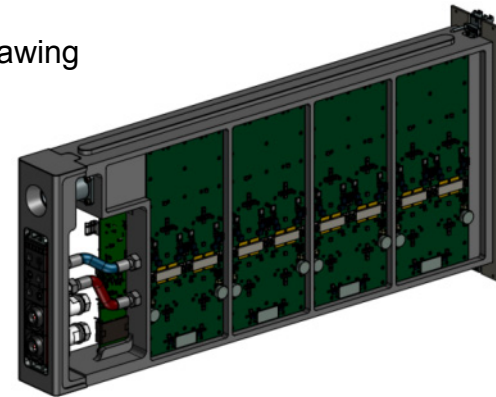


6x RF Modules dock-station
(front and back view)



RF Module test assembly with 4x 2 kW PA units

RF Module drawing

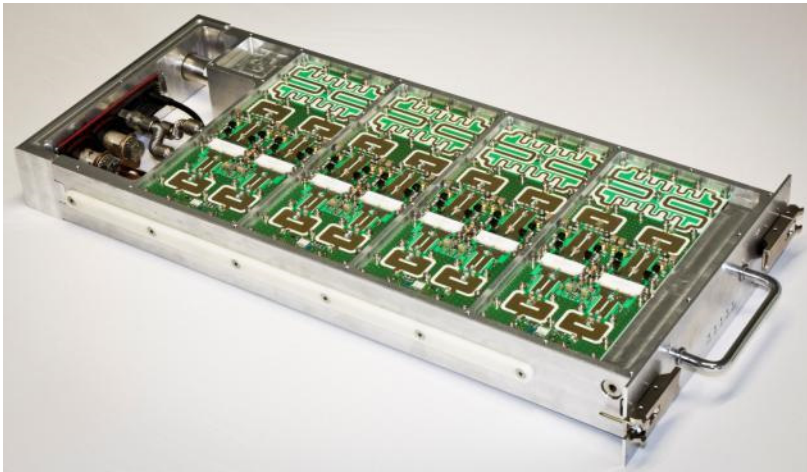
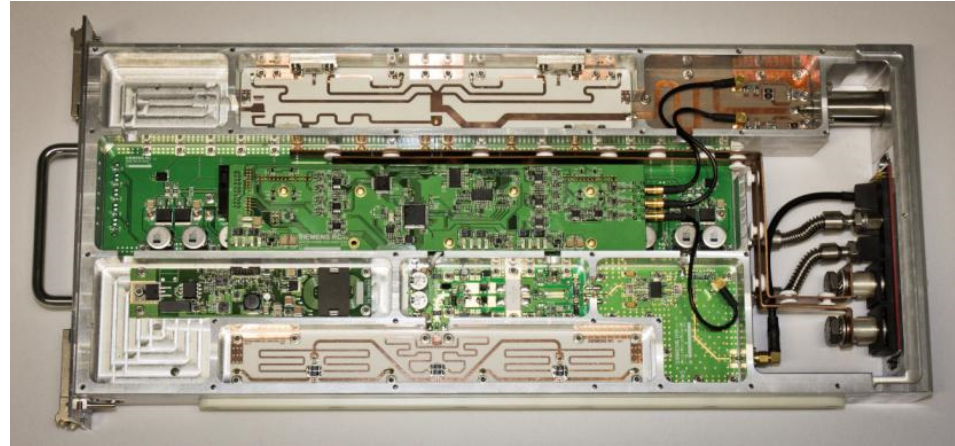


Design advantage

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

352MHz RF Module Series prototype

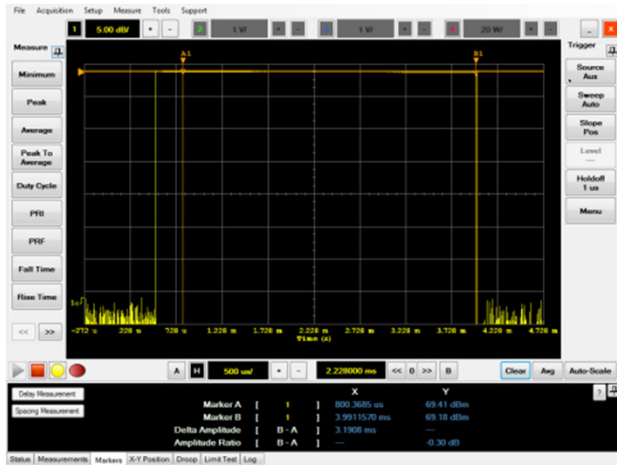
- 4 x2 transistor pallets
- Input/output splitter/combiner
- DC distribution
- MCU, power detectors
- RF switches inside the module
- Production for 100 kW subunit completed



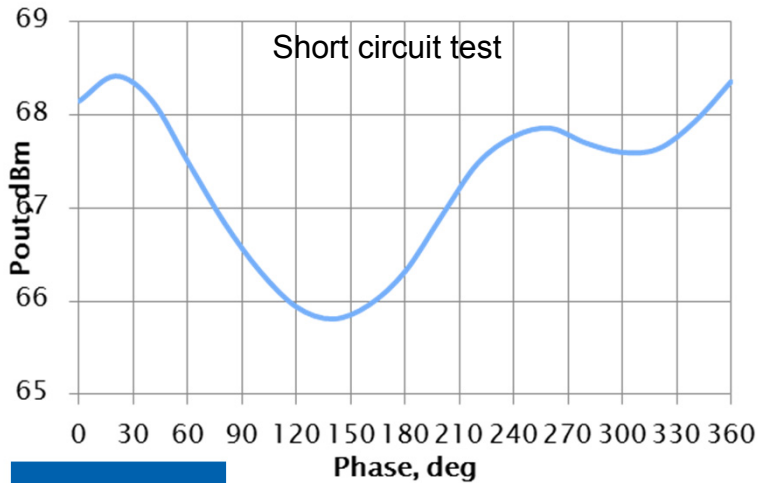
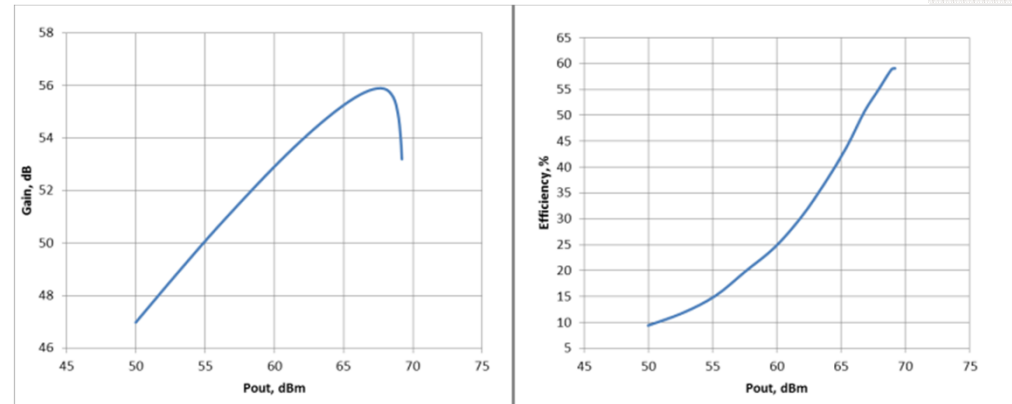
352MHz RF Module

Series prototype tests

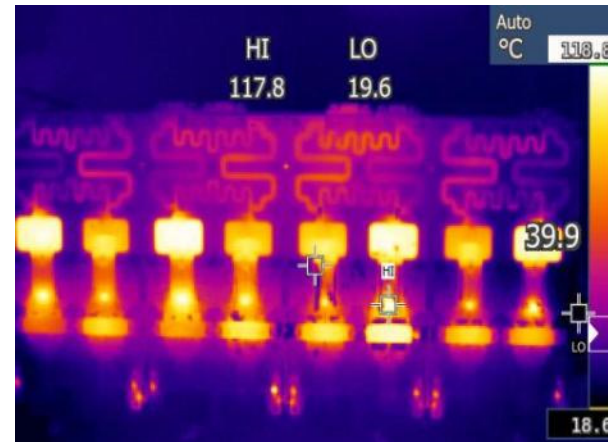
3.5 ms pulse shape at 8 kW



Gain and PAE dependence on Pout



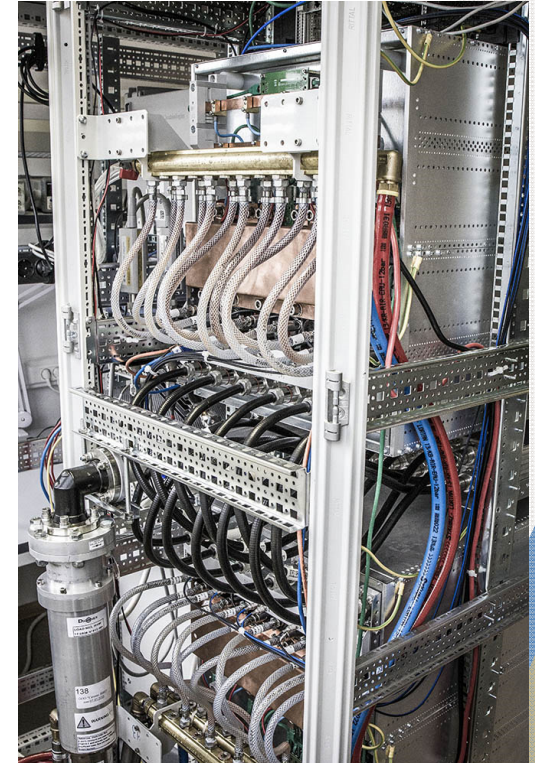
Heat dissipation at full reflection with "worst" phase



Assembled System Under Test Stand

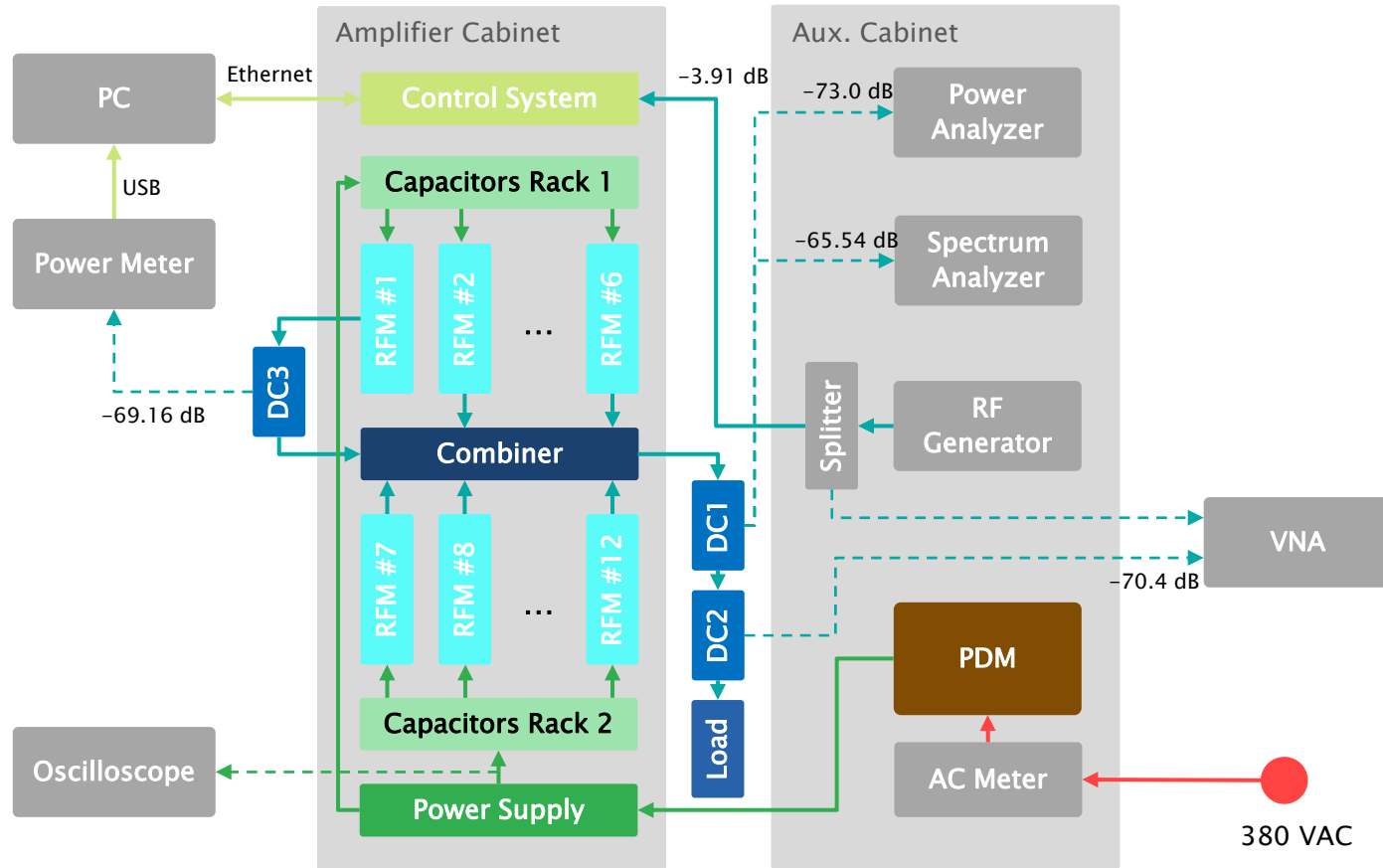


Front view of the amplifier cabinet and aux. cabinet with measurement equipment



Back view of the amplifier cabinet with connected dummy load

Test Stand Arrangement and Connections



Control System Web-Interface

Control panel

RFMs DC control

Water Valve

System status

Readings

Frequency	
Power	
Forward	
Reflected	
Gamma	
Fault Gamma Num	

Signal readings

	Mag	Phase
In	42567	20019
Fwd	43583	20079
Ref	1451	19751
Aux	43111	20082

System settings

System status

#1	#2	#3	#4
●	●	●	●
●	●	●	●
●	●	●	●

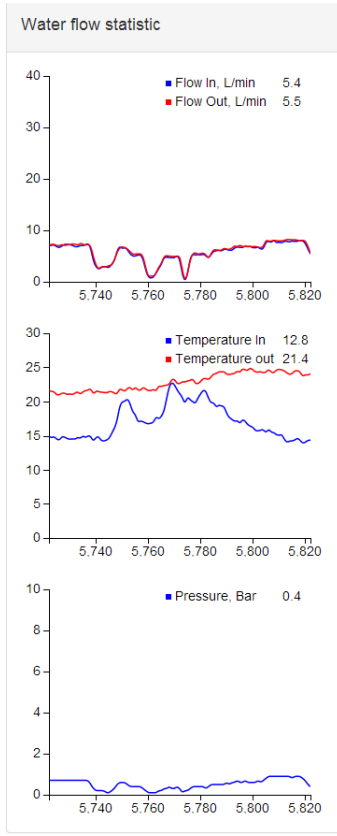
#1	#2	#3	#4	#5	#6
8318	8318	8128	8128	8710	7943
182	331	245	209	501	380

Input:	15.4	15.0	15.5	15.8	15.9	15.6
Curr:	276.4	267.4	279.4	276.5	271.2	282.6
Temp:	27.7	26.4	26.4	27.1	26.1	28.4
Vltge:	46.6	48.1	47.5	47.5	47.3	47.6
PWR	●	●	●	●	●	●
DC	●	●	●	●	●	●
RF	●	●	●	●	●	●
FAIL	●	●	●	●	●	●

#1	#2	#3	#4	#5	#6
8511	8128	8913	7943	8511	8318
214	214	224	1	282	229

Input:	15.2	15.9	15.8	15.9	16.8	15.8
Curr:	269.8	272.8	267.6	262.6	274.7	274.5
Temp:	26.0	26.4	27.4	25.9	25.9	27.6
Vltge:	47.8	47.5	48.2	47.1	47.7	47.6
PWR	●	●	●	●	●	●
DC	●	●	●	●	●	●
RF	●	●	●	●	●	●
FAIL	●	●	●	●	●	●

#1	#2	#3	#4
●	●	●	●
●	●	●	●
●	●	●	●



RF amplifier web-interface screenshot at 100 kW

RF modules reflection values are caused by RF power combiner inputs VSWR values



Test Results. Pulse Shape



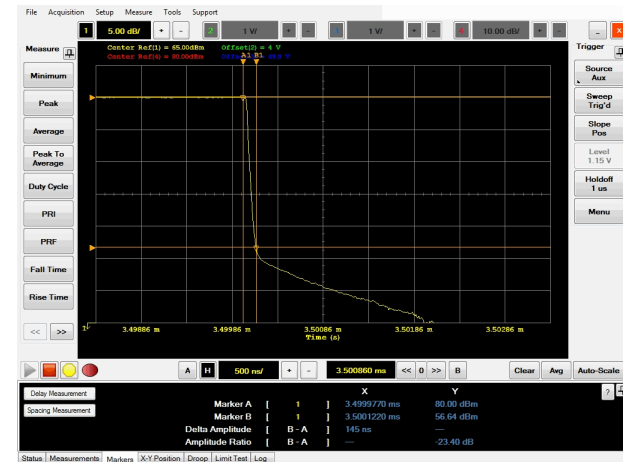
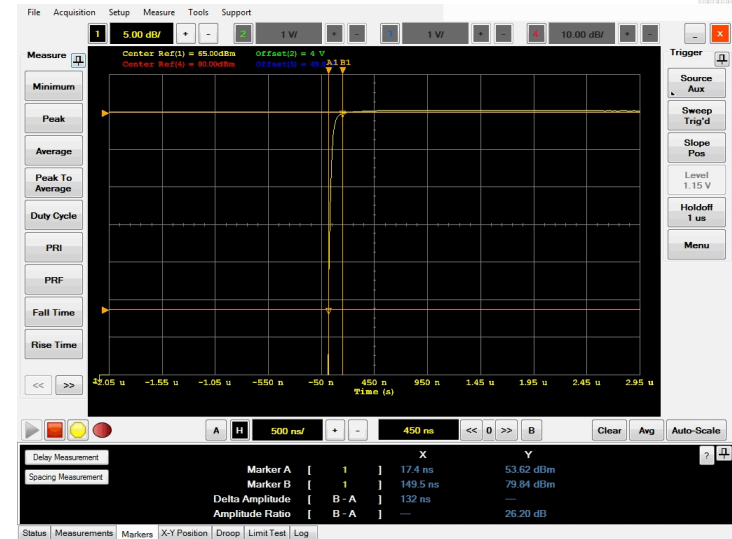
Rise time is 100 ns*

Fall time is 36 ns*

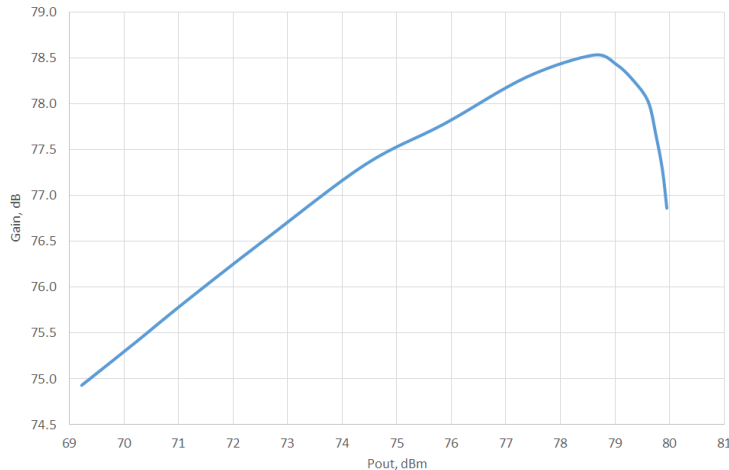
Pulse flat top drop during pulse is ~5%

* Measured within 10-90% boundaries

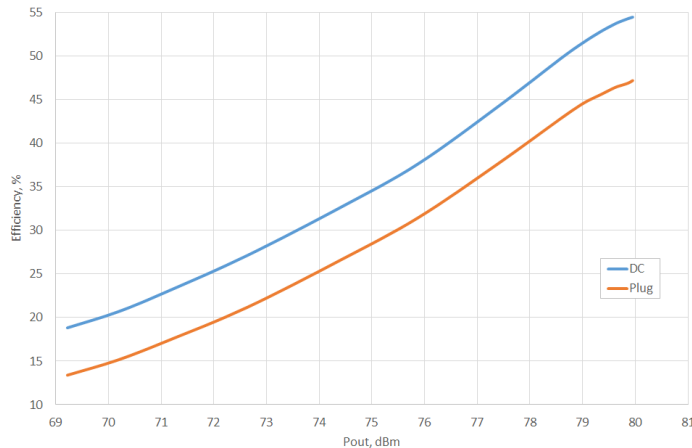
** Pulse leading edge overshoot and falling edge trailing tail are caused by RF generator behavior



Test Results. Gain and Efficiency



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

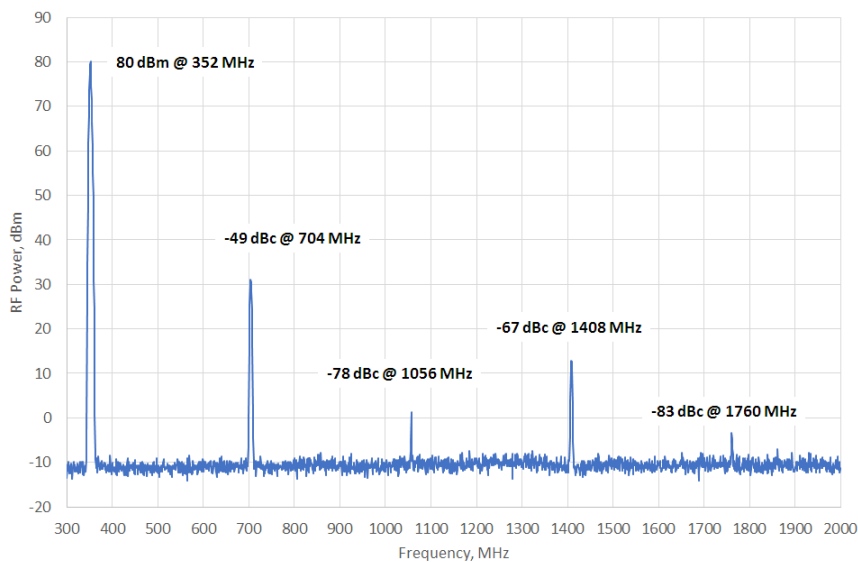


RF amplifier plug efficiency at 100 kW output RF power is **47%** (DC efficiency is 55%)

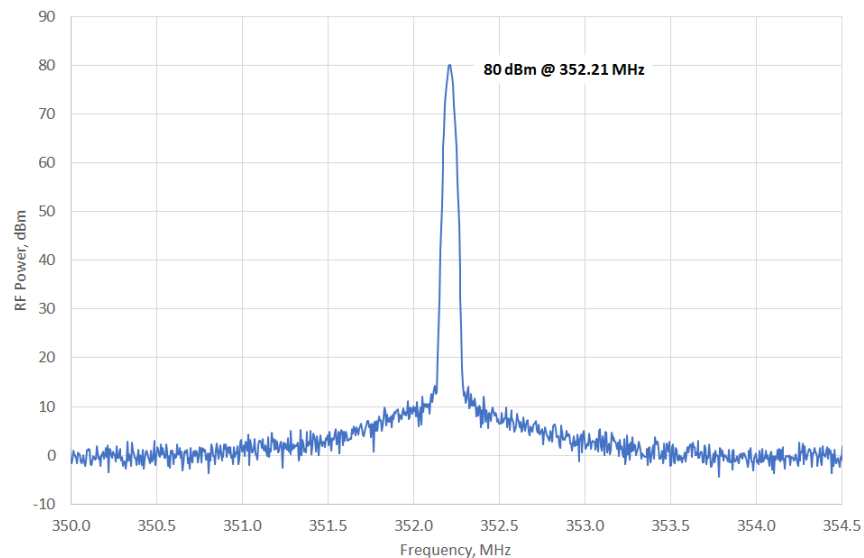
Plug efficiency value include continuous power consumption (~700 W) for supporting subsystems like control system (~100 W), power supply unit (~350 W), and measurement detectors (~250 W)

Test Results. Spectrum

RF amplifier spectrum at 100 kW

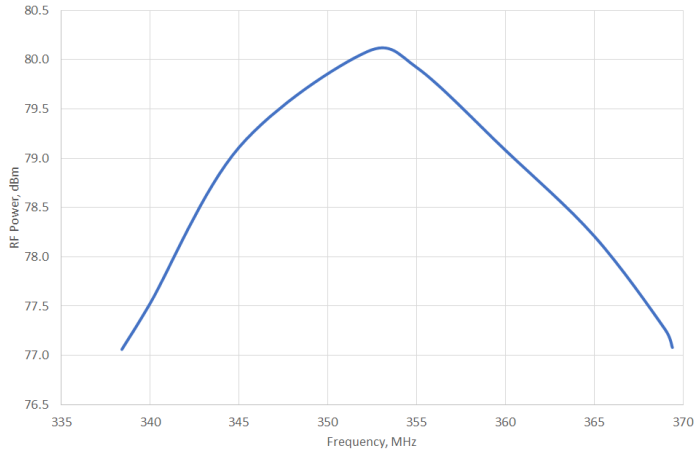


Harmonics are better than -49 dBc



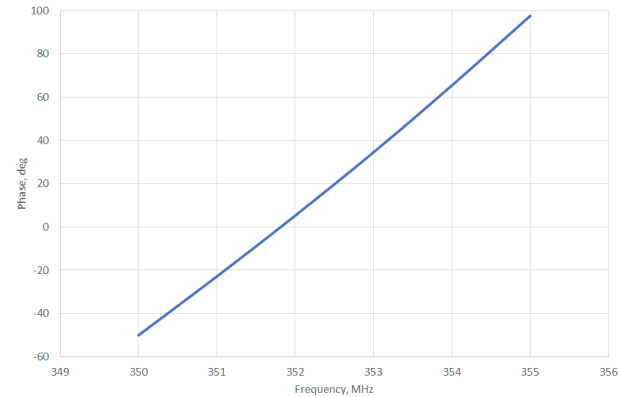
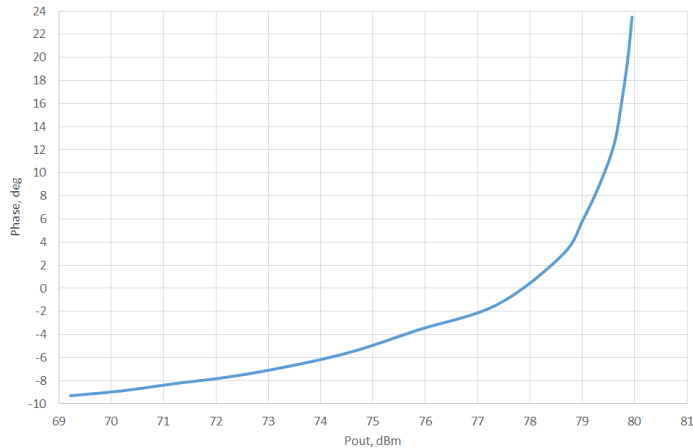
Spurious are better than -65 dBc

Test Results. Output Power and Phase Dependencies



-3dB bandwidth is ± 15.5 MHz

Phase dependencies on output RF power and frequency



Conclusion

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

Acknowledgements

Considerable thanks are due to the design team lead by:
Stepan Polikhov and Georgy Sharkov at NIITFA / Rosatom

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