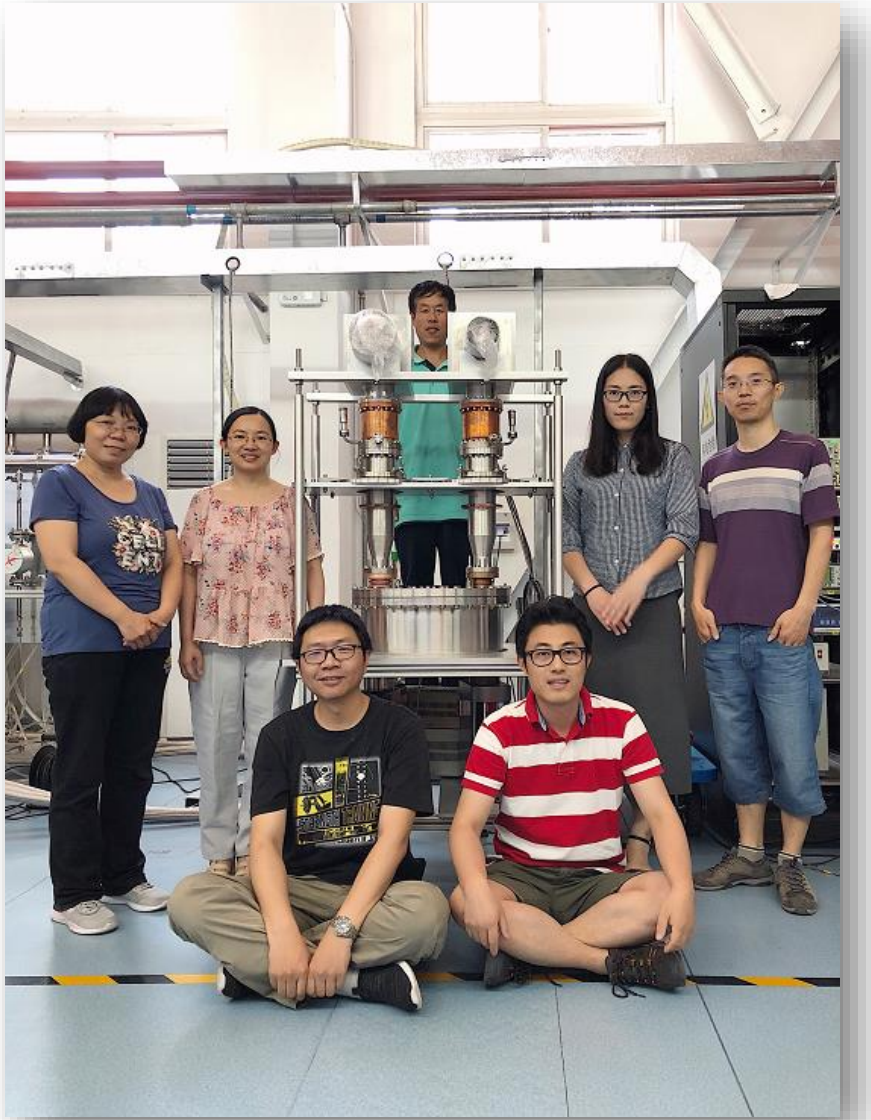
The HPRF system for a new 6 GeV synchrotron light source in Beijing

Pei Zhang
(RF group, IHEP)

The HEPS HPRF team



Power coupler & power source

Researcher (3): T.M. Huang, W.M. Pan, P. Zhang

Engineer (3): Q. Ma, H.Y. Lin, Q.Y. Wang

Technician (1): L.S. Feng

Postgraduate (2): F. Bing, Y.L. Luo

Outline

- HEPS
- HPRF for HEPS main ring (166MHz)
- HPRF for HEPS booster (500MHz)
- Power coupler
- Summary & Questions

High Energy Photon Source

The new light source in 7 years

Location in Beijing

HEPS

IHEP campus

Beam parameters

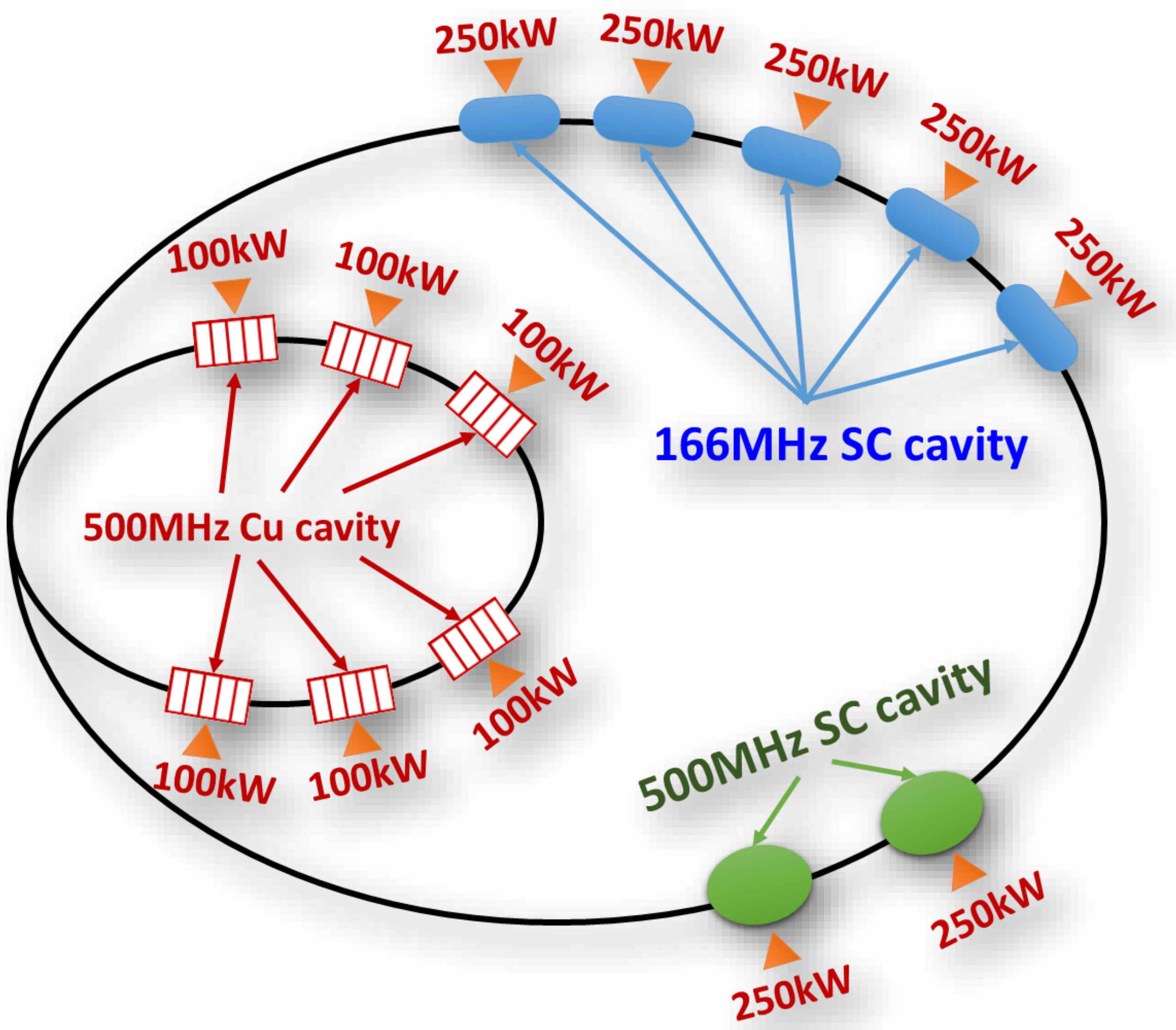
High **E**nergy **P**hoton **S**ource (**HEPS**)

Energy	6 GeV
Circumference	~1300 m
Beam Current	200 mA
Natural emittance	<60 pm·rad
U_0 (w/ ID)	4.5 MeV
Total SR power	900 kW

2016 – 2018 HEPS-TF: R&D phase

2018 – 2025 HEPS (CD0 passed, CD1 review soon)

RF system



Fundamental SRF (SR)

- RF frequency: 166.6 MHz
- RF voltage in total: 5.5 MV
- Min. power per cavity: 180 kW

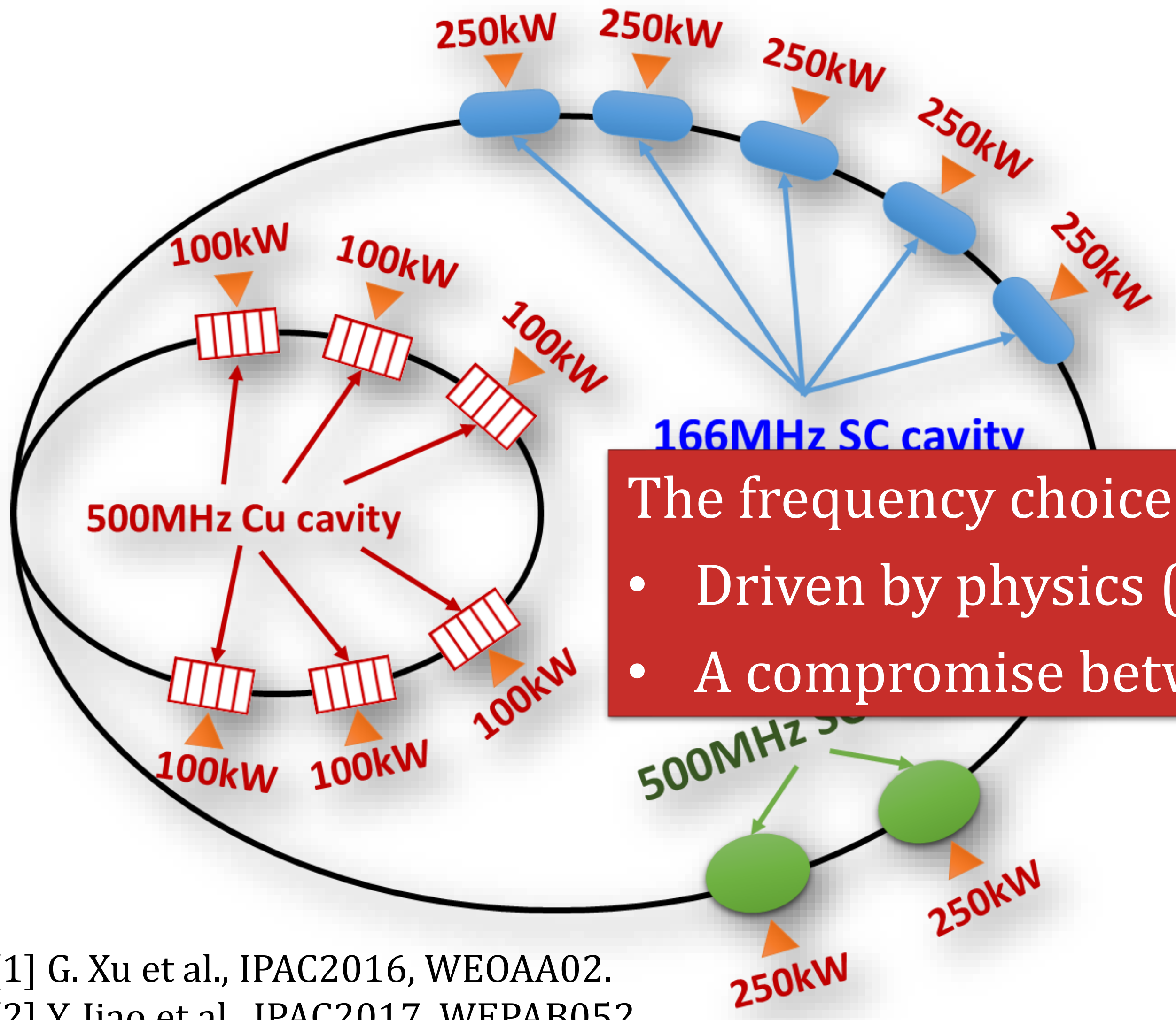
Third harmonic SRF (SR)

- RF frequency: 499.8 MHz
- RF voltage in total: 1 MV/3.2 MV
- Passive/Active cavity

Booster NC RF

- RF frequency: 499.8 MHz
- RF voltage in total: 8 MV
- Min. power per cavity: 80 kW

RF system



The frequency choice was

- Driven by physics (mainly injection scheme)
- A compromise between kicker and RF

Fundamental SRF (SR)

- RF frequency: 166.6 MHz
- RF voltage in total: 5.5 MV
- Min. power per cavity: 180 kW

Third harmonic SRF (SR)

- RF frequency: 499.8 MHz
- /3.2 MV

Booster NC RF

- RF frequency: 499.8 MHz
- RF voltage in total: 8 MV
- Min. power per cavity: 80 kW

[1] G. Xu et al., IPAC2016, WEOAA02.
[2] Y. Jiao et al., IPAC2017, WEPAB052.

Power source

Accelerator	Frequency	Technology	RF power /station	# of RF station	Total RF power
Main ring	166.6 MHz	Solid-state	250 kW	5	1.25 MW
	499.8 MHz		250 kW (active) ~10 kW (passive)	2	500 kW 20 kW
Booster	499.8 MHz		100 kW	6	600 kW

- **Technology readiness**

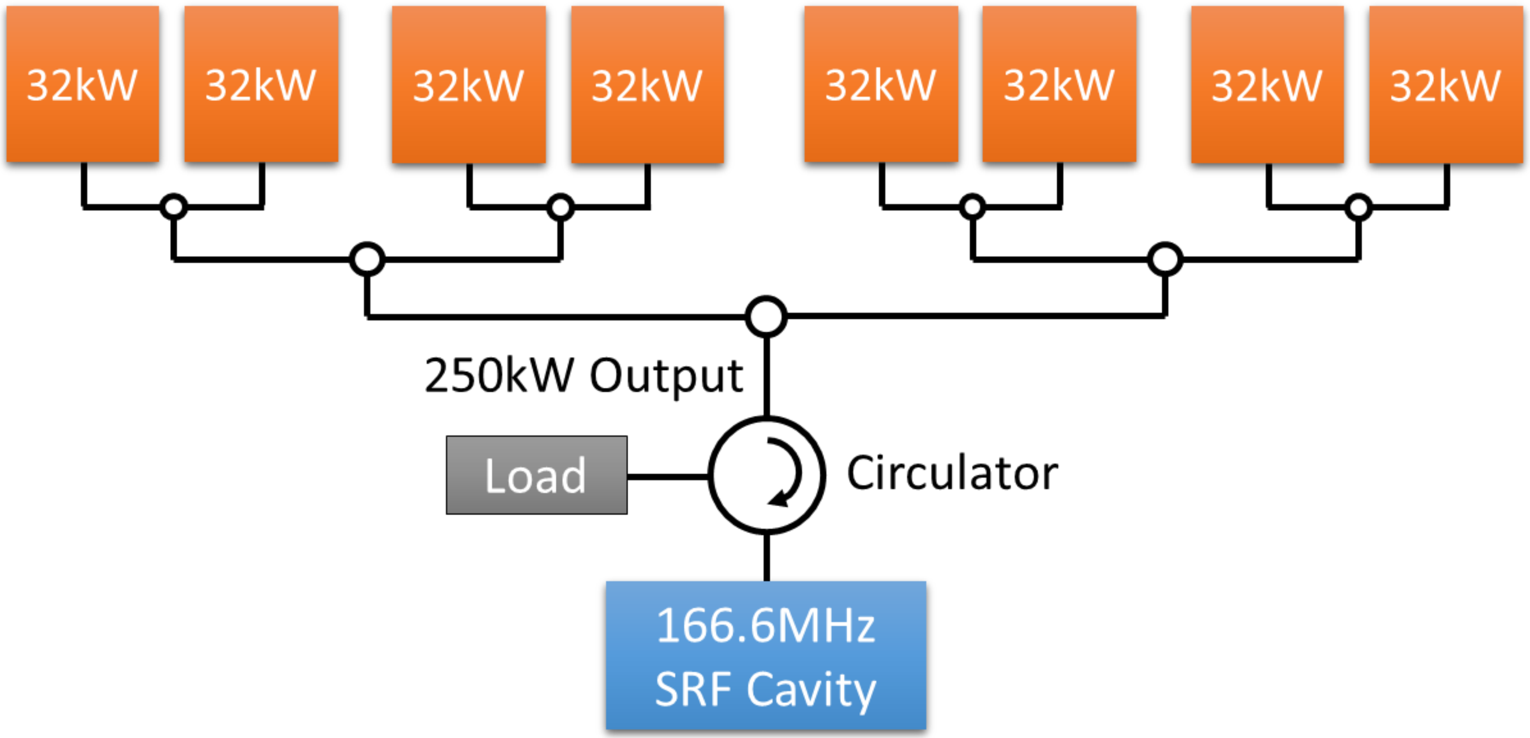
  - 166MHz: broadcasting and television frequency

  - 500MHz: popular frequency for light sources

166.6MHz SSPA

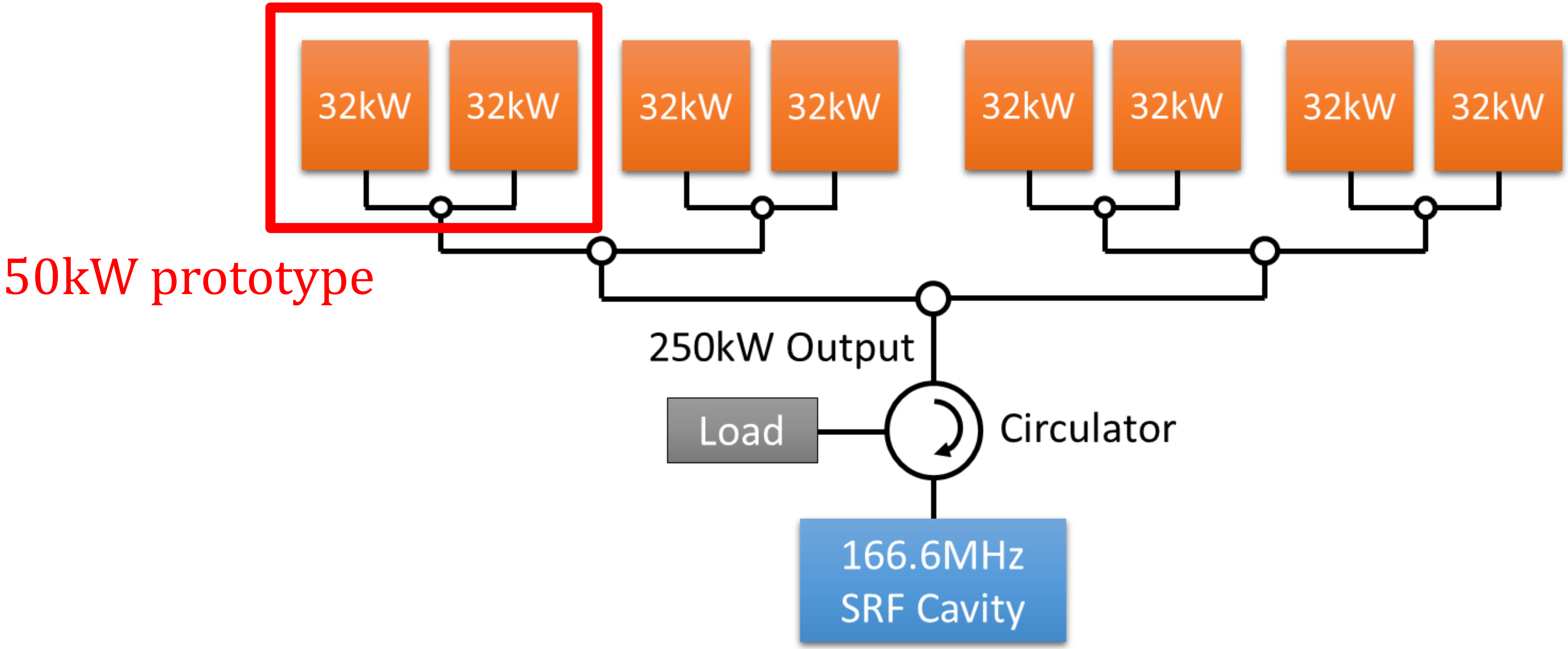
Architecture

- 4-stage coaxial combiner following the 1st stage strip-line combiner
- Final stage circulator between cavity and SSPA



Architecture

- 4-stage coaxial combiner following the 1st stage strip-line combiner
- Final stage circulator between cavity and SSPA

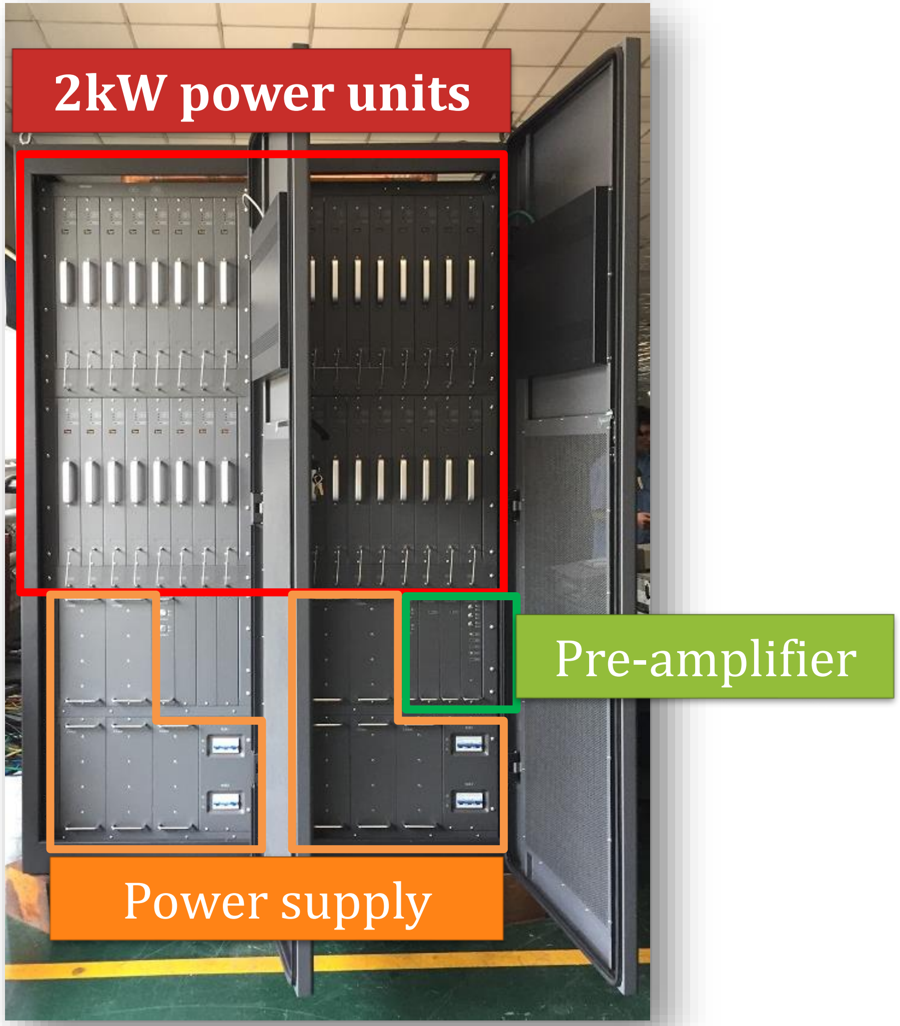


166.6MHz 50kW prototype

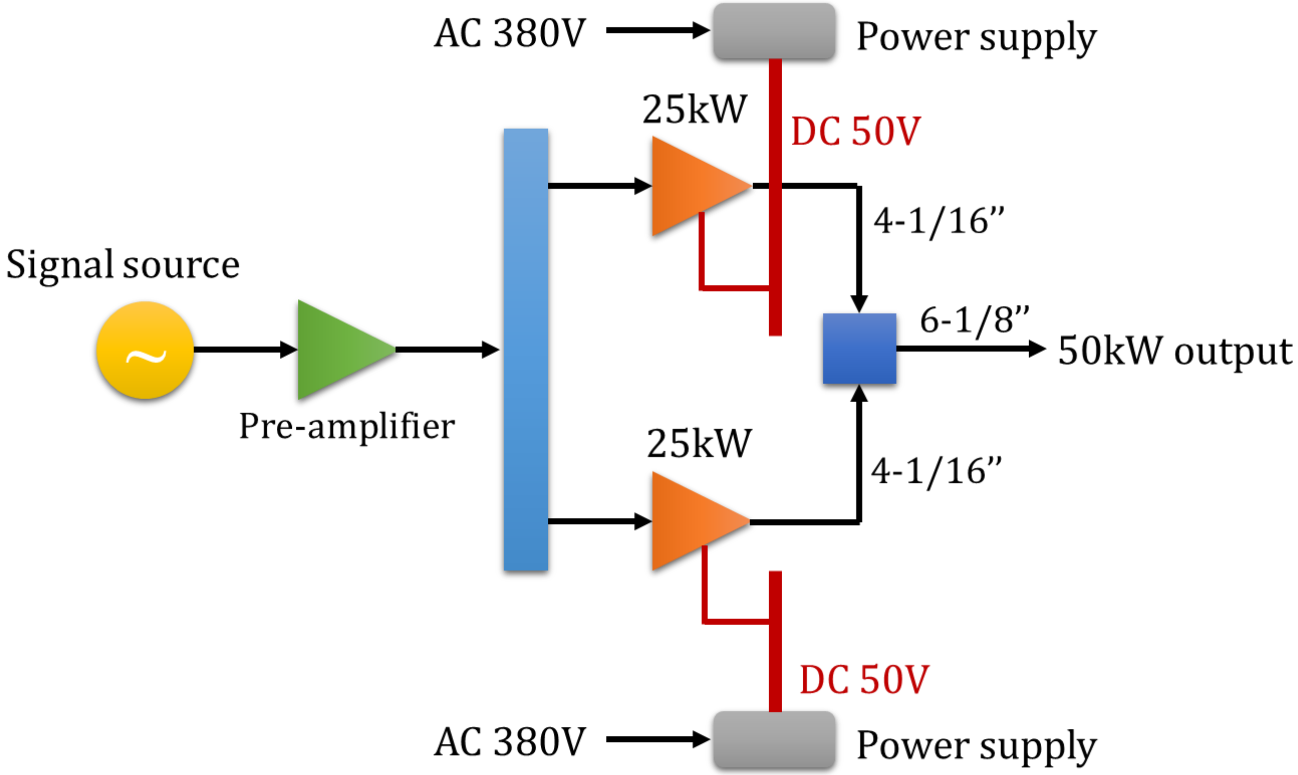
成都凯腾四方数字广播电视设备有限公司
Chengdu Weingarten Quartet digital radio and Television Equipment Company Limited

07.2016	Call for tender
08.2016	Contract awarded to KTSF630
02.2017	2kW unit passed factory acceptance test
06.2017	50kW SSPA passed factory acceptance test
08.2017	Reception at IHEP
10.2017	50kW SSPA passed final tests

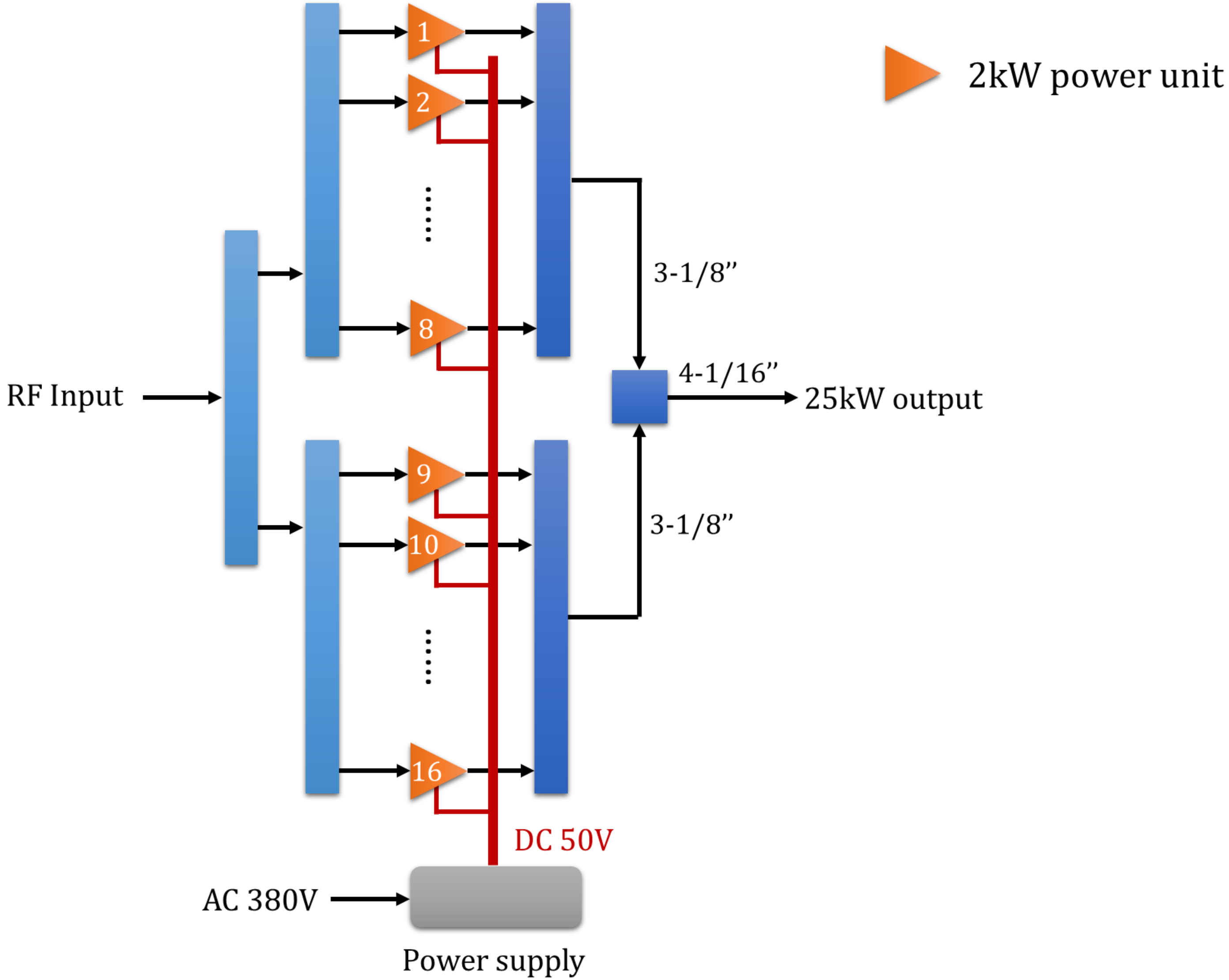
166.6MHz 50kW prototype



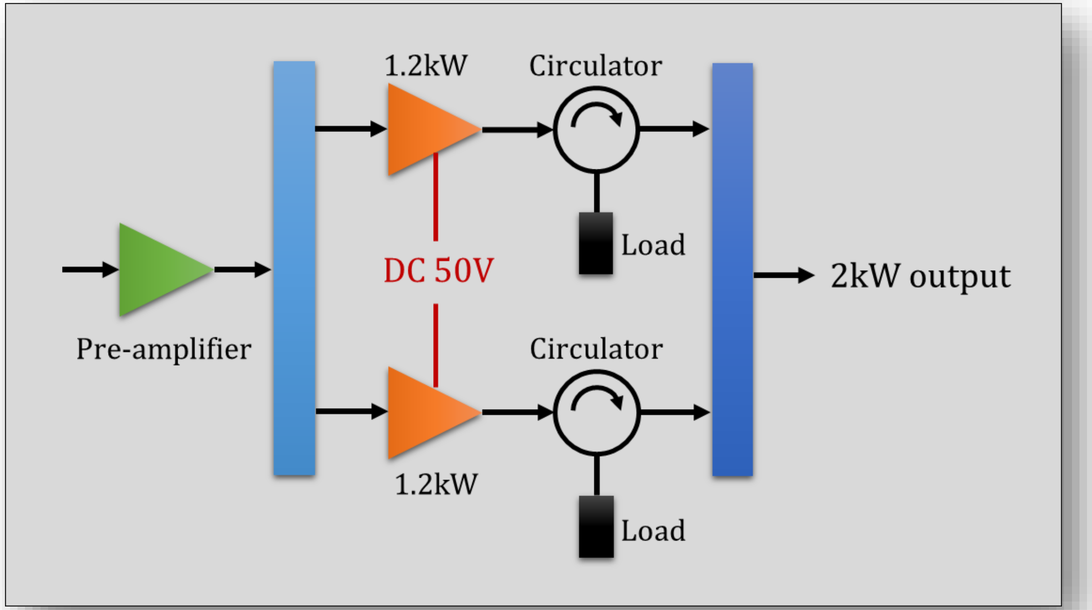
- 2×32kW power cabinet
- 16×2kW power units/cabinet
- 50V uniform power supply
- 2-stage coaxial power combiner



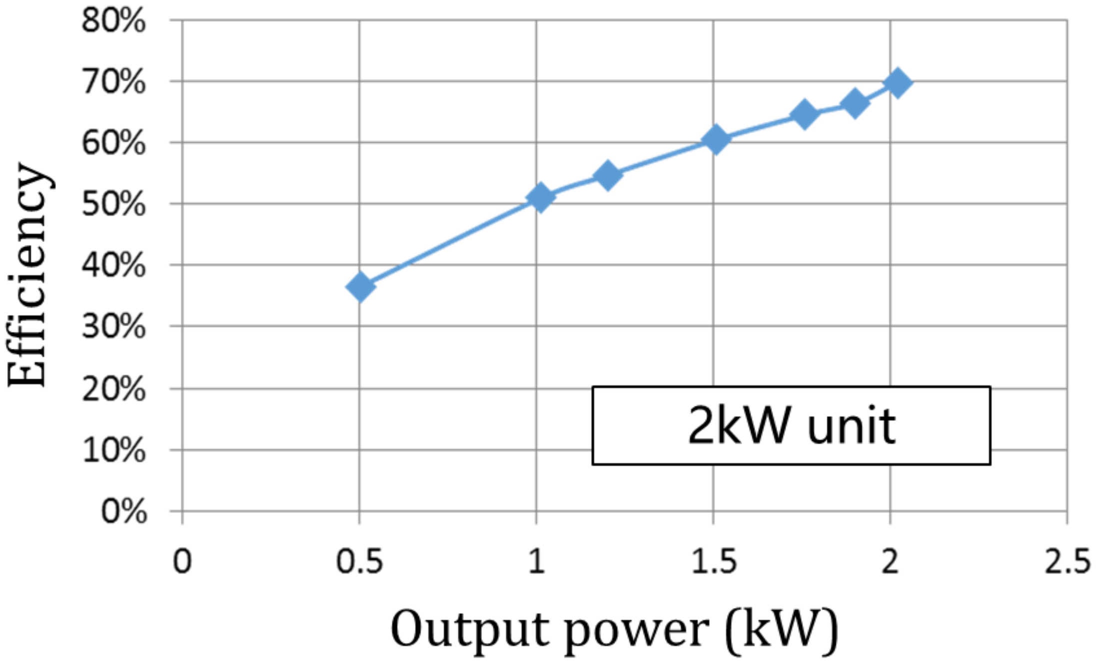
166.6MHz 25kW cabinet



2kW power unit



- 2kW power unit
  - 2 ×LDMOS transistor
  - 1 circulator per transistor
  - water-cooled

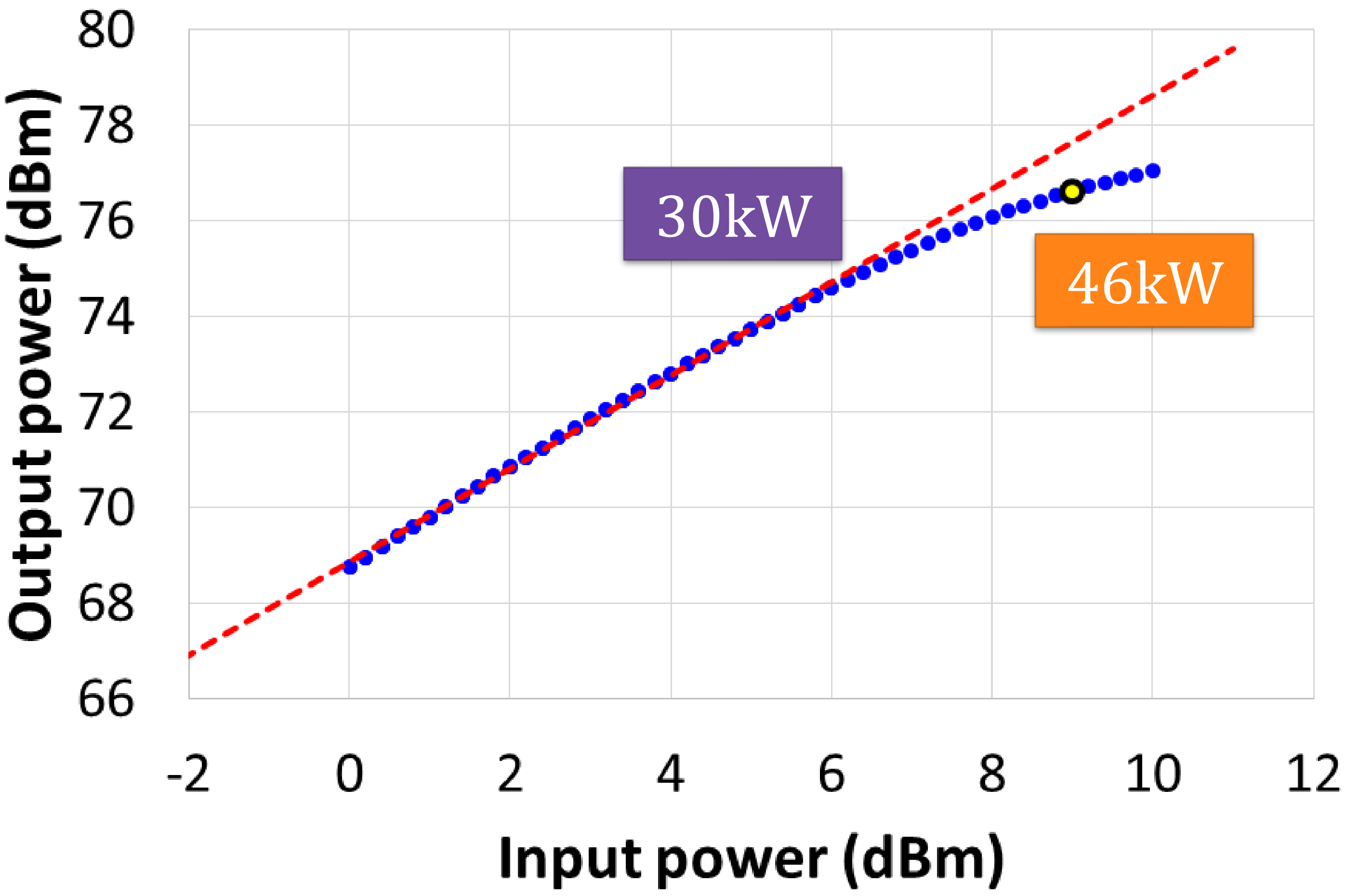


Main parameters

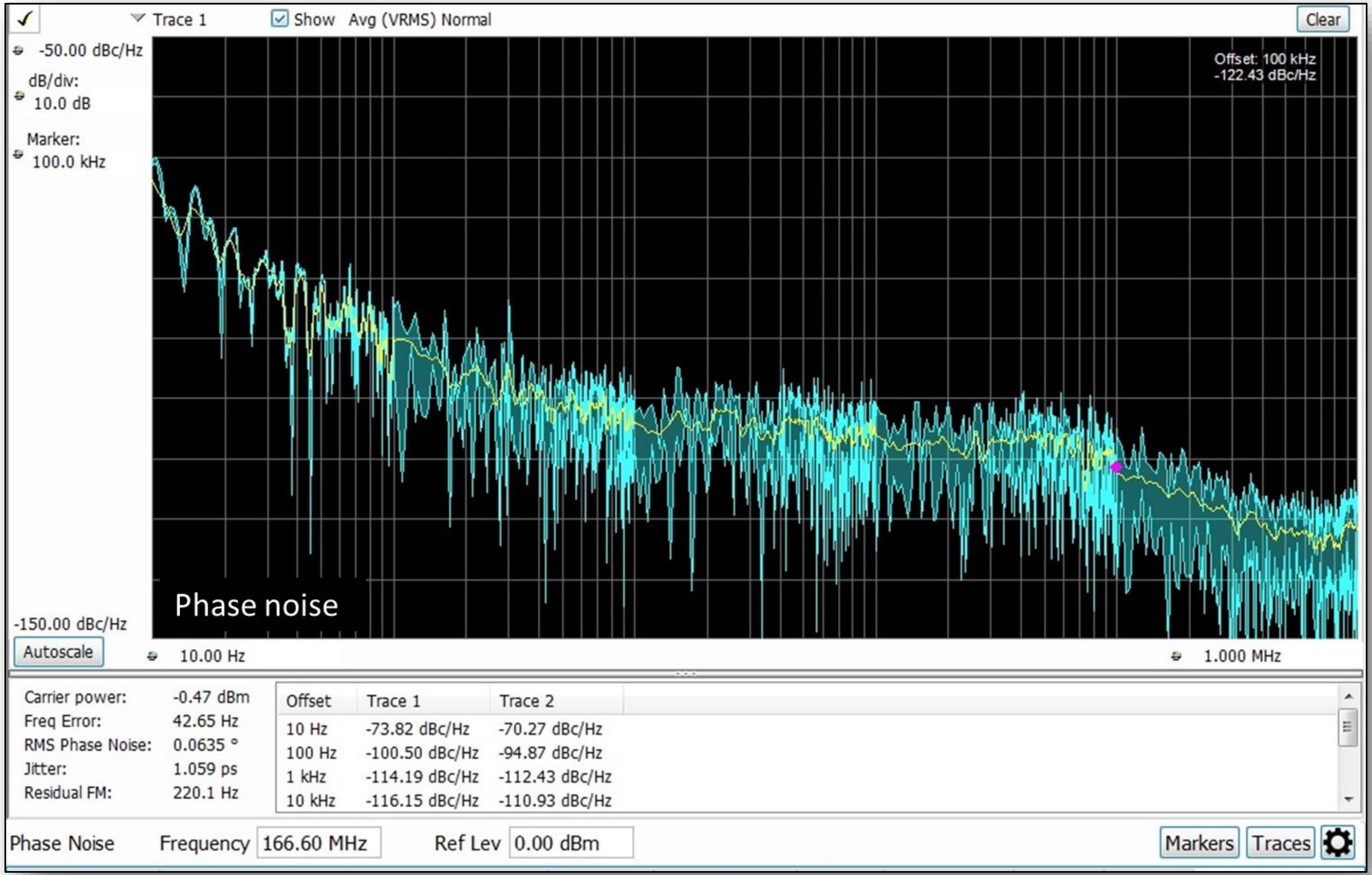
No.	Parameter	Target value	Measured at IHEP
1	RF frequency	166.6MHz	166.6MHz
2	Bandwidth	±2MHz (50kW output)	9.1MHz (3dB)
3	Mode	CW/Pulse	OK
4	Nominal output power	50kW	50kW
5	Power output at 1dB compression	50kW (linear up to 40kW)	46kW
6	Amplitude stability	±1% and ±1°@50kW	±0.06%, ±0.15°
7	Redundancy	6.25%	OK
8	Phase noise (1kHz carrier offset)	≤-70dBc	-114.2dBc
9	Harmonic suppression	≤-30dBc	-38.6dBc
10	Spurious suppression (offset > 1kHz)	≤-70dBc	-98.2dBc
11	Overall efficiency	≥50%	57%

Output power

Early compression observed

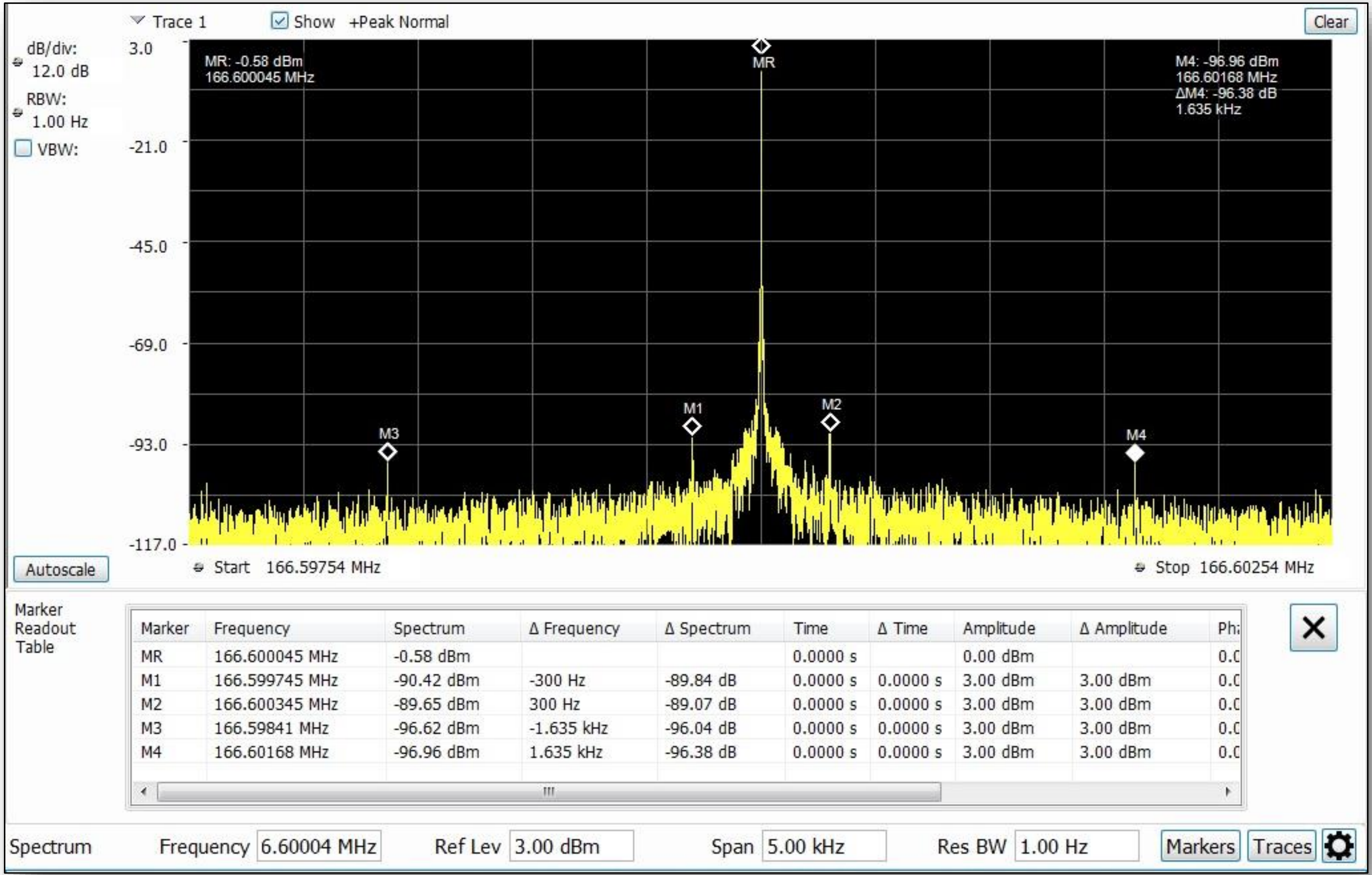


Phase noise

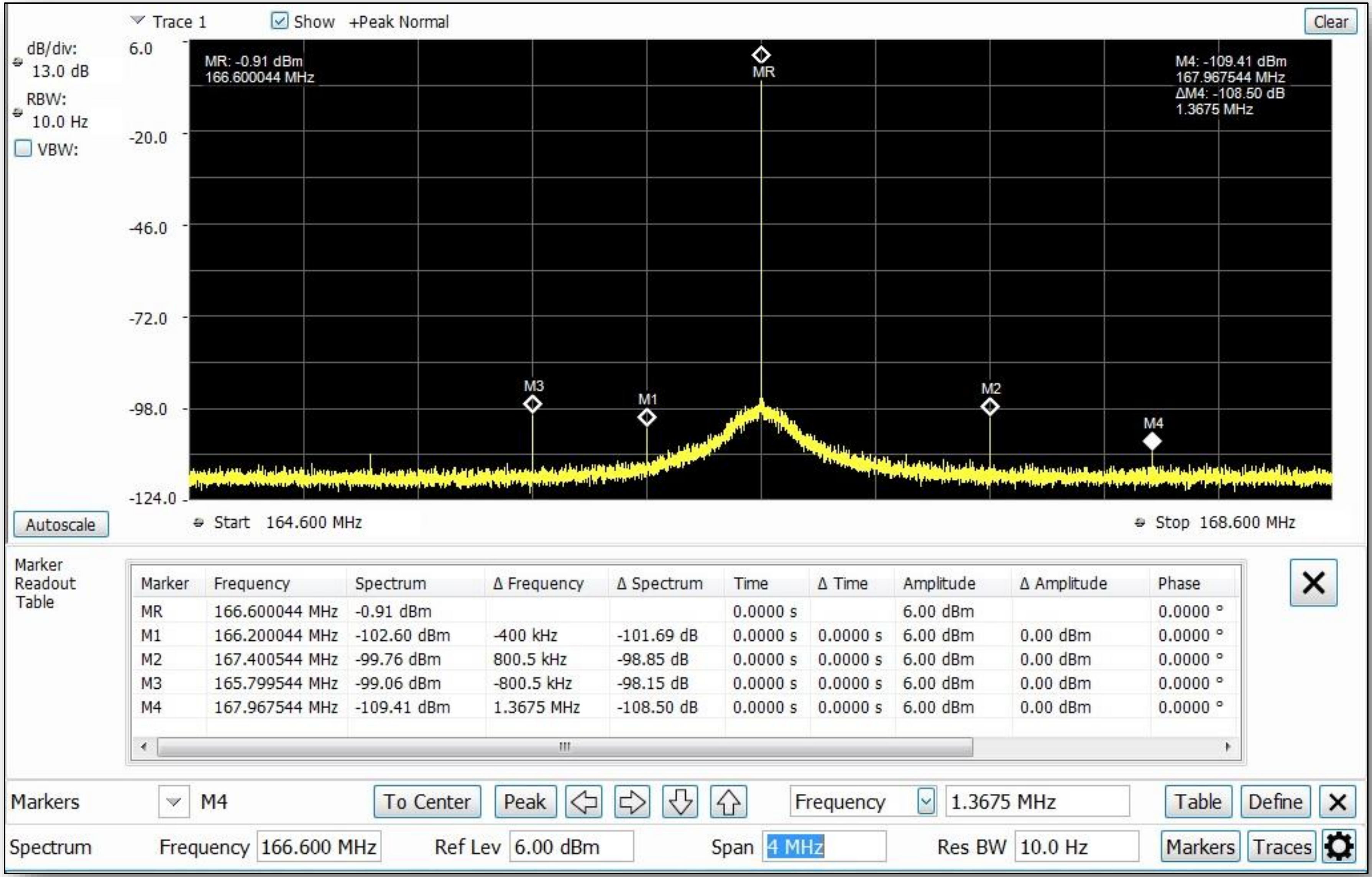


Carrier offset	Phase noise
10 Hz	-73.8 dBc/Hz
100 Hz	-100.5 dBc/Hz
1 kHz	-114.2 dBc/Hz
10 kHz	-116.2 dBc/Hz
100 kHz	-122.4 dBc/Hz

Spurious suppression

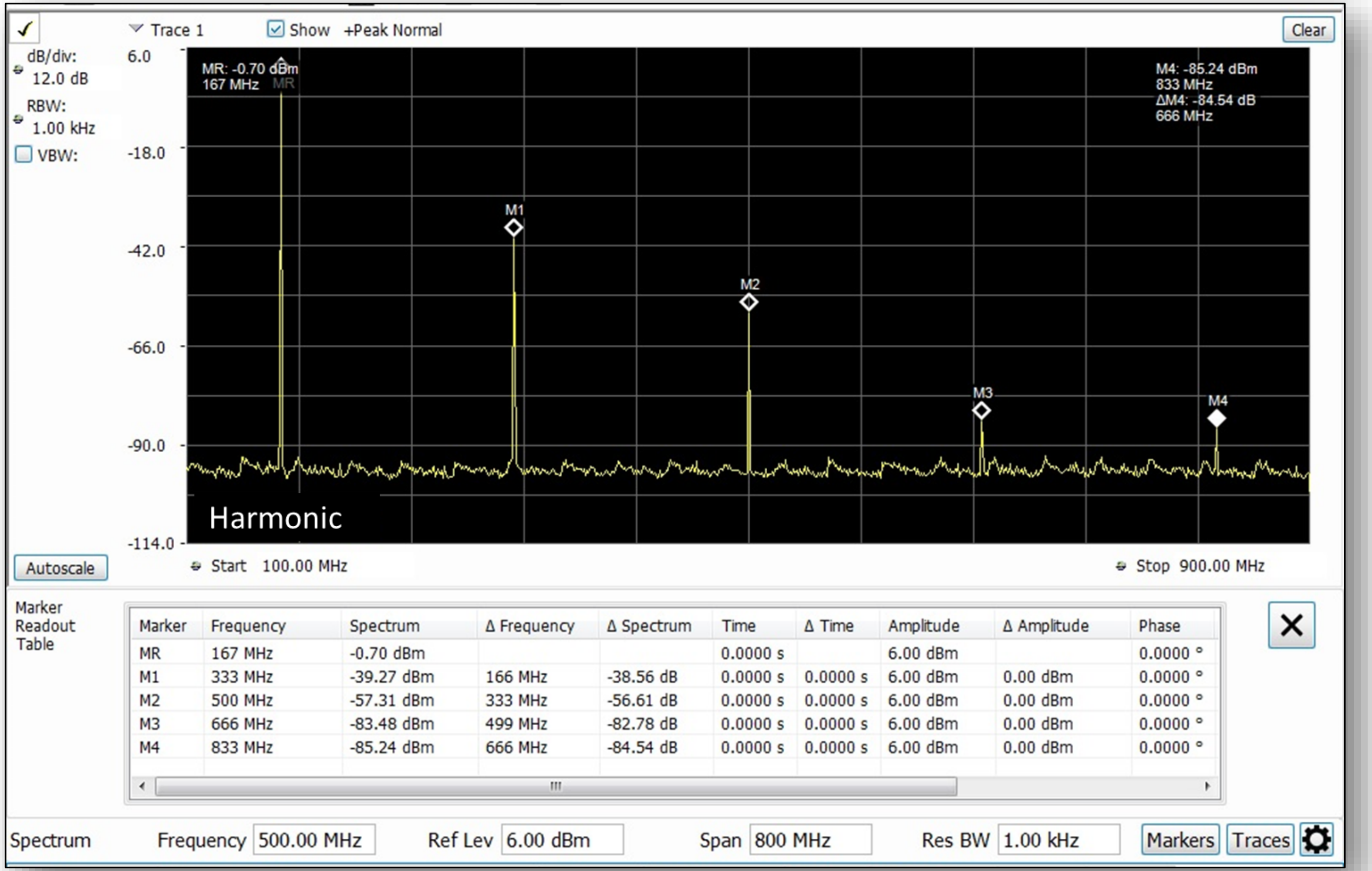


Spurious suppression



Marker	Frequency	Spectrum	Δ Frequency	Δ Spectrum	Time	Δ Time	Amplitude	Δ Amplitude	Phase
MR	166.600044 MHz	-0.91 dBm			0.0000 s		6.00 dBm		0.0000 °
M1	166.200044 MHz	-102.60 dBm	-400 kHz	-101.69 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °
M2	167.400544 MHz	-99.76 dBm	800.5 kHz	-98.85 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °
M3	165.799544 MHz	-99.06 dBm	-800.5 kHz	-98.15 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °
M4	167.967544 MHz	-109.41 dBm	1.3675 MHz	-108.50 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °

Harmonic suppression



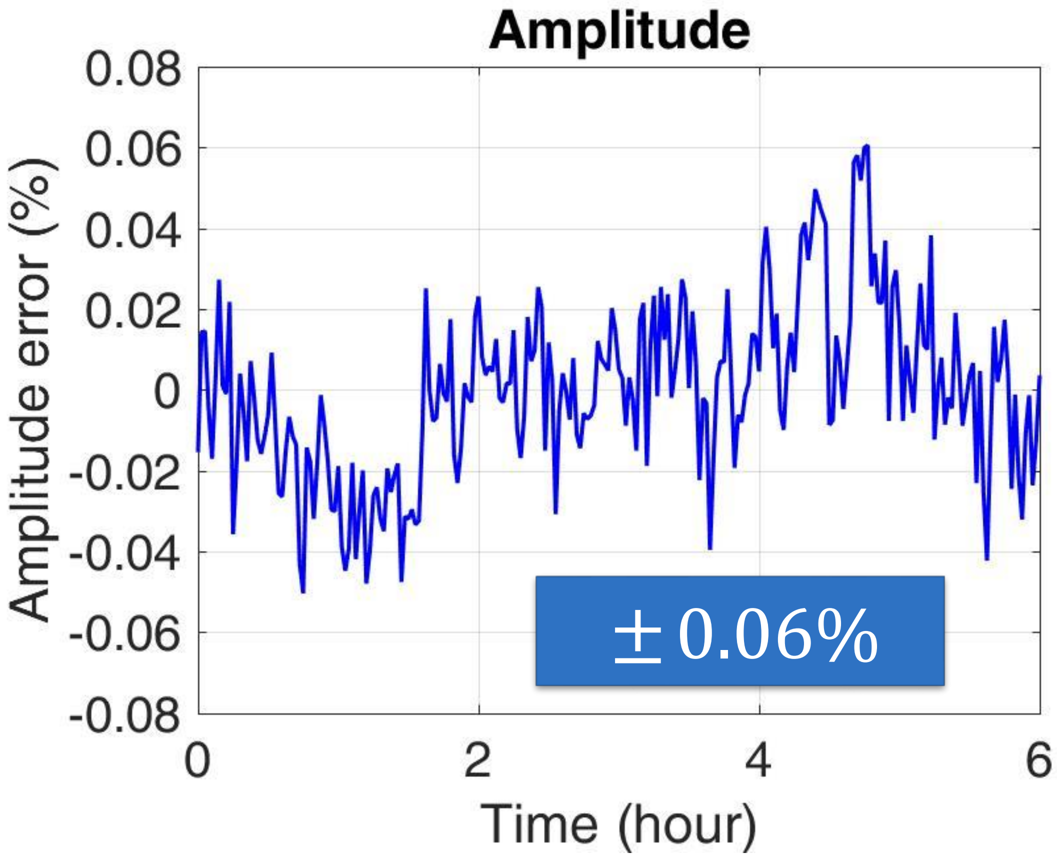
Marker	Frequency	Spectrum	Δ Frequency	Δ Spectrum	Time	Δ Time	Amplitude	Δ Amplitude	Phase
MR	167 MHz	-0.70 dBm			0.0000 s		6.00 dBm		0.0000 °
M1	333 MHz	-39.27 dBm	166 MHz	-38.56 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °
M2	500 MHz	-57.31 dBm	333 MHz	-56.61 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °
M3	666 MHz	-83.48 dBm	499 MHz	-82.78 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °
M4	833 MHz	-85.24 dBm	666 MHz	-84.54 dB	0.0000 s	0.0000 s	6.00 dBm	0.00 dBm	0.0000 °

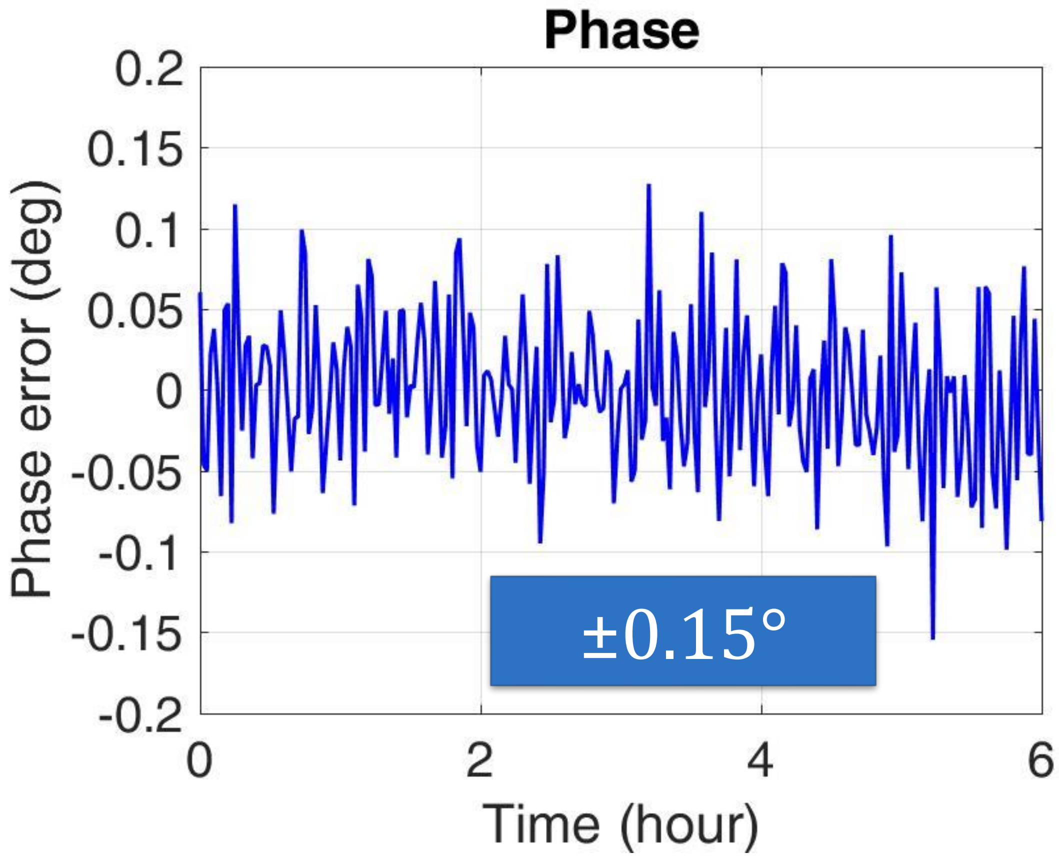
Harmonic f_0	Δamplitude
333 MHz (2nd)	-38.6 dB
500 MHz (3rd)	-56.6 dB
666 MHz (4th)	-82.8 dB
833 MHz (5th)	-84.5 dB

Amp & Phase stability

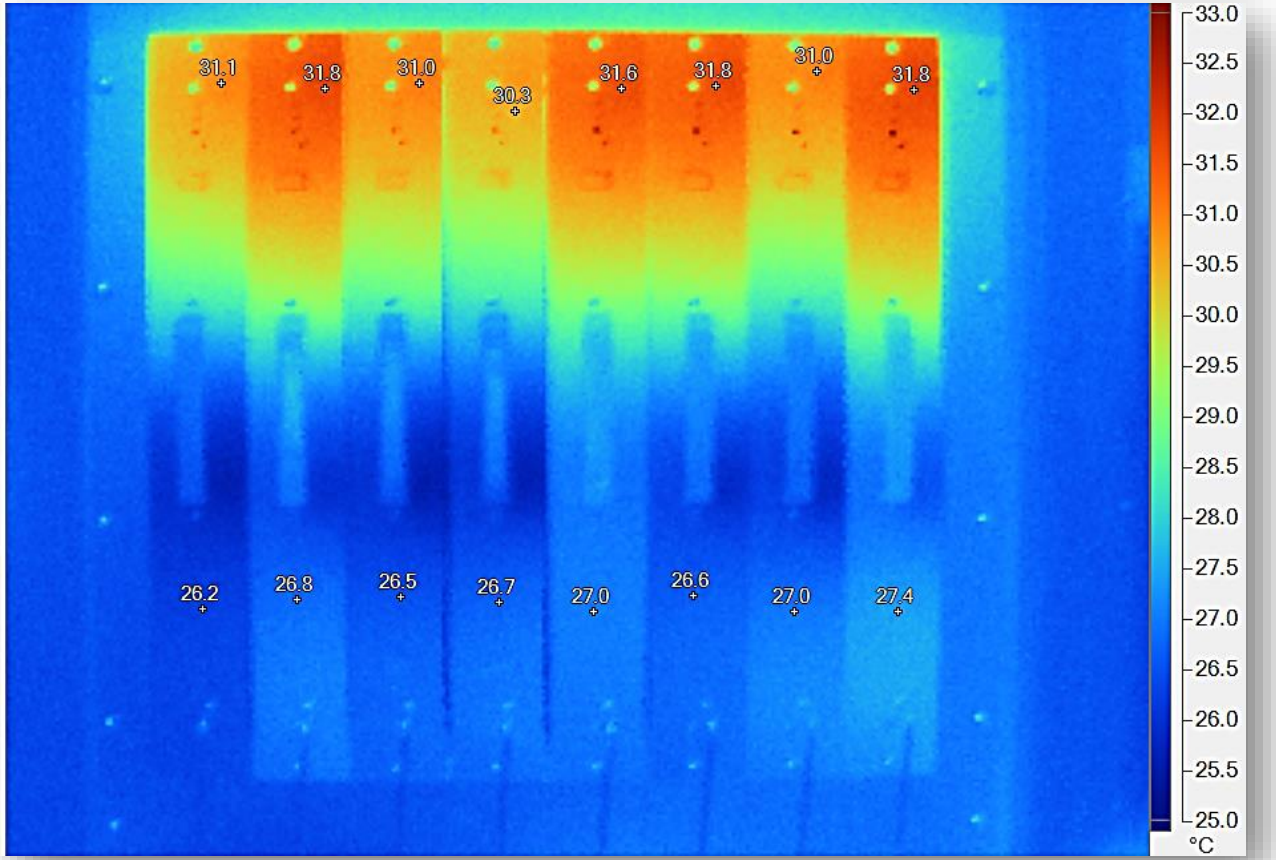
Output power: 50kW

Water inlet temperature stability: +/- 0.4°C





Temperature distribution



Output power: 50kW keep for 1 hour
Termination: matched load

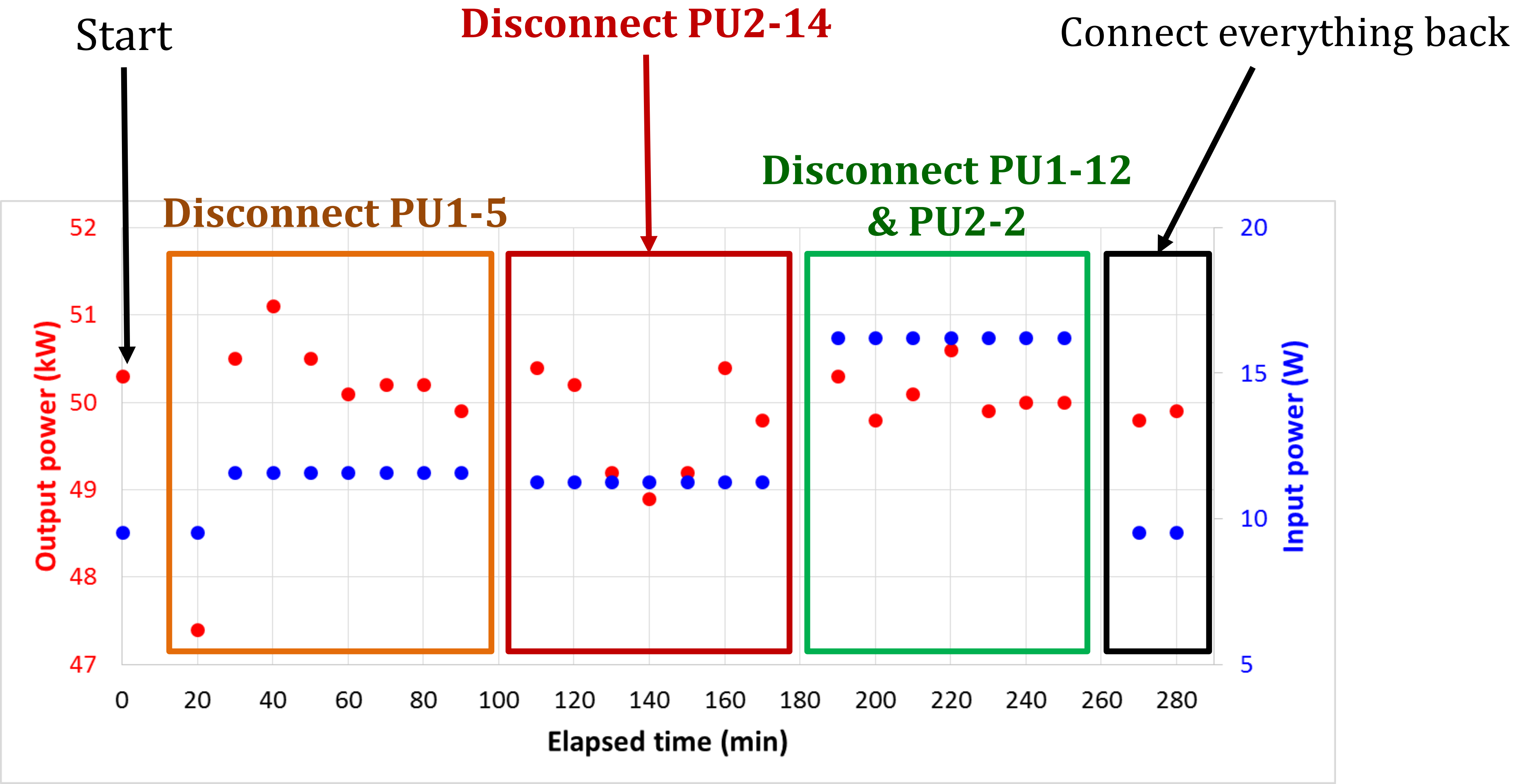
Redundancy

Cabinet 2 Cabinet 1

- Disconnect PU1-5
- Disconnect PU2-14
- Disconnect PU1-12 & PU2-2

- Redundancy requirement: >6%
- One 2kW power unit allowed to fail per cabinet to maintain 50kW output

Redundancy


Start
Disconnect PU2-14
Connect everything back
Disconnect PU1-12
& PU2-2
Disconnect PU1-5
Output power (kW)
52
51
50
49
48
47
Input power (W)
20
15
10
5
0
20
40
60
80
100
120
140
160
180
200
220
240
260
280
Elapsed time (min)

Control

- **Monitoring**

  - 2kW power unit: temperature, voltage, current, output power

  - Power supply

  - Pre-amplifier: temperature, voltage, current, input/output power

  - 50kW SSPA: water flow, forward/reflected power, etc.

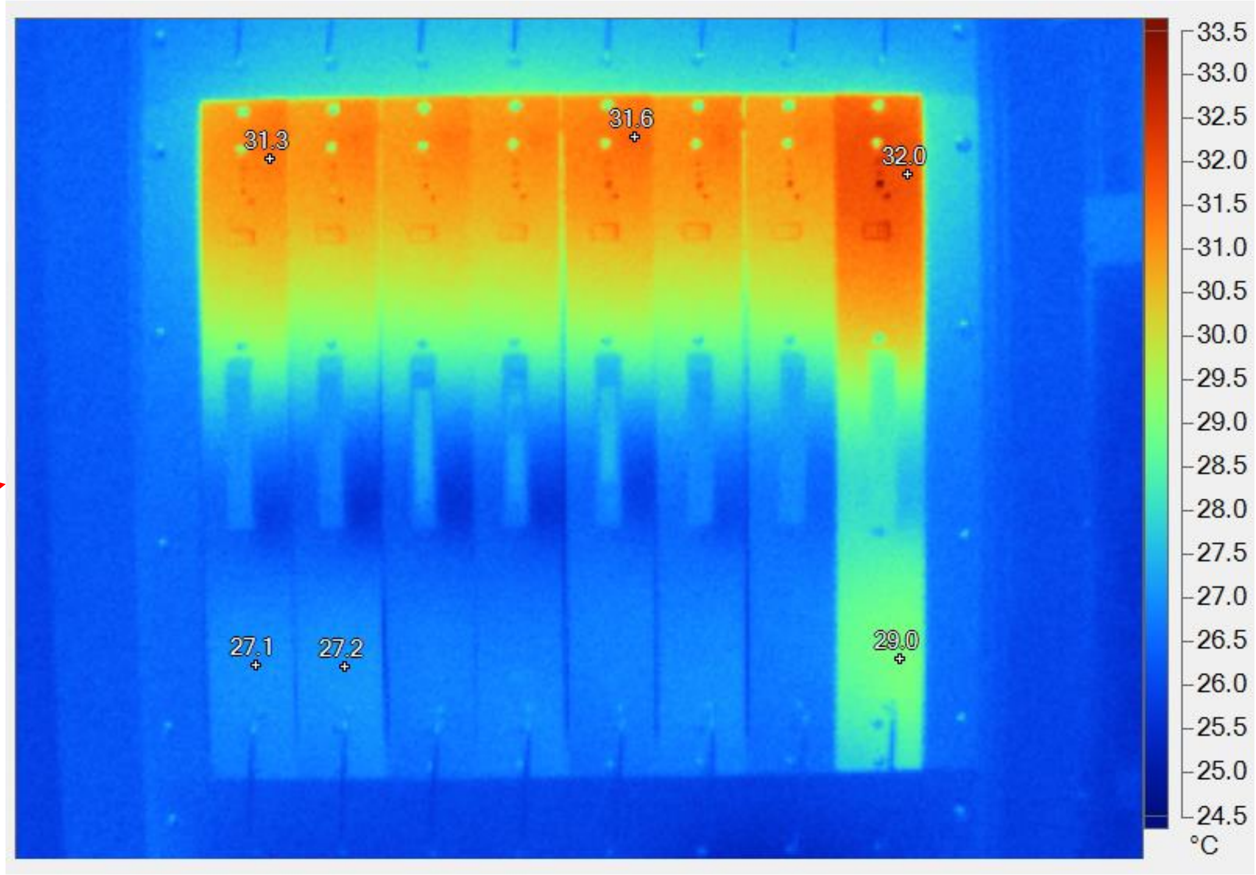
- **Interlock**

  - Temperature, water flow, power supply (2kW RF power unit)

  - Input overdrive, output overload

  - Other external signal (4 channels), etc.

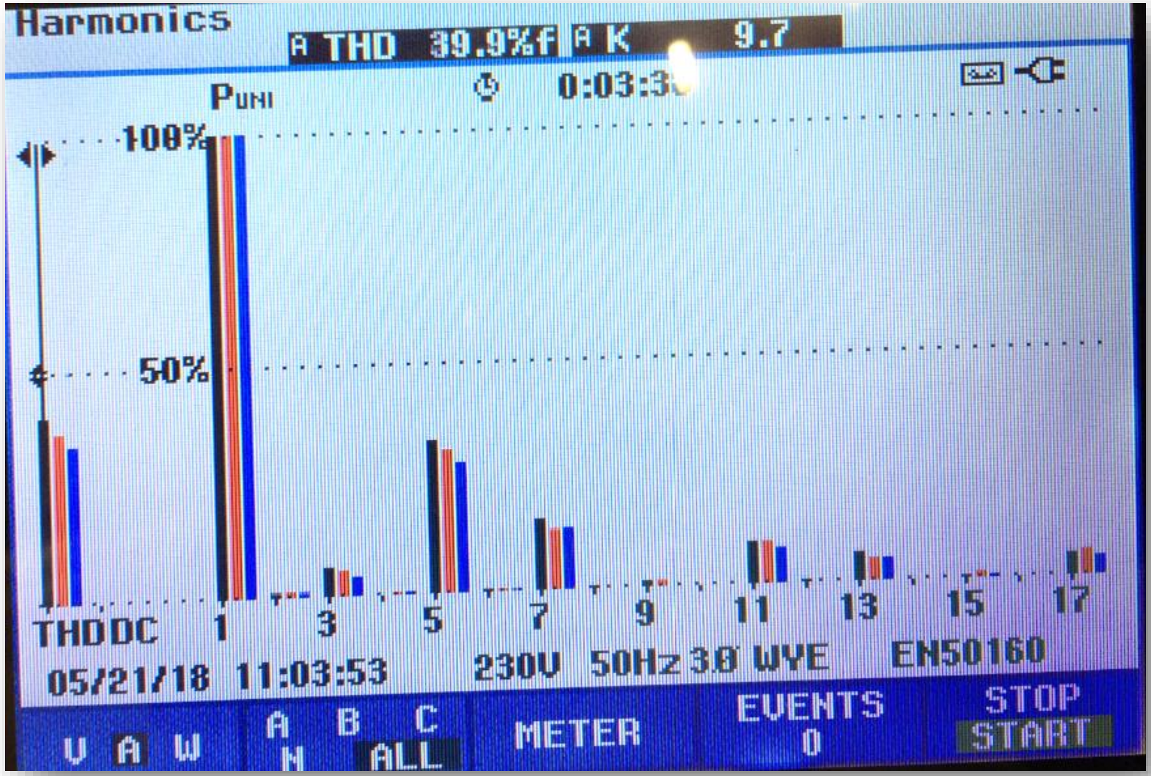
Abnormal temperature

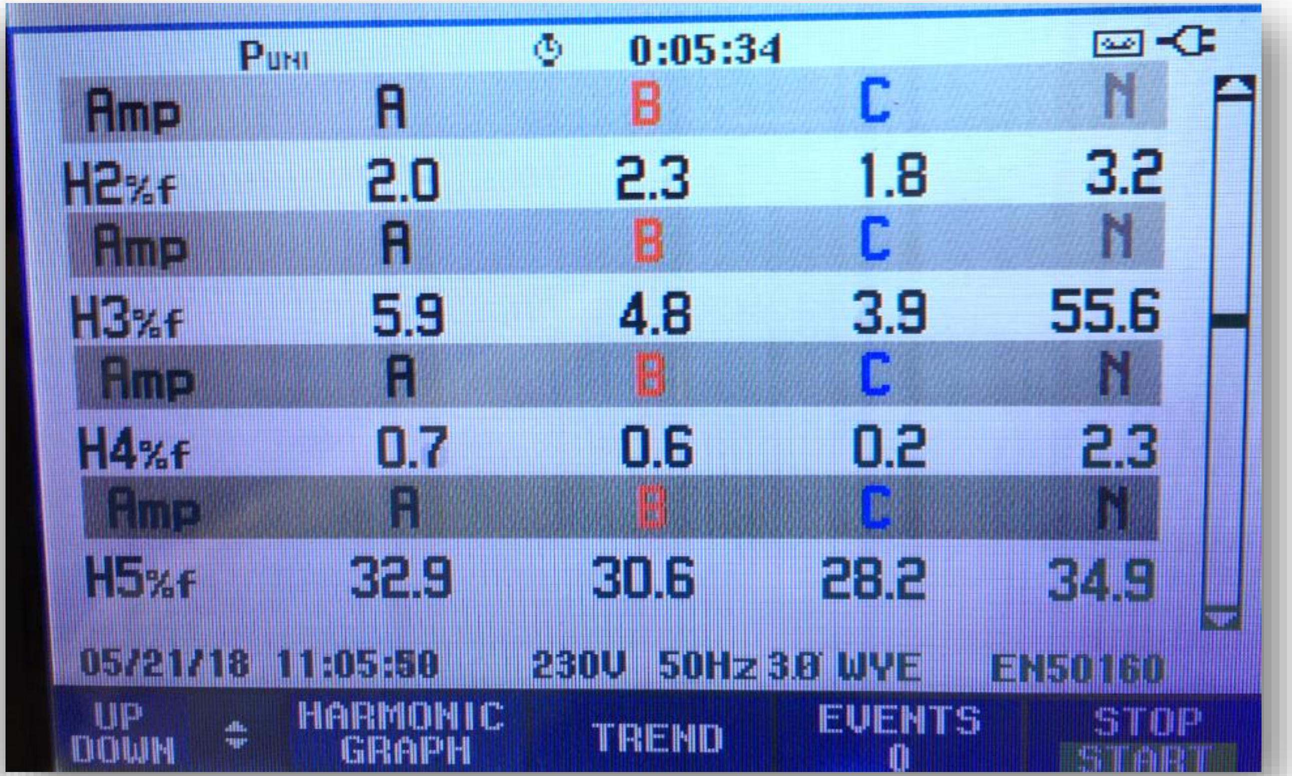


Output power: 50kW keep for 1 hour
Termination: matched load

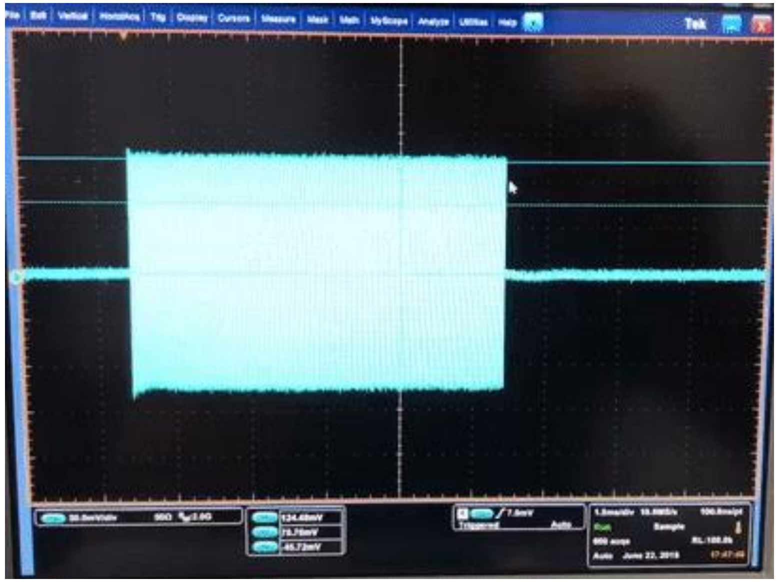
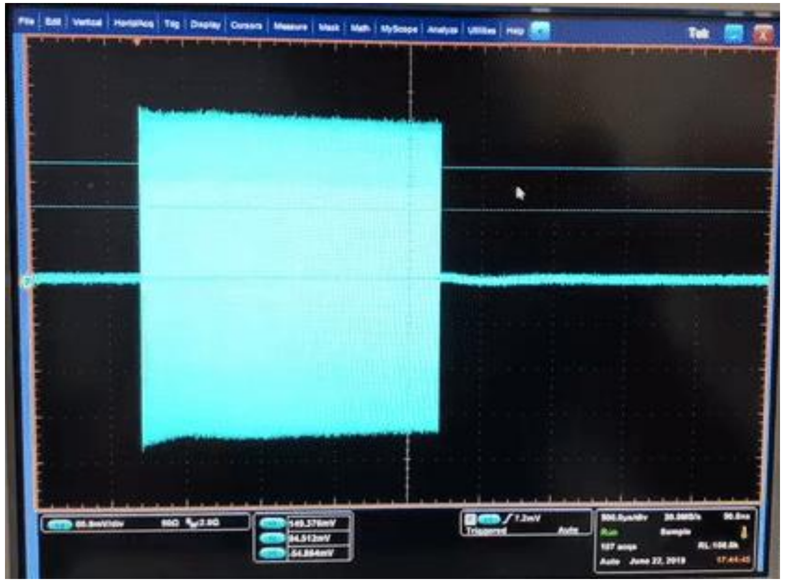
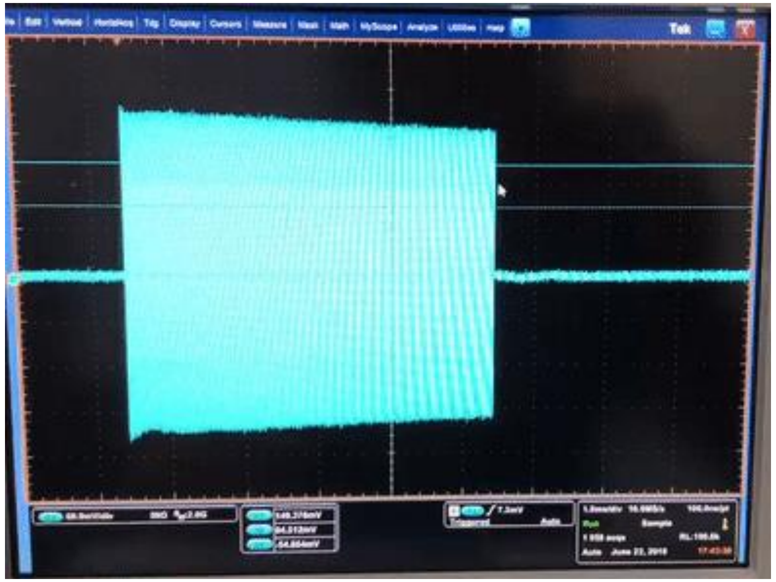
Current harmonics

- Substantial 5th order current harmonic observed
- Need to be reduced





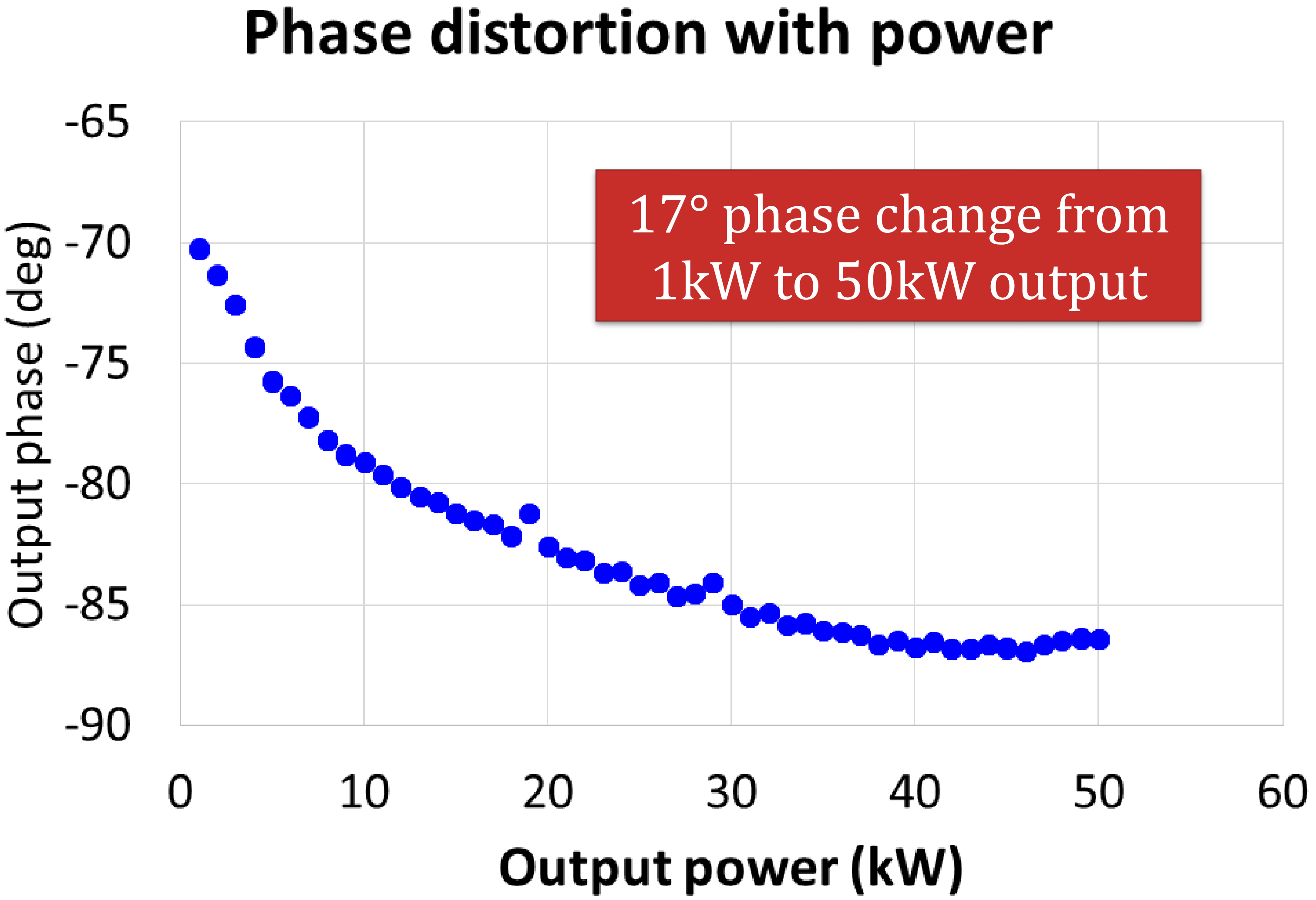
Long pulse

Pulse length = 1ms	Pulse length = 2ms	Pulse length = 5ms
		

The capacity of energy storage in the power supply is not sufficient.

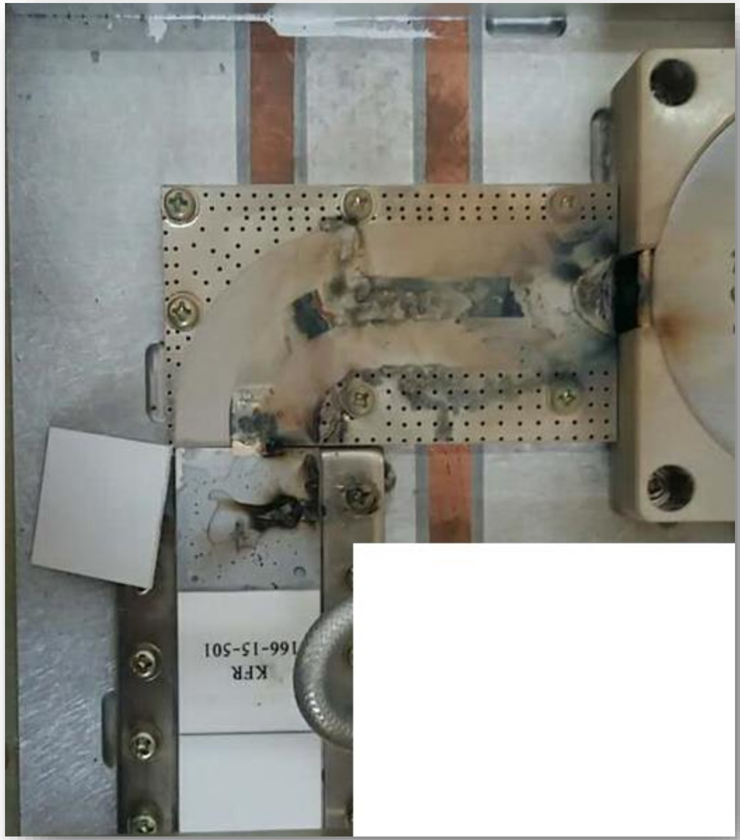
Rep rate: 10Hz

Phase distortion

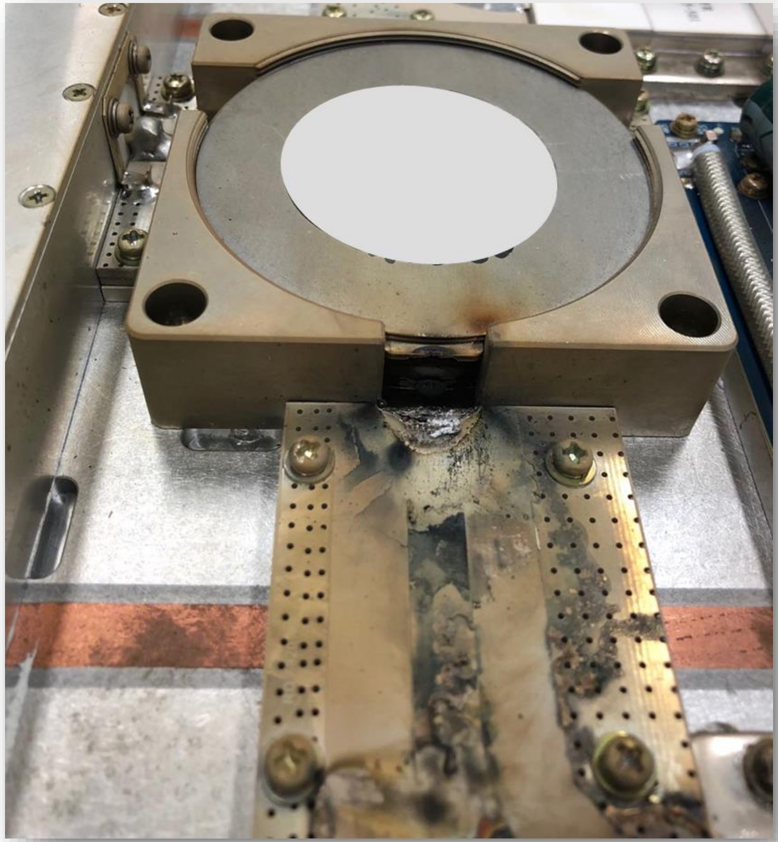


Something burnt

Load



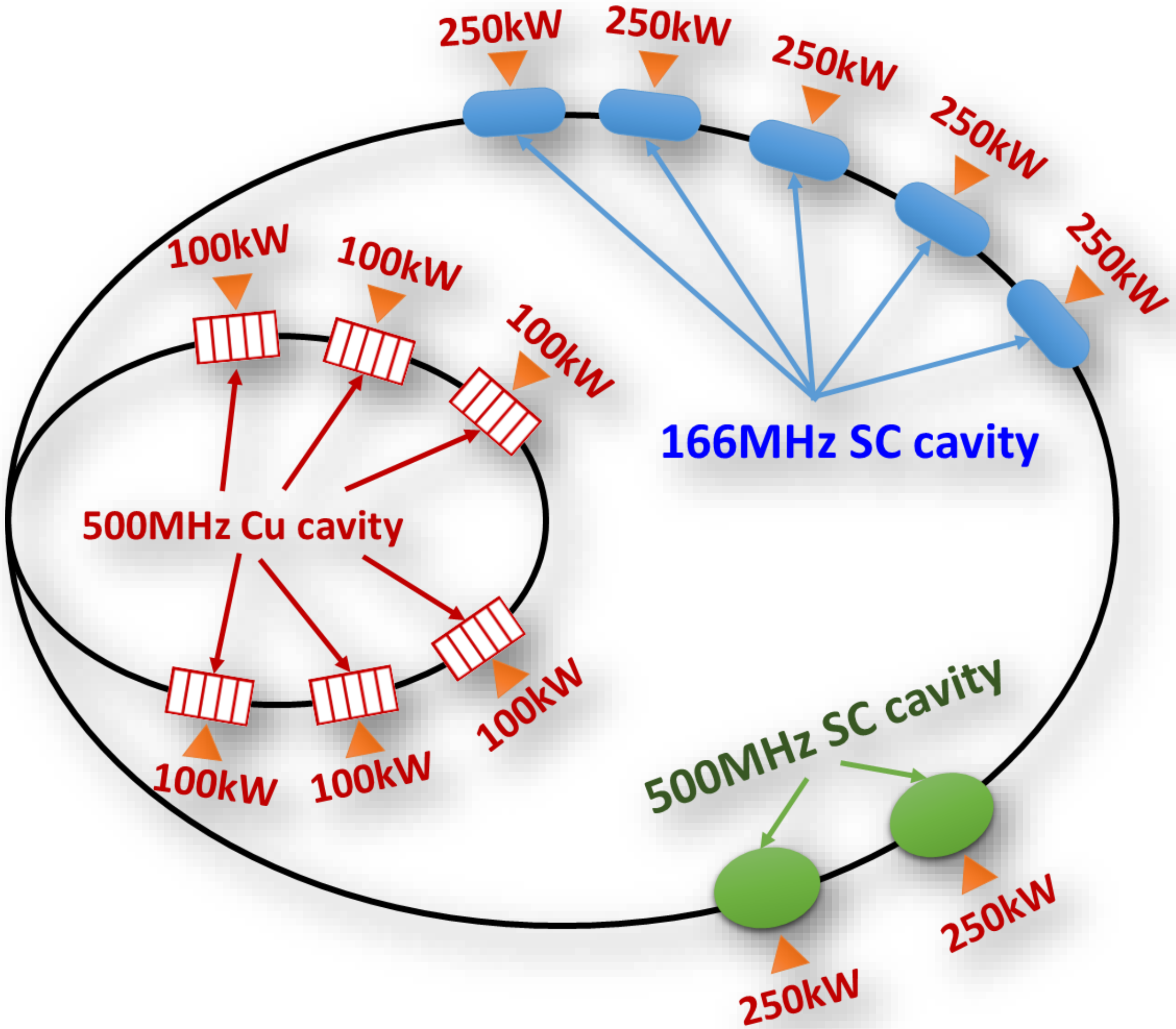
Circulator



Transistor

500MHz 100kW SSPA

HEPS RF system



The prototype

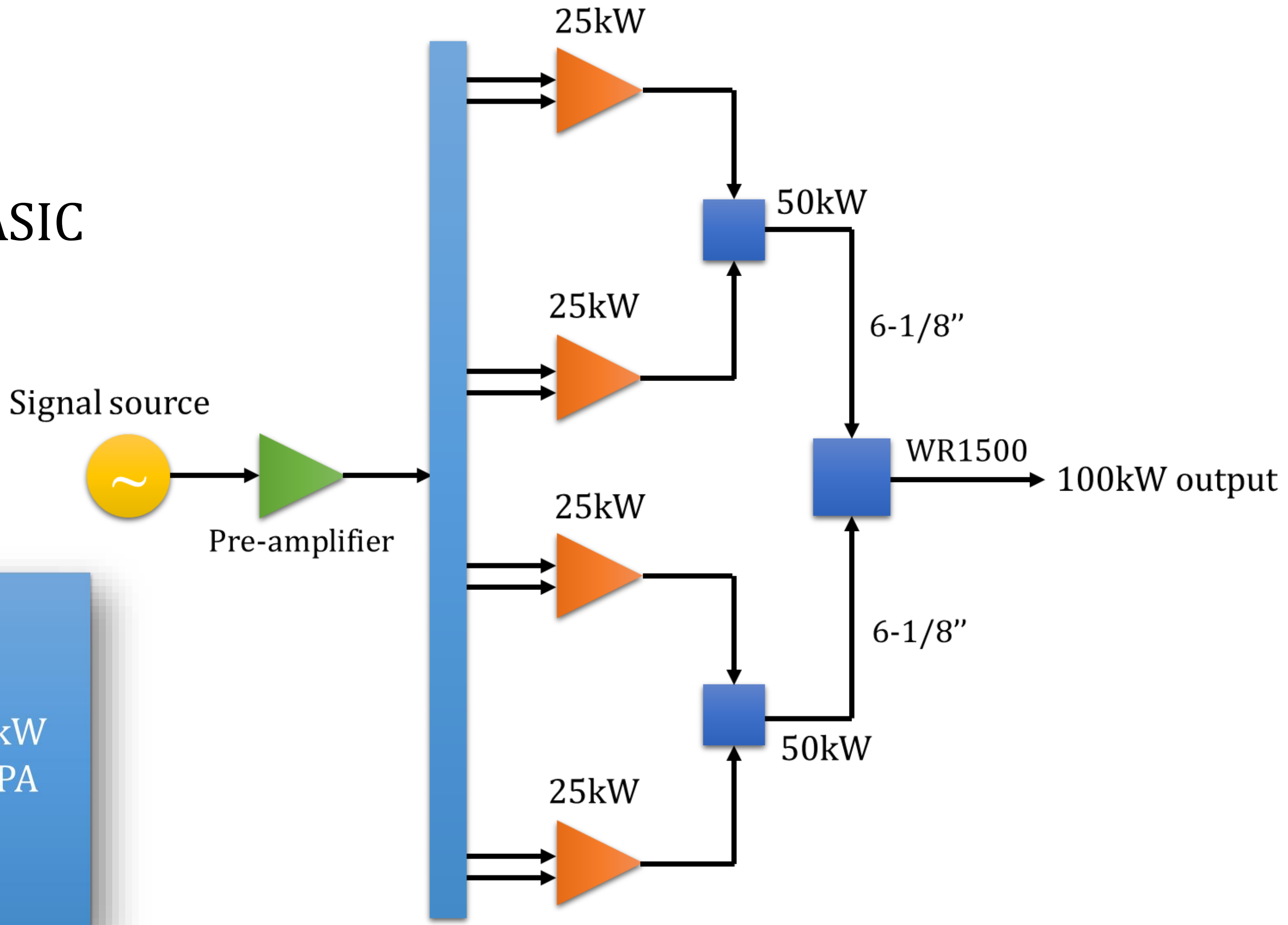
中国航天科工集团第二研究院二十三所

05.2018 Call for tender

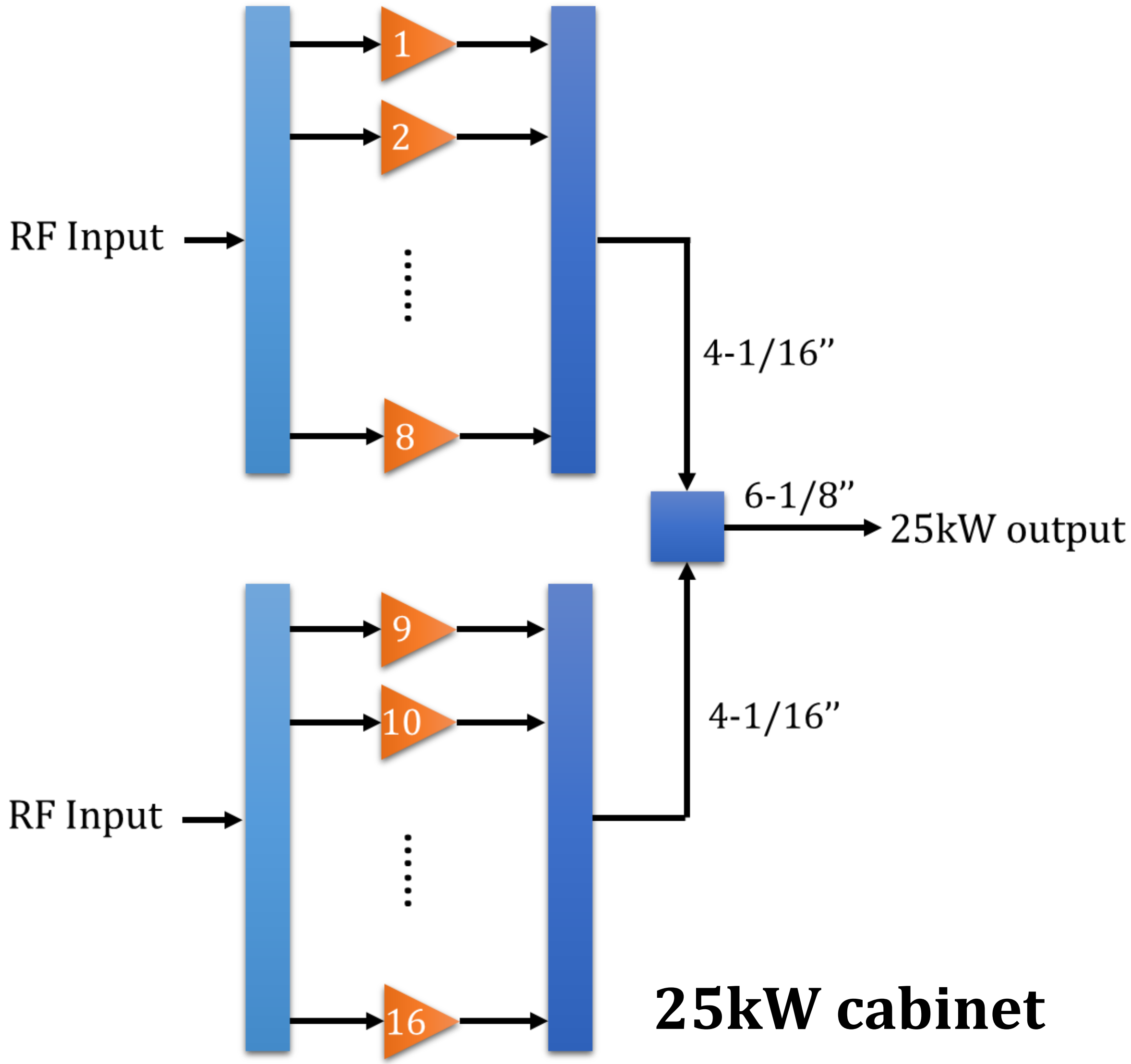
06.2018 Contract awarded to CASIC

07.2019 Deliver to IHEP

- 2-stage coaxial combiner
- Final stage waveguide combiner

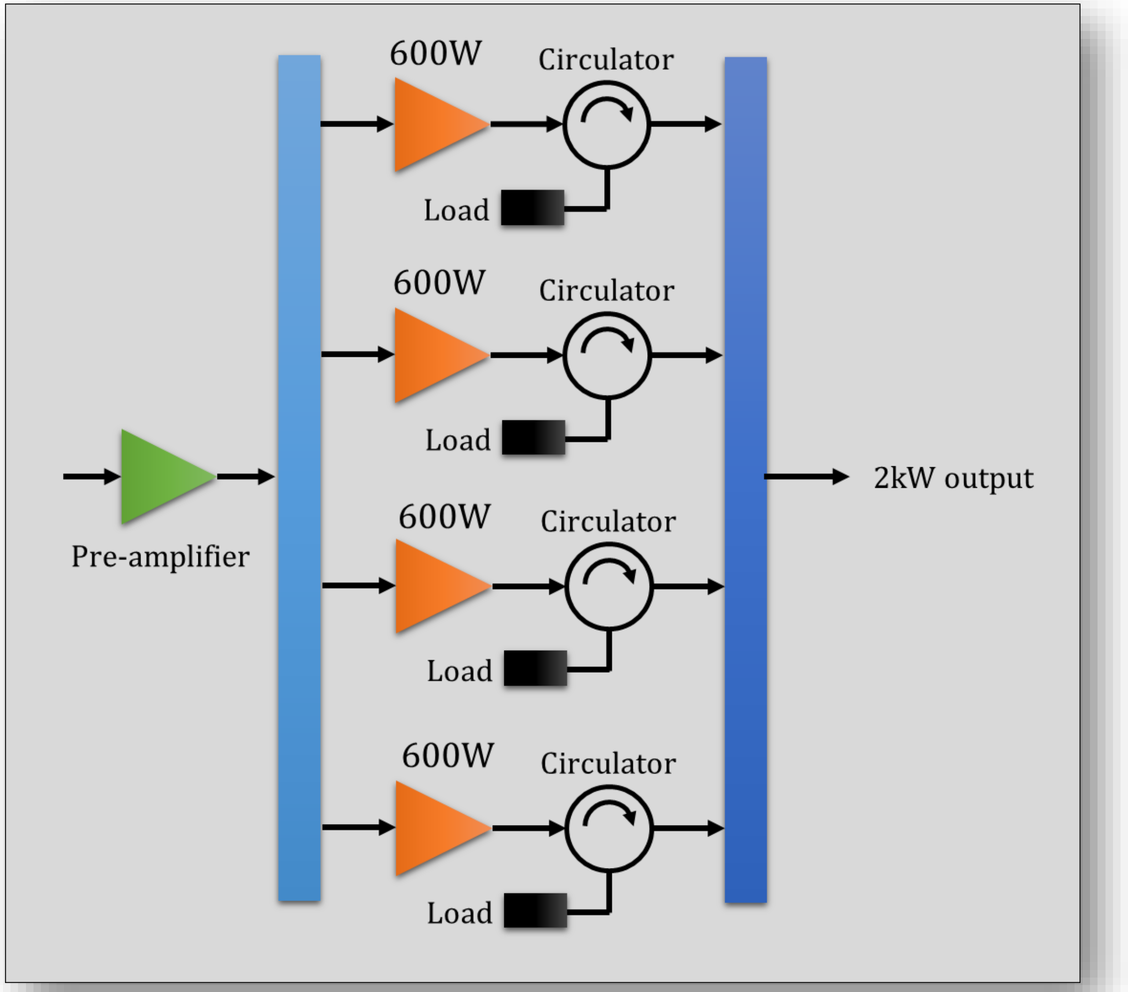


The design



25kW cabinet

2kW power unit

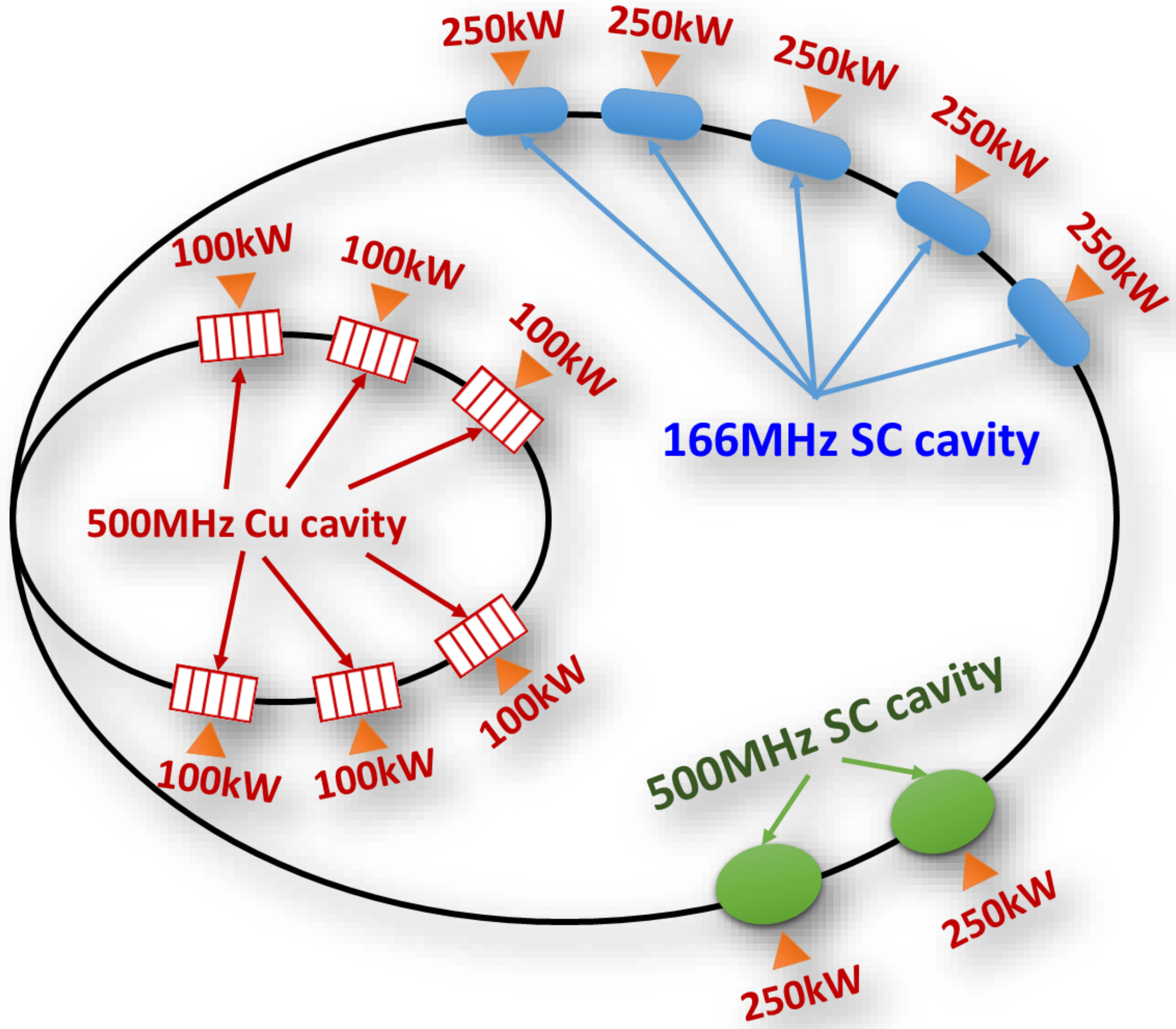


Design requirements

No.	Parameter	Target value
1	RF frequency	500MHz
2	Bandwidth	±2MHz (50kW output)
3	Mode	CW/Pulse
4	Nominal output power	100kW
5	Power output at 1dB compression	100kW
6	Amplitude & phase stability	±1% and ±1°@100kW
7	Phase noise (1kHz carrier offset)	≤-70dBc
8	Harmonic suppression	≤-30dBc
9	Spurious suppression (carrier offset > 10kHz)	≤-70dBc
10	Overall efficiency	≥50%
11	Redundancy	>6%

Power coupler

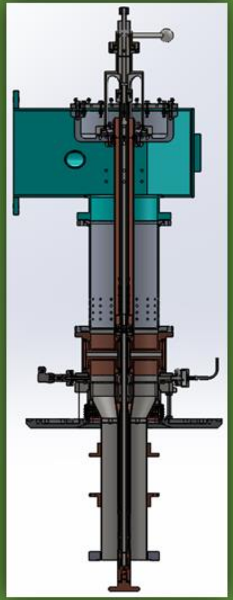
HEPS RF system



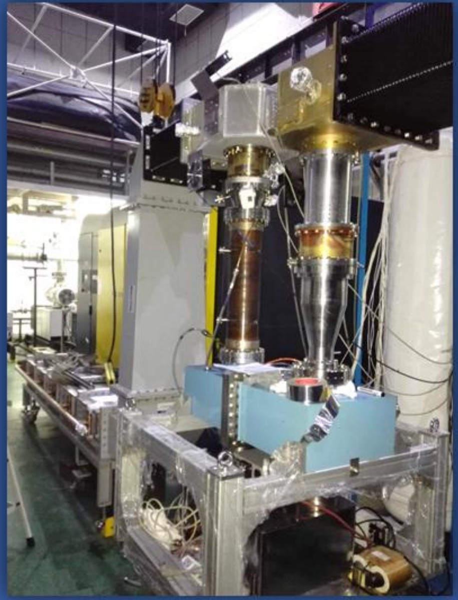
FPCs developed at IHEP

BEPCII 500MHz

CEPC 650MHz

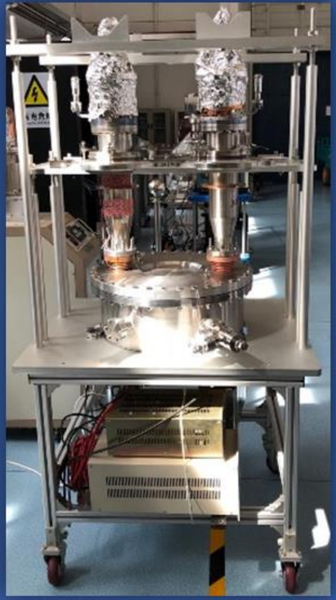


CADS 650MHz



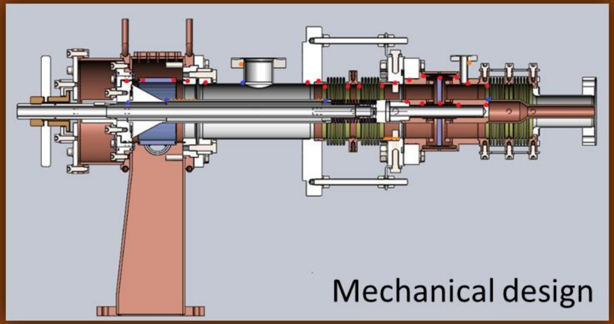
CADS 325MHz (Spoke, RFQ)

CADS 162.5MHz



The RF group has over a decade of experience on design, fabrication and power testing of FPCs and their beam operations.

ERL 1.3GHz FPC (double-window)



- Coax, variable, capacitive, double-window
- Test: CW 70 kW (TW & SW)
  Op: Not yet specified
- Under production
  To be tested in 2018

Doorknob

166.6MHz FPC for SCC

Parameter	Value
Frequency	**166.6 MHz**
RF power	**200 kW CW**
External Q	3.78E4
Impedance of the coaxial line	50 Ω
Ceramic type	coaxial, planar
Cooling type	Window & inner conductor: water-cooled Outer conductor: helium gas cooled
Reflection coefficient	S11< –20 dB Bandwidth: ~15 MHz
Vacuum	Leak rate: 1E-9 mbar·l/sec
Interface with power source	Coaxial line, 9-3/16”

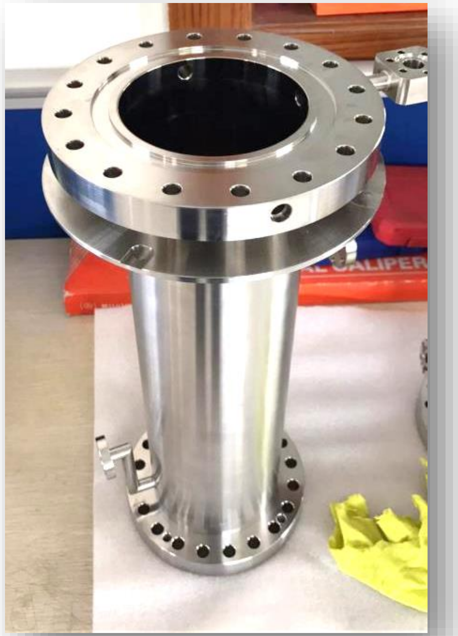
Fabrication

Window

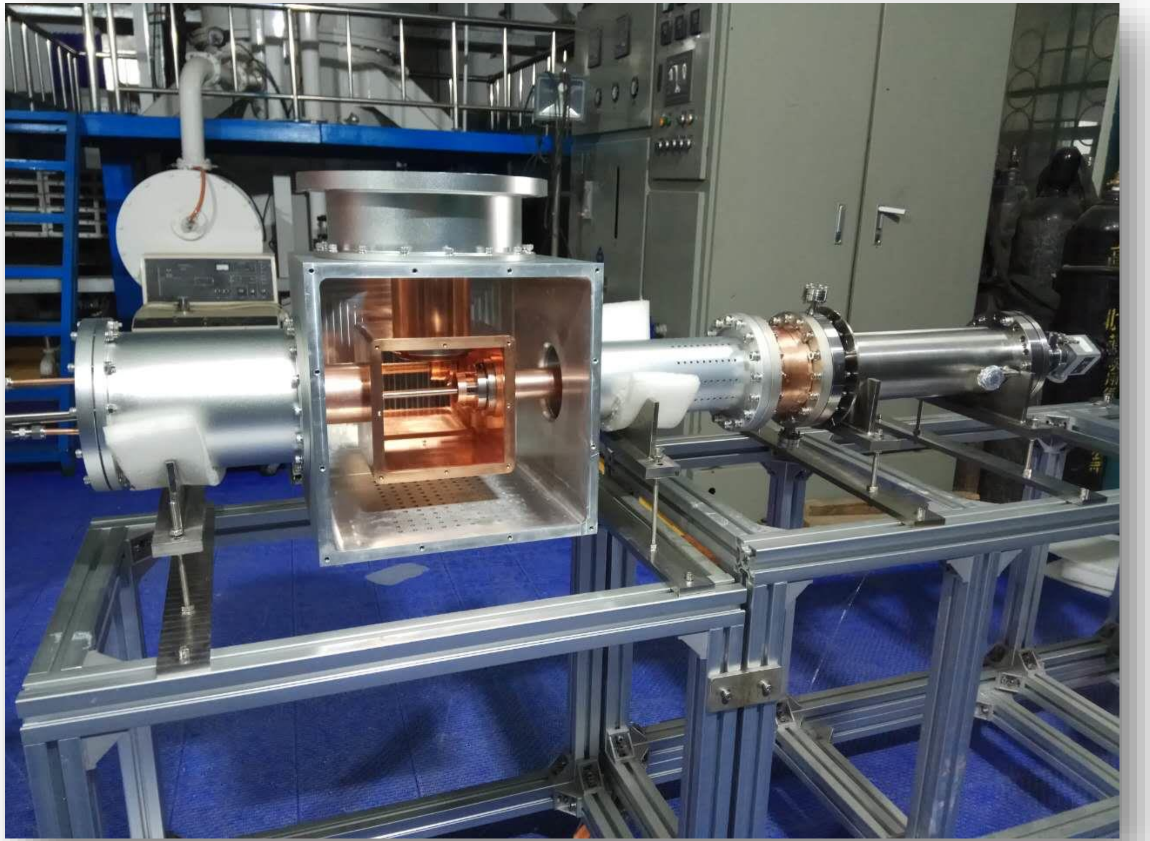
T-box

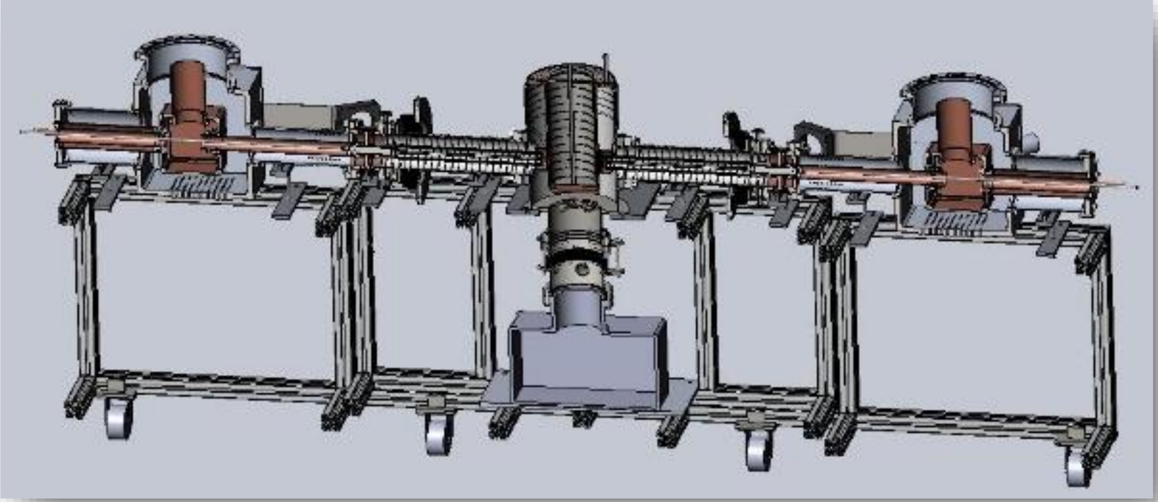
Launched in 03.2017
Completed in 06.2017

Outer conductor



The FPC





High power conditioning

SSPA: **S**olid-**S**tate **P**ower **A**mplifier
TW: **T**ravelling **W**ave
SW: **S**tanding **W**ave

	Power source	Conditioning mode	Remarks
Phase I	166.6MHz 50kW solid-state amplifier	TW & SW	Limited by available SSPA power
Phase II	650MHz 150kW solid-state amplifier	TW	Use a modified test stand

The setup

166MHz SSPA

The complete setup for FPC high power conditioning using 166.6MHz 50kW SSPA

166.6MHz 50kW SSPA

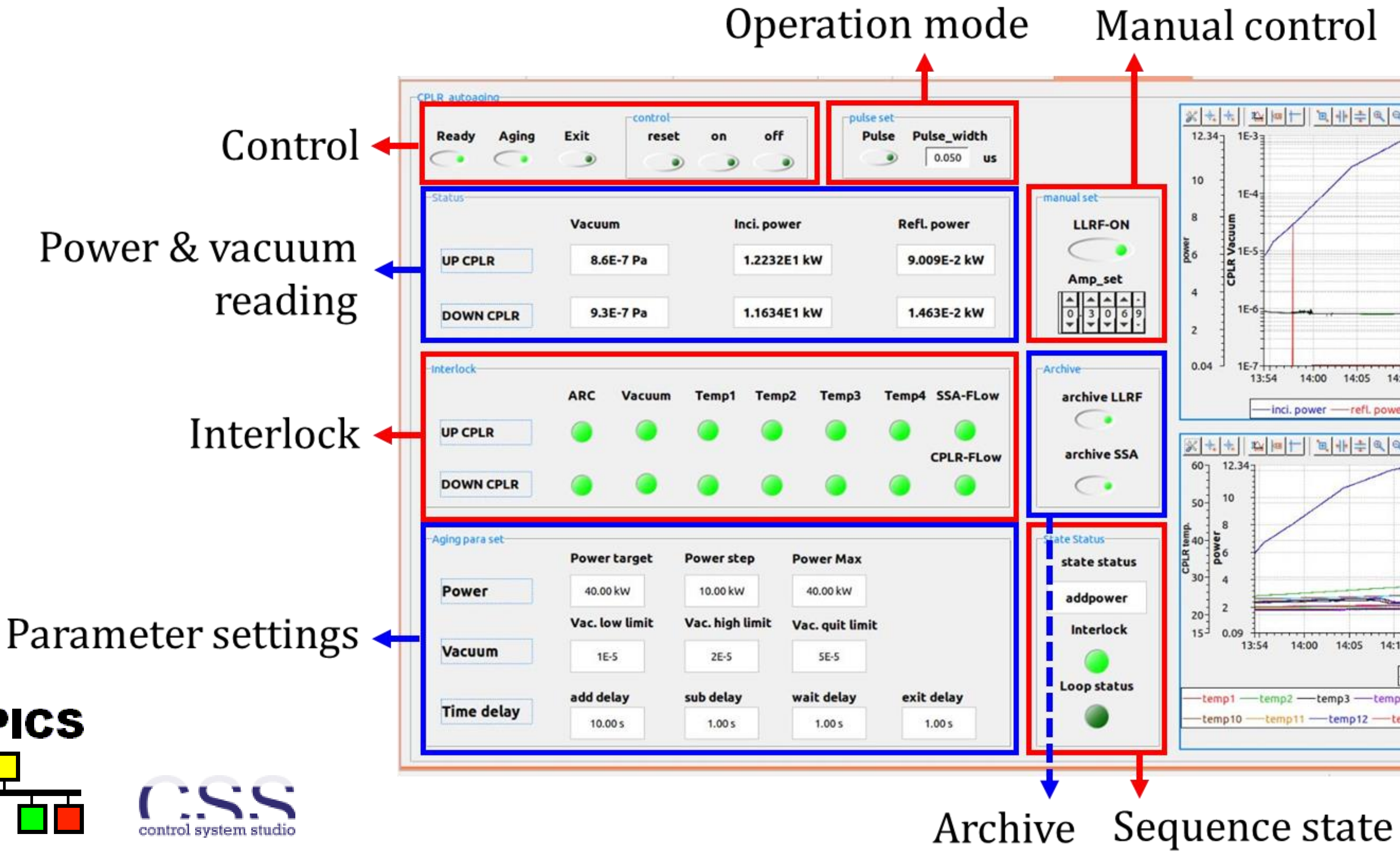
6-1/8” coaxial line

Test bench system

Water load

LLRF control & monitoring

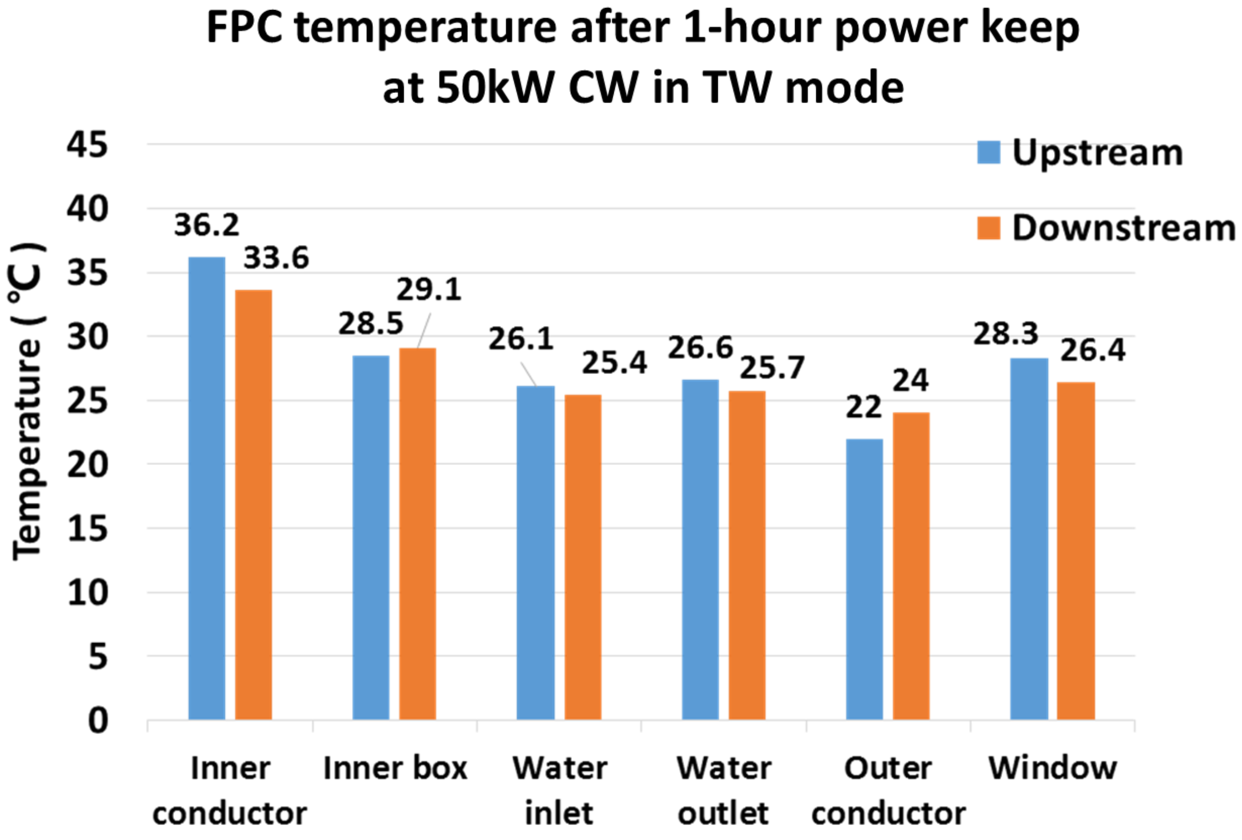
Automatic conditioning system



Conditioning in TW mode

166MHz SSPA

- Maximum power reached: 50kW CW
- After 1-hour power keep at 50kW CW: normal vacuum & temperature readouts

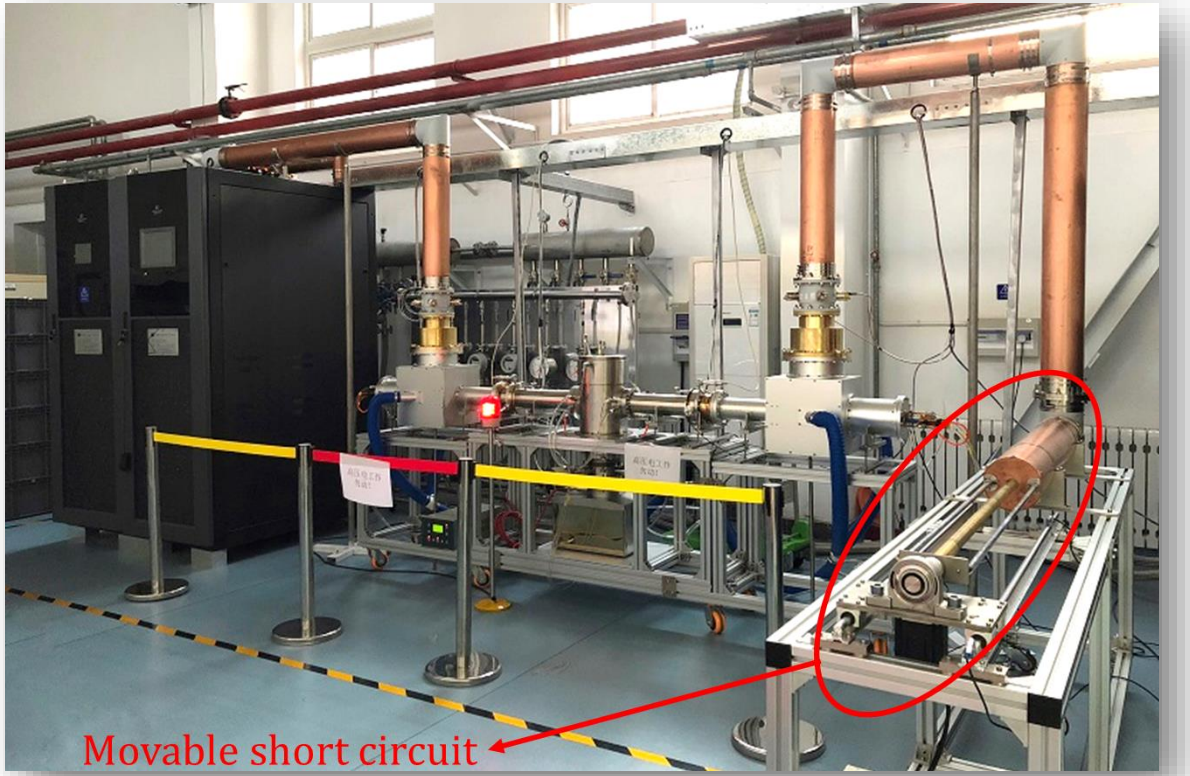


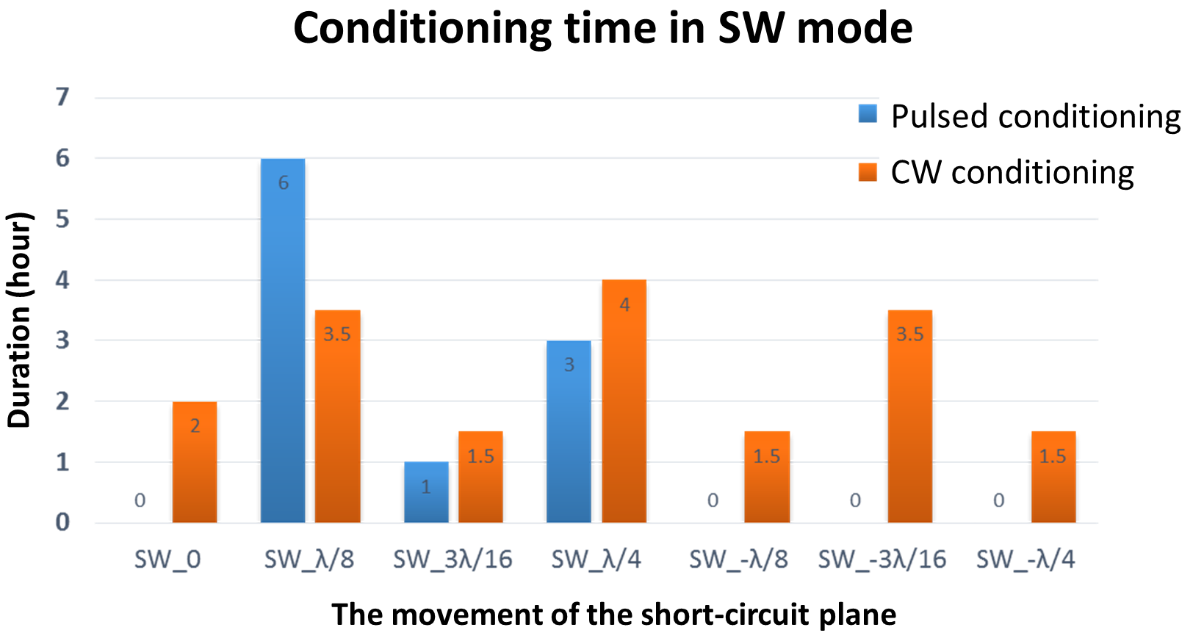
- **Conditioning method**
  - Pulsed mode (20 hours)
  - CW mode (10 hours)
  - Alternating pulsing and CW

Conditioning in SW mode

166MHz SSPA

- The short-circuit plane was moved by λ/8 (~225 mm) each time
- Maximum power reached: 50kW CW
- Conditioning method：pulsed mode and CW mode

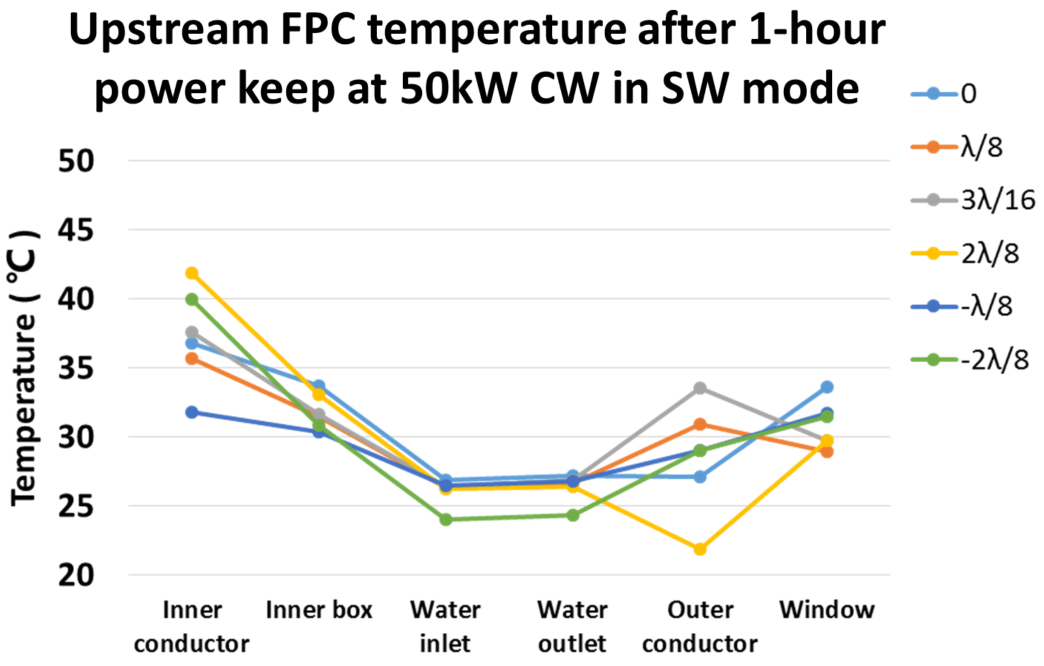


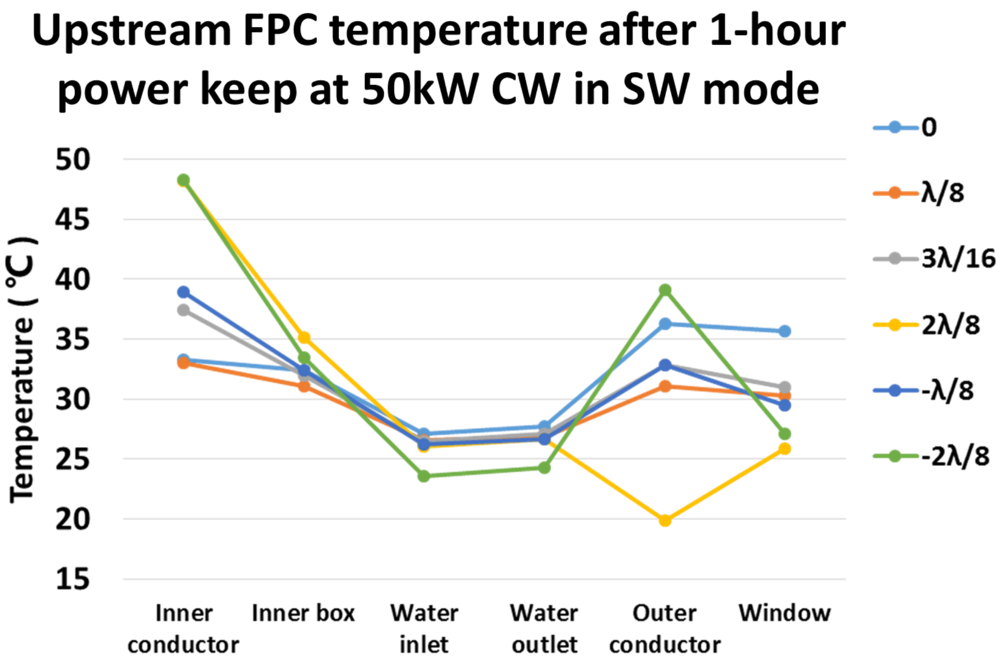


Conditioning in SW mode

166MHz SSPA

- The electric antinode was moved along the FPC
- After 1-hour power keep at 50kW CW (E_{max} on the ceramic window)
  - The temperature rise <4°C (6°C) on the upstream (downstream) window
  - Vacuum and temperature was normal during power keep

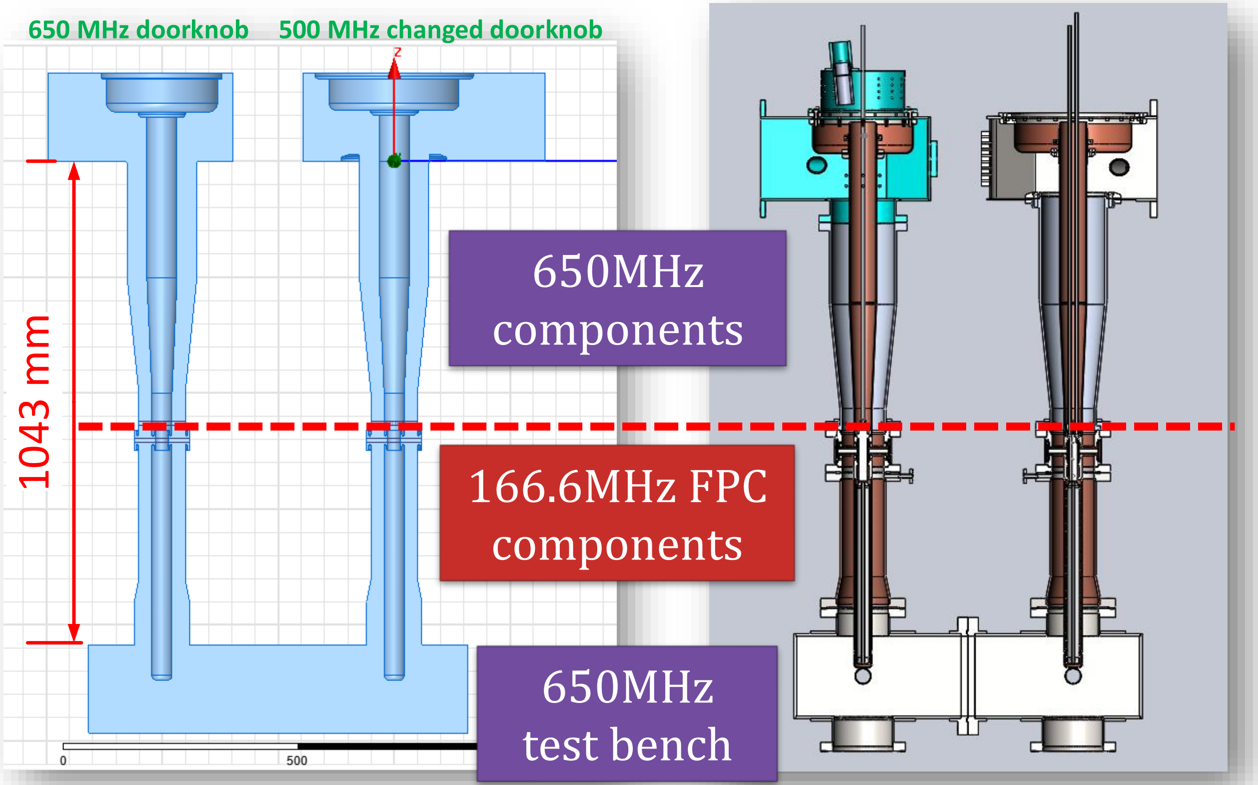




HPC by 650MHz SSPA

650MHz SSPA

To examine high power handling capability of the window, power conditioning at 150kW CW was implemented by using the existing 650MHz 150kW SSPA with a hybrid test bench setup.



The RF optimization   The mechanical drawing

- The test bench system consists of
  - Two window inner-conductor assemblies of the 166.6MHz FPC
  - One doorknob from existing 650MHz FPC
  - One modified doorknob from existing 500MHz FPC (scaled to 650MHz)
  - One WG-box used for BEPCII 500MHz FPC conditioning

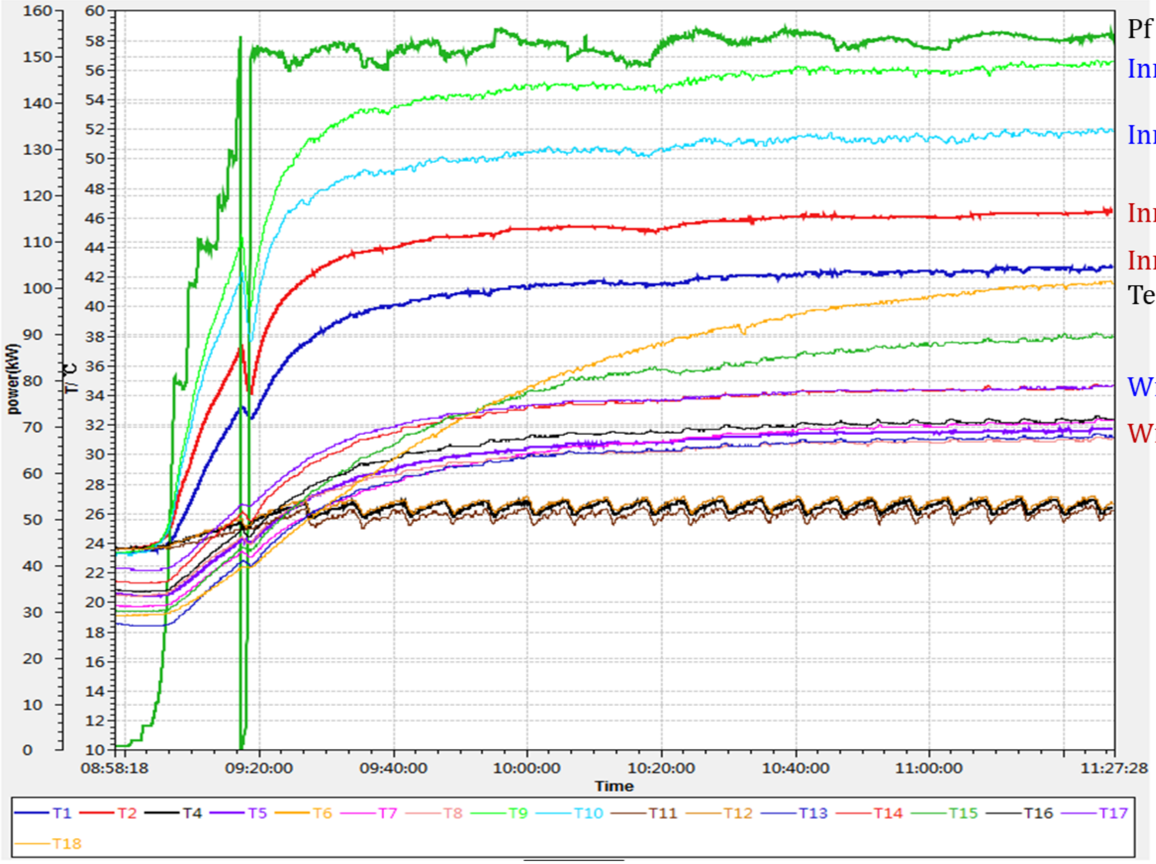
The setup

650MHz SSPA

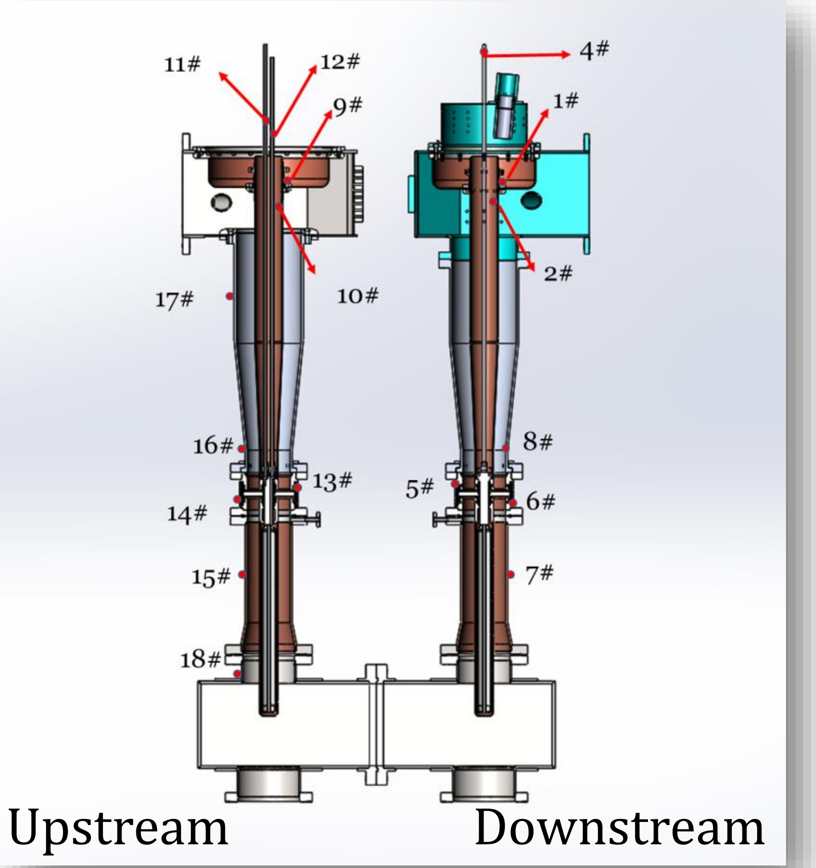
Temperature

650MHz SSPA

- The temperatures were recorded during power keep at 150kW CW
- Maximum temperature reached 55°C at T-sensor 9# of upstream FPC
- Window temperature below 35°C

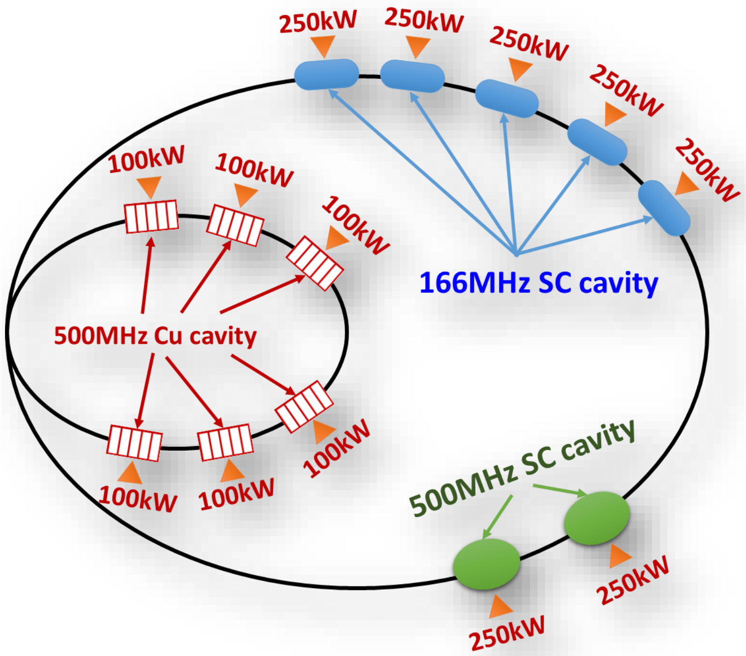


T-sensors



Summary

- HPRF system for the HEPS project has been designed
- 1.25MW@166.6MHz and >600kW@500MHz power sources are required
- Solid-state technology are adopted
- Power couplers at 166.6MHz for SRF cavity have been successfully conditioned



What's next

- **Working closely with our vendors for both 166.6MHz and 500MHz SSPA**
  - ✓ Better cooling for the 2kW power unit (power supply)
  - ✓ Suppress current harmonics (40% → 10%)
  - ✓ Longer pulse (increase power storage elements in the power supply)
  - ✓ Evaluate power combination schemes

- **Questions?**
  - ✓ Output power linearity, early compression (efficiency)? From operation point of view?
  - ✓ Output signal phase distortion, the cause?

Backup slides

Power handling capability

650MHz/166.6MHz = 3.9

Dielectric loss: $\sim f$

Metal surface loss: $\sim f^{0.5}$

Scaled to 166.6MHz

	166.6MHz 50kW SSPA [kW]	650MHz 150kW SSPA [kW]
Ceramic window	50	585
Metal part	50	296