

# X-band Solid State Amplifier for the PAL-XFEL

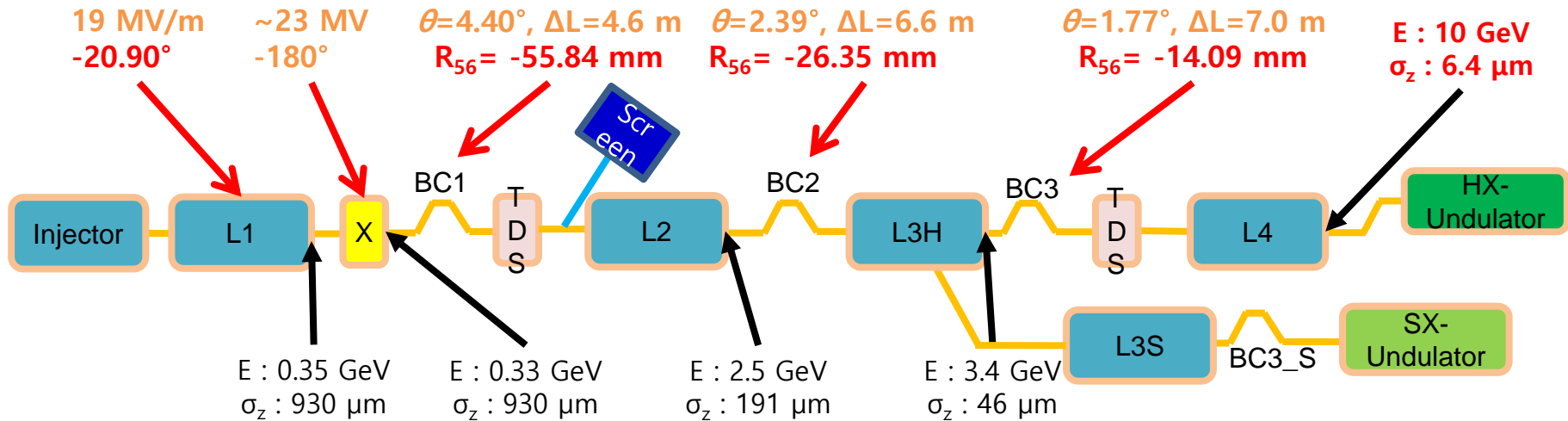
Hoon Heo

Pohang Accelerator Laboratory

# Contents

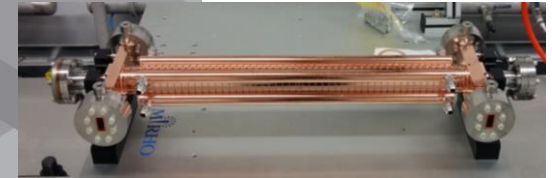
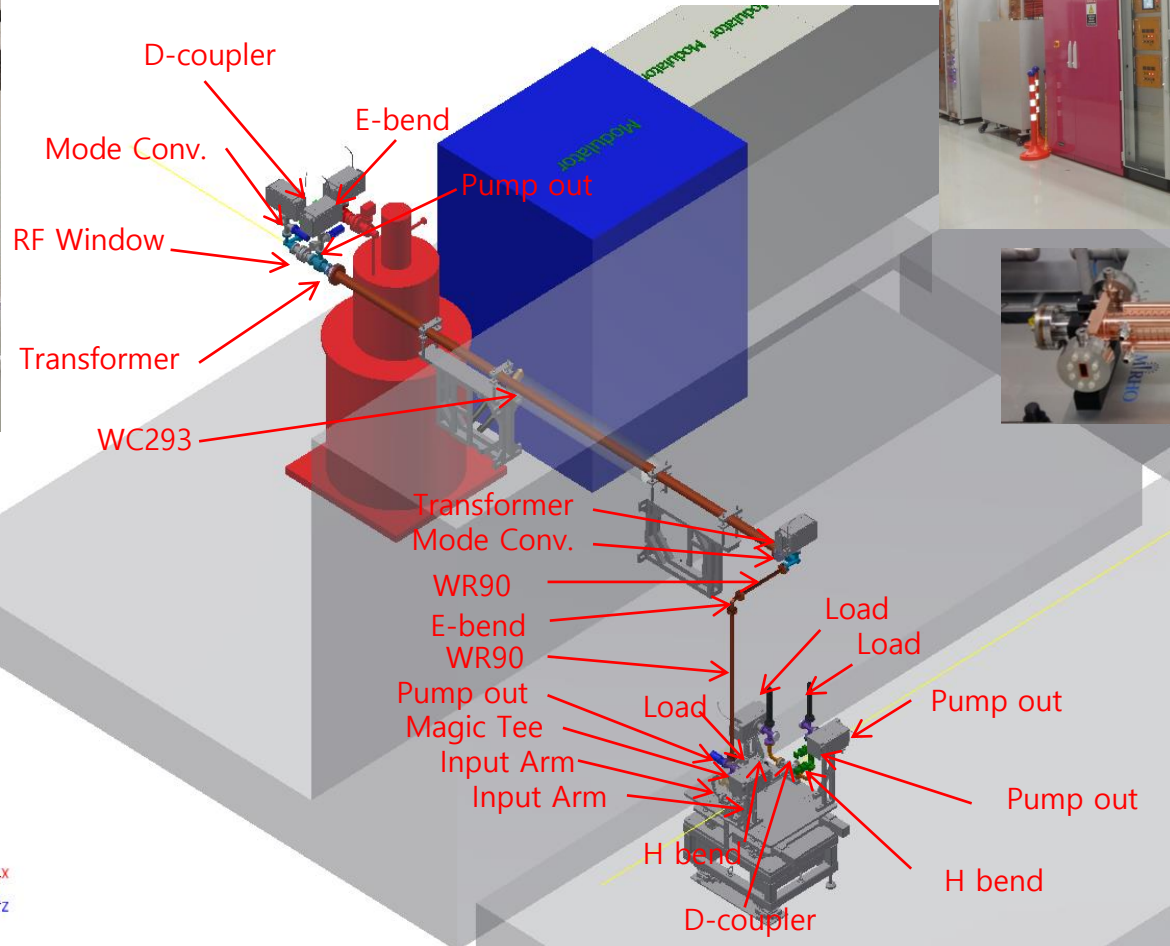
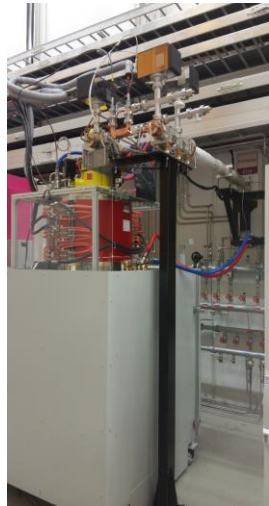
- X-band linearizer for the PAL-XFEL
- Design of a SSPA for the PAL-XFEL
- Performance of the SSPA
- Future plan for a better SSPA for XFEL
- Summary

# PAL-XFEL Layout

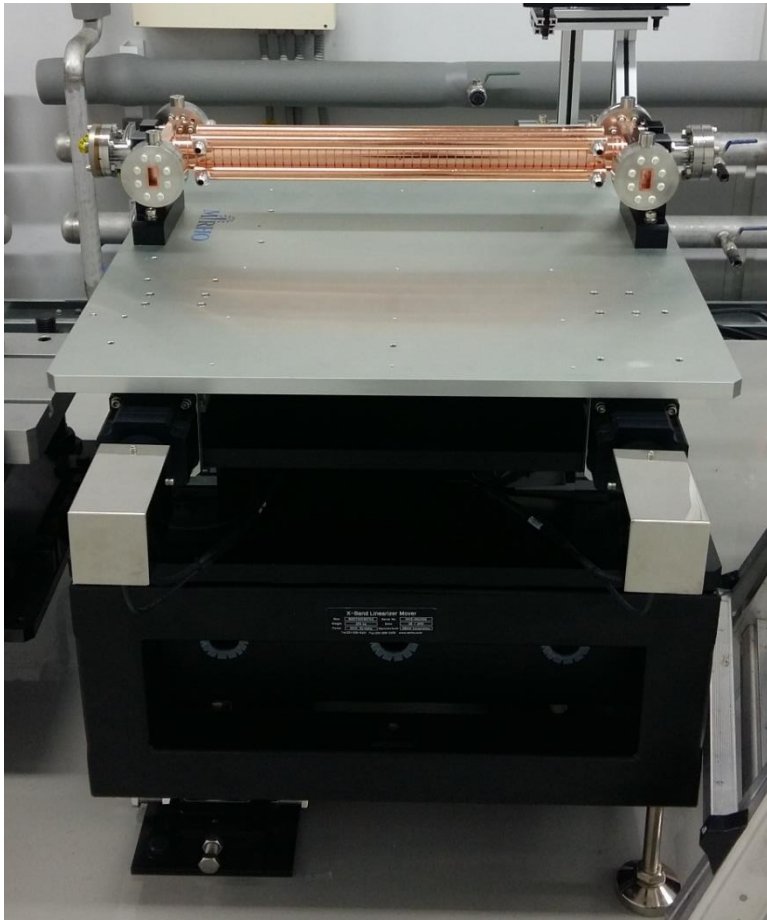


Sector	# of klystrons	Tolerance(rms)	
		Phase [deg.]	Voltage [%]
L1 (S-band)	2	0.02	0.015
<b>X band linearizer</b>	<b>1</b>	<b>0.06</b>	<b>0.05</b>
L2 (S-band)	10	0.04	0.025
L3 (S-band)	4	0.1	0.05
L4 (S-band)	27	0.1	0.05

# X-band RF System



# X-band Accelerating Structure



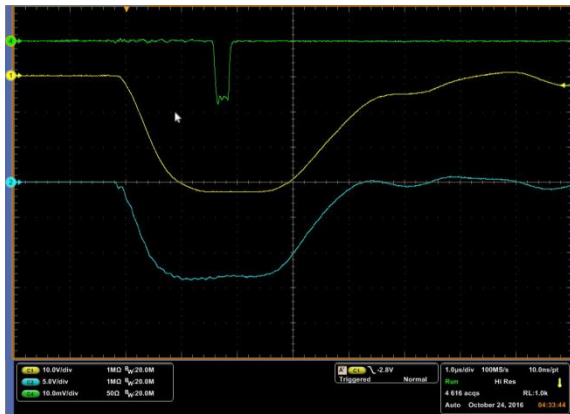
## H60VG3 X-band Accelerating Structure

Operating Frequency	11.424	GHz
Length	60	cm
Phase advance per cell	$5\pi/6$	MW
Filling time	105	ns
Shunt impedance	48.8~78.8	M $\Omega$ /m
Group velocity	3.2 ~ 1.2	vg/c (%)
Fundamental mode Q	~6955	
Attenuation	0.54	Np
Power needed acc. gradient of 50 MV/m	37.4	MW
Gain	50	dB

## Moving Stage

Dir.	Moving range	Moving resolution	Position accuracy
X	$\pm 2$ mm	5 $\mu$ m	20 $\mu$ m
Y	$\pm 2$ mm	5 $\mu$ m	20 $\mu$ m
Pitch	$\pm 0.4^\circ$	0.005 $^\circ$	0.01 $^\circ$
Yaw	$\pm 0.4^\circ$	0.005 $^\circ$	0.01 $^\circ$

# X-band Klystron & Modulator



## XL-4 Klystron

Operating Frequency	11.424	GHz
RF Pulse Length	1.5	$\mu$ s
Peak Output Power	>50	MW
Repetition rate	60	Hz
RF Efficiency	40	%
Bandwidth	120	MHz
Max. Beam Voltage	440	kV
Perveance	1.2	$\mu$ P
Gain	50	dB

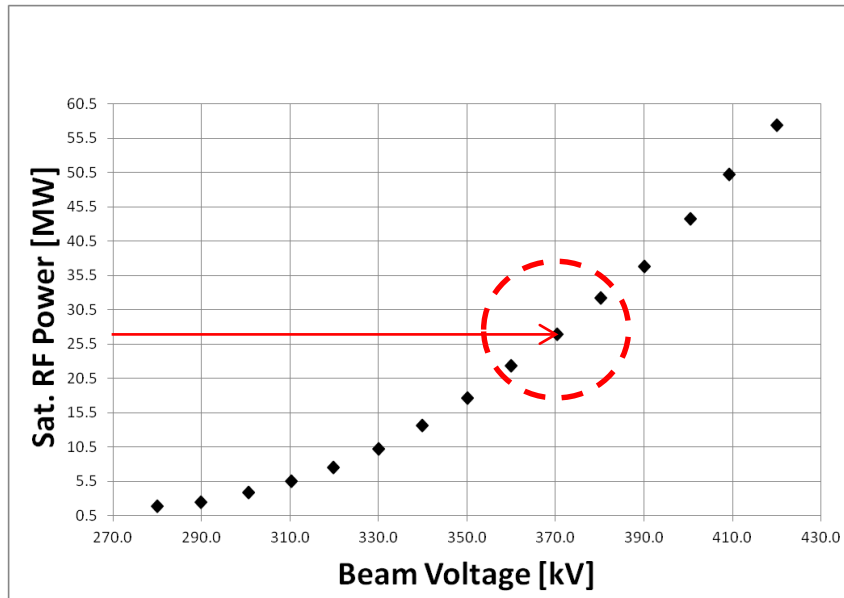
## Klystron Modulator

Max. Voltage	> 410	kV
Pulse Length	2	$\mu$ s
Max. Repetition rate	60	Hz
Focusing Magnet Power supply	300	A
Voltage stability	< 30	ppm

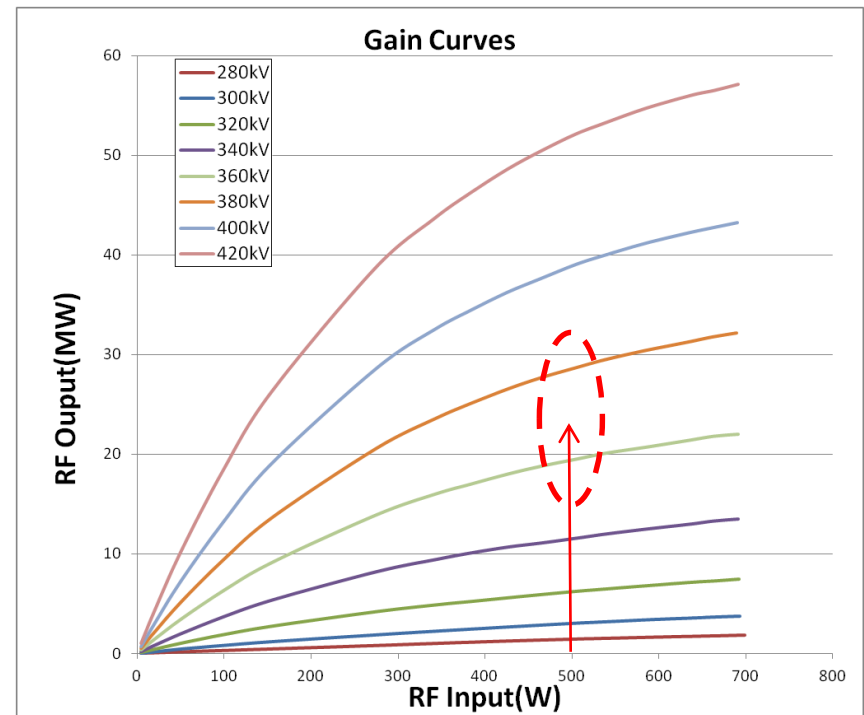
# X-band Klystron Test



## Saturation RF Power



## Gain



Required driver power > 1 kW

# X-band LLRF Controller



## X-band LLRF

Frequency	REF : 2.856 GHz
	PAD & PAC : 11.424 GHz
PAD Ch. number	10 (8 Ch + 2 REF)
Phase stability	0.1 (RMS, Degree)
Amp. stability	0.04 (> -5dBm) (RMS, Voltage(%))
PAC pulse rising time	< 15ns
PAD input power range	Ref : 0 ~ 5 dBm
	CH : -8 ~ +8 dBm
PAC output power range	-8 ~ +8 dBm



# X-band Klystron Drive Amp.



## TWTA



## SSPA



### X-band TWTA

Max. RF Power	1.2	kW
Max. Repetition rate	100	kHz
Amplitude Variation	< 0.1	dB
Phase stability	+ - 1	Deg.

### X-band SSPA

Max. RF Power	1.4	kW
Max. Repetition rate	60	Hz
Amplitude Variation	< 0.1	dB
Phase stability	< 0.1	Deg.

# Key Design Features



- Main amp. transistor type : GaN HEMT
- Power combining : 20 ways radial power combiner
- Bias class : Near B class
- Band width : Narrow band
- Cooling : Forced air
- Protection : Isolator and temp. sensor

# Main Amp. Transistor



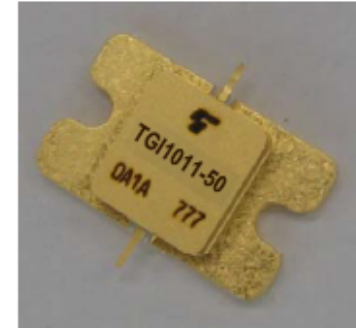
**TOSHIBA**

**MICROWAVE POWER GaN HEMT  
TGI1011-50-771**

MICROWAVE SEMICONDUCTOR TECHNICAL DATA

## FEATURES

- **BROAD BAND INTERNALLY MATCHED HEMT**
- **HIGH POWER**  
Pout= 47.0dBm at Pin= 41.5dBm
- **HIGH GAIN**  
GL= 9.0dB at 11.424GHz
- **HERMETICALLY SEALED PACKAGE**



## RF PERFORMANCE SPECIFICATIONS ( Ta= 25°C )

CHARACTERISTICS	SYMBOL	CONDITIONS	UNIT	MIN.	TYP.	MAX.
Output Power	Pout	VDS= 24V IDSset= 1.5A f= 11.424 GHz @Pin= 41.5dBm	dBm	46.0	47.0	—
Drain Current	IDS		A	—	5.0	6.0
Power Added Efficiency	$\eta_{add}$		%	—	30	—
Linear Gain	GL	@Pin= 20dBm	dB	7.0	9.0	—
Channel Temperature Rise	$\Delta T_{ch}$	(VDS X IDS + Pin - P1dB) X Rth(c-c)	°C	—	130	160

**Recommended Gate Resistance(Rg): 13.3  $\Omega$**

# Main Amp. Transistor



## ELECTRICAL CHARACTERISTICS ( Ta= 25°C )

CHARACTERISTICS	SYMBOL	CONDITIONS	UNIT	MIN.	TYP.	MAX.
Transconductance	gm	VDS= 5V IDS= 5.0A	S	—	4.5	—
Pinch-off Voltage	VGSoff	VDS= 5V IDS= 23mA	V	-1.0	-4.0	-6.0
Saturated Drain Current	IDSS	VDS= 5V VGS= 0V	A	—	16.0	20.0
Gate-Source Breakdown Voltage	VGSO	IGS= -10mA	V	-10.0	—	—
Thermal Resistance	Rth(c-c)	Channel to Case	°C/W	—	1.4	1.6

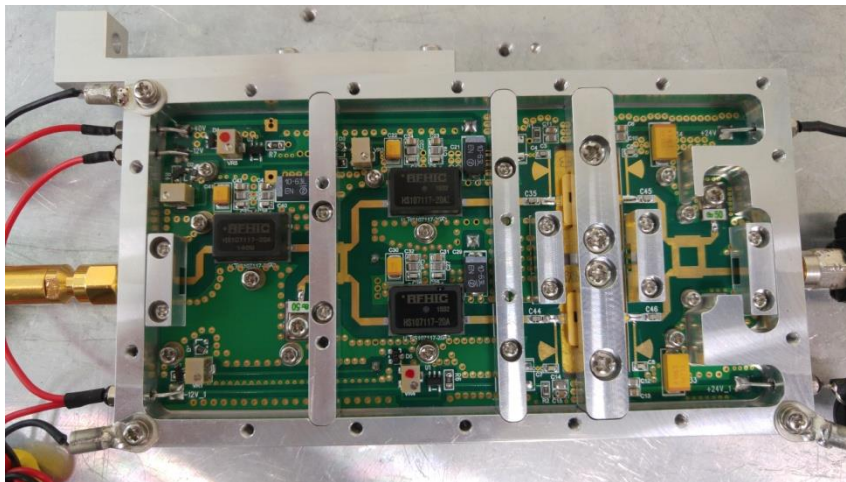
## ABSOLUTE MAXIMUM RATINGS ( Ta= 25°C )

CHARACTERISTICS	SYMBOL	UNIT	RATING
Drain-Source Voltage	VDS	V	50
Gate-Source Voltage	VGS	V	-10
Drain Current	IDS	A	15.0
Total Power Dissipation (Tc= 25°C)	PT	W	140
Channel Temperature	Tch	°C	250
Storage Temperature	Tstg	°C	-65 to +175

# Main Module



## Main Module Test



## Test Results

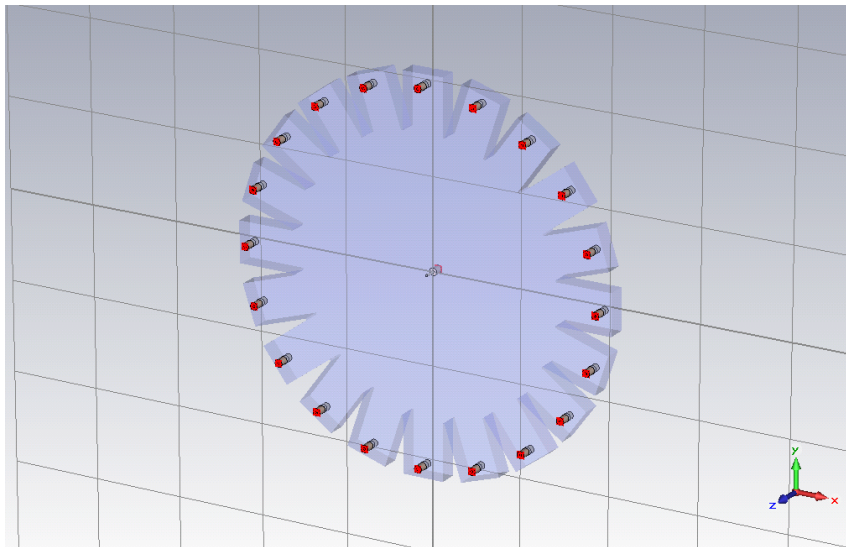


Test module	Pout [dBm]	Gain [dB]	Phase [deg]
# 1	49.21	29.16	149.06
# 2	49.40	29.73	155.81
# 3	49.30	29.54	157.06

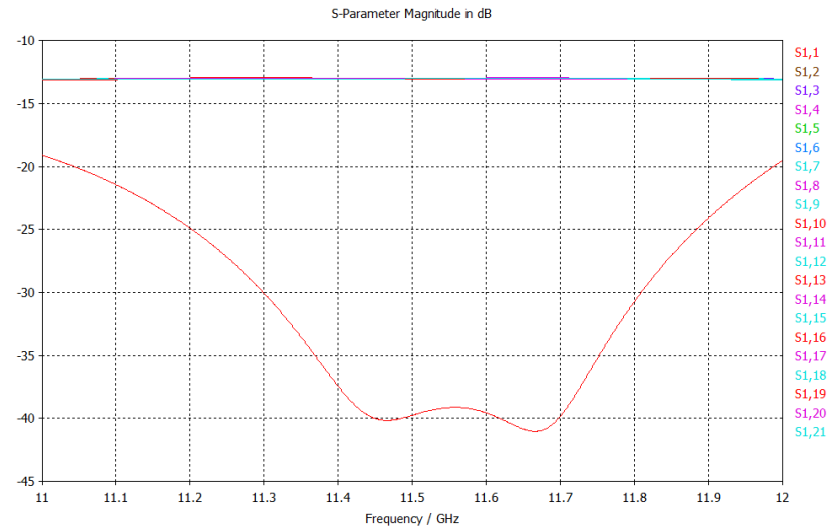
# Radial Power Splitter Design



## Design model

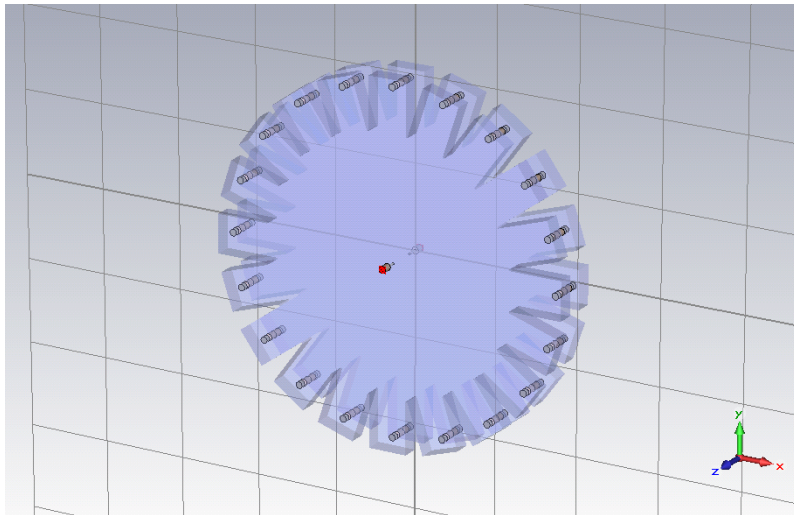


## Simulation result

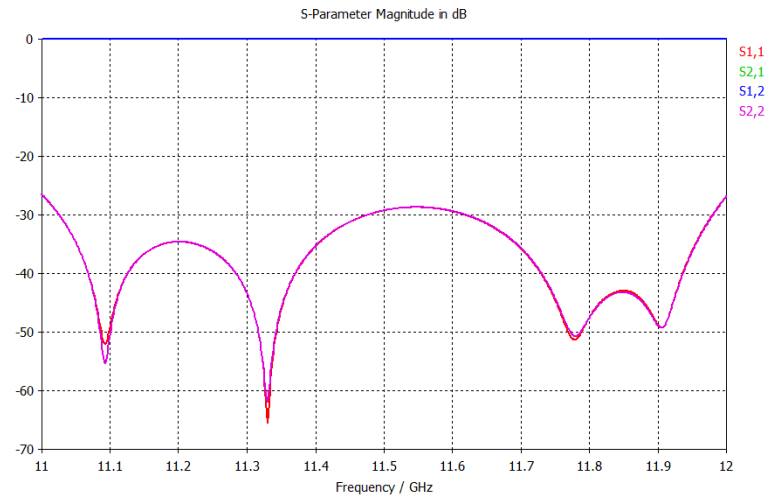


# Radial Power Combiner Design

## Design model



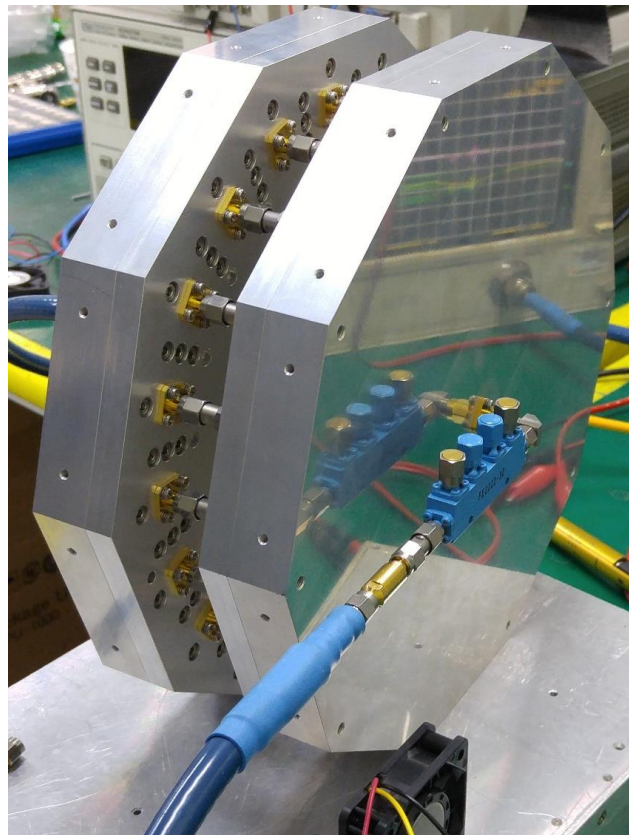
## Simulation result



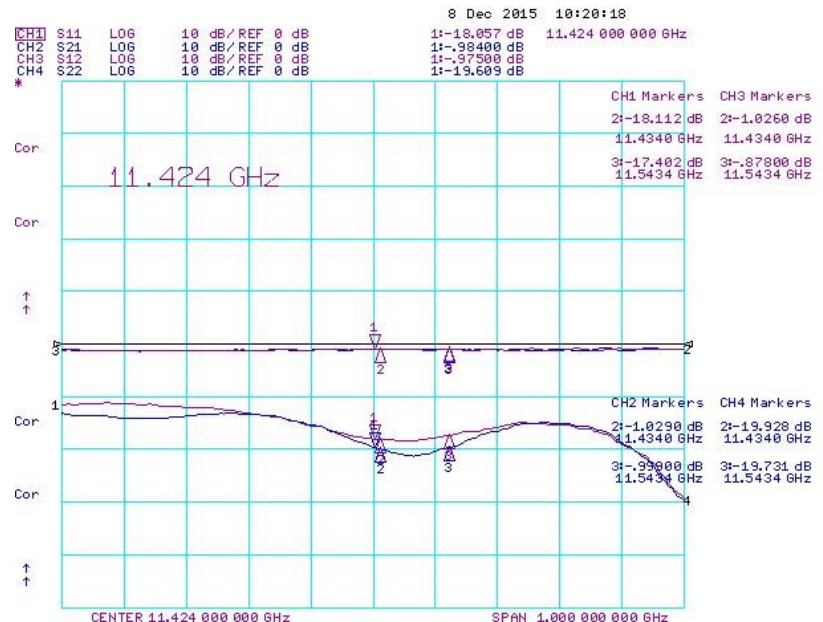
# Radial Power Combiner Test



## Back to Back test



## Test result

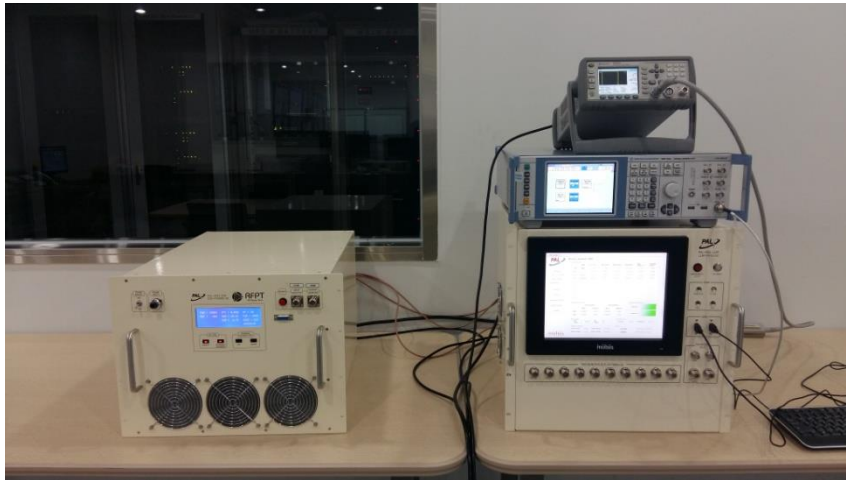




# Pulse to Pulse Stability Lab Test



## Test setup



## Test Equipment

- Signal source :  
Rodhe&Schwarz signal generator
- Pulse RF generator : X-band LLRF PAC
- Pulse RF stability measurement: X-band LLRF PAD

# Typical Lab Test Result



Parameter	Design target	Unit	Measured Results			Note
			Min	Typ	Max	
Band width		MHz	11423.95	11424	11424.05	
Power gain	60dB $\pm$	dB	60.01	59.99	60.01	@1.2kW Pout
Input power range	+4 ~ -10	dBm	-10	0	4	
Saturation power @ P <sub>SAT</sub>	$\geq$ 1kW	W		1200		
Pulse rise time	< 30nsec	nsec		8.53		
Pulse over shoot	< 10%	%		-		
Pulse droop	< 0.1dB	dB		0.55		
Pulse to pulse amp. stability	< 0.05%	%		0.08		
Pulse to pulse phase. stability	< 0.06°	°		0.07		
Harmonics level	< -40dBc @ P1dB	dBc		-68.93		
Spurious signal level	< -60dBc @ P1dB	dBc		-62.02		
Noise Figure	< 10dB	dB		-		9.73
Input VSWR	< 1.22:1		1.0213	1.0216	1.0219	
Output VSWR	< 1.22:1		1.1297	1.1291	1.1293	

# TWTA V.S. SSPA



## TWTA Stability

Amp. : ~ 0.07 %  
Phase: ~0.15 °

The screenshot shows the PAL software interface for TWTA stability monitoring. The main window is titled 'main\_page' and contains several sections:

- Monitor Tab:** A table showing PAD Monitor data for various channels.
- Device:** INJ, LLRF03
- Run mode:** Operating
- Buttons:** Monitor, Control, Manager Control, Admin Control, Graph
- Klystron Monitor:** A table showing Mean and Stability for Time window 1 and Time window 2 for channels KBV and KBC.
- Interlock Monitor:** Internal IL and External IL status indicators (green).
- PAC Power:** ON, PAC Status, PM
- Temperature:** System 40.438, RF Module 31.624

Name	Power(dBm)	Org. Power	Peak Power	Phase(Deg.)	RMS Power (%)	Diff RMS Phase
REF	REF	-1.649	-1.649	-1.627	324.125	0.027
CH9		3.286	3.286	3.331	168.009	0.027
CH3	SSA In	-37.283	-40.483	-37.520	296.468	6.124
CH4	SSA Out	56.648	0.688	56.744	206.828	0.071

	Time window 1		Time window 2	
	Mean	Stability	Mean	Stability
KBV	0.00000	0.053	0.00000	2.382
KBC	0.00000	0.042	0.00000	3.080

## SSPA Stability

Amp. : ~ 0.08 %  
Phase: ~0.07 °

The screenshot shows the PAL software interface for SSPA stability monitoring. The main window is titled 'main\_page' and contains several sections:

- Monitor Tab:** A table showing PAD Monitor data for various channels.
- Device:** INJ, LLRF03
- Run mode:** Operating
- Buttons:** Monitor, Control, Manager Control, Admin Control, Graph
- Klystron Monitor:** A table showing Mean and Stability for Time window 1 and Time window 2 for channels KBV and KBC.
- Interlock Monitor:** Internal IL and External IL status indicators (green).
- PAC Power:** ON, PAC Status, PM
- Temperature:** System 37.965, RF Module 29.880
- Target & Output:** Target Power 3.000, Target Phase -312.300, Output Power 3.000, Output Phase -312.300
- Time:** Current 2016-09-21 15:43:47, Uptime 05:21:19 up 0 days

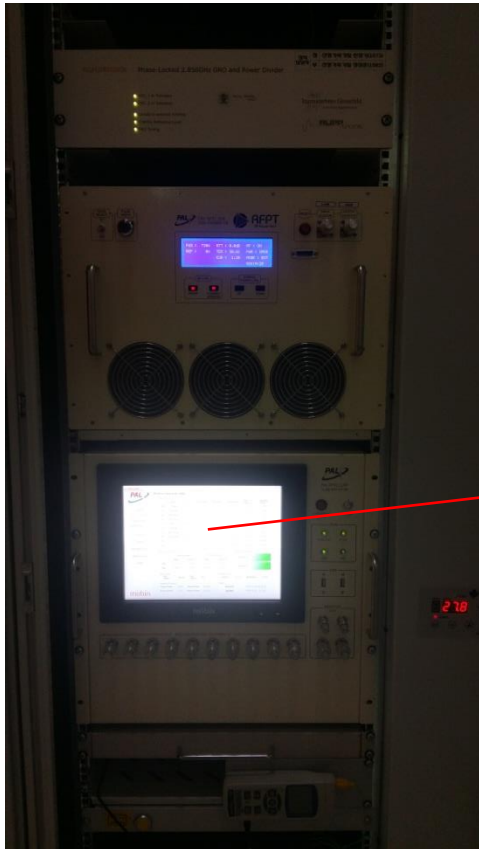
Name	Power(dBm)	Org. Power	Peak Power	Phase(Deg.)	RMS Power (%)	Diff RMS Phase
REF	REF	-1.403	-1.403	-1.381	332.526	0.028
CH9		3.627	3.627	3.649	129.766	0.029
CH3	SSA In	-2.455	-2.455	-2.238	356.815	0.080
CH4	SSA Out	5.469	5.469	6.128	254.539	0.077

	Time window 1		Time window 2	
	Mean	Stability	Mean	Stability
KBV	0.00000	0.064	0.00000	0.204
KBC	0.00000	0.043	0.00000	17.137

# But Pulse to Pulse Stability at Linac Gallery



## DRO, SSPA, and LLRF in a Rack



## Amp. stability degrade

Amp. :  $\sim 0.12\%$

Phase:  $\sim 0.05^\circ$

main\_page 33

**PAL**

Run mode  
Operating

Monitor  
Control  
Admin Control  
Graph

Monitor Interlock SSPA HL1:LLRFXL1

PAD Monitor

Name	Power(dBm)	Org. Power	Peak Power	Phase(Deg.)	RMS Power (%)	Diff RMS Phase	
REF	CW	5.075	5.075	5.081	162.688	0.007	0.006
CH3	SSA IN	2.032	-3.468	3.727	141.283	0.108	0.070
CH4	SSA OUT	59.636	5.736	60.769	261.999	0.115	0.045
CH6	Kly In F	53.560	-9.440	54.262	276.587	0.417	0.220
CH7	Kly F	102.613	2.613	103.119	275.494	0.149	0.068
CH5	Kly R	75.407	-23.593	83.967	39.077	1.664	0.673
CH8	ACC Out F	97.906	0.806	98.967	303.889	0.112	0.072
CH2	ACC Out R	70.902	-19.198	77.903	65.069	0.710	0.382
CH1		-21.841	-50.112	-7.864	171.964	13.341	220.752
CH9		0.341	0.341	0.372	304.705	0.045	0.045

Klystron Monitor

	Time window 1		Time window 2	
	Mean	Stability	Mean	Stability
KBV	3.22301	0.013	3.23155	0.002
KBC	5.26669	0.003	5.26670	0.002

Interlock Monitor

Internal IL

External IL

PAC Power  
PAC Power ON PAC Status PM

Temperature  
System 41.383 RF Module 31.694

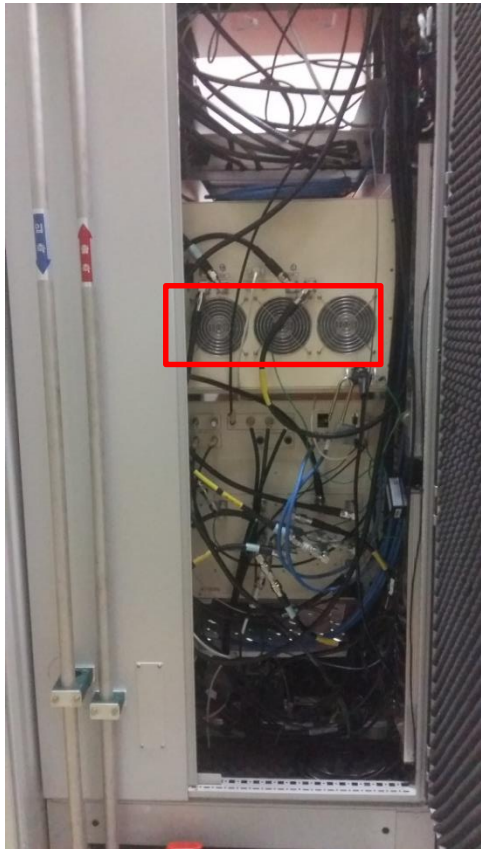
Target & Output  
Target Power 5,000 Target Phase 83,980  
Output Power 5,000 Output Phase 84,003

Time  
Current 2016-10-24 08:40:46  
Uptime 18:37:19 up 32 days

# Amp. Stability Degradate



## Rear View Inside RF rack



## Some Degradation Sources

- Vibration from the cooling fans
- Case distortion due to its weight

# Summary

- This SSPA shows successful performance for our application, comparing the TWTA.
- But it is required to fix the degradation problem in amplitude stability by reinforcing the mechanical stability.