Development of a cavity-type power combiner for 509 MHz solid state amplifiers

June 21, 2016, CWRF 2016 in Grenoble, France

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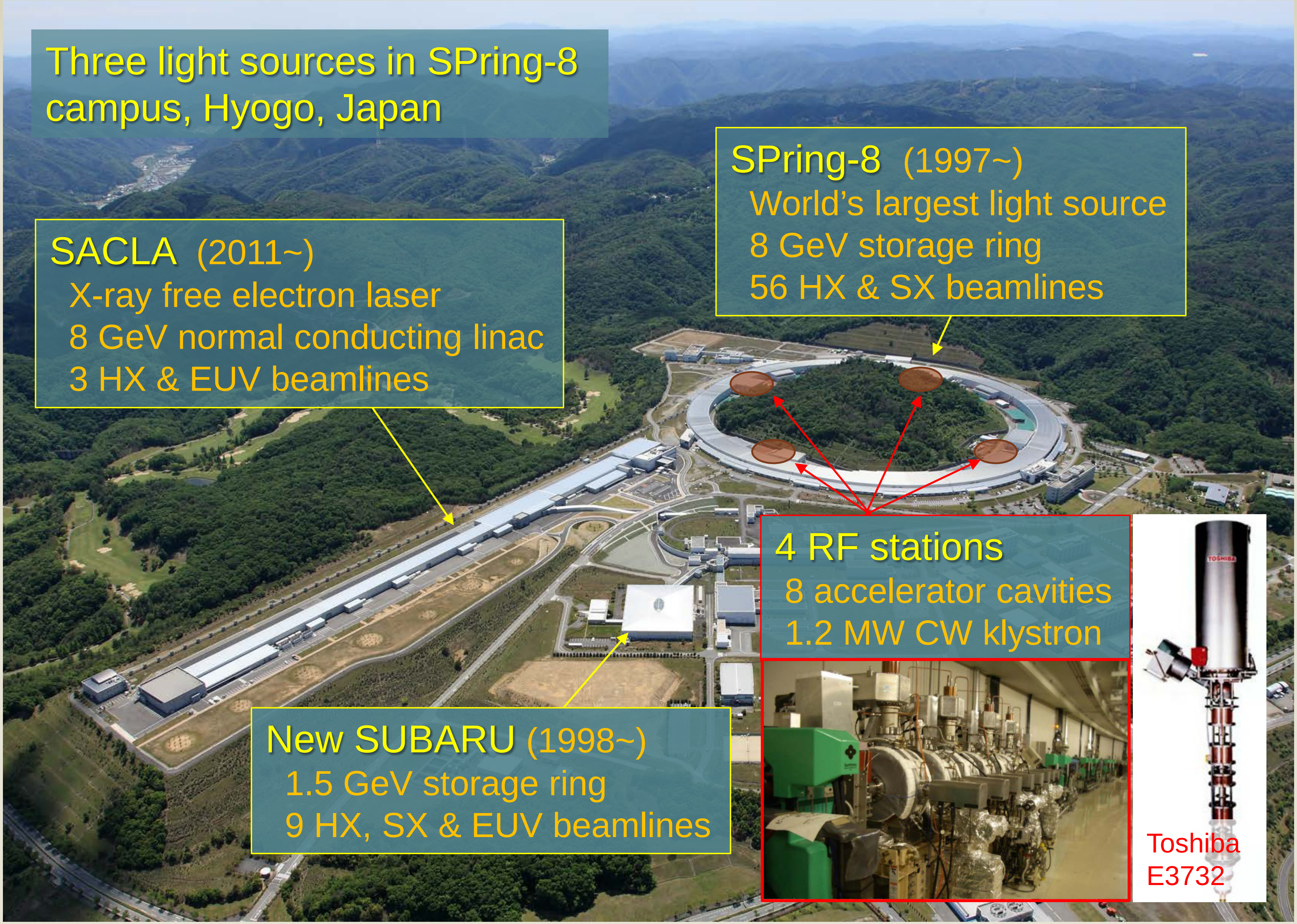
RIKEN SPring-8 JASRI MITSUBISHI ELECTRIC Changes for the Better

Outline

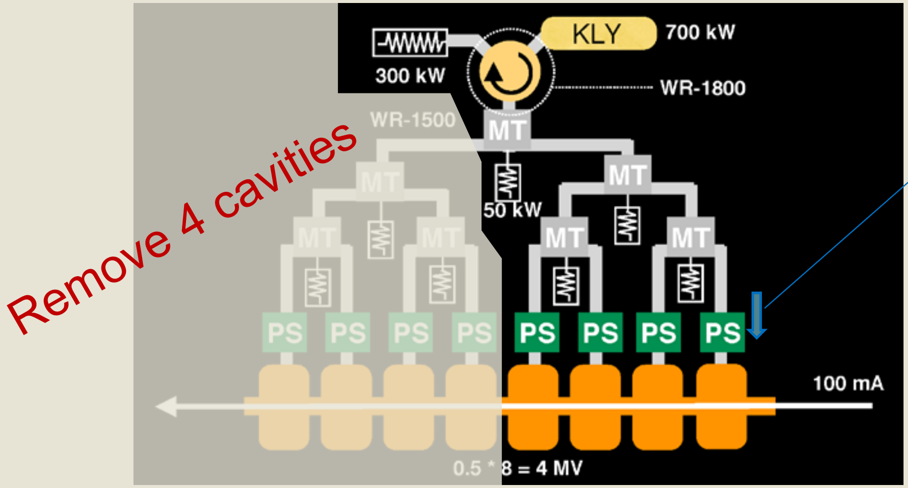
- Introduction
- Concept and design
- Prototype combiner measurement
- Summary



Three light sources in SPring-8 campus, Hyogo, Japan
SPring-8 (1997~)
World’s largest light source
8 GeV storage ring
56 HX & SX beamlines
SACLA (2011~)
X-ray free electron laser
8 GeV normal conducting linac
3 HX & EUV beamlines
4 RF stations
8 accelerator cavities
1.2 MW CW klystron
New SUBARU (1998~)
1.5 GeV storage ring
9 HX, SX & EUV beamlines
Toshiba
E3732

SPring-8-II project (proposal, ~early 2020s)

	SPring-8-II	SPring-8
• 20 enhanced X-ray brilliance	~10^{21}	~10^{20}
• Lower natural emittance	0.1 nmrad	2.4 nmrad (non-acromat)
• Multi-bend lattice	5-bend acromat	2-bend
• Lower electron beam energy	6 GeV	8 GeV
• Beam acceleration voltage	7 MV/turn	16 MV/turn
• RF cavity	4 x 4 stations	8 x 4 stations



Cavity parameters for SPring-8-II

Impedance	6 MΩ
Input power	64 kW
Cavity loss	32 kW
Beam loading	32 kW (100mA)
Acceleration voltage	440 kV

Solid state amplifier is practically available in this power. (Motivation)

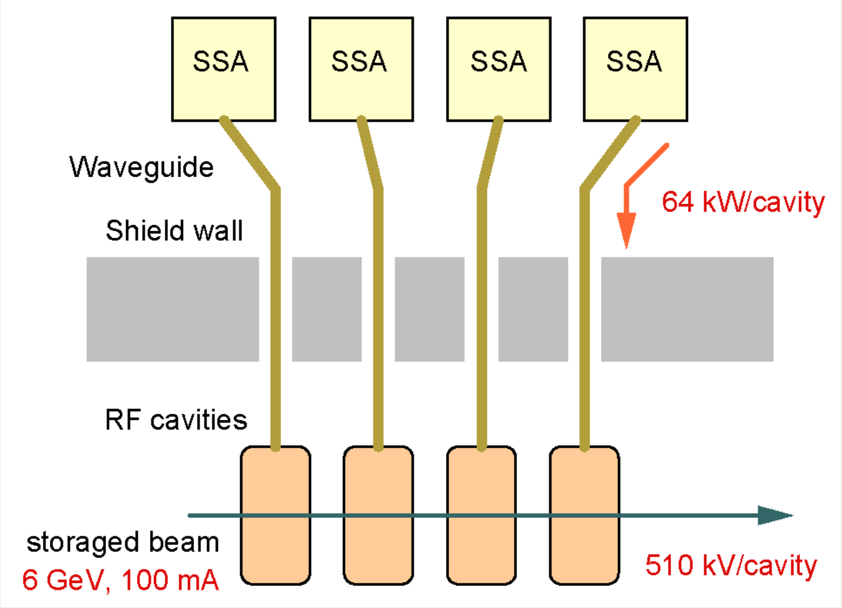
Solid state amplifier option for future upgrade

- We designed the SSA for future replacement of the SPring-8-II RF source
- Target performance
  - Frequency 508.762 MHz (RF frequency for Spring-8-II ring)
  - Output power: >110 kW (99 kW in 3-station operation)
  - Power efficiency: > 60% (klystron >60%)

- Power efficiency is one of the critical issues for SSA (typically 40~50%).
- LDMOS transistor itself; η_D>70%

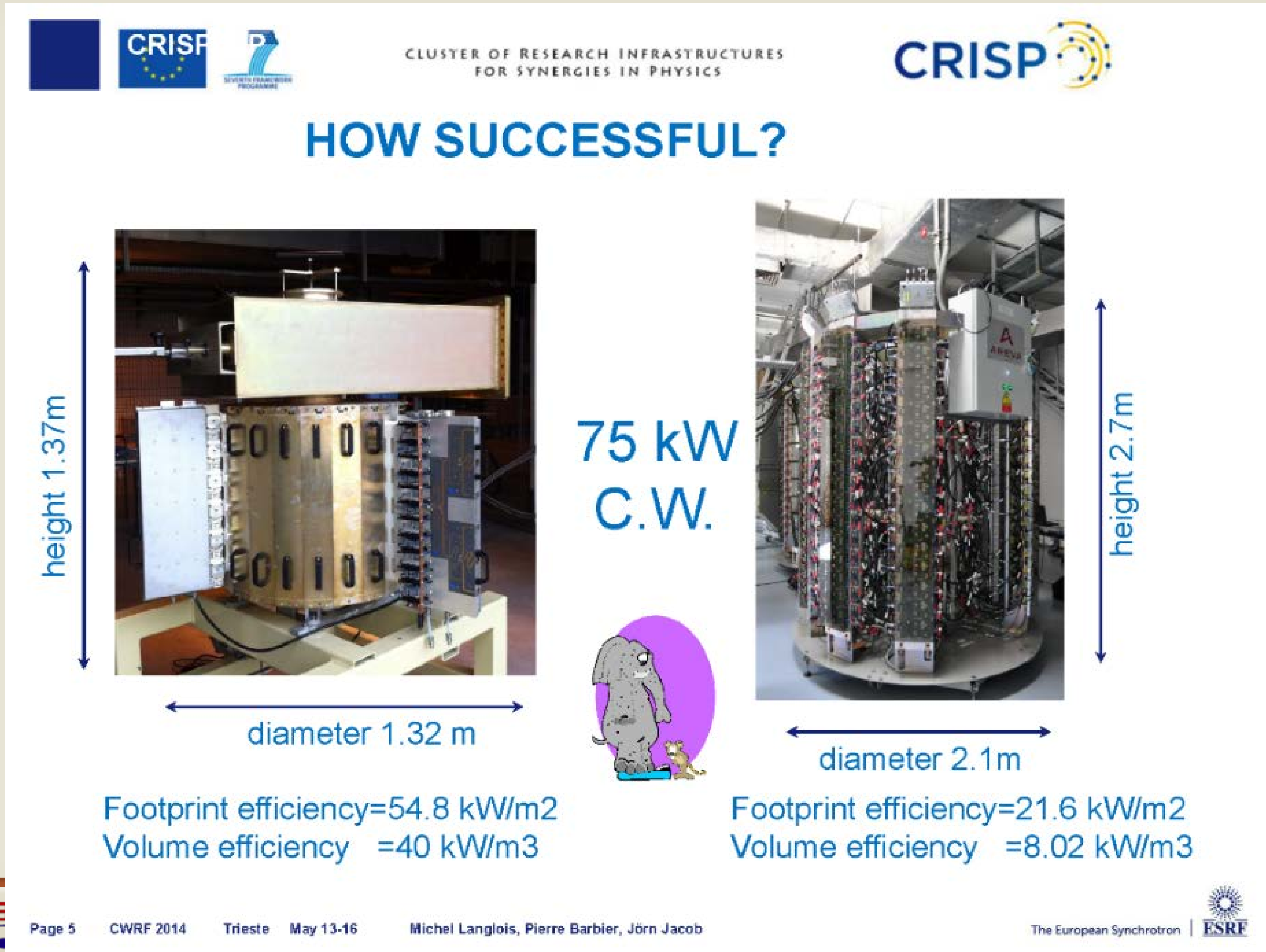
  but…..
  - Cable loss
  - Combiner loss
  - Circulator loss, ….

Low loss cavity-type combiner (Cable loss, Combiner loss)



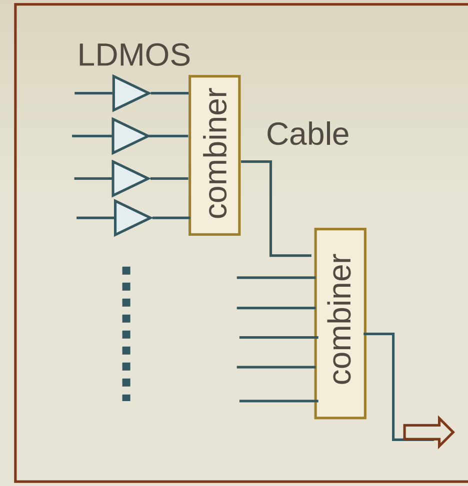
Example of the cavity combiner development

Presented by Michel Langlois,   in CWRF 2014

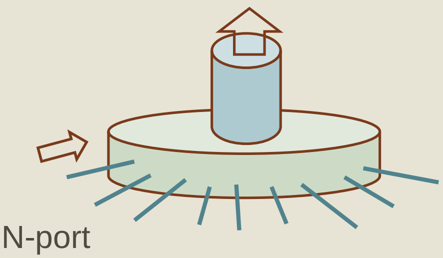


Power combining scheme

- We have to combine the RF power of 100~200 LDMOS transistors to obtain 110 kW.

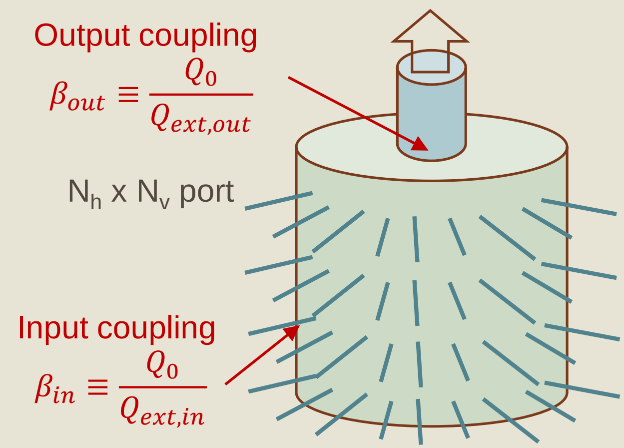


- Tournament type
  - Large insertion loss (many combiners & cables)
- Radial combiner
  - Number of port N is limited by the cavity size.



- Cavity combiner
  - Number of port N' = N_h x N_v
  - Minimum cavity loss $\sim \frac{1}{N' \cdot \beta_{in}} = \frac{Q_{ext,in}}{N' \cdot Q_0}$

    at $N' \cdot \beta_{in} = \beta_{out}$
- Large N' and Q_0 are preferable.



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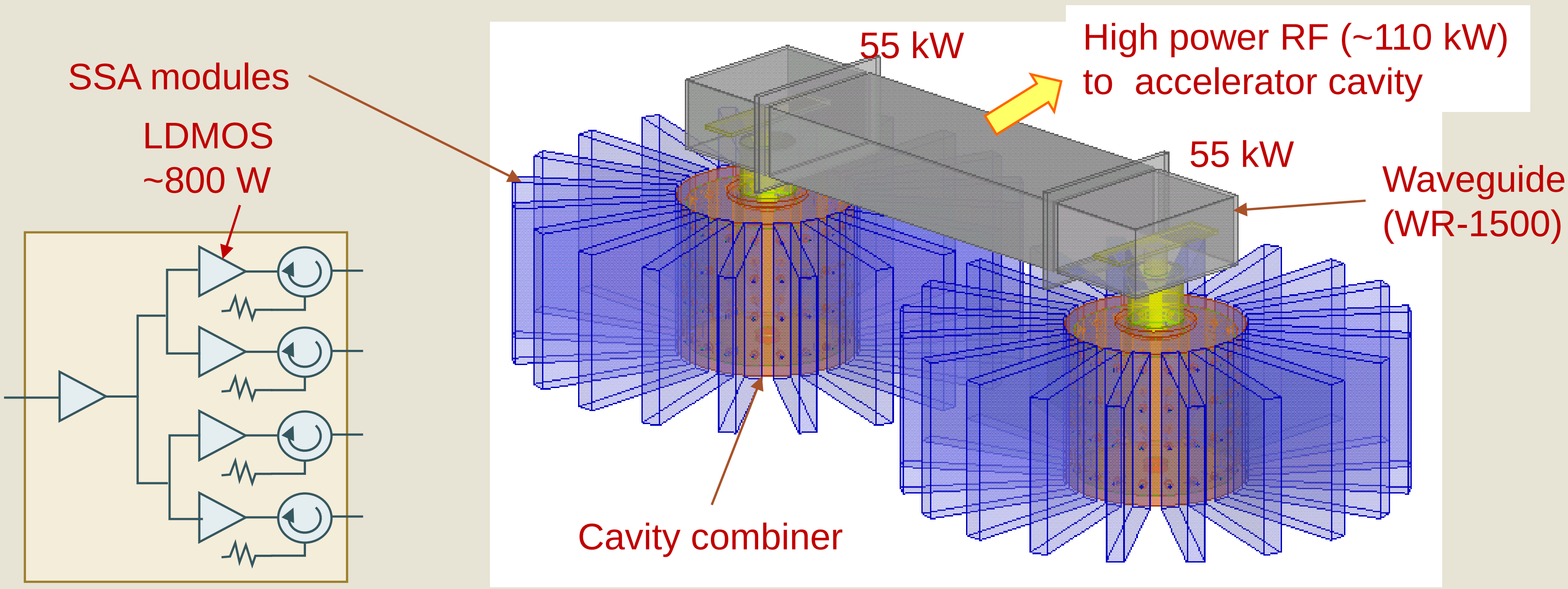
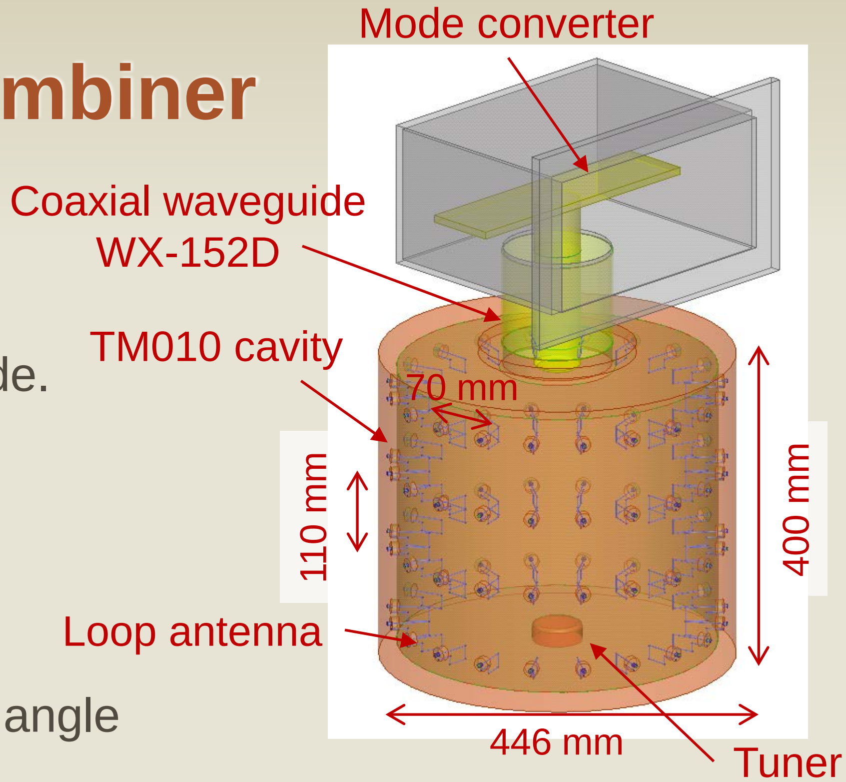
Concept of our solid state amplifier

- SSA module (20 modules x 2 units)
  - 4 LDMOS, circulators, and pre-amp. are on the heat sink.
  - Modular design, for maintainability and productivity.
- Cavity combiner
  - Efficiently combining RF power from 20 SSA modules

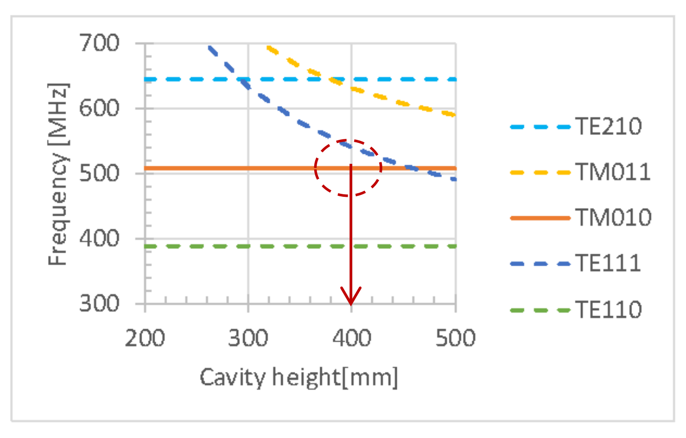


Concept of our cavity combiner

- TM010 cavity
  - Axially symmetric (uniform) EM field
  - Height is selected to separate TE mode.
  - Frequency tuner at the bottom
- Input port
  - 80 loop antennas (4 x 20)
  - Coupling is adjusted by loop size and angle
- Output port
  - Electrical coupling to coaxial waveguide
  - Coupling is adjusted by the inner conductor
- Waveguide mode converter
  - T-type mode converter



RF mode chart (r=226 mm)



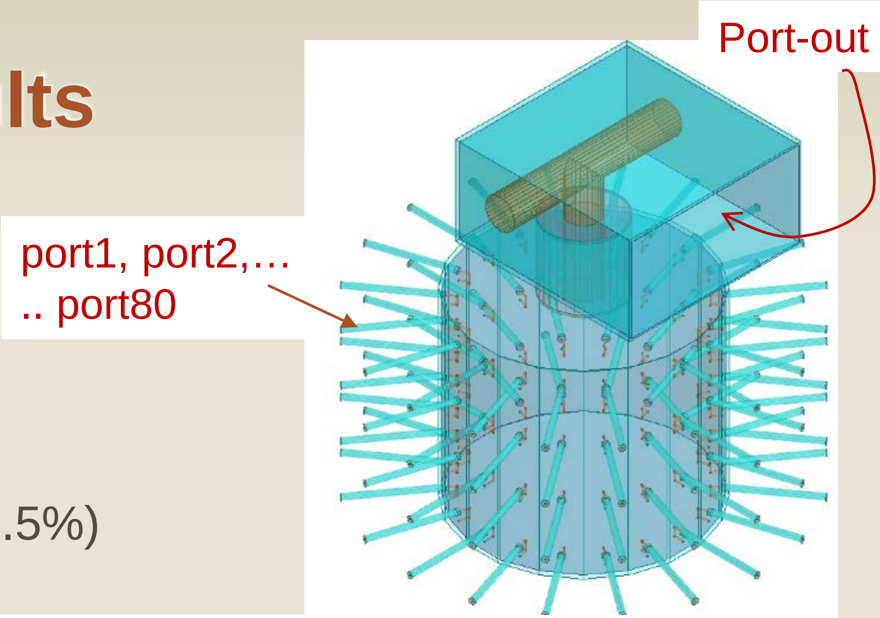
Cavity combiner, design parameters

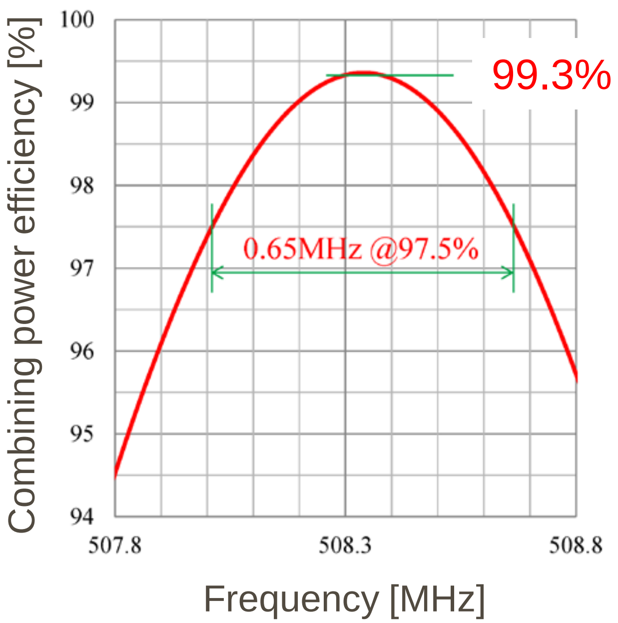
	Design	
Frequency (f)	508.762 MHz	
Cavity diameter	446 mm	
Cavity height	400 mm	
Unloaded Q (Q_0)	46,600	95% of ideal copper cavity
Number of input N	80	
Input coupling β_{in}	2.9	Loop antenna, 18 x 18 mm
Output coupling β_{out}	233	Coax. Waveguide, WX-152D
Loaded Q (Q_L)	100	$(= Q_0/(1 + N \cdot \beta_{in} + \beta_{out}))$
-3dB band width (Δf_{3dB})	5.1 MHz	$(= f/Q_L)$
Combining efficiency (η)	99.6%	$(\sim 1 - 1/\beta_{out})$

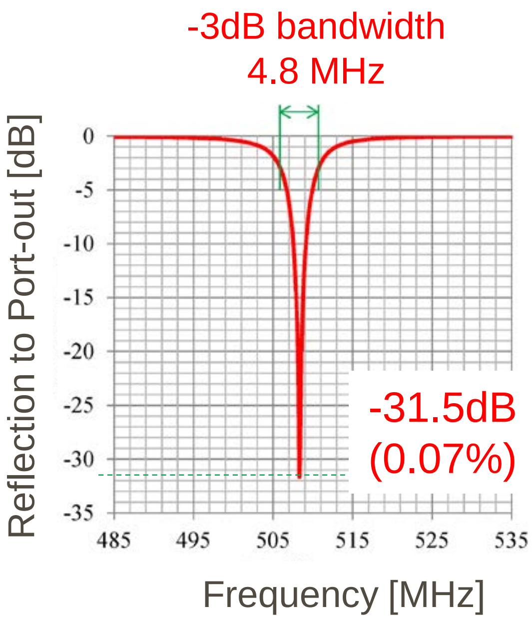
Assumed maximum operation $\boldsymbol{P_{in} = 800\ W,\ P_{out} = 64\ kW}$		
Cavity loss (P_{cav})	270 W	$(\sim P_{out}/\beta_{out})$
Stored energy	3.9 mJ	$(\sim P_{cav} \cdot Q_0/\omega)$

HFSS simulation results

- We obtained design performance
  - Combining efficiency > 99%
  - Power reflection < 0.1%
  - Frequency range ~ 0.65 MHz (>97.5%)







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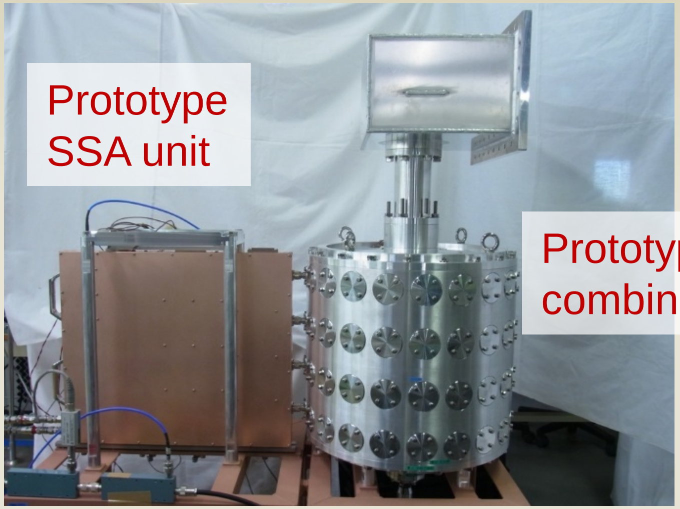
Prototype combiner test

Practically confirm and demonstrate

- TM010 cavity properties
- Adjust frequency and coupling
- Combining RF power of SSA unit

Today

- High power performance and cooling



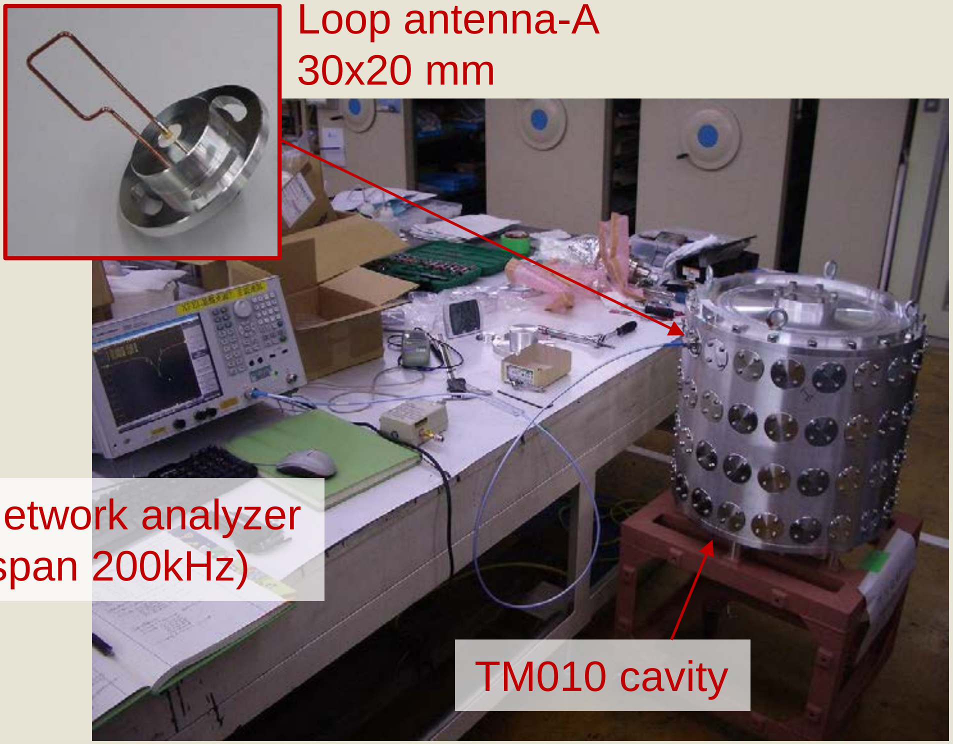
	Real combiner	Prototype combiner	
Cavity material	Copper	Aluminum (AL5052)	
Unloaded Q (Q_0)	46,600	27,600 (95% of ideal cavity)	
Output coax.	WX-152D	WX-77D (for lower coupling)	
Input antenna	80	80	4
Input coupling (β_{in})	2.9	1.7	4.8
Output coupling (β_{out})	233	136	19
Power efficiency	>99%	99%	95%
-3dB band width (Δf_{3dB})	5.1 MHz	5.1 MHz	0.7 MHz

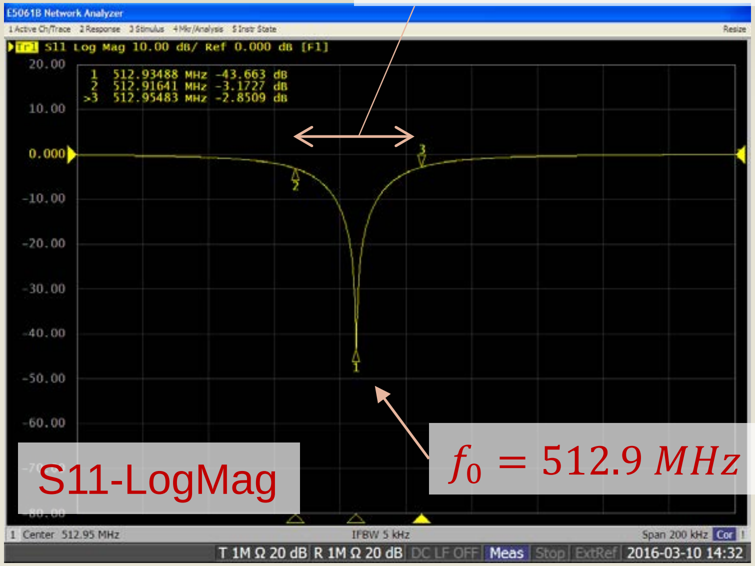
For combining test with SSA

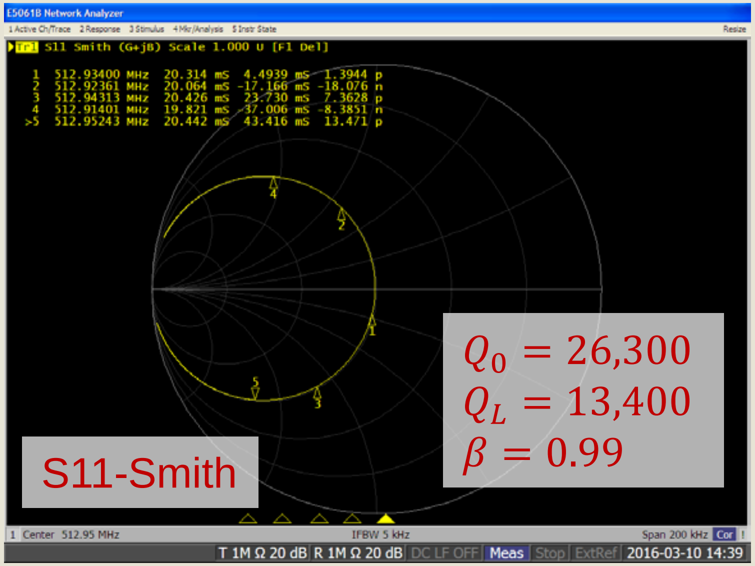
1) Measurement of the TM010 cavity

$\Delta f = 38\ kHz$
$Q_L = f_0/\Delta f = 13{,}400$

- Measure the reflection from the cavity.
  - Resonant frequency (f_0)
  - Q-factor (Q_0, Q_L)
  - Coupling (β_{in}) of the loop antenna



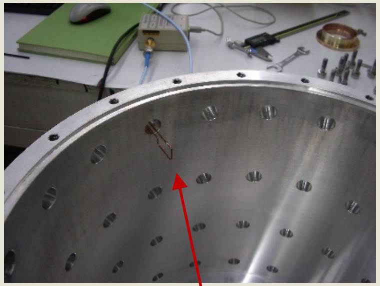




Measured cavity parameters

- Measured Q_0 is 90% of the ideal cavity.
- After machining 80 holes
  - Frequency shift ~ 300 kHz
- After machining of the cylinder diameter
  - $\Delta f / \Delta D = 1.1\ MHz/mm$

✓ Confirm TM010 resonance and high Q_0, well agreed with the simulation.



Coupling hole	Diameter	f_0 [MHz]	Q_0	Q_L
1 hole	440.9 mm	520.391	26,300	13,400
80 holes	440.9 mm	520.078	25,500	13,400
80 holes	447.2 mm	512.935	26,300	13,400
Simulation Ideal AL cavity	455 mm	504.733	29,200	

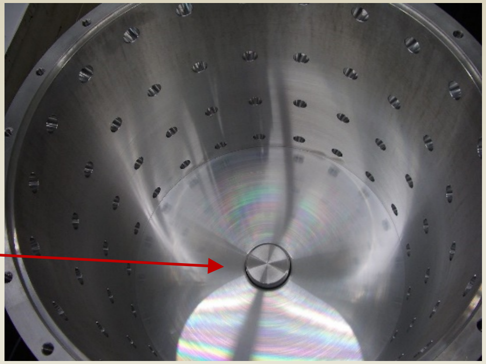
2) Frequency adjustment

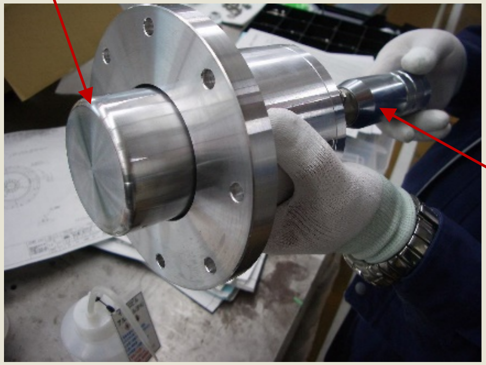
✓ Enough tuning range of 503~513 MHz.

- But insertion of the tuner decreases Q_0 (-40%) and distorts the TM010 field.

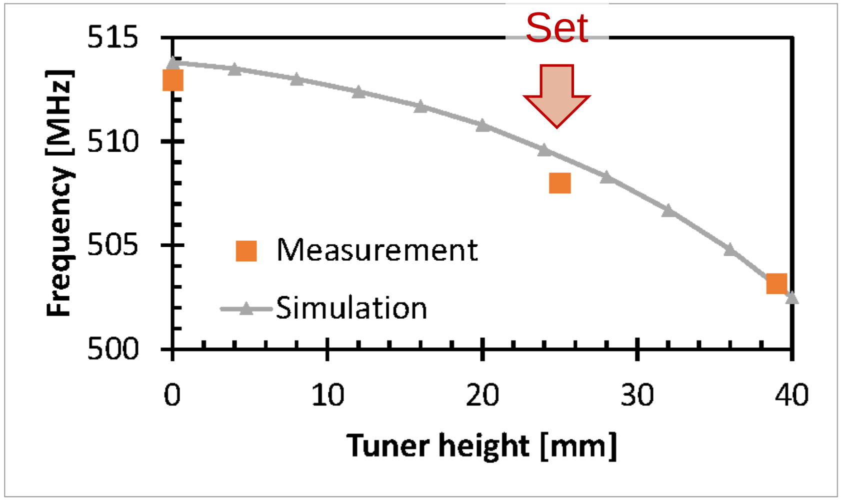
✓ When we make actual combiner, narrower tuning range and lower tuner height is better.

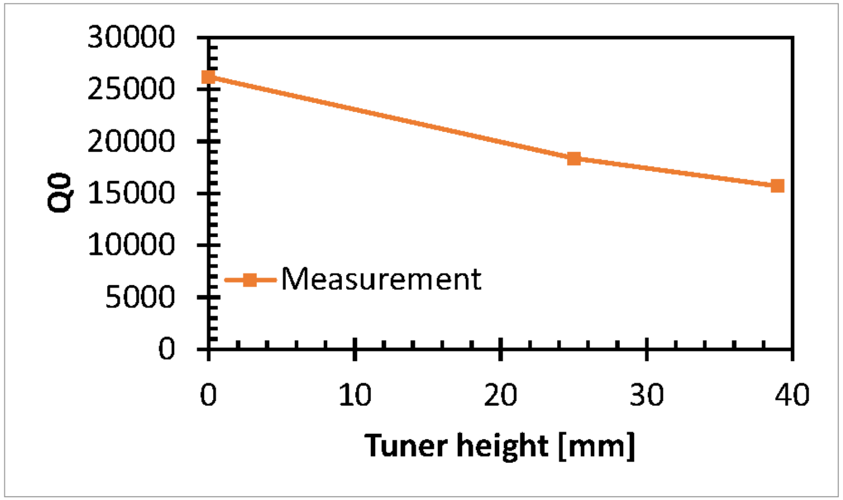
Tuner head ϕ70 mm





Screw 0-40mm

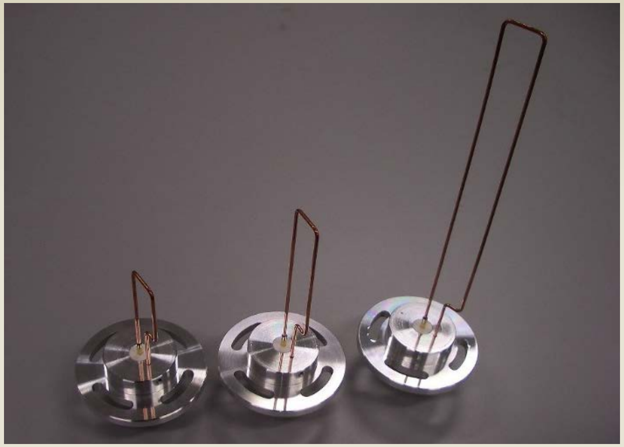




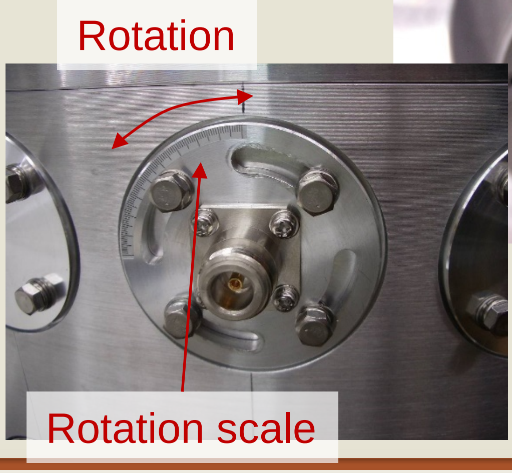
3) Input coupling adjustment

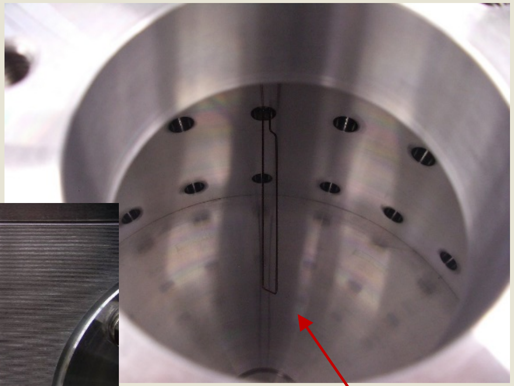
✓ Confirmed the coupling can be changed and proportional to $cos\theta$.

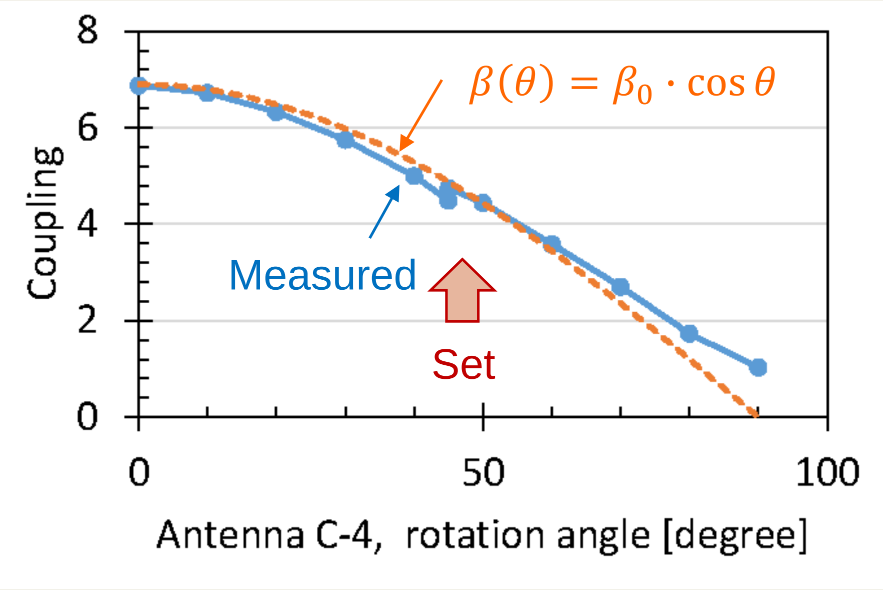
- We prepared 3 sizes of loops.
- For 4-port combining test, we use largest loop and set at $\theta = 45\ deg.$ and $\beta_{in} \sim 4.8$



Antenna-A	Antenna-B	Antenna-C
30 x 20 mm	60 x 20 mm	140 x 20 mm
$\beta_{in}\sim 1.0$	$\beta_{in}\sim 1.5$	$\beta_{in}\sim 7$



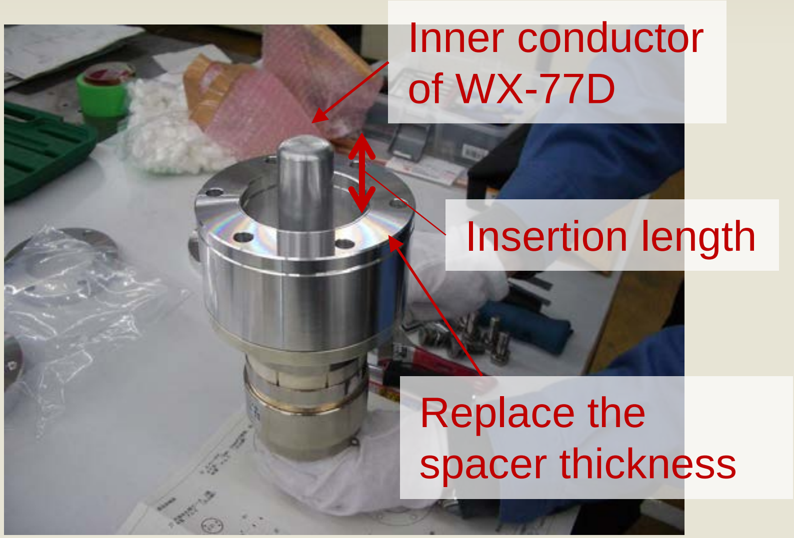


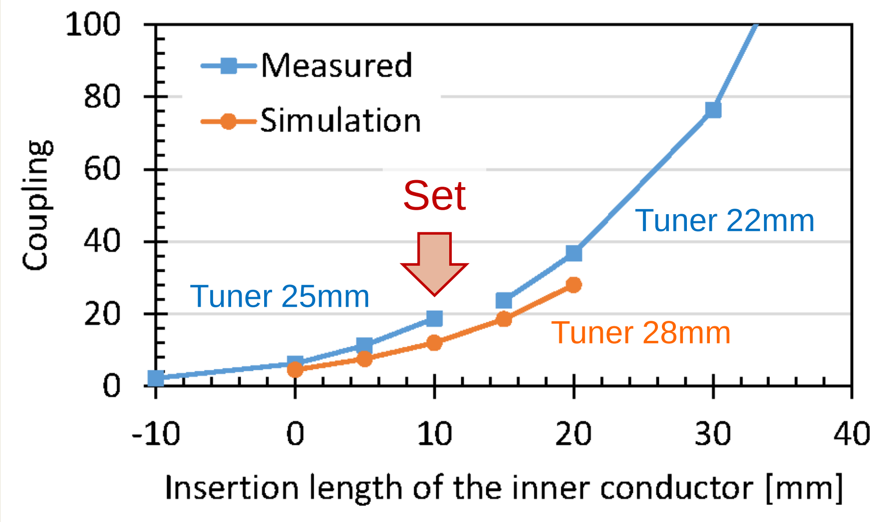


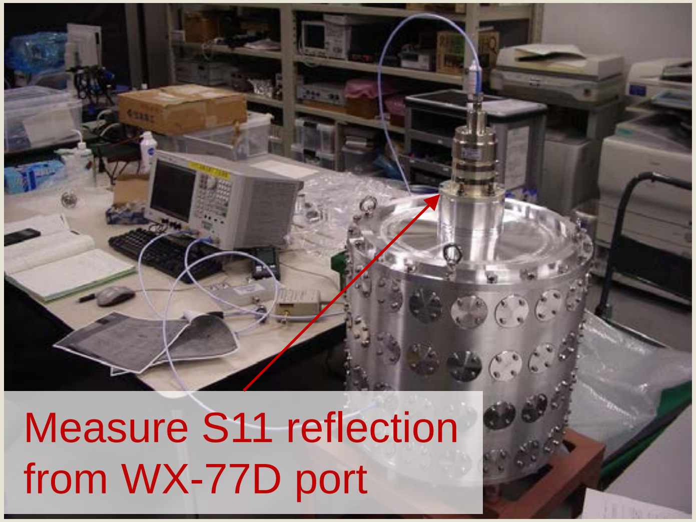
4) Output coupling adjustment

✓ Confirmed the coupling factor was adjusted by changing the insertion length of the inner conductor.

- For 4-port combining test
  - Insertion length: 10 mm
  - Coupling factor: $\beta_{out} = 19$



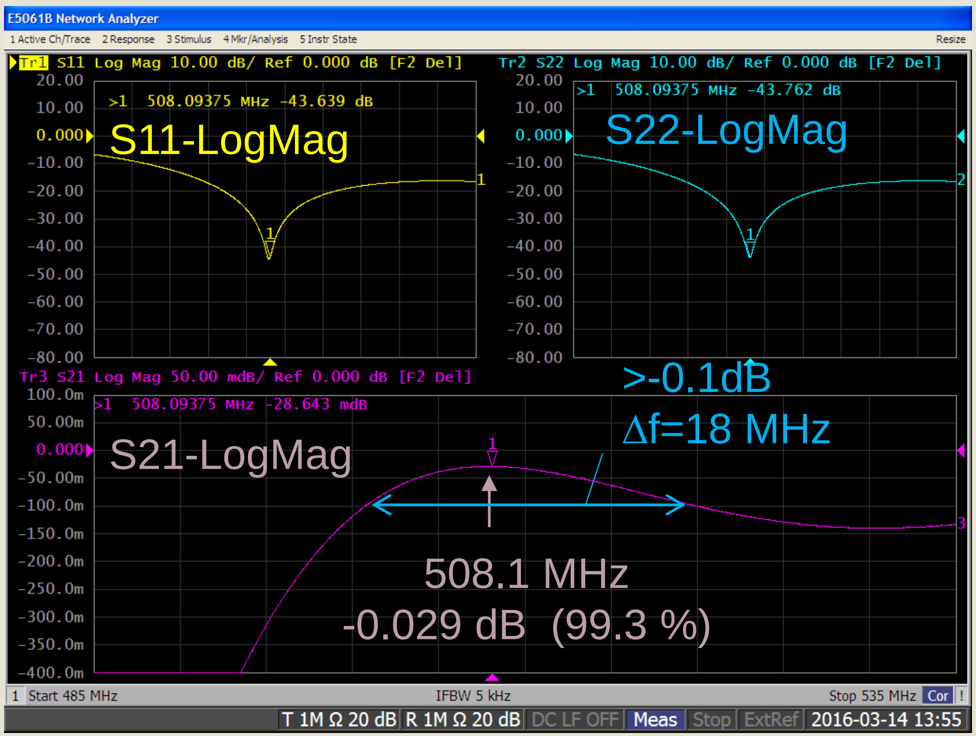


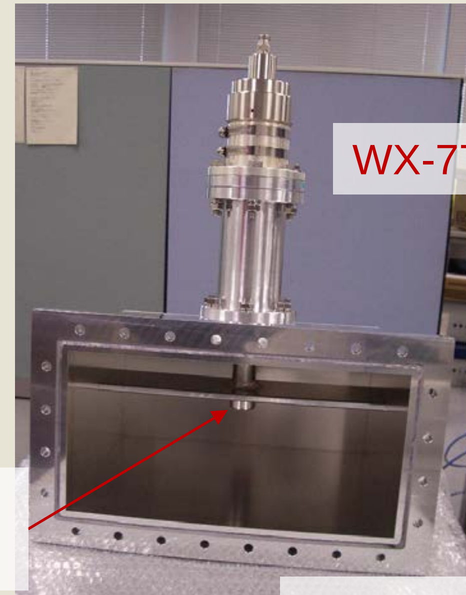


5) Transmission of the waveguide mode converter

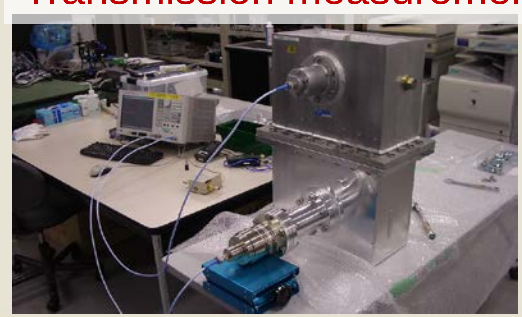
✓ Confirmed the RF power transmission.

- Insertion loss ~ 0.7%
- Operation area ~18 MHz



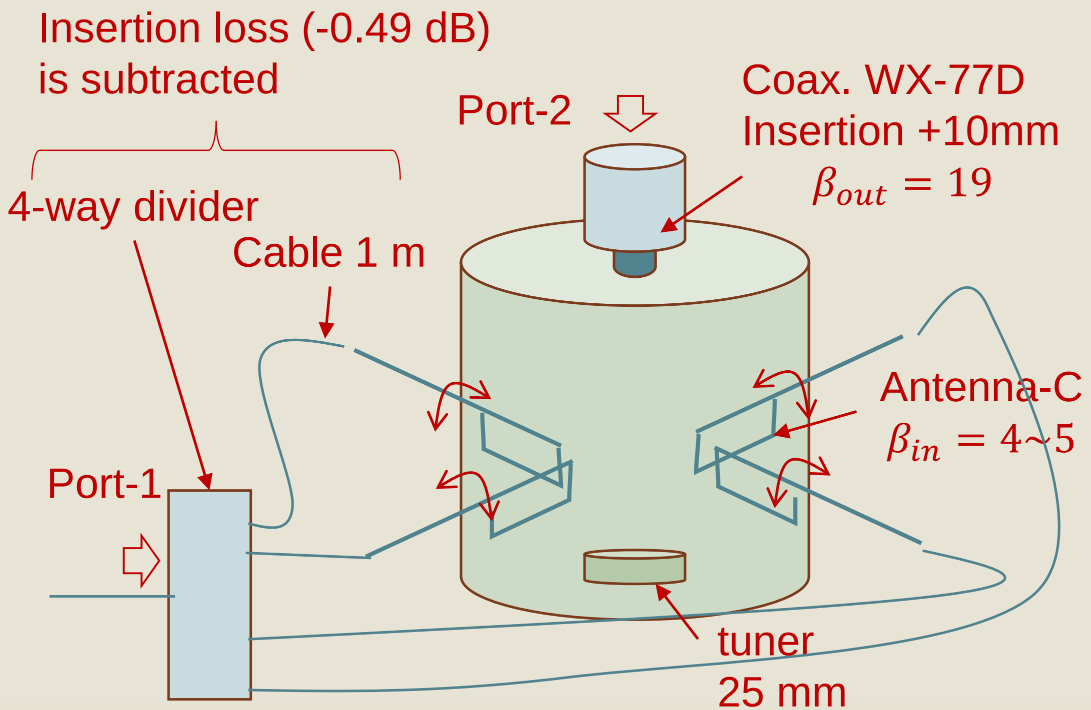


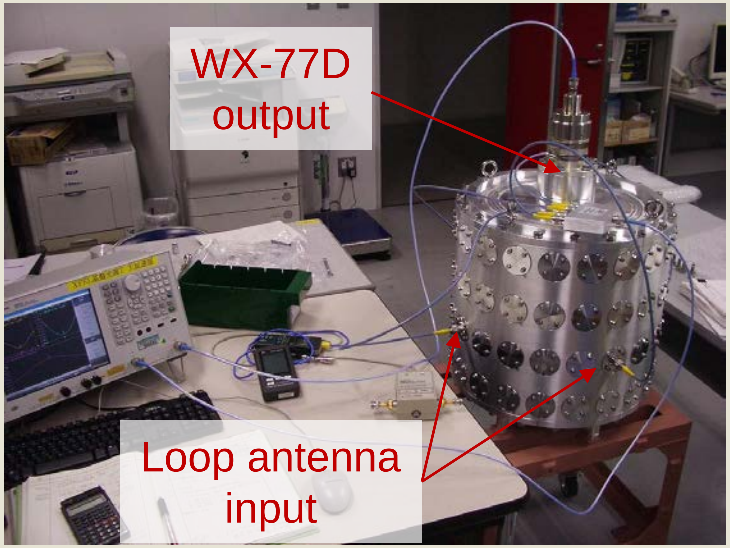
Transmission measurement



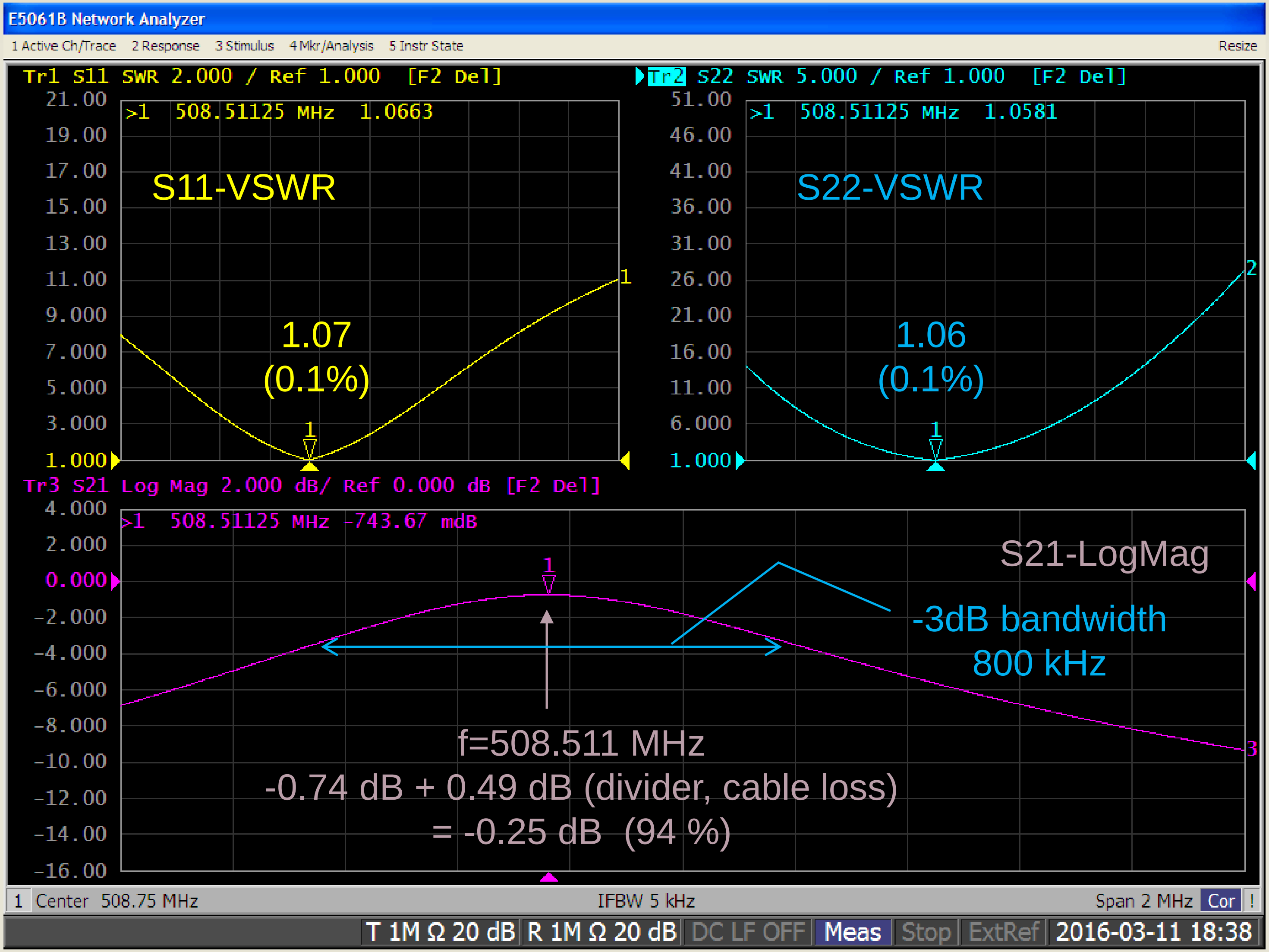
6) 4-port combining efficiency measurement

- Input port: 4 loop antennas
- Output port: coax. waveguide WX-77D
- Changed the rotation of the antenna and measured the transmission (S21) and reflection (S11, S22) characteristics using the network analyzer.





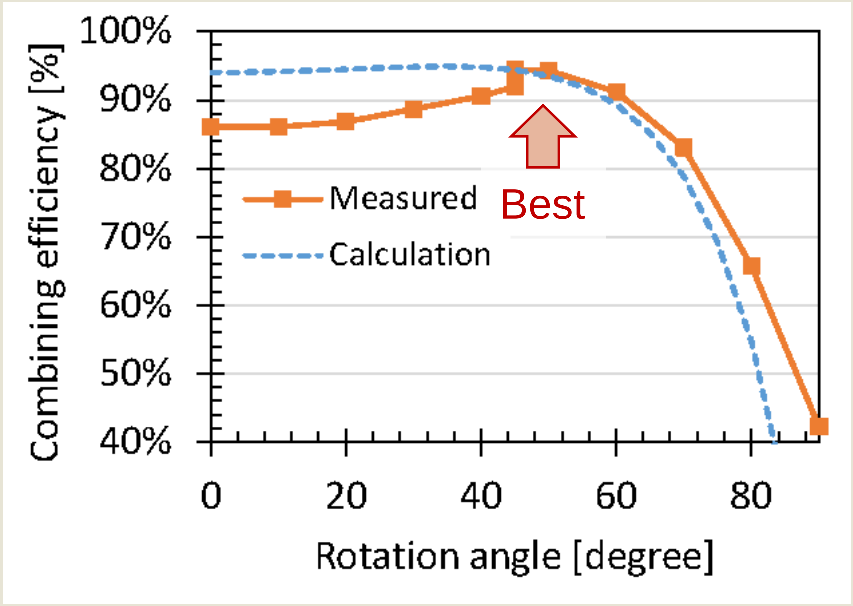
Result at optimum condition ($\theta = 50\ deg.$)

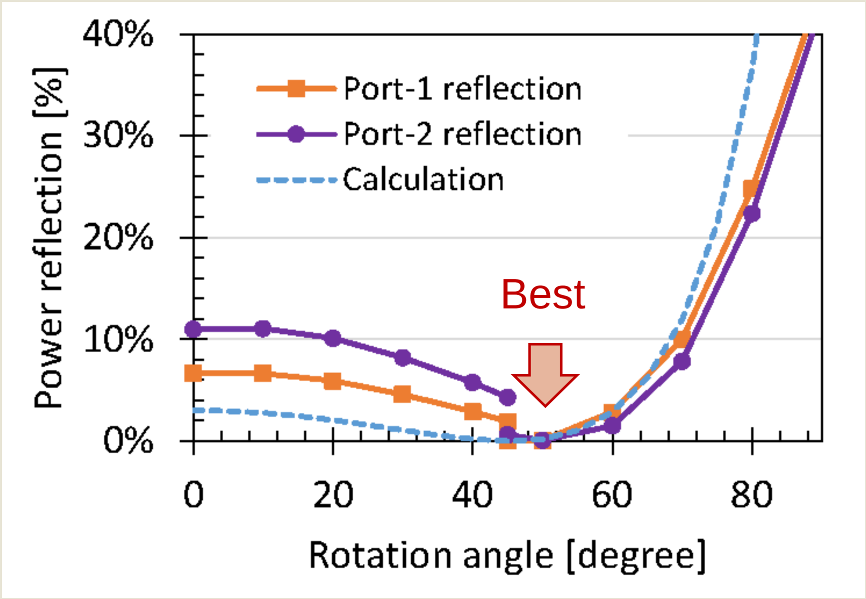


Combining efficiency

- ✓ Obtained the power efficiency $\eta = 94\%$

  which is consistent with the theoretical calculation: $\eta = 95\%$
- ✓ Reflection power is also low enough (~0.1%).



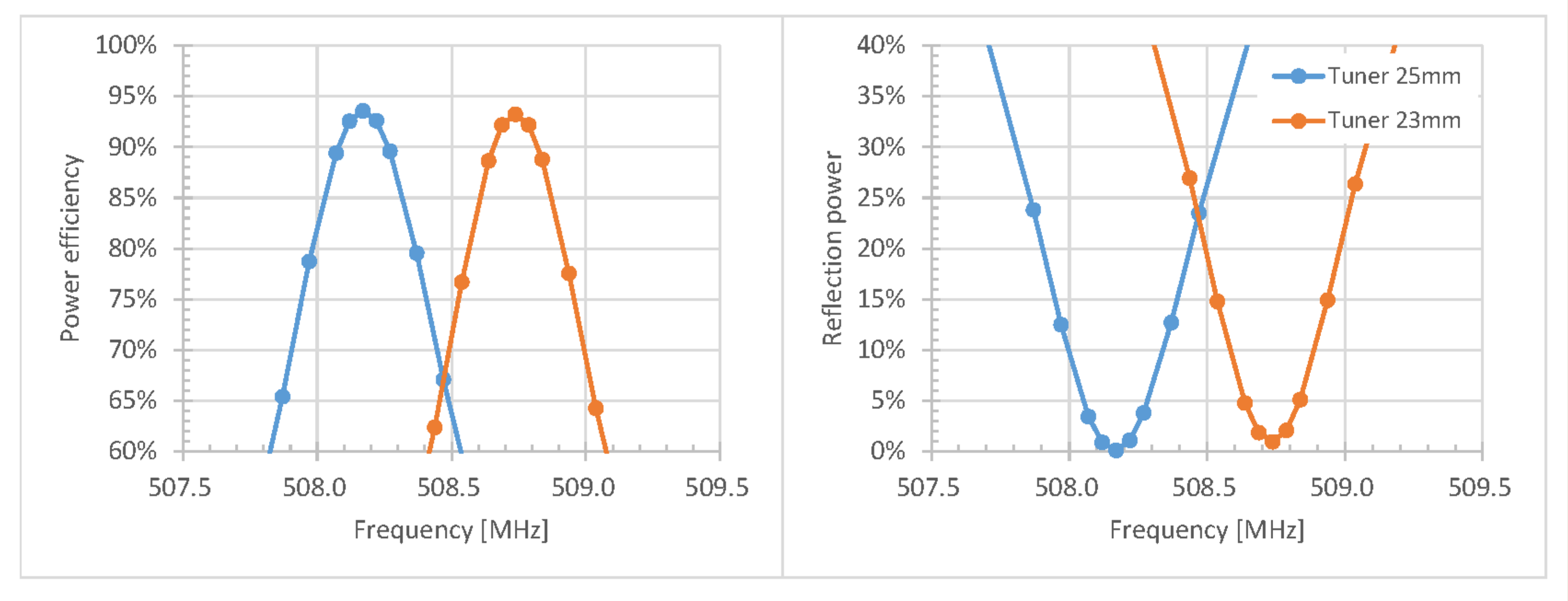


7) Frequency range and adjustment

- Due to the narrow bandwidth, we should adjust the cavity frequency within ±50 kHz.

✓ We can easily adjust the frequency by the tuner.

- For actual 80-way combiner, 7 times wider than the present 4-way combiner



8) Effect of the unbalanced input

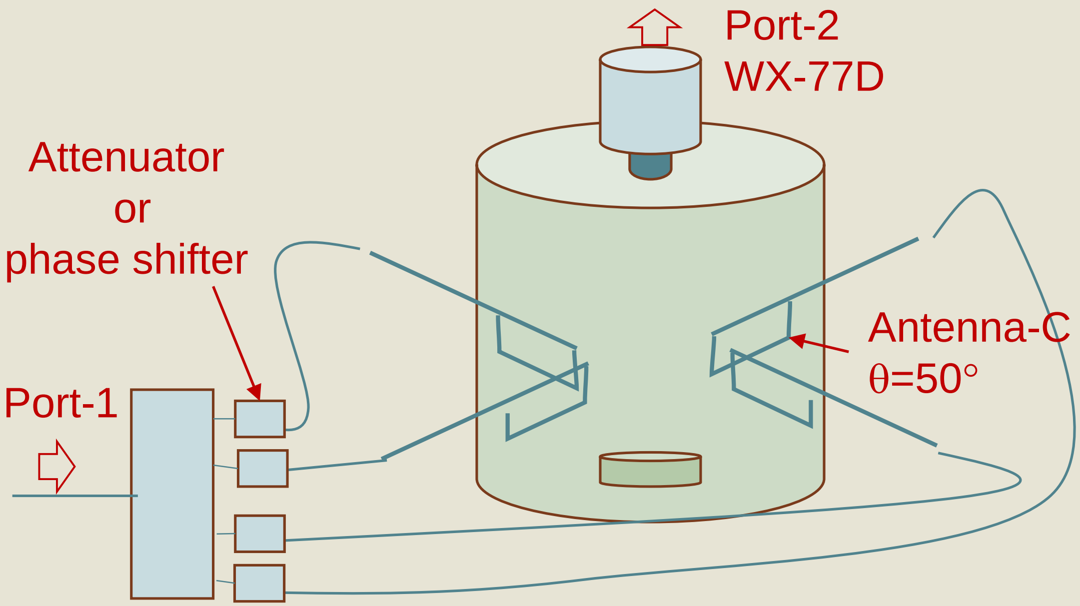
- Simulation of the unbalanced input from SSA.

✓ Insensitive to the power unbalance.

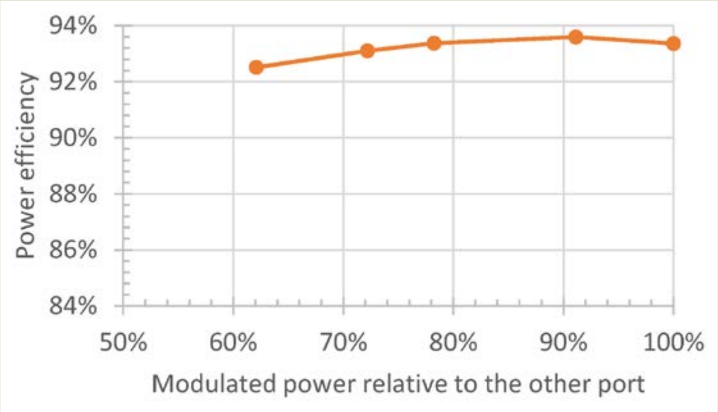
30% difference is acceptable

✓ Sensitive to the phase difference.

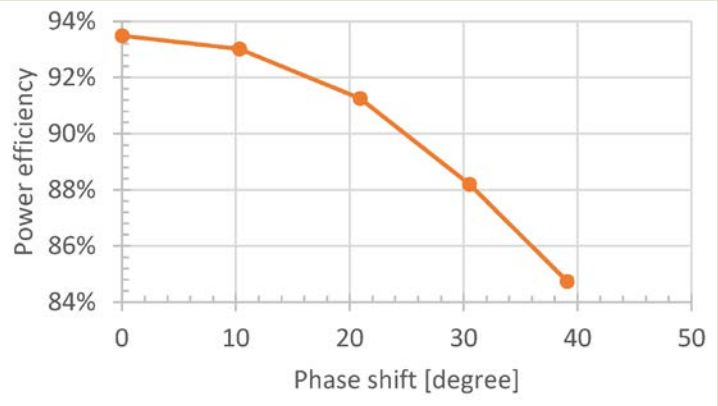
Should be adjusted within 10 deg.



Power balance vs. efficiency

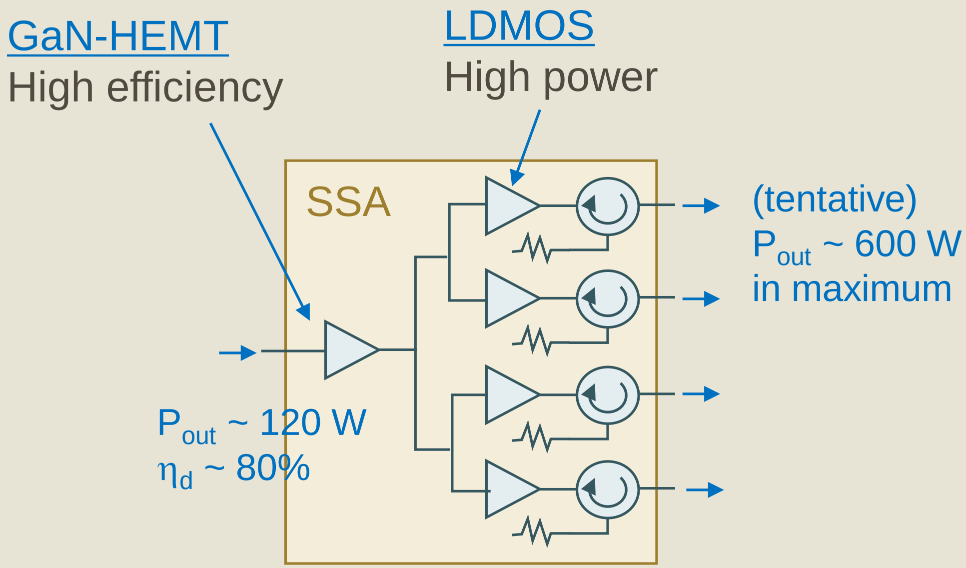


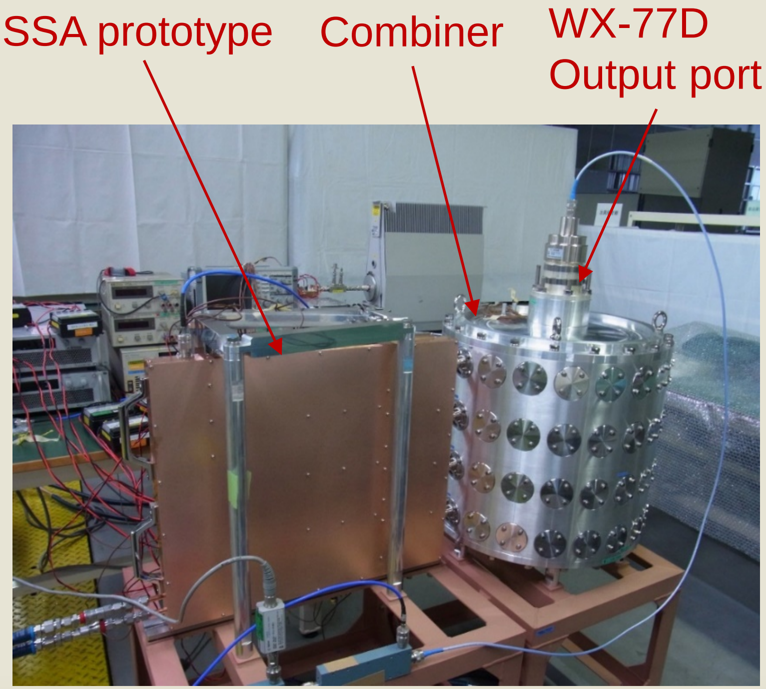
Phase shift vs. efficiency



9) Power combining test with SSA

- Demonstration of the actual power combining from SSA prototype.
- Low power test (today's report)
  - Output power: ~200 W, terminated by coaxial load.
- High power test (planned in the next month)
  - Output power: 2~3 kW, terminated by waveguide water load.





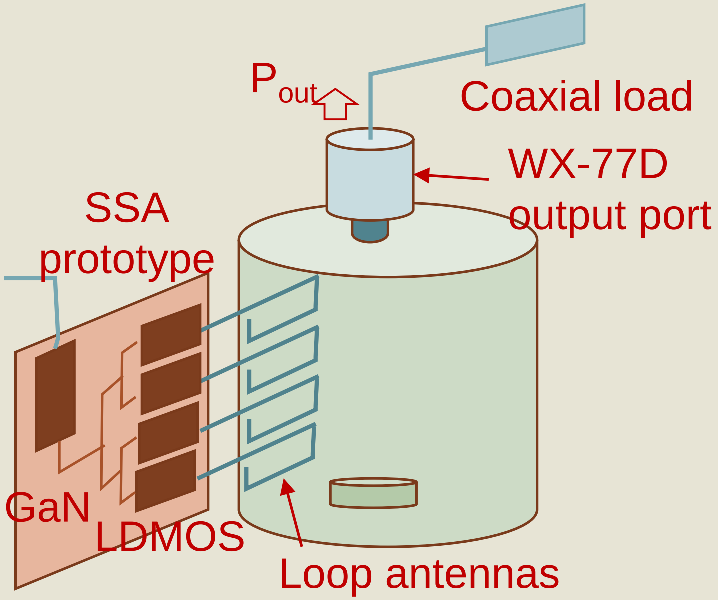
Results of the low power test (tentative)

✓ Obtained power combining efficiency $\eta = \frac{215W}{243W} = 89\ \%$

- Reason for worse efficiency than the network measurement (94%)…
  - Loop coupling mismatch (position dependence, cross coupling) ~2%   due to the large loop…
  - Frequency mismatch (50 kHz) ~1%
  - Phase mismatch (<10°)
  - Existence of harmonics and spurious.

  } will be checked next time

	Measured power	Total
SSA-1	58 W	243 W
SSA-2	61 W	
SSA-3	59 W	
SSA-4	65 W	
Combiner output (P_{out})	215 W	



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Summary

- Power combining is the key issue for high power SSA.
- We designed TM010 cavity type combiner with more than 99% efficiency.
- We made a prototype and performed the low power measurement..
  - Cavity Q-factor: 90% of the ideal case.
  - Input/output coupling and resonant frequency can be tuned.
  - 4-port combining; power efficiency ~94% (theoretical 95%)
- We demonstrated combining of the RF power from the SSA module.
- Low power RF characteristics of the cavity combiner is experimentally confirmed.
- We plan to test with high power RF.