

#3490

Results of electron cyclotron heating and current drive system operation in the integrated commissioning phase on JT-60SA

H. Yamazaki, M. Terakado, M. Sawahata, S. Hiranai, F. Sato, N. Toida, J. Hinata, T. Ishii,
K. Asakura, H. Sugiyama, K. Ishita, T. Shinya, R. Ikeda, T. Kobayashi and K. Kajiwara

National Institutes for Quantum Science and Technology (QST)



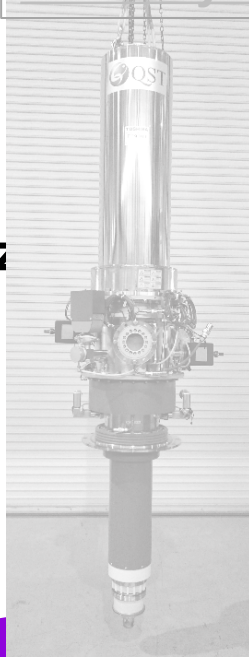
QST activity: ECRH system for current and future fusion devices

#2693 by H.Yamazaki *et.al*



- Freq.: 82/110/138 GHz
- Power: 1/1/1 MW
- Pulse: 1/100/100 s

#3197 by K.Kajiwara *et.al*



- Freq.: 170 GHz
- Power: 1 MW
- Pulse: 3600 s

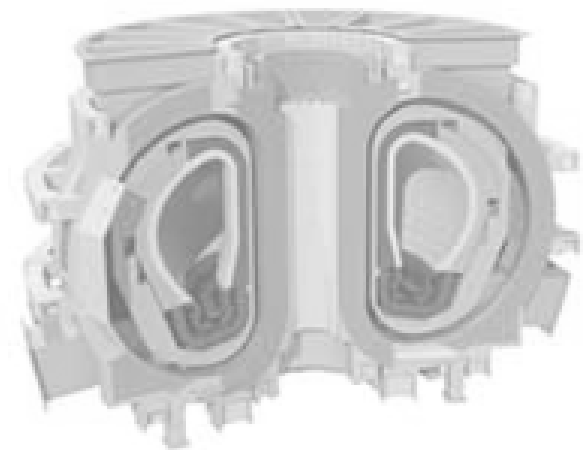
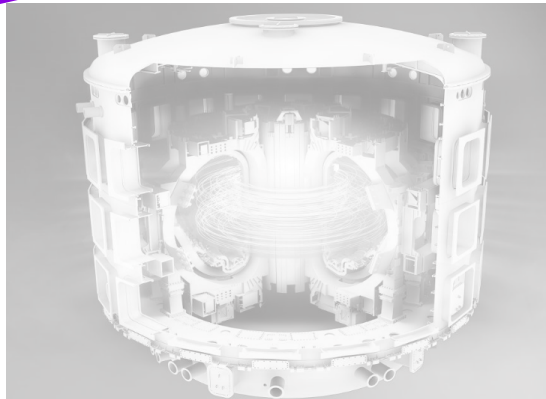
#2703 by T.Shinya *et.al*



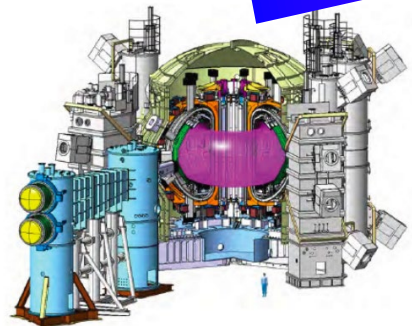
- Freq.: ≥ 200 GHz
- Power: ≥ 1 MW
- Continuous wave

DEMOs &
Fusion devices

ITER



JT-60SA

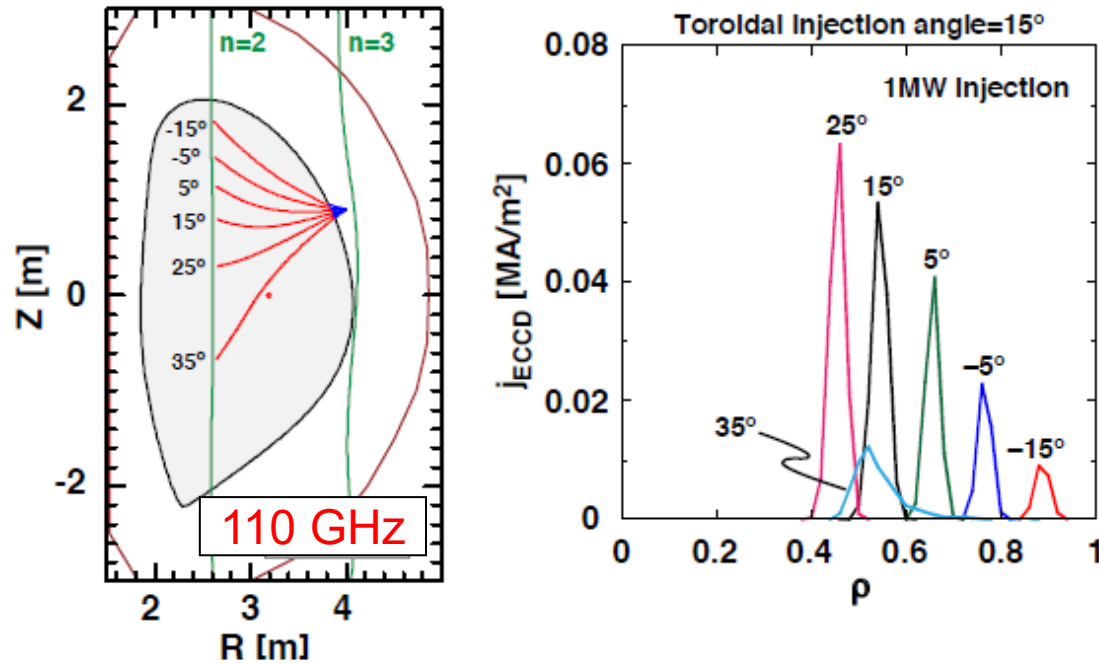


*K. Tobita *et al* 2019 *Fusion Sci.Tech.* 75 5 372–383.

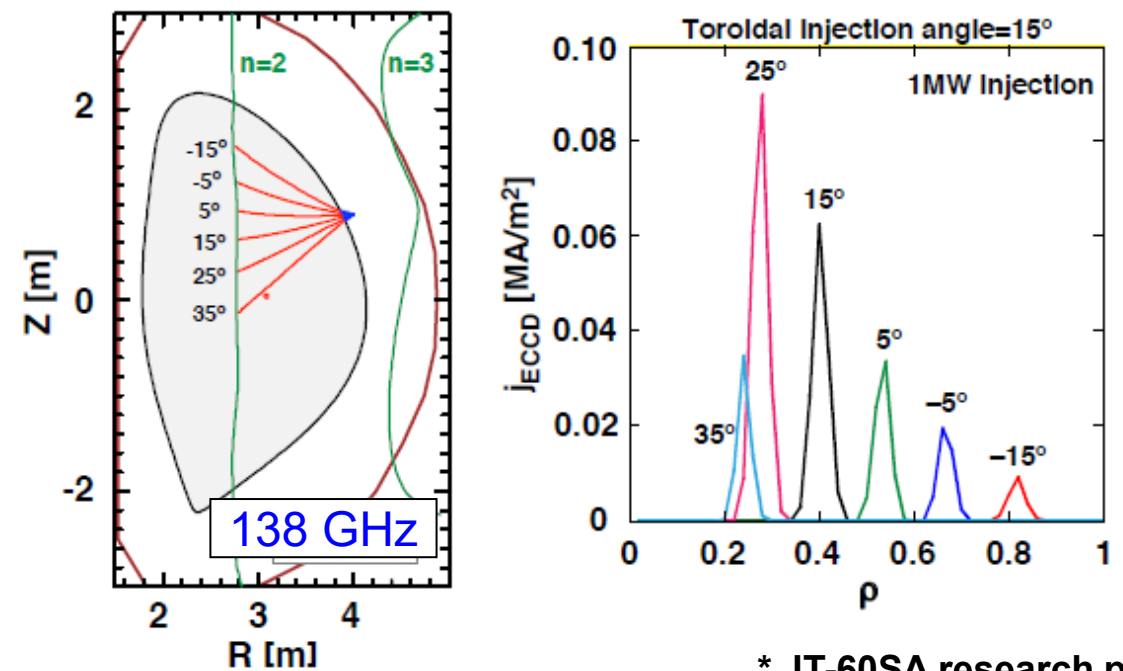
Multi-frequency ECRH system for JT-60SA

- Multi-frequency ECRH system has developed & constructed on JT-60SA for EC H/CD, NTM control, plasma startup and wall cleaning under various experimental conditions

Scenario 5 (high-beta, $B_T \sim 1.7$ T)



Scenario 2 ($I_p=5.5$ MA, $B_T \sim 2.25$ T)



* JT-60SA research plan v4.1

- Heating/current drive at different B_t by 110 GHz and 138 GHz
- Additional 82 GHz for fundamental injection for plasma startup and ECWC

The multi-frequency gyrotron expands experimental flexibility

Developments of key ECRH components

❑ Multi frequency gyrotron (82 GHz /110 GHz/138 GHz)

✓ ECRH operation for JT-60SA

- 1 MW/100 s (110 GHz & 138 GHz)
- 1 MW/1 s (82 GHz)

✓ High-power / long-pulse records

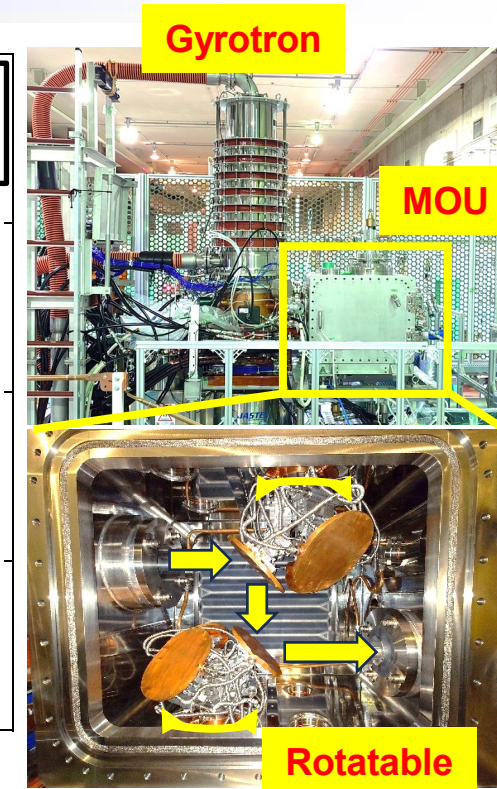
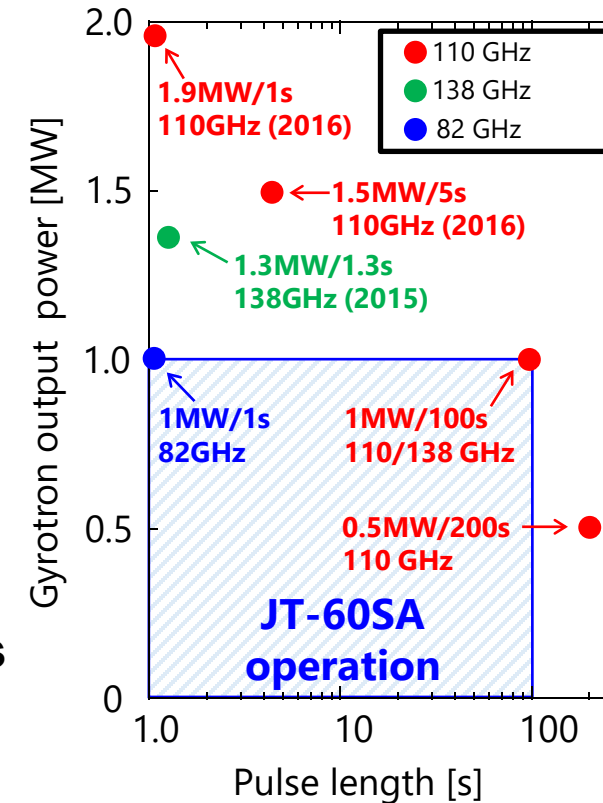
- 1.9 MW/1 s, 1.5 MW/5 s, 0.5 MW/200 s at 110 GHz etc.
- 1.3 MW/1.3 s at 138 GHz

❑ Matching Optics Unit (MOU)

- ✓ MOU with three sets of rotatable phase-correcting mirrors
- ✓ RF can be coupled into the WG with high mode purity

❑ Broad-band polarizers

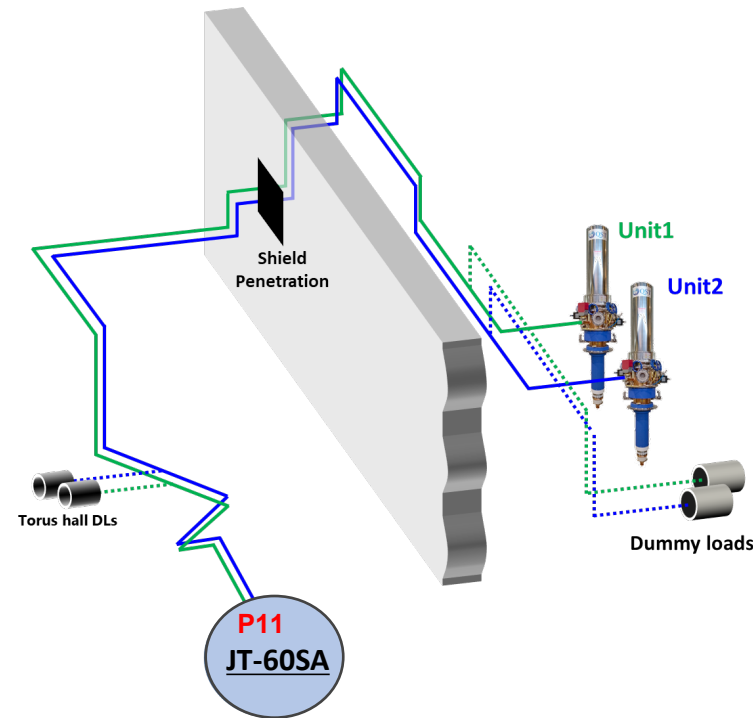
- ✓ A broadband polarizer that can produce almost all polarizations in 3 frequencies developed by collaborative research between MTC & Ibaraki University



* T. Kobayashi, *et al.*, Nucl. Fusion, vol.62(2), 026039, 2022

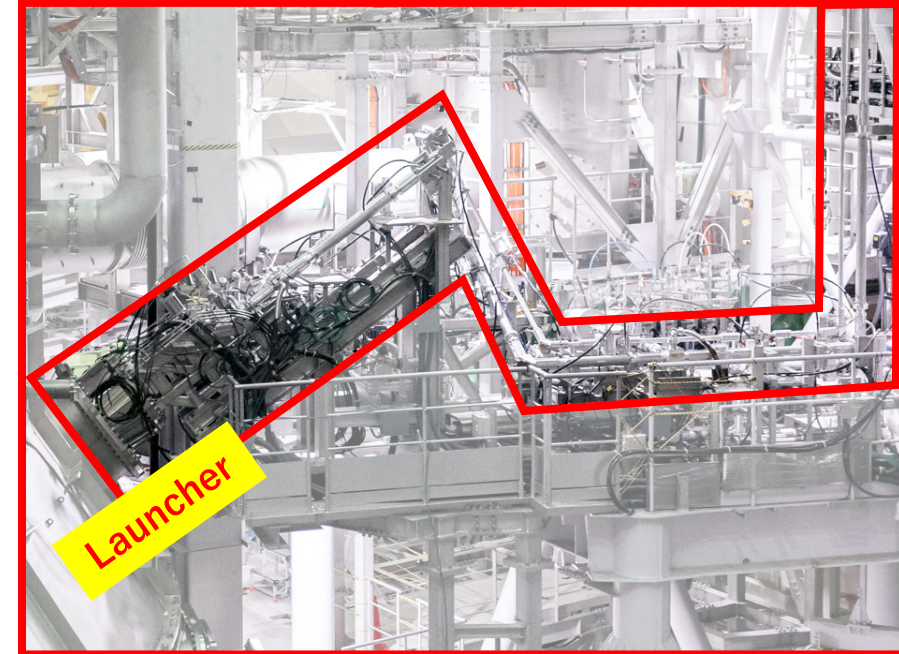
Development of key components are completed !

Installation of the transmission line components



JT-60U components Multi-frequency

Gyrotron		Unit#1	Unit#2
	Frequency	110 GHz	82/110/138 GHz
	Output power	1 MW	1 MW
Transmission line	Pulse duration	5s	110/138 GHz: 5 s 82 GHz: 1s
	WG	ϕ 31.75 mm	ϕ 60.3 mm
	Total length	95 m	105 m
	No. of MBs (incl. polarizers)	15	15
	Transmission efficiency (calc.)	66% (74%)	79%/85%/84% (80%/83%/83%)
Launcher		P11UO Waveguide launcher	



* H. Yamazaki, et al., Fusion Eng. Des., vol.196, 114015, 2023

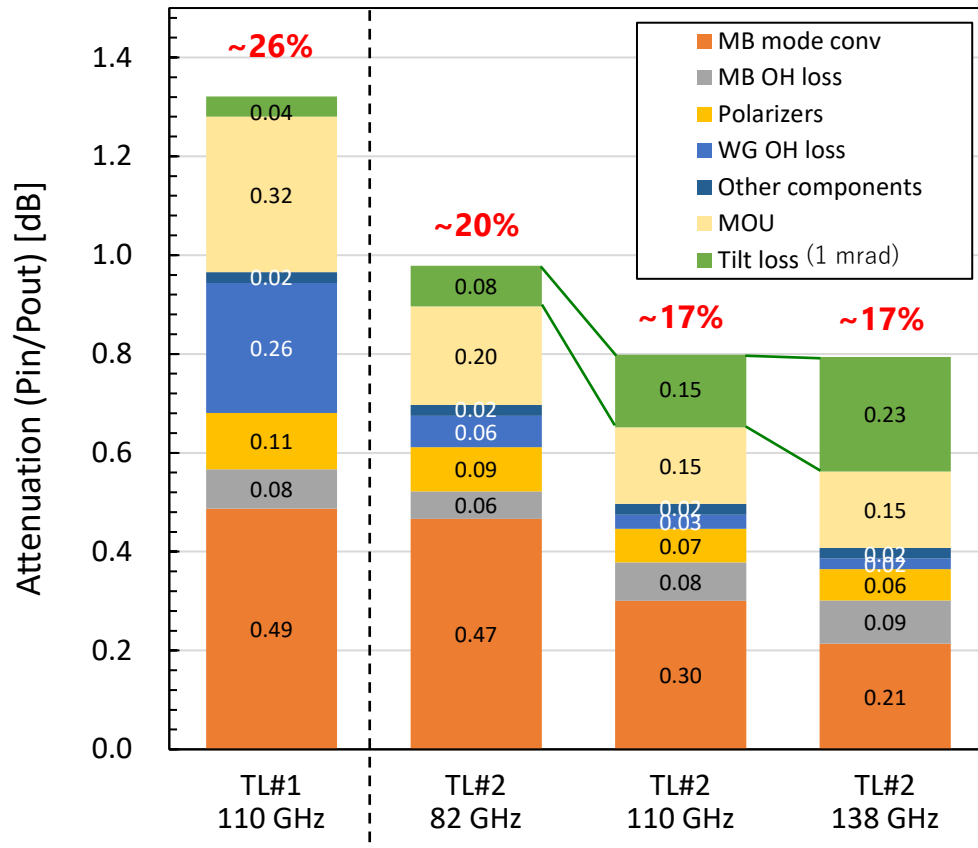
Applicability of multi-frequency system in large fusion devices such as JT-60SA has not been verified

➡ Two ECRH units have been operated during the Integrated Commissioning phase

Objectives: Operation with (1) output power: **1 MW**, (2) pulse duration: **5 seconds**

Evaluation of transmission efficiency

Calculated loss (Assuming pure HE11)



Measured results of transmission efficiency

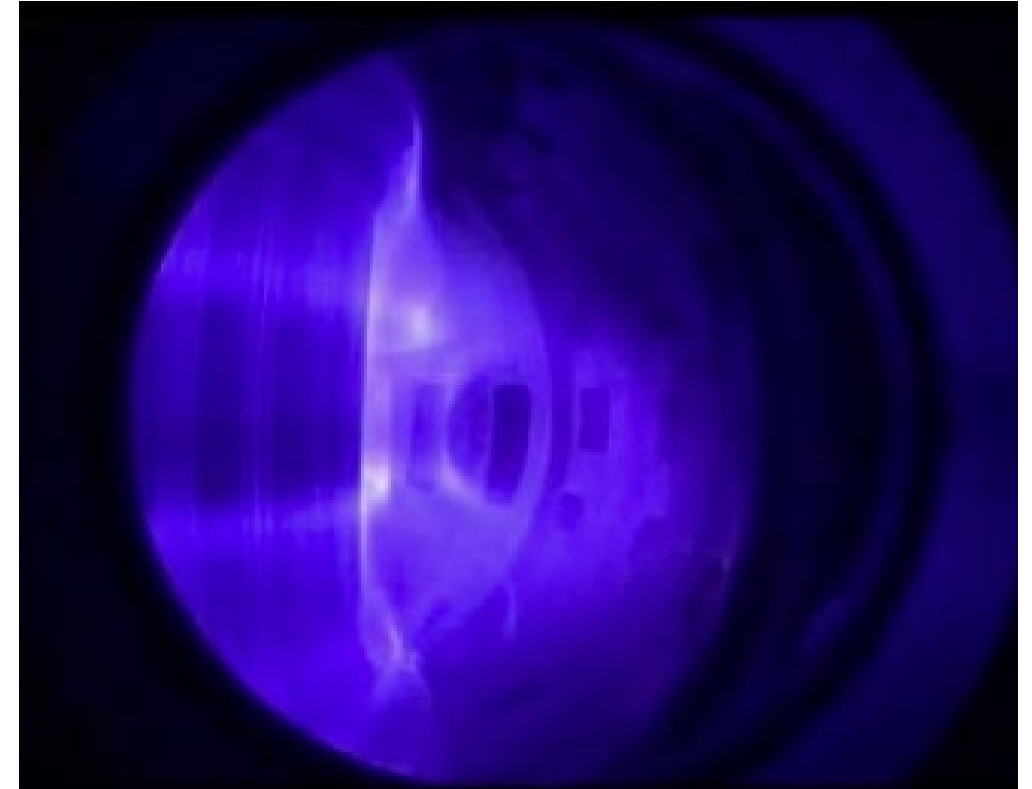
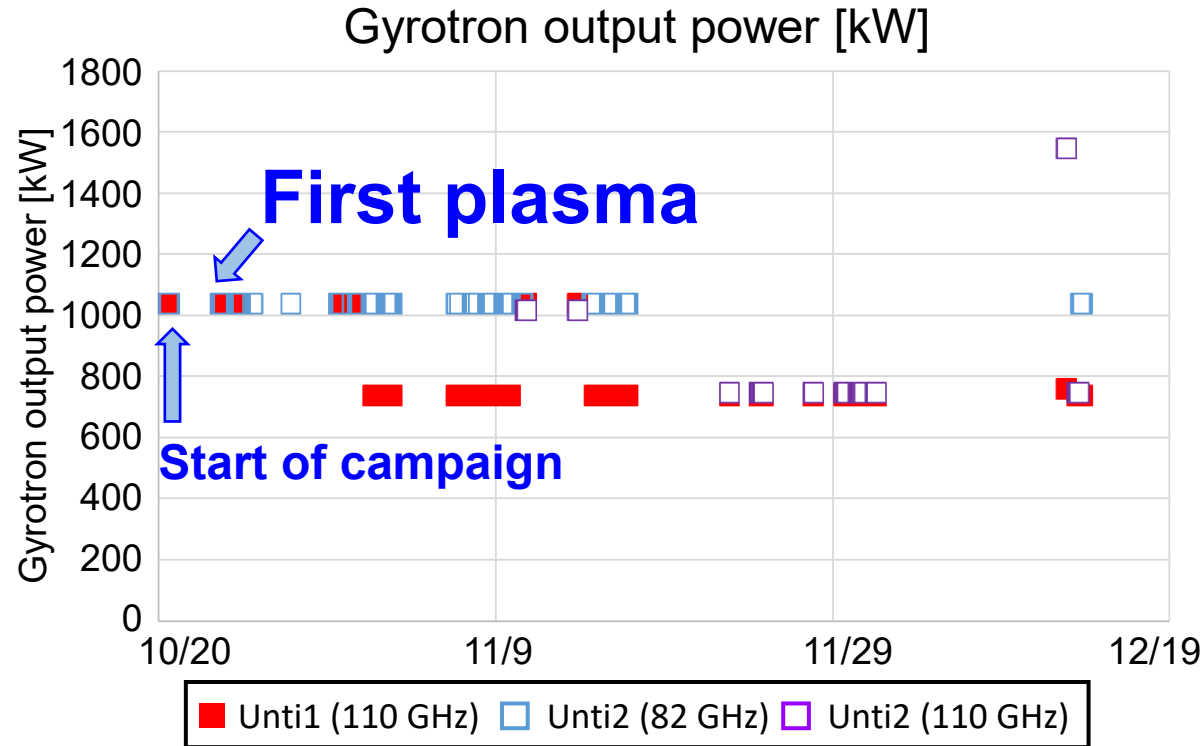
	TL#1 110 GHz	TL#2 82 GHz	TL#2 110 GHz	TL#2 138 GHz
Measured power Torus hall	358 kW ($\sigma \sim 1.9\%$)	418 kW ($\sigma \sim 0.4\%$)	384 kW ($\sigma \sim 1.0\%$)	335 kW ($\sigma \sim 1.1\%$)
α_{tokamak}	0.97	0.98	0.98	0.98
P_{tokamak}	348 kW	408 kW	378 kW	329 kW
Measured power Gyro. Room	426 kW ($\sigma \sim 0.2\%$)	462 kW ($\sigma \sim 1.1\%$)	424 kW ($\sigma \sim 1.0\%$)	361 kW ($\sigma \sim 0.9\%$)
α_{gyrotron}	0.87	0.90	0.93	0.93
P_{GY}	492 kW	511 kW	459 kW	389 kW
Transmission efficiency	66%	79%	85%	84%
Calculation	74%	80%	83%	83%

Unit #1 (Φ 31.75 mm) : 3-8% lower than calculation but comparable to the previous result.

Unit #2 (Φ 60.3 mm): No significant loss even at high frequency of 138 GHz.

The measured values of three frequencies are in good agreement with calculation.

First plasma achievement by ECRH injection



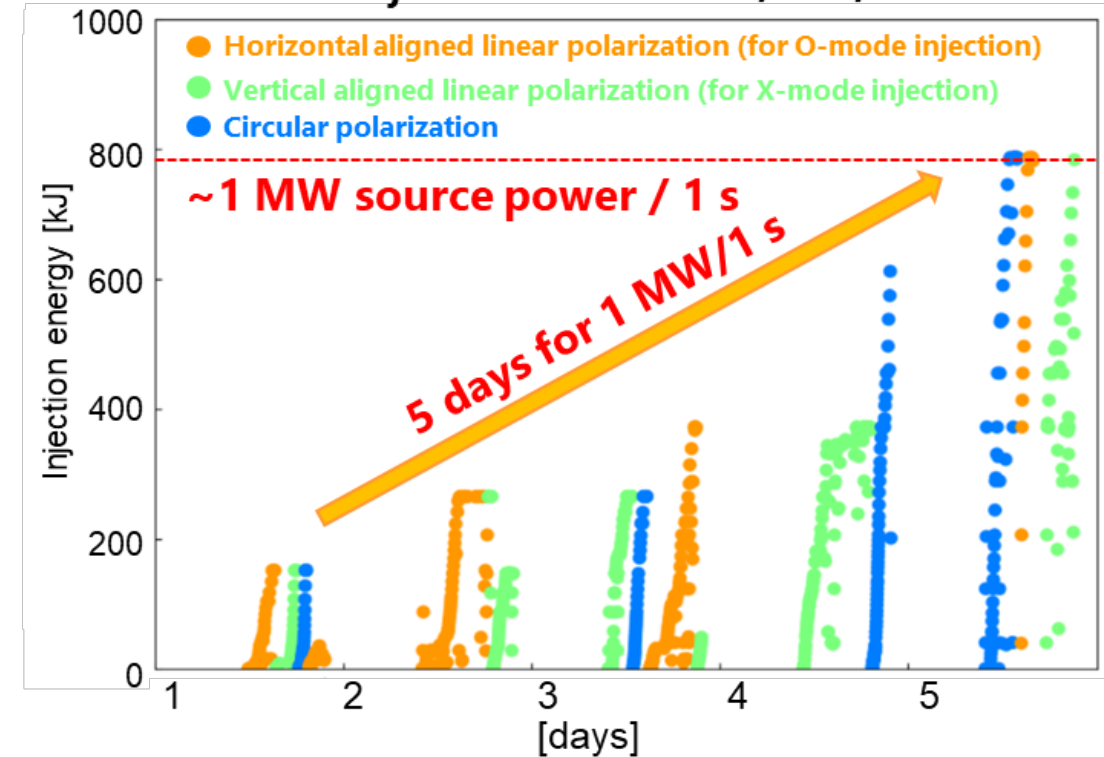
- Unit 1 (110 GHz) and Unit 2 (82 GHz) were successfully injected up to 1 MW / 1 s from the first day of the experiment.
- At the second day, first plasma was achieved by ECRH injection with 110 GHz/1 MW & 82 GHz/1 MW

❑ Operation reliability

<u>Unit1 (110 GHz)</u>	Number of pulses	Failed	Success [%]
Plasma experiment sequence	340	34	90.0%
<u>Unit2 (82/110/138 GHz)</u>	Number of pulses	Failed	Success [%]
Plasma experiment sequence	350	34	90.3%
82 GHz (< 1 s)	235	6	97.4%
110 GHz (< 5 s)	115	28	72.4%
138 GHz	0	0	-

Progress of the TL conditioning

925 injection to v.v. from 6/26-6/30 for Unit2

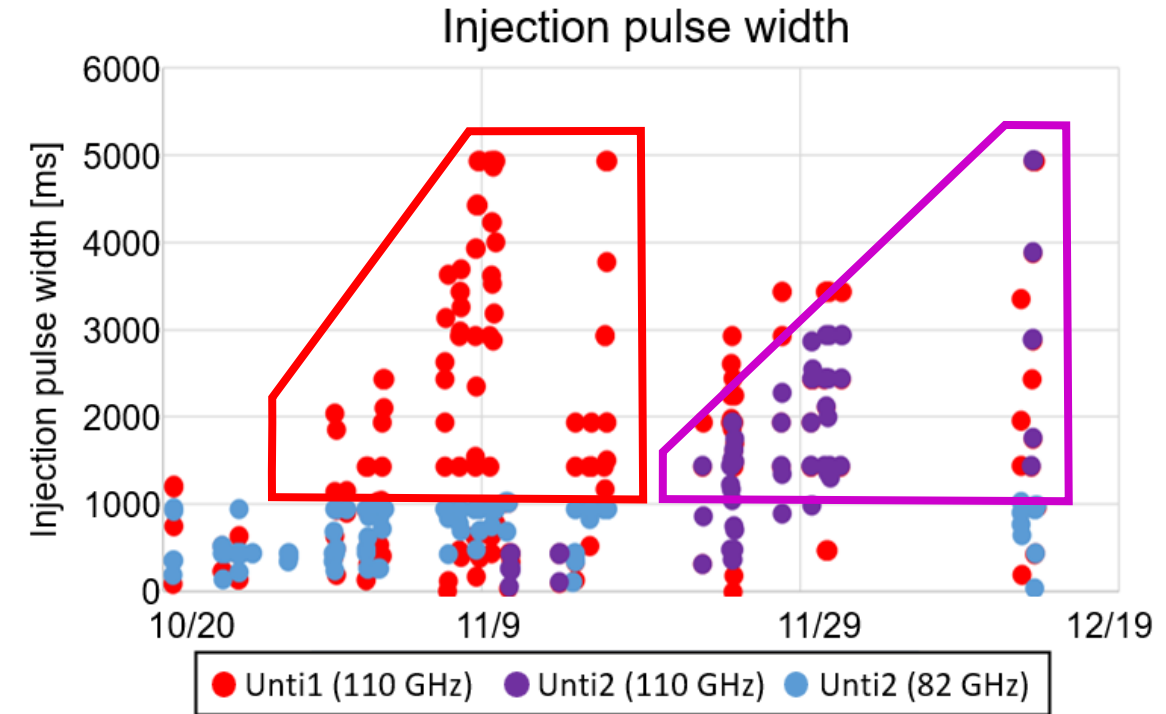


❑ Averaged success rate is ~90%, demonstrating highly reliable system operation.

❑ To achieve high reliability, TL components were conditioned by injecting RF waves into the vacuum vessel at a power of up to 1 MW for 1 second.

❑ Operation reliability

<u>Unit1 (110 GHz)</u>	Number of pulses	Failed	Success [%]
Plasma experiment sequence	340	34	90.0%
<u>Unit2 (82/110/138 GHz)</u>	Number of pulses	Failed	Success [%]
Plasma experiment sequence	350	34	90.3%
82 GHz (< 1 s)	235	6	97.4%
110 GHz (< 5 s)	115	28	72.4%
138 GHz	0	0	-

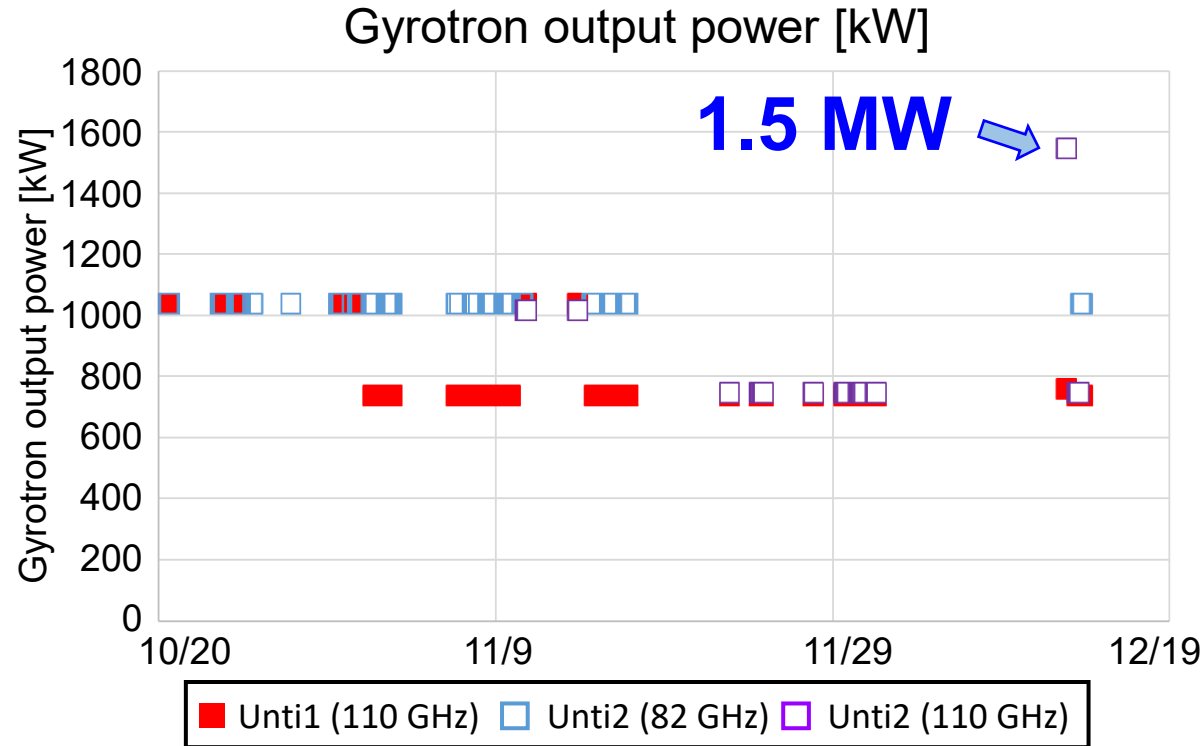


❑ Averaged success rate is ~90%, demonstrating highly reliable system operation.

❑ To achieve high reliability, TL components were conditioned by injecting RF waves into the vacuum vessel at a power of up to 1 MW for 1 second.

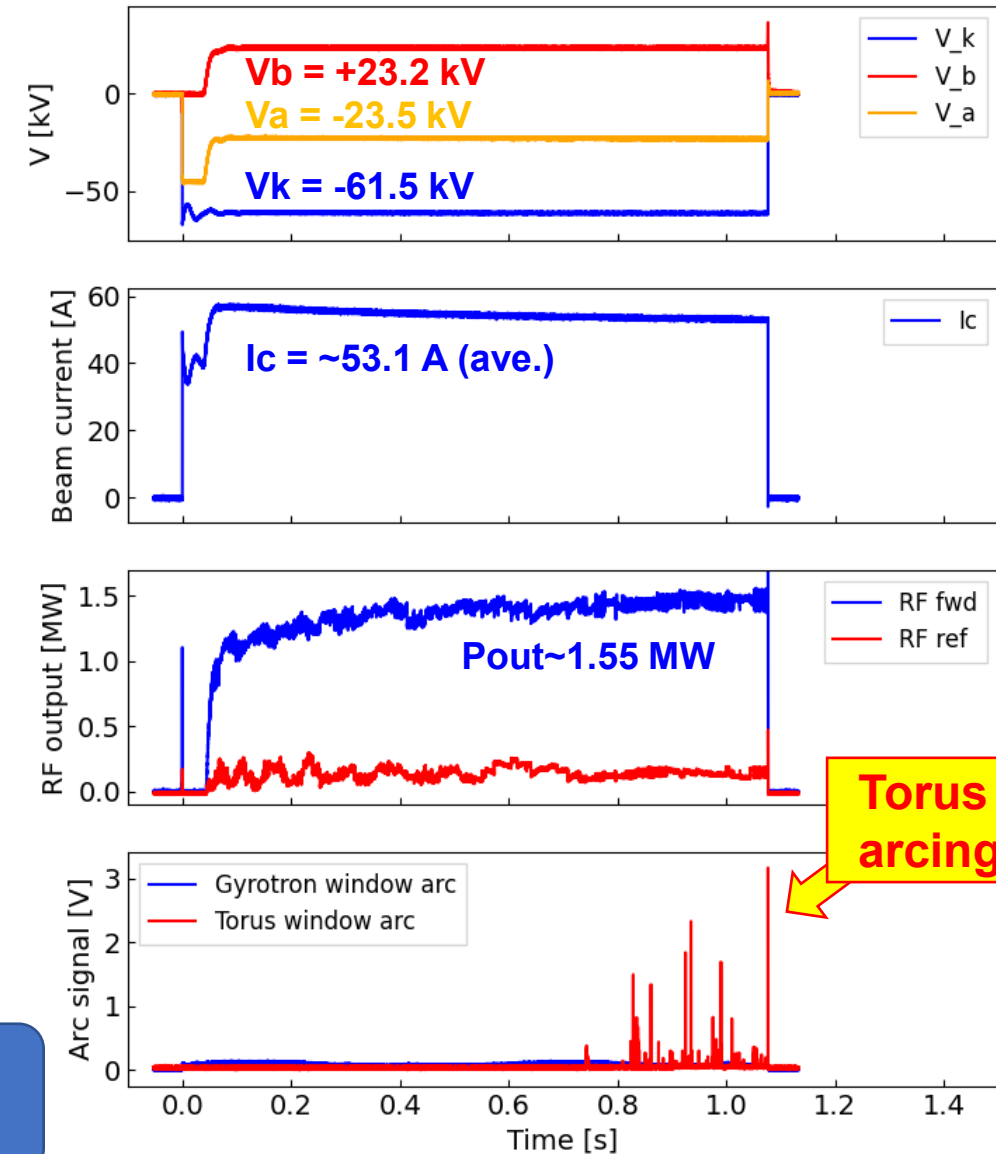
❑ 5 seconds injection was achieved after the conditioning during the experiment

1.5MW challenge for further high-power operation



- RF stopped by only torus window arc signal
- Could be extended by performing more conditioning operation

This achievement demonstrates the potential to upgrade the ECRH power in the future.



Layout design for initial research phase TLs

□ Determined transmission line layout for initial research phase

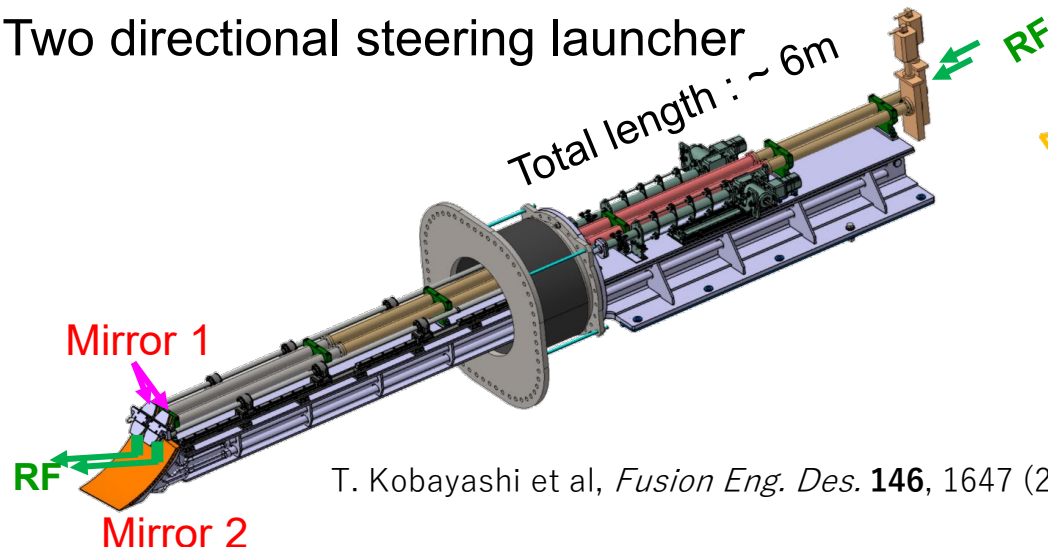
Unit1/Unit2: Transmission efficiency >85%

- total length of ~60 m
- 9 miter-bends including polarizers
- Connected on **P11-UO** launcher

Unit3/Unit4: Transmission efficiency >80%

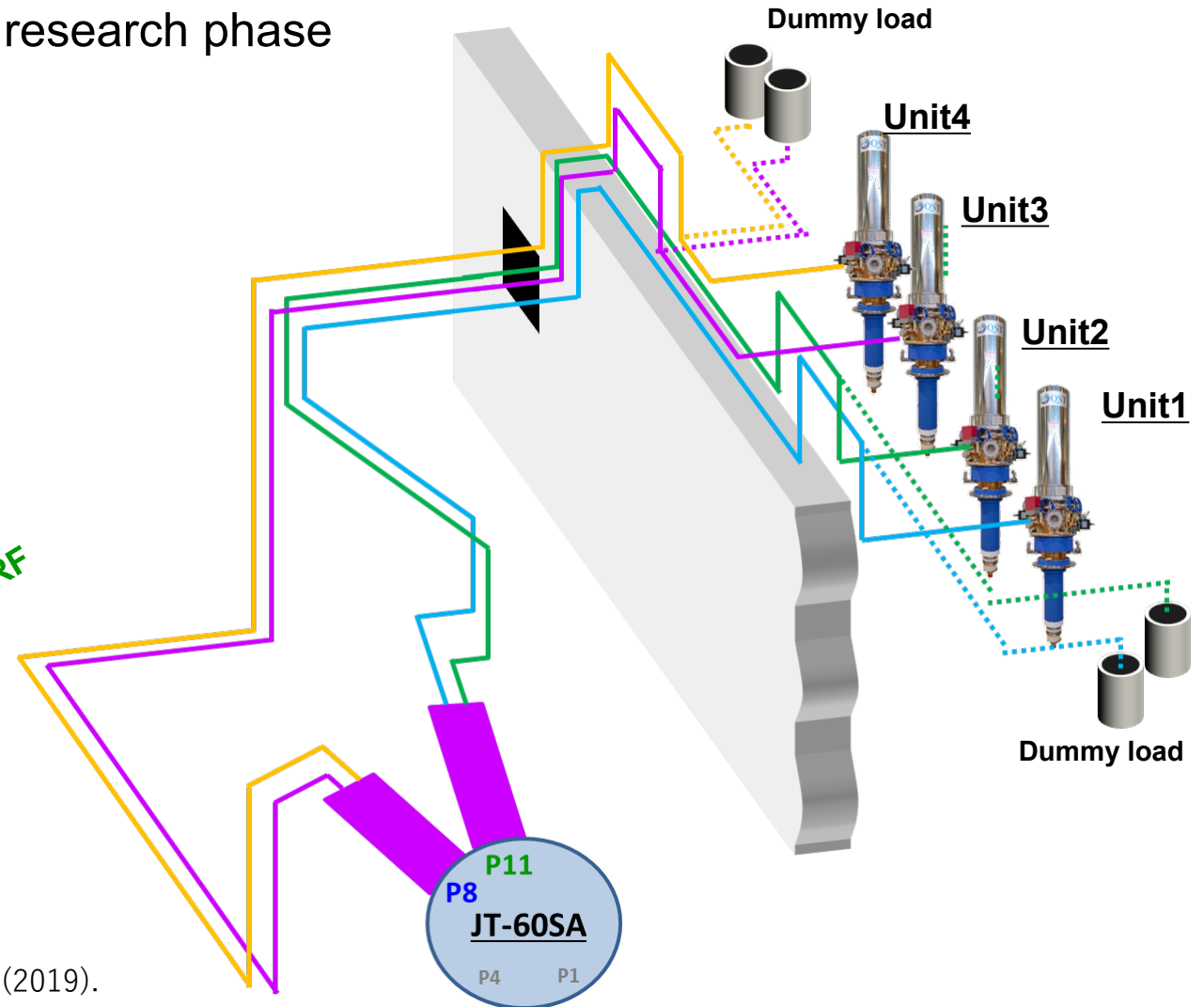
- Total length of ~115 m
- 10 miter-bends including polarizers
- Connected to **P8-UO** launcher

□ Two directional steering launcher

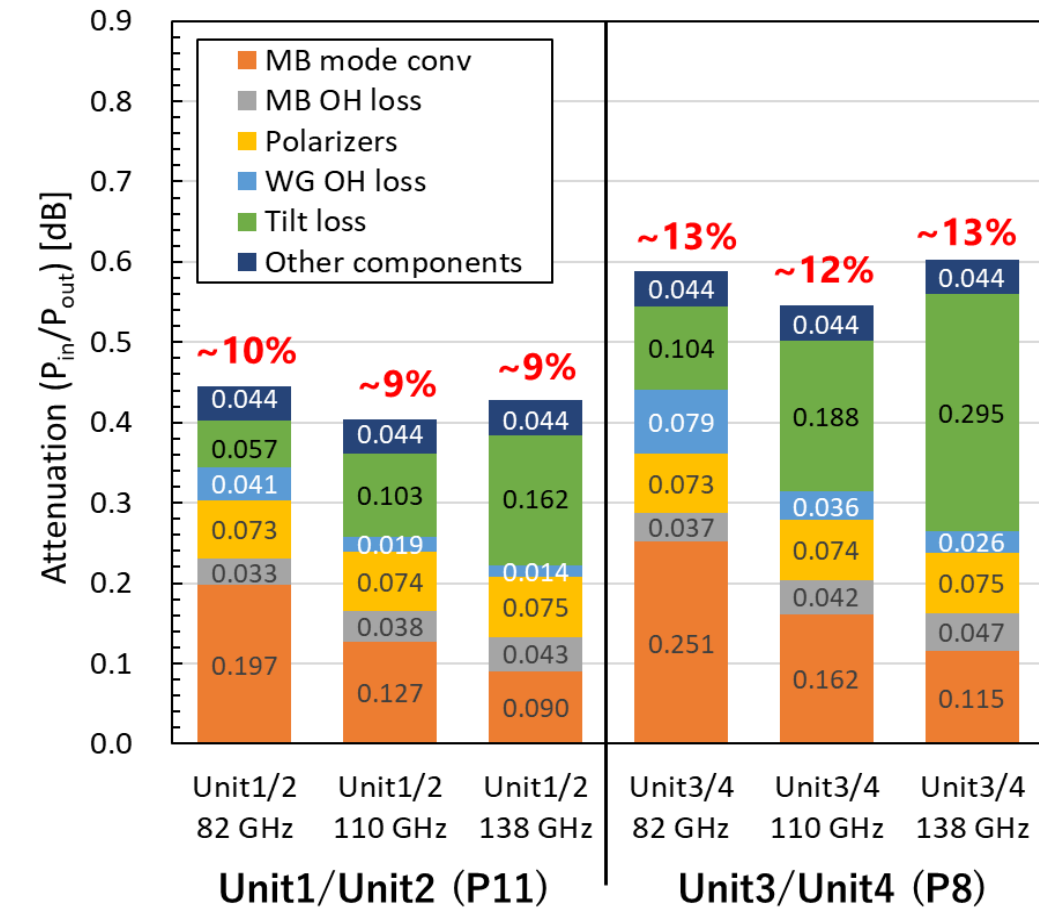


T. Kobayashi et al, *Fusion Eng. Des.* **146**, 1647 (2019).

Design target of 3 MW (75% efficiency x 4 units) of tokamak injection power can be achievable



Transmission efficiency evaluation for init.R.P TLs



		Loss (w/o MOU)	Transmission efficiency (w/o MOU)	Target values
P11 (Unit1/2)	82 GHz	10%	90%	85%
	110 GHz	9%	91%	
	138 GHz	9%	91%	
P8 (Unit3/4)	82 GHz	13%	87%	80%
	110 GHz	12%	88%	
	138 GHz	13%	87%	

- ❑ The transmission efficiencies are >85% (P11) and >80% (P8)
 - ❑ <5% difference between calculated and measured values as demonstrated during the integrated commissioning phase
- ⇒ **Design target of 3 MW (75% efficiency x 4 units) of tokamak injection power can be achievable**

- High transmission efficiencies of 80/82/84% at 82/110/138 GHz were achieved by large-diameter WG
- Two units were successfully injected with up to 1 MW/1 s from the first day of the experiment, contributing to the achievement of the first plasma.
- The ECRH was used in almost all plasma experiments, with an average success rate of 90%
- For further increase the tokamak injection power, 1.5 MW operation by single gyrotron was demonstrated

Design, fabrication, and installation of the four EC systems are in progress