TEC/5-3b
#2693

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)

TEC/5-3a
#2703

First performance test of multi-frequency gyrotron for ITER and fusion devices

T. Shinya[1], R. Ikeda[1] , K. Ishita[1] , T. Nakai[1] , M. Tsuneyama[1], K. Masuda[1], S. Yajima[1], Y. Yoshimura[1], H. Yamazaki[1] , T. Kobayashi[1], K. Irie[2], T. Nakatani[2], Y. Matsueda[3], K. Kajiwara[1]

[1]QST, [2]Tokyo Univ., [3]Canon Electron Tubes & Devices

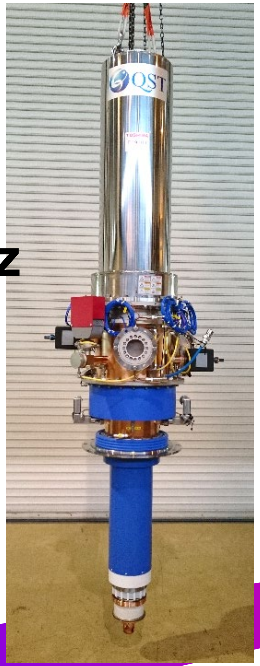
IAEA Fusion Energy Conference (FEC) 2025

QST activity: ECRH system for current and future fusion devices

#2693 by H.Yamazaki *et.al*

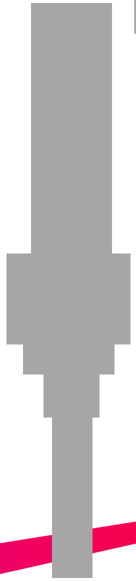
- Freq.: 82/110/138 GHz
- Power: 1/1/1 MW
- Pulse: 1/100/100 s

#3197 by K.Kajiwara *et.al*



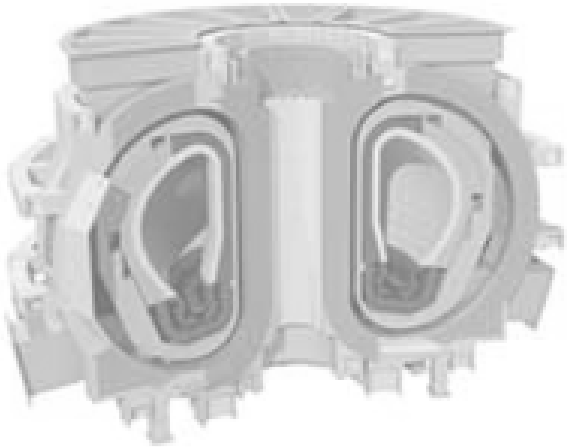
- Freq.: 170 GHz
- Power: 1 MW
- Pulse: 3600 s

#2703 by T.Shinya *et.al*

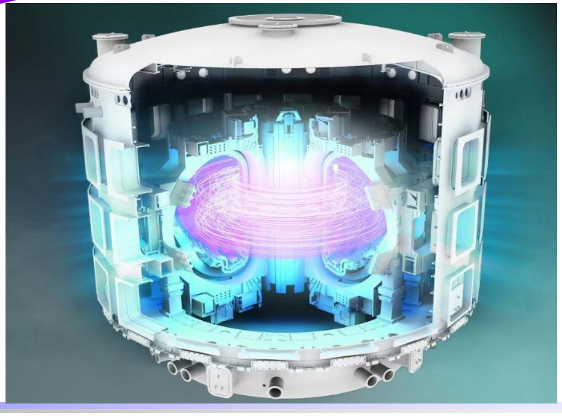


- Freq.: ≧ 200 GHz
- Power: ≧ 1 MW
- Continuous wave

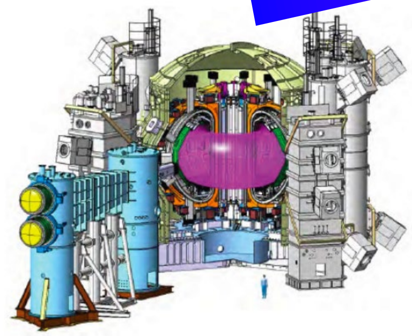
DEMOs & Fusion devices



ITER



JT-60SA

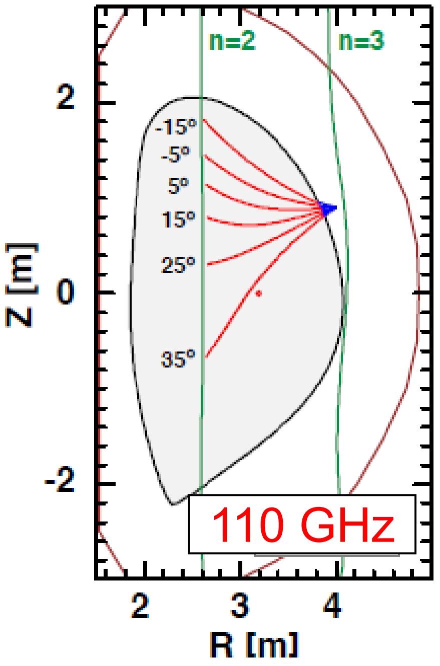


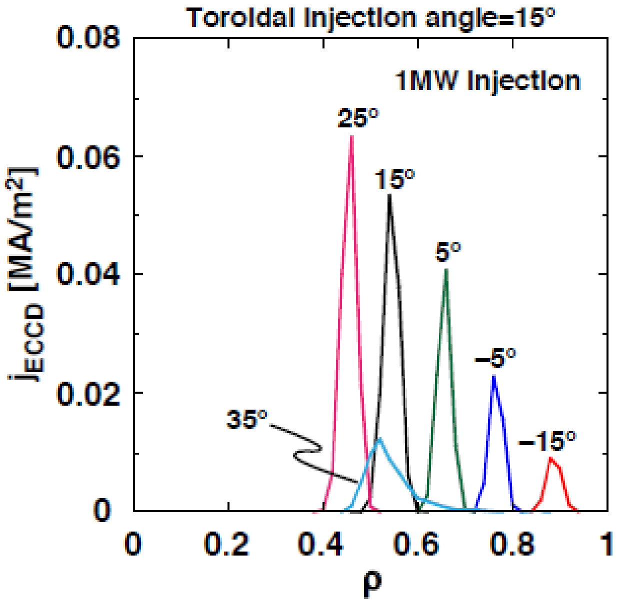
*K. Tobita *et al* 2019 *Fusion Sci.Tech.* 75 5 372–383.

Multi-frequency ECRH system for JT-60SA

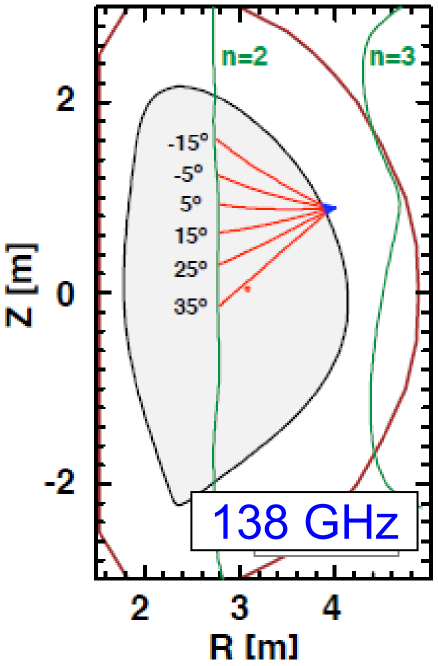
- Multi-frequency ECRH system has developed & constructed on JT-60SA for EC H/CD, NTM control, plasma startup and wall cleaning under various experimental conditions

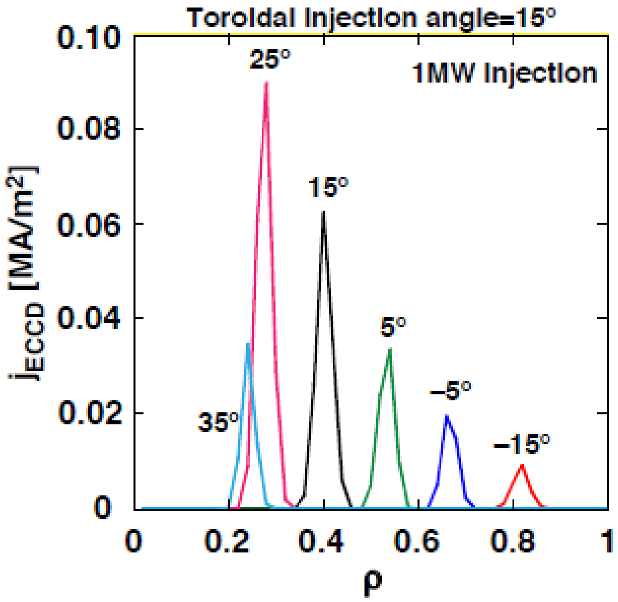
Scenario 5 (high-beta, B_T ~ 1.7 T)





Scenario 2 (Ip=5.5MA, B_T ~ 2.25 T)





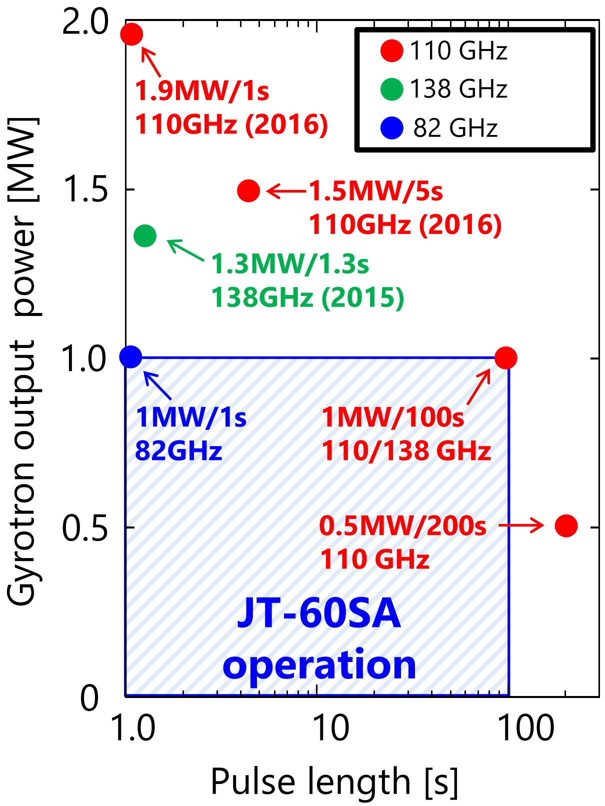
* JT-60SA research plan v4.1

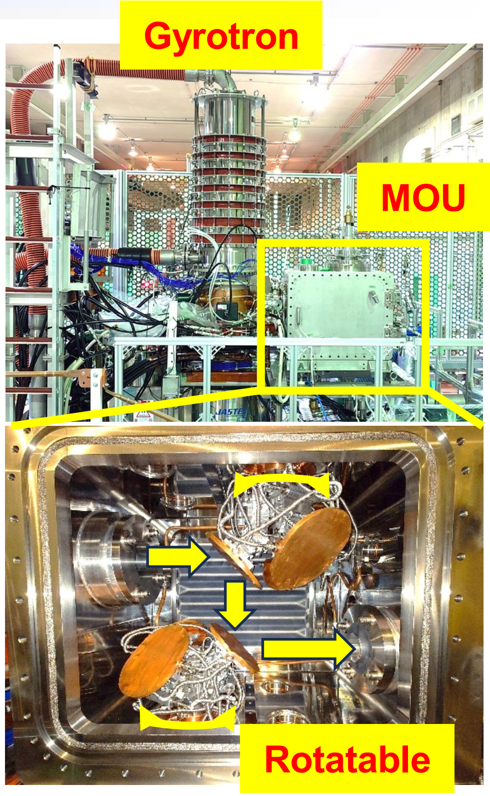
- Heating/current drive at different Bt by 110 GHz and 138 GHz
- Additional 82 GHz for fundamental injection for plasma startup and ECWC

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





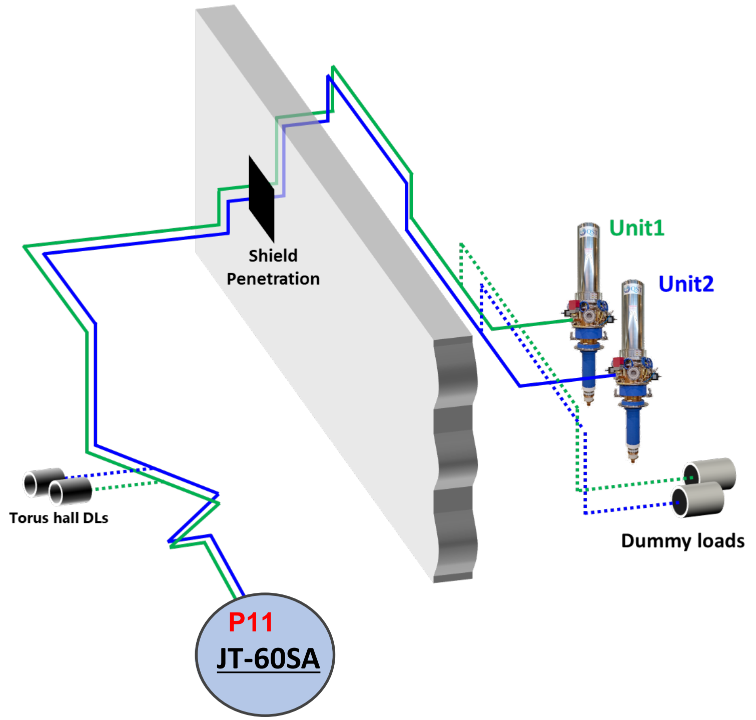
- Matching Optics Unit (MOU)
  - ✓ MOU with three sets of rotatable phase-correcting mirrors
  - ✓ RF can be coupled into the WG with high mode purity

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

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

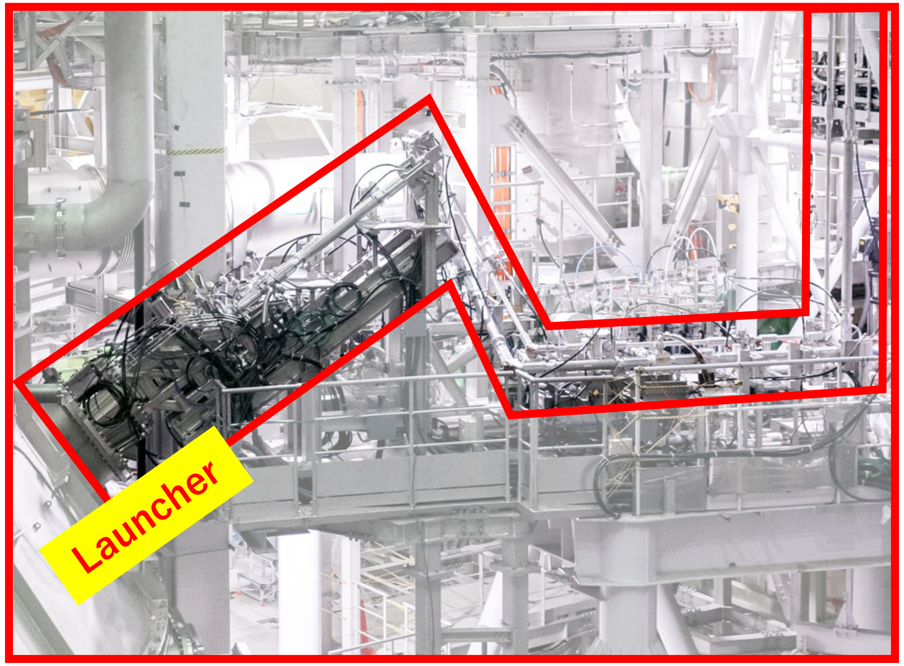
Development of key components are completed !

Installation of the transmission line components



		JT-60U components	Multi-frequency
		Unit#1	Unit#2
Gyrotron	Frequency	110 GHz	82/110/138 GHz
	Output power	1 MW	1 MW
	Pulse duration	5s	110/138 GHz: 5 s 82 GHz: 1s
Transmission line	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	

Measured



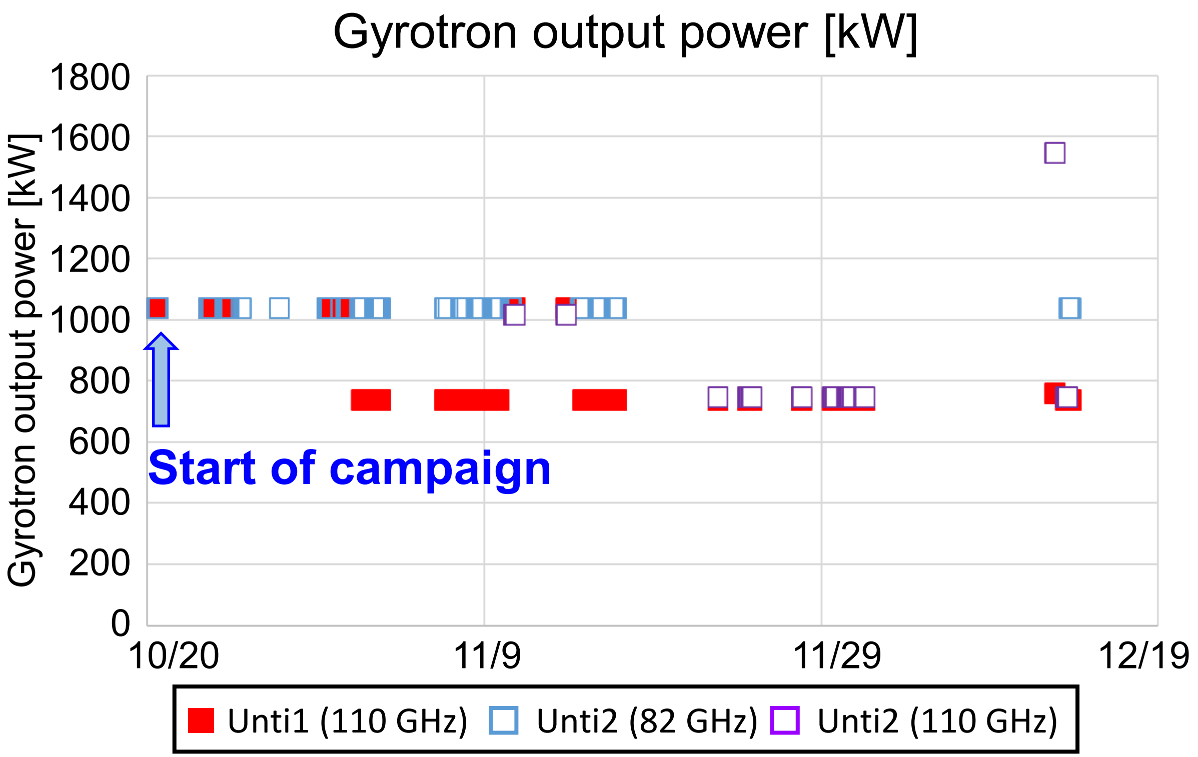
* H. Yamazaki, et al., Fusion Eng. Des., vol.196, 114015, 2023

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**

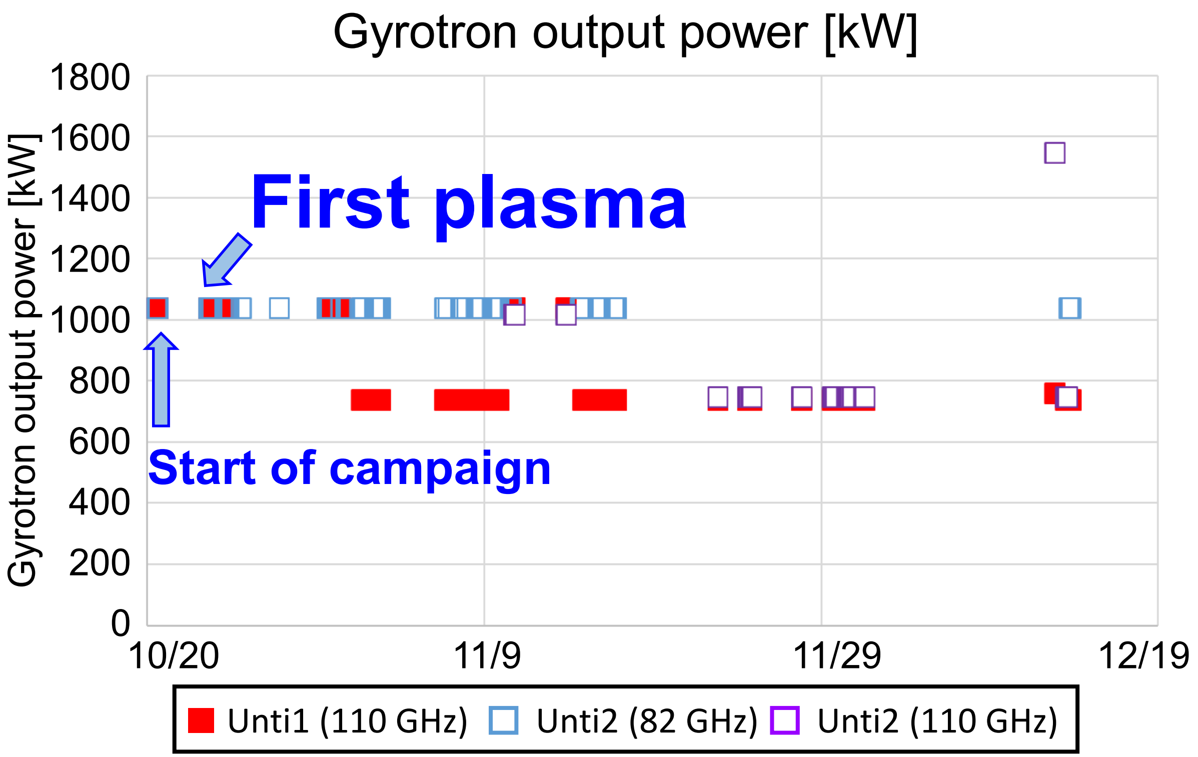
Objectives: Operation with (1) output power: 1 MW, (2) pulse duration: 5 seconds

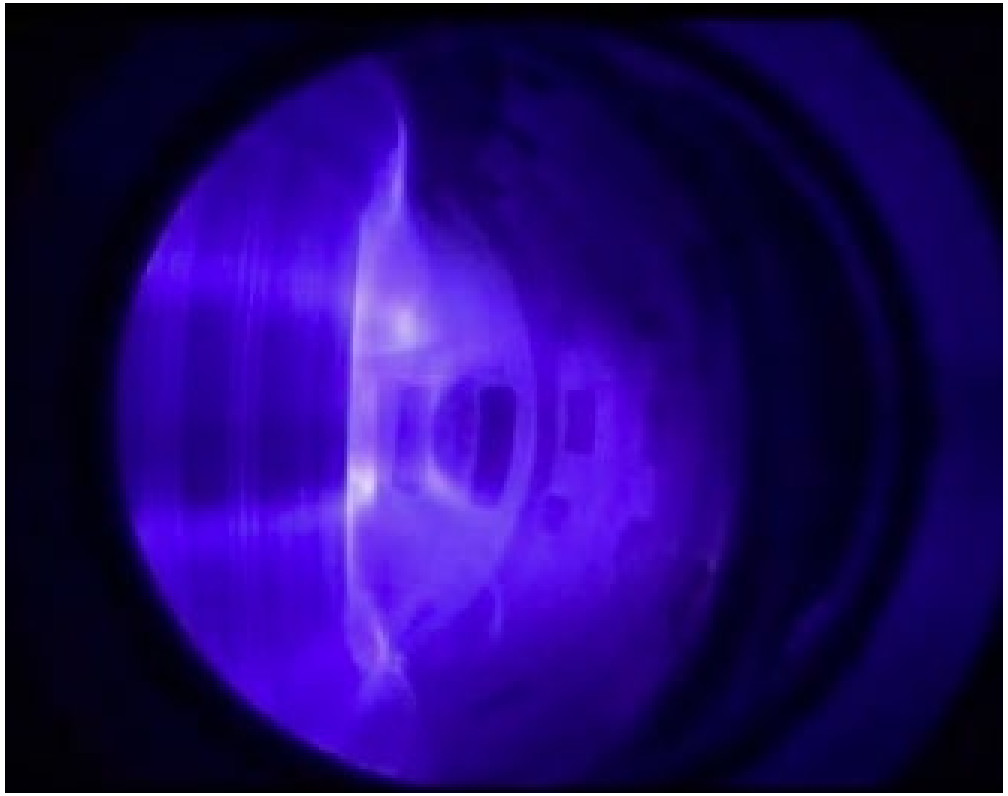
Operation summary during the plasma experiments



- **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.**

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 summary during the plasma experiments

❑ Operation reliability

Unit1 (110 GHz)	Number of pulses	Failed	Success [%]
Plasma experiment sequence	**340**	**34**	**90.0%**

Unit2 (82/110/138 GHz)	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.**

Operation summary during the plasma experiments

❑ Operation reliability

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Plasma experiment sequence	**350**	**34**	**90.3%**
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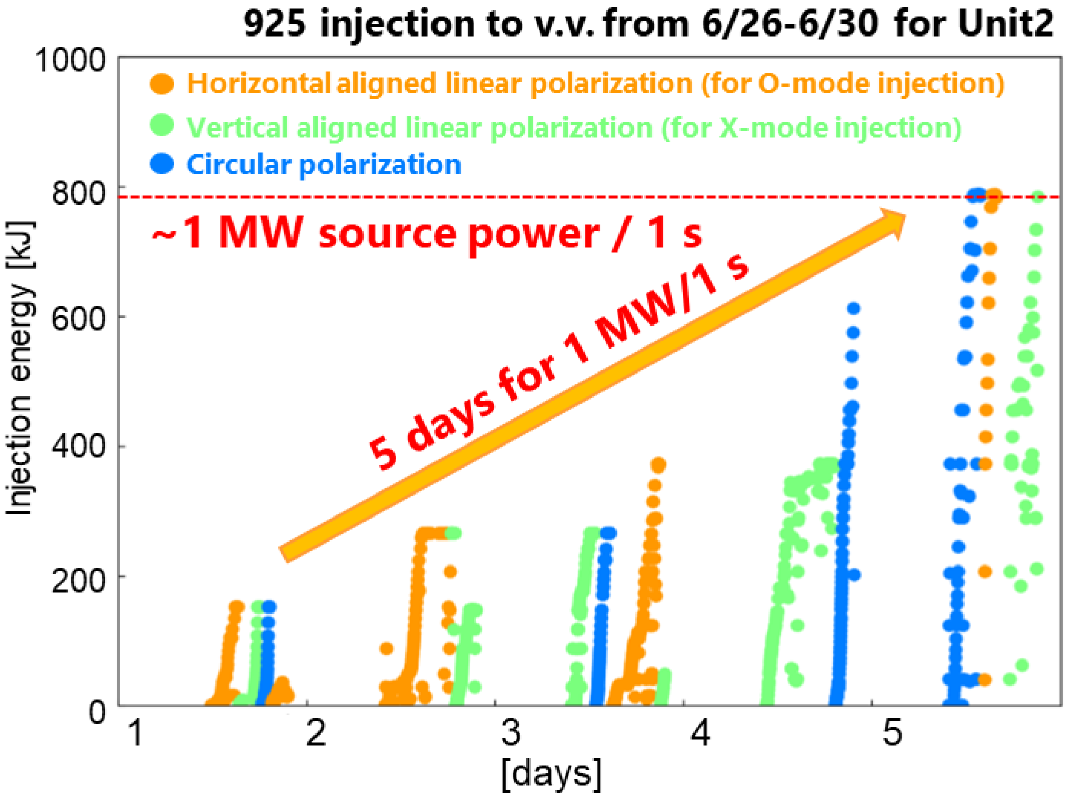
138 GHz	0	0	-

Progress of the TL conditioning



❑ **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.**

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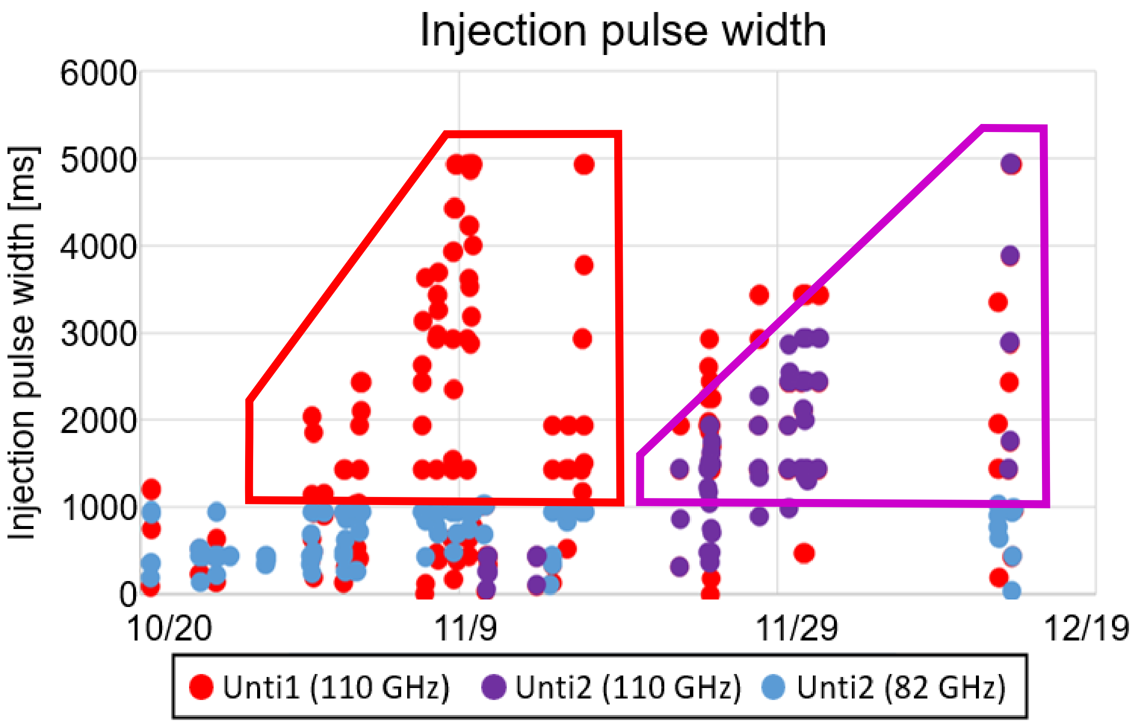
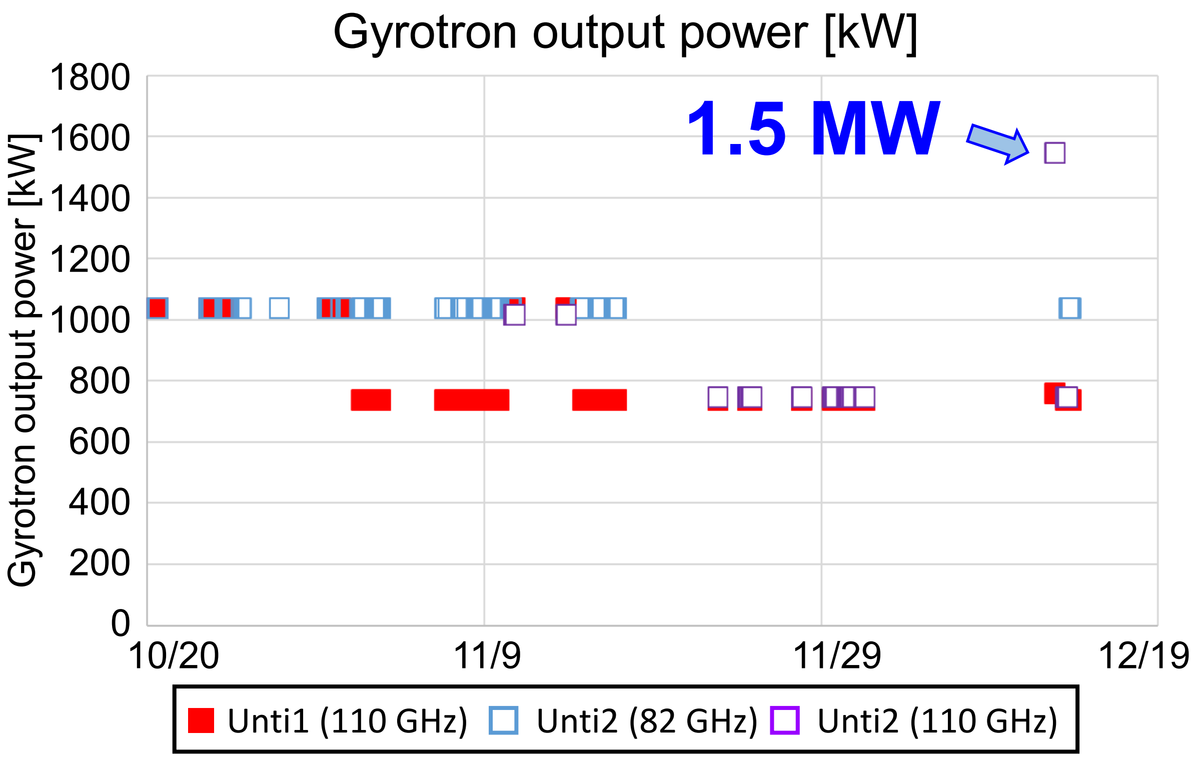
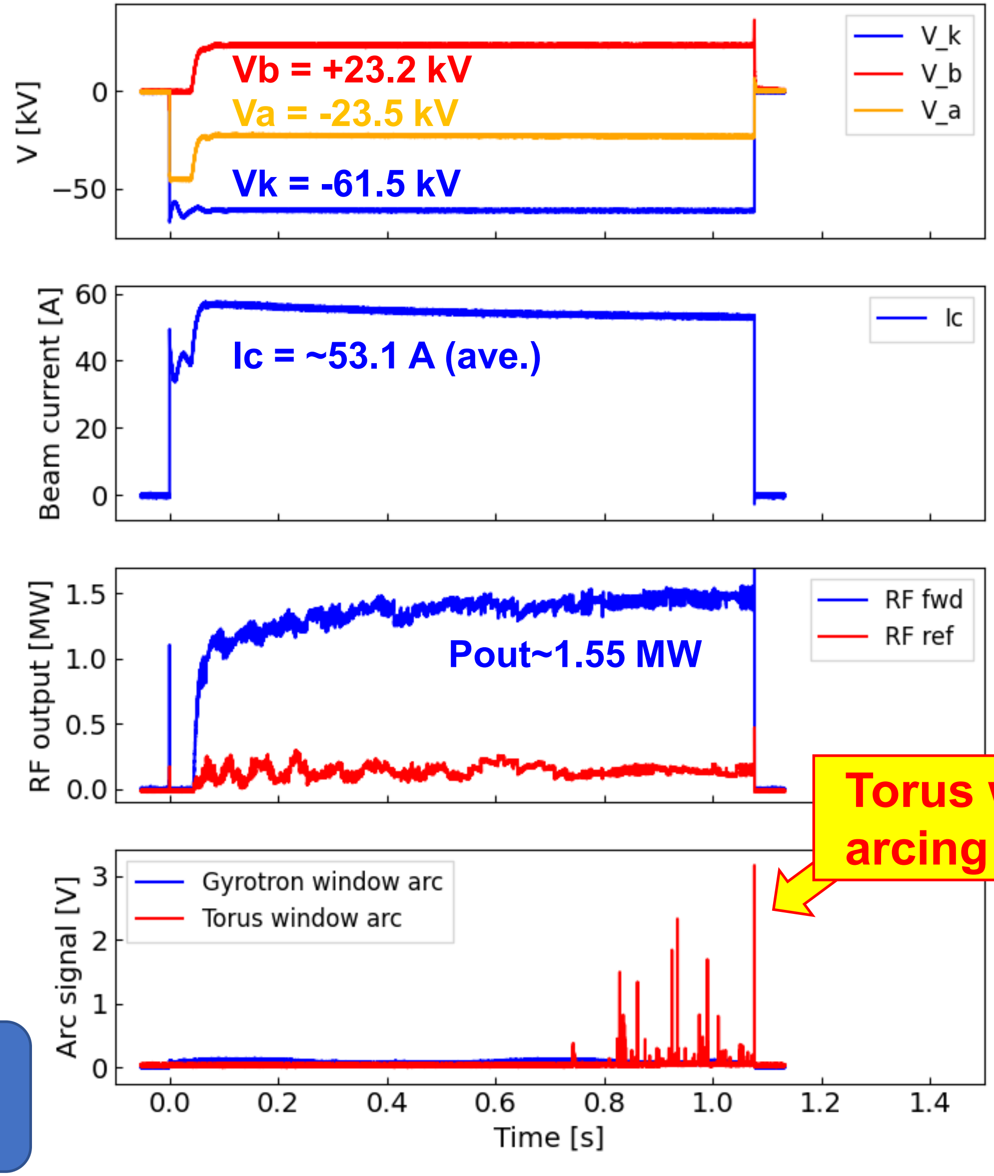


- ❑ **Averaged success rate is ~90%, demonstrating highly reliable system operation.**
- ❑ **To achieve high reliability, TL components were conditioned by injecting RF waves into the vacuum vessel at a power of up to 1 MW for 1 second.**
- ❑ <u>5 seconds injection was achieved after the conditioning during the experiment</u>

1.5MW challenge for further high-power operation





- ❑ **RF stopped by only torus window arc signal**

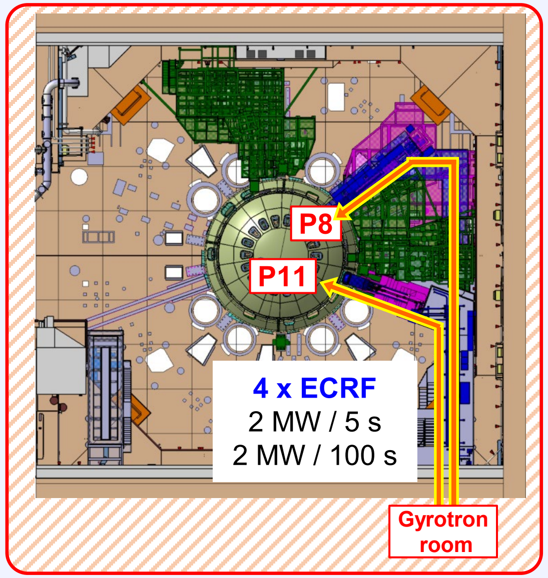
→ Could be extended by performing more conditioning operation

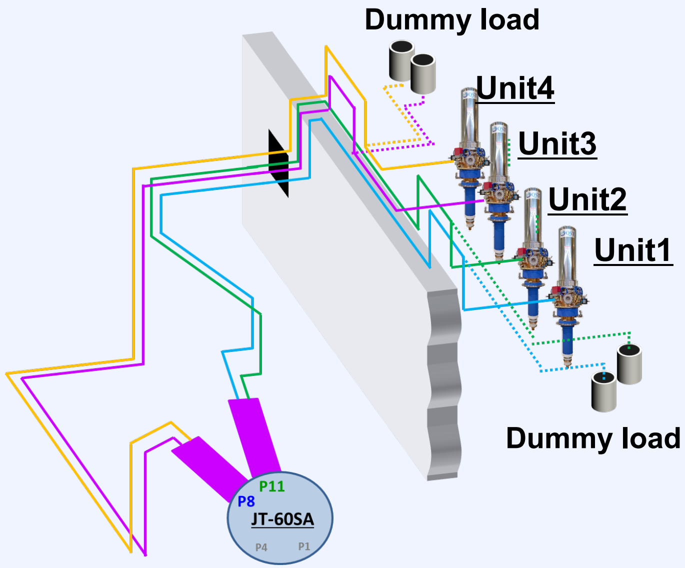
This achievement demonstrates the potential to upgrade the ECRH power in the future.

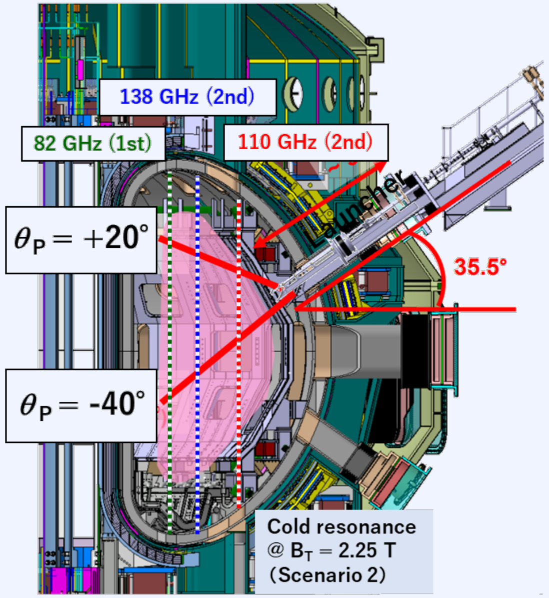
Summary

- 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





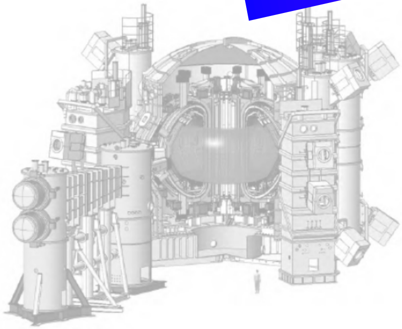


Introduction: Gyrotrons for current and future fusion devices

Higher frequencies than 200 GHz to be needed for future fusion devices.

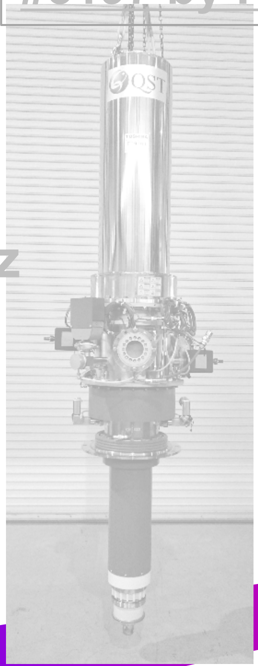
#2693 by H.Yamazaki *et.al*

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



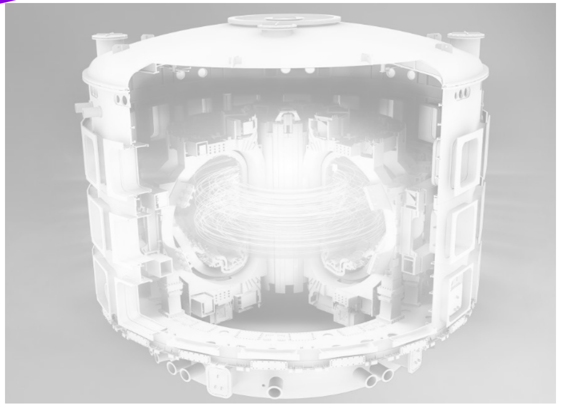
JT-60SA

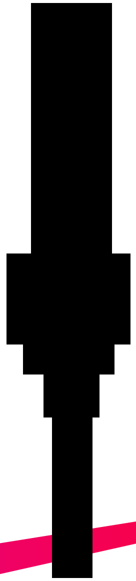
#3197 by K.Kajiwara *et.al*



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

ITER

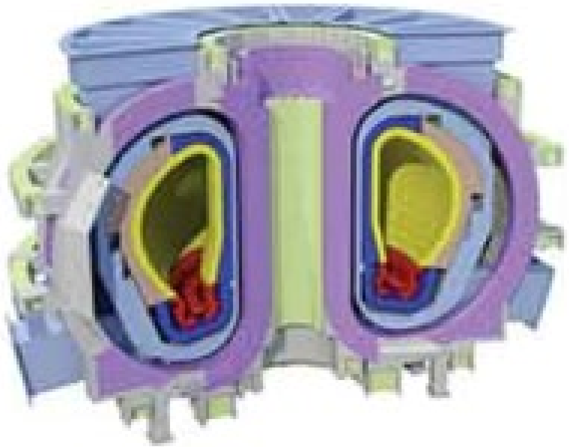




#2703 by T.Shinya *et.al*

- **Freq.: ≧ 200 GHz**
- **Power: ≧ 1 MW**
- **Continuous wave**

DEMOs & Fusion devices

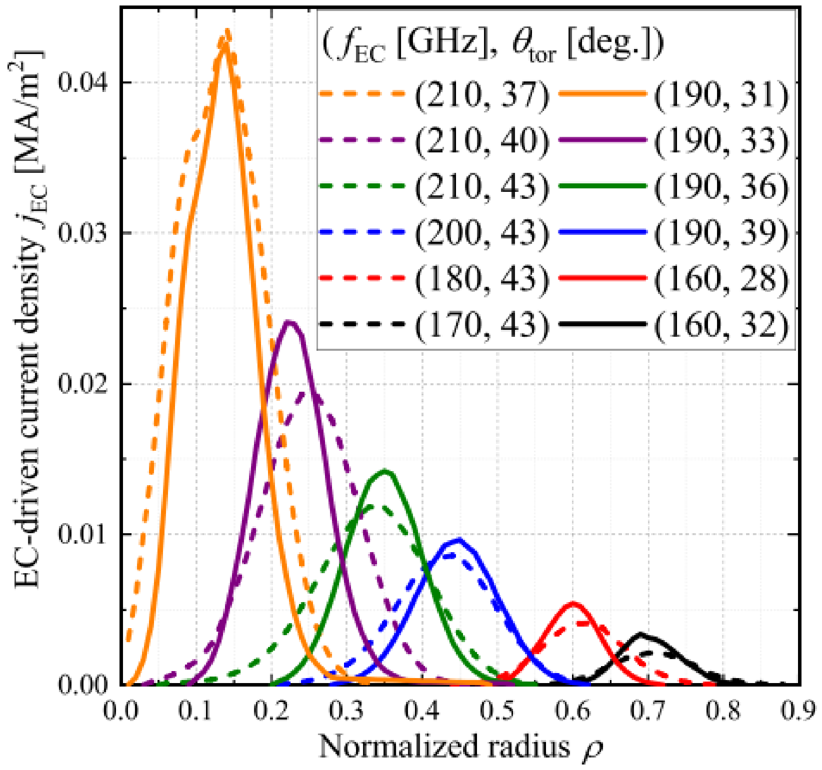


*K. Tobita *et al* 2019 *Fusion Sci.Tech.* 75 5 372–383.

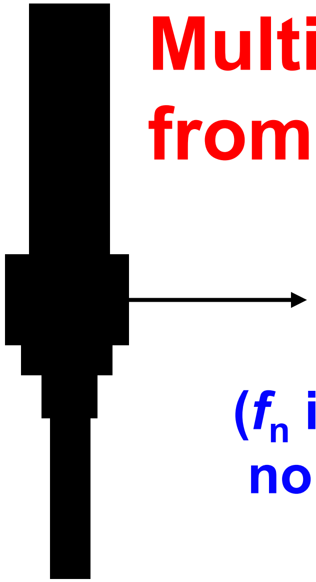
Introduction: Advantage of using multi-frequency gyrotron

EC-driven current density profile can be controlled by changing the gyrotron frequency.

- This compensate for an injection angle limitation of the launcher caused by the design constraints in 3-D space and by neutron flux on the components.



*S. Sugiyama *et al* 2024 *Nucl. Fusion* 64 076014



Multi-frequency output from single gyrotron

f_1 or f_2 or f_3 or ,,,,

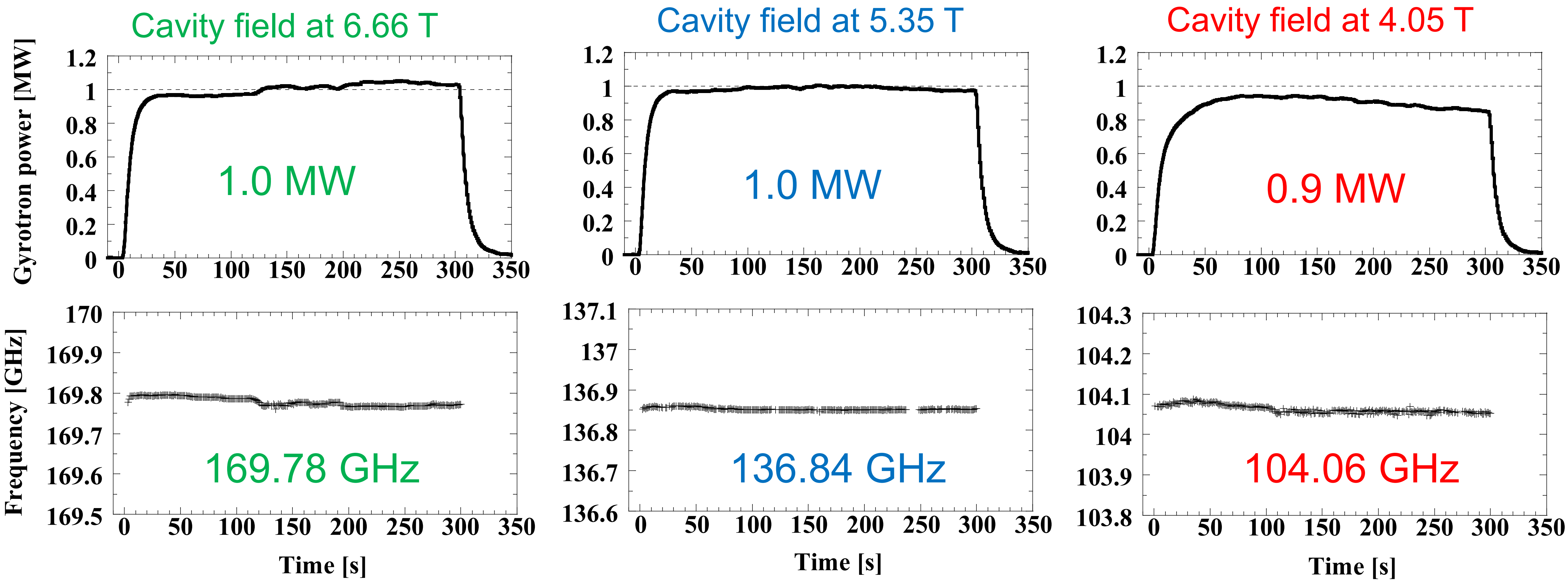
(f_n is selectable, but non-simultaneous output)

Our challenge:

170 GHz & ≧ 200 GHz (Multi-freq. gyrotron)

Previous study: Multi-frequency gyrotron for 104/137/170 GHz

QST successfully developed a multi-frequency gyrotron at 104/137/170 GHz.
The achievement was presented orally at the previous IAEA-FEC in 2023*.



*R. Ikeda *et al* 2023 *Nucl. Fusion* **63** 066028

Development of 170/203/236GHz multi-frequency gyrotron for fusion devices in QST

- The ITER prototype gyrotron was modified to demonstrate 170/203/236 GHz operation at high power.
- The electron gun of ITER prototype gyrotron was replaced to new one whose shape was redesigned to produce a high-quality electron beam at 170 GHz, 203 GHz, and 236 GHz.

List of frequencies satisfying the multi-frequency condition[1]

Freq. [GHz]	104	137	170	203	236
Mode	$TE_{19,7}$	$TE_{25,9}$	$TE_{31,11}$	$TE_{37,13}$	$TE_{43,15}$
Achieve-ment	0.9 MW/ 300 s	1 MW/ 300 s	1 MW/ 300 s	1 MW/ 2 s[3]	-

Previous study[2] (IAEA-FEC 2023) → **Target frequencies**

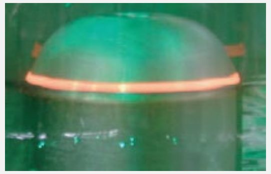
ITER prototype gyrotron (optimized for 170 GHz)

Target values

- Power: ~1 MW
- Electrical eff.(P_{out}/P_{in}) =~50%
- Pulse: ~ 100 s

Electron gun

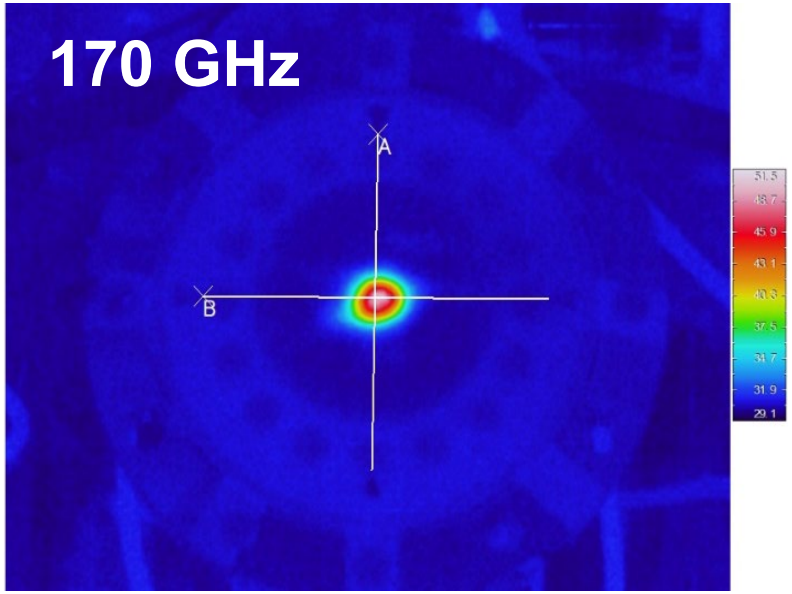
Electron gun shape was optimized for 170/203/236 GHz.



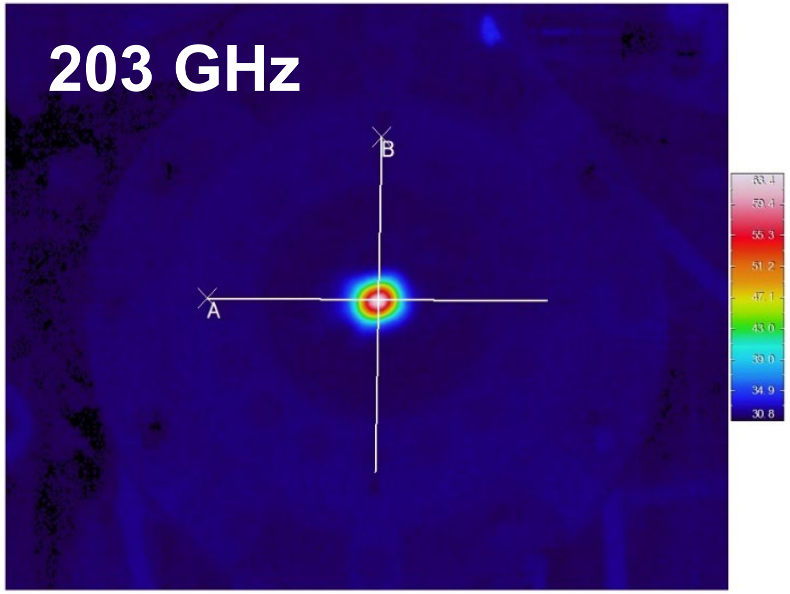
[1] K. Kajiwara *et al* 2011 Appl. Phys. Express **4** 126001
[2] R. Ikeda *et al* 2023 Nucl. Fusion **63** 066028
[3] K. Sakamoto *et al* 2017 42nd IRMMW-THz 1-3

Beam pattern measurements at output window

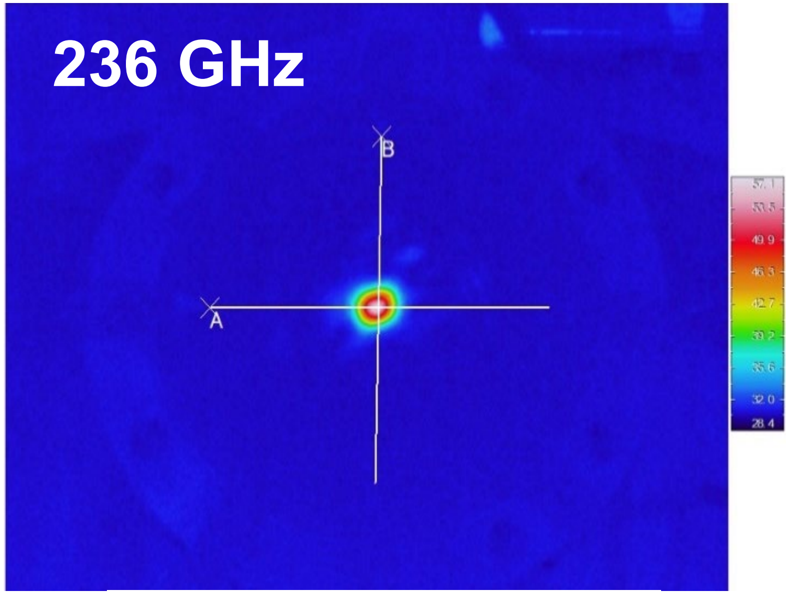
- Those beams passed through the center of the output window even if the different frequencies, without adjusting an angle of a gyrotron internal mirror.
- High quality of quasi-Gaussian beam profiles were obtained at the three frequencies of 170 GHz, 203 GHz, and 236 GHz.



Cavity field at 6.58 T



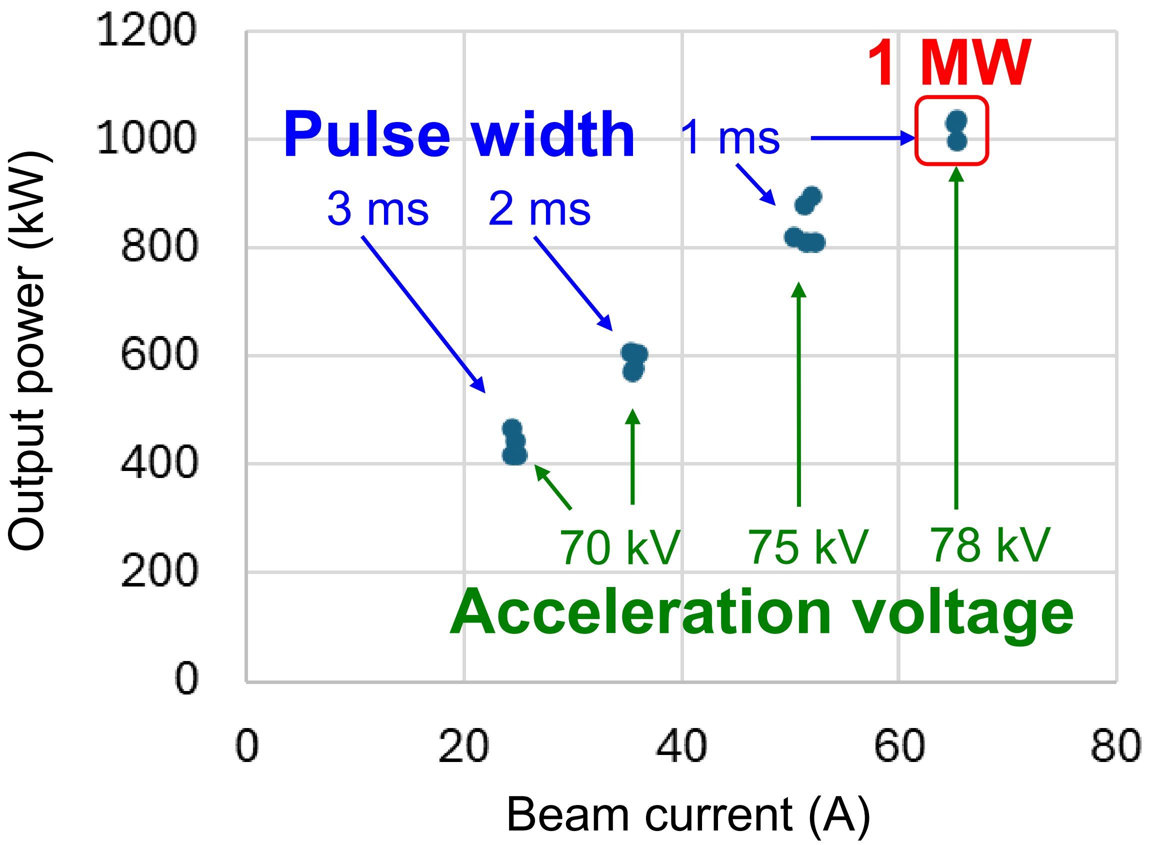
Cavity field at 7.88 T

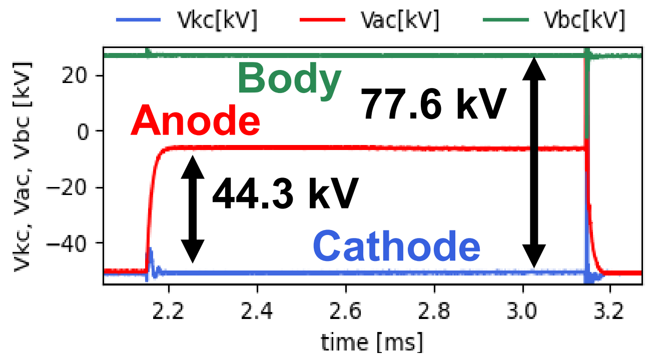


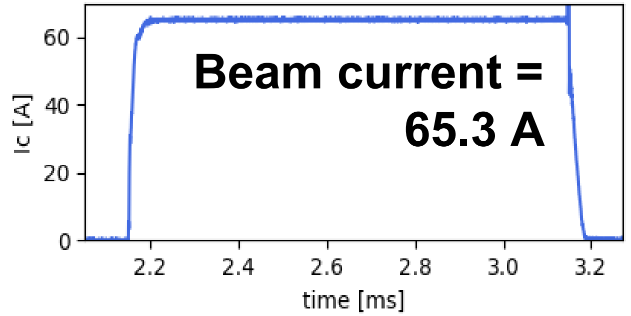
Cavity field at 9.21 T

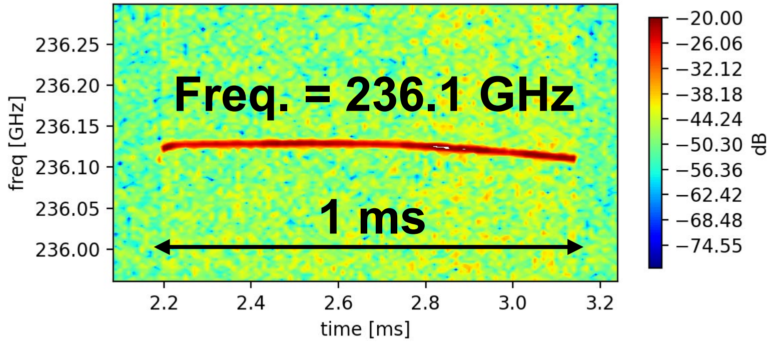
236 GHz: High power operation for 1~3 ms

❑ 1 MW was achieved at 236 GHz in the short pulse operations for 1~3 ms.





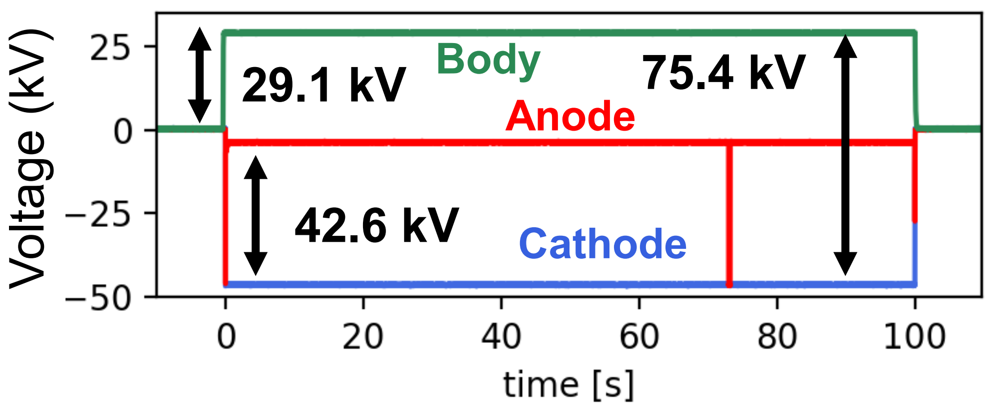


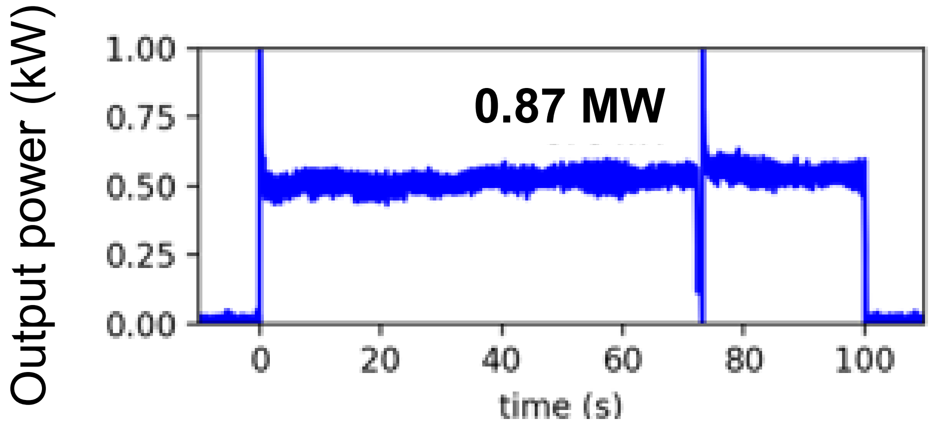


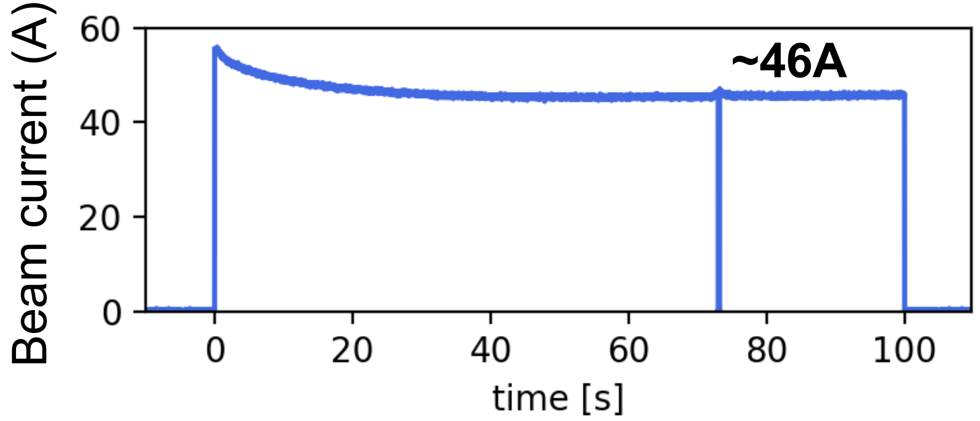
203 GHz: High power operation for 100 s

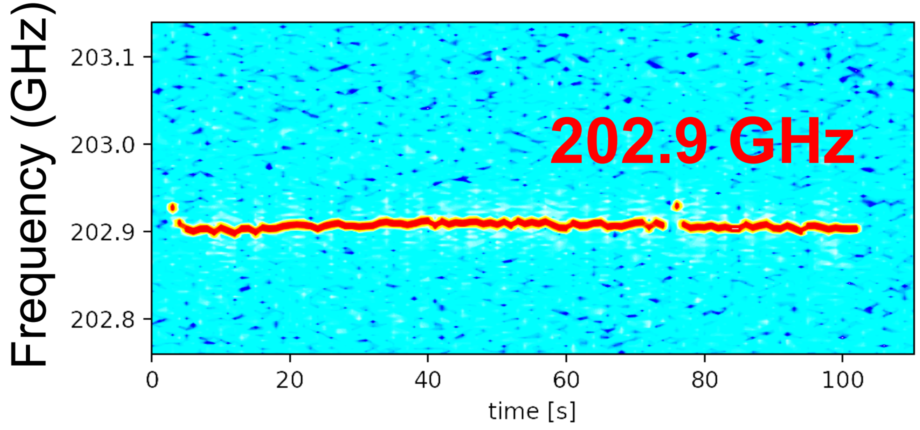
At 203 GHz, 0.87 MW was achieved in the long pulse operation for 100 s with an electrical efficiency of 41% without optimize of depressed collector voltage (oscillation efficiency of 25%).

- ➢ This is the first result showing ITER-class performances in such long pulse operation at ≧ 200 GHz.









Summary

- Multi-frequency operations at 170 GHz, 203 GHz, and 236 GHz with high power were successfully demonstrated.
- The pulse width was successfully extended to 100 s at 203 GHz, and the output power achieved 0.87 MW.
- Moreover, the output power achieved 1 MW at 236 GHz in the 1 ms operation.
  - ➢ These initial results show a possibility of achieving ITER-class performance at the frequencies of 170 GHz and higher than 200 GHz for ITER and future fusion devices.