Development of Over 1 MW and Multi-Frequency Gyrotrons for Present ST and Fusion Experiments in University of Tsukuba

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Outline

- The development of **wide frequency range from 14 to 300 GHz** of high power MW gyrotron for fusion is in progress in **University of Tsukuba**. The strong development activity was carried out **in collaboration with NIFS, JAEA, TETD and Universities (as all Japan efforts)**.

Challenge to 14 GHz - 300 GHz Gyrotron Developments

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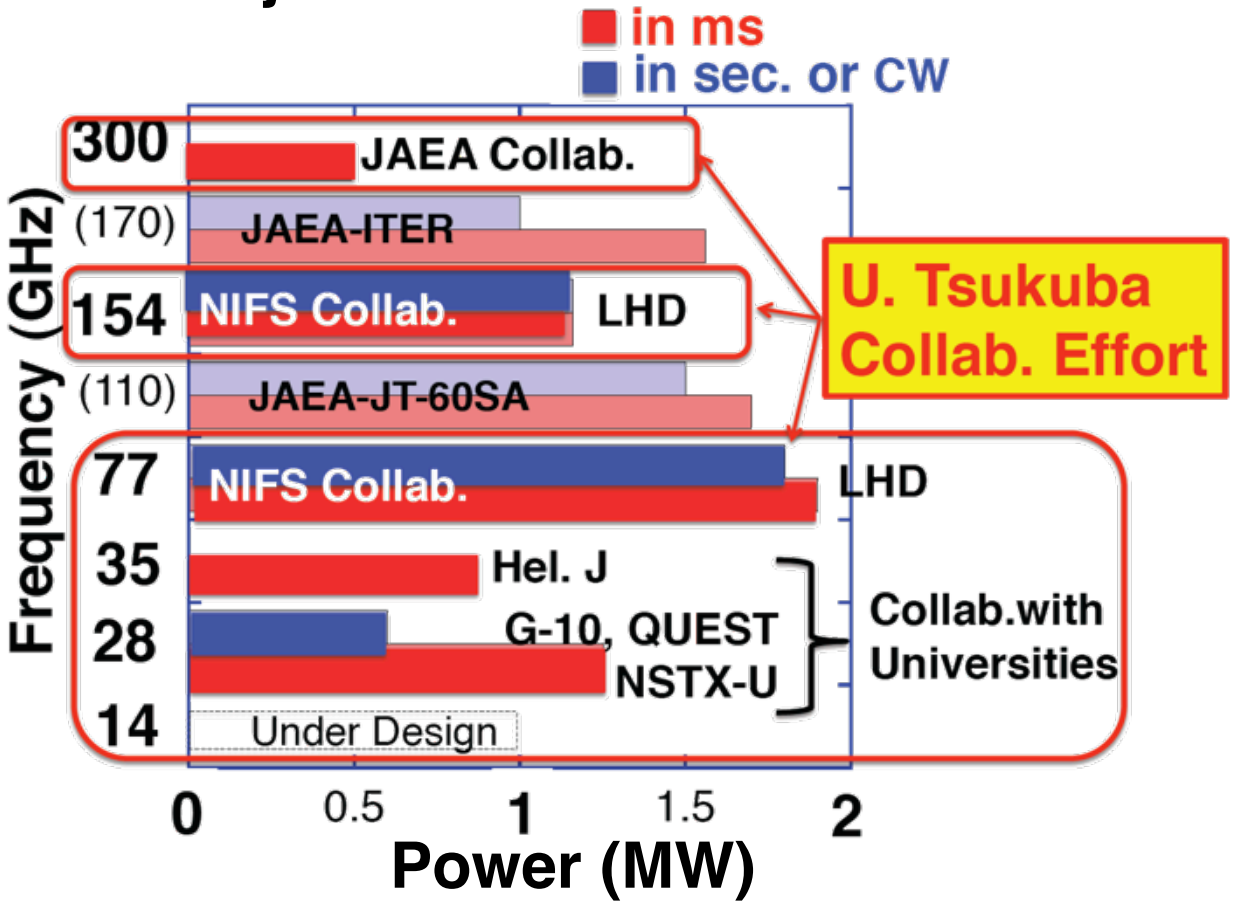
●Summary of the major results



→ **Lower Freq. (14, 28 & 35 GHz)** over 1 MW ECH Gyrotron for **GAMMA 10/PDX (Univ. of Tsukuba), QUEST , Heliotron J and NSTX-U.**

→ **Higher Freq. (77, 154 & 300 GHz)** over 1 MW ECH Gyrotron for **LHD and Demo Reactor.**

Schedule of Gyrotron Development in PRC

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Gyrotrons		-2015	2016	2017	2018	2019	2020	2021
Machine	Frequency							
GAMMA 10, QUEST and NSTX-U	28 GHz range	Dual frequency, 1.25 MW at 28 GHz and 0.87 MW at 35 GHz was achieved.						
		QUEST Exp. & GAMMA 10 Exp.						
		1.5-2 MW gyrotron for NSTX-U						
			Fabrication	NSTX-U Exp.				
	14 GHz range	For GAMMA 10/PDX and QUEST in the near future.						
		Design & Test						
LHD	77/ 154 GHz range	77 GHz tube ($TE_{18,6}$) demonstrated 2 MW performance. 1.8 MW for 1 s (World Rec.).						
		Plasma Exp.						
				Development of 154/ 116 GHz Dual frequency gyrotron				
				Fabrication				
Demo	300 GHz/ Multi MW	Improvement of 300 GHz gyrotron for Demo.						
		Operation Test		Higher power (Multi MW)				

Achievements in LHD Gyrotron Development

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●Achieved performances of 77 GHz & 154 GHz gyrotrons for LHD

Tube No.	Short Pulse Operation	Long Pulse Operation
77GHz#1	(1.4 MW 0.2 s)/1 MW 5 s	0.29 MW 60 s/0.13 MW 935 s
77GHz#2	(1.3 MW 0.4 s)/1 MW 5 s	0.24 MW 1800 s
77GHz#3	(1.9 MW 0.1 s)/1.8 MW 1 s	0.3 MW 1800 s/0.22 MW 4500 s
154GHz#1	1.25 MW 4 ms/(1.16 MW 1 s)	0.35 MW 1800 s
154GHz#2	1.2 MW 1 s	0.2 MW 1800 s

(power-pulse width) : two-step anode-rise voltage control

●Achievements of High Power ECH Experiments

→ 154 GHz: **1.16 MW for 1 s**

4.4 MW into LHD plasma with three 77 GHz tubes,
contributed to **T_e of 20 keV**.

28 GHz 1 MW Gyrotron for GAMMA 10

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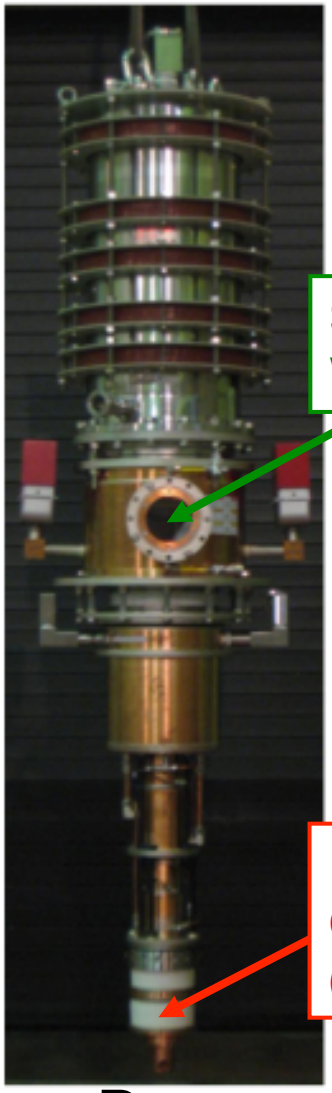

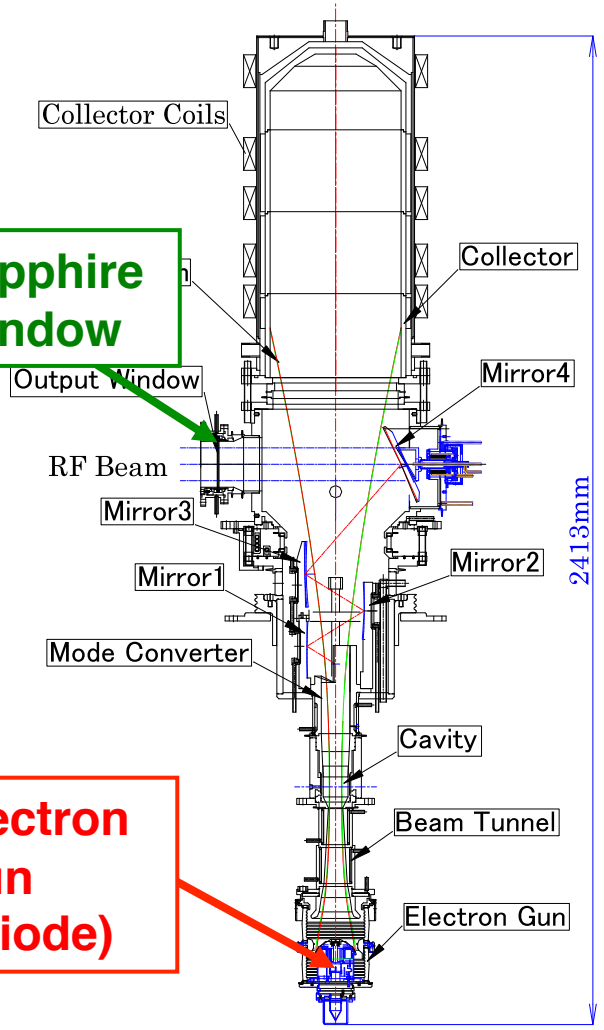

● Design Parameters of First tube

Frequency:	28 GHz
Oscillation Mode:	$TE_{8,3}$
Output:	1 MW
Pulse Length:	>1 s
	CW for 0.3 MW
Efficiency:	35% (w/o CPD)
Electron Gun:	Triode
Collector:	w/o CPD
Output Mode:	Gaussian
Height:	2413 mm
Weight:	700 kg

Advantages

First tube can be operated by use of **the same SCM** of 77 GHz Gyrotron.

→ Demonstrated **more than 1.25 MW** (2 ms) & **0.6 MW for 2 s**.
Both are limited by the DC Power Supply.

Setup of RF Test Bed in PRC

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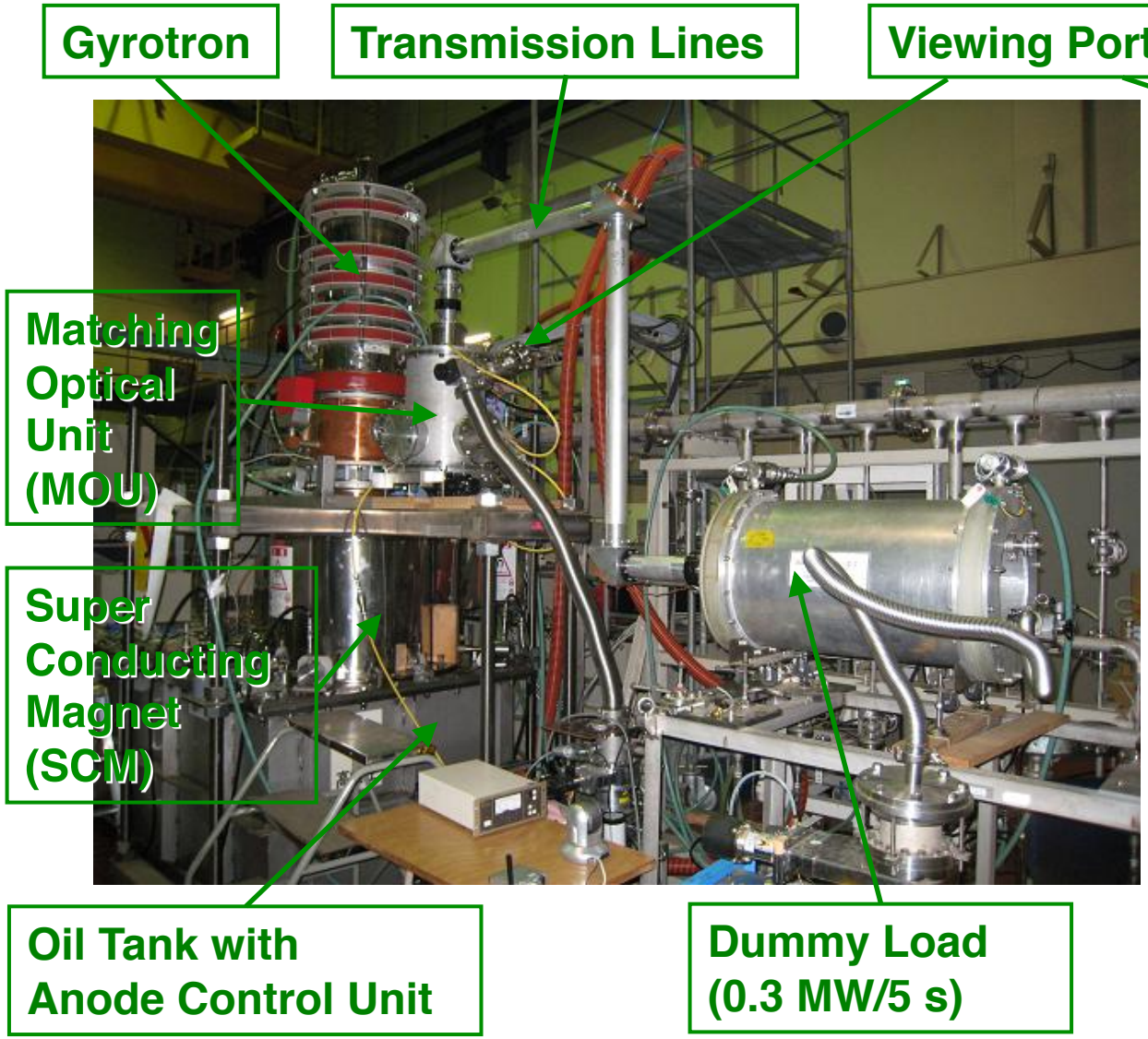
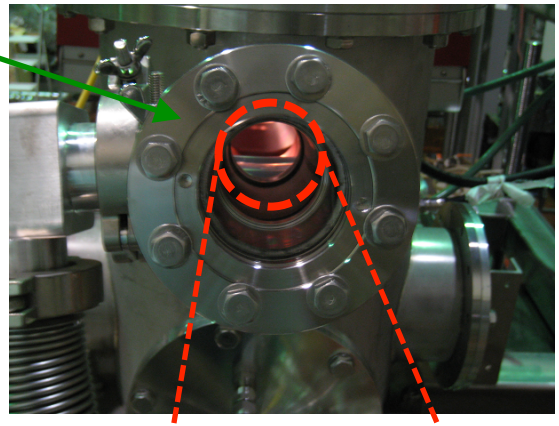
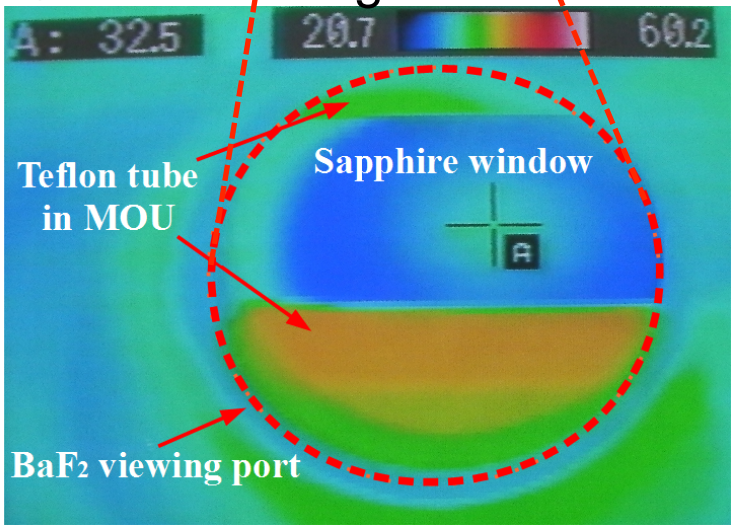


●Window Temperature Measurement



○Infrared Image



Dual-frequency over 1 MW demonstration of First 28 GHz Tube

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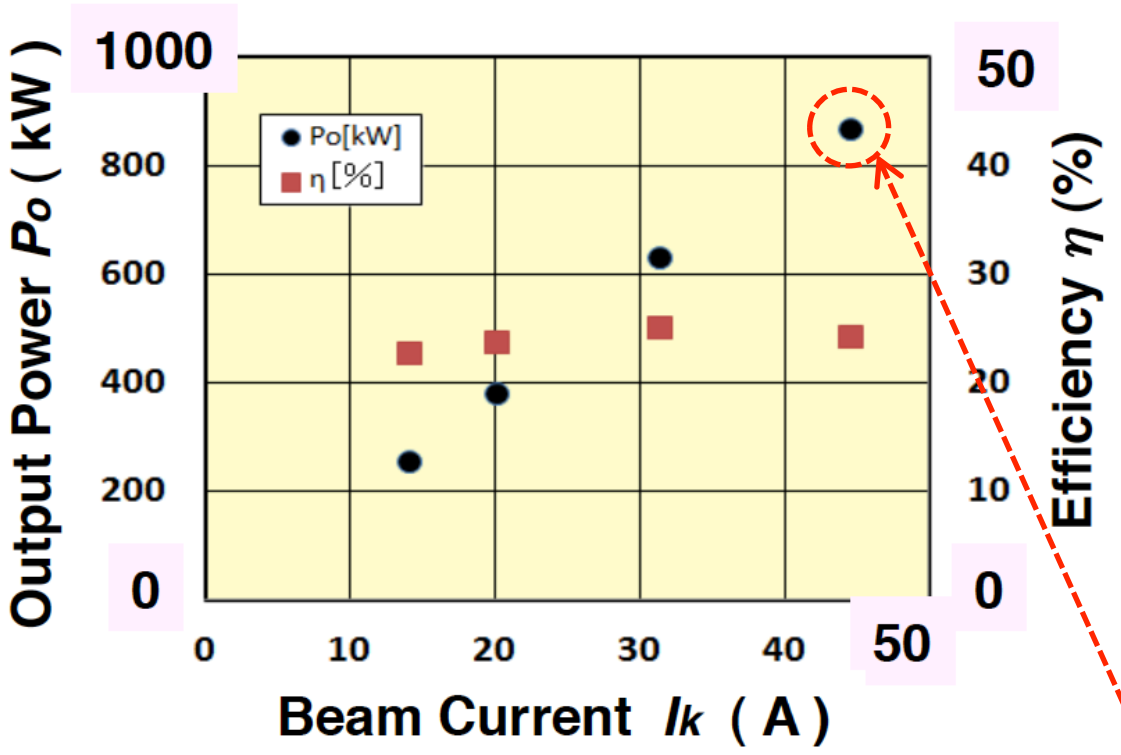
● **Installed 28 / 35 GHz window for dual-frequency test on First 28 GHz tube**



→ **Achieved MW-level dual frequency performance.**
0.9 MW/ 35 GHz corresponding to 1.2 MW oscillation power.
(from transmission efficiency 72%)

Application to QUEST Experiment

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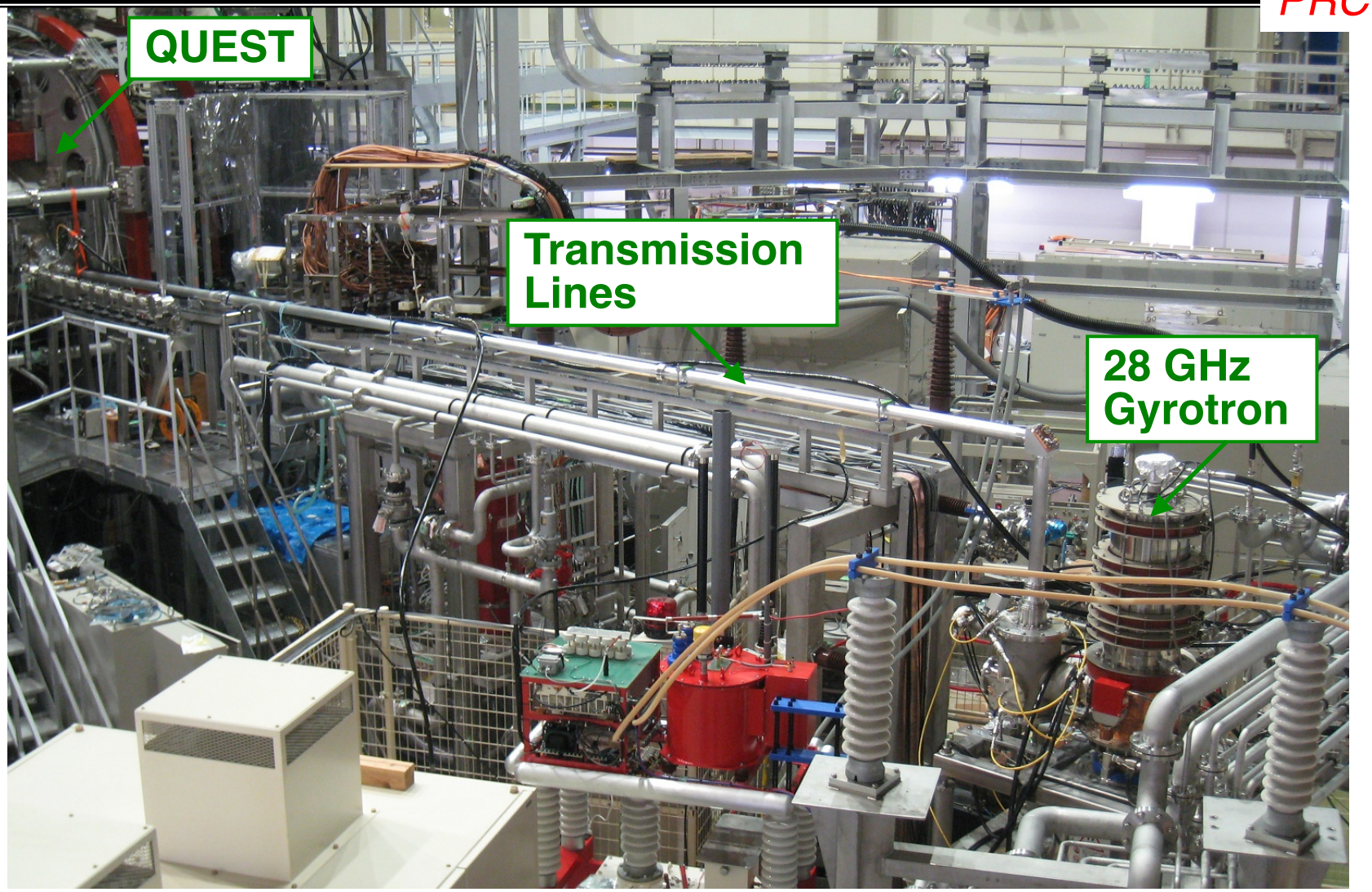

→ The successful result of **high EC non-inductive driven current around 60 kA** has been obtained.

Summary of Recent Progress of over 1 MW Gyrotron

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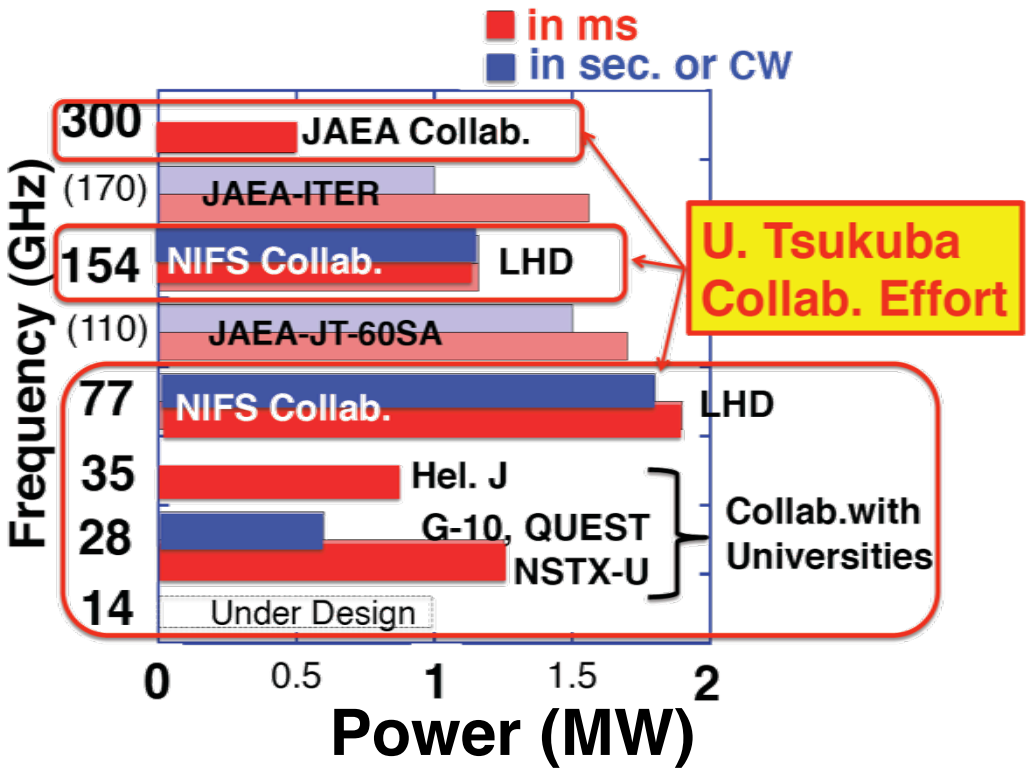

→ $T_{e0} > 10$ keV with $n_{e\_ave} = 2 \times 10^{19}$ m^{-3} (LHD). Total injection power > 5 MW.

→ I_p of 66 kA was non-inductively attained with 28 GHz injection (QUEST).

→ Dual frequency, 1.25 MW at 28 GHz and 0.87 MW at 35 GHz was achieved (PRC).

→ Long pulse: 0.6 MW / 2 s (28 GHz) was achieved (PRC).

The limit of output power and pulse length was due to the specifications of power supply (not gyrotron). Upgrade of power supply is in progress.

Application of 28 GHz Gyrotron

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● **After Successful Results of 28 GHz MW tube,**

→ we put the emphasis on the development of **multi-purpose gyrotrons**.

Research Extension

○ **more than 1.5 MW** a few seconds operation in **28 GHz**

→ for **GAMMA 10** high heat flux experiment (GAMMA 10/PDX project)

→ for **NSTX-U** of PPPL (EBW heating / current drive)

○ 1 MW level operation in **35 GHz range**

→ for **Heliotron J** of Kyoto University (EBW heating / current drive)

○ 0.4 MW **CW operation in 28 GHz**

→ for **QUEST** of Kyushu University (EBW heating / current drive)

New 28 / 35 GHz dual-frequency gyrotron with the following targets:

(1) **2 MW 3 s at 28 GHz** (for NSTX-U and GAMMA 10/PDX)

(2) **0.4 MW CW at 28 GHz** (for QUEST)

(3) **1 MW 3 s at 34.8 GHz** (for Heliotron J)

Next Step of New 28 / 35 GHz Gyrotron Development

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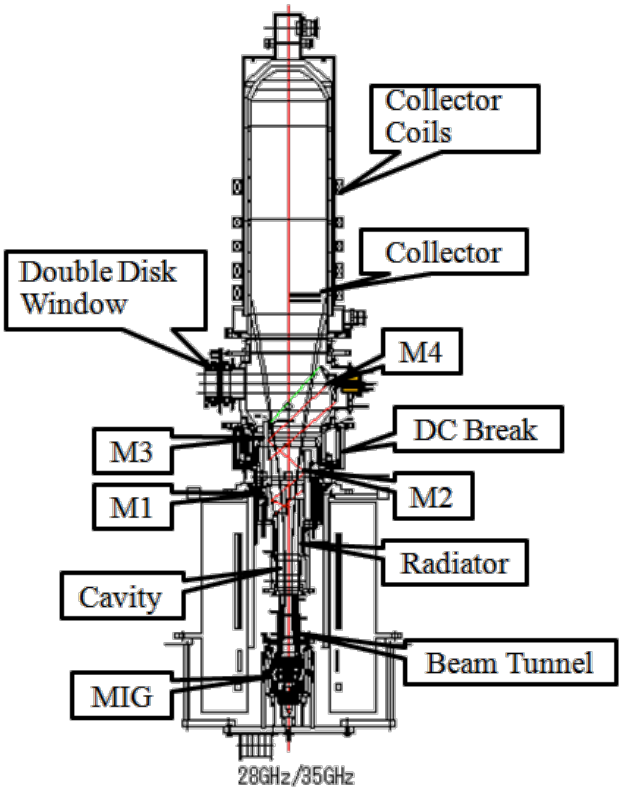
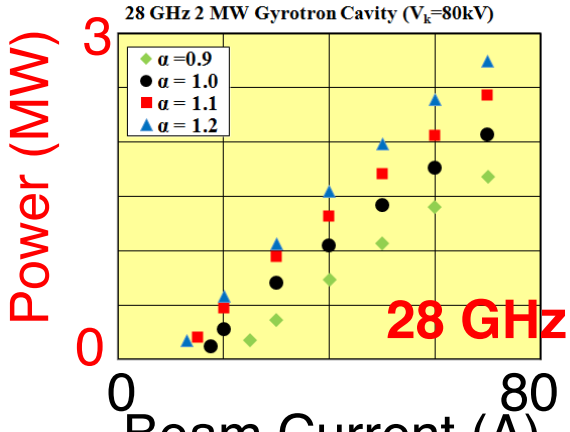
○The first tube was limited up to 1 MW due to α dispesion (Δα). ($\alpha = V_{\perp} / V_{//}$)

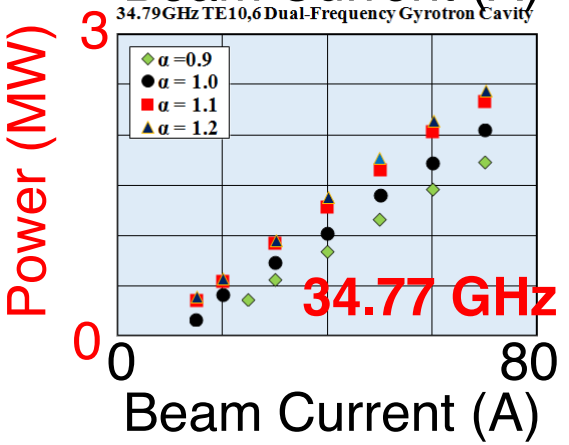
→ **Design improvement of the MIG to get better laminar flow.**

●Design Parameters of New Tube

28 GHz 2 MW Dual-frequency Gyrotron for GAMMA 10/PDX, QUEST, NSTX-U			
Frequency	28 GHz		34.77 GHz
Output Power	2 MW	0.4 MW	1 MW
Pulse Width	3 s	CW	3 s
Output Efficiency	50% (with CPD)		
Beam Voltage	80 kV	70 kV	80 kV
Beam Current	70 A	20 A	40 A
MIG		triode	
Cavity mode	$TE_{8,5}$		$TE_{10,6}$
Output mode	Gaussian like		
Output Window	Sapphire Double Disk		
Collector	Depressed Collector		
	Sweeping coils		







→ Determined from the selection rule
$TE_{8,5}$ (28 GHz) & $TE_{10,6}$ (35 GHz) and optimized the cavity,
2 MW calculated outputs at both 28 & 35 GHz are obtained.
We started the fabrication.

Design Study of 14 GHz Gyrotron

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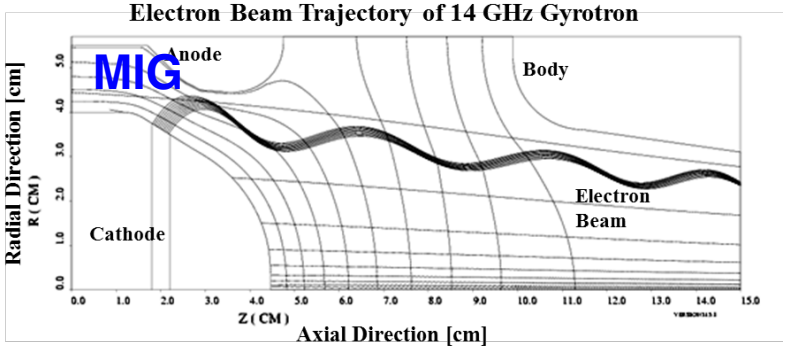
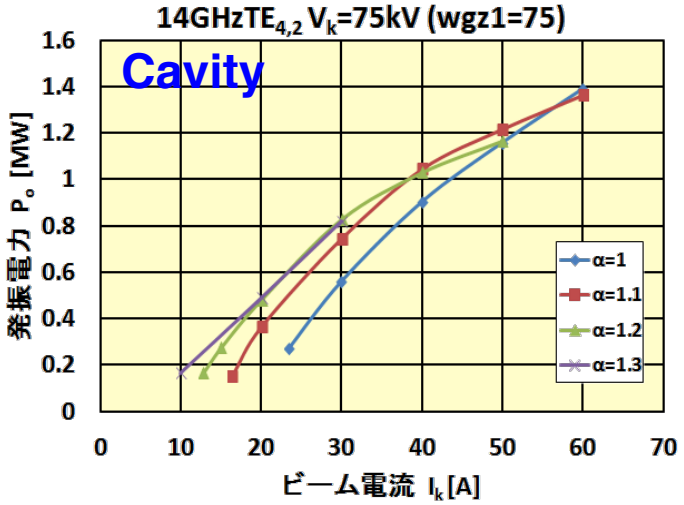
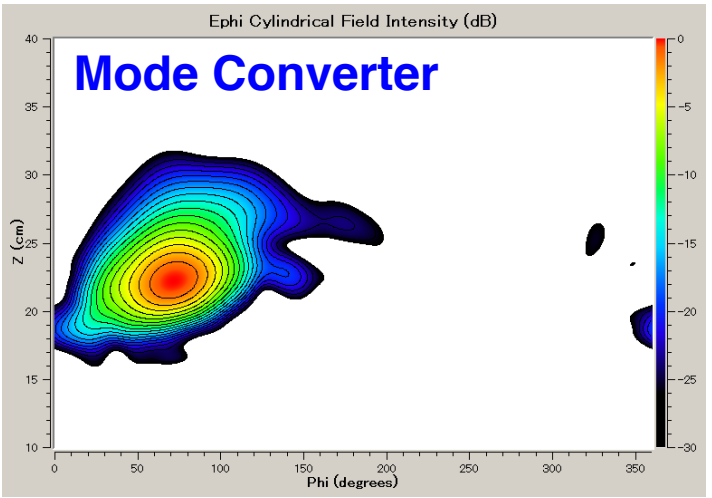
○**14 GHz** gyrotron for GAMMA 10/PDX and QUEST in the near future
→ For a fundamental heating at the mid-plane of GAMMA 10 central-cell
→ The optimal frequency for an EBW experiment in magnetic field at QUEST

●High quality electron beam





●High efficiency mode conversion



○ Improved Points

● **Magnetron Injection Gun (MIG) and Cavity**:
to improve the effective pitch factor α degradation in high beam current.

● **Internal Mode Converter and Mirrors:**
to minimize the electric field at the window edge and diffraction loss.

→ 1 MW/ 14 GHz/ $TE_{4,2}$ cavity design accomplished.

300 GHz Challenge for Demo Reactor

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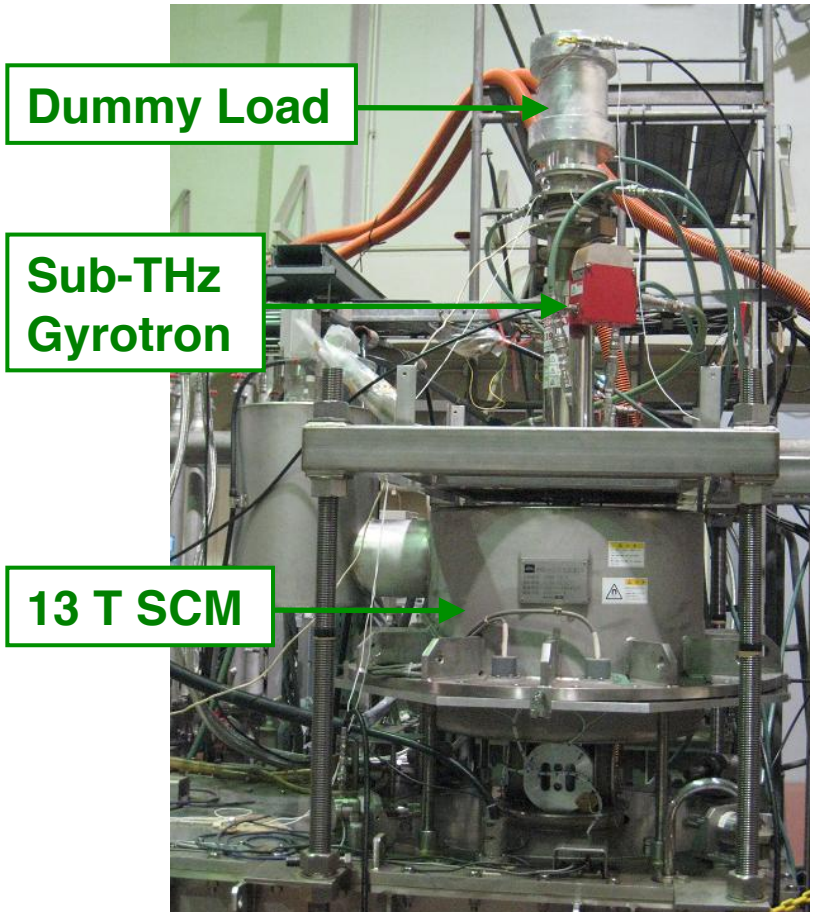
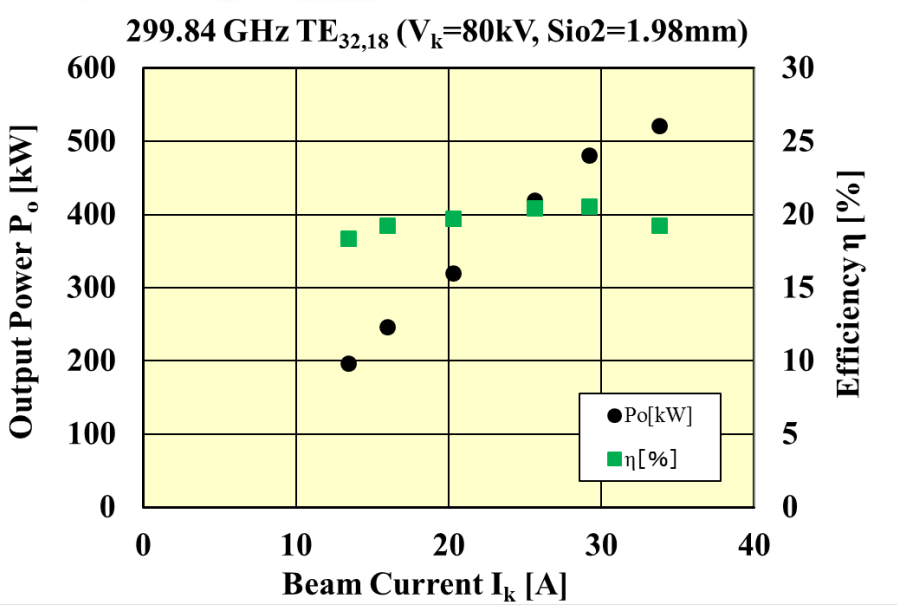
●300 GHz Test on the Tsukuba T.B.



●Power Profile at the Window

○Experiment

Appeared 300 GHz/ $TE_{32,18}$ from the burned pattern.



→ ~ 0.5 MW for 1 ms (η = 19 %) achieved with V_k = 80 kV. (Joint Exp. with JAEA).

Summary

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●**Development of High Power Gyrotron for LHD**

→ **Three 77 GHz gyrotrons and Two 154 GHz gyrotrons** have demonstrated **4.4 MW injection** into LHD plasma contributing to producing the **electron temperature T_e of 20 keV**.

→ **T_{e0} > 10 keV with $n_{e\_ave} = 2 \times 10^{19}$ m^{-3}. Total injection power > 5 MW.**

●**Development of 28 GHz Gyrotron for GAMMA 10**

→ **Design improvement of the MIG** to get better laminar flow and **application of the dual-frequency window** have been carried out.

→ **Dual frequency, 1.25 MW at 28 GHz and 0.87 MW at 35 GHz** has been achieved.

→ **I_p of 66 kA** has been non-inductively attained with 28 GHz injection in **QUEST.**

●**Development of 14 GHz Gyrotron for GAMMA 10 and QUEST**

→ **1 MW/ 14 GHz/ $TE_{4,2}$** cavity design has been accomplished.

●**Development of 300 GHz Gyrotron for DEMO Reactor**

→ **~ 0.5 MW for 1 ms (η = 19 %) has been achieved with V_k = 80 kV.**

University of Tsukuba is challenging to 14 GHz - 300 GHz Gyrotron development for present & future Demo ECH and obtained MW level or over 1 MW in 28, 35, 77, 154 and 300 GHz.

Future Plans

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○Based on Above Successful Results,

→ 28 GHz tube has applied to **QUEST for EBW experiment** and **GAMMA 10 for high heat flux and high potential experiment**.

→ Fabrication of new **28 GHz / 35 GHz** dual frequency gyrotron is in progress.

→ Development of new **154 GHz / 116 GHz** dual frequency gyrotron **for LHD** will start.

→ Development of **28 GHz / 1.5-2 MW / a few sec. gyrotron for GAMMA 10 and NSTX-U** has started.

→ Improvement of **300 GHz gyrotron for Demo** has started.