Development of MW Gyrotrons for Fusion Devices by University of Tsukuba

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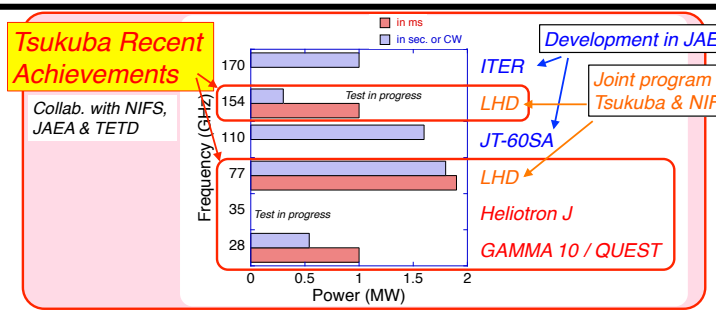
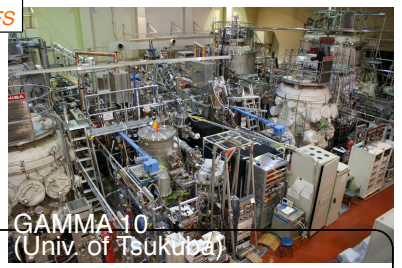
Abstract

Over-1 MW power gyrotrons for electron cyclotron heating (ECH) have been developed in the joint program of NIFS and University of Tsukuba. The obtained maximum outputs are 1.9 MW for 0.1 s on the 77 GHz Large Helical Device (LHD) tube and 1.0 MW for 1 ms on the 28 GHz GAMMA 10 one, which are the new records in these frequency ranges. In long pulse operation, 300 kW for 40 min at 77 GHz and 540 kW for 2 s at 28 GHz were achieved. A new program of 154 GHz 1 MW development has started for high density plasma heating in LHD and the first tube has been fabricated. These lower frequency tubes like 77 GHz or 28 GHz one are also important for advanced magnetic fusion devices, which use the Electron Bernstein Wave (EBW) heating / current drive. As a next activity of 28 GHz gyrotron, we have already started the development of over-1.5 MW gyrotron and a new design study of 28 GHz / 35 GHz dual frequency gyrotron, which indicates the practicability of the multi-purpose gyrotron.





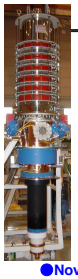
Schedule of Joint Program Tsukuba & NIFS

	-2010	2011	2012-
for LHD	77 GHz Gyrotron: Three- 77 GHz Gyrotrons were used in LHD experiment. CW & Multi-MW LHD Exp.	#1: first tube	
	154 GHz Gyrotron: Design	Fabrication, Test	LHD Exp.
for G10, QUEST, etc.	28 GHz Gyrotron: Long Pulse Test (400 kW Level)	#1: first tube; Long Pulse Test (1 MW Level)	Long pulse (50A / a few sec.)
	RF Test Stand (Power Supply)	Upgrade	

○Achievements (-2011)
→ Maximum output: **1.9 MW** (77 GHz) and **1.0 MW** (28 GHz).
→ Long pulse: **300 kW/ 40 min** (77 GHz) and **540 kW/ 2 s** (28 GHz).
○Next Step (2012-)
→ **154 GHz / 1 MW gyrotron** has been fabricated and tested.
→ **1 MW / a few sec. at 28 GHz in GAMMA 10** will be tested in 2012.
→ **28 GHz / 0.4 MW/ CW for QUEST** will be started.
→ **28 GHz / 1.5-2 MW / a few sec. for GAMMA 10, NSTX** will be started.

Development of 77 GHz and 154 GHz Gyrotrons for LHD

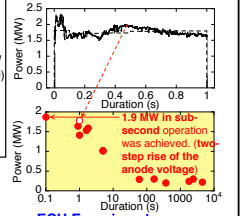
Achievements in 77 GHz Gyrotron Development



Frequency:	77 GHz
Oscillation Mode:	$TE_{18,6}$
Output:	1 MW
Pulse Length:	>5 s CW for 0.3 MW
Efficiency:	50% (with CPD)
Electron Gun:	Triode
Collector:	CPD
Output Mode:	Gaussian
Height:	3104 mm
Weight:	800 kg

Three- 77 GHz Gyrotrons were used in LHD experiment.

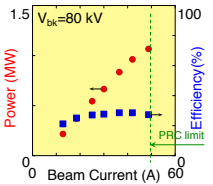
● Stable operation in the 77 GHz gyrotron



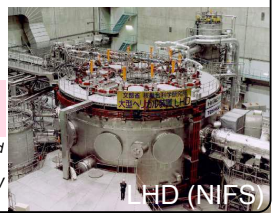
●Novel Achievements of High Power ECH Experiments
→ **Three 77 GHz gyrotrons** have demonstrated **3.4 MW injection into LHD plasma** contributing to producing the electron temperature T_e **of 20 keV.**

Preliminary Results in 154 GHz Gyrotron

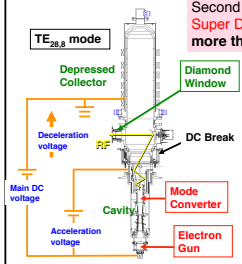
●Power Measurement at the Window



○ Improved Points
→ for **more than 1.5MW** output
● **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.



154 GHz 1 MW Gyrotron for LHD



Second Harmonic ECH Experiments for Super Dense Core (SDC) Plasma **more than 10^{21} m^{-3}**

Frequency:	154 GHz
Output:	1 MW
Pulse Length:	>5 s CW for 0.3 MW
Efficiency:	50% (with CPD)
Electron Gun:	Triode
Collector:	CPD
Output Mode:	Gaussian
Height:	3104 mm
Weight:	800 kg

→ **1 MW/ 27%**(w/o CPD) was achieved at short pulse.
→ Long pulse operation is in progress.

The ECH upgrade is essential for LHD in NIFS to achieve the efficient transport control, high T_e plasma and high performance CW operation.
The first 154 GHz tube was fabricated and has been testing and conditioning, aiming to the EBW experiment of the Super Dense Core Plasma in LHD.

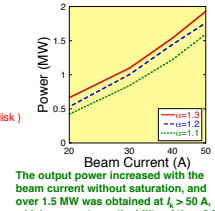
Development Program of 28 GHz Gyrotron for GAMMA 10 and Other Low Field Devices

28 GHz 1 MW Gyrotron

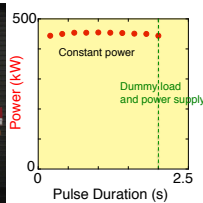
●Design Parameters of First tube

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

●Power Measurement at the Window

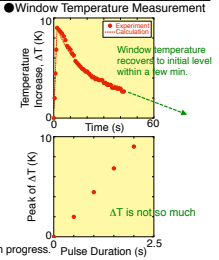


●Power Measurement by Dummy Load



No power degradation in pulse duration.
Upgrade of dummy load and power supply is in progress.

●Window Temperature Measurement

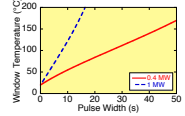


→ **1.0 MW/ 30%** was achieved at short pulse.
→ **540 kW/2 s** oscillation was achieved.

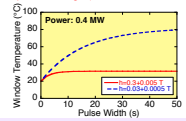
Long Pulse Test in 28 GHz Gyrotron

New Design Study for 28 GHz Gyrotron

●Simulation Results of Window Temperature
○First tube design (Single sapphire disk)



○Improved design (Surface cooled double disk)



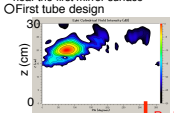
●Simulation Results of Oscillation Power at the Cavity

The output power increased with the beam current without saturation, and over 1.5 MW was obtained at I_b > 50 A, which suggest practicability of the ~2 MW power gyrotron output.

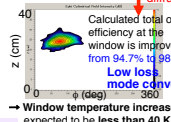
*After the successful results of 28 GHz Mega-Watt tube, we put the emphasis on the development of multi-purpose gyrotron, which has the performance of more than 1.5 MW a few seconds operation in 28 GHz which is required in **GAMMA 10** high heat flux experiment and **NSTX of PPPL**, 0.4 MW CW operation for **QUEST of Kyushu University** and 1 MW level in 35 GHz range operation for **Heliotron J of Kyoto University**.*

New Design of 28 Gyrotron for CW Operation

●Radiated field patterns near the first mirror surface
○First tube design



○Improved design



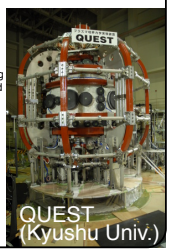
→ **Window temperature increase** is expected to be **less than 40 K for 0.4 MW/ CW operation**, which is required in QUEST.

●Field Intensity ○Window **Surface cooled double disk window**

Good axi-symmetrical profiles

In lower frequency, the **diffraction (stray RF)**, which affects many sub-components yielding *the limit of operation* and sometimes causes *crucial damage of the tube*, are the key issues design due to **larger wavelength**.

It is started to apply the first Tsukuba 28 GHz tube to the preliminary ECH/ECCD experiment in QUEST, under the NIFS bilateral collaboration.



Achievements

○**Tsukuba-NIFS joint program**
→ **Three 77 GHz gyrotrons** have demonstrated **3.4 MW injection** into LHD plasma contributing to the **electron temperature T_e of 20 keV**.
→ The obtained maximum output is **1.9 MW 38%** at **77 GHz** with depressed collector operation (CPD).
→ **154 GHz / 1 MW gyrotron** has been fabricated and **1 MW oscillation** was achieved. Higher power and long pulse operation is in progress.
○**Improvement of 28 GHz gyrotron**
→ **Over 1.0 MW** oscillation at **28 GHz gyrotron** was achieved. **540 kW 2 s** oscillation was achieved.
→ **New design study** of **28 GHz gyrotron** have carried out. It is expected to achieve the operations of **0.4 MW CW** and **> 1.5 MW in a few seconds**.

The strong step to the multi-MW & multi-purpose gyrotron development.

Acknowledgments

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