FIP/2-2Rb

Development of Dual Frequency Gyrotron and Launcher for the JT-60SA ECH/ECCD System

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FIP/2-2Ra

Prototype Development of the ITER EC System with 170GHz Gyrotron

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FIP/2-2Rc

Development of Over 1 MW and Multi-Frequency Gyrotrons for Fusion

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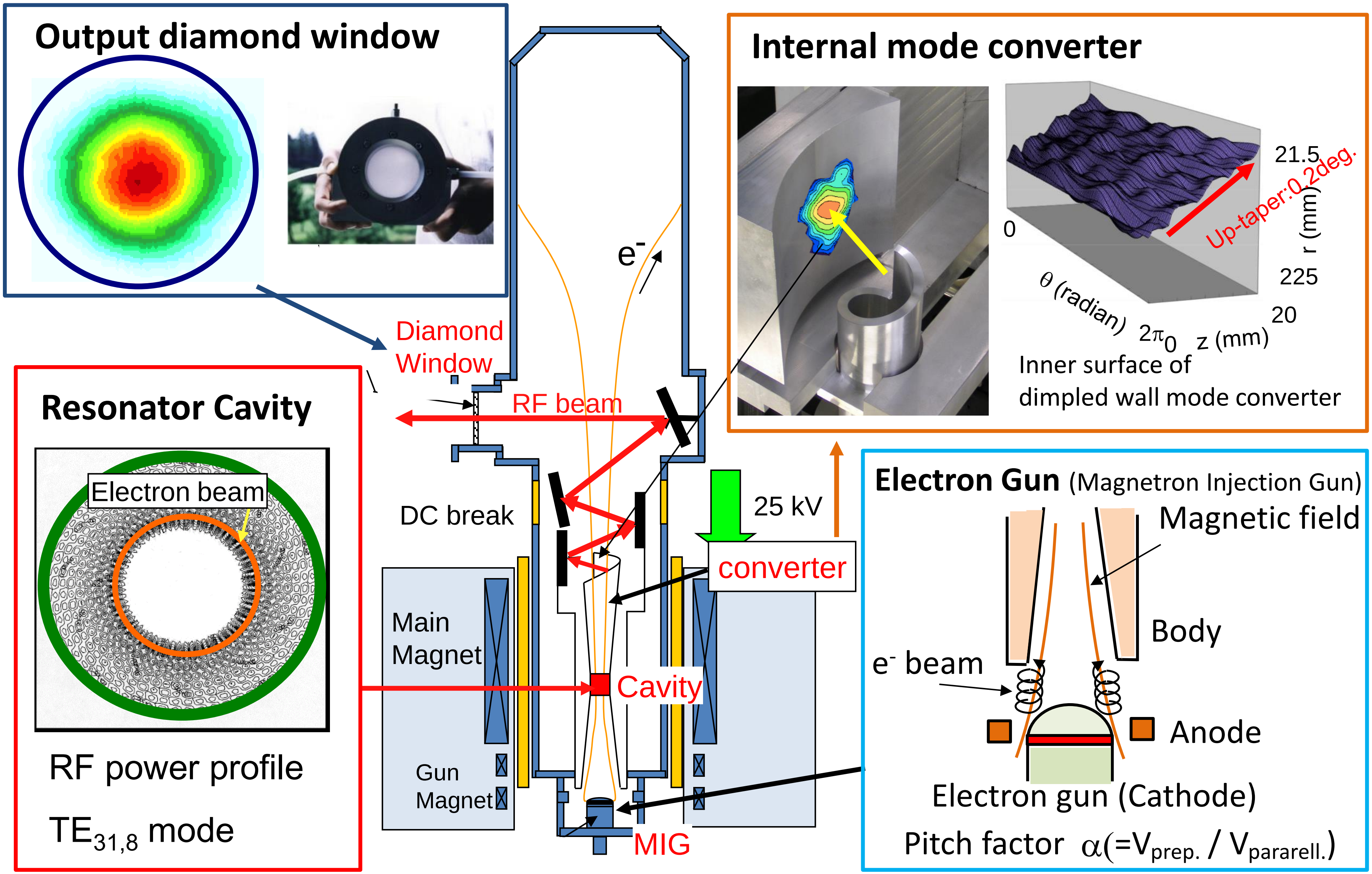
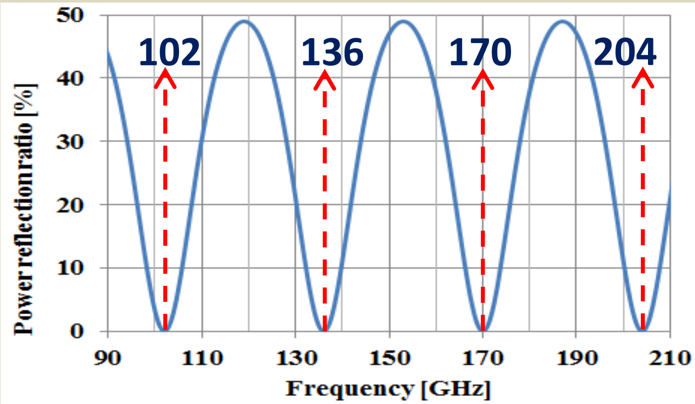
JAEA
170GHz gyrotron

Introduction: Key components of high power Gyrotrons



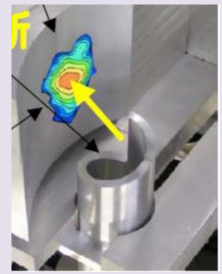
Introduction: Key point of multi-frequency gyrotron design

Window thickness and frequency

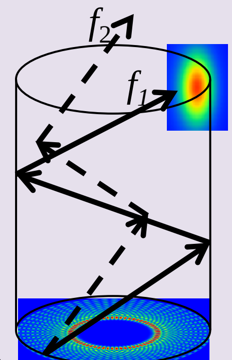


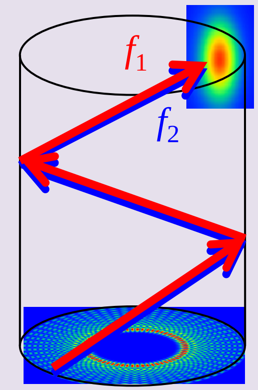
Case of window thickness d_w=1.853 mm $d_w = n_w \frac{\lambda}{2}$

Mode converter design and mode



Mode converter

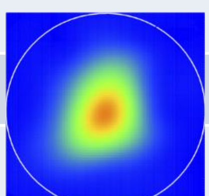




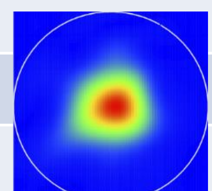
$\theta_{\mathrm{rad}} = N_r \cos^{-1}\left(\frac{m}{\chi_{m,n}}\right)$ Conventional **Multi Frequency**

Design of multi-frequency gyrotron in JAEA

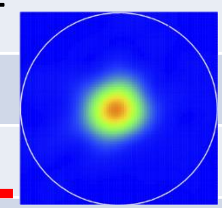
Cavity mode $TE_{m,n}$	$TE_{19,7}$	$TE_{25,9}$	$TE_{31,11}$
Frequency	104 GHz	137 GHz	170 GHz
Beam radius	9.25 mm	9.19 mm	9.13 mm
Radiation angle	**65.30°**	**65.32°**	**65.35°**
Cavity field	4.08 T	5.32 T	6.63 T
Beam voltage	72 kV	76 kV	76 kV
Anode-cathode	**24.5 kV**	**34 kV**	**38 kV**
Pitch factor α ($\alpha = V_{prep.} / V_{pararell.}$)	**1.3**	**1.3**	**1.3**



Output RF profile



Output RF profile

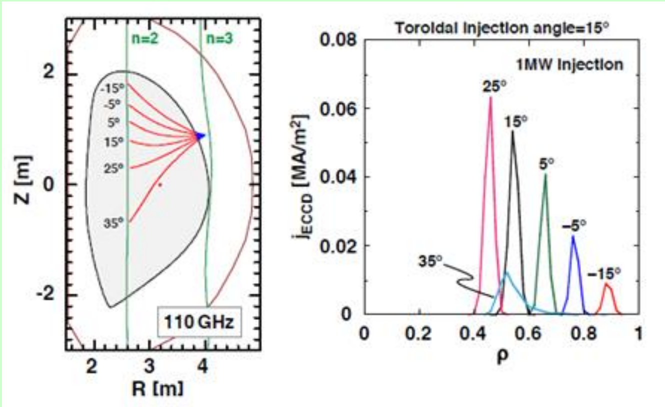


Output RF profile

Dual-frequency Gyrotron for JT-60SA

Original specification: 110 GHz, 1MW, 100s

Scenario 5 (B_t ~ 1.7 T) High-beta, Full non-inductive

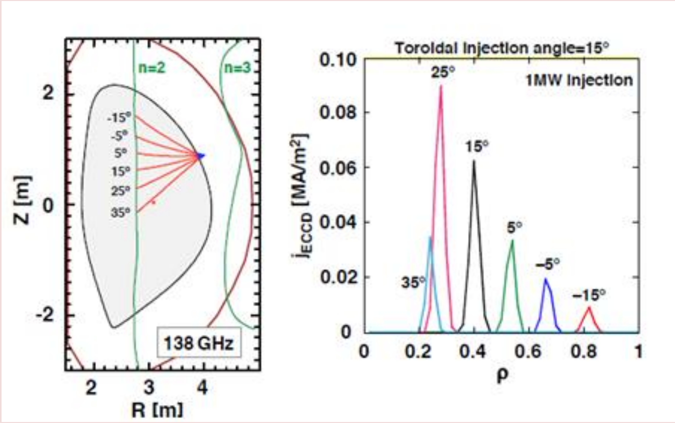


Target of this development

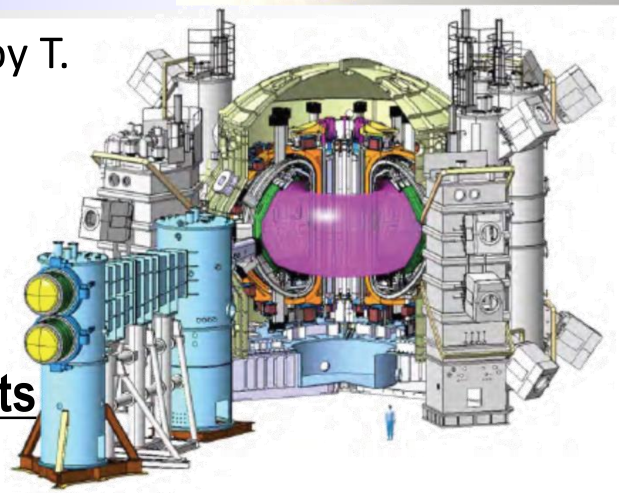
Dual frequency (**110 GHz, 138 GHz**) 1MW, 100s

138 GHz

Scenario 2 (B_t ~ 2.3 T) Maximum B_t, Ip = 5.5 MA



Poster presented by T. Kobayashi
Thursday P5
FIP/2-2Rb



Remarkable results (2013-2014)

(i) Successful oscillations of **1 MW for 100 s** at **both 110 GHz and 138 GHz**

- ✓ New record of a **dual-frequency gyrotron**.
- ✓ The target for JT-60SA fully satisfied

(ii) Demonstration of an oscillation at **82 GHz** as an additional frequency

- ✓ A possibility of the use of **fundamental harmonic waves** (<1MW, <1s) in JT-60SA.

Achievement of 1 MW/100 s oscillations at both 110 GHz and 138 GHz

Key points on the design of dual-frequency gyrotron

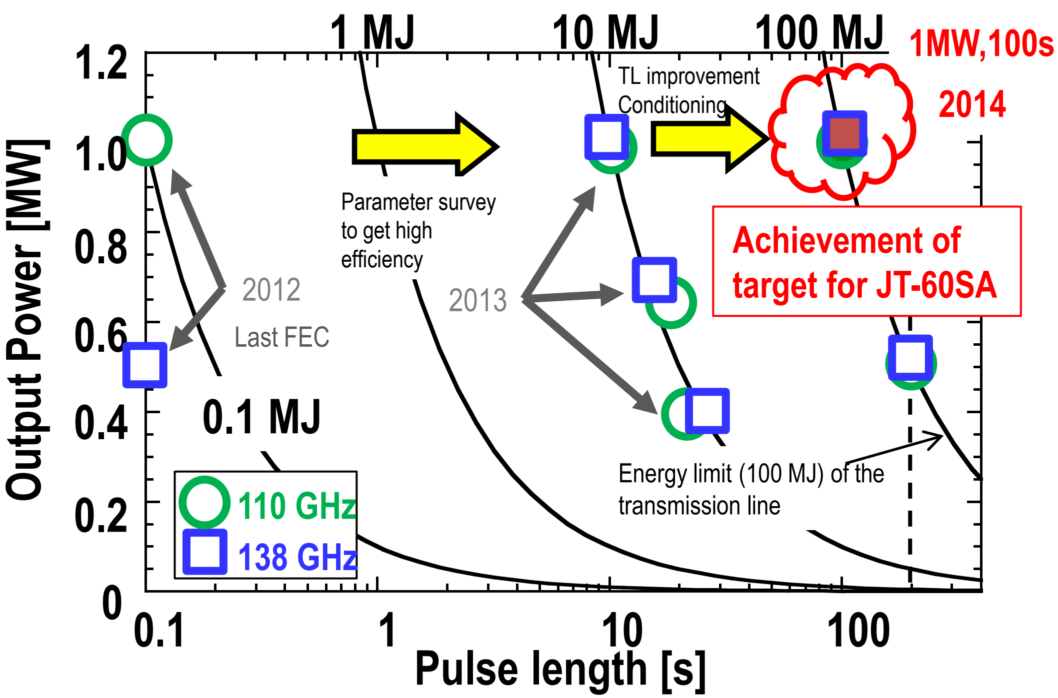
Selection of oscillation mode in cavity

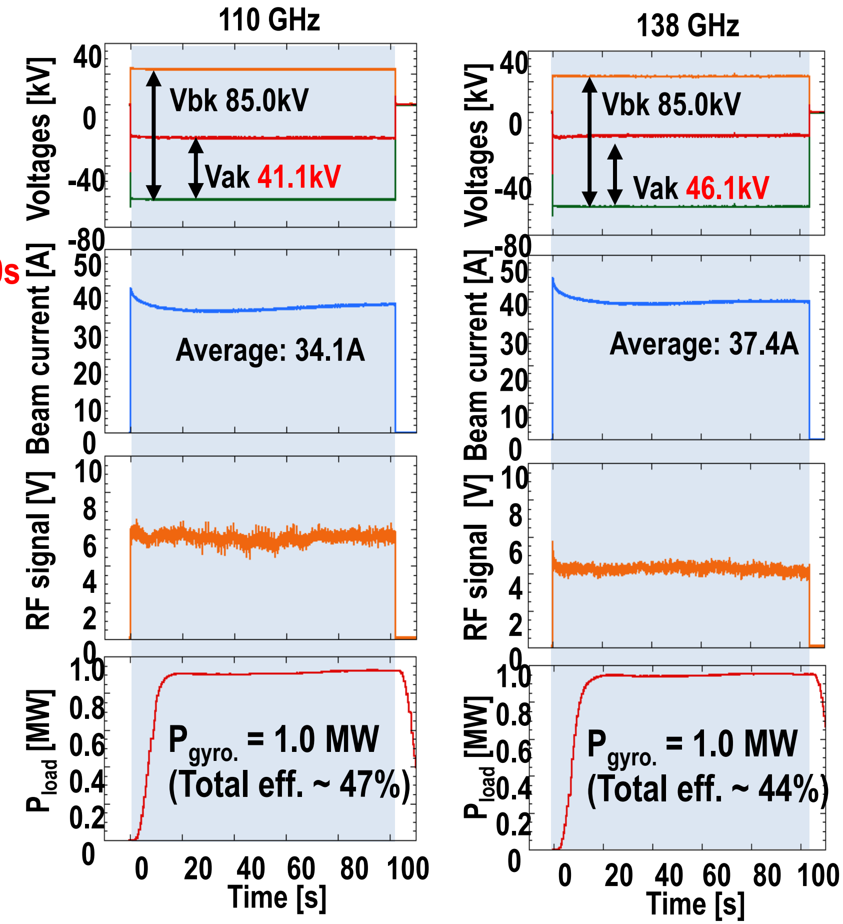
To satisfying design restriction of gytoron for both frequencies, simultaneously

138 GHz : $TE_{27,10}$ 110 GHz : $TE_{22,8}$

Progress in long-pulse operations

New record as a dual-frequency gyrotron

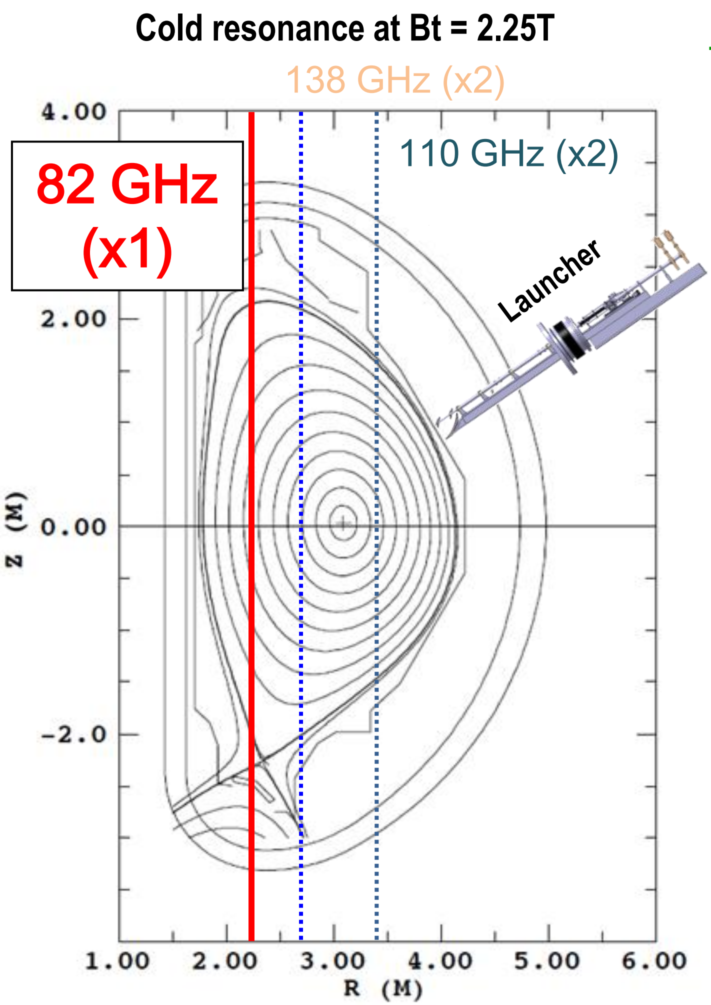




Successful oscillations of 1 MW for 100 s at both 110 GHz and 138 GHz

The target for JT-60SA fully satisfied.

An additional frequency of 82 GHz enables to use fundamental harmonics waves



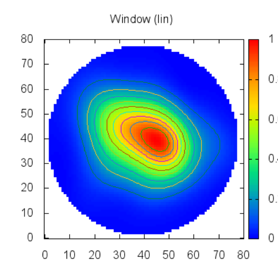
Motivation

Use of the fundamental harmonic waves for

- EC-wall cleaning between plasma discharges (In JT-60SA, TDC is not available)
- EC assisted start-up (reduced power compared with 2nd harmonics)

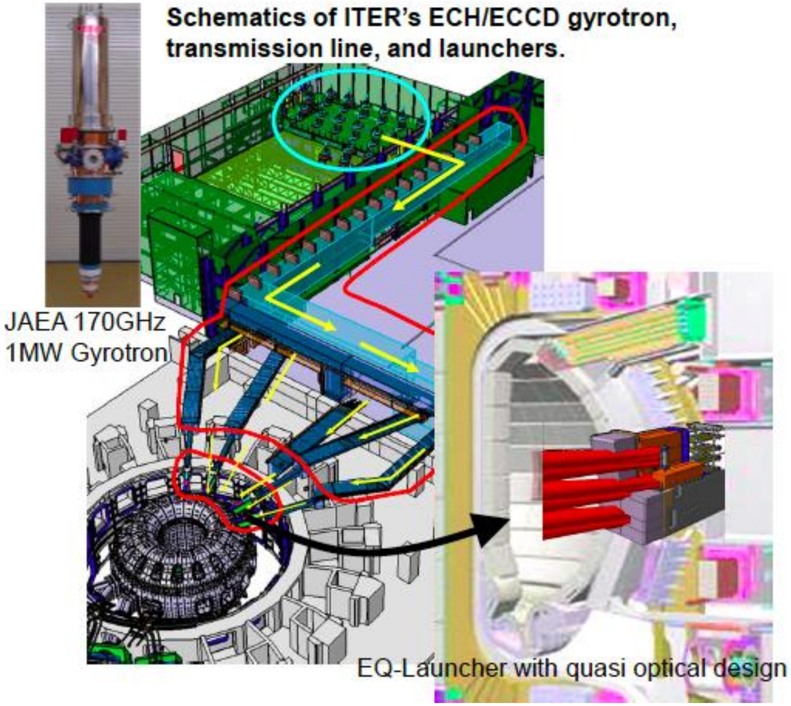
Challenge for additional frequency operation

Target at 82 GHz
Output power < 1MW
Pulse length < 1 s



- **Oscillation at 82 GHz was demonstrated.**

ITER 170GHz Gyrotron



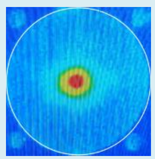
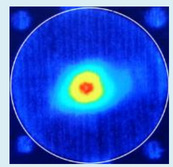
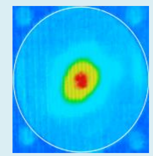
$TE_{31,8}$ mode gyrotron
1MW / 800 s (2007)
0.8 MW / 3600 s (2007)
at efficiency of 57%
(max. 60% @0.6MW)
Output energy: >250GJ

increase power > 1MW

Recent results

- $TE_{31,11}$ mode 170 GHz gyrotron demonstrated 1.4 MW (short pulse)
- Multi-frequency operation with **>1MW output at 170/137/104GHz**.
- High power RF transmission demonstrated **91～85% efficiency at 40m ITER-relevant transmission line at 170/137/104 GHz**.
- **5kHz power modulation** with prototype of ITER power supply system.

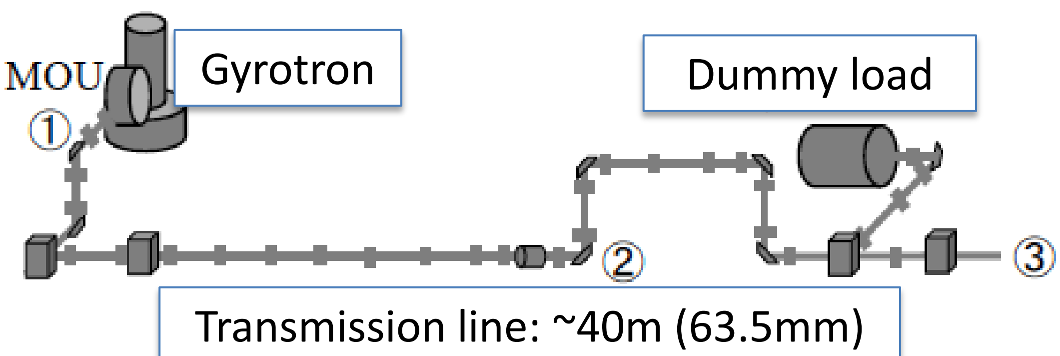
JAEA Multi-Frequency Gyrotron

Frequency	170 GHz	137 GHz	104 GHz
Mode	TE31,11	TE25,9	TE19,7
Beam current	50 A	51 A	52 A
Power	**1.02 MW**	**1.0 MW**	**1.04 MW**
Gyrotron Efficiency	45 %	42 %	41 %
RF pattern @gyrotron window			
WG coupling eff. HE_{11} mode purity	**94 %**	**93 %**	**93 %**
Transmission Eff. =Dummy load power/ Gyrotron power	**91 %**	**90 %**	**85 %**

Transparent at 1.853mm Diamond window

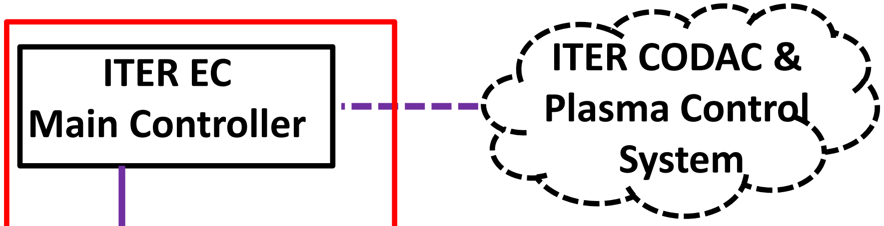
Same bounce angle θ~ 65.3deg.
Mode converter works similarly.
Gaussian beams are obtained at the window center for all modes.

Very good RF beam coupling into transmission line (>93%) was realized even using the same coupling mirror.

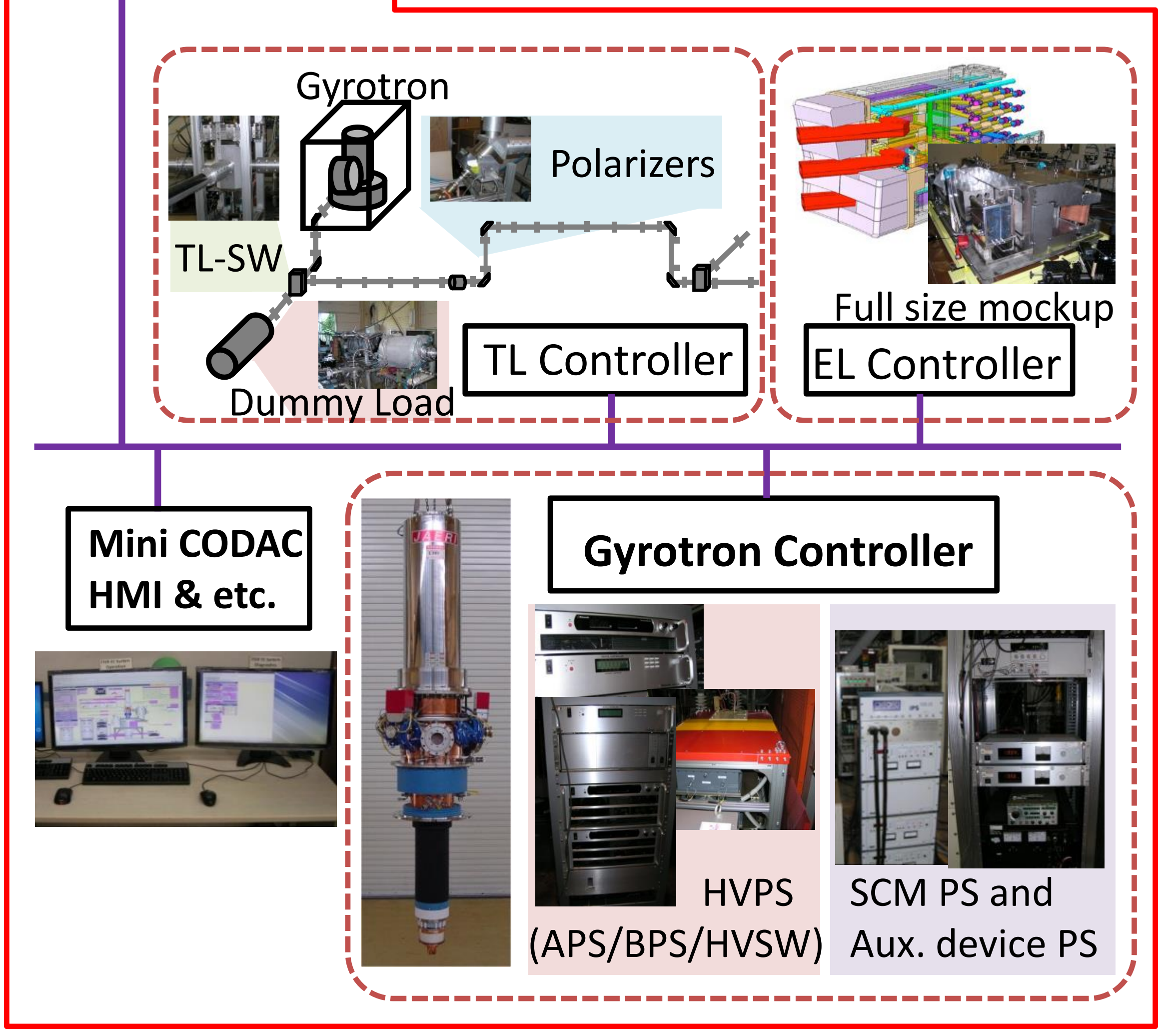


High power RF transmission with 91～85% of efficiency were successfully demonstrated for multi frequency operation.

ITER EC system prototype in JAEA



JAEA EC lab. has major EC components,
Gyrotron, TL test stand, and EL mockup



ITER EC system prototype

Validation of EC system operation for ITER EC system.

ITER relevant TL experiment

RF transmission demonstration

Coordination of multi subsystem

Gyrotron and TL

Gyrotron power modulation

Modulation with **ITER relevant PS**

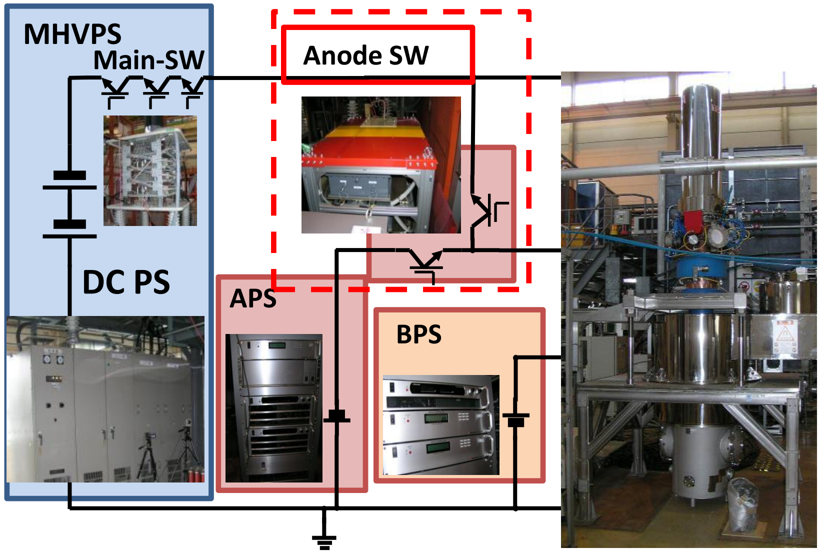
*Demonstration of **5 kHz mod.***

ITER relevant control system

Gyrotron and EC system control with **ITER CODAC system / EPICS**

Synchronous control via network

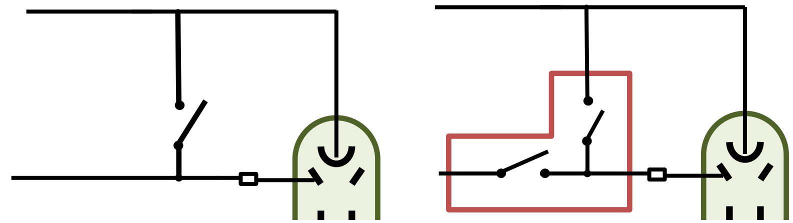
Prototype of ITER Power Supply System



ITER relevant gyrotorn PS system

Gyrotron

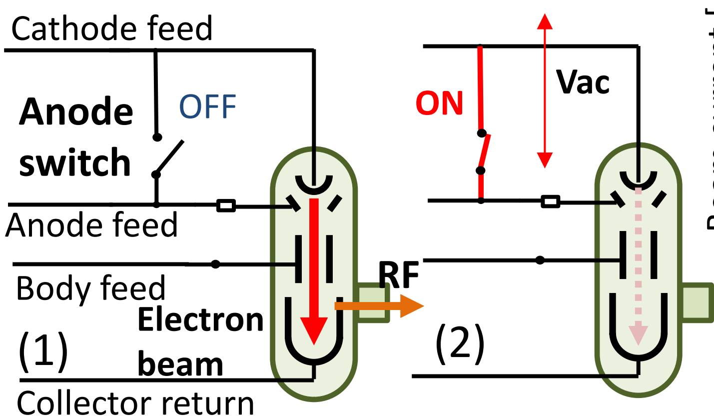
Advantage of double switch



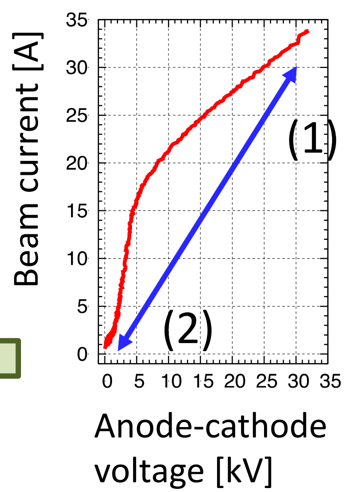
Single switch **Double switch**

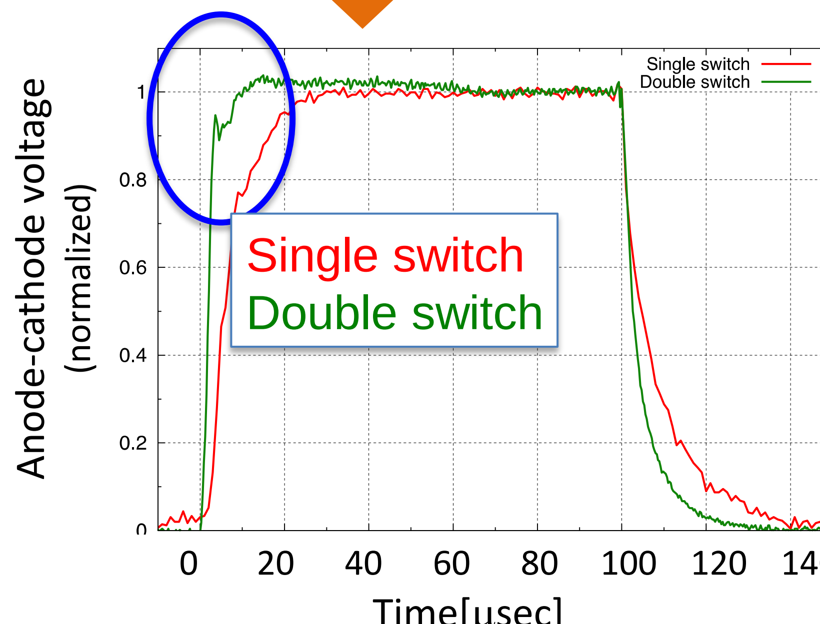
The **double switch** avoids influence of the stray capacity of PS system for **sharp ramp up of voltage**.

Modulation control with anode switch



Gyrotron





Anode switch can directly control on/off of gyrotron beam current

Ramp up in pulse start was improved

High Frequency Power Modulation

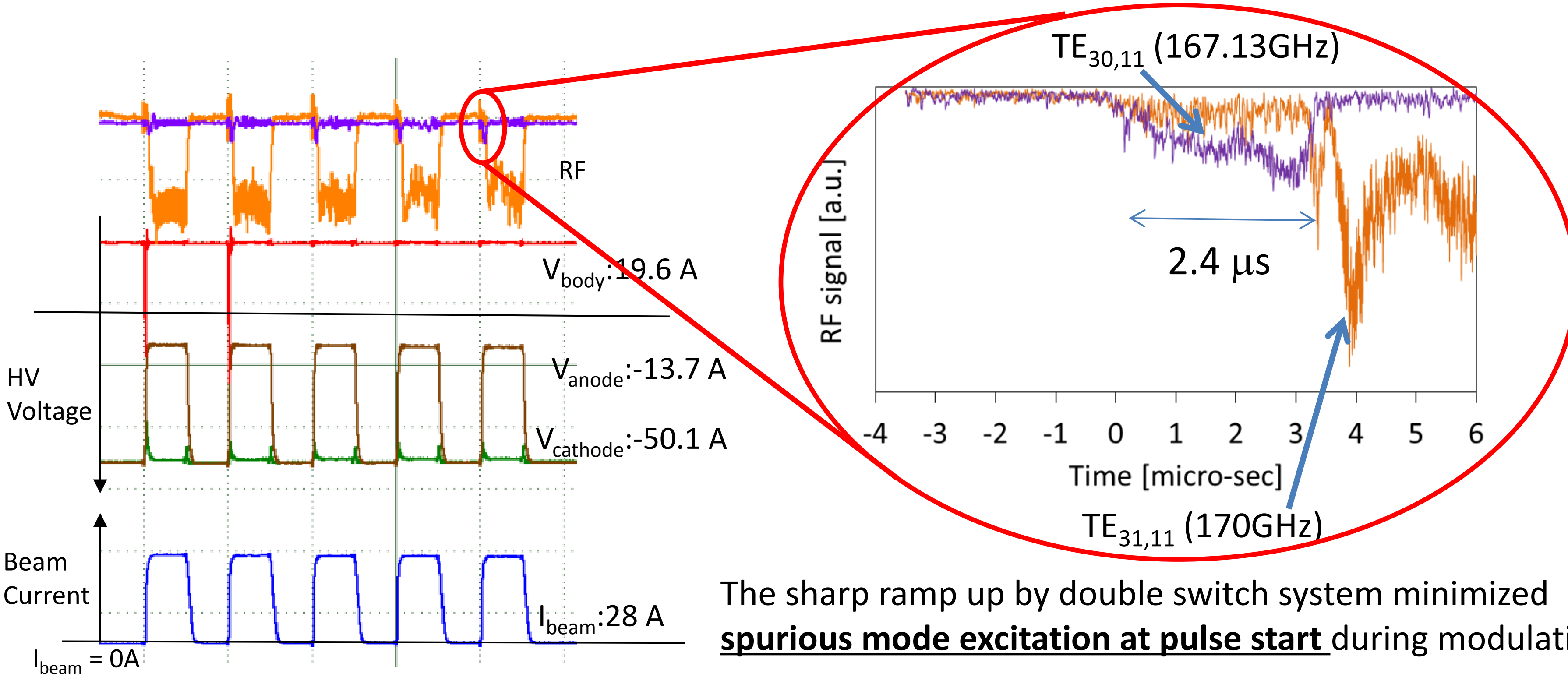
Key point for 5 kHz modulation

Reduction of heat load on collector.

Spurious RF oscillation (167GHz) of pulse start must be **minimized** to reduce internal loss.

Double switch can adapt

- **100% beam modulation**
- **Sharp ramp up at pulse start**



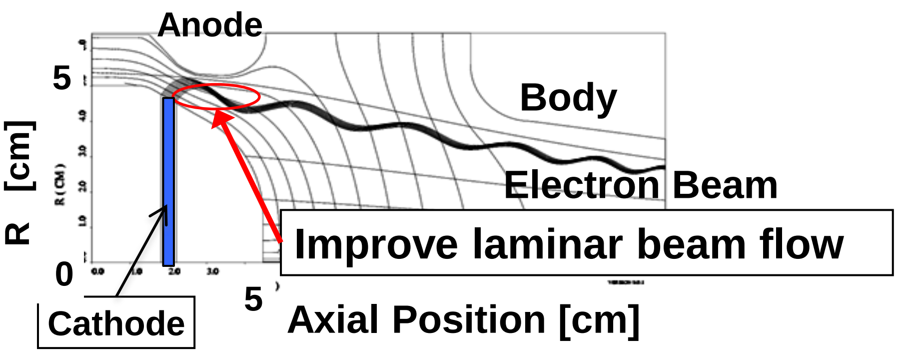
The sharp ramp up by double switch system minimized **spurious mode excitation at pulse start** during modulation.

Succeeded 5kHz modulation with prototype of ITER PS system.

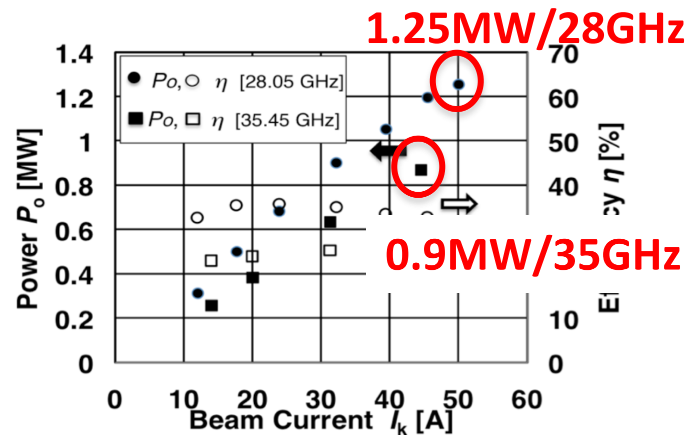
Development of Lower Freq. (28, & 35 GHz)

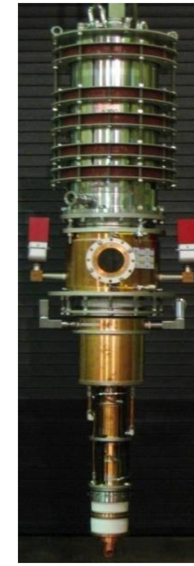
1.1. 28 GHz Gyrotron

1. Electron gun improvement for over 1MW tube development.
   - Demonstrated more than 1.25 MW (2 ms), 0.6 MW for 2 s at 28 GHz (TE8,3). Applied to QUEST (66 kA ECCD)
2. Installation of 28/35 GHz window for dual-frequency test
   - 0.9 MW-35GHz (TE9,4) correspond to 1.2MW osc. power.



Electron gun and beam trajectory



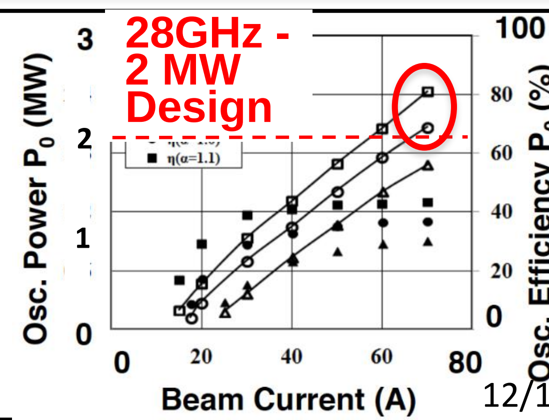

28 GHz U.Tsukuba gyrotron

1.2. New 28/35 GHz gyrotron Design

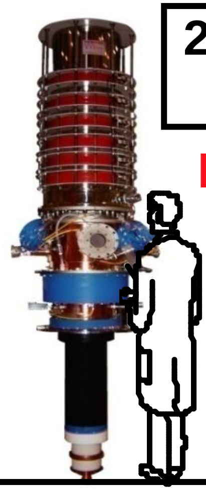
Selection of cavity mode for multi frequency design
TE8, 5 (28 GHz) & TE10, 6 (35 GHz)

Designed output : 2 MW at 28/35 GHz.

Gyrotorn fabrication started.



Higher frequency (77 – 300 GHz) MW ECH Gyrotron



2.1. Over-1MW Gyrotron for LHD (NIFS collaboration)

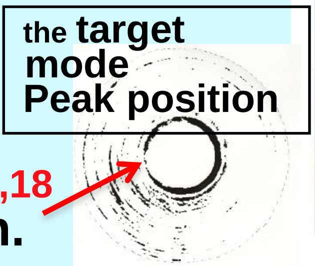
Demonst. 2 MW performance
77GHz : 1.8 MW for 1 s (World Rec.)
154GHz: 1.16 MW for 1 s

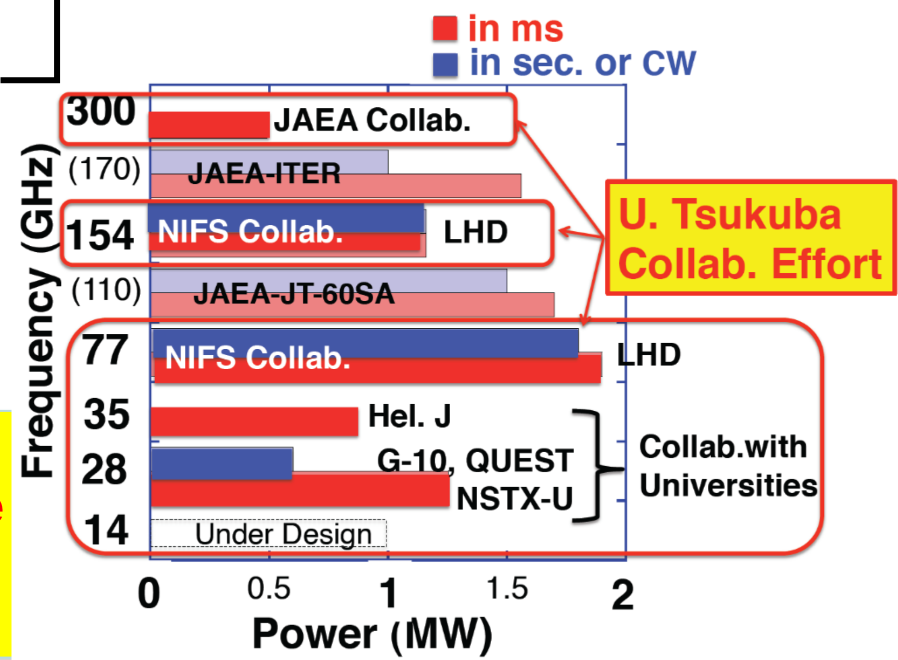
4.4 MW into LHD-plasma
with three 77 GHz tubes,
Contributed to Te ~ 20 keV

Gyrotron No.	Pulse	CW
77GHz - #1	1.4 MW-0.1 s 1 MW-5 s	0.13 MW - 935 s
77GHz - #2	1.3MW-0.45 s 1MW-5 s	0.24MW - 1800 s
77GHz - #3	1.9MW-0.1 s 1.8MW-1 s	0.3MW - 1800 s
154GHz - #1	1.16MW-1 s	0.35MW - 1800 s

2.2. 300 GHz Challenge for Demo Reactor (JAEA, collaboration)

~ 0.5 MW for 1 ms
(η = 19 %) achieved
with V_k = 80 kV.
(Joint Exp. with JAEA)
Appeared 300GHz-$TE_{32,18}$
from the burned pattern.





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

Summary

JT-60SA EC H&CD system (FIP/2-2Rb T. Kobayashi et al.)

- **1 MW / 100 s achievement of the dual freq. gyrotron (110 GHz/138 GHz)**
  - Achieved parameters **fully satisfied the target for JT-60SA**.
  - Demonstration of an oscillation at **82 GHz** as an additional frequency

ITER EC H&CD system (FIP/2-2Ra Y. Oda et al.)

- **170 / 137 / 104 GHz operation with 1 MW of the multi freq. gyrotron**
  - **Multi frequency high power RF transmission** in **ITER relevant TL** were demonstrated **91～85% efficiency for 3 frequencies**.
- **Development of EC system prototype**
  - Gyrotron operation with **ITER relevant PS and control system**.
  - **5kHz modulation was successfully demonstrated with prototype of ITER PS system**.

U. Tsukuba gyrotron (FIP/2-2Rc T. Imai et al.)

- **Over 1 MW oscillation of dual / single freq. gyrotrons.**
  - **1.25MW at 28 GHz** and **1.2MW cavity oscillation at 35 GHz** were achieved.
  - **77 / 154 GHz single freq. gyrotrons for LHD** achieved **1.8 / 1.16 MW** output respectively.
  - JAEA / U. Tsukuba joint project succeeded **0.5 MW oscillation at 300 GHz**.