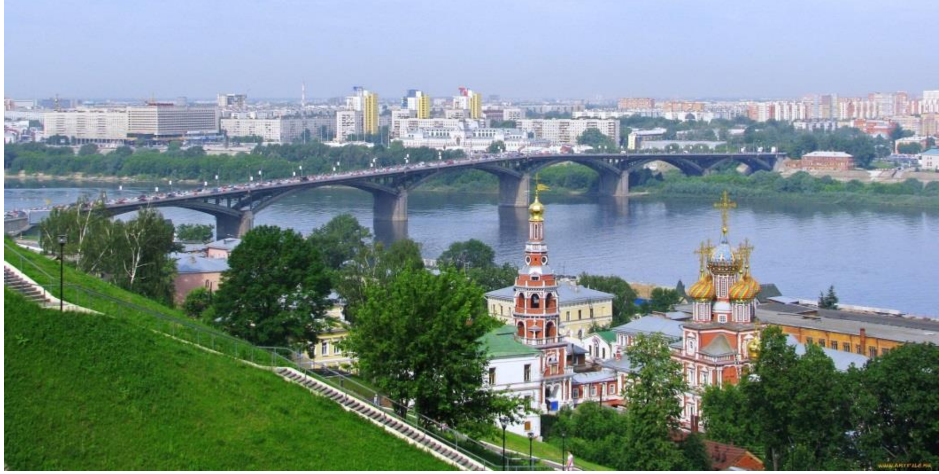


New Results of Development of Gyrotrons for Plasma Fusion Installations

Presented by G.G. Denisov

Institute of Applied Physics, Russian Academy of Sciences, 603950, Russia
Gycom Ltd, Nizhny Novgorod, 603155 Russia

26th IAEA Fusion Energy Conference

17–22 October 2016 Kyoto, Japan

こんばんは

Main results of

FIP/1-6Ra G. Denisov New Results of Development in Russia of Gyrotrons for Plasma Fusion Installations

Institute of Applied Physics, Russia
Gycom Ltd, Nizhny Novgorod, Russia

FIP/1-6Rb Development of Multifrequency Megawatt Gyrotrons for Fusion Devices in JAEA

R. Ikeda. National Institutes for Quantum and Radiological Science and Technology (QST), Naka, Japan

FIP/1-6Rc Development of over-MW Gyrotrons for Fusion at Frequencies from 14 GHz to Sub-THz

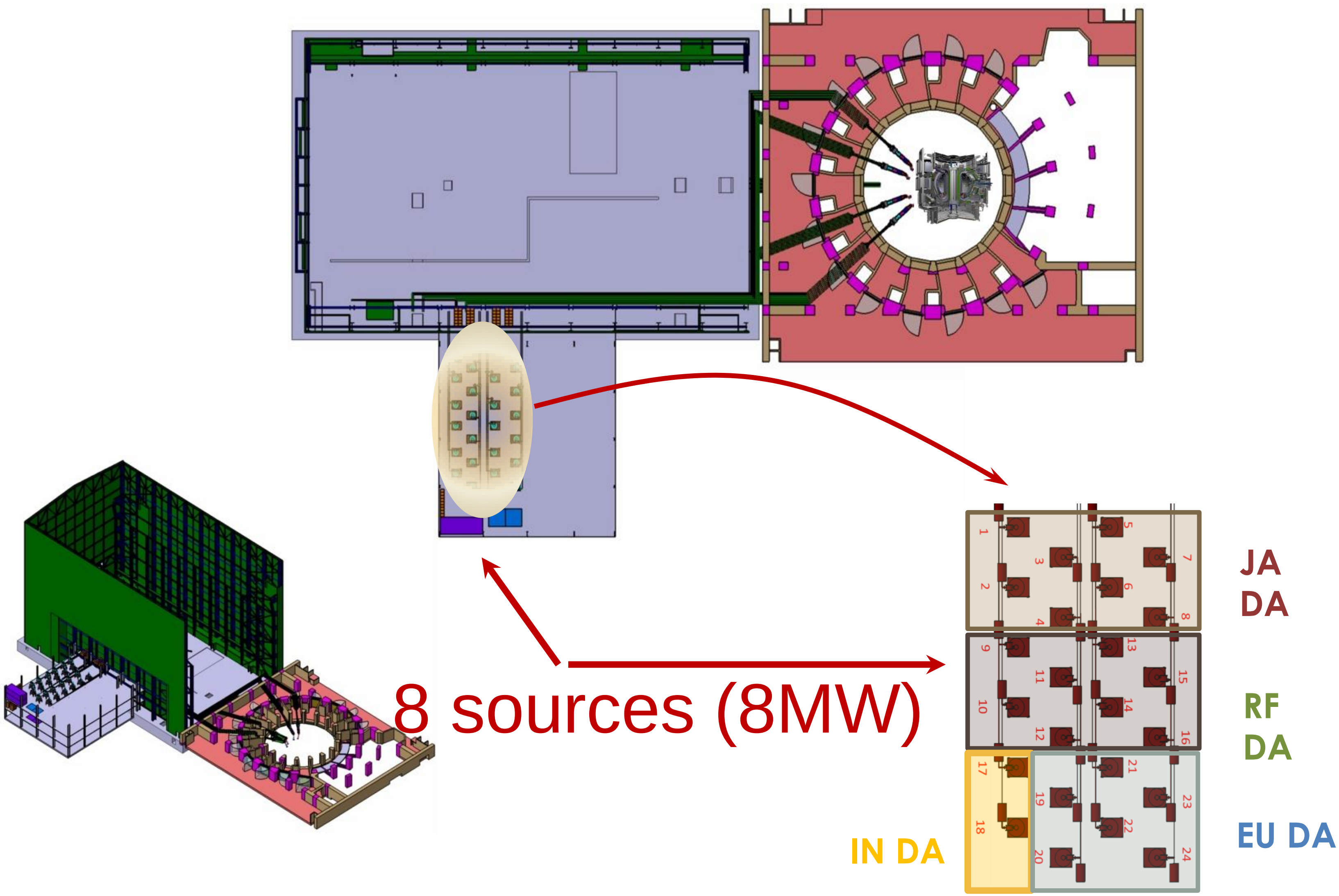
T. Kariya. University of Tsukuba, Japan

List of the main activities on gyro-devices in IAP/GYCOM

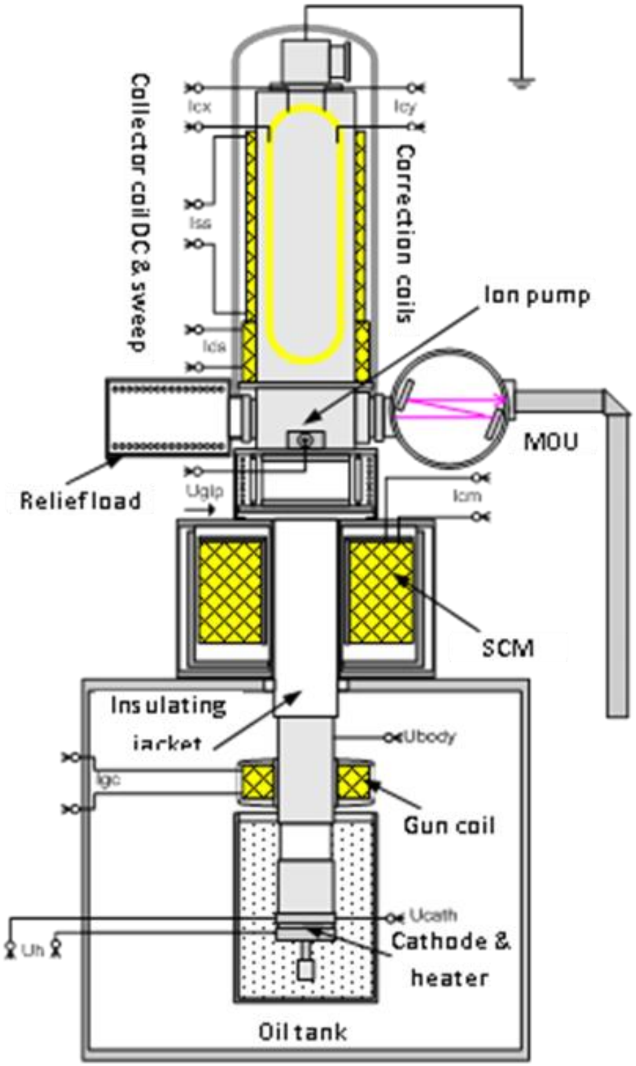
- Gyrotron for plasma fusion (2015-2016)
  - **ITER activity**
  - EAST (first ECW experiment) +1
  - KSTAR (first delivery in 2015, acceptance test completed) +1
  - Asdex Upgrade
  - TCV
  - EU DA…..

- Gyrotrons for Tecnology/CVD diamonds/ECRIC/neutrons
- Gyro-TWT for radars
- THz gyrotrons
- Gyro-devices based on relativistic electron beams
- New ideas
  - Oscillation locking by external signal / stabilization by reflection
  - Generation of ultra short pulses

RF-DA gyrotrons: RF power sources for ITER ECRH plant



Gyrotron tube: main item of RF power source

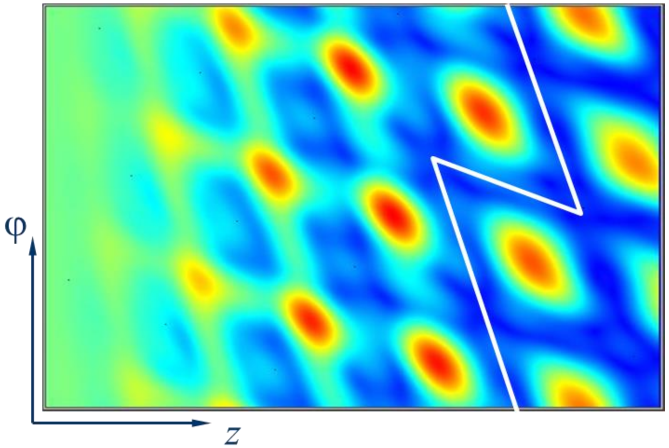


Gyrotron performance

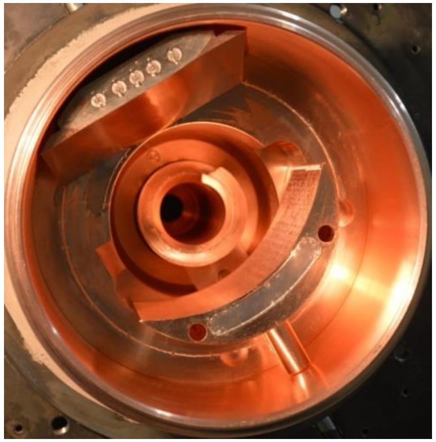
Item	Specification
Nominal output power	0.96 MW at MOU output
Nominal frequency	170 ± 0.3 GHz including initial transient phase
Pulse length	1000/3600 sec
RF power generation efficiency	50 % (with CPD)
HE_{11} mode content	95 % at output waveguide (63.5 mm) of MOU
Modulation from 0 to 5 kHz	100 % power depth modulation
Height	~2.6 m
Weight	~250 kg

Dimpled wall converter

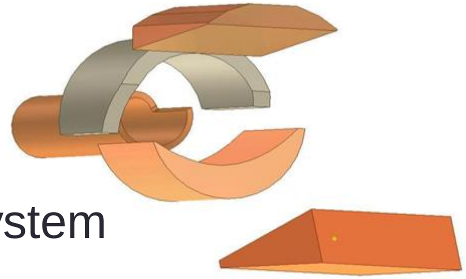
***H_z* field component**



$TE_{25.10}$



Four mirror QO system



- 0.2^0 taper
- Azimuthal and axial ripples with ~0,1-mm perturbations

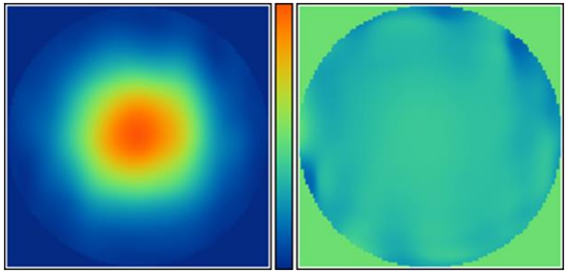
Synthesizing

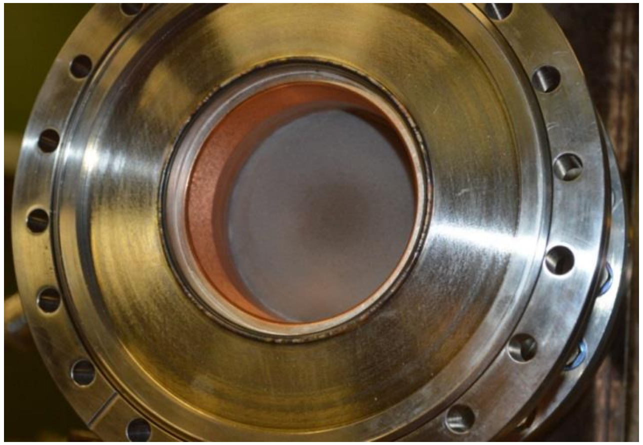
- LOT/Surce-3D code
- 20 modes involved

Efficiency

- From the launcher to first parabolic mirror 99.5%
- From the cavity to output window 97.7%

Field amplitude and phase distribution at gyrotron window

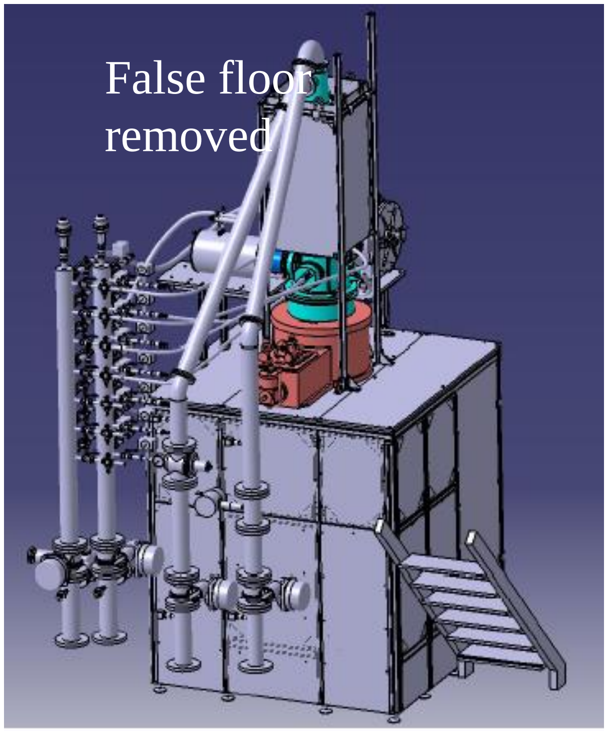


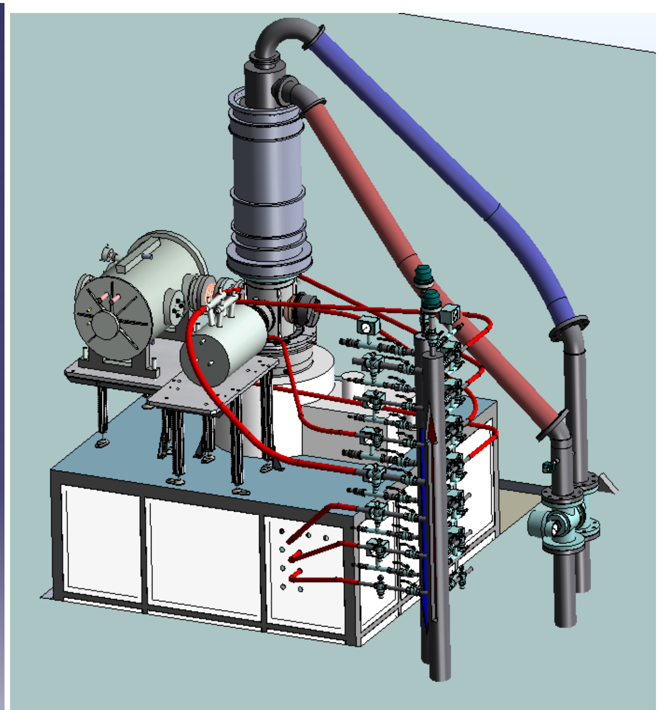


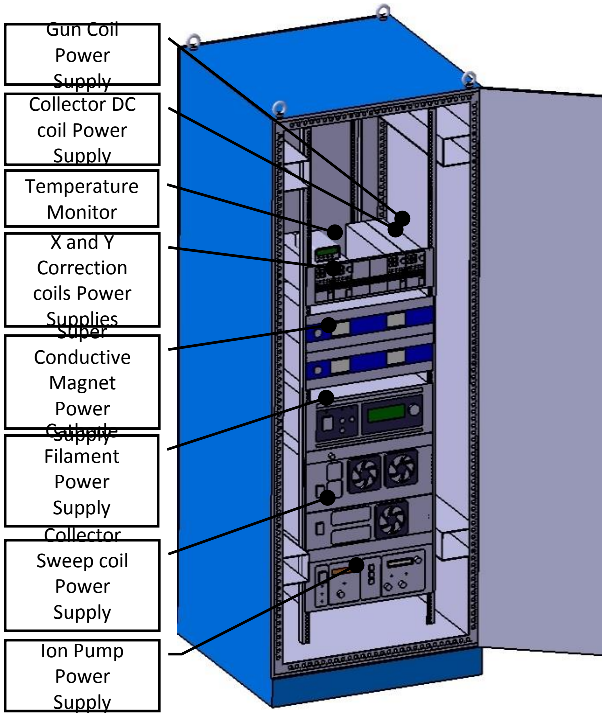
Diamond window

- Thickness of the diamond disk 1.853 mm, 5 × λ/2
- The disk diameter 106 mm, window aperture 82 mm
- As very high thermal conductivity, edge cooling possible

ITER RF Source prototype







PROTOTYPE OF RF-DA RF POWER SOURCE, TEST REPORT
May 11 – 15, 2015, Nizhny Novgorod, Russia

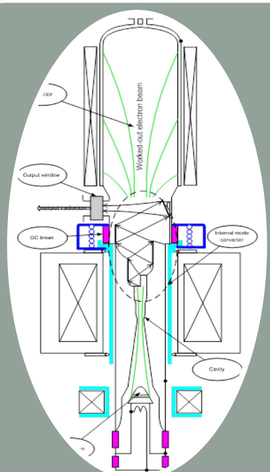
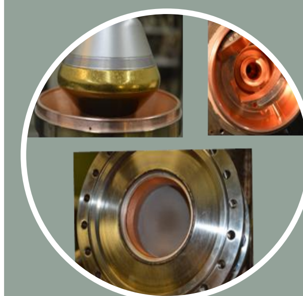
Gyrotron together with SCM, MOU and relief load in the support structure
left picture

Waveguide with terminal load and cooling manifolds
top right

Operator console with control &protection cubicles
bottom right

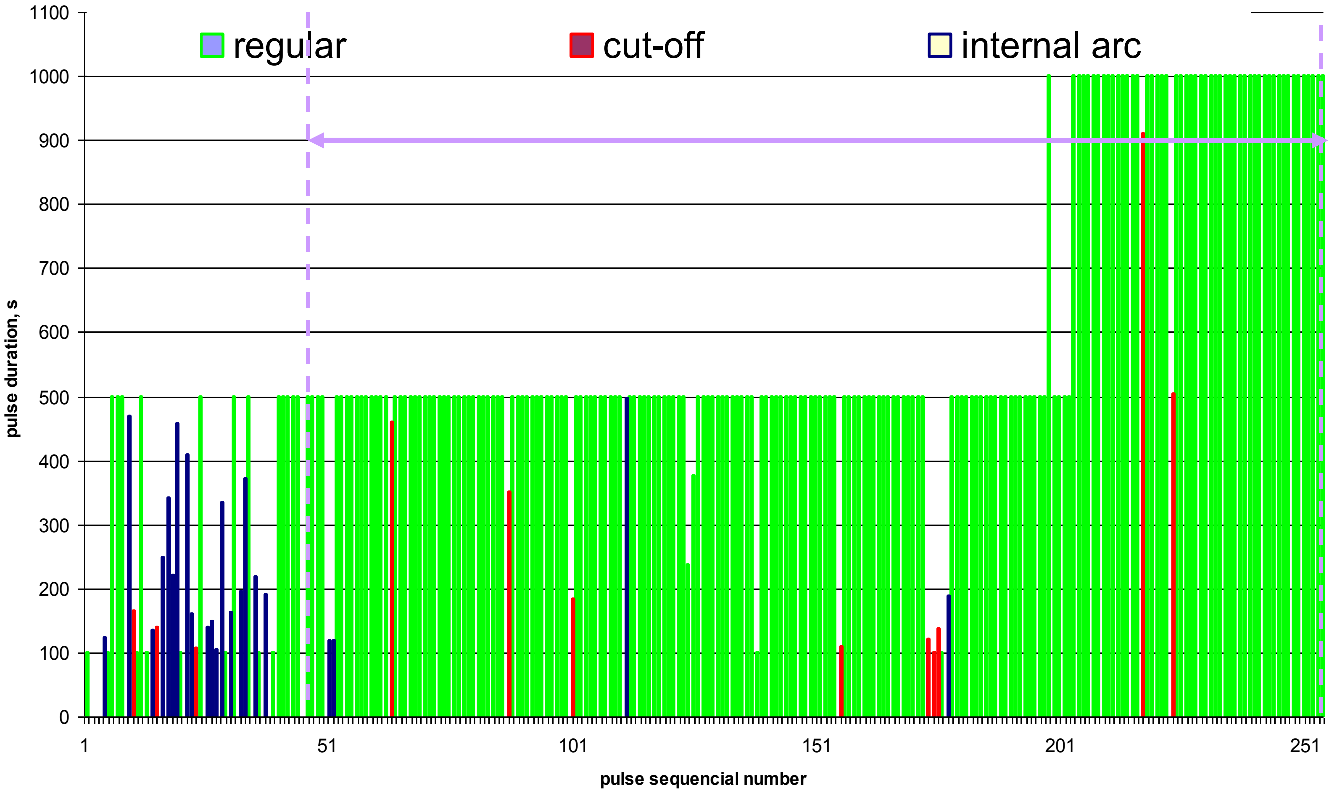
ИТЭР РФ ITER RF | ИПФ РАН | GYCOM | RTSoft средства и системы автоматизации

Gyrotron for ITER: Recent Development Steps

Conceptual design	Run tests	Final design	Manufacture	Delivery
				
Long pulse operation of gyrotron pre-prototype in presents of IO representatives , April 2011	Run tests of gyrotron pre-prototype, 2014 1MW output power 500s – 160 pulses 1000s – 55 pulses Reliability > 95%	Factory tests of Power Source Prototype successfully passed (IO representatives), May 2015 FDR Procedure (Cadarache, October 2015)	Manufacture and Inspection Plan. Quality Plan Manufacture readiness review Start of Manufacture 2016	Planned Delivering of the 1st Gyrotron System 2017 RF Building Readiness 2018

Russian ITER RF Source pre-prototype

Gyrotron run test (2014) at 1MW output power
with pulse duration 500s and 1000s



Reliability > 95%

500s – 160 pulses

1000s – 55 pulses

PROTOTYPE OF RF-DA RF POWER SOURCE TEST REPORT (Section 5)
May 11 – 15, 2015, Nizhny Novgorod, Russia

PRFS testing was carried out on Factory site following RF source prototype FAT Program IDM_NCNC85 v.1.0 in presence of ITER organization (IO) representatives: **C. Darbos, F. Gandini and P. Vertongen.**

5. PRFS main output parameters measurement and verification for compliance for specified ones:	Required	Measured
- operation frequency,	170±0.25 GHz	170.07 GHz
- power at the MOU output,	≥0.96 MW	0.96 MW (±5%)
- generation efficiency	≥50%	58%
- HE_{11} mode content at MOU output	≥95%	97±1%
- pulse length	≥1000s	1000s
- duty factor	≤1/4	1/4

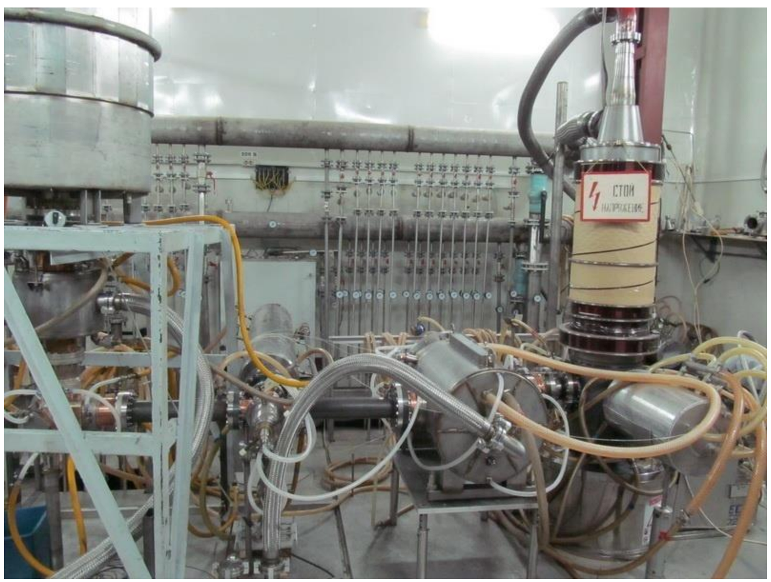
FDR, October 2015; Manufacturing began in 2016

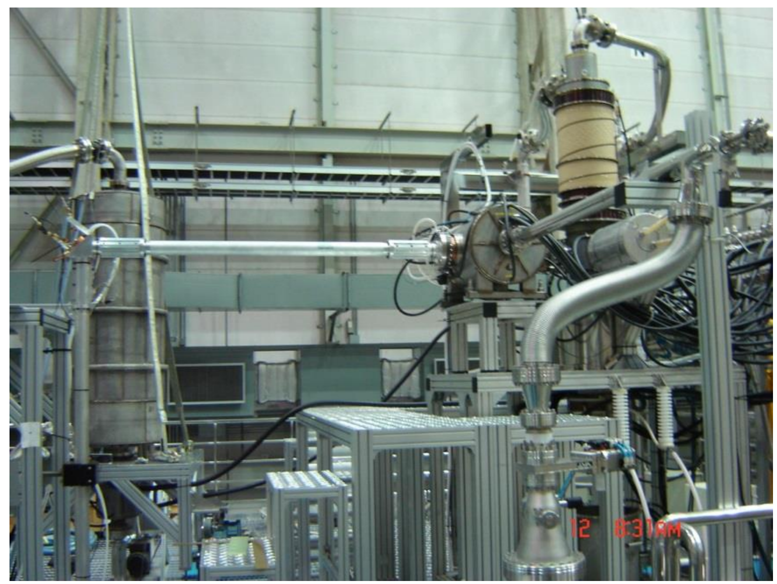
Other gyrotrons for fusion installations (2/6)

Two-frequency 140 / 105 GHz gyrotron with 1 MW output power and maximum pulse duration 300 s. The parameters were successfully demonstrated at the customer site – NFRI / Korea. At present time gyrotron operates at plasma machine **KSTAR**. Second two-frequency gyrotron is planned for delivery to NFRI at the end of 2017.

140 GHz / 1 MW / 1000 s gyrotron operates at **EAST** machine / ASIPP / China since mid of 2015 year. Second tube passed factory tests at July, 2016 and delivered to China.

The deliveries besides the gyrotrons include other components: cryomagnets (JASTEC, Japan), matching optic units, elements of evacuated transmission lines and full power evacuated dummy load.





Gyrotrons at factory and customer sites

New developments

- phase locking of gyro-oscillator by external signal
- stabilization of gyrotron frequency by the optimal reflection from a remote object
- generation of ultra-short pulses in gyro-TWT with non-linear absorber in the feedback loop

Aim:

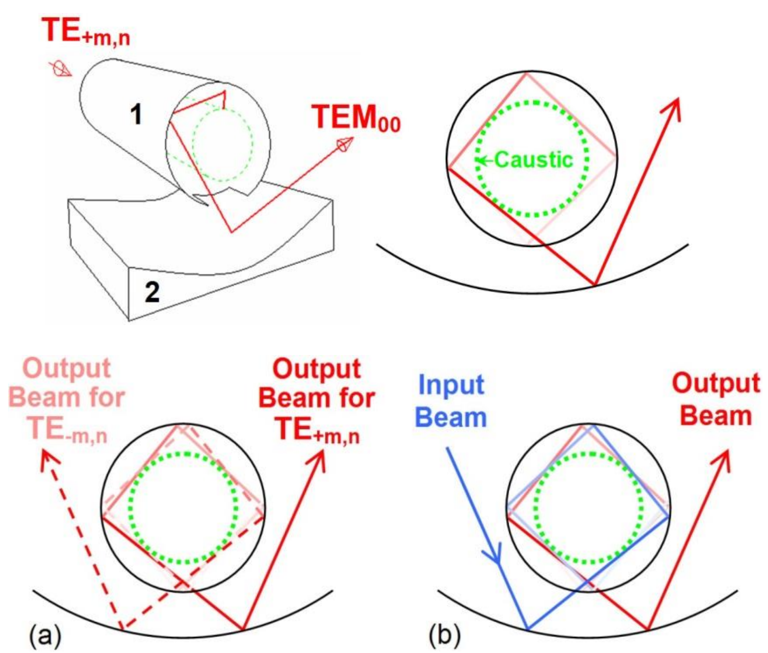
- Provide single mode gyrotron operation at very high-order modes
- Stabilize frequency while e-beam parameters are not stable
- Enhance efficiency
- Lock frequency and phase / Make several gyrotrons coherent

Simulations show very promising perspectives in gyrotron frequency stabilization by an optimized (amount and position) reflection.

The new quasi-optical converter allows one to direct reflected signal precisely back into gyrotron cavity.

Experiment on frequency stabilization in the 170 GHz/2MW gyrotron (A.Kuftin, A.Chirkov, G.Denisov, 2016) is very encouraging.

For rather high voltage variation of 95-100 kV the frequency was stable within 2 MHz comparing with 30-40 MHz without reflection.



Conventional converter to transform gyrotron operation mode $TE_{m,n}$ into Gaussian beam:
1 – launcher,
2 – quasi-parabolic mirror.

Two operation regimes of novel mode converter: conversion of the both co- and counter modes – a) Input signal for freq./phase locking regime – b)

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Development of Multi-Frequency Mega-Watt Gyrotrons for Fusion Devices in QST [FIP/1-6Rb]

R. Ikeda, T. Kobayashi, Y. Oda, K. Kajiwara, K. Takahashi, S. Moriyama and K. Sakamoto

National Institutes for Quantum and Radiological Science and Technology (QST)
Naka, Japan

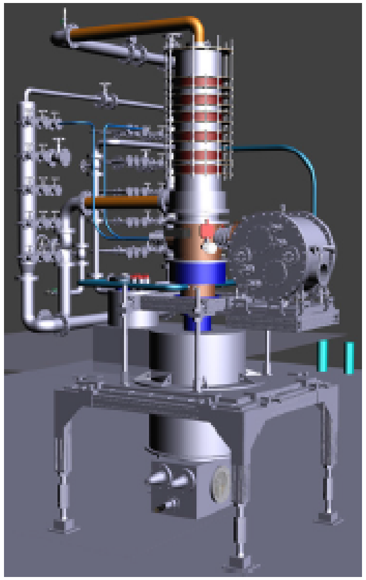
Two types of multi-frequency gyrotrons equipped with a triode magnetron injection gun for ITER and JT-60SA have being developed.

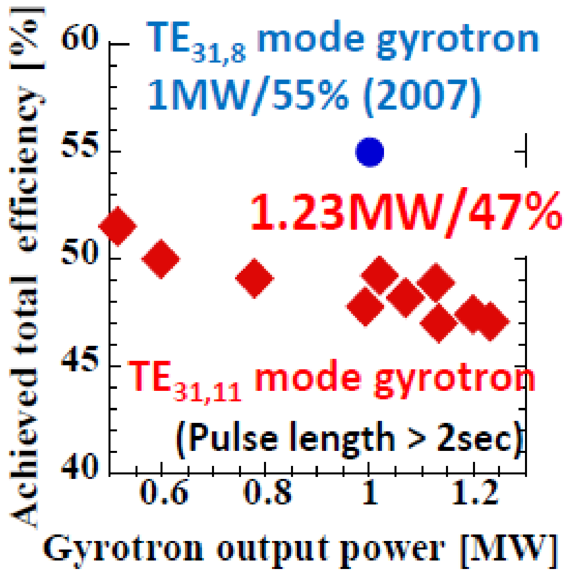
Progress on development of JADA ITER gyrotron

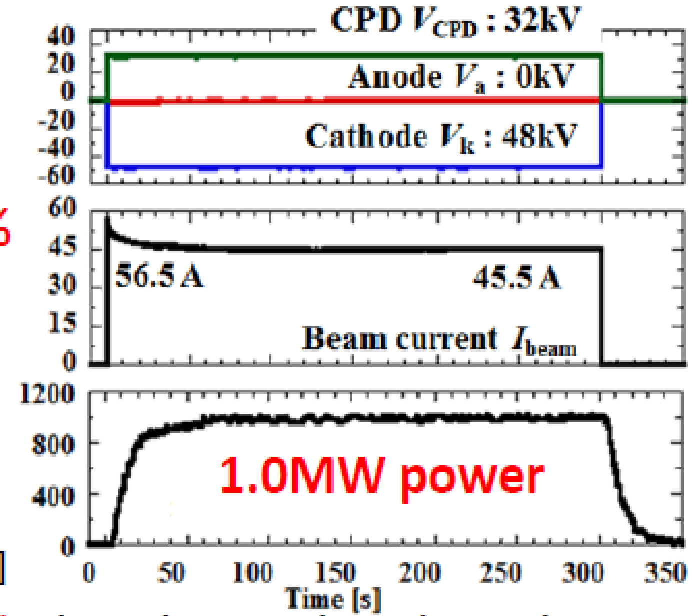
JADA procures 8 sets.

1.2MW/~ 50 %

300sec steady-state operation



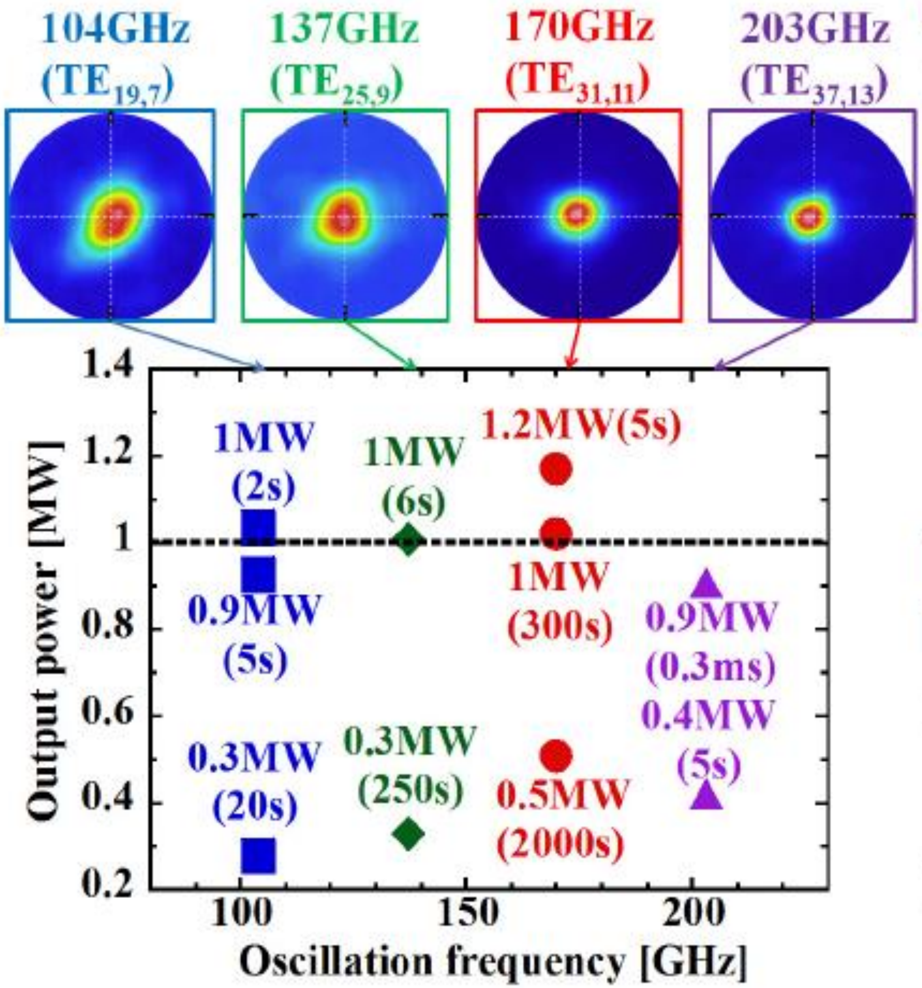




- Over-1MW gyrotron by $TE_{31,11}$ mode has been developed
- 1.2MW power and ~ 50% efficiency have been demonstrated.
- 1.0MW long-pulse operation has been reached steady-state.
- 1.3MW long-pulse operations will be planed for ITER.
- Final design review of RF source was finished at 2015 and manufacturing of ITER gyrotrons (#1&#2) are started.

Demonstration of Quad-frequency oscillations

JA ITER gyrotron has ability of multi-frequency oscillations with uniform directional beam.



For Next generation

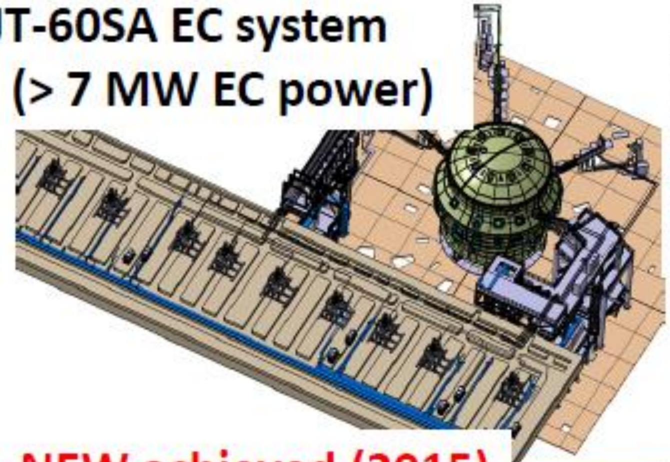
- **Achievement of 203GHz oscillations using high order mode ($TE_{37,13}$ mode)**
- **0.4MW for 5s (World first) (Max : 0.9 MW / 0.3ms)**

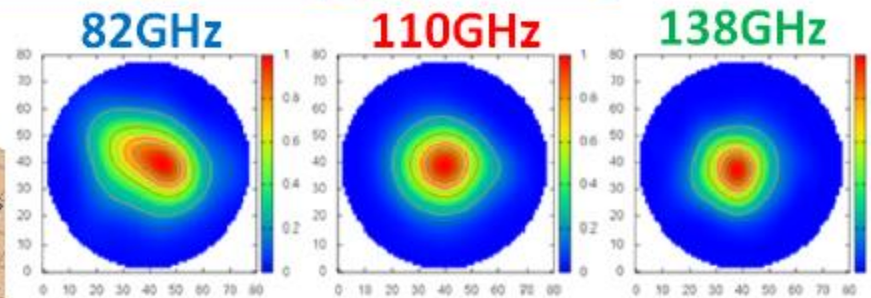
Expansion of pulse length for lower frequencies

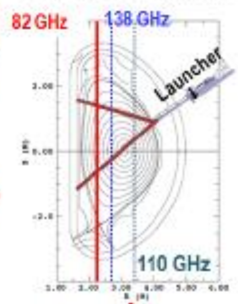
- **137GHz ($TE_{25,9}$ mode) 1.0MW up to 6s**
- **104GHz ($TE_{19,7}$ mode) 0.9MW up to 5s**

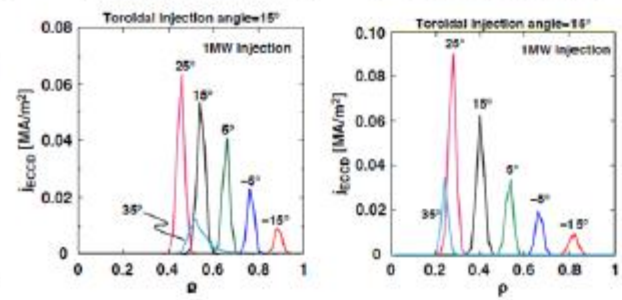
Multi-scenario by Triple-frequency gyrotron

JT-60SA EC system
(> 7 MW EC power)









NEW achieved (2015)

- *82GHz*(O1) [1MW/1s]

  B_T ~ 2.25 T : Plasma start-up assist
  EC wall cleaning

Achieved (2014)

- *110GHz*(X2) [1MW/100s]

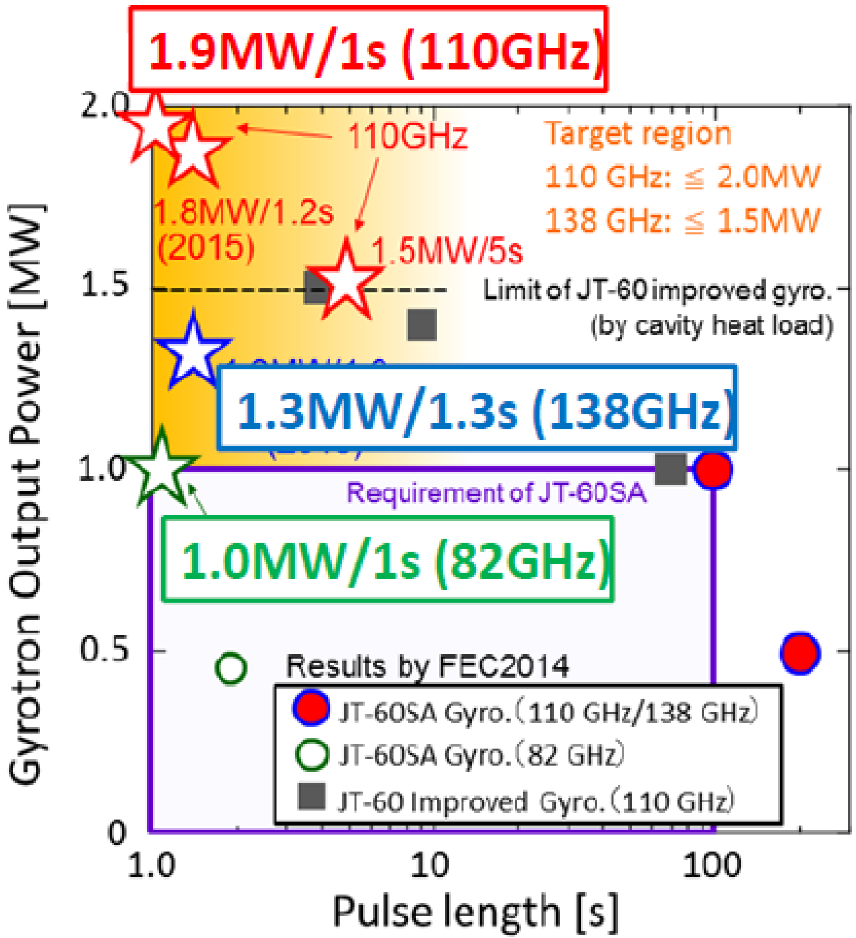
  B_T ~ 1.7 T: High-beta operation
- *138GHz*(X2) [1MW/100s]

  B_T ~ 2.3 T: Large current operation (Ip=5.5MA)

JT-60SA gyrotron will support attractive operations for fusion plasma research !

Demonstration of 2MW-class output power

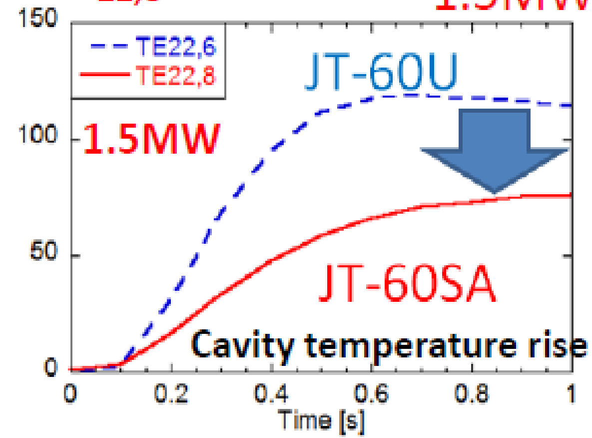
- **World record of 1.9MW has been achieved !**



Maximum output power :

JT-60U gyrotron : 1.5MW/4s
($TE_{22,6}$ mode)

JT-60SA gyrotron : **1.9MW/1s**
($TE_{22,8}$ mode) 1.5MW/5s



The output power is close to maximum acceptable power for the cavity in design.

- **Maximum power at 138GHz has been enhanced to 1.3MW(1.3 s).**

Development of Over MW Gyrotrons for Fusion at Frequencies from 14 GHz to Sub-terahertz

FIP1-6Rc Presented by T. Kariya (Univ. Tsukuba)

T. Kariya, T. Imai, R. Minami, T. Numakura, K. Tsumura, Y. Ebashi, Y. Endo, R. Ikezoe, Y. Nakashima : *Plasma Research Center (PRC), University of Tsukuba*

K. Sakamoto, Y. Oda, R. Ikeda, K. Takahashi, T. Kobayashi, S. Moriyama : *National Institutes for Quantum and Radiological Science and Technology (QST)*

T. Shimozuma, S. Kubo, Y. Yoshimura, H. Takahashi, H. Igami, S. Ito, K. Okada, S. Kobayashi, T. Mutoh : *National Institute for Fusion Science (NIFS)*

H. Idei, K. Hanada : *Research Institute for Applied Mechanics, Kyushu University*

K. Nagasaki : *Institute of Advanced Energy, Kyoto University*

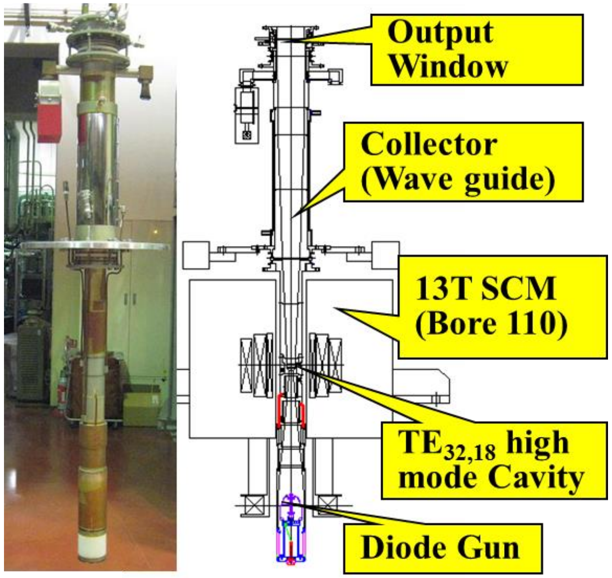
M. Ono : *Princeton University Plasma Physics Laboratory (PPPL)*

T. Eguchi, Y. Mitunaka : *Toshiba Electron Tubes and Devices Co., Ltd (TETD)*

Univ. of Tsukuba has been developing over 1 MW gyrotrons of 14GHz to sub-THz for Fusion Devices and for Demo-Reactor in collaboration with QST, NIFS, Kyushu Univ., Kyoto Univ., PPPL and TETD, based on 2 MW level result on the LHD 77 GHz gyrotron tube.

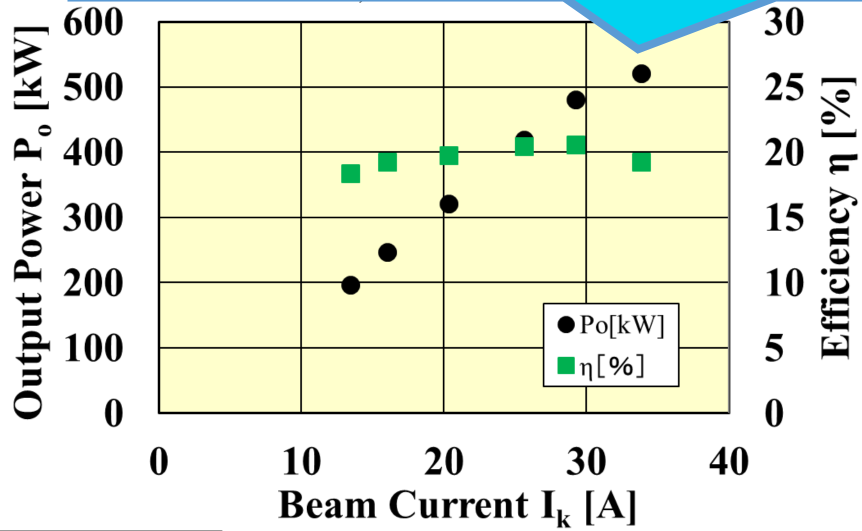
Develop. of Sub-Terahertz (300 GHz) Gyrotron

For ECH and ECCD at the DEMO reactor (Collabo. with QST)



Conventional type gyrotron
(W/O mode converter)

Achieved 299.8 GHz, 522 kW, 2 ms with $TE_{32,18}$ single-mode

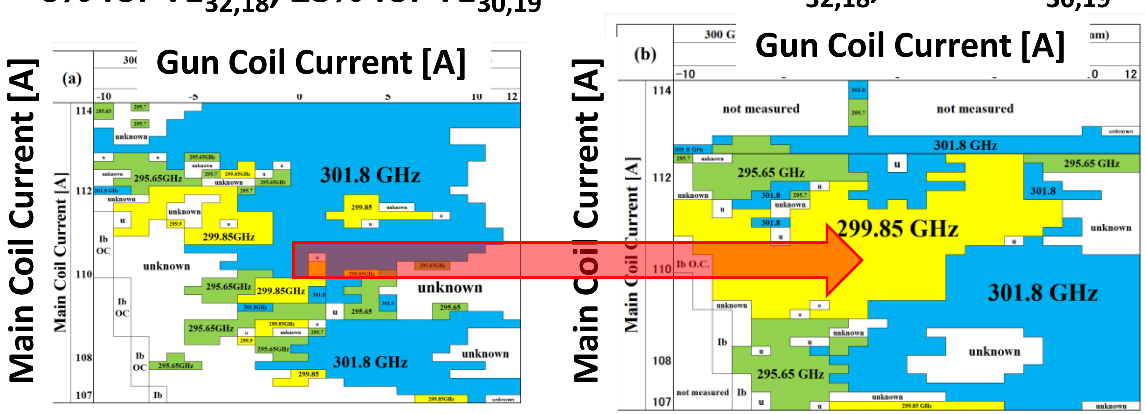


295.65 GHz, 542 kW ($TE_{31,18}$)
301.8 GHz, 528 kW ($TE_{30,19}$)

Mode maps (cavity vs. gun coil current)

Output Window Reflectance :
0% for $TE_{32,18}$, 23% for $TE_{30,19}$

With SiO_2 disk
20% for $TE_{32,18}$,2% for $TE_{30,19}$

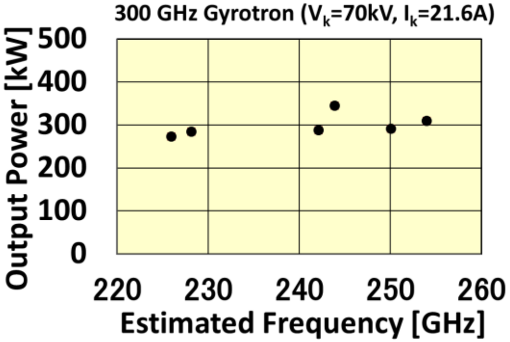


Window reflection affects the oscillation mode characteristics, which can be removed by installing a built-in mode converter. The aimed design single mode would be realized.

Develop. of Sub-Terahertz (300 GHz) Gyrotron

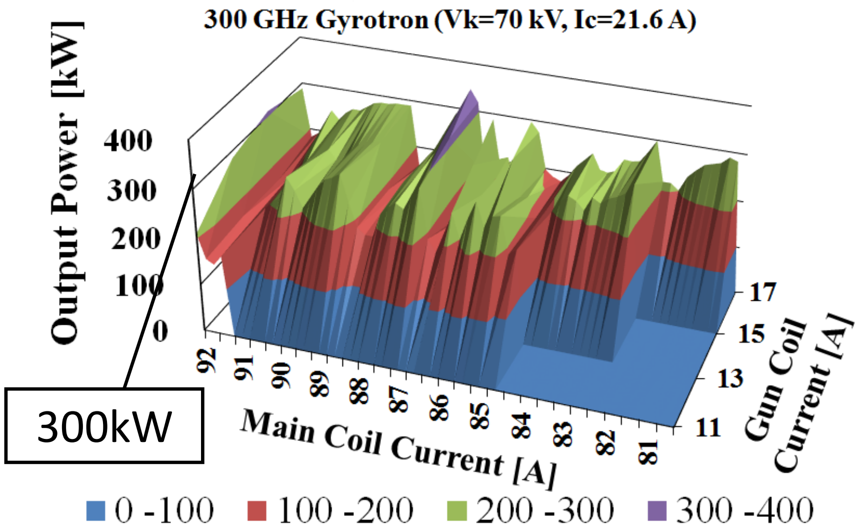
For ECH and ECCD at the DEMO reactor (Collabo. with QST)

Stable single mode oscillation at each tuned freq. in 225–254 GHz band



220 - 240 GHz Oscillation by 300 GHz Gyrotron

Magnetic Field at Cavity [T]	Beam Radius [mm]	Estimated Oscillation Mode	Estimated Frequency [GHz]
10.11	5.57	$TE_{28,15}^{(-)}$	253.99
9.80	5.58	$TE_{27,15}^{(-)}$	250.04
9.60	5.59	$TE_{28,14}^{(-)}$	243.9
9.54	5.59	$TE_{25,15}^{(+)}$	242.1
9.43	5.6	?	?
9.07	5.61	$TE_{24,14}^{(+)}$	228.13
8.90	5.62	$TE_{26,13}^{(-)}$	225.96



It was found that designed ultra-high volume mode of sub-THz would be stably obtained with conventional cylindrical cavity. Step tunable single mode oscillations were also confirmed. These result contributes greatly to the step frequency tunable gyrotron in the sub-THz region for the DEMO-Reactor.

Develop. of 28/35 GHz Dual-frequency Gyrotron

For ECH, ECCD & EBW heating on GAMMA 10/PDX, QUEST, Heliotron J, NSTX-U (Collabo. with Kyushu Univ., Kyoto Univ., PPPL and NIFS)

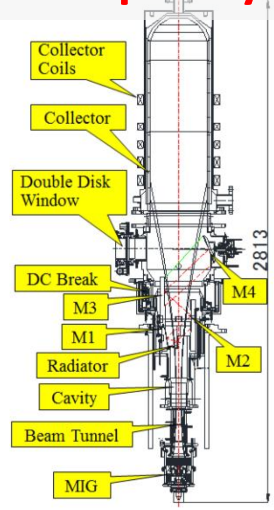
QUEST experiment using Tsukuba 28 GHz gyrotron :

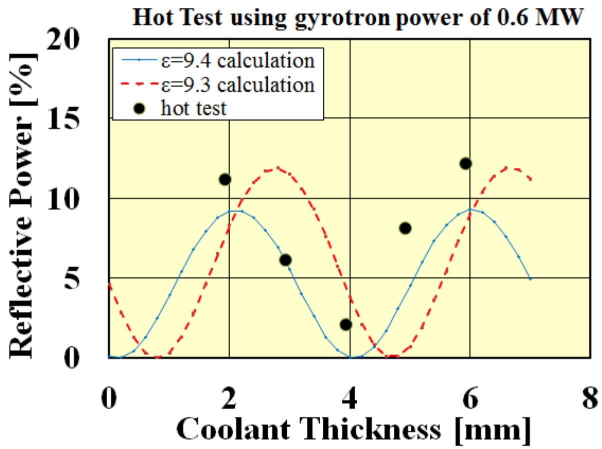
Over-dense plasma with a density in excess of 1×10^{18} m^{-3} (higher than the cut-off density of 8.2 GHz) was produced. An EC-driven plasma current of 70 kA was achieved non-inductively for a 28 GHz injection [EX/P4-50 : H. Idei].

Next step Collaboration → **New Dual-frequency Gyrotron**

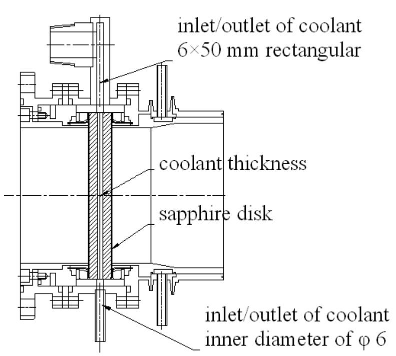
28 GHz 2 MW Dual-frequency Gyrotron

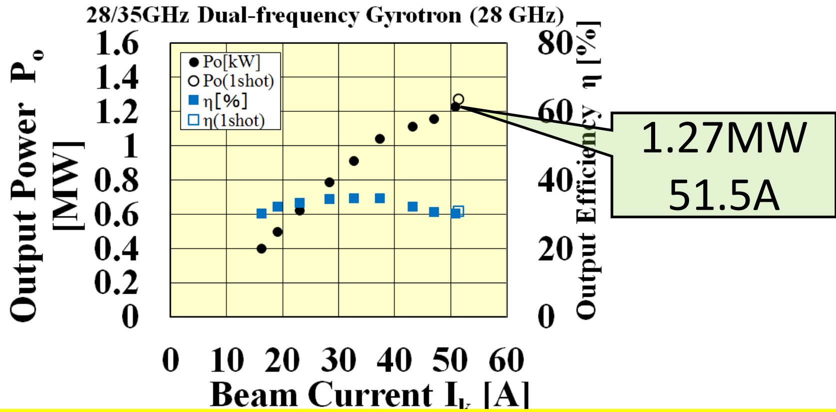
Frequency	28 GHz		34.77 GHz
Output Power	2 MW	0.4 MW	1 MW
Pulse Width	3 s	CW	3 s
Output Efficiency	50% (with CPD)		
Beam Voltage	80 kV	70 kV	80 kV
Beam Current	70 A	20 A	40 A
MIG	Triode		
Cavity mode	$TE_{8,5}$		$TE_{10,6}$
Mode Converter	Built-in		
Output mode	Gaussian like		
Output Window	Sapphire Double Disk		
Collector	Depressed Collector		
	Sweeping coils		





Double-disk window





The frequency characteristics of the double-disk window were optimized. The results suggest the flexibility of the window transparent frequency.

Oscillations of 28.04 GHz, 1.27 MW and 34.83 GHz, 0.48 MW were obtained with Gaussian-like beams.
Maximum Efficiency 50% was obtained at 0.63MW with V_{cpd} = 30 kV

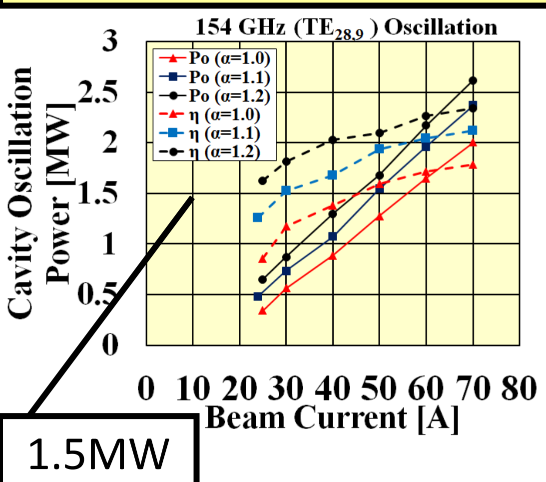
Design study of 154/116 GHz Dual-frequency gyrotron
For ECH and EBW heating at LHD (Collab. With NIFS)

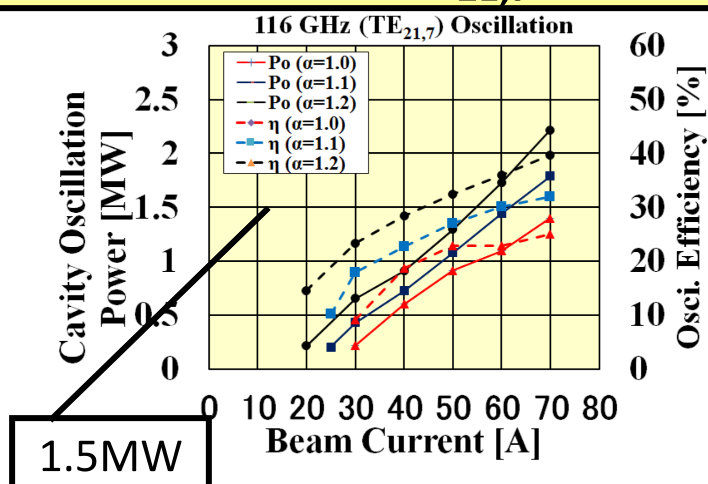
Three 77 GHz and two 154 GHz gyrotrons have contributed greatly to extending the LHD plasma performance with their total plasma injection power of 5.4 MW.

- **High Te plasma** : Te = 20 keV
- **Steady-state plasma** : line averaged $n_e = 1.1 \times 10^{19}$ m^{-3} $T_e = 2.5$ keV was sustained for 2351 s.

Based on the above and the 2 MW level 77 GHz gyrotron development results, a new 154/116 GHz dual-frequency gyrotron is desired for expanding the LHD plasma parameters.

Best matching of cavity, Mode convertor and window was obtained with combination of Cavity oscillation modes $TE_{28,9}$ at 154 GHz and $TE_{21,7}$ at 116 GHz.





The simulation of the MIG indicates the operation at $\alpha = 1$–1.2 with $\Delta\alpha/\alpha < 5$ %, implying high efficient oscillations in the cavity.

Oscillations with the power exceeding 1.5 MW are expected at 154 and 116 GHz.

Summary

- Significant progress in gyrotron development was demonstrated (Russia and Japan) in two last years

- Aims and achievements of the new developments are:
    - Reliability of gyrotron operation (ITER)
    - Higher power and higher frequency
    - Multi-frequency operation (e.g. 104, 137, 170, 203 GHz)

Thank you!

ありがとうございます