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JT-60SA電子サイクロトロン加熱装置の大電力･長パルス化開発の進展

Progress in high-power long-pulse ECH system development for JT-60SA

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Introduction

A gyrotron and a waveguide transmission line (TL), which were developed for electron cyclotron heating and current drive (ECH/CD) in JT-60SA, have been tested to evaluated its high-power, long-pulse capabilities at multi-frequency.

Gyrotron development

- High-power oscillations of the JT-60SA gyrotron toward demonstration of 1.5 – 2 MW have been carried out. The gyrotron was operating at the higher order mode of TE22,8 at 110 GHz.

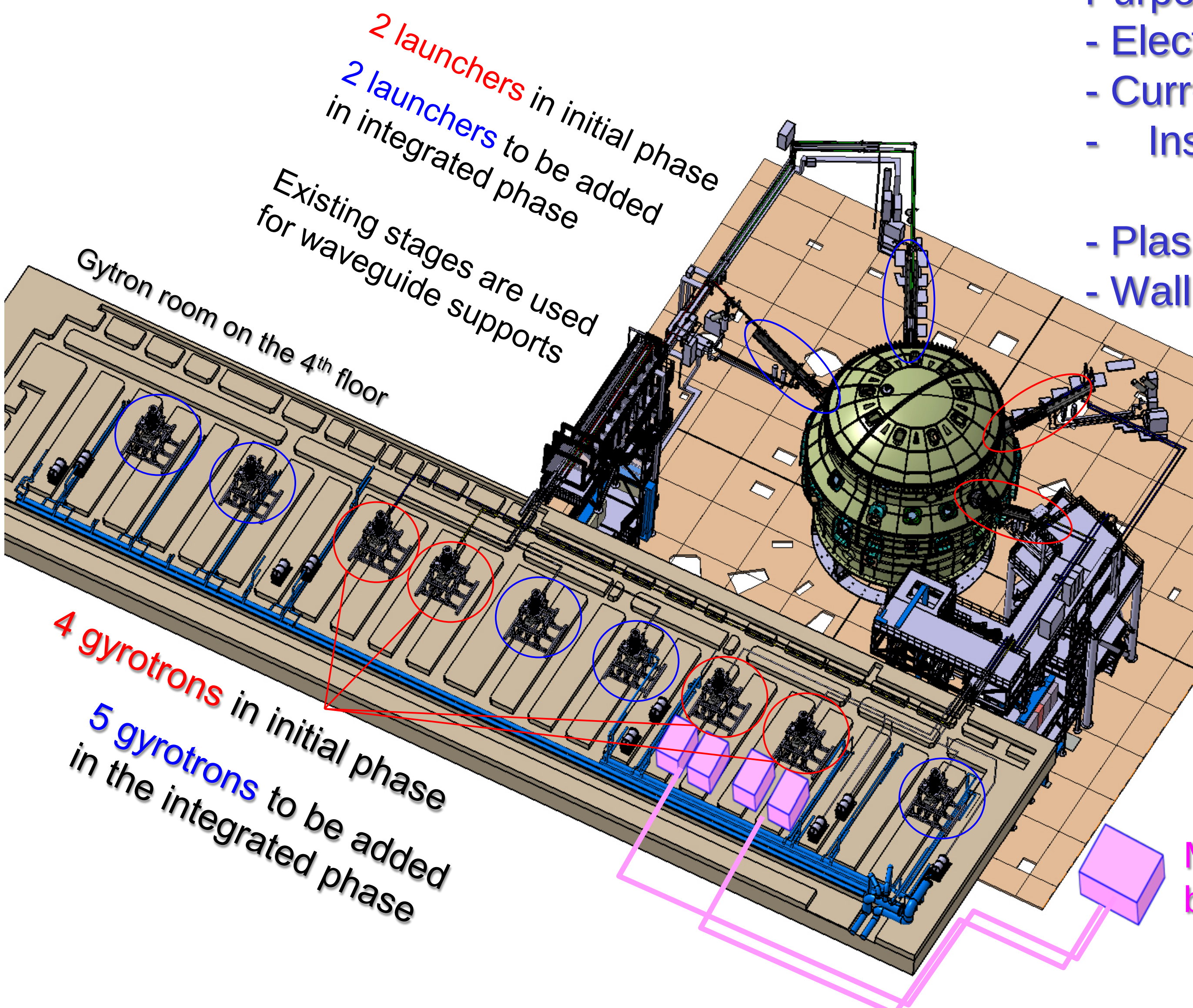
TL development

- The spatial distribution of the temperature rise of the TL with 7 miter-bends (~37 m), which simulated the TL in JT-60SA, has been measured at both 110 GHz and 138 GHz.

- Temperature rise of the stainless steel waveguide was experimentally compered with that of the aluminum waveguide.

- An efficient direct water cooling jacket, which can be installed using O-rings, has been developed.

Outline of the JT-60SA ECH system



Purposes:
- Electron heating
- Current drive
- Instability control (particularly NTM)
- Plasma initiation
- Wall cleaning

} Required for the first plasma

JT-60U: 1 MW, 5 s, 4 sets

⬇

Phased construction

⬇

JT-60SA: 1 MW, 100 s, 9 sets

Main specifications and gyrotron R&D

Frequency	110 GHz, 138 GHz **82 GHz (< 1s)**
Max. Power into Plasma	7 MW
Max. Pulse Duration	**100 s**
Duty cycle	1/18
Number of Gyrotrons	9
Number of Launchers	4
Max. Power at Gyrotron Window	**1 MW**
Transmission Line	Corrugated waveguide Inner diameter 60.3 mm
Transmission Efficiency	75 - 80% (including loss in MOU)
No. of Trans. Lines	9
Power modulation	5 kHz

Achieved R&D target of the JT-60SA gyrotron

- **1MW for 100s at both 110 GHz and 138 GHz**

  Achieved in 2014.

  Applicable for high-power, long-pulse heating/current drive at 2nd harmonic EC resonance.

- **1MW for 1s at 82 GHz**

  Achieved in 2015.

  Applicable for effective start-up assist and EC wall cleaning at fundamental EC resonance.

Next R&D target of the same gyrotron

- ☐ **Higher power oscillation up to 2 MW for several seconds at 110 GHz.**
- ☐ **~ 1.5 MW for > 10 s at both freq.**

Higher order mode oscillation to reduce cavity Ohimic loss

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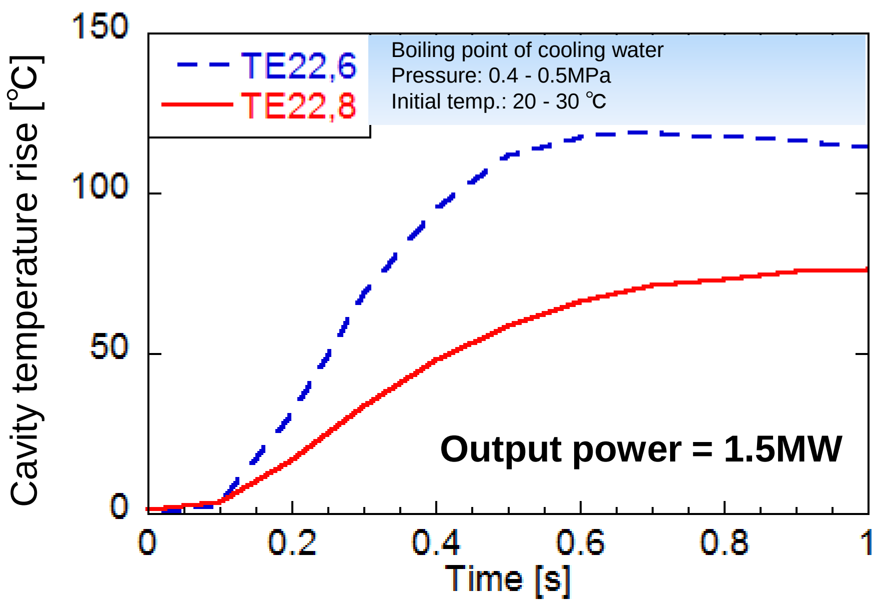
JT-60 Gyrotron
Cavity radius：19.8mm
mode： $TE_{22,6}$ at 110GHz

Previous record: 1.4MW/9s, 1.5MW/4s

T. Kobayashi et al., Nuclear Fusion **51** (2011) 103037.
A. Isayama, T. Kobayashi et al., 24th IAEA FEC, FTP/P1-16 (2012).



Measured by a thermocouple at the cooled surface of the cavity for both JT-60 (TE22,6) gyrotron and the JT-60SA gyrotron (TE22,8).

Cavity heat load limited the output power of the previous gyrotron (1.2kW/cm² @ 1MW)

Higher mode (TE_{mn})

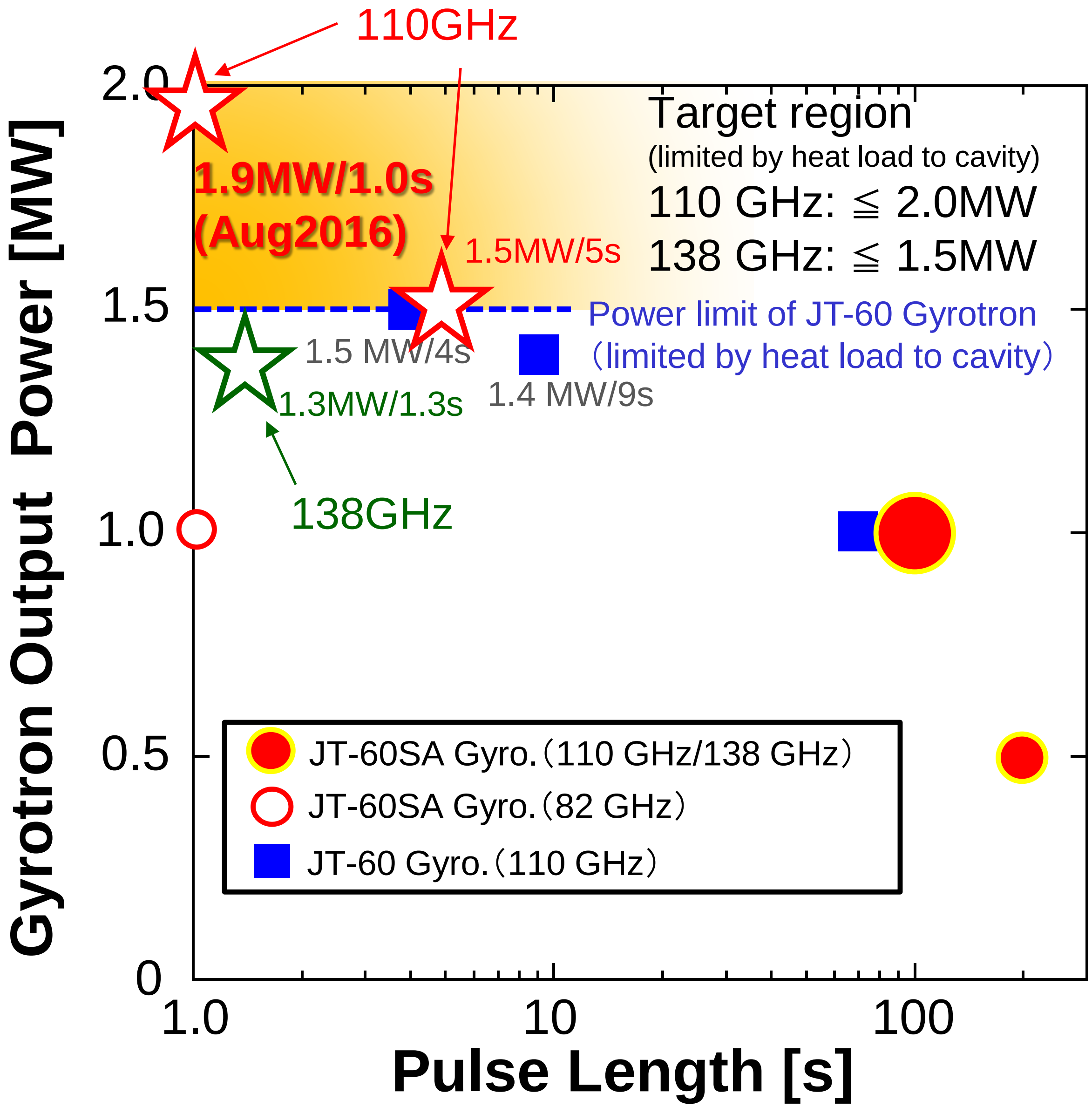
Heat load $H_{mn} \propto \dfrac{f^{2.5}}{\chi'^{2}_{mn} - m^2}$

JT-60SA Gyrotron
Cavity radius： 22.9mm
Oscillation mode： $TE_{22,8}$ at 110GHz
$^*H_{22,8} = 0.7 \times H_{22,6}$
(applicable up to 2 MW, in design)

Issue: Mode competition at high order mode
Solution: Optimization of anode voltage (Triode MIG)

- **Experimental result consistent with design.**
- **Power limit by the cavity heat load has been improved.**

High-power gyrotron oscillation at three frequencies



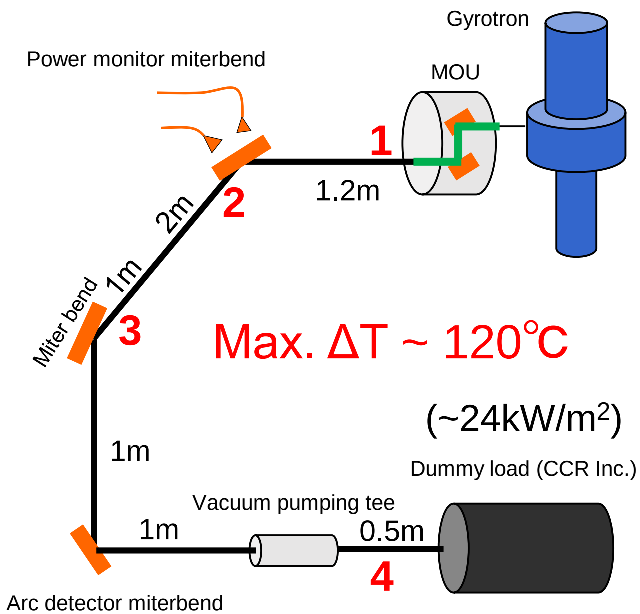
<u>Tentative results by 2016.</u>

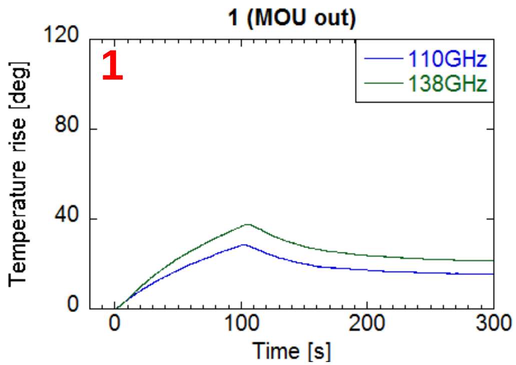
1.9MW/1.0s, 1.5MW/5s

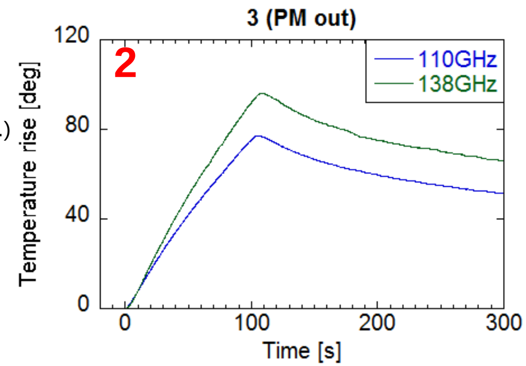
- Record of high power at >1s has been updated.
- Further optimization of the anode voltage during the start-up pulse, in future.

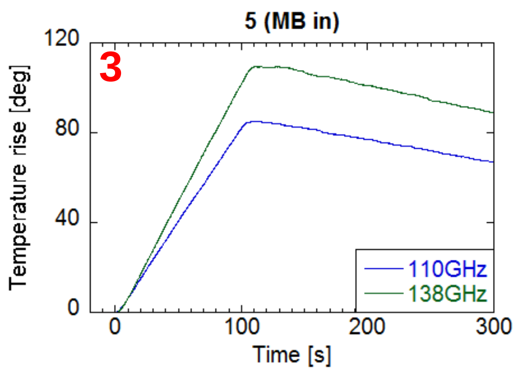
Issue in the waveguide temperature rise during 1MW/100s operation in 2014.

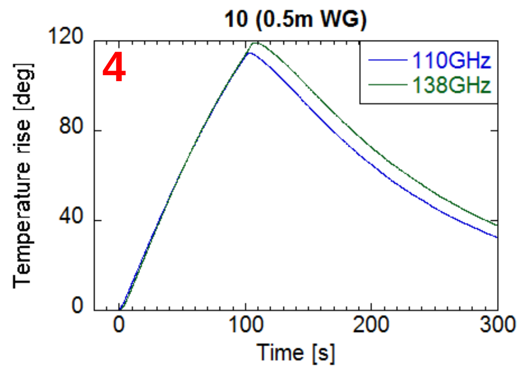
Example of the waveguide temperature rise in 1MW/100 s operation with short TL (7m).











- Maximum temperature close to the operational limit of Aluminum. (~150 ℃)
  (initial temp. ~ 30 ℃)
- Averaged temperature rise ~ 60 ℃ results in too large waveguide expansion.

$2.3\times10^{-5} \times 10\text{m} \times 60℃ = 13.8\text{mm}$

Coefficient of thermal expansion for AL. / Typical length of TL between two miter bends.

Note: The shape of the phase correcting mirrors in MOU was optimized for only 110 GHz. At 138 GHz only the angles of the mirrors were adjusted.
HE11 purity at 110 GHz ~ 90%, 138 GHz ~ 80%
(phase retrieval with IR-camera measurements)

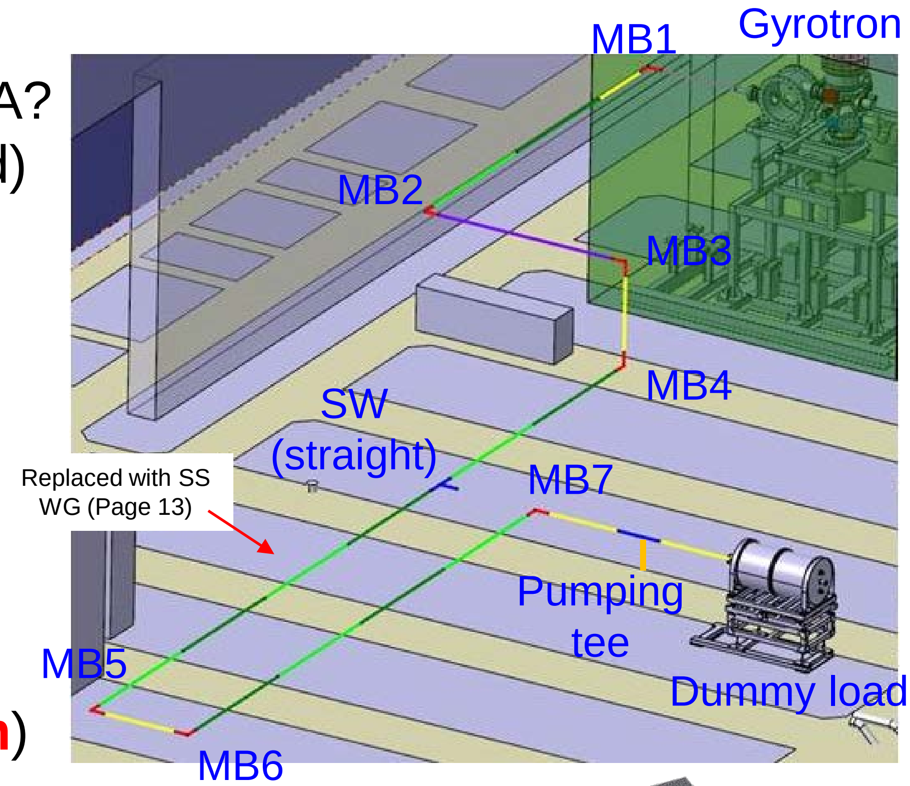
Installation of long TL for temperature measurements simulating the TL in JT-60SA

Question:

Is the high temperature rise expected in JT-60SA?
(long TL, more miter bends, without dummy load)

Origin of the loss should be identified.

Possible origins.
- Misalignment of waveguides.
- Higher order modes generated between two miter-bends.
- Reflection from the dummy load.



The previous TL was too short to identify the origin of the loss.

→ New TL (in gyrotron room).
7 miter-bends (total TL length **~ 37m**)

Alignment by traditional tools.

Target: tilt of waveguide < 1mm/1000mm.

Same as the previous specification to install the waveguide in JT-60 (Inner diameter: 31.75 mm), which was not sensitive to misalignment.

To simulate the worst case for the TL in JT-60SA (inner diameter 60.3 mm).
(Equivalent or better alignment is expected in JT-60SA)

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Precise measurement by **laser tracker** to confirm experimental condition

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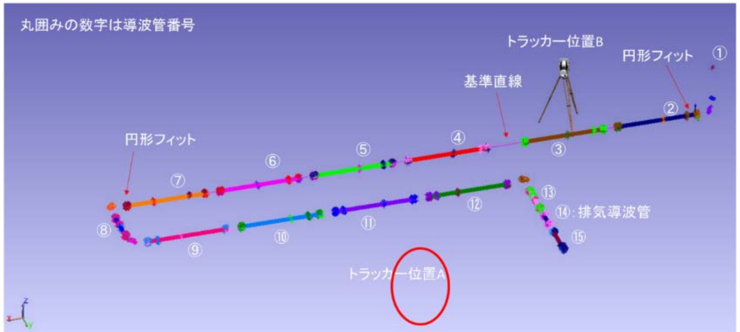
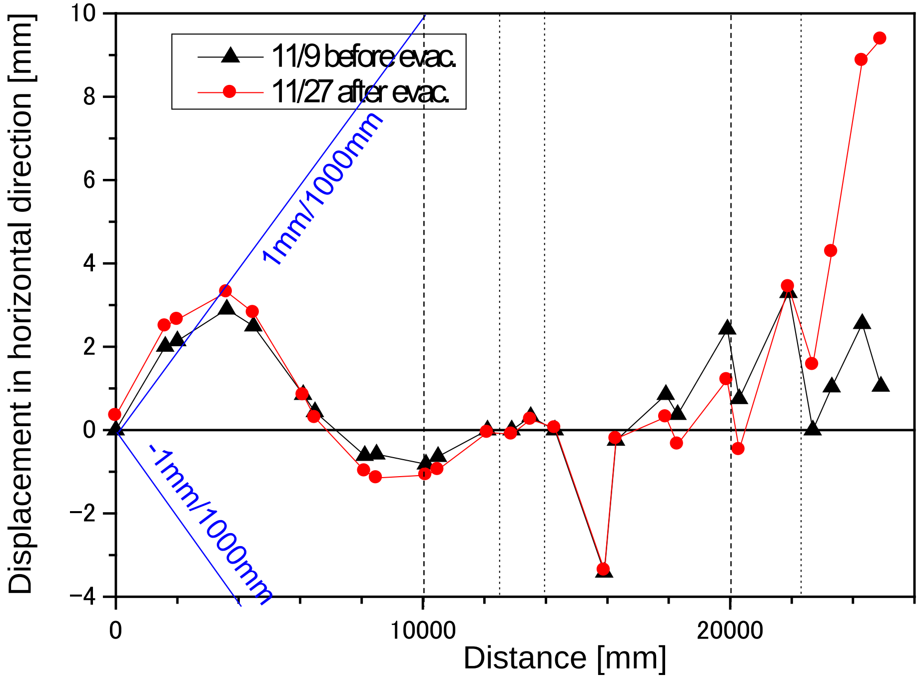
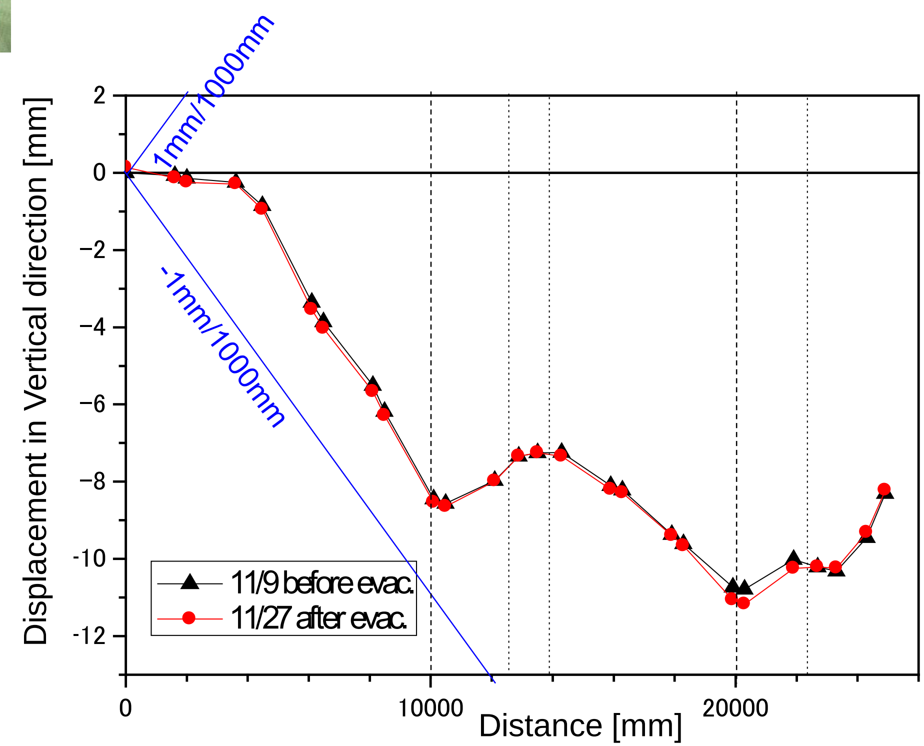
Measured displacement is almost smaller than the target (1mm/1000mm) in the long distance while at some places it was relatively large locally.



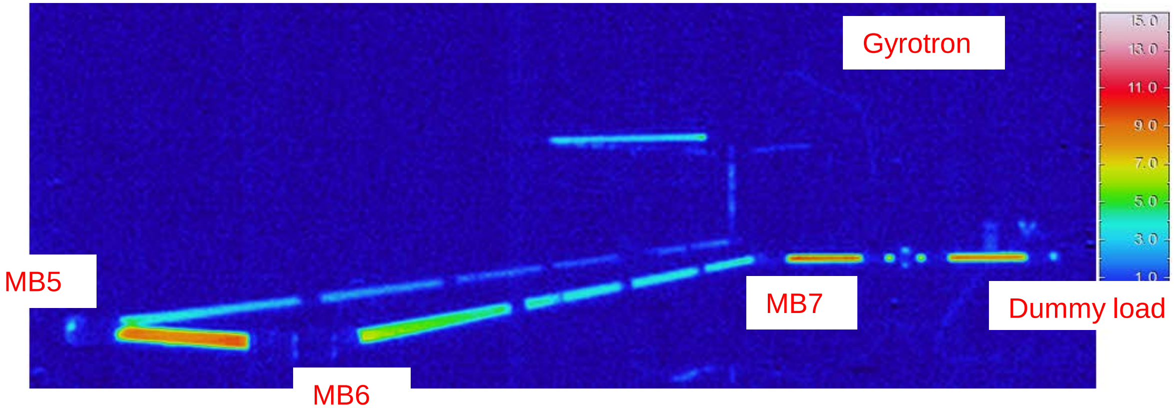
The temperature distribution was measured by IR-camera with this experimental condition.

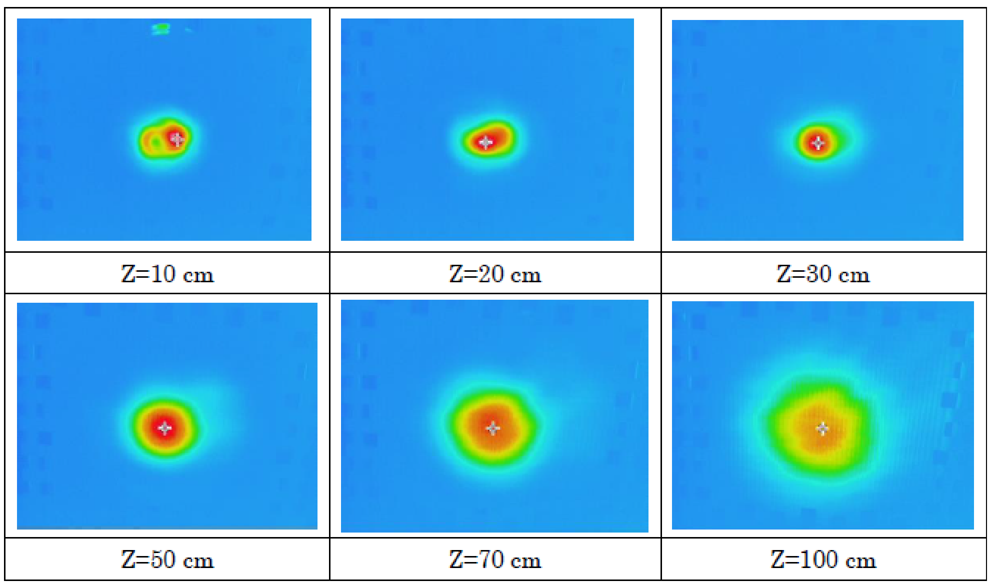




Temperature distribution at 110 GHz

110 GHz, 500kW, 20s = 10 MJ





Output beam pattern at the output of MB7.

- Temperature rise of the waveguide close to the gyrotron is relatively small.
- Relatively high temperature rise > 1 ℃ /MJ. (similar to the previous result at the short TL)

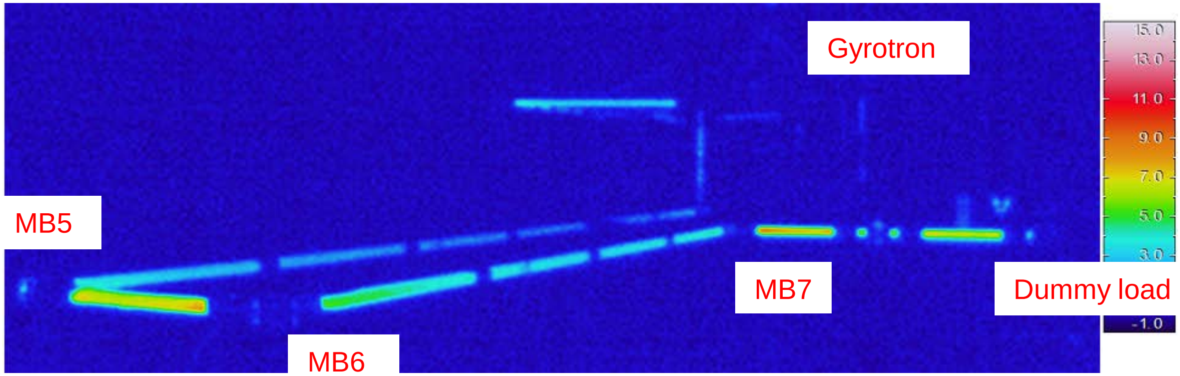
Temparature rise > 10℃/10MJ.
- ➢ Between MB7 and dummy load.
- ➢ Between MB5 and MB6.

- Gaussian like (HE11 like) pattern was obtained at the output of the miter-bend close to the dummy load (MB7). Similar results were obtained at many positions from MB4 to MB 7.

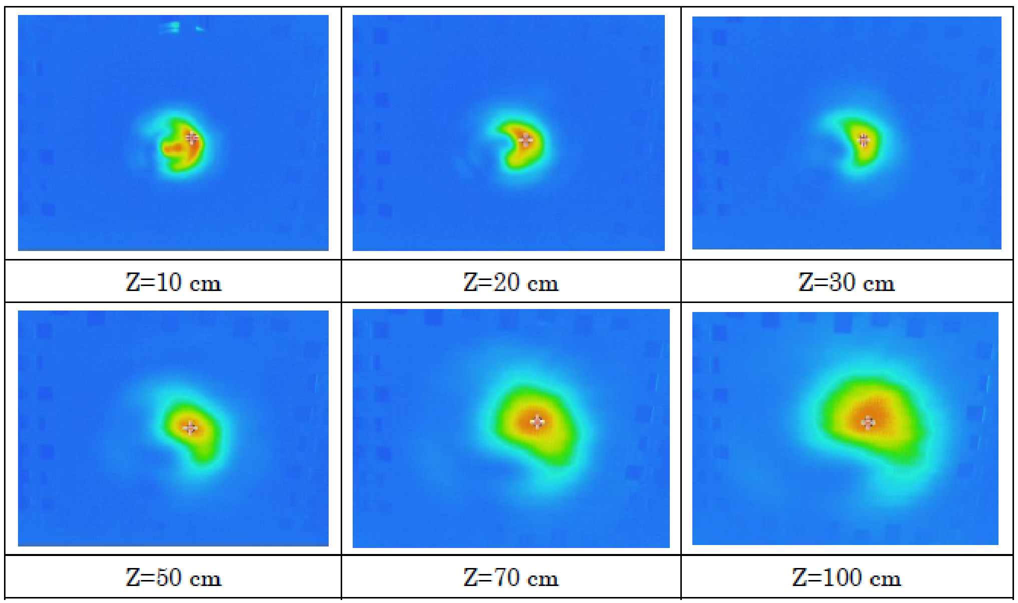
Detailed analysis of the mode purity is underway.

Temperature distribution at 138 GHz

138 GHz, 500kW, 20s = 10 MJ



Measured temperature rise.



Output beam pattern at the output of MB7.

- Temperature distribution similar to that of 110 GHz.
- **Temperature rise is slightly lower than that of 110 GHz.**
- Beam pattern with **relatively low HE11 purity** was observed at 138 GHz. Similar from MB4 to MB7.

Note:

- ✓ The MOU mirrors were optimized for 110 GHz.
- ✓ Misalignment of waveguide makes the larger mode conversion at the higher frequency.

These results suggested that the higher order modes generated at the MOU output or those generated by waveguide misalignment may not be a cause of the large temperature rise.

Evaluation of the temperature rise and decay length

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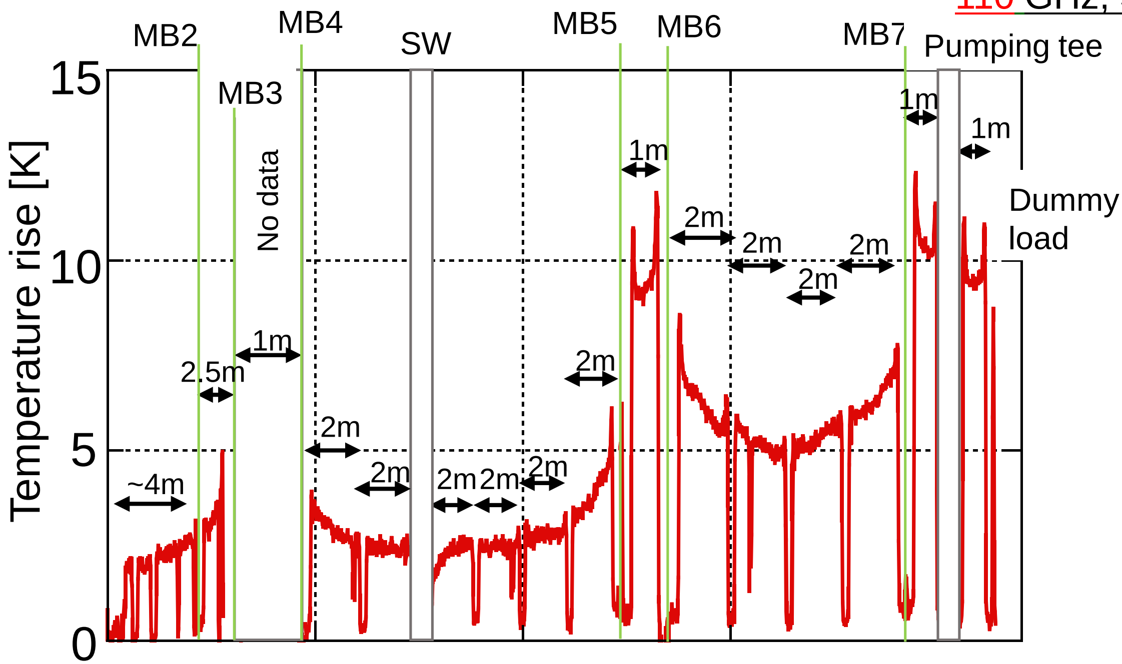
110 GHz, 500kW, 20s = 10 MJ



- **The higher order modes generated at the miter-bends are absorbed within ~ 2m.**
- The reflection from the dummy load may have long decay length of ~ 10 m. (not problem for tokamak experiments!)

Results: Expected temperature rise and required cooling in JT-60SA

□ **Near miter-bends (< 2m):** 0.5 – 1 ℃/MJ (50-100℃ for 1MW/100s)

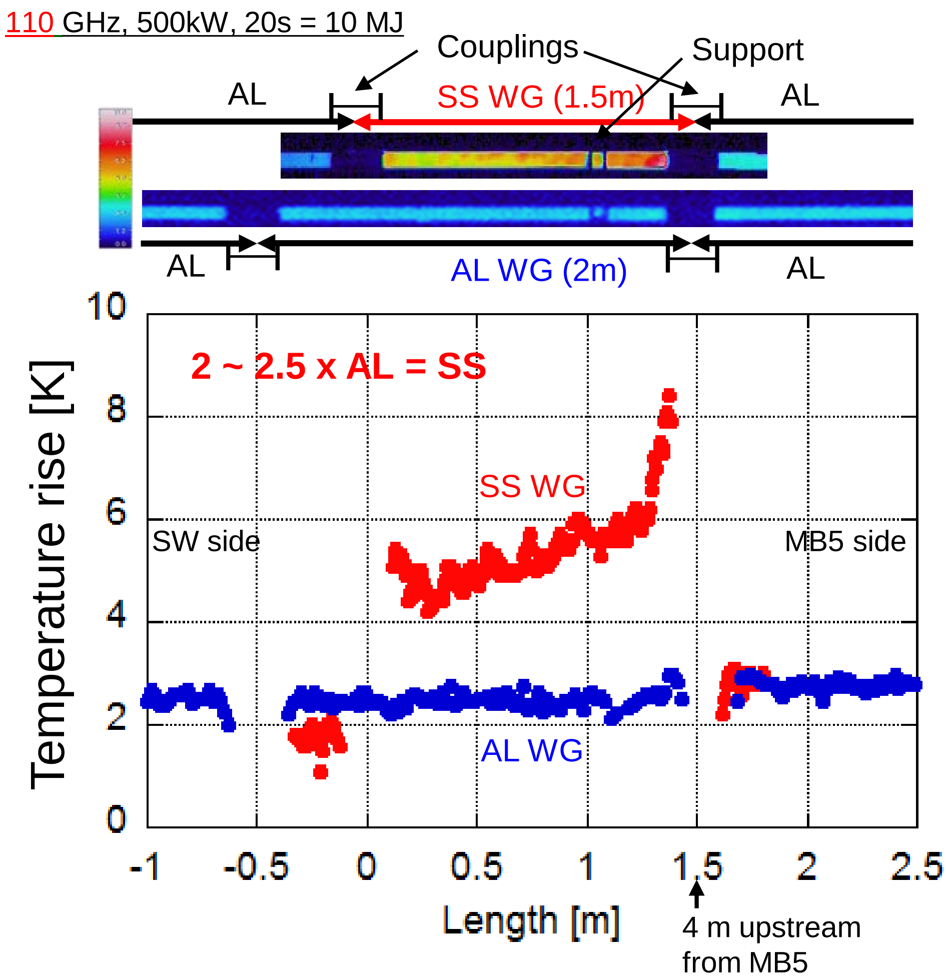
➡ Efficient cooling (short time constant << 100 s) to cool waveguide during the pulse (100 s).

□ **Far from miter-bends (> 2m):** 0.2-0.5 ℃/MJ (20-50 ℃ for 1MW/100 s)

➡ Simplified cooling with long time constant to avoid heat accumulation during the day of operation (duty cycle 1/18).

Stainless steel waveguide for launcher

1.5 m long SS waveguide fabricated by GA with the dimension the same as that of the aluminum waveguide.



Note:
- The outer surface of the SS waveguide near the couplings (0.2 m from both ends) are smooth and accurate temperature measurement by IR-camera was possible. And this region has smaller diameter of 74.6 mm (smaller heat capacity).
- At the other 1.1 m, the surface is rough and the measured temperature may be underestimated. And this region has larger diameter of 76.2 mm (larger heat capacity).
- Thermal contact of coupling may be different.

The waveguide used in air is made of aluminum alloy (AL) while the launcher, the stainless steel (SS) waveguide may be used in JT-60SA.

Electrical resistivity (at room temp.)
AL alloy: 4 – 5 x10^{-8} [Ωm]
SUS316L: 72x10^{-8} [Ωm]   x 14 - 18
~ 4 times larger Ohmic loss.

Heat capacitance
AL alloy: 2.5x10^{6} [J/m^{3}K]
SUS316L: 4.0x10^{6} [J/m^{3}K]
~ 1.6 times larger heat capacitance.

The temperature rise of **~ 2.5 times larger** than that of the AL waveguide is expected for the SS waveguide if the volume is the same.

The experimental result agreed well with the theoretical estimation.

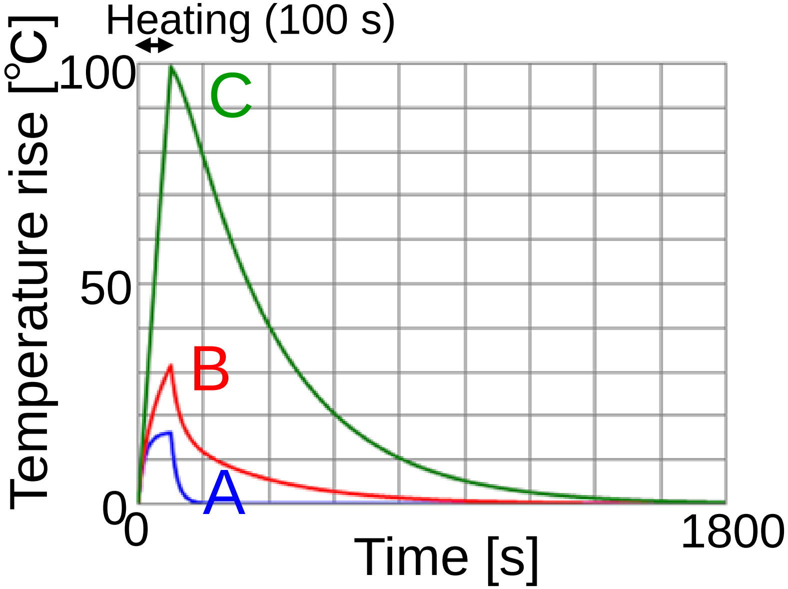
Effective cooling and/or Cu (or Nickel) coating for Ohmic loss reduction will be applied for the launcher waveguides in JT-60SA.

FEM design of direct cooling jacket for effective waveguide cooling

Design/FEM

To be used for aluminum WG (in air) near miter-bends.

- A direct water cooling jacket has been developed.
- Relatively low heat transfer coefficient (1kW/m^{2}K) was assumed (conservative value).



Input to FEM calculation

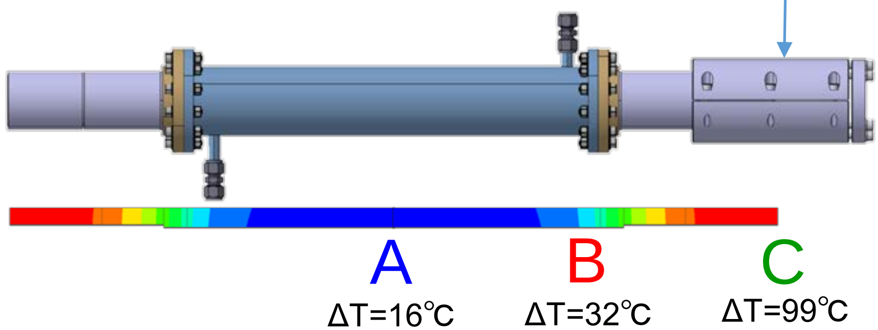
Initial temperature: 20℃

Heat transfer (cooling): 1kW/m^{2}K (coolant: 20℃)

Heat flow (heating): 20kW/m^2

(corresponds to ΔT=100℃ if not cooled)

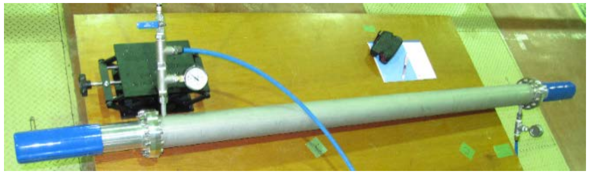
Note: Coupling was not modeled in FEM.

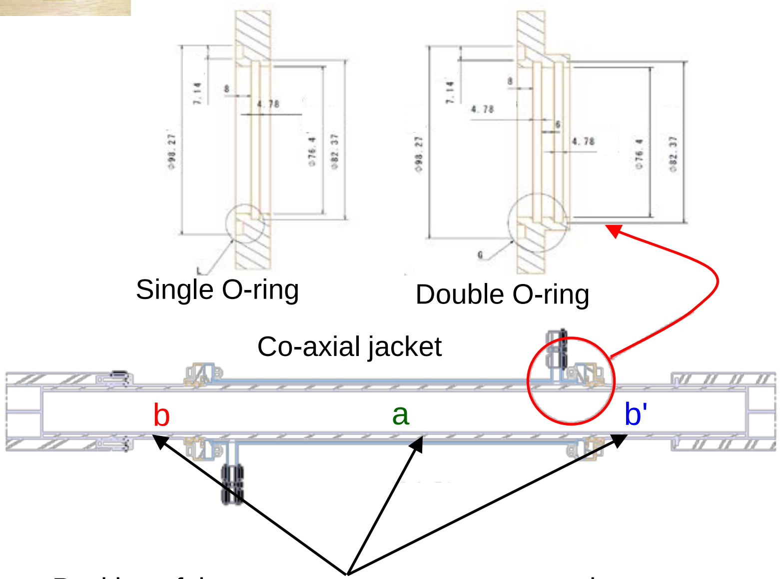


- ✓ Cooled part (Pos. A): almost saturated within 100 s.
- ✓ Non-cooled part (Pos. C): temperature is linearly increased during the heating (100 s), while it can be cooled within 1800 s (duty cycle 1/18).
- ✓ It enables to reduce thermal expansion of 1m and 2m long WGs by, at least, 50% and 68%, respectively. If the heat transfer coefficient is much higher than 1kW/m^{2}K, the expansion can be reduced more.

Fabrication and high-power test of the direct water cooling jacket

Jackets for 1 m and 2m waveguides were fabricated and tested with two types of O-ring seals.

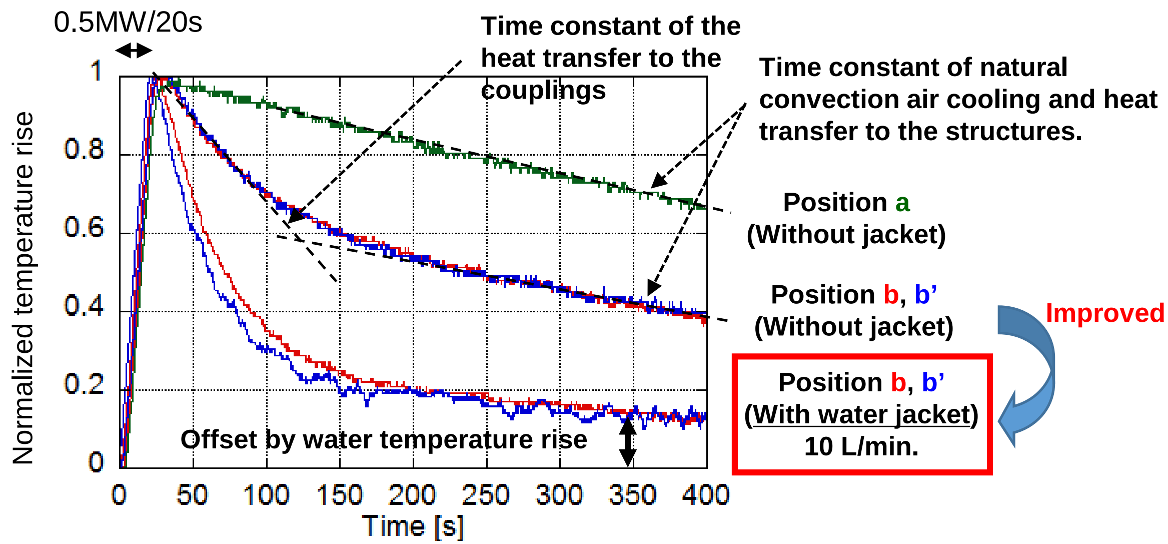




Position of the temperature measurements by thermo-couples in high-power experiments.

Middle of the waveguide (pos. a) was measured only without jacket.

Both single and double O-ring(s) types were successfully tested. (water pressure up to 1 MPa)

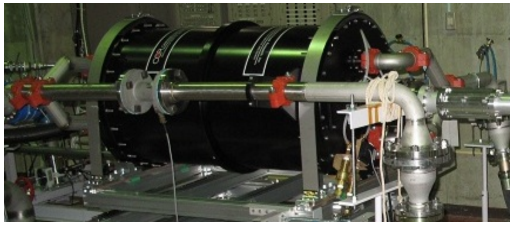


- The measured pressure drop is sufficiently small. (<10kPa@10L/min, <30kPa@20L/min).
- The time constant of the waveguide temperature decrease has been improved significantly even at the non-cooled positions (pos. b, b').
- The time constant at the cooled part is estimated to be several tens of seconds as expected in FEM.

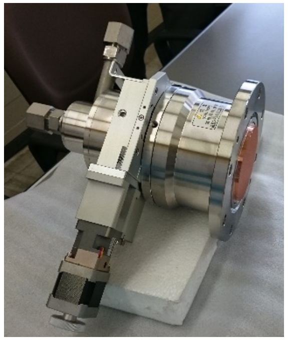
Other activities for ECH/CD in JT-60SA

◆Collaborative TL components R&Ds

- 1.5MW CW wideband dummy load (CCR),
- Power monitor miter-bend (NIFS)
- Fast directional switch (Kyushu univ.)
- Wide band polarizer (Ibaraki univ. and MTC) 30aP43



1.5MW CW dummy load



Wide band polarizer

◆Gyrotron power supply

- Procurement arrangement signed in 2015 (EU/F4E and JA/QST).
- Contract signed in 2016 (JEMA in Spain)
- Detailed design is ongoing. To be installed in 2018.

◆ECH/CD control system

- Three contracts (PLC slow controller, FPGA fast controller, PC supervisor/controllers with Ethernet network and reflective memory link) were signed in July 2016.
- Detailed designs are ongoing. To be installed/tested by March 2017.
- Integrated control test in two units of ECH system in 2017.

◆ECH/CD Launcher

- R&Ds for linear motion concept have been carried out.
- Bellows cyclic tests were successful (linear: 100,000 cycles, rotation: 10,000 cycles)
- Cyclic test of bearing structure for rotational motion (10,000 cycles) has been carried out successfully. The test for linear motion is planned in Dec. 2016 – Feb. 2017.

Summary

Gyrotron development

- **110 GHz: 1.9 MW/1s, 1.5MW/5s.**
- **138 GHz: 1.3 MW1.3s**
- **82 GHz: 1 MW/1s**

TL development

- The spatial distribution of the temperature rise of the TL with 7 miter-bends (~37 m) have been measured in high-power (0.5MW/20s) transmission.
  - Temperature rise far (> 2m) from miter-bends is expected to be 20 – 50 K. Simple cooling is enough for cooling between shots (1800s)
  - Temperature rise close (< 2m) from miter-bends may be 50 – 100 K. Efficient cooling during short (100s) is needed.
  - Ohmic loss of stainless steel waveguide is ~4 times higher than the aluminum waveguide as predicted in calculation.
- In order to cool the waveguide close (< 2m) to miter-bends, direct water cooling jackets have been developed.
  - FEM calculation shows sufficient cooling capability.
  - Two types of O-rings water shields worked well with static water pressure of 1 MPa.
  - The reduction of the cooling time constant was confirmed in high-power experiment.