Design of the HE11 Mode Measurement System for the ITER Gyrotron

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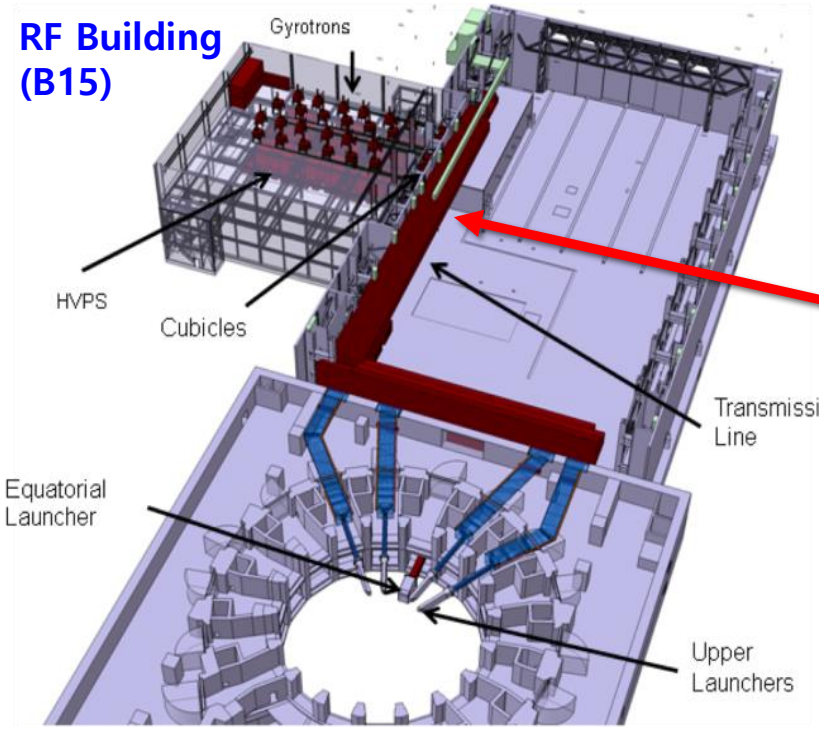
Contents

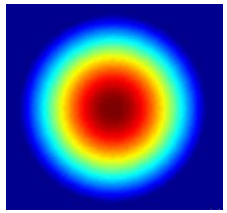
Introduction

- Gyrotron commissioning is planed for First plasma (FP) and Pre Fusion Plasma Operation (PFPO)

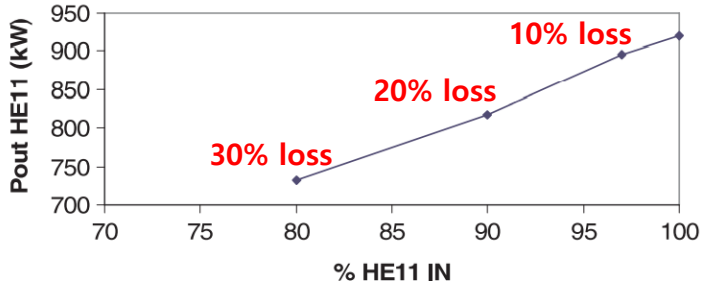
1. 7 of Gyrotrons will be installed in RF building (B15) for FP operation (Since 2023 ~)
2. Gyrotron commissioning and Site Acceptance Test (SAT) will be scheduled.
3. Beam quality test is required for low loss transmission because misalignment cause EC beam loss in tokamak.



Electron Cyclotron Heating (ECH) system in ITER Organization



HE11 mode
in transmission lines
(Corrugated waveguide)

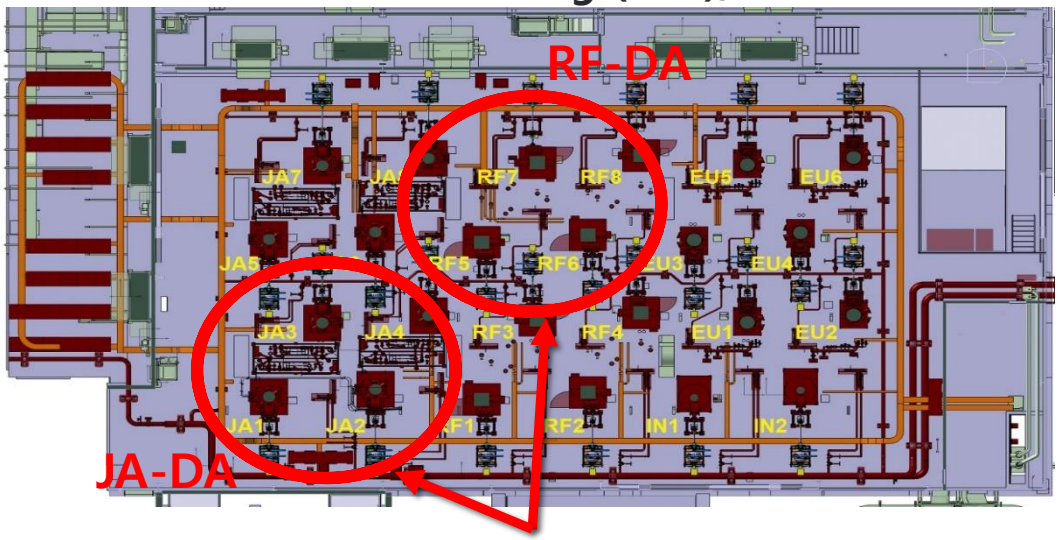


Output power in the HE11 mode versus percentage of HE11 in the input (ITER Transmission lines)

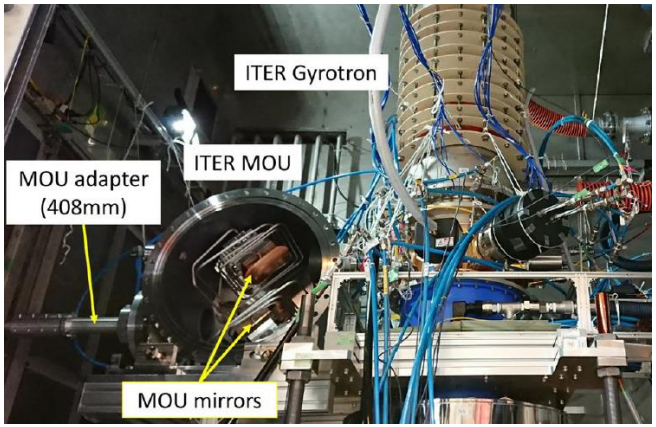
Ref article: M.A. Shapiro (MIT) et al. (2010)

Gyrotron Commissioning and Site Acceptance Test (SAT)

Schematic of RF building (B15), 3rd floor



Gyrotron for First Plasma (FP) operation

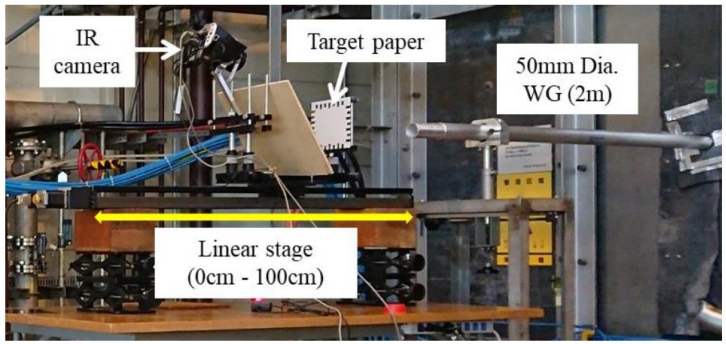


Gyrotron from JA-DA

First goal in Gyrotron SAT: EC beam quality test (HE11 mode measurement)

Gyrotron condition for beam quality test

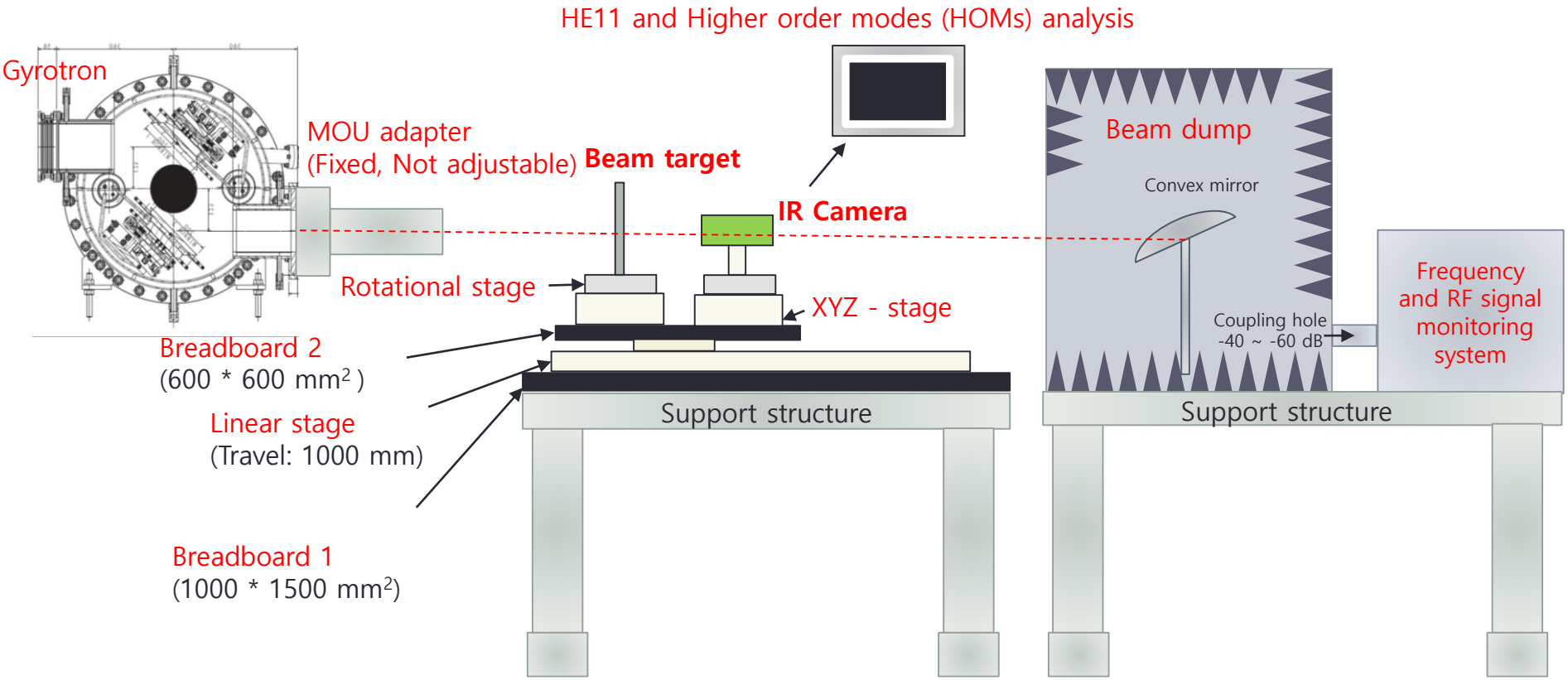
1. Operation type: Short pulse
2. Frequency: 170 GHz ($\pm$ 0.3 GHz)
3. RF pulse length: 1 ms
4. Output RF power: ~ 0.2 MW
5. HE11 mode purity: > 95 %



Experimental setup for HE11 mode measurement in QST

Beam quality test : HE11 mode measurement setup

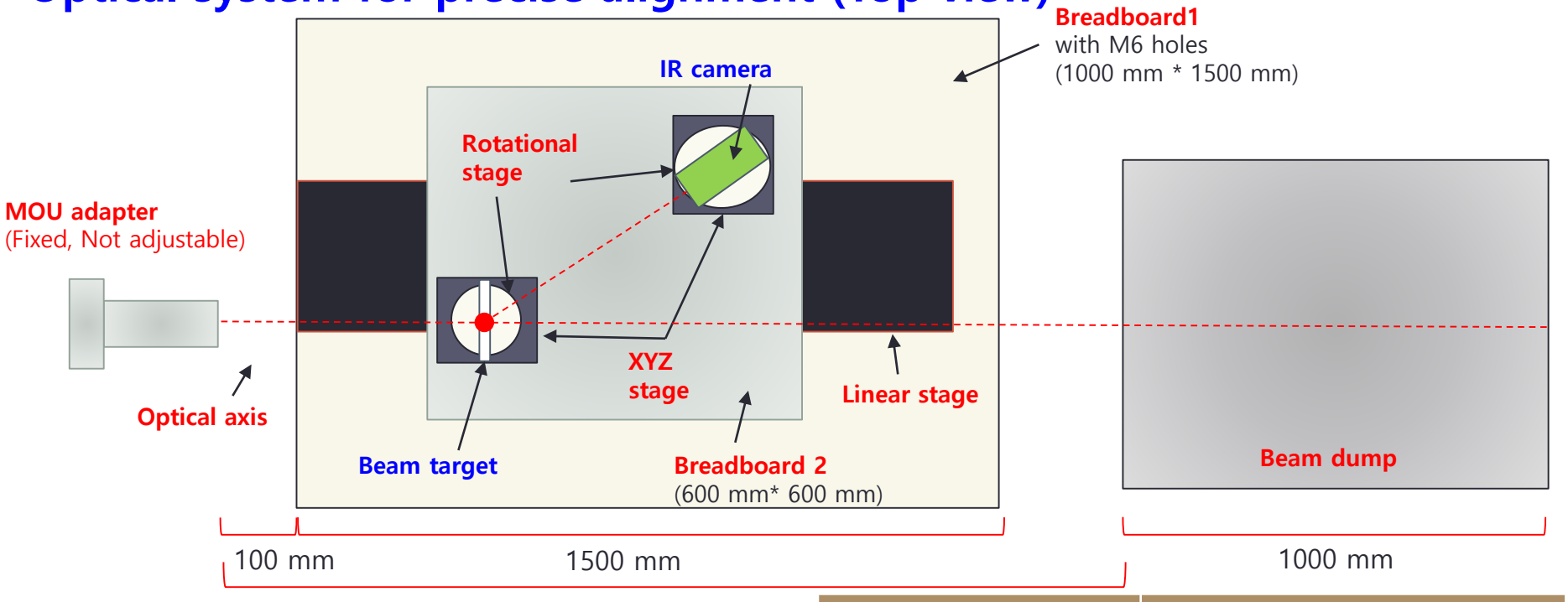
Schematic of HE11 mode measurement (Side view)



1. **Optical system with linear stage is configured for far field measurement.**
2. **Beam dump will be installed for safely beam dissipation (ITER safety regulation)**
3. **Frequency and RF signal are monitored through coupling hole in Beam dump.**
4. **Beam pattern by Infrared (IR) camera is analyzed by homemade code (Phase retrieval, mode contents)**

Beam quality test : HE11 mode measurement setup

Optical system for precise alignment (Top view)



Metrology plan for alignment

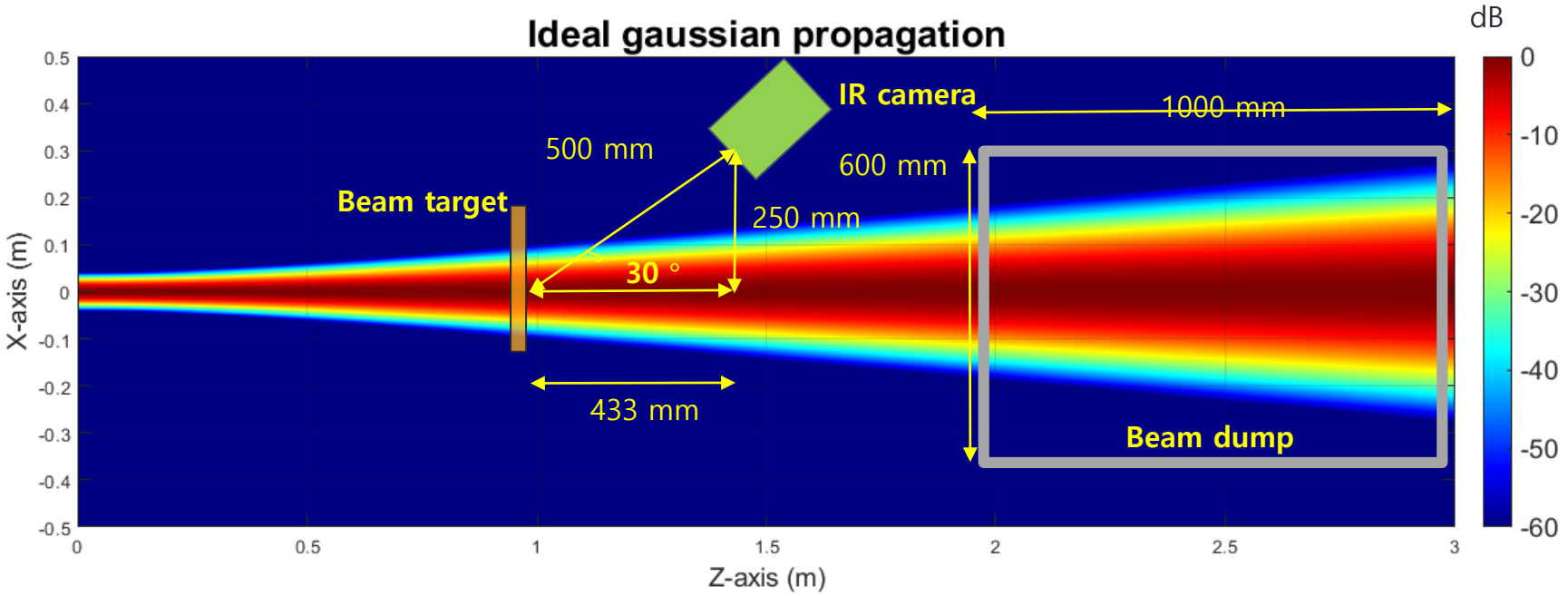
1. Parallel alignment of Breadboard 1 with optical axis using line laser (Generation of optical coordinate system).
2. Beam target and IR camera are positioned by tuning XYZ and rotational stages on Breadboard 2 (Micro tuning).
3. Breadboard 2 move on linear stage for far-field measurement (each 200 mm distance)
4. Measuring tilt and offset of beam target on every distance of far-field -> Re-alignment of optical components

Optical components	Tolerance
Linear stage	± 0.004 mm (Repeatability)
XYZ stage	± 0.01 mm
Rotation stage	± 0.5 °
Breadboard	± 0.5 mm

Tolerance between beam target and optical axis will be determined in engineering phase.

Beam quality test : HE11 mode measurement setup

Estimation of beam propagation in free-space for system setup



- Beam target, IR camera and beam dump are positioned based on theoretical beam propagation

Theoretical calculation of beam size in free-space

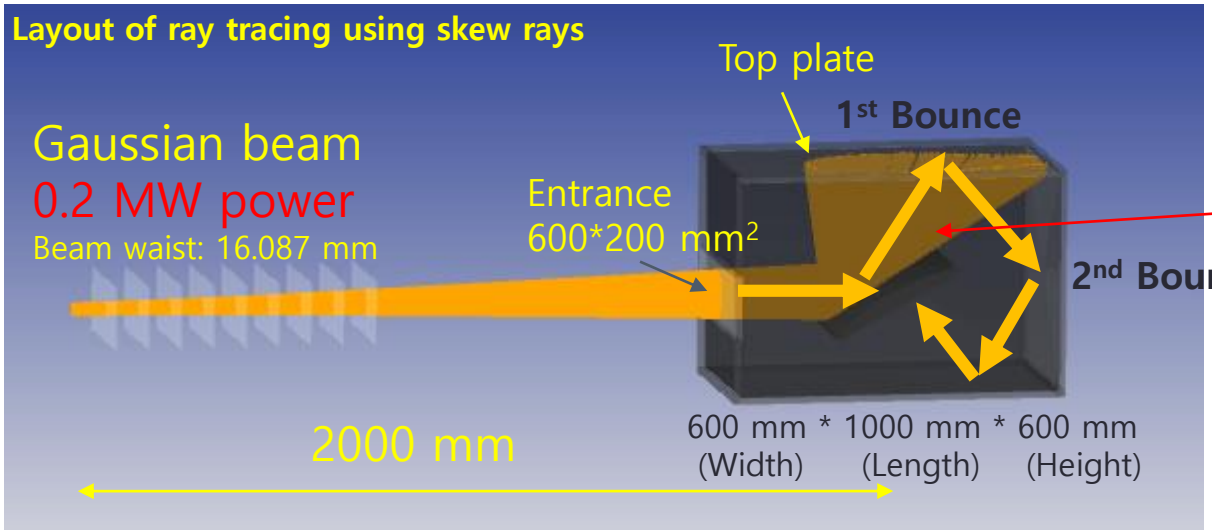
Distance [mm]	0	200	400	600	800	1000	2000 (at Beam dump)
Beam radius	16.087	17.535	21.298	26.402	32.218	38.422	71.615 mm
4 w (99.97 %)	64.35	70.143	85.192	105.611	128.872	153.69	286.462 mm

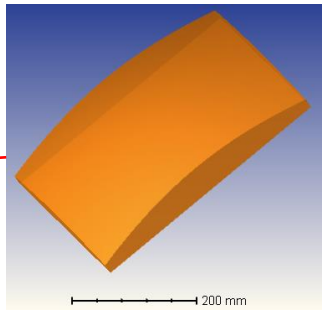
Conceptual design of Beam dump by Zemax® simulation

- Beam dump are required to dissipate EC beam for French safety regulation (ITER safety regulation) – **Exposure limits of RF in France : 0.5 mW/cm² (or 5 W/m²)**
- Enclosed type of metallic box having small entrance is conceptually designed
  Inner surfaces of the box are concealed by absorber (Eccosorb AN and PVC).

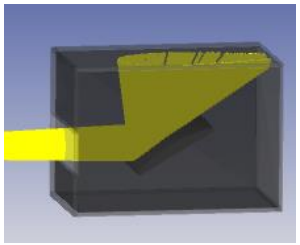
Absorber on Top plate: PVC (50% absorption) – Peak power density of beam on Top plate is too high

Absorbers on other plates (Left, Right, Front, Back and Bottom plates): Eccosorb AN (96% absorption)
(Microwave absorber)

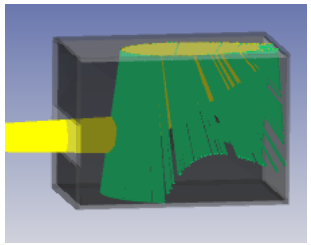




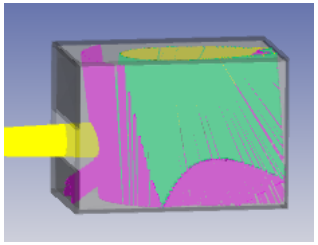
Reflection plate (Convex mirror)



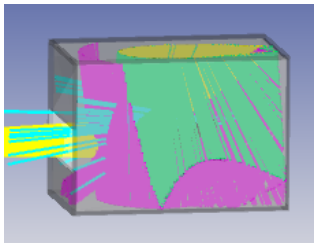
1st Bounce



2nd Bounce



3rd Bounce



4th Bounce

Peak power density of stray field at 30 cm distance from entrance : ~ 0.1 MW/m² (Exceed standard)

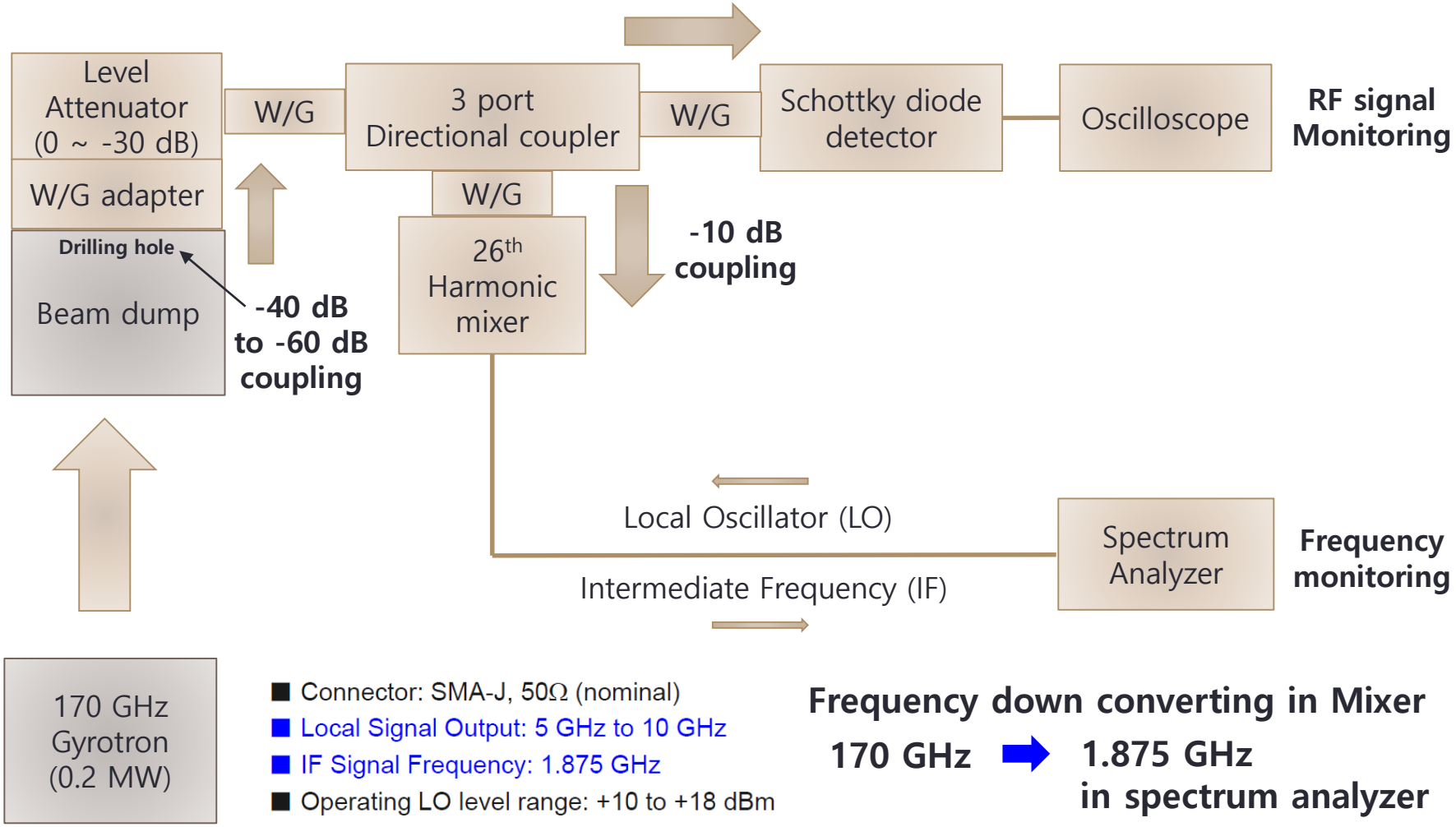
Stray power escaping from entrance of beam dump : 9.88 kW

~ 95% power absorption
Optimization is required

RF signal and frequency monitoring system

- Abnormal EC Beam can be estimated by RF signal level and frequency shift

Schematic of frequency and RF signal monitoring system



Specification of IR camera

- IR camera detect heat diffusion by absorption of EC beam in beam target
- IR image can be analyzed as EC beam pattern -> Raw data for beam analysis

IR camera

General specification of IR camera	
Model	NoxCam 640HSi BBMW
Resolution	640 × 512 pixels
Thermal sensitivity of the sensor	≤ 22 mK
Focal length of Lens	25 mm
Pixel width(@D=50 cm)	0.3 mm
Maximum size of IR image	19.2 cm * 15.4 cm
Size of IR image for beam analysis	15 cm * 15 cm

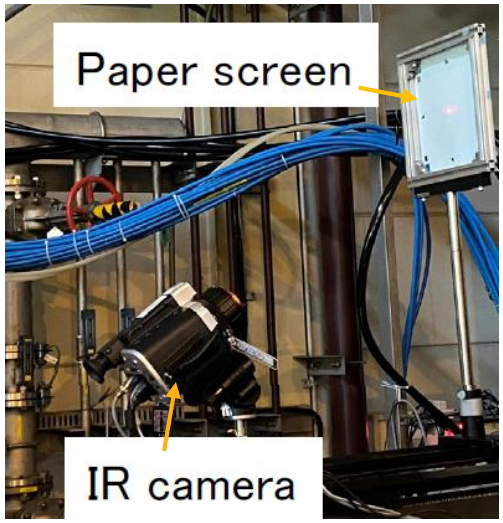
Distance Camera to Target	25mm Lens	1m	0,65m	0,50m
	50mm Lens	2m	1,3m	1m
Observed Scene		**38,4cm x 30,7cm**	**25cm x 20cm**	**19,2cm x 15,4cm**
Spatial Resolution		**0.6mm / pixel**	**0.39mm / pixel**	**0,3**
Distance Target to Gun (cm)	Beam diameter (mm)	Beam size on the target (pixels)		
40	85.04	**142**	**218**	**283**
60	105.48	**176**	**270**	**352**
80	128.8	**215**	**330**	**429**
100	153.4	**256**	**393**	**511**

Beam target for IR pattern measurement

Table for materials of beam target

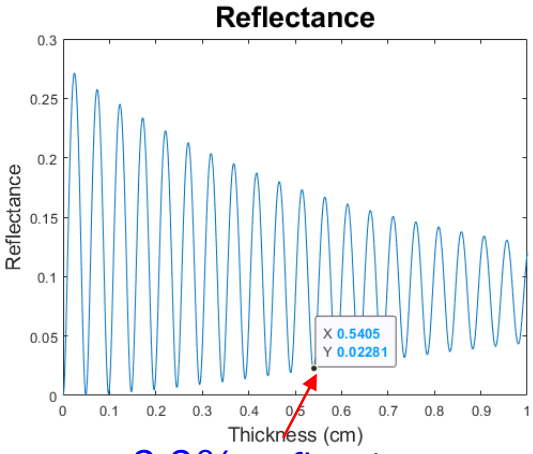
Material	Thickness [mm]	Dielectric constant	Loss tangent	Reflection
Paper (Primary)	0.05 ~ 0.1	3 ~ 4	N/A	N/A
Liquid crystal paper (LCP)	0.1778	N/A	N/A	N/A
PVC (Secondary)	5.4	3.234	0.011	2.2 %
ROBAX	4.1	7.8	0.019	18 %

*Paper is validated as material of beam target in QST.
It is easy to burn and no information of properties in microwave

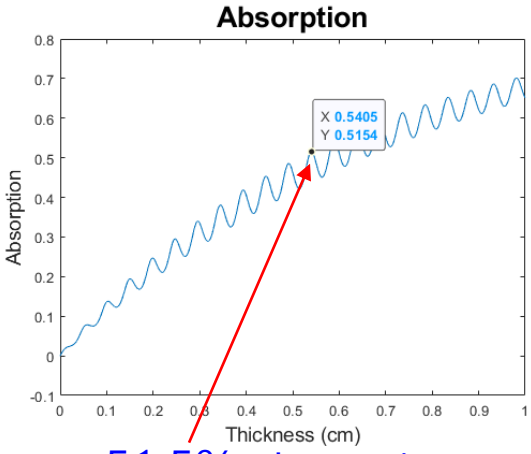


HE11 measurement in QST

PVC properties at 170 GHz microwave



2.2% reflection



51.5% absorption

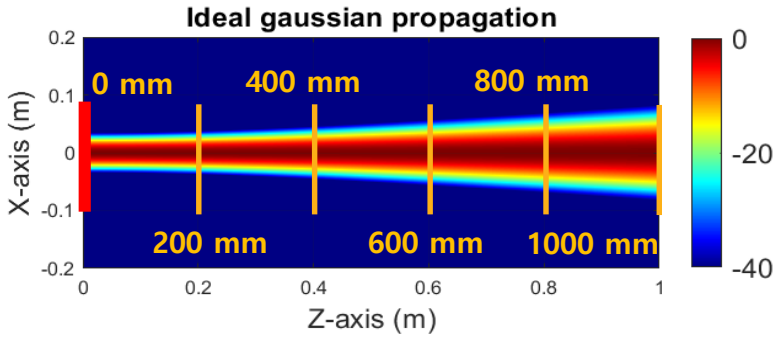
1. **Primary material for beam target : Paper**
2. **Alternative materials: PVC and LCP**

Properties of PVC can be estimated by theoretical calculation. it have small reflection (2.2 %) with high absorption (51.5%) but heat resistance is low. (< 65°C)

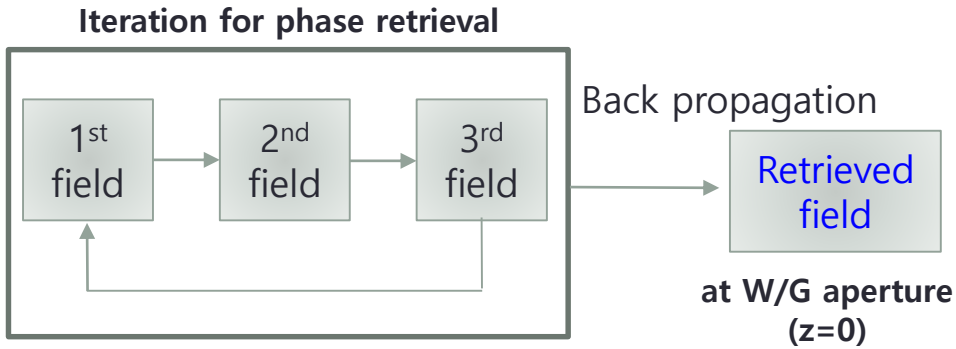
***PVC can be easily melted during beam test**

EC Beam analysis: HE11 mode and Higher order modes (HOMs) analysis

Far field measurement by IR camera



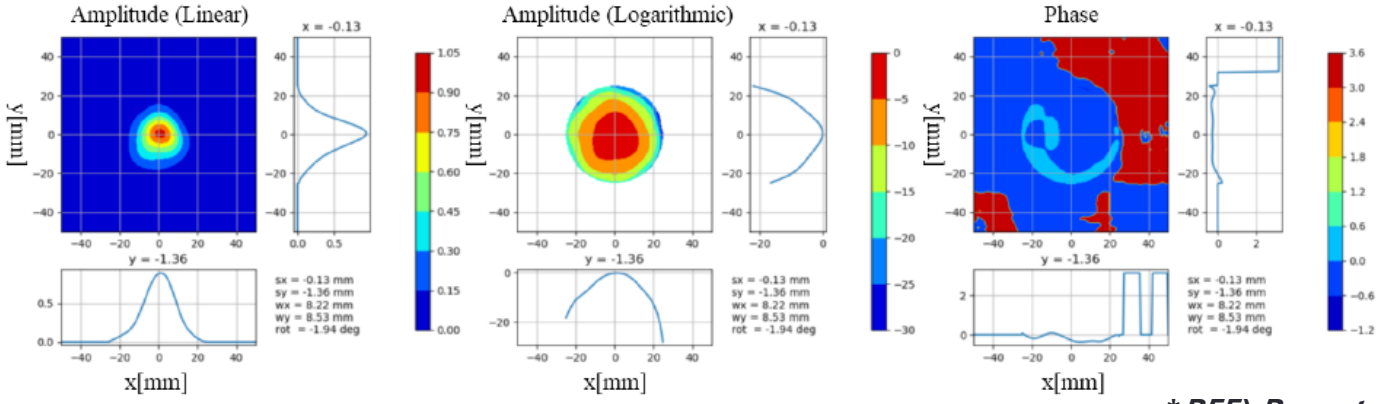
Phase retrieval technique
(Rayleigh Somerfield Diffraction Integral, RSDI)



- Far field data will be analyzed to estimate the field at 0 mm (at aperture of MOU Adapter)

- Homemade code have been developed in ITER
*Support from Dr. Sudheer Jawla in MIT Group

Reference data from QST (Phase retrieval data of JA-DA Gyrotron)



Retrieved field of JA-DA Gyrotron
by phase retrieval technique (QST analysis)

*REF) Report of MOU revision and Renovation of RF test facility with 50mm waveguide system, JADA (2020)

EC Beam analysis: HE11 mode and Higher order modes (HOMs) analysis

Mode contents
(Irradiance moment technique)

List of HOMs	Physical parameter
1. LP01 (HE11)	1. Tilt/offset (LP11e and LPE11o)
2. LP11e	2. Beam radius (LP02 and LP03)
3. LP11o	
4. LP02	
5. LP03	
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.	
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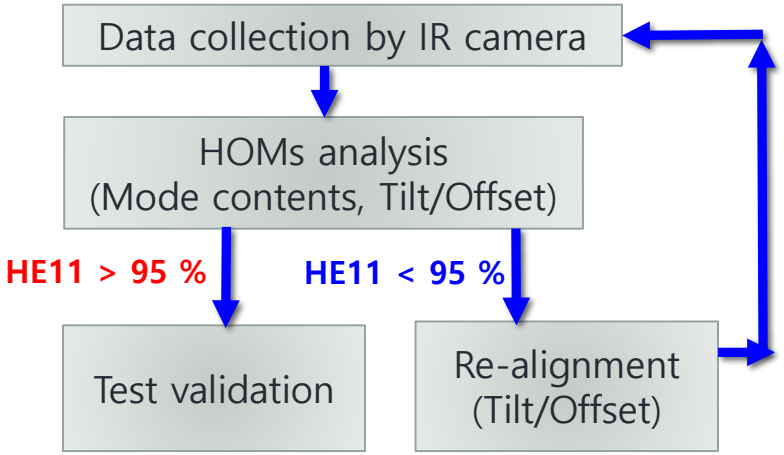
Homemade code have been developed in ITER

Strategy for suppression of HOMs

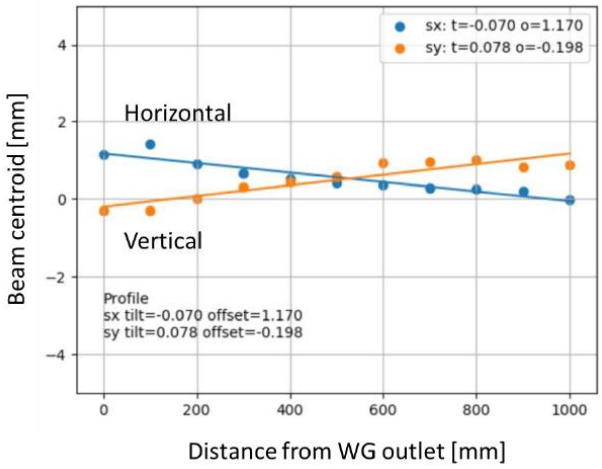


Reference data from QST (HOMs analysis of JA-DA Gyrotron)

Mode contents

Mode	Measure	Design
LP01 (HE11)	95.63 %	96.07 %
LP02	0.26 %	0.78 %
LP11(odd)	1.34 %	0.05 %
LP11(even)	0.45 %	0.19 %
LP12(odd)	0.31 %	0.03 %
LP12(even)	0.32 %	0.28 %

Tilt and offset



Horizontal tilt: -0.07°
Horizontal offset: 1.2 mm
Vertical tilt: 0.08 °
Vertical offset: -0.2 mm

**REF) Report of MOU revision and Renovation of RF test facility with 50mm waveguide system, JADA (2020)*

EC Beam analysis: HE11 mode and Higher order modes (HOMs) analysis

Homemade code benchmark

- Homemade code for EC beam analysis have been developed in ITER Organization
- The code is being benchmarking based on DA's analysis below the tables
- However, Beam analysis are different among each of DA's (Need to discuss with DA's)

JAEA Beam (TL output)	IAP analysis	JAEA analysis	KIT analysis	MIT analysis	ITER analysis
Mode content evaluated at Z =	0	0	-	0	0
TEM_{00} content (amplitude)	-	99.1 %	-	98.5 %	99.5 %
TEM_{00} content (complex field)	-	97.1 %	-	95.2 %	91.99 %
Beam radius (x-y) mm	-	23.6 – 23.8	-	21.4 – 23.1	21.95 - 22.18
HE_{11} content	96.41 %	96.7 %	-	95.6 %	88.27 %
MIT Beam (Gyrotron)	**IAP analysis**	**JAEA analysis**	**KIT analysis**	**MIT analysis**	**ITER analysis**
Mode content evaluated @ Z =	790	0	995	0	0
TEM_{00} content (amplitude)	98.84 %	98 %	97.02 %	97.3 %	TBD
TEM_{00} content (complex field)	97.54 %	95 %	94.12 %	96.0 %	TBD
Beam radius (x-y) mm	40.28 – 44.39	29 - 33	48.52 – 42.42	27 - 31	22.71 – 19.3
HE_{11} content	-	-	-	-	-
KIT Beam (Gyrotron + MOU)	**IAP analysis**	**JAEA analysis**	**KIT analysis**	**MIT analysis**	**ITER analysis**
Mode content evaluated @ Z =	860	560	?	0	560
TEM_{00} content (amplitude)	95.70 %	92 %	93~94 %	96.5 %	98.51 %
TEM_{00} content (complex field)	94.30 %	87 % (*)	-	-	81.12 %
Beam radius (x-y) mm	22.81 – 29.67	30 - 36	-	33.8 – 28.5	50.4 – 36.94
HE_{11} content	-	-	-	-	-
IAP Beam (Gyrotron + MOU)	**IAP analysis**	**JAEA analysis**	**KIT analysis**	**MIT analysis**	**ITER analysis**
Mode content evaluated @ Z =	362	0	62	0	TBD
TEM_{00} content (amplitude)	99.21 %	97.80 %	86.13 %	-	TBD
TEM_{00} content (complex field)	98.31 %	93.50 %	-	-	TBD
Beam radius (x-y) mm	19.95 – 24.32	23.4 – 23.5	31.16 – 29.91	20.32 – 19.08	TBD
HE_{11} content	-	94.7 %	-	94.5 %	TBD

Conclusion

1. **Prototype of HE11 mode measurement setup is designed for Gyrotron SAT.**
   - It will be finalized in engineering phase.

2. **The beam dump is conceptually designed by ZEMAX® simulation.**
   - It will be further optimized to satisfy the French safety regulation (0.5 mW/cm^2 at 30 cm distance from beam dump opening)

3. **ITER homemade code for EC beam analysis is being developed.**
   - First results have been compared with experimental data in DA's and several inconsistencies are detected because of the differences in the theoretical methods. Additional work is required if this code is used during Gyrotron SAT

Thank you