Development of high power gyrotron and mm-wave launching antenna for ITER and JT-60SA

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Japan Atomic Energy Agency

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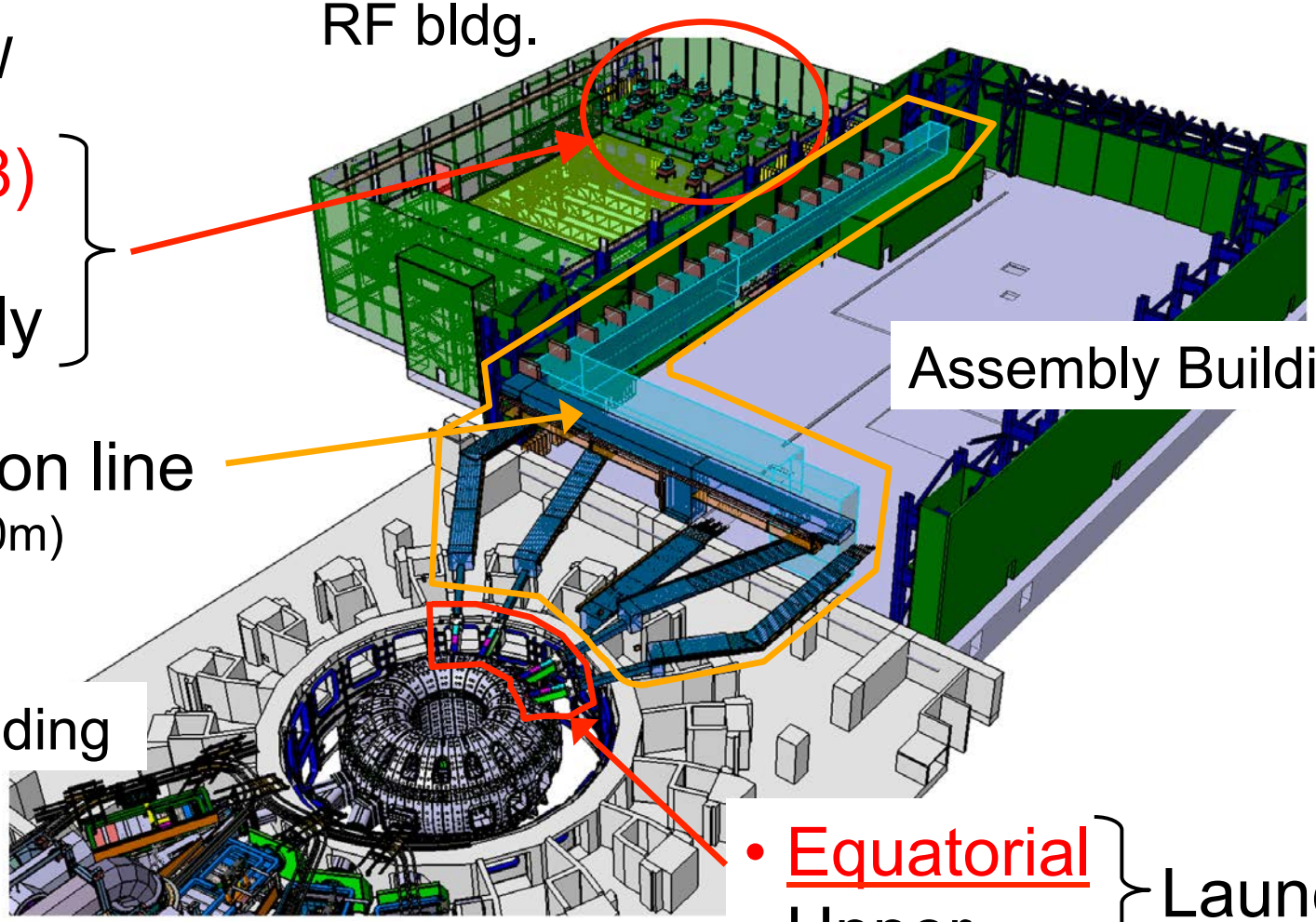
Outline

- Introduction of ITER EC System
- Development of ITER Gyrotron
- Design of ITER Equatorial Launcher
- Development of JT-60SA EC System
- Summary/Outlook

ITER EC H&CD System

- 170GHz
- 20MW/CW
- 1~5kHz

Gyrotrons (8)
&
Power supply



Transmission line
(150~170m)

- Equatorial
- Upper

Launcher

- Introduction of ITER EC System
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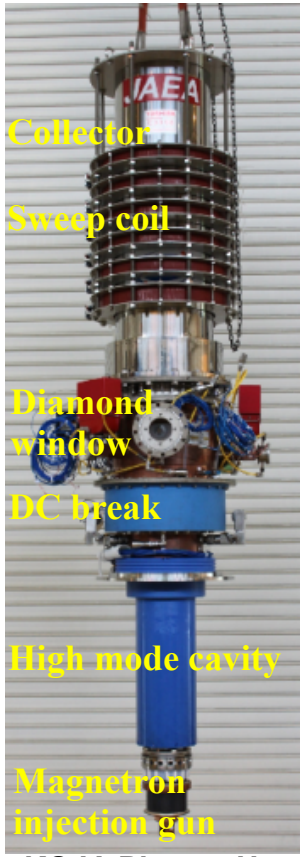
Design specification for JA gyrotron procurement

- ✧ 1MW operation of $TE_{31,8}$ gyorotron was marginal due to the heat load, 2.0 kW/cm^2 at a cavity resonator.
- ✧ To achieve safely and stably more than 1MW, higher mode gyrotrons are under development.



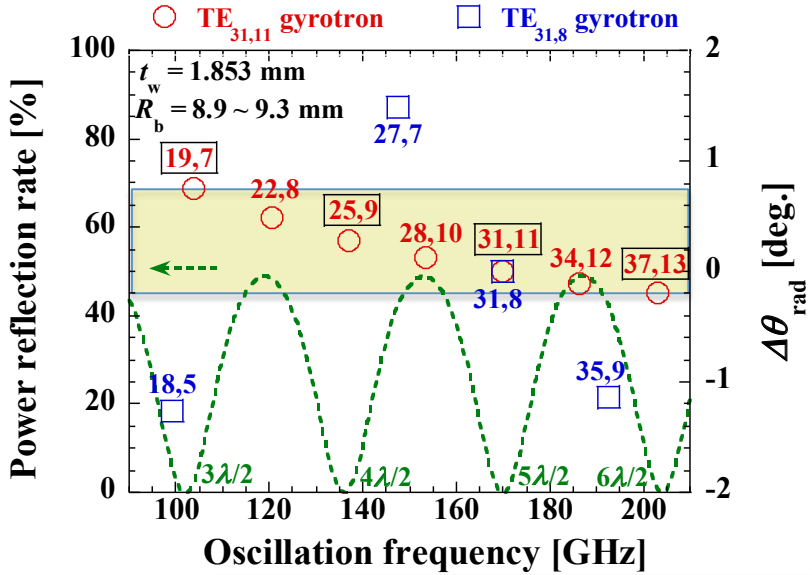
Mode	$TE_{31,8}$	$TE_{31,9}$	$TE_{31,11}$
Cavity	R_c = 17.90 mm 2.0 kW/cm^2	R_c = 18.89 mm 1.6 kW/cm^2	R_c = 20.87 mm 1.4 kW/cm^2
Triode MIG	R_e = 46.5 mm	same	same
Beam radius	R_b = 9.13 mm	same	same
Diamond window	D_w = 82 mm t_w = 1.853 mm	same	same
Size	3m / 800 kg	same	same
Remark	1MW/55%/800s 0.8MW/57%/1h 5 kHz modulation	1.2 MW CW	1.5 MW CW Multi-frequency

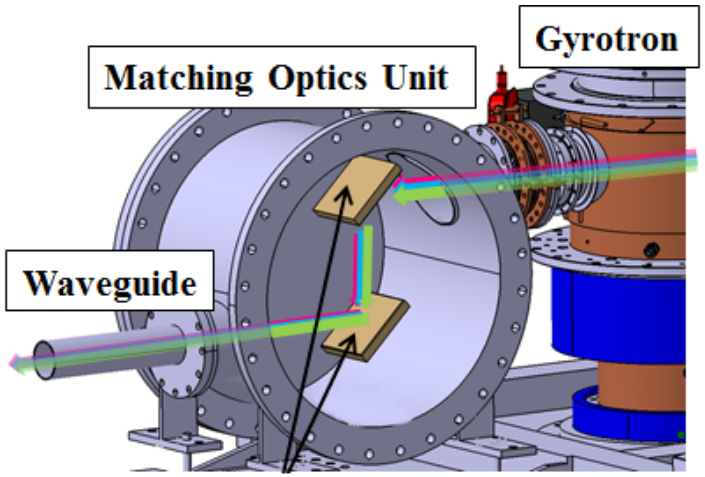
Possibility of multi-frequency oscillation

- with $TE_{31,11}$ gyrotron for ITER -

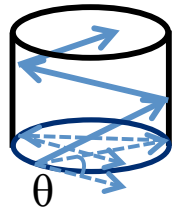
- Oscillation mode within selectable beam radius
- Radiation angle of modes ≤ 1°
  → Beam at each mode is radiated at ~same direction.
- No reflection at window for each modes

$$\Delta\theta_{\mathrm{rad}} = N_{\mathrm{r}}\left(\cos^{-1}\left(\frac{m_{\mathrm{main}}}{\chi_{m,n\,\mathrm{main}}}\right) - \cos^{-1}\left(\frac{m_{\mathrm{sub}}}{\chi_{m,n\,\mathrm{sub}}}\right)\right)$$



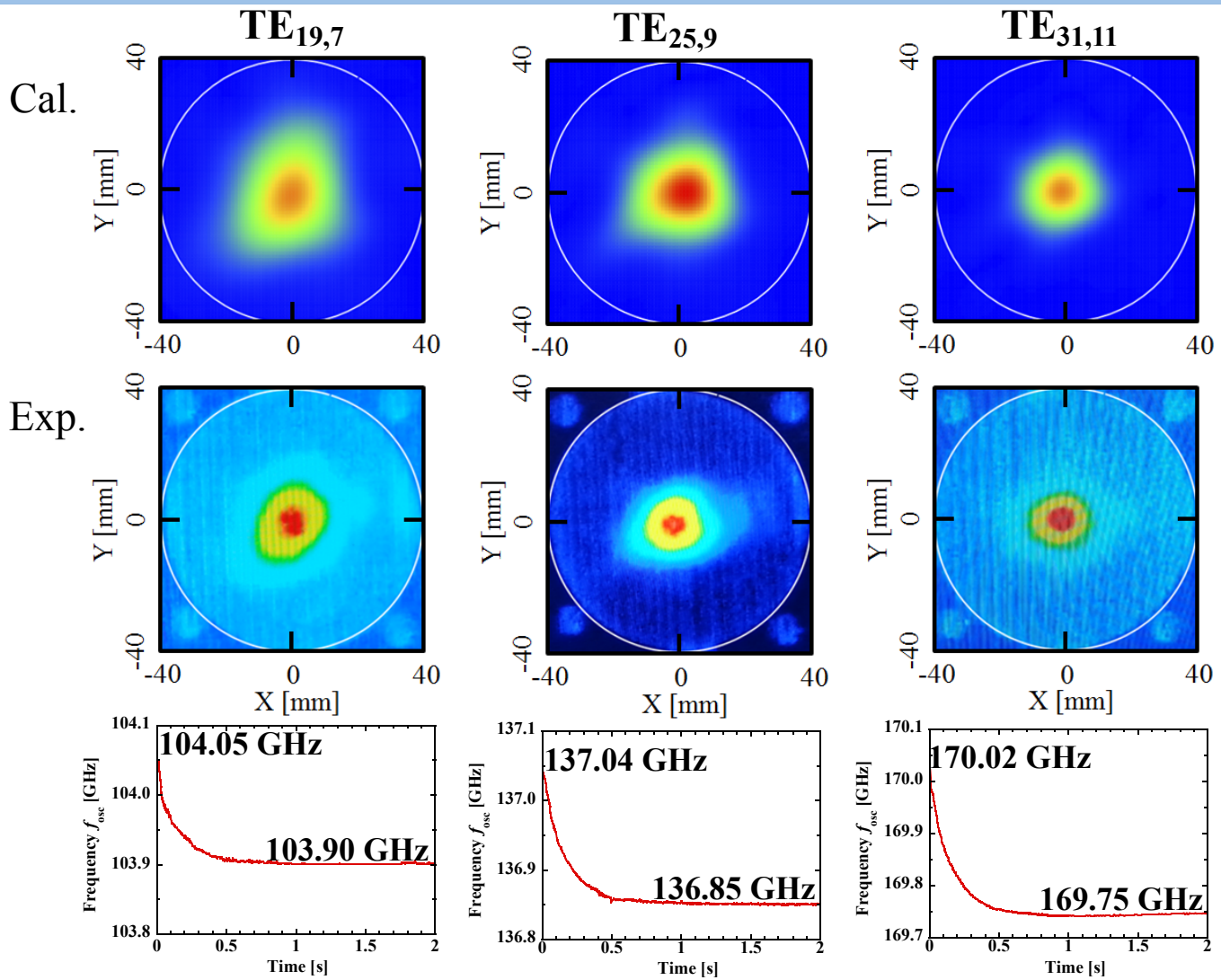


Same angle / position for each frequency



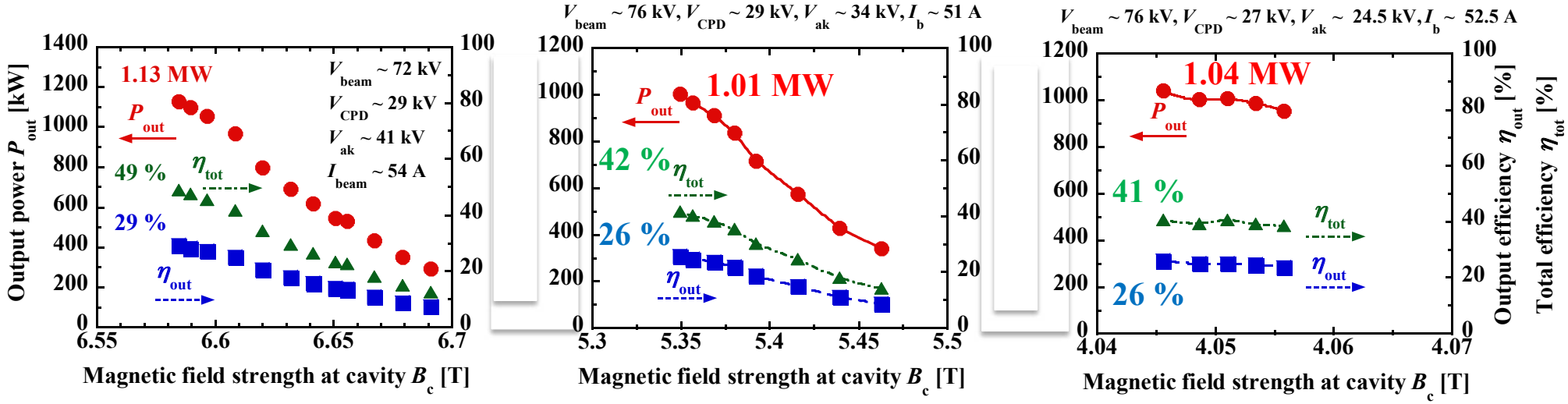
Cavity mode	$TE_{19,7}$	$TE_{25,9}$	$TE_{31,11}$	$TE_{37,13}$
Frequency	104 GHz	137 GHz	170 GHz	203 GHz
Cavity field	4.08 T	5.32 T	6.63 T	7.98 T
Gun field	0.172 T	0.21 T	0.28 T	0.31 T
Beam radius	9.25 mm	9.19 mm	9.13 mm	9.10 mm

Radiation profile at each modes



✧ Measured radiation patterns were agreed with calculation results.

Oscillation tests at 3 frequencies



170GHz 137GHz 104GHz

- ✧ 1 MW output power for 3 frequencies demonstrated.
- ✧ Maximum output power of 1.24 MW (45 %) at 80 kV / 56 A.
- ✧ Oscillation of 1MW, 200sec was performed.

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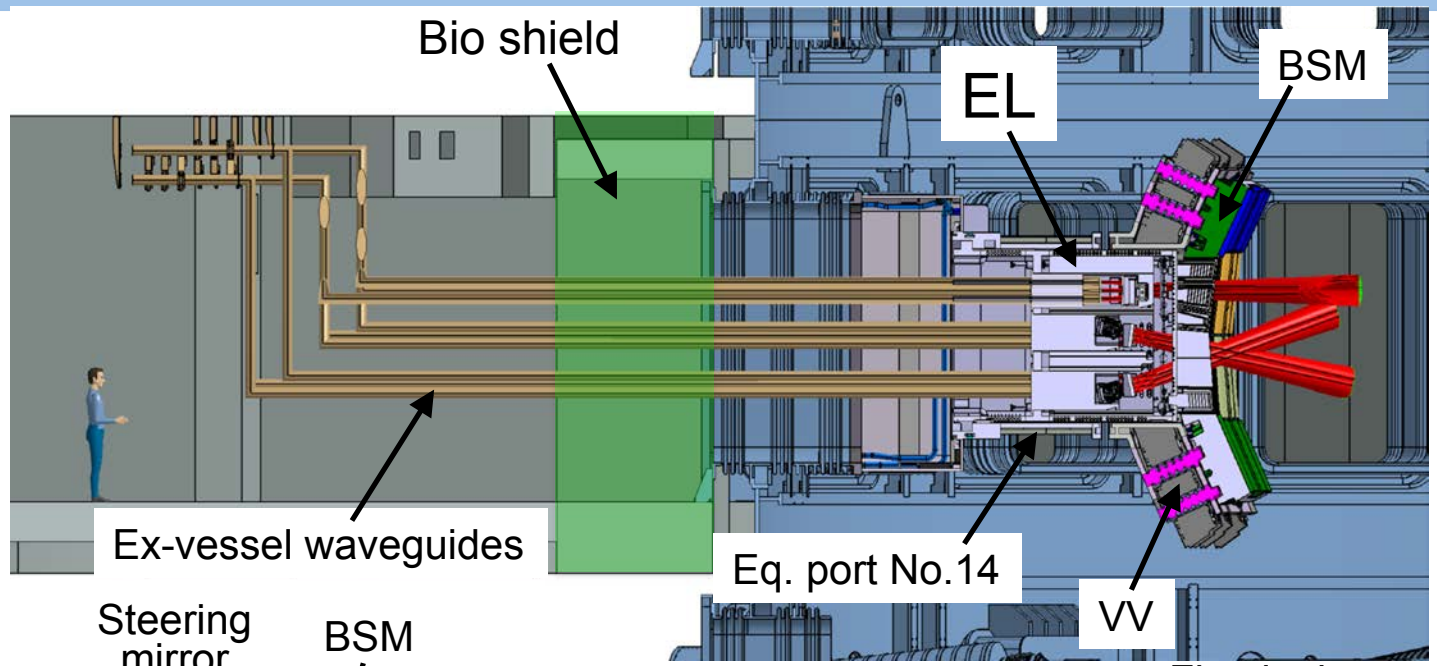
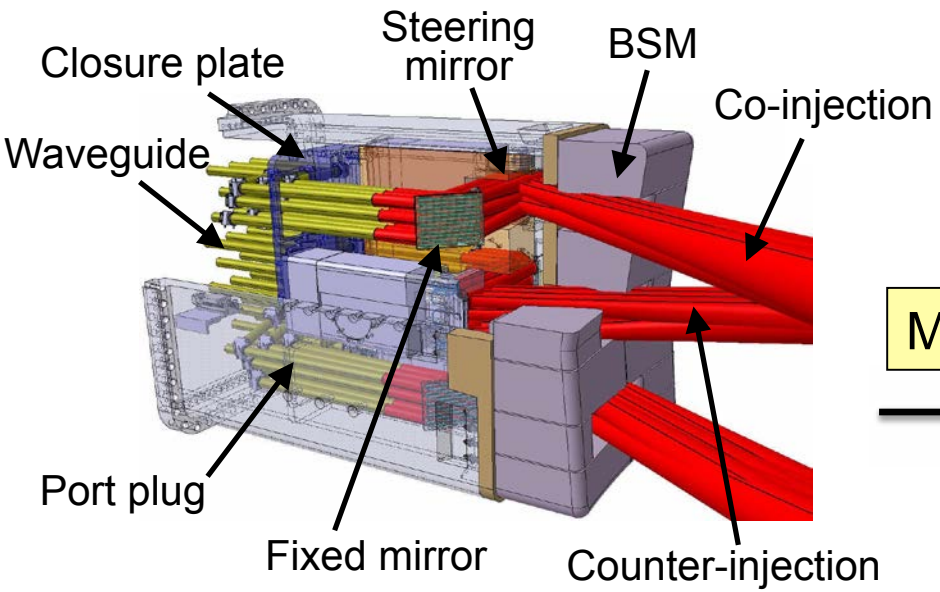
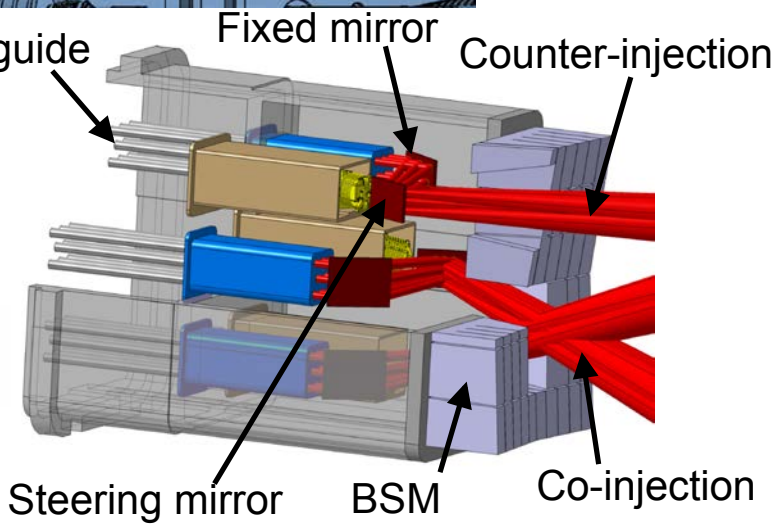
Equatorial Launcher(EL)





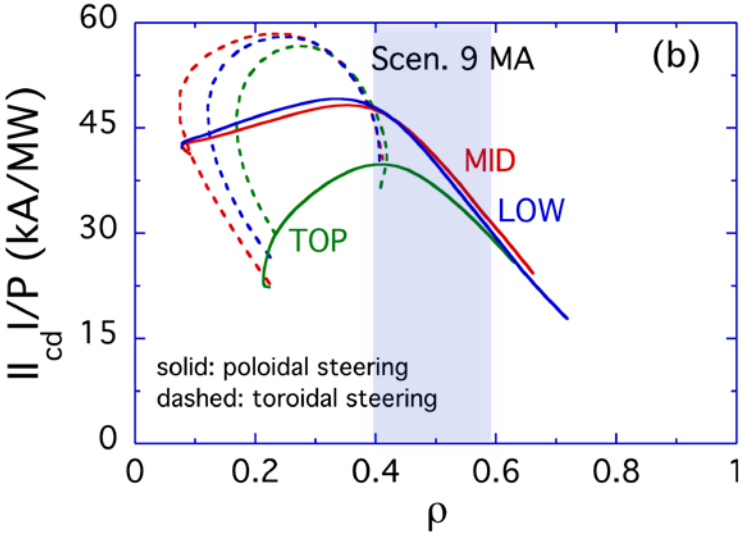
Modification



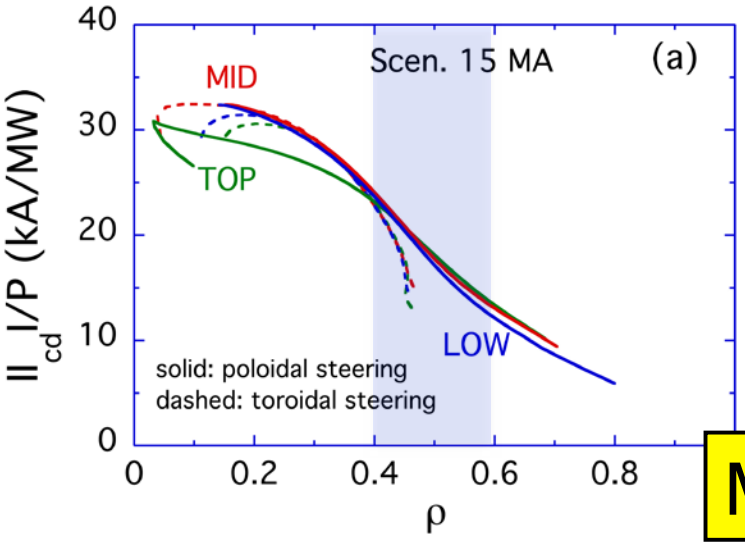
Design Change Request

- Enhancing driven current at peripheral region of plasma -

Non-inductive
weak negative
shear
Ip = 9 MA



Inductive
500MW, Q=10
Ip = 15 MA



D. Falina et al., Phys Plasmas 21 (2014) 061504.

Toroidal steering

- 15MA : 350/240kA (ρ=0.4/0.45)
- 9MA : 640kA (ρ=0.4)
- Beam can reach.
  ρ>0.4(9MA) and ρ>0.45(15MA)

Change of steering direction

Poloidal steering

- 15MA : 350/240/200kA
  (ρ=0.4/0.5/0.6)
- 9MA : 640/530/430kA
  (ρ=0.4/0.5/0.6)

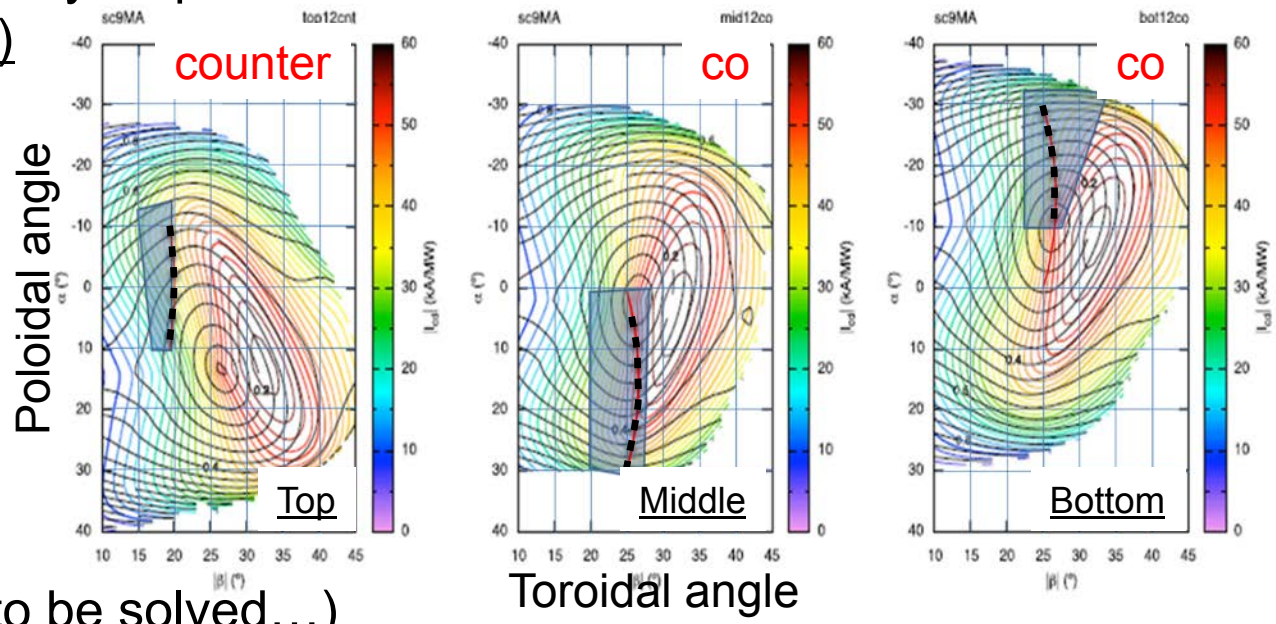
More driven current at edge !

EL Design Requirements / Issues

- Current baseline -

Millimeter wave transmission

- 170GHz, 20MW injection in total (However, 1.5MW/1line for future upgrade)
- As low heat load as possible
  Max peak HL on M1/M2 ~ 5.0 MW/m^2 / ~ 3.0 MW/m^2
- As high transmission efficiency as possible : 99 %
- Poloidal steering (modified)
  Top : -10º ~ +10º, counter
  Mid.: -5º ~ -30º, co
  Bot. : 10º ~ 30º, co



Structural integrity

- Electromagnetic force
- Thermo-mechanical
- Seismic vibration

Nuclear shielding (Issue to be solved…)

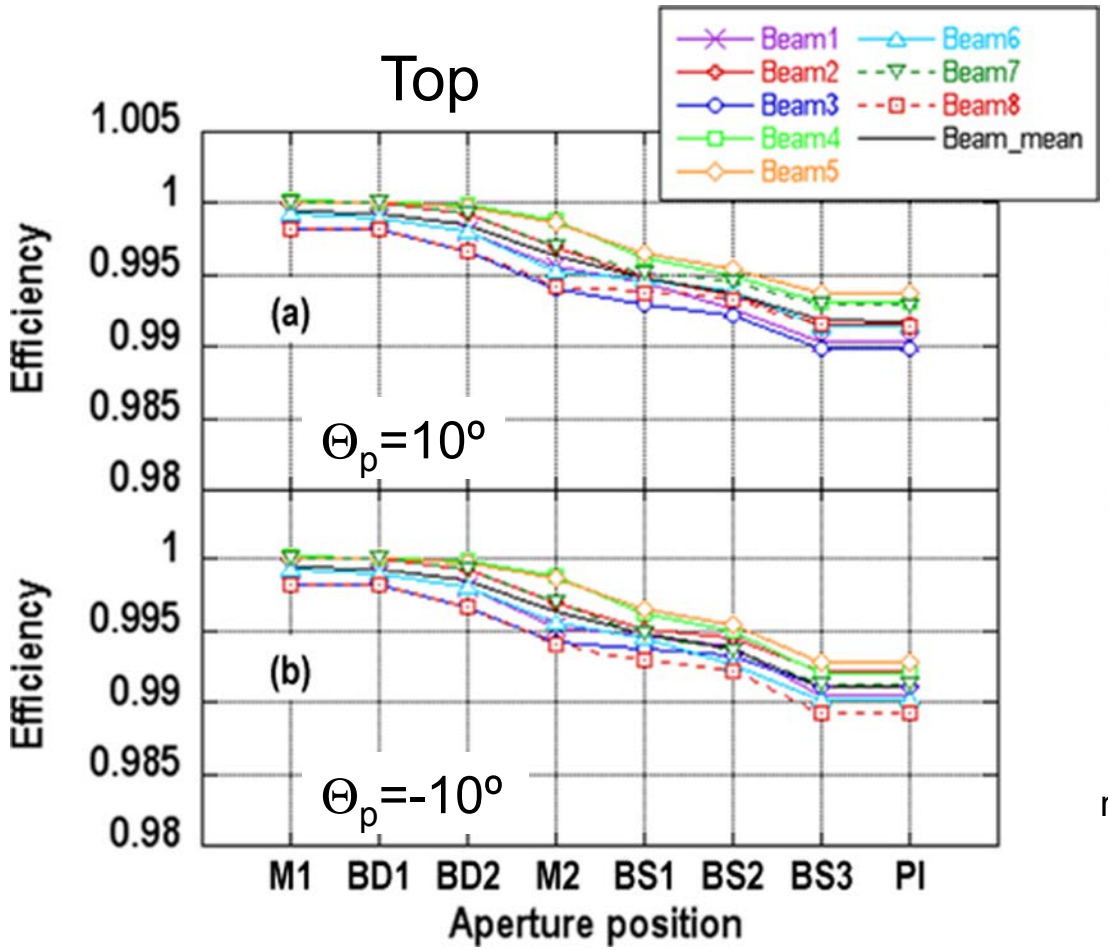
- Nuclear heating for coils
- Shut down dose rate at the rear region of EL : ≤100 μSv/h

MM-Wave Design output 1

- Transmission efficiency -

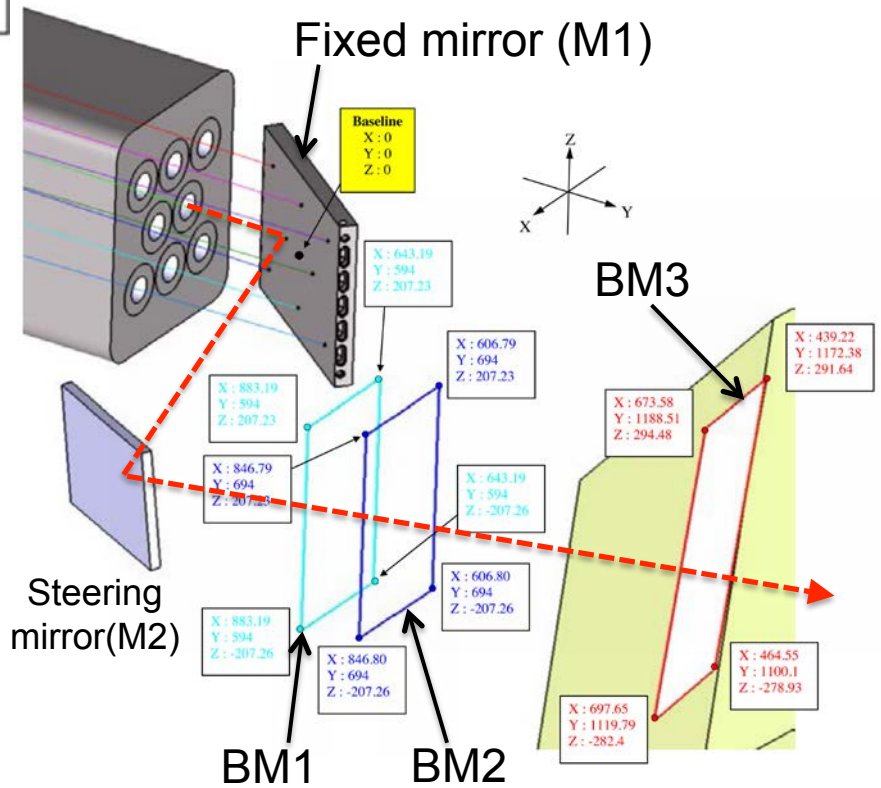
Transmission Efficiency

(Waveguide outlet – BSM outlet)



Initial condition

- Pure HE_{11} mode
- Waveguide – M1 : 500 mm
- M1 size : ≥(h)360mm x ≥(w)420mm
- M2 size : ≥(h)240mm x ≥(w)360mm
- BM size : showing in previous page



MM-Wave Design output 2

- Heat load on mirrors & Beam size @ plasma, pure HE_{11} -

Optimized parameters (Top)

Mirror shape : Curved surface

M1 size : (h)365 mm x (w)460 mm

M2 size : (h)250 mm x (w)360 mm

M1 : R_{M1x} 11.64 m, R_{M1y} 2.15 m

M2 : R_{M1x} 20.50 m, R_{M1y} -3.3 9m

Waveguide installation :

M1 - Waveguide outlet : 500 mm

Angle : Θ_- 1.39º, Θ_+ 1.53º

BSM opening :

BM1 : (h)415 mm x (w)240 mm

BM2 : (h)415 mm x (w)240 mm

BM2 : (h)580 mm x (w)280 mm

Results of mm-waves (Top)

- Heat load on mirrors

M1/M2 : 4.95/3.0 MW/m^2

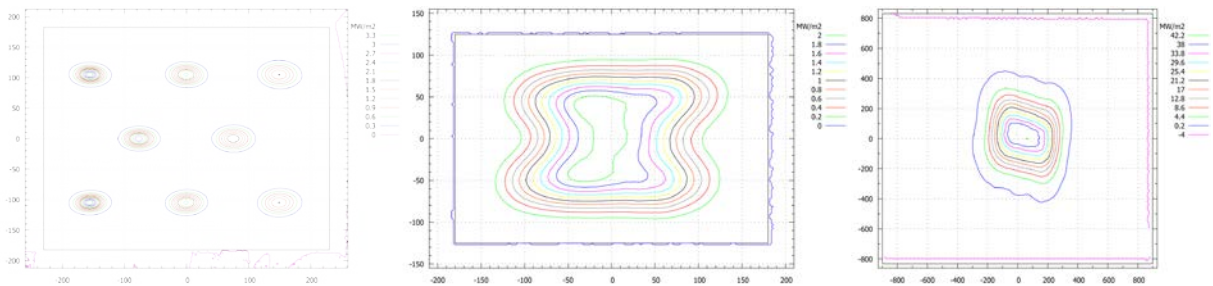
(Transmission power/line : 1.5MW)

- Trans. efficiency : ~ 99%

(pure HE_{11} mode)

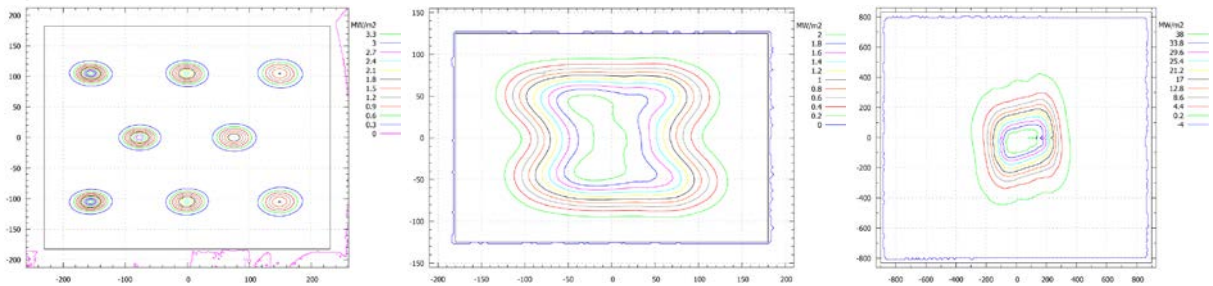
- Beam radius : ~25 cm

Θ_p=10º



Fixed mirror (M1) | Steering mirror (M2) | Plasma

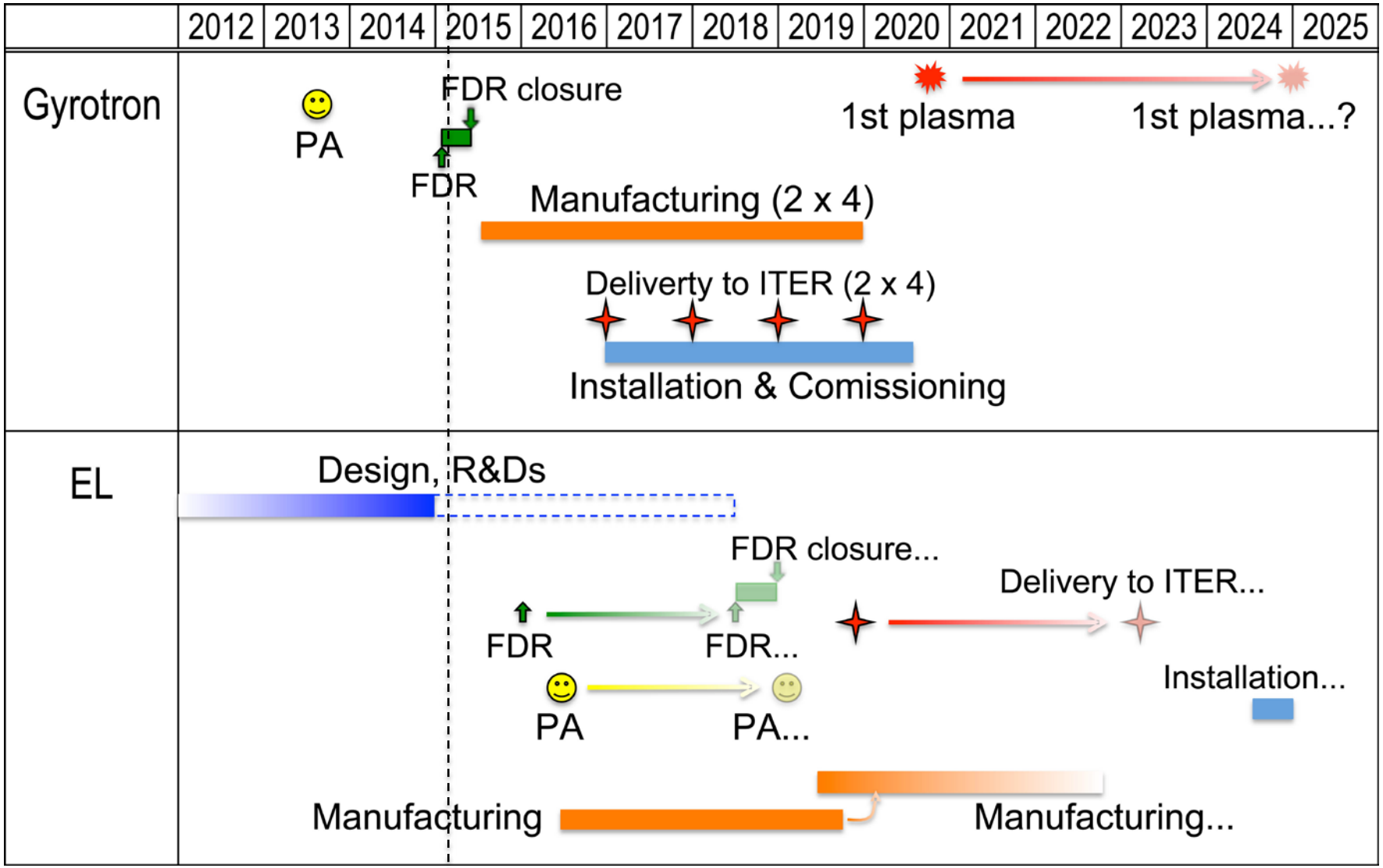
Θ_p=-10º



Fixed mirror (M1) | Steering mirror (M2) | Plasma

Distribution of heat load(M1/2) and power density, MW/m^2

Schedules


2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
Gyrotron
PA
FDR closure
FDR
1st plasma
1st plasma...?
Manufacturing (2 x 4)
Deliverty to ITER (2 x 4)
Installation & Comissioning
EL
Design, R&Ds
FDR closure...
Delivery to ITER...
FDR
FDR...
Installation...
PA
PA...
Manufacturing
Manufacturing...

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ECH system in JT-60SA

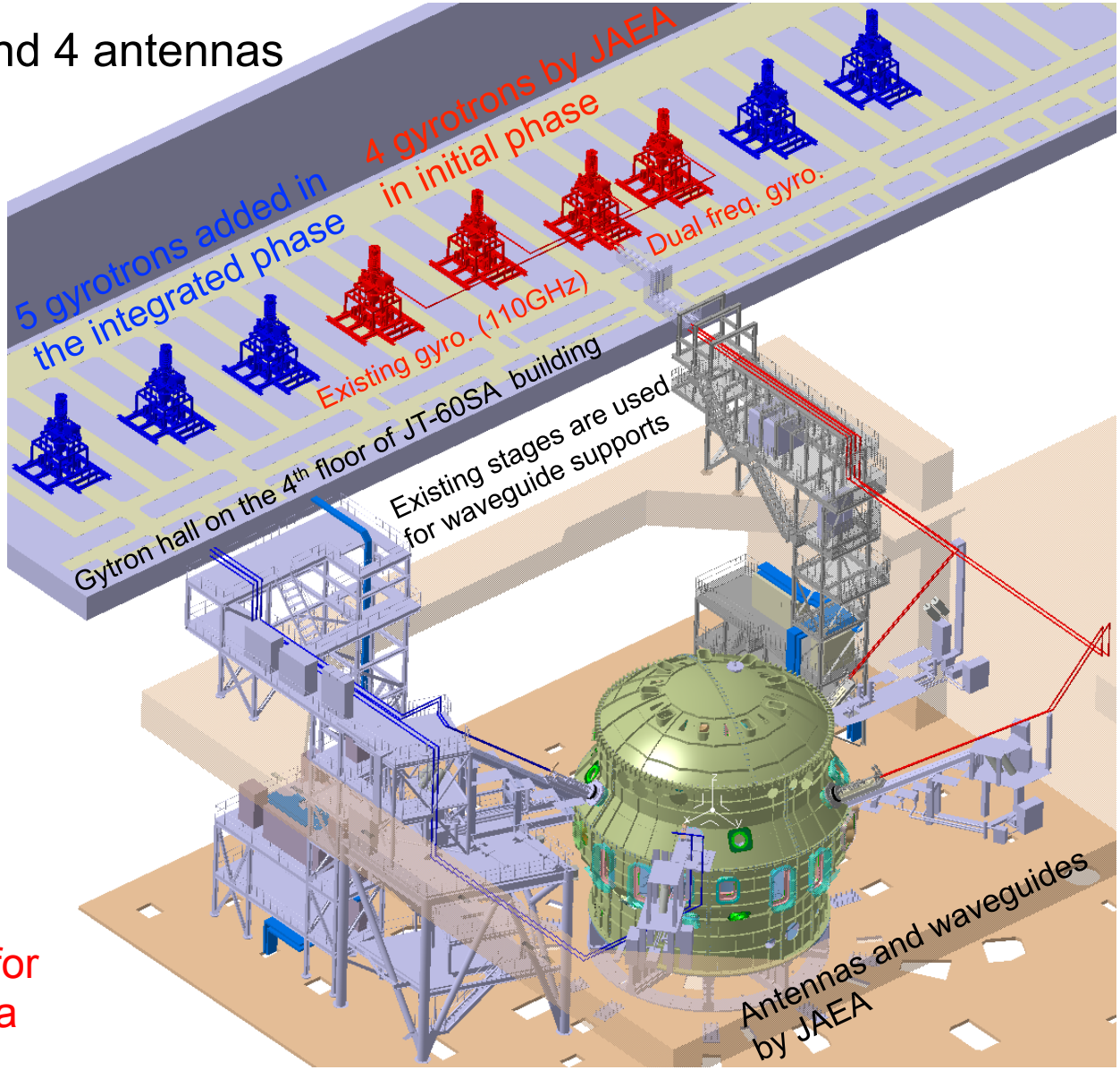
7MW injection by 9 gyrotrons and 4 antennas enables ECH/CD for 100s

Plan : 2-phase constuction
Initial : 4 sets of 1MW gyrotron
110GHz existing one and dual freq., 110 GHZ ($TE_{22,8}$) & 138 GHz ($TE_{27,10}$)

Integrated : 5 sets
Specification is TBD.

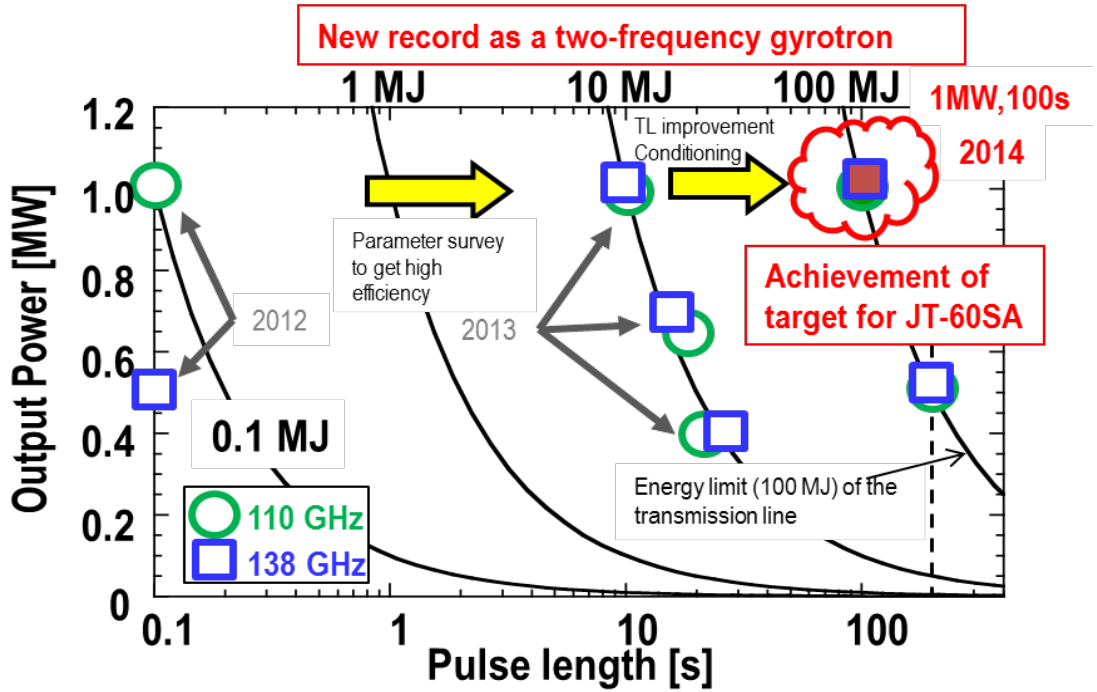
Purposes:
- Electron heating
- Current drive
- Instability control (particularly NTM)
- Plasma initiation
- Wall cleaning

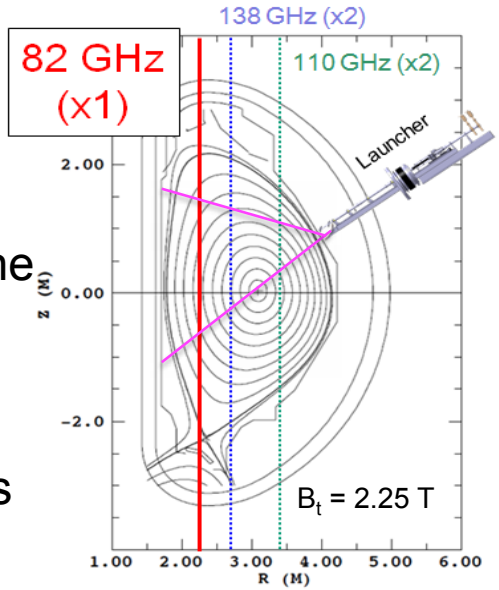
} Expected for first plasma



Gyrotron development for JT-60SA

The first **two-frequency gyrotron** (110 & 138GHz) has reached the development target of **1MW x 100s at both frequencies**.

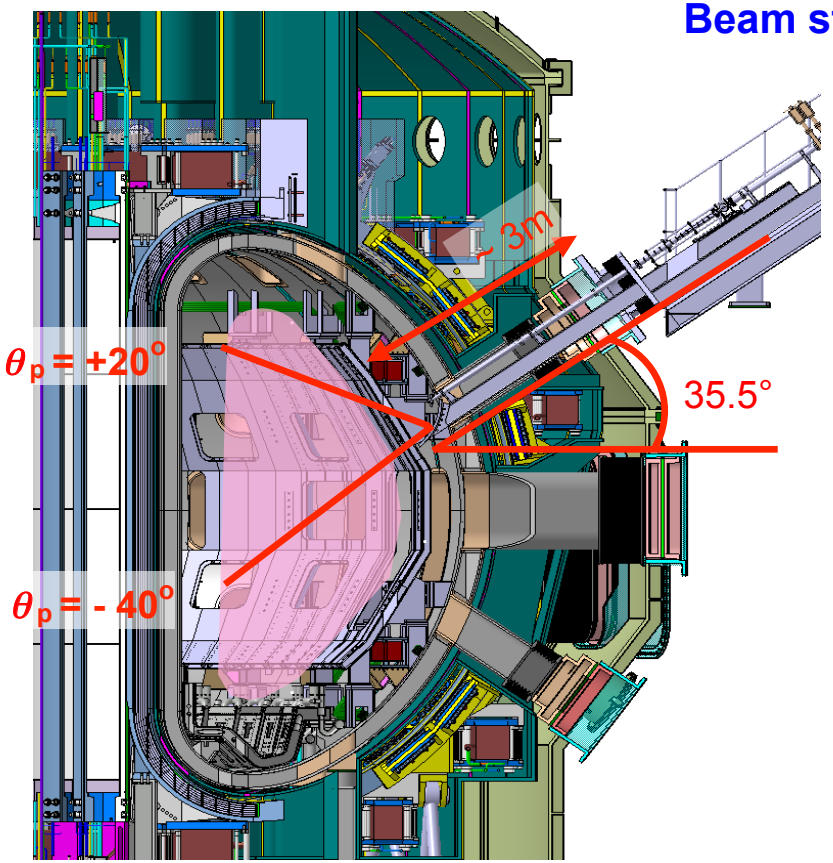




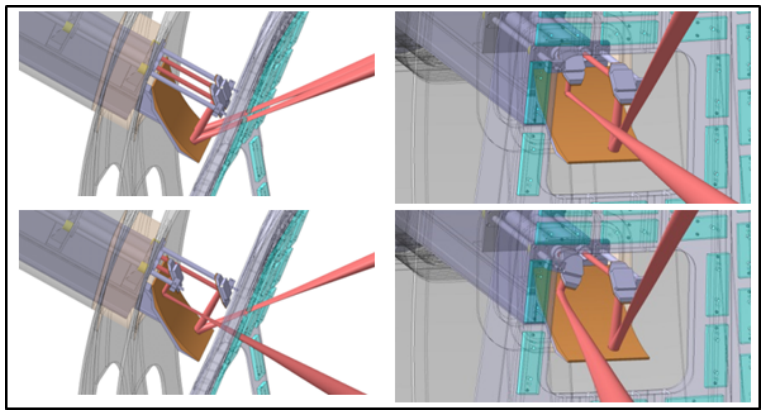
Oscillation at 82GHz (0.5MW,1s) was also confirmed with the two-frequency gyrotron.

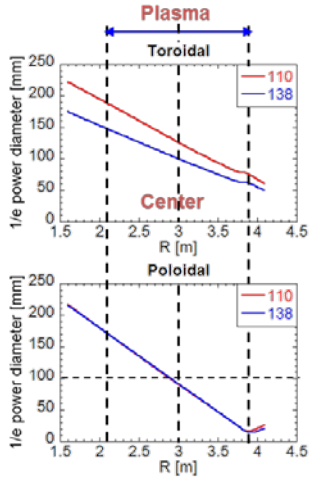
- applicable for start-up assist and wall cleaning at fundamental resonance
- Conditioning and parameter adjustment toward 1MW, 1s is planed.

Launcher development for JT-60SA



Beam steering in poloidal/toroidal directions





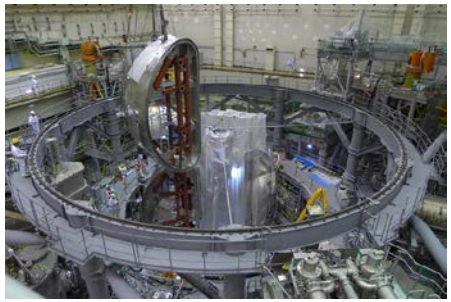
Parameters	Values
Port size	480 mm x 480 mm (at narrower duct) ~ 3 m (length)
Aperture size	706 mm x 659 mm (at stabilizing plate)
Port angle	35.5° (from horizontal plane)
Location (R,Z)	(4033, 869) (at aperture center)
Target range of beam direction	Poloidal (θ_p) -40° ~ +20° Toroidal (θ_t) -15° ~ +15°

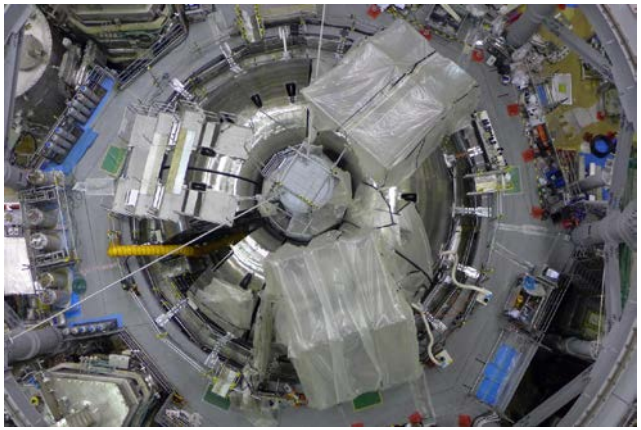
θ_p = -5° ~ +5° for NTM stabilization at q = 2 surface (ρ ~ 0.6)

θ_p = -35.5° ray goes to the plasma center

θ_t = +15° co-ECCD θ_t = 0° pure heating θ_t = -15° cntr-ECCD

JT-60SA manufacture and assembly going on schedule





Assembly started : Jan. 2013

340/360deg of VV was installed in Jan. 2015

First Plasma in Mar. 2019

Tokamak

Year	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Construction													Experiment	
Operation		Preparation		Disassembly				Assembly						
									Commissioning			Integrated Commissioning		

ECH system

Dual feq. gyrotron	1st gyrotron, Conditioning/test
Power Supply	
Antenna/Waveguide	Design/Development, Fabrication, Installation, test
Control system	

Summary / Outlook (ITER Gyrotron & EL)

Summary

1. Gyrotron

✧ $TE_{31,11}$ mode gyrotron with 1MW, multi-frequency oscillation was developed.
1.24 MW/45% (170 GHz), 1.01 MW/42% (137 GHz), 1.04 MW/41% (104 GHz)

✧ Operation of 1MW-200sec was demonstrated.

✧ TL experiment at 3 frequencies were demonstrated on ITER relevant TL.
Power transmission efficiency in 40 m TL :
94% (170 GHz), 95% (137 GHz), 94 % (104 GHz)

2. Equatorial EC Launcher

✧ MM-wave design modification
Optimum beam path is obtained under pure HE_{11} mode propagation.
Transmission efficiency : 99%, Peak heat load on M1/2 : 3.0/4.95 MW/m^2 ≤ Criteria
$0.9 \cdot HE_{11} + 0.1 \cdot HE_{21}$: wider BSM opening is necessary.

Outlook

✓ CW operation of $TE_{31,11}$ mode with > 1 MW / 50% for ITER experiment
✓ Demonstration of 203 GHz oscillation for a Demo-reactor-class
✓ Detail design of poloidal EL with resolving the uncertainty of port environment
✓ Optimization of nuclear shield compliant with the requirements

Summary of R&Ds for JT-60SA EC system

1. Dual frequency gyrotron

- The first two-frequency gyrotron (110 & 138GHz) has reached the development target of 1MW x 100s at both frequencies.
- Oscillation at 82GHz (0.5MW,1s) was also confirmed.

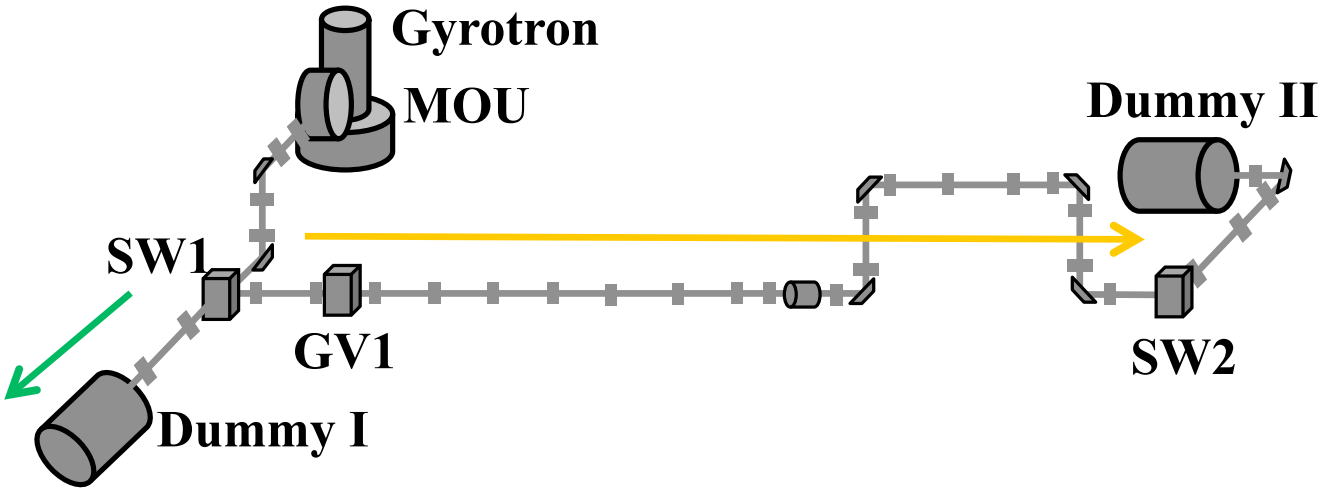
➢ Power increase is planned at 82GHz and 110GHz.

2. Launcher

- Repetition steering test of bellows in mock-up was successful .
- Manufacturing process was checked with mock-up of large curved 2nd mirror having water cooling channels.

➢ Further repetition steering test for bearings will be in 2015.

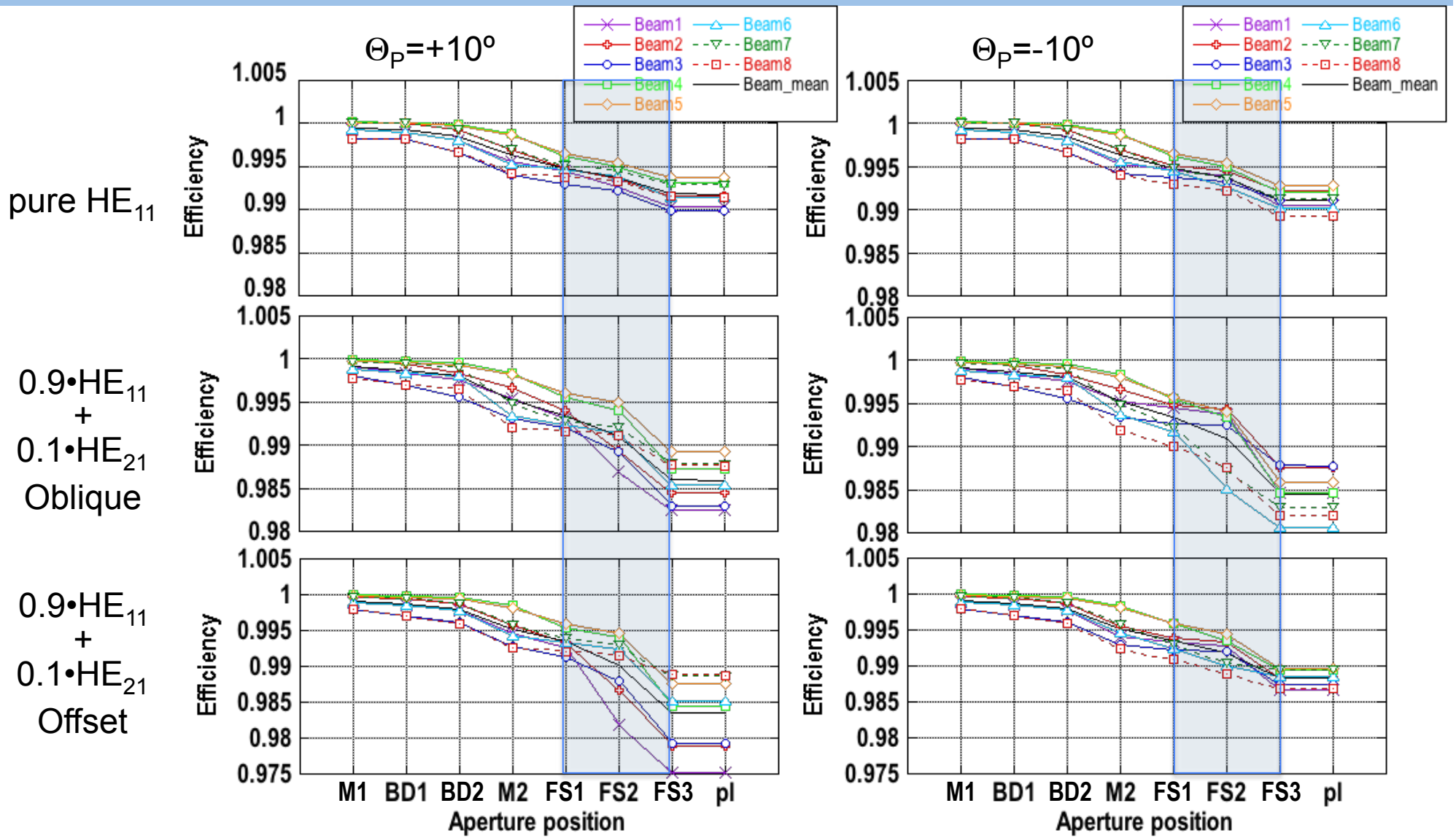
Transmission line tests at 104, 137 and 170 GHz



Power measurement with 20 sec operation	**170 GHz**	**137 GHz**	**104 GHz**
Power at gyrotron window	430 kW	328 kW	264 kW
Power at MOU output Diffraction loss ratio at MOU	416 kW (3.3%)	309 kW (5.8 %)	238 kW (9.8%)
Power at **Dummy load I (Short TL)** Transmission efficiency at Short TL	411 kW (**98.8** %)	305 kw (**98.7** %)	236 kW (**99.1** %)
Power at **Dummy load II (Long TL)** Transmission efficiency at Long TL	390 kW (**93.8** %)	294 kW (**95.1** %)	223 kW (**93.7** %)

MM-Wave Design output 3

- Dependence of modes on transmission efficiency (Top) -

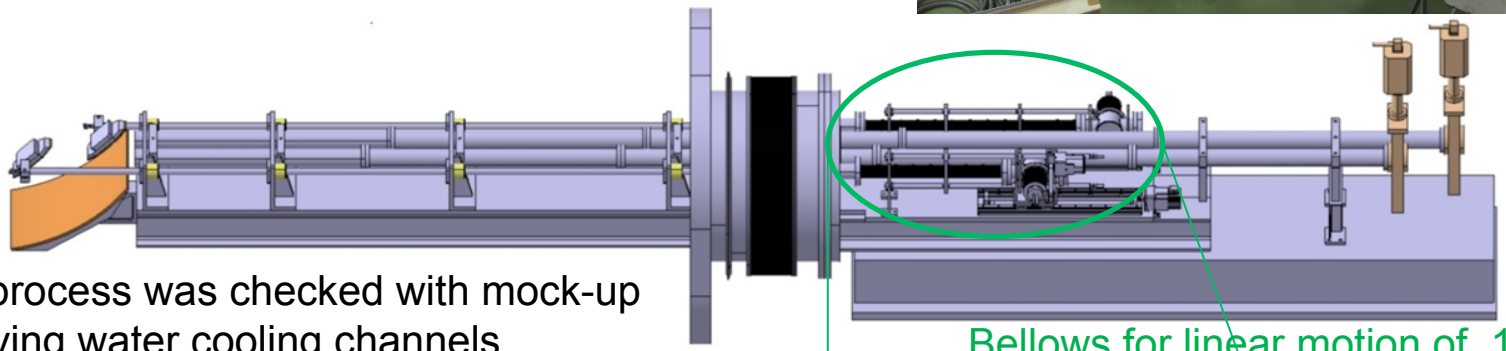


Launcher development for JT-60SA

Repeated motion test of 1st mirror has been successful with mock-up launcher to check bellows.

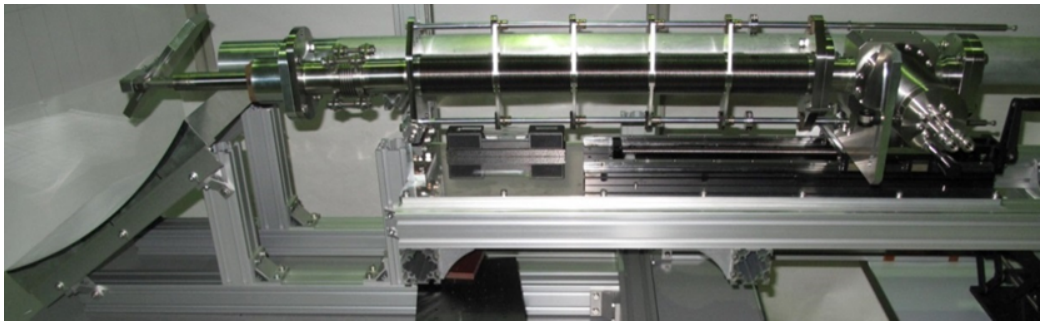
- 10^5 cycles of linear motion for poloidal beam steering
- 10^4 cycles of twist for toroidal beam steering

Test with real full-size mock-up with 3m of shaft is ready to check durability of the bearings.

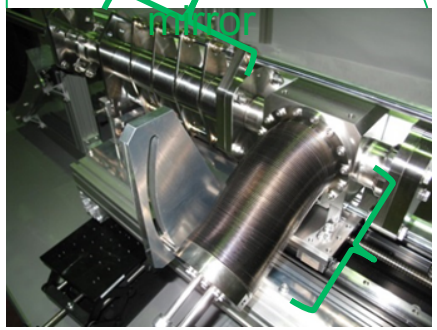


Manufacturing process was checked with mock-up of 2nd mirror having water cooling channels

Bellows for linear motion of 1st mirror



Full-size mock-up with shortening shaft for 1st Mirror



Bellows for twisting 1st mirror