FIP/1-2Ra

Completion of 1st ITER Gyrotron Manufacturing and 1 MW Test Result

Y. Oda[1], R. Ikeda[1], T. Nanaki[1], K. Kajiwara[1], T. Kobayashi[1], K. Takahashi[1], K. Sakamoto[1], S. Moriyama[1], C. Darbos[2], M. Henderson[2]

1 National Institute for Quantum and Radiological Science and Technology(QST), 2 ITER Organization

FIP/1-2Rb

Outcome of R&D program for ITER ICRF Power Source System

R. Trivedi[1], A. Mukherjee[1], R. Singh[1], K. Rajnish[1], D. Soni[1] , S. Verma[1] , G. Suthar[1], A. Jha[1], P. Ajesh[1] , M. Patel[1], R. Anand[1], R. Agarwal[1], K. Mohan[1], J.V.S. Hari[1], H. Machchhar[1], P. Vasava[1], H. Patel[1], H. Dalicha[1], U. Baruah[1], A. Patel[1], N.P. Singh[1], N.S. Goswani[1], K.R. Mehta[1], D.V. Upadhyay[1], H. Dhola[1], B. Raval[1], S. Gajjar[1], A. White[2], D. Francois[2], J. Sainz[2], K. Kozard[2]

1 ITER India, Institute of Plasma Research, 2 Continental Electronics

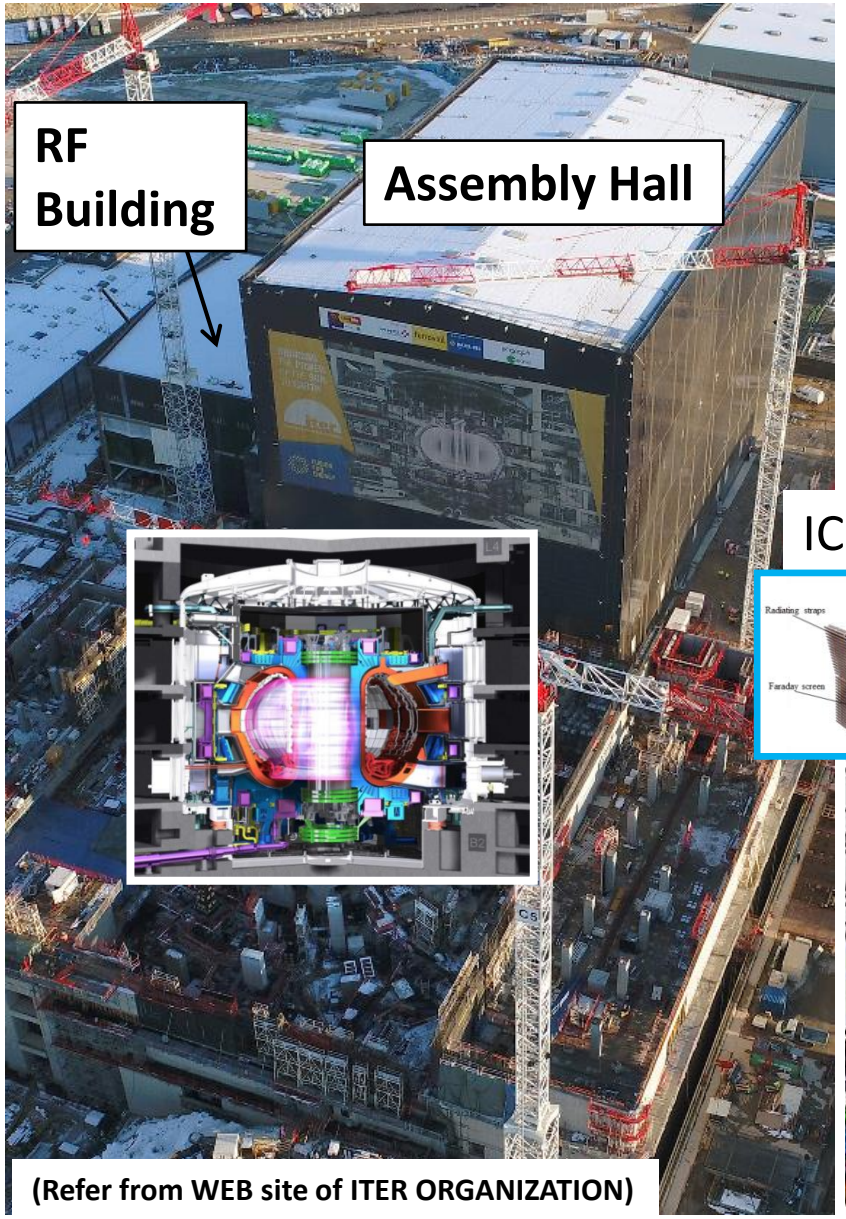
FIP/1-2Rc

Recent progress in the development of the European 1 MW, 170 GHz CW gyrotron for ITER

G. Gantenbein[1], F. Albajar[2], S. Alberti[3], K. Avramidis[1], W. Bin[4], A. Bruschi[4], J. Chelis[5], F. Fanale[4], J.-P. Hogge[3], S. Illy[1], Z. C. Ioannidis[1], J. Jelonnek[1], J. Jin[1], W. Kasparek[1], G. Latsas[1], C. Lechte[1], F. Legrand[7], I. G. Pagonakis[1], T. Rzesnicki[1], P. Sanchez[2], C. Schlatter[3], M. Schmid[1], M. Thumm[1], I. G. Tigelis[5], A. Zein[1], A. Zisis[5]

1 Karlsruhe Institute of Technology (KIT), 2 Fusion For Energy (f4E), 3 Swiss Plasma Center (SPC), EPFL
4 Consiglio Nazionale delle Ricerche (CNR), 5 National and Kapodistrian University of Athens
6 IGVP, University of Stuttgart, 7Thales Electron Devices (TED)

Overview of ITER RF Heating System



(Refer from WEB site of ITER ORGANIZATION)

RF Building

EC RF Power Source

IC RF Power Source

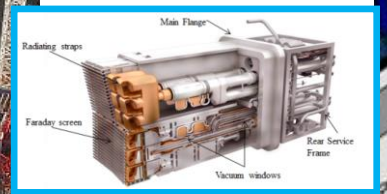
IC 40-55 MHz

EC 170 GHz

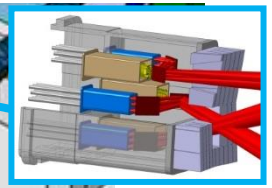
EC/IC Transmission Line

Assembly Hall

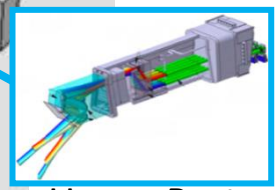
IC Antennas



EC Launchers



Eq. Port



Upper Port

EC ≥ 20 MW

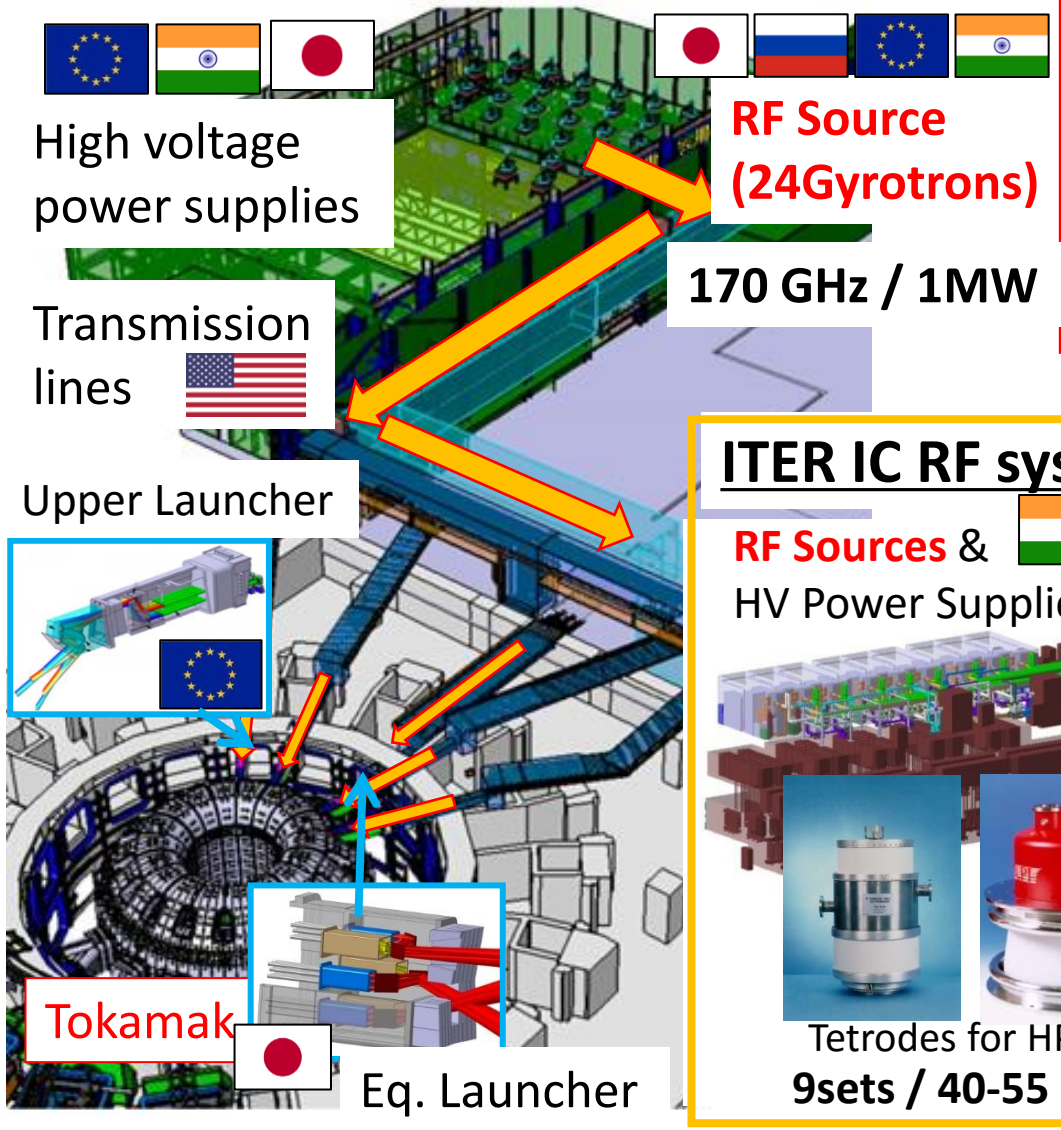
IC ≥ 20 MW

Tokamak

Configuration of EC RF & IC RF system

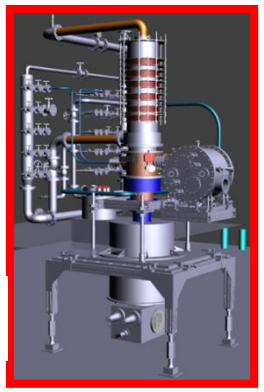
ITER EC RF system configuration

FIP/1-2Ra, FIP/1-2Rc



RF Source (24Gyrotrons)

170 GHz / 1MW



JA Gyrotron

RF Gyrotron

EU Gyrotron

ITER IC RF system configuration

FIP/1-2Rb

RF Sources & HV Power Supplies

Transmission Line

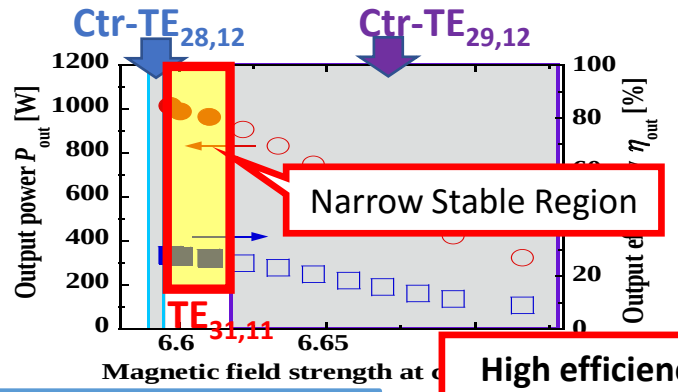
Tetrodes for HPA-3

Antennas

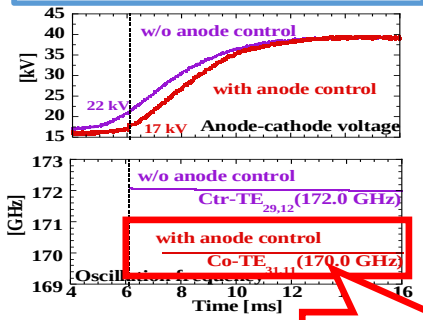
9sets / 40-55 MHz / 3MW each

Manufacturing of 1st ITER Gyrotron was Completed

Strategy for stable $TE_{31,11}$ oscillation was established.



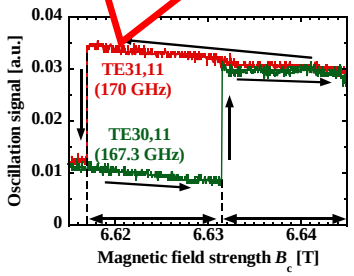
Active anode control



Suppression of ctr-$TE_{29,12}$ mode start

Stable oscillation

High efficiency

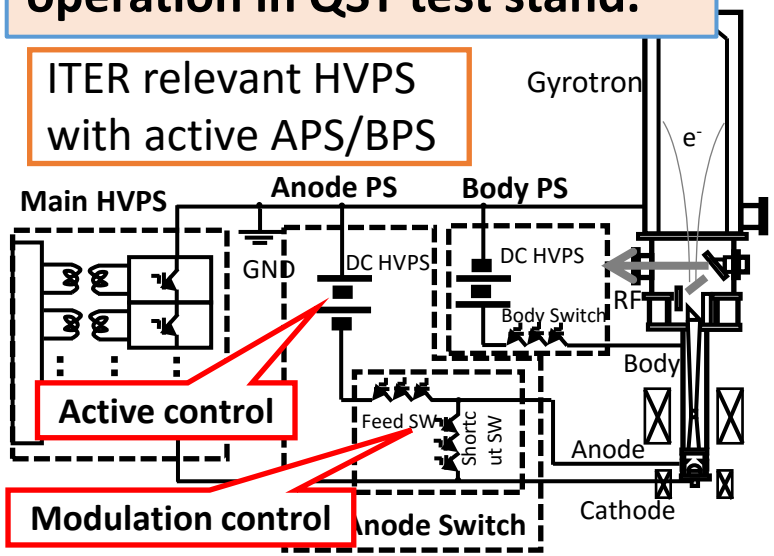


co-$TE_{31,11}$ mode oscillation map

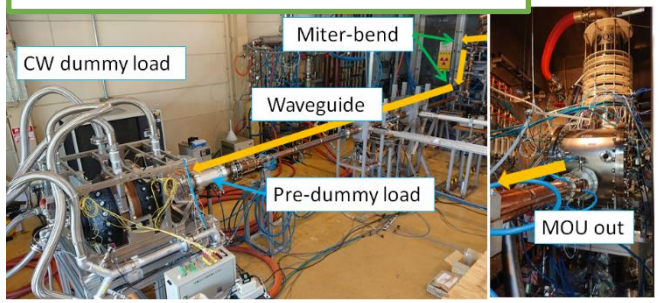
1st ITER gyrotron

Preparation for ITER gyrotron operation in QST test stand.

ITER relevant HVPS with active APS/BPS



TL and DL for CW operation

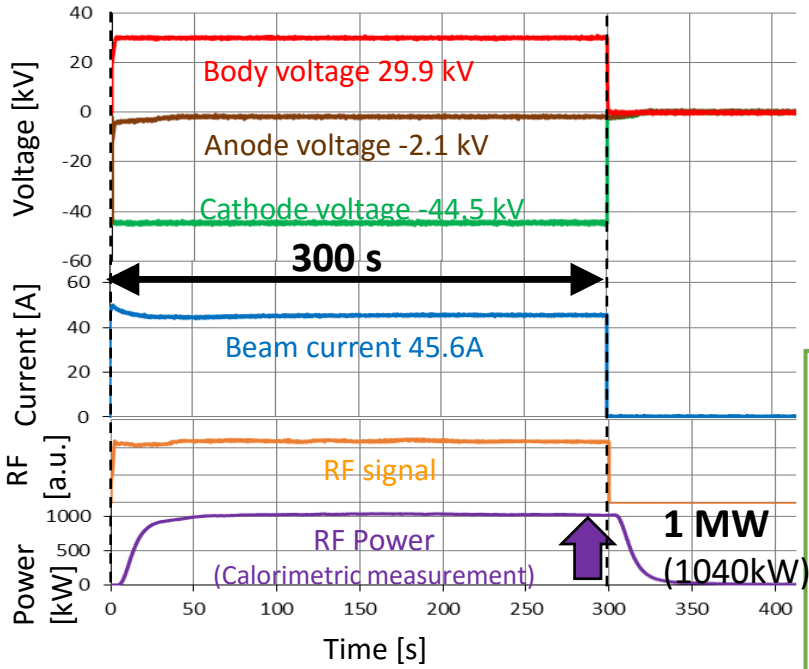


- **Manufacturing of 1st ITER gyrotron was completed in 2017** and QST started its Acceptance Test.

Success of Steady State Operation

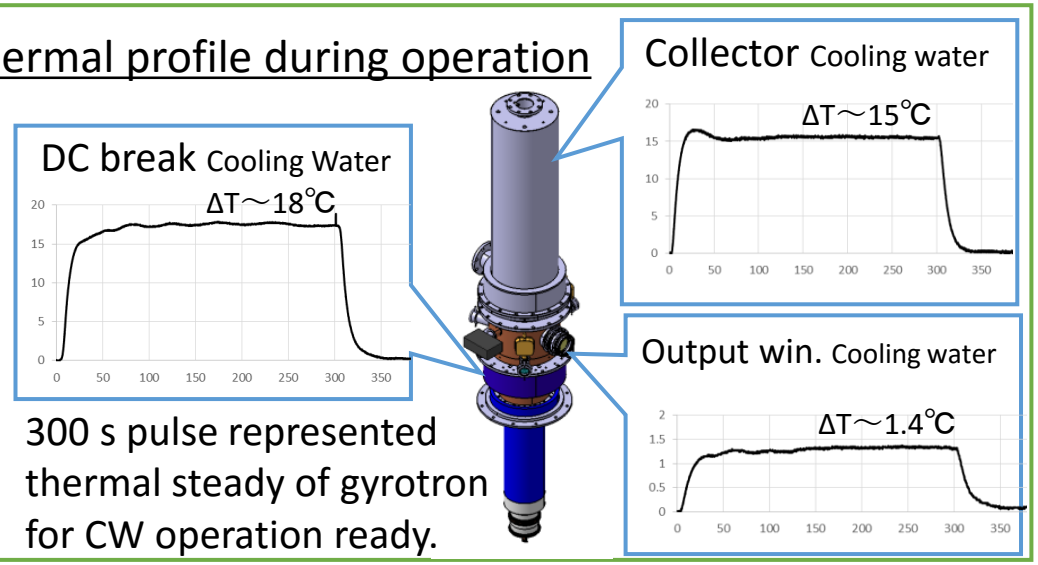
Long pulse operation

Requirement:
1MW output, 50% efficiency, 170 ± 0.3 GHz



300 s pulse operation succeeded with 1MW output and 51% efficiency at 169.85 GHz.

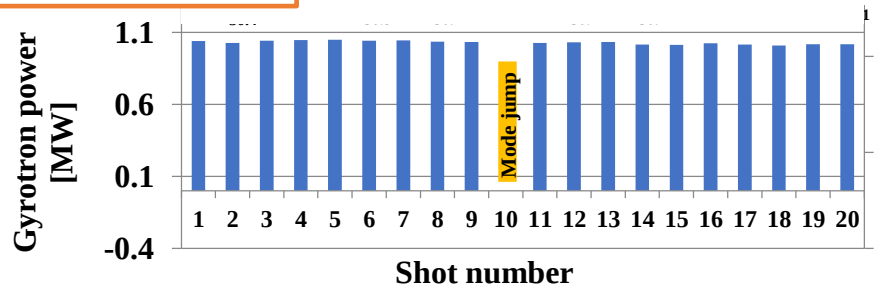
Thermal profile during operation



300 s pulse represented thermal steady of gyrotron for CW operation ready.

Reliability test

Requirement: >95 % reliability

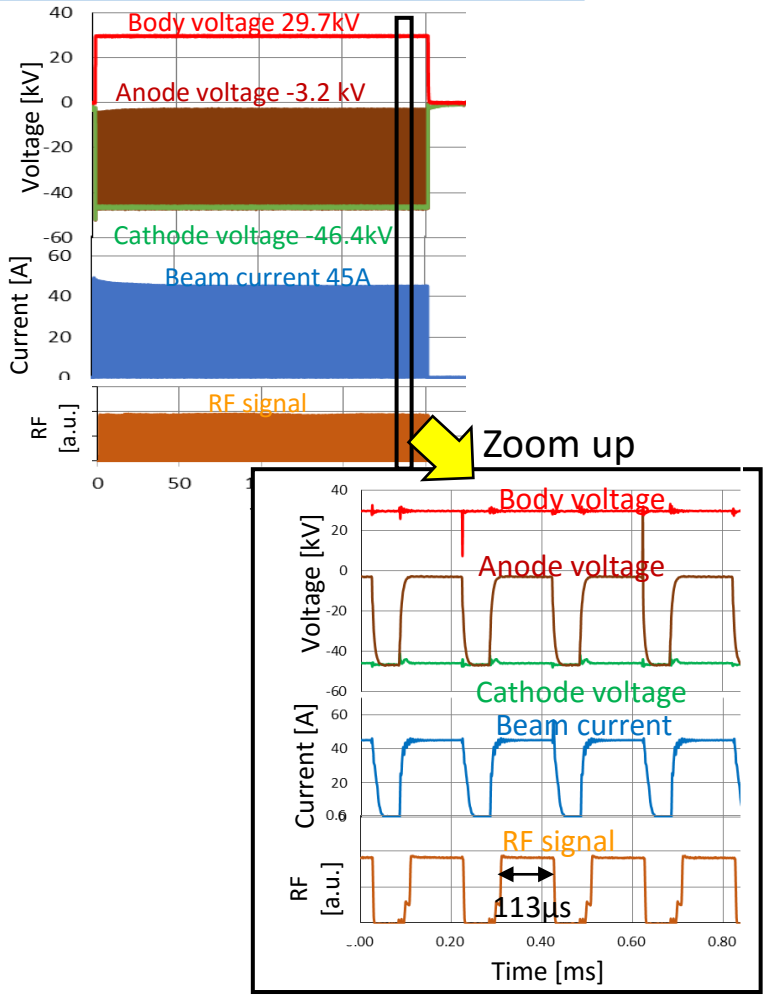


20 shots of 1MW / 300 s pulse with 19 successful shot achieving 95% reliability.

► Demonstration of 170 GHz / 300 s pulse with **1.04 MW output power** at **51% electric efficiency** succeeded with **95% of reliability**.

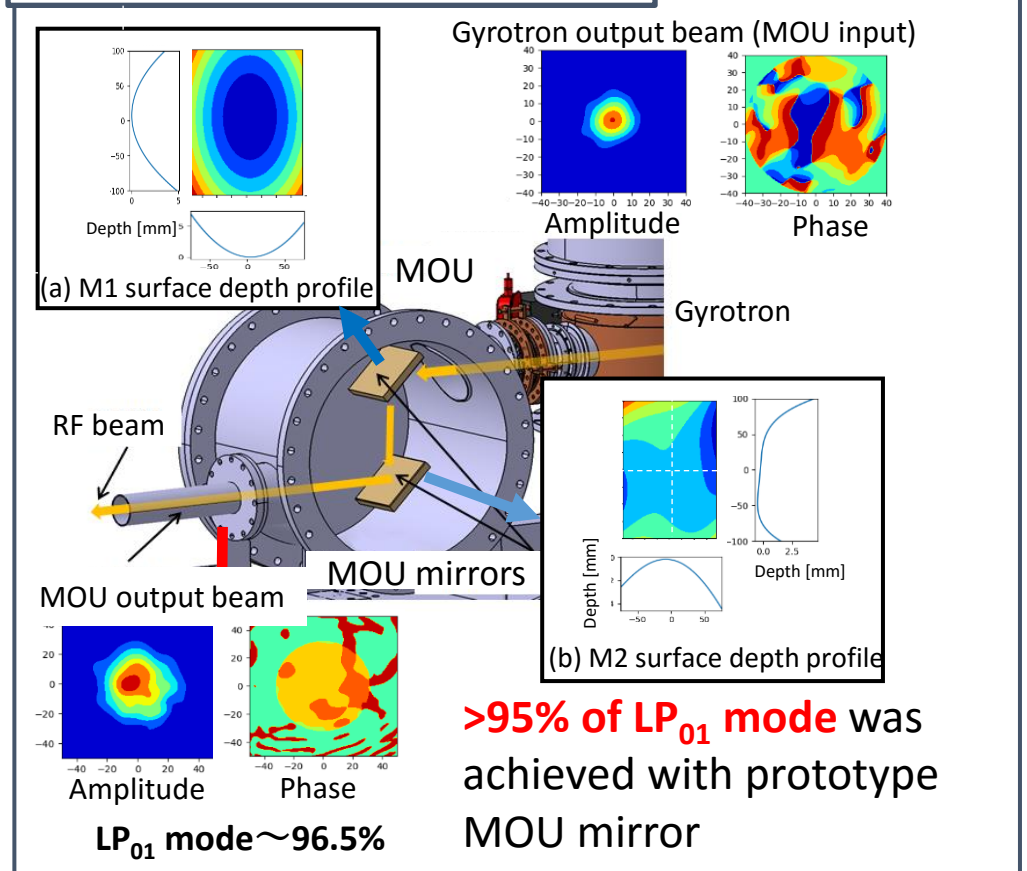
Achievement of Acceptance Test Criteria

5 kHz power modulation



200 s pulses with **1, 3, 5 kHz power modulation** at >0.8 MW were demonstrated.

Gyrotron RF power profile



LP_{01} mode～96.5%

>95% of LP_{01} mode was achieved with prototype MOU mirror

- **1st ITER gyrotorn achieved all the acceptance test criteria in success.**

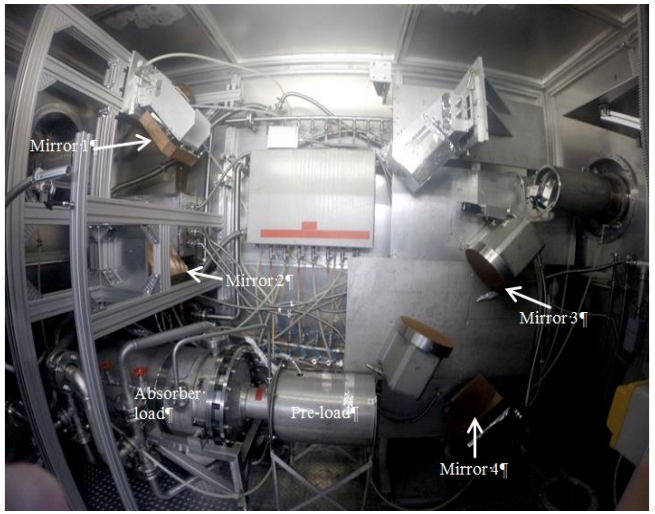
Now Ready for Shipment!

European 1MW, 170 GHz CW gyrotron for ITER
Design parameter and test set-up

- European 1 MW, 170 GHz industrial prototype CW gyrotron for the ITER: conventional (hollow-cavity) gyrotron
- Developed by the European GYrotron Consortium (EGYC) in cooperation with Thales Electron Devices (TED) and under the coordination of the European Joint Undertaking for ITER and the Development of Fusion Energy (F4E)
- Physical design of main components (i.e. magnetron injection gun (MIG), cavity, internal mode converter) based on a modular short-pulse (SP) prototype and technical design based on the 1 MW, 140 GHz CW gyrotron for W7-X
- First step: Short-pulse experiments to optimize the gyrotron alignment in the magnetic field, verify the optimum operating parameters (i.e. voltage, current, magnetic field profile) for maximum generated RF power.
- Second step: Long pulse operation up to 180 s (limitation of the HV power supply at KIT).

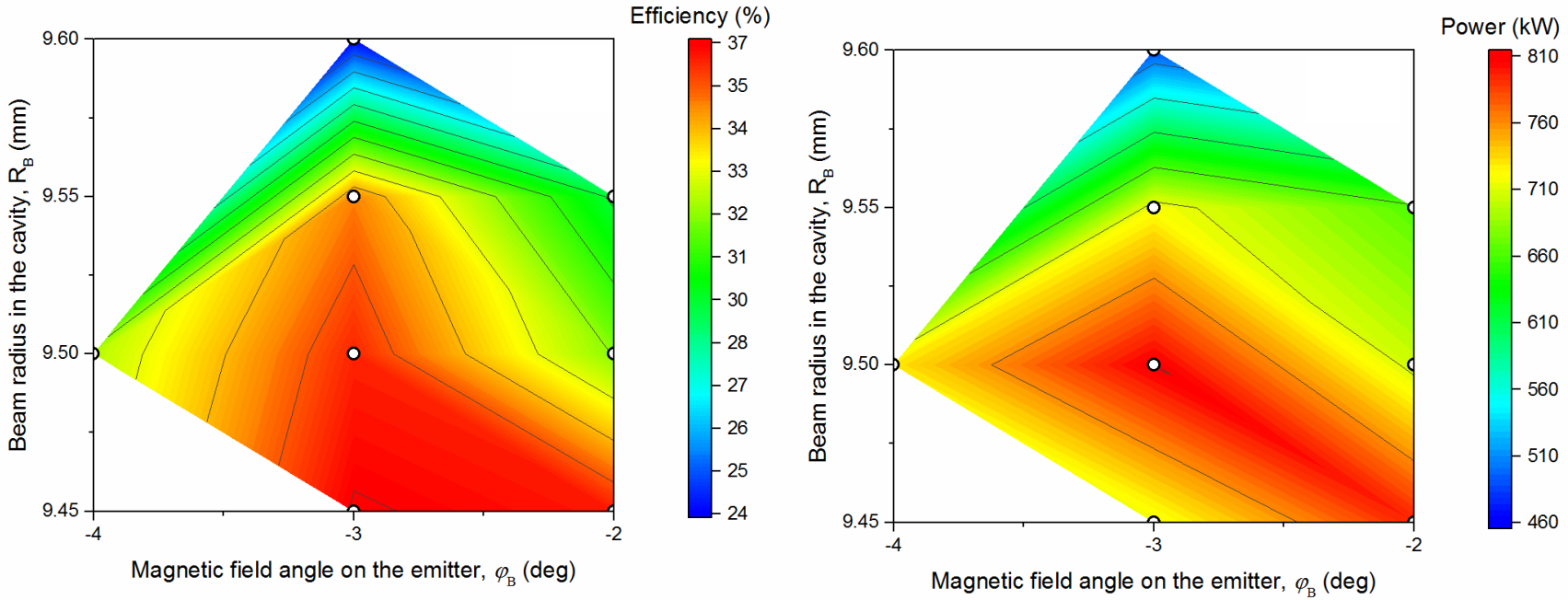
Typical parameter for CW operation	
Parameter	Value
Operating mode	$TE_{32,9}$
Magnetic field	6.78 T
Accelerating voltage	79.5 kV
Depression voltage	35 kV
Beam current I_b	40 A
Beam radius R_b	9.44 mm
Pitch factor α	1.29
Output power at window	1 MW
Frequency	170.23 GHz
Interaction efficiency	35 %
Total efficiency, w/o depressed collector	32 %
Total efficiency, w/ depressed collector	>50 %
Peak Ohmic wall loading in the cavity	2.1 kW/cm²

The European 1 MW 170 GHz CW ITER gyrotron installed at the KIT test facility.



Microwave measurement chamber with transmission system and absorber load.

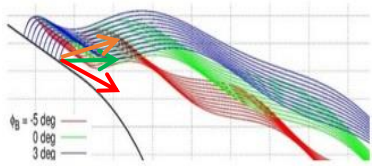
Experimental Results (I)



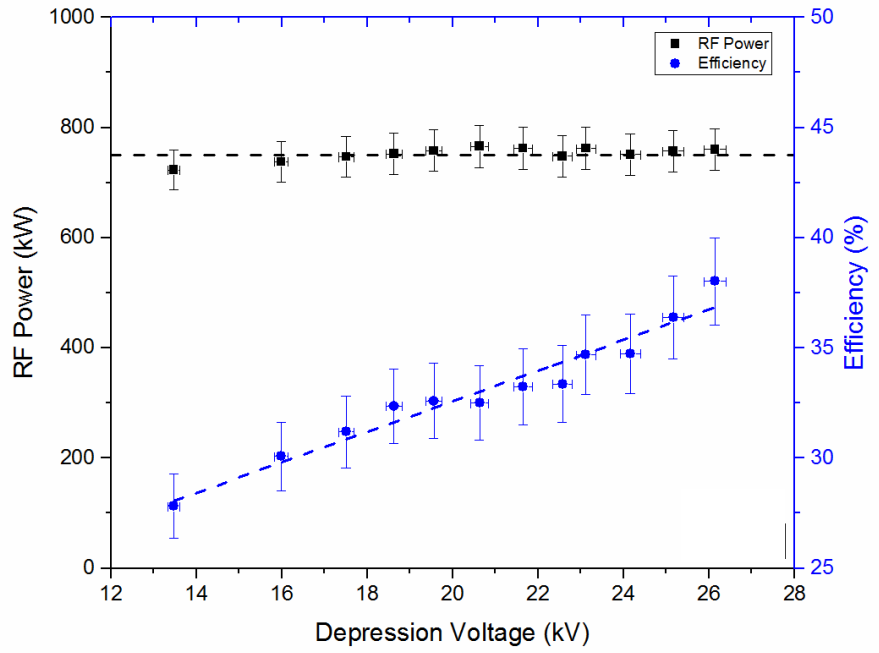
RF power (left) and efficiency (right) with respect to the magnetic field angle at the cathode emitter and the radius of the electron beam in the cavity

For each (φ_B, R_b) combination the voltage and beam current has been optimised with the collector depression voltage set to 20 - 25 kV

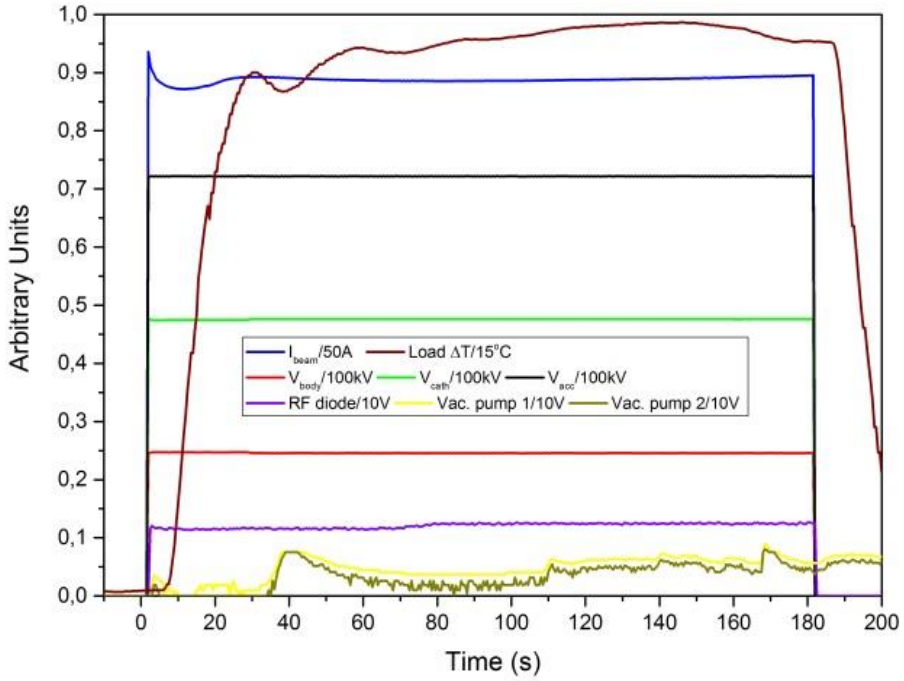
811 kW @ (φ_B = -3°, R_b = 9.50 mm) with 36 % efficiency (single stage depressed collector operation)



Experimental Results (II)



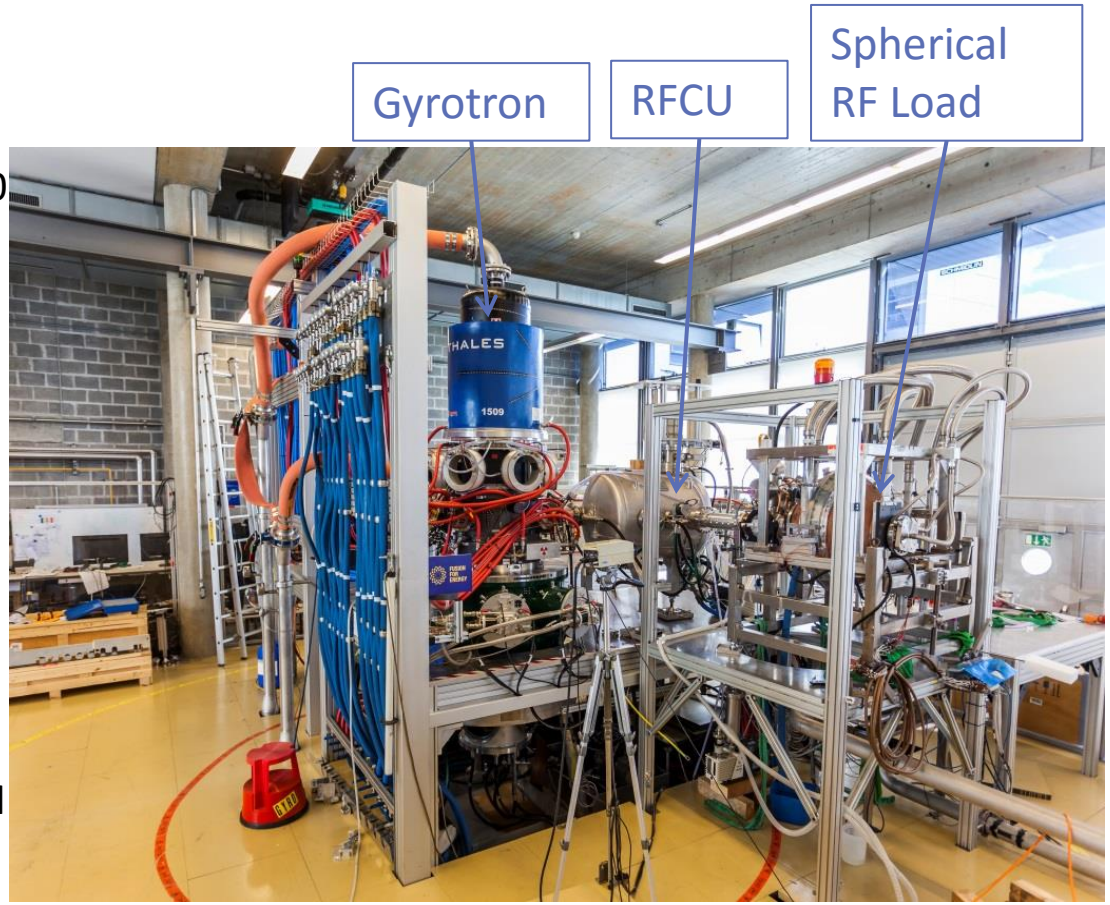
RF power and efficiency versus the depression voltage (φ_B = -3°, R_b = 9.50 mm).
Pulse length= 60 s



Typical 180 s pulse achieved during the experiments, the temperature measurement in the load (proportional to RF power) is delayed and shows oscillations at the beginning of the pulse due to the KIT cooling system only (all measurements normalised to the indicated values).

Conclusions and Next Steps

- Tests of the gyrotron at SPC, EPFL
- Goal: increase pulse length up to 3600 s
- Intermediate results
  - Pulse length up to 215 s
  - 1 MW RF power in short pulse operation (~ ms)
  - 810 kW RF power in long pulse operation
  - Limitations by external transmission components
- Next experimental campaign (until end of 2018) with improved RFCU and RF load



EU 1 MW 170 GHz gyrotron installed at SPC teststand

Status of ITER gyrotrons

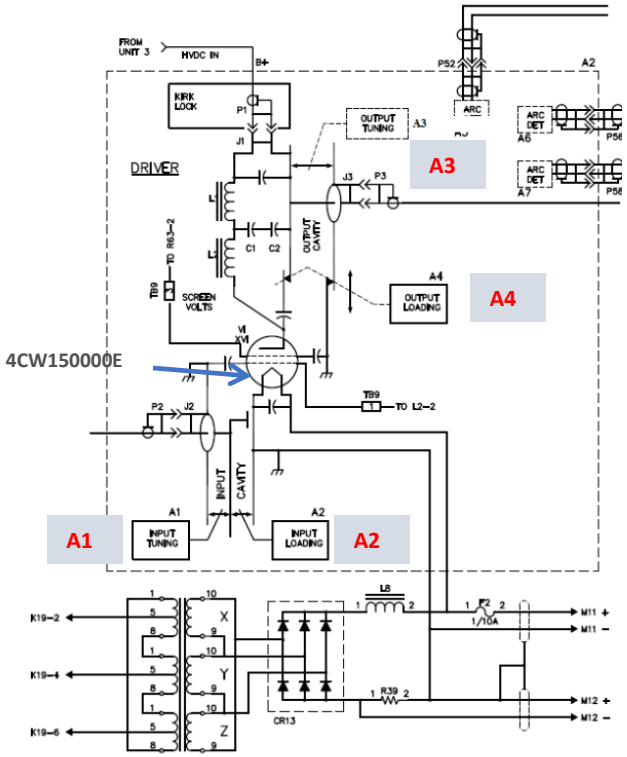
	JA gyrotron	RF gyrotron		EU gyrotron	IN gyrotron
					
Status	**1st tube completed**	**1st & 2nd completed**		Prototype	Design
Frequency	169.85 GHz	169.9 GHz		170 GHz	170 GHz
Power	1.04 MW	0.96 MW (MOU output)		0.81 MW	-
Efficiency	51 %	55%	53%	36 %	-
Pulse	300 s	1000 s		215 s	-
Reliability	95% 20 shots of 300 s	95%	100%	-	-
		40 shots of 1000 s			
Modulation	5 kHz (200s, 0.8MW)	1kHz (200s, 0.8MW)		-	-
Beam profile	96.5 % HE_{11} mode	97% HE_{11} mode		-	-

First plasma components are ready for operation

Specification for R&D chain & design criteria

Major Specification

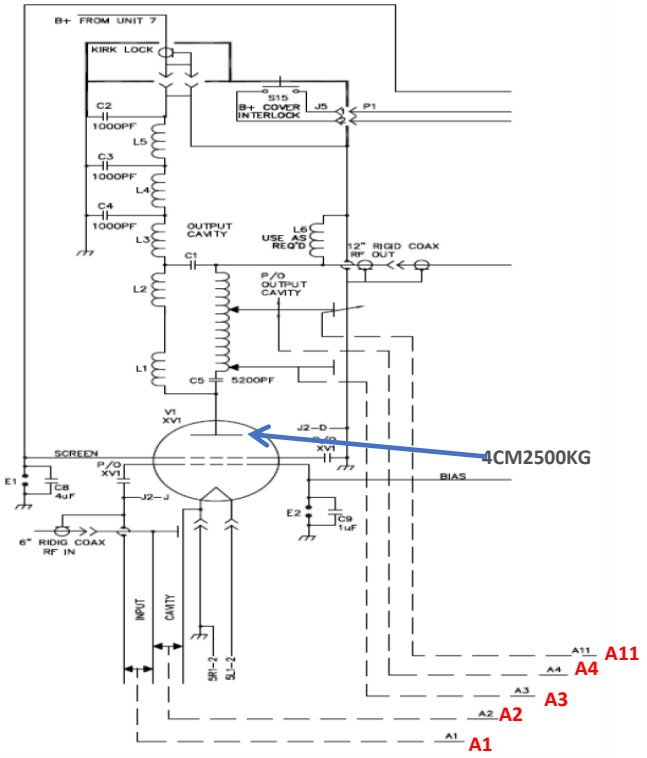
- Tunable frequency range: 35 to 65 MHz with 180s with static parameter & HoM tests
- O/P RF power: 1.5 MW, 2000s @ Lower & higher edge frequency up to VSWR 2:1 & 1dB BW for ±1MHz @ match load
- O/P RF power: 1.7 MW, 3600s @ lower edge frequency up to VSWR 1.5:1 & 1dB BW for ±1MHz @ match load



Driver Amp. 100kW HPA-2

Design Criteria

- A3-A4 motors for output matching
- A1-A2 motors for input matching
- A11 for Harmonic suppression

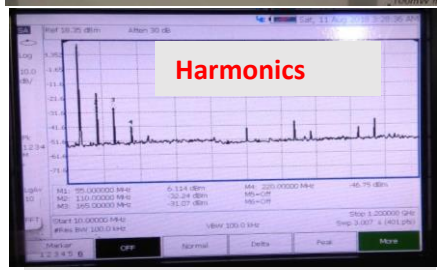


End stage Amp. 1.5 MW HPA-3

Test results with matched load

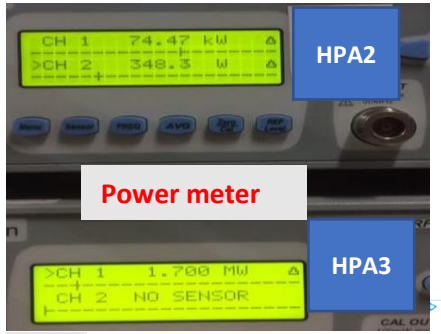
Freq.	HPA3 Pf	HPA3 Pr	HPA2 Pf	HPA2 Pr	SSPA Pf	Va-3	Ia-3	Eff-3	Diss-3	Gain-3
MHz	kW	kW	kW	kW	kW	kV	A	%	kW	dB
35	1248	4.2	79.4	16.54	4.17	22.50	106	52.3	1137	11.96
36	1497	3.22	67.77	0.29	4.17	22.50	102.8	64.7		13.44
37	1234	1.54	72.18	3.16	4.17	22.50	106.2	51.6	1155.5	12.33
54	1173.4	6.74	51.7	8.10	3.58	23.00	85.8	57.97	829.4	13.45
55	1513.0	7.78	61.6	0.06	3.58	23.00	99.0	66.45	764.0	13.90
56	1131.0	4.38	70.6	10.56	3.58	23.00	99.3	51.14	1115.9	12.19

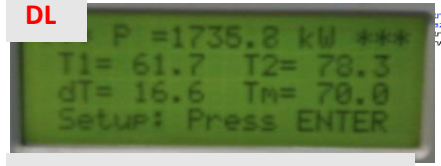
1dB BW measurement @ 36 & 55 MHz @ 1.5 MW



55 MHz @ 1.5 MW, 2000s

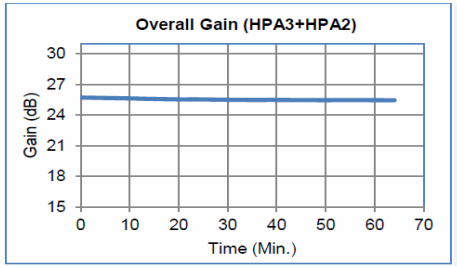
Freq.	HPA3		HPA2		SSPA	
(MHz)	Fwd. (kW)	Rev.(kW)	Fwd.(kW)	Rev.(W)	Fwd. (kW)	Rev.(W)
36.00	1700	1.77	74.47	348	4.68	54

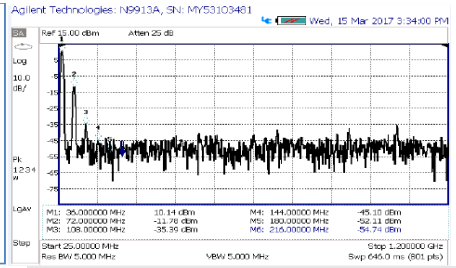


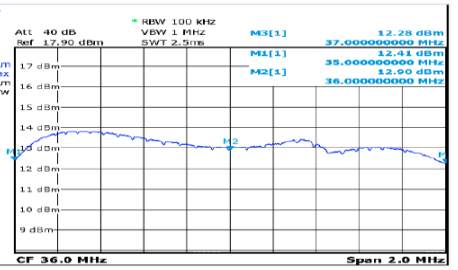


DL

36 MHz @ 1.7 MW, 3600s



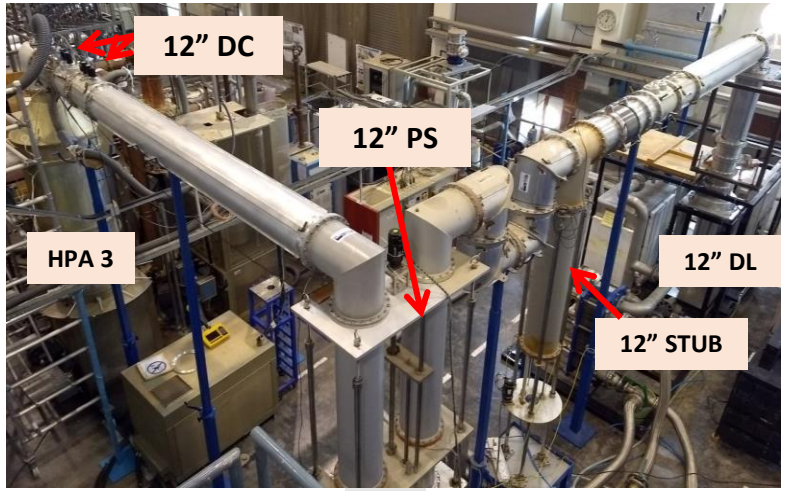




Gain, Harmonics and Band Width for 36 MHz @ 1.7 MW

Note: The system was also tested for 1MW, 2000s including measurement of 1dB BW at 40, 45, 50 and 55 and 60 MHz.

RF Test on Mismatched Load

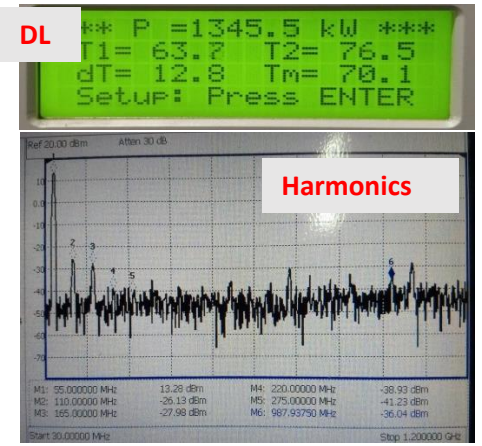


Fre q.	HPA3				HPA2		SSPA	
(MHz)	Fwd. (kW)	Rev. (kW)	VSWR	Phase	Fwd. (kW)	Rev. (W)	Fwd. (kW)	Rev. (W)
36	1713	66.8	1.49	100°	87.8	840	5.41	45

Constant O/P power 1.7MW @ 36 MHz @ VSWR 1.5

Ref. angle (Deg.)	P_{output} (kW)			V_{Anode} (kV)		I_{Anode} (A)		$Anode_{dis}$ (kW)	SG_{dis} (kW)
	SSPA	HPA 2	HPA3	HPA2	HPA3	HPA2	HPA3	HPA3	HPA3
0	2.73	41.3	1506	11.1	23	8.95	68.5	273.3	3.6
45	2.89	45.4	1506	11.1	21.0	9.5	78.0	341	3.9
90	4.28	74.9	1515	11.1	19.5	12.5	108.5	828.2	4.23
135	4.89	90.7	1514	11.1	18.1	14.0	129.0	1075.5	8.16
180	4.85	93.6	1515	11.6	20.5	14.2	133.3	1465.7	7.8

Constant O/P power 1.5 MW @ 55 MHz @ VSWR 2 with different angles



Measurement of power and Harmonics @ 1.5 MW, 2000s, 55 MHz

Run test was conducted for 55 MHz, 1.5 MW, 2000s for five consecutive RF pulses with 25 % duty cycle

Summary

ITER EC System

FIP/1-2Ra Completion of 1st ITER Gyrotron Manufacturing and 1 MW Test Result

- Manufacturing of 1st ITER gyrotron completed and its acceptance test started.
- **300 s pulse with 1.04MW output / 51% efficiency** achieved representing thermally steady state and 95% reliability.
- **1,3,5kHz full power modulation** and **>95% LP_{01} mode purity** were also achieved.
- **1st ITER gyrotron achieved all the test criteria in success.**

FIP/1-2Rc Recent progress in the development of the European 1 MW, 170 GHz CW gyrotron for ITER

- Intermediate results from Tests of the gyrotron at SPC, EPFL
- Pulse length up to 215 s
- **1 MW RF power** in short pulse operation (~ ms)
- **810 kW RF power in long pulse operation**

ITER IC System

FIP/1-2Rb Outcome of R&D program for ITER ICRF Power Source System

- R&D RF source using tetrode tubes are tested at INDA test facility.
- **5 consecutive 2000s shots with 25% duty cycle at 1.5MW/55MHz** tested successfully.
- **Electrical efficiency of complete RF chain is around 55% - 60%.**