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ECRF stray radiation studies in preparation of the operations of JT-60SA

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Introduction /1

- For its initial research phase, the JT-60SA tokamak will be equipped with four gyrotrons units delivering up to 3 MW at 110 GHz to the plasma.
- Together with 6 MW of P-NBI and 10 MW of N-NBI the ECRF power will be used to sustain and control stable operation at high current with a lower single null CFC divertor plasma configuration.
- The development of the current ramp-up up to full-current operation (5.5 MA) is among the first scientific objectives of this phase.
- In preparation of this, predictive modelling of the current ramp-up in scenario 2 (type I ELM, H-mode scenario, B_T=2.25 T, q_{95}=3) is being done, based on parameters published in V. Ostuni *et al* 2021 *Nucl. Fusion* **61** 026021. In this scenario the ECRF power is injected from an early phase of the current ramp.

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Introduction /2

- Such modelling provides the T_e ad n_e profiles giving the opportunity to estimate the expected amount of EC stray radiation during the ramp-up phase when the EC power absorption might be less than 100% and consequently the potential risk of damage of the in-vessel components is higher.
- This paper deals with the current ramp-up phase with ECRF settings compatible with the Integrated Commissioning capabilities (see next table) in order to analyse the low EC absorption scenarios. These are being considered also for the design of the EC stray detection system, which is presently based on the adaptation to the JT-60SA parameters of the differential bolometers in development for ITER.
- In particular, expected locations and EC stray power loads on PFCs due to shine-through of the EC beams are identified.

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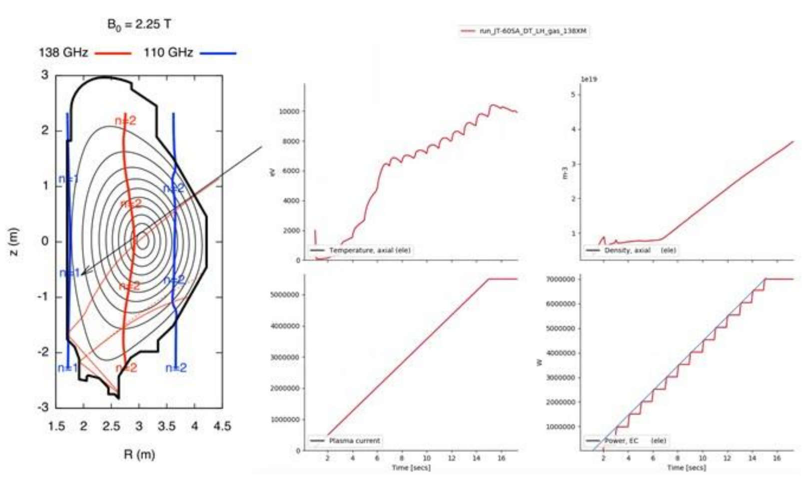
Three phases in ECRF system upgrading

	Integrated commissioning			Initial research			Integrated research	
Number of Gyro. & TLs	1	1		2	2		9	
Frequency [GHz]	110	110 138	82	110	110 138	82	110 138	82
Gyrotron Power [MW]	1	1		1	1		1	1
Max. Injection Power / Max. Pulse length	~1.5 MW/5 s (110 GHz) ~0.75 MW/5 s (138 GHz) ~0.6 MW/1 s (82 GHz)			3 MW/5 s (110 GHz) 1.5 MW/100 s (110/138 GHz) ~1.2 MW/1 s (82 GHz)			7 MW/100 s (110/138 GHz) ~5.4 MW/1 s (82 GHz)	
Polarization	any	any	TBC	any	any	TBC	any	TBC
WG Diameter [mm]	31.75	60.3		31.75/60.3	60.3		60.3	
Number of Miterbends	15	15		7-12	7-12		7-12	
Transmission Eff. [%]	~75	~75	~60	~75	75~80	~60	75~80	~60
Max. Pulse Length [s]	5	5	1	5	100	1	100	1
Max. Duty Cycle*	TBD	~1/60	TBD	TBD (similar to JT-60U)	1/18	TBD (~3MJ/30min)	1/18	TBD (~3MJ/30min.)
Launcher	1 x Waveguide Launcher - 2 x 60.3 mm dia. WGs in parallel - Fixed angle parallel to port axis: 35.5° - No mirrors			2 x 2-directional steering launchers - 2 x 60.3 mm dia. WGs in parallel - 2 x independently movable 1st mirrors - 1 x shared large fixed curve mirror			3 x 2-directional steering launchers - Same as that in the Initial research phase 1 x 3-beam launcher	

* Detail of duty cycle for high repetition rate with limited duration should be discussed depends on the experimental purposes and scenarios.



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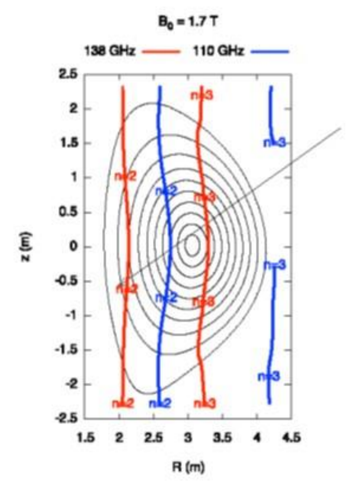
Scenarios

Parameters	JT-60SA #1 Full Ip Inductive DN 41MW	#2 Full Ip Inductive SN 41MW	#3 Full Ip Inductive SN 30MW High density	#4-1 ITER like Inductive SN 34MW	#4-2 Advanced inductive (hybrid) SN 37MW	#5-1 High βN Full CD SN 37MW	#5-2 High βN Full CD SN 31MW
Plasma current, I_p (MA)	5.5	5.5	5.5	4.6	3.5	2.3	2.1
Toroidal magnetic field, B_T (T)	2.25	2.25	2.25	2.28	2.28	1.72	1.62
Major radius, R_p (m)	2.96	2.96	2.96	2.93	2.93	2.97	2.96
Minor radius, a (m)	1.18	1.18	1.18	1.14	1.14	1.11	1.12
Aspect ratio, A	2.5	2.5	2.5	2.6	2.6	2.7	2.6
Elongation, κ_x, κ_{95}	1.95, 1.77	1.87, 1.72	1.86, 1.73	1.81, 1.70	1.80, 1.72	1.90, 1.83	1.91, 1.84
Triangularity, δ_x, δ_{95}	0.53, 0.42	0.50, 0.40	0.50, 0.40	0.41, 0.33	0.41, 0.34	0.47,0.42	0.45, 0.41
Safety factor, q_{95}	3.2	3.0	3.0	3.2	4.4	5.8	6.0
Shape Factor (=q95Ip/(aBt))	6.7	6.3	6.2	5.7	5.9	7.0	7.0
Plasma Volume (m3)	132	131	131	122	122	124	124

- The flexibility of the ECRF system allows to consider a number of reduced B_t and I_p scenario besides that can be instrumental to the development of the main ones and for specific studies such as disruptions, vertical displacement events (VDEs) and run-aways build up.



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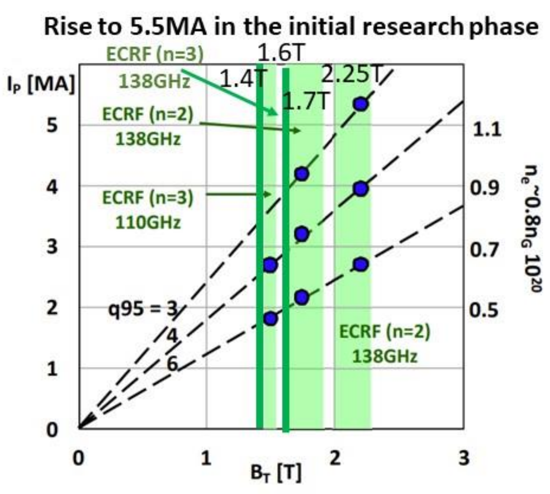
Possible operational path



case	B_T (T)	f_{EC} (GHz), harm.	P_{EC} (MW)
1	2.25	138 n=2	0.75
2	1.7	110 n=2	1.5
3	1.97	110 n=2	1.5
4	1.6-1.7	138,n=3 + 110, n=2	0.75+ 0.75
5	1.6	138 n=3	0.75
6	1.4	110 n=3	1.5

Power available in the Integrated Commissioning phase

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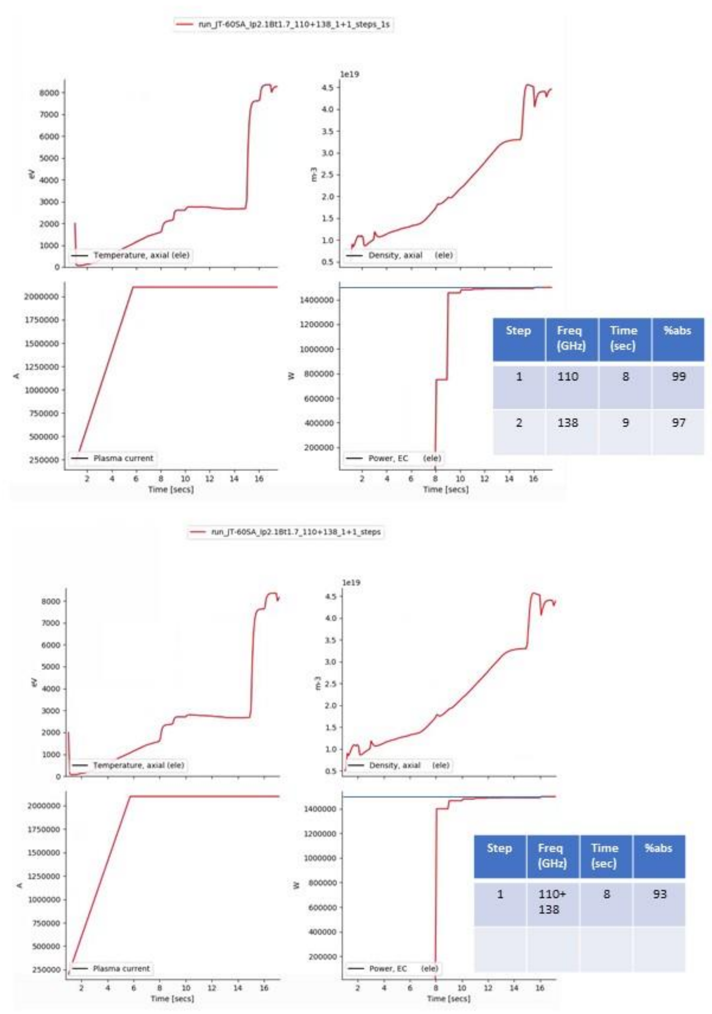
Ip=2.1MA, Bt=1.7T, 110GHz + 138 GHz



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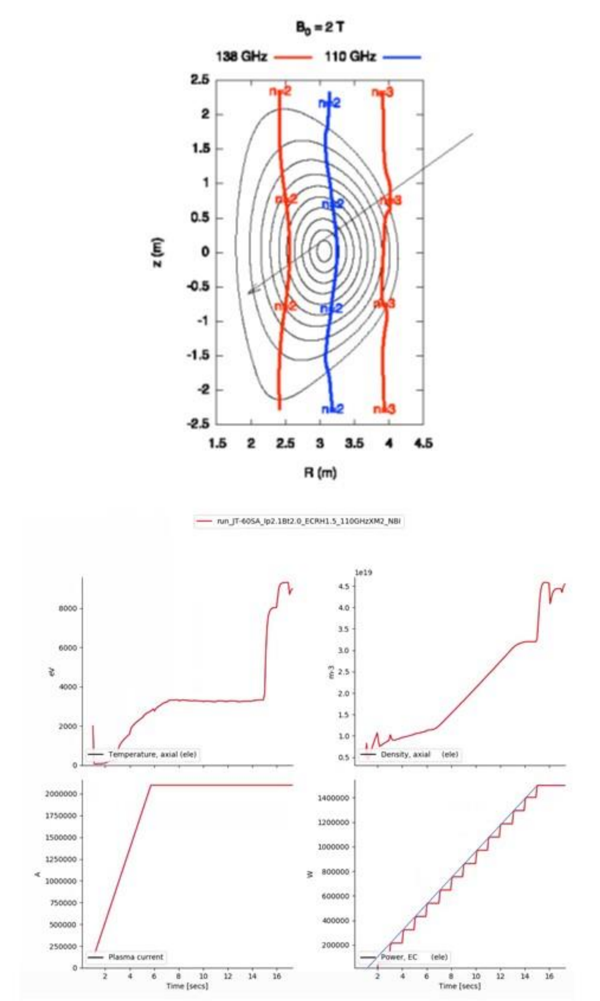
Ip=2.1MA, Bt=2T, 110GHz



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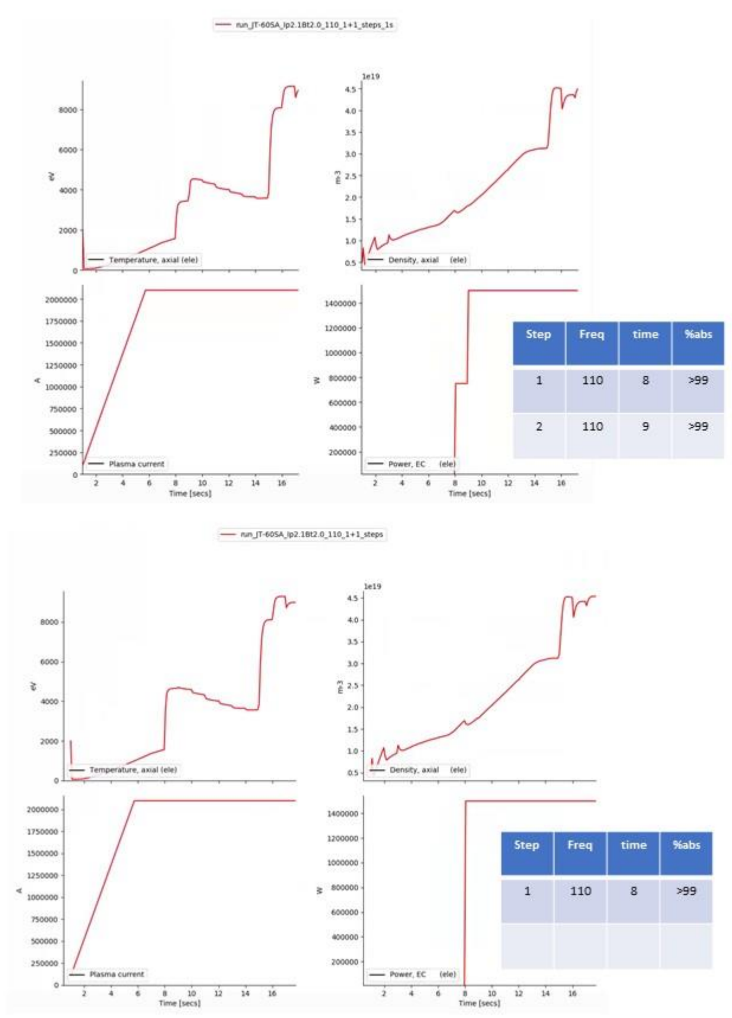
Ip=2.1MA, Bt=2T, 110GHz



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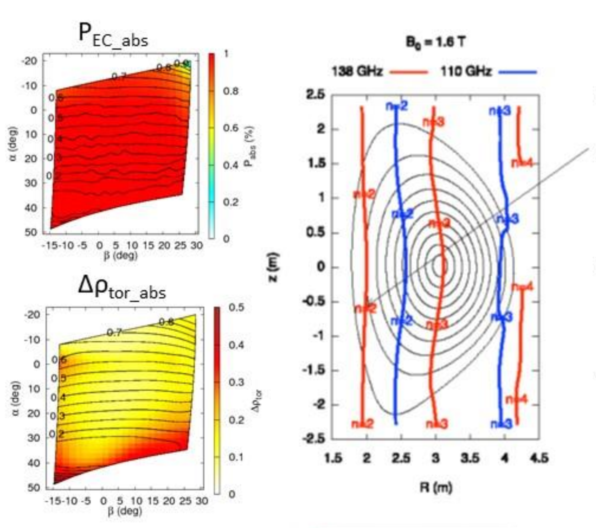
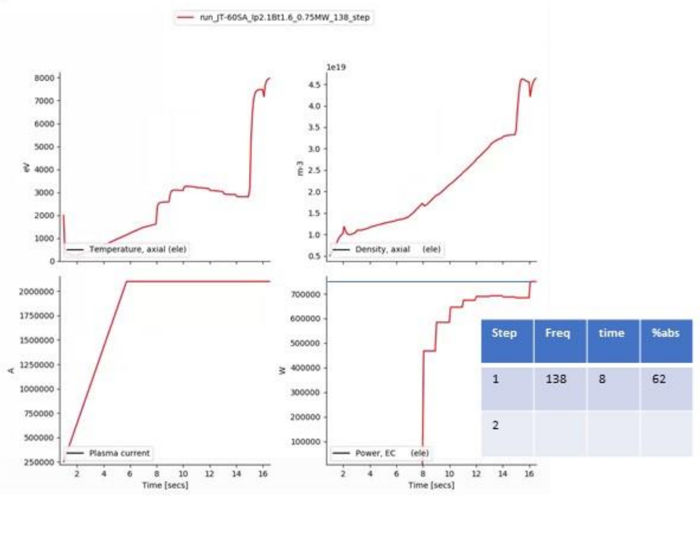
Ip=2.1MA, Bt=1.6T, 138 GHz



- Pabs ~100% for ρ_t <0.8
- Relatively good localization $d\rho_t$<0.15 for 0.1<ρ_t <0.8
- Minor effects of higher harmonics absorption
- n=3 at 138 GHz for core heating



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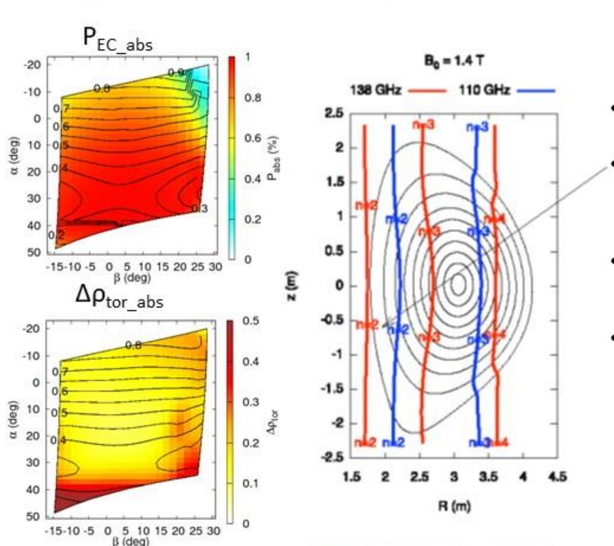
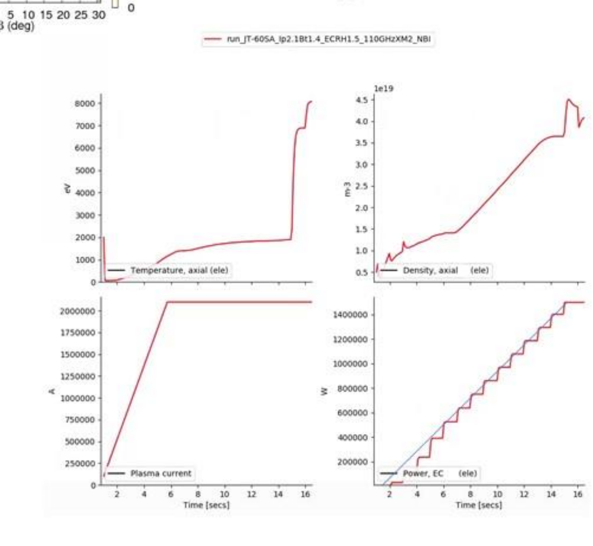
Ip=2.1MA, Bt=1.4T, 110GHz



- Pabs>90% for ρ_t <0.5
- Relatively good localization $d\rho_t$<0.15 for 0.3<ρ_t <0.6
- Minor effects of higher harmonics absorption
- Mid radius heating



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Estimated EC load on the vessel

Residual cross polarized fraction (5%) at 5 keV plasma temperature									
(kW/m² per 1MW injected beam)	peak incident power density (scen 2)		estimated peak absorbed power density on CFC (scen 2)		peak incident power density (scen 4)		estimated peak absorbed power density on CFC (scen 4)		duration
poloidal angle	1st bounce	2nd bounce	1st bounce	2nd bounce	1st bounce	2nd bounce	1st bounce	2nd bounce	
0	508.50	18.68	45.26	1.66	1017.00	99.60	90.51	8.86	pulse length
-20	375.00	10.75	33.38	0.96	70.50	6.06	6.27	0.54	
-35.5	334.50	41.40	29.77	3.68	61.33	13.41	5.46	1.19	

Low absorption scenario at low plasma temperature (50 eV)									
(kW/m² per 1MW injected beam)	peak incident power density (scen 2)		estimated peak absorbed power density on CFC (scen 2)		peak incident power density (scen 4)		estimated peak absorbed power density on CFC (scen 4)		duration
poloidal angle	1st bounce	2nd bounce	1st bounce	2nd bounce	1st bounce	2nd bounce	1st bounce	2nd bounce	
0	6780.00	16.60	603.42	1.48	16950.00	1660.00	1508.55	147.74	1-1000 ms
-20	3000.00	8.60	267.00	0.77	9000.00	180.60	801.00	16.07	
-35.5	669.00	0.28	59.54	0.02	3345.00	276.00	297.71	24.56	

Distribution of the non-absorbed EC power fraction after 1 and 2 passes was calculated considering:

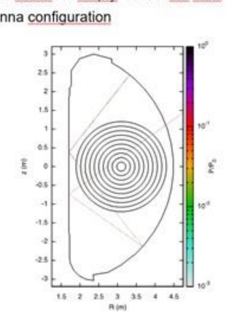
- a small fraction (5%) of (wrong) OM2 polarization
- main XM2 component, with higher absorption, in low T_e conditions

Antenna parameters for 1st plasma	
Beam waist radius w_0 [mm]	19.42
Launching point coordinates (R,Z) [mm]	(5214.0, 1722.0)
Poloidal injection angle a [deg]	-35.5

Incident power density (MW/m² per 1 MW injected beam)				
Frequency [GHz]	1st bounce (@ R=1.708 m, Z= -0.733 m, θ=35.5 deg)		2nd bounce (@ R=3.661 m, Z=-2.123 m, θ=8.86 deg)	
	$P_{dens}(0,z)$	$P_{av}(z)$	$P_{dens}(0,z)$	$P_{av}(z)$
82	7.702	0.963	3.852	0.482
110	13.8	1.725	6.92	0.865
138	21.59	2.699	10.86	1.358

Incident power density at first bounce (MW/m² per 1 MW injected beam)				
Frequency [GHz]	n [10^{19} m^{-3}]	T [keV]	$P_{dens}(0,z)$	$P_{av}(z)$
82	0.01	0.1	7.69	0.96
	0.1	0.3	7.32	0.91
	1.0	1.0	2.37	0.30
110	0.01	0.1	13.74	1.72
	0.1	0.3	11.72	1.46
	1.0	1.0	0.07	0.01
138	0.01	0.1	21.49	2.69
	0.1	0.3	18.48	2.31
	1.0	1.0	0.14	0.02

- Divergent gaussian beam
- Lower loads on 'empty' vessel wrt final antenna configuration



- Circular plasma, R_{ax} = 3.1 m, z_{ax}=0 m, a=1.2 m (compatible with EC-assisted BKD studies assumptions)

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Conclusions

- ECRF during ramp-up can be applied also to scenarios with reduced parameters
- If the ECRF is switched on towards the end of the current ramp, the absorption is generally higher that 90%
- In case of mixed ECRF frequency, the absorption of the higher harmonics (n=3) is favored previously injecting of the lower one (n=2)
- Power ramps with early start (1-2 s) show initial low absorption that progressively increases

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JT-60SA Advanced Superconducting Tokamak — BA-Satellite Tokamak Program

ISTP Consiglio Nazionale delle Ricerche

21st joint workshop on electron cyclotron emission (ECE) and electron cyclotron resonance heating (ECRH)

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