EUROfusion

WPSA annual meeting

Electron Cyclotron Wall Conditioning for JT-60SA

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LPP
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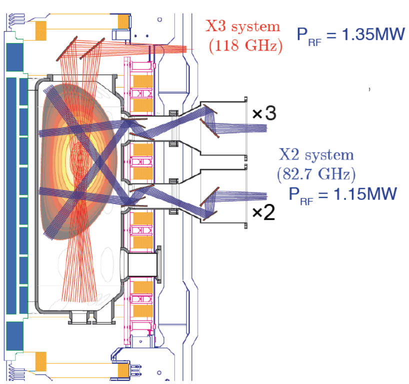
Introduction and Content

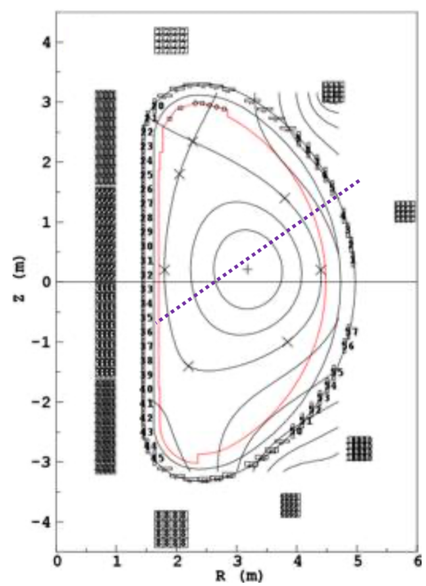
- Conditioning challenge in JT-60SA commissioning
  - Keep up the plasma performance throughout an experimental day / week while the superconducting coils remain energized
  - Glow discharge conditioning is not operable in the presence of magnetic fields
  - Electron Cyclotron Wall Conditioning

- Content
  - Analysis of wall conditions during JT-60SA commissioning
  - Modeling of ECWC to complement experimental observations, TCV exp.
  - Requirements for ECWC in JT-60SA

TCV



JT-60SA



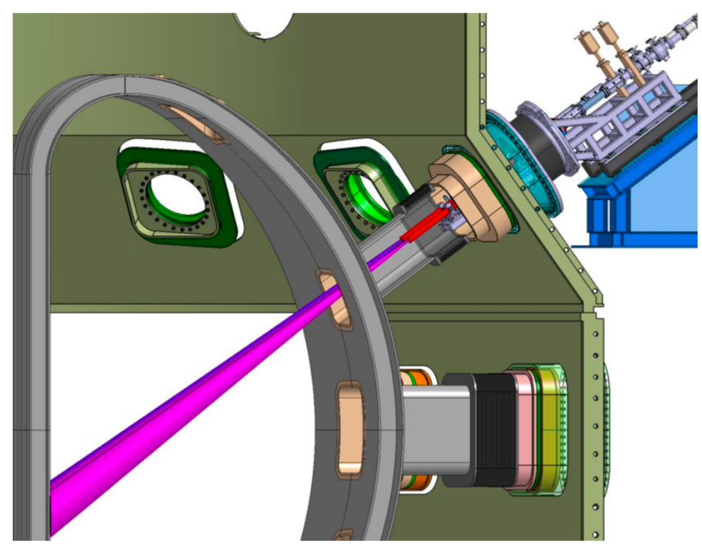
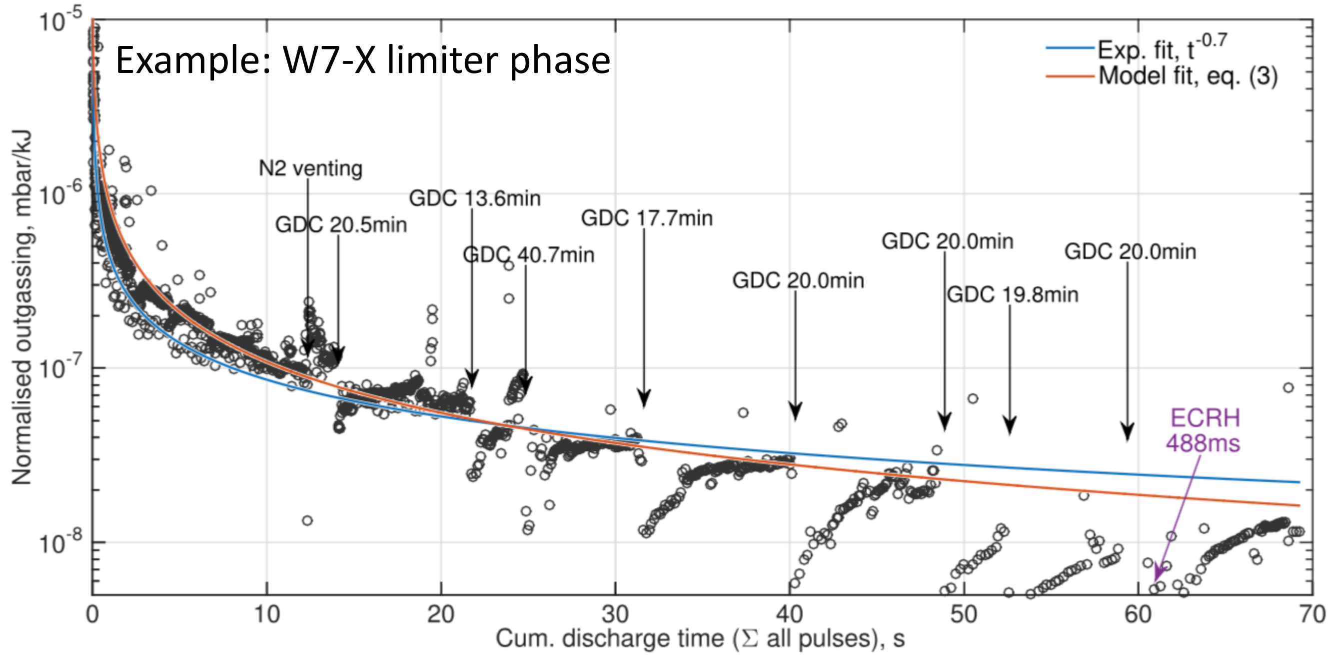


Figure 2.23-3 Schematic view of the ray and the launcher

- Effect of conditioning and plasma operation on wall conditions
  - Outgassing



[Wauters T., Nucl. Fusion 58 (2018) 066013]

Figure 2. Normalised outgassing in subsequent He ECRH discharges (20 151 211.1 to 20 160 128.27) as function of the cumulated ECRH discharge duration: experimental data (circles) overlaid with typical experimental $t^{-0.7}$ trend (blue line) and fitted by equation (3) (red line, see section 3). The discontinuities in the data trend result from He-GDC operation, indicated by the arrows.

Main diagnostics: pressure gauges, mass spectrometry, spectroscopy, P_{EC}, P_{ohm}

- Effect of conditioning and plasma operation on wall conditions
  - Gas balance

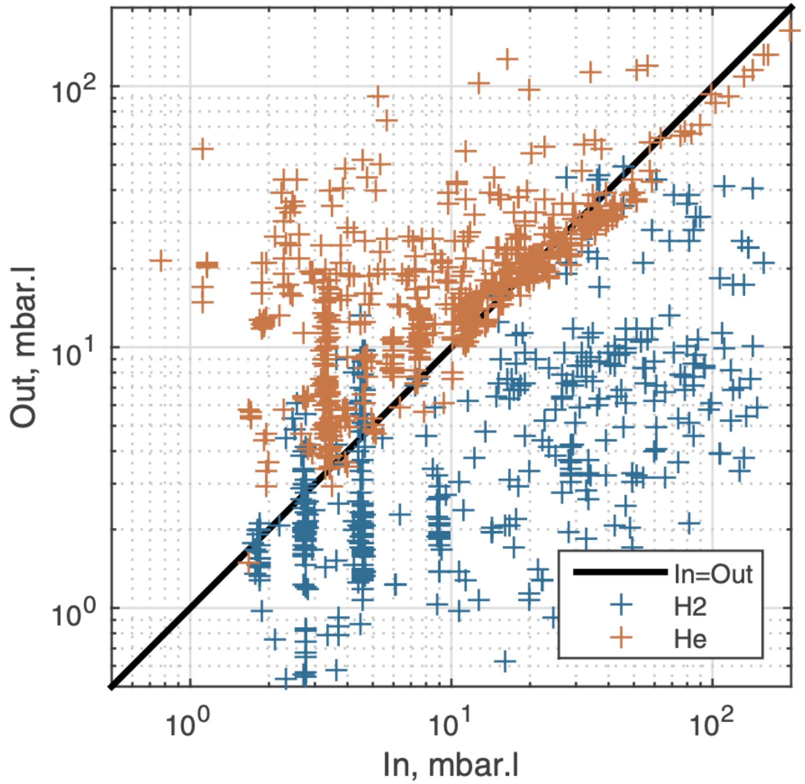


Fig. 3. Gas balance for all ECRH experiments of OP1.2a. He and H_2 discharges are shown as red and blue markers respectively.

Example: W7-X first divertor operation (Op1.2a)

[Wauters T., Nuclear Materials and Energy 17 (2018)]

Main diagnostics: pressure gauges, mass spectrometry, spectroscopy, P_{EC}, P_{ohm}

- Optimization of EC conditioning
  - Gas balance

Example EC duty cycle optimization: W7-X divertor operation (Op1.2b)

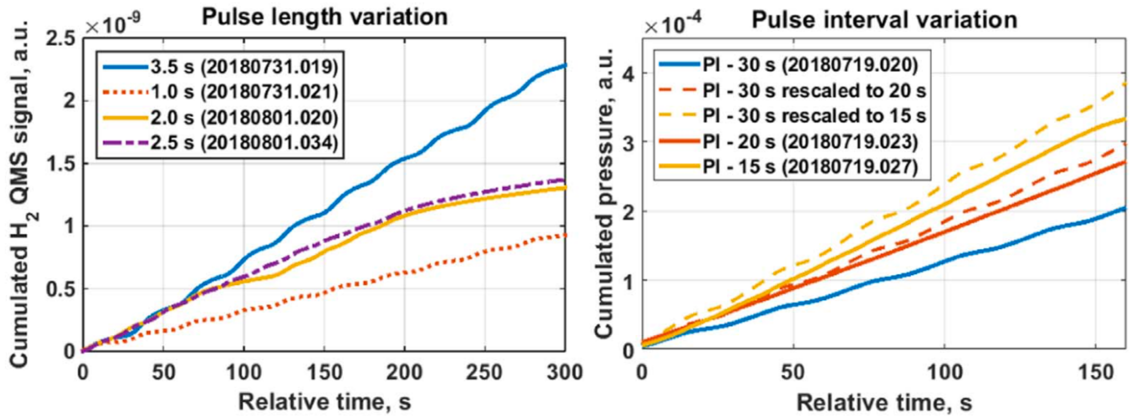


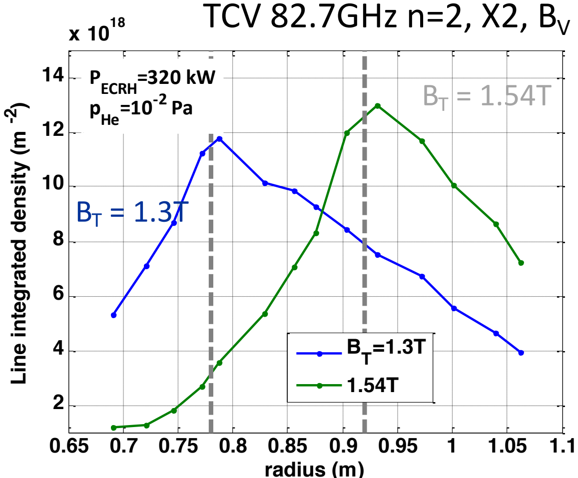
Figure 3. He pulse train optimisation by variation of the pulse length (left) and pulse interval (right). The cleaning efficiency is shown by cumulated hydrogen removal calculated from the partial pressure measurements of the QMS. Relative time equal to 0 indicates the beginning of the first pulses. The dashed lines on the right figure show the predicted hydrogen removal for 30 s pulse intervals rescaled to pulse intervals of 20 s and 15 s.

[Goriaev A., Phys. Scr. T171 (2020)]

Main diagnostics: pressure gauges, mass spectrometry, spectroscopy, P_{EC}, P_{ohm}

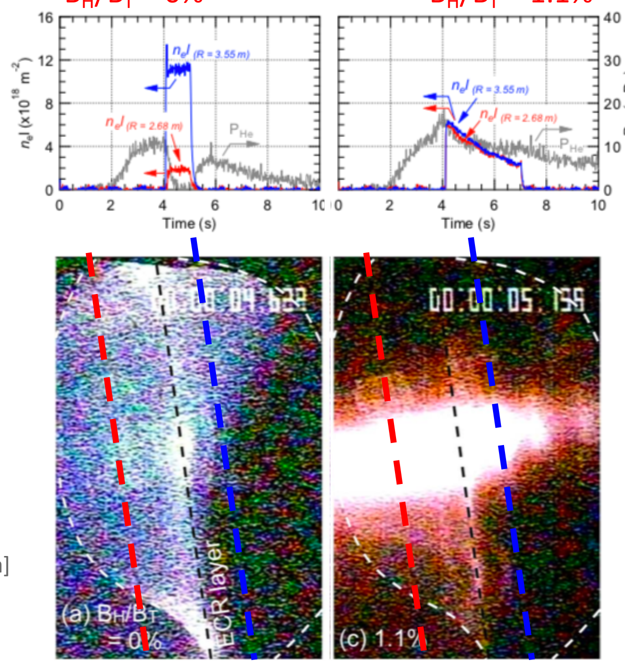
- ECRH plasma: produced and sustained by localized absorption of RF power at EC resonance/harmonics
- Poloidal fields are applied to maximize plasma wetted area and RF absorption
  - Horizontal B component: B_H
  - Vertical B component: B_V

TCV 82.7GHz n=2, X2, B_V



[D. Douai RCM-5 Naka]

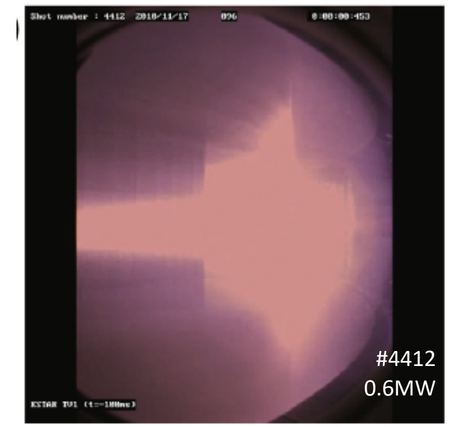
B_H/B_T = 0% JT-60U, X2 B_H/B_T = 1.1%



2.5MW, 1.86 T [M. Fukumoto et al, NME 2017]

KSTAR, X2

B_V + B_H



[K. Itami, S. Hong JNM 2013]

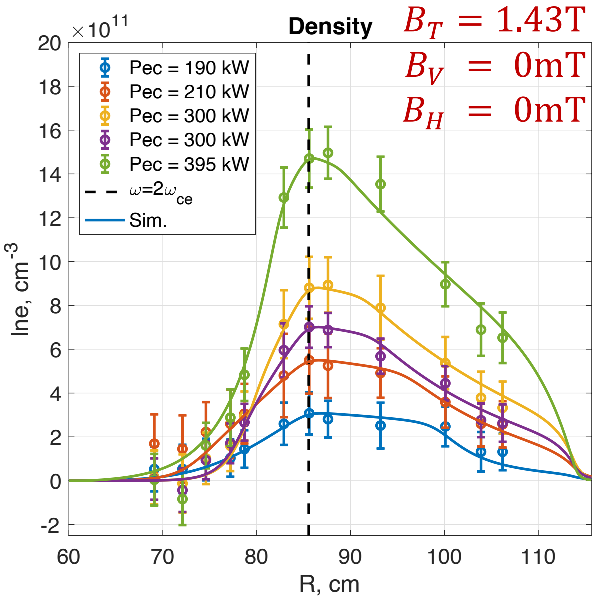
MODELING OF ECWC TO COMPLEMENT EXPERIMENTAL OBSERVATIONS

- Insights that modeling can deliver during campaign:
  - How much of the launched power is absorbed?
  - Does the plasma reach inboard, outboard?
- TOMATOR-1D studies radial transport and absorption in tokamak RF plasmas
  - Partially ionized plasma: He, H_2, CI-V
  - Reaction-Diffusion-Convection
    - Includes elementary collisions (EIRENE), elastic collisions, RF power and losses along field
  - 1D radial
    - Stiff equations, strong coupling. Computation time: hour(s)/simulation
  - Code is benchmarked to TCV data
    - Input: Experimental He and H_2 pressure, experimental density profile, vessel dimensions, toroidal and poloidal magnetic field, location of resonance layer
    - Output: Transport coefficients and absorption
    - EC TCV : X2 @ 82.7GHz
    - EC JT-60SA : X2 @ 110GHz + X1 @ 82GHz (HFS)

	Collisional reaction	Ref.
	Electron collisions with H and H^+	
1	$e + H \rightarrow e + H^*$	[4]
2	$e + H \rightarrow e + H^+ + e$	[4]
3	$e + H^+ + e \rightarrow e + H$	[4]
4	$e + H^+ \rightarrow H + h\nu$	[4]
	Electron collisions with H_2, H_2^+ and H_3^+	
5	$e + H_2 \rightarrow e + H_2^*$	[8]
6	$e + H_2 \rightarrow e + H + H$	[4]
7	$e + H_2 \rightarrow e + H_2^+ + e$	[4]
8	$e + H_2 \rightarrow e + H + H^+ + e$	[8]
9	$e + H_2^+ \rightarrow H_2 + h\nu$	[4]
10	$e + H_2^+ \rightarrow e + H + H^+$	[8]
11	$e + H_2^+ \rightarrow H + H$	[8]
	$e + H_2^+ \rightarrow H + H^*$	[8]
12	$e + H_3^+ \rightarrow H + H + H$	[8]
	$e + H_3^+ \rightarrow H_2 + H$	[8]
13	$e + H_3^+ \rightarrow e + H^+ + H + H$	[8]
	Electron collisions with He, He^+ and He^{2+}	
14	$e + He \rightarrow e + He^+ + e$	[4]
15	$e + He^+ \rightarrow He + h\nu$	[4]
16	$e + He^+ \rightarrow e + He^{2+} + e$	[4]
17	$e + He^{2+} \rightarrow He^+ + h\nu$	[4]
	Ion impact reactions	
18	CX: $H^+ + H$	[9]
19	CX: $H^+ + H_2$	[8]
20	CX: $H_2^+ + H_2$	[8]
21	CX: $He^+ + H$	[10]
22	CX: $He^+ + He$	[8]
23	CX: $He^{2+} + H$	[11]
24	CX: $He^{2+} + He \rightarrow He^+ + He^+$	[12]
25	CX: $He^{2+} + He \rightarrow He + He^{2+}$	[8]
26	$H_2^+ + H_2 \rightarrow H_3^+ + H$	[8]
27	$H^+ + H \rightarrow H^+ + H^*$	[8]
28	$H^+ + H_2 \rightarrow H^+ + H_2^*$	[8]
29	$H^+ + H \rightarrow H^+ + H^+ + e$	[8]
30	$H^+ + He \rightarrow H^+ + He^+ + e$	[8]
31	$H^+ + H_2 \rightarrow H^+ + H_2^+ + e$	[8]
32	$H^+ + H_2^+ \rightarrow H^+ + H^+ + H$	[8]
33	$He^+ + H_2 \rightarrow He + H^+ + H$	[8]

- Simulation vs. TCV He-ECRH plasma: Density profiles

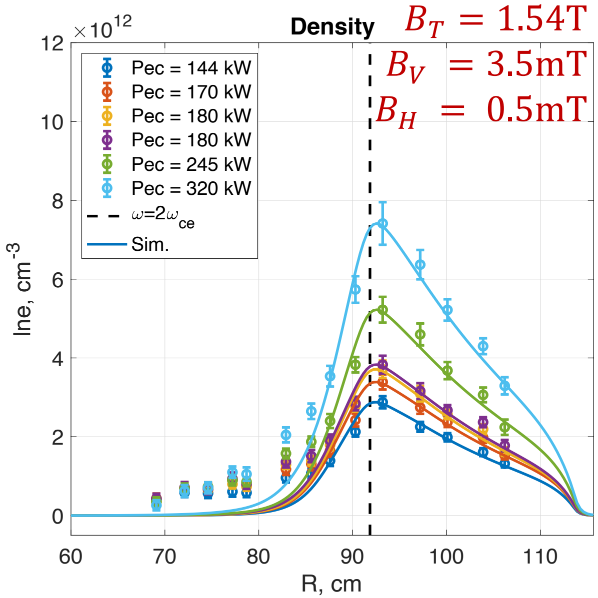
EC power scan @ 1.43T



$n_e = 0.3 - 1.5 \cdot 10^{12}\text{cm}^{-3}$

~8 hours, 500ms
5 parallel simulations

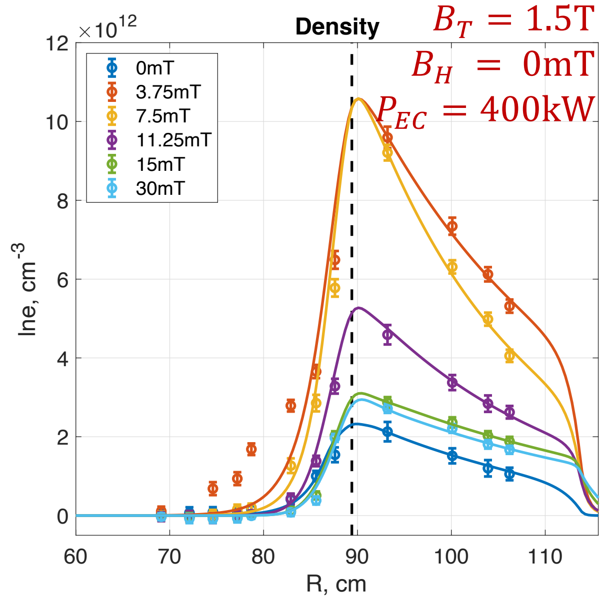
EC power scan @ 1.54T



$n_e = 3 - 7.5 \cdot 10^{12}\text{cm}^{-3}$

~11 hours, 200ms
6 parallel simulations

Vertical B scan @ 400kW

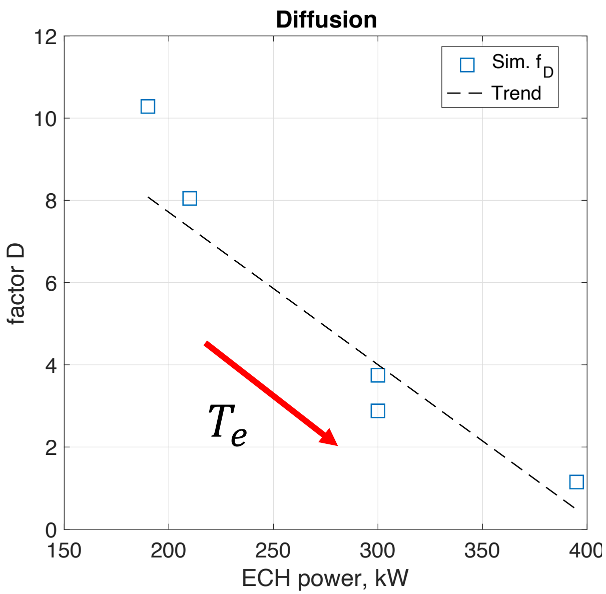


$n_e = 3 - 11 \cdot 10^{12}\text{cm}^{-3}$

~10 hours, 250-500ms
6 parallel simulations

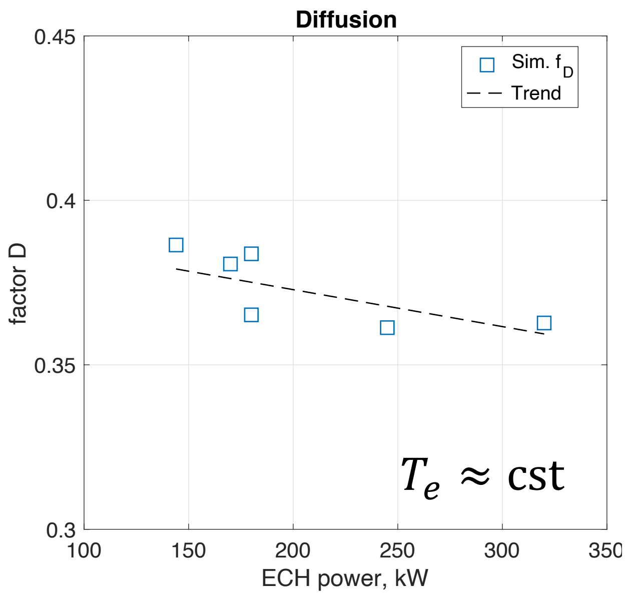
- Simulation vs. TCV He-ECRH plasma: Diffusion

EC power scan @ 1.43T



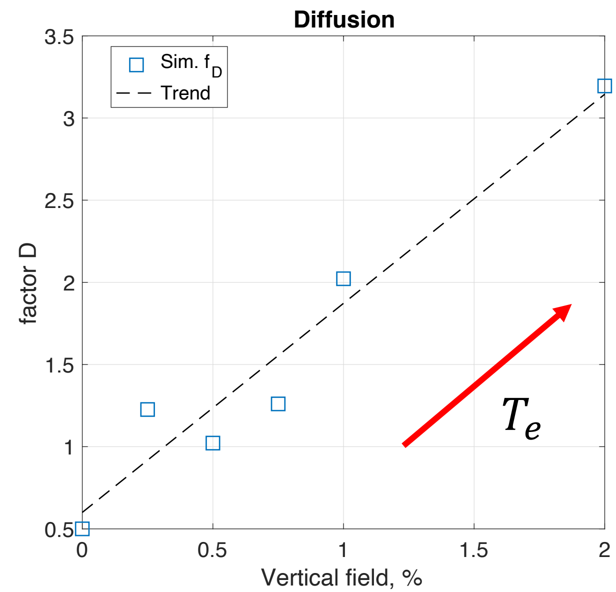
$n_e = 0.3 - 1.5 \cdot 10^{12} \text{cm}^{-3}$

EC power scan @ 1.54T



$n_e = 3 - 7.5 \cdot 10^{12} \text{cm}^{-3}$

Vertical B scan @ 400kW



$n_e = 3 - 11 \cdot 10^{12} \text{cm}^{-3}$

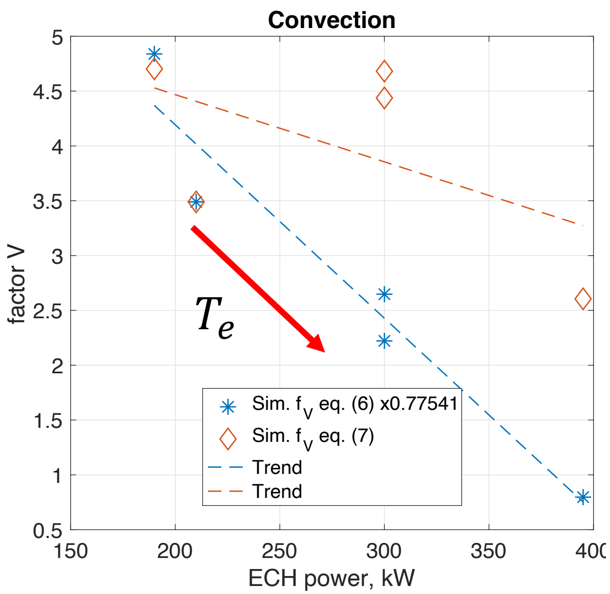
$$D_r = \underbrace{\frac{1}{3} f_D \nu_{c,i}}\left(r_i + \lambda_i \frac{B_r}{B_\varphi}\right) \underbrace{\lambda_i}$$

Bohm scaling

→ f_D = 1/16 (Bohm)
→ f_D = 0.21 (Spitzer)

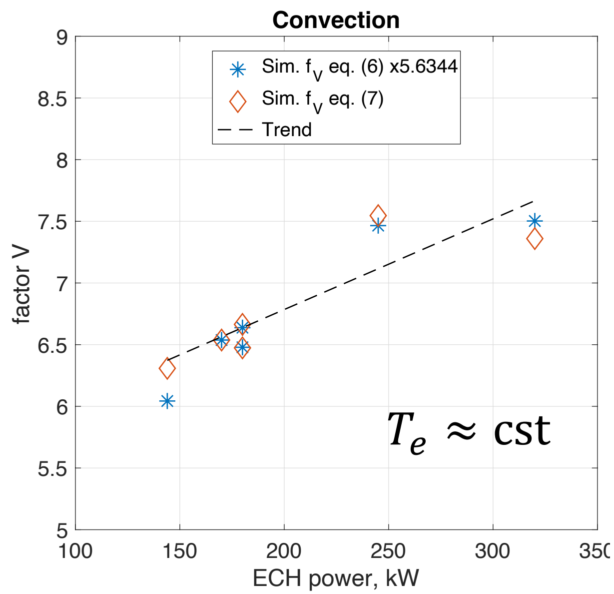
- Simulation vs. TCV He-ECRH plasma: Convection

EC power scan @ 1.43T



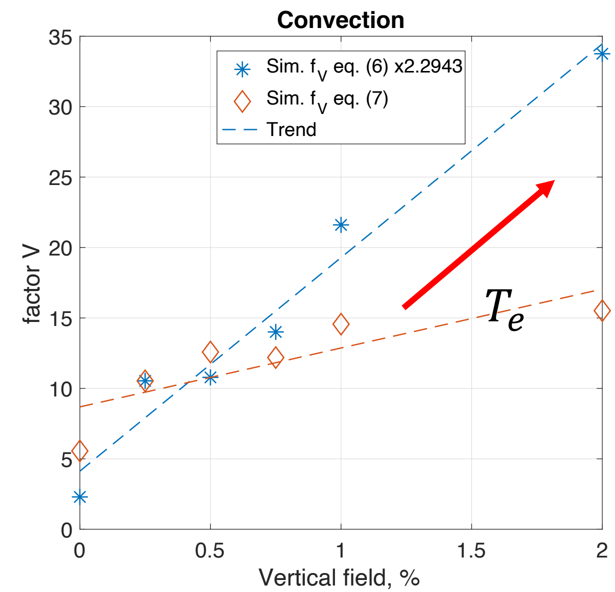
$n_e = 0.3 - 1.5 \cdot 10^{12}\mathrm{cm}^{-3}$

EC power scan @ 1.54T



$n_e = 3 - 7.5 \cdot 10^{12}\mathrm{cm}^{-3}$

Vertical B scan @ 400kW



$n_e = 3 - 11 \cdot 10^{12}\mathrm{cm}^{-3}$

$$V_r = \frac{q_e\, v_{\nabla B}}{\sigma_o B_T} = f_{V,(6)} \frac{T_e + T_i}{R B_T}$$

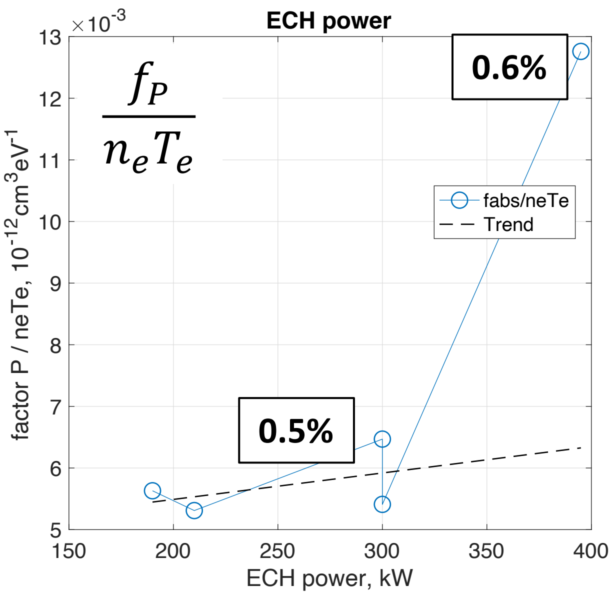
$$V_r = f_{V,(7)} \frac{2 D_r}{R}$$

V assumed independent on r

MODELING OF ECWC TO COMPLEMENT EXPERIMENTAL OBSERVATIONS

- Simulation vs. TCV He-ECRH plasma: EC power $$P_{EC,coupled} = f_P P_{EC,launched}$$

EC power scan @ 1.43T

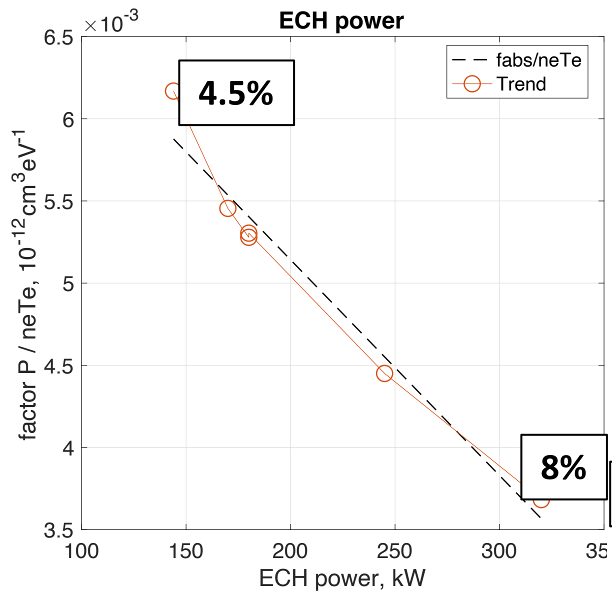


$n_e = 0.3 - 1.5 \ \cdot 10^{12}\mathrm{cm}^{-3}$

Pol. inj. angle 19°

Tor. inj. angle 7.5°

EC power scan @ 1.54T

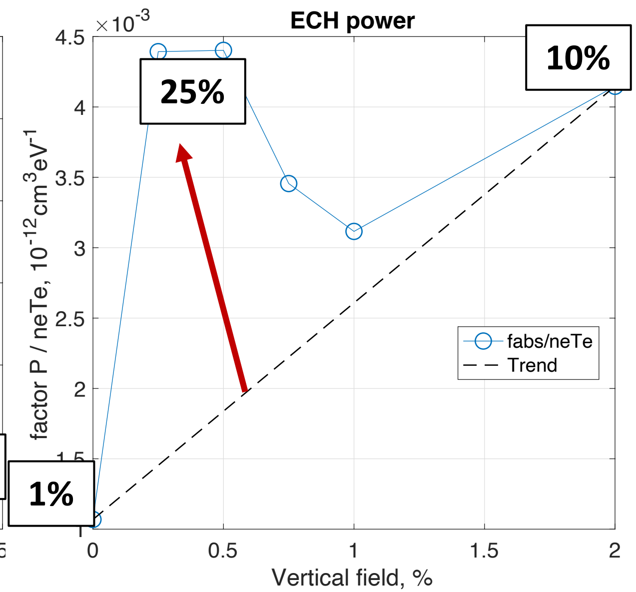


$n_e = 3 - 7.5 \ \cdot 10^{12}\mathrm{cm}^{-3}$

Pol. inj. angle $-10°$

Tor. inj. angle 5°

Vertical B scan @ 400kW



$n_e = 3 - 11 \ \cdot 10^{12}\mathrm{cm}^{-3}$

Pol. inj. angle 19°

Tor. inj. angle 7.5°

- $n_e < 10^{12}$: Absorption is about 0.5%
- $n_e > 10^{12}$: It seems better to reduce EC power density at the resonance layer
- Improved absorption at $B_V = 0.25 - 0.5\%$

MODELING OF ECWC TO COMPLEMENT EXPERIMENTAL OBSERVATIONS

- Required data from JT-60SA: density and temperature profiles, pressure
  - Thomson scattering for radial density and temperature profiles
  - Interferometry: $n_{e,l} > 5 \cdot 10^{18}\mathrm{m}^{-2}$ with 1ms time resolution
  - Camera images, EDICAM full frame ROI (adjust frame rate, test filter)
  - Gas content (pressure gauges, mass spectrometry)

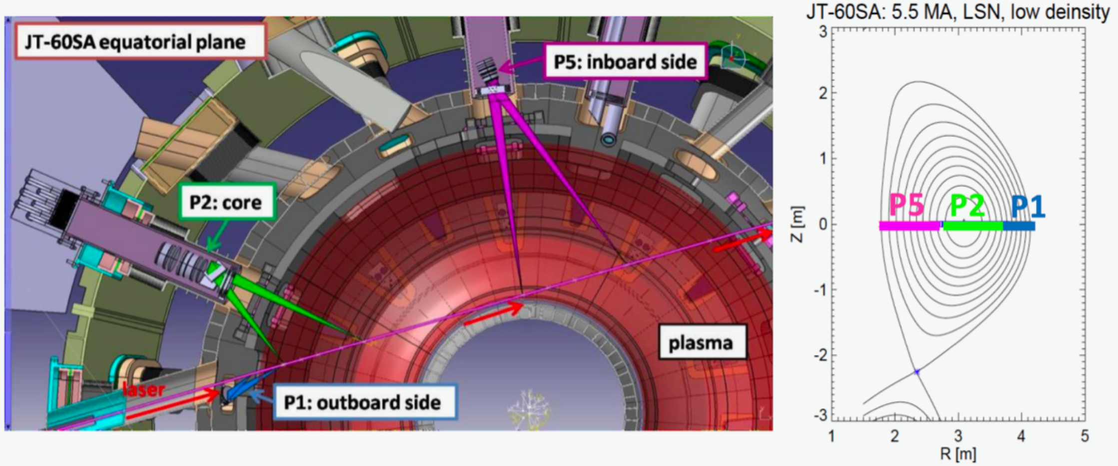


Figure 2.16-19 **(Left) Laser beam path of viewing fields in the vacuum vessel. (Right) Poloidal cross section of the measured area from each collection optics.**

<u>TS sensitivity</u>

$n_e > 5 \cdot 10^{18}\mathrm{m}^{-3}$

P1: $T_e > 10\mathrm{eV}$

P2: $T_e > 100\mathrm{eV}$

- Study transport scalings in multi-machine study, bridge the gap between TCV and JT-60SA
  - $D, V = f(\dots, R, a, b)$ and ECRH power absorption
  - ITPA DSOL proposal is being prepared : DIII-D and KSTAR

CONCLUSION

- Analysis of wall conditions during JT-60SA commissioning
  → contribute to development of the conditioning strategy
  - Evolution of outgassing after discharges + effect of conditioning on outgassing
  - Particle balance for all discharges : contribution of wall fueling
  - Gas content, mass spectrometry spectroscopy : impurity content

- Modeling of ECWC to complement experimental observations
  → Provided that density profiles are available
  - Reproducing plasma profiles using the code TOMATOR-1D gives insight on :
    - Transport processes
    - Required coupled power to equilibrate the power balance
    - Particle fluxes to HFS and LFS