EUROfusion

Edge and Divertor Modelling: Status and Perspectives

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Overview

Based on contributions by K. Galatzka (IPPLM), L. Balbinot (Uni PD), G. Rubino (ENEA), G. Falchetto (CEA)

- “Integrated” scenario modelling
- Modelling for C wall
- Modelling for W wall
- Future requirements and perspectives

Key scenarios addressed: nos. 2, 5 & 3

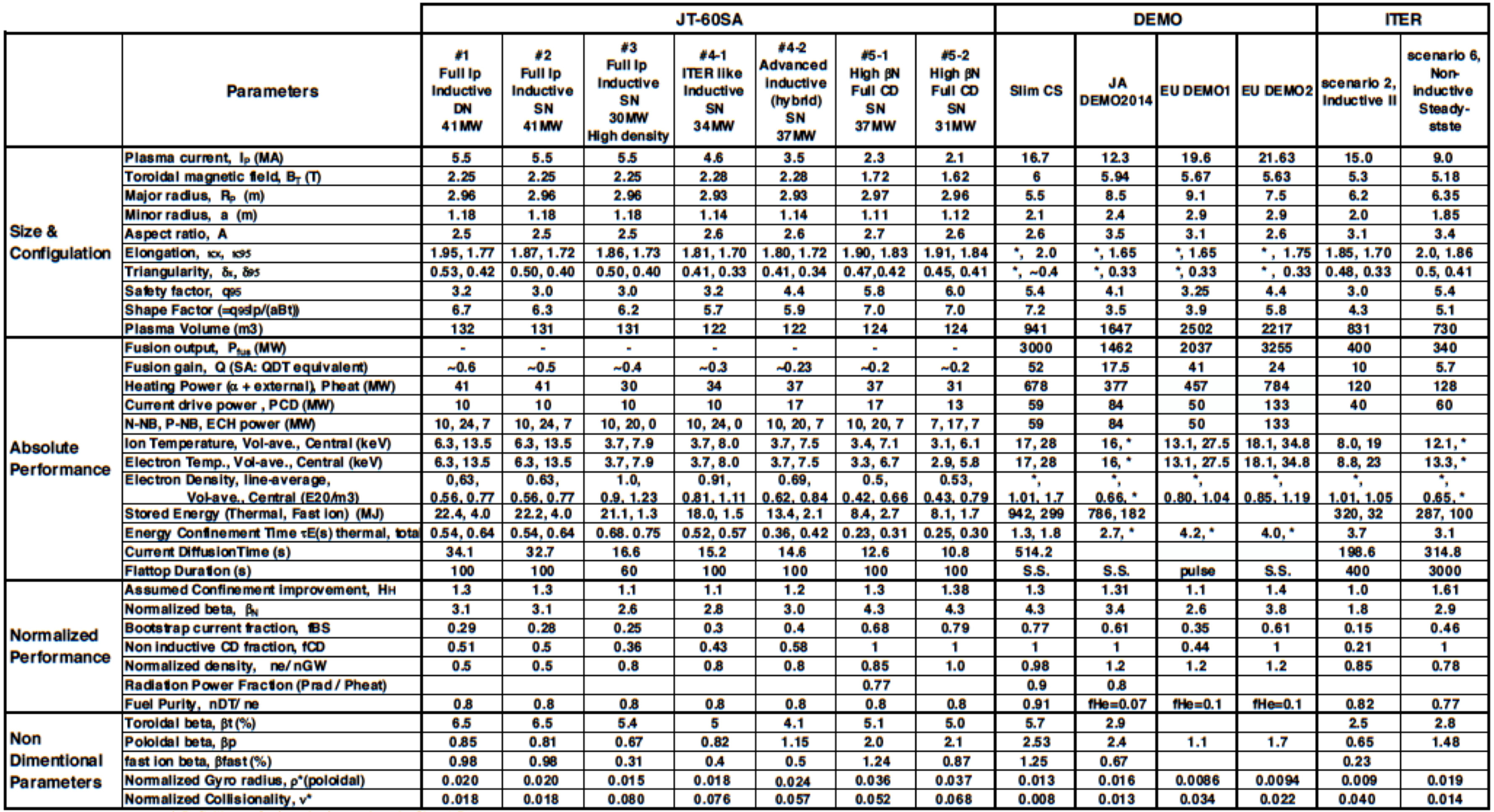


Table 1-3: Plasma Parameters for JT-60SA, DEMO and ITER

		JT-60SA							DEMO				ITER	
	Parameters	#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	Slim CS	JA DEMO2014	EU DEMO1	EU DEMO2	scenario 2, Inductive II	scenario 6, Non- inductive Steady- stste
Size & Configulation	Plasma current, I_p (MA)	5.5	5.5	5.5	4.6	3.5	2.3	2.1	16.7	12.3	19.6	21.63	15.0	9.0
	Toroidal magnetic field, B_T (T)	2.25	2.25	2.25	2.28	2.28	1.72	1.62	6	5.94	5.67	5.63	5.3	5.18
	Major radius, R_p (m)	2.96	2.96	2.96	2.93	2.93	2.97	2.96	5.5	8.5	9.1	7.5	6.2	6.35
	Minor radius, a (m)	1.18	1.18	1.18	1.14	1.14	1.11	1.12	2.1	2.4	2.9	2.9	2.0	1.85
	Aspect ratio, A	2.5	2.5	2.5	2.6	2.6	2.7	2.6	2.6	3.5	3.1	2.6	3.1	3.4
	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	*, 2.0	*, 1.65	*, 1.65	*, 1.75	1.85, 1.70	2.0, 1.86
	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	*, ~0.4	*, 0.33	*, 0.33	*, 0.33	0.48, 0.33	0.5, 0.41
	Safety factor, q_{95}	3.2	3.0	3.0	3.2	4.4	5.8	6.0	5.4	4.1	3.25	4.4	3.0	5.4
	Shape Factor (=q95Ip/(aBt))	6.7	6.3	6.2	5.7	5.9	7.0	7.0	7.2	3.5	3.9	5.8	4.3	5.1
	Plasma Volume (m3)	132	131	131	122	122	124	124	941	1647	2502	2217	831	730
Absolute Performance	Fusion output, P_{fus} (MW)	-	-	-	-	-	-	-	3000	1462	2037	3255	400	340
	Fusion gain, Q (SA: QDT equivalent)	~0.6	~0.5	~0.4	~0.3	~0.23	~0.2	~0.2	52	17.5	41	24	10	5.7
	Heating Power (α + external), Pheat (MW)	41	41	30	34	37	37	31	678	377	457	784	120	128
	Current drive power , PCD (MW)	10	10	10	10	17	17	13	59	84	50	133	40	60
	N-NB, P-NB, ECH power (MW)	10, 24, 7	10, 24, 7	10, 20, 0	10, 24, 0	10, 20, 7	10, 20, 7	7, 17, 7	59	84	50	133		
	Ion Temperature, Vol-ave., Central (keV)	6.3, 13.5	6.3, 13.5	3.7, 7.9	3.7, 8.0	3.7, 7.5	3.4, 7.1	3.1, 6.1	17, 28	16, *	13.1, 27.5	18.1, 34.8	8.0, 19	12.1, *
	Electron Temp., Vol-ave., Central (keV)	6.3, 13.5	6.3, 13.5	3.7, 7.9	3.7, 8.0	3.7, 7.5	3.3, 6.7	2.9, 5.8	17, 28	16, *	13.1, 27.5	18.1, 34.8	8.8, 23	13.3, *
	Electron Density, line-average, Vol-ave., Central (E20/m3)	0,63, 0.56, 0.77	0.63, 0.56, 0.77	1.0, 0.9, 1.23	0.91, 0.81, 1.11	0.69, 0.62, 0.84	0.5, 0.42, 0.66	0.53, 0.43, 0.79	*, 1.01, 1.7	*, 0.66, *	*, 0.80, 1.04	*, 0.85, 1.19	*, 1.01, 1.05	*, 0.65, *
	Stored Energy (Thermal, Fast Ion) (MJ)	22.4, 4.0	22.2, 4.0	21.1, 1.3	18.0, 1.5	13.4, 2.1	8.4, 2.7	8.1, 1.7	942, 299	786, 182			320, 32	287, 100
	Energy Confinement Time τE(s) thermal, total	0.54, 0.64	0.54, 0.64	0.68. 0.75	0.52, 0.57	0.36, 0.42	0.23, 0.31	0.25, 0.30	1.3, 1.8	2.7, *	4.2, *	4.0, *	3.7	3.1
	Current DiffusionTime (s)	34.1	32.7	16.6	15.2	14.6	12.6	10.8	514.2				198.6	314.8
	Flattop Duration (s)	100	100	60	100	100	100	100	S.S.	S.S.	pulse	S.S.	400	3000
Normalized Performance	Assumed Confinement improvement, HH	1.3	1.3	1.1	1.1	1.2	1.3	1.38	1.3	1.31	1.1	1.4	1.0	1.61
	Normalized beta, β_N	3.1	3.1	2.6	2.8	3.0	4.3	4.3	4.3	3.4	2.6	3.8	1.8	2.9
	Bootstrap current fraction, fBS	0.29	0.28	0.25	0.3	0.4	0.68	0.79	0.77	0.61	0.35	0.61	0.15	0.46
	Non inductive CD fraction, fCD	0.51	0.5	0.36	0.43	0.58	1	1	1	1	0.44	1	0.21	1
	Normalized density, ne/nGW	0.5	0.5	0.8	0.8	0.8	0.85	1.0	0.98	1.2	1.2	1.2	0.85	0.78
	Radiation Power Fraction (Prad / Pheat)						0.77		0.9	0.8				
	Fuel Purity, nDT/ ne	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.91	fHe=0.07	fHe=0.1	fHe=0.1	0.82	0.77
Non Dimentional Parameters	Toroidal beta, βt (%)	6.5	6.5	5.4	5	4.1	5.1	5.0	5.7	2.9			2.5	2.8
	Poloidal beta, βp	0.85	0.81	0.67	0.82	1.15	2.0	2.1	2.53	2.4	1.1	1.7	0.65	1.48
	fast ion beta, βfast (%)	0.98	0.98	0.31	0.4	0.5	1.24	0.87	1.25	0.67			0.23	
	Normalized Gyro radius, ρ*(poloidal)	0.020	0.020	0.015	0.018	0.024	0.036	0.037	0.013	0.016	0.0086	0.0094	0.009	0.019
	Normalized Collisionality, ν*	0.018	0.018	0.080	0.076	0.057	0.052	0.068	0.008	0.013	0.034	0.022	0.040	0.014

* Definitions of ρ* and ν* are given in Chapt.5.

➔ Low (2,5) and high (3) density scenarios; PFCs: 2,5 ➔ C, 3 ➔ C, W

Modelling of Impurity seeding for scenarios of Initial Research Phase II

Aim: Verify if it is possible to allow safe handling of divertor PFCs at 10MW/m^2 with C first wall by radiative energy exhaust for Scenario #5 and Scenario #3

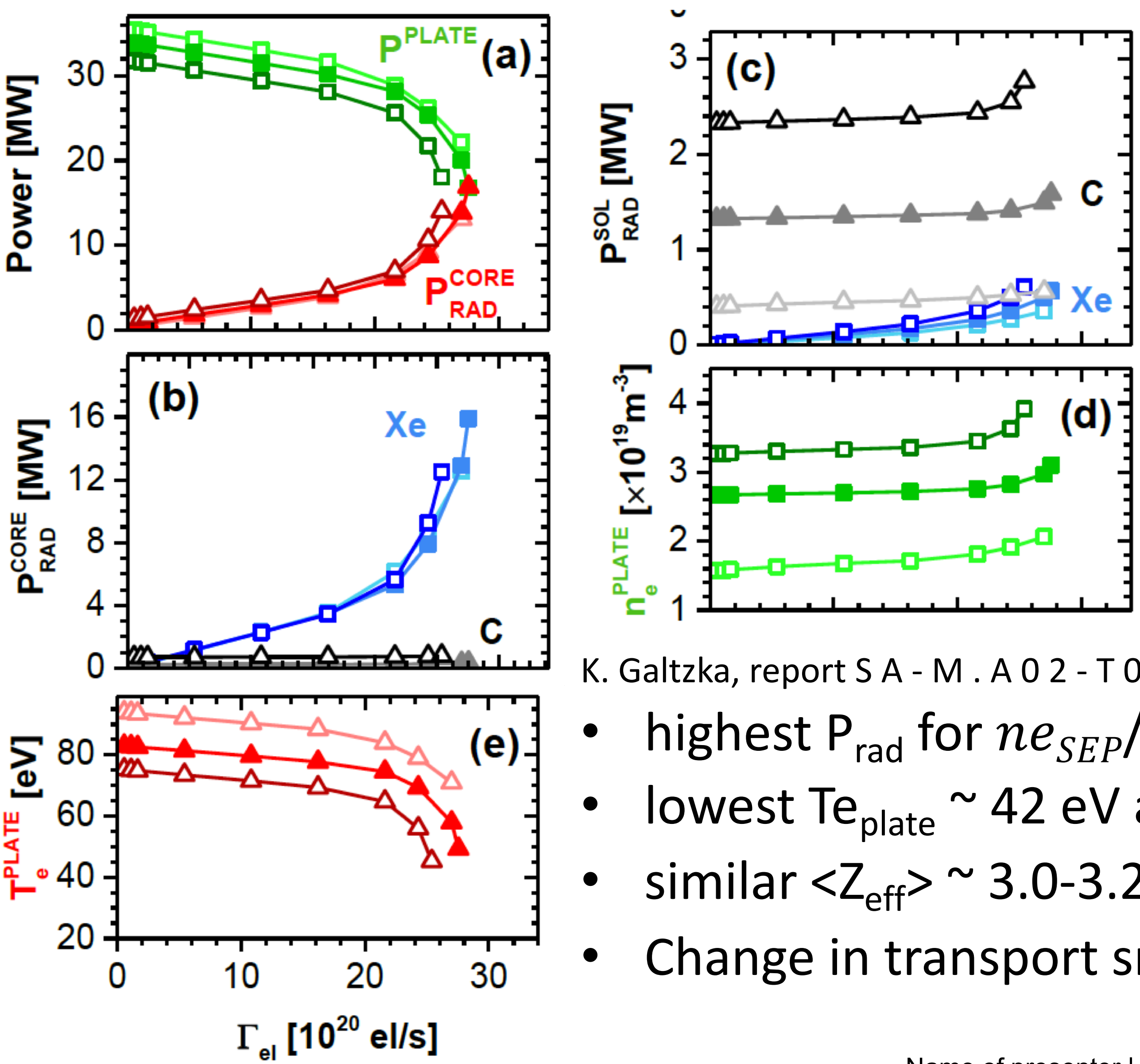
Requires: Compatibility of Exhaust solution with core impurity content AND „edge“ density

Tool: Integrated simulations, e.g. COREDIV or COCONUT (includes EDGE2D-EIRENE)

COREDIV:

- recycling Xe
- non-recycling Sn
  - initial value $ne_{SEP}/<ne>$= 40% (30% & 50% variation)
  - D_{perp}, Chi_{perp} 0.5 m2/s (0.25 m^2/s, 0.75 variation)

COREDIV results for Xe and C wall



Similar results for Ne, Ar, Kr – reported in past

K. Galtzka, report SA-M.A02-T003-D003

- highest P_{rad} for ne_{SEP}/<ne>=0.5
- lowest Te_{plate} ~ 42 eV and P_{plate}17.7 MW
- similar <Z_{eff}> ~ 3.0-3.2 for Xe and Sn
- Change in transport small effect on P_{rad}

COREDIV / EDGE2D-EIRENE / Coconut Scenario no. 3

- Comparison of COREDIV and EDGE2D-EIRENE results was made
  - → radiation and power to target similar (~10%)
- Therefore motivation to attempt Coconut

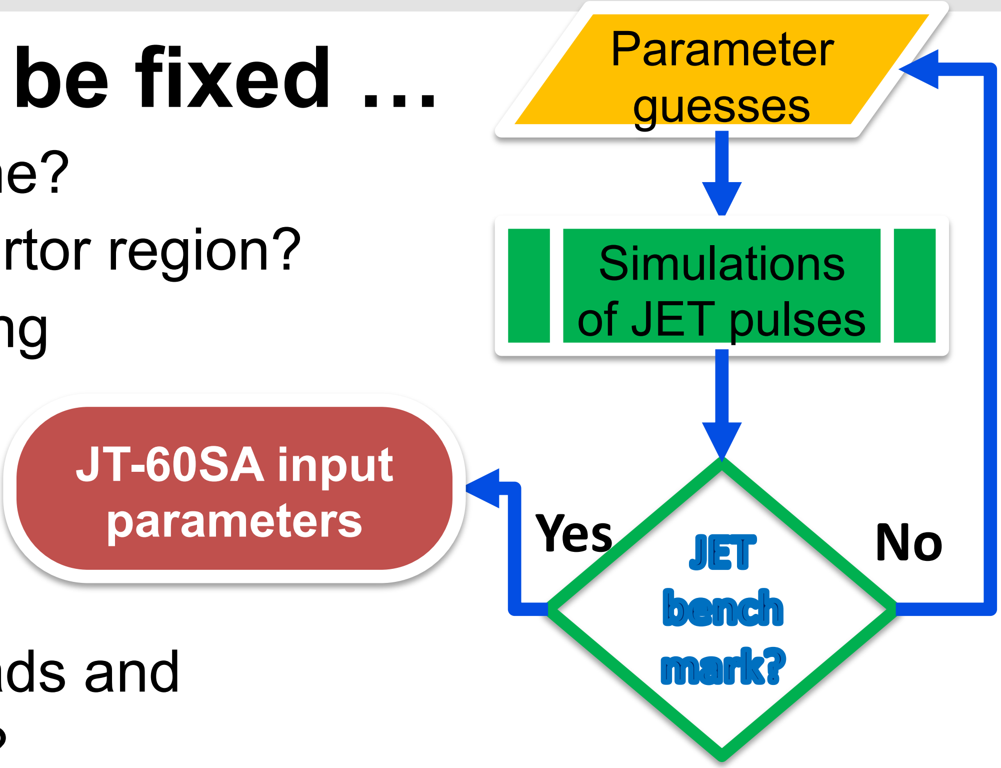
  → lack of time and manpower

  → intermediate results stored

Project concept for transport simulations

Free parameters to be fixed …

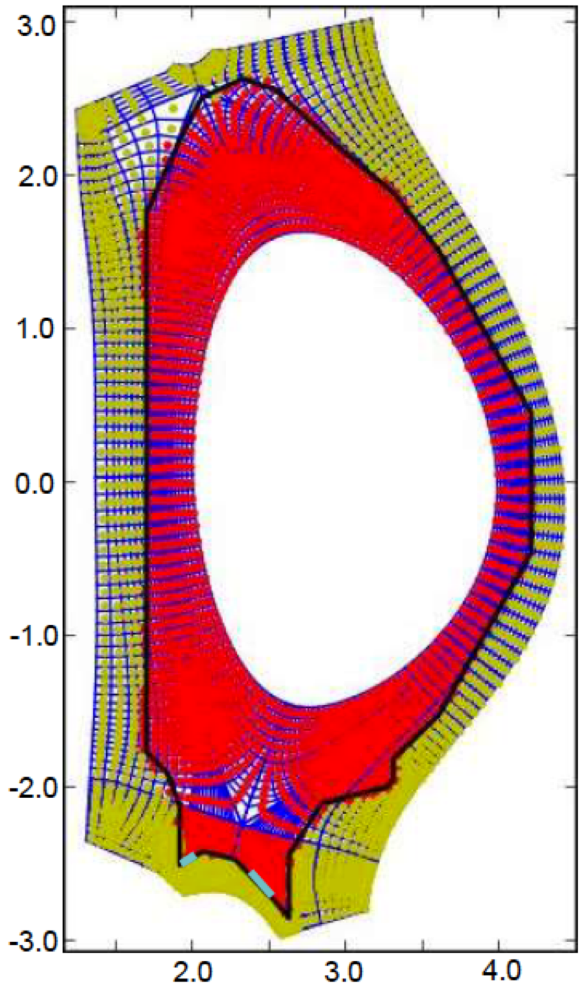
- Transport profile at midplane?
- Transport profile in the divertor region?
- Is C production and recycling well estimated?



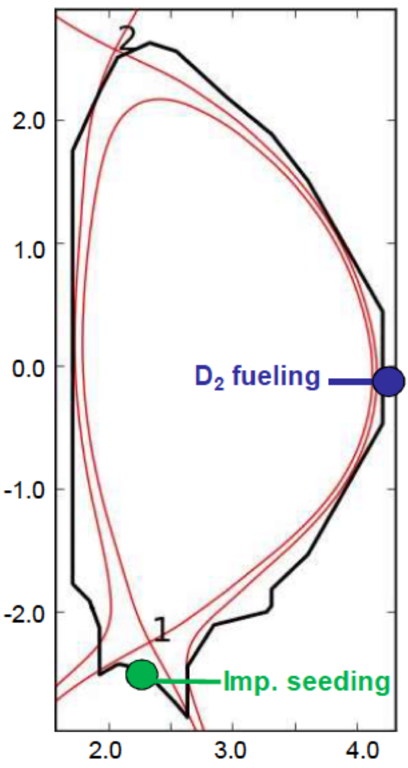
… to evaluate

- Which are the predicted loads and temperature to the divertor?
- Which is the minimum radiatiated power to have sustainable power flux to the divertor?
- Which is the impurity level required to radiate such power? Ne and Ar performances
- Is the scenario realistic? If not, how can it be modified?

SOLEDGE2D-EIRENE for C wall and scenario 2



	Standard Input parameters
Input power P_{sol}	36 MW [5]
Recycling D/Ar/Ne	1.0
Recycling C	0.0
D puffing	1.0×10^{22} s^{-1}
Ar seeding	$1.0\times10^{20}s^{-1}$
Ne seeding	$4.0\times10^{20}s^{-1}$

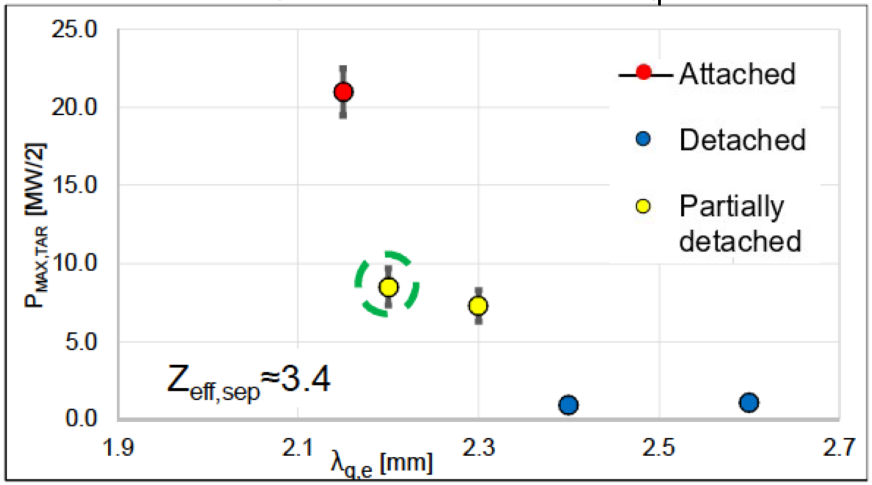


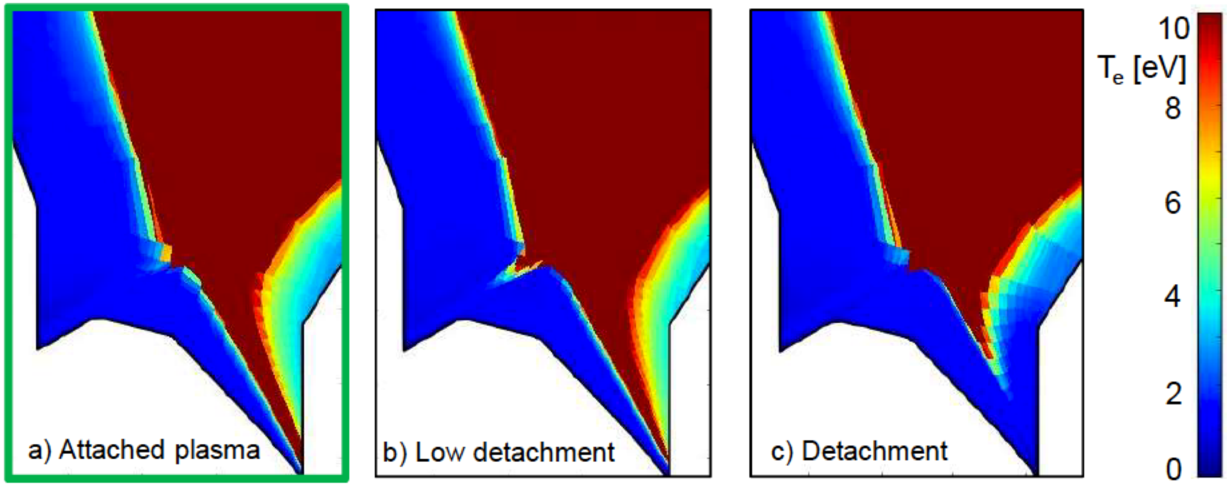
L. Balbinot et al. 3rd IAEA TM Div Concepts, 2019, Vienna

Preliminary results for C wall w. SOLEDGE2D

- To reduce power to divertor plates below 15MW/m^2 [1], $n_{e,sep}$ minimum value is ≈ 2.0x10^{19}m^{-3} [*Tab 4*]
- Eich scaling predicts $\lambda_{q,e}$ < 2mm; with $Z_{eff,sep}$ ≈ 3.5, higher $\lambda_{q,e}$ is required to have sustainable power flux to the outer divertor [*fig. 10*]
- Higher impurity level is required if the scaling is respected.

Power to target as function of λ_q





- ❖ High asymmetry level between inner and outer divertor
- ❖ Validated transport model predicts attached plasma at outer divertor with using standard input parameters

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Preliminary key results from SOLEDGE2D

- The model has been applied to JT-60SA ITER-like scenario
- 20 MW is the maximum input power to obtain sustainable heat flux to the divertor in simulations with only carbon impurities;
- Full power scenario may be sustainable with $_{Zeff,sep} \geq 4$ with Ar impurities only if $n_{e,sep} \approx 2.0x1019m^{-3}$ if the Eich scaling respected
- Lower density would require higher $Z_{eff,sep}$, ➔ higher core radiation.

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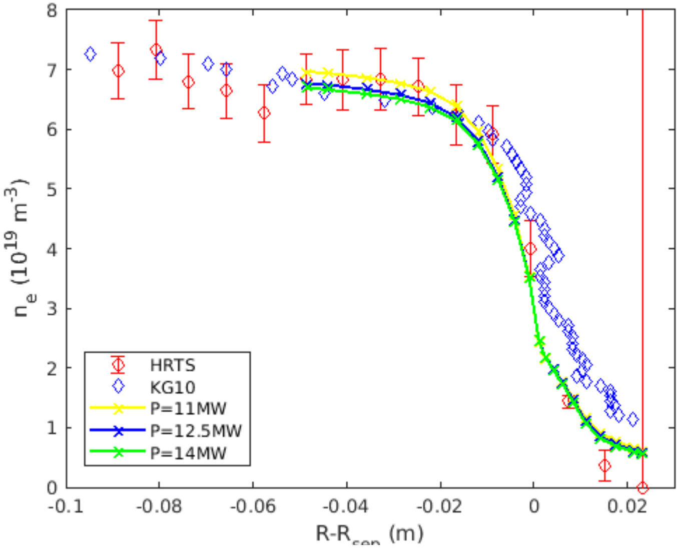
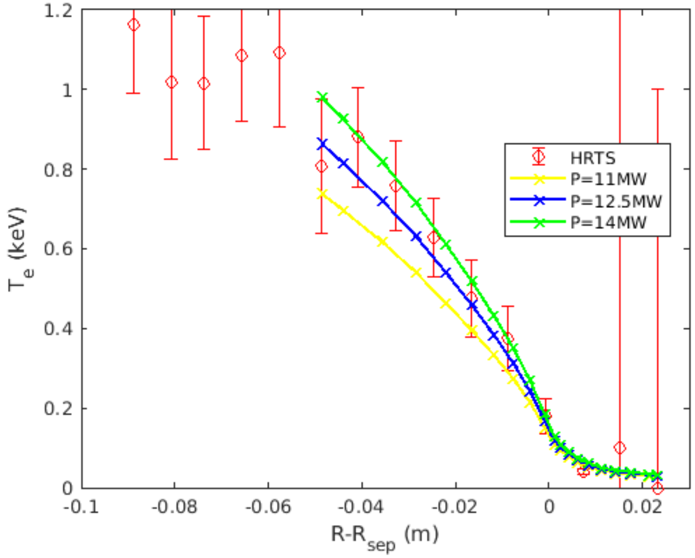
Preparation for W wall: Defintion of JT-60SA input parameters

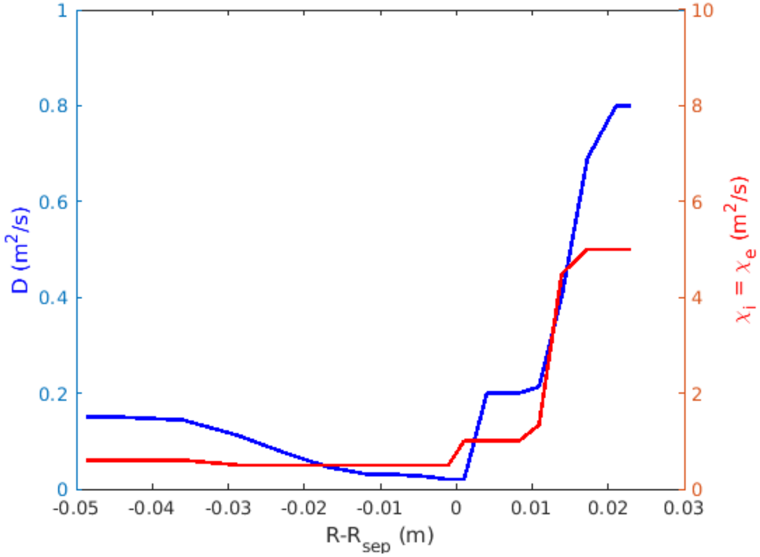
- Assessment of the divertor conditions in high radiating scenario (N injection) and metallic wall (W) in Scenario 3 of JT60SA by means of SOLPS-ITER
- Validation with JET experiment (85419 @ t=18s) to define D and χ in JT-60SA simulations

	JET	**JT-60SA**
B_T (T)	2.7	2.25
I_p (MA)	2.5	5.5
R (m)	3	2.96
r (m)	0.9	1.18
k_x	1.72	1.86
δ	0.4	0.4
q_{95}	3.2	3
$<n_e>$ (10^{19} m^{-3})	7	10
P_{AUX} (MW)	18	30
P_{IN} (MW)	12.5	20
$\lambda_{q,Eich}$ (mm)	1.7	1.4

“calibrating” against JET upstream profiles



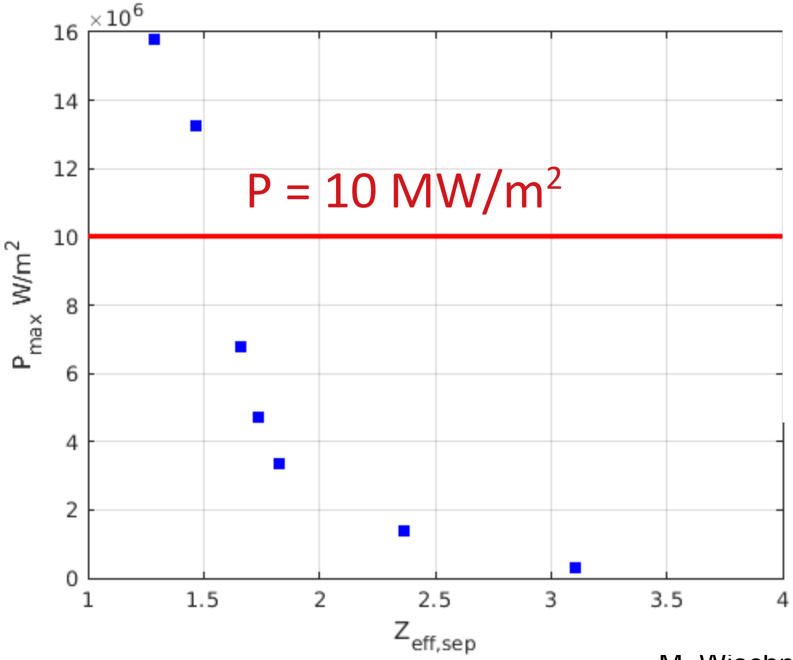


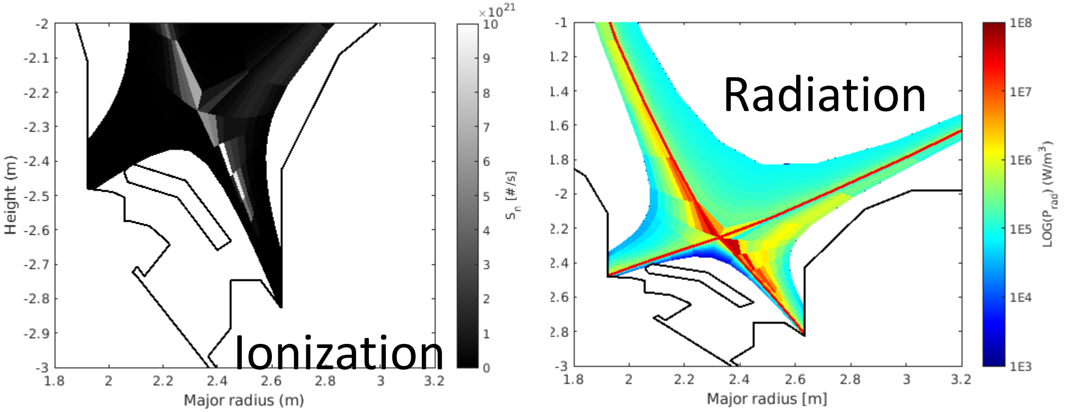


- $n_{e,OMP}$ and $T_{e,OMP}$ profiles compared with HRTS and KG10 ones
- Rescaling ~2 in JT-60SA to get extrapolated $\lambda_{q,Eich}$

First analysis of divertor plasma conditions (I)

- First “rapid” scan to assess ‘contamination’ (Z_{eff} @separatrix) to reach detachment and safe operation conditions ($P_{max,t}$=10 MW/m^2 , $T_{e,t}$ < 5 eV in steady state)
- T_e < 5 eV is the most demanding constrain (➔ Zeff > 2 and f_{rad} > 50%)
- Manageable values $P_{max,t}$ for smaller value of Z_{eff}
- To achieve full detachment an X-point radiation and Z_{eff} > 3 are needed

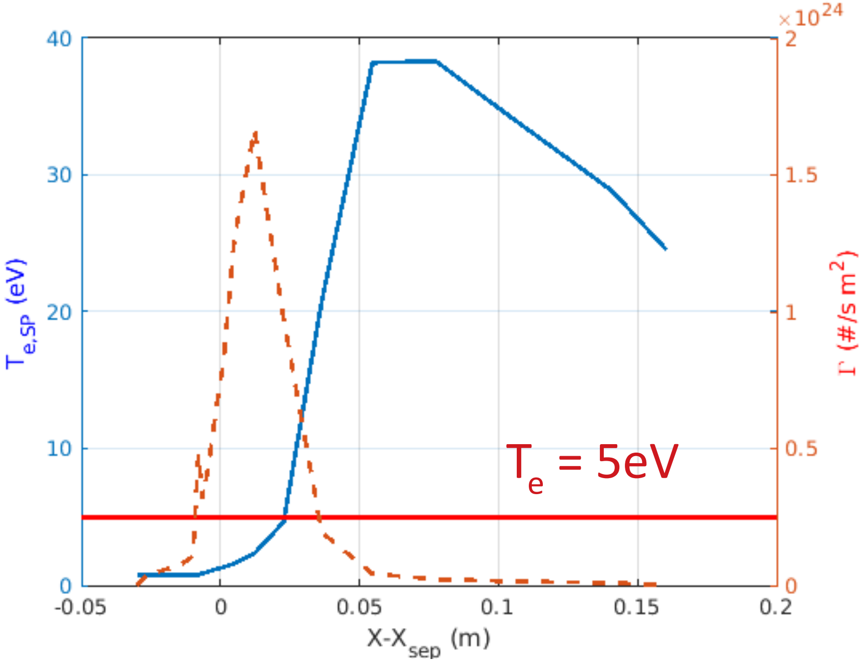




Z_{eff} = 3.1

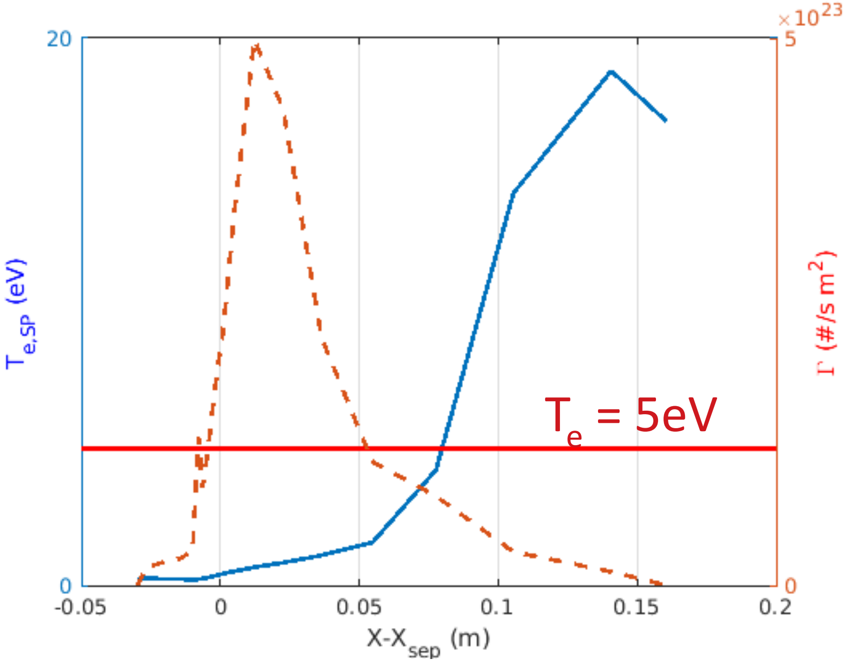
First analysis of divertor plasma conditions (II)

$Z_{eff} = 1.66$



NOT Safe!!!

$Z_{eff} = 2.36$



Safe

Driving mechanism for detachment

- Analysis of individual terms in balance equations ➔ verify balances and identify most important terms leading to detachment

- Analysis of energy balance in outer divertor shows role of the heat diffusion into PFR along separatrix.

- Transport across separatrix to PFR and corner position of outer strike point in V-shaped divertor geometry ➔ decrease the $T_{e,OSP} < 5eV$, not sufficient to trigger the detachment (in model)

- For high f_{rad} (>50%) radiation dominant term to decrease T_e and trigger detachment

- **Future and ongoinng work**

- Analysis of particles and momentum equations are on going

Preliminary results of divertor plasma conditions

- More accurate study by considering 2 puffing slots (D and N) and pump
- Starting point, fixed Γ_D, P=20MW and varying Γ_N
- Preliminary results: increase of Γ_N (and Z_{eff} up to 3.5) leads to
  - sudden drop in $n_{e,sep}$ by ~30% as seen in previous SOLPS5.0 simulations of AUG (F. Reimlod, NME, 2017)
  - increase in T_e (> 10eV @ sep.) and $P_{max,OT}$ (> 10 MW/m^2) on target
  - limited increase in $P_{rad,tot}$ (f_{rad} ~15% @ Z_{eff}=1.5 vs. f_{rad} ~32% @ Z_{eff} = 3.5)

Future and ongoing work

- Scan Γ_D and Γ_N to define possible operational window
- 2 different power levels (P=20MW and P=25 MW) to deal with uncertainty
- Analysis of terms of balance equations ➔ identify driver to detachment

Proposal to use *SOLEDGE3X*

[Bufferand et al., Nucl. Mat. Energy 18 (2019)]

- propose to use β version of the new SOLEDGE3X code
  - offers advantage of enabling modelling a **scenario with arbitrary species mix**
  - is being verified against SOLEDGE2D on ITER cases
  - ! converter exists for grid/mesh and outputs SOLEDGE2D ➔ SOLEDGE3X
- Equilibria/mesh of the desired scenario are welcome ☺

Fmerges the capabilities of SOLEDGE2D & TOKAM3X

✓Zhdanov collisional closure: **multi-component plasma**

✓englobes **in a single code** a hierarchy of models for edge-SOL modelling :

2D/3D transport simulation

3D turbulence simulations

✓**improved parallelization** hybrid MPI/OpenMP : different species solved in parallel

✓**coupled to EIRENE**

G. Falchetto 18/02/2020 Modelling kick-off meeting

Future requirements and perspectives

- Still appear to miss a reliable solution for low density C scenarios
- Comparison with Sonic results
- Running transport simulations with active drift terms and for high divertor collisionality w. high SOL transport → may modify operational window
- Re-examine particle through put and feedback with work on pumping system
- Better integration with models and analysis of core / pedestal transport and pedestal stability
- 3D SOL simulations (e.g. EMC3-EIRENE) for impact of MP coils and power load compatibility of PFCs
- Better prescription of perpendicular SOL transport assumptions especially for $d_{sep} > \lambda_q$
- Model of high Z impurity transport for migration studies in view of W wall (IMPGYRO, EIRENE(KIT), DIVIMP)