Where to locate DEMO in a one-step-to-an-FPP strategy

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1. Introduction

In the EU 'fast track' strategy to a Fusion Power Plant (FPP), DEMO is the single step between ITER and an FPP, allowing a safe extrapolation to an industrial plant [1]. It is however not obvious how to derive from this goal a DEMO design point. Here, we argue that for the plasma scenario, there must not be a large development step from DEMO to FPP, since there is no machine other than DEMO itself to qualify it. In a similar manner, ITER should prepare the DEMO scenario since it will be the largest device of its kind and the one that allows to study α-particle dynamics and self-heating. It follows that there should be a stepladder approach ITER-DEMO-FPP that keeps the plasma scenario as close as possible such that DEMO effectively becomes a technology demonstrator and not a plasma physics experiment. The stepladder must be designed starting from an attractive FPP and then deriving a DEMO from it that is not necessarily economically attractive, but extrapolates credibly to the FPP. Likewise, scaling down to ITER will inform how ITER has to be operated in phase 2 (steady state after achieving Q=10 in phase 1) to prepare the DEMO scenario.

We describe the plasma scenario in terms of dimensionless quantities β_N, q, H and f_{GW}. In addition, we chose a constant absolute value of the density since this will be a key parameter for divertor performance. Different from previous approaches, this means that ρ^* and ν^* will vary throughout the stepladder, but we assume the three machines to be big enough, i.e. ρ^* low enough [2], that gyro-Bohm scaling holds and ν^* so low that collisionless physics prevails in all three. This leaves open the choice of machine parameters A, R and B. Fixing A to the ITER value, constant f_{GW} and absolute density lead to B/R = const. Then, at constant q, β_N and A, and employing a simple 0-D model [3], this leads to a scaling $P_{fus} \propto R^7 \propto B^7$ which means that both B and R will increase according to $P_{fus}^{1/7}$ in the stepladder. Furthermore, the power needed to drive the current in steady state varies surprisingly weakly through the stepladder, only with $P_{fus}^{1/7}$, so that going from DEMO to an FPP will lead to a significant decrease in recirculating power. Concerning the exhaust problem, we assume that DEMO and the FPP use the ITER divertor solution. As figure of merit for divertor performance, we use $P_{sep}B/(qR) < P_{sep}B/(qR)|_{ITER}$, assuming that the width of the wetted area scales with poloidal gyroradius. On the other hand, in order to stay in H-mode, P_{sep} must exceed the power threshold P_{LH} by a fraction f_{LH}, so that, $P_{sep} > const.\ f_{LH} (nB)^{0.78} R^2$. This gives a window for P_{sep} that must be finite for all machines in our stepladder. In section 2, we will present a stepladder based on these arguments.

While these simple scaling arguments can be used to scope the stepladder, more detailed modelling of the plasma scenario is required to account for profile effects and physics not captured in the simple approach, such as the deviation of the fusion reactivity from the T^2 scaling in the optimum range. In section 3, we therefore present 1-D ASTRA simulations that confirm and refine the results from the 0-D arguments. A summary and conclusions are presented in section 4.

2.) 0-D stepladder

We now present an example of a stepladder based on 0-D scaling arguments [3] that serves as an illustration for the approach outlined in the previous section. Starting from an FPP that could be attractive as a base load energy supply, we chose a steady-state tokamak with electrical energy output around 1 GW, and aim for a minimum recirculating electrical power, which we assume to be dominated by P_{CD}. Minimizing P_{CD} means operation at high β_N and q. However, increasing q will decrease Q, which can be compensated by assuming a regime with higher H. The operation at higher q also has the benefit of reduced disruptivity, and increasing β_N usually leads to a regime of higher H, such as the 'improved H-mode' regime [4]. We hence set a target of β_N=3.5, q = 4.5 and H=1.2, which have been obtained together in improved H-mode discharges, albeit not under fully non-inductive conditions yet. We also note that recently, fully non-inductive operation in this regime has been shown on ASDEX Upgrade at slightly lower current, i.e. q_{95}=5.4 [5] and lower β_N. For the absolute value of the density, we note that it should not be much smaller than in the ITER Q=10 scenario to have confidence in the divertor solution developed there, although lowering the density will decrease P_{CD}. Based on considerations about the density limit in future low collisionality devices [6], we set f_{GW}=1.2 and aim for $n \approx 10^{20}$ m^{-3}.

Guided by PROCESS runs that indicate a solution in this range with P_{fus} = 3.5 GW and 60 % bootstrap fraction at B=6.1 T and R=8.5 m, resulting in $P_{CD} \approx 120$ MW, we chose this as a model point for an FPP. Assuming a thermodynamic efficiency of 0.35, this plant will generate an electrical power of 1.225 GW (neglecting heat generated in the blanket), so that assuming a 50% wall plug efficiency for P_{CD}, the net electrical output is of the order of 1 GW (assuming P_{CD} is the dominant internal sink), and the recirculating power fraction is about 20 %. From q=4.5 and assuming the ITER aspect ratio and shape, we get I_p = 16.6 MA. At f_{GW} = 1.2, the absolute value of the average density is 8.4 x 10^{19} m^{-3}.

We now analyse where a DEMO should sit on the stepladder. Assuming we want to generate several 100 MW, we aim for P_{fus} = 2 GW which would give close to 0.5 MW net electric power at a recirculating power fraction of 35 %, which would be unacceptable for an economic FPP, but the credibility of achieving the 20% mentioned above for the FPP would be quite high. This means that B and R should be lower by $(3.5/2)^{1/7}$ = 1.083, so that DEMO sits at 7.85 m and 5.6 T, with I_p = 14 MA. Next, we determine how ITER should be operated to demonstrate this scenario. Scaling down the radius, the fusion power will be around 400 MW, and ITER should be operated at I_p = 9 MA, B = 4.5 T. However, to be consistent with the planned heating upgrade of ITER to 120 MW, the H-factor should rather be 1.4. While challenging, such H-factors have been achieved in improved H-mode and we will see in the next section that they can be relaxed using a 1-D model.

Finally, we examine how the exhaust problem will vary throughout the stepladder. For ITER, P_{LH}=60 MW, so unseeded operation at will be well above the threshold (f_{LH} = 2.4). On the other hand, limiting P_{sep} to the Q=10 value, which means that the divertor solution qualified in ITER can be used in DEMO and the FPP, the maximum allowable P_{sep} is 143 MW, so that after subtracting 30% of intrinsic radiation, there is almost no need for an additional core radiation. Testing the radiative scenario, however, can be done by adding seed impurities down to f_{LH} = 1, i.e. P_{sep}=60 MW and $f_{rad,core}$ = 0.7 (i.e. 60 MW intrinsic and 80 MW seeded radiation). It also means that a large window of core radiation fraction can be explored in ITER in this scenario. As expected from the arguments above, this window shifts and becomes narrower in DEMO and FPP. In DEMO, we find f_{LH}=1.25 and $f_{rad,core}$=0.725 (which can still be tested in ITER). The same exercise for the FPP shows that the operational window shrinks to f_{LH} = 1 and $f_{rad,core}$ = 0.825, and it has to be assessed in further work how significant this is, i.e. what the margins in P_{sep} and P_{LH} are.

3.) 1-D ASTRA modelling

We have modelled the plasma scenario using the 1-D time dependent ASTRA code [7]. The kinetic profiles are based on the 'improved H-mode' scenario [4], i.e. sit on a pedestal from which the

	ITER		DEMO		FPP	
	ASTRA	0D-Ansatz	ASTRA	0D-Ansatz	ASTRA	0D-Ansatz
$P_{fus}\,[MW]$	390	400	2000	2000	3650	3500
$R_{tor}\,[m]$	6.2	6.2	8.09	7.85	9.28	8.5
$a\,[m]$	2.066	2.066	2.695	2.616	3.089	2.833
$B_{tor}\,[T]$	4.50	4.50	5.77	5.60	6.66	6.10
$I_P\,[MA]$	9.00	9.00	14.85	14.00	19.80	16.60
H	1.3	1.4	1.2	1.2	1.2	1.2
β_n	2.99	3.5	2.96	3.5	3.02	3.5
q_{95}	4.8	4.5	4.87	4.5	4.62	4.5
f_{bs}	0.546	0.62	0.475	0.62	0.482	0.62
$f_{rad,core}$	0.512	0.3 - 0.7	0.709	0.72 - 0.78	0.814	0.825
Q	3.92	3.3	17.4	∞	30.4	∞
f_{LH}	1.45	1.0 - 2.4	1.24	1.0 - 1.25	0.876	1

Table. 1: Stepladder device parameters from ASTRA and 0-D

temperature profile is continued via a 'stiff gradient' transport assumption while the density profiles come from theoretical expectations based on TGLF [6]. Since the latter are quite peaked, the line-averaged density values exceed the Greenwald-Limit, but the pedestal top stays below, consistent with the approach outlined in [6]. The absolute value of energy transport is adjusted such that the target H-factor from the 0-D assumption is met. Table 1 shows the results for both 0-D and 1-D approach.

As can be seen, the 0-D stepladder can be reproduced, but we had to slightly increase the major radius, field and current for DEMO and the FPP, mainly due to the fact that the high temperatures reached in these devices lead to a weaker than quadratic scaling of P_{fus} with T_i. Note that the ASTRA bN values are thermal, while the 0-D mode used the total bN, but adding the fast particle pressure for all three devices will still put them below the 0-D Ansatz. We also note that, as expected, FPP is close to the LH threshold, but the value given in the table is calculated subtracting the total radiation, while the scaling used has an intrinsic radiation of about 30% that was not corrected for. Using P_{sepLH}=0.7P_{totLH} brings this value to f_{LH}=1.25, indicating sufficient margin. Finally, the ITER target could be reached with H=1.3 instead of H=1.4 in the 0-D approach.

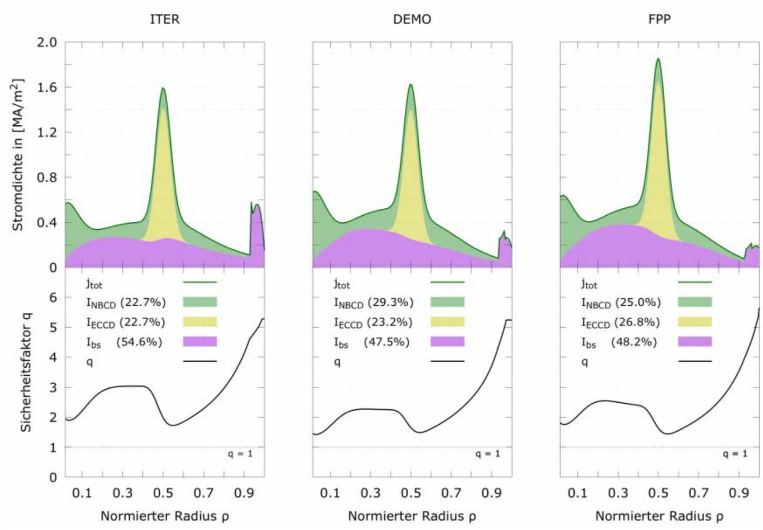

Fig. 1: modelled current and q-profiles for the three devices

Concerning the current and q-profiles, Fig. 1 shows the results for the three devices. It can clearly be seen that the profiles are quite similar, verifying the idea of a common operational scenario. In the simulations, we have split the CD power 50:50 between NBCD and ECCD, with NBCD providing a broad contribution while ECCD is localized around the deposition radius ρ_{dep}. We fixed the total power and the NBCD efficiency (γ_{15}=0.3 for ITER and γ_{15}=0.45 for DEMO and FPP, where the values are normalized to 15 keV and in agreement with [8]), and varied the ECCD efficiency to obtain steady state. This procedure makes sure the operational point does not change when changing the ECCD driven current and the resulting $\gamma_{15,ECCD}$ can then be evaluated. With 120 MW for all three devices (used in Fig.1), we obtain $\gamma_{15,ECCD}$=0.13 for ITER, well within reach, $\gamma_{15,ECCD}$=0.31 for DEMO (at the upper limit of what was found in [8]), and $\gamma_{15,ECCD}$=0.48 for FPP, which is beyond the presently expected values. However, an increase in power to 150 MW would bring this back to $\gamma_{15,ECCD}$=0.28, indicating that this can be cured at the expense of reduced Q. A scan in ρ_{dep} shows that the optimum position for ECCD is around ρ_{dep}=0.5, due to a balance of increasing j_{bs} (due to increasing central q) and decreasing j_{ECCD} (due to reduced T_e).

H-Faktor	$I_P\,[MA]$	$\bar{n}_{e,v}\,[10^{19}m^{-3}]$	$I_{Ohm}\,[MA]$	$U_{ind}\,[mV]$	$\beta_{N,therm}$	$\tau_{pulse}\,[h]$
1.2	14.85	7.81	0.00	0.00	2.99	∞
1.15	15.15	7.97	1.17	3.65	2.89	10.26
1.1	15.55	8.18	2.19	7.38	2.80	4.94
1.05	16.00	8.41	3.34	12.58	2.70	2.81
1.0	16.45	8.65	4.59	17.02	2.60	2.02
0.95	16.80	8.83	5.77	22.76	2.46	1.47

Table 2: pulse length in DEMO for decreasing H-factor

We have also studied the option of a 'flexi-DEMO', i.e. the use of our DEMO device as designed with ASTRA as a pulsed tokamak in case the envisaged scenario turns out to be too optimistic. Table 2 shows the result of a scan in H-factor – reducing H leads to a loss in confinement which can be recovered by increasing the current and density (at constant f_{GW}), but will, for given CD power, lead to a pulsed operation. However, the resulting numbers, which have been obtained using simple scaling relations and hence need to be refined in future work, indicate that even at H=1.0, this device would still provide a pulse length of about 2 hrs, in line with the EU conservative DEMO design.

4.) Summary and conclusions

In this contribution, we have outlined a coherent strategy to develop a stepladder ITER-DEMO-FPP has been outlined. We assume that the plasma scenario is similar in all three devices to ensure a credible extrapolation from device to device. Starting from an economically attractive FPP, i.e. a device that operates in steady state recirculating electrical power below 20%, we determine the DEMO design point by scaling the FPP down to a machine that generates several 100 MW of electrical power at higher recirculating power fraction, keeping in mind that for DEMO, sound extrapolability and not economic attractiveness is the main goal. The plasma scenario employed also informs how to run ITER in phase 2 (i.e. after demonstrating Q=10 in phase 1).

A first exploration of this strategy is encouraging: we have shown that a consistent set of steady state devices can be designed that leads to an attractive FPP under conditions representative of 'improved H-mode' operation. A validation of this scenario should be possible in the next years in present day tokamaks, albeit without the possibility to demonstrate the integration with the exhaust scenario (i.e. high radiation fraction). Finally, we note that the DEMO step on the stepladder can be operated as an attractive pulsed device as a fallback solution, opening up the possibility to combine the present EU approach of two alternative scoping studies for a conservative and an advanced DEMO.

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5.) References

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