Plasma scenarios for JT60SA

(as part of the EFDA task on the review of version 2.1 of JT60SA research plan)

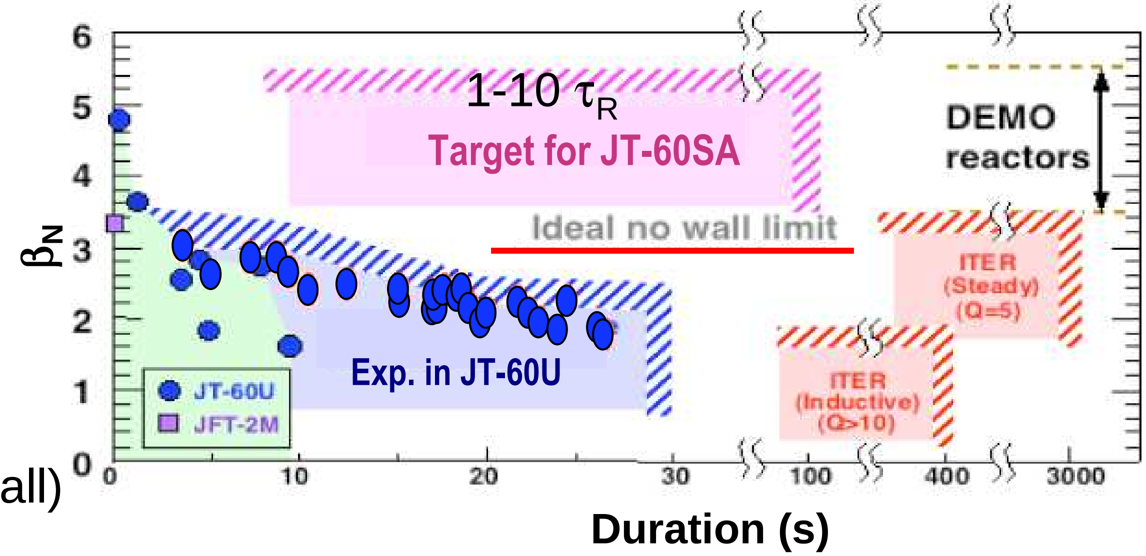
The JT-60SA objectives

- **Objectives (chap 3)**
  - **Support and contribute to ITER as a large SC tokamak**
  - **Develop advanced tokamak operation scenario for DEMO: $\beta_N \geq 4.5$ for 100s**

- **Assumptions**

JET – class machine

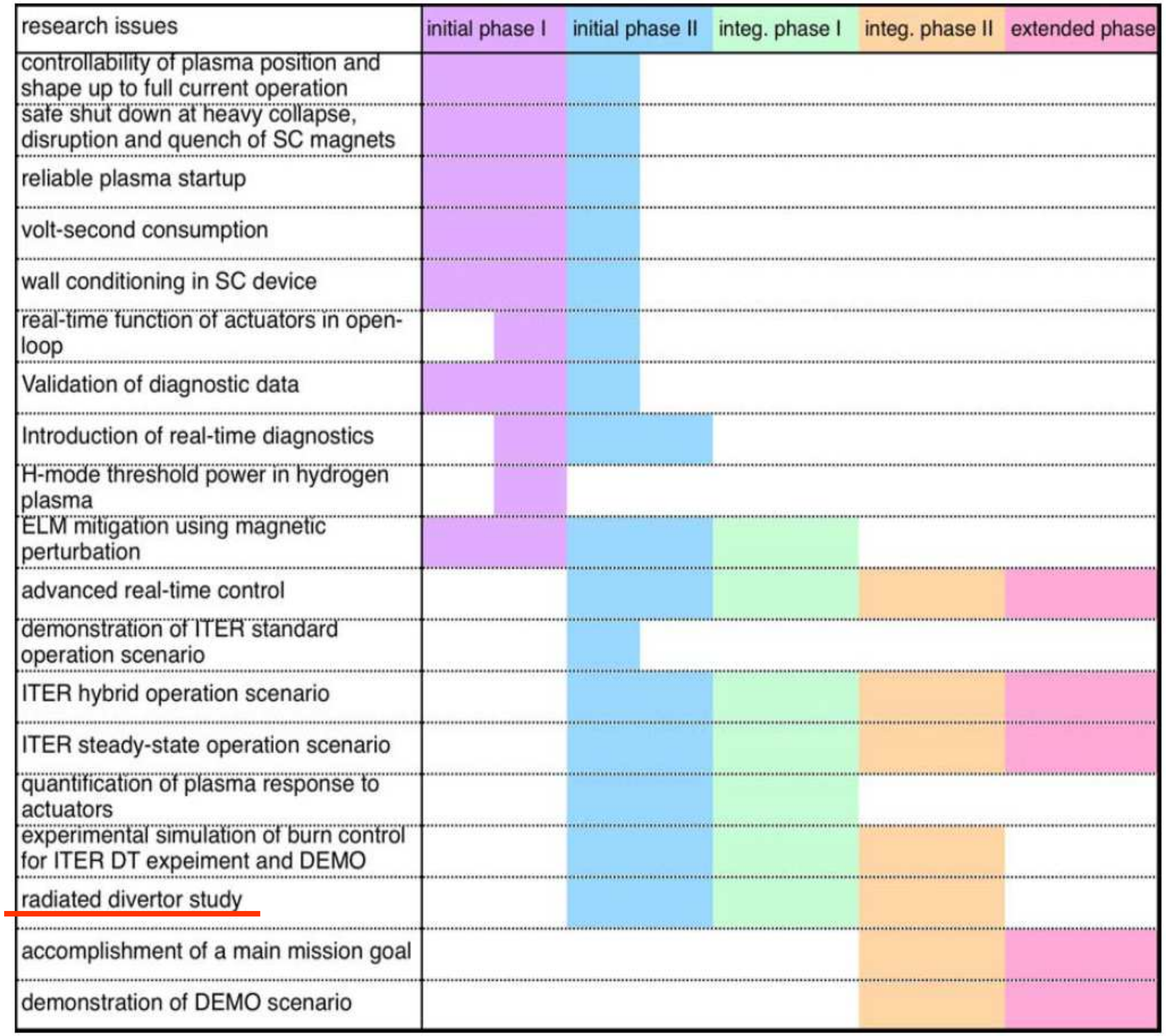
- High δ and κ shaped plasma
- 10MW of N-NB off-axis 500keV
- 24MW of P-NB balanced
- ECH system 7MW
- Stabilisation coils for RWM/ELMs
- Water-cool divertor (but not the wall)
- 100s pulse capability.
- DMV, pellet,
- (…)



DEMO Slim-CS design (R=5.5 m, βN=4.3), Tobita et al., Nucl. Fusion 49 (2009) 075029

➔ Links with ITER & DEMO research plan is described in Chapter 2

JT-60SA experimental programme for scenario development



research issues	initial phase I	initial phase II	integ. phase I	integ. phase II	extended phase
controllability of plasma position and shape up to full current operation	🟪	🟦			
safe shut down at heavy collapse, disruption and quench of SC magnets	🟪	🟦			
reliable plasma startup	🟪	🟦			
volt-second consumption	🟪	🟦			
wall conditioning in SC device	🟪	🟦			
real-time function of actuators in open-loop	🟪	🟦			
Validation of diagnostic data	🟪	🟦			
Introduction of real-time diagnostics	🟪	🟦			
H-mode threshold power in hydrogen plasma	🟪				
ELM mitigation using magnetic perturbation	🟪	🟦	🟩		
advanced real-time control		🟦	🟩	🟧	🟥
demonstration of ITER standard operation scenario		🟦			
ITER hybrid operation scenario		🟦	🟩	🟧	🟥
ITER steady-state operation scenario		🟦	🟩	🟧	🟥
quantification of plasma response to actuators		🟦	🟩		
experimental simulation of burn control for ITER DT expeiment and DEMO		🟦	🟩	🟧	
radiated divertor study		🟦	🟩	🟧	
accomplishment of a main mission goal				🟧	🟥
demonstration of DEMO scenario				🟧	🟥

- machine commissioning
- test in-vessel components
- optimise scenario reliability
- define operational domain
- test real-time controls

ITER scenarios

DEMO scenarios

Chapter 3 present structure

1. Initial Research Phase I

1-2. Safe shut down at heavy collapse, disruption and quench of SC magnets
1-3. Reliable plasma start-up
1-4. Volt-second consumption
1-5. Wall conditioning in SC devices
1-6. Real-time functions of actuators in open-loop
1-7. Validation of diagnostic data and introduction of real-time diagnostics
1-8. H-mode threshold power in hydrogen plasmas and ELM mitigation using magnetic perturbation

2. Initial Research Phase II

2-1. Advanced real-time control
2-2. ITER hybrid operation scenario study
2-3. Steady-state (SS) operation scenario study
2-4. Quantification of plasma response to actuators
2-5. Experimental simulation of burn control for ITER DT experiments and DEMO
2-6. Radiative divertor study
2-7. Demonstration of ITER standard operation scenario

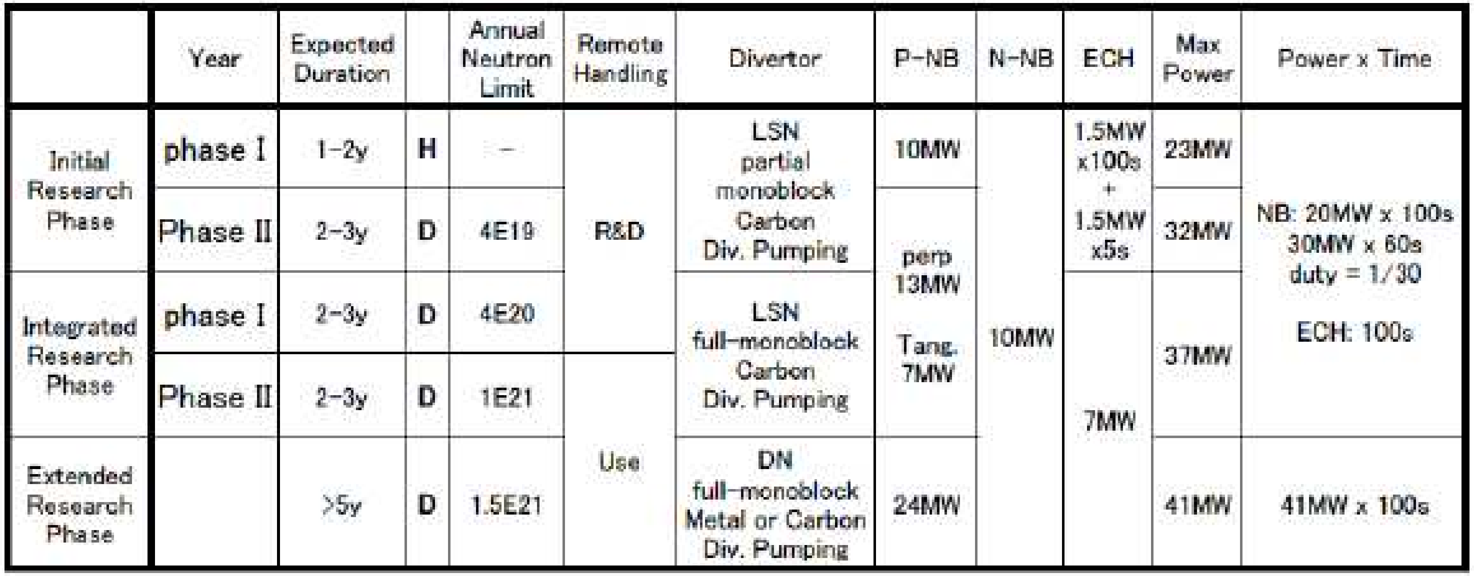
3. Integrated Research Phase I

4. Integrated Research Phase II

5. Extended Research Phase

5-1. Accomplishment of the main mission goal
5-2. Demonstration of DEMO scenario (another main mission goal)

Scenario plan boundary limits

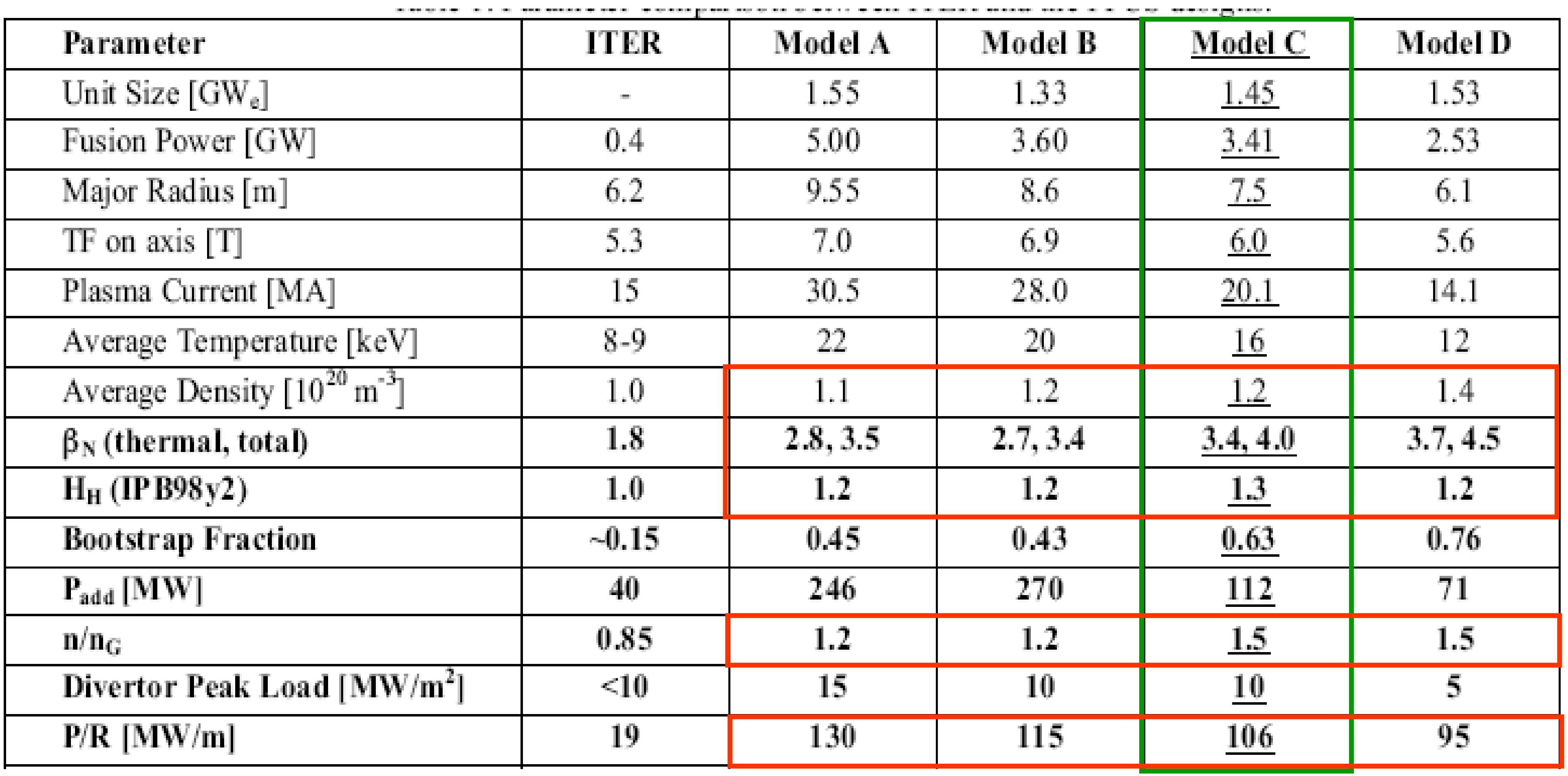


	Year	Expected Duration		Annual Neutron Limit	Remote Handling	Divertor	P-NB	N-NB	ECH	Max Power	Power x Time
Initial Research Phase	phase I	1-2y	H	–	R&D	LSN partial monoblock Carbon Div. Pumping	10MW	10MW	1.5MW x100s + 1.5MW x5s	23MW	NB: 20MW x 100s 30MW x 60s duty = 1/30 ECH: 100s
	Phase II	2-3y	D	4E19			perp 13MW Tang. 7MW			32MW	
Integrated Research Phase	phase I	2-3y	D	4E20		LSN full-monoblock Carbon Div. Pumping			7MW	37MW	
	Phase II	2-3y	D	1E21	Use						
Extended Research Phase		>5y	D	1.5E21		DN full-monoblock Metal or Carbon Div. Pumping	24MW			41MW	41MW x 100s

Operation regime development: scenarios

	#1	#2	#3	#4	#5	#6	ITER	ITER
	Full Current Inductive DN, 41MW	**Full Current Inductive SN, 41MW**	**Full Current Inductive SN, 30MW High density**	**ITER like Inductive SN, 34MW**	**High β_N full-CD 37MW**	**High β_N 300s 13MW**	**Scenario 1**	**Scenario 4**
Plasma current, I_p (MA)	5.5	5.5	5.5	4.6	2.3	2.0	15	9.0
Toroidal field, B_t (T)	2.25	2.25	2.25	2.28	1.71	1.41	5.3	5.2
q_{95}	~3	~3	~3	~3	~5.6	~4	~3	5
R/a (m/m)	2.96/1.18	2.96/1.18	2.96/1.18	2.93/1.14	2.97/1.11	2.97/1.11	6.2/2.0	6.35/1.85
Aspect ratio A	2.5	2.5	2.5	2.6	**2.7**	2.7	3.1	**3.42**
Elongation, κ_x	1.95	1.87	1.86	1.81	1.92	1.91	1.85	1.85
Triangularity, δ_x	0.53	0.50	0.50	0.41	0.51	0.51	0.48	0.48
Normalised beta, β_N	3.1	3.1	2.6	2.8	**4.1**	3.0	2.0	**2.95**
Electron density ($10^{19}m^{-3}$)	6.3	6.3	10.	9.1	5.0	2.0	11	6.7
Greenwald fraction f_{GW}	0.5	0.5	0.8	0.8	0.85	0.39	0.94	0.82
P_{add} (MW) **$P_{NNB}/P_{PNB}/P_{EC}$ (MW)**	41 10/24/7	41 10/24/7	30 10/20/-	34 10/24/-	37 10/20/7	13.2 3.2/6/4	51	59
Thermal confin. time (s)	0.54	0.54	0.68	0.52	0.22	0.3	3.4	3.1
$H_{H98\,(v.2)}$ (assumed)	1.3	1.3	1.1	1.1	**1.2**	1.3	1.0	**1.6**
Bootstrap fraction	0.29	0.28	0.25	0.3	**0.68**	0.79	0.15	**0.46**
Duration/τ_R	~5-10	~5-10	~5-10	~5-10	~5-10	~5-10	~5	~10

DEMO scenario derived from PPCS study



Parameter	ITER	Model A	Model B	Model C	Model D
Unit Size [GW$_e$]	-	1.55	1.33	1.45	1.53
Fusion Power [GW]	0.4	5.00	3.60	3.41	2.53
Major Radius [m]	6.2	9.55	8.6	7.5	6.1
TF on axis [T]	5.3	7.0	6.9	6.0	5.6
Plasma Current [MA]	15	30.5	28.0	20.1	14.1
Average Temperature [keV]	8-9	22	20	16	12
Average Density [10^{20} m^{-3}]	1.0	1.1	1.2	1.2	1.4
β_N (thermal, total)	**1.8**	**2.8, 3.5**	**2.7, 3.4**	**3.4, 4.0**	**3.7, 4.5**
H_H (IPB98y2)	**1.0**	**1.2**	**1.2**	**1.3**	**1.2**
Bootstrap Fraction	**~0.15**	**0.45**	**0.43**	**0.63**	**0.76**
P_{add} [MW]	**40**	**246**	**270**	**112**	**71**
n/n_G	**0.85**	**1.2**	**1.2**	**1.5**	**1.5**
Divertor Peak Load [MW/m^2]	**<10**	**15**	**10**	**10**	**5**
P/R [MW/m]	**19**	**130**	**115**	**106**	**95**

L.D. Horton TRANSACTIONS OF FUSION SCIENCE AND TECHNOLOGY VOL. 53 FEB. 2008

DEMO physics issues

Main physics issues for DEMO	What can JT60SA do
Confinement improvement relative to the existing H factor	**Yes:** developing high β regimes should help in solving this question albeit at only slightly lower ρ^* than JET. The ETB confinement is as much important as the core confinement.
The MHD limit at high β	**Yes:** JT60SA is equipped with the right systems to study the operation above the no-wall limit and the dependence of the limit with the q and pressure profiles
The density limit above $Ip/\pi.a^2$	**No:** it is unlikely that the density limit will change significantly from existing device with a carbon wall. For making progress, would mean **changing the wall material** to minimise recycling.
Divertor and first wall power load/exhaust	**Partially:** Disruption and ELM heat load can be addressed in relevant DEMO regime. Peak heat load scaling to DEMO may on the other hand be difficult. JT60SA must address the steady state power **load control in a metallic wall**.
Non-inductive current drive efficiency	**Yes:** JT60SA can definitely address the current drive efficiency by developing high Te scenario. The question is whether the amount of ECCD or NBCD is really sufficient.
Steady state operation	**Yes:** This is the main objective of JT60SA. But here one should concentrate on viable controllable scenario away from the known limits where operation becomes miserable.

List of proposed elements which could be introduced in chapter 3

Task no	Task description	Persons involved
1	1. Although it is envisaged in the text, a scenario should be added to table 3-1 to represent ITER-baseline operation (e.g. H=1, βN~1.8) 2. A hybrid scenario should be added at q95~4 assuming B=2.25T, H~1.3, full power and whatever βN can be achieved in those conditions 3. A DEMO scenario should be added with modest confinement (H~1.1-1.2) high βN (~4) and high Greenwald fraction (n/nG~1.3), just to see what may be possible. Again the operation at high Greenwald fraction is envisaged in the text	Challis, Mailloux, Nunes, Joffrin …
2	1. Define the control requirements consistently with the physics objectives. Give clear indication for each control which direct sensors and actuator latency is required. Establish a list of diagnostic for direct control. 2. Make control oriented modelling an integrated part of the scientific programme to assess the controllability and optimise the sensor-actuator park.	De Baar, Joffrin, Orsitto…
3	The access conditions and limits (L-H, q profiles) to the target scenario should be added, described and documented	Litaudon, E. Joffrin, JF Artaud
4	ECRH + NBCD capabilities for off-axis current need to be documented during the main heating phase for scenario #4 and #5	Litaudon, Sozzi, G. Garcia, JF Artaud
5	A JET scenario should be added and compared with a real pulse since JET is the closest in terms of shape and geometry. More generally, from the set of target scenario the extrapolation method to ITER and DEMO should be made clearer. And JT60U/JET check point. Similarity experiment?	Joffrin, Challis
6	The objectives (scientific and operational) of the hydrogen phase need to be strengthened: system commissioning, disruption force/mitigation, scenario termination, diagnostic commissioning ➔ compile physics elements present in the document.	Sips, Nunes, Sartori.
7	Requirements for disruption prevention and mitigation in JT60SA scenario at high βp possibly with ITB	De Vries, Bolzonella
8	JT60SA work Programme should include scenario making the transition to a metallic wall or preparing this transition.	Joffrin, Giruzzi, Neu ?

Possible additional JT60SA scenarios

Scenario	**ITER baseline**	**Hybrid**	**High n_e DEMO**
I_P, B_T (MA,T)	4.6, 2.28	**3**, 1.72	4.6, 2.28
q_{95}	3.1	~4.4	~3
R,a (m)	2.93, 1.14	2.97, 1.11	2.93, 1.14
κ_x, δ_x	1.81, 0.41	1.9, 0.47	1.81, 0.41
$\beta_{N,th}/\beta_{N,total}$	1.56, 1.62	3.3, ?	2.81, 2.96
$\langle n_e \rangle_l, \langle n_e \rangle_v (10^{19} m^{-3})$	**9.6, 8.5**	5.0, 4.2	**13.6, 12.1**
$n_{Gw}(10^{19} m^{-3}), f_{Gw}$	11.3, 0.85	7.8, 0.65	11.3, 1.2
W_{th}, P_{loss}(MJ,MW)	10.8, **10**	11.3, **41**	19.9, **25**
$P_{NNB}/P_{PNB}/P_{EC}$(MW)	0, 15.8, 0	10, 24, 7	23, 10, 0
$\tau_{th}(s)/H_{98}$	1.08, **1**	0.28, 1.3	0.8, **1.2**
Comment	Based on #4	Based on #5.1	Based on #4

Parameter	77933	JT60SA target
ref pulse	H=1.25	identity of H
t (s)	49s	
beta ratio		1
B ratio		0.75
a ratio		1.213
a/R ratio		1.196
Ip (A)	2.00E+06	2.18E+06
B (T)	2.296	1.724
ne (m-3)	5.56E+19	3.78E+19
PTOT [MW] from YTO	1.88E+07	
PTOT [MW] predicted		1.19E+06
Wth (J)	5.02E+06	4.23E+06
TauE-th	2.67E-01	3.56E-01
betaN,th	2.294	1.907
Te[rho=0.5] (eV)	3.33E+03	2.77E+03
Ti[rho=0.5] (eV)	3.70E+03	3.07E+03
ne[rho=0.5] (m-3)	5.93E+19	4.03E+19
omega-tor[rho=0.5] (rads/s)	6.25E+04	5.61E+04
a (m)	0.915	1.110
R (m)	2.927	2.970
a/R	0.313	0.374
kappa-X	1.690	1.690
delta-upper-X	0.355	0.355
delta-lower-X	0.372	0.372
q95	3.610	3.610
kappa-vol	1.520	1.520
ng=Ip/pi/a^2	0.760	0.563
Gfrac	0.731	0.671
I/aB (1/q)	0.952	1.138
Shape factor (q95 Ip/a/BT)	3.437	4.110
q-cyl=5*BT*a^2/R/Ip*kappa	2.496	2.496
vol (m3)	73.540	109.815
Ti^1/2/aB (rho* rho=0.5)	0.916	0.916
nT/B^2 (beta rho=0.5)	7.911	7.911
nR/Ti^2 (nu* rho=0.5)	1.268	1.268
omegaR/Te^1/2 (Mth rho=0.5)	10.025	10.025

Identity discharge between JET (77933) and JT60SA

Identity methodology to strengthen the confidence in the prediction:

$B.\tau$ conserved

Values of Te, Ti, ne and ω_T taken at r/a=0.5

Step to JT60SA aspect ratio

$Ip \propto a^{1/4}$; $n \propto a^{-2}$

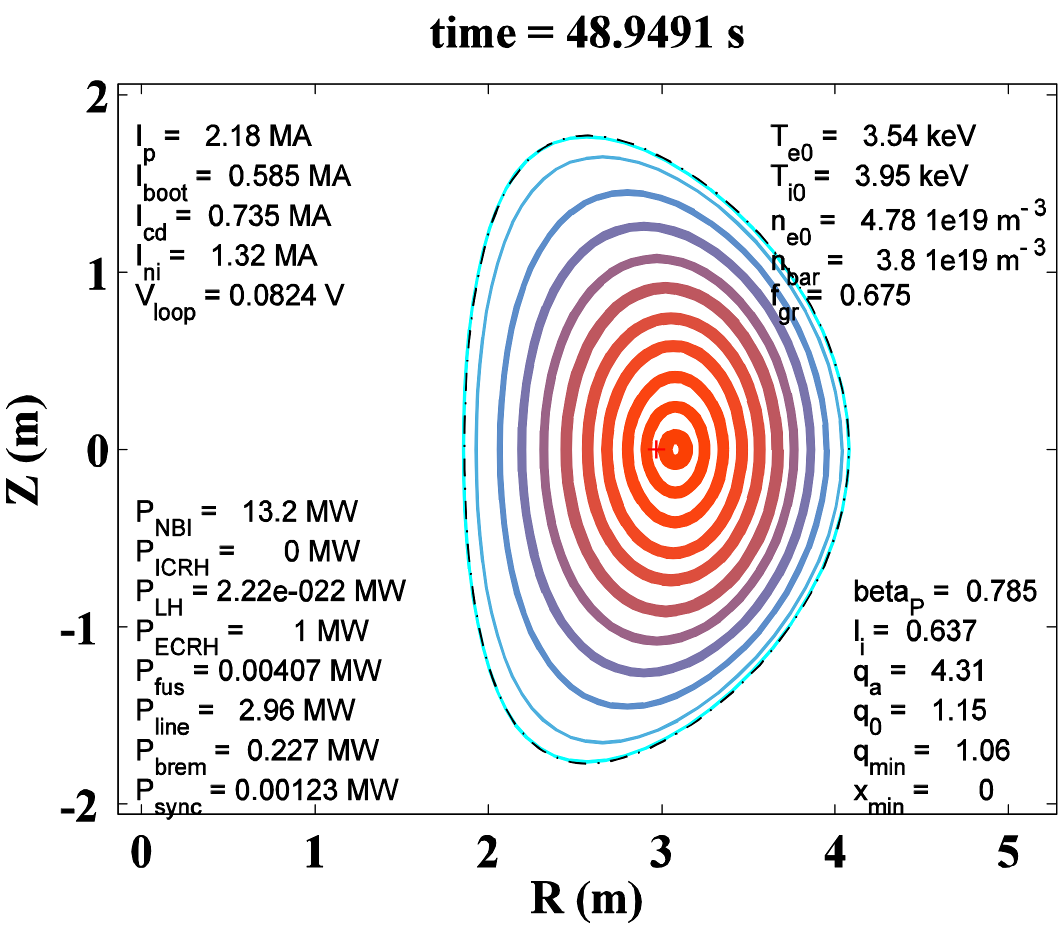
$B \propto a^{-5/4}$; $T \propto a^{-1/2}$

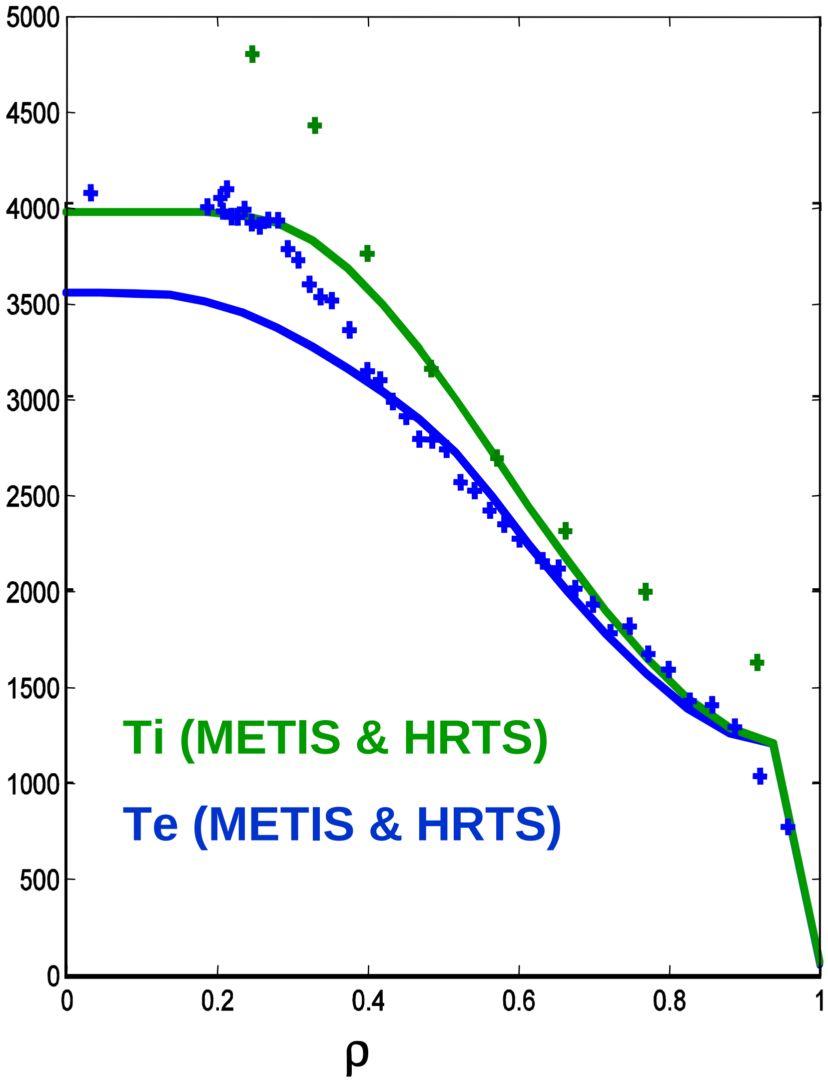
$\omega_T \propto a^{-5/4}$; $\tau \propto a^{5/4}$

Dimensionless parameters conserved

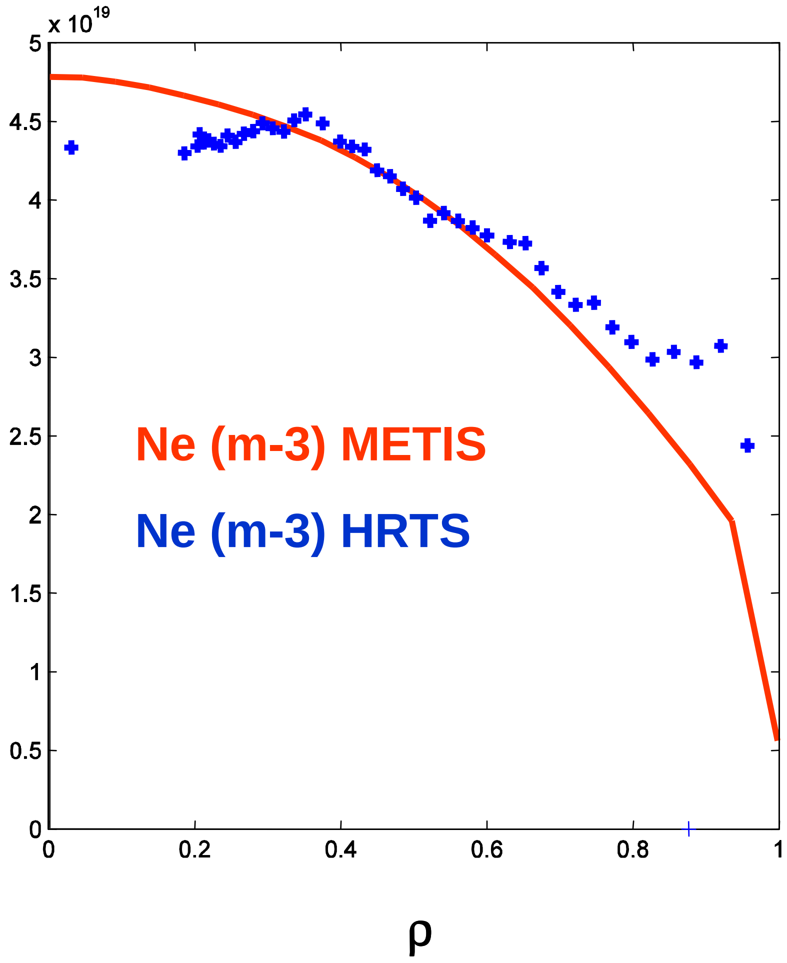
➔ Ne peaking, heat transport, impurity level adjusted to match kinetic profiles and radiation (bremsstrahlung, line radiation, etc..) level using C and O.

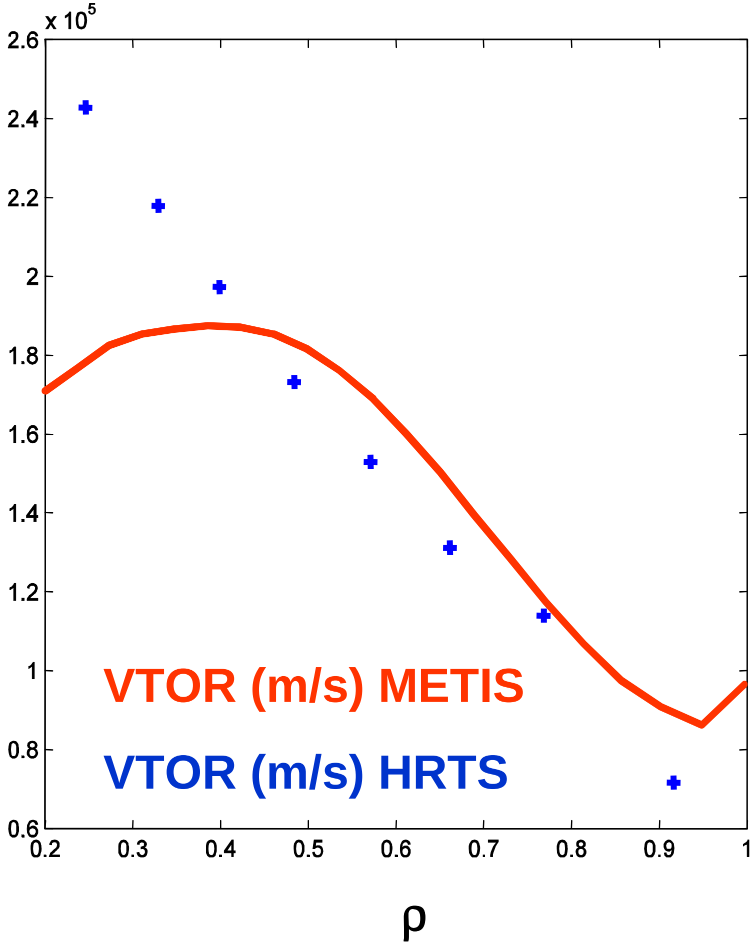
Case of hybrid Scenario with identity to JET with METIS



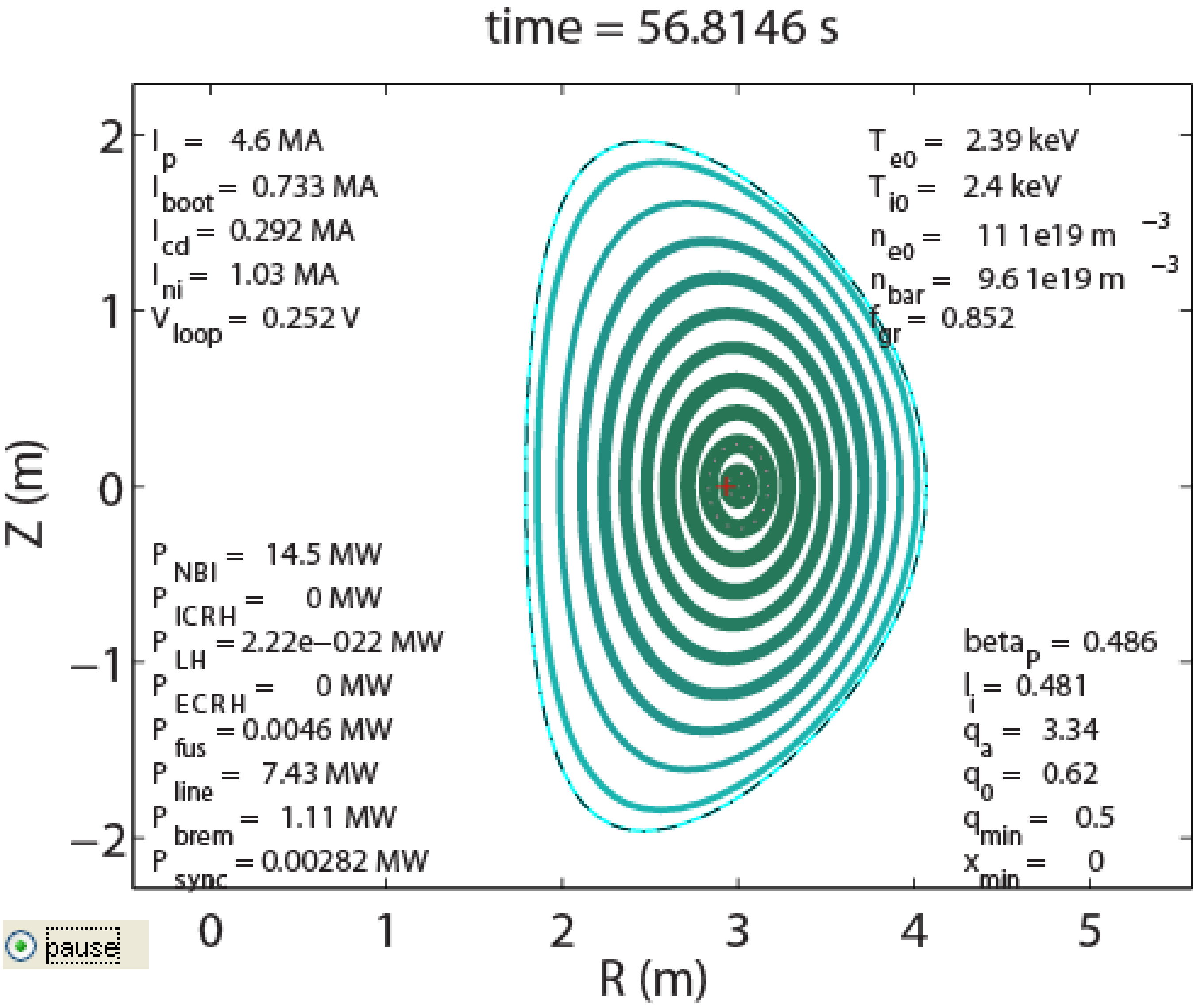


Case of hybrid Scenario with identity to JET with METIS: profiles

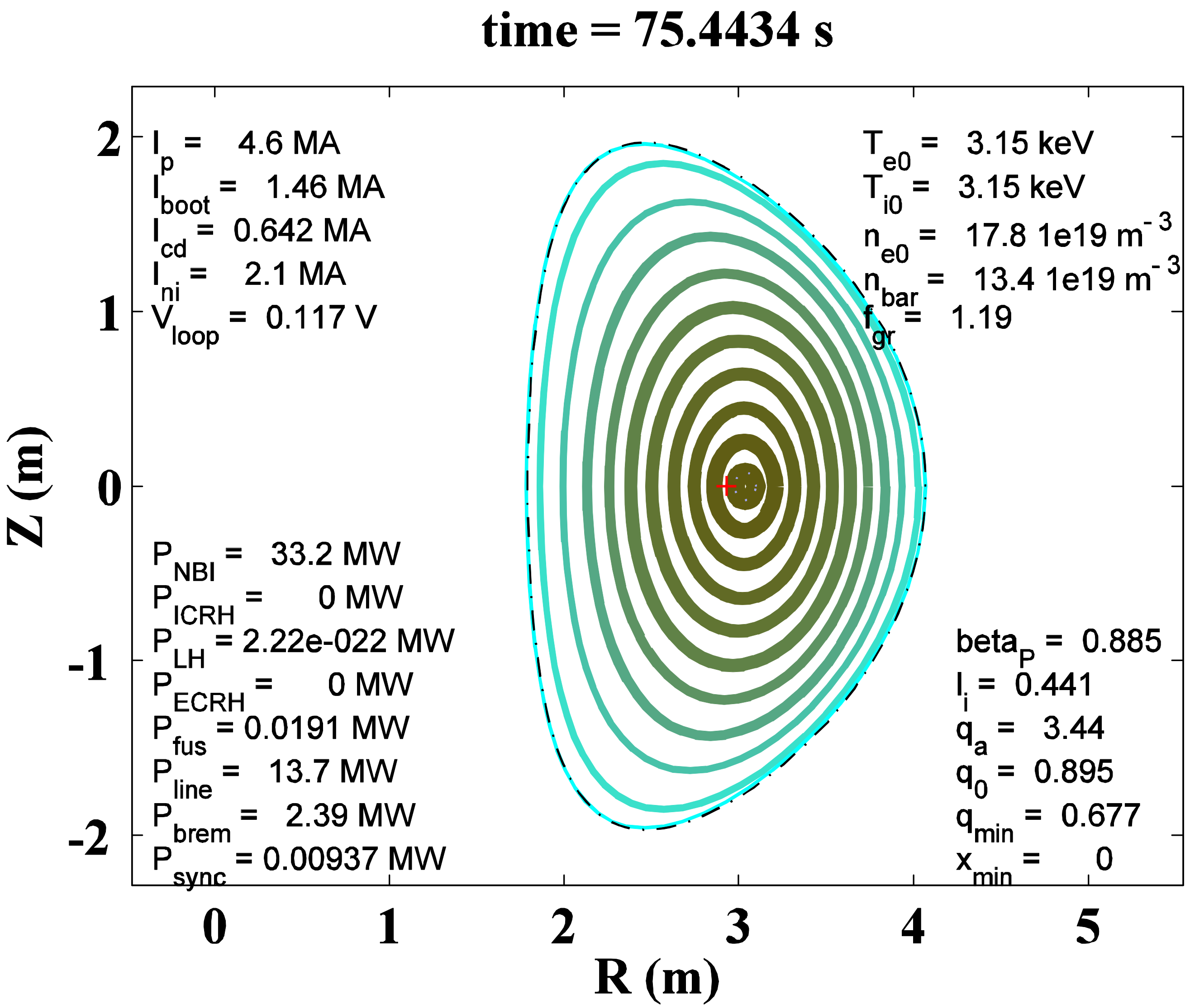




Main kinetic profiles gradients at r/a~0.5 are all very similar, thus giving confidence in the results of the simulation in particular on the bootstrap current and confinement



Case of Scenario Baseline ITER with METIS



Case of DEMO Scenario at high ne with METIS

Status of the work

1- First meeting with the japanese counter-part done on the 24th of August

➔ Proposed a staged approach to the scenario in each research phase.

➔ Link with chap 8 (divertor) to elaborate on the metallic divertor transition and the compatibility of scenario with divertor requirements (pumping, heat load…)

➔ Make an emphasise the electron heating scenario crucial for DEMO (Te will maximise synchrotron radiation, current drive efficiency and minimise large core impurity concentration)

➔ Connect the scenario with the main DEMO physics scenario issues: full steady state, high density operation, control.

➔ Develop radiative layer scenario in connection with the divertor configuration (link with chapter 8 here!)

2- Next meeting on chapter 3 on the 12th of September: objective is to elaborate a full scenario strategy.

3- Next meeting with the japanese on the 5th of october, where a first draft and structure of chapter 3 will be discussed.

Summary of the first meeting with JRO and team

Remarks on Chapter 3

1. Closely linked with chapter 2 (strategy) and also chapter 8 (divertor)
2. The milestone of each presented task should be examined: identify what task should be done for version 3 and what should be done after version 3.

Task 1:

- Has been considered as very important for chapter 3.
- Intermediate target scenario should be defined
- Electron dominant electron heating (with NNBI) scenario should be examined.
- It is important to look into the compatibility of each scenario with the divertor in terms of heat load and pumping requirements.
- Look into the possibility of 300s discharges with wide capability for the extended phase of JT60SA programme
- The scenario should take into account the key physics element of DEMO
- The full steady state target should be considered as the most important

Task 2: This task has to be considered in parallel with the scenario development task (task 1) as a scenario tool. At this stage, it is sufficient to determine the control goals/targets.

Task 3: This task should be also attached to the scenario development task. Current ramp up scenario (MHD limits, non-inductive ramp-up, etc ..) for current access should be included in the scenario development

Task 4: If more ECCD is needed for the scenario this should be clarified. ECCD deposition profile assessment is important to be assessed for full CD scenario. ➔ T. Suzuki to provide the latest details about the ECH system (done)

Task 5: No comparison with JET scenario needed in the plan.

Task 6: The commissioning plan of sub-systems should be based and synchronized with the scenario development. Machine capability in H and He (such as NBI power) should be defined using the scenario proposed for this phase.
➔ Evaluate here the level of JT60SA contribution to ITER H phase

Task 7: Preliminary risks analysis to the scenarios should be assessed shortly and included. The level of risk determines the time required for developing the scenario. Disruption control, safe termination, exit from high beta H-mode should be considered in the scenario plan and development.
➔ E. Joffrin to coordinate disruption control with T. Bolzonella (Chap 4)

Task 8: The transition to metallic wall should be an integrated part of the scenario plan. ➔ E. Joffrin will discuss this point with R. Neu (Chapter 8)

Physics issues related to DEMO that may drive the scenario choice

Confinement under DEMO conditions

- What are the plasma performance and confinement extrapolation at high normalised pressure in the DEMO domain?
- How should we treat the contribution of radiation in the performance extrapolation given that DEMO will have to operate at a high value of radiative fraction?
- How to develop relevant scenario with radiative radiative layer?

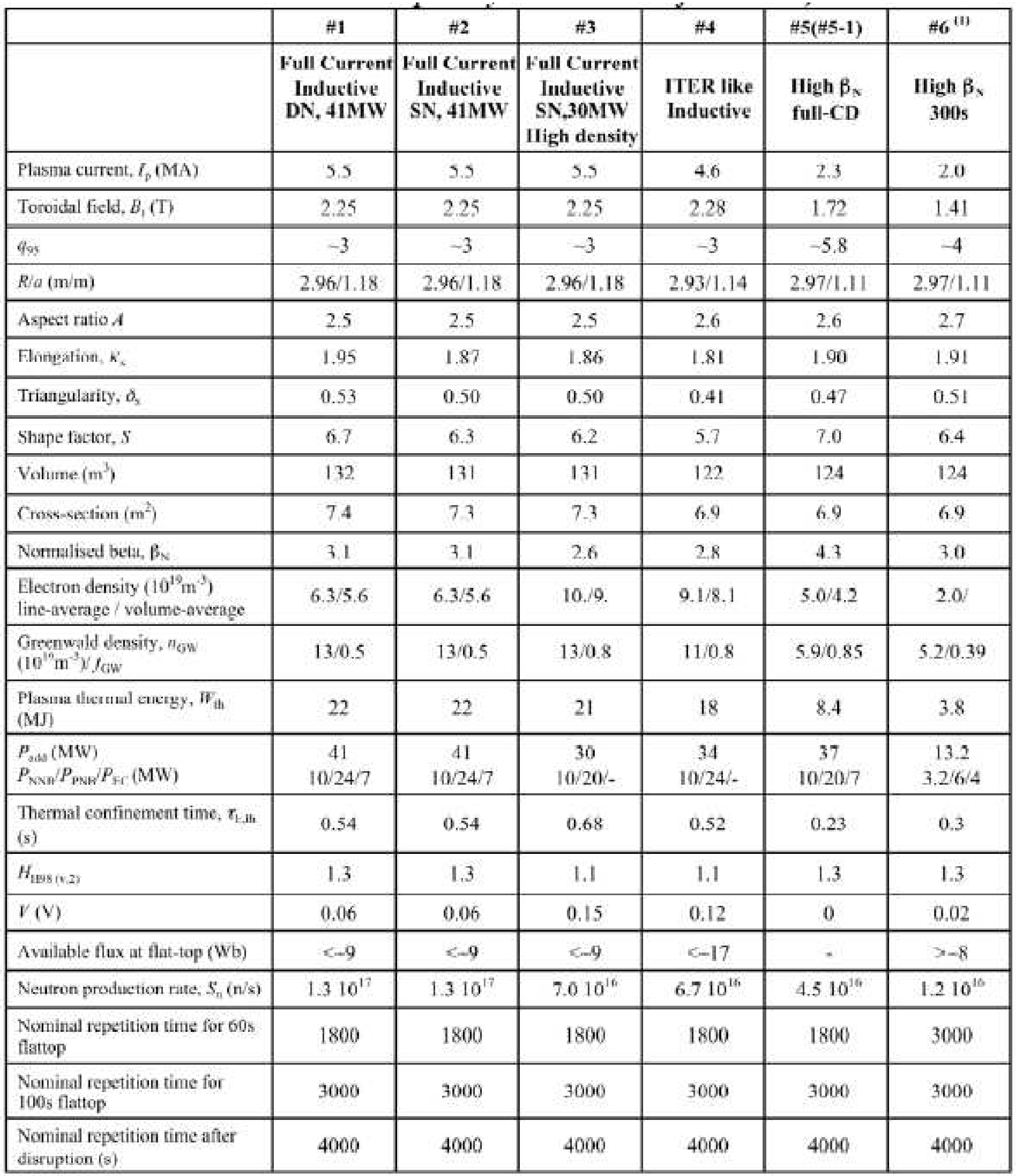
Plasma purity

- What is the optimum plasma impurity (in Z) combination for a plasma in DEMO? Low Z impurity in scenario is not desirable because the increased dilution.

High Te scenario

- How to develop relevant scenarios at high electron temperature? DEMO plasmas will be dominantly electron heated. High Te will maximise synchrotron radiation (thus reducing divertor heat loads), current drive efficiency and minimise large core impurity concentration.

Proposed scenarios presently included in Chapter 3



	#1	#2	#3	#4	#5(#5-1)	#6 [1]
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Plasma current, I_p (MA)	5.5	5.5	5.5	4.6	2.3	2.0
Toroidal field, B_t (T)	2.25	2.25	2.25	2.28	1.72	1.41
q_{95}	~3	~3	~3	~3	~5.8	~4
R/a (m/m)	2.96/1.18	2.96/1.18	2.96/1.18	2.93/1.14	2.97/1.11	2.97/1.11
Aspect ratio A	2.5	2.5	2.5	2.6	2.6	2.7
Elongation, κ_x	1.95	1.87	1.86	1.81	1.90	1.91
Triangularity, δ_x	0.53	0.50	0.50	0.41	0.47	0.51
Shape factor, S	6.7	6.3	6.2	5.7	7.0	6.4
Volume (m^3)	132	131	131	122	124	124
Cross-section (m^2)	7.4	7.3	7.3	6.9	6.9	6.9
Normalised beta, β_N	3.1	3.1	2.6	2.8	4.3	3.0
Electron density ($10^{19}m^{-3}$) line-average / volume-average	6.3/5.6	6.3/5.6	10./9.	9.1/8.1	5.0/4.2	2.0/
Greenwald density, n_{GW} ($10^{19}m^{-3}$)/ f_{GW}	13/0.5	13/0.5	13/0.8	11/0.8	5.9/0.85	5.2/0.39
Plasma thermal energy, W_{th} (MJ)	22	22	21	18	8.4	3.8
P_{add} (MW) $P_{NNB}/P_{PNB}/P_{EC}$ (MW)	41 10/24/7	41 10/24/7	30 10/20/-	34 10/24/-	37 10/20/7	13.2 3.2/6/4
Thermal confinement time, $\tau_{E,th}$ (s)	0.54	0.54	0.68	0.52	0.23	0.3
$H_{H98(y,2)}$	1.3	1.3	1.1	1.1	1.3	1.3
V (V)	0.06	0.06	0.15	0.12	0	0.02
Available flux at flat-top (Wb)	<~9	<~9	<~9	<~17	-	>~8
Neutron production rate, S_n (n/s)	$1.3\ 10^{17}$	$1.3\ 10^{17}$	$7.0\ 10^{16}$	$6.7\ 10^{16}$	$4.5\ 10^{16}$	$1.2\ 10^{16}$
Nominal repetition time for 60s flattop	1800	1800	1800	1800	1800	3000
Nominal repetition time for 100s flattop	3000	3000	3000	3000	3000	3000
Nominal repetition time after disruption (s)	4000	4000	4000	4000	4000	4000