EUROfusion

Status of “no ELMs/small EL” discussion between FSD and DCT

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with support by M. Siccinio, S. Wiesen and input from E. Viezzer, A. Merle, L. Gil, M. Faitsch, M. Bernert for RT08/09/13

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Input

- Discussion inside WP TE:
  - RT08 [Eleonora Viezzer, Antoine Merle]: QH-mode and I-mode assessment in view of DEMO
  - RT09 [Luis Gil, Michael Faitsch]: Extension of EDA and QCE performance towards DEMO
  - RT13 [Matthias Bernert, Sven Wiesen]: X-point radiation and control (here impact on ELMs)
- Revived recent discussions at JET among JET TFLs ➔ Presentations by J. Garcia and A. Huber on small/no-ELM regimes on JET presented at the FSD-FTD meeting 08/09/21
- Discussion on prioritization schemes inside CDT
- No direct involvement of TSVVs yet – but codes that are integral part of TSVVs are being used for interpretative analysis
- Ideally would have been preceded by EUROfusion Science Meeting

Disclaimer

- State of the discussion is fluid and possibly incomplete
- Small/no-ELM topic is driven by DEMO requirement to have a reliable scenario compatible with constraints of the device
- ITER operation might profit of the outcome and it is likely one would want to test a DEMO relevant scenario at a later ITER operative phase (beyond Q=10).
- Prolongation of JET operation was justified for addressing ITER relevant high priority topics ➔ fundamental question: **Do these scenarios fit into the JET priority?**
- Outcome may impact scenarios in JT-60SA with metallic wall (>2030)
- Question of possible maximum ELM or filament size and their buffering not yet clarified – statement on "no ELMs" on DEMO based on ELM energy scaling and assuming a ITER like pedestal scaling
- Compatibility of small/no ELM regime with ADC not systematically addressed yet

Approach: clarification of current status of RTs

1) Accessibility and stability of the scenario - including typical risks

2) Compatibility with confinement requirements in view of DEMO

3) Compatibility with exhaust requirements in view of DEMO (He pumping, PFC protection)

4) Status of interpretative modelling and understanding: open questions?

5) Known attempts of extrapolation of the regime parameters to DEMO conditions?

6) Limitations/Caveats for exploring the regime on the present WP TE devices (MAST-U, TCV, WEST, AUG) and need to try on JET?

7) Thoughts on what you believe needs to be done in the present WP TE devices to prepare possible experiments on JET (end 2022/2023)

Complete material is collected and should be made available (somehow) on a shared drive to personnel involved

Philosophy

- Gather the perspective of SCs from Research Topics 08, 09 & 13
  - Status of interpretative modelling and understanding: open questions?
  - Limitations/Caveats for exploring the regime on the present WP TE devices (MAST-U, TCV, WEST, AUG) and need to try on JET?
  - Thoughts on what you believe needs to be done in the present WP TE devices to prepare possible experiments on JET (end 2022/2023)
- Identify *if/what physics questions should be addressed with increased priority* in 1st half of 2022
- A DEMO physics gaps document exists that has been one of the WP TE reference documents – but items listed are not prioritized ➔ *discuss possible procedures for prioritization*

RT08: Status of understanding & questions

QH-mode

- Rotation can be important, but first JOREK sims obtained EHO without $v_{E\times B}$
- Many different models: exfernal mode theory (Brunetti et al), current ribbon (Solano et al), etc.
- *Nature of EHO not completely clear – affects both particle and energy transport? Or just one?*
- Role of $\omega_{E\times B}$ shearing rate? Phase-slip model by Guo-Diamond provides qualitative picture

I-mode

- Gyrofluid simulations reproduce main features of I-mode → Dynamics parallel to the magnetic field can induce difference in transport channels
- ITG weak at the plasma edge (higher separatrix T_i and flatter T_i gradient compared to T_e) → DW turbulence dominant → decoupling of n and T fluctuations through parallel heat conduction
- Nonlinear MHD modelling (JOREK, NIMROD) show EHO is saturated kink-peeling mode driven by edge current
- *Role of Z_{eff} unclear (➔ compatibility with detachment?)*

RT08: Limitations/Caveats on present WP TE devices and need to try on JET

QH-mode

- AUG: most QH-modes achieved with some level of counter-current NBI → *reversed I_p/B_t combined with fresh boronization very scarce resource* (3 reversed I_p/B_t mini-campaigns in the last 6 years, each only 1 week)
- TCV: more NBI power/torque would be advantageous
- MAST-U: to be seen (experiments in week of Sept 13th)
- JET: T provides higher pedestal temperatures, potentially enabling easier access to QH-mode with low-medium density, high temperature and moderate divertor heat flux.
- Spontaneous EHOs have been identified in hybrid plasmas at JET-ILW, with co-NBI, in D, T and DT (JET-C and JET-ILW). They have hot pedestals and varying duration: scenario development typically aimed to eliminate them.
- More spontaneous EHOs in JET Tritium campaigns? ➔ no specific EHO investigation planned at JET so far. Proposal available, but no experimental time allocated in the past.

I-mode

- TCV: B_t may to be too low for I-mode access window
- AUG: for detachment studies, lower divertor better equipped → reversed I_p/B_t
- JET: never observed with forward B_t, LSN. Reversed B_t operation or USN never tried.

RT08: to be done in present WP TE devices to prepare possible experiments on JET (end 2022/2023)

QH-mode:

- Aim to obtain QH-mode reliably. Attempts at AUG limited (developing a new operating regime requires a lot more time than a few shots per year), and often plagued by hardware difficulties and/or late in the boronization cycle.
- then investigate domain and map out parameter space; i.e. entry into QH-mode often at low n_e, but high n_e can be studied once in QH-mode. Questions:
  - Proximity to EHO related to palm-tree mode? Do rational surfaces play a role?
  - Localization of EHO, pedestal top or gradient region?
  - Can the Brunetti et al model (infernal modes) explain domain of EHO?
  - Can we obtain the wide-pedestal QH-mode?

I-mode:

- WEST experiments as intermediate point (in terms of major radius and B_t) between AUG/DIII-D and JET. May give valuable input for possible experiments at JET

RT09: Status of understanding and interpretative modelling

QCE:

- Main hypothesis: high-n ballooning modes close to the separatrix provide enhanced transport, preventing large ELMs
- HELENA calculations: ideal infinite-n ballooning modes unstable close to separatrix

EDA:

- Main hypothesis: quasi-coherent mode (QCM) provides enhanced transport, prevent ELMs
- GENE simulations reproduce core transport reasonably well, but pedestal is challenging (speculative)
- GEMR: QCM is a kinetic ballooning mode, code does not include important physics
- MISHKA calculations provide contradictory results regarding pedestal stability, but we have plausible explanations for this, *the main problem: lack of manpower*

Open questions:

- Overarching question: How is the pedestal structure determined and ELMs avoided?
- Likely requires answers to: What is the nature, driven transport, and role of the observed instabilities in each regime?
- In additional question regarding core plasma: is the Te/Ti ratio well understood? How does it extrapolate to large-scale devices?

RT09: Limitations/Caveats & to be done in view of JET

Limitations/Caveats for exploring the regime on the present WP TE devices (MAST-U, TCV, WEST, AUG) and need to try on JET?

- Low collisionality cannot be achieved in medium sized machines in these regimes
- ***Experiments in JET-ILW are crucial***
- QCE: tried in JET-C, was possible at high q, open question at low q

Thoughts on what you believe needs to be done in the present WP TE devices to prepare possible experiments on JET (end 2022/2023)

- Try JET-compatible shapes in present WPTE devices
- EDA: Try with ICRF, because JET does not have ECRH

RT13: Interpretative modelling and understanding & to be done in view of JET

Status of interpretative modelling and understanding: open questions?

- SOLPS modeling by F.Reimold & O.Pan
  - Work ongoing, broad database existing
  - Scaling not existing yet → L. Aho-Mantila for DEMO
- SOL/pedestal coupling missing!

<u>To be done on present devices to prepare for experiments on JET</u>

- Predictive SOLPS modeling
- Understand stability limits
- Better understand the SOL/pedestal coupling
- Test control based on spectroscopy?

RT13 - Limitations/Caveats on the WP TE devices

TCV:
- Carbon PFCs
- Scenario reproducibility
- Low heating power
- Shot duration

MAST-U:
- Carbon PFCs
- Heating power (?)
- Diagnostic & scenario set (yet)
- N seeding not allowed yet
- Shot duration

AUG:
- Strongly covered
- Missing size scaling

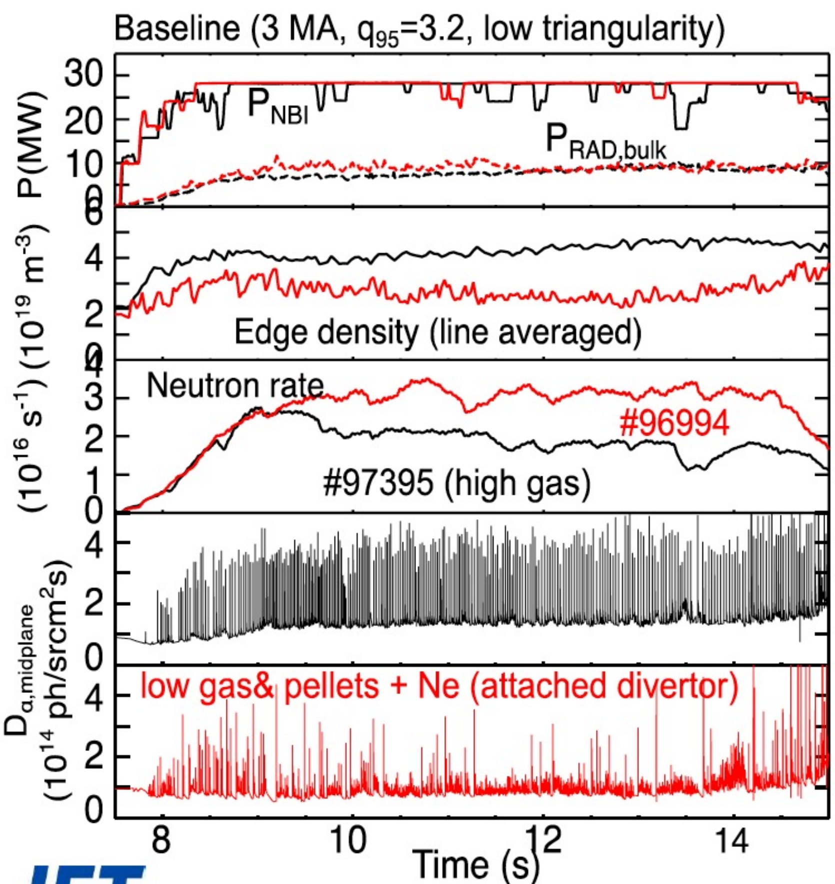
WEST:
- H-mode missing yet
- Limited Heating power (?)
- Limited Diagnostics
- Open divertor geometry

JET:
- XPR observed
- ELMs might diminish
- Essential for size & confinement scaling
- Diagnostics might be limited
- Control maybe not possible

High-performance H-mode plasmas with small ELMs in JET-ILW (1/3) (J. Garcia)

(see J. Mailloux [IAEA-2021] and J. Garcia [IAEA-2021])

High H-mode performance achieved by operation with low gas & pellet injection (45Hz)
→ best performance obtained so far in the JET-ILW baseline scenario



Compared to conventional ELMy H-mode:

- better confinement : H_{98}=1.05, β_N = 2.2, β_p < 1, n_e/n_{GW}=0.7
- lower pedestal collisionality: ν_{ped}^*~0.4
- high DD fusion rates (in steady state)
- mixed ELM regime, with long periods of small & faster ELMs → substantial reduction in ELM size

- Divertor in 'attached' conditions for #96994, unlike highly radiating scenarios with Ne [S. Gloggler et al 2019 Nucl. Fusion 59 126031] or recent Ne seeded experiments at high triangularity [C. Giroud, IAEA 2021]

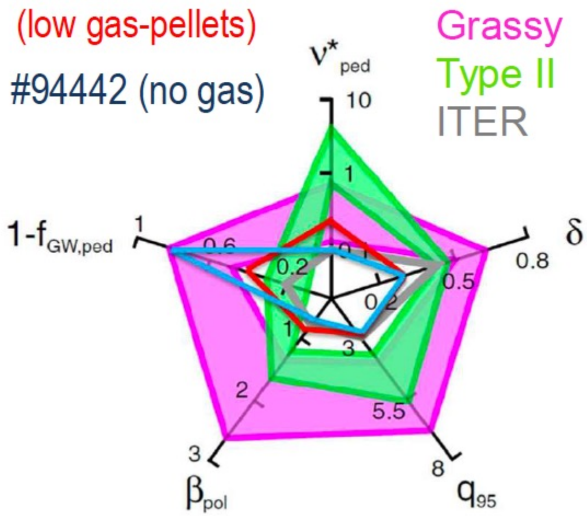
JET

J. Garcia| FSD-FTD coordination meeting 5

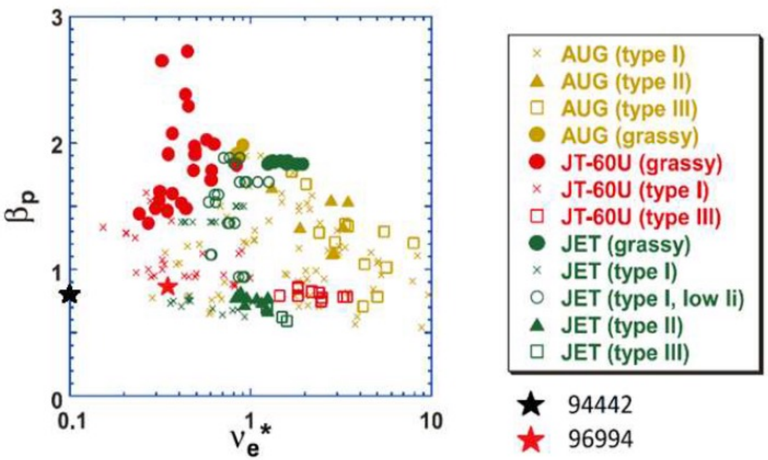
High-performance H-mode plasmas with small ELMs in JET-ILW (2/3) (J. Garcia)

Comparison to other small ELM regimes: JET covers different operational space

E. Viezzer et al. Nucl. Fusion 58 (2018) 115002



N. Oyama et al. PPCF 48, (2006) A171



Small ELMs discharges obtained at JET cover a different operational space than other H-mode regimes with small ELMs:

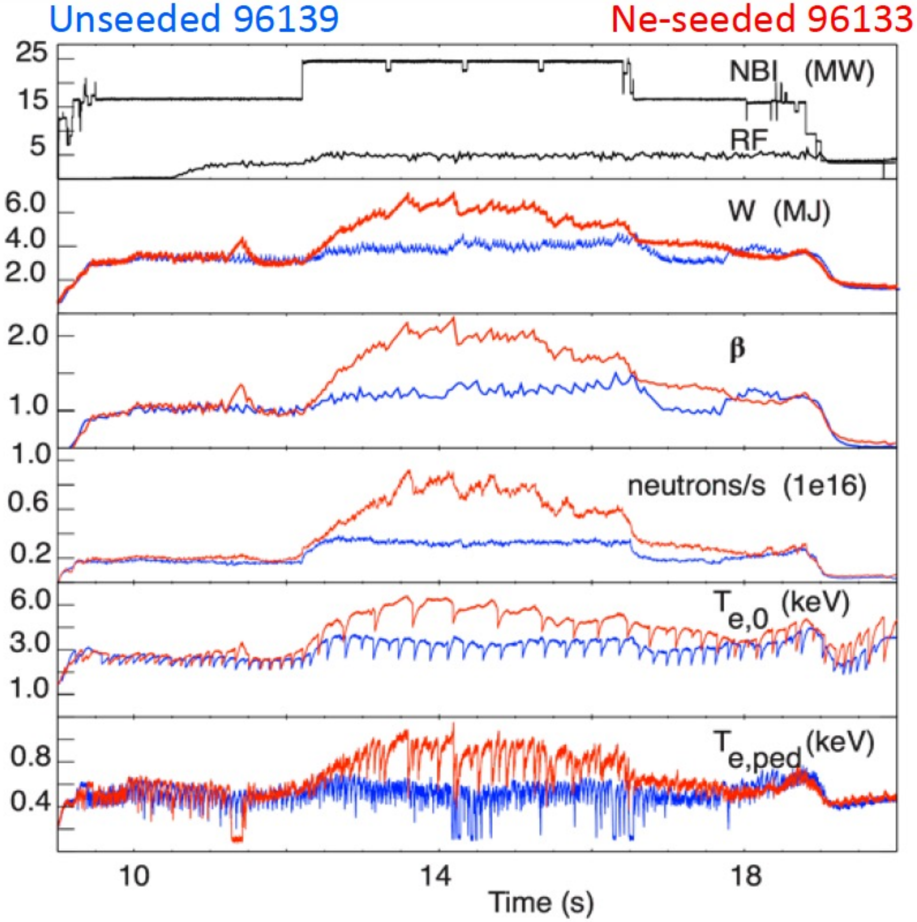
→ Plasmas with low gas+pellets close to ITER conditions

JET

High-performance H-mode plasmas with small ELMs in JET-ILW (3/3)

- Results in JET-ILW have demonstrated a new H-mode operating regime that allows simultaneous access to good energy confinement, small ELMs and low core impurity content
- Small ELMs plasmas with high thermal confinement and neutron rate found in several plasma conditions:
  - operation with ´no gas´
  - low gas + pellets
  - low gas + pellets + (small amount) Ne
- Broken paradigm of type-I ELM necessity to reach high confinement
- Discharges with small ELMs show stable pedestal against P-B modes
- W is not accumulated due to strong rotation: Outward neoclassical W pinch
- Screening pedestal at low collisionality (as expected in ITER)

Seeded plasmas with naturally small ELMs 1/2
(A. Huber)



High-δ shape, vertical targets, edge conditions close to ITER

At Γ_D=3x10^{22} el/s

With Neon

f_{GW}: 0.82

n_{ped}/n_{GW}:0.7

Z_{eff}: 2.0

f_{rad}: 0.76

C_{Ne}=1.0 % (top pedestal)

Striking improvement of performance

H_{98}: 0.6 → 0.9 T_i ~ 1.1 × T_e

β_N: 1.1 → 2.0 Higher neutron rate obtained

The electron pedestal pressure was increased by 20 % in Ne seeded pulse

Seeded plasmas with naturally small ELMs 2/2

- JET demonstrated that Ne-seeded plasmas are compatible with high-performance and can achieve higher normalized confinement and neutron rate than equivalent N-seeding plasmas.
- Decrease of electron pedestal density and rise in pedestal ion temperature is key in this improvement but the improved core confinement also plays a role via the increased ExB shearing rate, impurity content and higher ratio of Ti/Te.
- Reduction of the heat load is observed at the strike-point with neon; Full detachment obtained with N-seeding.
- ITER benchmark activities with SOLPS-ITER on Ne and N-seeded JET plasmas are underway.
- Simultaneous small/no ELM stationary regime with Ne seeding and high thermal energy confinement with strong divertor radiation

Ad hoc group report on ELM free scenarios exists (January 2020)

- Report of the EUROfusion Ad Hoc Group on ELM-free scenarios in preparation of DEMO operation (Mattia & Eli co-authors)
- Focuses on QH, WPQH and I mode; mentions EDA H-mode
- Description of the physics observations and various interpretative models for QH and I mode
- Introduction of a classification of knowledge gaps:
  - Show Stoppers (to be resolved by Gateway Review 2, GR2): Compatibility with divertor detachment, Compatibility with radiative mantle, Definition of access conditions, Extrapolation to high Q operations, Compatibility with pellet fuelling
  - Design Drivers (to be resolved by Gateway Review 3, GR3): Compatibility with divertor concepts, Edge transport properties, Strategy to burn access, Definition of existence conditions, Dependence of the threshold power on the main discharge parameters
  - Performance Assessment (during Milestone 4): Scenario optimisation ($\boldsymbol{Zeff}$, impurity accumulation isotope mix), Physics basics for control strategies,
- Identification of strategy tables on machine prioritization for QH and I modes in view of the the classification of knowledge gaps.
- Report emphasizes the very important role of JET, i.e. I-mode

Suggested "time" schedule for assessment of knowledge gaps by ad-hoc group

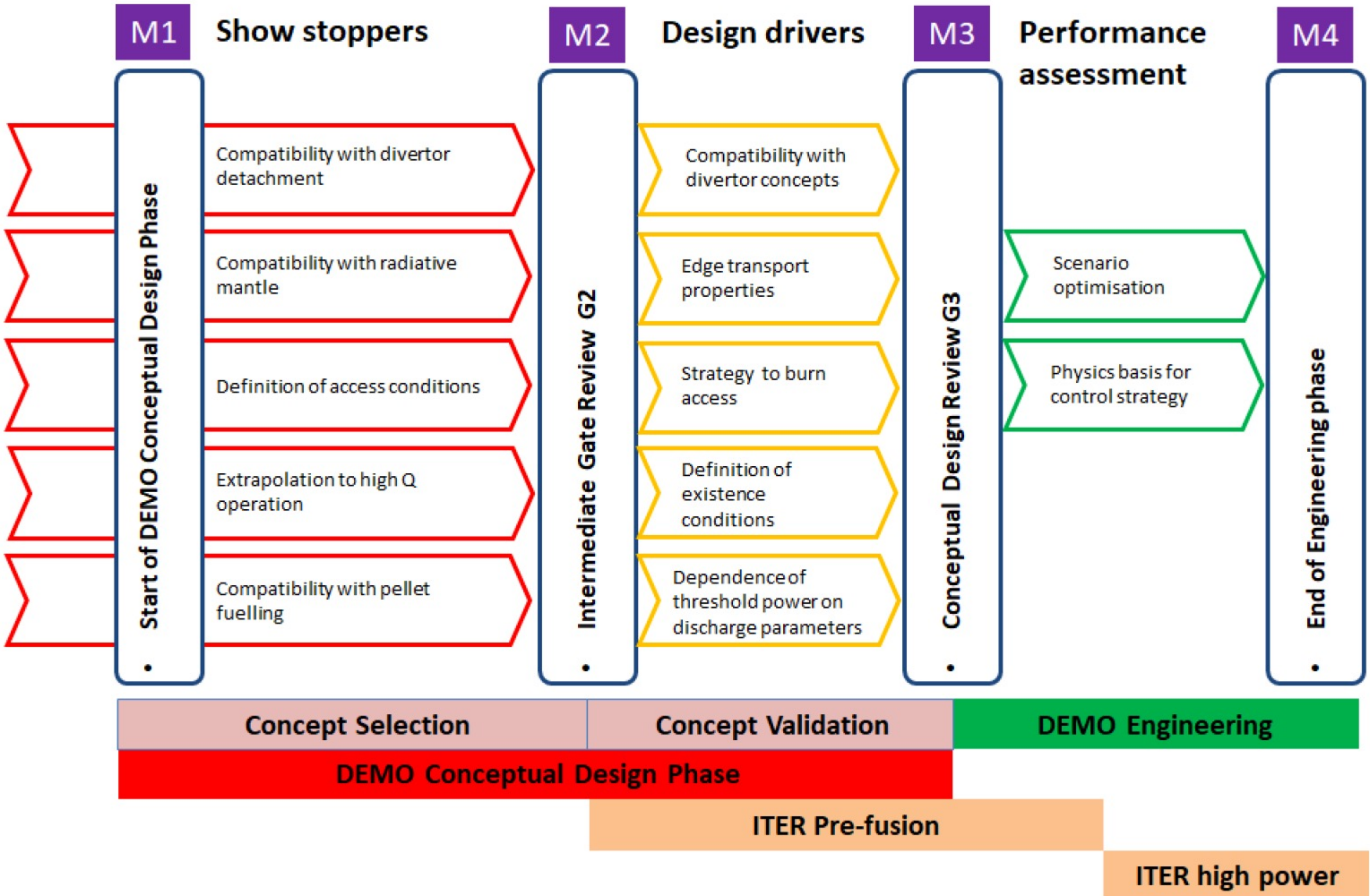


Fig.17: Suggested time schedule for the assessment of the knowledge gaps in correspondence with the actual DEMO

From *Ad-hoc Group Final Report – January 2020*

EFPW matrix – would need an update(?)

Column labels refer to the mechanism limiting pedestal pressure, not to the plasma scenario as a whole.

	EDA H-mode (QCM)	QH-mode (EHO)	I-mode (beta stab.)	Negative δ	XPR scenarios	QCE (ballooning modes separatrix?)
High energy confinement (H98 ~ 1)				with DEMO relevant Ti		
High pressure (βN)	*			Ideal beta limit		*
High density (fGW)						
Compatibility with low collisionality (ped.top)						
Low impurity content (Zeff)				less screening with smaller pedestal T gradient?		
High current (low q)						
Low torque					*	*
Dominant electron heating					*	*
Accessible low power						*
Impurity seeding		?		?		
Tungsten PFCs				?		
Robustness against appearance of ELMs (uncontrolled transition to H-mode)						
Compatibility with pellet fueling (inboard)	?	?		*	*	
Compatible with steady-state/long pulse scenarios	?	?		*	*	
Compatible with alternative divertors	?	?	?	*		*
Compatible with "conventional" tokamak design						
Detachment control	*	?	?	?		*
Ramp-up/Ramp-down	?	?			?	?
Possible qualification in ITER						
Main modelling required/issues	MHD	MHD		Global+edge turb.	SOL + pedestal	

(green)	No known/foreseen issues
(orange)	Possible issues
(red)	Challenging
?	No information available
*	Not yet demonstrated

Compatibility of the listed items on a DEMO scale?

Prioritization vs "Down-selection"

- A down selection at this stage does not appear to be a viable or reasonable option – too many open physics questions

- *Need a prioritization* of physics topics to be addressed:

  the ad-hoc group document provides a metric (show stoppers, design drivers, performance) that could be transposed into terms of reference ➔ define terms of reference, check schedules (e.g. given by gate reviews or other time stamps inside EUROfusion [e.g. device availability, TSVV readiness])

- Propose "inspired by ITER Research Plan" for small/no-ELM regimes

  similar to categories (set by urgency) in ITER research plan devise a temporal and resource prioritization across these scenarios

  → specific with clear quantifiable decision criteria for all scenarios

  → Discuss in view of 2 options: with / without access to JET

Categories (currently being discussed inside the DCT)

Cat 1 to fulfil the following 3 weighted criteria

- C1 A scenario for which a model exists has been demonstrated to be repeatable in various devices (various sizes, currents and fields)
- C2 A scenario has been demonstrated to be compatible with a W-wall with DEMO unavoidable boundary conditions (e.g. detached divertor, pellet fuelling, high confinement)
- C3 A scenario is robust and controllable; the sensors/actuators have to be DEMO compatible

Key milestone: G2 (@Milestone2) which is scheduled for 2024 ➔

- ➢ Have at least one scenario that fulfils the 3 Cs sufficiently
- ➢ Prioritization should address likelihood for a scenario to be brought to state by 2024
- ➢ ➔ Guide definition of milestones and review of these defined milestones inside the FSD-FTD

Items for discussion

- How to best coordinate the effort on small/no-ELM regimes?
- Does the topic require experimental time on JET ? Does it make "sense" in view of diagnostic availability?
- Does EUROfusion want to provide experimental time on JET? ("despite" or even "because of" the formal prioritization to address ITER RP priorities)
- Are we still timely to define WP TE experiments (w/o JET) in view of potential experiments on JET? (only makes sense if one decides that these regimes should be investigated on JET)
- Are the TSVVs set-up adequately do be able to address these regimes? (several codes being used for the interpretation of current experiments are part of the TSVVs)
- *Viable Interpretative tools for modelling integrated scenarios at high density, high dissipation and "highish"* Z_{eff} *at pedestal are lacking (SOL/pedestal/core) and associated skilled scientists*