

Overview of the european tokamak programme in the new European Framework Programme

Emmanuel Joffrin, M. Wischmeier, B. Labit, A. Hakola, Emmanuelle Tsitrone, N. Vianello

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Overview of the European Tokamak Programme in the new European Framework Programme

E. Joffrin, M. Wischmeier, A. Hakola, B. Labit, E. Tsitrone, N. Vianello and contributors (see next slide)

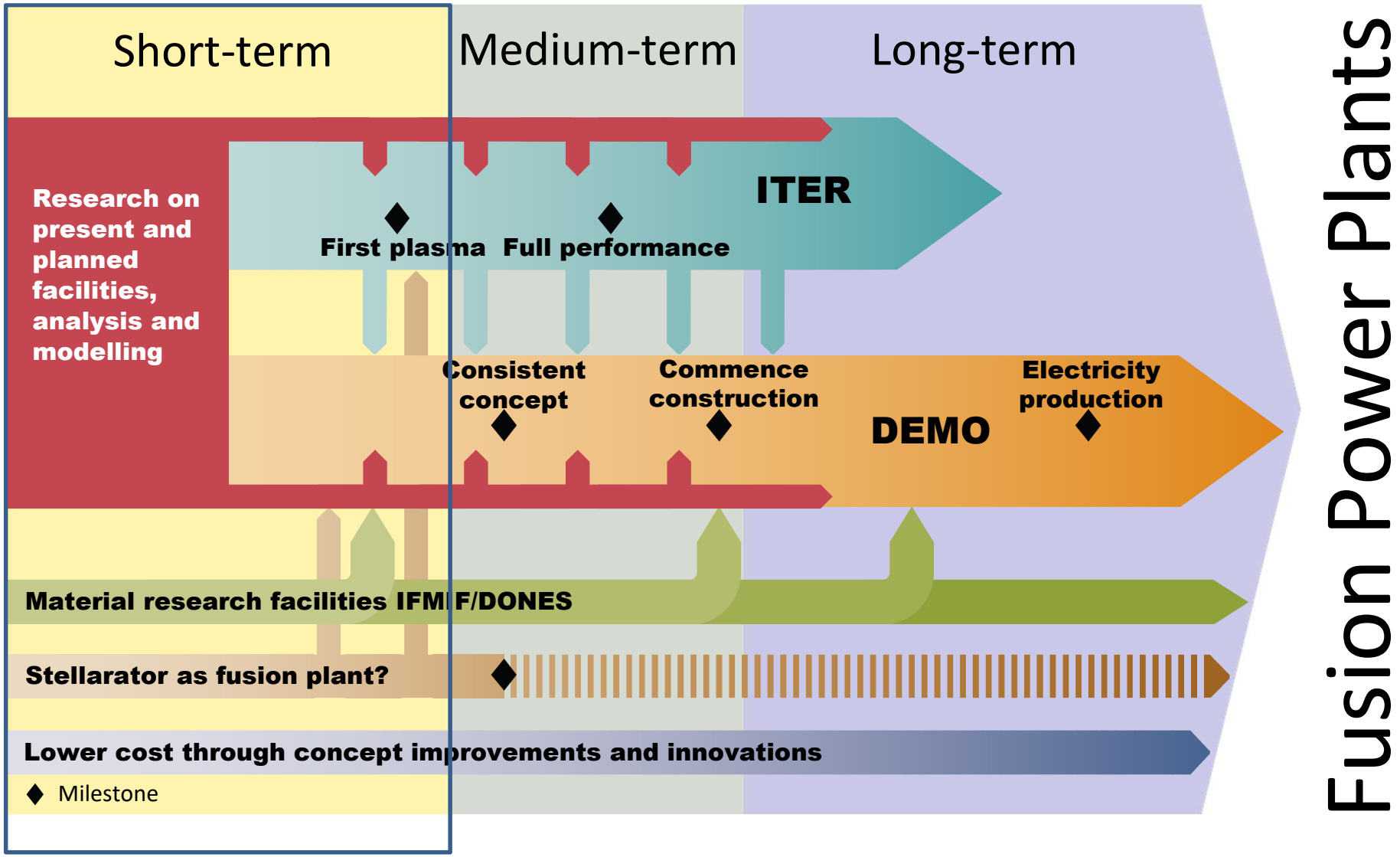
***MF-PL2**
E. Joffrin (CEA Cadarache)

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EUROfusion contributors



EUROfusion Roadmap: Horizon Europe, a decisive period

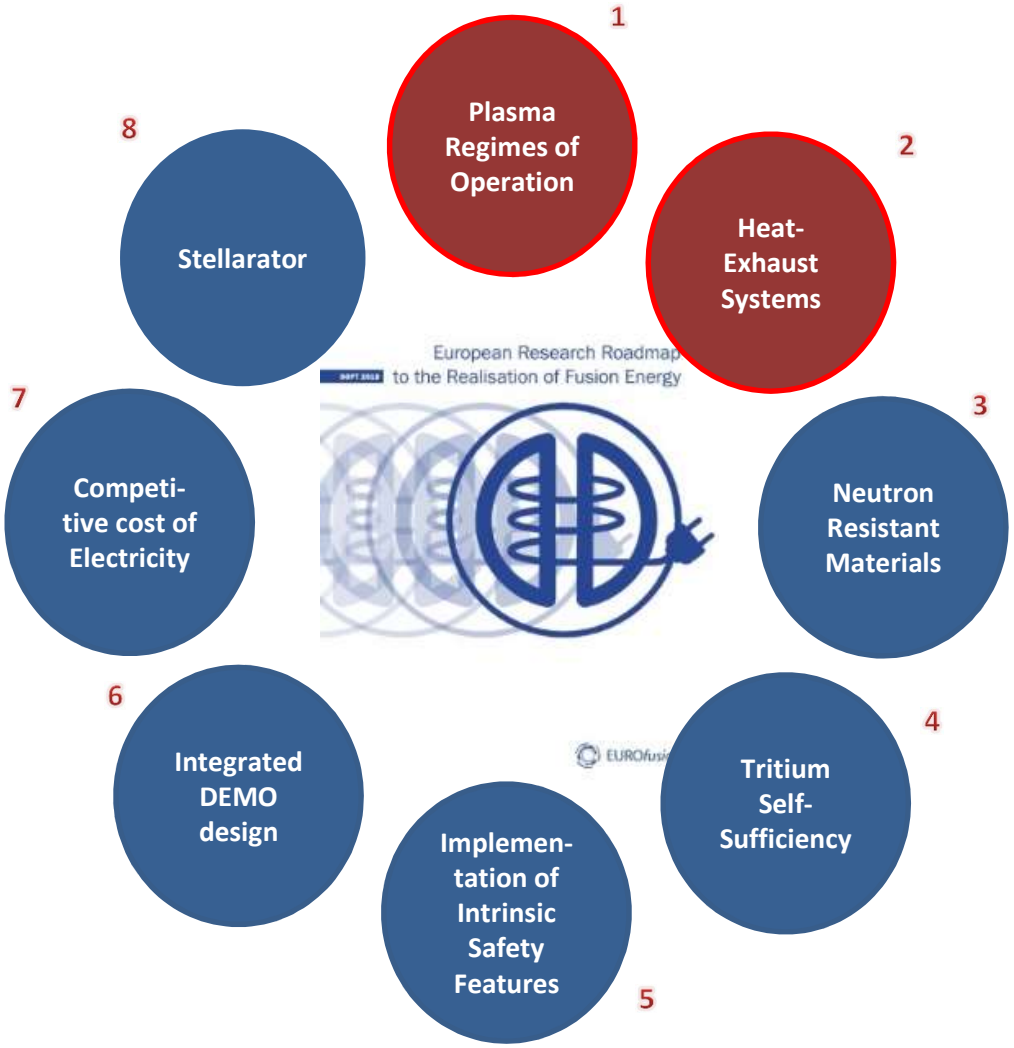


Horizon Europe: 2021-2027

A consistent set of 8 missions towards the reactor

European Research Roadmap

to the Realisation of Fusion Energy



Mission 1

Plasma Regimes of Operation

M1.1 Demonstrate and qualify MHD-stable high-performance operation with metallic plasma facing components for ITER and DEMO;

M1.2 Enhance the physics understanding in order to control the operation of burning plasmas in ITER and DEMO;

M1.3 Develop integrated scenarios with controllers for long pulse, ultimately steady-state, operation for ITER and DEMO.

Mission 2

Heat Exhaust Systems

M2.1 **Detachment control for ITER, DEMO baseline and HELIAS (the helical-axis advanced stellarator line)operation;**

M2.2 **Prepare efficient Plasma Facing Components (PFC) operation for ITER, DEMO and HELIAS;**

M2.3 **Investigate alternative innovative divertor geometries for DEMO;**

M2.4 **Develop a liquid-metal based divertor solution for DEMO.**

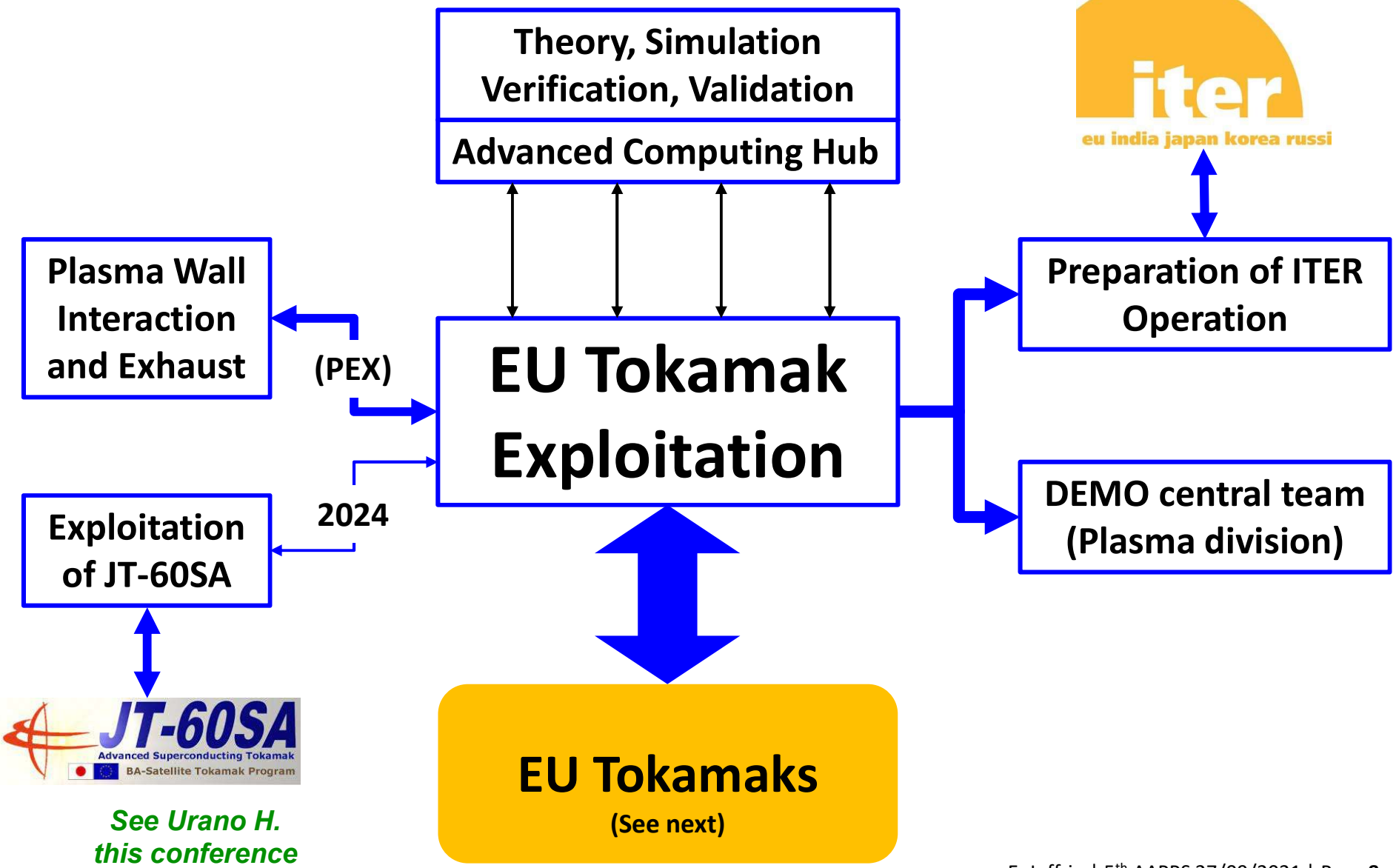
Overarching priorities for Tokamak Exploitation

1. Prepare ITER exploitation (ITER Research Plan)
2. Provide *Physics Basis* for guiding DEMO design
3. Exploit recent machine enhancements: PEX (Plasma EXhaust) strategy.

Address objectives of EUROfusion Roadmap:

- Mission 1 (Plasma Regimes of Operation)
- Mission 2 (Heat exhaust System)

Tokamak Exploitation embedded in a strong scientific environment within EUROfusion



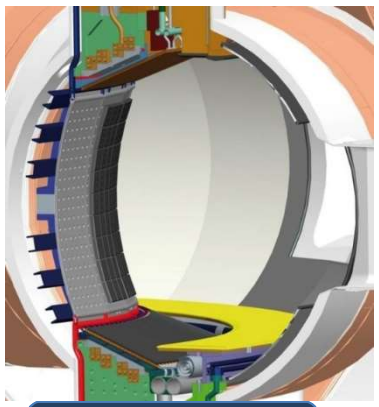
See Urano H. this conference

The EUROfusion Programme is exploiting a portfolio of devices with complementary capabilities

W-wall

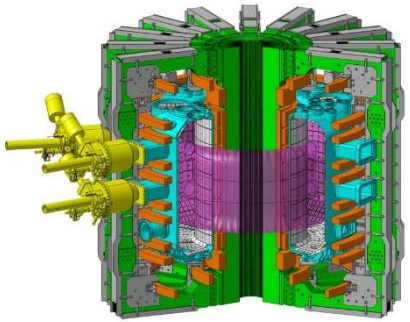


ASDEX Upgrade, Munich, DE



WEST, FR

C-wall



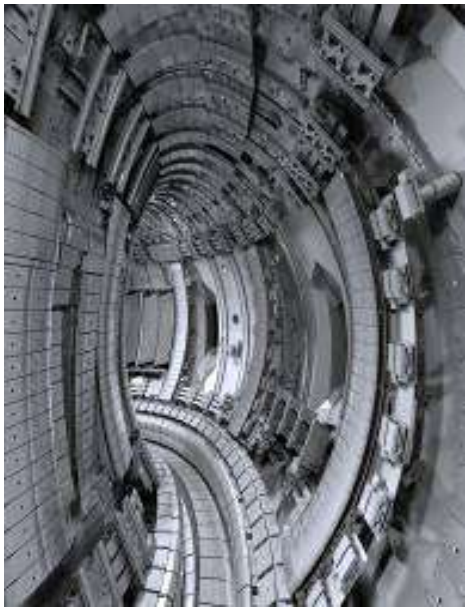
TCV, CH

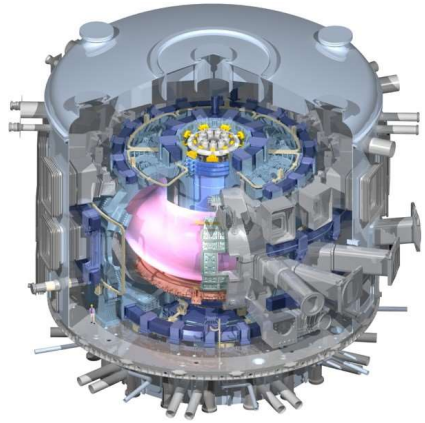


MAST Upgrade, UK

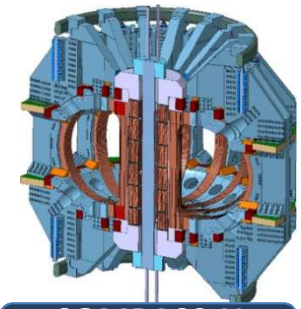
Be/W-wall

JET, UK 2022



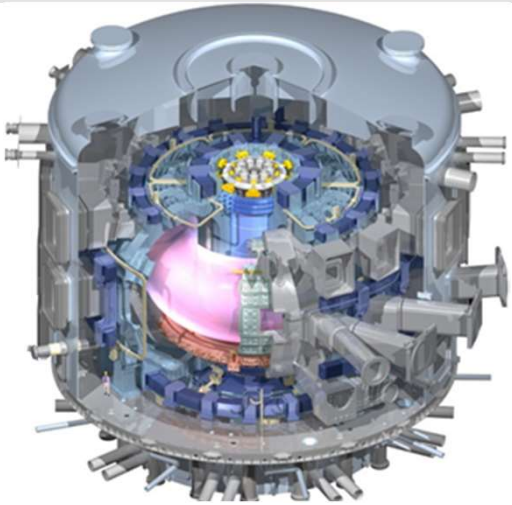


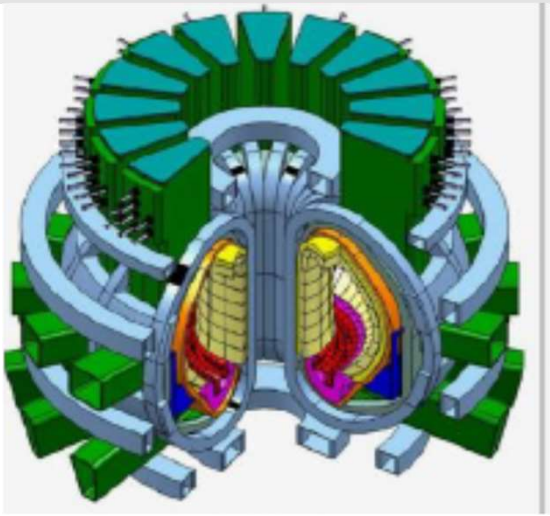
ITER (Our target device)



COMPASS-U (Start in 2023)

ITER and DEMO are overarching priorities





- **Risk reduction** and optimisation of reaching the goals described in the ITER RP
- **Cost and time savings** for ITER on the path to Q=10;
- **Key technology demonstration** (e.g. heating methods, diagnostics, shattered pellet injector)
- **Improving the performance** of ITER, aiming at higher fusion power and / or pulse length.

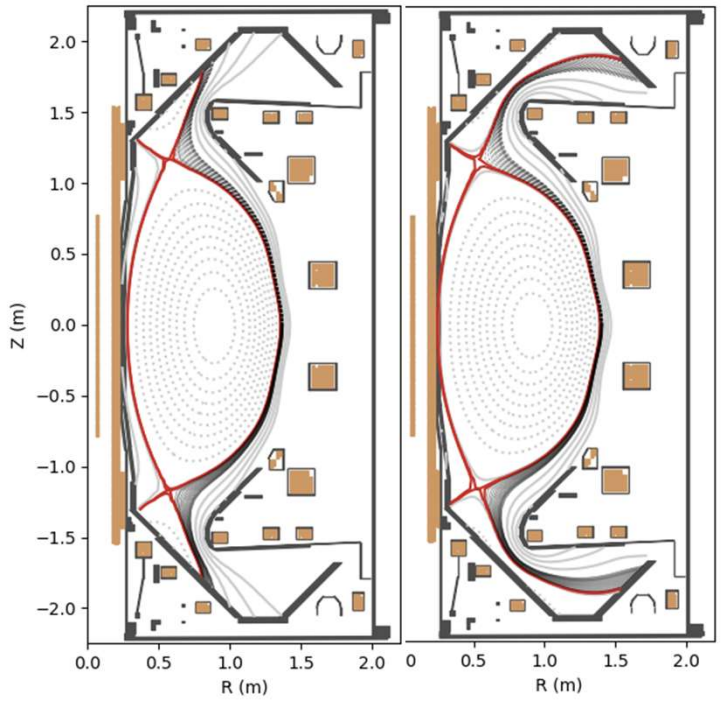
- **Ensuring detailed assessments** of technical feasibility, safety, maintenance and licensing issues.
- **Reducing the risk** of significant changes during the Engineering Design Phase
- Ensuring that correct attention is given to **industrial feasibility**, plant efficiency and availability,
- Exploring/testing/validating DEMO physics for **engineering design**

PEX: the EU Plasma EXhaust strategy

Developed to explore alternative divertor configurations and target components for DEMO ➔ key enhancements in AUG, MAST-U, TCV, WEST

MAST-U

Harrison J., et al., IAEA 2021 & this conference

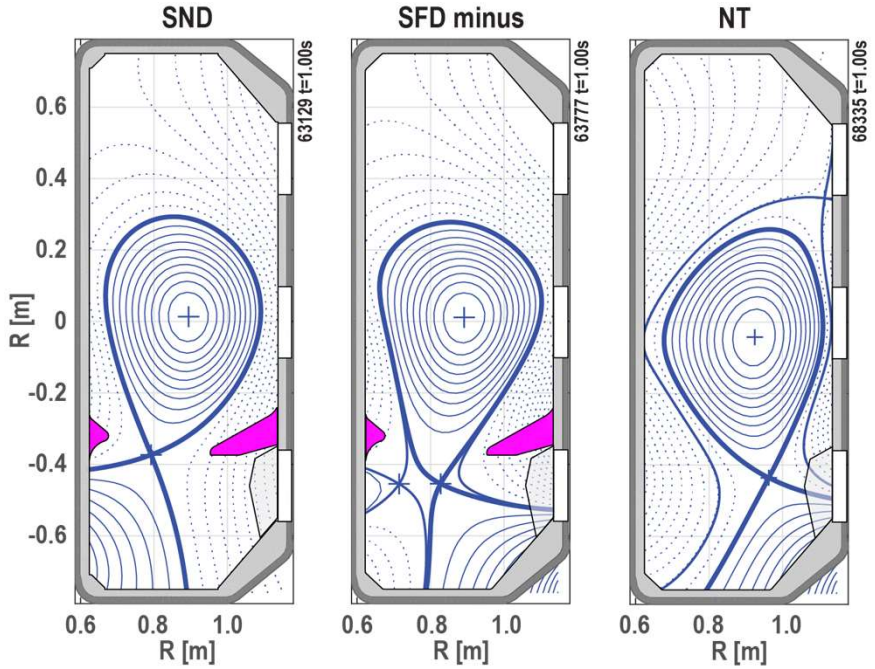


Variety of divertor configurations including the Super-X + cryo-pump

➔ Exploited in 2021

TCV

Fasoli A., et al., NF (2020)



New removable baffle to increase divertor neutral compression from 5-10 to ~200

➔ Exploited in the 2021

PEX: the EU Plasma EXhaust strategy

… making the full use of the European devices capabilities

WEST

Tsitrone E. PFMC 2021



Full-actively cooled divertor with ITER-like plasma facing units

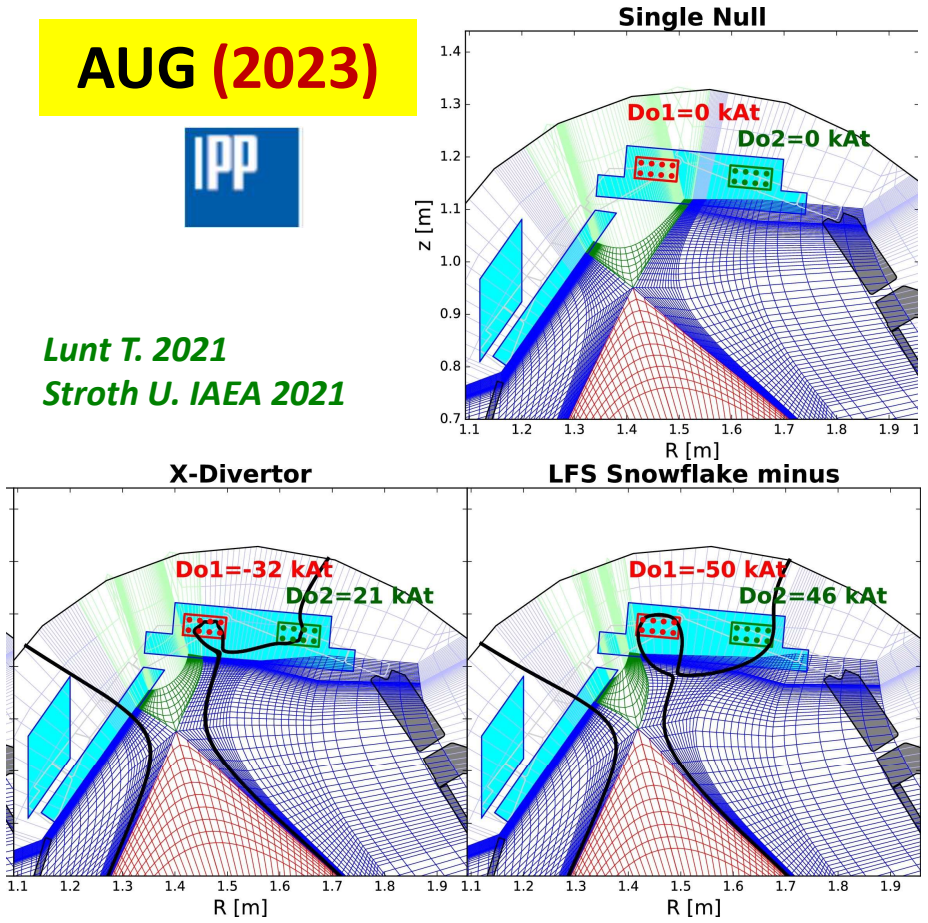
➔ **Installation completed in June 2021**

➔ **Exploitation in 2022**

AUG (2023)

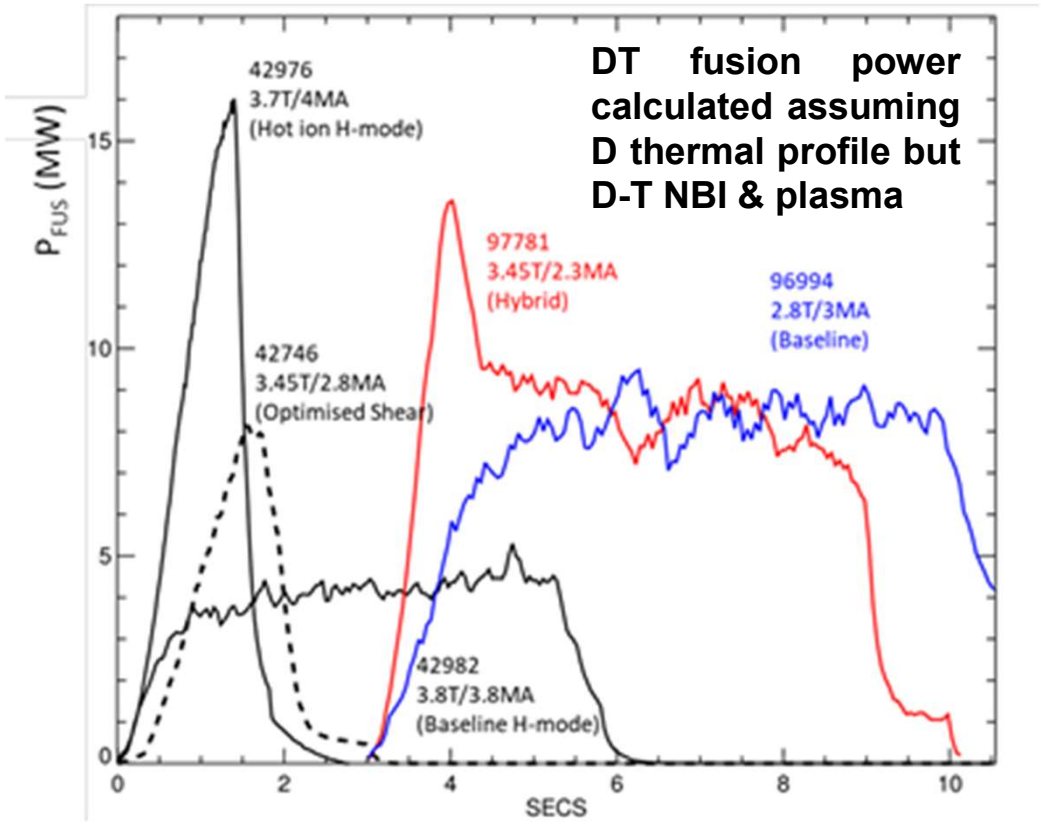
Lunt T. 2021

Stroth U. IAEA 2021

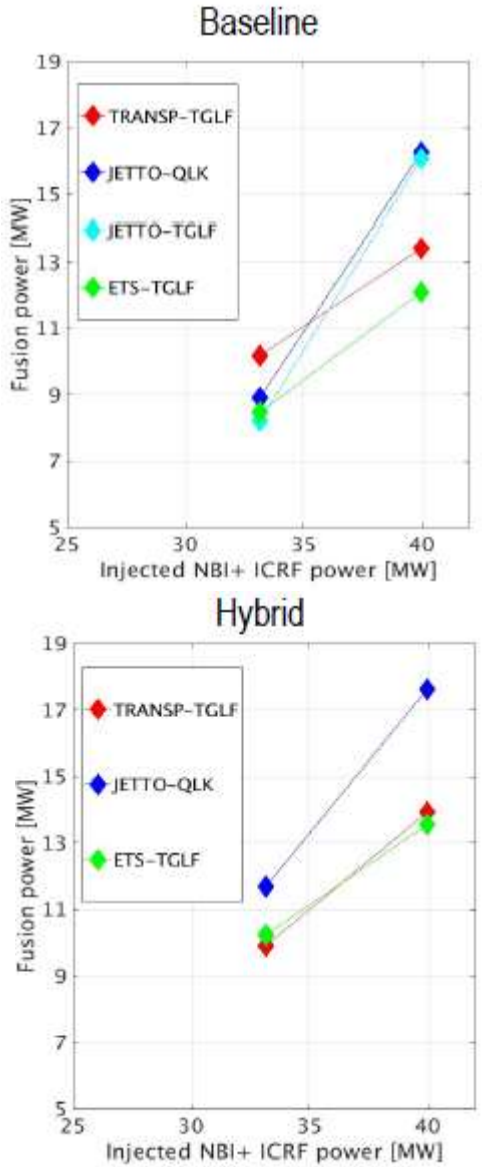


New upper divertor to study a series of ‘alternative’ divertor configurations

JET scenarios ready for DT operation (started!)



Mailloux J. IAEA 2021 & Garcia J. IAEA 2021

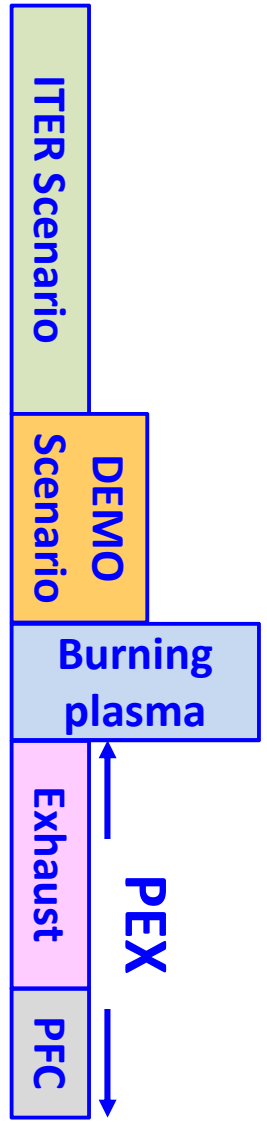


- Recent plasmas far exceeds sustained fusion power achieved in DTE1
- P_{DT} ~12MW-17MW predicted when including isotope and energetic particle effects

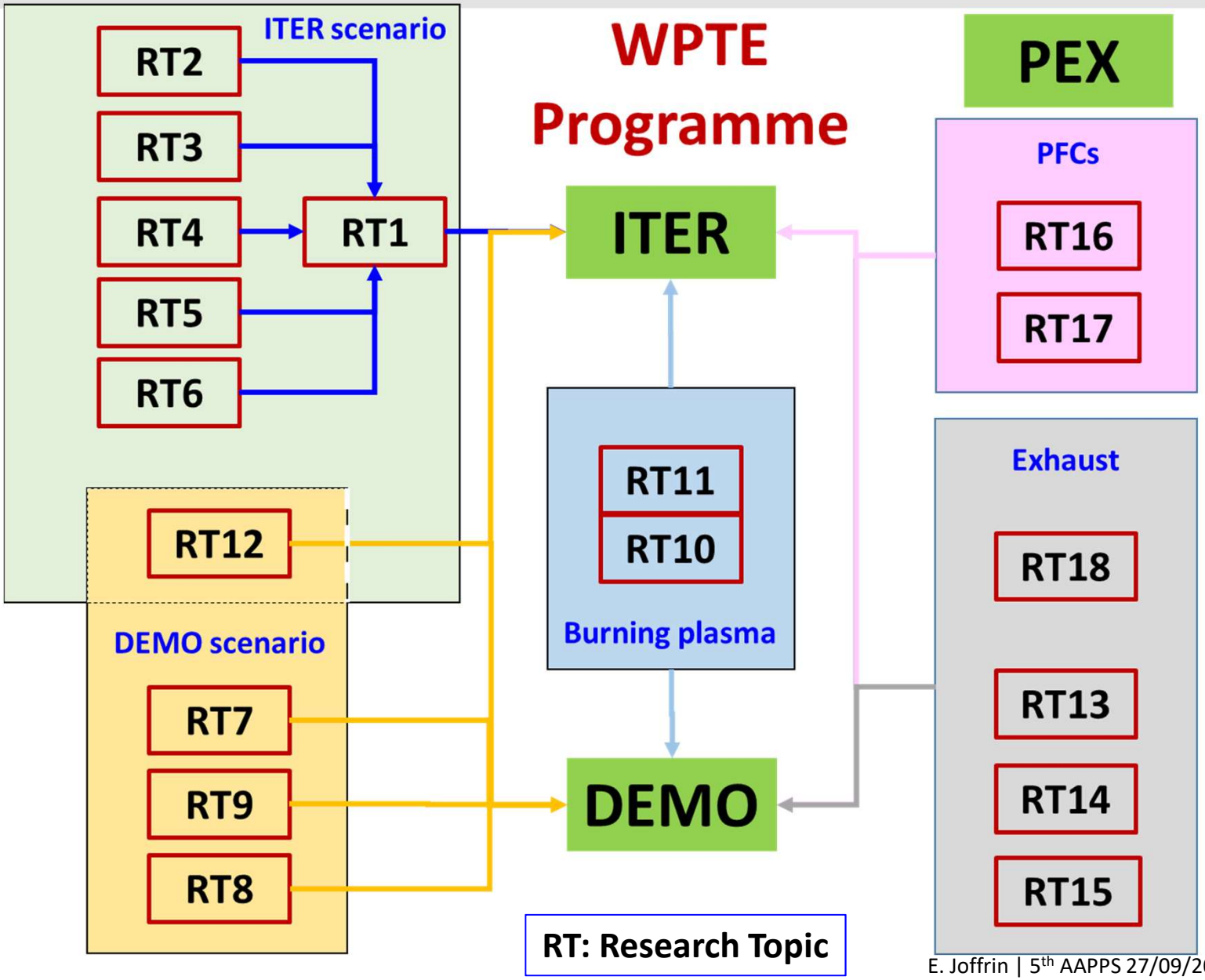
JET

Tokamak exploitation: 2021-22 research topics

	Research Topics
RT1	ITER Baseline scenarios towards low collisinality and detachment
RT2	H-mode entry and pedestal dependence with impurities and isotopes
RT3	RF-assisted breakdown and current ramp-up optimization
RT4	Disruption avoidance and control for ITER and DEMO
RT5	Run-away electron generation and mitigation
RT6	ELM mitigation and suppression in ITER/DEMO relevant condition
RT7	Negative triangularity scenarios as an alternative for DEMO
RT8	QH-mode and I-mode assessment in view of DEMO
RT9	Extension of EDA and QCE performance towards DEMO
RT12	Development of the steady state scenario
RT10	Fast-ion physics with dominant ICRF heating
RT11	Impact of MHD activity on fast ion losses and transport
RT13	X-point radiation and control
RT14	Physics of plasma detachment / impurity mix/ heat load patterns
RT15	Extrapolation of SOL transport to ITER and DEMO
RT18	Alternative divertor configurations
RT16	PFC damage evolution under tokamak conditions
RT17	Material migration and fuel retention mechanisms in tokamaks



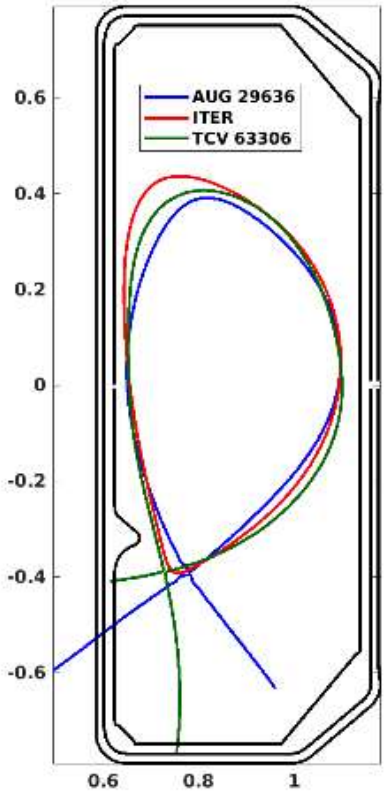
Tokamak Exploitation Programme in a nutshell

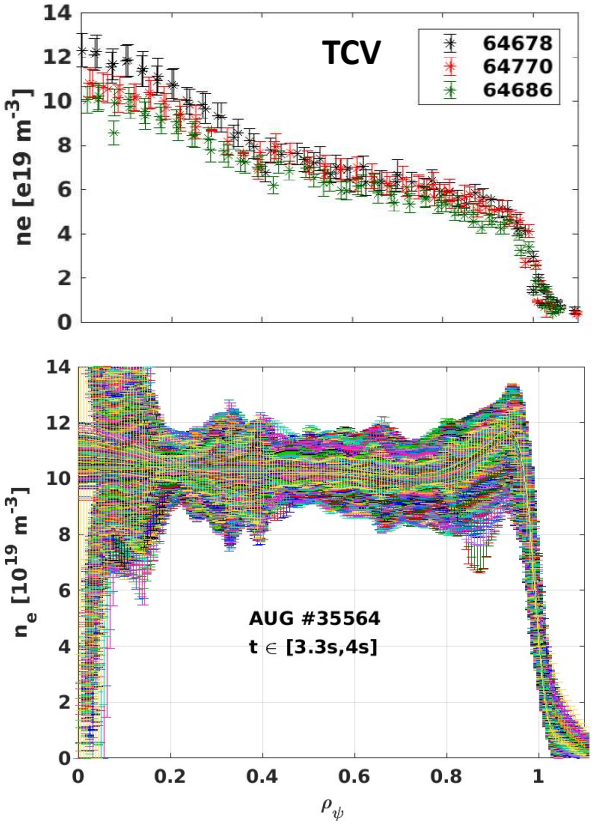


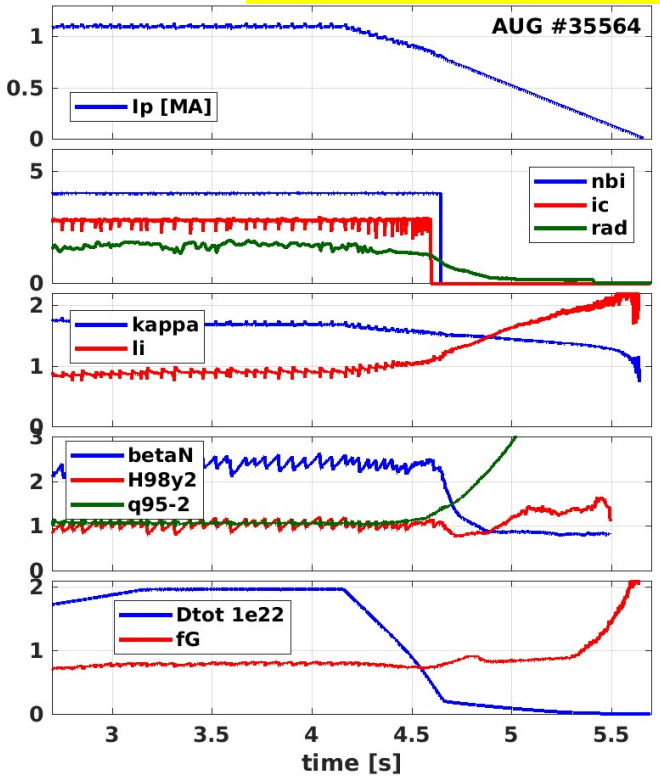
Recent selection of highlights from the Tokamak Exploitation and 2020 Medium Size Tokamak Programmes

ITER baseline scenario development

Mission 1: TCV& AUG







Sauter O, IAEA 2021
Pütterich T, EPS 2021

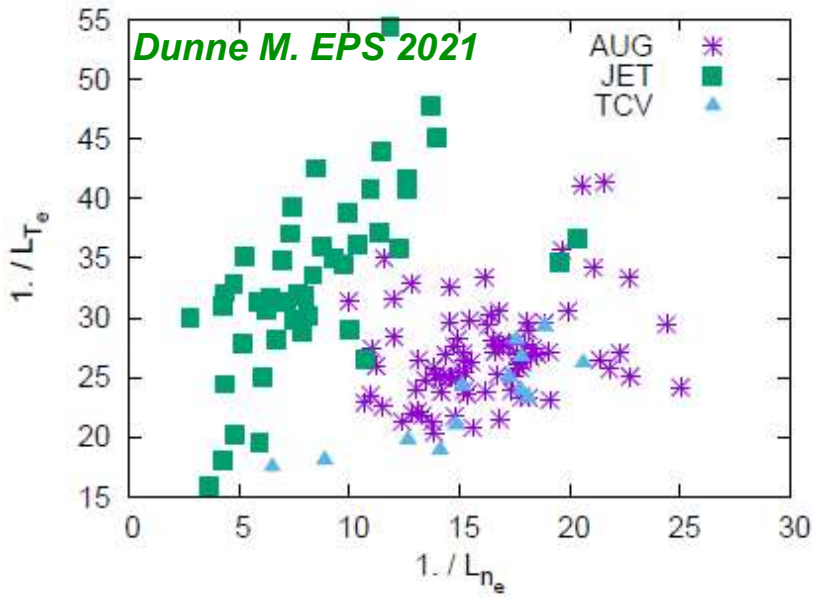
- TCV and ASDEX Upgrade using similar shapes than ITER
- Density profile systematically more peaked in TCV than in ASDEX Upgrade in general
- Safe termination validated in ASDEX Upgrade at q95 with Ip and κ ramp-down like in JET.

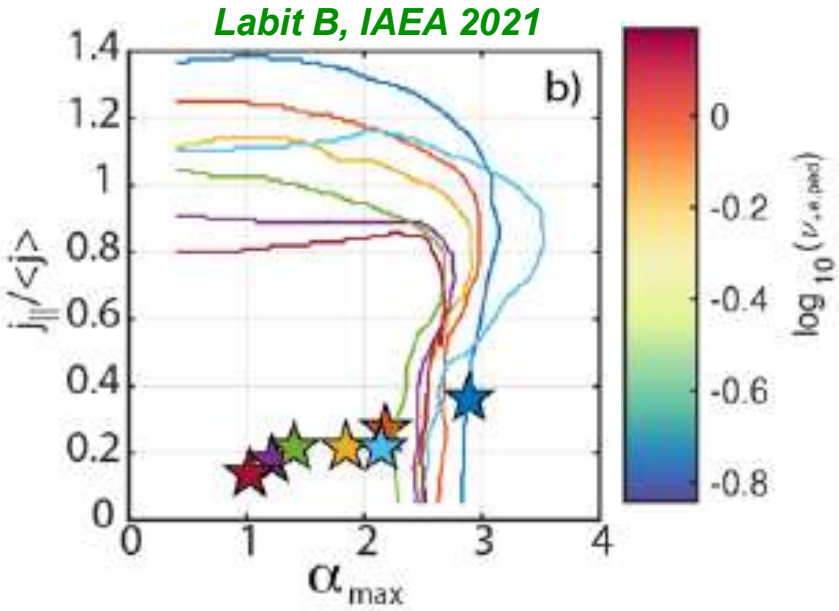
Low torque and electron heating dominated ITER Baseline scenario in development this year

Pedestal approaching ITER conditions

A pedestal database has been developed by EUROfusion with common variable definitions

Mission 1: TCV, AUG, JET





Machine comparison shows that JET pedestal are shifted to higher 1/Lte implying higher transport for a given temperature gradient

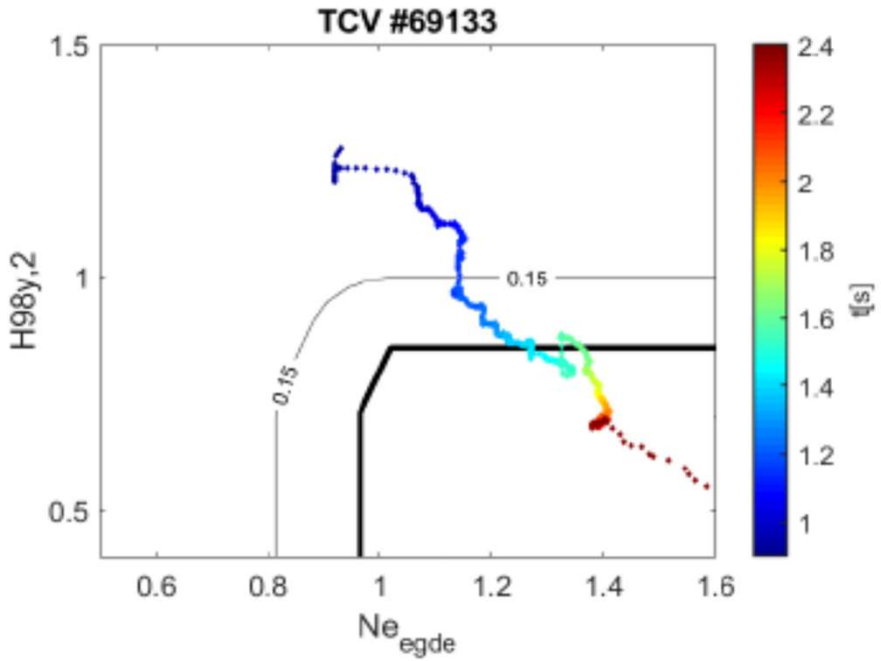
Pedestal closer to Peeling-Ballooning boundary as collissionality decreases at the boundary (dominant electron heating)

This research continues exploring the collisionality space in ASDEX Upgrade, TCV and MAST-U approaching the ITER conditions.

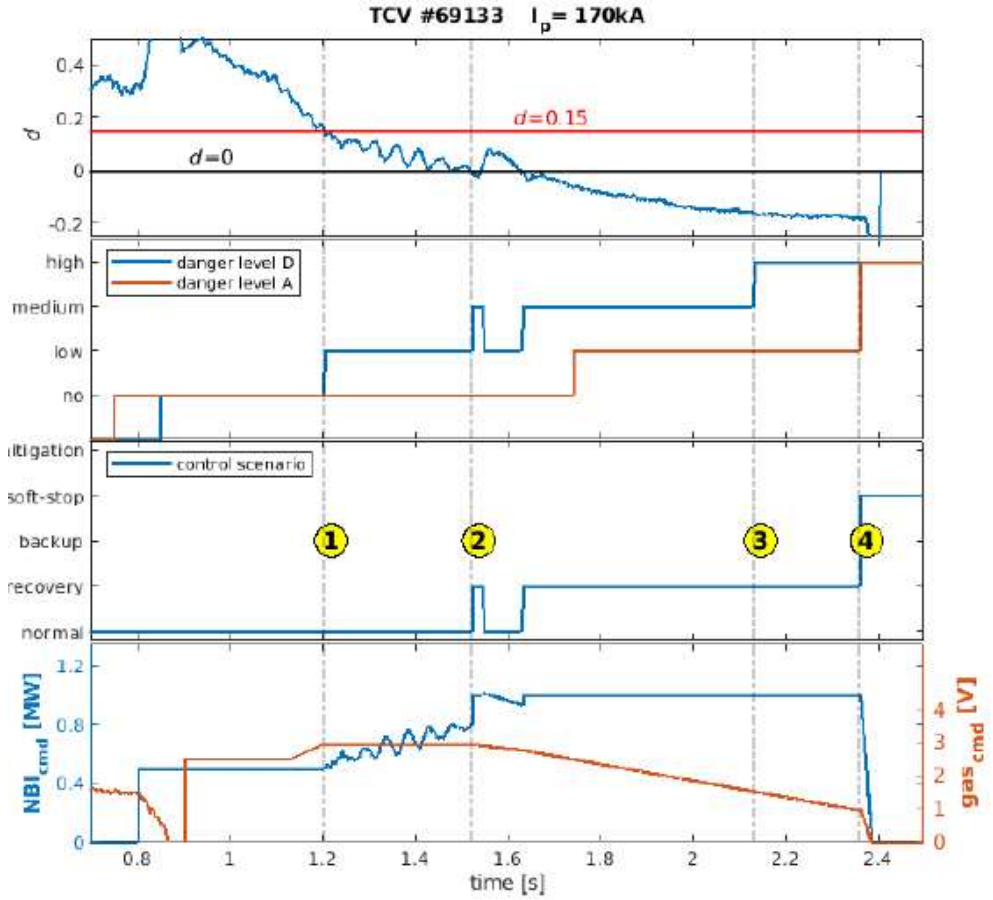
Disruption avoidance: high density limit

Felici F, IAEA 2021

Mission 1: TCV



Density limit danger level characterized in the H vs ne_{edge} space



Real time control scheme developed initially in ASDEX Upgrade will be applied to more devices and made machine generic.

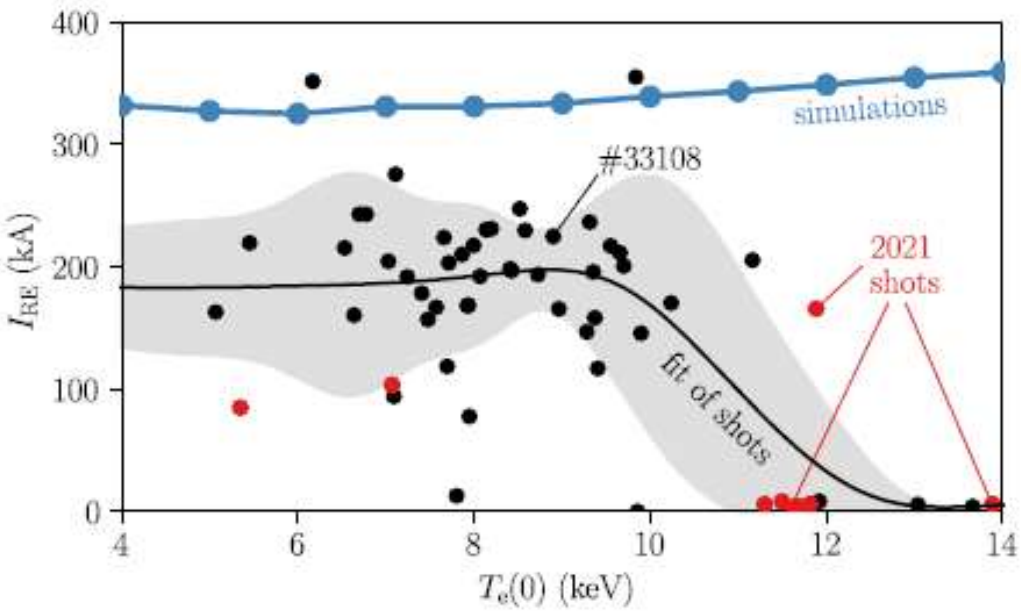
Run-away generation in the ITER domain

O. Linder, Disruption WS, Princeton 2021

Mission 1: AUG

For Te <9keV

- **Experiment and simulation show constant Run-away current (simulation larger due to the absence of RE losses)**



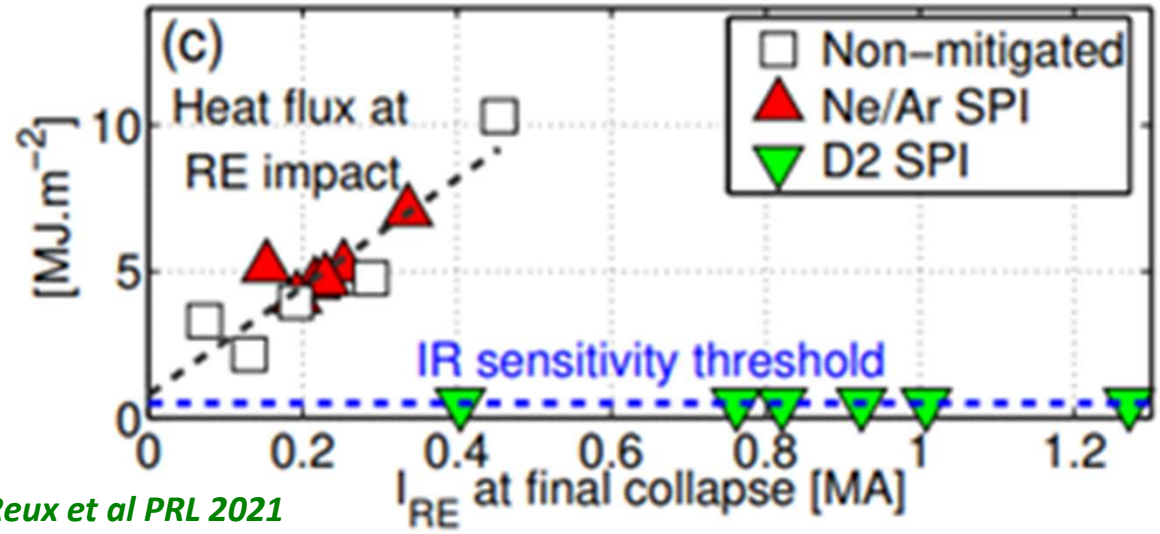
For Te >9keV

Simulation predicts an increase of IRE: hot tails mechanism.

- **New data in 2021: one pulse at 12keV**
- **Loss of RE seed during magnetic break-up?**

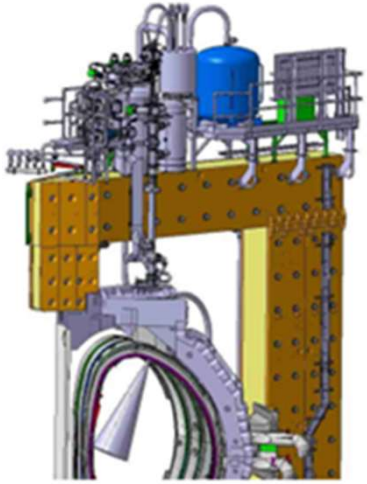
This research is also addressing run-away generation conditions and mechanisms in AUG, TCV and WEST.

Run-away mitigation demonstrated in JET with the SPI



C. Reux et al PRL 2021
S. Jachmich et al., IAEA 2021

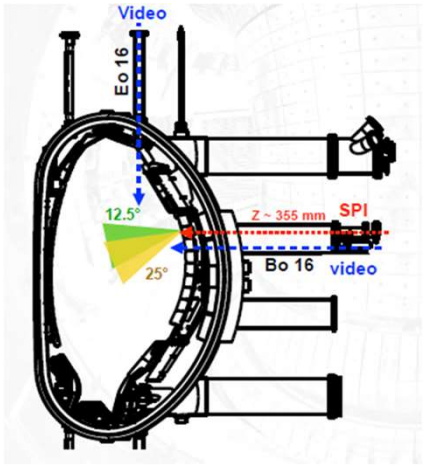
Mission 1: JET, AUG



- **RE suppression with SPI demonstrated**
- **D_2 SPI applied to high current RE beam leads to benign impacts on the first wall**

➔ **D_2 SPI potential new solution for RE control in ITER**

- **Run-away & disruption mitigation further explored in 2022 in AUG (new SPI) and JET with IO in support of the ITER disruption mitigation system.**

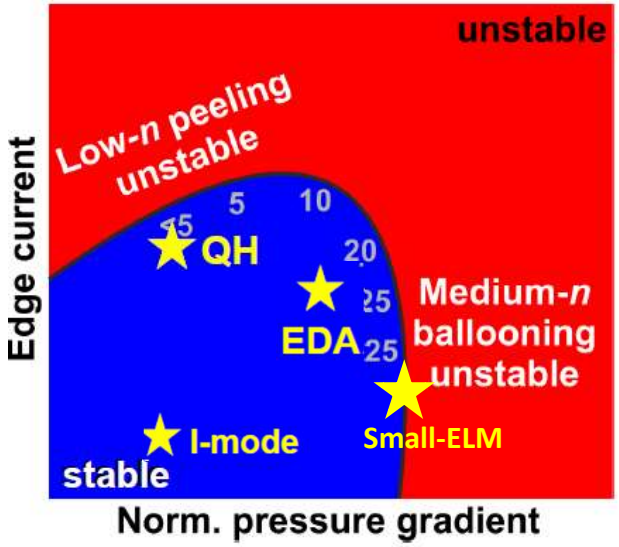


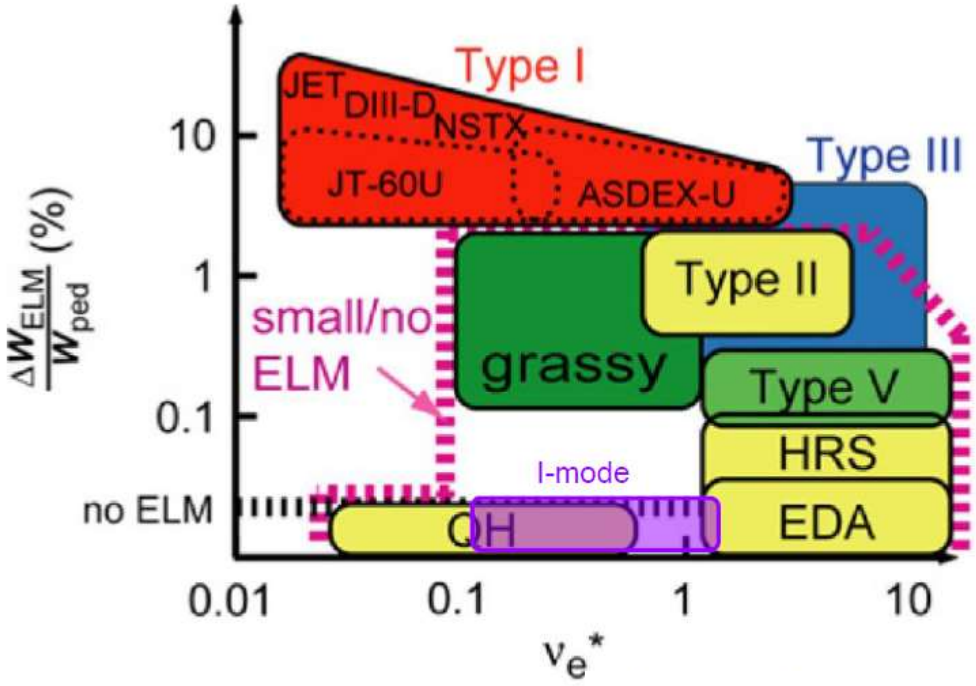
ELM-free regime developments actively pursued in the tokamak Programme

Mission 1: all devices

Natural ELM-free regimes can be achieved using several types of actuators: ExB shear, magnetic shear, shaping …
There are essential for DEMO that cannot accept ELMs bursts!

Viezzer E. Nuc Fus 2018 & EU-US TTF 2021

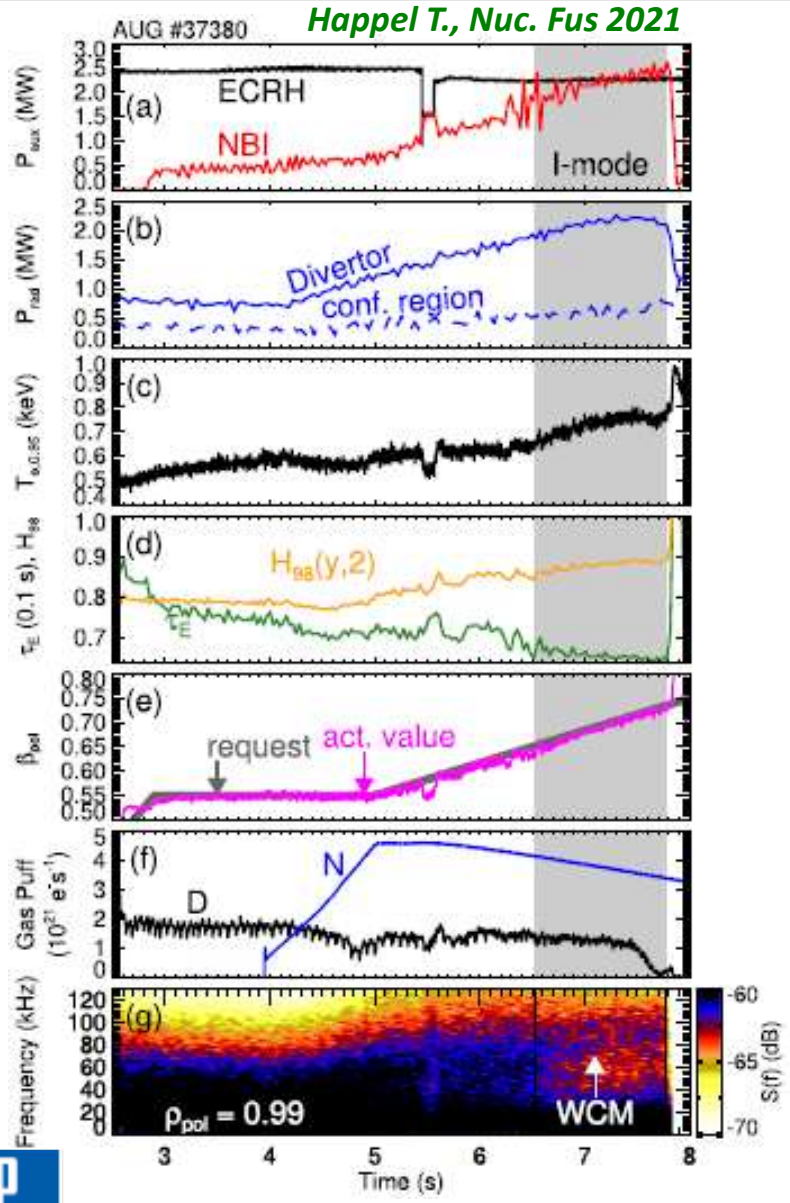




Kamiya K. PPCF 2007

➔ **EDA ELM-free regime: see presentation by L. Gil, this conference**

Detachment of inner divertor leg achieved for the first time



Mission 1: AUG

I-mode occurs at the transition between the L- and H-mode when VB drift is away from the target

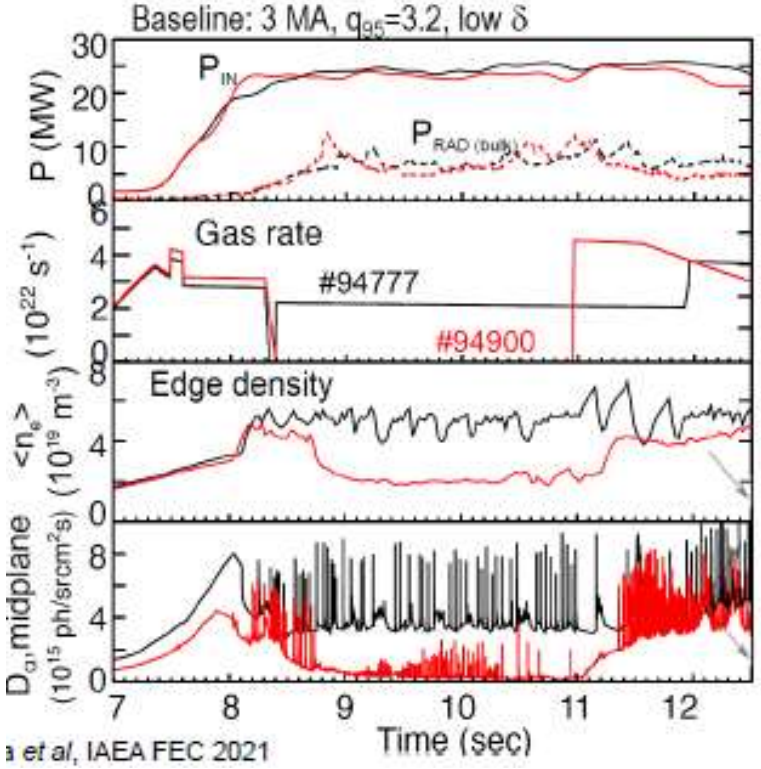
- **Detachment of inner divertor leg obtained with high N seeding levels into L-mode and using β_{pol} feedback control**
- **Inner divertor detaches during L-mode, confinement increases even before I-mode starts**

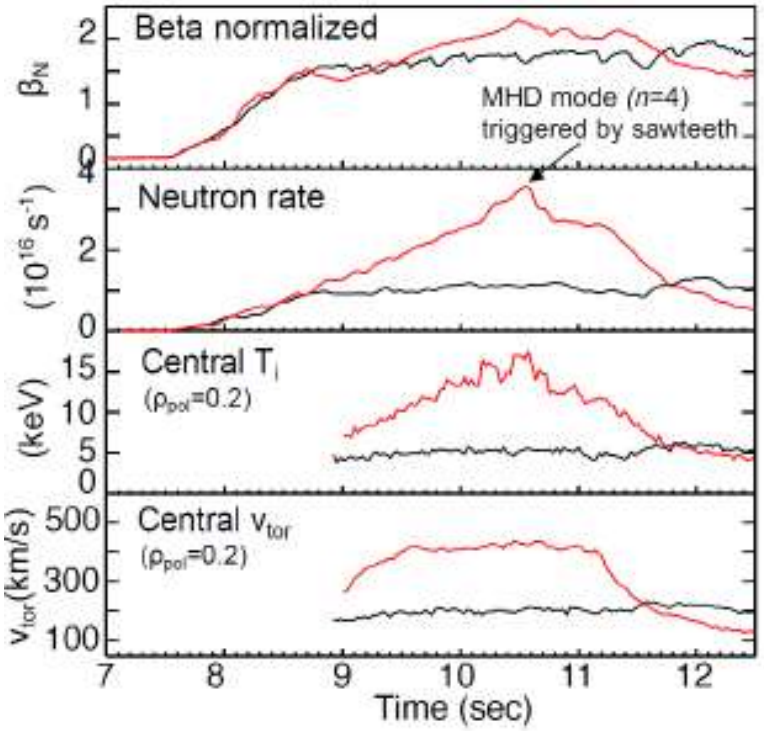
Extend cross-machine scaling of P_{L-I} threshold in all devices and introduce DEMO constraints in the scenario development.

Small ELM regime found at JET-ILW with no gas

Mission 1: JET

- ❑ **Stationary density, increased ion temperature, neutrons**
- ❑ **Higher level of rotation inducing strong impurity outward pinch**
- ❑ **Improved pedestal stability due to the inward shift of the maximum of gradP**



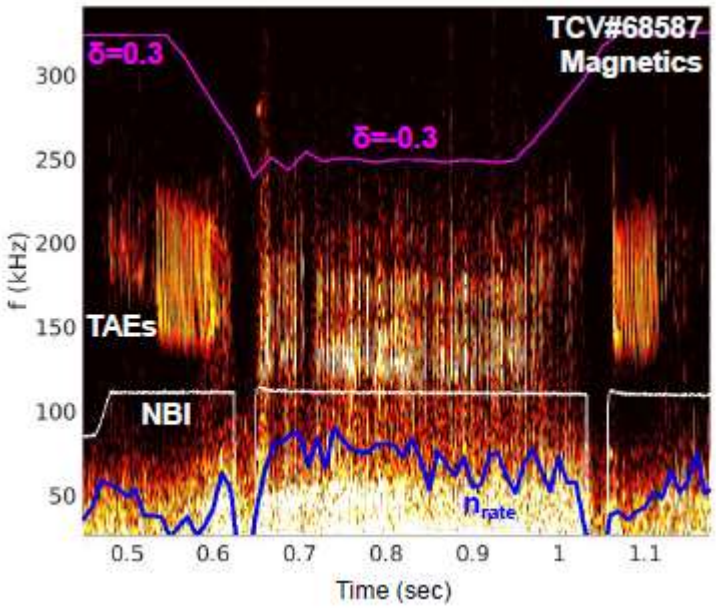


De la Luna E. IAEA 2021
Garcia J., IAEA 2021

Plans for testing ELM-free scenarios (QH-mode, EDA) in JET are also been developed for the next 2 years

JET

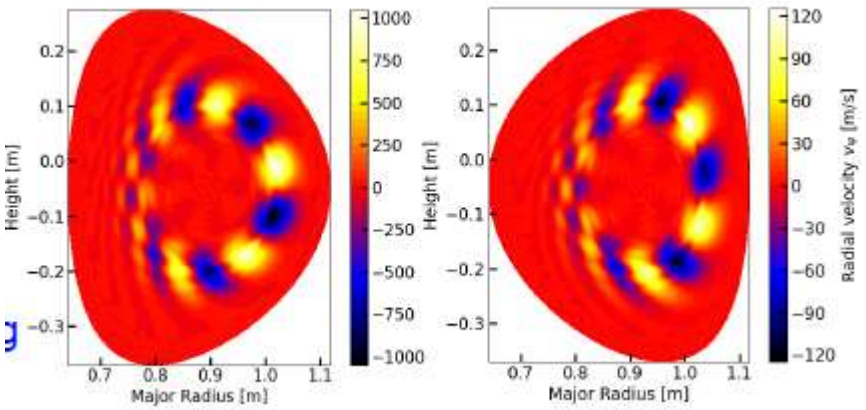
Negative triangularity has major impact on observed TAE activity



- TAEs appear with lower frequency and amplitude during –d phase
- Also, slightly higher neutron rate

Garcia-Munoz, EPS 2021

Mission 1: TCV



MEGA used to isolate negative δ effect

- Lower linear growth rate
- lower amplitude in saturated phase
- Same location and frequency

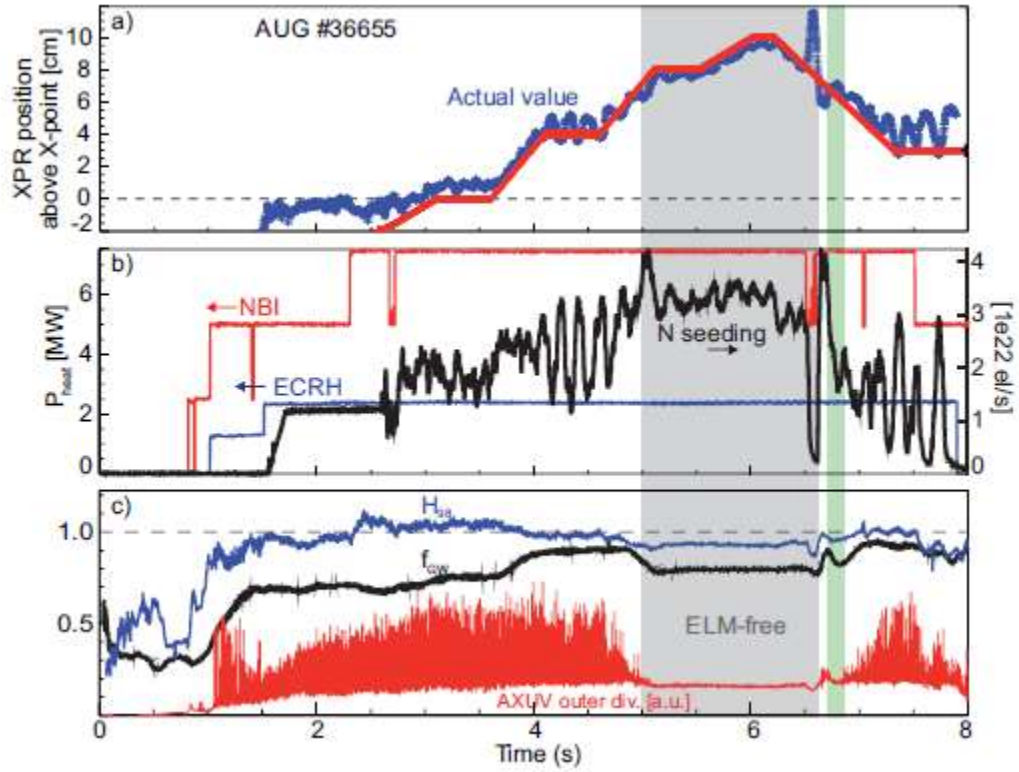
This research is also addressing the identification of the relevant actuators (such as ECRH or RMPs) to minimize AE-induced fast-ion losses in AUG, TCV and MAST-U in view of ITER and DEMO.

First control of full detachment and X-point radiation

Bernert M., IAEA 2021

Mission 2: AUG

- X-point radiation is a stable regime, shown in AUG & JET
- The X-point radiator can be actively controlled by N2 seeding
- A high location of the radiator leads to ELM suppression

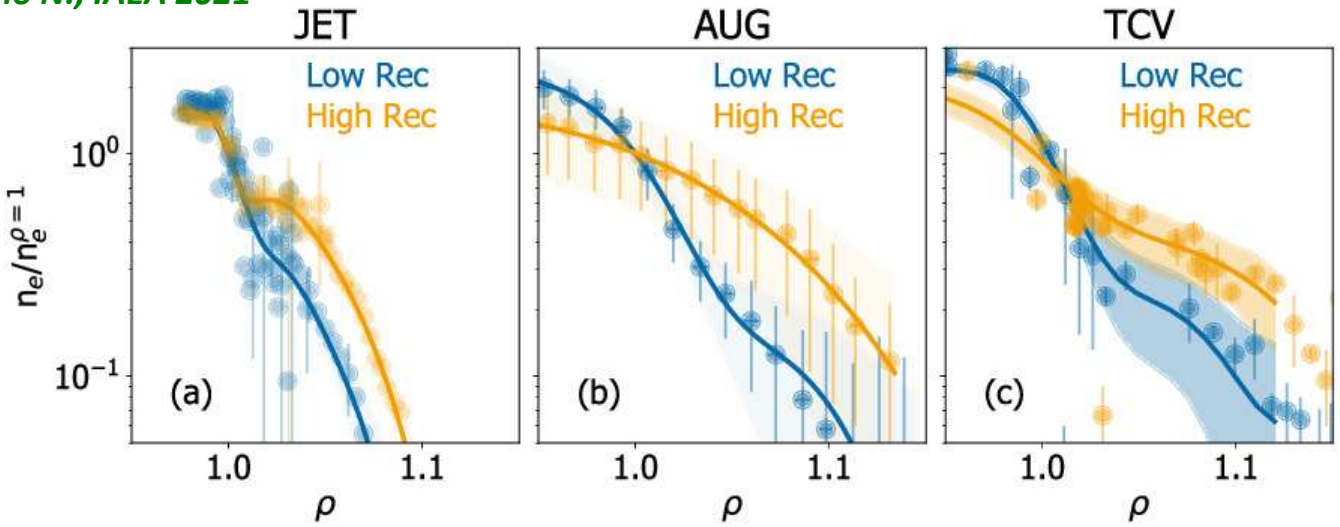


- X-point radiation is studied on all tokamaks (AUG, MAST-U, TCV and WEST) in comparable H-mode scenario.
- X-point radiation control schemes is also tested in multiple device

Impact of high recycling on H-modes

Mission 2: AUG, JET, TCV

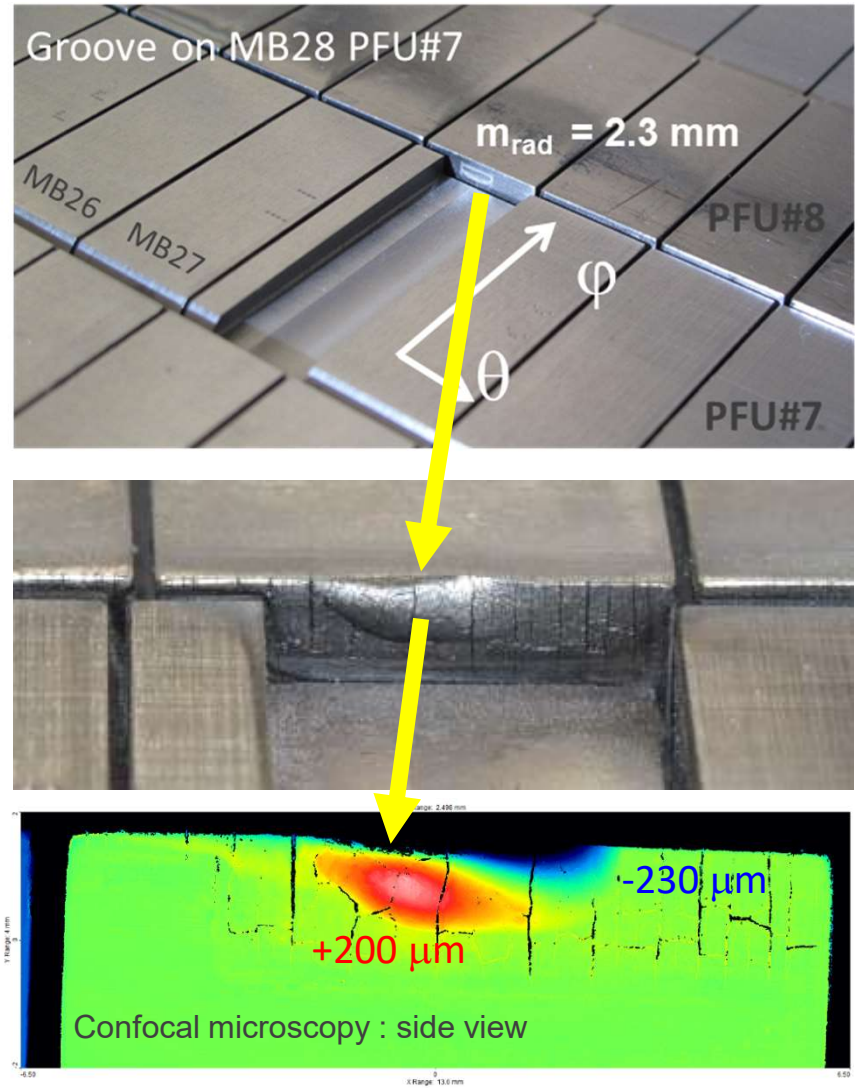
Vianello N., IAEA 2021



- ❑ **Increase of the far SOL e-folding length in high fueling H-mode**
- ❑ **More ballooning turbulence dominated**
- ❑ **Increase in filamentary activity in the far SOL.**

- ❑ **Role of ion/electron channel transport in the near and far SOL.**
- ❑ **Quantify particle and heat load in the near and far SOL in different regime.**
- ❑ **Document associated turbulence properties near the X-point and in divertor region.**

Melting experiment performed under steady state heat flux in WEST



Corre Y, PFMC 2021

Mission 2: WEST

Exploration of the melt dynamics for steady state / transients (JET/AUG) and 2 mm deep groove machined on ITER like PFU:

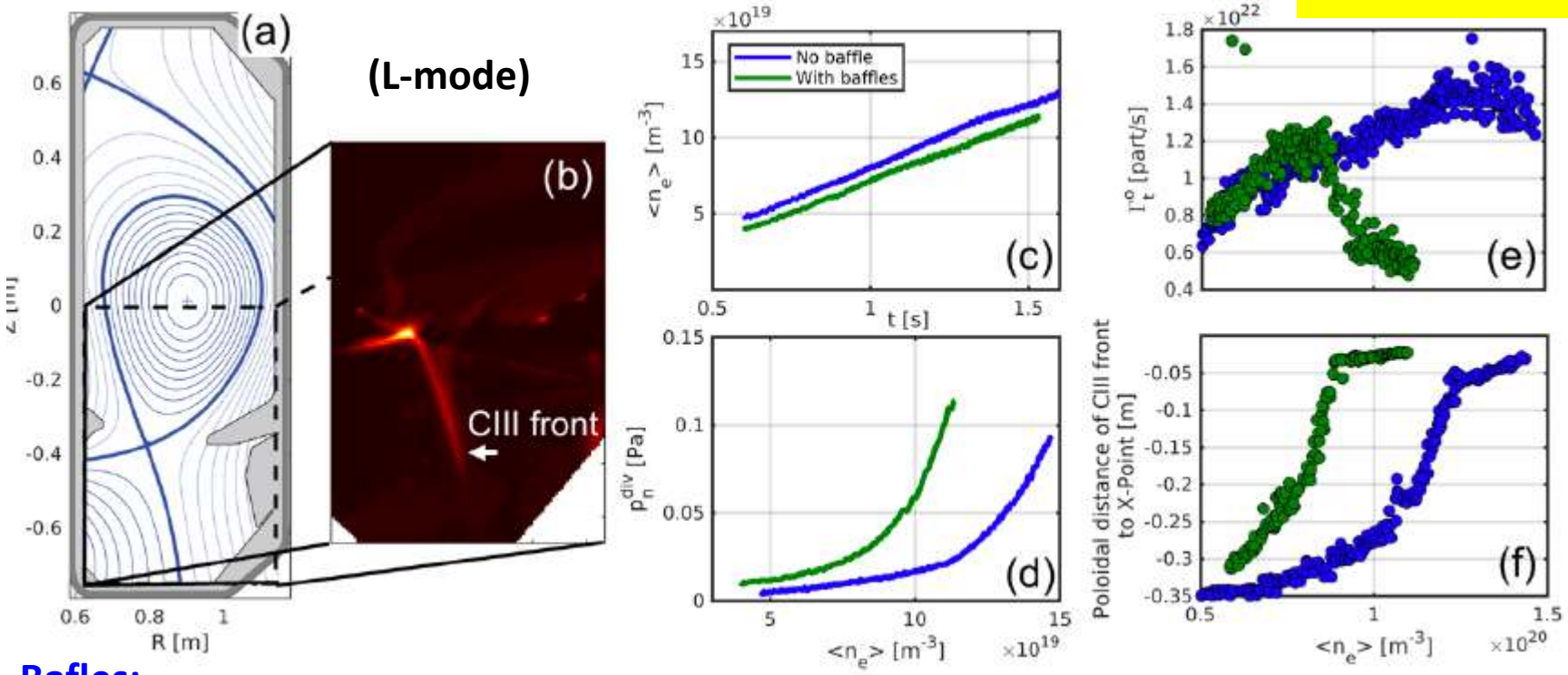
- ❑ **Significant melt material displacement achieved**
- ❑ **Validation of the modelling for actively cooled PFU on-going**

These AUG and WEST data are used to develop the predictive modelling (MEMOS) of local power load distributions at castellated and shaped PFCs for ITER and DEMO

Power exhaust physics is progressing thanks to the PEX Upgrade

Theiler C., IAEA 2021

Mission 2: TCV (PEX)



Bafles:

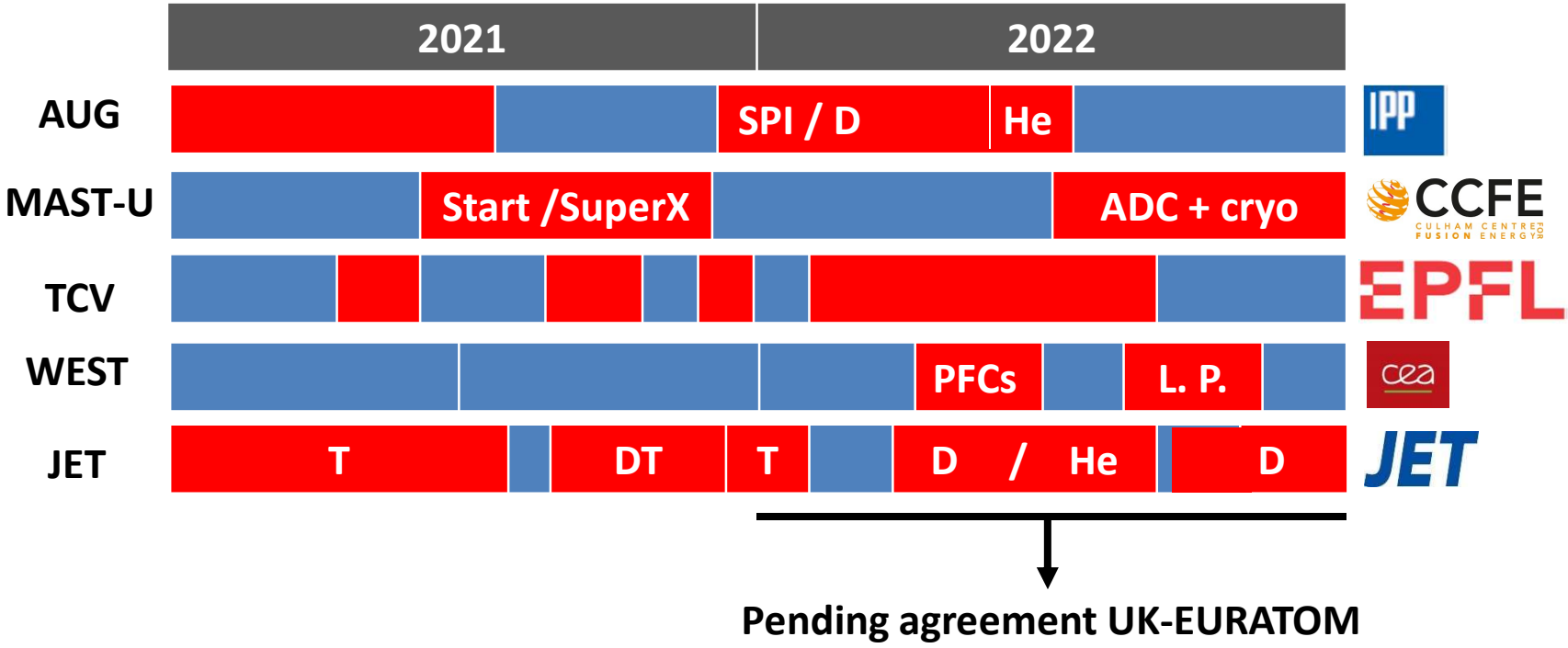
➔ **Increase in divertor pressure ➔ earlier roll-over of the total ion flux ➔ CIII front location to the X-point at lower density**

SOLPS-ITER drift simulation reproduce these changes

These experiments are now extended to high power H-mode scenario in parallel with similar experiments on MAST-U

A challenging agenda ahead in 2022

In 2022, all five devices AUG, JET, MAST-U, TCV and WEST will operate



The EUROfusion Programme operates a fraction of typically 30 to 45% of the time of each machine, except JET: 100%.

Conclusions

The ambition of Tokamak Exploitation activity in Europe is to use the complementary capabilities of the EU devices to address essential questions for the future exploitation of ITER and the design of DEMO.

The recent cross machine work illustrate the benefit for testing physics on different scales and geometries and should enhance our predictive capabilities for the next steps with more robust models.

The PEX strategies is expecting to provide a divertor solution to the DTT tokamak demonstrator presently in its design phase in Italy in the 2027 horizon.

Tokamak Exploitation is aiming at developing an integrated scientific Programme using 5 devices (if JET is prolonged) to achieve the objectives of the road map in this framework Programme 2021-25.

We do hope to report to you about this exciting Programme in the next APPS conferences !

Back-up slides

Linking WP TE RTs with TSVVs and Thrusts

TSVV / Research topic No	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
TSVV 01 Physics of the L-H Transition and Pedestals																		
TSVV 03 Plasma Particle/Heat Exhaust: Fluid/Gyrofluid Edge Codes																		
TSVV 04 Plasma Particle/Heat Exhaust: Gyrokinetic/Kinetic Edge Codes																		
TSVV 05 Neutral Gas Dynamics in the Edge																		
TSVV 06 Impurity Sources, Transport, and Screening																		
TSVV 07 Plasma-Wall Interaction in DEMO																		
TSVV 08 Integrated Modelling of Transient MHD Events																		
TSVV 09 Dynamics of Runaway Electrons in Tokamak Disruptions																		
TSVV 10 Physics of Burning Plasmas																		
TSVV 02 Physics Properties of Strongly Shaped Configurations																		
TSVV 11 Validated Frameworks for the Reliable Prediction of Plasma Performance and Operational Limits in Tokamaks																		
TSVV 14 Multi-Fidelity Systems Code for DEMO																		

Thrust 1 Thrust 2 Thrust 3 Thrust 5

➔ Interaction between WPs, E-tasc SB and TSVVs is organised in thrusts and WPTE acts as facilitator for Thrust 1

Research Topics linked to Mission 1

Mission 1-1: Demonstrate and qualify MHD stable high performance operation with metallic plasma facing components for ITER and DEMO

RT1	IBL scenarios towards low detachment and low collisionality
RT2	H-mode entry and pedestal dependence with impurities and isotopes
RT3	RF-assisted breakdown and current ramp-up optimization
RT4	Disruption avoidance development for ITER and DEMO
RT5	Run-away electron generation and mitigation
RT6	ELM mitigation and suppression in ITER/DEMO relevant condition
RT7	Negative triangularity scenarios as an alternative for DEMO
RT8	I-mode and QH-mode studies assessment in view of DEMO
RT9	Extension of EDA and QCE performance towards DEMO

Mission 1-2: Improve physics description (experiments, theory / simulation) of energetics particles including their non-linear interplay with thermal plasmas in order to control burning plasmas in ITER and DEMO.

RT10	Fast-ion physics with dominant ICRF heating
RT11	Impact of MHD activity on fast ion losses and transport

Mission 1-3: Develop integrated scenarios with controllers for long pulse, ultimately steady state, operation for ITER and DEMO.

RT12	Development of the steady state scenario

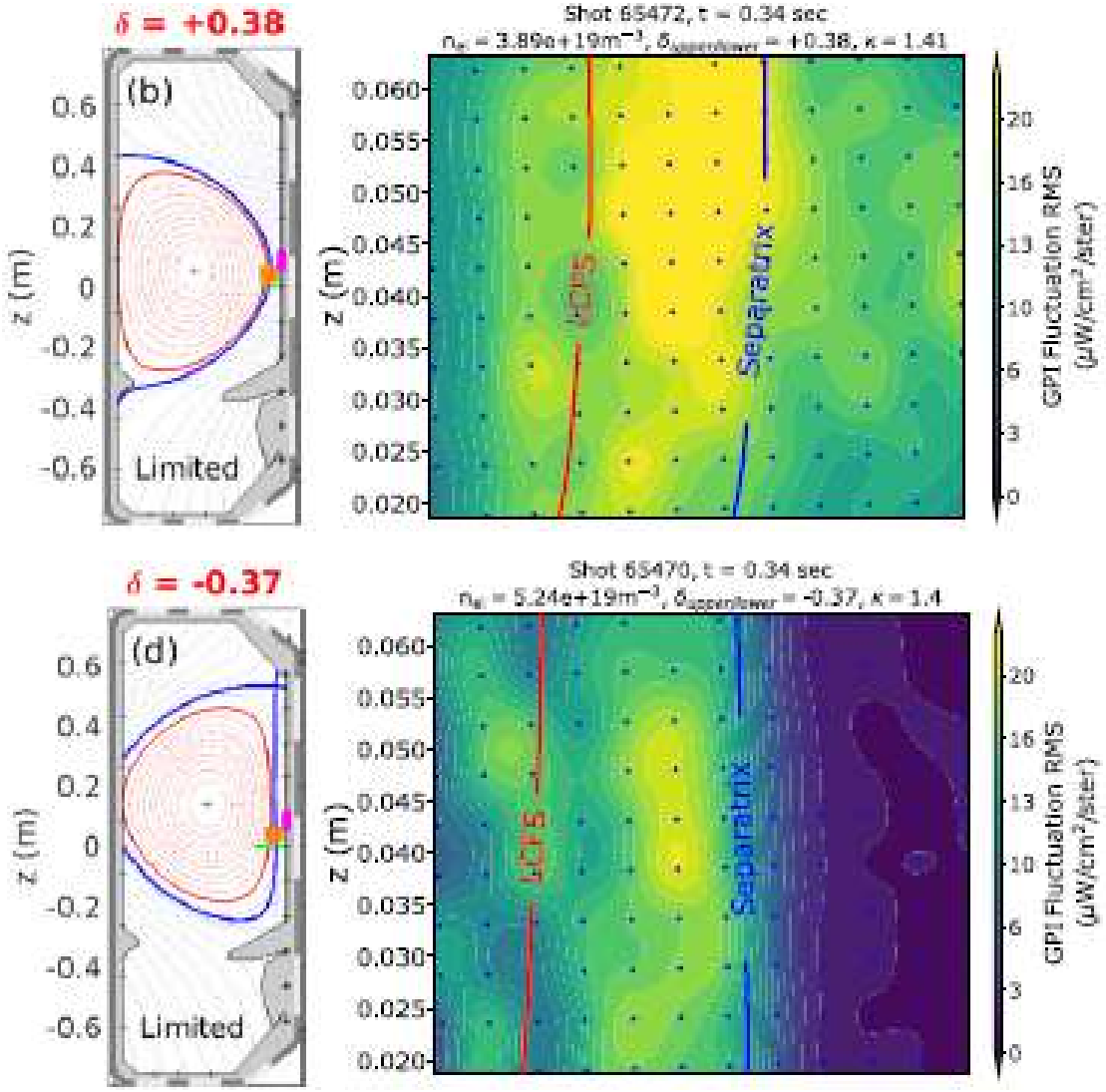
Research Topics linked to Mission 2

Mission 2-1: Detachment control for ITER, DEMO baseline and HELIAS operation.	
	RT13 X-point radiation and control
	RT14 Physics of plasma detachment / impurity mix/ heat load patterns
	RT15 Extrapolation of SOL transport to ITER and DEMO
Mission 2-2: Prepare efficient Plasma Facing Components (PFC) operation for ITER, DEMO and HELIAS.	
	RT16 PFC damage evolution under tokamak conditions
	RT17 Material migration and fuel retention mechanisms in tokamaks
Mission 2-3: Investigate alternative innovative divertor geometries for DEMO.	
	RT18 Alternative divertor configurations

Negative triangularity exploration (TCV & AUG)

Han et al, Nuc Fus 2021

Mission 1: TCV



Fluctuation in the scrape-off (by Lang. Probes and Gas puff imaging) **is showing a dramatic decrease** when going to the negative δ

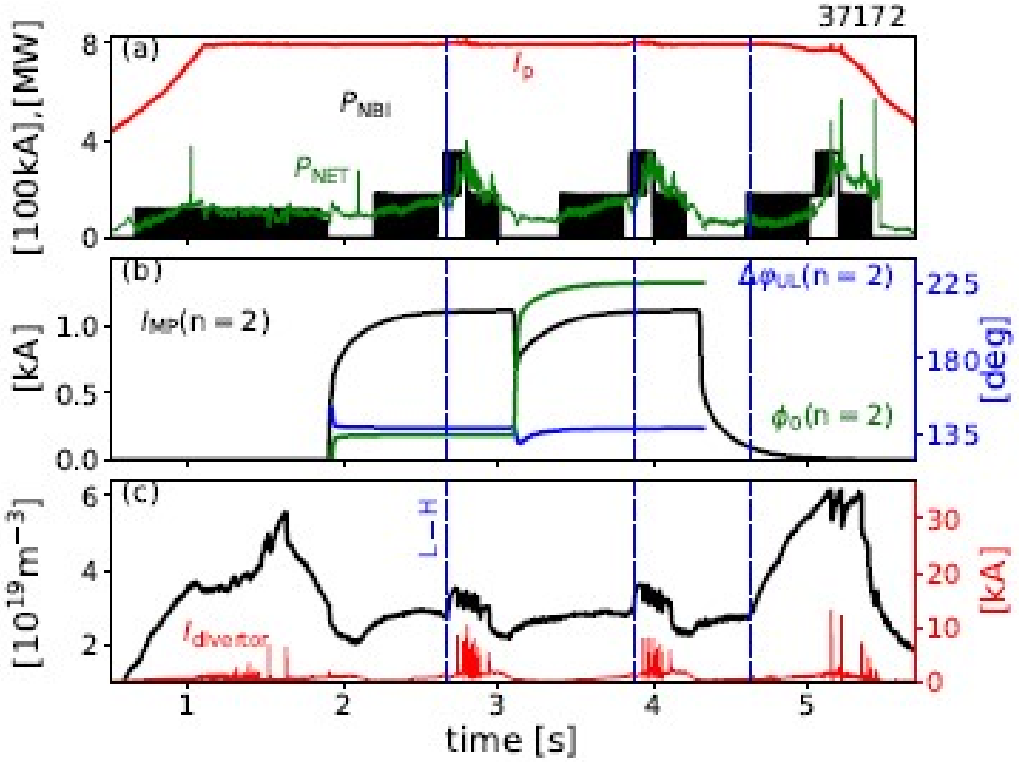
Plasma-wall interaction is also **almost fully suppressed**: linked with the reduced connection length

➔ **More experiments are in discussion for 2022 in devices with negative δ capabilities (AUG & TCV)**

Programme interne

Resonant magnetic perturbation for ELM mitigation impacts on the L-H threshold

Mission 1: AUG



Not to be shown

The L-H threshold is postponed with respect to the NBI onset ramp when the RMP is applied

RMP ELM suppression is further explored in 2021-22 in AUG, TCV and MAST-U:

- **Compatibility of ELM suppression with low torque, dominant electron heating, and radiative divertor**
- **Exploration of ELM suppression in hydrogen for ITER FPO and DEMO**