9 – 10 November 2026

RT-08: "Physics and operational basis for high beta long pulse scenarios"
Discussion on proposals and 2027 priorities

Vito Konrad Zotta

On behalf of WP TE TFLs
E. Tsitrone, N. Vianello, A. Hakola, V. Igochine, Y. Kazakov, D. Keeling, B. Labit, V.K. Zotta

Research Topic Coordinators:
F. Auriemma, S. Blackmore, C. Piron

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Scientific deliverables

1. Consolidate understanding of **flux pumping** mechanism and extrapolate to ITER/DEMO/**JT-60SA**.

2. Quantify **compatibility of high β_N long-pulse with mitigated ELMs and/or with exhaust in metallic wall devices** in view of extrapolating scenario to **JT-60SA** W-wall operation.

3. **Characterize** the fast and thermal ion **transport** together with the ExB, magnetic shear, turbulence conditions in steady-state scenarios at high-q.

4. **Validate state of the art models** for scenario extrapolation towards future devices.

5. **Develop** intrinsically steady-state solutions at **high β_N** (>3) in terms of q/pressure profile with mild MHD activity. Investigate the **dependence** of the scenario **to** the available **actuators** and compare it to the expected **JT-60SA** and DEMO scenarios particularly in terms of **extending operational space toward high Greenwald fractions.**

6. **Develop steady-state scenarios in metallic devices** at high β_N in conditions of MHD characteristics close or above the no-wall ideal limit. Investigate the dependence of the scenario to the actuators and characteristics expected to be used in **JT-60SA**.

Deliverables strongly oriented in support of JT-60SA – RT-08 Team expected to be involved in OP2

RT-08 experiments prioritized for 2026

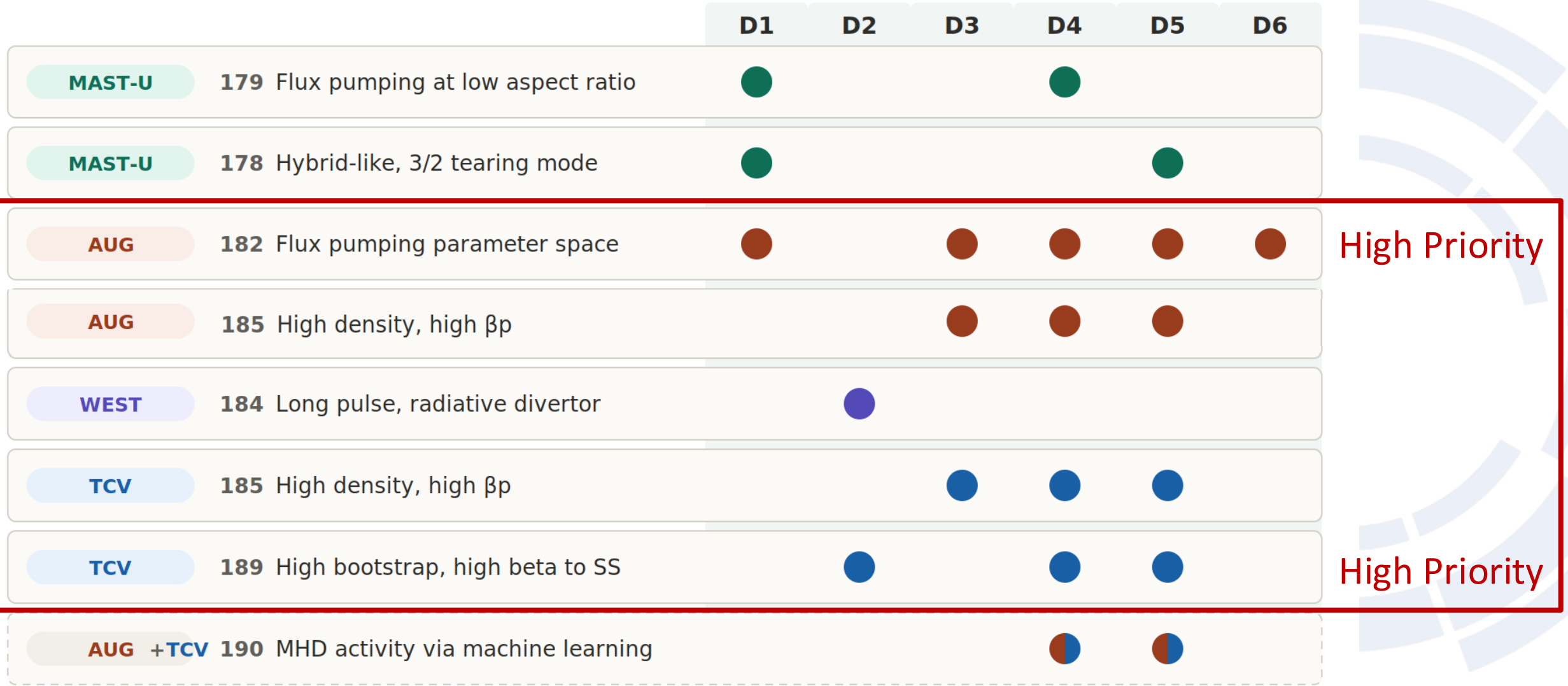
			D1	D2	D3	D4	D5	D6
MAST-U	179	Flux pumping at low aspect ratio	●			●		
MAST-U	178	Hybrid-like, 3/2 tearing mode	●				●	
AUG	182	Flux pumping parameter space	●		●	●	●	●
WEST	184	Long pulse, radiative divertor		●				
TCV	185	High density, high βp			●	●	●	
TCV	189	High bootstrap, high beta to SS		●		●	●	
TCV	203	Internal transport barriers			●	●		
AUG +TCV	190	MHD activity via machine learning				◐	◐	

RT-08 Progress in 2026

Device	Number	Topic	Progress	Status
MAST-U	179	Flux pumping at low aspect ratio	100%	Experiments complete
MAST-U	178	Hybrid-like, 3/2 tearing mode	100%	Experiments complete
AUG	182	Flux pumping parameter space	40%	Ongoing – Priority for pulses in late 2026/27
WEST	184	Long pulse, radiative divertor	100%	Experiments completed for 2026
TCV	185	High density, high βp	0%	No pulses in 2026 – **Priority 2027**
TCV	189	High bootstrap, high beta to SS	0%	No pulses in 2026 – **Priority 2027**
TCV	203	Internal transport barriers	70%	Some pulse allocation completed in 2026.
AUG + TCV	190	MHD activity via machine learning	40%	Database work complete, NN development not started

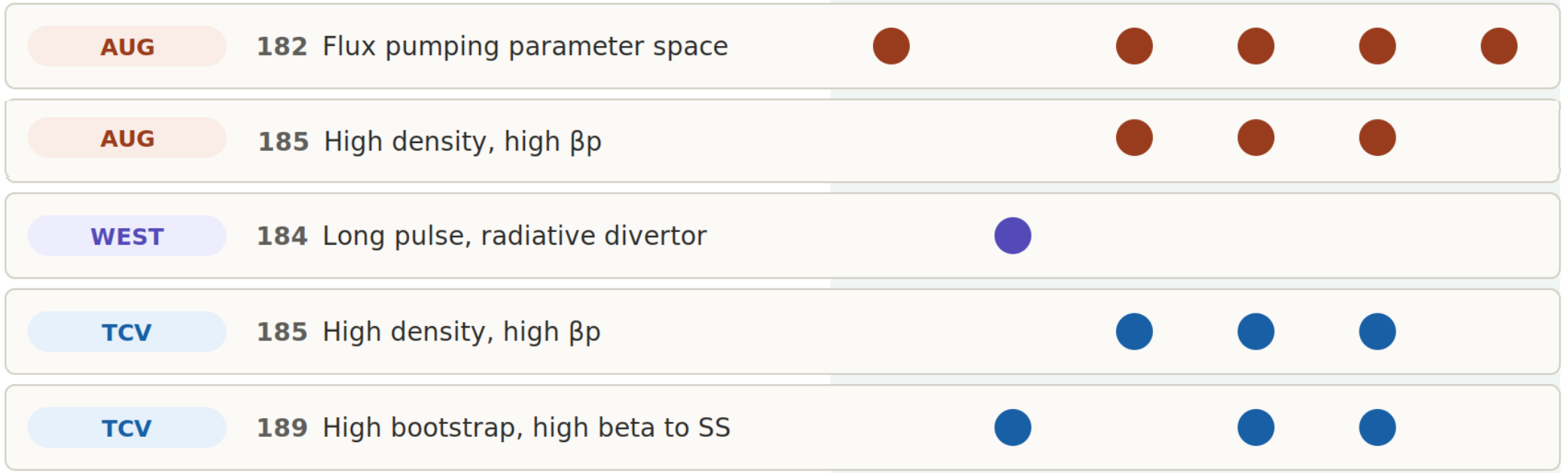
More details on the results achieved in 2026 available in the material presented at the Review Meeting

RT-08 Priorities for 2027



Flux pumping experiments [182] to be executed in AUG fall Campaign 2026

RT-08 tentative pulse allocation for 2027



High Priority

High Priority

	AUG		TCV		MAST-U	WEST	
	2026	2027	2026	2027	2026	2026	2027
Tentative allocation	*29*/32*	25*	23/70	170	31/32	17/15	15**
Total 2026-2027	54		193		31	32**	

*** 13/32 AUG experiments on schedule for CW50; Prioritization to FP pulse budget 2027 to be consolidated**

****RT-08 experiments performed last week on WEST: pulse budget to be consolidated after the analysis**

AUG Summary 2026

Successes

- Fuelling optimisation performed to facilitate access flux pumping regime.
- Inner leg optimisation improved H98.
- Preparation of tools for emissivity profile reconstructions.
- Widening of AUG knowledge and data analysis capability across the RT-08 team.
- Improved links between AUG and MAST-U for physics and diagnostics for flux pumping

Limitations encountered

- 1MA scenario not feasible with machine constraints, Ip scan not yet performed due to EZ2 technical issue.
- Remaining challenge: Mitigate NTMs appearing later during flat-top

AUG Priorities for 2026/2027

Strategy

1. Increasing gas fueling in flat top phase for higher overall density => reduced confinement but tends to be less prone to NTMs (cf. #36663 from Burckhart 2023)
2. Use predictive modelling (TORBEAM) to maximise experimental pulse efficiency of remaining pulses.
3. Sweeping ECRH across resonant surfaces to preemptively stabilise NTMs

- Once achieved: Complete study using q95 scan
- Optional if budget allows; Shape scan towards higher triangularity.
- Complete the development and optimize the high beta-p scenario

AUG high beta-p: optimized startup for low shear, high q_{min}

Campaign 2026

Initial idea: Ip-undershoot for early X-point

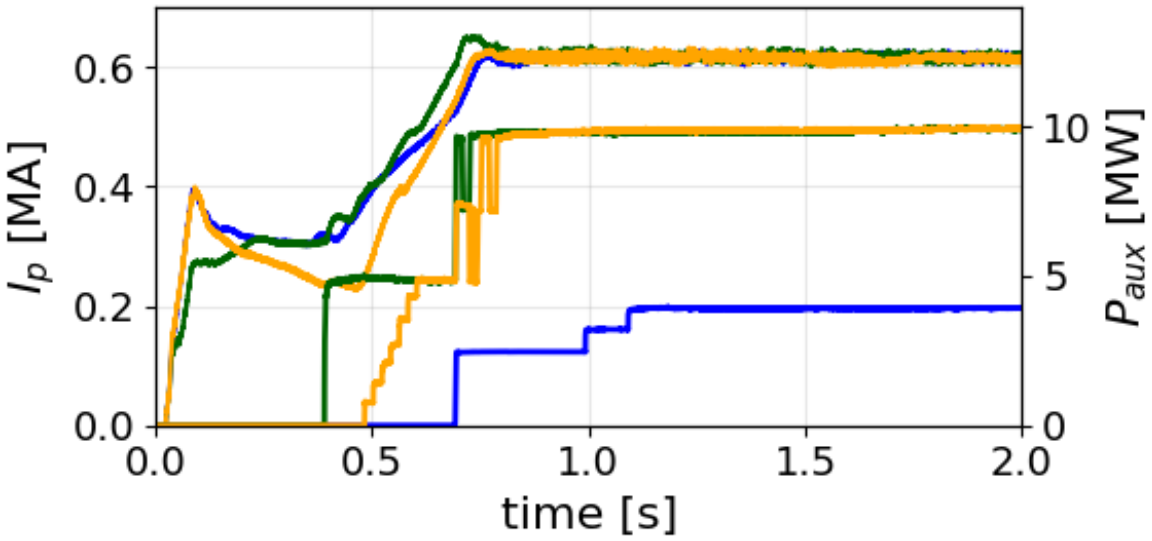
PF coils scale with Ip: Low Ip → lower PF currents → Early X-point
- → Fine-tuning during Ip-ramp challenging
- → Mismatch: CoIs quickly saturate and loose control → VDE
  - → Highly elongated during X-point formation → VDE
  - → High internal inductance

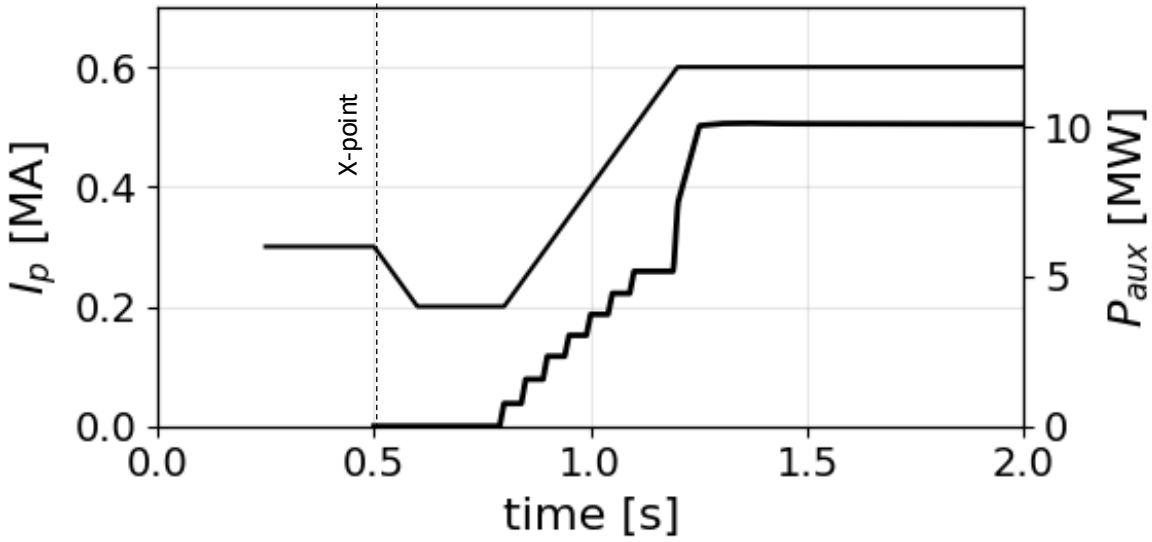
Campaign 2026/27

Ip-undershoot without a hurry

Separate X-point formation and current undershoot
- → Easier fine-tuning at constant Ip
- → Constant shape during ramp-down

#44030, #44033, #44276





High beta-p scenario will be attempted in CW50 within the AUG internal campaign

High beta-p priorities for 2027

- **Synergy with AUG internal campaign**: RT-08 team helps to extend the forward modelling and interpretation of internal campaign results (Bock, Hollendonner)
- **Development of the high beta-p scenario** with large radius barrier: support from DIII-D experts (Garofalo, Ding)

- **Analysis and interpretation**: larger RT08 team involved: Ham, Plamen

- **TCV**: exploit TCV flexibility and CD capability to test the high qmin, broad low shear q profile modelling (modelling to be performed)

- **Aim**: acquire expertise on high beta-p scenario (C and W wall) development to be potentially exported to JT-60SA with an integrated European team

Long pulse operation in radiative divertor regime in WEST

Objectives

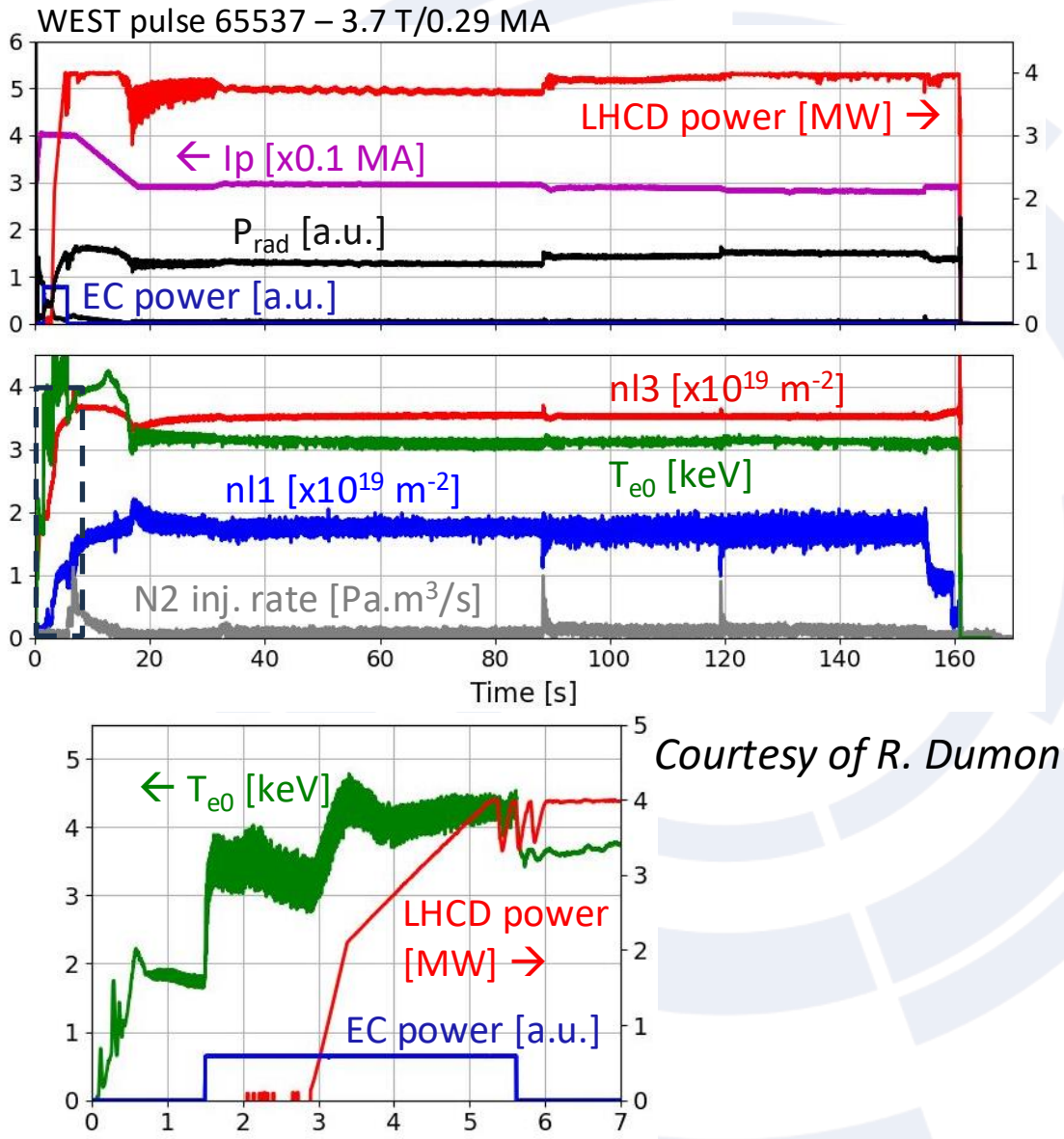
Achieved* in 2026

1. **Extend fully non-inductive scenarios to XPR regimes**
   - Demonstrate RT control of loop voltage in the presence of controlled N2 (or Ne) injection to maintain XPR at low currents
   - Qualify confinement, W sources and contamination. Compare to attached regime

2. **Maximize performance of detached steady-state pulses**
   - Continue ramp-up/current profile optimizations
   - Apply ECRH/CD to enlarge parameter space
   - Test Ne injection (better exhaust than N_2), depending on progress on XPR developments in internal program & RT05 (divertor detachment)), RT06 (PFC testing, high fluence)

High Priority in 2027

*** Pending the completion of the analysis – experiments performed last week.**



Courtesy of R. Dumont

Priorities on TCV for 2027

According to Paux availability:

ECRH (fully) + NB-1 + NB-2:

- P189: Development and optimization of high-bootstrap, high-beta tokamak scenarios towards steady-state

High Priority

NB-1 + NB-2:

- P185: High density, high betap

NB-1 + ECRH (G11)

- P203: Investigation of internal transport barriers induced on TCV

- P190: no shots required

Development and optimization of high-bootstrap, high-beta tokamak scenarios towards steady-state

Main proponents: S. Coda, C.Piron, I. Voitsekhovitch
[189] → D2 (exhaust carbon machine), D4, D5

Objective:

1. Continue the development and integration of the 2024/25 high-beta non-inductive (NI) scenarios in LSN (RU + FT) and XPTR (FT) configuration

Experimental strategy:

- ❑ Add the additional power from G12 (and NB-2) to the heating mix of NI-RU+FT LSN scenario for scenario optimisation and transport studies
  - Perform scans of multi-launcher X2 ECRH deposition location and power mix, of vertical plasma position (thus NBI deposition location), of NBI-1/2 power mix and of density, with guidance from modelling predictions
  - Expand the parameter space by switching part of the EC power from X2 to X3 and attempt to improve performance further.

- ❑ **Continue the development of the NI-FT XPTR scenario**
  - optimize the heating recipe (in terms of power and timing to avoid MHD) and plasma shape control (X-point control)
  - once a reliable recipe is found, verify if it is possible to access detachment in this scenario and document the performance
  - Develop a CS-free RU scenario in XPTR, taking benefit from the lessons learnt with the development of the NIRU LSN scenario

- ❑ Experiment bulk to be executed with [ECRH: G1+G10+G11+G12] and [NB: 1+2]

Modelling:

- ❑ Transport modelling with ASTRA, TRANSP (CRONOS, JINTRAC, ACCOME are additional possibilities), validate empirical and theory-based transport models
- ❑ Analyze fast-ion dynamics with NUBeam, ASCOT
- ❑ Model selected discharges with gyrokinetic codes (GENE and/or ORB5) and apply synthetic diagnostics for comparisons to data

MAST-U: Summary

Successes

- Control room analysis tools developed by RT-08 team members improved inter-shot analysis capability (E. Giovannozzi et al.)
- **RT-08 experiment plans completed.**
- Optimisation of gas and NBI injection timings aided **development of a high beta hybrid-like scenario**.
- **Cross-machine flux pumping analysis now includes MAST-U.**
- **Cross-machine comparison on high beta-p** in synergy with the internal program.
- **Systematic parameter scans** collected to **facilitate current diffusion modelling with transport codes**.
- **JINTRAC+TGLF modelling tools** available for RT-08 predictive simulation.
- **Broadening team and knowledge base within RT-08** for MAST-U data analysis and simulation capabilities.

Limitations encountered

- Nascent 600kA scenario at time of RT-08 experiments.
- Availability of NBI / power limitations during initial hybrid sessions limited development rate and capped the achieved beta once NBI timings were optimised.

Summary of the Priorities for 2027

AUG:

1. Complete Flux Pumping experiments: clear definition of the experimental domain for achieving FP
2. Establish and develop the high beta-p scenario to be compared with MAST-U [and potentially to TCV*]

TCV:

1. Extension of the operating space of the non-inductive LSN scenario towards higher betaN (additional heating required)
2. Development of the non-inductive XPTR scenario (high additional heating required)
3. Explore the possibility of performing high beta-p scenario [in support of potential proposals for JT-60SA]: assuming NI scenario successfully consolidated and maximum heating available
4. Complete ongoing analysis and modelling towards the validation of predictive modelling tools and extend the predictive capability to high beta scenarios

WEST:

1. Extend the integration of long pulse operations with XPR
2. Room for further optimization if additional machine time available

MAST-U:

1. Complete ongoing analysis and modelling increasing the synergies with other RTs and internal programme;
2. Complete/start cross-machine comparison to increase the extrapolation capability to other devices

JET:

1. Complete ongoing analysis and modelling (JET/JT-60SA similarity experiments in prep. to OP2);
2. Complete the knowledge transfer towards JT-60SA (especially for high beta and hybrid scenario, potential exploration of advanced scenario development done at JET including C-wall)

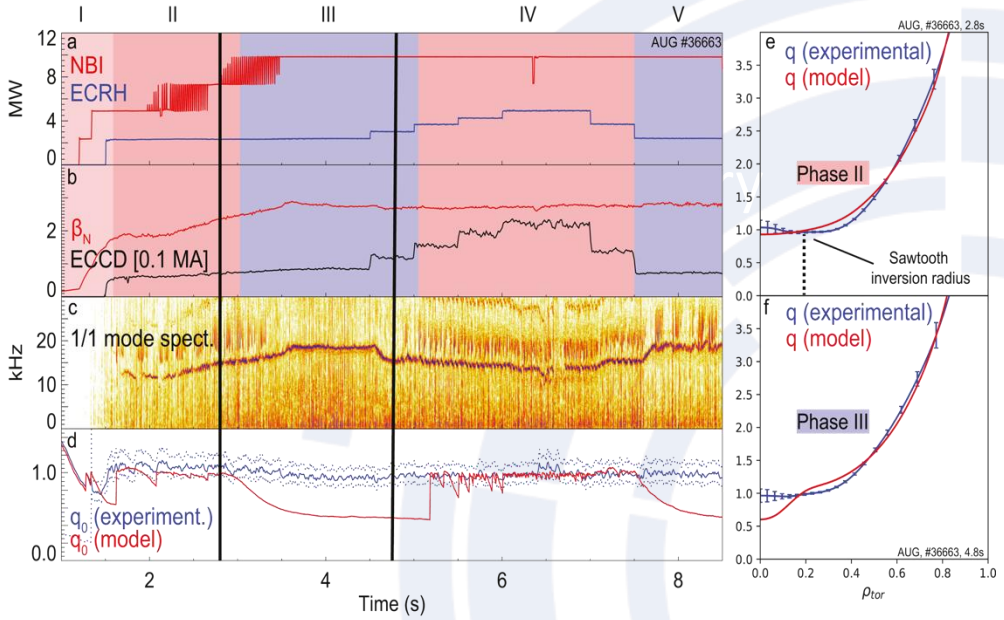
Back-up slides: Proposals and Strategy

Investigating 1,1 Flux Pumping Parameter Dependence

- **Proponents and contact person:**
  Alexander Bock alexander.bock@ipp.mpg.de
  A Burckhart, V Igochine, T Pütterich, J Stober

- **Scientific Background & Objectives**
  Quantitative knowledge of FP params still lacking, incl. whether β_{N} or β_{pol} is a better proxy for the drive or what ideal/resistive MHD limits exist. These need to be understood for robust extrapolation to future FPPs.

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  Scan between existing/potential AUG FP scenarios and, as far as possible, dimensionless parameter-matched reproductions of recent FP JET pulses. Start with ramp-up fueling scans to optimize access to FP regime. Continue with q_{95} scans to discriminate β_{N} and β_{pol}, and also variations of δ. Dedicated comparisons between existing AUG FP pulses with 1,1-mode and fishbones could shed light on the physics differences leading to one or the other.



Proposed pulses

Device	# Pulses/Session	# Development
AUG	25	30
MAST-U		
TCV		
WEST		

Machine req AUG: 15MW NBI, 5MW ECRH, (I)MSE

(1,1) Flux Pumping studies

Main proponents: A. Bock, A. Burckhart, V. Igochine, T. Pütterich, J. Stober
[182] → D1, D3, D4, D5, D6

Objectives:

1. Reproduce the reference pulse for flux-pumping regime on AUG
2. **Scan the parameter space for FLXPMP access condition: gas, q95**, δ

Experimental strategy:

- keep track of the progresses re-establishing the scenario and make a decision after 33% budget used:
  - if feasible, continue with gas, q95 and δ scans.
  - If not, switch to P187-P185 proposal to access null/negative magnetic shear at large radius (good also for FLXPMP)

Analysis and Modelling strategy:

- MHD analysis of the new database
- Comparisons between existing AUG FP pulses with 1,1-mode and fishbones to shed light on the physics differences
- ASTRA modelling of the candidates and counter-examples

High density, high β_p scenario

- **Proponents and contact person:**
  Christopher.Ham@ukaea.uk, Chiara Piron, Stefano Coda, Fulvio Auriemma, Alex Bock, Olivier Sauter
- **Scientific Background & Objectives**
  - Increase plasma performance
  - (high β_p) on MAST-U and TCV and show that very high Greenwald fraction is possible. Recent DIII-D experiments have shown high β_p exists with high density. This is very power plant relevant
  - P1 proposal in 2025. Initial work on MAST-U showed route to higher power density with USN. Initial work on TCV had significant MHD which is being worked on.
  - Establish this regime on AUG. Support ITPA-IOS JEX3.2
- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - In MAST-U use USN to reduce plasma volume and increase power density, then increase density with early on-axis NBI
  - In TCV reduce plasma current from initial attempts and optimise ECRH heating. Use Raptor modelling to assist scenario development
  - In AUG develop scenario

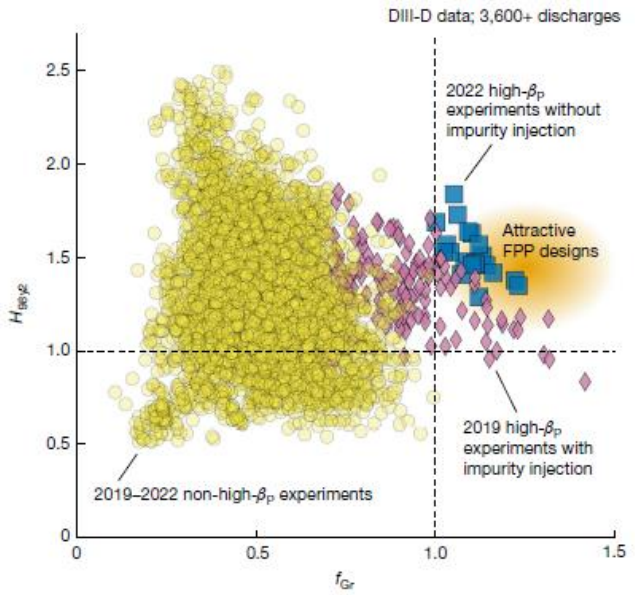


Fig. 1 | Database of H_{98y2} and f_{Gr} for DIII-D discharges. More than 3,600 discharges are included. Violet diamonds show high-β_p experiments performed in 2019 with impurity injection. Blue squares are the new high-β_p experiments performed in 2022 without impurity injection. Yellow circles represent all other experiments performed in 2019–2022. The area shaded in orange indicates the parameter space for attractive FPP designs. Vertical and horizontal dashed lines show $f_{Gr} = 1.0$ and $H_{98y2} = 1.0$, respectively.

Ding, S., Garofalo, A.M., Wang, H.Q. *et al.* A high-density and high-confinement tokamak plasma regime for fusion energy. *Nature* **629**, 555–560 (2024).

Proposed pulses

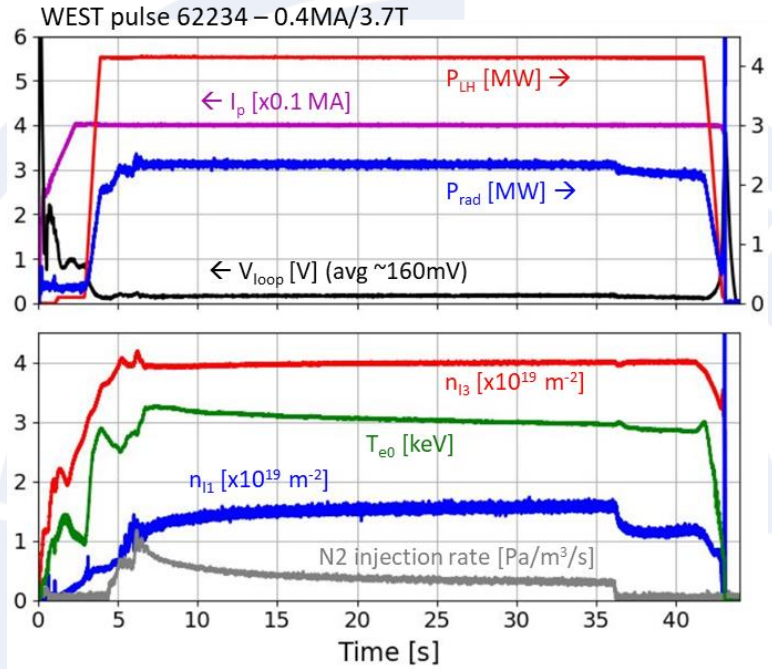
Device	# Pulses/Session	# Development
AUG	16 shots	
MAST-U	16 shots	
TCV	16 shots	
WEST		

Long pulse operation in radiative divertor regime

- **Proponents and contact person:**
  - R. Dumont (remi.dumont@cea.fr), P. Maget , P. Manas, N. Fedorczak, A. Fil, T. Fonghetti, P. Forestier-Colleoni, J. Gunn, E. Lerche, J. Morales, N. Rivals

- **Scientific Background & Objectives**
  - **Background**
    - Radiative divertor regime required to prevent UFO events on long plasma durations
    - Demonstrating a fully controlled radiative divertor regime on long durations is challenging
    - Achieving high performance (high β) in XPR/low loop voltage pulses requires optimization
    - Development work in detached regime has already started within RT08
    - Challenges to address:
      - N2 injection rate optimization
      - XPR transition identification at low plasma currents
      - LHCD efficiency optimization (could be compensated by confinement improvement)
  - **Objectives**
    - Extend fully non-inductive scenarios to XPR regimes
      - Demonstrate RT control of loop voltage in the presence of controlled N2 (or Ne) injection to maintain XPR at low currents
      - Qualify confinement, W sources and contamination. Compare to attached regime
    - Maximize performance of detached steady-state pulses
      - Continue ramp-up/current profile optimizations
      - Apply ECRH/CD to enlarge parameter space
      - Test Ne injection (better exhaust than N_2), depending on progress on XPR developments in internal program & RT05 (divertor detachment)), RT06 (PFC testing, high fluence)

- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Reference pulse : WEST pulse 62234 (V_{loop}~160 mV) - LSN plasma with LHCD, N_2 seeding
    - Decrease current, add ECRH/ECCD
    - For each value of current, test various levels of N2 injection in feed-forward
      - several plateaus in development pulses, checking XPR transitions using Langmuir probes
    - Once adequate N2 level determined for a given current, go to feedback control on edge interf. measurement
    - Scans in plasma current, electron density, …
  - Essential diagnostics: SXR, HXR, XICS, visible and VUV spectroscopy, **Langmuir probes**



Overview of XPR pulse 62234 (V_{loop}~160 mV)

Proposed pulses

Device	# Pulses/Session	# Development
AUG		
MAST-U		
TCV		
WEST	40/2	20

Development and optimization of high-bootstrap, high-beta tokamak scenarios towards steady state

- **Proponents and contact person:**

S. Coda, C. Piron, I. Voitsekhovitch

- **Scientific Background & Objectives**

This proposal extends the work done at TCV within WPTE RT08 in 2024/25 [WPTE-RT08 Review Meeting]

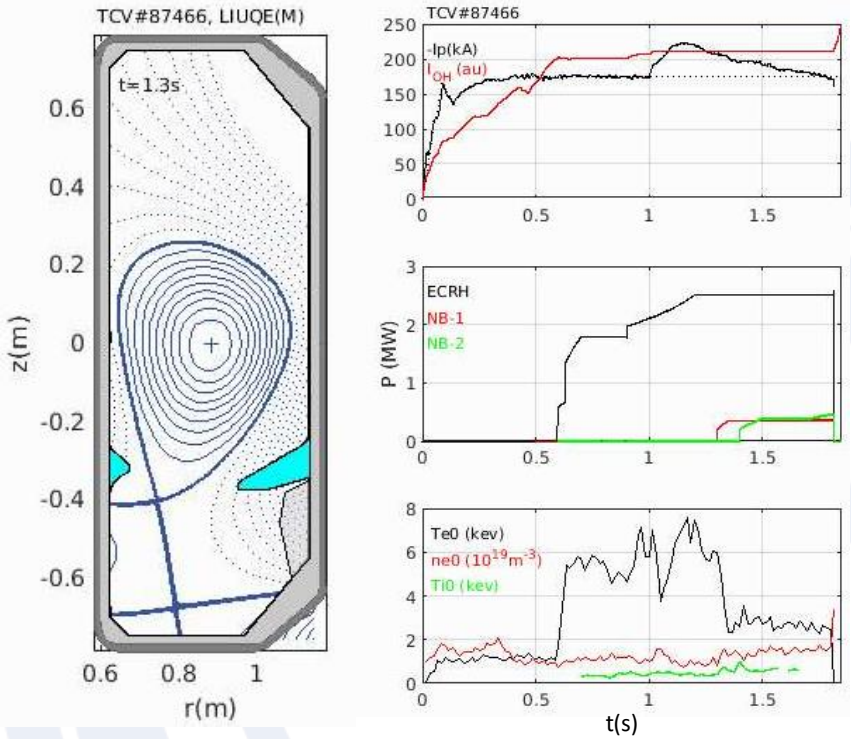
- ❑ Identify maximum achievable betaN in fully non-inductive mode and in stationary conditions with the additional ECRH power that will be available.
- ❑ Explore parameter space to determine whether, for equal betaN, steeper gradients can be achieved to increase bootstrap current fraction.
- ❑ Achieve CS-free operation from the RU to the end of FT with the maximum possible plasma current and maximum possible betaN, enabling the NBI operation with the minimised fast-ion losses.
- ❑ Demonstrate CS-free exhaust-compatible operation in the X-point Target Radiator configuration, and document core transport and confinement relative to the previously standard LSN configuration.
- ❑ Validate transport models in reversed/low-shear plasmas and identify the dominant micro-instabilities controlling the anomalous transport in such configurations.
- ❑ Fully document roles of fast electrons and fast ions in long-pulse scenarios developed, as well as scrape-off layer characteristics (width, fluctuations, etc).

- **Experimental Strategy/Machine Constraints and essential diagnostic**

- ❑ Optimize shape and ECCD deposition to reach Ip>130kA in CS-free RU scenario in LSN. Develop a similar CS-free RU scenario in XPTR.
- ❑ Fine-tune the heating recipe in the 2025 CS-free FT scenario in XPTR to avoid MHD. Verify if detachment can accessed in this scenario.
- ❑ Exploit the additional P_{EC}=0.95MW from G12 for scenario development and MHD control

NINO/SILO configuration, P_{EC}=2.6(+0.95)MW + $P_{NB\text{-}[1,2]}$=2.6MW

Essential diagnostics: TS, MAG, CXRS, cECE, TPCI, FIDA, SPR, THB, LPs, IR, MSE



Proposed pulses

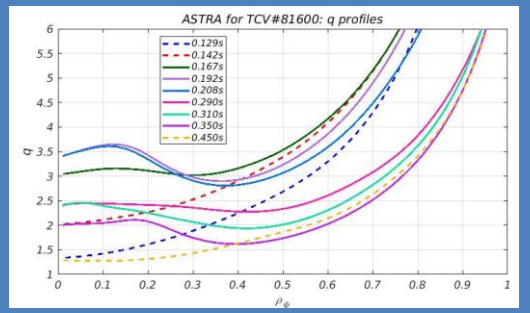
Device	# Pulses/Session	# Development
AUG		
MAST-U		
TCV	80	80
WEST		

Density versus Temperature ITBs in TCV

- **Proponents and contact person:**
- Sergei.Sharapov@ukaea.uk

- **Scientific Background & Objectives**
  - During previous RT09 experiments on TCV on “Physics understanding of energetics particles confinement and their interplay with thermal plasma” a number of transient ITBs was observed. Some of these ITBs were in plasma density, but not in temperature (similar to, e.g. C-MOD), and other – in temperature, but not in density (like on JET). Technically, the switch on TCV was simple. However, we still don’t understand how this switch works as not all diagnostics were available and more data is needed.
- **Experimental Strategy/Machine Constraints and essential diagnostic**
  - Type of plasma scenario or parameter explored to answer the main questions: Reference pulse #81511
  - Scan in vertical position of plasma with dominant NBI heating
  - Thomson scattering, CXRS, MSE, and NPA are essential diagnostic

Evolution of q-profile in these reversed-shear TCV plasmas



Proposed pulses

Device	# Pulses/Session	# Development
AUG		
MAST-U		
TCV	20/2	10/1
WEST		

Study of MHD activities with machine learning in high beta scenarios.

Proposed pulses

Device	# Pulses/Session	# Development
AUG	0	0
MAST-U		
TCV	0	0
WEST		

• Proponents and contact person:

- Luca Bonalumi (luca.bonalumi@istp.cnr.it)
- Edoardo Alessi
- Carlo Sozzi
- Edmondo Giovannozzi

• Scientific Background & Objectives

- Neural networks shown potential in predicting tearing mode triggering probability (tearability) starting from snapshot representing the plasma state
- Interpreting network's behavior can provide physical insight, revealing key parameters that precede the instability and are hidden by the black-box nature of neural networks

Aim of the present proposal is to:

- Compare the network behavior across different devices to highlight possible physical differences in the triggering mechanisms of NTMs.
- Assess how far the interpretation of tearability can be generalized to other machines (JT-60SA), offering insights for high-β studies

• Experimental Strategy/Machine Constraints and essential diagnostic

- **Development** of the network for tearability
- Train **two** separate NNs for high beta scenarios in **TCV** and in **AUG**
- Evaluate the **reliability** of the NNs
- **Interpret** the behavior of the NNs (**XAI**, eXplainable Artificial Intelligence; L. Bonalumi et al. *Front.Phys.* 12 2024)
- **Extrapolate** results for **JT-60SA** high beta scenario