EUROfusion

The European path towards fusion electricity

Tony Donné

A.J.H. Donné | NIFS | Toki, JA| 15 September 2023

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…also for kindly making slides available

EUROfusion

EUROfusion integrates R&D in fusion science and technology

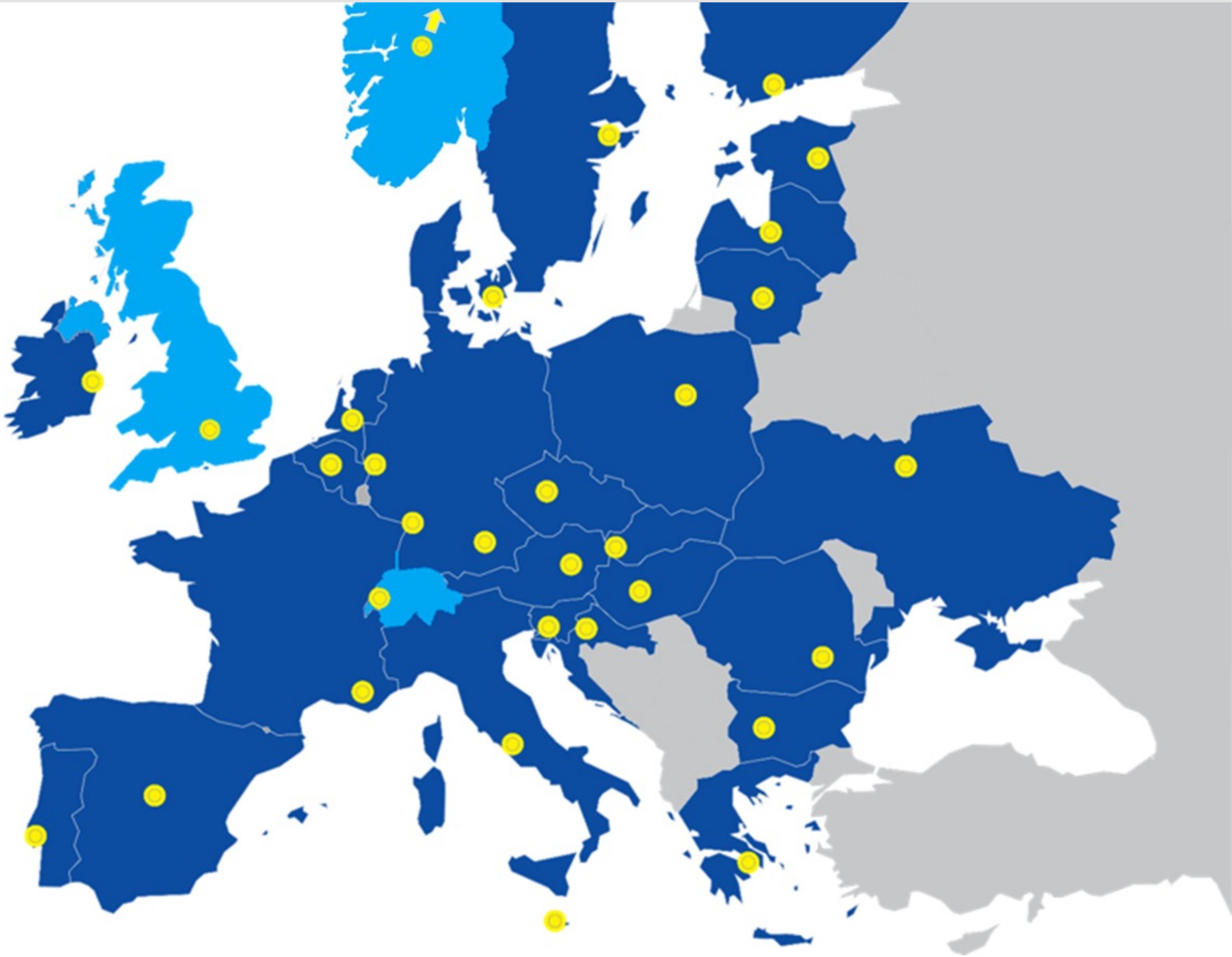
29 Countries

31 Research Institutions

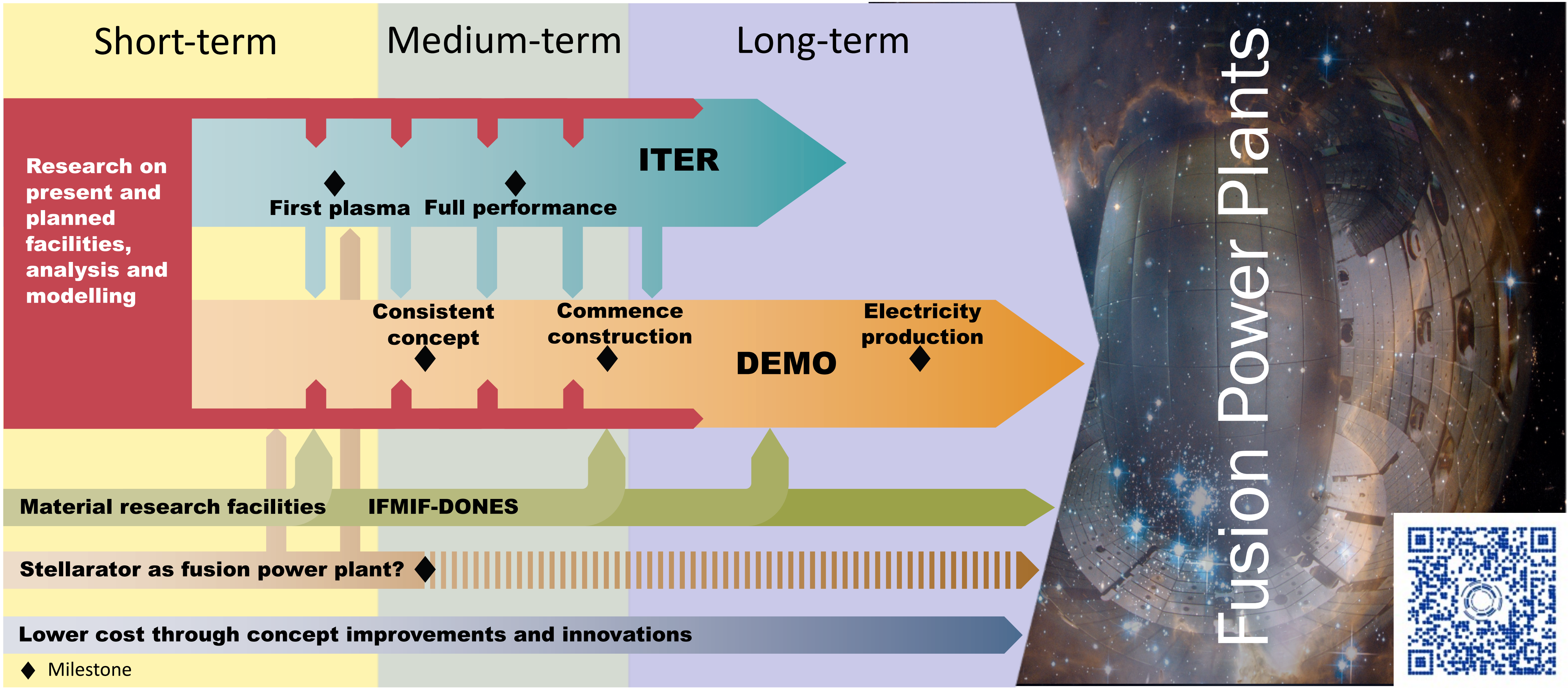
164 Universities

800 MSc and PhD students

4000 Fusion Researchers & Support Staff



European Fusion Research Roadmap – under revision



Eight Roadmap Missions

1. Plasma Regimes of Operation
2. Heat Exhaust Systems
3. Neutron Resistant Materials
4. Tritium Self-Sufficiency
5. Implementation of Intrinsic Safety Features
6. Integrated DEMO Design
7. Competitive Cost of Electricity
8. Stellarator

A revised approach to the Roadmap is needed

Interest in fusion has grown enormously thanks to:

- Fusion research successes at JET, NIF, W7-X, Medium-Sized Tokamaks, and the almost completed ITER assembly
- Realization that baseload electricity power plants are essential for energy transition & security
- Booming of private fusion efforts

Current Roadmap contains all the linked elements of a reactor-oriented program, but is mostly based on a sequential JET-ITER-DEMO approach

- Delays have impacted ITER, but also JT-60SA, IFMIF-DONES and DTT
- Unique and valuable lessons learned from every stage of the ITER project must be integrated into the Roadmap

Main elements of the Roadmap revision

- Definition of the DEMO step
- Gaps to be addressed
- Measures to accelerate the DEMO and FPP programs
- Parallelization of ITER and DEMO activities
- Public-Private Partnerships

These points are in addition to the specific activities for the ITER project, which remain central

Definition of the DEMO step – high level goals

Demonstration of performance of key technologies with tolerable failure rates to achieve adequate levels of availability, and their integration

- Net electricity output to grid of a few hundreds of MWs
- Self-sufficient fuel cycle: supply tritium for itself & to start a new plant
- Robust plasma operation scenario and power-exhaust system
- Demonstration of intrinsic safety and tolerable impact of waste
- Maintenance systems that ensure plant availability and accessibility

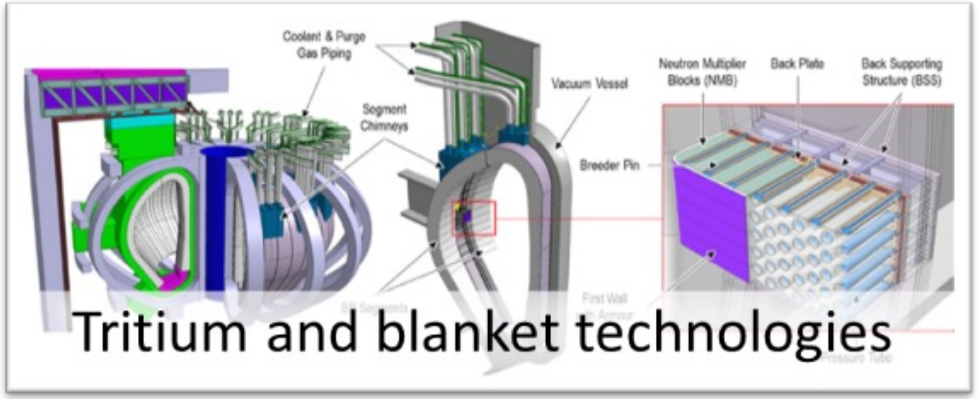
Tokamak configuration

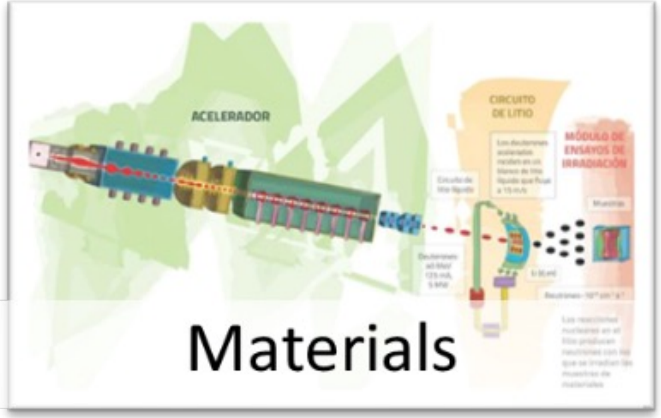
Target: start operations /commissioning ~20 years after kick off

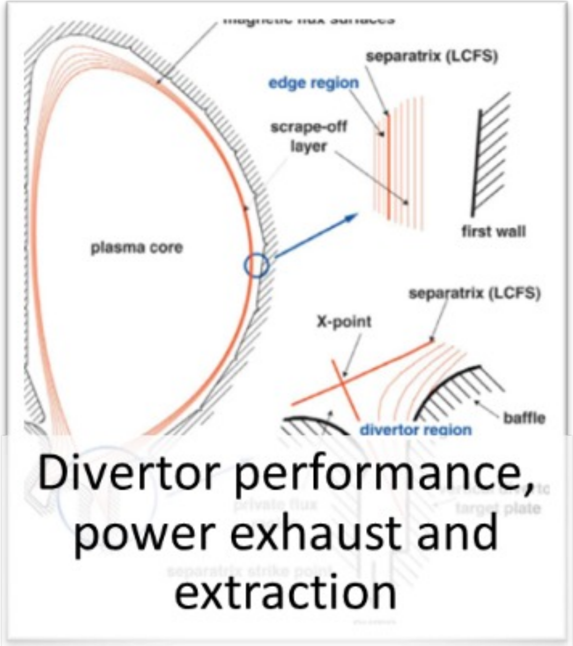
Definition of the DEMO step – requirements

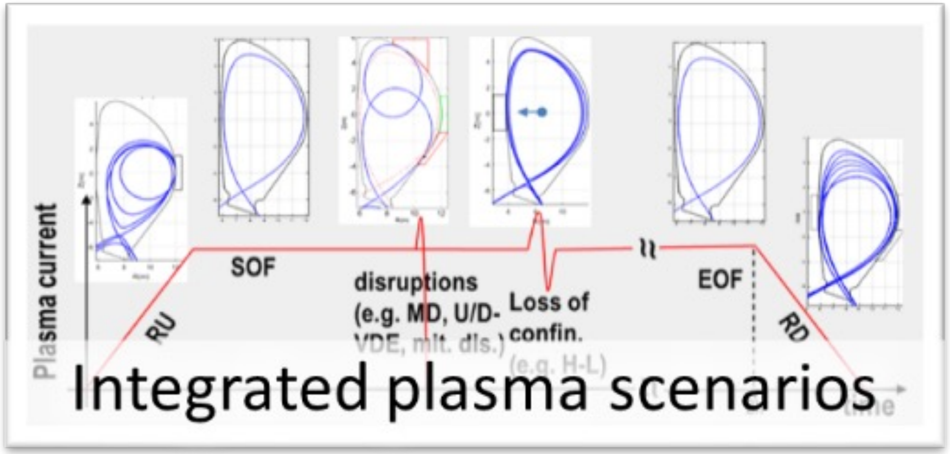
Stakeholder requirements	Plant requirements
Net electrical power of 100s of MW	$P_{el,net}$ ~ 300-500MW
Pulse length	t_{pulse} >> dwell time (several hours)
Tritium self-sufficiency	Tritium Breeding Ratio TBR > 1
Blanket lifetime and radiation exposure	~20dpa first phase (6-7y); ~50dpa second phase (16-17y)
Doubling time for FPP deployment	$\tau_D \leq 10y$
Safety	No countermeasure to the population and to the environment in accidental conditions Minimization of intermediate- and low-level radioactive waste, and avoidance of high-level waste

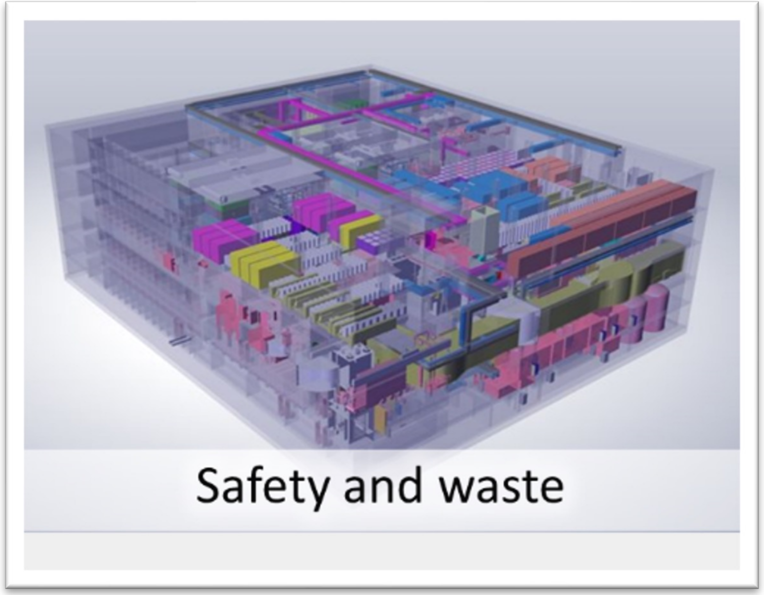
Gaps to be addressed











Gain technical insights from ITER

- The work on EU DEMO benefits largely from the experience gained from ITER
- **ITER remains the crucial machine for the validation of the DEMO physics and part of the technology**

- RoX from ITER emphasises the importance of safety and licensing, design integration, quality, shielding, fabricability, costs, RH
- These play an important role in the design of DEMO

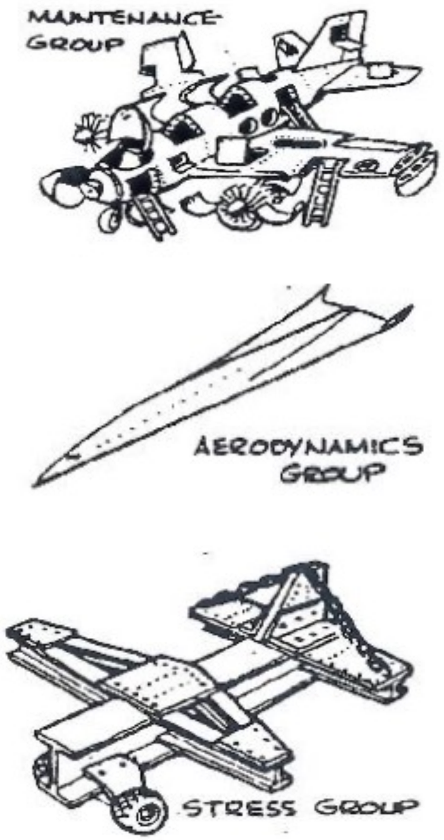
- There are still major technology gaps beyond ITER
- Low TRLs of DEMO enabling technologies for systems (i.e., breeding blanket, materials, RH) even after ITER
- The role of ITER in de-risking DEMO in the area of breeding blanket is questionable and risk mitigation options are studied

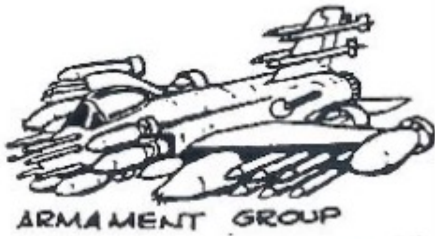
TRL Now	TRL after ITER
Water BoP (TRL 7-8)	Magnets Nb_3Sn LTSC
Divertor RH (TRL 6)	Buildings
ECH 170 GHz (TRL 6)	Vacuum Vessel
Magnets Nb_3Sn LTSC (TRL 6)	Cryopumps
Divertor (TRL 4)	Divertor and div RH (TRL 7-8)
He BoP (TRL 4-5)	ECH 170 GHz (TRL 6-7)
NB (1MeV) (TRL 3)	NB (1MeV)
Blanket RH (TRL 3)	DEMO Blanket RH
Blanket (TRL 2-3)	DEMO Blanket – TBM (TRL 4-5)

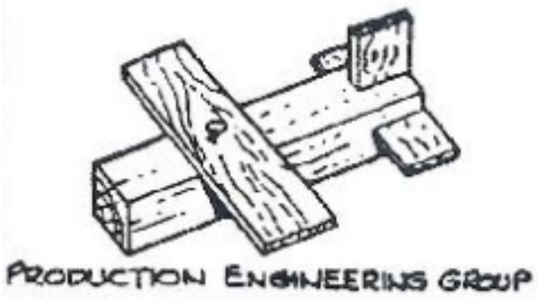
Search for the optimum DEMO design – EUROfusion approach

A system-oriented dimensioning process

If everyone is let to go on his own way you end up having something that does not work







***Dream Airplanes** by C.W. Miller. Optimal airplane design from the perspective of engineers of different specialties 2010. Reston, VA: American Institute of Aeronautics and Astronautics.

G. Federici "FPA 40th Annual Meeting, Washington DC, USA, Dec. 3-4, 2019

- Many discussions to make fusion smaller, cheaper, and faster, **but there is no magic bullet to solve the integrated design problems.**
- **What makes a design sound:**
  - ✓Realistic physics and technology assumptions
  - ✓A sound operating scenario and a consistent strategy for the power exhaust to be validated by ITER
  - ✓Robust design with margins considering all the loads and the constraints often coming from system interdependencies
  - ✓Early attention to nuclear design integration and safety/licensing
  - ✓Sufficiently mature technologies for all the systems

Lesson learnt from DEMO pre-concept design

Still large plasma physics uncertainties that impact the design

Integration of multiple design drivers across different systems

Many systems interdependencies with key nuclear systems

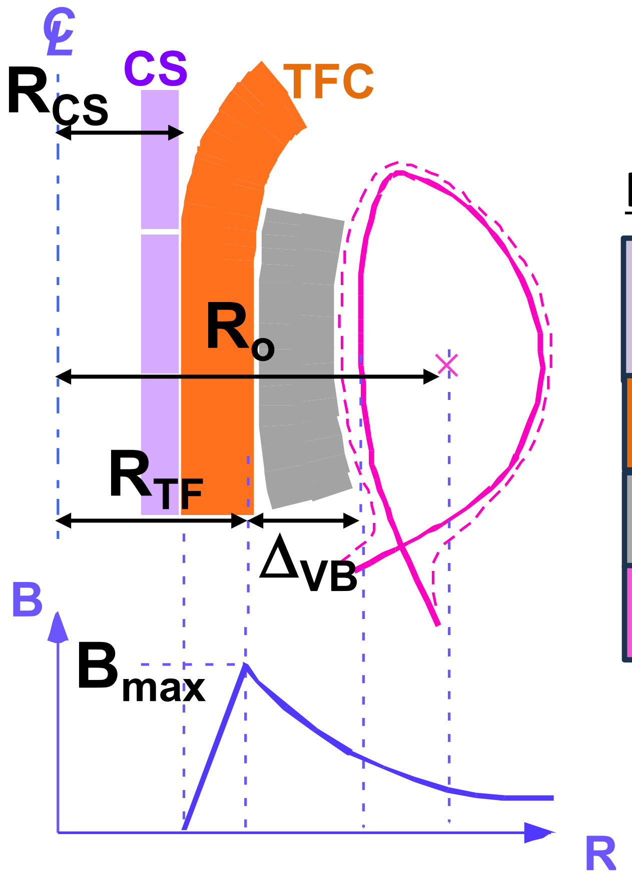
Low technology readiness of essential enabling technologies

https://www.sciencedirect.com/journal/fusion-engineering-and-design/special-issue/10RRZQ6LW4H

What defines the size of DEMO?

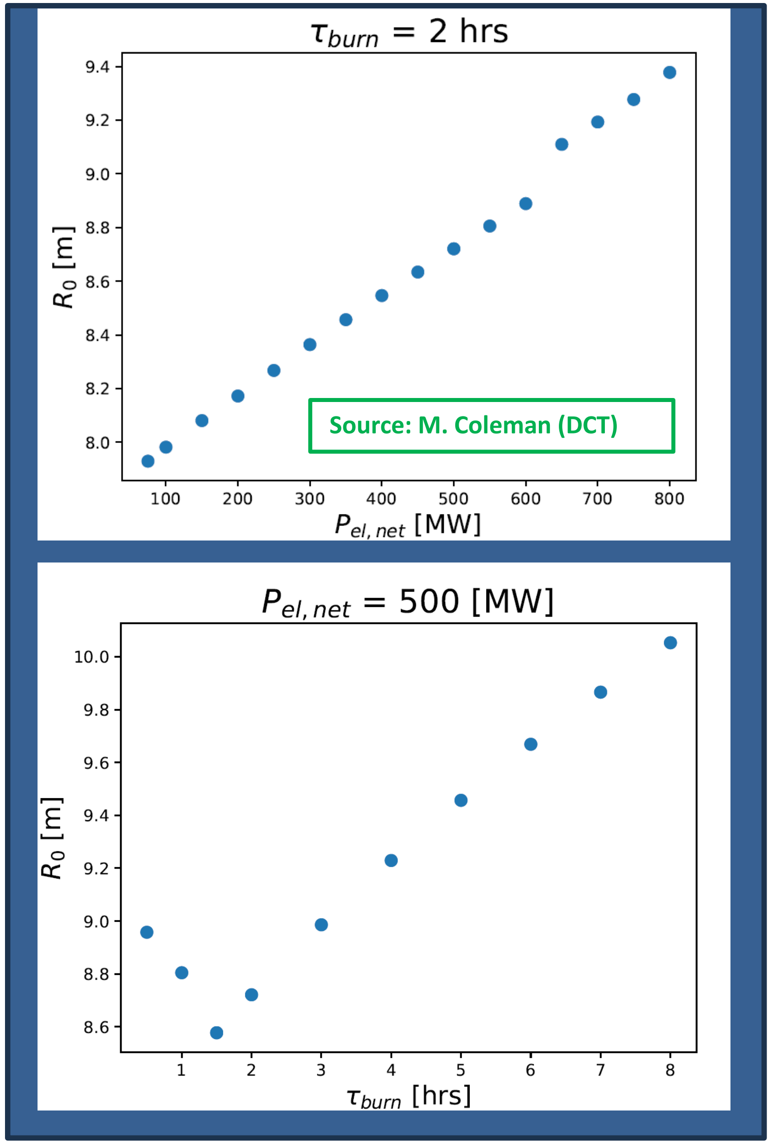
Key engineering constraints/ design drivers

Inboard space utilization is a crucial design aspect in tokamak design: trade-off plasma/shielding/magnets



Key engineering drivers

Central Solenoid: (pulsed machine – become constraining at low aspect ratio)
TF coil radial build (see next slide)
Shield/ breeding blanket (1.3-1.4 m inboard)
Plasma: divertor heat load at reattachment



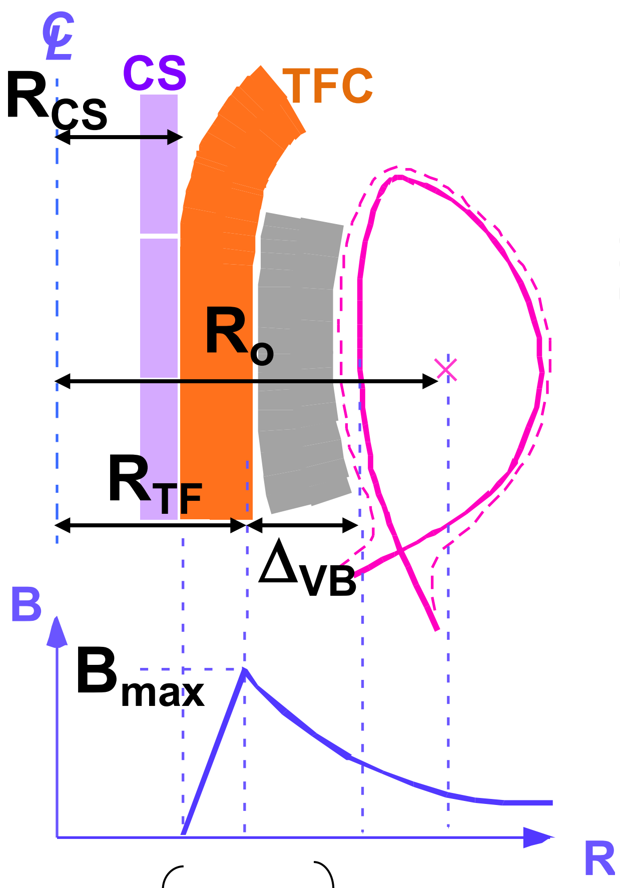
Study to analyze **sensitivity of machine size** to **plant electrical output**, **pulse duration**

- Reducing electricity output does not bring significant size reduction
- The CS size increases as a function of the pulse duration but also at very low pulses because of fatigue considerations

Use of high field coils

Impact of the TF coil field on the size of the machine

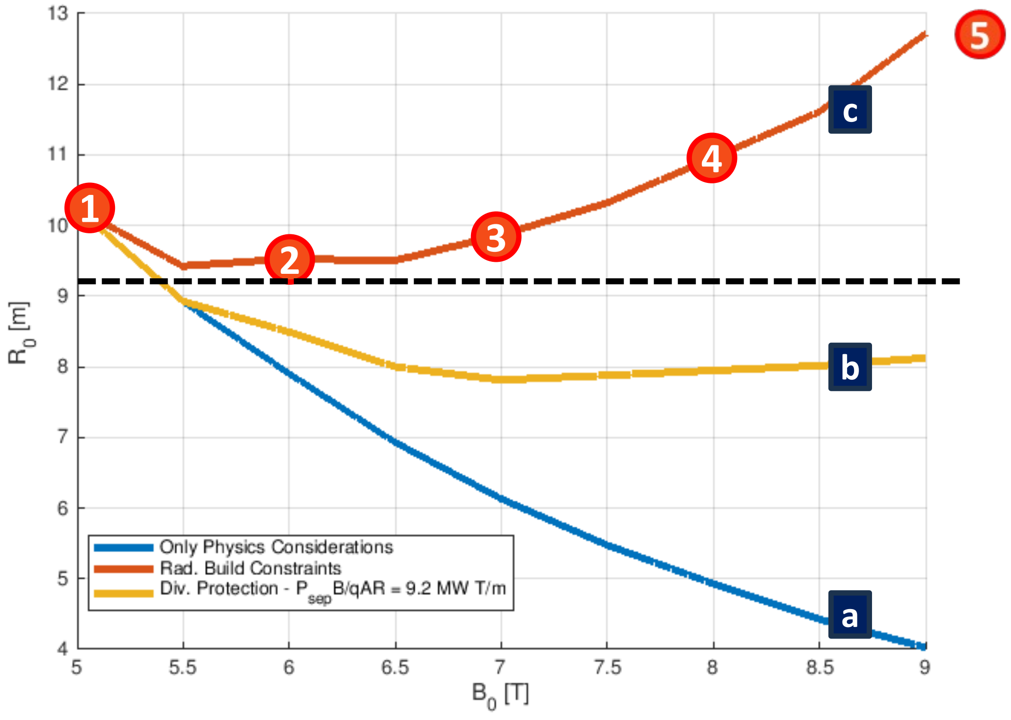
TF Inner Leg Space Allocation



Δ_{VB} { Breed BLK, n-shield, VV, TH-Shield }

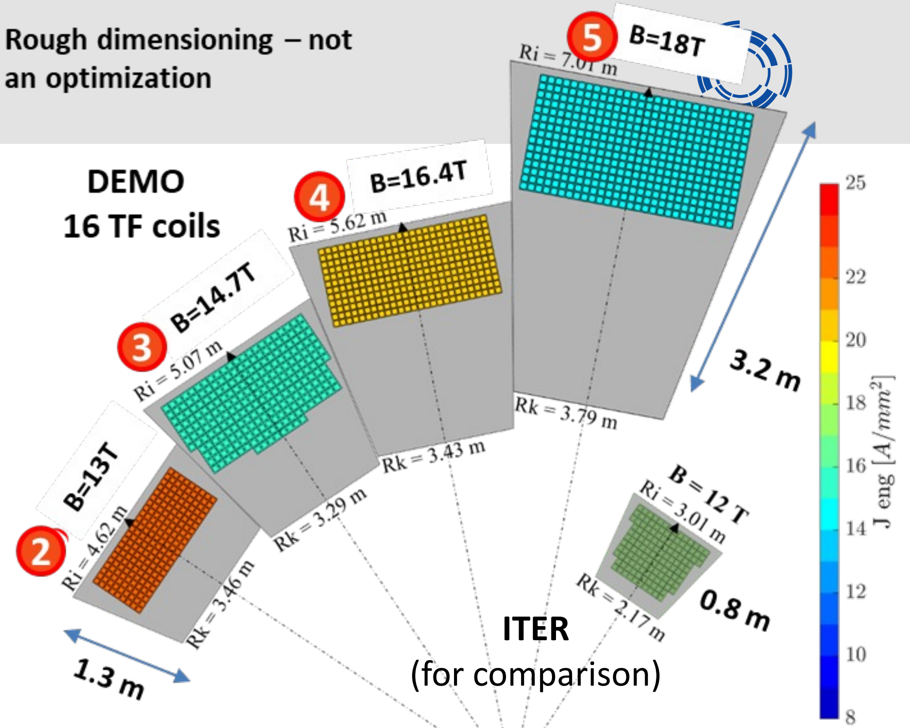
Rule of thumb 1.3-1.4 m

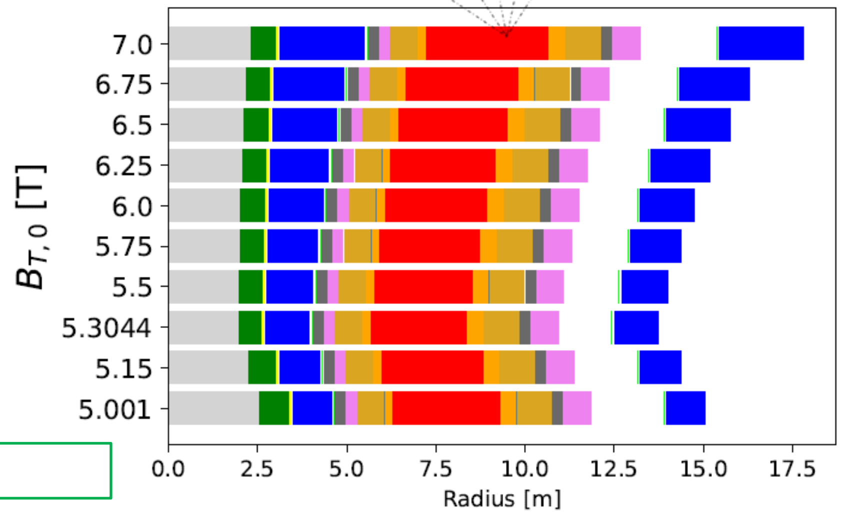
P_{fus}=2000 MW, pulse = 2 hrs, A=3.1



M. Siccinio, C. Bachmann. L. Giannini

Rough dimensioning – not an optimization





Source: PROCESS M. Coleman

→**for higher B-field**, large structures are required to resist radial/vertical forces TF inner leg.
Alternative mechanical concepts are very challenging or do not bring significant improvements

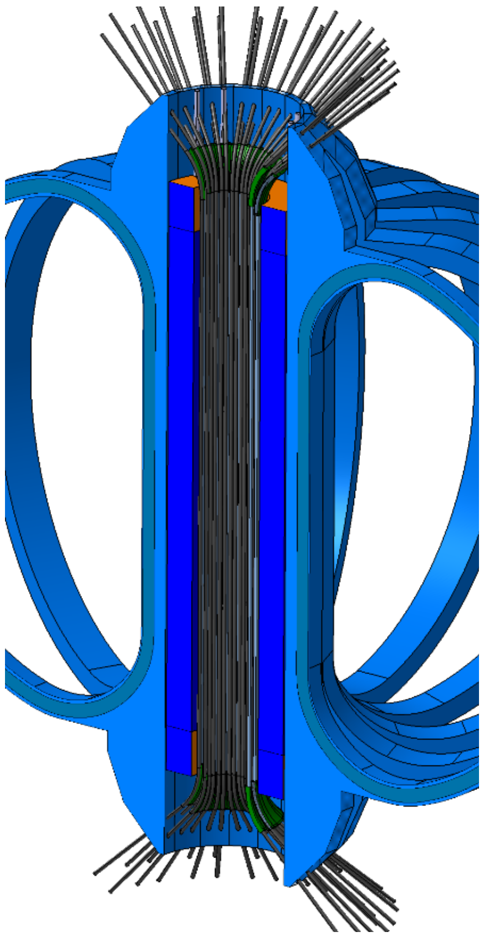
USE OF HIGH FIELD COILS

Alternative mechanical concepts for DEMO are challenging or do not bring improvements

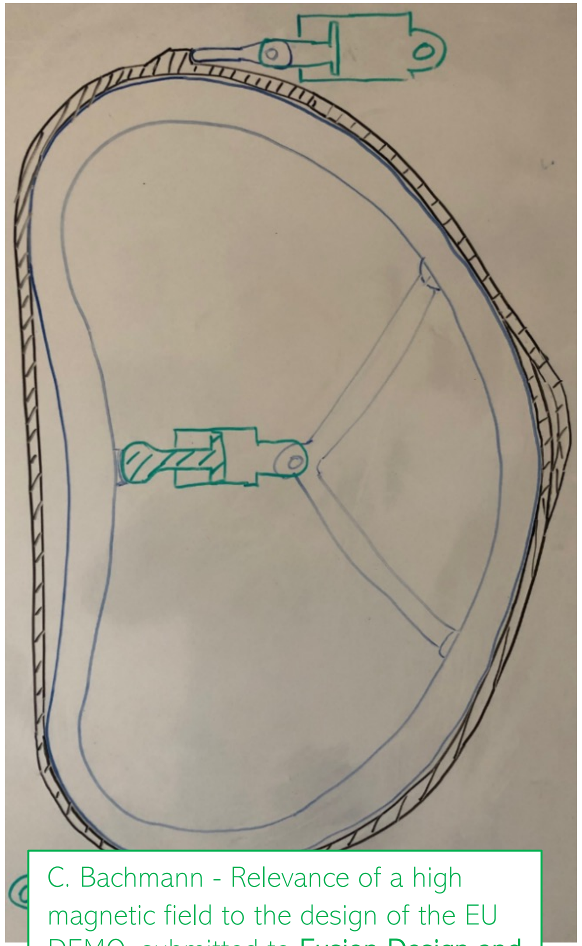
Source: C. Bachmann

Concepts of TF vertical pre-compression

Steel cables @ 1200 MPa tension generate vertical + radial pre-compression



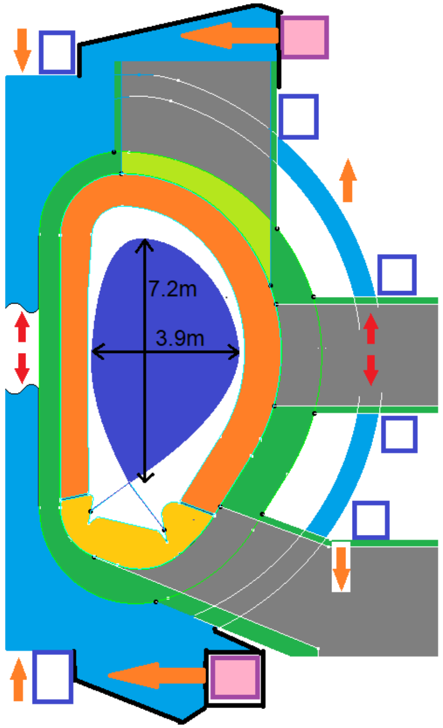
Steel cable wound around TF coil in assembly hall to generate overall pre-compression of coil



C. Bachmann - Relevance of a high magnetic field to the design of the EU DEMO, submitted to Fusion Design and Engineering

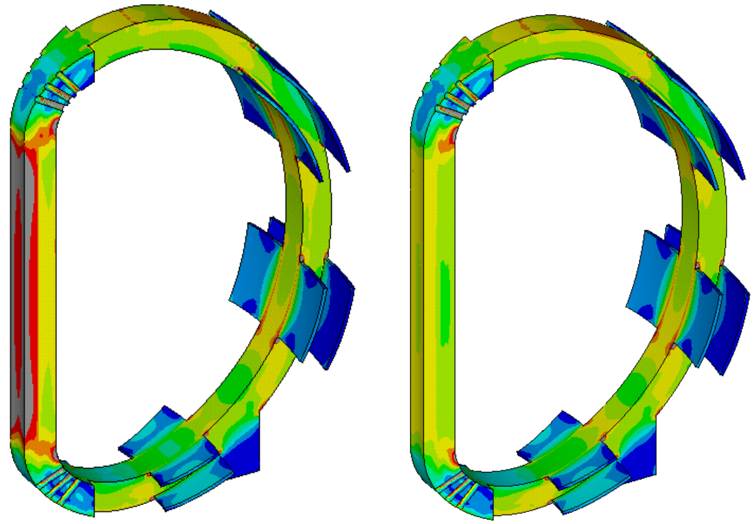
C-clamp principle [P. Titus, FNSF, TOFE-2020]:

- Large pre-compression rings cause a vertical pre-compression of the TF
- Transfer of vertical loads to the outboard side



Bucked + wedged concept:

- Release TF inboard leg from EM forces through transfer of radial force to CS
- Reduce stress cycle on CS conductor
- This relies on wedged inboard legs: only possible if an assembly gap of ~3mm ± 1mm between CS and TF can be ensured which is very unlikely!



Assembly gap = 5mm

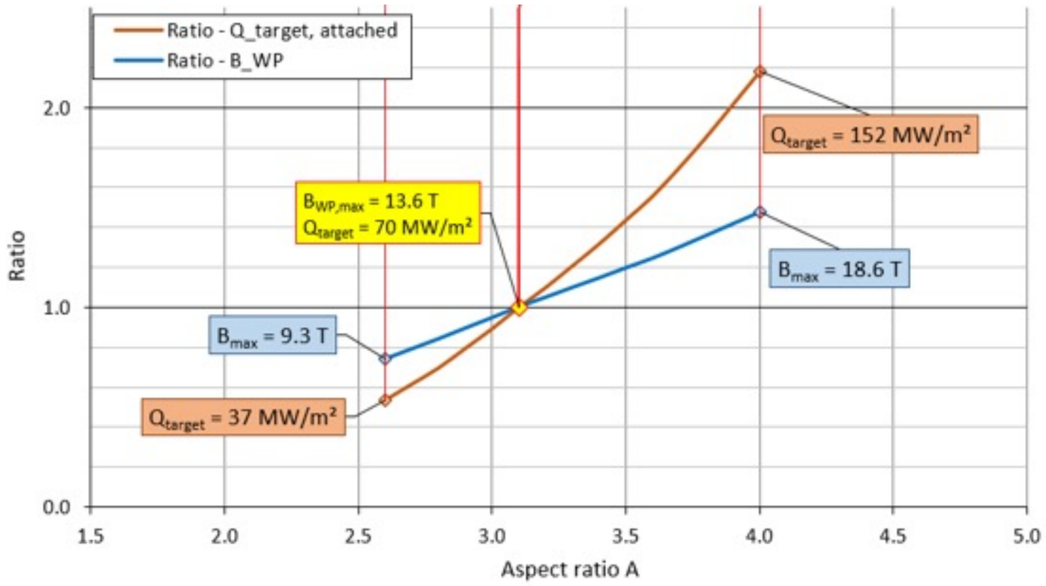
Assembly gap = 1mm

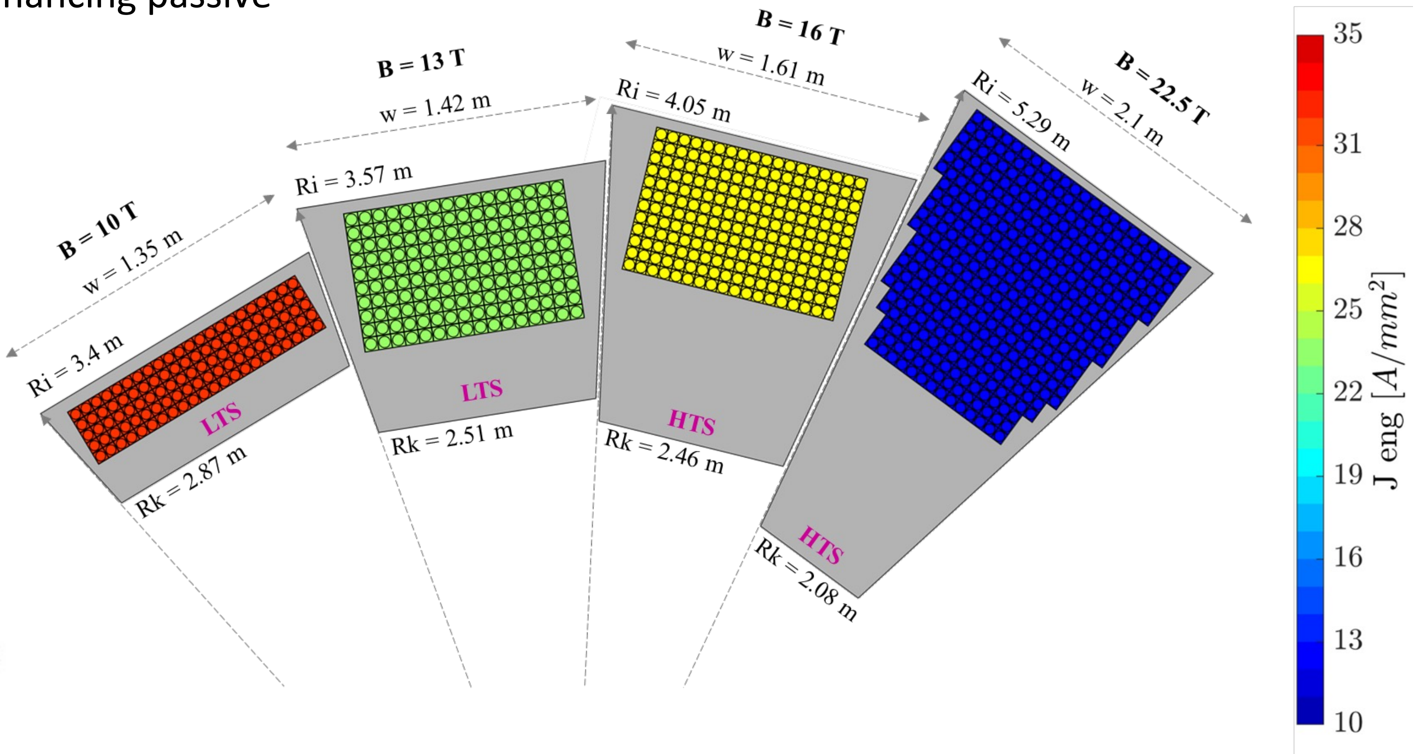
Re-baselining

Impact low aspect ratio

- It allows for a lower field (plasma, and TF coils).
- It reduces the maximum heat flux at the divertor in case of reattachment. This reduces the risk of the machine operation, enhancing the control margins and, possibly, simplifies the whole design.
- It allows for a higher κ → a larger P_F for a given machine radius. This is due to the higher natural κ, and to the fact that this reduces the relative distance between plasma and passive structures, thus enhancing passive stability.

	B_o [T]	B_{max} [T]	Heat Flux @reatt [MW/m²]
A=2.6	3.9	9.6	36.9
A=3.1	5.95	12.9	69.5
A=3.6	8.1	15.9	108.5
A=4.5	13.25	22.4	220.4

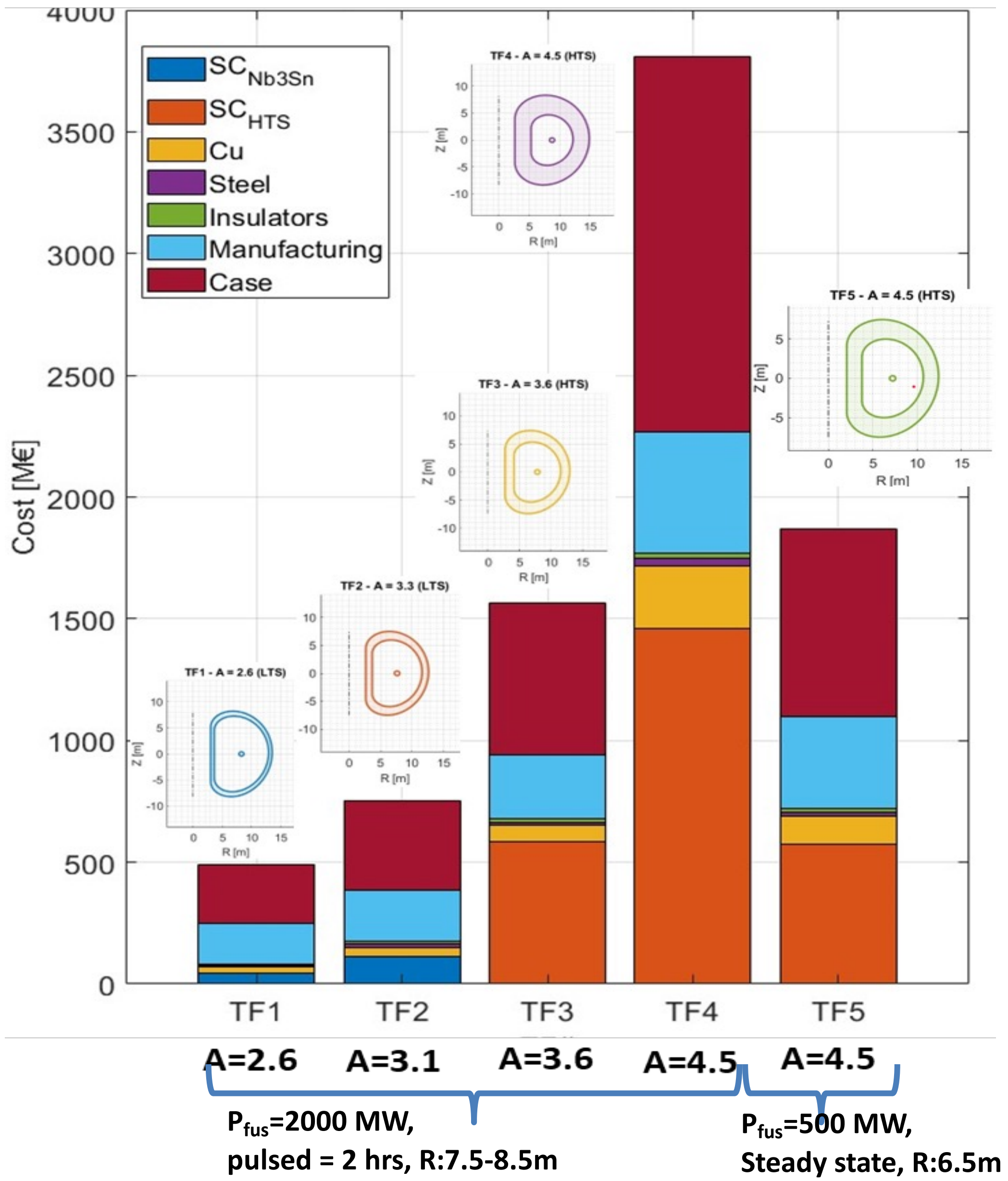




Industrial coil feasibility and cost issues

Benefits from coil designs that minimises TF structures

- There is a practical limit to the max. thickness of the TF nose based on manufacturability (given by size of forgings)
- There is also a limit to weldability of segments and weld deformation, which becomes hard to control in large and thick structures. Mock-ups are required
- For DEMO-sized machines, the cost of the structures alone (just the coil case) is a significant fraction of overall cost of TF coils
- In ITER, the material procurement and manufacture of the TF coil cases was what drove the schedule of TF coil deliveries (even with an intense three-supplier approach)
- The same DEMO industrial study concluded a minimum of 12 years for structure production, assuming two suppliers in parallel



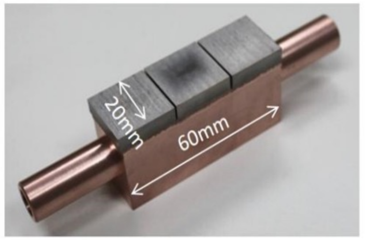
Source: L. Giannini, M. Siccinio, M. Lungaroni

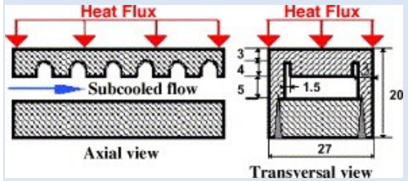
Performance and Reliability of Critical Core Technologies

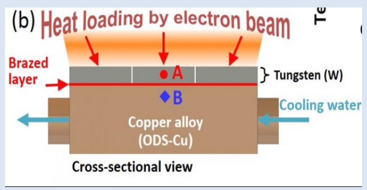
Long lead times for R&D needed: (15-25 years)

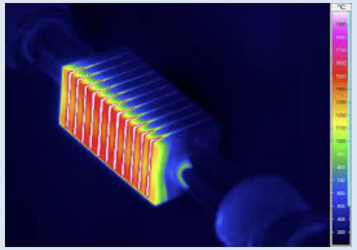
Divertor targets

- ✓ Impressive advances thanks to ITER R&D (1990's-2000's)
- ✓ Fabrication of many (**> 100**) types of small- and medium-scale mock-ups (e.g., different tube, mtls, geometries, armors and geometries, fabrication methods, joints types)
- ✓ Qualification/industrialization of key processes High heat flux testing campaigns: investigating degradation after repetitive thermal loads in HHF tests stands (Gladis, Judith, US, RF, JA EBs etc.)







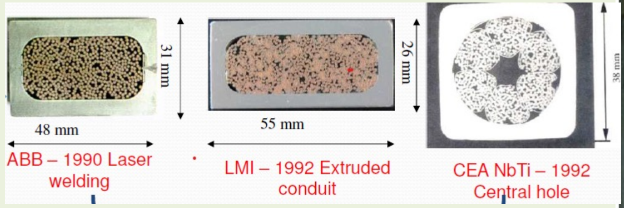


Superconductor samples

- ✓ Development and testing of many types of conductors (mtls., void fraction, twist pitch etc.) incl. HTS. Tests in SULTAN and EDIPO (EPFL-PSI as of 1992)
- ✓ Qualification and industrialization of key components and technologies
- ✓ Model coil fabrication and testing e.g., FENIX (MFTF-B choke coil in Nb_3Sn ITER TF and CS 2000's)

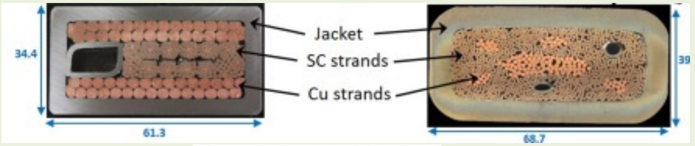
DPC Nb3Sn cable in conduit 1985

CICC 1991

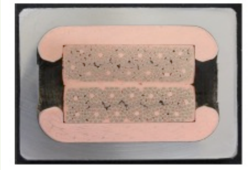


ITER TF 1993

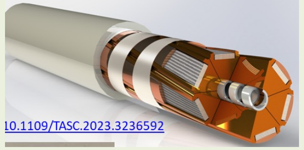
ITER CS



DEMO



LTS joint

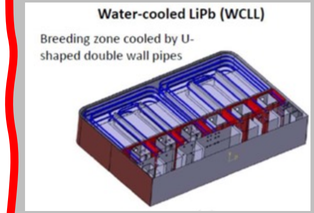


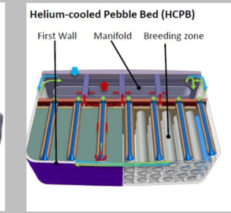
HTS

Sultan

Breeding blanket

Most novel and complex system





- ✓ Heat transfer across breeder/RAFM plates and coolant pipes
- ✓ High temp./pres. coolants→ strong influence on reactor design
- ✓ T generation and extraction in Li-based solid/ liquid breeders
- ✓ n-irradiation damage→ structural material properties
- ✓ Power and particles on first wall

No breeding blanket has ever been built or tested under relevant integrated conditions.

- Still large uncertainties/ feasibility concerns → very low TRL
- Strong impact on machine availability

There is a technology gap in this area that needs to be urgently addressed

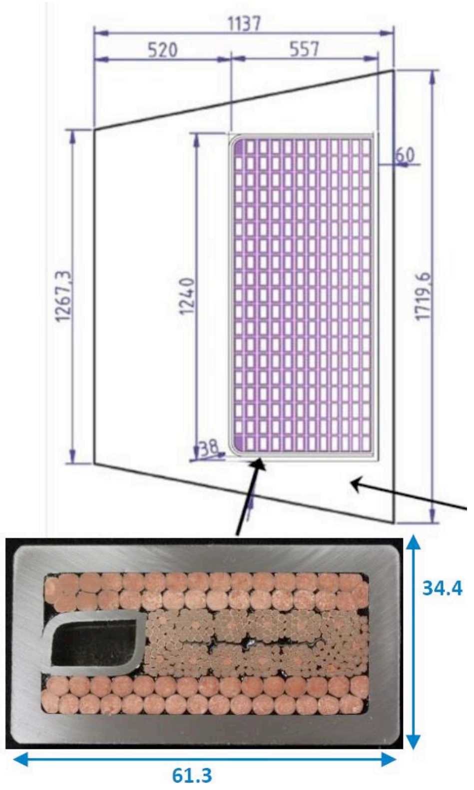
Magnet Systems

Recent achievements

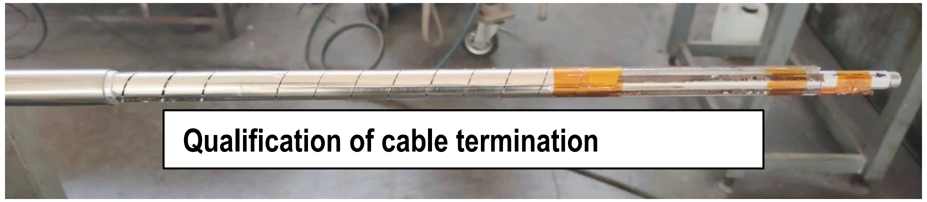
Source: Project Leader - Valentina Corato (ENEA)

- R&D on important DEMO magnets technologies
- Qualification and industrialization of key components and technologies
- Development and test of full-scale conductors (tests at EPFL-PSI), also joints
- Development of conductor concepts based on HTS
- DEMO design activities: winding pack design, thermo-hydraulics, quench detection, etc.

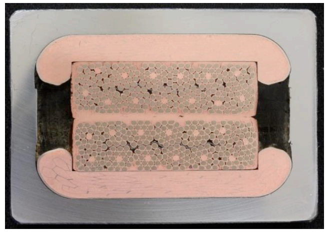
TF conductor and winding pack design



Conductor test sample



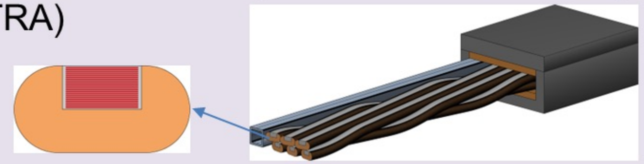
Qualification of cable termination



LTS joint

Design and preliminary tests of HTS conductors for the Central Solenoid (60kA@18T, 4.5K)

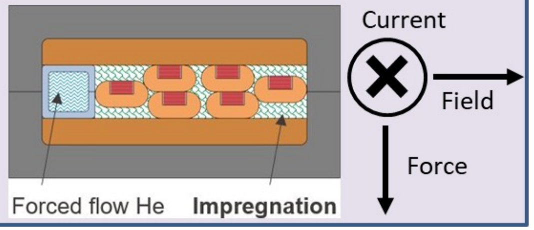
Aligned Stacks Transposed in Roebel Arrangement (ASTRA)



https://doi.org/10.1109/TASC.2022.3153248

Cable design:

- Roebel cabling
- Jacket pre-compression
- Separate cooling channel
- Cable space impregnation



SECtor ASsembled (SECAS) CICC

BRAided STAcks (***BRAST***) of tapes:

- Flexible
- Compact
- Easy to handle

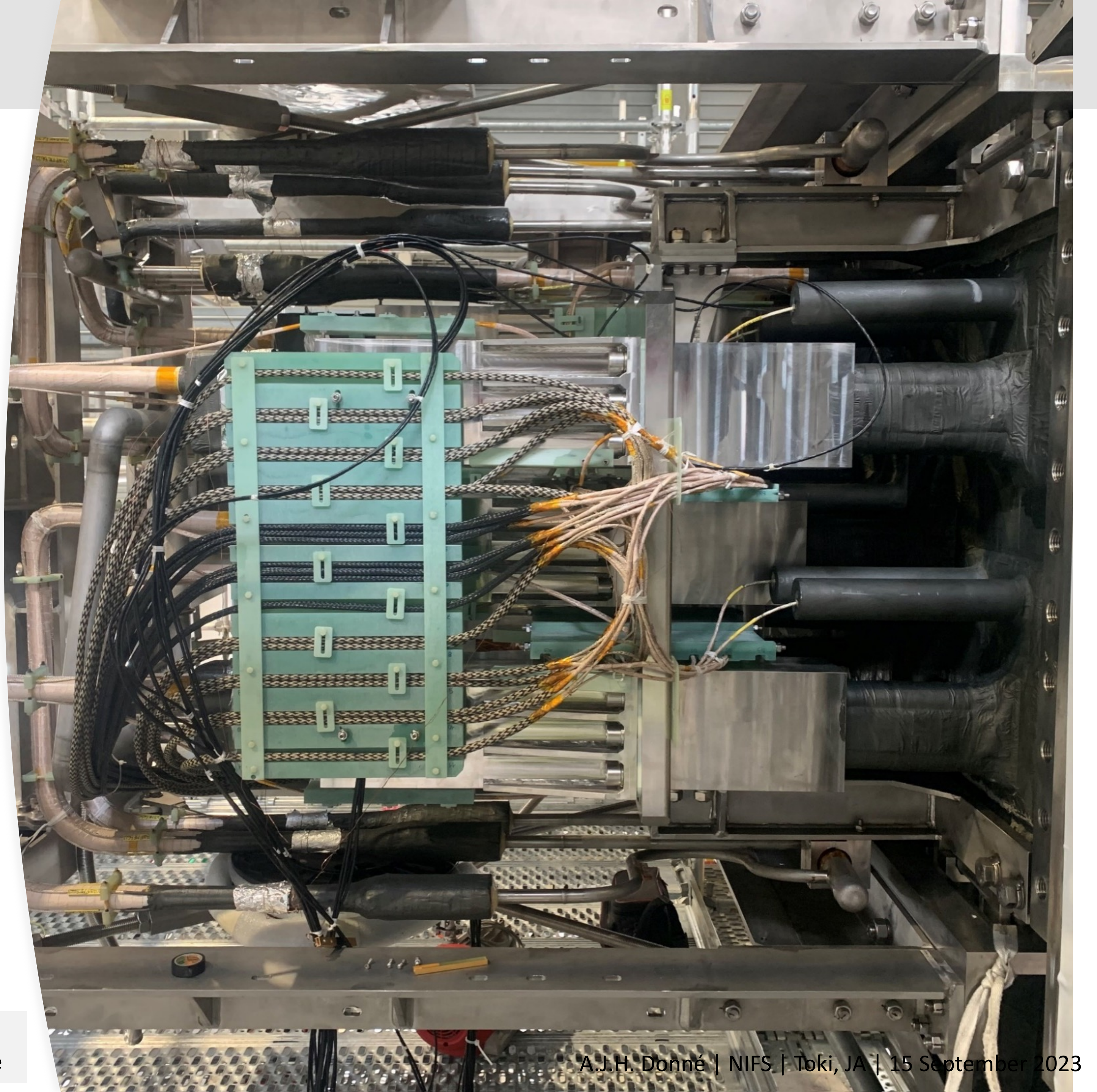
https://doi.org/10.1109/TASC.2023.3236592

SULTAN sample in preparation: test expected in 2024

Magnet with HTS conductors

Strategy recommendations

- HTS offer the promise of operating at both higher magnetic fields and higher current density (for Non-Insulated coils)
  - Quench protection of NI coils for large-scale magnets is an area in which development and qualification is still needed (maturity level)
- However, even if we do not operate at high field and start within conventional insulated coils, HTS can still offer benefits:
  - **Simplification** of the magnet cooling scheme thanks to increased temperature margin (indirect conduction cooling)
  - This in turn can greatly simplify coil construction and **minimize High-Voltage risks** at the terminals by decoupling coolant and current-carrying functions of the conductor



ITER TF coil terminals
Leads, wires, and pipes with electrical breaks, all penetrating the ground plane

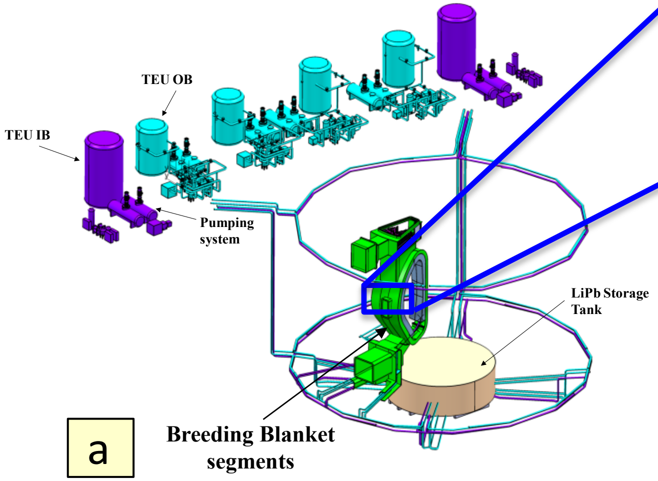
Breeding Blanket System

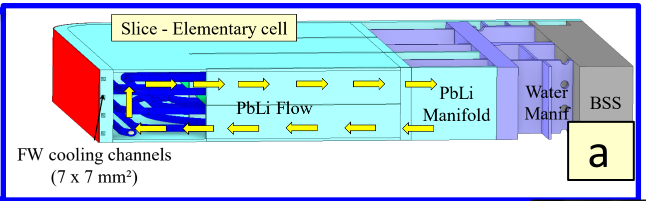
Recent achievements

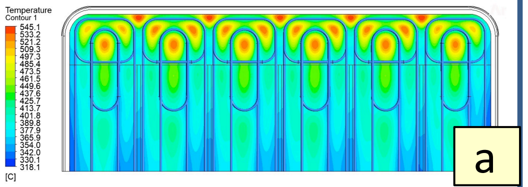
Source: Project Leader - Francisco Hernandez (KIT)

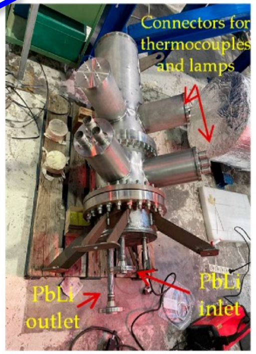
WCLL

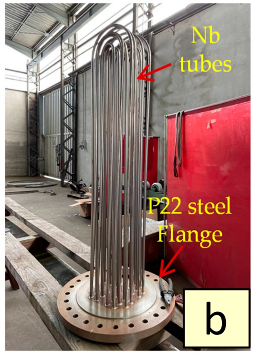
a) Advanced stage in BB and TER design with several studies aimed at the optimisation of their overall performances
b) Increased expertise in T-extraction from PbLi (GLC, PAV)
c) Increased capability to model PbLi/water interaction through dedicated numerical and experimental activities

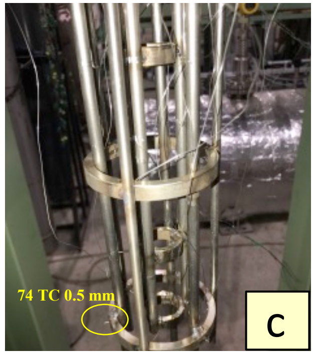






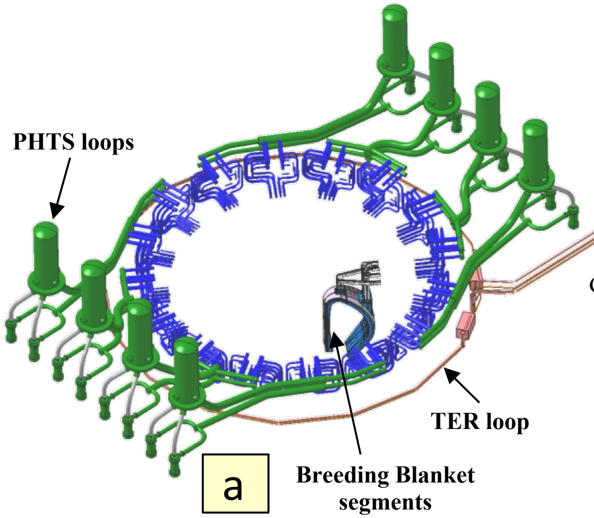


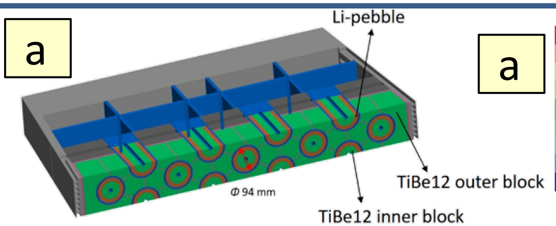


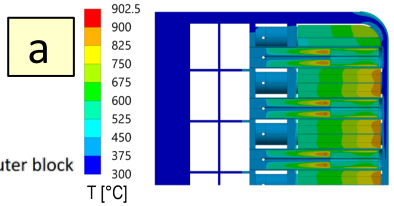


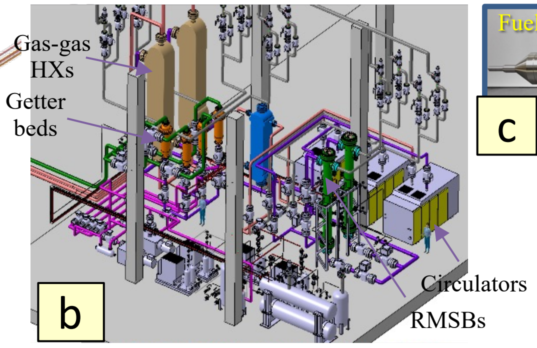
HCPB

a) Maturation of the BB and TER designs for operation at high pressure purge gas
b) The 1:10 RMSB mock-up manufactured and under qualification; Activities replacing the cryogenic process with getter beds is well advanced
c) Testing of a prototypical mock-up of a fuel-pin in HELOKA ongoing; assembly of FW with relevant fabrication route and manifolds well advanced

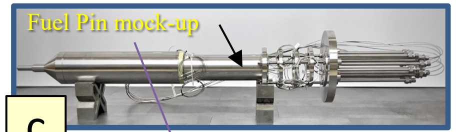


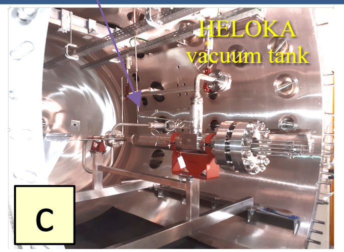






HCPB TER with getter beds





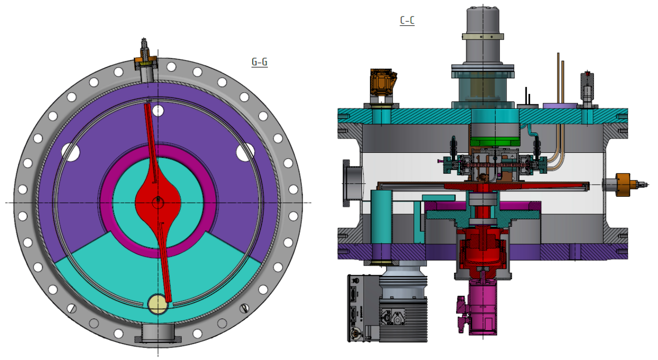
1:10 RMSB mock-up

Tritium, Fuelling and Vacuum Systems

Recent achievements

Source: Project Leader - Christian Day (KIT)

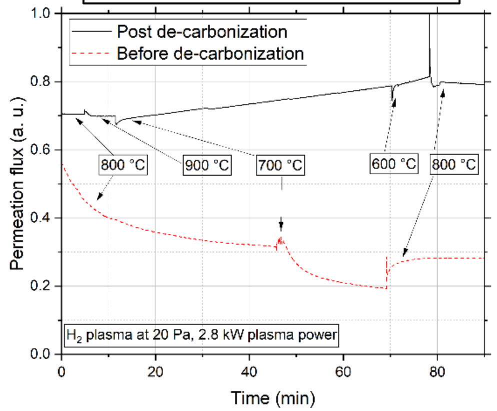
Pellet Injection | Continuous and highly repetitive: Detailed design ongoing based on a single screw extrusion, and a centrifuge to accelerate DT pellets continuously and highly repetitive.

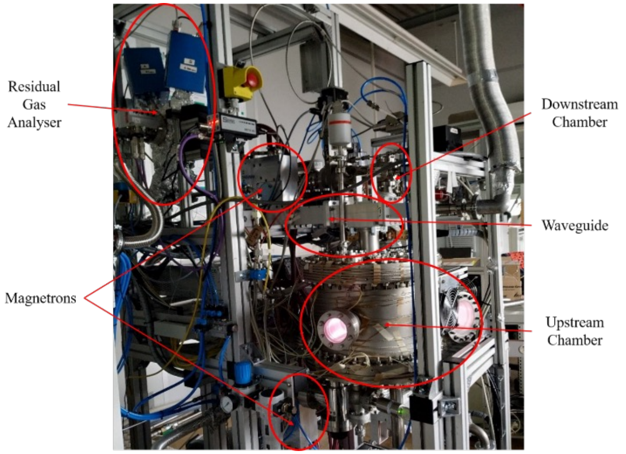


Design

Direct Internal Recycling | Metal foil pumping: Lifetime of metal foil - Methods developed to re-constitute pump performance following contamination

Supporting R&D





Superpermeation test facility HERMES.

Vacuum Pumping | Continuous: Three-stage mercury-based pumping train (Diffusion pump + ejector pump + ring pump).

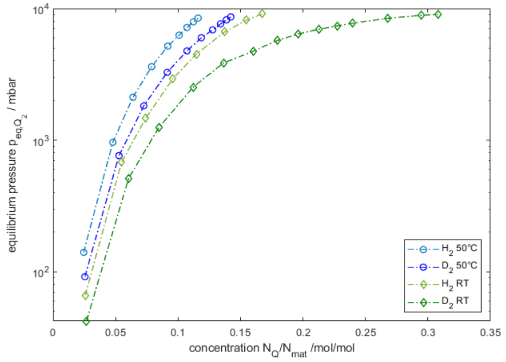
Test & Validate

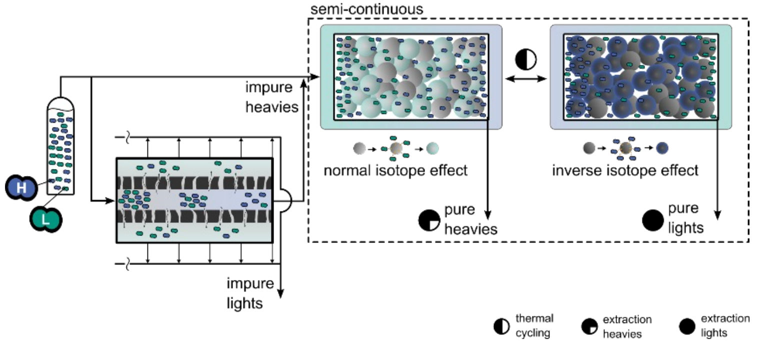
Nozzle set-up in the mercury lab

Serial testing of diffusion and ring pumps.

Isotope Rebalancing: Temperature Swing Absorption combining materials with normal and inverse isotope effect: Characterisation of candidate inverse isotope effect alloys.

Supporting R&D





Divertor

Recent achievements

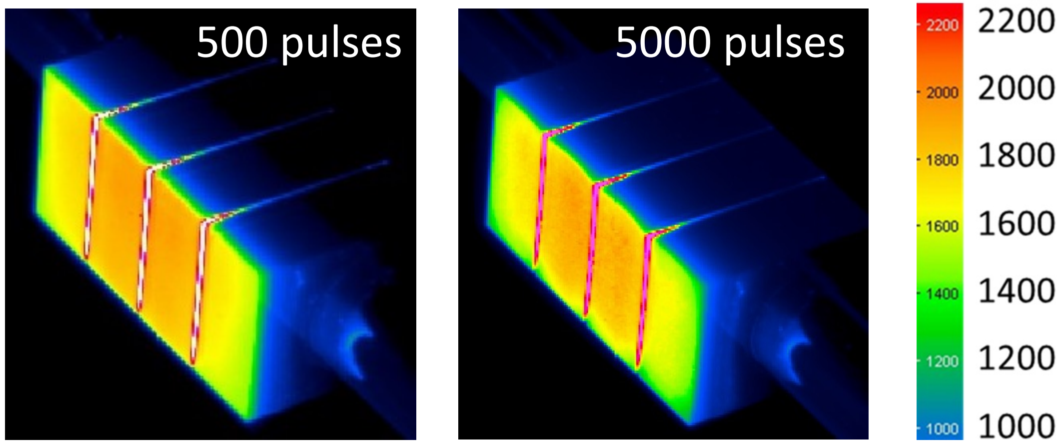
Source: Project Leader (DEMO DIV) - Jeong-Ha You (IPP)

High-heat-flux test to simulate strike-point sweeping on a divertor target

40 MW/m², 5000 loading cycles (pulse: 0.4 s, frequency: 0.63 Hz, coolant: 20 °C)

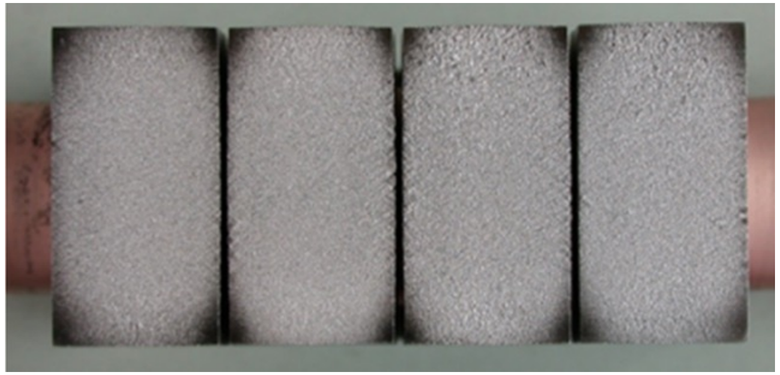
IR thermography (H beam irradiation)

J.H. You et al. Nucl. Mater. Ener. 33 (2022)

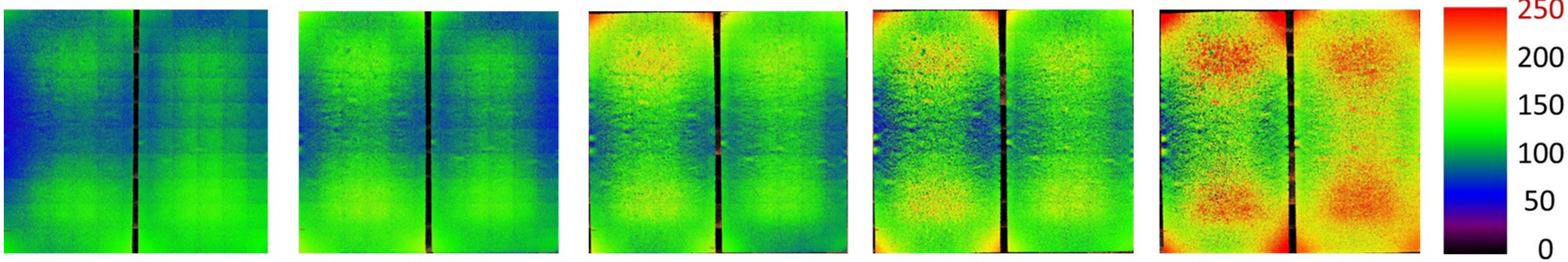


(GLADIS, IPP Garching)

Front face after the test (Tungsten: A.L.M.T.)

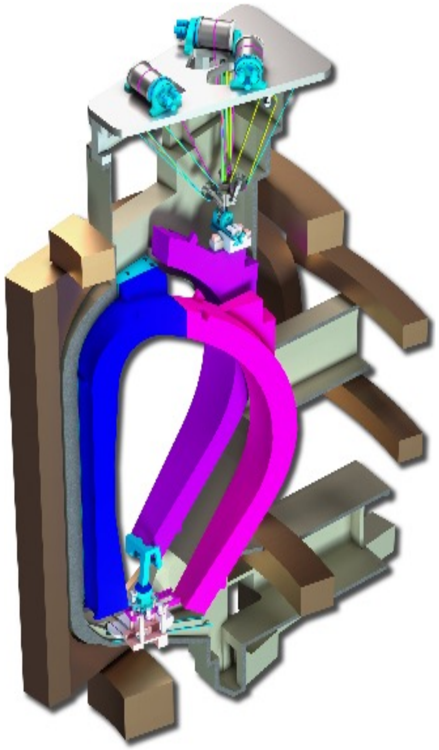


Front face topography measured by laser profilometry (visco-plastic deformation)



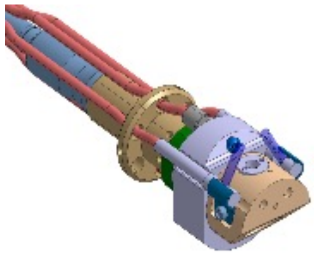
500 pulses | 1000 pulses | 2000 pulses | 4000 pulses | 5000 pulses

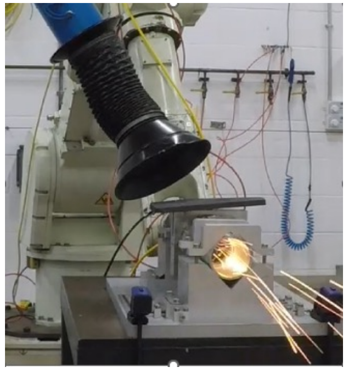
Source: Project Leader - Oliver Crofts (UKAEA)



Blanket handling

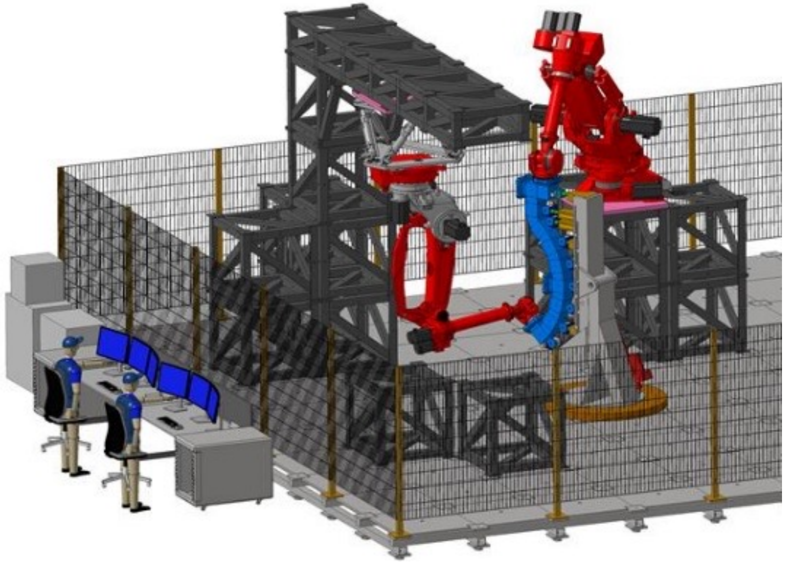
Further development of the Two Port, High Payload, Precision Mover and co-operative handling control. This mover holds the blanket at the top and the bottom.
(UKAEA RACE, EK-CER, VTT, ENEA)





Service joining

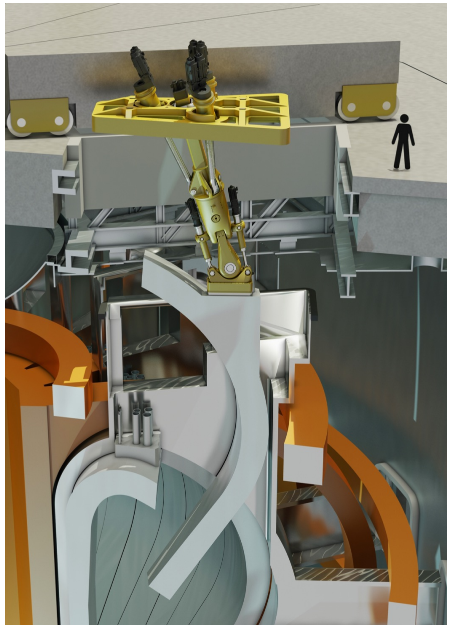
Miniaturised in-bore laser welding head upgraded and tested to 2.2kW (UKAEA)



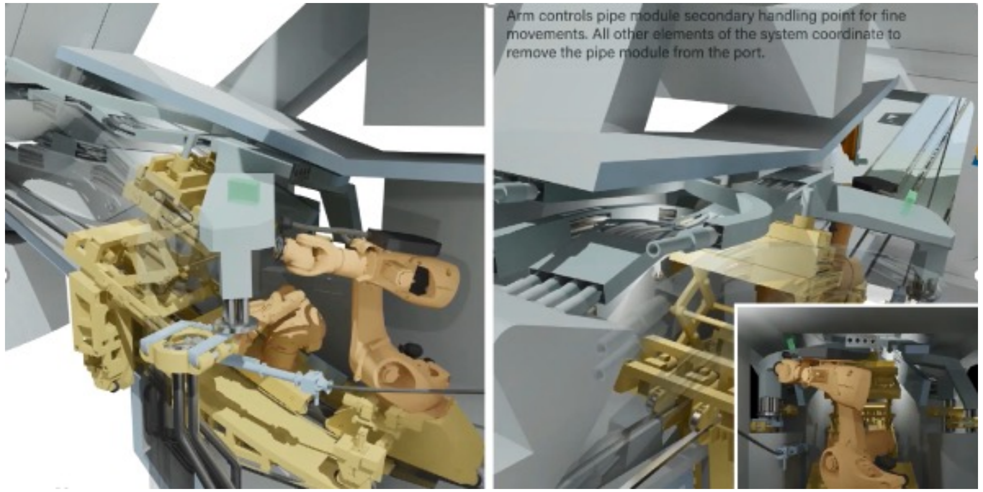
RMTF

Concept design developed for the Remote Maintenance Test Facility to develop and test the integrated performance of remote handling equipment, control algorithms and sensor technology for the precision handling of large flexible loads.
Tender released for the initial test rig, TR0, including test payload (UKAEA)

DEMO Remote handling and maintenance

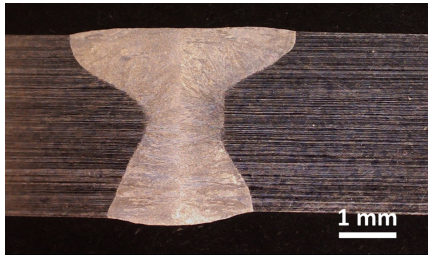


Blanket maintenance

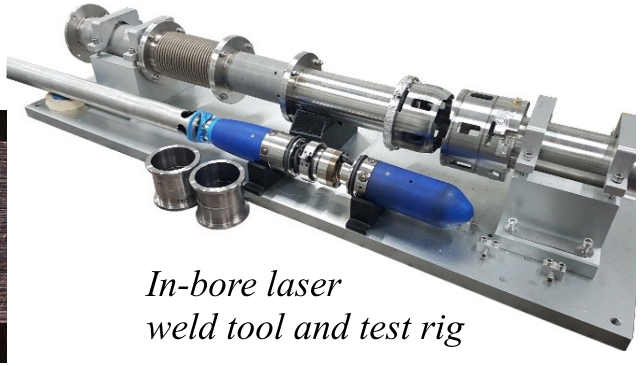


Divertor maintenance and pipe module handling

TARM handling system

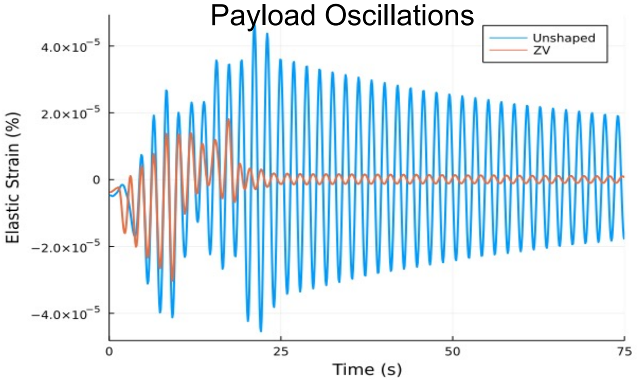


In-bore laser weld sample



In-bore laser weld tool and test rig

Pipe alignment testing

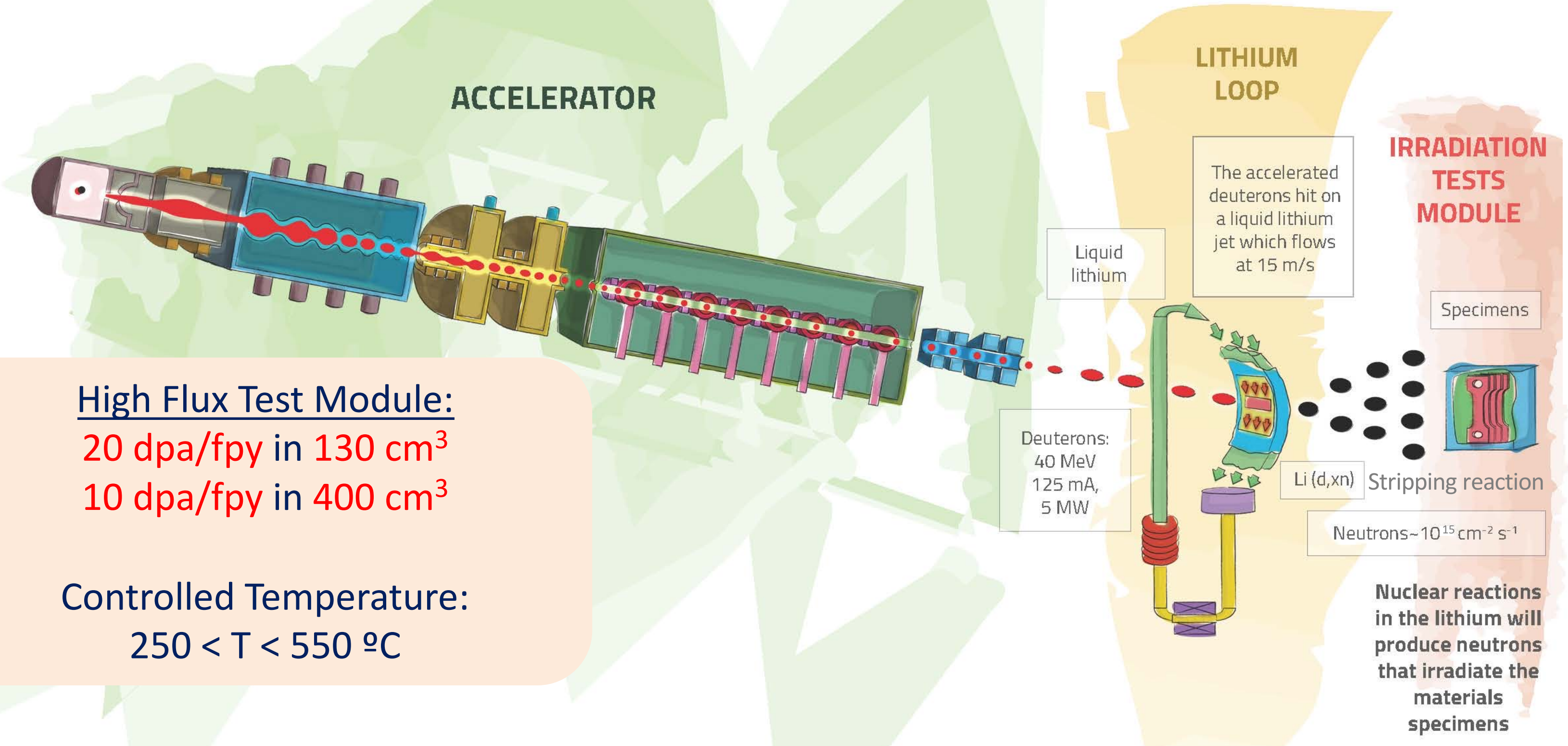


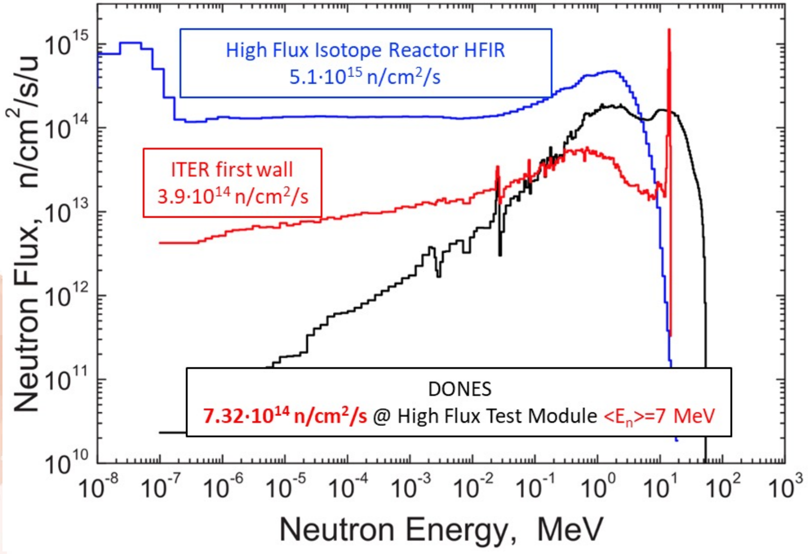
Damped oscillations achieved with control input-shaping

O. Crofts et al., EU DEMO Remote Maintenance System development during the Pre-Concept Design Phase, Fusion Engineering and Design 179 (2022) 113121
https://doi.org/10.1016/j.fusengdes.2022.113121

The IFMIF-DONES Facility

An accelerator based fusion-like neutron source to be mainly used for the qualification of the materials to be used in the DEMO Reactor



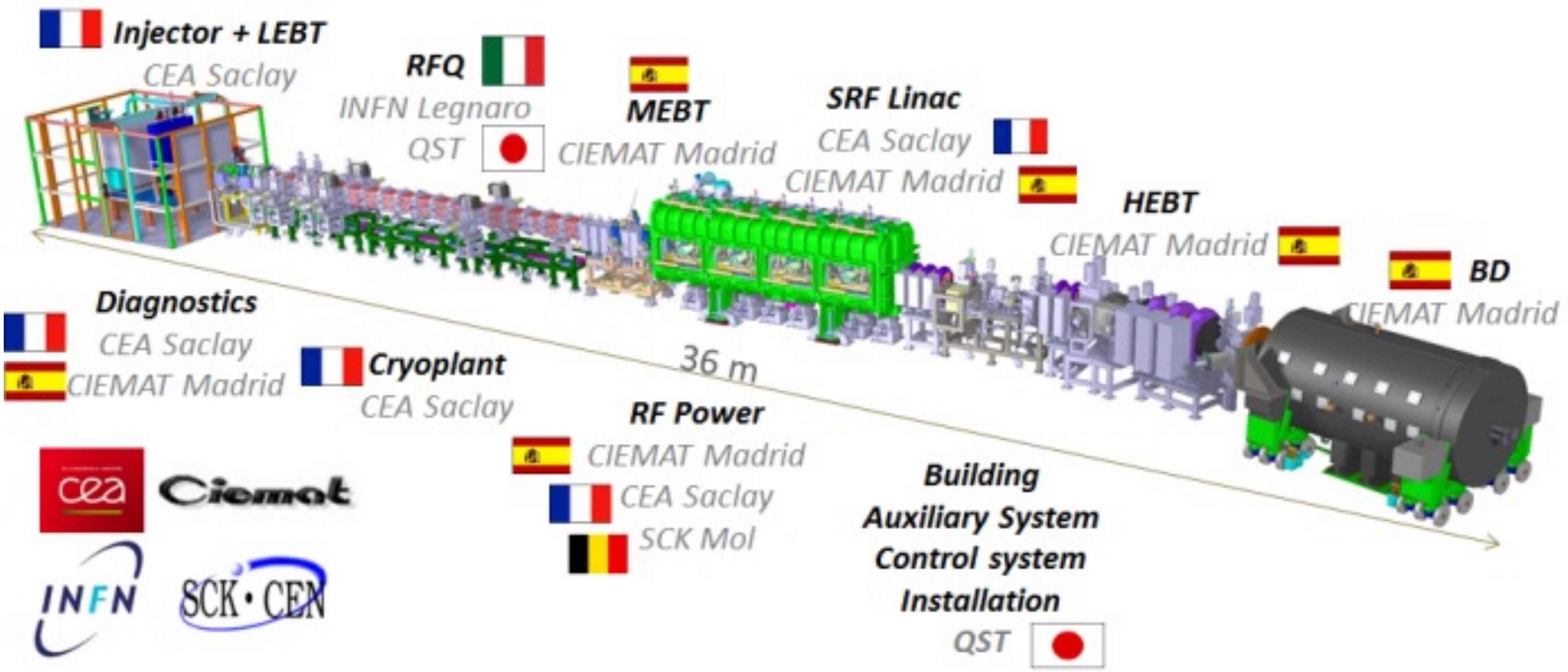


<u>High Flux Test Module:</u>
20 dpa/fpy in 130 cm^3
10 dpa/fpy in 400 cm^3

Controlled Temperature:
250 < T < 550 ºC

A neutron flux of ~ 10^{15} n/cm^2/s is generated with a neutron spectrum up to 55 MeV energy

LiPAc (Prototype Accelerator)



EUROfusion involved in commissioning of LIPAc (Japan) and responsible for Engineering Design of IFMIF-DONES

IFMIF-DONES: Construction of First Auxiliary Buildings

GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN | Ciemat

Junta de Andalucía

The site is located at Escúzar – 18 km southwest from Granada city – Spain

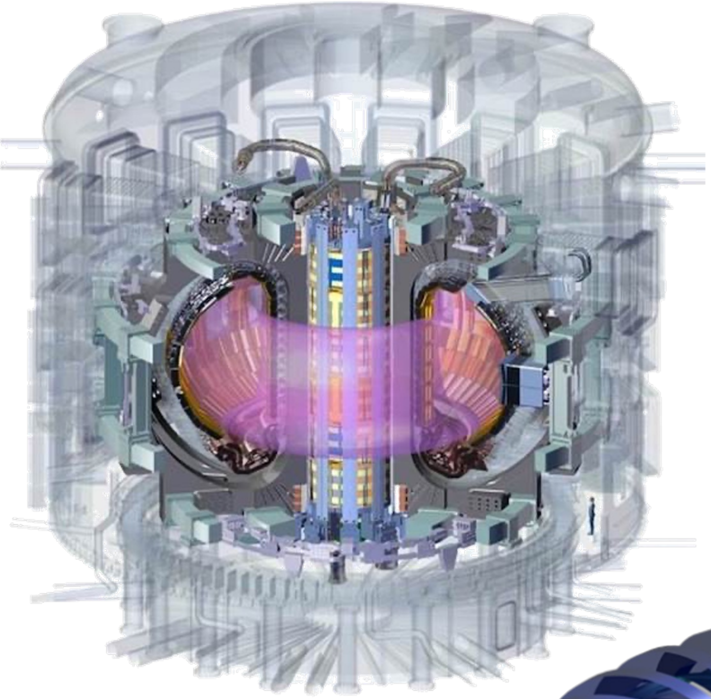
Operation starts ~2034

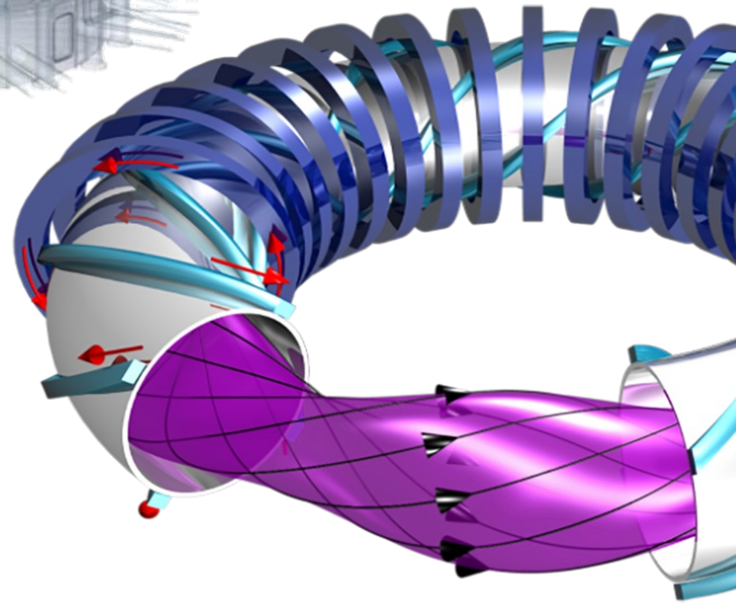
Measures to accelerate the DEMO program

- Parallelization of activities to reduce the sequential coupling of ITER milestones and DEMO decision points
- Strengthening R&D in the identified gap areas
- Increased effort in simulations for plasma and for engineering
- Mutually beneficial new international collaborations
- Development and maintenance of adequate workforce
- Knowledge management
- Streamlining licensing towards a regulatory framework for fusion and rapidly identifying site
- Involvement of industry in DEMO design & construction (PPPs)

Measures to accelerate the FPP program beyond DEMO

- Dedicated test facilities to qualify technologies for FPPs that will be different from DEMO
- Investigations to increase attractiveness of FPPs
  - Stellarator FPP design studies
  - HTS magnets
  - Advanced structural materials
  - Alternatives to water as primary coolant

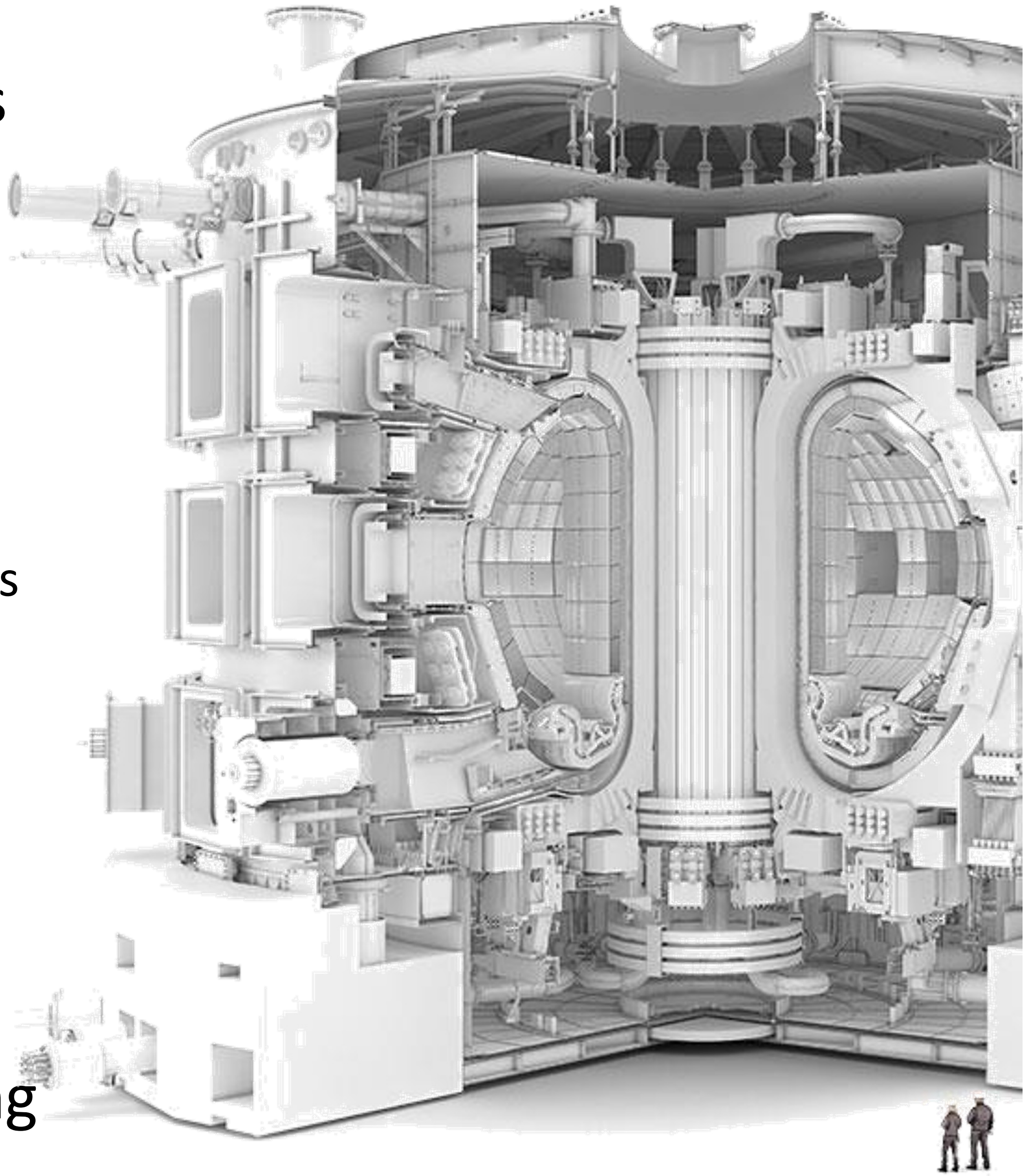




Parallelization of ITER and DEMO and the role of ITER

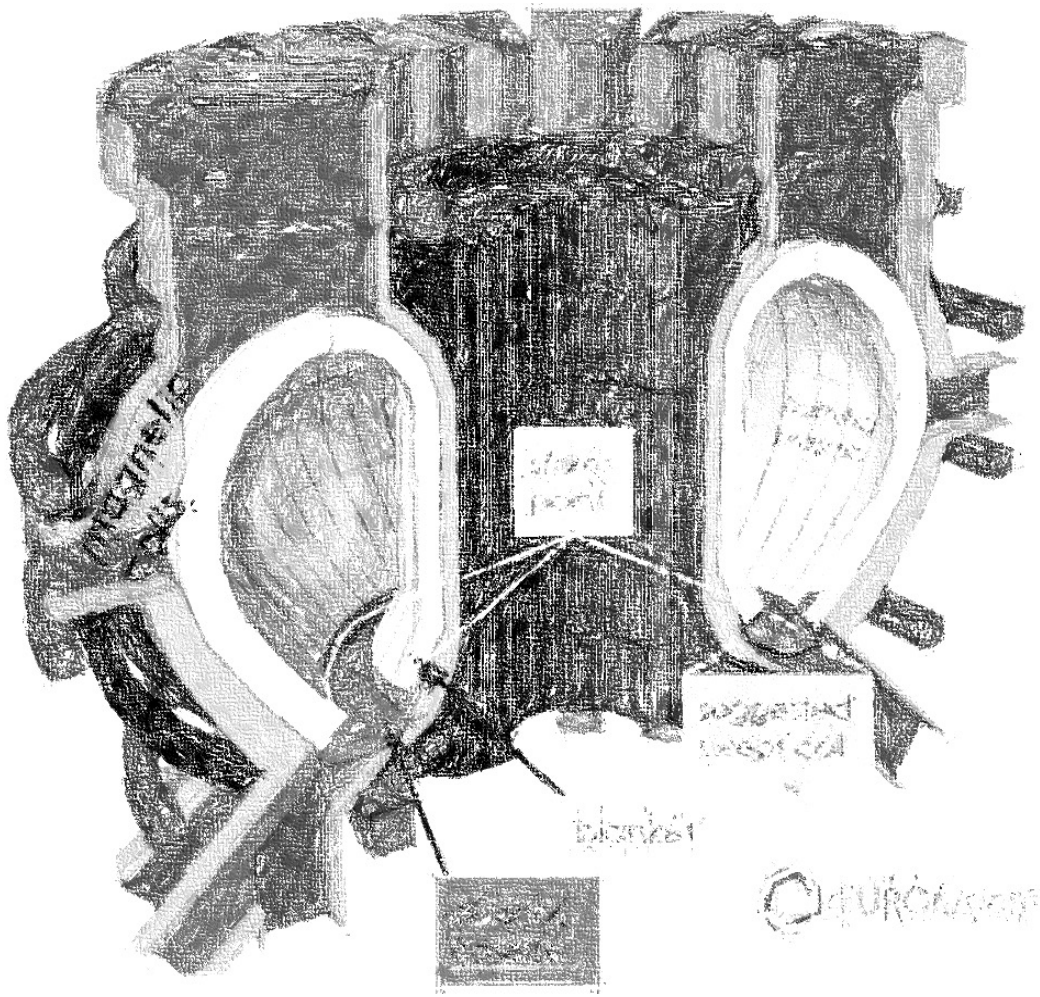
ITER is a key milestone for fusion: crucial lessons are drawn through all its phases

- Info on how to design and construct components at reactor scale in nuclear environment, and on relevant licensing
  - Vacuum vessel, cryogenics, magnets, H&CD systems
- The ongoing assembly of ITER is giving information to inform the DEMO design process
- ITER lessons during commissioning may not influence DEMO design, but will be in time and of highest value for DEMO commissioning



Parallelization of ITER and DEMO and the role of ITER

- ITER demonstration of Q=10 & burning plasma regime will provide basis for DEMO scenarios
- ITER TBM program will likely not be in time for DEMO design
  - Emphasis on development & validation of blanket technology before DEMO, so that DEMO can be an integrated demonstrator and not a blanket test facility
- Yet, TBMs will yield crucial information for DEMO on qualification, licensing, manufacturing and integrated operation of blankets in nuclear plasma environment
- ITER's experience with safety and waste production, RH, civil engineering, the hot cell, the management of T and radioactive waste, is an essential reference for DEMO



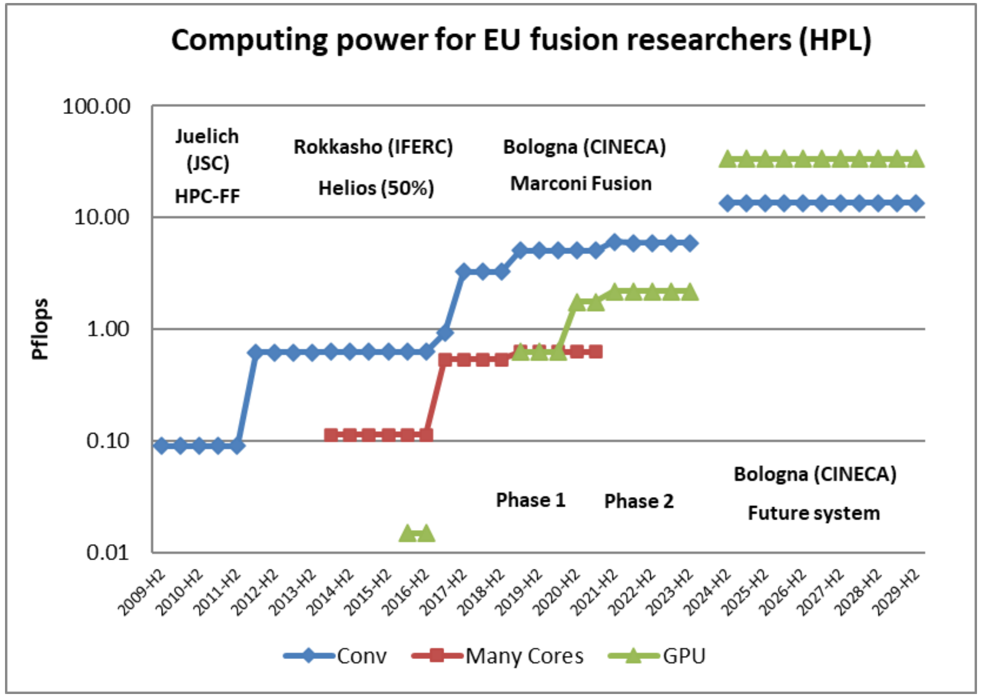
Thus far I spoke a lot about DEMO….. but support to ITER should not be forgotten

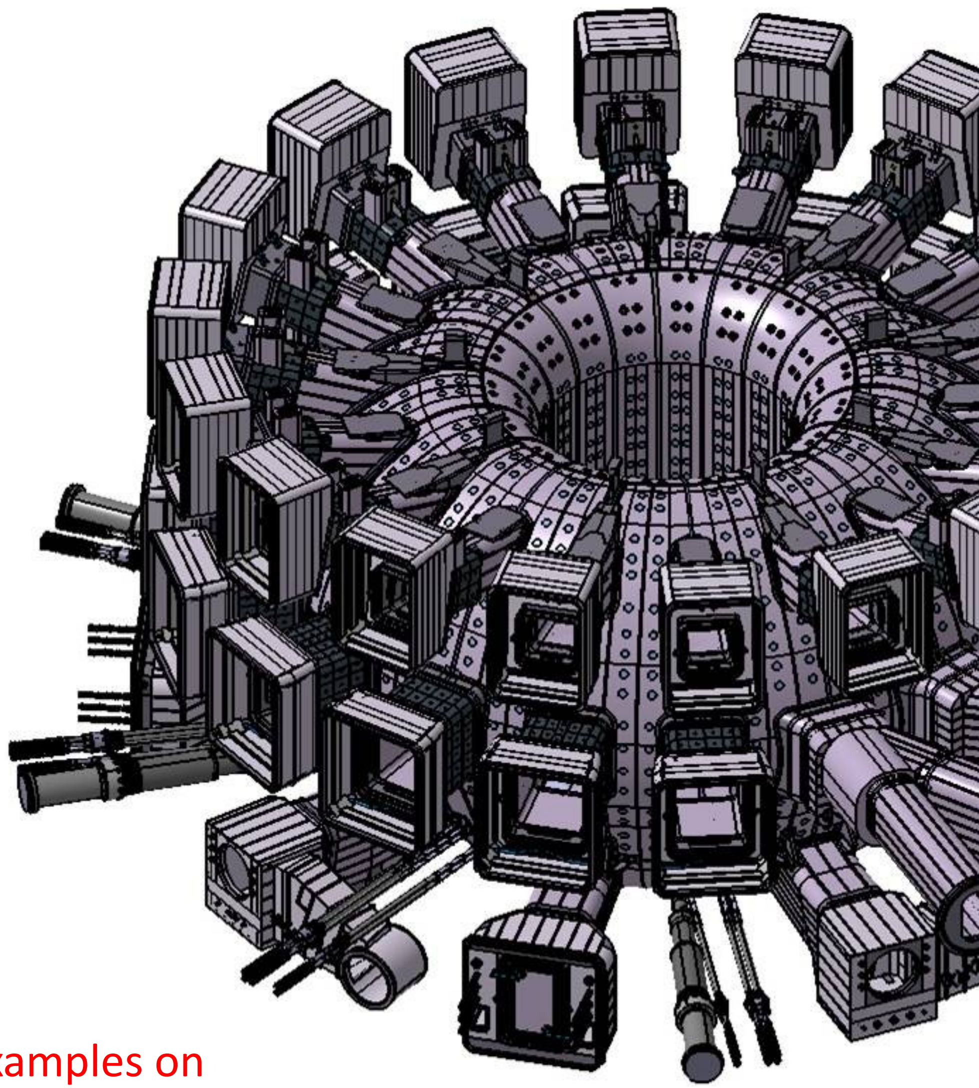
A.J.H. Donné | NIFS | Toki, JA| 15 September 2023

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.

Support for the ITER programme is key

- EUROfusion continues to support ITER
  - By dedicated experimental campaigns on ASDEX Upgrade, COMPASS Upgrade, JET, MAST U, TCV, WEST, W7-X and many linear devices
  - By detailed theoretical modelling using a.o. a ~50 Pflops dedicated High Performance Computer



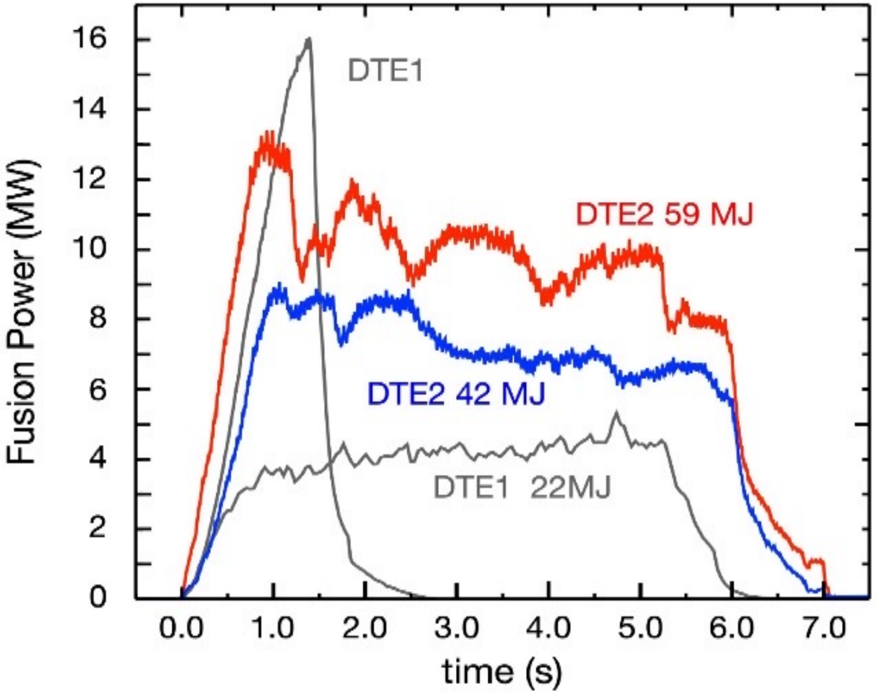


Some examples on following slides

EUROfusion

5. JET achieved record fusion energy

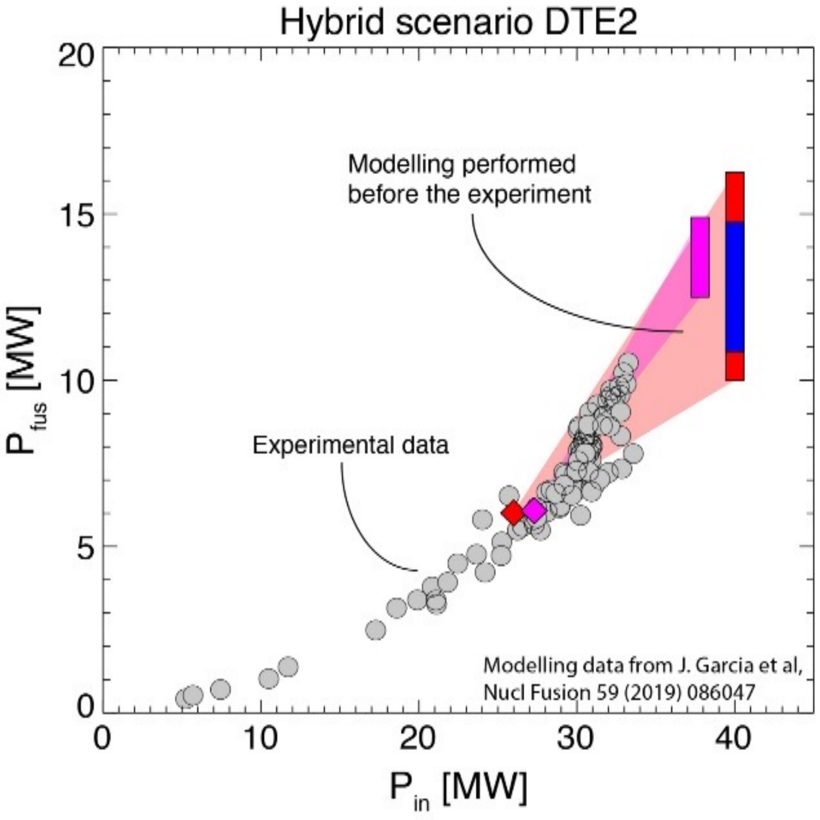
High fusion power produced and sustained for 5 seconds



- **First-ever high confinement plasmas using D-T with Beryllium / Tungsten wall**
- Confirming **predictions** of plasma behaviour advances development of ITER high performance scenarios

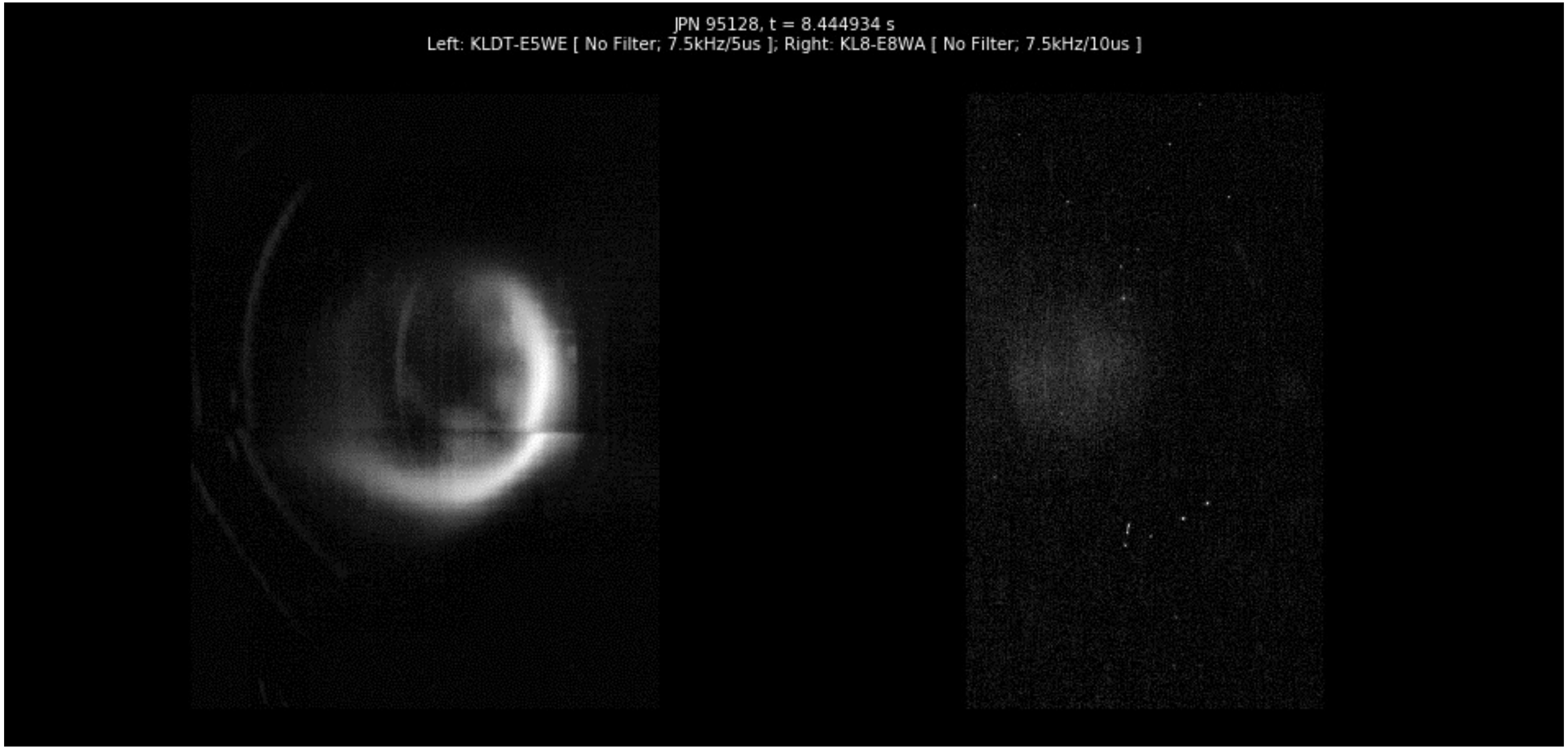
JET

4. D-T results confirm modelling predictions



- D-T fusion power achieved matches predictions
- New JET data are crucial to predict fusion in ITER and future machines
- Wealth of new JET data to validate the models and extrapolate to ITER and beyond

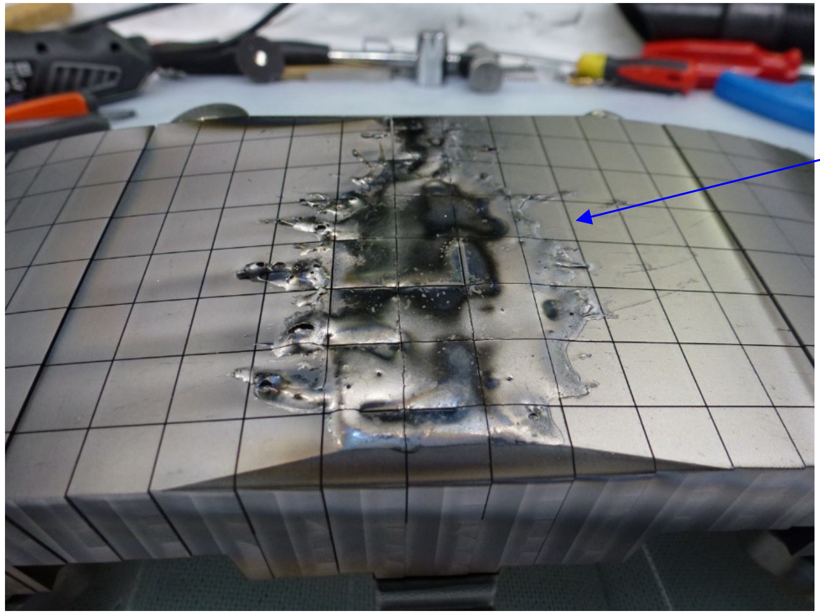
Shattered Pellet Injector (disruption mitigation)



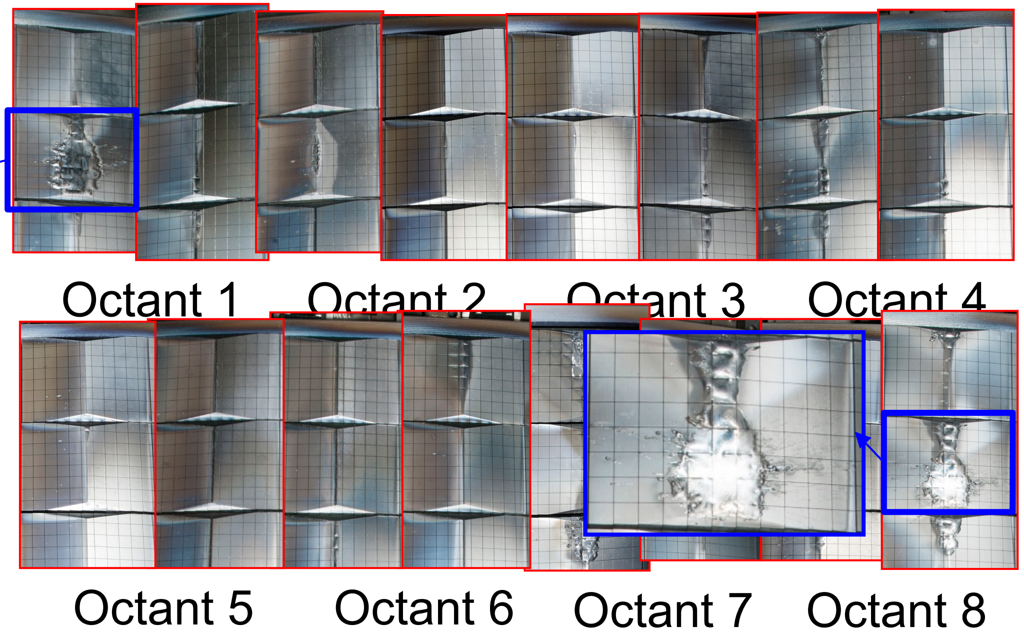
Runaway Electron (RE) load characterization in JET

WPPWIE

- **Critical ITER topic: *Be wall damage by RE events***
- Dedicated JET RE experiments to explore damage footprint (JPN 86801)
  - RE power deposition on inner wall Be limiter tile during single event
  - Post-mortem analysis: Be sectioning and metallography, microscopy, damage material properties
- MEMOS-U simulations were validated to improve confidence in ITER predictions about potential Be tile damage during RE events (in progress)



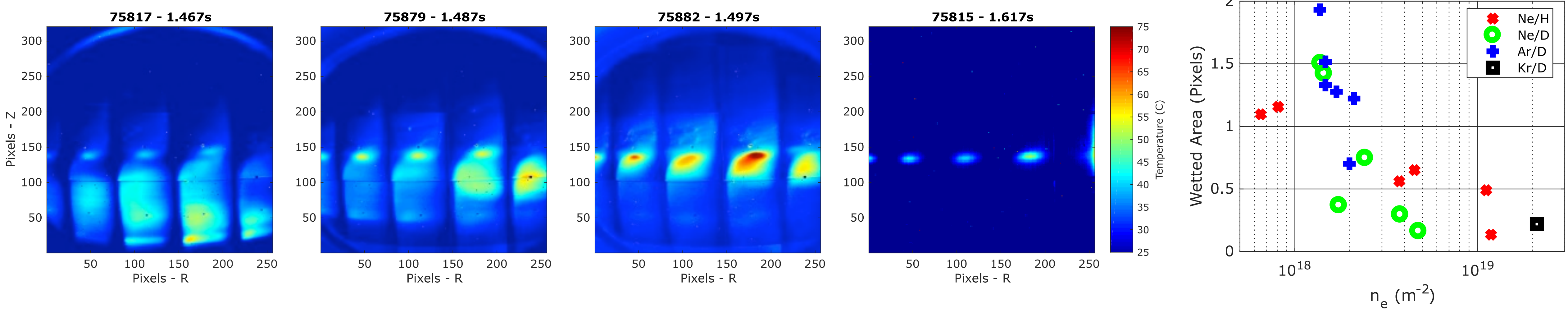
I. Jepu et al.



Benign termination of runaway electron beam

- TCV disruption and runaway electron studies via EUROfusion
- Control via gas injection to maximize power spread on wall
- Increased wetted area and conversion of magnetic energy to radiation prevents localized heat flux from runaway electrons
- Models developed using multimachine database to extrapolate technique to ITER

Benign Termination — Increasing Density → Non-Benign Termination

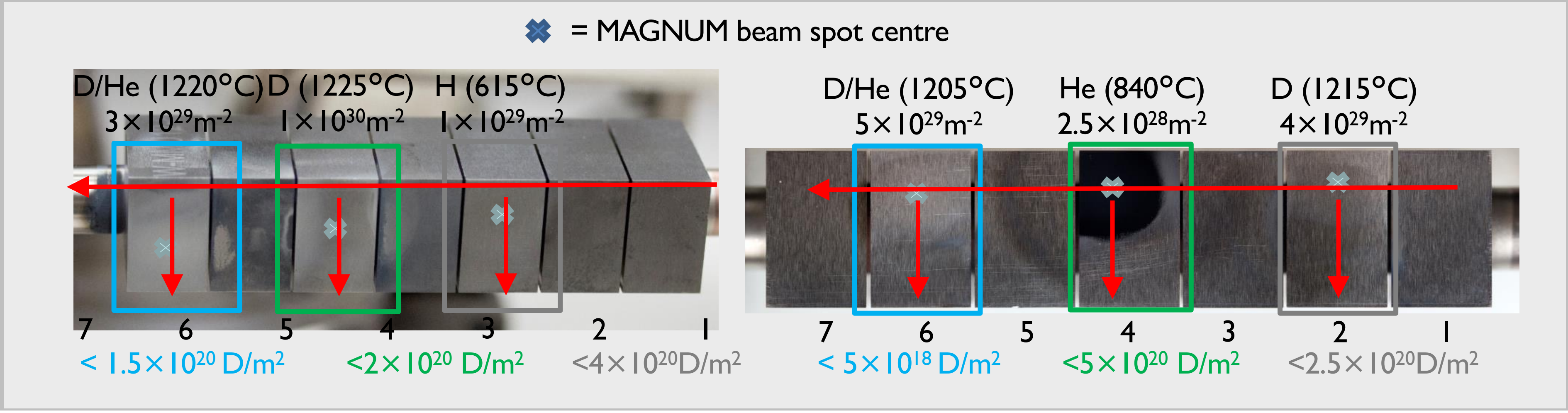


World record plasma exposure in Magnum-PSI

T. Morgan, PFMC 2019
M. Balden, PFMC 2019

ITER relevant conditions (~1 Full Power Year):

Target	1200 C°
Heat load	20 MWm^{-2}
Particle load	1.5 10^{25} particles $m^{-2}s^{-1}$
Duration:	18,5 hours

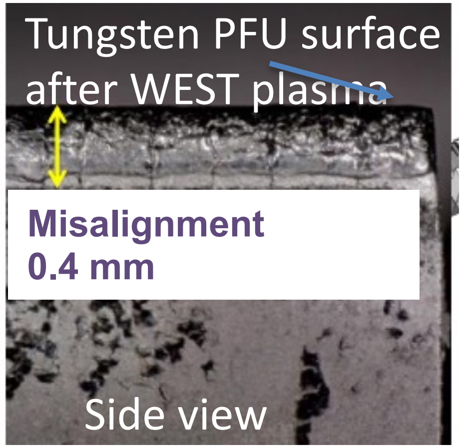


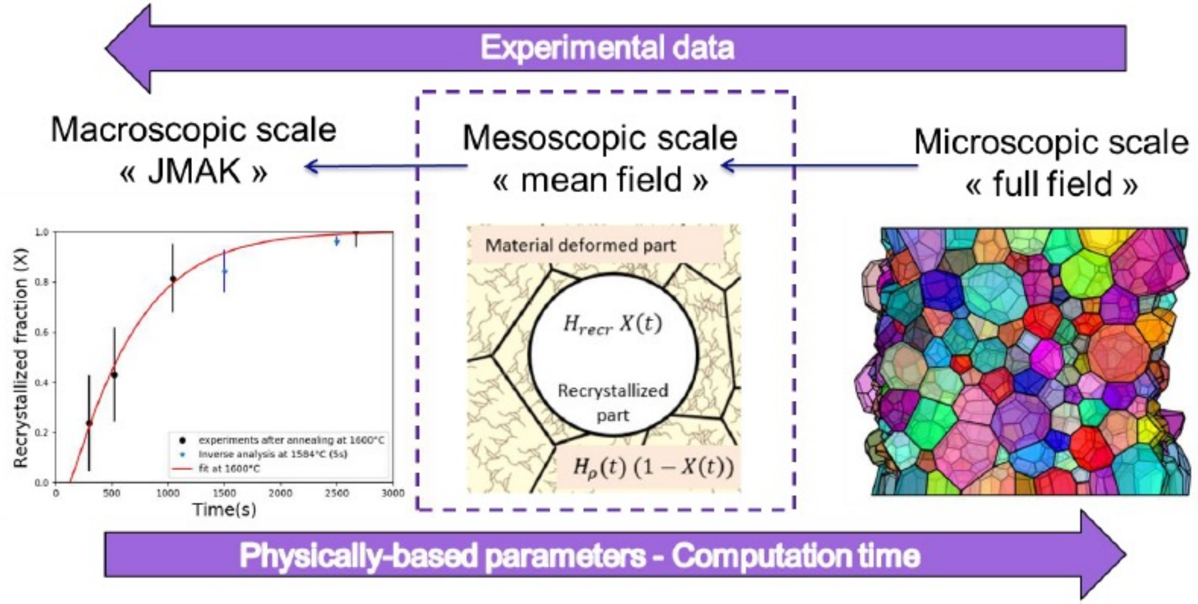
Tungsten recrystallisation and softening studies

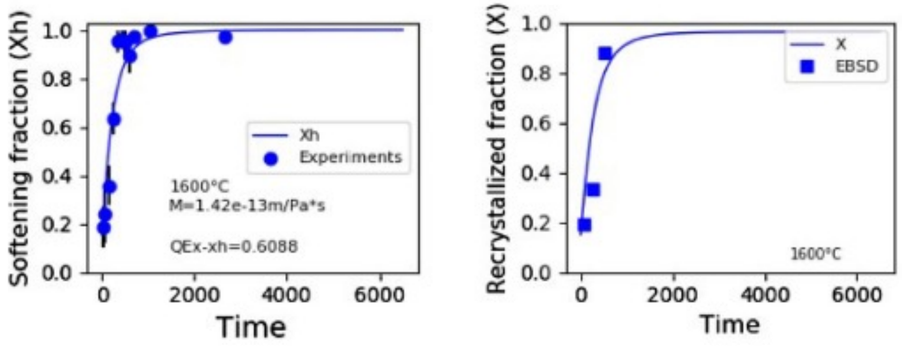
WPPWIE

Critical ITER topic: *W divertor operational window*

- Study recrystallization and softening of W plasma-facing unit (PFU) surfaces under WEST plasma loading
- Aim to benchmark models regarding recrystallization and softening kinetics of W in view of ITER predictions
- Post-mortem analysis:
  - Loss of mechanical properties (Xh) -> Hardness measurements
  - Modification of the microstructure (X) -> EBSD measurements





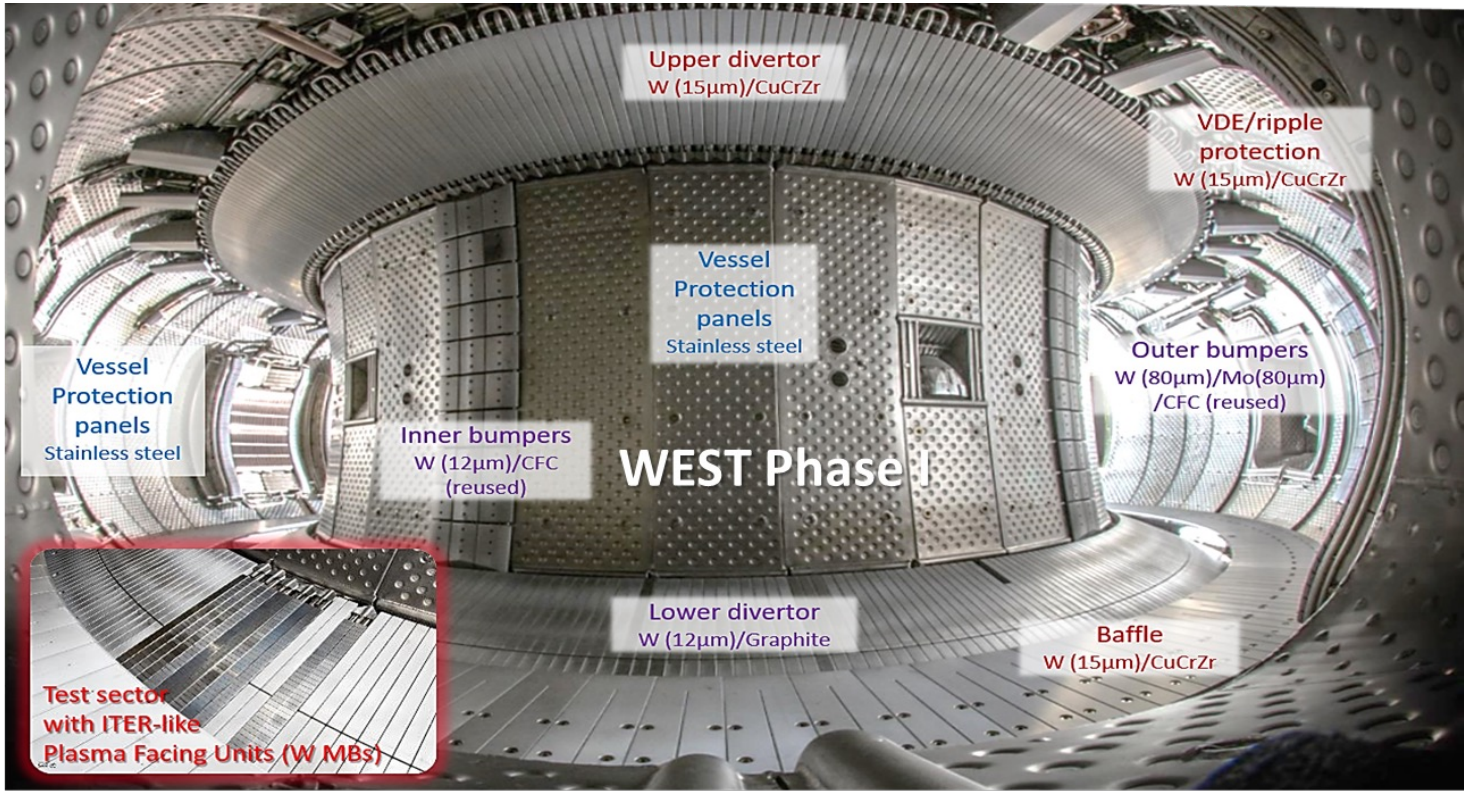


A. Durif

Test of ITER-like divertor prototypes

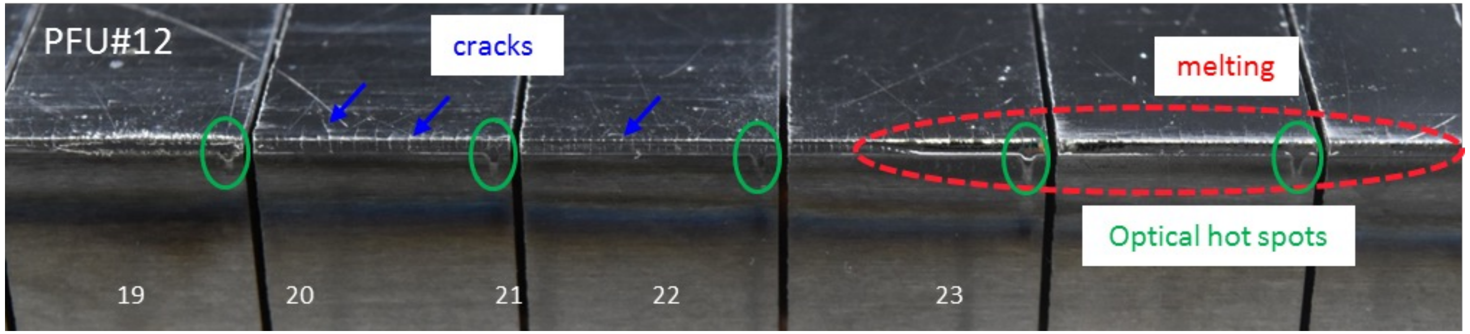
WEST first phase of operation with ITER prototypes (W monoblocks on CuCrZr heat sink) in lower divertor

Long pulses up to 1 min with upper actively cooled divertor



Damages observed on ITER-like plasma facing unit after exposure

- Cracking and melting on leading edges (transients)
- Hot Spots at toroidal gap crossing, as predicted for ITER



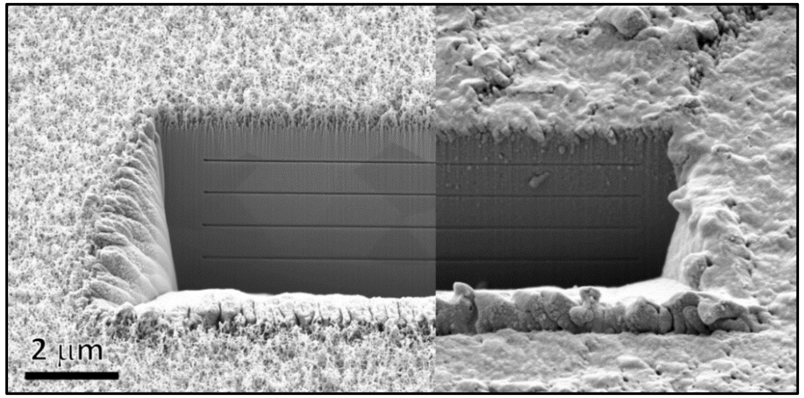
Tungsten morphology changes in He plasmas

He campaigns at JET and ASDEX-Upgrade to study W-fuzz formation and erosion, a critical issue for ITER, and validate relevant models

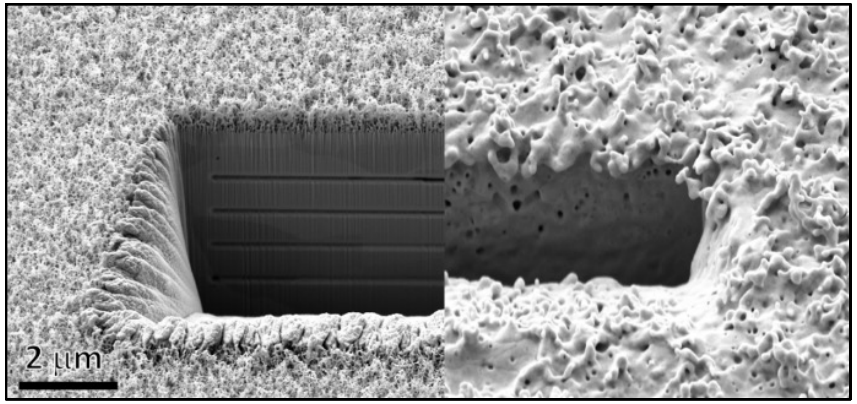
- Plasma loading in “W-fuzz growth regime”
- Pre-formed W-fuzz in PSI-2 exposed in ASDEX-Upgrade H-modes with ELMs

Post-mortem analysis with SEM & FIB cuts

Erosion at strike-line conditions

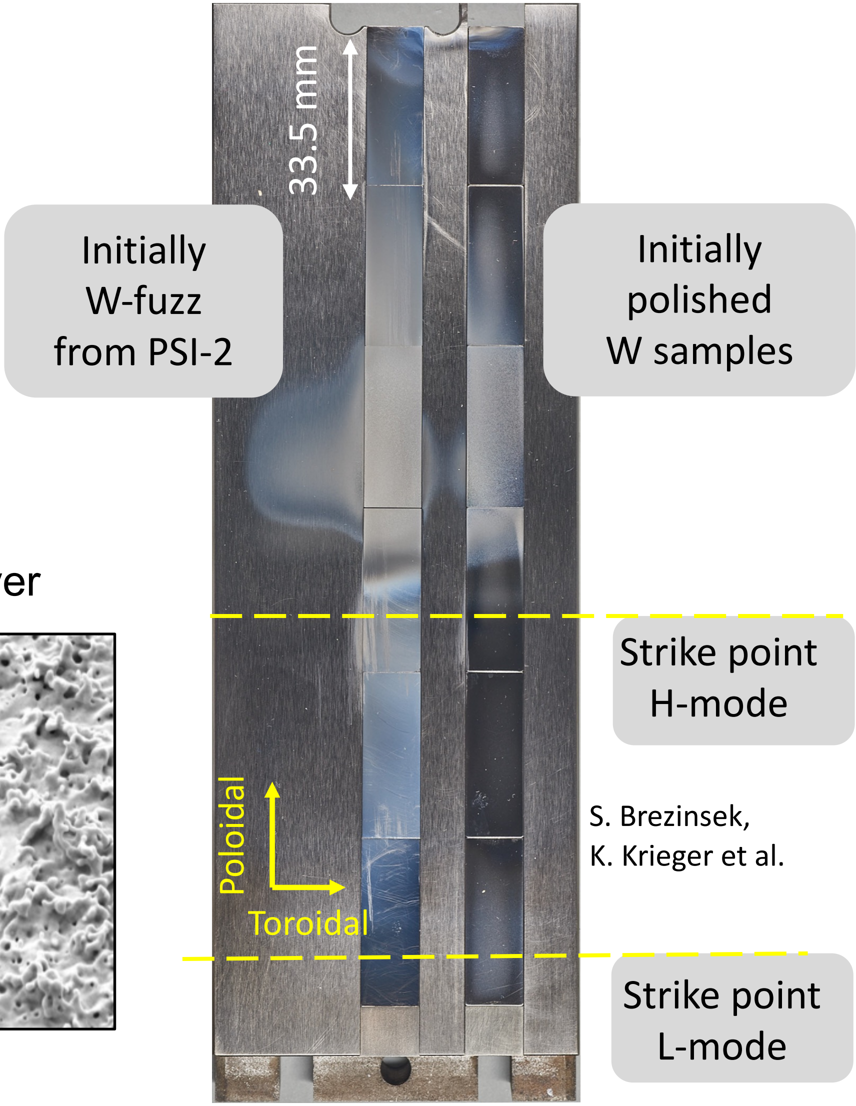


Further W growth in the scrape-off layer



M. Rasinski et al.

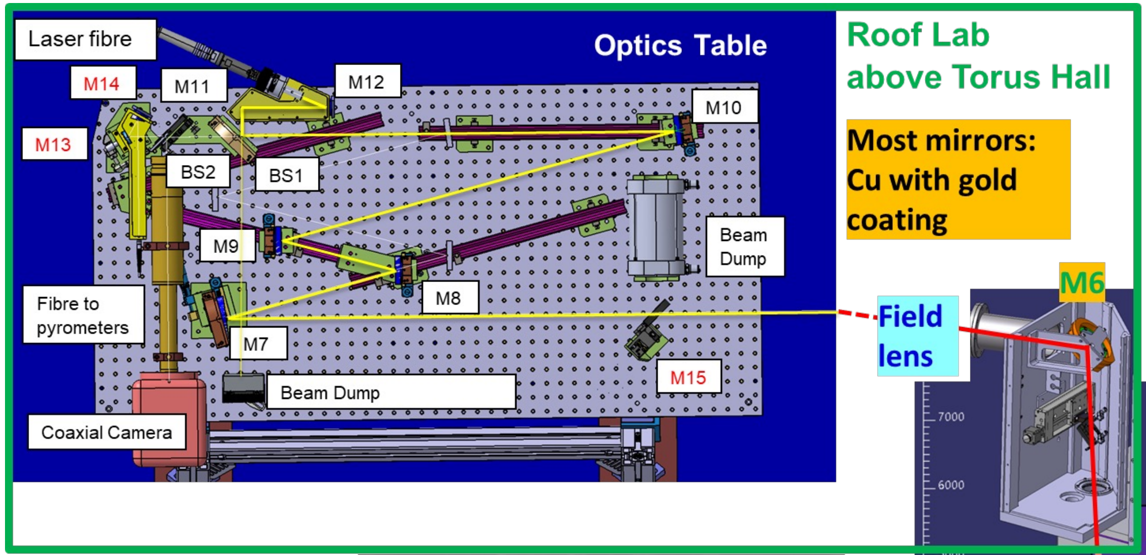
Samples after exposure in ASDEX-Upgrade



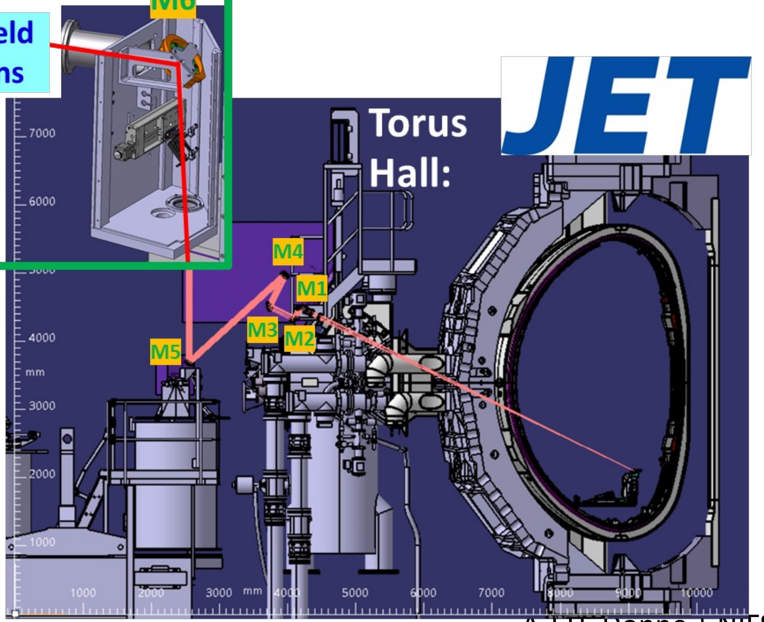
S. Brezinsek, K. Krieger et al.

Laser-induced desorption diagnostic in JET

- **Critical ITER topic: *Tritium retention and monitoring diagnostic***
- Transfer ex-situ laboratory technology (FREDIS) into the JET tokamak
- Demonstrate in-situ laser-induced T desorption from Be layers and quantification via quadrupole mass spectrometry of hydrogen isotopomers (H_2, D_2, T_2, HD, TD)
- Validate the technical approach for the T-monitor diagnostic in ITER



- Design completed
- Laboratory testing completed
- Installation in preparation
- Operation in early 2023



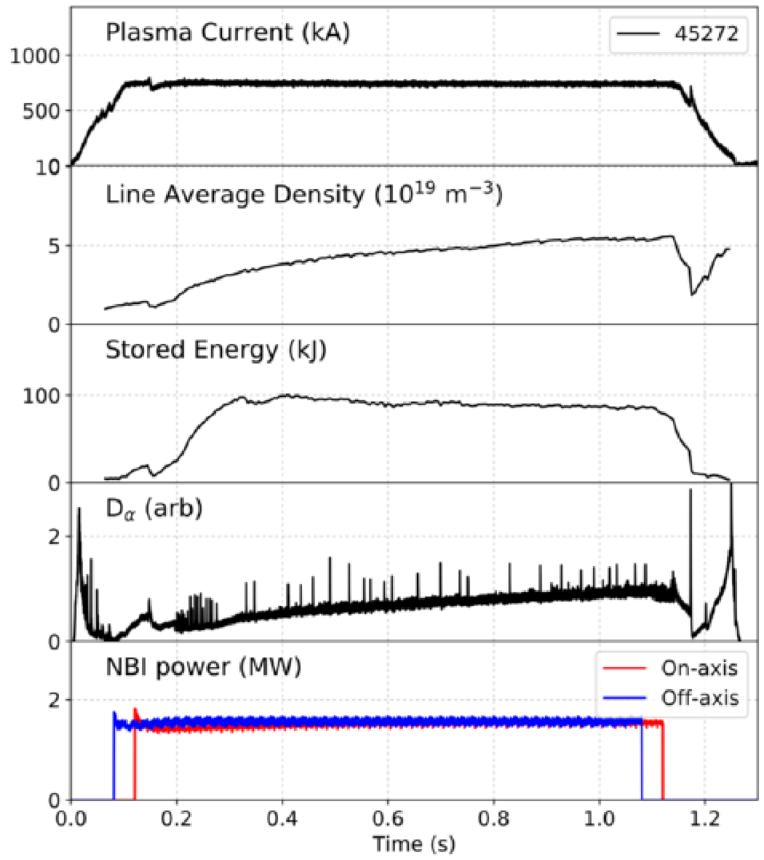
Measurement at inner divertor where Be layers identified by tile analysis

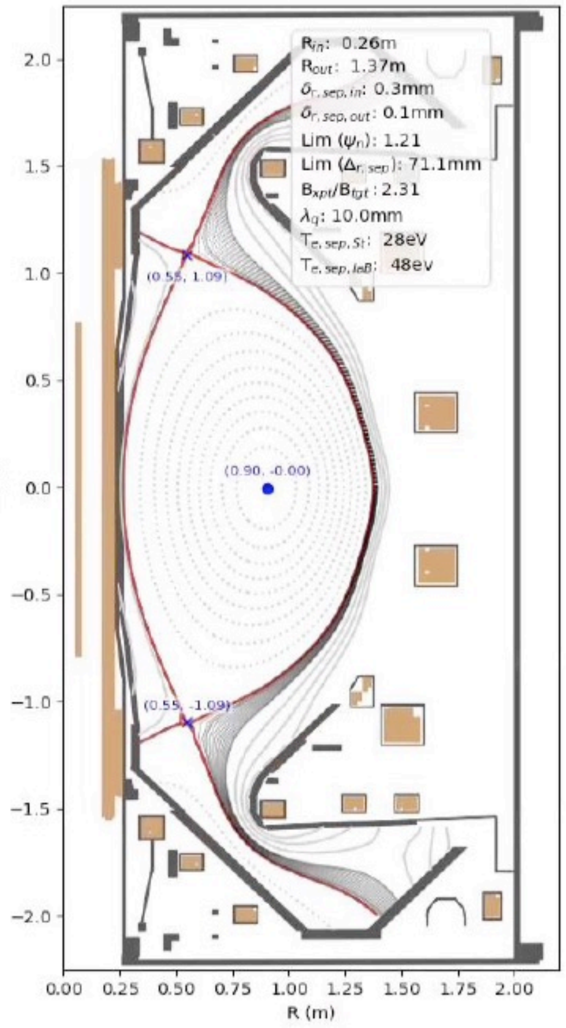
FZJ & UKAEA

M. Zlobinski et al.

Super-X divertor in MAST-U works

750kA plasma with 1s flat-top achieved



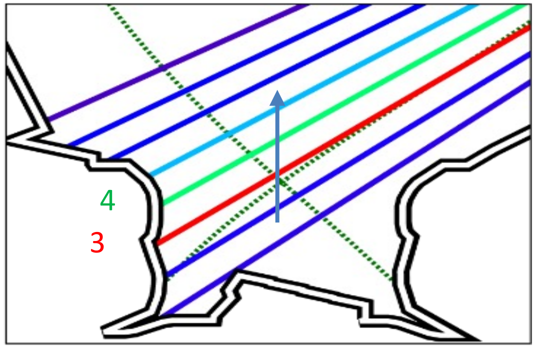


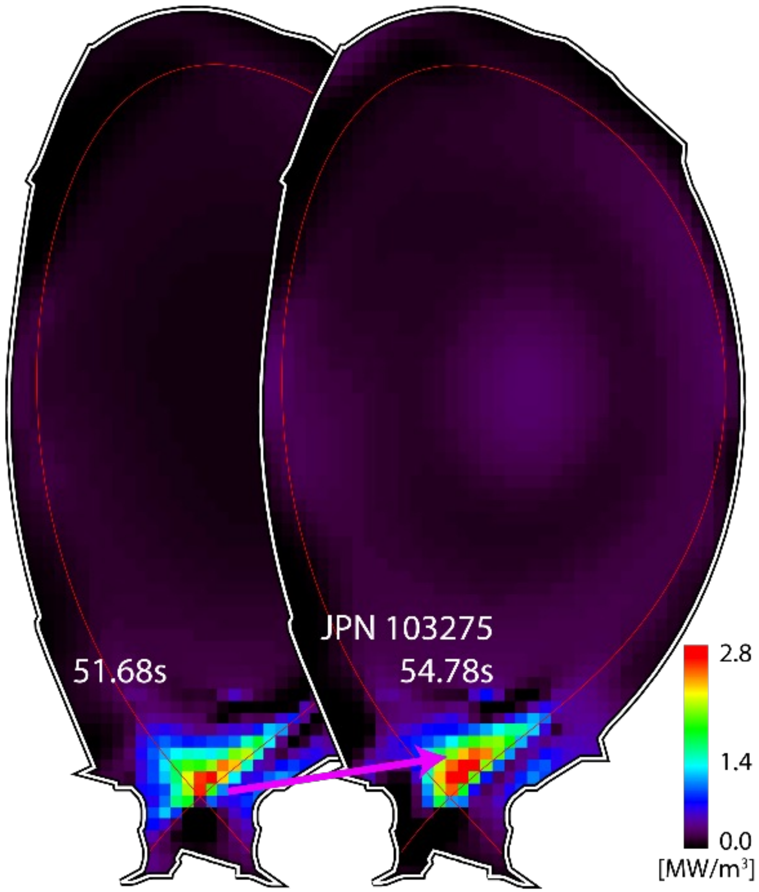
Super-X divertor compared to conventional divertor in L-mode

- ~10 times reduction in divertor heat flux
- ~2 times reduction in upstream density to detach outer divertors

X-point radiator control

- X-Point radiator (XPR) has promising features
  - Full detachment
  - Maximum power dissipation
  - Controllable
- Observed at Asdex-Upgrade, TCV, WEST, JET
- At JET
  - Created with N_2, Ne and Ar seeding
  - Movement tracked with bolometry camera
  - XPR location controlled within 4mm
  - ELMs diminish
  - First control of full detachment





[RT22-05: M.Bernert, D.Brida, H.Reimerdes, N.Fedorczak + RT22-04: B. Sieglin, P.Fox, T.Bosman, M.Lennholm]

Fast-ion physics studies

Heating scenarios with MeV-range fast ions at JET

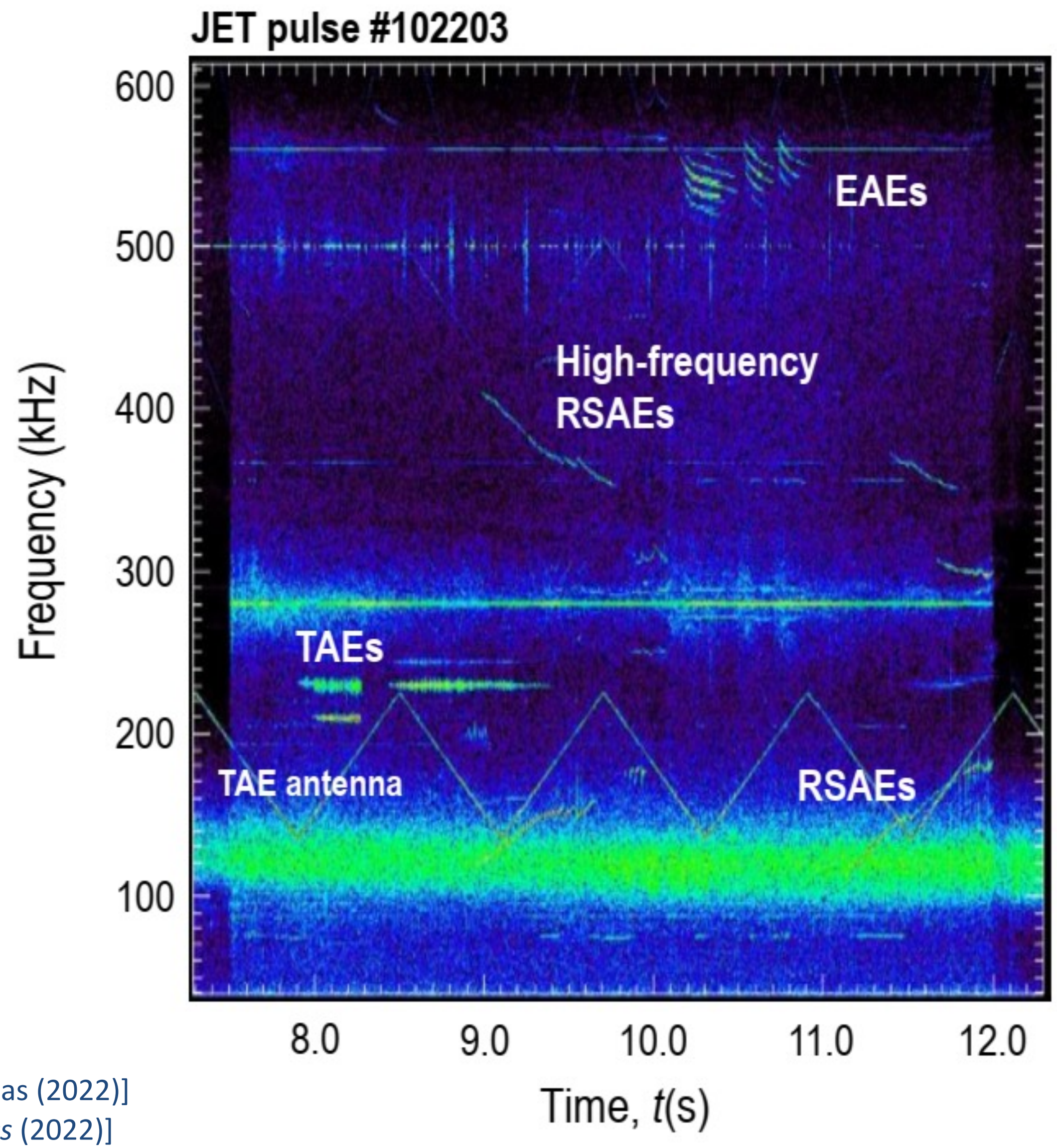
Dominant electron heating as in ITER

Access to high T_i

Destabilization of Alfvén Eigenmodes, which do not appear to be detrimental

Stabilizing impact on microturbulence

Non-linear interplay between fast ions, ITG and AEs



[Y. Kazakov et al., Phys. Plasmas (2022)]
[S. Mazzi et al., *Nature Physics* (2022)]

Quasi-Continuous Exhaust regime

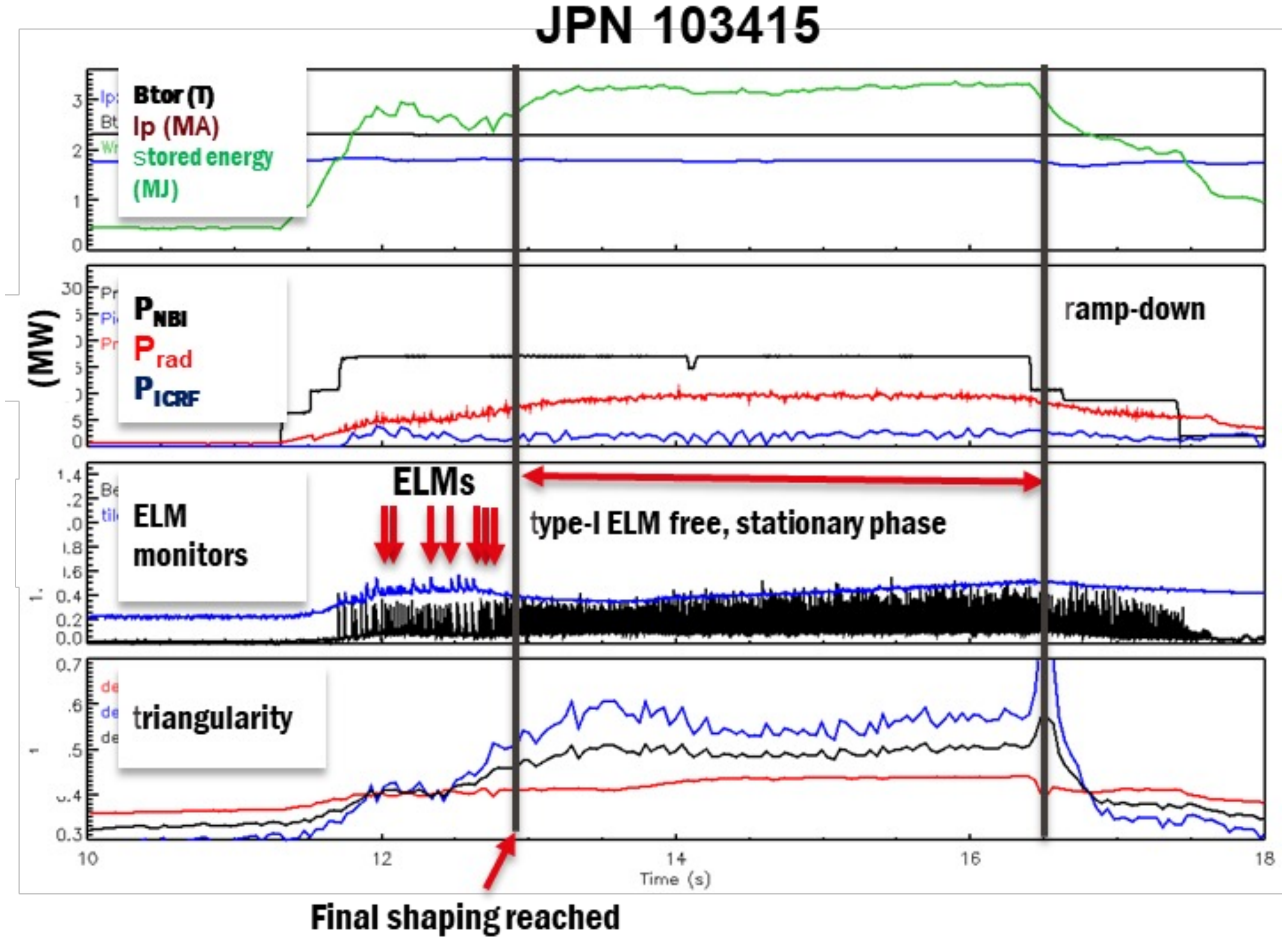
QCE regime obtained on JET building on expts in ASDEX-Upgrade and TCV

Main features

- no type-I ELMs
- high line-averaged and SOL density
- only modest decrease of confinement compared to type-I ELMy data base

Key access parameters

- shaped plasma cross-section (κ, δ, closeness to double null)
- high pressure in the vicinity of the separatrix through strong gas puffing



Joint progress on plasma control on EU devices

Tokamak plasma control through deep reinforcement learning

[Degrave Nature 602, 414 (2022)]

Supervisory control & dynamic pulse scheduling

[Vu IEEE TNS 2021]

State observer implementations using RAPTOR / RAPDENS on ASDEX-Upgrade and TCV

[Bosman F.E.Des. 2021, Blanken F.E.Des. 2019, Felici IAEA 2016]

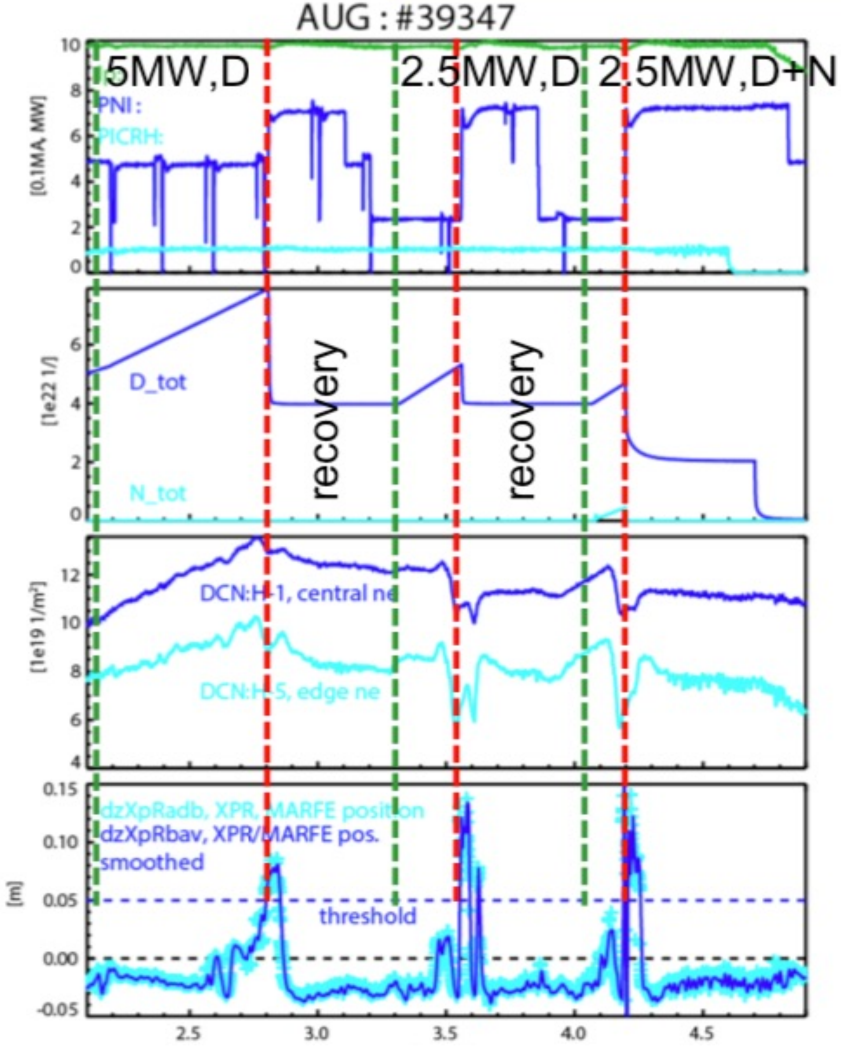
Real-time disruption proximity monitoring and control to avoid high-density H-mode limit

[Pau EPS 2022]

'Virtual actuators' and optimization methods

[Kudlacek Fus. Eng. Des 146 (2019), Maljaars Fus. Eng. Des 122, 2017]

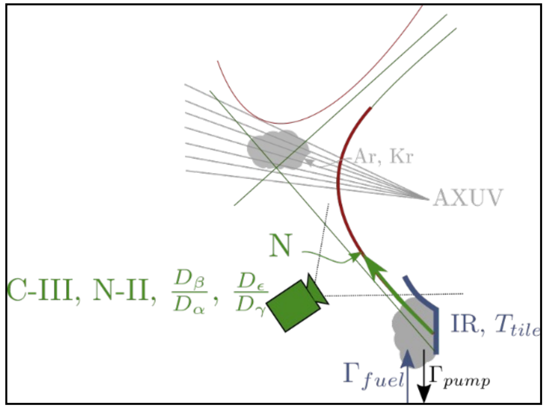
Ex: recovery of discharge in Asdex-Upgrade based on MARFE position monitoring, acting on gas & heating



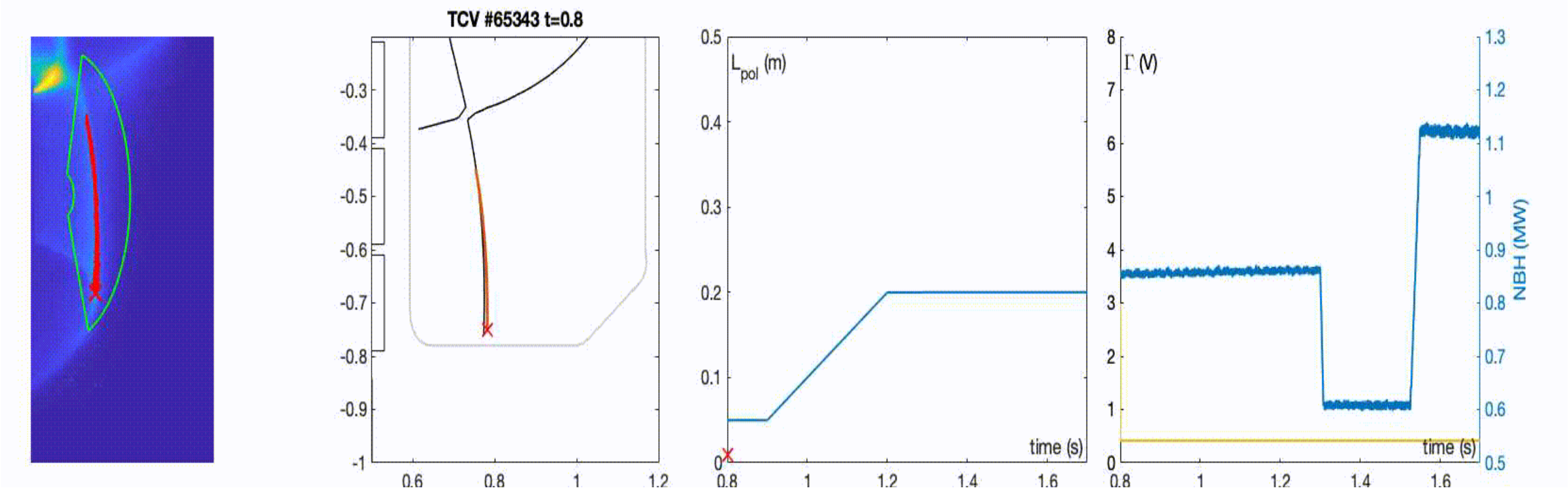
[B. Sieglin, M. Maraschek, M. Bernert - ASDEX Upgrade]

Divertor detachment control

System identification approach applied to characterize dynamic behaviour on Asdex-Upgrade, TCV, JET and MAST-U, using different diagnostics



Ex. real-time feedback control of the C-III emission front in TCV based on MANTIS 10-channel, 400Hz camera



W.A.J. Vijvers *et al* 2017 *JINST* **12** C12058
A. Perek *et al.* Rev. Sci. Instrum. **90** (12) 2019

EUROfusion

The stellarator is the 8th mission of the European Roadmap

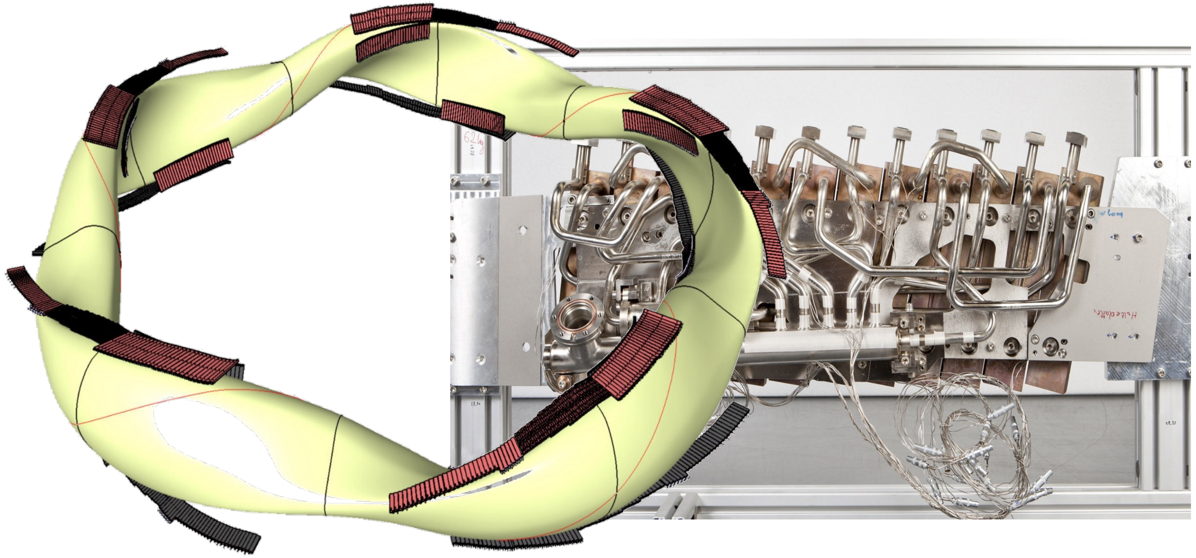
A.J.H. Donné | NIFS | Toki, JA| 15 September 2023

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.

W7-X high energy-turnaround

1.3GJ in plasma on 15.02.2023

All upgrades are commissioned



Spektrum.de

ABO

HEUTE AKTUELL / MEISTGELESEN / NEUERSCHEINUNGEN

Video | 14.03.2023 | Lesedauer ca. 1 Minute

URKNALL, WELTALL UND DAS LEBEN

Neuer Meilenstein in der Fusionsforschung am Stellarator Wendelstein 7

TAGESSPIEGEL

Politik | Berlin | Gesellschaft | Wirtschaft | Kultur

Coronavirus | Archäologie | Hochschulen | Biomedizin | Umwelt und Nat

Wissen | Acht Minuten Leistungsplasma: Versuchsreaktor für Kernfusion erreicht Ener

© dpa/Stefan Sauer

Acht Minuten Leistungsplasma Versuchsreaktor für Kernfusion erreicht Energie-Etappenziel

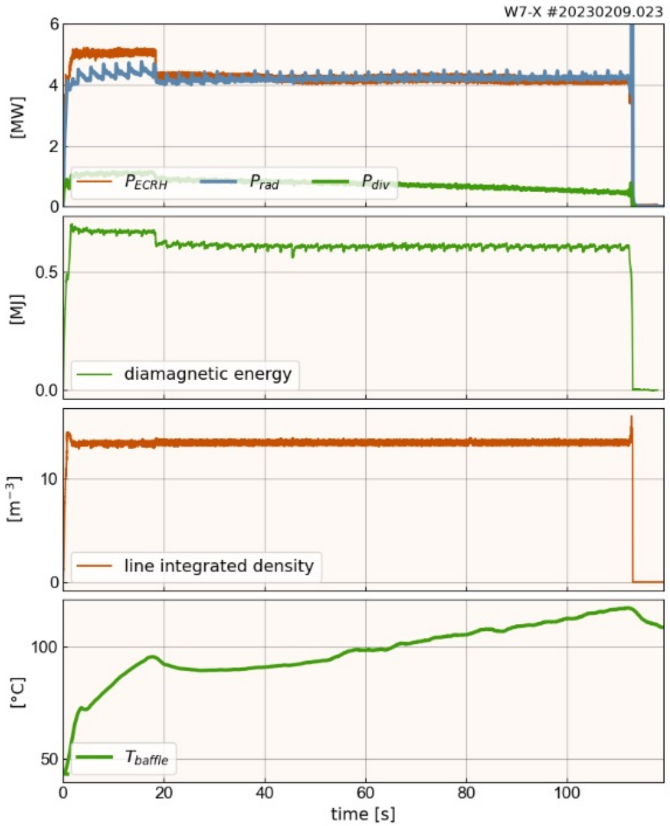
Nach dreijährigen Umbauarbeiten wurden im Greifswalder Kernfusionsexperiment 1,3 Gigajoule Energieumsatz und ein neuer Bestwert für die Entladungszeit erreicht.

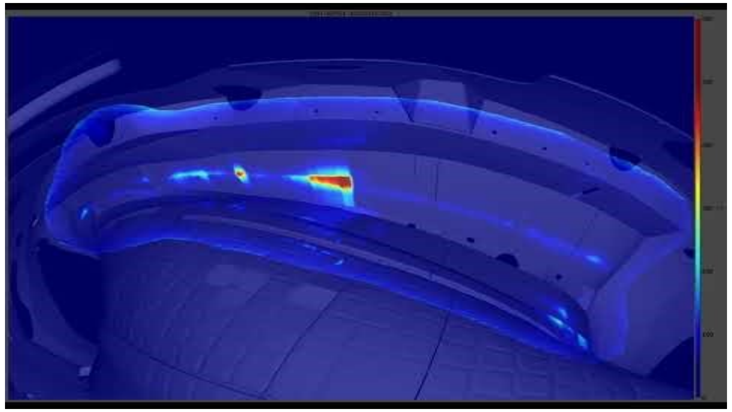
24.02.2023, 15:39 Uhr

3 KOMMENTARE

Im Greifswalder Kernfusionsexperiment Wendelstein 7-X haben die Forschenden einen Energieumsatz von 1,3 Gigajoule erreicht. Das heiße Plasma konnte acht Minuten lang im Versuchsreaktor aufrechterhalten werden – ein neuer Bestwert für die Entladungszeit.

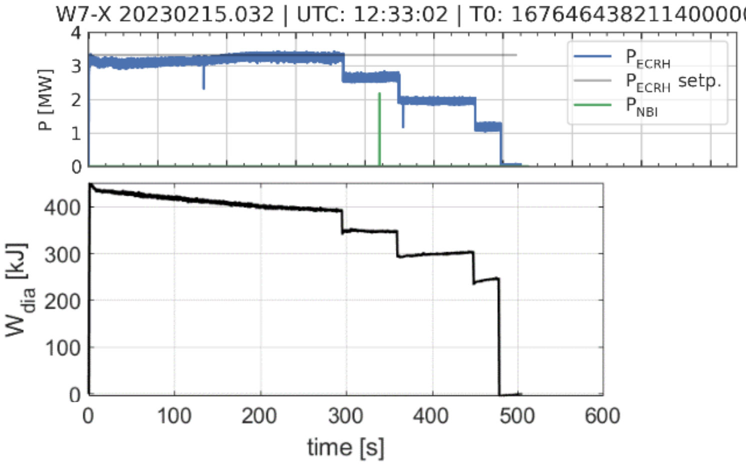
Long detached plasmas
(100s, almost no temperature increase on divertor by series of Ne seeding puffs)





https://youtu.be/GTmje2qsVgY

Progress in long-pulse operation



Waveforms of a 480s attached plasma discharge
($4x10^{19}m^{-3}$, 3MW, T_e~ 2.3keV, T_i~1.5keV)

Large benefit from intnl collab: strong interaction with NIFS

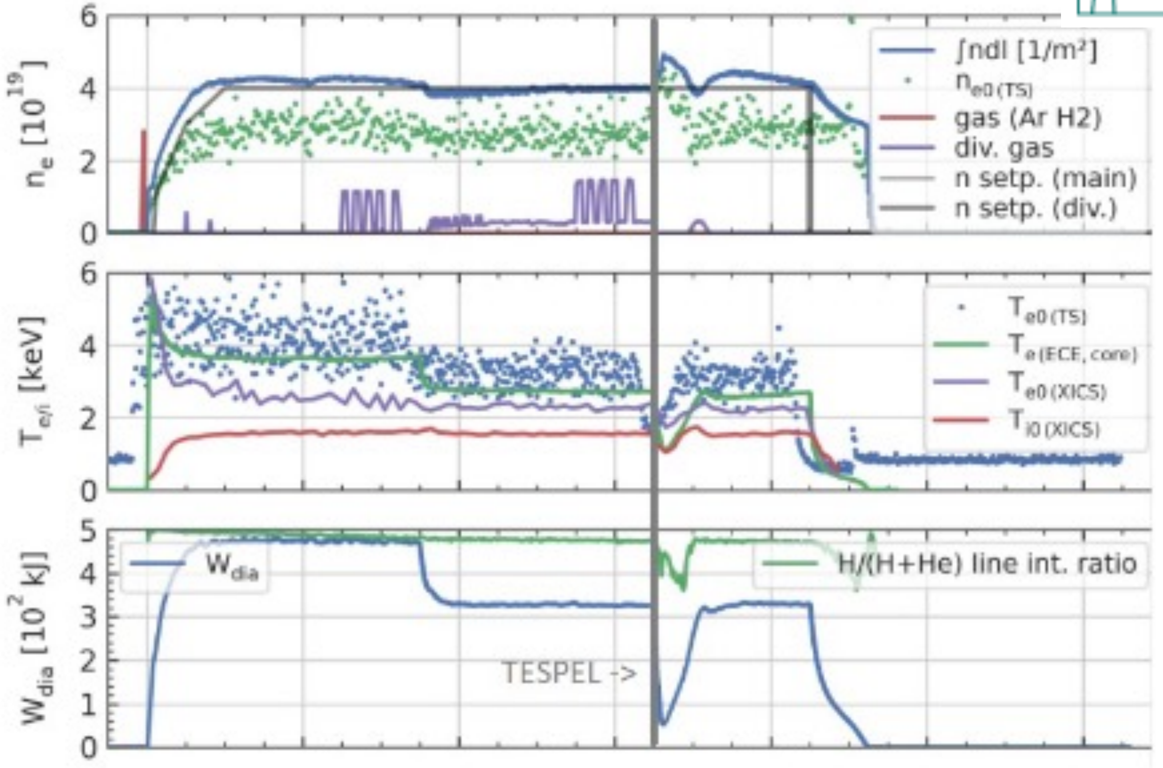
- Dedicated actions for the preparation of W7-X experiments
- Mutual participation in the experimental programs of LHD, W7-X, Heliotron-J and TJ-II
- Synergies within the cooperation framework: IEA TCP Stellarators and Heliotrons since 2003 (CWGM)
- Benefits from joint actions and complementary capabilities

- Examples: FILD detectors, TESPEL, cryogenic pellet injector, pressure gauges, wall conditioning, plasma break-down, joint experiments and contributions to the stellarator/heliotron physics basis

Benefit from mutual program involvement: physics studies employ different accessible magnetic configurations and complementary capabilities

Example: impurity studies

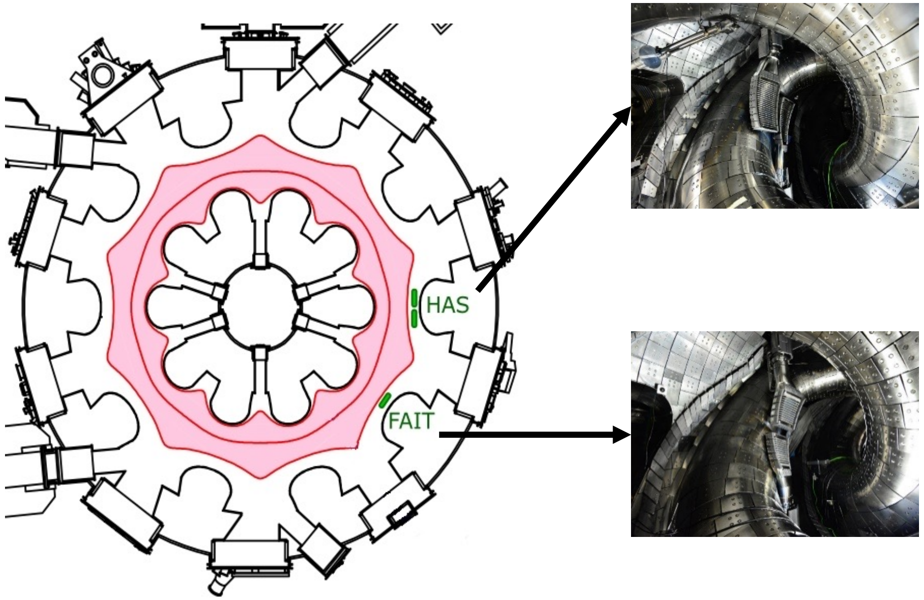
NIFS development
TESPEL laboratory @CIEMAT
Experiments: core impurity injection of large amounts of tungsten
-> inform metallic divertor developments
-> conduct impurity transport experiments

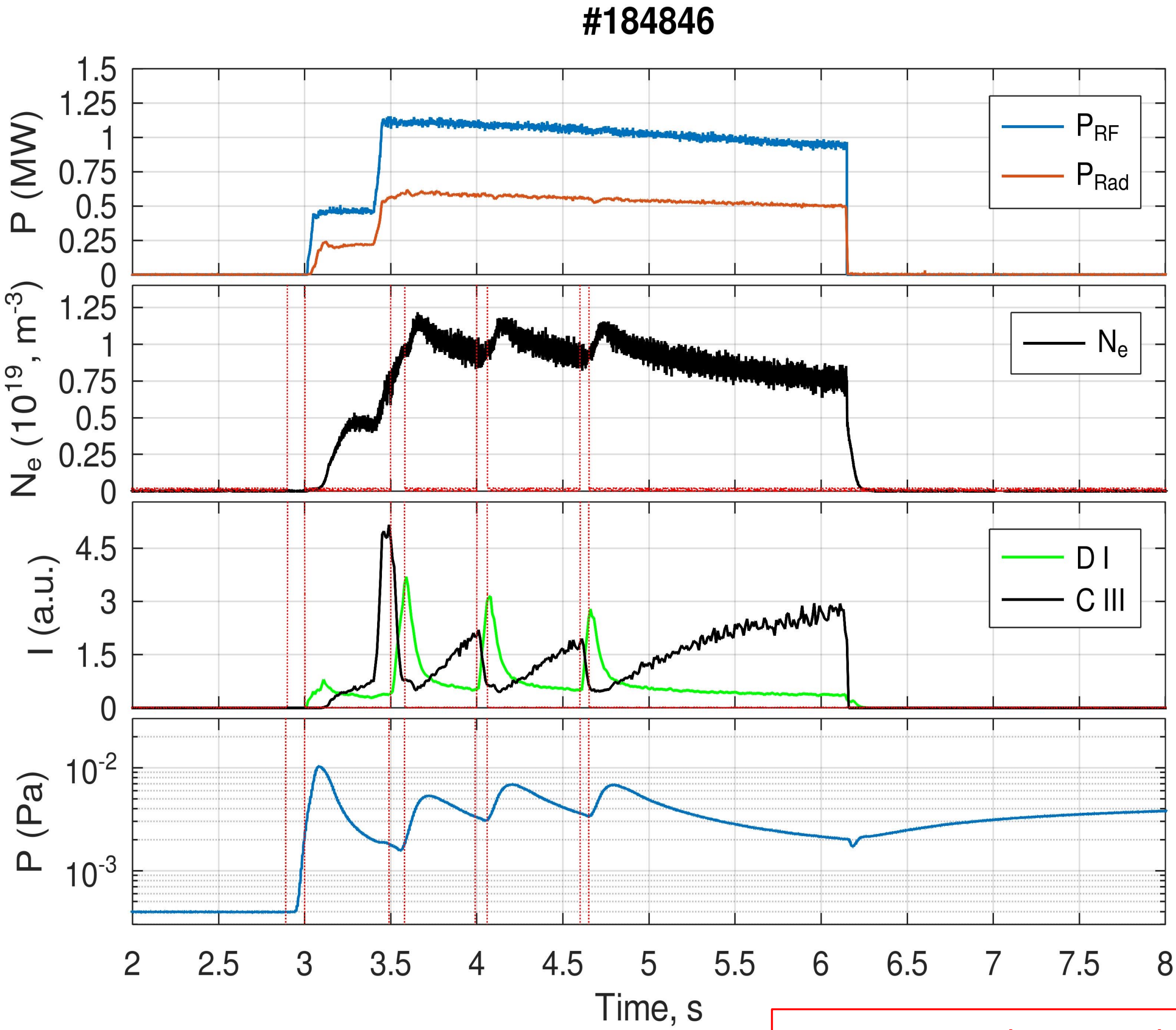


Demonstration of high resilience of stellarators against thermal quenches

Bouvain, Tamura et al., IAEA2023

Scenario preparation for W7-X: Plasma break-down studies

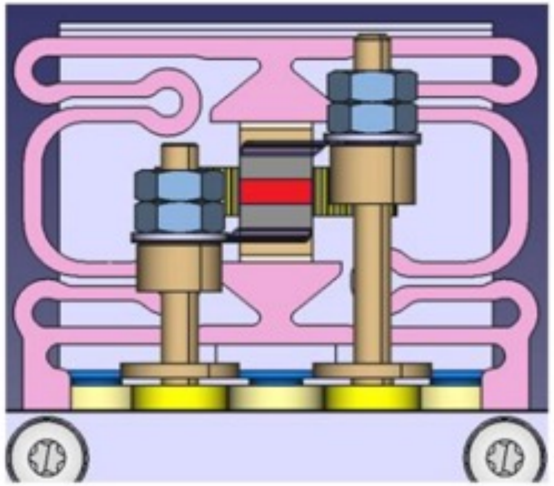


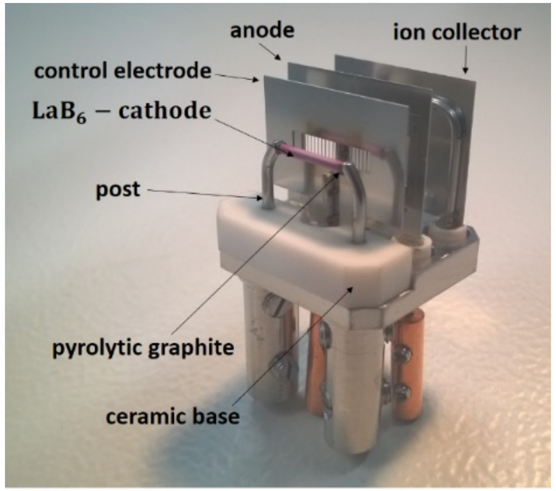


- Preparation of low-B operation in W7-X
- ICRH break-down on W7-X achieved
- Next step: qualification of plasma start-up schemes

Kovtun, Kasahara et.al.

Test of different neutral gas pressure gauges at LHD: ITER support





ITER test pressure gauge using a ZrC-emitter (left) and neutral gas pressure gauge with a LaB6-emitter (right)

Activities at LHD

- Tests of neutral gas pressure gauges with respect to long term stability during plasma operation since campaign 2019/2020
- Investigation of different emitter materials such as LaB_6, W and ZrC
- Development of different designs for neutral gas pressure gauges

Planned activities for campaign 2024

- Operation of ITER test pressure gauge for a second campaign to study long-term behaviour
- Installation of a new neutral gas pressure gauge using either LaB6 or HfC as emitter material
- Visit to LHD for commissioning and calibration of the neutral gas pressure gauges (Victoria Haak, March 2024)

Team

- Gen Motojima (LHD, motojima.gen@nifs.ac.jp)
- Uwe Wenzel (uwe.wenzel@ipp.mpg.de)
- Victoria Haak (IPP, victoria.haak@ipp.mpg.de)

EUROfusion

Towards a new roadmap

A.J.H. Donné | NIFS | Toki, JA| 15 September 2023

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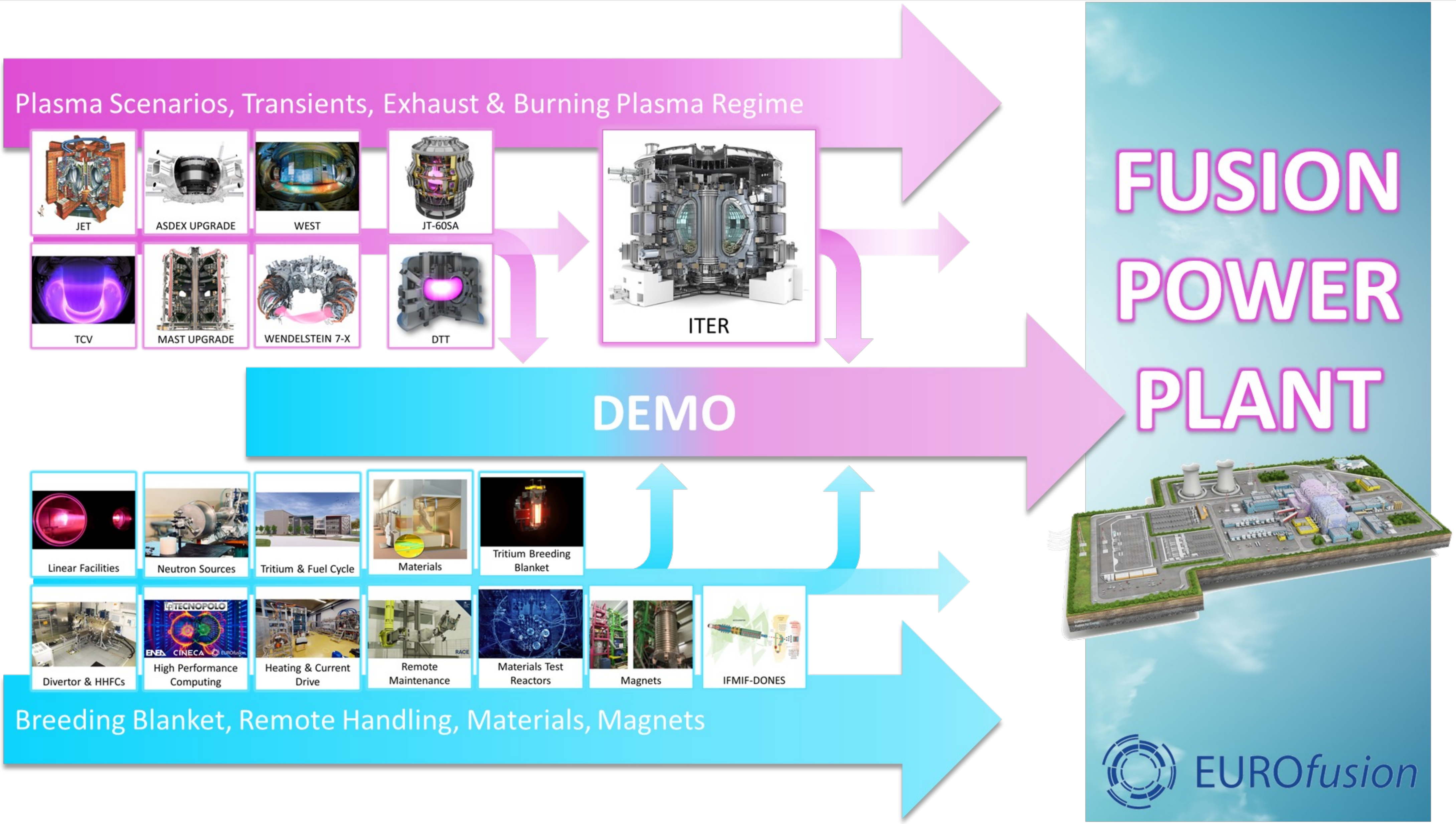
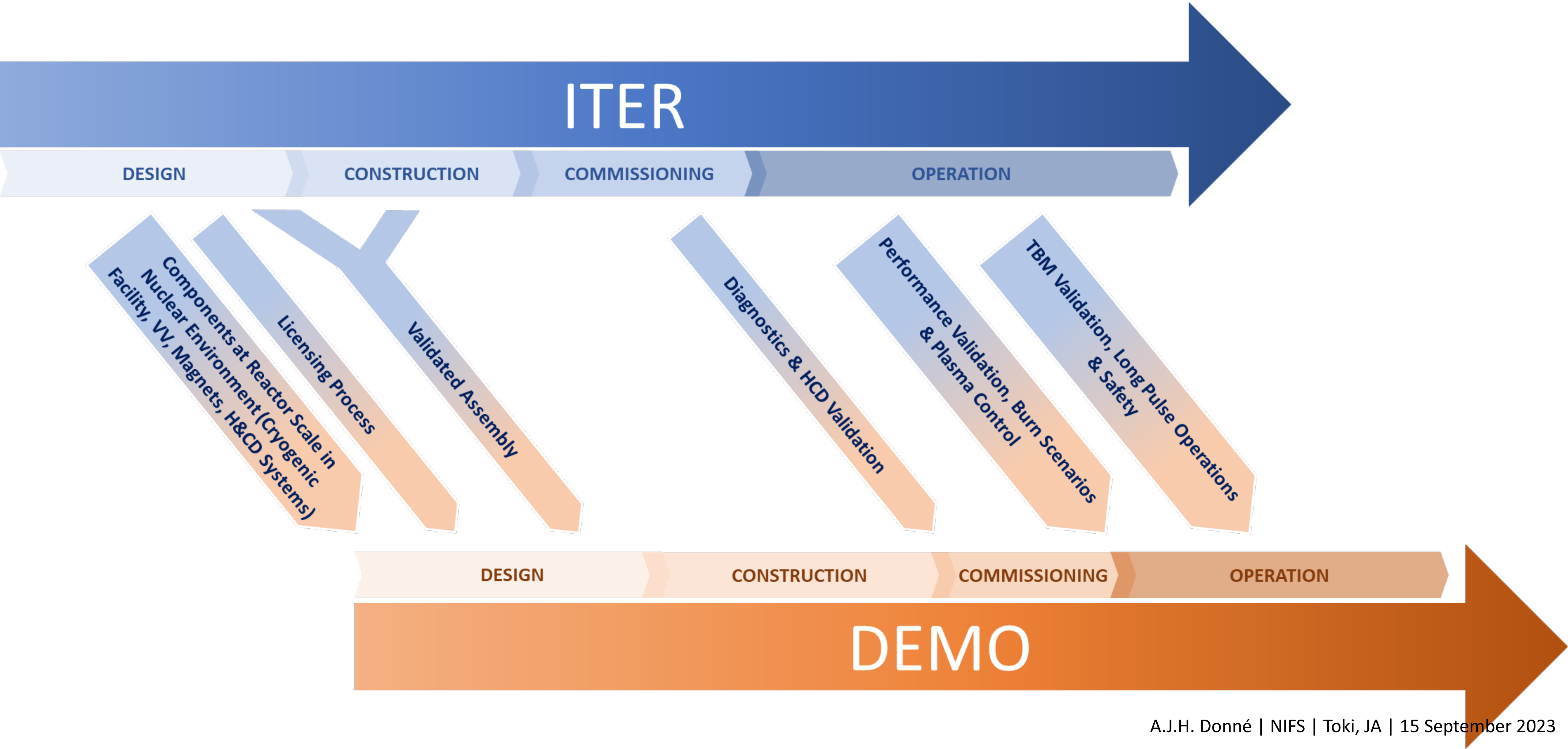
Parallelization of ITER and DEMO



ITER vs. DEMO


ITER
DESIGN
CONSTRUCTION
COMMISSIONING
OPERATION
Components at Reactor Scale in Nuclear Environment (Cryogenic Facility, VV, Magnets, H&CD Systems)
Licensing Process
Validated Assembly
Diagnostics & HCD Validation
Performance Validation, Burn Scenarios & Plasma Control
TBM Validation, Long Pulse Operations & Safety
DESIGN
CONSTRUCTION
COMMISSIONING
OPERATION
DEMO

Public-Private Partnerships

- The key to a swift development of DEMO and FPP is combining industrial and entrepreneurial approaches with the extensive know-how, and the ambitious yet realistic vision of the public-funded European fusion program (including EUROfusion, F4E, the EU Commission, member and associated states)

- DEMO will be built within an industrial framework, utilizing fully industrial practices

- Industrial input is also crucial for a program on technological gaps prior to DEMO design

Conclusions

EUROfusion plays an increasingly important role

- Assist ITER developments and have a crucial role in ITER operation
- Feed increasing demand for education & training
- Allow R&D and exploration of new technologies for ITER, DEMO and FPPs
- Ensure cohesion in the European fusion programme

Strong support for ITER and the present re-baselining

- ITER continues to be an essential element of the European Roadmap

Fusion R&D programme in support of DEMO will be:

- Focused on addressing the remaining technology gaps
- Carried out in parallel to the ITER programme
- Making maximum use of lessons learned from ITER

Public-private-partnerships need to be established to:

- Address and accelerate the long-lead R&D issues (T breeding, materials)
- Take ownership of the DEMO and FPP design


FAIRNESS
Transparency
Collaboration
Loyalty
OPENNESS
Open doors
Open hearts
Open minds
Open ears
COMMITMENT
Ownership
Critical thinking
Determination
Respect
DIVERSITY
Cooperation
Equal opportunities
Inclusion