Integrated Modelling Activities in Support of the ITER Re-Baseline

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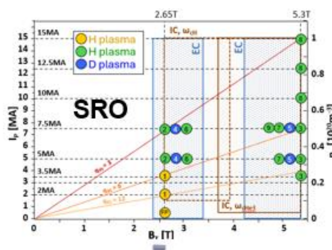
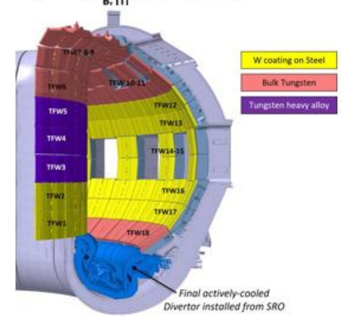
The ITER new baseline

- Change of FW material Beryllium (Be) → Tungsten (W)
  - → New operational phases
    - New staged approach
    - New scenarios
  - → New plant (system) configuration
    - First Wall (FW)
    - Heating and Current Drive (H&CD) mix
    - Boronization system
- How do we make these choices?
  - Observations from current-day experiments
  - Integrated Modelling (IM) activities → the topic of this talk!
- More details in this morning talks:
  - Siwoo Yoon "2024 baseline" 15/10 10:40
  - Alberto Loarte "Be→W in new baseline" 15/10 11:00

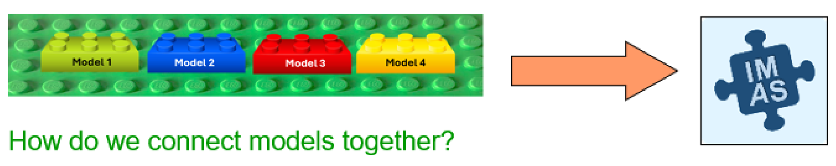




	SRO Start of Research Operation		DT1 Fusion Power Operation 1		DT2 Fusion Power Operation 2
IC-I (~18m)	Inertially cooled FW 27 months H, D plasmas ECH 40 MW ICH 10 MW	IC-II (~10m)	Water-cooled FW 5 x 2 years H, D, DT plasmas ECH 60-67 MW ICH 10-20 MW NBI 33 MW	IC-III (TBD)	Water-cooled FW TBD DT plasmas ECH 60-67 MW ICH 10-20 MW NBI 49.5 MW
	• H-mode in D (5-7.5MA / 2.65T) • L-mode in H at full W_{mag} (15 MA / 5.3T)		• $Q \geq 10$ and $P_{fus} = 500\ MW$ for 300-500s • Neutron budget: $3.5 \cdot 10^{25}$		• Long pulse, steady-state $Q \geq 5$ for 1000-3000s • Neutron budget: $3 \cdot 10^{27}$

Integrated Modelling

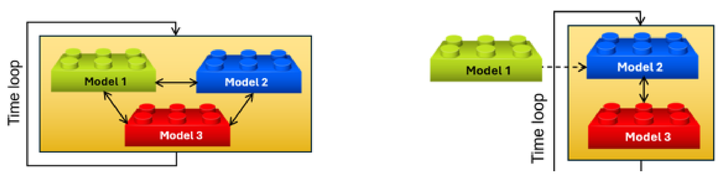
- What is Integrated Modelling?
  Integrated modelling combines multiple models into a single framework
- What is a framework?
  A structured environment (tools, methods, standards) to connect models together



- How do we connect models together?

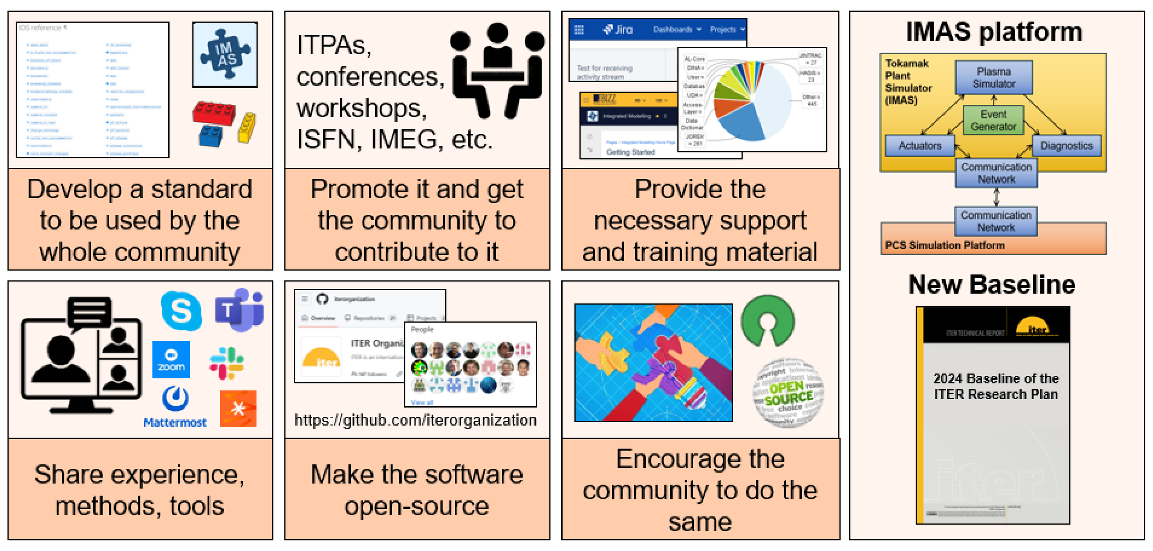
Ideally: by building self-consistent simulation workflows

Until workflows are ready: externally prescribe the result of a model into another one



→ The two routes have been taken to produce the results shown in this presentation.

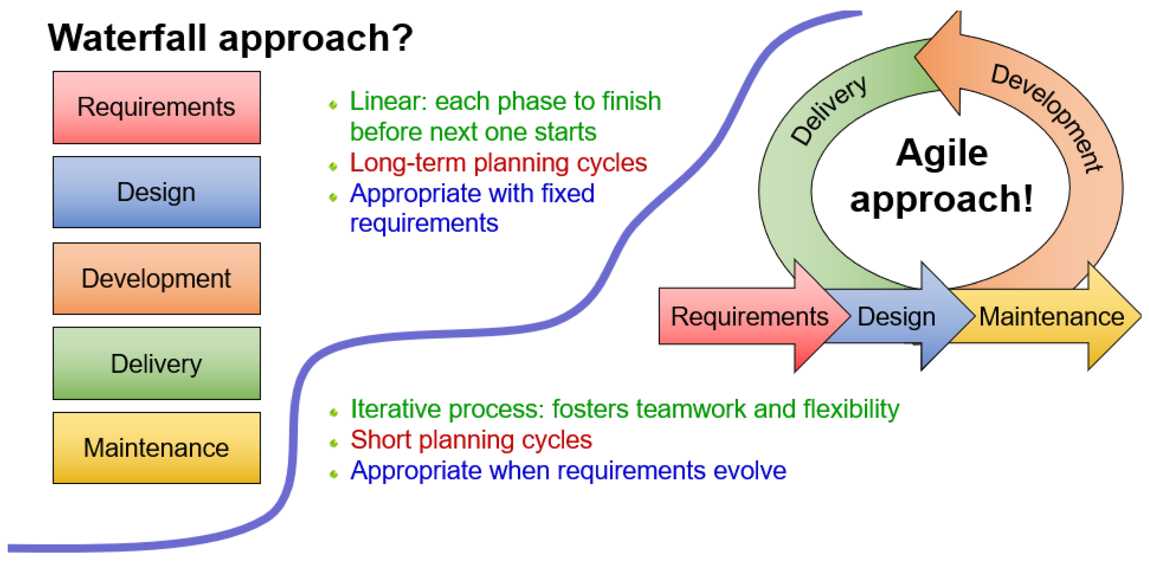
How to best foster collaboration and teamwork?



- Develop a standard to be used by the whole community
- Promote it and get the community to contribute to it
- Provide the necessary support and training material
- Share experience, methods, tools
- Make the software open-source
- Encourage the community to do the same

Developing the ITER Integrated Modelling Platform

Waterfall approach?

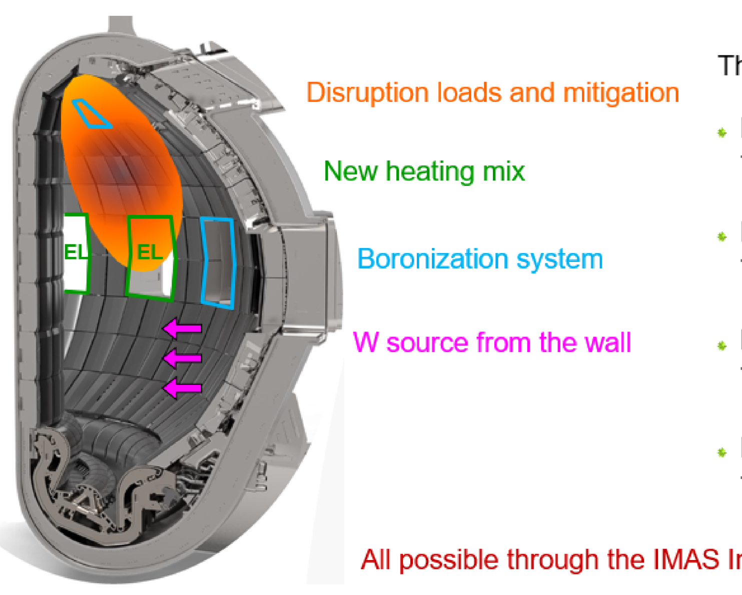


- Linear: each phase to finish before next one starts
- Long-term planning cycles
- Appropriate with fixed requirements

- Iterative process: fosters teamwork and flexibility
- Short planning cycles
- Appropriate when requirements evolve

→ The agile approach is the one adopted to develop the ITER Integrating Modelling platform:
- Users feedback
  → Adapt the tools to the user needs!
- Intermediate results
  → Already help defining the ITER new baseline!

Modelling studies for the new baseline

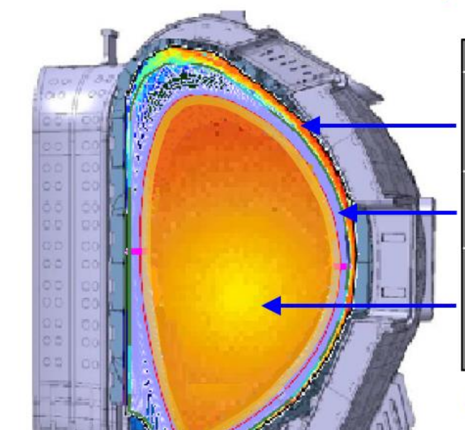


The new baseline implies:
- Extra W source from the wall
  → Modelling of W source & transport
- New Heating and Current Drive mix
  → Modelling impact of H&CD on W
- Boronization system
  → Modelling for optimal configuration
- Disruption mitigation strategy
  → State-of-the-art 2D-3D modelling

All possible through the IMAS Integrated Modelling & Analysis Suite!

Towards self-consistent wall-SOL-edge-core modelling

Goal: to predict full dynamics of temperature, density, rotation and current from the wall to the core



	Source / transport		
Wall	WallDYN2D, WallDYN3D, DIVIMP ERO, ERO2 MEMOS-U, MEMENTO		
SOL/divertor	SOLPS-ITER EMC3-Eirene EDGE2D-Eirene	Transient transport	Runaway Electrons
Core/Pedestal	JETTO-SANCO DINA ASTRA CORSICA METIS	JOREK	DREAM

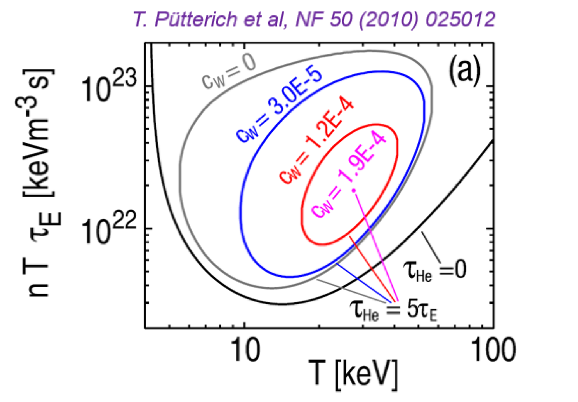
(JINTRAC)

- JINTRAC = JETTO-SANCO+EDGE2D-Eirene
- DINA-JINTRAC: High Fidelity Plasma Simulator (HFPS)
  → ITER workhorse for core-edge integrated modelling!
  S.H. Kim "HFPS" 17/10 14:00

Why is W detrimental for fusion performance?

- Tungsten (W) accumulated in the core significantly increases radiation losses
- Lawson criterion fulfilled when α heating compensates for energy losses → Minimum $nT\tau_E$ for ignition

T. Pütterich et al, NF 50 (2010) 025012



- n = Plasma density
- T = Plasma temperature
- τ_E = Energy confinement time
- τ_{He} = Helium confinement time
- C_w = W concentration

→ The operational space to get plasma ignition is considerably reduced when the W concentration increases.

Tungsten transport

- Which mechanisms lead to W accumulation?
- W particle flux:

$$\Gamma_W = -D_W \nabla n_W + V_W n_W$$

n_W = W density

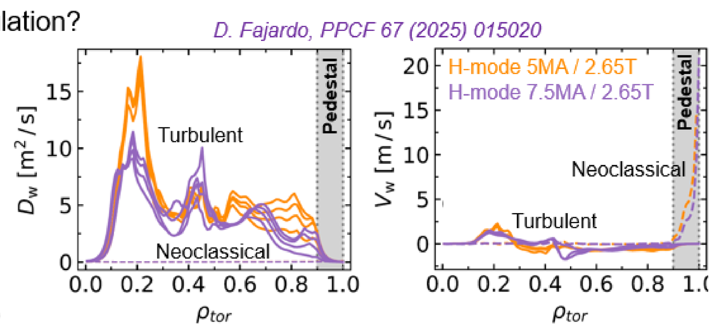
Diffusion: $D_W = D_{turb} + D_{neo}$

Convection: $V_W = V_{turb} + V_{neo}$

→ Neoclassical: induced by collisions

→ Turbulent: induced by microscopic instabilities

D. Fajardo, PPCF 67 (2025) 015020

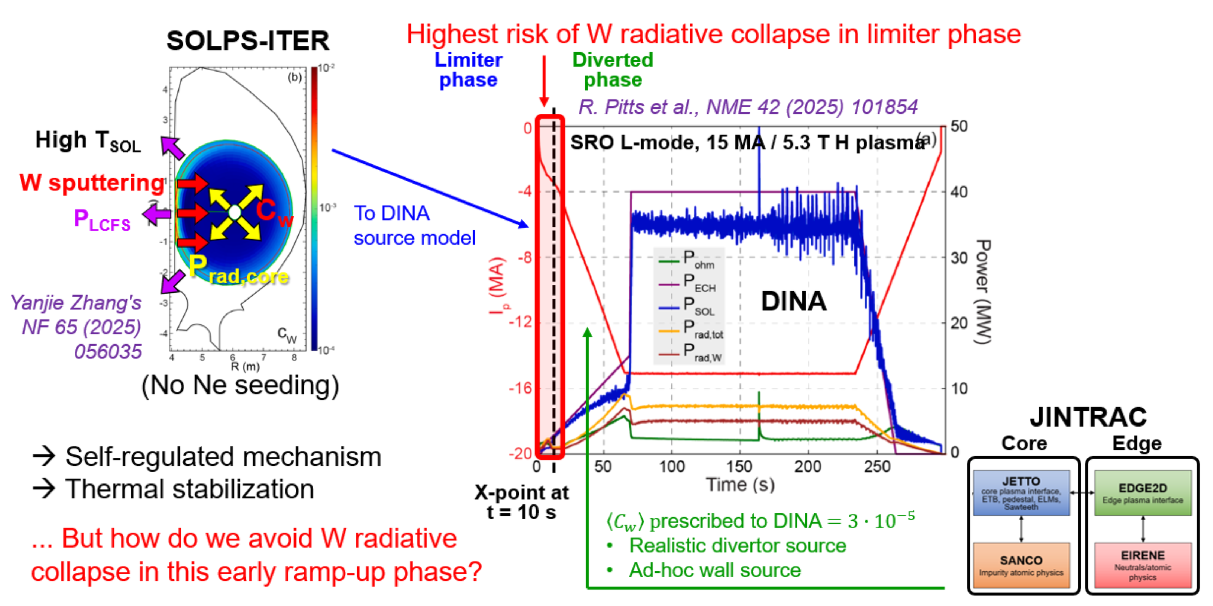


How does tungsten travel to the plasma core?

- Mechanisms leading to W transport:

	SOL	Edge / Pedestal	Core
	Transport assumed turbulent	Competition turbulent / neoclassical	
Today's devices		• $\left\lvert \frac{R}{L_n} \right\rvert > \left\lvert \frac{R}{2L_T} \right\rvert$: dominant inwards neoclassical pinch • Efficient W exhaust with small ELMs	• L-mode: low confinement, high core-edge transport (no barrier), low power → More C_w in H-mode
ITER (+ high T_i JET)		• $\left\lvert \frac{R}{L_n} \right\rvert < \left\lvert \frac{R}{2L_T} \right\rvert$: outwards neoclassical pinch • W screening in H-mode • ELMs induce higher W core accumulation	• L-mode: more neoclassical transport, locally high W radiative losses • H-mode: dominant turbulent transport → More C_w in L-mode

W source and transport in ITER L-mode plasmas



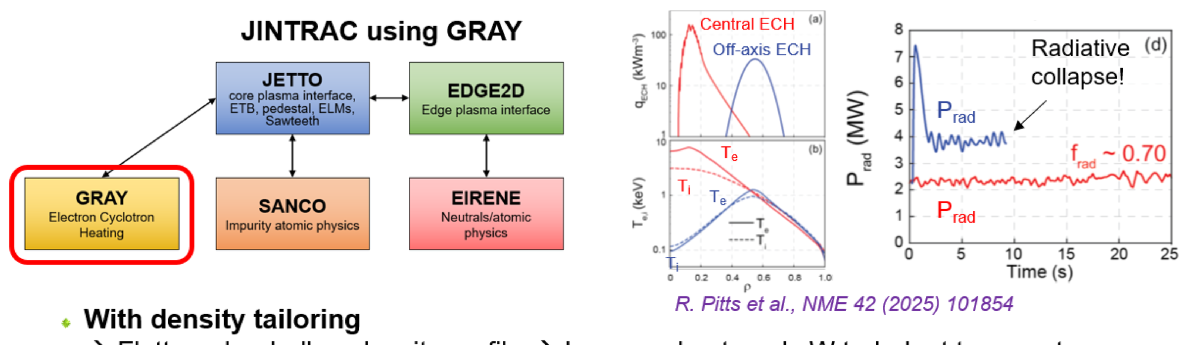
→ Self-regulated mechanism
→ Thermal stabilization

... But how do we avoid W radiative collapse in this early ramp-up phase?

(C_w) prescribed to DINA = $3 \cdot 10^{-5}$
- Realistic divertor source
- Ad-hoc wall source

- **With central ECH**
  → T_e rise → Increased heat turbulent transport → Outwards convective W flux

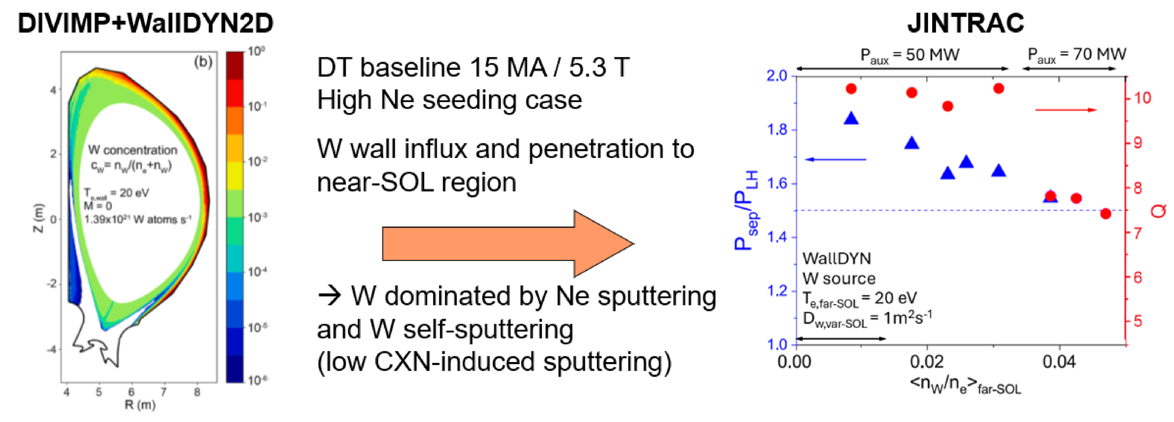
JINTRAC using GRAY



- **With density tailoring**
  → Flattened or hollow density profile → Increased outwards W turbulent transport
- **With Low-Z impurity injection (Neon)**
  → Cool down plasma edge → Reduced W sputtering

W source & transport in ITER ELM-free H-modes

- ELMs to be suppressed for $I_p \geq 7.5\ MA$ to not melt W monoblocks → No ELM in simulations
- Restricted EDGE2D-Eirene grid in JINTRAC → Wall source to be provided externally



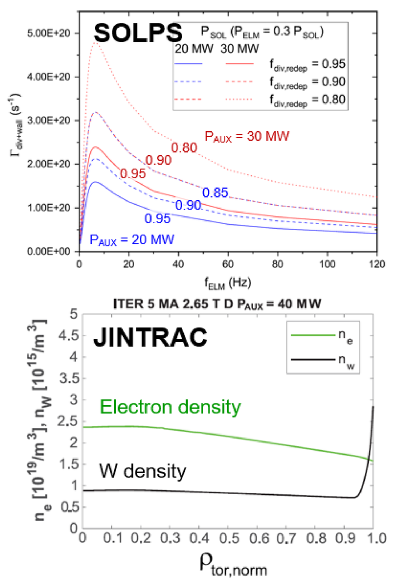
- Confirmed by more self-consistent preliminary results with **SOLPS-ITER + ERO2 + JINTRAC**
- In the future to come: **EMC3-Eirene|SOLEDGE3X + ERO2|WallDYN3D + JINTRAC**

W source & transport in ITER ELMy H-modes

- Integrated modelling of W source and ELM control for SRO H-mode conditions (40 MW ECH): **SOLPS+JINTRAC**
  - W gross divertor source (+ prompt redep.): SOLPS
  - W gross wall source: 10% of divertor source

$$\Gamma_W^{ELM-avg} = \underbrace{(1 - f_{div,redep})\Gamma_{W,div}^{no-redep}}_{\text{Divertor source}} + \underbrace{\frac{\Gamma_{W,div}^{no-redep}}{10}}_{\text{Wall source}}$$

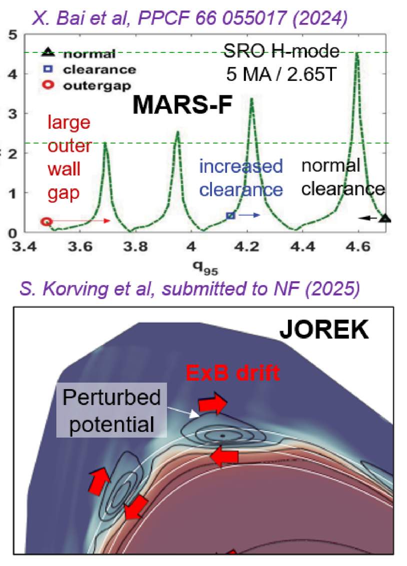
- **ELM-averaged approach** (continuous ELM model for pedestal)
  → H-mode resilient to W influx due to W neoclassical screening and to high core T_{e0} → P_{rad} ~ 25% even for C_W ~ 10^{-4}
- **Full-ELM resolved* approach**: P_{rad} ~ 18% but instantaneous P_{rad} ~15 MW → Robust ELM control needed!
  (*Simplified ELM model; for high fidelity: JOREK)



ELM control strategies

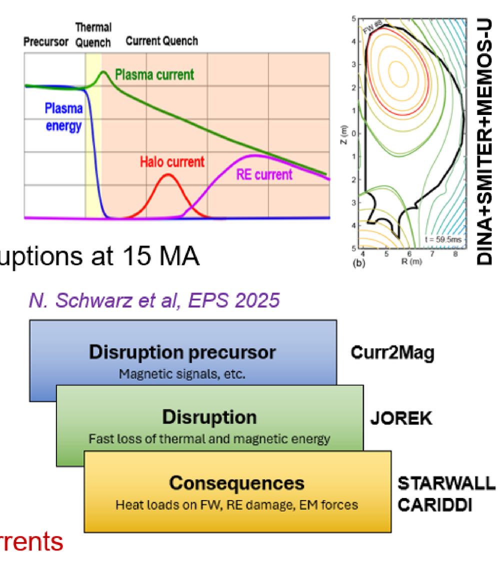
- **ELM pacing**: 27 ELM coils + 4 pellet injectors
  - If inwards W transport and peaked edge W profiles (today's devices) → Efficient W exhaust with ELMS
  - If dominant W screening and hollow edge W profiles (ITER) → Inwards W flux from ELMs
- **Higher wall clearance**:
  - Reduces ELMs but degrades plasma vertical stability
  - → Increase current in VS coils (× 2 in SRO 5 MA/2.65 T)
  - → Adjust plasma shape and n_e (to preserve pedestal)
- **Caveat**: 3D fields affect W edge neoclassical transport:
  - With inwards pinch (today's devices)
    → Enhanced outwards W transport
  - With W edge screening (ITER)
    → Reduced outwards W transport → W core accumulation

→ Balance needed to preserve pedestal with 3D ELM control



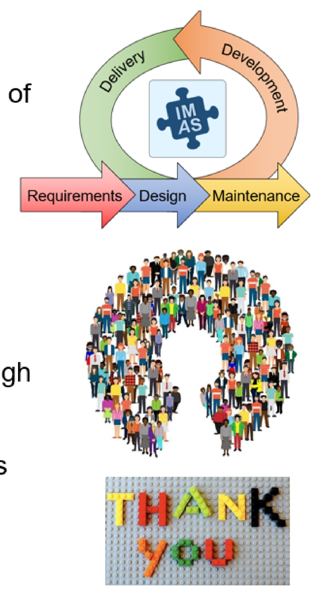
Disruption loads and mitigation

- 2D disruption modelling:
  DINA (scenario) + **SMITER** (power load on FW) + **MEMOS-U** (FW melt motion)
  → Need to direct disruption upwards to preserve divertor
  → **JOREK**: possible with VS coils a few 10ms before TQ
- 3D non-linear MHD modelling:
  JOREK → Marginal W FW melting from unmitigated disruptions at 15 MA
  [J. Artola "Thermal loads during VDE" 18/10 8:30]
- RE damage assessment:
  DINA/JOREK (RE loading) + **Geant4** (RE vol. depos.) + **MEMENTO** (heat transfer to FW)
  → W tiles to be thickened to 12mm in localized areas
- RE mitigation:
  DREAM → SPI of H or Ne can lead to acceptable RE currents except in DT 15 MA plasmas (T β decay and Compton scattering from wall γ's)



Conclusion

- Substantial IM effort to support the new re-baseline
- IMAS tools continuously developed to achieve self-consistent modelling of physics processes from the wall to the plasma core
- Many models & assumptions successfully validated on present experiments to support the ITER new baseline
- Improvements required such as extending models to higher fidelity to refine ITER predictions
  → Requires the involvement of the international fusion community through sharing of state-of-the-art models
  → Facilitated when models publicly available for worldwide contributions by fusion experts
  → Drive for new open-source software campaign launched by IO



IMAS Data Dictionary

IMAS Data Mapping

30th IAEA Fusion Energy Conference (FEC 2025)
16 October 2025
Mireille SCHNEIDER – mireille.schneider@iter.org
"Integrated Modelling Activities in Support of the ITER Re-Baseline", IAEA-TH-C/3415

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