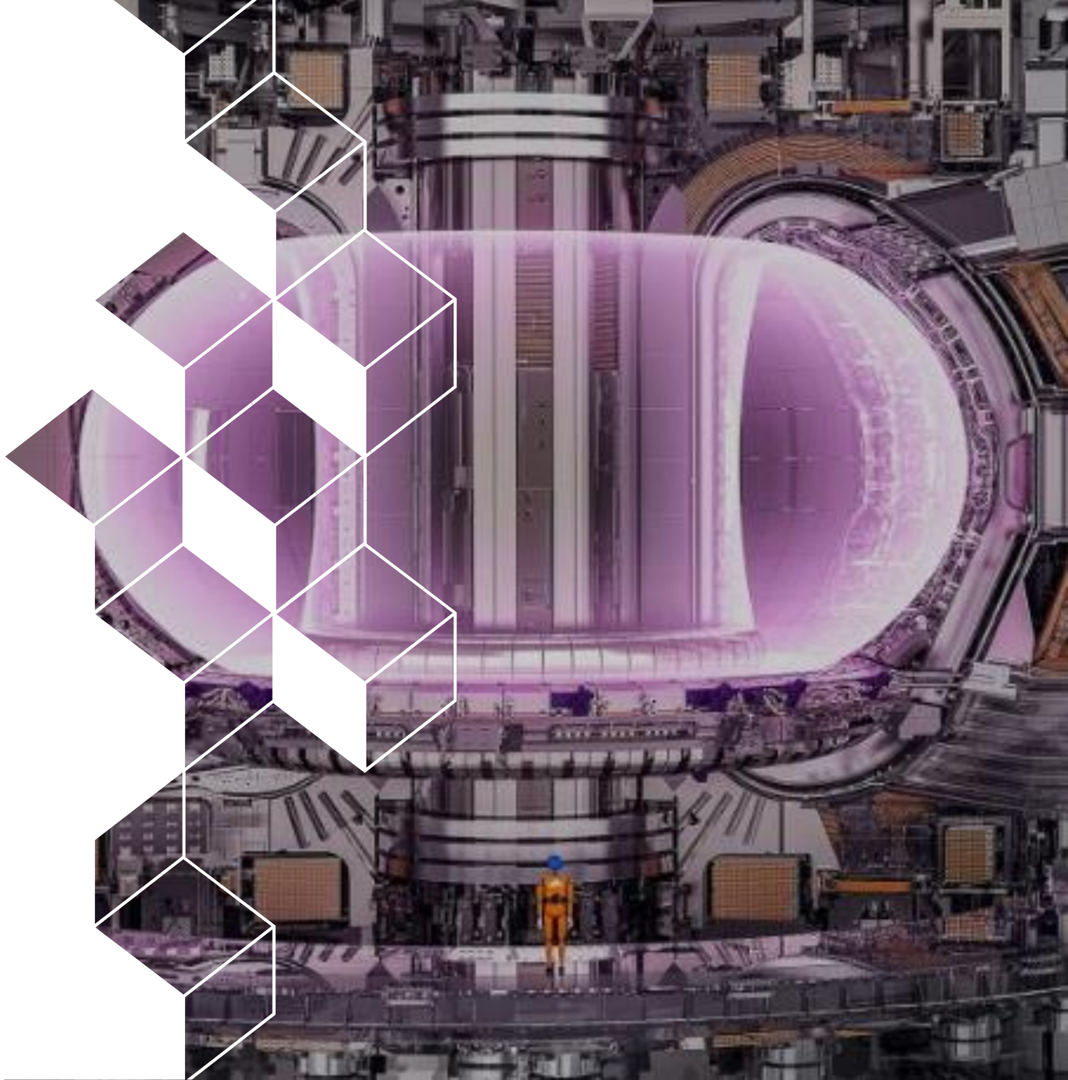
General Introduction to Integrated Modelling

14th ITER International School

Clarisse Bourdelle

30/06/2025, Aix-en-Provence



outline

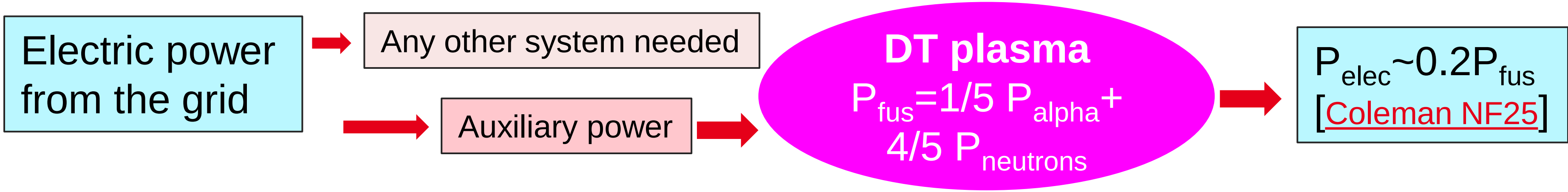
1. General Context for tokamak plasma integrated modelling
2. Integrated modelling in tokamak plasmas: what for?
3. Validation of High Fidelity Integrated Modelling: some (non-exhaustive!) illustrations
4. Perspectives towards ITER operation and DEMO design
5. Conclusions

Aiming at burning DT plasmas

$$ {}^{2}_{1}D + {}^{3}_{1}T \rightarrow {}^{4}_{2}He(3.5\ MeV) + {}^{1}_{0}n(14.1\ MeV) $$

energy freed by fusing 1g of D-T ≡ energy freed by burning 1 ton of coal

DT fusion power: 1/5th on He (called alpha particle) and 4/5th on 14 MeV neutrons



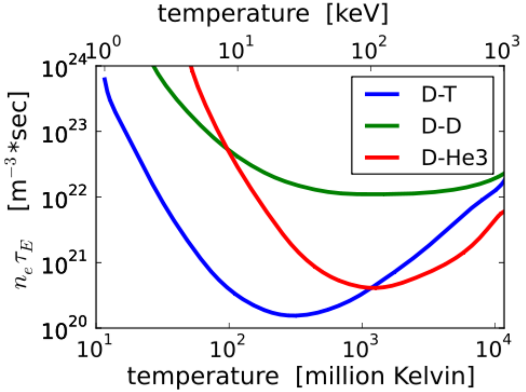
- **Physics interest**: Burning plasma $P_{alpha} > P_{aux}$ if $Q = P_{fus}/P_{aux}$ means Q > 5
- **Net electricity production** possible for Q > ~30 and good availability + plasma /dwell time ratio, T breeding, neutron resilient materials, etc

More on neutrons
A. Khodak

Aiming at burning DT plasmas in tokamaks

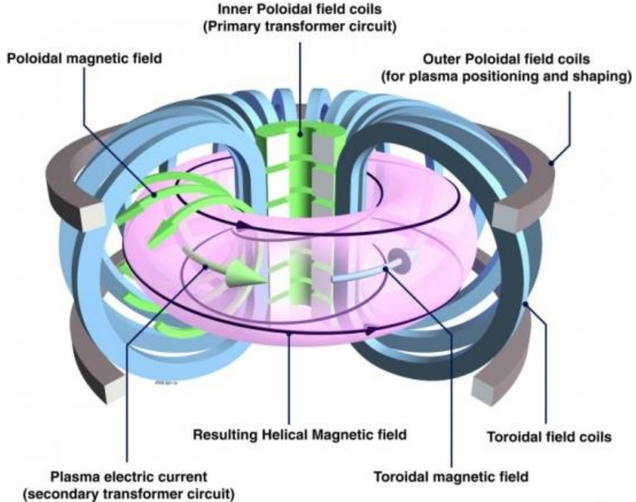
Wanted minimum T ~ 10 keV
and
$$nT\tau_E \geq 3\times 10^{21} keV.s.m^{-3}$$

$$\tau_E = \frac{Plasma\ Energy}{P_{fus}+P_{aux}}$$ in s



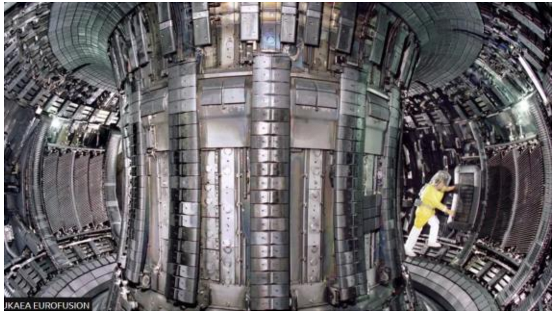
2 strategies:

- large density and short confinement time
  $n{\sim}10^6 \times n_{atmo}$ and $\tau_E{\sim}10ps$
  H bomb, inertial fusion
- low density and long confinement time
  $n{\sim}10^{-5} \times n_{atmo}$ and $\tau_E{\sim}1\ s$



Tokamak: Torus in which plasma of D,T, e confined by helical magnetic field

From today’s tokamaks to ITER: a significant gap



JET
Plasma volume 90 m^3
DT record **P_{fus}=14 MW**
P_{aux} = 35 MW
Q=0.4 during ~5 s
[Kappatou PPCF2025]

WEST
Plasma volume 15 m^3
DD operation, Q N/A
record pulse length > 1000 s (22 min)
[Maget PPCF 2025]

ITER
Plasma volume 800 m^3
DT expected **P_{fus}=500 MW**
P_{aux} = 50 MW, Q = 10 > 300 s
[Eriksson NF2024]

Integrated modelling validation needed to prepare ITER operation

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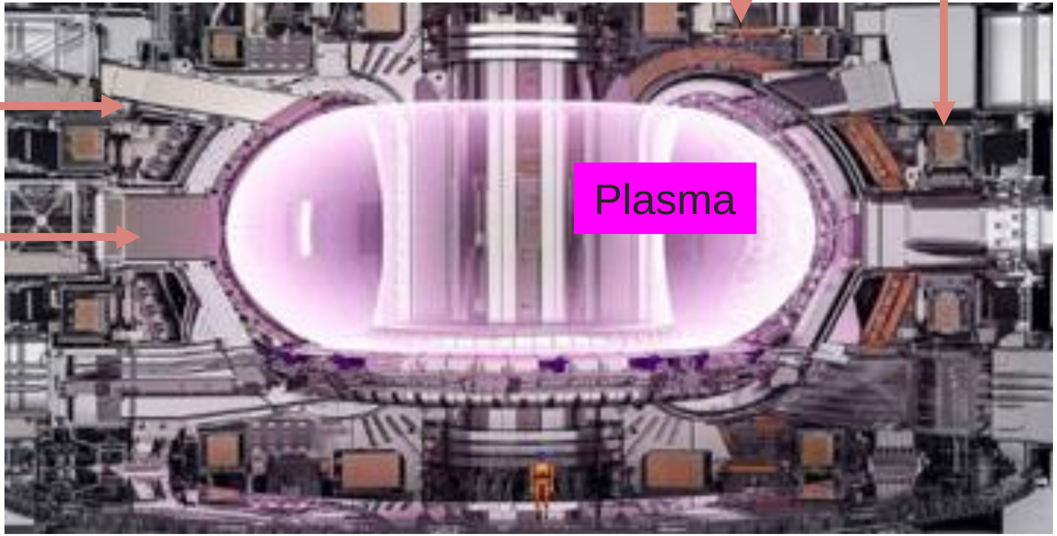
Tokamak plasma surrounded by engineering actuators

Toroidal and poloidal field coils current/voltage

Central Solenoid flux inducing current

Auxillary heating systems

Auxillary fuelling/pumping systems



More on coils/plasma
S. McIntosh

ITER

Understand impact of control room actuators on plasma and vice-versa…

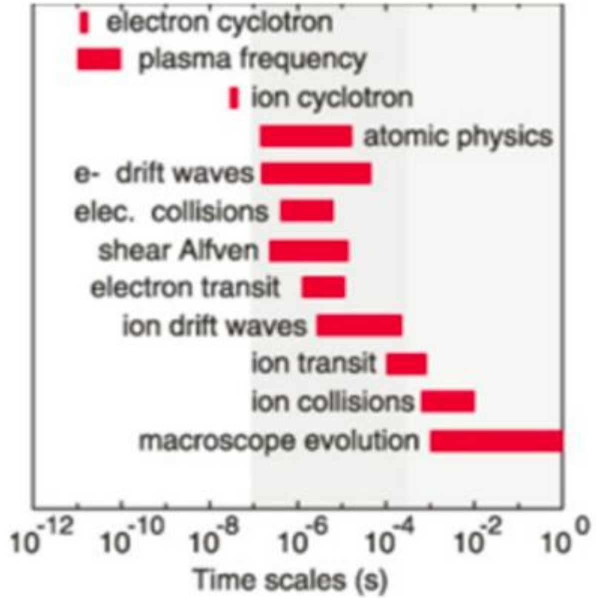
Central Solenoid flux inducing Current

Toroidal and poloidal field Coils current/voltage

Auxillary heating and fuelling systems

WEST control room 12/02/2025 Record pulse length >22 min

Plasma physics
Multiple orders of magnitude in spatiotemporal scales



From control room actuators to plasma response: highly non-linear physics coupling, a (not-exhaustive) illustration

From the control room

+ Wall condition

Acting directly on

Heating waveforms

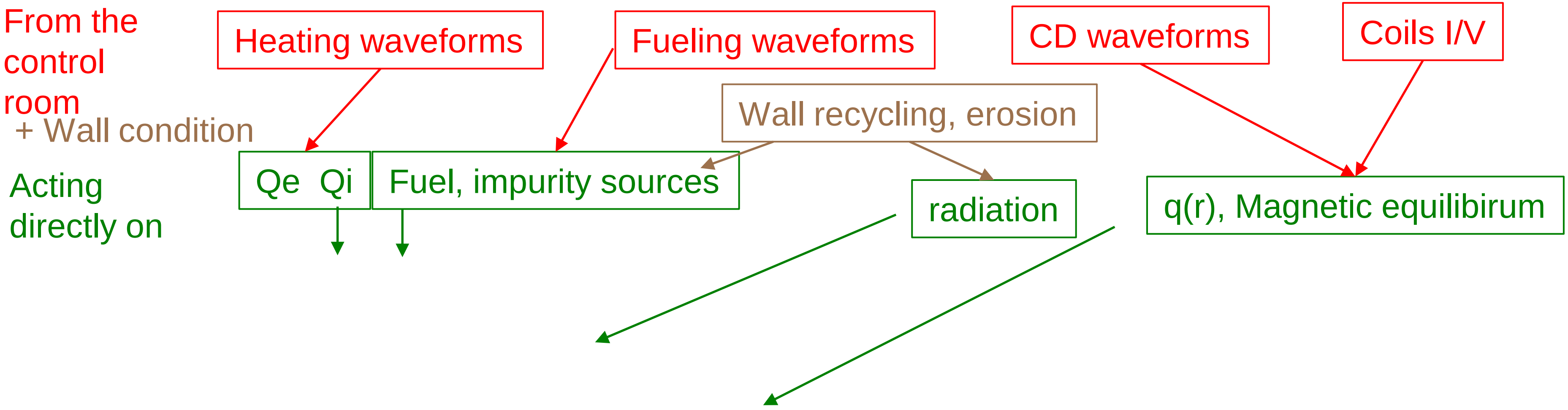
Fueling waveforms

CD waveforms

Coils I/V

Wall recycling, erosion

From control room actuators to plasma response: highly non-linear physics coupling, a (not-exhaustive) illustration



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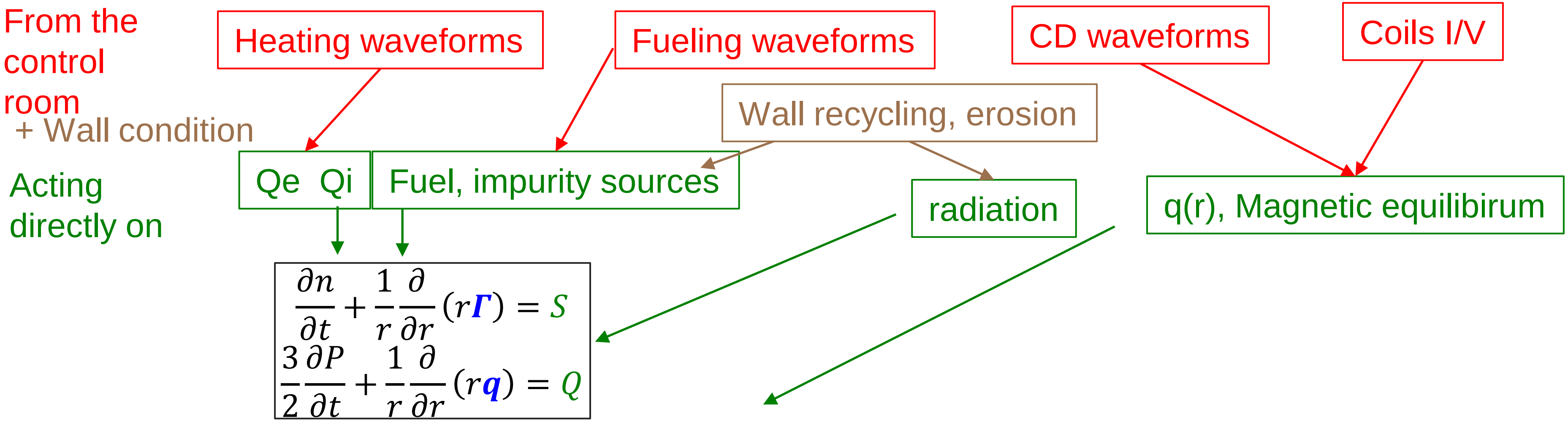


From control room actuators to plasma response: highly non-linear physics coupling, a (not-exhaustive) illustration

From the control room
+ Wall condition

Heating waveforms

Fueling waveforms

CD waveforms

Coils I/V

Wall recycling, erosion

Acting directly on

Qe Qi

Fuel, impurity sources

radiation

q(r), Magnetic equilibirum

$$\frac{\partial n}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\boldsymbol{\Gamma}) = S$$

$$\frac{3}{2}\frac{\partial nT}{\partial t} + \frac{1}{r}\frac{\partial}{\partial r}(r\boldsymbol{q}) = Q$$

Triggering non-linear couplings & feedback

Turbulent fluxes: $T_{eq}(r)$ & $n_{eq}(r)$ coupled

$$\begin{pmatrix} \frac{\Gamma}{n_{eq}} \\ \frac{q}{T_{eq}} \end{pmatrix} = -\begin{bmatrix} D_{nn} & D_{nT} \\ D_{nT} & D_{TT} \end{bmatrix} \cdot \begin{pmatrix} \frac{\nabla n_{eq}}{n_{eq}} \\ \frac{\nabla T_{eq}}{T_{eq}} \end{pmatrix}$$

W collisional convection significant & coupled to $T_{eq}(r)$ & $n_{eq}(r)$

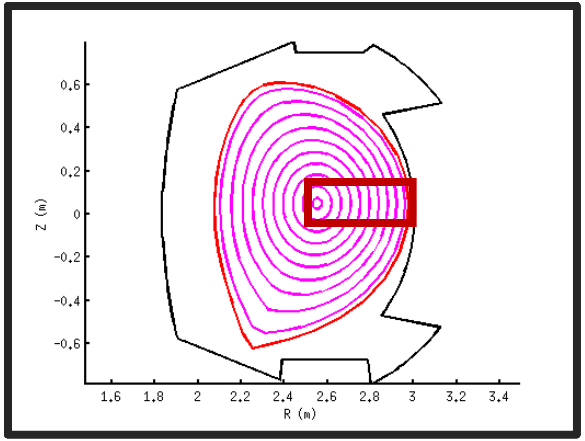
$$\Gamma_W = ZD\left[\frac{1}{Z}\frac{\nabla n_W}{n_W} - \frac{\nabla n_{eq}}{n_{eq}} + H\frac{\nabla T_{eq}}{T_{eq}}\right]$$

η, bootstrap

Integrated modelling frameworks to orchestrate iterations btw physics modules

WEST

Long standing know-how
JETTO Cennacchi G., Taroni A. 1988
ASTRA Pereverzev G.V. et al 1991
CRONOS/METIS Artaud J.F. et al NF 2010 NF 2018
etc [F.M. Poli PoP 2018, C. Bourdelle PPCF 2025]



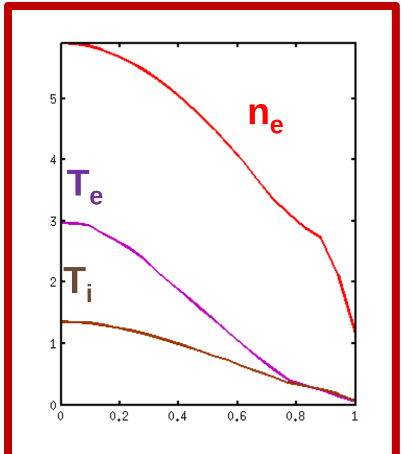
More on heating
A. Fukuyama

Source/sink modules

2D magnetic eq

Initial profiles → transport PDE solver $t \rightarrow t + \Delta t$ → Predicted temp, density, and rotation profiles

Transport fluxes
collisional and turbulent



More on infrastructure
O. Hoenen

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Multiple goals for integrated modelling: steady-state, whole pulse modelling, tests of controllers, inform design of future device

Physics understanding		Prepare operation	Design future devices
1^{st} principle codes	**High Fidelity Integrated Modeling**	**Pulse Design Tools** Full pulse, testing controllers	**System codes** in/out are engineering parameters only

Validation against tokamak experiments

More on pulse design tools
J. Citrin, P. David

Various levels of non-linear couplings, some plasma parameters are evolved some kept fixed : current+heat only with density and momentum fixed, current+heat+particle only, etc,

Various boundary conditions: pedestal top, separatrix, divertor targets

Various model fidelity: empirical scaling, verified reduced physics model etc

More on pedestal physics integration T. Luda
BC at divertor/wall S. Wiesen

More on validation/prediction
J. Garcia

Validation of High Fidelity Integrated Modelling: some (non-exhaustive!) illustrations

On each validation example you will find:

In purple information on: initial, boundary conditions, on predictive vs interpretative quantities.

As well as the **physics question** that was addressed by the modelling.

And the **understanding** gained thanks to non-linear couplings enabled by integrated modelling.

Train your critical eye! as all integrated modelling results are only addressing a time frame of a plasma pulse, a radial zone, and do not evolve all quantities… is the time frame sufficient? the radial zone ? The evolved physics quantities vs the fixed ones?
I am expecting… QUESTIONS!

cea

Maximizing the ion temperature in an electron heated plasma

- Non-linear couplings:

j, T_e & T_i : NN-QuaLiKiz, equipartition, ohmic, P_{rad} **up to ρ=1** (L mode)

- Fixed quantities:

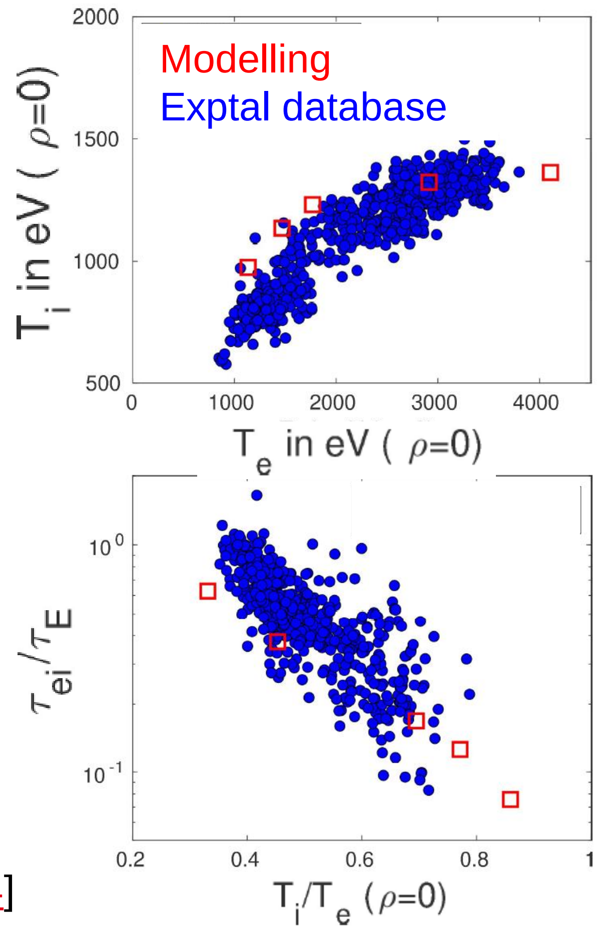
n_e and plasma compo., LHCD source profile shape, separatrix values

Question: how T_i saturation observed in electron heated W7X, AUG, WEST extrapolates towards ITER?

Understanding: if τ_{ei} is longer than the τ_E T_i saturates but in ITER shorter τ_{ei} and longer τ_E, hence higher $T_i(0)/T_e(0)$~0.75

[Manas NF 2024]

WEST



METIS

local nature of the plasma response to 'cold pulses': key interplay T and n

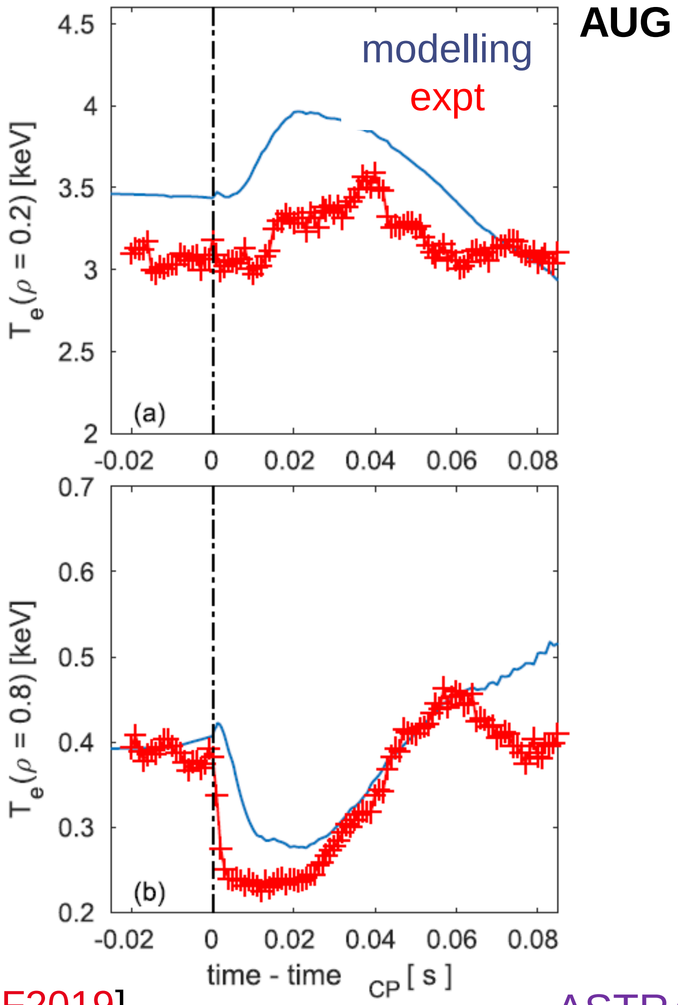
- Non-linear couplings:

j, T_e T_i **& n_D n_C** : TGLFsat1, equip., ohmic, P_{rad}, NBI/ECRH **up to ρ=1**

- Fixed quantities: plasma compo, sep. values

Question: fast increase of central T_e in response to C entry / edge T_e drop, proof of 'non-local' turbulence?

Understanding: C entry, $\frac{\nabla n_{eq}}{n_{eq}}$ reduction in core, reduction of turbulence driven by TEM, T_e core increase. Dynamics of central T_e captured by **local turbulent models** in integrated modelling framework.



[Angioni NF2019]

ASTRA

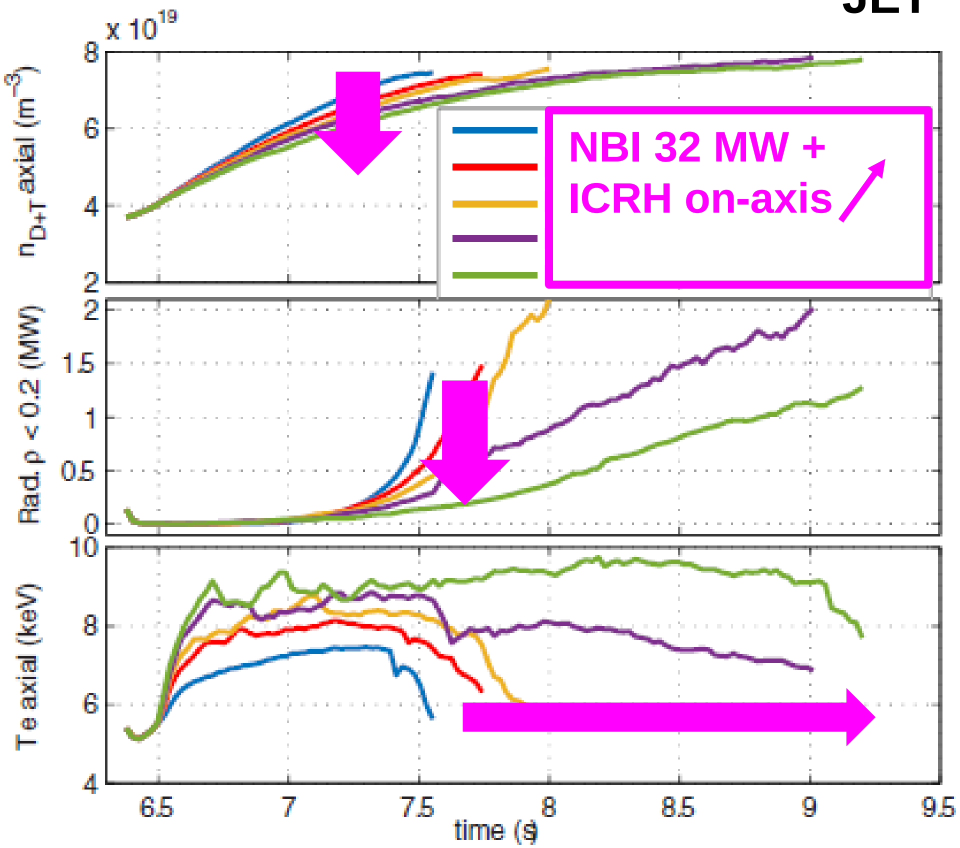
W-accumulation avoidance : role of ICRH vs NBI heating

JET

- **Non-linear couplings:**
j, T_e T_i n_D $\mathbf{n_{Be}}$ $\mathbf{n_{Ni}}$ $\mathbf{n_W}$ $\mathbf{V_{tor}}$: QuaLiKiz, P_{rad}, NBI, ICRH
- Fixed: sep. values, ETB ad-hoc to **match T_{ped}, n_{ped}**. W, Be, Ni total content

Question: actuator to avoid radiative collapse in presence of W in NBI heated pulses

Understanding: enhanced outward turbulent particle transport → flater n_i core profile → reduced W neoclassical inward transport → delayed radiative collapse



[Casson NF 2020]

JETTO

Full radius ohmic Ip ramp-up : better prediction if density self-consistently evolved

TCV

- **Non-linear couplings:**

j, T_e T_i **& n_D n_C** QuaLiKiz / TGLFsat2, equipartition, ohmic, neutrals feedback on nl

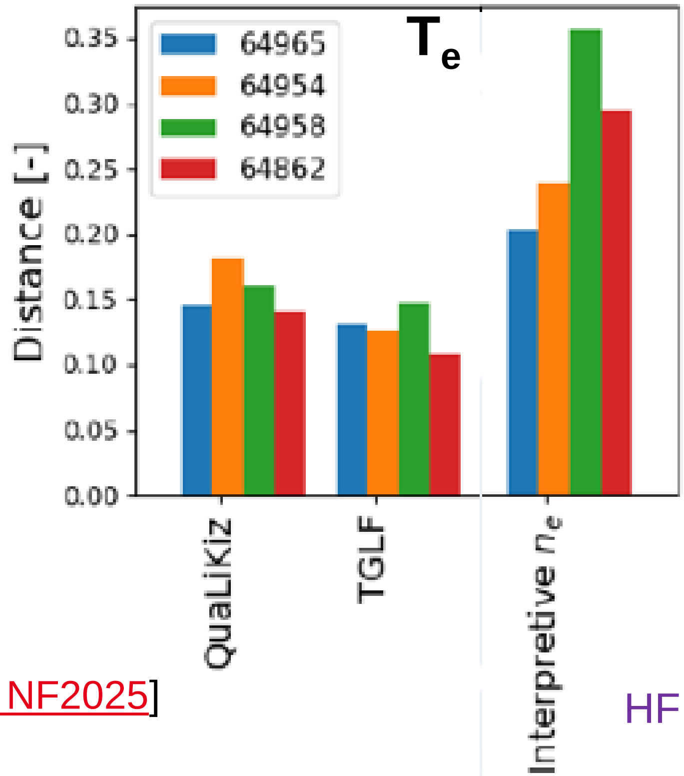
up to ρ=1 I_p ramps 70 to 300 kA

- fixed quantities: sep. values

Question: validity of reduced turbulent models up to LCFS in ramp up? Crucial to prepare operation

Understanding: in C envt, reliable I_p ramp modelling up to ρ=1, predictions better with self-consistent n_D and n_C

Metrics averaged over multiple radii/times $d = \sum_{\rho=sep}^{axis} 2 \left|\frac{d_{fit}^{\rho} - d_{model}^{\rho}}{d_{fit}^{\rho} + d_{model}^{\rho}}\right|$



[M. Marin NF2025]

More on UQ for validation O. Meneghini

HFPS

Large-scale validation thanks to automated extraction, fitting, setup & execution

Metrics on T_e, Ti and n_e

$$M = \sqrt{\frac{1}{6}\left(M^2_{T_e,3} + M^2_{T_i,3} + 4M^2_{n_e,3}\right)}$$

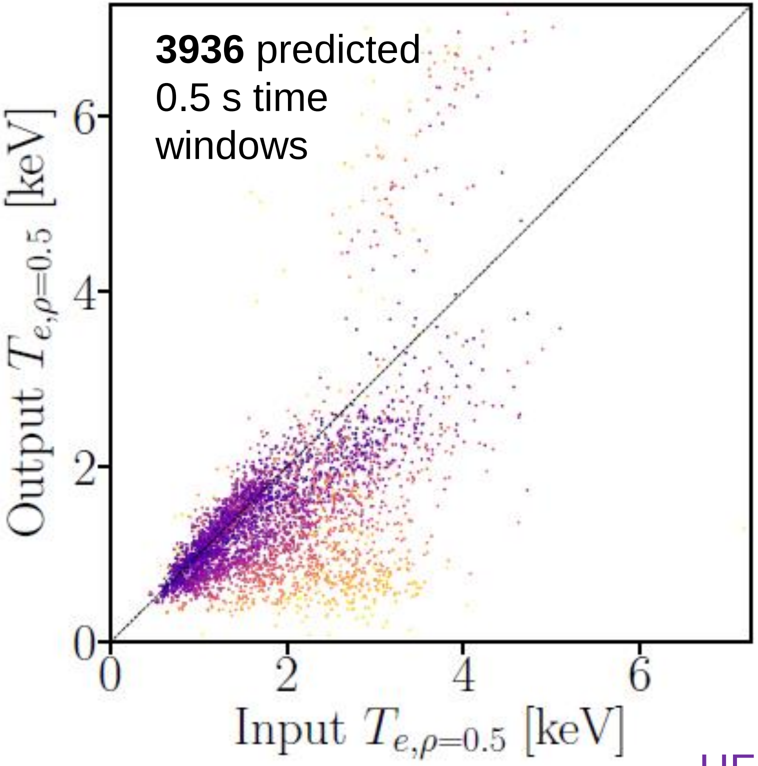
JET

- **Non-linear couplings**: j, T_e T_i n_D NN-QuaLiKiz
- Fixed: from database NBI, Z_{eff}, P_{rad}, exptal measurements at **ρ=0.9**

Question: for which range of parameters model prediction best/worse (NN, QuaLiKiz, TGLF), to guide future model devt needs

Understanding: can we do better than empirical scaling laws? on-going

[A. Ho EPS/TTF 2023, C. Bourdelle PPCF 2025]



More on synthetic diagnostics for validation
A. Medvedeva

HFPS

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Burning plasma: coupling btw profiles and source

$P_{fus} \propto n_{fuel}(0)^2 T_i(0)^2$ **+10% on** $T_i(0)$ **&** $n_{fuel}(0) \rightarrow$ **+40% on** P_{fus}

EU-DEMO A=2.8
[Coleman NF25]

- **Non-linear couplings:**

j, T_e & T_i, T_{ped} scaling, equip., oh., P_{rad} **,** $\mathbf{P_{fus}}$

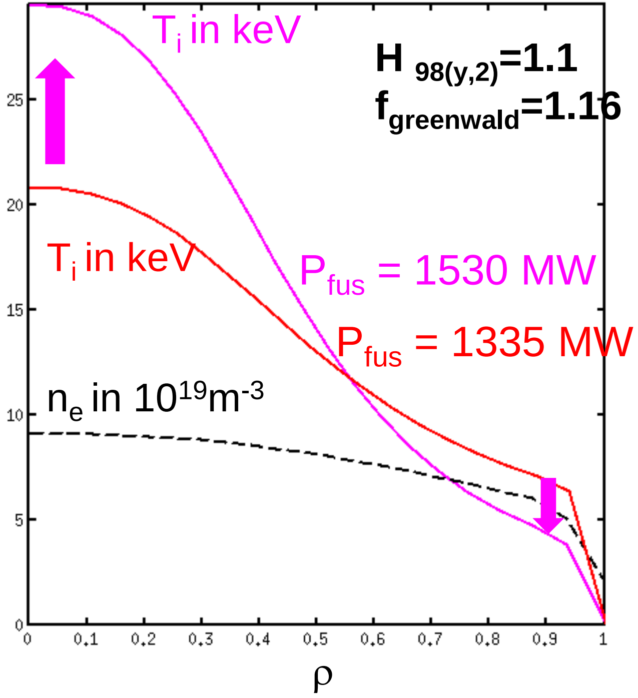
- core: **ad-hoc fixed** χ_{eff} **matching** $\mathbf{H_{98(y,2)}}$
- Ped and sep: scalings

- Fixed: n_e shape, $f_{Greenwald}$, plasma compo., ECRH

Question: can we predict P_{fus} using τ_E scaling laws?

Understanding: Same energy content, but different profiles, hence different P_{fus}. Need physics based turbulent transport models for Q>5 prediction.

[C. Bourdelle PPCF 2025]



More on burning plasma
Ph. Lauber

METIS

Illustration of importance of physics based understanding in burning plasma: impact of β on turbulence (w/o fast particles)

- **Non-linear couplings:**

j, **T_e T_i & n_T n_D**, equip., ohmic, P_{rad}, NBI **, P_{fus}**
- Core, ρ<0.93 **TGLFsat2, different low $k_\theta \rho_s$ settings**
- Ped: n_{ped} pellet feedback P_{ped}: ITER-EPED scaling
- n_{sep} T_{sep}, SOLPS-ITER scaling

- Fixed: plasma composition, ECRH, V_{tor}

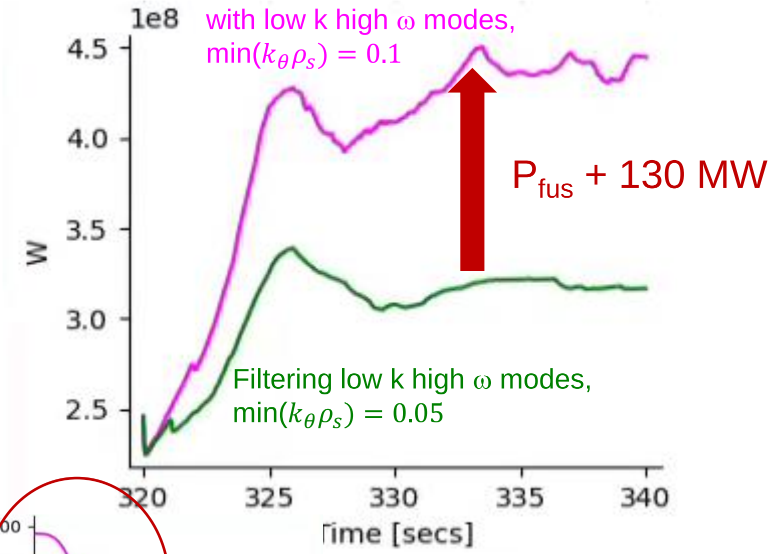
Question: can we predict turbulent transport at high β using physics based reduced el-mag model ?

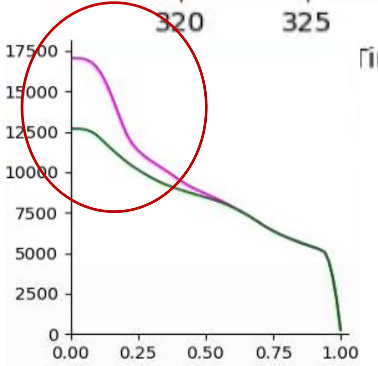
Understanding: Small changes on lowest k modes at high β (KBM) impact profiles ρ>0.6, hence P_{fus} need higher fidelity code verification at high β (on-going)

More on burning plasma Ph. Lauber

[C. Bourdelle PPCF 2025]

ITER 15 MA case





HFPS

How to close the physics gaps? go up the hierarchy of models and improve model reduction

Physics understanding		Prepare (ITER) operation	Design future devices (DEMO)
1st principle codes Turbulent transport SOL, Pedestal MHD Core: High β, fast ion	**High Fidelity Integrated Modeling**	**Pulse Design Tools** Full pulse, testing controllers	**System codes** in/out are engineering parameters only

Validation against tokamak experiments,
including high β (JT60-SA), P_{alpha}>P_{aux} hence **Q>5 experiments (ITER)**

More on high fidelity gyrokinetic
J. Dominski

More on high fidelity MHD
D. Hu

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conclusions

Guidlines for a critical eye on integrated modelling work:

- Which transported quantities, non-linearly iterated, vs fixed quantities?
- Where are the boundary conditions?
- Level of the reduced models used? verified against higher fidelity codes?

Progressing towards full discharge modelling from engineering control room parameters:

- **In today's tokamaks**
  - Successful OH/L mode full radius, incl. I_p ramp up. H mode with some empirical help in pedestal and at separatrix using engineering parameters better than scaling laws
  - To do: extend validation using more surrogate models and more automation, transfer understanding to Pulse Design Tools
- **Towards burning plasmas: even more non-linear** $P_{fus} \propto n_{fuel}(0)^2 T_i(0)^2$ and knowledge gaps to prepare operation/controller: go up the hierarchy to improve model reduction for core transport at high β, Alpha redistribution and Turbulence/MHD interplay, L-H and H-L transition, Pedestal transport, SOL transport of fuel, impurities compression, He ashes

For integrated modelling you need:
Integrated physics codes
Integrated understanding and validation
and an integrated team!

To the EUROfusion integrated modelling team I am coordinating since 2020:

THANK YOU!!

https://wiki.euro-fusion.org/wiki/TSVV-11

[C. Bourdelle PPCF 2025]

Questions?