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Time-dependent integrated modelling overview and DEMO aspects

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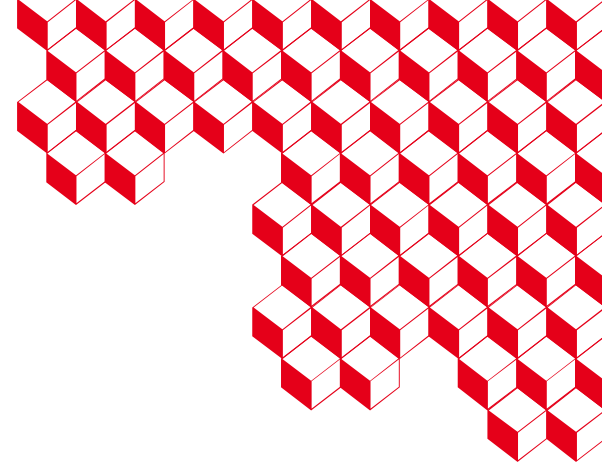
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Time-dependent integrated modelling Overview and DEMO aspects

C. Bourdelle

With input from: C. Angioni, N. Bonanomi, F. Casson, E. Fable, J. Garcia, L. Garzotti, M. Groth, F. Koechl, P. Mantica, P. Manas, P. Maget, M. Siccinio, P. Strand, ...

outline

- **W physics needs and integrated modelling framework availability**
- Validation of dynamical integrated modelling up to the separatrix
- Validation including pedestal and SOL, progresses
- Large scale validation perspectives
- DEMO predictions status, gaps and perspectives

Physics embedded in integrated modelling platform for time evolution of W and its radiation

[C. Angioni] to model W transport/radiation need:

- **neoclassical W transport:**
 - Proper background plasma profile prediction thanks to turbulence models for heat/particle/momentum
 - asymmetry effects due to T anisotropy and rotation
- **turbulent W transport,** especially if low neoclassical transport

This physics is in our integrated modelling platforms, including the self-consistent radiation feedback

	ASTRA	HFPS/JETTO	RAPTOR	ETS*
Background profiles up to ped top	TGLFsat2, QuaLiKiz	TGLFsat2, QuaLiKiz	QLKNN	TGLFsat2, QuaLiKiz
Ped profiles	IMEP (ad-hoc heat ped transport + MISHKA)	Europed, MISHKA stability, scalings	none	PENN
W neoclassical transport	NCLASS For asymmetry: NEO, FACIT	NCLASS For asymmetry: NEO, <i>FACIT</i>	none	<i>NCLASS For asymmetry: NEO</i>
W turbulent transport	TGLFsat2, QuaLiKiz	TGLFsat2, QuaLiKiz	none	<i>TGLFsat2 EDWM</i>
W radiation	STRAHL	SANCO	ADAS	<i>AMNS based</i>

* ETS not used yet with W transport/rad.

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Time-dependent flux driven integrated modelling over multiple confinement times: highly nonlinear coupling

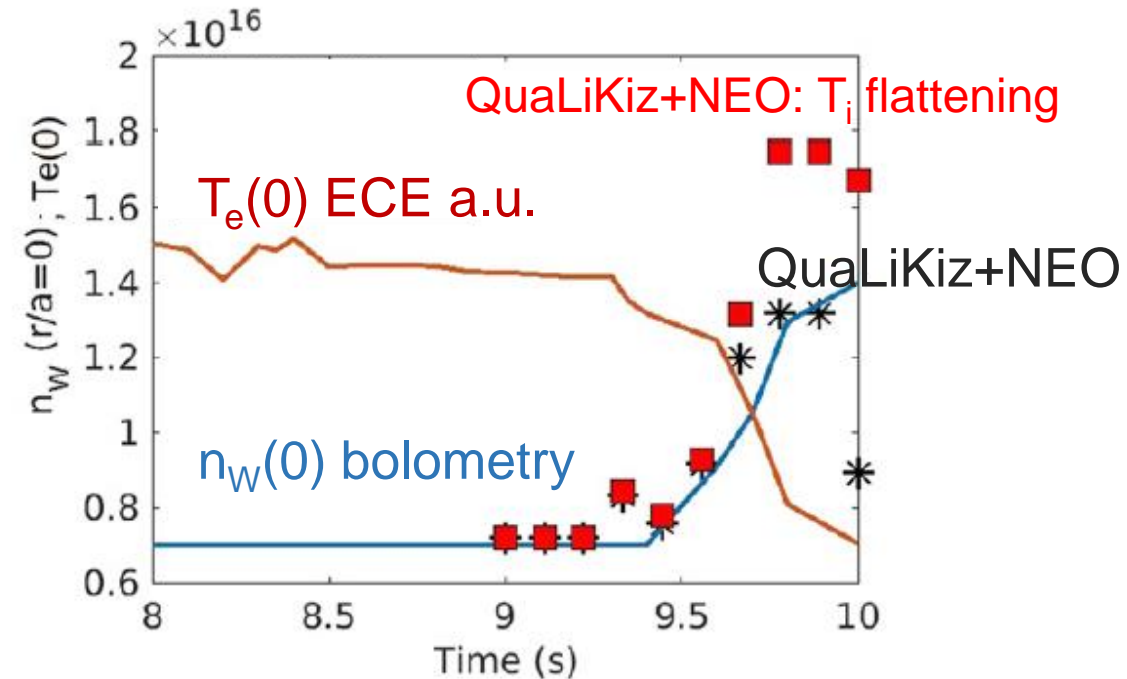
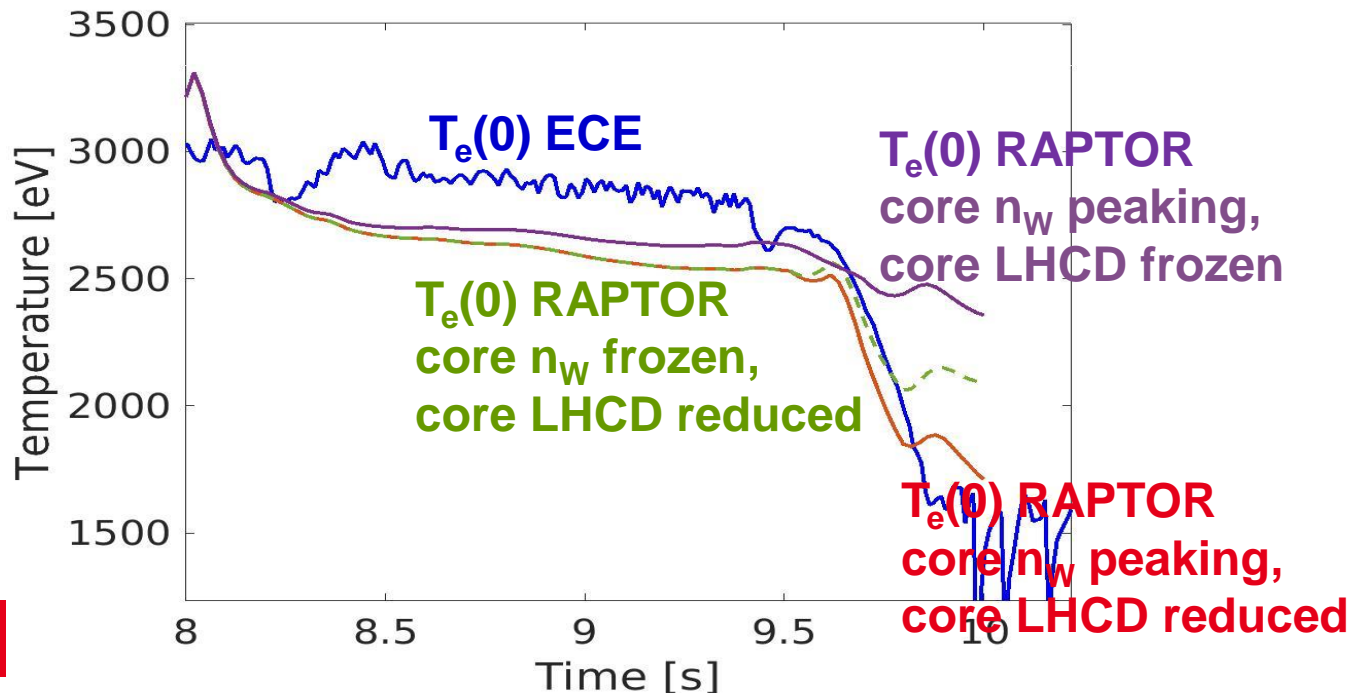
- **Level 1: j, T_i, T_e**
 - Forgiving: transport driven by temp. gradients and is “stiff”
 - Always predict T_i and T_e profiles otherwise turbulence amplitude wrong
- **Level 2: j, T_i, T_e, n_e**
 - Non-trivial: particle transport not stiff (off-diagonal transport)
 - Depends sensitively on turb. spectra, collisions, kinetic resonances
- **Level 3: $j, T_i, T_e, n_e, V_{tor}$**
 - Challenging: momentum transport from symmetry breaking
 - Feedback potential for barrier formation (ExB shear)
- **Level 4 : j, T_i, T_e, n_e, n_i multi-ion (isotopes, impurities), V_{tor}**
 - Exciting territory, complex non-linear interplays
 - Heavy Impurity transport needs all L3 channels (sets neoclassical transport and poloidal asymmetries), and provides radiation feedback
- **Level ++ : j, T_i, T_e, n_e, n_i multi-ion (isotopes, impurities), V_{tor} in burning plasmas**
where $P_{alpha} > P_{aux}$ ($Q > 5$), background profiles impact P_{alpha} accounting for EP-MHD, Alpha redistribution and impact EP/ β on turbulent transport

Level 1. WEST L mode radiative collapse due to large density LHCD off axis → T_i peaking reduction → increasing W inward neoclassical flux

RAPTOR-QLKNN-ADAS

T_e , T_i , j Predictive up to separatrix

Mixed with stand-alone W profile evolution checked against NEO+QuaLiKiz predictions using measured background profiles

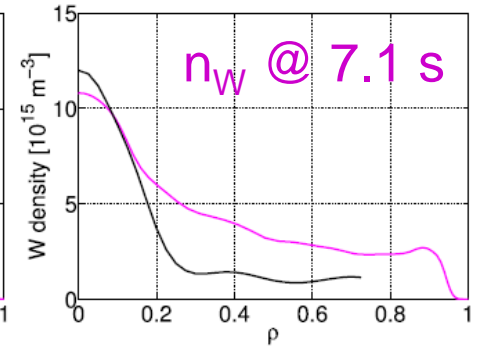
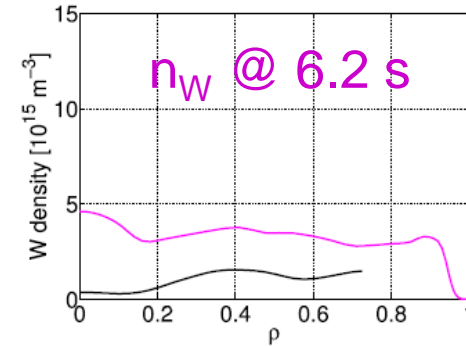
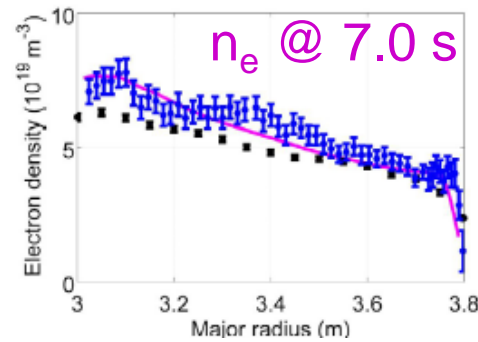
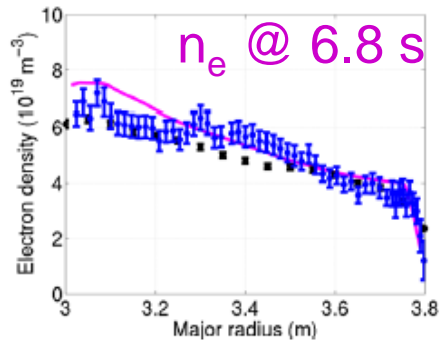
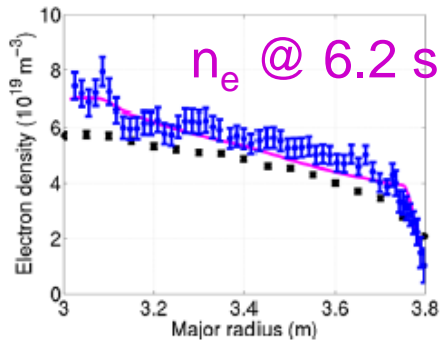


Need both W peaking and decrease of the central LHCD absorption to capture the radiative collapse

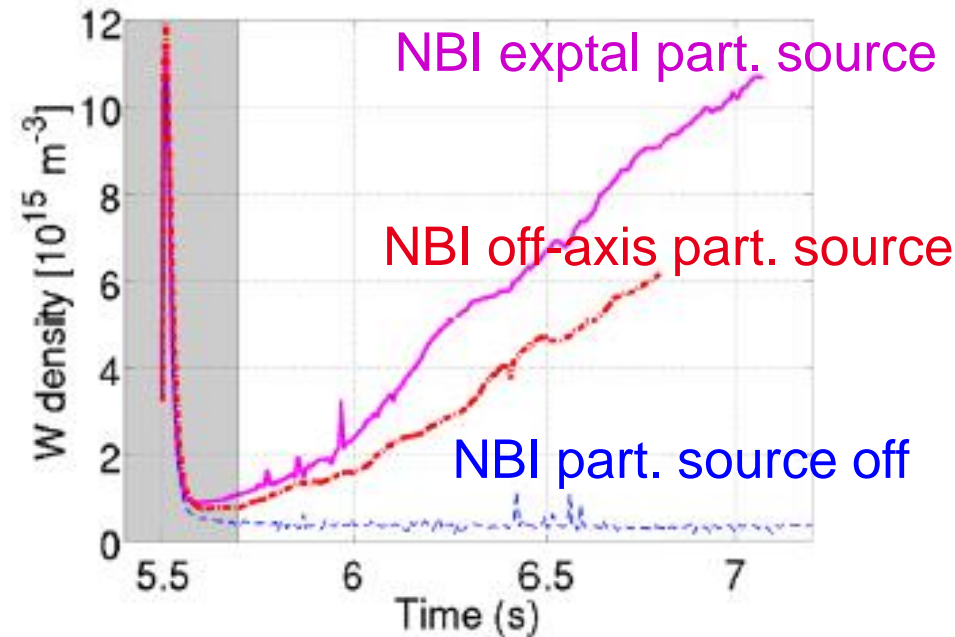
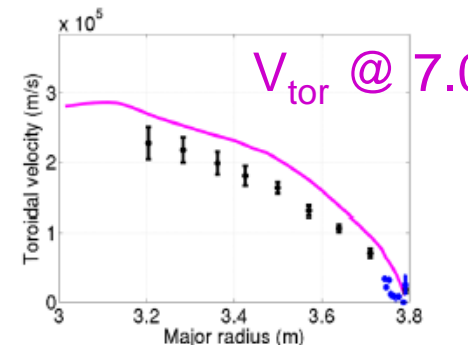
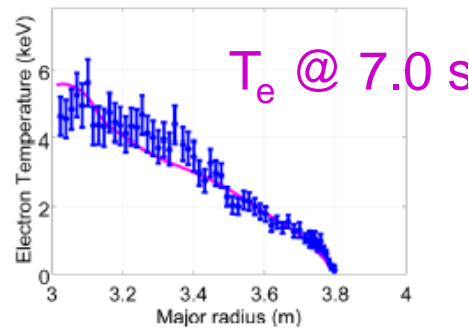
[Ostuni NF2022]

Level 4. W-accumulation at JET due to NBI central particle source → density peaking → W neoclassical accumulation enhanced by rotation

Prediction, 1.5 s of plasma evolution ($5 \times \tau_E$).



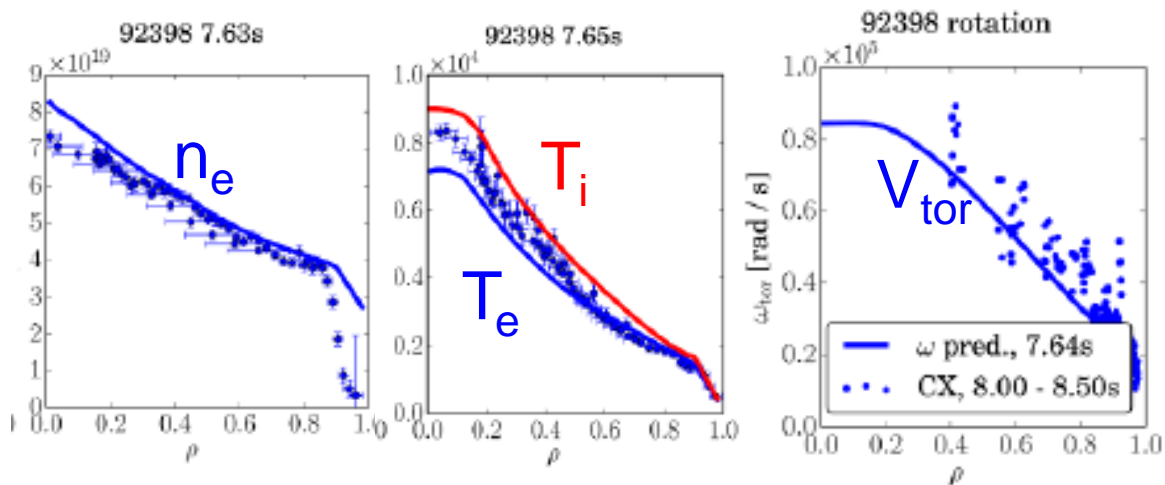
State-of-the-art core plasma integrated modelling evolving j , T_e , T_i , n_D , n_{Be} , n_{Ni} , n_W , ω , rad., NBI
 JETTO-SANCO-QuaLiKiz-NEO-PENCIL-FRANTIC-ad-hocETB
 successfully described **core W-accumulation due to NBI particle source** [Breton NF 2018]



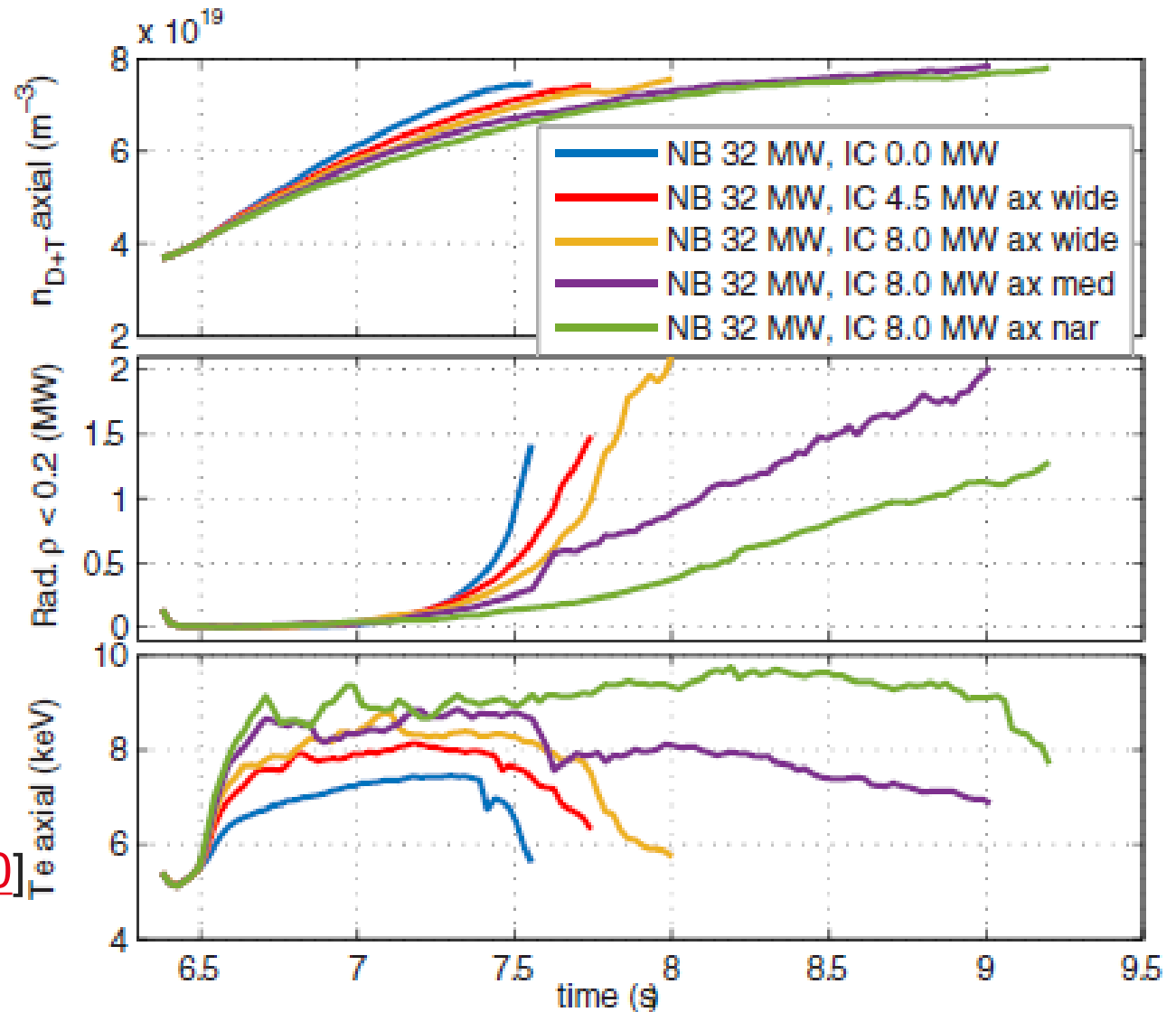
Level 4. W-accumulation avoidance at JET: ICRH → enhanced outward turbulent particle transport → flatter n_i core profile → reduced W neoclassical inward transport → delayed radiative collapse

Prediction: 1.5 s of plasma integrated modelling evolving j , T_e , T_i , n_D , n_{Be} , n_{Ni} , n_W , ω , rad., NBI, ICRH

JETTO-SANCO-QuaLiKiz-NEO-PENCIL-FRANTIC-ad-hocETB-PION

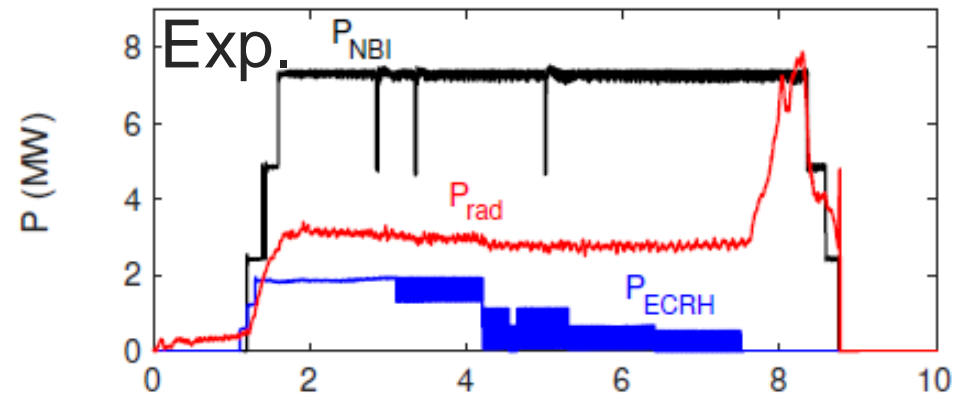


[Casson NF 2020]



Level 4 (w/o V_{tor}). W-accumulation avoidance at AUG: ECRH \rightarrow enhanced outward turbulent particle transport \rightarrow flatter n_i core profile \rightarrow reduced W neoclassical inward transport

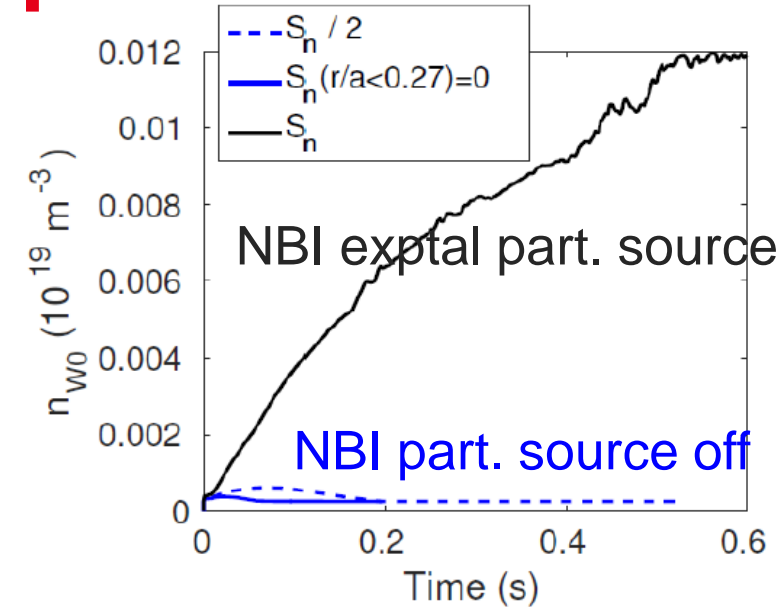
AUG #32408



Prediction: plasma integrated modelling evolving j , T_e , T_i , n_D , n_B , n_W , rad., NBI.
 Rot. CX, ECRH stand-alone
 ASTRA-QuaLiKiz-NEO-NBImodel-STRAHL

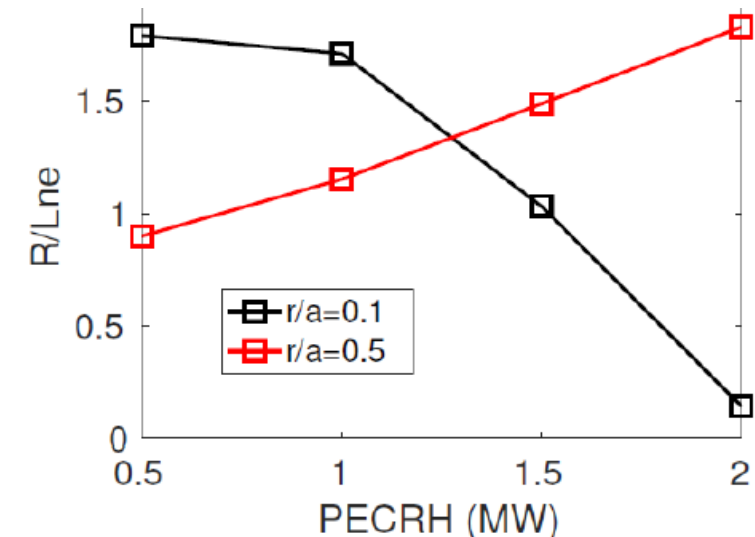
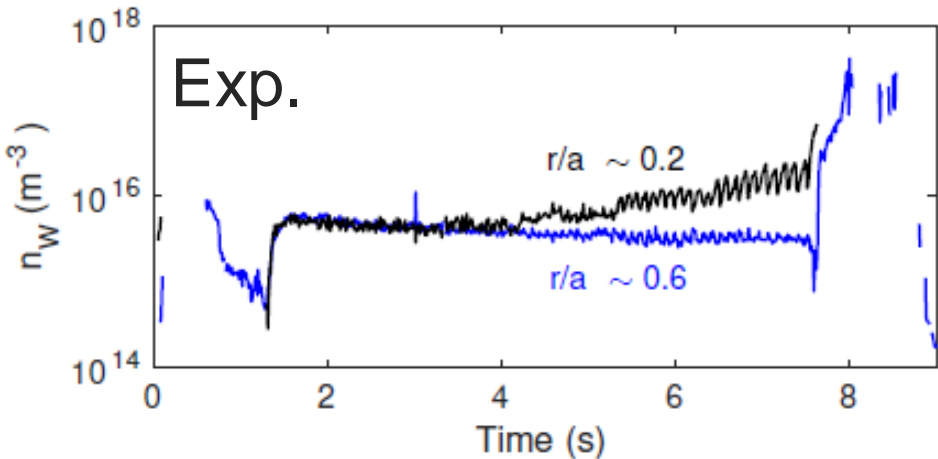
As on JET, NBI particle source enhances W inward neoclassical convection

As ICRH on JET, ECRH on $\rightarrow T_e/T_i$ increase \rightarrow turbulent particle diffusion \rightarrow reducing W inward neoclassical flux



NBI exptal part. source

NBI part. source off



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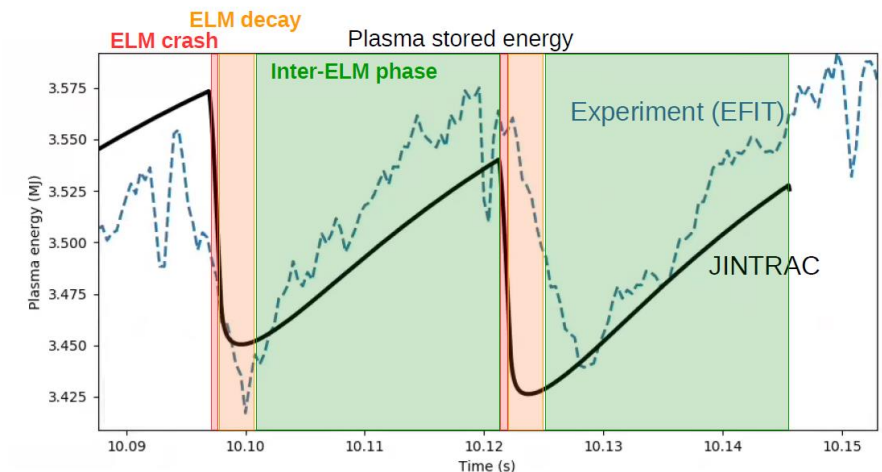
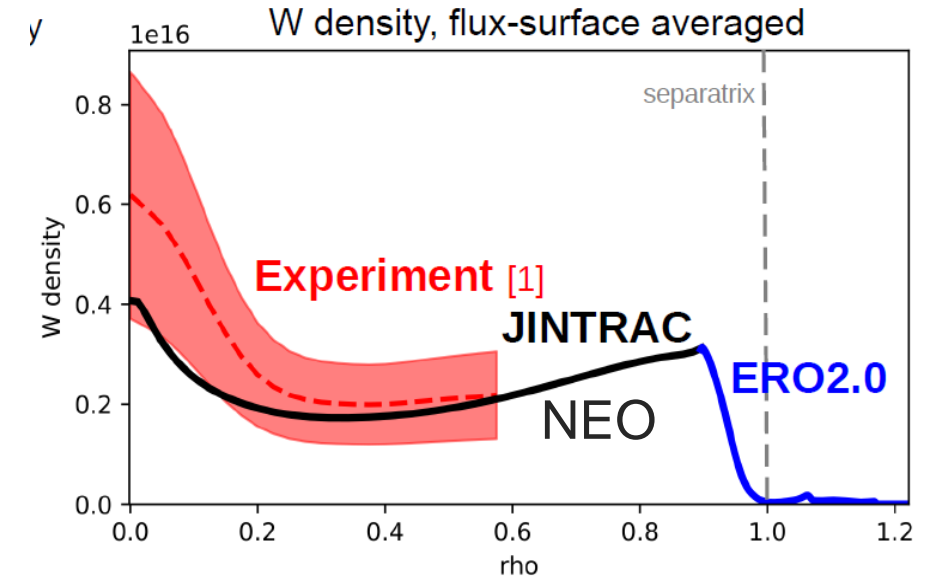
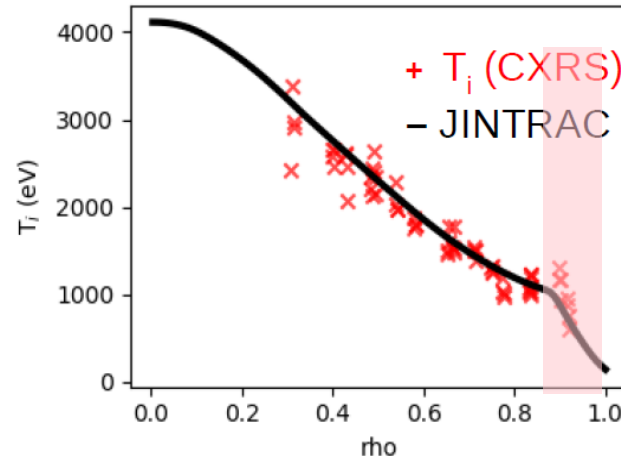
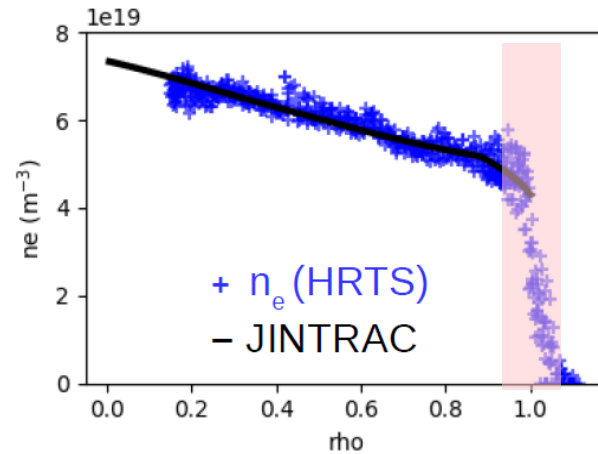
Merging the state-of-the-art level 3-4 core modelling (NEO or FACIT with QuaLiKiz or TGLF) with EDGE2D-ERO W state-of-the-art

[H. Kumpulainen EPS 2023, sub PPCF 2024](#)

Vs previous e.g. COREDIV work [[Telesca JNM 2013](#)] here **W** neoclassical (NEO) + turbulent (QuaLiKiz) transport in core and pedestal

NB: Background pedestal density and temperature impacting W penetration [cf Angioni's talk]: unknown dynamical particle source and heat+particle transport btw ELMs

JPN 94605 ($P_{aux} = 18$ MW)



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Large scale validation on all W EU tokamak possible now at large scale

Predictive int. modelling incl. W and radiation successfully used to prepare JET DTE2 [[Garcia NF2023](#)]

[TSVV11](#) made available the **High Fidelity Pulse Simulator**
Python-driven workflow based on **IMASified JINTRAC**

- NEO and FACIT available
- QuaLiKiz and TGLF available
- SANCO for self-consistent radiation
- EDGE2D

Coupled to experimental IMAS data from AUG, JET, TCV, WEST, on the **EUROfusion Gateway**

Adding IMEP could be done
More physics driven devt as needed ...

Large scale automated simulation launching tools operational (synergy project TSVV11-NL eScience center)

<https://github.com/duqtools/duqtools> (open-source)]

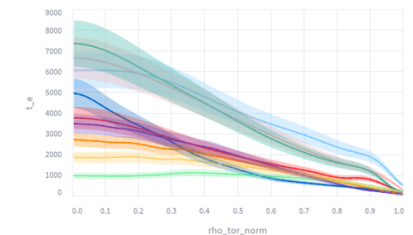
List of IMAS data

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g2aho/aug/36982/2
g2aho/jet/75225/2
g2aho/jet/90350/2
g2aho/jet/92432/2
g2aho/jet/94875/1
g2aho/tcv/64958/2
g2aho/west/54568/1
g2aho/west/54728/1
g2aho/west/55181/1
g2aho/west/55525/1
...
```

Canonical UQ template

```
create:
runs_dir: ./duqduq/{{ run.name }}
template: ./path/to/template/
template_data:
  user: {{ handle.user }}
  db: {{ handle.db }}
  shot: {{ handle.shot }}
  run: {{ handle.run }}
sampler:
  ...
dimensions:
  ...
system: jetto-v220922
```

duqduq



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Level 4 (w/o V_{tor}). DEMO W interplay with plasma up to sep., impact of W content \rightarrow radiation \rightarrow P_{fus}

DEMO baseline 2019/2021 5.74 T 19.5 MA R=9m
A=3.1 5°MW ECRH

Prediction: 70 s (τ_E 4-6s) of integrated prediction j , T_e , T_i , n_D , n_T , n_{He} , n_{Ar} , n_{Xe} , n_W , rad., ECRH, continuous pellet model, fusion power self-consistently calculated and iterated

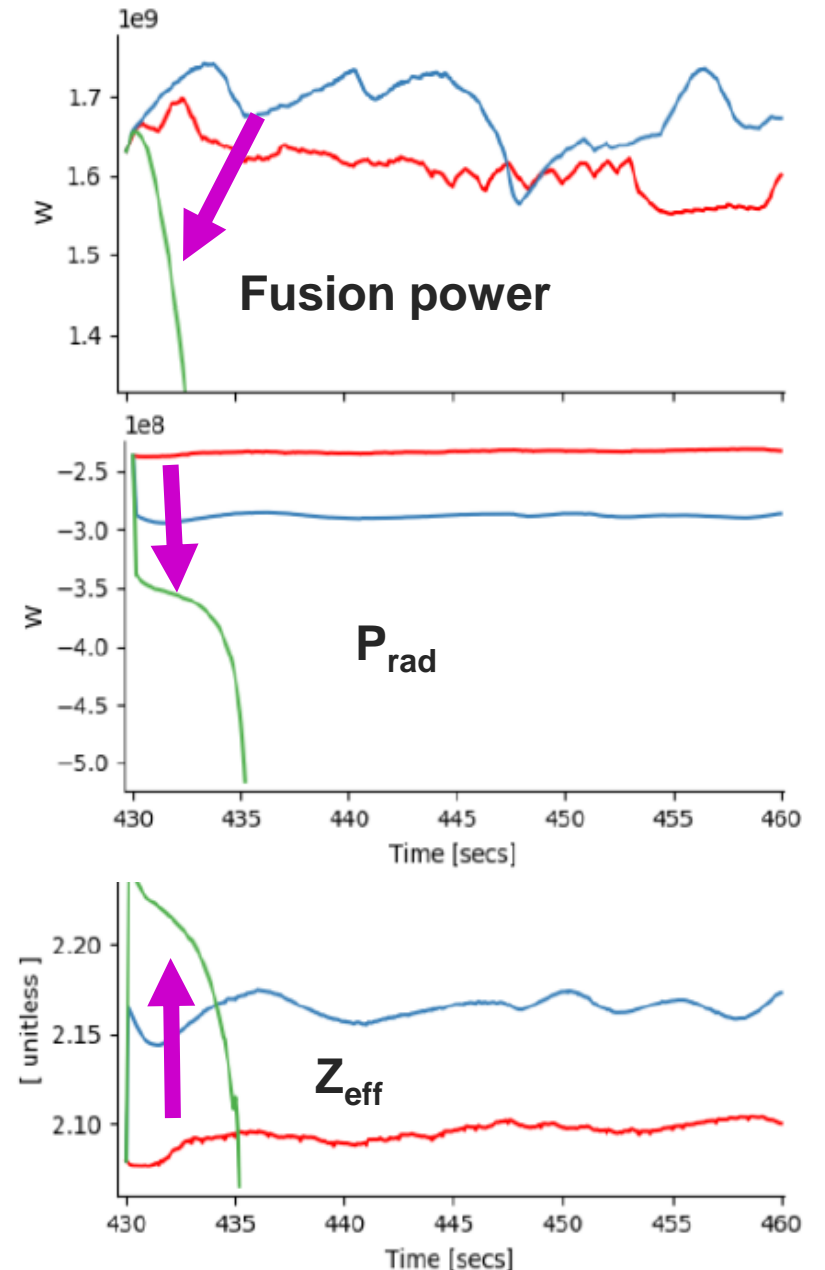
HFPS-NCLASS-TGLFsat2-SANCO

Pedestal: ITER-EPED scaling $P_{ped} = 0.54 B^{0.84} I_p n_{ped}$ such that pellet fueling feedback $n_{ped}/n_{Gr} = 95\% n_{Gr} \propto I_p/a^2$

Separatrix: ITER SOLPS scaling for n_{sep} and T_{sep}

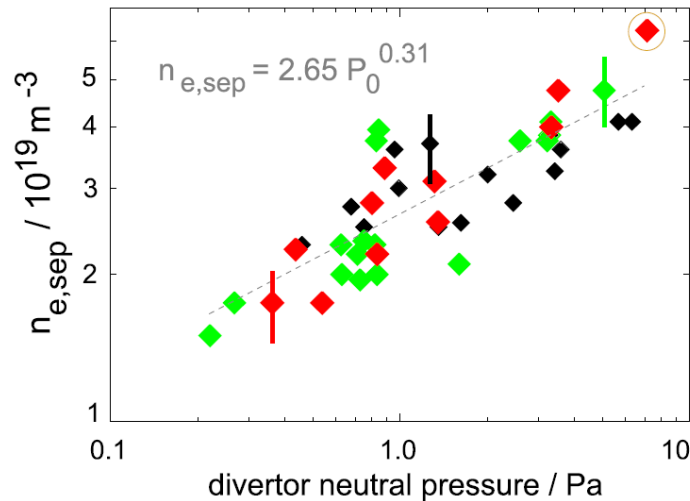
[Koechl Dec 2022 DCT]

W total content scanned

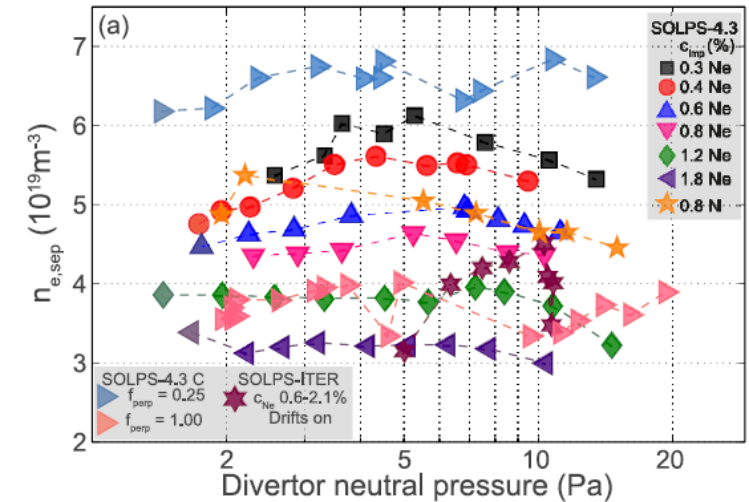


GAP 1/2: Improving the core-pedestal-SOL predictive modeling towards opaque/pellet fueled plasmas

AUG, experiment
[Kallenbach PPCF2018]



ITER SOLPS
modelling
[Pitts NME20019]



- **Shorter term (2024-2025 DEMO Central Team, PSD, transport): Explore more intensively impact of uncertainties on separatrix/pedestal parameters on DEMO scenarios incl. core W behavior and pellet interplay**, using both HFPS and ASTRA-IMEP with SOLPS-ERO-DEMO informed boundary conditions.
- **Longer term: 1st principle SOL + pedestal incl. W, transport and erosion**
 - **validation** on gas fueled present day experiments: Gyrokinetic or fluid turbulence + neutral models+ W, including SOL and confined plasmas: e.g. XGC1 on WEST [Dominski APS 2023]
 - **Predictions ITER/DEMO opaque/pellet fueled** challenging numerically, for now remains sensitive to initial conditions

Gap 2/2: Approaching Burning plasmas with a hierarchy of models

Workplan in DEMO Central Team, transport aspects 2024-2025

- **Standard integrated modelling HFPS extended to Alpha impact on MHD stability hence on Alpha redistribution** (ATEP Ph. Lauber et al) And iterate, expect P_{fus} oscillations in time. **could add W turbulent and neoclassical transport interplay > 2024**
- **Flux driven Alpha heated global gyrokinetic modelling** of ITER $Q=10$ and DEMO core $\rho>0.6$ using GENE-Tango GPU accelerated – at limit of Today’s computing capacity (A. Di Siena et al). ITER $Q=10$ 1st modelled burning plasma on-going. **could add W turbulent and neoclassical transport interplay > 2025**
- **Theoretical understanding and Global gyrokinetic mapping** GENE/ORB5, with varied fraction of fast ions and $T_{fast}/T_{thermal}=10$ and 100 (3.5 MeV Alpha)

Effect of fast ions on turbulent transport, hence T_i , hence P_{fus}	HFPS/AST RA-TGLFsat2	GENE - Tango
Thermal ion dilution	yes	yes
Shafranov shift stabilization by increase of α_{MHD} by suprathemal pressure	Yes	
Electrostatic stabilization by resonant fast ions	Yes	
EM-stabilization (enhanced by fast-ions)	Yes	
Increased nonlinear stabilization	No	

More in J. Citrin’s talk

Conclusion

- **Validation up to pedestal top in H mode and up to separatrix in L mode**
 - **Physics based Integrated modelling j , T_i , T_e , multi-ion (isotopes, impurities), V_{tor} HFPS-JETTO/ASTRA allowed to understand JET, AUG and WEST radiative collapses.**
In AUG and JET, key deleterious role of density peaking due to NBI 'erased' by turbulent particle transport enhancement by electron heating ECRH or ICRH. On WEST, central LHCD needed on-axis to maintain temperature screening
 - Core integrated modelling set up was successfully used to predict JET DTE2 [[Garcia NF2023](#)]
 - HFPS connected to all EU tokamak IDS ready on Gateway with large scale UQ tools
- **Validation up to W source started using high fidelity neoclassical transport (NEO [[Kumpulainen EPS 2023, soon PPCF2024](#)]) but:**
 - Pedestal turbulent transport remains ad hoc for heat and particle
 - Neutral source model validation in pedestal difficult, in int. modelling feedback on line averaged density with ad-hoc neutral energy and poloidally sym. [e. g. [Luda NF2023](#)]
 - SOL turb. codes including all species, heat, radiation self-consistently just starting, for ex. XGC1 on WEST [[Dominski APS 2023](#)]

perspectives

- **Validation up to pedestal top in H mode and up to separatrix in L mode**
 - HFPS machine agnostic, operational with IDS data on the Gateway together with large scale validation tools [@TSVV11]. **Larger scale validation, not cherry picking, now possible**
 - requires data access (FAIR4fusion, JET data center status?),
 - soft and hardware support for Long Term Storage Facility and simulation database. Incl. Validation against high β JET T/D/DT and JT60-SA N-NBI
 - Need strategy towards physics based pedestal + SOL transport and part. source TSVV11 + other TSVVs/ENRs. Need more well diagnosed core-ped-SOL including neutrals pulses 'à la [[Horvarth PPF2023](#)]' at JET, more to be expected at DIII-D Lyman-alpha diags
- **Physics based extrapolation towards opaque, pellet fueled devices + burning plasmas** remains challenging but 2024-2025 **more intensive exploration of uncertain SOL/pedestal in HFPS-TGLFsat2-NEO-SANCO**, including interplay with EP MHD and global GENE-TANGO modelling proceeding [TSVV10-TSVV11, DEMO CT / PSD]