MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Impurity transport & accumulation

F. Reimold on behalf of the W7-X Impurity Transport Team

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.

Impurity Transport Team

C.D. Beidler[1], D. Bold[1], C. Brandt[1], R. Bussiahn[1], B. Buttenschön[1], A. Demby[1], R. De Wolf[8], Y. Feng[1], O. Ford[1], T. Fornal[6], J.M. García-Regaña[2], B. Geiger[4], T. Gonda[3], M. Gruca[6], F. Henke[1], M. Kriete[3], I. Ksiazek[6], M. Kubkowska[6], A. Langenberg[1], N. Mazziz[1], K. McCarthy[2], N. Pablant[7], G. Partesotti[1], V. Perseo[1], P. Pölöskei[1], T. Romba[1], D. Medina Roque[2], H. Smith[1], C. Swee[4], N. Tamura[5], A. Tsikouras[1], T. Tork[1], J.L. Velasco[2], Th. Wegner[1], N. Wendler[6], V. Winters[1], D. Zhang[1], A. Zocco[1] and W7-X Team

[1]Max-Planck Institut für Plasmaphysik, Greifswald, Germany

[2]Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain

[3]Auburn University, Auburn, AL, USA

[4]University of Wisconsin, Madison, WI, USA

[5]National Institute for Fusion Science, Toki, Japan

[6]Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland

[7]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08540, USA

[8]KU Leuven, Leuven, Belgium

Deliverables & what to expect (outline)

Impurities:

Core

- Impurity accumulation database & scaling (TFI)
- Transport characterization (TFIII)
- Profile characterization (TFI+III)
- Validation of neoclassic (TFIII)

Edge

- Enrichment (low- & high-Z) (TFII)
- Tungsten transport (TFII)

Radiation:

- Radiation asymmetries (TFIII)
- Detachment access & control (TFII+III)

Core impurity transport

F. Reimold TF I

T. Romba TF III

Edge impurity transport

M. Kriete TF III

V. Winters TF III

Radiation

G. Partesotti TF III

Status of Core Impurity Transport OP2.1

***Achievements*:**

- **New or standard operation of non-stationary impurity diagnostics:**
  - Many LBO (100’s) & TESEPEL (10’s) injections
    → database approach & survey
  - He-puff modulation established, LBO-modulation pending
    → detailed transport analysis
- **New diagnostic & analysis approaches:**
  - Regular CXRS profile measurements & transport analysis (to be developed for blips)
  - CXRS high-n Rydberg approach for high(er)-Z element
  - New CIS-based diagnostic: CICERS (2D-profiles of n_{imp})

→ see TFIII talk by T. Romba

Status of Core Impurity Transport OP2.1

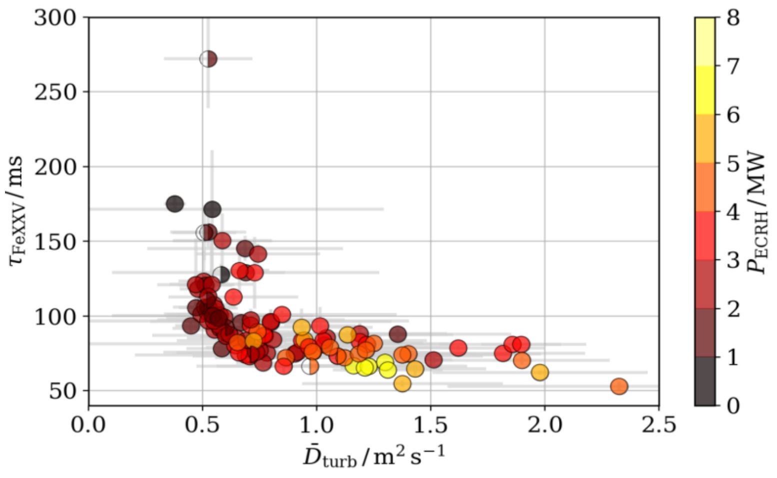
***Challenges*:**

- Data of limited use for quantitative analysis due to diagnostic issues (HEXOS, HR-XIS/XICS)
- Some recovery possible with additional effort:
  Bolometry, Spectroscopy, XMCTS, Zeff
  - Qualitative analysis (transport time) is possible for database approaches
  - Need for impurity accumulation proxy (HEXOS, Bolometer, Zeff)

Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)



T. Wegner JPP 89 (2023)

Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)

→ see TFIII talk by T. Romba

Actuators to reduce impurity accumulation

- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)

Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)

Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

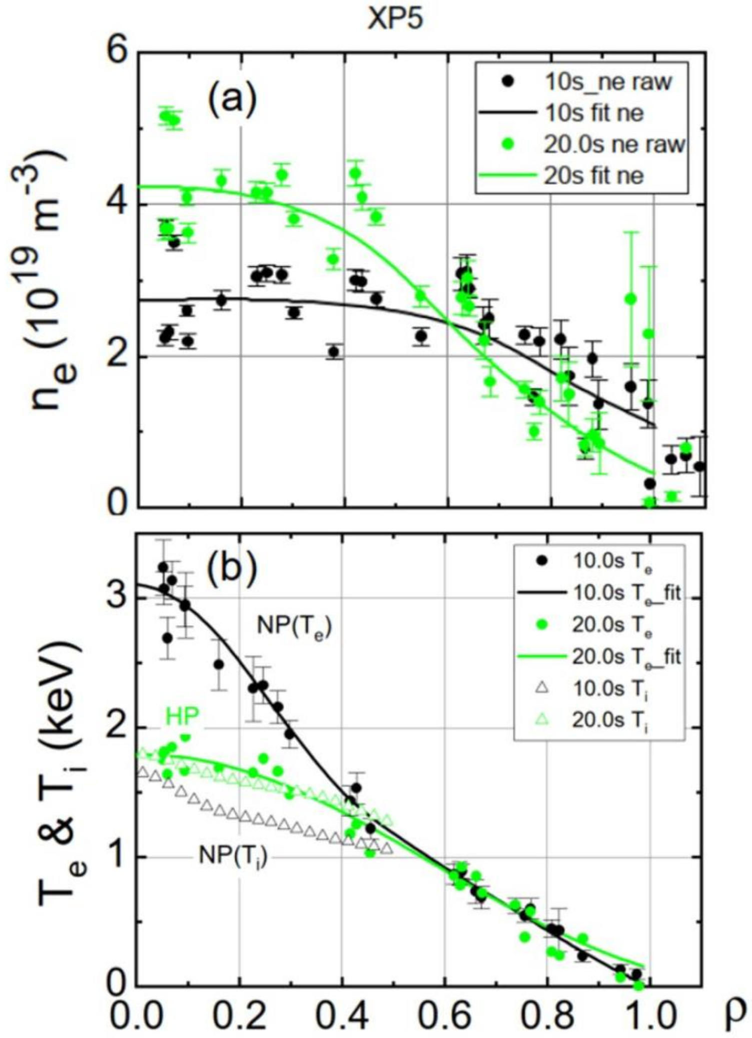
In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)

Pure NBI

Actuators to reduce impurity accumulation

- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)



Reference

Red. turbulence

D. Zhang PPCF 65 (2023)

Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)

Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

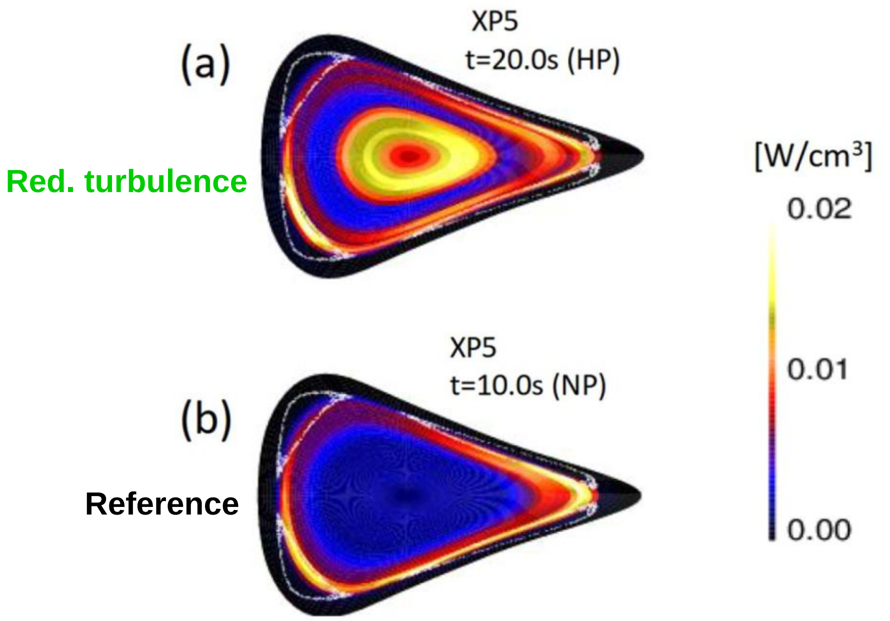
In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)

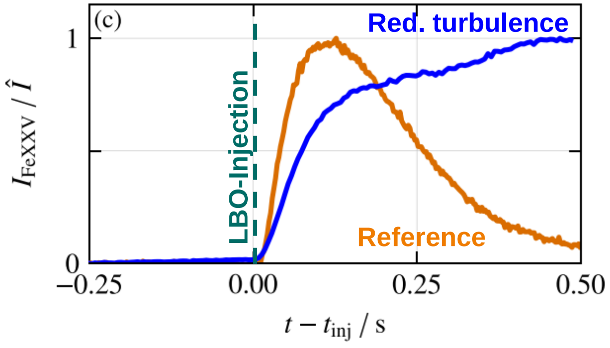
Pure NBI

Actuators to reduce impurity accumulation

- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)



D. Zhang PPCF 65 (2023)



J. Alcuson NF 63 (2023)

Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)

Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

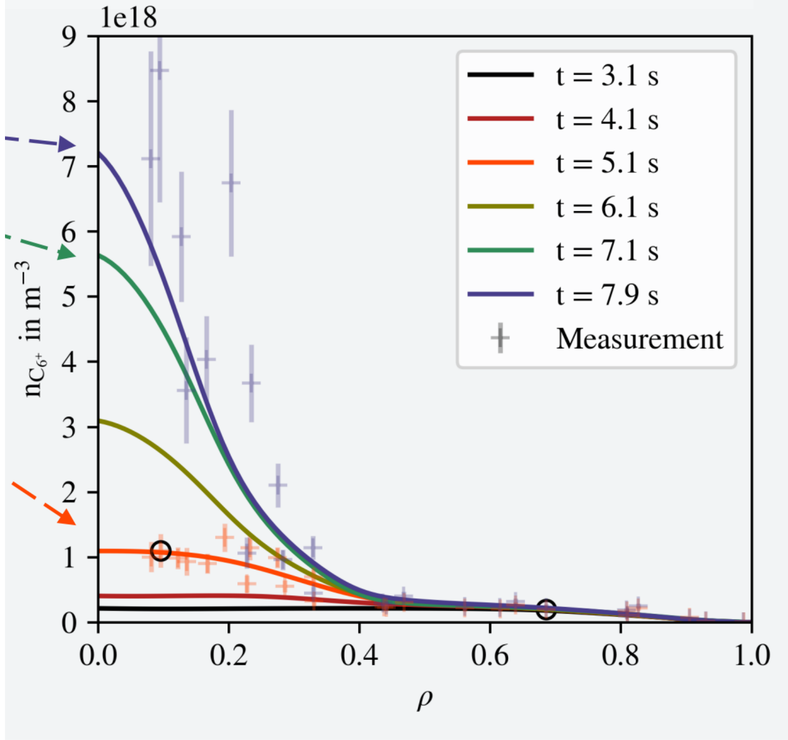
In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)

Actuators to reduce impurity accumulation

- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)

Courtesy of T. Romba



Density peaking in NBI-heated experiments

Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)

Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

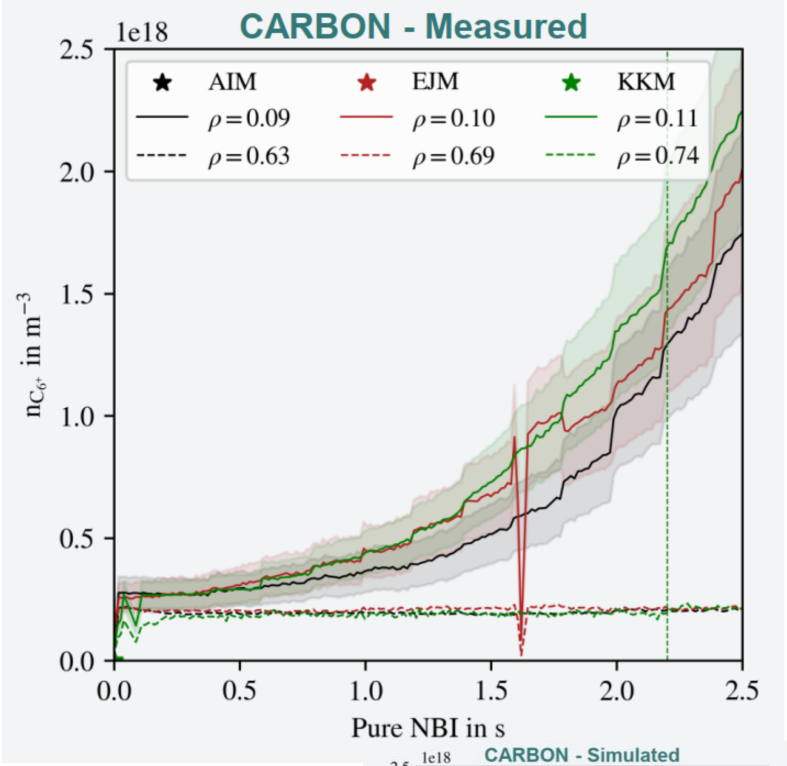
In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)

Actuators to reduce impurity accumulation

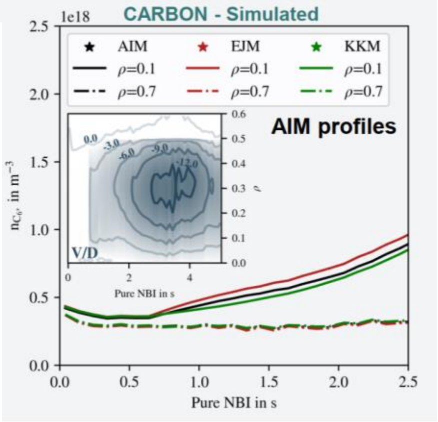
- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)

Experiment



Courtesy of T. Romba

Modeling



Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)

Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

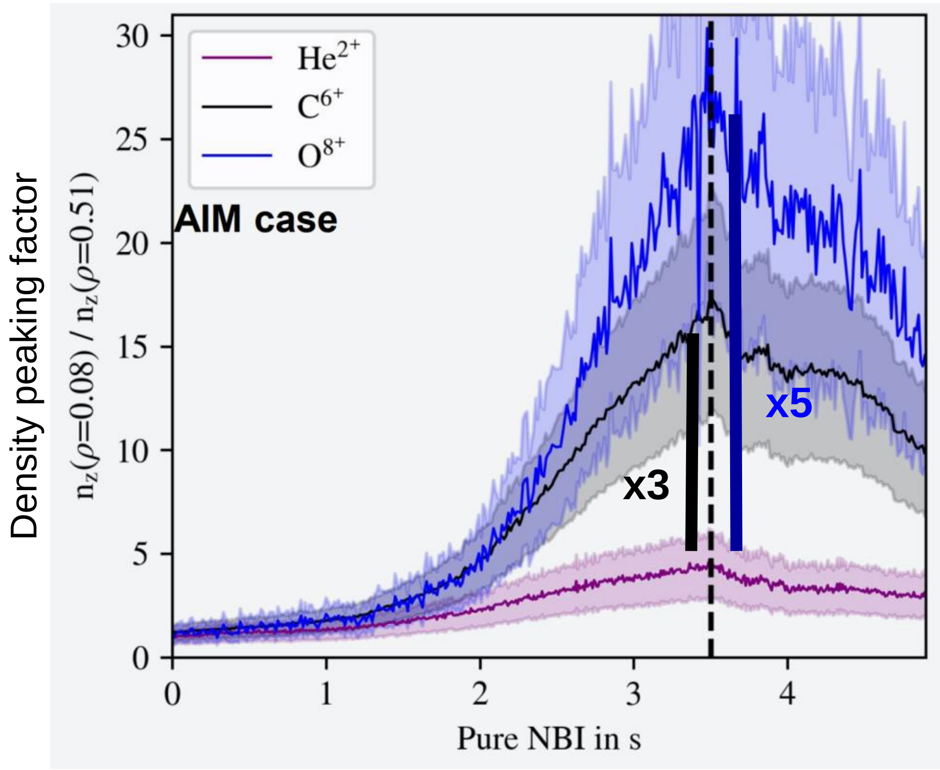
In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)

Actuators to reduce impurity accumulation

- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)

Courtesy of T. Romba

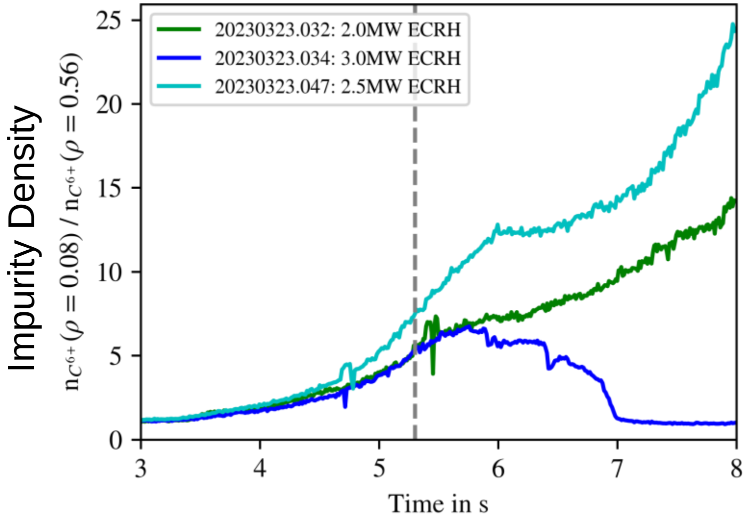


Tentative (!) key results consistent with OP1.2

Impurity transport in regular ECRH scenarios is turbulent transport dominated (timescale & species-dependence)

- No strong sign of mag. configuration dependence
- No (strong) accumulation (database analysis pending)

Courtesy of T. Romba

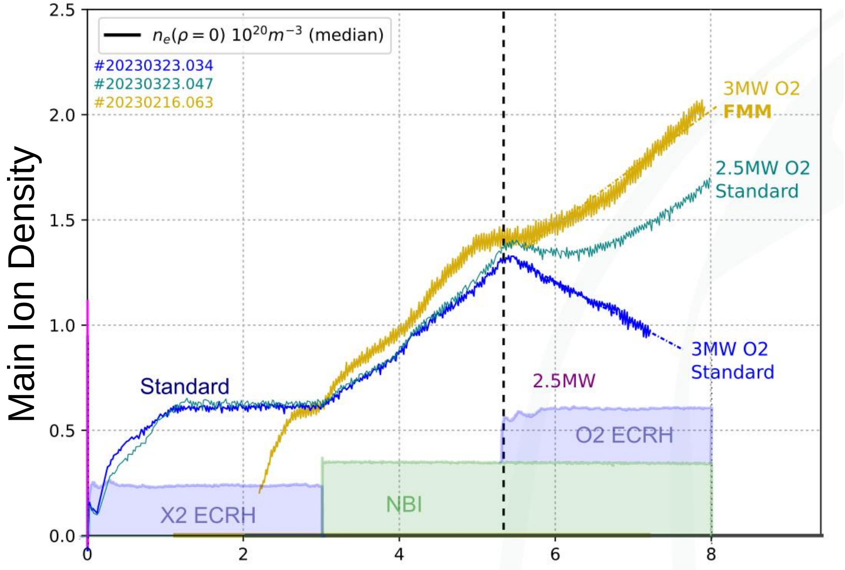


Impurities accumulate in improved performance scenarios

- Low density, freshly boronized; Impurity injection; Pure NBI

In pure NBI:

- Transport timescale not strongly dependent on mag. configuration
- Impurity peaking species dependent (Z-scaling)



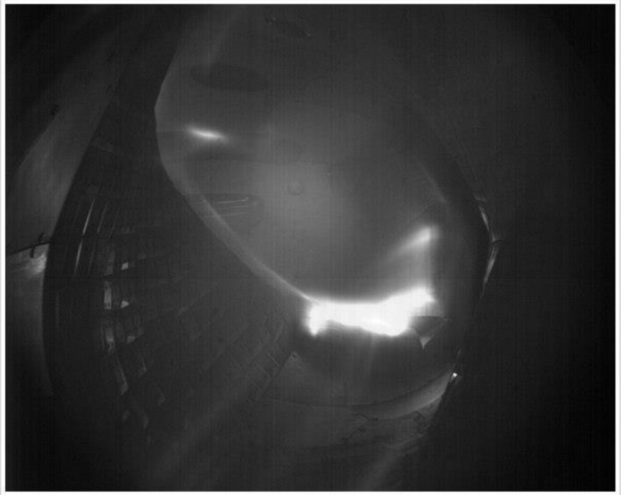
Courtesy of O. Ford

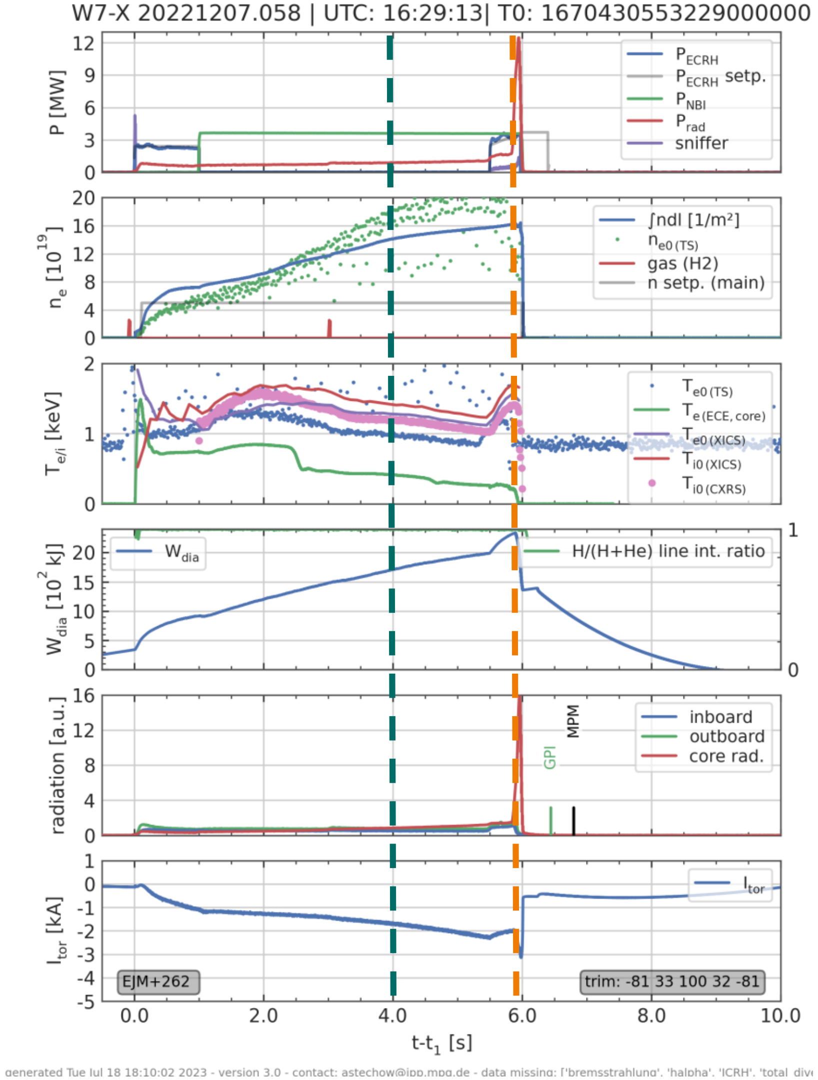
Actuators to reduce impurity accumulation

- (Sufficient) ECRH
- Gas puff (low density, freshly boronized)

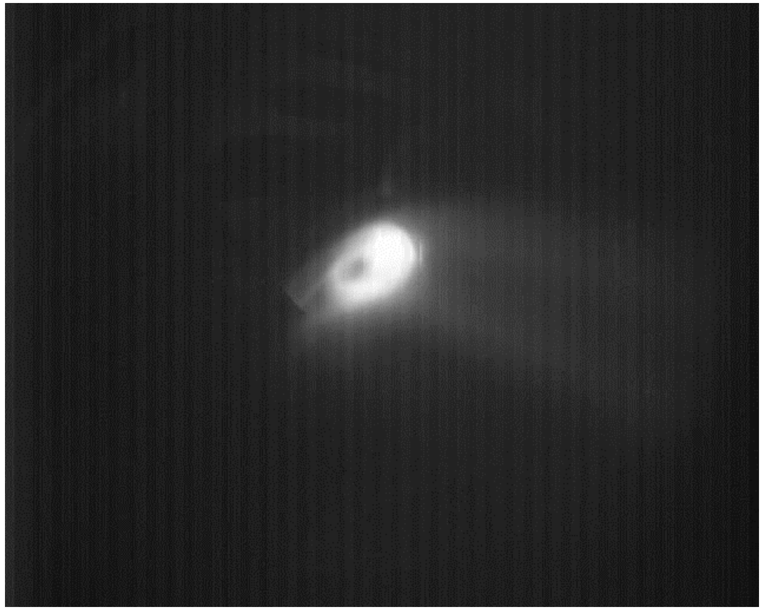
Tentative (!) key results consistent with OP1.2

Core accumulation of W





Erroneous MPM position (pin melting)



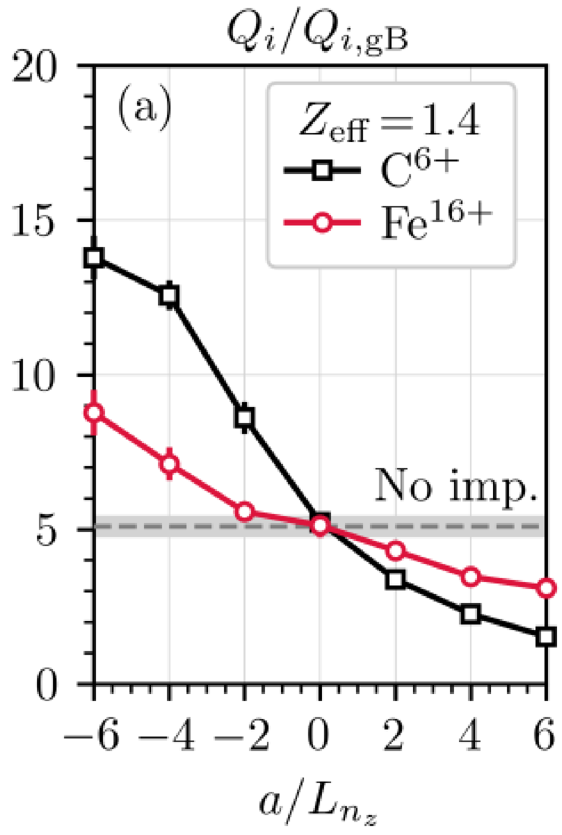
Important:

Impurity transport is NO safety issue

Progress in theoretical understanding & optimization

- **Influence of impurities on turbulent transport**
  - Progress in modeling tools and analysis (Stella, GENE, Euterpe)
    - First analysis of impurity transport in accumulating conditions still inconclusive
    - Impact of non-trace impurities on turbulence predicted
    - Detailed modeling datasets prepared
- **Impurity transport can be optimized**
  - Transport level optimization
  - Outward directed convection
    → temperature screening

Stella-Simulations



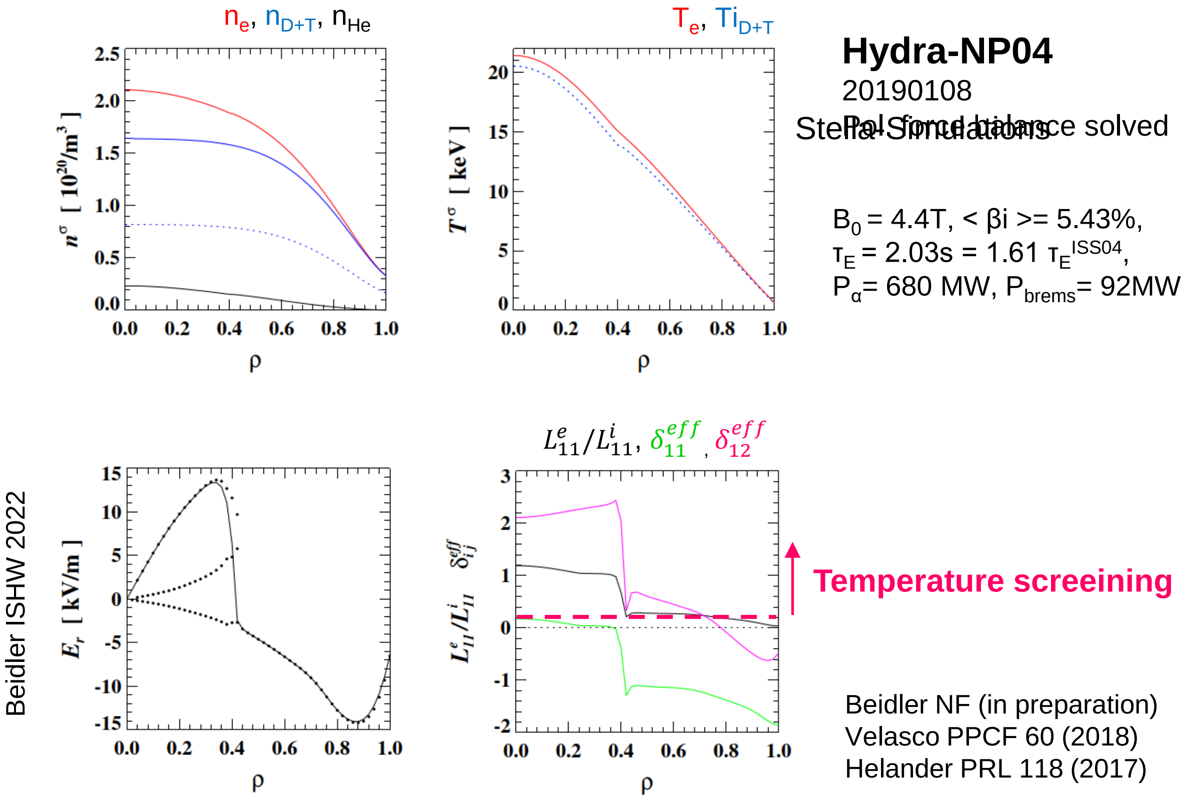
J.M. Garcia-Regana NF (submitted)

Progress in theoretical understanding & optimization

- **Influence of impurities on turbulent transport**
  - Progress in modeling tools and analysis (Stella, GENE, Euterpe)
    - First analysis of impurity transport in accumulating conditions still inconclusive
    - Impact of non-trace impurities on turbulence predicted
    - Detailed modeling datasets prepared

- **Impurity transport can be optimized**
  - Transport level optimization
  - Outward directed convection

    → temperature screening



Hydra-NP04
20190108
Stella Simulations
Pol force balance solved

B_0 = 4.4T, < βi >= 5.43%,
τ_E = 2.03s = 1.61 τ_E^{ISS04},
P_α= 680 MW, P_{brems}= 92MW

Beidler NF (in preparation)
Velasco PPCF 60 (2018)
Helander PRL 118 (2017)

$$\Gamma_z = -n_z L^Z_{11}\left(\frac{d\ln n_Z}{dr} + \delta^{eff}_{11}\frac{d\ln n_i}{dr} - \delta^{eff}_{12}\frac{d\ln T_i}{dr}\right)$$

Condition for temperature screening:

$$\delta^{eff}_{12} = \frac{\delta^Z_{12} - Z\delta^i_{12} + L^e_{11}/L^i_{11}(\delta^Z_{12} + Z\delta^e_{12})}{1 + L^e_{11}/L^i_{11}} > 0 \quad \rightarrow \quad \frac{L^e_{11}}{L^i_{11}} > \frac{Z\delta^i_{12} - \delta^Z_{12}}{Z\delta^e_{12} + \delta^Z_{12}}$$

Fundamental challenges for core impurity transport

At the moment we cannot attain fully reactor-relevant conditions in W7-X

Instead we should focus on:

→ **Database approach to identify special conditions & critical parameters**

- Transport suppression & scaling
- Separation of impurities vs. main ions vs. heat

→ **High quality experimental data for modeling validation**

- Characteristic conditions
- Complete experimental dataset
- High fidelity impurity transport analysis
- High fidelity modeling (GK)

→ **Development of faster models (QL) for predictions & new scenarios to validate (NC) required**

Conclusions & What would we want in OP2.2?

Expect more reliable operation

Diagnostic availability

NBI-heating & blips for CXRS

Encourage to include impurity tracers !

Most often not perturbative

With/without NBI:

- LBO & TESPEL

With NBI (!!):

- Gas puff modulation (He, Ne)
- Ne/Ar tracer puff

Operational regimes/parameters to be explored

- Low collisionality conditions (P/n limit!)
- Mirror-scan at low collisionality

New diagnostic developments in O2.1

- Puff modulation CXRS measurements
- Fast CXRS with high-n Rydberg lines (highZ)
- CIS-based CXRS (CICERS)
- CO-Monitor is commissioned
- Additional capabilities for HR-XIS (W-lines)

New diagnostic developments in O2.2

- HEXOS & HR-XIS back in operation
- UV-vis complement to HEXOS
- Improved CICERS & NBI availability (blips)
- Improved gas seeding capabilities
- Imp. density fluctuation measurements (scoping study)

Conclusions & What would we want in OP2.2?

Expect more reliable operation

Diagnostic availability

NBI-heating & blips for CXRS

Encourage to include impurity tracers !

Most often not perturbative

With/without NBI:

- LBO & TESPEL

With NBI (!!):

- Gas puff modulation (He, Ne)
- Ne/Ar tracer puff

Operational regimes/parameters to be explored

- Low collisionality conditions (P/n limit!)
- Mirror-scan at low collisionality

New diagnostic developments in O2.1

- Puff modulation CXRS measurements
- Fast CXRS with high-n Rydberg lines (highZ)
- CIS-based CXRS (CICERS)
- CO-Monitor is commissioned
- Additional capabilities for HR-XIS (W-lines)

New diagnostic developments in O2.2

- HEXOS & HR-XIS back in operation
- UV-vis complement to HEXOS
- Improved CICERS & NBI availability (blips)
- Improved gas seeding capabilities
- Imp. density fluctuation measurements (scoping study)

Conclusions & What would we want in OP2.2?

Expect more reliable operation

Diagnostic availability

NBI-heating & blips for CXRS

Encourage to include impurity tracers !

Most often not perturbative

With/without NBI:

- LBO & TESPEL

With NBI (!!):

- Gas puff modulation (He, Ne)
- Ne/Ar tracer puff

Operational regimes/parameters to be explored

- Low collisionality conditions (P/n limit!)
- Mirror-scan at low collisionality

Missing data & proposals:

- Detailed characterization of non-stationary transport analysis schemes (early campaign termination)
- Complete transport database with sufficient diagnostic data (LBO & TESPEL)
- Towards reactor-relevant conditions: low collisionality (P/n limit)
- B-dropper (failed trials & early campaing termination)

Backup

Feedback for impurity transport

Diagnostic issues:

B. Buttenschön: Limited HEXOS capabilities, Accumulation proxy

A. Langenberg: Limited XCIS capabilities

T. Gonda: Additional W-lines identified in HR-XIS

C. Swee: Fast CXRS measurements of high-n Rydberg

Logbook analysis:

T. Fornal: CO-Monitor & PHA

D. Medina: TESPEL injection highlights

Detailed transport analysis:

C. Swee: Transport analysis with CXRS of LBO-injection

T. Romba: He-puff modulation (Plume) in NBI-scenarios, Impurity accumulation & transport analysis in NBI-scenarios, Transport suppression for impurities

D. Zhang: Impurity accumulation in low density/boronized & NBI-conditions

Modeling

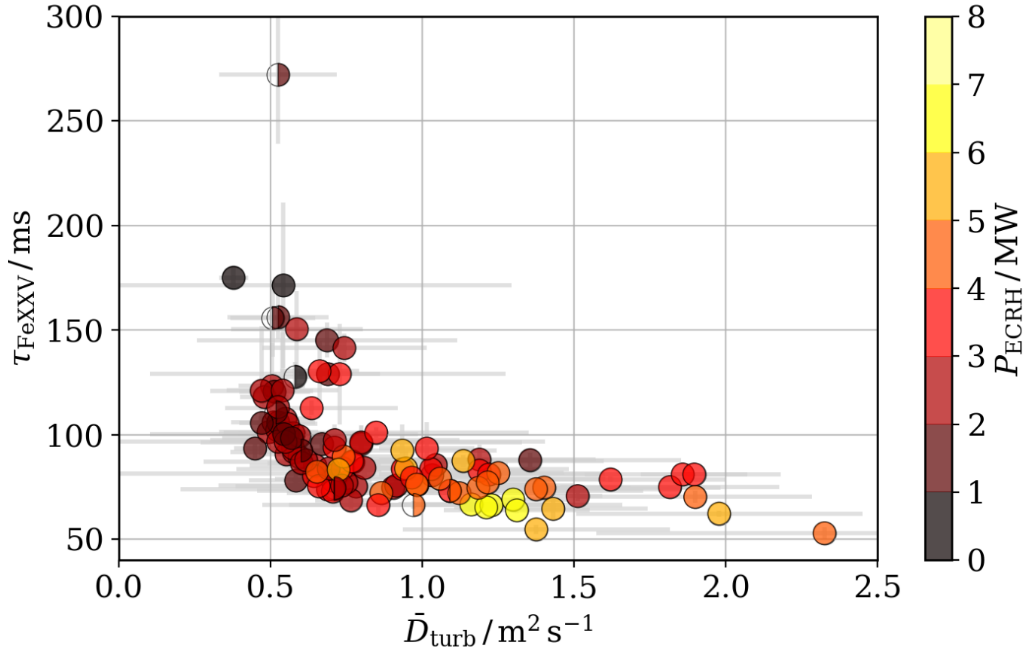
H. Cu Castillo: Gyrokinetic modeling of imp. transport

J.M. Regana: Modeling of impact of non-trace impurities on turbulent transport

Regimes with reduced turbulent transport

Reduced turbulence impacts impurity transport and is consistently correlated to profile effects:

- **Low power & low density scenarios**
  - Impurity accumulation for low edge densities
    - Wall conditioning & gas puff
- **Pure NBI-heating**
  - Decoupled turbulent impurity transport
  - Radial evolution of transport suppression
  - Complete suppression of turbulent impurity transport → purely (neo-)classical
  - ECRH ‘flushing’ observed



T. Wegner JPP 89 (2023)

Deliverables – TF I

Main Objective	Scientific Goal	Measures of Success / Deliverables
▪ Exploration of reduced turbulence / high performance scenarios w.r.t. stationary plasma conditions, kinetic-, density-, and impurity-profile control	▪ Demonstrate steady-state viability of increased performance scenarios after pellet / impurity injections as well as low ECRH/NBI heated plasmas ▪ Qualify actuators for the control of profiles and impurities	▪ High plasma performance in the order of seconds, including ○ T_i above clamping limit (1.5 keV) ○ τ_E equal or better to ISS04 scaling ▪ Avoidance of impurity accumulation ▪ Assessment of density profile control

Core impurity transport

F. Reimold TF I

T. Romba TF III

Deliverables – TF II

Main Objective	Scientific Goal	Measures of Success / Deliverables
▪ Integrated scenarios for long-pulse operation with PFC heat load control, efficient particle exhaust, and impurity screening	▪ Control of divertor/baffle loads and actuation of heat load distribution ▪ Studies on particle exhaust and optimization of plasma fueling schemes	▪ Demonstration of safe divertor scenarios to avoid overloaded plasma-facing components ▪ Determination of trim and/or control coil currents required to correct error fields ▪ Demonstration of effective pumping, high divertor compression, and qualification of fueling actuators ▪ Demonstration of long-pulse operation (1 GJ energy turnaround)
▪ Development of long, stationary divertor detachment scenarios with and without impurity seeding	▪ Creating conditions for detachment by tailoring edge plasma conditions and impurity seeding ▪ Compatibility of stationary detachment with high-performance scenarios ▪ Development of detachment scenarios with efficient exhaust	▪ Demonstration of scenarios with long, stationary divertor detachment; in particular, for the high-mirror, high-iota and standard configurations ▪ Characterize the conditions under which detachment is possible ▪ Achieve rapid transition to detachment
▪ Exploration of scenarios compatible with carbon-free operation and tungsten PFCs	▪ Migration (erosion, deposition) of tungsten-based materials and assessment of operation limits ▪ Edge scenario development for metallic plasma-facing components	▪ Definition of the operation limits associated with plasma-facing components containing tungsten materials ▪ Characterize the scrape-off layer retention for tungsten impurities (eroded from baffle and heat shield) ▪ Determination of erosion effects due to seeding impurities ▪ Characterize enrichment/accumulation for low-Z and high-Z impurities

Radiation

G. Partesotti TF III

Core impurity transport

F. Reimold TF I

T. Romba TF III

Edge impurity transport

M. Kriete TF III

V. Winters TF III

Deliverables – TFIII

Main Objective	Scientific Goal	Measures of Success / Deliverables
▪ Complete the core transport and stability physics basis in the extended operational space	▪ Identify fundamental heat and particle transport mechanisms ▪ Continue the assessment of W7-X optimization	▪ Documentation of relevant plasma profiles for detailed transport analysis and modelling. ▪ Assessment of the effects of heating and fueling actuators (profile shaping, fast ions) and magnetic configuration on turbulent transport. ▪ Documentation of core impurity profiles and perturbative experiments for detailed impurity transport analysis and modelling. ▪ Confirmation of neoclassical optimization at increased ion temperatures. ▪ Confirmation of reduced equilibrium currents at higher betas and different magnetic configurations. ▪ Documentation of MHD stability and limits and fast-particle driven MHD modes within the magnetic configuration space.
▪ Complete the edge and SOL physics basis in the magnetic configuration space of W7-X	▪ Characterization of parallel and perpendicular SOL transport regimes and validation of transport models ▪ Characterization of three-dimensional edge + SOL profiles and asymmetries	▪ Providing the experimental data base for understanding transport mechanisms in the island divertor SOL and across the LCFS, including flows, drifts, turbulence ▪ Validation of edge transport codes ▪ Studies of SOL width and target heat flux scalings ▪ Characterization of asymmetries of plasma conditions and radiation, mapping of diagnostic results in 3D island divertor

Core impurity transport

F. Reimold TF I

T. Romba TF III

Edge impurity transport

M. Kriete TF III

V. Winters TF III