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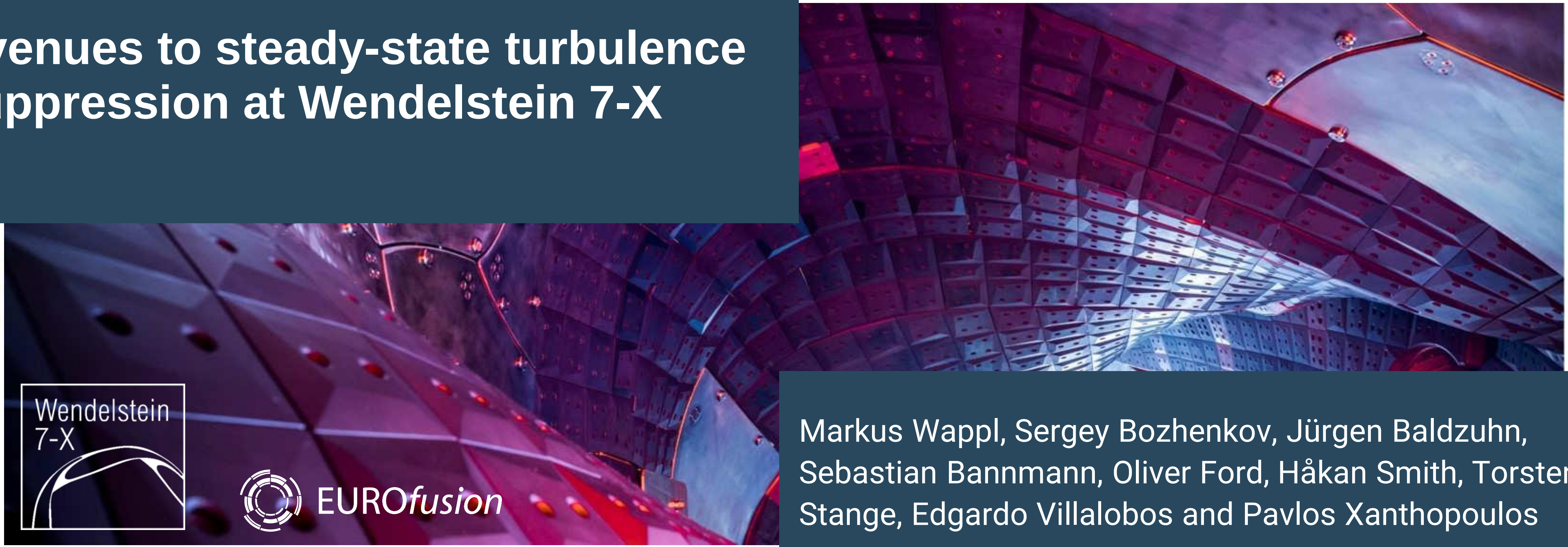
FÜR PLASMAPHYSIK

Avenues to steady-state turbulence suppression at Wendelstein 7-X



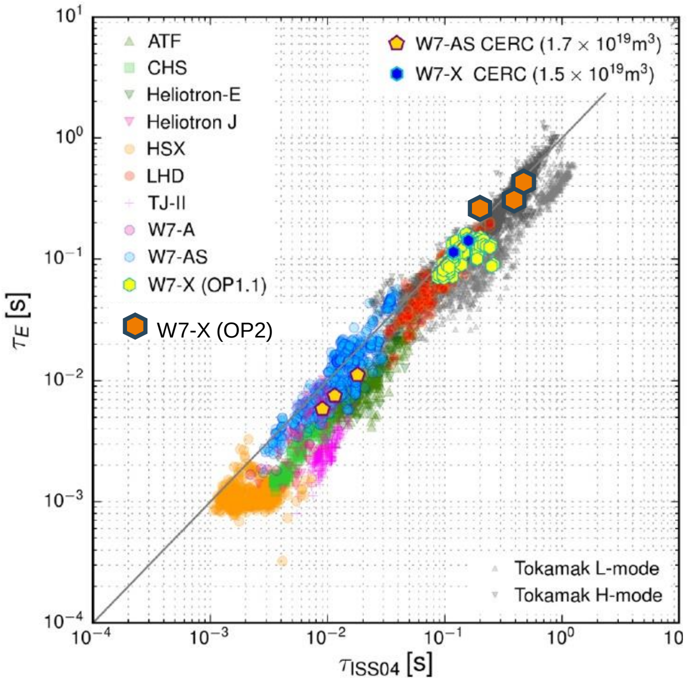
Markus Wappl, Sergey Bozhenkov, Jürgen Baldzuhn, Sebastian Bannmann, Oliver Ford, Håkan Smith, Torsten Stange, Edgardo Villalobos and Pavlos Xanthopoulos

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.

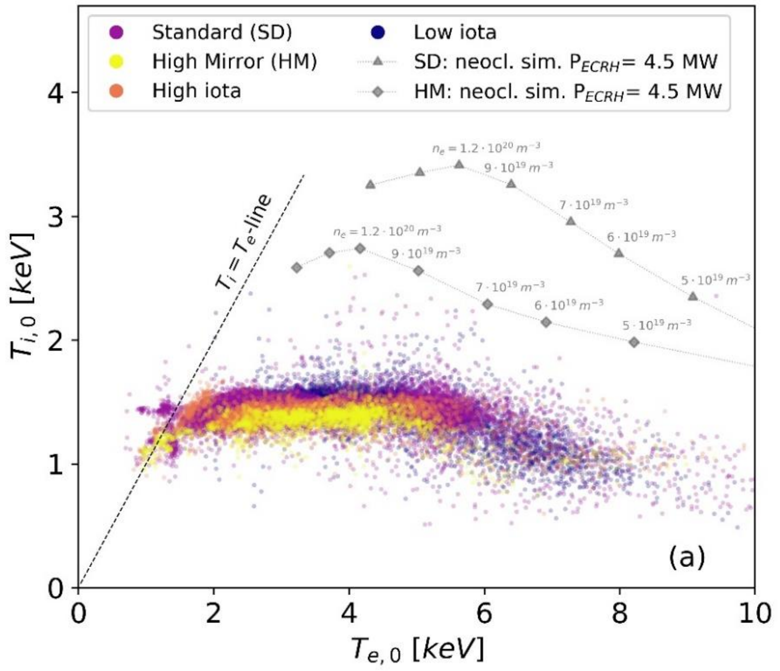
Wendelstein 7-X to stellarator-reactor

- Prospect of fusion power plant
  - Steady-state operation
- Tripleproduct $nT_i\tau_E$
  - Insufficient T_i, τ_E
  - Plasma turbulence
- Scenario development
  - Heating and Fueling
  - Transient high performance

M.N.A. Beurskens *et al* 2021 *Nucl. Fusion* 61 116072

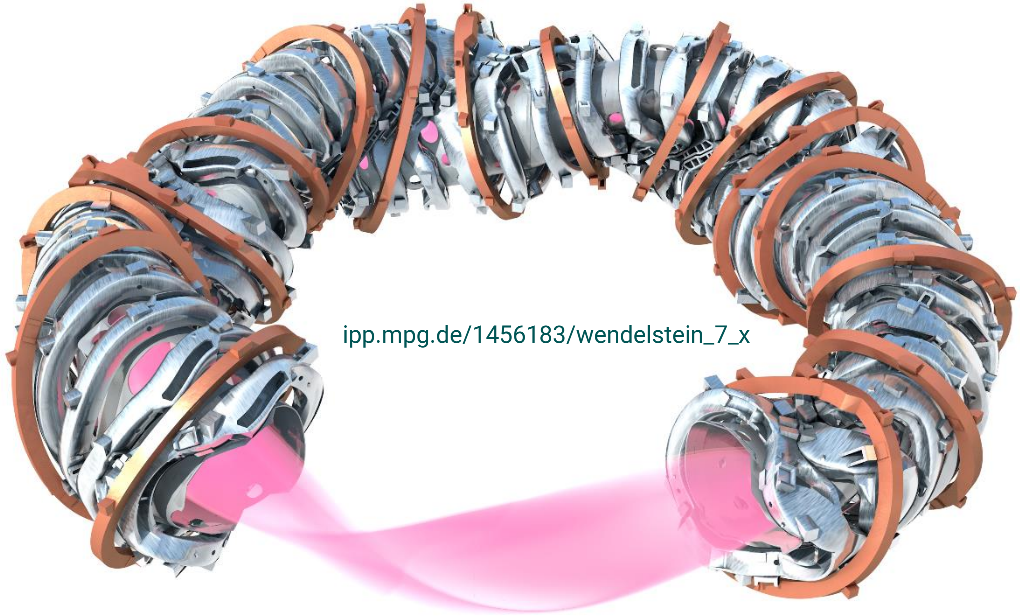


R.C. Wolf *et al* 2017 *Nucl. Fusion* 57 102020



Outline

- Plasma turbulence
  - Instabilities & Drivers
- Methods
  - Power balance analysis
- Database study
  - Correlations with turbulence drivers
- Identify steady-state high performance discharges



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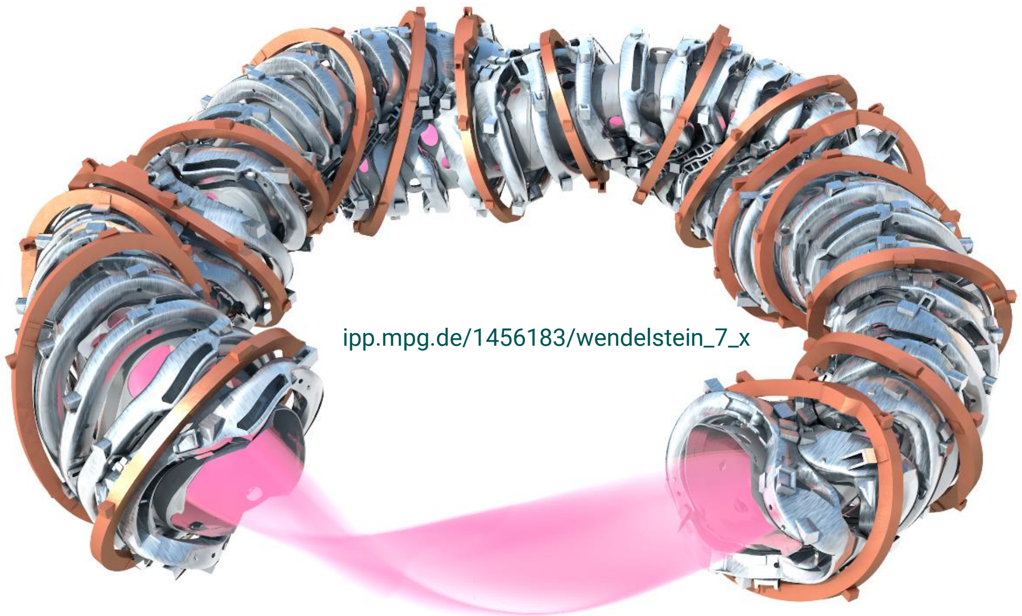


ipp.mpg.de/1456183/wendelstein_7_x

W7-X prone to ITG modes

- Driven by ion temperature gradient
- Suppressed by density gradient

$$a/L_{Ti} = -\frac{a}{T_i}\frac{\mathrm{d}T_i}{\mathrm{d}r_{\mathrm{eff}}}$$

- Strong turbulent transport
  - Limits confinement
  - Profile stiffness limits T_i
- Exacerbated by T_e/T_i

$$a/L_n = -\frac{a}{n}\frac{\mathrm{d}n}{\mathrm{d}r_{\mathrm{eff}}}$$

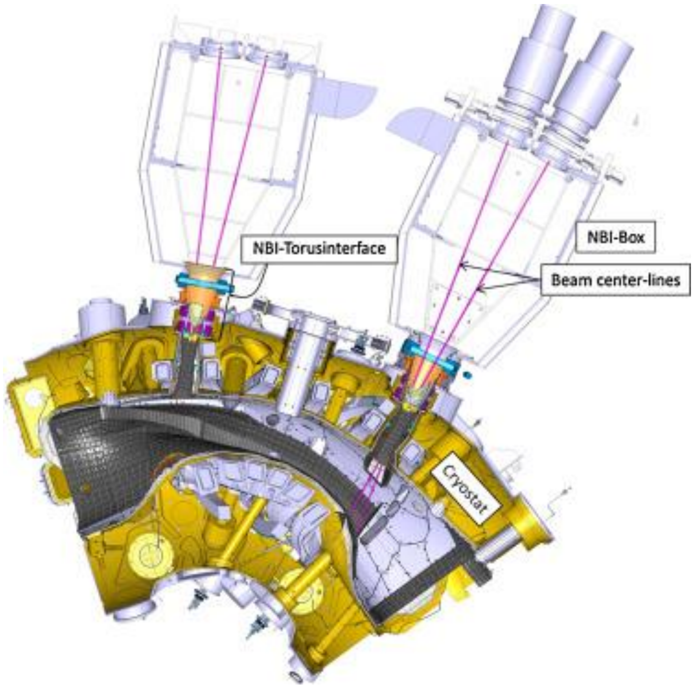
- Ion gyroradius scale
  - Transport normalization
  - gyro-Bohm scaling

$$\chi_{\mathrm{gB}} = \frac{r_L^2\, c_s}{a} \sim \frac{T^{3/2}}{a\, B^2}$$

NBI deposition

- 4 sources, 1.8 MW each
- 10^{20} particles/s
- Broad deposition profile
- Electron and ion heating
- Operational limit 5 s

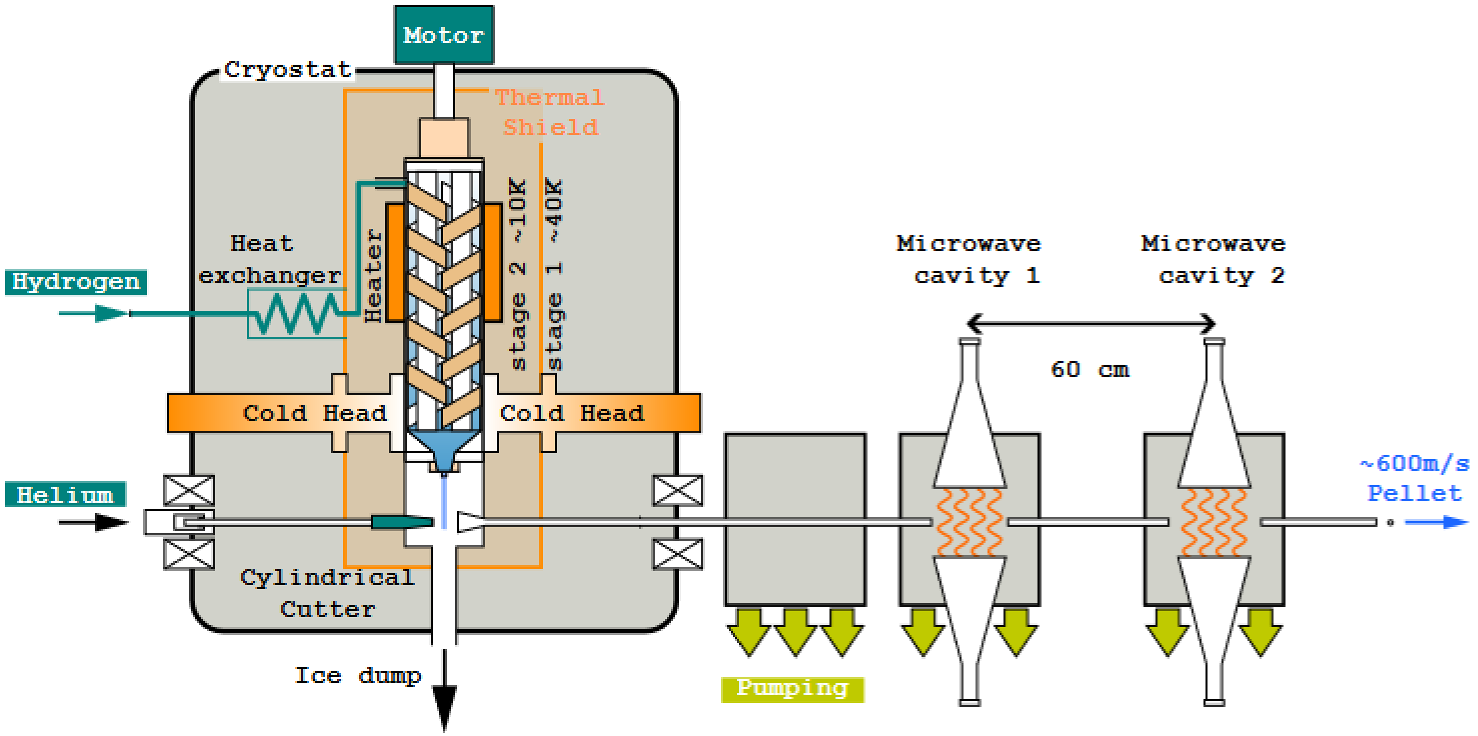
R. Nocentini *et al* 2015 *Fusion Engineering and Design* 100 pp. 453-460



Steady-state pellet injector

- Hydrogen ice pellets
  - 10^{21} amu
- Acceleration by He gas
  - Up to 600 m/s
- Low field side injection
  - 4 Hz for 30 min
- Mass & velocity measured
  - 2 microwave cavities

E.Villalobos 2024



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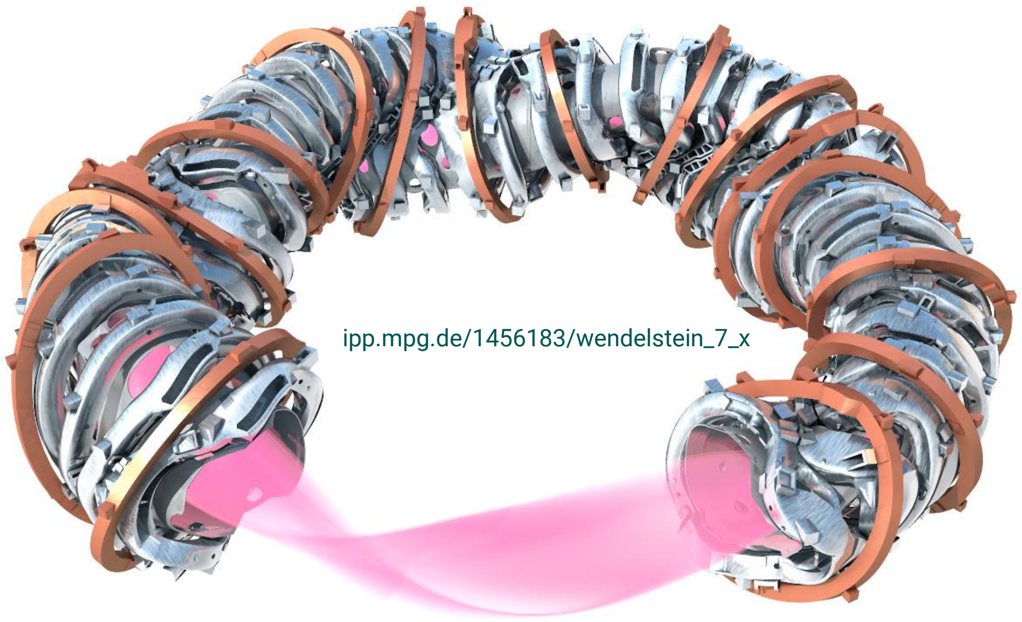
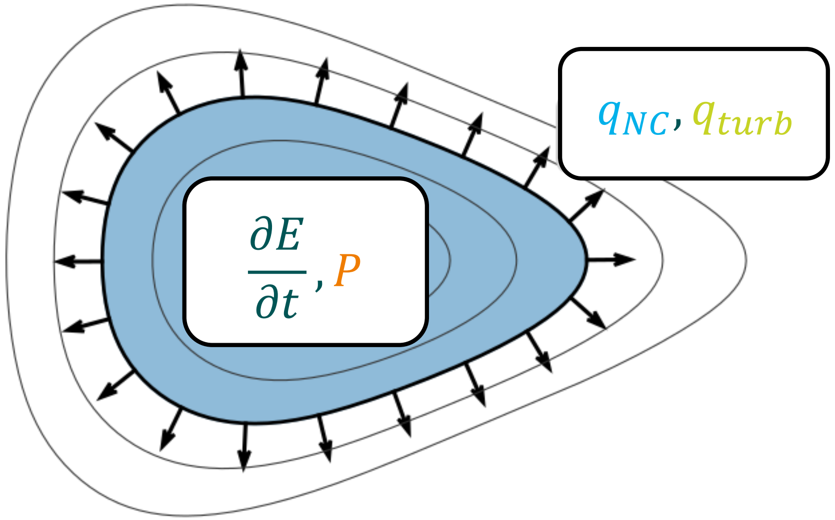


Power balance equation



$$\frac{\partial E_{\text{kin}}}{\partial t} = -(q_{\text{NC}} + q_{\text{turb}})V' + P_{\text{heat}} + P_{\text{exchange}} - P_{\text{rad}}$$

$$\chi_e = -\frac{q_{\text{turb},e}}{n_e T_e'}$$

$$\chi_i = -\frac{q_{\text{turb},i}}{n_i T_i'}$$

$$\chi_{\text{eff}} = -\frac{q_{\text{turb}}}{n_e T_e' + n_i T_i'}$$

- Turbulent transport coefficients
  - Diffusive model
  - Neoclassical transport subtracted
  - Figures of merit for turbulence
- Diagnostic limitation where $T_e \approx T_i$
  - Only χ_{eff} available

O. P. Ford, *et al. Rev. Sci. Instrum.* 2020; 91 (2): 023507

Power balance analysis

- Requires
  - Plasma profiles
  - Heating sources & sinks

- Thomson scattering
- CXRS/XICS
  - Chosen for each discharge

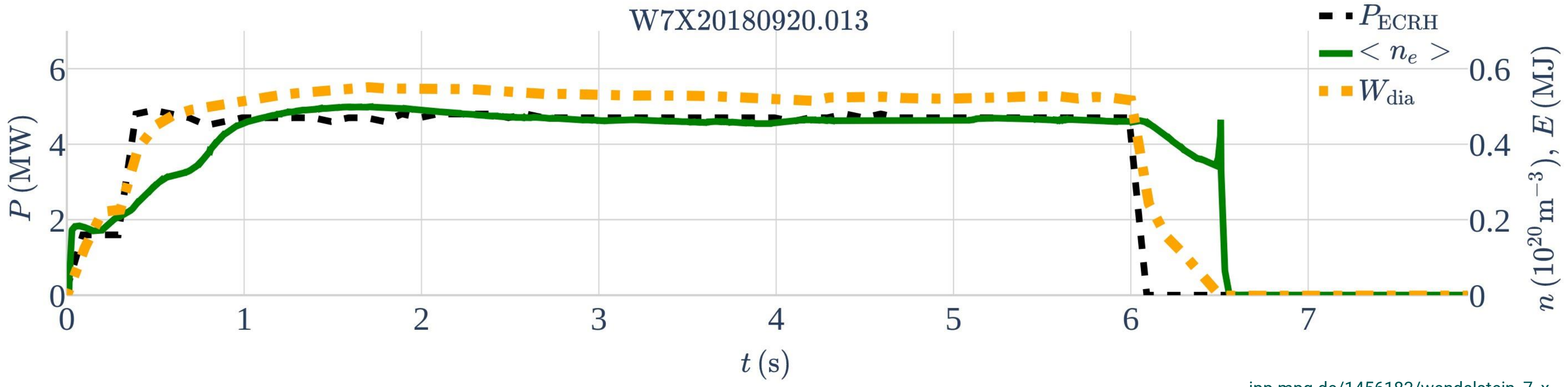
- Fitting in Profile Cooker app
  - Lowess fits
  - MC sampling of profile uncertainty

- ECRH gauss-shaped deposition
- NBI collisional-radiative beam model

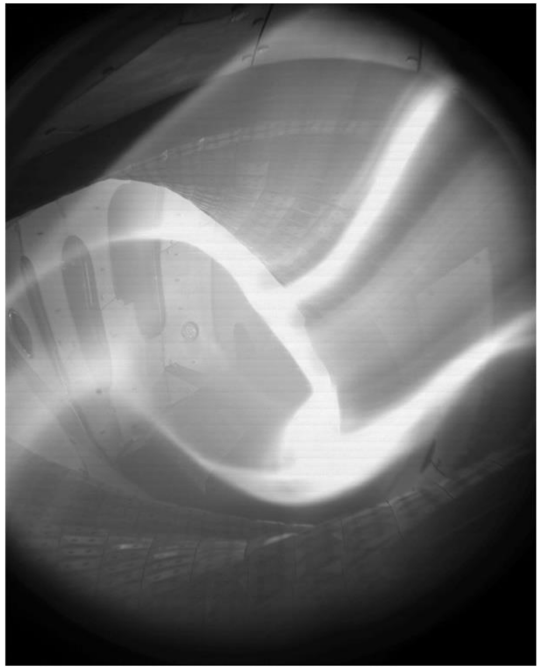
- Radiated power bolometer tomography

- Neotransp code
  - Neoclassical fluxes and electric field

- Power Balance equation
  - Solved in Power House app

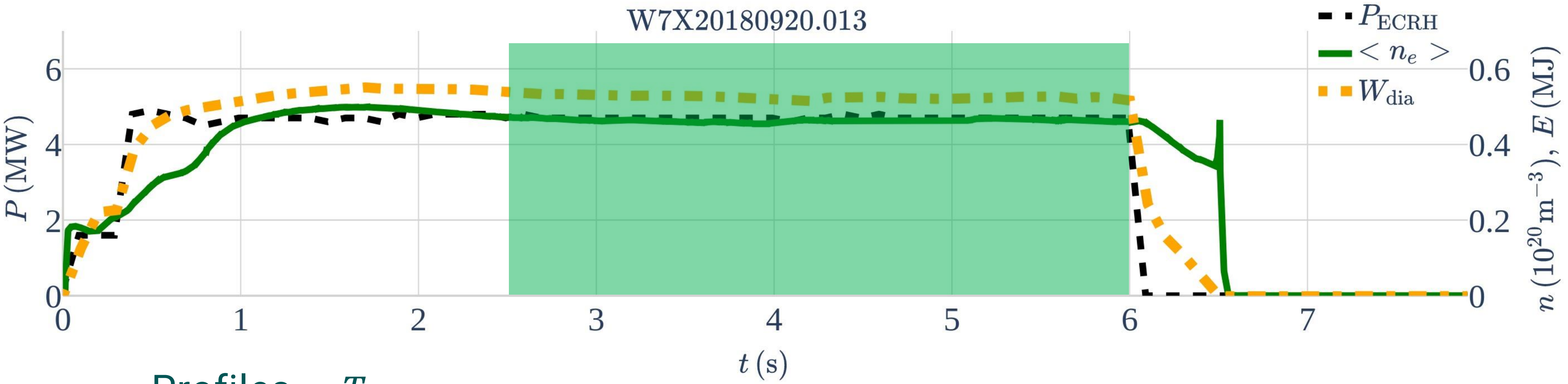


ipp.mpg.de/1456183/wendelstein_7_x



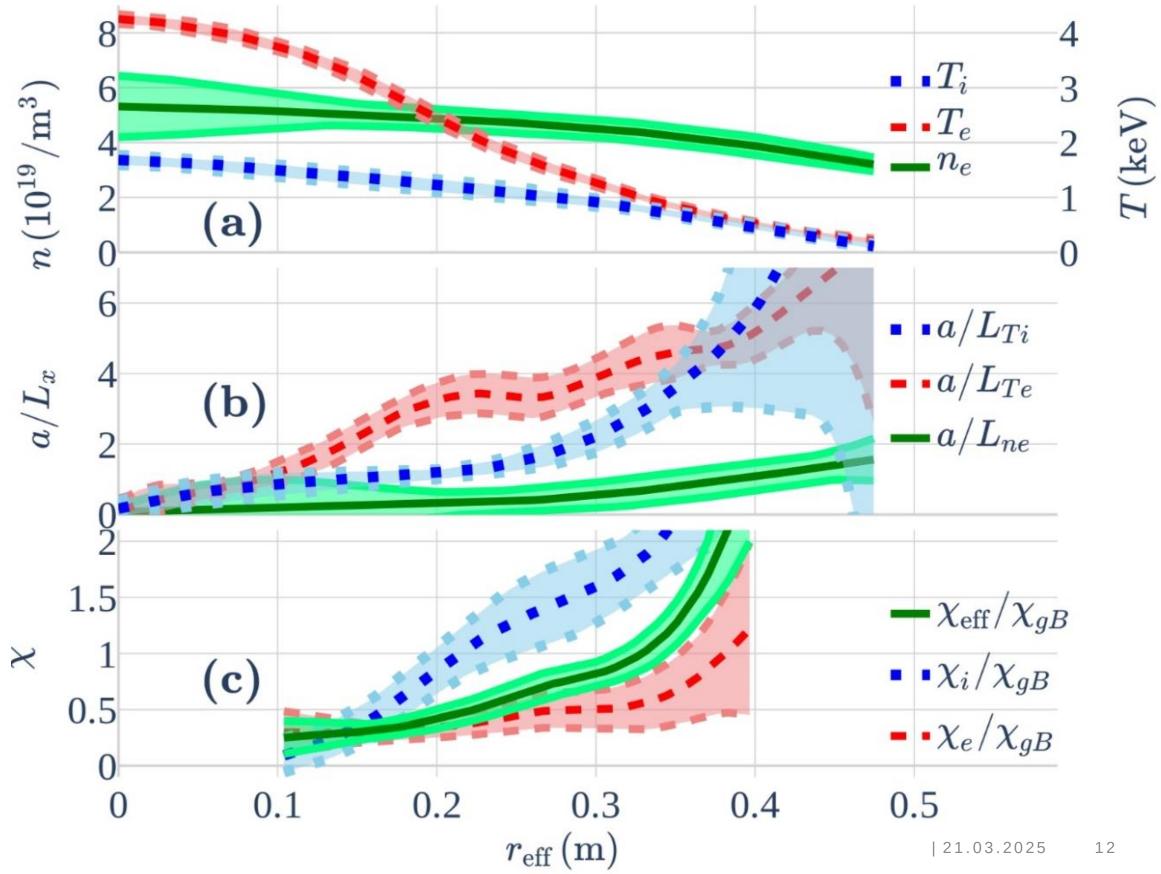
- Compare time traces
  - Heating power $P_{\mathrm{ECRH}}, P_{\mathrm{NBI}}$
  - Average electron density $< n_e >$
  - Stored energy W_{dia}

- Each discharge number indicated



- Profiles n, T
- Gradients a/L_x
- Turbulent transport coefficients χ

- Stationary plasma
  - Flat density profile
  - Ion temperature clamping
  - No turbulence suppression
- Benchmark case



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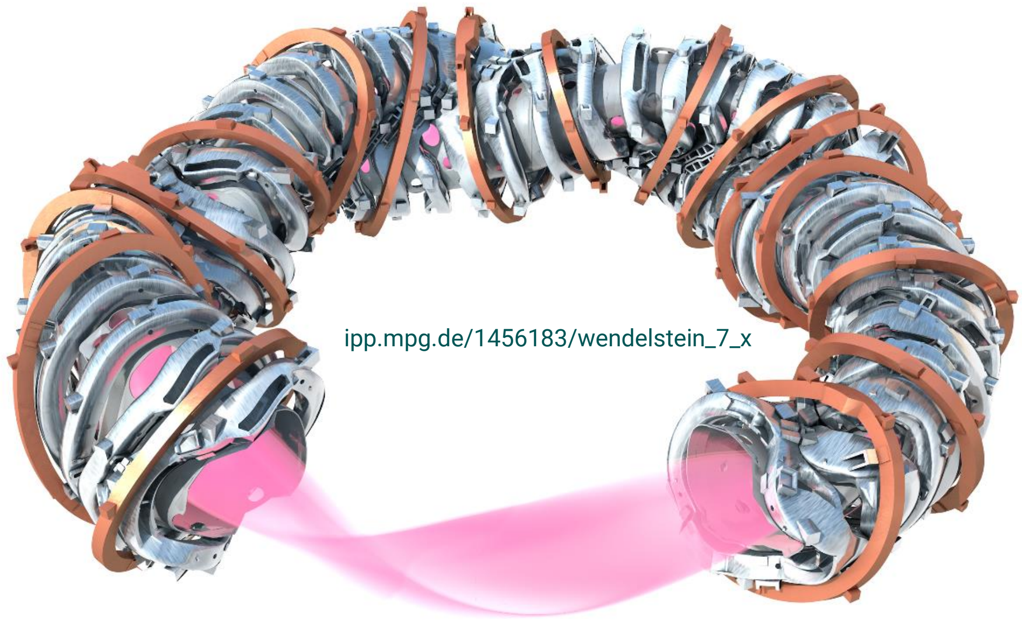
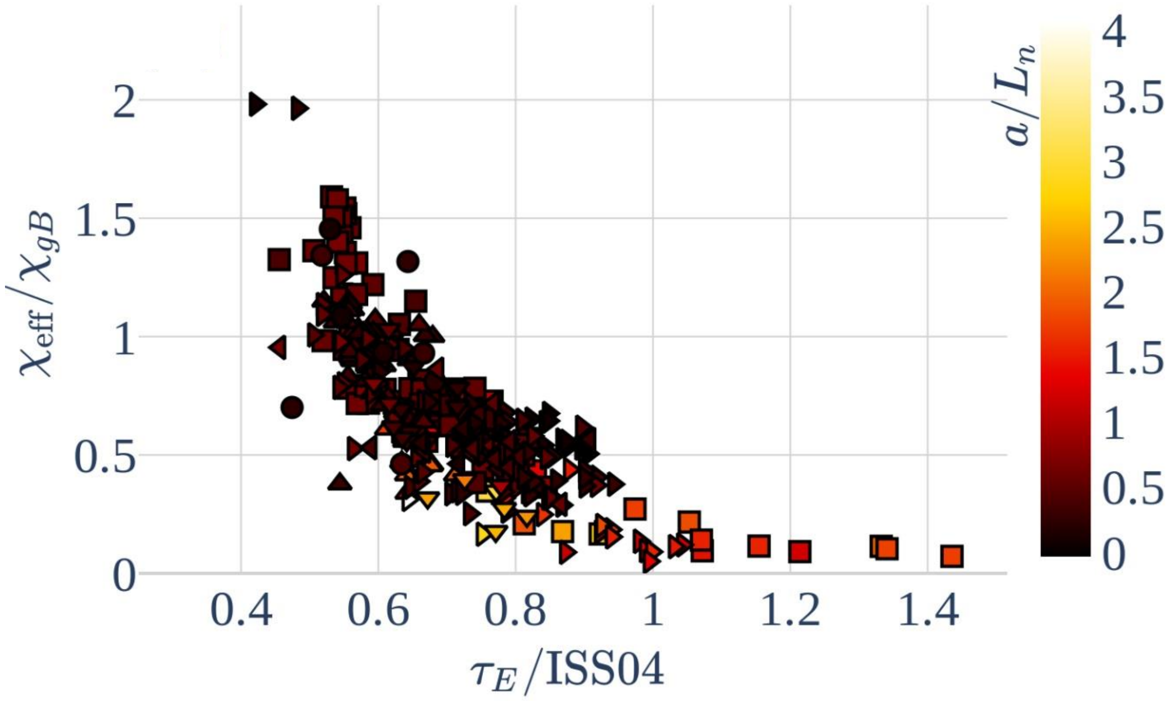

ipp.mpg.de/1456183/wendelstein_7_x

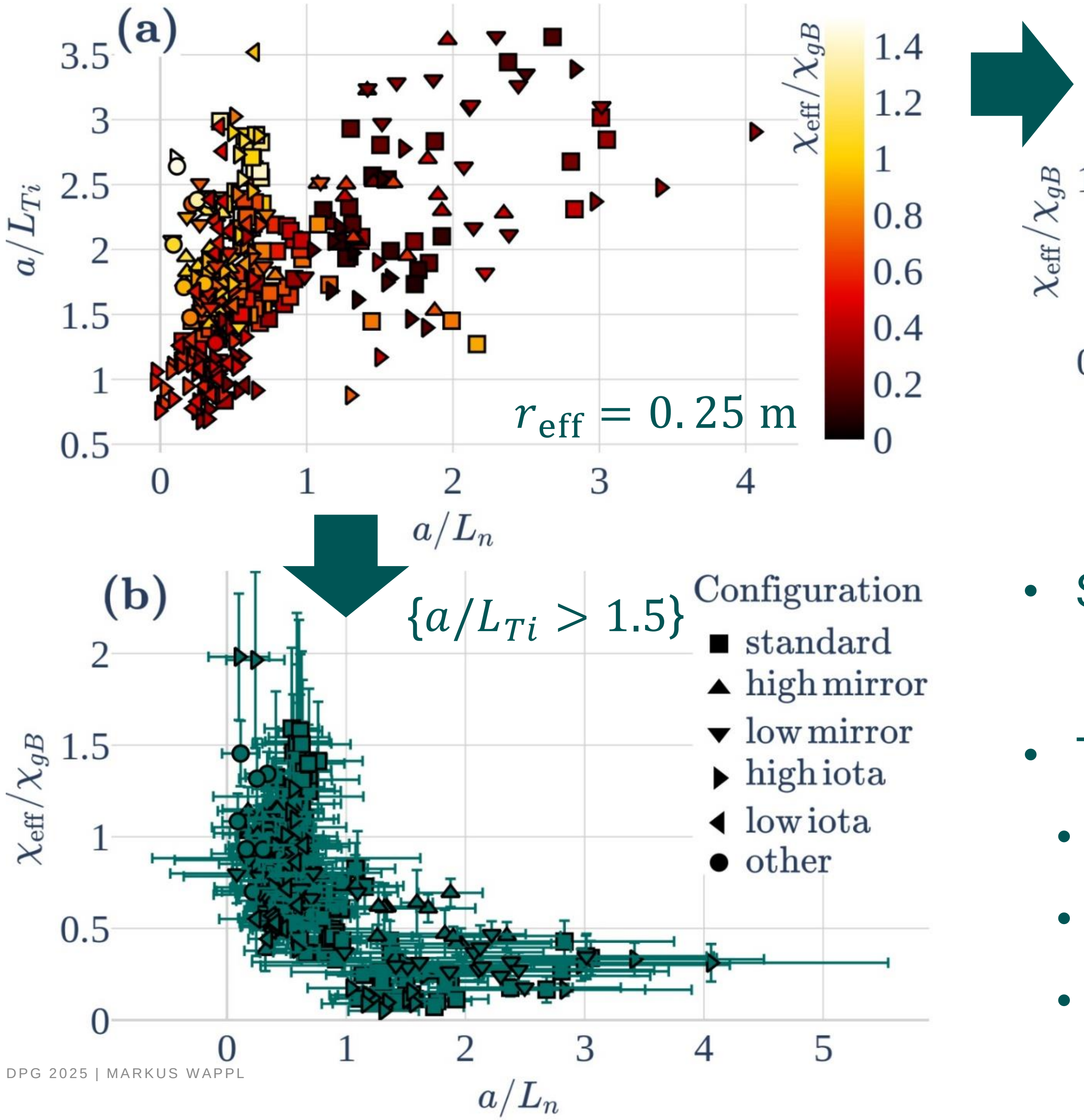
Power balance database

- 383 points from 164 discharges
  - Main gas hydrogen
- Evaluated at $r_{\mathrm{eff}} = 0.25\ \mathrm{m}$
  - Large stored energy & gradients
- Turbulent transport
  - Normalized to gyro-Bohm
- Confinement time
  - Normalized to ISS04
  - Separate from power balance
- Inversely proportional $\chi_{\mathrm{eff}}/\chi_{\mathrm{gB}} \sim 1/(\tau_E/\mathrm{ISS04})$



Ulrich Stroth 1998 *Plasma Phys. Control. Fusion* **40** 9

Power balance database

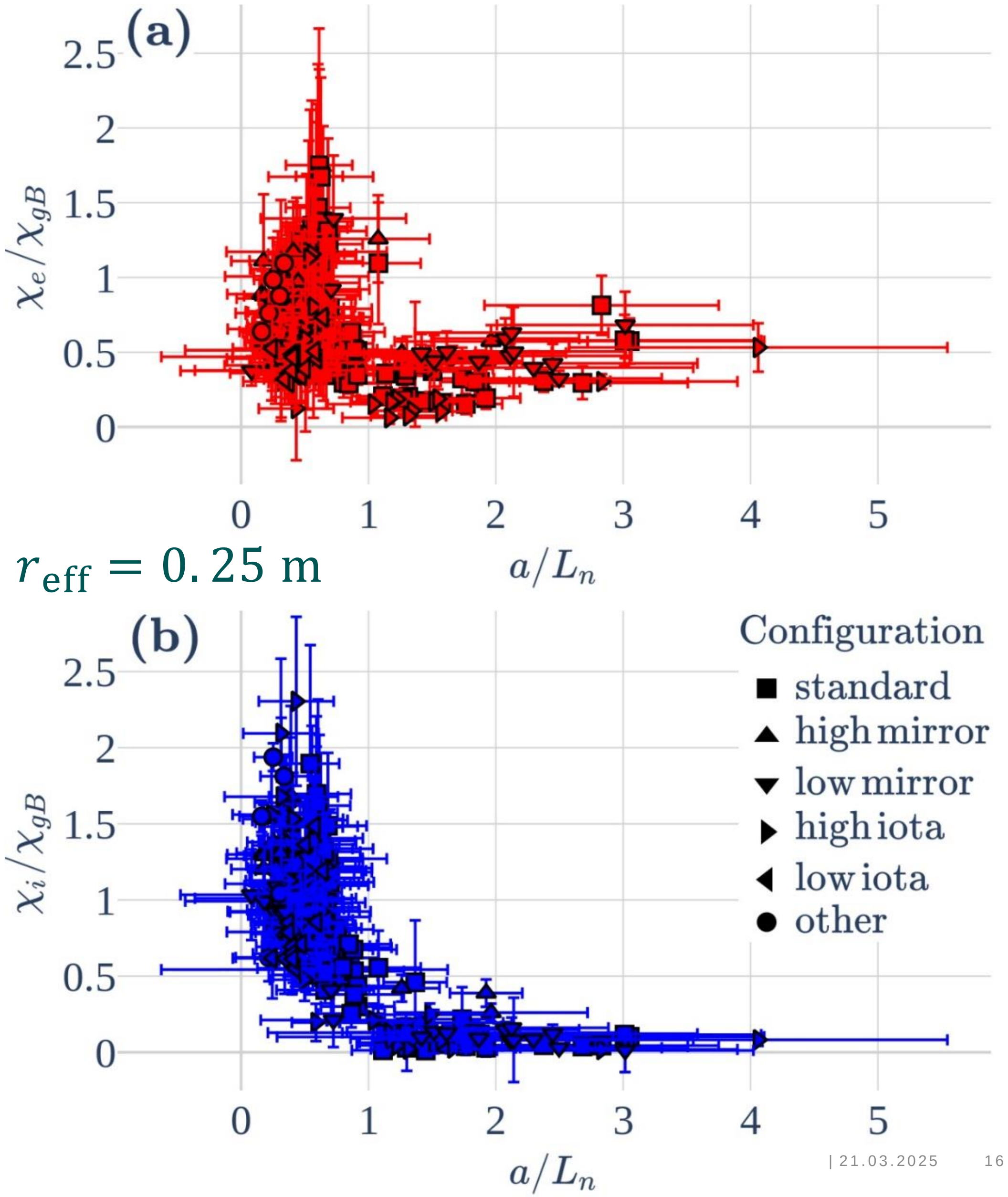


- Slicing 2-D plot a/L_{Ti} = 1.5, a/L_n = 1

- Turbulence suppression
  - With density gradient
  - Trend with ion temperature gradient
  - No clear configuration dependence

Density gradient effect

- Electron and ion channel
  - Reduced dataset
  - 316 points from 146 discharges
- Turbulence suppression a/L_n > 1
  - Electron channel remains at 0.5 gB
  - Ion channel suppressed to near 0
- Consistent to ITG modes
  - Remaining electron transport not clarified



$r_{\mathrm{eff}} = 0.25$ m

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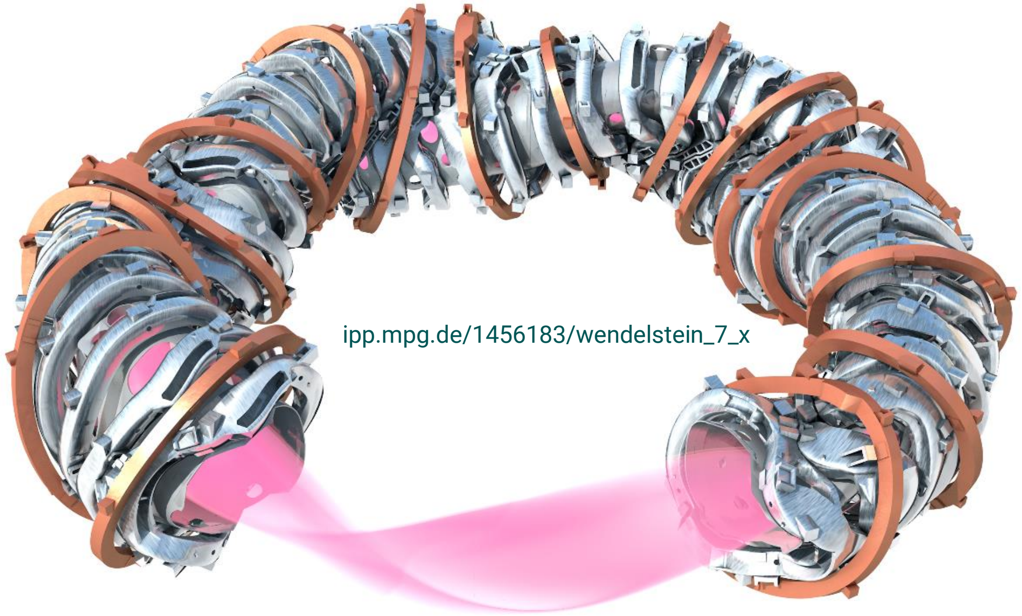

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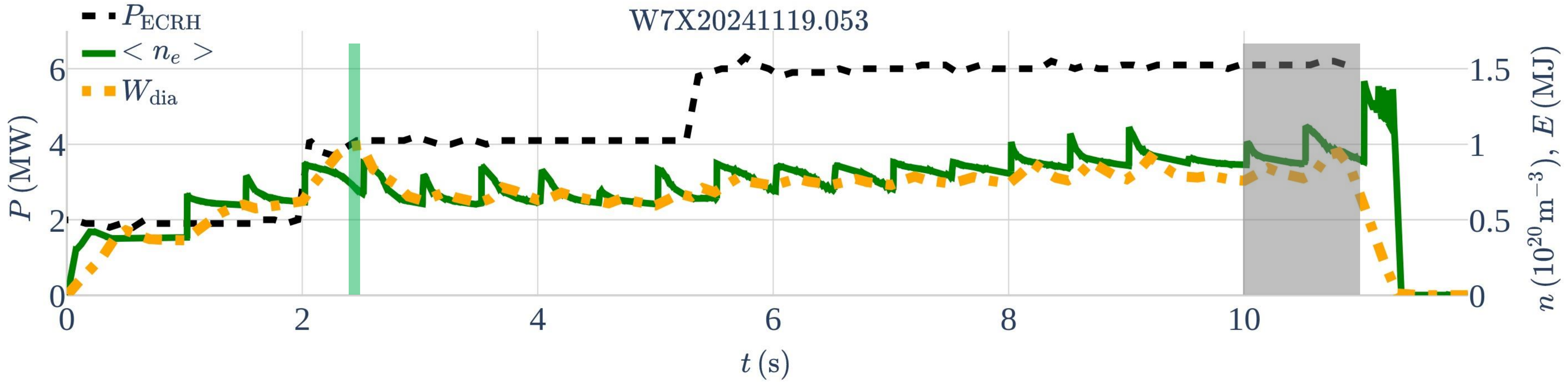
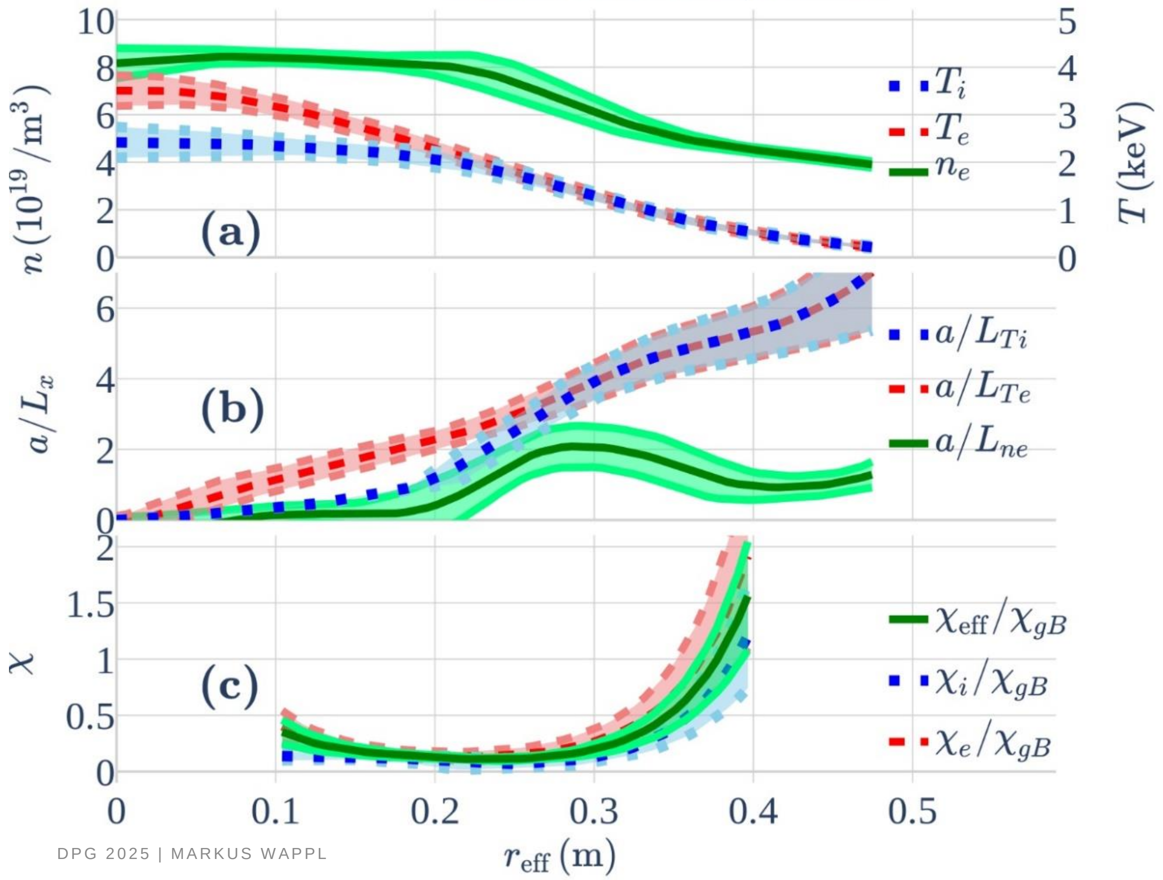
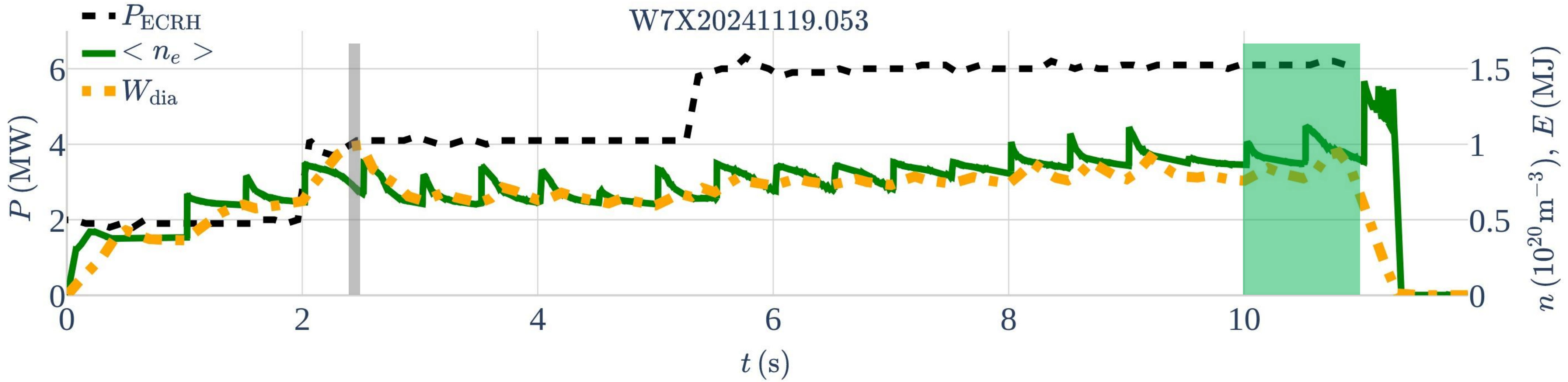


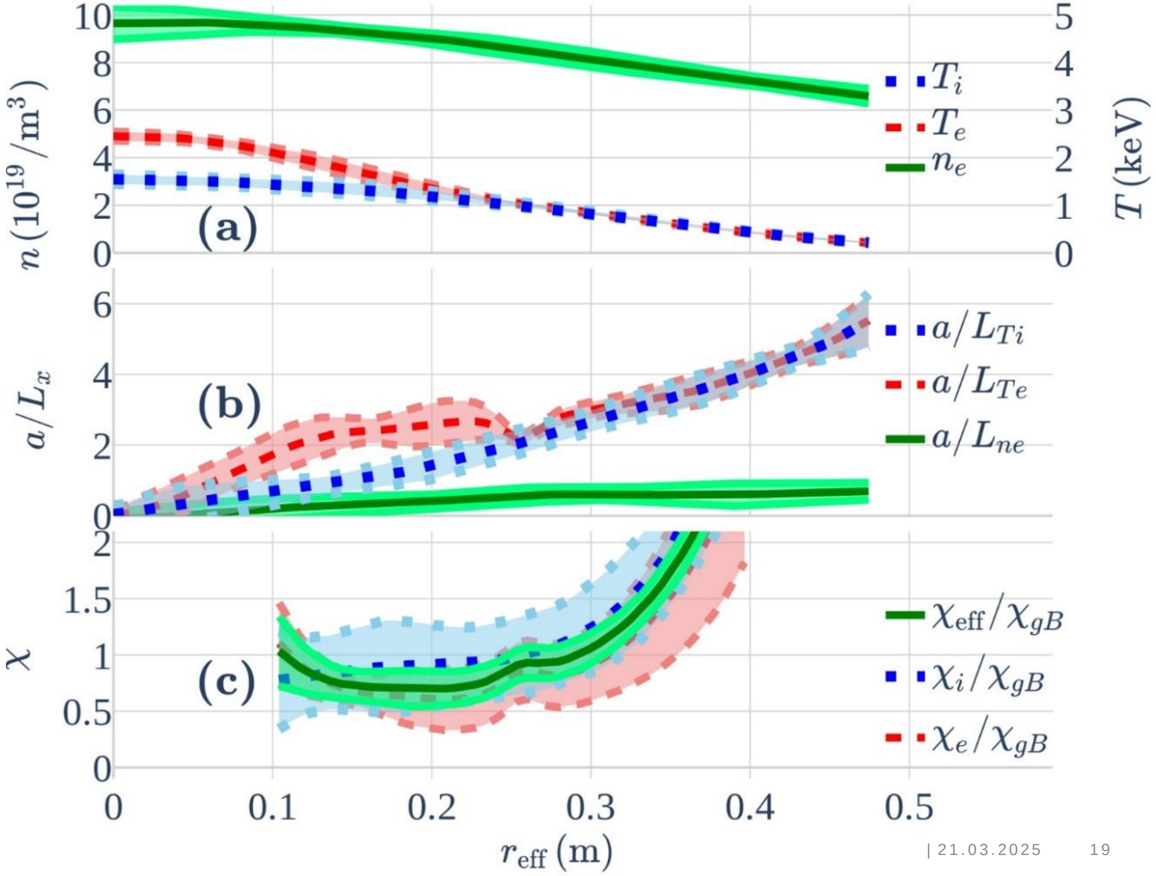


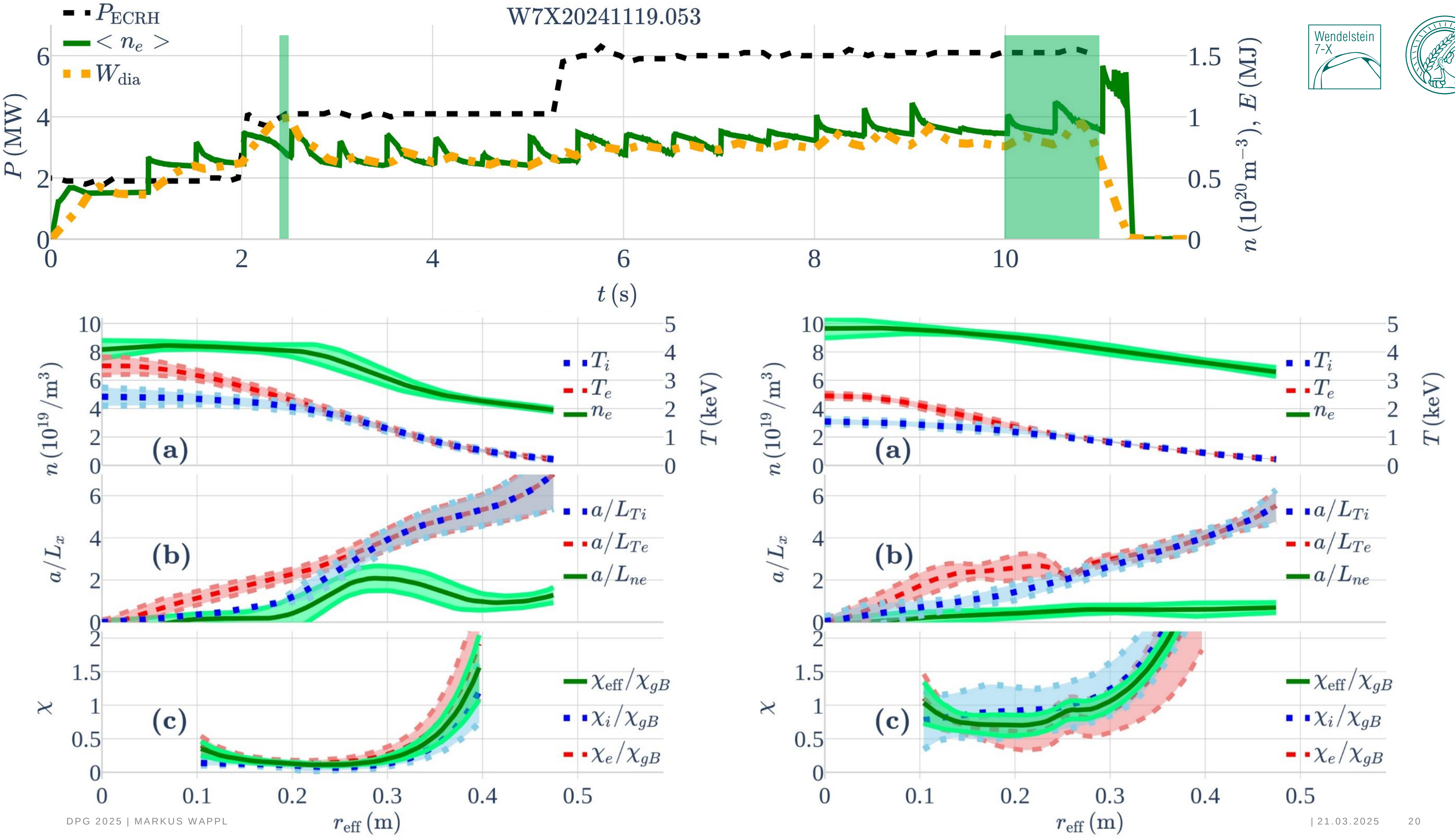
- Pellet injection
- ECRH power step-up

- Pronounced density gradient
- Short maximum stored energy
- 2.5 keV ion temperature
- Reduced turbulent transport
  - Especially in ion channel

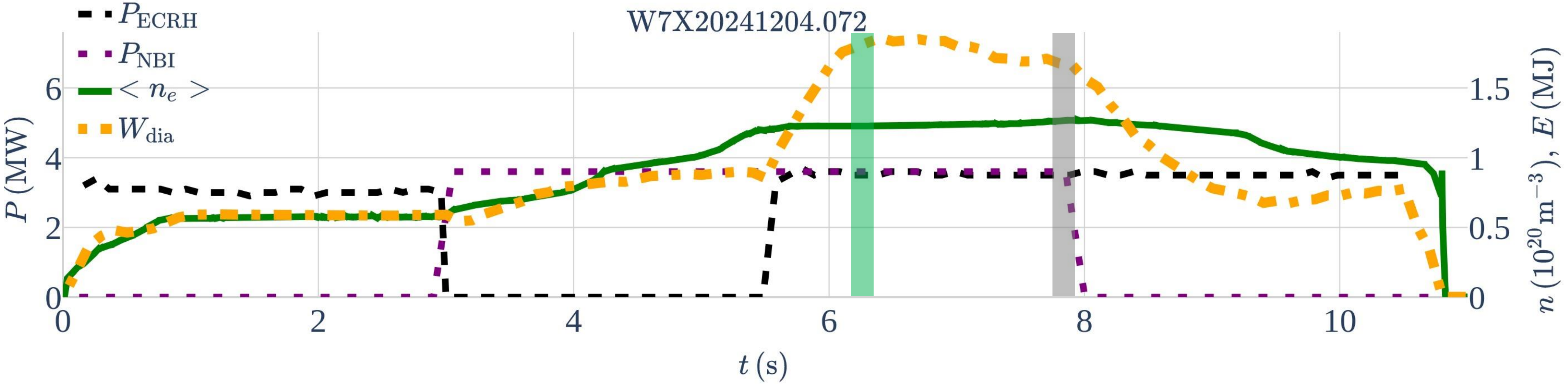


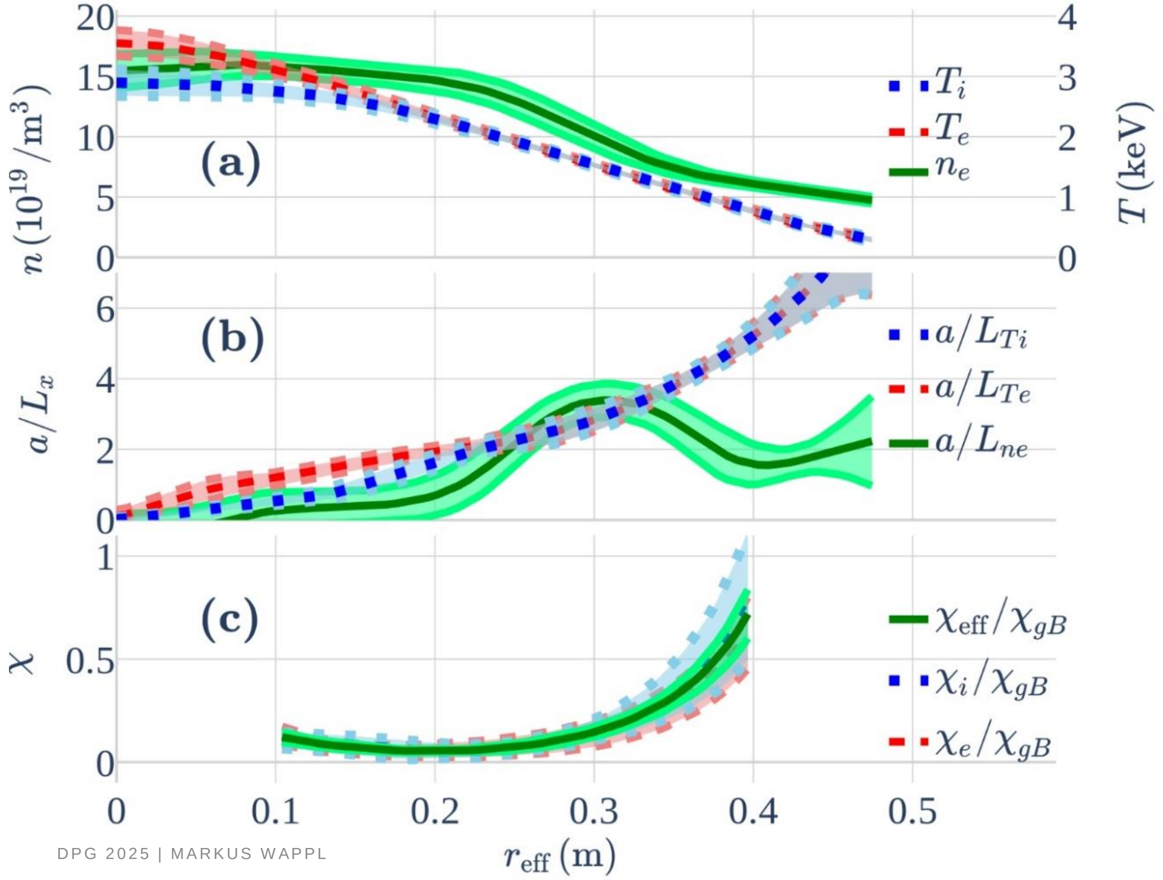
- Continuous pellet injection
- Density gradient collapsed
  - ECRH pump-out effect
- Return to conventional
  - Ion temperature
  - Turbulent transport





W7X20241119.053
P_{ECRH}
$< n_e >$
W_{dia}
$P\,(\mathrm{MW})$
$n\,(10^{20}\mathrm{m}^{-3}),\ E\,(\mathrm{MJ})$
$t\,(\mathrm{s})$
(a)
(b)
(c)
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
T_i
T_e
n_e
a/L_x
a/L_{Ti}
a/L_{Te}
a/L_{ne}
χ
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$r_{\mathrm{eff}}\,(\mathrm{m})$

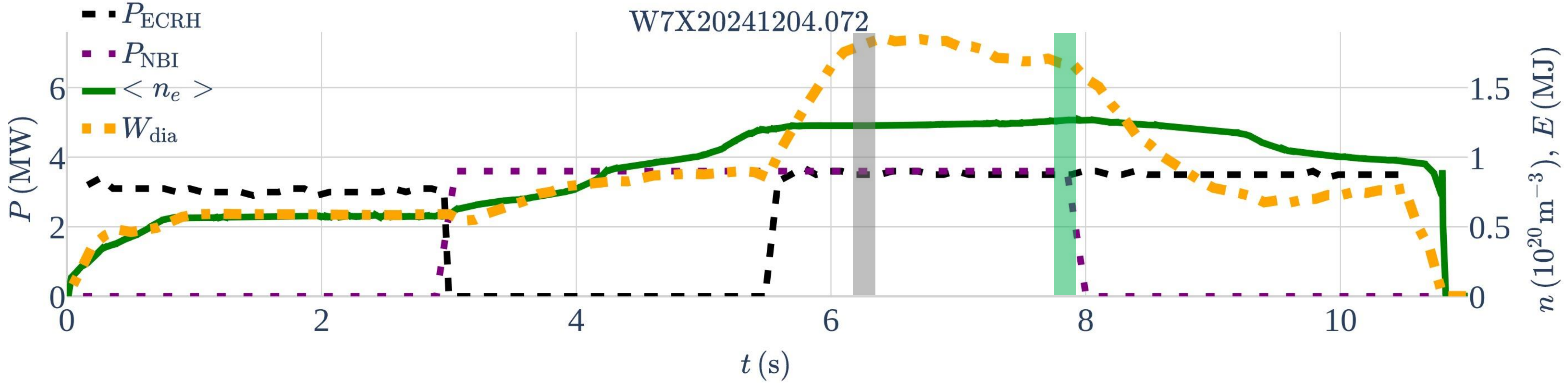




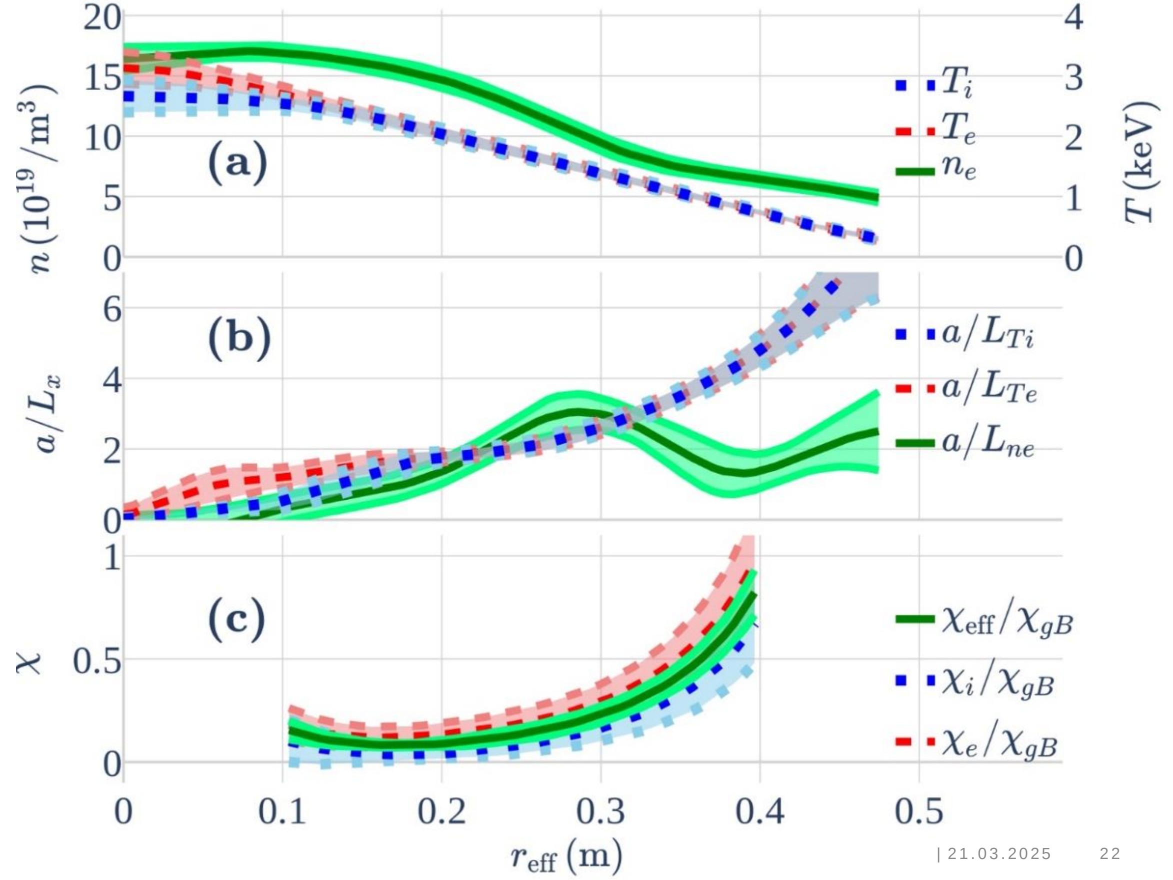
- Pure NBI phase 2 s
- ECRH reintroduction

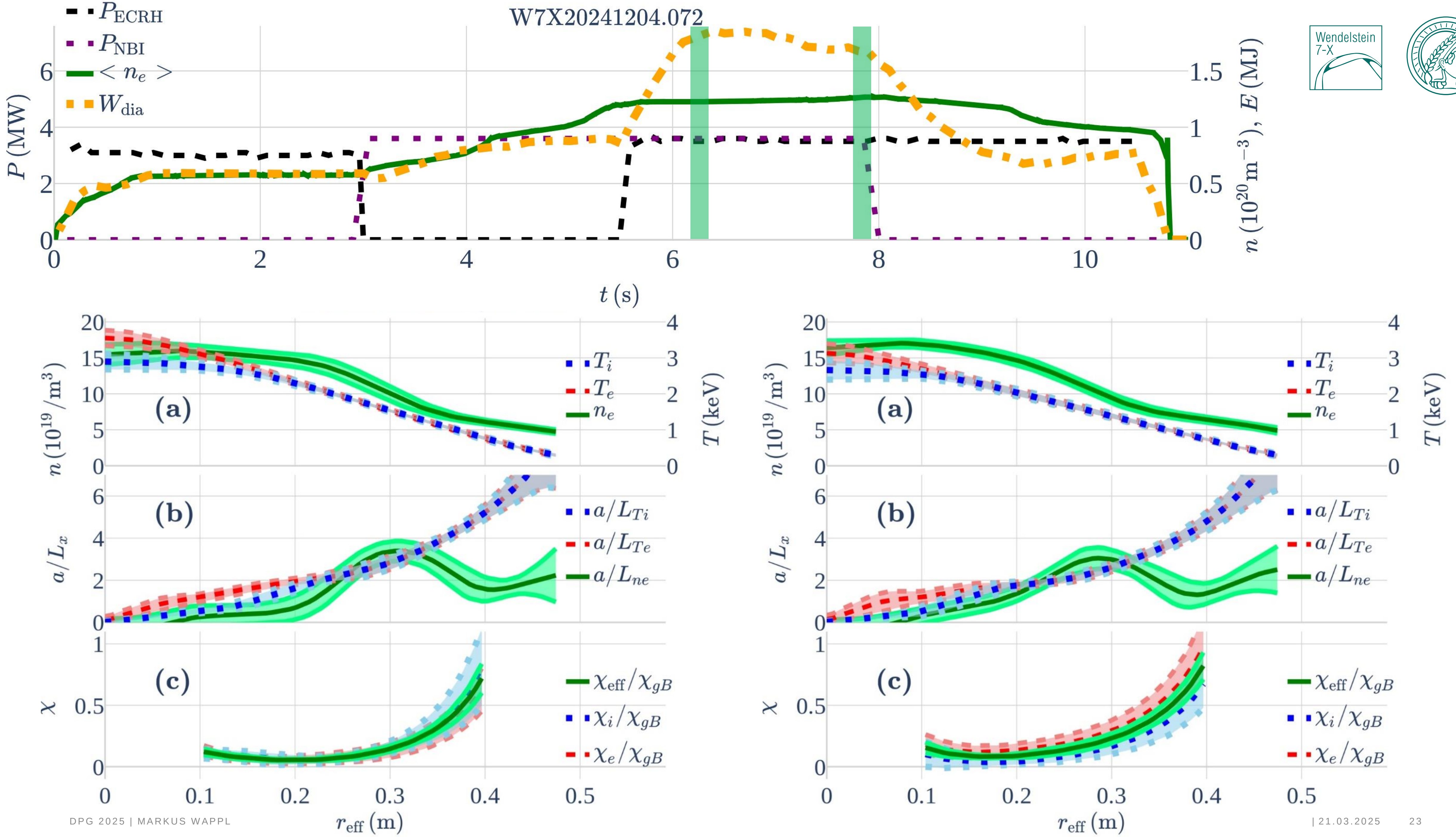
- Strong density gradient
- 3 keV ion temperature
- Turbulence suppression

- Record stored energy 1.8 MJ

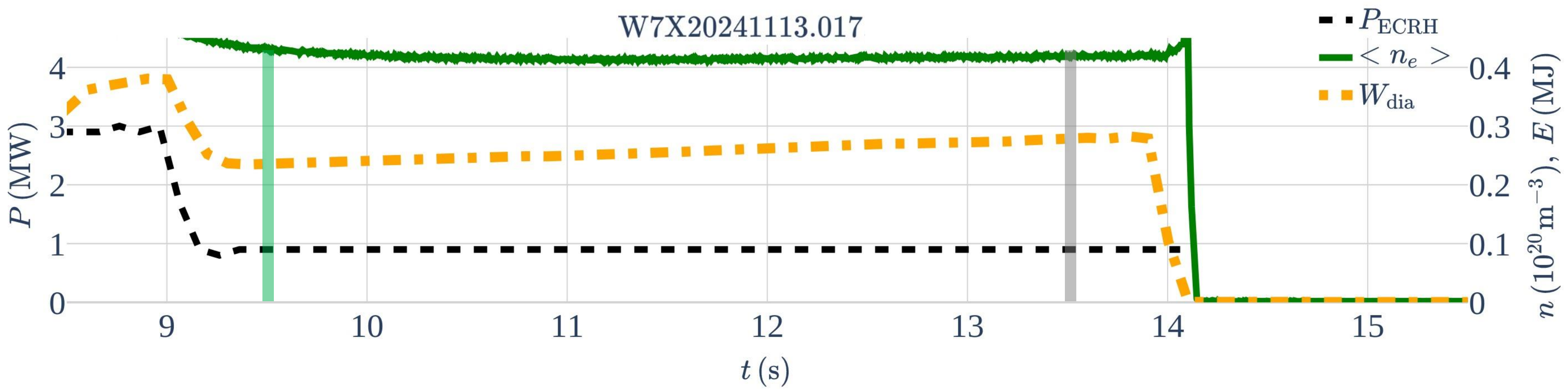


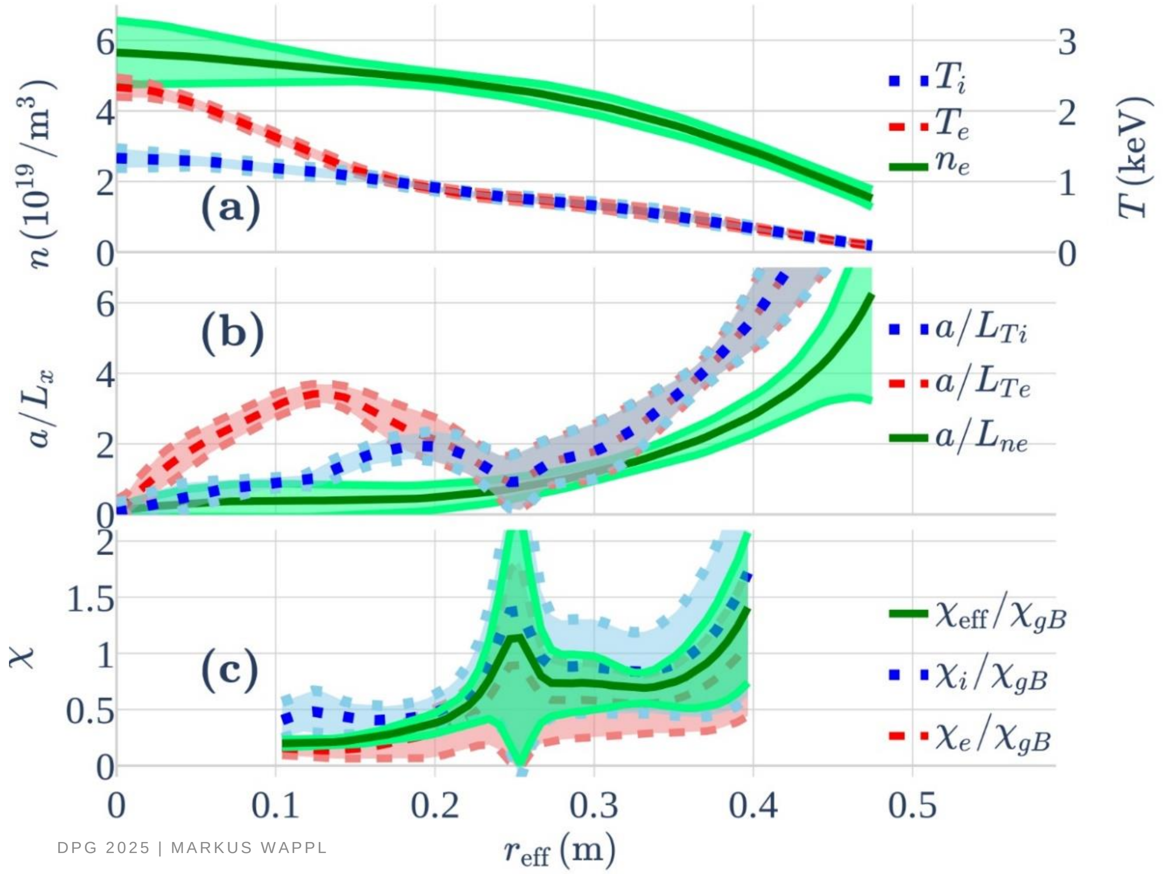
- Constant average density and gradient
  - Balance between fueling and pump-out
- 2.5 keV ion temperature
- Steady-state turbulence suppression
- NBI limited to 5 s
  - Loss of stored energy afterwards





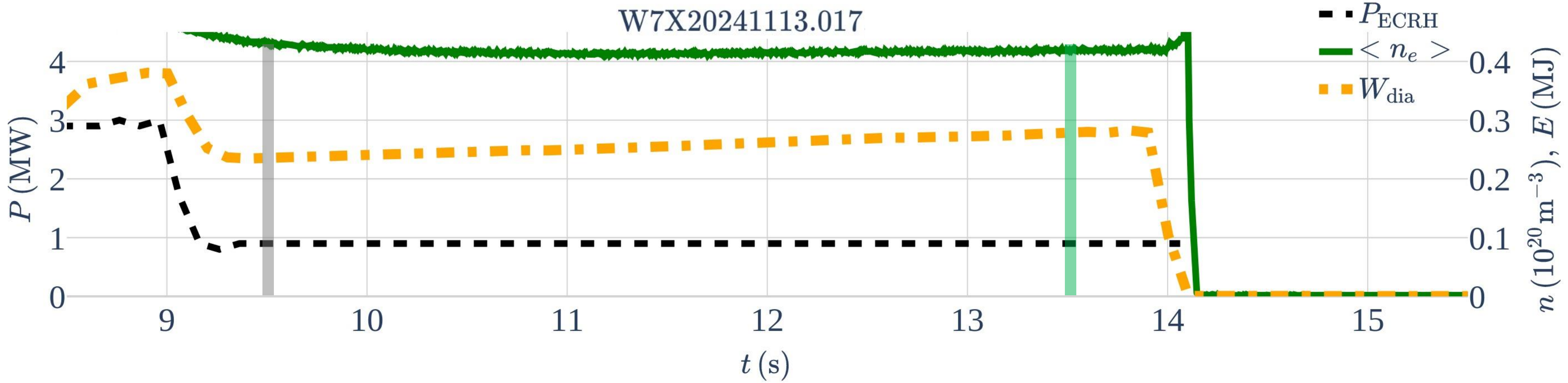
W7X20241204.072
P_{ECRH}
P_{NBI}
$< n_e >$
W_{dia}
P (MW)
$n\,(10^{20}\mathrm{m}^{-3}),\ E$ (MJ)
t (s)
(a)
(b)
(c)
T_i
T_e
n_e
$n\,(10^{19}/\mathrm{m}^3)$
T (keV)
a/L_{Ti}
a/L_{Te}
a/L_{ne}
a/L_x
χ_{eff}/χ_{gB}
χ_i/χ_{gB}
χ_e/χ_{gB}
χ
r_{eff} (m)



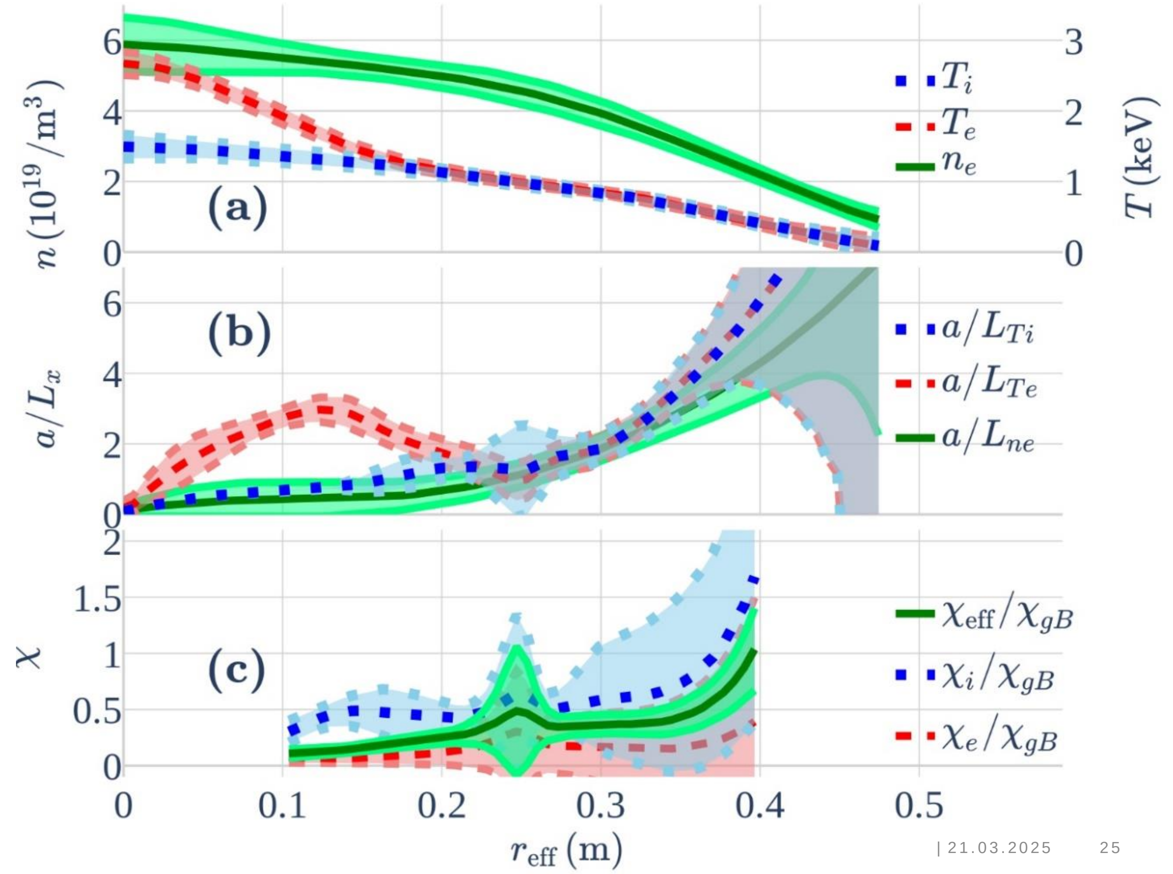


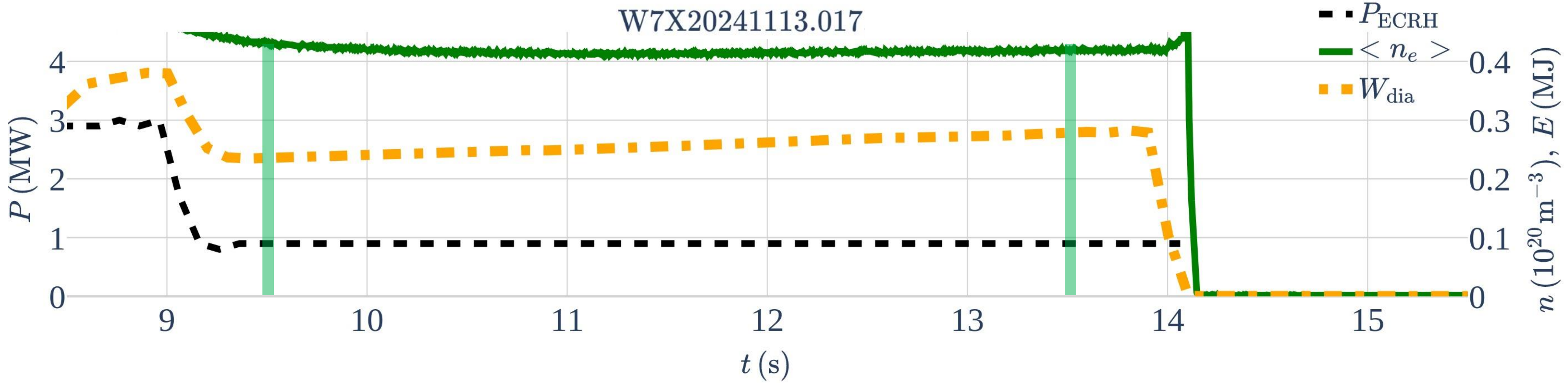
- Wall conditioning with boron
- High iota configuration
- Low heating power

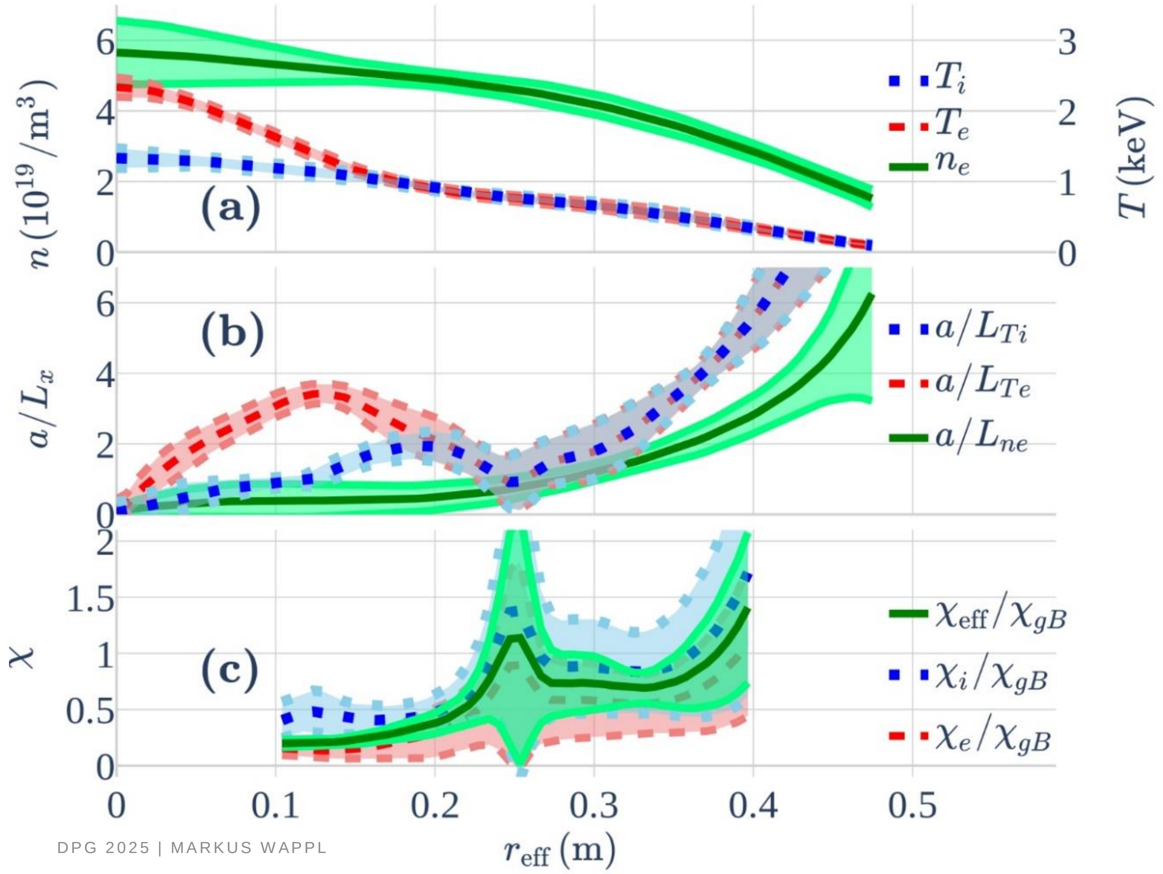
- Stationary inputs
  - Growing stored energy

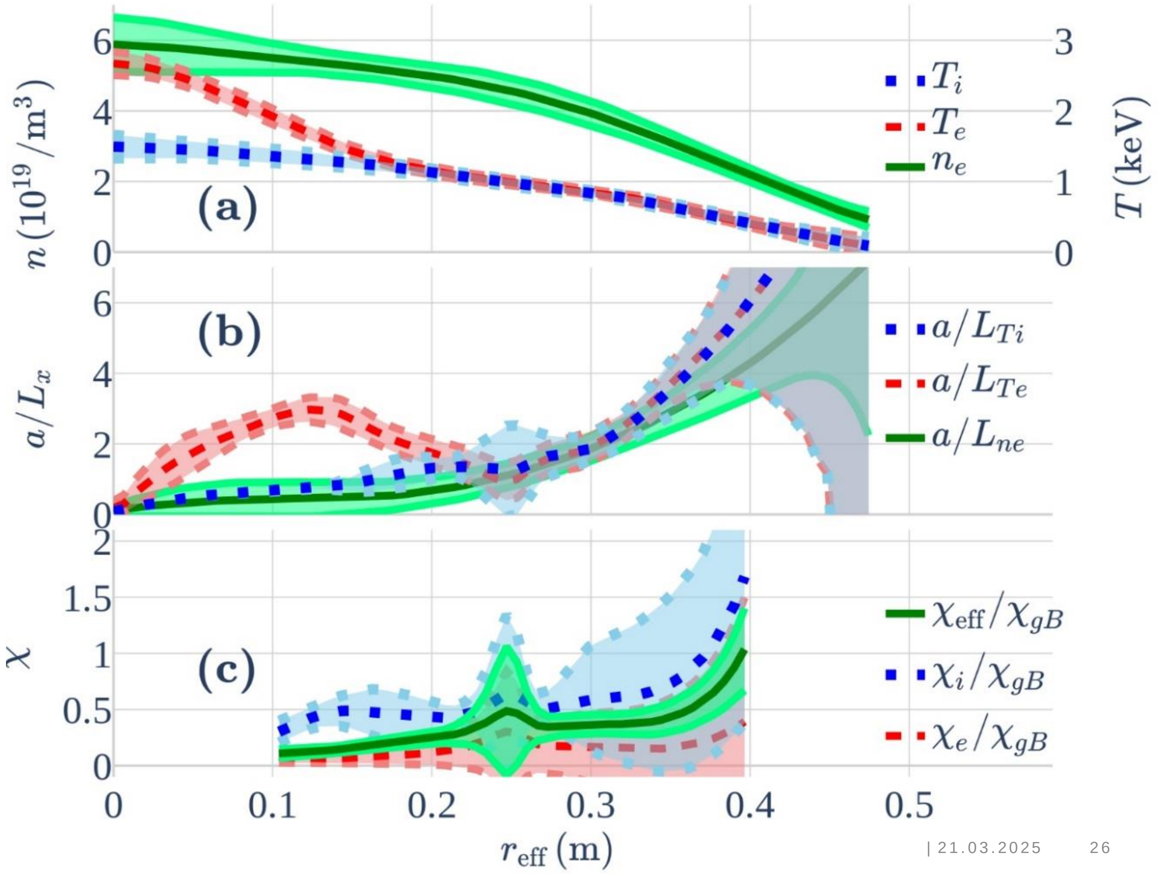


- Density gradient forms over time
  - Self-ordering
  - Observed only in high iota
- Partial turbulence suppression
- Explains growing energy
- 475 ms confinement time




W7X20241113.017
P_{ECRH}
$< n_e >$
W_{dia}
$P\,(\mathrm{MW})$
$n\,(10^{20}\,\mathrm{m}^{-3}),\ E\,(\mathrm{MJ})$
$t\,(\mathrm{s})$


(a)
(b)
(c)
T_i
T_e
n_e
a/L_{Ti}
a/L_{Te}
a/L_{ne}
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
a/L_x
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$


(a)
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T_i
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χ_i/χ_{gB}
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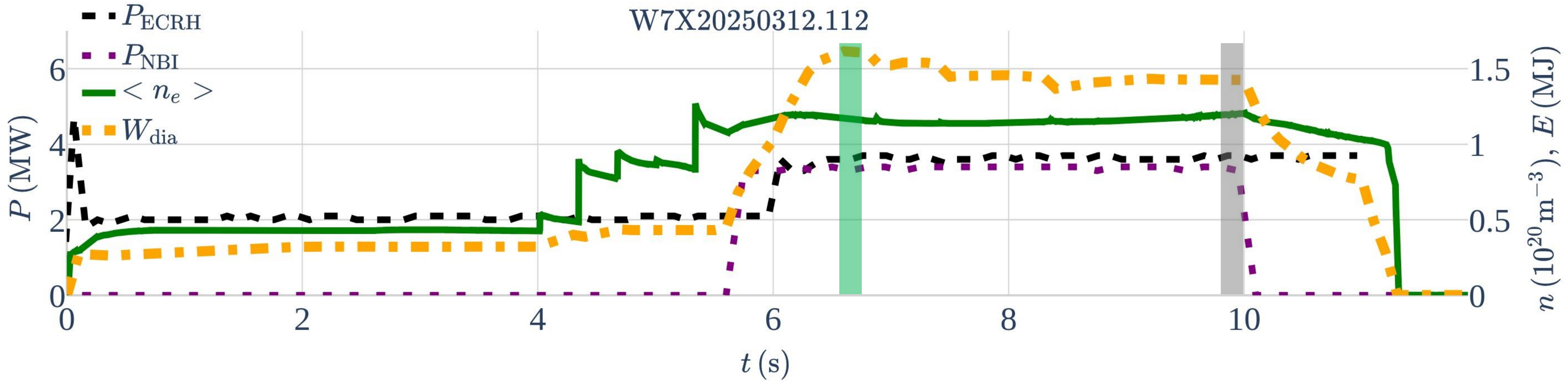
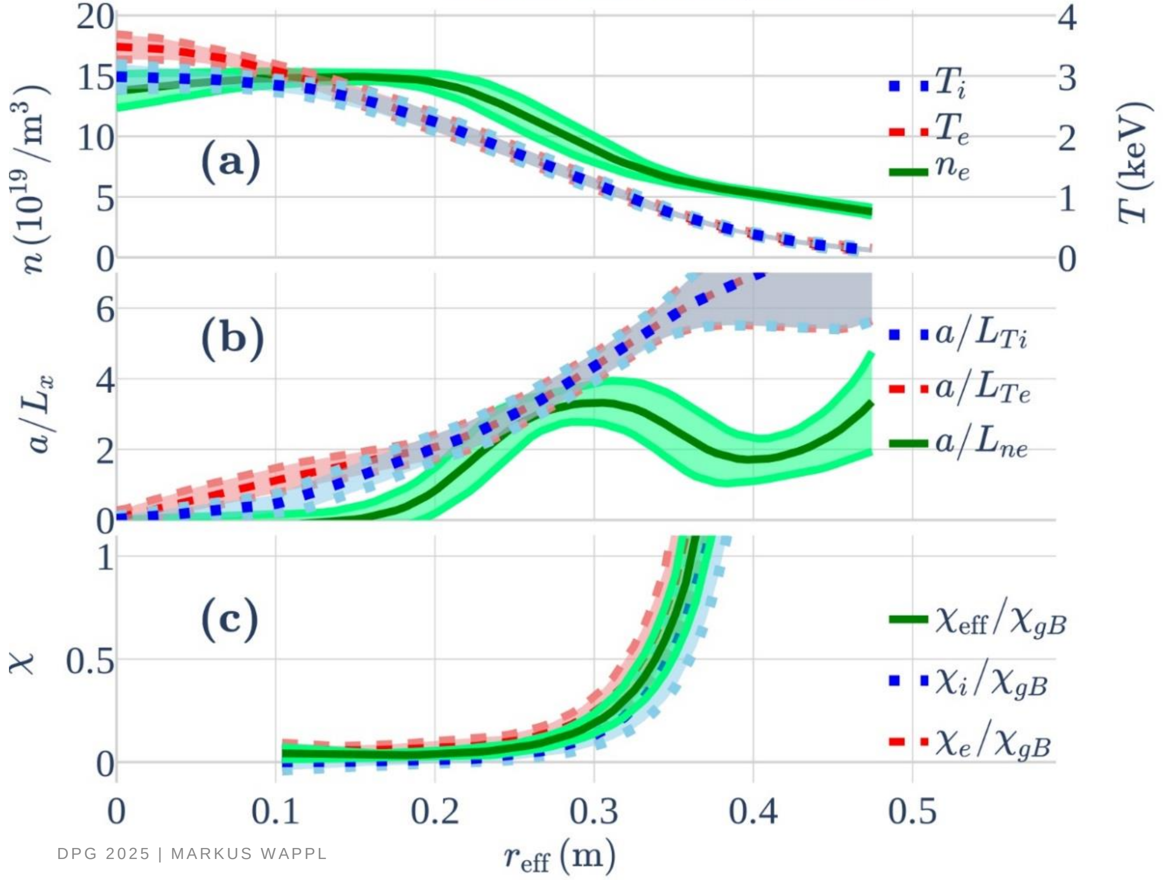
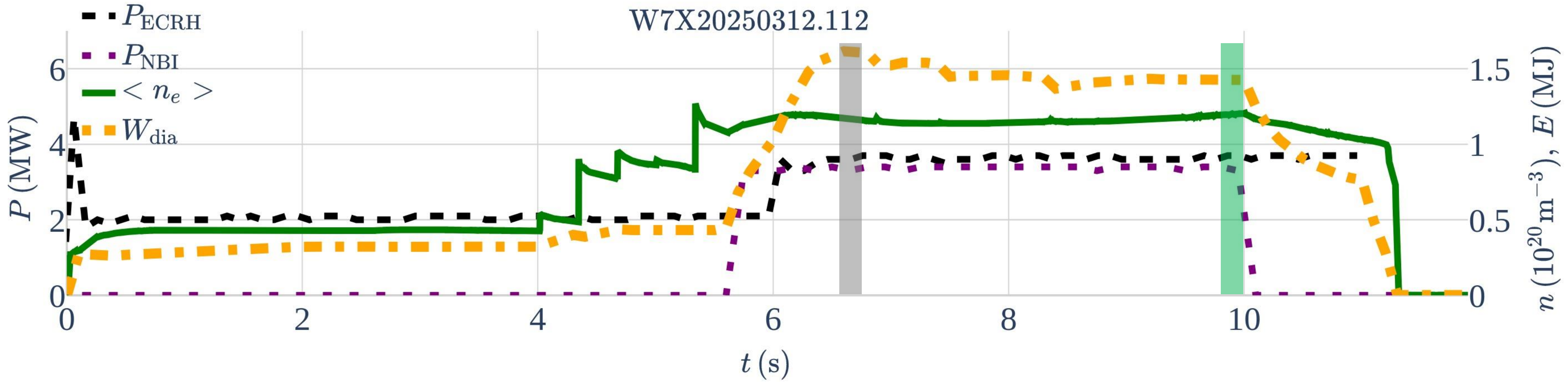


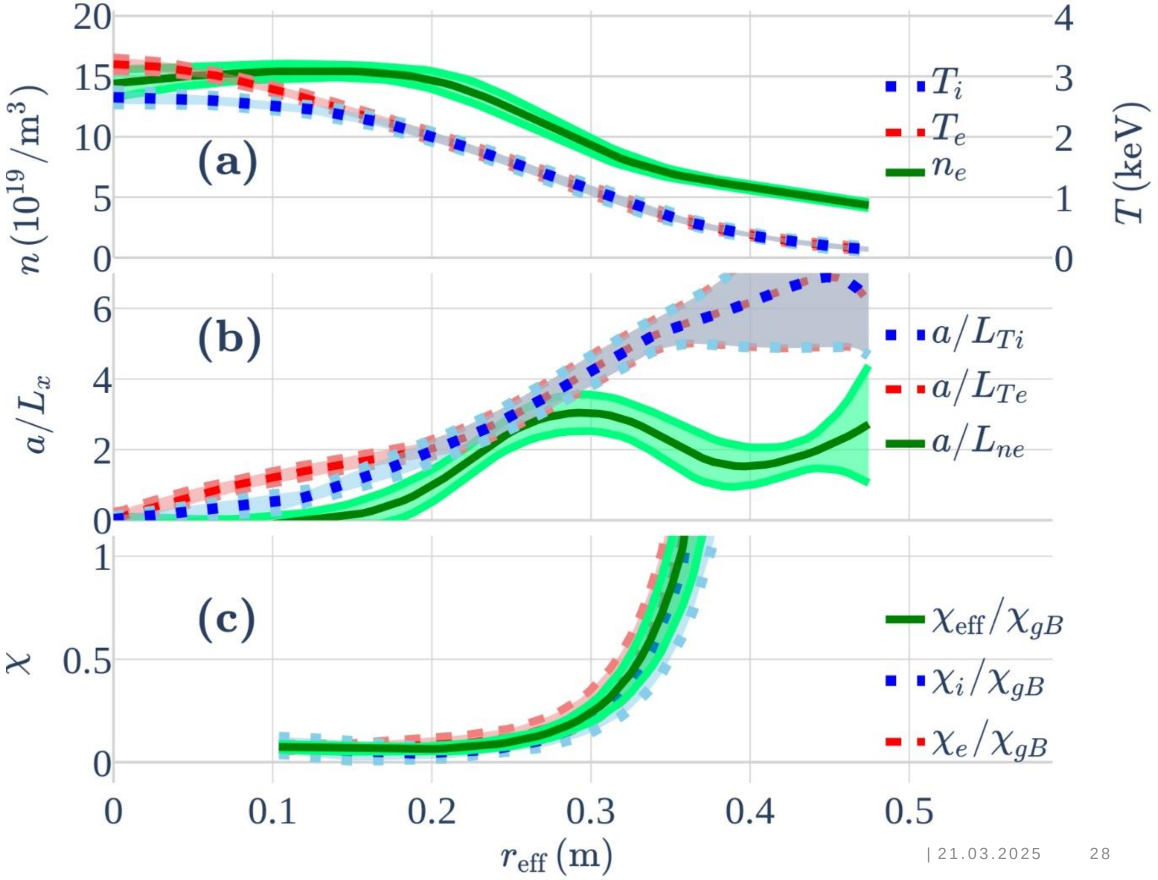


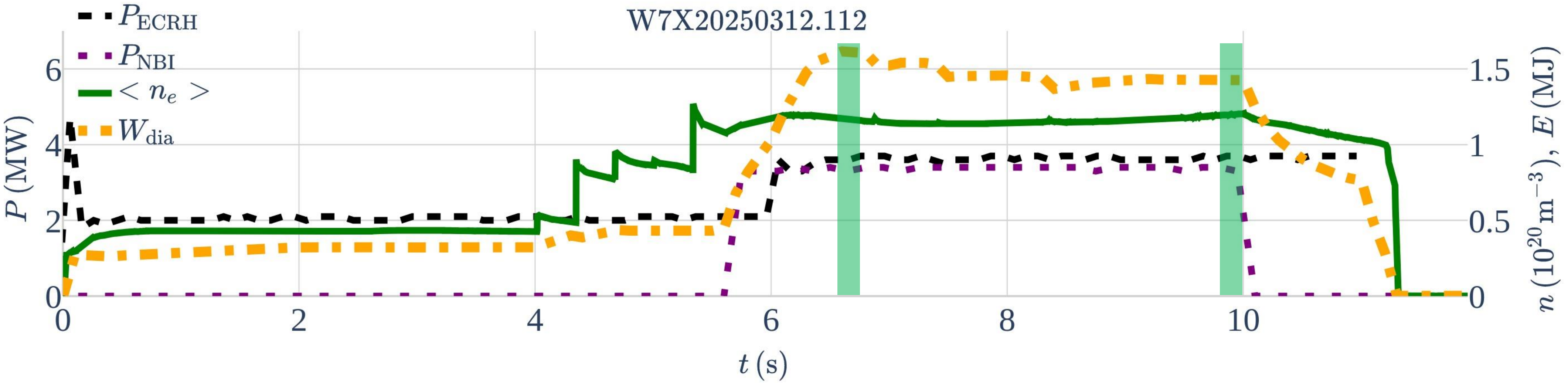
- High iota configuration
- Injection of 5 pellets
- NBI take-over
- ECRH power step-up

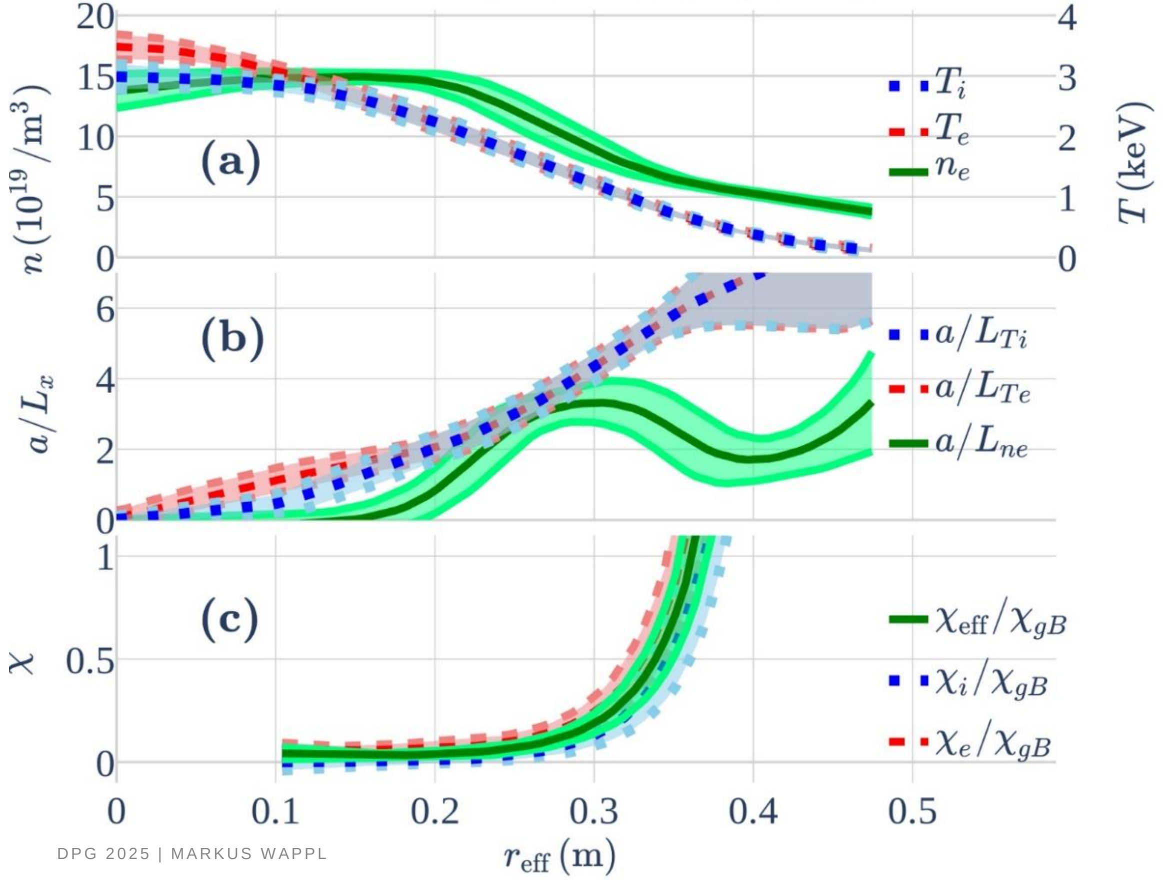
- Pronounced density gradient
  - 3 keV ion temperature
  - Strong turbulence suppression



- Maintained density gradient
  - Steady-state for 4 s
- Ended by NBI switch-off
  - No pure NBI phase needed
- Recent result
  - Further experience needed




W7X20250312.112
P_{ECRH}
P_{NBI}
$< n_e >$
W_{dia}
$P\,(\mathrm{MW})$
$n\,(10^{20}\mathrm{m}^{-3}),\ E\,(\mathrm{MJ})$
$t\,(\mathrm{s})$


(a)
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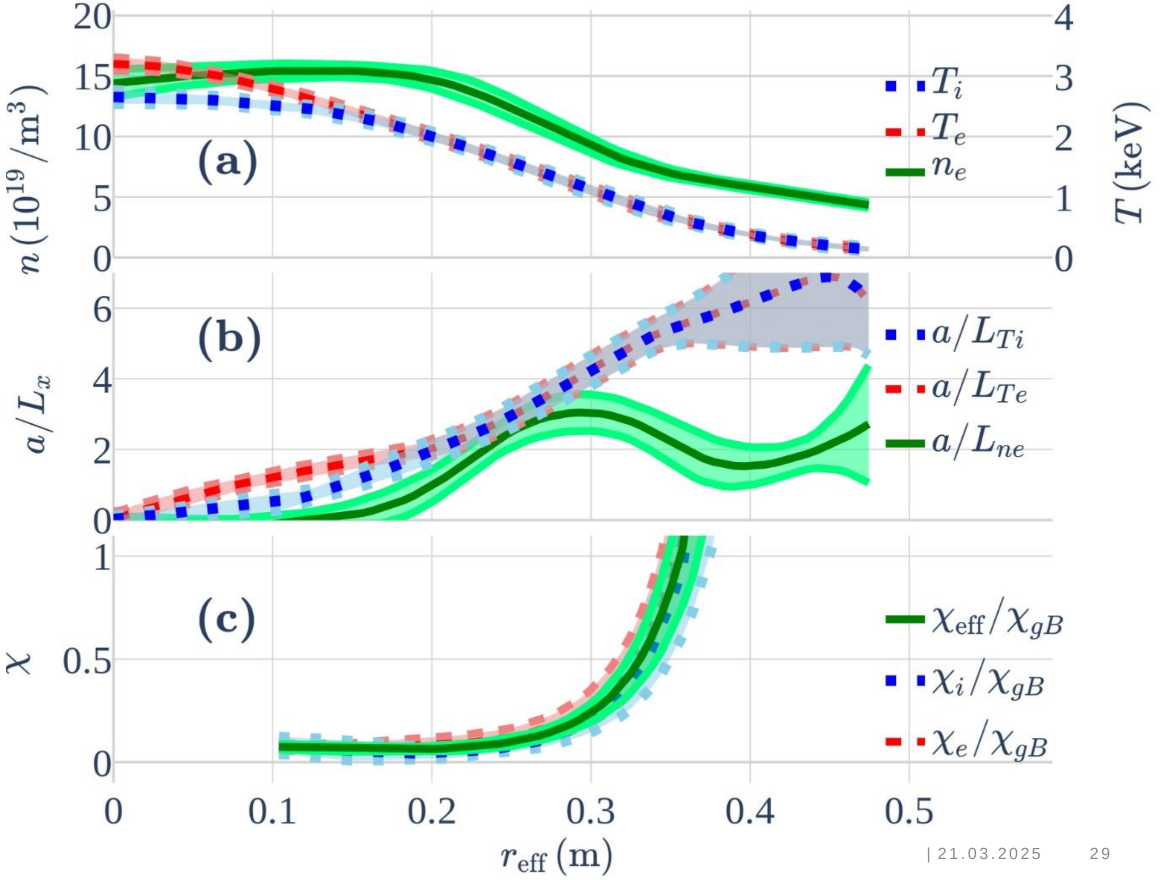
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$


(a)
(b)
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T_i
T_e
n_e
a/L_{Ti}
a/L_{Te}
a/L_{ne}
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
a/L_x
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$

Conclusion

- Extensive turbulent transport database
  - Effective turbulence suppression by density gradient
  - Partial in electrons, complete in ions at a/L_n = 1

- Equivalent across all heating and fuelling schemes
  - No clear configuration dependence
- Supports role of ITG modes

- Density gradient can be maintained by pellets and NBI
  - Steady-state turbulence suppression for 4 s
  - Self-ordering process in high iota configuration

Plasma instabilities

- ETG destabilized by electron temperature gradient
  - Electron gyroradius scale
  - Effective transport possible in W7-X?

$$a/L_{Te} = -\frac{a}{T_i}\frac{\mathrm{d}T_e}{\mathrm{d}r_{\mathrm{eff}}}$$

- TEM density- or temperature gradient driven
  - Both channels
  - Geometry-dependent stabilization with collisionality

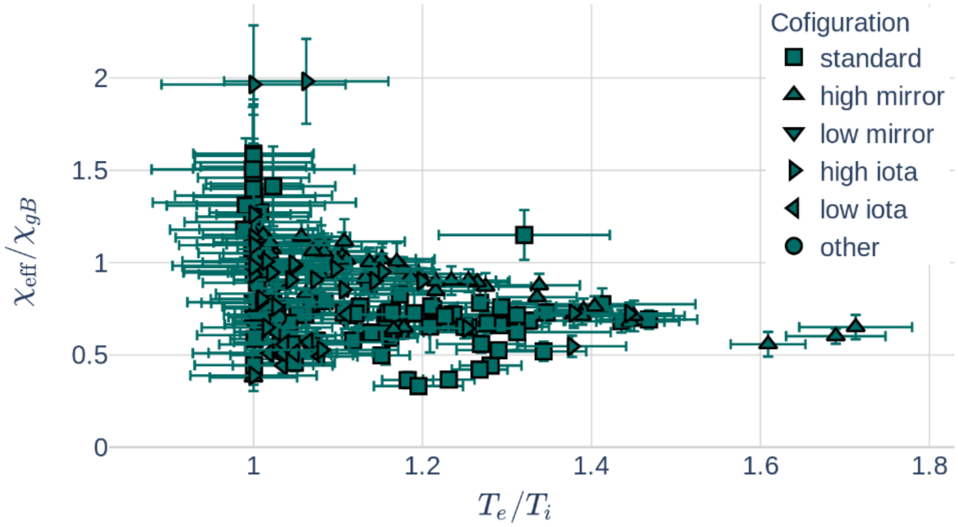
$$\nu^* = \frac{R\,\nu}{\iota\,v_e} \sim \frac{n_e}{T_e^2}$$

- KBM destabilized at β threshold
- Electrostatic modes stabilized at high β

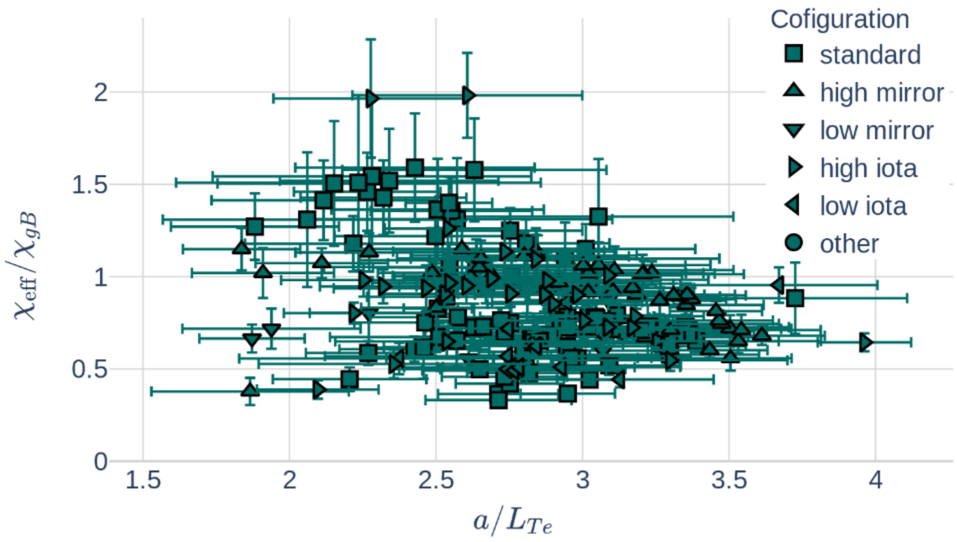
$$\beta = \frac{2\,\mu_0\,n\,T}{B^2}$$

Database results

- Dominant role of ITG modes
- No clear T_e/T_i exacerbation
  - Likely masked by gradient effect
  - Convergence for large T_e/T_i
- No stiffness in the covered range of $\frac{a}{L_{Te}}$
  - No turbulence suppression
  - No conclusion on ETG modes in plot

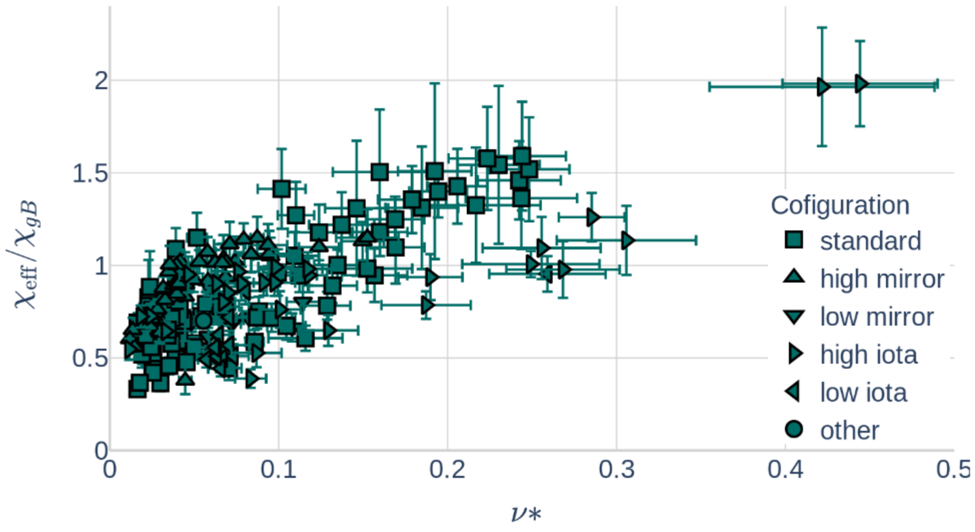


$r_{\mathrm{eff}} = 0.25\ \mathrm{m}$



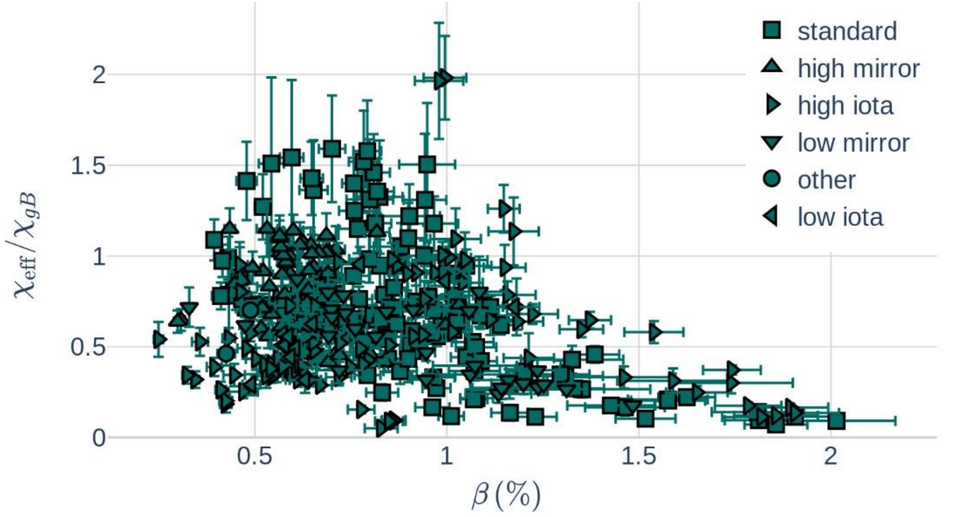
Database results

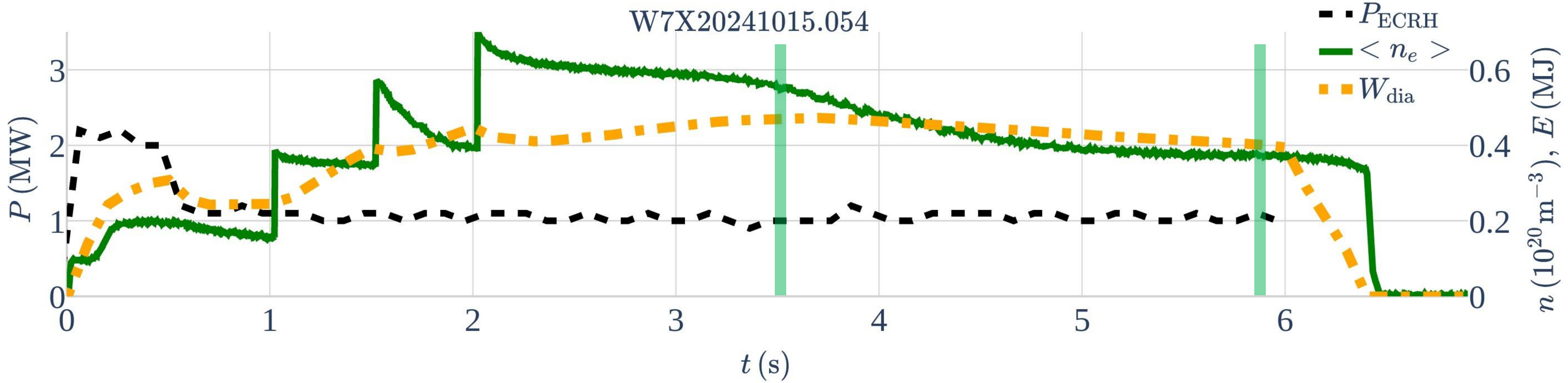
- Transport increases with collisionality
  - Contrast to expectation for TEMs
  - T_e dependence correlates ν^* to χ_{gB}
- More high-density discharges needed

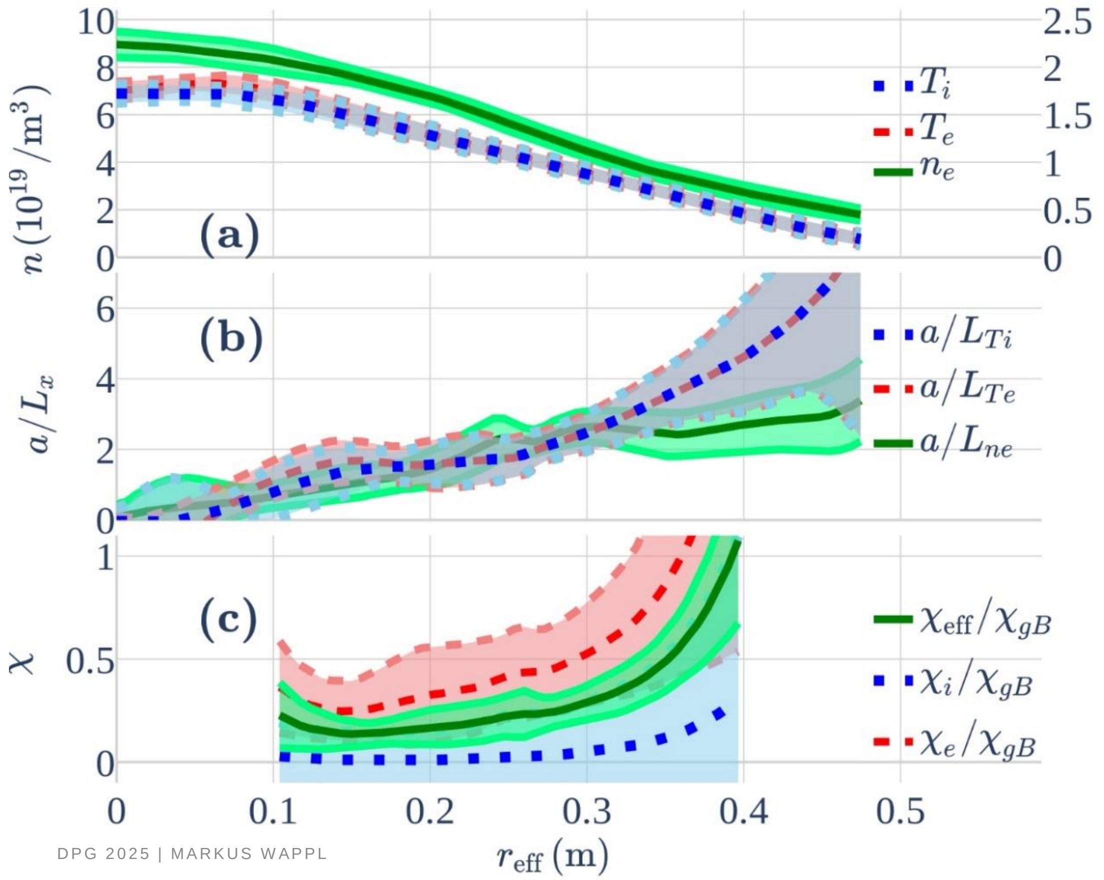


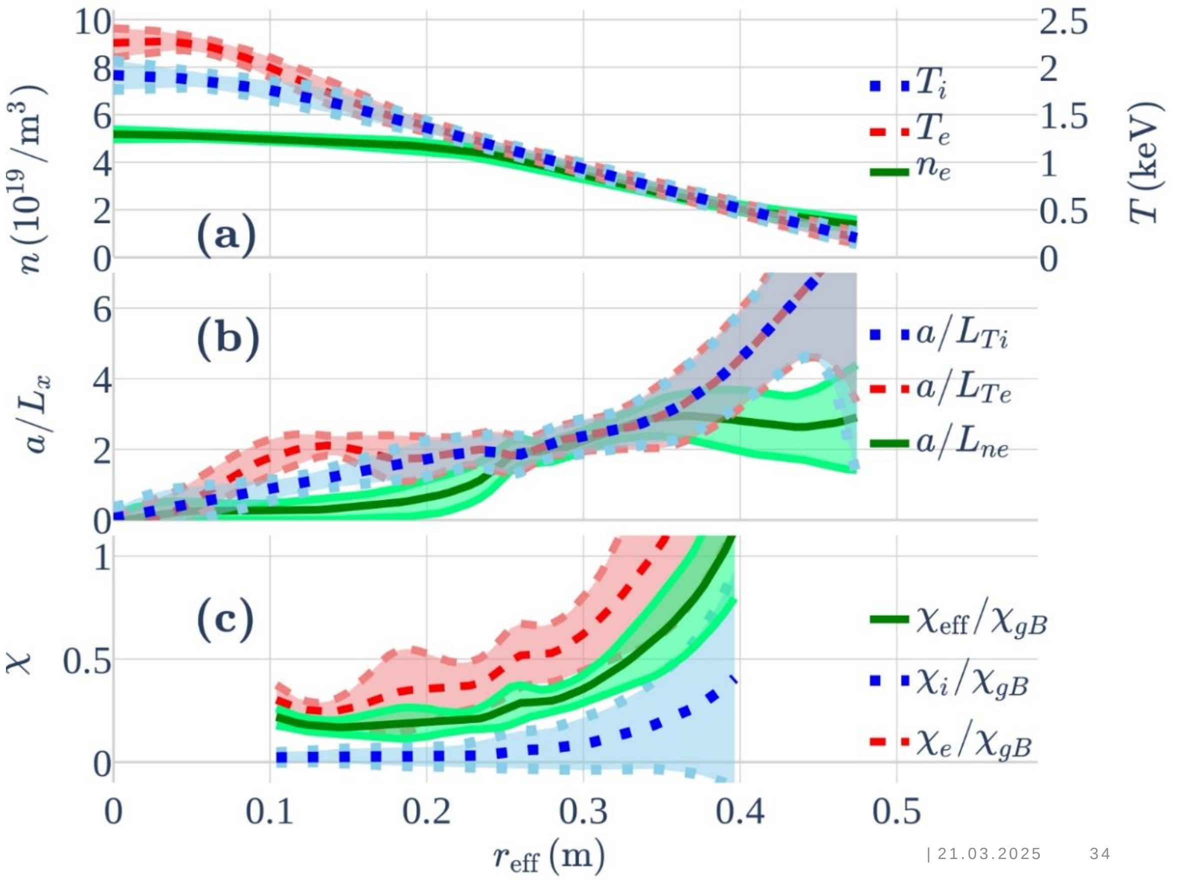
$r_{eff} = 0.25$ m

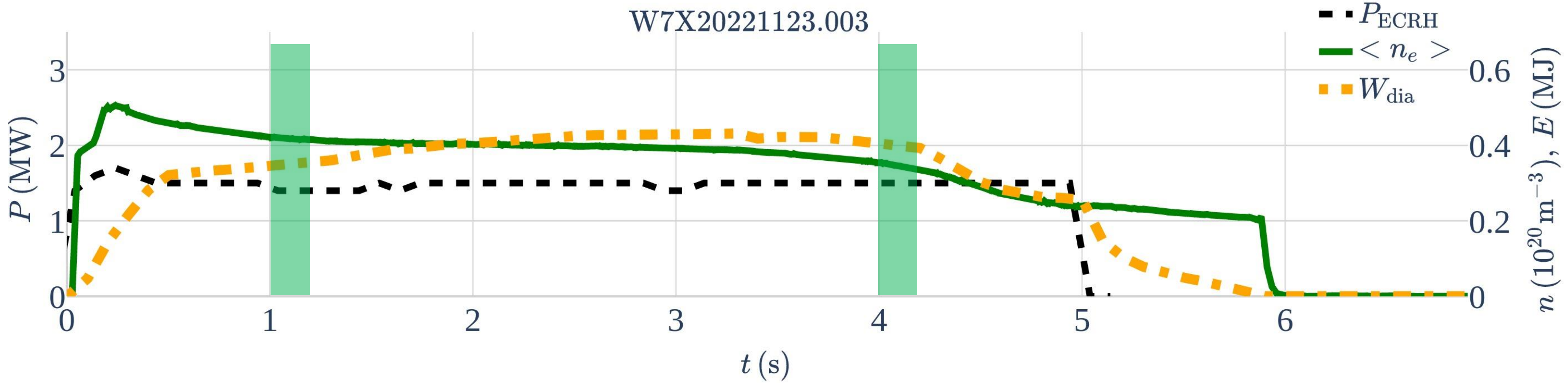
- Localized β
- Below KBM threshold
- Stabilization of electrostatic modes

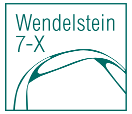


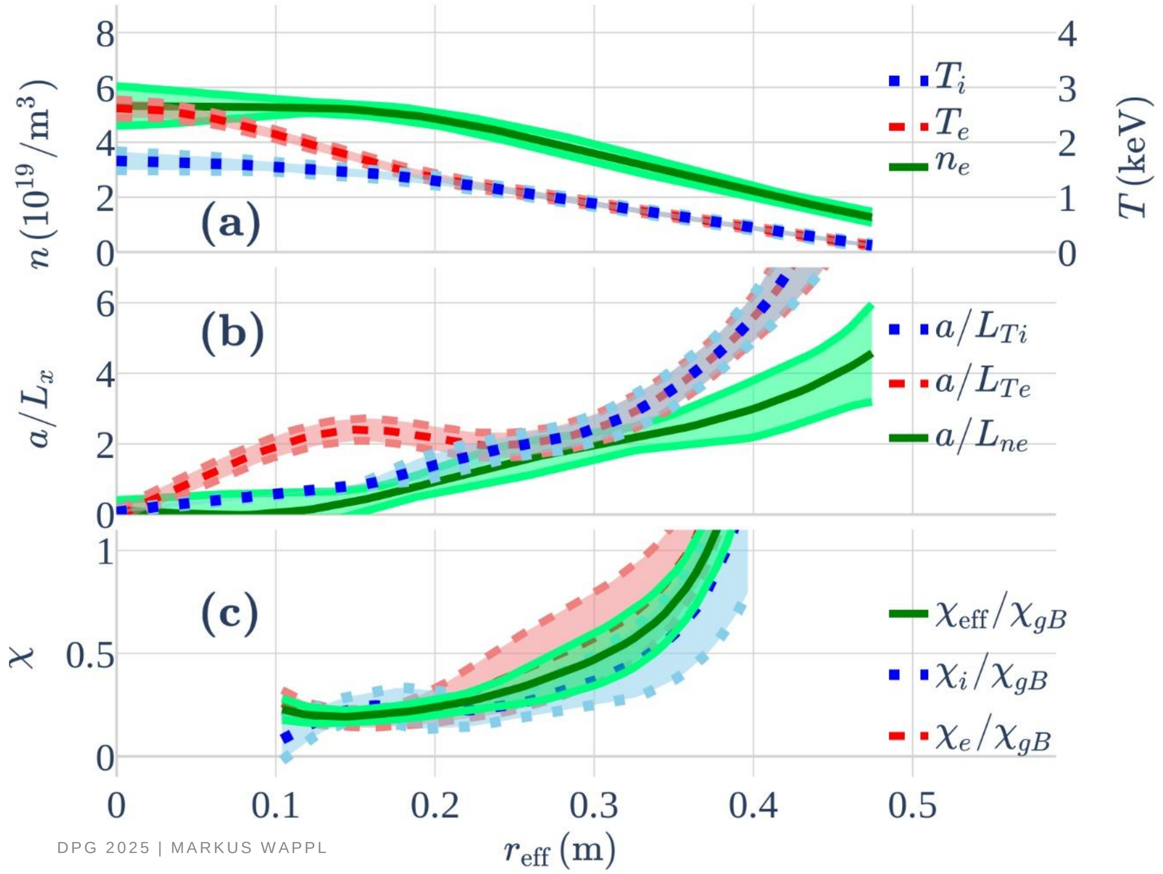

W7X20241015.054
P_{ECRH}
$< n_e >$
W_{dia}
$P\,(\mathrm{MW})$
$n\,(10^{20}\mathrm{m}^{-3}),\ E\,(\mathrm{MJ})$
$t\,(\mathrm{s})$

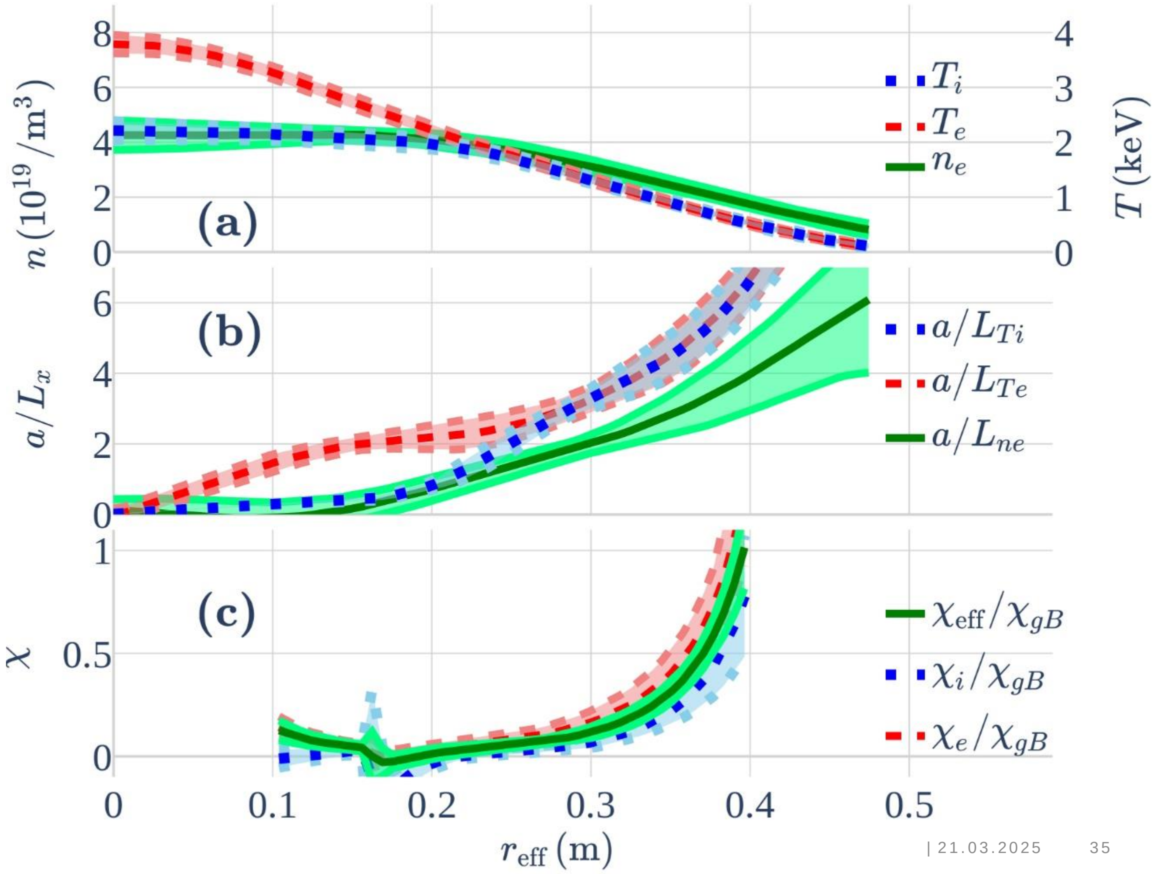

(a)
(b)
(c)
T_i
T_e
n_e
a/L_{Ti}
a/L_{Te}
a/L_{ne}
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
a/L_x
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$


(a)
(b)
(c)
T_i
T_e
n_e
a/L_{Ti}
a/L_{Te}
a/L_{ne}
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
a/L_x
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$


W7X20221123.003
P_{ECRH}
$< n_e >$
W_{dia}
$P\,(\mathrm{MW})$
$n\,(10^{20}\mathrm{m}^{-3}),\ E\,(\mathrm{MJ})$
$t\,(\mathrm{s})$

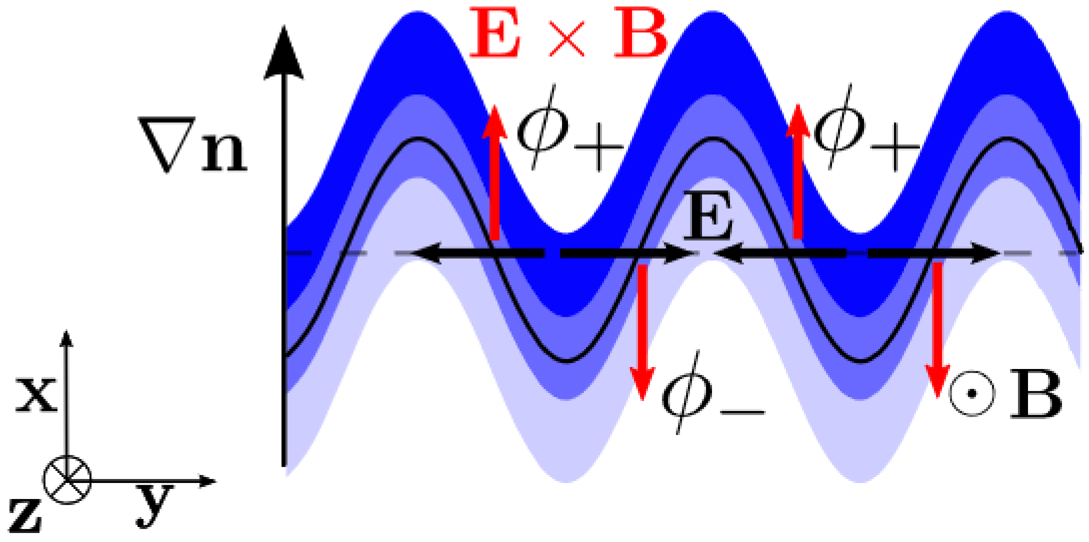

Wendelstein 7-X


(a)
(b)
(c)
T_i
T_e
n_e
a/L_{Ti}
a/L_{Te}
a/L_{ne}
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
a/L_x
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$

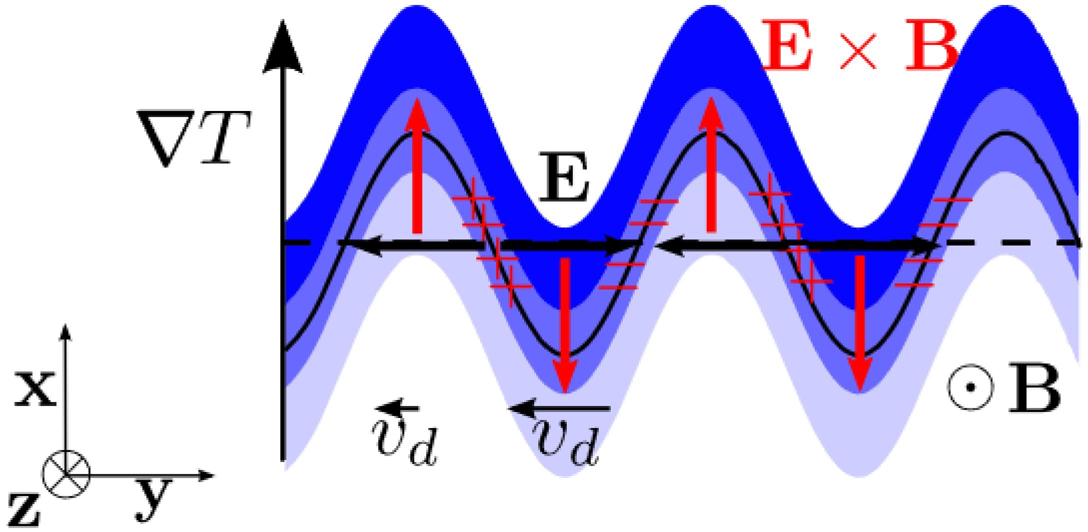

(a)
(b)
(c)
T_i
T_e
n_e
a/L_{Ti}
a/L_{Te}
a/L_{ne}
$\chi_{\mathrm{eff}}/\chi_{gB}$
χ_i/χ_{gB}
χ_e/χ_{gB}
$n\,(10^{19}/\mathrm{m}^3)$
$T\,(\mathrm{keV})$
a/L_x
χ
$r_{\mathrm{eff}}\,(\mathrm{m})$

ITG mechanism

- Drift wave mechanism
- Density and potential perturbation
- In phase
- Wave propagation



- Drifts faster in higher temperature
- Shifts potential phase
- Perturbation growth
- Competes with drift wave

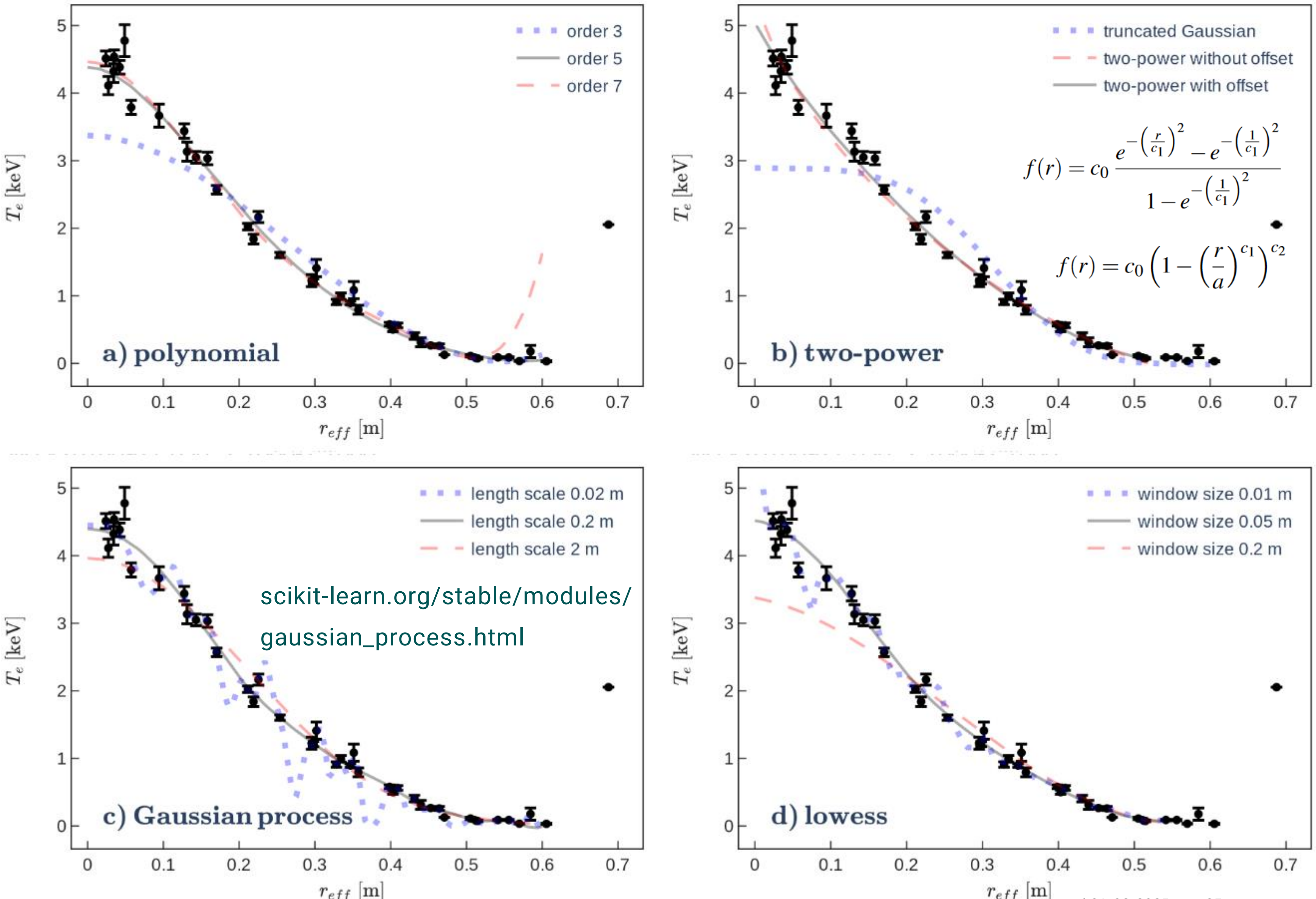


J. H. E. Proll, Trapped-Particle Instabilities in Quasi-Isodynamic Stellarators, Ph.D. thesis, Ernst-Moritz-Arndt-Universität Greifswald (2014)

Fitting functions

- Polynomial
- Truncated Gaussian
- Two-power
- Gaussian process
- Lowess

- Free parameters
  - Order
  - Length scale
  - others

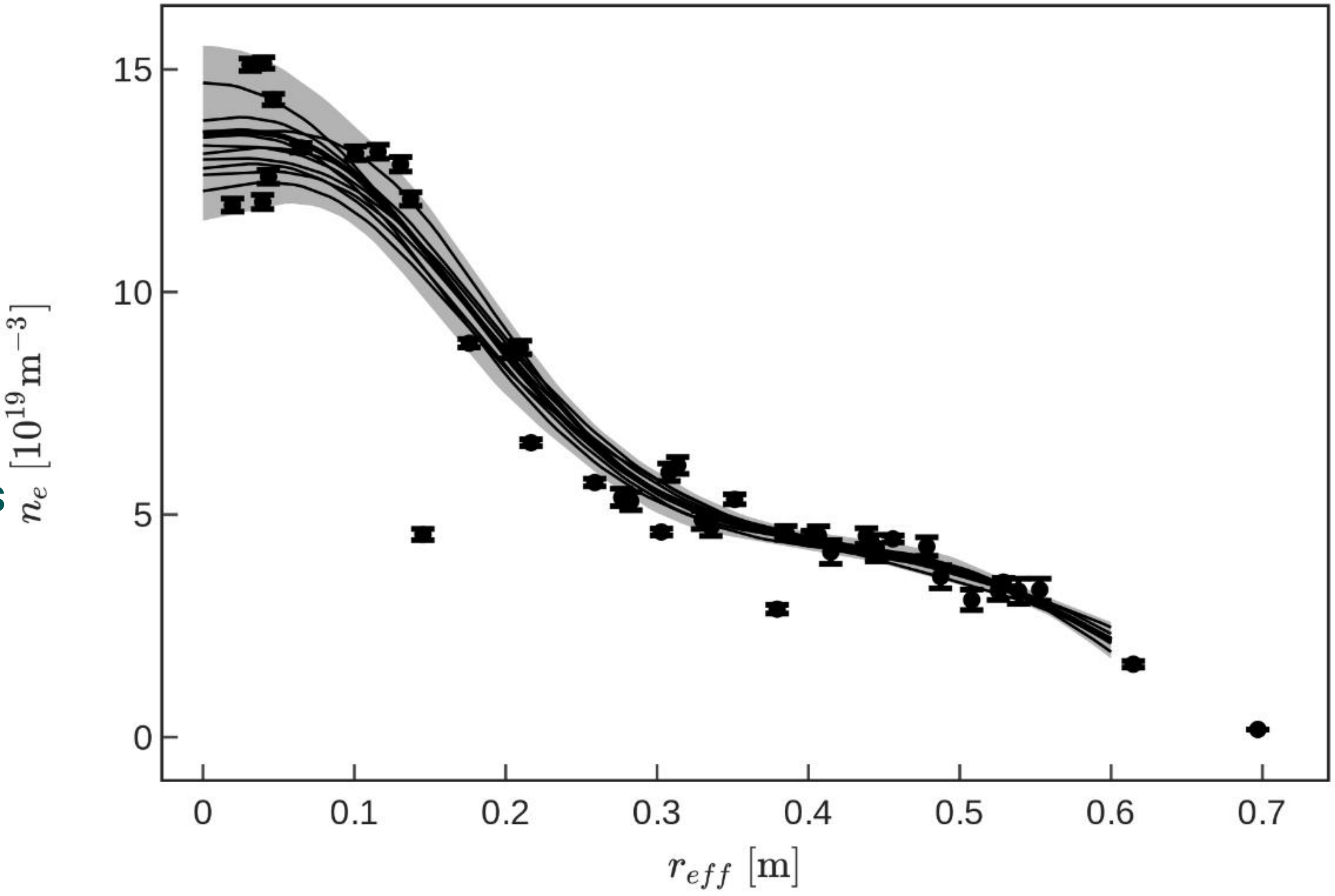


MC sampling

- Uncertainty estimation
  - “error”: Measurement errors
  - “std”: Temporal deviation
  - “dist”: Scatter in data points

- Individual data points
  - Generate distributed samples
  - According to weighting

- Repeat fitting function
  - Create samples of fit



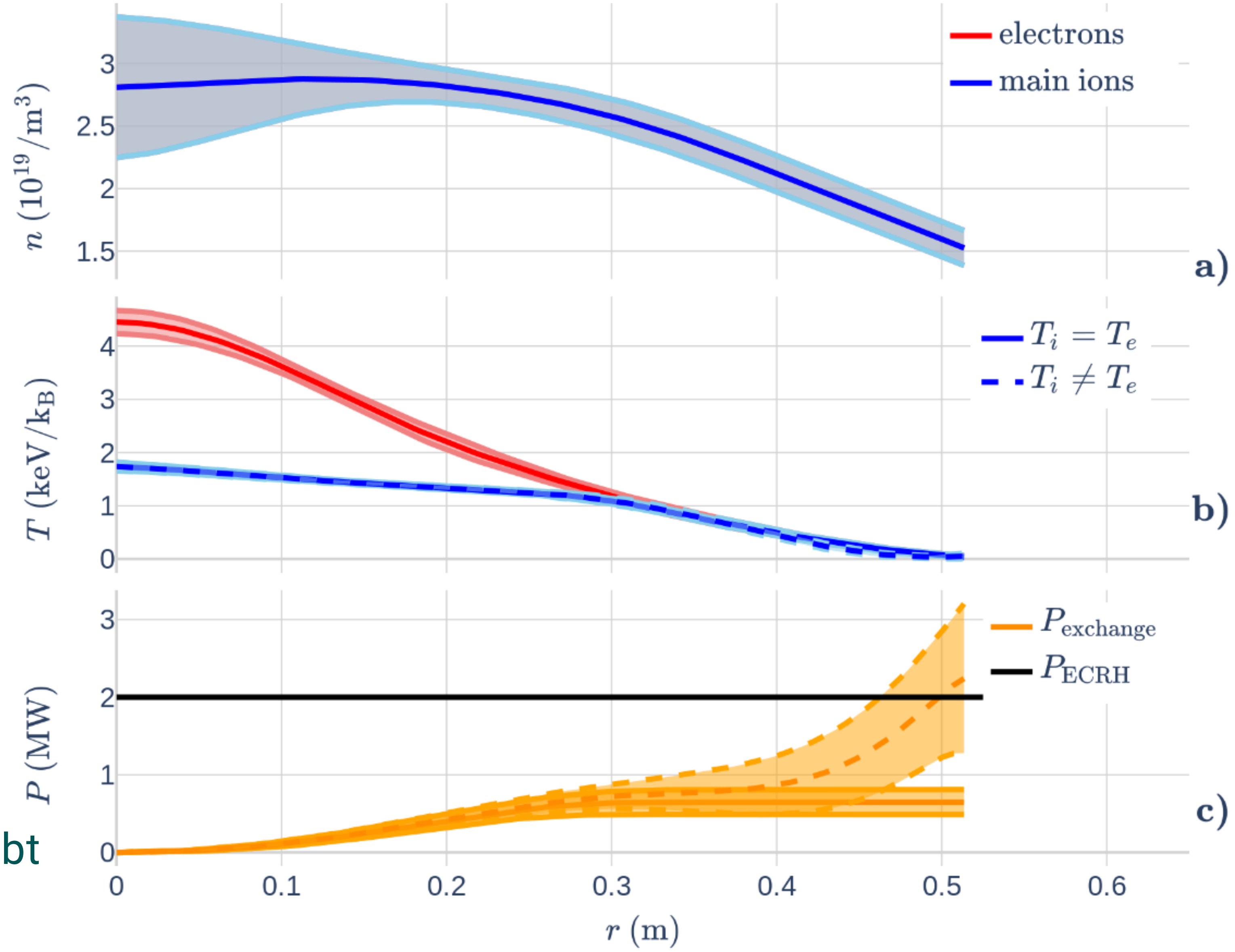
Collisional heat exchange

- Large uncertainty
  - In electron heated cases

- Small $T_e - T_i$ difference
  - Diagnostic uncertainty
  - Huge exchange power

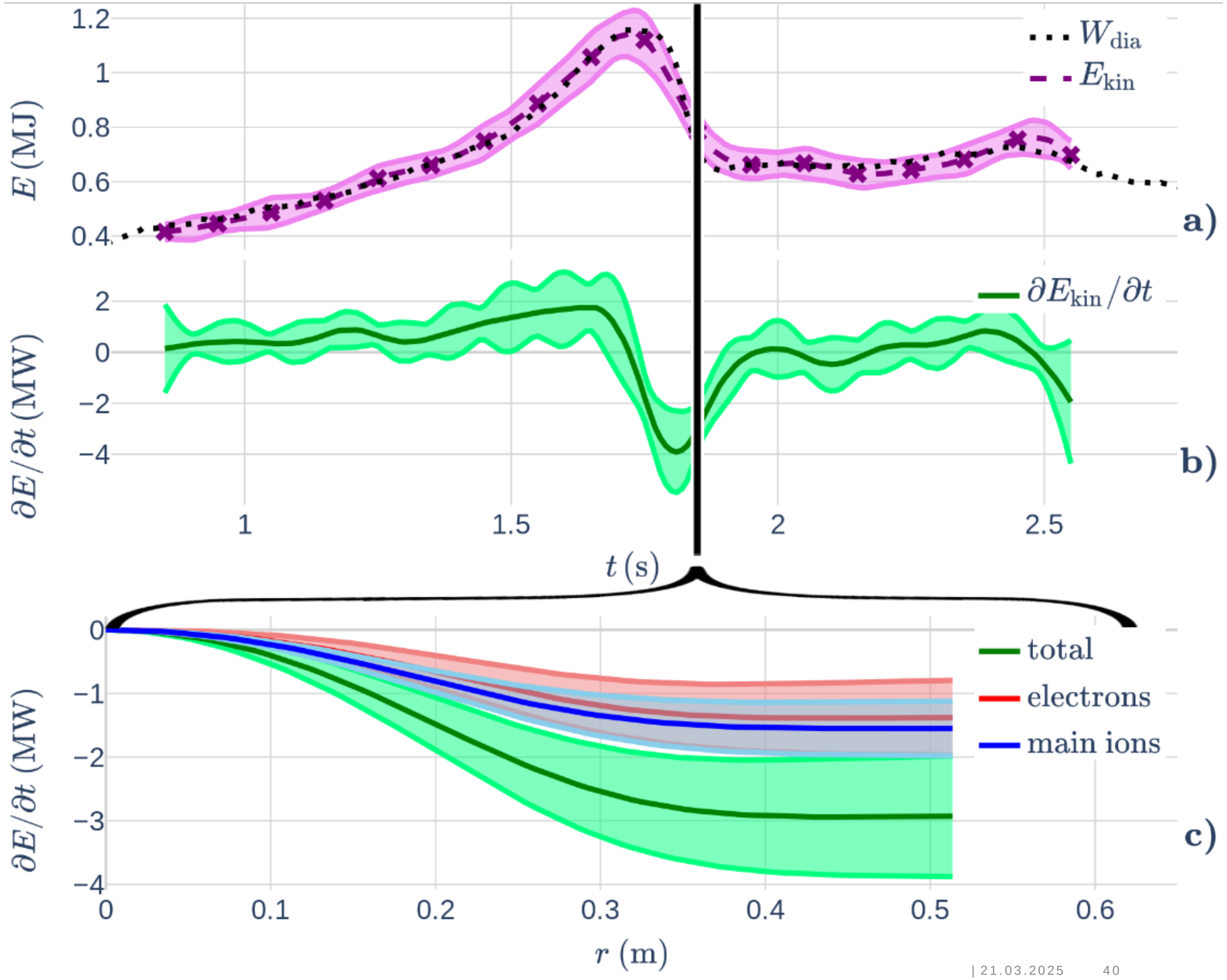
$$P_{\text{exchange}} \sim n_e^2 \frac{T_e - T_i}{\tau_{ei}} \sim n_e^2 \frac{T_e - T_i}{T_e^{3/2}}$$

- Set equal and smooth
  - Use single fluid in case of doubt



Non-stationary conditions

- Transient profiles
  - Three or more time points
  - Common radial grid
  - Compute kinetic energy table
- Cubic spline interpolation
  - Function of time
  - For each grid point
- Evaluate derivative of spline
  - Kinetic energy derivative

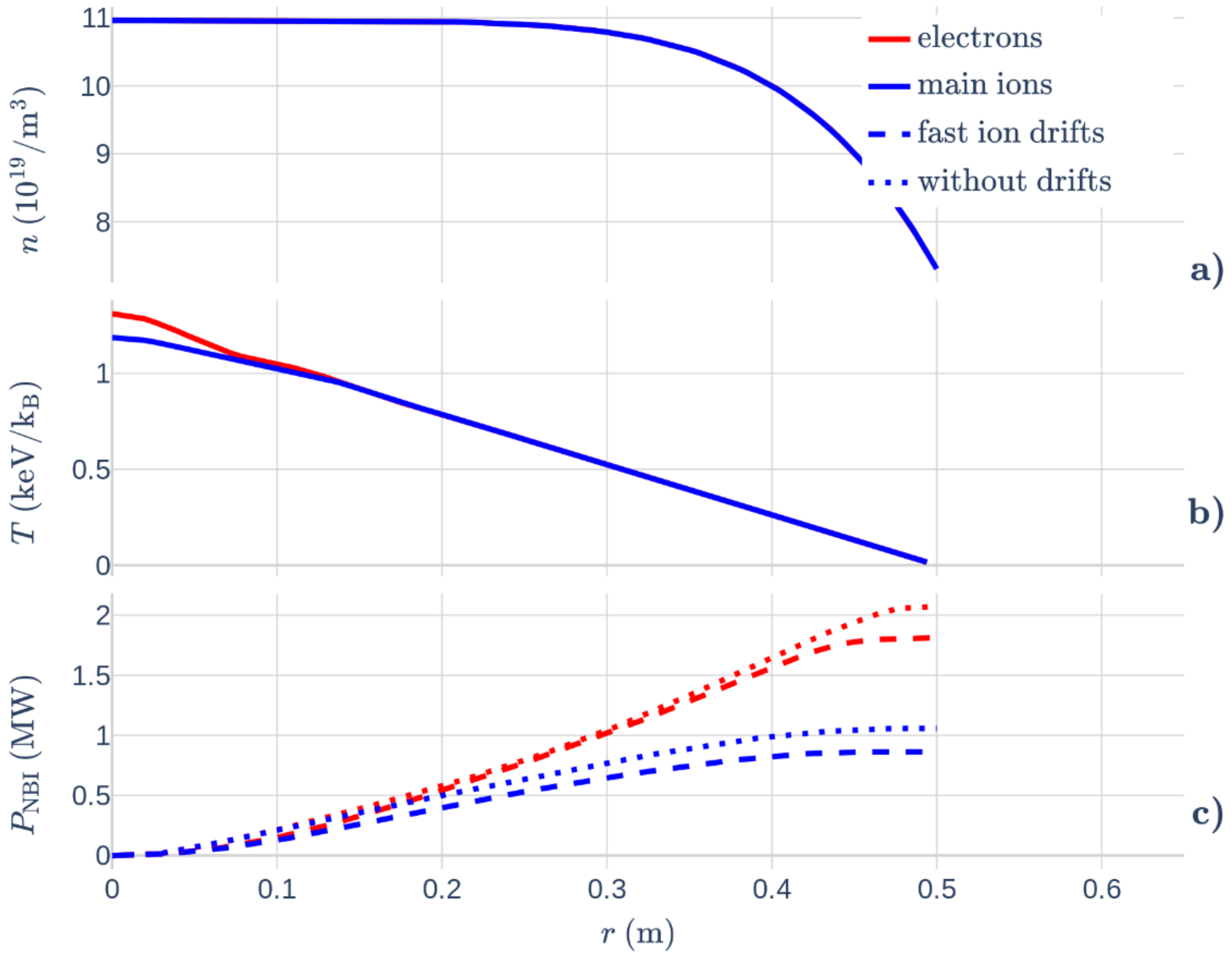


NBI power deposition model

- Voltage and current
  - Neutralizer spectroscopy
  - Three energy components

- FI drifts omitted
  - Comparison to BEAMS3D
  - 12 % more electron power
  - 19 % more ion power

- Consistent profiles used



S. Bannmann *et al* 2024 *DPG Frühjahrstagung*

Neoclassical simulation

- Transport equation

$$\begin{pmatrix} \Gamma_{\mathrm{NC}}\, T \\ q_{\mathrm{NC}} \end{pmatrix} = -n\,T \begin{pmatrix} D_1 & D_2 \\ D_2 & D_3 \end{pmatrix} \begin{pmatrix} \frac{n'}{n} - \frac{ZeE_r}{T} - \frac{3T'}{2T} \\ \frac{T'}{T} \end{pmatrix}$$

- Monoenergetic coefficients from DKES

- Ambipolarity

$$\Gamma_{\mathrm{NC},e} = Z_i\, \Gamma_{\mathrm{NC},i}$$

- Radial electric field
  - Root solutions

- Transition area
  - Diffusion model

$$\frac{\partial E_r}{\partial t} - \frac{1}{V'}\frac{\partial}{\partial r} D_E\, V'\, r \frac{\partial}{\partial r}\frac{E_r}{r} = \frac{|e|}{\varepsilon}\left(\Gamma_{\mathrm{NC},e} - Z_i\, \Gamma_{\mathrm{NC},i}\right)$$

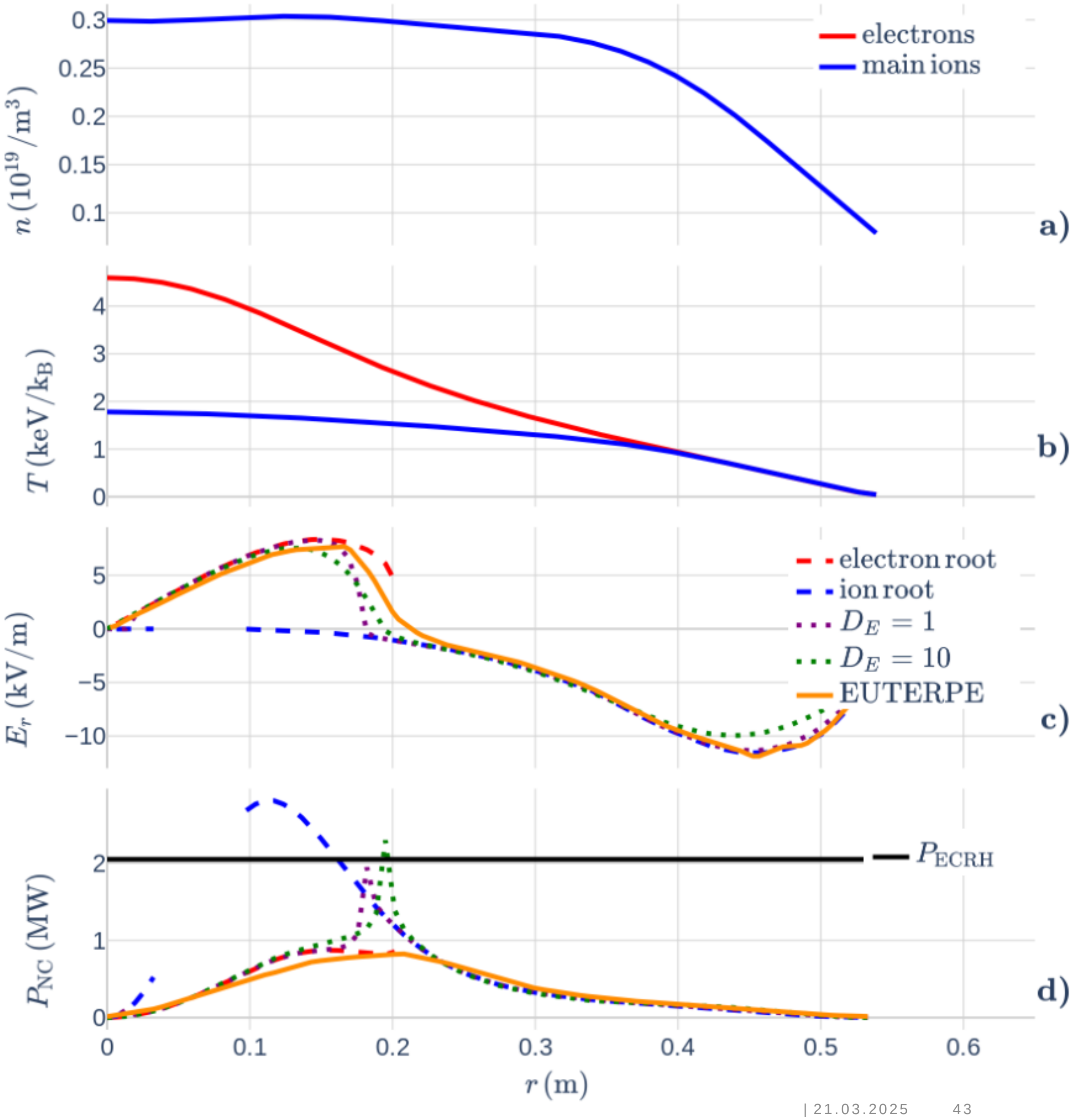
Y. Turkin *et al* 2011 *Physics of Plasmas* 18 022505

Global simulation with the code EUTERPE

- Self consistent without free parameters

M.D. Kuczyński *et al* 2024 *Nuclear Fusion* 64 046023

- Radial electric field
  - Steepness reproducible
  - Zero crossing different
- Transport spike in diffusion model
  - DKES at low collisionality
- Smooth transition in EUTERPE
  - Save choice to calculate roots separately



Plasma scenarios

- Stationary ECRH 1.5 MW, gas fuelling
- Following boronization

- Spontaneous large a/L_n, r_{eff} > 0.2 m
- Clamping overcome $T_i \approx 2$ keV

- Electron to ion root transition
- Strong E_r gradient

- χ_i < χ_e << χ_{gB}
- Coincides with root transition