MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Database Analysis of Profile and Turbulence Characteristics in NBI Experiments and Sensitivity Study for Transport Analysis

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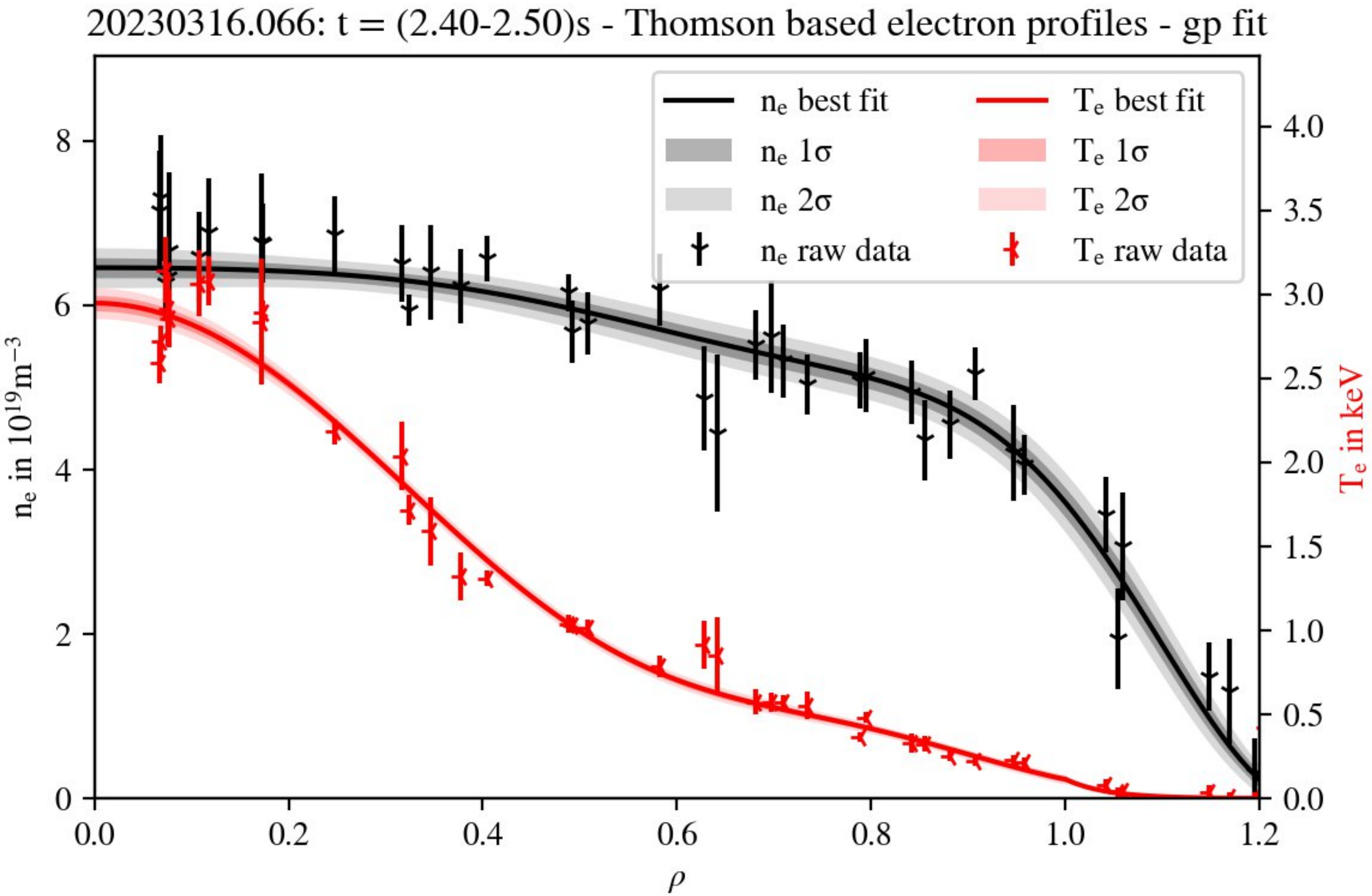
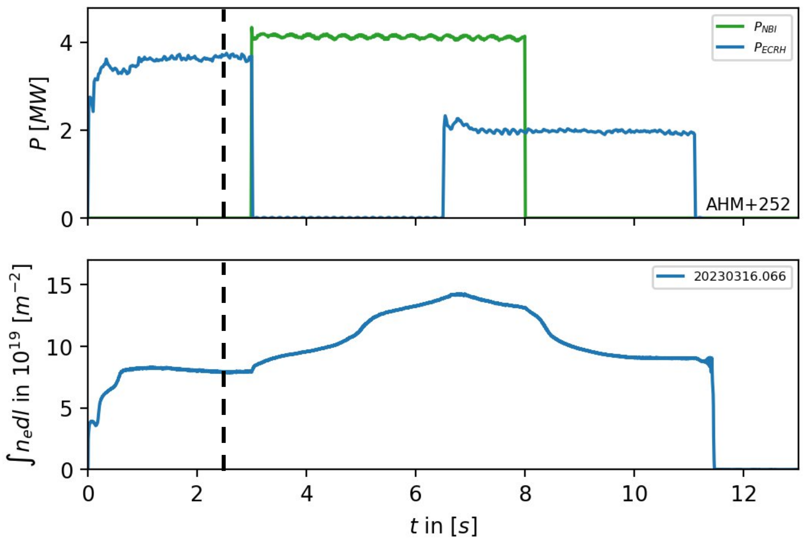
Outlook

- Main plasma species profiles
  - Accumulation phenomena
  - Non-accumulating behavior
  - ECRH reintroduction
  - Comparison of accumulation at different magnetic configurations
  - Additional main species observations by S. Bannmann
  - Concluding observations on main species
- Impurity profiles
  - Impurity profile fitting method - modified double tanh
  - Accumulation phenomena
  - Non-accumulating behavior
  - ECRH reintroduction
  - Comparison of accumulation at different magnetic configurations
  - Concluding observations on impurities
- Database approach for examining accumulation phenomena
  - Variable heatmap and strongest correlations
  - Kink location to determine separation of anomalous and neoclassical transport
  - Transport color-coded plots
- Remarkable observations
- Summary

Flat profiles are associated with pure ECRH heating

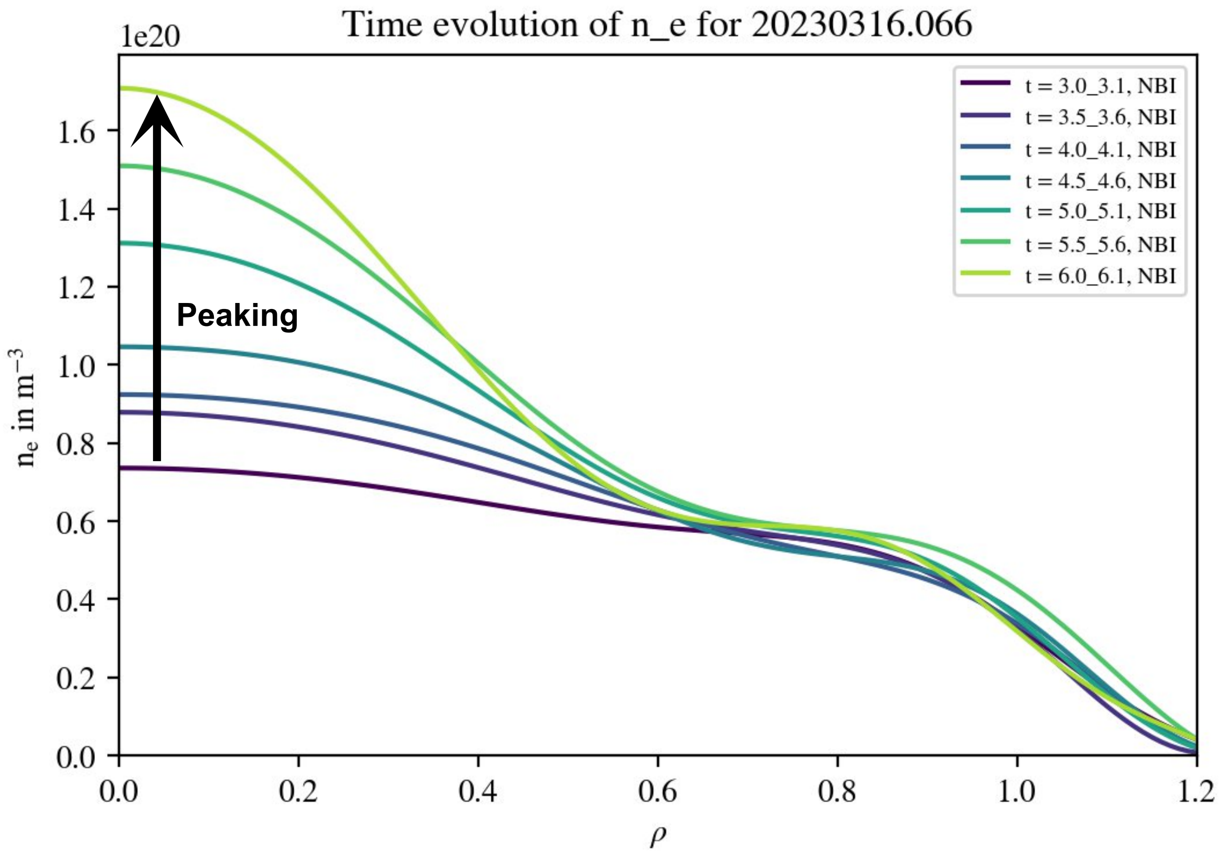
- **During the ECRH heating phase, we observe flat profiles**
  - **This is also evident by the flat line integrated density during the ECRH heating phase**

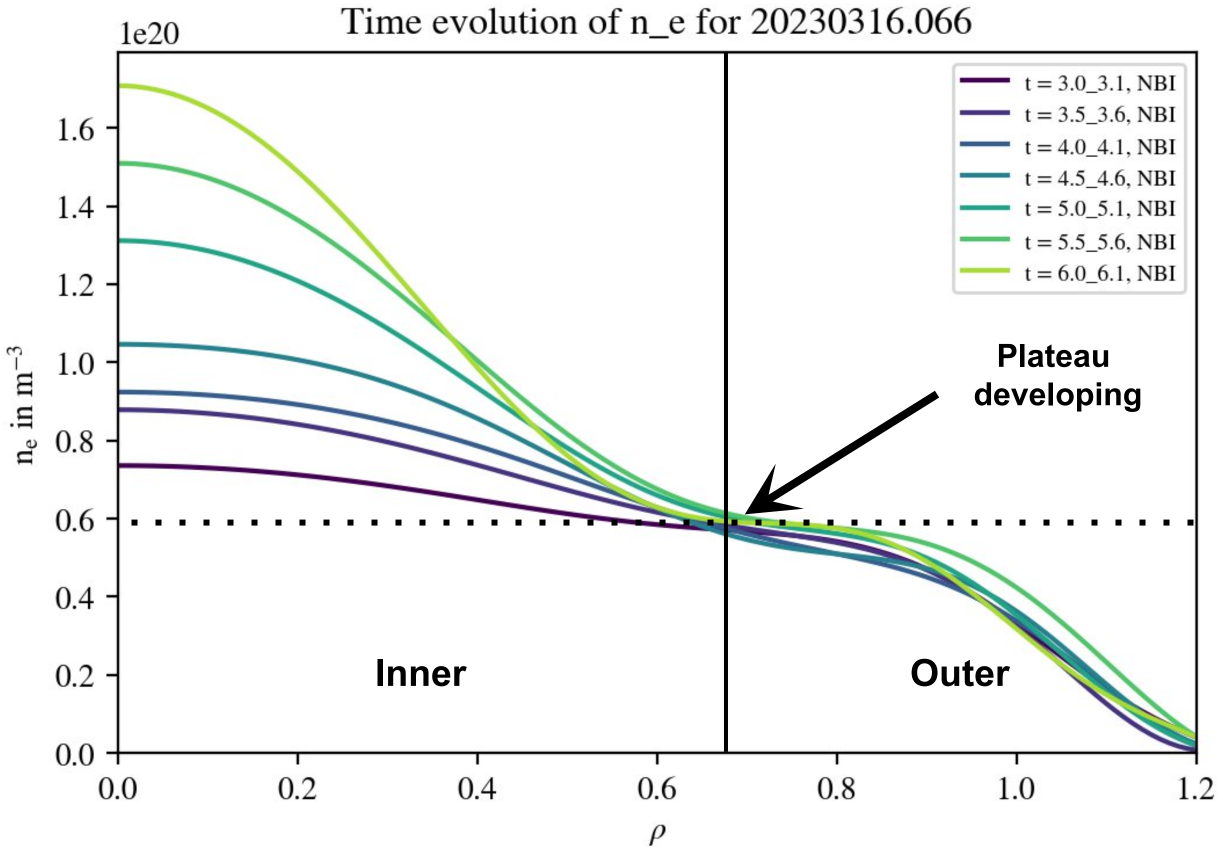




Terminology of central density accumulation phenomena

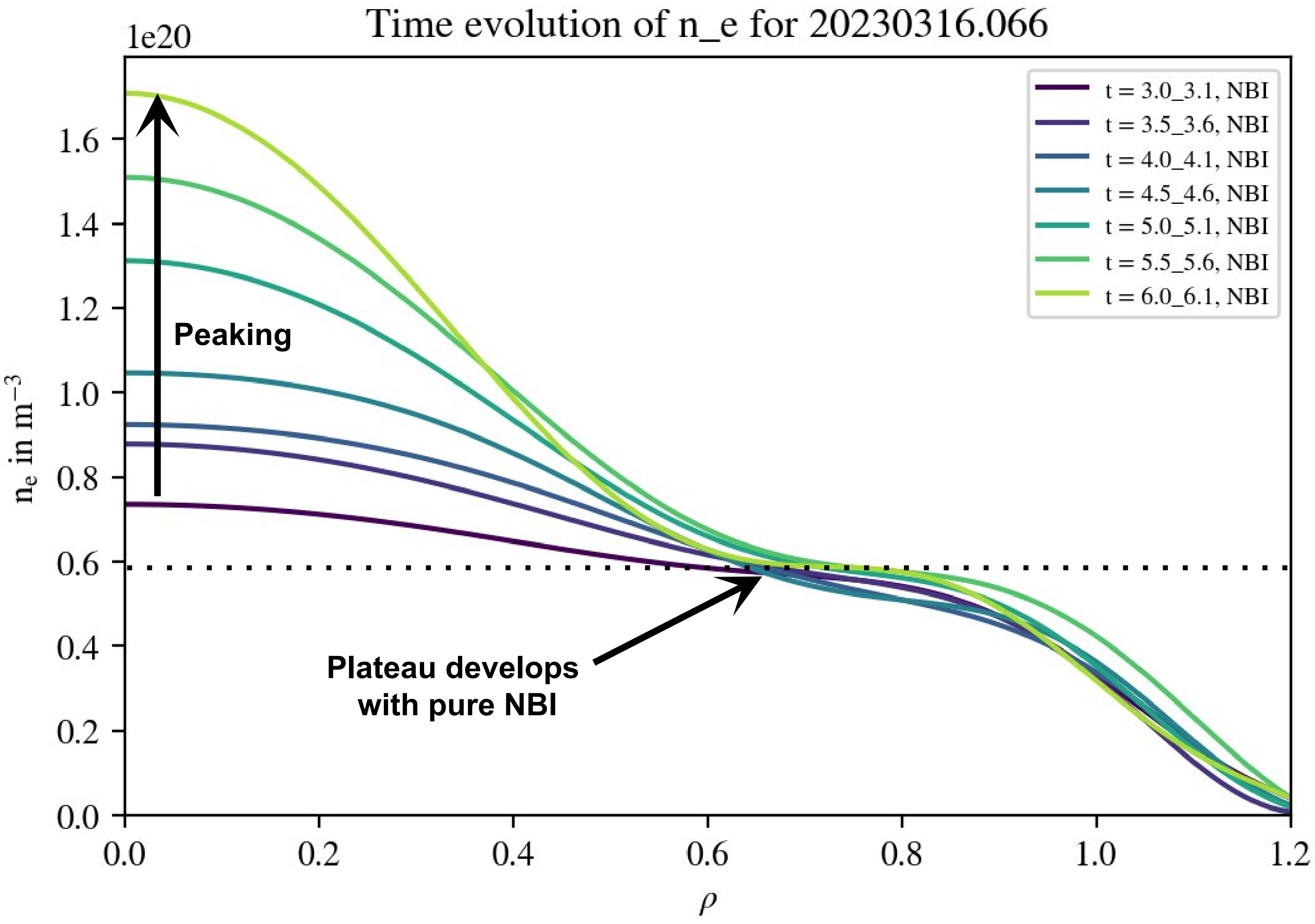
- **Peaking: the increase in amplitude of the region close to the plasma core**
- **Plateau: the the loss in slope around mid-rho**
    - **The plateau separates the profiles into two regions: inner and outer**

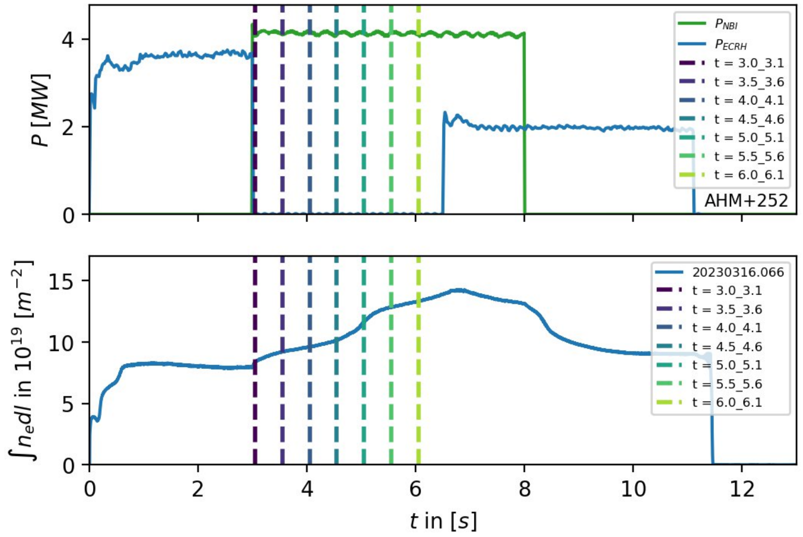




Central density accumulation is associated with pure NBI heating

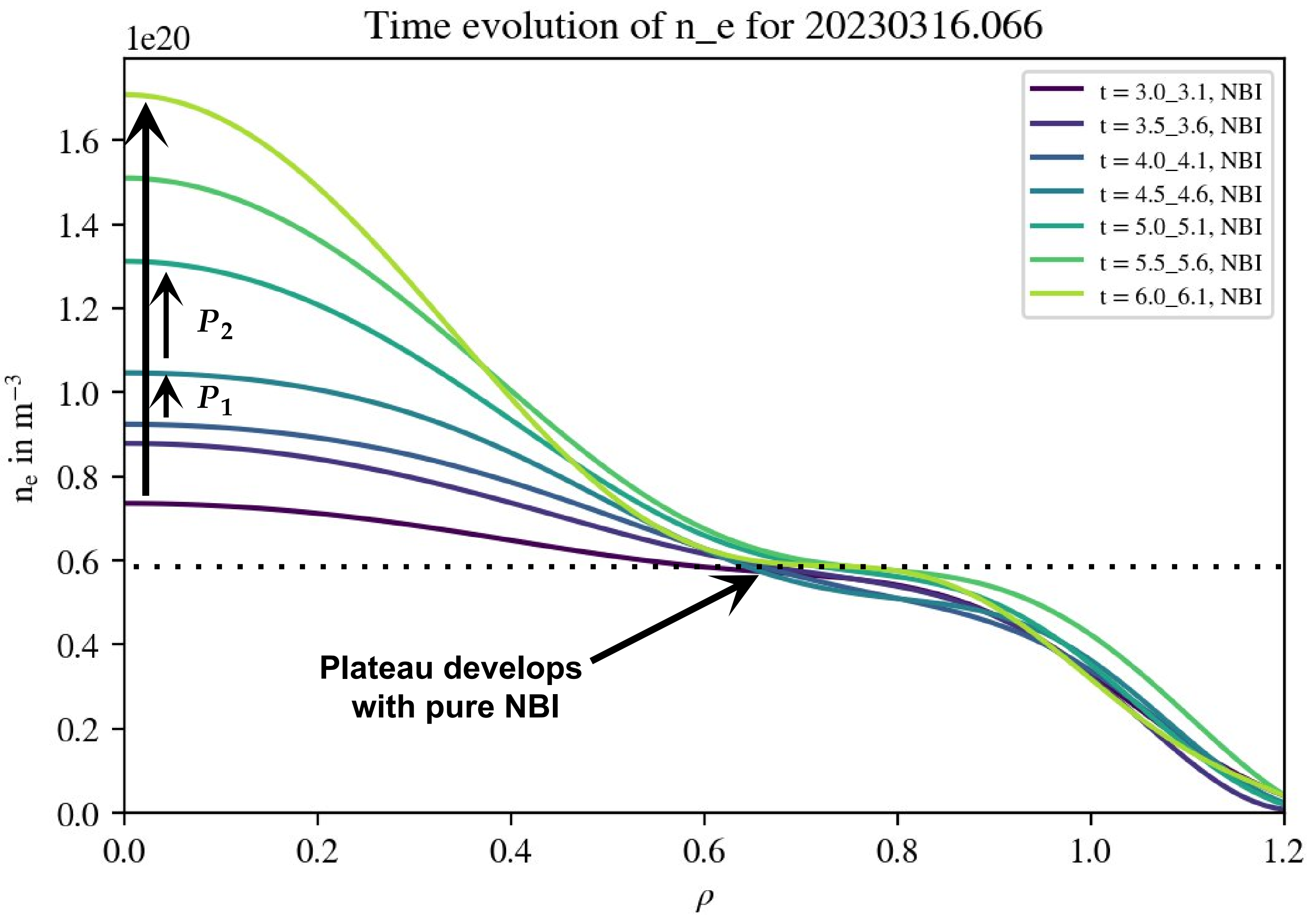
- **During pure NBI heating, we see the live development of the peaking and the plateau which characterize the central density accumulation**

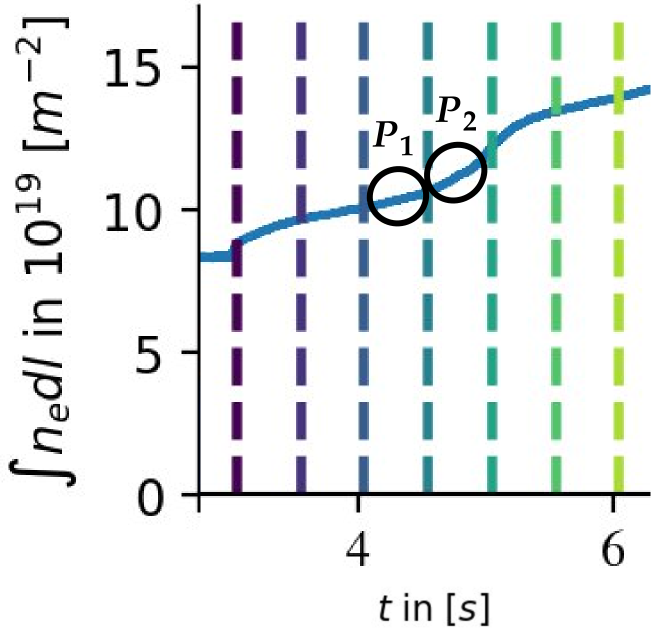




Central density accumulation is associated with pure NBI heating

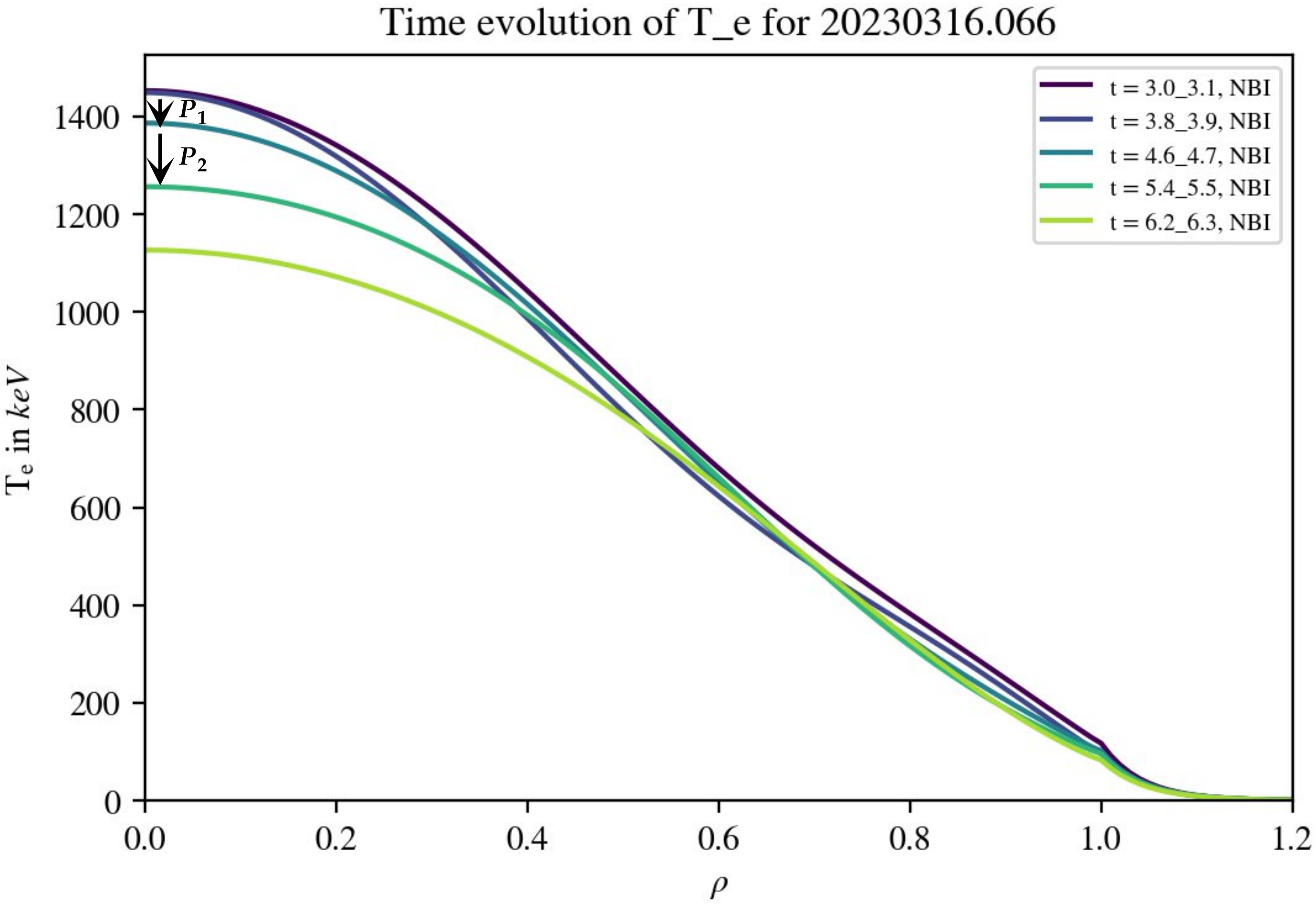
- **Paying attention to the line integrated density, we observe that according to the rising slope of the line, the peaking rate momentarily accelerates such that $P_2 > P_1$**

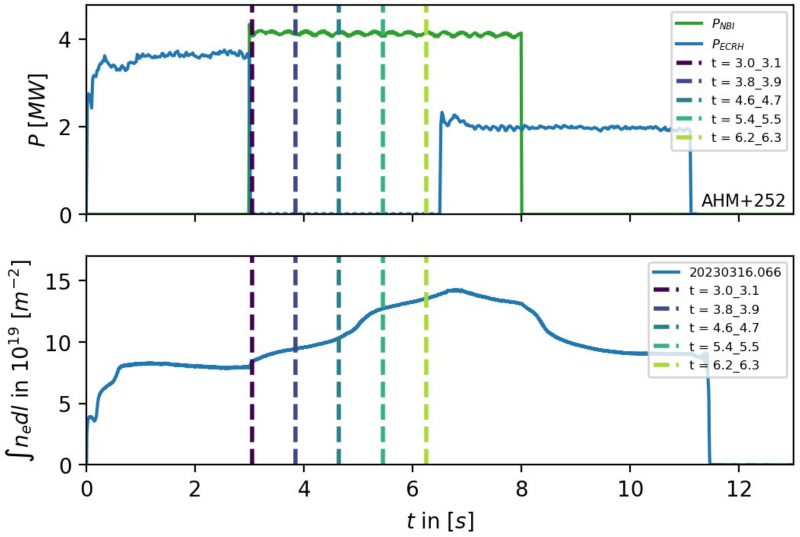


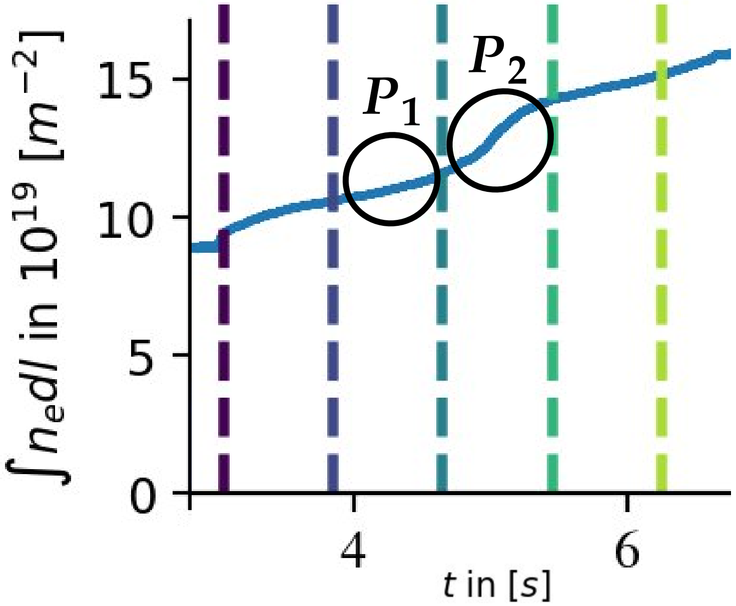


Electron temperature time evolution in general peaking cases

- **Due to the increase in particles with the NBI heating, inside $\rho = 0.4$ the electron temperature profile plunges as the density keeps rising**
  - **Paying attention to the line integrated density panel, we again observe that according to the rising slope of the line, the plunging rate momentarily accelerates such that $P_2 > P_1$**

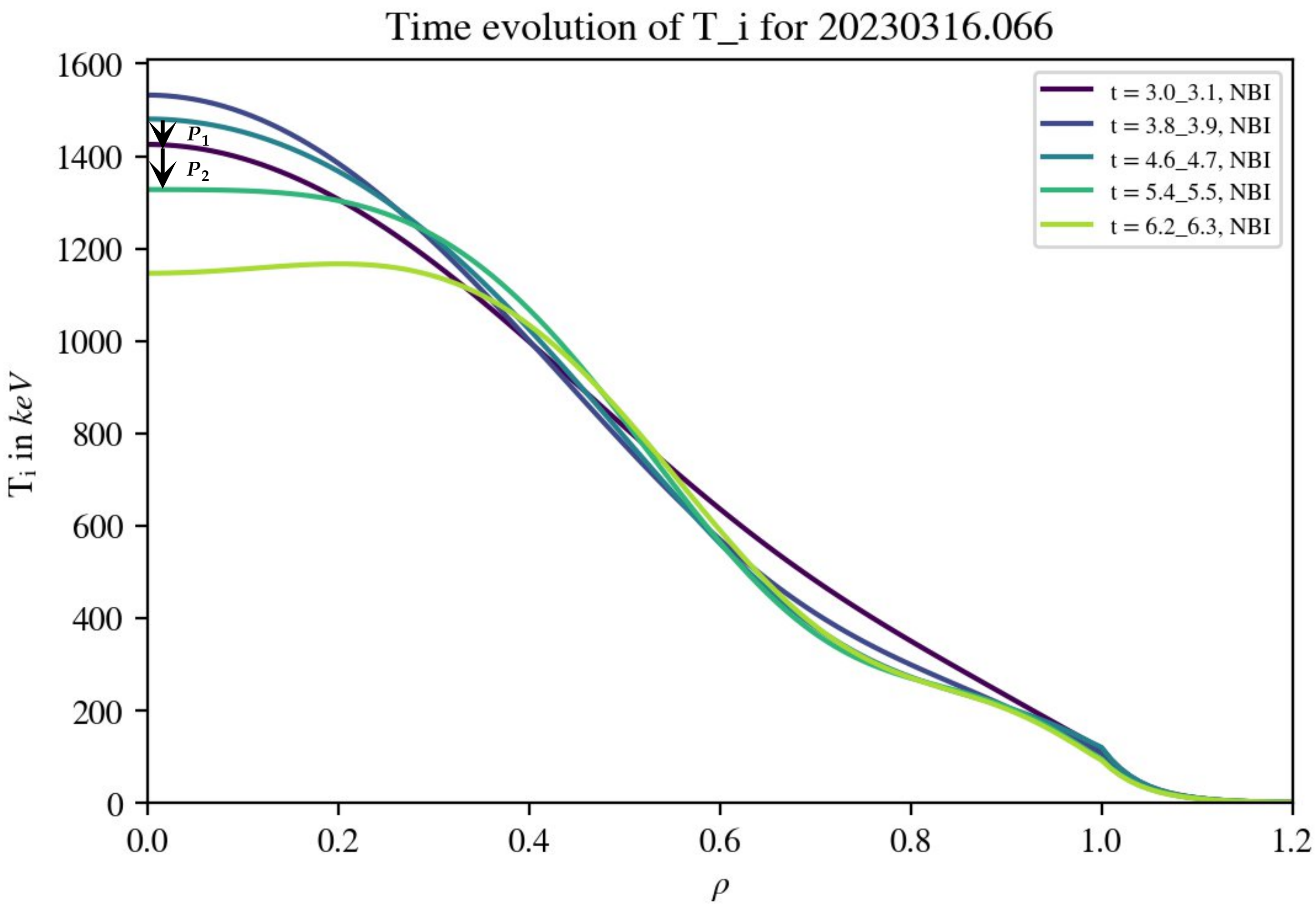


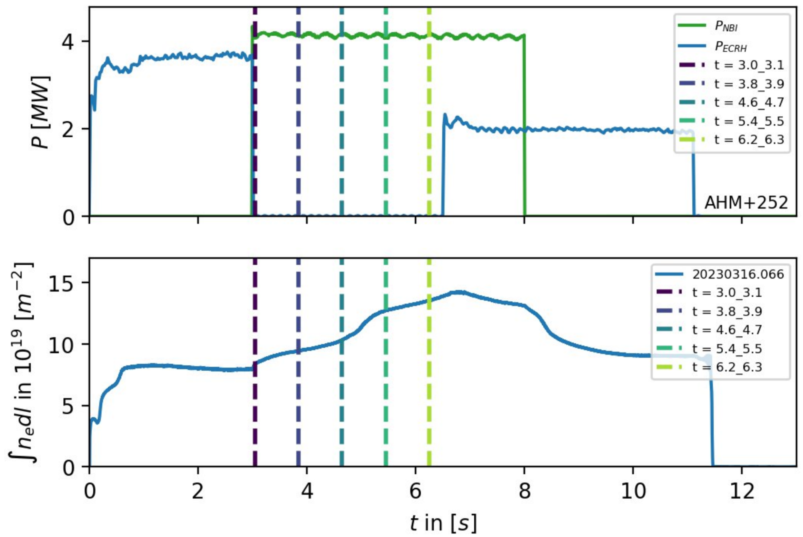


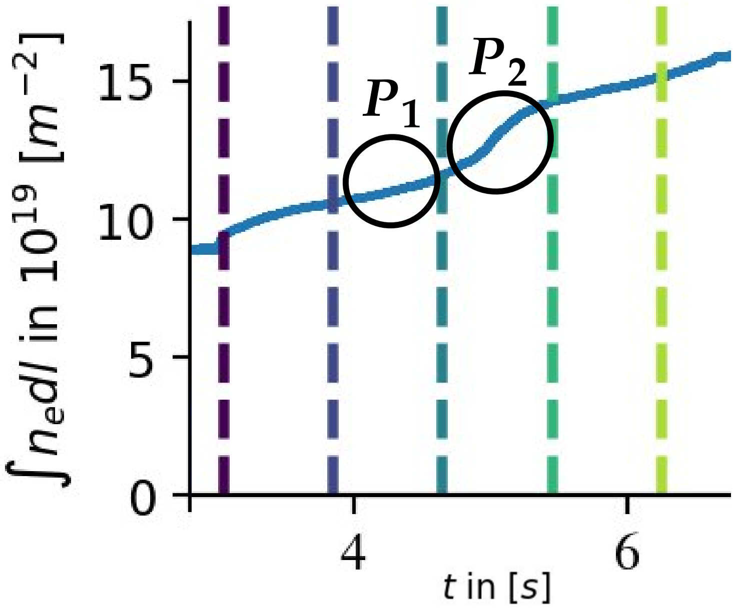


Ion temperature time evolution in general peaking cases

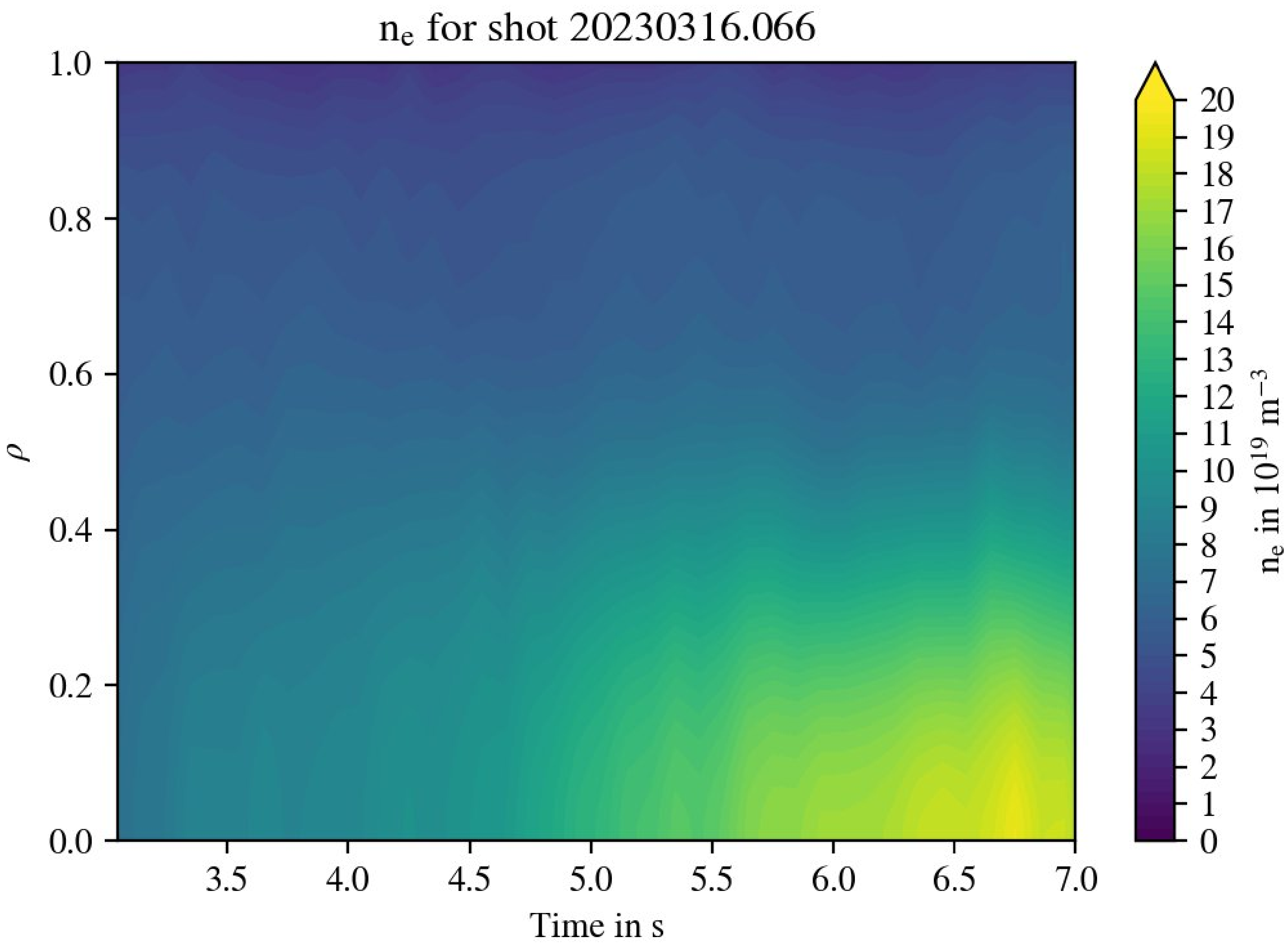
- **Due to the increase in particles with the NBI heating, inside $\rho = 0.4$ the ion temperature profile plunges as the density keeps rising**
  - **Paying attention to the line integrated density panel, we again observe that according to the rising slope of the line, the plunging rate momentarily accelerates such that $P_2 > P_1$**

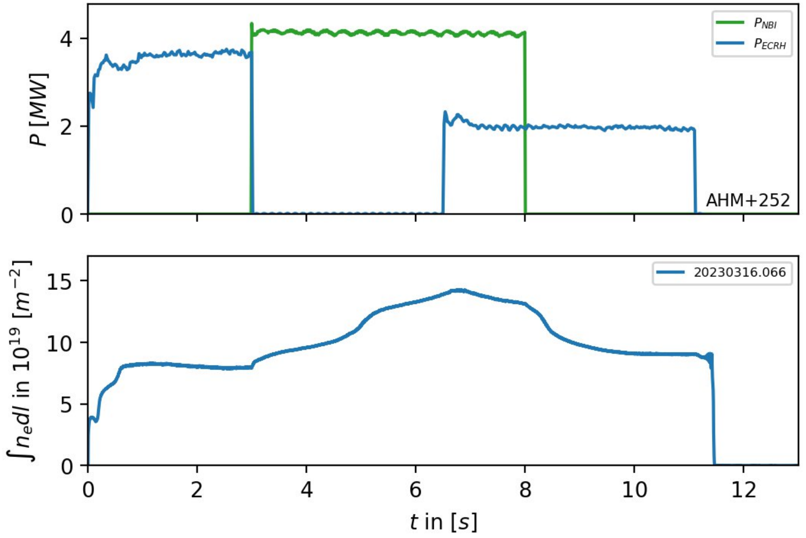






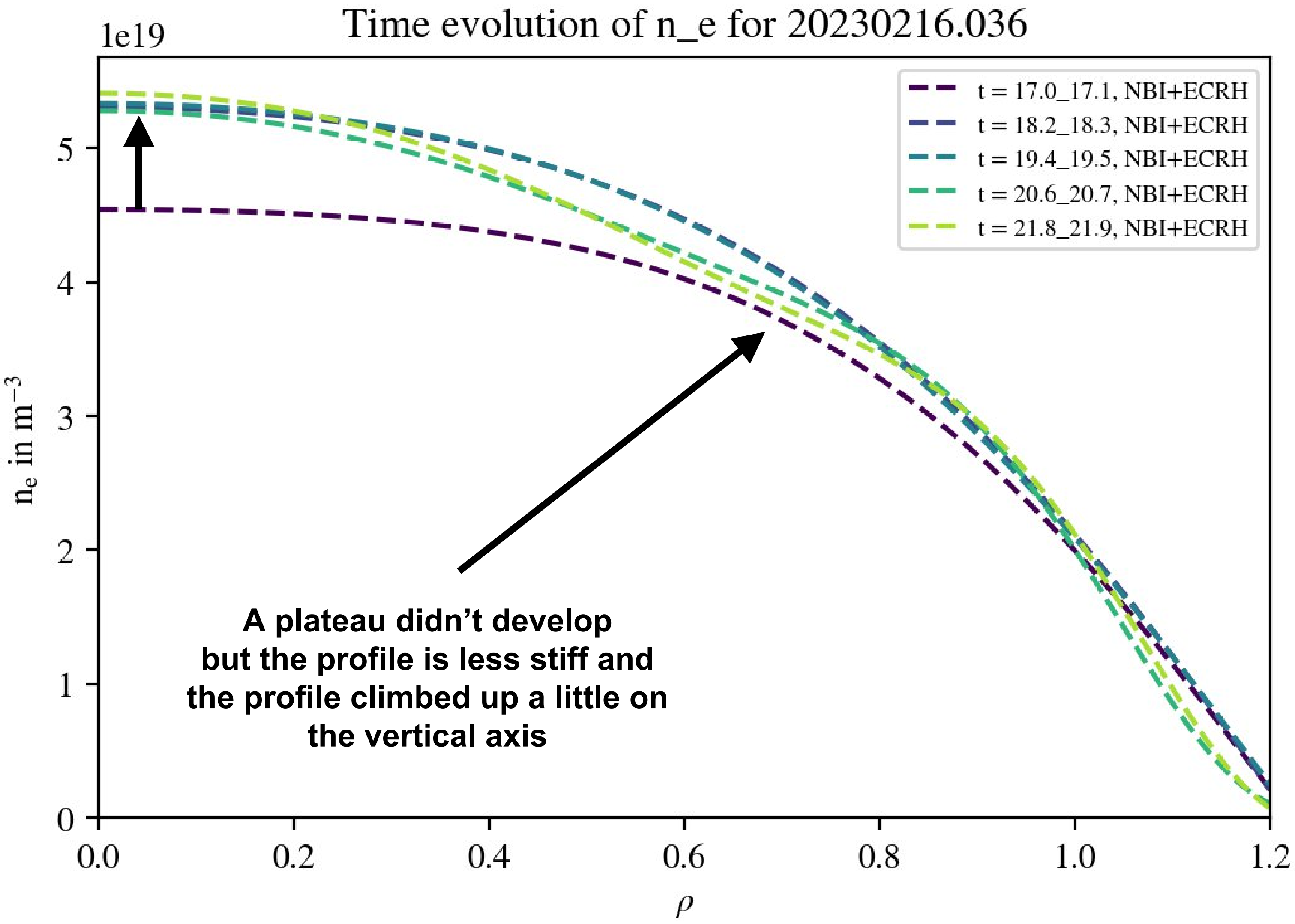
General accumulation case - electron density color plot

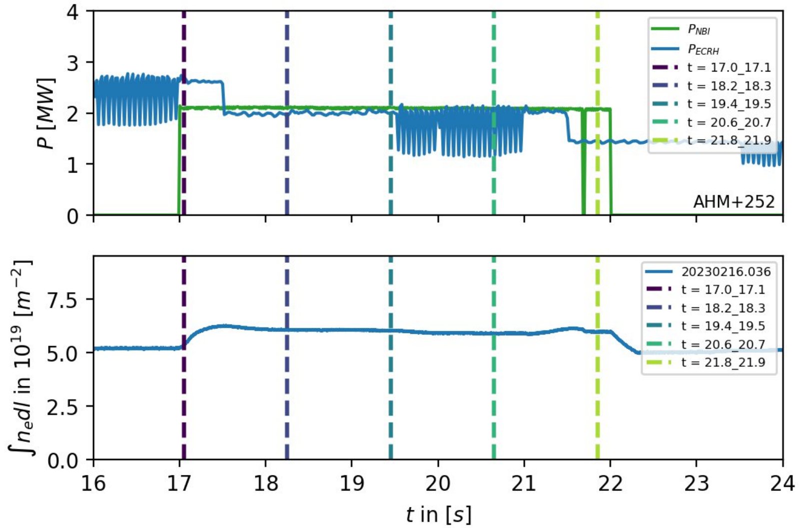




Non-peaking case 1 - continuous ECRH

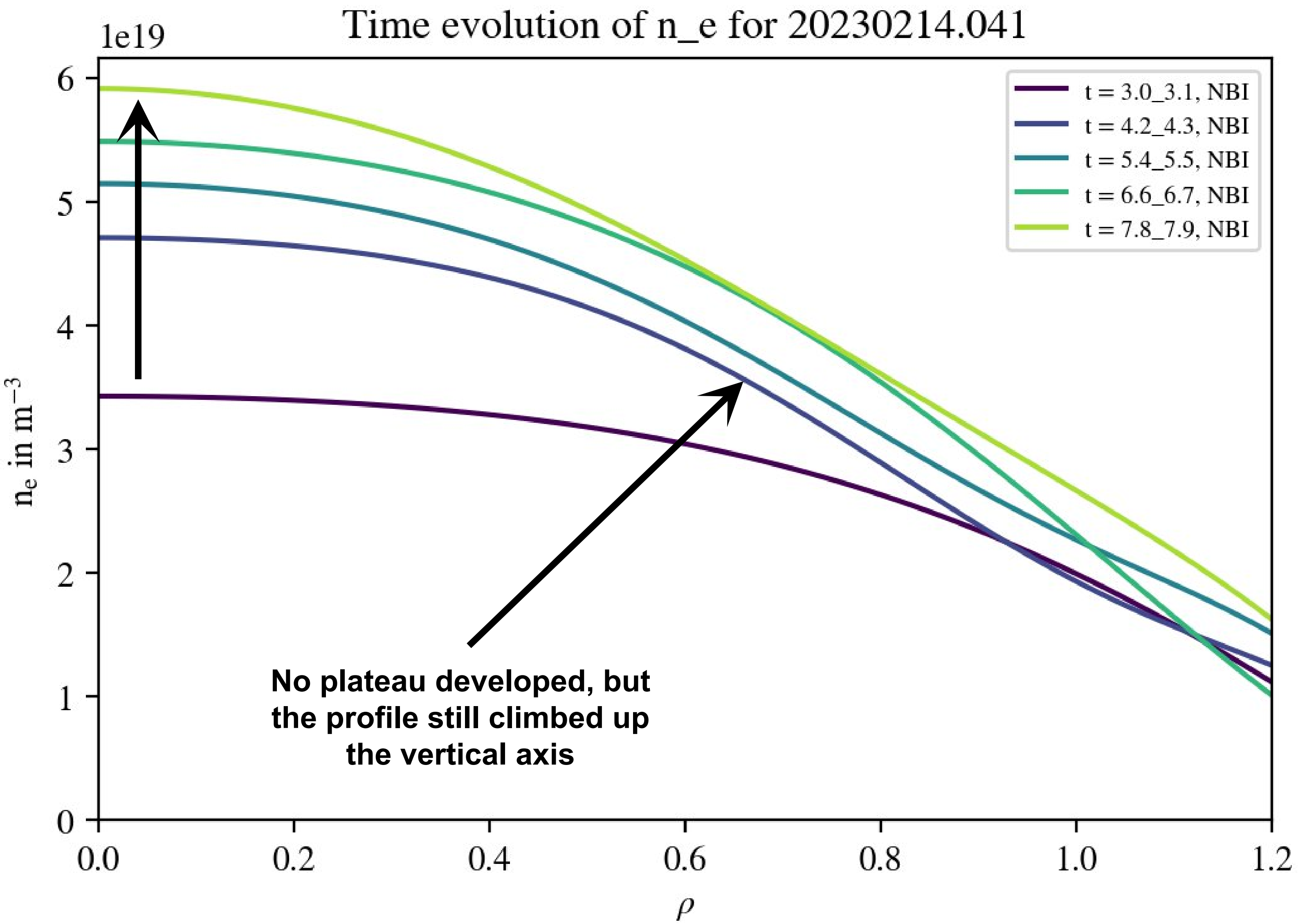
- Entering the combined heating phase does not show the development of a plateau in the electron density profile
- Still, an on-axis increase in the density is observed

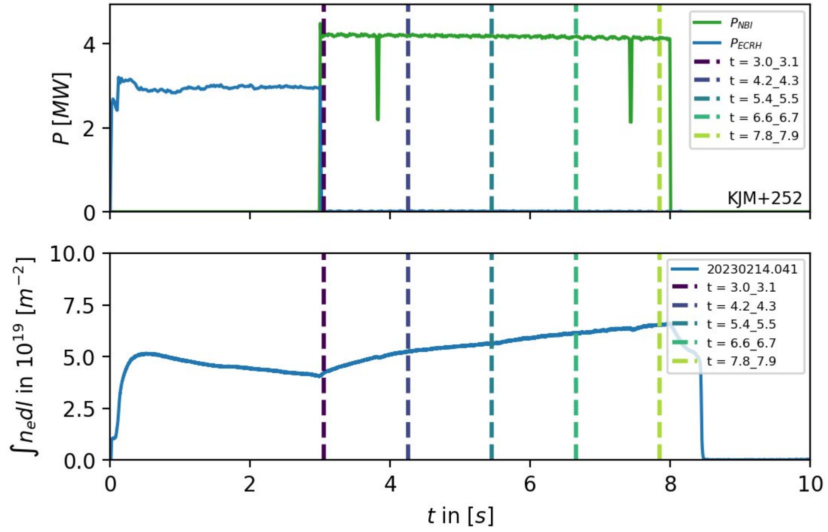




Non-peaking case 2 - pure NBI with low initial density

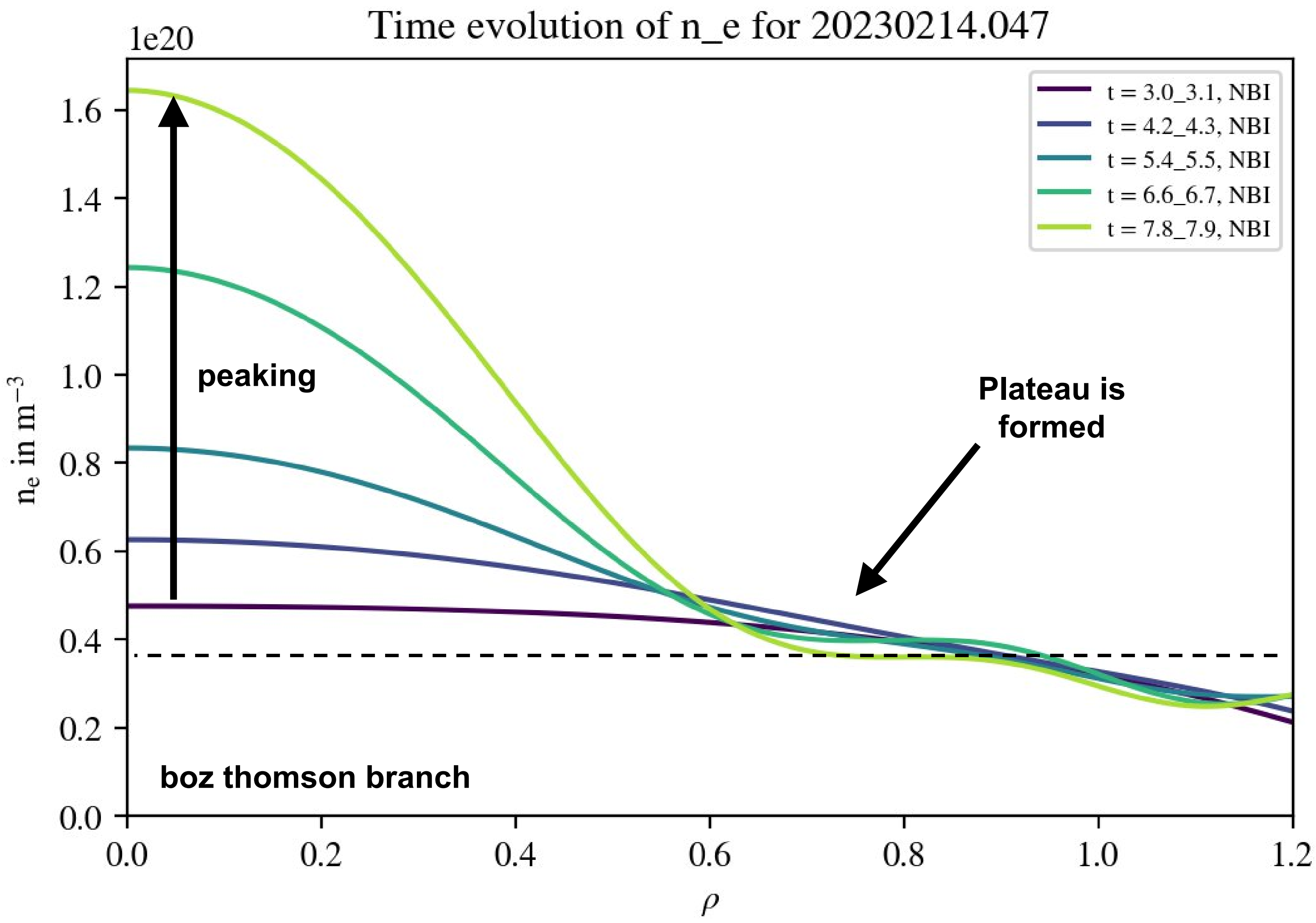
- **Despite entering pure NBI heating, no plateau develops**
  - **This could be explained by the low initial density**

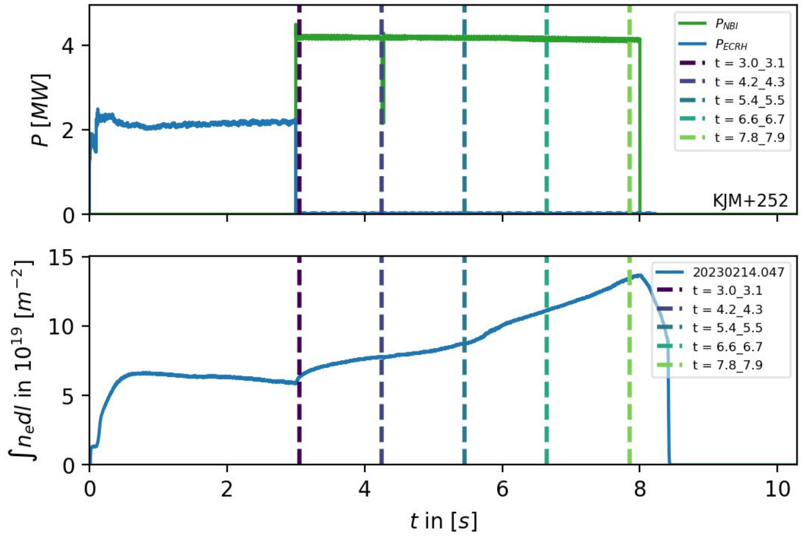




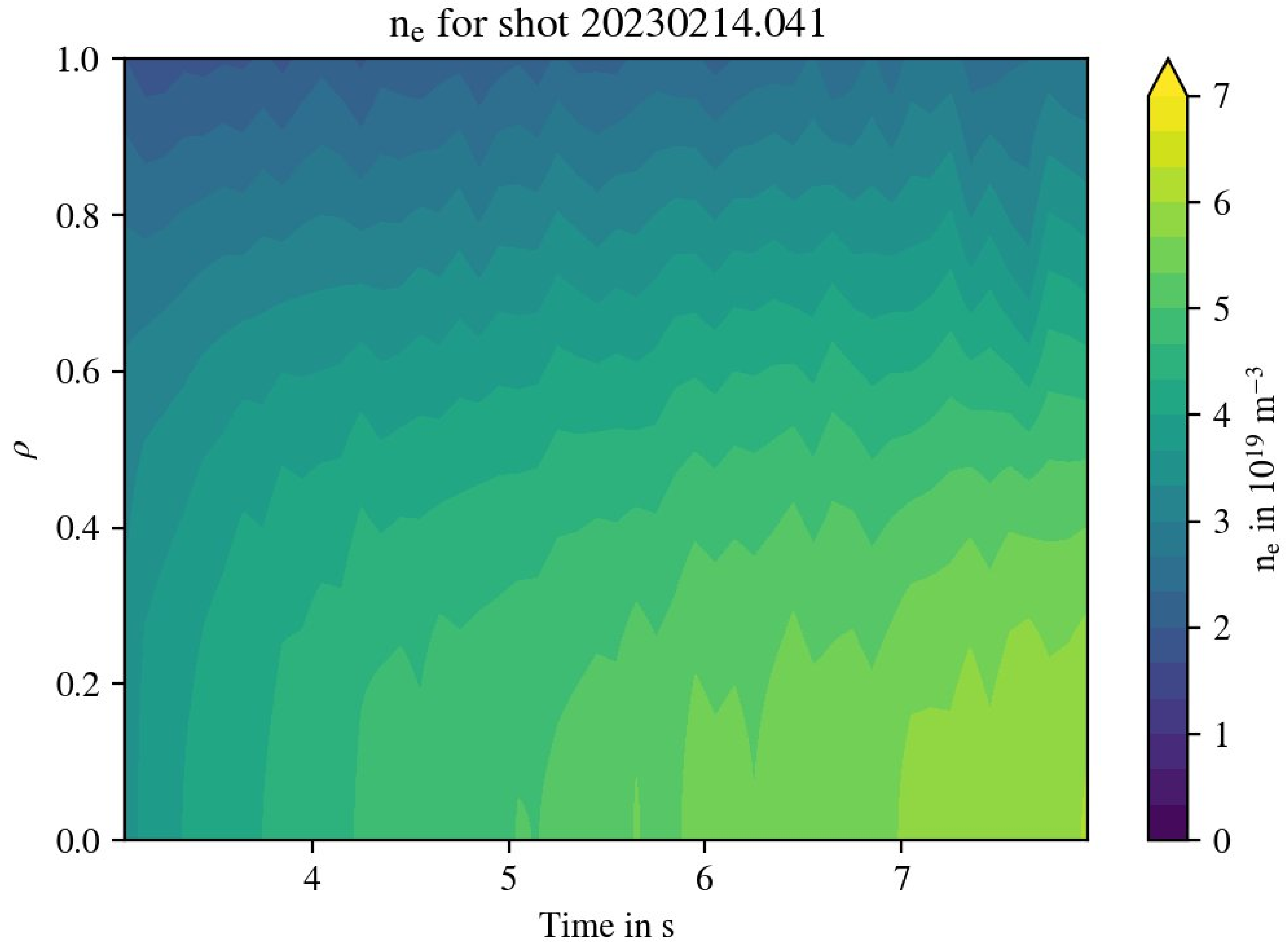
Non-peaking case 2, but with sufficient density - pure NBI

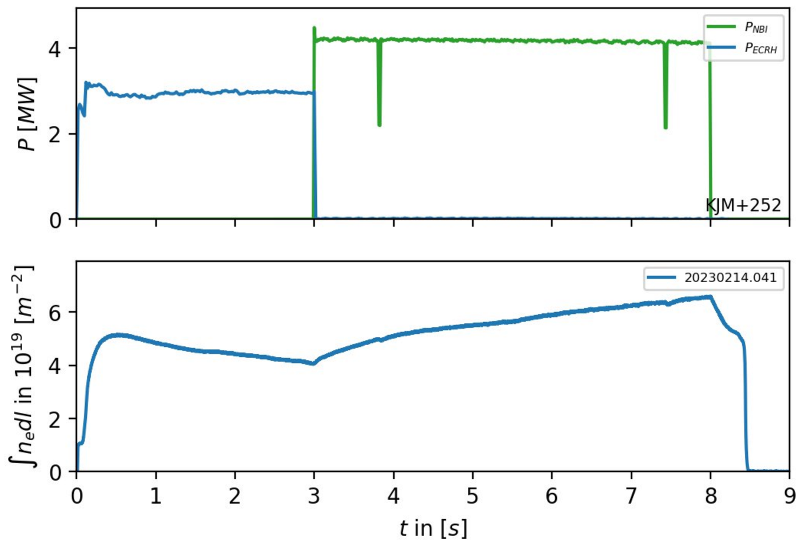
- **For a shot similar the previous, but where by contrast, <u>the critical density is achieved</u>, we see a central density accumulation**





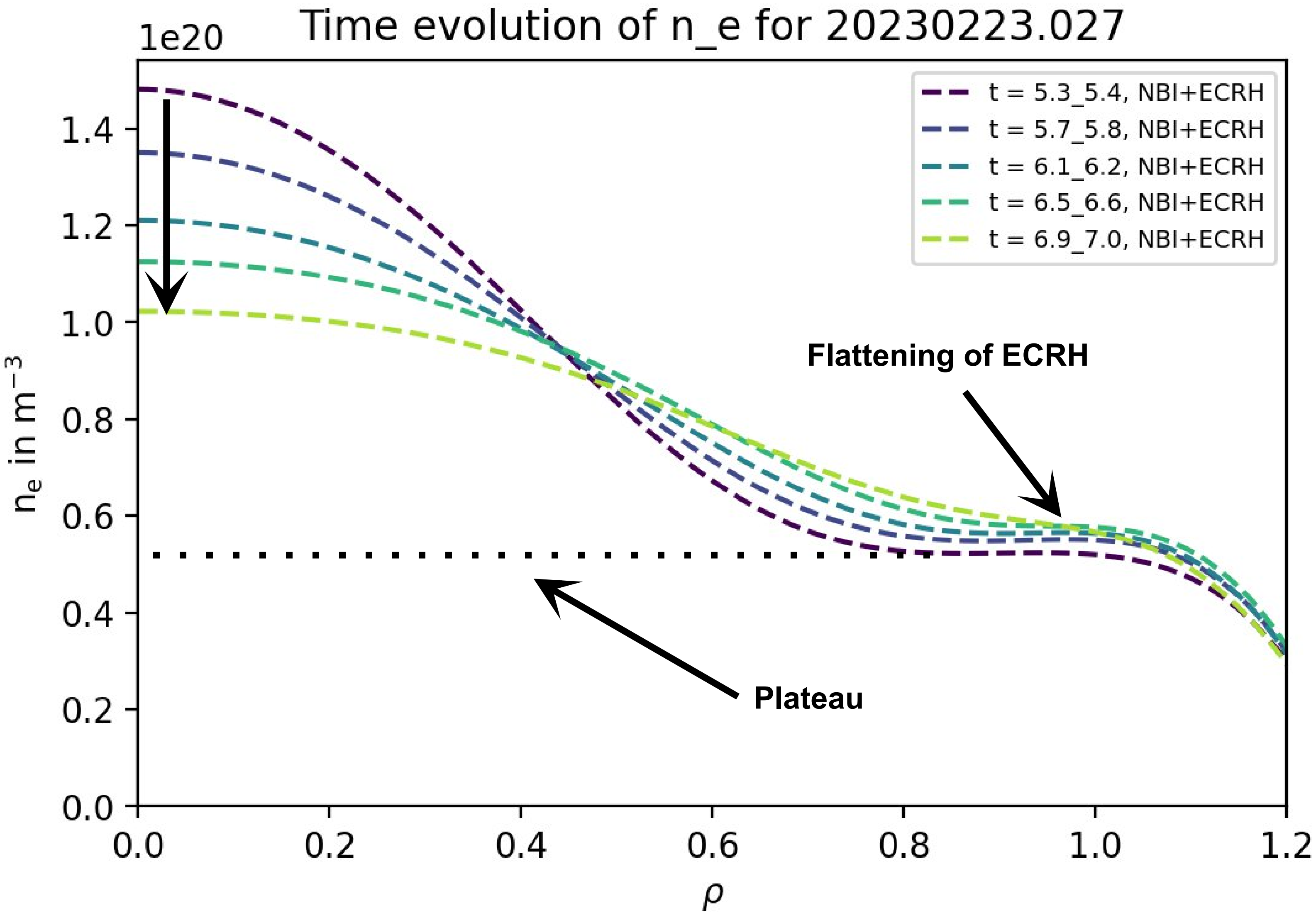
General non-accumulation case - electron density color plot

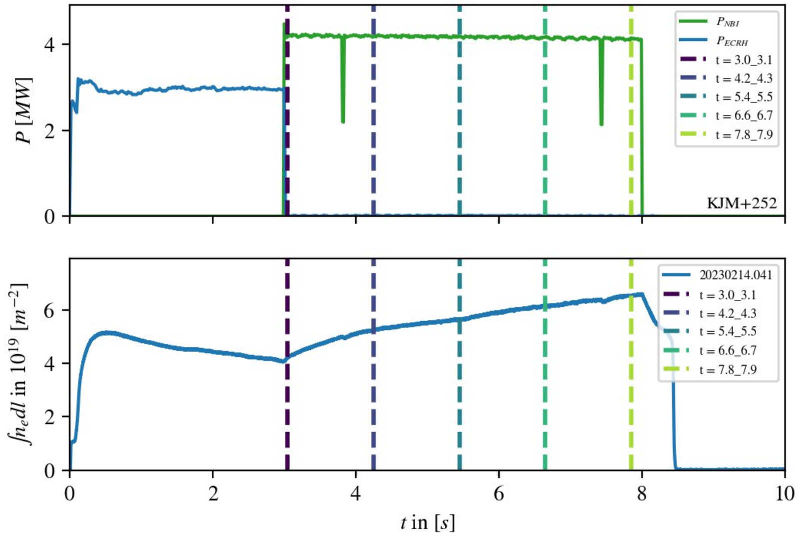




Combined heating phase - study case 0

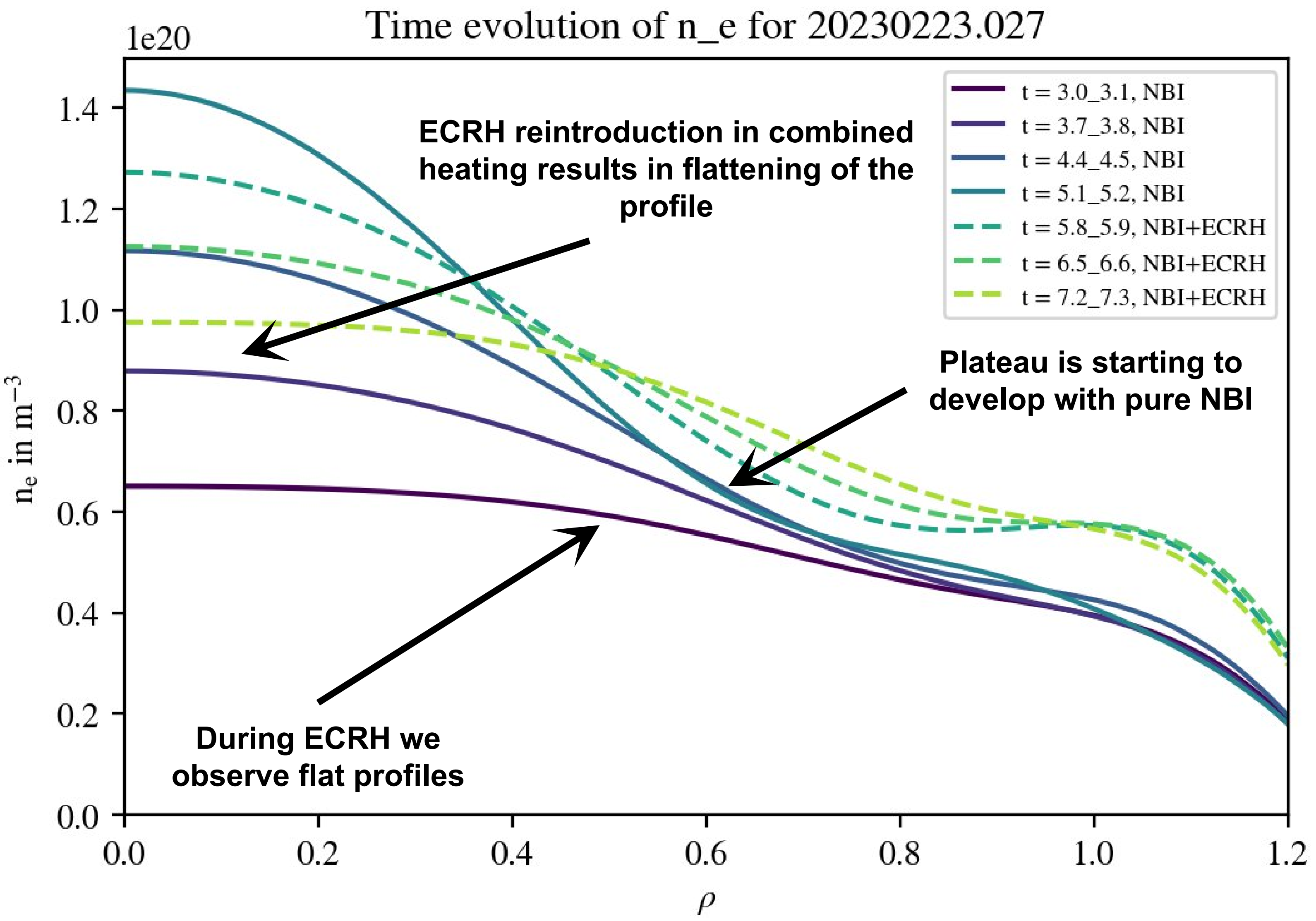
- **The reintroduction of the ECRH heating acts against the central density accumulation and aims to flatten the profiles**

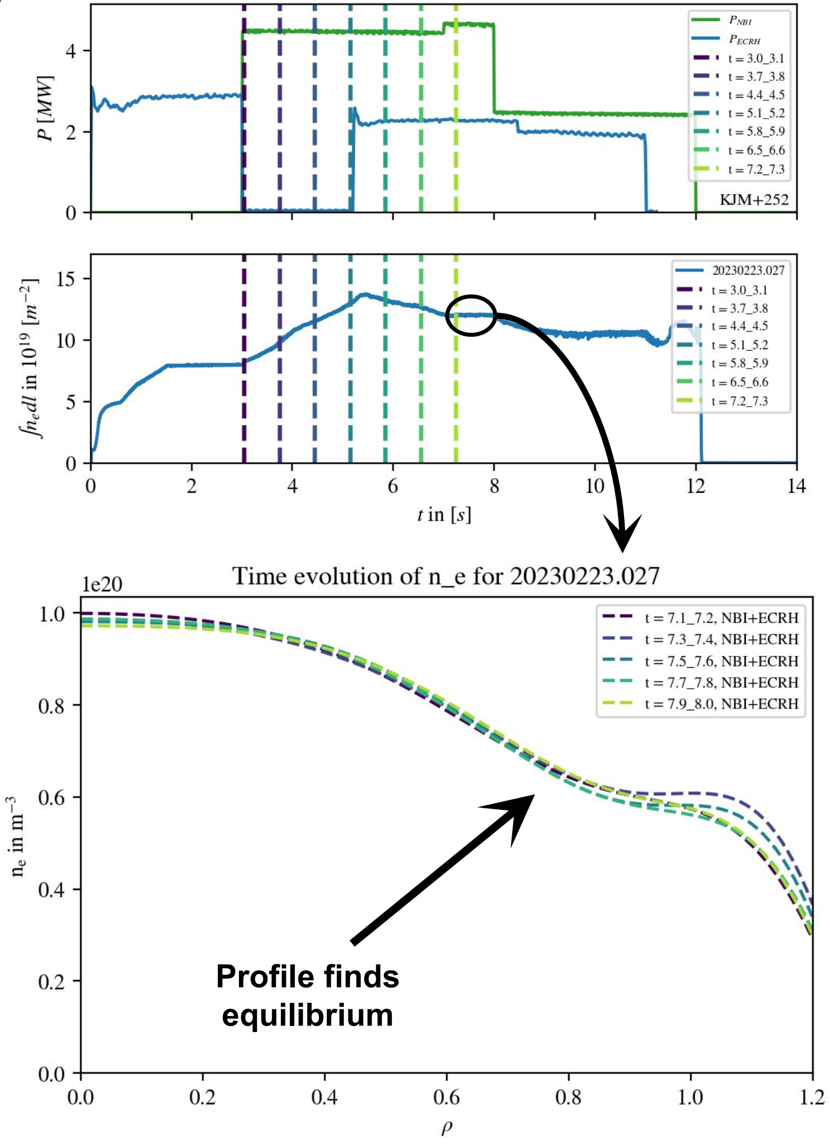




Combined heating phase - study case 1

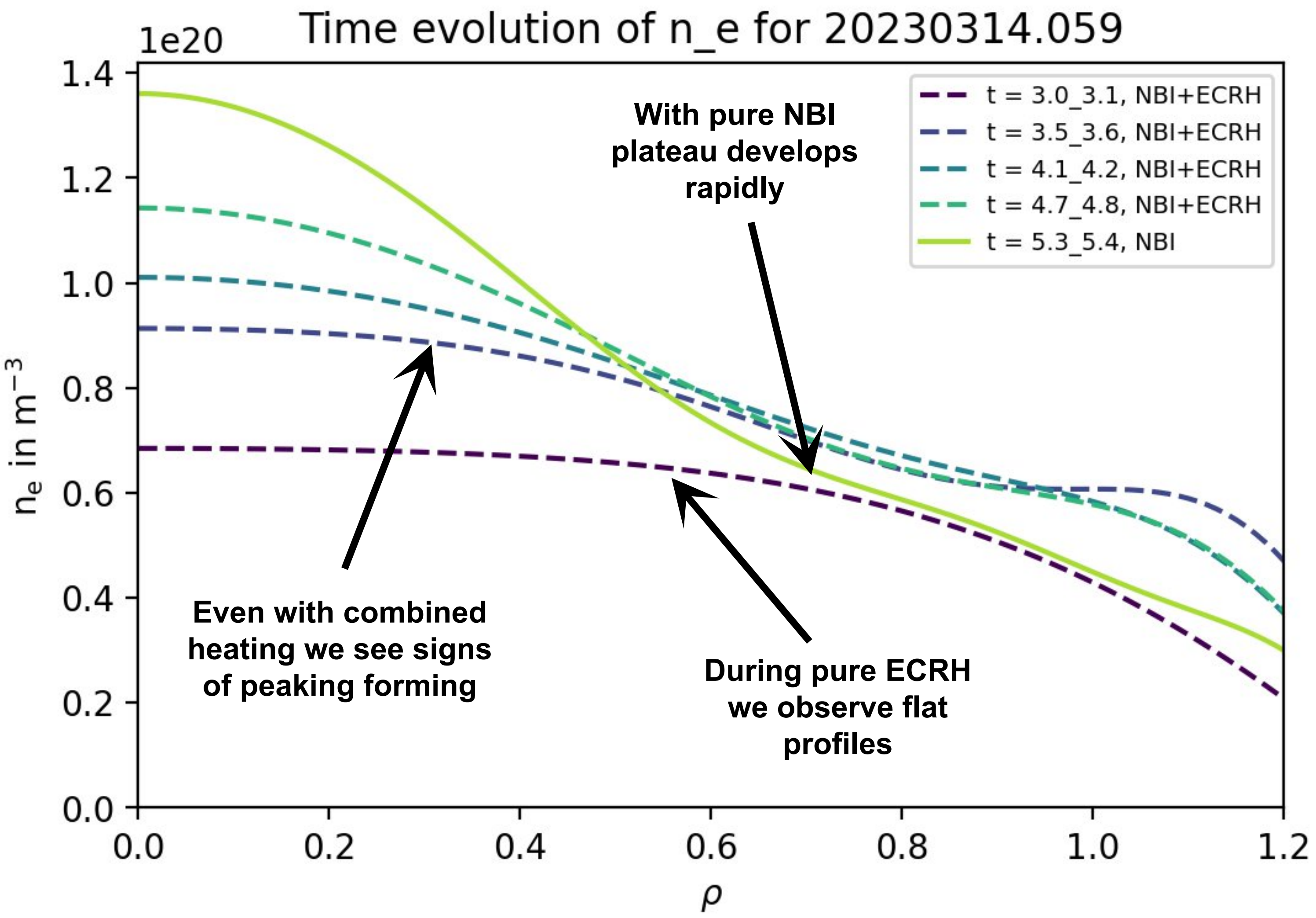
- **The reintroduction of the ECRH heating acts against the central density accumulation and aims to flatten the profiles**

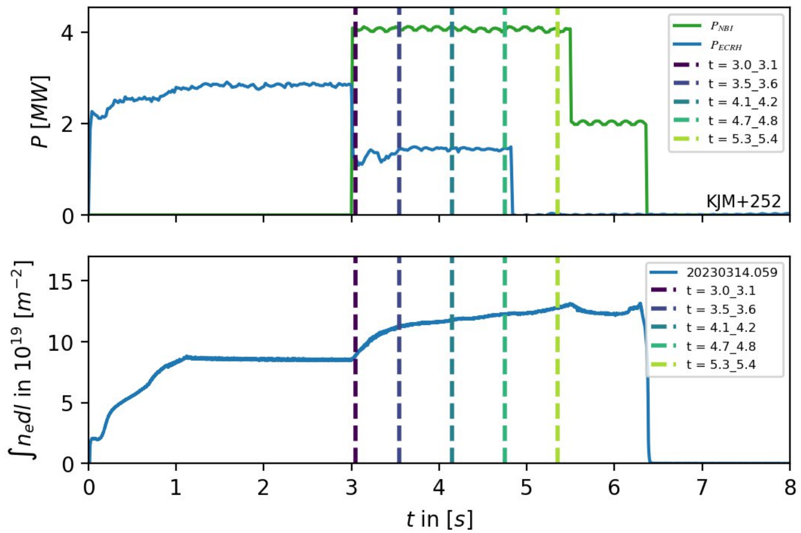




Combined heating phase - study case 2

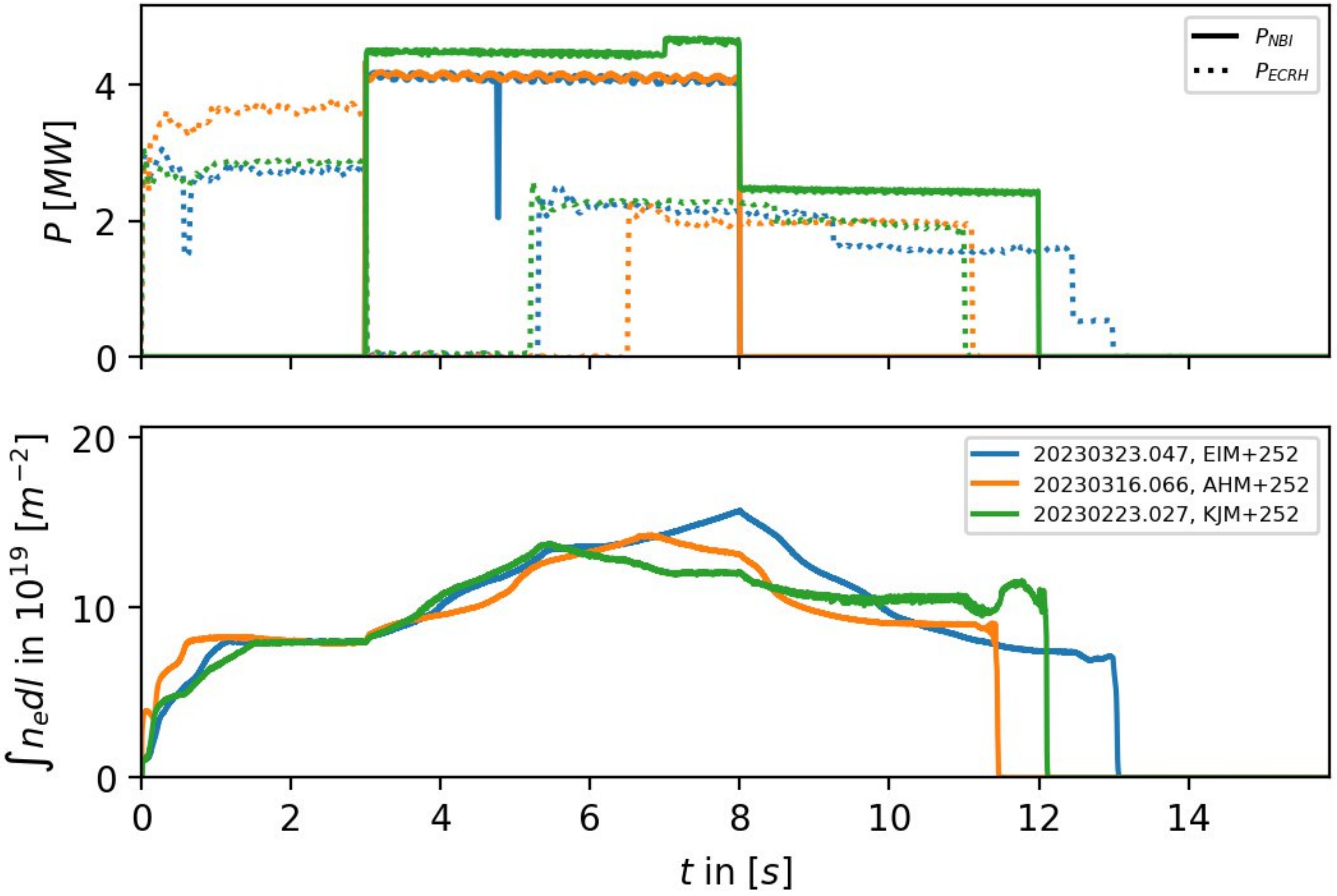
- **Despite the reintroduction of the ECRH heating, we still see the central density accumulation forming.**
  - **This hints at accumulation sensitivity to ECRH power**





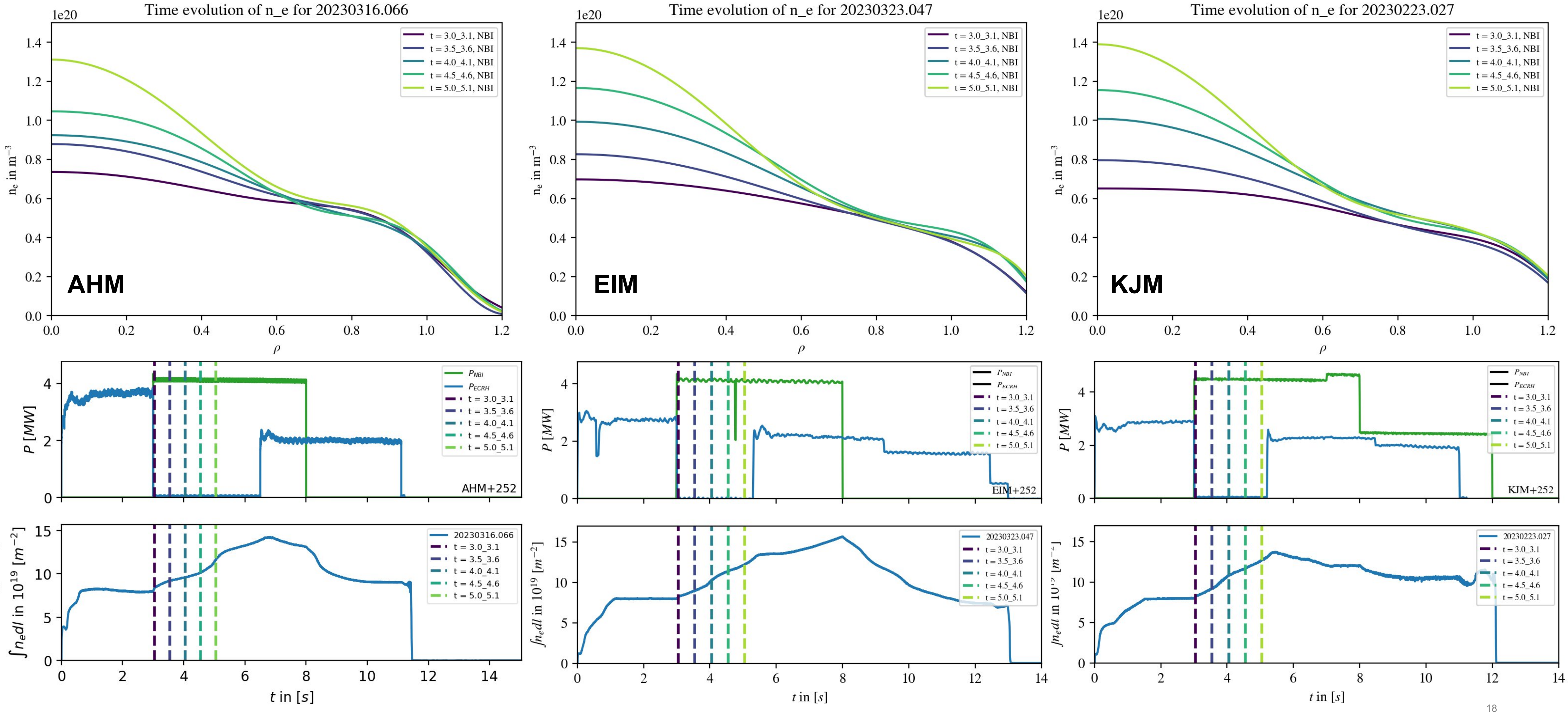
Comparison of accumulation in different magnetic configurations

- **Different magnetic configurations with similar heating patterns and power levels share similar evolution in line integrated density**
  - **AIM - Low Mirror; EIM - Standard; KJM - High Mirror**



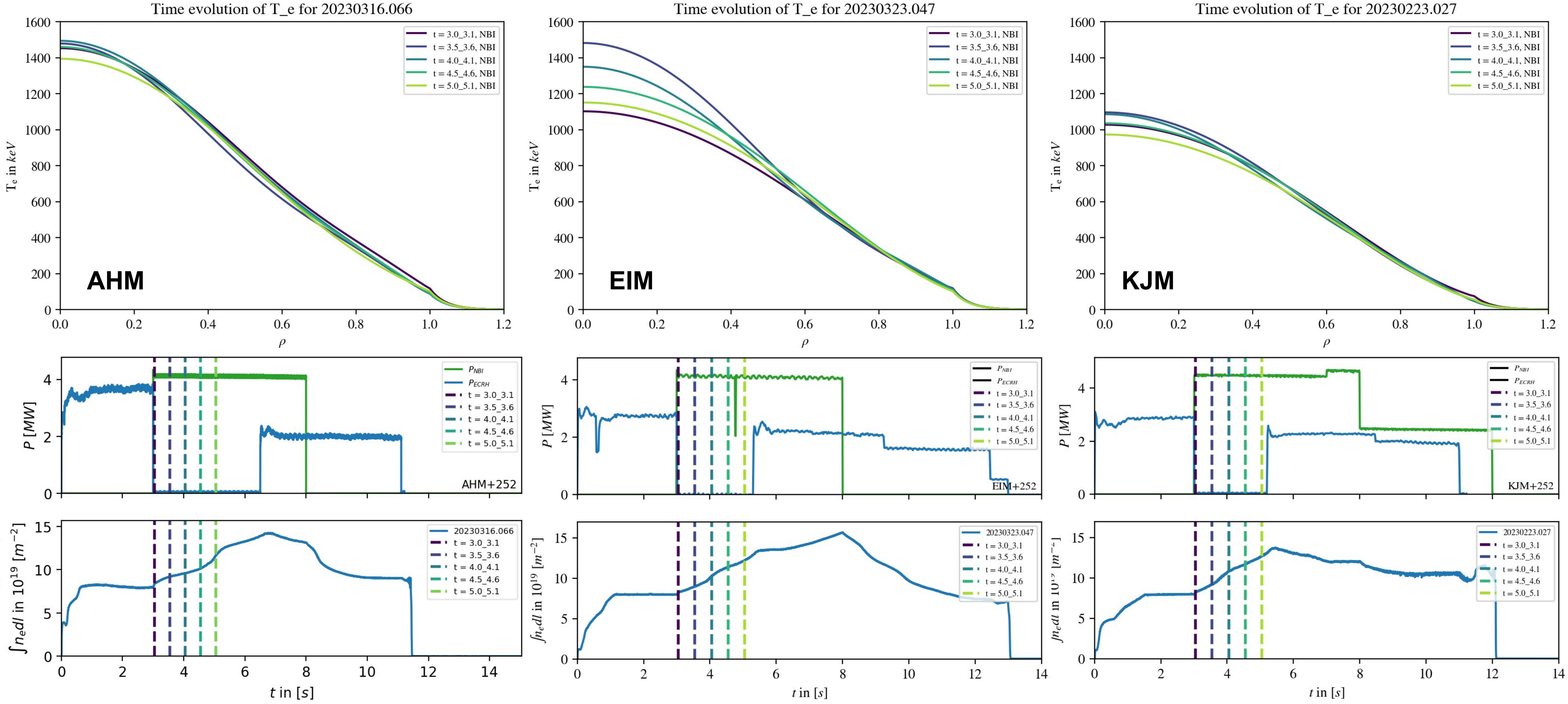
Comparison of peaking in different magnetic configurations - ne

- **AIM - Low Mirror; EIM - Standard; KJM - High Mirror**



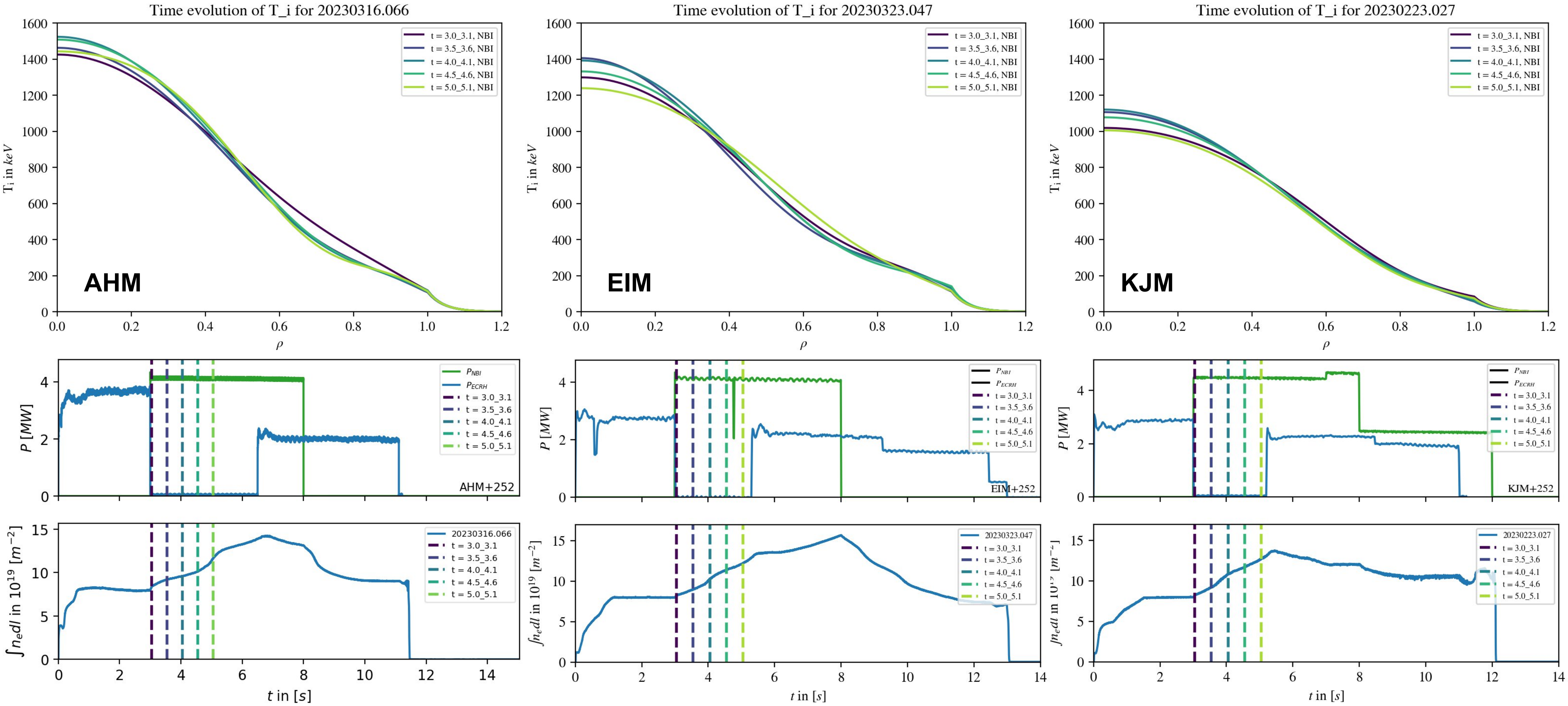
Comparison of peaking in different magnetic configurations - Te

- **AIM - Low Mirror; EIM - Standard; KJM - High Mirror**



Comparison of peaking in different magnetic configurations - Ti

- **AIM - Low Mirror; EIM - Standard; KJM - High Mirror**



Key observations of accumulation phenomena in main species

- Central density accumulation—which includes peaking and plateau development—in main species is observed during the pure NBI heating phase at high density
- Due to high collisionally, Ion and electron temperatures are coupled relatively strongly as evidenced by their temperatures and similar profile evolutions;
- Accumulation occurs only for high-density discharges, a critical density ($\sim 8.5 - 9.0 \cdot 10^{19} \mathrm{m}^{-2}$) has to be achieved for the peaking to occur
- In combined NBI and ECRH heating of high density, the accumulation depends on the power ratios such that the ECRH heating could either weaken the accumulation or disable it entirely
  - Low-power ECRH ($< \sim 1\,\mathrm{MW}$) is observed to weaken accumulation
  - High-power ECRH ($< \sim 2\,\mathrm{MW}$) is observed to prevent onset of accumulation
- No strong dependence of accumulation on different magnetic configurations is observed - smaller differences e.g. in increased-slope location

Outlook

- Main plasma species profiles
  - Accumulation phenomena
  - Non-accumulating behavior
  - ECRH reintroduction
  - Comparison of accumulation at different magnetic configurations
  - Additional main species observations by S. Bannmann
  - Concluding observations on main species
- **Impurity profiles**
  - **Impurity profile fitting method - modified double tanh**
  - **Accumulation phenomena**
  - **Non-accumulating behavior**
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  - **Comparison of accumulation at different magnetic configurations**
  - **Concluding observations on impurities**
- Database approach for examining accumulation phenomena
  - Variable heatmap and strongest correlations
  - Kink location to determine separation of anomalous and neoclassical transport
  - Transport color-coded plots
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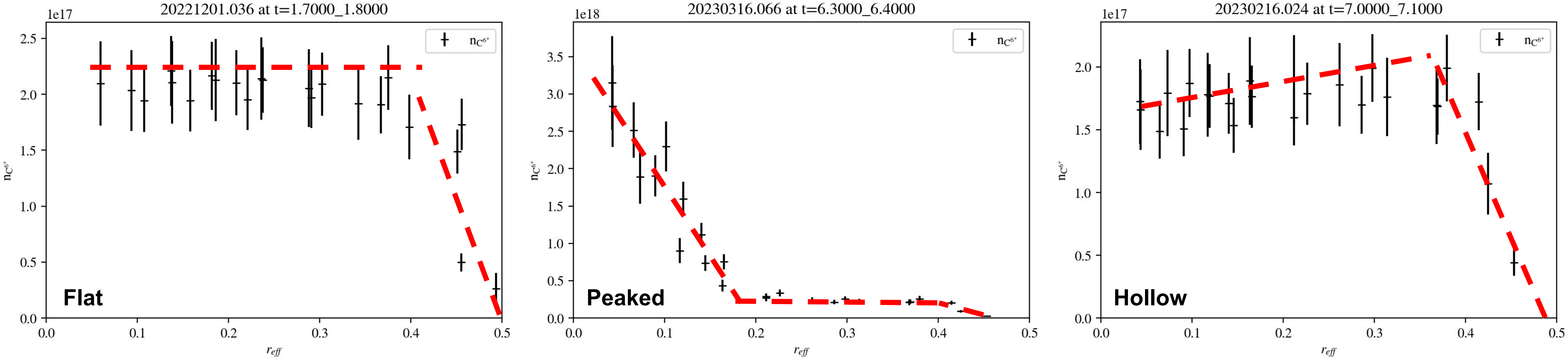
- Summary

Data fitting function must be able to fit the different cases

And transition between the in-between states of the main scenarios:

- Peaked profiles characterized by developed peaking and plateau
- Flat profiles characterized by no central density accumulation
- Hollow profiles characterized by plunging density towards the core



Impurity fitting function - modified hyperbolic tangent

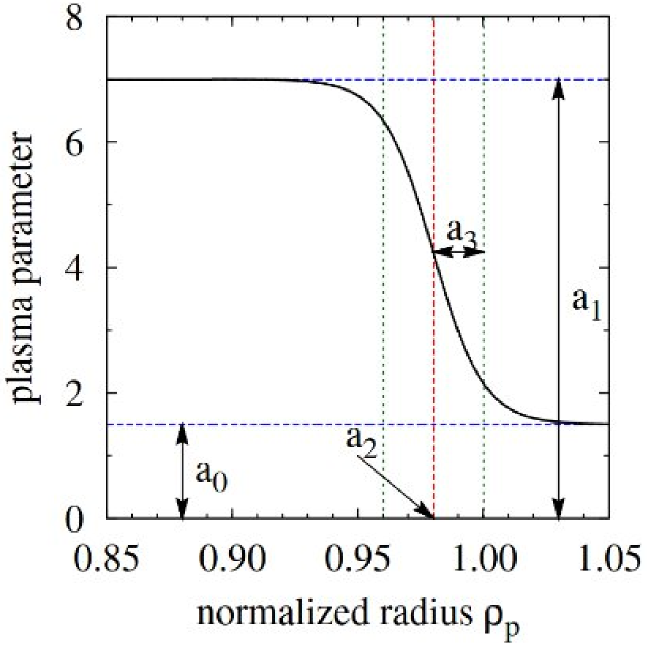
- **Modified tanh function allows for hollow profiles and offers quantification of accumulation parameters which can be inferred from mtanh's parameter values**

$$f_{mtanh}(x) = \frac{a_0 + a_1}{2} + \frac{a_1 - a_0}{2} \cdot \frac{(1 + a_4 x + a_5 x^2 + a_6 x^3)e^{z} - (1 + a_7 x + a_8 x^2 + a_9 x^3)e^{-z}}{e^{z} + e^{-z}}$$

$$z = \frac{a_2 - x}{a_3}$$

a_0	SOL value or offset
a_1	pedestal top value
a_2	symmetry radius
a_3	half width
a_4-a_6	core polynomial
a_7-a_9	edge polynomial

Adapted from Schneider Philip's thesis



Database fitting function - modified hyperbolic tangent

- **Modified tanh is customized further to match our needs**
  - **Quadratic and cubic terms are removed to prevent overfitting**
- a_4 **term allows for hollowness in profiles**
- a_0 **term is set to zero to match experimental observations**

$$f_{\text{mtanh}}(x) = \frac{a_0 + a_1}{2} + \frac{a_1 - a_0}{2} \cdot \frac{(1 + a_4\rho + \cancel{a_5\rho^2 + a_6\rho^3})e^z - (\cancel{1 + a_7\rho + a_8\rho^2 + a_9\rho^3})e^{-z}}{e^z + e^{-z}}$$

$$z = \frac{a_2 - \rho}{a_3}$$

a_0	SOL value or offset
a_1	pedestal top value
a_2	symmetry radius
a_3	half width
a_4-a_6	core polynomial
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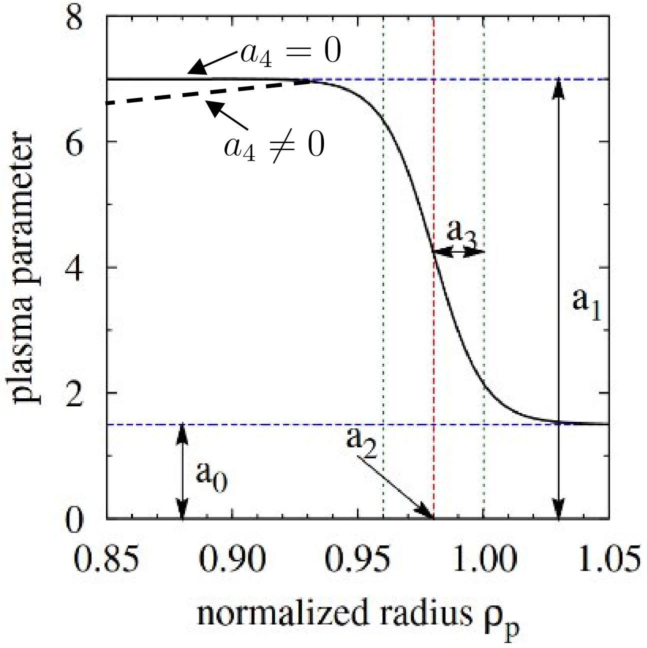
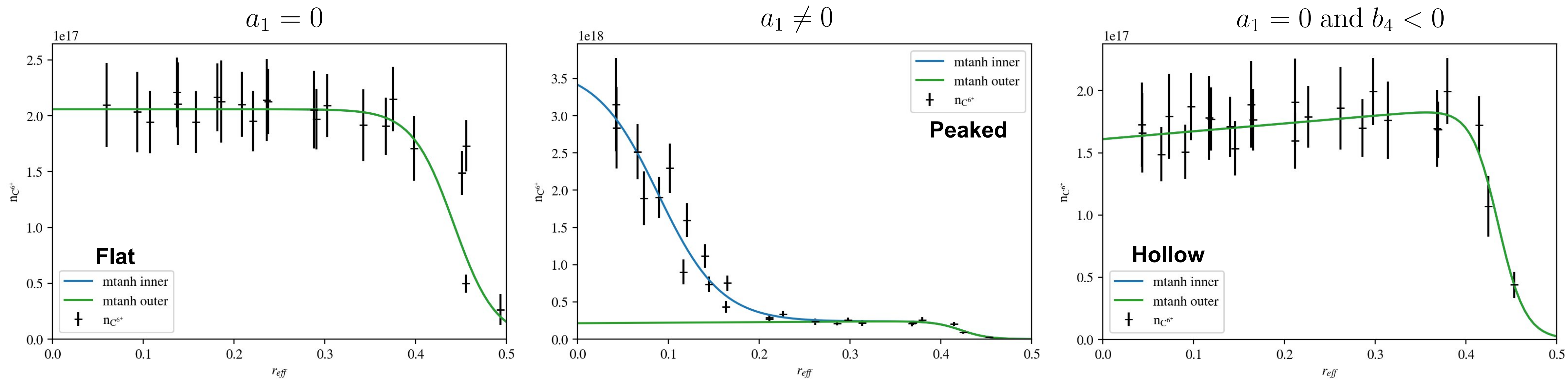


Adapted from [Schneider Philip's thesis]

Database fitting function - double modified hyperbolic tangent

- **By combining two modified tanh functions we get a function that can characterize the profile evolution**

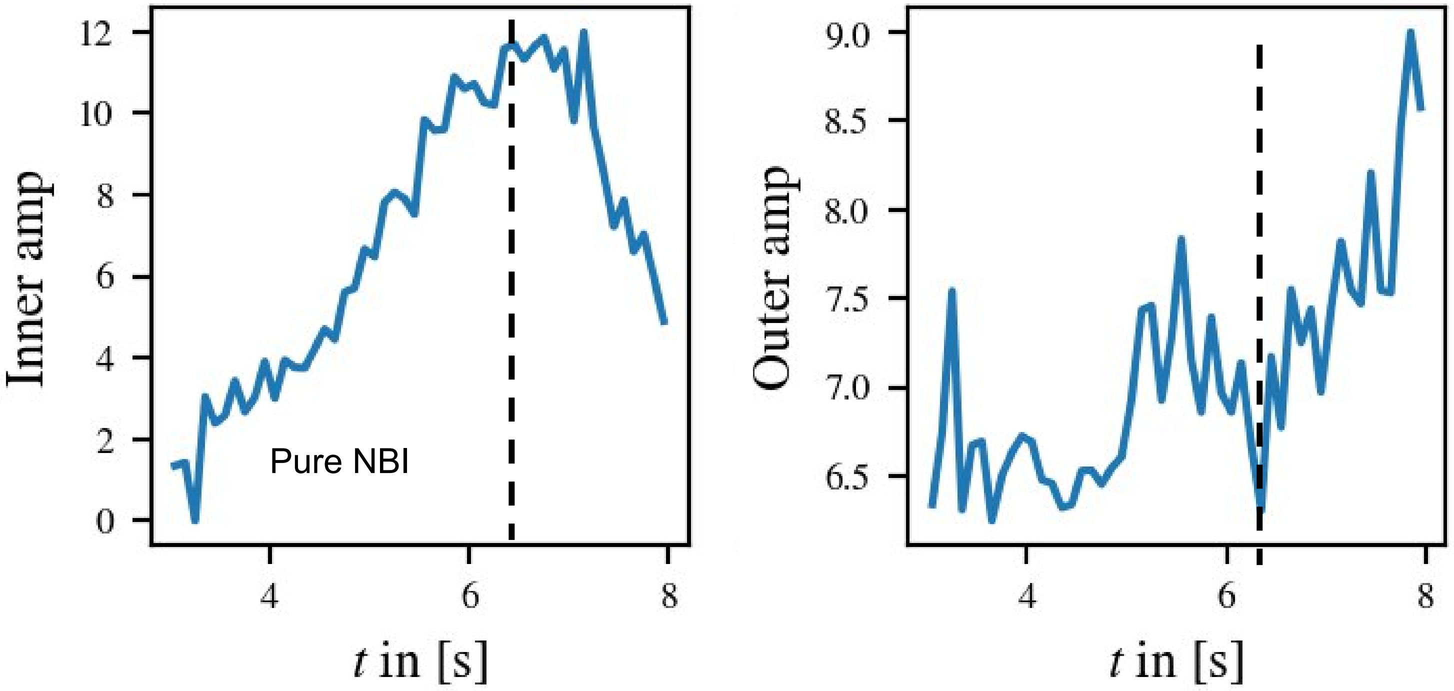
$$f_{\text{double mtanh}}(x) = \underbrace{\frac{a_1}{2} + \frac{a_1}{2} \cdot \frac{e^{z} - e^{-z}}{e^{z} + e^{-z}}}_{\text{Inner tanh}} + \underbrace{\frac{b_1}{2} + \frac{b_1}{2} \cdot \frac{(1 + b_4 \rho)e^{w} - e^{-w}}{e^{w} + e^{-w}}}_{\text{Outer tanh}}$$

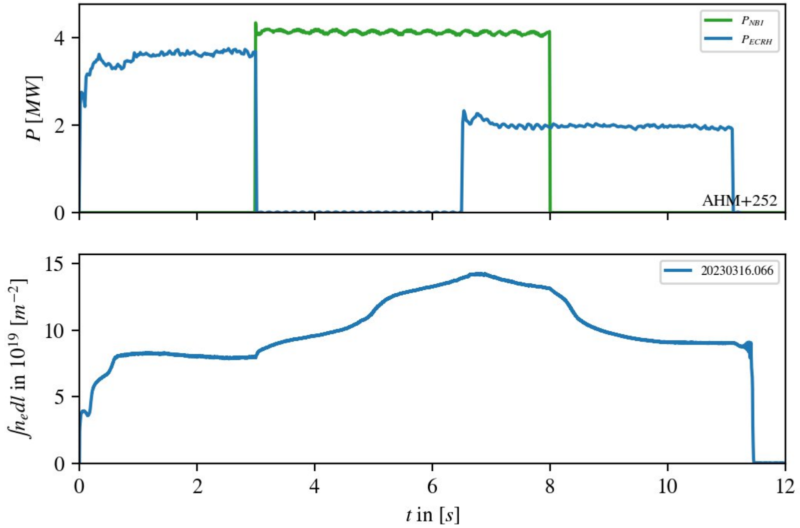


[Desmos demo]

Modified double tanh parameter-time plots for main species

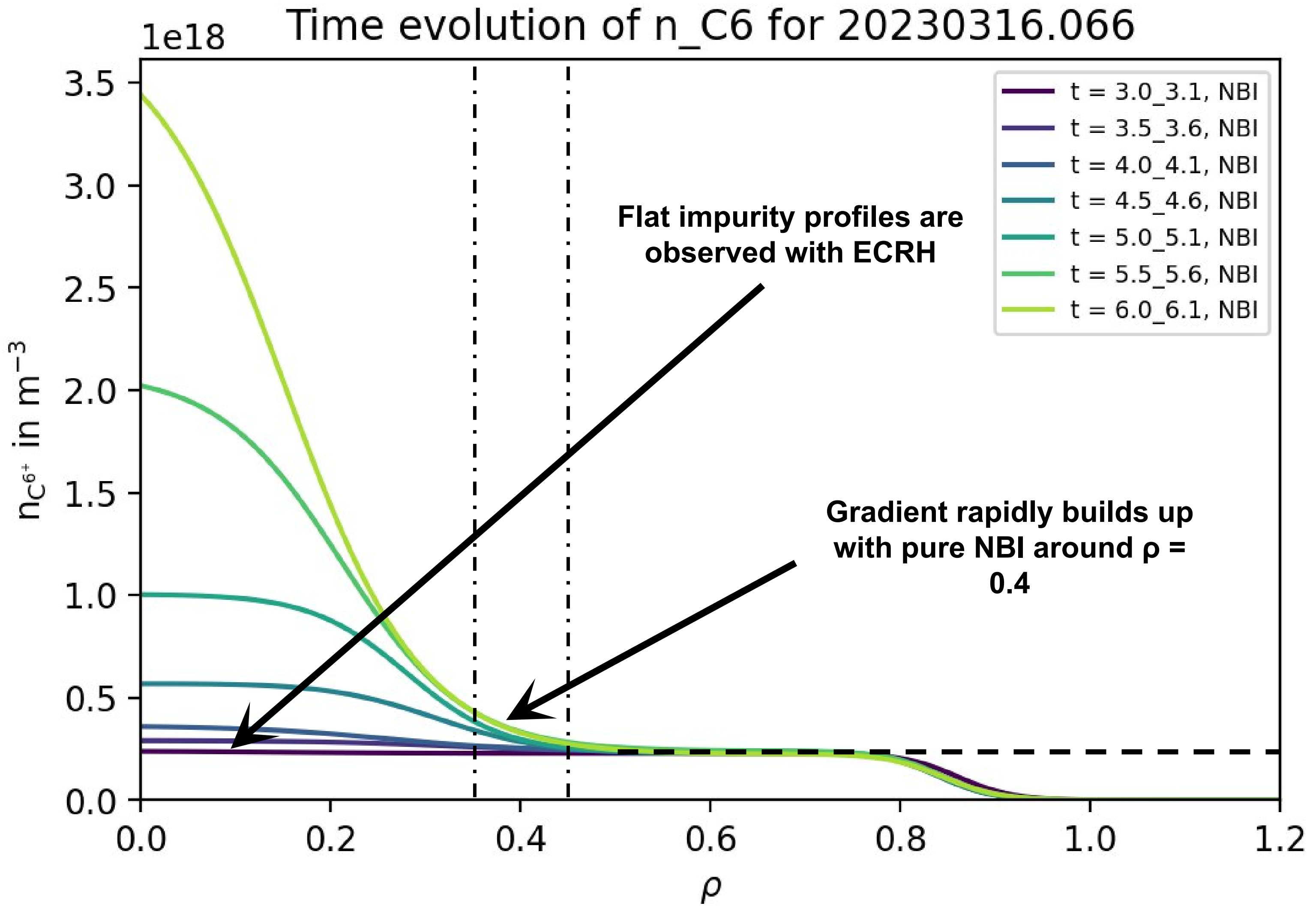
- **Accumulation behavior present in fitting: inner amplitude parameter increases with pure NBI and decreases with high-power ECRH**

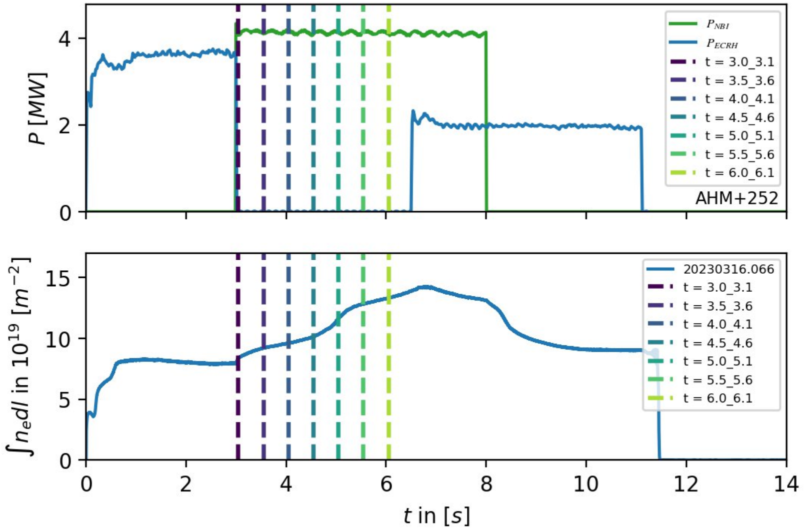


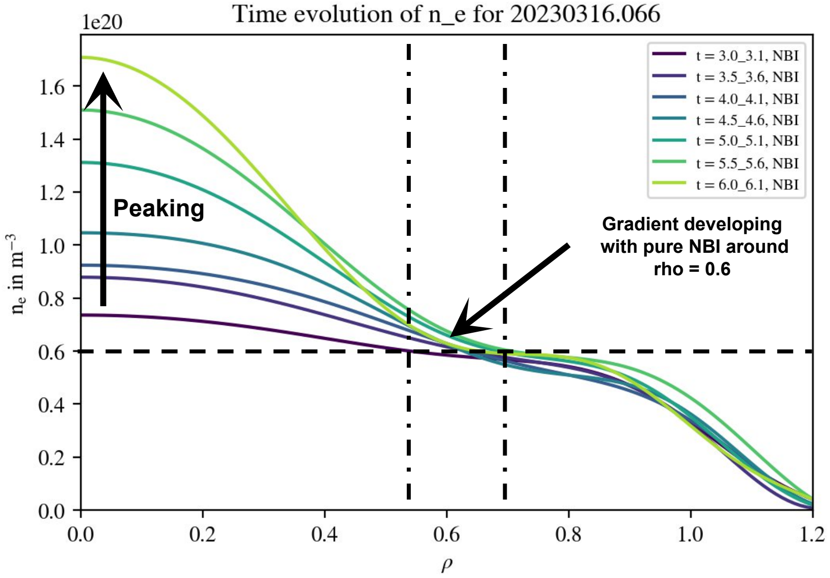


Accumulation in impurity profiles is associated with NBI

- **Impurity profiles peak stronger than the main species**
  - **While electron density profiles develop a plateau around $\rho \cong 0.6$, impurity profiles a develops plateau in $\rho \cong 0.4$**

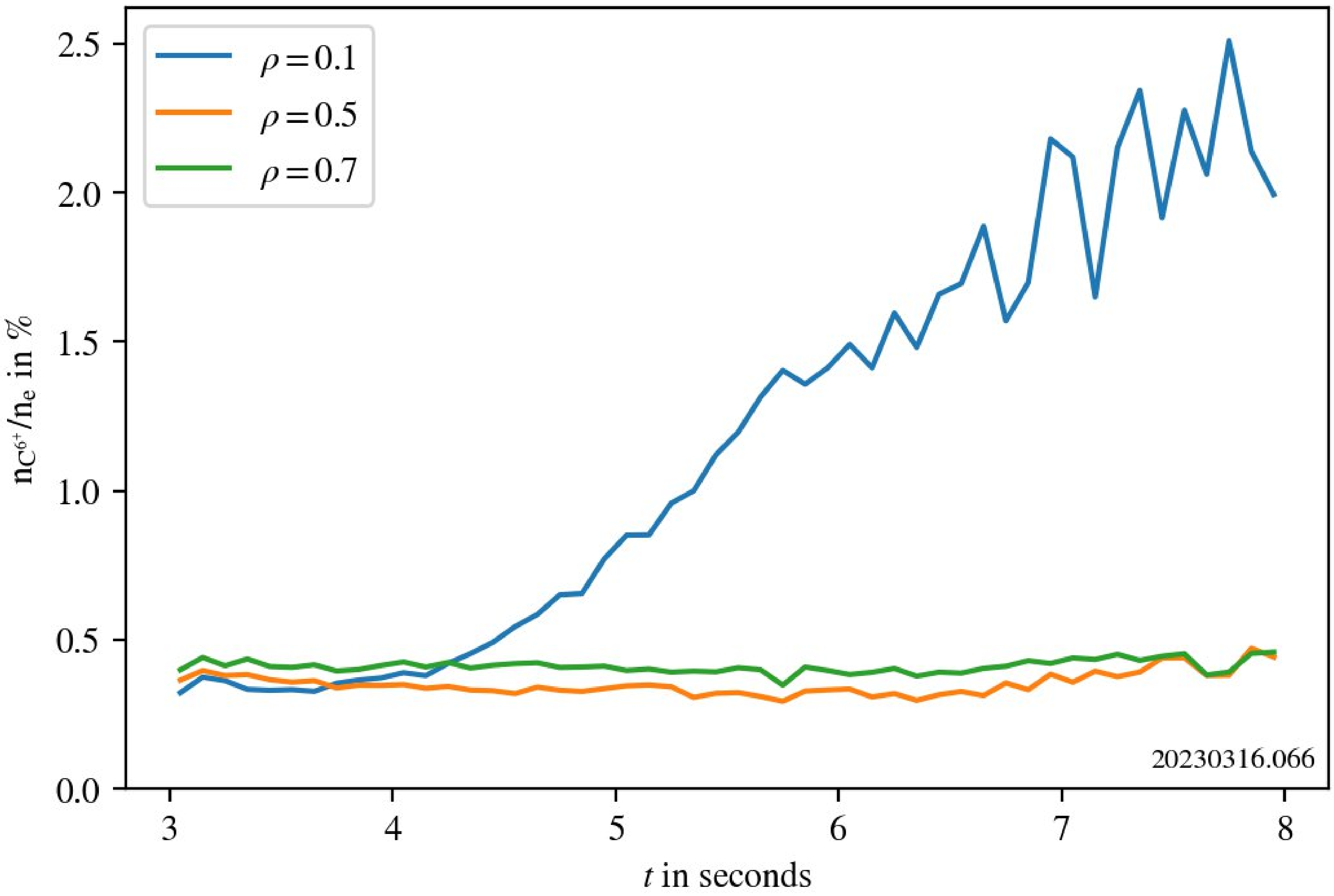


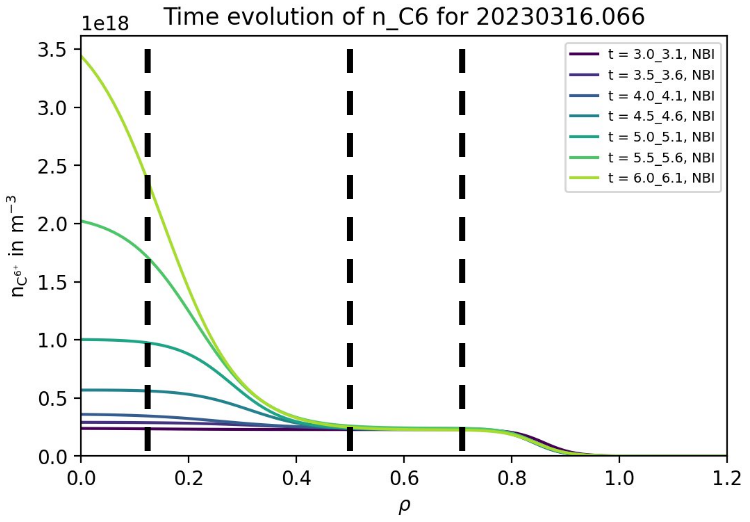


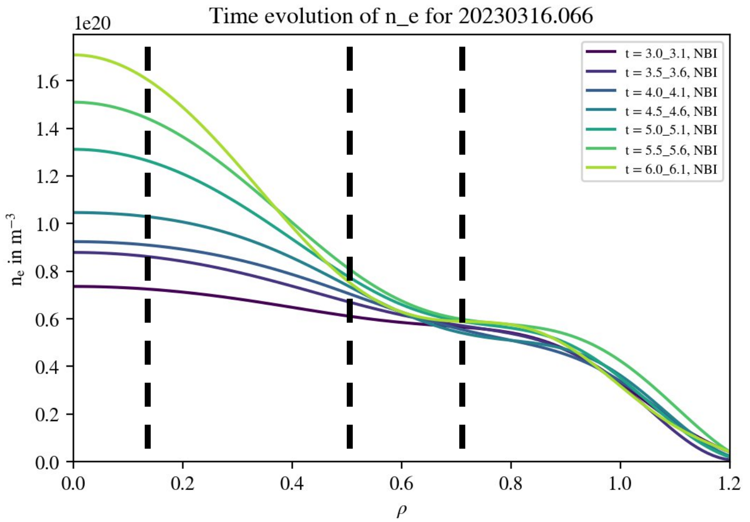


Peaking in impurities is stronger than in the main species

- **To compare the peaking between the main species and the impurities, we plot the concentration percentage with respect to time**

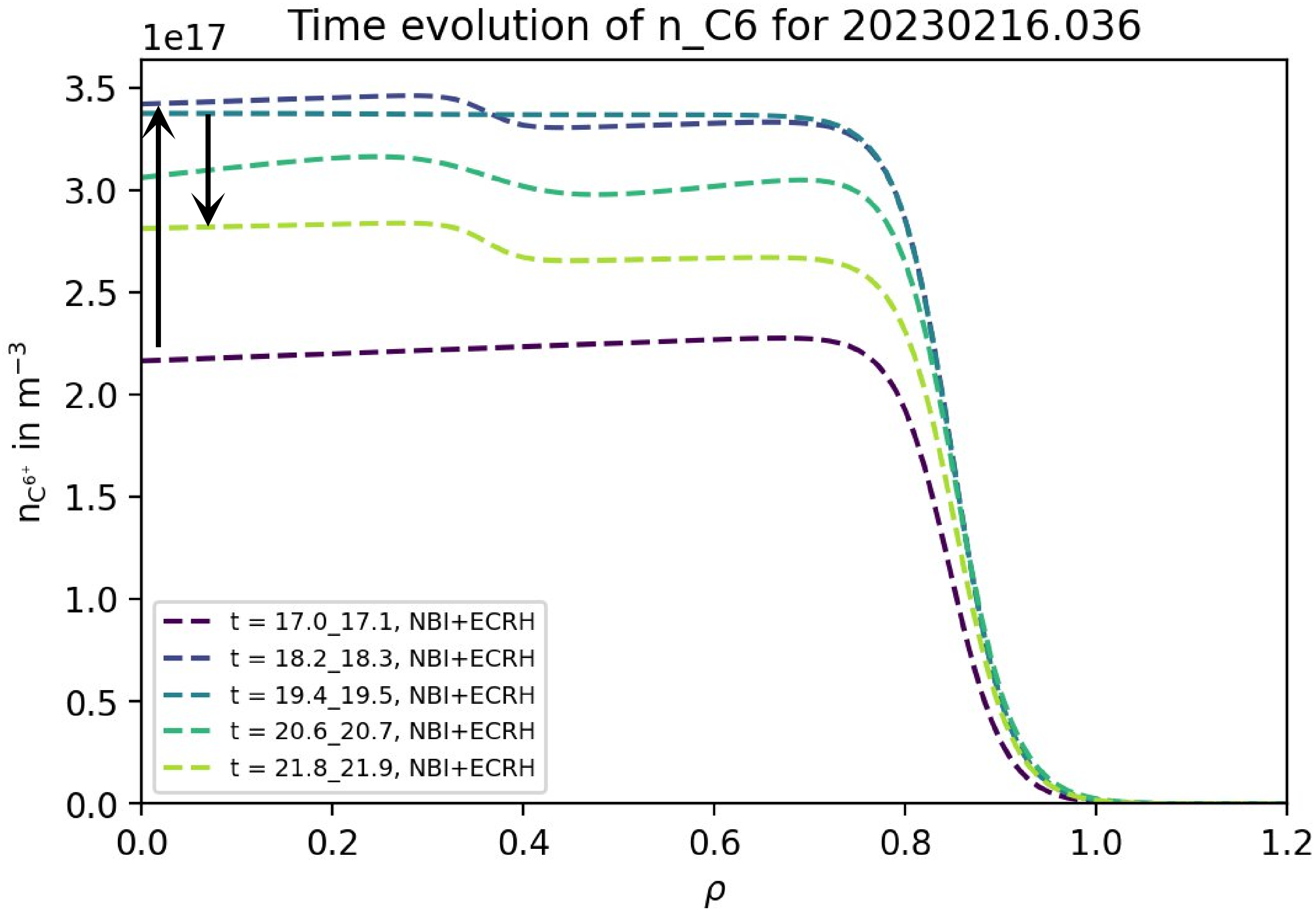


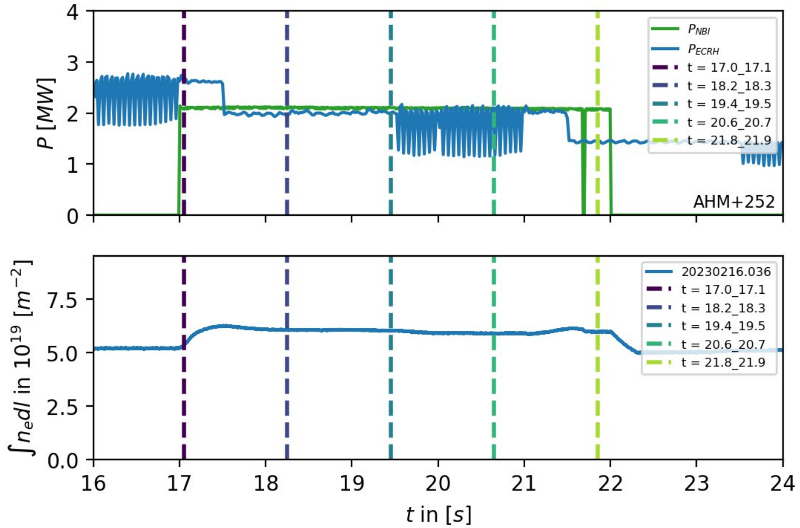


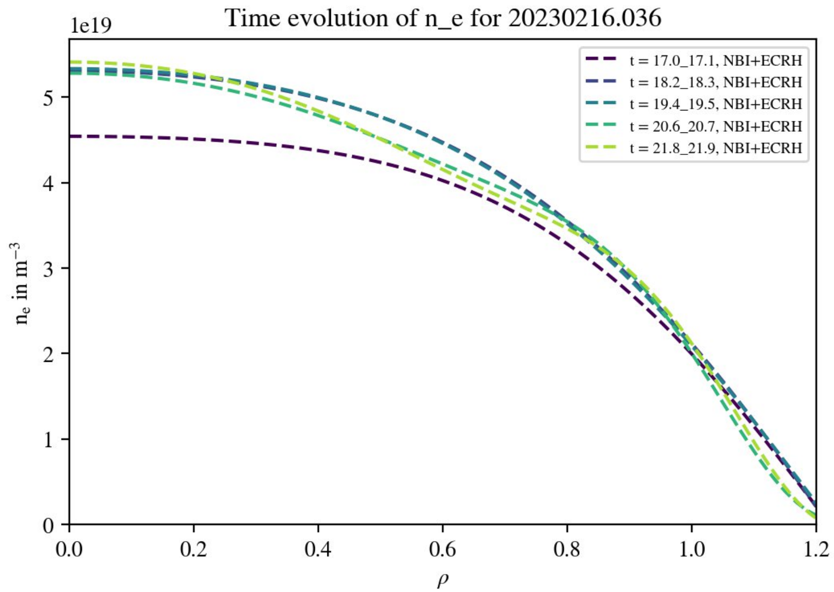


Non-peaking impurity profiles case 1 - continuous ECRH

- **ECRH heating is present throughout the shot, entering the combined heating phase does not change the shape of the profile, but only the amplitude**

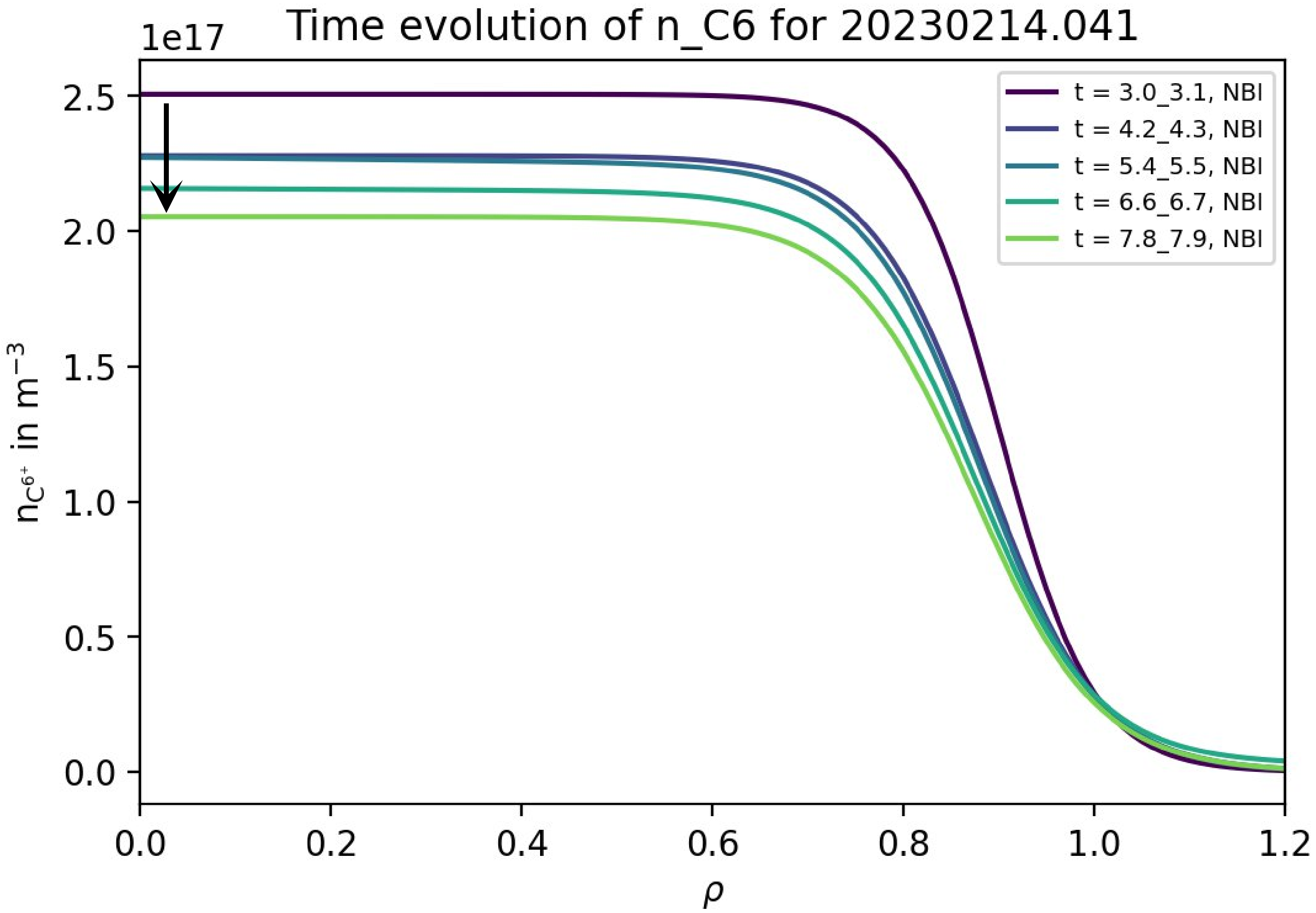


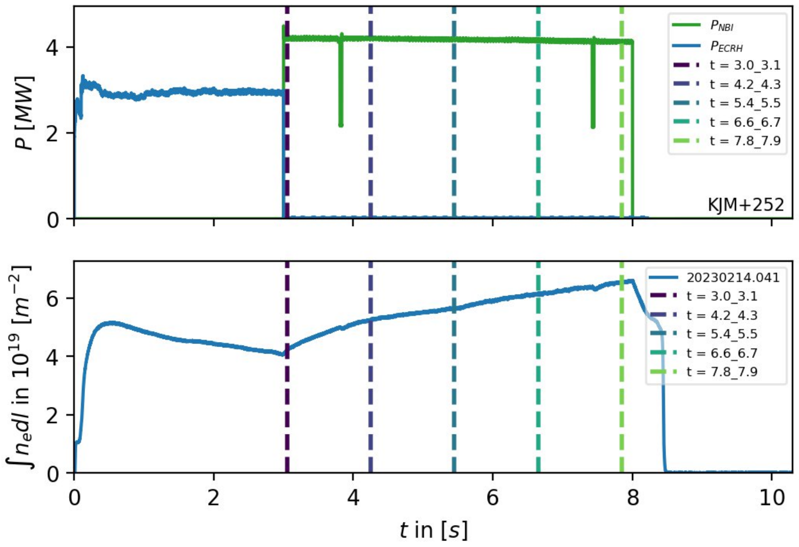


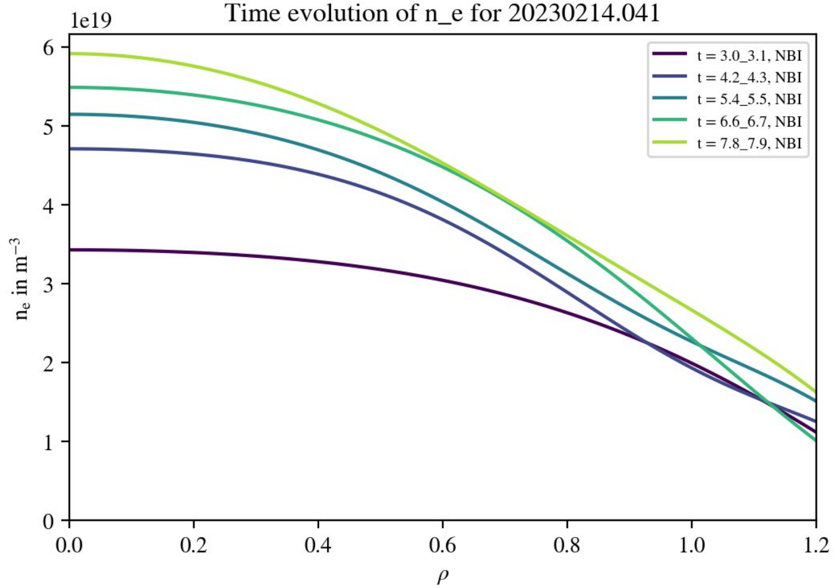


Non-peaking impurity profiles case 2 - pure NBI

- **While there is a slight decrease in density, the pure NBI phase does not change the shape of the profile**

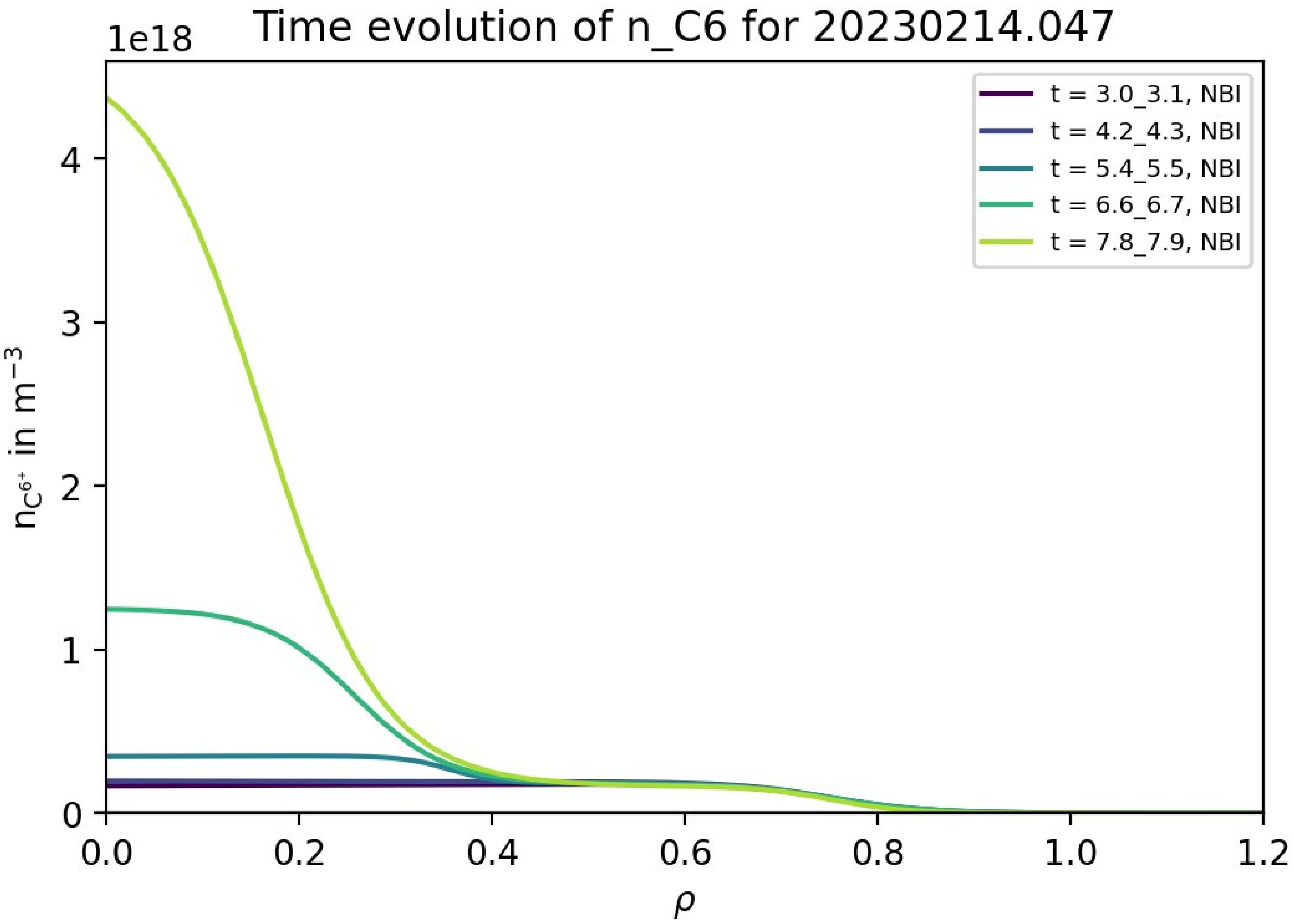


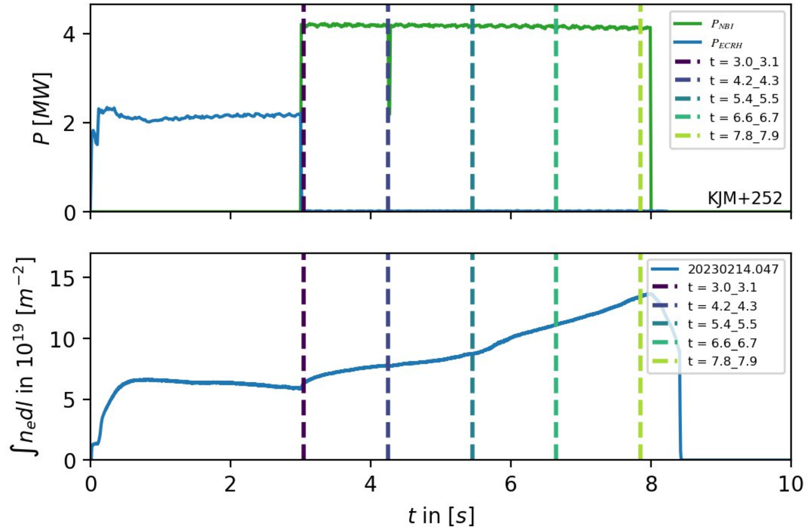


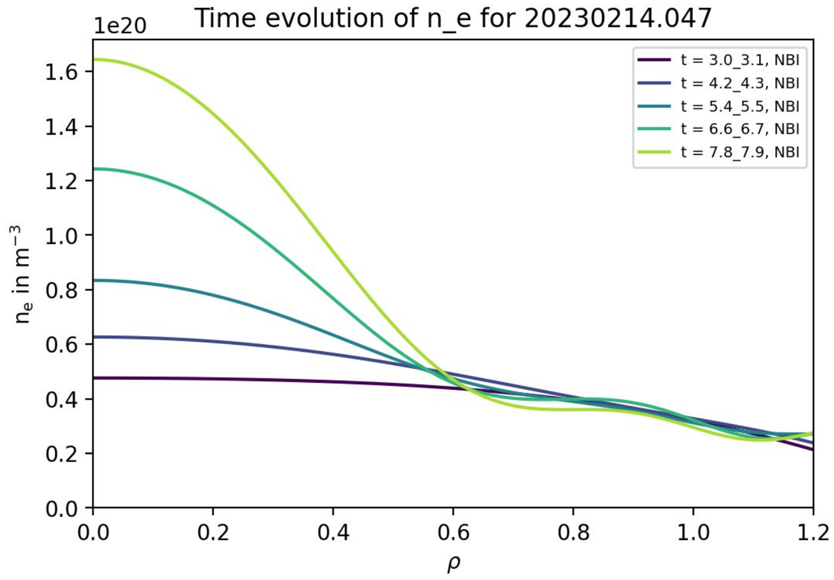


Non-peaking case 2, but with sufficient density

- **For a shot similar to the previous, but where by contrast, <u>the critical density is achieved</u>, we see a central density accumulation**

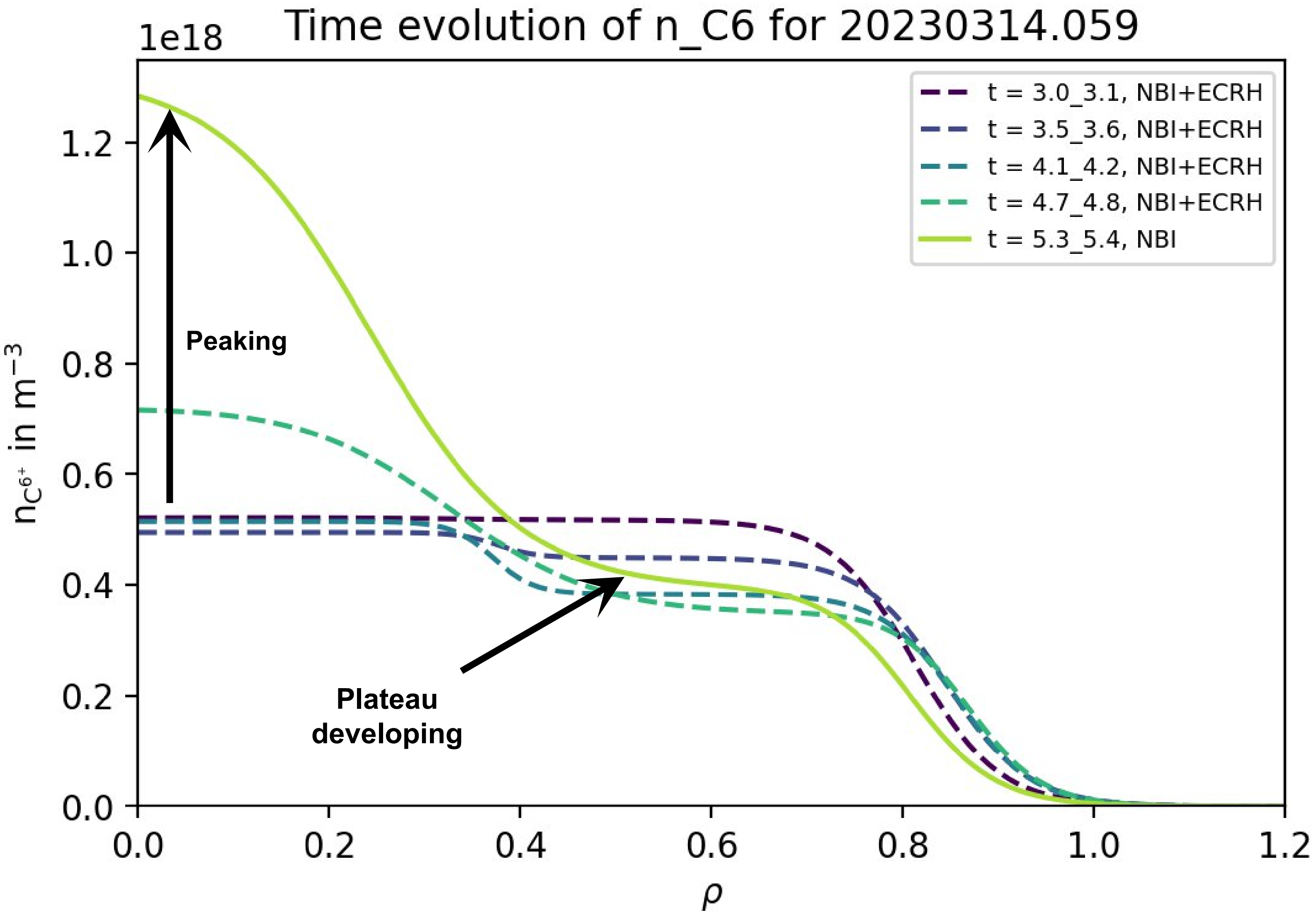


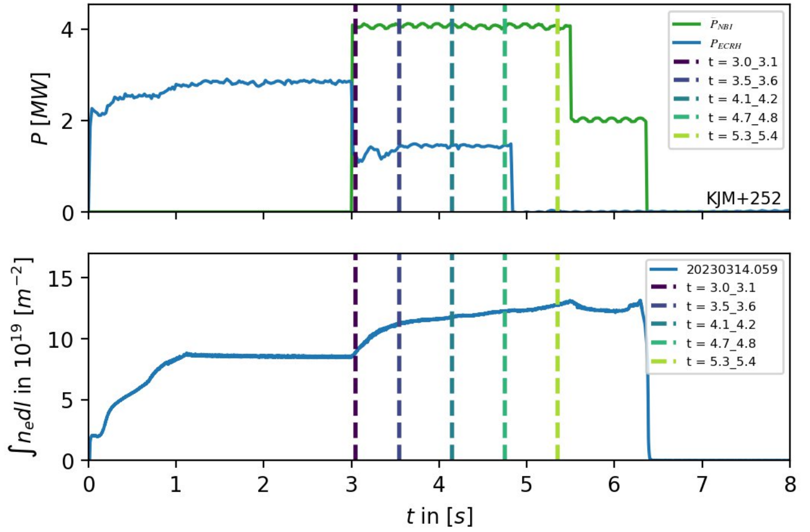


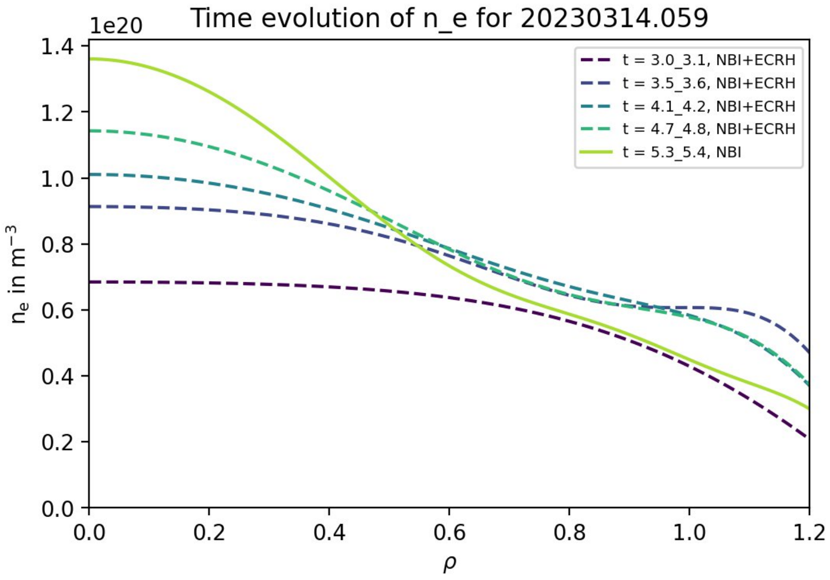


Peaking impurity profiles for non-peaking main species

- **While the low-power ECRH heating phase weakens the accumulation, entering the pure NBI allows the accumulation to fully develop**

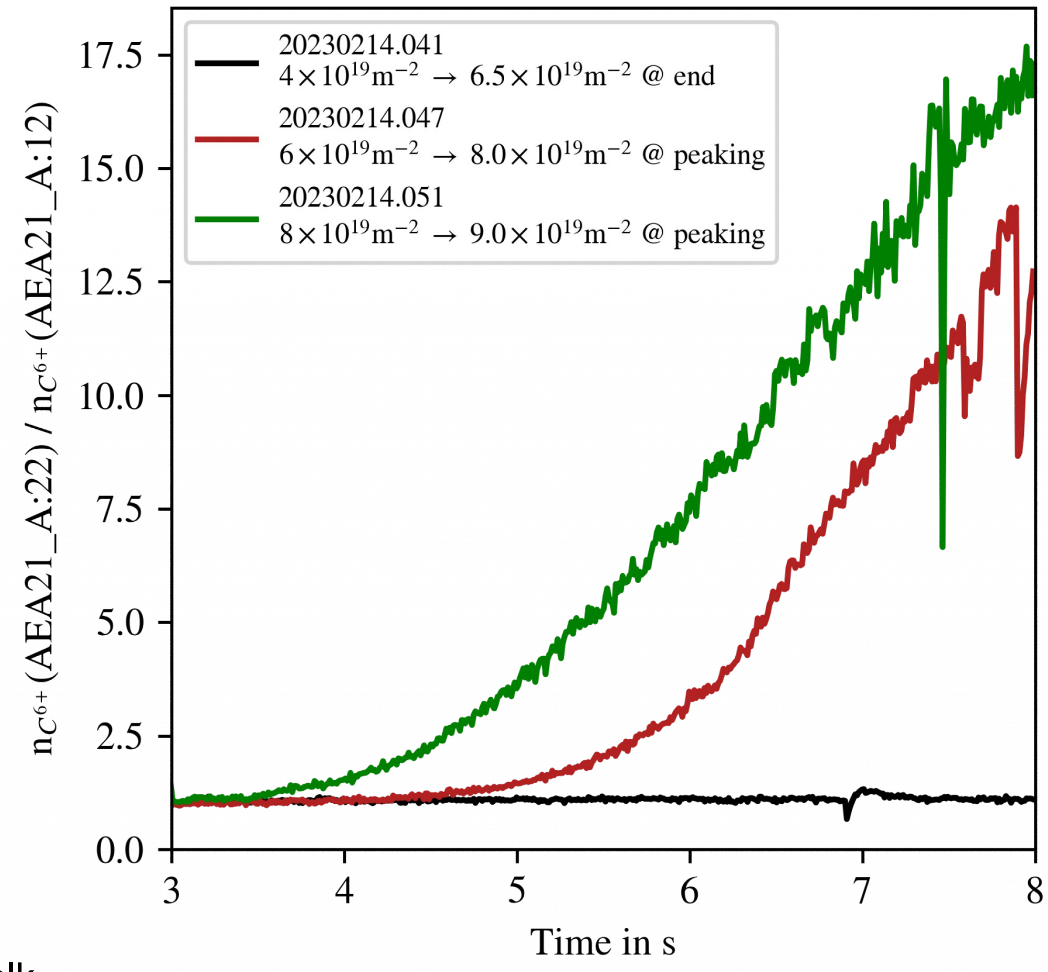






Peaking in impurity profiles occurs only for high densities

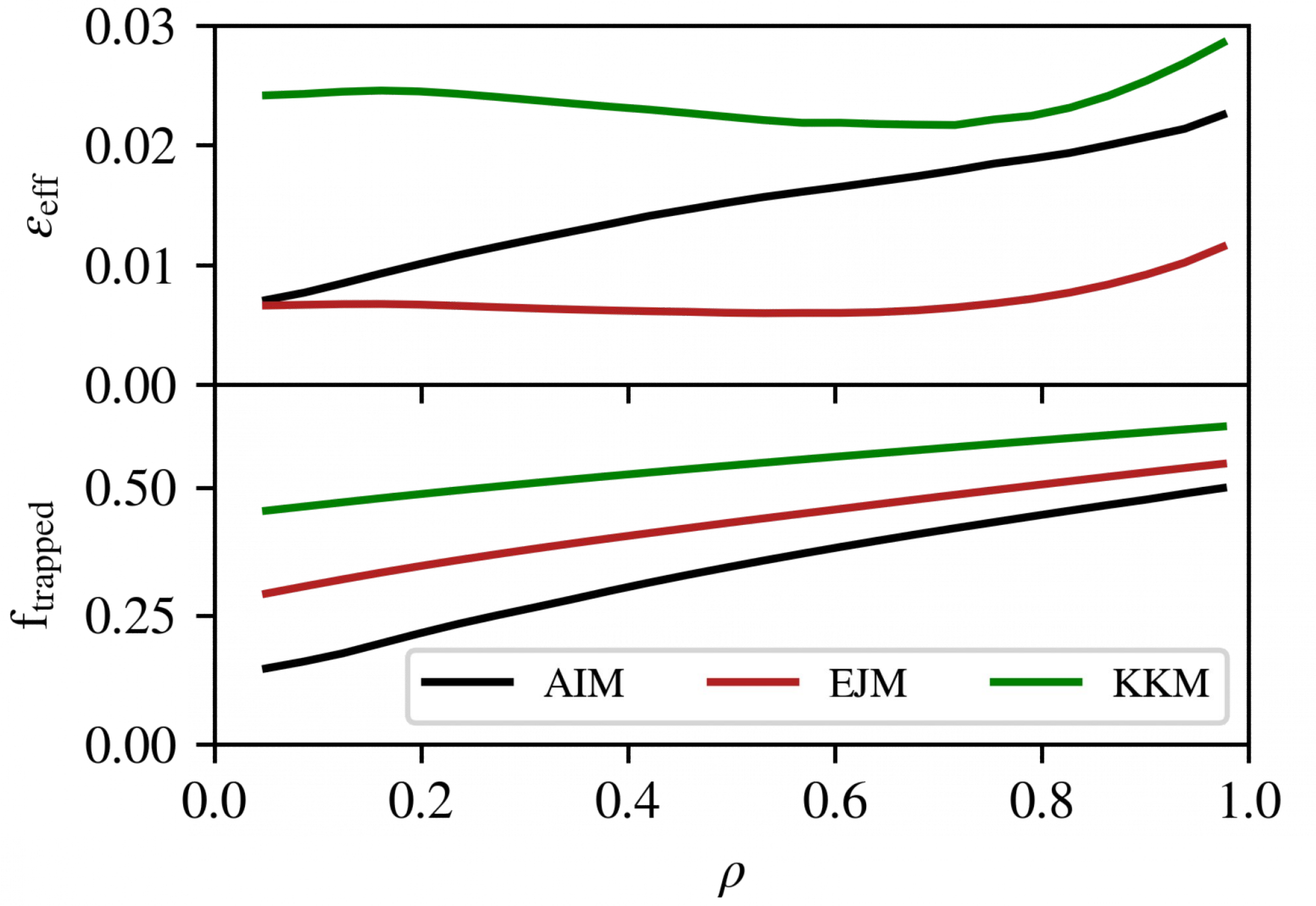
- **While the red and green lines peak, the black line does not peak**
  - **The difference between the shots is the initial density. This further solidifies that there is a critical density threshold required for peaking**



Adapted from T. Romba 2023, HEPP talk

Impurity peaking dependance on magnetic configuration

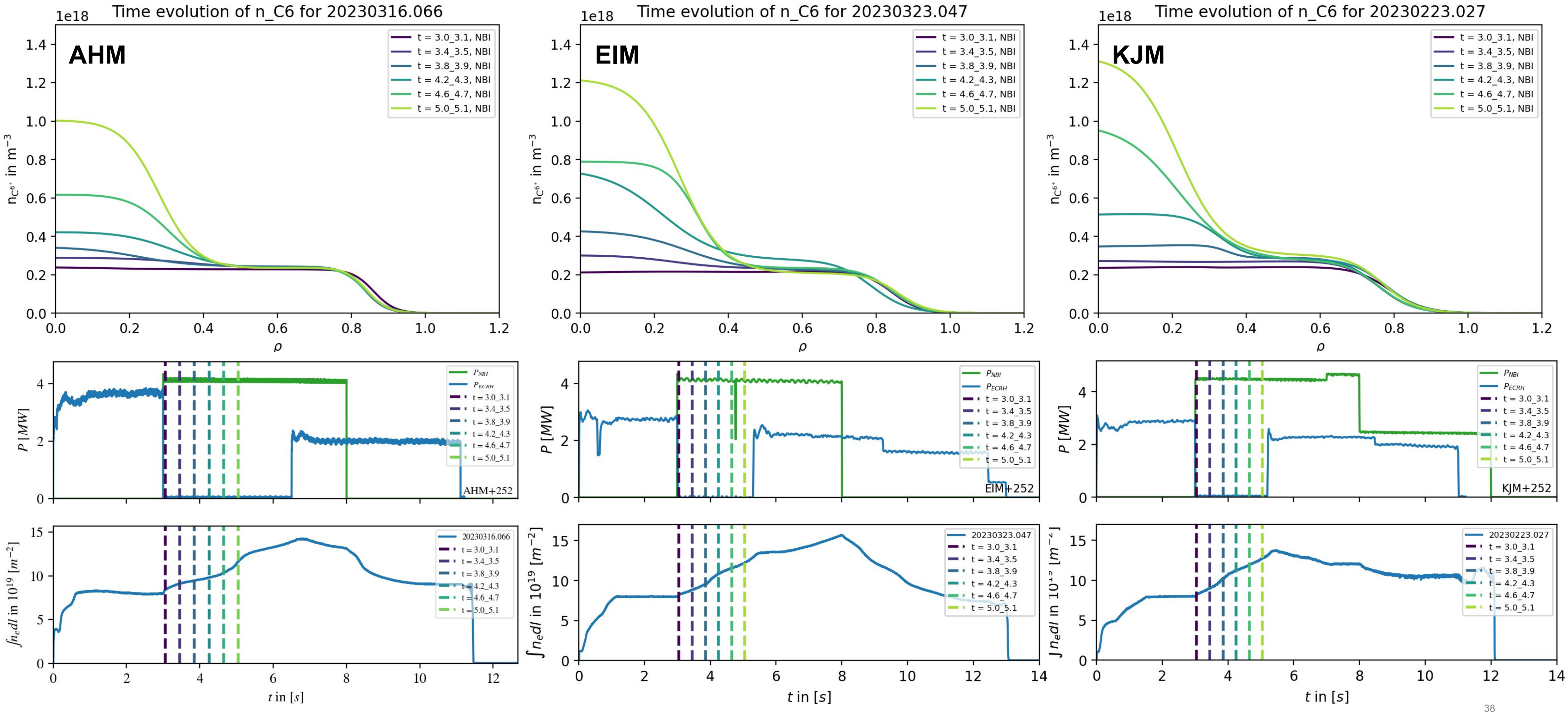
- **Initial assumption: peaked profiles are dominated by neoclassics**
- **Epsilon differs for different magnetic configurations thus we expect changes in neoclassical transport and different impurity transport across different magnetic configurations**



Adapted from T. Romba 2023, HEPP talk

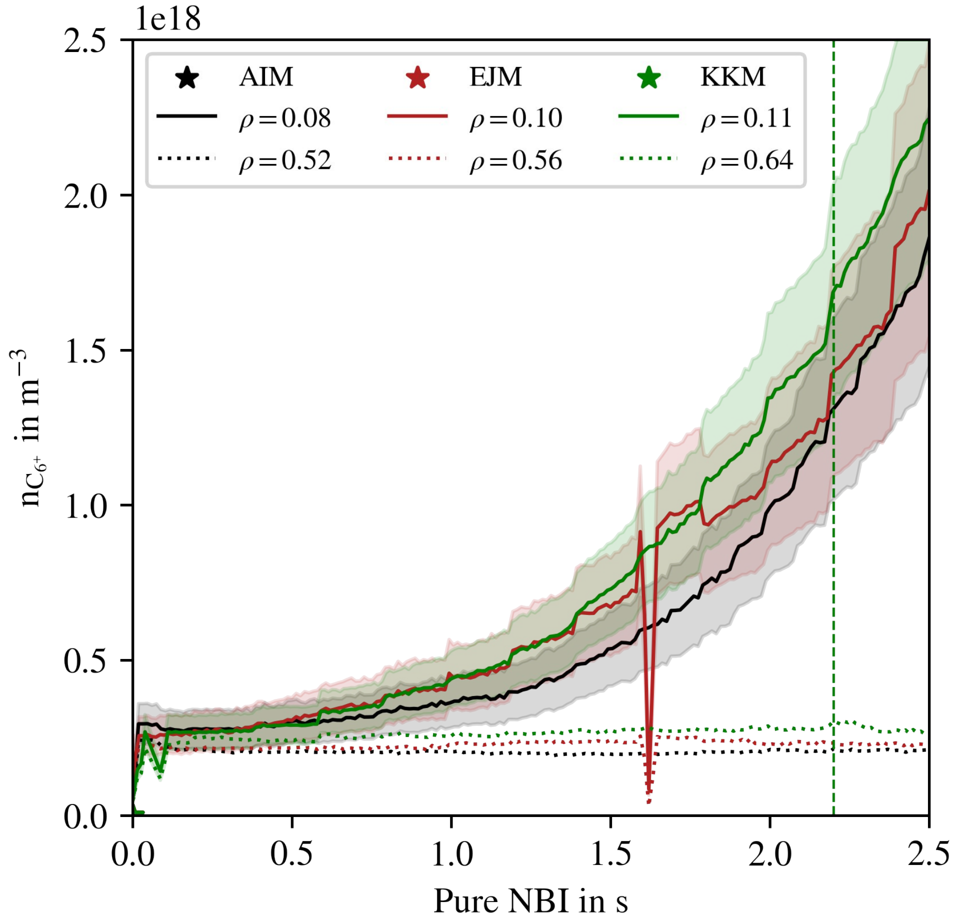
Comparison of peaking in different magnetic configurations

- **AIM - Low Mirror; EIM - Standard; KJM - High Mirror**



Impurity peaking dependance on magnetic configuration

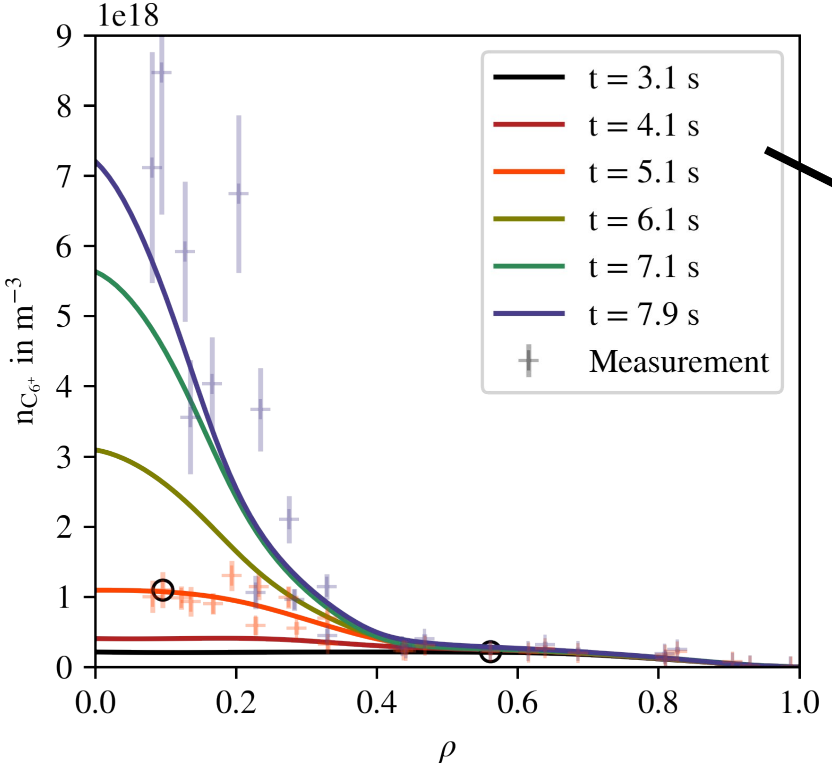
- **Plotting the near-core Carbon density for the different magnetic configurations, we were not able to observe a significant dependence on magnetic configuration**



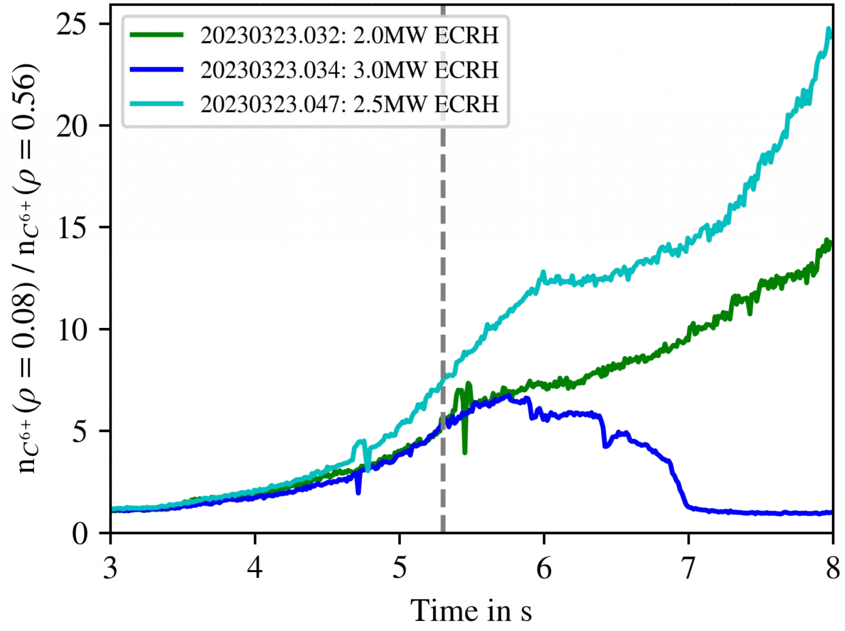
Adapted from T. Romba 2023, HEPP talk

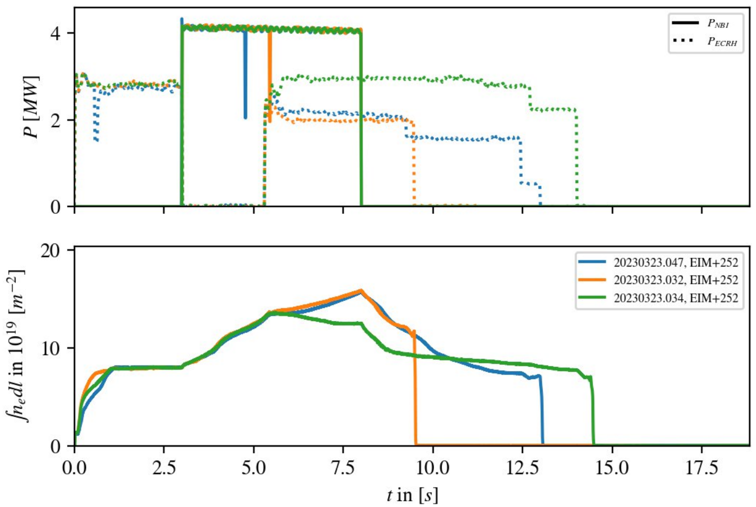
Peaking sensitivity to ECRH power - change colors

- **Peaking in impurity profiles is sensitive to ECRH power**
  - **While we still see weakened peaking for 2.5 MW and 2 MW ECRH, for 3 MW the high-power ECRH prevents the accumulation entirely**



The ratio between the encircled measurements is plotted

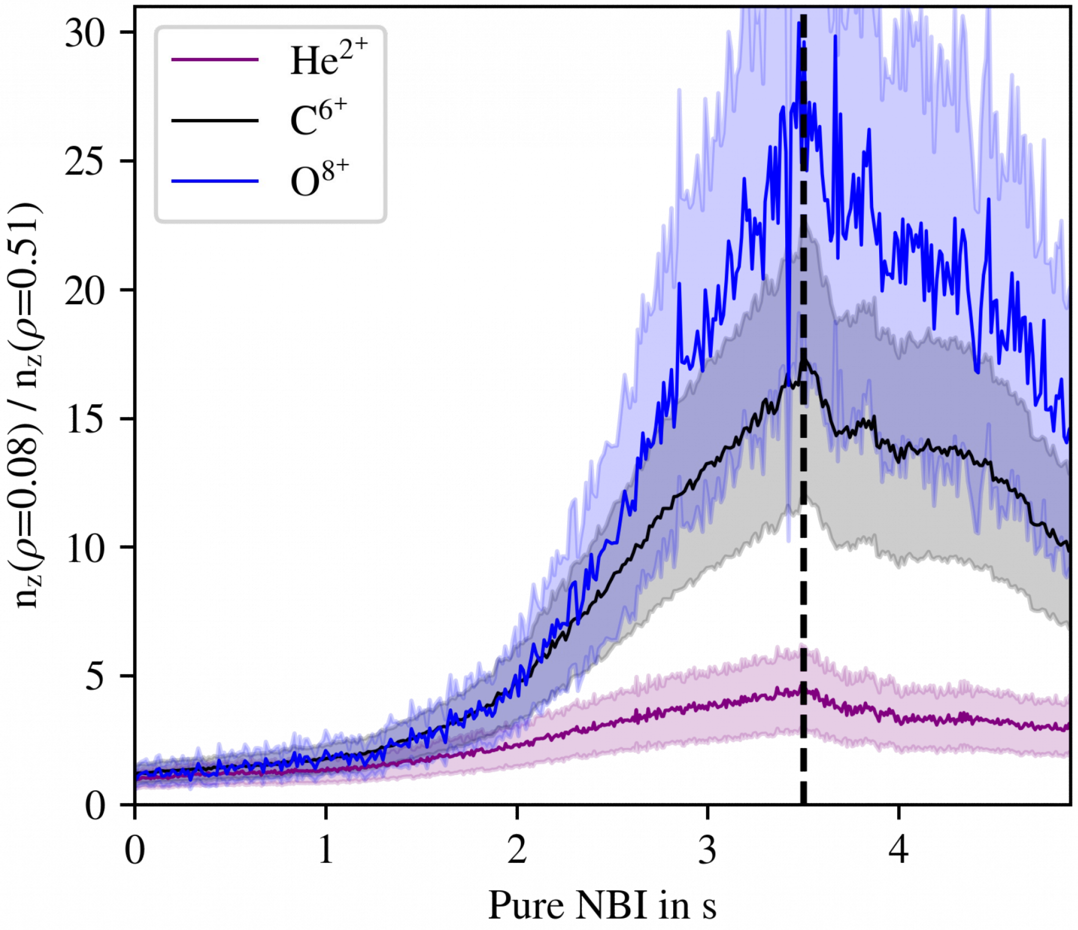




Adapted from T. Romba 2023, HEPP talk

Additional peaking behavior observations

- **Central peaking accumulation is consistent across various impurities, but is more dominant for higher-Z impurities**

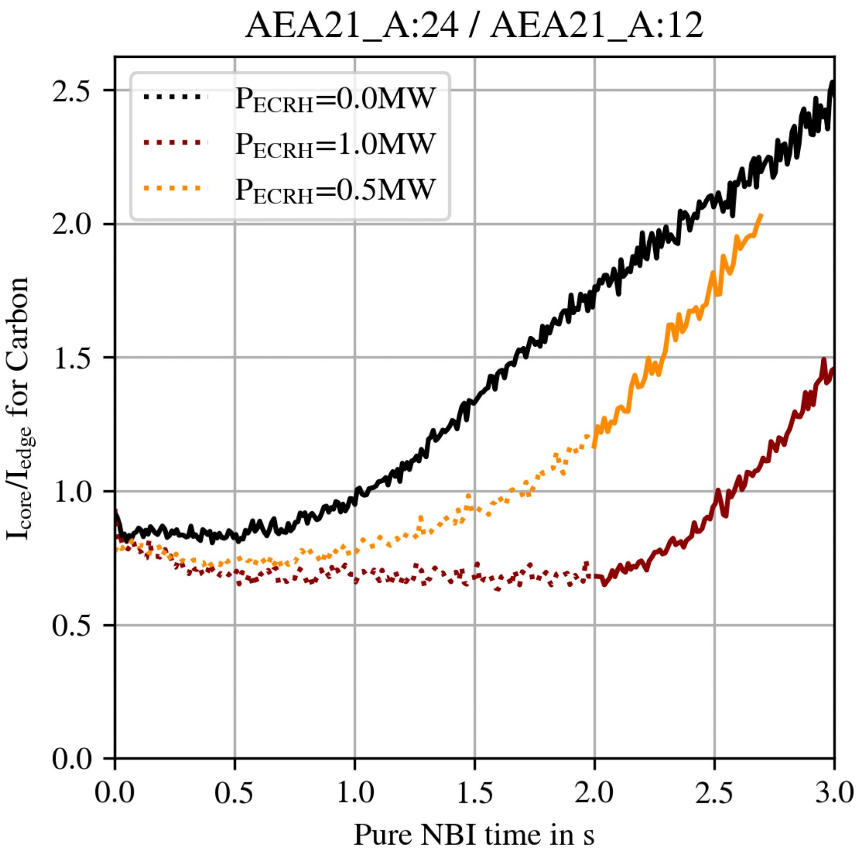


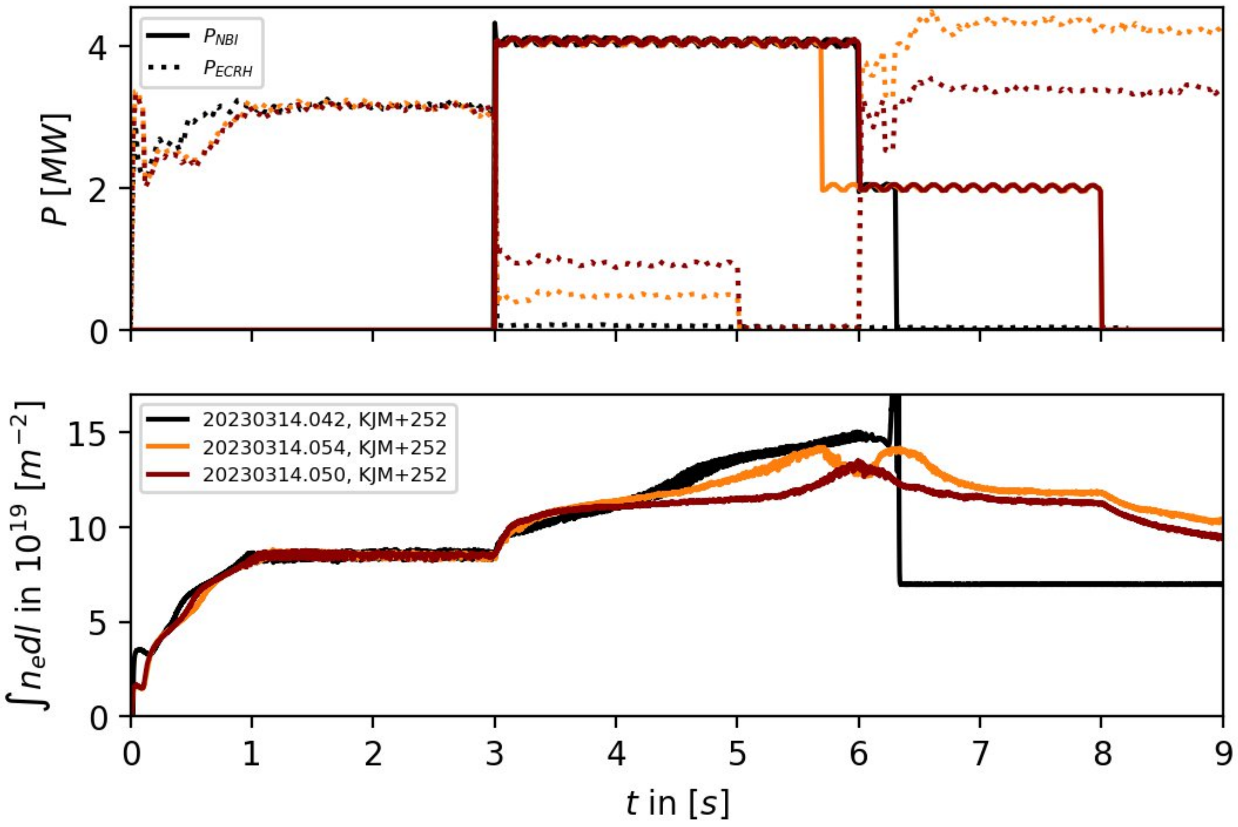
$$\langle \Gamma^{\alpha} \cdot \nabla r \rangle = -L_{11}^{\alpha} \frac{dn^{\alpha}}{dr} + n^{\alpha} + \left\{ L_{11}^{\alpha} \frac{q^{\alpha} E_r}{T^{\alpha}} - \left(L_{12}^{\alpha} - \frac{3}{2} L_{11}^{\alpha} \right) \frac{1}{T^{\alpha}} \frac{dT^{\alpha}}{dr} \right\}$$

Adapted from T. Romba 2023, HEPP talk

Accumulation development time for different ECRH powers

- **Black line** - at zero ECRH power we see peaking around 0.5 s into the pure NBI
- **Orange line** - at 0.5 MW ECRH power we see parking around 1 s into the combined heating
- **Red line** - at 1.0 MW ECRH power we see peaking around 2 s into the combined heating





Adapted from T. Romba 2023, HEPP talk

Key observations of accumulation phenomena in impurities

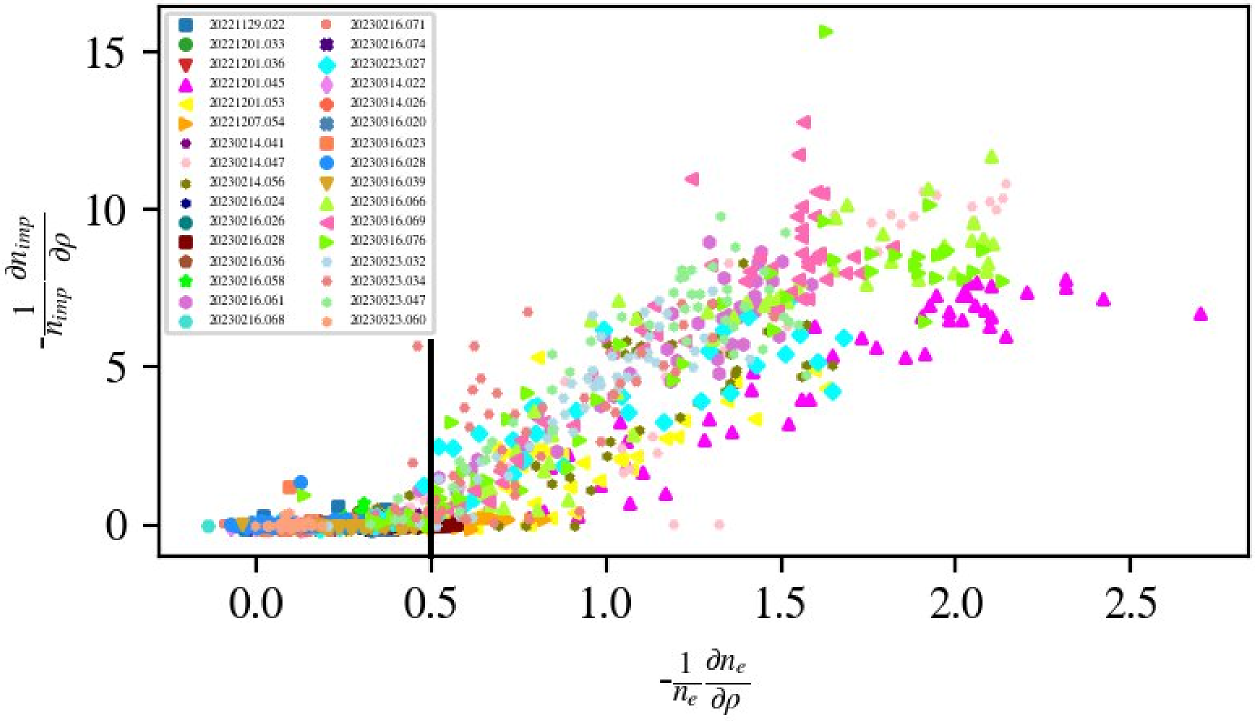
- **Central density accumulation in impurity profiles is stronger than in main species**
- **Central density accumulation for impurities is observed for pure NBI heating at high density**
  - **In the combined heating phase for impurities at high densities, the ECRH is observed to either weaken or prevent the accumulation for low and high power respectively**
- **While the density gradient for the electrons develops around $\rho = 0.6$, the density gradient for Carbon develops around $\rho = 0.4$**
- **For the impurities, central density accumulation is not observed to have strong dependence on magnetic configuration**
- **Accumulation is stronger for higher-Z impurities due to their larger carried charge**
- **Although only Carbon was analyzed, accumulation is universal for all impurities**

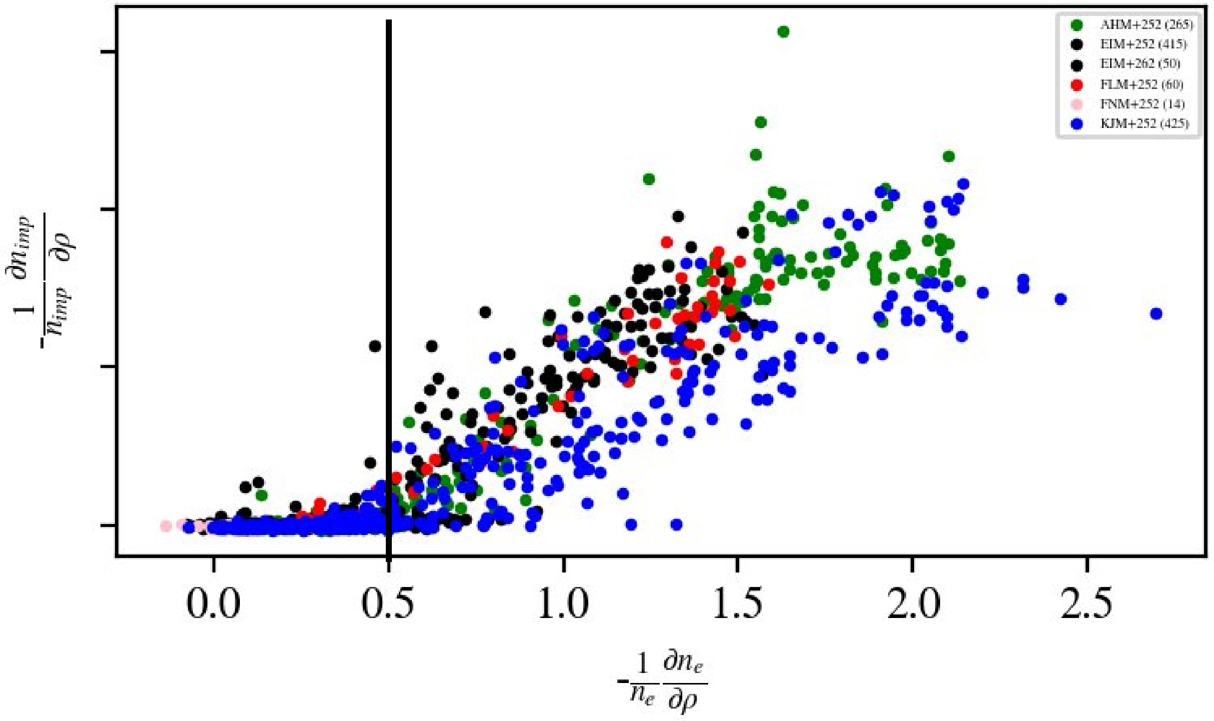
Outlook

- Main plasma species profiles
  - Accumulation phenomena
  - Non-accumulating behavior
  - ECRH reintroduction
  - Comparison of accumulation at different magnetic configurations
  - Additional main species observations by S. Bannmann
  - Concluding observations on main species
- Impurity profiles
  - Impurity profile fitting method - modified double tanh
  - Accumulation phenomena
  - Non-accumulating behavior
  - ECRH reintroduction
  - Comparison of accumulation at different magnetic configurations
  - Concluding observations on impurities
- **Database approach for examining accumulation phenomena**
  - **Variable heatmap and strongest correlations**
  - **Kink location to determine separation of anomalous and neoclassical transport**
  - **Transport color-coded plots**
- Remarkable observations
- Summary

Impurity transport database approach

- **Data is observed to be separated into two distinct groups:**
  - **Pre-kink (left to splitter) data shows flat distribution associated with flat profiles. This in turn implies at $\mathrm{V/D} << 1$ and anomalous transport respectively**
  - **Post-kink (right to splitter) data shows a clear relationship associated with peaking scenarios. This implies at $\mathrm{V/D} >> 1$ and neoclassical transport respectively**
- **Further indication of no significant dependence on the magnetic configuration**





Database correlations

- **Variable correlations are plotted in a 'heatmap' from which we can easily extract the strongest correlation parameters**

Filtering for absolute correlations above 0.7 we are left with the strongest correlations:

Positive Correlations:

$-\frac{1}{n_e}\frac{dn_e}{d\rho},\ -\frac{1}{n_{imp}}\frac{dn_{imp}}{d\rho} : 0.9$

$-\frac{1}{n_{imp}}\frac{dn_{imp}}{d\rho}$, density peaking ratio : 0.88

$n_e,\ -\frac{1}{n_{imp}}\frac{dn_{imp}}{d\rho} : 0.82$

$-\frac{1}{n_e}\frac{dn_e}{d\rho}$, density peaking ratio : 0.78

n_e, density peaking ratio : 0.76

$-\frac{1}{n_{imp}}\frac{dn_{imp}}{d\rho}$, density peaking ratio : 0.76

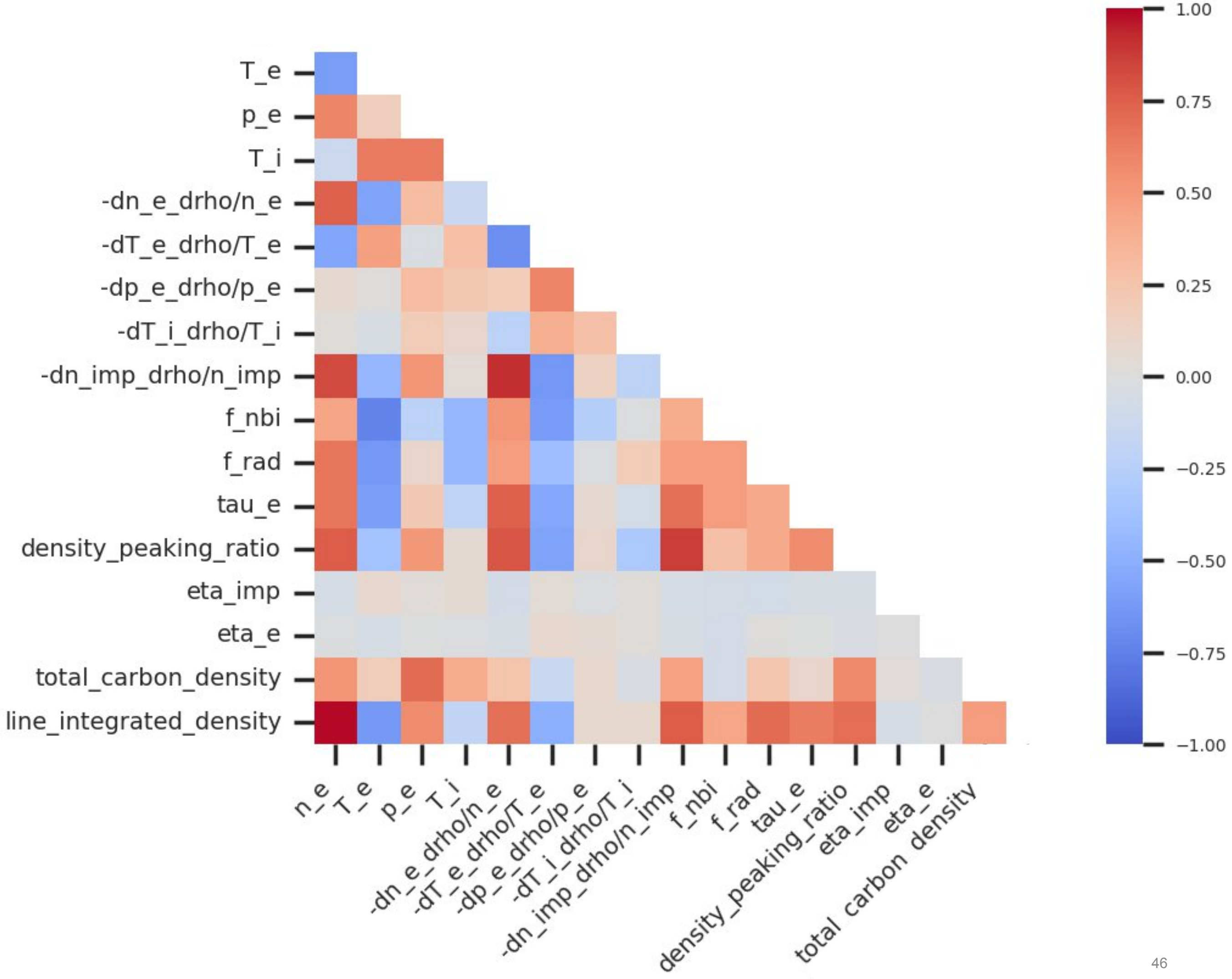
$n_e,\ -\frac{1}{n_e}\frac{dn_e}{d\rho}: 0.744$

$-\frac{1}{n_e}\frac{dn_e}{d\rho},\ \tau_e: 0.742$

p_e, total carbon density: 0.7

Negative Correlations:

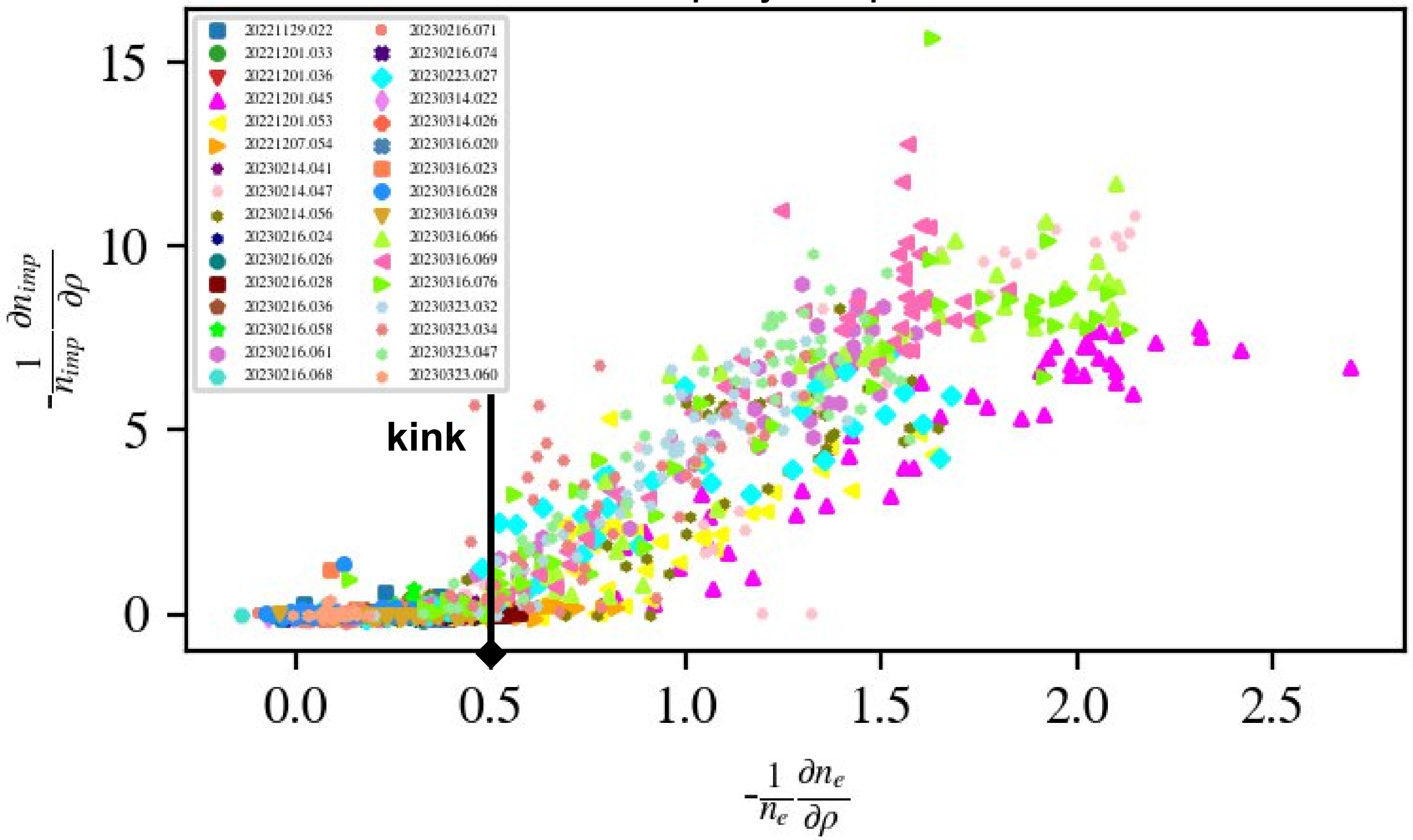
$T_{e,}f_{nbi}: -0.74$



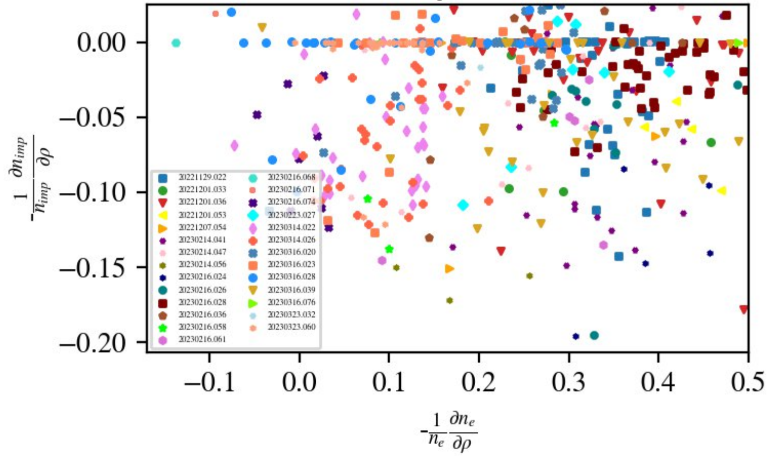
Impurity transport database - kink separation

- Data is observed to be split into two distinct groups:
  - Pre-kink (left to splitter) data shows flat distribution associated with flat profiles
  - Post-kink (right to splitter) data show a clear relationship associated with peaked profiles

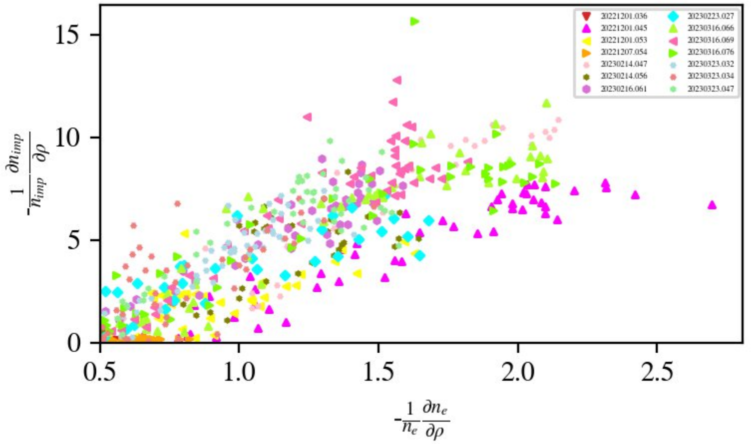
Full Impurity Transport Plot



Pre-kink Impurity Transport Plot

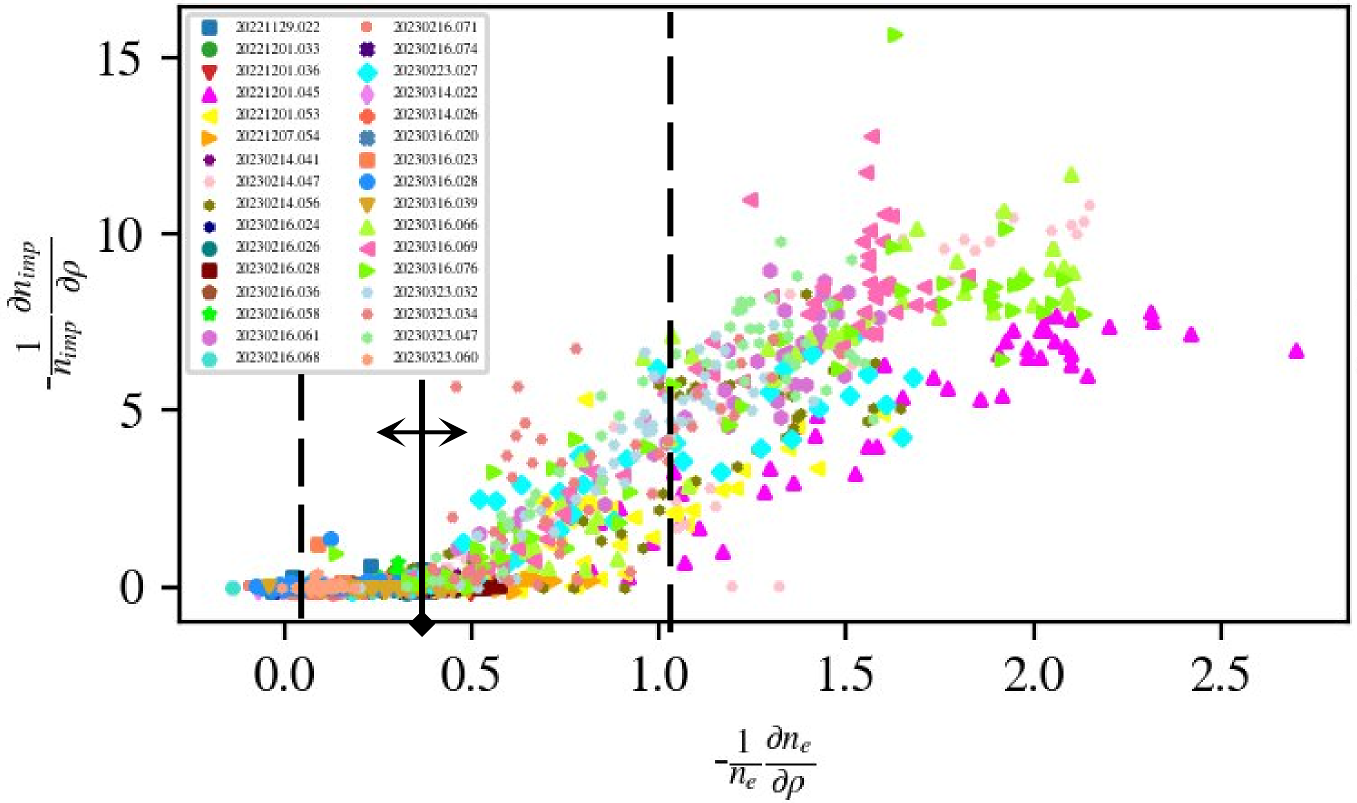


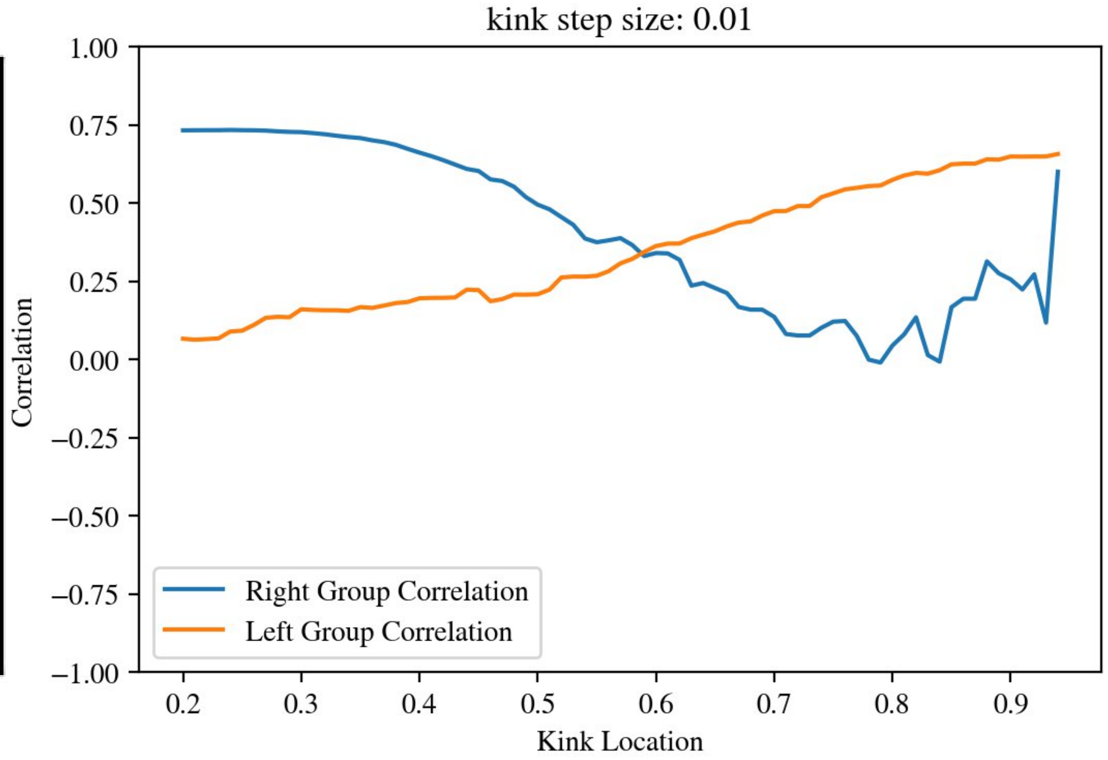
Post-kink Impurity Transport Plot



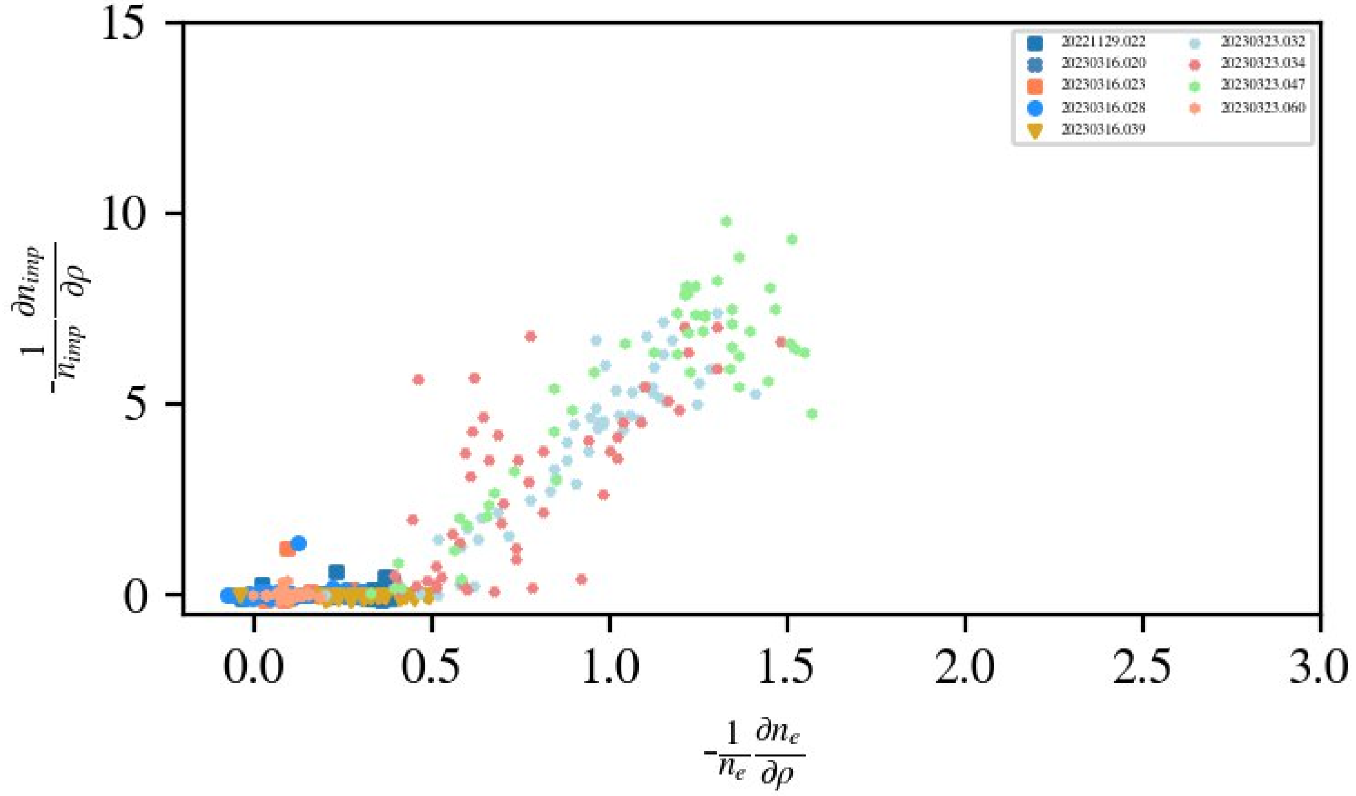
Where should the kink be?

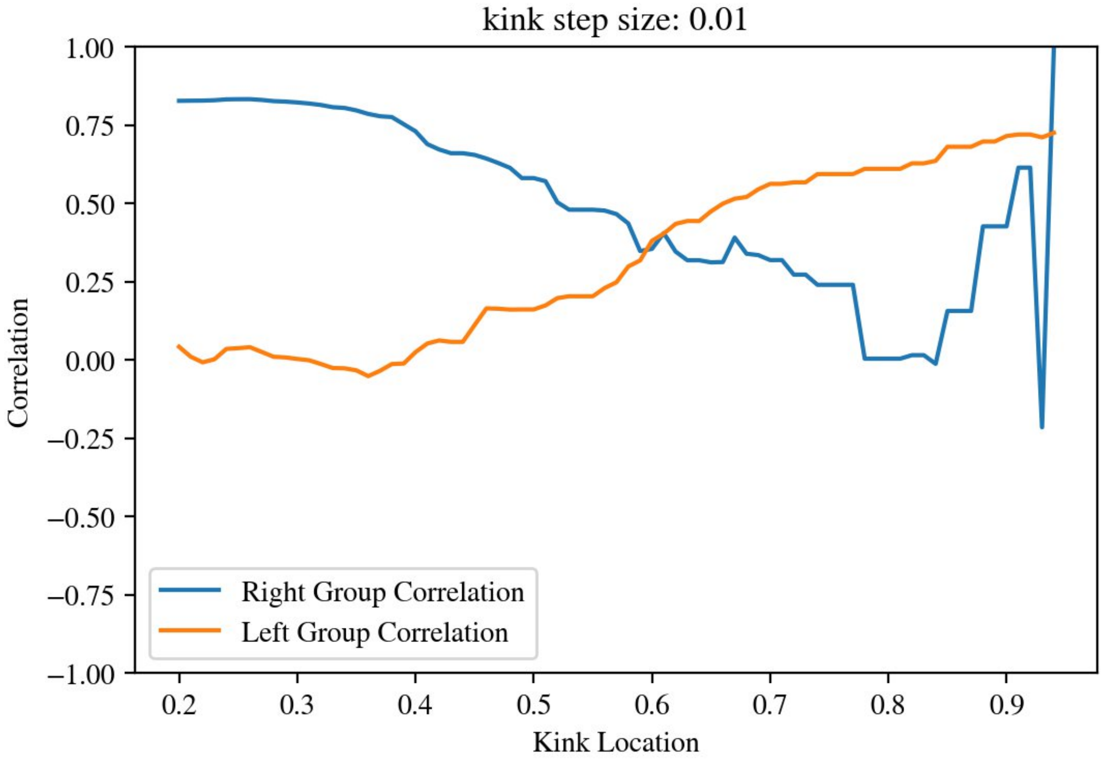
- To solidify understanding of the border between anomalous and neoclassical transport, kink location varies and correlations are measured to produce a correlation vs location plot
  - Pre-kink is desired to be close to zero, indicating a flat distribution with a weak correlation
  - Post-kink is desired to be close to one, indicating a strong correlation



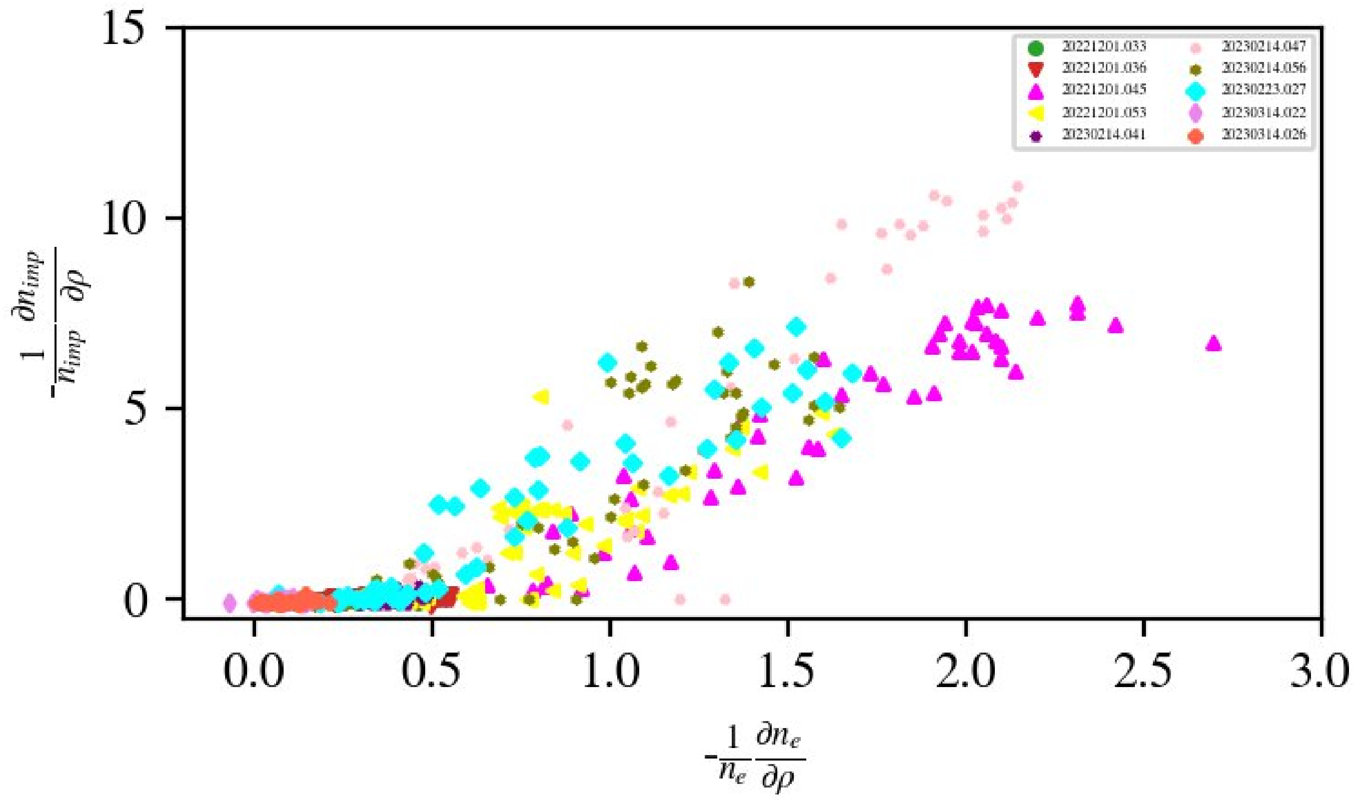


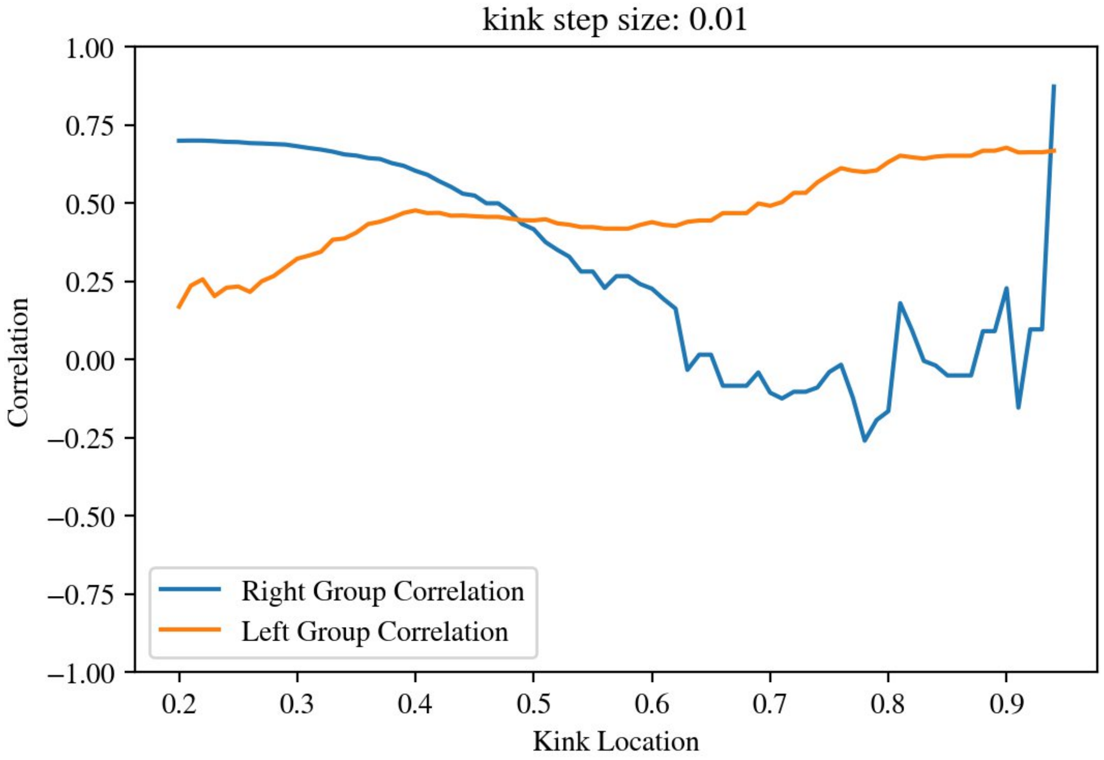
Kink-correlation plot for shots in EIM magnetic configuration



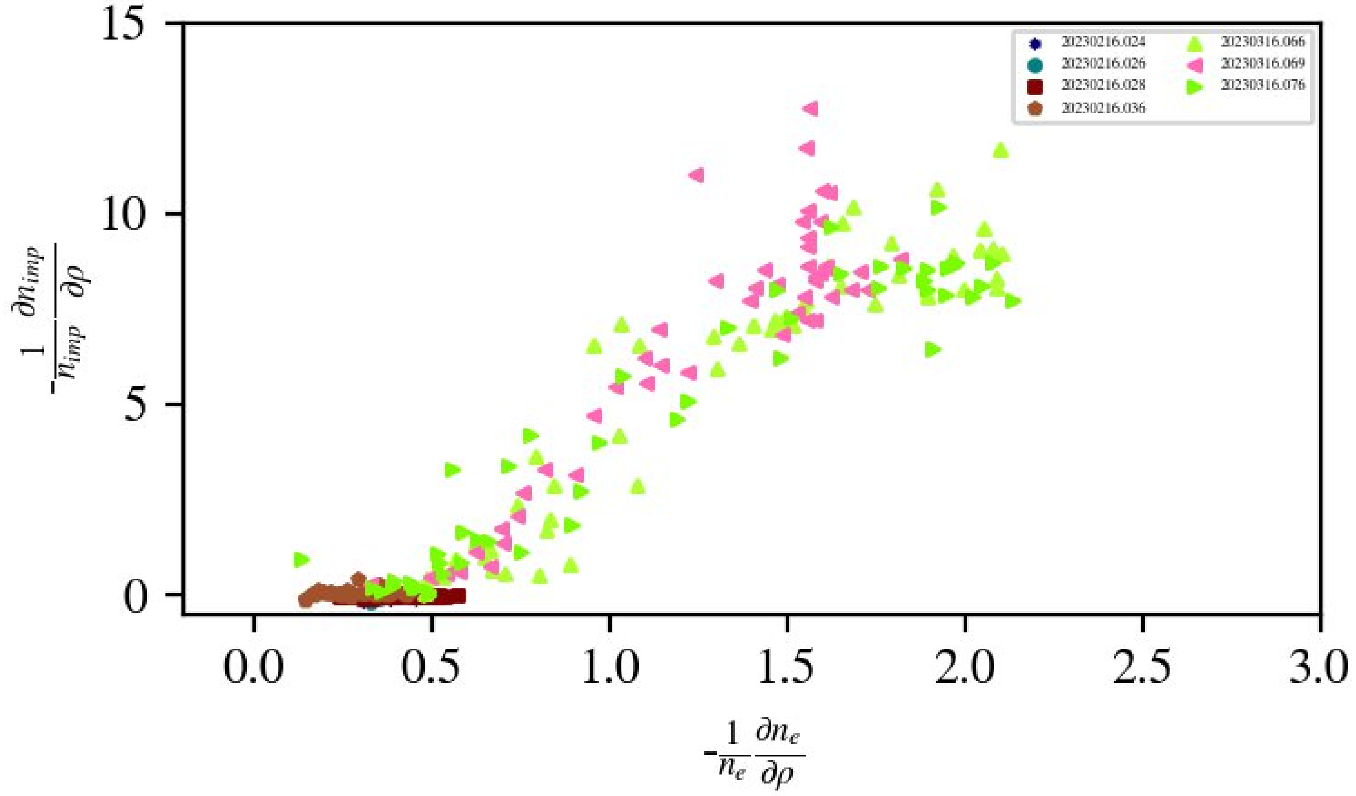


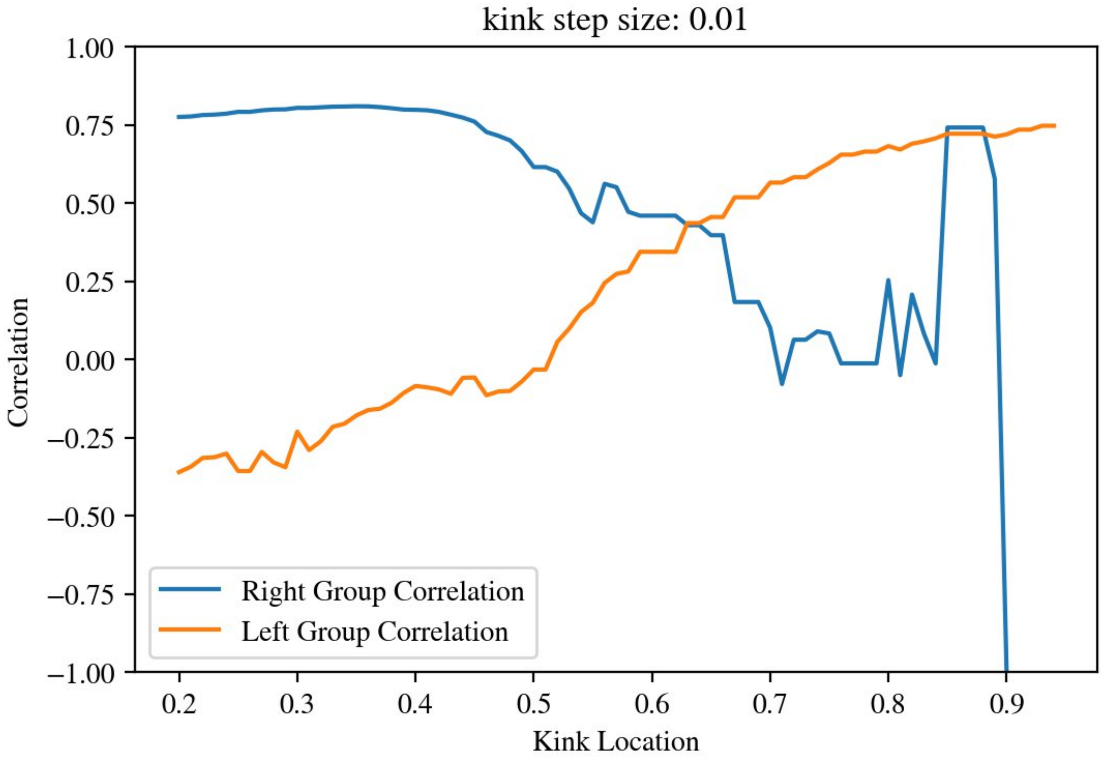
Kink-correlation plot for shots in KJM magnetic configuration



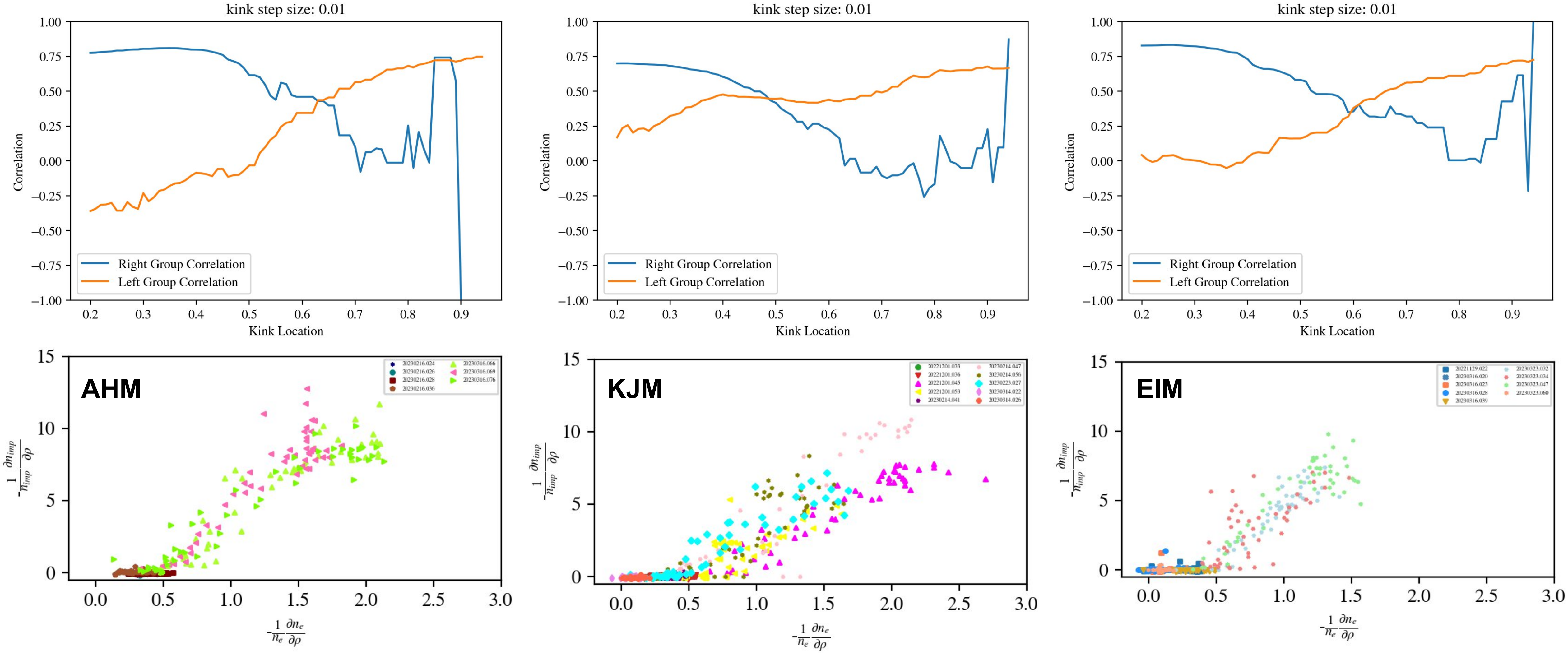


Kink-correlation plot for shots in AHM magnetic configuration

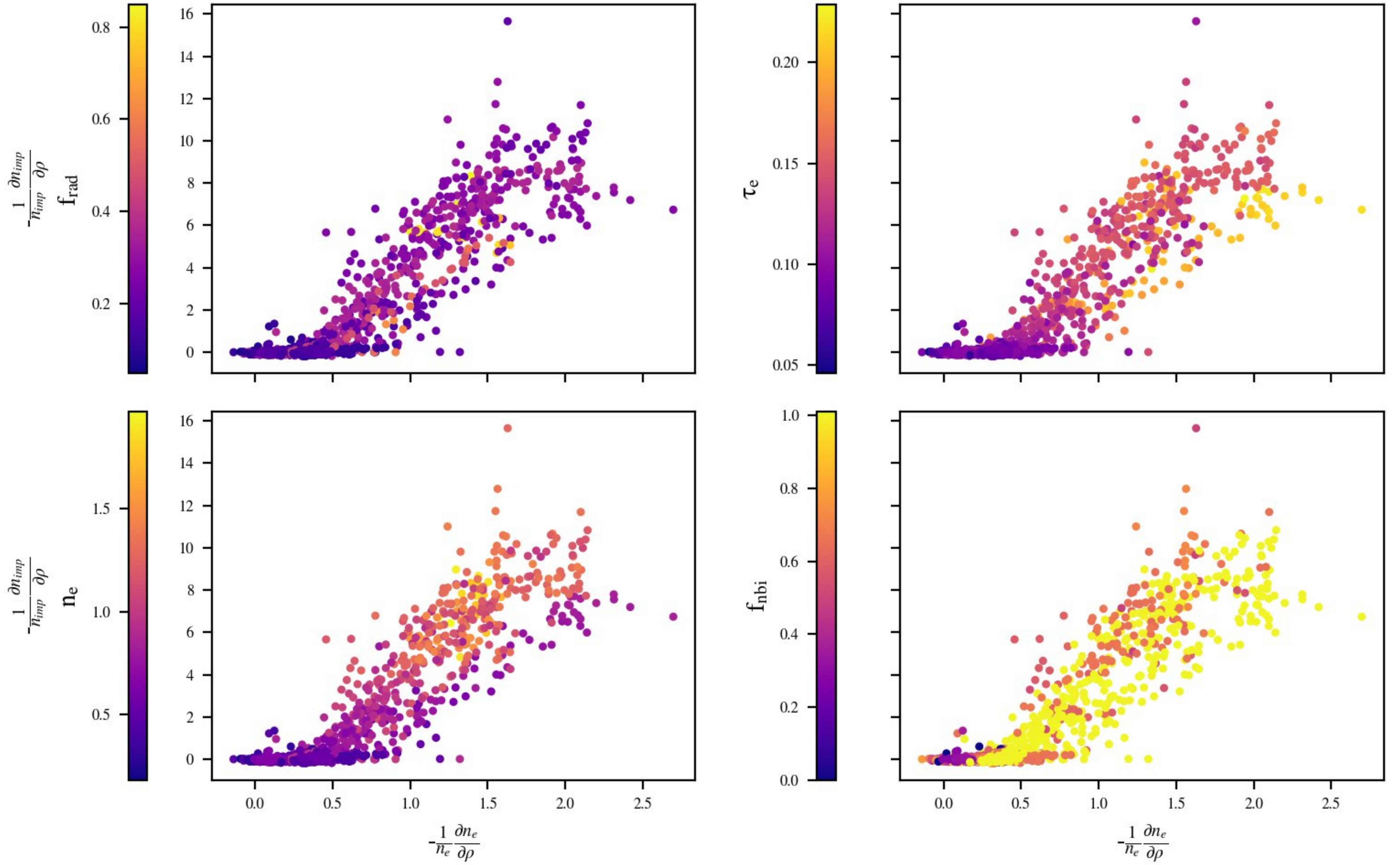




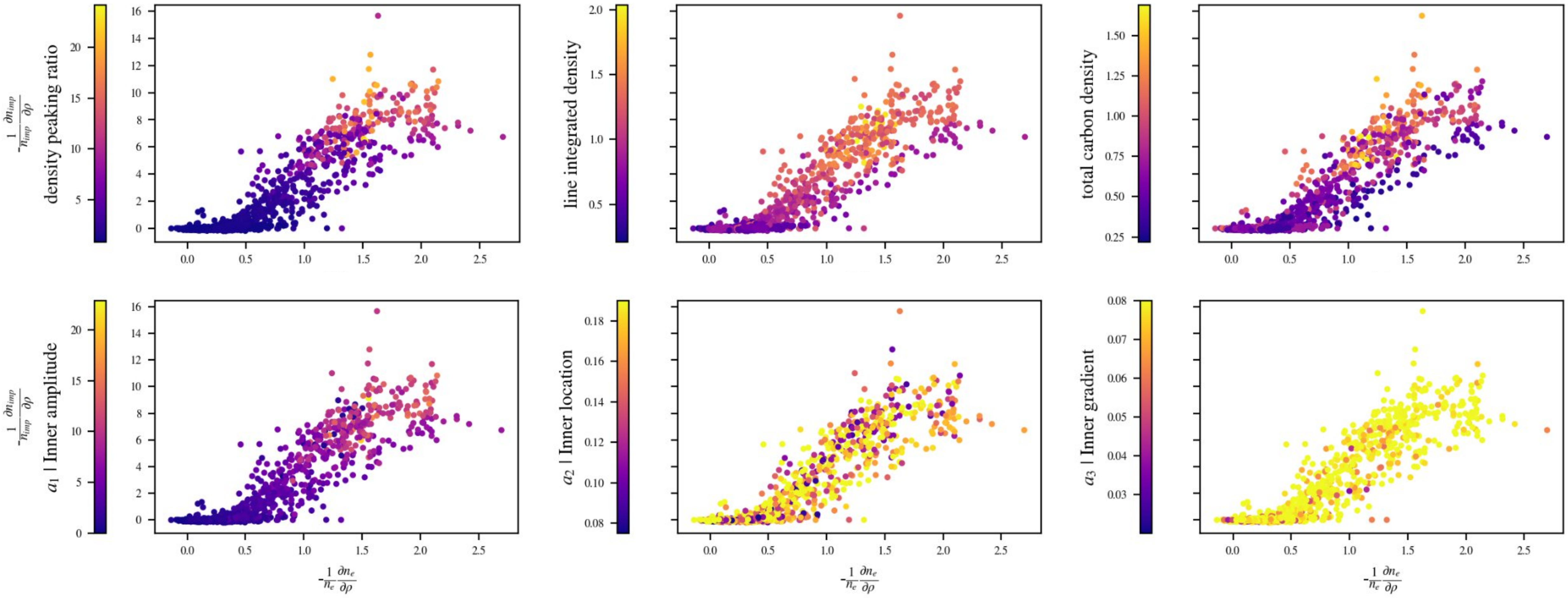
Kink-correlation plots for different magnetic configurations



Color coded transport plots



Color coded transport plots

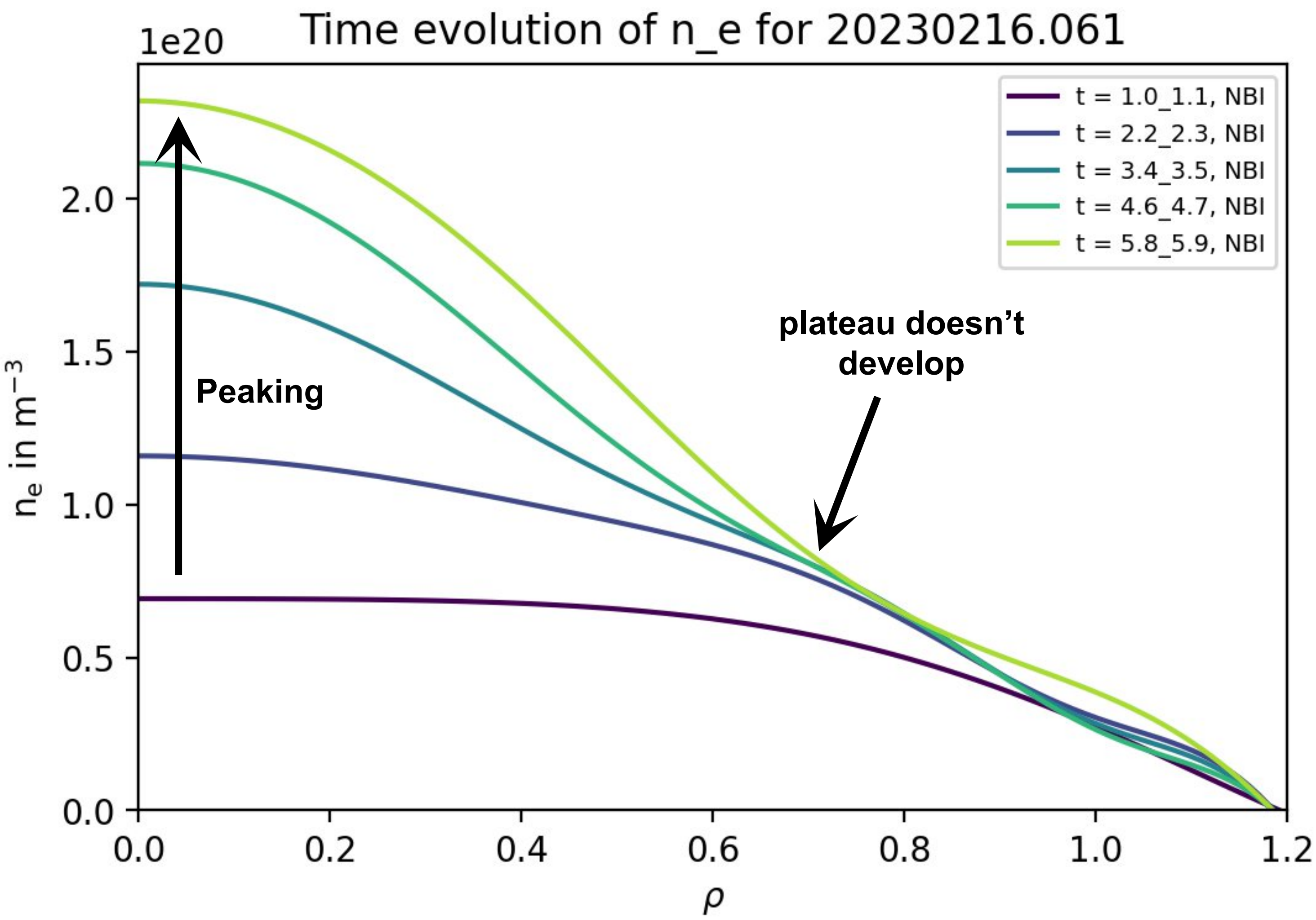


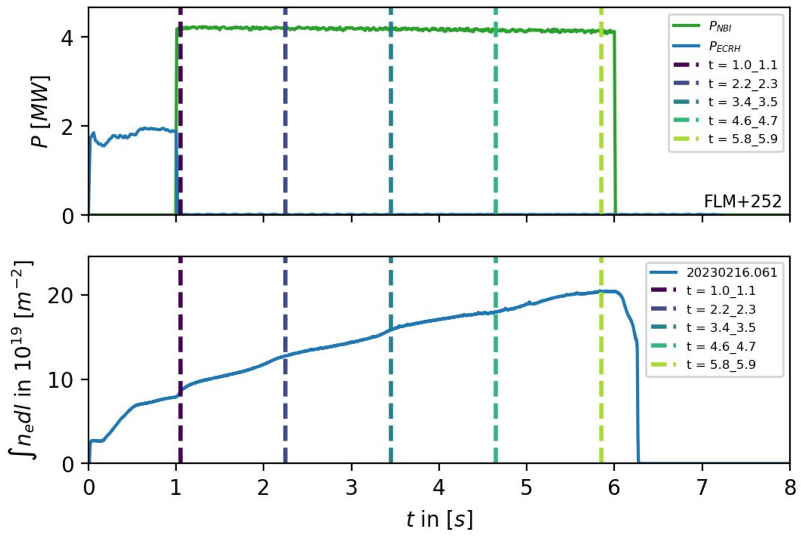
Key observations of accumulation phenomena in database

- Database populated with over 30 shots, solidifies consistent evidence of neoclassical transport domination in pure NBI heating scenarios
  - Anomalous transport is observed to be dominated for non-accumulating scenarios
- Kink location does not vary significantly for different magnetic configurations

Remarkable observations - peaking without plateau

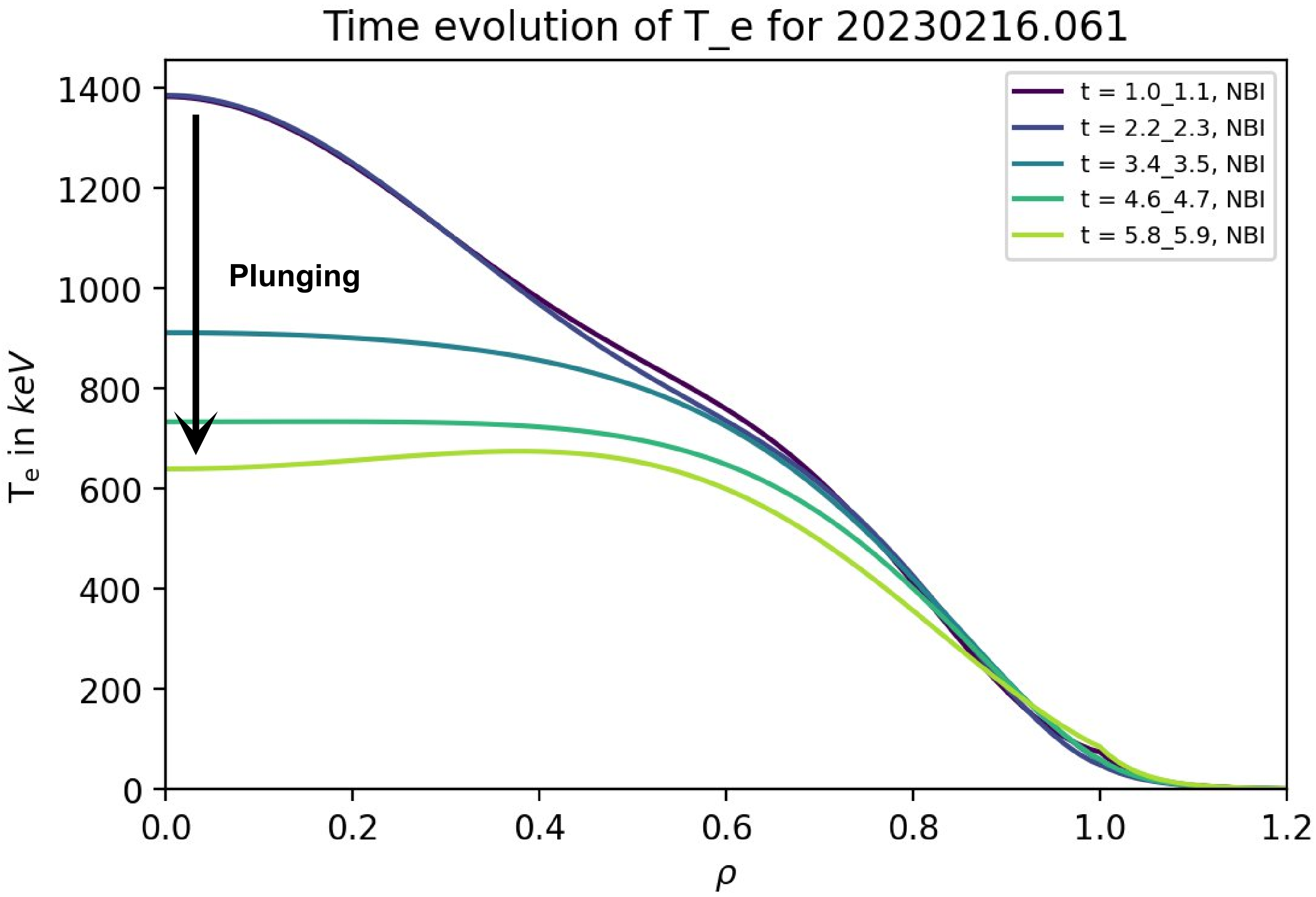
- In the FLM magnetic configuration, the plateau does not fully develop
  - Still, the profile is peaking

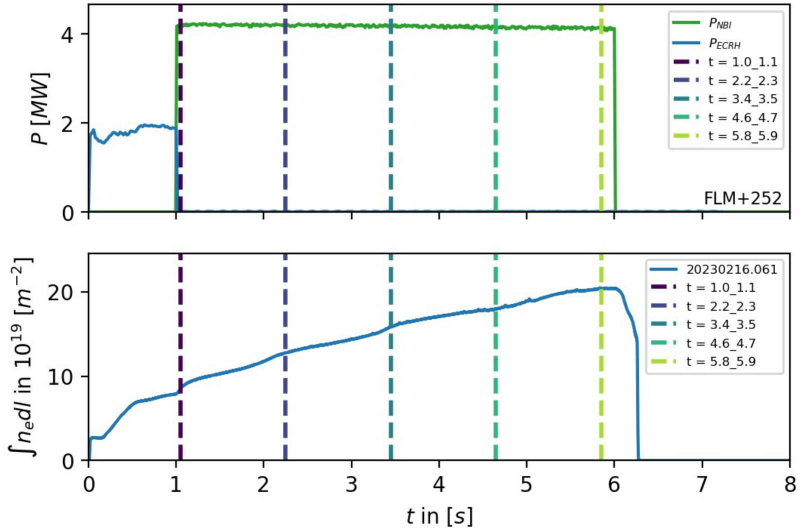




Remarkable observations - peaking without plateau

- **Due to the increase in particles with the NBI, inside $\rho = 0.4$ the electron temperature profile plunges as the density keeps rising**





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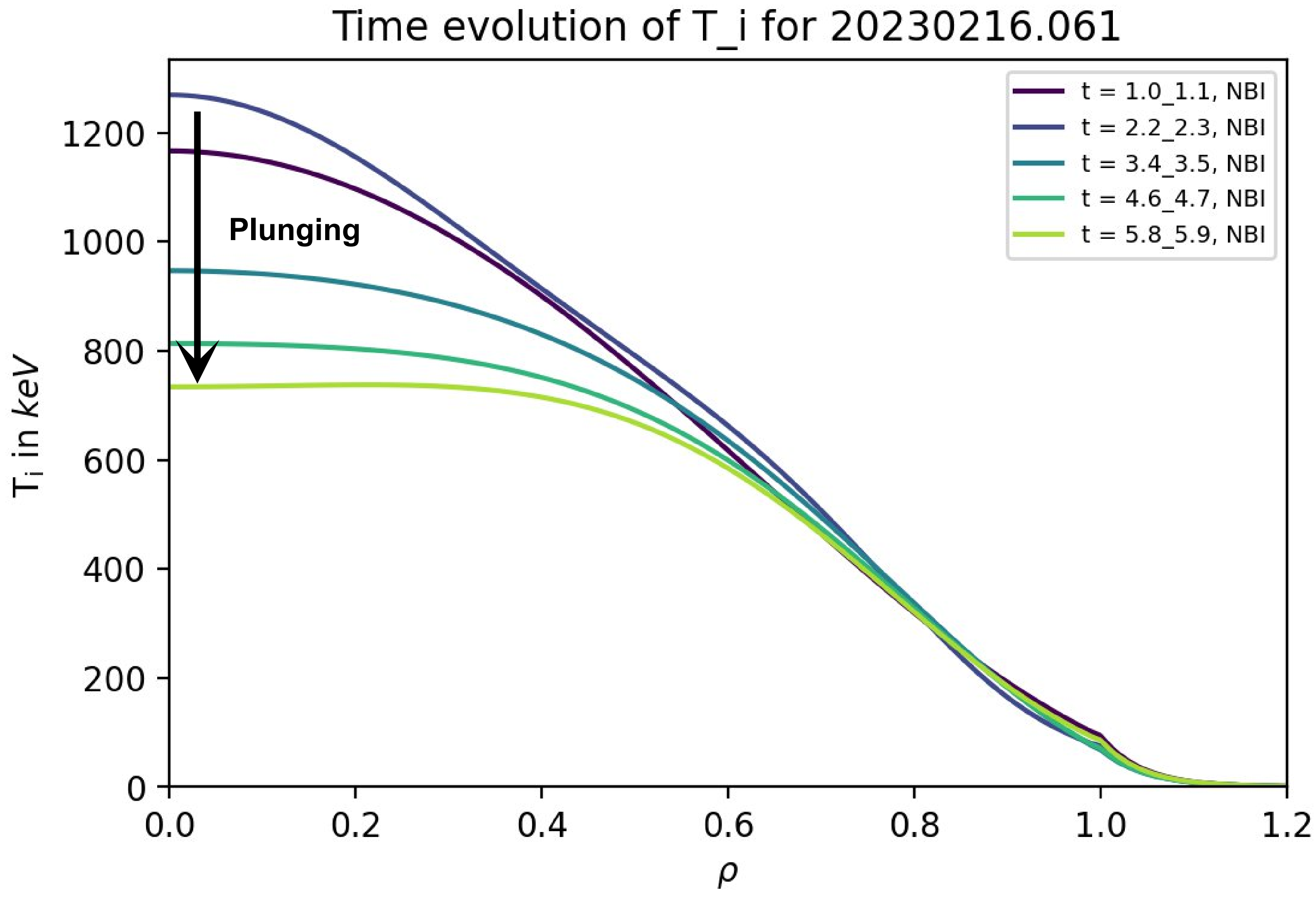
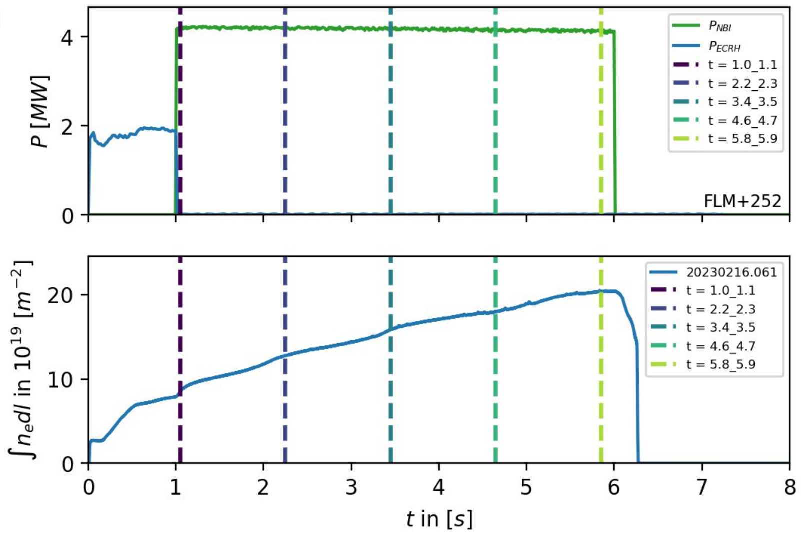
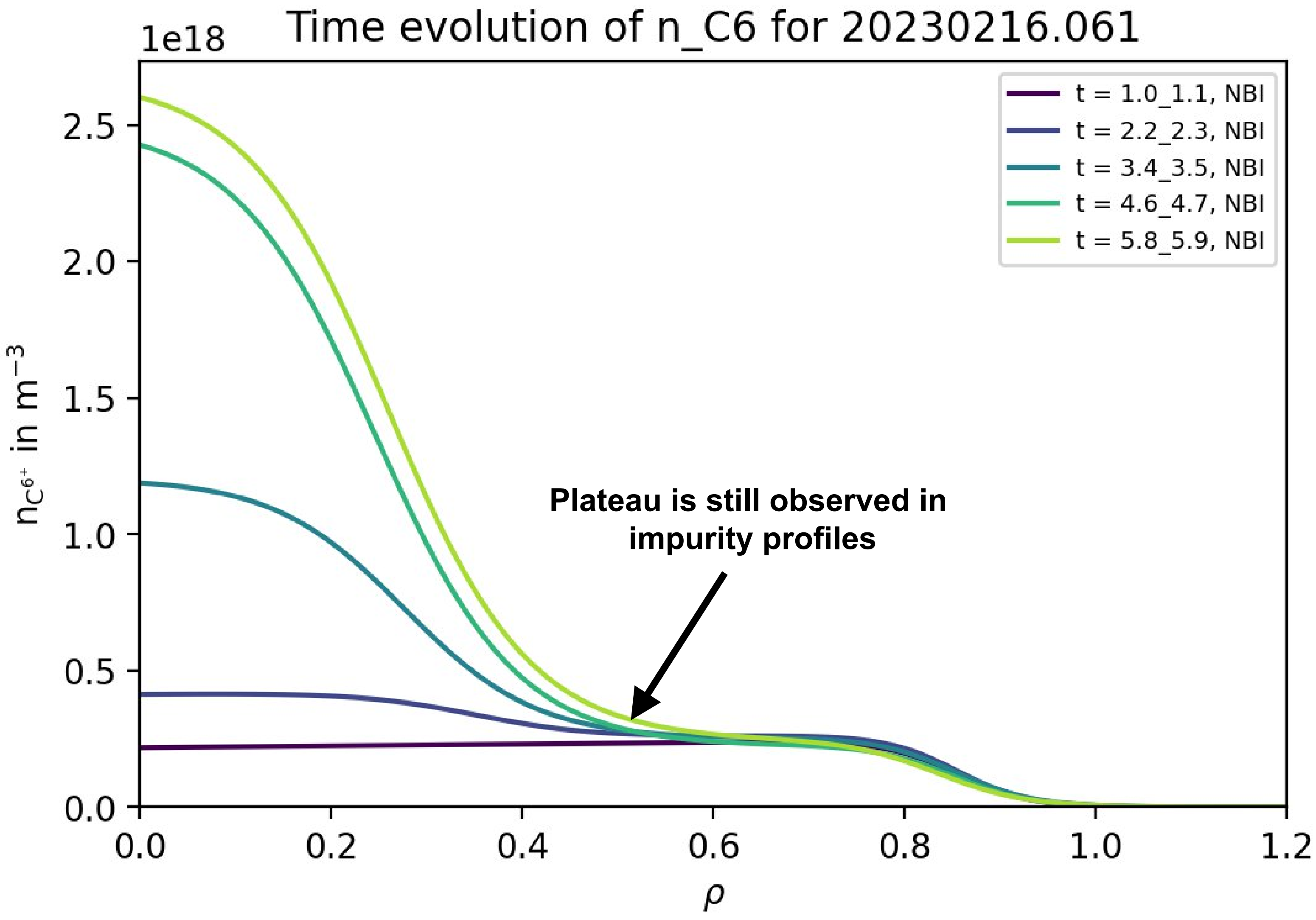
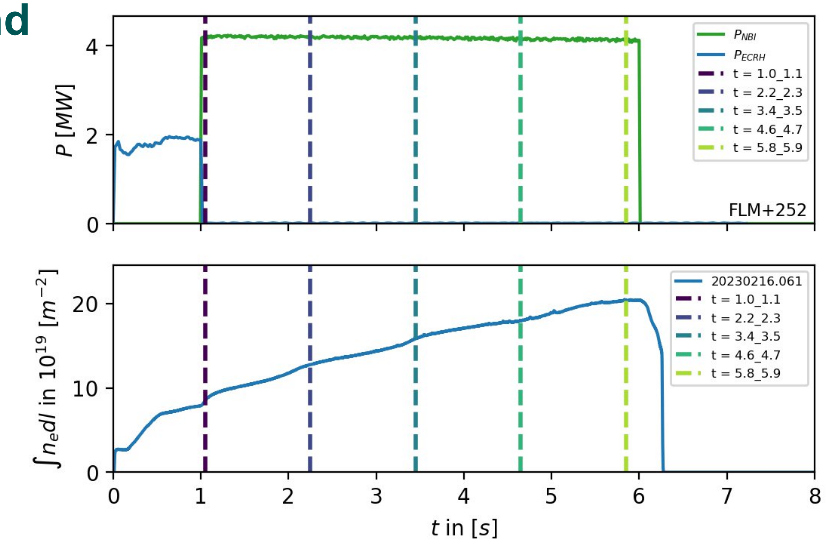




Remarkable observations - peaking without plateau

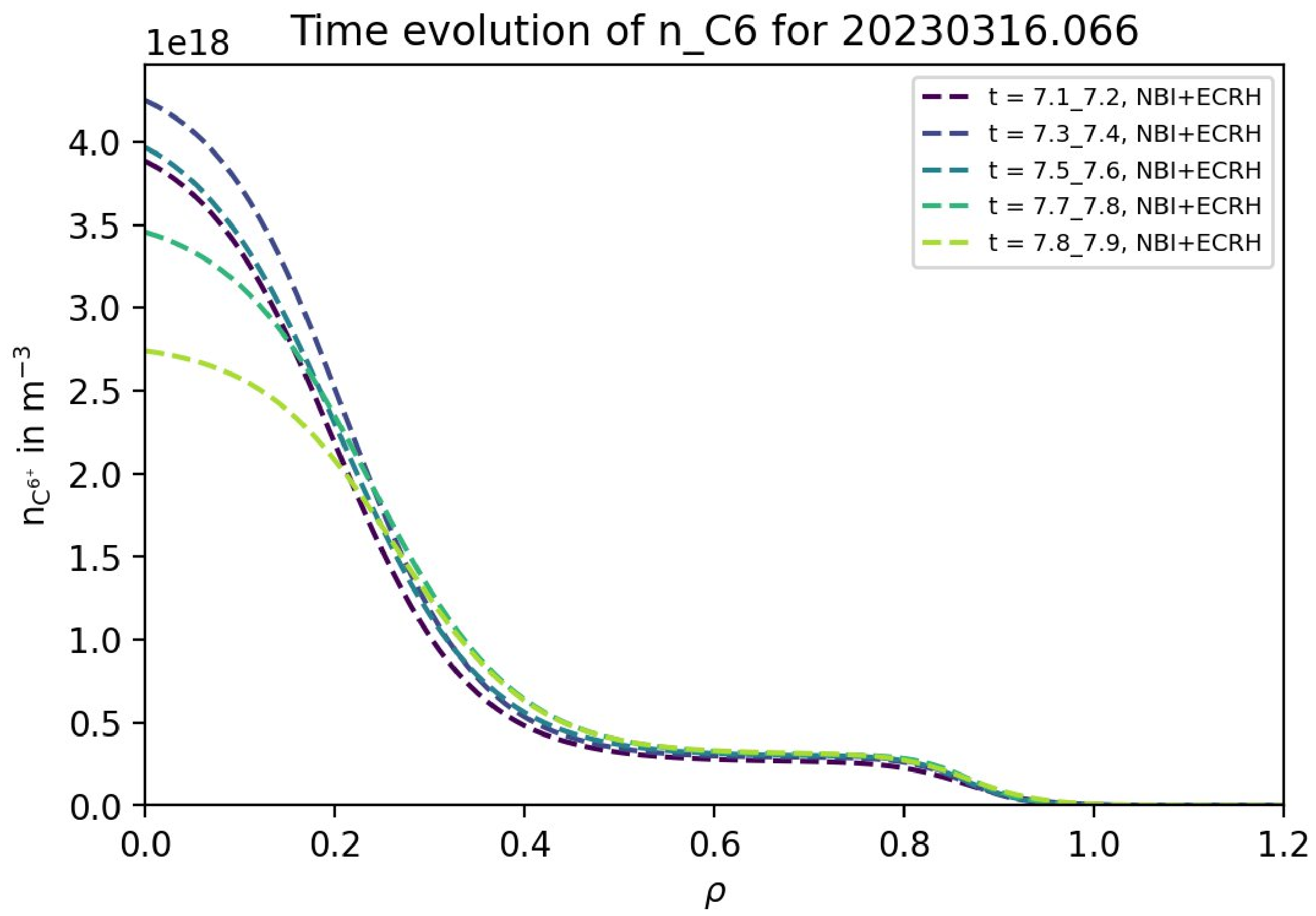
- **The impurity profile is still peaking dominantly with a flat slope around $\rho = 0.4$**

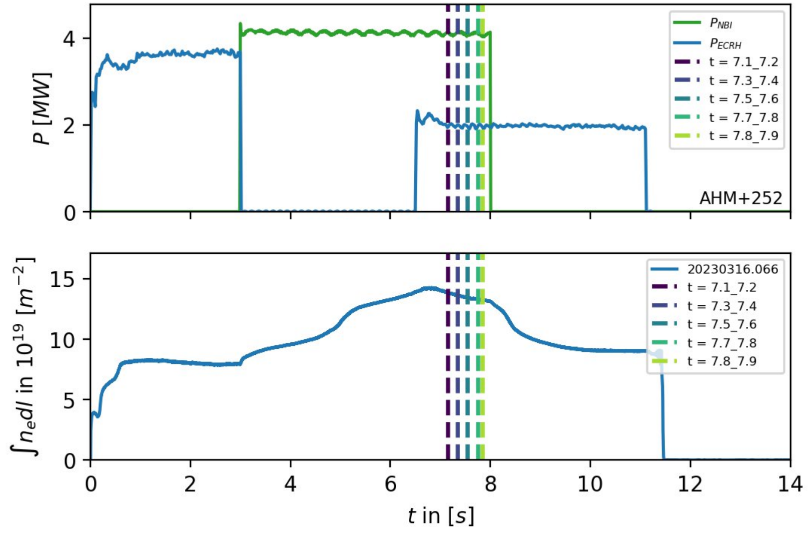


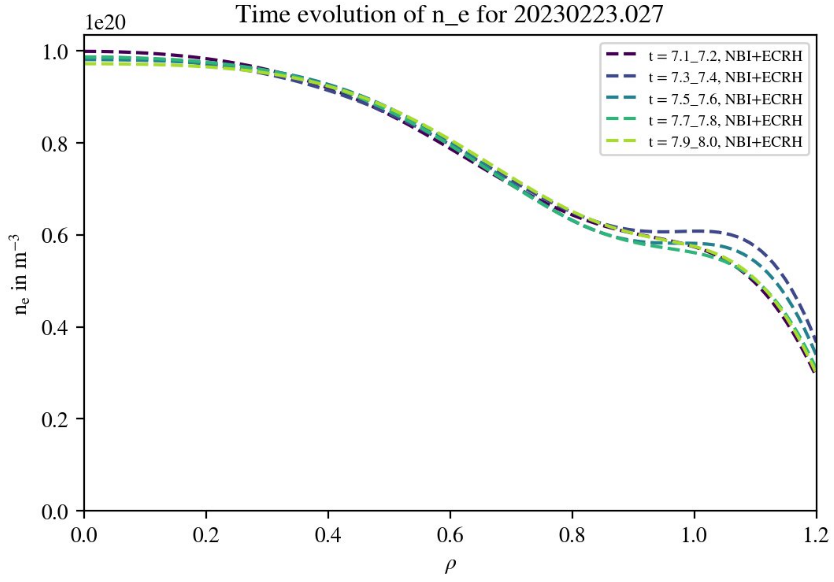


Combined heating for low power ECRH

- **While electron density finds equilibrium, impurity continues to peak**







Summary

- Central density accumulation—which includes peaking and plateau development—is observed during the pure NBI heating phase at high density
  - For both the main species and the impurities, combined NBI and ECRH heating can either weaken the accumulation or disable it entirely
- In main species and impurities evolution, as well as the database, no strong dependence on main magnetic configurations is observed
- Accumulation occurs only for high-density discharges, a critical density ($\sim 8.5 - 9.0 \cdot 10^{19}\,\mathrm{m}^{-2}$) has to be achieved for the peaking to occur
- Gradient development region changes between main species and impurities
- Accumulation is stronger for higher-Z impurities
- Database approach reveals clear relationship between the impurity and electron gradients, verifying neoclassical transport dominance during pure NBI heating
  - High ECRH powered or low density discharges verify anomalous transport dominance for flat (non-accumulating) profile
- Kink location does not vary significantly for different magnetic configurations

Future steps

- Implementation of neotransp and pystrahl on experimental profiles to solidify assumptions with transport simulation codes
- Improvement of data fitting with modified double tanh
  - Further adjustment to ranges for the double modified tanh parameters
- Filtering of database by manual examination using the ‘filter_data_by_figures’ function
- Parameterization and quantification of accumulation in main plasma species
- Database population with multiple impurity species, and validation of universal accumulation behavior for impurities
- Investigation of hollowness in profiles in the database
- Examination of ICRH heating effect on profile evolution