Taking predict-first to the next level: opportunities, challenges and limits

PPPL: F. M. Poli, M. Podesta', B. Grierson
GA: K. Thome, J. Ferron
LLNL: B. Victor, C. Holcomb

Why we love predict-first …

- Predict-first can be a powerful tool in the control room
  - To optimize the experimental time
  - To support decision making (including unexpected failures)

Will show an example of successful application of predict-first:

achievement of sustained q_{min} with early EC heating and CD

… and what we should be careful about

- In order to be successful it needs:
  - A *whole device*, comprehensive, time-dependent model (equilibrium, transport, MHD, fast ions)
  - Verified and validated physics models from high to low fidelity

We are not there yet …

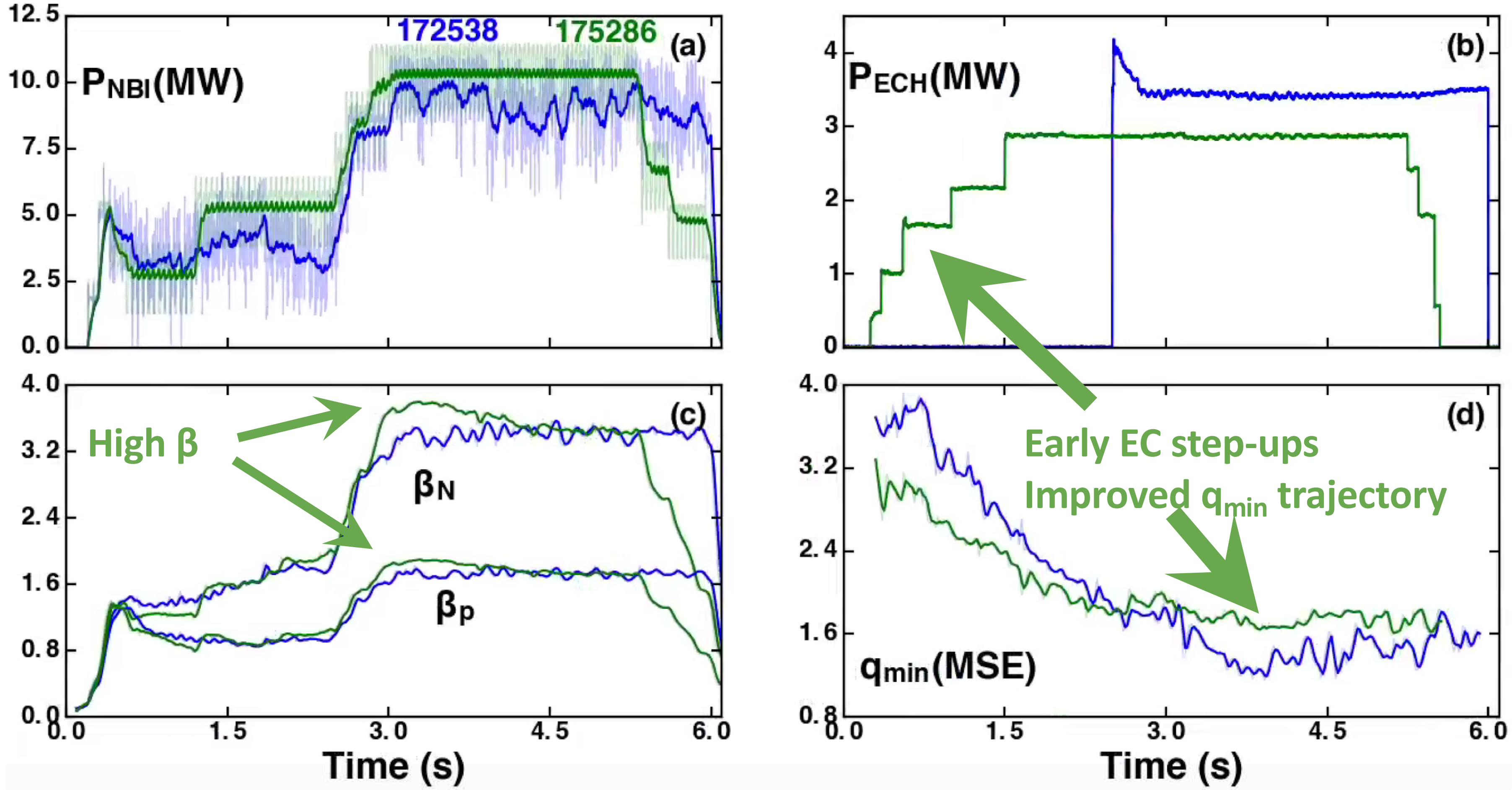
Will discuss limits of predictive models, challenges in experimental preparation and identify opportunities for improvement.

When things go well

Demonstrated sustained q_{min} with early EC heating and CD

- 100% success in use of resources with one shot planned and executed.

"Predict First" EC and NBI trajectory achieved high β access with no high gain feedback, obtaining smooth, elevated, sustained q_{min} with little MHD activity



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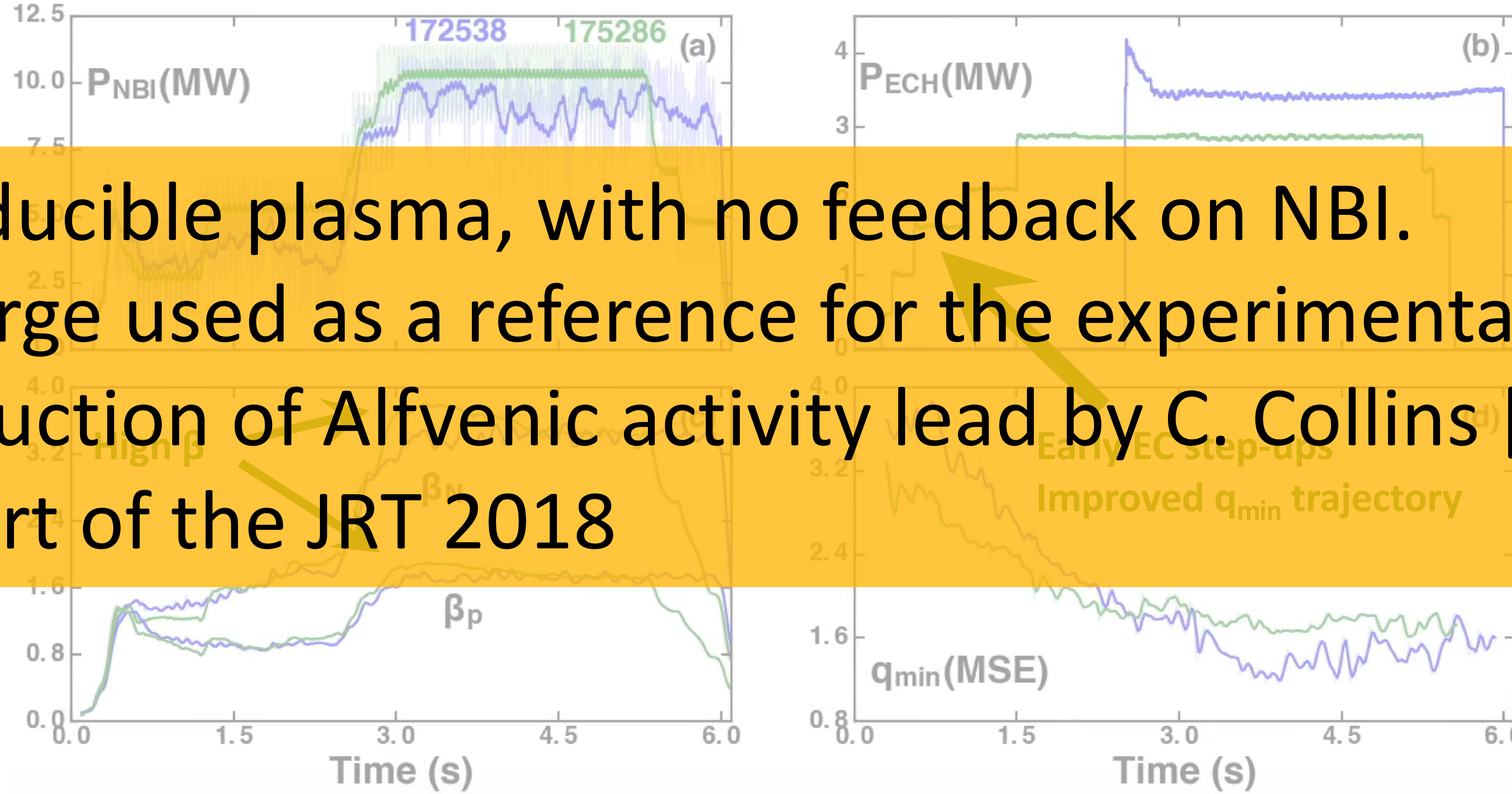
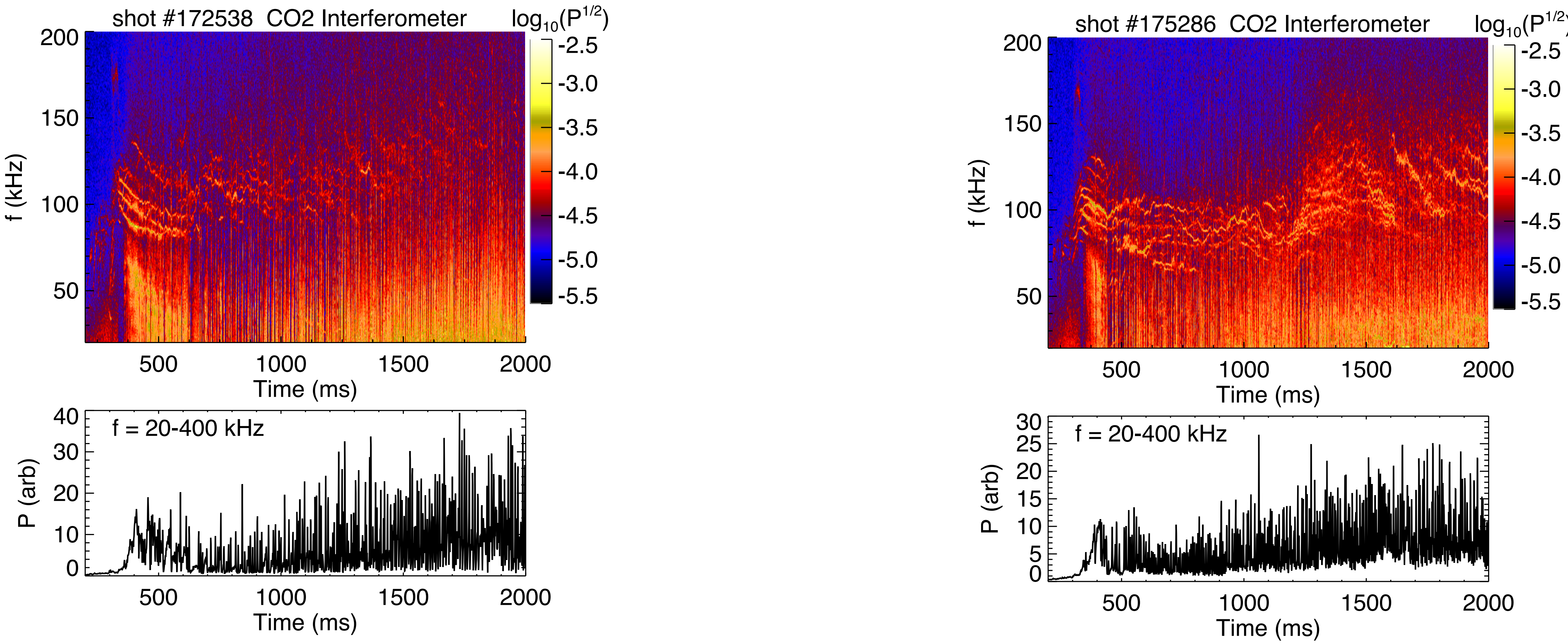


Reproducible plasma, with no feedback on NBI. Discharge used as a reference for the experimental day on reduction of Alfvenic activity lead by C. Collins [GA] and part of the JRT 2018

Significant Alfvenic activity present in higher q_{min} plasma

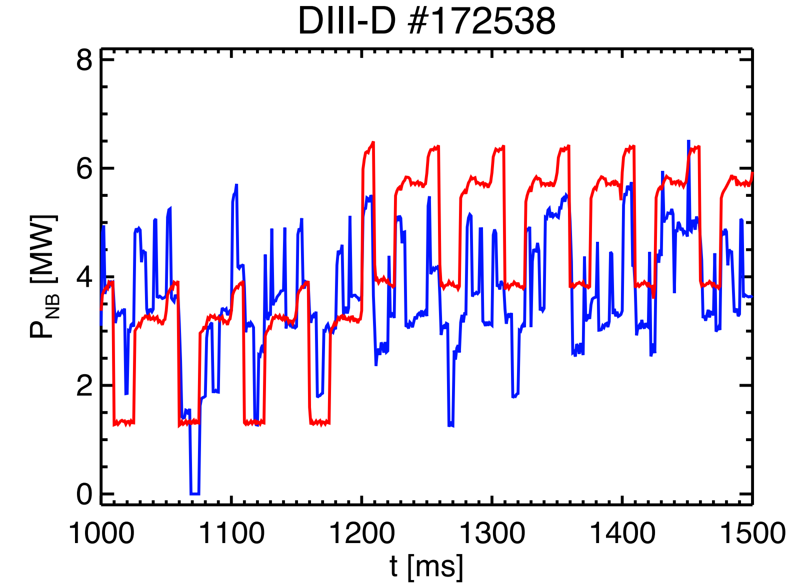


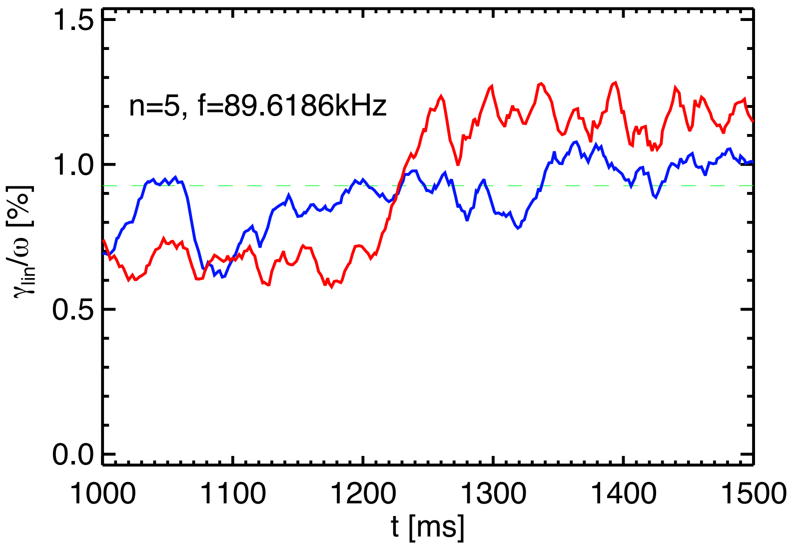
Due to the high(er) NBI power already in the ramp-up phase

AE activity triggered by NBI at low plasma current

- Linear AE stability performed with TRANSP + kick model [M. Podesta']
- Test:
    - Use NBI waveform from #175286 keeping same profiles as in reference #172538
    - *How much does AE drive change?*

- #175286 has ~1MW additional NB power after 1.2 sec
    - Enough to destabilize several AEs with respect to reference shot





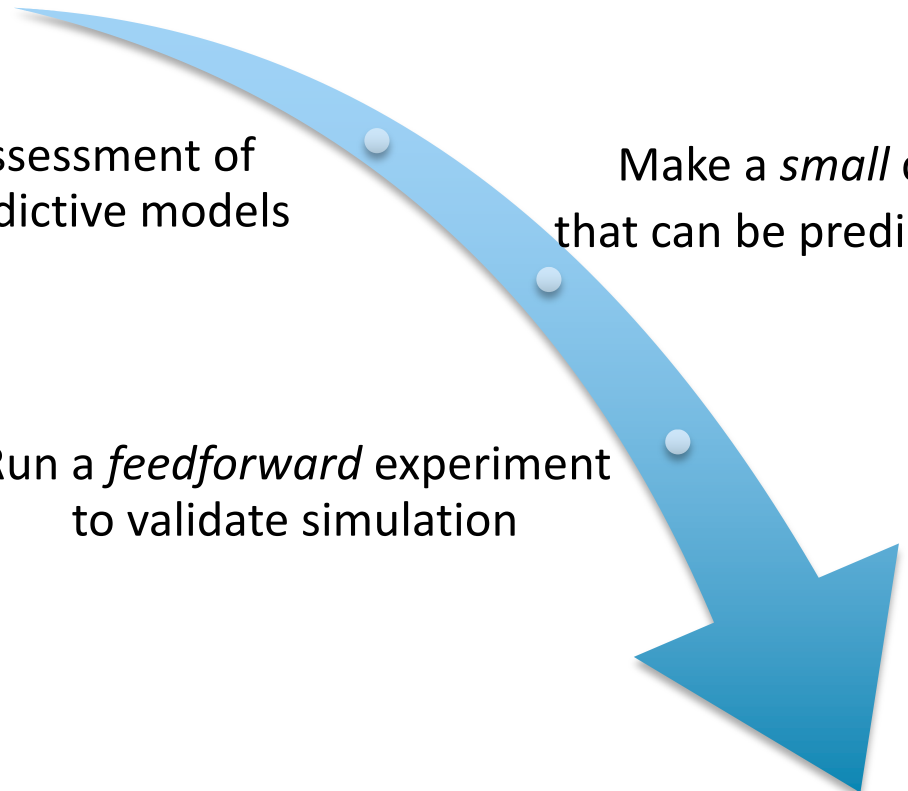
Our success resulted from careful step-forward planning

Start with a well diagnosed case

Assessment of predictive models

Make a *small* change to the reference that can be predicted within the limit of the models

Run a *feedforward* experiment to validate simulation



Post-process analysis and validation: assess what is missing, what could have been done better

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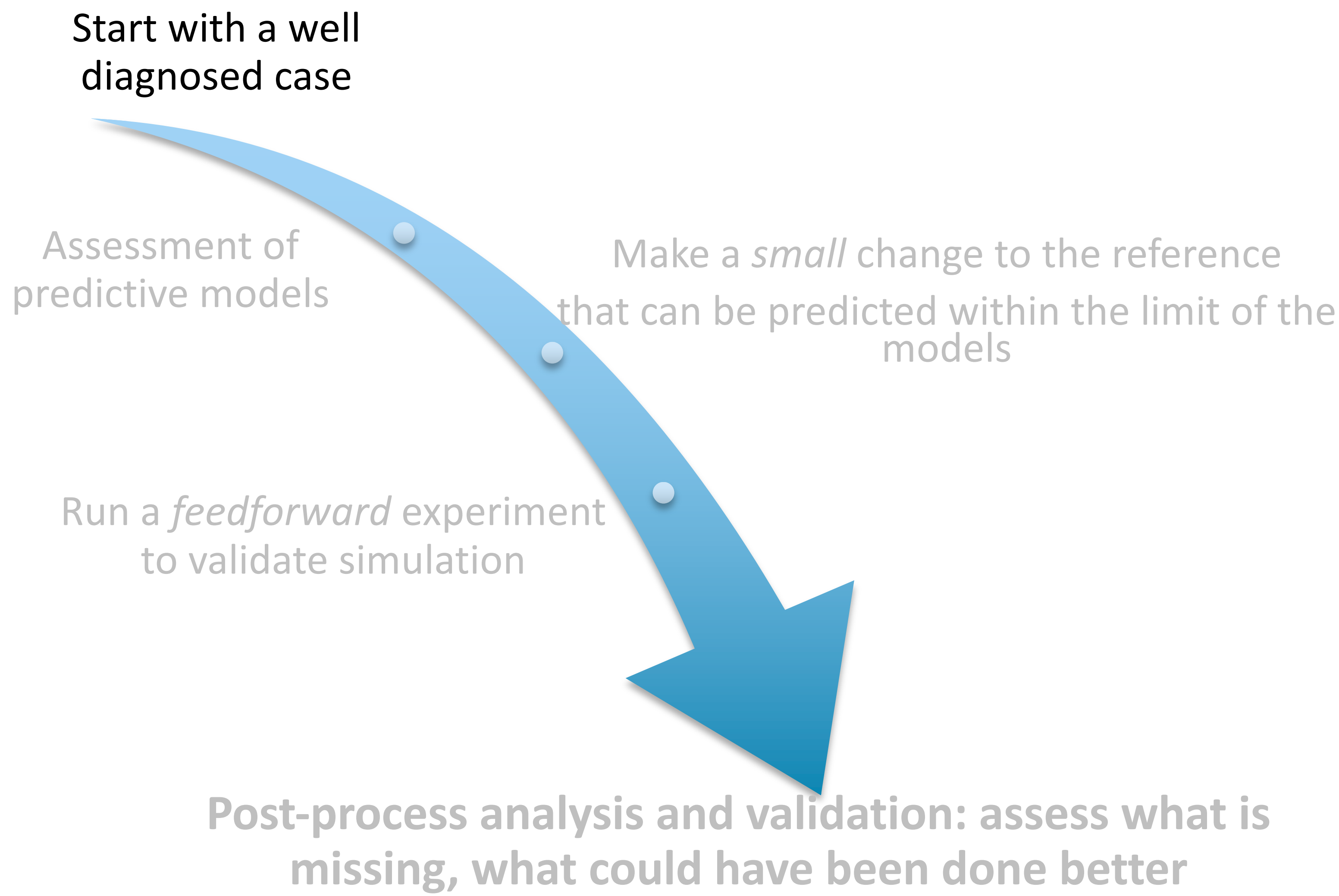
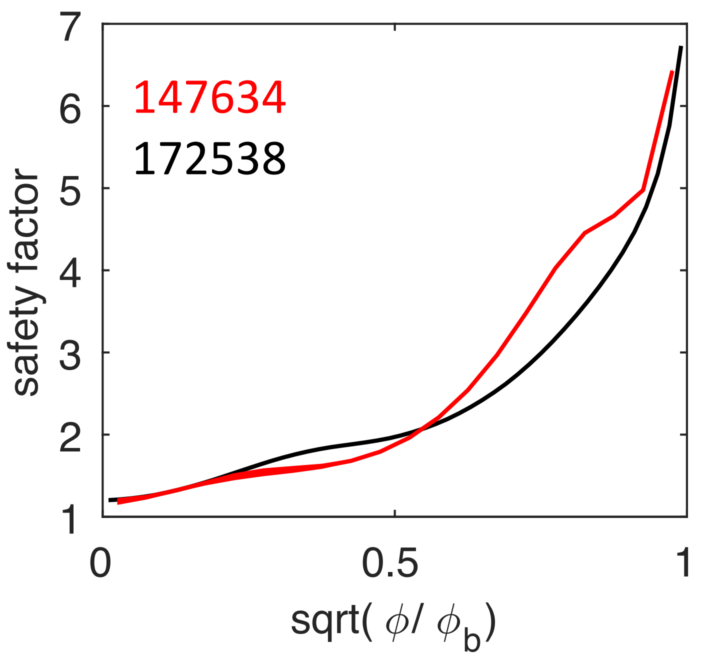


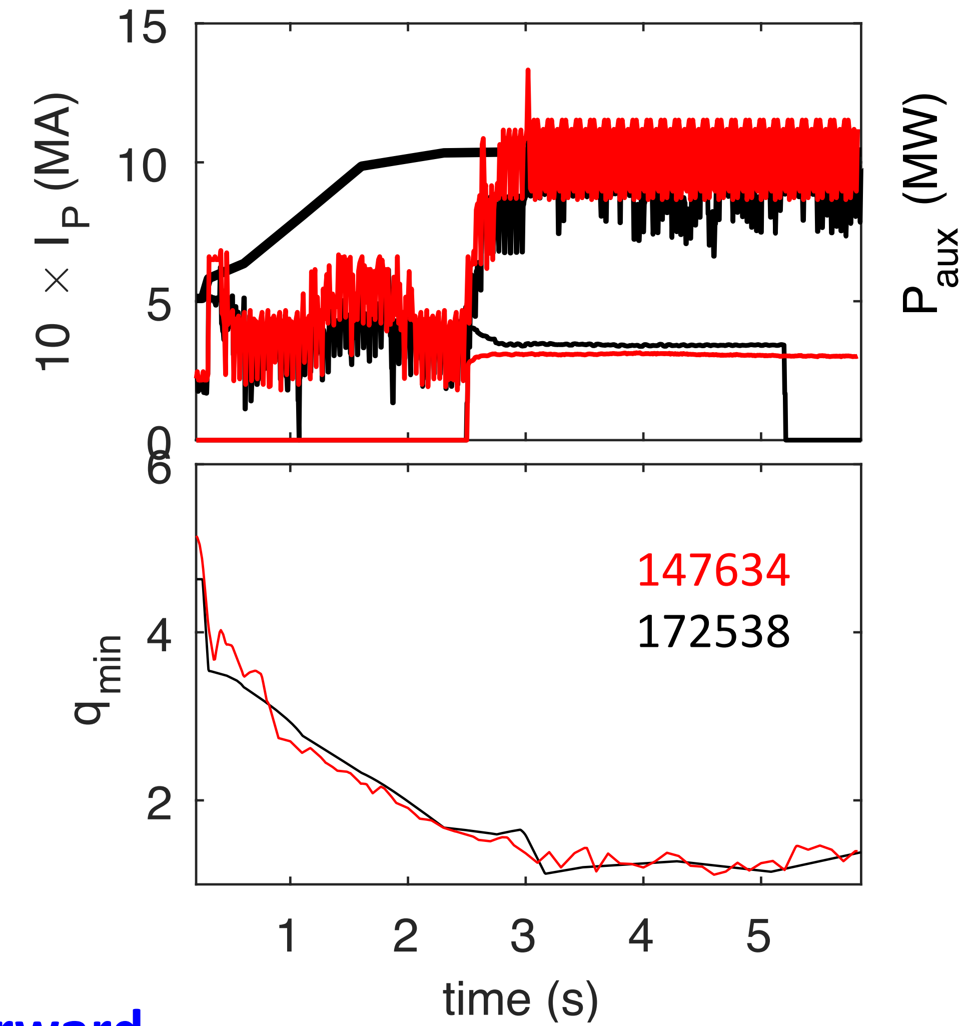
Goal: modify the q_{min} trajectory to sustain flat q profile

Two reference discharges with feedback on β_N:

$\Rightarrow$ q profile relaxes to monotonic in the stationary phase

$\Rightarrow$ MHD in the flattop phase





Can a good EC+NBI feed-forward improve q_{min} trajectory and MHD?

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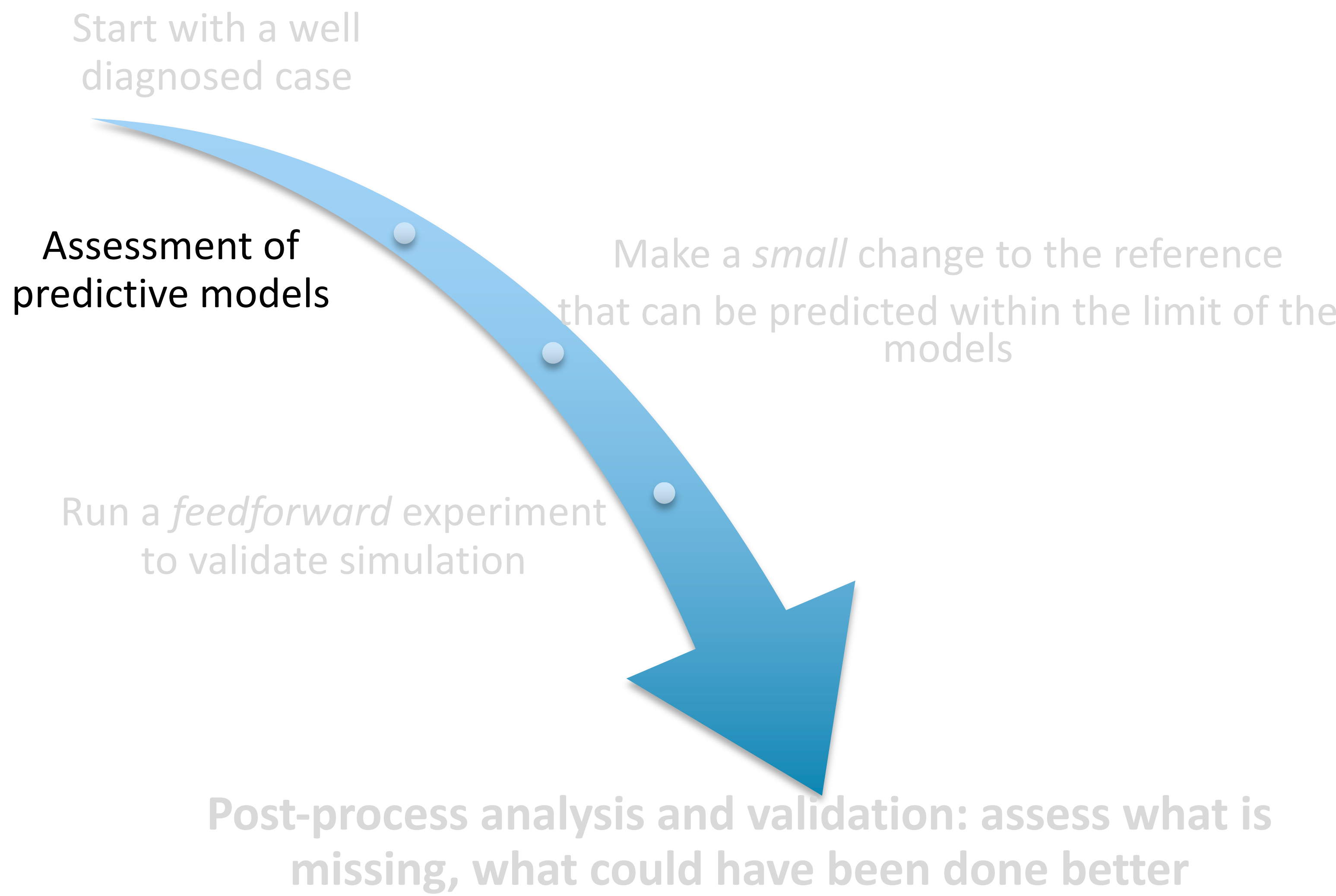


Since the goal is to modify the q_{min} trajectory, the validation focusses on the q profile

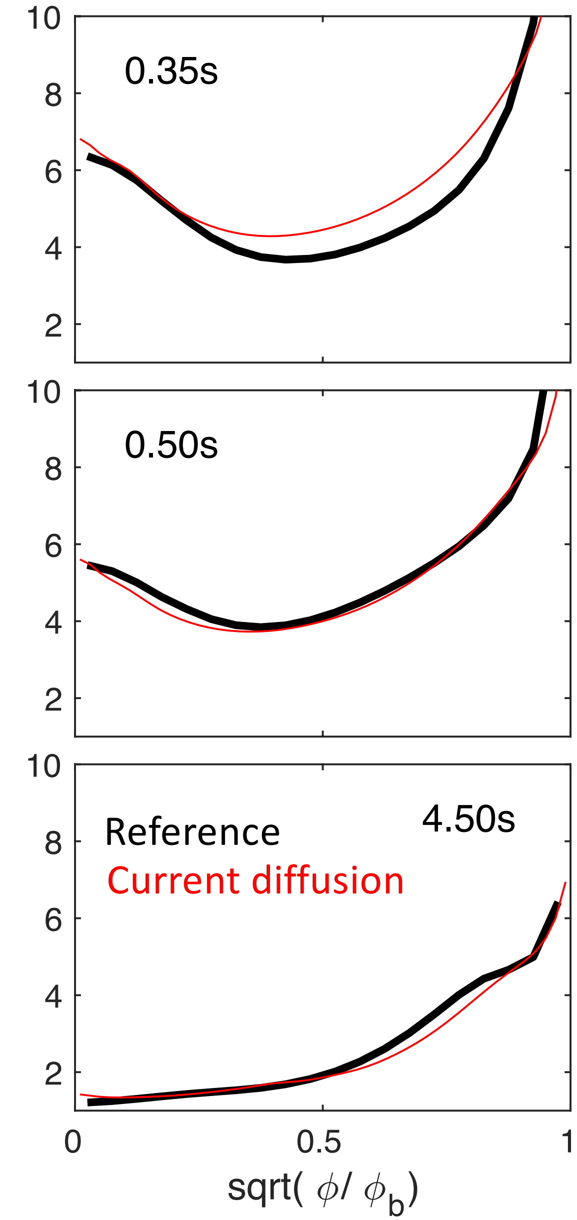
Step 1: evolve free-boundary magnetic equilibrium with prescribed n_e, n_C, T_e, T_i, v_ϕ, profiles

- Expect larger uncertainties in the early ramp-up, at low current (no good profile mapping available)

=> but initial condition important for full discharge predictions

- Assuming input profiles are 'good', differences due mostly to bootstrap current and neutral beam model

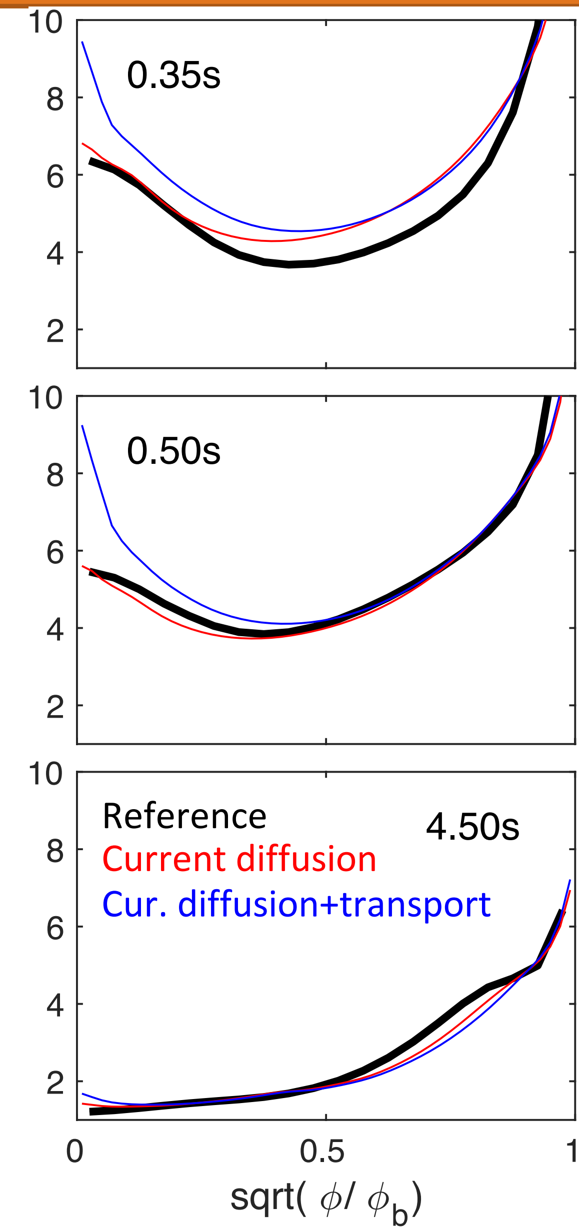
=> initial condition important for full discharge predictions



Since the goal is to modify the q_{min} trajectory, the validation focuses on the q profile

Step2: evolve free-boundary magnetic equilibrium with prescribed n_e, n_C, v_ϕ, but predict T_e, T_i with GLF23 inside the pedestal

- Our target is to change EC, which affects the electron temperature



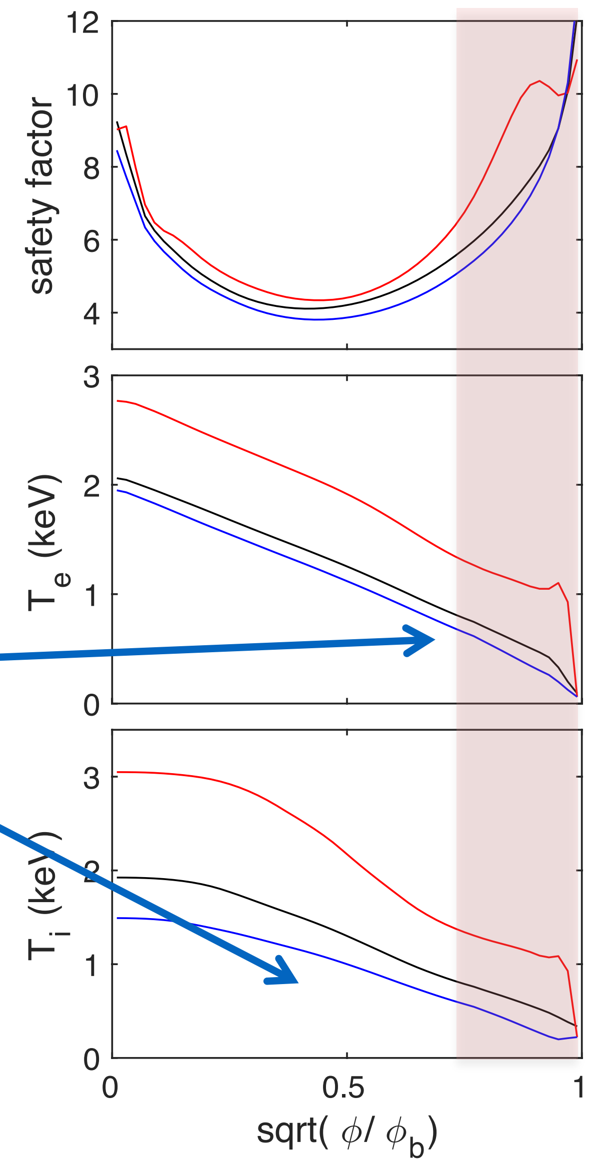
Predictions should include the pedestal region

PROBLEM: pedestal models are not designed for current ramp-up/ramp-down conditions

Step3: evolve free-boundary magnetic equilibrium with prescribed n_e, n_C, v_ϕ, but predicted T_e, T_i **including pedestal** (EPED1-NN)

⇒ Need to rescale the pedestal in the ramp-up phase (based on comparison between predicted and measured values)

TEPED_SCALE $= 11.0\left(\frac{I_P}{I_{flat}}\right)^3 - 26.0\left(\frac{I_P}{I_{flat}}\right)^2 + 21.0\frac{I_P}{I_{flat}} - 5.3$

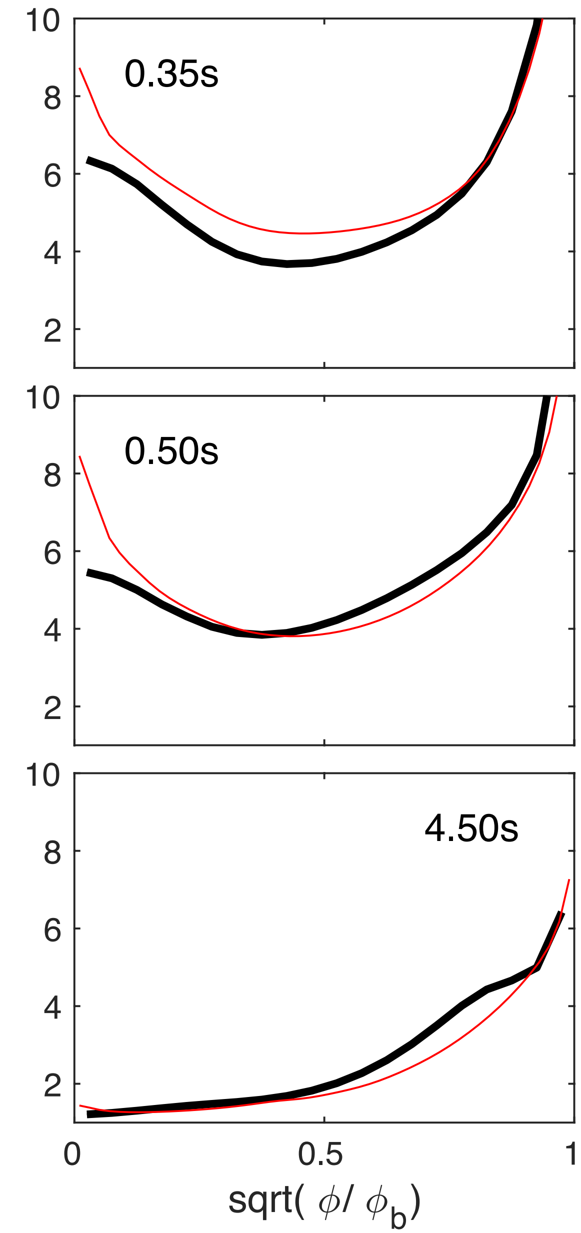


The selected model reproduces the measured q profile

... except at low current (remember: initial condition is important)

Step4: evolve free-boundary magnetic equilibrium with prescribed n_e, n_C, v_ϕ, but predicted T_e, T_i including pedestal (rescaled according to plasma current)

Stick to this model and move to the fun part



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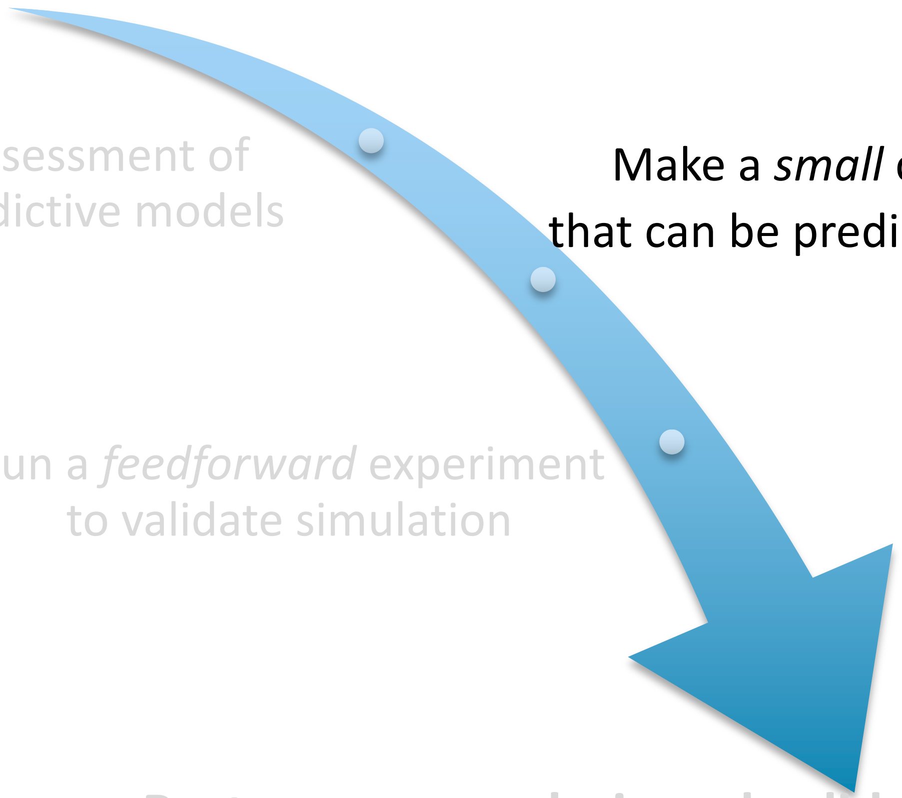


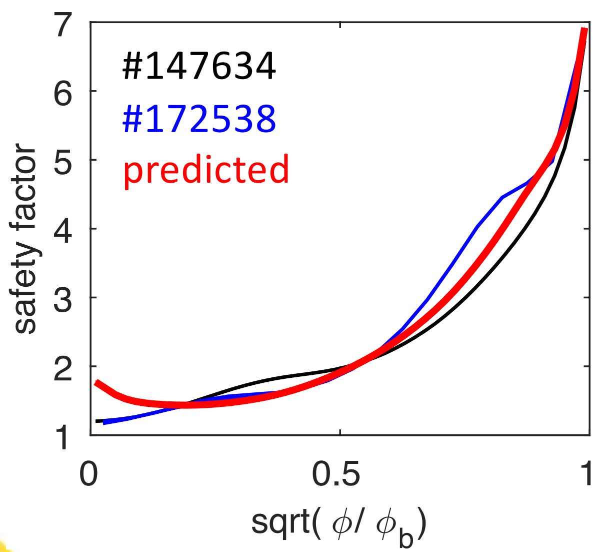
Make a *small* change to the reference that can be predicted within the limit of the models

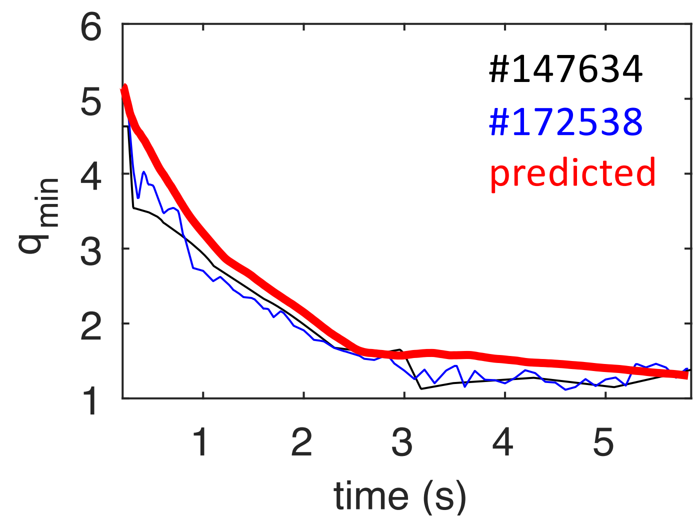
Run a *feedforward* experiment to validate simulation

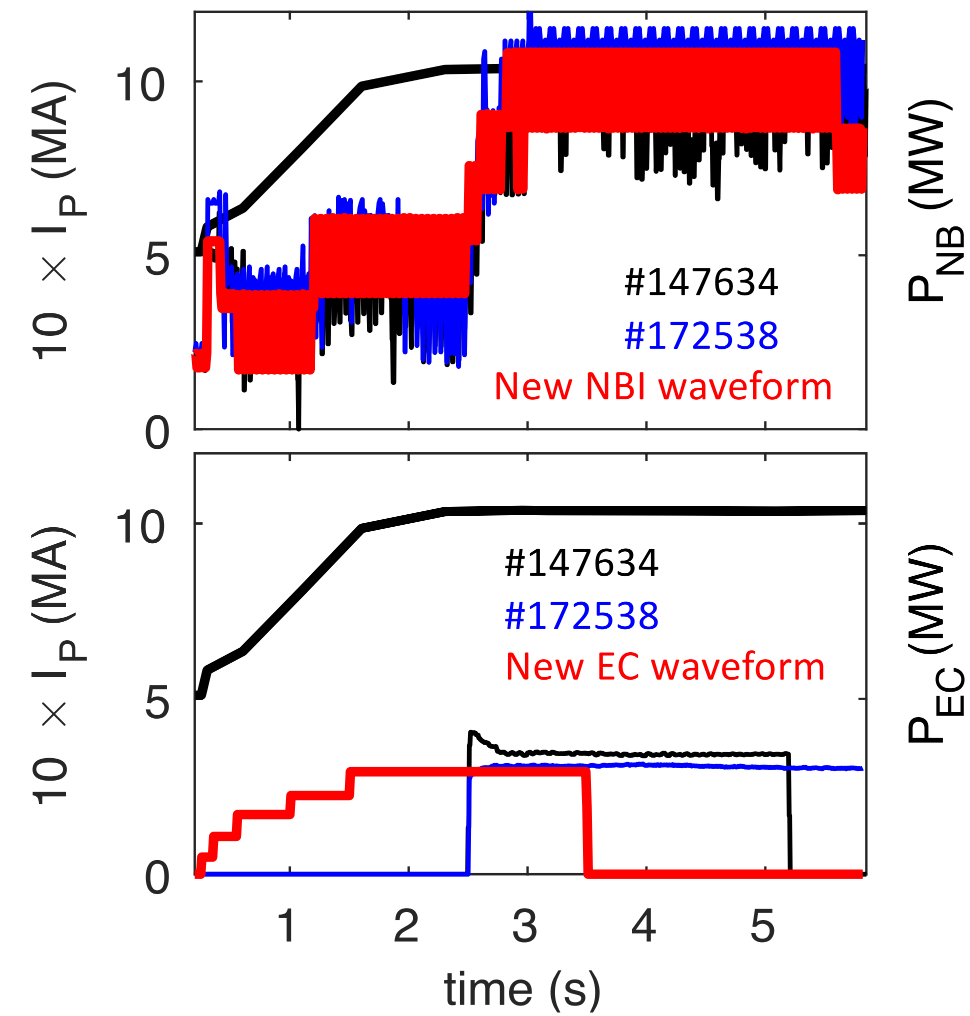
Post-process analysis and validation: assess what is missing, what could have been done better

We have used prior lessons learnt from ITER modeling

- H&CD from RF in ramp-up critical for access to steady-state **=> focus on core EC**
- keep NBI waveform close to reference
- Predict equilibrium and temperature
  - ⇒ Sustains higher q_{min}
  - ⇒ more flat q profile in the core







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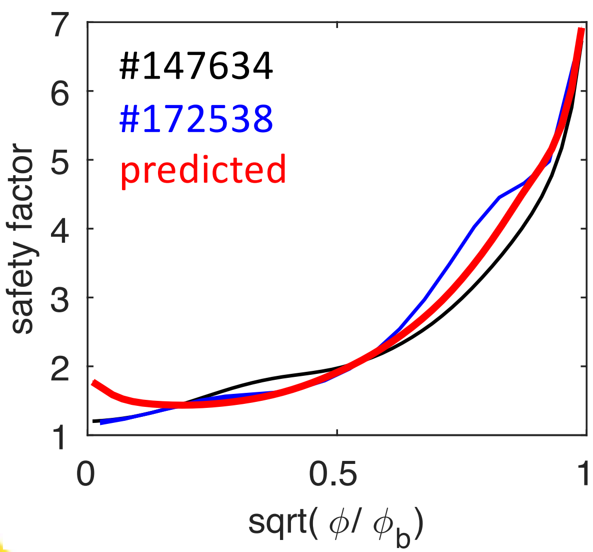
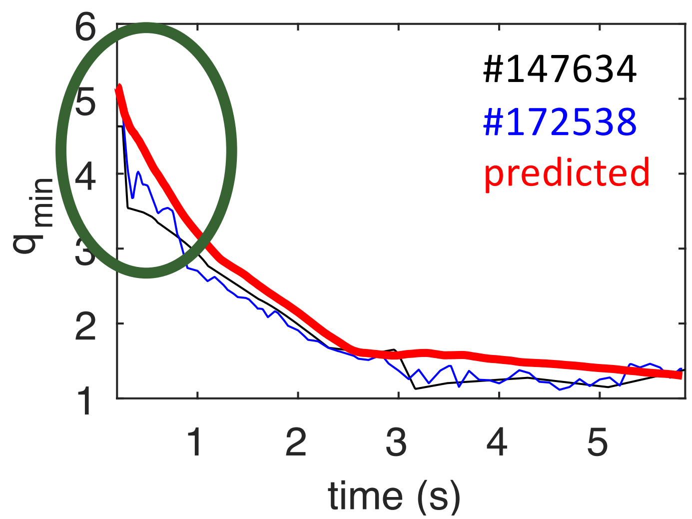
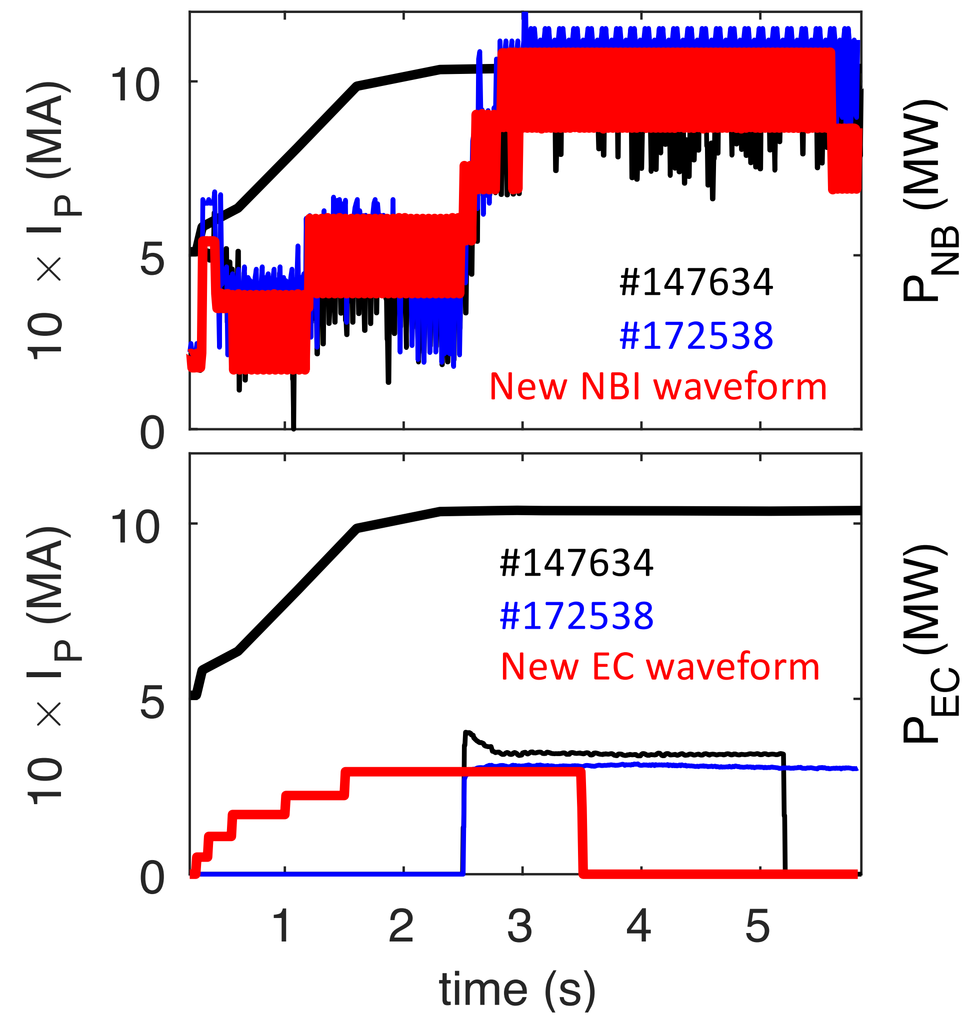
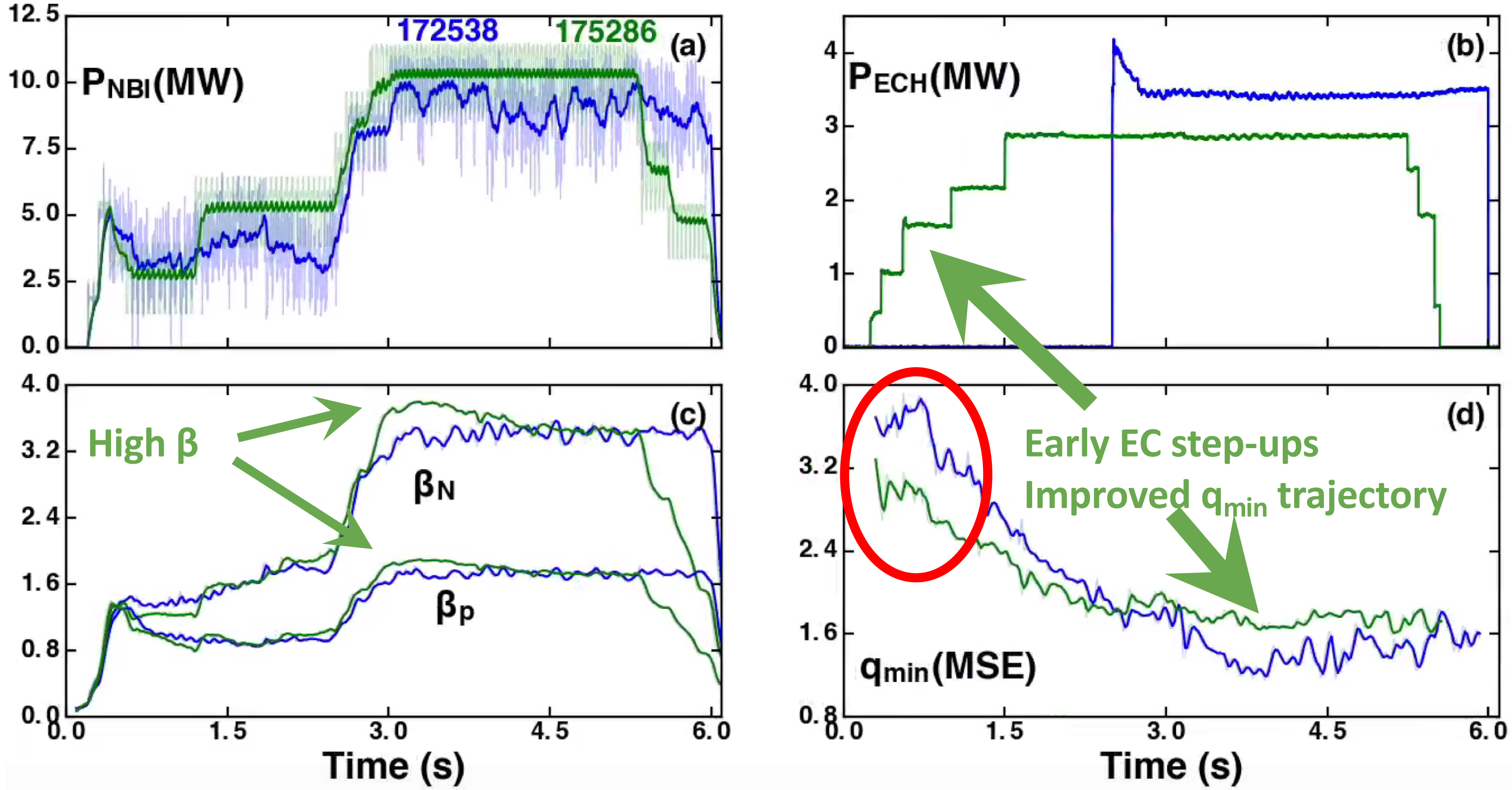


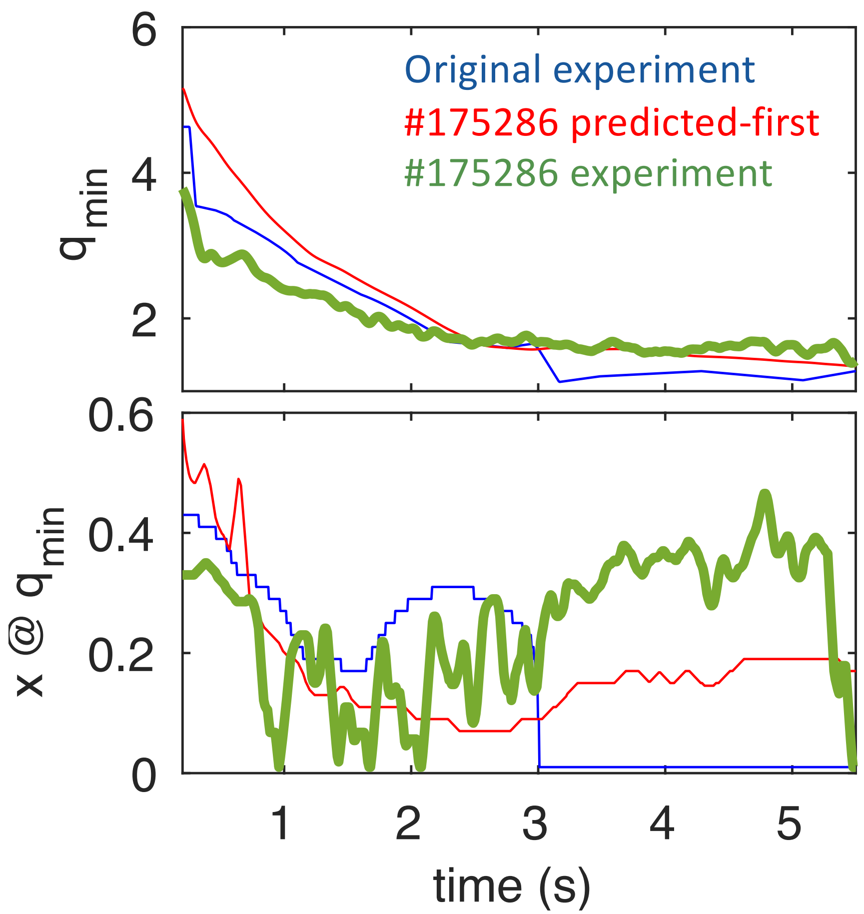




“Predict First” EC and NBI Trajectory achieved high β access with no high gain feedback, obtaining smooth, elevated, sustained q_{min} with little MHD activity



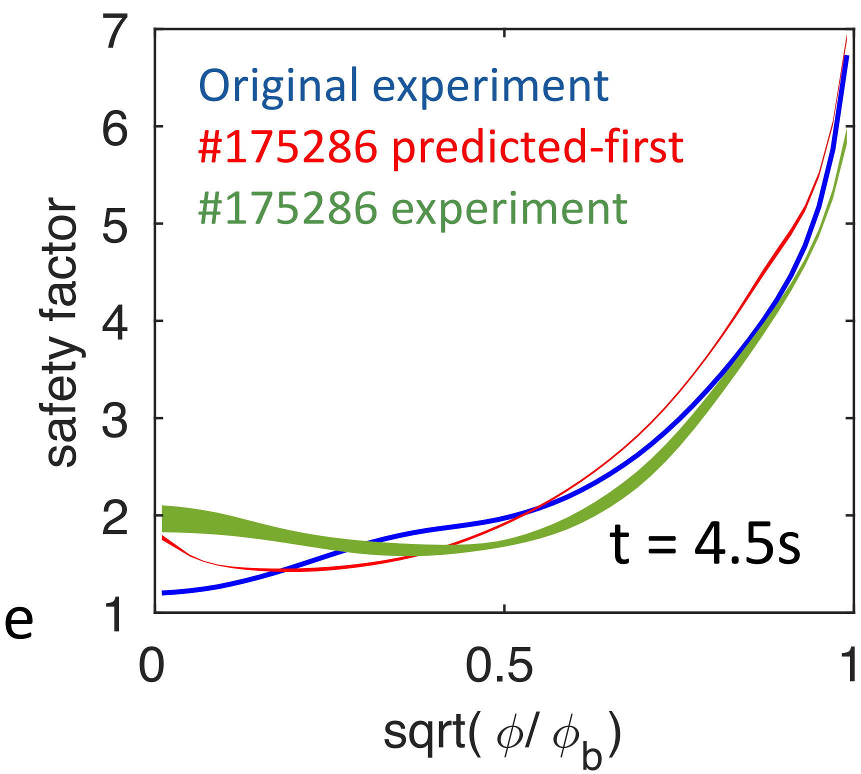
Preliminary analysis after the experiment indicated that we achieved all our targets



Sustained q_{min}

Sustained q_{min} at large radius

Flat/weakly reversed profile



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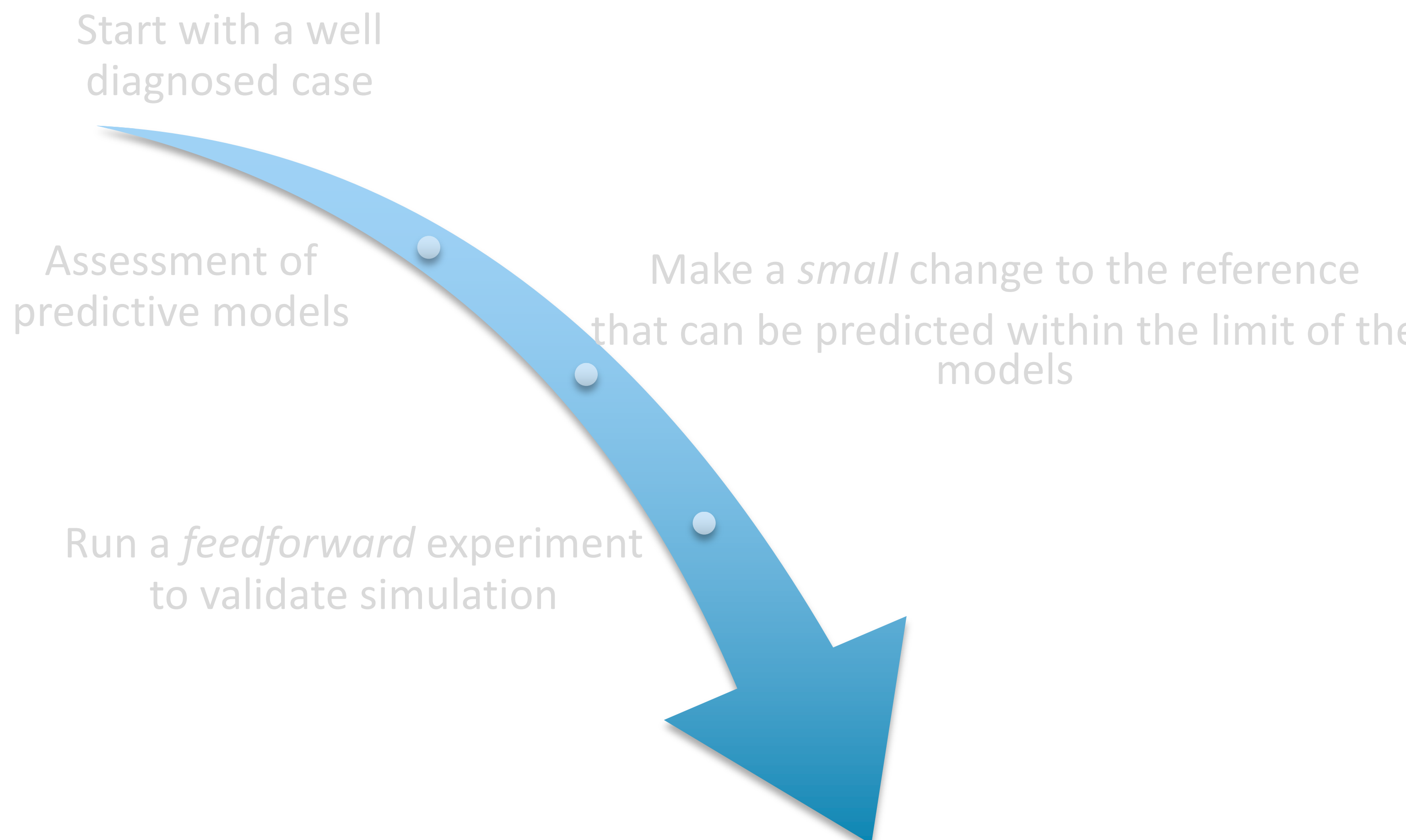
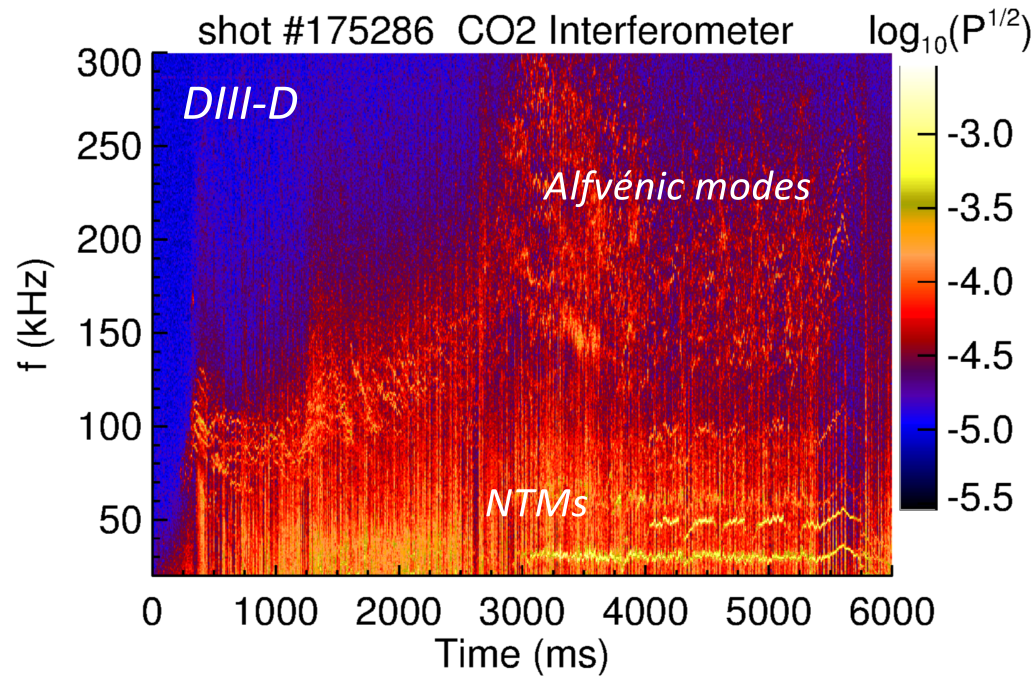
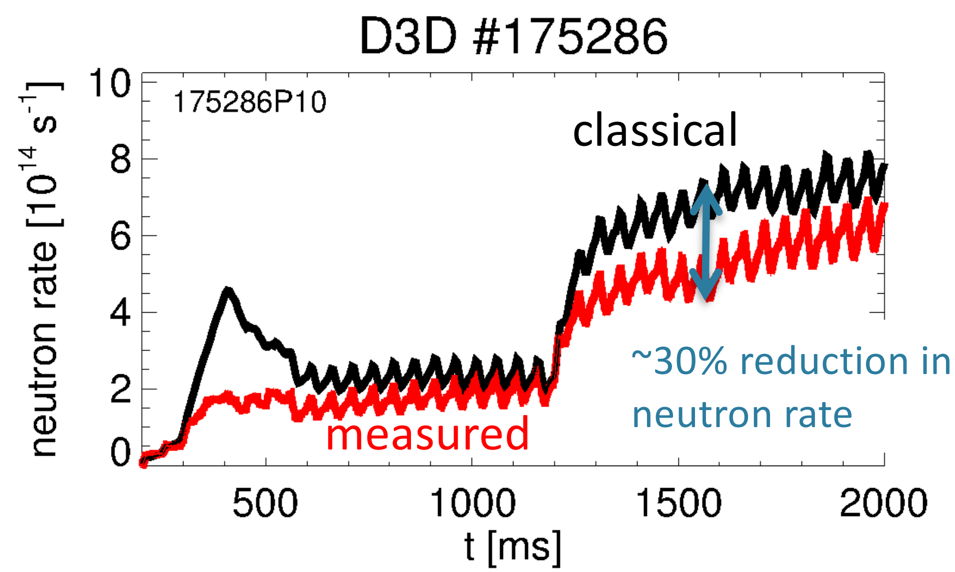
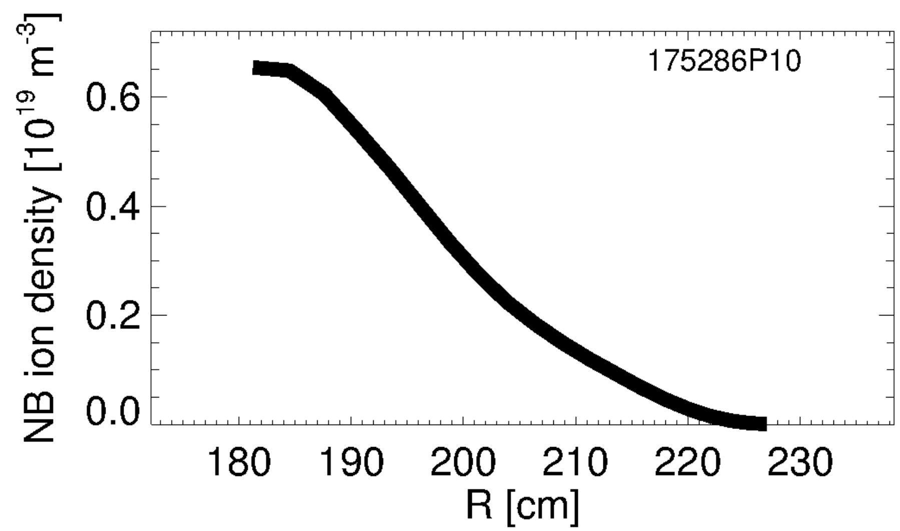


Post-process analysis and validation: assess what is missing, what could have been done better

Degradation in Energetic Particle confinement correlates with instabilities

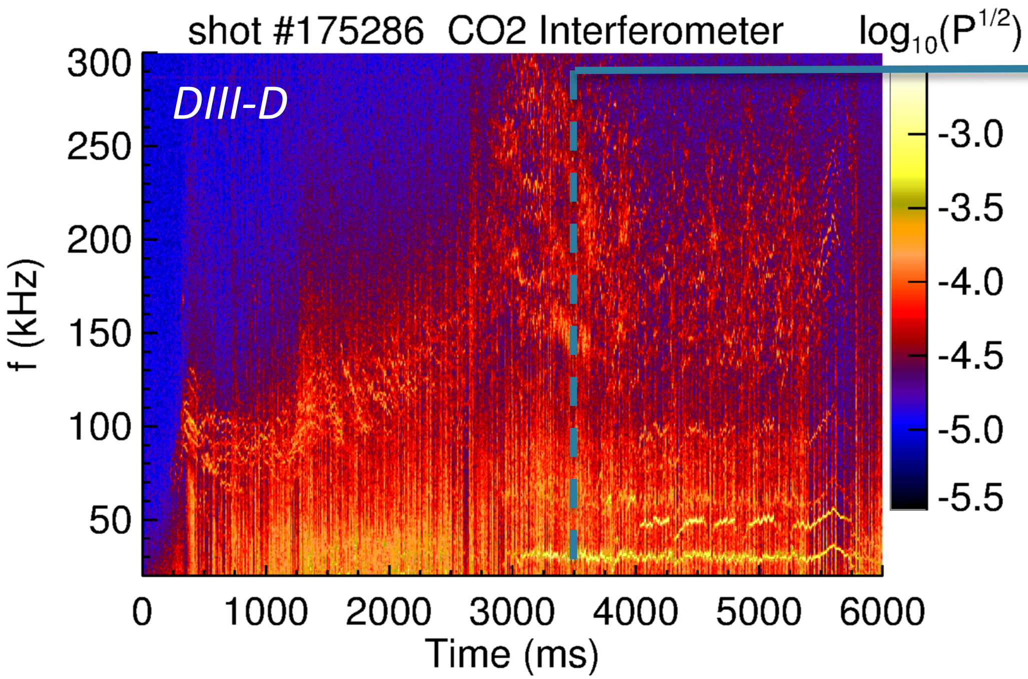


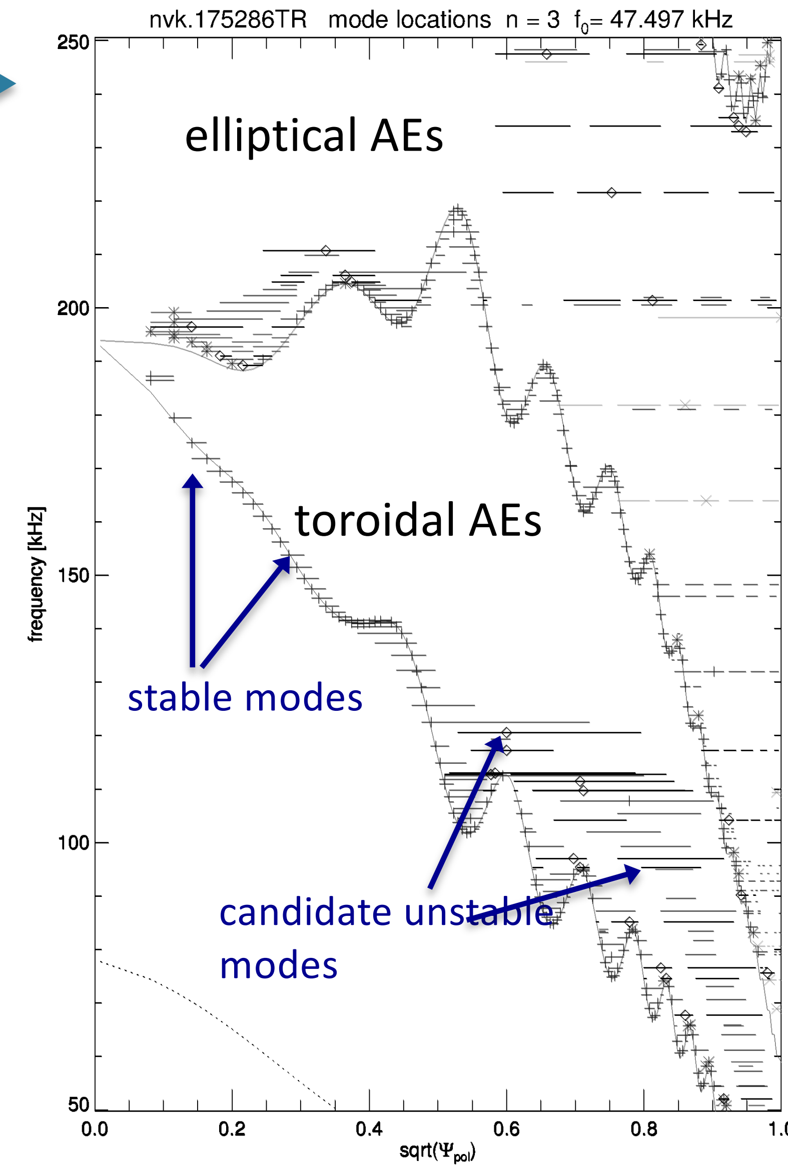




- Measurements deviates from "classical predictions"
- Use neutron rate as global metric of EP confinement

MHD codes (NOVA/NOVA-K) used as starting point: compute mode structure, damping rates

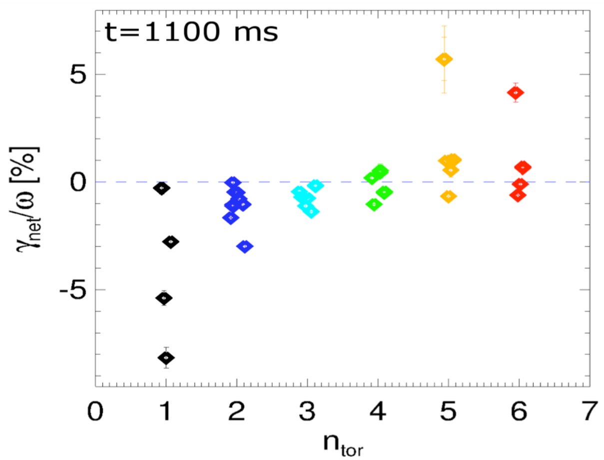


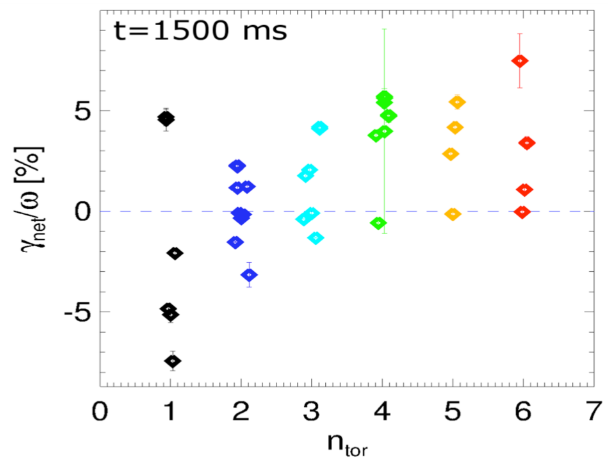


- Ideal MHD provides eigenmodes for each toroidal mode number
- Set of candidate modes selected based on <u>stability</u>

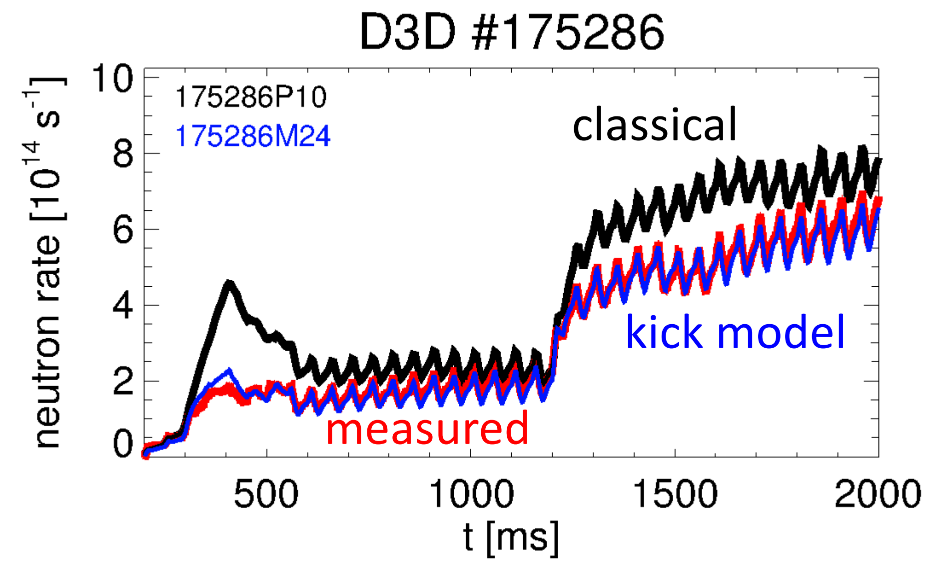
Reduced models (interpretive) reproduce loss of performance observed in experiments

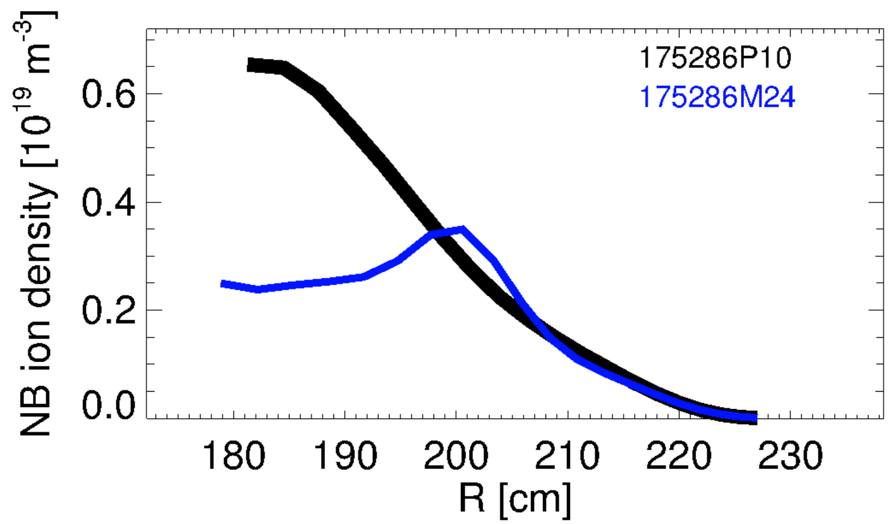
- Interpretive analysis
  - Adjust mode amplitudes to match measured neutron rate
- Linear stability analysis (kick model) indicates large number of unstable AEs





- Confinement degradation results in >50% dilution of EP density





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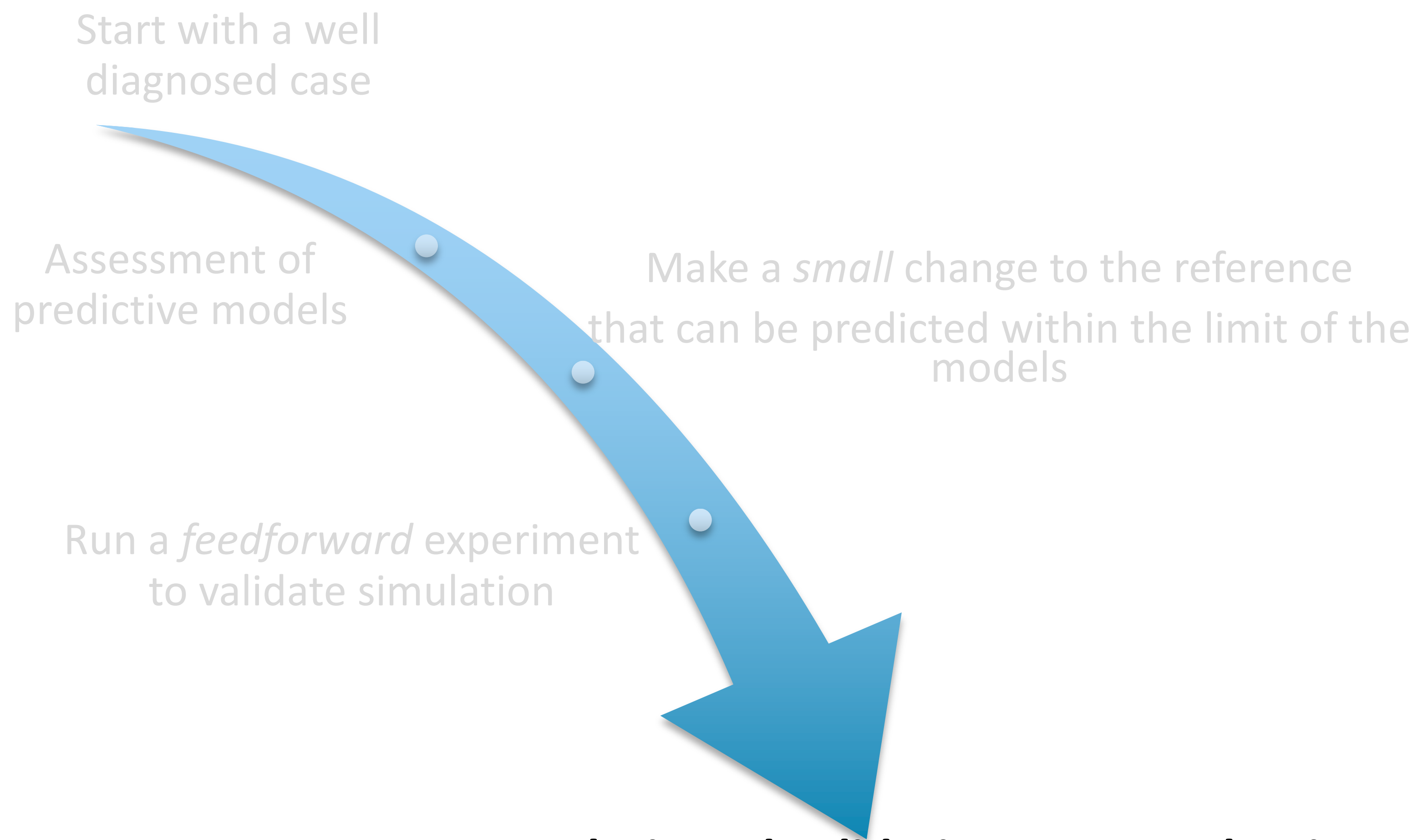


Post-process analysis and validation: assess what is missing, what could have been done better

New experiments should be predicted “from scratch”

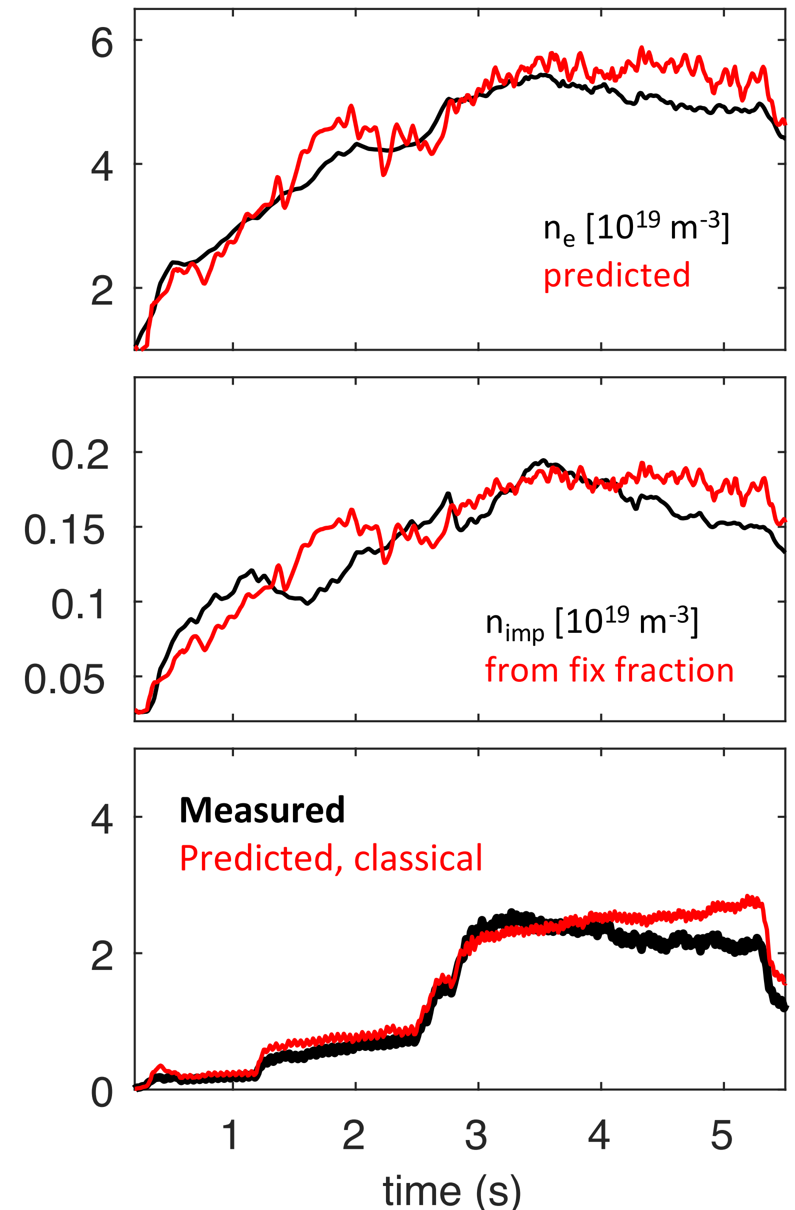
How well can a discharge be reproduced with minimum input?

- Fix n_e, T_e, T_i and v_ϕ at the separatrix
- Predict everything inside
- Set n_C as a fraction of n_e, read radiation from data

Obtain a good agreement with data

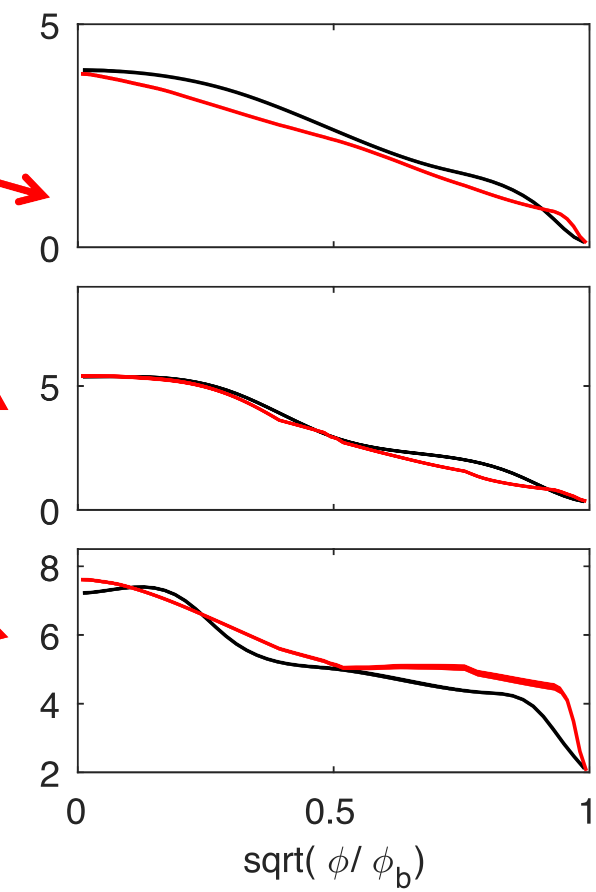
HOWEVER

this is A FORTUITOUS AGREEMENT



Challenge: pedestal predictions limited by available models

- Same height and width for $T_{e,ped}$ and $T_{i,ped}$
- Same width for T_{ped} and n_{ped}
- n_{ped} is an input to pedestal calculations
  - here assume $n_{ped} = 2.0\, n_{sep}$



Opportunities for improvement:

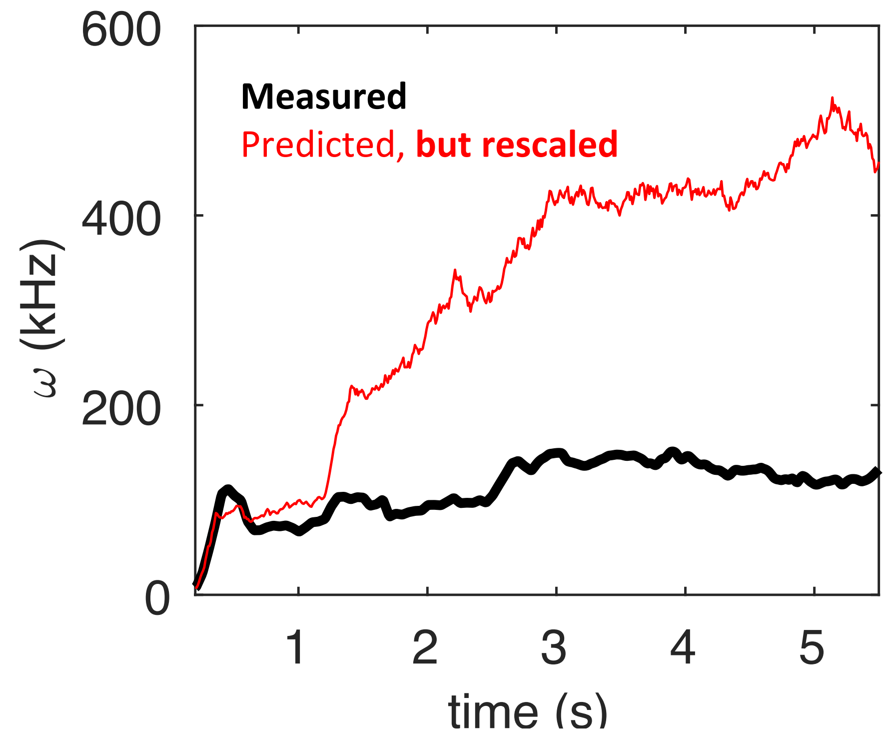
Semi-empirical model for n_{sep}, n_{ped}, $T_{e,ped}$, $T_{i,ped}$ based on large experimental database and neural networks

[*anybody interested, please come and talk to me*]

Looking into details: the rotation profile is over-predicted

How well can a discharge be reproduced with minimum input?

- Fix n_e, T_e, T_i and v_ϕ at the separatrix
- Predict everything inside
- Set n_C as a fraction of n_e, read radiation from data



Opportunities for improvement:
Can a reduced model for rotation help?
[*see work by T. Stolfzuck-Duek and B. Grierson*]

Experimental rotation results in poorer agreement

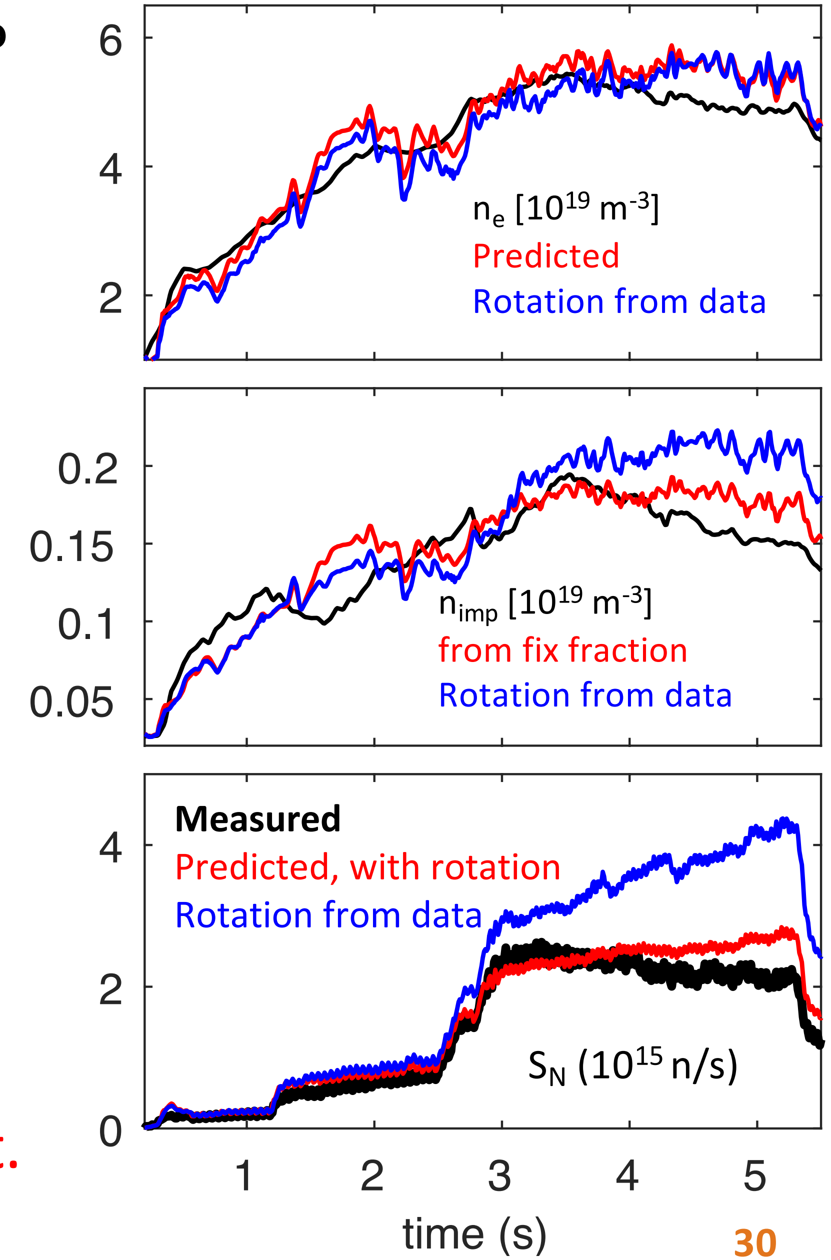
How well can a discharge be reproduced with minimum input?

- Fix n_e, T_e, T_i at the separatrix
- Predict everything inside
- n_C fraction of n_e, read radiation from data
- Read rotation from data

Believe it or not …

The disagreement with the measured neutrons rate and with the measured impurity density increases when the rotation profile is taken from the experiment.

Plasmas are nonlinear systems => better predicting everything and then compare quantities one-to-one to identify problems, than constraining one quantity and let the code adjust the rest.

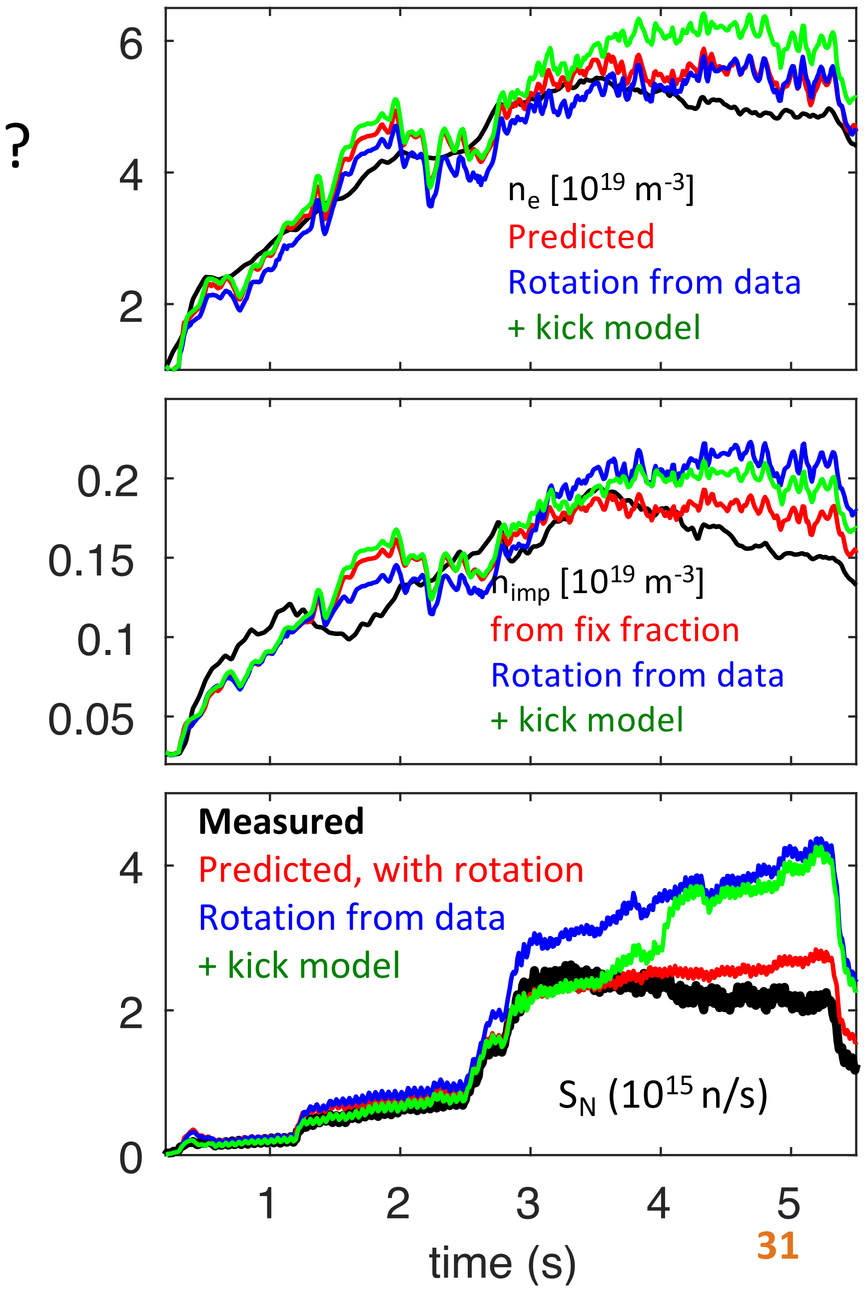


Kick model brings down neutrons, but density is over-predicted

How well can a discharge be reproduced with minimum input?

- Fix n_e, T_e, T_i at the separatrix
- Predict everything inside
- n_C fraction of n_e, read radiation from data
- Read rotation from data
- Apply kick model to NBI calculations

Opportunities for improvement:
Self-consistent modeling of NBI and fast ion transport needed inside TRANSP
[*see work by M. Podesta'*]



My one cent lesson learnt

- We had a successful example of predict-first approach
  - went to the control room with a simulated discharge
  - achieved target using one single shot
  - have been able to design EC trajectories during a failure and even generate a solution in-between shot => not ready yet for applications in the control room.

- Fairly good predictions can be done with some assumptions on the boundary conditions
- However, large uncertainties still remain:
  - radiation is largely over-predicted => cannot use it in electron power balance
  - impurity predictions have large uncertainties => cannot predict n_e, n_{imp} together
  - we have used coil currents from the experiment => in reality we should use gaps
  - more robust boundary conditions for n_e, T_e, T_i, v_ϕ at the separatrix needed

The things that nobody says … (our predictive models suck)

This was a nice exercise, but it is not going to work when the NBI waveform is modified

$\Rightarrow$ Because the beams fuel the plasma

$\Rightarrow$ Because the beams affect rotation

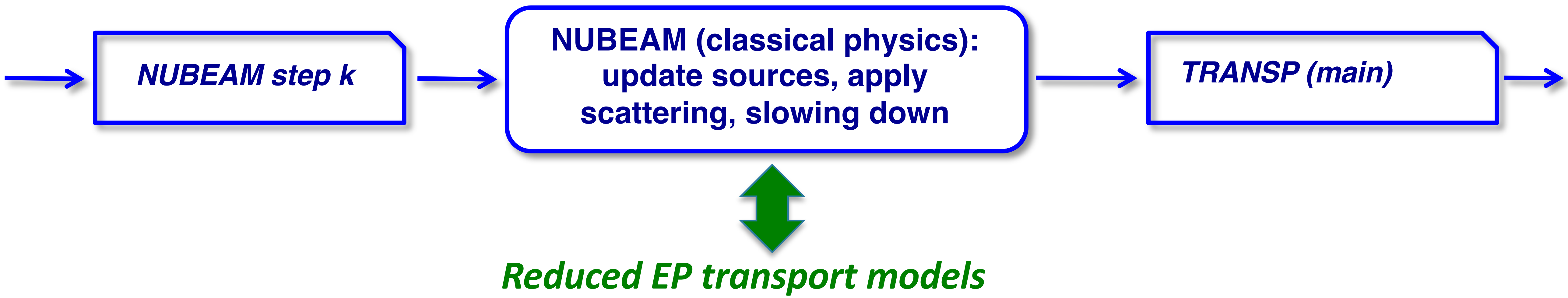
- thermal transport models do not include effect of fast ions among sources
- fast ion transport due to AEs/MHD needs to be included self-consistently
- present models for momentum transport are inadequate
- pedestal models do not separate among channels, do not predict density

$\Rightarrow$ semi-empirical models needed to guide theory development

- Boundary conditions at the separatrix are important => need reduced core-edge model
- with 2D neutral model
- self-consistent impurity transport with core+edge radiation
- Need more robust free-boundary equilibrium solver

Reduced models are used to include EP transport by instabilities in TRANSP

- A common framework has been developed and tested in FY18 to manage both kick and RBQ-1D models in TRANSP
  - Models compute phase-space resolved "transport probability" $p(\Delta E, \Delta P_{\zeta} | E, P_{\zeta}, \mu)$ associated with each mode
  - Probabilities are used in Monte Carlo NUBEAM module of TRANSP to compute fast ion evolution



Two approaches explored in FY18: numerical vs theory-based (quasi-linear)

- Models use mode structure, damping rate from MHD codes such as NOVA-K
- Difference: how is $p(\Delta E,\Delta P_\zeta\,|\,E,P_\zeta,\mu)$ inferred?
  - "Kick model": compute *p* numerically using particle-following code ORBIT
    - Retain possibility of sub/super diffusive or convective transport (non-gaussian *p*)
    - Include kicks in both energy and canonical momentum; μ conserved
  - "Resonance broadened Quasi-linear model" RBQ-1D: use improved quasi-linear theory to compute *p*
    - Diffusive approximation -> gaussian $p(\Delta P_\zeta)$; assume *E* and μ are conserved
    - More computationally efficient than kick model approach

- *Improve ad-hoc diffusive models previously available in TRANSP*
  - Physic based; enable both *interpretive* and *predictive* TRANSP simulations
    - Mode saturation levels inferred by balancing drive vs. damping

Approach: proceed from *interpretive* to *predictive* simulations, validate models

Let's first agree on the definitions…

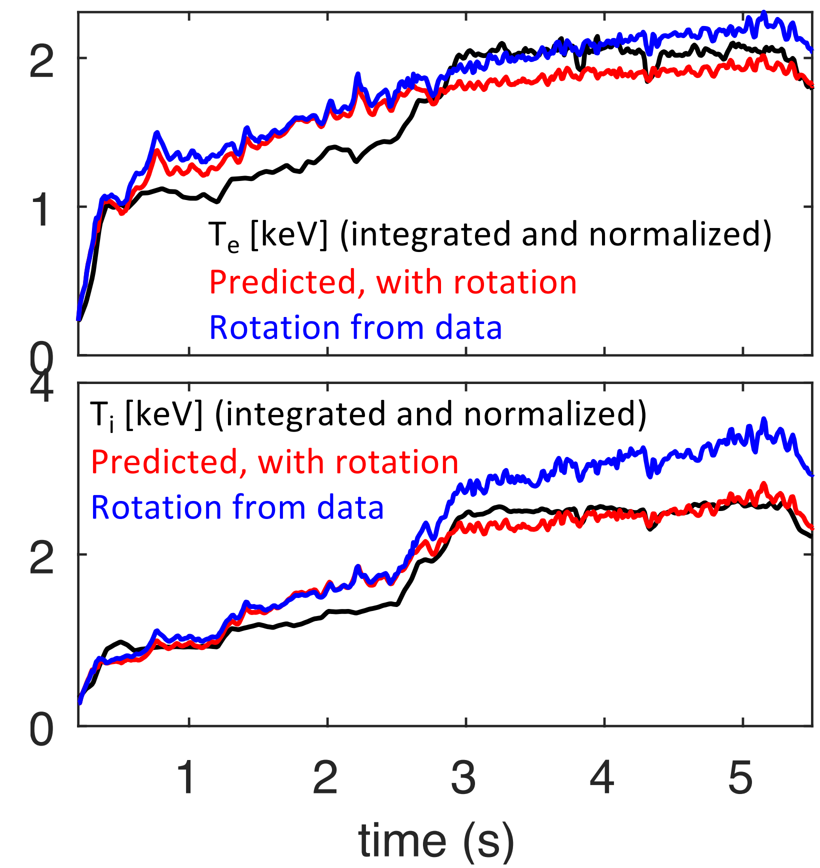
- Interpretive simulations:
  - Constrain simulations with available experimental data
  - Validate main physics assumptions of the models
  - Benchmark among models
  - Validate models against additional experimental data
- Predictive simulations:
  - Remove constraints
  - Increase number of parameters to be determined ("predicted") self-consistently by the models
  - Assess predictive capability
  - Identify missing physics

Metrics for success: use neutron rate as global metric, available EP diagnostics data for more detailed validation

- Historical approach for TRANSP simulations:
  - Introduce "anomalous fast ion diffusivity" when instabilities are present
  - Adjust diffusivity to match measured neutrons -> good!

- Will use the same approach for a first estimate of "success"
  - Allows quick experiment/modeling comparison
  - OK to infer overall degradation in plasma performance

- Will turn to more detailed measurements for validation
  - Compare modeling results to phase-space resolved EP data (FIDA, NPA)


2
1
0
T_e [keV] (integrated and normalized)
Predicted, with rotation
Rotation from data
4
2
0
T_i [keV] (integrated and normalized)
Predicted, with rotation
Rotation from data
1
2
3
4
5
time (s)