PPPL PRINCETON PLASMA PHYSICS LABORATORY

Integrated Operation Scenarios

Francesca M. Poli

July 28th, 2022

About myself:

a tokamak modeler, with a background in diagnostics and operation

The goal of this lecture

- What questions you should ask yourself
- How modeling can guide experiments
- …
- There are no equations in this lecture

The mindset of integrated operation scenario modeling

- You are modeling a plasma that must be controllable and operate safely, from start-up to termination.
- You need to think at the interface between physics and engineering
- The modeling needs to support experiments
  - by providing a combination of models with different physics hierarchy
  - by providing a realistic representation of the systems, including dynamics
  - by mimicking the plasma response to actuators, as seen from diagnostics

⇒ Focus on the big picture, not on details

⇒ Look at qualitative trends first, details later

- Introduction on scenario modeling
- Exercise: developing a feed-forward discharge at high q_{min}
  - Experimental validation
  - When things go wrong in the control room
- Example #1: modeling NTM control on ITER
- Example #2: modeling the ITER plasma ramp-down

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but we do not need to include everything to design a scenario …

ω_{EC}^{-1} ω_{LH}^{-1} ω_{IC}^{-1} τ_A τ_E τ_R τ_D

time (s): 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4}

space (m): 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2}

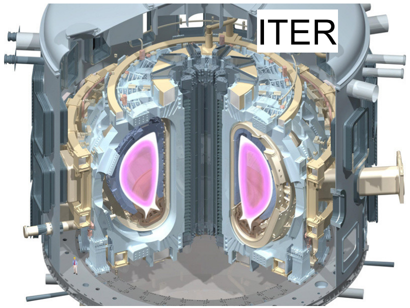
Wave propagation

Macroscopic stability

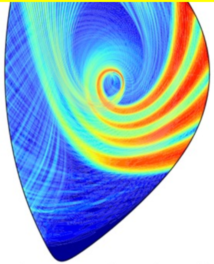
Transport

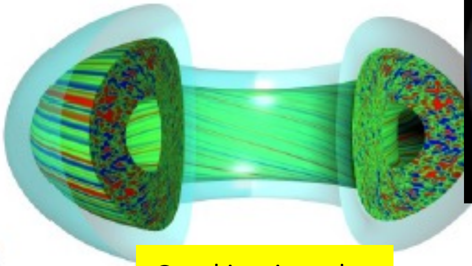
current diffusion

Plasma turbulence



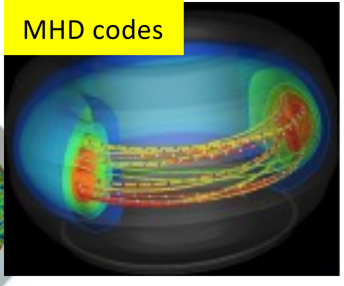
Full wave solvers
<1M CPU Hours



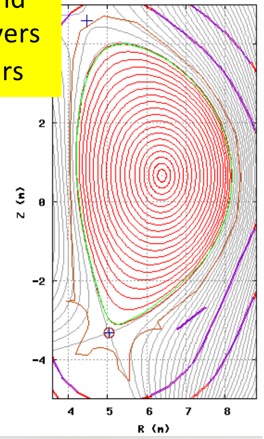


Gyrokinetic codes
<10M CPU hours

MHD codes



Equilibrium and
transport solvers
$<10^2$ CPU hours

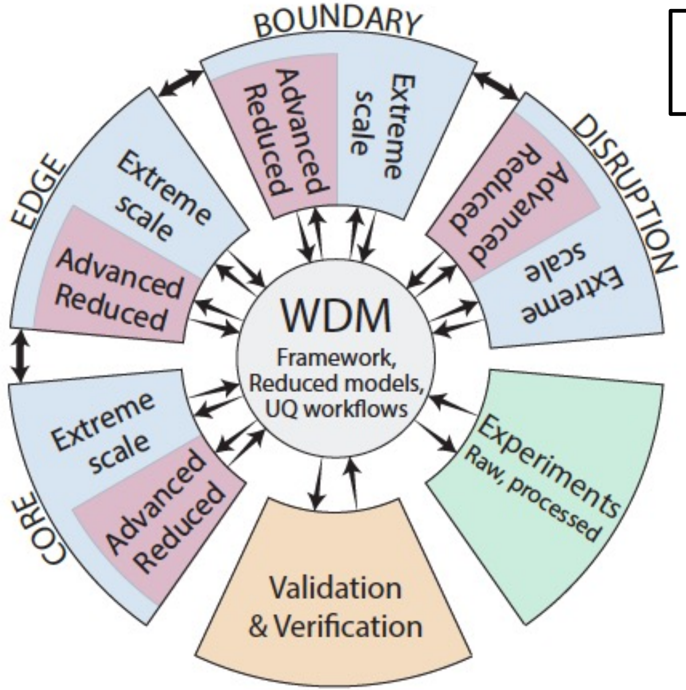


The models/data should be accessible within a framework

Extreme scale
First principle (Vlasov eq.)
Gyrokinetic codes
Full wave solvers

verification

Advanced reduced
Fluid codes
Reduced full wave solvers



uncertainty quantification
models and experiments

Validation
Experiments

Reduced
Ray tracing codes
Neural networks

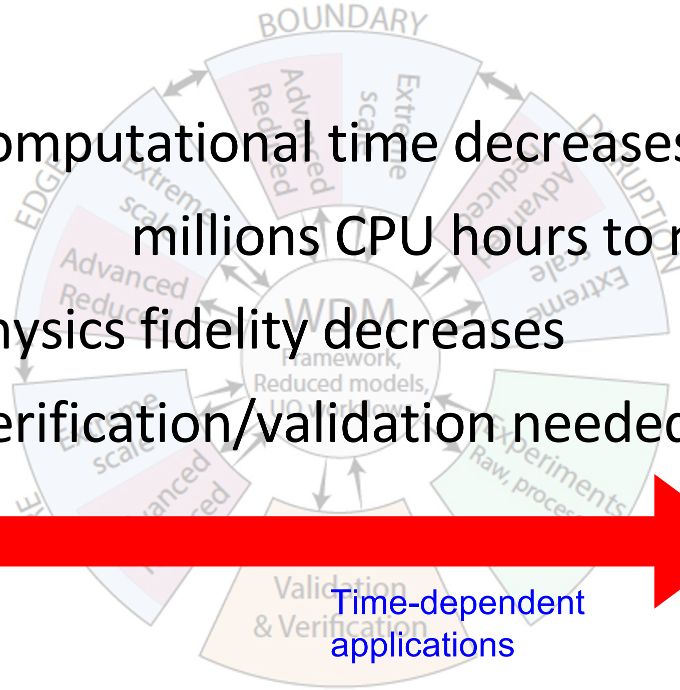
[FES *Integrated Modeling Workshop Report, 2015*]

So that you can choose according to the target

Extreme scale
First principle (Vlasov eq.)
Gyrokinetic codes
Full wave solvers

Time-slice applications

Advanced reduced
Fluid codes
Reduced full wave solvers



Computational time decreases:

millions CPU hours to minutes/seconds

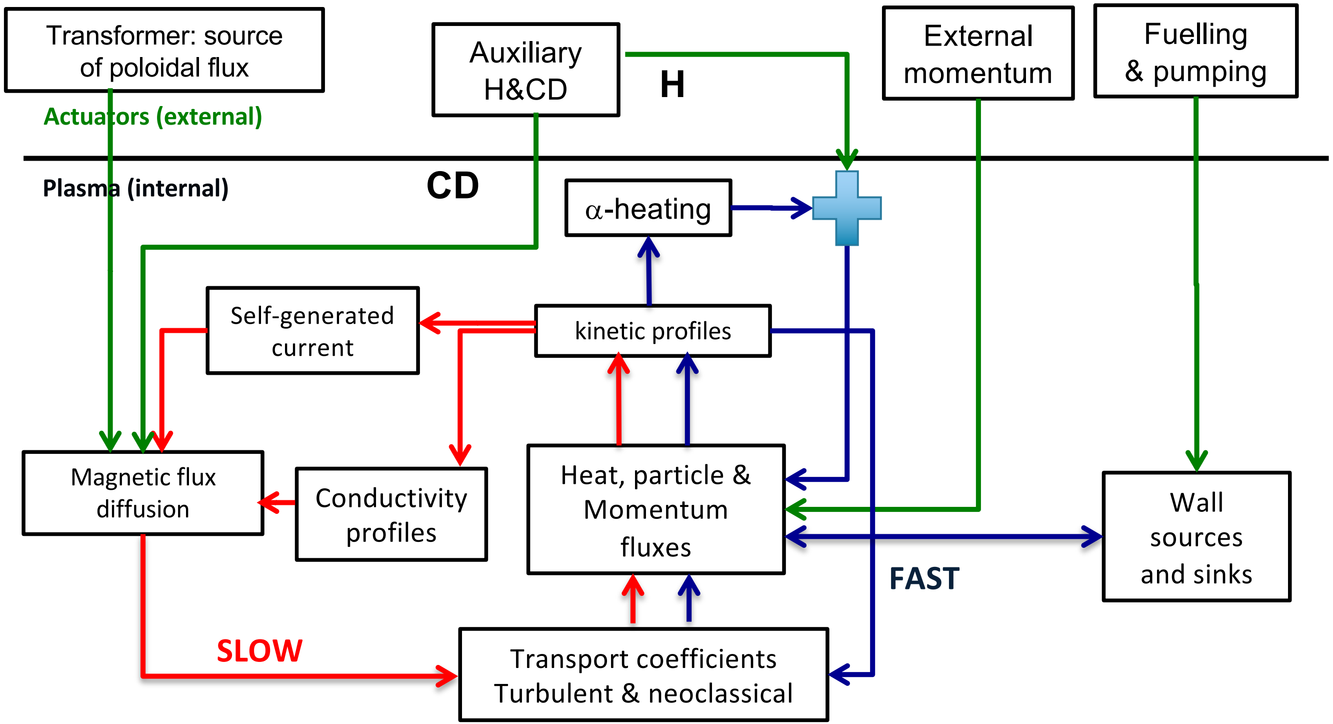
Physics fidelity decreases

Verification/validation needed at each step

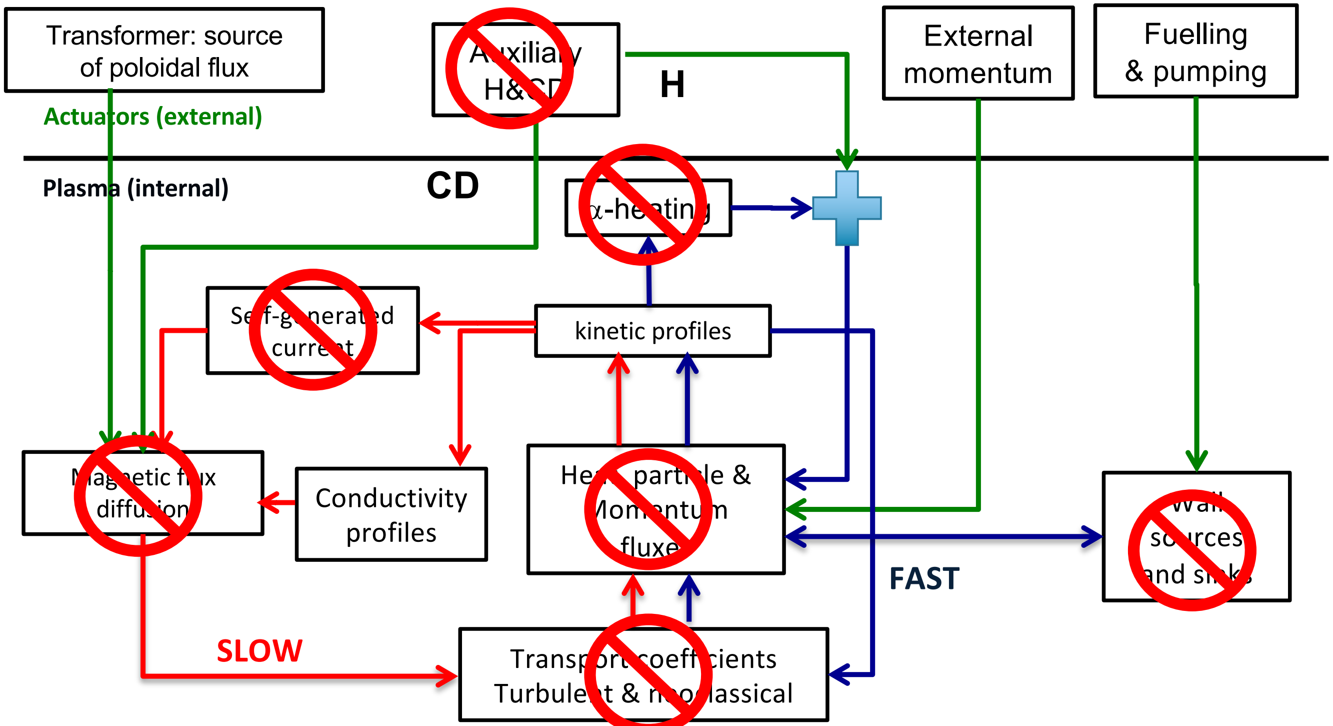
Time-dependent applications

Reduced
Ray tracing codes
Neural networks

This is a highly nonlinear system



But also a highly <u>incomplete</u> nonlinear system



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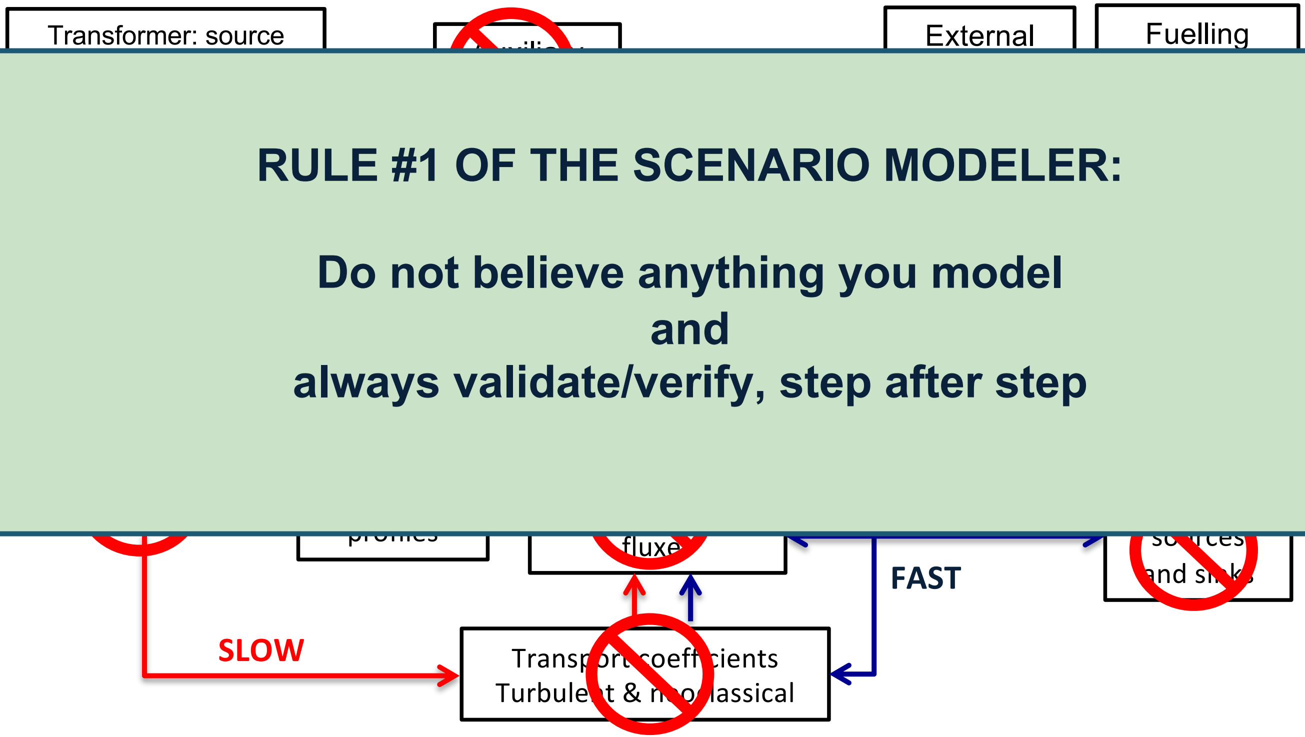
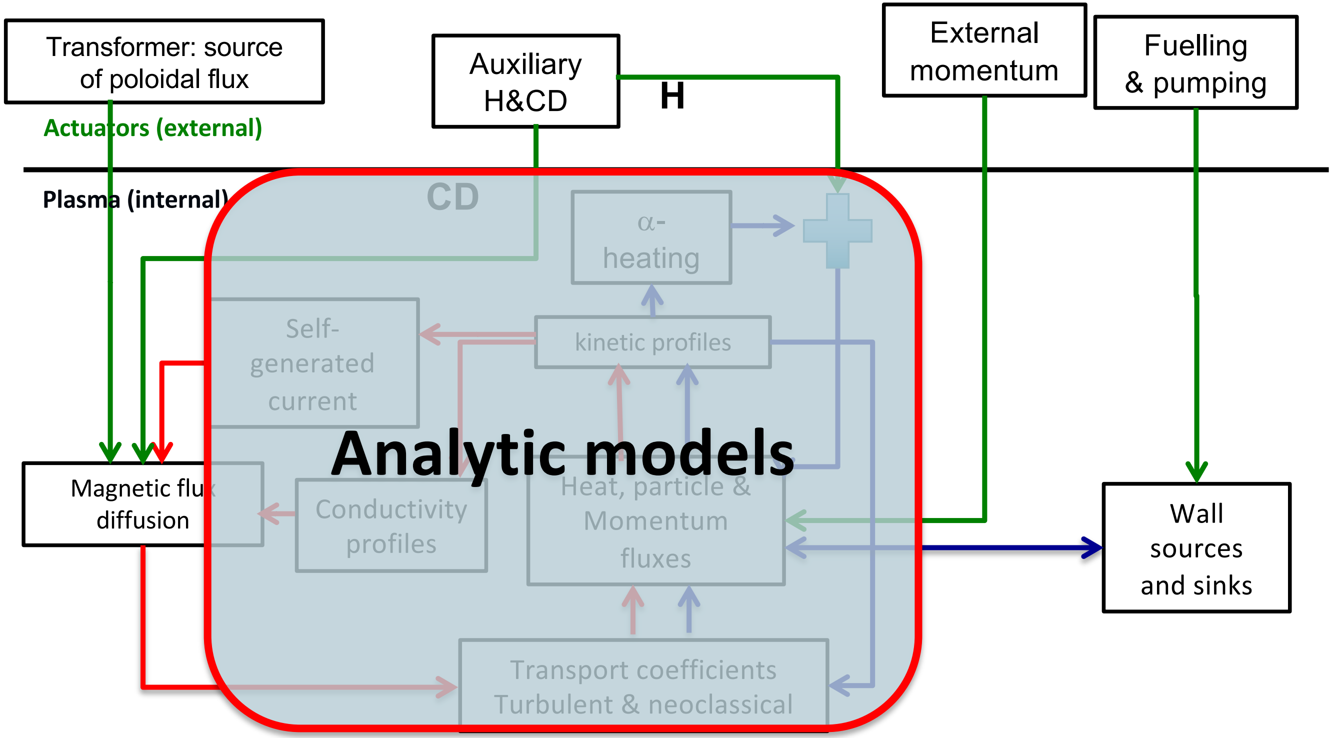


RULE #1 OF THE SCENARIO MODELER:

Do not believe anything you model
and
always validate/verify, step after step

The truth is … you do not need high fidelity physics to model a plasma that satisfies coil constrains and VS



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Develop strategy in support of EP experiments

Reference discharge with feedback on β_N

The problem:

⇒ q profile relaxes to monotonic in the stationary phase

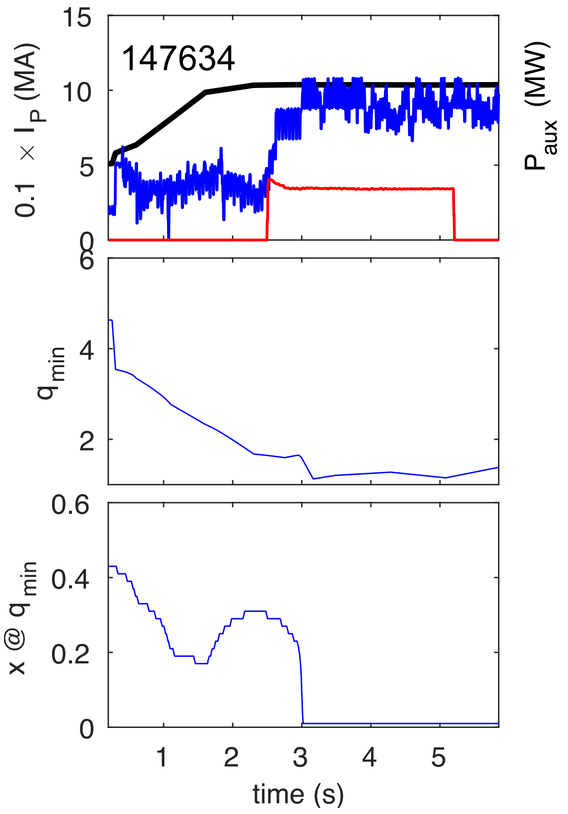
⇒ Develops MHD

The target:

⇒ Need to sustain flat/weak RS q profile

⇒ and q_{min} at larger radius

⇒ No MHD

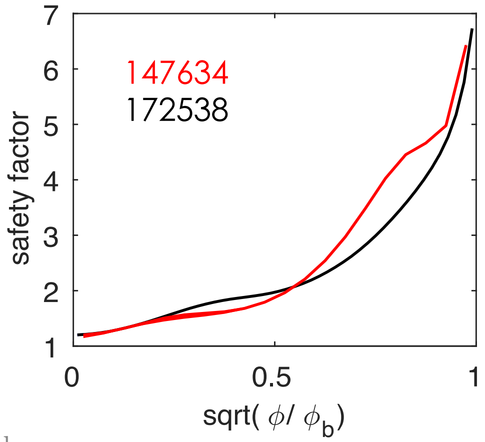


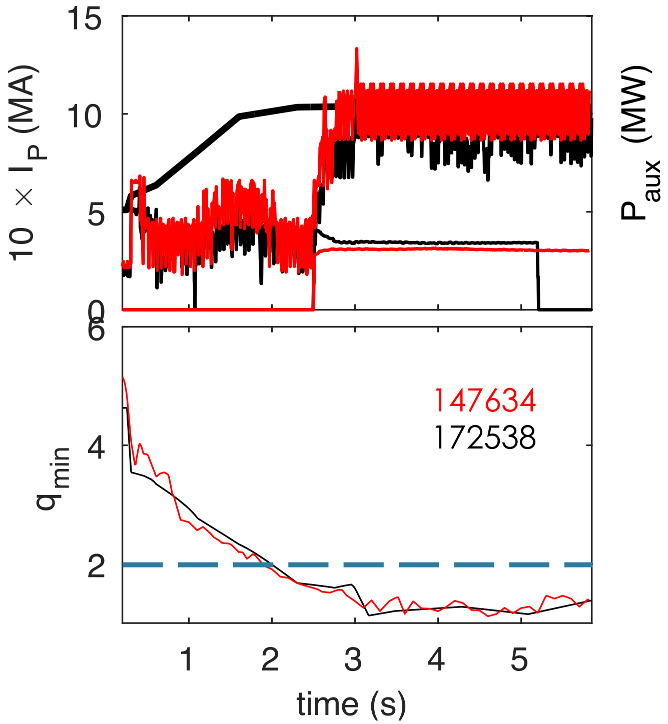
Other discharges display the same behavior

The problem:

⇒ q profile relaxes to monotonic in the stationary phase

⇒ Develops MHD





How would you achieve the target?

- Solution 1
- Solution 2
- Solution 3
- Solution 4

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How should you approach a problem like this?

Start with a well diagnosed case

Assess your models

Make a *small* change to the reference that can be predicted with your models

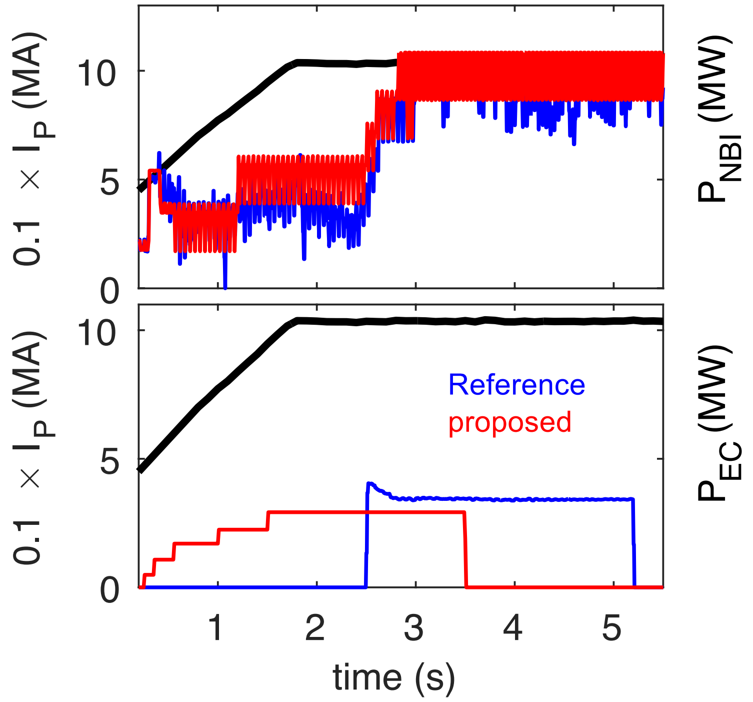
Run a *feedforward* experiment to validate your simulation

Validate models against the new experiment.

Assess what is missing, what could have been done better

Our approach: use EC to change resistivity and current diffusion during the ramp-up phase

- Prescribe density
- Choose NBI waveform such that
  - Total power comparable to original
  - Different on-axis/off-axis NB mix
  - Ensure diagnostics NBI are setup



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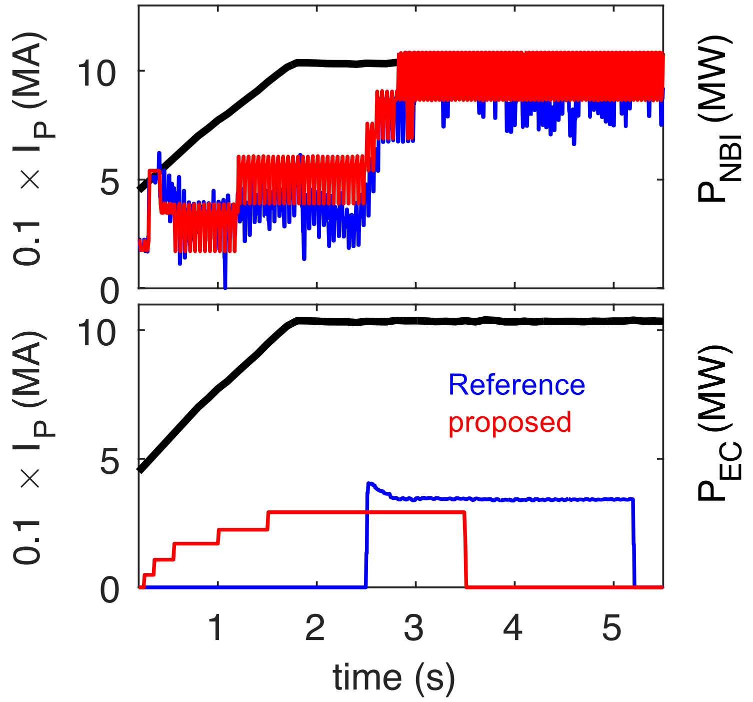
⇒ Need to ensure that fueling is as close as possible to the original discharge



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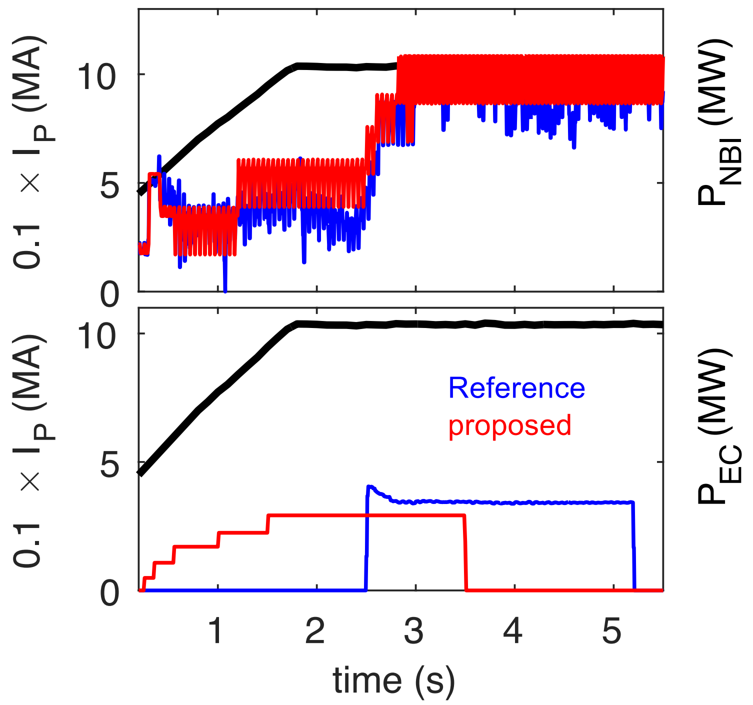
⇒ Need to ensure that fueling is as close as possible to the original discharge

- EC heating and current drive critical
  - Predict electron temperature
  - Evolve poloidal current diffusion



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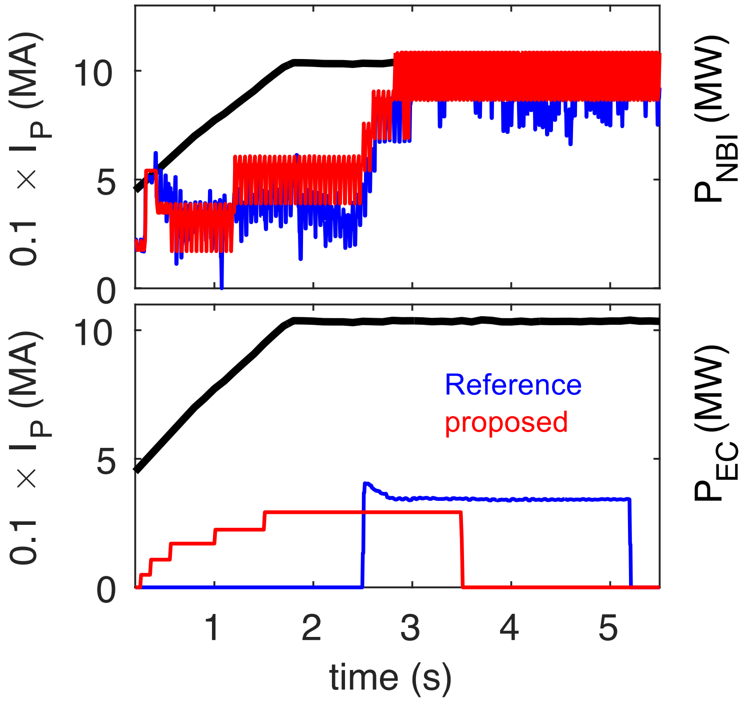
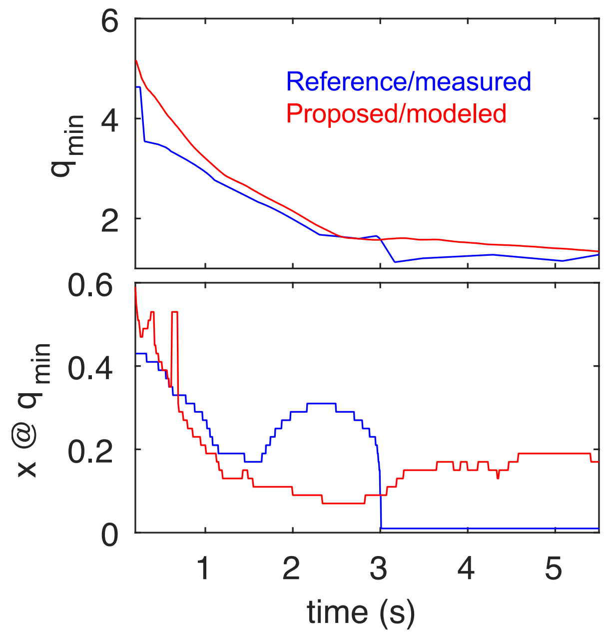
⇒ Need to ensure that fueling is as close as possible to the original discharge

- EC heating and current drive critical
  - Predict electron temperature
  - Evolve poloidal current diffusion
- H-mode => need to model pedestal
  - Models not valid in ramp-up
  - Use reference discharges to rescale

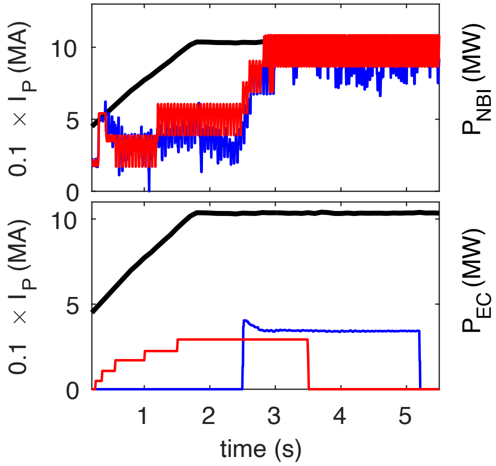


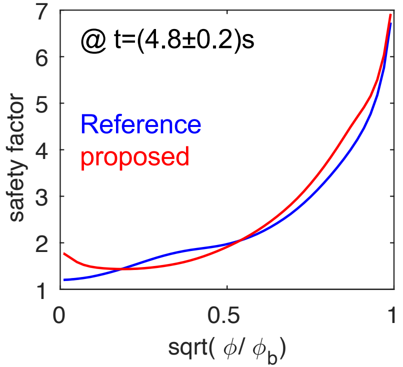
TRANSP simulations indicate these settings are adequate to achieve target



EC slows down q_{min} drop

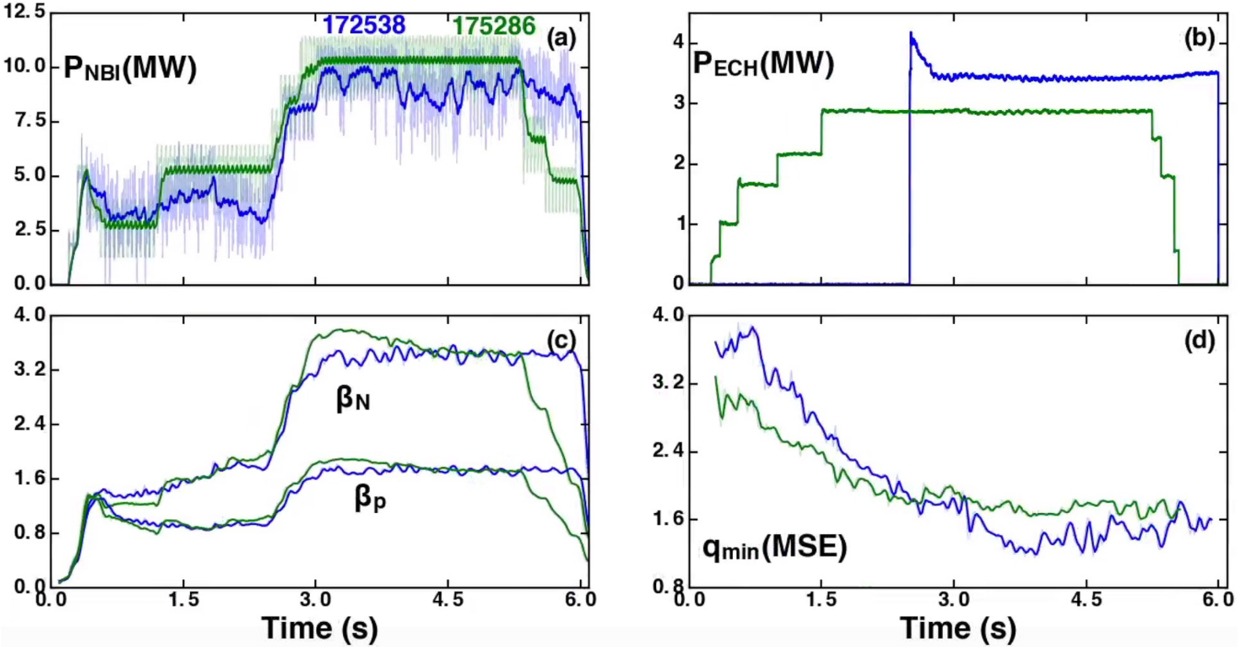
NBI mix tailors q profile





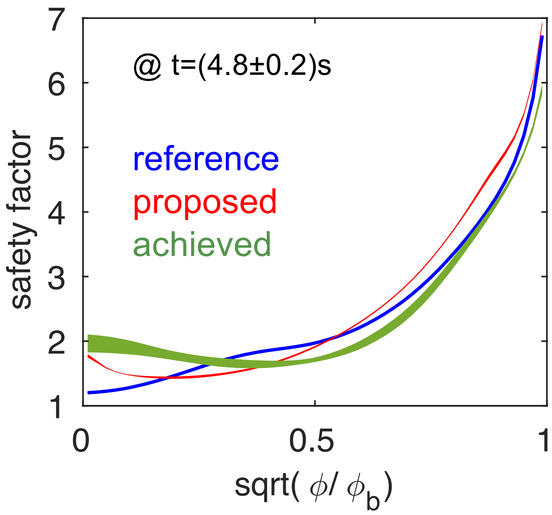
The real experiment reproduced the expected behaviour

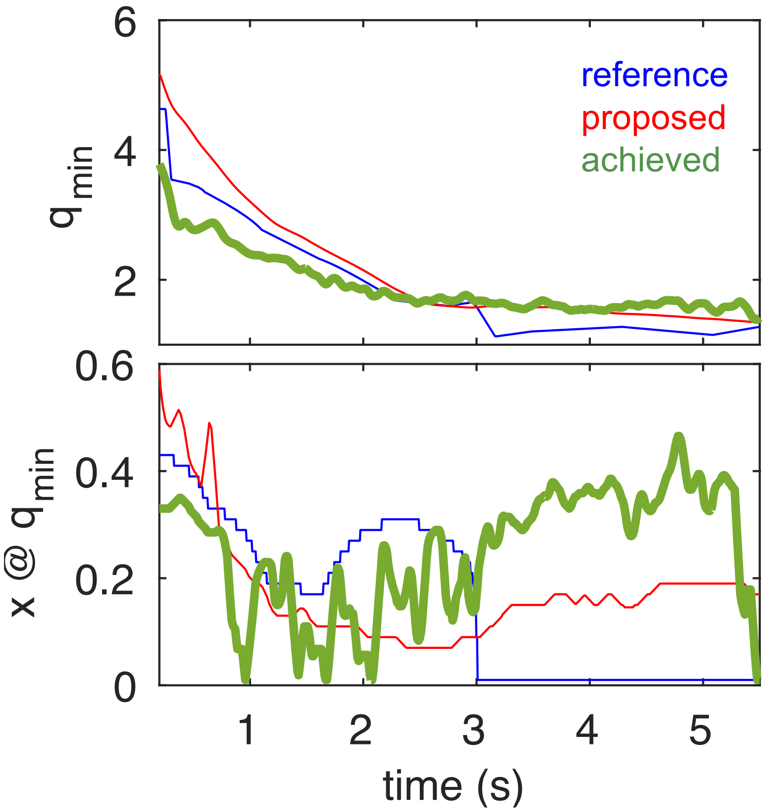
- Feed-forward NBI and EC predicted first with TRANSP (no feedback)
- Improved access to high beta with little MHD



The experiment was better than the simulation

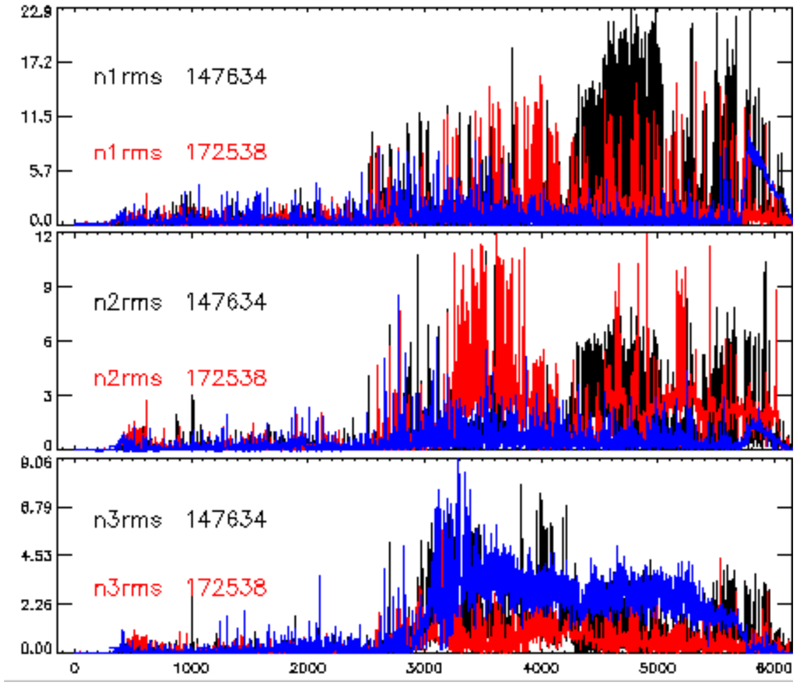
- Early EC delays current penetration
- Off-axis NBI does the rest





MHD activity with n=1 and n=2 was reduced

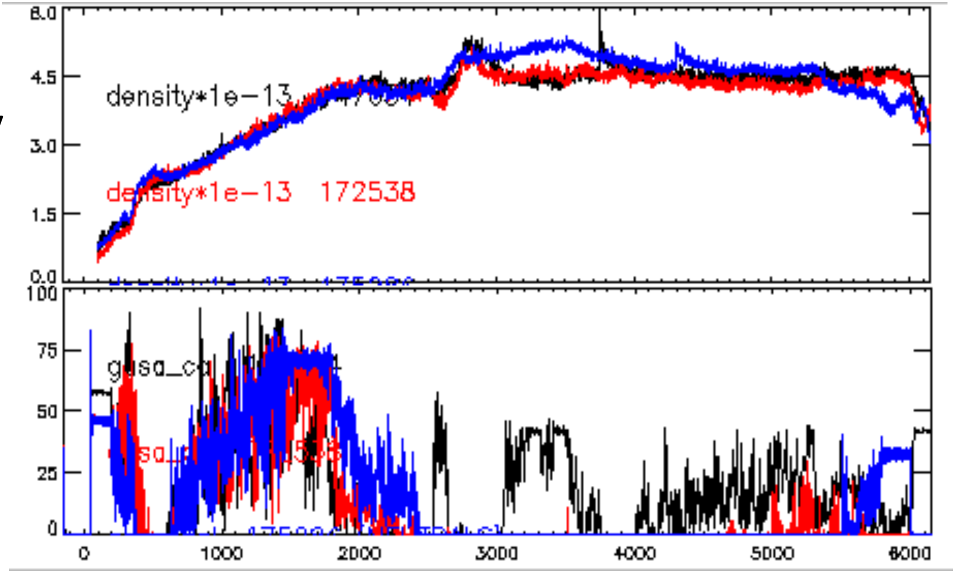
MHD activity with n=3 not so much



The importance of making small steps

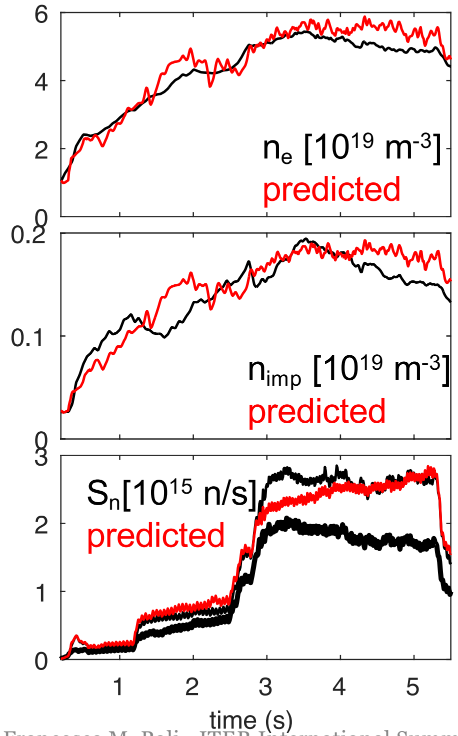
- We prescribed the density
- We choose a NBI waveform very close to the reference discharge
- Because we believe the NB model, but we don't believe the gas fueling model

⇒ Gas feedback puff is very close to the reference.



Always validate your model a posteriori

Some validation done a posteriori … try to predict also plasma density



$\Rightarrow$ Good agreement even w/o density feedback

NBI fueling dominates

$\Rightarrow$ Good agreement with incomplete impurity transport

only one impurity

$\Rightarrow$ Not good agreement with measured neutron rate

no model for anomalous fast ion transport

Hardware failures happen …

- The discharge 175286 was used as a reference for an EP session
  - Adapted the same early-EC approach to design new references at different B that sustains q_{min}
- The day before the session two (high power) gyrotrons failed

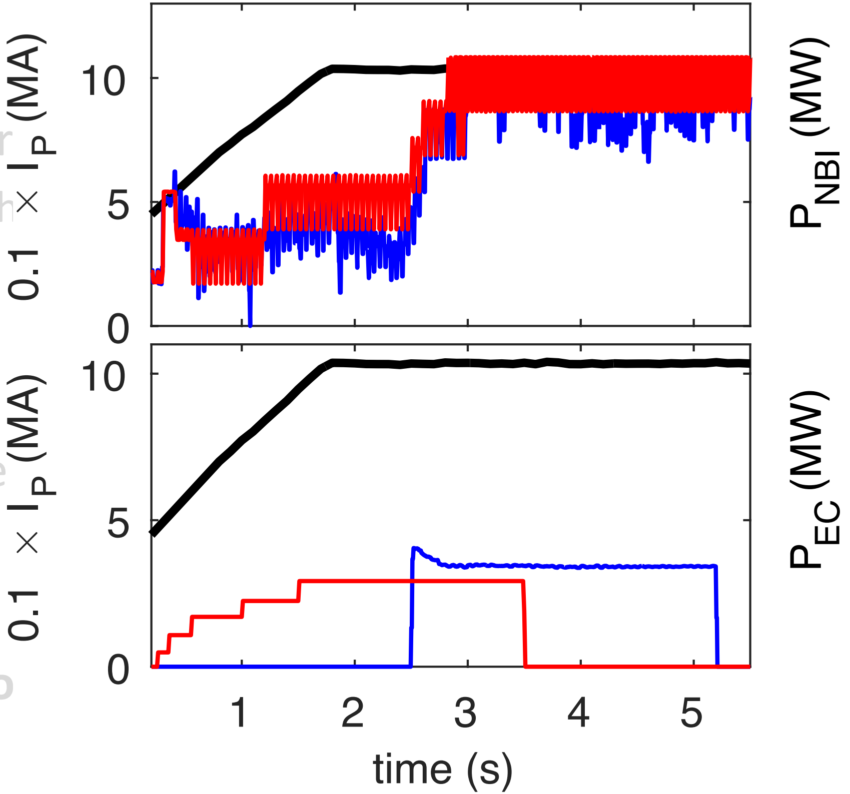
⇒ EC power staggering was critical to achieve/sustain high q_{min}

What would have you done if you were at my place?

Hardware failures happen …

- The discharge 175286 was used as a r
  - Adapted the same early-EC approach that sustains q_{min}
- The day before the session two (high

⇒ EC was critical to sustain q during the



What would have you done if yo

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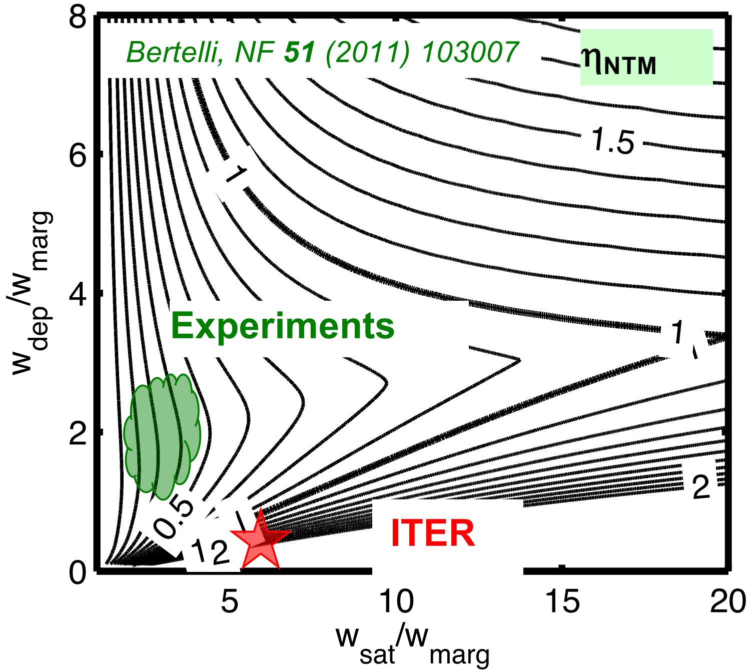
Extrapolation to ITER usually based on asymptotic solution

$$\frac{dw}{dt} = 1.22\frac{\eta}{\mu_0}\left[\Delta'_{m,n}(w) + \Delta'_{NC}(w) + \Delta'_{pol}(w) + \Delta'_{GGJ}(w)\right]$$ Modified Rutherford Eq.

+ $\Delta`_{CD}(w)=f(J_{CD},w_{EC})$



$J_{CD} \sim \eta_{NTM}\, J_{BS}$

η_{NTM} is a function of

w_{sat}/w_{marg} and w_{dep}/w_{marg}

$\Rightarrow$ the wider the EC deposition the better

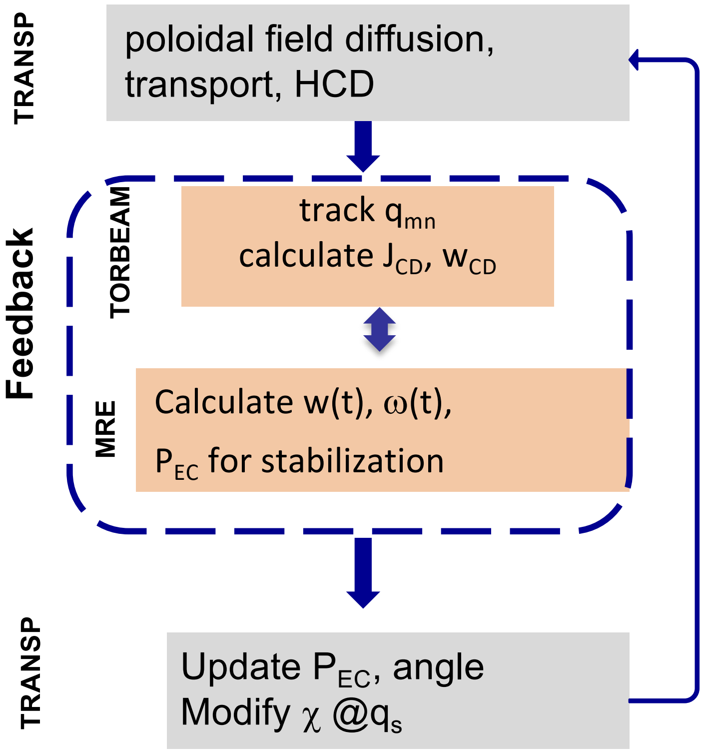
Asymptotic solutions don't account for dynamic response

- Effects of misalignment (systematic or transient)
- Threshold effects on detection of island (magnetics or ECE)
- Broadening of EC deposition (turbulence, pellet scattering, beam grouping)
- Plasma profile responses to EC heating and current drive
- Local modifications of current and safety factor profile (tearing effects)
- Hardware response (switching mechanisms, steering speed, etc)

Simulated NTM control should take all these effects into account

First step towards development of real (PCS) control algorithms

Implemented feedback loop in TRANSP to play with



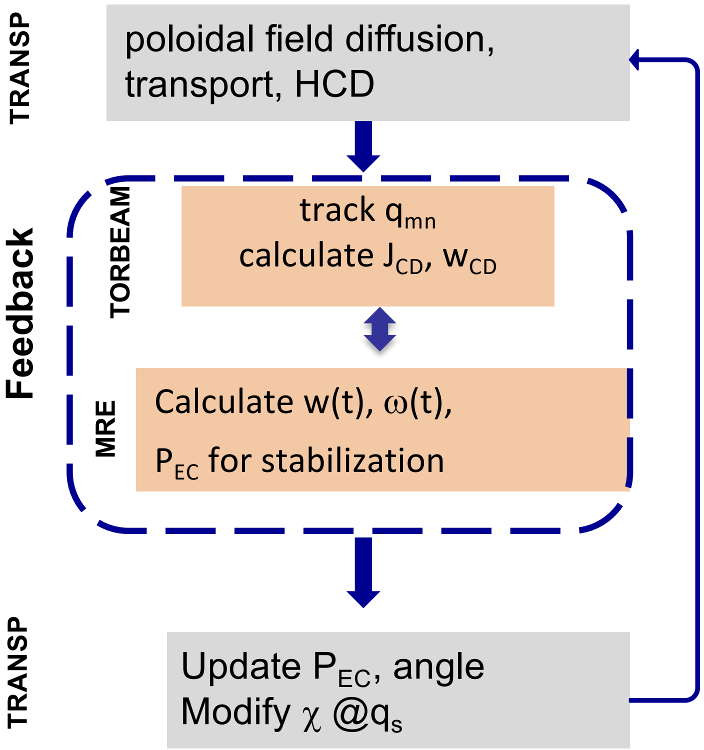
$\Delta`_{mn}$ calculated from integration of perturbed helical flux

$$\left[\frac{\partial^2}{\partial r^2} + \frac{1}{r}\frac{\partial}{\partial r} - \frac{m^2}{r^2} - \left(\frac{\partial J_0}{\partial \psi_0}\right)\right]\psi_{m,n} = 0$$

$$\Delta'_{m,n} = \left.\frac{\frac{\partial \psi^-_{m,n}}{\partial r} - \frac{\partial \psi^+_{m,n}}{\partial r}}{\psi_{m,n}}\right|_{r=r_s}$$

$\Delta`_{mn}$ responds to local variations of equilibrium and current

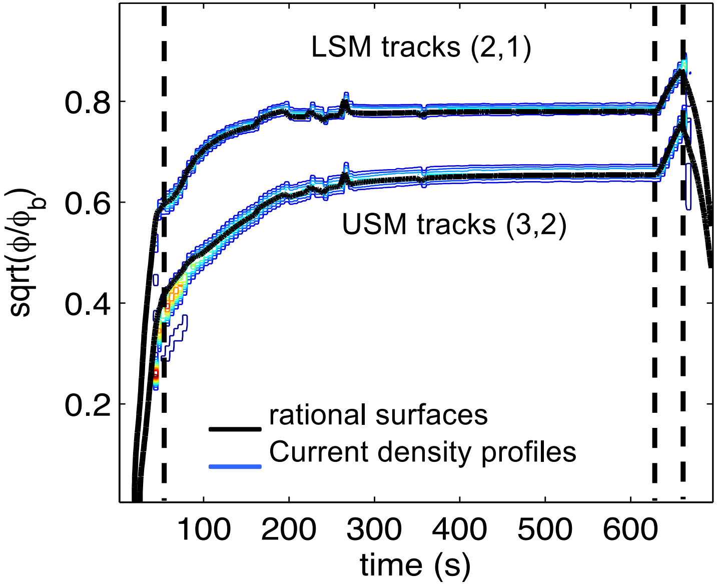
Effect of EC alignment dynamically taken into account



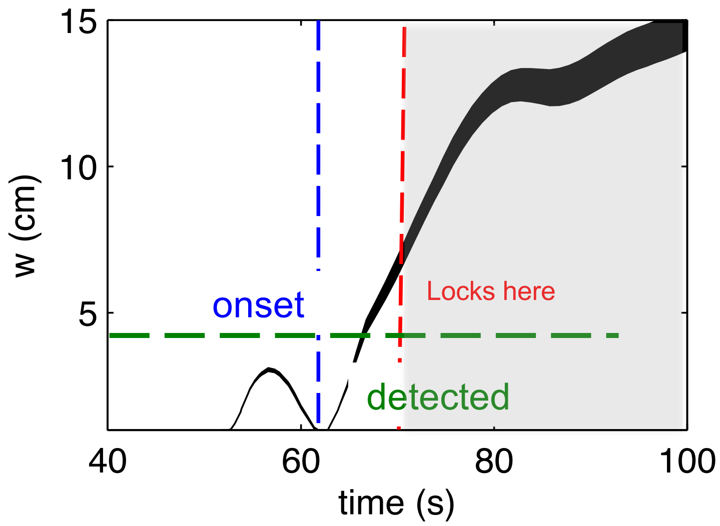
$$\Delta'_{CD} \propto \frac{J_{CD,max}}{\langle J_\phi \rangle\, s} F(\tilde{w}) G(\tilde{w}, x_{dep})$$

EC deposition profile

Alignment



Not enough time between detection of (2,1) and locking



Calibration simulation:
evolution of (2,1)-NTM in ITER ELMy H-mode discharge, no ECCD

TARGET:

prevent the (2,1) island

from growing larger than 6 cm

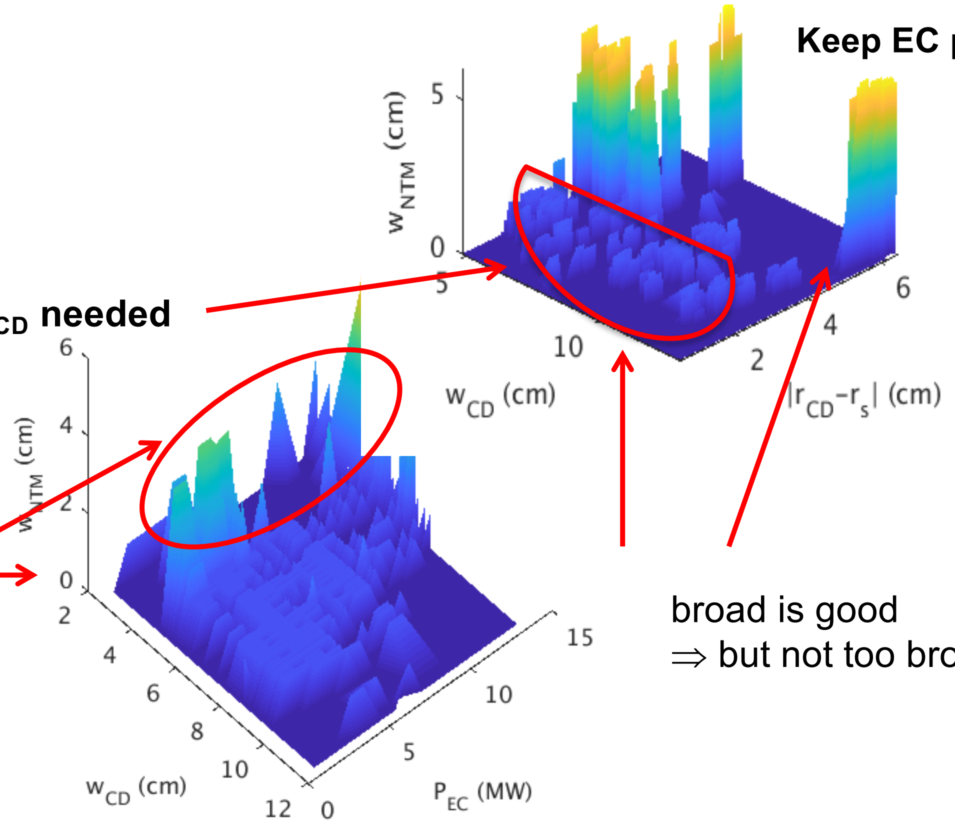
- Run time-dependent simulations, from ramp-up to ramp-down
- Track resonant surfaces => allow for misalignment up to 3 cm
- Observables: size of island (from ECE) and $\delta B/B$ (from magnetics) => allow for S/N
- Include broadening of ECCD (e.g. scattering due to fluctuations)
- Include hardware response (e.g. 3s delay when switching between transmission lines)

Pre-emptive control and really good tracking needed

Keep EC power fixed

Alignment within $0.5w_{CD}$ needed

too narrow leads to locking



broad is good
⇒ but not too broad

Keep $|r_{CD}-r_S|$=2.5 cm

The fine boundary between control scenarios and physics scenarios

- These are NOT simulations of control
- These are still physics scenarios, but they aim at modeling constrains on control.
- The target is to use a workflow over and over - as physics models improve - to identify critical phases and to inform control engineers on requirements for actuator sharing.

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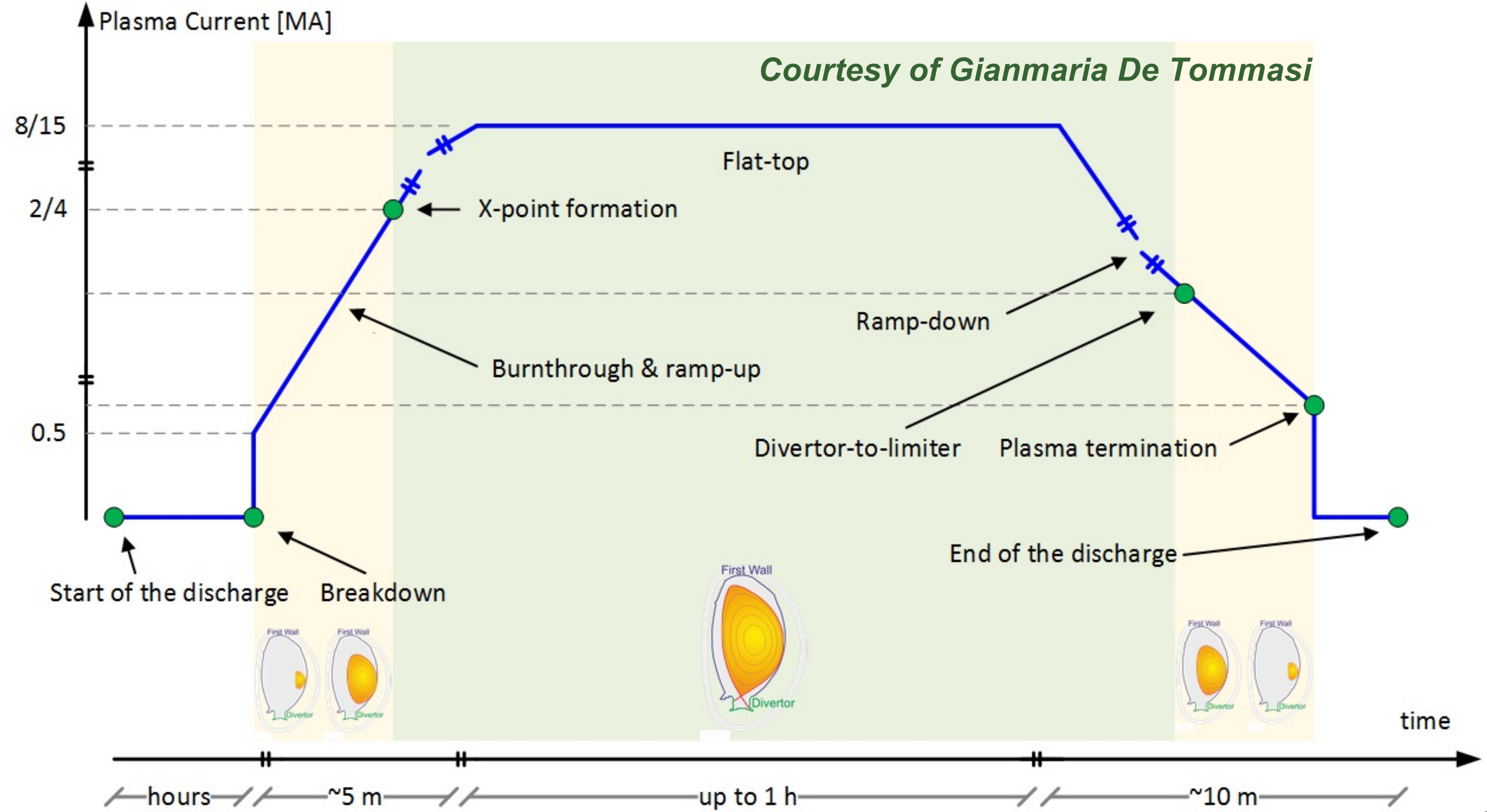
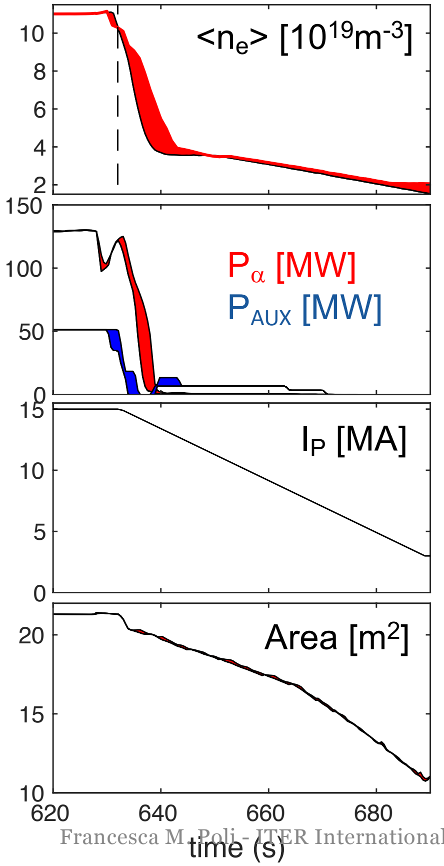

Plasma Current [MA]
Courtesy of Gianmaria De Tommasi
8/15
2/4
0.5
Flat-top
X-point formation
Ramp-down
Burnthrough & ramp-up
Divertor-to-limiter
Plasma termination
End of the discharge
Start of the discharge
Breakdown
First Wall
Divertor
time
hours
~5 m
up to 1 h
~10 m

There are only 4 actuators and many open questions



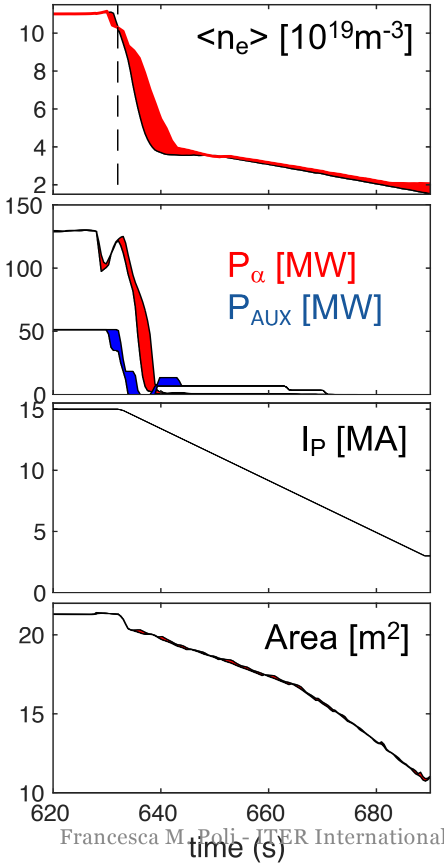
Shut-down fueling — Can the density decay be controlled?

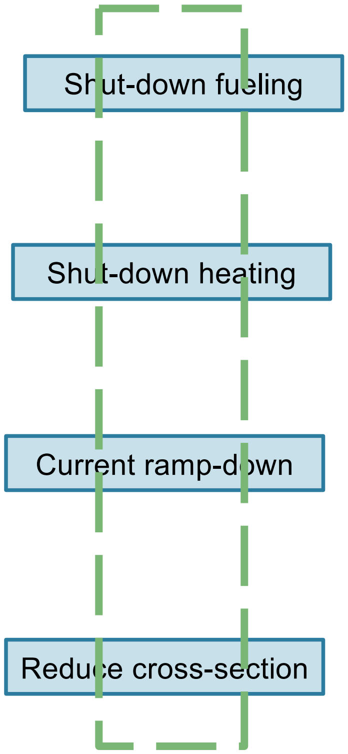
Shut-down heating — There are alphas on ITER, not enough experience

Current ramp-down — optimal value in ITER baseline <0.21MA/s

Reduce cross-section — to avoid loss of Vertical Stability when li increases

There are only 4 actuators and many open questions





Open area of research,

both for modeling and control

We have achieved a mature level of understanding both in modeling and control

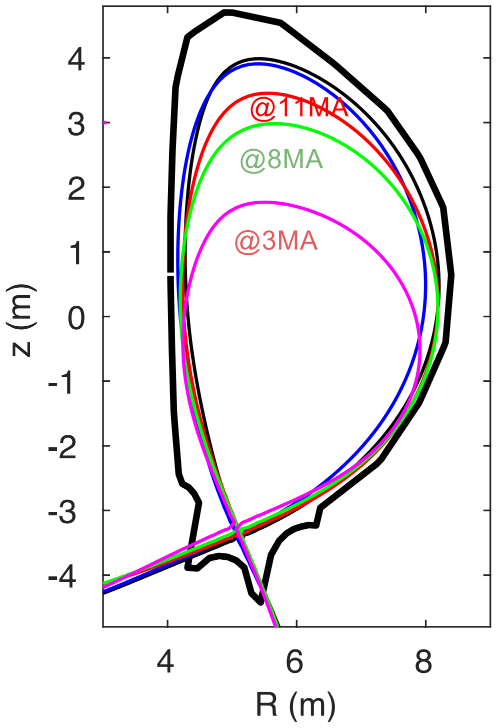
When plasma shrinks, combined core heating and MHD control might be challenging

⇒ Poor coupling of Ion Cyclotron waves (outer gap)

⇒ Only EC can follow the plasma down (steering)

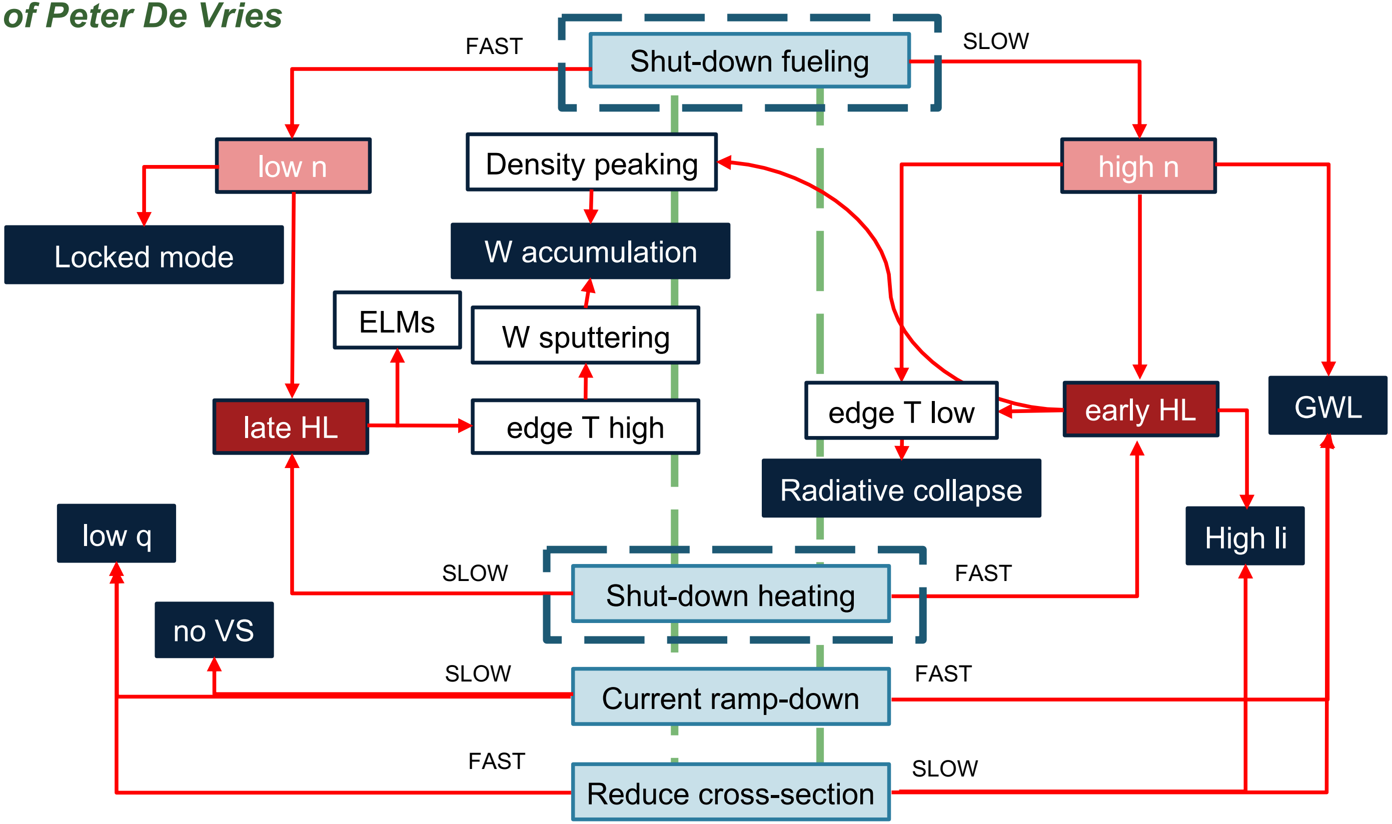
⇒ But EC is needed for NTM control (power sharing)

⇒ Constrains the lowest plasma current for
safe H-L transition w/o mode locking and/or Tungsten
accumulation to values between 10MA - 15MA

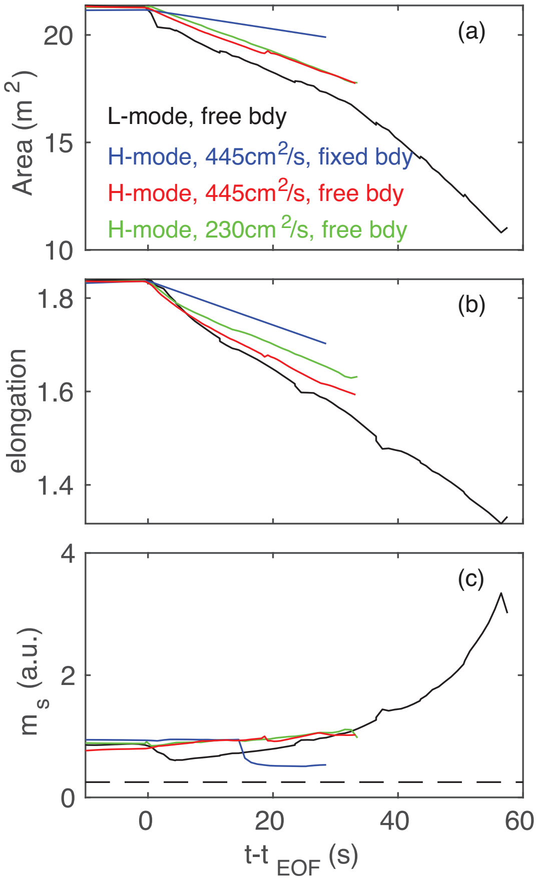


Let’s model the ITER plasma ramp-down. Where to start?

Courtesy of Peter De Vries



For a given plasma current ramp rate, there is minimum safe rate for the plasma cross-section reduction



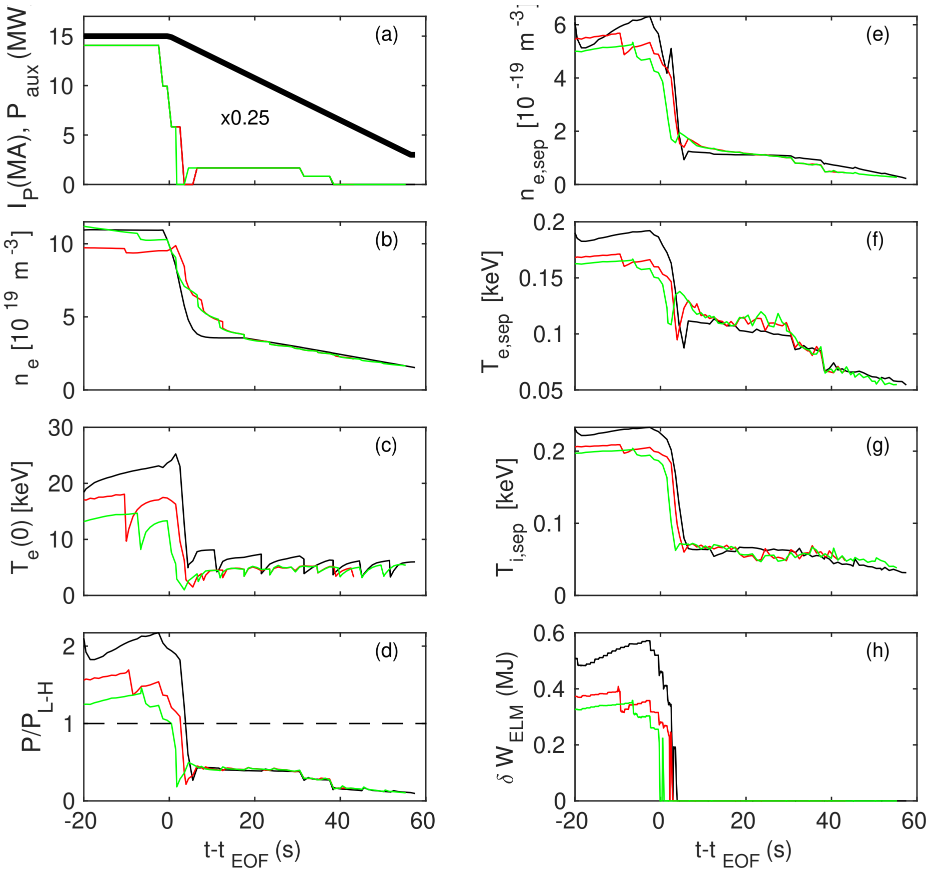
We use the nominal current ramp-down rate: 0.20MA/s

and explore safe range of cross-section reduction

Loss of VS when curves

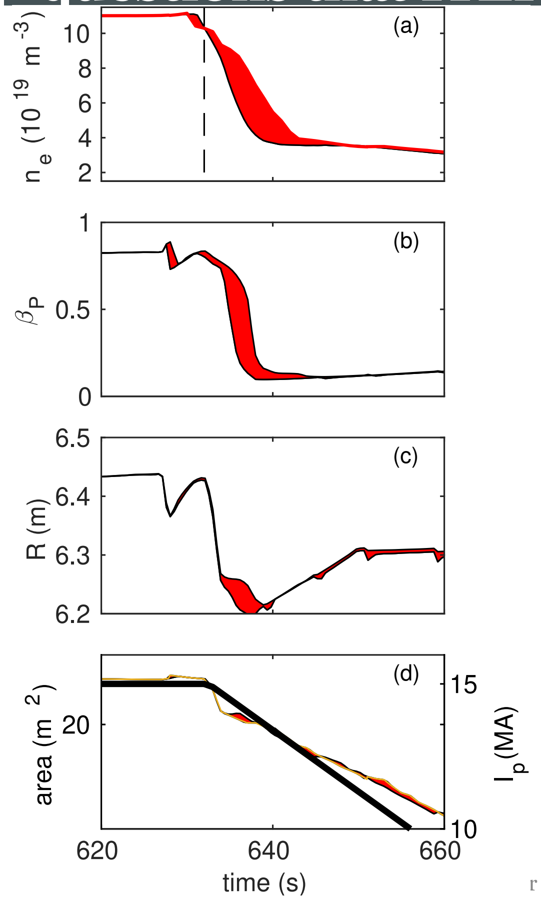
get close to the dashed line

What could possibly go wrong?



- Perturb density evolution and instruct the ‘control’ in the physics model scenario on allowed operations and in what sequence

How can experiments help answering some of the questions that ITER needs to be addressed?



- Density decay =>
- Large beta drop =>
- Radial inward excursion =>
- Vertical stability control =>

OPEN DISCUSSION