ML for nuclear fusion:
plasma diagnosis, prediction, and control

Jaemin Seo

Department of Physics, Chung-Ang University

jseo@cau.ac.kr

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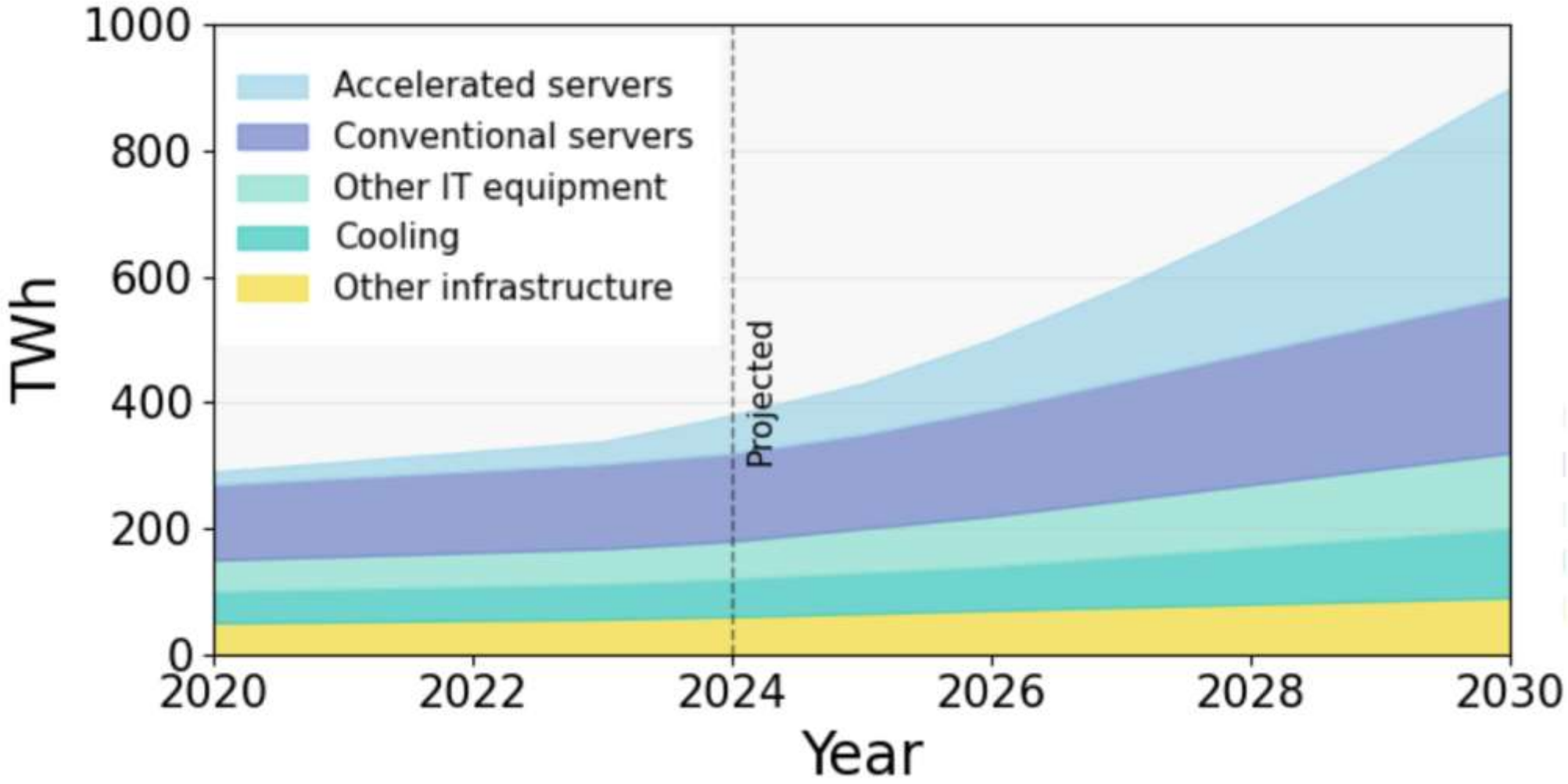
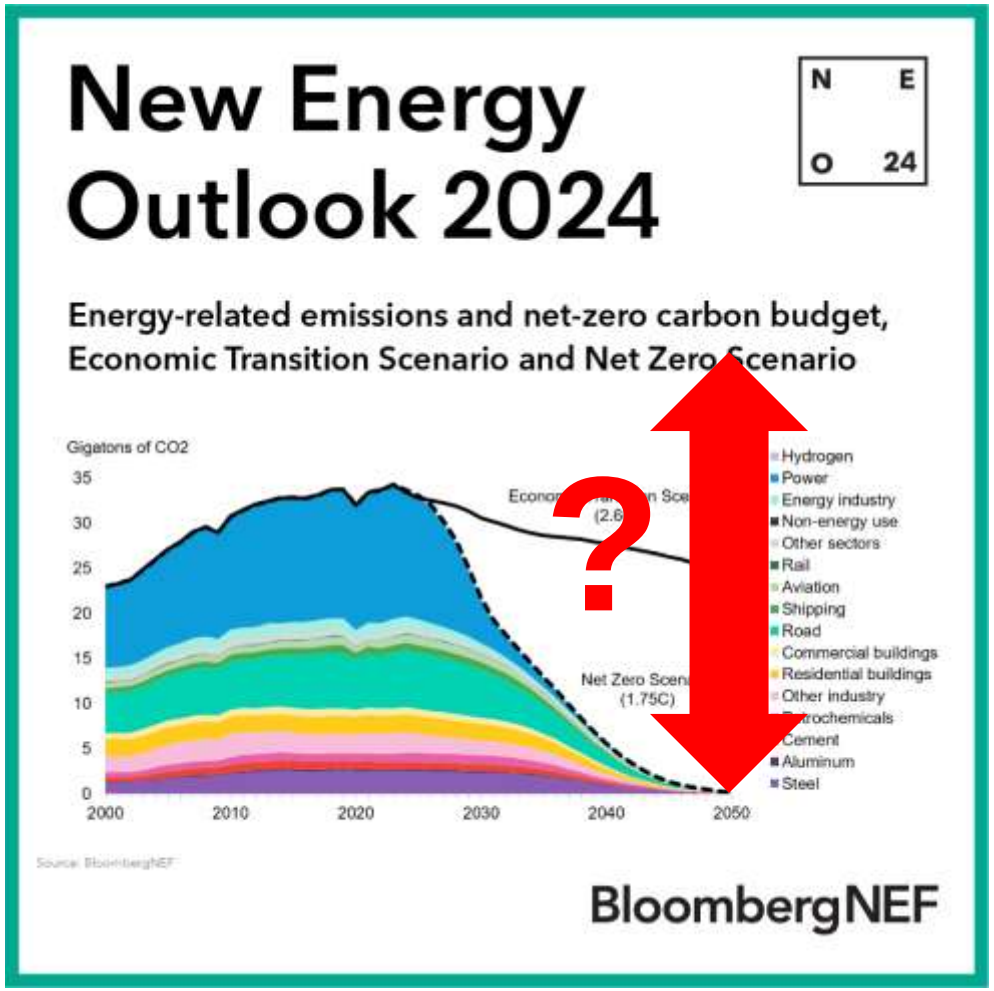
중앙대학교 물리학과
Department of Physics, Chung-Ang University

AI & Energy Consumption



https://www.iea.org/data-and-statistics/charts/global-data-centre-electricity-consumption-by-equipment-base-case-2020-2030

Net Zero 2050



We cannot use fossil fuels!

We need a new energy source:

“Nuclear Fusion” or “Artificial Sun”

Contents

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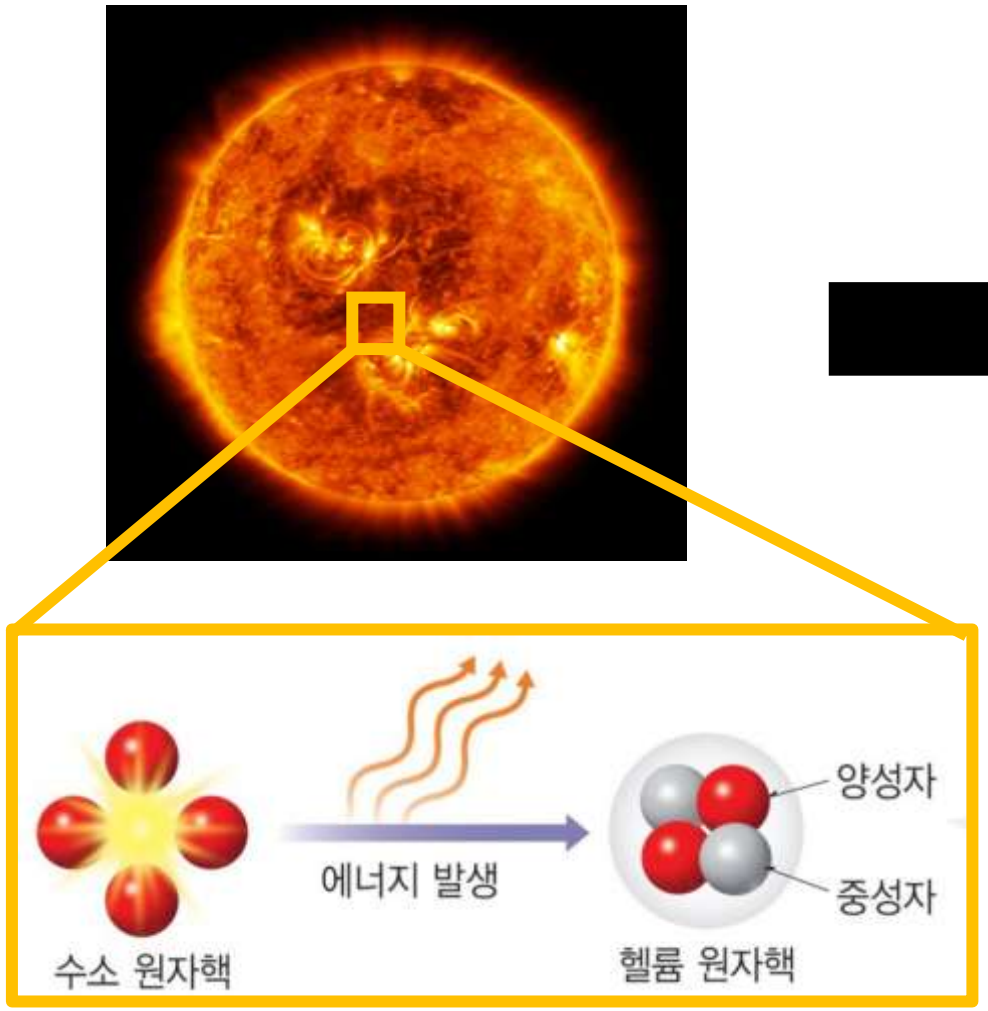
Artificial Sun?



Can we make it on Earth?

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Sun = Plasma = Ionized gas

It is an “electrically conducting gas.”

For nuclear fusion,
>100 million ˚C needed!

The 4th state of matter, plasma

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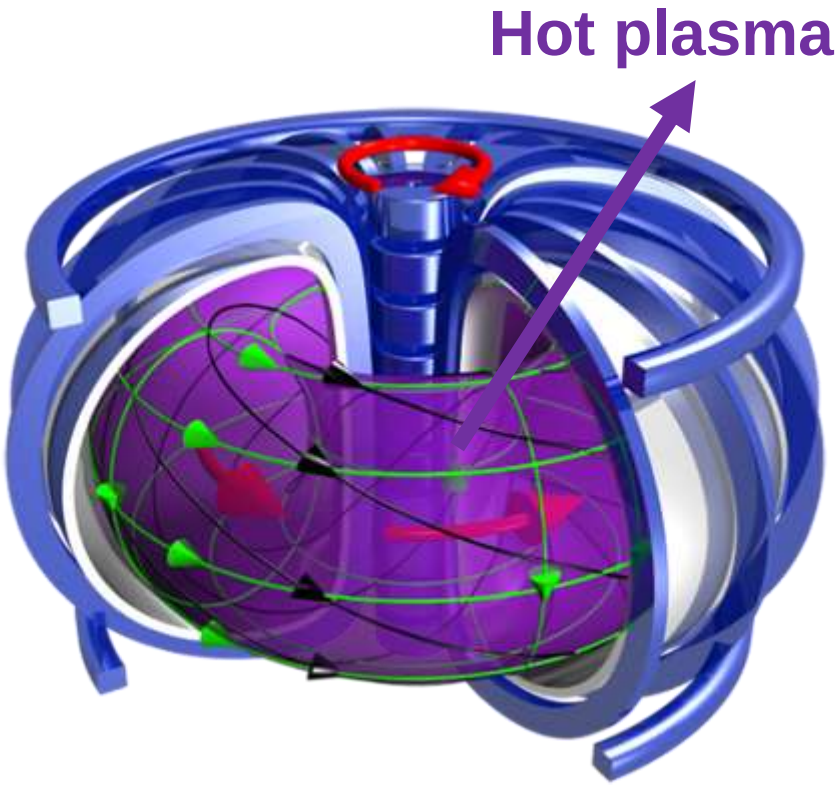
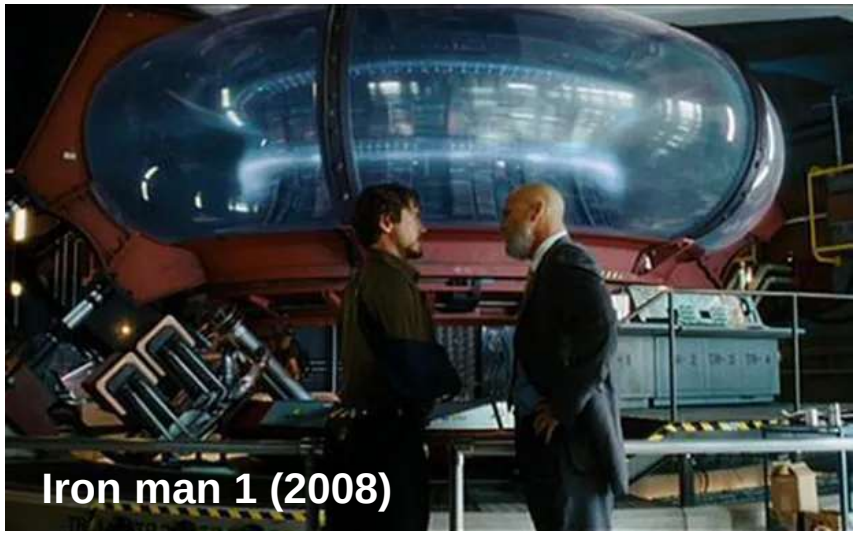
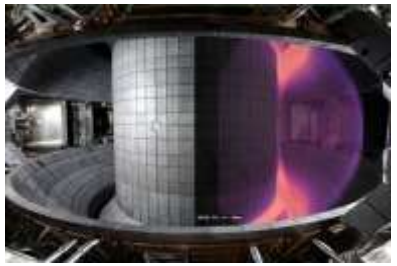
Tokamak: a "Sun Container"



Confines the plasma with magnetic field!





KSTAR (Korea)

DIII-D (US)

ITER (International)

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For fusion energy,

- We need to maintain the high-pressure plasma with stability.
- So we need

(1) High-temperature **“Plasma diagnosis”**

(2) Predict the plasma dynamics **“Plasma prediction”**

(3) Control the plasma **“Plasma control”**

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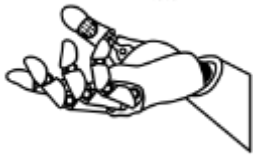
Let's use ML for nuclear fusion!

- **By using ML,**

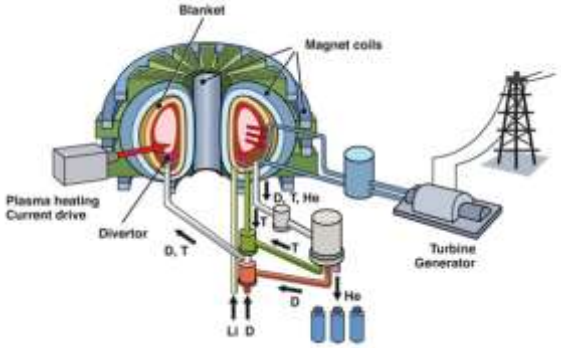
(1) How to <u>diagnose</u> the plasma

(2) How to <u>predict</u> the plasma

(3) How to <u>control</u> the plasma



ML



Unstable plasma

Stable energy source

Fusion commercialization!

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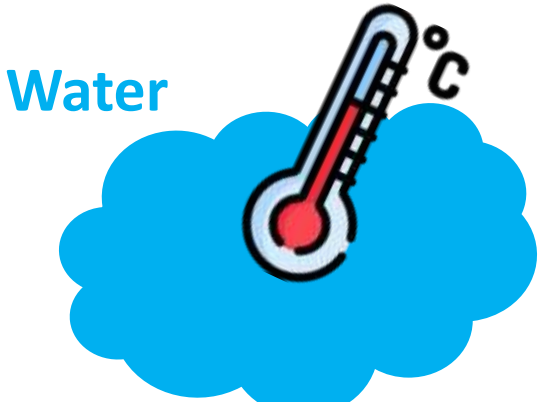
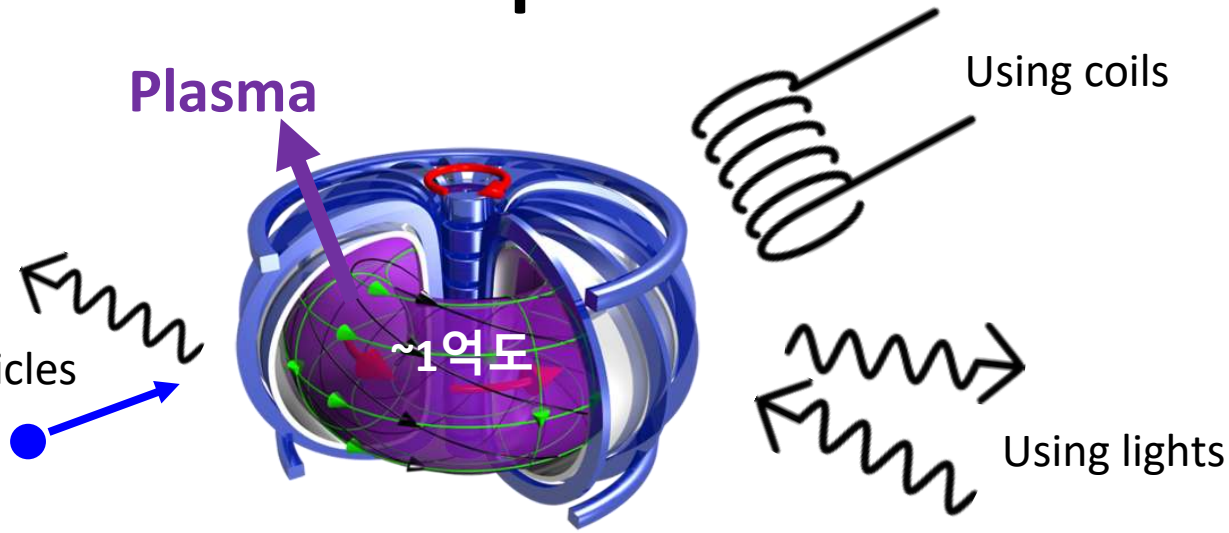
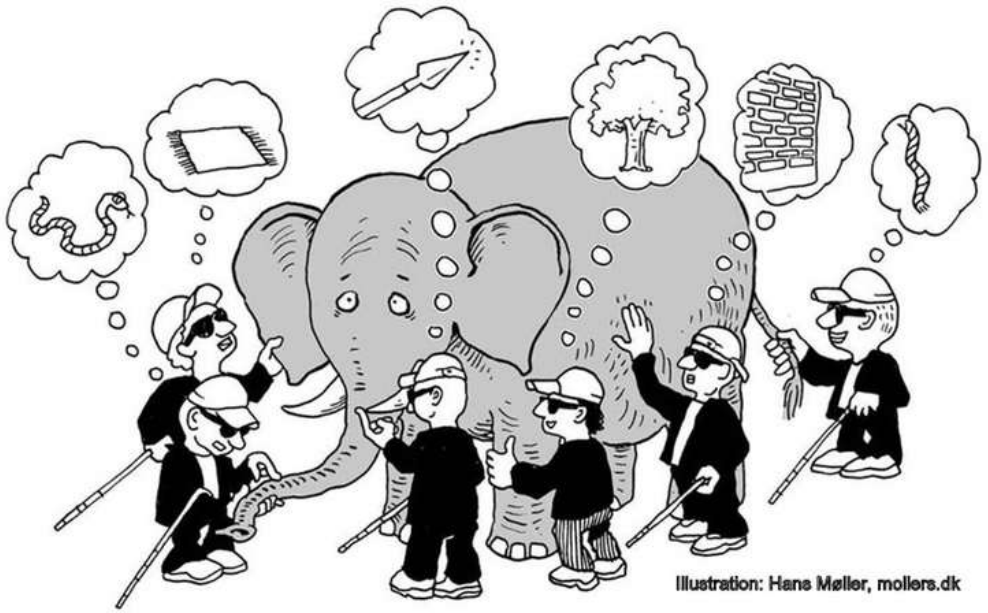
Plasma “diagnosis?”

- **How to measure the temperature of hot plasma?**







<u>Diagnostics</u>, not measurement!

Inverse &
ill-posed problem!

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A simple way: Data-driven diagnosis

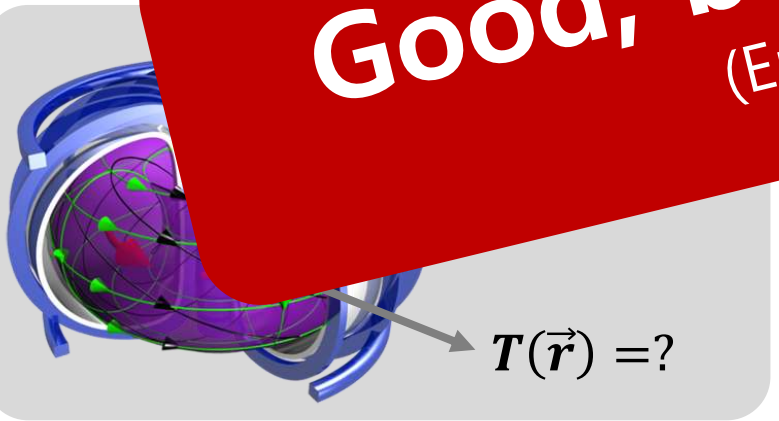
- **In the past,**

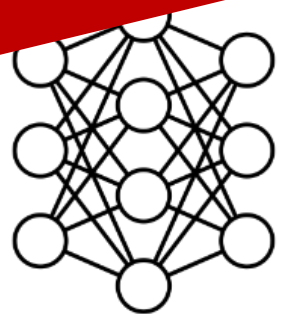
Good, but often physically invalid!

(Energy conservation, force balance, …)

plasma profiles

(Temperature, mag field, …)





Neural network θ

- **Data-driven**

R Shousha*, J Seo* et al, Nucl. Fusion 64 (2024) 026006

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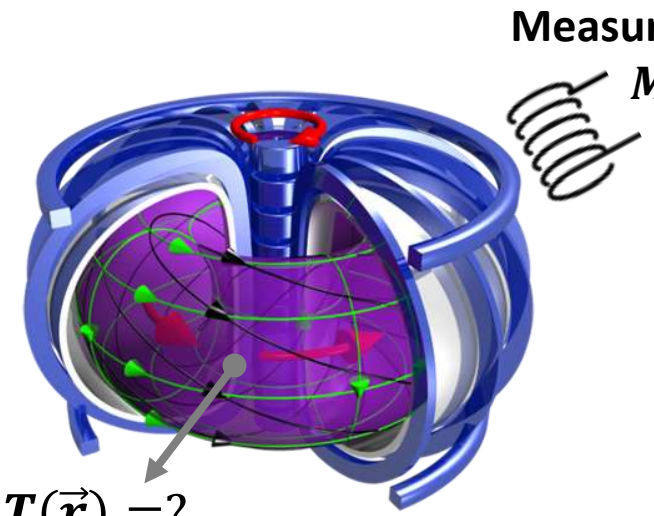
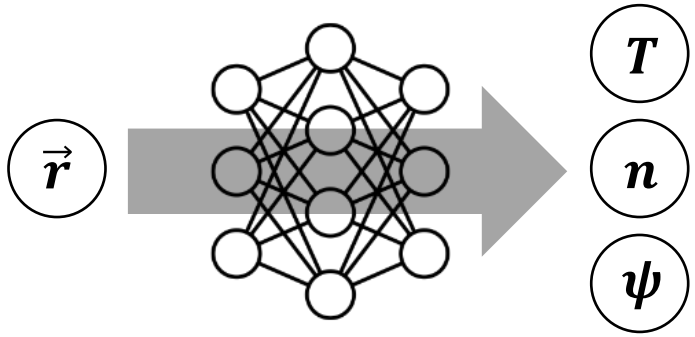
Another way: Physics-informed NN (PINN)



$$\frac{\partial^2\psi}{\partial r^2} - \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{\partial^2\psi}{\partial z^2} = -\mu_0 r^2 \frac{dp}{d\psi} - \frac{1}{2}\frac{dF^2}{d\psi},$$



1. How well it satisfies physics laws

$$L_{phys} = \|f(T, n, \psi; \vec{r})\|$$

2. How well its synthetic measurements match the true measurements

$$L_{meas} = \|M(y) - M_{true}\|$$

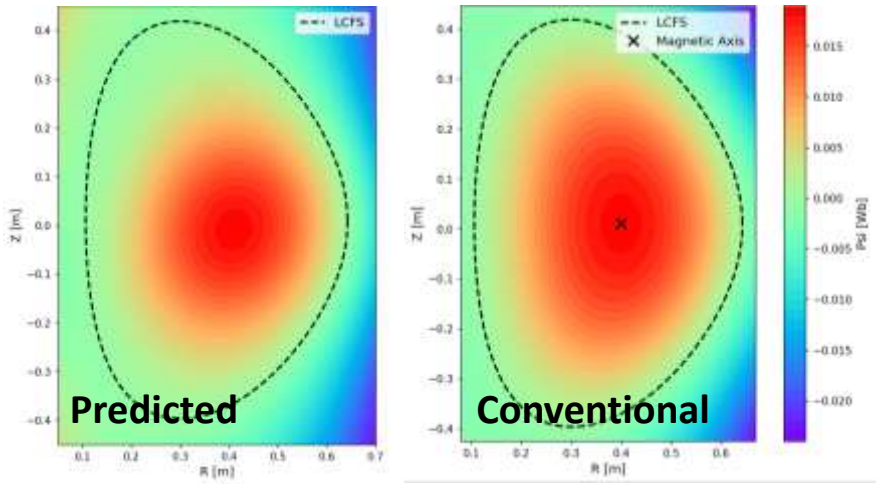
Normal ML:

$$\underset{\theta}{\mathbf{argmin}}(\|y - y_{true}\|)$$

But we don't know y_{true}!

Physics-informed ML:

$$\underset{\theta}{\mathbf{argmin}}(L_{phys} + L_{meas})$$



J Choi, J Seo† et al 2026 (in preparation)

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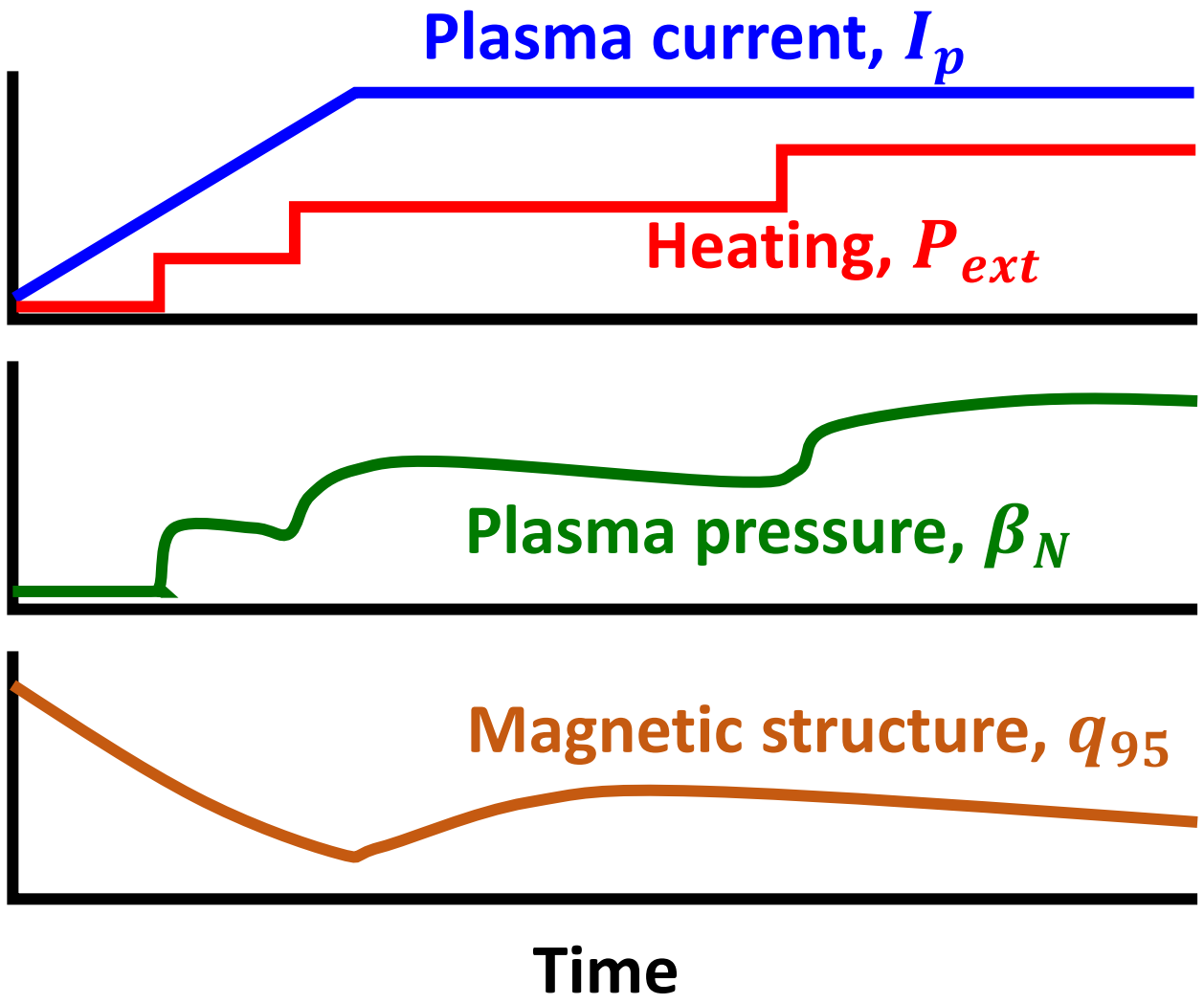
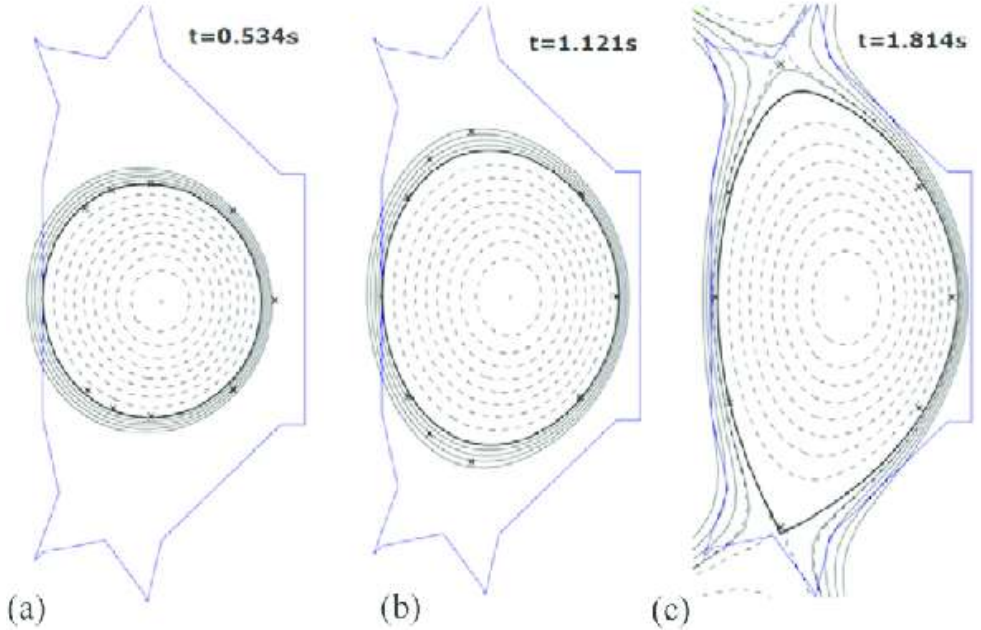
Typical plasma discharge in tokamak





Plasma shape evolution

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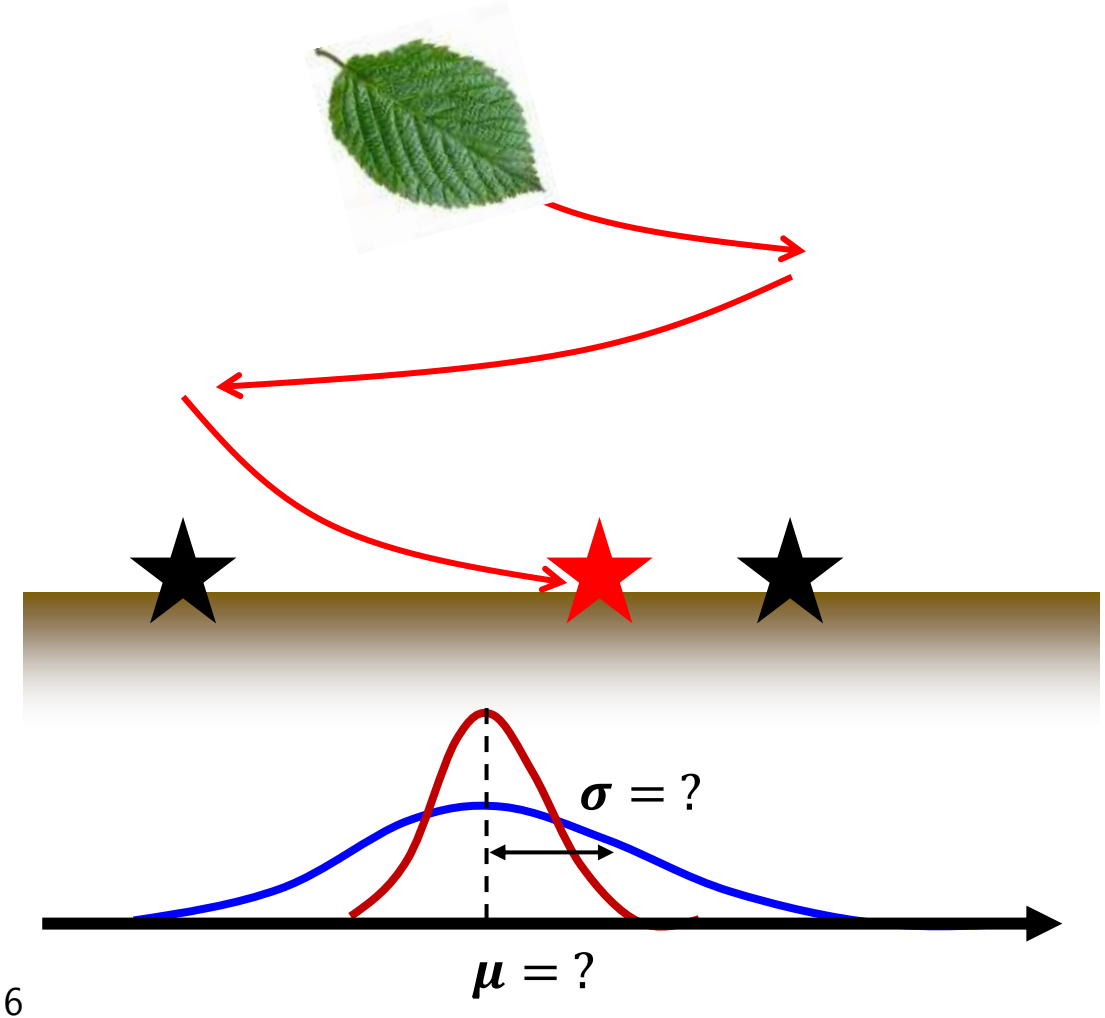
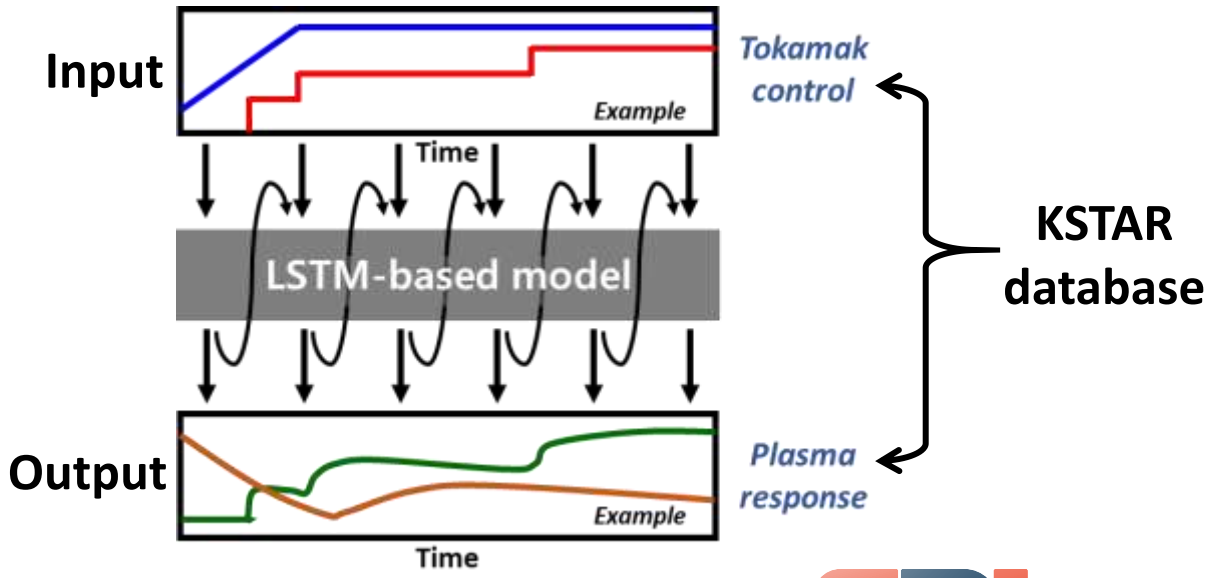
Difficulty of plasma prediction?

J Seo et al, Nucl. Fusion 61 (2021) 106010
J Seo et al, Nucl. Fusion 62 (2022) 086049



- Predict the “average” dynamics ($\mu(t)$)
  : LSTM or transformer

- Predict the “uncertainty” of the dynamics ($\sigma(t)$)
  : Bayesian or ensemble



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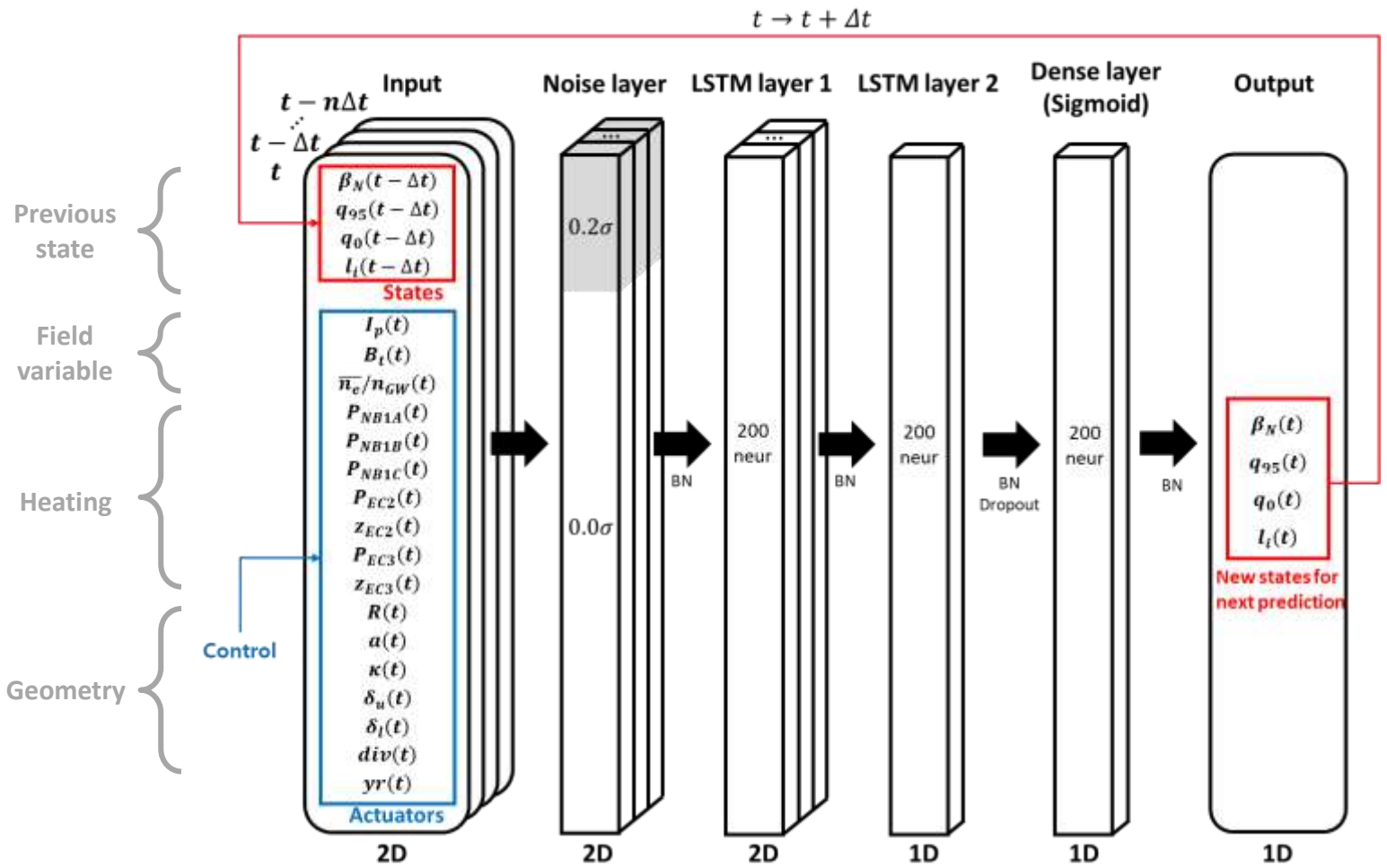
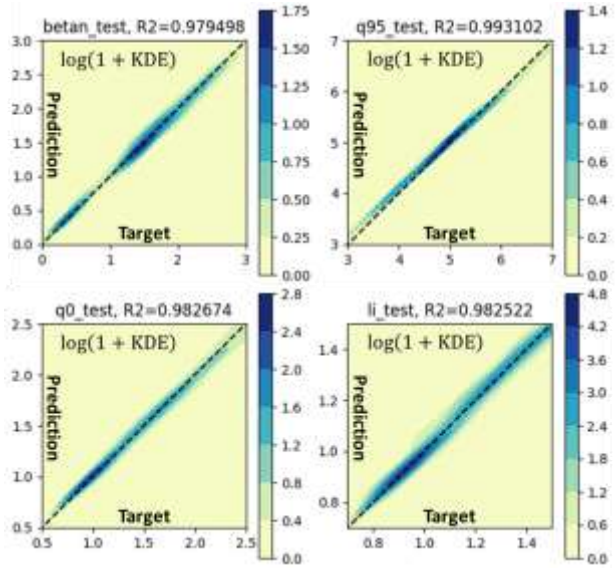
Data-driven plasma prediction

- **NN architecture & training with KSTAR database**

J Seo et al, Nucl. Fusion 61 (2021) 106010
J Seo et al, Nucl. Fusion 62 (2022) 086049



KSTAR database



Regression plot for testset

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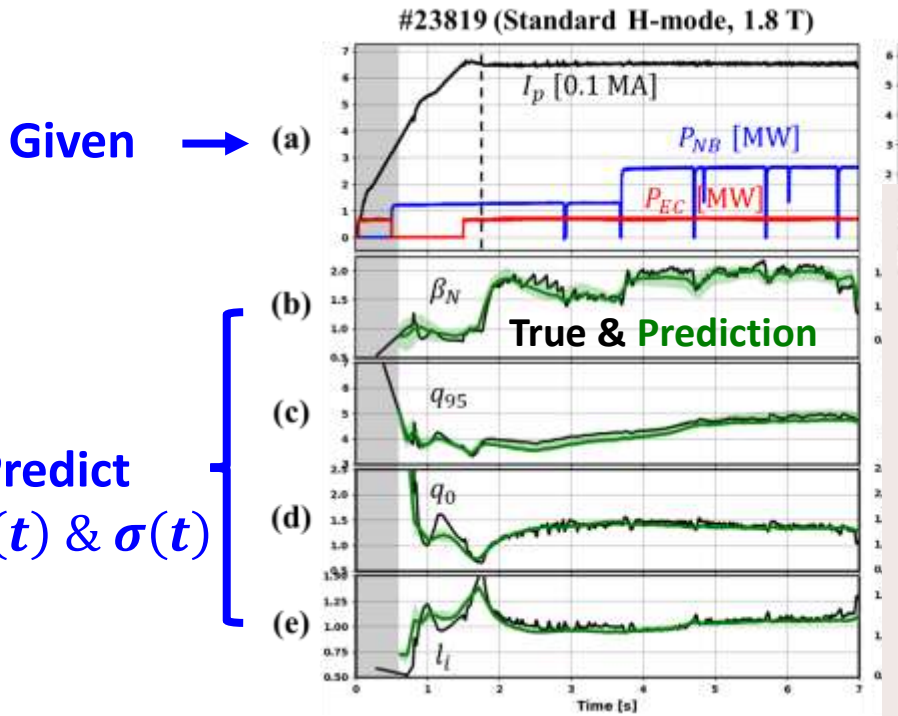
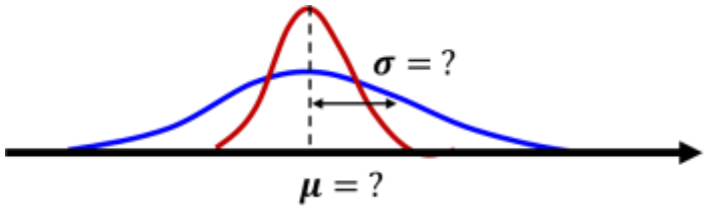
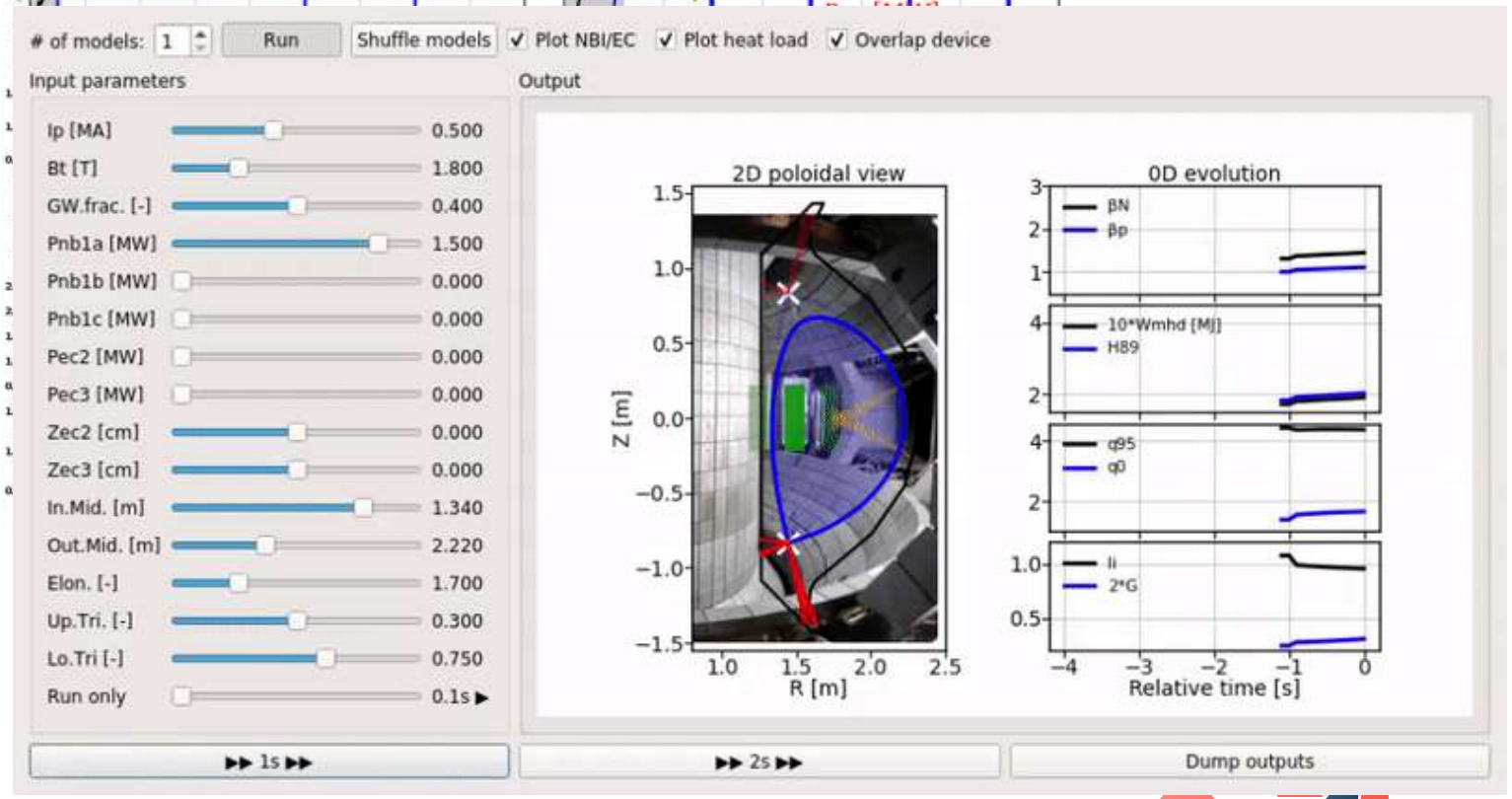
Data-driven plasma prediction

- **Plasma parameter prediction in KSTAR**

J Seo et al, Nucl. Fusion 61 (2021) 106010
J Seo et al, Nucl. Fusion 62 (2022) 086049







https://github.com/jaem-seo/KSTAR_tokamak_simulator

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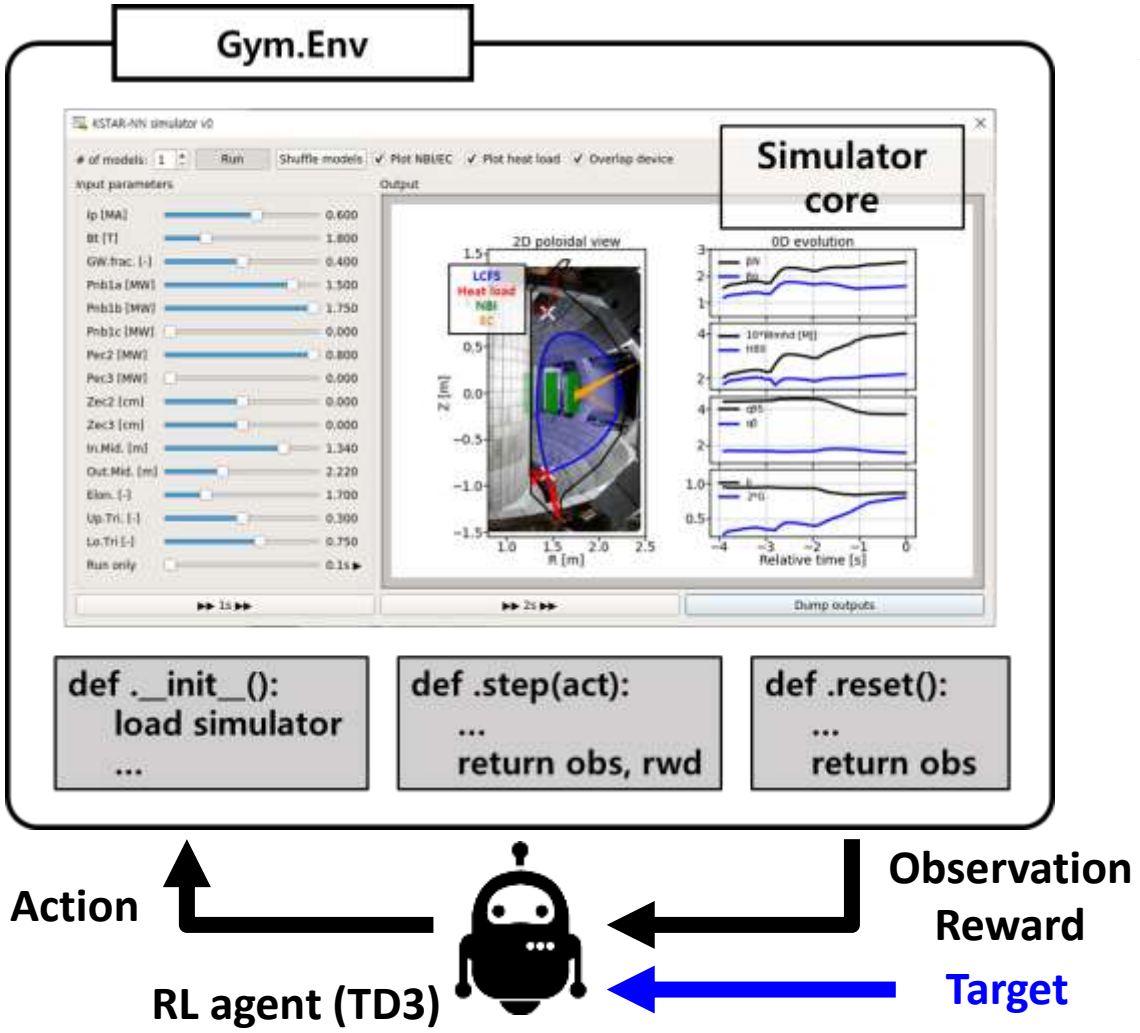
We can predict, then we can control!

J Seo et al, Nucl. Fusion 61 (2021) 106010
J Seo et al, Nucl. Fusion 62 (2022) 086049

- **Reinforcement learning for plasma control**



What we need to do is defining act, obs, and rwd!

- **Action**: Control variables
- **Observation**: Plasma response & target
- **Reward**: Higher if the plasma is close to the target

Action: $\{I_p, \kappa, \delta_u, \delta_l, R_{in}, R_{out}\}$

Observation: Previous action, $\{\beta_p, q_{95}, l_i\}_{old}$, $\{\beta_p, q_{95}, l_i\}_{target}$, $\{P_{NB}{}'s\}$

Reward: $-\mathrm{RMS}\left(\frac{y-y_{target}}{\epsilon_y}\right)_{y=\beta_p,q_{95},l_i}$

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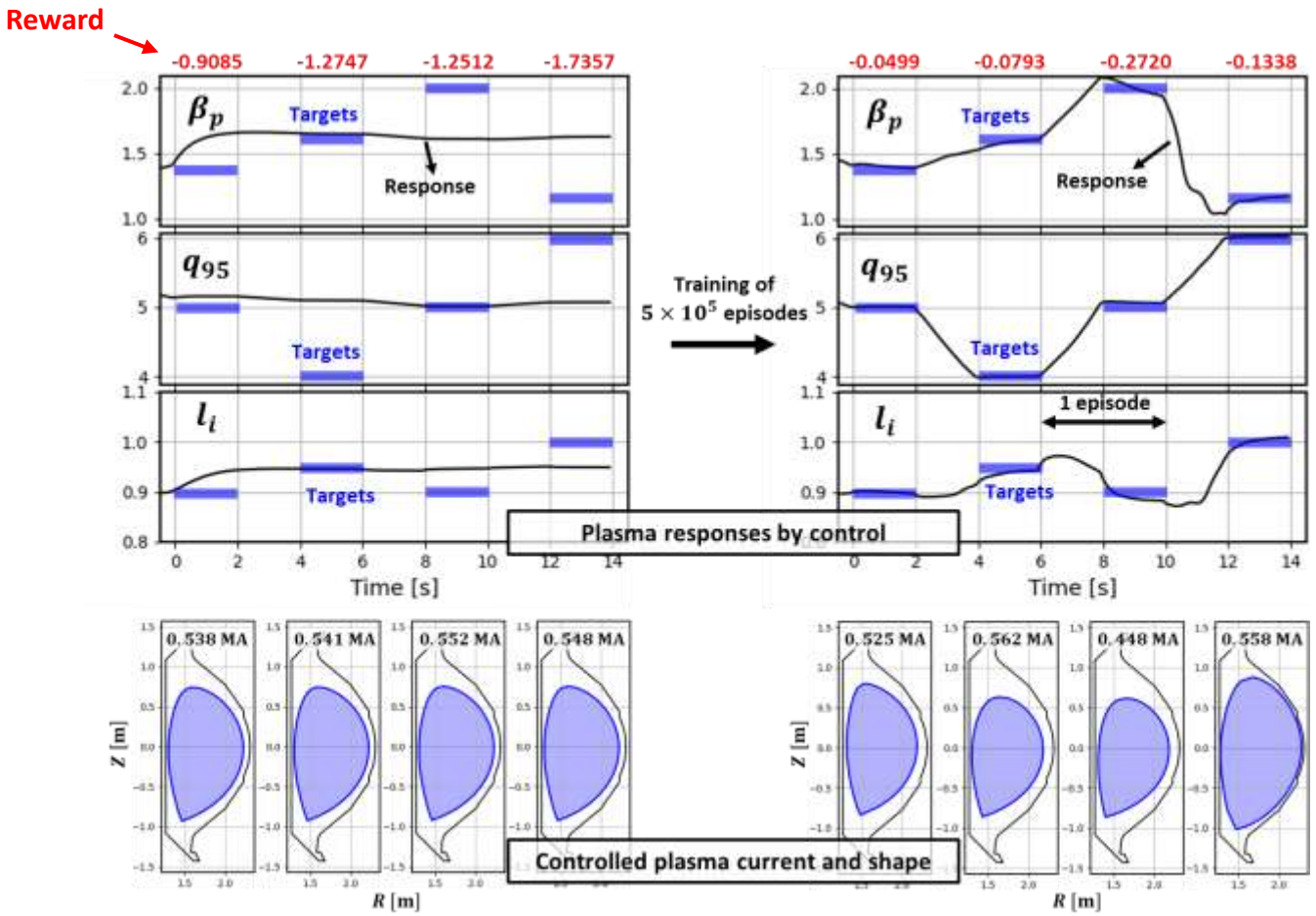
Plasma control with RL

- **Training in the simulation**



Before training **After training**

- After enough training, the AI determines reasonable solution of I_p and the boundary shape to reach the target of multiple parameters.

https://github.com/jaem-seo/AI_tokamak_control

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Plasma control with RL

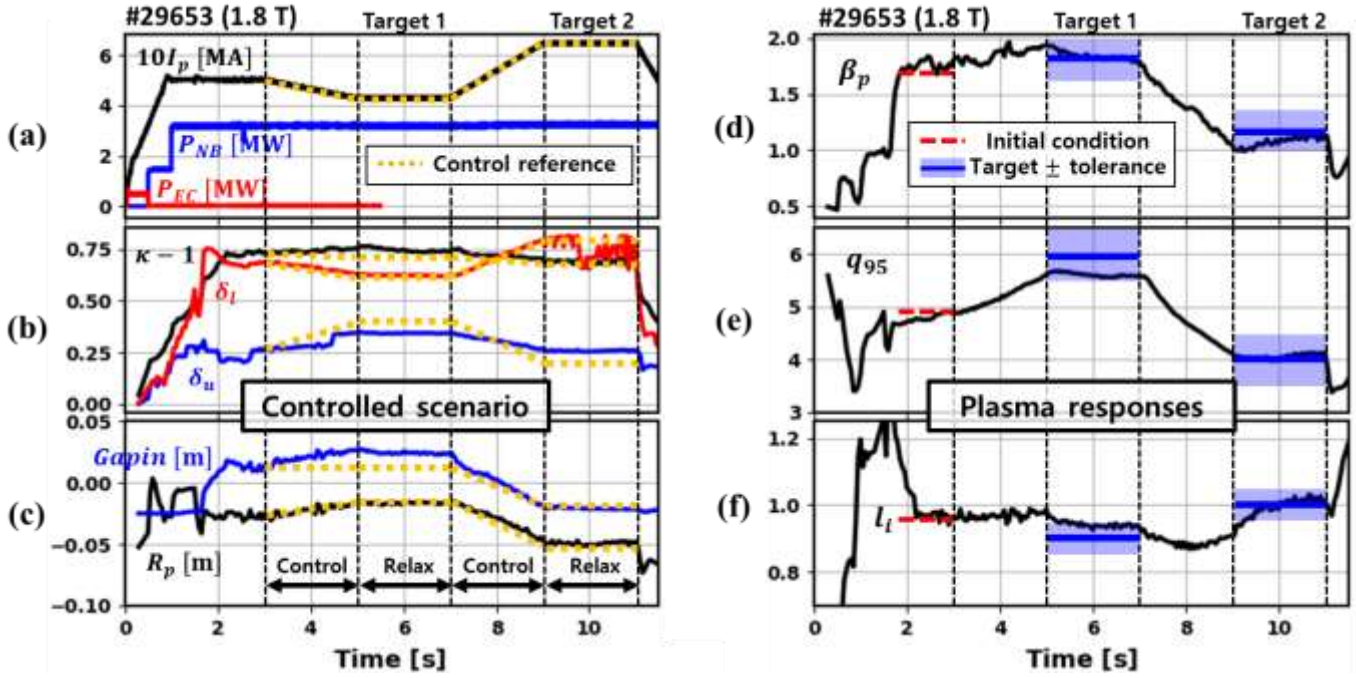
- **Validation in the KSTAR experiment**

Target setting

(β_p, q_{95}, l_i)

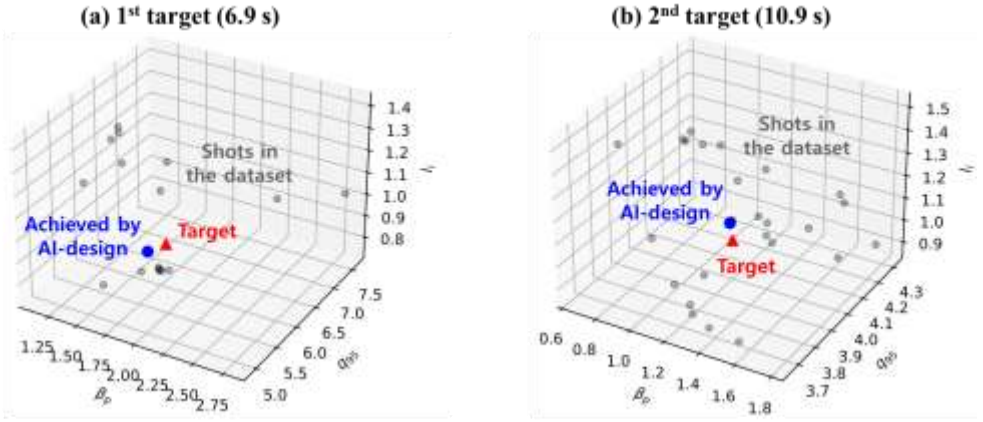
$= (1.8, 6.0, 0.9)$

$\&\ (1.2, 4.0, 1.0)$



- The plasma response followed the preset targets.
- However, actual shape controls were not perfect.

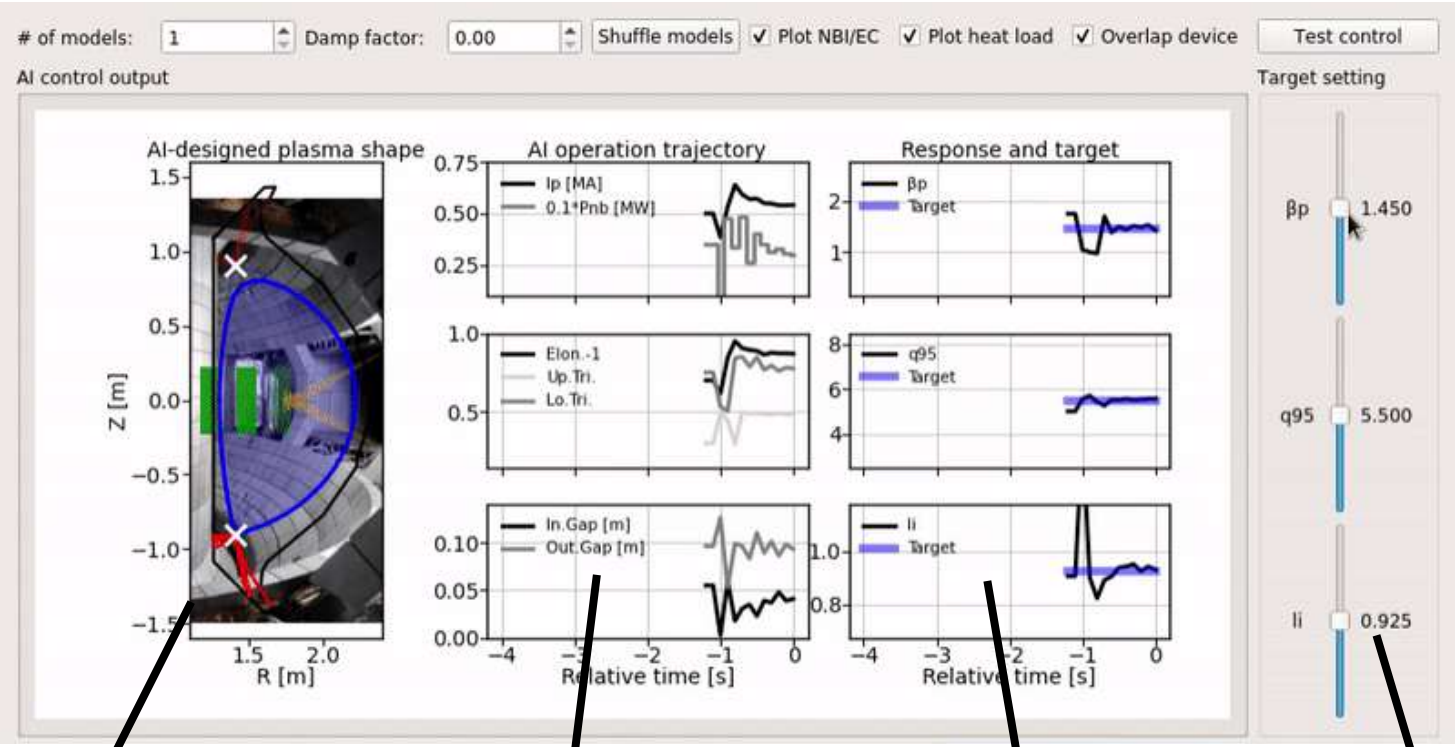
→ Control/diagnostics uncertainty should be reflected later.



Plasma control with RL

- **Now, let's try real-time control**

https://github.com/jaem-seo/AI_tokamak_control



- After RL training, the AI can control the command signals for $\{I_p, P_{NB}$, shape$\}$ to **track the time-varying targets**.
- It seems reasonable (β_p vs NBI / q95 vs shape).
- Will be tested with different RL settings and constraints.

AI-determined plasma shape

AI-determined command signals

Target & plasma response

Target setting

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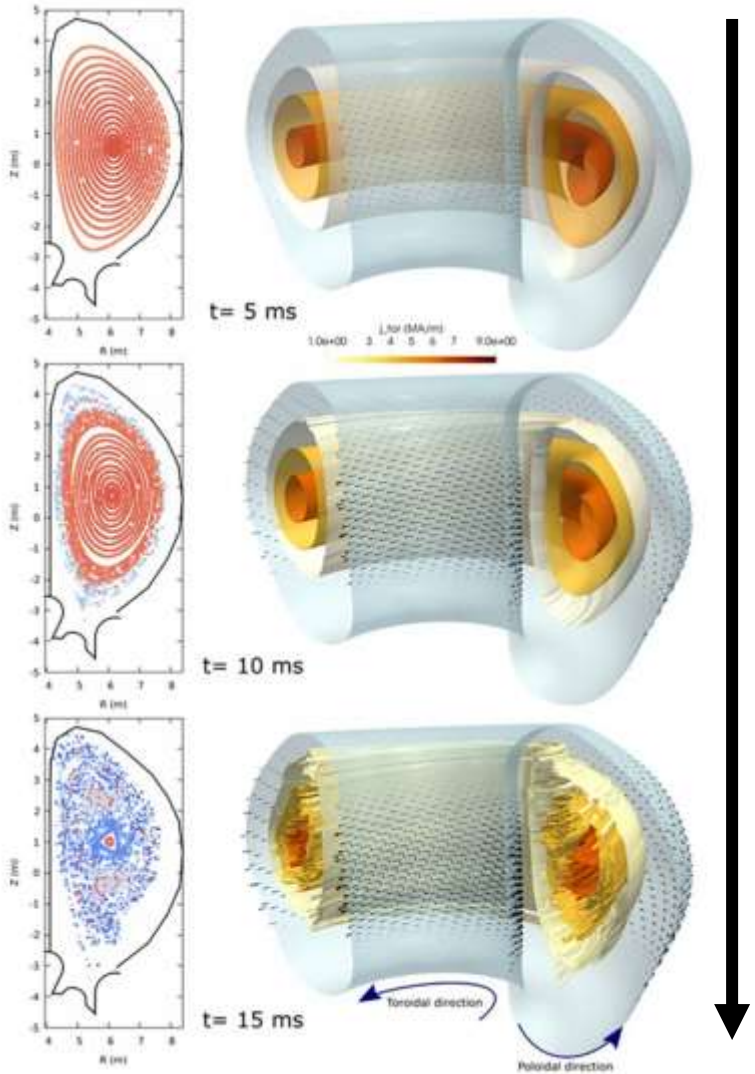
Plasma instability

- **Although we can control the plasma, the plasma can become very unstable!**



Normal

Tearing mode, TM (Unstable)

Disruption

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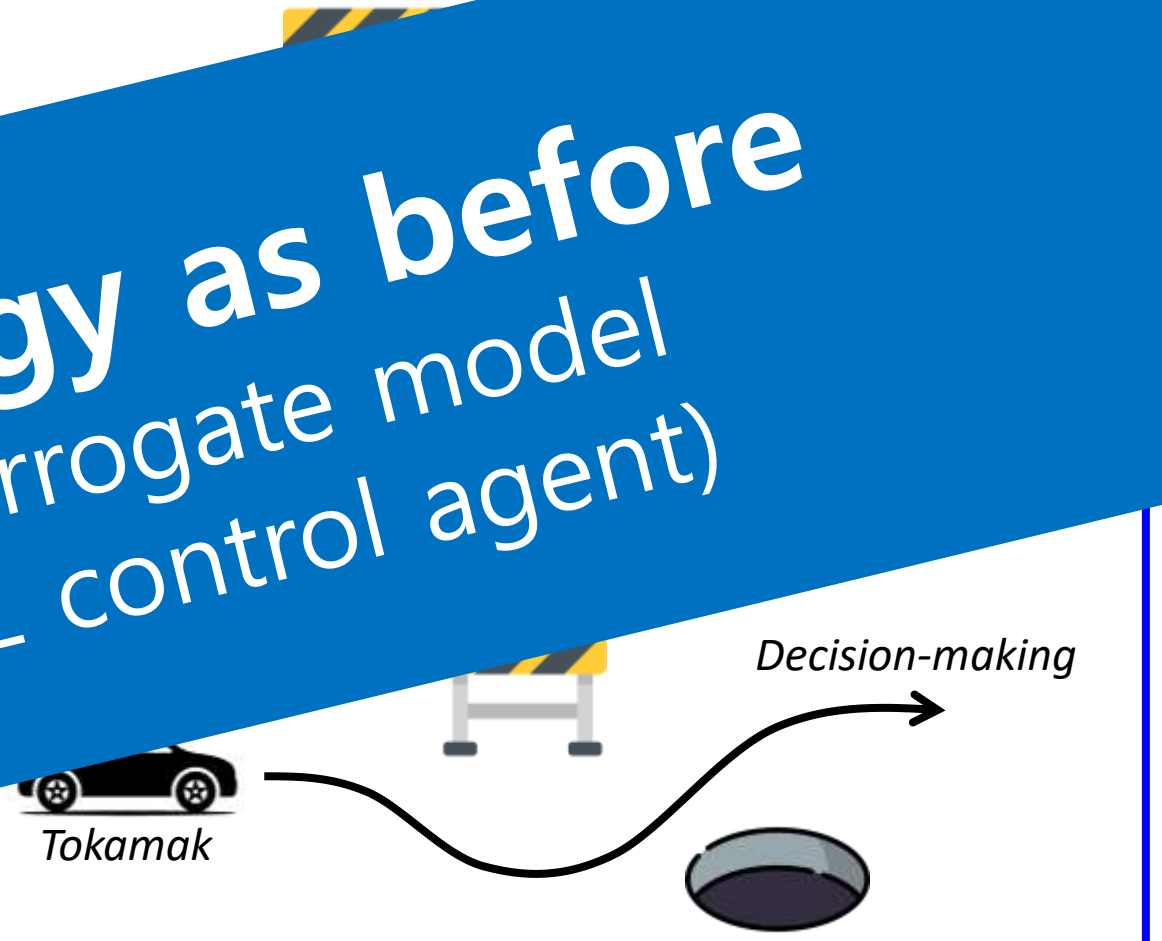
Avoiding plasma instability with ML

- **Let's use <u>two</u> different AIs: prediction & control**

AI 1: Predicting future TM possibility

Same strategy as before
(Making a surrogate model & training RL control agent)



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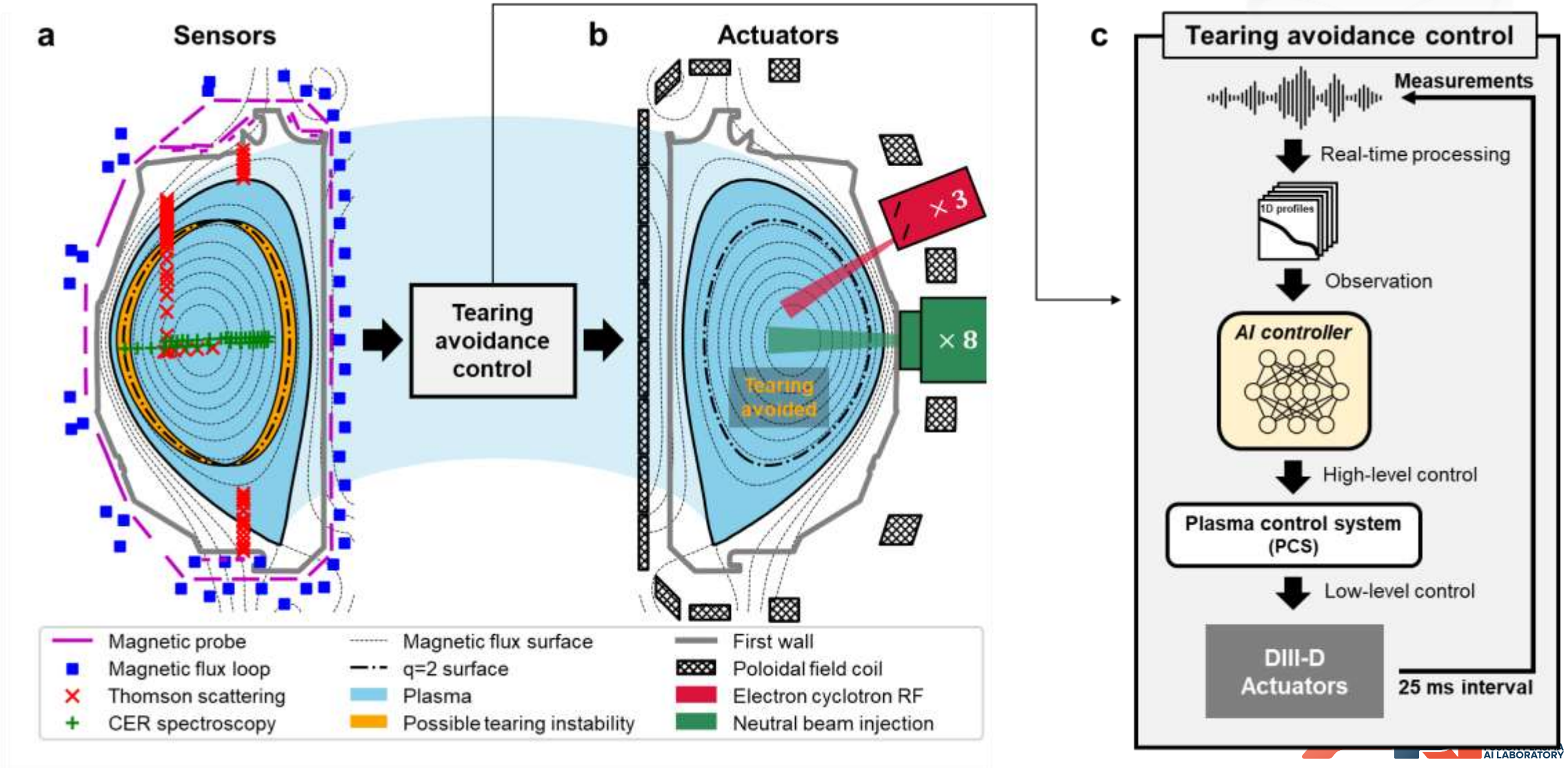
Avoiding plasma instability with ML

- **Implementation in DIII-D**

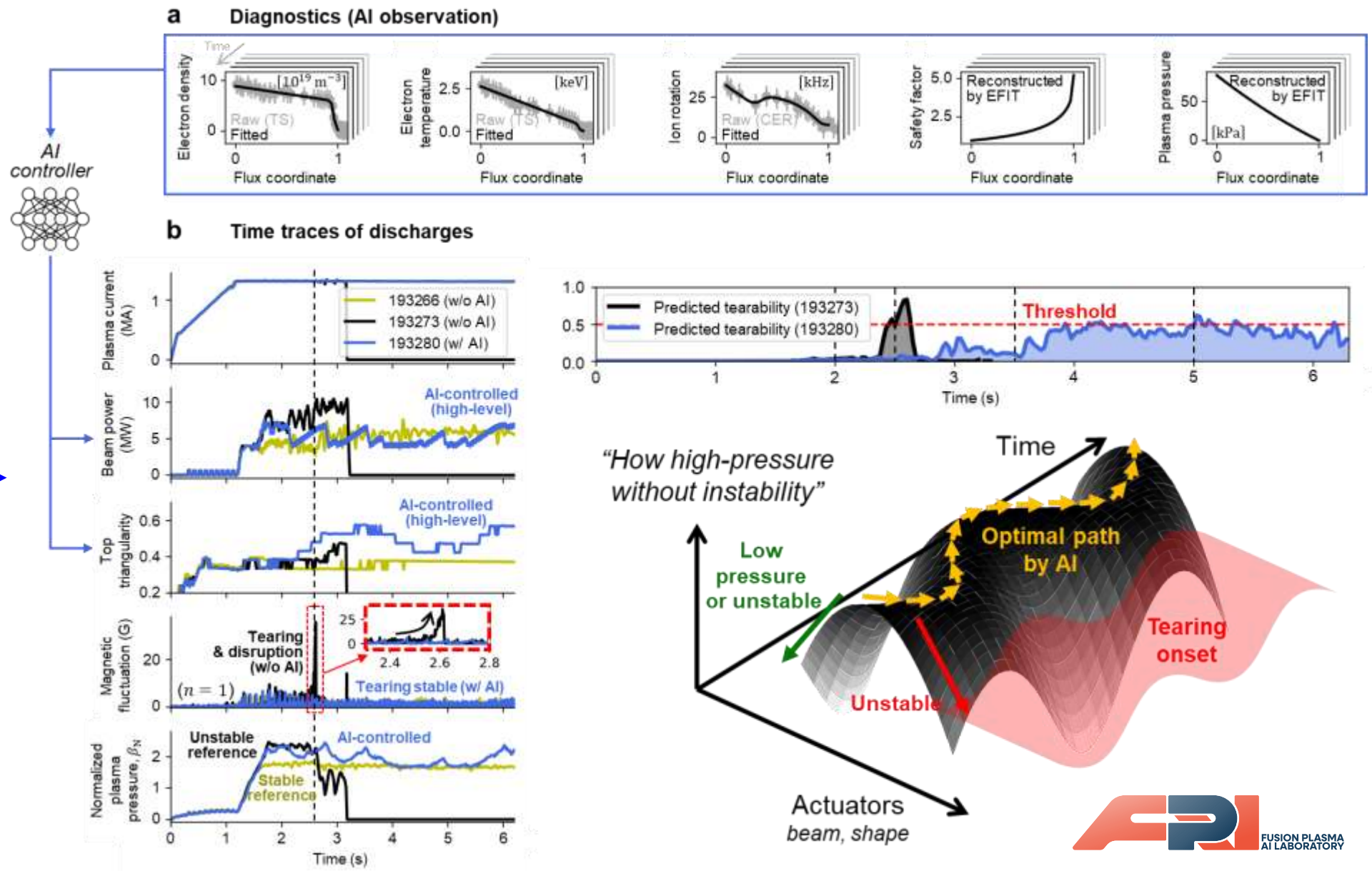


Avoiding plasma instability with ML

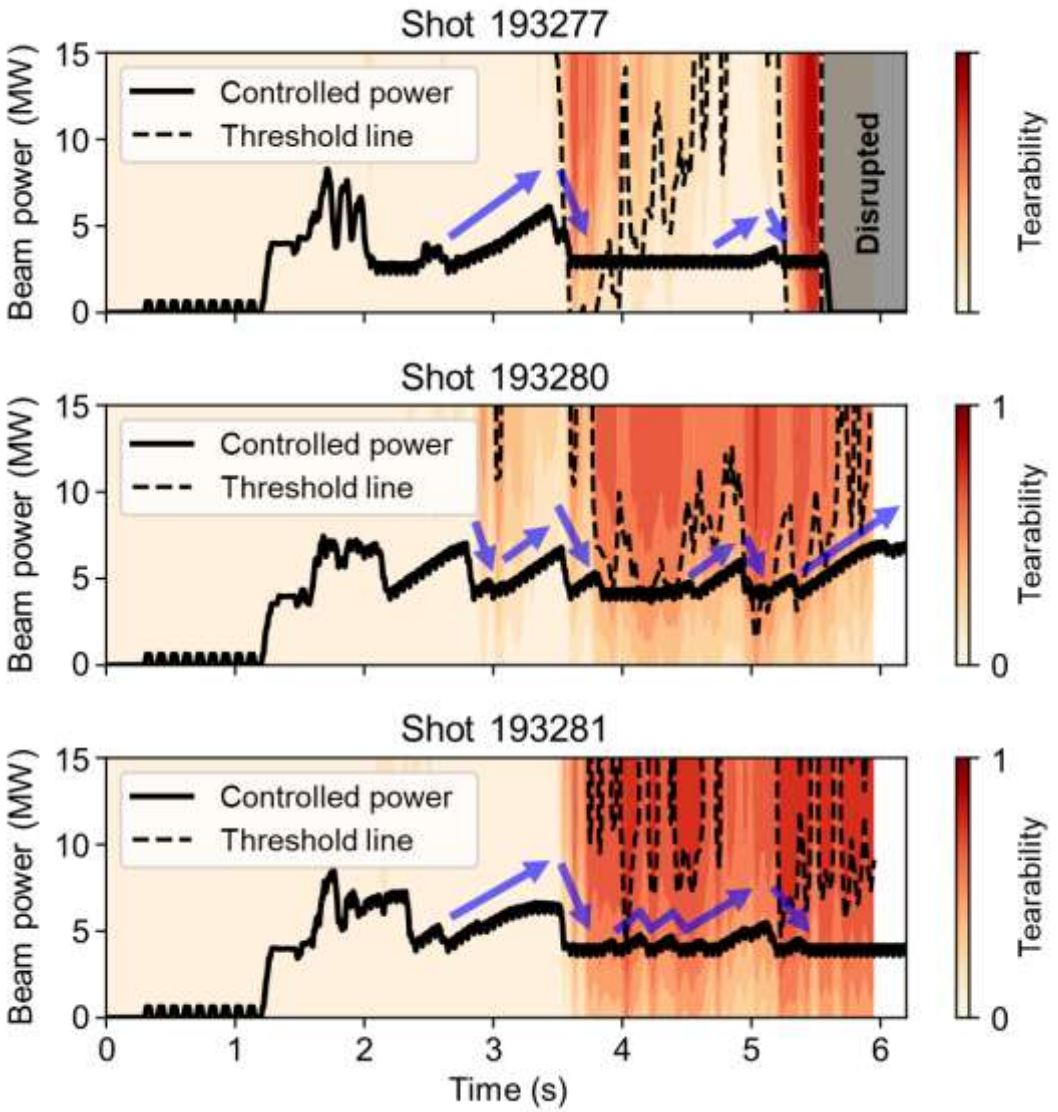
What AI sees ➡
Kinetic profiles

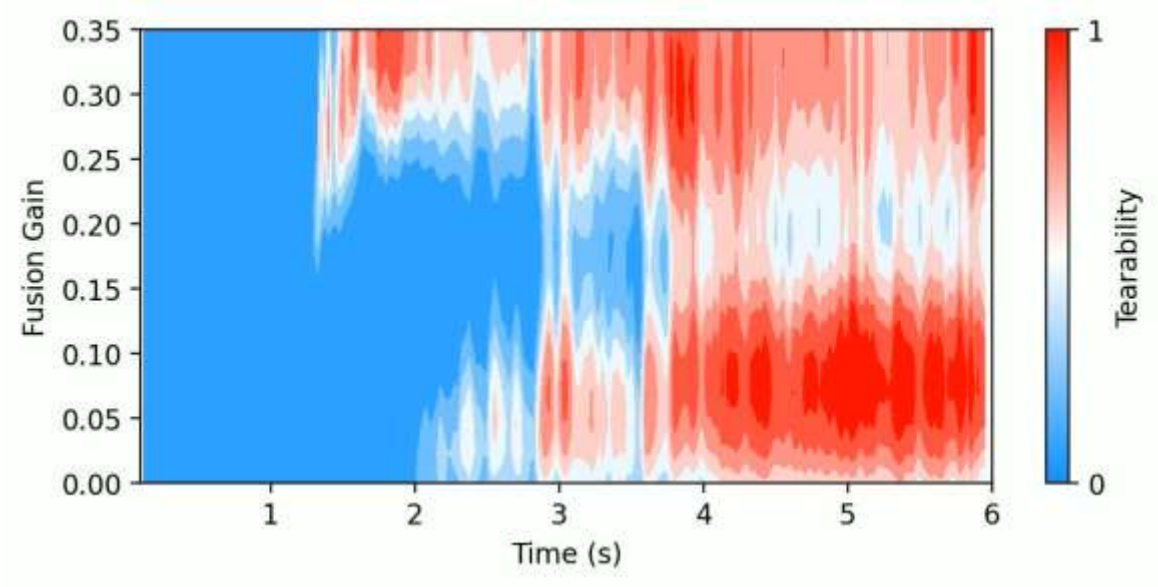
What AI handles ➡
P_{NB} & δ_t

What we want ➡
Higher β_N w/o TM



Avoiding plasma instability with ML





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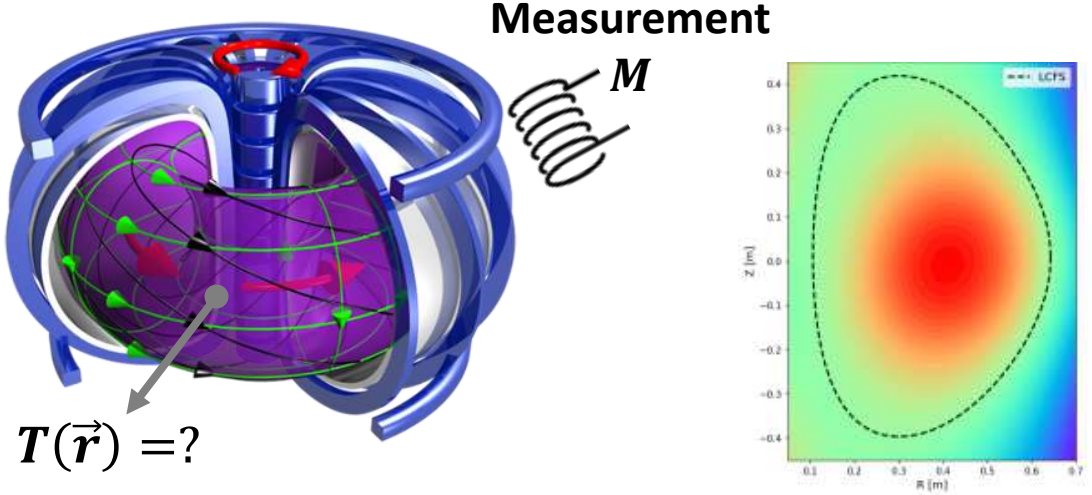
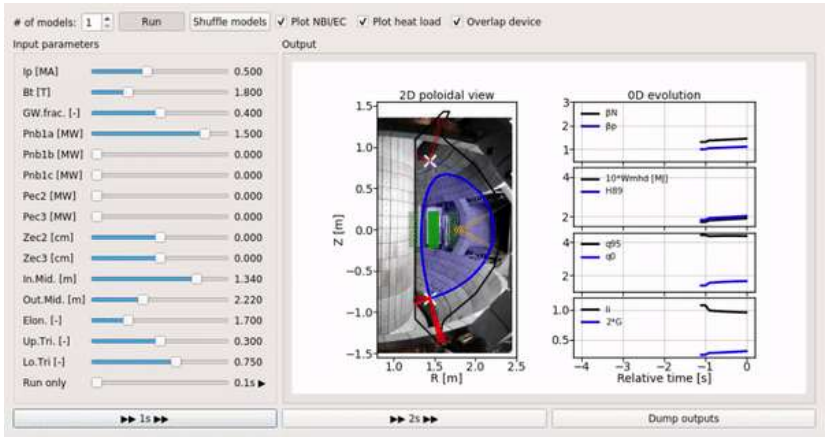
Summary

[1] R Shousha*, J Seo* et al, Nucl. Fusion 64 (2024) 026006
[2] J Seo et al, Nucl. Fusion 61 (2021) 106010
[3] J Seo et al, Nucl. Fusion 62 (2022) 086049
[4] J Seo et al, Nature 626 (2024) 746

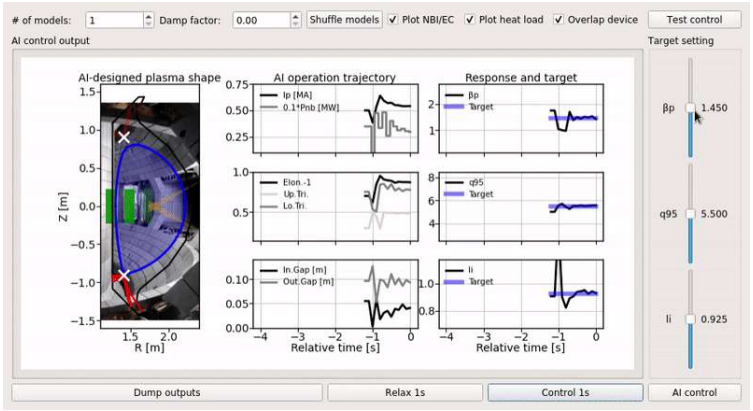
1. ML-based plasma diagnosis



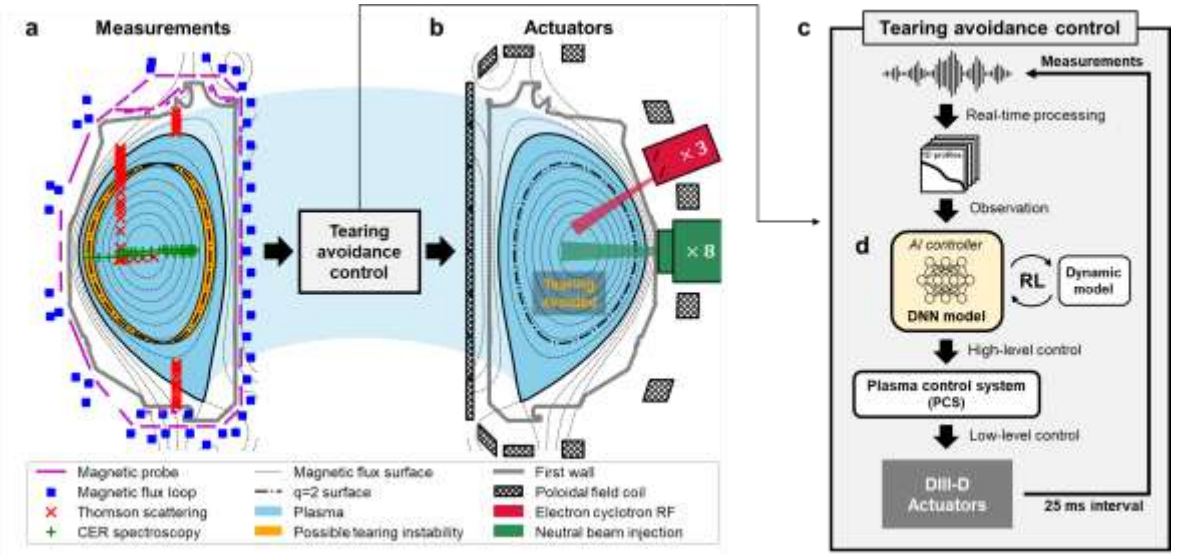
2. Data-driven plasma simulator



3. RL-based tokamak controller



4. RL-based instability avoidance



Thank you for your attention!

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