Artificial Intelligence applied to Plasma Spectroscopy

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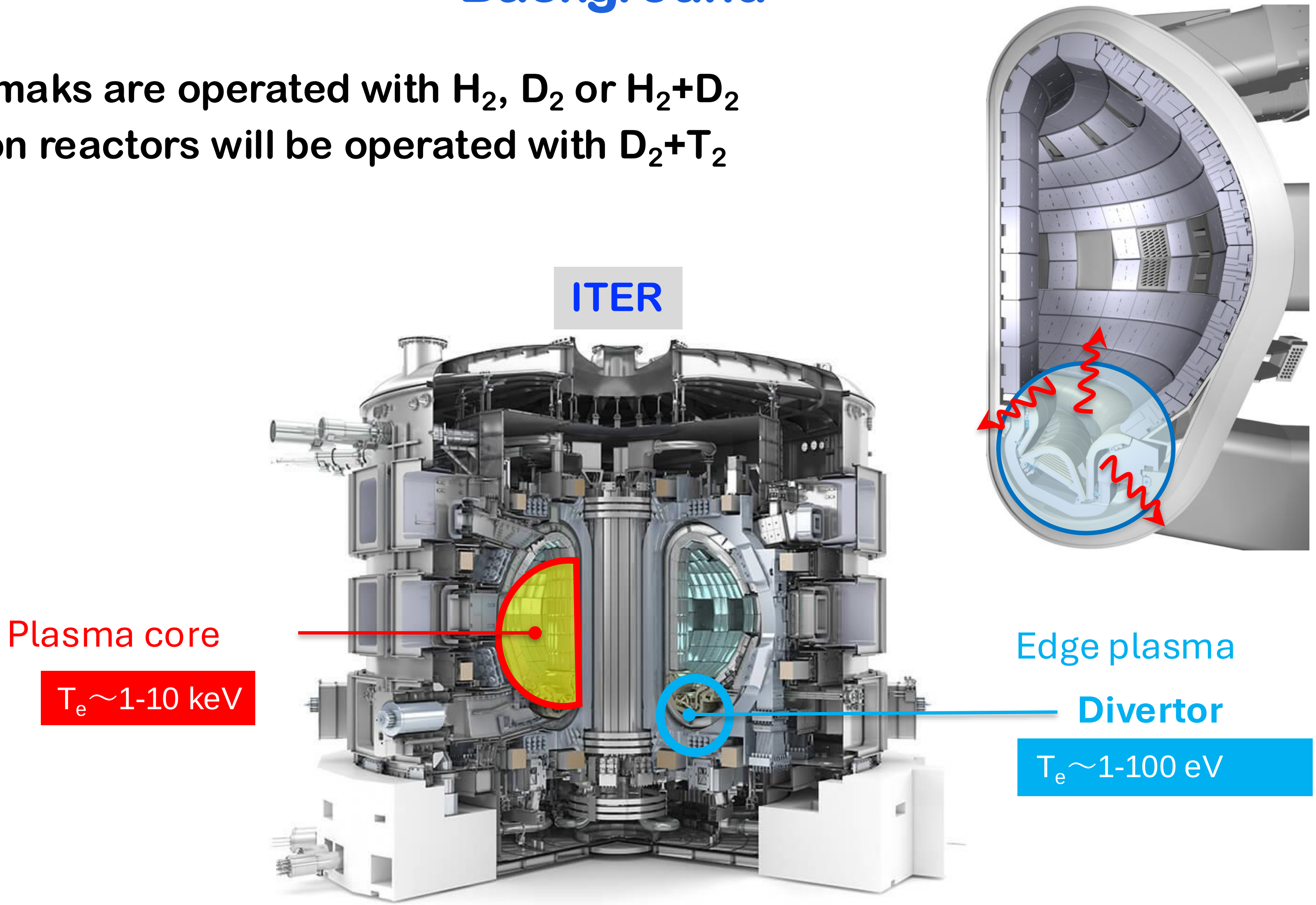
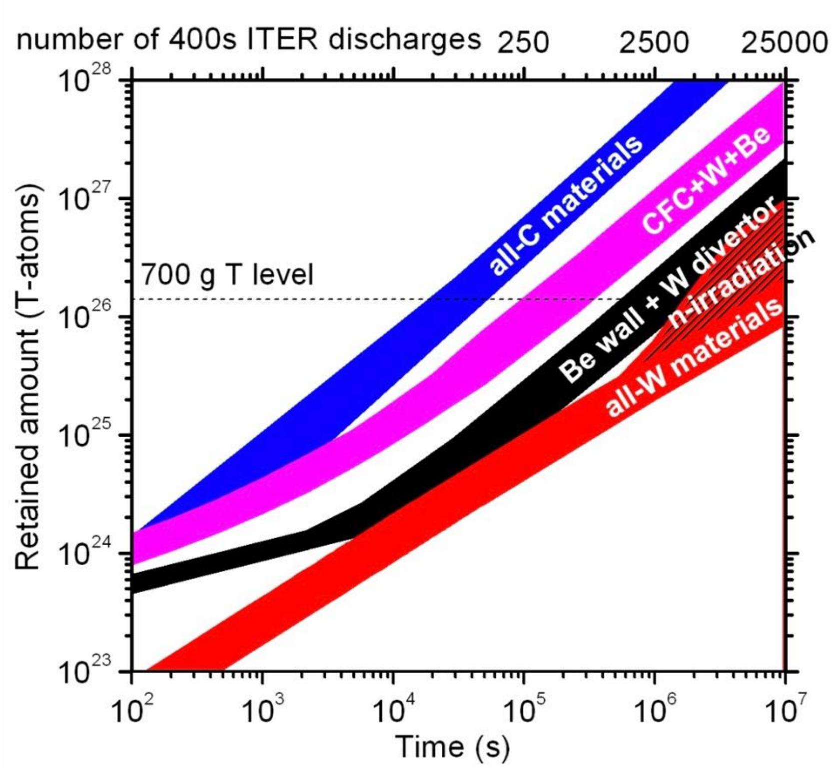
Background

- Tokamaks are operated with H_2, D_2 or H_2+D_2
- Fusion reactors will be operated with D_2+T_2



The issue of tritium retention

- **For Safety reasons, the quantity of tritium is limited by the Authorities to about 700g inside ITER → Control of the tritium content (isotopic ratio)**

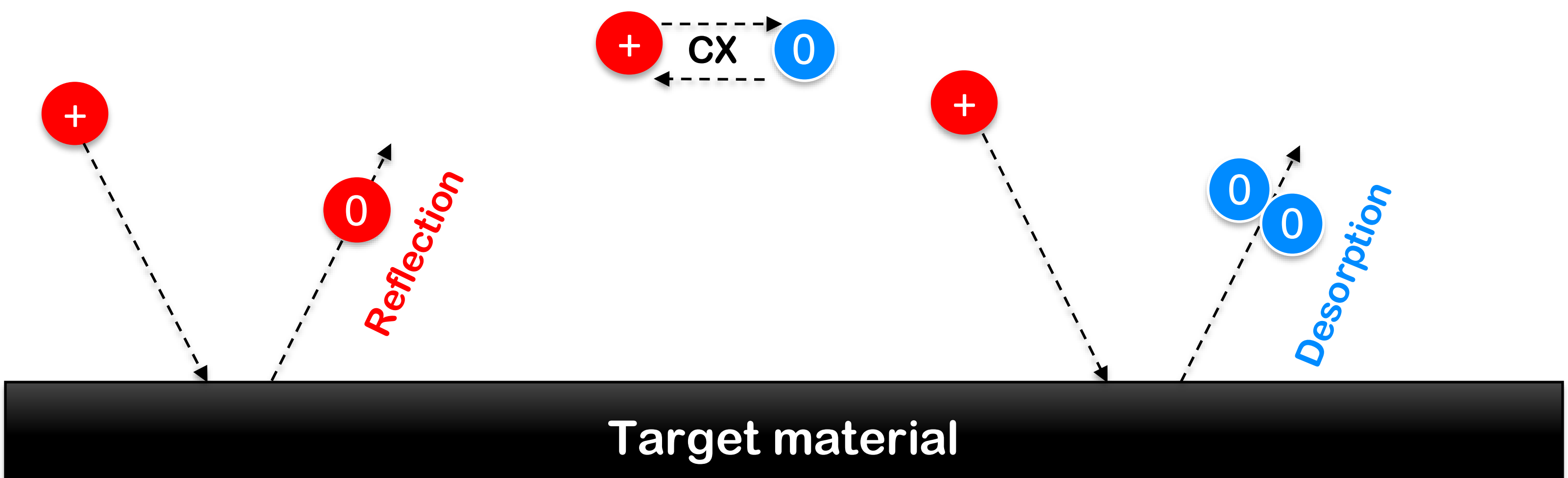


Roth et al 2008 PPCF ***50****, 103001*

Q: Why the radiation emitted by hydrogen isotopes comes from the divertor?

A: Release of hydrogen isotope neutrals

- Chemical desorption of H_2/D_2 molecules followed by dissociation processes: cold population (T_c= 0.5-3 eV)
- Neutrals released from the target material following H^+/D^+ ion impact (reflection) + Charge exchange processes between $H-H^+$ and $D-D^+$: warm population (T_w= 10-100 eV)



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How do the emitted line spectra look like?

Balmer-α line profiles governed by Doppler & Zeeman effects

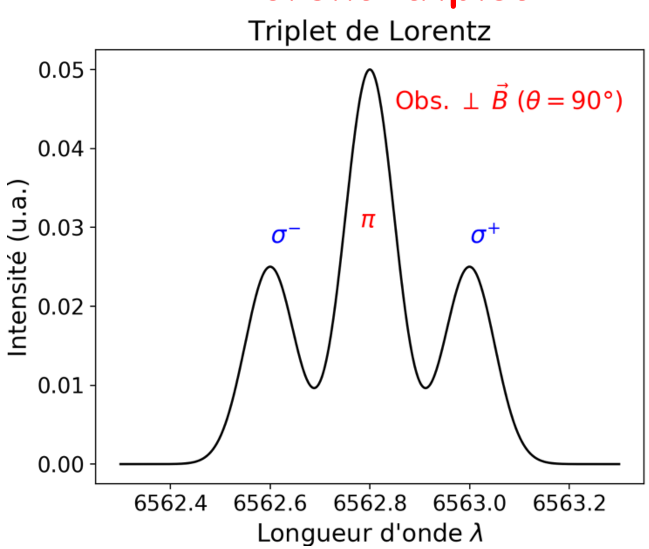
- Zeeman effect (B=1-4 T)
- The angle of observation with respect to the magnetic field line
- Doppler broadening: temperature and fraction of each neutral population
- Concentration of each H isotope

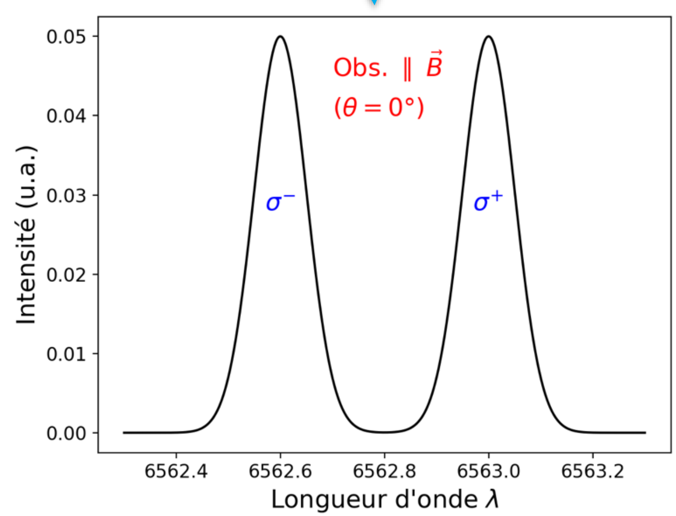
Hα line profiles for an “arbitrary” neutral population

- **For an angle of observation θ with respect to B:**

$$I_\theta = sin^2\,\theta \times I_\perp + cos^2\,\theta \times I_\parallel$$

Lorentz triplet



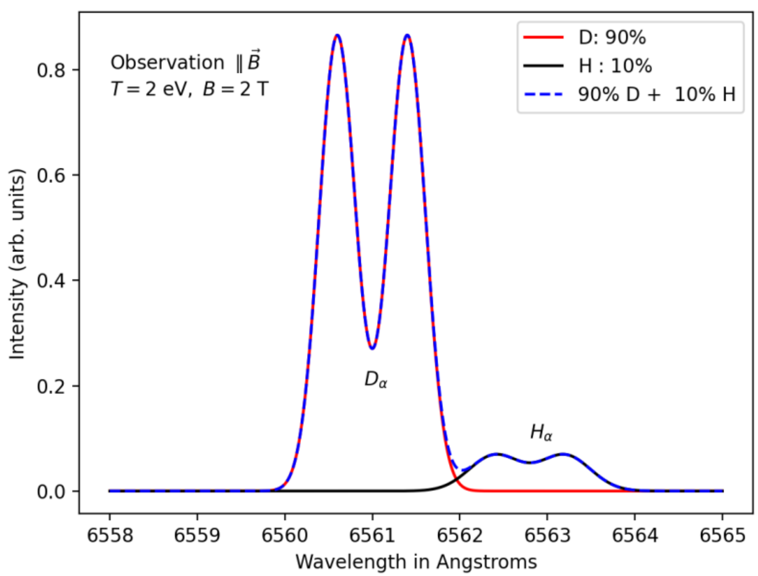


Parallel Hα/Dα line profiles for single populations

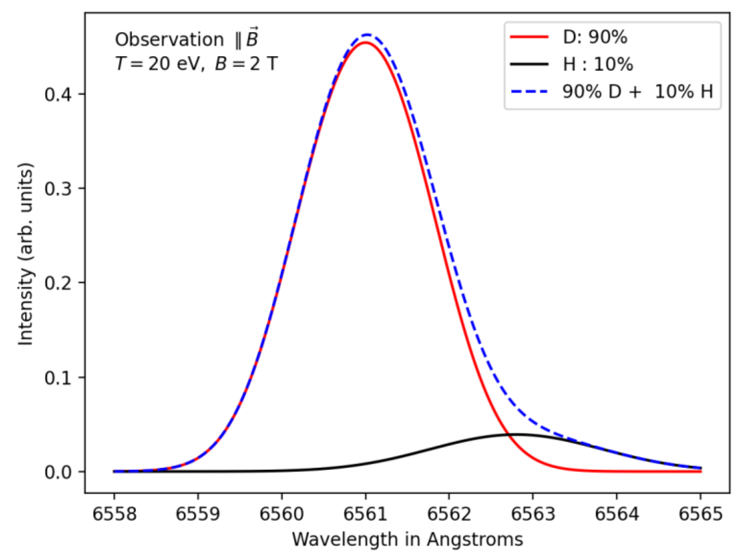
(90%D + 10%H)

Hα: 6562.8 Å / Dα: 6561.0 Å ⟹ Δλ(H-D)=1.8 Å

"Cold"

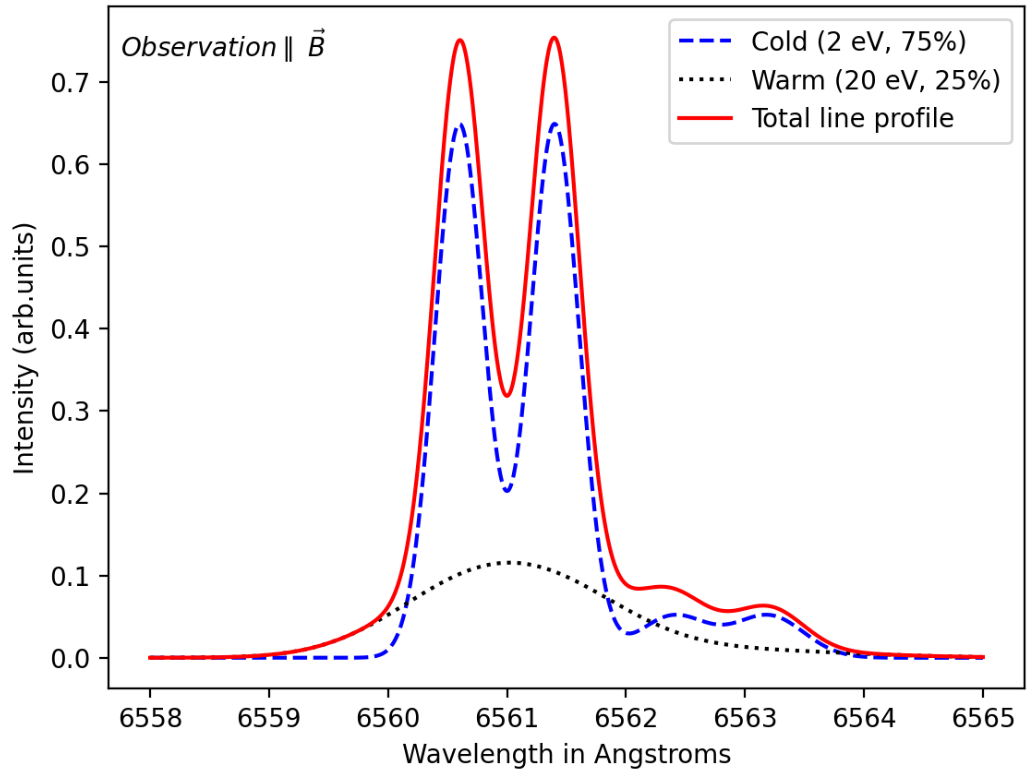


"Warm"



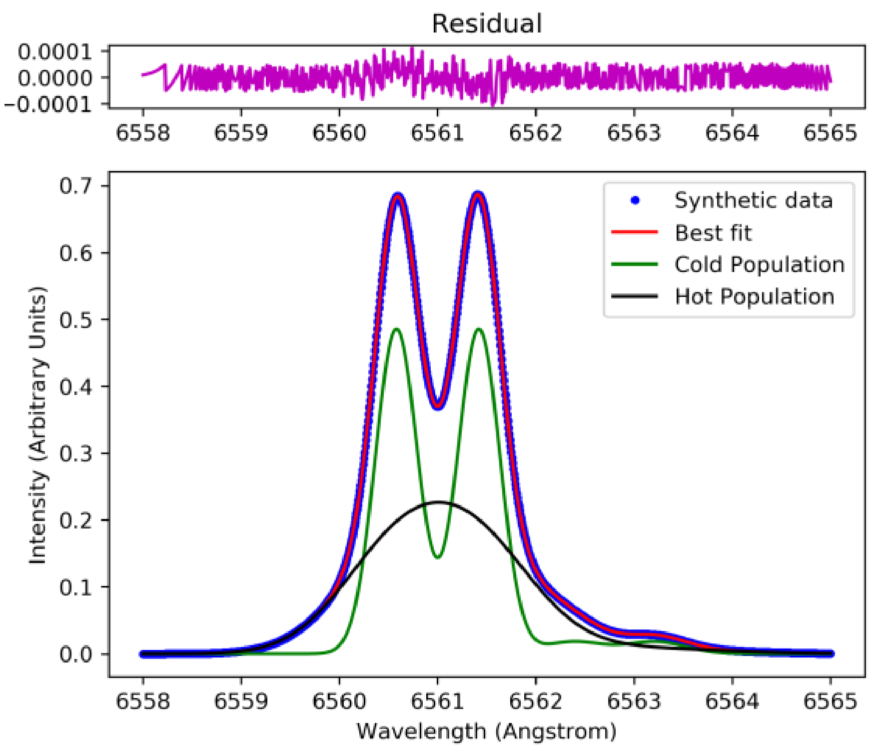
Parallel Hα/Dα line profile for both populations

(90%D + 10%H)



M. Koubiti and M Kerebel 2022 Appl. Sci. **12** 9891

Fitting synthetic Hα/Dα spectra



Optimization issue

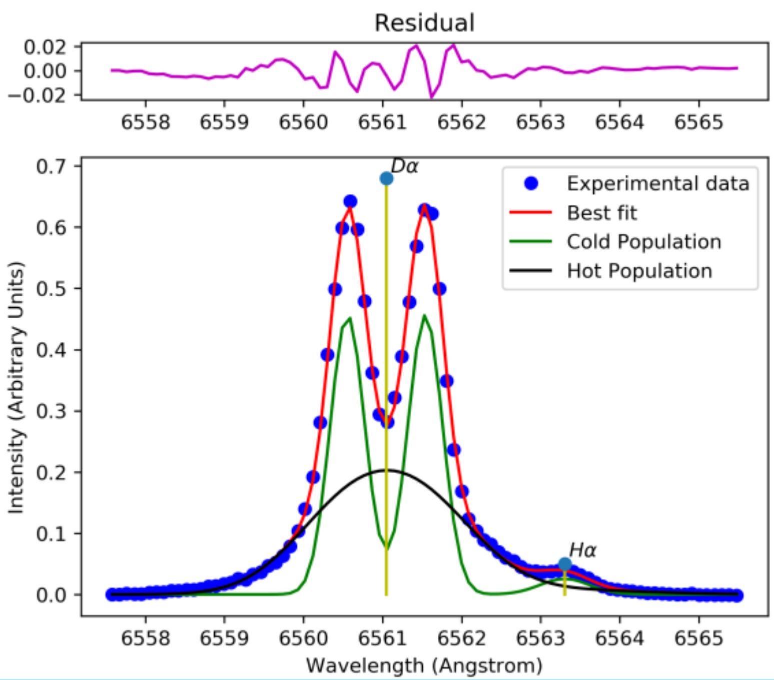
	known values	calculated values	errors
T_c	2 eV: 55 %	2.015 eV: 54.998 %	0.744 %: 0.0042 %
T_h	15 eV: 45 %	15.111 eV: 45.002 %	0.742 %: 0.0051 %
B	2 T	2.091 T	4.56 %
H/(H+D)	5 %	5.0007 %	0.01308 %
D/(H+D)	95 %	94.9993 %	0.00068

$$\eta_H = \frac{n_H}{n_H + n_D} \equiv \frac{H}{H + D}$$

$$\eta_D = \frac{n_D}{n_H + n_D} \equiv \frac{D}{H + D}$$

Fitting experimental Hα/Dα spectra

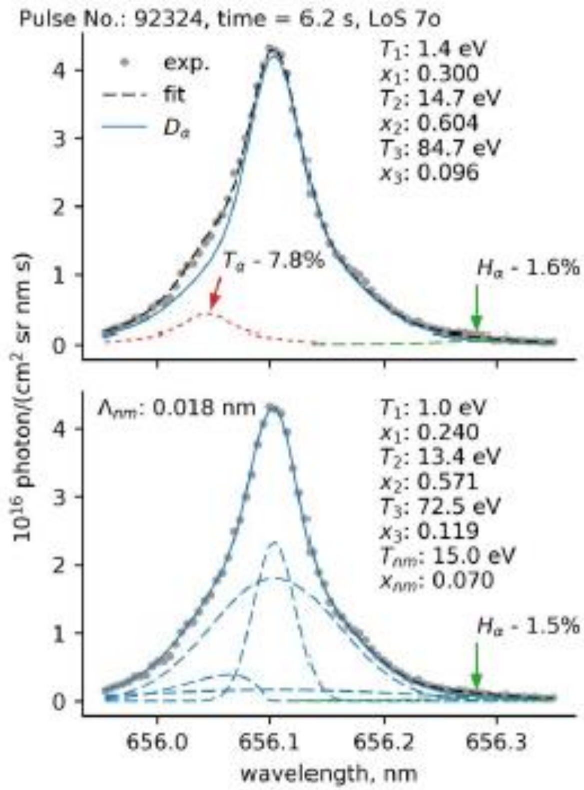
- **Analysis of measured spectra requires fitting to obtain important parameters like the isotopic ratio (relative isotopic concentration)**



	calculated values
T_c	2.1 eV: 47.8 %
T_h	22.3 eV: 52.2 %
B	2.45 T
H/(H+D)	3.8 %
D/(H+D)	96.2 %

Balmer-α line spectra under tritium operation

- Dα and Tα lines very close ($\Delta\lambda$~0.65 Å)
- Spectra more complicated to fit, questions about the accuracy of the deduced parameters
- ML can help

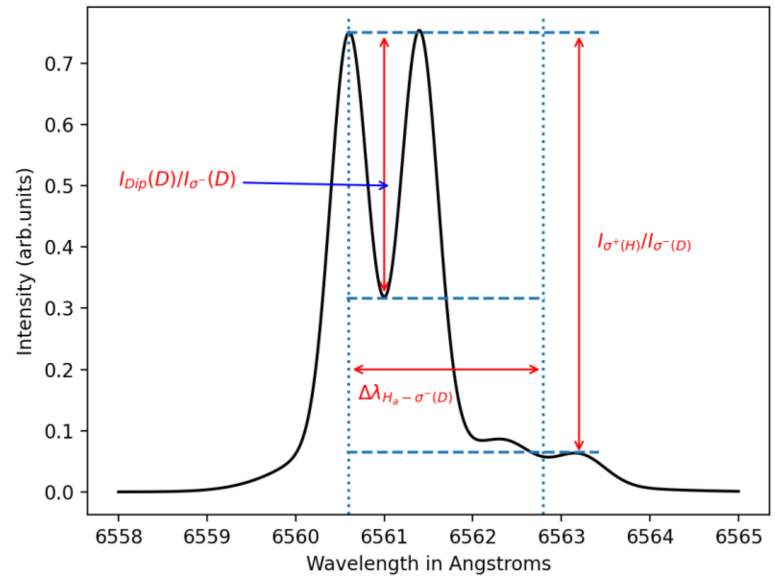


V.S. Neverov *et al,* Nucl. Fusion (2019) **59** 046011

Application of a basic neural network model

- Use a fully connected NN algorithm combined with few spectroscopic features (instead of whole spectra) to determine the H/H+D ratios:

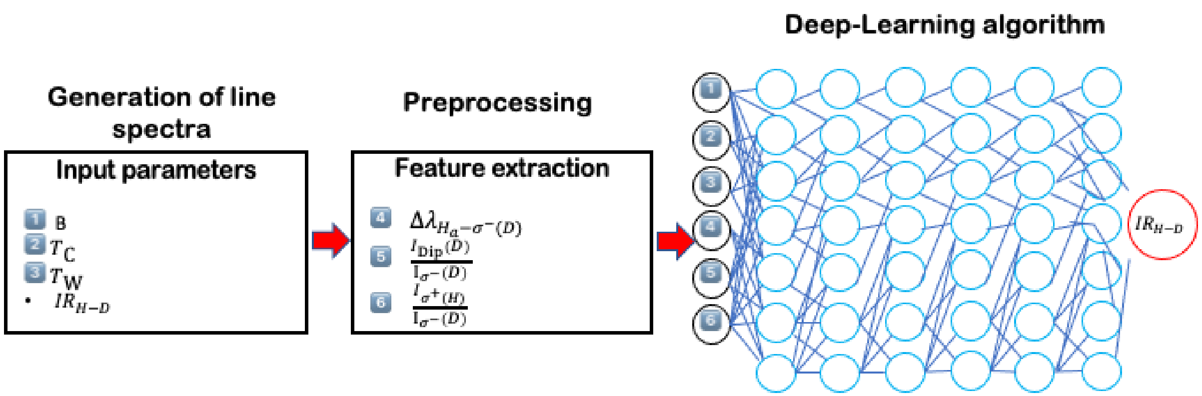
  - B-field
  - Neutral temperatures T_c and T_w
  - Wavelength separation: $\Delta\lambda_{H_\alpha-\sigma^-(D)}$
  - Peak-to-peak intensity ratio: $I_{\sigma^+(H)}/I_{\sigma^-(D)}$
  - Dip-to-peak intensity ratio: $I_{Dip(D)}/I_{\sigma^-(D)}$



- Spectra generated by varying several parameters and including a gaussian noise.
- Pre-processing code extracting input features for the NN model: It determines the spectral minima and maxima and then calculate wavelength separation, peak-to-peak and dip-to-peak intensity ratios.

The basic NN model (TensorFlow ML platform)

- **Input layer (6 nodes):** B, T_c, T_w, $\Delta\lambda_{H_\alpha - \sigma^-(D)}$, $I_{\sigma^+(H)}/I_{\sigma^-(D)}$, $I_{Dip(D)}/I_{\sigma^-(D)}$)
- **Output layer (1 node=H/H+D) :** $\eta_H = \frac{n_H}{n_H + n_D}$
- **Six intermediate layers with hundreds of neurons (nodes)**



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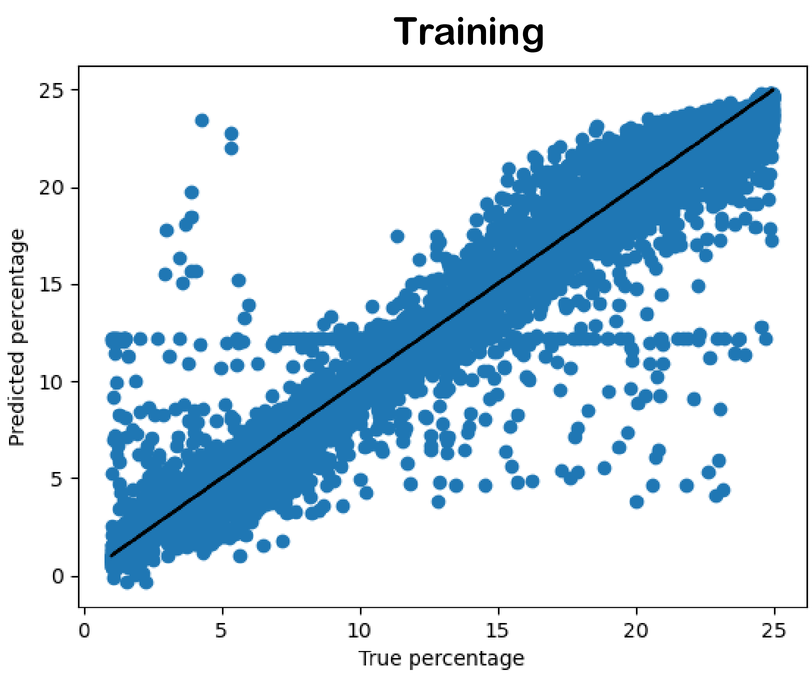
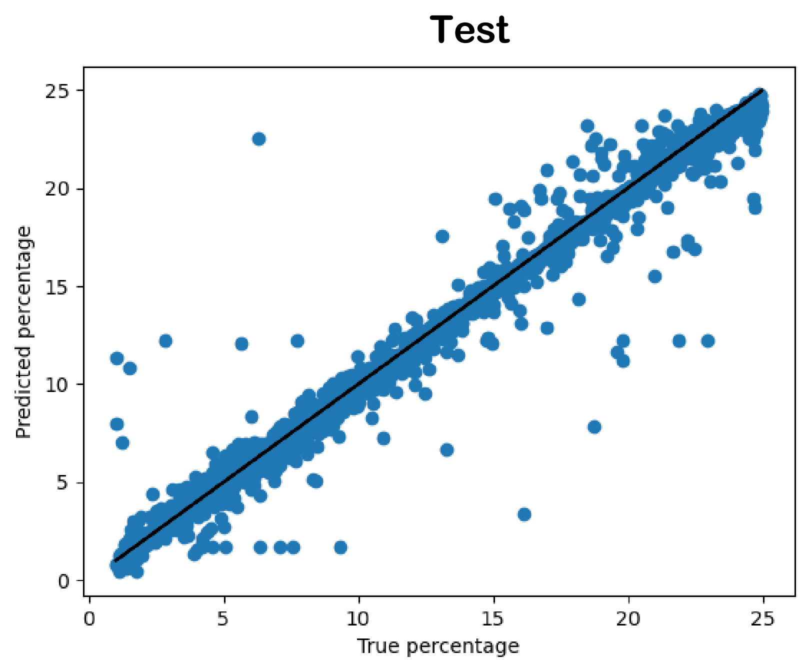
https://www.tensorflow.org/guide
https://keras.io/api/optimizers/adam/

Predictions of the basic NN model



MSE: 7.6%



MSE: 7.9%

- **These errors are not inherent to the NN algorithm but to the inaccuracy in the extraction of the spectroscopic features by the preprocessing code.**

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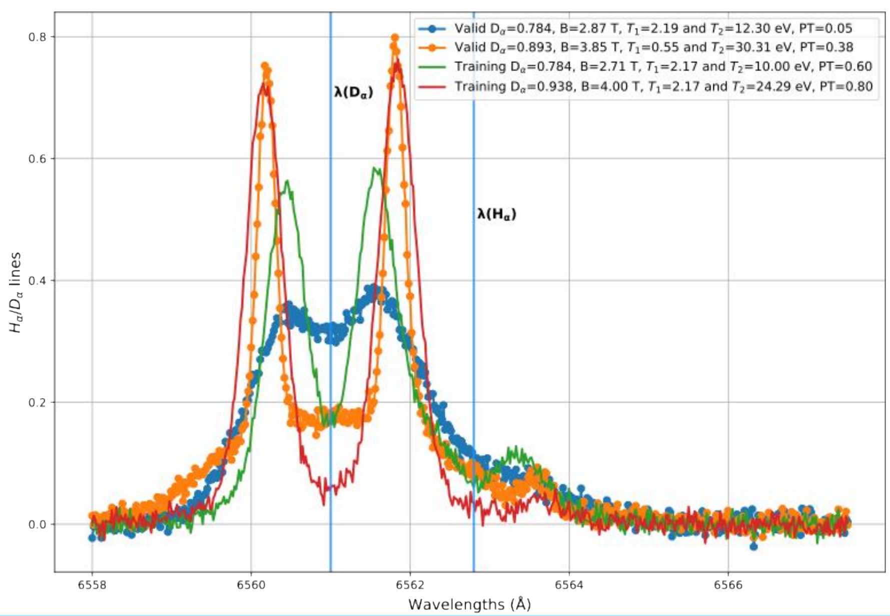
Use of an advanced 1D-CNN model

Generation of the Balmer α spectra to be trained instead of the few characteristics

- **Variation of the parameters:**
  - **B in the range 1-4 T**
  - **Concentration of D in the range 1-100%**
  - **Cold population fraction in the range 40-100%**
  - **Temperatures: 0.5-3 eV & 10-30eV**

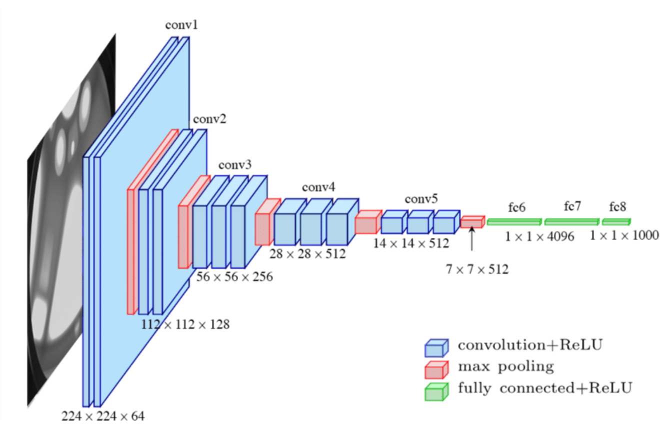
- **Training set: over 360 000 profiles & Test set: over 90 000 profiles.**

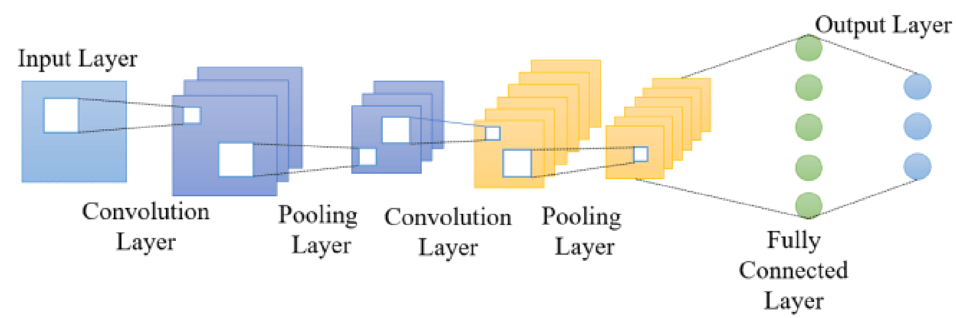


Use of an advanced 1D-CNN model

Use of whole Balmer α spectra instead of few characteristics

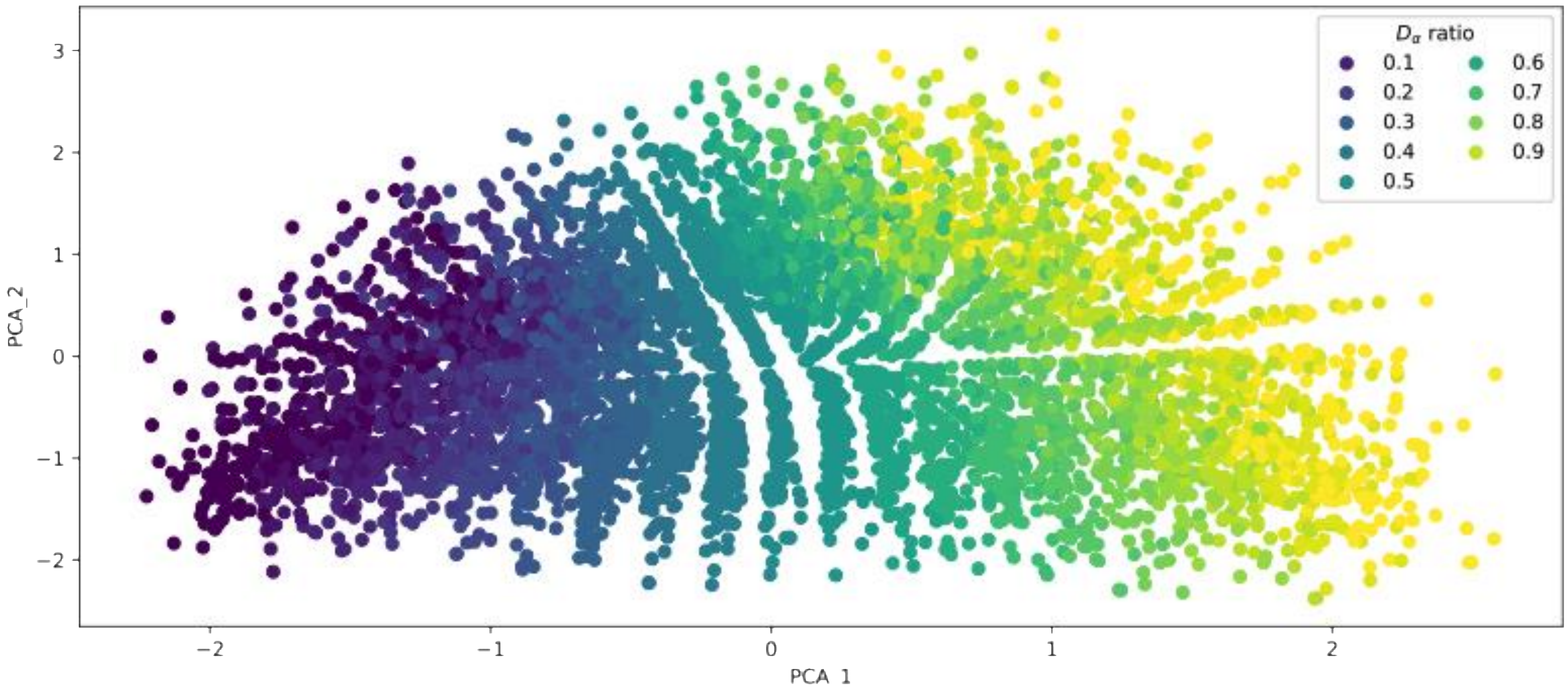
- **Use of 3 convolution layers, ReLU and swish activation functions**
- **Loss function:** $L = 0.5 \times \mathrm{MAE} + 0.5 \times \mathrm{MSE} + 10^{-4} \times \mathrm{Max}\left(y - y_{pred}\right)^2$





A. Krizhevsky et al, Advances in neural information processing systems, 25 (2012)

Visualization of the input data: Principal Component Analysis

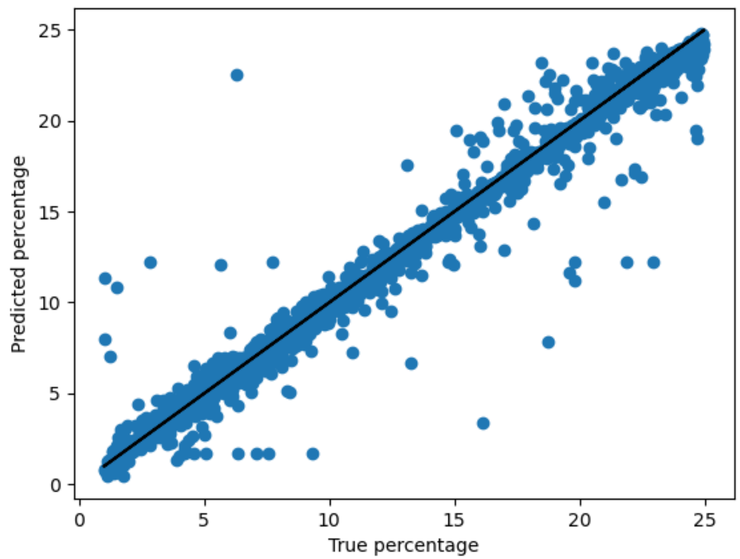


PCA projections of test set are clustered by isotopic ratio values → An efficient and generalized learning expected

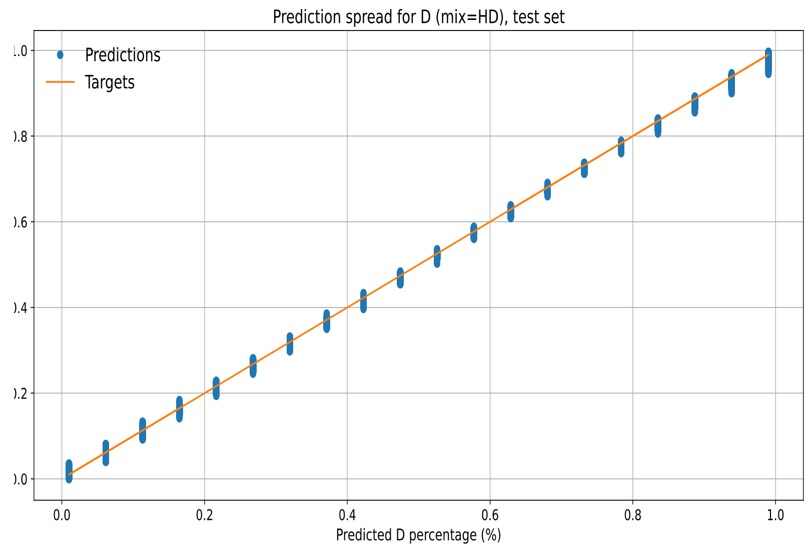
Results of the advanced 1D-CNN model for HD mixtures

H concentration predictions

Basic NN model



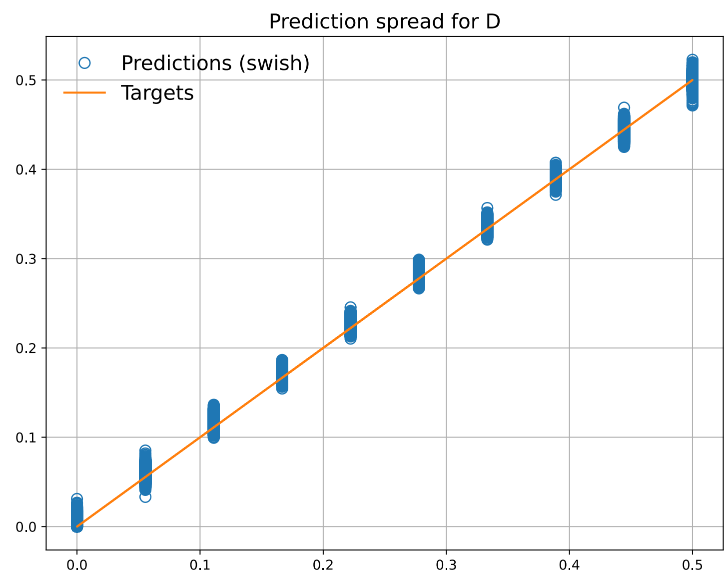
1D-CNN model

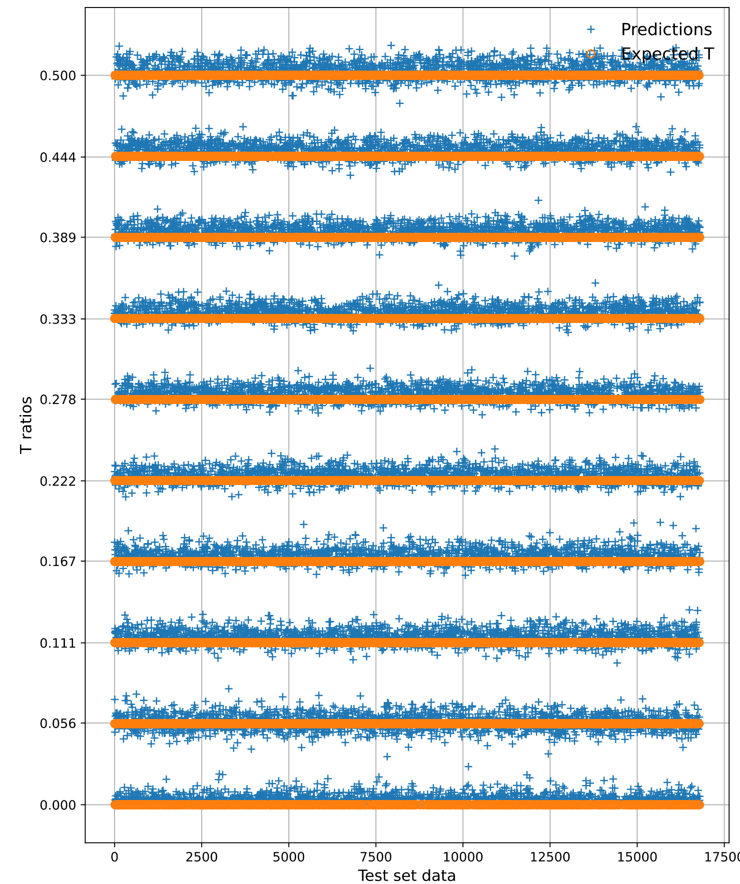


The CNN model gives better results than the basic NN model for HD plasmas

Predictions of the 1D-CNN model for DT mixtures

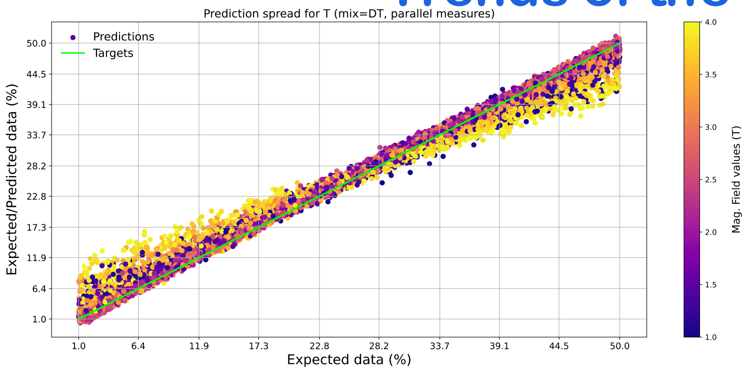
D concentration prediction in DT mixtures

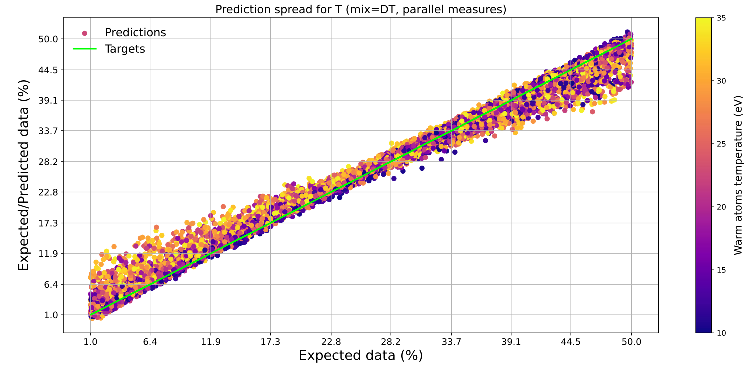


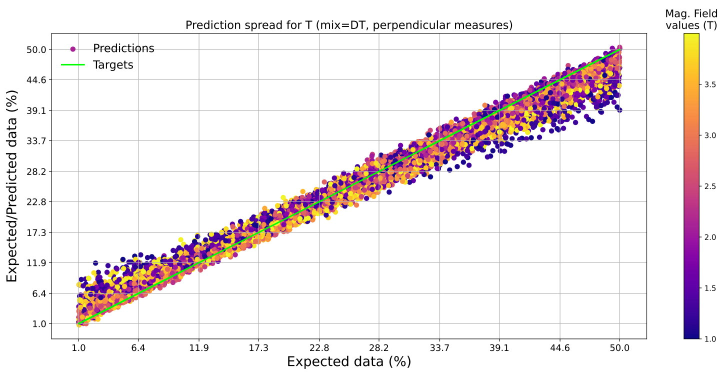


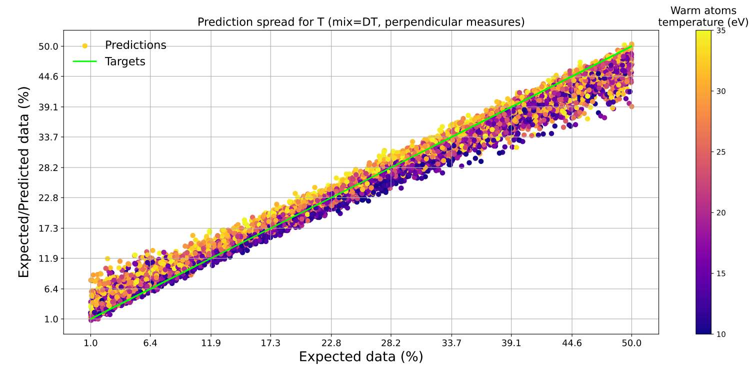
The CNN model predictions are better for HD plasmas than for DT plasmas

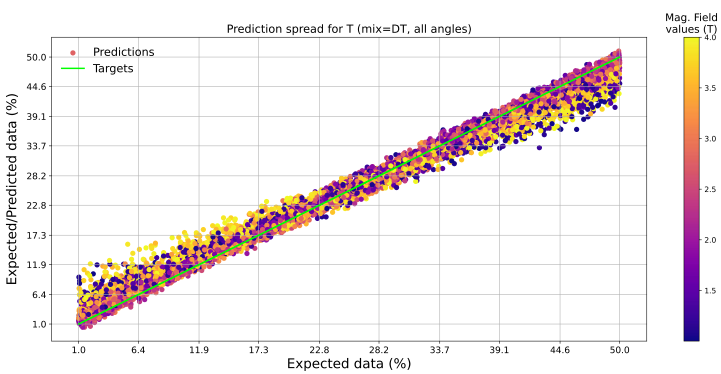
Trends of the 1D-CNN model predictions

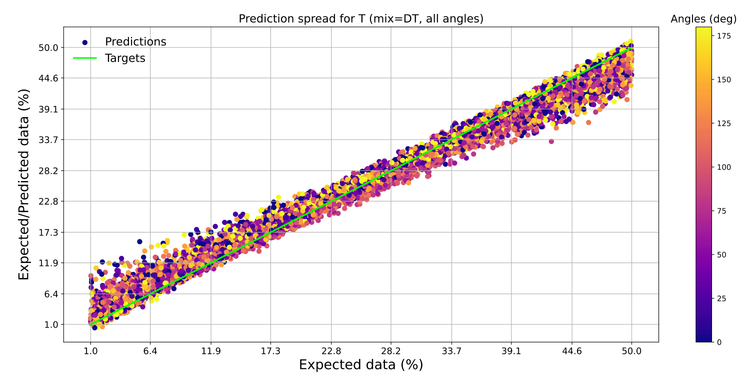






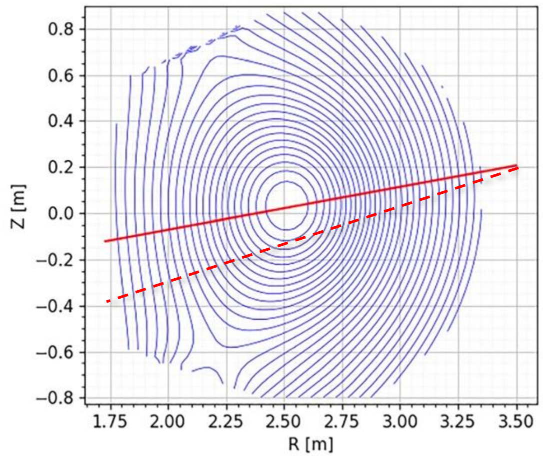


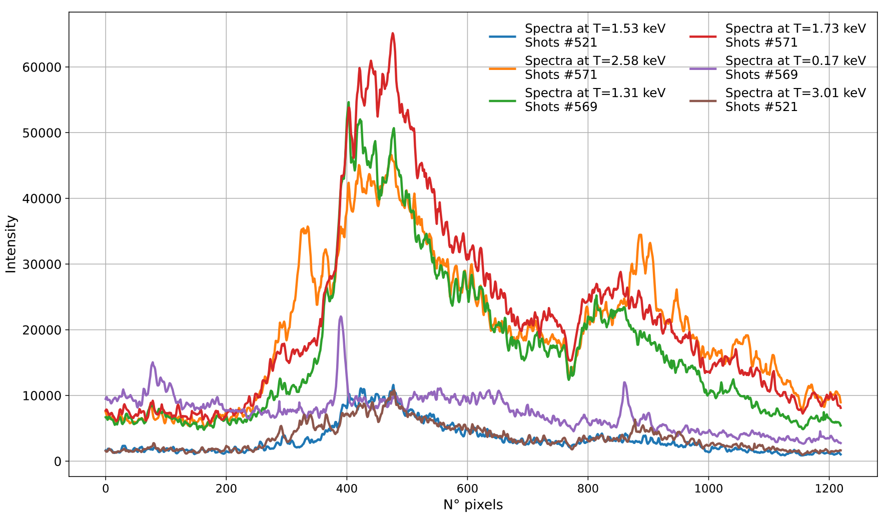




Tungsten EUV emission in WEST

Spectral range: 15-70 Å, ionization stages: W^{27+}-W^{45+}





Use of CRM modeling

Physics of Plasmas ARTICLE pubs.aip.org/aip/pop

Collisional-radiative modeling and radiative emission of tungsten in tokamak plasmas in the temperature range (800–5000) eV

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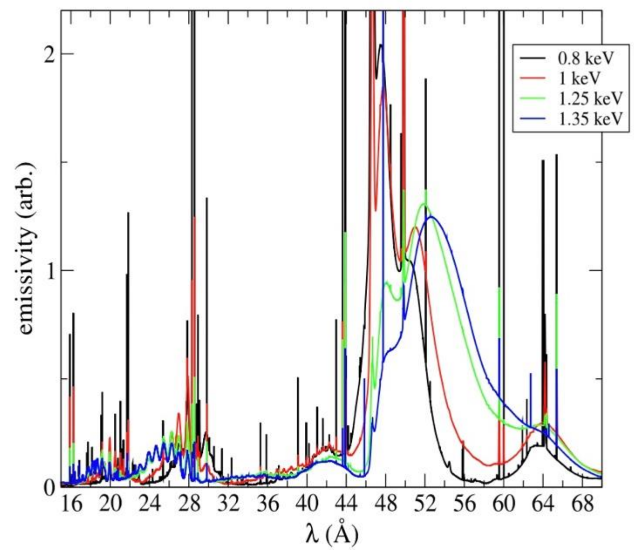
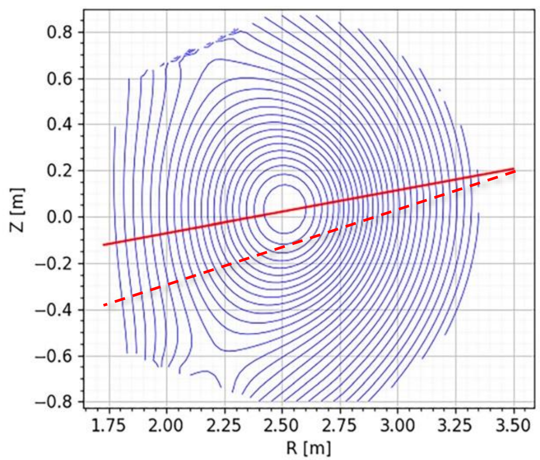
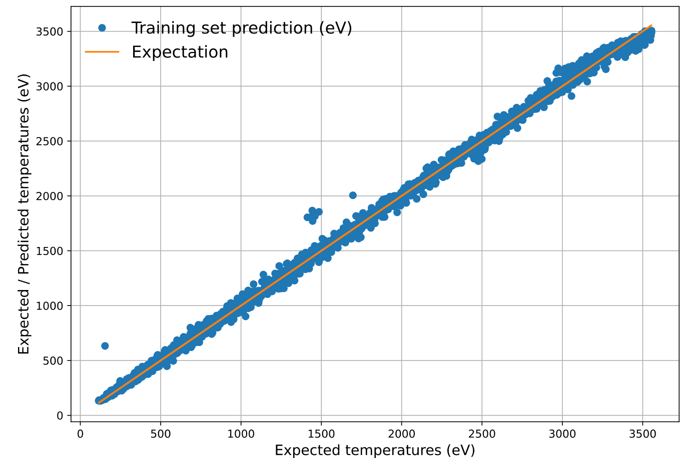
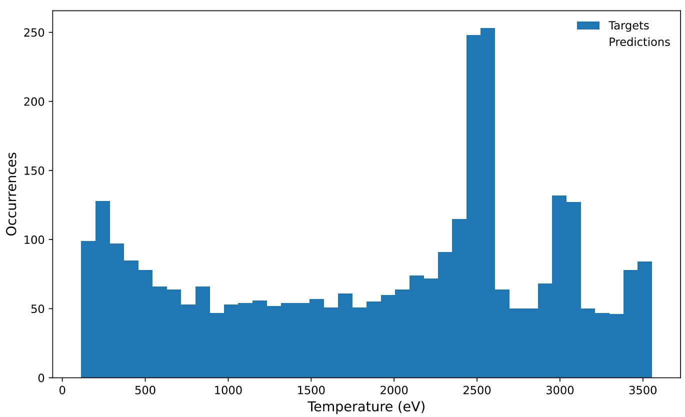


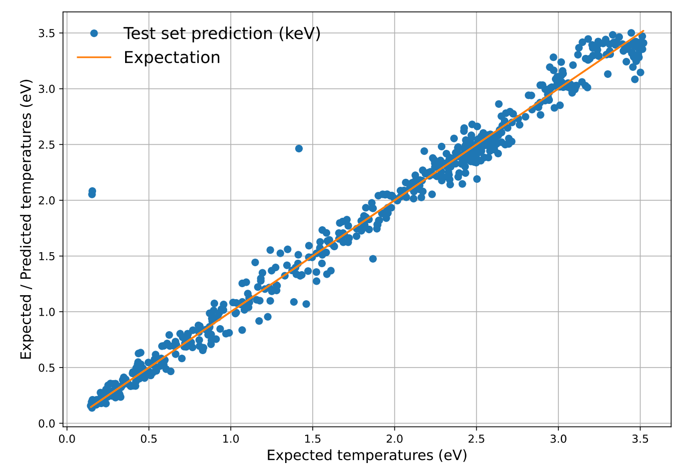
- **First idea: use 1D-CNN AlexNet to determine $T_{e,\,Max}$ for each spectrum**



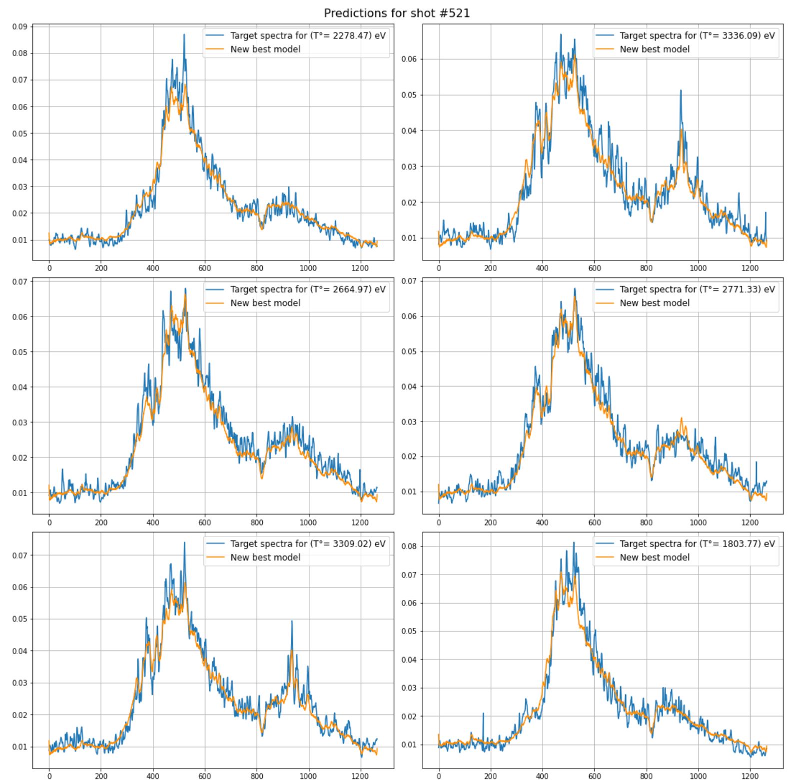
Model predictions







- **Second idea: use other models like Auto-Encoders (AE) to generate W spectra from $T_{e,\,Max}$.**



Preliminary results not satisfying $\Longrightarrow$ use spatial T_e profiles as targets for the model training

Summary

- **The application of the 1D-CNN model (adapted Alex-Net) to theoretical profiles of the Balmer-α line emitted by hydrogen isotopes for tokamak divertor conditions are promising: the model allows to predict the isotopic ratios in both HD and DT plasmas. However, its gives better results for HD than DT mixtures.**

- The model needs to be assessed by applying it to experimental spectra from different magnetic fusion devices (WEST and JET).

- **The application of the 1D-CNN model and other models like AEs to experimental EUV tungsten spectra from WEST give results which are not yet satisfying. Therefore, more data and more investigations are needed.**