Artificial Neural Networks (ANN) modeling of the pulsed heat load during ITER CS magnet operation

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Outline

- Background and approach
- 4C model of the CS coil
- Artificial Neural Network essentials
- ANNs for the ITER CS
  - Development and training
  - Predictions
- Conclusions and perspective

Background (I)

The pulsed heat load to the cryoplant is an issue in tokamak inductive scenarios (rapid load variation, large power)

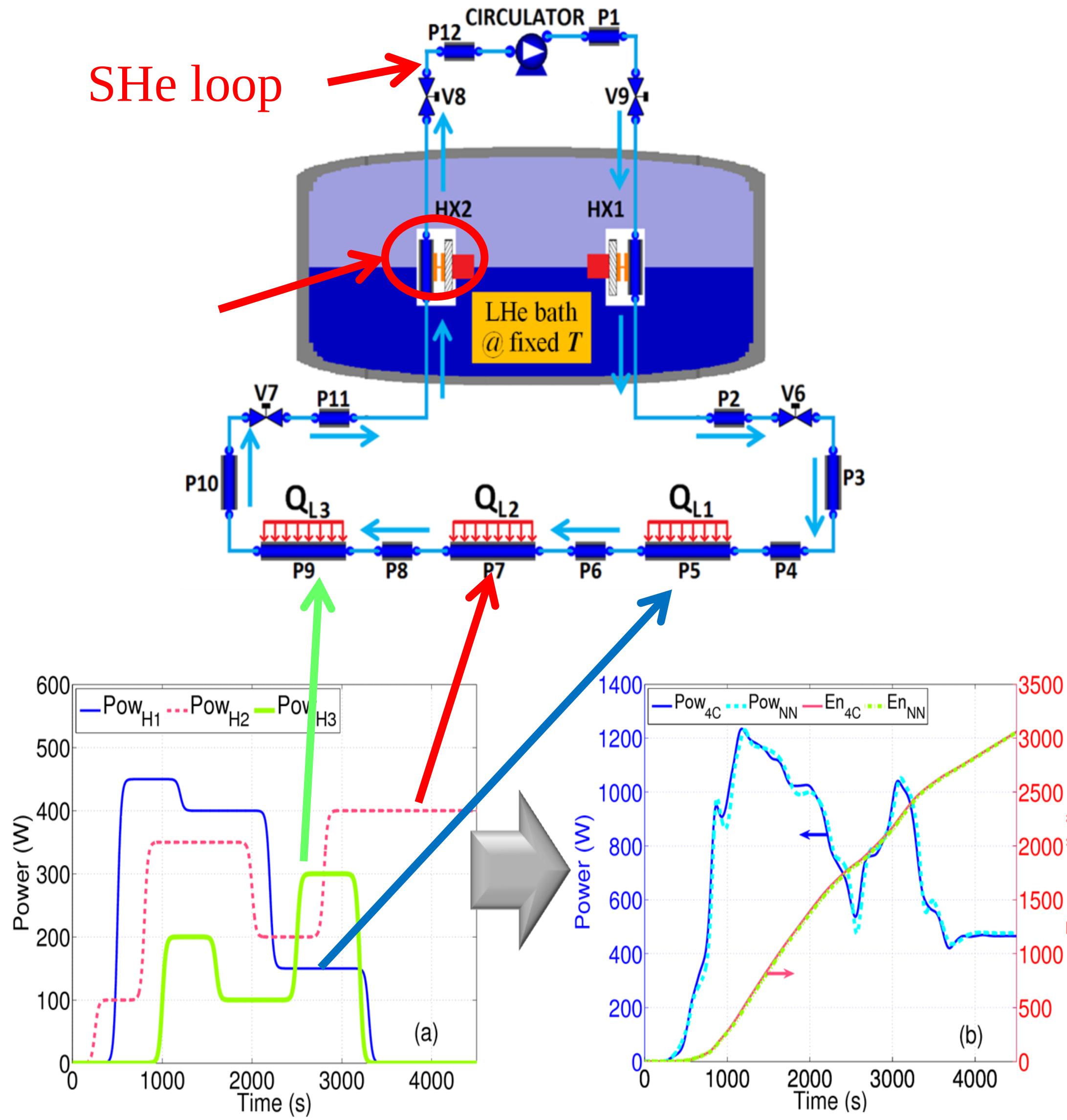
Smoothing of the heat load addressed experimentally (*HELIOS* loop at CEA Grenoble, France) and numerically (*4C code*,…)

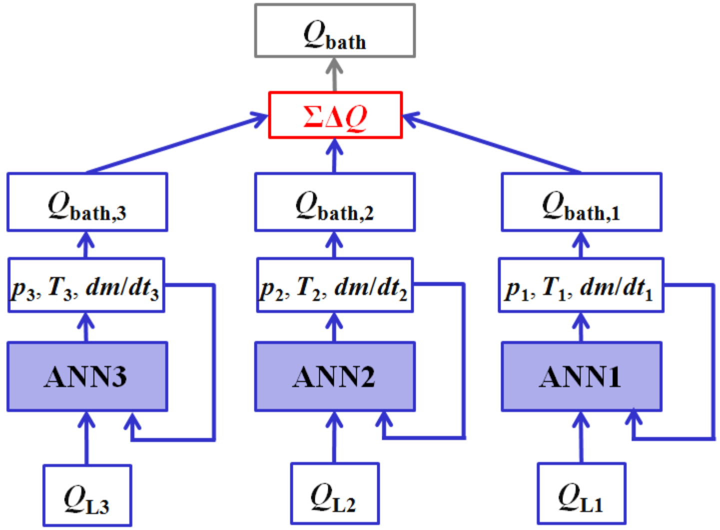
… "only" Q(t) from magnets to LHe baths is required for the assessment of the cryoplant operation

Background (II)

[L. Savoldi Richard *et al.*, Cryogenics, 2013]

- Dynamic response of the loop very well **predicted** by the 4C code
- Develop simplified but fast **Artificial Neural Networks** to predict the dynamic heat load to the LHe bath, **training/testing the ANN against the 4C results**





Accuracy: ε_{ave}~ 1%, CPU_{4C} / CPU_{ANNs} ~ 100

Our approach

Use the 4C code to train and validate simplified but fast ***Artificial Neural Networks***

Apply to ITER TF coils

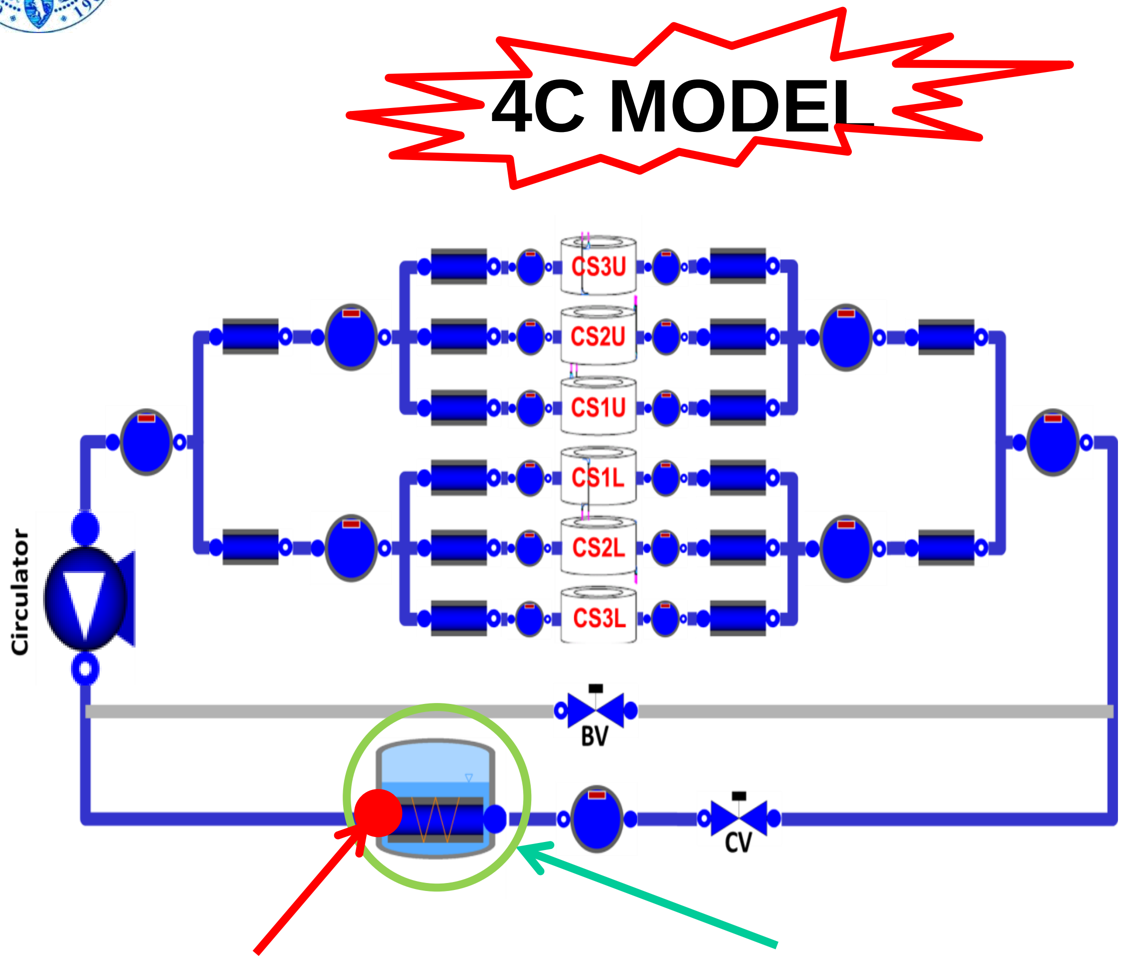
Apply to ITER CS coils

☑ Check flexibility, accuracy and speed on *HELIOS* loop

☑ Develop ANN model to estimate heat load on LHe bath

[L. Savoldi Richard et al, Cryogenics, 2013]

ITER CS coil



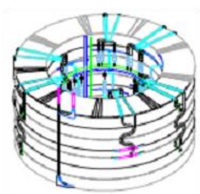
LHe bath @ constant temperature → power evolution at the HX only depends on inlet conditions

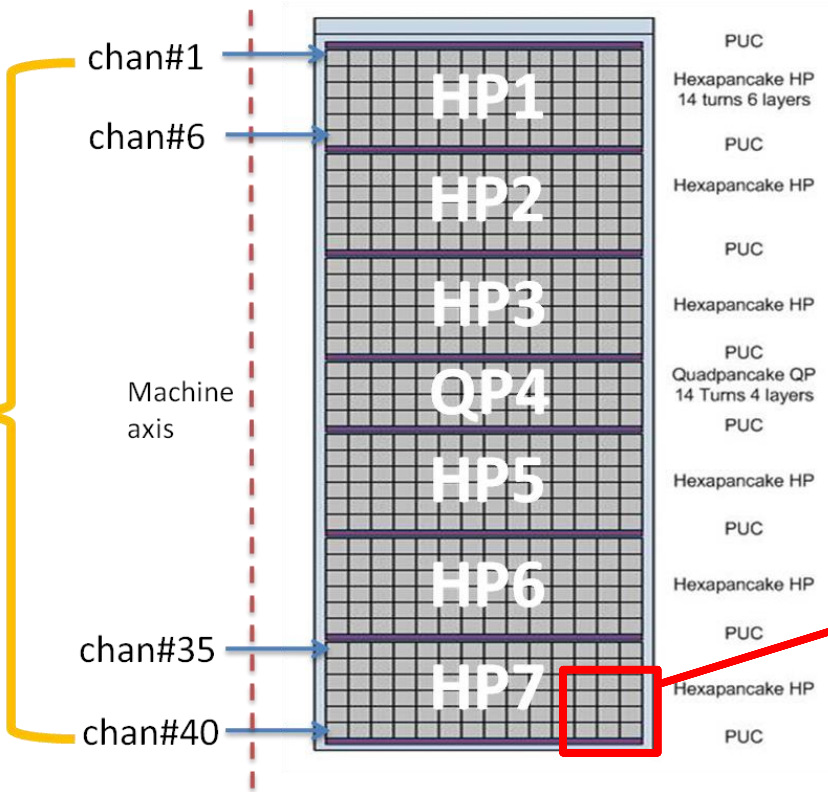
HX to LHe bath

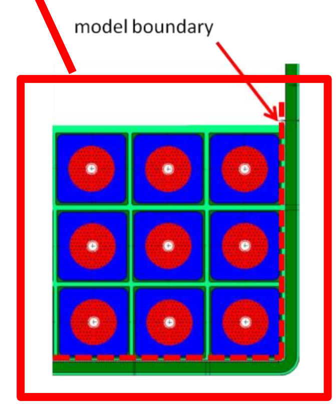
- Drivers = AC losses induced by current operation
- Dynamic response of the coil and of its cryogenic circuit can be predicted by the 4C code → Use 4C simulations to train and validate the ANN to predict power evolution at the HX

ITER CS winding pack

4C MODEL

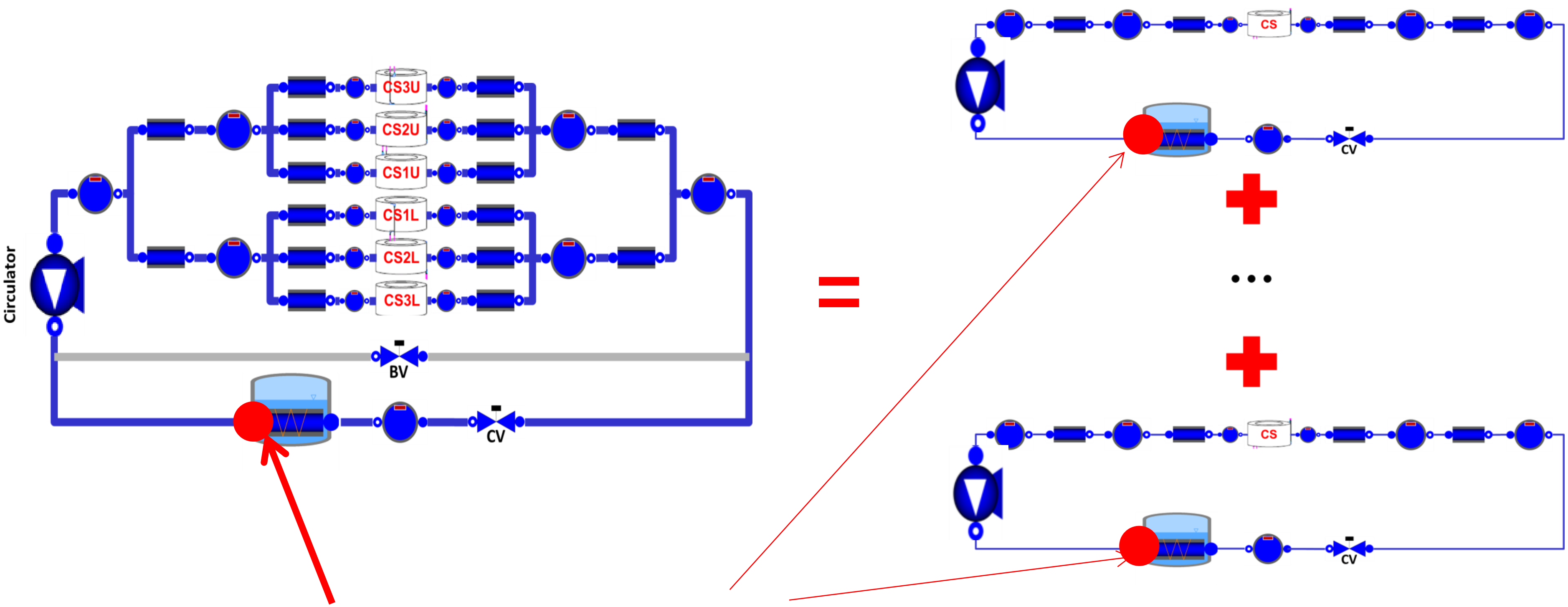






The 4C model includes all 6 x 40 hydraulic channels and their thermal coupling all along the winding pack

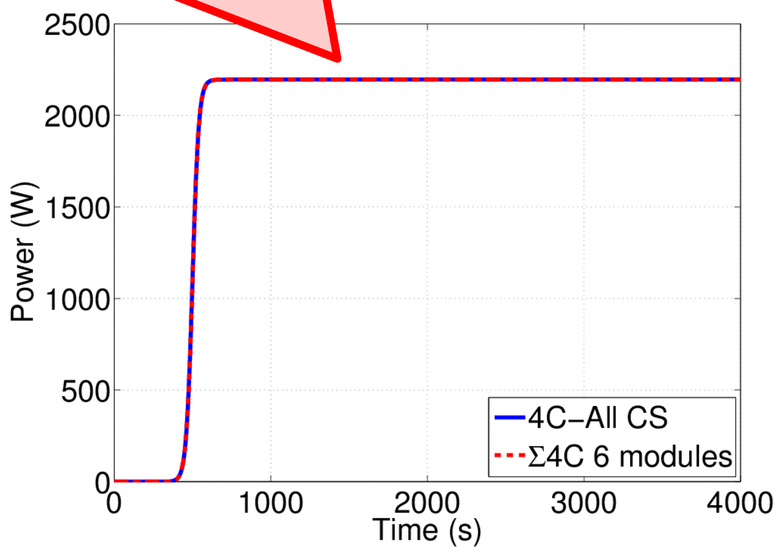
ITER CS coil: superposition of single modules

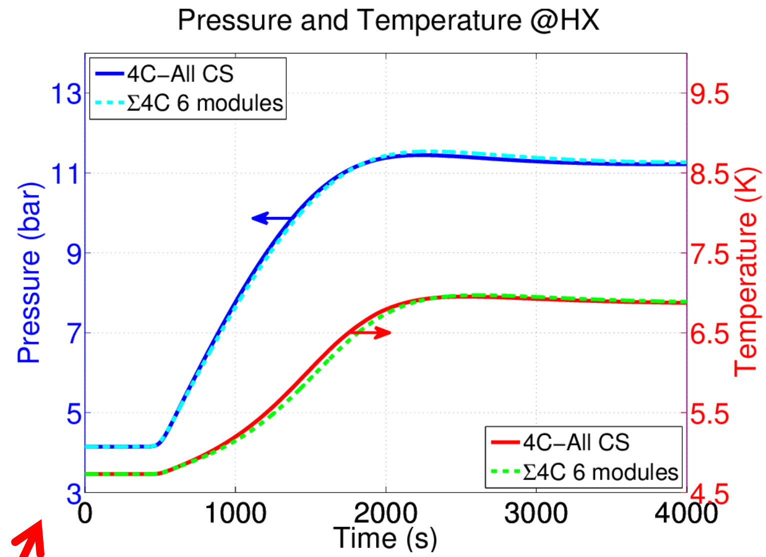


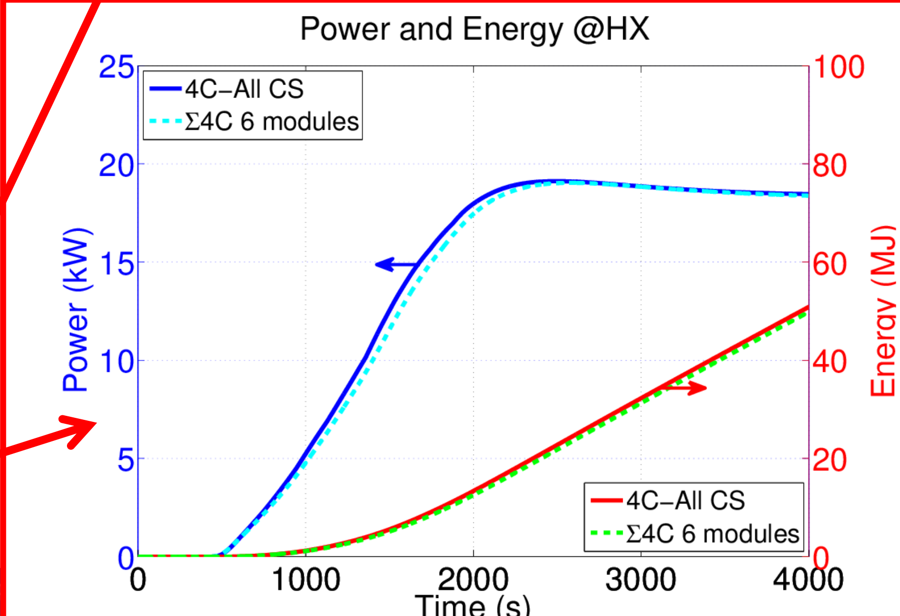
T(t), p(t) and dm/dt(t) at the HX inlet for whole CS coil can be well approximated by weighted sum of T(t), p(t) and dm/dt(t) obtained in partial models for each single module, with rescaled circuit

Superposition verification

Apply same driver = sigmoid heating
- *in all CS modules simultaneously*
- *in single modules (with rescaled circuit)*



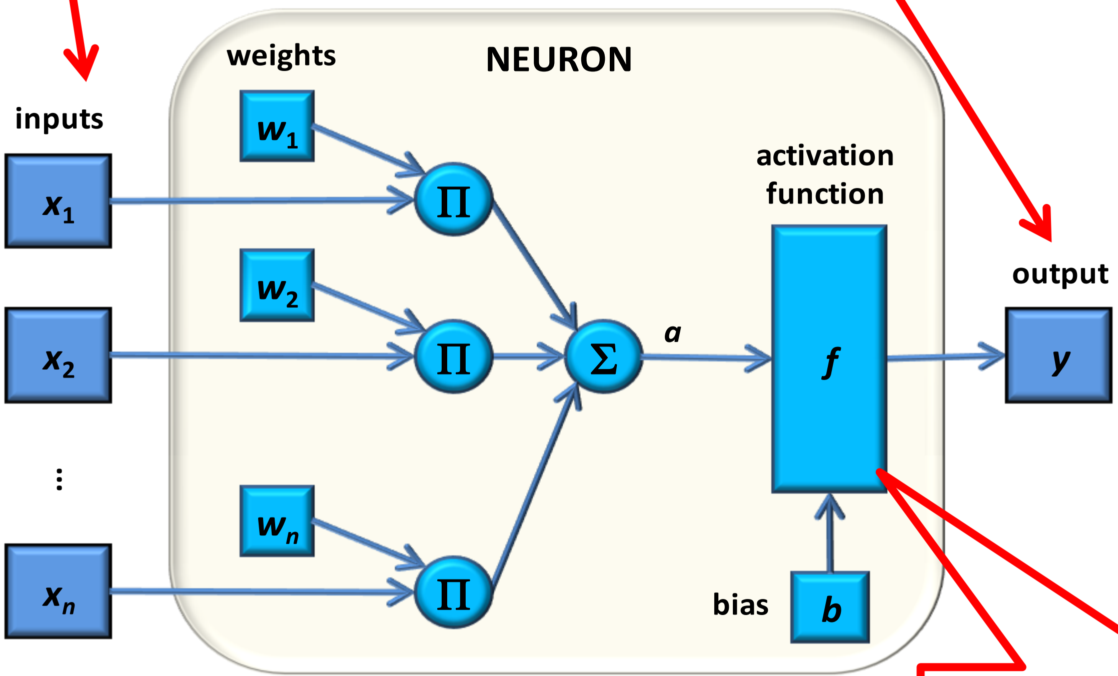




The whole CS dynamics can be obtained by superposition of single module
→ Develop an ANN for each module

ANNs (I). Artificial neuron

- In analogy with the brain neurons, combine more inputs x to produce a single output y

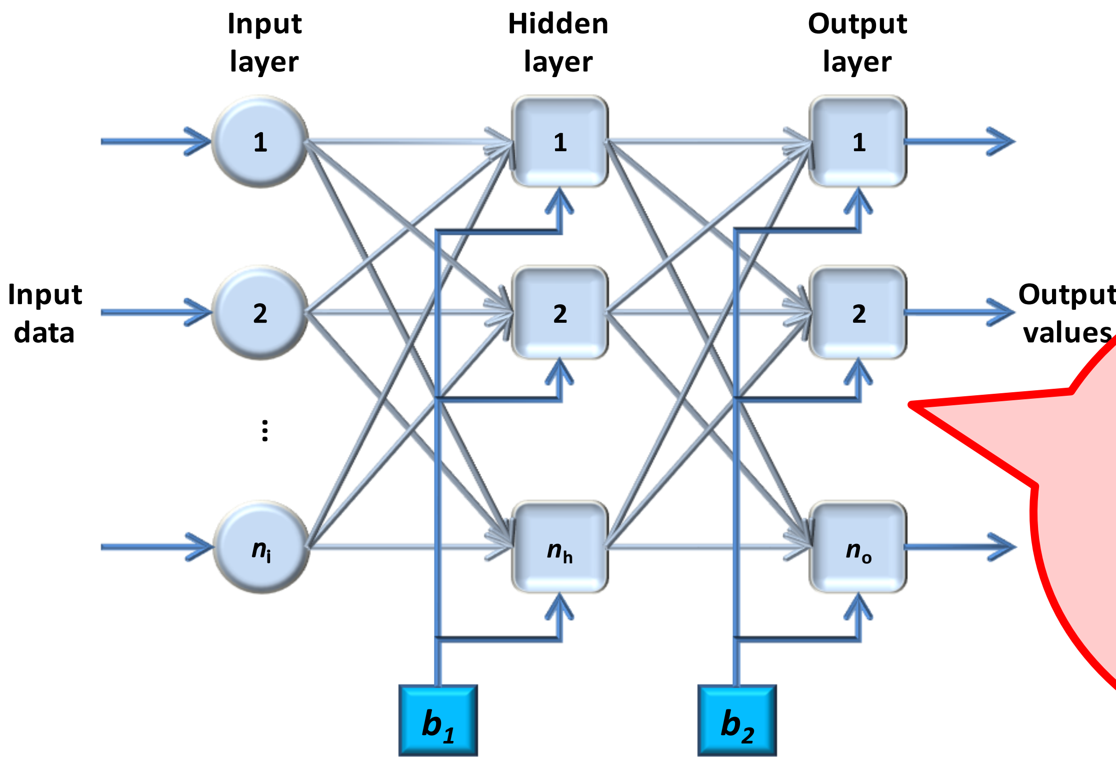


Transfer function

$$y = f\left(\sum_{i=1}^{n} w_i x_i - b\right)$$

ANNs (II). "Learning" network

- Combine several neurons together to build a network

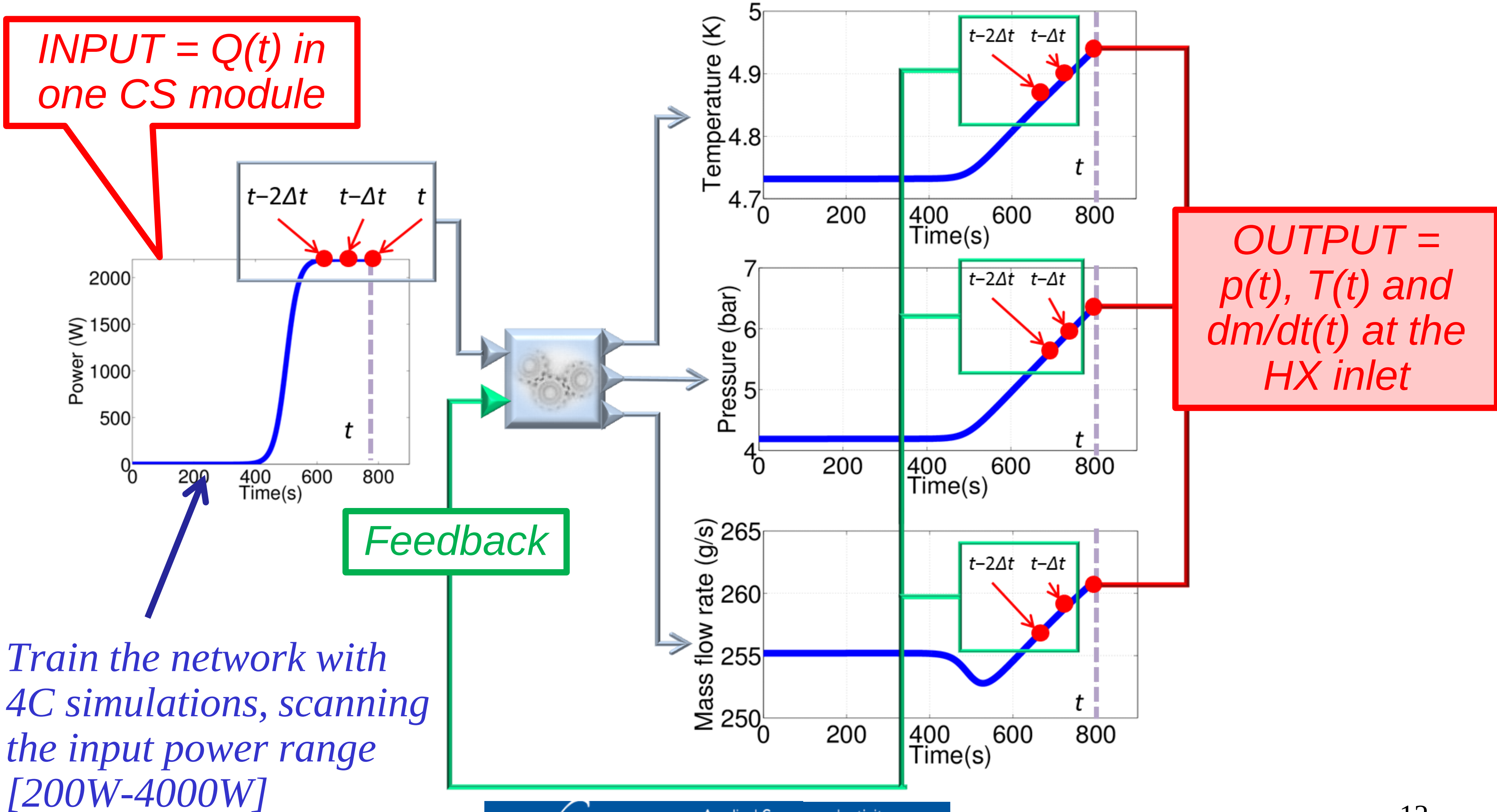


No physics content, except for the proper choice of input and output variables!

- "**Train**" the network = **feed inputs & outputs** to evaluate weights and biases through suitable training algorithms.

Single ANN development and training: CS1U

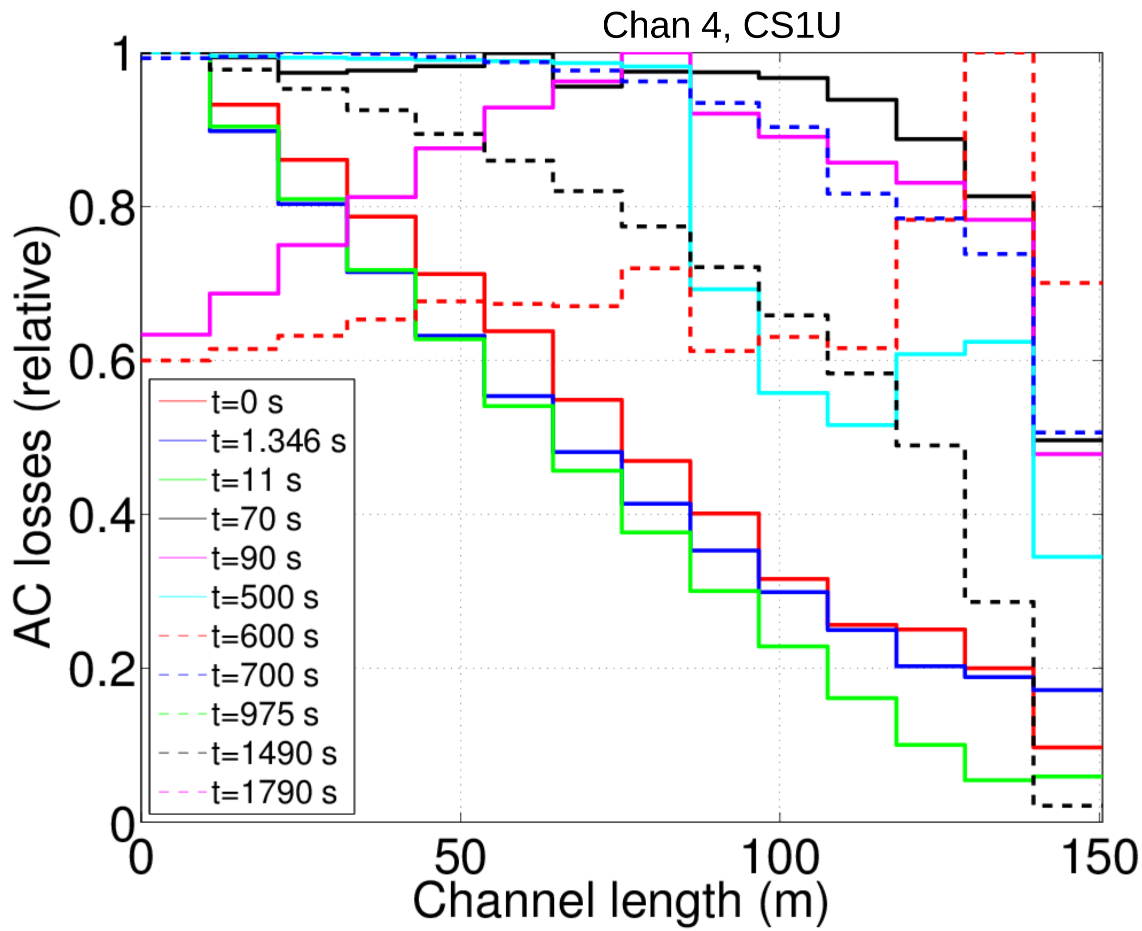
- For each CS module develop a single ANN



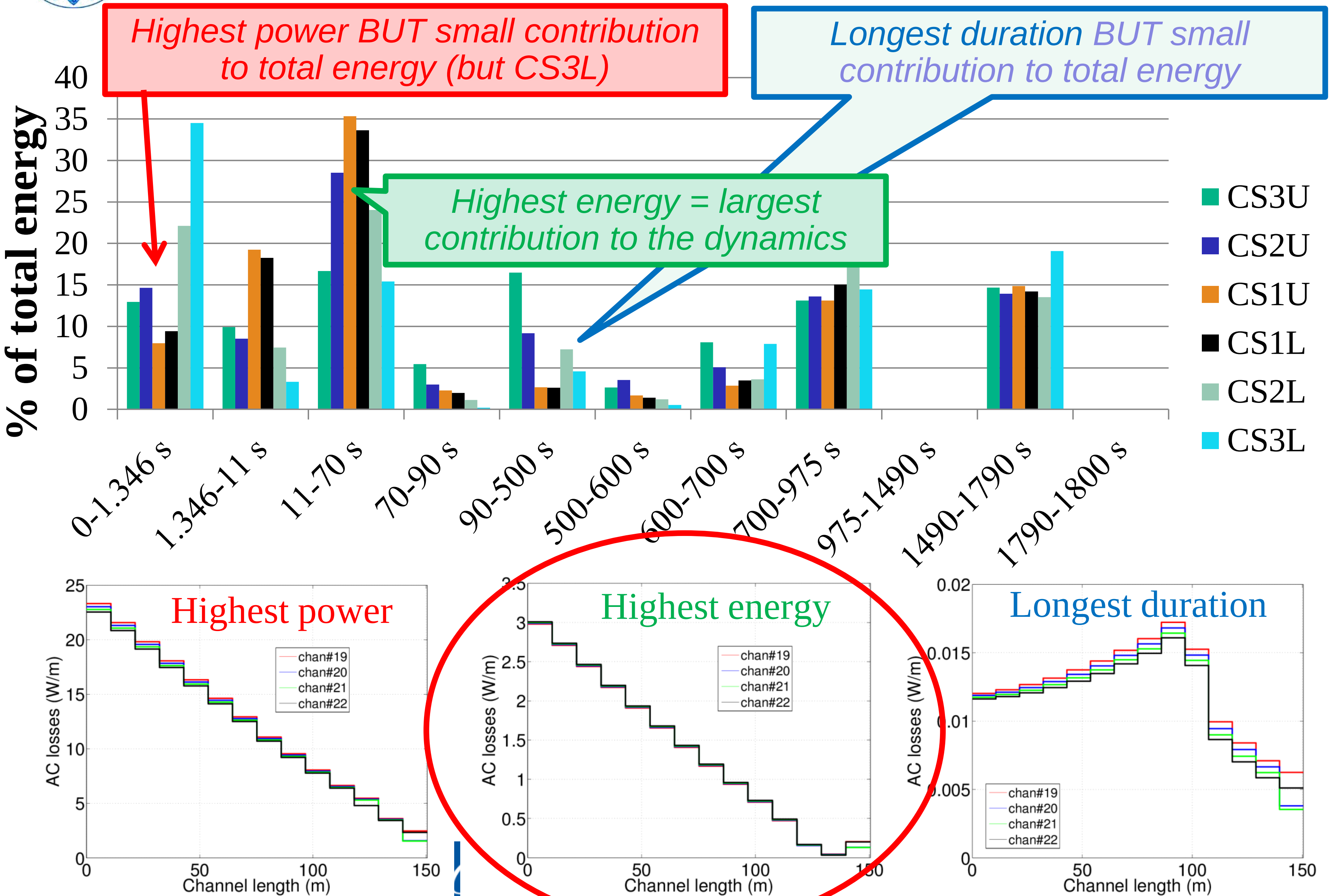
Training process (I)

- Distribution of power density changes in space and time along each hydraulic channel

- Choice of most suitable power distribution?

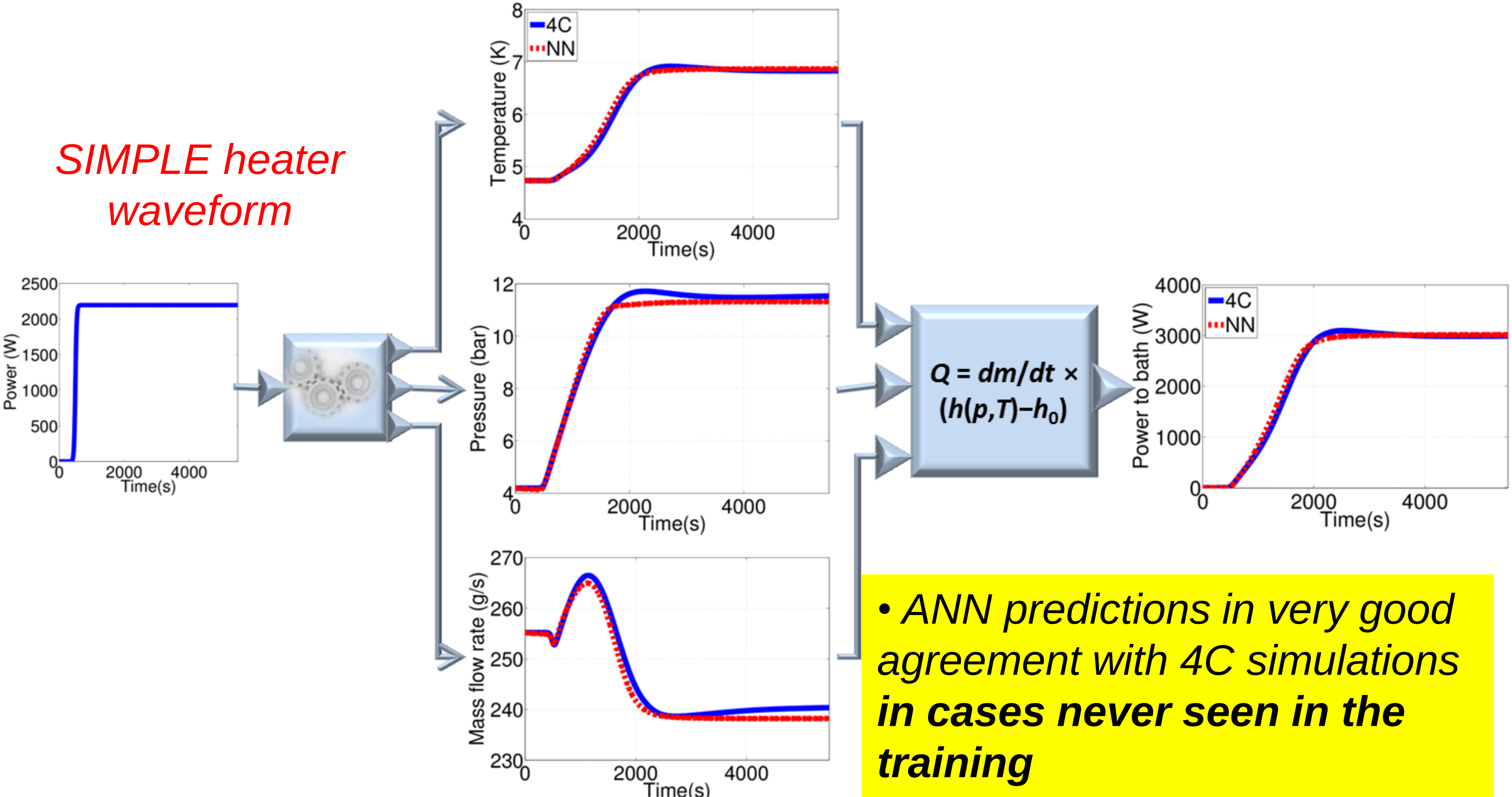


Training process (II)



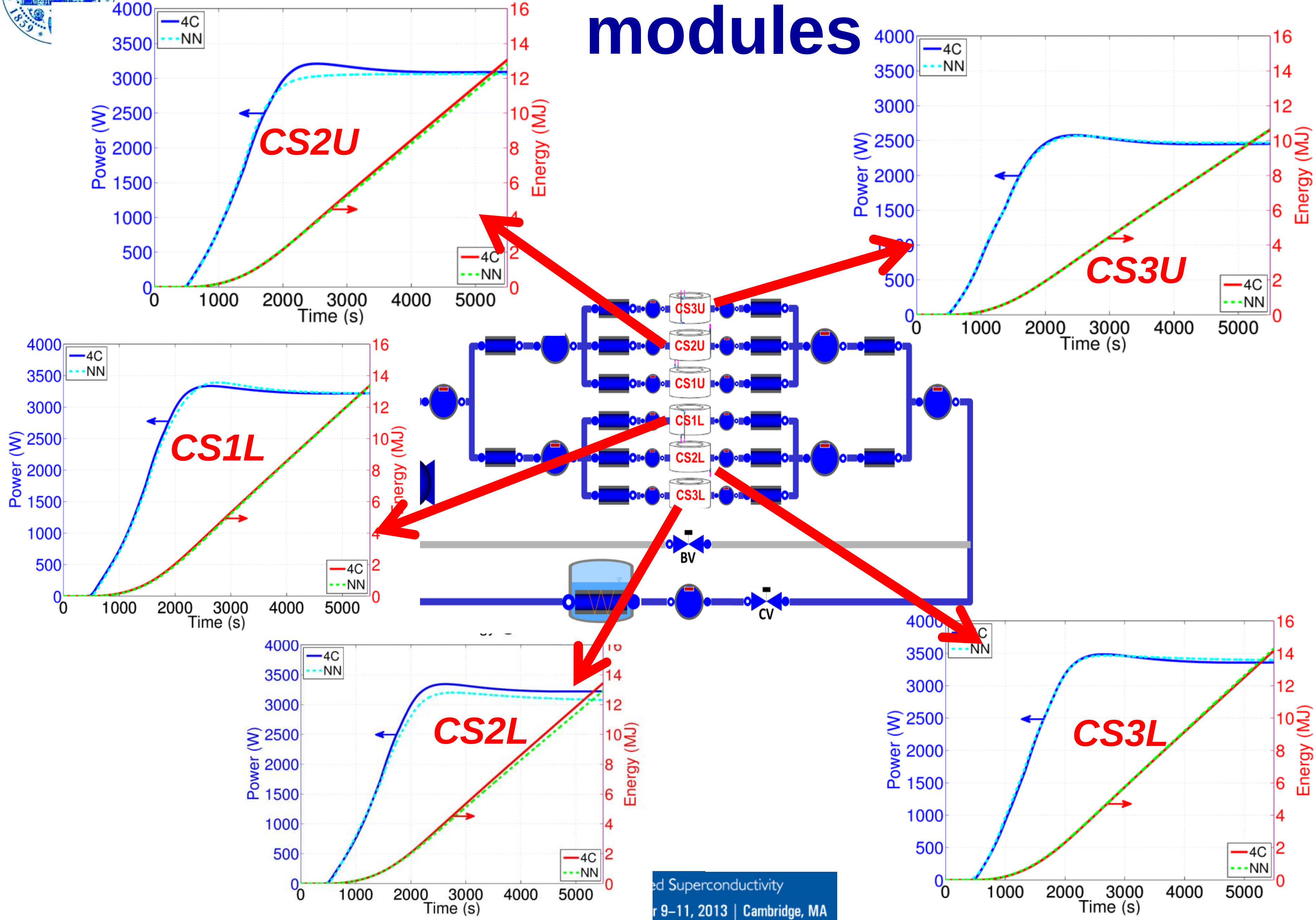
Single ANN prediction: simple waveform on CS1U

SIMPLE heater waveform



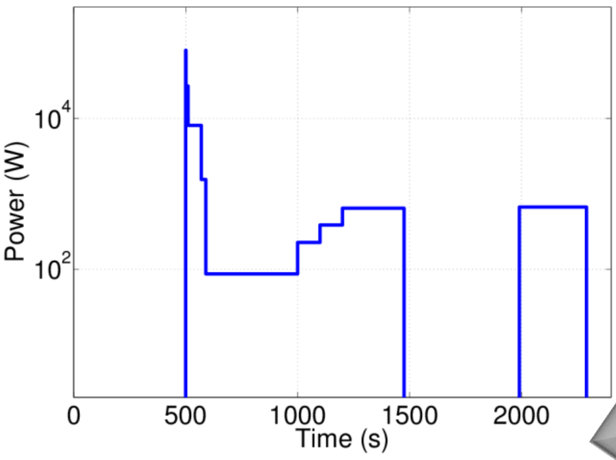
- *ANN predictions in very good agreement with 4C simulations* ***in cases never seen in the training***
- *CPU_{4C} / CPU_{ANN} ~25000!*

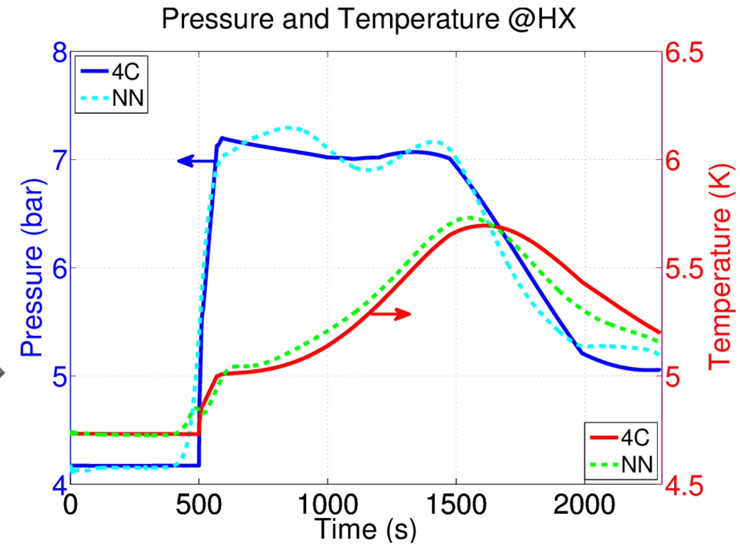
Single ANN prediction on other modules

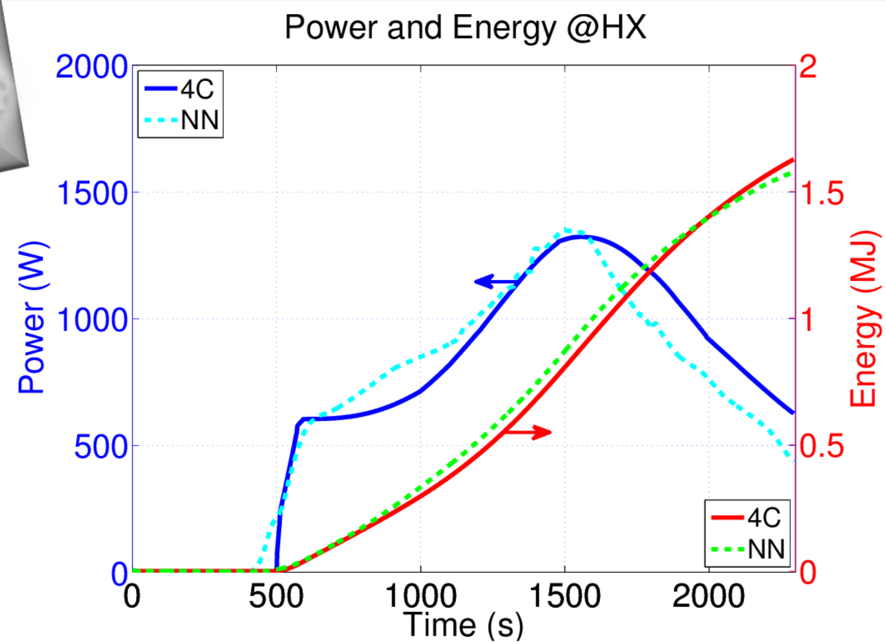


Single ANN prediction: ITER-like waveform on CS1U

GENERAL heater waveform



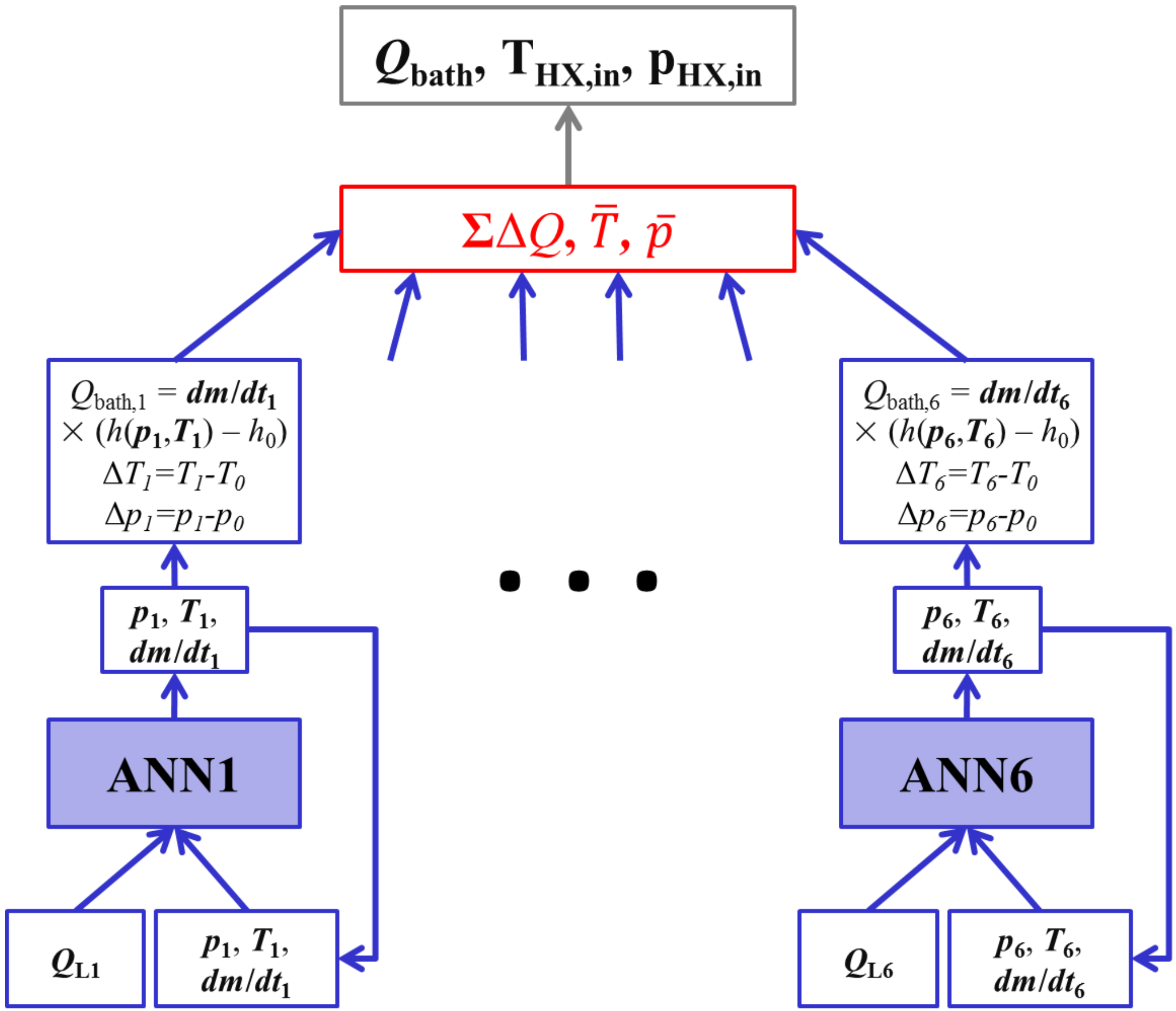




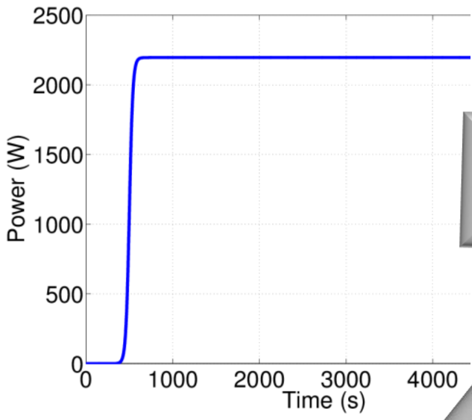
$\varepsilon_{ave} \sim 13\%,\ \varepsilon_{peak} \sim 3\%$

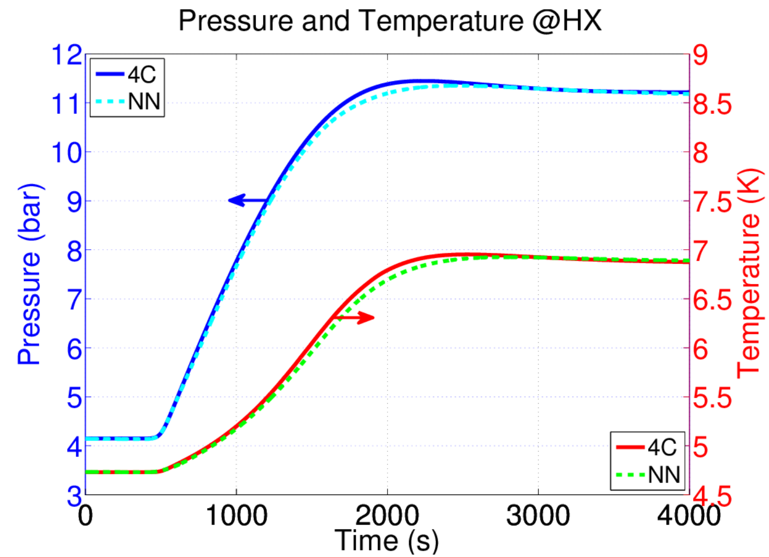
$CPU_{4C} / CPU_{ANNs} \sim 4000$

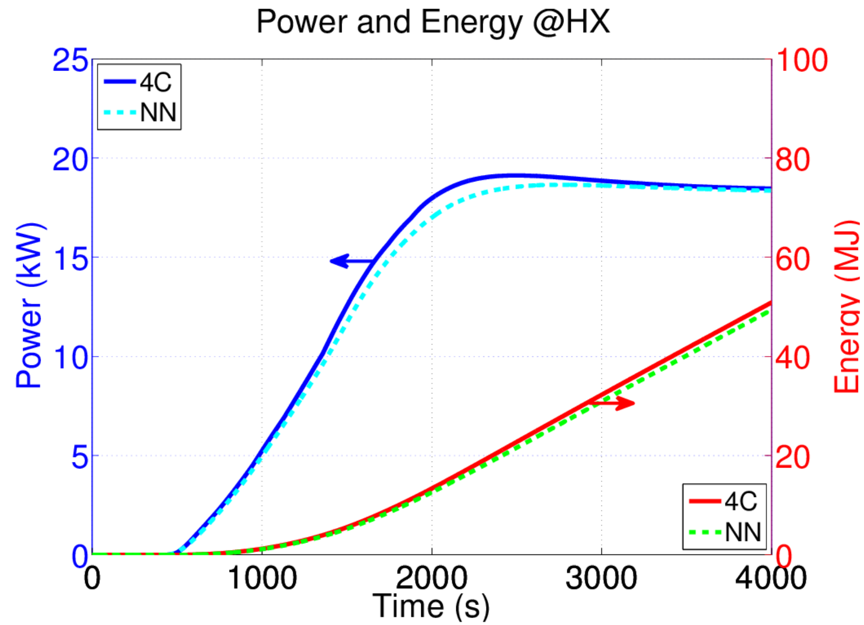
From single module back to CS coil



CS coil prediction: simple waveform





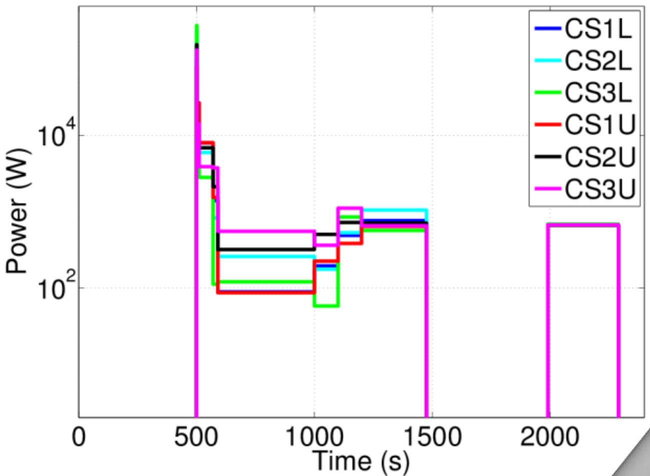


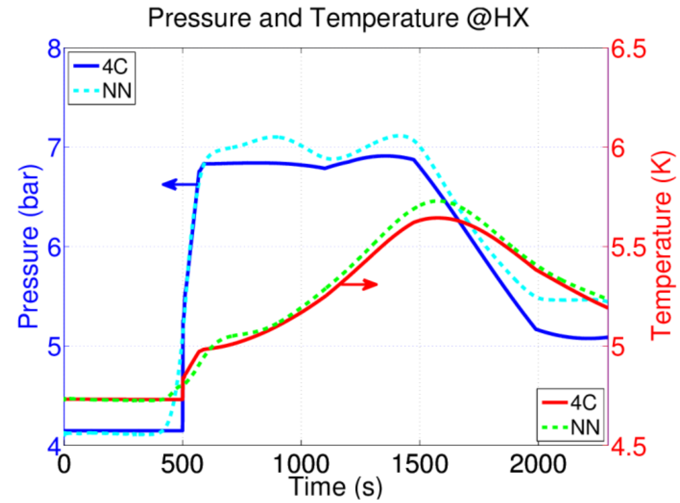
-Very good accuracy:

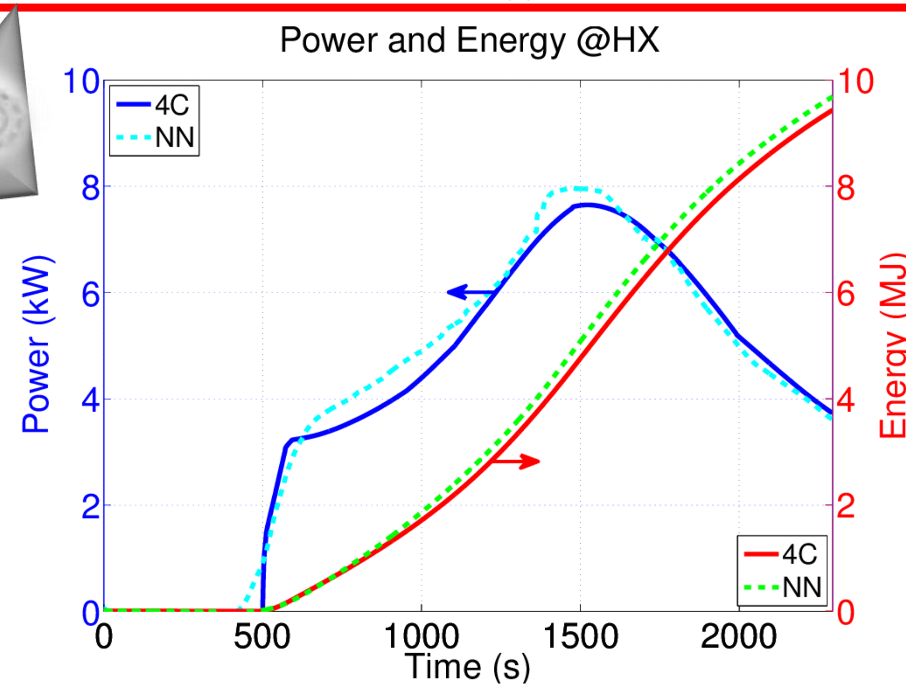
$\varepsilon_{ave} \sim 3.3\%$

\- $CPU_{4C} / CPU_{ANNs} \sim 12000$

<u>Final prediction</u>: waveform from plasma operation scenario on the whole CS coil







- Very good accuracy: ε_{ave}~ 5.9%

-CPU_{4C} / CPU_{ANNs} ~ 500

(ANN faster than realtime!)

Conclusions

- Recently proposed approach to the simplified model of heat load on LHe bath through ANNs has been <u>successfully applied to the ITER CS</u>

- The ANN model for the CS dynamic response developed and trained against data from the 4C code proved to be:
  - Flexible
  - Accurate
  - Fast (faster than realtime!)

BACKUP SLIDES

Accuracy and speed

	# of sigmoids	t_{4C}/t_{NN}	Average error (%)	Error at peak (%)
CS1L	70	3600	15.6	10.4
CS2L	136	1856	14.3	0.6
CS3L	154	1600	22.7	7.6
CS1U	66	3789	12.8	1.4
CS2U	102	2440	13.4	7.7
CS3U	92	2667	13.9	8.9
All CS	620	500	5.9	3.9