PPPL PRINCETON PLASMA PHYSICS LABORATORY

Enhancing Operational Safety: The NSTX-U Shorted Turn Protection (STP) System

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A Brief Overview

- **The NSTX-U tokamak, coils and model**
- **The STP algorithm**
- **Code generation and Real-time testing**
- **Results and Conclusion**

The NSTX-U Shorted Turn Protection (STP) System

- The STP system can detect shorted turn in the tokamak coils in real-time.
- Detection of shorted turns allows the prevention of collateral damage of other parts of the tokamak.
- Upon detection, it triggers a fault response that gradually reduces energy in the other coils, preventing further damage.
- The STP algorithm is based on the NSTX-U mode, enhancing its reliability and accuracy.

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Enhancing Operational Safety: The NSTX-U Shorted Turn Protection (STP) System

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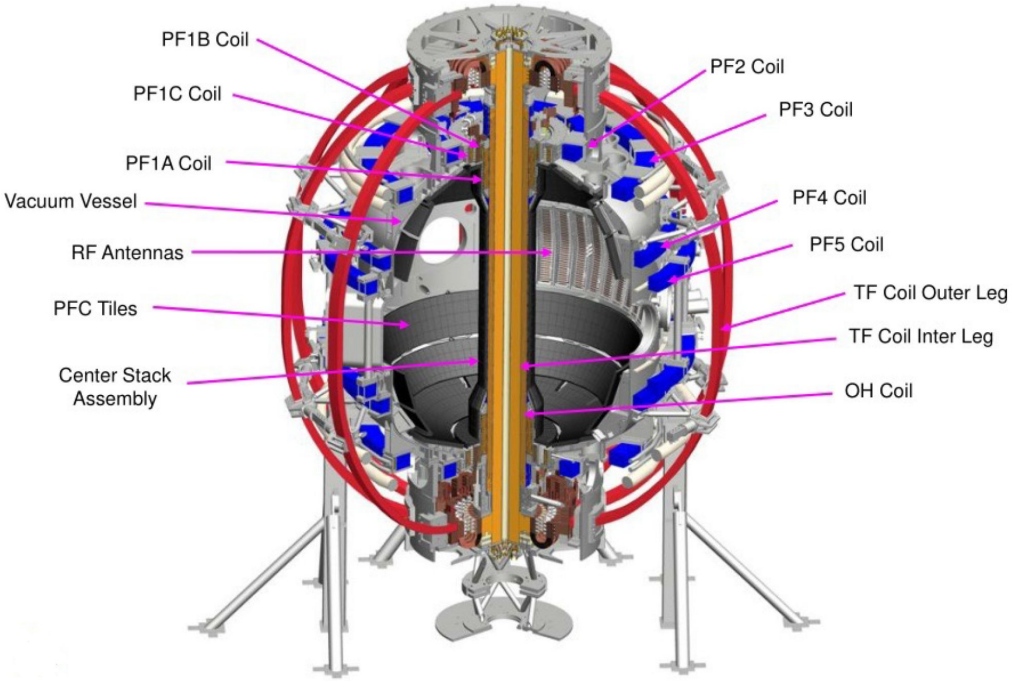
The NSTX-U tokamak

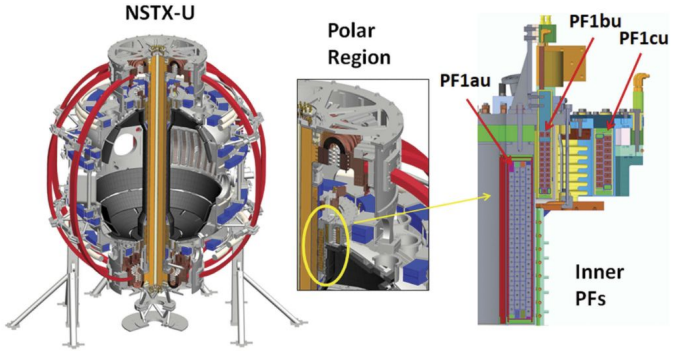


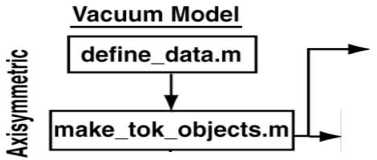
- National Spherical Torus Experiment Upgrade (NSTX-U)
- Study potential of the ST configuration
- ST's enable the confinement of highly pressurized plasma within lower magnetic fields than conventional tokamaks
- 13 PF coils + OH + TF
- Ip ≅ 1 MA

NSTX-U model

NSTX-U material and geometrical description of vessel elements and PF coils

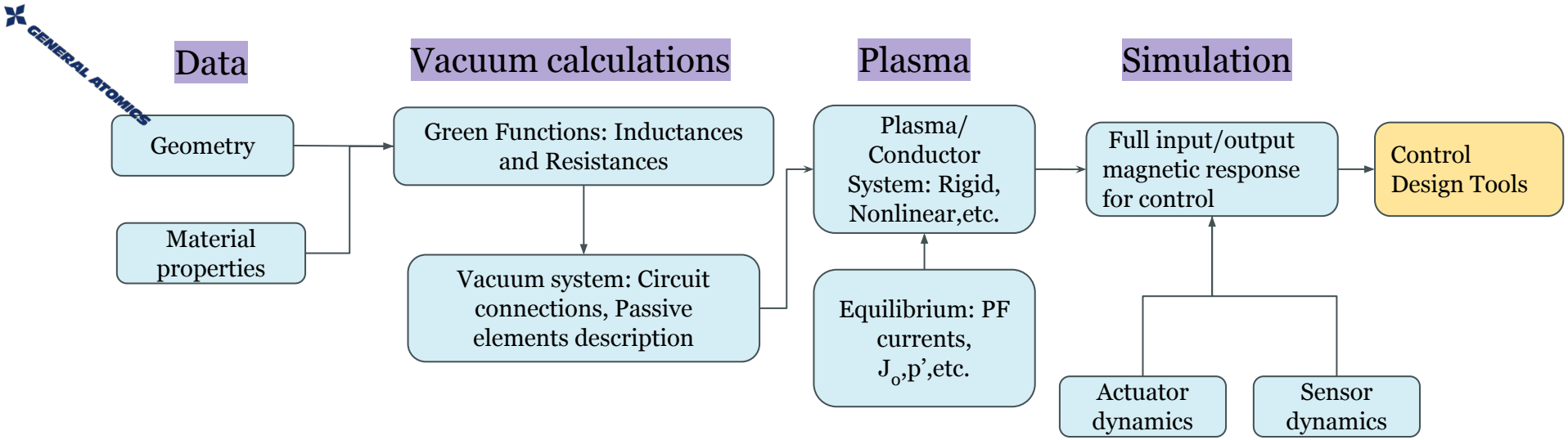
NSTX-U ToKSys Model (PF coils and passive elements resistances, inductances and mutual inductances)





NSTX-U vacuum model

- **ToKSys**: It is developed as a package of Matlab/Simulink codes in order to support control design with access to plasma response models.



L. Lao, *Reconstruction of current profile parameters and plasma shapes in tokamaks*
D. Humphreys, *Development of ITER-relevant plasma control solutions at DIII-D*

NSTX-U plasma model

Magnetic reconstruction of the plasma is **avoided**, uncertainties for the plasma are considered.

- The flux linked by the conductors to the plasma is given by: $\psi_{cI} = M_{cI}(t) I_p$

- The mutual inductance M_{cI} between conductors and plasma is written as time-varying to represent **changes in plasma current distribution over time**.

- The **induced voltage** at the conductors **due** to the **plasma** is:

$$V_{cI} = -\dot{\psi}_{cI} = -M_{cI}\dot{I}_p - \dot{M}_{cI} I_p$$

NSTX-U plasma model

- These plasma coupling terms will be avoided to be largely uncertain. **Uncertainty** will be considered to be a sum of independent **Gaussian noise** processes in the form of:

$$v_{cI} = -M_{cI} w_{dI/dt} - \dot{M}_{cI} w_I - v_{dMcI} \dot{I}_P - v_{dMcI/dt} I_p$$

- The measurement noise on the I_p measurement will be used to set the variance of $w_{dI/dt}$ and w_I. The covariance of v_{McI} will be set based on the covariance of M_{cI} in a **database** of **NSTX-U shots** and adjusted to ensure **false** fault signals do not occur during **disruptions**. Same for the covariance of $v_{dMcI/dt}$.

- The covariance of the noise due to plasma effects can be written as:

$$Q_{cI} = M_{cI}^T Q_{dI/dt} M_{cI} + \dot{M}_{cI}^T Q_I \dot{M}_{cI} + \dot{I}_p^2 Q_{M_{CI}} + I_p^2 Q_{dMcI/dt}$$

How the algorithm works

1) The NSTX-U model is used to construct a Kalman Filter.

2) The filter computer real-time predicted coil currents based on voltage, plasma current and coil current measurements.

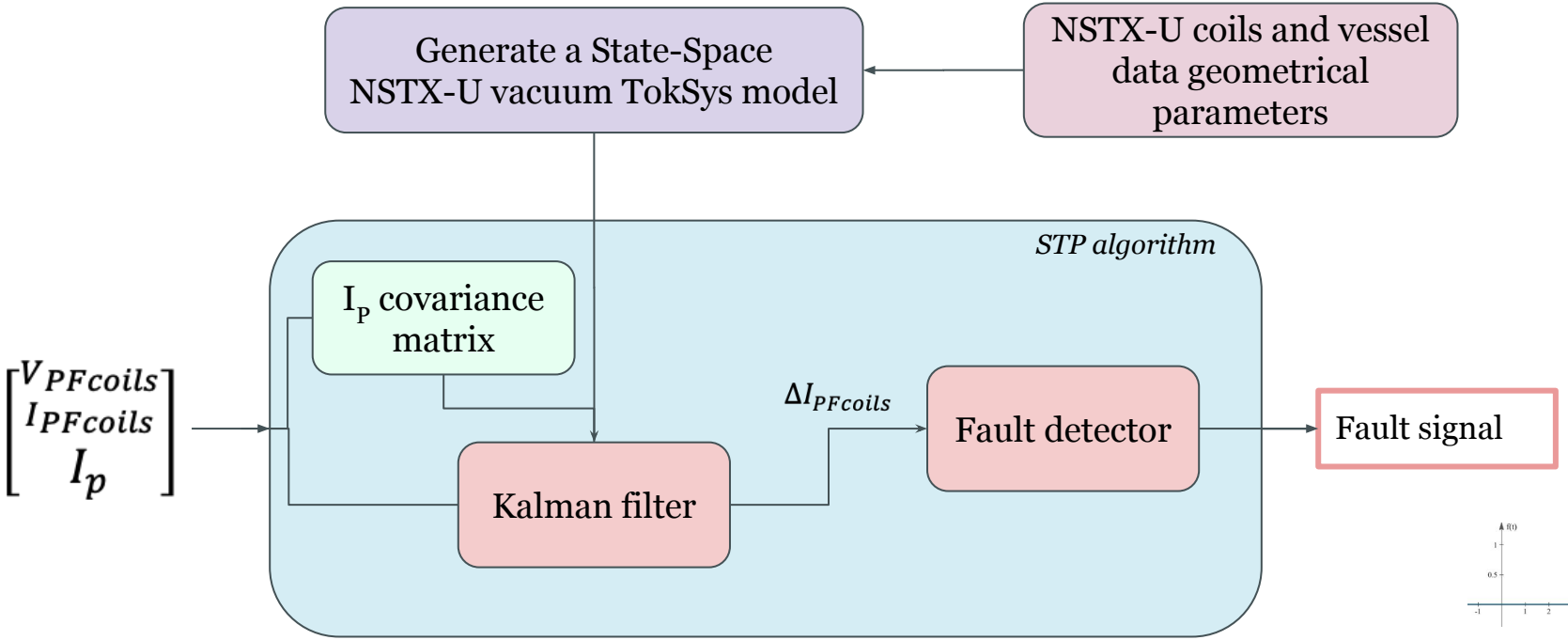
3) If the average difference between measured and predicted coil currents surpasses a threshold, a fault is raised in the system.

4) Upon fault detection, the energy in the coils is gradually reduced to zero.

5) The signals and parameters on every shot are saved to MDSplus.

The STP algorithm overview

- Developed in Matlab/Simulink



STP algorithm

- Reconstructs state of **uncertain system** from **limited noisy measurements** using dynamic model and updates every measurement
- **Predicts** coil and vessel **currents** from nominal **model**

Predict step

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k \qquad P_k = AP_kA^T + \Gamma Q \Gamma^T$$

Update step

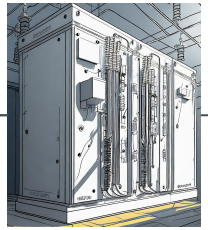
$$K_{k+1} = P_{k+1}C^T(CP_{k+1}C^T + R)^{-1}$$

$$\hat{x}_{k+1} = \hat{x}_k + K_{k+1}(y_{k+1})$$

$$P_{k+1} = (I - K_{k+1}C)P_k$$

- P - Error covariance matrix
- K - Kalman gain matrix
- Q,R - Measurement and noise covariance matrix, **need to be tuned**
- Γ - Process noise

STP algorithm



$I_{PFcoils\_meas}$

$u = \begin{bmatrix} V_{PF} \\ \dot{I}_p \end{bmatrix}$

NSTX-U TokSys model

$\dot{x} = Ax + BV_{PF}$
$y = Cx$

$y = [I_{PF}]$

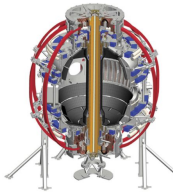
Kalman filter

$\hat{x} = \begin{bmatrix} \hat{I}_{PF} \\ \hat{I}_{vv} \end{bmatrix}$

$I_{PFcoils\_predicted}$

Adjustable scale factor for fault triggering

Fault prediction
$I_{PFcoils} - \hat{I}_{PFcoils}$



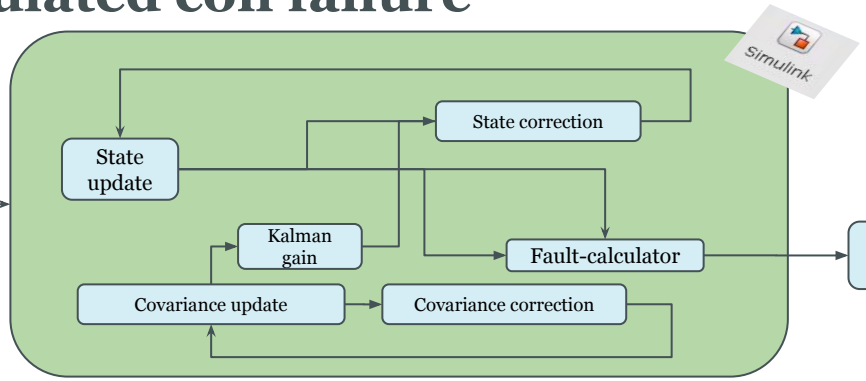
STP evaluation with a simulated coil failure

MDSplus data (STP model matrices,etc.)

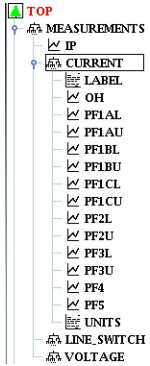
Set-up a faulted simulation

Shorted turns in 1 or more coils

$$\begin{bmatrix} V_{PFcoils} \\ I_{PFcoils} \\ I_p \end{bmatrix}$$

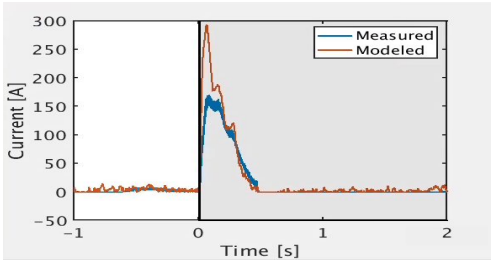


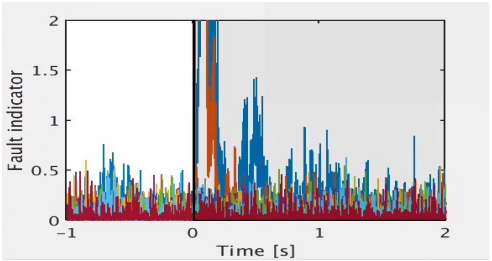
STP Real-time algortithm



PF1AU 7 shorted turns

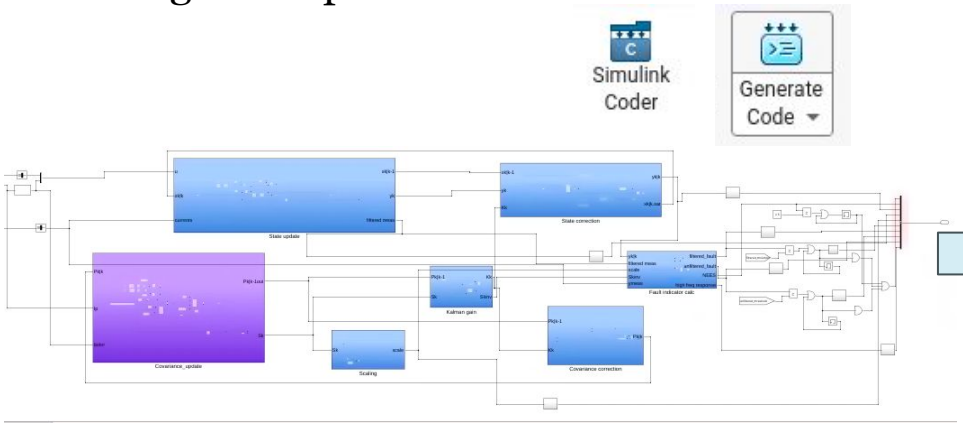
Artificial integration of a fault on top of MDSplus data





Auto Generated code

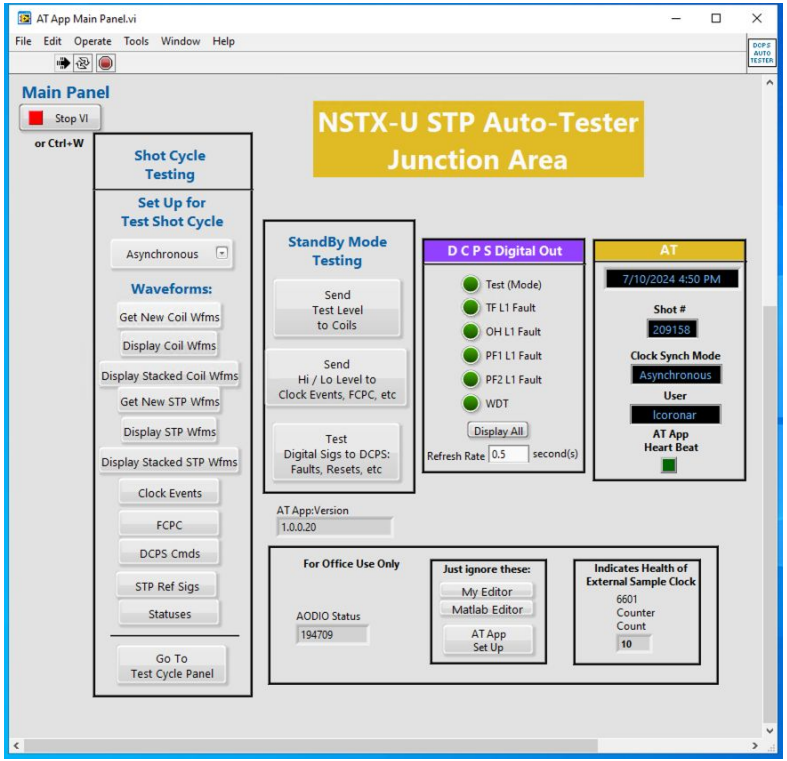
- Simulink enables auto-generation of C/C++ code
- Code embedded into a system providing the real-time infrastructure and fault signal output



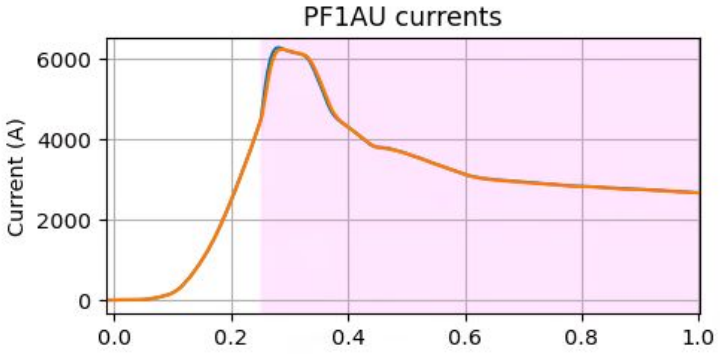

```
for (j = 0; j < 15; j++) {
  for (k = 0; k < 22; k++) {
    rtb_xkk[k] += STP_obs_B.B[22 * j + k] *
      STP_obs_DW.Memory2_PreviousInput_k[j];
  }
}

/* End of Product: '<S19>/Multiply' */

/* Product: '<S19>/Multiply1' incorporates:
 *  Memory: '<S19>/Memory'
 *  Product: '<S1>/Product2'
 */
std::memset(&tmp_1[0], 0, 22U * sizeof(real32_T));
for (j = 0; j < 22; j++) {
  for (k = 0; k < 22; k++) {
    tmp_1[k] += STP_obs_B.A[22 * j + k] * STP_obs_DW.Memory_PreviousInput[j
  }
}
```

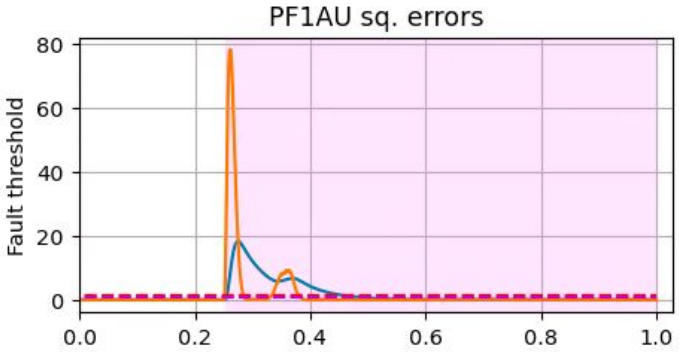
Real-time testing

- Real-time input stream fed by the testing system.
- Recorded artificial measurements to test the algorithm.
- STP does not differentiate between real and artificial data.
- Testing system -> PCI cards for input generation: PF coils, TF coil and Plasma current. LabView interface.

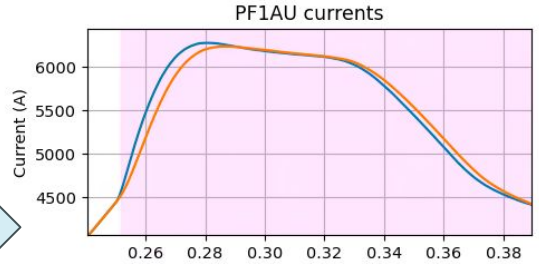


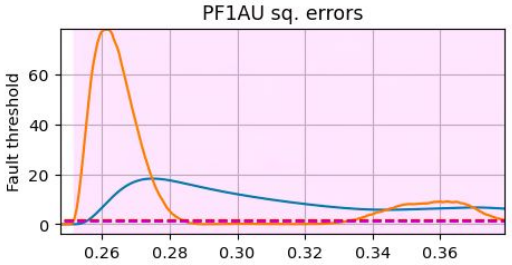
Results 1: PF1AU (60 turns) - 15 shorted turns at 0.25 seconds



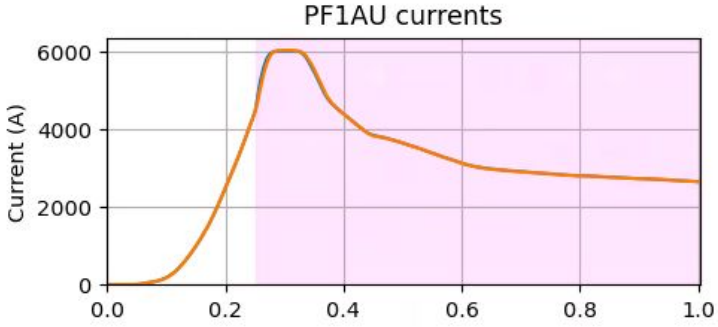


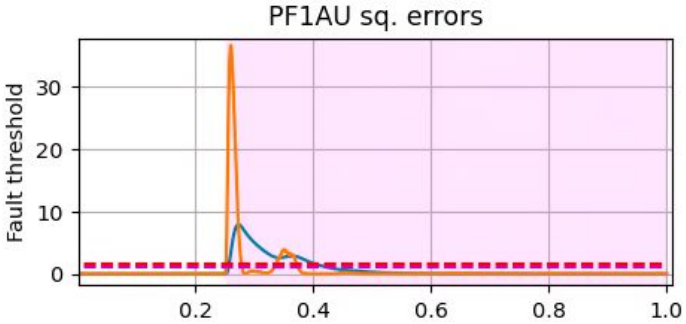
Ip ≅ 1 MA for 1.5 seconds



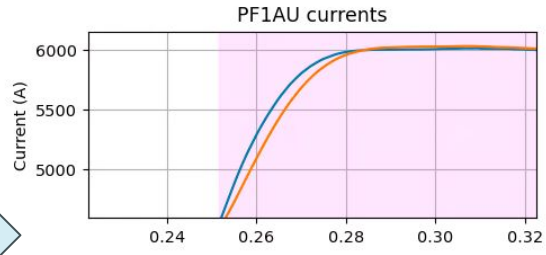


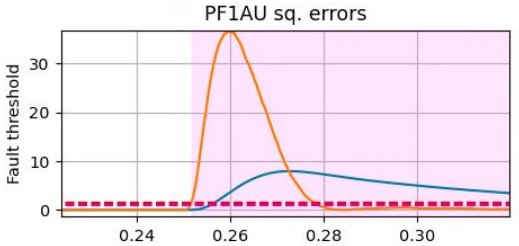
Results 3: PF1AU (60 turns) - 7 shorted turns at 0.25 seconds



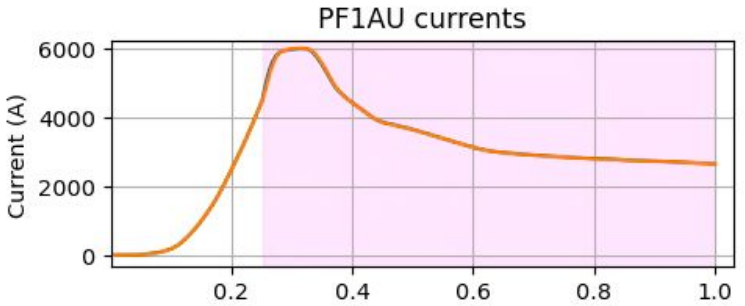


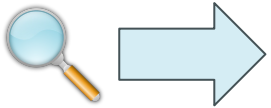
Ip ≅ 1 MA for 1.5 seconds



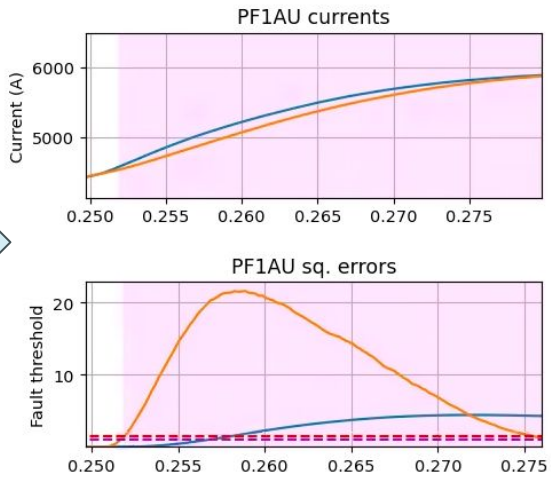


Results 1: PF1AU (60 turns) - 5 shorted turns at 0.25 seconds

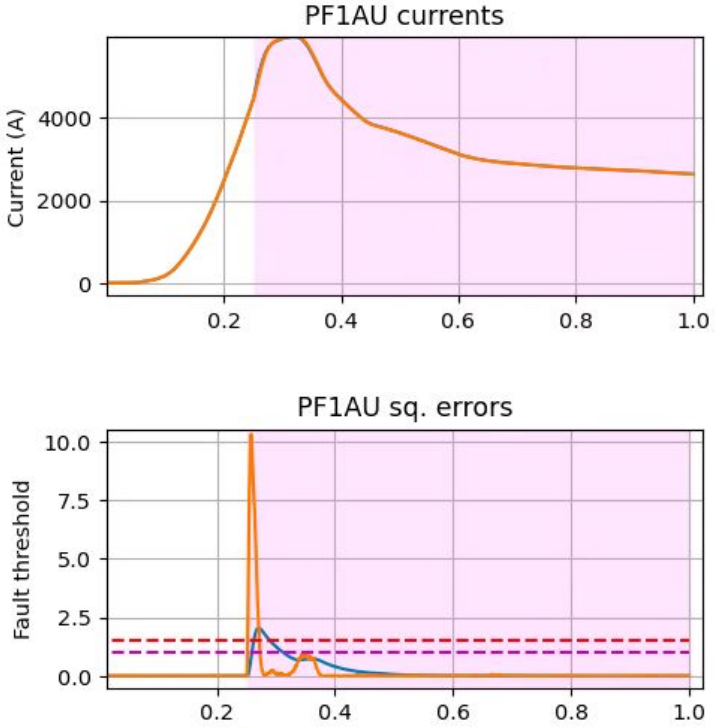




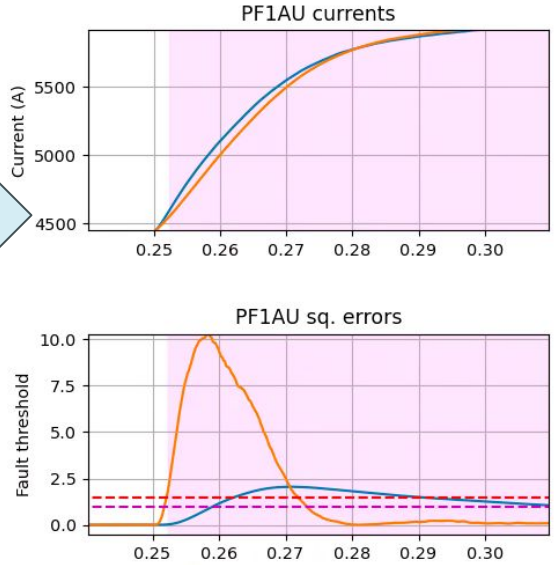
Ip ≅ 1 MA for 1.5 seconds



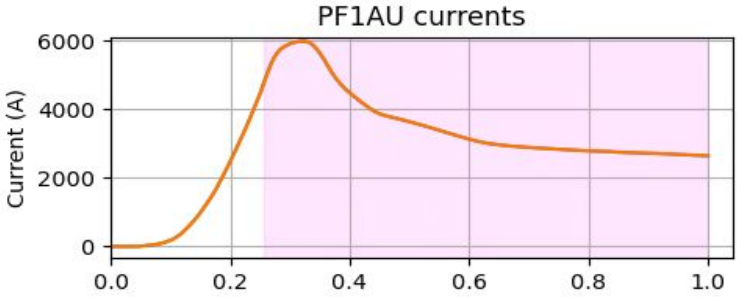
Results 1: PF1AU (60 turns) - 3 shorted turns at 0.25 seconds

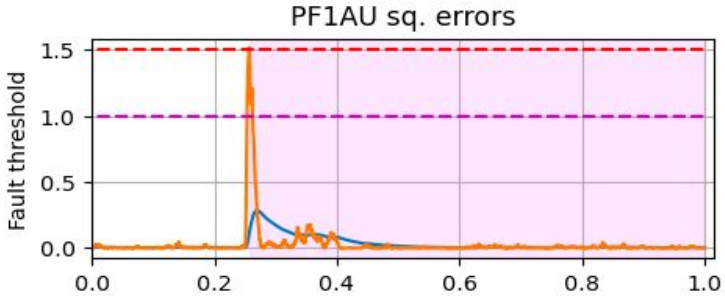


Ip ≅ 1 MA for 1.5 seconds

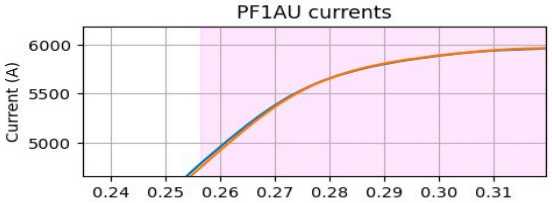


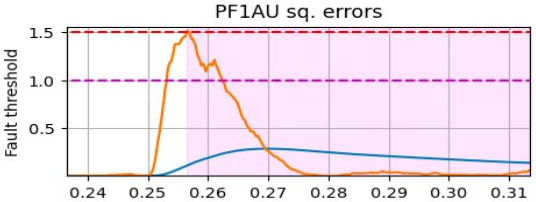
Results 3: PF1AU (60 turns) - 1 shorted turns at 0.25 seconds



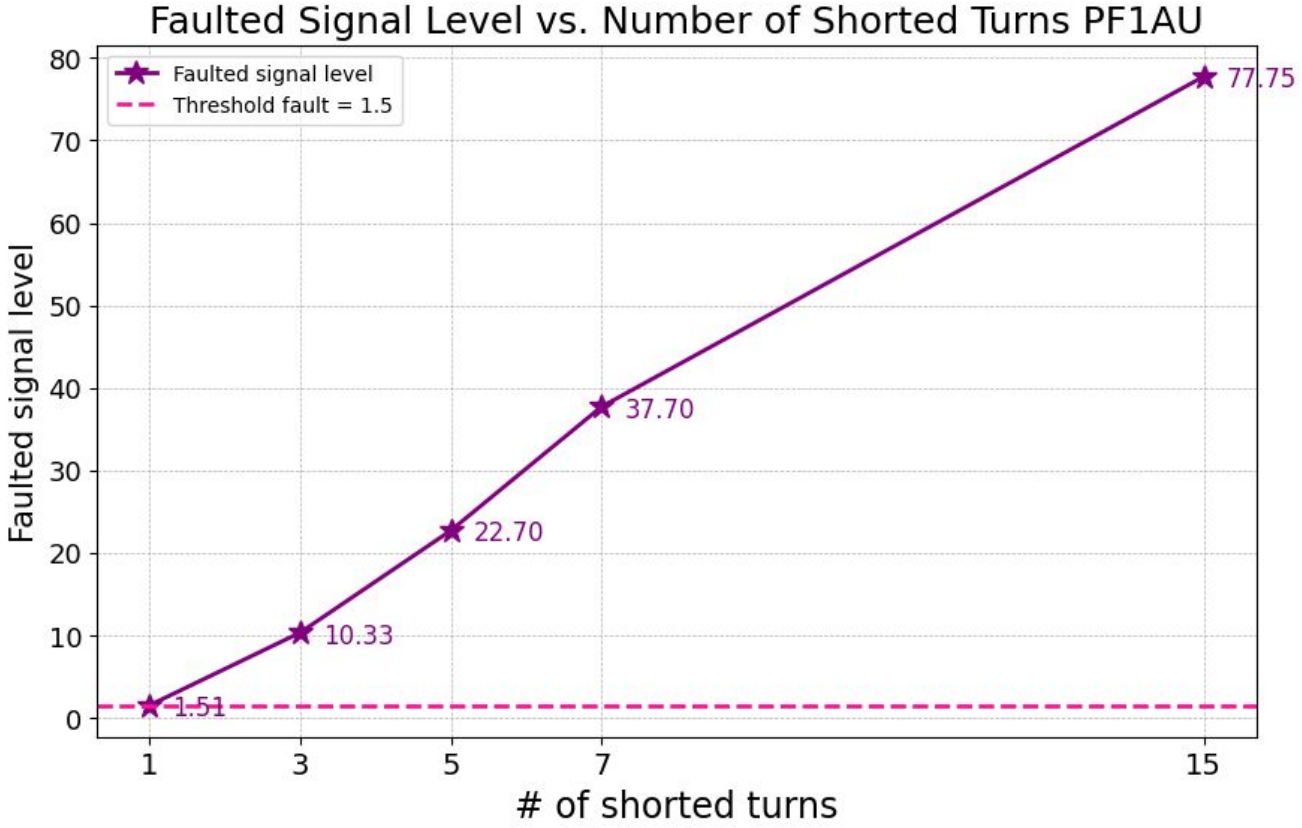


Ip ≅ 1 MA for 1.5 seconds





Results summary



Summary

- STP is a real-time **protection** and health diagnosis system for **impedance changes** on PF coils

- Implementation of a real-time **model based** algorithm non-dependant on an equilibrium reconstruction

- C/C++ **auto generated code** from Simulink model. Rapid development, match between designing and deployment.

- Successful tests driven Real-time algorithm test.

Future work

- Verify STP outcome with **non-simulated** single coil shots and multi coils shots
- **Extend** NSTX-U **model** for including a plasma model through the **magnetics diagnostics**
- Implementation and **fast deployment** of different models (passive elements changing, coils added)
- Possibility of testing STP in other tokamaks depending on the signals availability