PRINCETON PLASMA PHYSICS LABORATORY

The NSTX-U Shorted Turn Protection (STP) system

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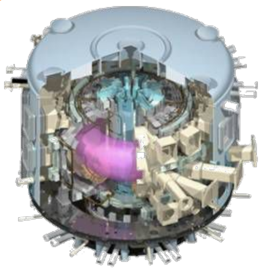
Overview

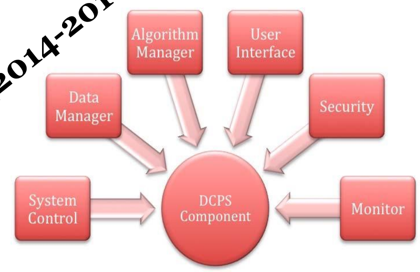
NSTX-U and Coils protection Timeline

(2016)



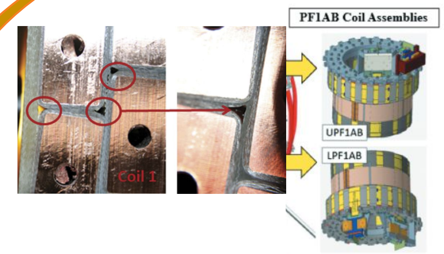
- NSTX upgrade -> NSTX-U
- Antecedents of an Analog Coils Protection

(2014-2016)



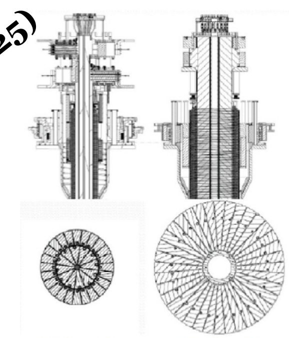
The Digital Coils Protection System (DCPS) is implemented for thermal and mechanical protection

(2016)



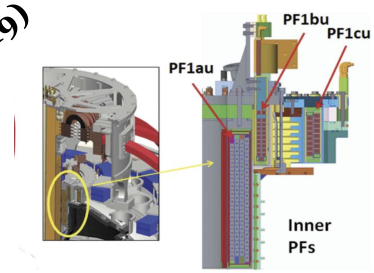
- Upper divertor Poloidal Field (PF) Coil failure
- Water leak into coils isolation causing a short circuit
- NSTX-U operation stops

(2016-2025)



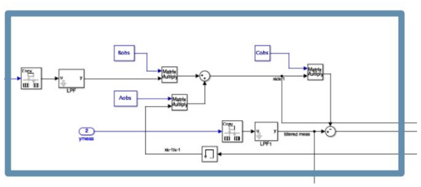
- NSTX-U enhancement: Replacement of PF coil, inner vessel new tiles, center stack rebuilt, etc.

(2019)



- PF coils voltages become available on the Real-Time stream

(2019-2023)



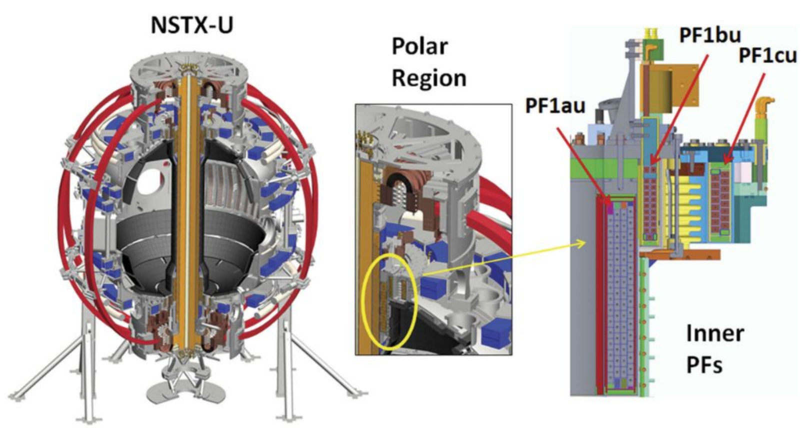
- STP is implemented in order to detect impedance changes and mitigate coil damages

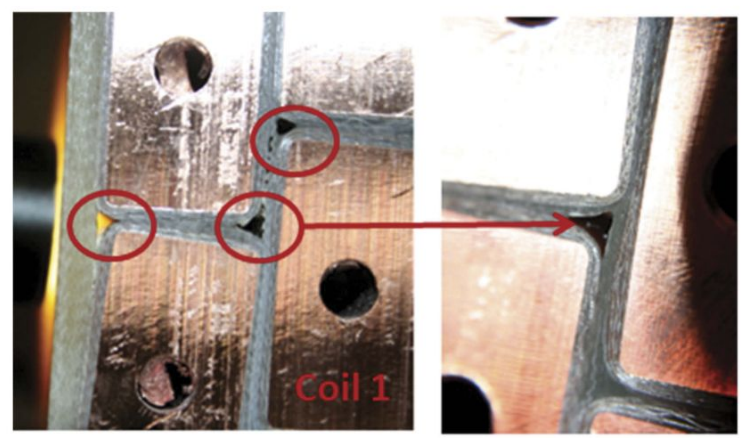
NSTX-U Inner Poloidal Field coil damage

In 2016, because of the failure of the **PF-1a** upper divertor **coil**, which experienced a **coolant blockage**, the NSTX-U operation was suspended.

A postmortem investigation indicated that an **undetected** gradual **deterioration** of **coil** inductance preceded the coolant blockage, very likely as an error during manufacturing. The internal **short** was not repairable.

It was decided to replace the three inner PF upper and lower coil pairs along with strict evaluation procedures like sectioning of prototype coils.

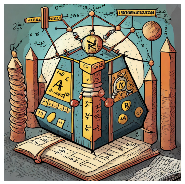




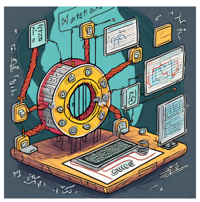
Y. Zhai, *Prototype Coil Evaluation for NSTX-U Replacement Inner Poloidal Field Coils*

J.E. Menard, *Overview of NSTX Upgrade initial results and modelling highlights*

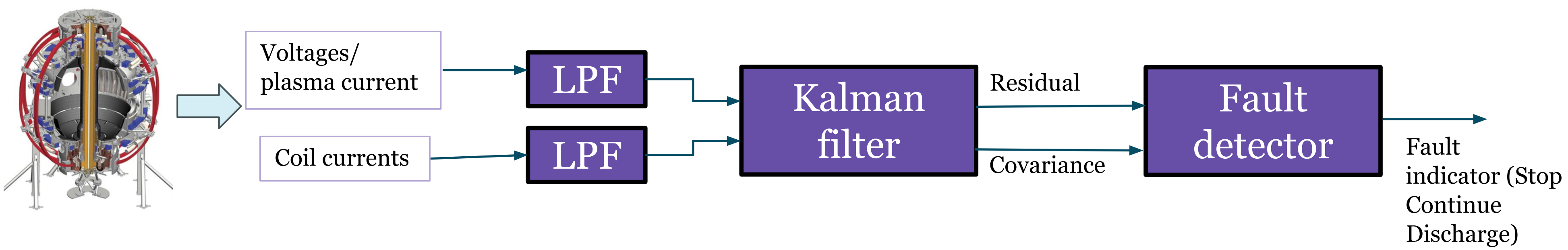
Protection Systems overview



DCPS, implemented during the upgrade for NSTX-U, provides protection with respect to **overheating**, **temperature** differences between TF and OH, **forces** on coils, PF coil **stresses** and **momentums**. No cover of electrical faults.



STP will be used to detect **shorts** between coil **windings** or terminals on Real-time. From the **current** and **voltage measurements** of PF coils and plasma the algorithm will **compare** against a model and declare a **fault** if changes take place.

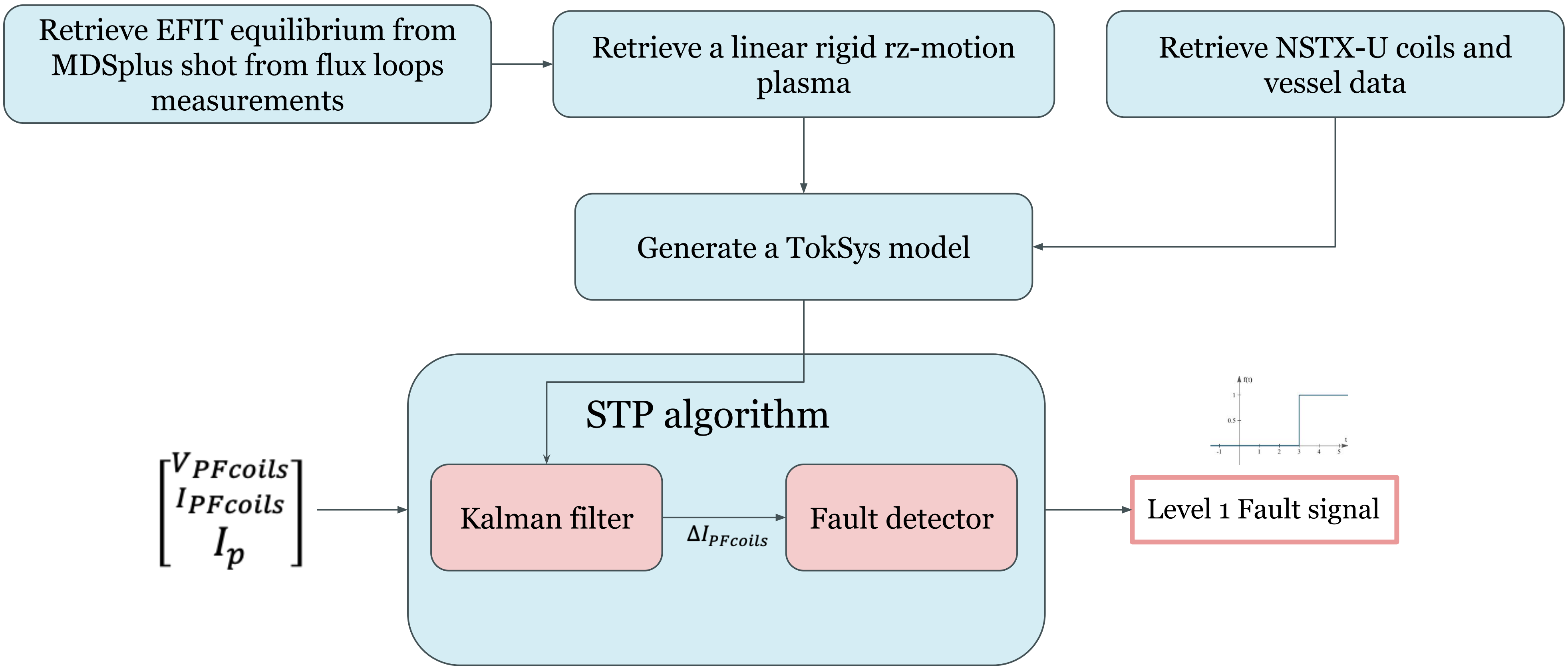


- **Low-pass filter** to reduce impact of thyristor switching, time constant ~1ms
- **Kalman filter** estimates coil/vessel currents from noisy measurements based on nominal model
- **Fault detector** monitors difference between estimation and measurements to determine a fault

K. Erickson, *NSTX-U Digital Coil Protection System Software Detailed Design*

STP algorithm overview

- Developed in Matlab/Simulink
- Avoids plasma real-time reconstruction (plama uncertainties)



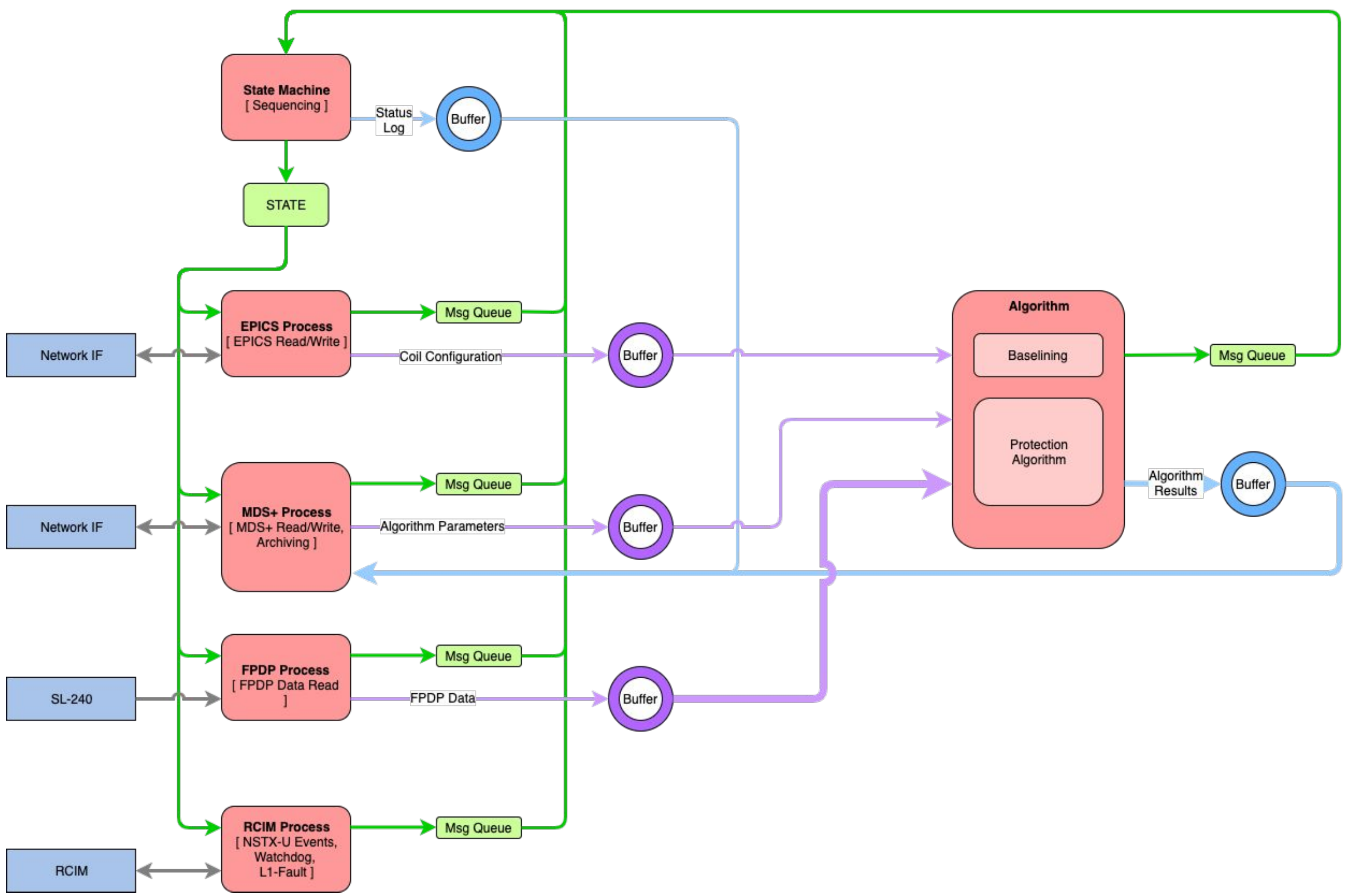
MDSplus: software tools for data storage, acquisition and retrieval system for scientific data, used in several tokamaks.

STP Real-time software architecture

Algorithm running in real-time machine (RT5) installed in the junction area

PTP (Preoperational test procedure) to test algorithm performed in 2023

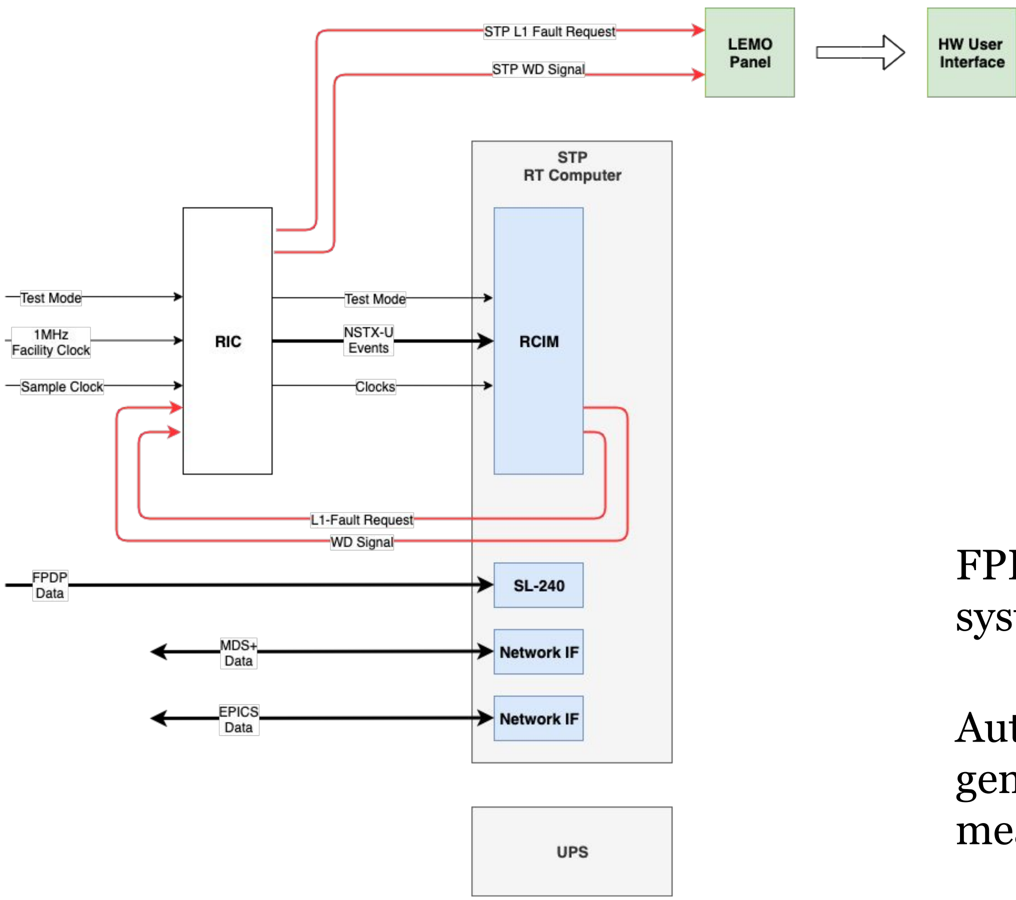
The Finite State Machine (FSM) process of the STP system realtime software provides the overall sequencing and coordination.

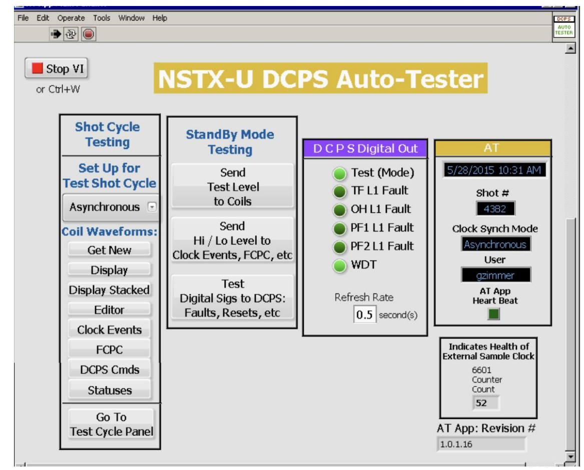


Status data
Input data
Output data

STP Real-time software/hardware architecture

The Finite State Machine (FSM) process of the Shorted Turn Protection (STP) system realtime software provides the overall sequencing and coordination.





FPDP input stream fed by the Auto Tester system.

Auto Tester system -> PCI cards for input generation: PF coils, TF coil and Plasma measurements. LabView interface.

G. Zimmer, The *NSTX-U Digital Coil Protection System Autotester*

STP algorithm overview

- Uses the RZIp linearized rigid plasma response included in the TokSys environment

$$M_{cc}^* \dot{I}_c + R_c I_c + M_{cv}^* \dot{I}_v + M_{cp}^* \dot{I}_p = V_c$$

PF Coil current dynamics

$$M_{vv}^* \dot{I}_v + R_v I_v + M_{vc}^* \dot{I}_c + M_{vp}^* \dot{I}_p = 0$$

Vessel (passive conductor) dynamics

$$L_p^* I_p + \dot{}R_p I_p + M_{pc}^* \dot{I}_c + M_{pv}^* \dot{I}_v = V_{nonohmic}$$

Plasma current dynamics

I_c , I_v , I_p — Currents in PF coils, vessel elements and plasma

V_c — PF coil voltages

$V_{nonohmic}$ — Voltage from non-inductive sources

M_{ab}^* — Plasma-modified mutual inductance matrices

M. L. Walker, *Valid Coordinate Systems For Linearized Plasma Shape Response Models In Tokamaks*

Kalman Filter and State-Space models

State-space models allow the design of high-order controllers

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

Eq.1 Dynamical system defined by the PF coils and plasma currents

$$\dot{I} = AI + Bv$$

States are associated with the **current** in **coils**, **passive** conductors and **plasma**

Inputs represent coils power supply **voltages**

Eq.2 Dependency on the PF coils currents and input voltages.

$$y = CI + Dv$$

The **outputs** represents magnetics **measurements** like fluxes

Kalman Filter and State-Space models

- 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

$$\hat{x}_{k+1} = A\hat{x}_k + Bu_k$$

$$P_{k+1} = AP_kA^T + \Gamma Q \Gamma^T$$

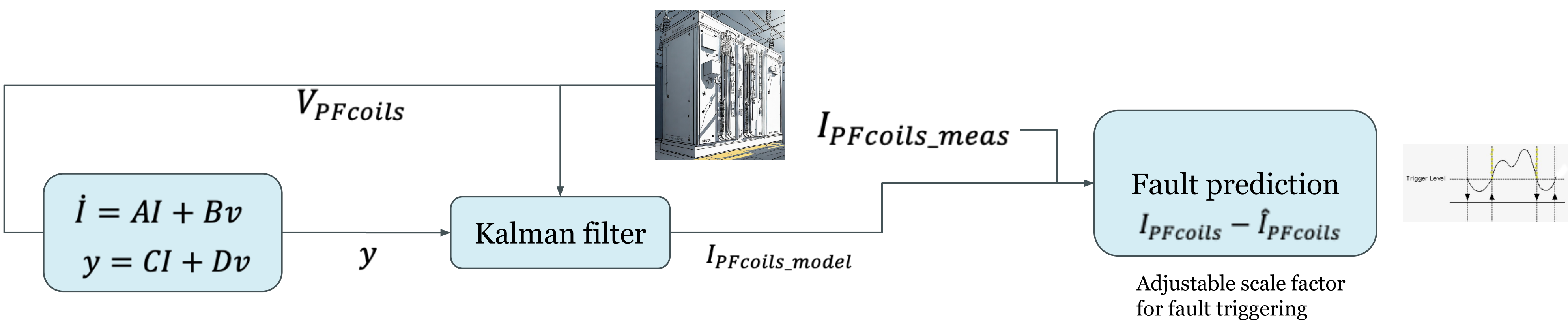
Update step

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

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

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

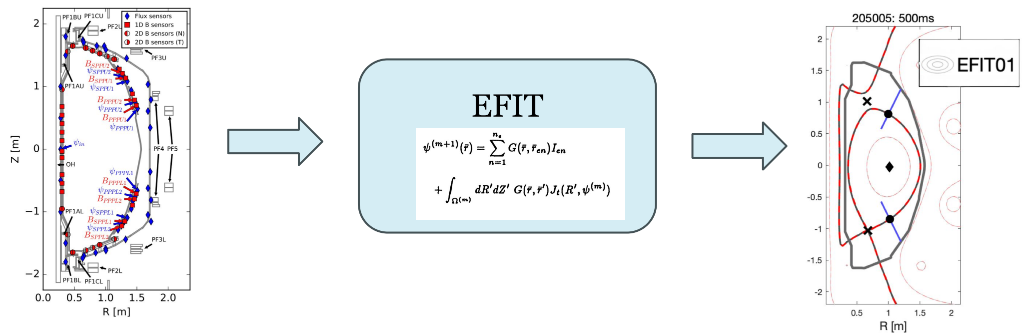
- P - Error covariance matrix
- K - Kalman gain matrix
- Q,R - Measurement and noise covariance matrix
- Γ - Process noise



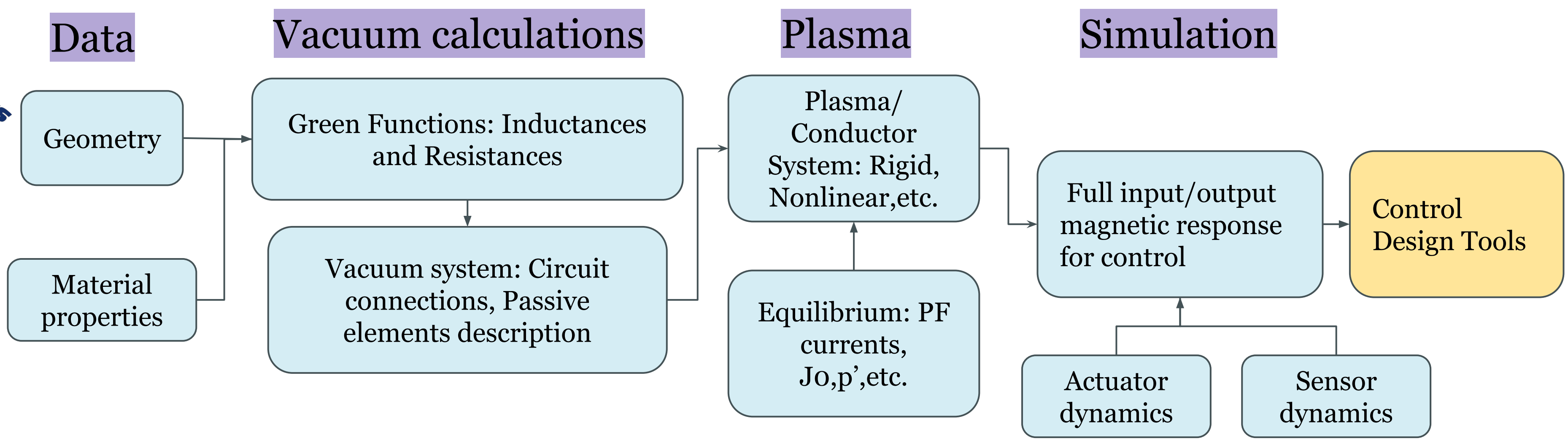
NSTX-U TokSys/EFIT model

ToKSys and EFIT

- EFIT : 2D equilibrium solver for Grad-Shafranov equation which translates measurements from plasma diagnostics into information like plasma equilibrium.



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

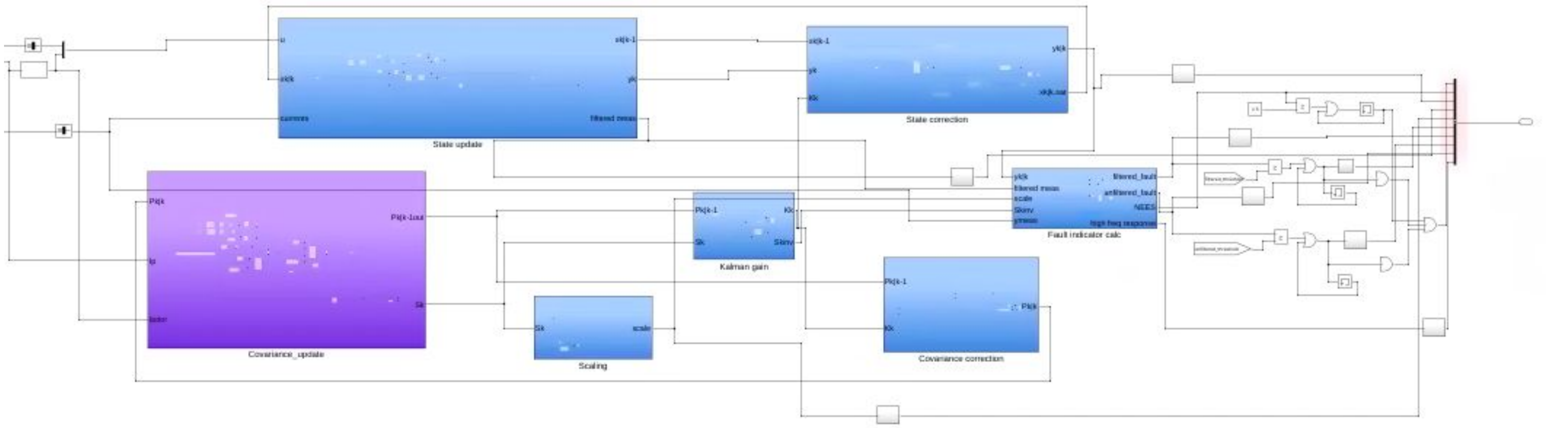


L. Lao, *Reconstruction of current profile parameters and plasma shapes in tokamaks*

D. Humphreys, *Development of ITER-relevant plasma control solutions at DIII-D*

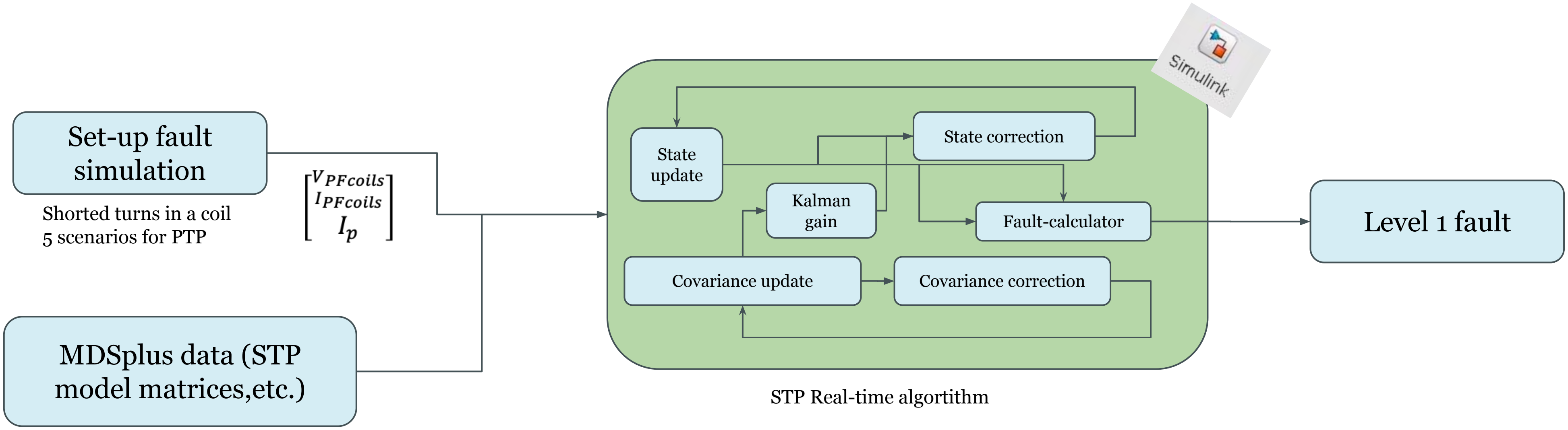
STP Simulink simulation and auto-generated code

- Simulink enables auto-generation of C/C++ code

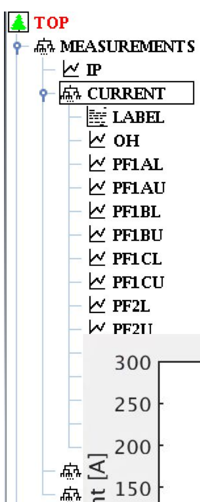



```
for (j = 0; j < 15; j++) {
  for (k = 0; k < 22; k++) {
    rtb_xkk[k] += STP_obs_B.B[22 * j + k] *
      STP_obs_DW.Memory2_PreviousInput_k[j];
  }
}

/* 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
  }
}
```

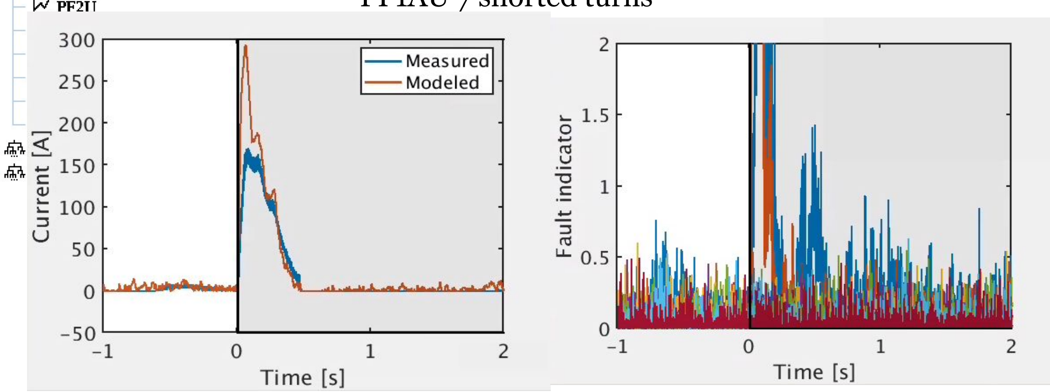
Fault modeling simulation

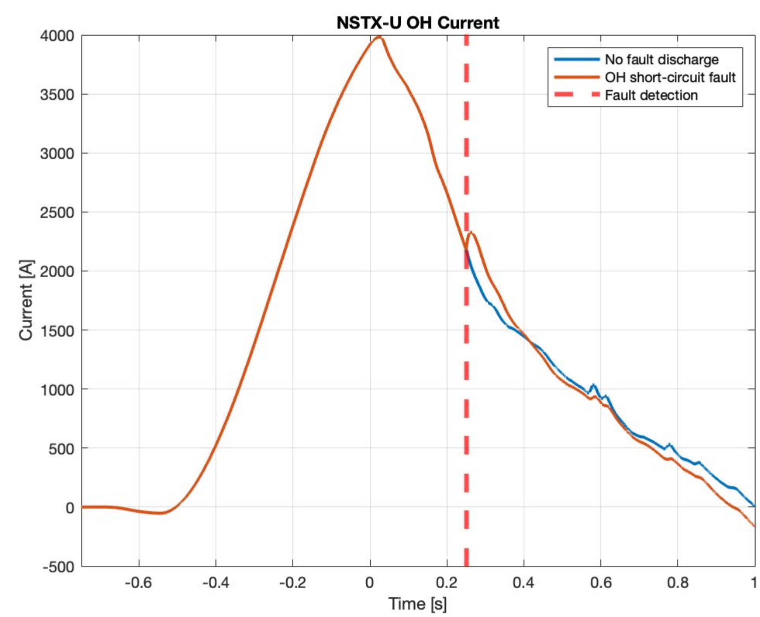


STP Real-time algortithm



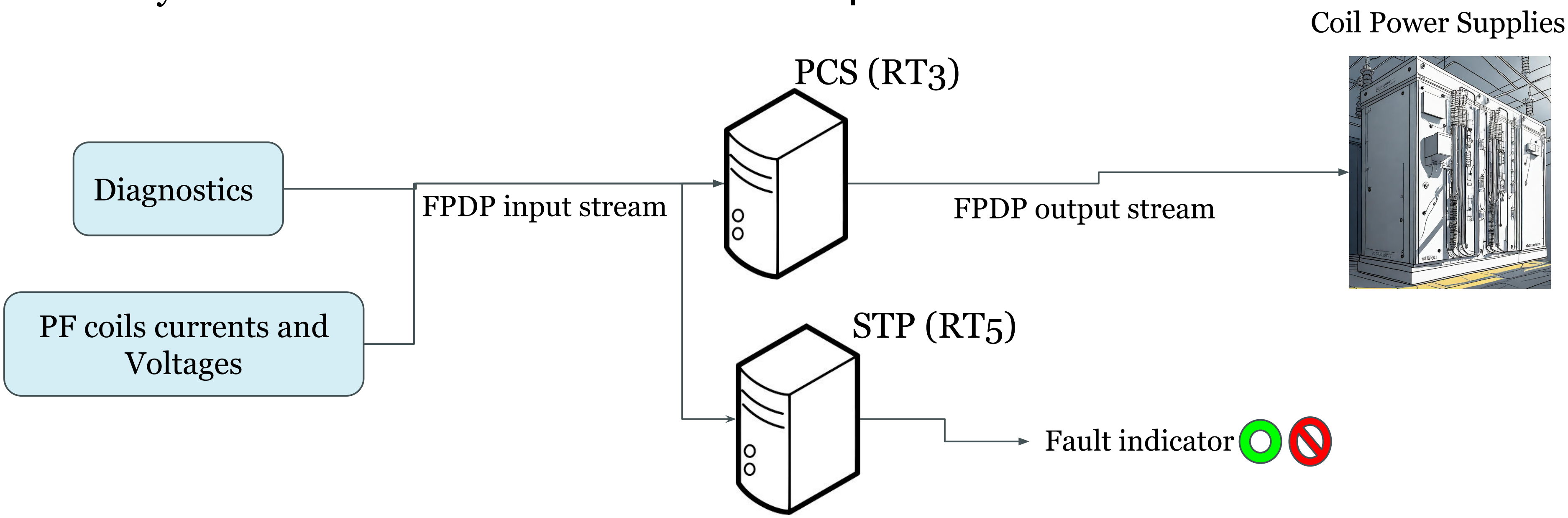
PF1AU 7 shorted turns





Future work

- Early Poloidal Field Coil Test Summer 2024.



- Update RT STP to Vacuum TokSys model for the early test. NSTX-U passive elements and 3 PF coils have changed.
- Create a database of simulation faults: Coil to fault, time of the fault, % of turns shorted.
- Analyze and set the algorithm sensitivity. How much should a fault be avoided?

Highlights

- STP is real-time PF coils **protection** and healthy diagnosis system for **impedance changes**
- Implementation of a real-time **model based** algorithm non-dependant on rtEFIT or EFIT
- C/C++ **auto generated code** from Simulink model. Rapid development, match between designing and deployment.
- Successful Auto-tester driven Real-time algorithm test (**PTP**).