Oak Ridge National Laboratory

Dynamic systems modeling of the Spallation Neutron Source Cryogenic Moderator System to optimize transient control and prepare for power upgrades

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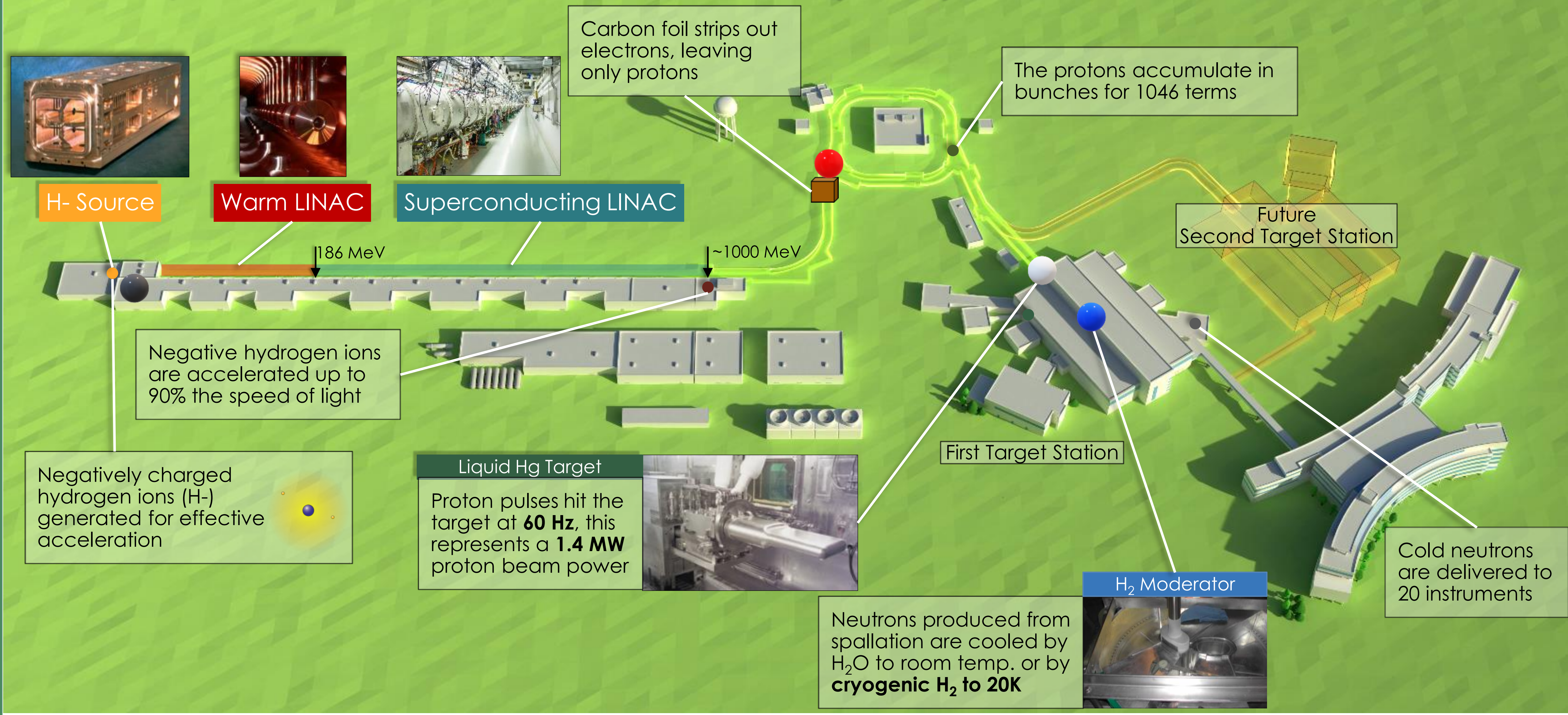
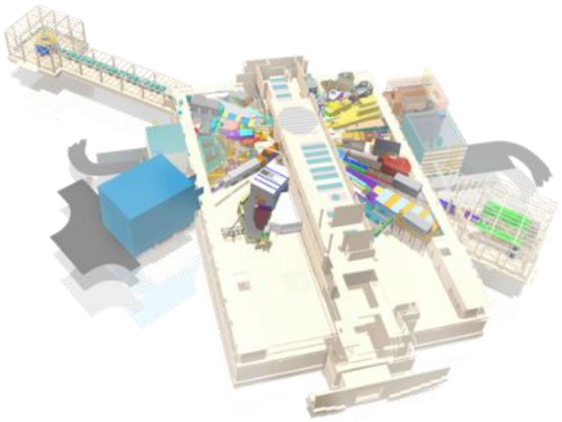
The Spallation Neutron Source (SNS)



SNS Upgrades (more power, more problems)

Today

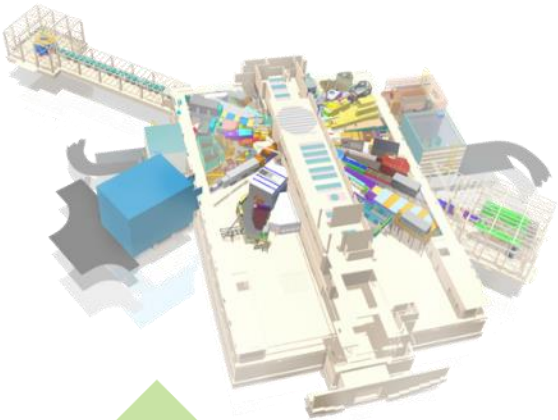


First Target Station
- 60 pulses per second
- 24 instrument positions
- 19 instruments built

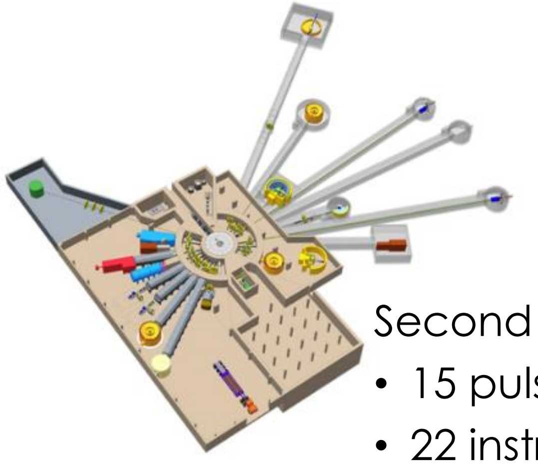
1.4 MW

Accelerator today

Future



First Target Station
- 45 pulses per second
- 24 instrument positions
- 21 instruments built



Second Target Station
- 15 pulses per second
- 22 instrument positions
- 8 initial instruments

2 MW

0.7 MW

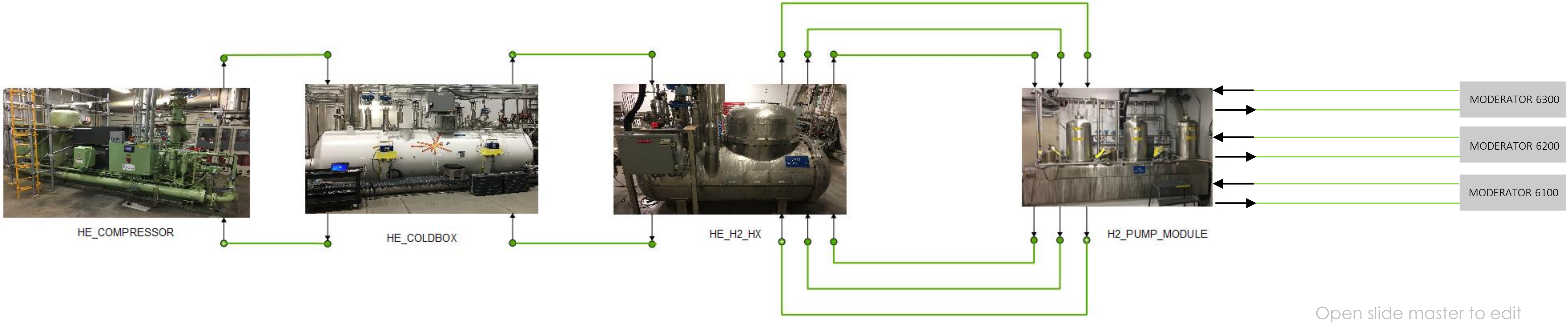
Accelerator after PPU

Cryogenic Moderator System Model Development EcoSimPro

ORNL is managed by UT-Battelle LLC for the US Department of Energy

Cryogenic moderator system overview

- Primary function
  - The cryogenic moderator system (CMS) reduces the energy of neutrons, born from spallation of liquid mercury, to low values sufficient to perform neutron science
- A refrigeration loop compresses and cools helium
  - High pressure side at 300 K and 17.4 bara [240 psig]
  - Low pressure side at 18 K and 3.75 bara [40 psig]
- Heat is removed from three supercritical hydrogen loops by the cryogenic helium gas
- Supercritical hydrogen vessels are located along several neutron flight paths between the spallation target and neutron science instrumentation



Why does ORNL need to develop numerical models of its cryogenic systems?

- The SNS CMS was largely designed using steady-state calculations for nominal operation
- To optimize the control system during beam transients and prepare for power upgrades, it is necessary to predict the dynamic response of the system
- To recalibrate the existing controllers to avoid large pressure swings observed after a beam trip occurs
- Plans include testing control systems virtually so that production operations are not disturbed
- Models may also be used to train future operators on the system like a traditional training simulator

Code selection: EcosimPro

- Simulation tool developed by Empresarios Agrupados for numerical modeling based on differential-algebraic equations and discrete events
- GUI and non-causal object-oriented modelling language to model continuous and discrete processes
- Libraries spanning mechanical, electrical, thermal, mathematical, and control concepts
- Applications include:
  - International Space Station air revitalization
  - OXY combustion plants
  - Desalination station
  - Internal combustion engines
  - Cryogenic plants and rocket engines

What is the CRYOLIB library within EcoSimPro?

- CRYOLIB is a modeling library available in EcosimPro for simulating cryogenic systems.
- The library is the result of the collaboration between CERN and CEA
- Components have been validated with experimental data from CERN and CEA installations

Cryogenic components

- Pipes
- Valves
- Pumps
- Tanks
- Compressors
- Heat exchangers
- Turbines
- Absorbers
- Phase separators

Thermophysical properties

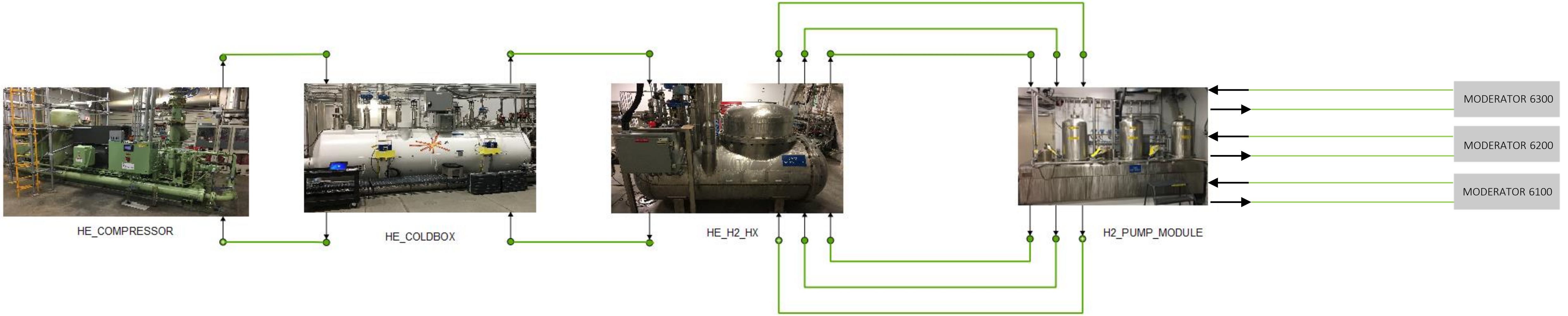
- Library for returning the complete thermodynamic state of a fluid or solid
- HEPAK for helium
  - Pre-tabulated values
  - Directly call HEPAK
- REFPROP from NIST
  - H_2 (ortho and para)
  - N_2, O_2, Ar, Xe, etc.
- Vapor, liquid, two-phase
- Supercritical

PLC components

- UNICOS compatible
- Proportional–integral–derivative (PID) controllers for control loops
- Analog actuators
- Signal generators
- Signal gates
- Boolean logic

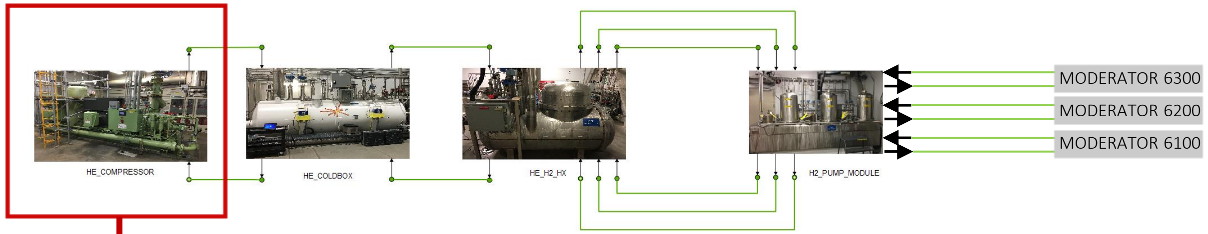
Overview of SNS CMS numerical model

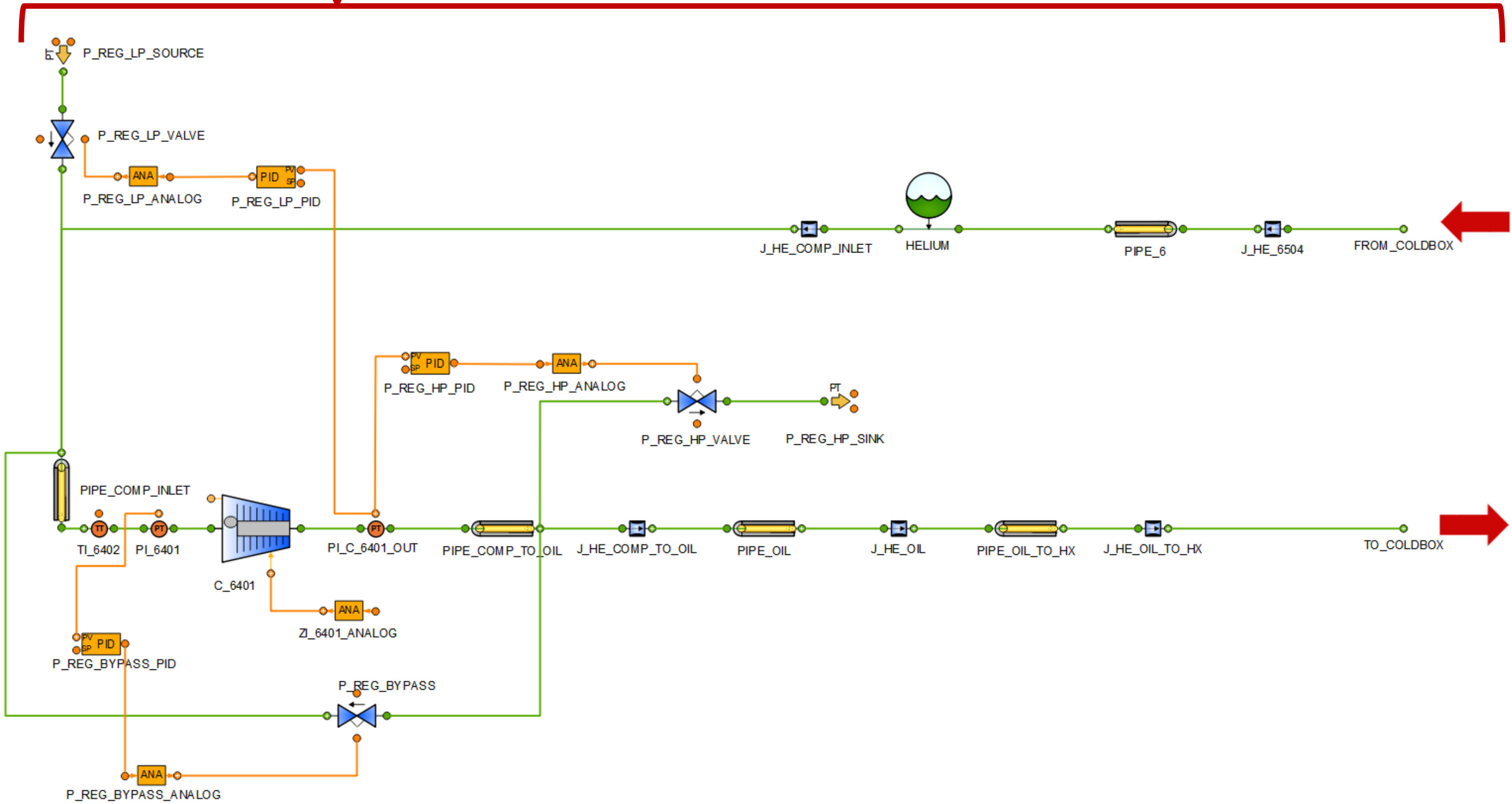
- The modeling effort focused on four subsystems of the CMS
  - Warm helium compressor station [300 K]
  - Helium coldbox [20 K]
  - Helium/hydrogen heat exchanger module [20 K]
  - Hydrogen pump module with three transfer lines to neutron moderator vessels [20 K]



Model description: Warm helium compressor station [300 K]

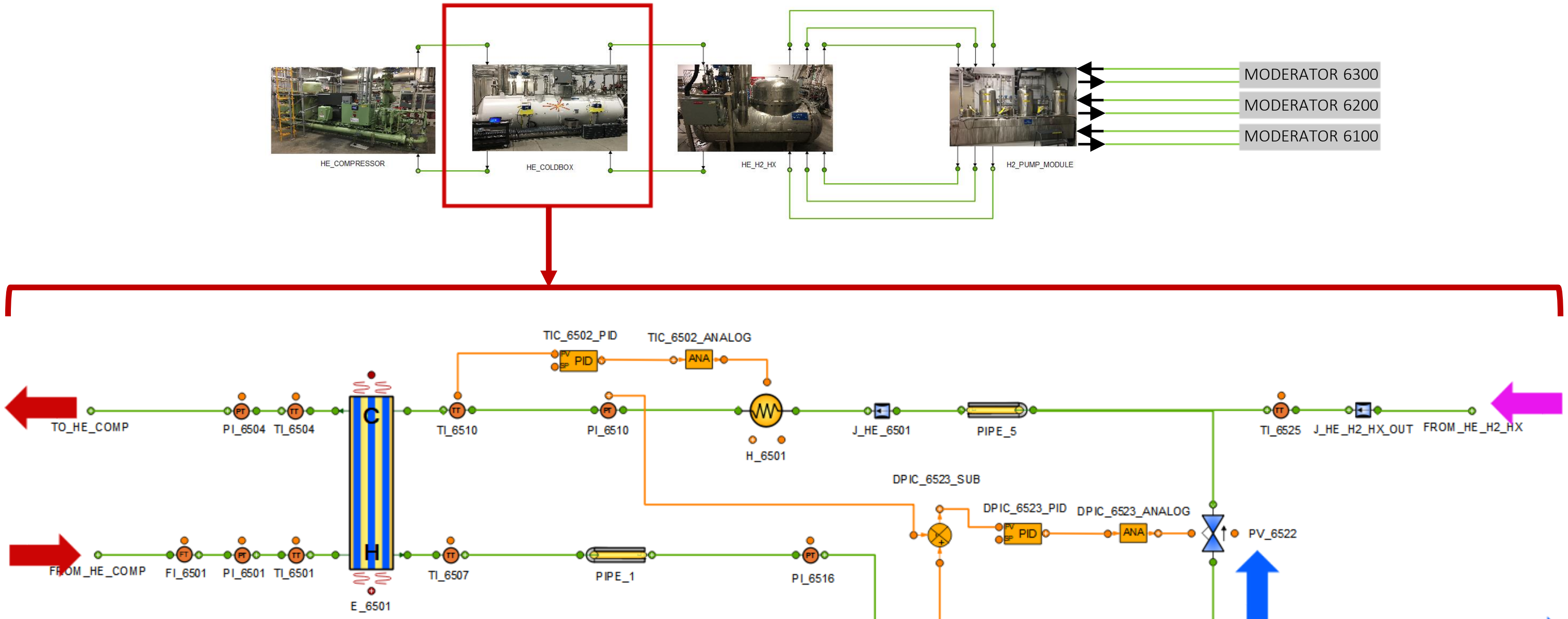
- Helium compressor
  - Screw compressor represented as an ideal compressor to simplify heat exchange
  - Operated at constant speed and constant outlet valve position
- Oil recovery skid
  - Neglected the complexity of oil recovery and helium purification operations when the focus is on dynamic refrigeration performance

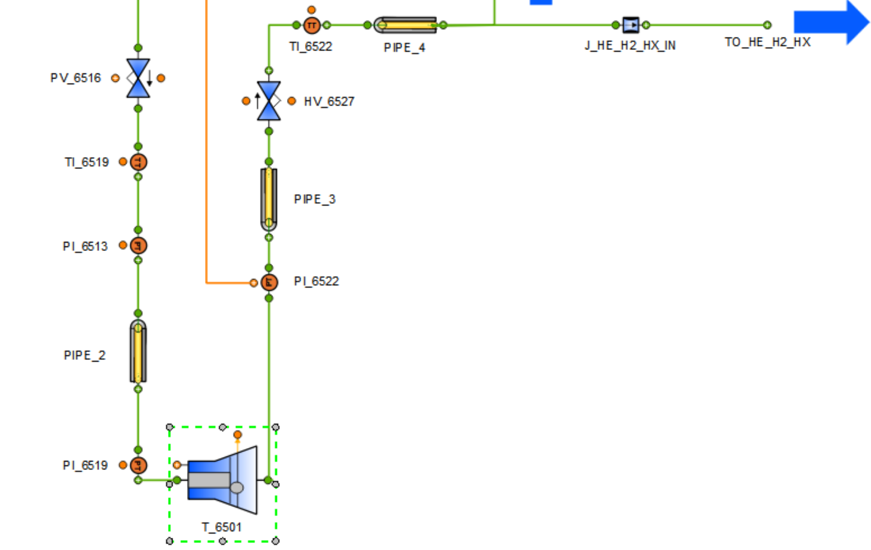




Model description: Helium coldbox [20 K]

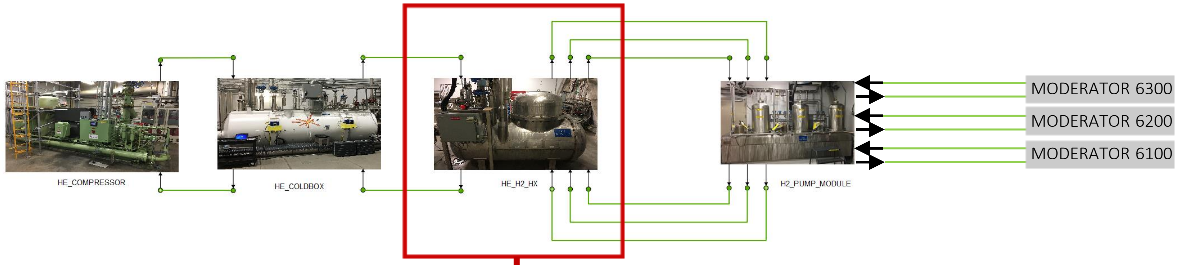
- Helium/helium regen HX
  - HP side temperature from 300 K to 28 K
  - LP side temperature from 22 K to 300 K
  - Highly instrumented with upstream and downstream sensors on both HP and LP sides
  - Having this information on each component would facilitate further development of the model
- Turbine
  - Decreases temperature from 28 K to 20 K
  - Rotation speed is a function of the pressure gradient across the turbine
- Bypass valve
  - Provides a flow path that bypasses the helium/hydrogen HXs
  - Seeks a 0.275 bar [4 psi] differential pressure between the turbine and heater
- Heater
  - Electrical heater with 8000 W capacity
  - Makes up the energy source when the SNS linear accelerator is shut down or tripped
  - Seeks a 22 K temperature at the inlet to the helium/helium regen HX
- Absorber
  - Neglected the complexity of cleanup function but accounted for pressure drop

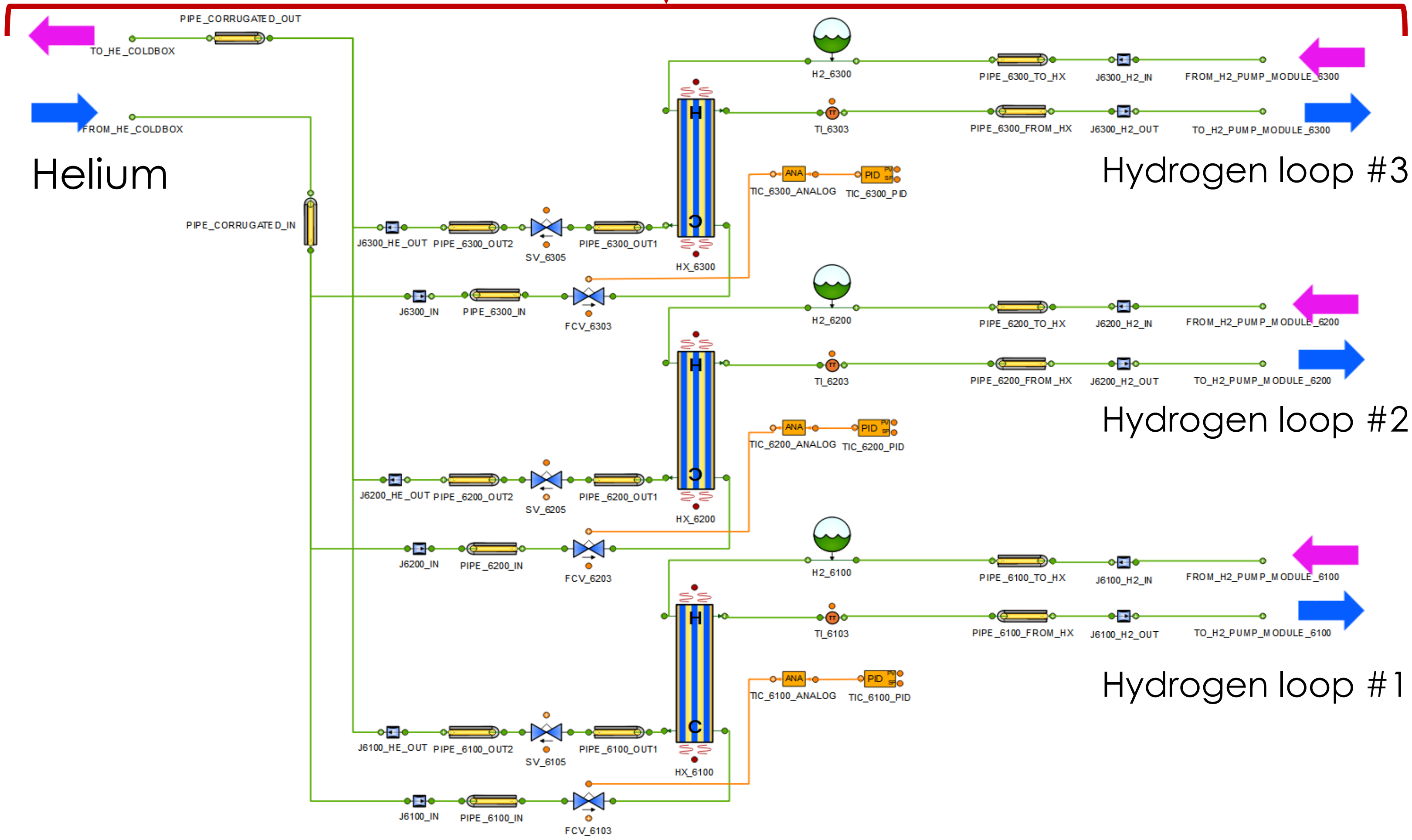


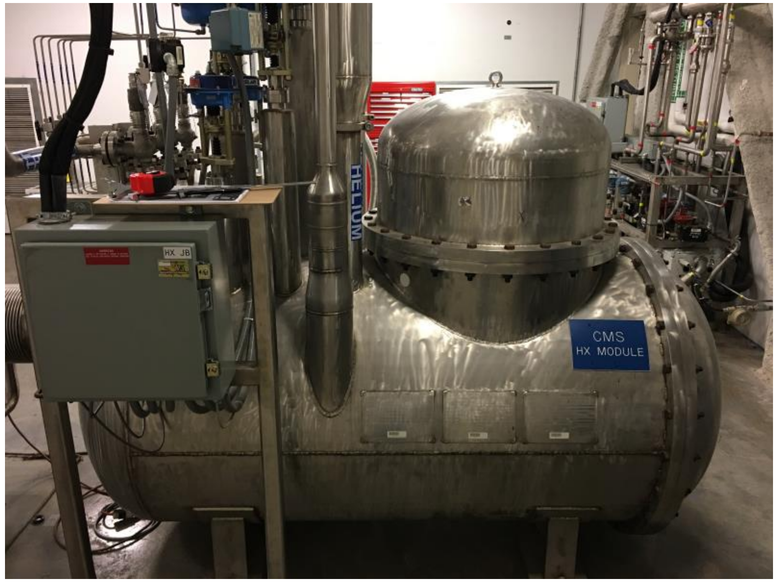


Model description: Helium/hydrogen heat exchanger module [20 K]

- Piping manifold to split the helium flow from one stream into three
- Helium/hydrogen HXs
- Helium HX flow control valves
  - The cooling helium flow for each HX is controlled by the associated hydrogen pressure in each loop
- Supply/return piping for three hydrogen loops

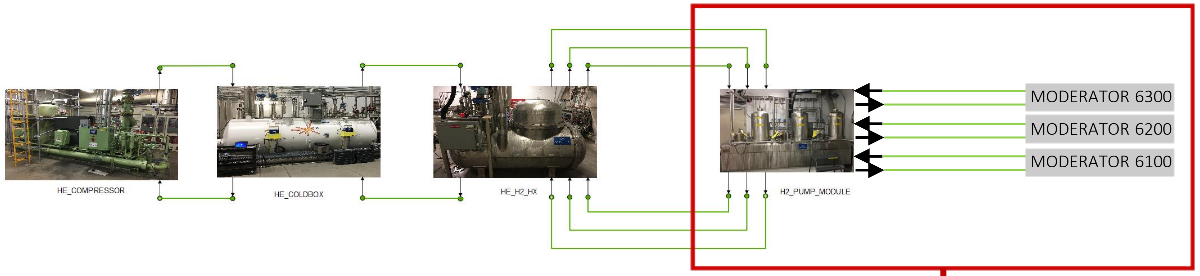


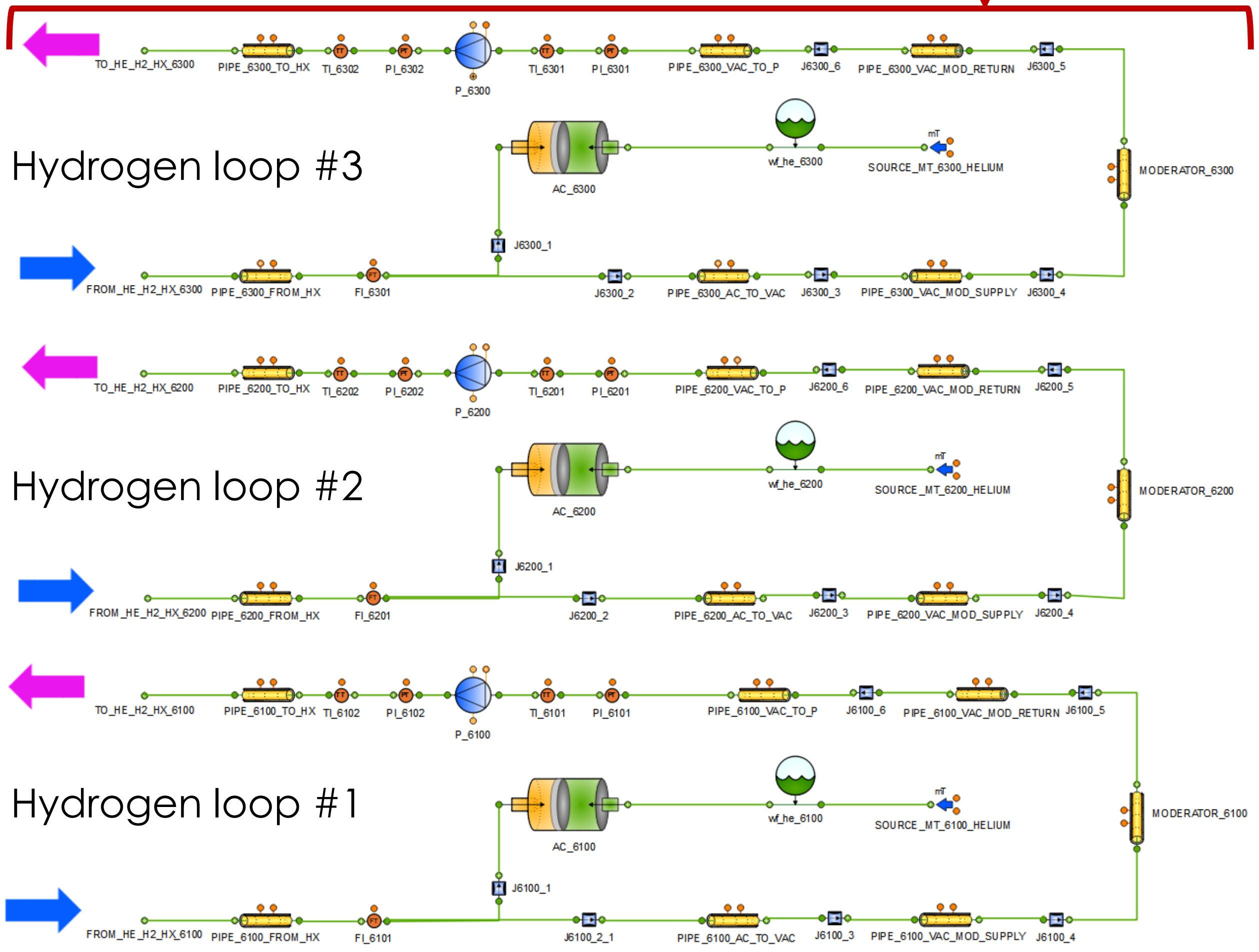




Model description: Hydrogen pump module and moderator vessels [20 K]

- Constant mass loops that have large transient heat loads
- Circulators
  - Provide work to move hydrogen between moderator vessels and helium/hydrogen HXs
- Accumulators
  - Helium-backed metal bellows provide pressure dampening during beam transients
- Moderator vessels
  - Flow stagnation region in the neutron beam path
  - Three separate moderators, each with unique geometry
- Transfer lines
  - Connect the pump module to moderator vessels
  - Co-axial jacketed tubing





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Preparing for transient beam power

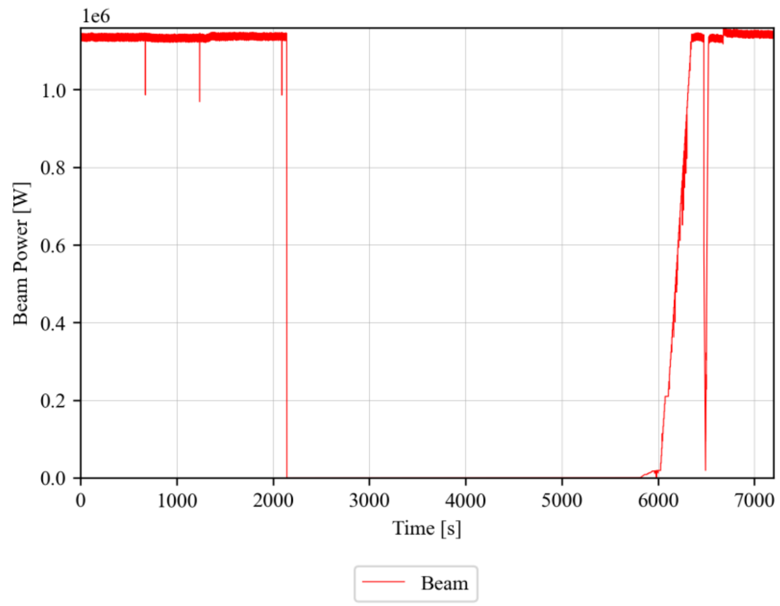
Converting beam power to moderator power

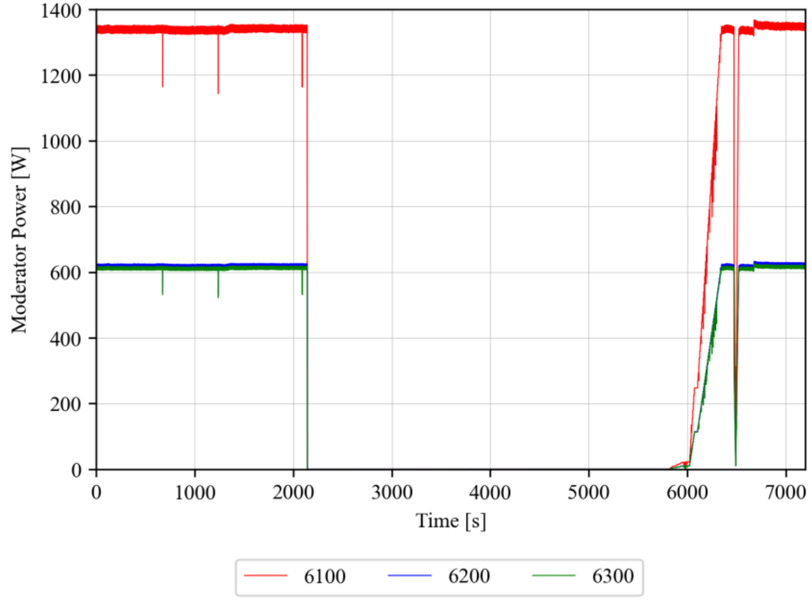
- Need to convert from beam power data to moderator power data
- Linearly scaling the Monte Carlo N-Particle code energy deposition rates from PPU studies at 2 MW to the time-dependent beam power of the AP studies
- Assuming all neutron energy from the moderator vessel must be extracted by the H_2
- $P_{mod_i,dataset}(t) = P_{beam,dataset}\,(t)\left(\frac{P_{mod_i,2MW}}{P_{beam,2MW}}\right)$
- EX: $P_{mod_{6100},data}(t) = P_{beam,dataset}\,(t)\left(\frac{2358\ W}{2E+6\ W}\right)$

Table 1. Energy deposited per material under PPU conditions

Material	3D-Calculation (2MW @ 1.3 GeV)					
	Volume (m^3)			Total Energy Deposited per Material (W/2MW)		
	TUM	*TDM*	*BDM*	6100 *TUM*	6200 *TDM*	6300 *BDM*
Al-6061	5.28E-4	4.69E-4	4.65E-4	895	547	548
Stainless Steel	7.96E-5	7.26E-5	6.02E-5	118	61.4	53.7
Gadolinium	2.3E-5	NA	NA	205	NA	NA
Liquid Hydrogen	1.21E-3	1.14E-3	1.11E-3	1140	486	476
Total	**98.784**	**81.96**	**79.85**	**2358**	**1094.4**	**1077.7**

2021 AP Study Comparison – System ID Training Dataset

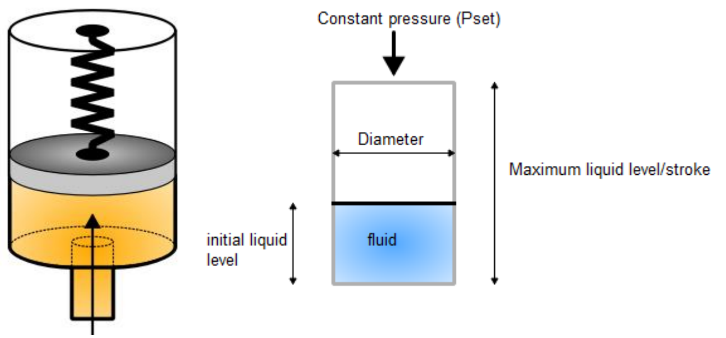




Expanding the CRYOLIB library: Accumulator development

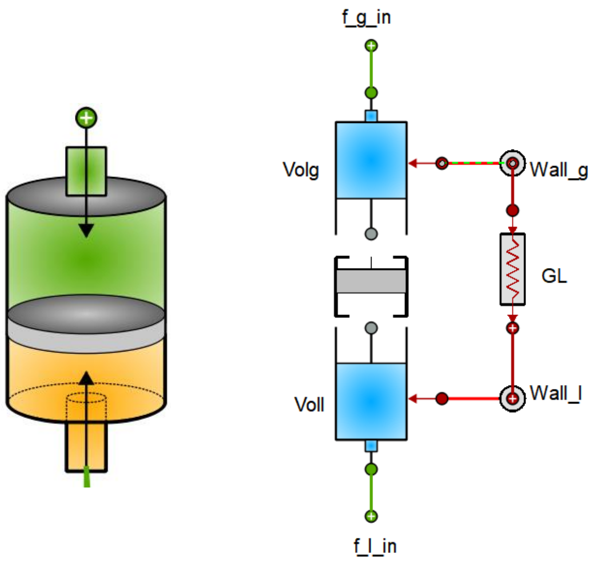
V1

Constant pressure



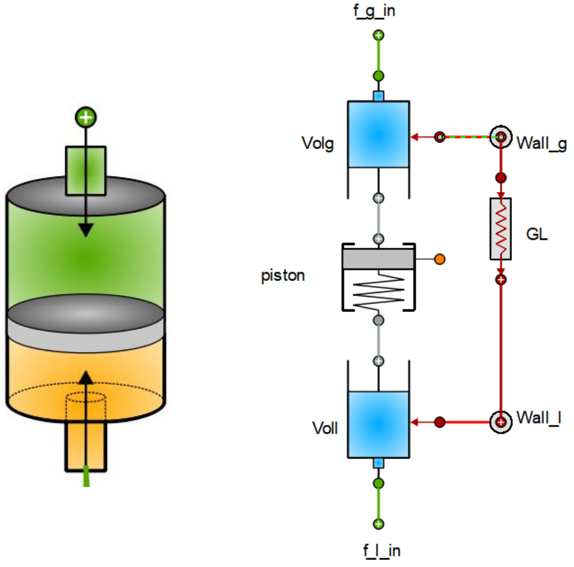
V2

Two-fluid buffer tank



V3

Two-fluid buffer tank with piston



Expanding the CRYOLIB library: Allen-Bradley Logix5000™ enhanced PID controller logic

- PV = process variable in engineering units
- SP = setpoint in engineering units
- E = error in percentage of PV span: $\mathrm{E_k} = \frac{SP_k - PV_k}{PV_{max} - PV_{min}} \times 100$
- CV = control variable: $CV_k = CV_{k-1} + K_P \Delta E_k + \frac{K_I}{60} E_k \Delta t$
- CV saturation ∈ $[0{,}100]$
- ΔE = change in percentage error = $\Delta E = E_k - E_{k-1}$
- CVEU = output of the controller in engineering units = $\mathrm{CV} \frac{\mathrm{CVEU_{max}} - \mathrm{CVEU_{min}}}{100} + \mathrm{CVEU_{min}}$

Control optimization problem
Dampen system response to beam trips

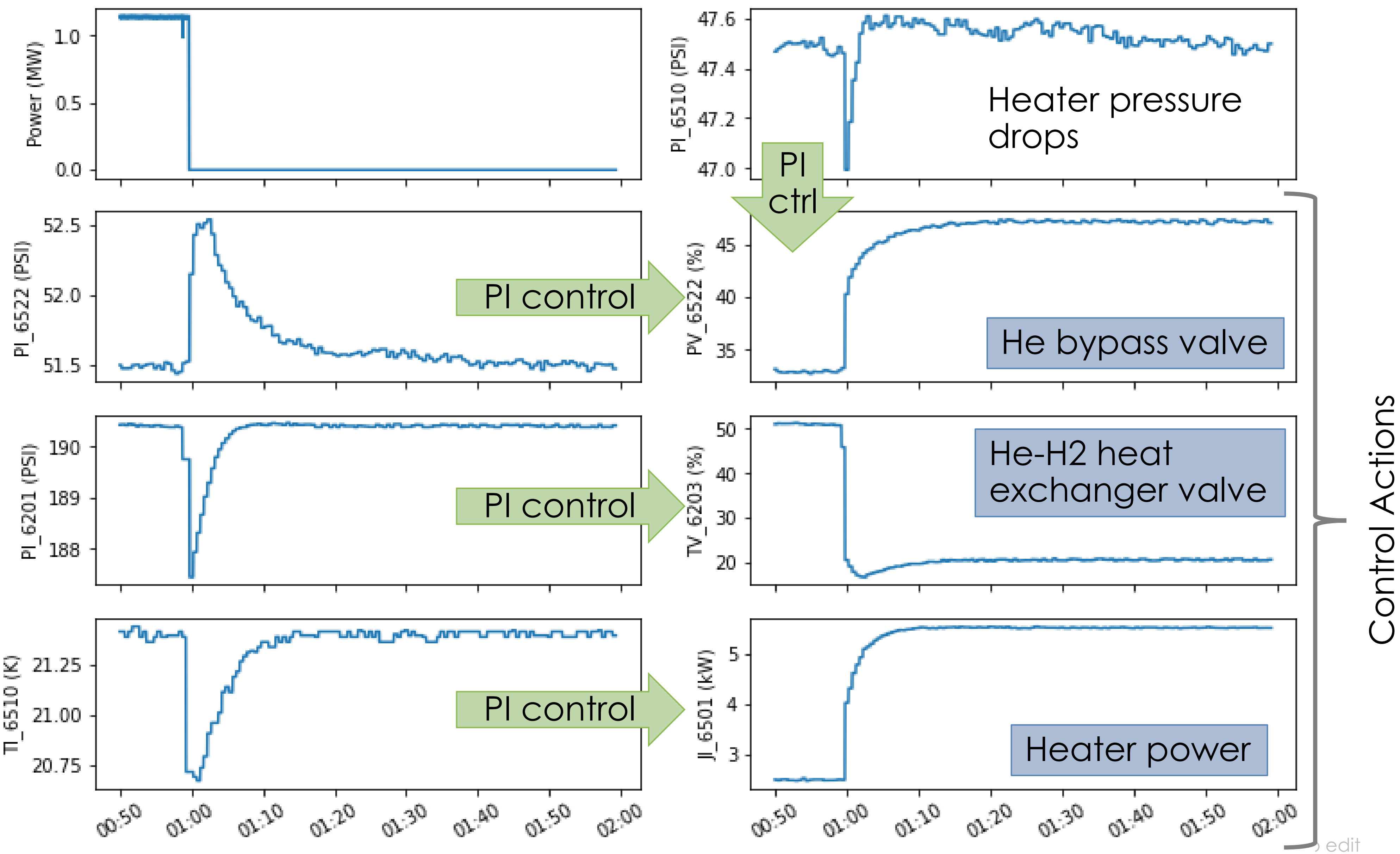
System reaction to beam trip

Beam power step change

Downstream turbine pressure increases (also affects turbine speed)

H_2 pressure drops

He temperature decreases



Numerical results

Steady-state simulation

- Sensor comparison
  - Relative difference
  - Green [0-5%]
  - Yellow [5-10%]
  - Red [>10%]
- Goal
  - Decrease difference between physical and virtual sensors
- Outcomes
  - Identified weak areas of the numerical model
  - Identified experimental sensors due for calibration

Warm Helium Compressor Station [300 K]

SUBSYSTEM	ID TAG	EXP DATA	SIM DATA	RELATIVE DIFFERENCE (%)
0_HE_COMPRESSOR	PI_6401	3.74	3.73	0.2
0_HE_COMPRESSOR	TI_6402	298.9	298.3	0.2

Helium/hydrogen heat exchanger module [20 K]

SUBSYSTEM	ID TAG	EXP DATA	SIM DATA	RELATIVE DIFFERENCE (%)
2_HE_H2_HX	TV_6103	67	67	0
2_HE_H2_HX	TI_6103	18.9	17.6	6.6
2_HE_H2_HX	TV_6203	43	43	0
2_HE_H2_HX	TI_6203	20.9	19.7	5.7
2_HE_H2_HX	TV_6303	50	50	0.1
2_HE_H2_HX	TI_6303	18.8	18.6	0.8

Helium coldbox [20 K]

SUBSYSTEM	ID TAG	EXP DATA	SIM DATA	RELATIVE DIFFERENCE (%)
1_HE_COLDBOX	PI_6501	16.62	16.59	0.1
1_HE_COLDBOX	TI_6501	300.3	300.0	0.1
1_HE_COLDBOX	FI_6501	0.254	0.256	-0.8
1_HE_COLDBOX	TI_6507	26.0	25.2	3.2
1_HE_COLDBOX	PI_6516	16.55	16.32	1.4
1_HE_COLDBOX	TI_6519	25.2	25.1	0.3
1_HE_COLDBOX	PI_6519	16.06	15.80	1.6
1_HE_COLDBOX	PI_6513	15.75	15.80	-0.3
1_HE_COLDBOX	PI_6522	4.29	4.40	-2.8
1_HE_COLDBOX	SI_6501	1164	1175	-0.9
1_HE_COLDBOX	TI_6522	17.7	17.3	2.7
1_HE_COLDBOX	PV_6522	24	24	0.1
1_HE_COLDBOX	TI_6525	19.9	20.2	-1.6
1_HE_COLDBOX	PI_6510	3.94	4.04	-2.6
1_HE_COLDBOX	DPI_6523	0.34	0.36	-4.9
1_HE_COLDBOX	TI_6510	22.0	22.0	-0.2
1_HE_COLDBOX	TI_6504	297.8	298.1	-0.1
1_HE_COLDBOX	PI_6504	3.68	3.75	-2.2

Hydrogen pump module and moderator vessels [20 K]

SUBSYSTEM	ID TAG	EXP DATA	SIM DATA	RELATIVE DIFFERENCE (%)
3_H2_PUMP_MODULE	FI_6101	0.075	0.075	0.3
3_H2_PUMP_MODULE	TI_6101	20.9	20.8	0.4
3_H2_PUMP_MODULE	PI_6101	13.95	13.95	0
3_H2_PUMP_MODULE	TI_6102	20.9	20.8	0.8
3_H2_PUMP_MODULE	PI_6102	14.27	14.26	0.1
3_H2_PUMP_MODULE	FI_6201	0.037	0.037	-0.1
3_H2_PUMP_MODULE	TI_6201	22.0	22.7	-3.3
3_H2_PUMP_MODULE	PI_6201	14.06	14.08	-0.1
3_H2_PUMP_MODULE	TI_6202	21.8	22.7	-3.9
3_H2_PUMP_MODULE	PI_6202	14.92	14.92	0
3_H2_PUMP_MODULE	FI_6301	0.038	0.038	-0.1
3_H2_PUMP_MODULE	TI_6301	21.5	21.7	-0.8
3_H2_PUMP_MODULE	PI_6301	13.95	13.98	-0.2
3_H2_PUMP_MODULE	TI_6302	22.2	21.6	2.6
3_H2_PUMP_MODULE	PI_6302	14.92	14.89	0.1

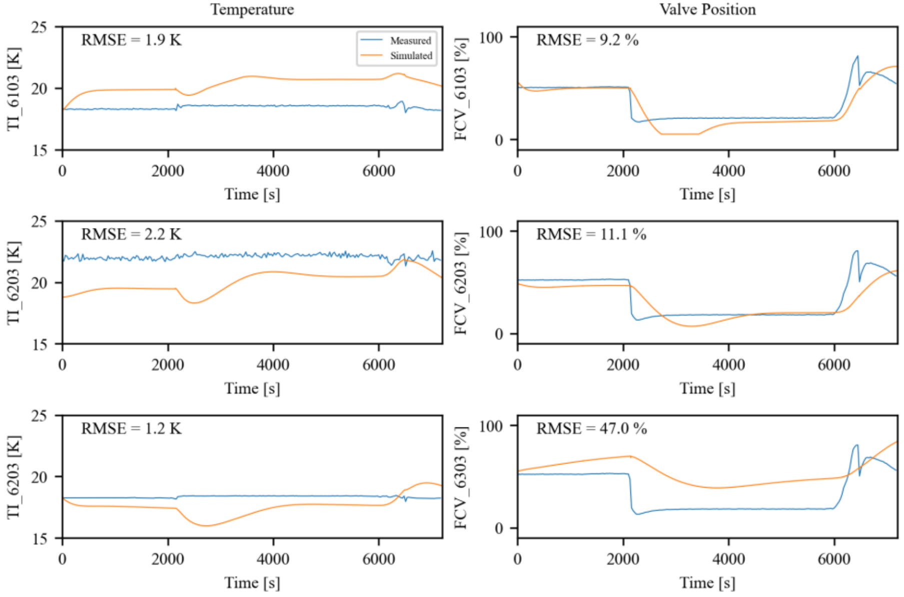
Transient simulation

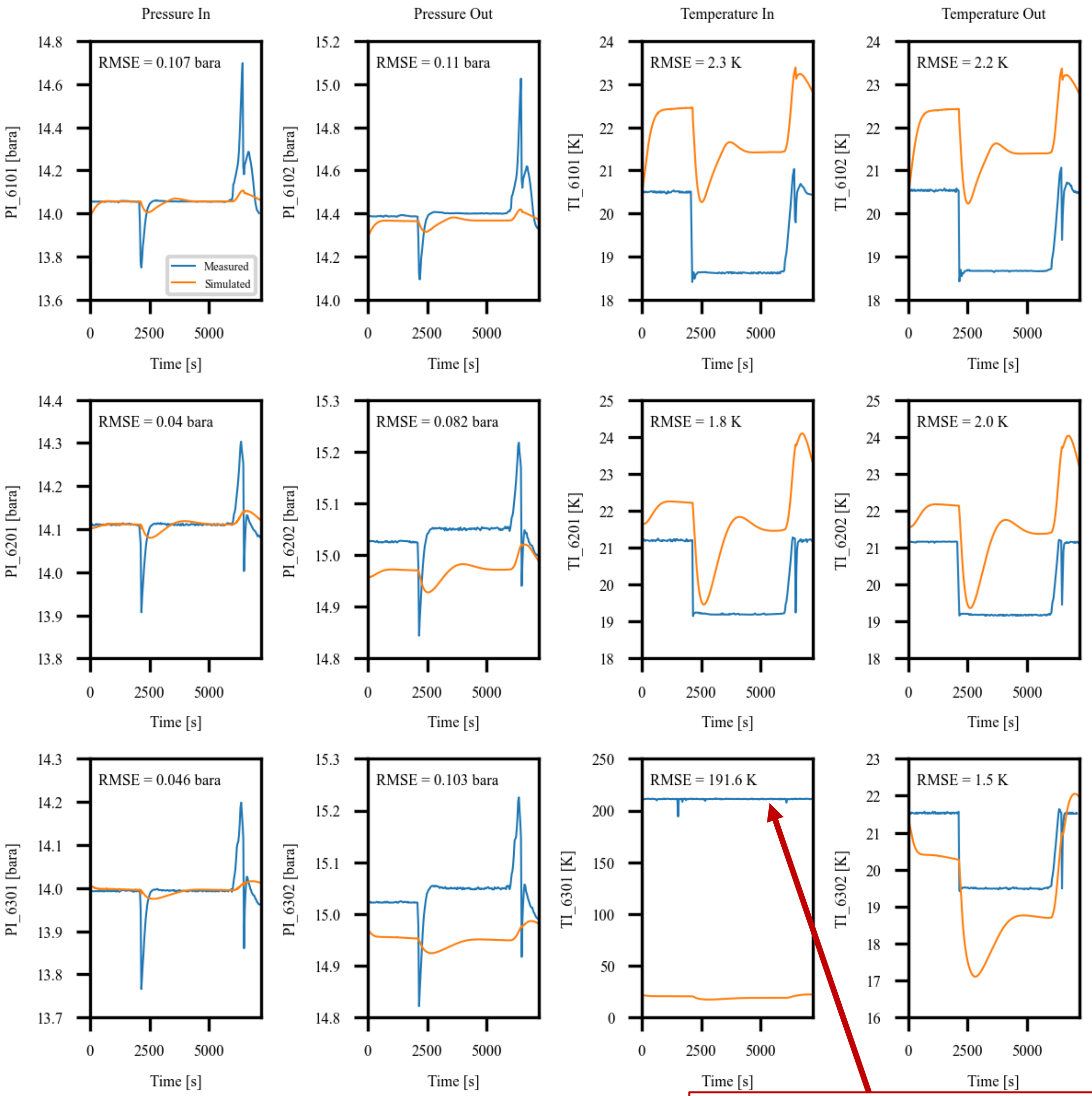
2021 AP Study Comparison – System ID Training Dataset

Case 1: Default EcoSim PID logic with experimental PID gain values

- Case 1: RMSE transient results
  - Strengths
    - Temperatures are within 2.5 K throughout
    - Pressures are within 0.1 bar
    - FCV positions for 6100 and 6200 are within 10%
  - Weaknesses
    - FCV position 6300 has an RSME of 47%

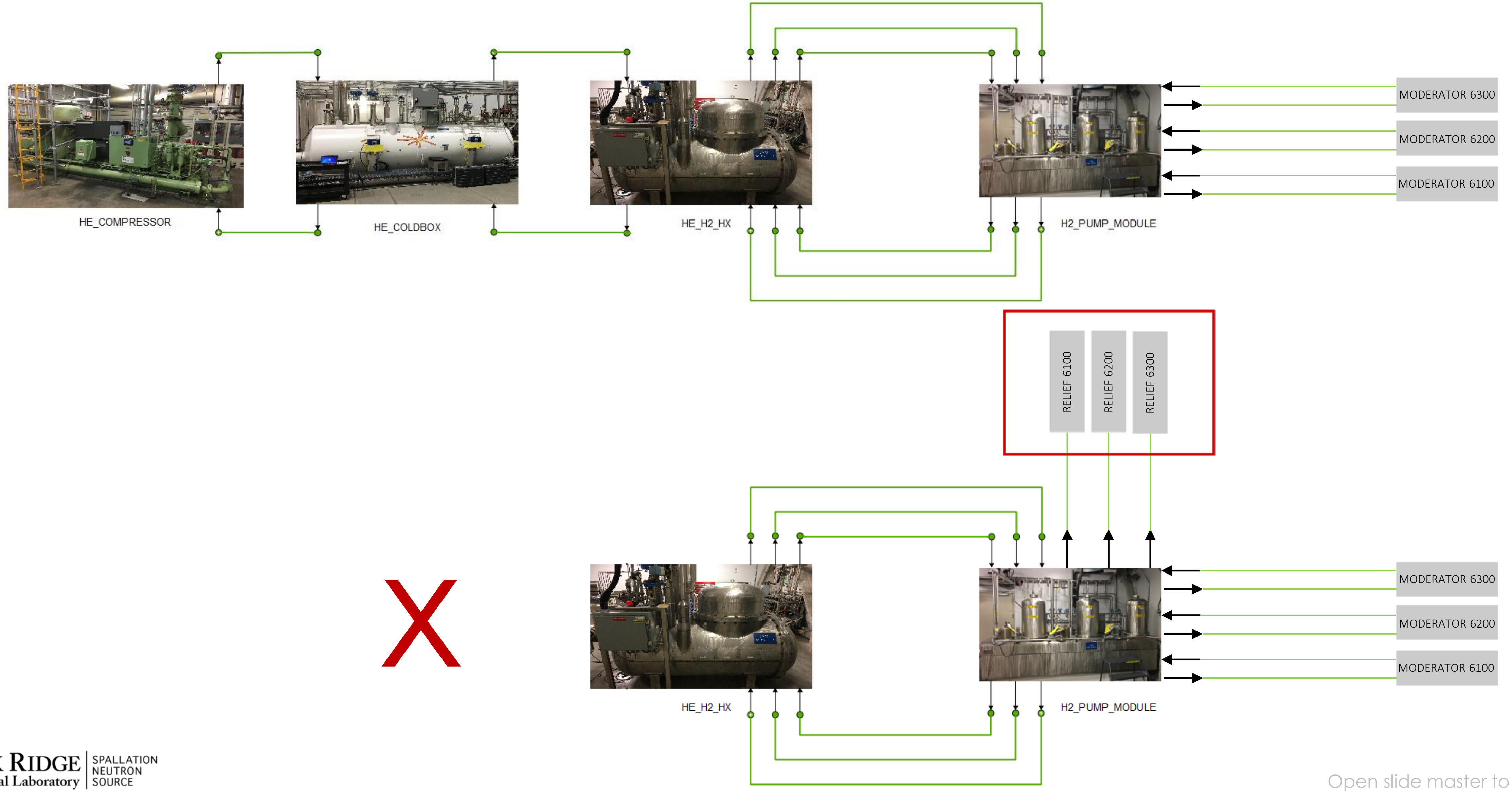
Helium – Hydrogen HX





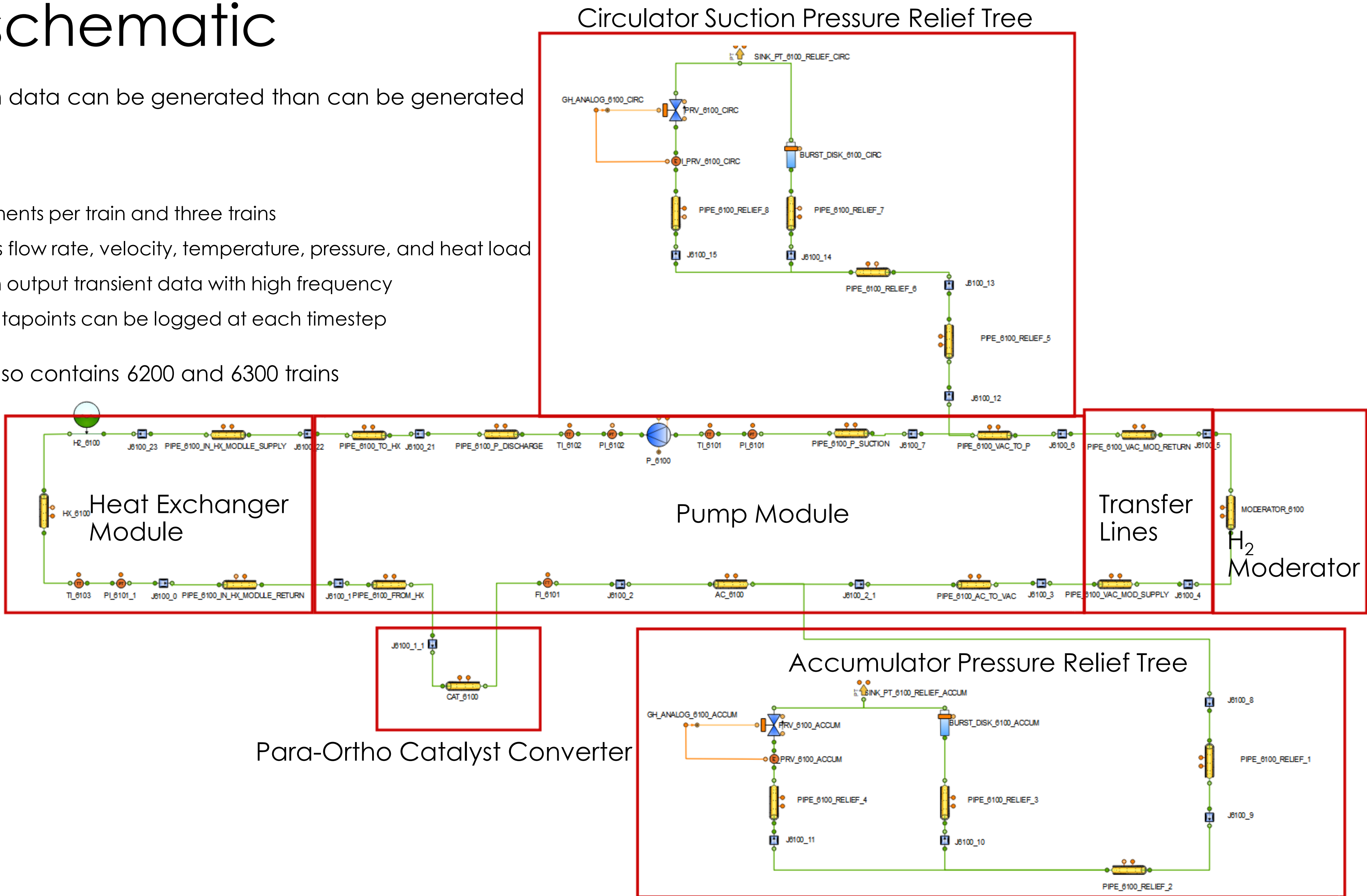
Malfunctioning thermocouple

Cryogenic moderating system – EcosimPro model adapted for pressure relief analysis



Cryogenic moderating system – EcosimPro model 6100 train schematic

- Significantly more system data can be generated than can be generated by existing sensors
- Numerical fidelity
  - Model has 40 components per train and three trains
  - Dataset includes mass flow rate, velocity, temperature, pressure, and heat load
  - Each component can output transient data with high frequency
  - Greater than 1,000 datapoints can be logged at each timestep
- Computational model also contains 6200 and 6300 trains



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Questions?