FERMILAB-SLIDES-23-322-AD-PIP2

State Machine Operation of Complex Systems

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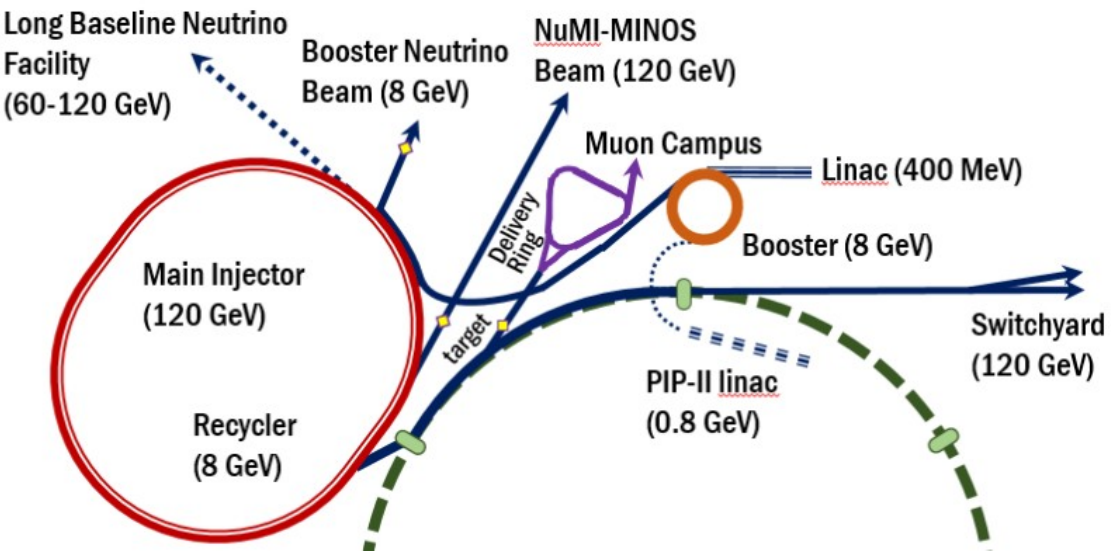
Content

Fermilab Accelerator Complex



Series of accelerators

Provides beam to several experiments

- LBNF, DUNE
- NuMI
- muon campus
- local neutrino experiments
- test beams

PIP-II will replace the existing LINAC

PIP-II is the first US/DOE accelerator to be built with significant international contributions/partnerships.

PIP-II Mission

PIP-II is an essential upgrade to Fermilab accelerator complex to enable the world’s most intense beam of neutrinos to LBNF/DUNE, and a broad physics research program for decades to come.

PIP-II Capabilities

Beam Power

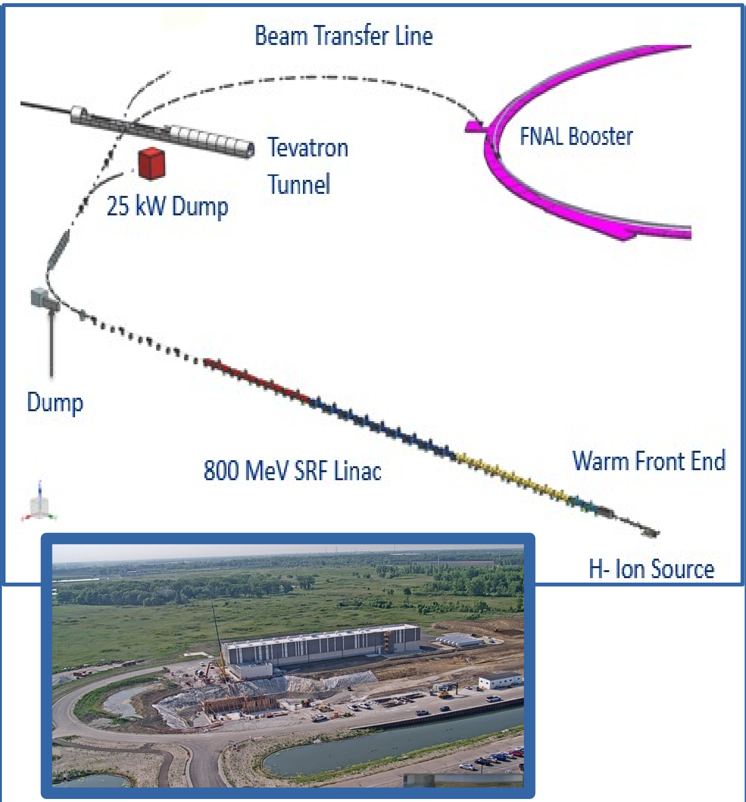
- 1.2 MW proton beam
- Upgradeable to multi-MW

Flexibility, multi-user capability

- CW-compatible
- Customized beams
- Multi-user delivery

Reliability

- Modernizes Fermilab accelerator complex



PIP-II Scope

800 MeV H^- SRF linac

- CW RF Operations

Linac → Booster transfer line

Accelerator Complex Upgrades

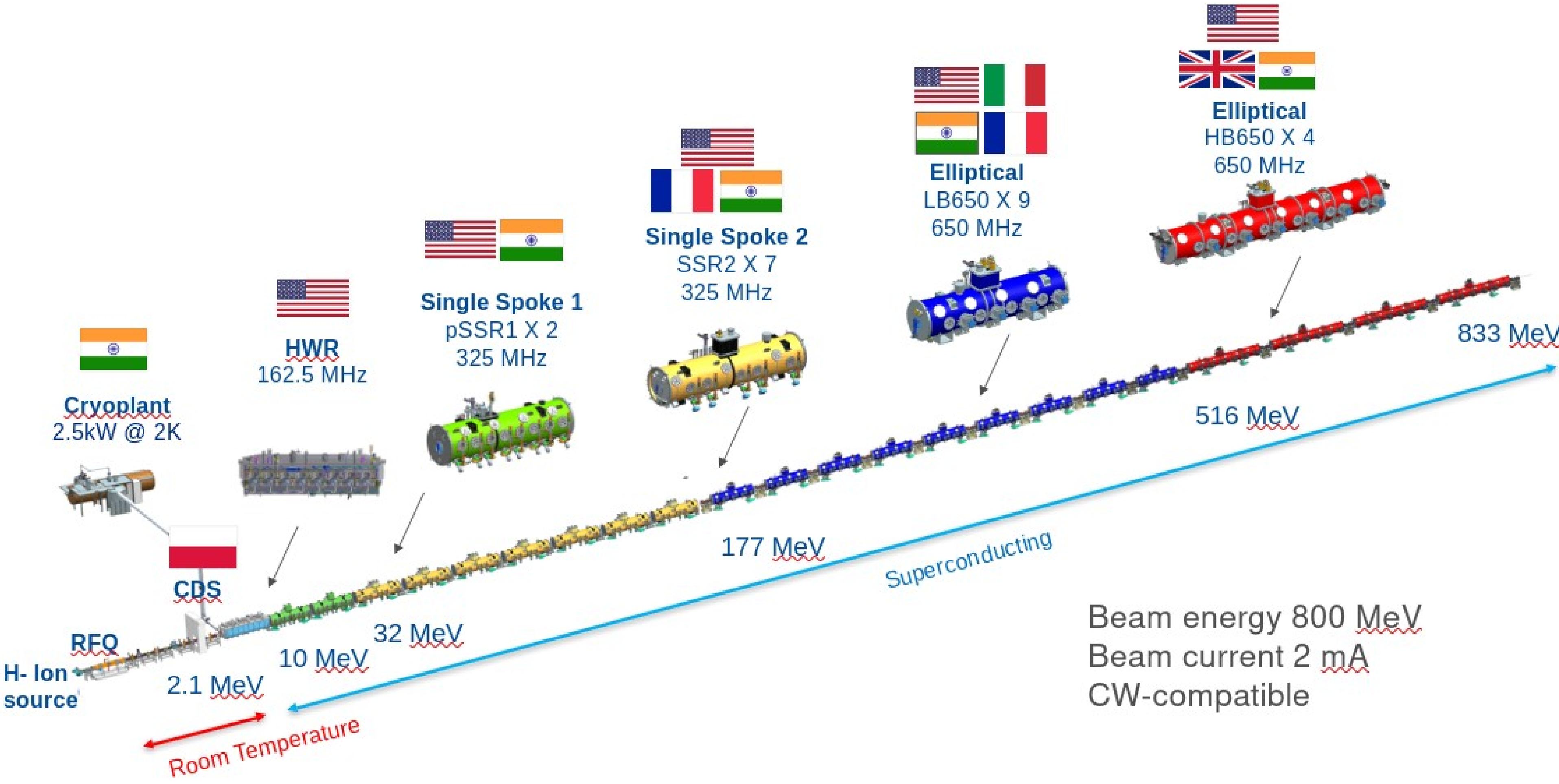
- Booster
- Recycler
- Main Injector

Conventional Facilities

- Space reserved for 2 CMs for 1GeV Upgrade

The PIP-II scope enables the accelerator complex to reach 1.2 MW p-beam on LBNF target

PIP-II Superconducting LINAC



Cryoplant
2.5kW @ 2K

HWR
162.5 MHz

Single Spoke 1
pSSR1 X 2
325 MHz

Single Spoke 2
SSR2 X 7
325 MHz

Elliptical
LB650 X 9
650 MHz

Elliptical
HB650 X 4
650 MHz

CDS

RFQ

H- Ion source

2.1 MeV
10 MeV
32 MeV
177 MeV
516 MeV
833 MeV

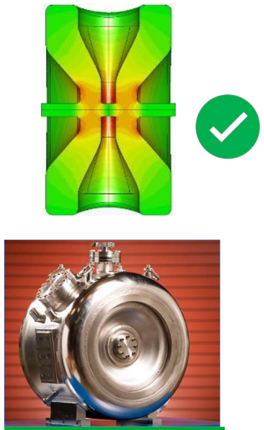
Superconducting

Room Temperature

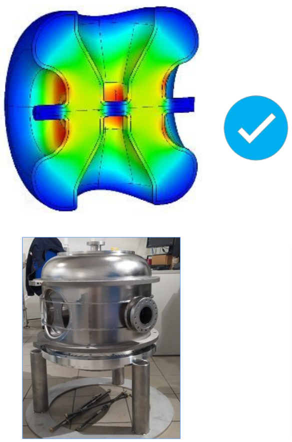
Beam energy 800 MeV
Beam current 2 mA
CW-compatible

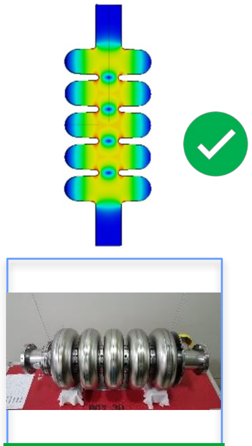
→ For more on PIP-II see D. Nicklaus FR1BCO02

PIP-II SRF Cavities[1,2]

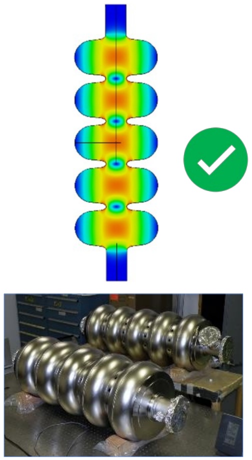


Production





Production



Production

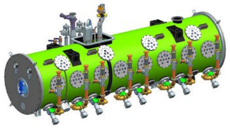
Name (Qty.)	**HWR (8)**	**SSR1 (16)**	**SSR2 (35)**	**LB650 (36)**	**HB650 (24)**	Units
Type	Half-Wave	Single Spoke	Single Spoke	Elliptical	Elliptical	-
β	0.11	0.22	0.47	0.61	0.92	-
Frequency	162.5	325	325	650	650	MHz
Design Q_0	0.5×10^{10}	0.6×10^{10}	0.8×10^{10}	1.5×10^{10}	2.0×10^{10}	-
Gradient	9.7	10	11.5	16.8	18.7	MV/m
N-doped	No	No	No	Mid-T bake	Yes	-

✓ *Prototypes validated*

PIP-II Cryomodule Development

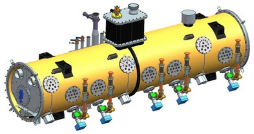
5.9 m

HWR ✓



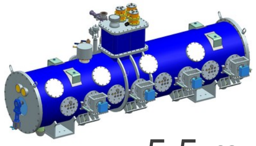
5.3 m

SSR1 ✓



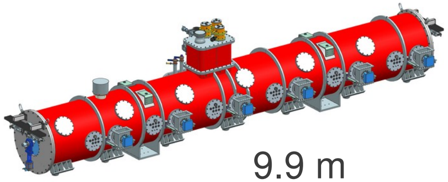
6.5 m

SSR2



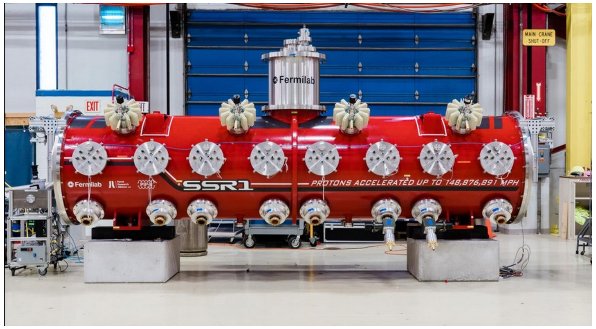
5.5 m

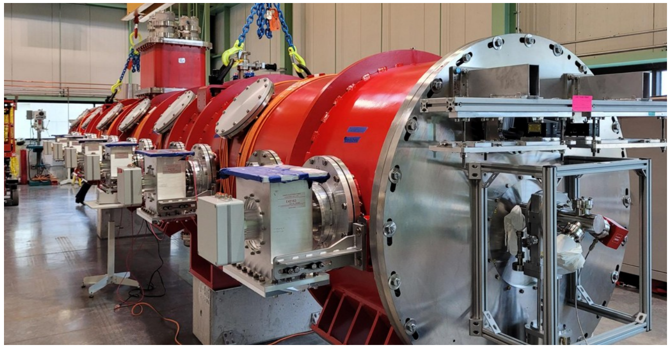
LB650

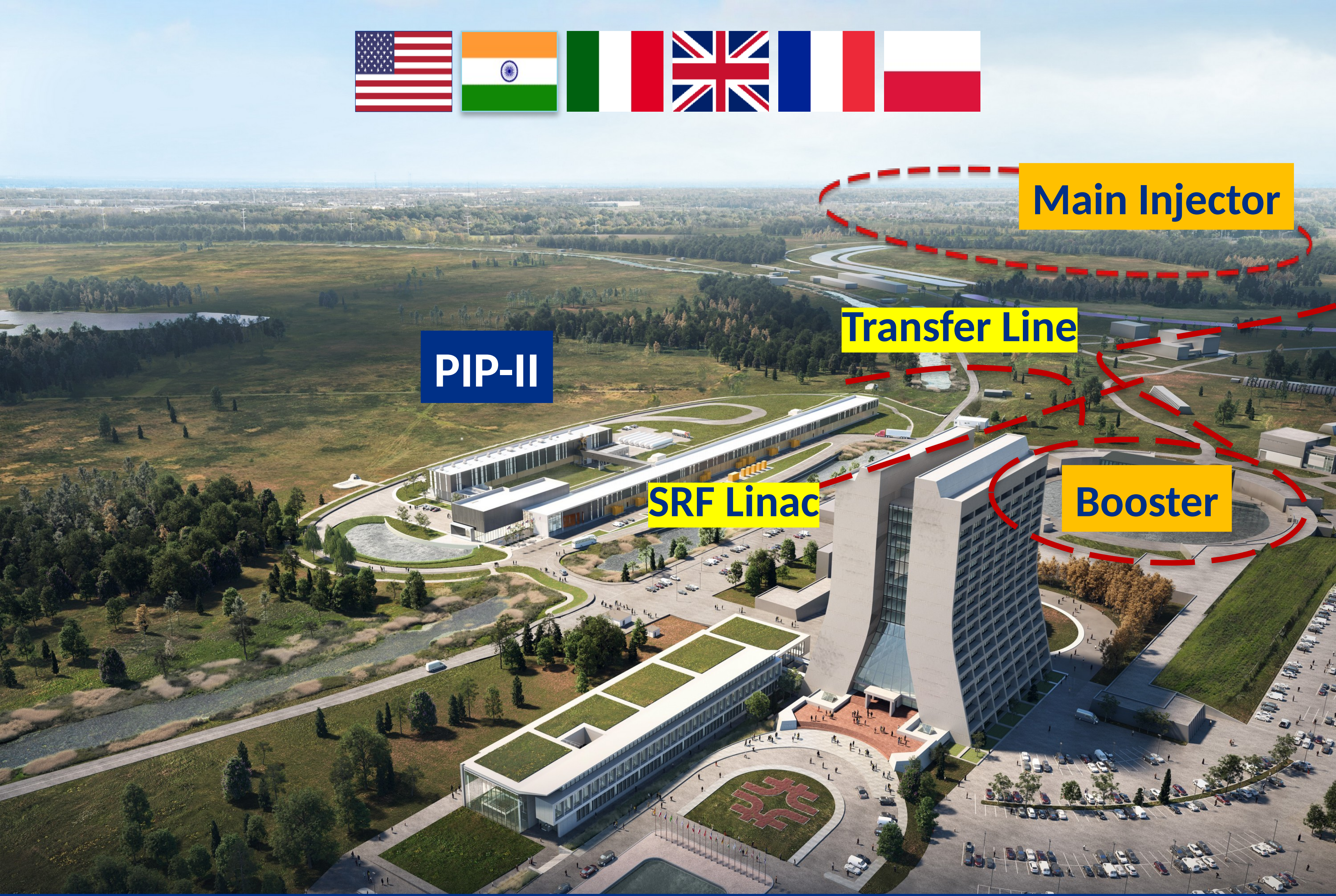


9.9 m

HB650 ✓







PIP-II will provide a highly capable, reliable, upgradeable and expandable scientific infrastructure with significant savings to DOE

Motivation: Complex Systems

In this context:

- A complex system can be any any field device or hardware to be controlled which has one or more sub-systems, and with many parameters, process variables (PVs)
- These systems have two – typically more – operational states
- For each state:
    - one, or more, sub-systems may be involved
    - different PVs of interest
    - different critical PVs
    - different alarm limits and severities for each PV
    - different archiving needs for each PV

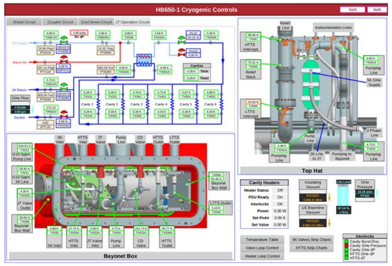
- States may be static or dynamic
- Generally, the combinatorics are very large
- Operators cannot to reliably change all of these parameters for each system for each state

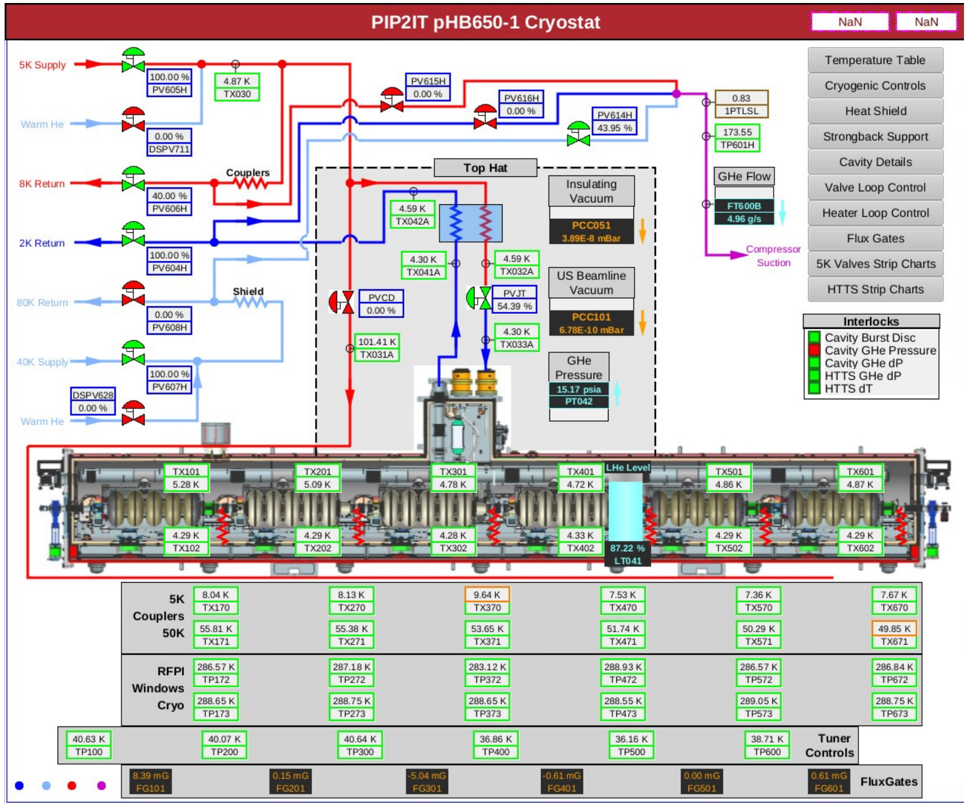
Motivation: Complex Systems

The consequences of ignoring operational states:

- the alarms limits may be set too loosely
  - do not notify operators and thus do not protect the operation
- the alarms limits may be set too tightly
  - alarms are continuous and ignored or disabled – again affecting operation
- archived data
  - if scanned may miss events
  - if monitored and deadbands not adjusted will collect data inefficiently, or not at all
- a change in PVs, defined as critical to operation, may go unnoticed
- system experts may miss notifications

Motivation: Complex Systems (w/out RF)





PV605H 100.00 %
TX030 4.87 K
DSPV711 0.00 %
PV606H 40.00 %
PV604H 100.00 %
PV608H 0.00 %
PV607H 100.00 %
DSPV628 0.00 %
PV615H 0.00 %
PV616H 0.00 %
PV614H 43.95 %
1PTLSL 0.83
TP601H 173.55
GHe Flow: FT600B 4.96 g/s
TX042A 4.59 K
TX041A 4.30 K
TX032A 4.59 K
PVCD 0.00 %
PVJT 54.39 %
TX031A 101.41 K
TX033A 4.30 K
Insulating Vacuum: PCC051 3.89E-8 mBar
US Beamline Vacuum: PCC101 6.78E-10 mBar
GHe Pressure: PT042 15.17 psia

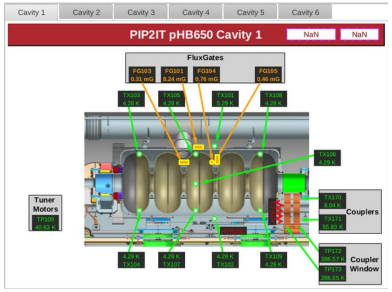
Interlocks
- 🟩 Cavity Burst Disc
- 🟩 Cavity GHe Pressure
- 🟩 Cavity GHe dP
- 🟩 HTTS GHe dP
- 🟩 HTTS dT

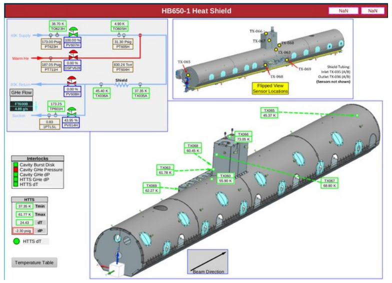
TX101	TX201	TX301	TX401	TX501	TX601
5.28 K	5.09 K	4.78 K	4.72 K	4.86 K	4.87 K

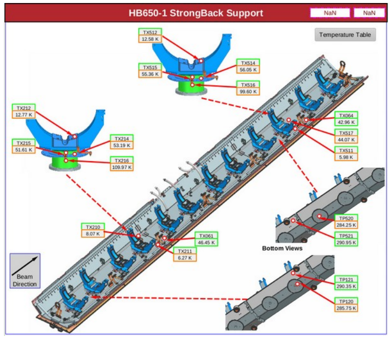
TX102	TX202	TX302	TX402	TX502	TX602
4.29 K	4.29 K	4.28 K	4.33 K	4.29 K	4.29 K

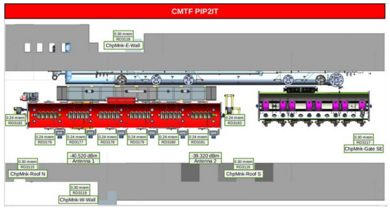
LT041 87.22 %

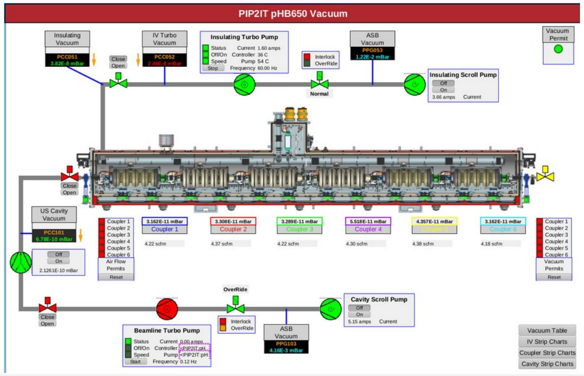
5K Couplers	8.04 K TX170	8.13 K TX270	9.64 K TX370	7.53 K TX470	7.36 K TX570	7.67 K TX670
50K	55.81 K TX171	55.38 K TX271	53.65 K TX371	51.74 K TX471	50.29 K TX571	49.85 K TX671
RFPI Windows	286.57 K TP172	287.18 K TP272	283.12 K TP372	288.93 K TP472	286.57 K TP572	286.84 K TP672
Cryo	288.65 K TP173	288.75 K TP273	288.65 K TP373	288.55 K TP473	289.05 K TP573	288.75 K TP673
Tuner Controls	40.63 K TP100 40.07 K TP200	40.64 K TP300	36.86 K TP400	36.16 K TP500	38.71 K TP600	
FluxGates	8.39 mG FG101	0.15 mG FG201	-5.04 mG FG301	-0.61 mG FG401	0.00 mG FG501	0.61 mG FG601

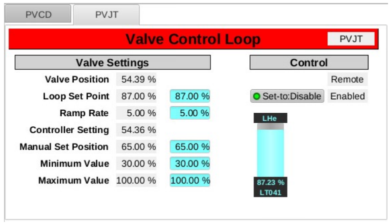










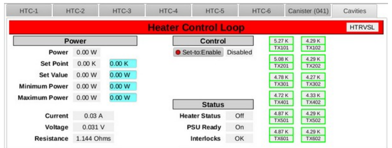


Valve Control Loop — PVJT

Valve Settings		
Valve Position	54.39 %	
Loop Set Point	87.00 %	87.00 %
Ramp Rate	5.00 %	5.00 %
Controller Setting	54.36 %	
Manual Set Position	65.00 %	65.00 %
Minimum Value	30.00 %	30.00 %
Maximum Value	100.00 %	100.00 %

Control: Remote; ● Set-to:Disable — Enabled

LHe: LT041 87.23 %



Heater Control Loop

Power		
Power	0.00 W	
Set Point	0.00 K	0.00 K
Set Value	0.00 W	0.00 W
Minimum Power	0.00 W	0.00 W
Maximum Power	0.00 W	0.00 W
Current	0.03 A	
Voltage	0.031 V	
Resistance	1.144 Ohms	

Control: ● Set-to:Enable — Disabled

Status	
Heater Status	Off
PSU Ready	On
Interlocks	OK

5.27 K TX101	4.29 K TX102
5.08 K TX201	4.29 K TX202
4.78 K TX301	4.27 K TX302
4.72 K TX401	4.33 K TX402
4.87 K TX501	4.29 K TX502
4.87 K TX601	4.29 K TX602

Motivation: States of a Complex System – Example

Example: Superconducting RF (SRF) Cryomodule

- Offline
- Vacuum Pumping – pumps, valves, gauges, interlocks (dynamic)
- Vacuum Pumped – same (static)
- Cooling HTTS – vacuum + valves, GHe flow, GHe pressure, temperatures, interlocks (dynamic – both vacuum and cryogenic)
- Cold HTTS – same PVs (static)
- Cooling 4K – vacuum + HTTS + additional valves, temperatures, LHe level, interlocks (dynamic – cavities, static for vacuum & HTTS)
- Cold 4K – same PVs (static)
- Cooling 2K – same + pump (dynamic)
- Cold 2K – same (static)
- … additional cryogenic states states
- Training RF – same vacuum & cryo PVs (static) + HPRF, LLRF, RFPI (dynamic)
- Powered RF – same vacuum, cryo, HPRF, LLRF, RFPI (static)
- Quenched …
- Error …
- Warming – all (dynamic)

Motivation: Complex Systems – Example

Example: Superconducting RF (SRF) Cryomodule

In the previous example:

- “dynamic” refers to states in which it is expected that some value(s) change
  - expect large alarm ranges for these PVs
  - expect data to be archived periodically
- “static” refers to states in which PVs are not expected to change
  - tight alarm limits
  - expect data to be archived only when changing outside of deadband
- “static” states occur when previous state’s dynamic PVs reach target
- when testing, one may stop at a static state, e.g. for the weekend

State Machine: What it is *NOT*

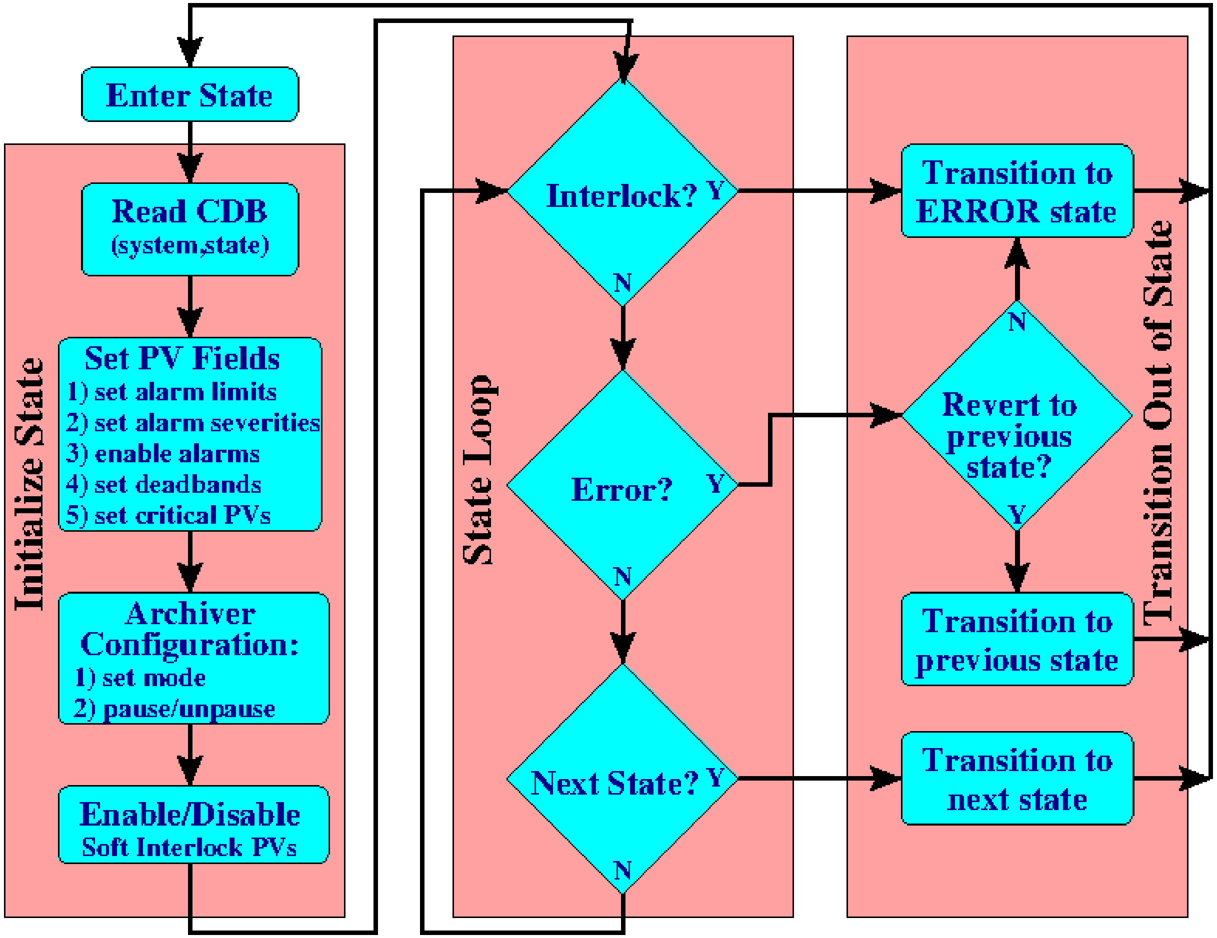
A state machine:

- is not intended to control the operation of a system
- in no way affects the operation of the system
- is not responsible for protecting equipment or personnel
- does not have user interactions

State Machine: What it *IS*

- A State Machine ***is*** a finite state machine
- It is a passive process that monitors the entire complex system and:
  - identifies its state by monitoring system PVs
  - identifies the pertinent PVs for each state
  - adjusts alarm limits and severities to be pertinent to the state
  - adjusts how data are archived depending on the state
  - identifies critical PVs for the state

State Machine: Algorithm



State Machine: Implementation

- The State Machine is implemented within the EPICS framework using the EPICS State Notation Language

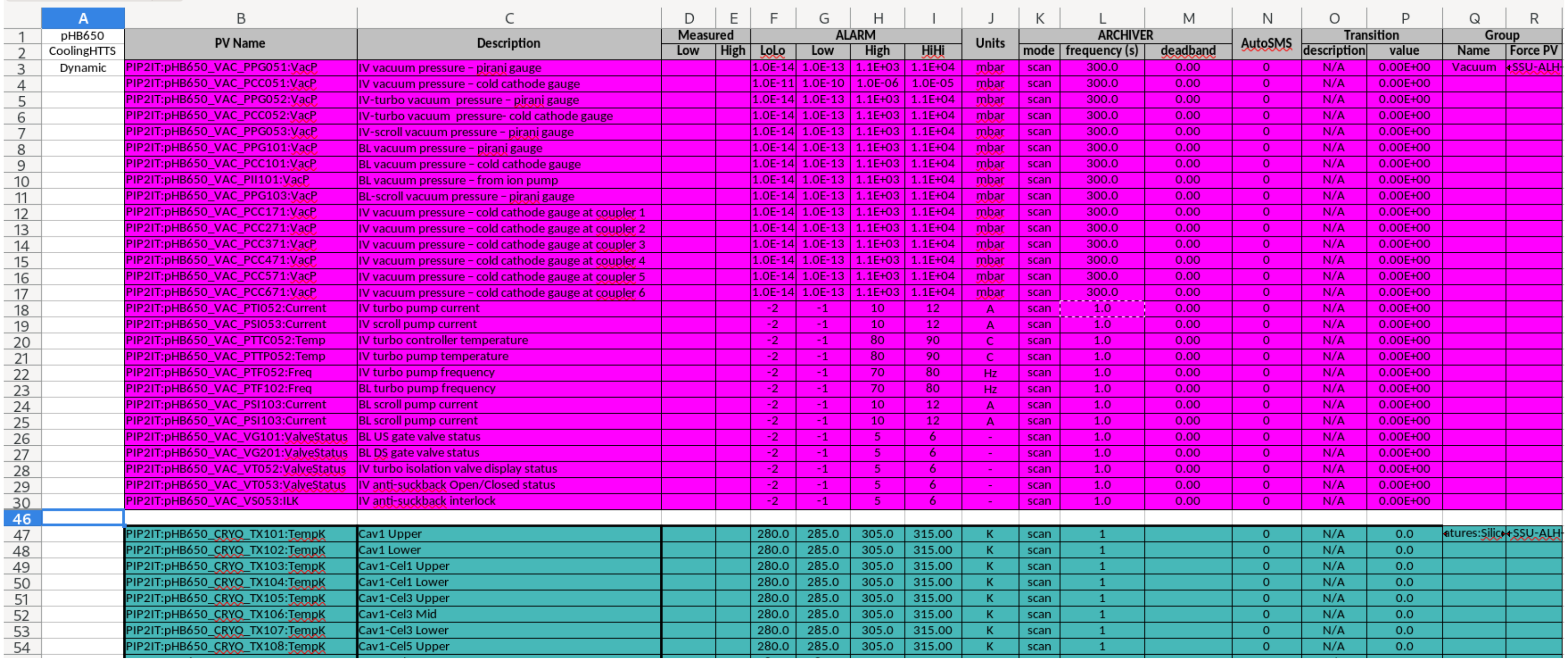
- 3 Components:
  1. state identifier – a passive program which monitors status or values of PVs, this can be a standalone IOC or part of another controls IOC
  2. database – relational database with identical tables (1 table for each state for each complex system)
  3. a sequence IOC implemented in EPICS state notation language
     - monitors state changes
     - reads database table associated with new state
     - dynamically changes PV alarm limits and severities
     - dynamically changes Archiver functionality
     - starts a monitor of critical PVs
       - typically used to notify sub-system experts

- IOC fields to be set: LOLO, LOW, HIGH, HIHI, LLSV, LSV, HSV, HHSV, ADEL

- The Archiver mode for each PV to be set as Monitor or Scan

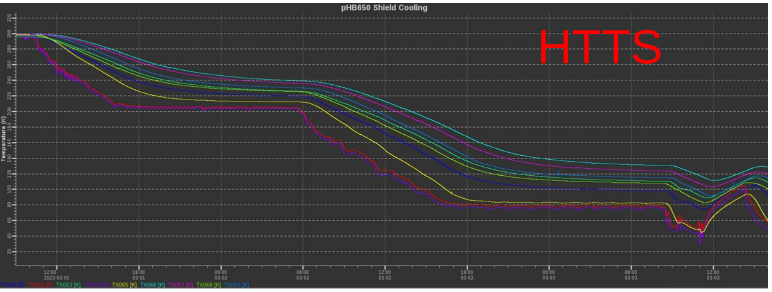
State Machine: Populating Database Tables

- populating the database tables requires the most effort
- sub-system experts begin with a template spreadsheet
- 1 sheet per state
- header corresponds to tables in database
- once populated, spreadsheets are loaded to database
- also helpful to ensure Archiver is correctly populated

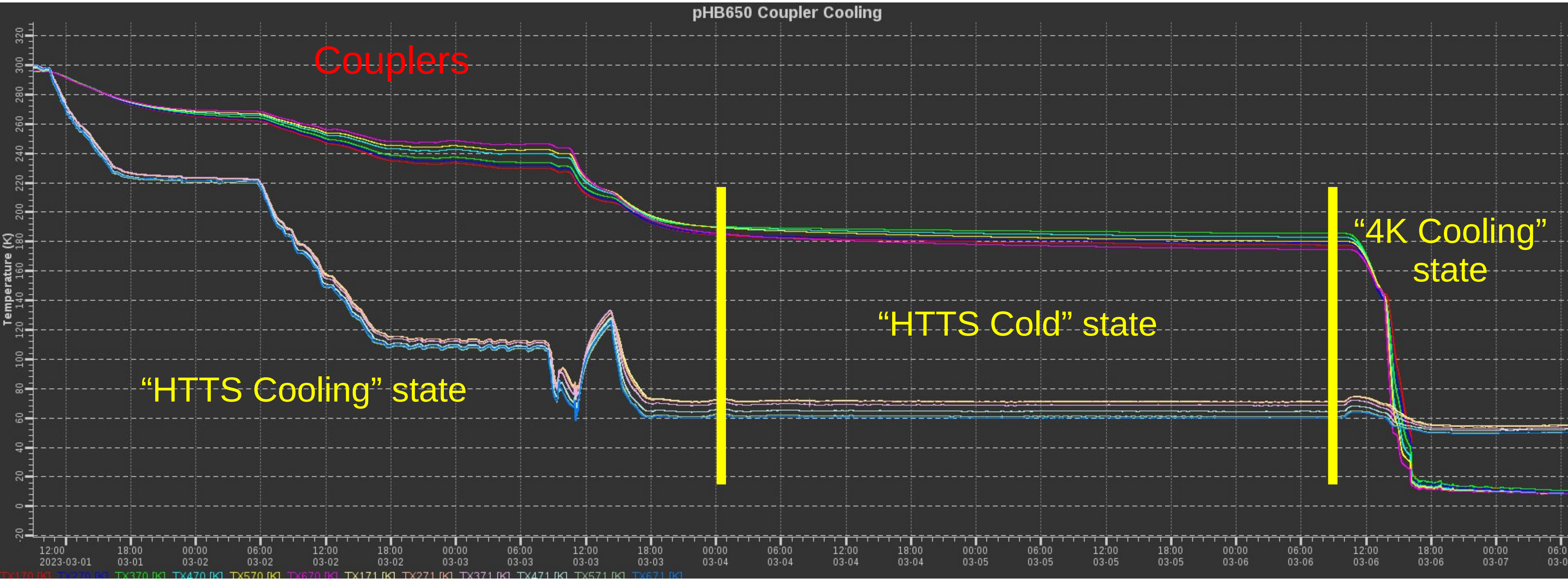


	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	pHB650	PV Name	Description	Measured		ALARM				Units	ARCHIVER			AutoSMS	Transition		Group	
2	CoolingHTTS			Low	High	LoLo	Low	High	HiHi		mode	frequency (s)	deadband		description	value	Name	Force PV
3	Dynamic	PIP2IT:pHB650_VAC_PPG051:VacP	IV vacuum pressure – pirani gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00	Vacuum	SSU-ALH
4		PIP2IT:pHB650_VAC_PCC051:VacP	IV vacuum pressure – cold cathode gauge			1.0E-11	1.0E-10	1.0E-06	1.0E-05	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
5		PIP2IT:pHB650_VAC_PPG052:VacP	IV-turbo vacuum pressure – pirani gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
6		PIP2IT:pHB650_VAC_PCC052:VacP	IV-turbo vacuum pressure- cold cathode gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
7		PIP2IT:pHB650_VAC_PPG053:VacP	IV-scroll vacuum pressure – pirani gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
8		PIP2IT:pHB650_VAC_PPG101:VacP	BL vacuum pressure – pirani gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
9		PIP2IT:pHB650_VAC_PCC101:VacP	BL vacuum pressure – cold cathode gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
10		PIP2IT:pHB650_VAC_PII101:VacP	BL vacuum pressure – from ion pump			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
11		PIP2IT:pHB650_VAC_PPG103:VacP	BL-scroll vacuum pressure – pirani gauge			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
12		PIP2IT:pHB650_VAC_PCC171:VacP	IV vacuum pressure – cold cathode gauge at coupler 1			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
13		PIP2IT:pHB650_VAC_PCC271:VacP	IV vacuum pressure – cold cathode gauge at coupler 2			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
14		PIP2IT:pHB650_VAC_PCC371:VacP	IV vacuum pressure – cold cathode gauge at coupler 3			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
15		PIP2IT:pHB650_VAC_PCC471:VacP	IV vacuum pressure – cold cathode gauge at coupler 4			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
16		PIP2IT:pHB650_VAC_PCC571:VacP	IV vacuum pressure – cold cathode gauge at coupler 5			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
17		PIP2IT:pHB650_VAC_PCC671:VacP	IV vacuum pressure – cold cathode gauge at coupler 6			1.0E-14	1.0E-13	1.1E+03	1.1E+04	mbar	scan	300.0	0.00	0	N/A	0.00E+00		
18		PIP2IT:pHB650_VAC_PTI052:Current	IV turbo pump current			-2	-1	10	12	A	scan	1.0	0.00	0	N/A	0.00E+00		
19		PIP2IT:pHB650_VAC_PSI053:Current	IV scroll pump current			-2	-1	10	12	A	scan	1.0	0.00	0	N/A	0.00E+00		
20		PIP2IT:pHB650_VAC_PTTC052:Temp	IV turbo controller temperature			-2	-1	80	90	C	scan	1.0	0.00	0	N/A	0.00E+00		
21		PIP2IT:pHB650_VAC_PTTP052:Temp	IV turbo pump temperature			-2	-1	80	90	C	scan	1.0	0.00	0	N/A	0.00E+00		
22		PIP2IT:pHB650_VAC_PTF052:Freq	IV turbo pump frequency			-2	-1	70	80	Hz	scan	1.0	0.00	0	N/A	0.00E+00		
23		PIP2IT:pHB650_VAC_PTF102:Freq	BL turbo pump frequency			-2	-1	70	80	Hz	scan	1.0	0.00	0	N/A	0.00E+00		
24		PIP2IT:pHB650_VAC_PSI103:Current	BL scroll pump current			-2	-1	10	12	A	scan	1.0	0.00	0	N/A	0.00E+00		
25		PIP2IT:pHB650_VAC_PSI103:Current	BL scroll pump current			-2	-1	10	12	A	scan	1.0	0.00	0	N/A	0.00E+00		
26		PIP2IT:pHB650_VAC_VG101:ValveStatus	BL US gate valve status			-2	-1	5	6	-	scan	1.0	0.00	0	N/A	0.00E+00		
27		PIP2IT:pHB650_VAC_VG201:ValveStatus	BL DS gate valve status			-2	-1	5	6	-	scan	1.0	0.00	0	N/A	0.00E+00		
28		PIP2IT:pHB650_VAC_VT052:ValveStatus	IV turbo isolation valve display status			-2	-1	5	6	-	scan	1.0	0.00	0	N/A	0.00E+00		
29		PIP2IT:pHB650_VAC_VT053:ValveStatus	IV anti-suckback Open/Closed status			-2	-1	5	6	-	scan	1.0	0.00	0	N/A	0.00E+00		
30		PIP2IT:pHB650_VAC_VS053:ILK	IV anti-suckback interlock			-2	-1	5	6	-	scan	1.0	0.00	0	N/A	0.00E+00		
46																		
47		PIP2IT:pHB650_CRYO_TX101:TempK	Cav1 Upper			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0	atures:Silic	SSU-ALH
48		PIP2IT:pHB650_CRYO_TX102:TempK	Cav1 Lower			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		
49		PIP2IT:pHB650_CRYO_TX103:TempK	Cav1-Cel1 Upper			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		
50		PIP2IT:pHB650_CRYO_TX104:TempK	Cav1-Cel1 Lower			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		
51		PIP2IT:pHB650_CRYO_TX105:TempK	Cav1-Cel3 Upper			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		
52		PIP2IT:pHB650_CRYO_TX106:TempK	Cav1-Cel3 Mid			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		
53		PIP2IT:pHB650_CRYO_TX107:TempK	Cav1-Cel3 Lower			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		
54		PIP2IT:pHB650_CRYO_TX108:TempK	Cav1-Cel5 Upper			280.0	285.0	305.0	315.00	K	scan	1		0	N/A	0.0		

State Machine: populating tables



- Can use history
- Group PVs, consider dynamic states, select range
- Static states – compute mean and std
  - used to set alarm limits
  - used to set dead bands



Testing at PIP2IT

- PIP2IT is the PIP-II Integration Teststand
- first iteration included beam transport studies and 2 cryomodules (CMs)
- teststand to be used for CM testing prior to installation in the accelerator → EPICS
- from date? To June 2023, much of the control infrastructure was established
  - IOCs
  - services – HMIs, archiver, alarms, channel finder
- in addition to testings CMs, the teststand is being used to vet and make robust the EPICS tools and services
- State Machine operation of CMs will be introduced in phase-III testing, January 2024

State Machines at PIP-II

- PIP-II Main Page HMI[3]
- Status at a glance
- Launcher for all systems

Other Targets

Other complex systems for which State Machines may be considered:

- Warm Front End
- Cryogenics Plant
- Beamline accelerator components
- Beamline instrumentation
- Accelerator controls modernization (ACORN)
- States from State Machines can be used to simplify complex sequences

For more on ACORN see D. Finstrom – TUMBCMO20

References

References

1. ``The PIP-II Reference Design Report", V. Lebedev et al., FERMILAB-DESIGN-2015-01, United States: N. p., 2015. Web. Doi:10.2172/1365571.
2. ``Fermilab Proton Accelerator Complex Status and Improvement Plans, V. Shiltsev,FERMILAB-PUB-017-129-APC.

3. ``PIP-II Parameters Physics Requirement Document (PDR), darft.

Summary

- The PIP-II scope enables the accelerator complex to reach 1.2 MW p-beam on LBNF target
- A State Machine will be used for all PIP-II complex systems
- A complex system is one with one, or more, subsystems and two, or more states such that the combinatorics lead to 10-10^5 PVs with which to reckon
- A State Machine is a finite state machine which monitors the system and serves to make alarms and archiving relevant and robust in all phases of operation

- Does the State Machine need a new name?

Questions?