October 2024

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Advanced Test Reactor
Reactor Engineering

ATR Power Indications

Battelle Energy Alliance manages INL for the
U.S. Department of Energy's Office of Nuclear Energy

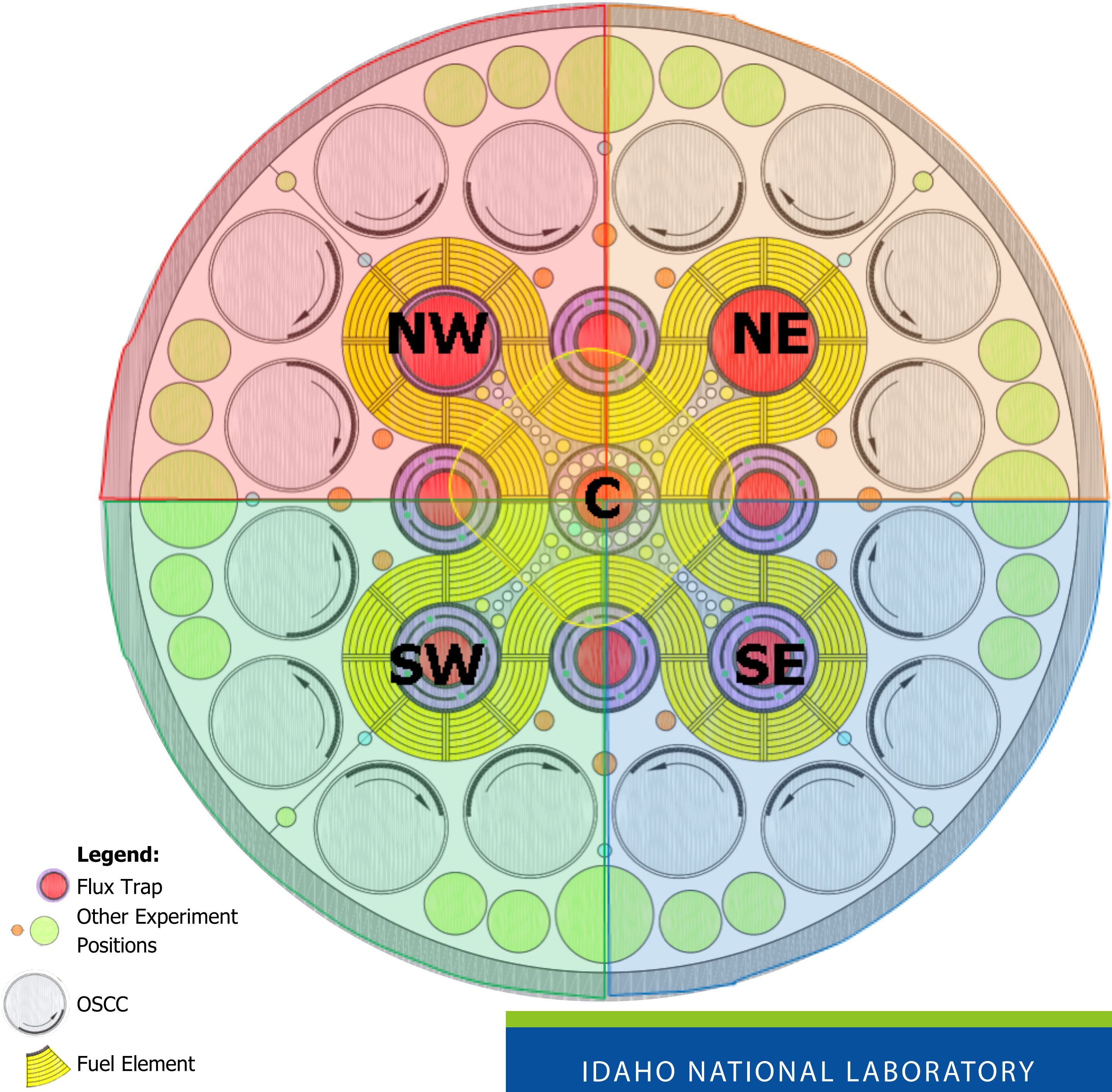
INL Idaho National Laboratory

Outline

- Introduction to Advanced Test Reactor (ATR)
  - Idaho National Laboratory
  - Fuel Arrangement
  - Flux Traps
- Power Indications
  - Nuclear instruments
  - LPCIS
  - WPC
  - No assumed symmetry!

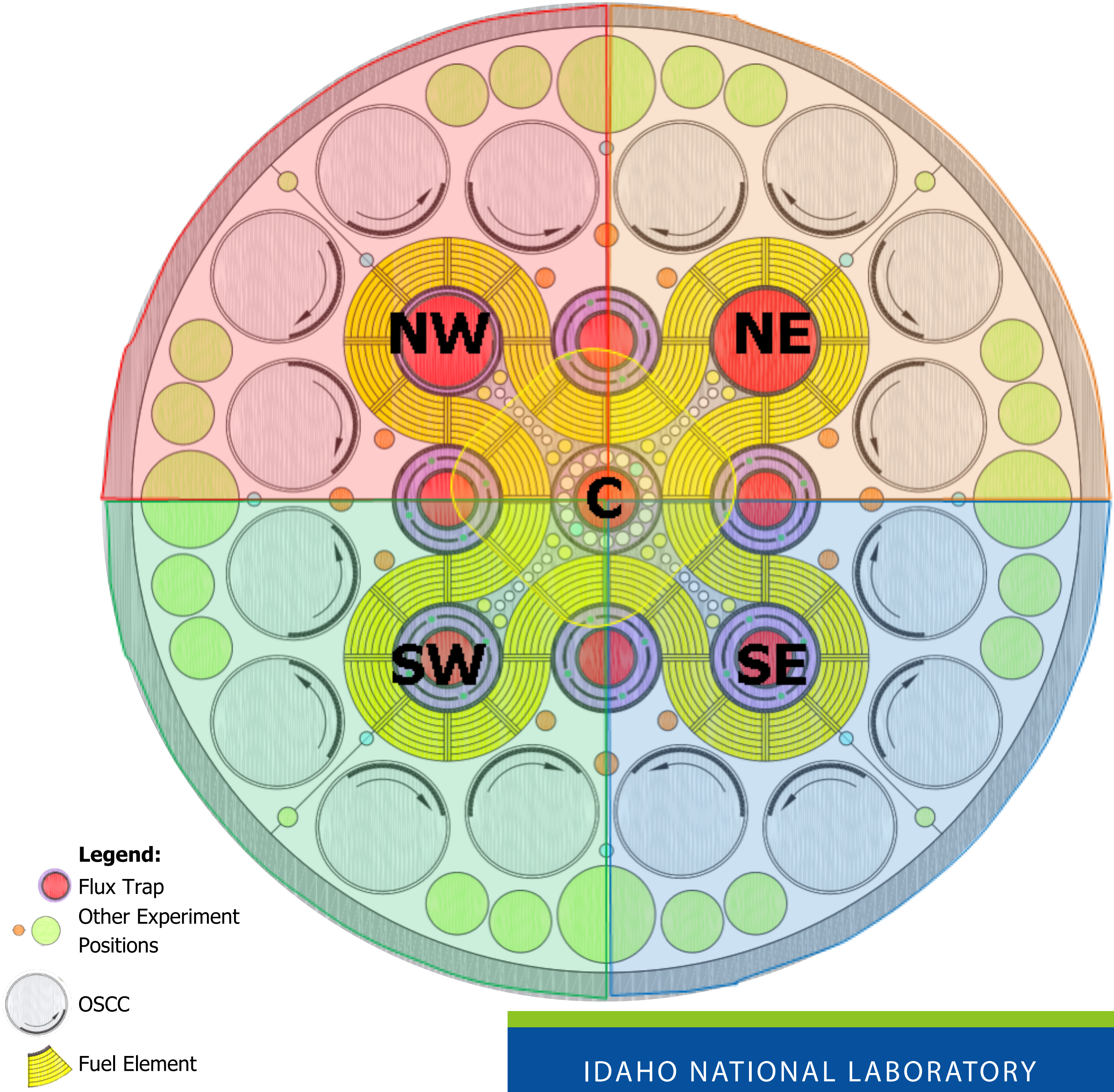
Introduction to ATR

- More than 70 test positions
  - 9 flux traps
  - 6 (of the 9) have loops
    - Independent Chemistry, temperature, and pressure
- Control Elements
  - 6 Safety Rods (annular)
  - 16 Outer Shim Control Cylinders (OSCCs)
  - 22 Neck Shims
    - +2 Regulating Rods
- 40 Fuel Elements
  - 19 plates
  - 48” (120cm) active length
  - Serpentine arrangement



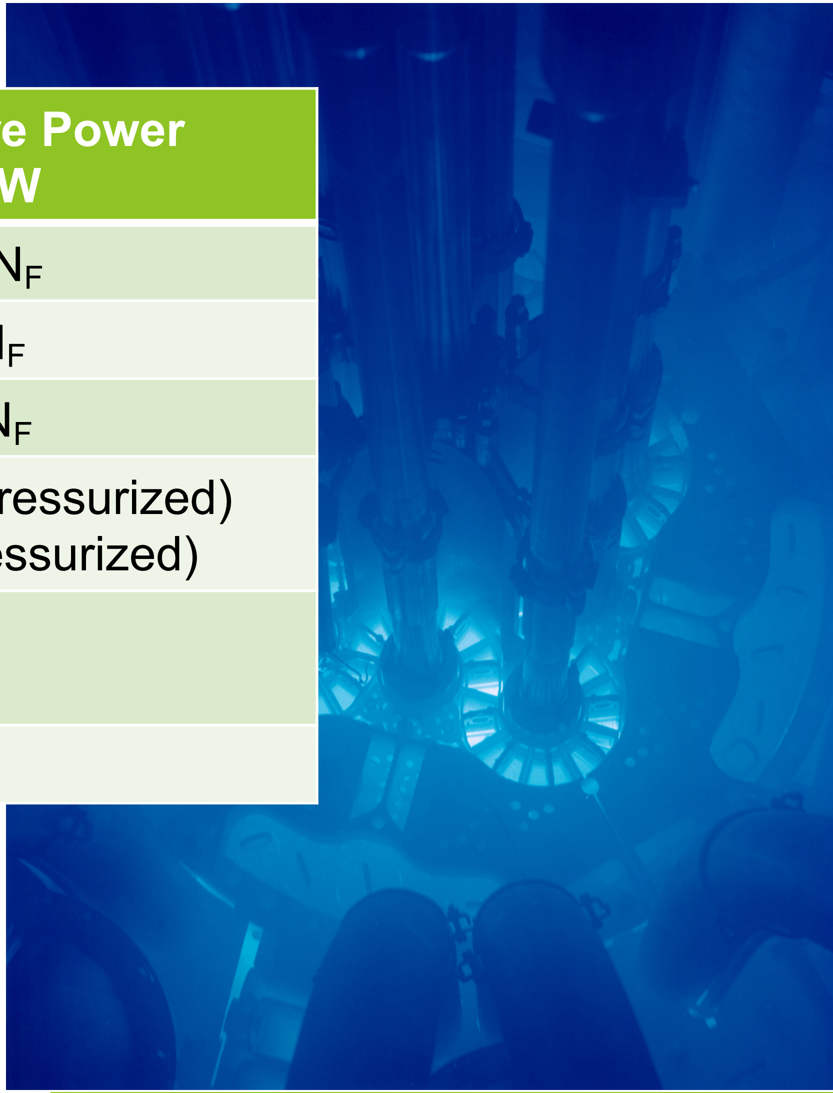
Introduction to ATR

- Design Summary
  - 250 MW_{th} (Typically 110MW_{th})
  - Max thermal flux:
    - 10^{15} n/cm^2-s
  - Max fast flux:
    - 5×10^{14} n/cm^2-s
- Companion ATRC
  - 5 kW_{th}
  - Pool type



Ordered by Increasing Power

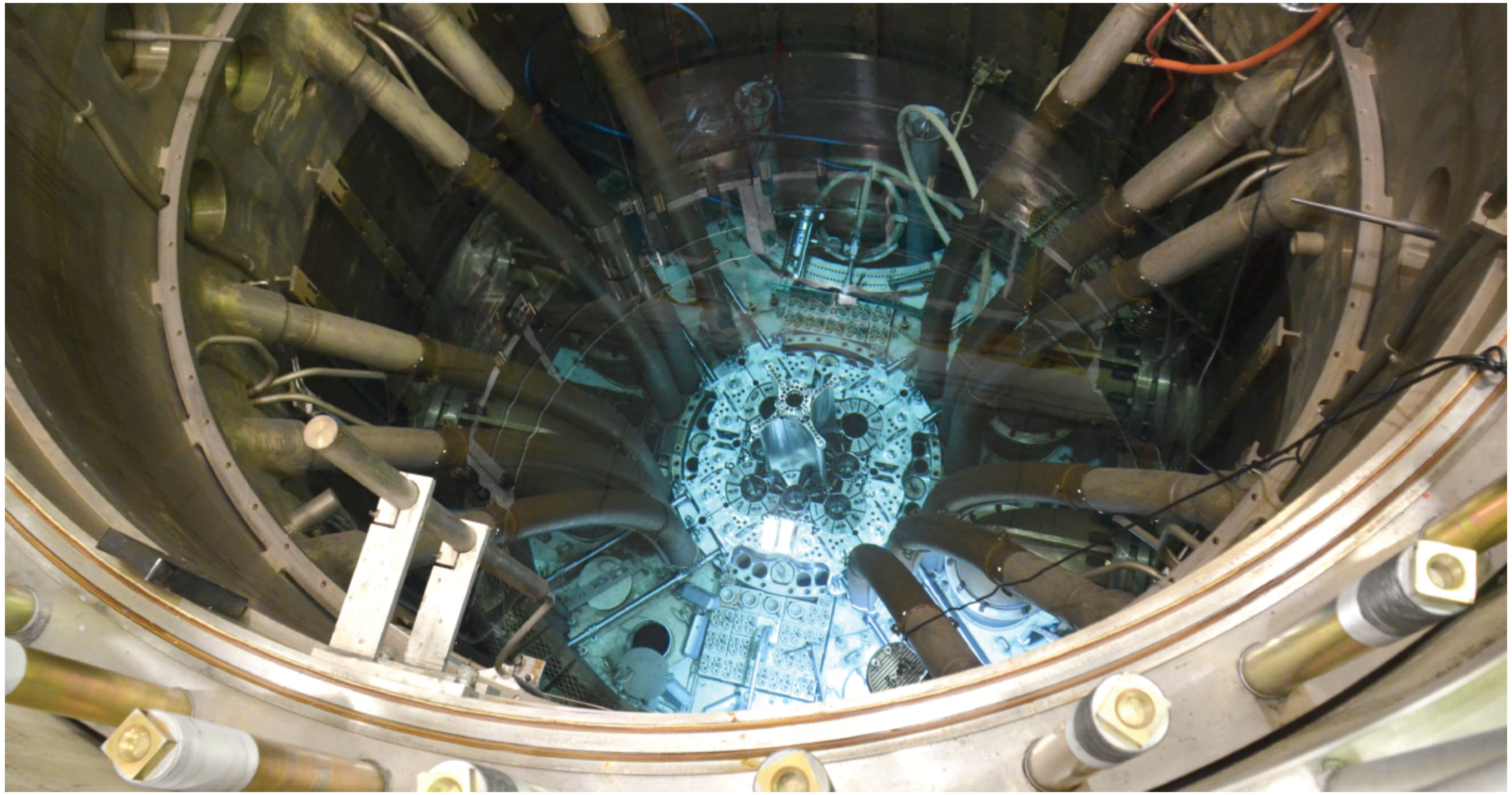
	Approximate Core Power $N_F \leq 250$ MW
Log Count Rate Meters (LCRMs)	$10^{-11} – 10^{-5}$ N_F
Log-N Periods (Log-Ns)	10^{-7} – 10 N_F
Wide Ranges (WRs)	10^{-6} – 1.5 N_F
Neutron Levels (NLs)	10^{-4} – 0.015 N_F (depressurized) 0.005 – 1.5 N_F (pressurized)
Lobe Power Calculation and Indication System (LPCIS)	>1 MW
Water Power Calculator (WPC)	>3 MW



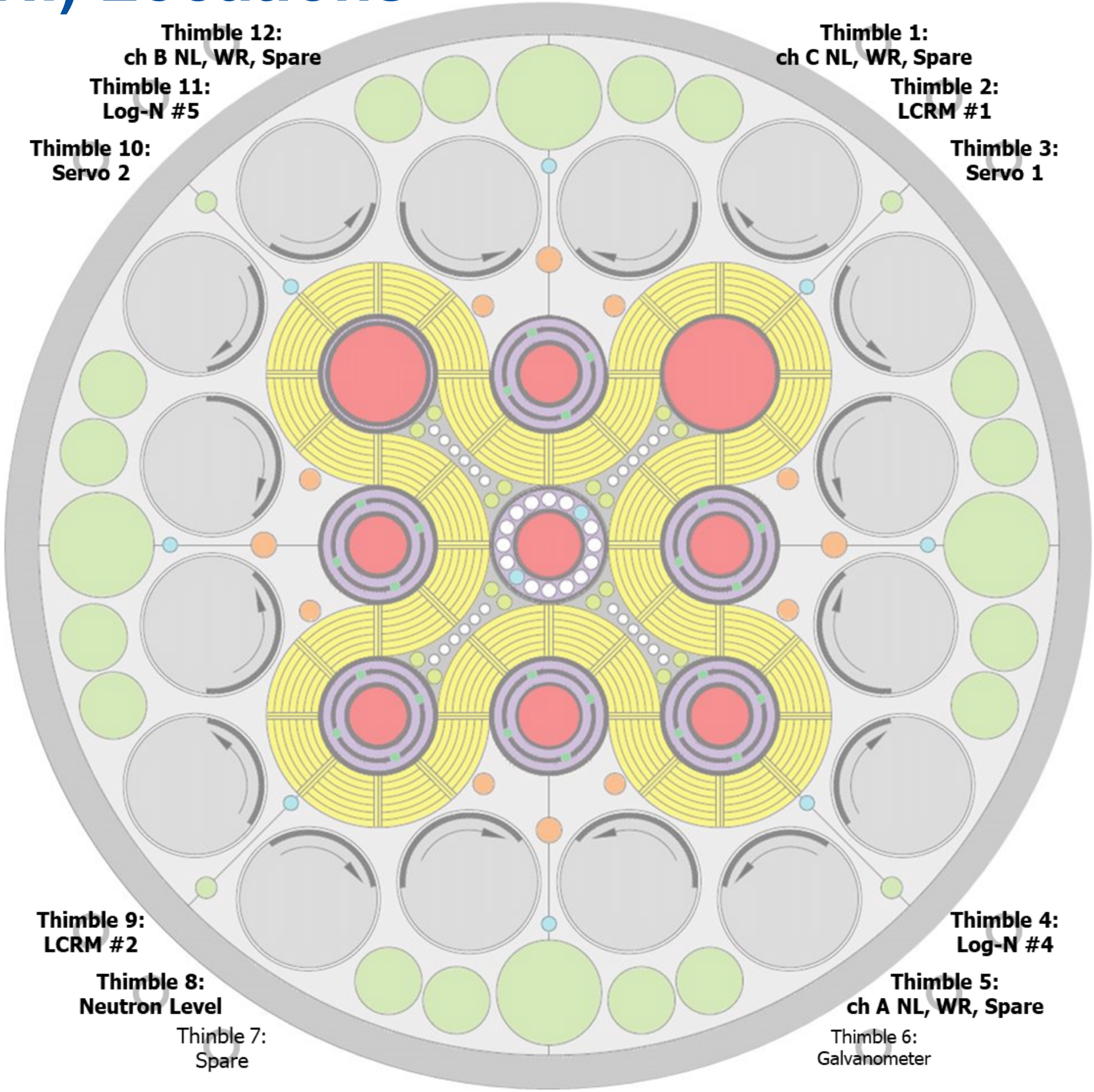
Nuclear Instrument (NI) Locations

Visible curved thimbles

Experiment tubes removed for Core Internals Changeout

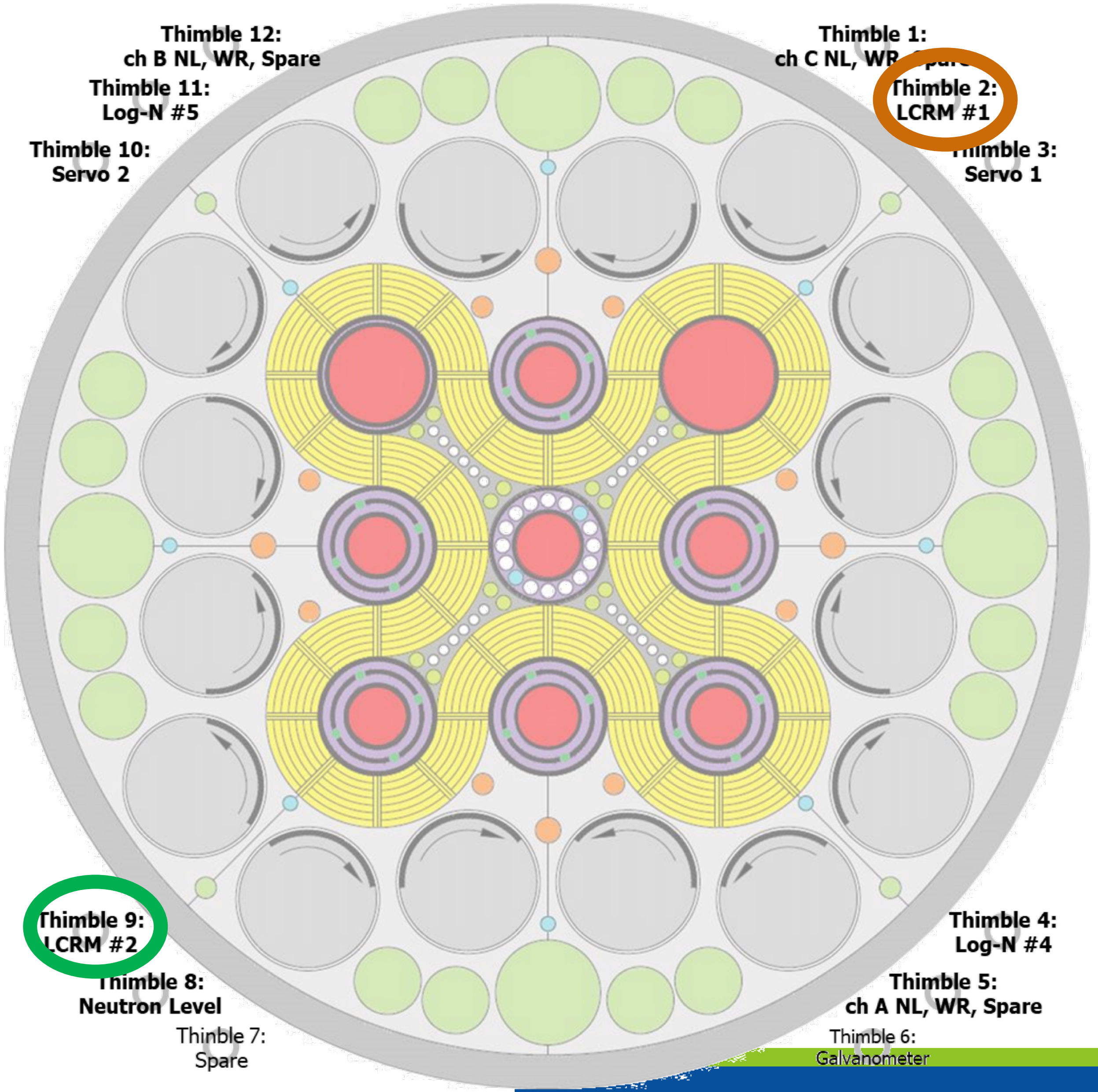


Nuclear Instrument (NI) Locations



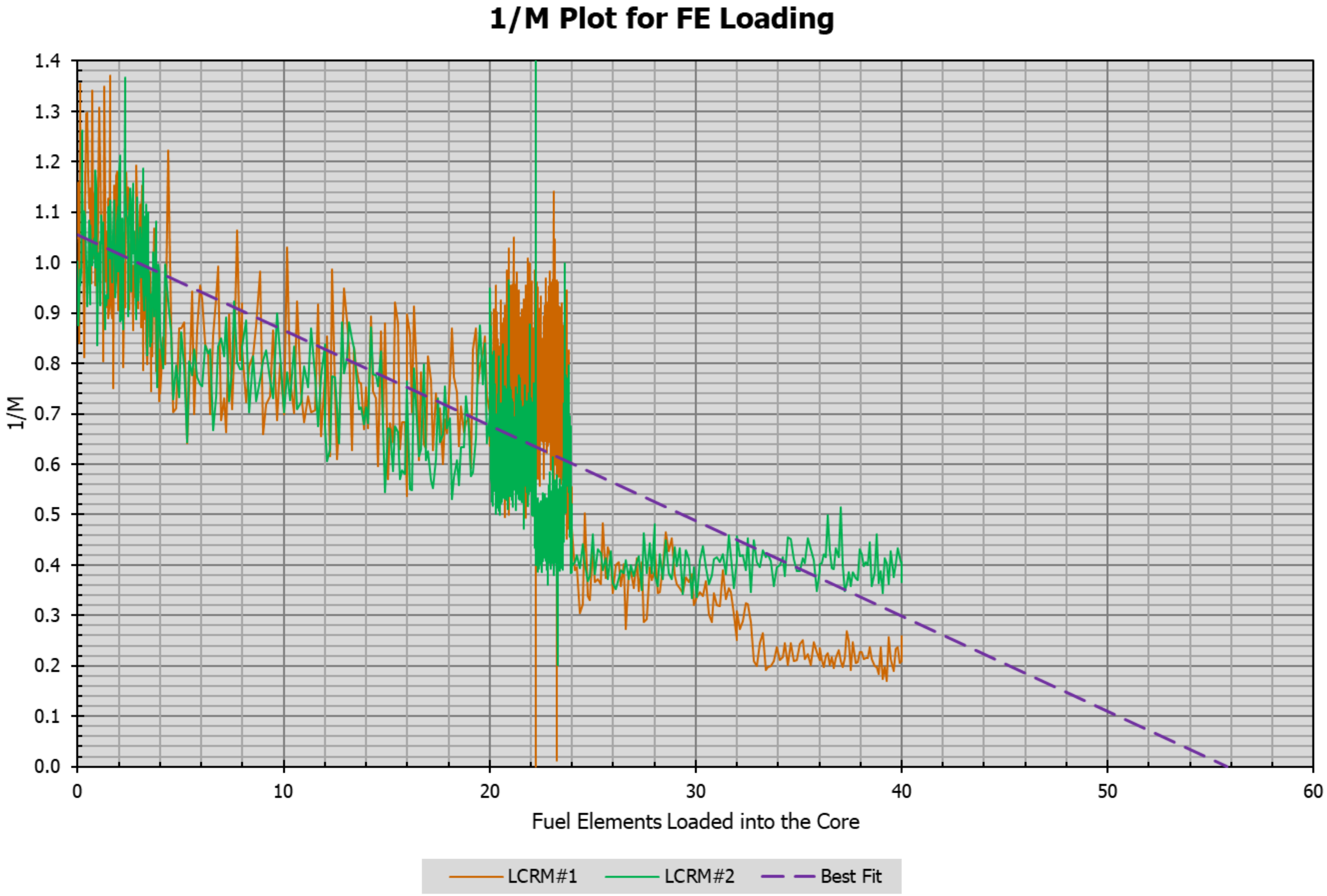
LCRMs

- Fission chambers
  - Really sensitive
- Adjust by physically raising
- While shutdown
- “Source range”



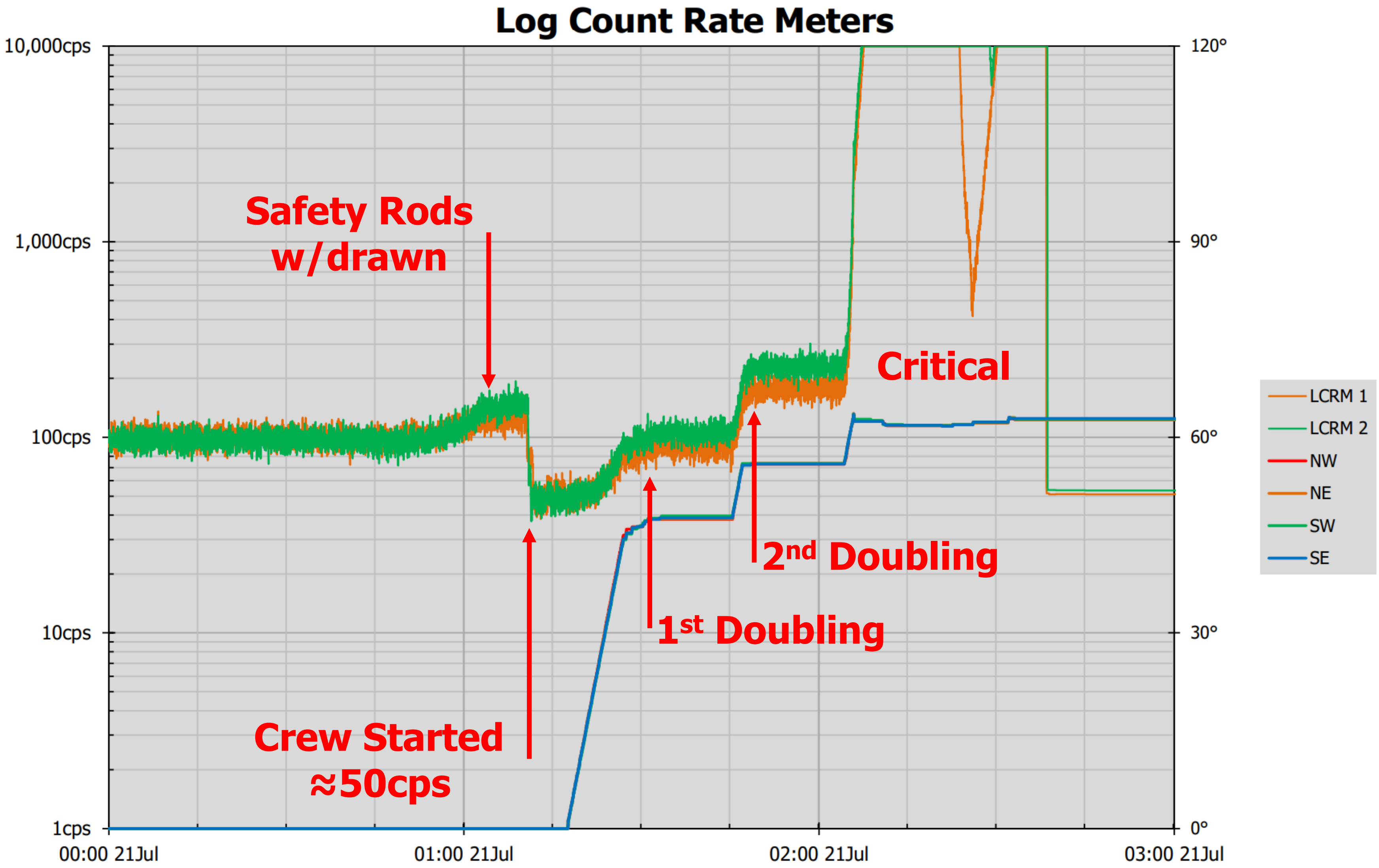
LCRMs

- Sb Source for >2cps
- Used for fuel loading after core reconfiguration



LCRMs

- Used for doubling

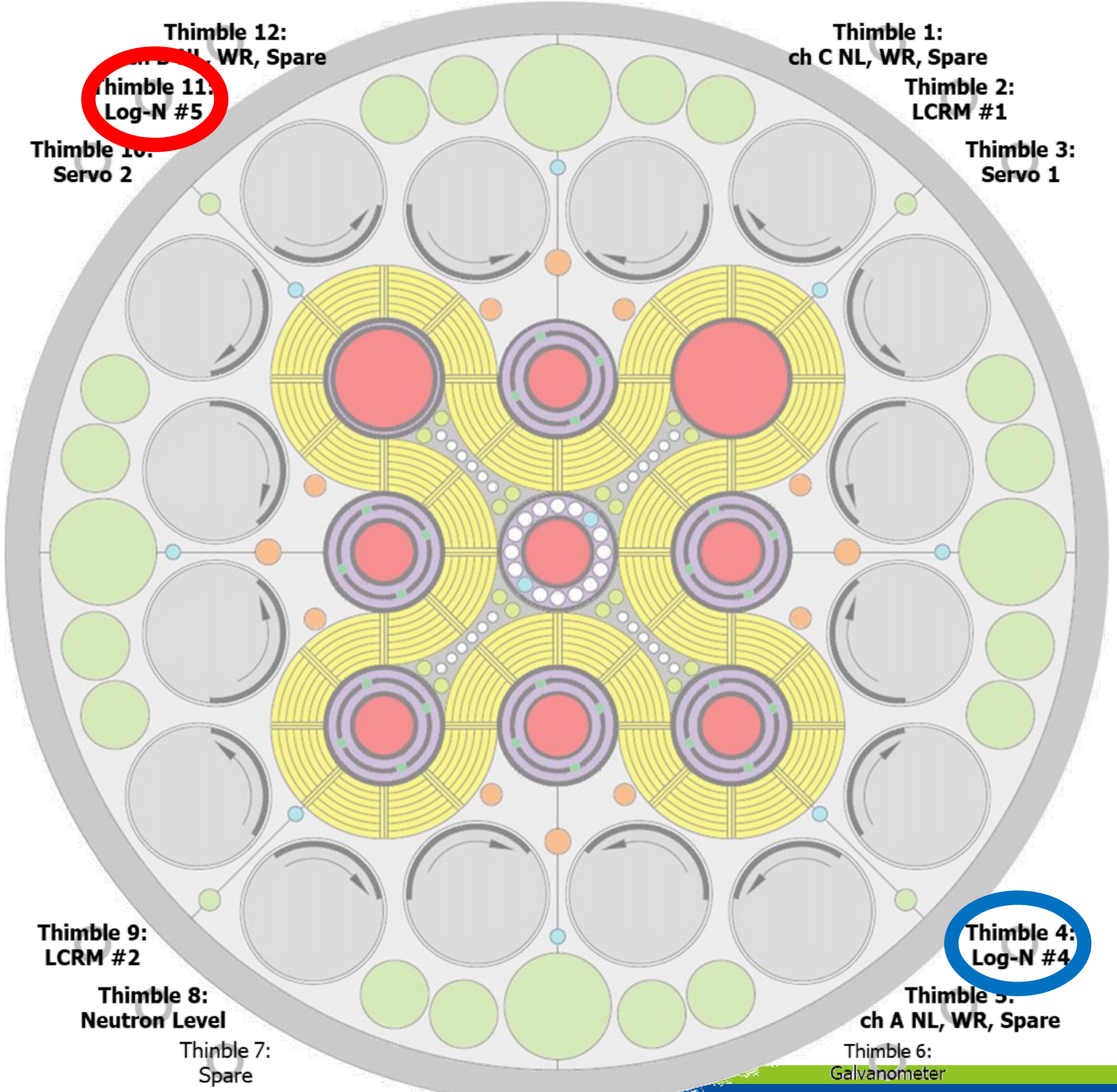


LCRMs

- Two panels in Control Room
- Now they’re digital

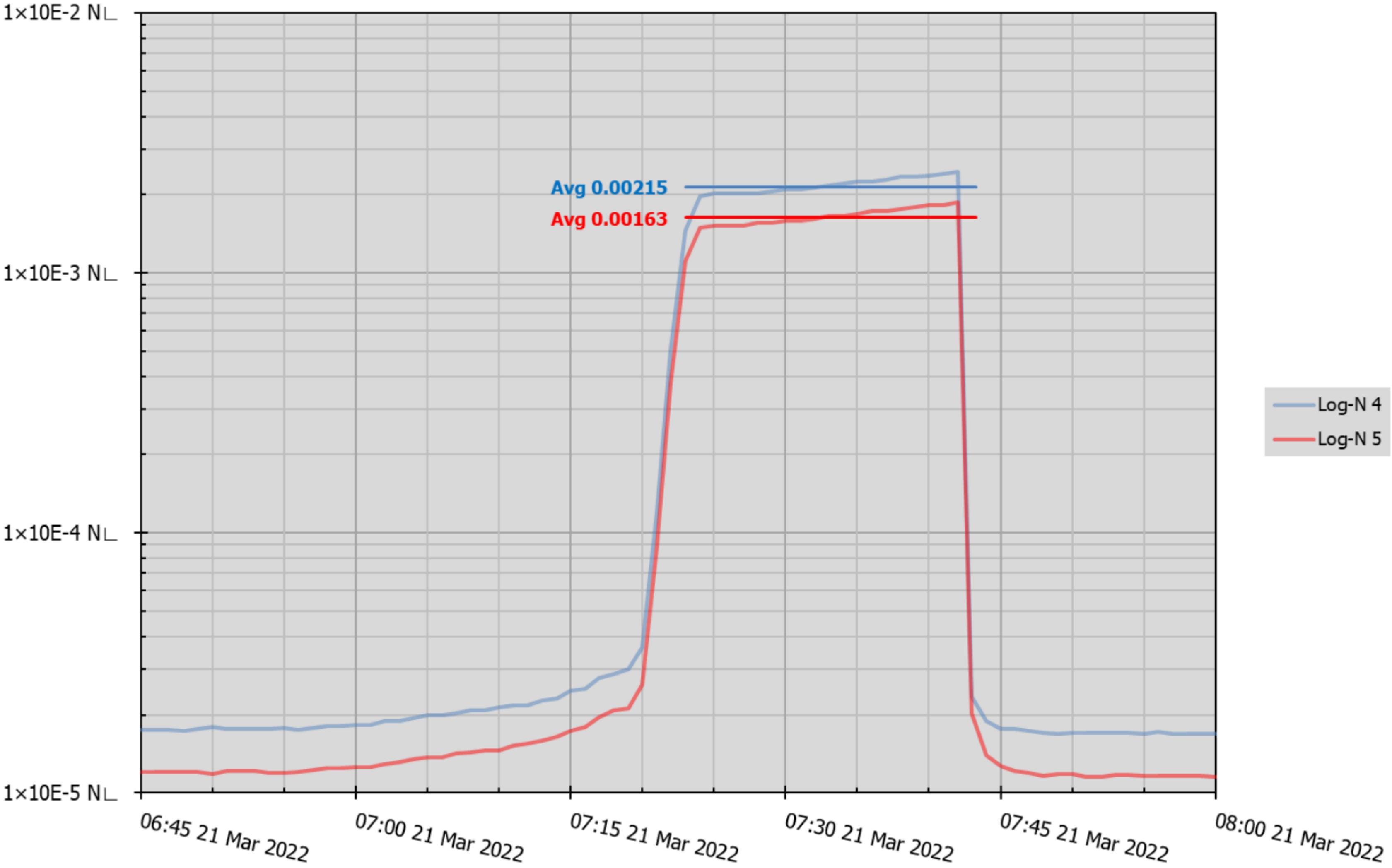
Log-Ns

- 2 Instruments
- Compensated ion chambers
- “Intermediate range”
- Depressurized operation



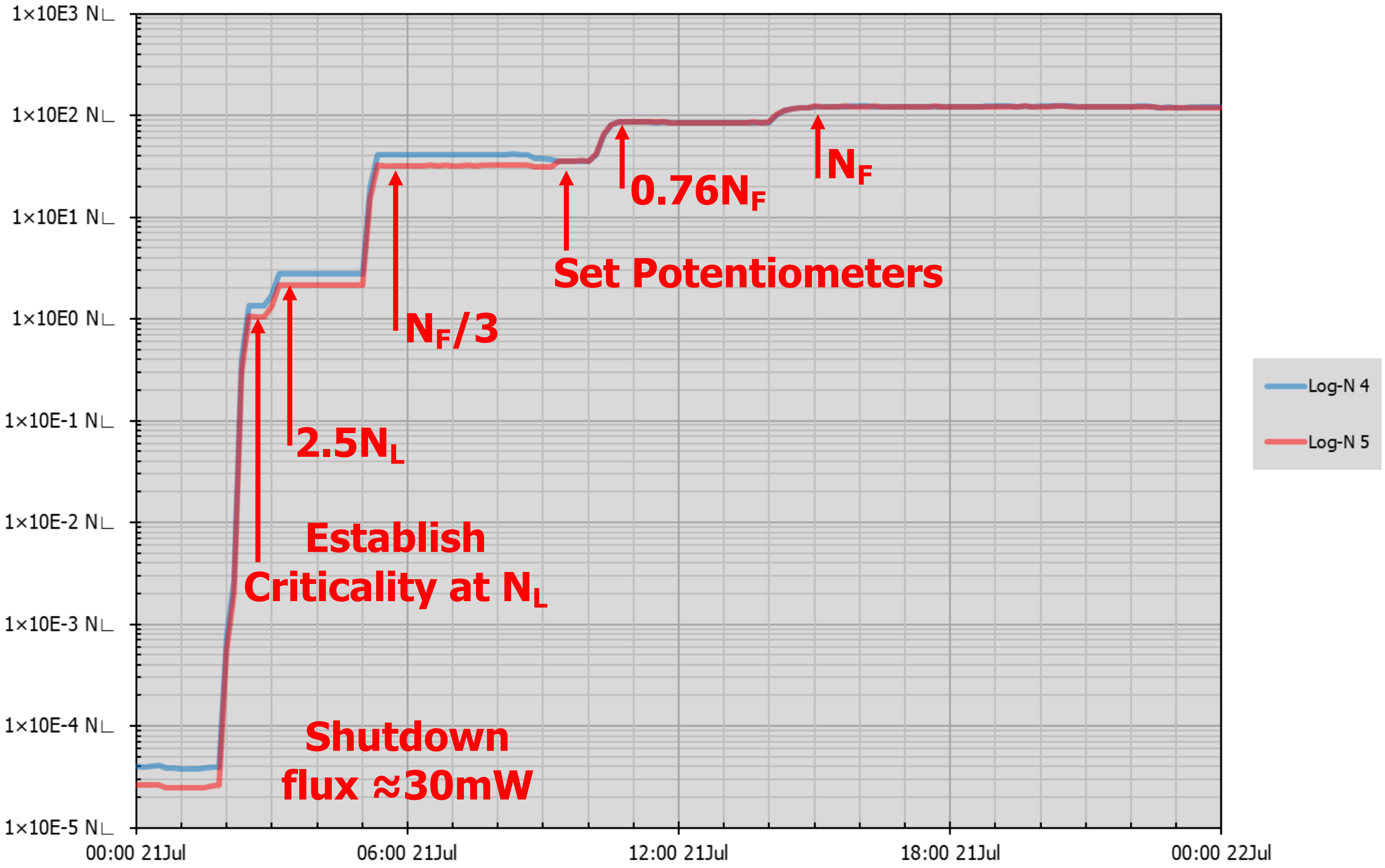
Log-Ns

- Log Scale: S/U to N_F
  - Reads in $N_L = 1\%N_F$
- Calibrate against known thermal indication or another measurement



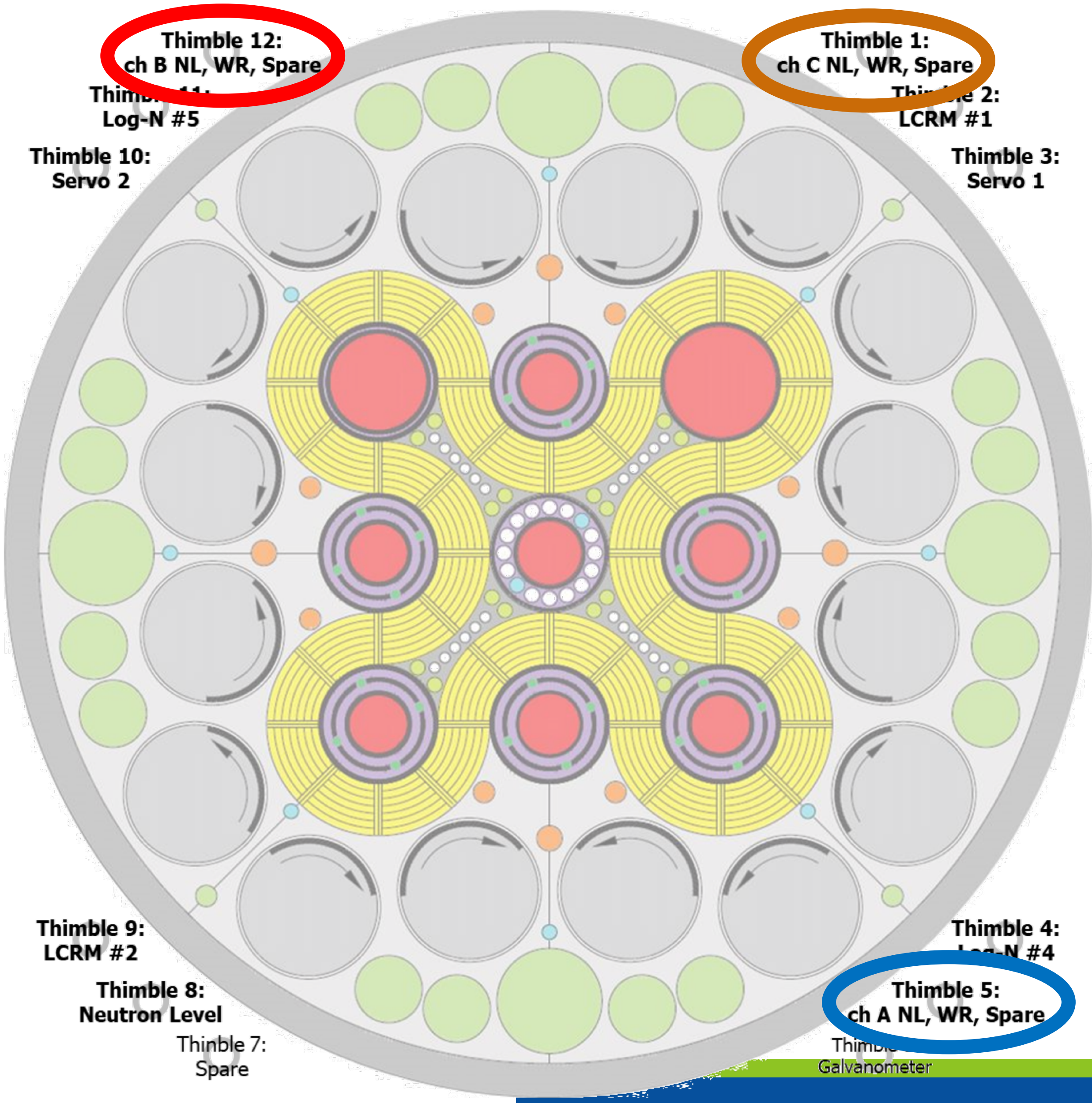
Log-Ns

- Used in power escalation <N_F/3



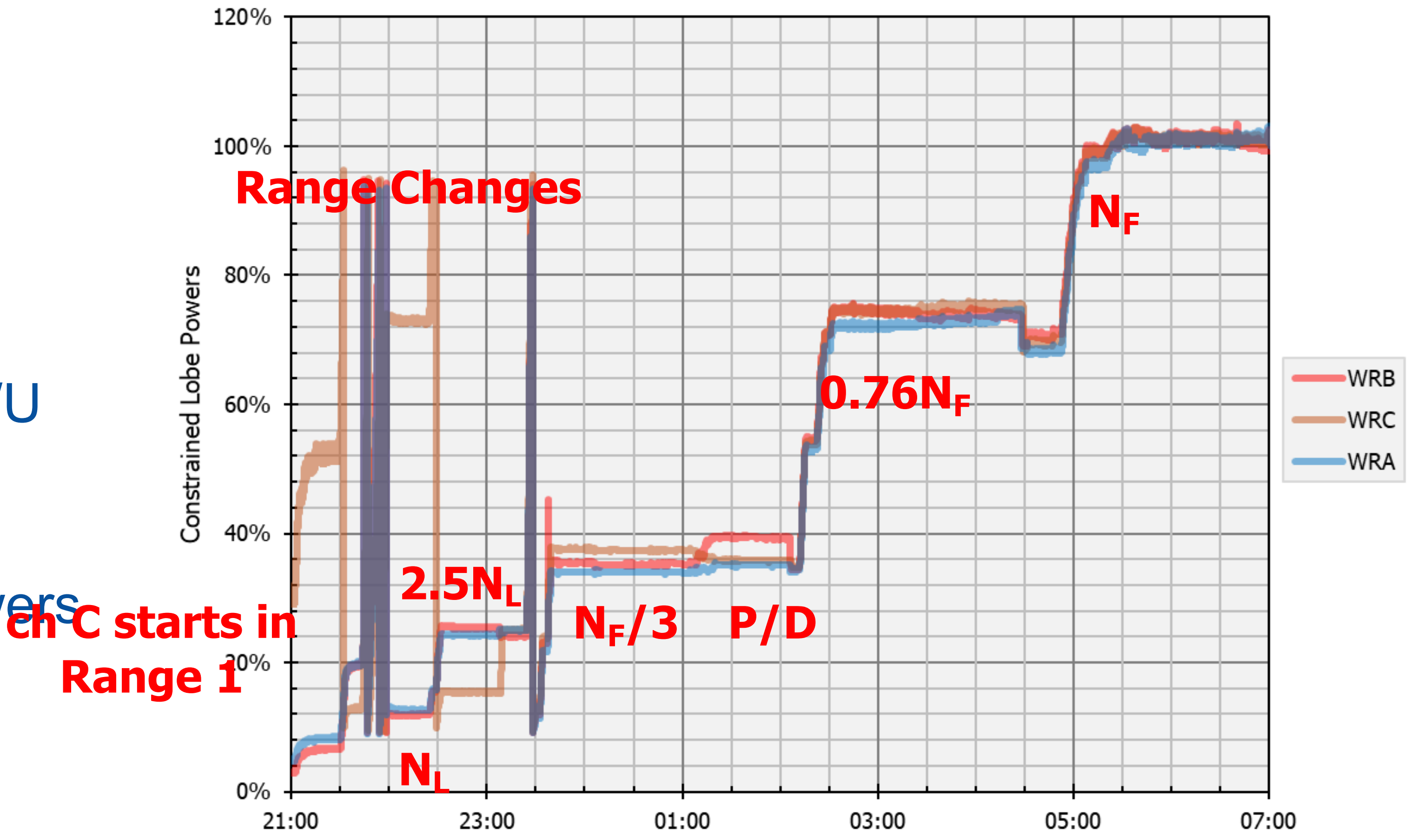
WRs

- 3 instruments
- Ion chambers
- 12 Ranges
  - 2 per decade
- 3 Plant Protection System (PPS) channels
  - Scram for 2/3 high powers
  - Conservatively high
    - Reduce on thermal power



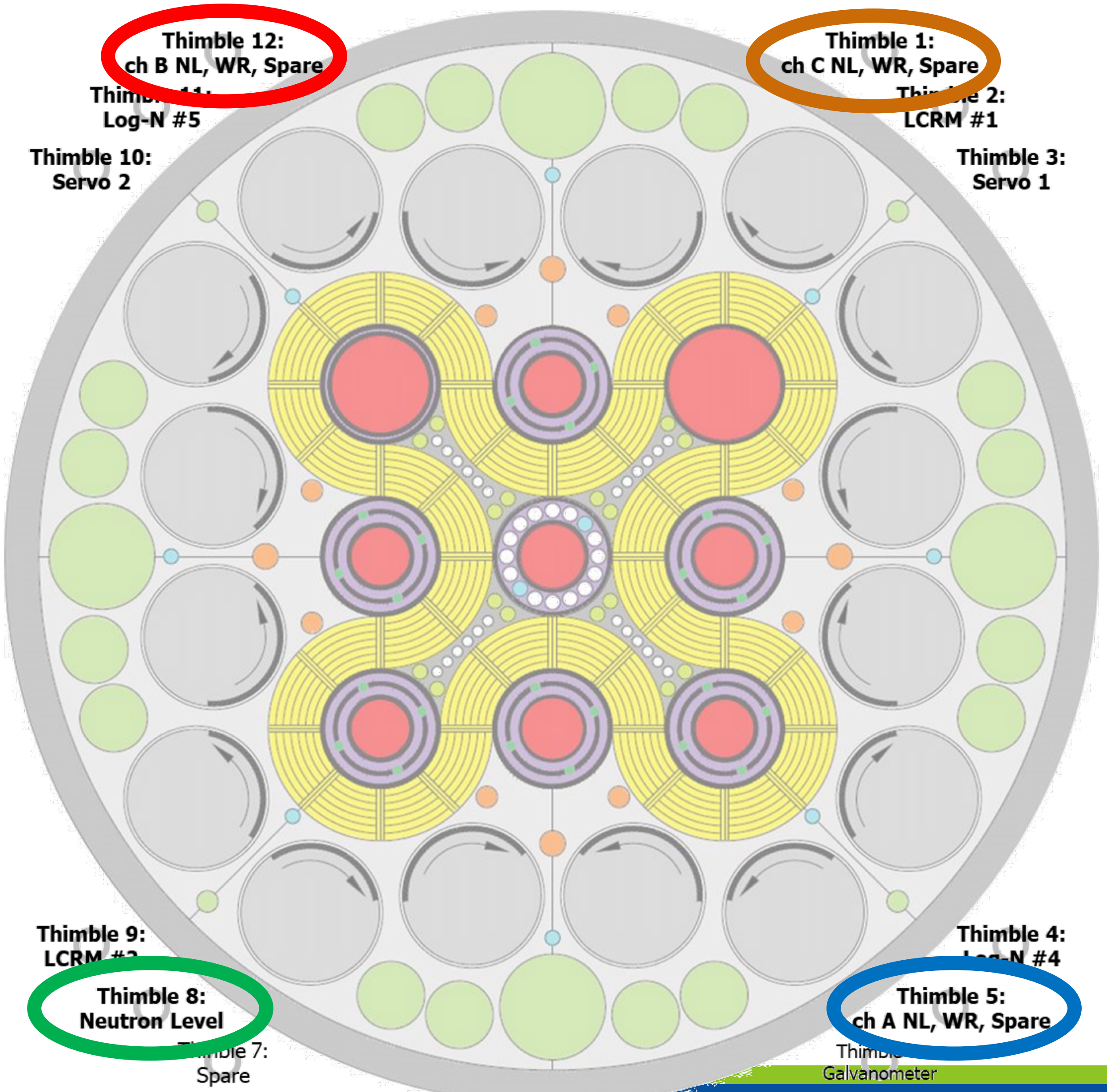
WRs

- 12 Ranges
  - 2 per decade
- 3 Plant Protection System (PPS) channels
  - min 1 in Range 1 for S/U
    - Range 3 → fewer alarms
  - Scram for 2/3 high powers
  - Conservatively high
    - Reduce on thermal power



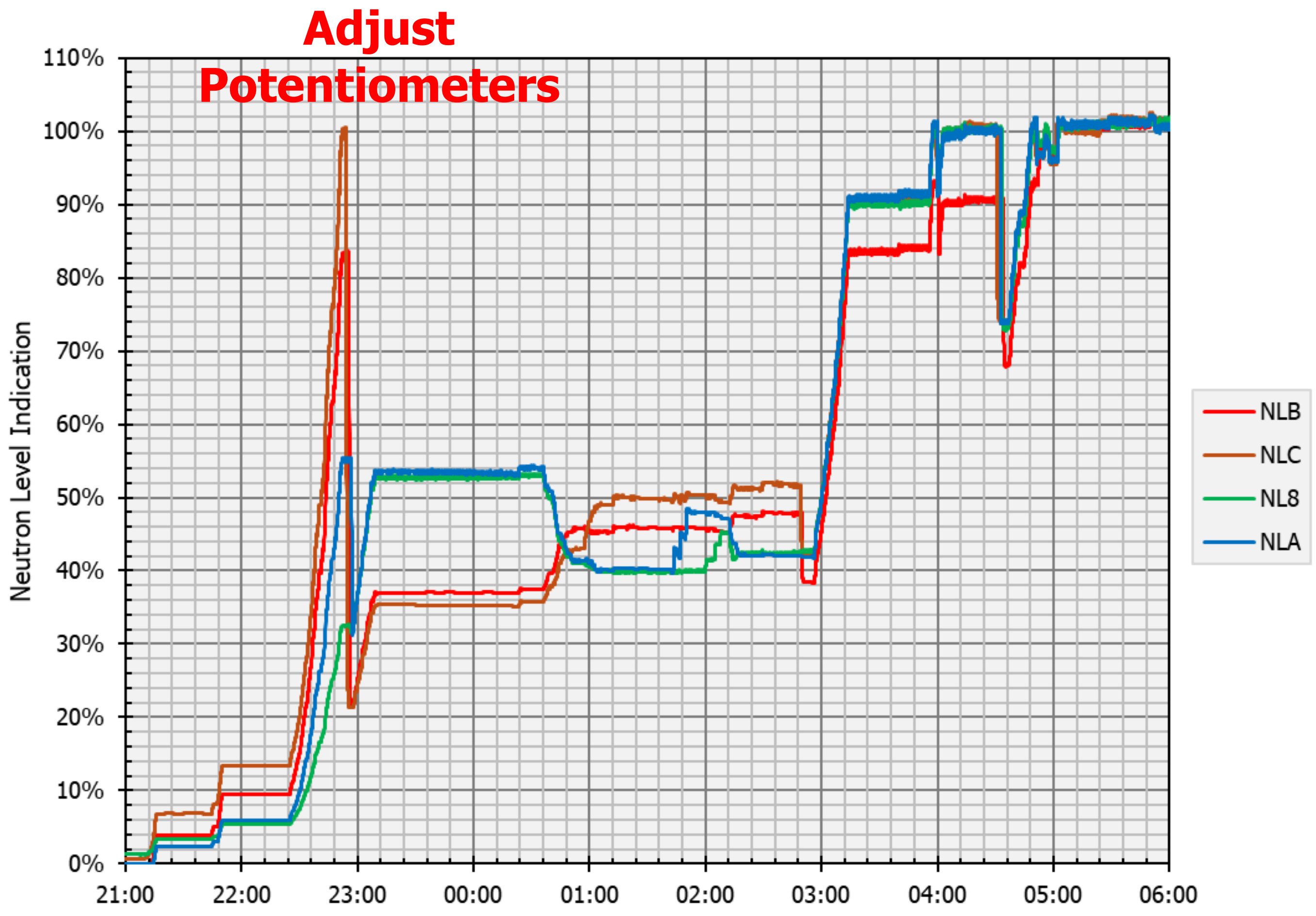
NLs

- Linear 0-100% N_F
  - Like Log-N, but not log
  - Like WR, but no ranges
- 3 Plant Protection System (PPS) channels
  - Scram for 2/3 high powers
  - Conservatively high
    - Reduce on thermal power



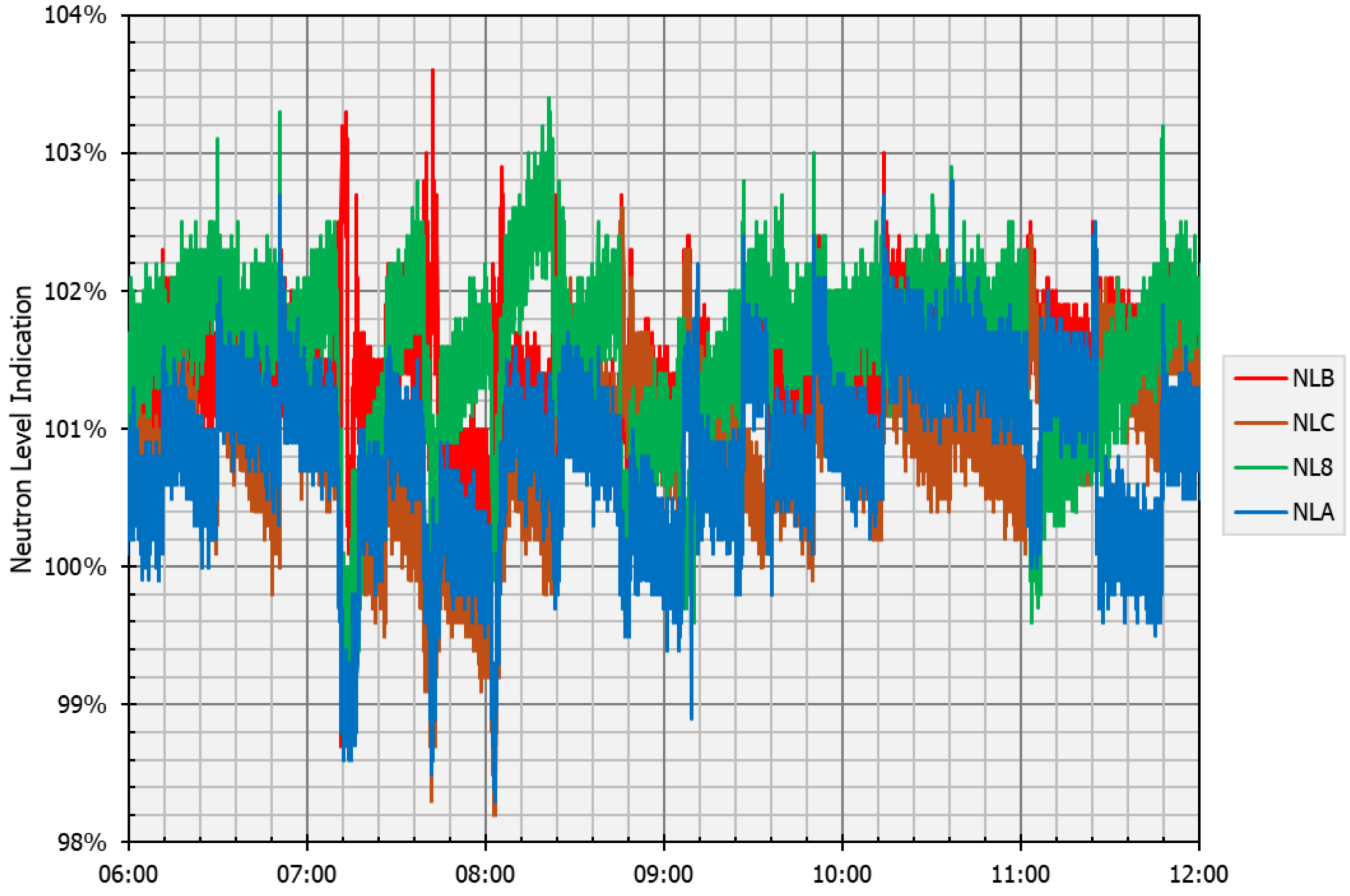
NLs

- Linear power increase
- Hard to see near 0%



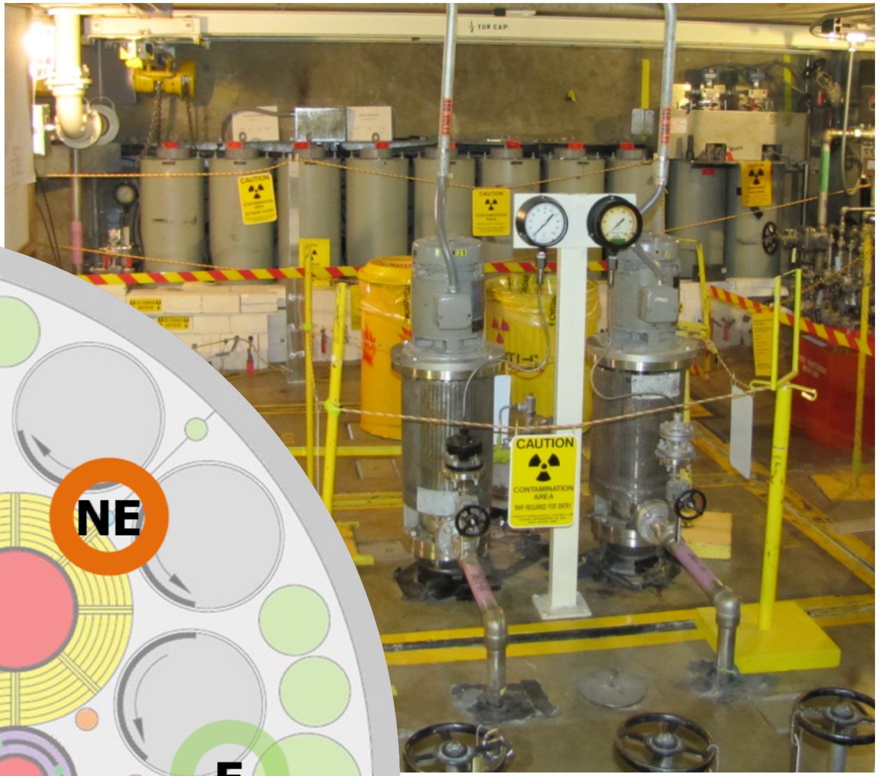
NLs

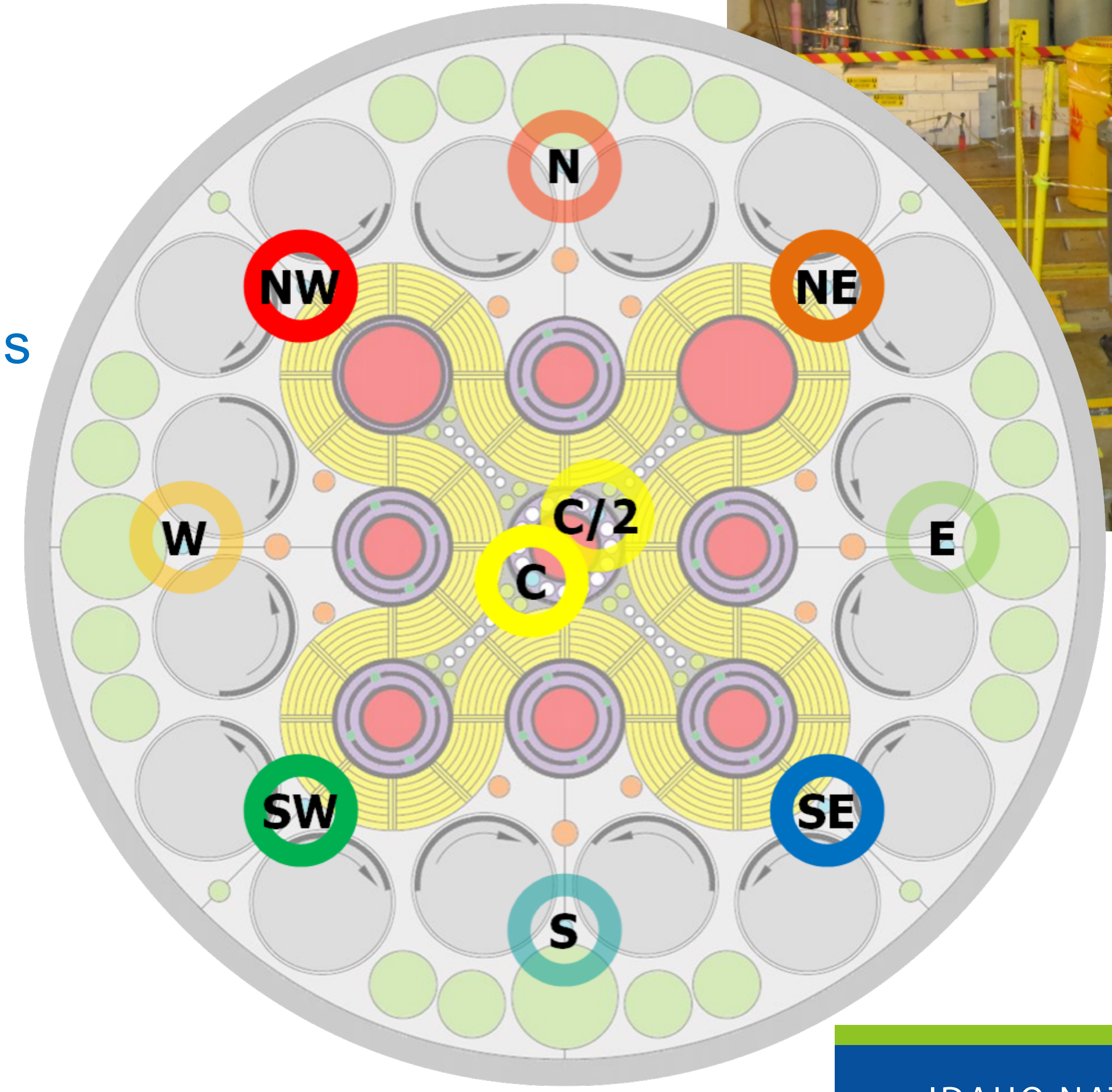
- Sensitive to changes near N_F

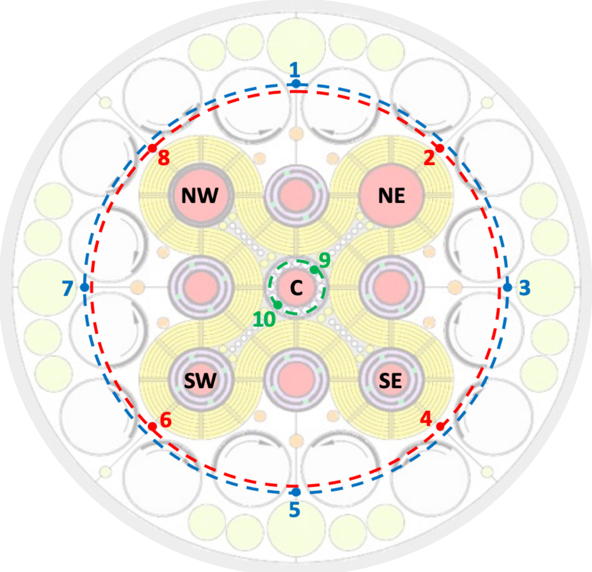


LPCIS
^{16}N Core Locations

- 10 ^{16}N Tubes
  - 4 “inner” at corners
    - Required
  - 4 “outer” outside shims
    - Not required
  - 2 in Center
    - Required

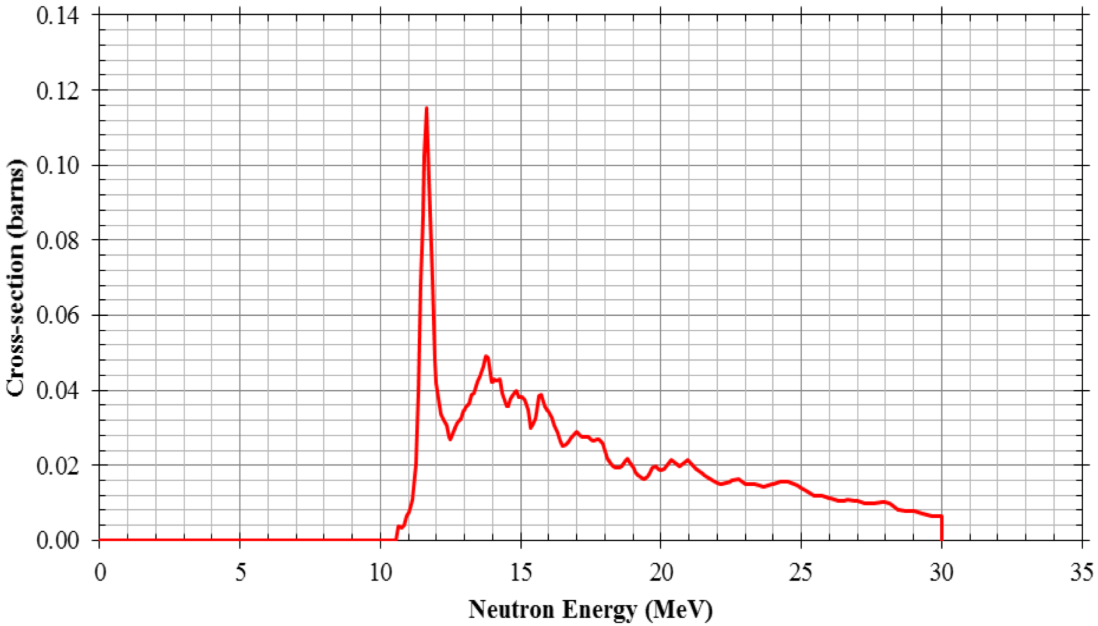






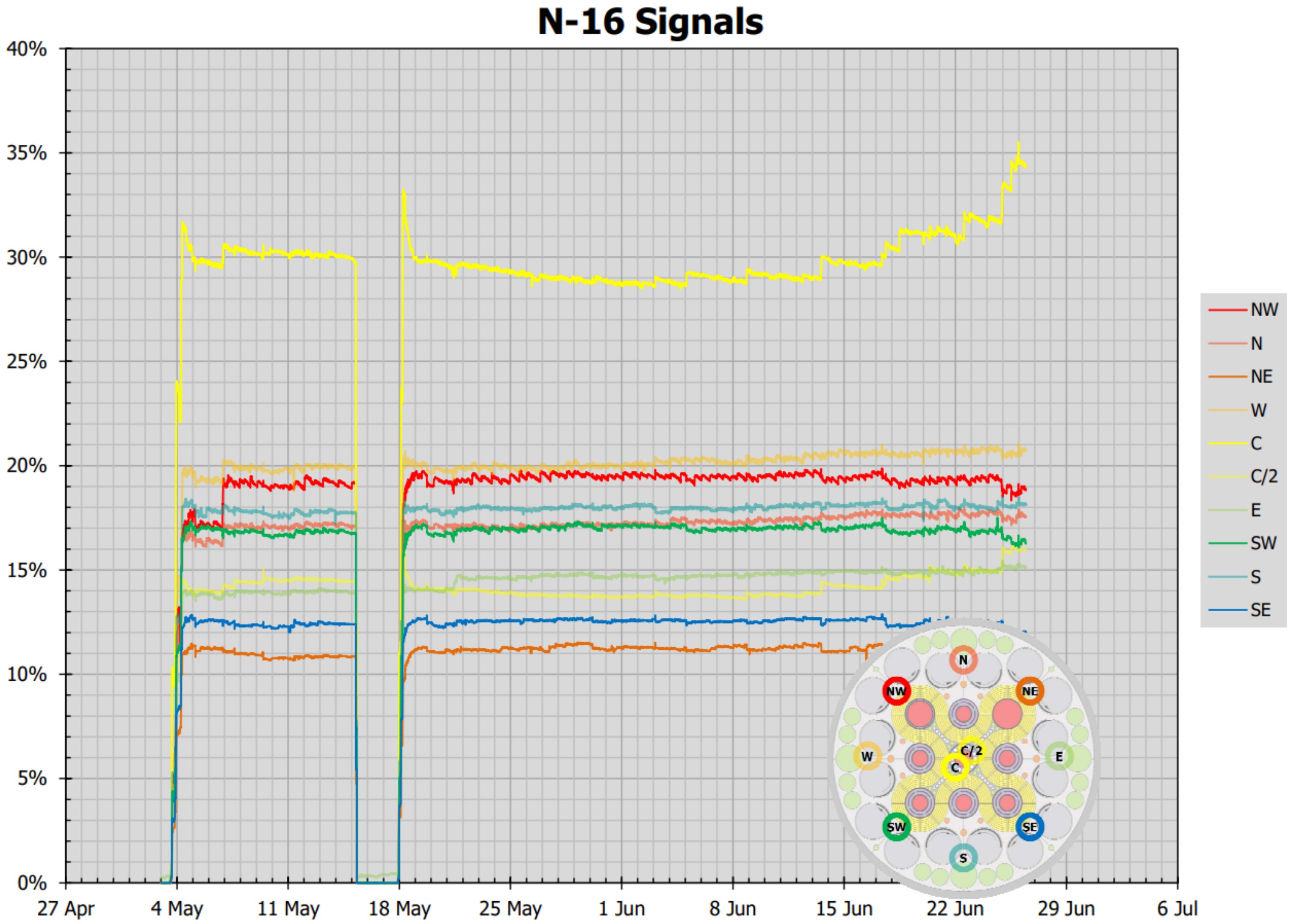
LPCIS

- Threshold Reaction $^{16}O(n,p)^{16}N$
  - Neutrons >10 MeV
  - LPCIS is Fission Power Only
- WPC includes Decay Heat



LPCIS

- 10 Signals
- 0-100%
- Usually constant w lobe powers



LPCIS

- Matrix Problem
  - 5 Unknown Lobe Powers
  - 10 Known Responses
    - Signal × Multiplier = Fission Rate
    - Multiplier compensates for sensitivity, decay in piping
  - + 1 Total Thermal Power
    - Normalization factor = 1 or 10,000
    - Can help LPCIS match WPC

$$\begin{bmatrix} c_{11} & c_{21} & c_{31} & c_{41} & c_{51} \\ c_{12} & c_{22} & c_{32} & c_{42} & c_{52} \\ c_{13} & c_{23} & c_{33} & c_{43} & c_{53} \\ c_{14} & c_{24} & c_{34} & c_{44} & c_{54} \\ c_{15} & c_{25} & c_{35} & c_{45} & c_{55} \\ c_{16} & c_{26} & c_{36} & c_{46} & c_{56} \\ c_{17} & c_{27} & c_{37} & c_{47} & c_{57} \\ c_{18} & c_{28} & c_{38} & c_{48} & c_{58} \\ c_{19} & c_{29} & c_{39} & c_{49} & c_{59} \\ c_{110} & c_{210} & c_{310} & c_{410} & c_{510} \end{bmatrix} \times \begin{bmatrix} P_1 \\ P_2 \\ P_3 \\ P_4 \\ P_5 \end{bmatrix} = \begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \\ R_5 \\ R_6 \\ R_7 \\ R_8 \\ R_9 \\ R_{10} \end{bmatrix}$$

- Least-squares Solution
  - Assume:

if $$[A] \cdot \vec{x} = \vec{b}$$

then $$\vec{x} = \left(([A]^T \cdot [A])^{-1} \cdot [A]^T\right) \cdot \vec{b}$$

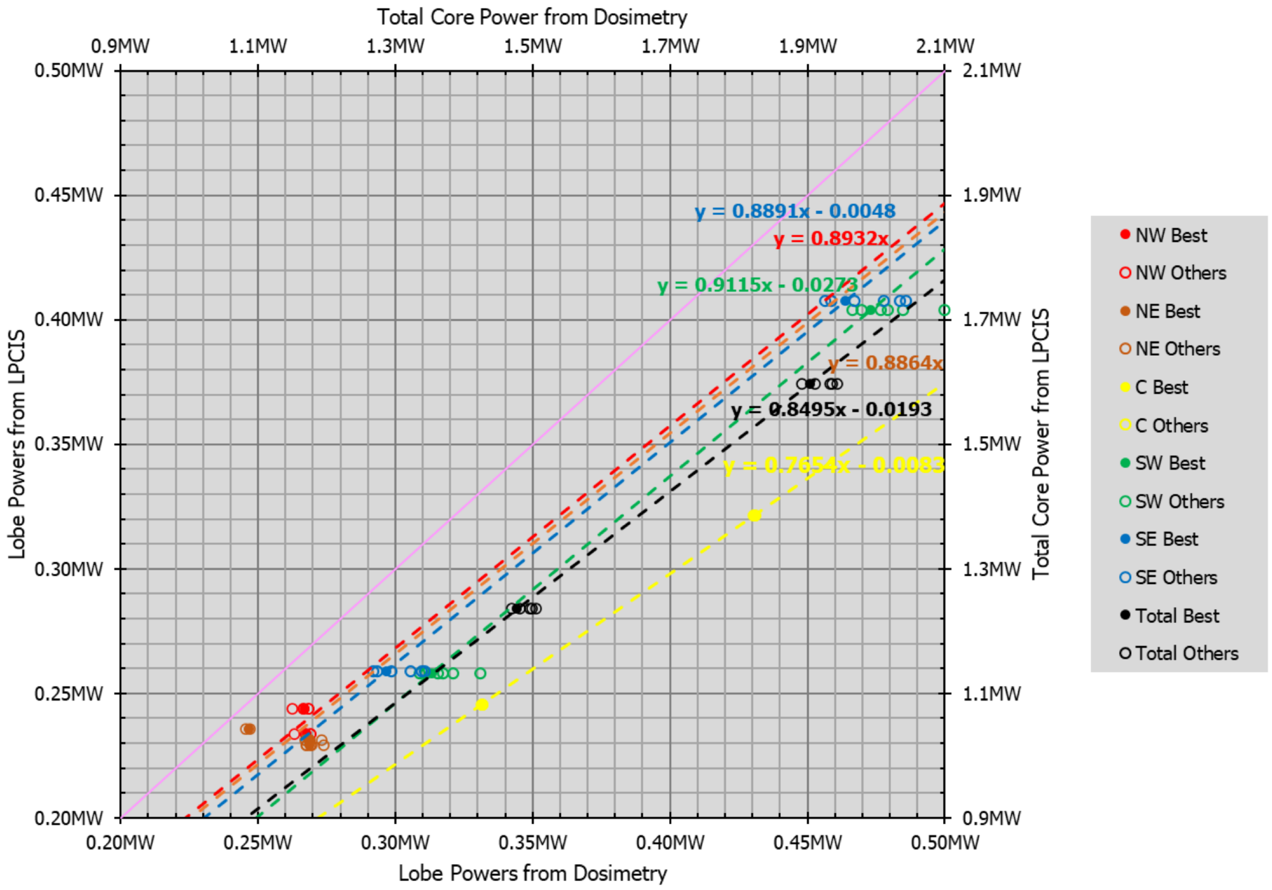
LPCIS

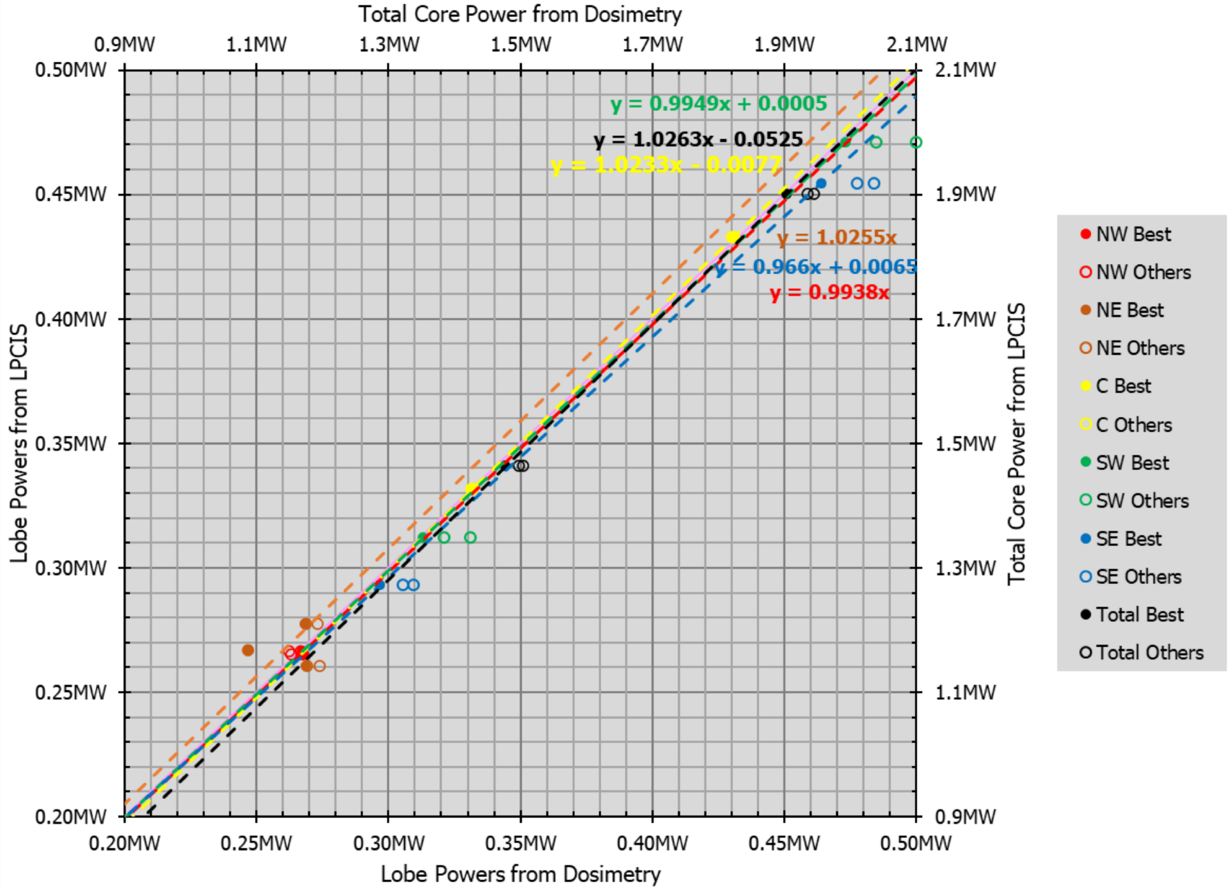
- Some coefficients based on optical distance
- Theoretical problems:
  - Signals strongly coupled to immediately adjacent fuel
  - < 0 ?
  - Magnitude primarily driven by distance
  - Multipliers (vice coefficients) changed when needed
- Pre-2022: Based on short sample of old data

	Lobe Powers				
Detector	NW	NE	C	SW	SE
N	6.002	5.778	−0.036	0	0
NE	0	56.722	−17.359	0	0
E	0	5.788	−0.113	0	6.180
SE	0	0	−17.359	0	55.559
S	0	0	−0.036	5.525	6.180
SW	0	0	−17.359	55.013	0
W	6.002	0	−0.113	5.525	0
NW	57.471	0	−17.359	0	0
C/2	3.333	11.904	60.933	−9.156	3.333
C	3.333	−9.155	60.933	11.904	3.333
Normalization Factor	10000	10000	10000	10000	10000

LPCIS Multiplier Changes

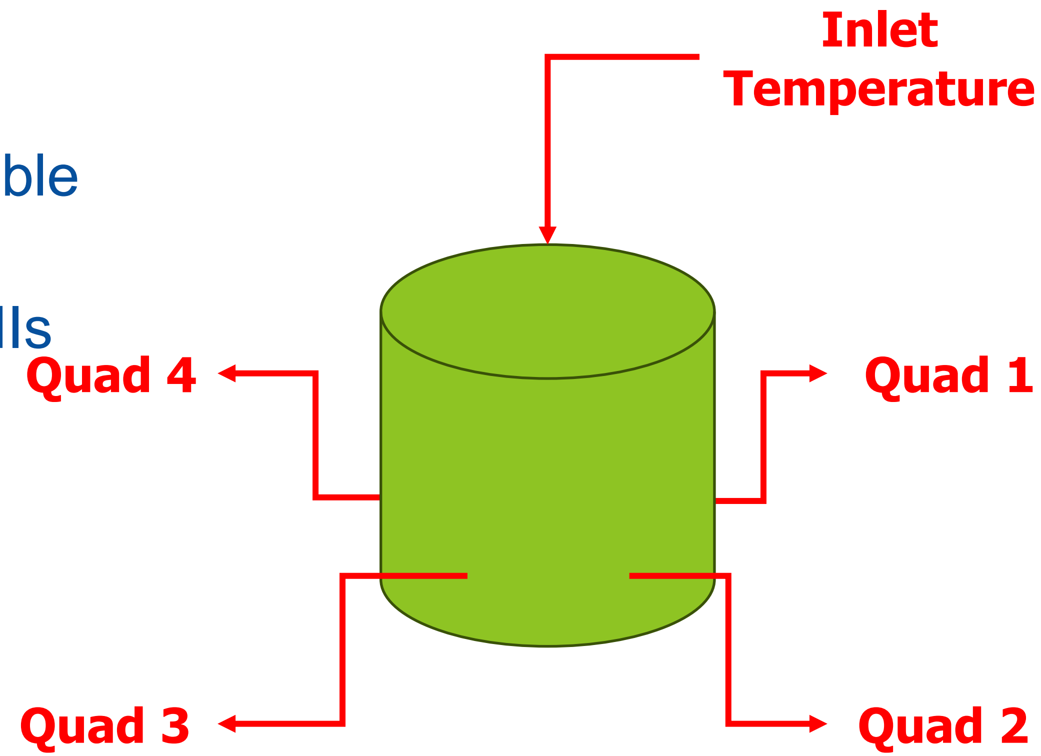
- 2 benchmark cases to validate model
- Model gave us appropriate multipliers for expected power divisions





WPC

- WPC "thermal" power is theoretically reliable
  - $Q = \dot{m} \cdot C \cdot \Delta T$
  - Includes fission heat, as LPCIS and NIs
    - + decay heat
    - + pump heat
    - + experiment heat
- 1 inlet temperature
- 4 quad outlet temperatures
- 4 outlet flow rates



Summary

	Approximate Core Power Range	Granularity	Safety Function	Inputs
LCRMs	< 1 W	Adjacent Lobe	Required >2cps	#1 (NE) #2 (SW)
Log-N	< 1 W – 2,500 MW	Adjacent Lobe	-	#4 (SE) #5 (NW)
WR	1 W – 1.5N_F	Adjacent Lobe	Scram	Channels A, B, C (SE, NW, NE)
NL	1 MW – 1.5N_F	Adjacent Lobe	Scram	Channels A, B, C (SE, NW, NE)
LPCIS	1 MW – N_F	5 Lobes	-	10 N-16 detectors
WPC	3 MW – N_F	Quadrants Core	Scram	Core T_{IN} 4× Quadrant Flow 4× Quadrant T_{OUT}

Idaho National Laboratory