# XENONnT Slow Control: Architecture, Challenges, & My Lessons Learned

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**Slow, but in control!**

# XENONnT Slow Control (XeSC) Overview

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**Distributed Architecture**

- 8 core subsystems: HV, CRY, DST, RSX, PUR, GEN, RAD, WLP
- Local independent operation via touch panels
- Centralized via GE's industrial SCADA platform (Cimplicity)
- Built on and extended from XENON1T system

**Control & Monitoring**

- Xxxx SCADA points
- ~5000 points/sec logged to Historian
- 2000+ alarms defined
- Semi/automatic procedures support key operations
- Interfaces: touch panels, SCADA, web viewer, API

**User & Access**

- 160+ users with role-based permissions via Active Directory
- VPN-secured remote access
- Authentication synced across SCADA, XeNTViewer, and panels
- Alarm notifications via email, SMS, and Slack

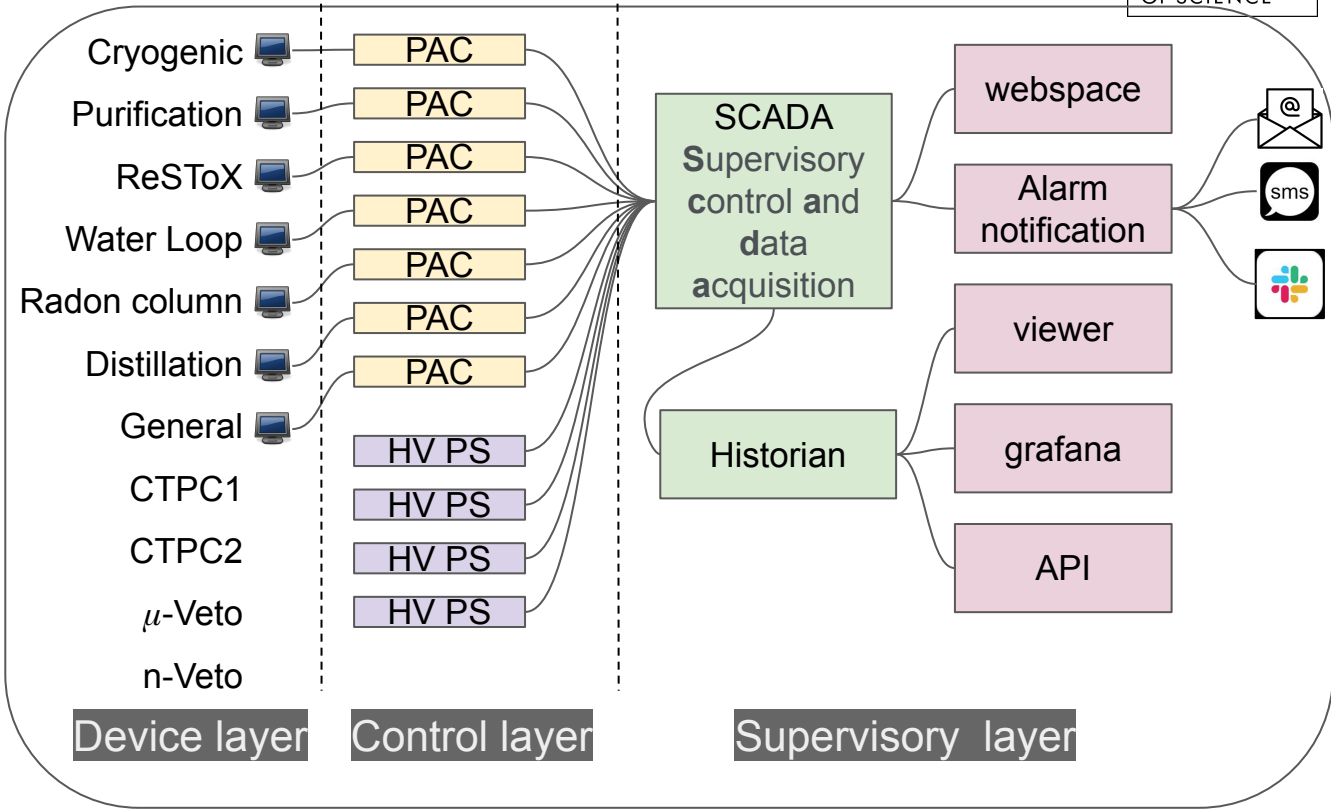
**Reliability & Infrastructure**

- Redundant SCADA servers, power supplies, and network paths
- Data backups: Historian via Bacula; full VM snapshots via NAKIVO
- System health monitored with Zabbix + redundant heartbeat checks

# Architecture

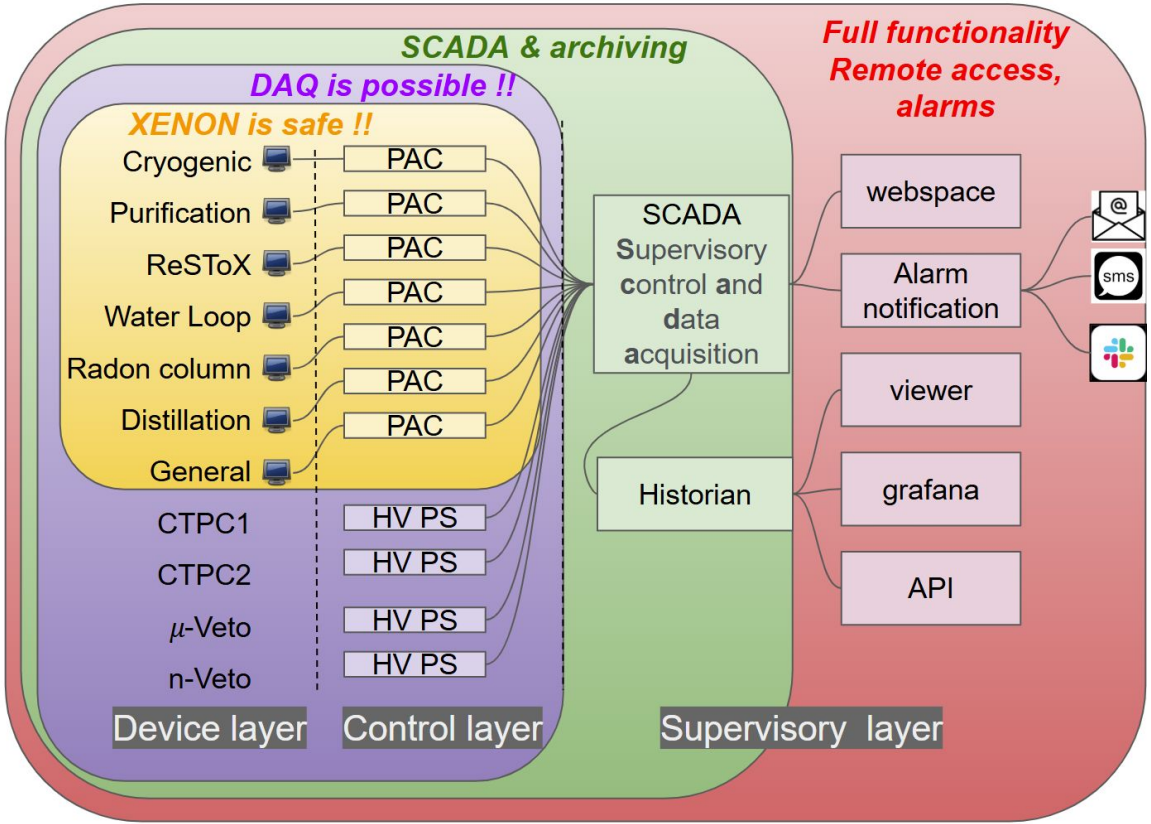
**Three-layer design**:

- **Device Layer**: sensors, actuators (~500 total).
- **Control Layer**: GE PACs (RX3i), local Beijer panels.
- **Supervisory Layer**: SCADA servers, Historian, Webspace/XeNTViewer.



# Hierarchical Access and Control Functionality

| Tier | Function | Notes |
|---|---|---|
| 0 | Failsafe | Ensures xenon safety (PAC local autonomy), Control via TS |
| 1 | DAQ | Enables physics, DAQ, |
| 2 | SCADA | Enables SCADA, XeSC-wide monitoring/control, calibration interfaces |
| 3 | Access | VPN/web interfaces for experts, with role-based permissions. Offline services, alarms |



# Interfaced Subsystems

<u>Controlled Susbsystems:</u>

- TPC Cryogenics (CRY): Redundant PTRs/LN2, thermal & pressure control.
- Purification (PUR): Dual GXe/LXe paths, real-time purity monitor.
- Radon & Krypton Columns (RAD/DST): Rn/Kr removal via cryo distillation.
- Recovery (RSX): Dual-vessel emergency xenon cryopumping.
- Water Systems (WLP/GdWPS): Water/Gd loop for neutron veto.
- Calibration & etc. (GEN): Source motion control, optical sync., Radon monitor,
- HV (TPC/MUV/NEV): CAEN supplies for PMTs/electrodes.

<u>Additional Susbsystems:</u>

- DAQ System: Bidirectional API via ODBC to/from Historian DB
- LNGS Safety Systems: Readout and alarms via Modbus interface

- PLCs - GE PACSystems RX3i
- SCADA - GE Cimplicity
- Archiving - GE Historian
- Custom tools

# Tools

# The PLC - GE PACSystems RX3i

- GE PACSystems RX3i series used as the main controller platform in XeSC
- Modular PLCs with Intel Atom-based CPUs, running VxWorks RTOS
- Connected via Ethernet Global Data (EGD) for fast real-time exchange
- Each subsystem has a dedicated PAC with:
  - Local touch panel for autonomous control
  - Hot-swappable I/O modules for analog/digital signals, serial devices, and PROFINET extensions
- PAC programming done in GE Machine Edition using:
  - Ladder logic (preferred for process automation)
  - Function block diagrams, structured text, and ANSI C (used for serial communication and complex logic)
- Guarded Operations: Built-in interlocks and confirmation dialogs for safety-critical actions
- Enables subsystem autonomy, critical during maintenance, emergencies, and network failures
- Interfaces seamlessly with GE SCADA (Cimplicity), Historian, and touch panels
- Industrial-grade reliability for continuous underground operation


# GE Cimplicity
## Core of the SCADA Layer

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- Industrial-grade HMI/SCADA platform developed by GE (now GE Vernova)
- Used as the supervisory layer in XeSC for real-time monitoring, control, and visualization
- Client-server architecture with active-passive failover for high availability
- Provides:
  - Graphical process screens (P&ID-style, or whatever graphics)
  - Alarm management and notification routing
  - Role-based control access (via Active Directory)
  - Interface to the GE Historian for data logging
  - Custom scripting enhances flexibility in VBScript and C (for both screen-level and SCADA-level logic)
- Integration-ready with OPC, Modbus, SQL, and custom APIs
- Supports Webspace for remote access and XeNTViewer for passive monitoring
- Proven in large-scale, high-reliability industrial systems

# SCADA Capabilities Utilized in XeSC

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- Screens
  - View/control system
  - Control alarms (thresholds, type)
  - Scripted screens for special purposes like Calibration sequences, HV Control
- System Scripts
  - Can be connected to alarms (e.g. turn off cathode when its raining)
  - Routine checks on the system (e.g. number of active HV channels)
  - Automatic procedures
  - Very Flexible
- Alarms
  - Severity, user group can be defined
  - Initiated by SCADA or by PLC

# GE Proficy Historian
## Industrial Time-Series Database

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- Interval-of-Validity (IoV) model stores values only when changes exceed thresholds
- High-speed, reliable data logging platform for SCADA systems (used with GE Cimplicity)
- Optimized for industrial use: Handles millions of tags and 100,000+ updates/sec - XeSC uses 5000 archived points (as licensed)
- Secure store-and-forward architecture: prevents data loss during network outages
- Flexible access: REST, ODBC, Excel, and Java APIs
- Cloud-ready: Supports AWS/Azure deployments and Parquet export
- Web-based tools for configuration and monitoring across distributed sites
- Supports multiple sampling modes, including: Raw values, Interpolated, Calculated….

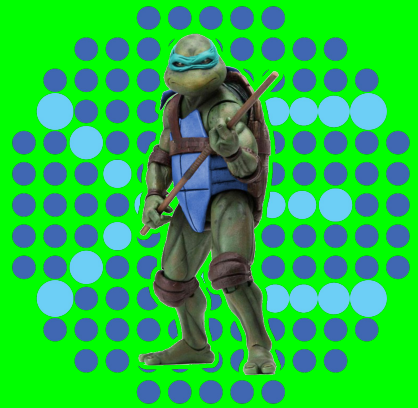
# Custom Tools by XeSC Group

In addition to SCADA-native features, the XeSC team developed several custom tools to enhance usability, diagnostics, and integration with external devices:

- ★ XeNTViewer: Web-based, passive viewer (cross-platform). Written in C#.
- ★ Historian Analysis: Long-term SQL trend tool for fault diagnostics and post-mortem analysis. Mostly in C#.
- ★ Alarm Notifier: Smart routing of alarms to email, SMS, and Webspace. Written in Python.
- ★ Heartbeat Monitoring: End-to-end monitoring from PACs to SCADA and mail server. Written in Python.
- ★ Custom OPC-UA Interfaces: For controlling external devices like the neutron generator and light sources. Developed in Python and C++.

- Touch Panels
- SCADA Screens
- Viewer Screens
- Historian API
- Grafana (Beta)

# User Interfaces



# User Interfaces

- Touch Panels
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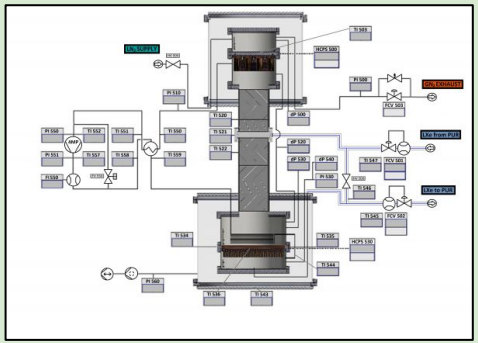
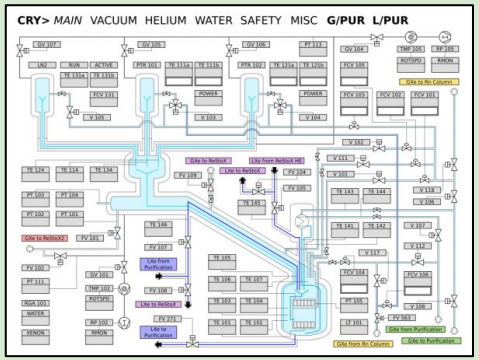
⇒ Installed underground on PAC cabinets
⇒ Communicate directly with the PACs
⇒ Fully autonomous: no network dependency



# User Interfaces

- Touch Panels
- SCADA Screens
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- Historian API
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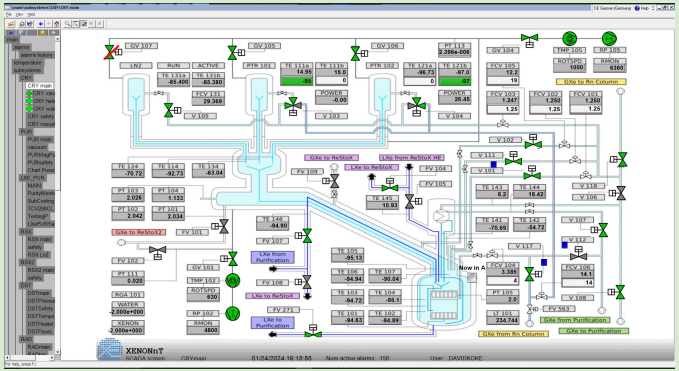
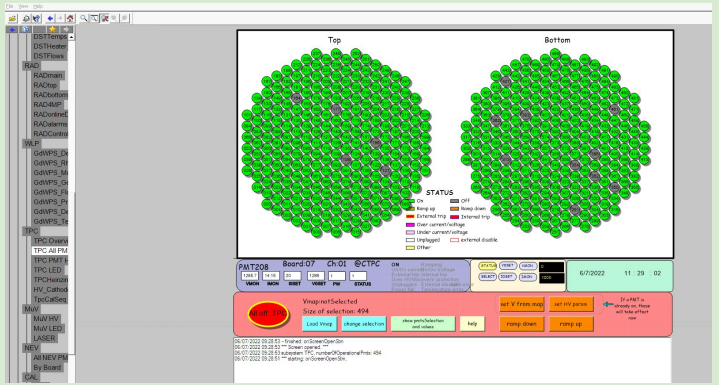
⇒ Based on GE Webspace
⇒ Cross platform, requires local installation
⇒ Real-time active control
⇒ Role-based access
⇒ limited number of simultaneous users





# User Interfaces

- Touch Panels
- SCADA Screens
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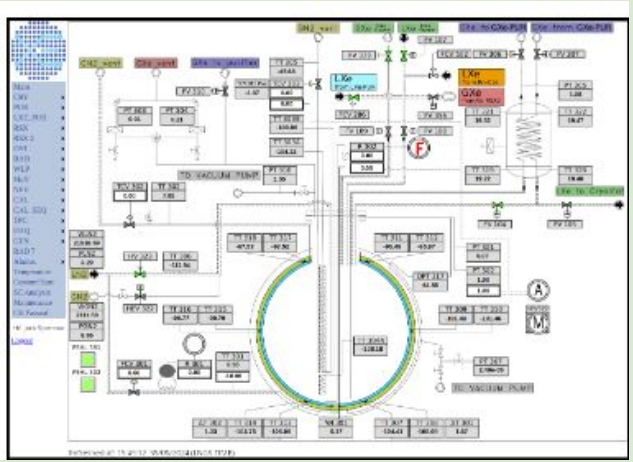
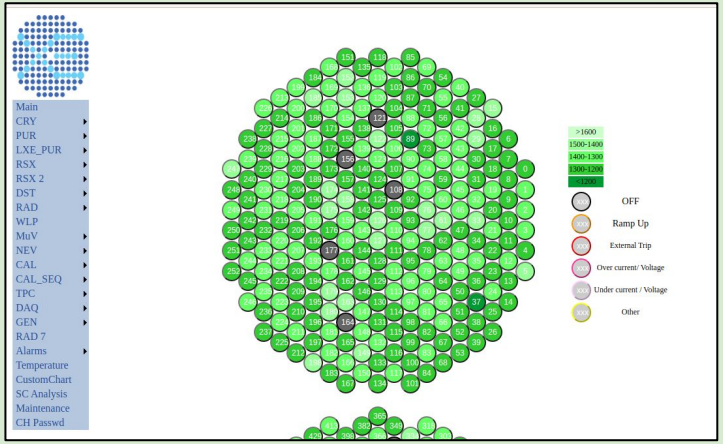
- Grafana (Beta)

⇒ Passive web-based interface
⇒ unlimited users
⇒ Updates every few seconds, data pulled from the Historian
⇒ includes data query interface with sampling options.





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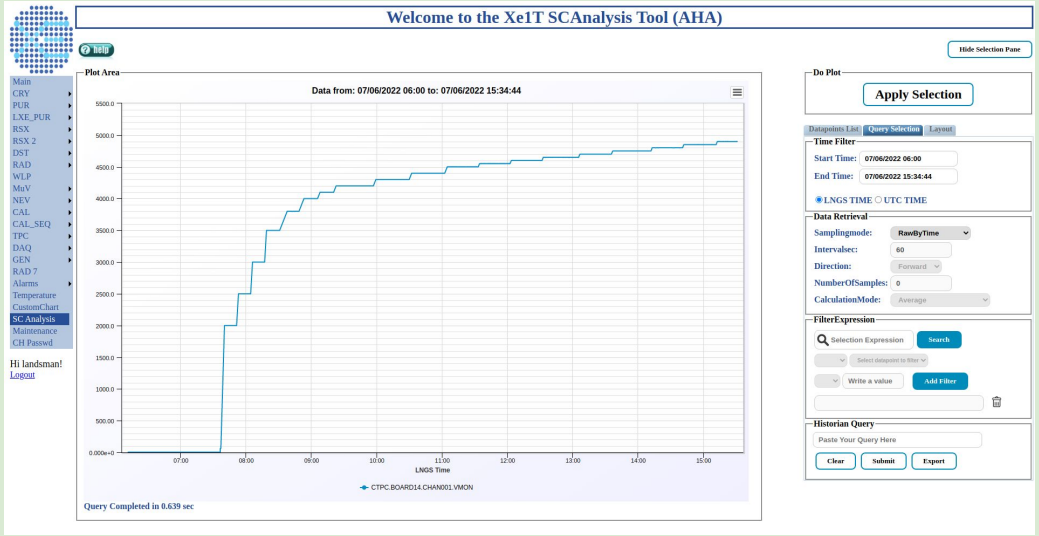


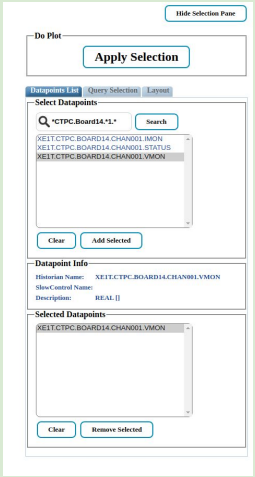

# User Interfaces

- Touch Panels
- SCADA Screens
- Viewer Screens
- Historian API
- Grafana (Beta)

⇒ Network level service to directly query the historian
⇒ Unlimited number of simultaneous users
⇒ Limited query options and volume by design
⇒ Incorporated in analysis

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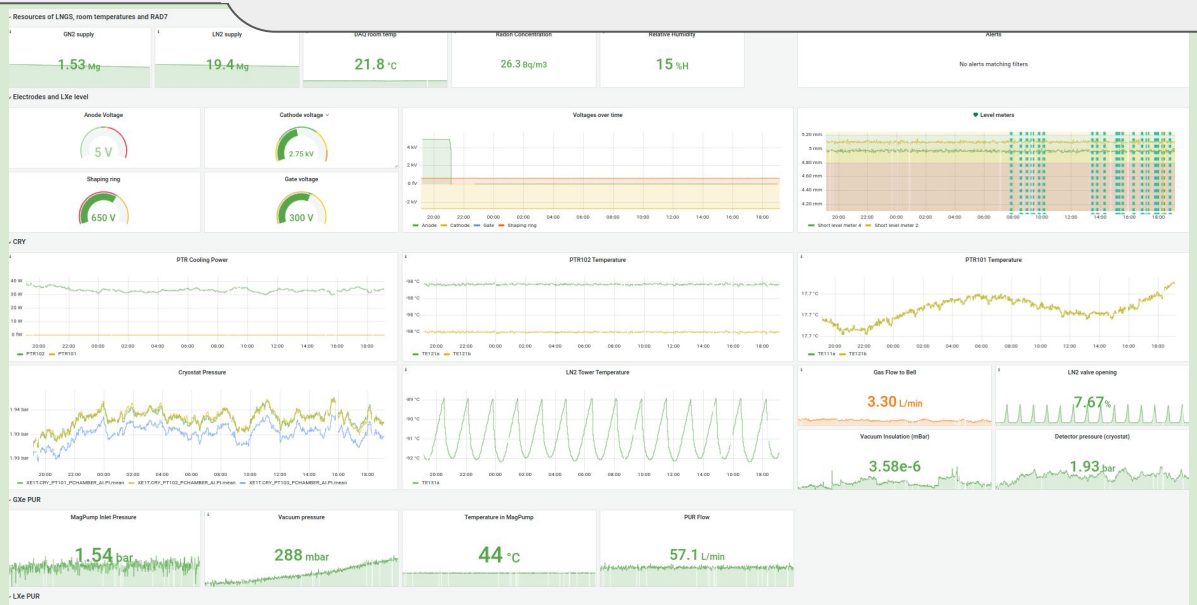
# User Interfaces

- Touch Panels
- SCADA Screens
- Viewer Screens
- Historian API
- Grafana (Beta)

⇒ Flexible and modern visualization interface,
⇒ uses historian data.
⇒ Not officially XeSC



# Interfaces

# User Management

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- Based on windows' Active Directory
- Enforced across SCADA, XeNTViewer, APIs
- **Independent from other collaboration services (wiki, daq…)**
- 160+ registered users: shifters, run coordinators, subsystem experts.
- VPN-secure remote access for off-site experts
- Role-based permissions via Microsoft Active Directory
  - View only
  - Base-access permission per subsystem (e.g. CRY, RSX)
  - Expert-access permission per susbsytem (e.g. CRY-EXP, RSX-EXP)
  - Combos for special roles (e.g. SHIFTER, RC)

# Network Infrastructure

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Dual-layered network:

- 2 Front-end network: isolated control networks for PACs and device interfaces
- Back-end network: connects SCADA servers, Historian, consoles, and external services

Redundant underground-to-surface links:

- Several fiber lines with separate physical routing for robustness

Remote access:

- VPN-secured entry for SC experts (limited to a few users)
- Most users access services via web interfaces (HTTP, Webspace)

Network health monitored via zabbix.

# Server Infrastructure

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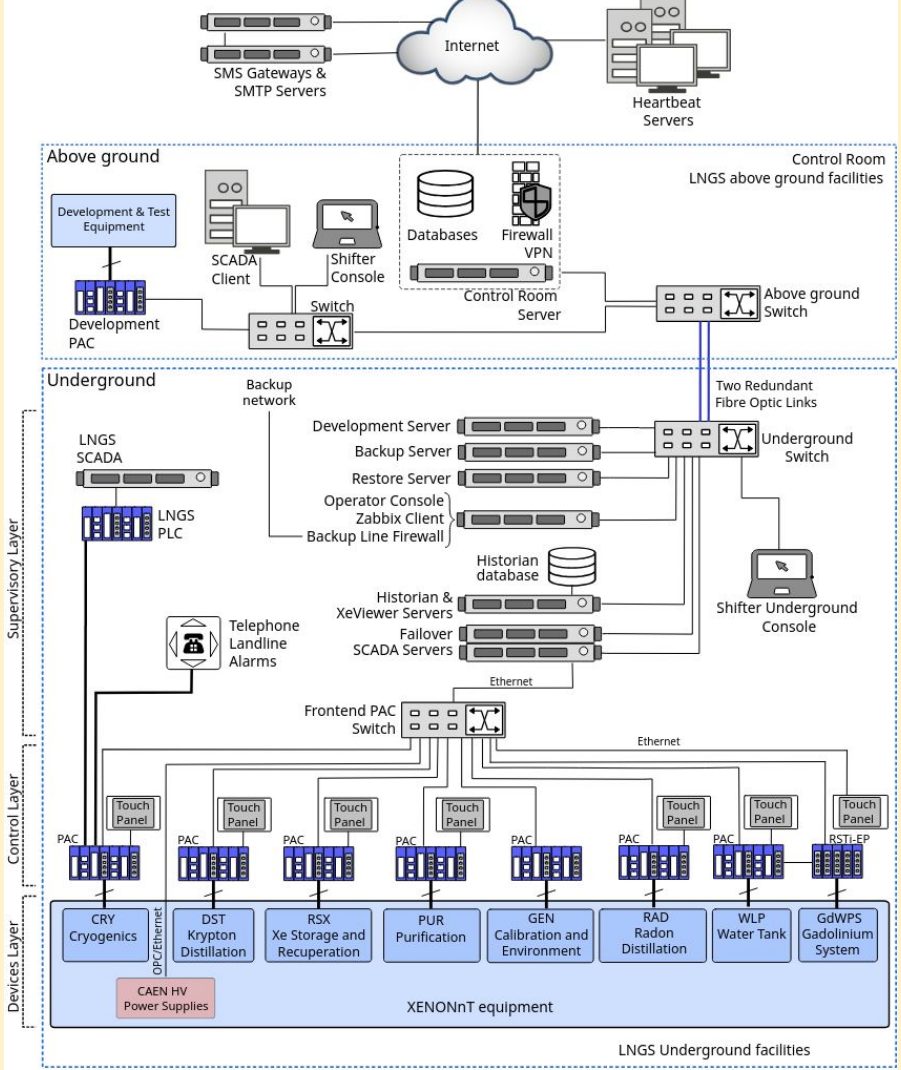
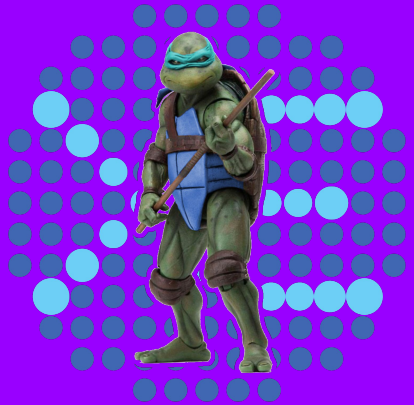
- Virtualized architecture: 19 VMs deployed across 5 physical machines
- Dual **backup** strategy:
  - Historian database backed up bi-weekly using Bacula (open-source)
  - Full VM snapshots (SCADA, Historian, XeNTViewer, etc.) created weekly using NAKIVO
- System **health monitoring** with Zabbix:
  - Tracks CPU, memory, disk, and service status
  - Sends automatic alerts via email and SMS
- Redundant **heartbeat** system:
  - Monitors external notification channels
  - Triggers alerts if communication is lost


Internet
SMS Gateways & SMTP Servers
Heartbeat Servers
Above ground
Control Room
LNGS above ground facilities
Development & Test Equipment
SCADA Client
Shifter Console
Databases
Firewall VPN
Control Room Server
Above ground Switch
Development PAC
Switch
Underground
Backup network
Two Redundant Fibre Optic Links
Development Server
Backup Server
Restore Server
Operator Console
Zabbix Client
Backup Line Firewall
Underground Switch
LNGS SCADA
LNGS PLC
Historian database
Historian & XeViewer Servers
Failover SCADA Servers
Shifter Underground Console
Telephone Landline Alarms
Ethernet
Frontend PAC Switch
Supervisory Layer
Control Layer
Devices Layer
Touch Panel
PAC
RSTI-EP
CRY Cryogenics
DST Krypton Distillation
RSX Xe Storage and Recuperation
PUR Purification
GEN Calibration and Environment
RAD Radon Distillation
WLP Water Tank
GdWPS Gadolinium System
OPC/Ethernet
CAEN HV Power Supplies
XENONnT equipment
LNGS Underground facilities

# My 2¢



# System Design & Architecture

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- **Use industrial-grade hardware and software:** Higher upfront cost, but ensures reliability, documentation, long-term support, and vendor stability - especially when there is a high turnover of users (students)
- **Design for subsystem autonomy:** Each subsystem should be able to operate independently as a standalone unit, and provide local control (e.g., touch panels)
- **Clarify interfacing responsibilities:** Know where subsystem hardware ends and SC ownership begins. Maintain clear subsystem interfaces - SC is responsible only from the point a clean, readable signal is provided, from a predefined list (e.g., OPC-UA, Modbus, Serial, 4–20 mA, 10 V…). That said, it is better to avoid serial communication when possible
- **Apply infrastructure segmentation:** Separate networks, servers, codebases, and development environments to isolate failures and improve security
- **Don’t over-automate:** Automation is powerful when it works, but makes failures harder to debug and harder for users to understand. Maintain transparency and human-readable status paths
- **Build for redundancy at every level:** Network paths, power sources, SCADA servers, alarm notifications (including heartbeat monitoring from A to Z)

# Access Control

- Implement **role-based access control** (e.g., shifter, expert, admin), applied uniformly across all SC interfaces.
- Use **shared authentication** infrastructure (e.g., same accounts for SC, DAQ, wiki) to avoid complexity
- Assign a **dedicated Slow Control point-of-contact** for each subsystem to improve response and coordination
- **Delegate access permissions** and role decisions to Run Coordination, not to the SC team - reduces confusion and improves alignment with operations

# Continuity

- Maintain version-controlled **backups** of everything: Archived data, VM snapshots, SCADA and PLC code, users and permissions…
- **Expect frequent turnover of students** and short-term staff: Prioritize clear documentation, onboarding material, system diagrams, and accessible code/comments
- Favor tools and logic representations maintainable by **non-developers** (e.g., SCADA visual editors, structured configuration files)

# Monitoring & Alarms

- Set up **KPI dashboards** to track detector health and system performance trends
- Use **multi-channel alarm routing** (email, SMS, Slack, etc.) with heartbeat validation to catch notification failures
- Provide an **alarm acknowledgment** and clearing system so experts can confirm, mute, or escalate alarms properly. Define alarm severity levels and escalation paths to avoid alert fatigue and reduce confusion

# Budget & Recognition

- Cost: Define early **who pays for what** - PLCs, I/O modules, licenses, cables, etc. Ensure SC costs are part of the overall detector lifecycle budget, not just the construction phase
- Ensure **SC costs are part of the overall** detector lifecycle budget, not just the construction phase
- Keep Slow Control **status visible in FieldView** and reports to highlight its critical role and ongoing effort - this supports recognition, budgeting, and recruitment for maintenance and operations