Vacuum Controls & Diagnostics

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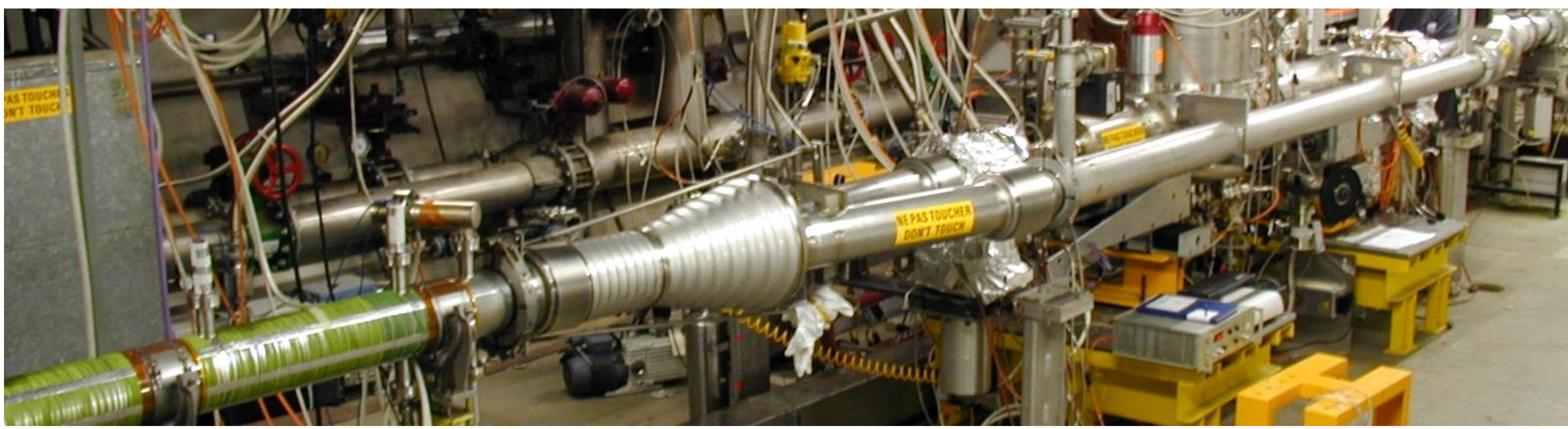
on behalf of TE / VSC / ICM
TE – Technology Department
VSC – Vacuum, Surfaces & Coatings Group
ICM – Interlocks, Controls & Monitoring Section



CERN

The CERN Accelerator School

TE VSC
Interlocks
Controls
Monitoring

Outline

Part 1: Field and control layers

- Vacuum Controls architecture
- Gauges & controllers
- Low current measurement
- Pumps & controllers
- Hardware interlocks & alarms
- Example of radiation effects on Vacuum electronics
- Future trends & developments

Part 2: Supervision layer

- SCADA
- WinCC-OA architecture
- Configuration of a large control system
- Vacuum Functionalities
- Applications, servers and networking
- Enterprise Asset Management

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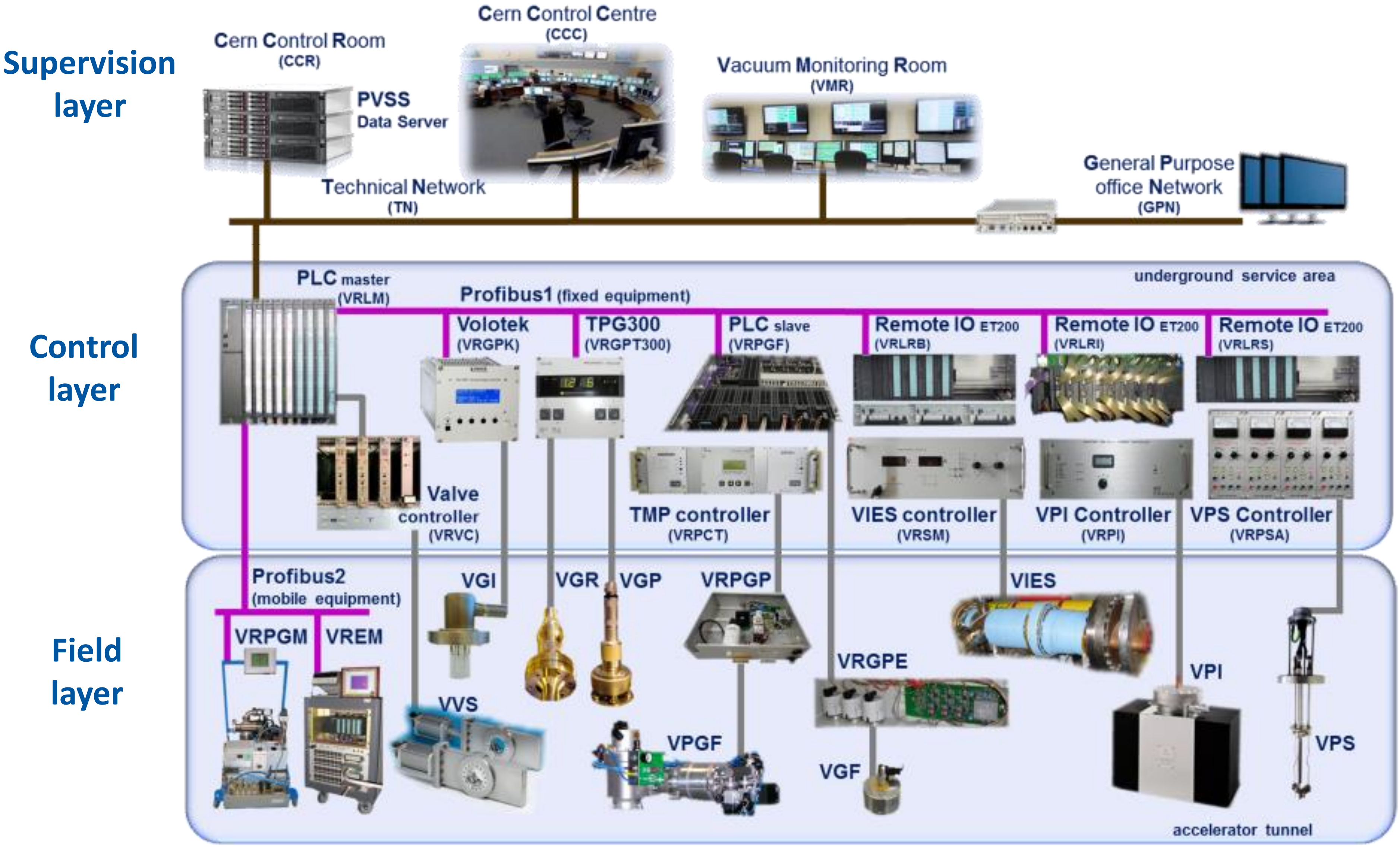
Vacuum controls architecture



Vacuum instruments count (all accelerators)

6 000+ vacuum instruments to be controlled and monitored

Along **130 km** of vacuum chambers
Pressure range **[10^{-4} .. 10^{-12} mbar]**

PLCs : **300+**

Gauges : **3 000**

Pumping groups : **250**
Ion pumps : **2 700**

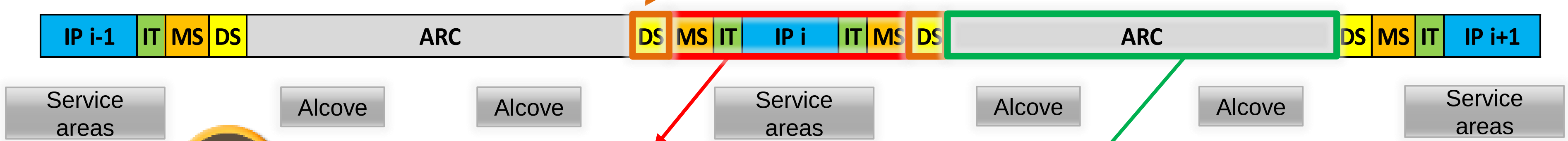
Sector valves : **500**

	L2,L3, PSB,PS	SPS	LHC beam	LHC insul.	other facilities	total
length [km]	2	16	59	50	1	128
log (P [mb])	-7..-10	-7..-9	-8..-11	-5..-7	-4..-10	-4..-11
PLC master	5	8	28		3	44
PLC other	0	10	7		0	17
PLC slave	0	0	100		155	255
VGM	0	0	10	231	0	241
VGR	102	113	428	348	61	1052
VGP	122	128	649	364	66	1329
VGF	0	13	4	0	0	17
VGI	28	0	167	0	16	211
VPGF	7	3	14	179	51	254
VPI	370	1429	825	0	69	2693
VPS	48	0	0	0	0	48
VVS	76	87	305	39	13	520
VVF	0	11	0	0	0	11
VVW	0	5	0	0	0	5

Vacuum instruments in the LHC tunnel

Dispersion Suppressors (<100 Gy/y)

- Active piezo gauges and local power supplies for pumping groups
- all other components are passive
- Controlled installed in radiation free areas
- Cable length up to 600m



Long Straight Section (>100 Gy/y)

- Only passive components except local power supplies for pumping groups (w/o turbo controller)
- Controllers installed in radiation free areas
- Cable length up to 400m

ARC (<10 Gy/y)

- Active gauges (Piezo, Pirani, Penning)
- Local power supplies for pumping groups (w/ radiation tolerant turbo-controller)
- PLCs installed in radiation free areas
- Cable length up to 1km

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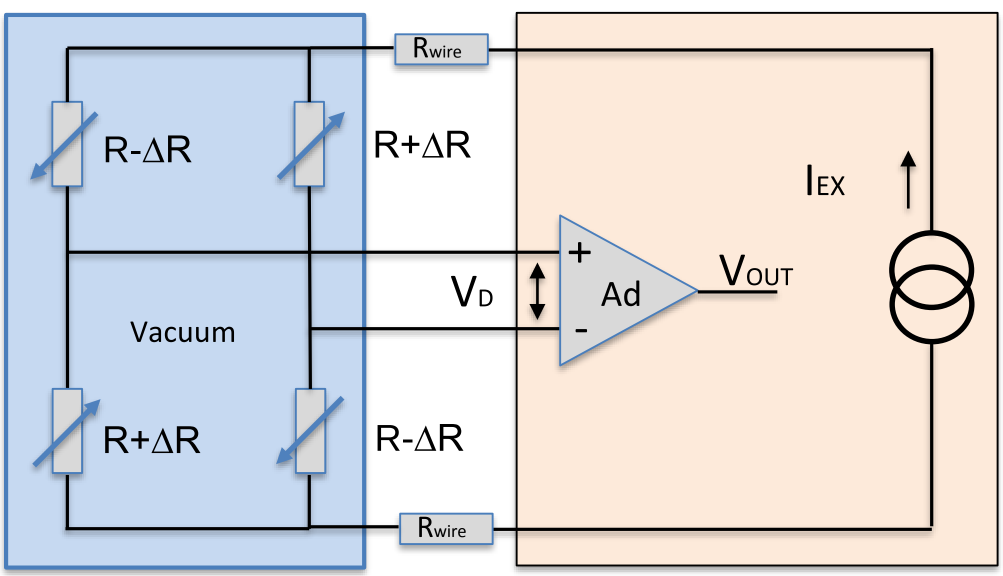
Membrane gauge (Piezo-resistive)

- Thin silicon crystal layer used as a membrane
- Membrane deformation induces piezo-resistive effect
- Measurement from **1 .. 2000 mbar; ~** 10% uncertainty

- Piezo-resistive elements constitute a full Wheatstone bridge
- Bridge supplied by a constant current (wire resistor)
- V_D (~mV) is a measure of the membrane deformation
- Up to 3 gauges per controller; needs calibration
- 0-10V, 4-20 mA, protection relays

Piezo gauge (Full-Bridge) **Piezo-resistive conditioning circuit**



$$V_D = I_{EX} \cdot \Delta R$$

$$\Delta R = f(P)$$

$$V_{OUT} = Ad \cdot V_{MEAS}$$

Thermal conductivity gauge (Pirani)

- Thin tungsten filament heated to constant temperature (~ 120 °C)
- Based on heat condutivity through a gas; gas dependent
- Pressure measurement from **10^3 .. 10^{-4} mbar; ~** 30% uncertainty

- The filament constitutes one element of a Wheatstone bridge
- The bridge is self compensated by an amplifier in feedback loop
- VOUT (~V) is a measure of the pressure
- Up to 2 gauges per controller; needs calibration
- Profibus DP connection; 0-10V; protection relays

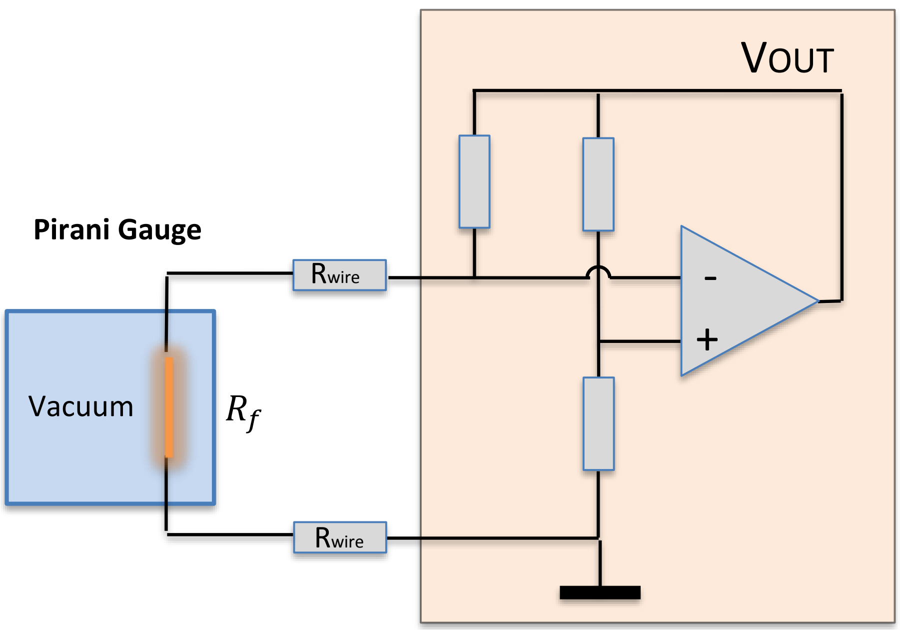
Twisted pair
single shielding

Up to
500m

Pfeiffer TPG300

Pfeiffer TPR18

Pirani conditioning circuit



$$V_{OUT} = \sqrt{2R_f\epsilon\left(p_0 + \frac{p}{1+gp}\right)}$$

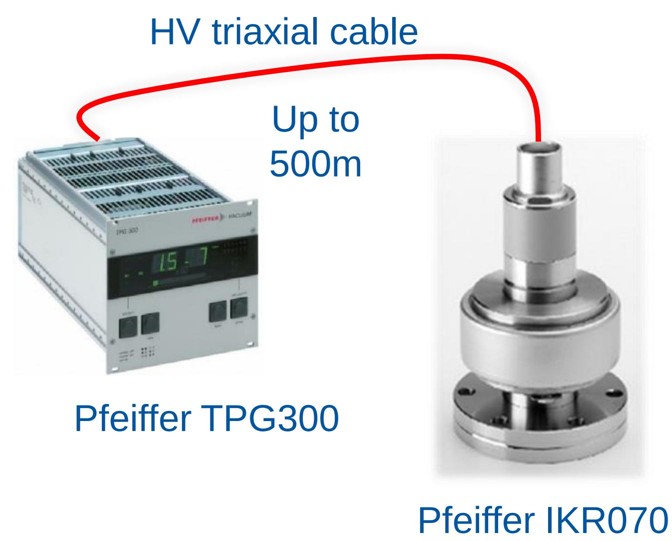
ϵ: sensitivity [W/mbar]
p_0: lower limit of the measuring range [mbar]
g: constant depending of the geometry

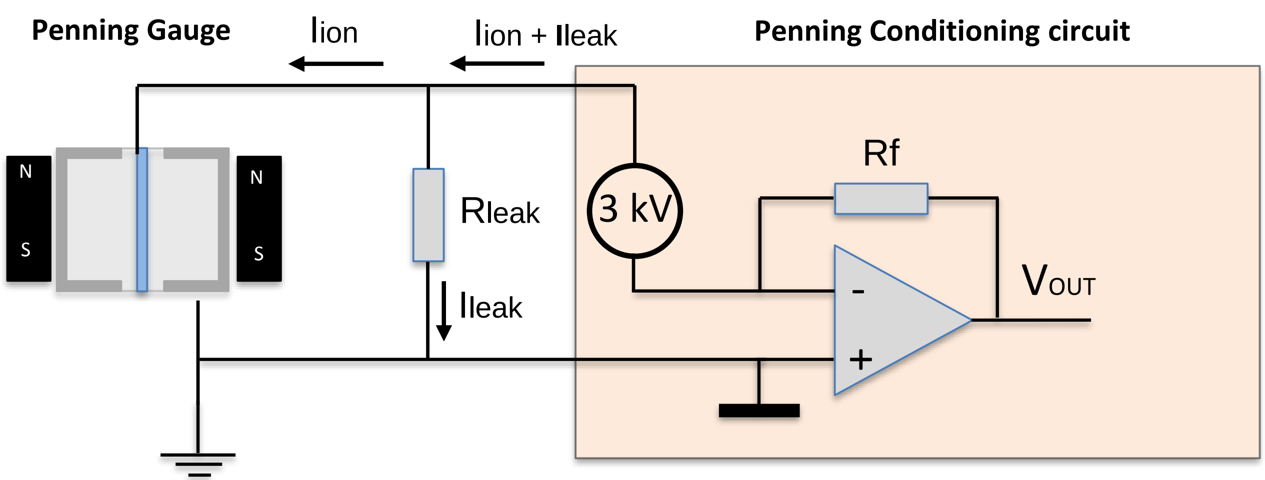
R_f ~ 130 to 150 Ω
Strong effect of R_{wire} (long cable)

Cold-cathode ionization gauge (Penning)

- High **E** field (3 kV) ; **B** field (0.1 T)
- Gas discharge
- **$I^+ = K.p^m$** , m ~ 1; current from **10^{-6}.. 10^{-12} A**
- Pressure measurement from **10^{-5}.. 10^{-11} mbar; ~** 50% uncertainty

- Controller has a HV power supply and electrometer
- Leakage simulates higher pressure
- Up to 2 Penning gauges per controller; factory calibrated
- Profibus DP connection; 0-10V; protection relays
- **Used as interlock source; robust**





$$V_{OUT} = R_f.(I_{ion} + I_{leak})$$

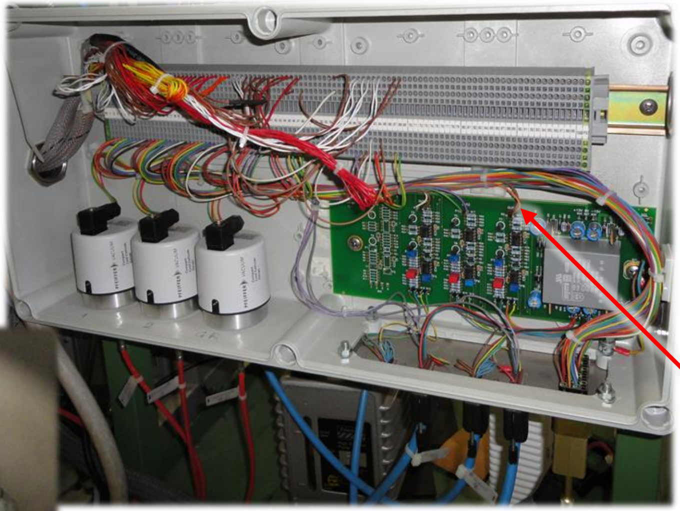
$$I_{leak} \ll I_{ion}$$

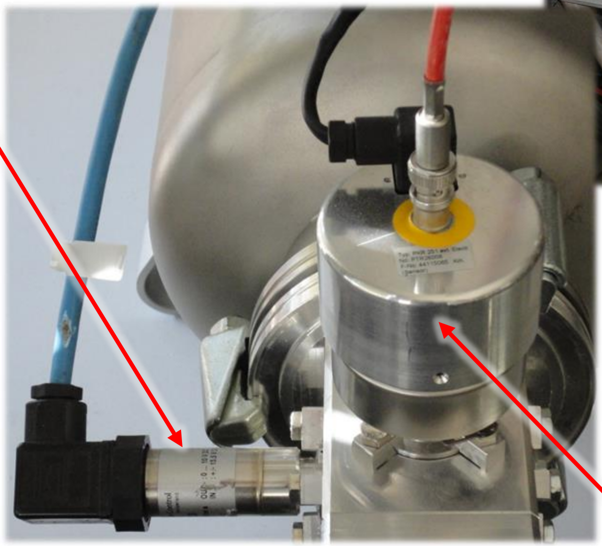
Active gauges (Piezo, Pirani, Penning)

- Active gauges have electronics incorporated in the sensor head
- Used in radiation free or low radiation areas
- Signal conditioning very close to the sensor allows cabling cost reduction

Pfeiffer PKR251

Huba Pressure transmitter 0-1.6 bar
+/-13.5VDC supply
0-10V output
Used in LHC arcs (QRL + MAG)





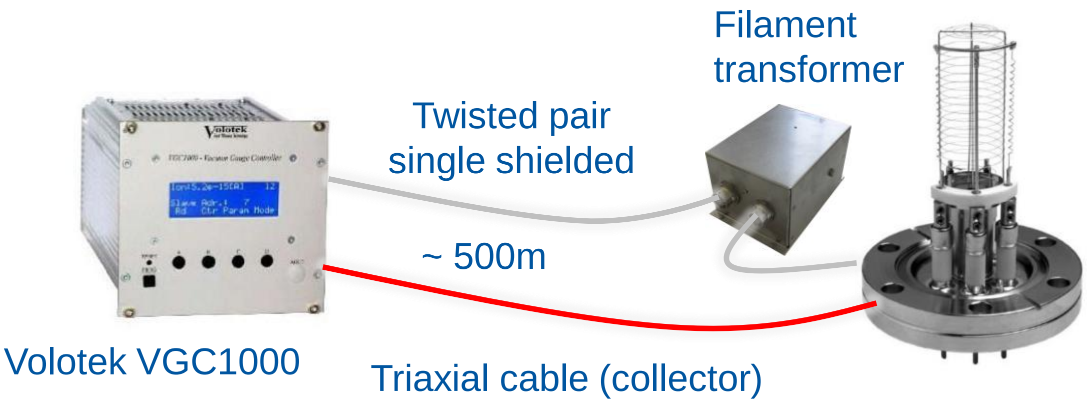
Penning electronics
Pirani custom electronics
24VDC supply
0-10V output
Used in **low** radiation areas

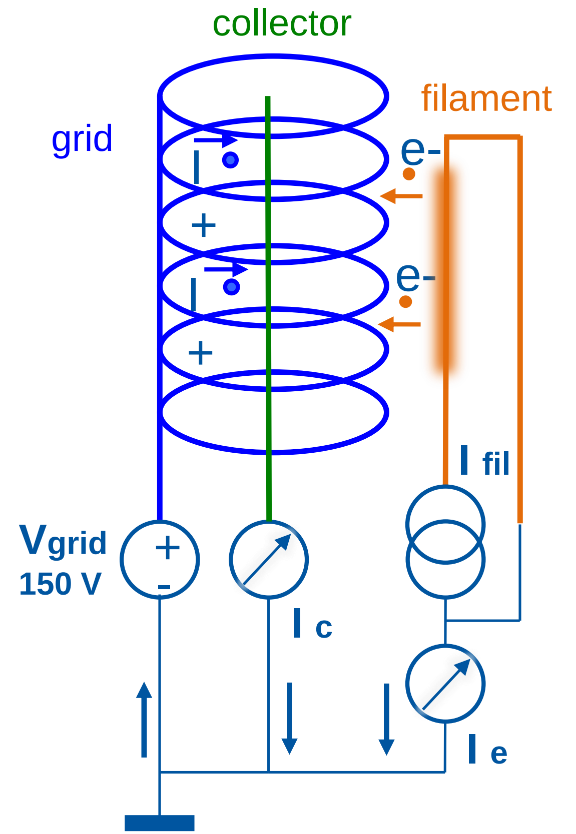
Pirani/Penning gauge head
Used in LHC arcs (QRL, MAG, beam)

Hot-cathode ionization gauge (Bayard-Alpert)

- Electrons are emitted by the heated filament and attracted by the grid potential (150V)
- Ionization of gas molecules inside the grid; ions are attracted to the collector
- $I^+ = S.Ie^-.p$, S ~ 100; current from **10^{-6} .. 10^{-13} A**
- Pressure measurement from **10^{-5} .. 10^{-12} mbar**; uncertainty ~ 10%

- Modular cards for: Electrommeter, grid and filament supplies, communication
- Needs calibration; 100fA resolution
- Voltage step-down transformer used for filament heating
- Profibus DP connection; 0-10V output measurement





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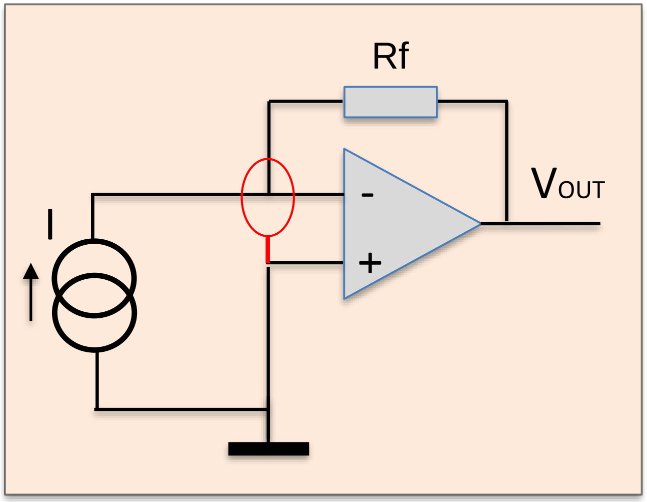
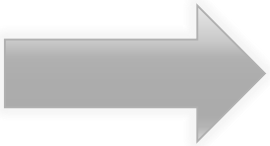
How to measure low current?

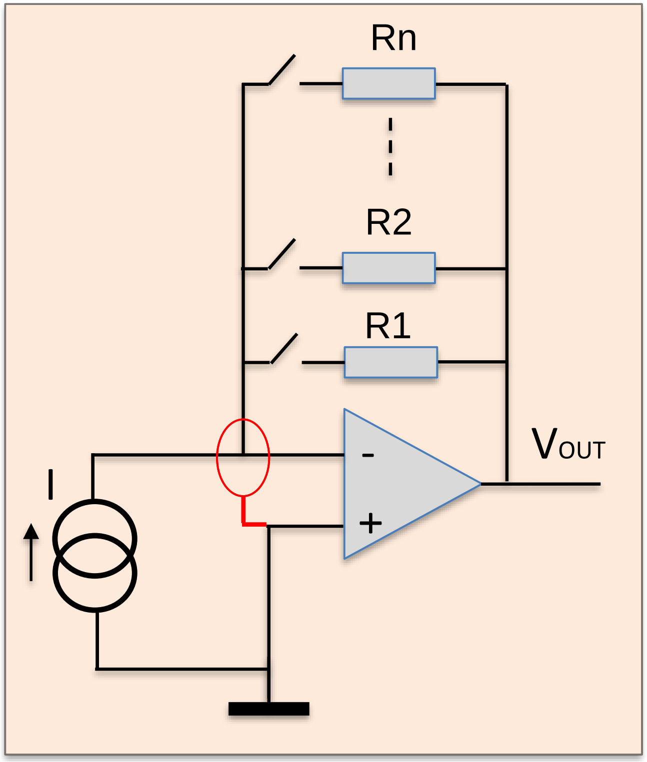
Electrometer



$$V_{OUT} = R_f . I$$



Electrometer, piece wise linear



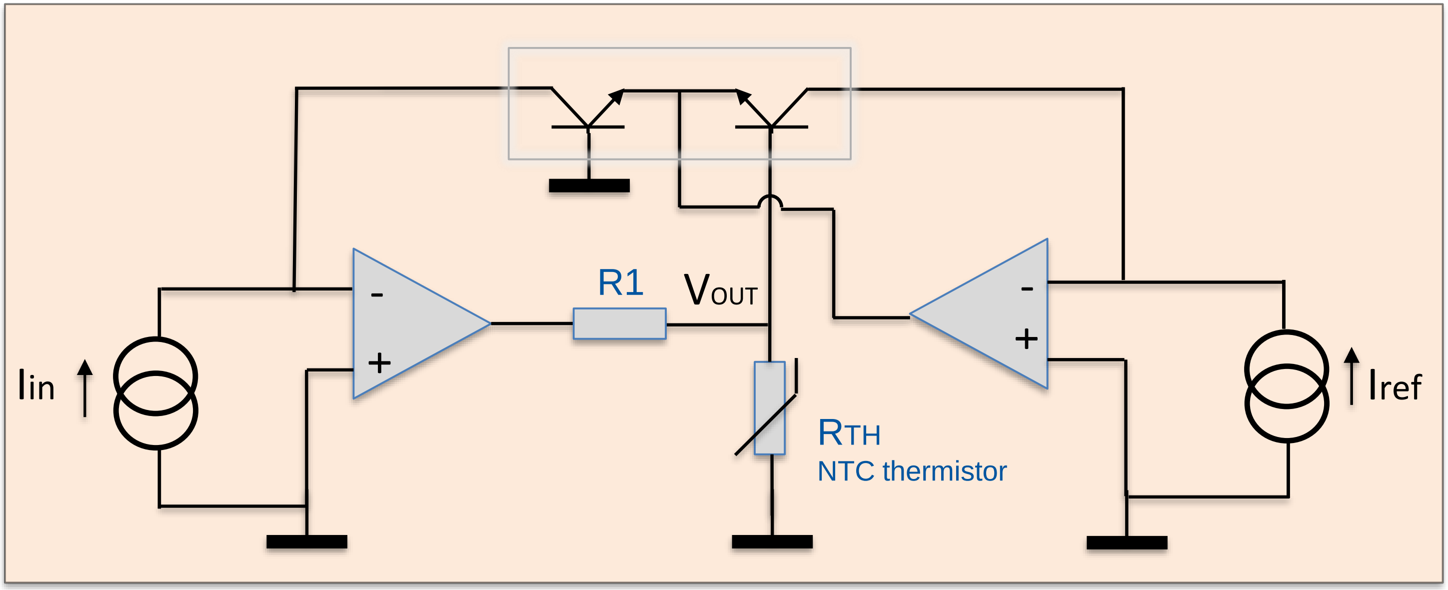
- Several decades of current (pressure) to measure
- Relays need to be controlled
- Special relays with low leakage current
- uC needs to know the combination of resistors
- Current measurement from 10^{-4} to 10^{-13} A
- GΩ resistance for high gain

$$V_{OUT} = R_k . I$$

R_k is a combination of R_1 to R_n

How to measure low current?

Logarithmic electrometer



$$V_{OUT} = \left(1 + \frac{R_1}{R_{TH}}\right)\frac{kT}{q.log_{10}e}.log_{10}\left(\frac{I_{in}}{I_{ref}}\right)$$

q: electron charge
K: Boltzmann constant
T: absolute temperature

- Log amp compress the dynamic range of signals
- Sensitive to temperature
- Can be slightly compensated
- Current range from 10^{-4} .. 10^{-13} A

Offset and noise current sources

- **Volume resistivity:** leakage of current directly through the material
- **Surface resistivity:** leakage across the surface due to surface contaminants and humidity
- **Water absorption:** leakage dependent on the amount of water that has been absorbed by the insulator
- **Piezoelectric effects:** charges created due to mechanical stress
- **Triboelectric effects:** charges created between a conductor and an insulator due to friction
- **Dielectric absorption:** tendency of an insulator to store/release charge over long periods
- **Temperature:** expansion or contraction of insulators; temperature drift of the electrometer
- **Ionizing radiation:** charges created in the cable, degradation of the insulator
- **Input bias current:** offset current when input of the electrometer left open; compensated by calibration

Material	Volume Resistivity (Ohm-cm)	Resistance to Water Absorption	Minimal Piezoelectric Effects[1]	Minimal Triboelectric Effects	Minimal Dielectric Absorption
Teflon® PTFE	$>10^{18}$	+	–	–	+
Sapphire	$>10^{18}$	+	+	0	+
Polyethylene	10^{16}	0	+	0	+
Polystyrene	$>10^{16}$	0	0	–	+
Kel-F®	$>10^{18}$	+	0	–	0
Ceramic	10^{14}–10^{15}	–	0	+	+
Nylon	10^{13}–10^{14}	–	0	–	–
Glass Epoxy	10^{13}	–	0	–	–
PVC	5×10^{13}	+	0	0	–

KEY: + Material very good in regard to the property.
0 Material moderately good in regard to the property.
– Material weak in regard to the property.

Mostly used at CERN (Polyethylene)

e.g. FR4 (PCB circuit)! (Glass Epoxy)

Properties of Various Insulating Materials

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Sputter Ion pumps (SIP)

Principle

- Composed of several Penning cells
- $\mathbf{I^+ = K.p^m}$, m ~ 1; current from $\mathbf{10^{-2}}$ **..** $\mathbf{10^{-8}}$ **A**
- Pressure measurement $\mathbf{10^{-4}}$ **..** $\mathbf{10^{-10}}$ **mbar;** uncertainty ~ 50%
- Ions bombardment of the Ti cathodes => Sputtering & deposition of Ti
- Reactive gases pumping effect (stable)

Controller

- Provides 0-10V output measurement; protection relays
- Needs to be calibrated
- Controlled through remote I/O station; up-to 40 controllers
- Linear power supply (heavy); HV transformer + voltage multiplier
- **Ion pumps are used as interlock source**

Remote I/O station

CERN designed controller

HV triaxial cable ~ 500m

Agilent Starcell500

Installed in ELENA
Under evaluation in other machines

Titanium Sublimation Pumps

Principle

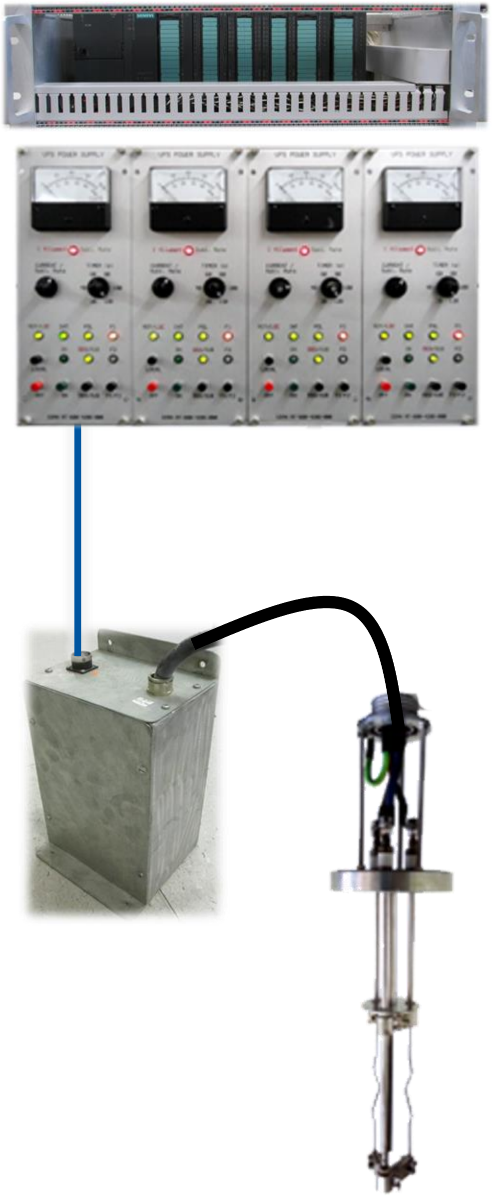
- Titanium filament supplied with high current (~ 40 A)
- Filament is heated until it reaches the sublimation temperature (1300 °C)
- The surrounding chamber walls are coated with thin film of clean titanium
- High pumping speed for getterable gases (CO_2 , CO, N_2 , H_2O, etc)

Power supply

- Power supply with 230VAC; power modulation using thyristor
- Due to long cable, voltage step-down transformer close to the sublimator
  230V; 1A => 6V; 45A
- Provides current and sublimation measurement

PLC-based

- Up to 8 Power supplies per remote I/O crate
- Can be remotely controlled by PLC (S7-300)
- Sublimation and degassing function, time management



Primary & Turbo Molecular Pumps

Primary Pump

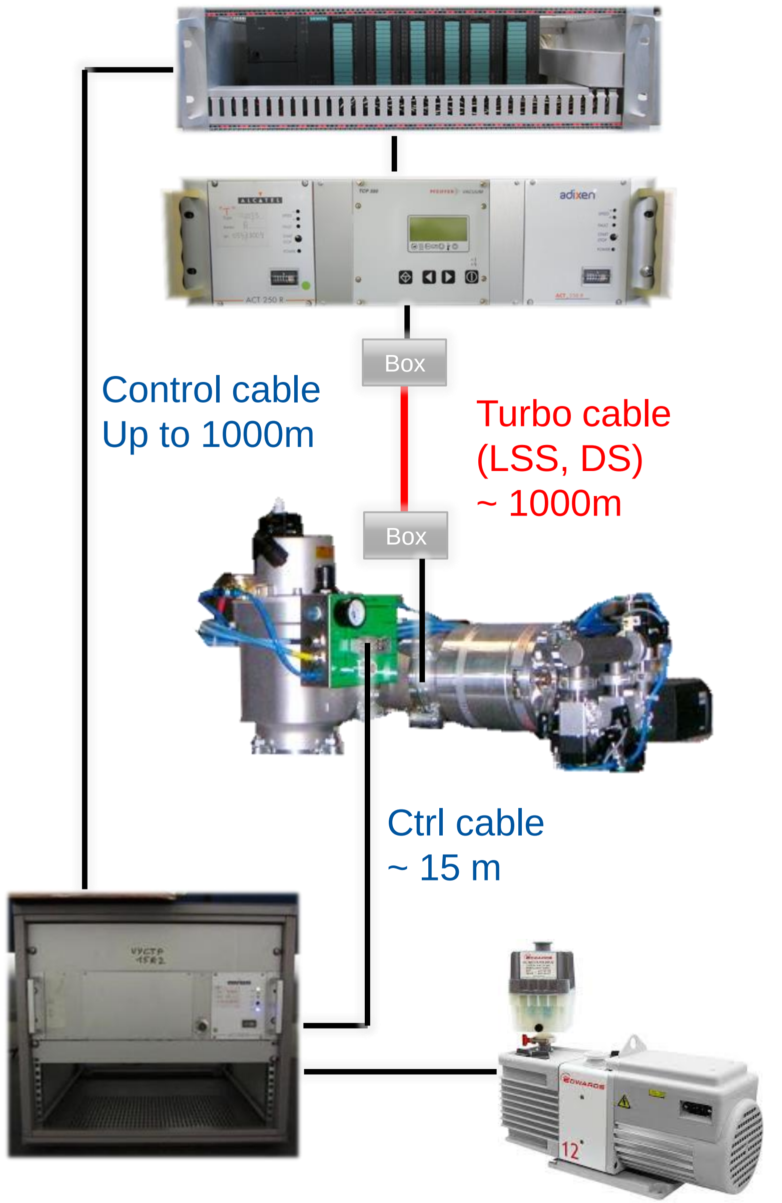
- Monophase 230VAC or triphase 380VAC induction motor
- Contolled by power relay; protected by thermal relay
- Power provided localy (in the tunnel)
- Pump used: Edwards RV12

Turbo Molecular Pump

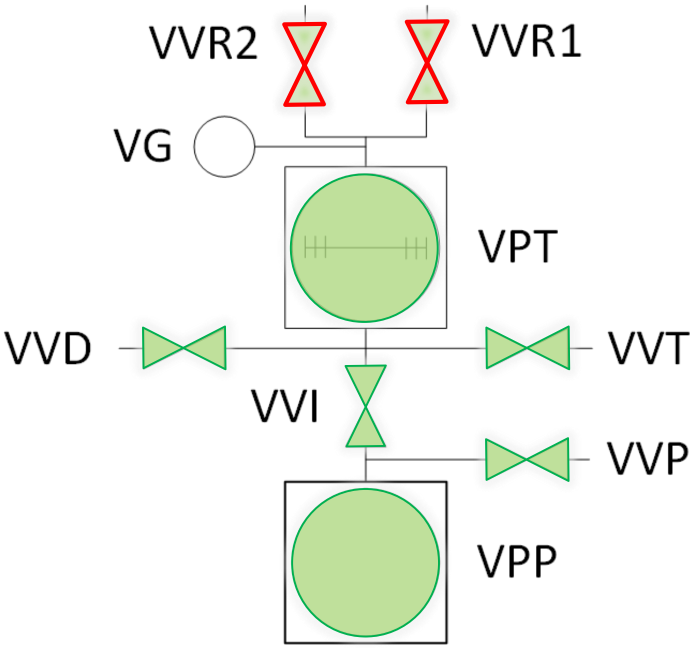
- Brushless DC motor, w/ or w/o position sensors (Hall)
- Ceramic ball bearings and permanent magnetic bearings
- Separated controller:
  - RadTol in tunnel, for ARCs ;
  - standard in service areas, for LSS)
- 24V, 48V or 72V; I < 10A; Frequency from 0 .. 1000Hz
- Pfeiffer HiPace300 + TCP350 (LSS+DS)
- Alcatel ATH300i + ACT250R (ARCs)

PLC-based

- S7-300 PLC used for the process control
- I/O signals to control the turbo controller + valves
- Connected to the master PLC as a slave PLC



Pumping Group Control Logic



Simplified VPG Control Process

1. Turn on Primary Pump (**VVP**).
2. Once VPP reaches nominal state, open intermediate valve (**VVI**)
3. Wait a fixed time for VPP to provide the required backing pressure and turn on the Turbo Molecular Pump (**VPT**)
4. Once VPT reaches nominal speed, enable the manual opening of the gate valves (**VVR1** and **VVR2**)
5. Manually open **VVR1** or **VVR2** to start pumping the volumes
6. Leak Detection with a Residual Gas Analyzer may be performed through valve **VVD**

Interlocks and Venting

1. In case of problems, valves **VVR1** and **VVR2** are automatically closed and interlocked to avoid accidental venting
2. Once the valves are closed, **VPT** and **VPP** are turned off and venting valves **VVP** and **VVT** are temporarily open to vent the pumps

Mobile Pumping Groups

Temporary pumping is performed by mobile pumping groups

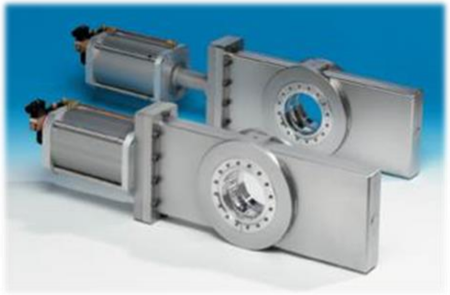
- Mobile & self-contained turbo-molecular pumping groups with all required components
- Connected to the Profibus network in the tunnel
- On-board PLC based control (S7-200, being upgraded to S7-1200)
- Integrated in the Vacuum SCADA using Profibus
- Control and monitoring locally (touch panel) or remotely (SCADA)

Mobile Bake-out Racks

The Bake-out process is managed by mobile Bake-out Racks

- Self-contained, compact and mobile solution
- PLC based (S7-300) , fully designed in-house
- 24 controllable bakeout channels
- Type-E thermocouples for temperature measurement
- PID control for the temperature regulation loops
- Actuation of the heating elements using solid state relays
- Integrated in the Vacuum SCADA using Profibus (available in the tunnel)
- Control and monitoring: locally (touch panel) or remotely (SCADA)

Sector Valves



Sector valves controlled by CERN-designed electronics

- Europa crate which can control up to 8 valves
- Up to 4 crates can be chained together to control a maximum of 32 valves
- Each valve is controlled by an individual CPLD-based card, providing basic functionality
- The crate communicates with the PLC through a parallel data bus, using a custom protocol
- All interlocks are implemented within the crate and cards, and thus independent of the PLC

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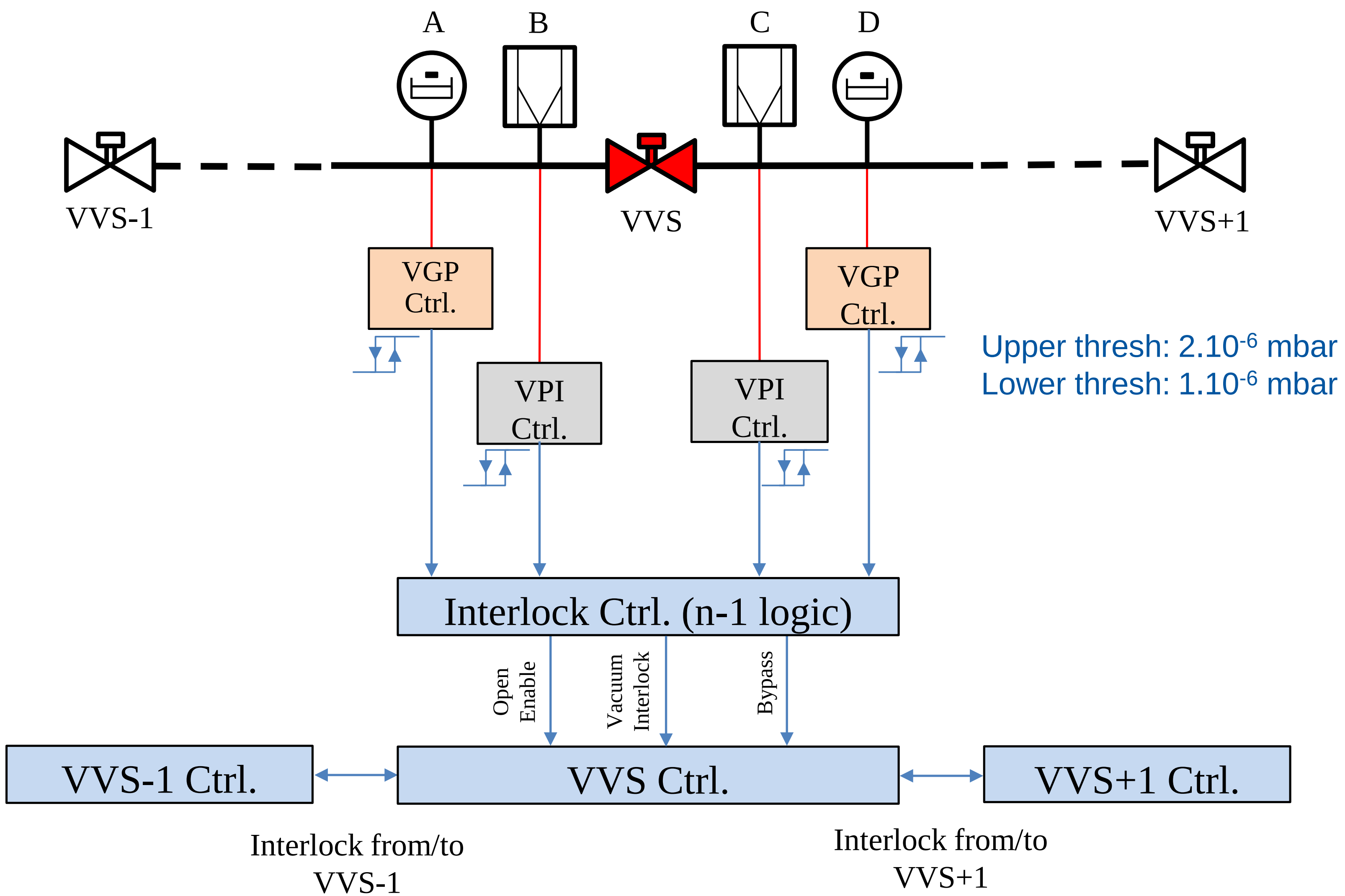
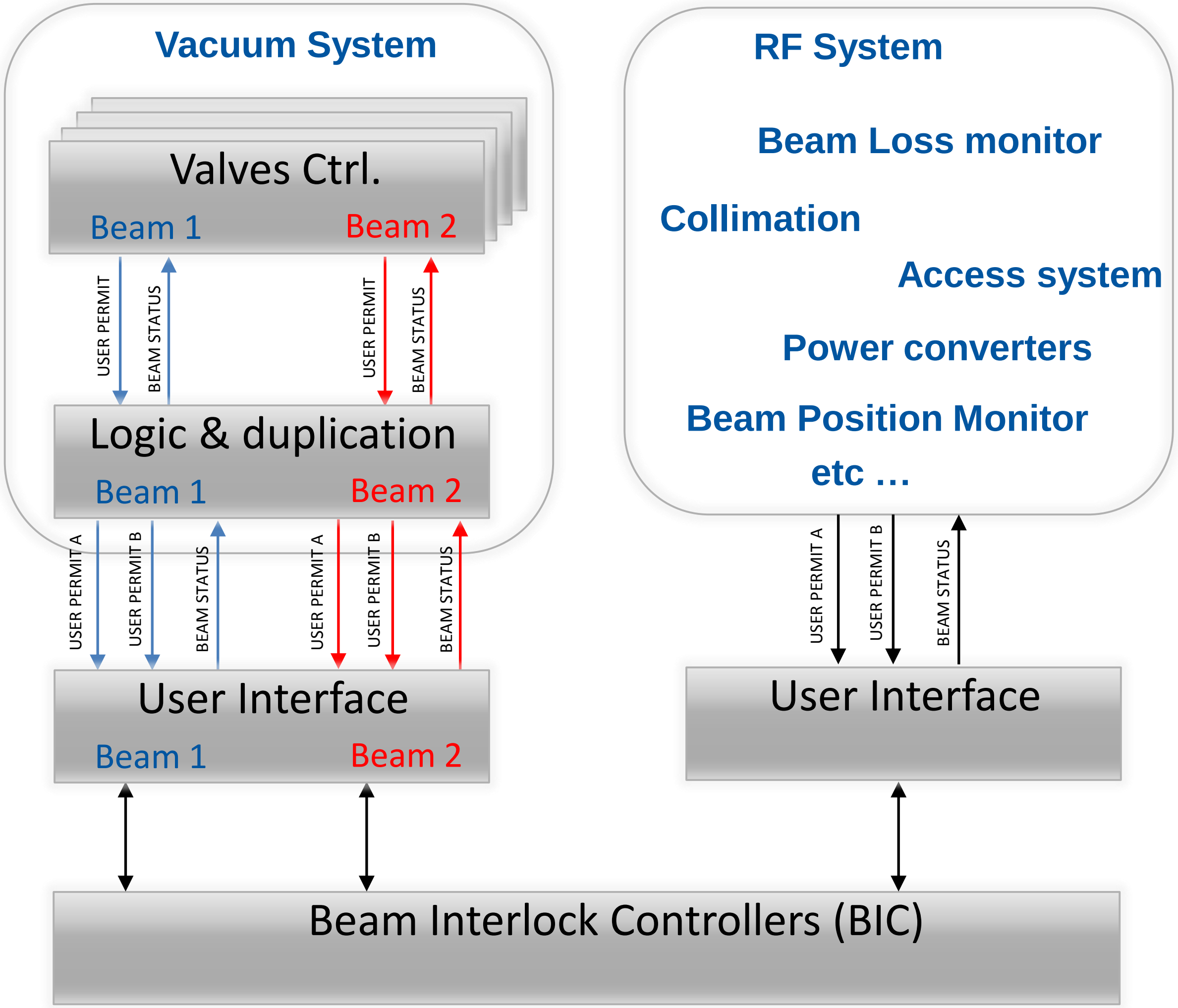
Sector valve Interlock chain (LHC)



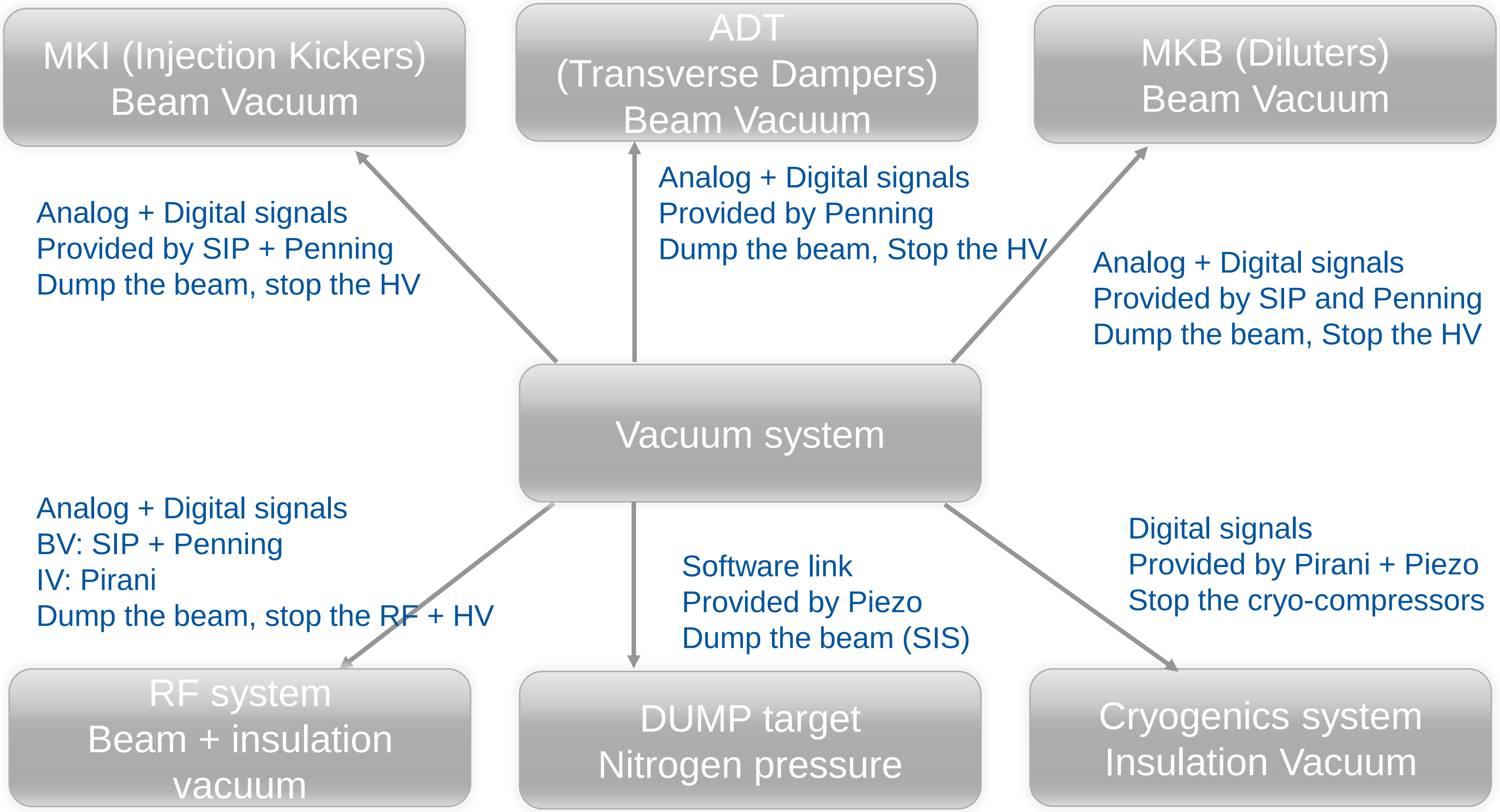
Interface to the Beam Interlock System

Direct beam dump request

- Pressure interlock
- Valve in a not-open position
- Vacuum system protection
- Machine protection



Interface with the other systems



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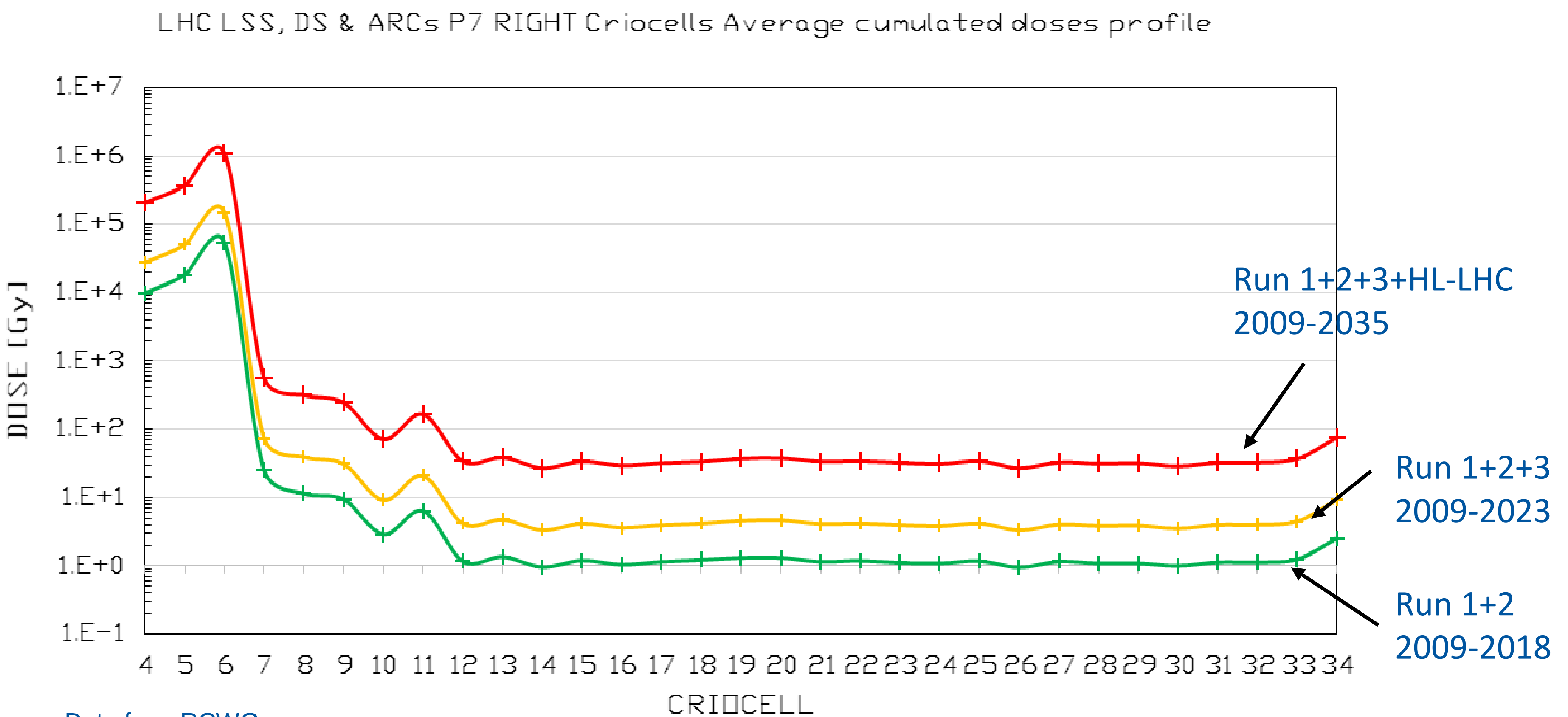
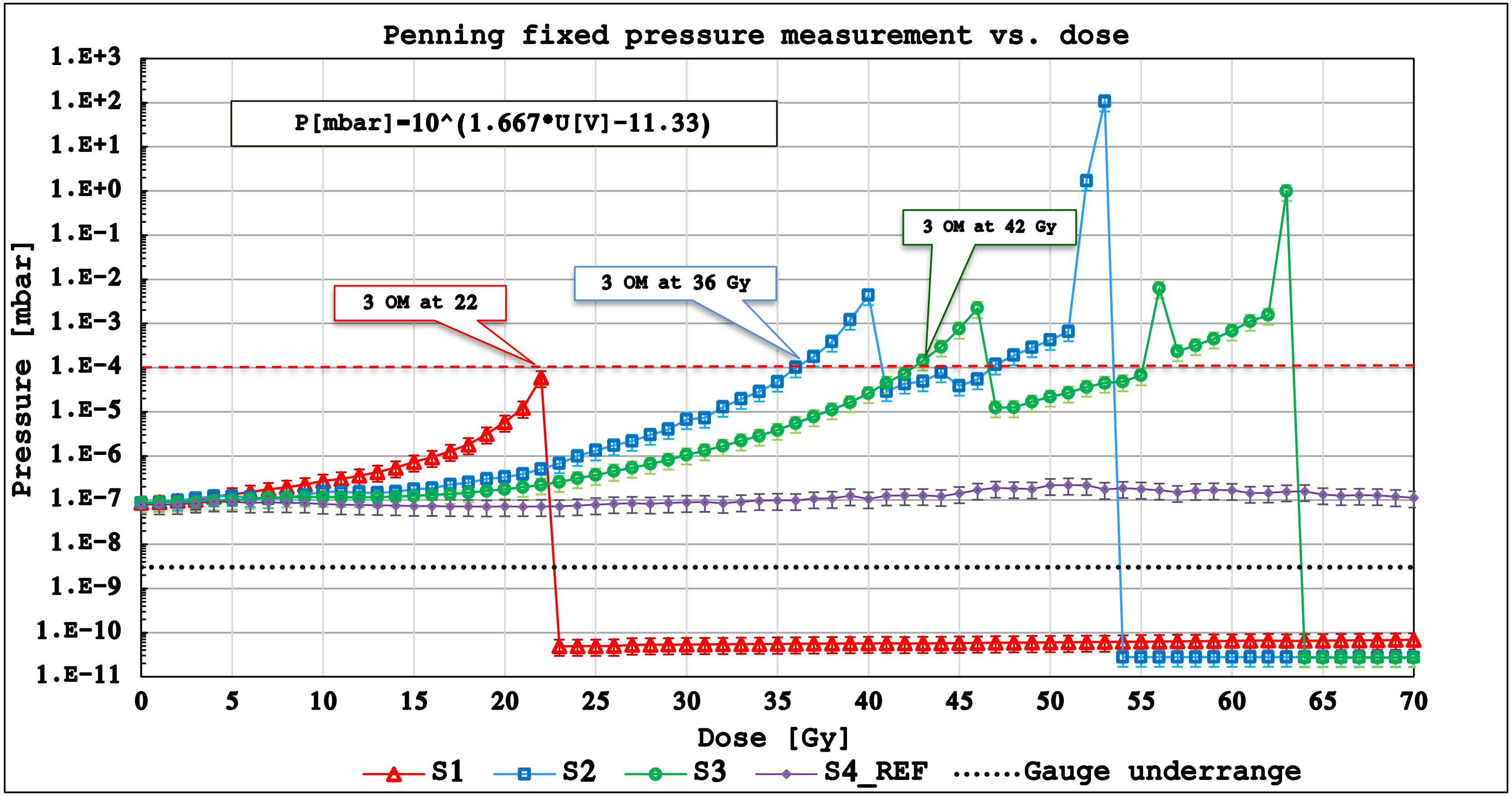
Radiation conditions

- Higher beam energy (was 3.5 TeV), now 6.5 TeV per beam, foreseen 7 TeV
- 25 ns operation (was 50 ns), now higher beam gas interactions
- Ion runs have high impact on TID (Total Ionizing Dose)
- **HL-LHC**: integrated luminosity will increase by a factor of 10 (from 300 to 3000 fb^{-1})
- Increase of luminosity will increase the TID in the LHC



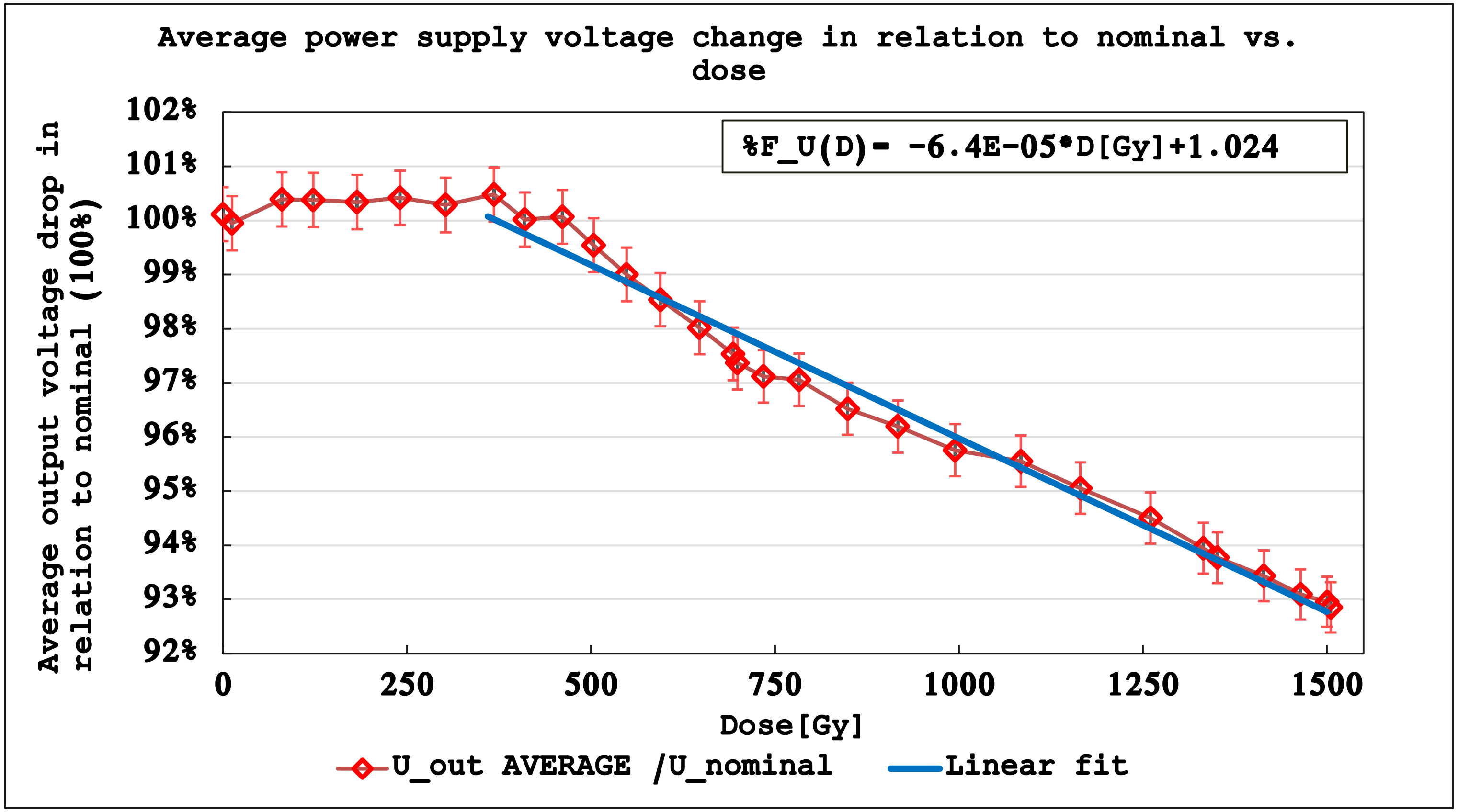
Data from RCWG

Radiation effect on Penning electronics



- Strong radiation-induced effects already at **15 Gy:** pressure readout 10x the non-irradiated reference
- At the end of the gauges lifetime under radiation: pressure readout 10 000x the non-irradiated reference
- First gauge stopped working at **22 Gy** and none survived more than **60 Gy**

Radiation effects on local PS for VPGF



- After 350 Gy, there is supply voltage drop of 7% / kGy
- Vmin to maintain valves open varies between 15-20 volts and depends of several parameters (age of the valve, mechanical stress, compressed air pressure, etc.)
- Drop of 20% in 3 years in some critical areas (IT): risk of closing pumping group valves

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Radiation tolerant electronics

Gauges

- Design a new radiation-tolerant conditioning circuits of all 3 gauges (Penning, Pirani, Piezo), able to stand cumulated dose beyond 2035

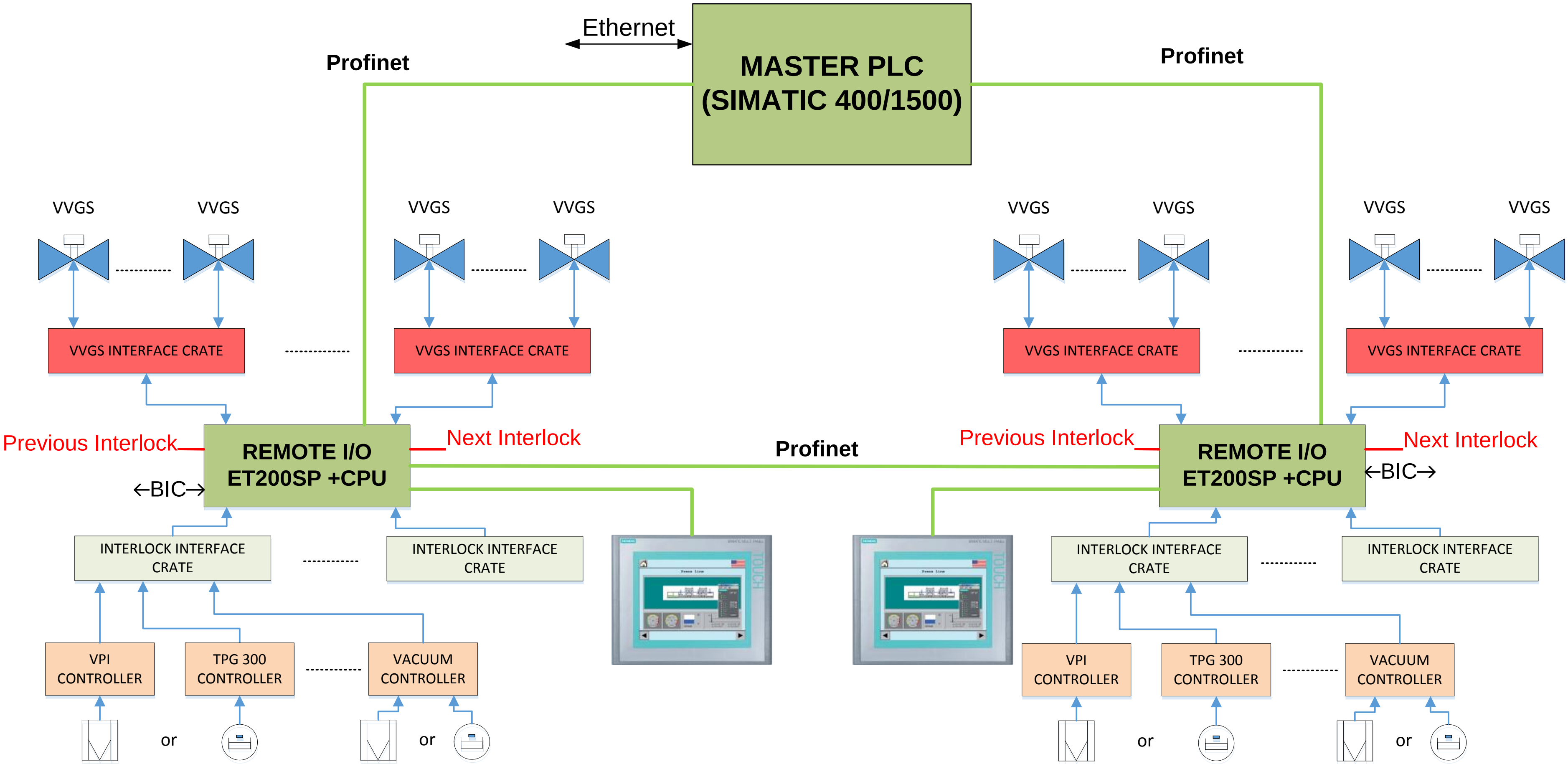
Active gauges	Penning #	Pirani #	Piezo #
DS (LS2)	16	16	48
ARC (LS3)	324	324	120

- Other issues not related to Radiation:
  - 4-20 mA signal transmission
  - Improved Pirani calibration circuit
  - Flexible design for different type of gauges
  - Modular and accessible to improve intervention time

Fixed pumping groups

- Remove completely electronics from local powering crate in the LSS areas
- Additional electromechanical devices, such as remote control of thermal relay and passive current measurement for the primary pump shall be included in the modified local crate to improve remote intervention

PLC-based Sector valves & Interlocks controls



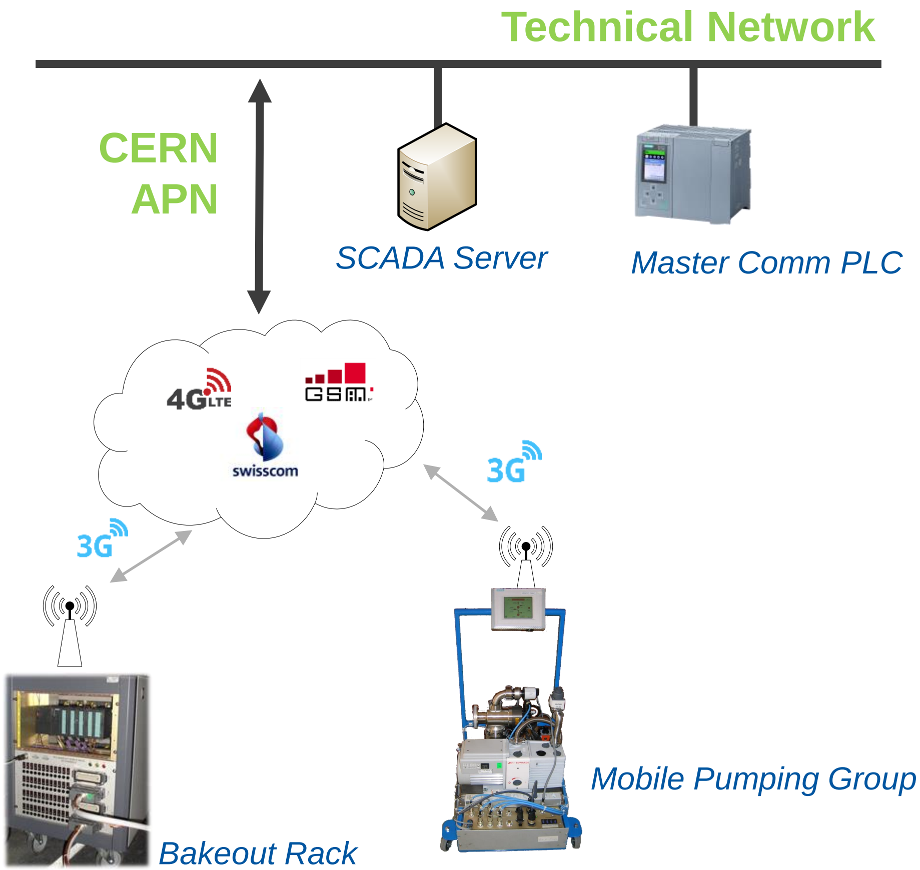
Networks for Mobile Communications

Profibus

- A Profibus network is permanently installed in the tunnel for the connexion of mobile devices to the master PLC
- Address conflicts due to large number of devices and limited number of addresses per network
- Wrong connection often bring down the whole network
- Wear and tear of the physical network components (connectors and cables)

Wireless – GPRS/3G/LTE

- A leaky feeder antenna already provides GPRS/3G/LTE connectivity in all the accelerator tunnels
- A wireless communication method for mobile devices is being developed based on this technology



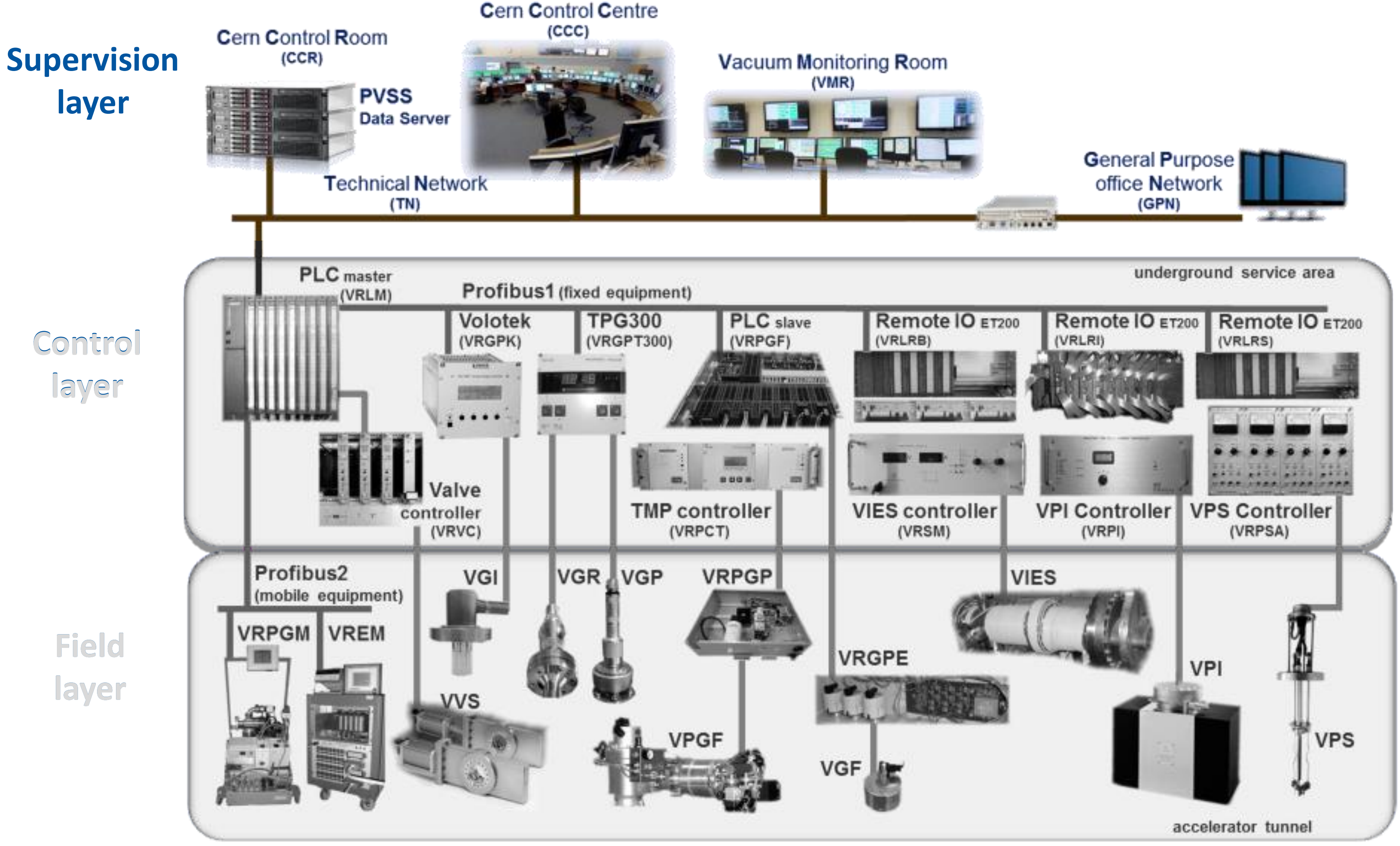
Part 1: Field and control layers

- Vacuum Controls architecture
- Gauges & controllers
- Low current measurement
- Pumps & controllers
- Hardware interlocks & alarms
- Example of radiation effects on Vacuum electronics
- Future trends & developments

Part 2: Supervision layer

- SCADA
- WinCC-OA architecture
- Configuration of a large control system
- Vacuum Functionalities
- Applications, servers and networking
- Enterprise Asset Management

Vacuum controls architecture



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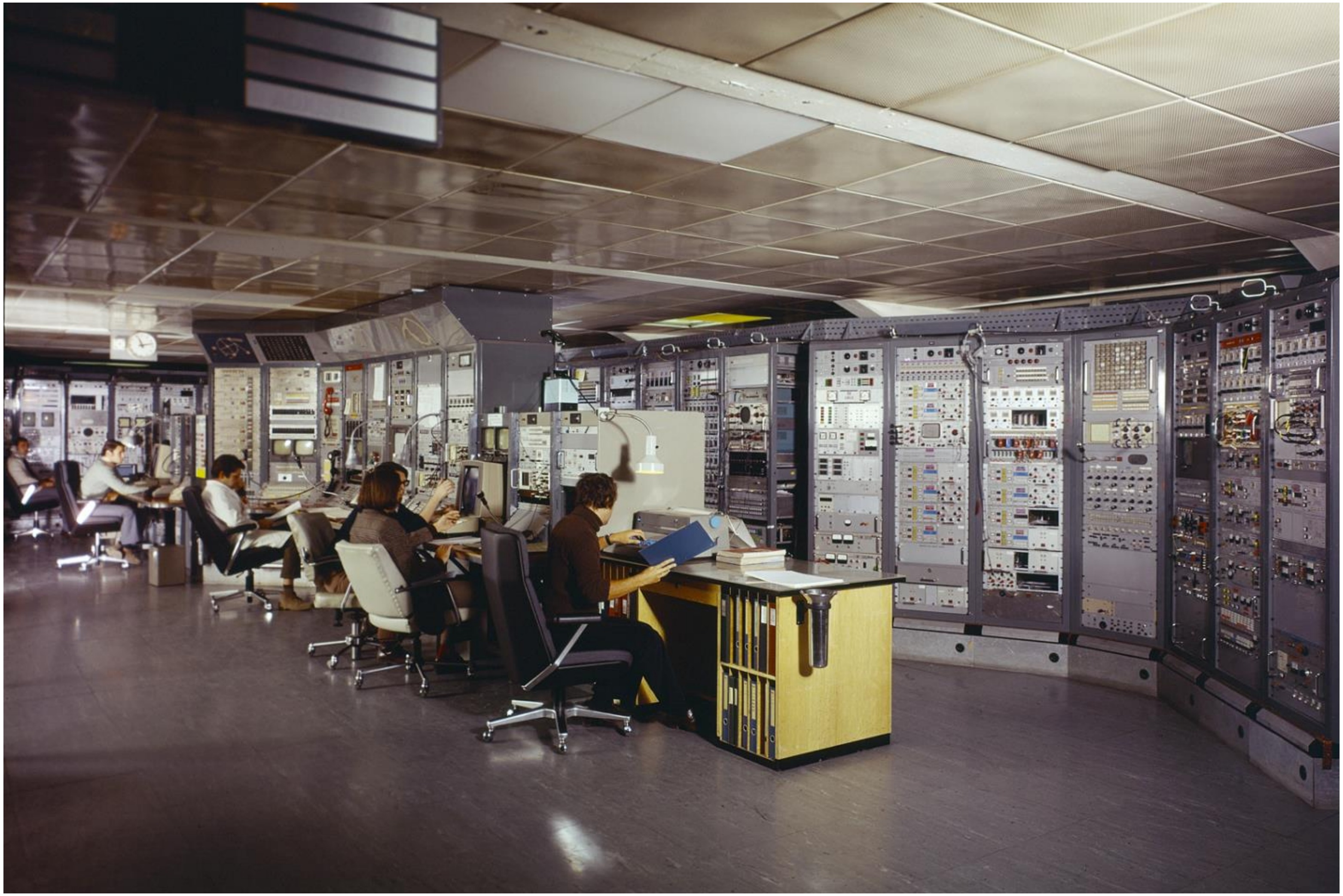
Supervision Layer



The Proton Synchroton Control Room – 1974 – Copyright CERN

Supervision Layer

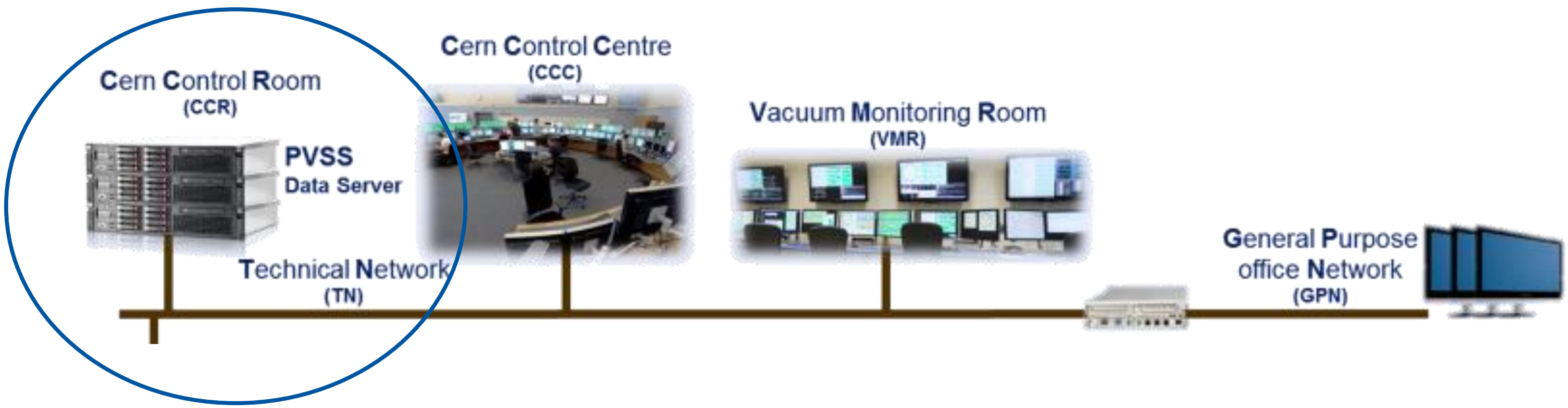
CERN control centre (CCC) – 2015 – Copyright Maximilien Brice/CERN

SCADA

What is SCADA ?

Supervisory **C**ontrol **A**nd **D**ata **A**cquisition – Software that:

- Communicates in real-time with controllers running the vacuum process
- Presents data to operators using a graphical user interface (GUI) in order to:
  - Check the process / react to alarms / interact with devices
- Archives historical data
  - Operators can check what happened in the past



CERN's vacuum SCADA is based on **WinCC-OA** (Open Architecture) from Siemens (former PVSS from ETM).

Choosing a SCADA system

Many other SCADAs are available. Examples:

EPICS - Experimental Physics and Industrial Control System (www.aps.anl.gov/epics/)

TANGO - (http://www.tango-controls.org/)

What are the factors to take into consideration when choosing a SCADA software ?

Openness

- How easy can custom features be built ?

Scalability

- How many devices can it handle ?
- How many users can it handle ?

Connectivity

- Which drivers does it support ?

Multiplatform

- Suitable for Windows and Linux users ?

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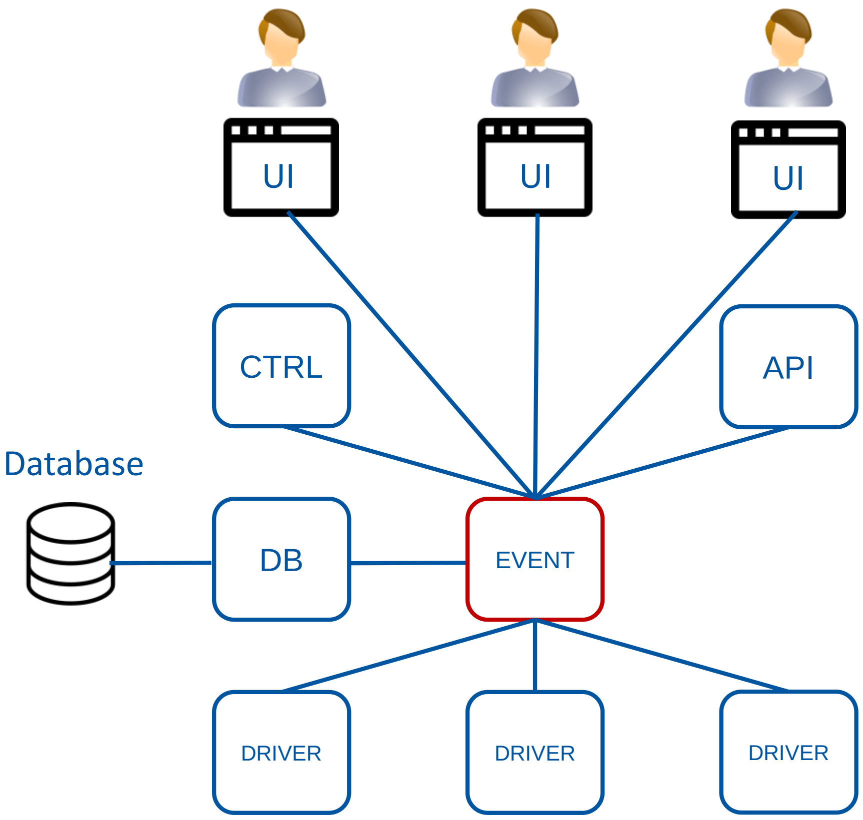
- ❑ Enterprise Asset Management

WinCC-OA Software Architecture

WinCC-OA is **modular**: each functionality is handled by a specific unit, called a manager.
The software architecture is built around the **Event Manager**:

- responsible for holding variable data in memory and distributing it to other managers.



User interfaces

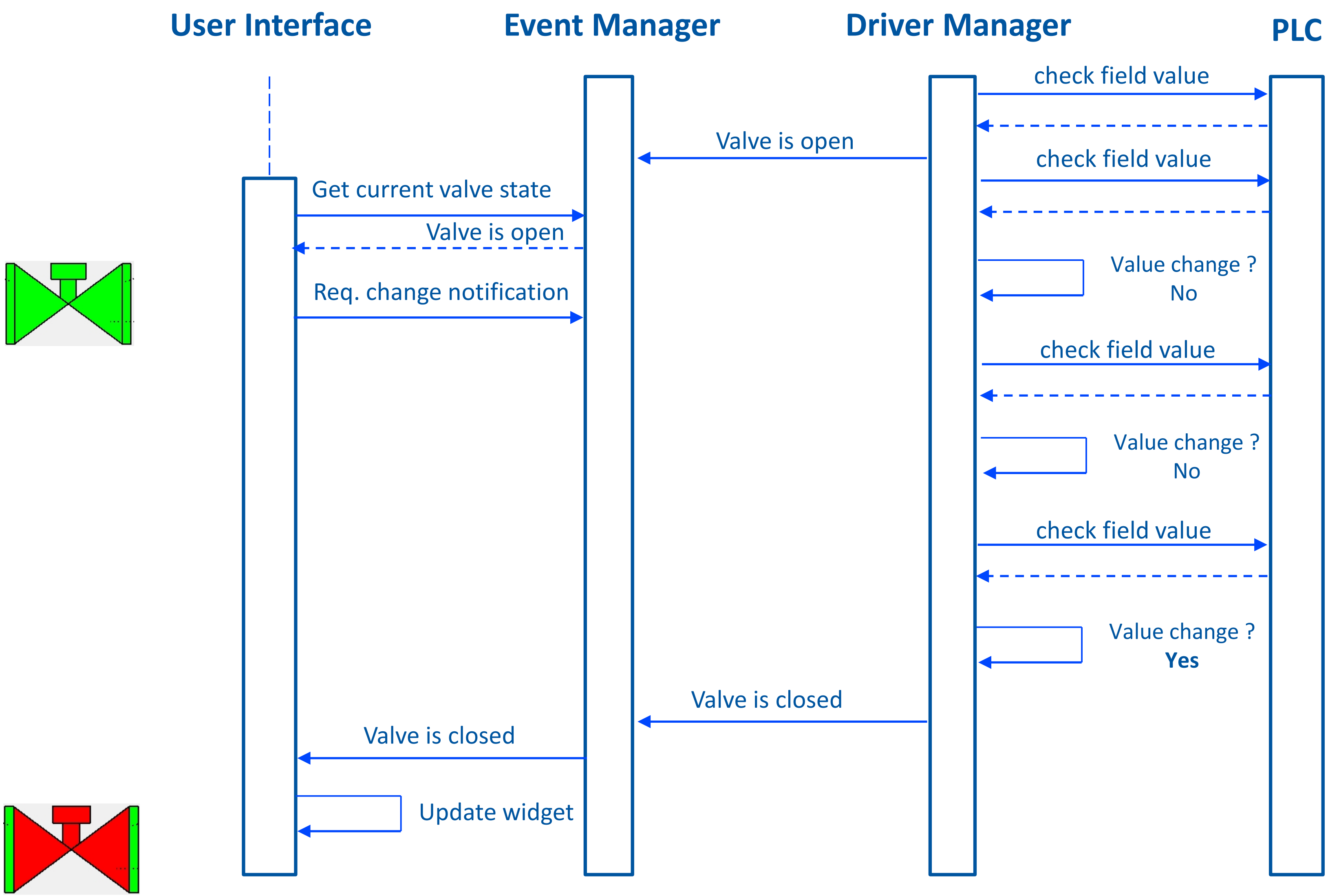
Control (CTRL) – Custom scripts (ex: SMS alerts)
Application Programmer Interface (API) – Interfaces with other systems

Process Image and History – provide current and past states of all variables

Driver Managers – handle the communication between the supervisory application and the PLCs

WinCC-OA Software Architecture

A practical example on data flow: what happens when a Valve changes state ?



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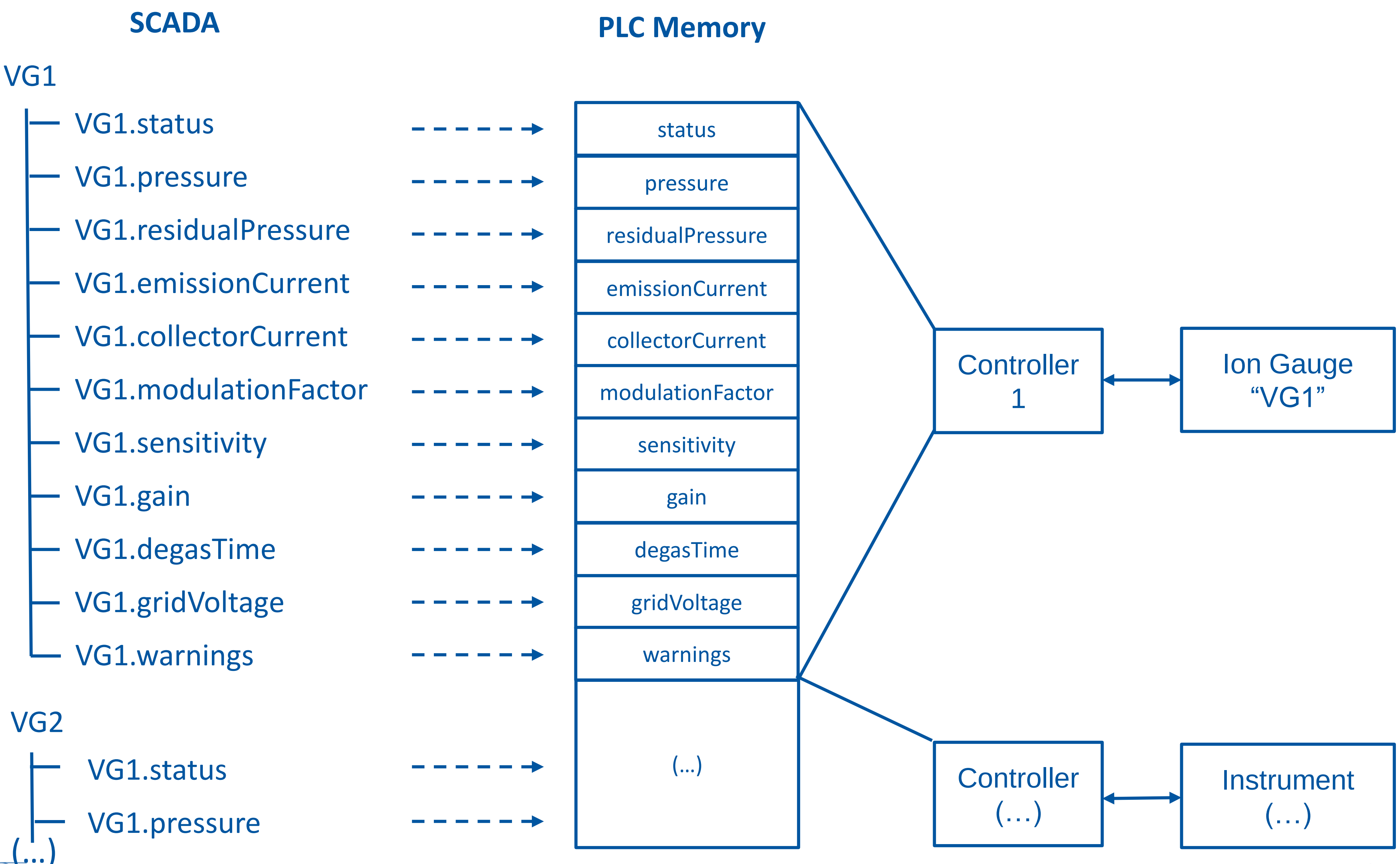
Control System Configuration

In theory, it can be done manually:

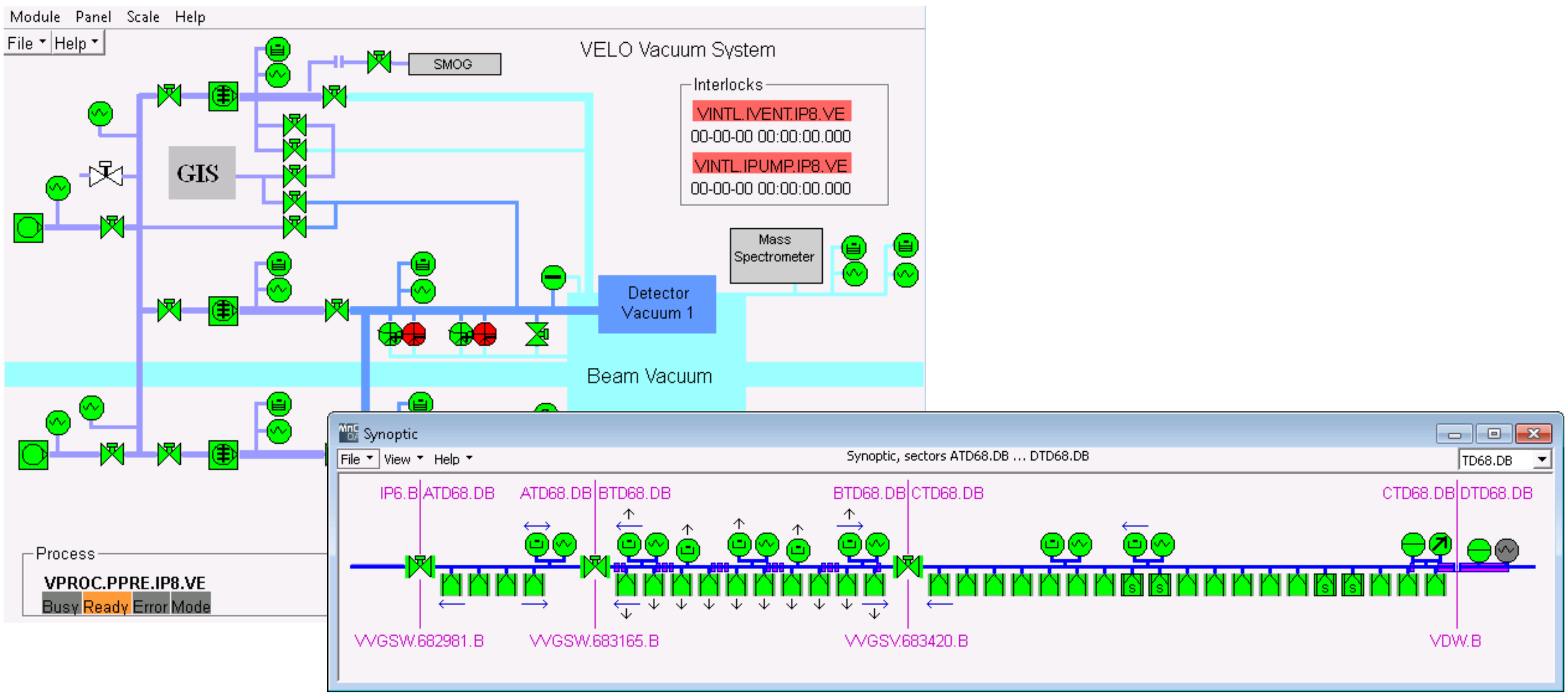


Control System Configuration

Other parameters need to be configured for each Datapoint:

- Archiving (short and long term archiving)
- Alarms
- Publishing to other services

Once the datapoints are all declared, panels (UIs) can be developed:



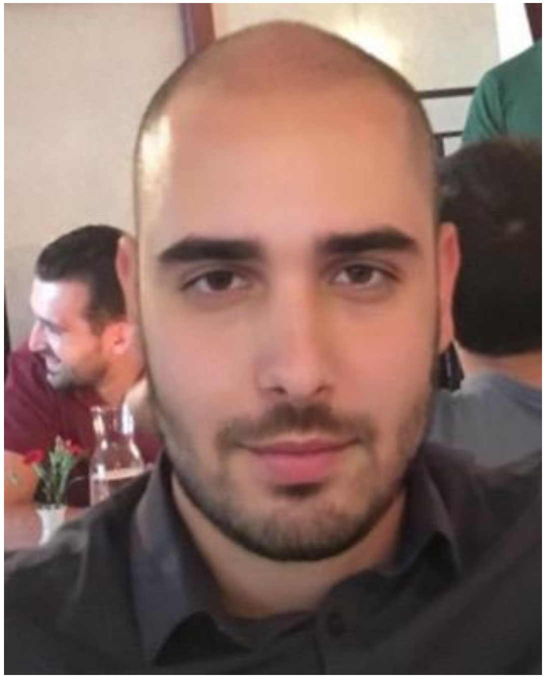
Control System Configuration

Why configuration cannot be done manually ?

On LHC alone there are nearly 92 000 vacuum datapoints and dozens of panels:

Just for the datapoints alone, If you were to configure all that manually

Datapoint 1

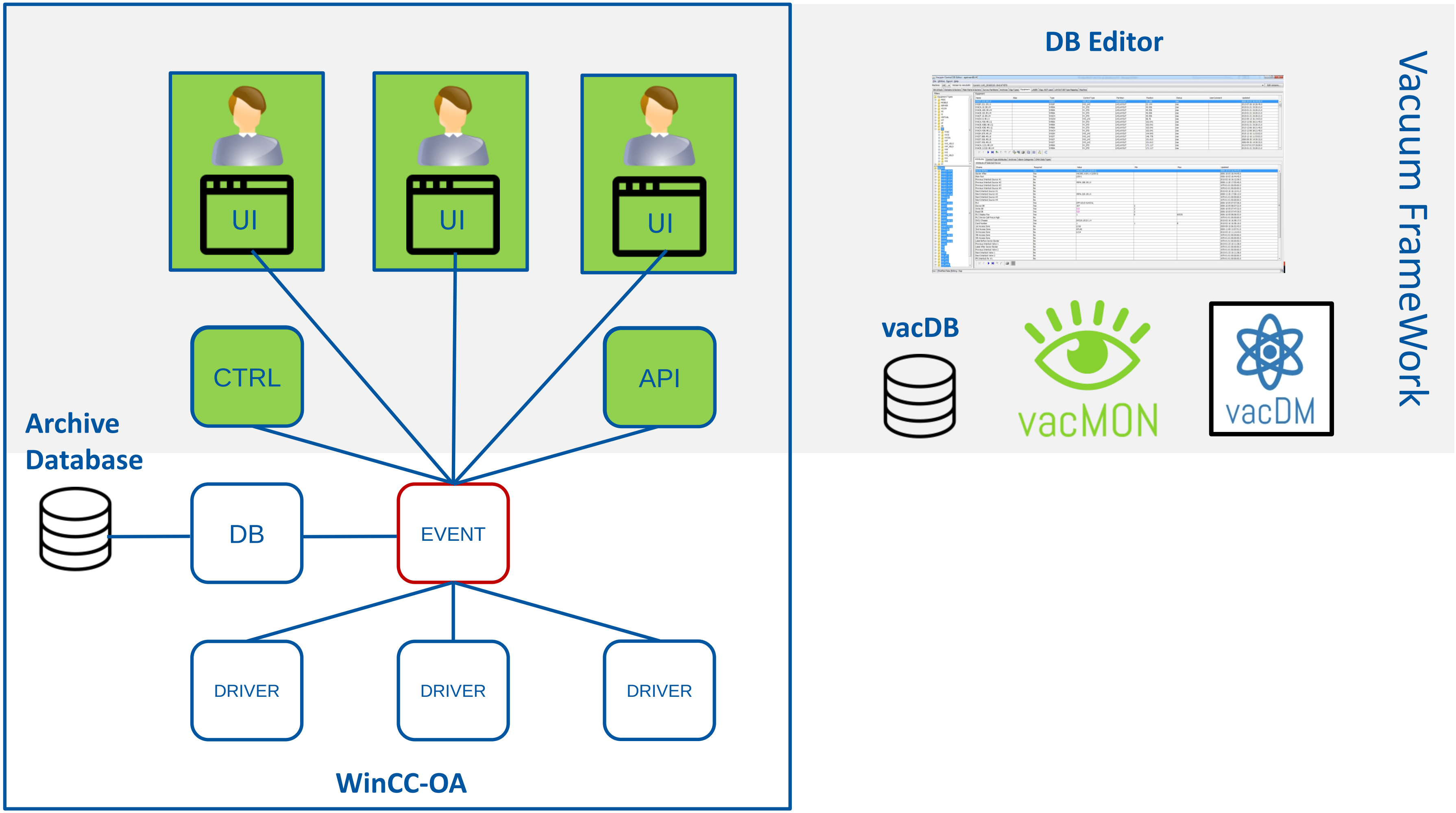


92000 datapoints later

Vacuum Framework (vacFW)

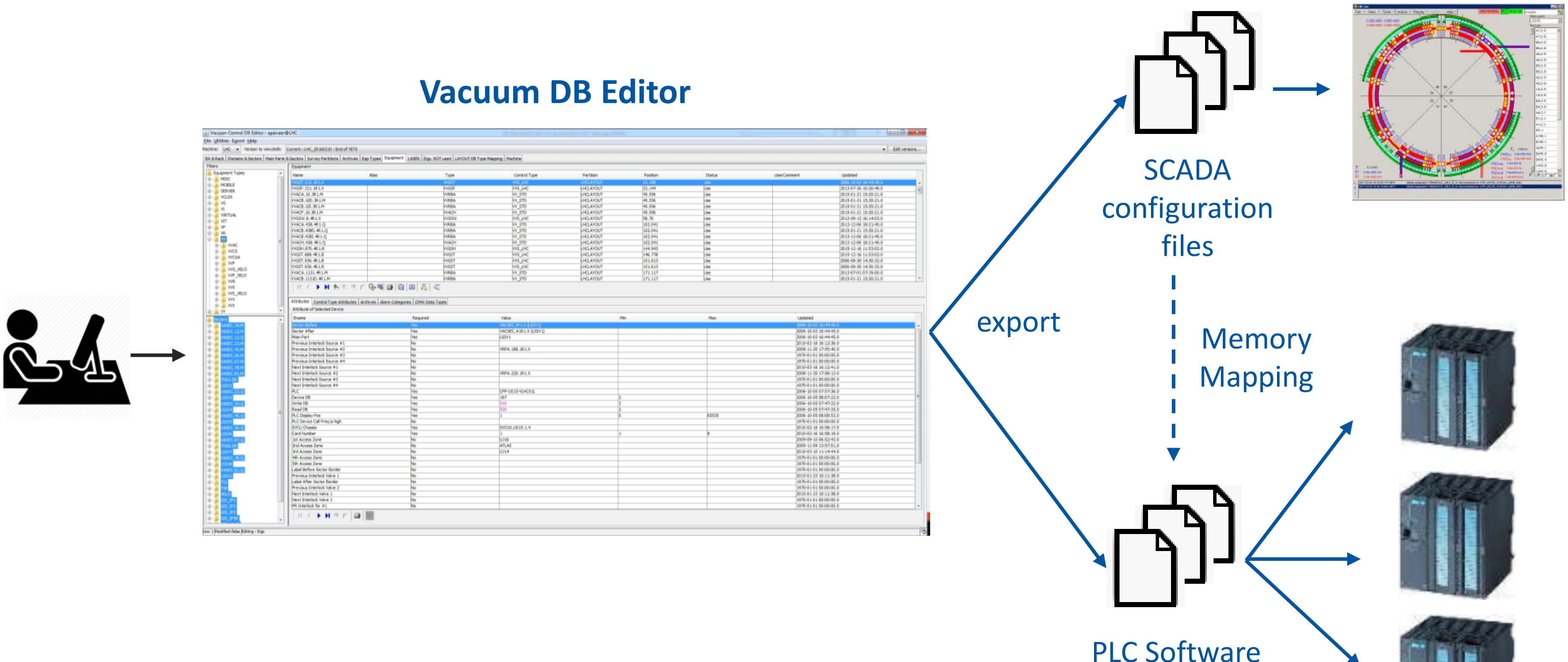
The vacuum FrameWork (vacFW):

- Automates configuration and synoptic building
- Provides vacuum functionalities on top of WinCC-OA



Control System Configuration

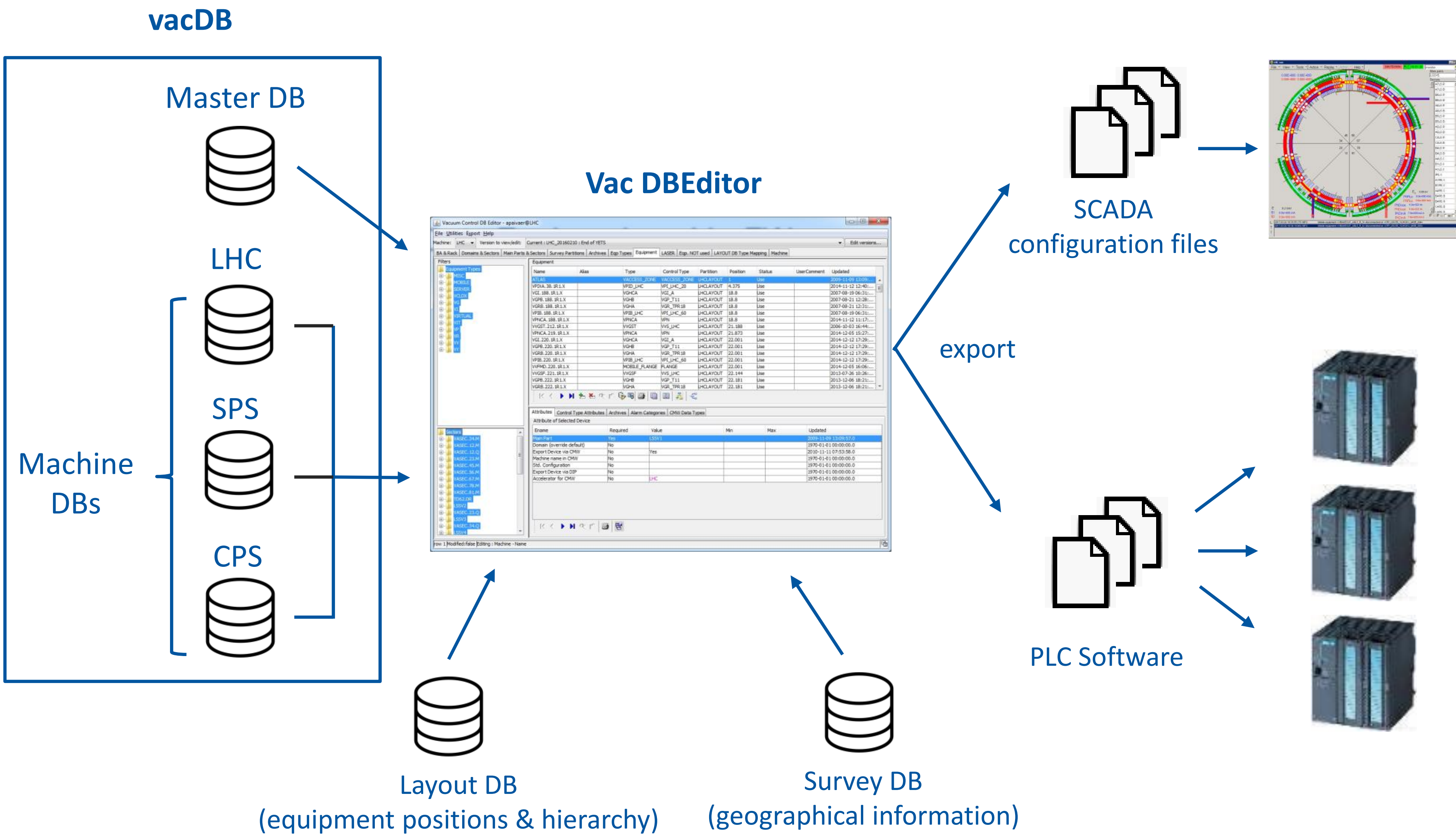
1. Users add, modify and remove equipment using the **Vacuum DB Editor**
2. Within the DB Editor, an Export software generates SCADA and PLC configuration files
3. SCADA configuration files are imported into the SCADA
4. PLC software is downloaded to PLCs
5. The PLCs will now communicate with new/modified devices and these will be displayed in the SCADA



SCADA and PLC memory mapping is done automatically by the DB Editor

Vacuum SCADA Databases

Behind the scenes, the Vacuum DB-Editor interacts with several databases, where the configuration data is stored.



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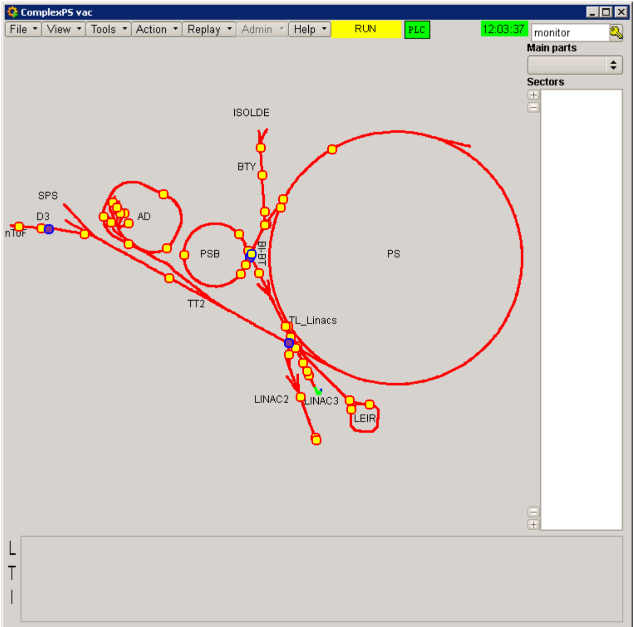
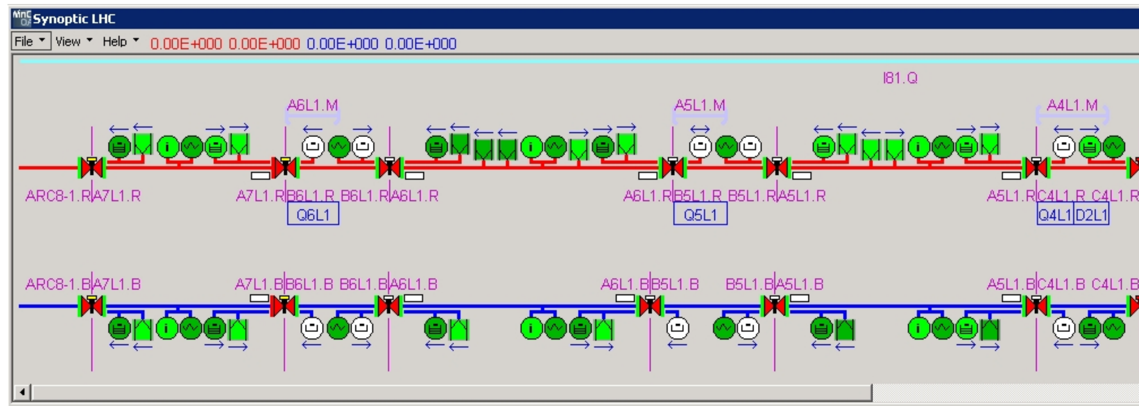
- ❑ Enterprise Asset Management

Functionalities of a Vacuum SCADA

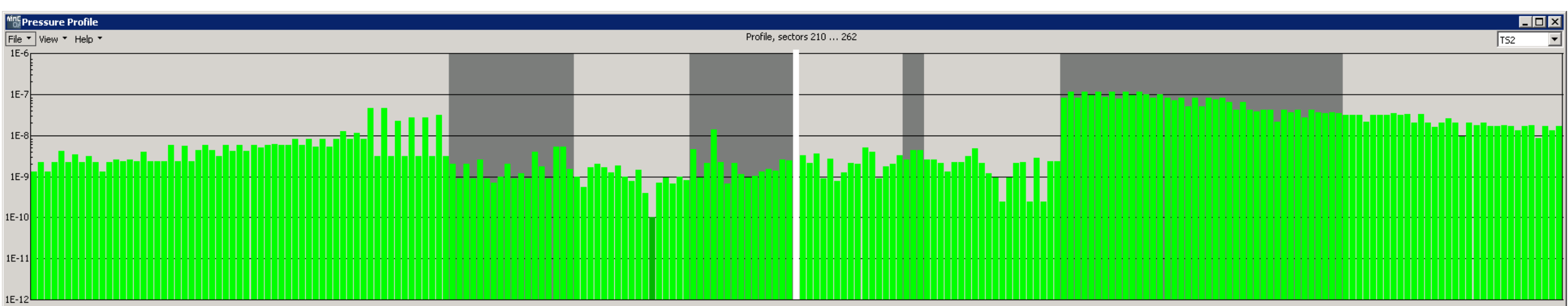
Automatic Drawing of Accelerator



Automatic Synoptic Drawing

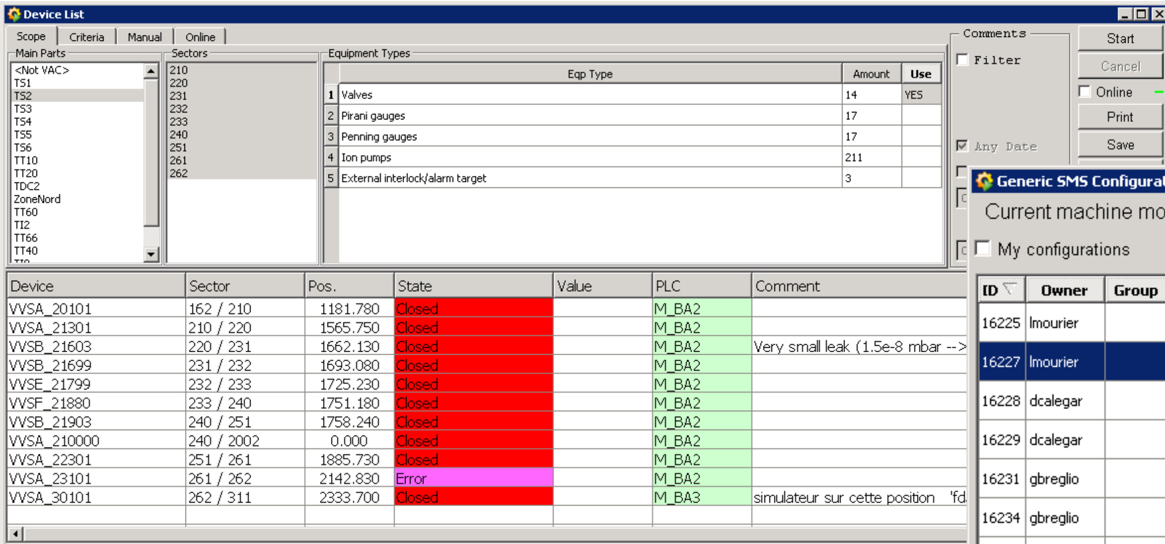


Pressure profiles

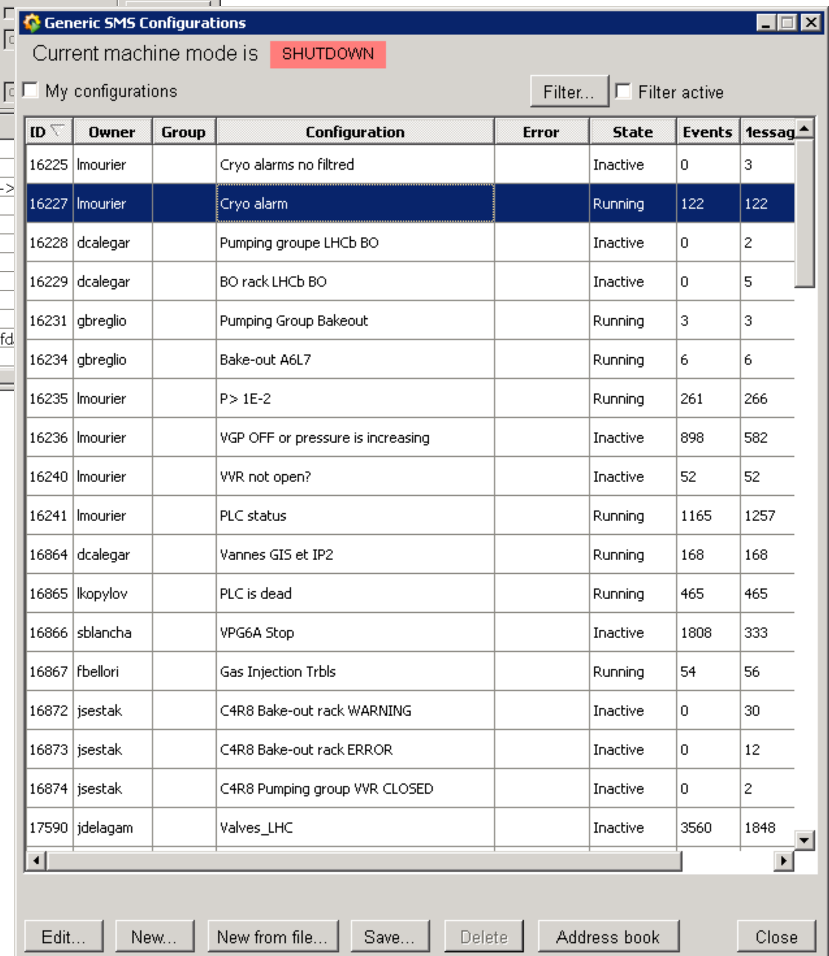


Functionalities of a Vacuum SCADA

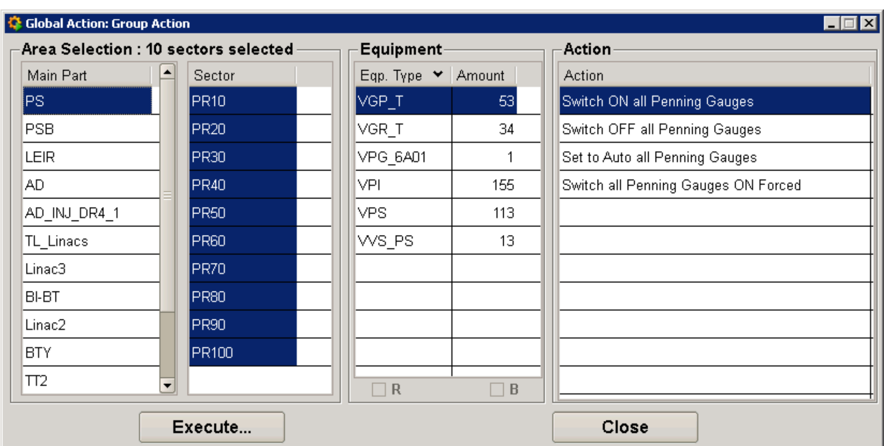
Device list



SMS Notifications

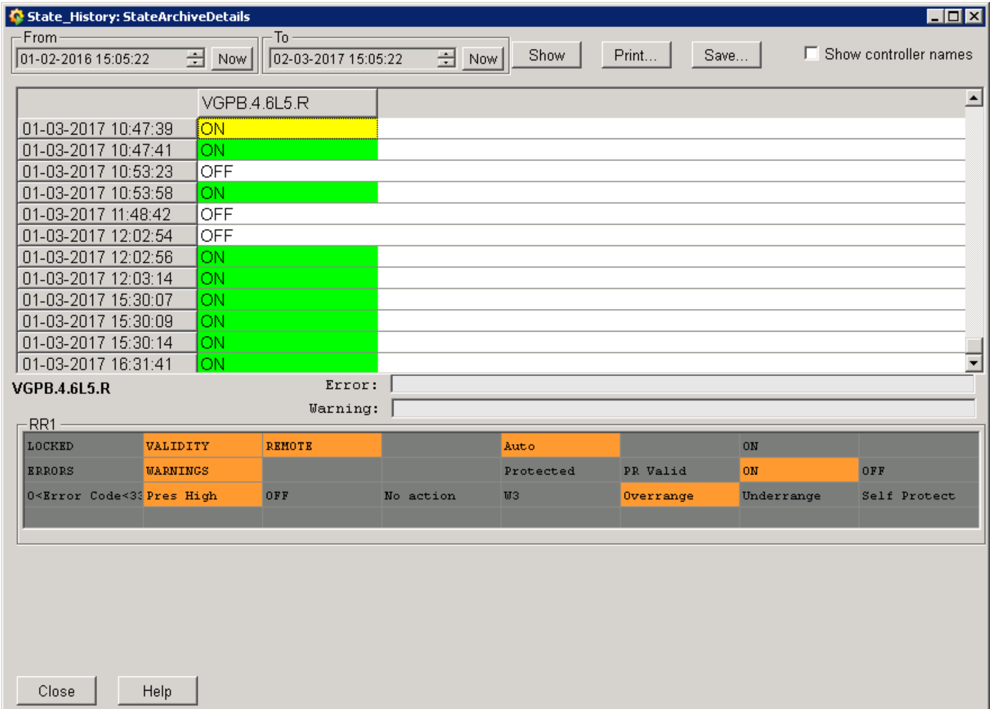


Global Actions

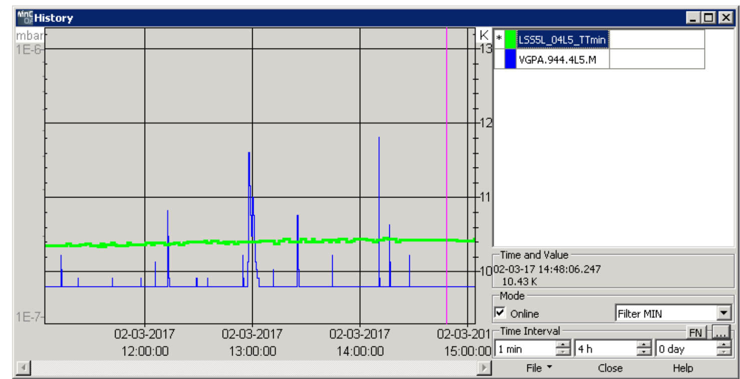


Functionalities of a Vacuum SCADA

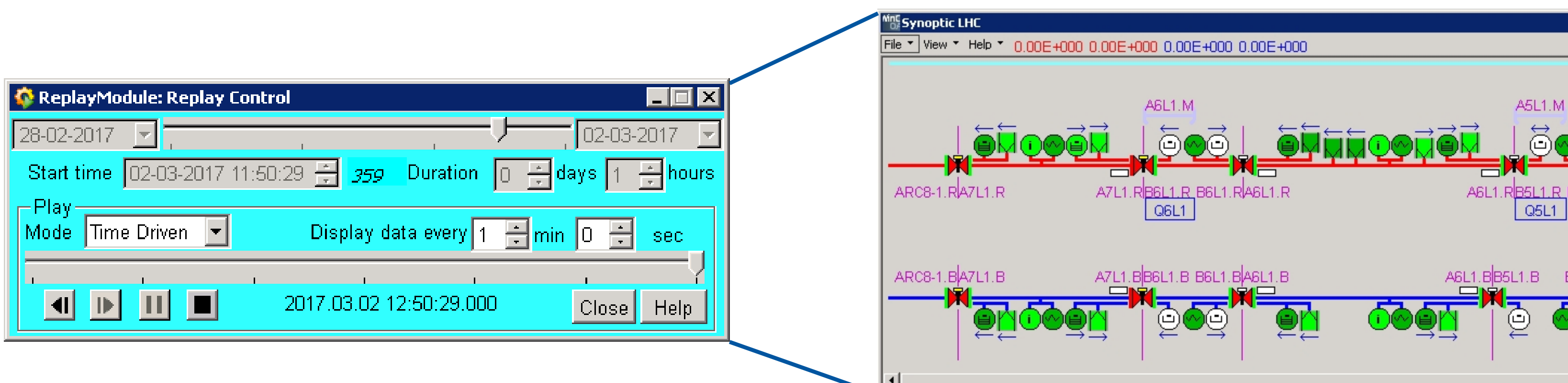
Equipment State history



Multi trend panel

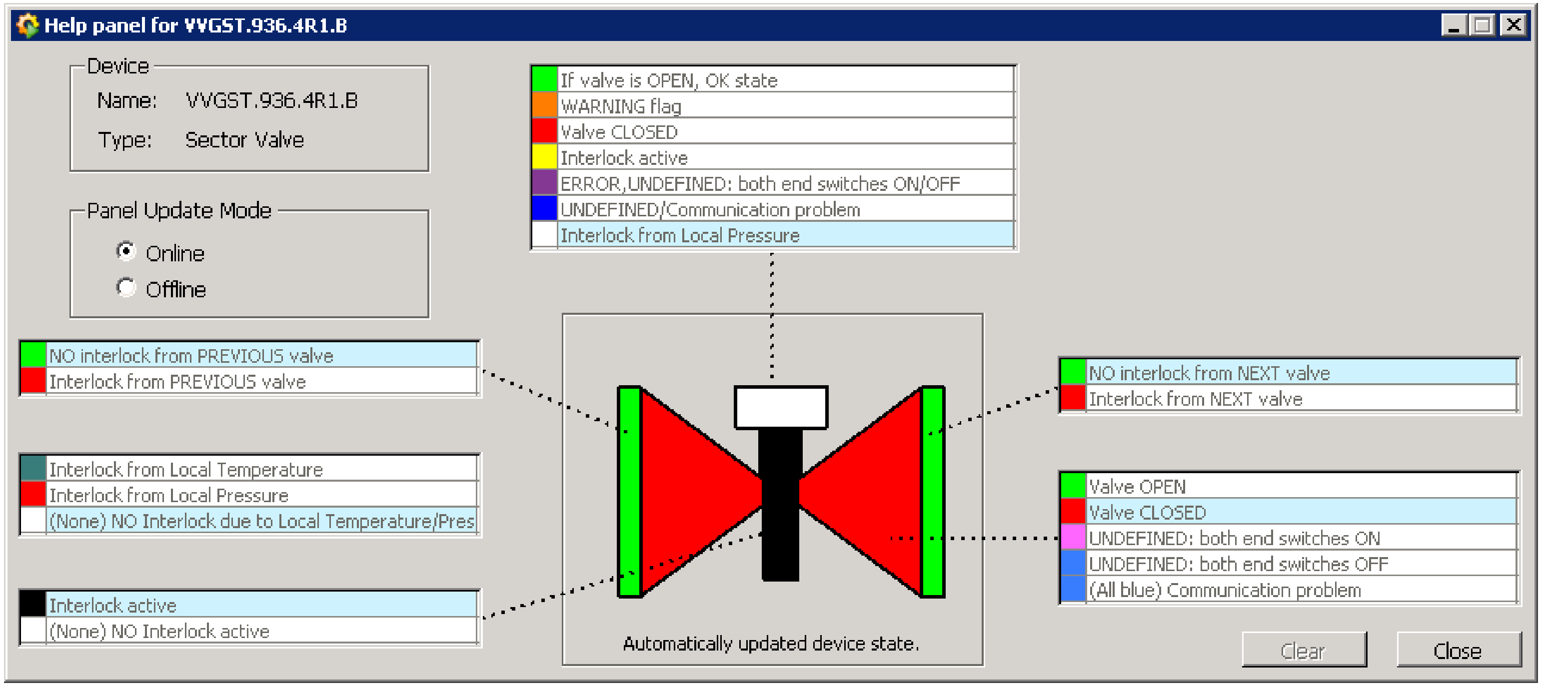


Replay



Functionalities of a Vacuum SCADA

Widget help panels

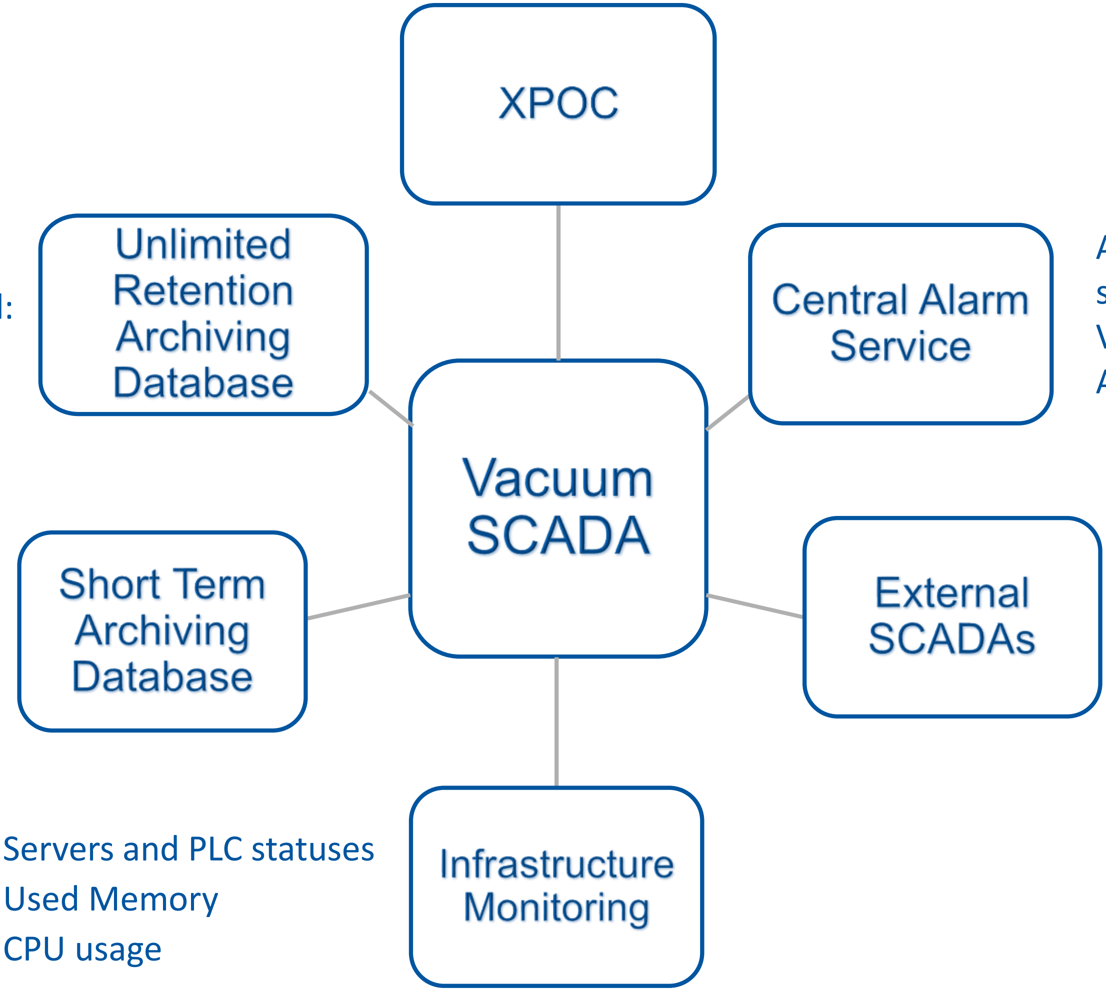


Sharing Vacuum Data

Vacuum pressures upon beam-dump

No archive data is deleted: slow

Alarms of all accelerator systems:
Vacuum, Cryogenics, Access Control, Magnets



Data retention period 1 year: fast

Cryogenics
Beam Instrumentation

Servers and PLC statuses
Used Memory
CPU usage

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SCADA applications and servers

Typically, each accelerator has a dedicated SCADA application

- Different accelerators = different schedules = different time windows for interventions/updates

Each application can run on a dedicated server, or share the server with another application.

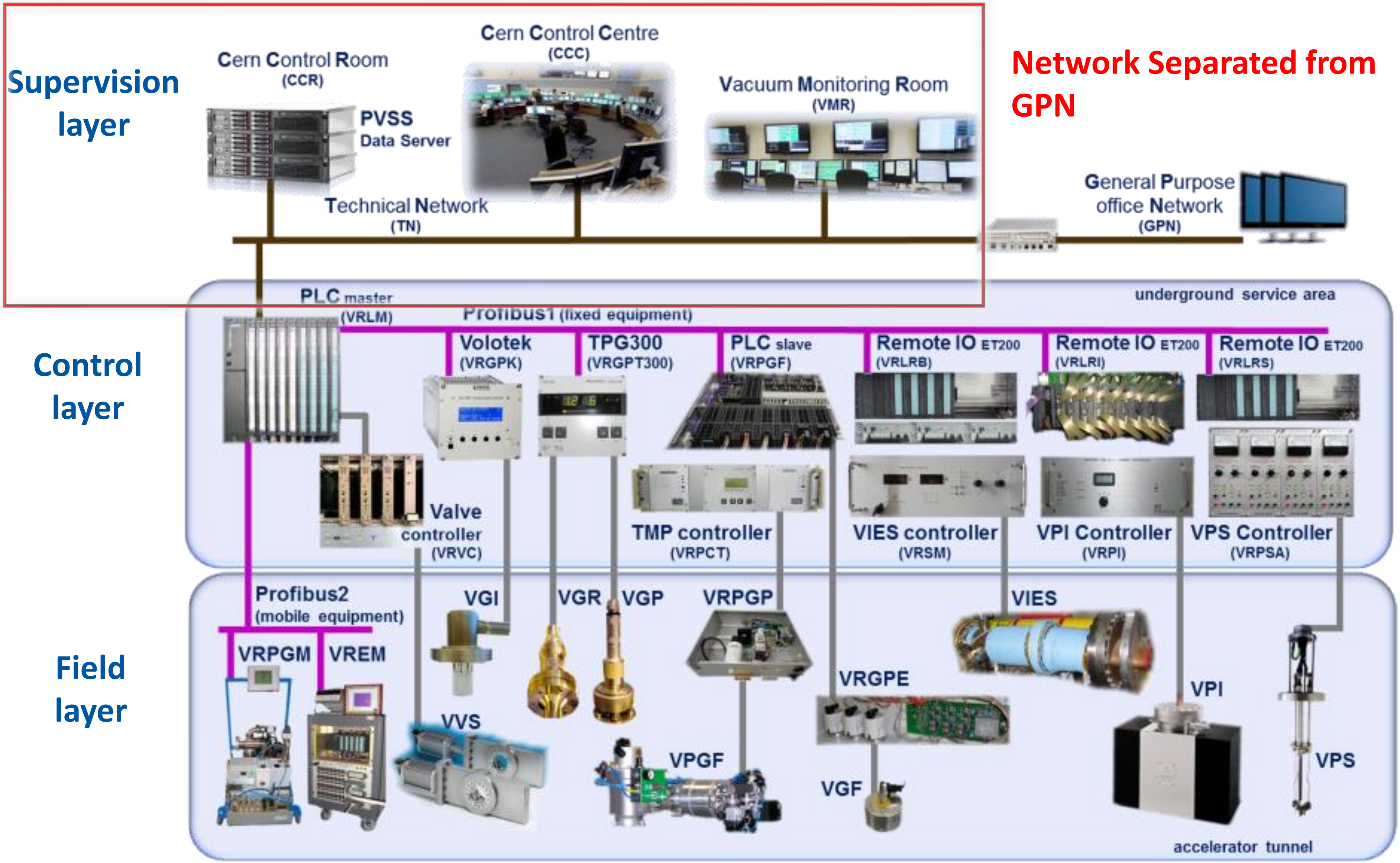
The distribution of applications between servers depend on the following factors:

- Expected load (number of devices / users)
- Criticality
- Cost

At CERN:

servers	**LHC**	**SPS**	**CPS**	**ISOLDE**	**Multi 1**
applications	LHC vac	SPS vac	CPS vac	ISOLDE vac REX vac HIEISL vac	HiradMat vac Linac4 vac NA62 vac

vac controls architecture



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ICALEPCS 2011 paper : http://accelconf.web.cern.ch/AccelConf/icalepcs2011/papers/mopms016.pdf

Supervision Layer - Networking

Why having a control system on a dedicated network is a good idea

Security

The potential damage that an unauthorized user can cause by accessing a vacuum control system is enormous:

- Activate NEG on atmospheric pressure – fire hazard – months of downtime
- Turning off vacuum gauges – causing beam dump
- Forcing ON penning gauges – equipment damage

To **minimize** the risk, the network should be designed to be directly inaccessible from outside the organization.

Performance

Network bandwidth is not shared with other services

Availability

Redundancy can be added to improve the availability of the network:

- Redundant switches
- Powering critical elements of the network with UPS

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- ❑ **Enterprise Asset Management**

Enterprise Asset Management

- Managing the lifecycle of equipment in a large installation is made easier by the usage of an **E**nterprise **A**sset Management system (**EAM**)

EAM

Equipment Management	Work Management	Stock Management
Equipment tracking: what do we have? where ?	Work dispatch creation of WorkOrders	Materials & Parts accounting how many? in which shelf?
Relationships between equipment	Work tracking: who did what? when ?	

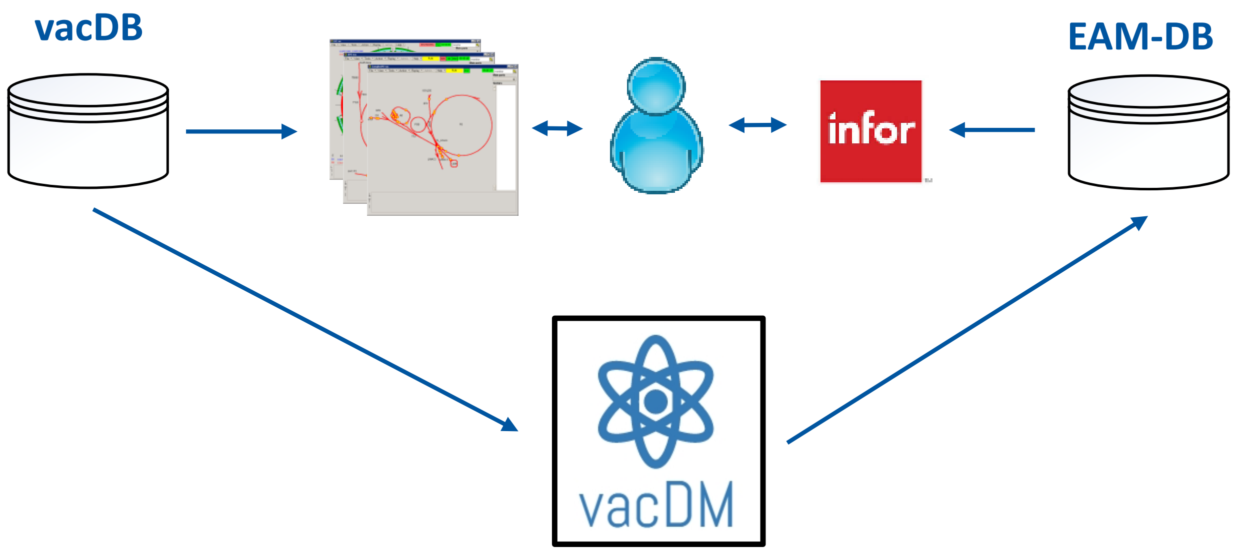
What does an Enterprise Asset Management system have to do with a control system ?

Enterprise Asset Management

The challenges:

- Equipment that users see on the SCADA might not be available in EAM
- Manual imports of equipment to EAM are **tim€** consuming and error-prone

Ensuring **continuous consistency** is of critical importance for the quality of data

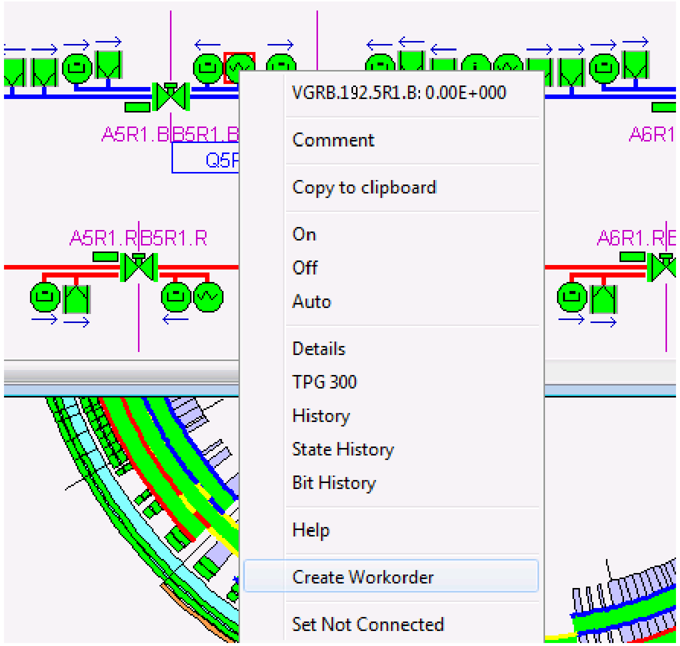


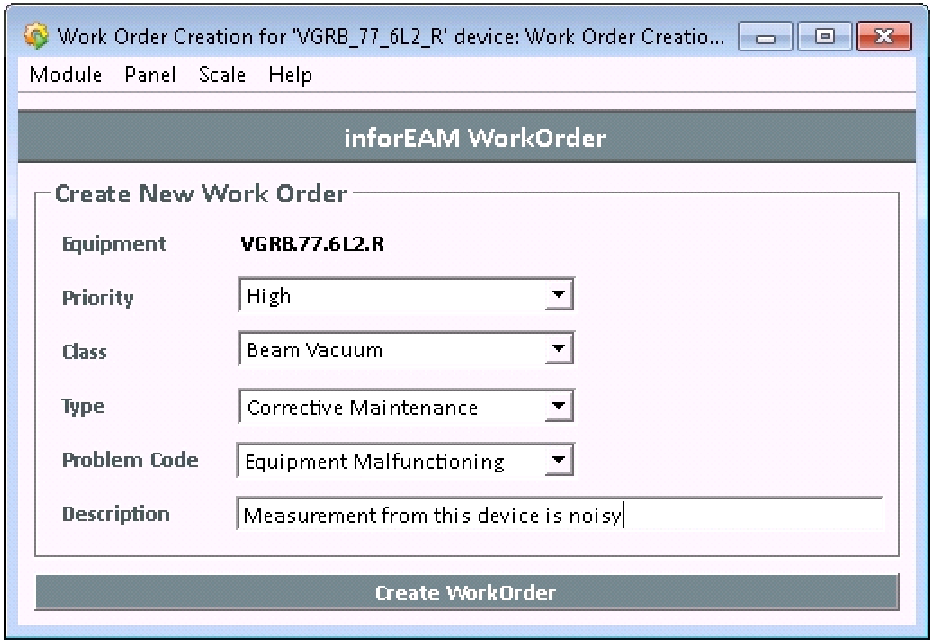
The solution:

Develop a tool that integrates the vacuum control system with the EAM system

Control System Integration with EAM

Users can generate WorkOrders directly from the SCADA





Other ideas:

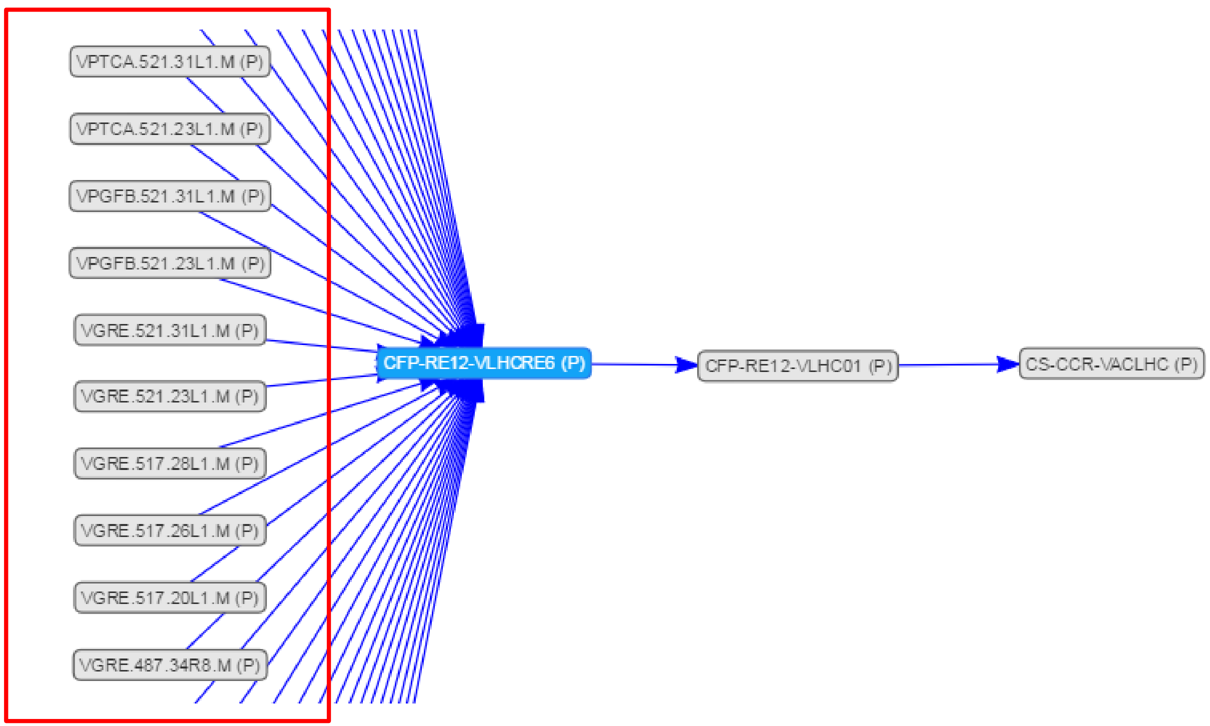
- WorkOrders can be automatically created when an alarm becomes active

Control System Integration with EAM

Users can see equipment relationships on EAM system.

Example of chain of control: gauge -> gauge controller –> PLC -> Dataserver

Equipment affected by intervention in a PLC:



Conclusion

- PLC-based architecture is well suited for vacuum controls
- Quality of connectors, grounding and cables are essential for reliable measurement
- For low current measurement (pA, fA), several external factors can strongly affect the results
- Interlocks and alarms must be reliable and tested extensively to assure the machine protection
- Electronics shall be tested under radiation before to be installed in radiation areas
- Wireless network can be used with mobile equipment to improve time intervention and cost

- Choose your SCADA software carefully
- If your control system is moderately large – automate configuration
- Distribute your applications between servers wisely
- Protect your control system by having your SCADA on a dedicated, secured network
- Enterprise Asset Management Software helps – specially if it is integrated with the control system

Thank you !

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