Leveraging PMU technology to monitor CERN grid infrastructure

KIVI Webinar, 16-04-2025

Project Overview

TOWARDS A MORE ENERGY-EFFICIENT AND SUSTAINABLE PATH

The RF2.0 partners envision a future where accelerators are designed, operated, and supplied with 100% renewable energy, ensuring secure and stable performance at any time. This approach aims to make operations nearly independent of the public power grid while significantly reducing environmental impact.

- Partners: 6 Accelerator Research Facilities, 4 High-tech SMEs
- 4 demonstrator projects
- Project duration: 1/2024-12/2026
- Budget: 5,6 Mio €
- EC Call: INFRA-2023-TECH-01-01

MAX IV · DESY · HZB Helmholtz Zentrum Berlin · Cryoelectra · KIT · Zaphiro · CERN · COMMTIA · ALBA · ELYTT ENERGY

Speakers

Isabel Amundarain Arguello

Electrical Engineer at CERN

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Product Development Manager at Eleq

Alice Maffezzoli

Sales & Business Development Manager at Zaphiro

Agenda

Project RF2.0 Overview
CERN contribution to Project RF2.0

Zaphiro and Synchroguard overview
PMU Technology
PMU Application at CERN for Project RF2.0

Eleq overview
ELEQ Contribution to Project RF2.0

RF2.0

Research Facility 2.0 – Towards a More Energy-Efficient and Sustainable Path

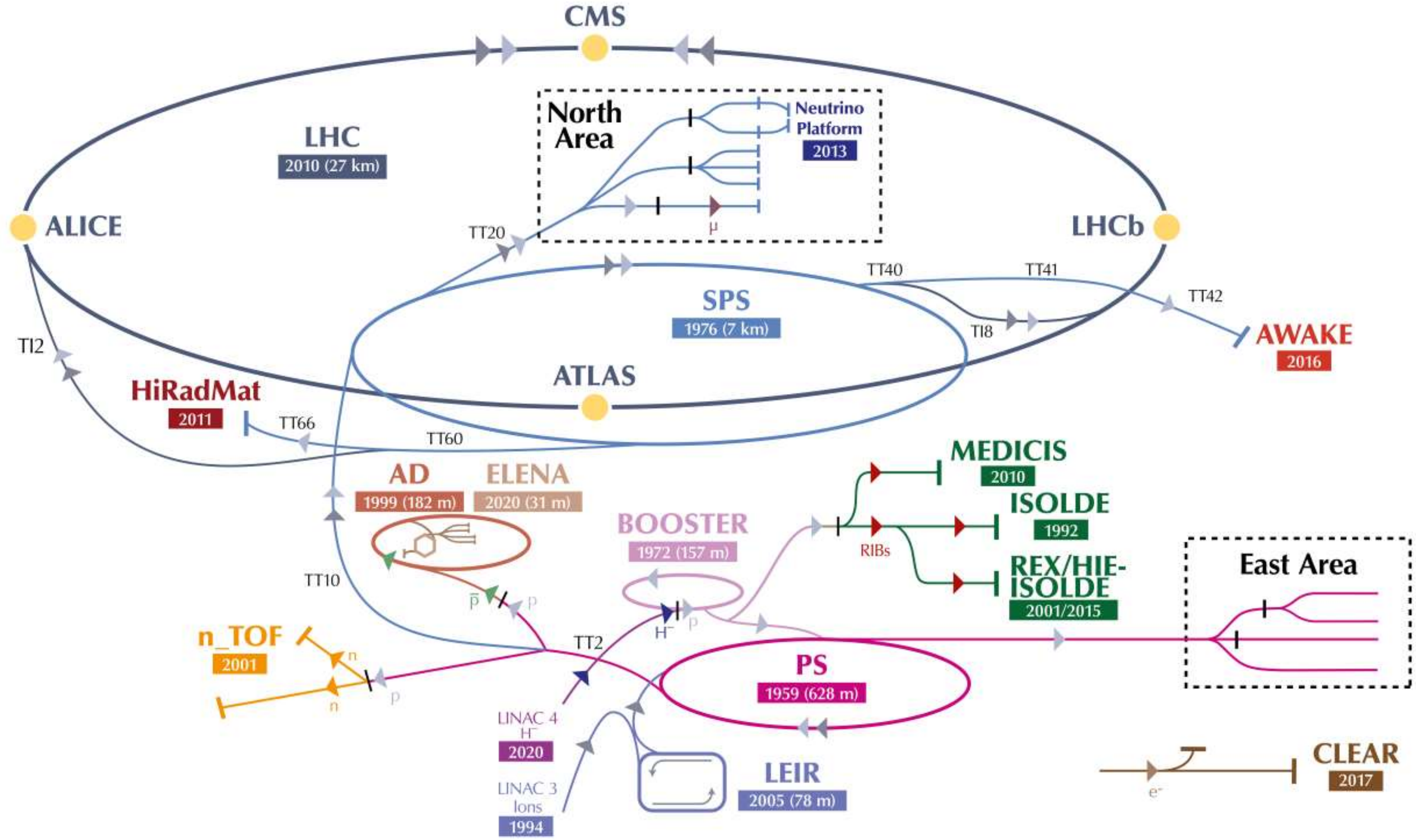
Isabel AMUNDARAIN ARGUELLO (CERN)

2025-04-16

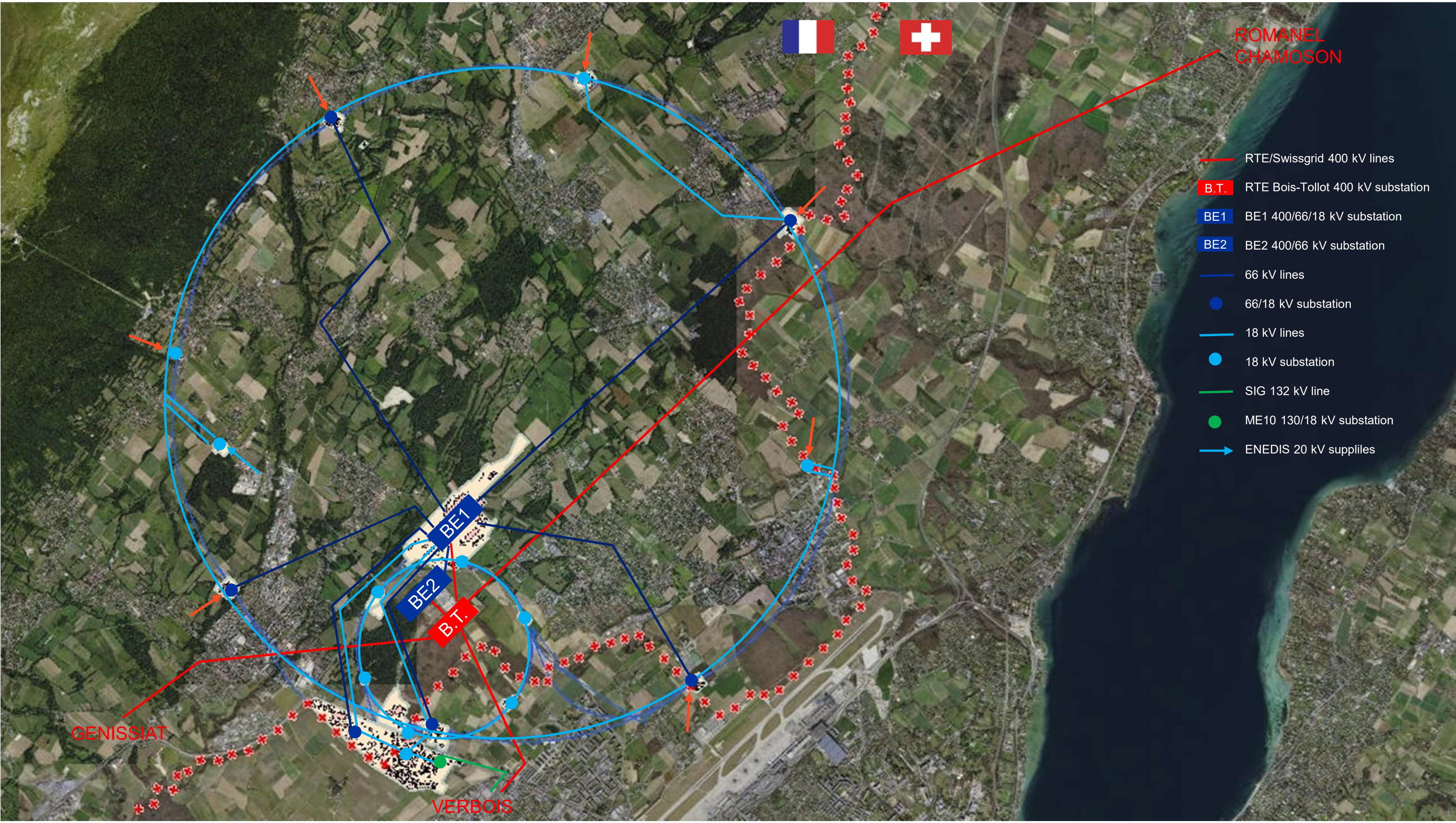
Content

CERN Electrical Network

What is CERN?



CMS
LHC
2010 (27 km)
North Area
Neutrino Platform
2013
ALICE
TT20
μ
LHCb
TT40
TT41
TT42
SPS
1976 (7 km)
TI8
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
MEDICIS
2010
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE-ISOLDE
2001/2015
East Area
TT10
p̄
p
n_TOF
2001
n
TT2
H⁻
PS
1959 (628 m)
LINAC 4
H⁻
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)
CLEAR
2017
e⁻


ROMANEL
CHAMOSON
GENISSIAT
VERBOIS
BE1
BE2
B.T.
RTE/Swissgrid 400 kV lines
B.T. RTE Bois-Tollot 400 kV substation
BE1 BE1 400/66/18 kV substation
BE2 BE2 400/66 kV substation
66 kV lines
66/18 kV substation
18 kV lines
18 kV substation
SIG 132 kV line
ME10 130/18 kV substation
ENEDIS 20 kV supplile

RF2.0 Project Overview

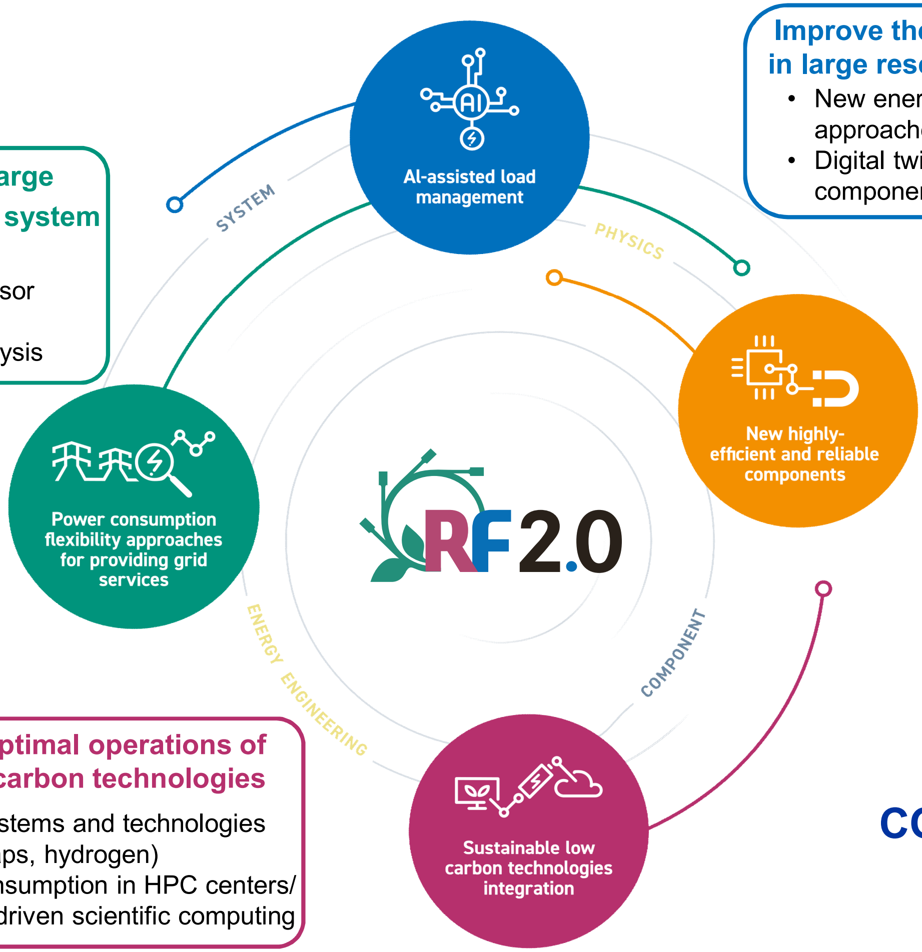
RF2.0 Approach

Increase the sustainability of large research facilities in the electrical system

- Power electronics and DC grids
- Fast measurement systems (phasor measurement units)
- Energy costs and resources analysis

Improve the efficiency operations in large research facilities using AI

- New energy management approaches using AI
- Digital twins of accelerators components and systems



New materials and components targeting an efficiency increase

- Permanent magnets
- Semiconductor technologies
- Solid-state amplifiers

Integration and optimal operations of sustainable low carbon technologies

- Energy storage systems and technologies (batteries, supercaps, hydrogen)
- Flexible power consumption in HPC centers/ renewable power-driven scientific computing

COMPONENT TO SYSTEM LEVEL

First comprehensive and systematic analysis of the energy use in large research facilities

RF2.0 Approach

Design of power systems of future accelerators

Dynamic measurement of critical systems

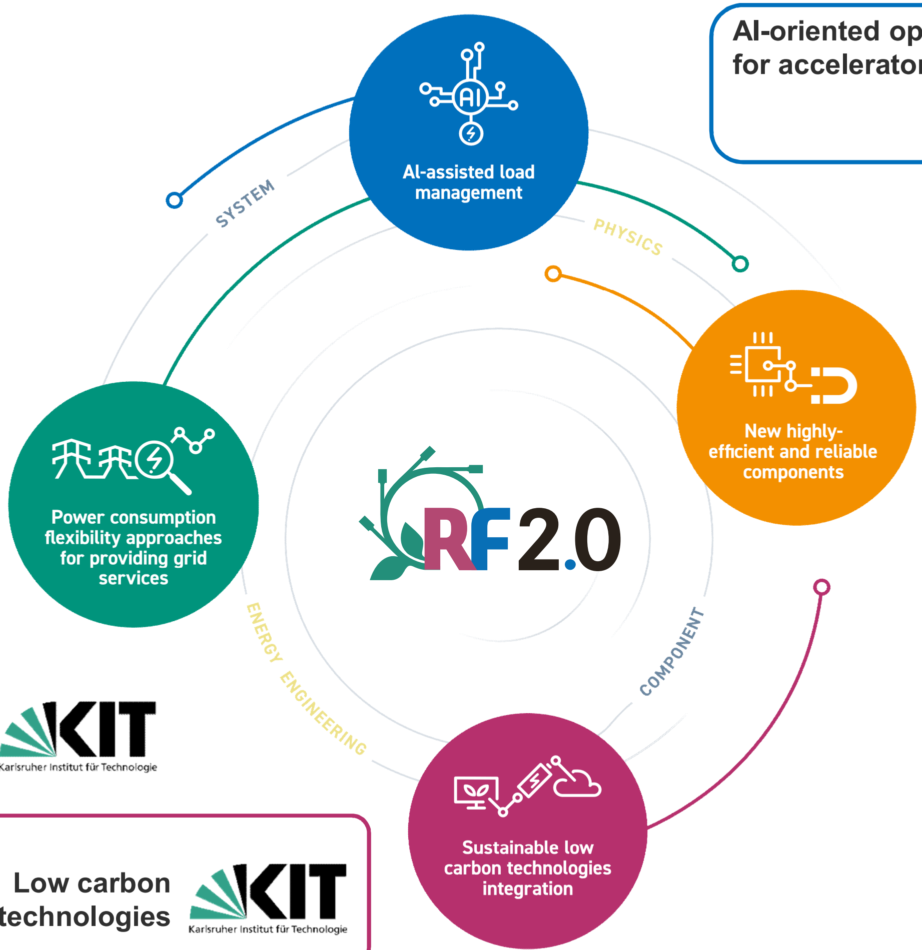
Zaphiro

Digital twins for data centers

Digital twins for accelerators

Green data centers for accelerators

Low carbon technologies



AI-oriented operations for accelerators

High power, high frequency power amplifiers:

Cryoelectra COMMTIA HZB Helmholtz Zentrum Berlin ALBA

Permanent magnets:

HZB Helmholtz Zentrum Berlin MAX IV

CERN Contribution to RF2.0

CERN Motivation

Perturbation analysis:
Enhance CERN’s understanding on the undergoing perturbations on the transmission grid.

Correlation with equipment:
Enhance CERN’s understanding on the correlations between disturbances and their impact on connected downstream loads.

Increase of grid resilience:
Develop methods to increase the resilience of existing **and future** accelerators against grid disturbances and thus their availability.

CERN Objectives

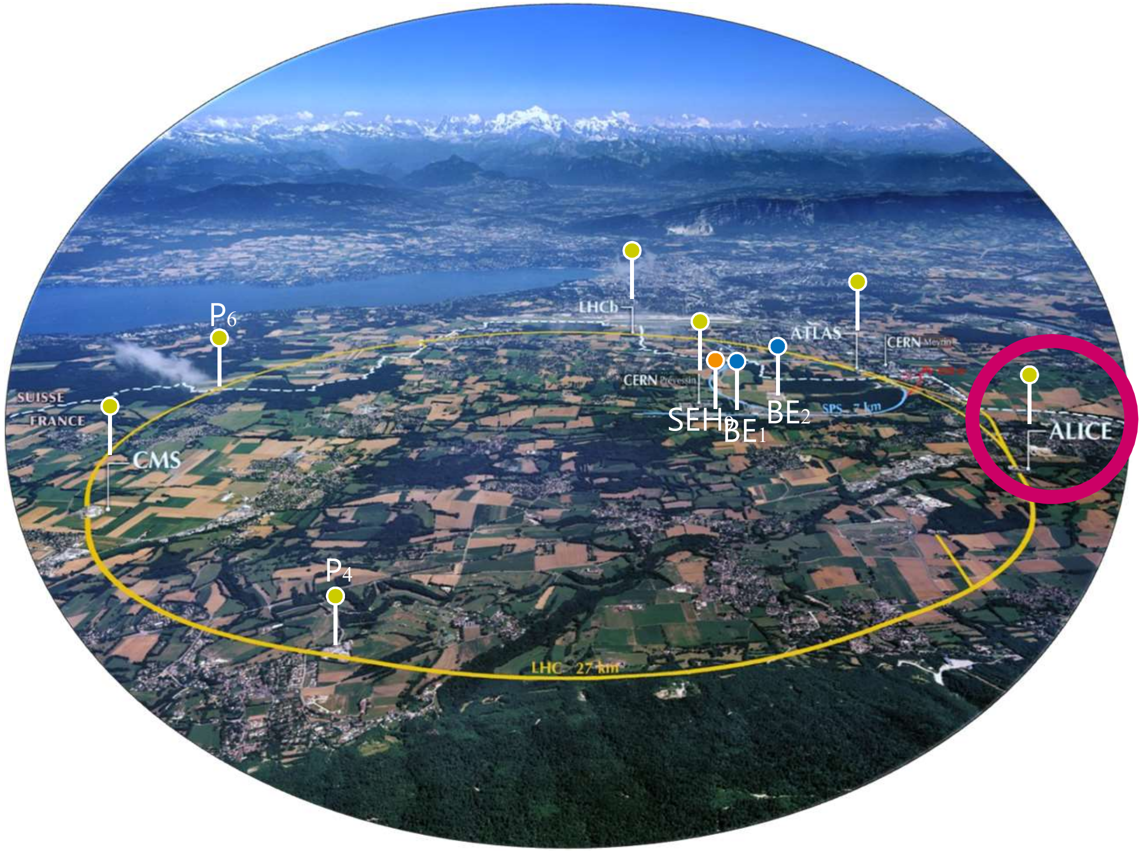
Digital Twins:
Develop real time digital twins for accelerators and green High Power Computing Centers.

Power Quality and Harmonic content analysis:
Enhance CERN’s understanding on the current power flows of its electrical grid and identify mitigation actions and possible improvements.

Integration of PMUs in the energy control of accelerators:
Develop dashboards to display the recorded data, investigate integration possibilities with CERN’s SCADA and the Accelerator’s Fault Tracking system.

PMU Installation at CERN

PMU Locations

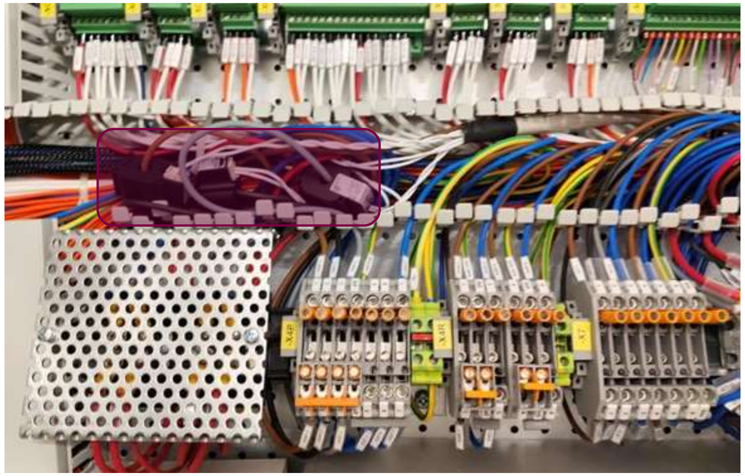


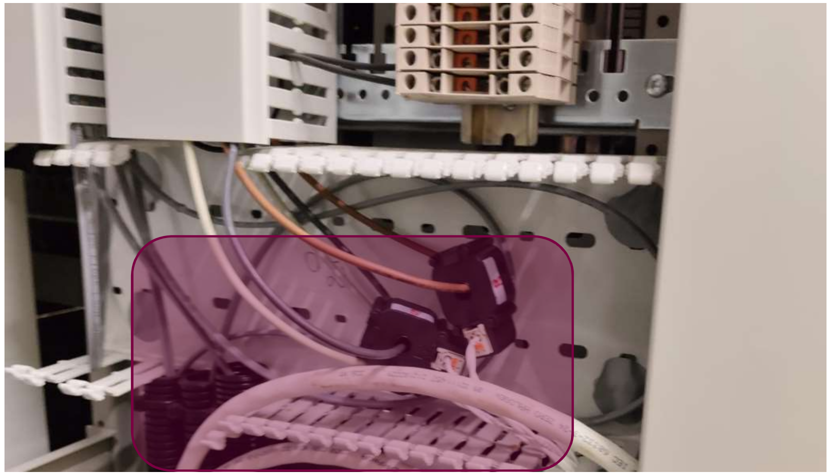
400 kV network
2 substations (BE1 and BE2)
1 PMU/substation

66 kV network
1 substation (SEH9)
2 PMUs

18 kV network
LHC loop + PCC
20 PMUs

PMU Locations



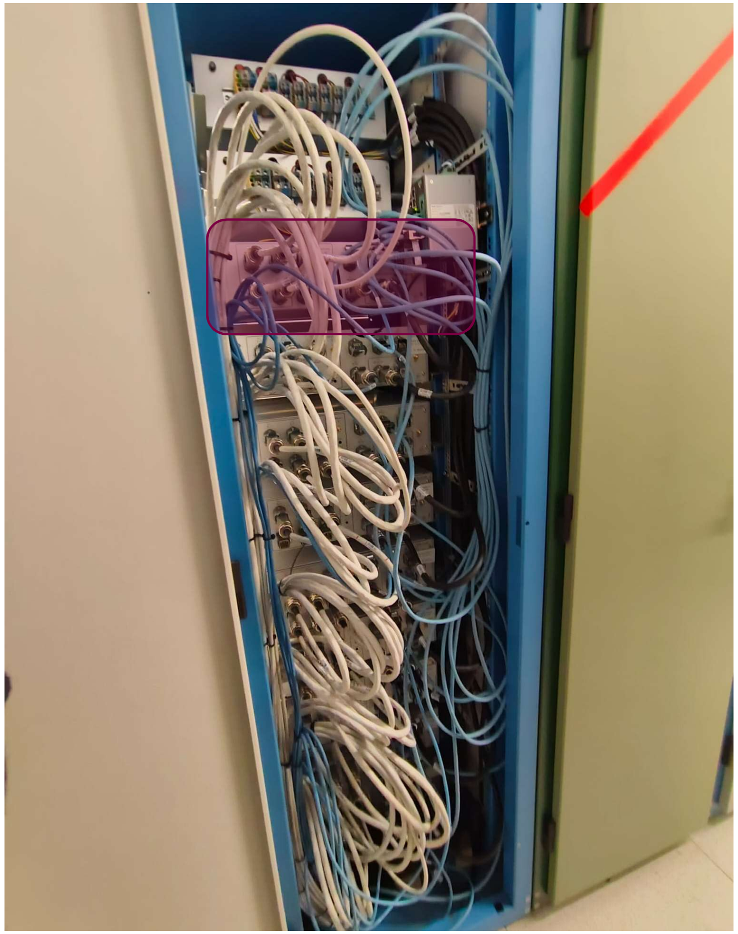


Engineering
Department

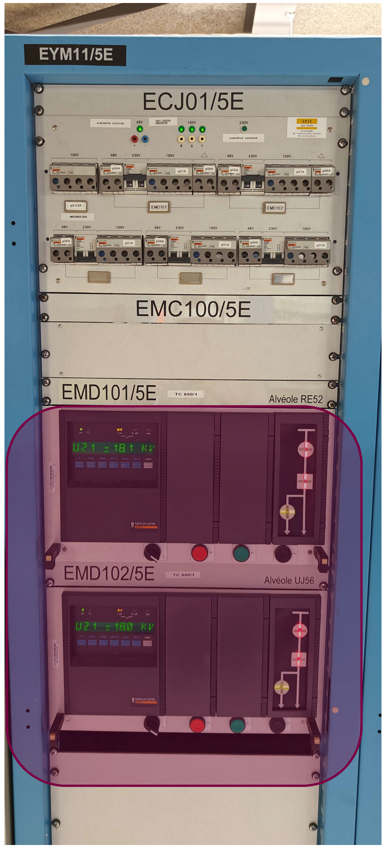
home.cern

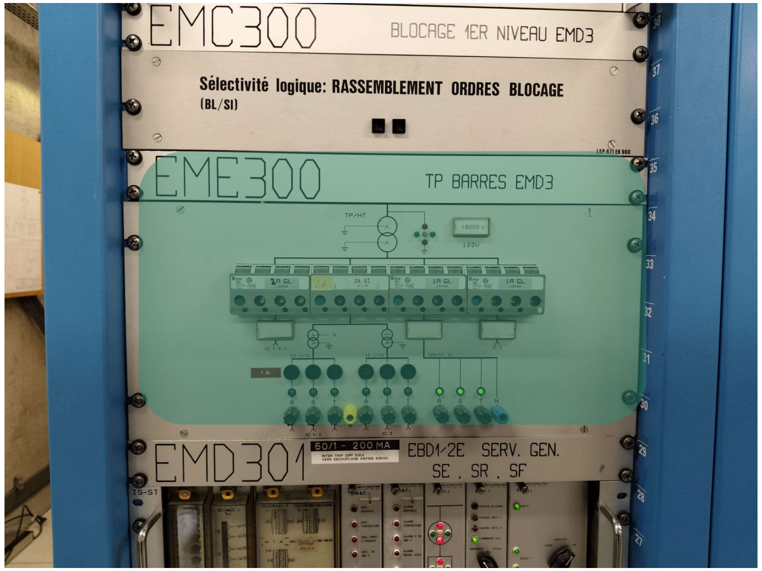
PMU Location – LHC Point 2

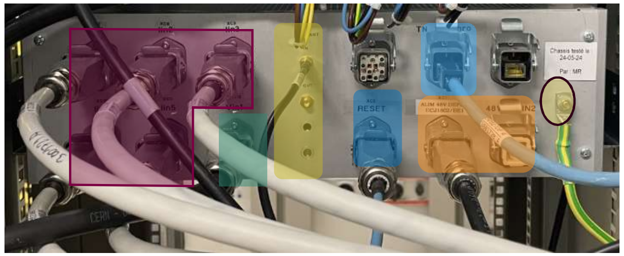
PMU Location – LHC Point 2

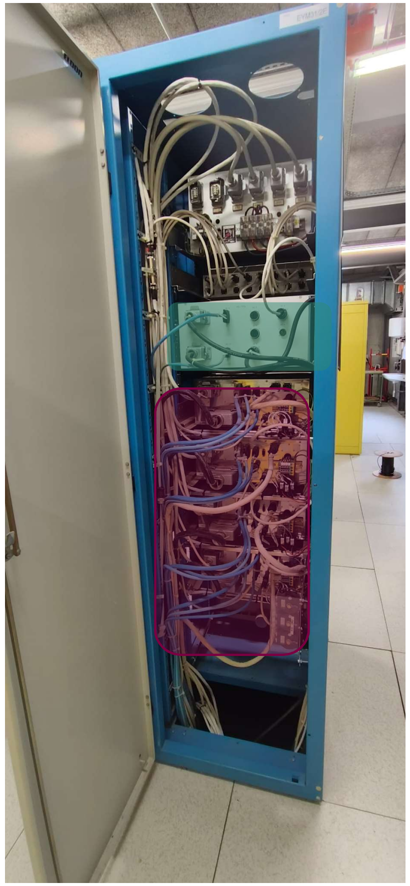


PMU Location – LHC Point 2

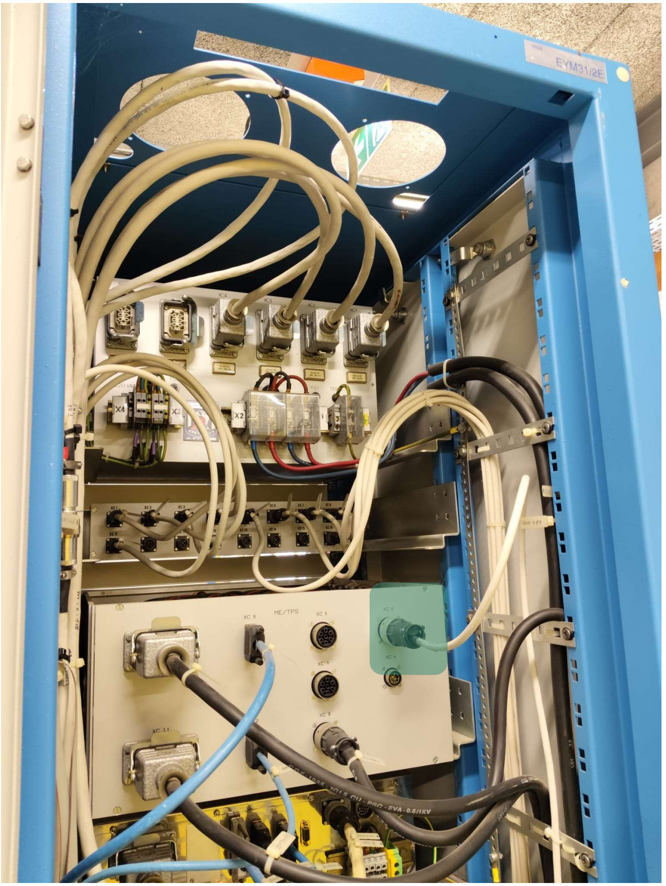


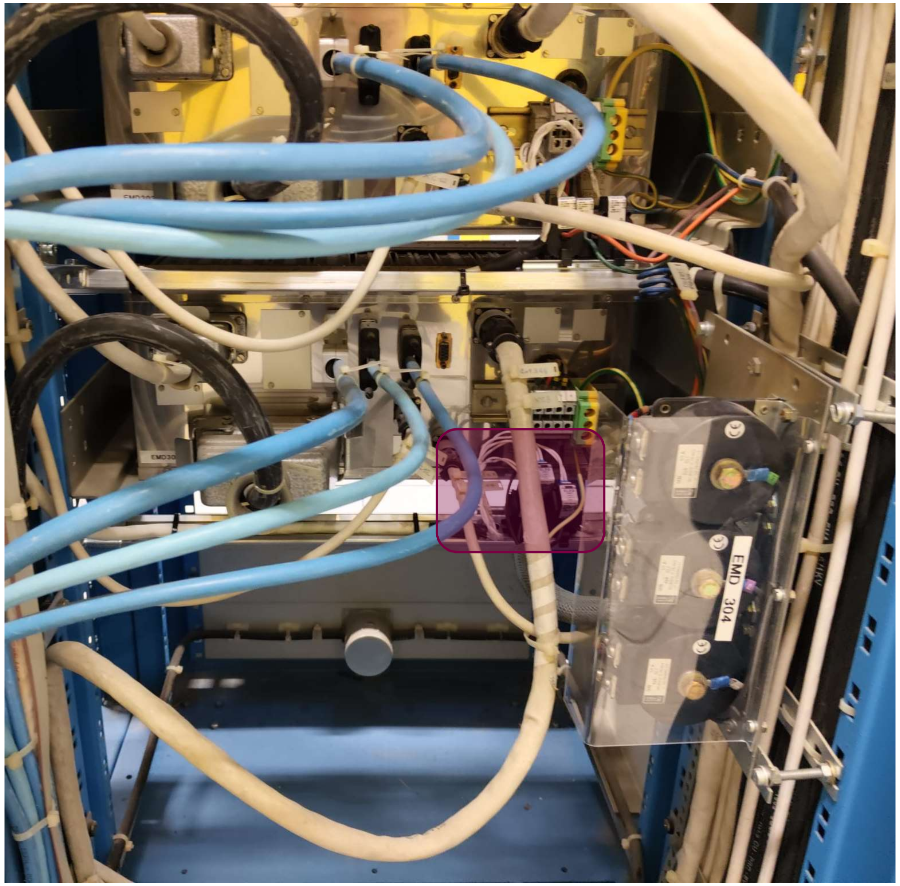




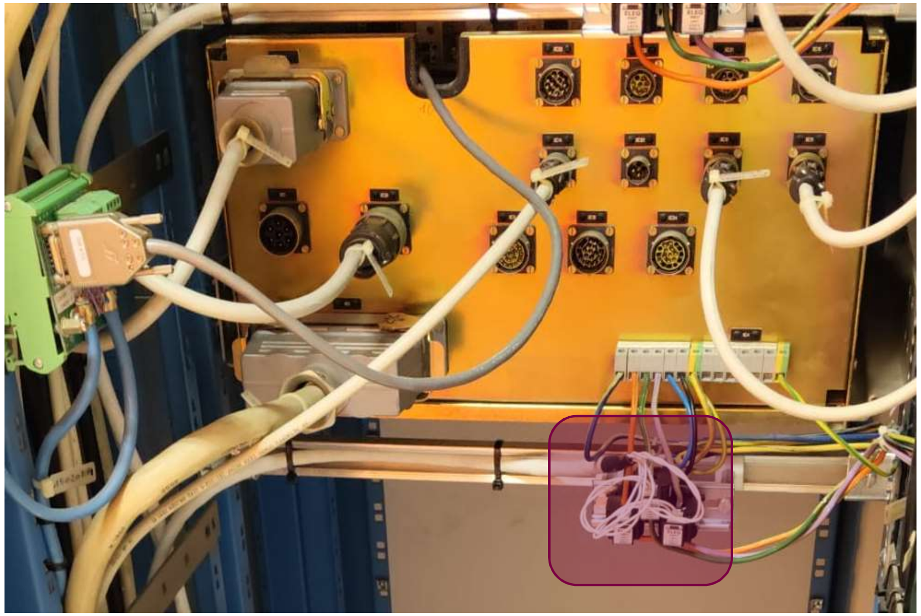


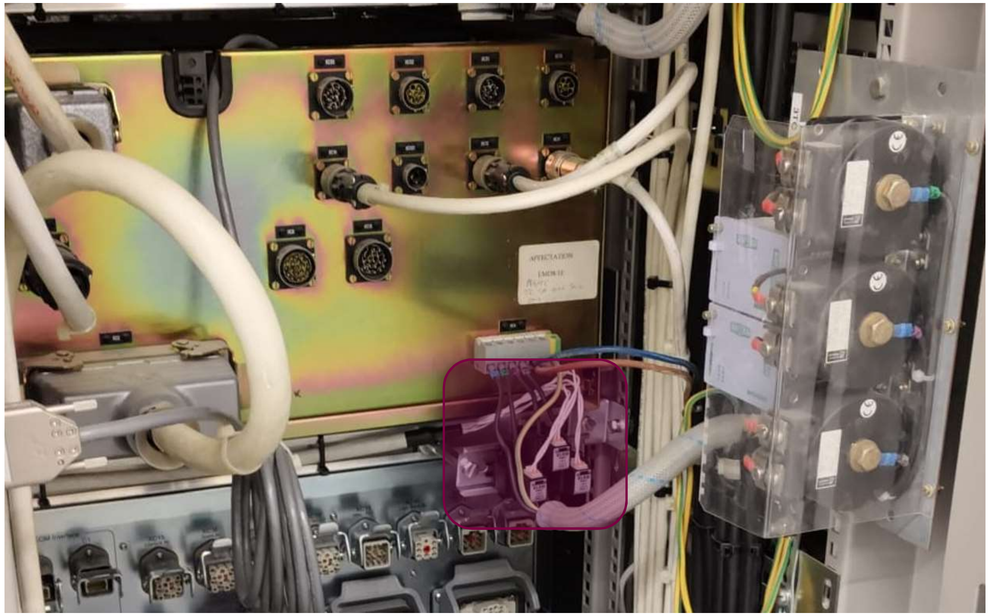
PMU Location – LHC Point 2





PMU Location – LHC Point 2





Zaphiro
Dynamic. Smart. Grid.

Alice Maffezzoli
Sales & Business Development Manager

Leveraging PMU technology to monitor CERN grid infrastructure

About Zaphiro

- **Smart grid** deep-tech company headquartered in Lausanne (CH), with IT subsidiary based in Milan
- **PMU-based** solutions to increase **distribution grids** observability, resiliency, and efficiency
- **+20** satisfied customers across the globe with repeating orders and **+300** SynchroSense devices installed in the field
- **Main investors:** ABB and CDP Ventures

Customers selection

Partners selection

D-PMU Solution

The distribution grid is reaching its capacity limits and requires tighter grid monitoring

The Swiss electricity network cannot absorb all the power produced from Solar PV

Le photovoltaïque se développe, mais le réseau électrique a de la peine à suivre. / 19h30 / 2 min. / le 20 octobre 2023

NL#TIMES

TOP STORIES HEALTH CRIME POLITICS BUSINESS TE

An Amsterdam street at twilight - Credit: brunocoelhopt / DepositPhotos - License: DepositPhotos

BUSINESS AMSTERDAM LIANDER POWER OUTAGE HELEEN MAKKINGA HEMWEG COAL PLANT
» MORE TAGS

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THURSDAY, 25 JANUARY 2024 - 10:20

Amsterdam could face more power outages in coming days, Liander says

Update 10:40 - Article updated with information about power outages on Thursday morning in last paragraph

An innovative grid monitoring system

Real-time distribution grid monitoring system based on D-PMU technology

SynchroSense

Distribution Phasor Measurement Unit (**D-PMU**) device:

- Time-synchronized + high-speed measurements.
- Few devices placed only at strategic grid nodes.
- Ideal for substation retrofitting: simplest and fastest installation on the market (mainly just current sensors).

SynchroGuard

Centralized software platform with real-time data analytics modules (see below)

Real-time grid monitoring (State Estimation)
Complete and reliable **visibility of grid voltages** and **power-flows** for **congestion management**, **voltage control**, **asset mgmt**, **grid planning**, etc.

Accurate fault location
Automated **fault location** to reduce the duration or even **prevent blackouts**.

Event detection
Categorization of PQ events and identification of root cause.

Benefits: Improved grid operations, asset management, predictive maintenance, and grid planning.

SynchroGuard

Unique Selling Proposition

powered by D-PMUs

High quality data generation & processing

- Unprecedented grid visibility thanks to high-speed, time-synchronized measurements
- Single source of truth for a wide range of smart grid applications
- Real-time data processing with model-based grid analytics

Full grid visibility via state estimation

- Full grid visibility (voltages, current/power flows) with 10-20% measurement coverage
- Real-time, unsupervised execution enabling distribution automation applications
- Automatic bad data detection (measurement/topological errors)

Improved QoS via automatic fault location

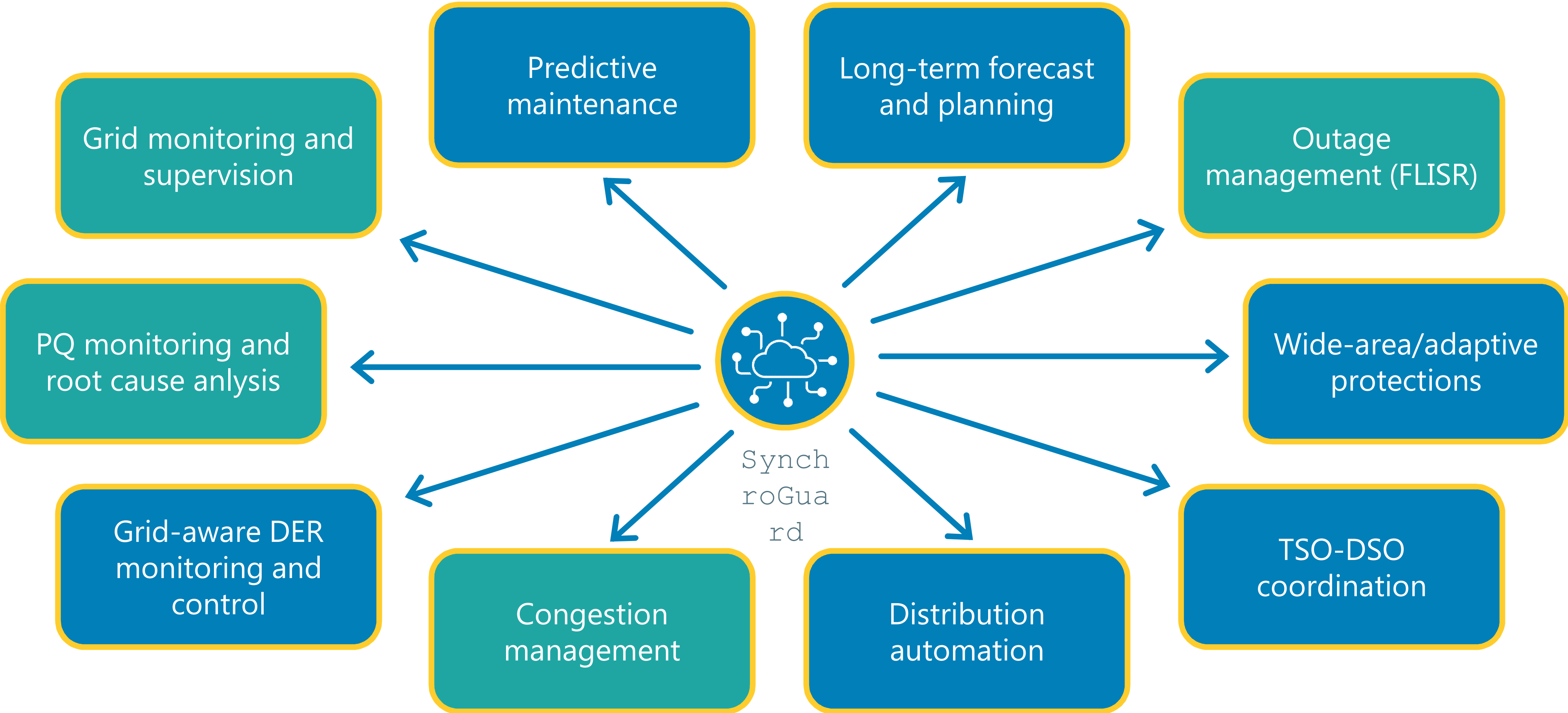
- Higher fault location accuracy and reliability than conventional approaches
- Guaranteed speed, enabling automated FLISR and wide area protection schemes
- Higher fault current sensitivity enabling predictive maintenance via incipient fault detection

Guaranteed scalability and interoperability

- 6x quicker, 10x cheaper & non-invasive installation (no substation shutdown required)
- Lowest Total Cost of Ownership by leveraging limited amount of strategically placed devices
- Seamless integration with substation technologies and control room solutions (e.g., SCADA, DMS)

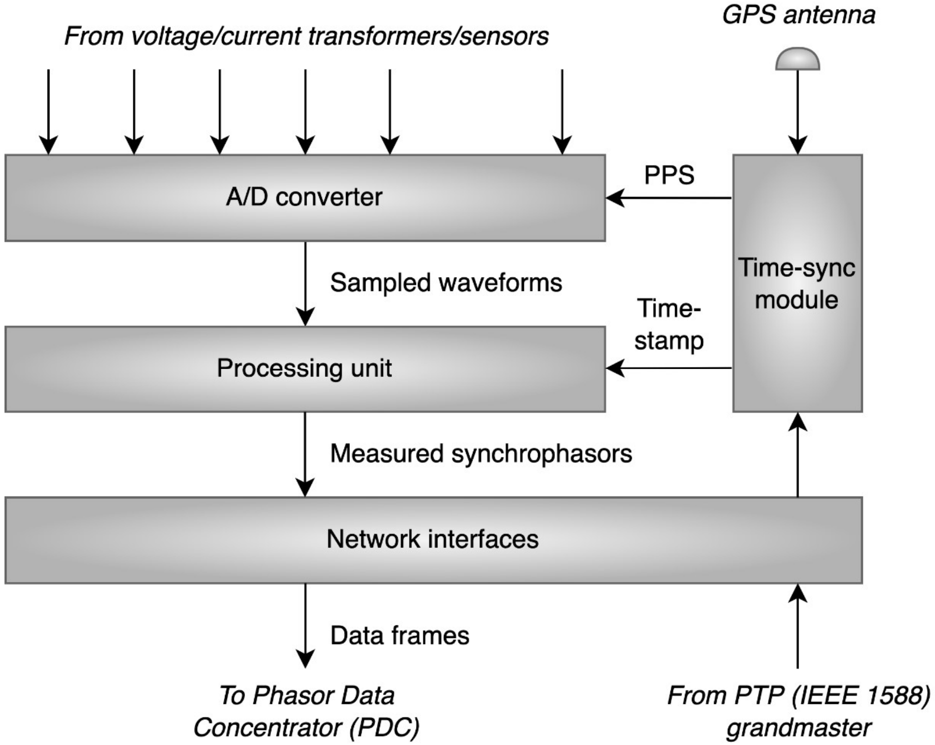
SynchroGuard

Enabled use-cases

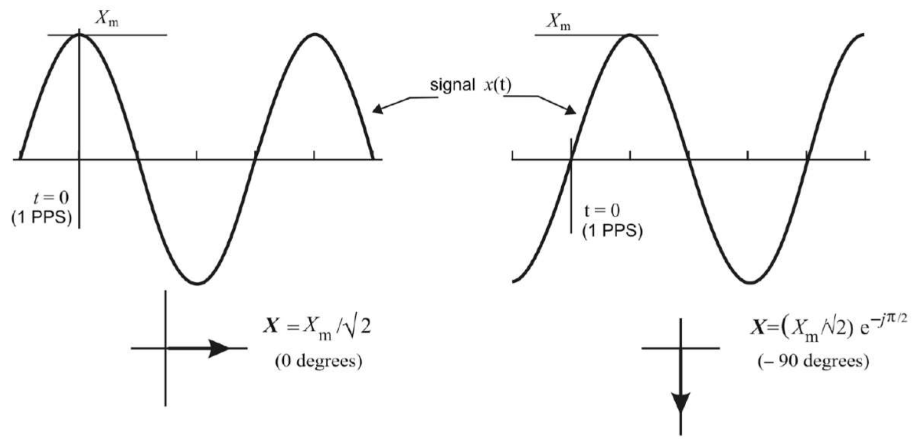


Synchrophasor basics

Phasor Measurement Unit (PMU):



- **Phasor**: compressed representation (complex number) of an AC waveform

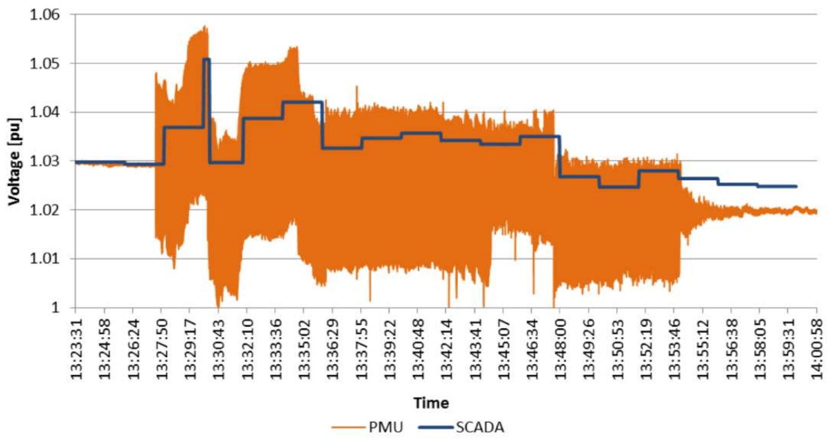


- **Synchrophasor**: phasor measurement synchronized to a common time reference (e.g., GPS) and reported at a very high rate (50/60 Hz)
- **Relevant PMU standards**: IEC-IEEE 60255-118-1, IEC 61850-90-5, IEEE C37.118.2

Synchro phasor's benefits

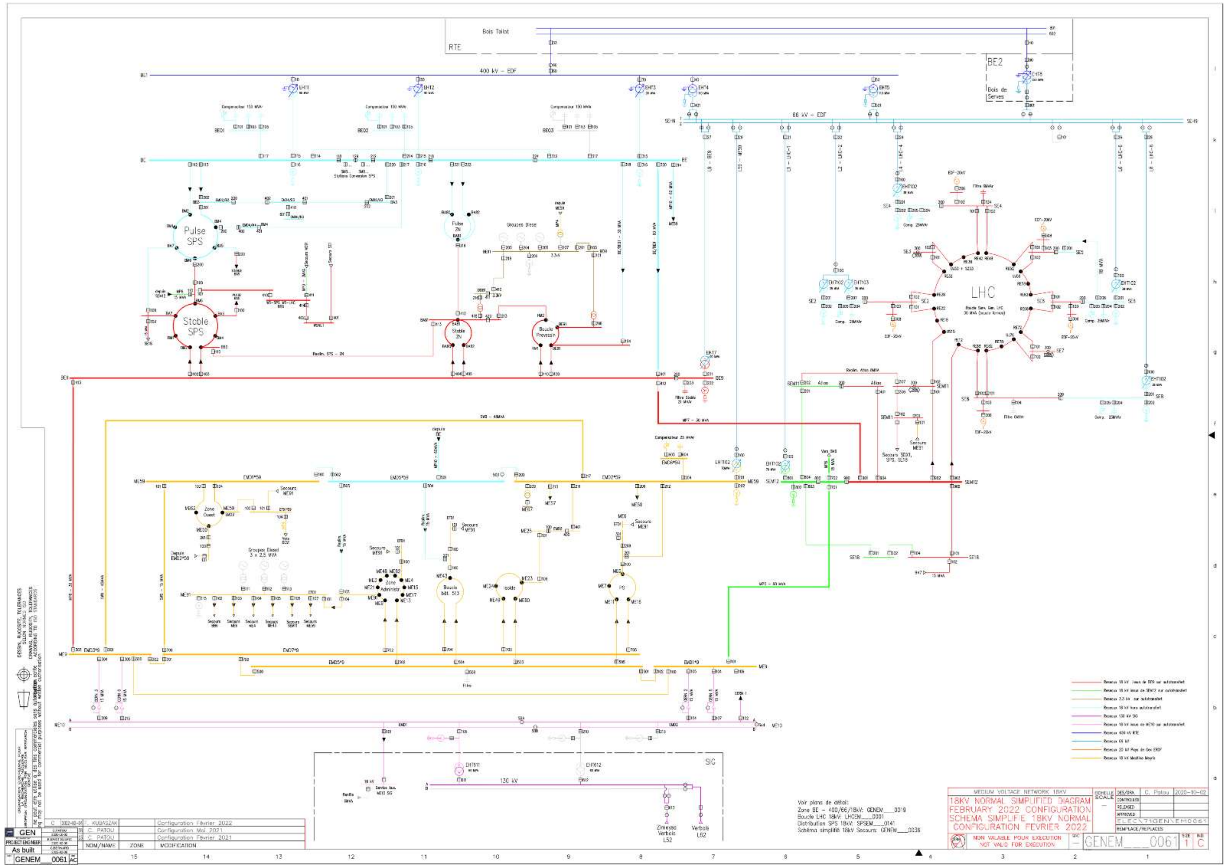
Visualize what SCADA can’t, due to time latency

	SCADA	PMU	Benefits
Measurement type	Voltage/current RMS (amplitude only)	Voltage/current phasors (frequency, amplitude, phase)	Precise reconstruction of fundamental (50/60 Hz) tone
Measurement speed/resolution	1 measurement every few seconds/minutes	Up to 100/120 measurements per second	Real-time grid transient (e.g., fault) monitoring
Measurement time-synchronization	<1 second (when present)	<1 micro-second	**Precise measurement correlation**



PMU deployment at CERN

CERN grid infrastructure

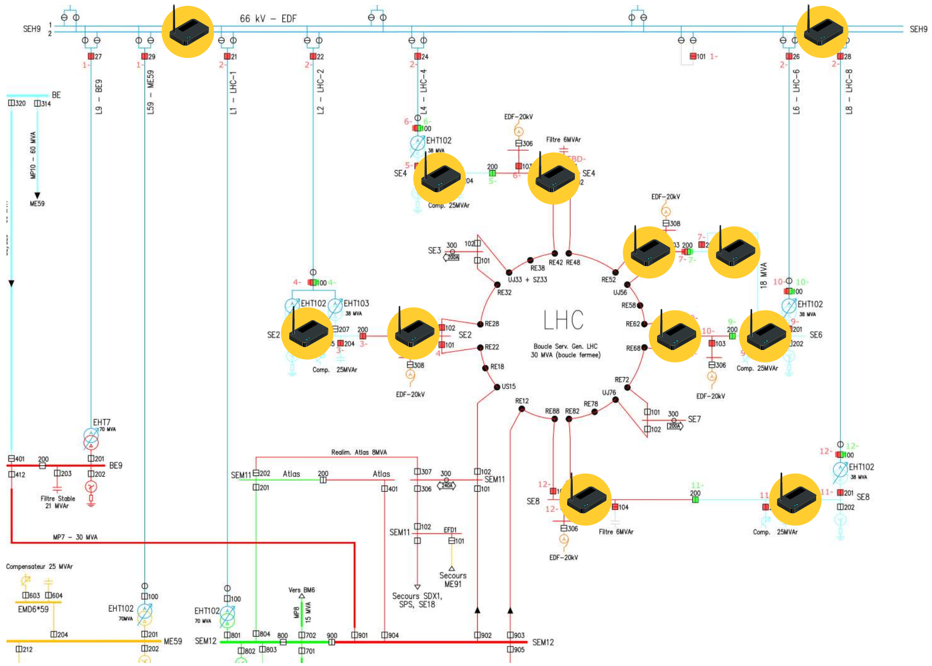


- To supply all the accelerators and the facilities around it, CERN has developed a complex grid infrastructure composed by **3 main voltage levels** (400 kV, 66 kV, and 18 kV)
- CERN sources energy mainly from RTE (France) grid (400 MVA) but also has backup connections to the local Swiss grid (60 MVA)

Context

The grid

- The network identified by CERN for the realization of the project is supplying the **LHC, SE2** and **PCC**.
- The network is composed of **8 secondary substations** (SEH9, and SE1, SE2, SE4, SE5, SE6, SE8, PCC) supplied by **2 primary substation** (BE1, BE2)
- The network is operated with 3 voltage levels: **400kV, 66kV and 18kV.**
- In the context of RF2.0, the installation of our system is proposed to test the validity of the solution from the following perspectives:
    - Infrastructure:
        - **Sensor**
        - **Measurement equipment**
        - **Communication & IT infrastructure**
    - Application:
        - **Power quality events monitoring**
        - **SW customization - TDB**



Single line diagram of a portion of the medium-voltage network supplying the LHC. This portion of the grid is equipped with 12 D-PMUs.

Criteria for successful demonstration

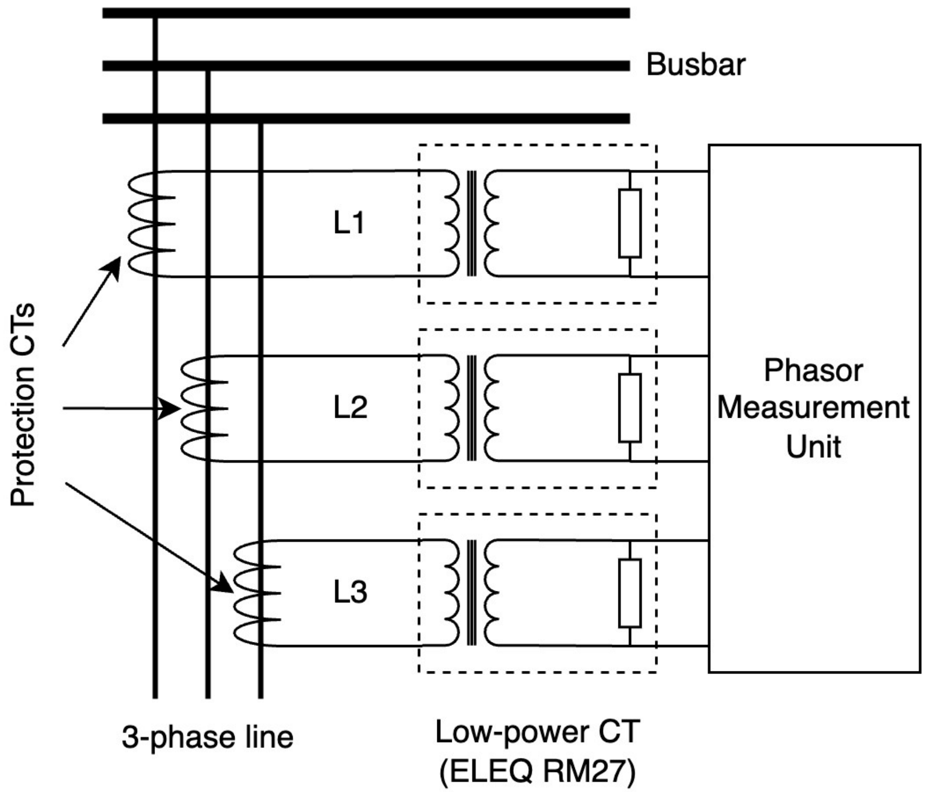
KPIs for success

- **Functionality validation/PMU commissioning**: all core functionalities of the PMUs are accurately validated and showcased; the dashboard accurately displays field measurements and recorded events.
- **User Interface and experience**: the dashboard is visually structured and aesthetically pleasing; the interface is intuitive and easy for operators to use.
- **Data accuracy and reliability**: the data displayed on the dashboard matches the readings from conventional monitoring tools; alerts and event notifications are timely and accurate.
- **Integration capability**: the dashboard or its content can be seamlessly integrated into CERN's SCADA system; there are no conflicts or issues when running the dashboard alongside existing SCADA tools.
- **Performance and responsiveness**: the dashboard responds quickly to new data and updates in real-time; there is no significant lag or delay in data presentation and alert generation.
- **User acceptance and trust**: Control Room Operators find the dashboard useful and reliable; abnormal operation events registered by the PMUs serve as an automated input to the Accelerator's Fault Tracking working group at CERN.
- **Identify energy-saving strategies**: with high precision measurements stemming from the PMUs, identify points of power losses and points of grid optimization.

Objectives to be achieved

- PMU successful commissioning (measurement, data communication, time synchronization).
- PMU data dashboard seamless operation.
- PMU data dashboard-SCADA integration testing.
- Data comparison and trust building.
- Accurate event register that can improve CERN's Accelerator Fault Tracking by automating the process and providing extra functionalities such as accurate timestamps of events.
- Optimize the energy consumption or identify the necessary actions to achieve it.

PMU installation



- The main technical challenge encountered in the project was to define a solution to **retrofit** PMUs in CERN substations, **as CERN was not allowing the deployment of new voltage/current sensors in their switchgears**

- For **voltage** measurement we decided to interface to existing VTs available in every substation (class 0.2 typically)

- For **current** measurement, as Zaphiro PMU solution only embeds low-power inputs, we decided to use **low-power CTs installed on the secondary of existing protection CTs** available in every substation (class 5P10 and 5P20)

Power Quality Event Detection

PQ event	SynchroGuard support	Comment
Continuous phenomena		
Power frequency variations	Yes[1]	Dedicated dashboard on Grafana
Voltage variations	Yes[1]	Dedicated dashboard on Grafana
Supply voltage unbalance	Yes[1,2]	Dedicated dashboard on Grafana
Harmonic voltage	No	Harmonics can be calculated from waveforms recordings
Temporary events		
Rapid voltage changes	Yes[1]	
Flicker	No	
Voltage dip	Yes[1]	
Voltage interruption	Yes[1]	
Overvoltage (voltage swell)	Yes[1]	
Transient overvoltage	No	

Event	Feature1	Feature 2	Feature 3
Voltage dip	Detection	Duration	Depth
Interruption	Detection	Duration	Depth
Swell	Detection	Duration	Depth
Rapid voltage change	Detection	Depth	

1. The events are identified using PMU measurements of voltage phasors (main tone 50Hz) at 20ms resolution with an observation window that can vary between 2 and 3 cycle (40-60ms) .
2. The voltage limit violation and voltage unbalances are currently only available together with State Estimation module (1-min resolution, 15-min observation window)

ELEQ
mastering electricity
worldwide
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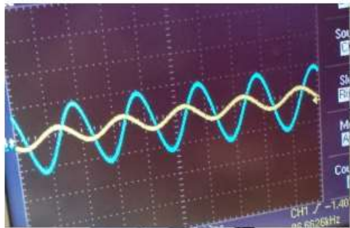
part of a smart world

ELEQ

Who are we and what do we do?

Measurement of Current and voltage



(Lean) Production

Mechanical Engineering Solutions

Compact Electric Connections

ELEQ

What do we make?

Energy management products

Low and medium voltage
transformers

Connection boxes

ELEQ \ mastering electricity worldwide

ELEQ

The challenge in this project

The initial project question:

- No footprint on the primary side (HV/MV)

The project challenge:
- How to reuse/repurpose the existing infrastructure
- CT repeater?

The initial product definition:

- Added to exisiting infrastructure
- Accuracy of 0.5% between 0.05A and 35A
- Fase angle of 30 minutes between 0.05A and 35A

The product challenge:
- Limited space
- Widerange of accuracy

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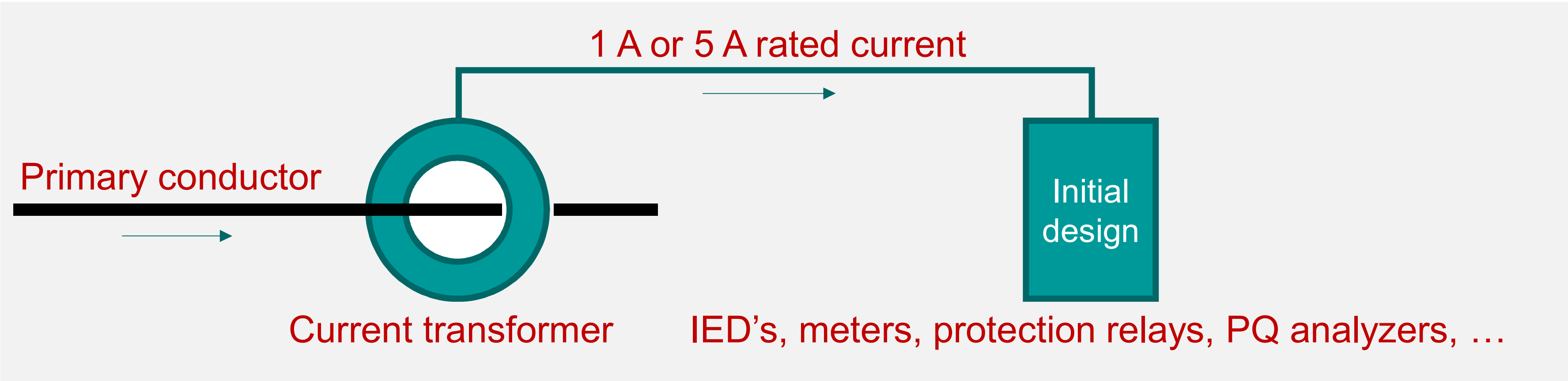
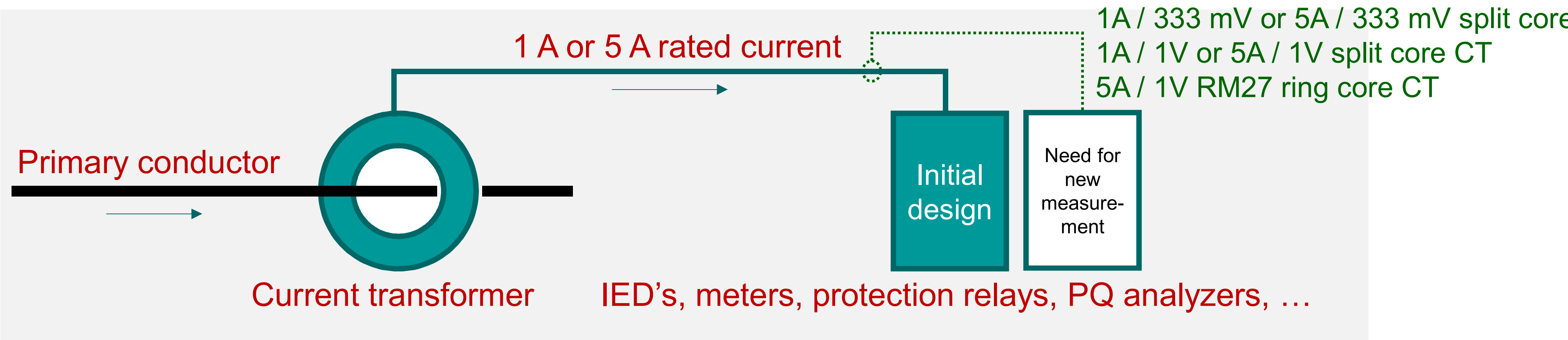
mastering electricity worldwide

The challenge in this project





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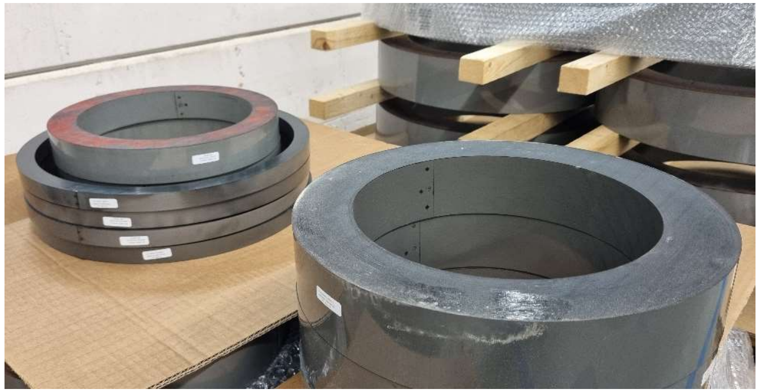
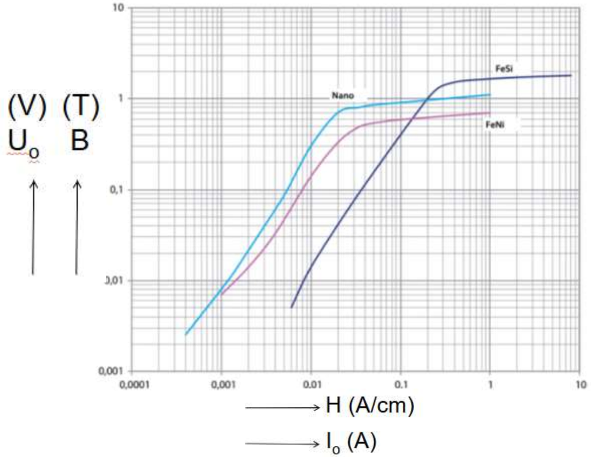
Design parameters of a CT

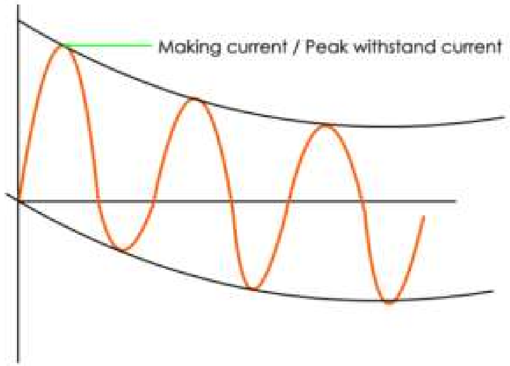


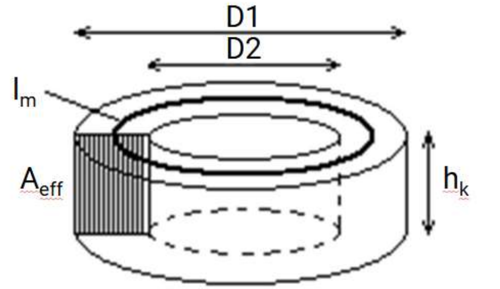
Type of core

Type of wire

Size of the product







$$U_o = B \cdot A_{eff} \cdot N_s \cdot \pi \cdot f \cdot \sqrt{2}$$

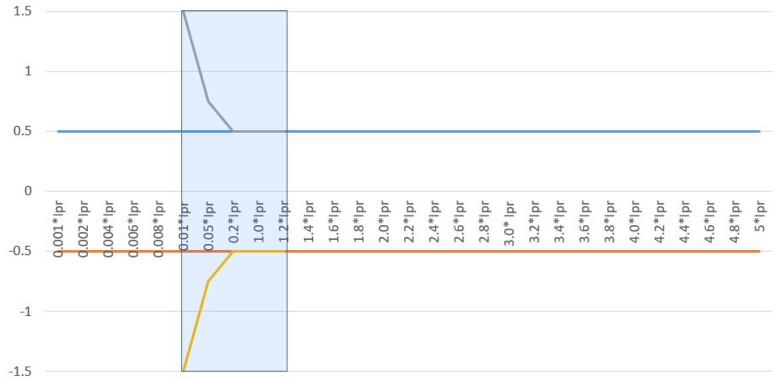
$$I_o = H \cdot \frac{l_m}{N_s}$$

ELEQ

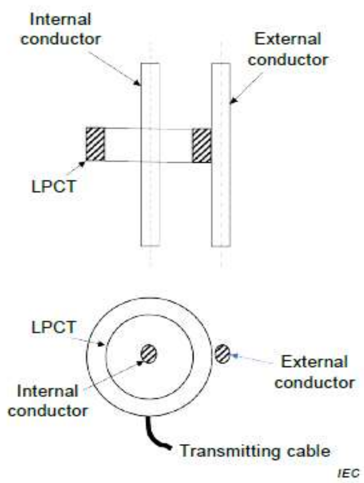
Testing of an LPCT

Product data

Article number	4R2749
Serial number	24530018
Model	RM27
Standard	IEC 61869-10
Insulation level	0.72/3/- kV
Rated frequency	50 Hz
Temperature category	-10/50 °C
Thermal class	e.g. 120 °C (E)
Degree of protection against ingress of foreign parts	IP20
Degrees of protection against external mechanical impacts	IK07
I_{cth}, rated cont. thermal current	120%
I_{th}, Short time thermal current	60 A / 1 s
I_{dyn}, dynamic current	2.5 x Ith



IEC61869-10: Influence of external conductors



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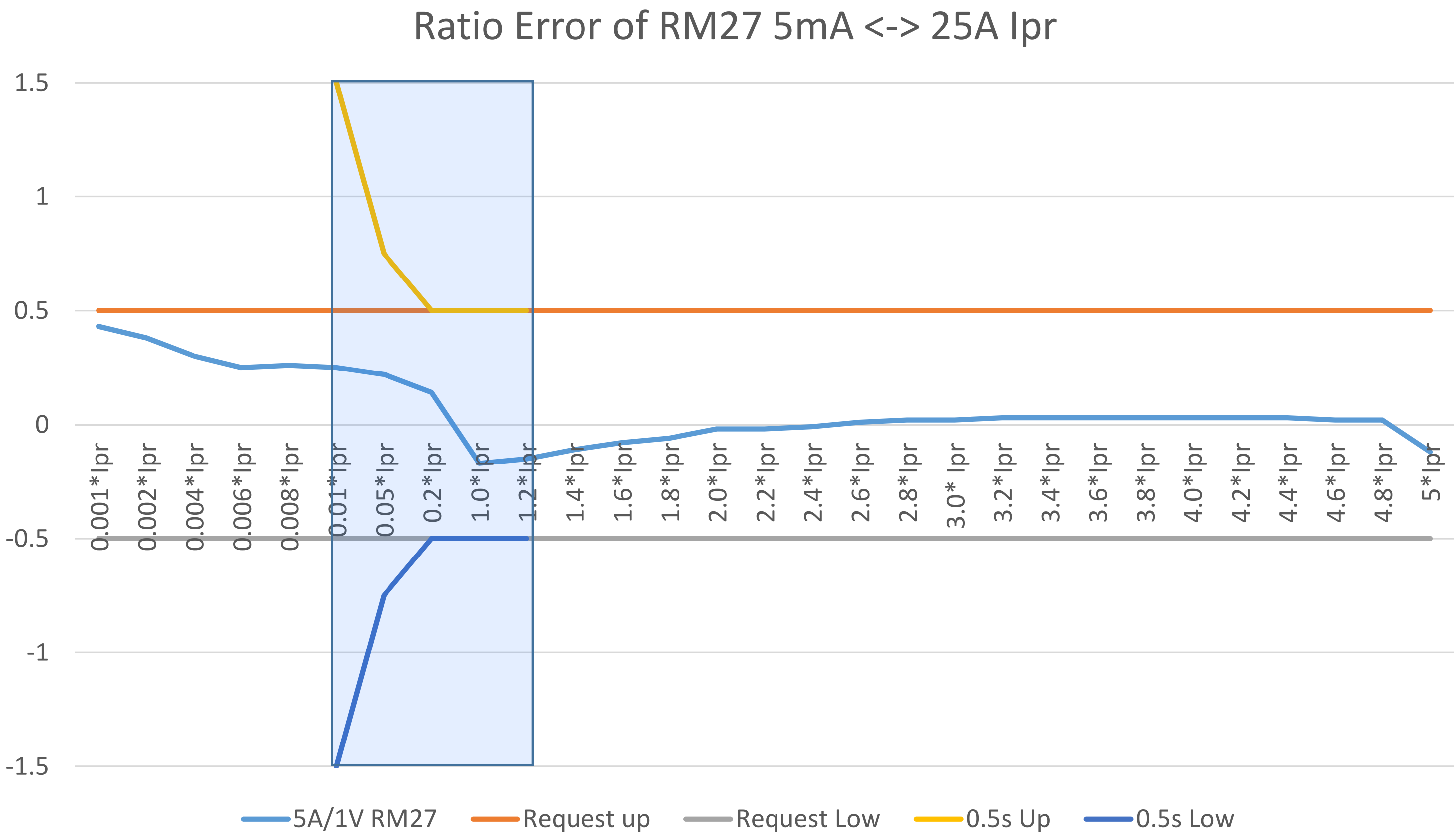
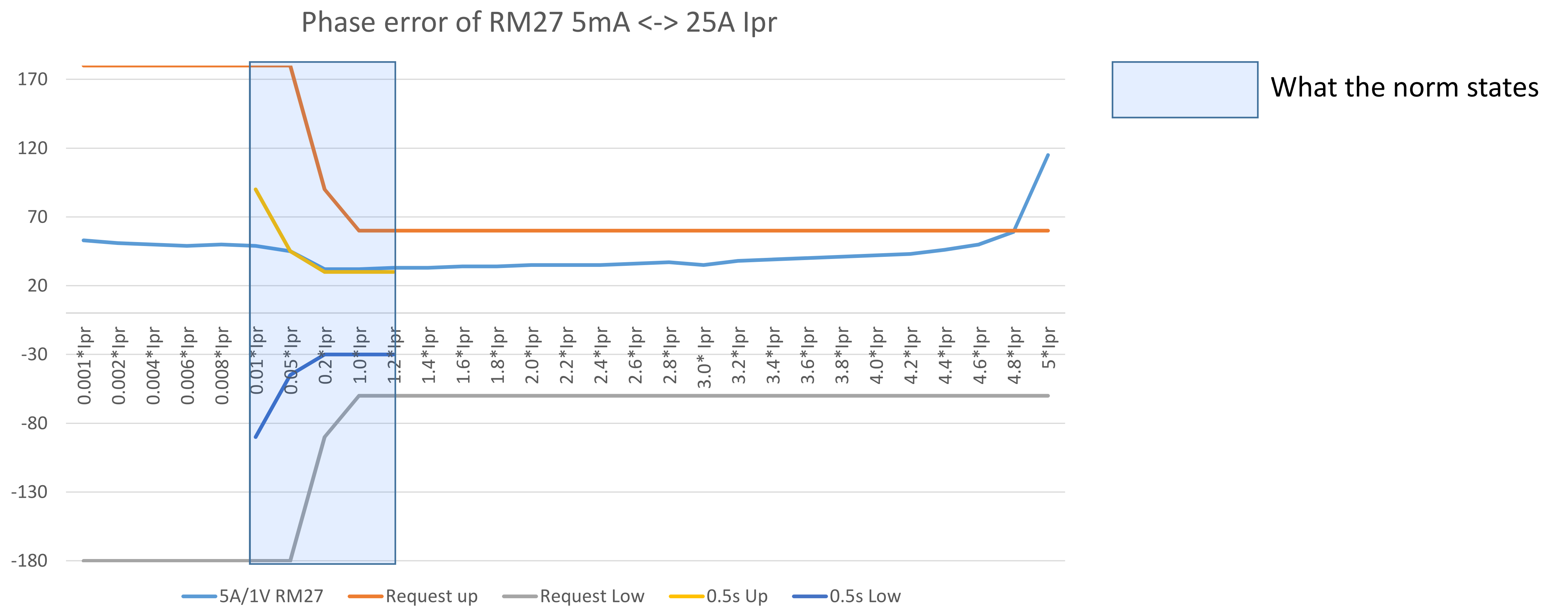


What the norm states

ELEQ



Phase error of RM27 5mA <-> 25A Ipr
170
120
70
20
-30
-80
-130
-180
0.001*Ipr
0.002*Ipr
0.004*Ipr
0.006*Ipr
0.008*Ipr
0.01*Ipr
0.5*Ipr
0.2*Ipr
1.0*Ipr
1.2*Ipr
1.4*Ipr
1.6*Ipr
1.8*Ipr
2.0*Ipr
2.2*Ipr
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3.8*Ipr
4.0*Ipr
4.2*Ipr
4.4*Ipr
4.6*Ipr
4.8*Ipr
5*Ipr
5A/1V RM27
Request up
Request Low
0.5s Up
0.5s Low
What the norm states

KIVI Engineering Society

RF2.0 RESEARCH FACILITY

Leveraging PMU technology to monitor CERN grid infrastructure

KIVI Webinar, 16-04-2025

CERN

Zaphiro Dynamic. Smart. Grid.

ELEQ mastering electricity worldwide