Adventures of an EPICS Developer:

Navigating Across International Control Systems

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EPICS SUMMER SCHOOL

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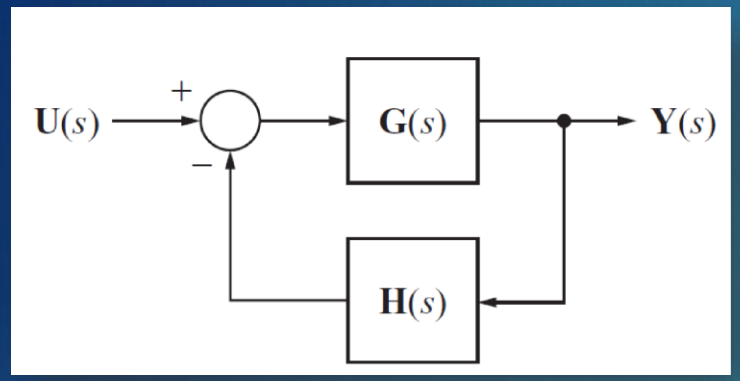
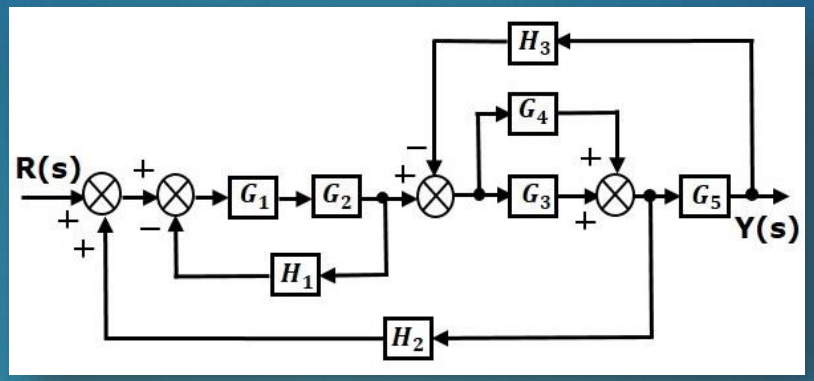
- What is a control system?
- LNL Facilities and SPES Project (Italy)
- ANTHEM Project (Italy)
- IFMIF Project (Japan)
- ESS Project (Sweden)
- Lessons Learned

What is a Control System?

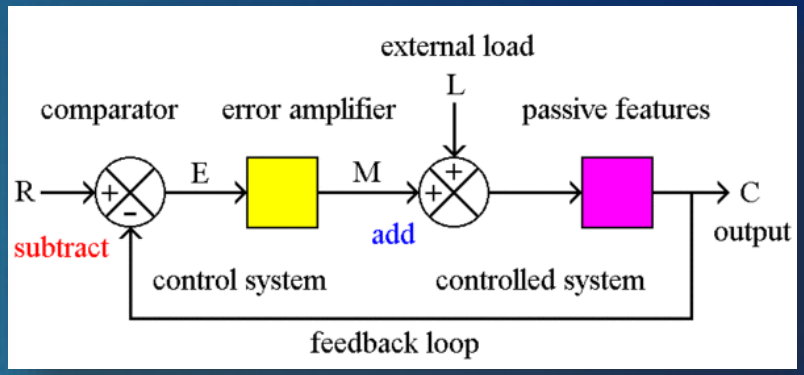
Control Systems - Theory



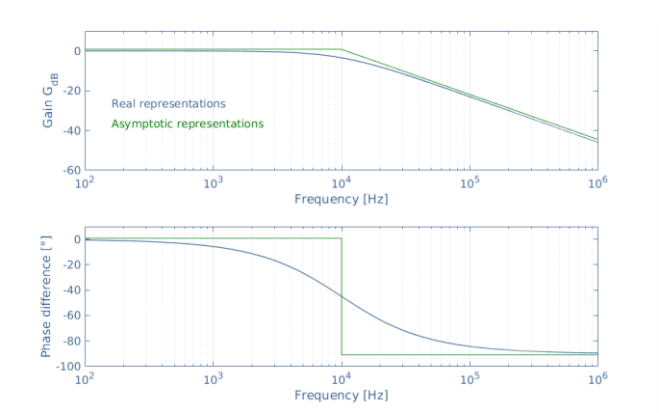
Mathematical modelling



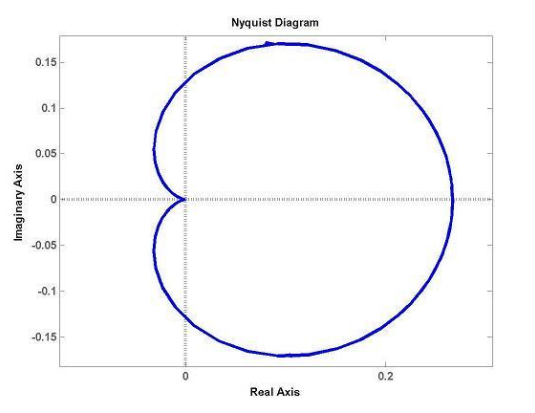
…More complex mathematical modelling



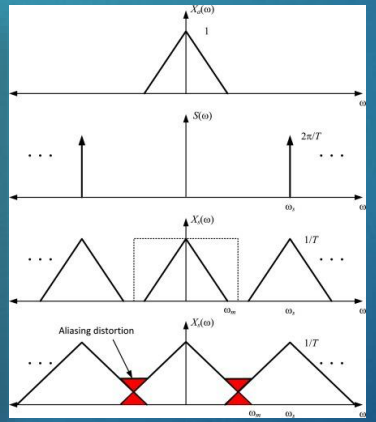
Feedback loop design



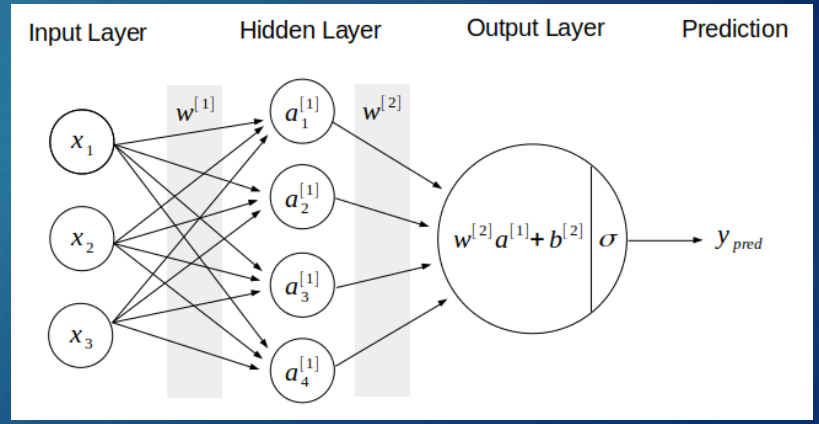
Bode Diagrams



Nyquist Diagrams

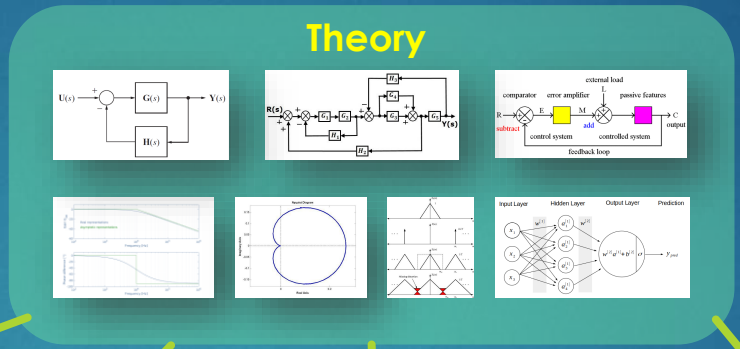


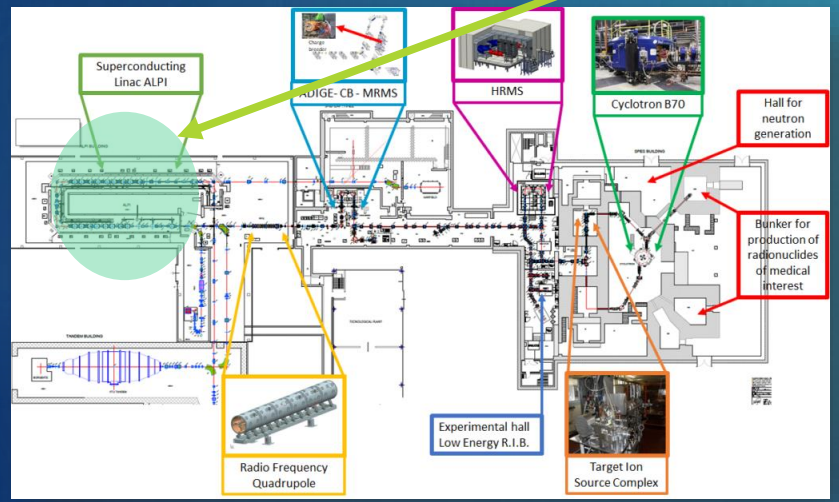
Shannon Sampling Theorem



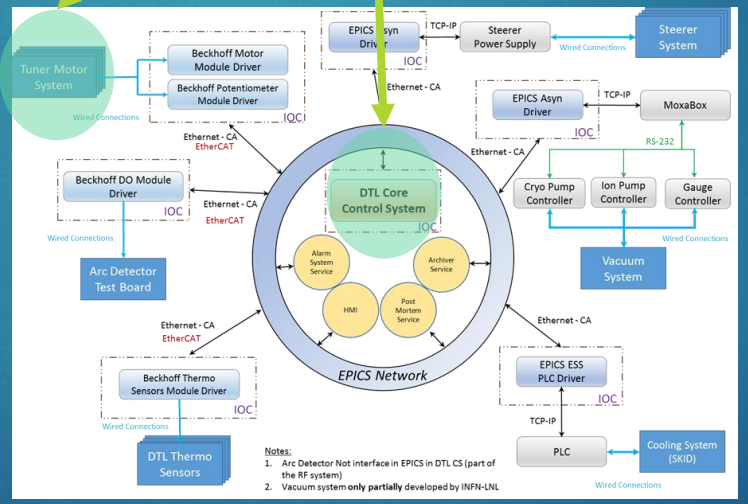
AI / ML / Neural Networks and beyond

Control Systems – not only Theory

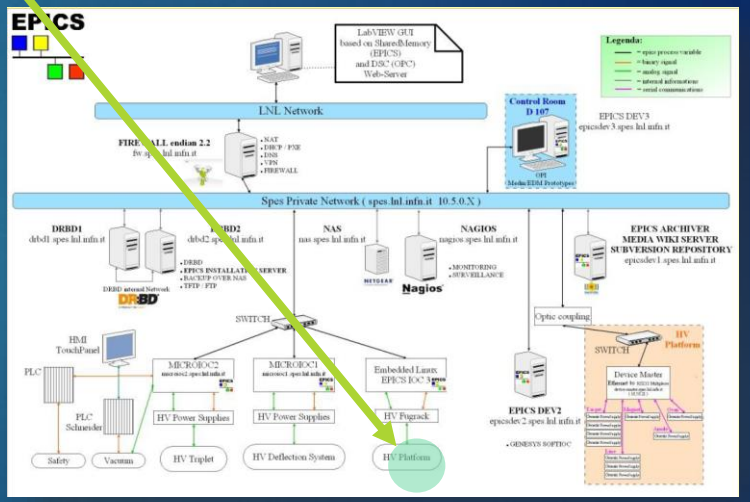




(Very) Complex System Modelling

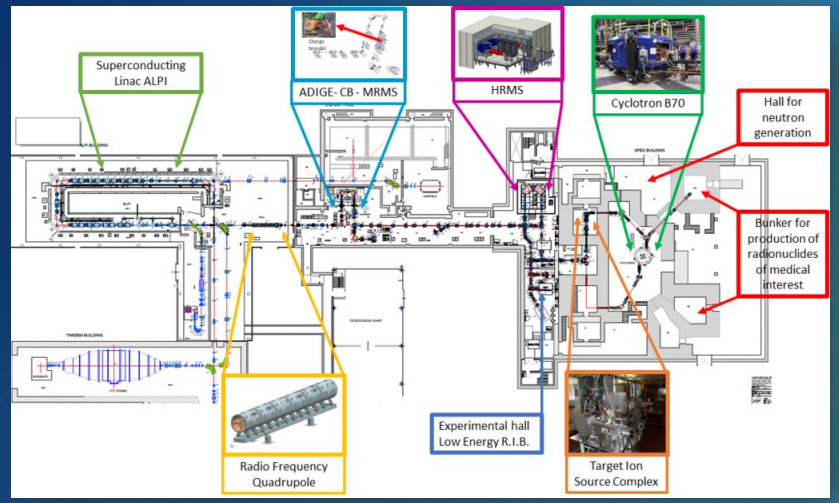


Heterogeneous kind of Hardware, Software, Protocols



Control System Architectures

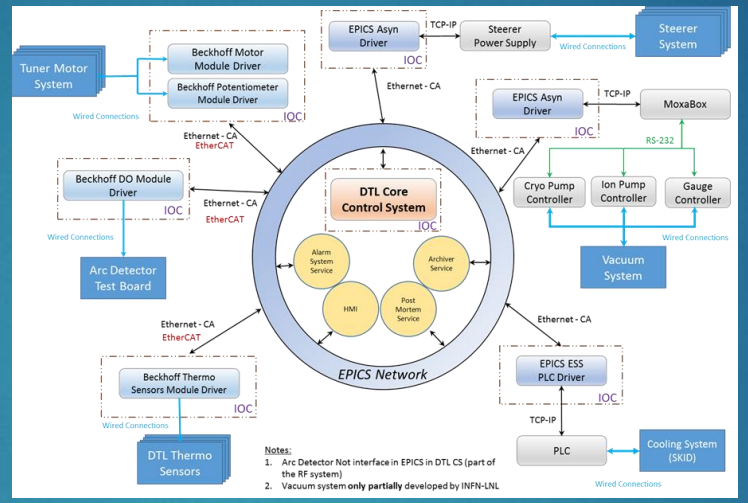
Control Systems Scenarios



(Very) Complex System Modelling

Divide-and-conquer approach

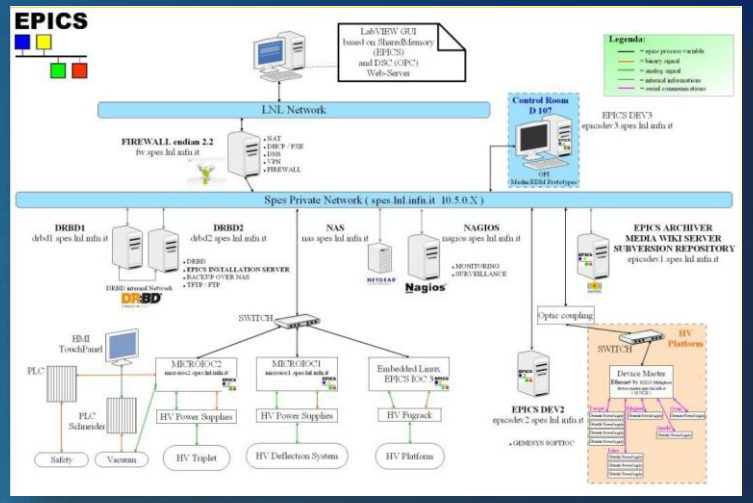
- R&D of a single apparatus / functional system
- High-level orchestraton



Heterogeneous kind of Hardware, Software, Protocols

Every single apparatus, and the entire facility, require and use different hardware and software solutions

Many times, hardware limits the options at software level

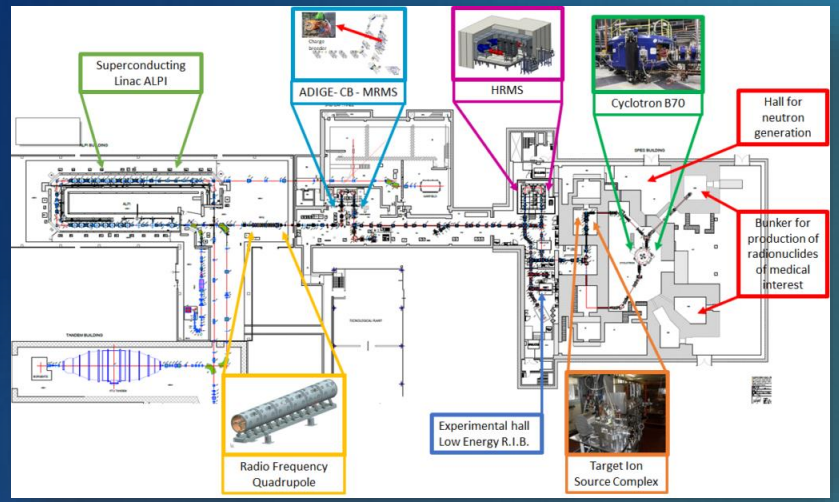


Control System Architectures

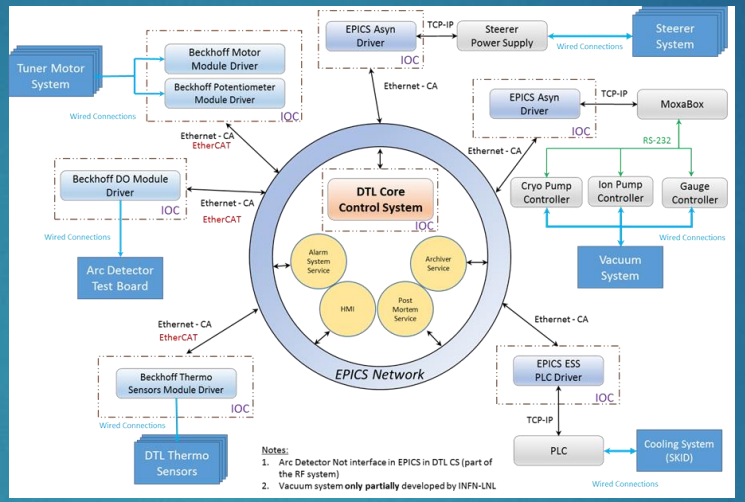
A control system engineer must have multiple knowledges in:

- Networking and IT architecture
- Protocols and field buses
- HW interfaces
- High-level services and GUIs design

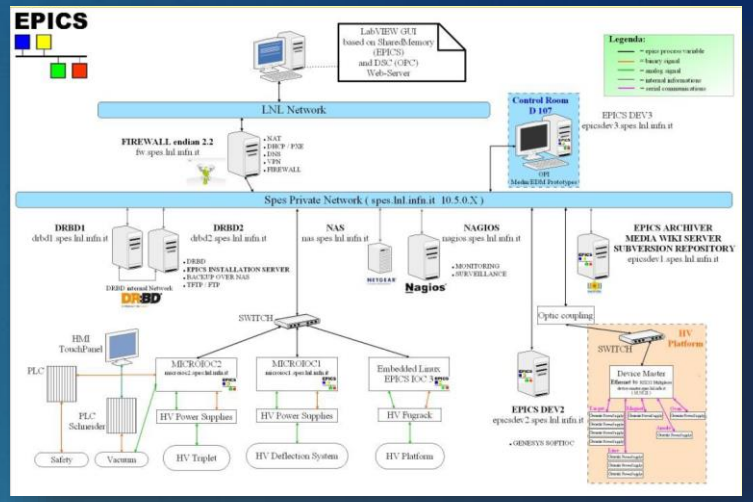
Control Systems



Many different apparatus



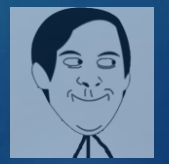
Heterogeneous kind of Hardware, Software, Protocols

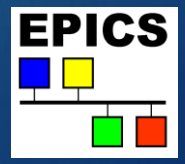


interface to the End User(Scientist, Operator, etc.) though proper services and applications

EPICS v7

EPICS v3
old but gold





INFN-LNL Facilities, SPES Project & ANTHEM Project

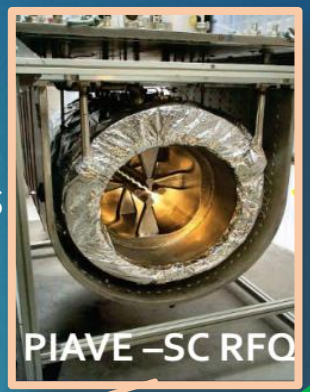
ITALY: WHERE EVEN THE TRAFFIC JAMS HAVE STYLE, AND ARGUING WITH YOUR HANDS IS CONSIDERED AN ART FORM

INFN and Legnaro National Labs

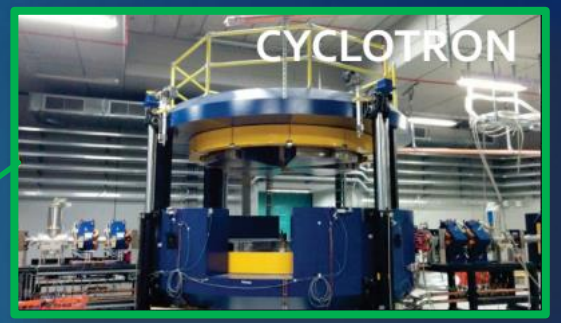
1980s

1990s

2000s

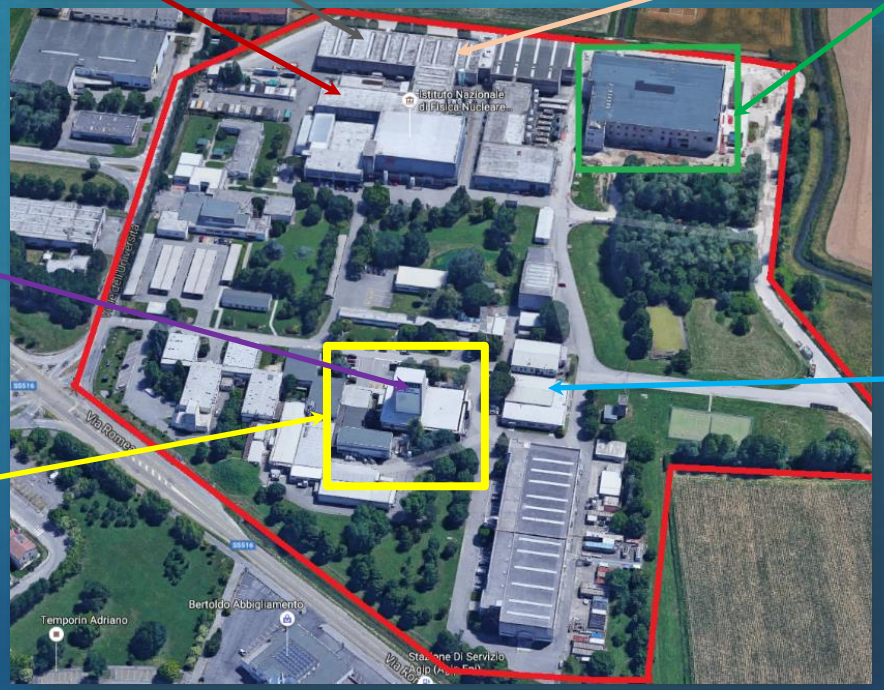


2010s

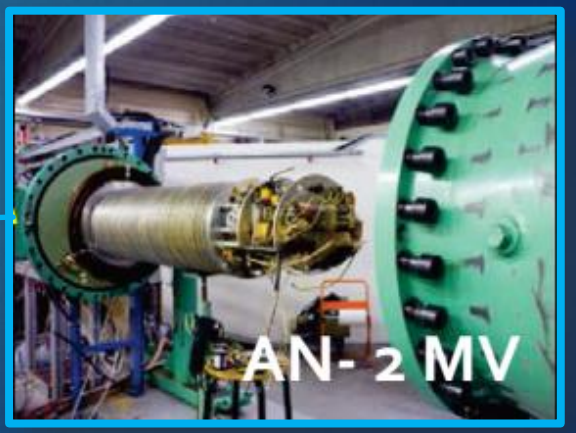


1960s

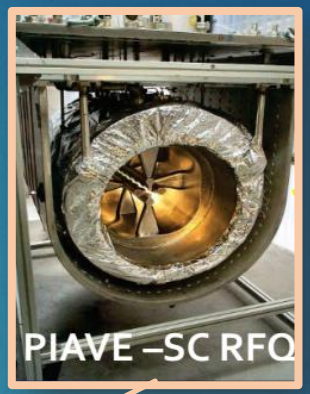
1960s

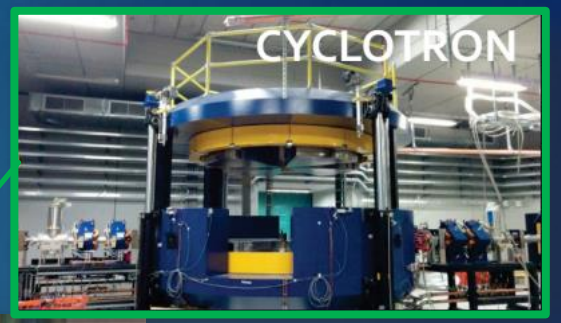


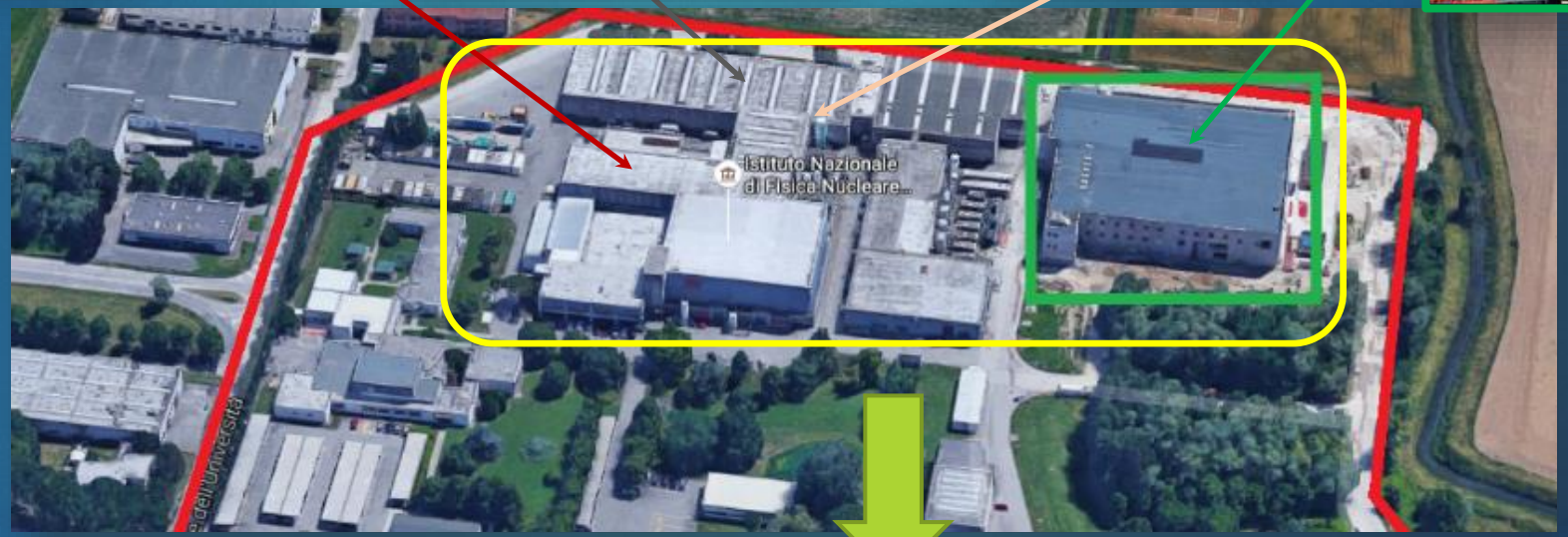
1970s



INFN and Legnaro National Labs

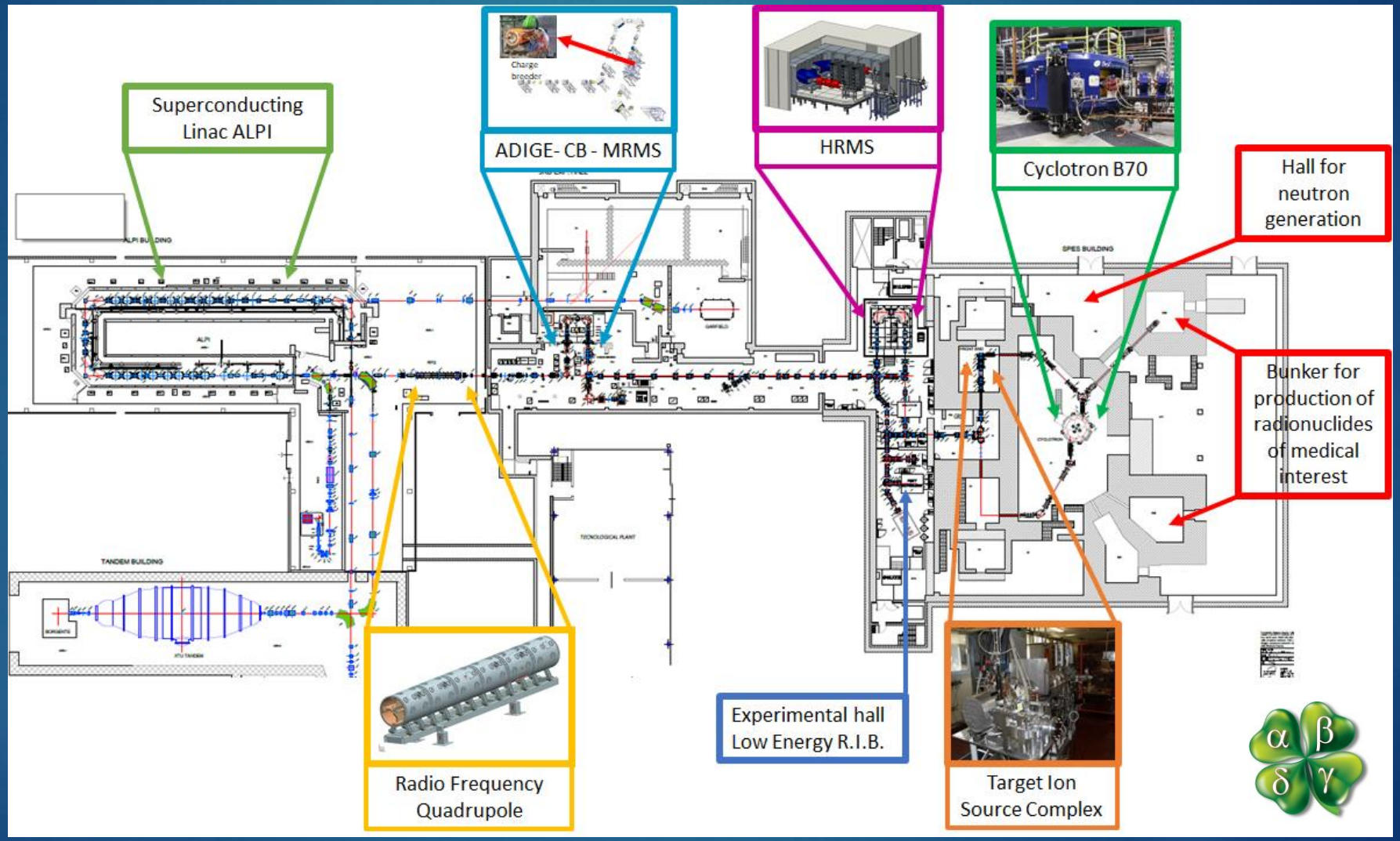




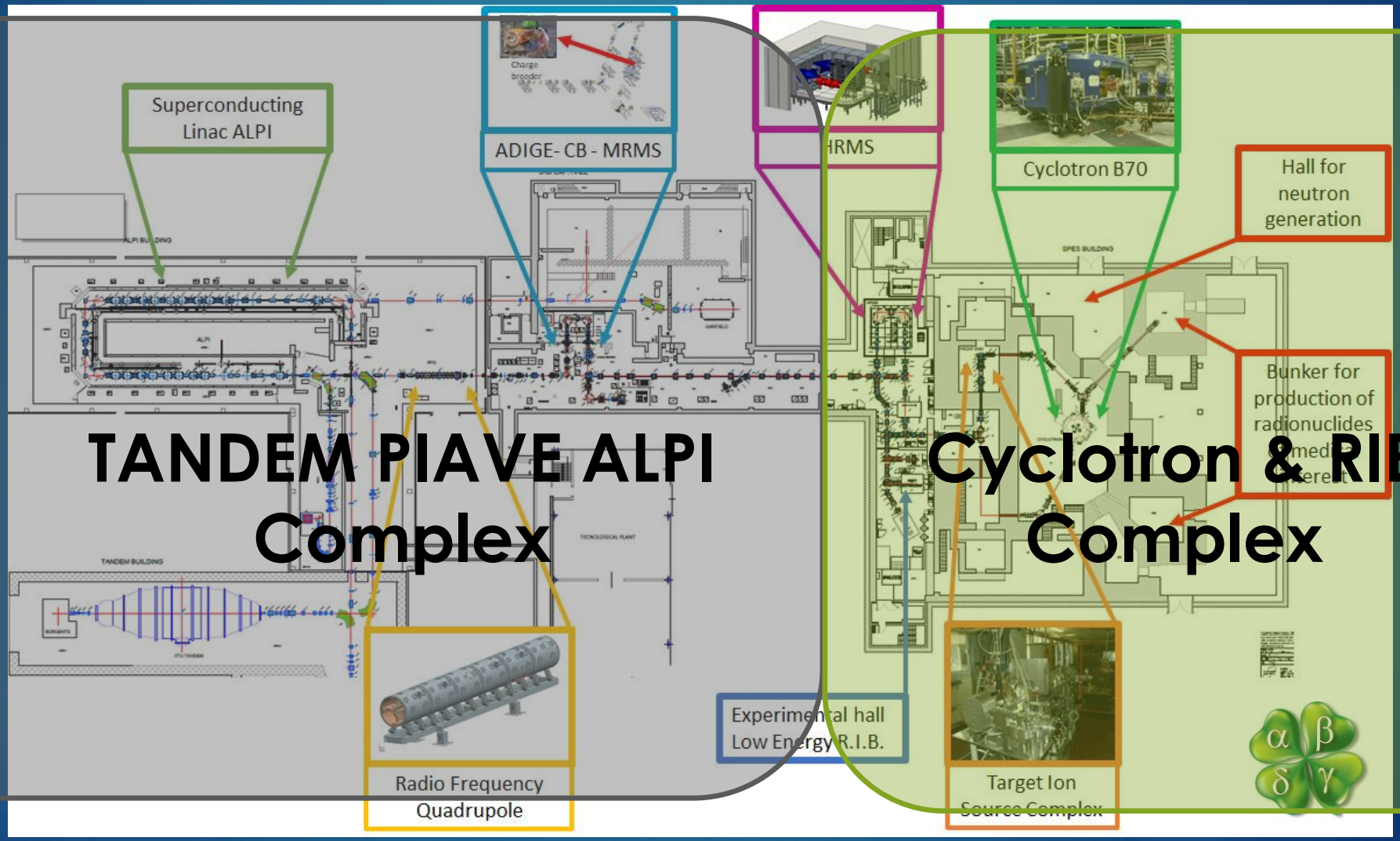


SPES Project

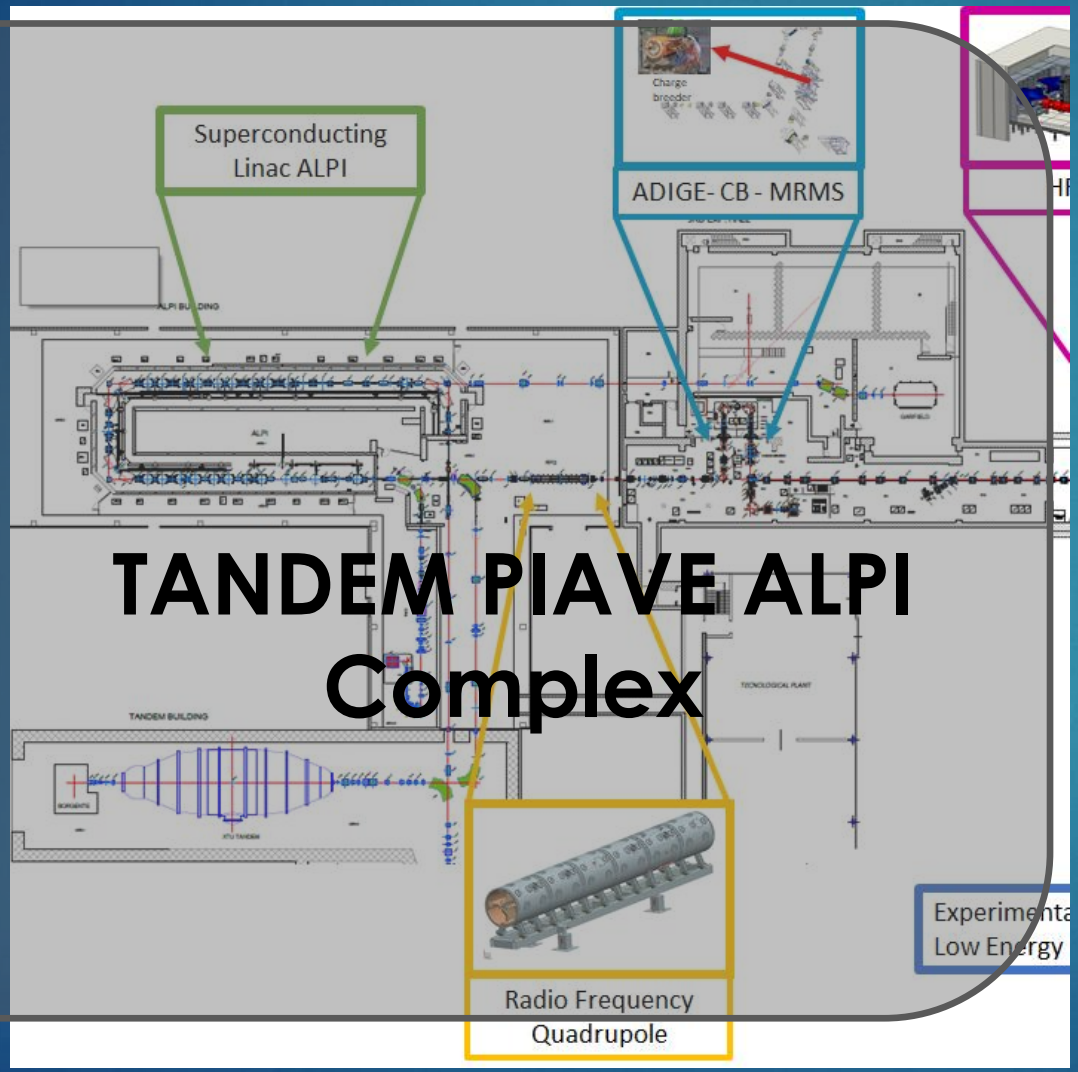
SPES Project at INFN-LNL



SPES Project at INFN-LNL



The *Beginning* of the EPICS Journey

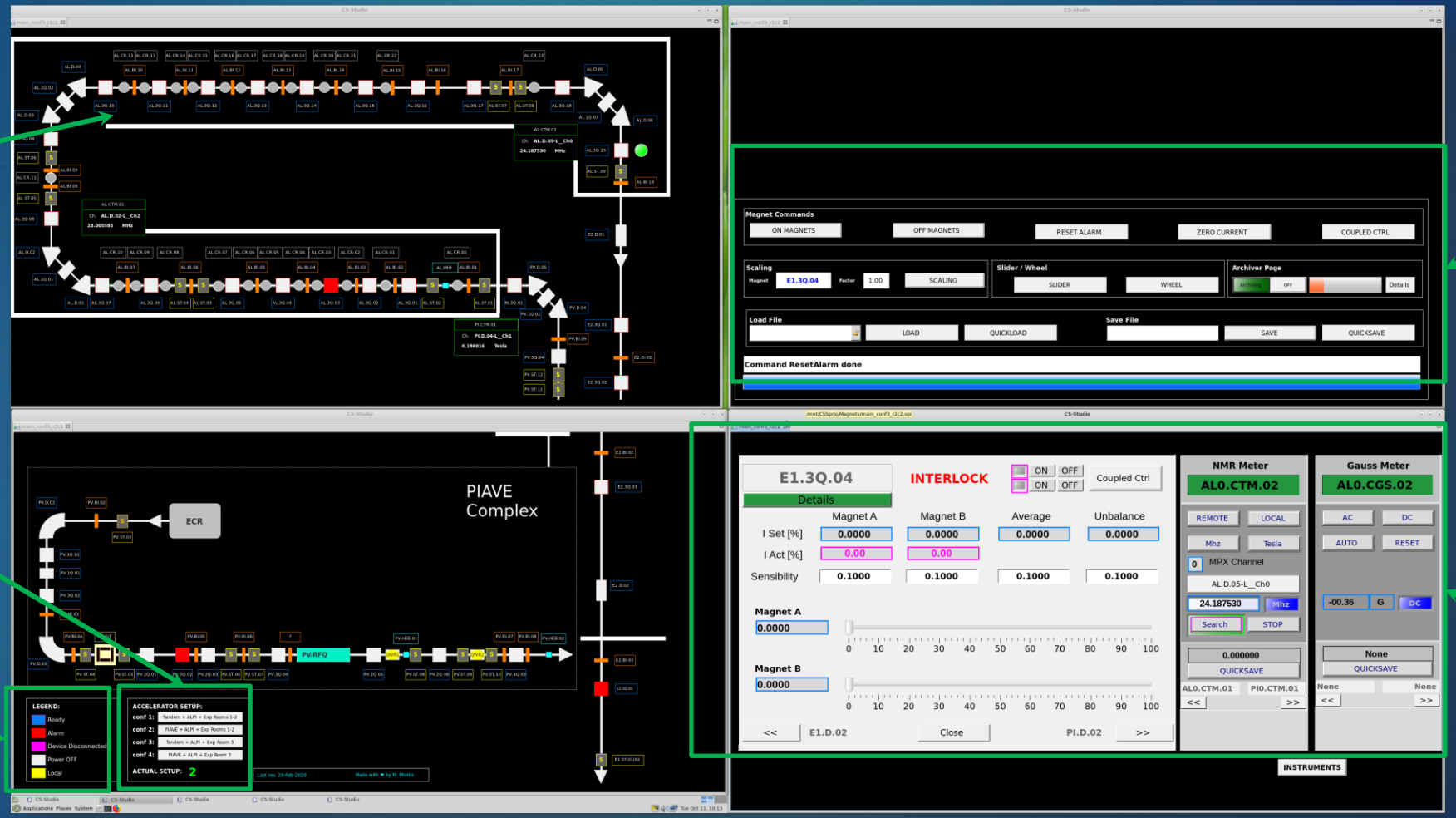


Main points (and challenges):

- Migration from an in-house control system solution (based on C/C++ and Java) to an EPICS based standard
- The accelerator lines are in operation (no long operation stops)
- Migrating the software without changing the hardware
- First system under analysis:
  PIAVE – ALPI Beam Trasport lines

PIAVE-ALPI Beam Transport Lines

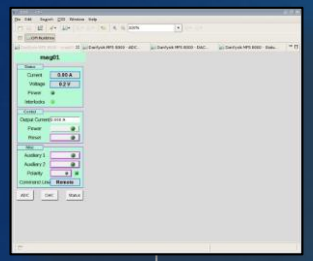
Synoptic from Human-Machine Interface in EPICS



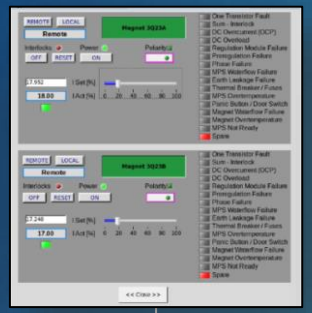
Beam Transport Control System Evolution - GUI

Upgrade Naming Convention

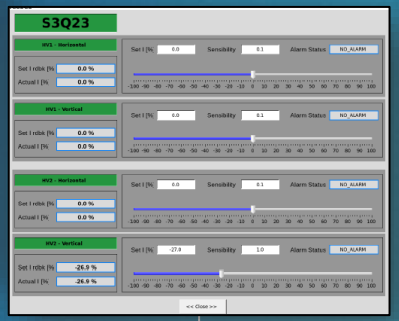
First Prototype



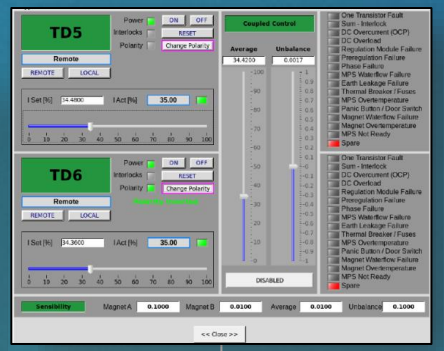
First Magnet GUI



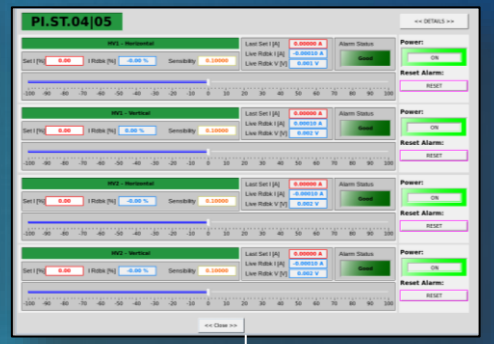
First Steerer GUI



Upgrade Magnet GUI



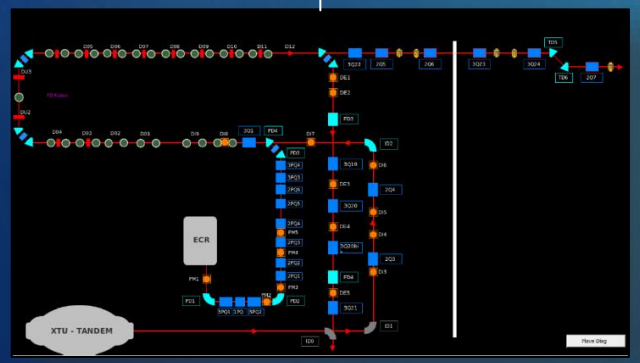
Add new Steerer GUI



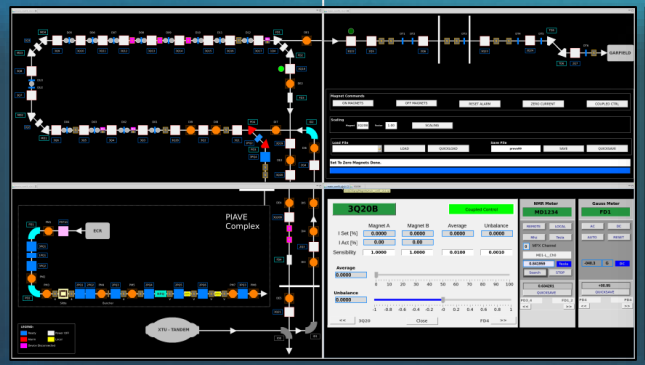
Add new Magnet GUI

Timeline

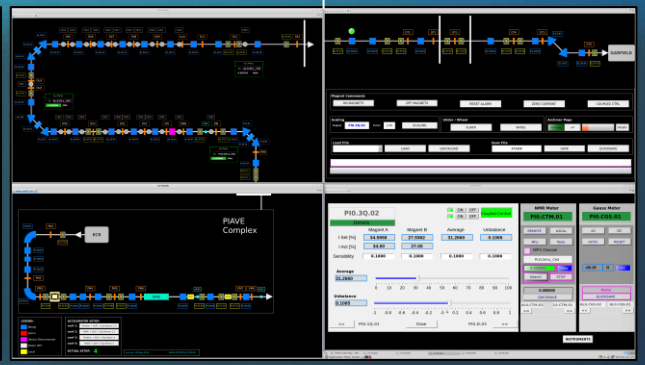
2013 — 2014 — 2015 — 2016 — 2017 — 2018 — 2019 — 2022



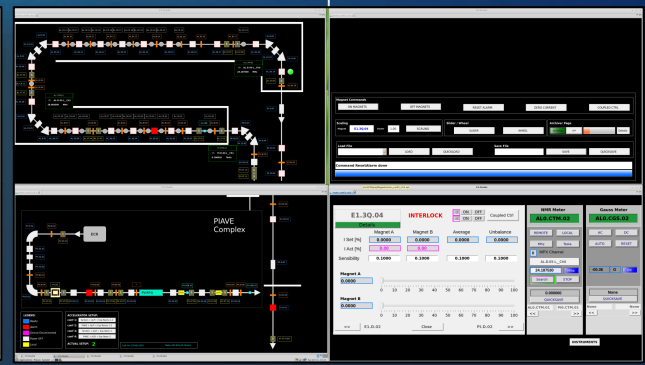
First Synoptic



New Synoptic with 4 monitor



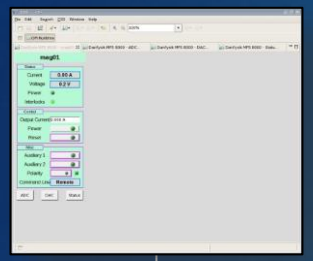
Upgrade Synoptic #1



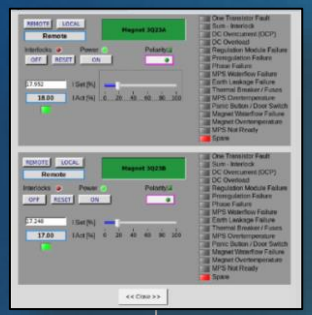
Upgrade Synoptic #2

Beam Transport Control System Evolution - HW

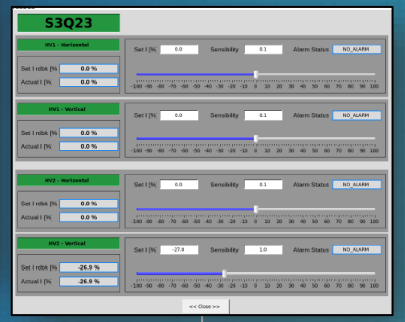
First Prototype



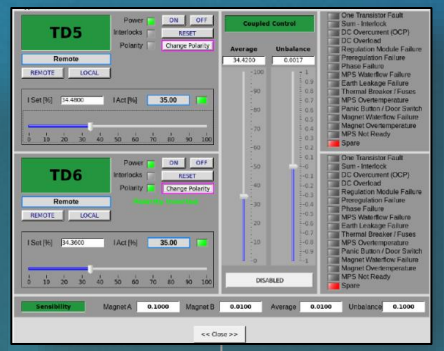
First Magnet GUI



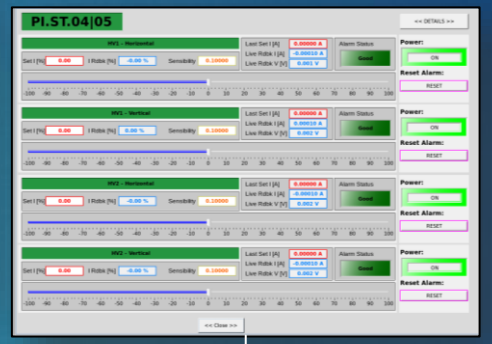
First Steerer GUI



Upgrade Magnet GUI



Add new Steerer GUI

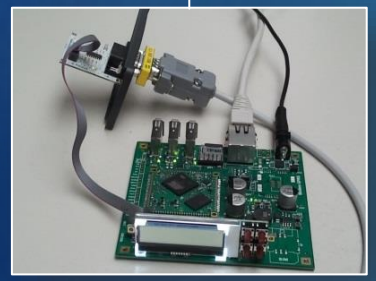


Upgrade Naming Convention

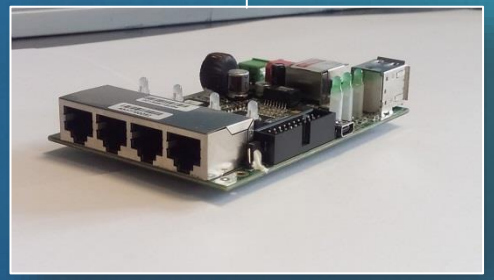
Add new Magnet GUI

Timeline

2013 — 2014 — 2015 — 2016 — 2017 — 2018 — 2019 — 2022



First Prototype



ARM Based EPICS IOC
In production since **December 2014**

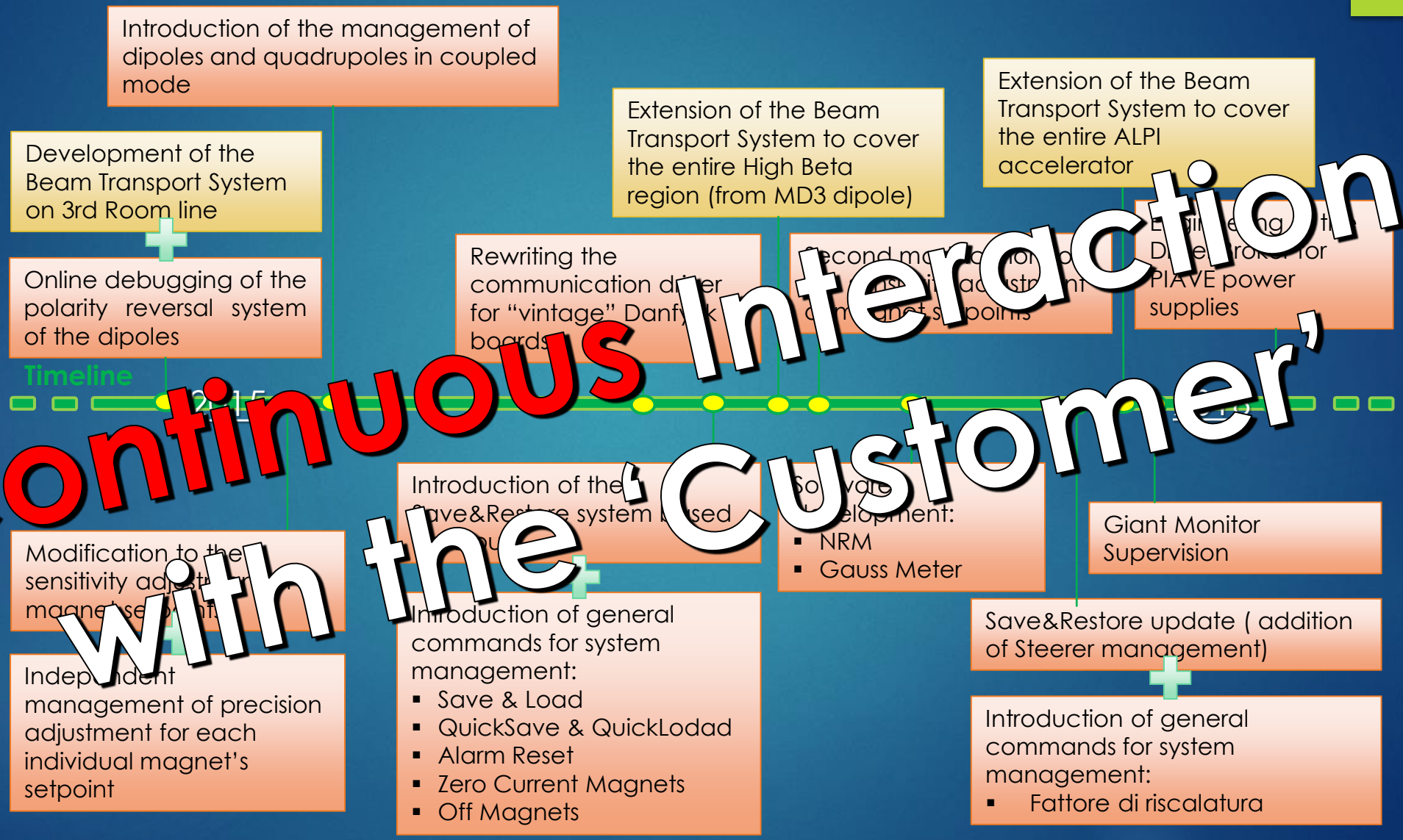
Devices with Ethernet communication

PROXMOX

Virtual Machines
(Only for new devices)

Devicemaster (Serial-to-Eth)
in production since **September 2022**
(in substitution of INTEL IOC)

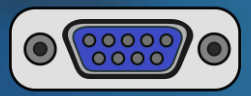
Upgrading a Control System Means…

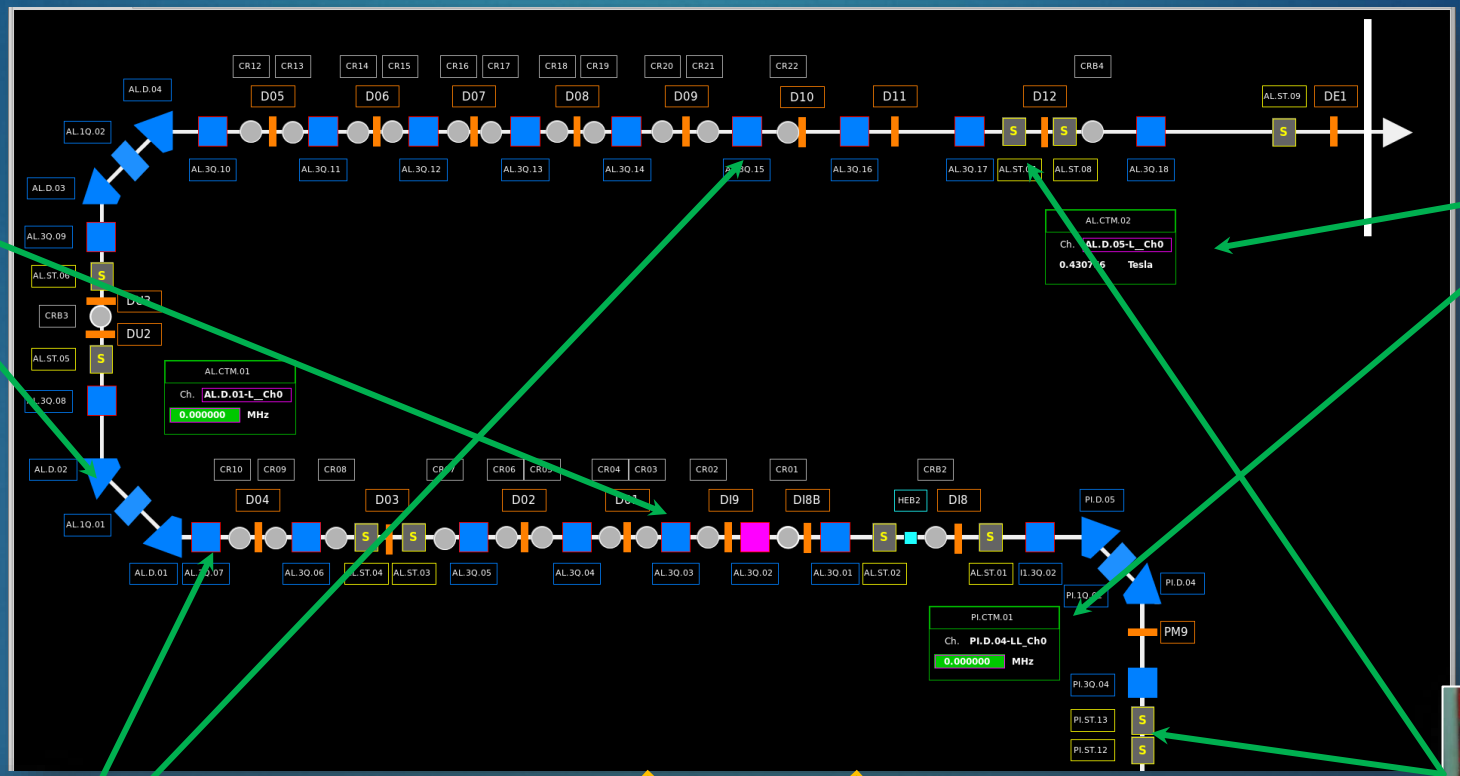


Continuous Interaction with the 'Customer'

Hardware used in the PIAVE-ALPI lines

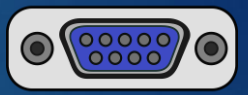
Lens PS

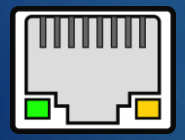




NMR Meter

Gauss Meter





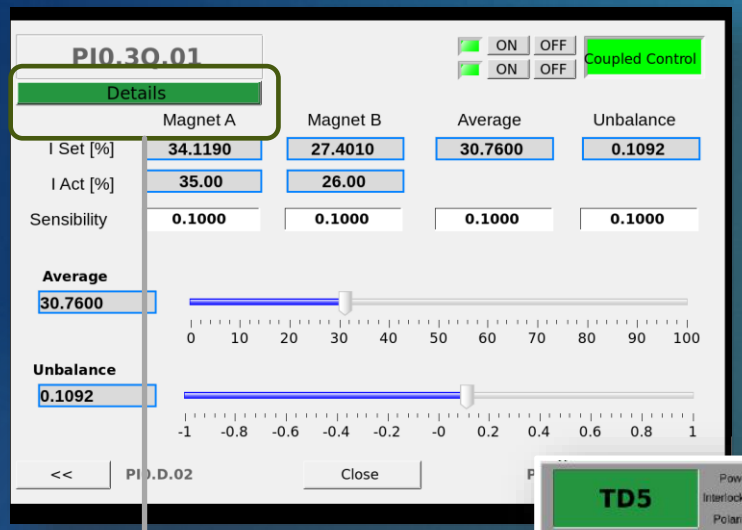
Lens PS (+ controller)

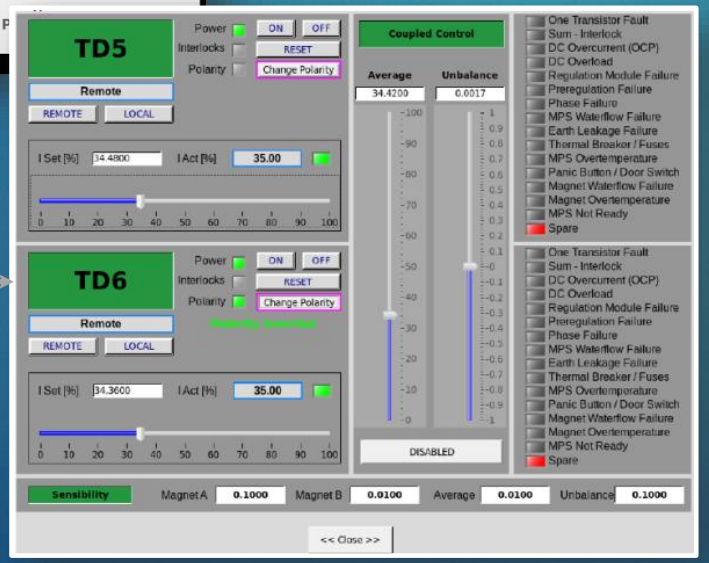
Old Steerer PS

New Steerer PS

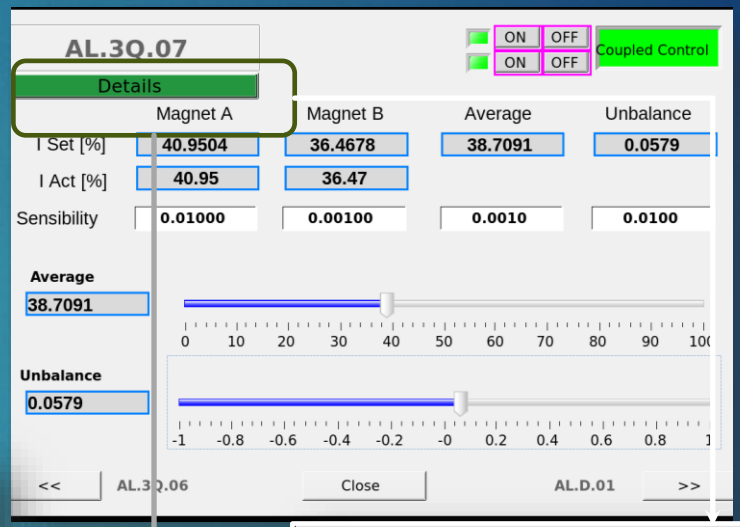
The importance of the User Experience

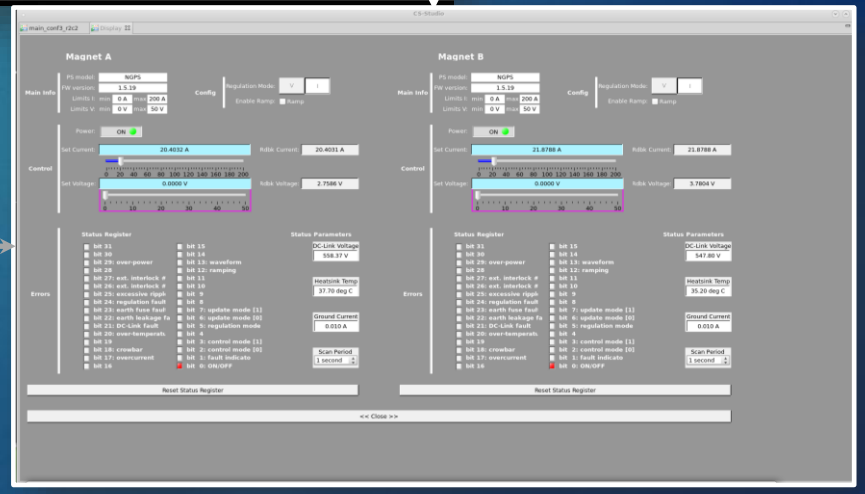
Danfysik Power Supply





Caenels Power Supply

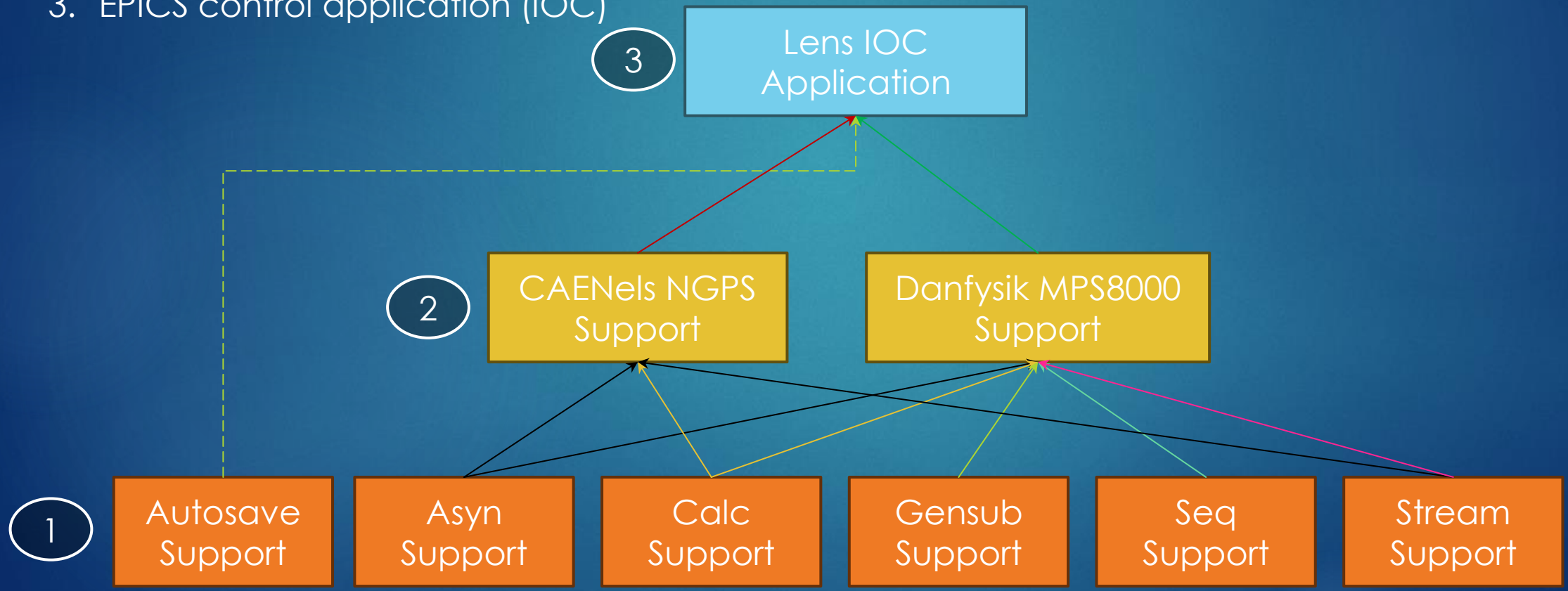




EPICS Software Structure for Lens Control

Main Groups:
1. EPICS Community Modules
2. LNL Custom Modules
3. EPICS control application (IOC)

Simplest way to work **with the** Community and **for the** Community



PIAVE-ALPI Beam Transport in Numbers

Parameter	Serial Communication	Ethernet Communication
Number of EPICS IOCs (*)	8 (lens) 1 (NMR) 1 (gauss meters)	11 (lens) 18 (steerers)
Number of Devices	Magnets: 70 NMR: 3 Gauss Meters: 3	Magnets: 11 Steerers: 18
Number of EPICS Variables	~ 5000 PVs	~ 8500 PVs

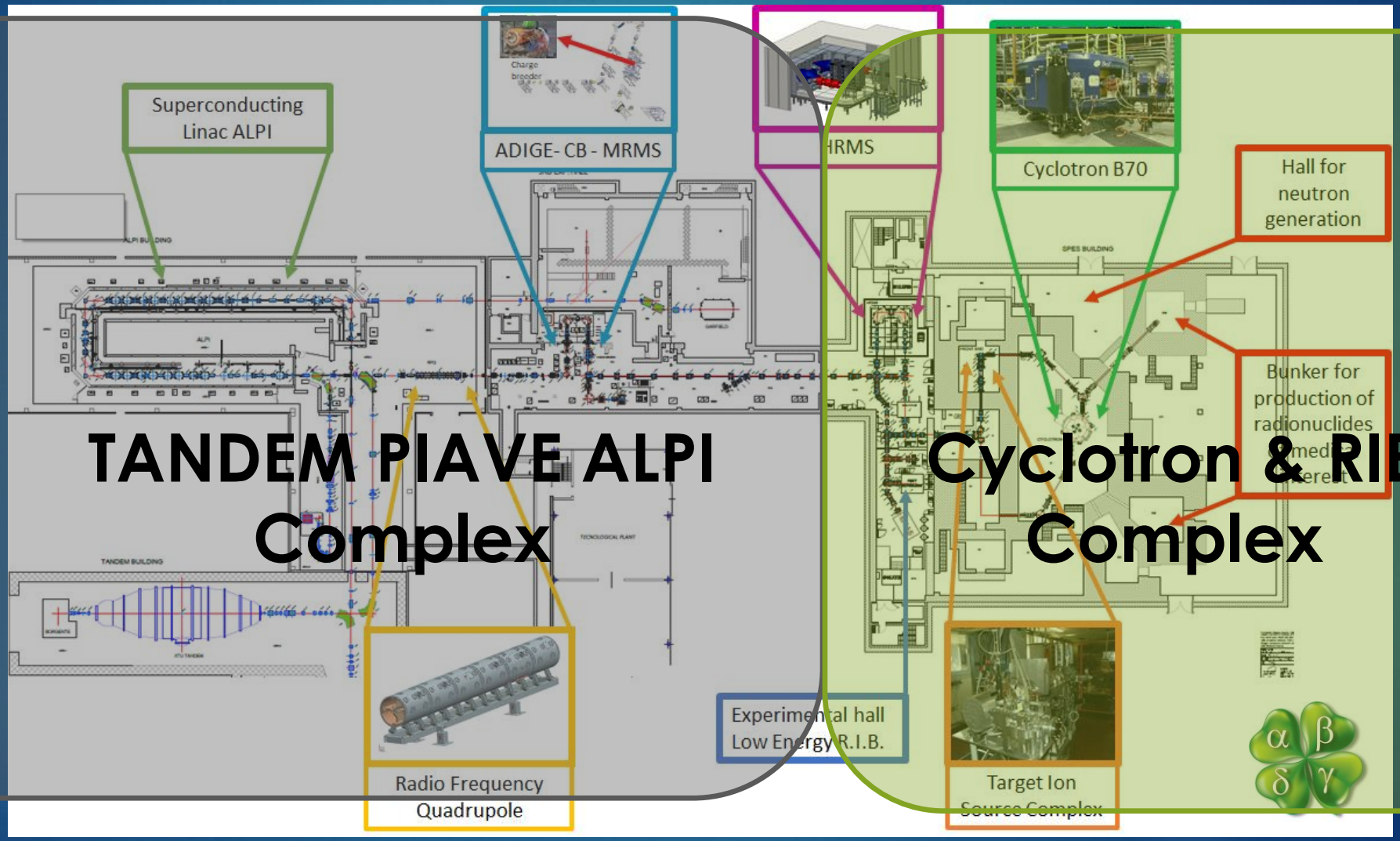
(*) All the IOCs run in Virtual Machines:

Hypervisor

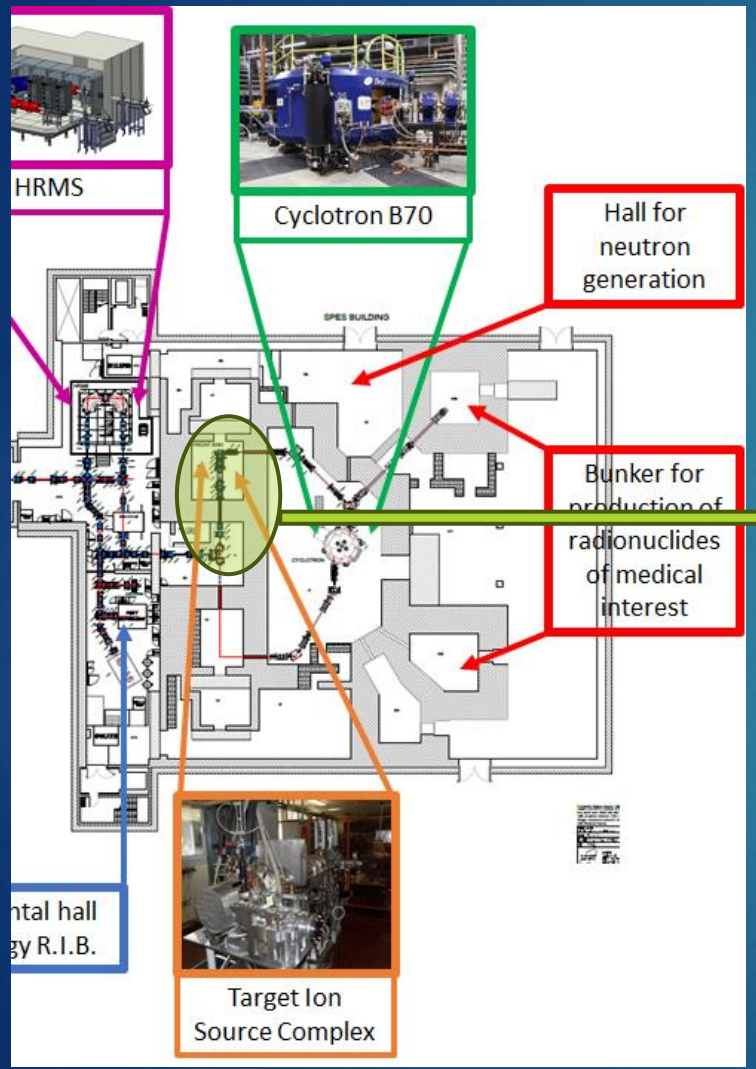
+

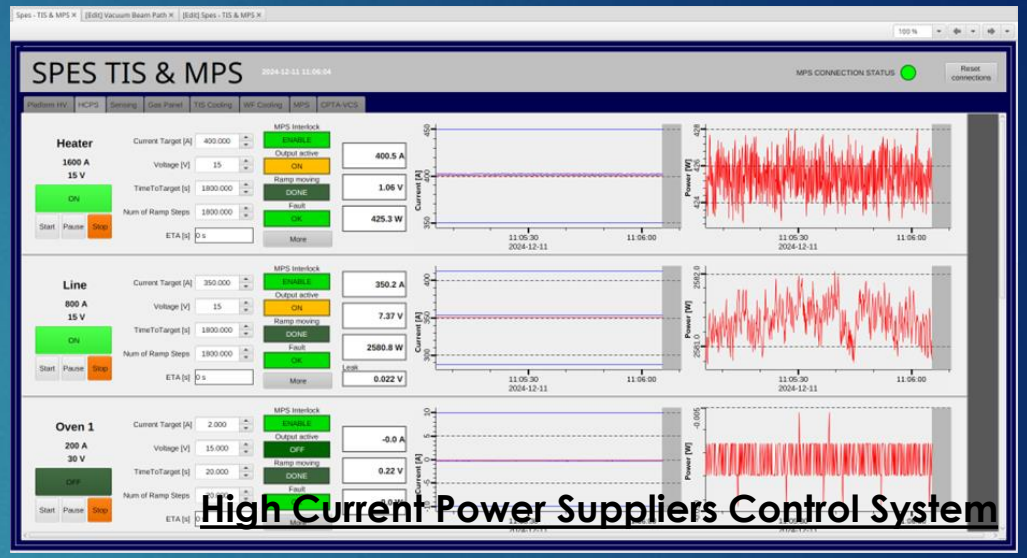
VMs

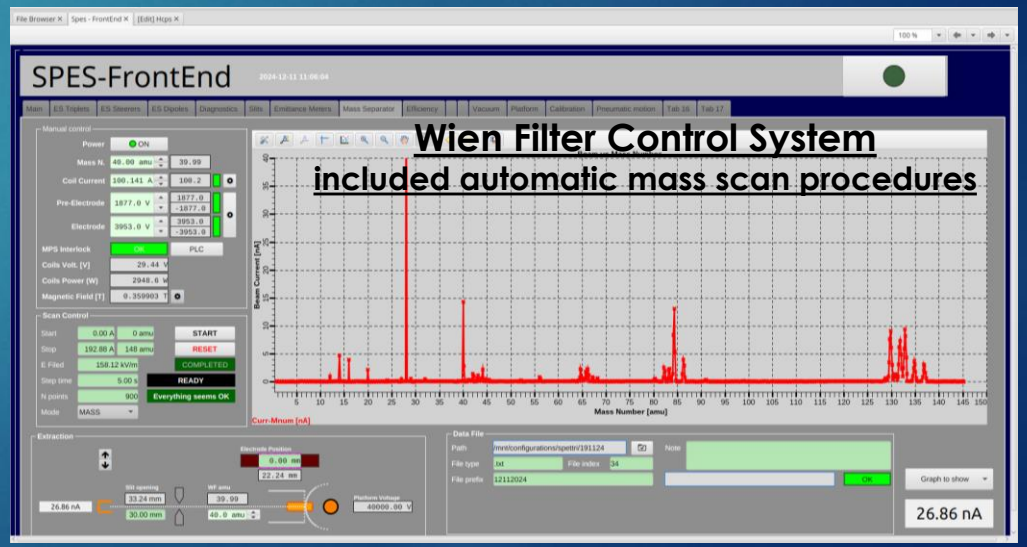
The New Cyclotron & RIB Complex



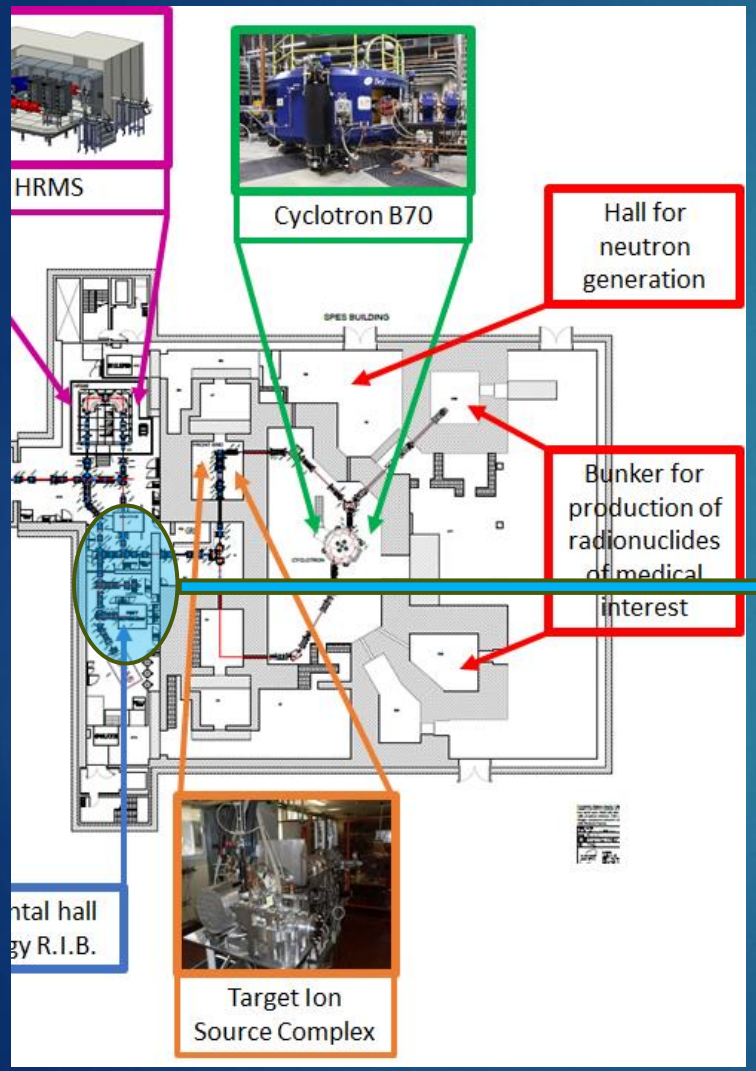
The Cyclotron & RIB Complex

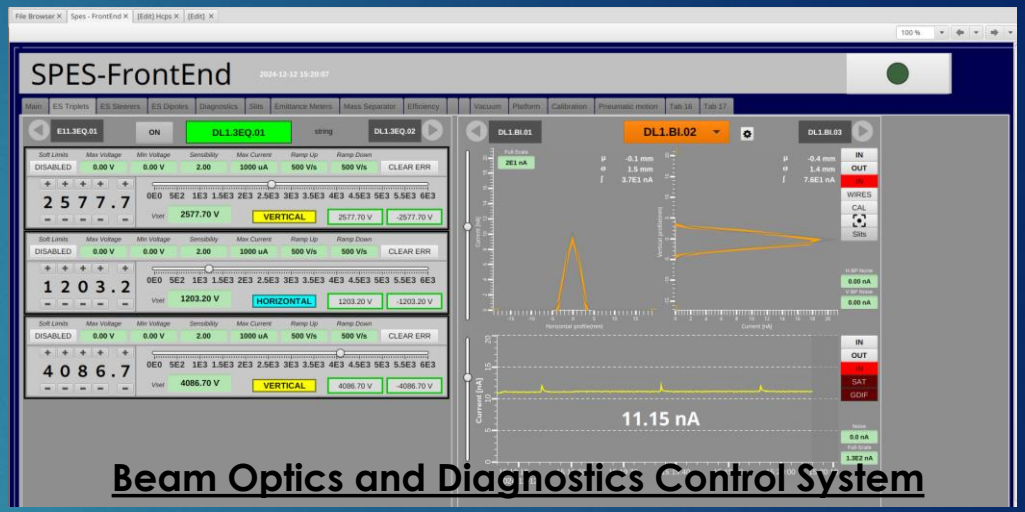




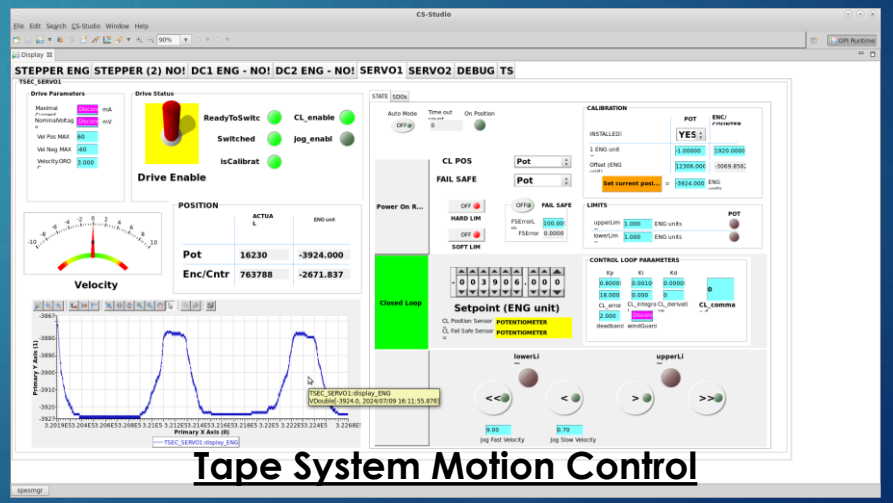


The Cyclotron & RIB Complex





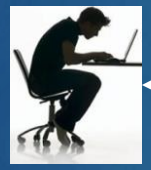
Beam Optics and Diagnostics Control System



Tape System Motion Control

The consequences of adopting EPICS



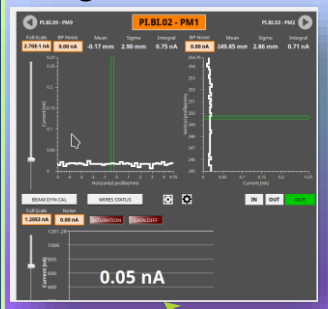

Integrated Distributed Control

EPICS

- Vacuum
- Beam Transport
- Diagnostics
- RF
- Cryo

The consequences of adopting EPICS

Diagnostics

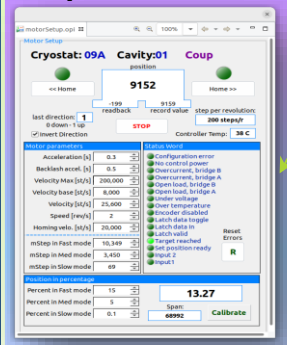


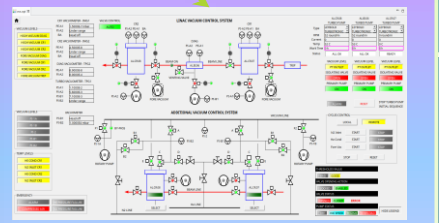
RF

EPICS

Beam Transport

Cryo





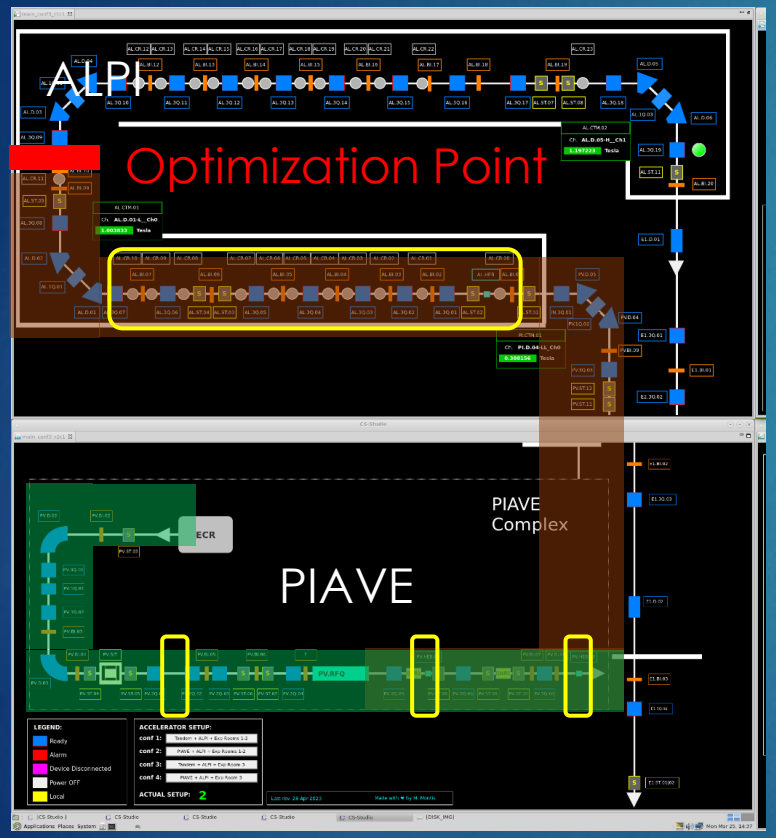
Vacuum

- Vacuum
- Beam Transport
- Diagnostics
- RF
- Cryo

Work done by INFN-LNL Controls Group

The Consequences of Adopting EPICS

Use of **Artificial Intelligence** and **Machine Learning Techniques**



48 parameters per iteration

Ion Source & PIAVE

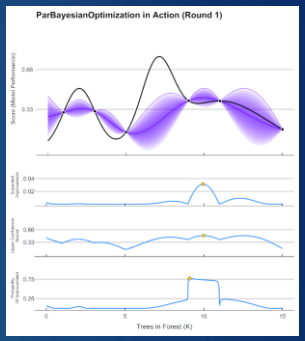
Trasverse Optic

Cavities
(Super Conductive & Normal Contuctive)

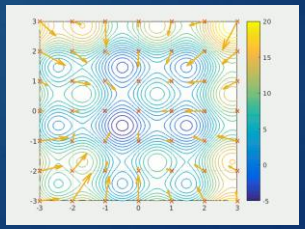
Final optimization in about 2 hours

AI/ML Techniques

Bayesian Technique



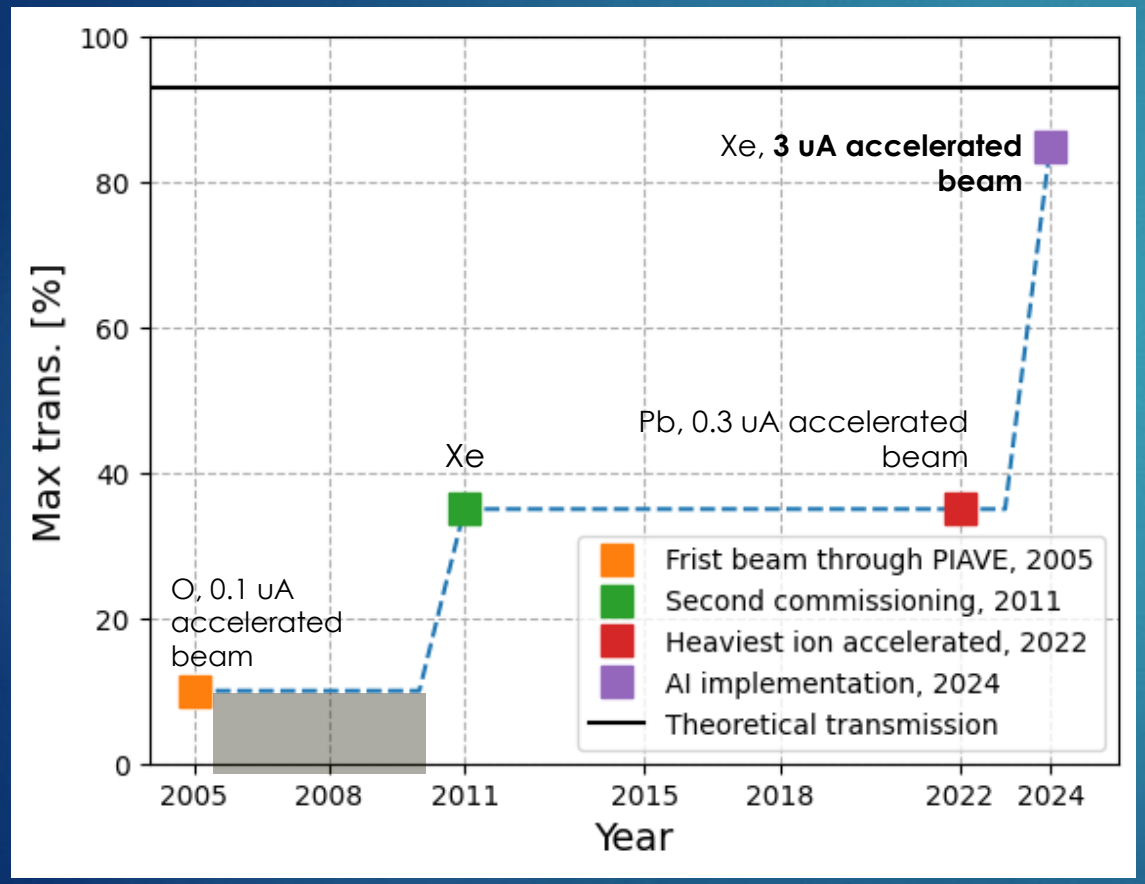
Particle Swarm Opt.



Pubblication: L. Bellan et al., "**New techniques method for improving the performance of the ALPI Linac**", Journal of Instrumentation, vol. 19, T03005, March 2024. DOI:10.1088/1748-0221/19/03/T03005

The Consequences of Adopting EPICS

Use of **Artificial Intelligence** and **Machine Learning Techniques**



Big Achievement (**thanks to EPICS**)

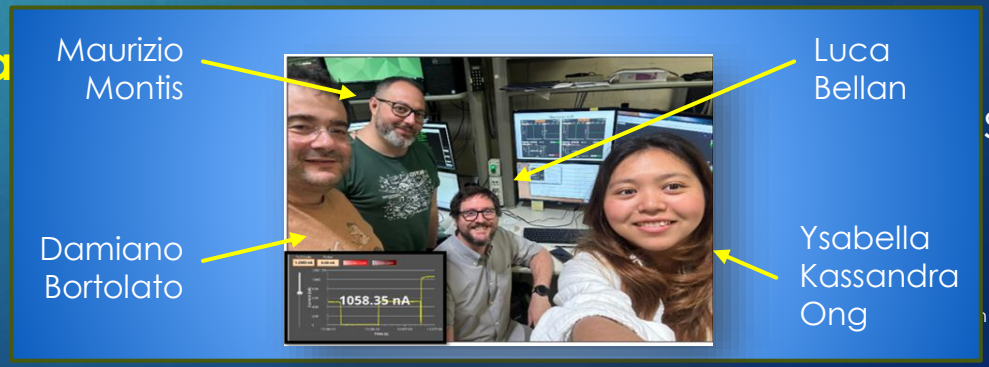
Official data and milestones related to PIAVE-ALPI

Recorded data of transmission of ALPI complex.
First beam commissioning from PIAVE in 2005

Main Achievements:

- In June 2024 **REACHED 85%** of ALPI transmission (cavities on).
  - Note: RECORD since its construction, roughly 20 years ago.

- **Ma**
  -



Opensource in Control Systems

Where possible, opensource solutions have been adopted in the Control Systems

- **Operative Systems**

- **Control System Framework**

- **Virtualization Hypervisors**

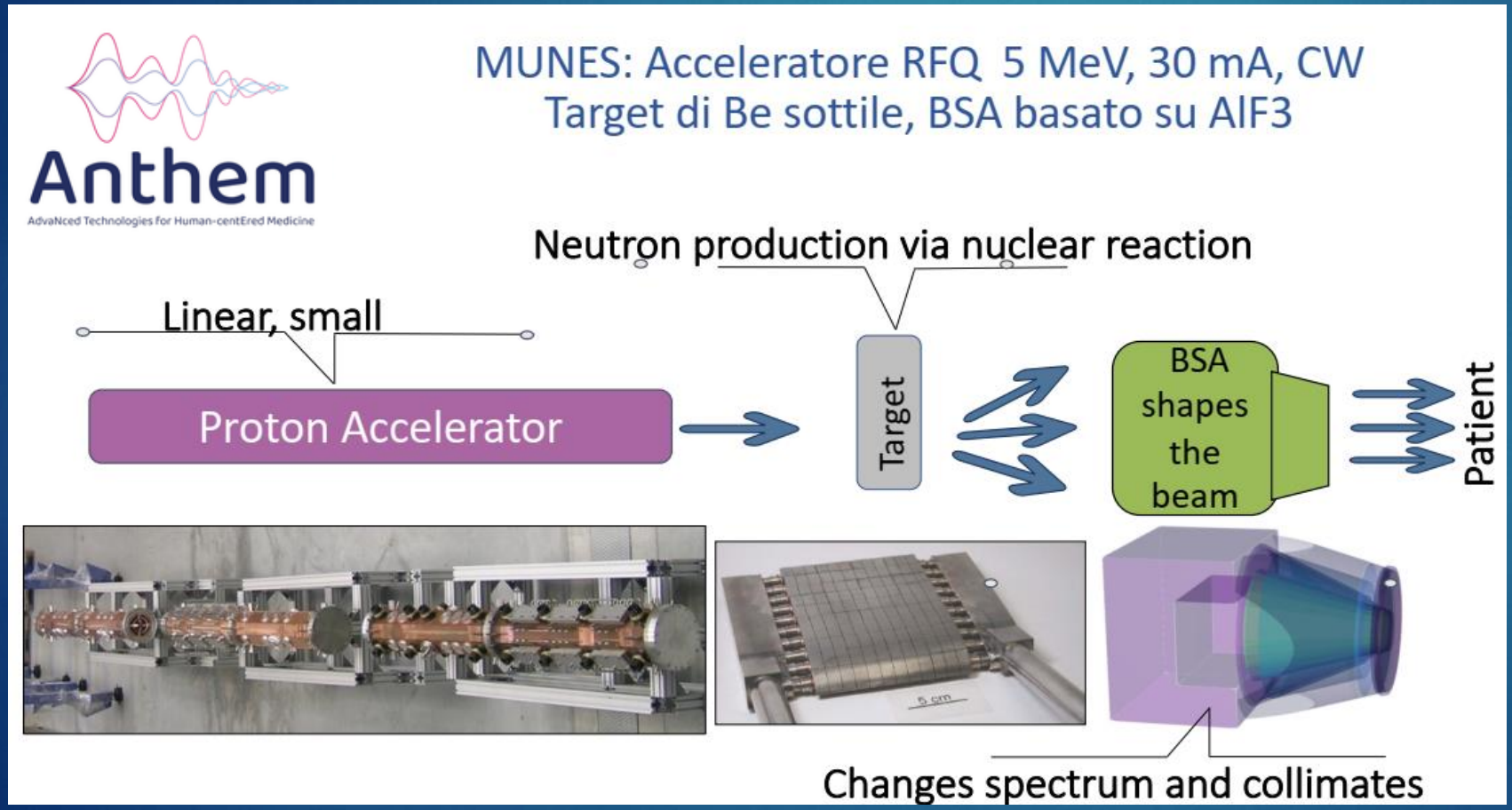
- **Applications and Services for IT architectures**

- **Program Languages and Libraries**

Not Only at LNL…

The ANTHEM Project

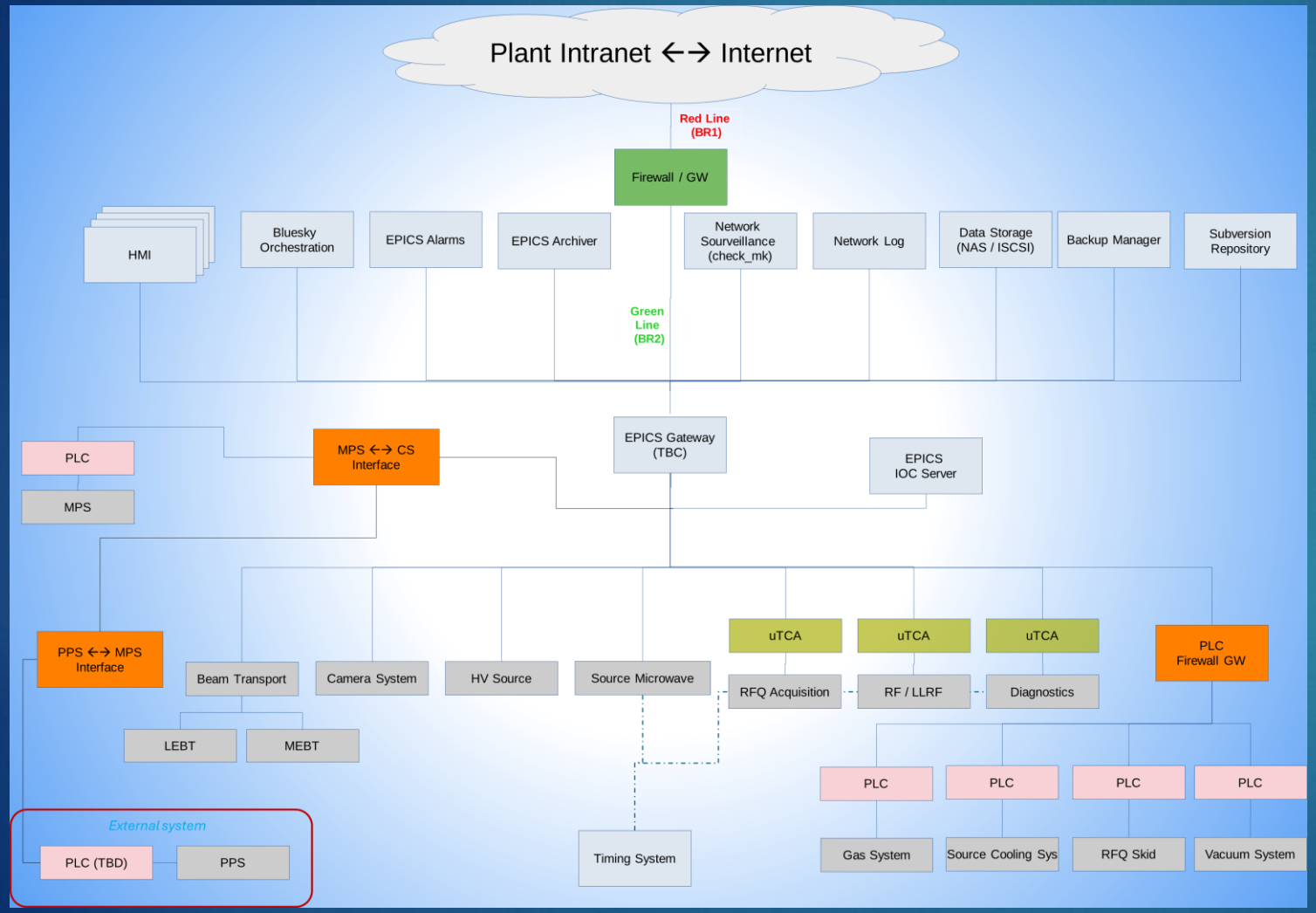
Adva**N**ced **T**echnologies for **H**uman cent**E**red **M**edicine



Based on BNCT (Boron Neutron Capture Therapy)

Final installation:
UniNa Vanvitelli - Caserta

ANTHEM Control System



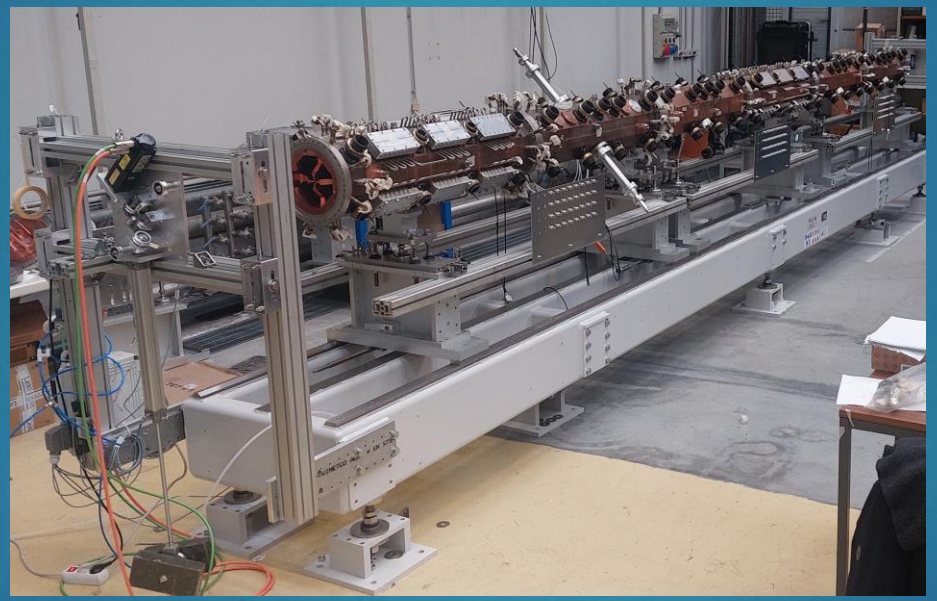
Characteristics of this design:

- Defined to be a **standalone control system**
- **3-Layer** architecture
- PLC network as a subnet to the EPICS network Managed via proper interface
- EPICS V7 framework (PVA)
- Virtualize as much as possible to optimize space, costs and maintenance

ANTHEM Control System - WIP

R&D Activities at INFN-LNL (not only controls...)

Proton Ion Source (TRIPS)

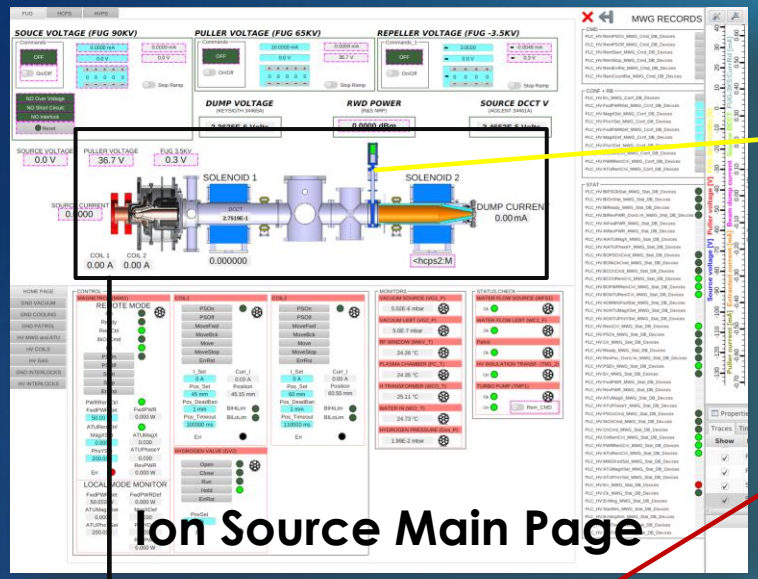


Radio Frequency Quadrupole (TRASCO)

Coupler Power Tests

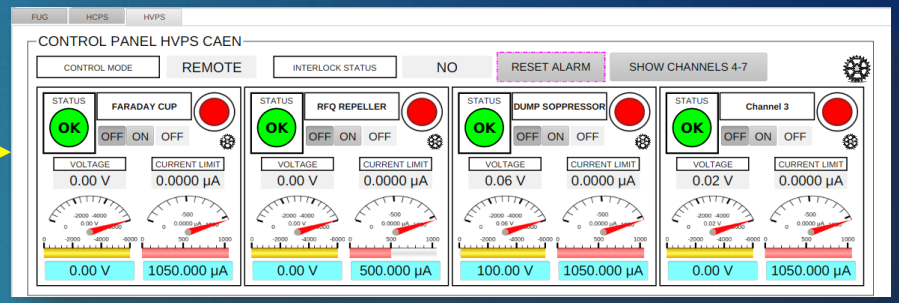
ANTHEM & EPICS Summer School

Activity done by Lorenzo Delgado for the ANTHEM Project (MS Thesis)

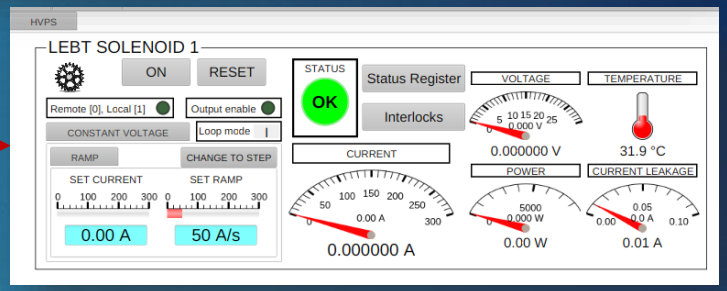


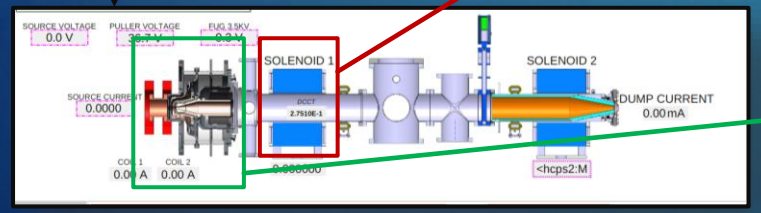
Ion Source Main Page

HV Power Supply

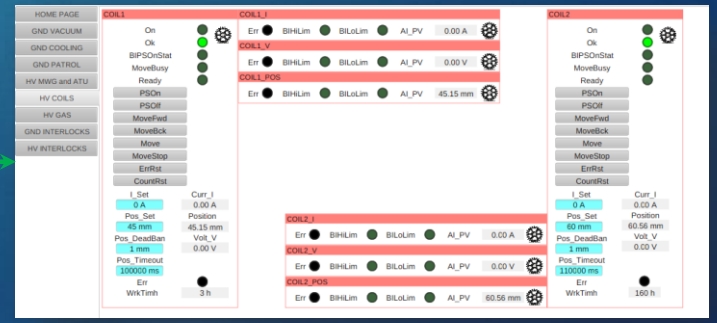


HC Power Supply





Motion (PLC Control)



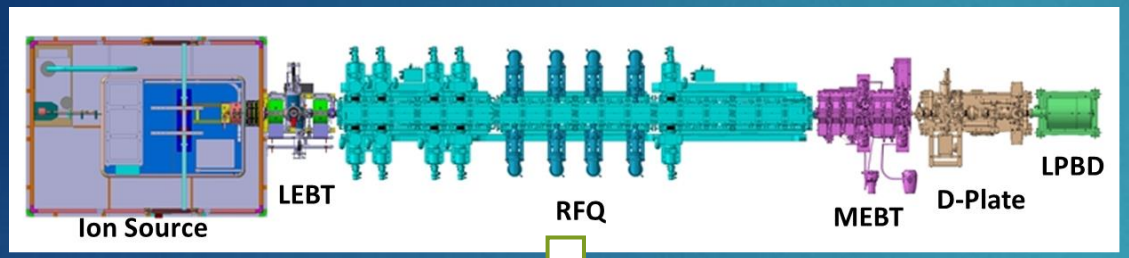
IFMIF Project

JAPAN: WHERE YOU CAN FIND VENDING MACHINES SELLING EVERYTHING FROM SUSHI TO SOCKS, AND TOILETS THAT GREET YOU WITH A SYMPHONY OF SOUNDS

IFMIF & IFMIF–LIPAc Project

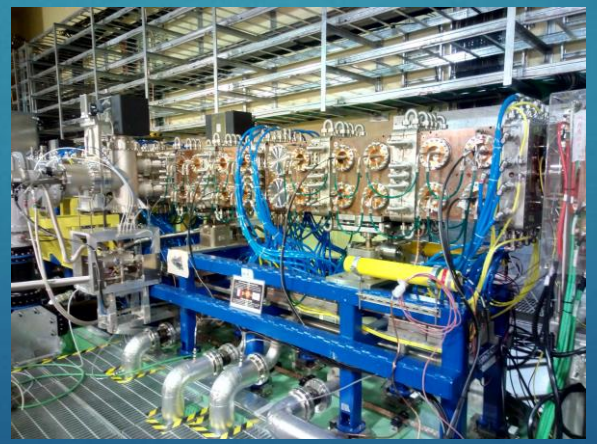
IFMIF (International Fusion Materials Irradiation Facility):

IFMIF-LIPAc: Linear IFMIF Prototype Accelerator



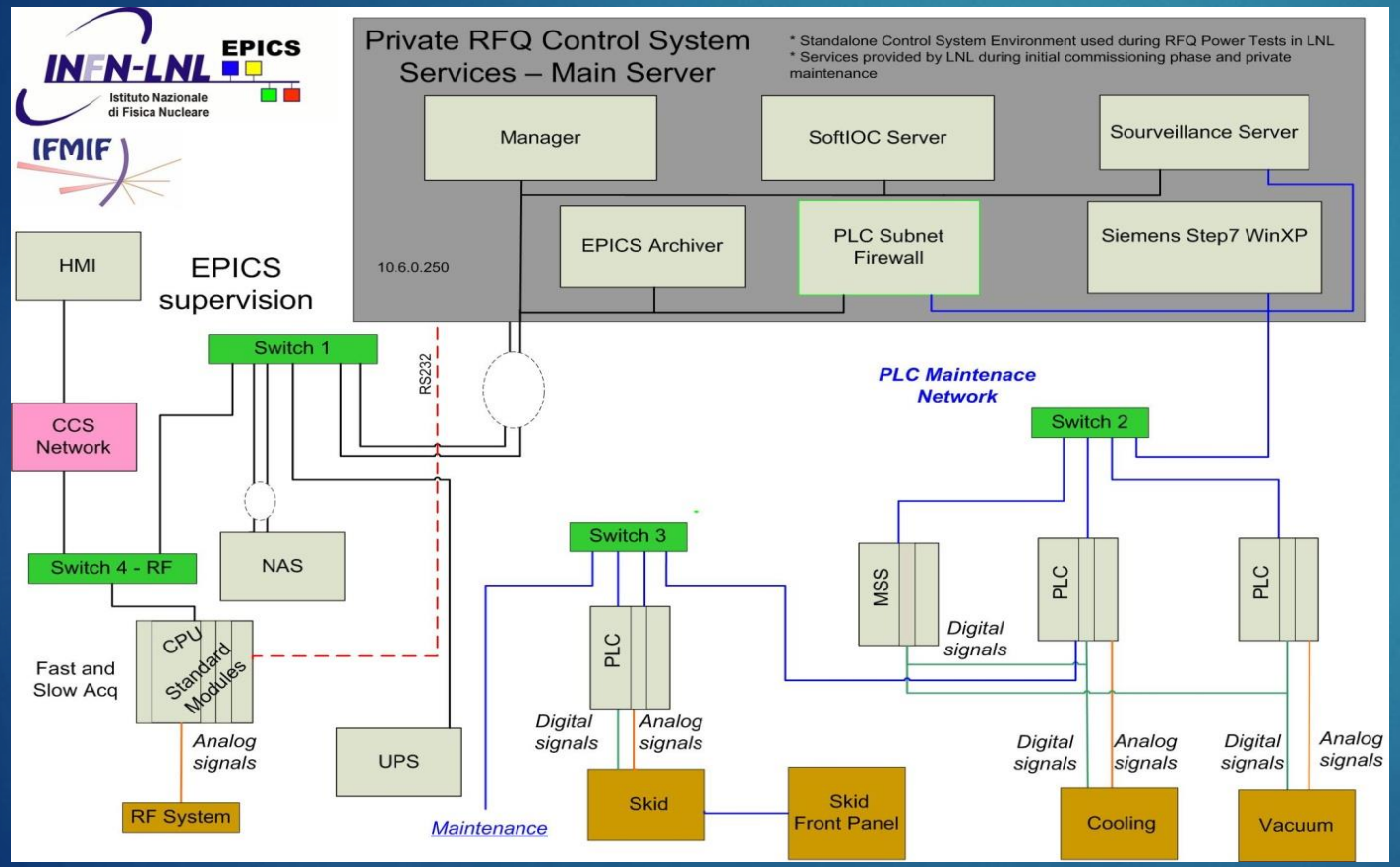
The RFQ will pre-bunch the DC beam from the ion source and will accelerate the beam from 0.1 to **5 MeV** at max **125 mA** current.

→ RFQ Apparatus is the Italian contribution to the IFMIF-LIPAc project (control included)



IFMIF RFQ LCS Architecture

LCS: Local Control System



- **Control Loop (between different systems):**

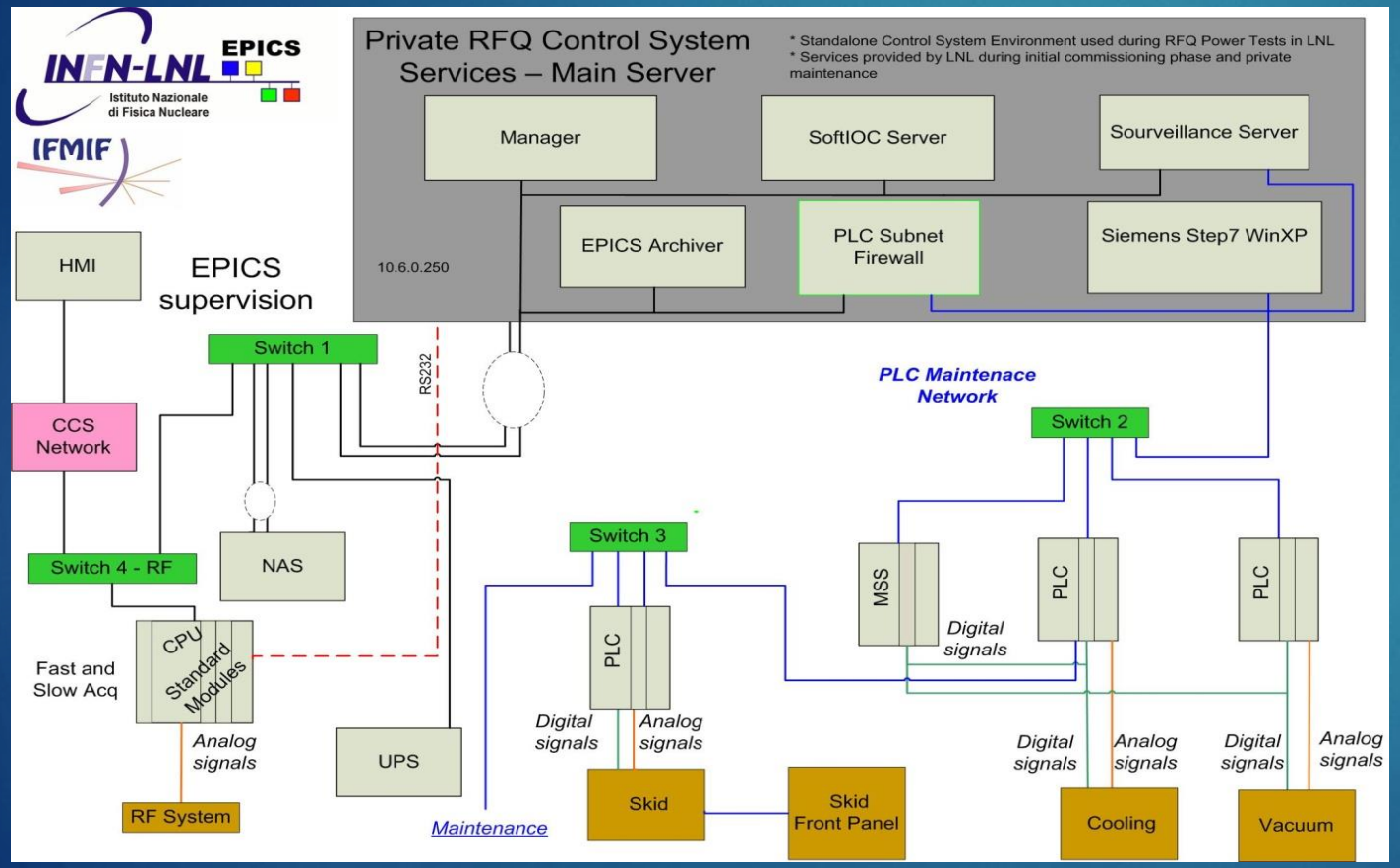
CL between RF and Cooling Systems to minimize frequency detuning into the cavity

- **Logics and Algorithms distributed between PLC and EPICS**

- **Functional Subsystems – HW:**
  - Vacuum: PLC
  - Cooling: PLC
  - RF acquisition: VME
  - RF analysis: general purpose PC (VM)

IFMIF RFQ LCS Architecture

LCS: Local Control System

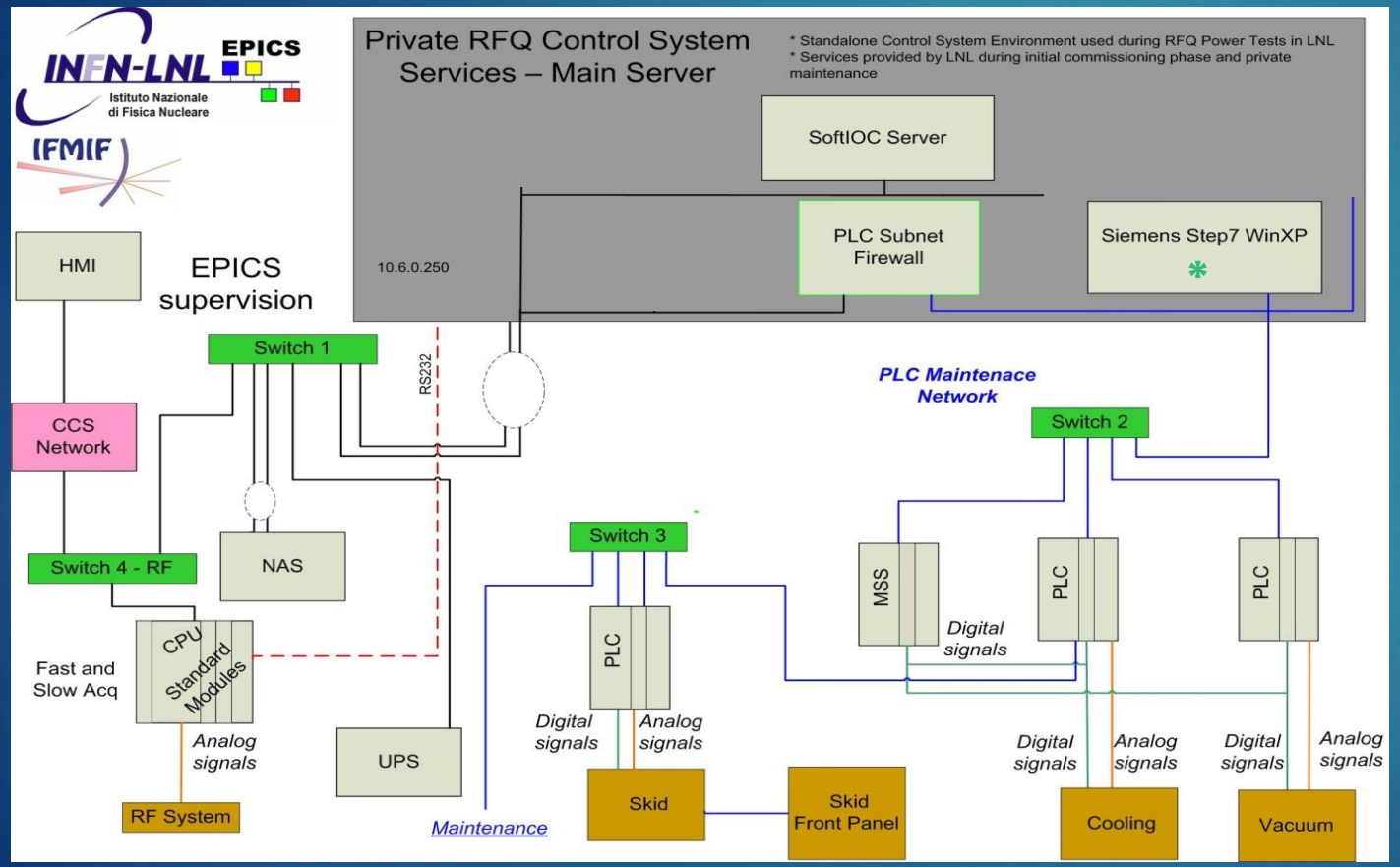


Control System Architecture **validated** during **RFQ power tests** performed at LNL in **2014**.

LCS started Installation in Japan in **July 2016.**

- At EPICS level, commissioning went smoothly and fast because:
  - Basic guidelines to follow
  - Simple EPICS architecture adopted
  - Central Control System under implementation in parallel

IFMIF RFQ LCS Architecture – Final Ver.



LCS started Installation in Japan in **July 2016**

RFQ LCS SAT (Site Acceptance Test) performed in **December 2017.**

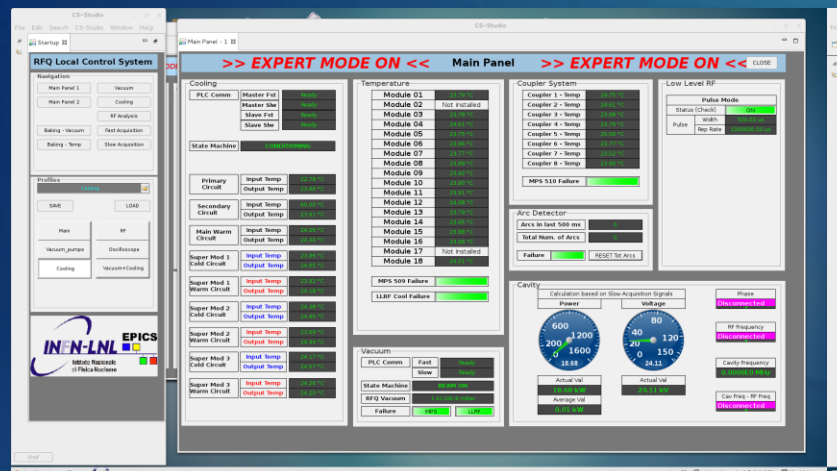
Tests included:

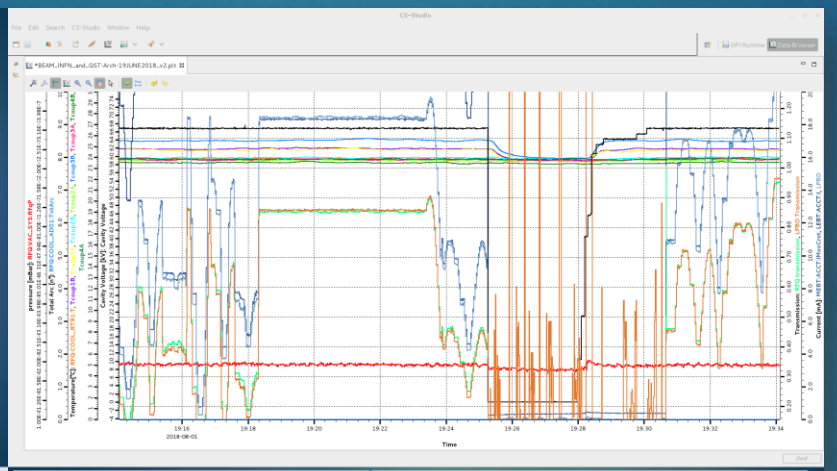
- **Documentation** (Manuals, Reports, etc.)
- Applications functionality and compliance with Guidelines (EPICS code and PLC code)
- Integration with central tools
- HW and SW interfaces with other LCSs , MPS, PPS and Central Control

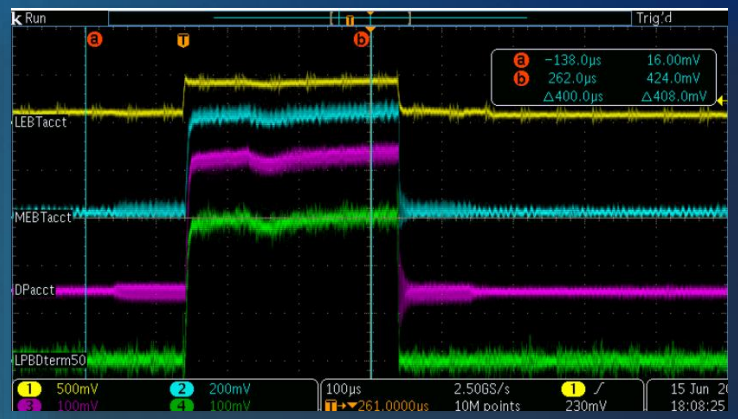
IFMIF RFQ LCS in Numbers

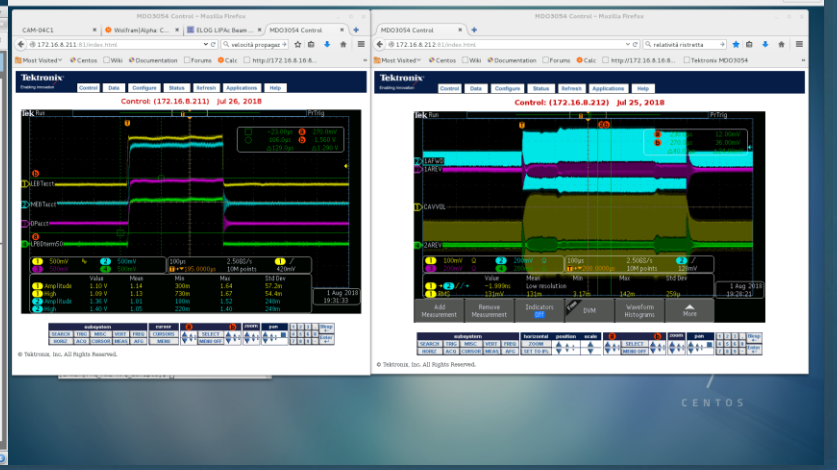
Number of	Power Test	Final Stage
IOCs	6	4
EPICS DBs	17	37
EPICS Variables (PVs)	1153	~8000
EPICS Variables Archived	970	~1600
GUI panels	15	14

IFMIF RFQ LCS in Action









First proton beam injected into the RFQ on 13 June 2018

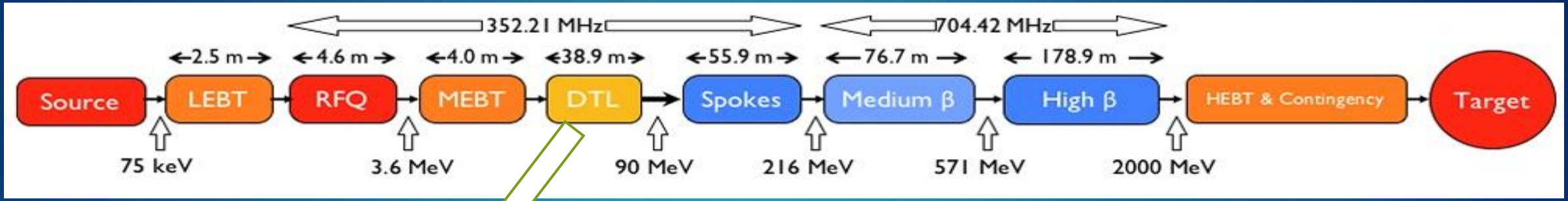
ESS Project

SWEDEN: WHERE MEATBALLS ARE A GOURMET DISH, AND THE ANSWER TO EVERYTHING IS OFTEN JUST A QUICK SAUNA SESSION AWAY

ESS Project

Project Description in the Presentation made by Timo

ESS Project – INFN Contribution



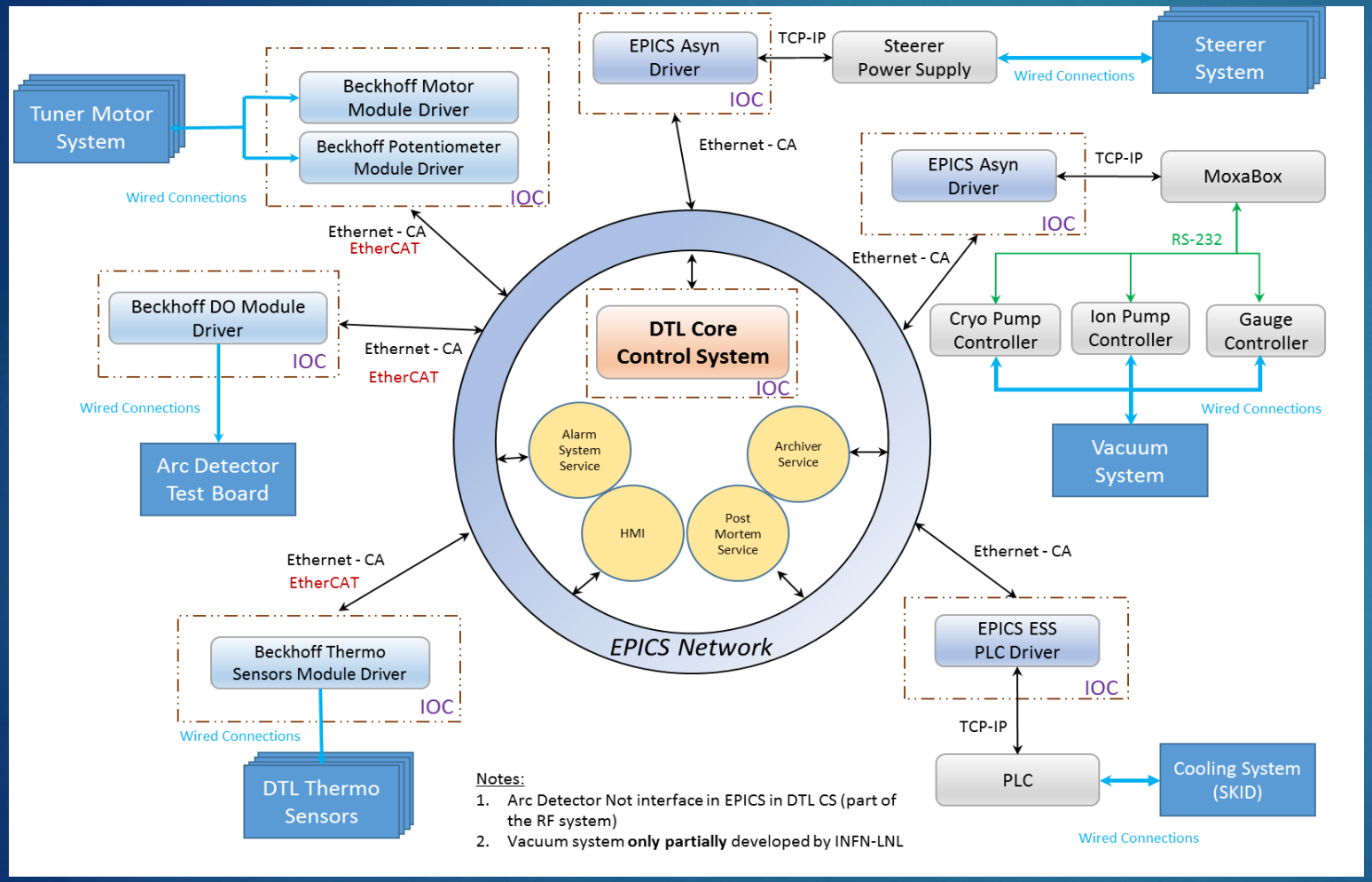
The DTL is designed to operate at 352.21 MHz, with a duty cycle of 4% (2.86 ms pulse length,14 Hz repetition period).

Permanent magnet quadrupoles (PMQs) are used as focusing elements on a lattice scheme that is, with half of the drift tubes left empty, leaving space for steerers and beam diagnostics.

The DTL apparatus is composed of 5 macro modules called tanks

→ DTL Apparatus one of the INFN contribution to the ESS project (control included)

DTL Control System - Technologies



Sub - System	Technology (SW – HW - Protocol)
Thermos Sensors	• EPICS integration and supervision • Beckhoff hardware • EtherCAT protocol
Tuners Motor System	• EPICS integration and supervision • Beckhoff hardware • EtherCAT protocol
Vacuum	• EPICS integration and supervision • Hardware provided by ESS • Serial / TCP-IP communication
SKID	• EPICS integration and supervision • Hardware provided by tender with PLC Siemens S7-1500 (low level I/O)
Steerer System	• EPICS integration and supervision • Hardware provided by tender • TCP-IP protocol communication
Arc Detector	• Hardware system based on AFT Microwave • Custom electronic board for Arc testing

E3 – ESS EPICS Environment

ESS' EPICS Environment (e3) is a design concept and a toolkit intended to

1. facilitate development by abstracting away some of the low-level complexities intrinsic to large EPICS implementations (primarily dependency management)

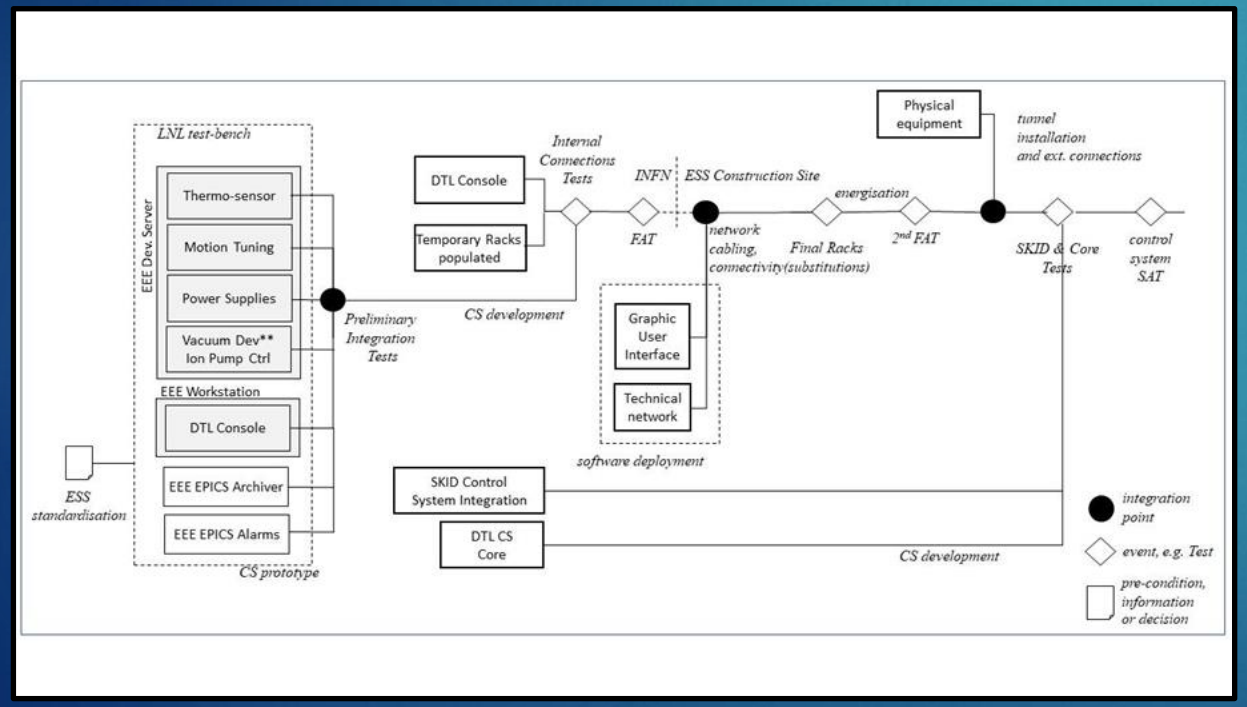
2. allow for more manageable quality control of released modules as well as IOCs

It allows for **easily building EPICS modules directly from source and automagically resolves module dependencies** and allows for site-specific modifications to EPICS modules without needing to directly modify source trees

Commissioning stage

A complex architecture (not only in terms of control system architecture) requires:

- Good plan
- Useful verification stages



Verification Strategy: 10 Steps

- **1st FAT**: hardware and software verification using only the control system racks (at INFN-LNL)
- **2nd FAT**: hardware and software verification using only the control system racks (at ESS-ERIC)
- **CT**: connection tests verification, checking the connection from DTL tank till the racks

- **Skid tests**: these tests cover the DTL Skid [ESS.ACC.A02.E05.G01] functionalities and the DTL Water Cooling system integration. Docs References: ESS-2979034 and ESS-3747673

- **SAT**: hardware and software verification using wired connections with the DTL, which is composed by:
  - SAT-1 related to DTL Tank 1 → SAT-1.a, SAT-1.b
  - SAT-2 related to DTL Tank 2,3,4
  - SAT-3 related to DTL Tank 5

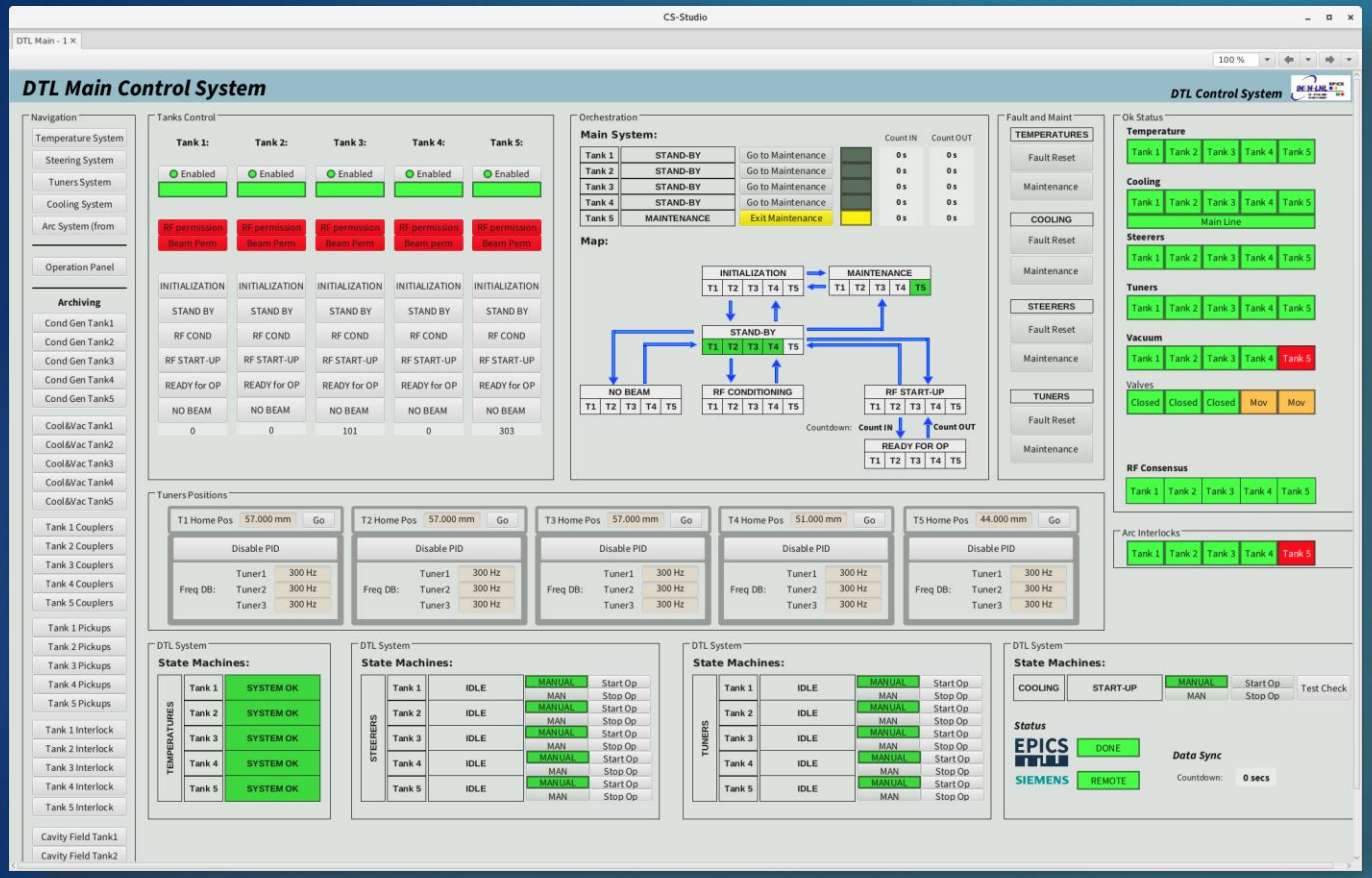
We are here

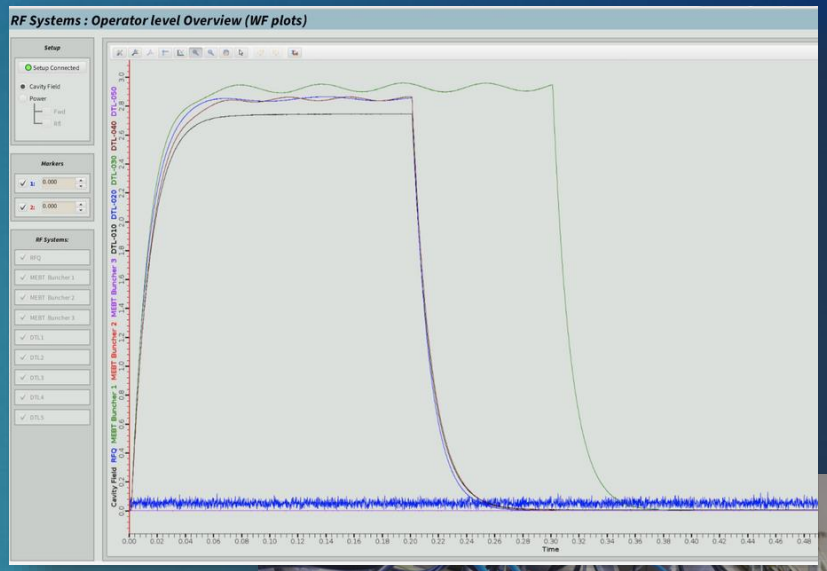
- **SIT**: hardware and software integrated verification, which is composed by:
  - SIT-1 related to DTL Tank 1
  - SIT-2, related to DTL Tank 2,3,4
  - SIT-3, related to DTL Tank 5

10 steps already done

NB: The entire apparatus won't be completely available from the beginning and the different tanks composing the DTL will be installed, tested and conditioned in different periods

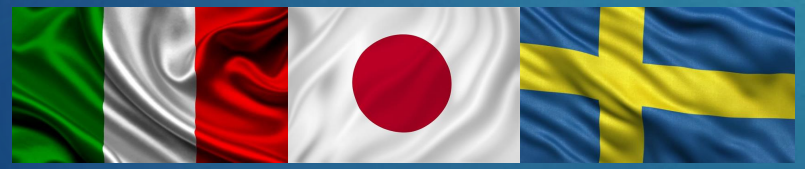
ESS DTL LCS in Action





DTL Conditioning: Tank1 started in 2022, Tanks 2,3,4 in 2023, Tank 5 in 2024

Lessons Learned



"LESSONS LEARNED" IS JUST A FANCY WAY OF SAYING, "OOPS, LET'S NOT DO THAT AGAIN!"

(Distributed) Lessons Learned

- **Long R&D and software architecture had an enormous (good) impact in maintenance and device extension**
  - New magnetic devices can be integrated in the beam transport system in term of days
  - End users can not distinguish between different devices
  - same GUI → easier learning curve for operators
  - GUIs designed and developed with operators → "happy wife, happy life" rule
- **Maintenance HW and SW**
  - HW: industrial PCs required several maintenances during preparation times
  - HW & SW: removed internal EPICS IOCs in Caenels models → optimized code structure
  - SW: virtualization has decreased downtimes and preparation times
  - SW: **great feedback from EPICS Community for code debug and driver exchange → big impact during development**

(Distributed) Lessons Learned

- **Usage of opensouce solutions**
  - Good impact in terms of €€ and important support from communities (….considering consolidated communities)
  - Possibility to customize service / application
  - **NOTE**: Requires dedicated skills and knowledge to proper configure and maintain systems
  - Dedicated teams are desirable, but difficult to achieve

- **The choice of the right hardware**
  - New Caenels devices with Eth → introduced virtualization for beam transport system
  - From industrial PCs to Virtual Machines → minimized bottleneck in the HW maintenance

(Distributed) Lessons Learned

- **The function of Power Test**
  - Possibility to validate control system architectures and technologies involved
  - Possibility to change (in time) solutions if required
- **The importance of documentation**
  - Keep track of the activity is a time-consuming activity
    - create and manage documentation could be required to be done in parallel with CS development and implementation
    - **Don't underestimate the time required…. Overestimate it!**
  - In a project, different documentations are required at different stages and for different scopes
    - Each kind of document requires different tools and services (i.e., wiki, git, etc.)
  - It is possible that documentation is connected to project's milestones and payments

(Distributed) Lessons Learned

- **Adopting EPICS as Control System Framework**
  - The EPICS architecture can be designed and implemented choosing only the tools and applications really required
  - **Fantastic framework to define a distributed control system where there is the need of integrate different HW and SW solutions**
  - Define a real distributed control system (sort of shared memory)
  - **It is open source and supported by a real active community**

(Distributed) Lessons Learned

- **Working with EPICS**
  - Require a good control architecture design in order to implement the best solution according to the project requirements
  - Size of the control system
  - Number of functional sub-systems involved and their sizes
  - Additional network services needed
  - Do not sub-estimate the network!

- **The Naming Convention is a critical point: understand your requirements and compare solutions from different laboratories**
  - A bad naming convention can have dramatic consequences in terms of maintenance, control system architecture and downtimes

Thank You for Your Attention