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Elke Zimoch :: Section Controls :: Paul Scherrer Institut

Accelerator Controls

JUAS 2021

Why talking about Accelerator Controls?

Soon in the future (and once upon a time):
Scientist **Dr. Example Guy** wants to do
VeryImportantMeasurement_OneDotOne
for that he creates some actuators and detectors
Super_Creative_HardwareSolution
puts it into the accelerator
and calls the Controls Group
"Please make it run".

I want to teach you a
minimum awareness about the control
system that «runs» the accelerator …

Table of Content

What is an Accelerator Control System?

Searching Wikipedia:

What ~~is~~ does an Accelerator Controls System (1/6)

- Controls the accelerator (Source, Magnets, RF)
- Provides diagnostics information (BPMs, Cameras)
- Monitors environment (Vacuum, Temperature)
- Feedback programs for beam parameters (orbit feedback)
- Makes "the machine" running and controllable …

… reliable, with good performance, flexible … economical safe (without producing black holes and destroying the world)

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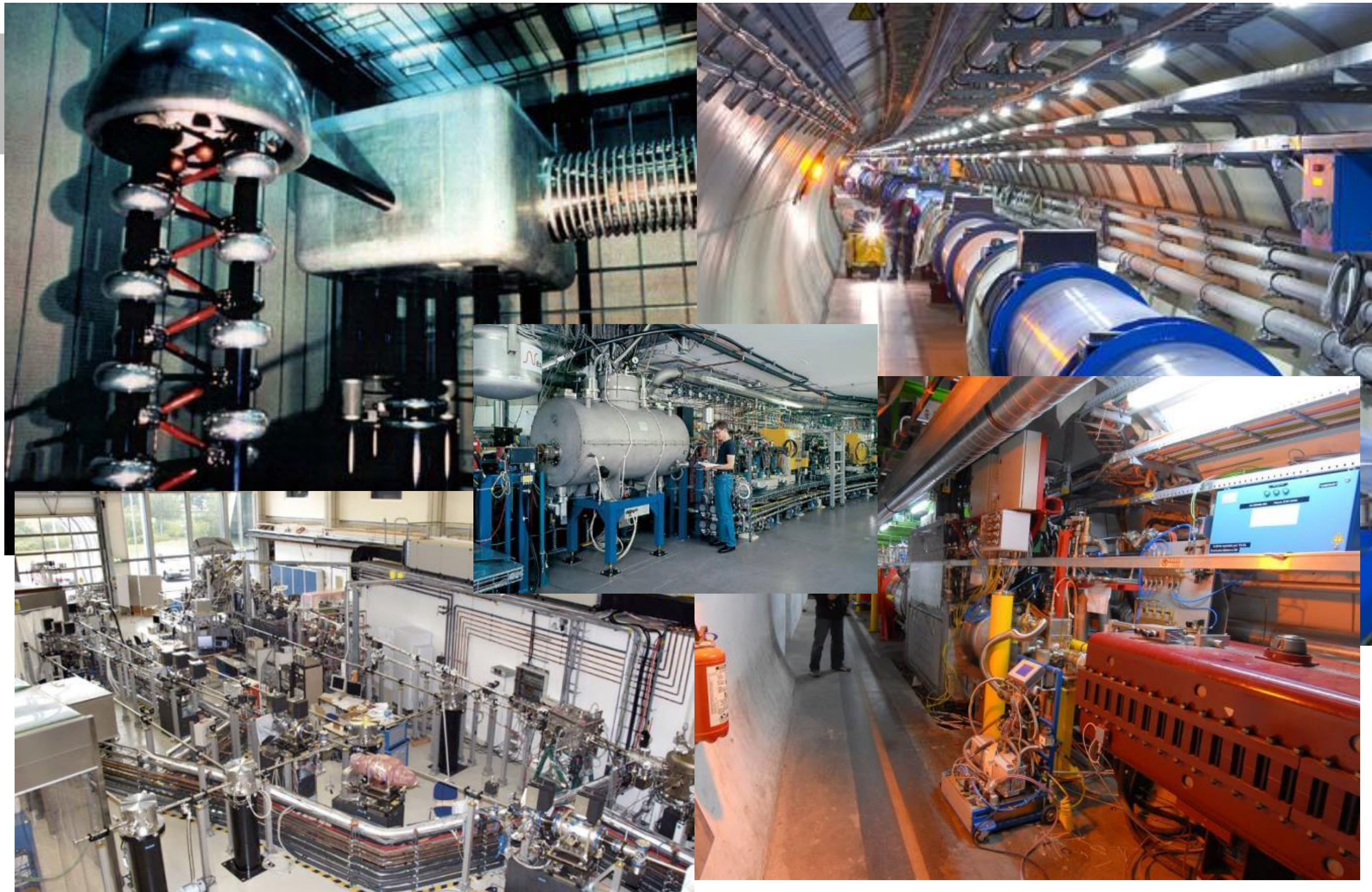
What does an Accelerator Control System? (2/6)

Controls the accelerator hardware:

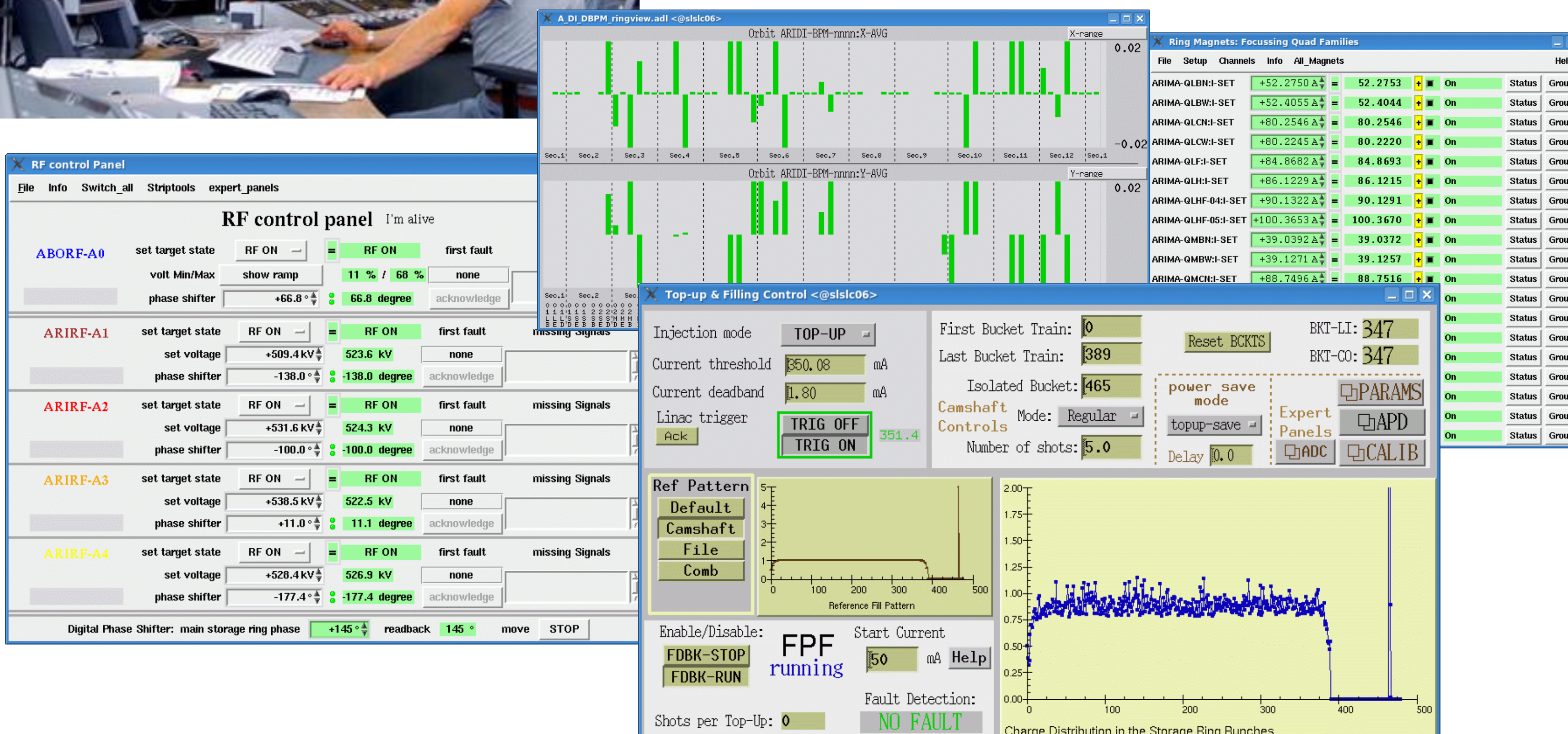


What does an Accelerator Control System? (3/6)

Make the accelerator controllable

… from a Control Room

… using Computer Systems



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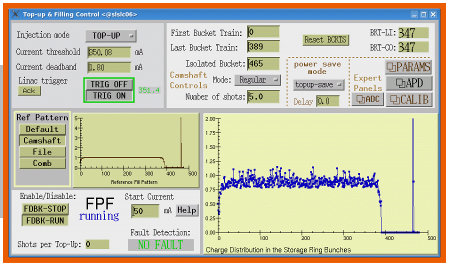
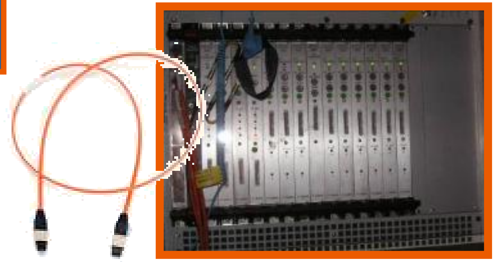
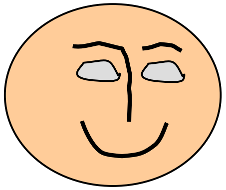
What does an accelerator control system? (4/6)



Control System





Operator
in Control Room

The control system connects the operator with the accelerator.

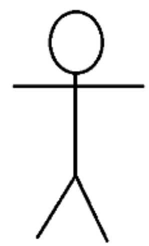
What does an Accelerator Control System? (5/6)

Accelerator Control System

Inputs

- Values from all diagnostic devices (BPMs, screens, ICT/PCT, etc.)
- Information from the experiment
- Read back values from devices (Magnets, RF, etc.)
- Read back values from environment (Vacuum, Temperature, etc.)

Operator



Outputs

- Set values from devices (Magnets, RF, etc.)
- Actuators of the environment (vacuum pumps, heaters, chillers, etc.)
- Triggers
- Alerts (SMS, emails, alarms, etc.)

What does an Accelerator Control System? (6/6)

The

Accelerator Control System

- does provide a keyhole view on the accelerator
- is the only way to access any component remotely

Who uses an Accelerator Controls System

Who they are

- Accelerator Physicists
- Operators (technical Staff, in most cases no theoretical background knowledge)
- System Experts (Vacuum Experts, RF Group, …)
- Experiment Users (not necessary Physicists)
- Sponsors (Politicians, General Public, etc.)
- Control System Specialists (Computer Scientists, Physicists, Nerds)

What they want from the system

- Access to ALL functions of the hardware (full control)
- Implementation of complex algorithms
- Easy and intuitive usage
- Low cost, low manpower
- Safe usage and reliable alarm handling
- Easy maintainable
- Easy extensible
- **fun**

What is the Technical Environment?

Control Systems (one way or another) have to deal with …

- **Distributed** end points and processes
- **Data Acquisition** (front end hardware)
- **Real-time** needs (where necessary)
- **Process control** (automation, feedback, PID controller)
- **Central Services** (Archive, Databases, Name Resolution)
- **Data transport** (control system protocol, network)
- **Security** (who’s allowed to do what from where?)
- **Time synchronization** (time stamps, cycle ids, etc.)

that is:

Computers (in different flavors) and **Computer Environment**

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What is an Accelerator Controls System

Definition:

An **Accelerator Control System** is a computer environment that allows remote access to the accelerator hardware with a lot of different functionality to satisfy the requirements of several different user groups.

In addition a modern

Accelerator Control System:

tries to unify the access to different

hardware

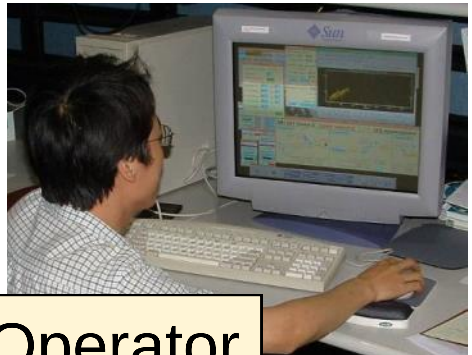
(one way to rule them all)

0110001010001001

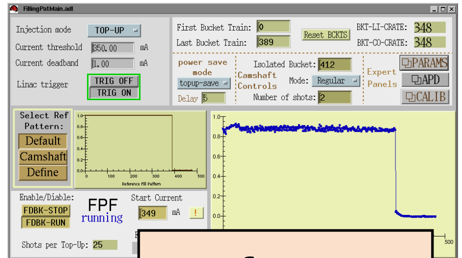
Table of Content

- What is an Accelerator Control System?
- Accelerator Control Systems Architecture
- Examples of Control Systems
- Control System Parts and Pieces
- Borderlands of Control Systems
- Conclusion

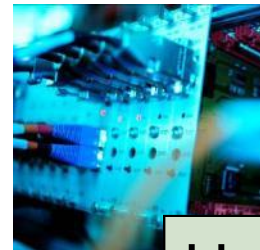
Requirements of an Accelerator Control System

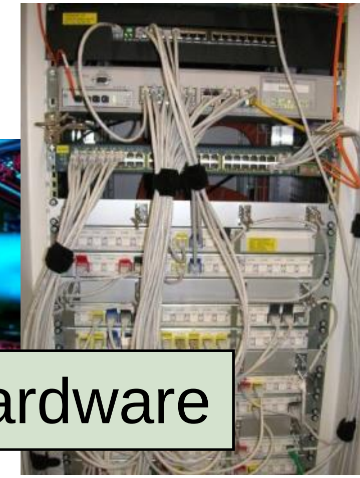


Operator



Software

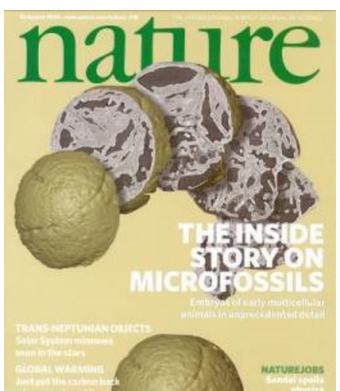




Hardware

- reliable
- good performance
- flexible
- easy maintenance

?

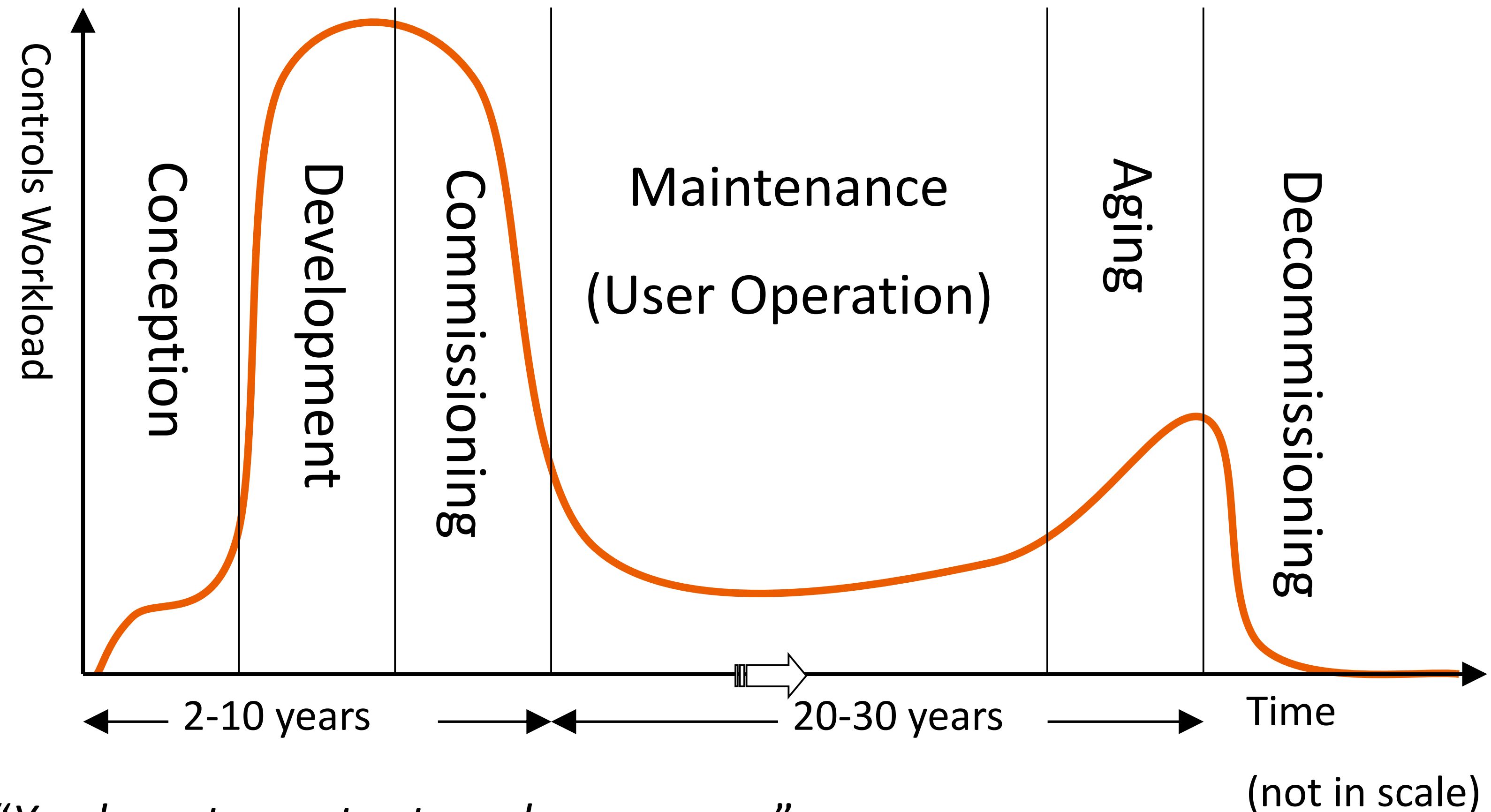


Experiment Scientist

Accelerator

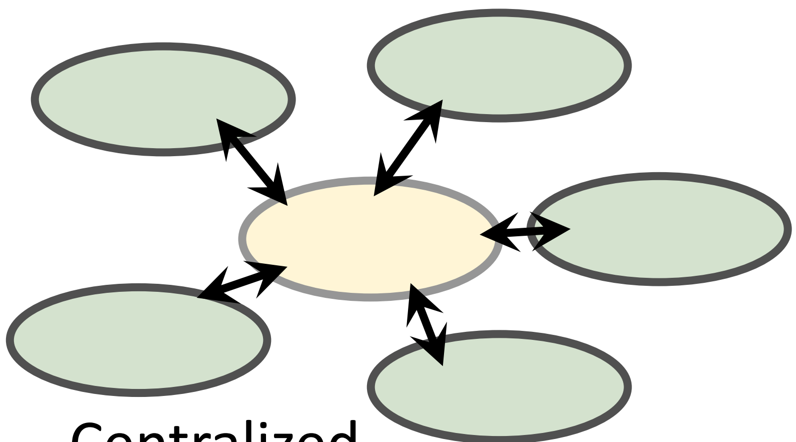
Why is easy Maintenance important?

Controls System Lifecycle:

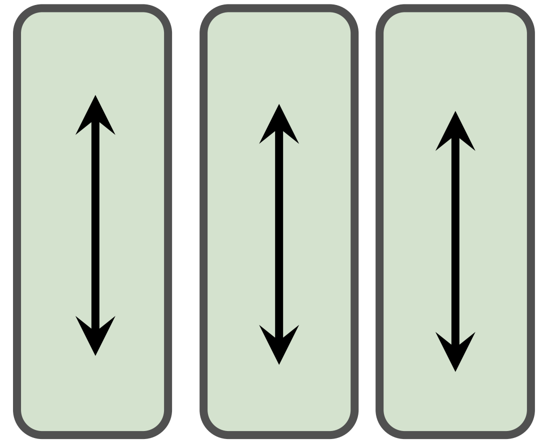


- *"You have to run to stay where you are"*
- Workload never got to zero during accelerator lifetime
- Normal accelerator lifetime ~ 30 to 40 years

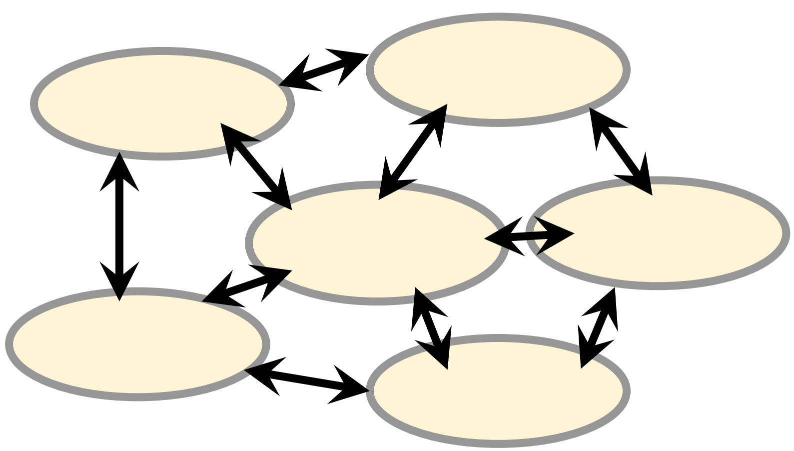
Possible Architectures



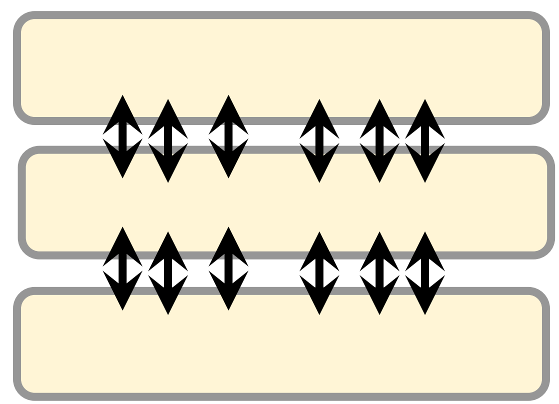
Centralized



Columns

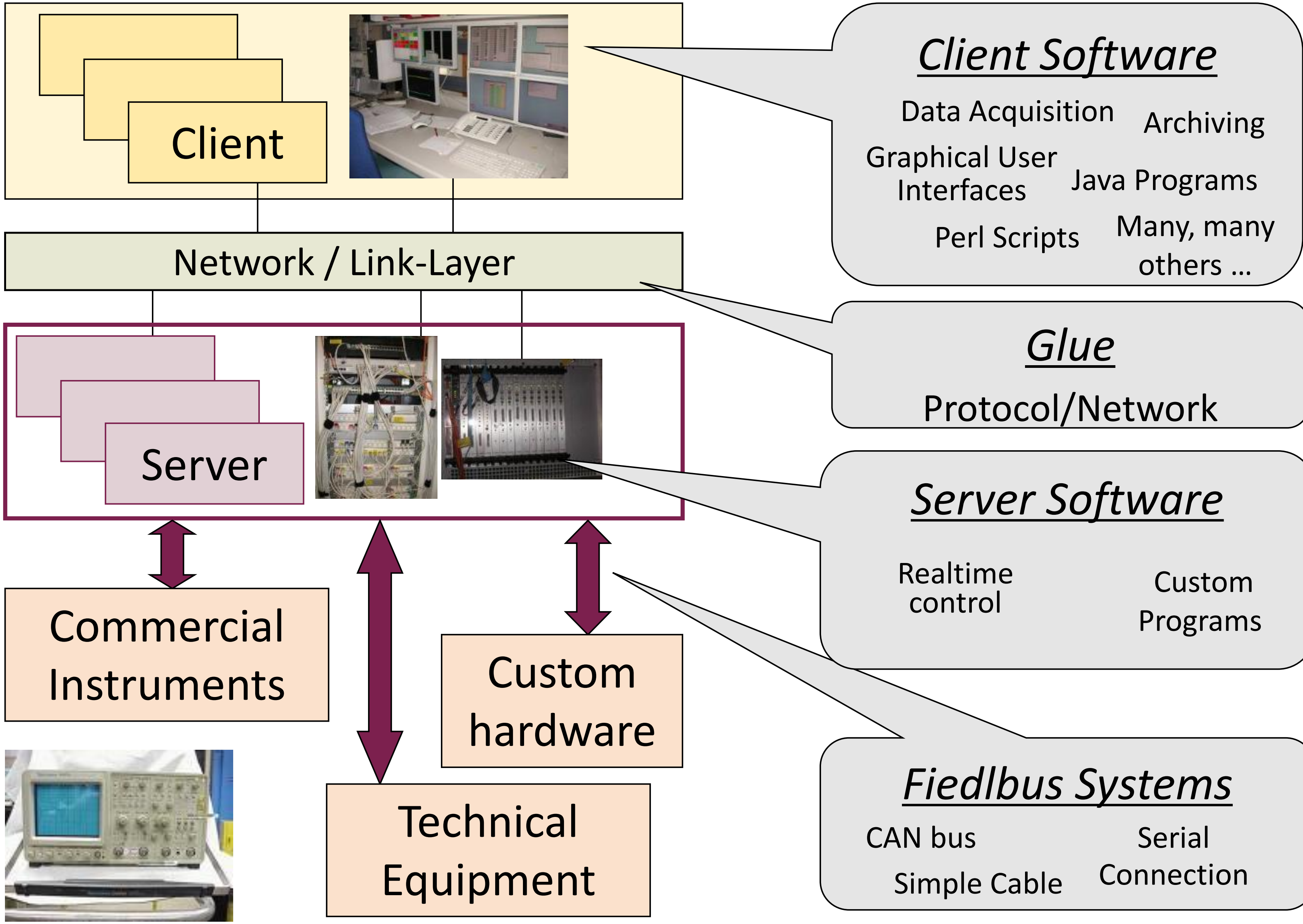


Network

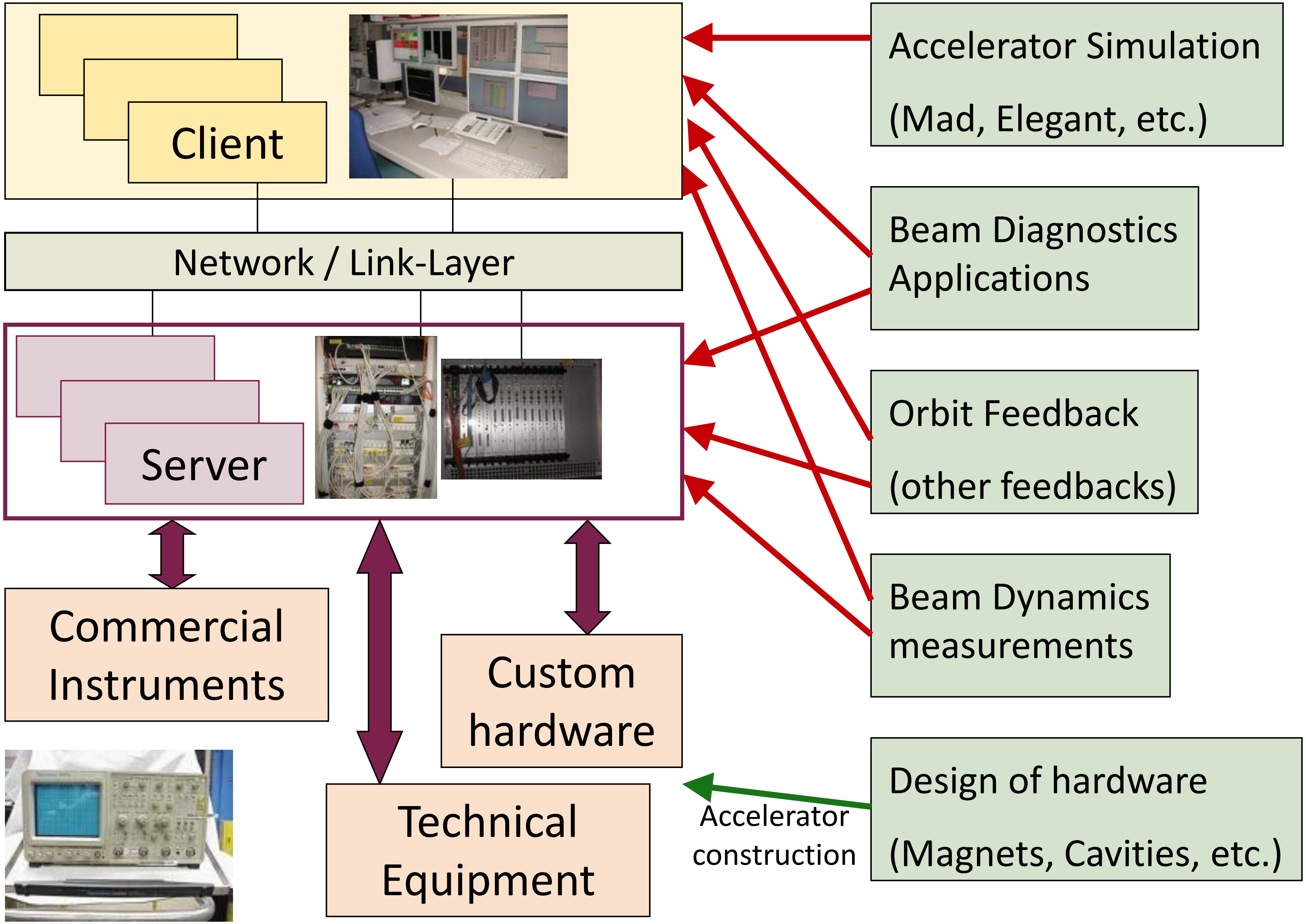


Layer

(Standard) Control System Layer Model



Where is Physics in there?



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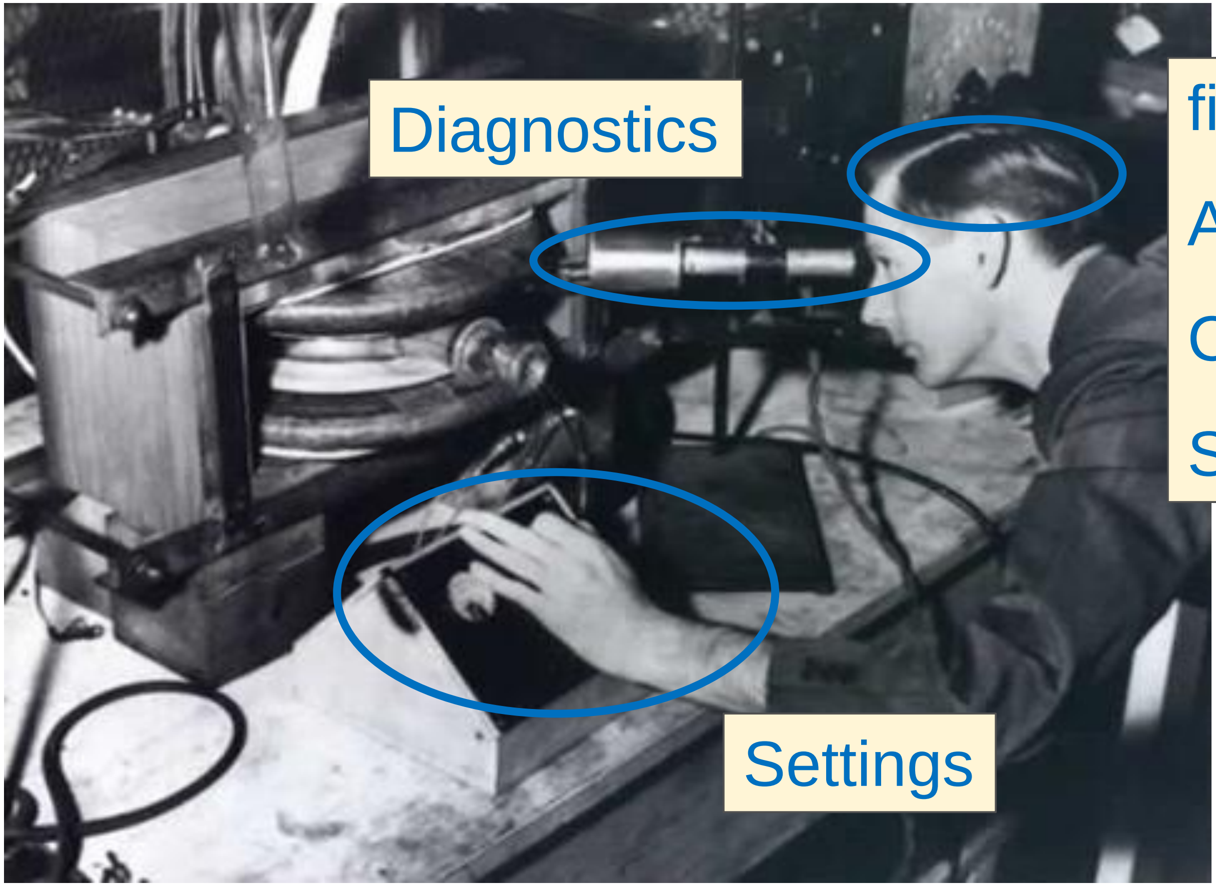
History of Accelerator Controls (1/3)



first Accelerator Control System

Donald Kerst with the first betatron, invented at the University of Illinois (USA) in 1940

History of Accelerator Controls (2/3)

AGS control room, circa 1966

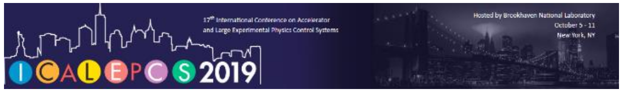
History of Accelerator Controls (3/3)

International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS)

First held in 1987 in Villars-sur-Ollon (Switzerland), hosted by CERN.

The term "Control Systems" in ICALEPCS is broadly interpreted to include:

- all components or functions, such as processors, interfaces, field-busses, networks, human interfaces, system and application software, algorithms, architectures, databases, etc.
- all aspects of these components, including engineering, execution methodologies, project management, costs, etc.



Solutions: Different Control System Examples

System Name:

EPICS
TANGO

Collaborations:
Used at more than one Lab

Pro:
Bugs are already found

Contra:
Complicated to adapt to your problems

DOOCS
ACS

Single Site Systems:
Developed and used in one Lab

Pro:
Your problems solved perfectly

Contra:
You are on your own (no one can help)

SCADA
(WINCCOA)

Commercial System

Pro:
Outsource your problems

Contra:
Expensive

What is EPICS?

- **EPICS** (**E**xperimental **P**hysics and **I**ndustrial **C**ontrol **S**ystem)
  - is a set of software tools and applications
  - supports distributed control systems for large research facilities like accelerators
  - uses Client/Server and Publish/Subscribe methods
  - uses the Channel Access (CA) network protocol

- In 1989 started a collaboration between Los Alamos National Laboratory (GTA) and Argonne National Laboratory (APS) (Jeff Hill, Bob Dalesio & Marty Kraimer)
- More than 150 licenses agreements were signed, before EPICS became Open Source in 2004

GTA: Ground Test Accelerator
APS: Advanced Photon Source

https://epics-controls.org/

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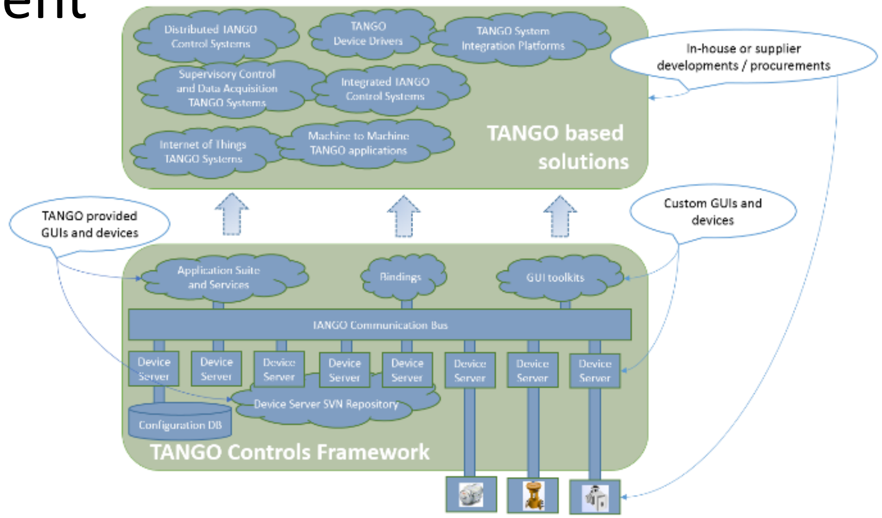
Who uses EPICS (Very Incomplete List)?

EPICS

What is Tango?

- **TANGO** (**TA**co **N**ext **G**eneration **O**bjects)
  - is a strictly object oriented toolbox for Control System development
  - is a set of software tools and applications
  - supports distributed control systems for accelerators



- Started in 2001 with three collaborators, now there are 49

ESRF | SOLEIL SYNCHROTRON | DESY | ANKA | ALBA | eli attosecond

MAX IV | Forschungs-Neutronenquelle Heinz Maier-Leibnitz (FRM II) | SOLARIS NATIONAL SYNCHROTRON RADIATION CENTRE | Elettra Sincrotrone Trieste | SKA SQUARE KILOMETRE ARRAY

http://www.tango-controls.org/

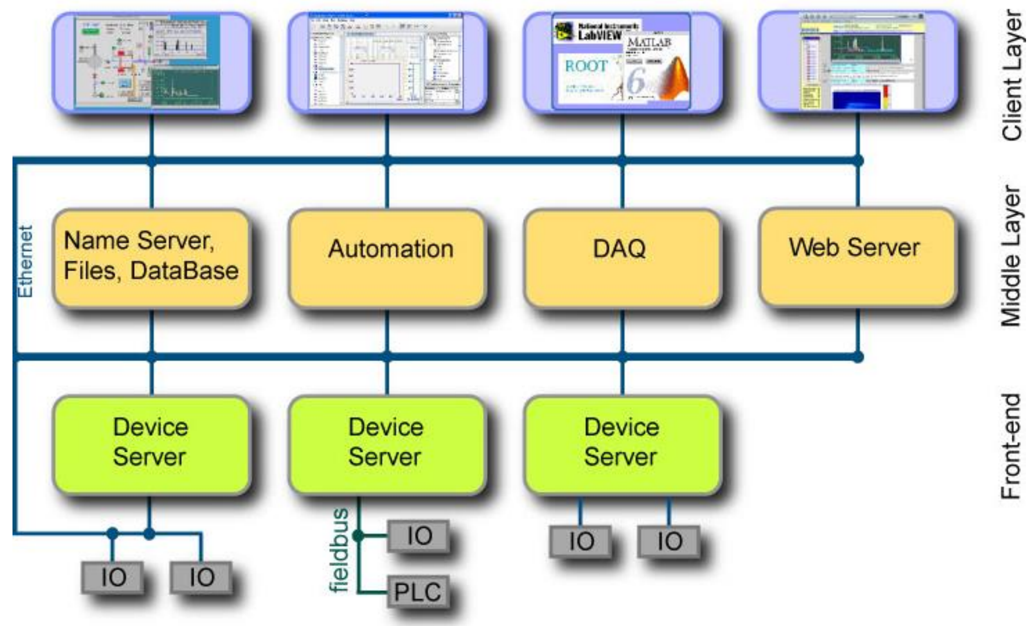
Who is using Tango?

What is DOOCS (at DESY)?

DOOCS (**D**istributed **O**bject **O**riented **C**ontrol **S**ystem)

- strictly object oriented system design (C++ and Java)
- Class libraries as building blocks

DOOCS.



- Build for FLASH, now used for European XFEL

https://doocs-web.desy.de/index.html

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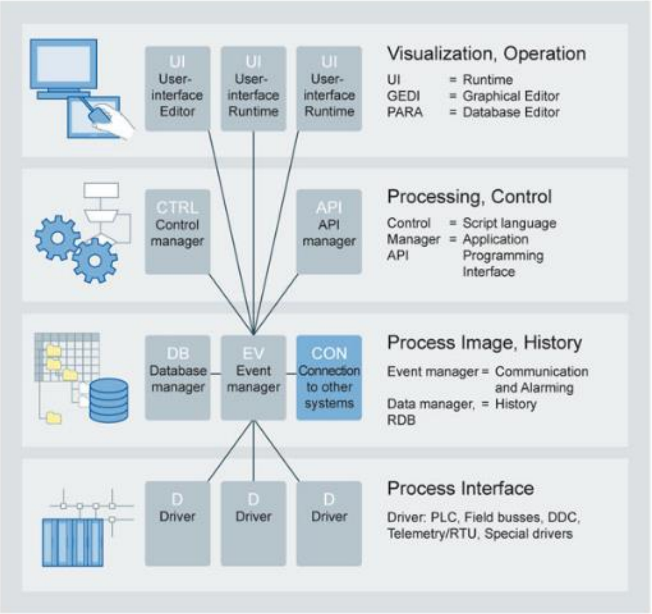
What is PVSS now WinCC-OA (at CERN)?

WinCC Open Architecture

former **PVSS II** (**P**rozess**v**isualisierungs- und **S**teuerungs**s**ystem 2)

– is an industrial SCADA product from the Austrian company ETM (bought by Siemens AG in 2007)



SCADA = **S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition

(commercial software systems used extensively in industry for the supervision and control of industrial processes)

http://www.etm.at/index_e.asp

http://www.etm.at/index_e.asp

Mixed Systems

- At DESY:
  Tango, EPICS, and DOOCS mixed
- At PSI:
  ACS – EPICS migration
- At PSI (former SLS beamline):
  Tango beamline at EPICS accelerator

- There are gateways between the systems

By Evan Swigart

The choice for one system is not exclusive

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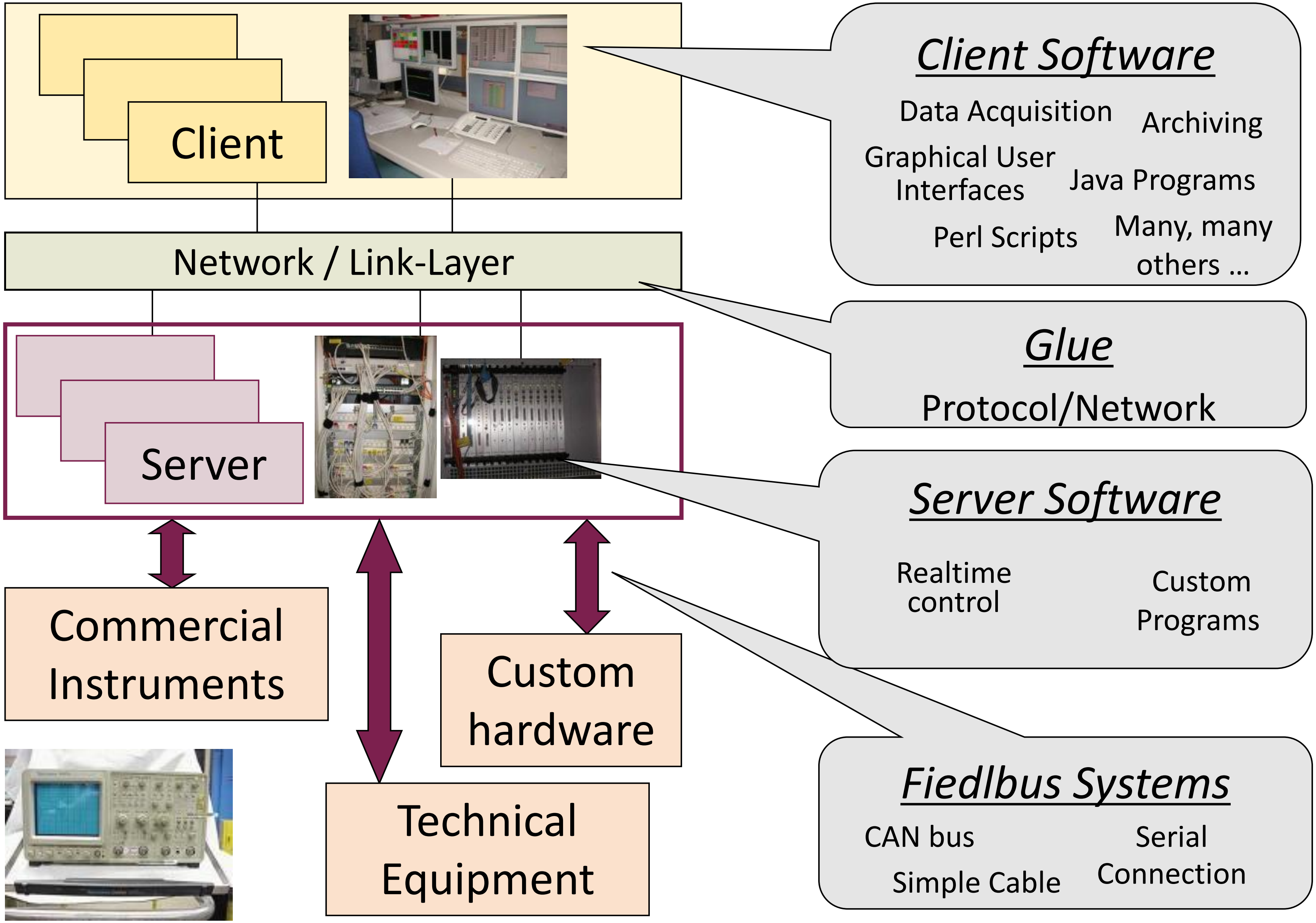
Technical Requirements

Use open source firmware/software.	• You can change things and you have control of further developments
Use commercial solutions based on open standards developed and sold by a large number of companies	• Don’t become dependent on single companies with proprietary solutions
Use standards with a long life-time (20 years+)	• Keep long lifecycles of accelerators in mind

Reminder: Control System Layer Model



High Level Software: Clients

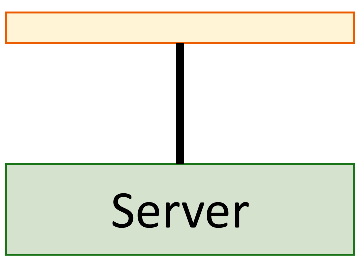
Usually clients run in a

control room

and are used by
operators

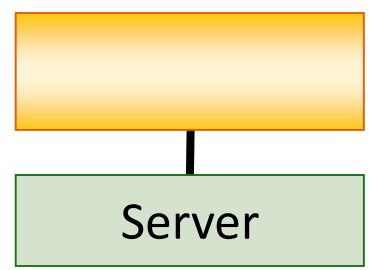
Where is the logic? Where are the computations?

Thin Client



Only display of results

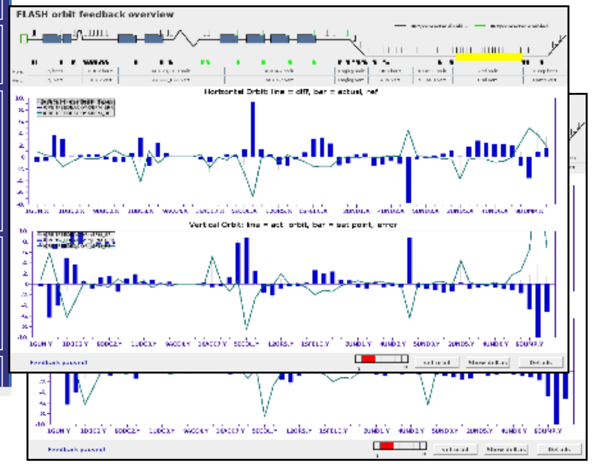
Fat Client

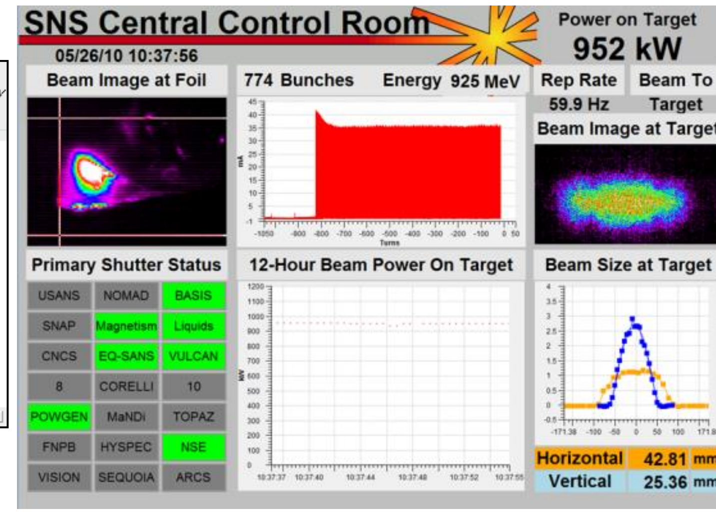


Production of results

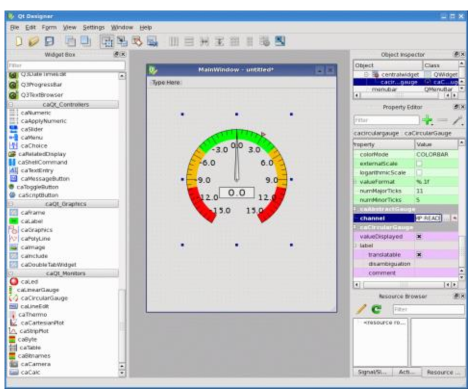
High Level Software: Graphical User Interfaces

GUIs: Usually thin clients





Example for an Editor



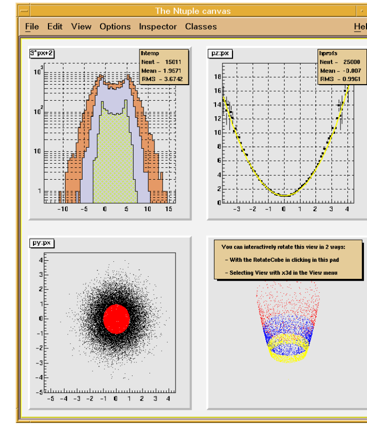
PSI is using a GUI builder called caQtDM (EPICS based):
http://epics.web.psi.ch/software/caqtdm/

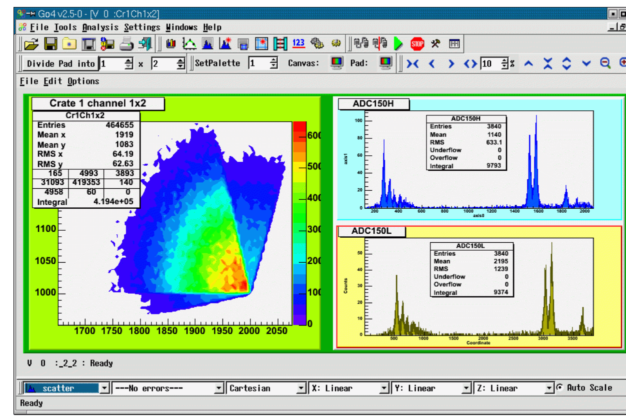
caQtDM

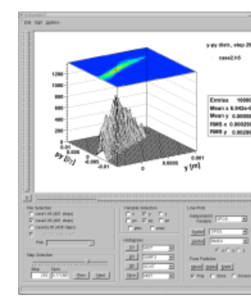
High Level Software: Science Applications

Examples for accelerator science applications:

- Tune measurement and correction
- Orbit correction
- Beam based magnet alignment
- Parameter scans
  (to find optimal working points)
- Filling pattern measurements
  and correction
- Correlation Plots





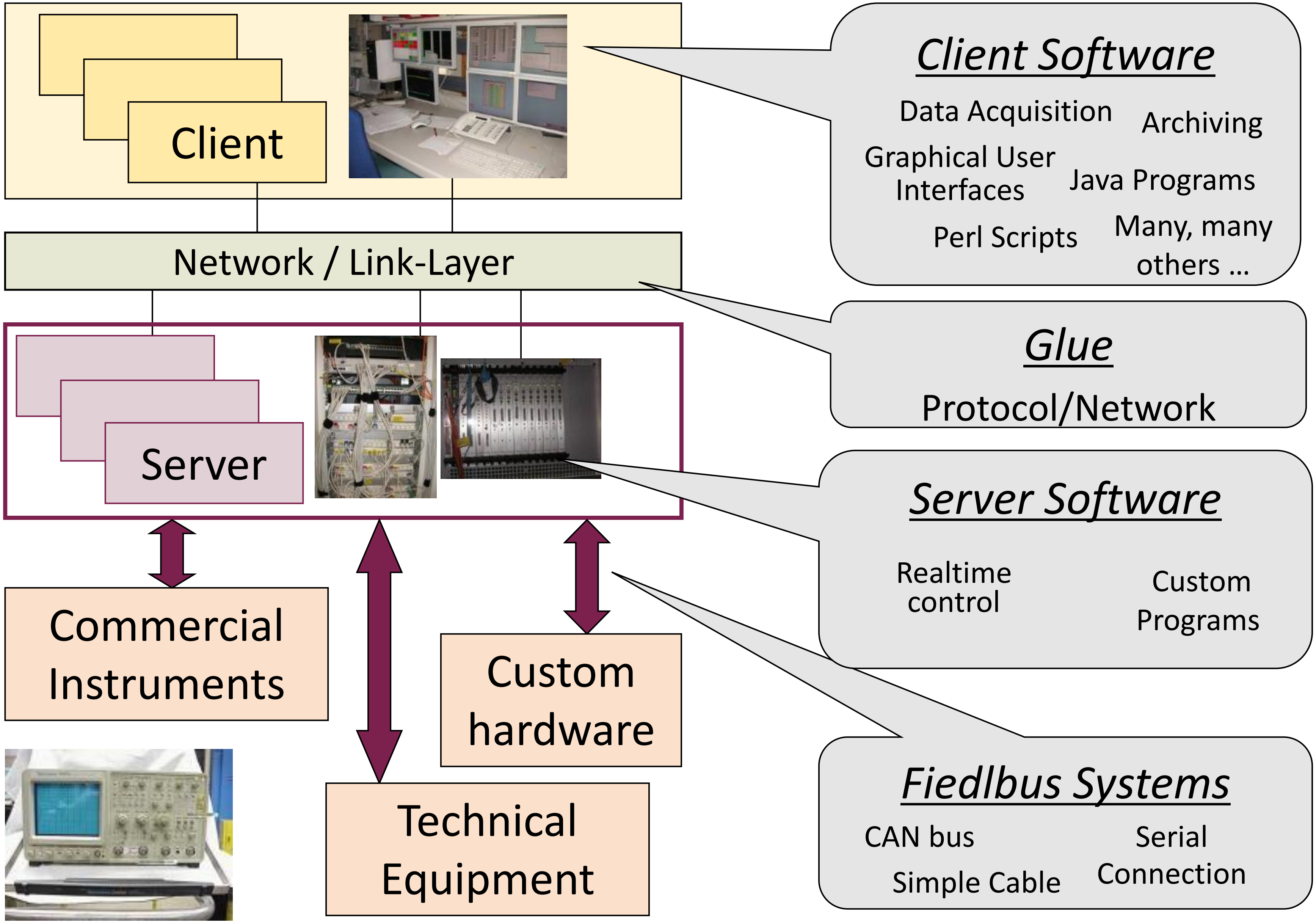


... general data analysis of accelerator data

Usually fat clients,

usually written by scientists (not by controls experts)

Reminder: Control System Layer Model



The Cheap Solution: PC based

user interface

Ethernet

Server Hardware

field bus (ethernet, serial, USB, firewire, …)

PCs are cheap, have standard network interfaces and support other field busses

PCs life cycles are short compared to accelerators (no spares available after some time)

The Classic Solution: VME based

user interface

Server Hardware

VME
(Operating System: e.g. vxWorks)

Ethernet

Dumb Hardware

Cable or field bus (analog I/O, digital I/O,…)

VME cards life cycle is long,
VMEbus is an open standard,
Supported by Industry

VME is expensive,
special operating system
(VxWorks)

What is a VME Computer?

- VME is an abbreviation for **V**ERSA**m**odule **E**urocard
- Industry Computer based on VMEbus
- Developed since 1980
- It is not a PC
- Real-time capable (i.e. delays are calculable)
- Common used operating system is VxWorks from Wind River company (open source alternative: RTEMS)
- Expensive (~800 Euro per interface card)

VME Crate

VME Card:

Eurocard size

VMEbus interface

https://en.wikipedia.org/wiki/VMEbus

A serial interface solution: Picotux based

user interface

Ethernet

Server Hardware

Linux PC

Example for tiny computers with single interface

Serial interface (RS232, …)

Cheap and tiny solution,

Supports distributed devices

All commercial chips have slightly different architecture (maintenance), life cycle yet unknown

The Embedded Solution: Device Integrated CPU

user interface

Ethernet

Embedded Hardware

=

Server Hardware

+

Instrument

Low cost, have standard network interfaces and support distributed devices

All commercial chips have slightly different architecture (maintenance), life cycle yet unknown

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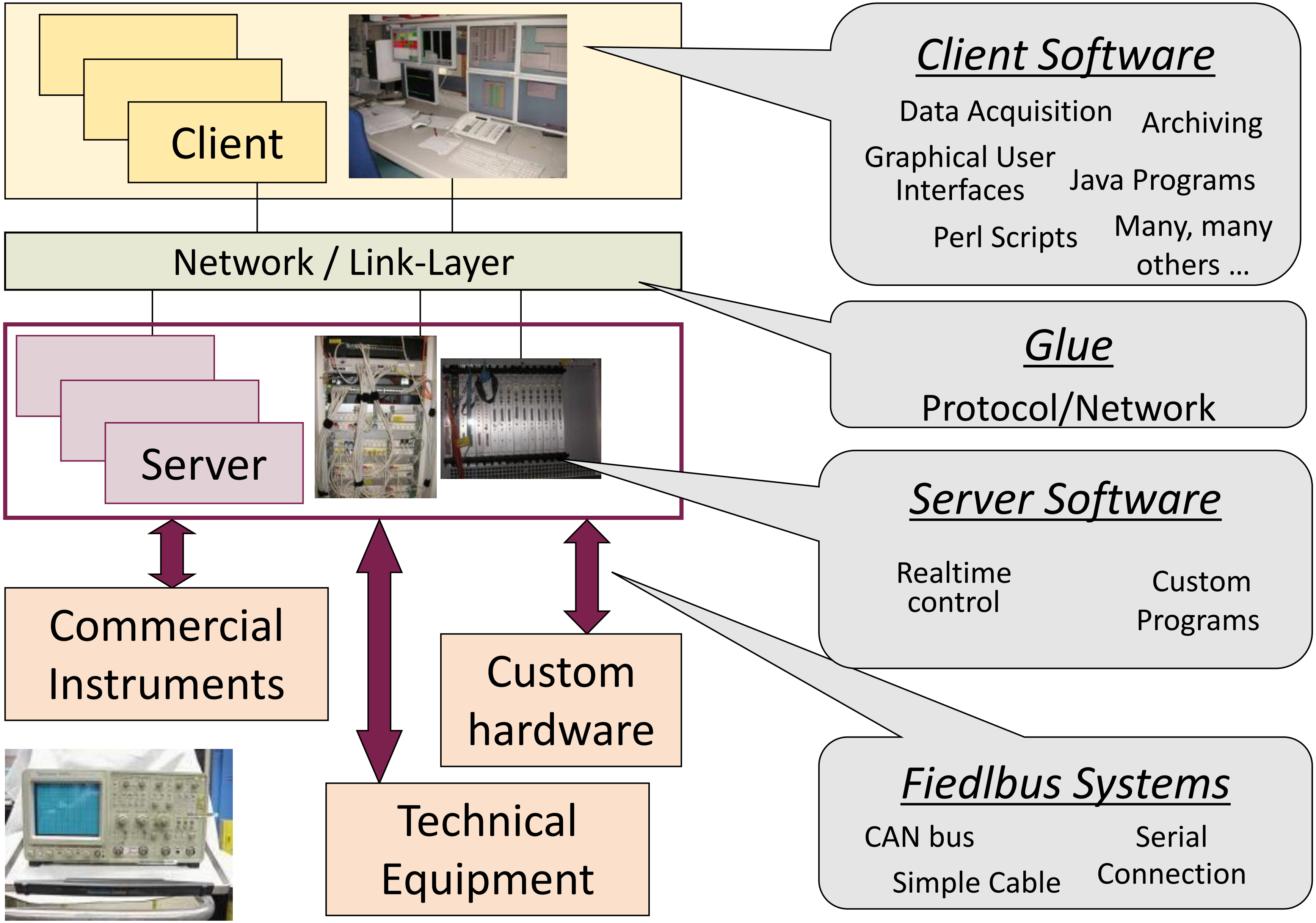
Reminder: Control System Layer Model



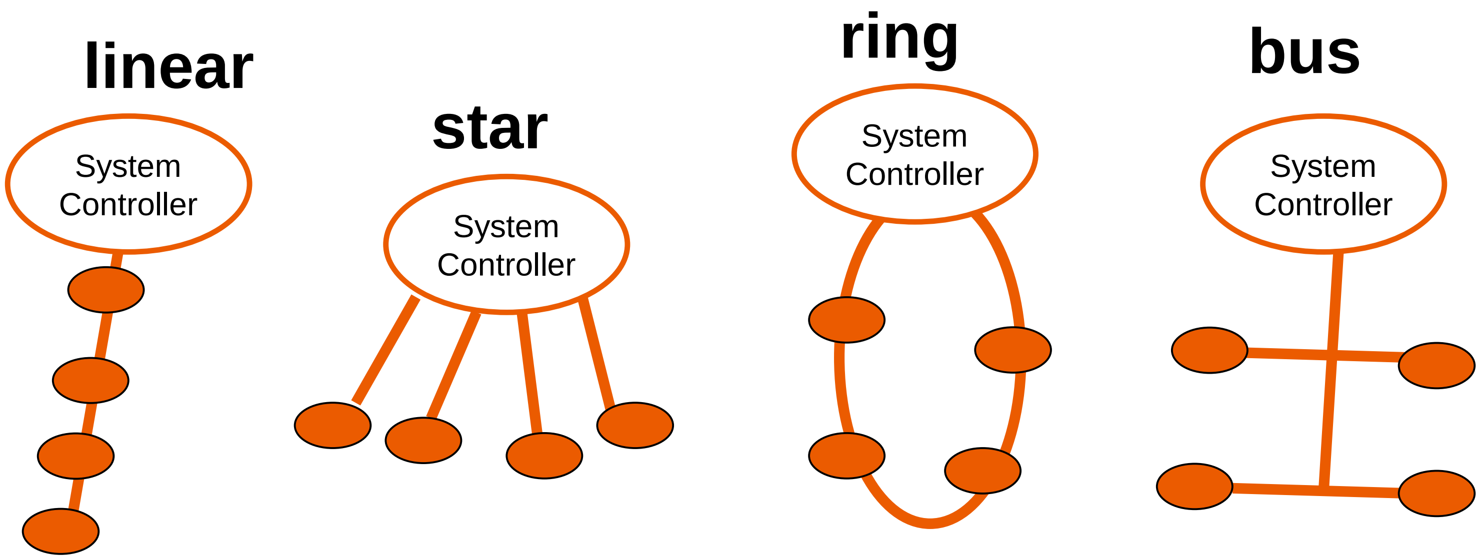
What are PLCs?

- **PLC** (**P**rogrammable **L**ogic **C**ontroller)
  - is a digital computer used to connect “dumb” devices

- the PLC is designed
  - for multiple inputs and outputs
  - extended temperature ranges
  - immunity to electrical noise
  - resistance to vibration and impact
  - as a real time system
- Programs are typically stored in battery-backed or non-volatile memory
- Products from different providers can **NOT** be mixed!

Field Busses

- Field busses connect hardware to servers
- A lot different busses available with different purposes and different specifications as
  - –number of allowed devices
  - –speed
  - –allowed cable length
  - –topology (ring, star, linear, …)



Field Busses

Some example field bus systems:

- **CANbus** (Controller area network)
  https://en.wikipedia.org/wiki/CAN_bus
- **PROFIBUS** (Process Field Bus)
  https://en.wikipedia.org/wiki/Profibus
- **IEEE 1394** (Firewire)
  https://en.wikipedia.org/wiki/IEEE_1394
- **EtherCAT** (Ethernet based real time bus)
  https://www.ethercat.org/en/technology.html

Difference to Ethernet and USB?

Field busses are real time capable (IEC 61158 specification)

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Accelerator Control Systems have fussy borders.

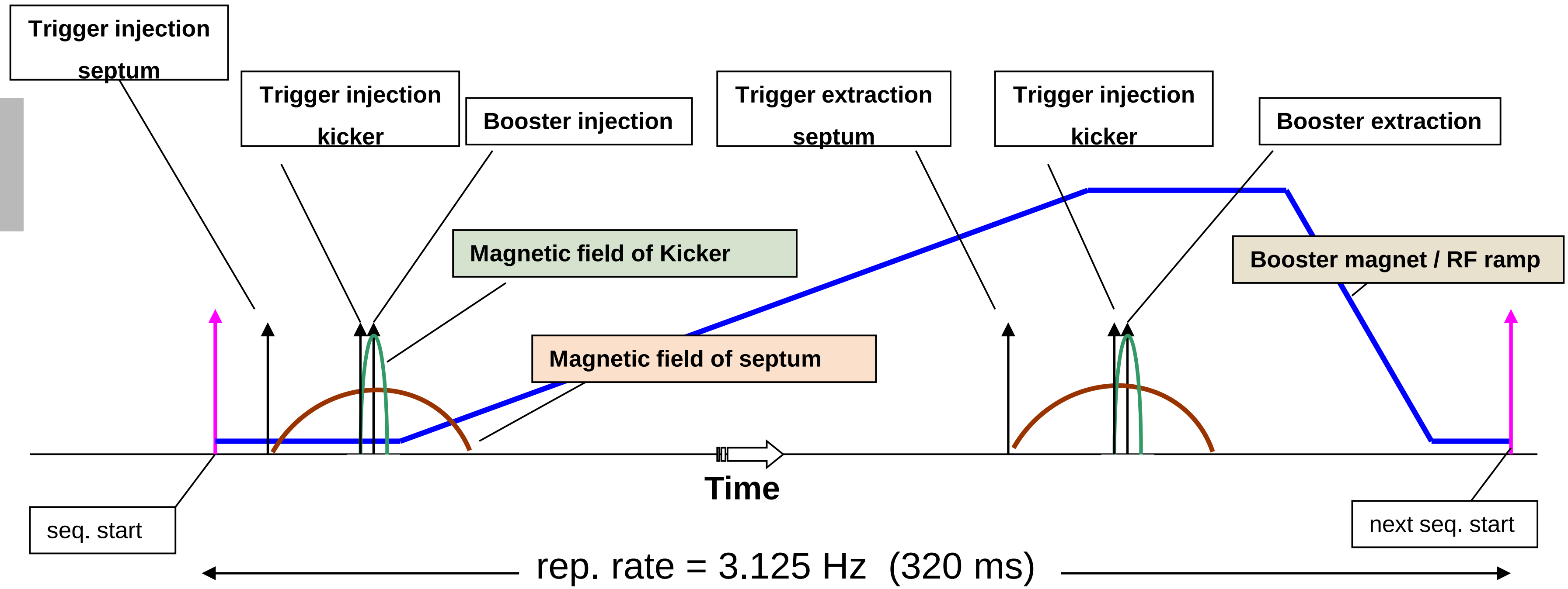
Some example for these borders are:

1. Timing and Synchronisation
2. Feedback Systems
3. Interlock-, Alarm-, and Machine Protection Systems
4. Experiment Data Acquisition
5. Relational Databases
6. Relationship of IT (Information Technology) and Controls

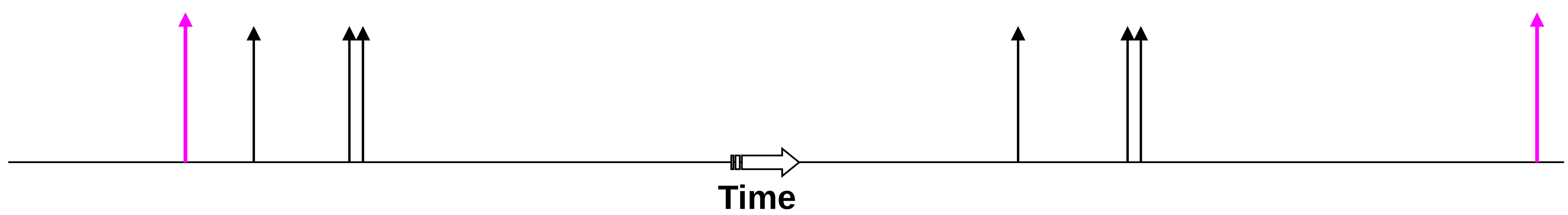
For example

1. Timing and Synchronisation

Why Synchronize?



Event sequence for booster synchronization:



Solutions for Timing Systems

- Master oscillator + delay cables
  (1 trigger and measured cable lengths)

- Master oscillator + digital delay generators
  (https://www.thinksrs.com/products/DG535.htm)

- (Master oscillator +) event generators/receiver cards in computers (PC , VME, µTCA)
  (http://www.mrf.fi/)

- Timing and synchronization is needed to run an accelerator
- Various solutions available and used

Timing and synchronization can be part of the Control System.

Clarify who is responsible for timing and synchronization to avoid problems!

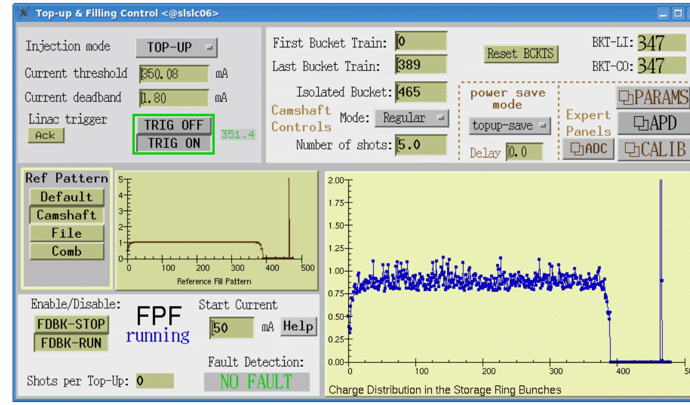
For example

2. Feedback Systems

Feedback Systems

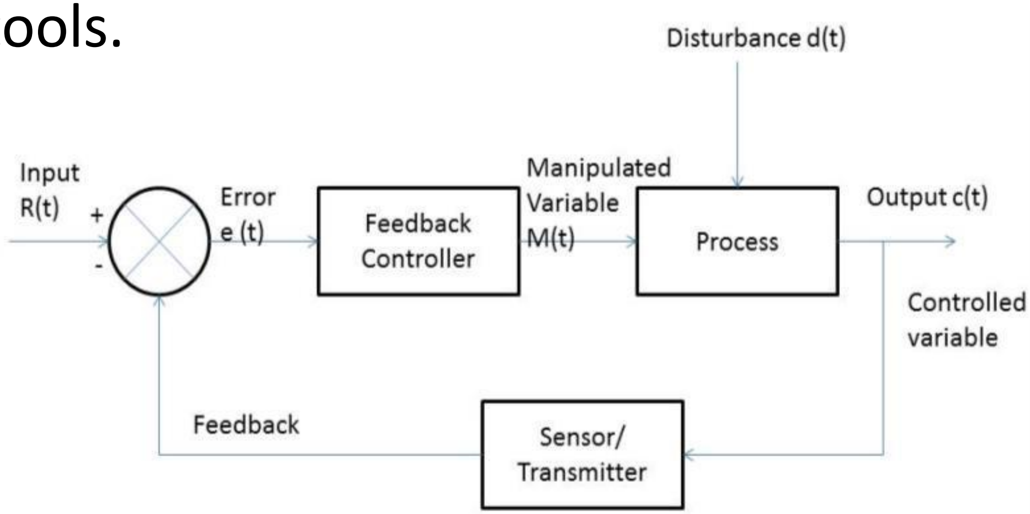
For example:

- Orbit Feedback (Position)
- Energy Feedback
- Filling pattern Feedback



If it needs to be fast, it needs separate cables!

Slow feedbacks can be realised with standard control system tools.



Example: Orbit Feedback

Needed for beam position stability.

Measurement (once in a time):

- Measure beam response matrix (complete orbit for different corrector magnet settings)
- Invert the matrix (normally not possible analytical, use numerical methods) a stable method is singular value decomposition (SVD)

Feedback during runs:

- Measure the beam position and correct it with the appropriate set of correctors

For example

3. Interlock-, Alarm-, and Machine Protection Systems

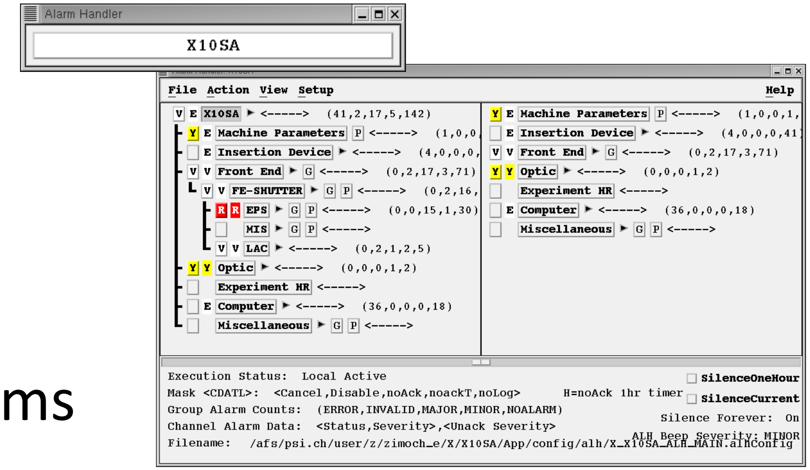
What are Interlocks?

Everything is fine (No Alarm) Example: Vacuum pressure 1e-10 mbar	Go on working
Something is strange (Warning) Example: Vacuum pressure 1e-7 mbar **Something is wrong (Error)** Example: Vacuum pressure 1e-6 mbar	**Alarm states** Alert people to take some actions
Stop it or suffer from severe consequences (Interlock) Example: Vacuum pressure 1e-5 mbar Automatic beam dump executed	**Interlock** Automatic reaction needed

What are Alarms

Murphy's law:

Anything that can go wrong
will go wrong.



EPICS Alarmhandler

- Alarms help to avoid Real Problems
- Alarms help to find problems
- Example:
  - –Beam position more than 1 mm of from reference
  - –Vacuum pressure higher than 1e-6 mbar
  - –Orbit Feedback Program not running

- People should react on alarms

Interlock Systems

- Interlock Systems have to be
  - taking automatic actions (no people involved) - fast
  - Reliable (99% might not be enough)
  - as simple as possible (see Murphy's law)
- Avoid computers in Interlock Systems

  Decouple "running" the accelerator (=Control System) from "stopping" the accelerator (=Interlock System)
- There can/will be more than one Interlock System in an accelerator (local, global, different goals, etc.), for example:
  - Vacuum Interlock
  - Equipment Protection System
  - local RF Interlock Systems

Clarify who is responsible for Interlock Systems to avoid problems!

For example

4. Experiment Data Acquisition

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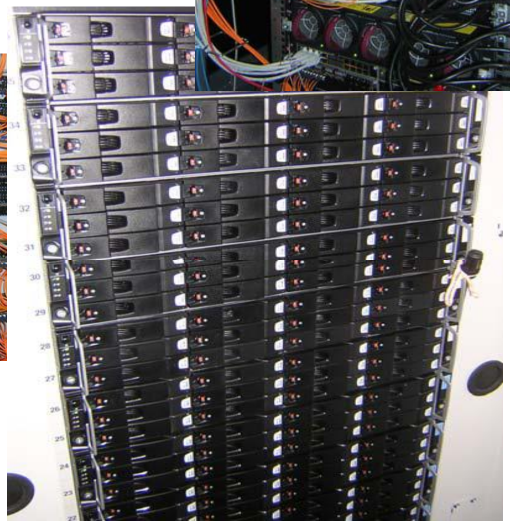
Data Acquisition (Examples)

- **EIGER X 9M Detector** (Synchrotron-Beamline at SLS):
  - two-dimensional hybrid pixel array detectors, which operate in single-photon counting mode
  - composed of 3110 x 3269 = 10,166,590 Pixel
  - maximum frame rate 238 Hz
    ca. 10 MB → 2.3 GB/s
    →**more than 8 TB per hour**

(5 years ago:
2 TB in 8 hours with Pilatus)



https://www.dectris.com/

Data Acquisition (Examples)

- The Large Hadron Collider will produce roughly 15 petabytes (15 million gigabytes) of data annually – enough to fill more than 1.7 million dual-layer DVDs a year!
  – GRID computing to allow access





https://en.wikipedia.org/wiki/Worldwide_LHC_Computing_Grid

Is Data Acquisition Controls?

- Data Acquisition requires
  - Network infrastructure
  - Computer storage infrastructure
  - Server infrastructure for data access
  - Environment (e.g. Grid) for data access
  - Manpower for setup and maintenance
- Detectors
  - can provide information about accelerator (beam position)
  - need to be adjusted to accelerator setup (connection to control system needed)
- Some detectors (e.g. BPMs) are part of the accelerator anyway

Not necessary

Yes its needed

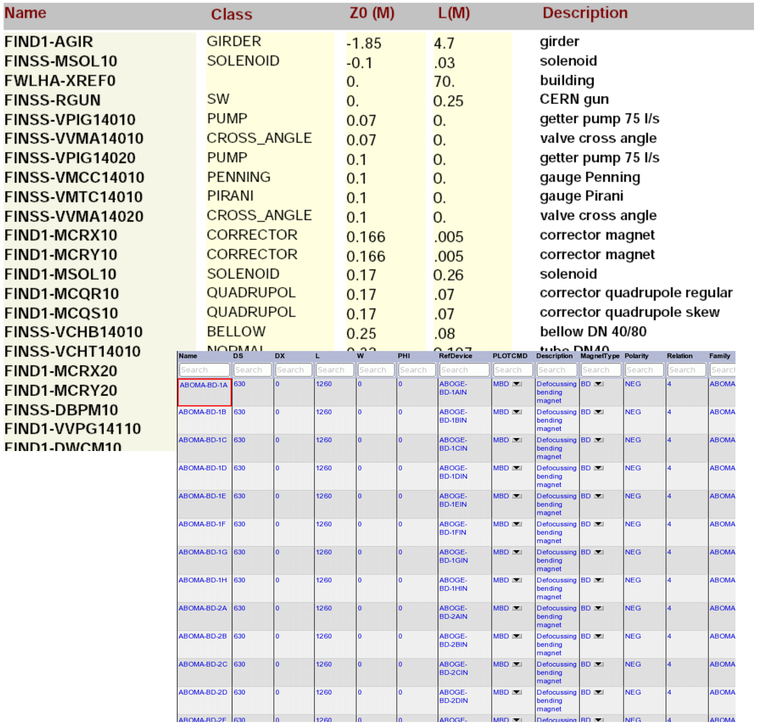
Has to be discussed to avoid problems!

For example

5. Relational Databases

What is a Relational Database?

- Used for "stable" Data (Lattice, Magnet Data etc.)
- Good for searching
- Might be slow for runtime data
- Examples:
  - –Oracle
  - –MySQL
  - –MSAccess
- Language to access data is SQL (Structured Query Language) for all examples



Name	Class	Z0 (M)	L(M)	Description
FIND1-AGIR	GIRDER	-1.85	4.7	girder
FINSS-MSOL10	SOLENOID	-0.1	.03	solenoid
FWLHA-XREF0		0.	70.	building
FINSS-RGUN	SW	0.	0.25	CERN gun
FINSS-VPIG14010	PUMP	0.07	0.	getter pump 75 l/s
FINSS-VVMA14010	CROSS_ANGLE	0.07	0.	valve cross angle
FINSS-VPIG14020	PUMP	0.1	0.	getter pump 75 l/s
FINSS-VMCC14010	PENNING	0.1	0.	gauge Penning
FINSS-VMTC14010	PIRANI	0.1	0.	gauge Pirani
FINSS-VVMA14020	CROSS_ANGLE	0.1	0.	valve cross angle
FIND1-MCRX10	CORRECTOR	0.166	.005	corrector magnet
FIND1-MCRY10	CORRECTOR	0.166	.005	corrector magnet
FIND1-MSOL10	SOLENOID	0.17	0.26	solenoid
FIND1-MCQR10	QUADRUPOL	0.17	.07	corrector quadrupole regular
FIND1-MCQS10	QUADRUPOL	0.17	.07	corrector quadrupole skew
FINSS-VCHB14010	BELLOW	0.25	.08	bellow DN 40/80
FINSS-VCHT14010	NORMAL	[illegible]	[illegible]	tube DN40
FIND1-MCRX20				
FIND1-MCRY20				
FINSS-DBPM10				
FIND1-VVPG14110				
FIND1-DWCM10				

Name	DS	DX	L	W	PHI	RefDevice	PLOTCMD	Description	MagnetType	Polarity	Relation	Family
Search	Search	Search	Search	Search	Search	Search	Search	Search	Search	Search	Search	Search
ABOMA-BD-1A	630	0	1260	0	0	ABOGE-BD-1AIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1B	630	0	1260	0	0	ABOGE-BD-1BIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1C	630	0	1260	0	0	ABOGE-BD-1CIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1D	630	0	1260	0	0	ABOGE-BD-1DIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1E	630	0	1260	0	0	ABOGE-BD-1EIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1F	630	0	1260	0	0	ABOGE-BD-1FIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1G	630	0	1260	0	0	ABOGE-BD-1GIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-1H	630	0	1260	0	0	ABOGE-BD-1HIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-2A	630	0	1260	0	0	ABOGE-BD-2AIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-2B	630	0	1260	0	0	ABOGE-BD-2BIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-2C	630	0	1260	0	0	ABOGE-BD-2CIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-2D	630	0	1260	0	0	ABOGE-BD-2DIN	MBD	Defocussing bending magnet	BD	NEG	4	ABOMA
ABOMA-BD-2E	630	0	1260	0	0	ABOGE-	MBD	Defocussing	BD	NEG	4	ABOMA

- Relational Databases are useful for Control Systems
- Some accelerator control systems have integrated relational databases
- Setup and Maintenance require knowledge and manpower

For example

6. Relationship of IT (Information Technology) and Controls

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Who is Responsible for What?

- Most large research institutes have a Controls Group in addition to a IT Group
- Why separate IT from Controls?

IT	Controls
• Office PC installation	• Accelerator computer installation
• Operating Systems for Office applications	• Integration of accelerator hardware
• Infrastructure (network cables)	• Control Room applications
• Central Services (Computing Cluster, Server Room …)	• Distributed processes

Databases, Timeserver, Network, Security

Controls is dependent on IT.

Responsibilities have to be discussed to avoid problems!

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Table of Content

Summary: What is Accelerator Controls

- It is hard to define – but every Accelerator has one
- It is organized in layers separating hardware from applications
- It is (has to be) a distributed system, involving some network protocols
- The borders are not clearly defined
  - For example: Where starts the hardware responsibility (PLCs, embedded systems)?

Definition:

An **Accelerator Control System** is a computer environment that allows remote access to the accelerator hardware with a lot of different functionality to satisfy the requirements of several different user groups.

References

Bad news: There is no book on Accelerator Control Systems
Good news: You can find some things in the Internet

- ICFA Newsletter Number 47 (December 2008) on Control System: http://icfa-usa.jlab.org/archive/newsletter/icfa_bd_nl_47.pdf

- EPICS: https://epics-controls.org/
- Tango: http://www.tango-controls.org/
- CERN Controls Group: https://be-dep-co.web.cern.ch/
- PSI Controls Group: http://epics.web.psi.ch/

…search the institute web pages …

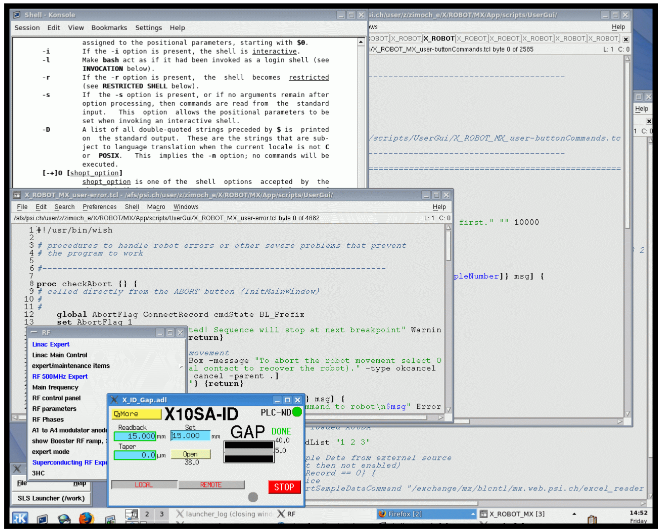
- International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS): https://www.icalepcs.org/

What to Learn as a Controls Guy?

1. Be curious about what your customers do (accelerator physics, experiments, medical treatment, etc.)
2. Enjoy programming
   – Script Language (python or similar)
   – Object Oriented (Java, C++, etc.)
3. Enjoy computer environments

Quick test:

Do you feel comfortable with this



• Useful skills include (non-essential)
   – Basic knowledge in Accelerator Physics or general Physics
   – Database structures/sql commands
   – Linux and/or Windows administration
   – Network administration
   – PLC, FPGA or DSP programming (nearly electronics)
   – Graphical User Interface design

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Wir schaffen Wissen – heute für morgen