# Control System of the European Spallation Source

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www.europeanspallationsource.se
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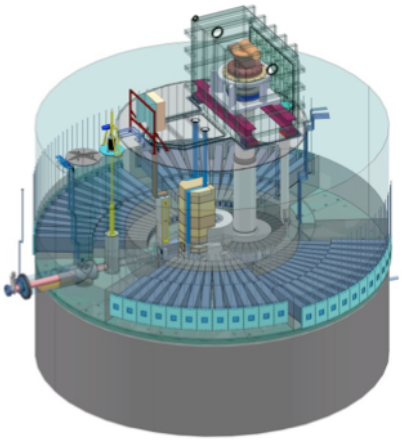
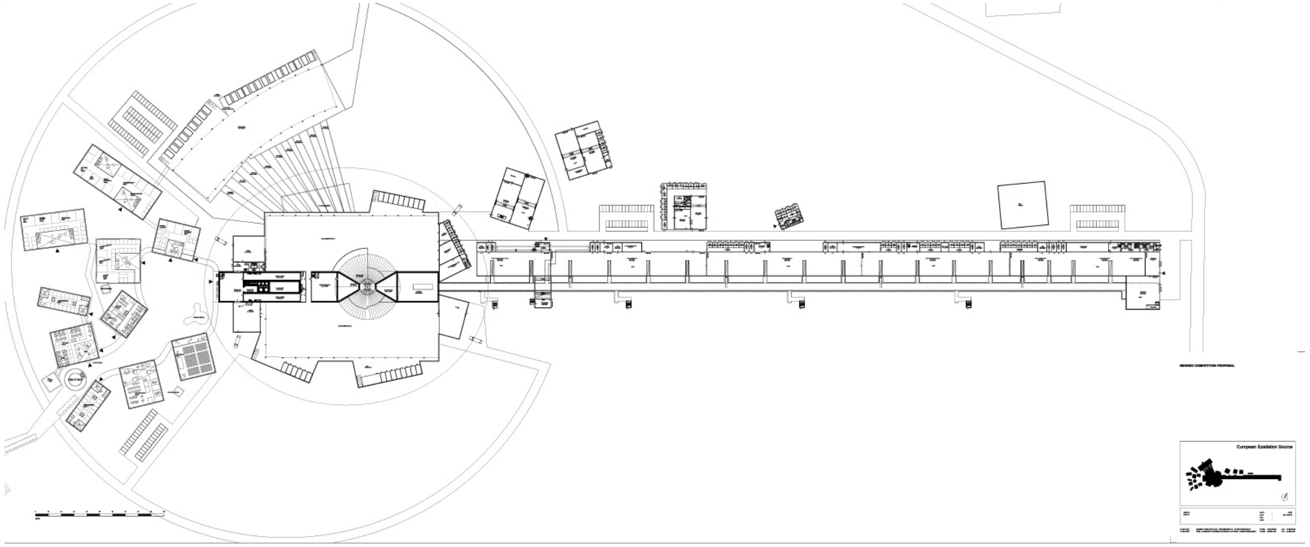
# Outline

- Short recap of the ESS
- Functions of a control system
- Technologies
  - Hardware (Electronics)
  - Software
- System structures
- Summary

# The European Spallation Source

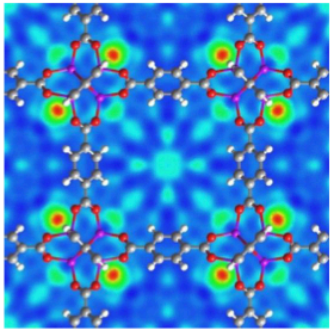
- The European Spallation Source (ESS) consists of :
  - a pulsed accelerator that shoots protons into
  - a rotating metal (tungsten) target to produce neutrons
  - (up to ) 22 neutron instruments for various experiments





# The European Spallation Source

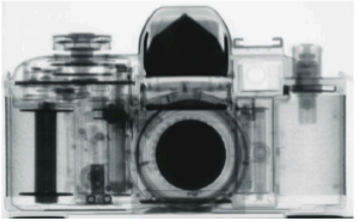
- ESS is a neutron spallation source for neutron scattering measurements.
- Neutron scattering can reveal the molecular and magnetic structure and behavior of materials:
  - Structural biology and biotechnology, magnetism and superconductivity, chemical and engineering materials, nanotechnology, complex fluids, etc.



Neutron scattering of hydrogen in a metal organic framework

Neutron radiograph of a flower corsage

X-Ray Image



Neutron radiograph

# The European Spallation Source

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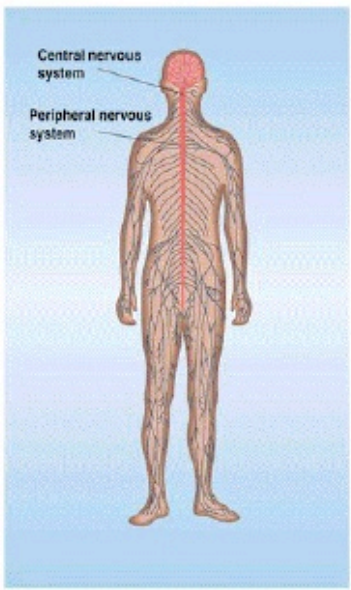
- The European Spallation Source (ESS) will house the most powerful proton linac ever built.
  - The average beam power will be 5 MW.
  - The peak beam power will be 125 MW
- At 5 MegaWatts, one beam pulse
  - has the same energy as a 7.2kg shot traveling at 1100 km/hour (Mach 0.93)
  - Has the same energy as a 1000 kg car traveling at 96 km/hour
  - Happens 14 x per second

# The Integrated Control System (ICS)

## CENTRAL NERVOUS SYSTEM

▸ Human Central and Peripheral Nervous Systems





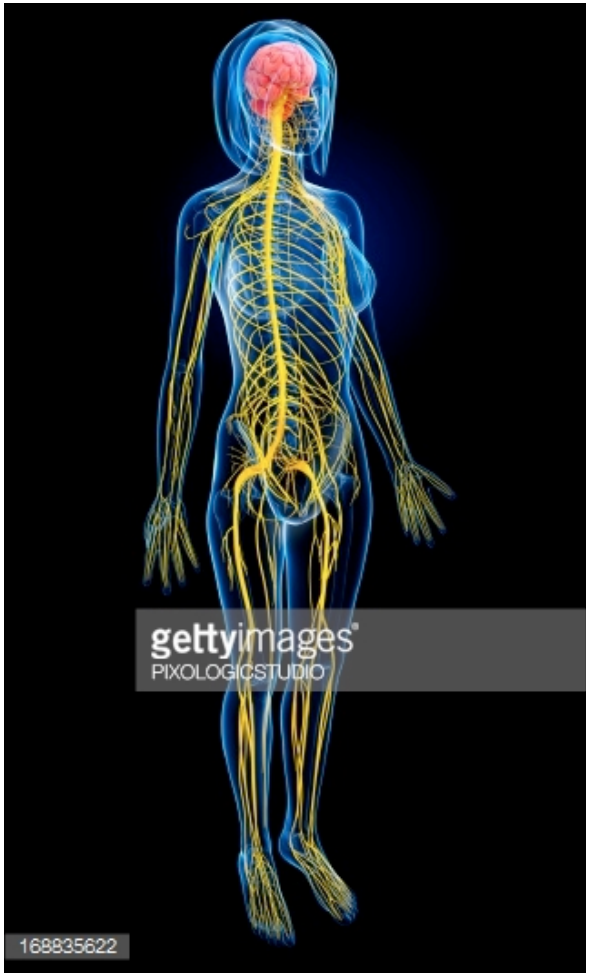

### FUNCTIONS

:

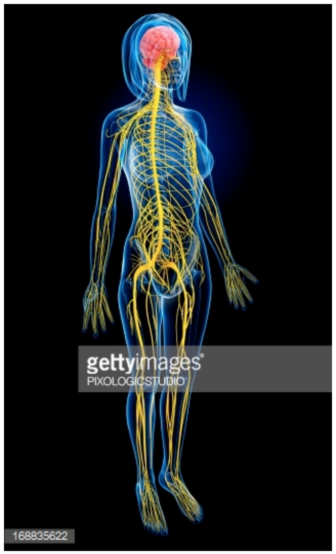
- Relays messages
- Processes information
- Analyzes information

# Functions of the control system

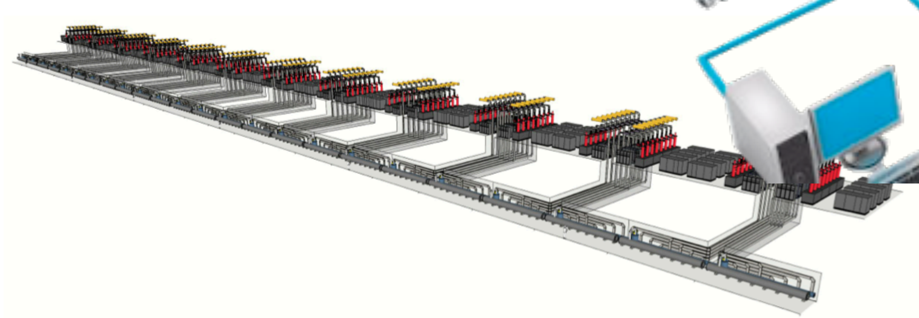
- A good analogy: central nervous system of a human being
  - Connects components together
  - Collects and stores information
  - Sends commands to "actuators"
  - Some autonomous functions like in the brain: react to dangers
- Enables the operation of the facility
  - Thousands of devices, millions of control points

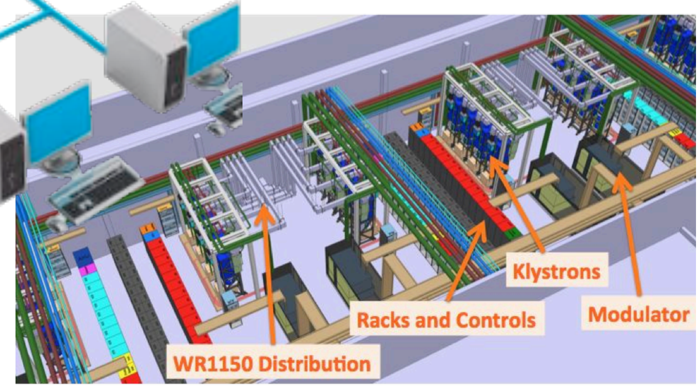


# Can you see the similarities?





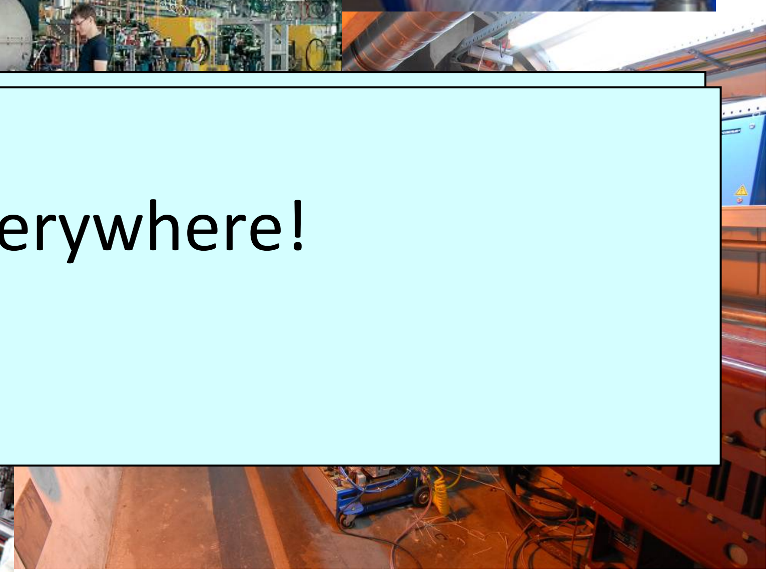




# Motivation 1







**Observation:**

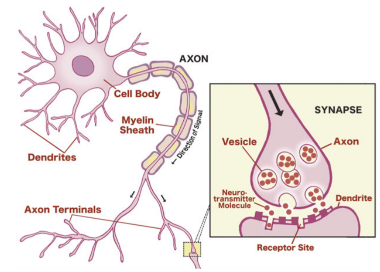
Control System is Everywhere!

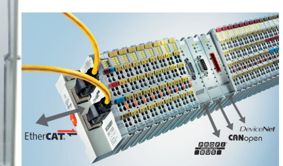
# Requirements for the control system

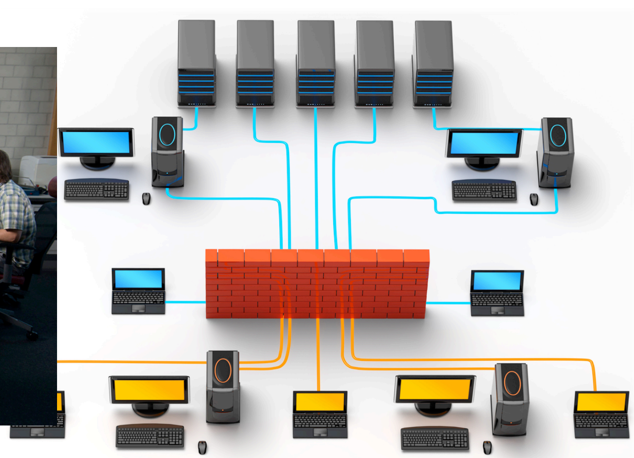
- Enable operation of the whole ESS from a single control room
- High reliability: 95% for the whole ESS, 99.99 for ICS (exact numbers for ICS to be defined, high in any case)
- 24 hours, 7 days a week operation
- Long lifetime (accelerator planned lifetime 40 years)
  - Upgrades will happen in between
  - High maintainability
- Support (up to) 14 Hz operation of ESS
- Provide controls for the Accelerator, Target, Site infrastructure, Neutron Instruments (excl. data handling)

# Control system Functions #1

- Connects components together
  - Distributed control system, connected over a computer network
    - (Ethernet)
  - Computers on the field are the neurons, with I/O cards as synapses



# Control system Functions #1

- Connects components together
  - A lot of things to connect!
    - Management of complexity
    - Ideally, one button in the control room: Switch beam on or off
    - Reality is not quite that simple
  - Each subsystem may (usually does) have its local control system

# Control system Functions #2

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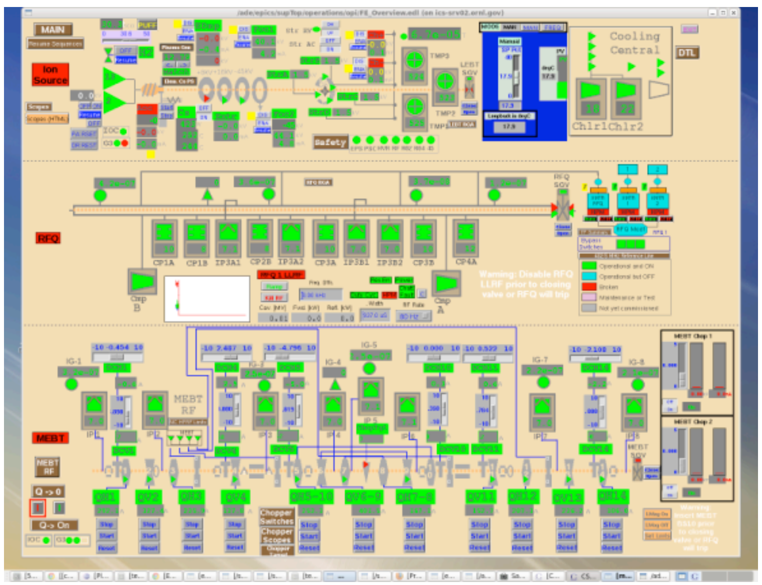
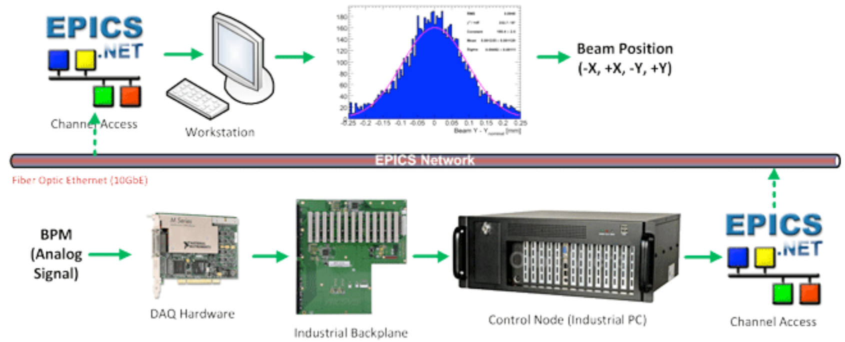
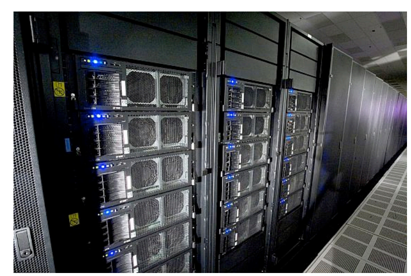
- Collect, display and store information
  - Device status & control displays in the control room
  - Store status data into archive to be analyzed later
    - How did the system perform last night? What happened on beam pulse # 102364?



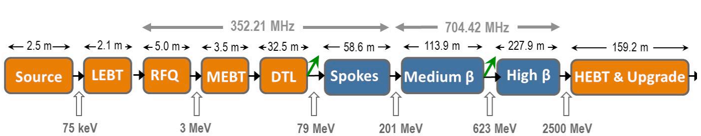


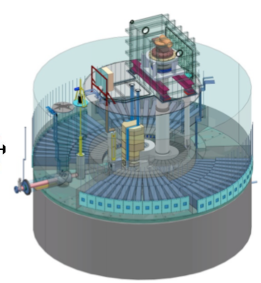



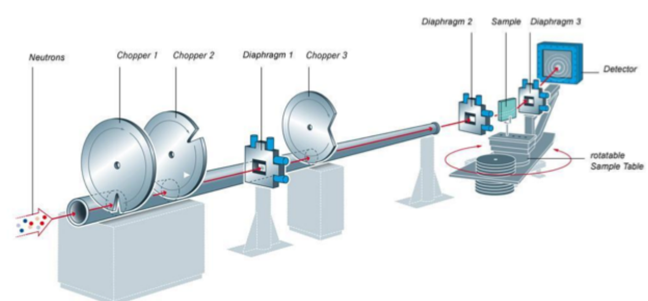
# Control system Functions #3

EUROPEAN SPALLATION SOURCE

- Send commands to actuators
  - Switch on/off, set current, chop beam, etc.
- Synchronized – 14 Hz operation
  - Start the beam
  - RF pulses have to be there when the beam comes
  - Monitors have to be triggered when the beam is there
- – Timing system
  - Synchronizes actions
  - Distributes time for the whole facility

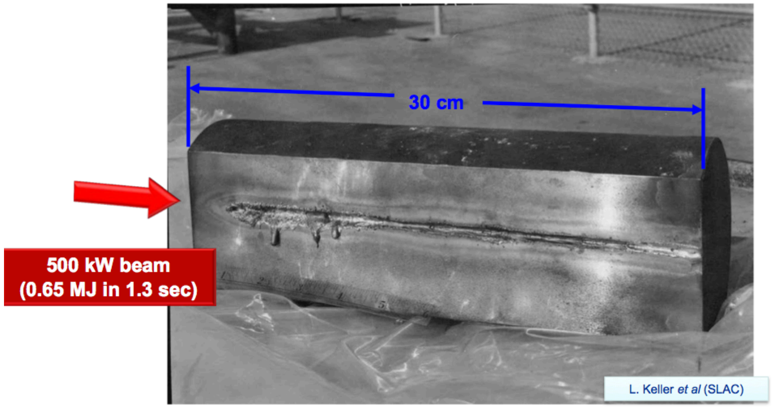


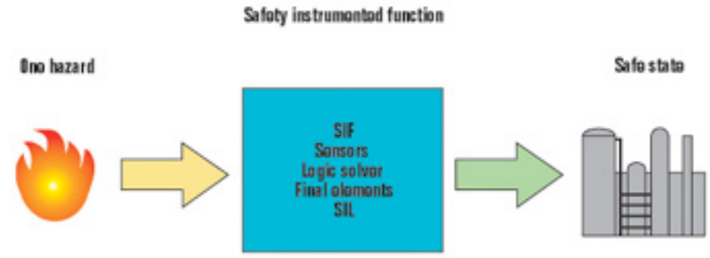





# Control system Functions #4

- React to dangers: Machine Protection
  - Remember: 5 MegaWatts of average beam power!
- Beam can damage accelerator components
  - Much faster than a human can react – in microseconds!
- – The accelerator has to be protected against itself
- – Task of a Machine Protection System
- – Consisting of
  - sensors to detect dangerous situations (beam loss)
  - Beam Interlock System
  - Actuators to stop the beam
- Fast logic in hardware (FPGA)
  - Autonomous, but close relation to equipment control
  - Configuration and operation via software
  - Rigorous development and testing



# Control System Technologies

Hardware (Electronics)

- Industrial control electronics
  - PLCs: robust, reliable, well proven
- Real-time capable
  - React within one pulse (14 Hz, 71 milliseconds)
- Fast
  - Fast measurements and reactions (microseconds, nanoseconds)

# Control System HW Technologies #1

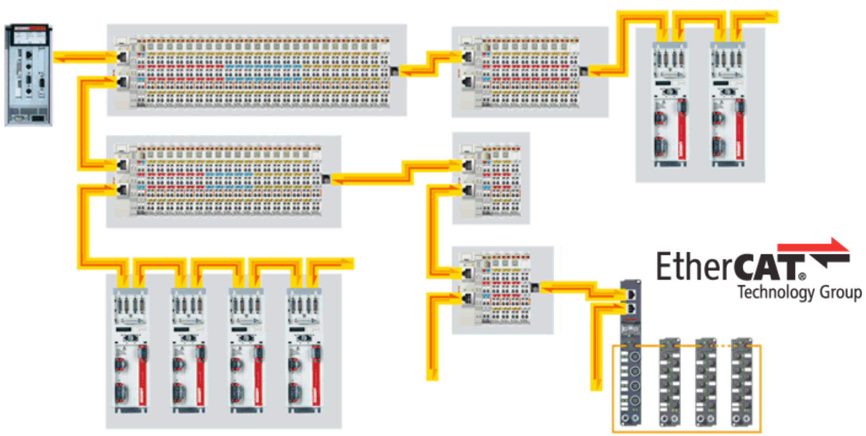
PLCs for distributed control
(Programmable Logic Controller)

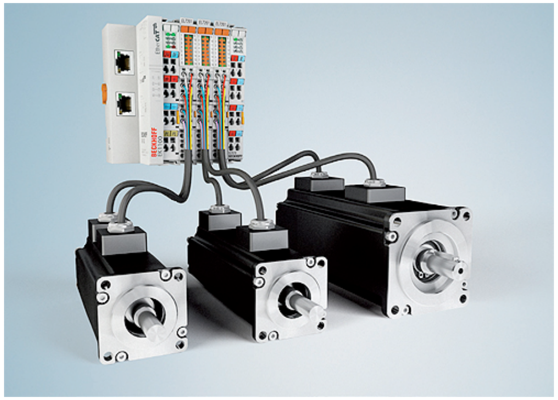
- Vacuum systems
  - pumps, gauges
- Cryogenics control
  - Cooling down helium to 2 Kelvin
  - Takes two weeks from room temperature to cool down a cryomodule for operation
    - Reliability is essential – speed (as far as sufficient) secondary
- Building (aka Site Infrastructure, or Conventional Facilities)
  - Is an important part for operation of the facility
    - Cooling, electric power, etc.
- Target systems
  - Cooling, gas and liquid flows, etc.

# Control System HW Technologies #2



- Event-synchronized real-time systems
  - Need to react within one pulse (14 Hz, 71 milliseconds)
  - Use the EtherCAT standard (https://www.ethercat.org)
    - Real-time capable Ethernet protocol
    - Widely used in industry
  - Use with an open-source driver on a regular computer



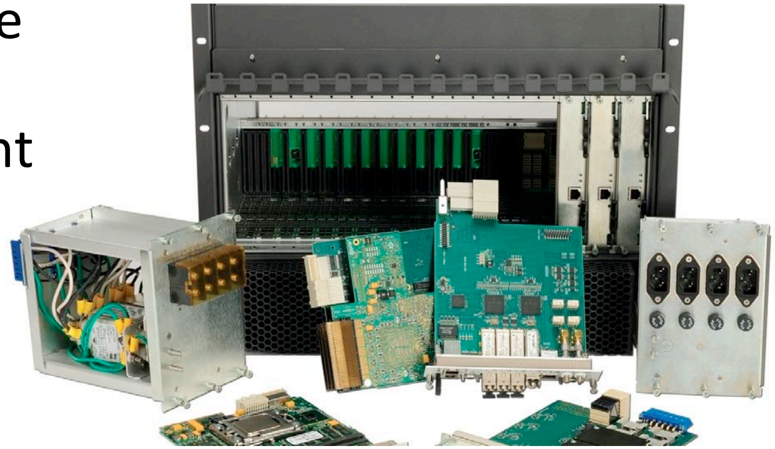



# Control System HW Technologies #3

- Ultrafast systems (by today's standards)
  - Need to measure/react in nanoseconds
  - Implemented in direct logic (FPGA, Field Programmable Gate Array)
- Large amounts of data to handle
  - Analog-to-digital converters in 100 MSPS range
  - Sometimes needs to be stored for analysis
- Fastest industrial systems of today
  - Telecommunication : MTCA (Micro TeleCommunications Architecture)
  - Adapted for physics applications: MTCA.4

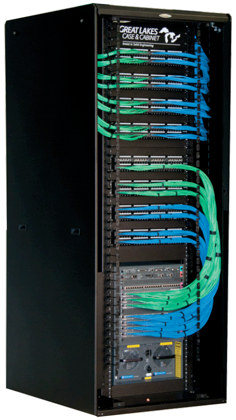
# MicroTCA.4 systems

- Modular (multi)computer system
  - Plug-in modules (I/O, CPU)
  - Based on PCI Express (MTCA.4)
  - High data bandwidth
  - Multi-CPU systems
  - High-performance electronics, FPGA (Field Programmable Gate Array), fast I/O
  - Extensive platform management
- Rather expensive
  - Use only where justified by performance needs



# Control System (HW) Technologies #4

- Networking
  - Thousands of computing nodes in one network
    - SDN (Software Defined Networks)
  - Potentially high traffic volumes
    - Archiving millions of process variables, detector data, images, etc.
  - Flexibility required
    - Computers and controllers may come and go
    - Traffic may need segmentation (not all data interests everybody)
    - But some data may be needed by anybody/everybody
- Servers and storage
  - Virtualization (reduce number of PC boxes)
    - High availability
  - High-speed storage
    - Big volumes, data retention requirements

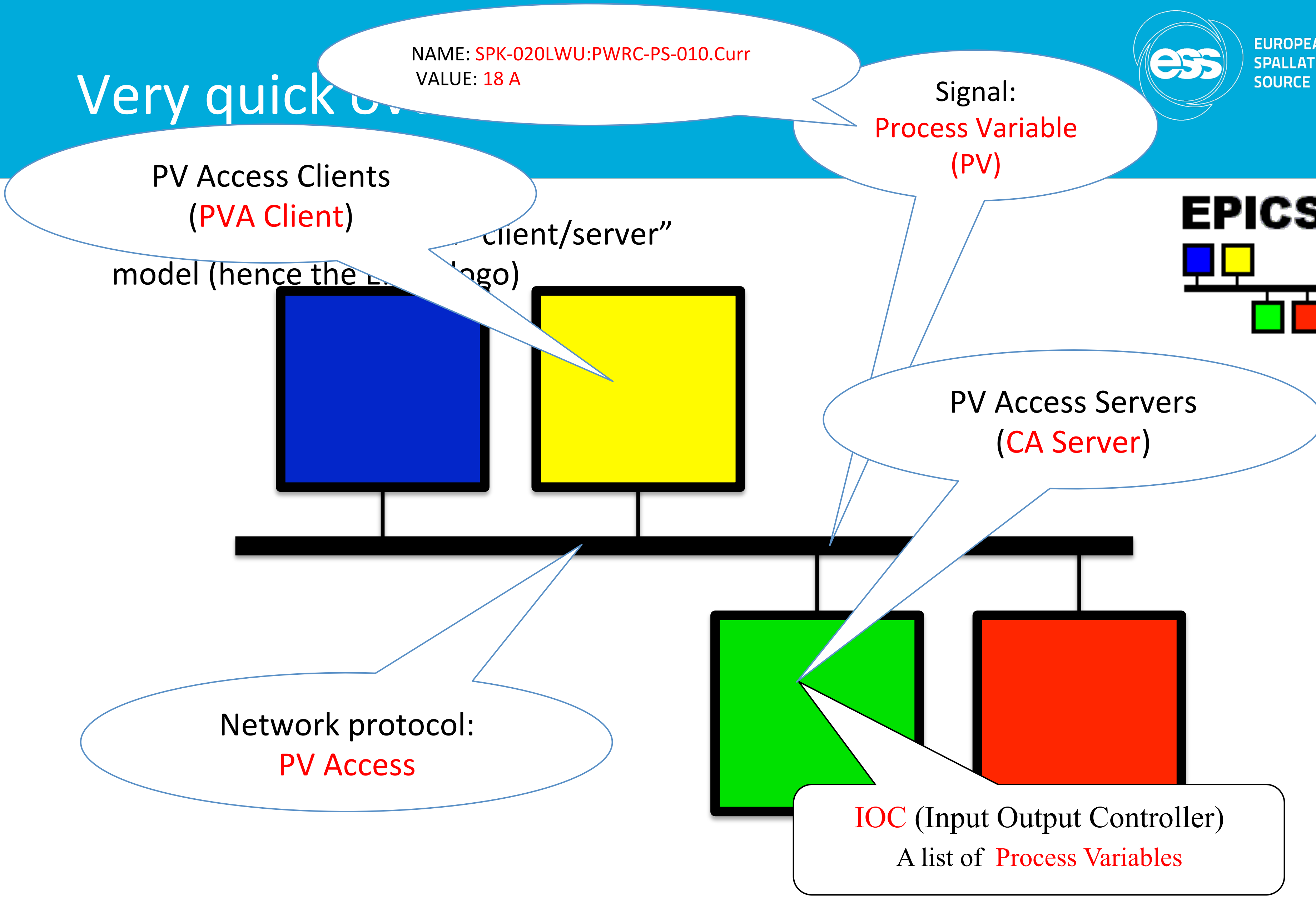


# Software technologies

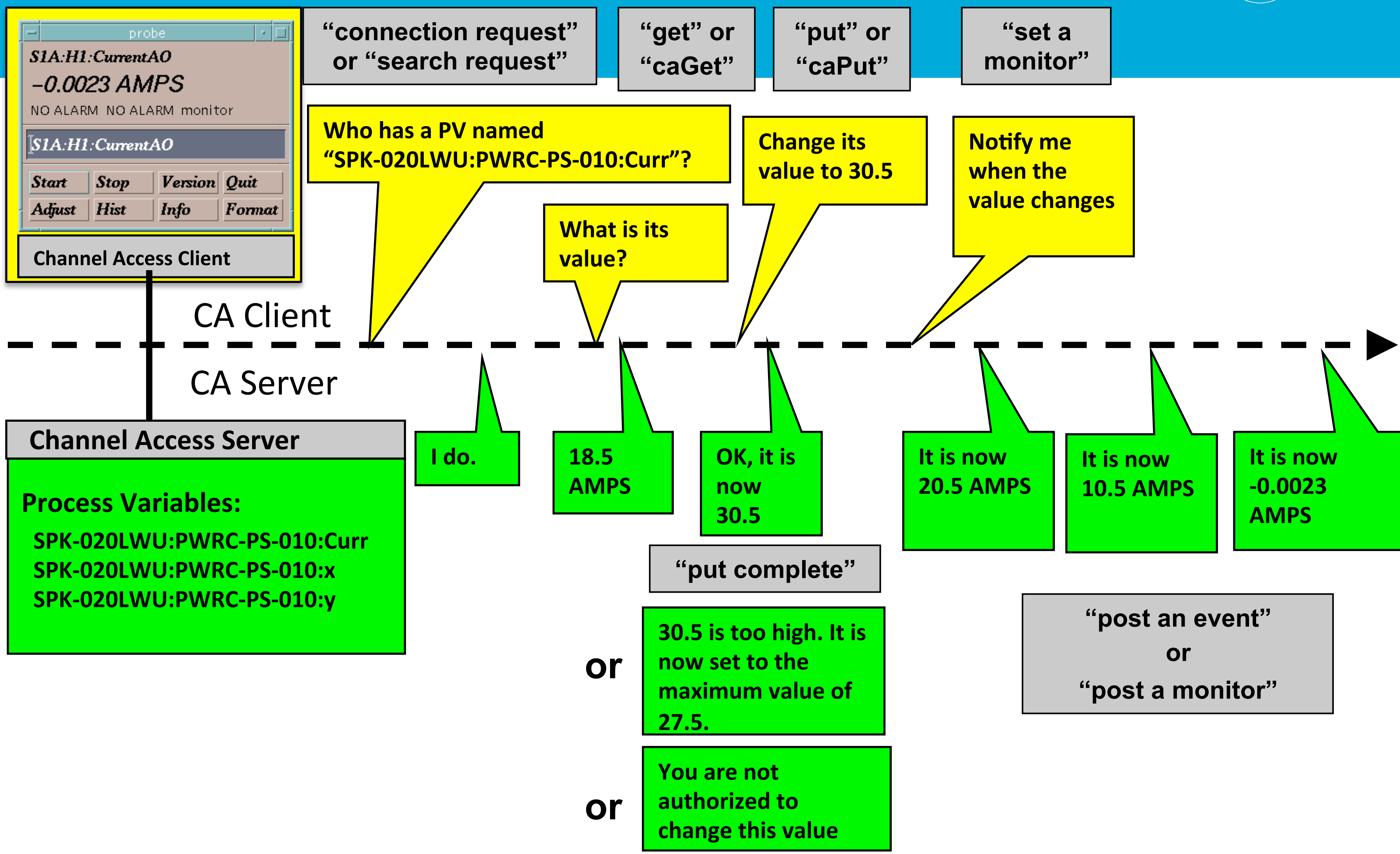
- Control System Toolbox: EPICS
  - Experimental Physics and Industrial Control System
  - One of a few **software packages** specialized for accelerator and experimental systems
    - Others: TANGO (ESRF, MaxIV, etc), DOOCS (DESY), FESA (CERN), etc.
  - Open source, collaborative effort
    - Not precisely known, but over 100 labs and installations use EPICS
      - From huge scientific installations to beer brewing (really!)
- EPICS allows us to connect to the signals in the field
  - Read, write, monitor over network
  - Scales from a few signals up to millions of signals
- Server-client model
  - Like a small-scale Internet of Things (Intranet of Things)

# Very quick ov

client/server"
model (hence the E logo)



# Connect to I/O via EPICS PV Access



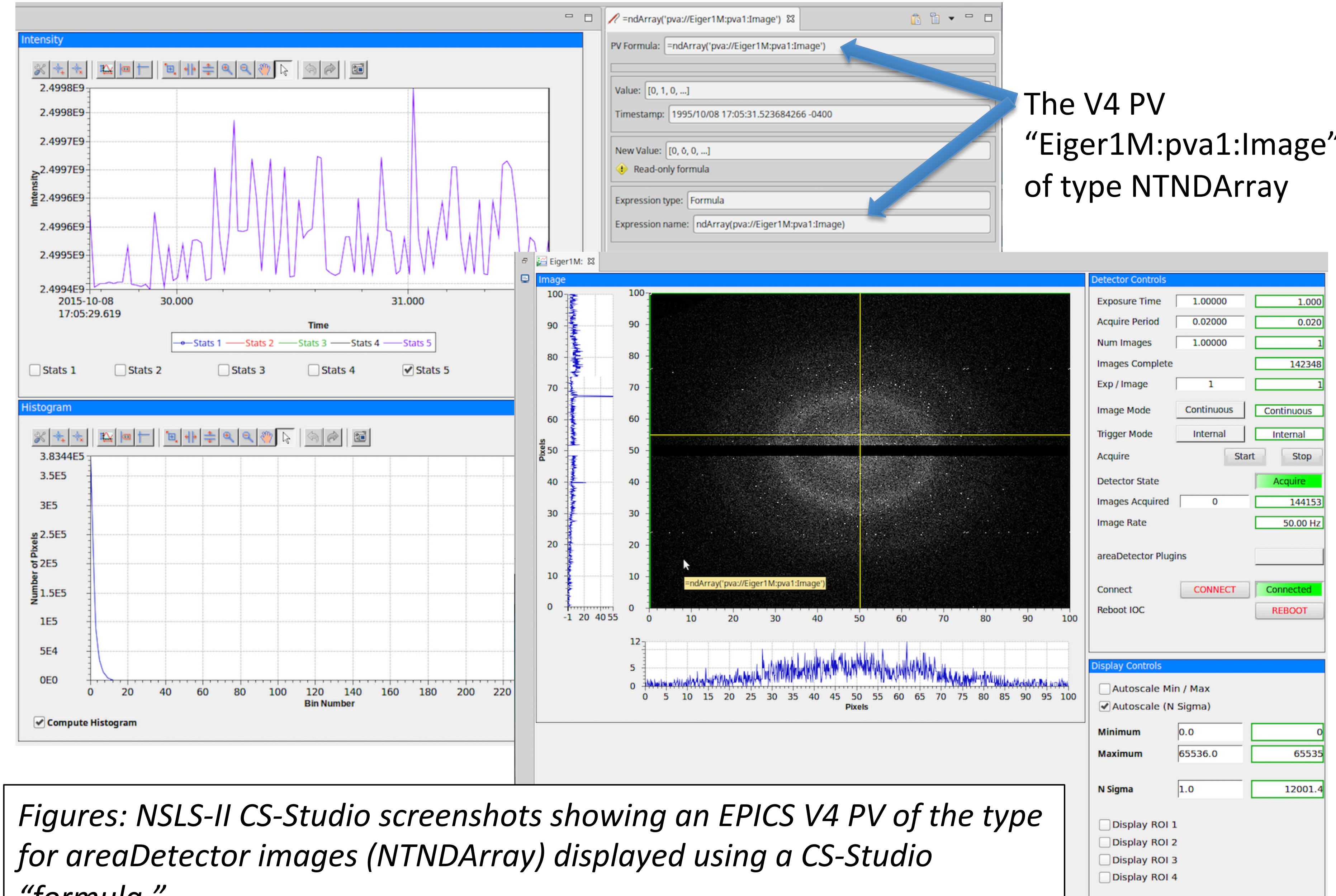
# EPICS Technologies

- Programming languages
  - C, C++ (most of the low-level layer, also client code)
  - Java (Client software, associated services)
  - Python is a popular scripting language, many others are supported
- Operating systems
  - EPICS runs on many operating systems
    - Linux, Windows, MacOS
    - Real-time operating systems (usually I/O layer only)
      - vxWorks, RTEMS, etc
- Platforms
  - From big to small
    - Raspberry PI to large server machines
    - On a toaster – almost.
  - A lot of I/O devices supported
    - And (relatively) easy to write your own support.

# Application and GUI/HMI development

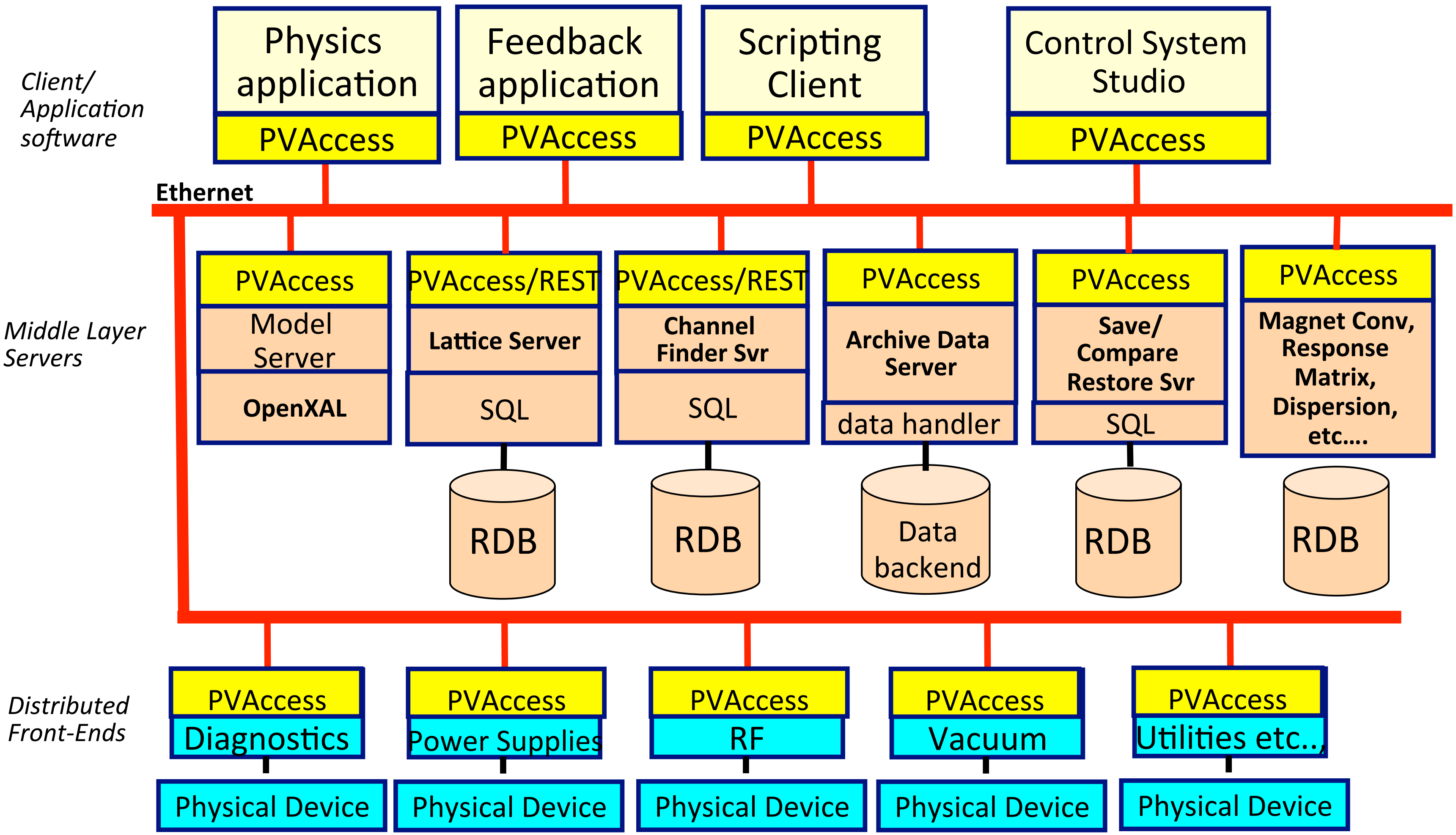
- Several tools available from the community
  - GUI (graphical User Interface) builders
  - Tools for data archiving, alarm management, etc.
- ESS has selected the Control Systems Studio as a standard tool
  - Based on ECLIPSE (Java), plug-in architecture
    - Can be configured to user's needs and extended
  - Several tools available as plug-ins:
    - GUI Builder (BOY), (Archive) Data Browser, Alarm Handler

# Example: image data transport and fanout




*Figures: NSLS-II CS-Studio screenshots showing an EPICS V4 PV of the type for areaDetector images (NTNDArray) displayed using a CS-Studio "formula."*

# Composition of the Control System



# Control System Applications

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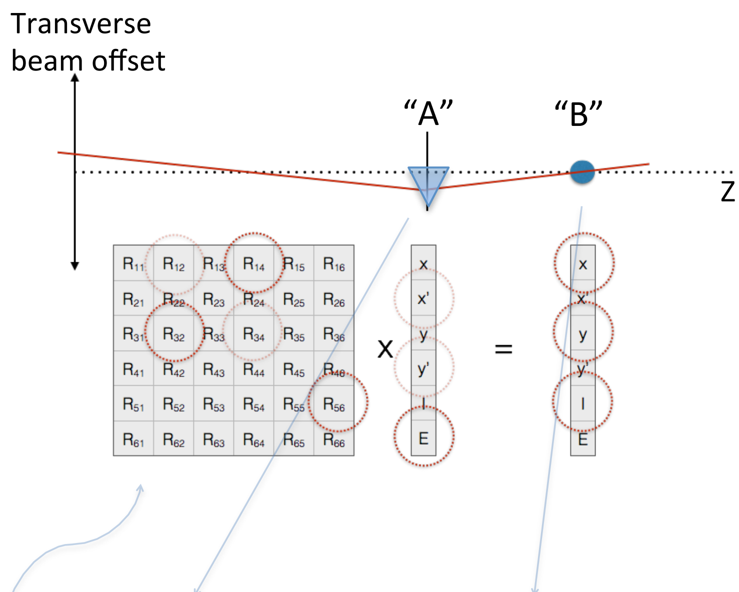
- General-purpose services
  - Process variable archiving for analyzing what happened
    - Continuous or "post mortem"
  - Handling alarms
    - Notify operators or engineers if something is going wrong
- Sub-system controls
  - Starting up and tuning the RF (or magnet, vacuum, etc) systems for operation
- Accelerator Physics applications
  - Use control system facilities to steer and shape the beam
  - Optimize the beam quality and behaviour
- Operation Sequencer
  - Steer the accelerator (and target) from low power beam to full power in a controlled way
- Support applications
  - Properties of the equipment, status displays, operation logbook, error and event logging, etc.

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             0              0        1.33379       0.966896              0              0
             0              0       0.358415        1.00957              0              0
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   1.00974e-28              0              0              0              0              1
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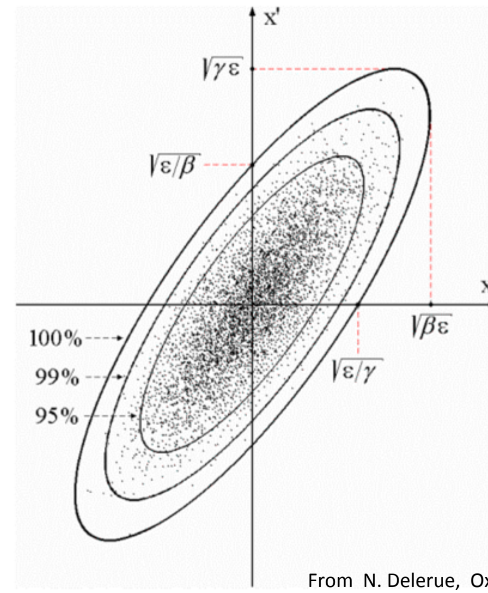


From N. Delerue, Oxford Univ.

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    betax -2.78671
    etax -0.00698294
    etaxp 0.00107115
    psiy 31.9488
    alphay 116.762
    betay 5.2592
    etay 0
    etayp 0
    z 2438.72
```

*Figure: EPICS V4 modelling service giving orbit response matrices and Twiss parameters for given devices. These are the basis of 95% of emittance minimization applications – feedback, steering, bumps, etc*

Greg White, Murali Shankar SLAC; Ivo List, ESS

# Summary

- Control system touches almost every aspect of the ESS facility – thus: Integrated Control System
- Enables the operation of the (very complex) facility as a single entity
- Technology spectrum is very wide
  - 9 orders of magnitude in timespan (nanoseconds to weeks)
  - Networking, servers, datacenter
  - FPGAs, Gigabytes/sec data handling to high reliability (and safety) systems
  - Software ranging from databases to accelerator physics, from GUIs to low-level kernel drivers
  - Hard- and firmware development

# Summary (cont)

- Very high reliability and availability requirements
  - Datacenter level, 24/7 operation, 99.99xx availability
- Handling of millions of Process Variables
  - Offer different abstractions to different users
    - Subsystem engineer, accelerator physicist, neutron scientist, manager,…
    - Ease of use
  - Storage and manipulation of data
    - How to find and access the required data

- If you are interested in how a very complicated system works, controls is the place to be!