Status of the *Karabo* Control and Data Processing Framework

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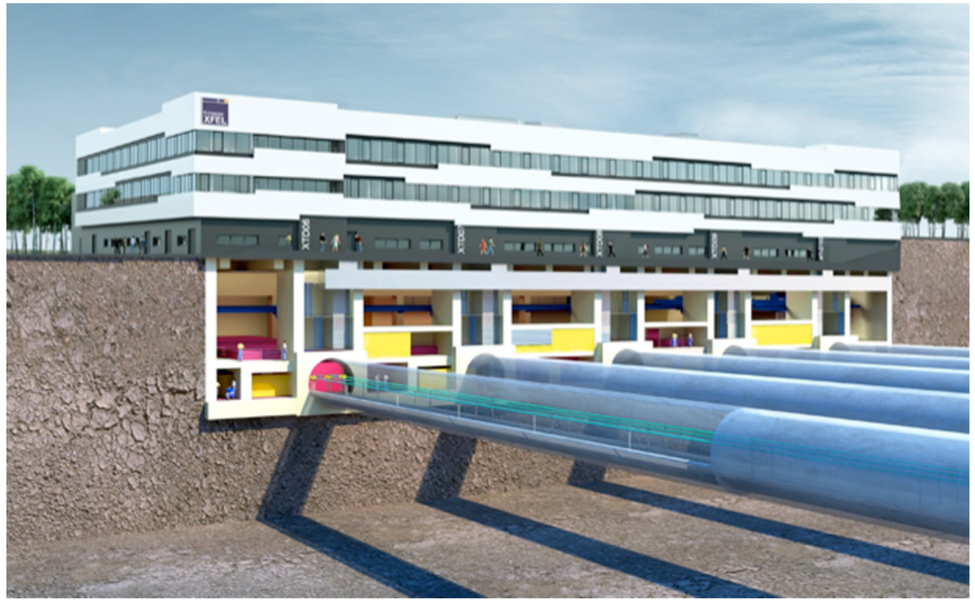
Outline

- Why there is Karabo?
  - The European XFEL
- Karabo Overview
  - Communication
  - Services and Interfaces
- Achievements and Lessons Learned
- Future Directions

The Home of Karabo: European X-ray Free Electron Laser (XFEL):

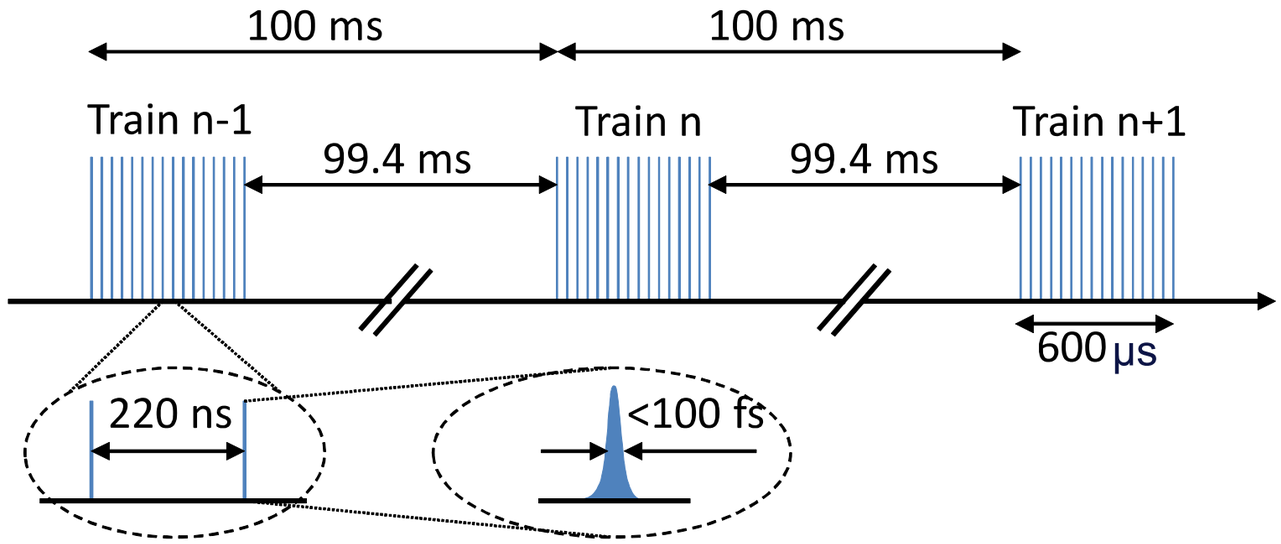
- Linear electron accelerator
  - run by DESY
- Undulators creating X-ray laser photons
- Photon beam steered
  - through 3 tunnels
  - to 6 instruments



Karabo:
Designed and developed for control, data acquisition, analysis

Why a New Control System?

- Photon beam at European XFEL has a particular pattern:
  - 10 Hz of "trains" of up to 2700 pulses
  - Inter-pulse spacing 220 ns (4.5 MHz)
- Custom-made MHz-capable 2D detectors
  - Single pulse resolution: 16 GB/s
  - Calibration required for online preview



- ➔Tight integration of control and online analysis required

European XFEL decided in 2011 to develop a custom *control and data processing* framework

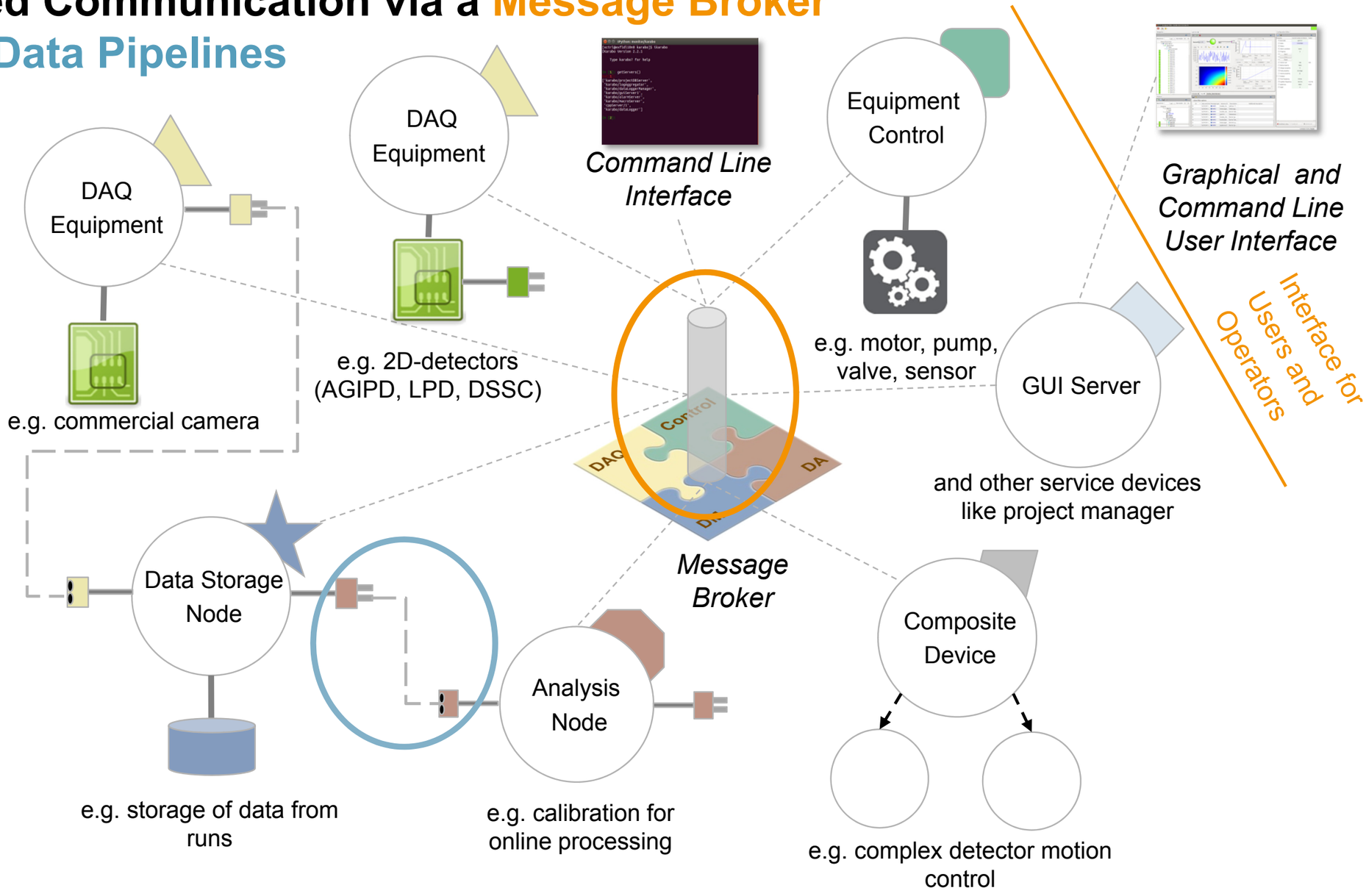
➔Karabo

(presented at ICALEPCS2013)

Karabo: Device Based Communication via a Message Broker and TCP/IP Data Pipelines

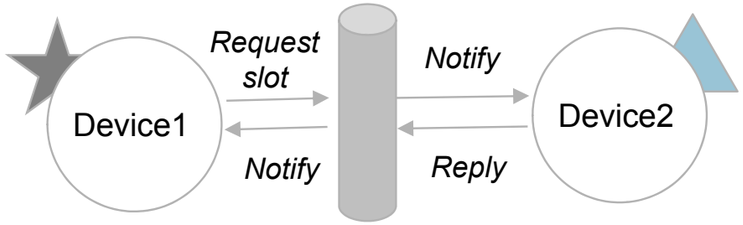
Self-describing
Karabo Devices

- Equipment control, e.g. motors, valves,…
- Detectors like
  - 2D detectors,
  - cameras
- Data storage
- Online data analysis, e.g. calibration
- System services

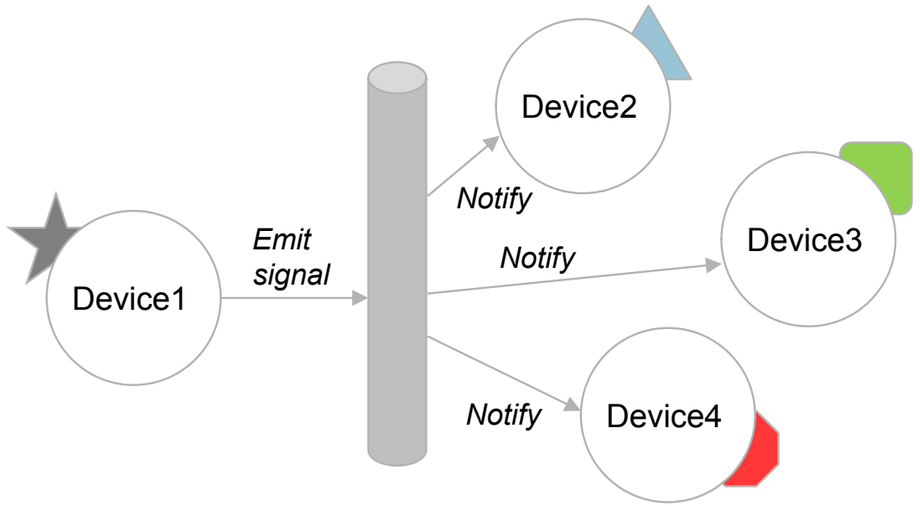


Karabo Communication Patterns

- Request/reply
  - Device registers methods as "slots".
  - Call from remote
    - ► with up to four arguments and return values.

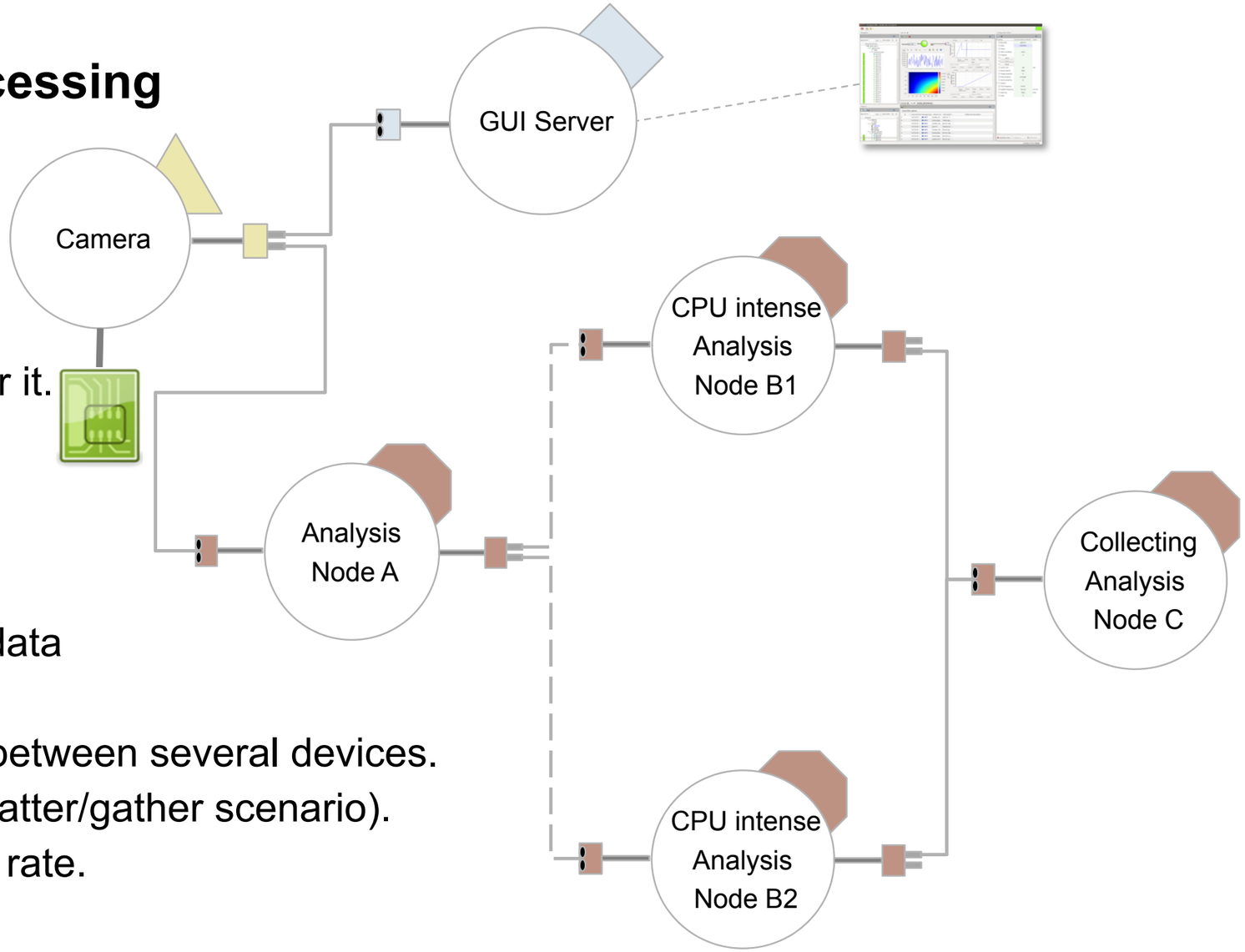


- Publish/subscribe
  - Devices subscribe slots to a remote "signal".
  - When signal is "emitted",
    all subscribed slots are called.
    - ► No publishing overhead for "popular" devices
    - ► **Karabo framework is completely event-driven**:
      regular **polling obsolete**.



Karabo Pipelines for Data Processing

- Complement broker communication
  - Using direct TCP/IP connections.
- Designed for (large) multi-D data.
  - Sent only when receiver ready for it.
  - But processing and transferring in parallel.
- Offer flexible configuration:
  - Sender can *wait*, *drop* or *queue* data when receiver not ready yet.
  - Individual *copy* vs. data *shared* between several devices.
  - Collect from several senders (scatter/gather scenario).
  - Delay readiness report to reduce rate.



Hash: Karabo's Flexible Data Container

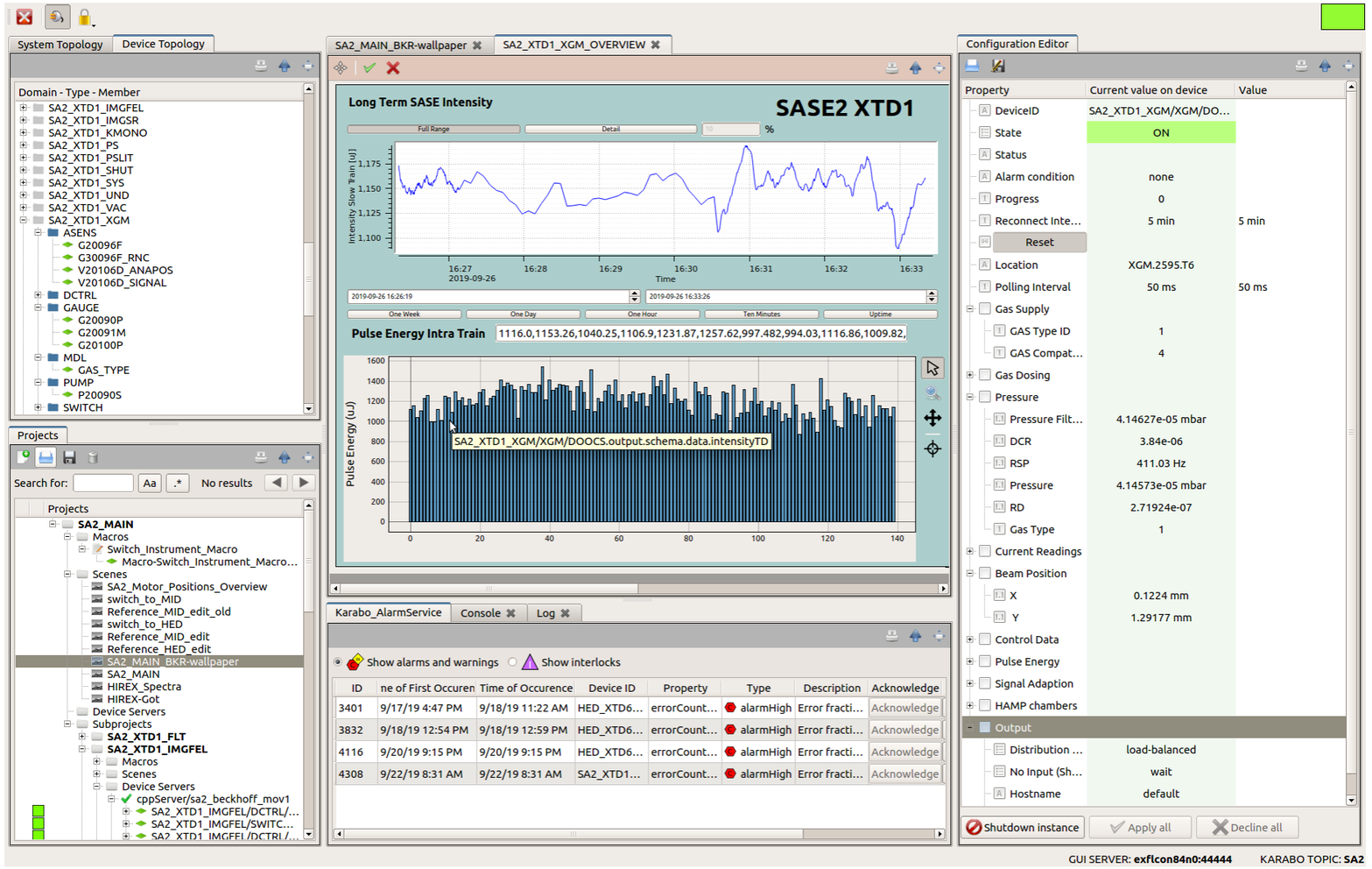
- A nested key-value container with attributes:
  - key: string
    - ▶ direct nested access: separate key levels by dot: `h.get("key1.key2.key3")`,
  - value: any type,
  - attributes per value: key-value container.

- Hash available in all three Karabo APIs:
  - C++
  - Python
    - ▶ "Bound" (C++ bindings)
    - ▶ "Middlelayer" (pythonic)

- Serialisation to Hdf5, XML and binary format.
  - Supported data types:
    - ▶ Scalars, complex, strings and vectors thereof,
    - ▶ "NDArray" for pipelines,
    - ▶ "ImageData": NDArray and meta data
      - not yet (!) or "Middlelayer" API.

```
In [1]: from karabo.bound import Hash

In [2]: h = Hash('a', 'square')

In [3]: h['b.c'] = 42

In [4]: h
Out[4]:
'a' => square STRING
'b' +
  'c' => 42 INT32

In [5]: h.setAttribute('a', 'colour','red')

In [6]: h
Out[6]:
'a' colour="red" => square STRING
'b' +
  'c' => 42 INT32
```

Graphical User Interface (PyQt)



Unified integrated cockpit:

- For experts:
  - Full system view.
  - Detailed access to configurations and commands.
  - Integrated command line.
- For everybody:
  - Customizable "scenes"
    - ► no coding required,
    - ► drag-and-drop properties.
  - Rich set of widgets.
- For operation:
  - Standalone scenes.

System Services

- Shipped as part of Karabo framework
  - GUI server device
  - Server to centrally run macros and GUI command lines
  - Project Database
    - ► Joint storage of GUI scenes, macros, device configurations
  - Alarm service: 

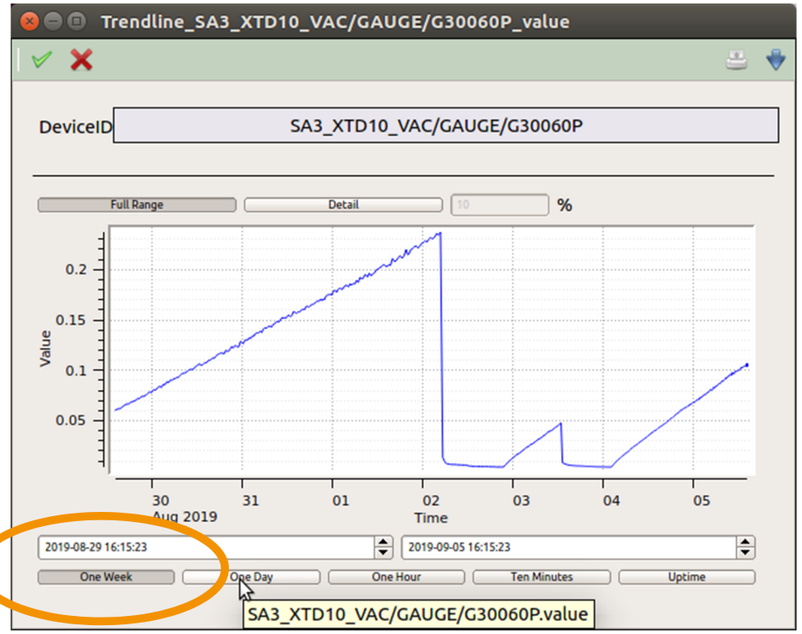
    - ► Track device properties outside normal operation value
  - **Data Logging**

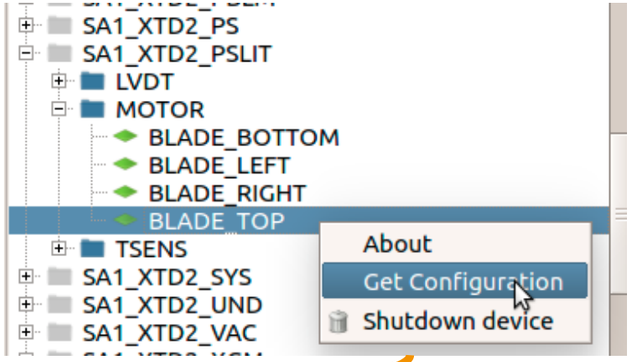
- Outside Karabo framework by independent software devices
    - ► E.g. to allow faster release cycle
  - **Data acquisition**
  - Scan tool

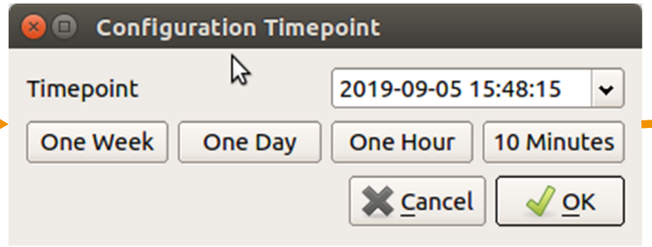
Karabo Data Logging

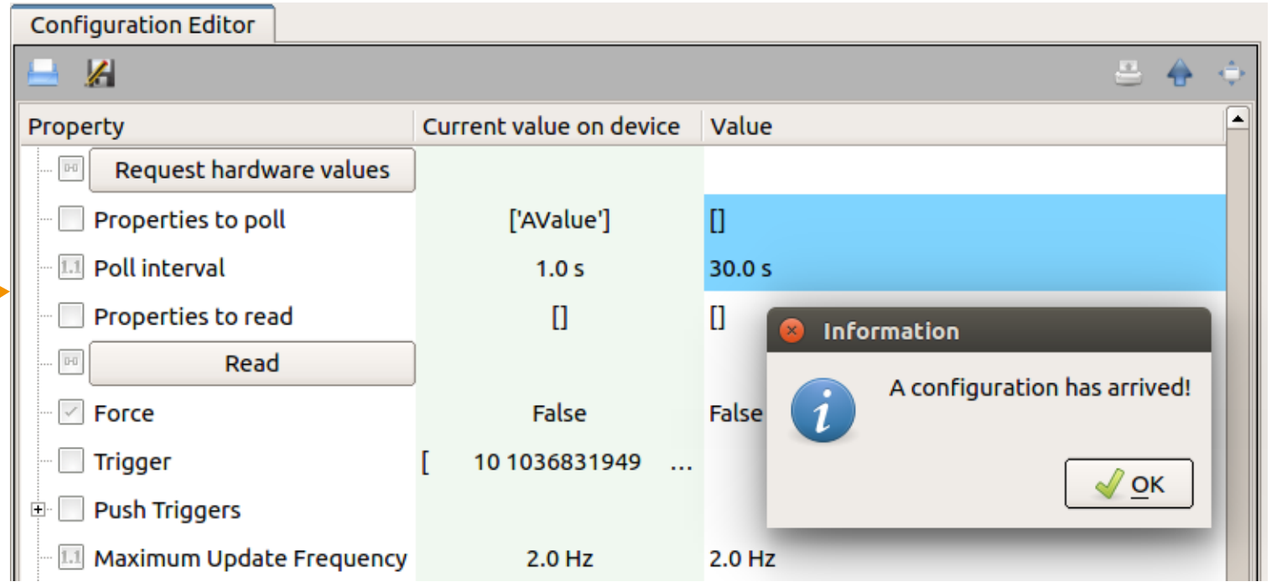
- In-built data logging and retrieval mechanism.
  - Control data only, no pipelines.

- Main control use cases:
  - Past data for trendlines: single scalar property vs time.
  - Past configurations: all device properties at point in time.



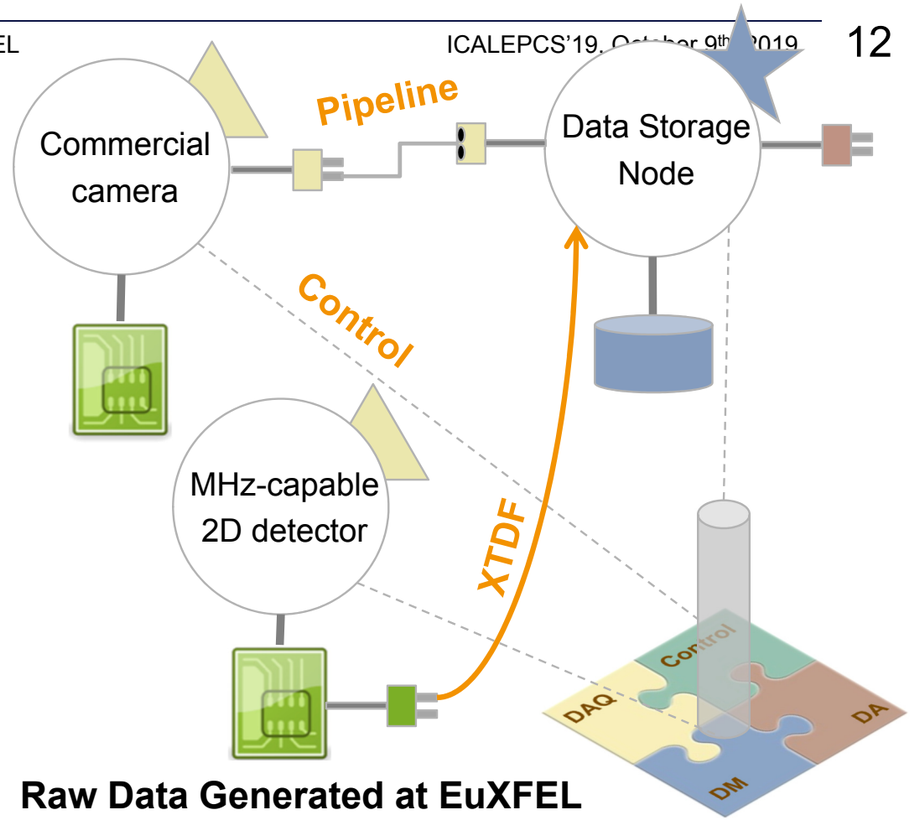


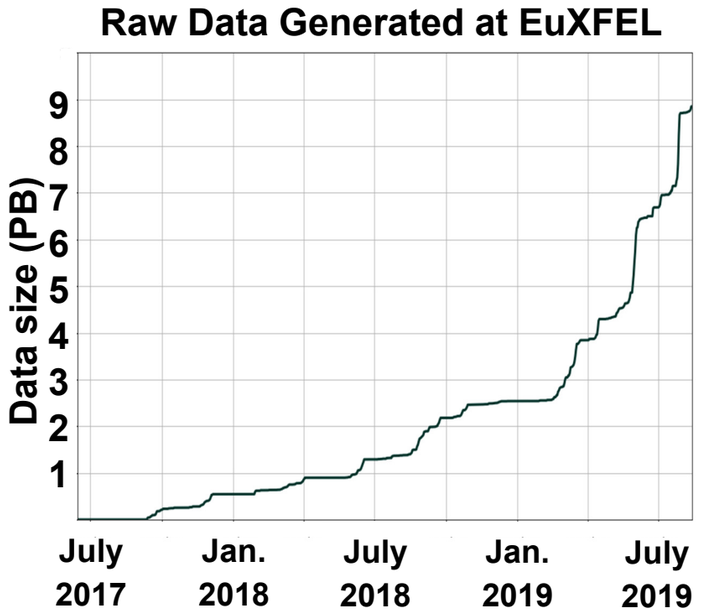




Karabo Data Acquisition (DAQ) Integration

- Focus on scientific instrument data with long term storage: EuXFEL data policy
- Support for different types of data sources:
  - **Control** data with train resolution: e.g. sensors, motors → **slow data**
  - 2D or pulse resolved data: e.g. **pipeline** from cameras, digitizers → **fast and/or medium sized data**
  - MHz-capable 2D detectors (XFEL train data format - **XTDF**) → **big & fast data**
- Data stored in HDF5 files, indexed per train
  - 9 PB raw data stored since experiments started
  - 12 GB/s achieved (600 images per train)
- Provide data stream for online display and analysis:
  - Calibration of big 2D detectors (1.8 GB/s, 2s latency),
  - External tool via Karabo-to-ZeroMQ bridge

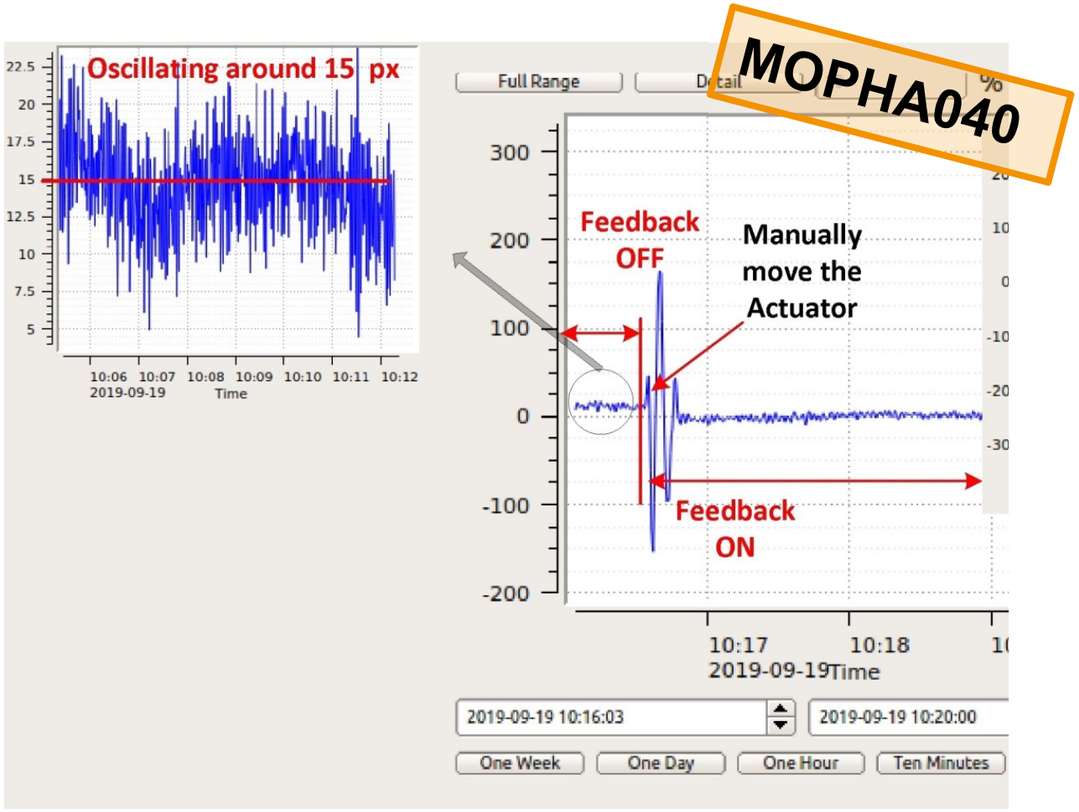




Achievements

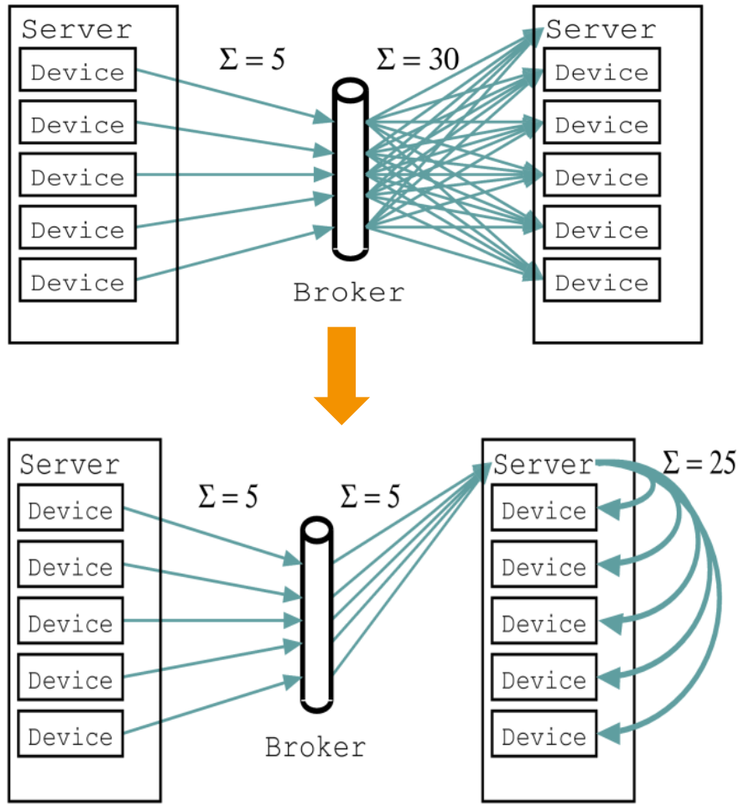
- Karabo in use at EuXFEL:
  - Commissioning since 2016
  - First user experiments 2017
    - ► meanwhile on all 6 instruments
  - Almost 14,000 devices,
    - ► more than 1.6 million "control points" (properties, commands)
    - ► average broker rate per installation: up to 1 kHz

- Example application combining processing and control: "Beam Position Feedback System Supported by Karabo at European XFEL"
  - Compensates drift for EuXFEL beam pointing stability
  - See poster MOPHA040.



Lessons Learned

- Early versions of Karabo had serious communication delays
  - ► Especially for C++ servers hosting many hundred devices in one process
  - Measure 1: No blocking calls in shared event loop,
    - ► use asynchronous coding patterns
  - Measure 2: Broadcast messages only once per process
    - ► Before: 500 devices start, 500 other devices receive
      - ➔ 250 k messages



- Calibration pipelines suffered from slow (de-)serialisation
  - Now avoid copies of NDArray data

- Rare, but serious issues with message ordering
  - Respect that posting functions on multi-threaded event loop has no order guarantee

```
set("motor/A",
    "targetPosition", 2);
execute("motor/A", "move");
```

Developing and Releasing Karabo Framework

- Unit and integration tests are vital:
  - Running with continuous integration
  - No new functionality without test
  - Good test coverage
    - ► 67% of C++ and 74% of Python,
  - Final release test cycle includes device classes
- Code review mandatory
- Karabo shall be released with an open source license
  - Planned since the beginning
  - Discovered conflicting licenses in dependencies: GPLv2 *only* and Apache 2.0
  - Cleaning this up has progressed, but still steps to go…

Future Directions

Steered by experiences gained in European XFEL operation:

- Data logging:
  - Replace custom text and index file based backend
  - Time series database **InfluxDB** tested
    - ► Will need enterprise edition in production
- Device configuration storage
  - Current solution with independent "projects" very flexible
  - Central storage more applicable for commissioned system
- Authentication and authorisation foreseen in original design, but not implemented
  - Becomes a limiting factor in more and more stable system: Who did what?
- JMS broker is very stable
  - but openMQc client library not maintained,
    - ► C++ prototype of communication unit for MQTT broker developed

Summary

- European XFEL endeavored the development of a **new control and data processing framework: Karabo**
  - Broker based control communication
  - TCP/IP pipelines for big data transport
  - Fully event-driven
  - C++ and two Python APIs
- Many **lessons learned** to make it scale:
  - Now operate reliably about 14,000 devices with 1.6 million control points at European XFEL
  - Online calibration of MHz-capable 2D detectors with < 2 s latency, 1.8 GB/s throughput
- **Future directions** driven by needs to control European XFEL instruments
  - Improve **data logging**, more **central configuration** storage, add **authentication/authorisation**
- Goal: publish with an open source license
  - Even before we manage that: If interested, do not hesitate to contact us.

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