Digital Twinning:
Activities on the European XFEL Accelerator Side

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Olaf Hensler, Raimund Kammering, Torsten Limberg,
Sascha Meykopff, Vladimir Rybnikov, Matthias Scholz,
Sergey Tomin, Josef Wilgen, Igor Zagorodnov, and many more

2021-05-11

Virtual XFEL

A *copy* of the accelerator control system

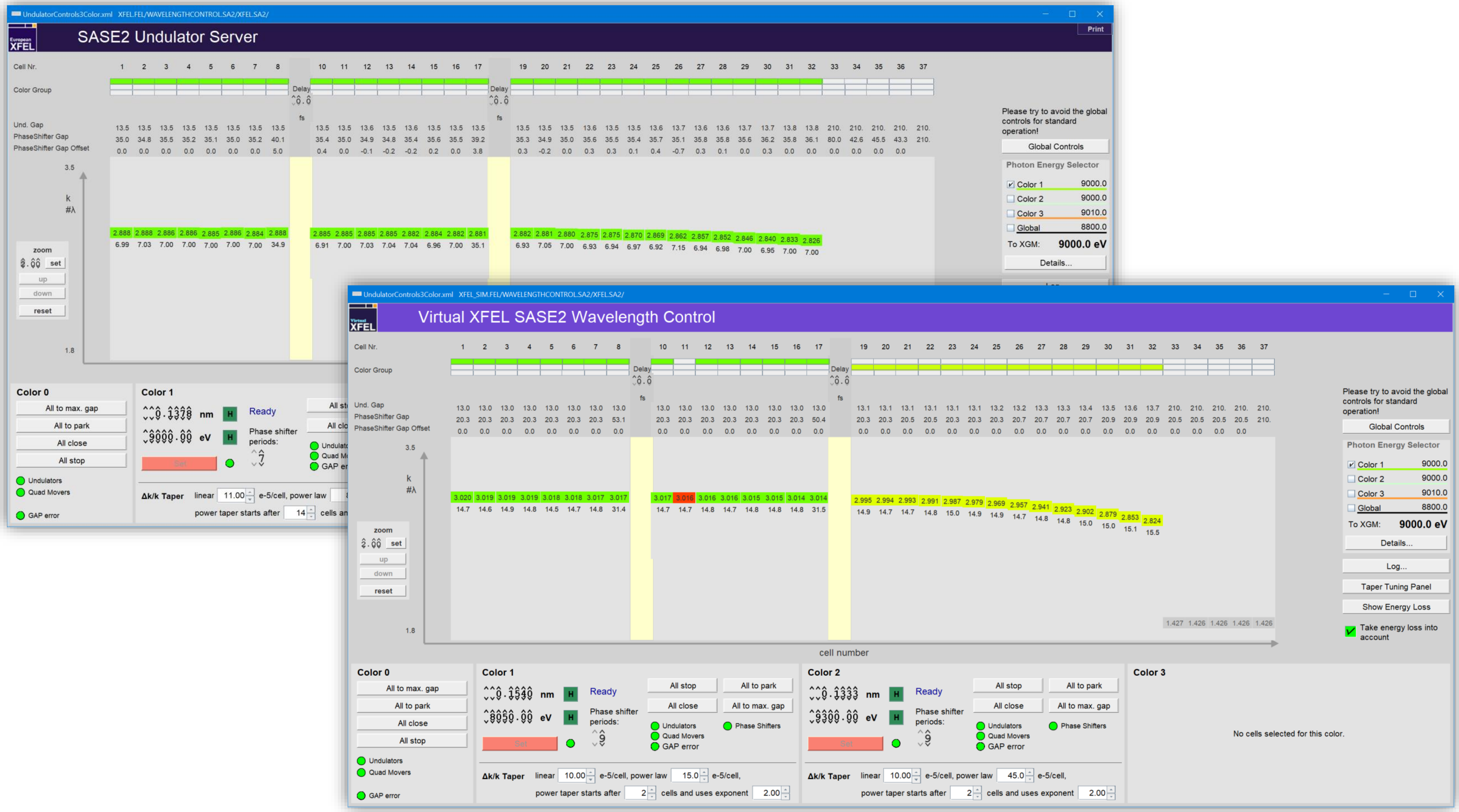
… to test software, procedures, algorithms
… before the real machine is available
… while the real machine is in operation
… when it is too hard to test on the real machine

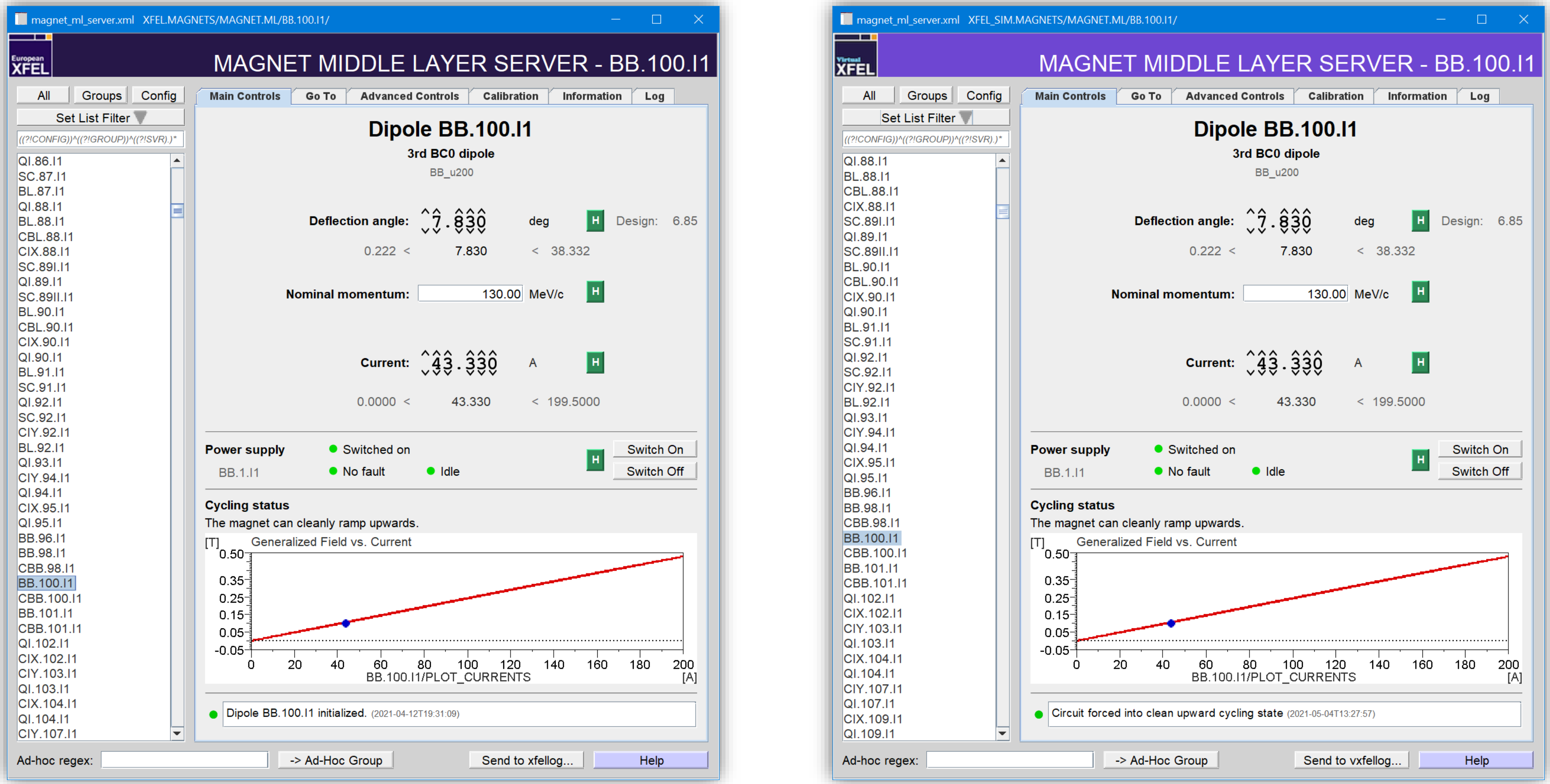
SINBAD–ARES
Linear Accelerator

FLASH
Free-Electron Laser

European XFEL
Free-Electron Laser

Virtual XFEL
“Digital Twin” of European XFEL


UndulatorControls3Color.xml XFEL.FEL/WAVELENGTHCONTROL.SA2/XFEL.SA2/
SASE2 Undulator Server
Print
Cell Nr.
Color Group
Delay
fs
Und. Gap
PhaseShifter Gap
PhaseShifter Gap Offset
Please try to avoid the global controls for standard operation!
Global Controls
Photon Energy Selector
Color 1 9000.0
Color 2 9000.0
Color 3 9010.0
Global 8800.0
To XGM: 9000.0 eV
Details...
zoom
set
up
down
reset
Color 0
All to max. gap
All to park
All close
All stop
Undulators
Quad Movers
GAP error
Color 1
nm
eV
Ready
Phase shifter periods:
Δk/k Taper
linear
e-5/cell, power law
power taper starts after
UndulatorControls3Color.xml XFEL_SIM.FEL/WAVELENGTHCONTROL.SA2/XFEL.SA2/
Virtual XFEL SASE2 Wavelength Control
Log...
Taper Tuning Panel
Show Energy Loss
Take energy loss into account
cell number
Color 2
All stop
All to park
All close
All to max. gap
Phase Shifters
cells and uses exponent
Color 3
No cells selected for this color.



magnet_ml_server.xml XFEL.MAGNETS/MAGNET.ML/BB.100.I1/
European XFEL
MAGNET MIDDLE LAYER SERVER - BB.100.I1
All
Groups
Config
Set List Filter
((?!CONFIG))^((?!GROUP))^((?!SVR).)*
QI.86.I1
SC.87.I1
BL.87.I1
QI.88.I1
BL.88.I1
CBL.88.I1
CIX.88.I1
SC.89I.I1
QI.89.I1
SC.89II.I1
BL.90.I1
CBL.90.I1
CIX.90.I1
QI.90.I1
BL.91.I1
SC.91.I1
QI.92.I1
SC.92.I1
CIY.92.I1
BL.92.I1
QI.93.I1
CIY.94.I1
QI.94.I1
CIX.95.I1
QI.95.I1
BB.96.I1
BB.98.I1
CBB.98.I1
BB.100.I1
CBB.100.I1
BB.101.I1
CBB.101.I1
QI.102.I1
CIX.102.I1
CIY.103.I1
QI.103.I1
CIX.104.I1
QI.104.I1
CIY.107.I1
Main Controls
Go To
Advanced Controls
Calibration
Information
Log
Dipole BB.100.I1
3rd BC0 dipole
BB_u200
Deflection angle:
7.830
deg
H
Design: 6.85
0.222 < 7.830 < 38.332
Nominal momentum:
130.00
MeV/c
H
Current:
43.330
A
H
0.0000 < 43.330 < 199.5000
Power supply
Switched on
BB.1.I1
No fault
Idle
H
Switch On
Switch Off
Cycling status
The magnet can cleanly ramp upwards.
[T]
Generalized Field vs. Current
0.50
0.35
0.25
0.15
0.05
-0.05
0
20
40
60
80
100
120
140
160
180
200
BB.100.I1/PLOT_CURRENTS
[A]
Dipole BB.100.I1 initialized. (2021-04-12T19:31:09)
Ad-hoc regex:
-> Ad-Hoc Group
Send to xfellog...
Help
magnet_ml_server.xml XFEL_SIM.MAGNETS/MAGNET.ML/BB.100.I1/
Virtual XFEL
MAGNET MIDDLE LAYER SERVER - BB.100.I1
All
Groups
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((?!CONFIG))^((?!GROUP))^((?!SVR).)*
QI.88.I1
BL.88.I1
CBL.88.I1
CIX.88.I1
SC.89I.I1
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BB.98.I1
CBB.98.I1
BB.100.I1
CBB.100.I1
BB.101.I1
CBB.101.I1
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CIX.102.I1
CIY.103.I1
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CIX.104.I1
QI.104.I1
CIY.107.I1
QI.107.I1
CIX.109.I1
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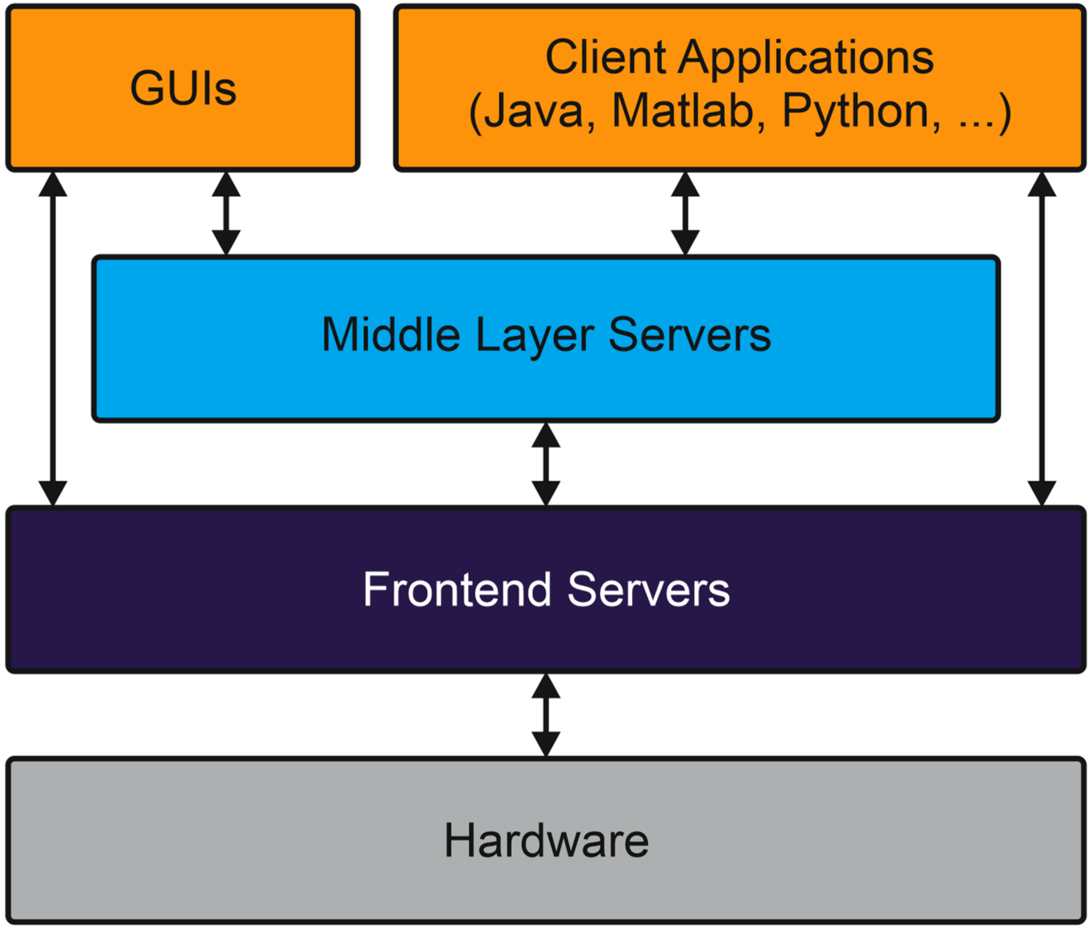
-0.05
0
20
40
60
80
100
120
140
160
180
200
BB.100.I1/PLOT_CURRENTS
[A]
Circuit forced into clean upward cycling state (2021-05-04T13:27:57)
Ad-hoc regex:
-> Ad-Hoc Group
Send to vxfellog...
Help

Control System Addresses

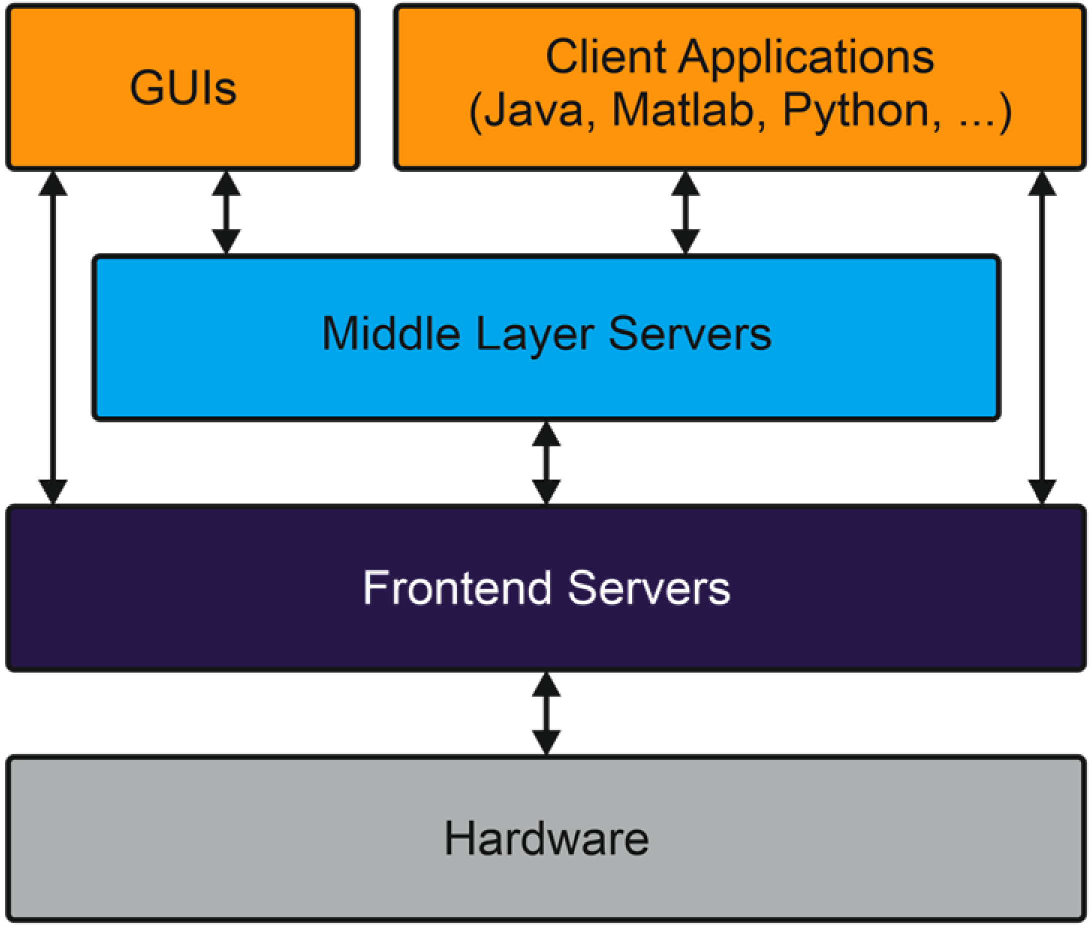
XFEL.MAGNETS/MAGNET.ML/BB.100.I1/STRENGTH.SP

XFEL_SIM.MAGNETS/MAGNET.ML/BB.100.I1/STRENGTH.SP

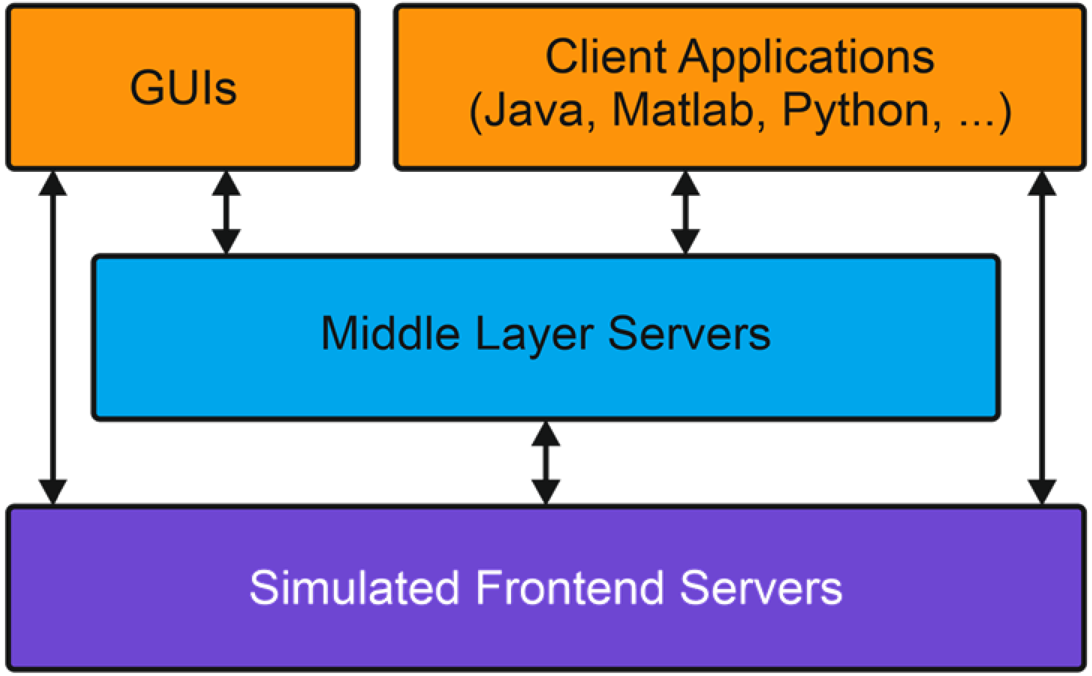
XFEL Control System



XFEL Control System



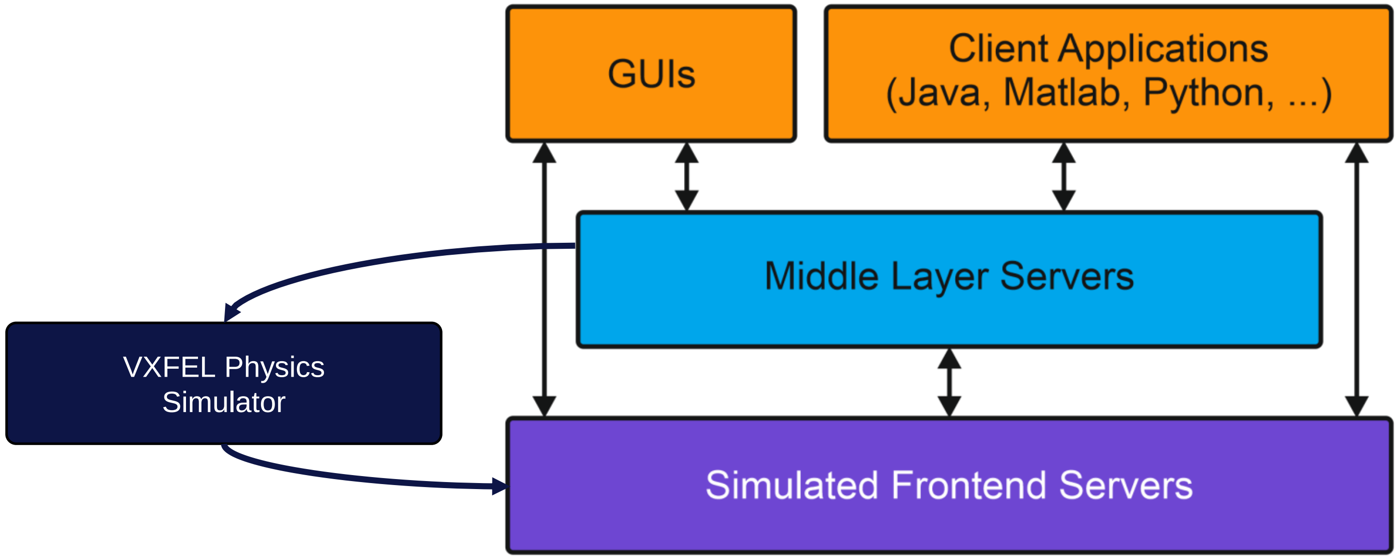
Virtual XFEL Control System



- GUIs, apps, ML servers: identical to real machine
- Simulated frontend servers instead of access to hardware
- Physics simulation

VXFEL Physics Simulation

- Single-particle tracking through multiple branches of the accelerator
- Outputs:
  - Beam position
  - Charge (full transmission up to $|x|^2 + |y|^2 > r_{max}^2$)
  - Screens with Gaussian beam spots
- Tracking in “real time” (at 10 Hz)
- Custom C++ tracking library
  - Mostly linear optics (few nonlinear elements)
  - Ready for multi-particle tracking
  - Limited physics: No collective effects etc.

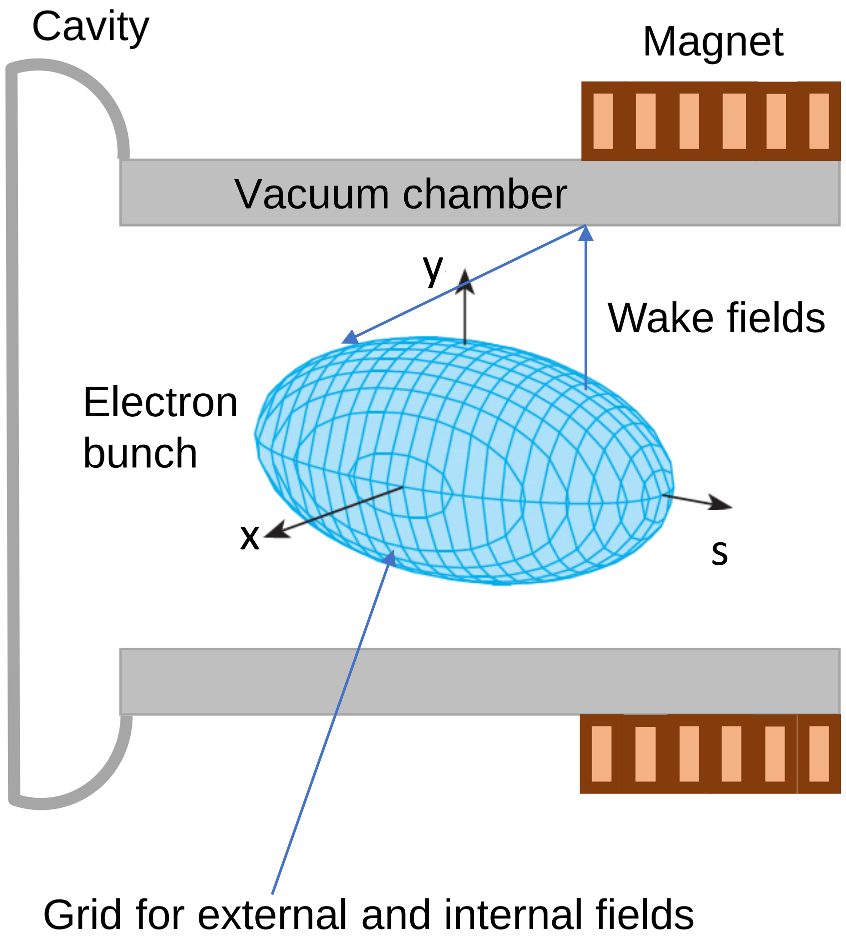


Start-to-End (S2E) Beam Dynamics Simulations

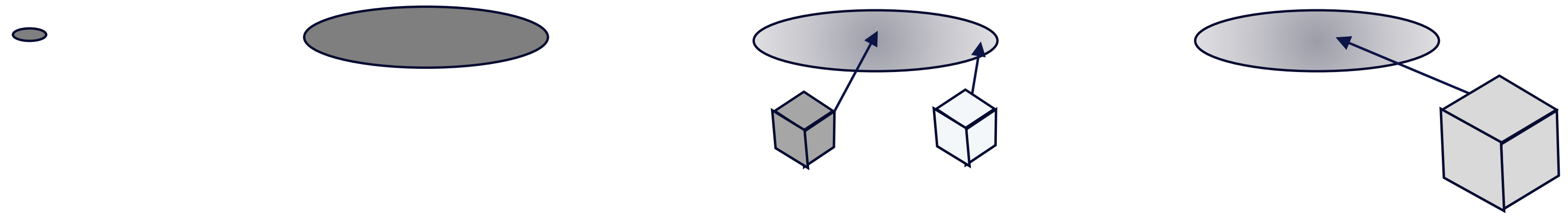
Tracking simulated particle bunches from the gun to a point of interest (e.g. an undulator)
… to understand how to improve beam quality
… to optimize machine parameters
… to explain observed beam behavior or predict it

Start-to-End Simulations

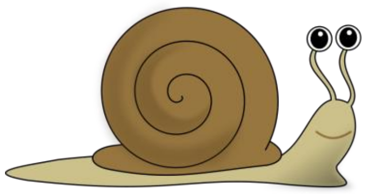
- Simulate many (macro-)particles
  - In extreme cases 1:1 with real bunch (6×10^9 for 1 nC)
- Take all electromagnetic fields into account
  - External: Magnets, cavities
  - Internal: Space charge, coherent synchrotron radiation (CSR), intra-beam scattering
  - Wake fields, CSR shielding
- Tradeoff between accuracy and calculation speed
  - Use adaptive 2D and 3D grids (particle-in-cell approach) instead of particle-to-particle interaction



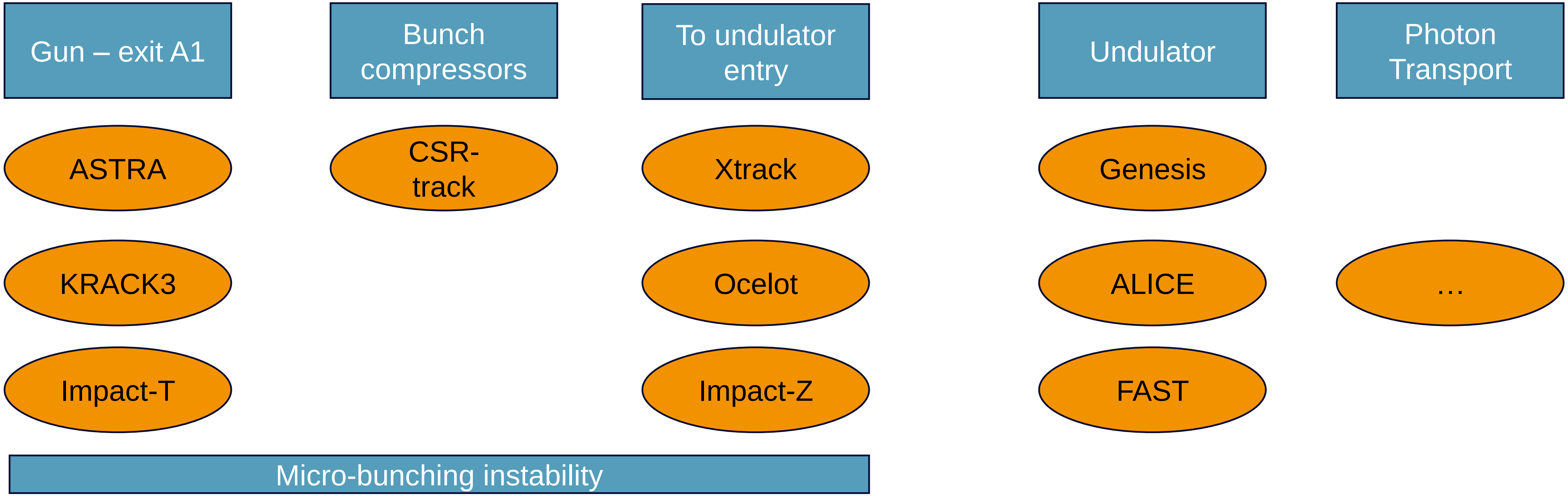
More Particles Reveal More Physics



Particles	1	~10^3	~10^6	~10^9
Effects	Orbit tracking	6D (non-)linear optics: Bunch envelope, emittance growth, dynamic aperture	Collective effects of 'continuous' distributions: Space charge, CSR, wake fields	Noise-driven effects: µ-bunching instability, intra-beam scattering, ISR
Code examples	MAD, PETROS	MAD, RACETRACK, elegant, …	ASTRA, CsrTrack, Xtrack, Ocelot, …	Impact-Z, …



Codes: Start-to-End Schemes for the European XFEL



- Select code, method, grid by region (injector with v≠c) and beam parameters (longitudinal spike after compression)
- Expand and shrink particle numbers along the way without changing noise characteristics

Summary & Outlook

- The **Virtual XFEL** allows us to …
  - test control system aspects: data throughput, timing, bunch pattern handling, naming conventions.
  - develop and test GUI and display concepts.
  - test high level & middle layer software before deploying it to the accelerator.
  - simulate limited physics: single-particle trajectory & basic envelope
- Ideas for upgrades:
  - Multi-particle tracking
  - Simulate (fake) FEL output to test FEL optimizer tools
  - Use fast (ML?) models for collective effects etc.
- Our **start-to-end simulations**…
  - allow in-depth study of collective effects on the electron bunch.
  - provide critical input for accelerator design and optimization.
  - require time and, often, manual fine-tuning of parameters.
- Outlook:
  - More work on photon transport to experiments
  - Integrate and benchmark against measurement results