Progress on the IDEA vertex detector implementation in Key4hep full simulation

FCC Week 2023, London

Armin Ilg
University of Zürich

08.06.2023

Thanks to all the people who helped/are helping on the way!
Goal of the FCC feasibility study

A lot of work to be done for the feasibility study...

For the experiments:
- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?
Goal of the FCC feasibility study

A lot of work to be done for the feasibility study...

For the experiments:

- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?

Goal: Establish feedback-loop

Sensor perf. $\rightarrow$ detector sim. $\rightarrow$ Subdetector perf. $\rightarrow$ sample analysis $\rightarrow$ physics perf. $\rightarrow$ theory input $\rightarrow$ sensor specification

Need to perform simulation and analysis of realistic detectors at FCC-ee! → **Full simulation of complete detectors, using particle flow**

Our software toolkit should be...
Goal of the FCC feasibility study

A lot of work to be done for the feasibility study...

For the experiments:

- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?

**Goal: Establish feedback-loop**

Sensor perf. \(\rightarrow\) detector sim. \(\rightarrow\) Subdetector perf. \(\rightarrow\) sample analysis \(\rightarrow\) physics perf. \(\rightarrow\) theory input \(\rightarrow\) sensor specification

Need to perform simulation and analysis of realistic detectors at FCC-ee! → **Full simulation of complete detectors, using particle flow**

Our software toolkit should be...

- deploying new software and detector technologies, ease adaption by current experiments
- efficient and easy to learn, use and develop (people with limited time on future colliders)
Goal of the FCC feasibility study

A lot of work to be done for the feasibility study...
For the experiments:

- Requirements to the accelerator? (backgrounds, space constraints, etc.)
- Expected performance? What can we do with the particles we get?
- What next-gen detector technologies can benefit the FCC-ee physics program? Different detector concepts?

**Goal: Establish feedback-loop**

Goal now: Full simulation of IDEA in Key4hep/DD4hep! (see slides of B. Francois)

Need to perform simulation and analysis of realistic detectors at FCC-ee! → Full simulation of complete detectors, using particle flow
Our software toolkit should be...

- deploying new software and detector technologies, ease adaption by current experiments
- efficient and easy to learn, use and develop (people with limited time on future colliders)
IDEA vertex detector: Layout

Refer to F. Palla’s slides for full layout details

**Vertex inner barrel**
- Small beam pipe of 10 mm inner radius
- Three barrel layers to cover down to $\theta = 140$ mrad
- Consisting of staves of dual ARCADIA DMAPS, with pixels of $25 \times 25 \, \mu m^2$ ($\sim 3 \, \mu m$ single point resolution)

**Outer Vertex**
- Quad ATLASPix3 DMAPS with $150 \times 50 \, \mu m^2$ pixels
- **Vertex outer barrel**
  - Intermediate layer at $r = 13$ cm, outer layer at $r = 31.5$ cm
- **Vertex disks**
  - Three disks per side
  - Disks of 8 petals with 4-6 staves going from small to large $r$
IDEA vertex detector: Design

- Vertex detector by F. Palla and F. Bosi (INFN- Pisa)
- Support tube done by F. Fransesini and M. Boscolo (INFN-LNF), see next talk by F. Fransesini. Holding:
  - Luminosity calorimeter
  - Vertex detector
  - Beam pipe (R_{inner} = 1 cm)
- Rather advanced design, let's implement this in Key4hep full simulation!
IDEA vertex detector: Design

- Vertex detector by F. Palla and F. Bosi (INFN- Pisa)
- Support tube done by F. Fransesini and M. Boscolo (INFN-LNF), see next talk by F. Fransesini. Holding:
  - Luminosity calorimeter
  - Vertex detector
  - Beam pipe ($R_{\text{inner}} = 1\,\text{cm}$)
- Rather advanced design, let's implement this in Key4hep full simulation!

Where to start?
Existing (vertex) full simulation in CLD

Detector model in k4geo/FCCDetectors (smaller beam pipe)
- Linear collider reconstruction (iLCSoft/CLICPerformance)
- Can generate EDM4hep output using k4MarlinWrapper

Access to all LC tools: PandoraPFA, LCFI+, etc.

D0 resolution in CLD [1]

CLD vertex barrel

CLD endcap and vertex barrel
Existing (vertex) full simulation in CLD

Detector model in `k4geo/FCCDetectors` (smaller beam pipe)
- Linear collider reconstruction (`iLCSoft/CLICPerformance`)
- Can generate EDM4hep output using `k4MarlinWrapper`

Access to all LC tools:

Want full simulation for IDEA, but using native Key4hep/DD4hep and more detail!

Armin Ilg (UZH)
IDEA Vertex FullSim using Key4hep
FCC Week 2023, London
08.06.2023
IDEA vertex detector in DD4hep
Adapted **CLIC vertex barrel constructor** to enable...

- individual sensors along stave, can have insensitive area in $r - \phi$ or $z$
- ARCADIA duals implemented as 6.4 mm active + 2 mm periphery $(r - \phi) \times 32$ mm $(z)$, with 0.2 mm distance between sensors in $z$
- multiple layers of support and include readout
  - Support e.g consists of 20 $\mu$m of carbon fleece, 120 $\mu$m of carbon fiber and 25 $\mu$m of paper graphite
- Use DDCAD [2] to import conical vertex support
  - Don’t get correct $X/X_0$ yet, overlap check fails (investigating...)

Todo: Add stave holder and end-of-stave structures
Vertex outer barrel

Same detector construction code as inner barrel

- Correct readout flex and stave support material stacks
- Simplified ATLASPix3 periphery (only implemented in $r - \phi$)
- Missing cooling pipes
- Missing lightweight reticular support structure

→ Import using DDCAD or adding simplified support
Vertex disks

Most complicated system to implement in DD4hep, based on CLIC vertex endcaps

Building the disks:
- Build quad sensors out of four sensitive and many insensitive rectangles
- Place quads along stave support structure, add readout
- Place staves with correct number of sensors to build a petal
- Place all petals to form a disk, repeat for all disks
- Correct orientation and arrangement of all staves/petals

Still missing:
- Non-stave supports and cooling pipes
Sensitive surfaces in IDEA vertex implementation in DD4hep
Vertex detector: Overall system

Complete geometry in IDEA vertex implementation in DD4hep

Missing parts:
- Complex support structures and cooling (use DDCAD or simplified shape with equivalent material budget)
- Off-detector cabling (not designed yet)

Such a detailed geometry description enables...
- Accurate material budget distribution in both $\theta$ and $\phi$
- Accurate description of angular coverage, #hits in vertex: Are there cracks in the coverage?

Pull request in k4geo

Armin Ilg (UZH)
IDEA Vertex FullSim using Key4hep
FCC Week 2023, London
08.06.2023
Vertex detector: Overall system

Complete geometry in IDEA vertex implementation in DD4hep

Missing parts:
- Complex support structures and cooling (use DDCAD or simplified shape with equivalent material budget)
- Off-detector cabling (not designed yet)
Vertex detector: Overall system

Complete geometry in IDEA vertex implementation in DD4hep

Missing parts:
- Complex support structures and cooling (use DDCAD or simplified shape with equivalent material budget)
- Off-detector cabling (not designed yet)

Such a detailed geometry description enables...
- Accurate material budget distribution in both $\theta$ and $\phi$
- Accurate description of angular coverage, #hits in vertex: Are there cracks in the coverage?

Pull request in k4geo
First look at performance...
Particle gun to shoot 10 GeV muons, $\theta = 10^\circ$

Get Key4hep stack (latest has issues currently):
source /cvmfs/sw.hsf.org/spackages6/Key4hep-stack/2022-12-14/
x86_64-centos7-gcc11.2.0-opt/zkjui/setup.sh

Run simulation on detector compact file (xml), using FCC steering file to generate EDM4hep output:
ddsim --compactFile k4geo/FCCee/compact/FCCee_IDEA_o01_v01.xml
--enableGun --gun.thetaMin 9.999 --gun.thetaMax 10.001
--gun.distribution uniform --gun.energy 10*GeV --gun.particle mu-
--steeringFile fcc steer.py --numberOfEvents 1000
--outputFile ddsim_edm4hep.root

Run linear collider reconstruction (iLCSoft/CLICPerformance) using
k4MarlinWrapper:
k4run fccRec_e4h_input.py --EventDataSvc.input
ddsim_edm4hep.root -n 1000
Particle gun to shoot 10 GeV muons, $\theta = 10^\circ$

Get Key4hep stack (latest has issues currently):
source /cvmfs/sw.hsf.org/spackages6/Key4hep-stack/2022-12-14/x86_64-centos7-gcc11.2.0-opt/zkjui/setup.sh

Run simulation on detector compact file (xml), using FCC steering file to generate EDM4hep output:
```
ddsim --compactFile k4geo/FCCee/compact/FCCee_IDEA_o01.v01.xml
--enableGun --gun.thetaMin 9.999 --gun.thetaMax 10.001
--gun.distribution uniform --gun.energy 10*GeV --gun.particle
mu- --steeringFile fcc_steer.py --numberOfEvents 1000
--outputFile ddsim_edm4hep.root
```

Run linear collider reconstruction (iLCSoft/CLICPerformance) using k4MarlinWrapper:
k4run fccRec_e4h_input.py --EventDataSvc.input
ddsim_edm4hep.root -n 1000

It runs! Performance to be assessed properly... (need IDEA drift chamber)
Preliminary (!) material budget estimation

Preliminary (!) estimation of the material budget of IDEA vertex in DD4hep

- Best-described detector: Vertex inner barrel
  → F. Palla’s slides: $3 \times 0.25\% \, X/X_0$ for complete vertex → Roughly agreeing

- Vertex outer barrel clearly underestimated, expect truss support structure and cooling to have largest $X/X_0$ contribution

Todo:
- Add missing components or appropriate placeholder
- Remake plot in $\theta$ and $\cos(\theta)$, compare with standalone Geant4 description and CLD
Summary

Done

- First implementation of the IDEA vertex detector in DD4hep → Can get vertex simHits for other studies
- Track+vertex reconstruction using iLCSof with k4MarlinWrapper → It’s working!
- Preliminary material budget estimation

Next steps

- Complex services and support structures, reassess material budget
- Accurate sensor periphery description in barrels (done in disks already)
- Add digitisation inside Key4hep
- Implement silicon wrapper, aim to have complete IDEA description in DD4hep
Summary

Done

- First implementation of the IDEA vertex detector in DD4hep → Can get vertex simHits for other studies
- Track+vertex reconstruction using iLCSoft with k4MarlinWrapper → It’s working!
- Preliminary material budget estimation

Next steps

- Complex services and support structures, reassess material budget
- Accurate sensor periphery description in barrels (done in disks already)
- Add digitisation inside Key4hep
- Implement silicon wrapper, aim to have complete IDEA description in DD4hep

What else can we do?

Goal: Establish feedback-loop

Sensor perf. detector → sim.

Subdetector perf. sample → analysis

Physics perf. theory → input sensor specification
Summary and outlook!

Done

- First implementation of the IDEA vertex detector in DD4hep → Can get vertex simHits for other studies
- Track+vertex reconstruction using iLCSoft with k4MarlinWrapper → It’s working!
- Preliminary material budget estimation

Next steps

- Complex services and support structures, reassess material budget
- Accurate sensor periphery description in barrels (done in disks already)
- Add digitisation inside Key4hep
- Implement silicon wrapper, aim to have complete IDEA description in DD4hep

What else can we do?

Goal: Establish feedback-loop

- Sensor perf. → detector sim.
- Subdetector perf. → sample analysis
- Physics perf. → theory input
- Sensor specification
R&D for better detectors

Should not close the eyes to new and unproven technologies.

→ Estimate possible performance gain of such new technologies using full simulation!

Example: DMAPS in 65 nm TPSCo process

- More logic per cm²
- Lower power consumption
- Air cooling
- Enables 12" wafers
- Wafer-scale bent sensors! See M. Mager's talk on Thursday!
R&D for better detectors

Should not close the eyes to new and unproven technologies.

→ Estimate possible performance gain of such new technologies using full simulation!

Example: DMAPS in 65 nm TPSCo process

- More logic per cm²
- Lower power consumption → Air cooling
- Enables 12” wafers → Wafer-scale bent sensors! See M. Mager’s talk on Thursday!
R&D for better detectors

Should not close the eyes to new and unproven technologies.

→ Estimate possible performance gain of such new technologies using full simulation!

Example: DMAPS in 65 nm TPSCo process

- More logic per cm$^2$
- Lower power consumption → Air cooling
- Enables 12” wafers → Wafer-scale bent sensors! See M. Mager’s talk on Thursday!

L. Freitag (BSc. thesis [5]) and A.I @ Krakow 2023

Material budget in ALICE ITS2 (left, [4]) and silicon only (M. Mager)
R&D for better detectors

Should not close the eyes to new and unproven technologies.

→ Estimate possible performance gain of such new technologies using full simulation!

Example: DMAPS in 65 nm TPSCo process

- More logic per cm²
- Low power consumption

→ Air cooling

→ 12" wafers

→ Wafer-scale bent sensors! See M. Mager’s talk on Thursday!

Plan to do full simulation performance study of ALICE ITS3-like vertex detector for (parts of) the IDEA vertex detector

Layers 2+1+0

Layer 2

Layers 2+1

Material budget in ALICE ITS2 (left, [4]) and silicon only (M. Mager)

Layer assembly concept for ALICE ITS3 [3]

Layer 2

Layers 2+1

Layers 2+1+0

15Magnus Mager (CERN) | bendable MAPS in 65 nm | CEPC 2021 | 08.11.2021

L. Freitag (BSc. thesis [5]) and A.I @ Krakow 2023

FCC Week 2023, London 08.06.2023 13 / 13
R&D for better detectors

Should not close the eyes to new and unproven technologies.
→ Estimate possible performance gain of such new technologies using full simulation!

Example: DMAPS in 65 nm TPSCo process

- More logic per cm²
- Lower power consumption
- Enables Air cooling
- Enables 12” wafers
- Enables wafer-scale bent sensors! See M. Mager’s talk on Thursday!

Contributing to testing of 65 nm test structures as well

Material budget in ALICE ITS2 (left, [4]) and silicon only (M. Mager)

Plan to do full simulation performance study of ALICE ITS3-like vertex detector for (parts of) the IDEA vertex detector

- Contributing to testing of 65 nm test structures as well

Armin Ilg (UZH) IDEA Vertex FullSim using Key4hep

L. Freitag (BSc. thesis [5]) and A.I @ Krakow 2023

Layer 2 Layers 2+1 Layers 2+1+0

FCC Week 2023, London 08.06.2023 13 / 13
Thanks!


Module concept **inspired by ARCADIA INFN R&D**

- Depleted Monolithic Active Pixel Detectors (DMAPS) sensor and back-side processing already tested on silicon
- Pixel size 25x25 $\mu$m$^2$, 50 $\mu$m thick
- Active area 640 pixel (16 mm) in z and 256 pixels (6.4 mm) in $r-\phi$
- Chip periphery plus an inactive zone: total of 2 mm in $r-\phi$
- Chips are side-abuttable in z

**Composed of 2 pixelated parts: total of 8.4 mm ($r - \phi$) $\times$ 32 mm (z)**

- Power budget not established yet: assume (reasonably) 50 mW/cm$^2$

---

F. Palla, see talk at FCC US week at BNL
Outer tracker module

- Based on ATLASPIX3 R&D
  - DMAPS
  - 50 x 150 µm²
  - Up to 1.28 Gb/s downlink
  - TSI 180 nm process
  - 132 columns of 372 pixels

- Active (total) length (r-phi x z):
  - 18.6 (21) mm x 19.8 (20.2) mm
- Module is made of 2x2 chips – total length:
  - size 42.2 mm x 40.6 mm

- Power budget not established yet: assume 100 mW/cm²

F. Palla, see talk at FCC US week at BNL
The common software vision: Key4hep

**Key4hep** is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis, see also PE&D: Software and Computing / Detectors session

- **Event data model:** **EDM4hep** for exchange among framework components
  - **Podio** as underlying tool, for different collision environments
  - Including truth information
- **Data processing framework:** **Gaudi**
- **Geometry description:** **DD4hep**, ability to include CAD files
- **Package manager:** **Spack**: source /cvmfs/sw.hsf.org/Key4hep/setup.sh

---

**EDM4hep DataModel Overview (v0.6)**

- **SimCalorimeterHit**
- **CalcHitConstruction**
- **MCParticle**
- **Monte Carlo**
- **Raw CalorimeterHit**
- **Digitization**
- **Track**
- **Vertex**
- **ParticleID**
- **Cluster**
- **ReconstructedParticle**
- **TrackHit**
- **TrackerHit Plane**

---

**Event Data Model: EDM4hep**

- **Generator**
  - Wizard, PyNt, ...
- **Simulation**
  - C++, Python
- **Reconstruction**
  - Event Display, Orphan Event Tracking, IFA
- **Analysis**
  - Vertexing, Jet Clustering, Flavor Tagging

---

**DD4hep - Detector Description**

- **Complete detector description**: geometry, conditions, alignment, ...
- **Used by CLIC, ILC, CEPC, FCC, EIC, CMS, LHCb, …**

---

**Armin Ilg (UZH)**

**IDEA Vertex FullSim using Key4hep**

**FCC Week 2023, London**

08.06.2023 17 / 13
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis, see also PE&D: Software and Computing / Detectors session

- Event data model: **EDM4hep** for exchange among framework components
  - **Podio** as underlying tool, for different collision environments
  - Including truth information

- **Standalone full simulation of IDEA in Geant4 available**

- Geometry description: **DD4hep**, ability to include CAD files

- Package manager: **Spack**: source /cvmfs/sw.hsf.org/Key4hep/setup.sh

---

**DD4hep - Detector Description**

- Complete detector description: geometry, conditions, alignment, ...
- Used by CLIC, ILC, CEPC, FCC, EIC, CMS, LHCb, …

**Standalone full simulation of IDEA in Geant4 available**

**IDEA Vertex FullSim using Key4hep**

---

Armin Ilg (UZH)  
IDEA Vertex FullSim using Key4hep  
FCC Week 2023, London  
08.06.2023 17 / 13
The common software vision: Key4hep

Key4hep is a huge ecosystem of software packages adopted by all future collider projects, complete workflow from generator to analysis, see also PE&D: Software and Computing / Detectors session

- Event data model: EDM4hep for exchange among framework components
  - Podio as underlying tool, for different collision environments
    - Including truth information

- Standalone full simulation of IDEA in Geant4 available

- Geometry description: DD4hep, ability to include CAD files

- Package manager: Spack:
  - source /cvmfs/sw.hsf.org/Key4hep/setup.sh

Goal now: Full simulation in Key4hep/DD4hep!
IDEA: Innovative Det. for $e^+e^-$ Accelerators

Schematic layout of the IDEA detector concept for FCC-ee [6]

- Vertex detector adopting DMAPS (depleted monolithic active pixel sensor) to minimise material budget
- Tracker consisting of light-weight drift chamber ($dN_{\text{ionisation}}/dx$) and silicon wrapper with timing information (time-of-flight)
- Dual-readout calorimeter with preshower
- Low-mass 2 T solenoid coil inside calorimeter system
- Muon system composed of $\mu$RWell in the return yoke

Status of simulation: Full simulation in Geant4
Goal now: Full simulation in native Key4hep!
IDEA: Innovative Det. for $e^+e^-$ Accelerators

- **Vertex detector** adopting DMAPS (depleted monolithic active pixel sensor) to minimise material budget
- Tracker consisting of light-weight **drift chamber** ($dN_{\text{ionisation}}/dx$) and silicon wrapper with timing information (time-of-flight)
- **Dual-readout calorimeter** with preshower
- Low-mass 2 T solenoid coil inside calorimeter system
- Muon system composed of $\mu$RWell in the return yoke

**Focus on these!**

More: P. Azzi @ FCC US Workshop

Status of simulation: Full simulation in Geant4
Goal now: Full simulation in native Key4hep!