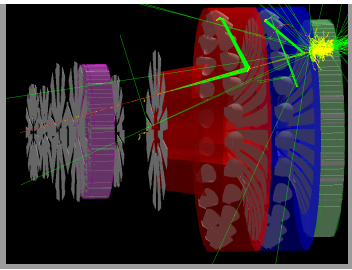
Towards an End-to-End Simulation



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Argonne NATIONAL LABORATORY

Introduction

- Goal: Full end-to-end simulation and reconstruction
- Software Toolkit
- Recent simulation progress
- A path towards a modern SoLID end-to-end simulation framework

Software Toolkit

Primary Toolkit

- **DD4hep** – Detector description
- **Acts** – A Common Tracking Software
- **PODIO** – Data model tool

Our tools:

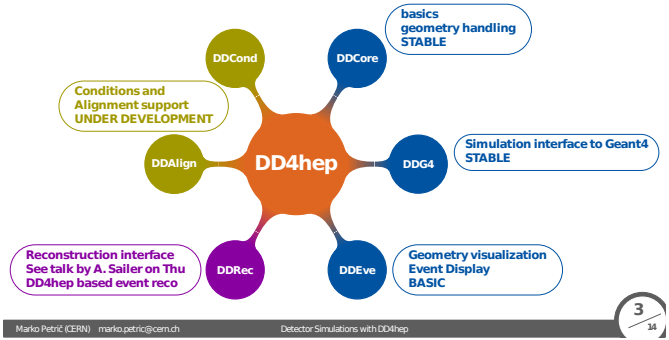
- **NPDet** – Detector Library
- **EIC Container** – Software Container Build

DD4hep

Detector Description

The result of a study from the *Advanced European Infrastructures for Detectors at Accelerators* (EU AIDA 2020) initiative.

Structure and packages



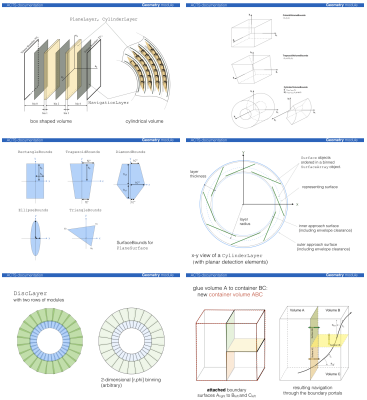
- Thoughtfully designed for future (thread-safe)
- Simulation interface with **full access to Geant4 features**
- **Single source of geometry**
- Simple geometry hook
  → **better algorithm development**
- Full geometry definition defined in human readable compact detector description file
- Easily used in a ROOT/python scripts and works well with external tools.

DD4hep solves the "geometry problem" for end-to-end simulation and reconstruction.

Nearly all big HEP experiments, current and future, are moving to DD4hep.

ACTS

A common tracking software.



- Spin off from ATLAS tracking code.
- Development is very active (recently moved to github)
- Focused on performance, not framework
- **DD4hep and Acts work together nicely!**
- **Acts documentation**, examples, and tests growing by the day.

Acts rapidly becoming the center of tracking development in the HEP/NP software community

Data Model DD4hep and PODIO

DD4hep Built-in SD types

- calorimeter
- tracker
- *maybe a photon detector in the future...*

Uses built-in data model
`dd4hep::Geant4Tracker::Hit`
`dd4hep::Geant4Calorimeter::Hit`
Added PMT hit class for cherenkov detectors:
`npdet::PhotoMultiplierHit`

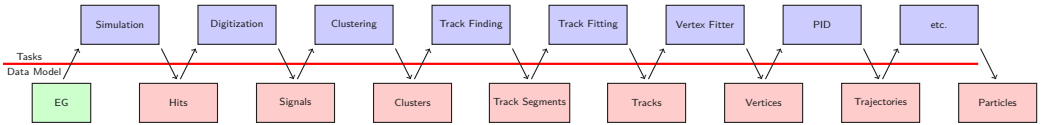
External Event Data Model: LCIO2

LCIO2 is an extension of the LCIO data model
PODIO builds LCIO2 classes from YAML file:

```
lcio2::RawCalorimeterHit:
  Description: "LCIO raw calorimeter hit"
  Author : "F.Gaede, B. Hegner"
  Members:
    - int64_t cellID0   // The detector specific (geometrical) cell id.
    - int64_t cellID1   // The second detector specific (geometrical) cell id.
    - int64_t amplitude // The amplitude of the hit in ADC counts.
    - int64_t timeStamp // The time stamp for the hit.

lcio2::CalorimeterHit:
  Description: "LCIO calorimeter hit"
  Author : "F.Gaede, B. Hegner"
  Members:
    - int64_t cellID0  // The detector specific (geometrical) cell id.
    - int64_t cellID1  // The second detector specific (geometrical) cell id.
    - float energy // The energy of the hit in [GeV].
    - float time   // The time of the hit in [ns].
    - std::array<float, 3> position // The position of the hit in world coordinates.
    - int type // The type of the hit
  OneToOneRelations:
    - lcio2::RawCalorimeterHit rawHit // The RawCalorimeterHit
```

Can use built-in data model or define your own

A good Event Data Model (EDM) defines task boundaries and decouples algorithms/frameworks.



DD4hep Geometry Hooks

C++ in a ROOT script

```
dd4hep::Detector& detector = dd4hep::Detector::getInstance();  // Get the DD4hep instance
detector.fromCompact("my_awesome_detector.xml");               // Load the compact XML file
dd4hep::rec::CellIDPositionConverter converter(detector);      // Position/cellid converter tool
[...]
    for(const auto& h: hits) {
      auto cell     = h->cellID;                       // Unique segment/volume identifier
      auto pos1     = converter.position(cell);        // The segmentation hit postion
      auto cell_dim = converter.celldimensions(cell); // Dimensions of segment/volume
      [...]
      }
[...]
auto    bField = detector.field().magneticField(pos); // Get the magnetic field
double  Bz     = bField.z()/dd4hep::tesla;
```

That's it.

See NPDet examples for a tutorial (work in progress).

Add a new detector

Detector construction (.cpp)

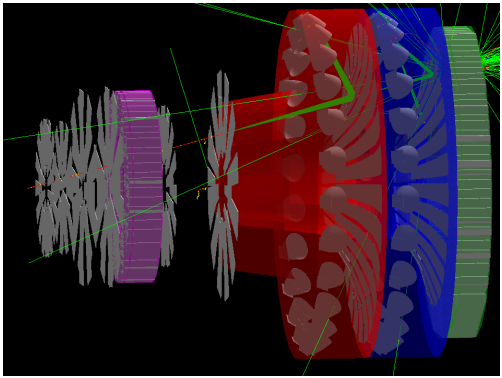
```
static Ref_t build_detector(Detector& det, xml_h e, SensitiveDetector sens)
{
  xml_det_t   x_det     = e;
  Material    air       = det.air();
  double z_offset = dd4hep::getAttrOrDefault(x_det, _Unicode(zoffset), 10.0*dd4hep::cm);
... [ Build geometry ]
}
DECLARE_DETELEMENT(SimpleRomanPot, build_detector)
```

Compact detector description (.xml)

```
<detector id="1" name="MyRomanPot" type="SimpleRomanPot"
          vis="RedVis" readout="RomanPotHits" zoffset="1.0*m">
</detector>
[...]
<readouts>
  <readout name="RomanPotHits">
    <segmentation type="CartesianGridXY" grid_size_x="1.0*mm" grid_size_y="1.0*cm" />
    <id>system:5,layer:9,module:14,x:32:-16,y:-16</id>
  </readout>
</readouts>
```

Current Status of SoLID Simulation

- Full solid detector implemented
- Magnetic field from maps complete
- Light and heavy gas Cherenkov detectors complete.
- Hexagonal Shashlyk EM Calorimeter complete
- GEM Modules (3 different sizes) complete



GEM Tracker (solid/gem_sidis.xml)

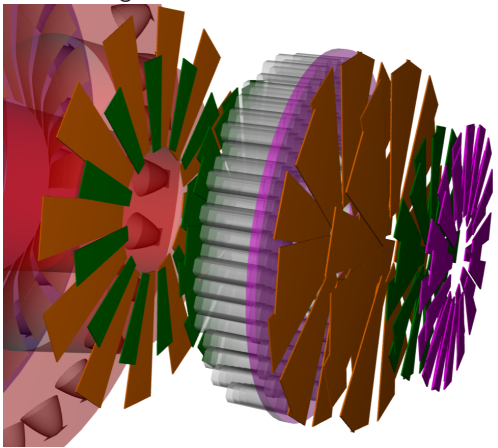
```
<detector id="2" name="GEMTracker_SIDIS" vis="RedVis"
          type="GaplessGEMTrackerDisc" readout="GEMTrackerHits" >
  <module name="Module_A" id="1" inner_r="50.0*cm"  outer_r="118.0*cm" segments="30">
    <slice name="drift_cathode" material="Kapton" thickness="0.100*mm"/>
    <slice name="drift_gas1" material="GEMGas" thickness="3.0*mm"/>
    <slice name="gem_foil_1" material="Kapton" thickness="0.100*mm"/>
    ...
    <slice name="v_readout_plane" material="Kapton" thickness="0.200*mm" sensitive="true"/>
  </module>
  <module name="Module_B" id="2" inner_r="61.0*cm"  outer_r="140.0*cm" segments="30">
    <slice name="drift_cathode" material="Kapton" thickness="0.100*mm"/>
    ...
    <slice name="v_readout_plane" material="Kapton" thickness="0.200*mm" sensitive="true"/>
  </module>
  <module name="Module_C" id="2" inner_r="110.0*cm"  outer_r="228.0*cm" segments="30">
    <slice name="drift_cathode" material="Kapton" thickness="0.100*mm"/>
    ...
    <slice name="u_readout_plane" material="Kapton" thickness="0.200*mm" sensitive="true"/>
    <slice name="v_readout_plane" material="Kapton" thickness="0.200*mm" sensitive="true"/>
  </module>
```

GEM Tracker (solid/gem_sidis.xml)

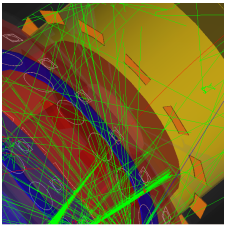
```
  <layer id="1" z="-175*cm" inner_r="36*cm" outer_r="87.0*cm" phi0_offset="0.0*deg" Nmodules="30">
    <module name="Module_A"/>
  </layer>
  <layer id="2" z="-150*cm" inner_r="21*cm" outer_r="98.0*cm" phi0_offset="0.0*deg" Nmodules="20">
    <module name="Module_B"/>
  </layer>
  <layer id="3" z="-119*cm" inner_r="29*cm" outer_r="112.0*cm" phi0_offset="0.0*deg" Nmodules="16">
    <module name="Module_C"/>
  </layer>
  <layer id="4" z="-80*cm" inner_r="32*cm" outer_r="135.0*cm" phi0_offset="0.0*deg" Nmodules="18">
    <module name="Module_C"/>
  </layer>
  <layer id="5" z="5*cm" inner_r="42*cm" outer_r="100.0*cm" phi0_offset="0.0*deg" Nmodules="28">
    <module name="Module_B"/>
  </layer>
  <layer id="6" z="92*cm" inner_r="55*cm" outer_r="123.0*cm" phi0_offset="0.0*deg" Nmodules="24">
    <module name="Module_B"/>
    <module name="Module_C"/>
  </layer>
</detector>
```

GEM Tracker

SIDIS configuration:

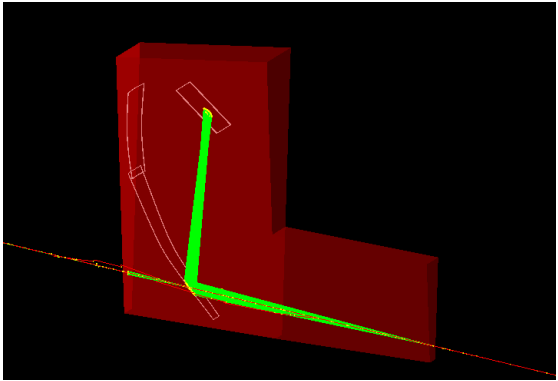


- Inconsistencies in Pre-CDR (number, min radius,etc...)
- Adjusted positions and number of modules to prevent overlap.

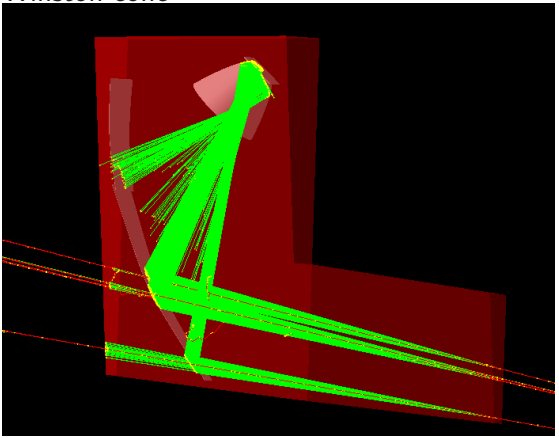


Gas Cherenkov

Optical photon processes:



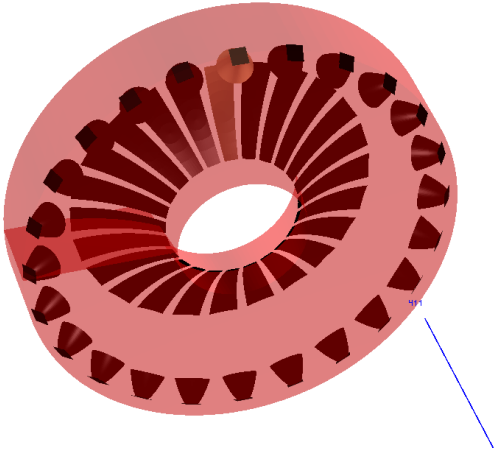
Winston cone

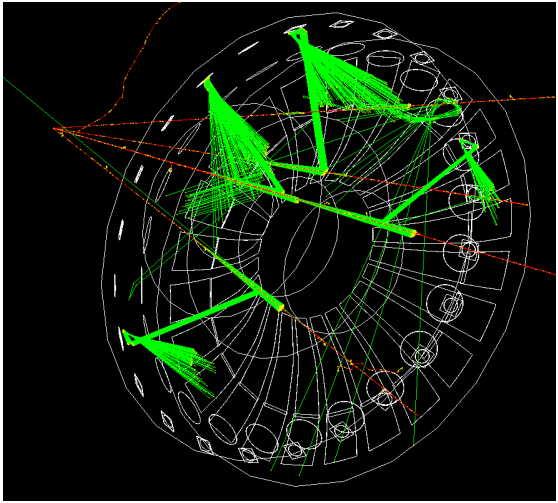


Constructed from scratch using the pre-CDR text.

Gas Cherenkov

All 30 sectors

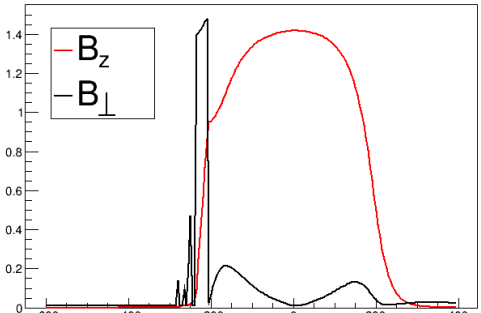




Magnetic Field

DD4hep tools - npdet_fields

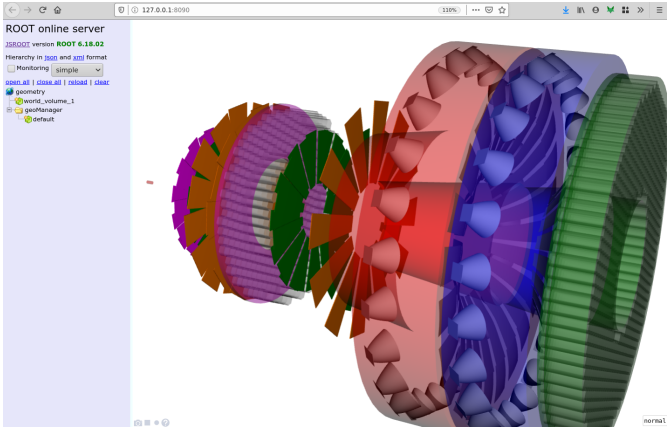
```
npdet_fields -h
You need to provide an input xml filename as the last argument!
DESCRIPTION
 Tool for quickly looking at magnetic fields.

SYNOPSIS
        npdet_fields [-v] [-h] draw [--Nsteps <Nsteps>] [--step <step>] [--
        npdet_fields [-v] [-h] draw [--Nsteps <Nsteps>] [--step <step>] [--

OPTIONS
        user interface options:
            -v, --verbose
                    show detailed output

            -h, --help
                    show help

        draw [--Nsteps <Nsteps>] [--step <step>] [--
        draw [--Nsteps <Nsteps>] [--step <step>] [--
                    draw mode:

        <file>      compact description should probl

EXAMPLES
   npdet_fields --start 0 0 -600 solid_sidis.xml
```



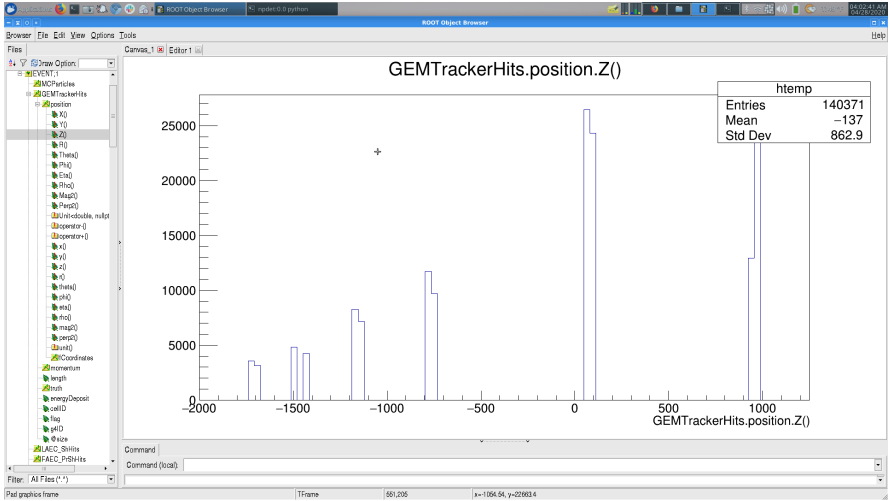
jsroot Web Display

DD4hep tools - `dd_web_display`

- Useful for working on remote server
- Quickly debugging geometry



Geant4 simulation output



Output Hits for all detectors (and then some more)

Material Scans

Material scan between: x_0 = (0.00, 0.00,-300.00) [cm] and x_1 = (0.00, 170.00, 400.00) [cm] :

Num. Layer	Material Name	Atomic Number/Z	Mass/A [g/mole]	Density [g/cm3]	Radiation Length [cm]	Interaction Length [cm]	Thickness [cm]	Path Length [cm]	Integrated X0 [cm]	Integrated Lambda [cm]	Material Endpoint (cm,	cm,	cm)
1	Air	7	14.784	0.0012	30528.8407	71998.1725	5.145	5.15	0.000169	0.000071	(0.00,	1.21,	-295.00)
2	Air	7	14.784	0.0012	30528.8407	71998.1725	149.215	154.36	0.005056	0.002144	(0.00,	36.43,	-150.00)
3	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	154.37	0.005419	0.002328	(0.00,	36.43,	-149.99)
4	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.309	154.68	0.005451	0.002341	(0.00,	36.50,	-149.69)
5	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	154.69	0.005814	0.002525	(0.00,	36.51,	-149.68)
6	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	154.90	0.005835	0.002534	(0.00,	36.55,	-149.48)
7	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	154.91	0.006198	0.002718	(0.00,	36.56,	-149.47)
8	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	155.11	0.006220	0.002726	(0.00,	36.61,	-149.27)
9	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	155.12	0.006582	0.002910	(0.00,	36.61,	-149.26)
10	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	155.33	0.006604	0.002919	(0.00,	36.66,	-149.06)
11	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	155.35	0.007329	0.003287	(0.00,	36.66,	-149.04)
12	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	155.37	0.008054	0.003655	(0.00,	36.67,	-149.02)
13	Air	7	14.784	0.0012	30528.8407	71998.1725	30.893	186.26	0.009066	0.004084	(0.00,	43.96,	-119.00)
14	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	186.27	0.009429	0.004268	(0.00,	43.96,	-118.99)
15	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.309	186.58	0.009461	0.004281	(0.00,	44.03,	-118.69)
16	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	186.59	0.009824	0.004465	(0.00,	44.03,	-118.68)
17	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	186.80	0.009846	0.004474	(0.00,	44.08,	-118.48)
18	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	186.81	0.010208	0.004658	(0.00,	44.09,	-118.47)
19	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	187.01	0.010230	0.004666	(0.00,	44.13,	-118.27)
20	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	187.02	0.010592	0.004850	(0.00,	44.14,	-118.26)
21	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	187.23	0.010614	0.004859	(0.00,	44.19,	-118.06)
22	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	187.25	0.011339	0.005227	(0.00,	44.19,	-118.04)
23	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	187.27	0.012065	0.005595	(0.00,	44.20,	-118.02)
24	Air	7	14.784	0.0012	30528.8407	71998.1725	39.125	226.39	0.013346	0.006138	(0.00,	53.43,	-80.00)
25	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	226.41	0.013709	0.006322	(0.00,	53.43,	-79.99)
26	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.309	226.71	0.013741	0.006335	(0.00,	53.50,	-79.69)
27	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	226.72	0.014104	0.006519	(0.00,	53.51,	-79.68)
28	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	226.93	0.014125	0.006528	(0.00,	53.55,	-79.48)
29	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	226.94	0.014488	0.006712	(0.00,	53.56,	-79.47)
30	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	227.15	0.014510	0.006721	(0.00,	53.61,	-79.27)
31	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	227.16	0.014872	0.006905	(0.00,	53.61,	-79.26)
32	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	227.36	0.014894	0.006913	(0.00,	53.66,	-79.06)
33	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	227.38	0.015619	0.007281	(0.00,	53.66,	-79.04)
34	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	227.40	0.016344	0.007649	(0.00,	53.67,	-79.02)
35	Air	7	14.784	0.0012	30528.8407	71998.1725	86.462	313.87	0.019177	0.008850	(0.00,	74.07,	5.00)
36	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	313.88	0.019539	0.009034	(0.00,	74.07,	5.01)
37	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.309	314.18	0.019571	0.009047	(0.00,	74.15,	5.31)
38	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	314.19	0.019934	0.009231	(0.00,	74.15,	5.32)
39	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	314.40	0.019956	0.009240	(0.00,	74.20,	5.52)
40	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	314.41	0.020318	0.009424	(0.00,	74.20,	5.53)
41	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	314.62	0.020340	0.009432	(0.00,	74.25,	5.73)
42	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	314.63	0.020703	0.009616	(0.00,	74.25,	5.74)
43	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	314.83	0.020724	0.009625	(0.00,	74.30,	5.94)
44	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	314.85	0.021449	0.009993	(0.00,	74.30,	5.96)
45	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	314.87	0.022175	0.010361	(0.00,	74.31,	5.98)
46	Air	7	14.784	0.0012	30528.8407	71998.1725	88.520	403.39	0.025074	0.011591	(0.00,	95.20,	92.00)
47	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	403.40	0.025437	0.011775	(0.00,	95.20,	92.01)
48	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.309	403.71	0.025469	0.011788	(0.00,	95.28,	92.31)
49	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	403.72	0.025832	0.011972	(0.00,	95.28,	92.32)
50	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	403.93	0.025853	0.011980	(0.00,	95.33,	92.52)
51	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	403.94	0.026216	0.012164	(0.00,	95.33,	92.53)
52	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	404.15	0.026238	0.012173	(0.00,	95.38,	92.73)
53	Kapton	6	12.701	1.4300	28.3749	55.9194	0.010	404.16	0.026600	0.012357	(0.00,	95.38,	92.74)
54	GEMGas	8	16.809	0.0037	9559.7011	23915.1216	0.206	404.36	0.026622	0.012365	(0.00,	95.43,	92.94)
55	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	404.38	0.027347	0.012733	(0.00,	95.43,	92.96)
56	Kapton	6	12.701	1.4300	28.3749	55.9194	0.021	404.40	0.028073	0.013102	(0.00,	95.44,	92.98)
57	Air	7	14.784	0.0012	30528.8407	71998.1725	7.739	412.14	0.028326	0.013209	(0.00,	97.26,	100.50)
58	N2cherenkov	7	14.007	0.0013	30390.5672	67516.7614	201.996	614.14	0.034973	0.016201	(0.00,	144.93,	296.79)
59	PyrexGlass	10	20.495	2.2300	12.6748	43.5474	0.245	614.38	0.054296	0.021825	(0.00,	144.99,	297.03)
60	N2cherenkov	7	14.007	0.0013	30390.5672	67516.7614	15.921	630.30	0.054820	0.022061	(0.00,	148.75,	312.50)
61	Air	7	14.784	0.0012	30528.8407	71998.1725	7.718	638.02	0.055073	0.022168	(0.00,	150.57,	320.00)
62	N2cherenkov	7	14.007	0.0013	30390.5672	67516.7614	82.325	720.35	0.057782	0.023387	(0.00,	170.00,	400.00)
0	Average Material	8	15.059	0.0028	12466.6609	30800.6493	720.347	720.35	0.057782	0.023387	(0.00,	170.00,	400.00)

- Tools available in DD4hep and Acts to study material thicknesses from detector description.
- Good opportunity to place strategic material scans in CI testing.

To do list

- Check materials and update to latest design.
- GEM SIDIS configuration geometry problem.
- Parameterize Cherenkov mirror alignment and optimize.
- Setup CI for design tests: overlaps, single particle acceptances, etc, to quickly identify regressions.
- Add a CI for performance benchmarks: J/psi and DIS at first, then others?...

Documentation and Framework

- We have reached the need for a processing framework to really use full set of software tools.
- Documentation for a Solid Framework is progress.
- NPDet documentation is coming along.
- NPDet Reference documentation too.

A Minimal Solid Framework Strategy

- Follow pattern from Acts' examples.
- Components (algos, io, etc.) are compiled into libraries.
- Robust set of executables assembled for end-to-end processing chain.
- Full configuration is exposed for each component via boost's program options (eg command line args)

Note, this is not a full Event Processing Framework for long term use. It is the minimal framework needed to stitch tools together for reconstruction.

Summary and Outlook

- Full SoLID (geant4) simulation with DD4hep complete.
- End-to-end simulation nearly complete.
- Documentation and demo project soon to come.