

Development of a Low-Mass Carbon-Fiber Wire Drift Chamber for Low-mass tracking Detectors

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CPAD – RDC6 Gaseous Detectors Session(October 20th, 2026) – University of Washington

Motivation

The main question:

What can we expect if we were to replace a tungsten-based drift chamber(DCH) with a carbon-fiber-based alternative, with applications in future detectors?

Electron Colliders:

- FCC-ee is a leading proposal for the next large collider
- Lower track density compared to hadron
- Cleaner events from fundamental particles
- Higher Luminosity

Why A Drift Chamber?

- Low mass, large active tracking volume
- Limited by event rate, perfect for e+e- colliders

Why change the sense wires?

- Tungsten sense wires contribute a non-negligible amount of material to the total DCH material budget, especially in the barrel region



MEG2 Drift Chamber [Eur.Phys.J.C 84 \(2024\)](#)

IDEA Drift Chamber and why carbon fiber?

Pros of Carbon Fiber

Low number of protons $Z=6$ (W, $Z=74$)

- Higher X_0 = lower material budget x/X_0
- X_0 is the mean distance a high-energy electron travels before losing all but $1/e$ of its energy through Bremsstrahlung.
- Reduces background from multiple scattering

Higher radiation resistance

- Lattice structure coupled with less protons

Less stressful on support structures

- Less sag due to Gravity

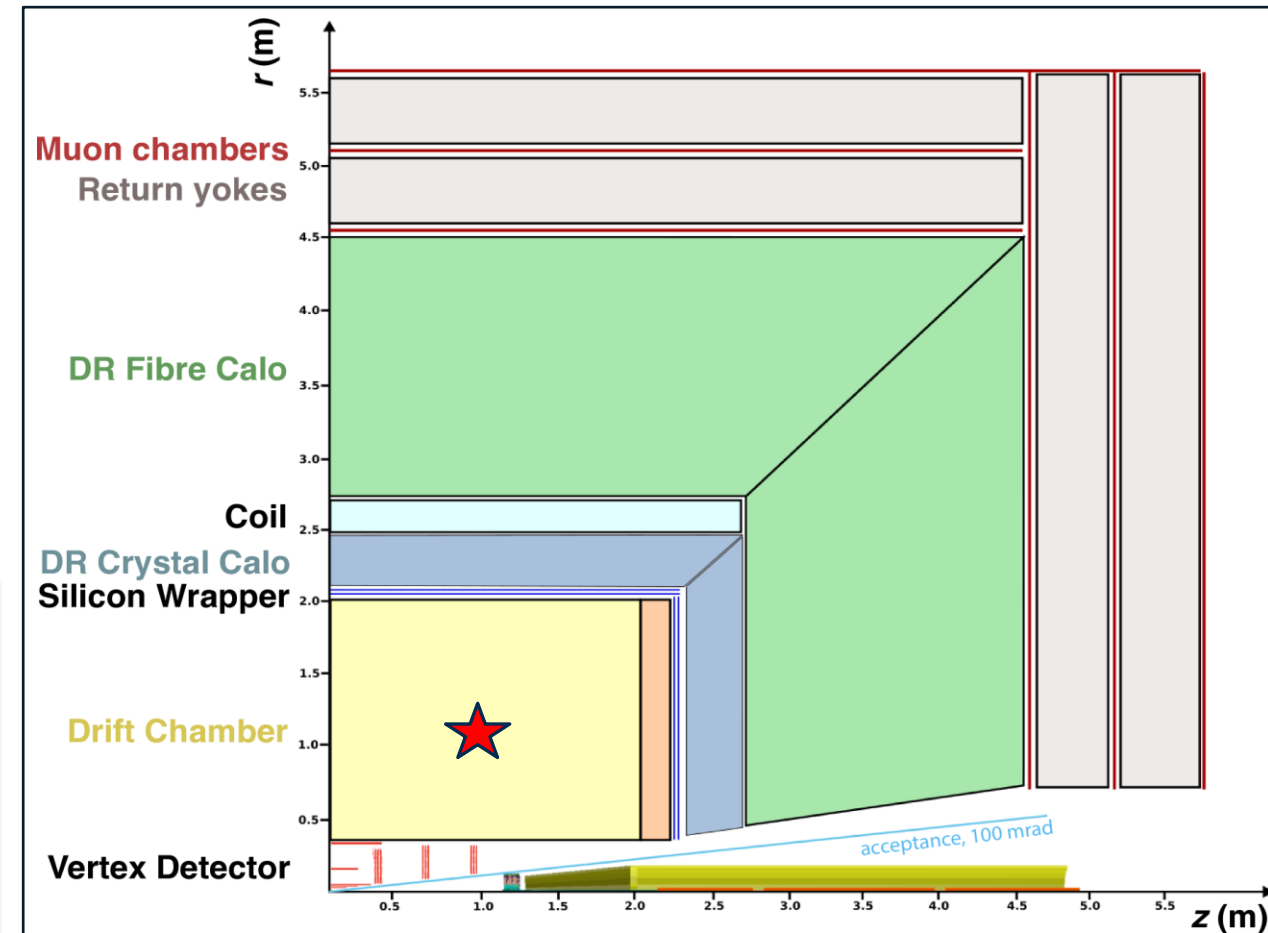
Cons of Carbon Fiber

Difficult to achieve preferred surface smoothness and roundness

- Nonuniform radius affects drift and field properties
- Surface imperfections can cause field hot-spots

Coating capabilities are severely lacking compared to metal wires

- Requires custom setups and further research and development



IDEA Study Group, M. Abbrescia et al.,
'[The IDEA detector concept for FCC-ee](#)', e-print arXiv:2502.21223
[physics.ins-det] (2025).

Simulations

Geant4 Material Budget

Common workflow

- Start from k4geo IDEA_o1_v03.xml
- Remove subdetectors based on desired output
- Run DDG4/geant4 material scanner
 - 15GeV geantinos (energy does not change x/X_0 for geantinos)
 - 2048 uniform $\cos(\theta)$ points
 - Each averaged over a distribution of phi samples
 - Overlap-weighted rebinning to 100 bins for unfolded $\cos(\theta)$ (50 bins for $|\cos(\theta)|$)

Brief k4geo material definition issue
Ratio: fixed/legacy for 25CF+2.227Au at eta=0
sense = 2.5
Total DCH ~ 1.036
(More details in back-up)

2. Phi convergence: wire-structure sensitivity

Comparison	Observable	Median rel. diff.	p95	p99	Max	Conclusion
2048 -> 4096	Wire-only, native bins	7.73%	30.04%	50.27%	100%	Discrete wire structure still strongly phi-sensitive

Difference per eta bin (W20baseline) of 4096 phi vs. 2048

- median difference ~7.73%
- maximum of a 100% difference.



4096 bins chosen over 2048

IDEA DCH Variant Wire Definitions

1. Field:sense ratio from baseline diameters (side ~ 1.985 , central ~ 2.478)
2. Apply to variant sense wire CF core + Au diameter added
3. Equals scaled field wire diameters
4. Subtract 0.3 μ m for Au coating to get Al contribution to field wire diameters

Variant	Core	Core diameter [μ m]	Au diameter-added [μ m]	Sense outer [μ m]	Side field outer [μ m]	Central field outer [μ m]
W20_Au0p3_defaultlike	W	20.000	0.3	20.3	40.3	50.3
CF20_Au0p3_scaledfield	CF	20.000	0.3	20.3	40.3	50.3
CF20_Au1p0_scaledfield	CF	20.000	1	21	41.689655	52.034483
CF20_Au3p273DCmatched_sc	CF	20.000	3.273396	23.273396	46.202851	57.667578
CF25_Au0p3_scaledfield	CF	25.000	0.3	25.3	50.226108	62.689163
CF25_Au1p0_scaledfield	CF	25.000	1	26	51.615764	64.423645
CF25_Au2p227DCmatched_sc	CF	25.000	2.226776	27.226776	54.051185	67.46339
CF35_Au0p3_scaledfield	CF	35.000	0.3	35.3	70.078325	87.467488
CF35_Au1p0_scaledfield	CF	35.000	1	36	71.46798	89.20197
CF35_Au0p689DCmatched_sc	CF	35.000	0.68876	35.68876	70.850099	88.430769

DCH-only material budget comparison

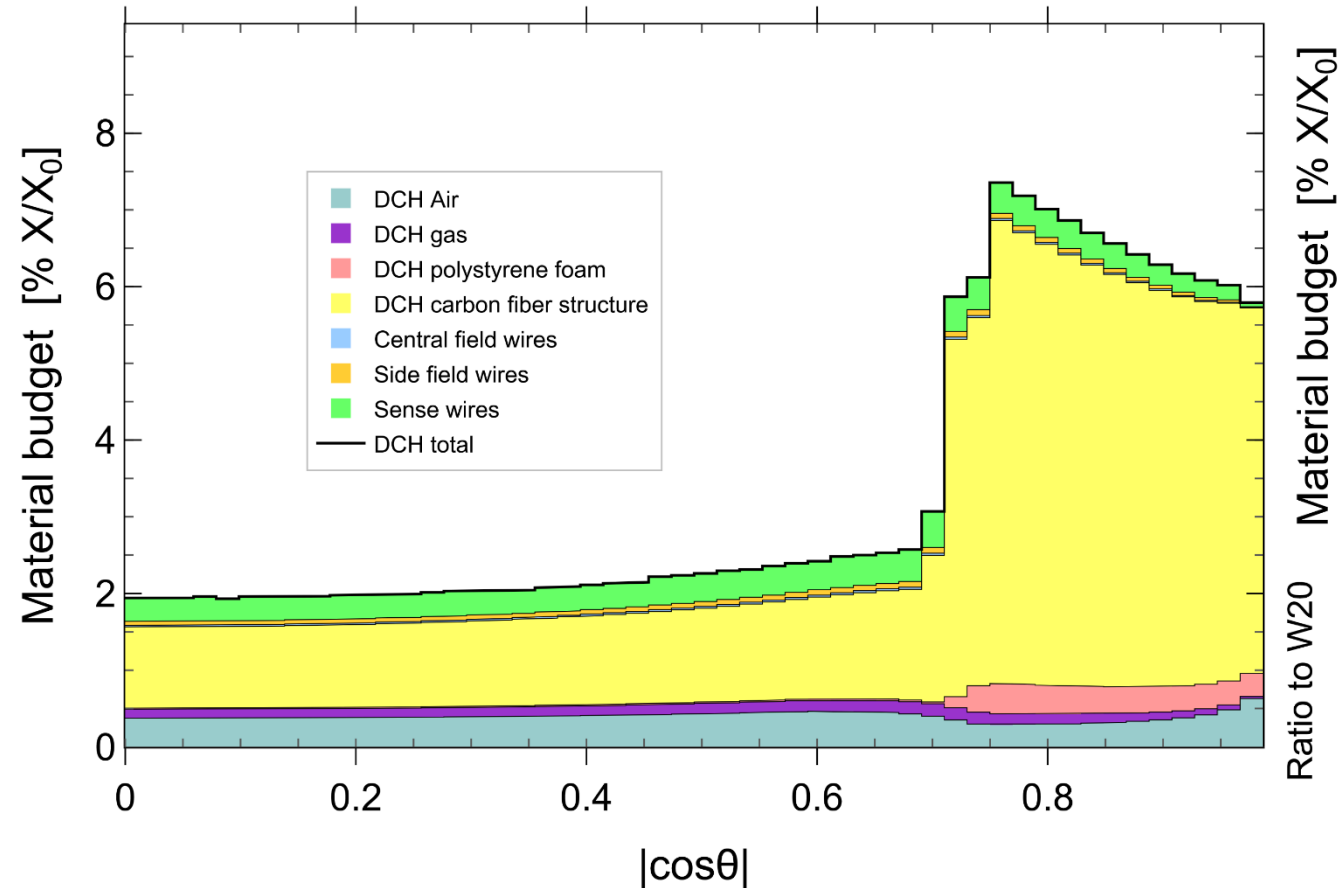
CFDCH

Simulation

Tungsten Baseline

FCC-ee IDEA simulation

20 μm W + 0.3 μm Au



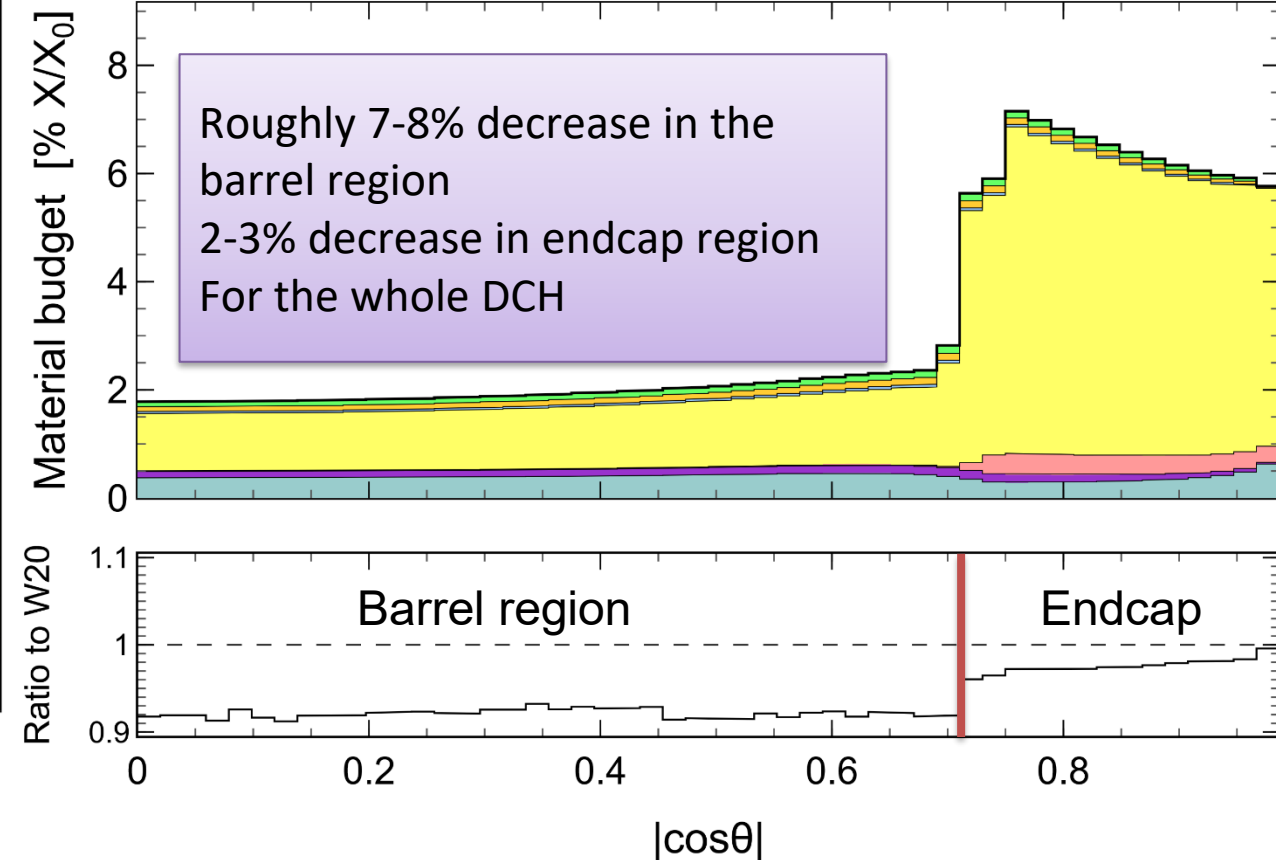
CFDCH

Simulation

Carbon Fiber

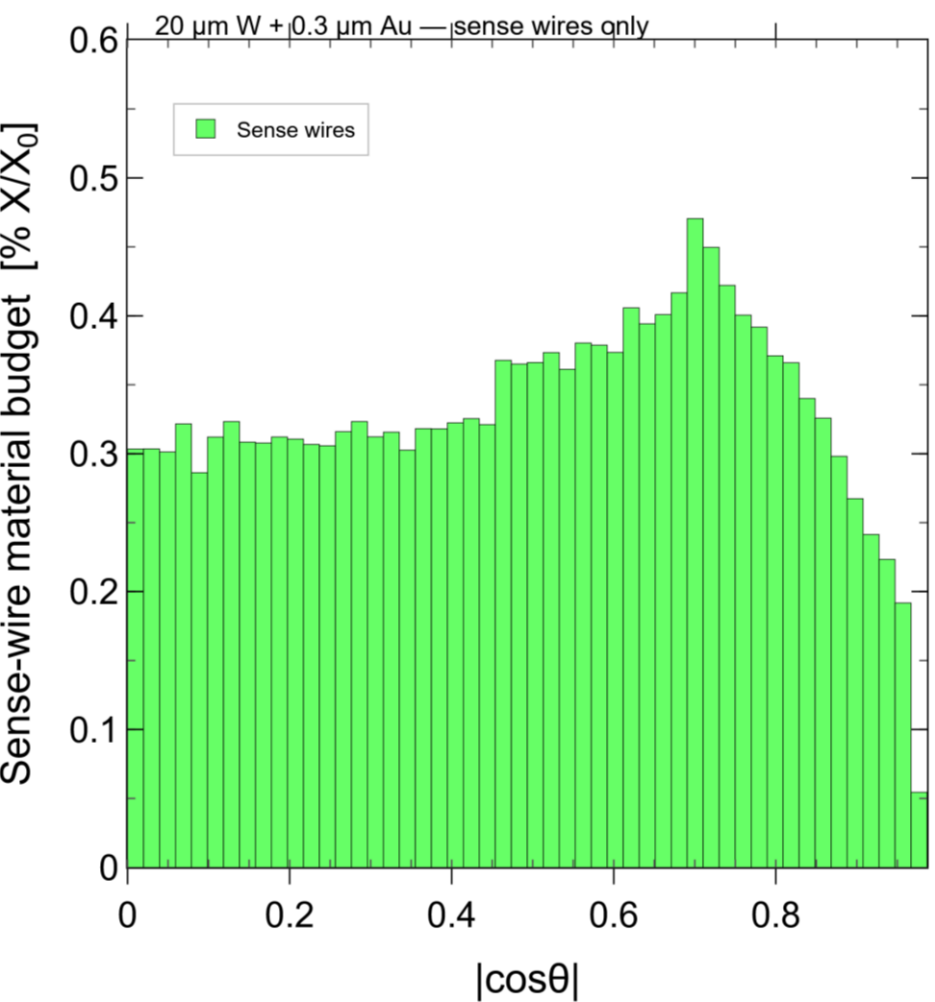
FCC-ee IDEA simulation

25 μm CF + 2.227 μm Au (DC-matched)

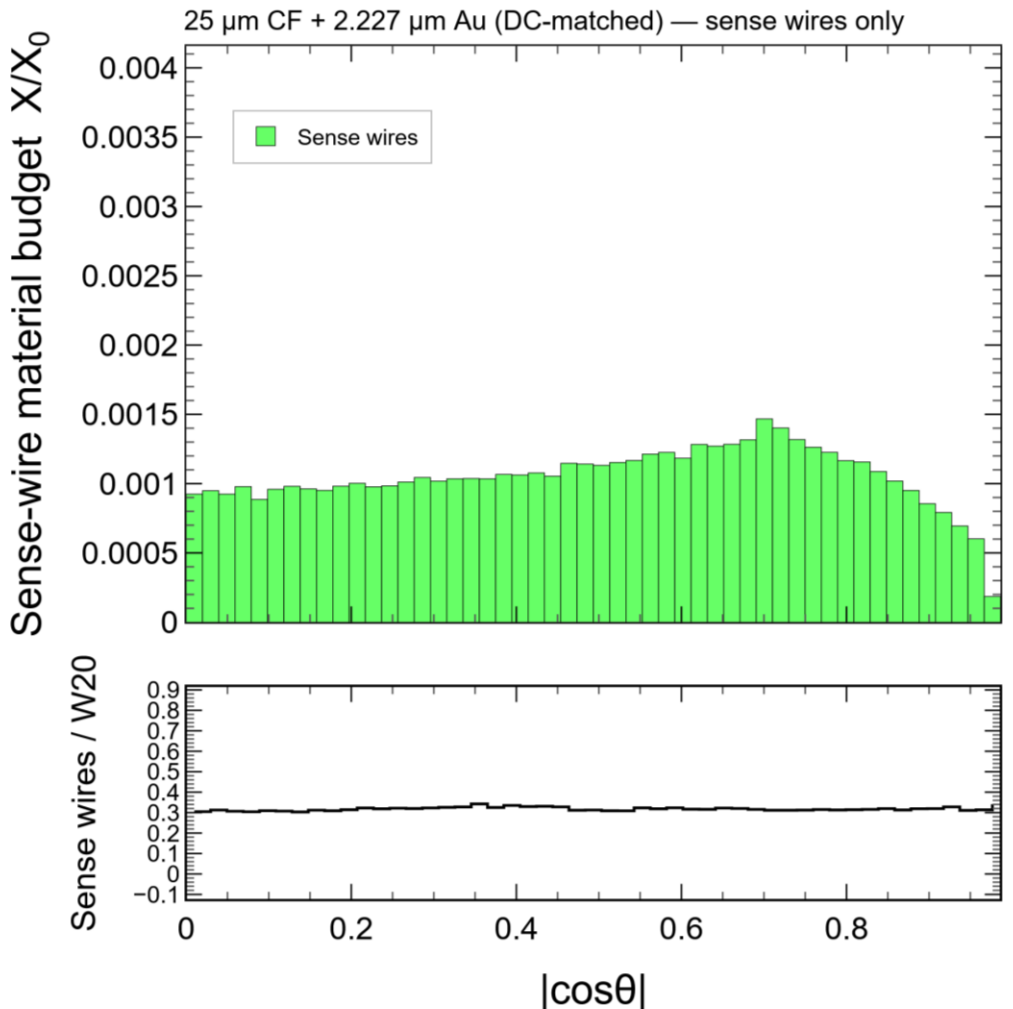


Sense wire only

CFDCH
Simulation FCC-ee IDEA simulation
Tungsten Baseline

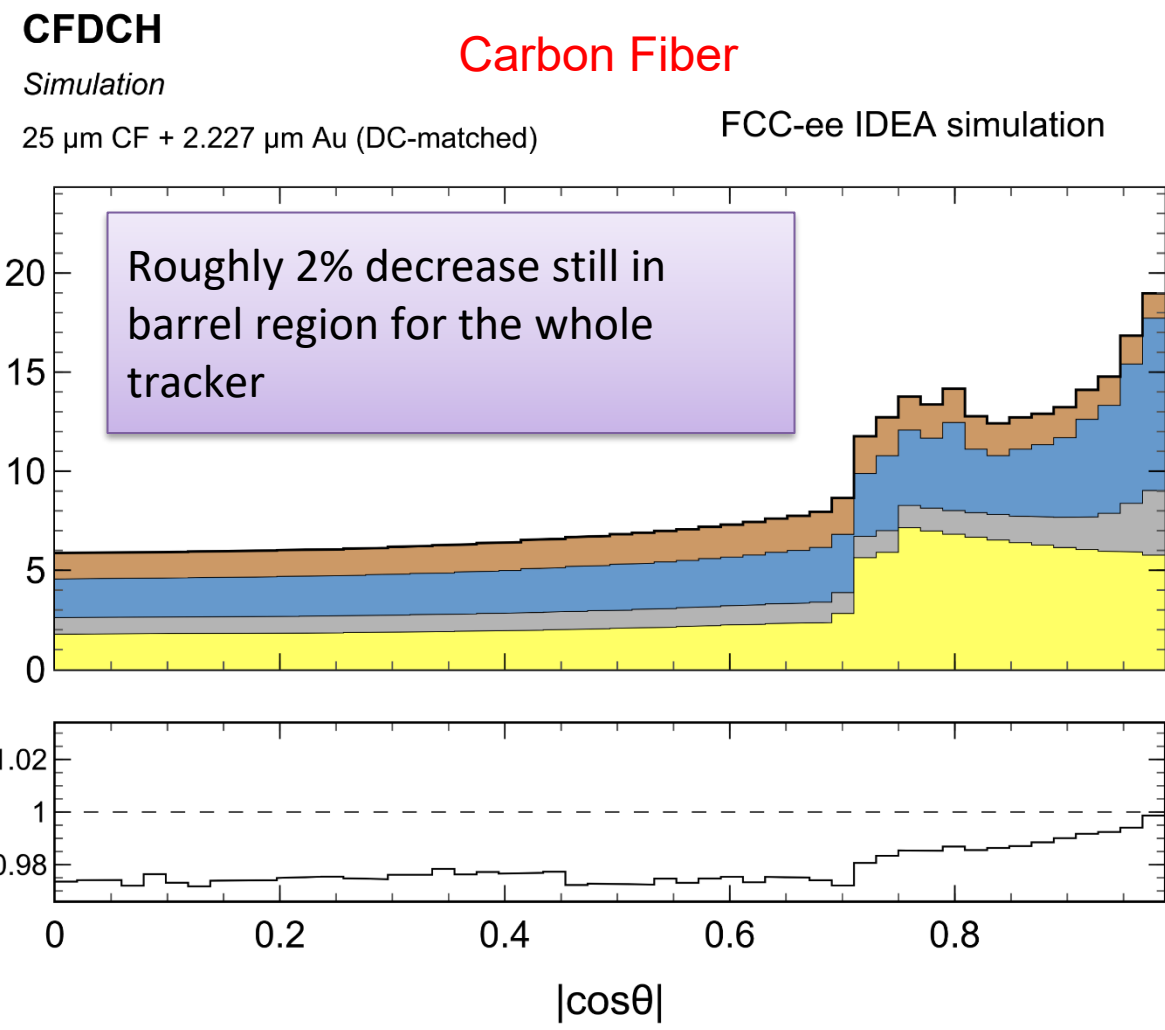
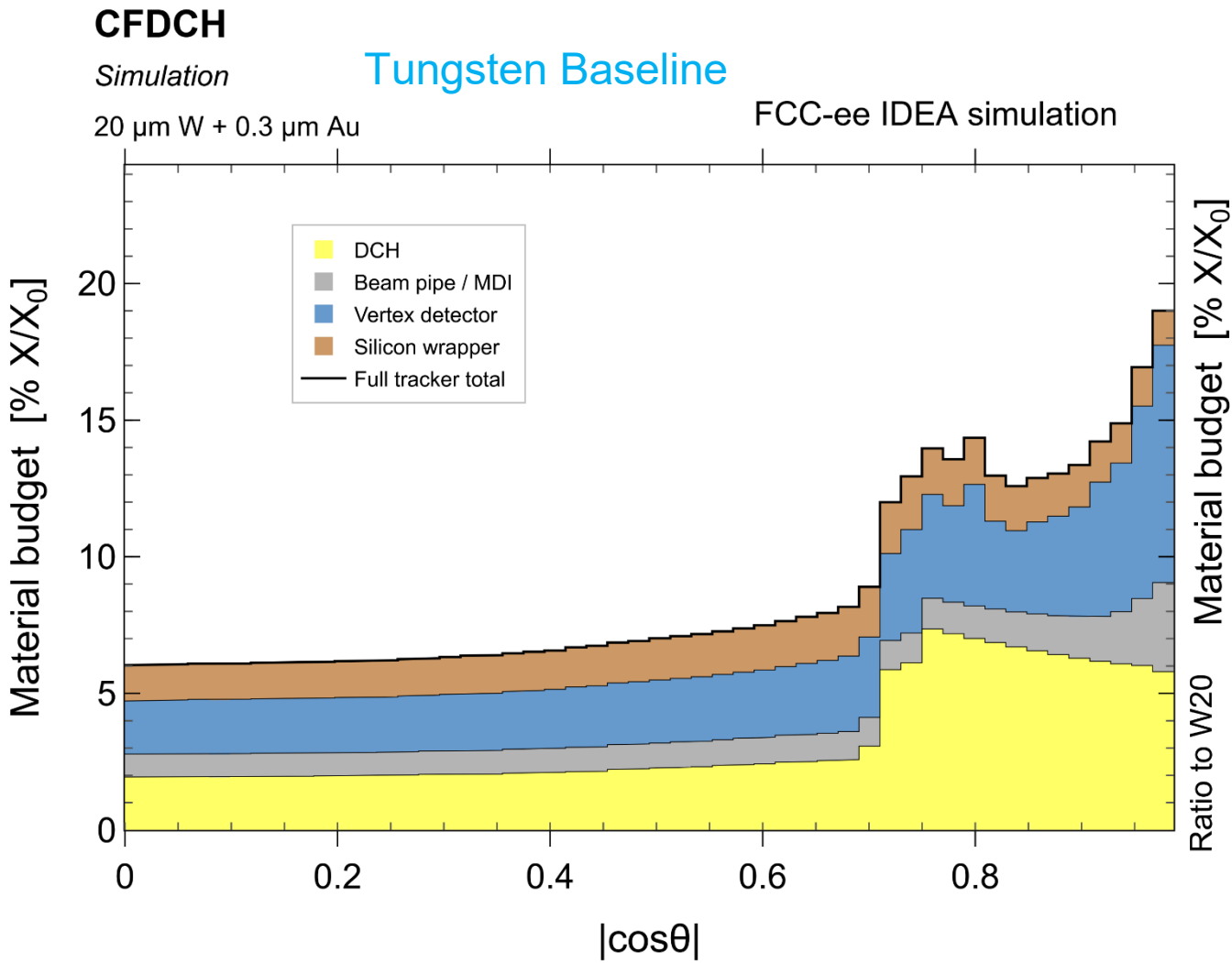


CFDCH
Simulation FCC-ee IDEA simulation
Carbon Fiber



Sense wires see a 70% reduction in material budget when comparing CF-based to Tungsten-based for the chosen variant.

Whole-tracker comparison



p_T Resolution Estimation

Use extended Gluckstern formula with multiple scattering

Constants:

- $B = 2\text{T}$ from [1]
- $\sigma_{r\phi} = 100\text{ }\mu\text{m}$ from [1]
 - Keeping the spatial resolution consistent across all variants

Variable values

- $L_0 = 1.65045\text{ m}$ centrally but the usable lever arm decreases in the forward region as a function of θ
- $N = 111$ centrally (112 layers – 1) but also decreases as a function of θ
- Use ray-integrated x/X_0 directly from our Geant4 material scans for 5 selected θ values
- pT values selected from 0.6 to 100GeV

$$\begin{aligned}\frac{\Delta pT}{pT} \Big|_{\text{res}} &= \frac{\sigma_{r\phi} pT}{0.3 B_0 L_0^2} \sqrt{\frac{720 N^3}{(N-1)(N+1)(N+2)(N+3)}} \\ \frac{\Delta pT}{pT} \Big|_{\text{m.s}} &= \frac{N}{\sqrt{(N+1)(N-1)}} \frac{0.0136 \text{ GeV/c}}{0.3 \beta B_0 L_0} \sqrt{\frac{d_{\text{tot}}}{X_0 \sin \theta}} \left(1 + 0.038 \ln \frac{d}{X_0 \sin \theta}\right)\end{aligned}$$

Drasal, Riegler, <https://doi.org/10.1016/j.nima.2018.08.078>

Implementation note: G4 provides x/X_0 along the actual inclined ray; no additional x/X_0 material correction is applied.

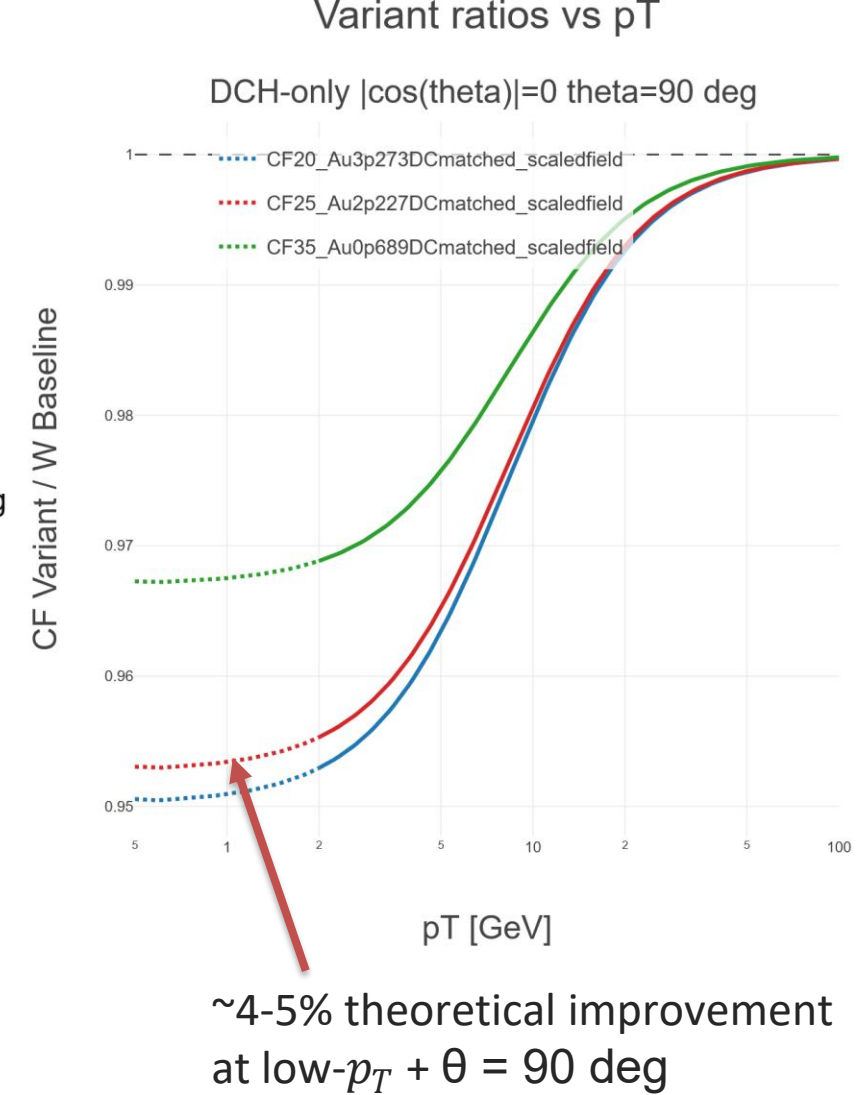
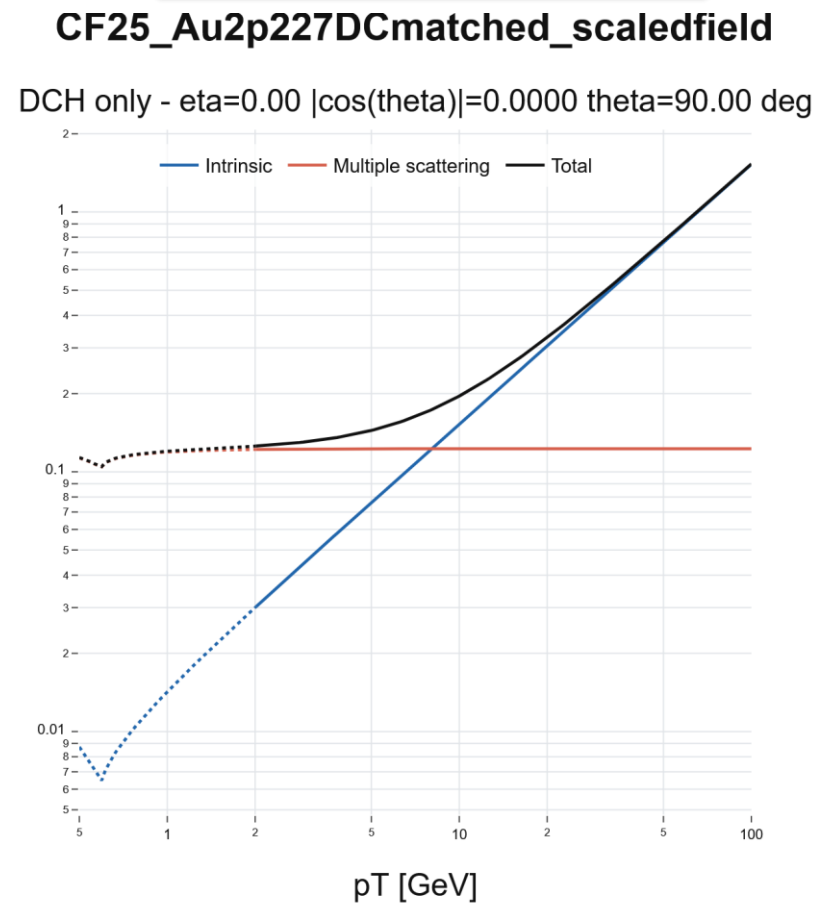
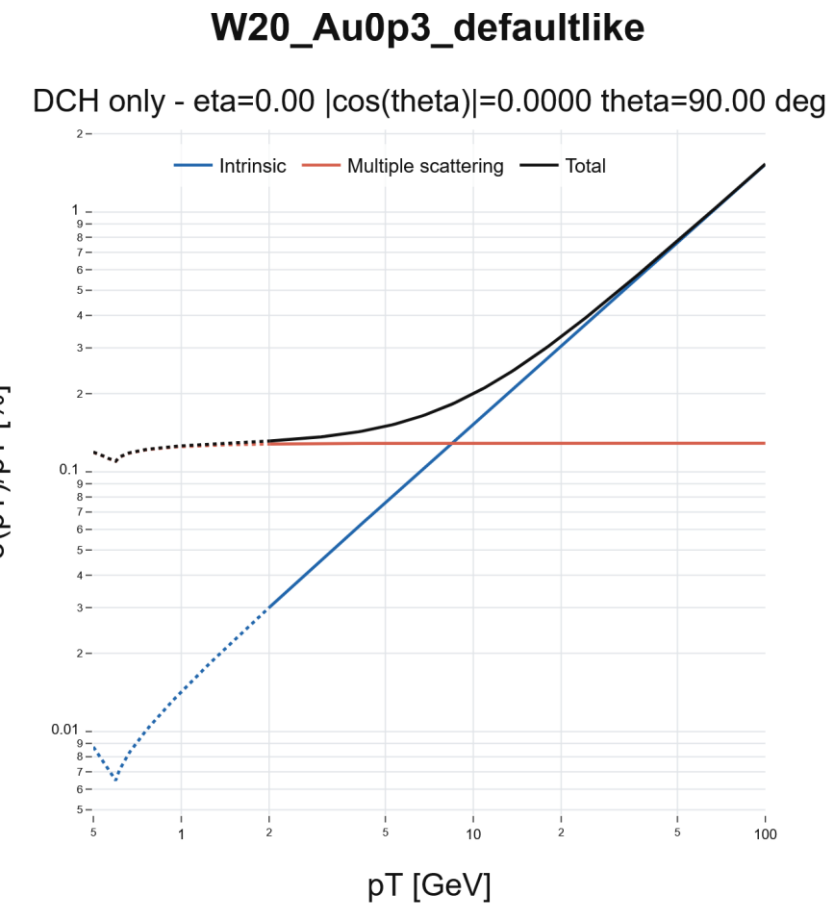
Improved p_T resolution supports FCC-ee's precision-physics program, with low-material tracking especially beneficial where multiple scattering is important

[1] [Francesco Grancagnolo, 'Conceptual designs and R&D challenges for drift chambers', ECFA WG3: Topical workshop on tracking and vertexing – CERN, 2023](#)

DCH-only p_T resolution

Multiple Scattering term:
W: 0.12403
CF: 0.11818
CF/W: 0.953

 $p_T = 0.9 \text{ GeV}, \theta = 0$



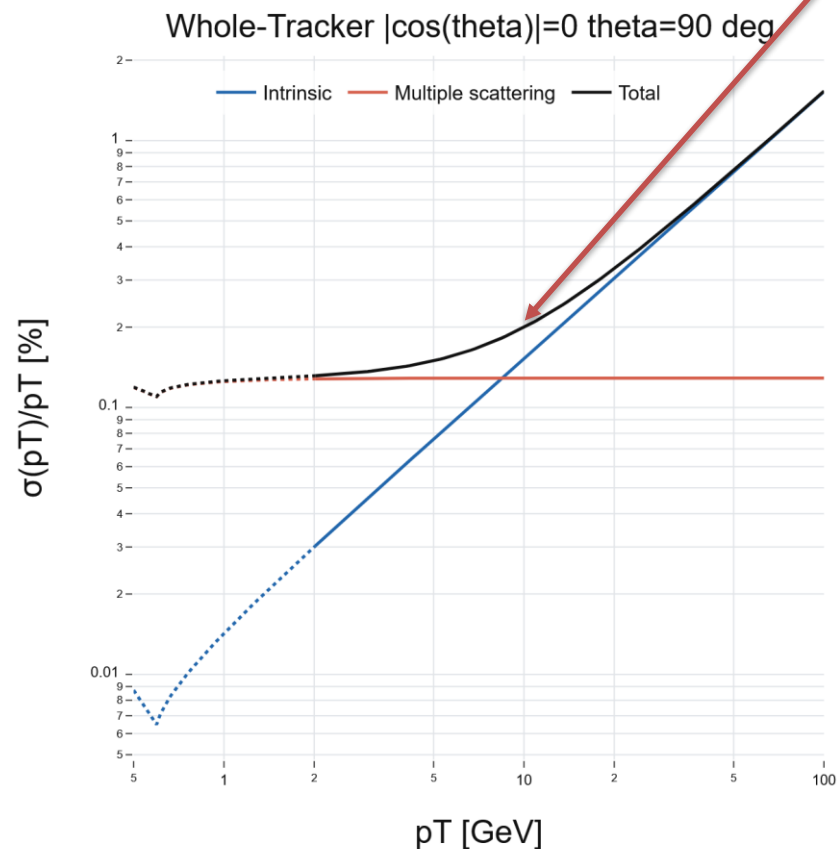
Whole-tracker p_T resolution

“defaultlike” IDEA has
~0.20407% at $p_T = 49.34\text{ GeV}$,
matching prior conservative
tracker resolution requirements

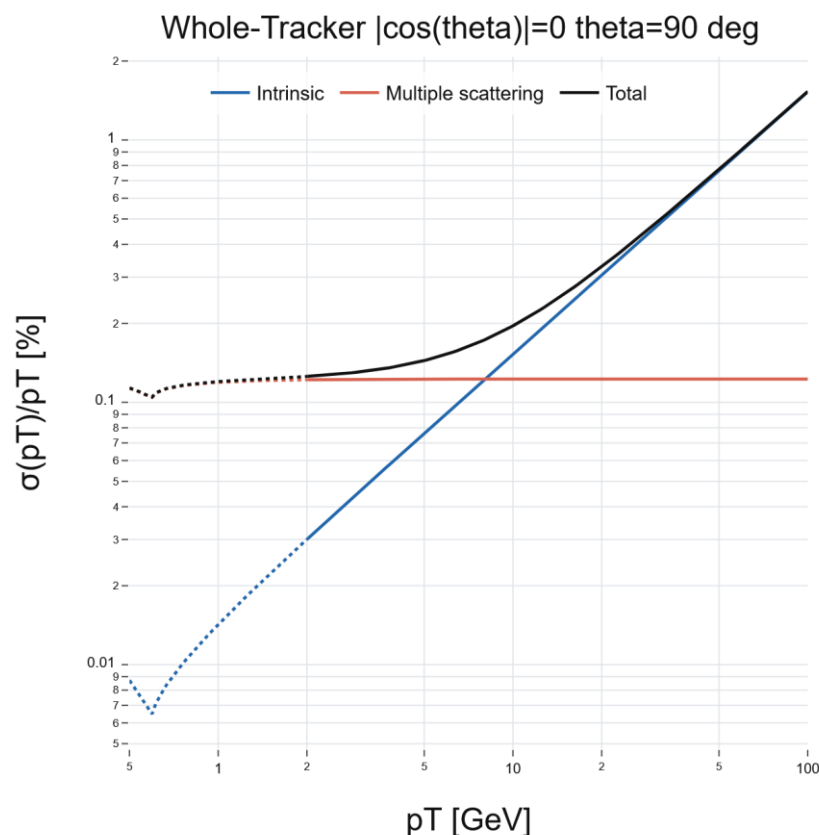
Multiple Scattering term:
W: 0.11486
CF: 0.10981
CF/W: 0.956

$p_T = 0.9\text{ GeV}$, $\theta = 90\text{ deg}$

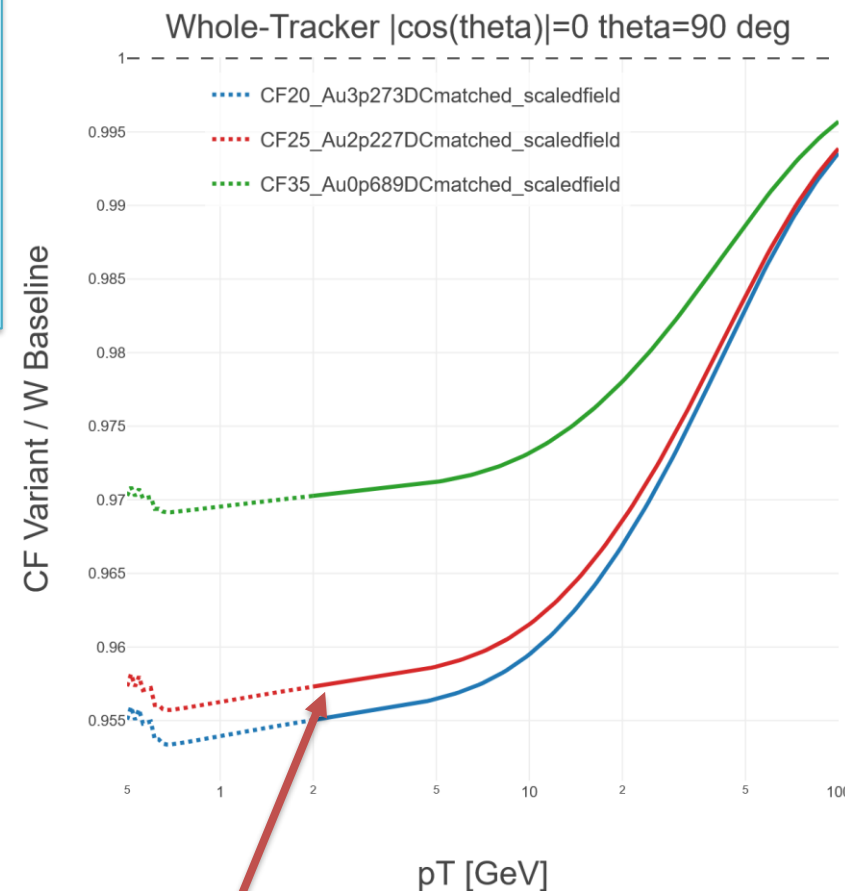
W20_Au0p3_defaultlike



CF25_Au2p227DCmatched_scaledfield



Variant ratios vs p_T



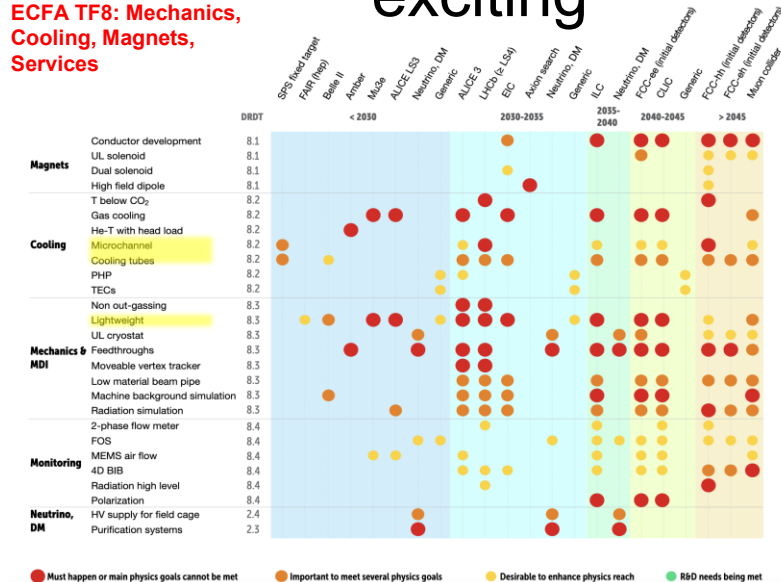
~4-5% theoretical improvement at
low- p_T + $\theta = 90\text{ deg}$

Hardware

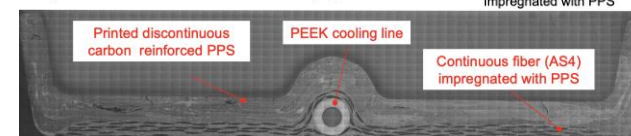
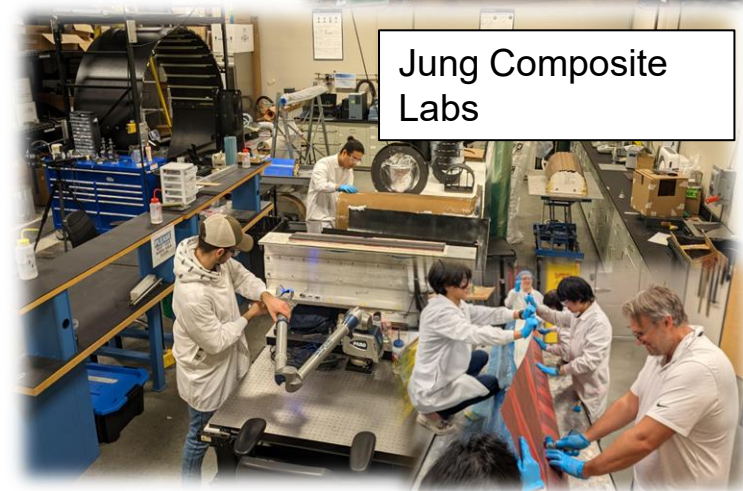
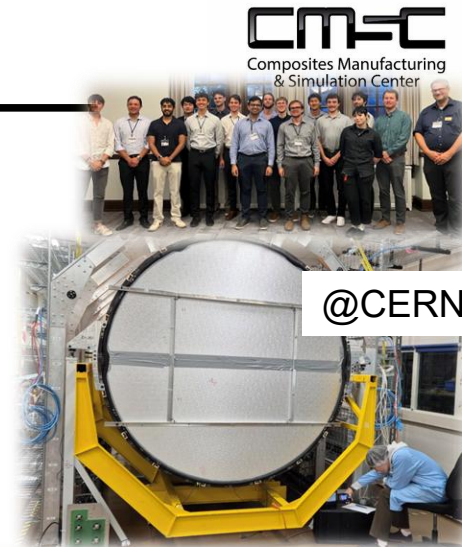
Critical need for detector R&D

- Detector “Mechanics” is a critical need; any future facility & detector concept depends on it!
 - Chip packaging, thermal aspects, cooling, 3D integration and more ...
- Interdisciplinary R&D and manufacturing projects
 - CoE: Mechanical Engineering, Aero, Materials, ...
 - Things can go wrong ... still exciting

ECFA TF8: Mechanics, Cooling, Magnets, Services



More information can be found here (email: anjung@purdue.edu): <https://www.physics.purdue.edu/jung>

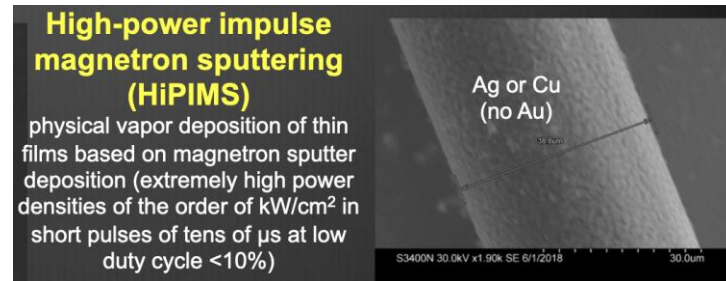


Critical need for “Mechanics” R&D

DOE BlueSky R&D funded

Drift chamber, e.g.
using “CF” wire
chambers...

Dual readout
calorimetry w
carbon fiber
supports...



→ This example: **factor 5 reduction** in material when moving from W+Al to C+Ag/Cu

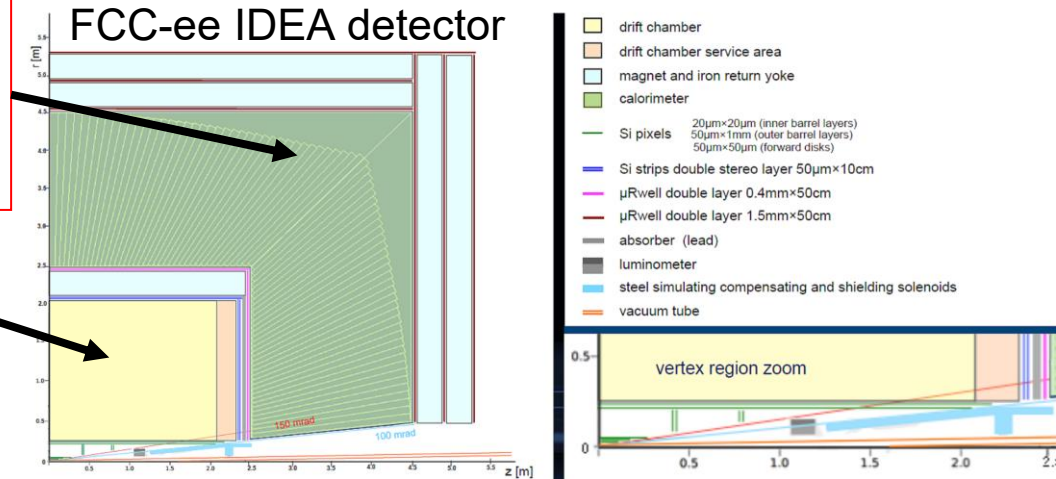


Figure 6: Cross section of the proposed layout for the IDEA detector concept.

[NIM A Vol 855, 2017](#)

- **FCC IDEA: example of “large detector”**
- Detector mechanics/cooling play a significant role in a detector's performance
- **Electron-Ion Collider & highly relevant also to small experiments**

Exchange of ideas & progress across existing collaborations:

- “CPAD RDC 10”: R&D Collaboration for “Detector Mechanics R&D” <https://cpad-dpf.org>
- Bridges nuclear, high energy physics & space applications / satellites too – broad field!
- CERN DRD 8 Detector Mechanics collaboration

The chamber setup

Machined aluminum

Copper-taped panels for low-resistance contact

Current Sense Wires:

- Uncoated 25 μm CF : $R/L = 442.1 \text{ } \Omega/\text{m}$
- Uncoated 25 μm Tungsten : $R/L = 114.5 \text{ } \Omega/\text{m}$

1 sense sled
2 field sleds

Keithley 2290-5 HV PSU

Gas inlet and outlet

(closeup of stacked sleds)

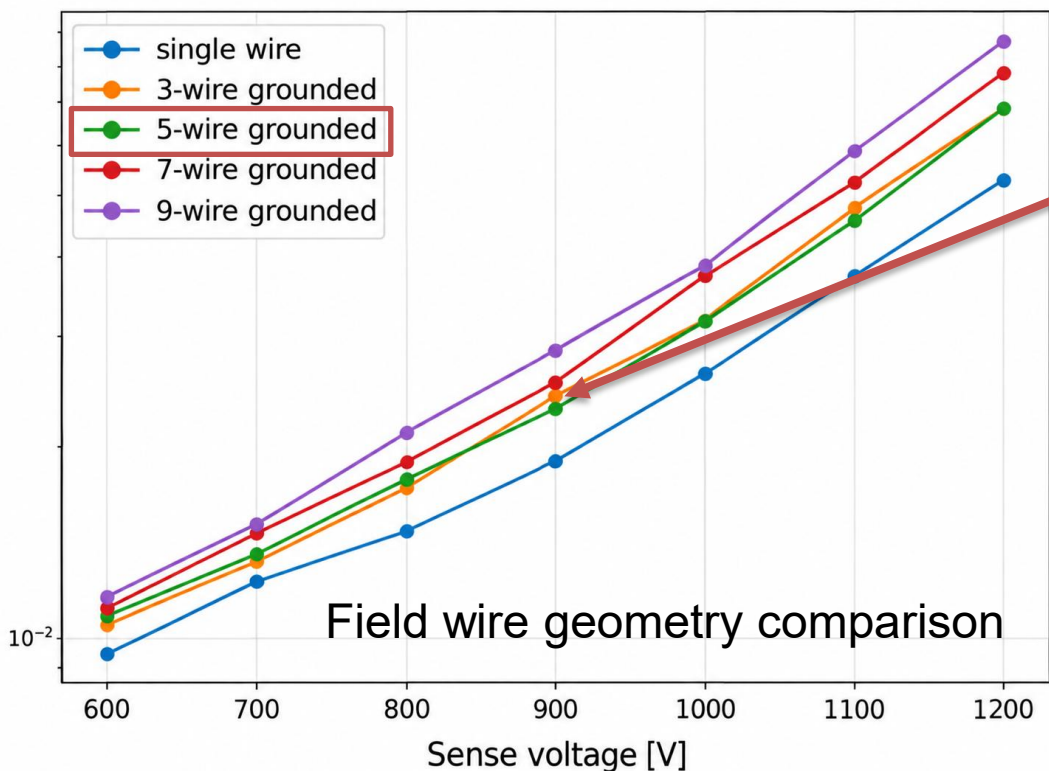
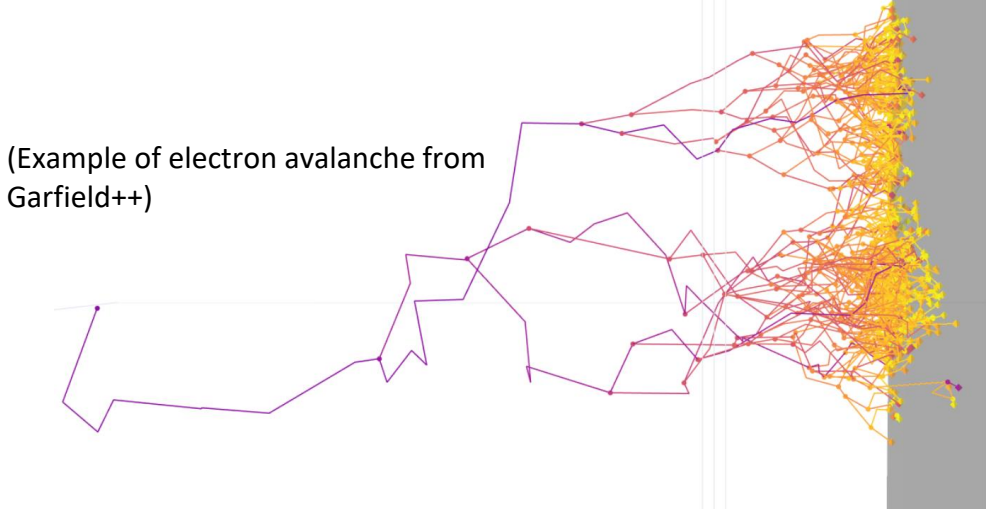
Oscilloscope

External SHV
circuit box

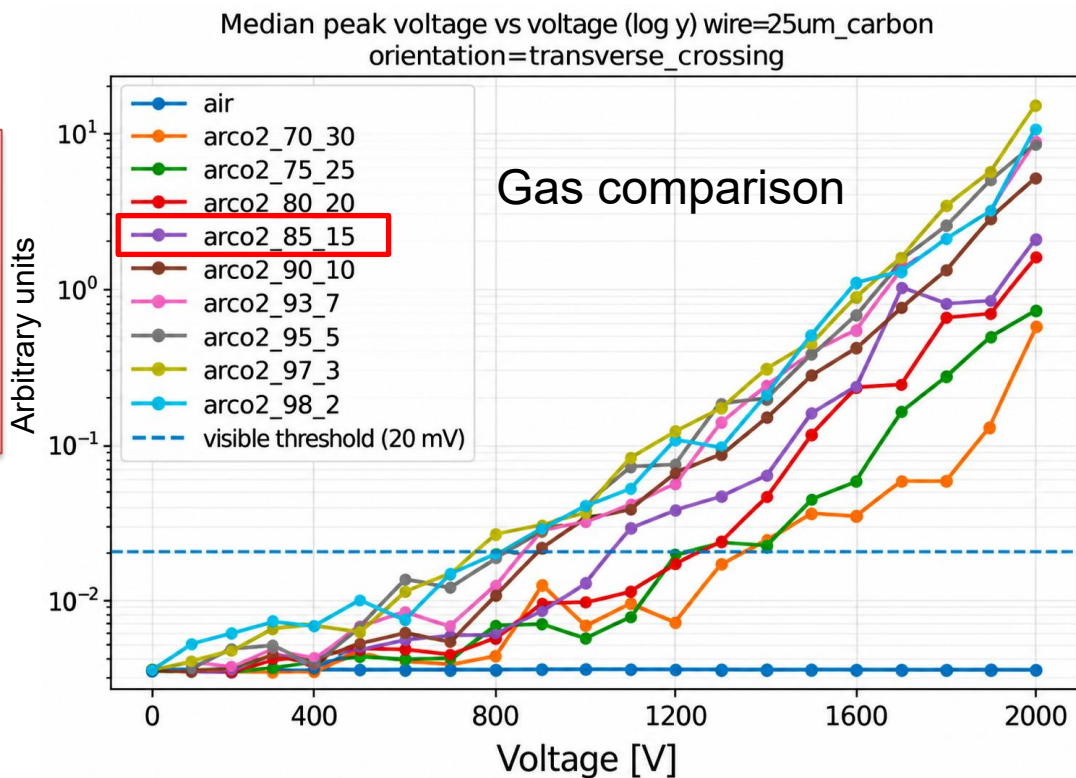
SHV input (single-sided readout)

Design Specifications

- Gas choice of 85/15 ArCO2 based on balancing gain and stability
- HV PSU choice based on availability and capability
- External circuit design based on LTSpice + Garfield++
- Number of field wires based on Garfield++ scan
- Field wires 80 μm stainless steel chosen based on availability



5-wire tends to require 100V less than single-wire to reach the same signal



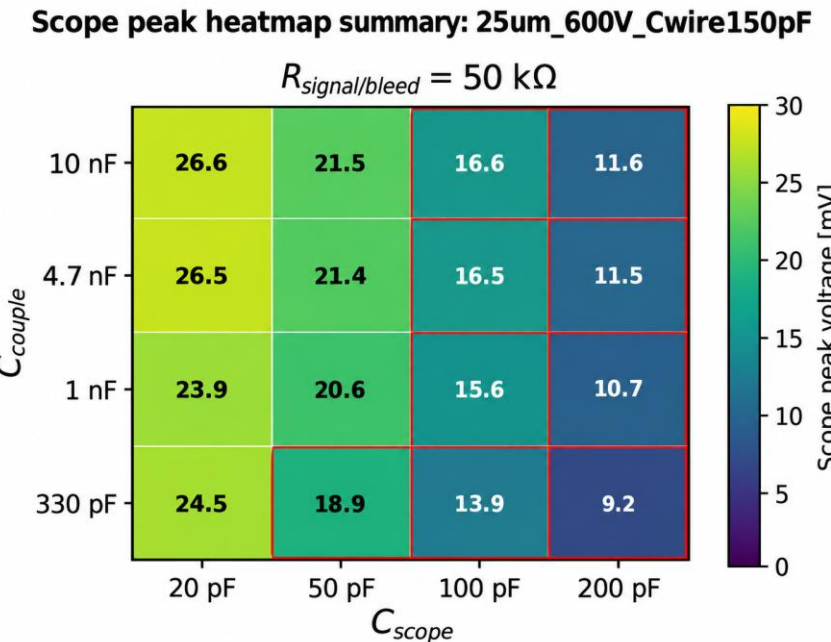
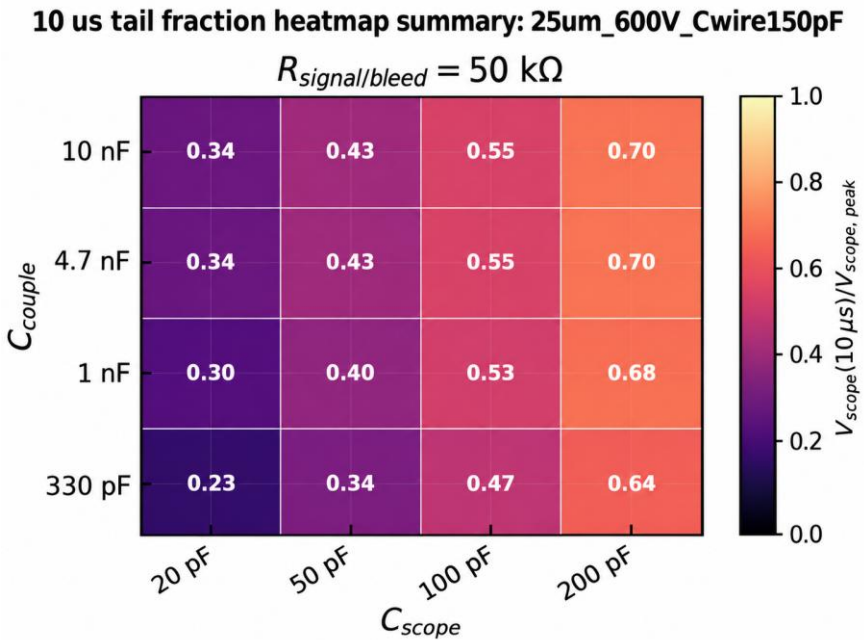
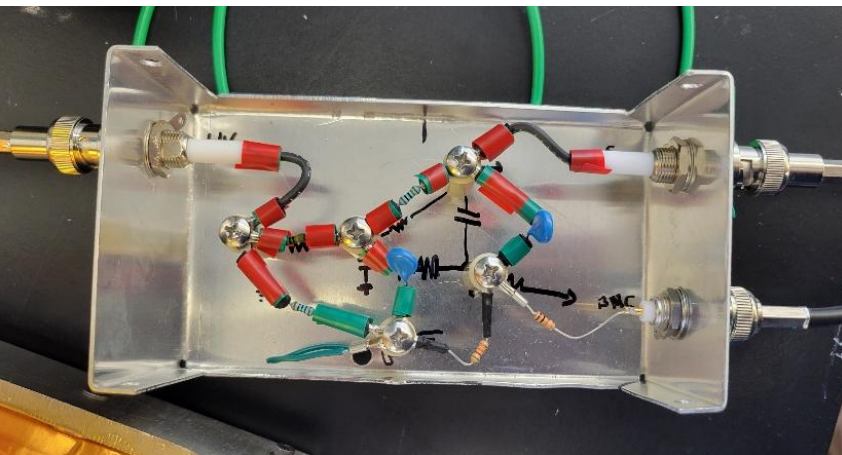
External circuit box

Goal: Apply a constant voltage to the sense wire and only allow the AC signal to pass to the oscilloscope with low noise.

- SHV in from PSU, to sense wire, capacitively decouple AC to oscilloscope.
- Spacing and ceramic standoffs are primary safety measures, mastic tape covering potential arc points.

Garfield+ LTSpice setup

- Simulated cosmic-muon-like particle passing near a wire outputs raw current waveform.
- Input waveform into LTSpice as the pulse from the sense wire.
- Ran over a matrix of different capacitor and resistor values to maximize peak signal and minimize the tail.



INFN Bari, Lecce - Purdue Collaboration

INFN are extremely well-versed in drift chambers and wire mechanics. As well as being integral to the design and implementation of the IDEA concept itself.

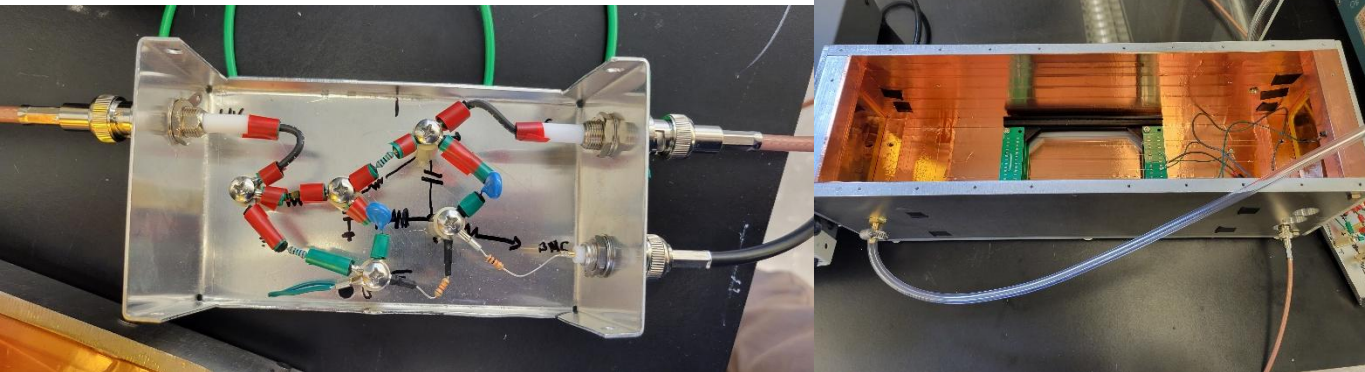
Purdue has experience in carbon fiber composites and is working towards fiber coating. In addition to experience in simulations utilizing carbon-fiber variants.

Together we are looking to combine experience to both cross-validate results such as material budgets, and to work towards creating a proper metal-coating process for carbon fiber wires.

Next steps

Simulation

- Finalize track reconstruction process for DCH-only and full tracker
- Potentially implement Garfield-informed digitizer which will need custom settings for CF variants
- Delphes studies
- Fullsim studies once ready

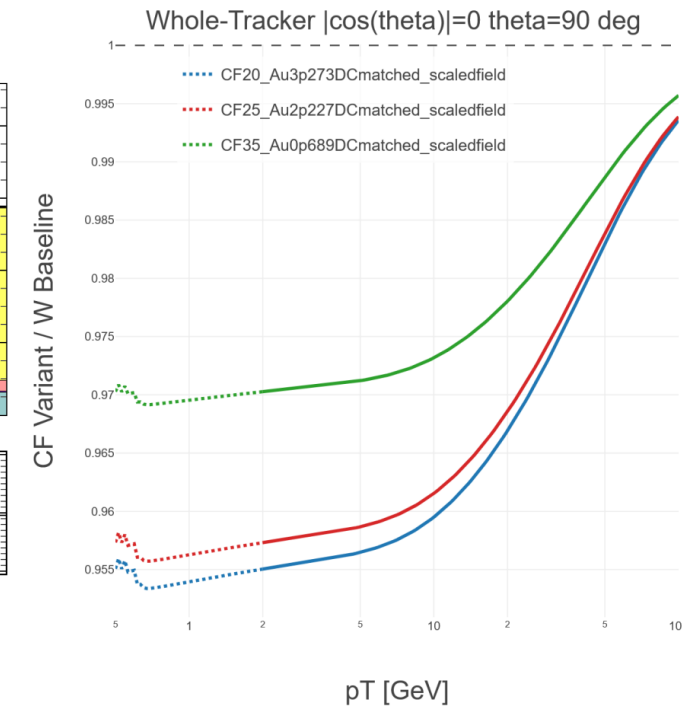
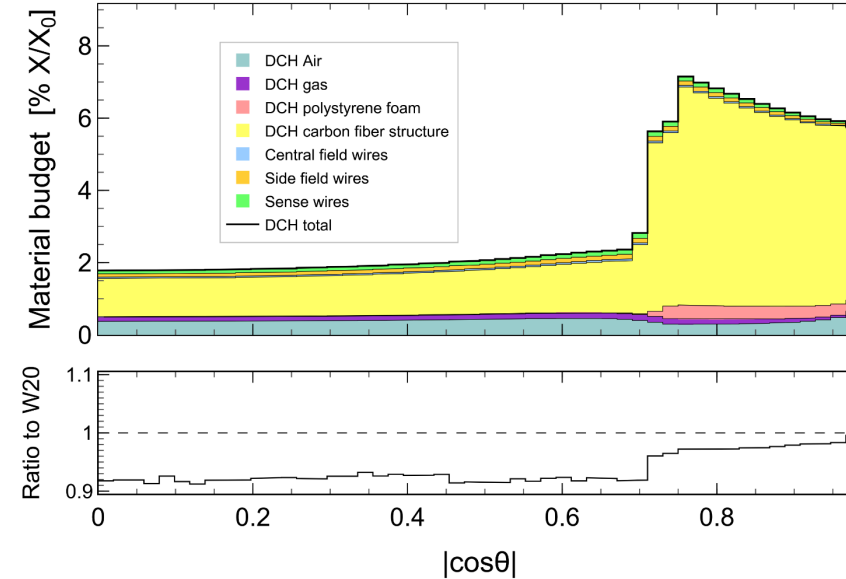


CFDCH

Simulation

25 μm CF + 2.227 μm Au (DC-matched)

FCC-ee IDEA simulation



Hardware

- Low-voltage and initial gas testing
- HV control tests with oscilloscope
- Begin carbon fiber testing with what we have
- INFN Collaboration and hopefully finding coating solutions

Thank you for listening!

Questions?

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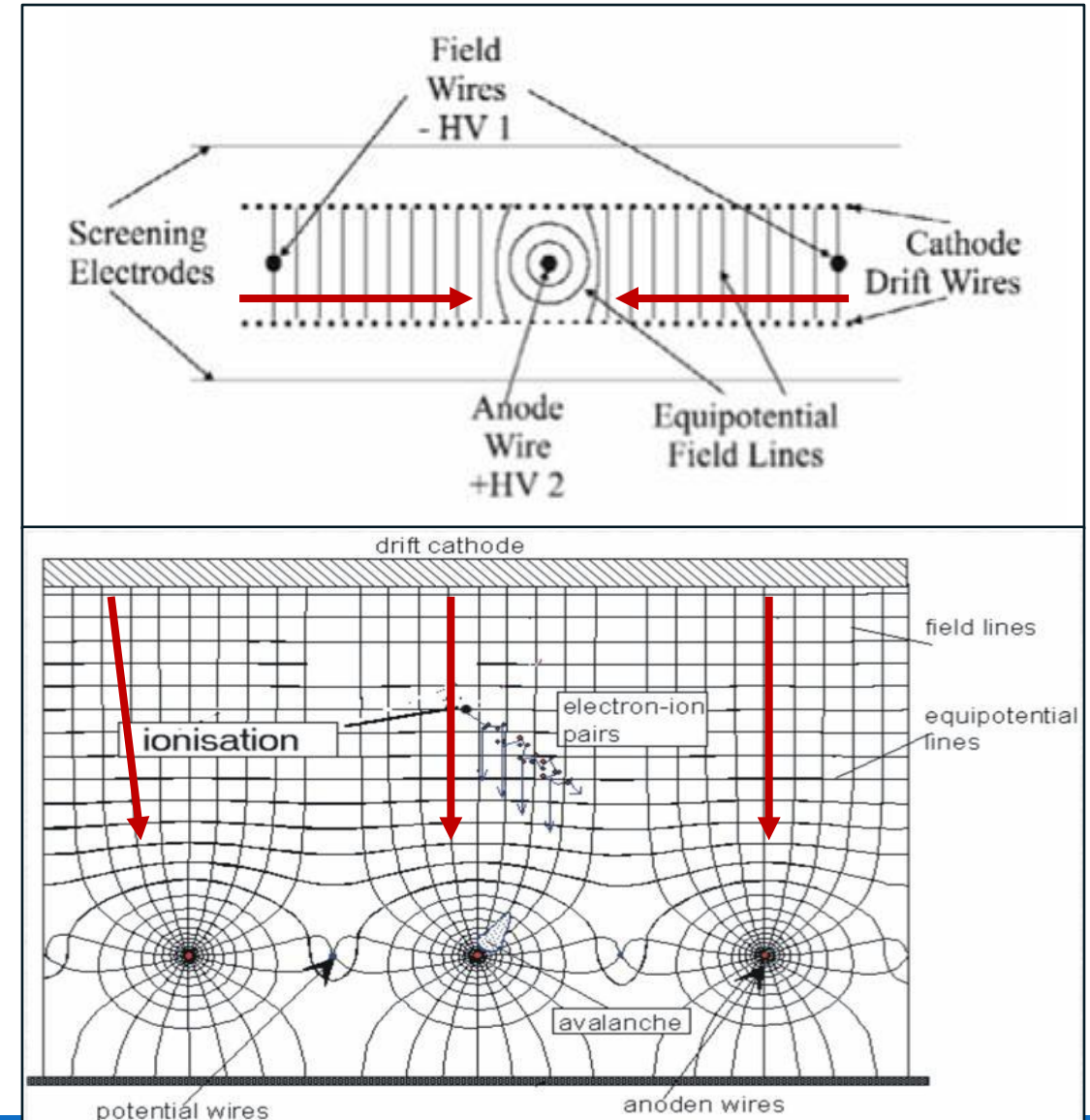


Backup Slides

Wire Drift Chamber

Ix-B Garcia Ferreira et al, 'The Drift Chambers Handbook', 2005 J. Phys.: Conf. Ser. 18 346

- Charged particles ionize gas
 - Electrons drift towards anode
 - Ions drift towards cathode
 - Cathodes serve to produce equipotential field lines
- Large E Field closer to anode energizes electrons and creates avalanche to produce signal
- Drift time and velocity allows us to determine position of incoming particle



Minor issue with k4geo definitions

The wire material definition blocks were partially incorrect

- Current definitions use area fraction for both density and the material composition <fraction>
- DD4hep requires “fraction” to be the mass fraction not area fraction
- For the baseline sense wires their densities are so close that the difference is zero
- The field wires and especially our CF sense wire “materials” require the change

```
<!-- average material for wires -->
<material name="DCH_FCentralWireMat">
  <comment> 0.98810714*2.7 + 0.011892860*10.49 </comment>
  <D type="density" value="2.7926454" unit="g/cm3"/>
  <comment> field wire center:      50 um Al (core), 0.3 um Ag (coating) </comment>
  <fraction n="0.98810714" ref="Al"/>
  <fraction n="0.011892860" ref="Ag"/>
</material>
<material name="DCH_FSideWireMat">
  <comment> 0.98516708*2.7 + 0.014832922*10.49 </comment>
  <D type="density" value="2.8155485" unit="g/cm3"/>
  <comment> field wires top/bottom: 40 um Al (core), 0.3 um Ag (coating) </comment>
  <fraction n="0.98516708" ref="Al"/>
  <fraction n="0.014832922" ref="Ag"/>
</material>
<material name="DCH_SWireMat">
  <comment> 0.97066175*19.28+0.029338250*19.3 </comment>
  <D type="density" value="19.280587" unit="g/cm3"/>
  <comment> sense wire:      20 um W (core), 0.3 um Au (coating) </comment>
  <fraction n="0.97066175" ref="W"/>
  <fraction n="0.029338250" ref="Au"/>
</material>
```

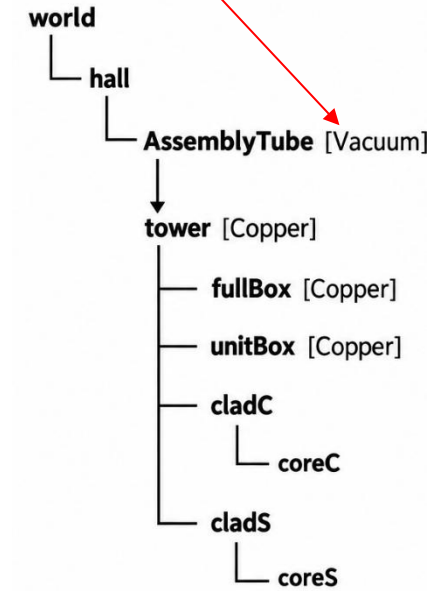
Ratio: fixed/legacy for W20 baseline at eta=0
sense = 1.00000
field_side = 1.06615
field_central = 1.05389
Total DCH ~ +1.002285

Ratio: fixed/legacy for 25CF+2.227Au at eta=0
sense = 2.5
Total DCH ~ 1.036

Issue in DRCalo and Geant4

G4 and DDRec stopped here

- All other subdetectors are seen properly by geant4 over their expected radii
- G4 and DDRec/MaterialManager see vacuum for the entire DRCalo range
- TGeo does see the copper towers of the Calo assembly
 - But mixing backends was deemed not appropriate for this study
 - A full TGeoNavigator/FindNode material budget could be possible once all other structures are validated



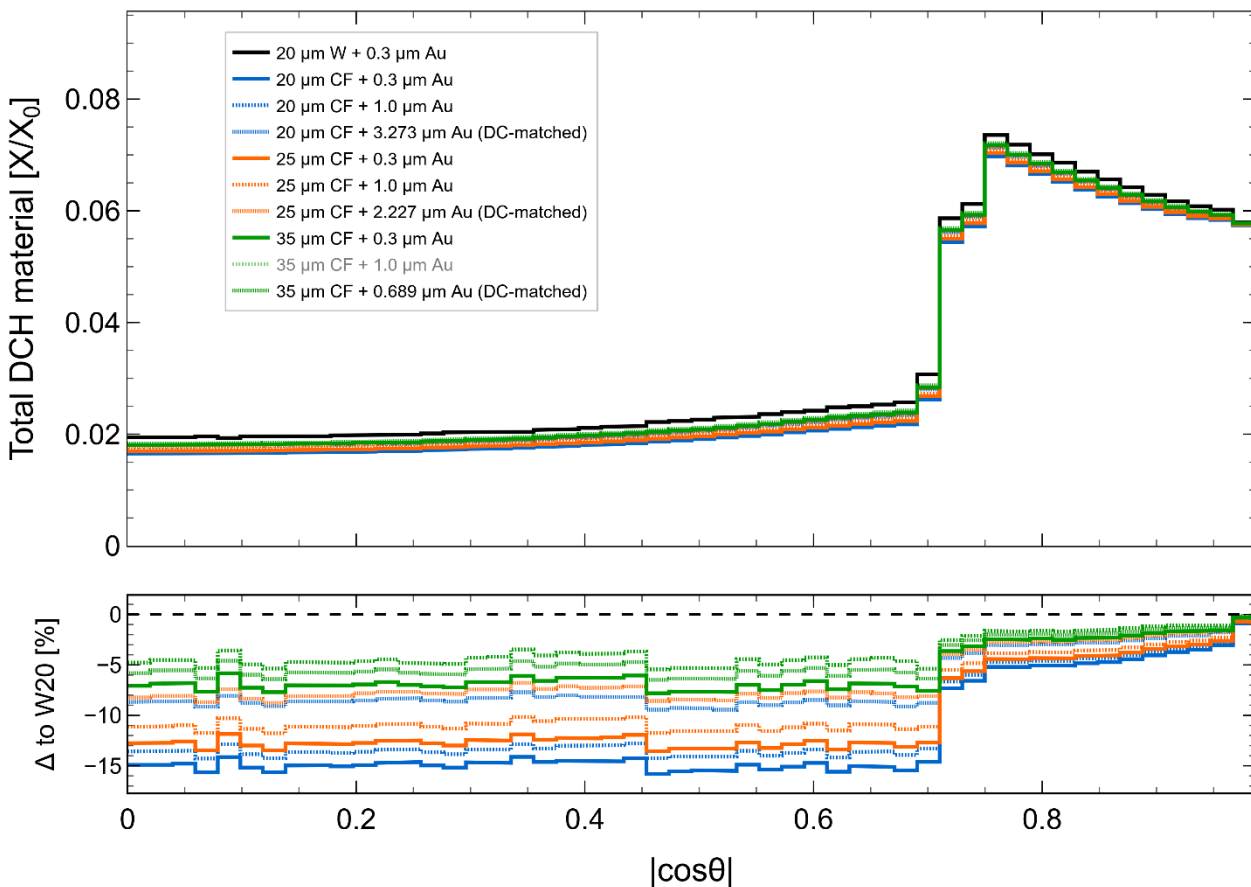
DCH and Tracker Material Budget Overlays

DCH-only

CFDCH

FCC-ee IDEA simulation

Simulation

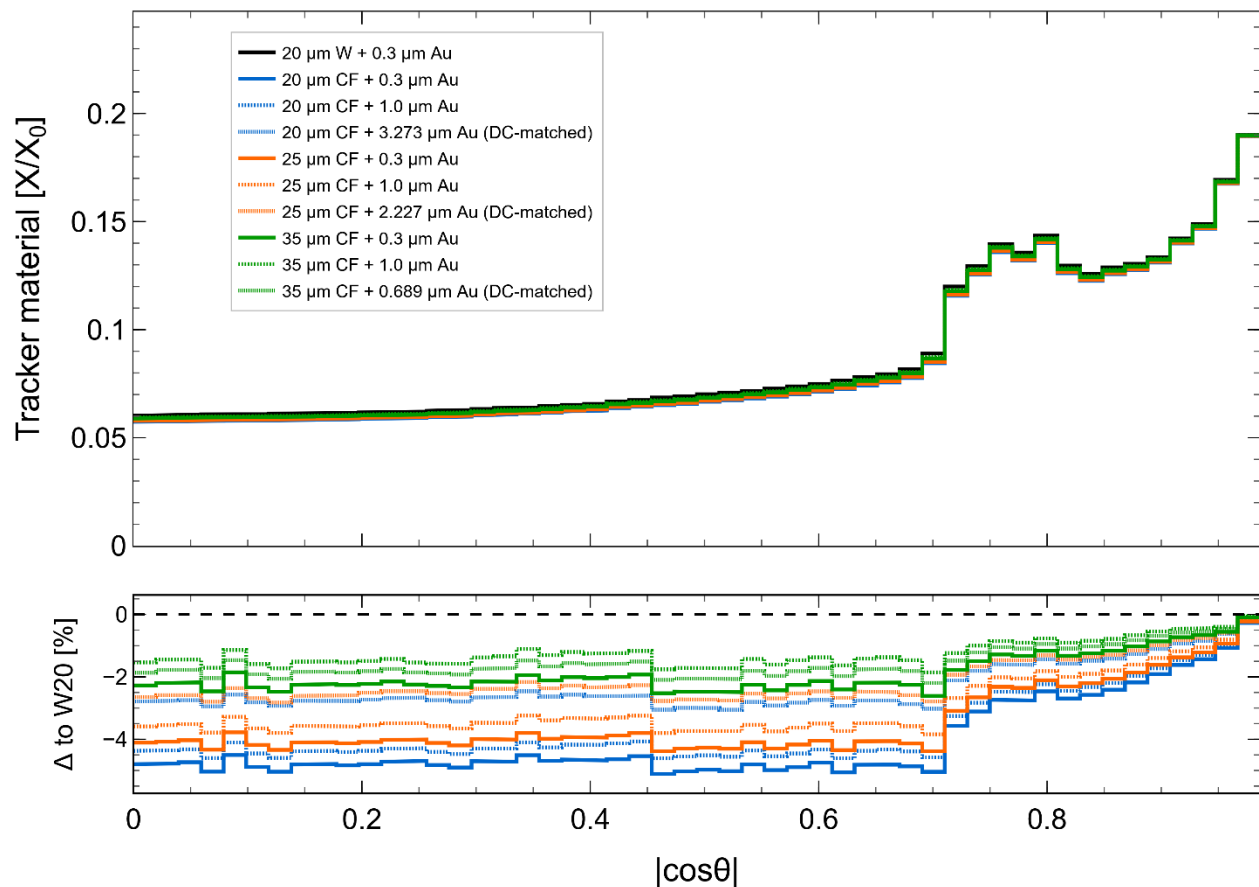


Full Tracker

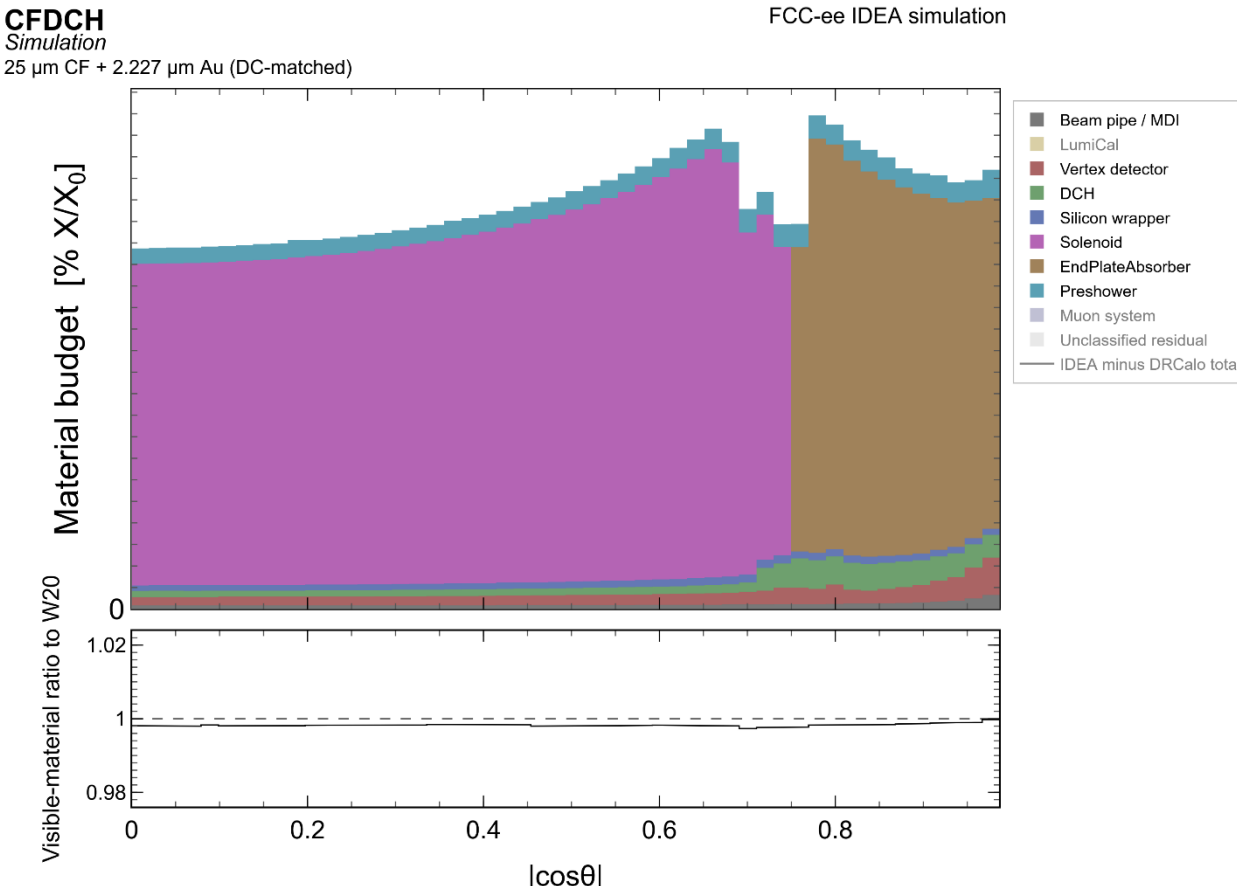
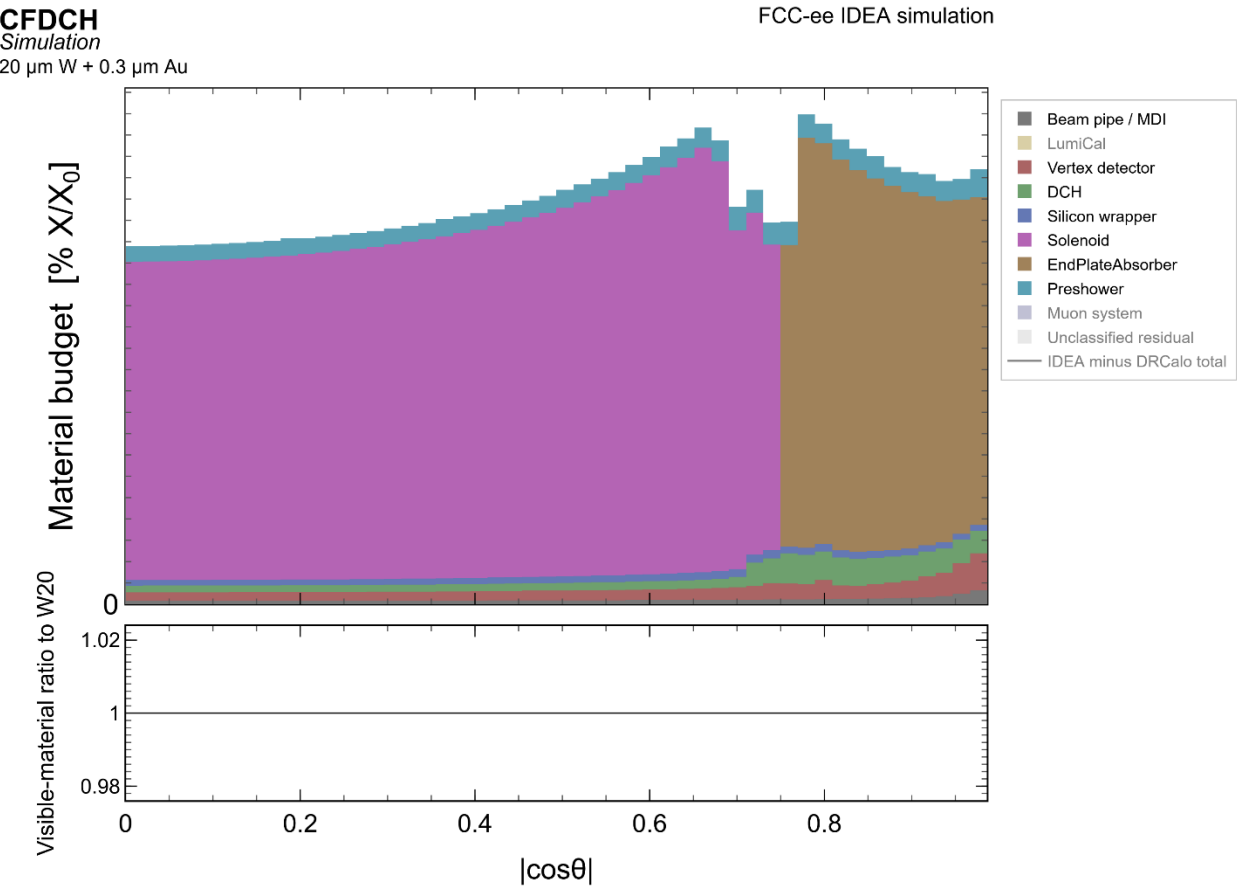
CFDCH

FCC-ee IDEA simulation

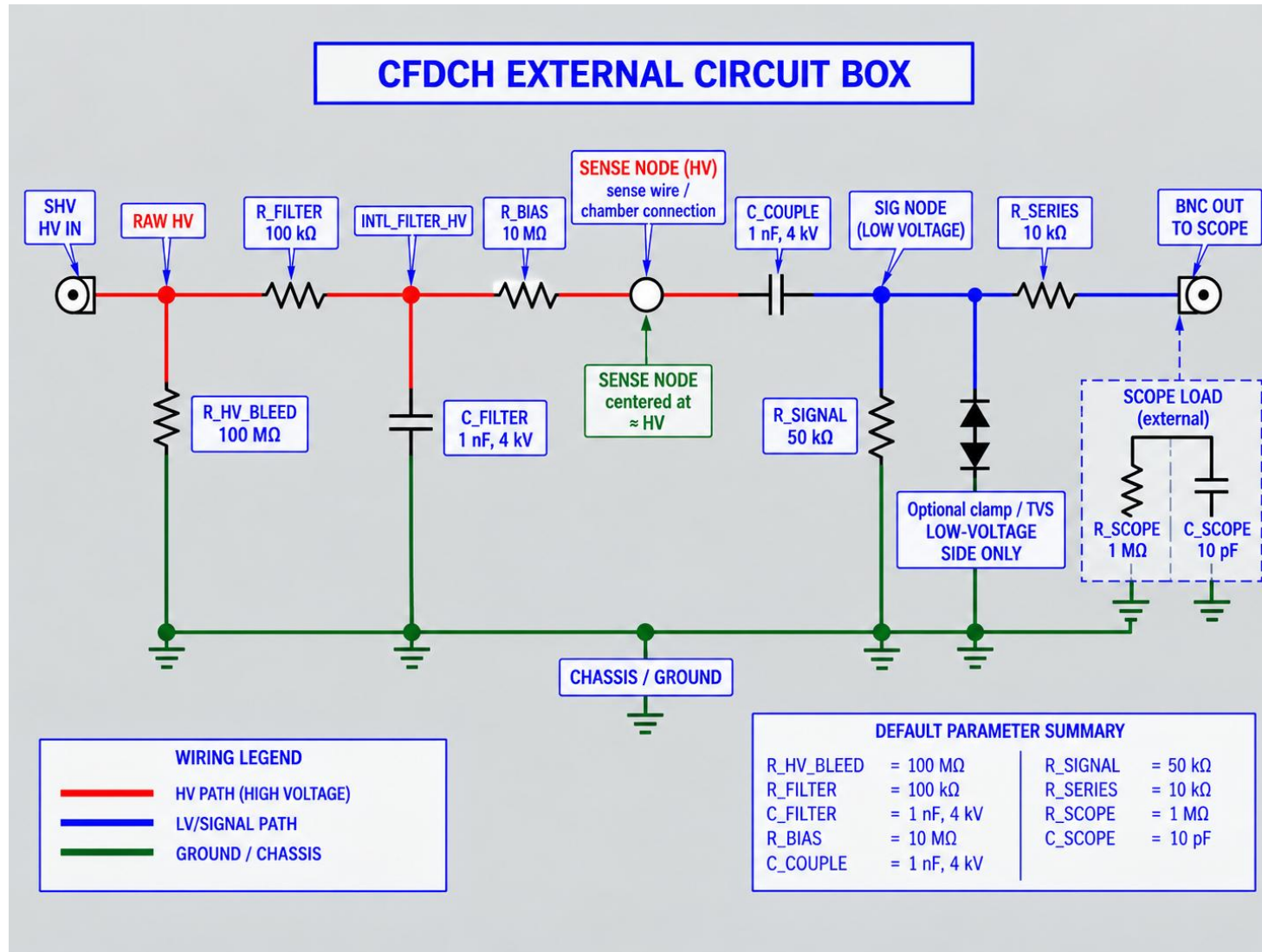
Simulation



Whole IDEA plots

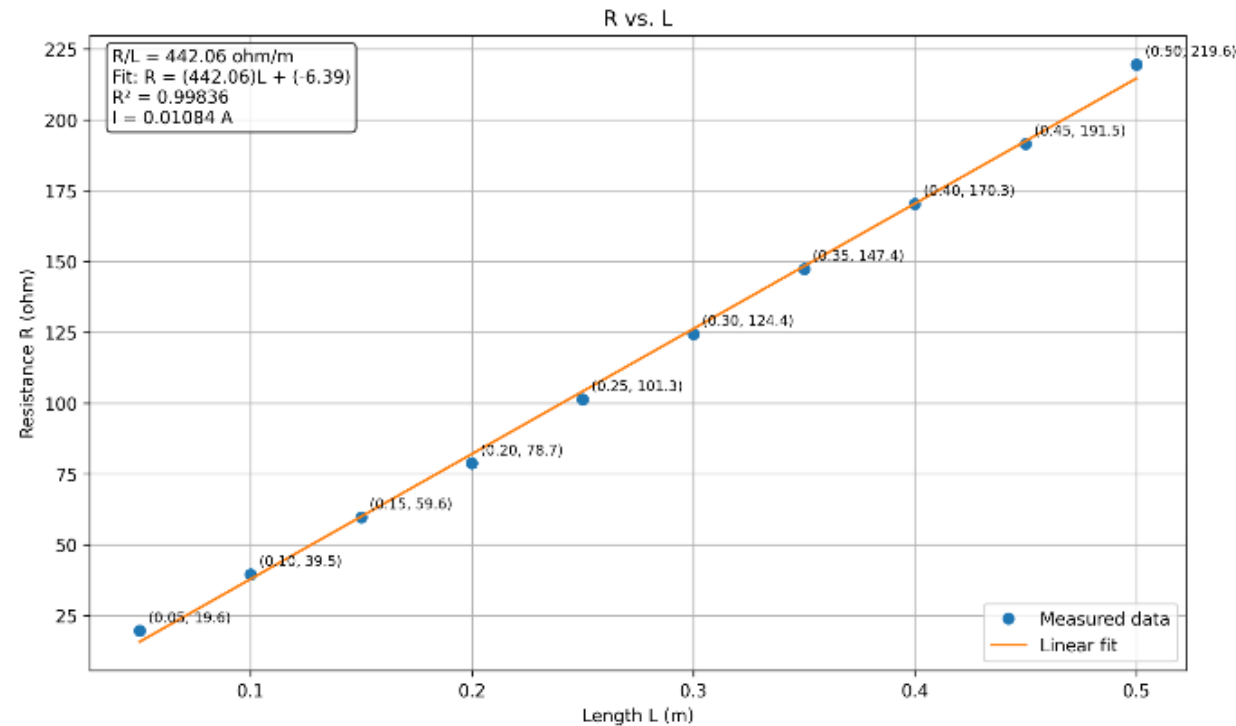


External Circuit Box Chosen Values



Current Wires

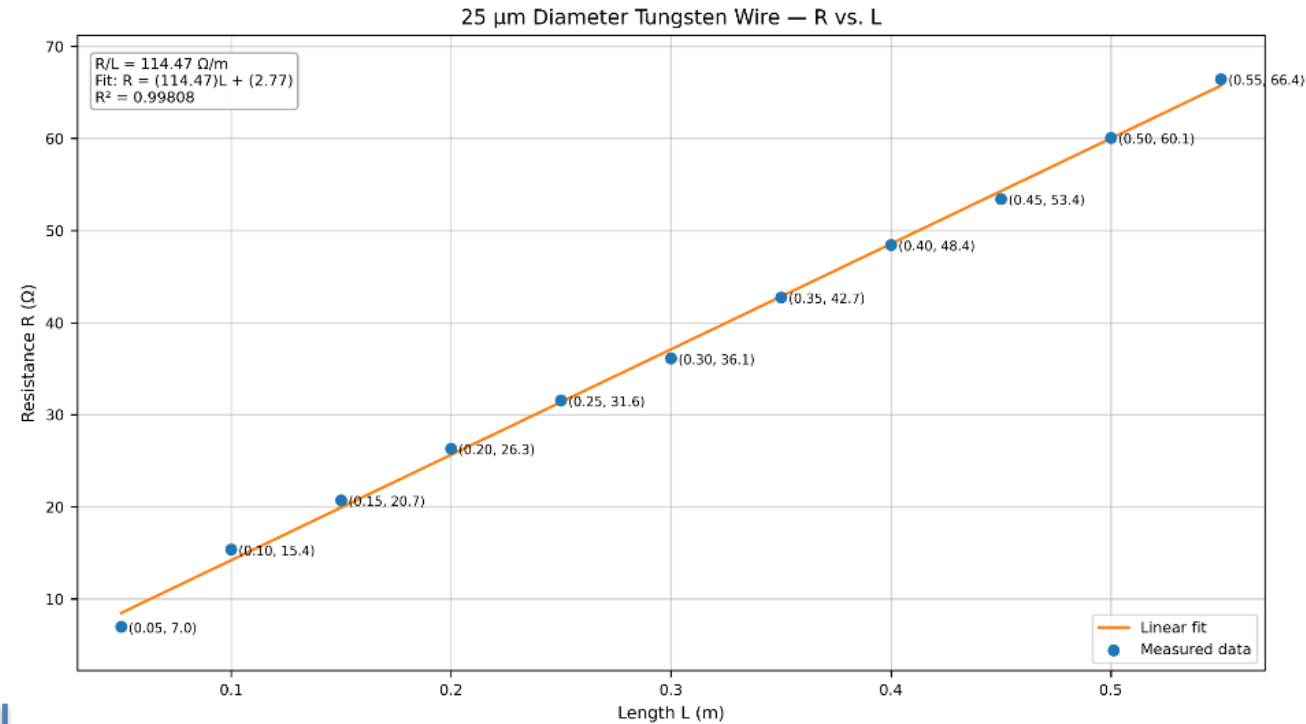
25 μm Dexmat uncoated Carbon Fiber



Issues:

- Manufacturer stated cross section is oblong with 20 to 45 μm diameter depending on orientation.
- Coating remains a major challenge

25 μm uncoated Tungsten



Serving as our “control” for how a metal wire should perform under the same conditions.