FCC week summary and next Steps

May 11th 2016

W. Riegler

Presenters at the Rome FCC meeting:
Martin Aleksa, Ilaria Besana, Sergei Chekanov, Dmitri Denisov, Zbynek Drasal, Benedikt Hegner, Clement Helsens, Julia Hrdinka, Ashutosh Kotwal, Matthias Mentink, Dave Newbold, Estel Perez, Walter Snoeys, Ian Shipsey, Hans Kristian Soltveit, Herman Ten Kate, Marianna Testa, Georg Viehhauser, Anna Zaborowska,

Baseline Parameters for the FCC-hh Machine

5 year long operation periods

- 3.5 years operation periods with
- 1.5 year shutdown

2 periods at baseline parameters (10 yrs) Phase1

- Peak luminosity $5x10^{34}cm^{-2}s^{-1}$, 25ns, pileup 170
- Total of $2.5ab^{-1}$ (per detector)

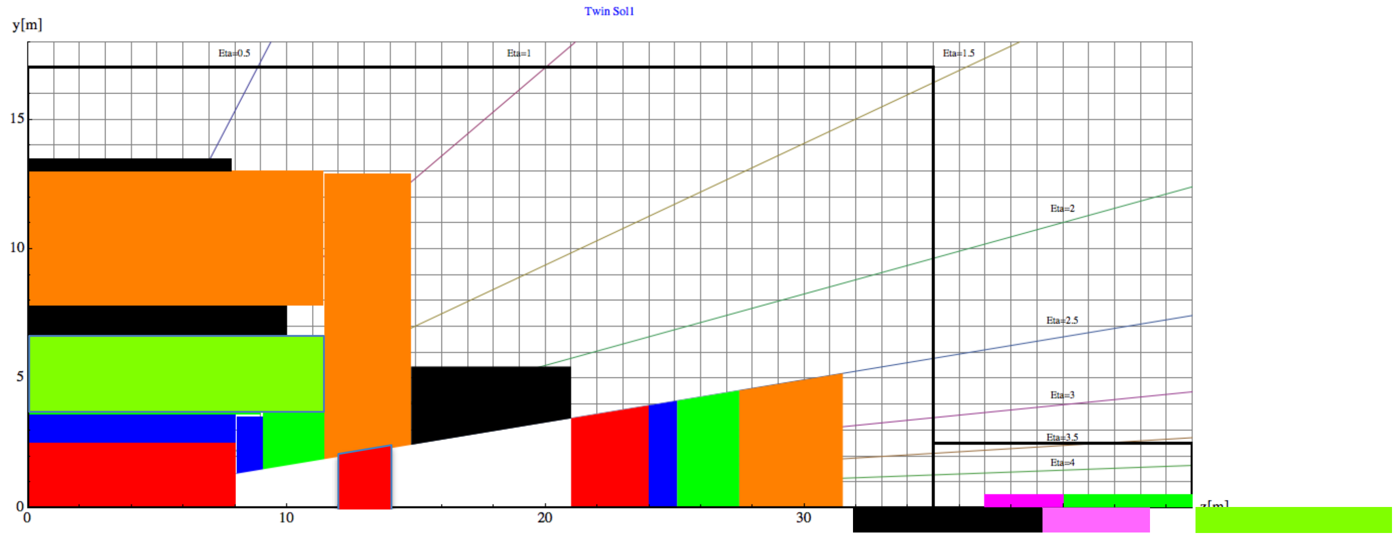
3 periods at ultimate parameters (15 yrs) Phase 2

- Peak luminosity <=$30x10^{34}cm^{-2}s^{-1}$, **25(5)ns, pileup 1020(204)**
- $5ab^{-1}$ per period total of $15ab^{-1}$

→ **Although some of us are confident about prospects of being able to deal with high pileup, the 5ns option should be considered 'at least with equal priority' as 25ns.**

→ **The transition from Phase1 to Phase2 luminosity is not related to major hardware changes in the accelerator, so it may be continuous. Important aspect for experiment strategy.**

Baseline Geometry used up to now , Twin Solenoid, 6T, 12m bore, 10Tm dipole



Barrel:

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R= 3.6m → dR= 1.1m

HCAL available space:
R= 3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R= 6m to R= 7.825 → dR = 1.575m, L=10.1m

Muon available space:
R= 7.825m to R= 13m → dR = 5.175m
Revision of outer radius is ongoing.

Coil2:
R=13m to R=13.47m → dR=0.475m, L=7.6m

Endcap:

EMCAL available space:
z=8m to z= 9.1m → dz= 1.1m

HCAL available space:
z= 9.1m to z=11.5m → dz=2.4m

Muon available space:
z= 11.5m to z= 14.8m → dz = 3.3m

Forward:

Dipole:
z= 14.8m to z= 21m → dz=6.2m

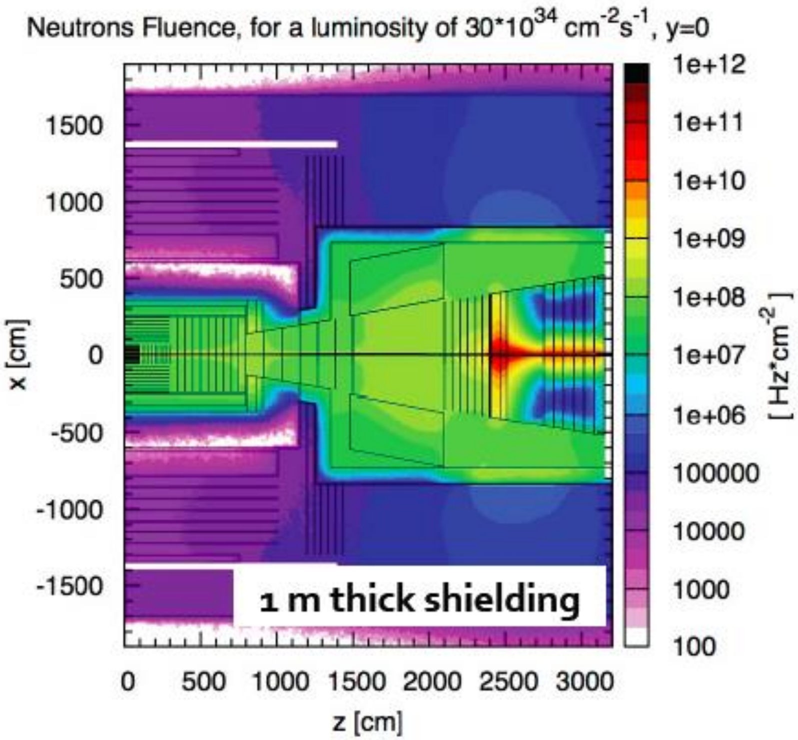
FTracker available space:
z=21m to R=24m, L=3m

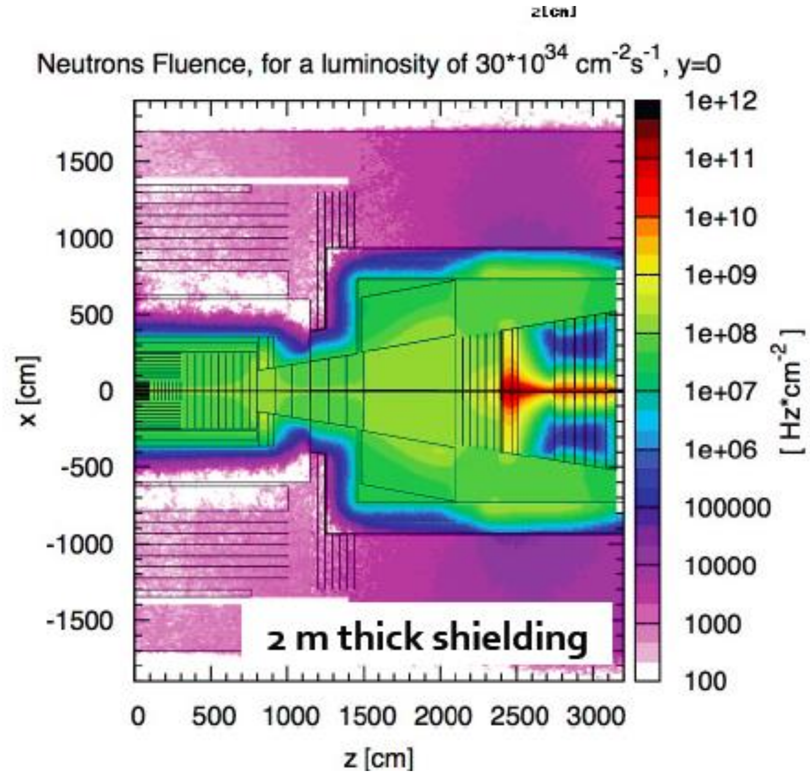
FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

FMuon available space:
z= 27.5m to z=31.5m → dz=4m

Radiation Calculations



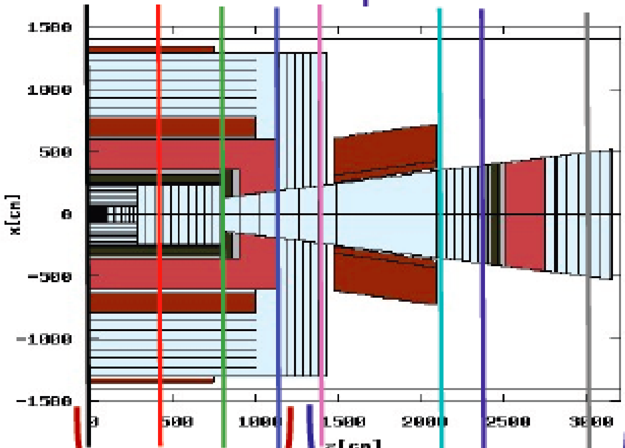


In the central tracker, close to the beampipe, the radiation is dominated by the primary hadrons.

In the forward tracker there is in addition a significant neutron flux from the calorimeter.

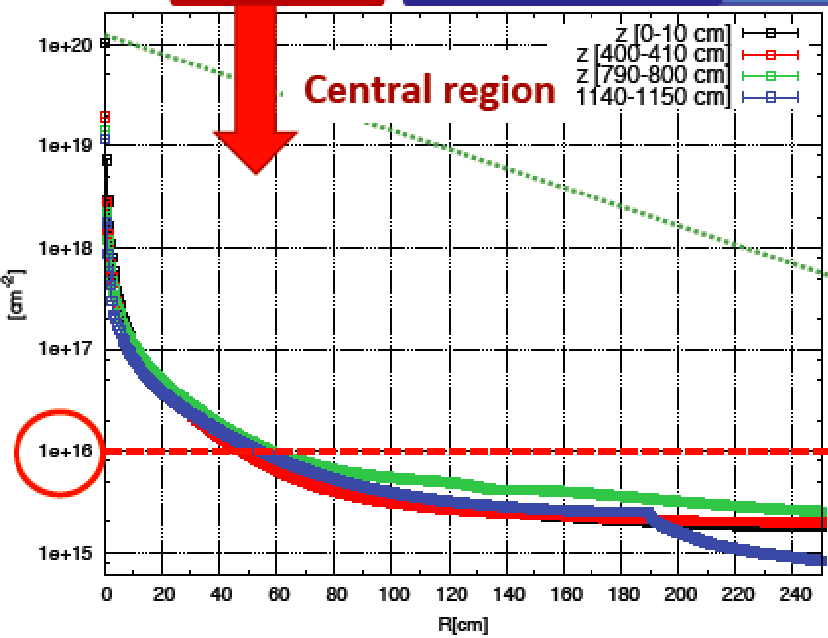
Radiation Calculations

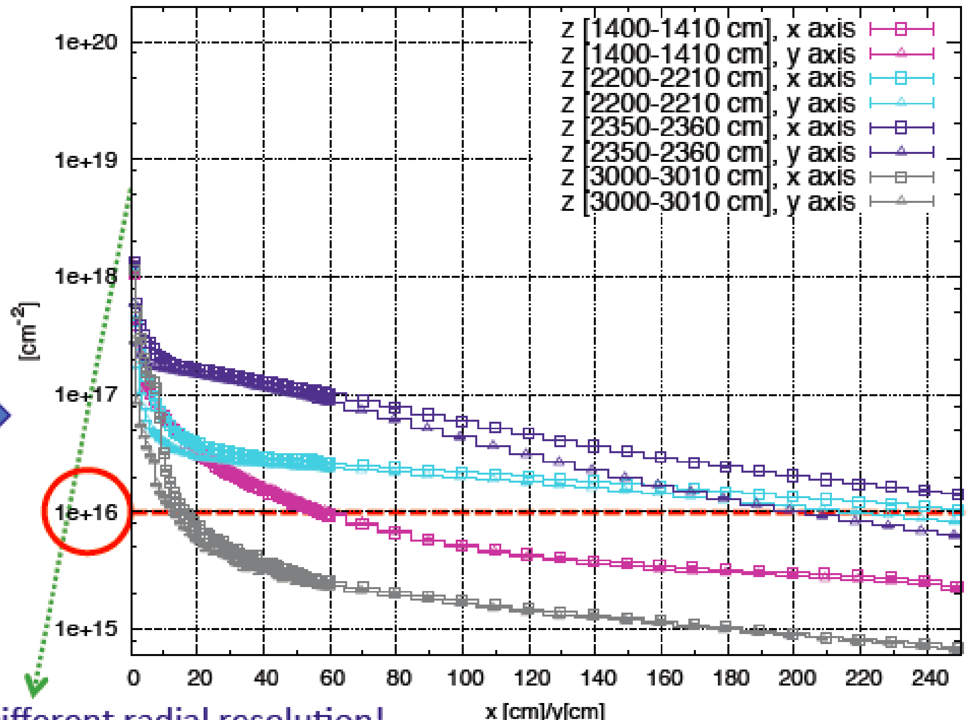
1 MeV neutron equivalent fluence vs R at different z positions **in the tracker:**



Forward region

Central region





Different radial resolution!

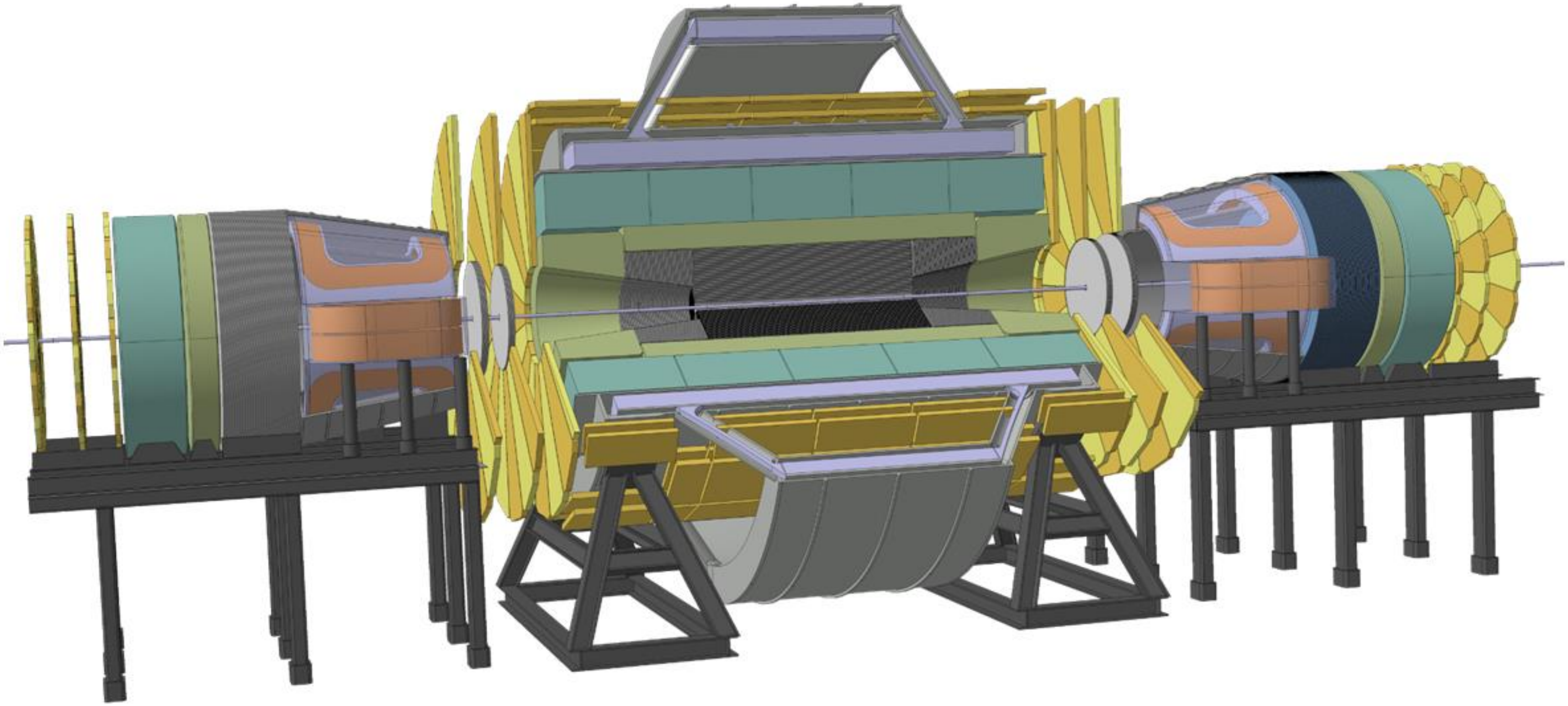
For radii < 50 cm the fluence exceed the value expected at HL-LHC (10^{16} cm^{-2}) by up to 2 orders of magnitude → Technology challenge!

Fluence is even higher close to forward calorimeter: at z= 23.5 m the fluence vs x > 10^{16} cm^{-2} for x<2.5 m

Note: For 10^{16}-10^{18} cm^{-2} the sensor technology does not yet exist

Ilaria Besana

Twin Solenoid 6T, 12m bore, Dipoles 10Tm



Herman Ten Kate, Matthias Mentink

Development of 'Detector Baseline'

Considering that the experiment cost should be a reasonable fraction of the accelerator cost one could naively assume a very large budget for the detectors.

The magnet group studied the 6T, 12m bore, 10Tm dipole as engineering challenge.

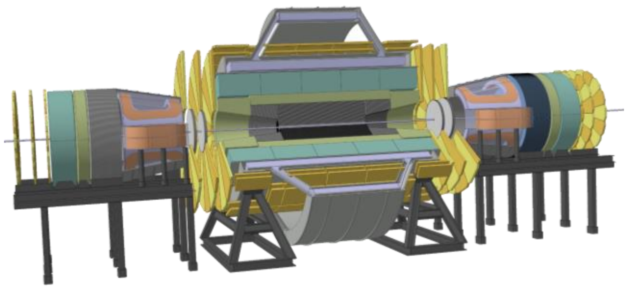
This geometry allows comfortably a 2.4m tracker cavity, 2.4m HCAL for 12 lambda.

Considering that such a magnet system costs on the order of 0.7-0.9 BEuros, and that for a reasonable balance the magnet system should represent between 20-30% of the detector cost, we are talking about a multi Billion cost for such a detector.

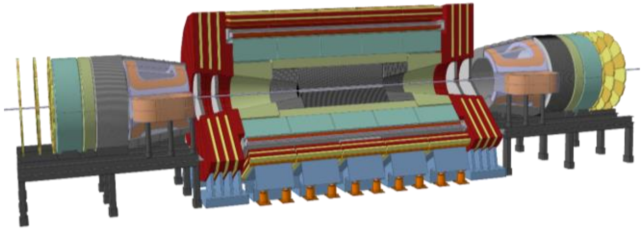
Scaling down the magnet system to 4T/10m and 4Tm dipoles reduces the cost by about a factor 2 to 0.35 to 0.45 BEuros, which brings the detector cost closer towards the 'one Billion' range.

We should therefore think about a more realistic baseline for the 2018 report.

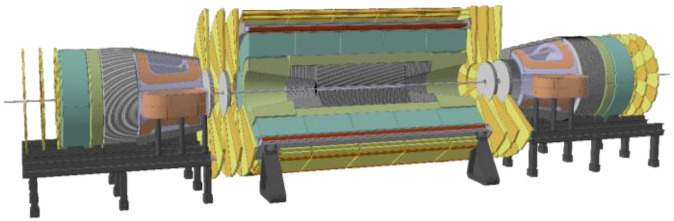
Magnet systems under consideration



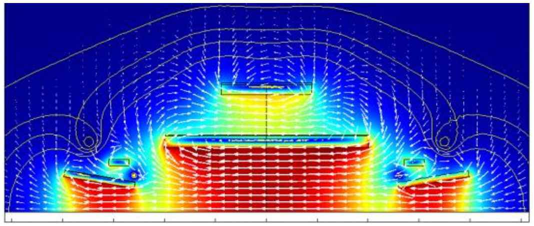
Twin solenoid with dipoles
(min. shaft diameter 27.5m)



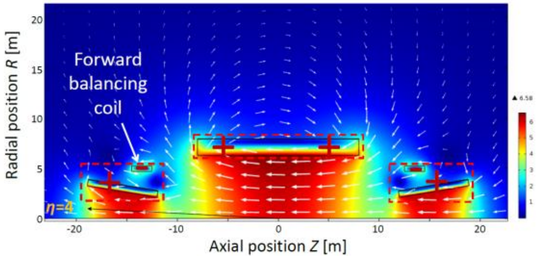
Partially shielded solenoid with dipoles



Unshielded solenoid with dipoles
(min. shaft diameter 16.3m, if rotated under ground)



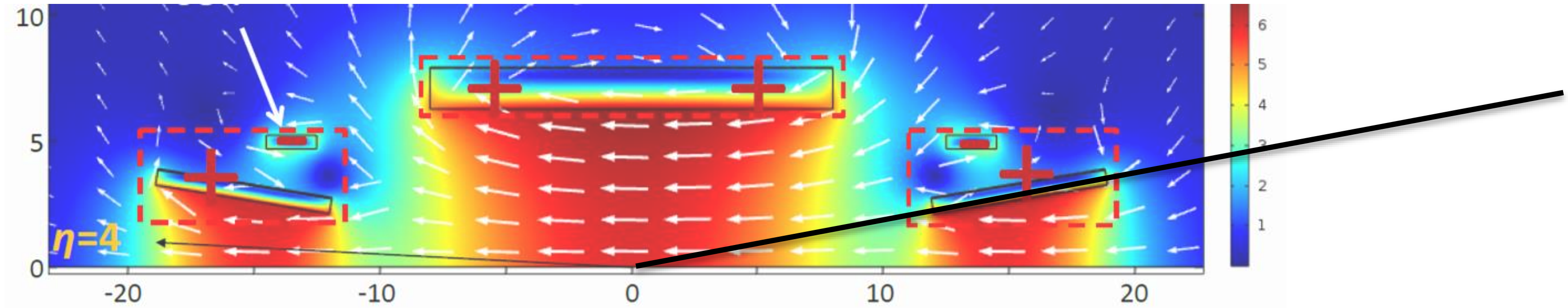
Twin solenoid with balanced conical solenoid

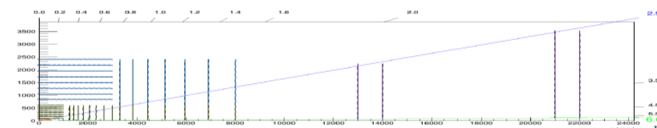


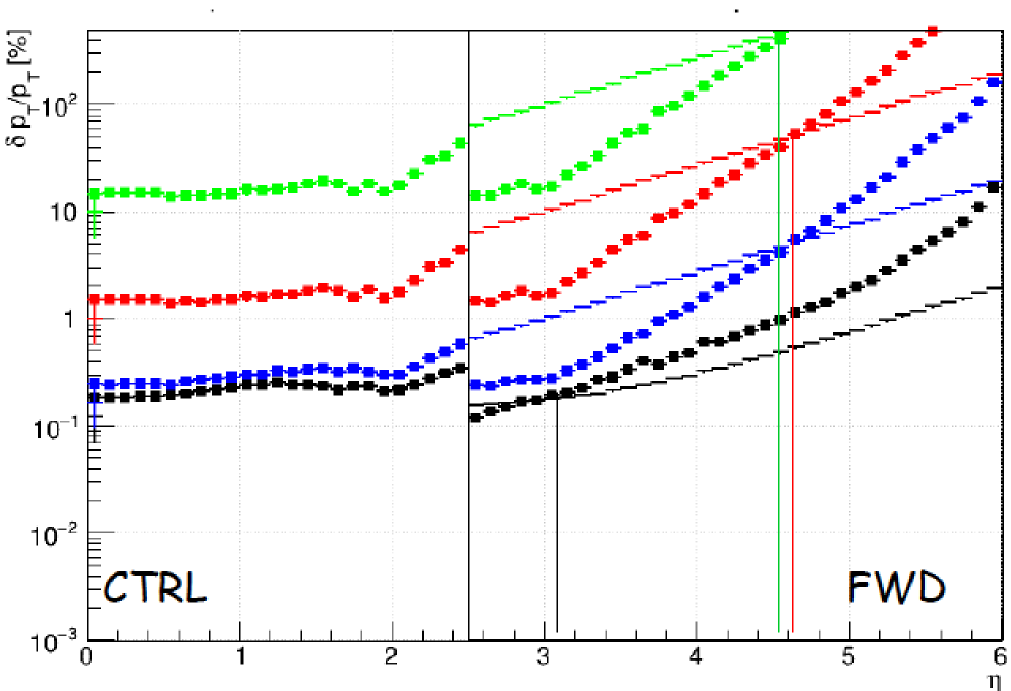
Unshielded solenoid with balanced conical solenoid

Herman Ten Kate, Matthias Mentink

Tracking Resolution for Dipole and Solenoid







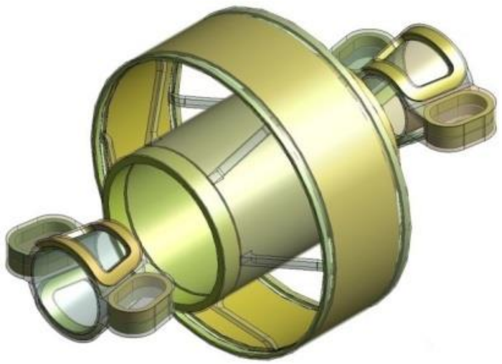
Simulated p_T:

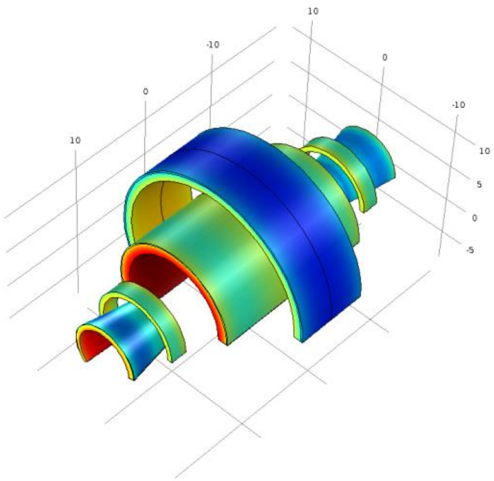
- 10 GeV
- 100 GeV
- 1 TeV
- 10 TeV

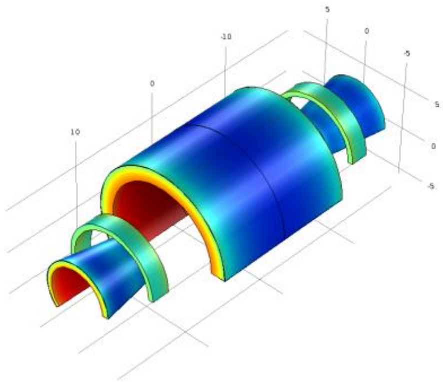
■ solenoid

– dipole

Advantages of a Forward Solenoid





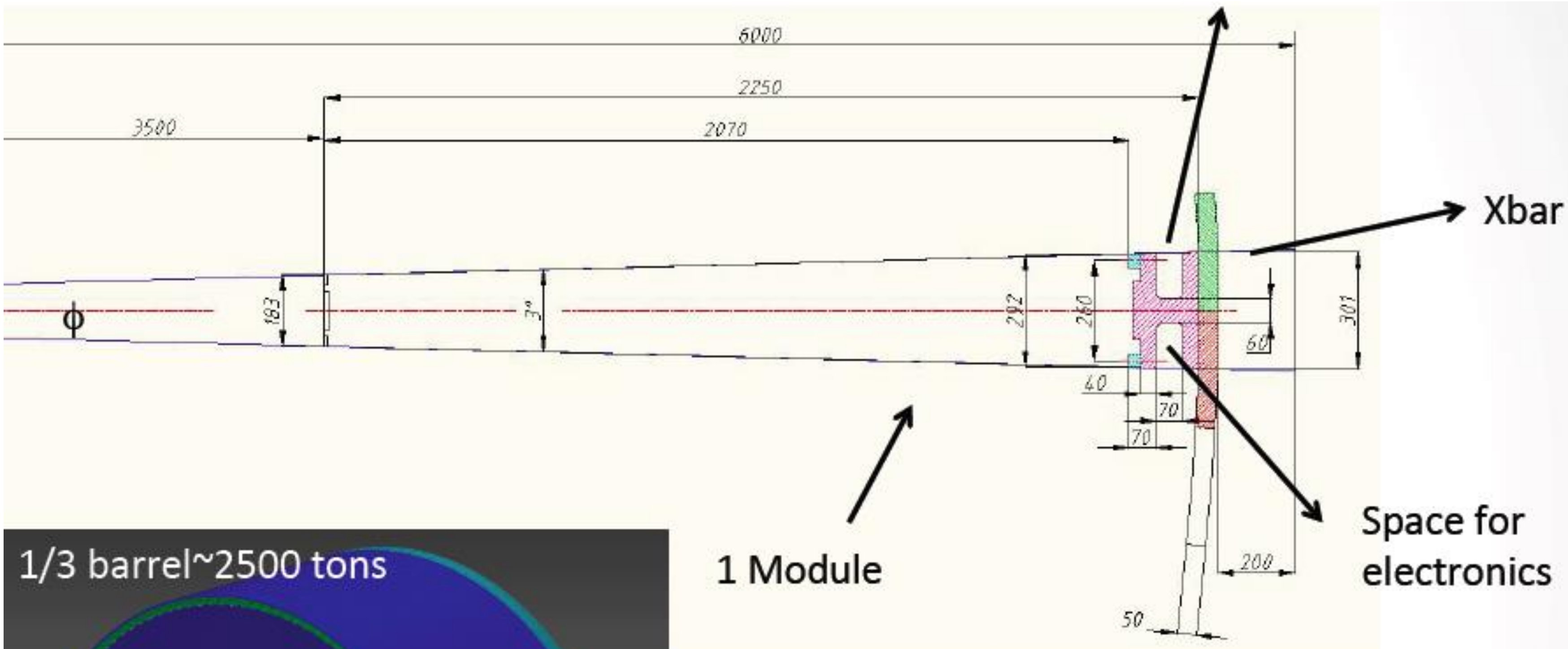


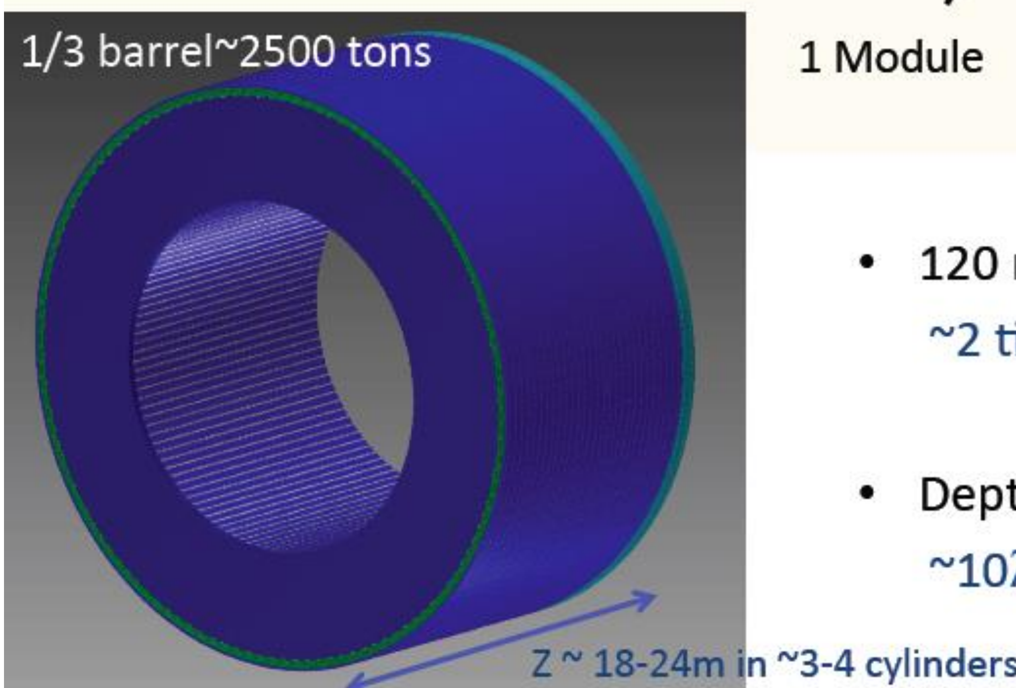
→ **Construction is easier**
→ **No need for compensation in the machine**
→ **Keeping the rotational symmetry is a big advantage (Missing E_T etc.)**

Some more performance parameters have to be understood before deciding on the 'reference design'.

Herman Ten Kate, Matthias Mentink

HCAL Studies





- 120 modules in ϕ,
  ~2 times better than ATLAS

- Depth active cells
  ~10λ -> ~2m (+29% than ATLAS)

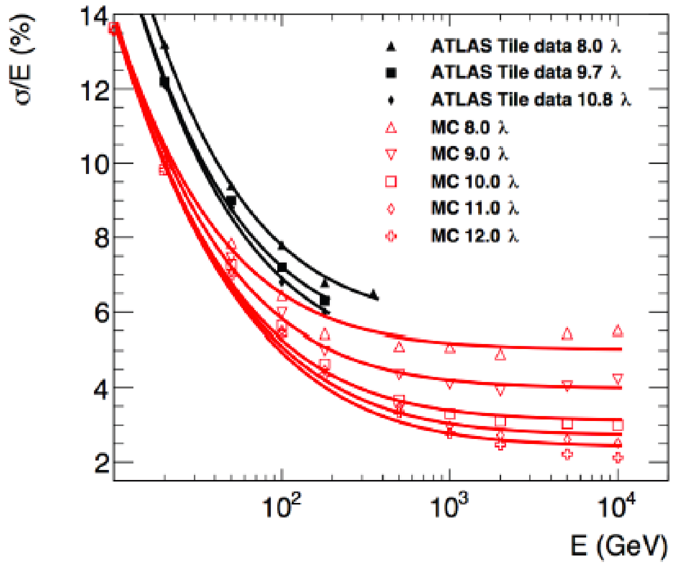
Clement Helsens

Calorimeter Studies

Single Pion E resolution

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

Assuming noise (b) = 0



- Single pion simulations
  - comparable with ATLAS test-beam data
- By increasing the depth of the calorimeter
  - we reduce the constant term
- Energy resolution achievable
  - at 12 λ: $\sigma_E/E \sim 43\%/\sqrt{E} \oplus 2.4\%$

	Simulation				Data			
	Sigma		RMS		Sigma		RMS	
Depth (λ)	a (%GeV$^{1/2}$)	c (%)	a (%GeV$^{1/2}$)	c (%)	a (%GeV$^{1/2}$)	c (%)	a (%GeV$^{1/2}$)	c (%)
8	41	5.0	42	6.9	52.9	5.7	-	-
9	43	4.0	43	5.3	-	-	-	-
10	43	3.1	45	4.0	49.8	5.2	41.1	5.6
11	43	2.7	45	3.4	50.3	4.7	45.0	5.0
12	43	2.4	45	2.9	-	-	-	-

HCAL concept 13/04/2016

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Clement Helsens

Common Detector Technologies

Comments on Future of MAPS

Optimization of power consumption will be essential to profit from single point resolutions of 5 μm or even better, which can be achieved even on thin sensitive layers:

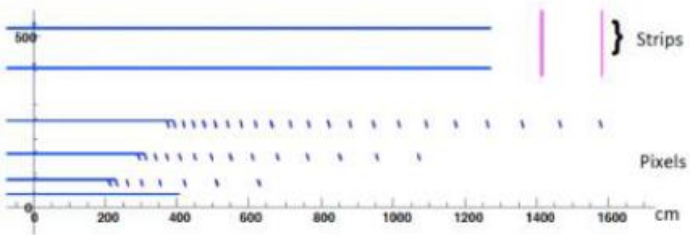
- Thin layers to contain sensor leakage
- Low C to reduce or eliminate analog power (C < 1fF ?)
- No clock distribution and special hit-driven architectures for low digital power
- Efficient data transmission

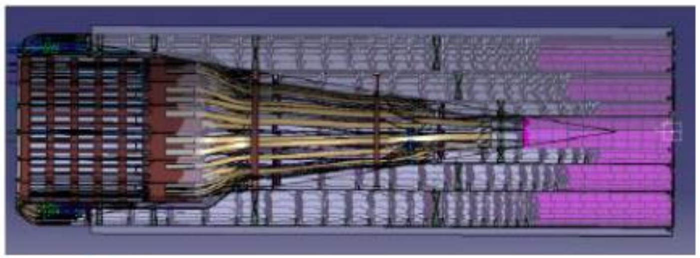
Monolithic CMOS detectors (or advanced hybrid) offering low mass, high granularity, low cost wafer-scale integration, are an excellent candidate for FCC.

Making significant progress on this in advanced CMOS technologies requires sufficient funding for submissions in the R&D phase.

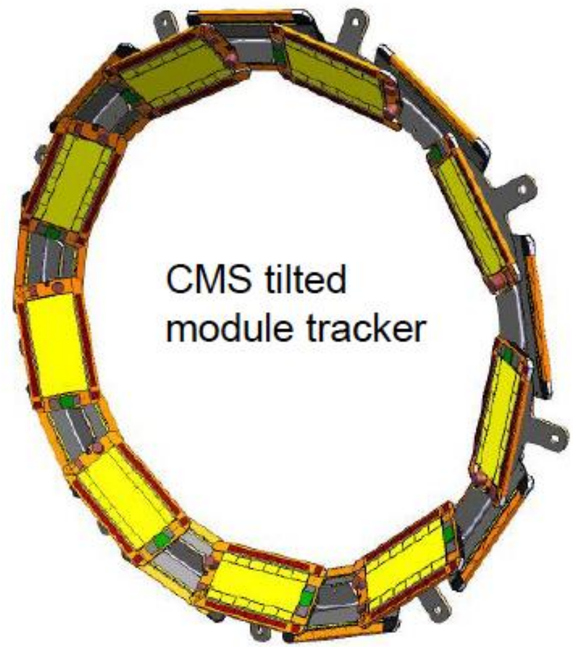
Did not mention many developments, like LGAD, DEPFET, etc

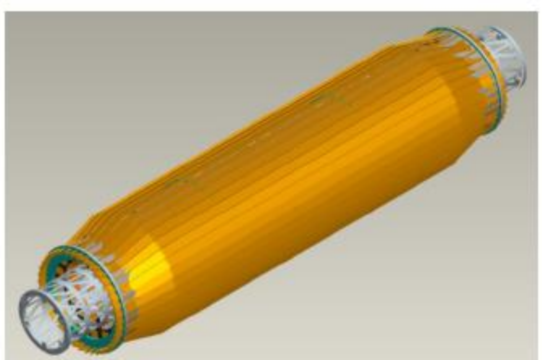
Tracker Mechanics





ATLAS Alpine pixels





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ATLAS I-beams with tilted ends

We should study alternatives to the traditional tracker layouts.

Georg Viehhauser

Q: 'Can we build an FCC-hh GPD with triggerless readout?'

- A: 'No'
  - Recording the full data stream is inconceivable even in 203x
  - But 'trigger' may mean something different to today

- First rough estimates (within factor of two)
  - Tracking and calo *each* have raw data rates of ~2000TB/s
  - Using 10Gb/s modularity links, this is 4M optical fibres
    - Also implies an event-building network of 40Pb/s capacity
- For comparison:
  - 'Entire internet WAN' today is ~500Tb/s; largest Google data centre is ~1Pb/s
- A very scary number, even for 2035, but perhaps not impossible

Dave Newbold

Technology Issues

- How much power do rad-hard data links take?
  - 'Best in class' *today* seems to be lpGBT at ~500mW for 5Gb/s (plus laser)
    - If no progress on this, indicates a power budget of 2MW for links alone – infeasible
  - There are no commercial applications for these links, so no COTS
  - Technology will improve, but there are some fundamental limits
    - New ideas for power saving are coming forward, but may not be applicable for us
- What are the limits?
  - Electrical signalling places a fundamental limit of ~10mW per link
    - But Shannon's limit also mandates a move to PAM / FEC → more tx and rx power
    - ~10mW for 5Gb/s in lab with 'fancy technology' (high mass, expensive, not rad hard)
  - Reducing to this level would require substantial investment in R&D
    - Not clear when / if we will have access to the required technology nodes
  - The real limit is likely to be cost
    - Also bearing in mind that COTS rx ports are ~$100, and not decreasing
    - This implies aggregation onto fast (100Gb/s+) fibres from lower speed local links
- Cost & power budget of on-detector electronics is *the* problem

Dave Newbold

Possible Approaches

- 'Conventional trigger'
  - Extreme processor performance
  - On-detector primitives logic
  - On-detector front end buffers
  - Emphasis on on-detector processing
- 'Sequential readout'
  - Stage out event to multi-level trigger
  - Successive levels of details with time
  - All data through event-builder network
  - Trigger implemented in software
  - Implement large 'bulk memory' in low radiation zone of detector
  - Emphasis on on-detector buffer
- 'Triggerless'
  - Massive bandwidth
  - Little on-detector logic
  - Small front end buffers
  - Emphasis on data transmission

Dave Newbold

Science & Technology Facilities Council Rutherford Appleton Laboratory University of BRISTOL

Concluding Remarks

A lot of of progress since the last FCC week.

A few reality checks required rescaling of some ‘dimensions’.

The FCC hadron detector studies can heavily draw from the LHC experiments and their upgrade plans.

It is very important to plant the thinking about pp physics at 100TeV into the heads of people who work on the 14TeV physics analysis.

The FCC hadron detectors require significant R&D on detectors and electronics. Once the LHC Phase II R&D is finished, which is soon, we must install dedicated R&D programs.

Access to state of the art electronics processes for readout electronics and sensor (e.g. MAPS) is very expensive, so this R&D will require significant funding.

The FCC project is an excellent environment to transfer the vast amount of knowledge and experience in the field to the young generation.

How to proceed from here ?

We need a reference design for which we make a consistent study of magnet, performance, radiation levels, installation, machine detector interface, costing.

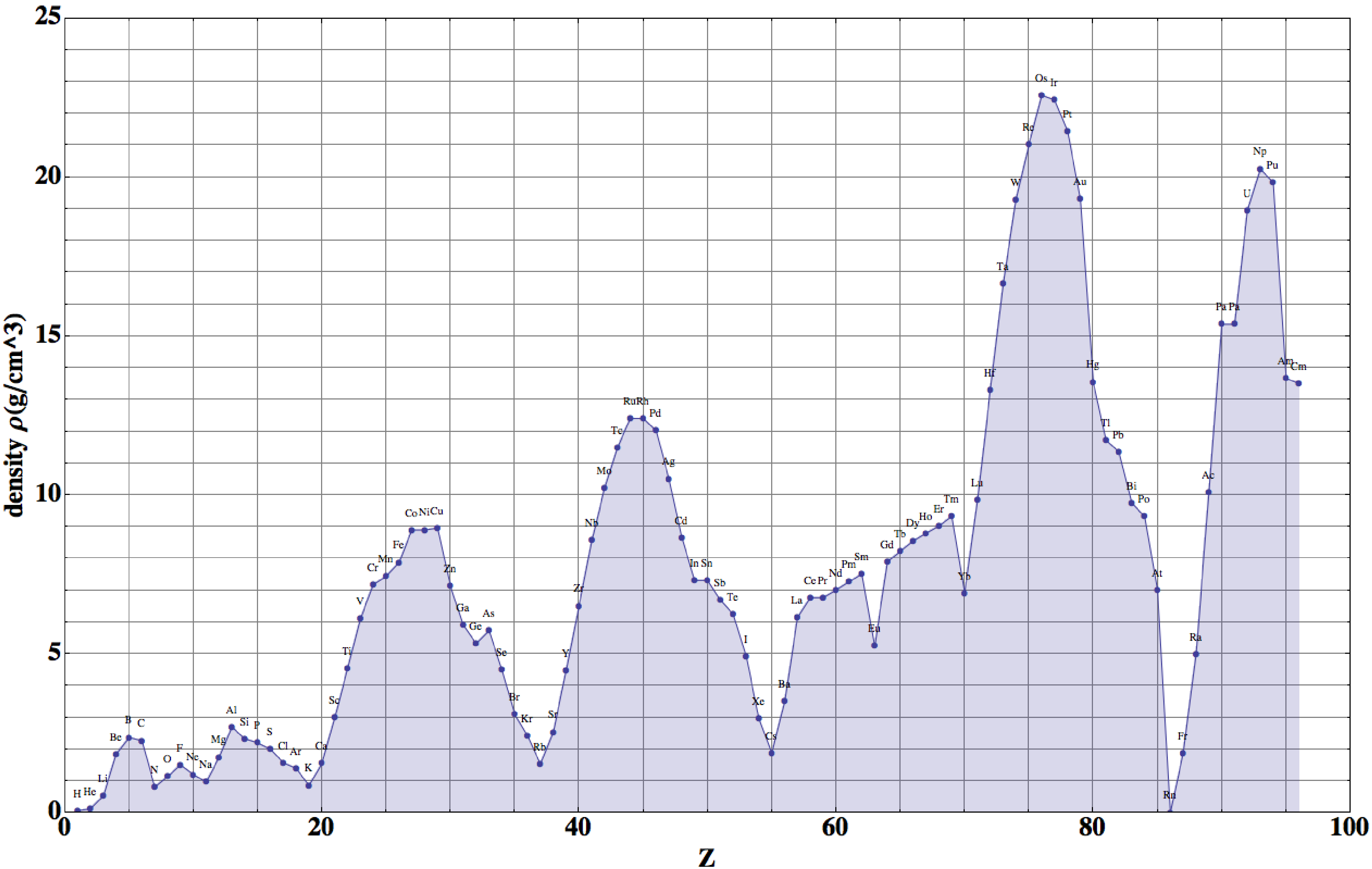
The physics studies with parametrized detector performance will of course vary the detector around this reference.

Possibly we need two reference designs to compare from the start some key differences.

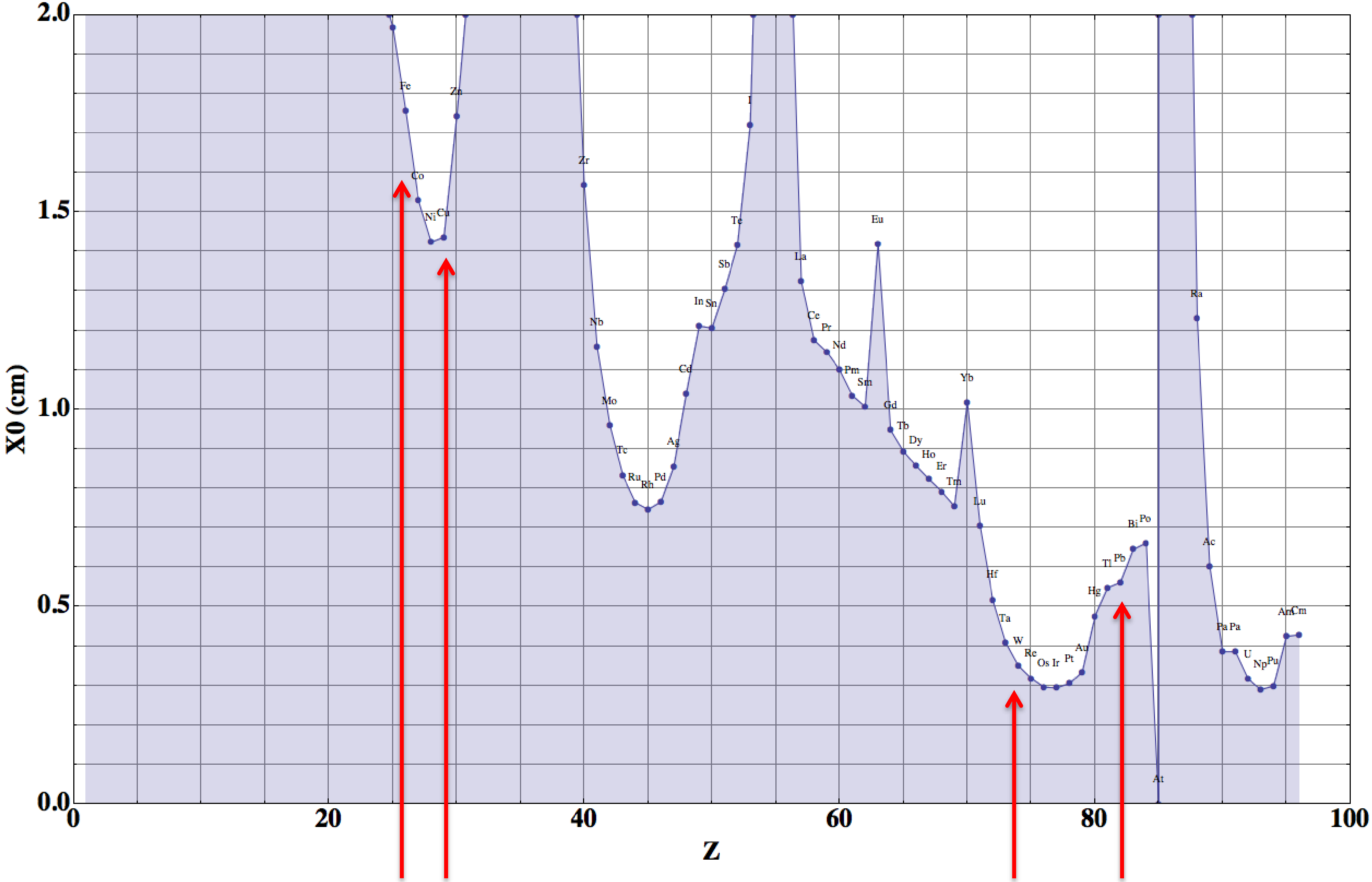
Definition of distribution of space between Tracker, ECAL, HCAL inside 5m bore are the prime consideration.

Some reminders on material properties:

Density

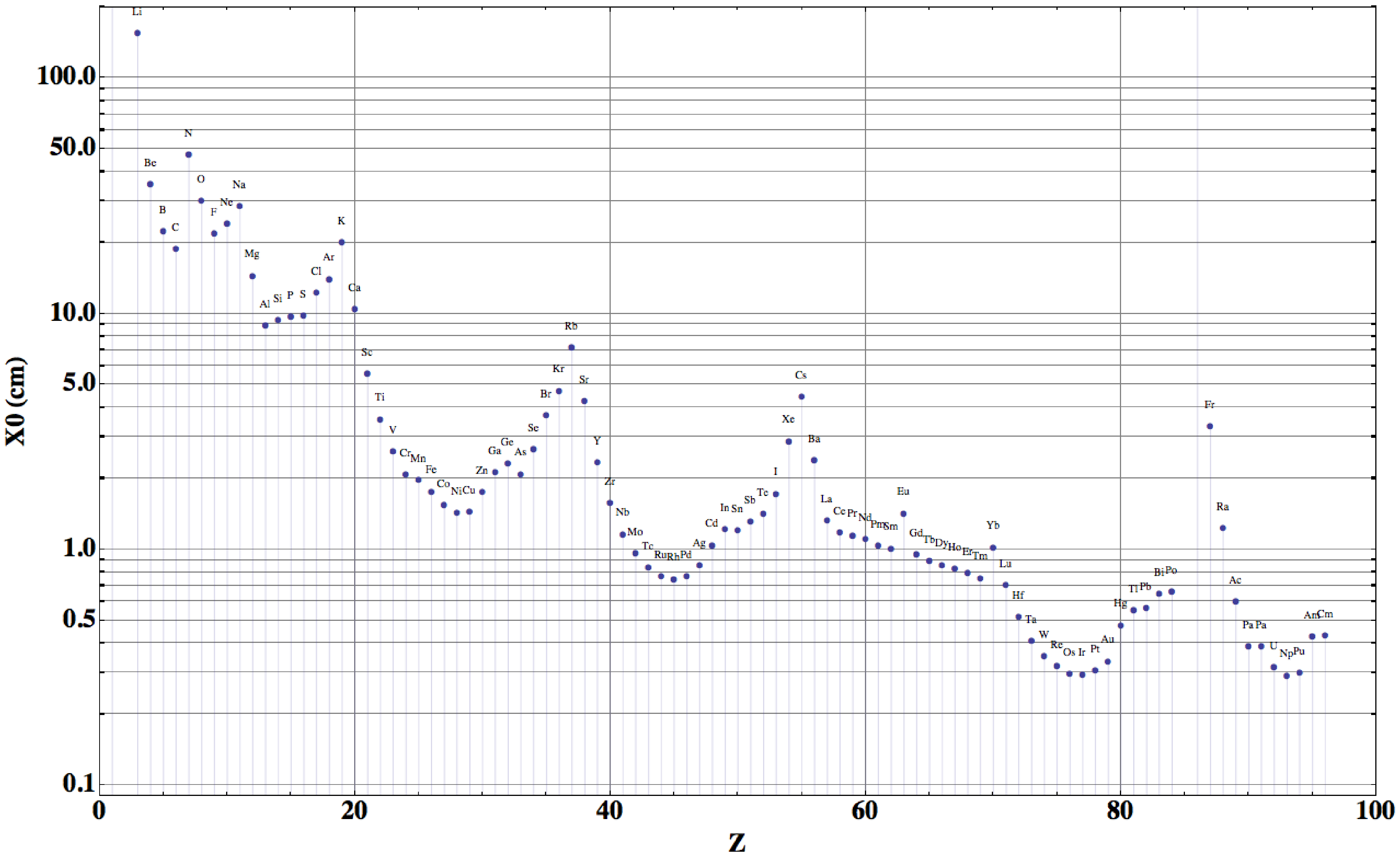


Radiation Length



Fe: 1.76cm Cu: 1.44cm W: 0.35cm Pb: 0.56cm

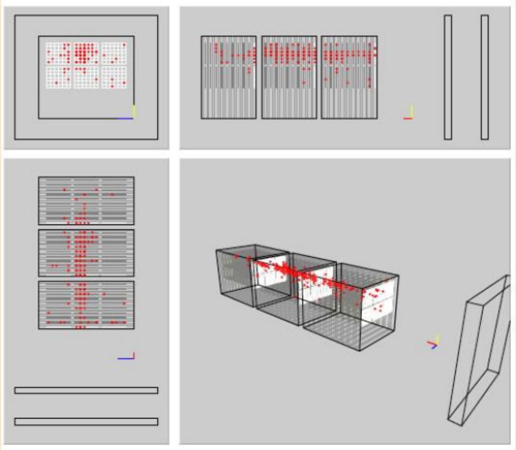
Radiation Length



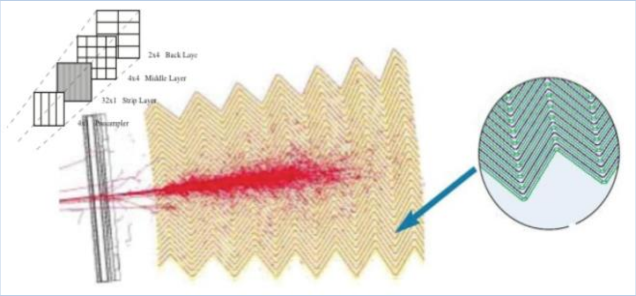
Some Examples

Si/W (CALICE type)

- 525µm Si (1x1cm^2), W absorbers with changing thickness t_{abs}, 30 layers
- e.g. testbeam module:
  - $t_{1\text{-}10}$=1.4mm, $t_{11\text{-}20}$=2.8mm, $t_{21\text{-}30}$=4.2mm
  - 24X_0 in 10cm thickness
  - a_{meas}=16.6%, c_{meas}=1.1%
- e.g. FCC barrel, 30X_0, 1λ (r=2.6m, Δr=12.5cm, length=16m):
  - 8000m^2 Si in barrel only (80M channels) in 30 layers
  - ≈30m^3 of W (≈600t) → 14MCHF for W (23CHF/kg)
  - **Challenging**: Huge surface Si sensors, many channels

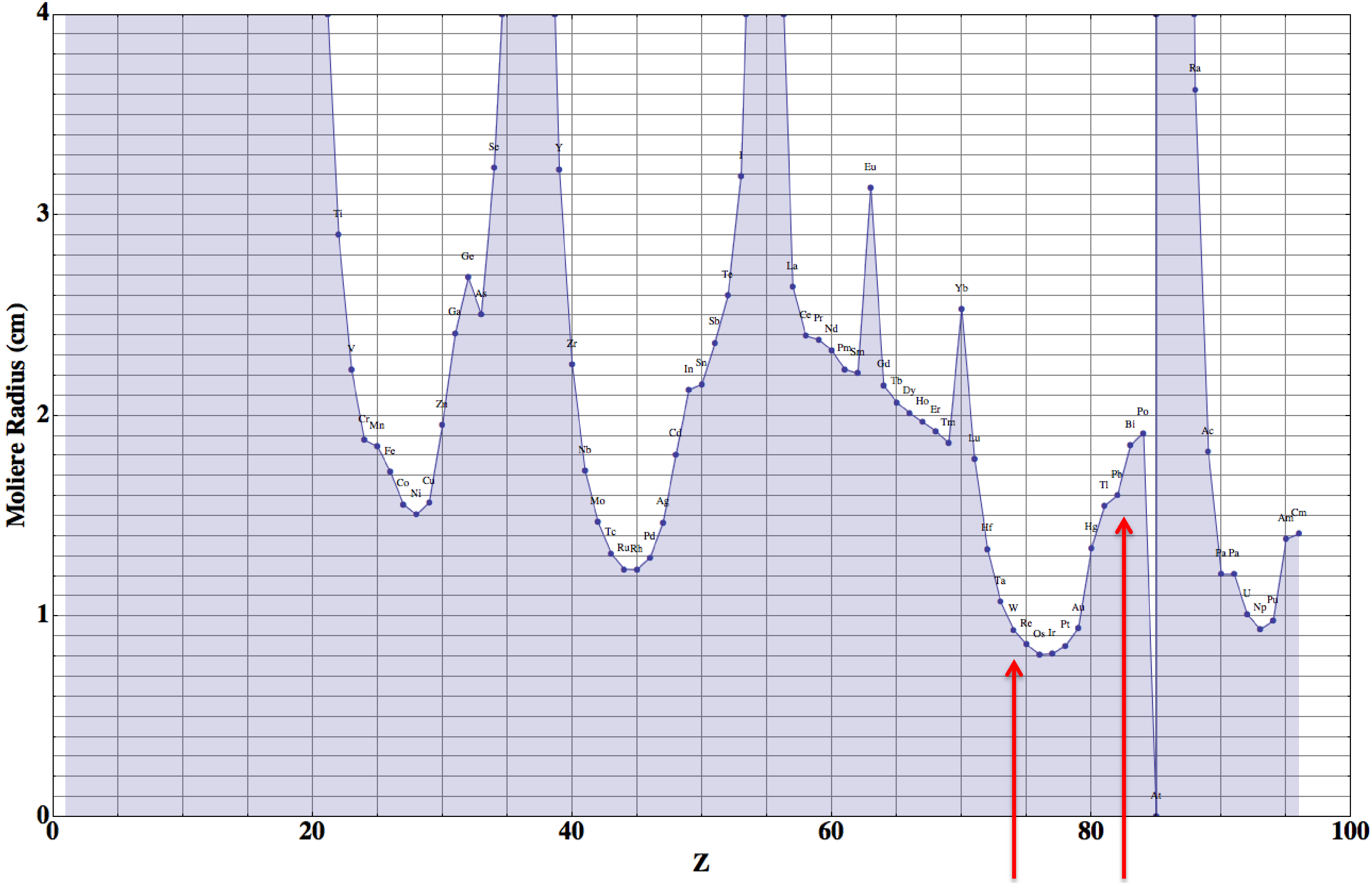


LAr/Pb (ATLAS type)



- 4mm LAr, 2mm Pb/steel absorbers
  - a_{meas}=10%, c_{meas}=0.7%
  - 22X_0 in 50cm thickness
- e.g. FCC barrel, 30X_0, 1.5λ (r=2.7m, Δr=60cm, length=16m):
  - ~500k channels (2x2 granularity with respect to ATLAS)
  - ≈45m^3 Pb (≈500t), ≈15m^3 stainless steel (≈120t), ≈120m^3 LAr (≈170t)
  - **Challenging**: Low-material cryostat and feed-throughs!

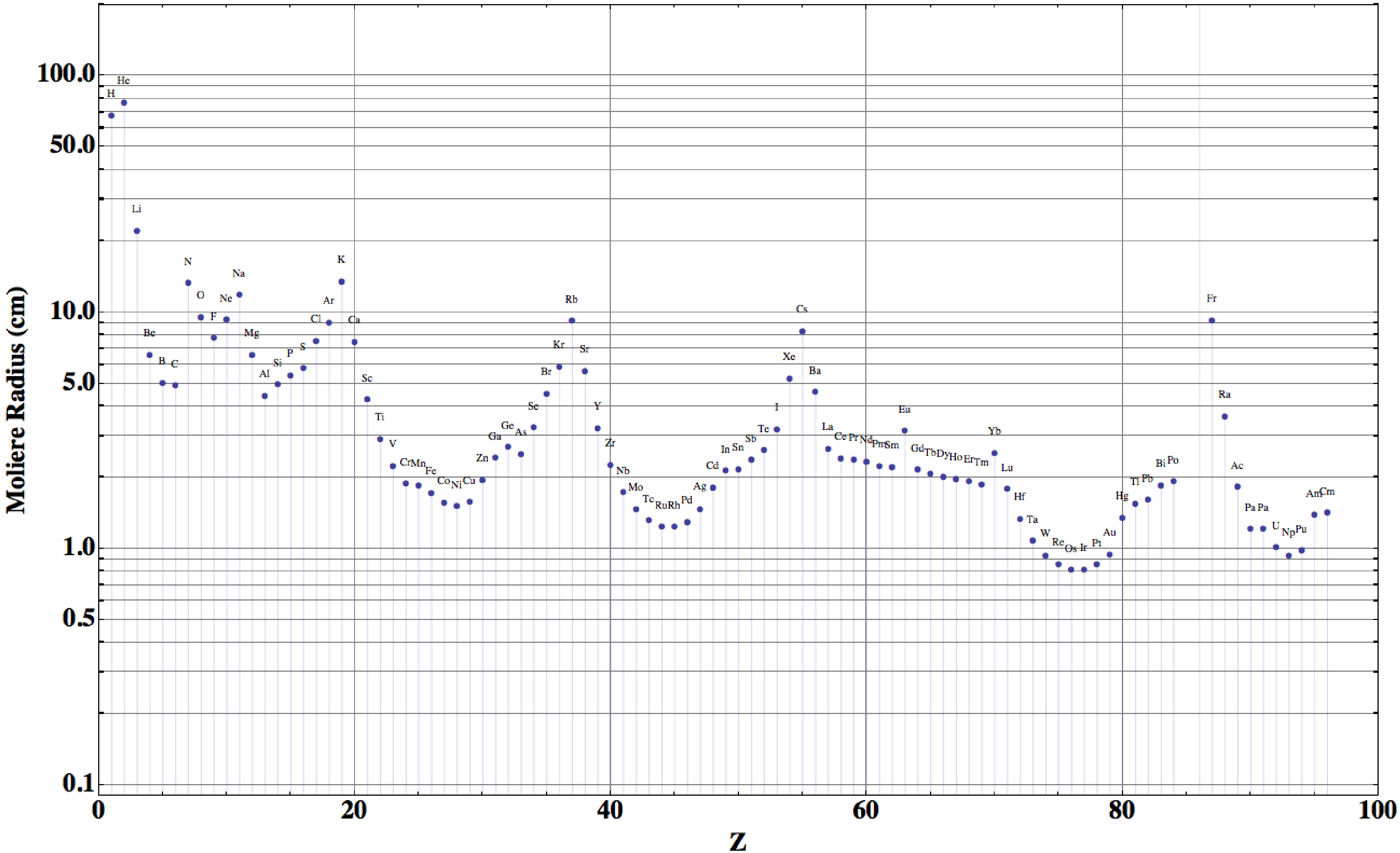
Moliere Radius

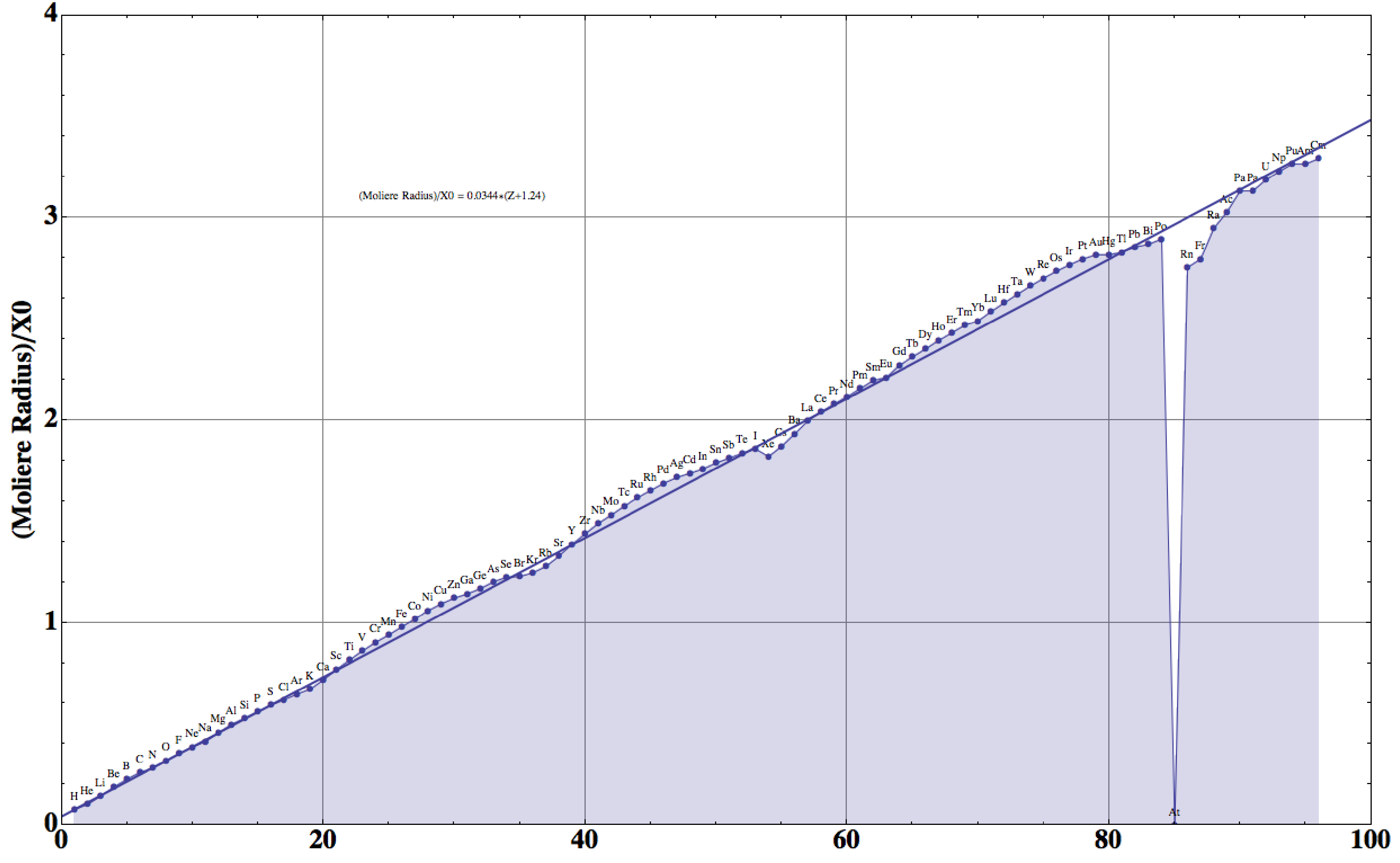


W: 0.93cm

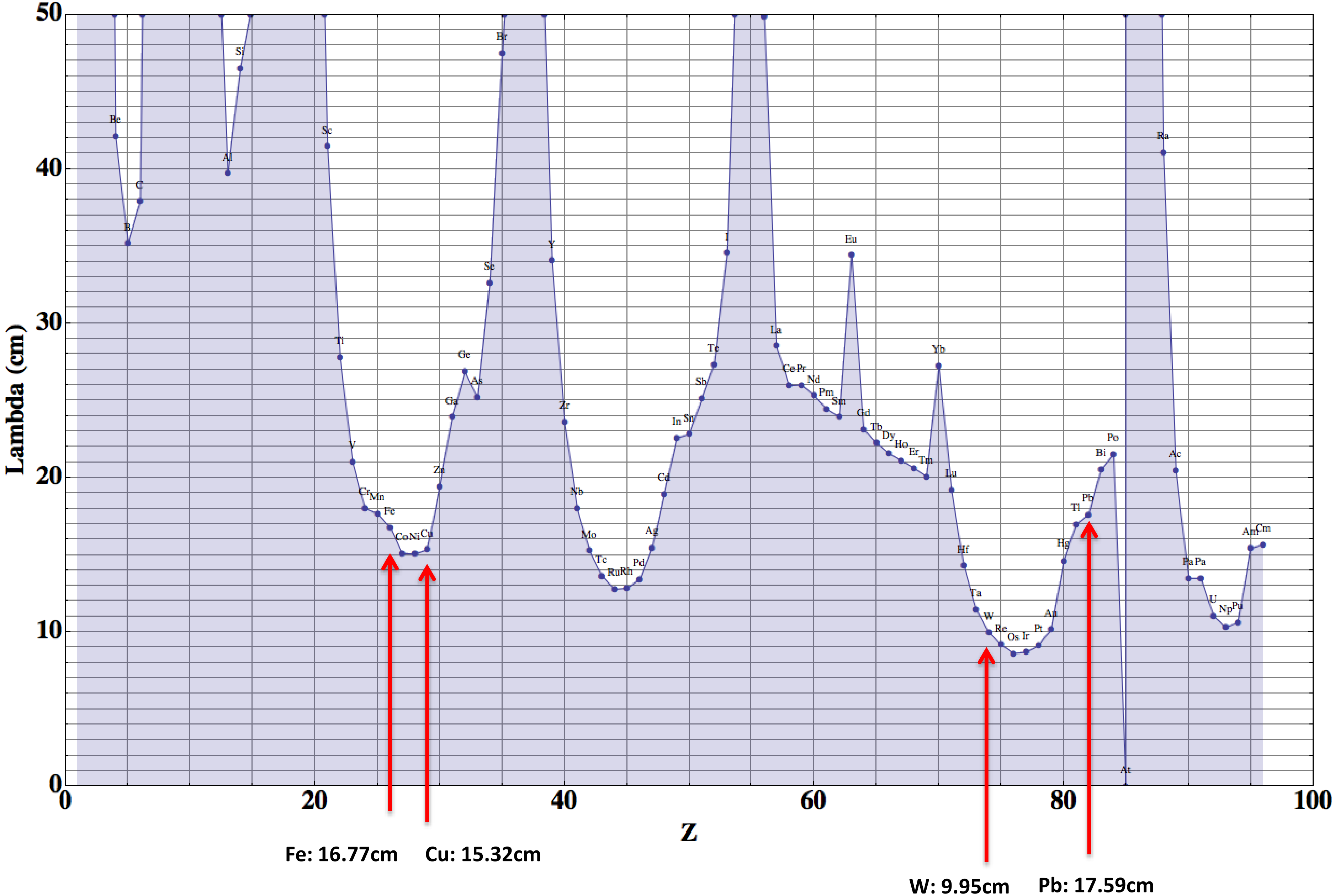
Pb: 1.6cm

Moliere Radius

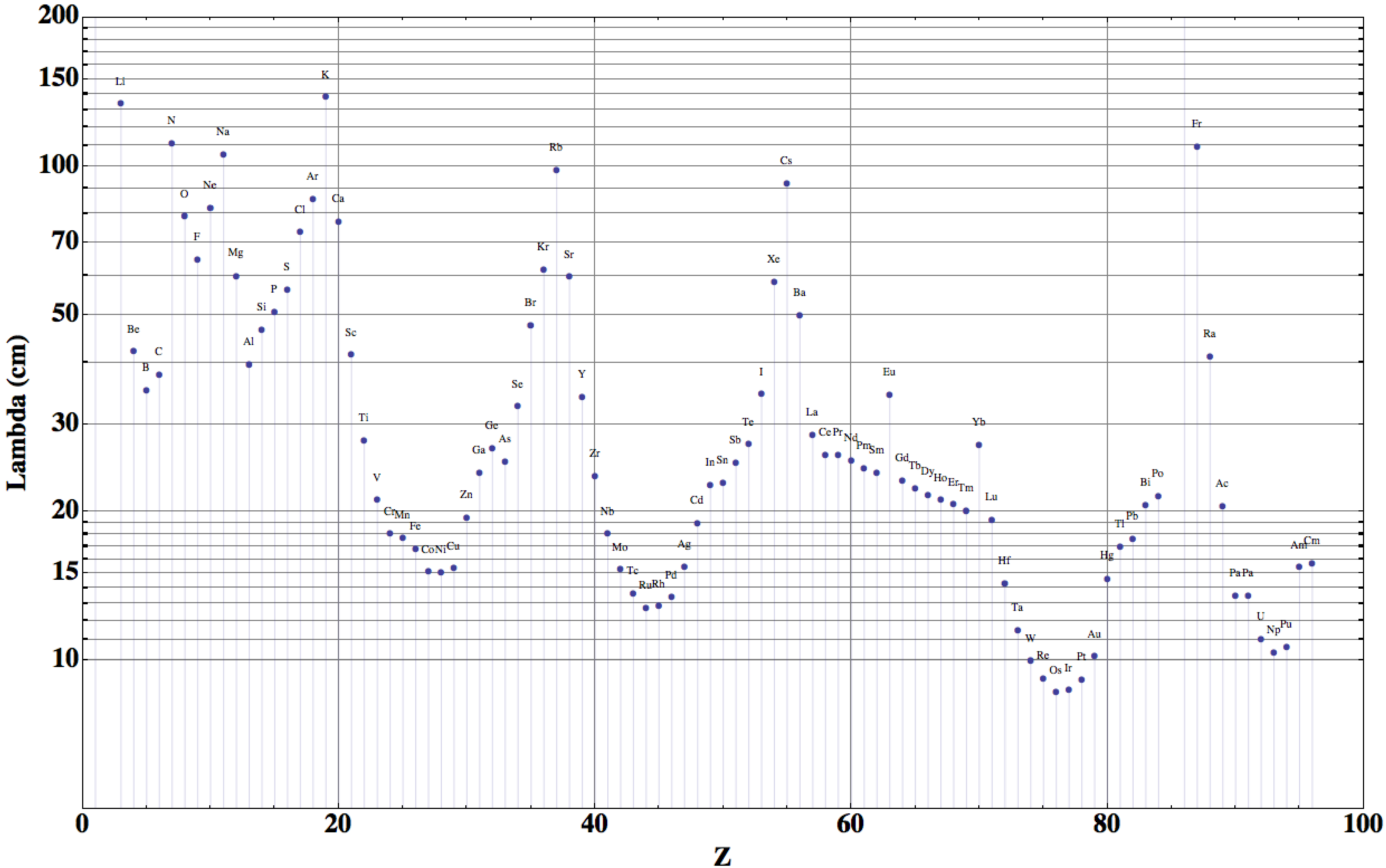


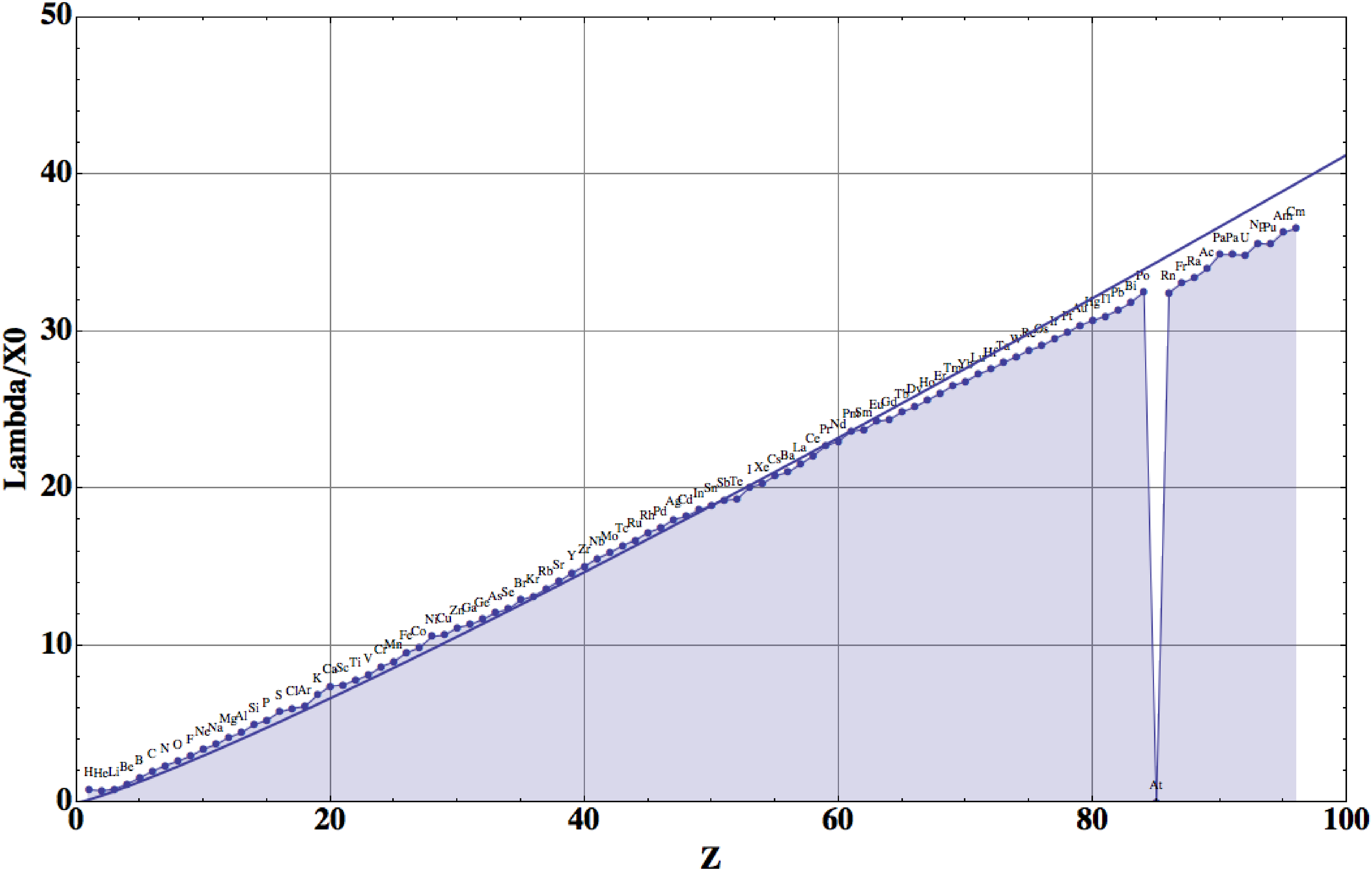

(Moliere Radius)/X0 = 0.0344*(Z+1.24)
(Moliere Radius)/X0
Z
0
1
2
3
4
20
40
60
80
100

Nuclear Interaction Length



Nuclear Interaction Length





Lambda/X0
Z
0
10
20
30
40
50
0
20
40
60
80
100

CLIC detector parameters,
2 reference designs

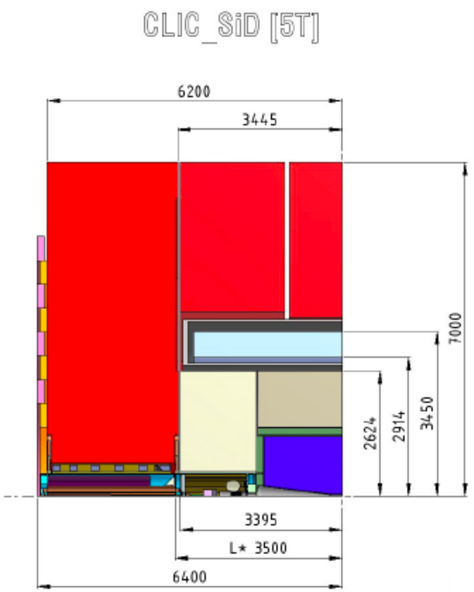


Fig. 11.1: Quarter View of CLIC_SiD

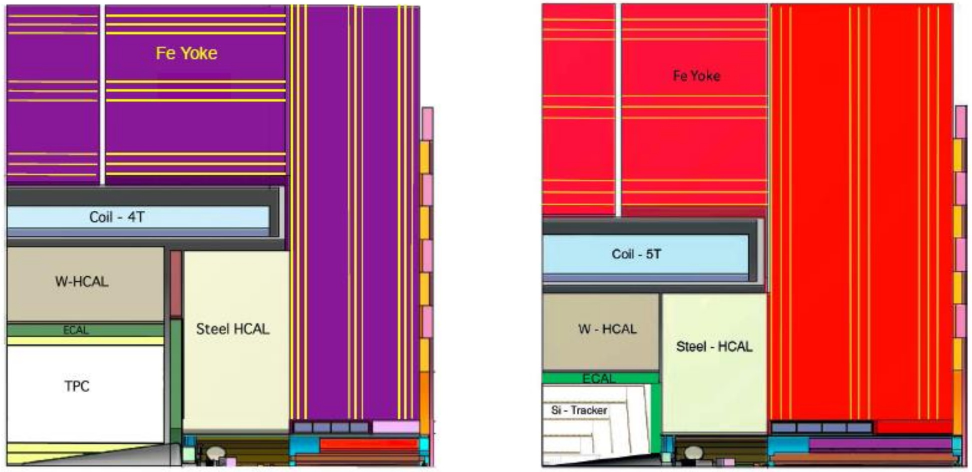


Fig. 3.1: Longitudinal cross section of the top quadrant of CLIC_ILD (left) and CLIC_SiD (right).

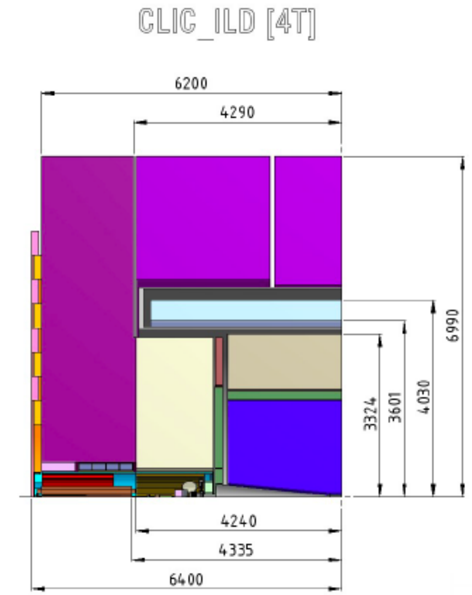


Fig. 11.2: Quarter View of CLIC_ILD

CLIC detector parameters, 2 reference designs

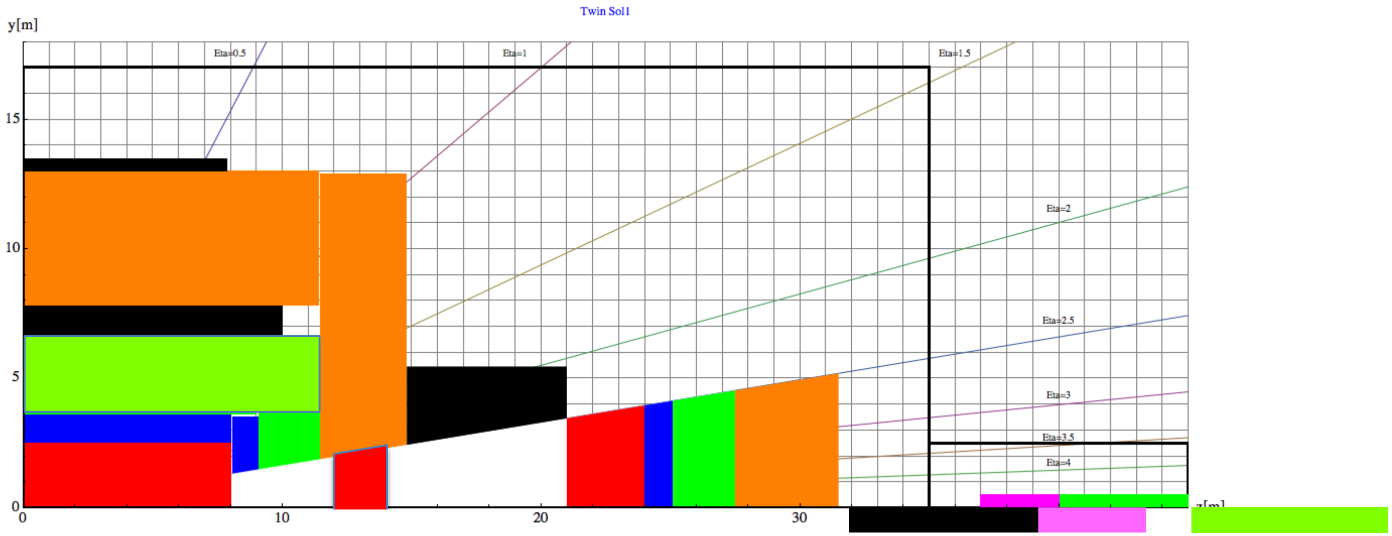
: 3.2: Some key parameters of the CLIC detector concepts. The inner radii refer to the insc
: of the polygon. All dimensions are given in millimetres.

	CLIC_ILD	CLIC_SiD
Overall Dimensions		
Outer size [W×H×L]	14000 × 14000 × 12400	14000 × 14000 × 12400
Estimated total weight	12200 tons	12500 tons
Beam-line height	7900	7900
Vertex Detector		
Inner radius	31	27
Outer radius	60	77 (barrel), 169 (disks)
Max. Z	125 (barrel), 257 (disks)	99 (barrel), 830 (disks)
Barrel layers	6 (3 double layers)	5
Forward disks	6 (3 double layers)	7
Barrel Tracker		
Technology	TPC (Silicon strips)	Silicon strips
Inner radius	329 (165)	230
Outer radius	1808 (1835)	1239
Max. Z	2250	578 to 1536
Max. samples	2 (Si), 224 (TPC), 1 (Si)	5
Forward Tracker		
Technology	Silicon strips	Silicon strips
Inner radius	47 to 218	207 to 1162
Outer radius	320	1252
Max. Z	1868	1556
Max. samples	5	4
ECAL: Barrel		
Absorber	Tungsten	Tungsten
Active elements	Silicon pads	Silicon pads
Sampling layers	30 (20 × 2.1, 10 × 4.2)	30 (20 × 2.5, 10 × 5)
Cell size	5.1 × 5.1	3.5 × 3.5
X_0 and λ_I	23 and 1	26 and 1
Inner radius	1847	1290
Outer radius	2020 dR≈0.173m	1430 dR≈0.14m
Max. Z	2350	1765

Table 3.2: continued

	CLIC_ILD	CLIC_SiD
ECAL: Endcap		
Absorber	Tungsten	Tungsten
Active elements	Silicon pads	Silicon pads
Sampling layers	30 (20 × 2.1, 10 × 4.2)	30 (20 × 2.5, 10 × 5)
Cell size	5.1 × 5.1	13 mm^2 hexagons
X_0 and λ_I	23 and 1	26 and 1
Inner radius	270	222
Outer radius	2270	1269
Min. Z	2450	1657
Max. Z	2622	1800
HCAL: Barrel		
Absorber	Tungsten	Tungsten
Sampling layers	75 × 10 mm	75 × 10 mm
Cell size	30 × 30	30 × 30
λ_I	7.5	7.5
Inner radius	2058	1447
Outer radius	3296 dR≈1.238m	2624 dR≈1.187m
Max. Z	2350	1765
HCAL: Endcap		
Absorber	Steel	Steel
Sampling layers	60 × 20 mm	60 × 20 mm
Cell size	30 × 30	30 × 30
λ_I	7.5	7.5
Inner radius	400	509
Outer radius	3059	2624
Min. Z	2650	1800
Max. Z	4240	3395
Coil + cryostat		
Field on central axis	4 T	5 T
Free bore	3426	2744
Outer radius	4290	3710
Max. Z	4175	3245
Yoke & Muon System: Barrel		
Material	Steel	Steel
Inner radius	4404	3914
Outer radius	6990	7000
Number of layers	9	9
Yoke & Muon System: Endcap		
Material	Steel	Steel
Inner radius	690	690
Outer radius	6990	7000
Max. Z	6200	6200
Number of layers	9	9

Baseline Geometry used up to now , Twin Solenoid, 6T, 12m bore, 10Tm dipole



Barrel:

Tracker available space:
R=2.1cm to R=2.5m, L=8m

EMCAL available space:
R=2.5m to R= 3.6m → dR= 1.1m

HCAL available space:
R= 3.6m to R=6.0m → dR=2.4m

Coil+Cryostat:
R= 6m to R= 7.825 → dR = 1.575m, L=10.1m

Muon available space:
R= 7.825m to R= 13m → dR = 5.175m
Revision of outer radius is ongoing.

Coil2:
R=13m to R=13.47m → dR=0.475m, L=7.6m

Endcap:

EMCAL available space:
z=8m to z= 9.1m → dz= 1.1m

HCAL available space:
z= 9.1m to z=11.5m → dz=2.4m

Muon available space:
z= 11.5m to z= 14.8m → dz = 3.3m

Forward:

Dipole:
z= 14.8m to z= 21m → dz=6.2m

FTracker available space:
z=21m to R=24m, L=3m

FEMCAL available space:
Z=24m to z= 25.1m → dz= 1.1m

FHCAL available space:
z= 25.1m to z=27.5m → dz=2.4m

FMuon available space:
z= 27.5m to z=31.5m → dz=4m

Two reference designs, with large and small tracker radius ?

We could use two reference designs, one with large tracker radius and W HCAL and one with small tracker radius and Fe HCAL, e.g.

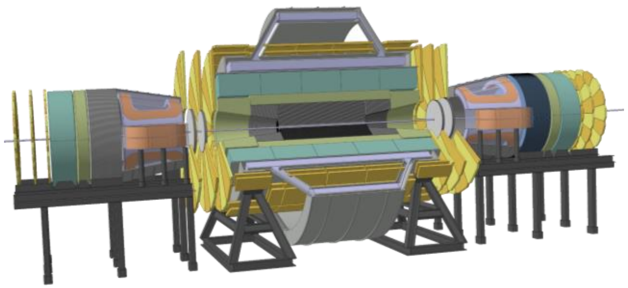
2.5m (tracker cavity) + 1m ECAL (1 lambda + supports) + 1.5m (9 lambda W + supports)

1.5m (tracker cavity) + 1m ECAL (1 lambda + supports) + 2.5m (9 lambda Fe + supports)

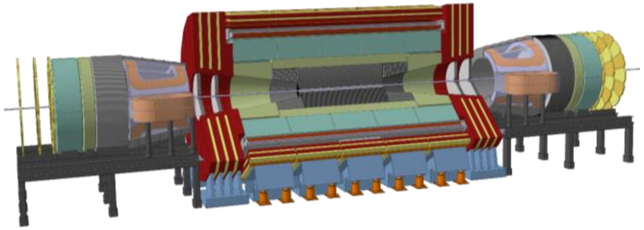
This would be two very interesting limiting cases that show the influence of tracking performance, radial distance of the calorimetry, Bremsstrahlung & ECAL, Radiation load when comparing W and Fe etc.

We have to come up with two proposals for the next hadron detector meeting in about 4 weeks time.

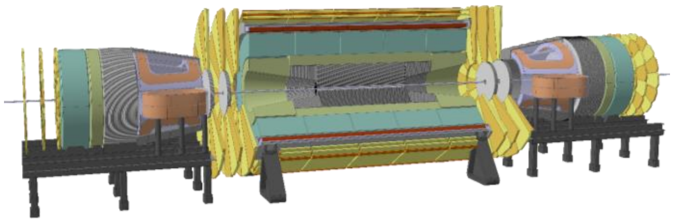
Magnet systems under consideration



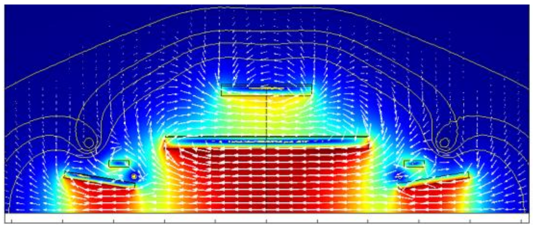
Twin solenoid with dipoles
(min. shaft diameter 27.5m)



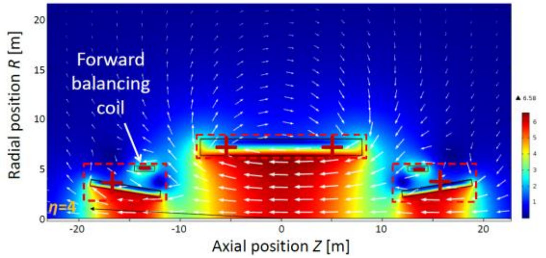
Partially shielded solenoid with dipoles



Unshielded solenoid with dipoles
(min. shaft diameter 16.3m, if rotated under ground)



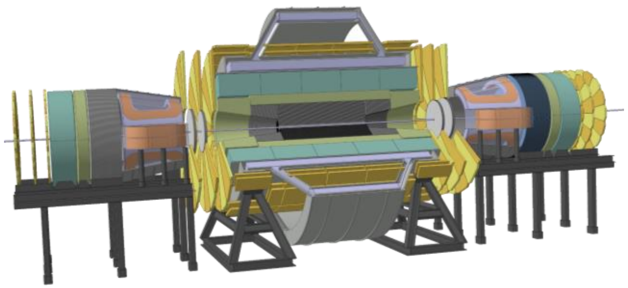
Twin solenoid with balanced conical solenoid

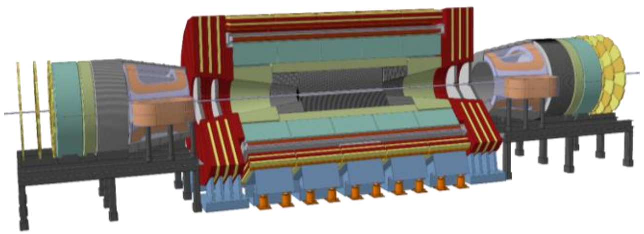


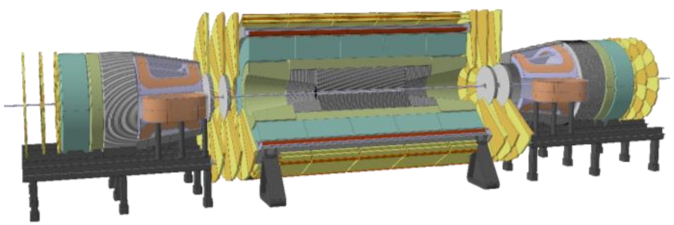
Unshielded solenoid with balanced conical solenoid

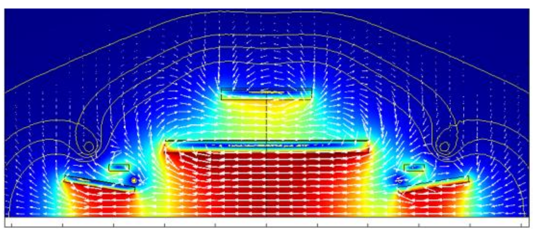
Herman Ten Kate, Matthias Mentink

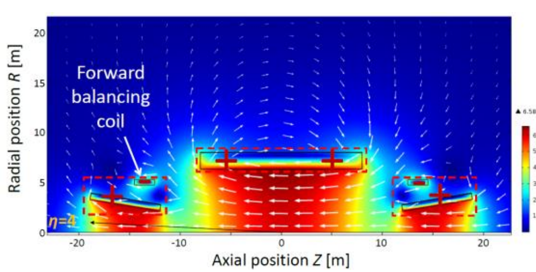
Magnet Systems











Concerning the shielded and unshielded options we still have to evaluate the muon performance ! Clearly the unshielded version is preferred in terms of cost and shaft size.

The decision on how to proceed with the forward solenoid and dipole is difficult.

It is clear that the forward solenoid is preferred in terms of construction, and it also preserves the phi symmetry which is crucial.

Specifically the MET trigger performance, that is crucial for dark matter search, will be very complex without phi symmetry.

We should probably first evaluate the performance of the forward solenoid version and then try to understand where the dipole could give the improvement ?

Trigger versus continous readout

Continuous readout of the tracker will be very challenging, so we also must investigate a scheme using a first level 'hardware' trigger.

Sampling the Calorimeters at the full bunch crossing rate might be in reach, since this is already done e.g. for the ATLAS EMCAL and HCAL for Phase II.

Are Calorimeter and Muon Triggers then sufficient to bring down the tracker readout rates to acceptable levels e.g. to 1MHz ?

CMS will use a track trigger at 40MHz for PhaseII, but ATLAS does not, so we have to look into the specific reasons and difference in order to establish a baseline strategy for an FCC detector.

Probably this will result in a specification on the Calo and Muon resolution at L1, so we could envisage as a baseline for the triggered readout:

Full digitization of calorimeters and muons to arrive at a tracker readout rate of 1MHz ?

→ Work with ATLAS/CMS trigger experts.

Proposal for next Step

Provide two detailed reference designs for the next meeting.

Provide a baseline triggering strategy (in addition to the continuous readout idea) for the next meeting.

Use forward solenoid geometry as a baseline.

Establish muon trigger performance (t.b.d. who/how).