Compact HCal for the CLIC Detector

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Outline

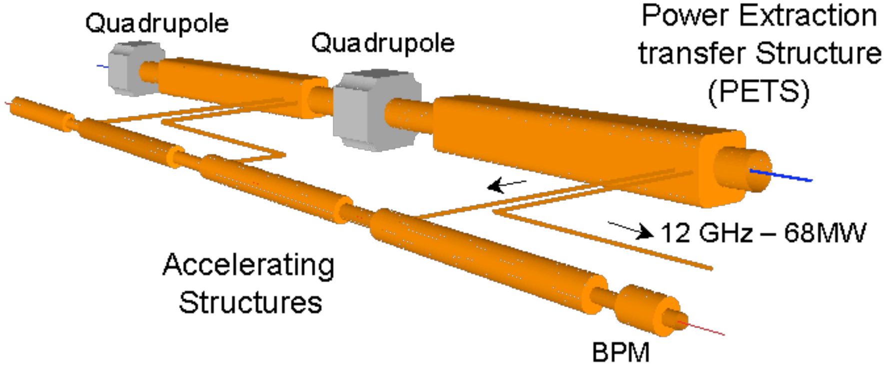
- CLIC and its detectors – a brief introduction
- Tungsten HCal: Simulation Studies
- Particle Flow Calorimetry at multi-TeV energies
- Tungsten HCal: Mechanical Issues
- Future Plans

CLIC and its detectors

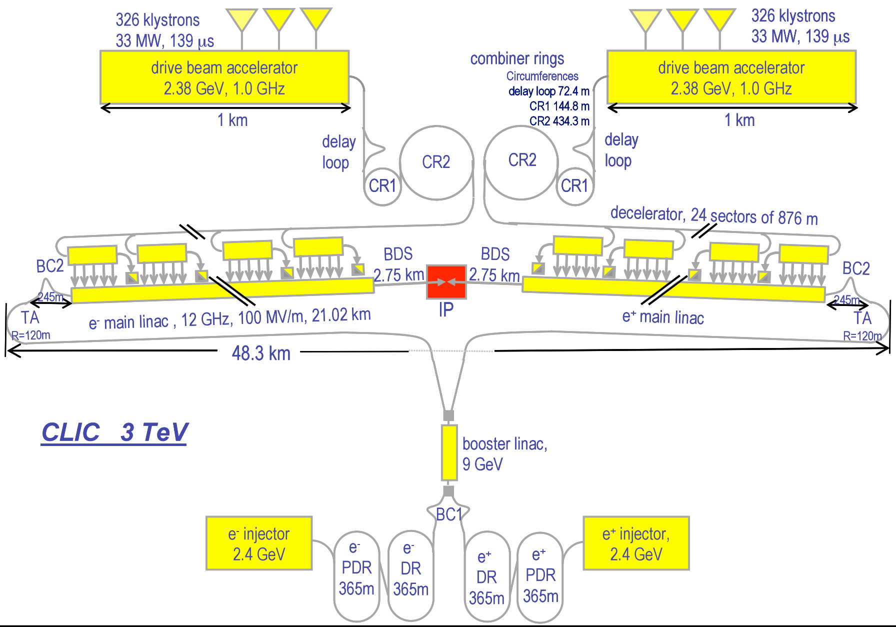
The Compact Linear Collider

- $e^+ e^-$ with up to E_{cm} = 3 TeV
- Length: ~ 50 km (10km @ 0.5 TeV)
- Two accelerators:
  - Drive beam with low energy and high intensity
  - Main beam with high energy and low intensity
- Luminosity: ~ 10^{34} $cm^{-2}s^{-1}$
- Timing:
  - 50 trains per second
  - 312 bunches per train
  - 0.5 ns between bunches

Drive beam – 100 A, 240 ns
from 2.4 GeV to 240 MeV



Main beam – 1.2 A, 156 ns
from 9 GeV to 1.5 TeV

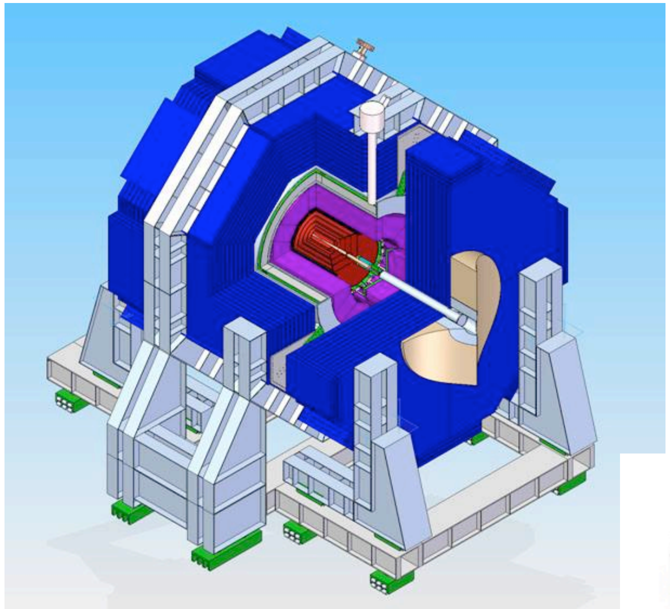


CLIC 3 TeV

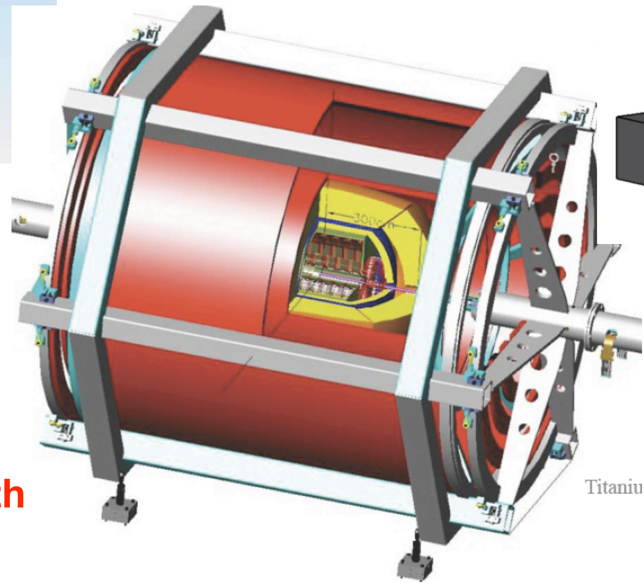
- Previous Studies:
  - Physics at the CLIC Multi-TeV Linear Collider (2004): http://cdsweb.cern.ch/record/749219?ln=en
- Revived in late 2008 and since beginning of 2009 official CERN project
  - http://lcd.web.cern.ch/LCD/
- Collaboration with the ILC detector concepts and the ILC R&D collaborations (CALICE, EUDET, FCAL, LCTPC)
- Mainly preparation for the CLIC CDR, scheduled for end of 2010

ILC Detector Concepts

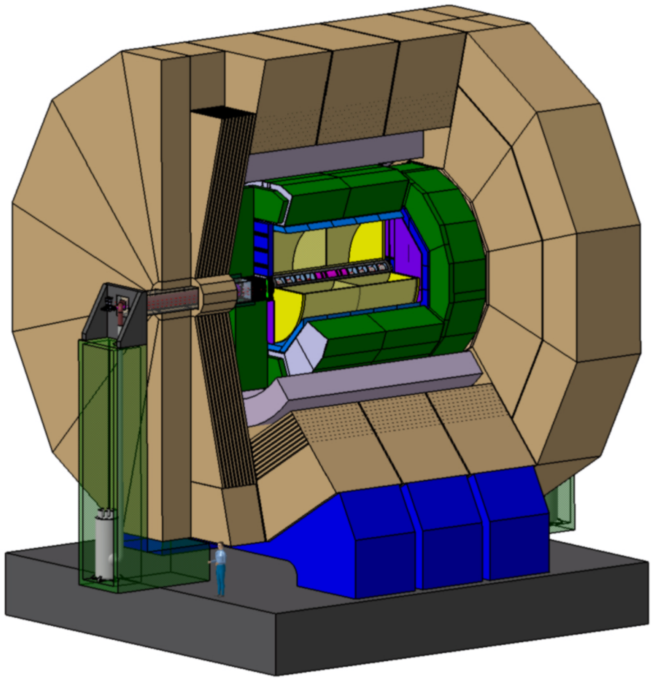
- Start from existing ILC detector concepts
- Test and optimize performance at multi-TeV energies



SiD



4th



ILD

ILC HCal Parameters

- SiD (LoI version)
  - HCAL
    - R_{min} = 141 cm, R_{max} = 253 cm
    - 40 layers of Steel/Gas (2.0 cm + 0.8 cm)
    - λ = 5.1 , X_0 = 46.5
    - Readout: 1.0 cm x 1.0 cm digital
    - 12 fold
  - Coil
    - R_{min} = 255 cm, R_{max} = 338 cm
    - B = 5.0 T

- ILD (LoI version)
  - HCAL
    - R_{min} = 206 cm, R_{max} = 333 cm
    - 48 layers of Fe/Scint (2.0 cm + 0.5 cm)
    - λ = 6.0 , X_0 = 55.3
    - Readout: 3.0 cm x 3.0 cm analog
    - 16 fold (outside), 8 fold (inside)
  - Coil
    - R_{min} = 344 cm, R_{max} = 419 cm
    - B = 3.5 T

Why Tungsten?

- Need shorter longitudinal shower size
  - High energetic jets require more HCal material in terms of interaction lengths – to achieve better containment
  - Strong constraints by coil – cost and feasibility
- Need smaller lateral shower size
  - High energetic jets are more boosted
  - PFA performance is decreasing because of overlapping showers
- Tungsten might solve both problems
- We consider tungsten only for the HCal barrel since space constraints for the endcaps are not severe

Tungsten HCal: Simulation Studies

Questions to answer?

- Stack Simulations:
  - How many interaction lengths do we need?
  - Which sampling frequency is optimal?
- Full detector and PFA studies
  - Readout cell sizes?
  - Magnetic field strength?
  - Aspect ratio of the detector?

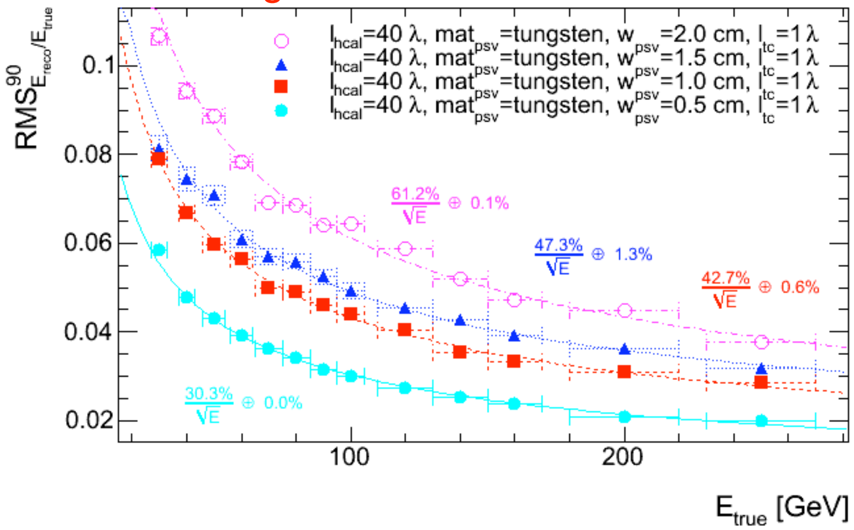
HCal-Stack Simulations

- Simple HCal geometry to investigate materials and sampling ratios
- Materials: tungsten, steel, steel-tungsten-sandwich (various thicknesses)
- Constant gap size: 5.0 mm Scint + 2.5 mm G10
- Dimensions: 5x5m and more than 25 λ in depths to guarantee shower containment
- Simulated 100k π^+ between 1 GeV and 300 GeV for each geometry
  - This should cover the energy range of jet main constituents of events with #jets $\geq$ 4 @ 3 TeV
- Defined active and dead layers during reconstruction – corresponding to different HCal, coil and tailcatcher sizes
- Reconstruction with a neural network (TMVA)
- Using simple shower variables: width, length, center, energy density, etc.

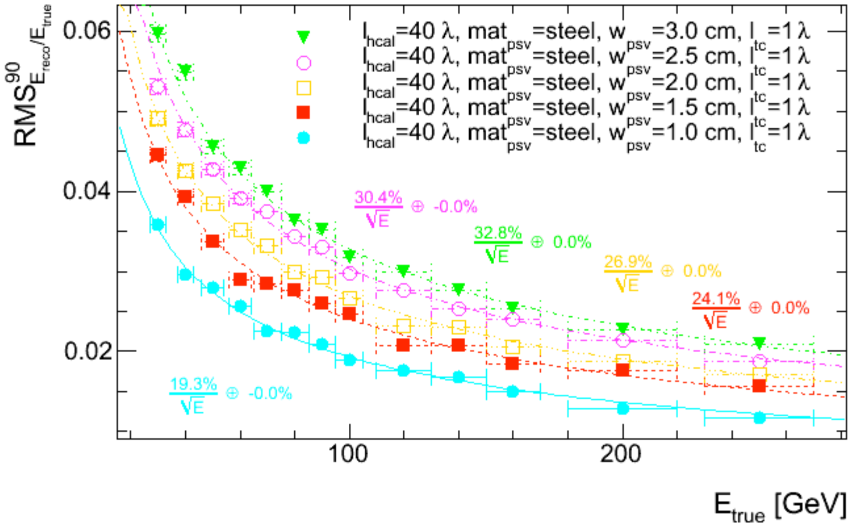
HCal-Stack Simulations

- “extremely deep”-HCal performance

Tungsten



Steel

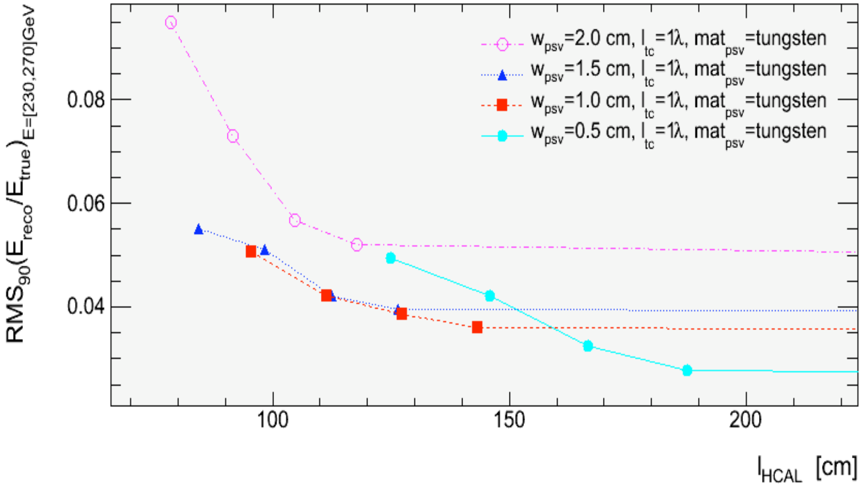


- Linearity is better than 2% (not shown)
- “extremely deep”-case:
  - Finer passive layers are better
  - Steel performs better than tungsten

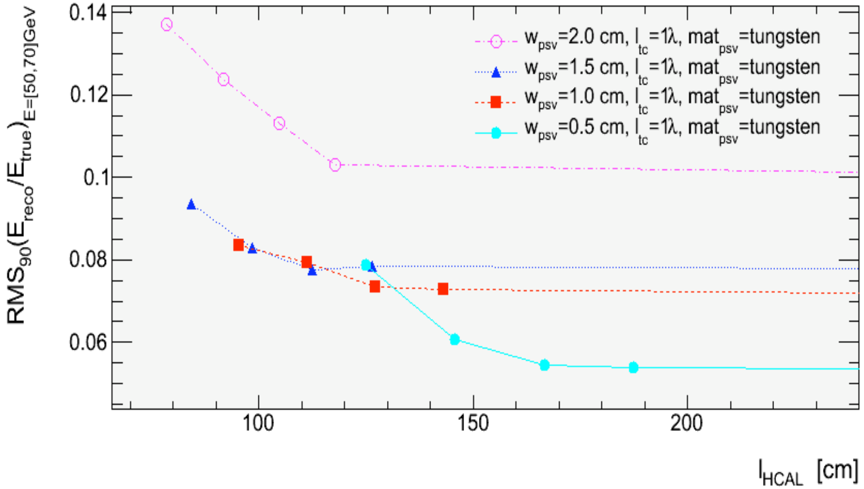
CLIC-PH-Note, Speckmayer & Grefe (in preparation)

- Performance vs HCal depth (tungsten)

E_{MC} ~ 250 GeV



E_{MC} ~ 60 GeV



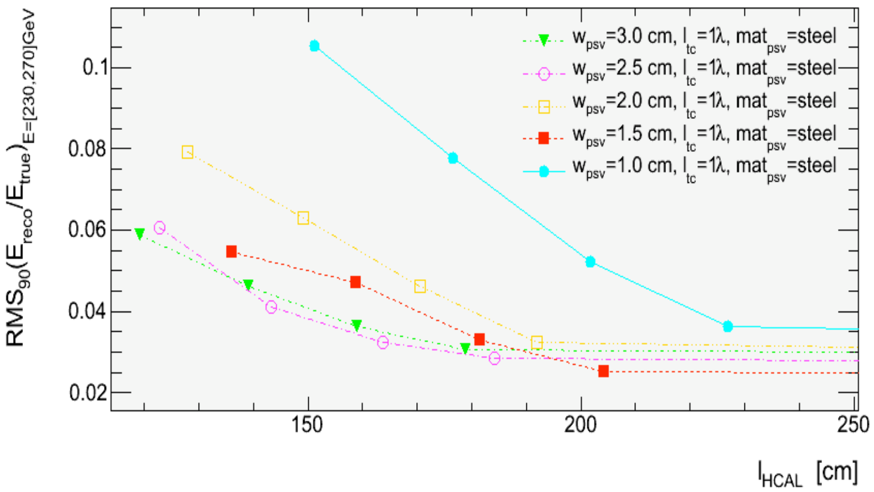
The 4 points of each graph correspond to 6, 7, 8 and 9 λ total calorimeter material

- For an HCal depth of around ~ 140 cm an absorber thickness of ~ 1 cm tungsten seems optimal
- This corresponds to ~ 8 λ; taking into account 1 λ of ECal, a 7 λ HCal appears to be sufficient for CLIC energies
- Stay away from the steep areas where leakage becomes the dominating factor

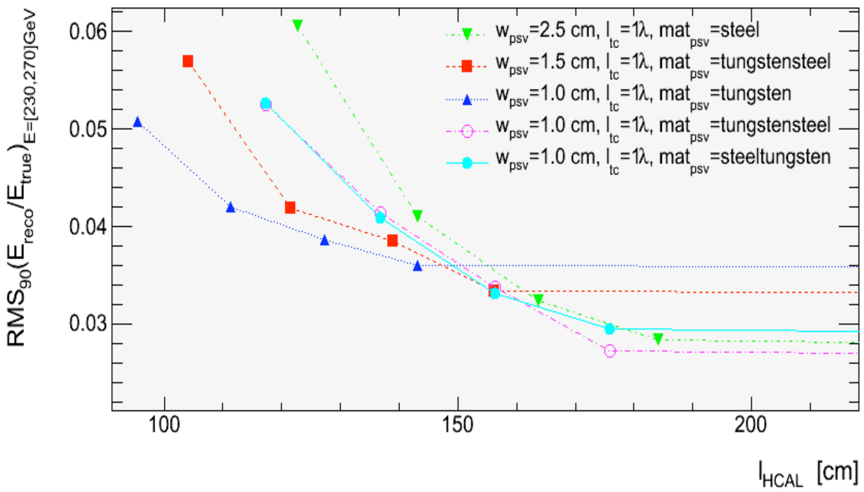
CLIC-PH-Note, Speckmayer & Grefe (in preparation)

- Performance vs HCal depth (tungsten vs steel)

Steel



Steel, Tungsten, Steel & Tungsten

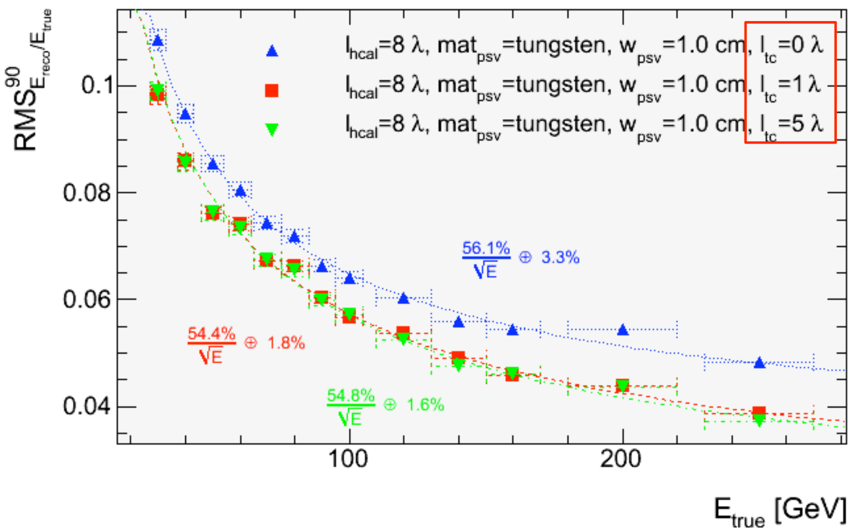


- Steel can perform better than tungsten, but only at a significantly bigger HCal size

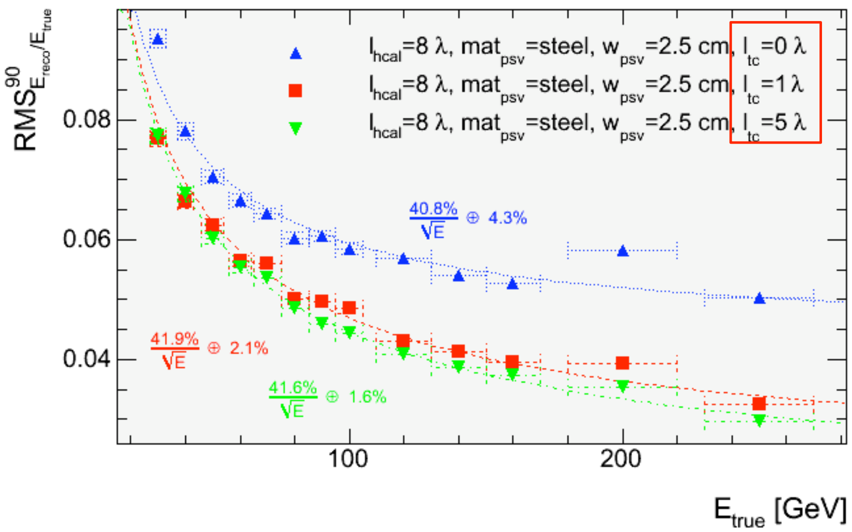
CLIC-PH-Note, Speckmayer & Grefe (in preparation)

- Impact of a Tailcatcher

Tungsten



Steel



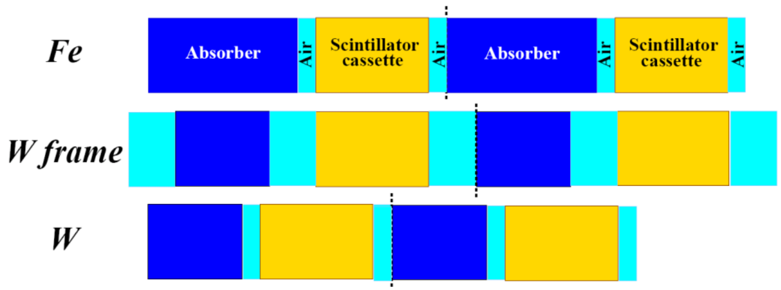
- Resolution is improved by adding a tailcatcher of ~1 λ
- The effect of a bigger tailcatcher is negligible
- In this case: 0 λ implies no active material after the coil

CLIC-PH-Note, Speckmayer & Grefe (in preparation)

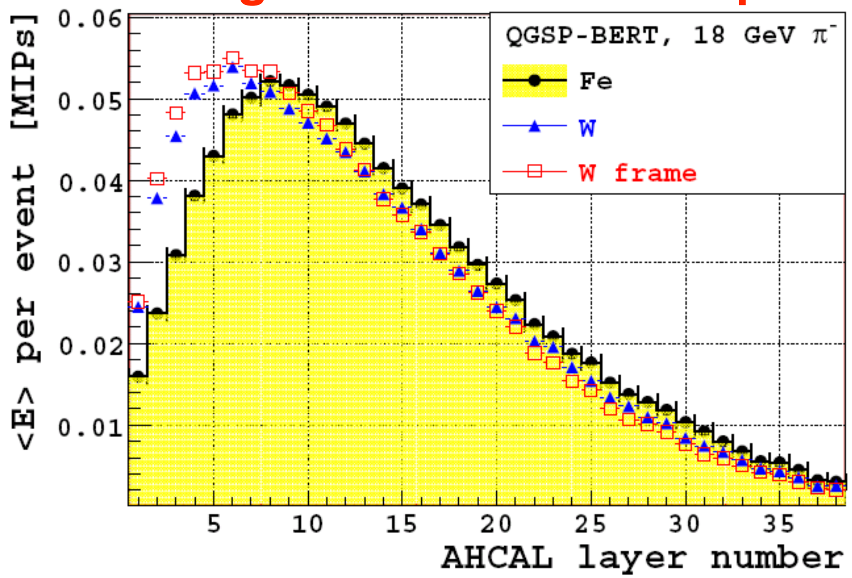
HCal Barrel Dimensions

calculated for 18 fold symmetry	ILD-flavor		SiD-flavor	
	10mm W	20 mm Fe	10 mm W	20 mm Fe
layers	70	60	70	60
R_{min} [cm]	200	200	141	141
R_{max} [cm]	320	370	270	310
Length [cm]	540	540	364	364
weight [t]	1200	930	650	500
Channels (1cm x 1cm)	$3.4*10^6$	$3.2*10^6$	$1.8*10^6$	$1.7*10^6$
Channels (3cm x 3cm)	$3.8*10^5$	$3.5*10^5$	$2.0*10^5$	$1.9*10^5$
λ	7.6	7.6	7.7	7.7
X_0	200	70	200	70

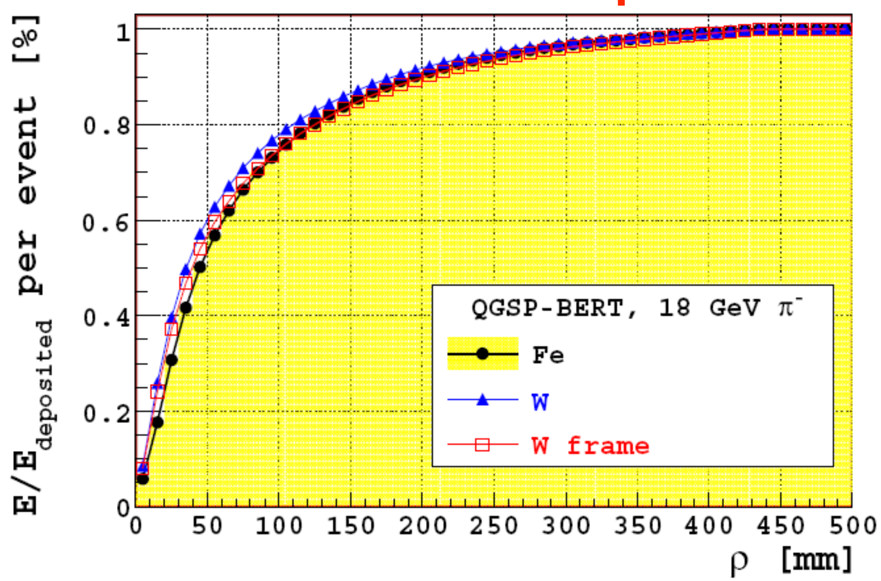
- Effect on lateral shower shape is less than expected
- Ratio of passive and active thickness is not optimal, but gap size of 0.8 mm seems minimum
- http://ilcagenda.linearcollider.org/getFile.py/access?contribId=16&sessionId=1&resId=0&materialId=slides&confId=3699



Longitudinal shower shape



Lateral shower shape

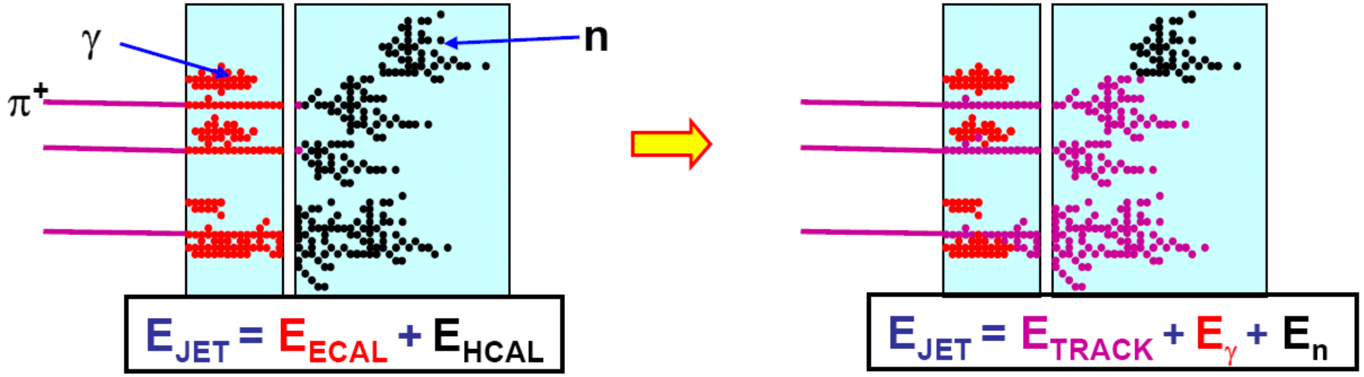


Angela Lucaci-Timoce

Particle Flow Calorimetry at multi-TeV energies

Particle Flow

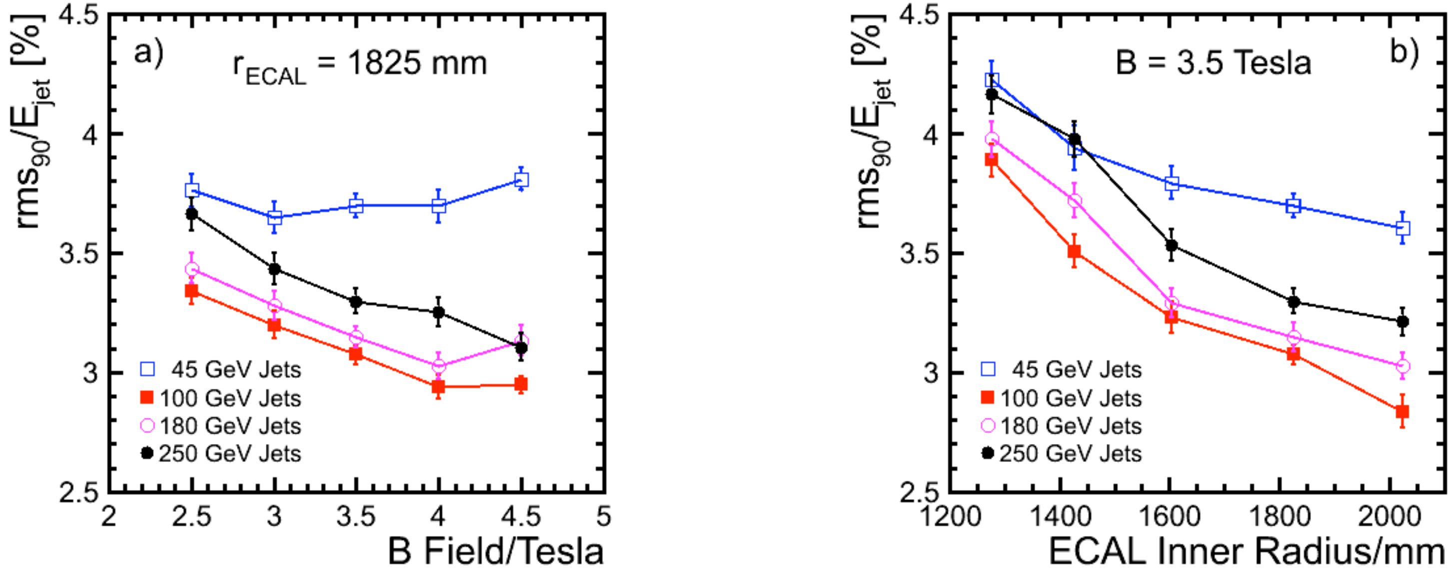
- Use tracking information to improve jet energy reconstruction
- Need to associate tracks with clusters
- Ideally only neutral cluster energy is taken from calorimeter



- “Confusion” is main source of errors
  - Need to separate neutral and charged clusters (B + radius)
  - Need highly granular calorimeter to see cluster structure

PFA Detector Requirements

- Impact of magnetic field and inner radius on PFA performance (Pandora)



$$\text{Confusion} \propto B^{-0.3} R^{-1.0}$$

- For PFA radius is most important → Motivation for ILD design

Mark Thomson

PFA Performance

- Extension towards higher energies
- To resolve W and Z bosons need approximately σ_E/E_j < 3.8 %

Default ILD: B = 3.5 T, 6 λ HCal

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ |cosθ|<0.7	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	29.2 %	2.9 %
180 GeV	40.3 %	3.0 %
250 GeV	49.3 %	3.1 %
375 GeV	81.4 %	3.6 %
500 GeV	91.6 %	4.1 %

Modified ILD: B = 4.0 T, 8 λ HCal

E_{JET}	$\sigma_E/E = \alpha/\sqrt{E_{jj}}$ |cosθ|<0.7	σ_E/E_j
45 GeV	25.2 %	3.7 %
100 GeV	28.7 %	2.9 %
180 GeV	37.5 %	2.8 %
250 GeV	44.7 %	2.8 %
375 GeV	71.7 %	3.2 %
500 GeV	78.0 %	3.5 %

- The modified version of ILD fulfills the jet energy resolution requirements also for CLIC energies

Mark Thomson

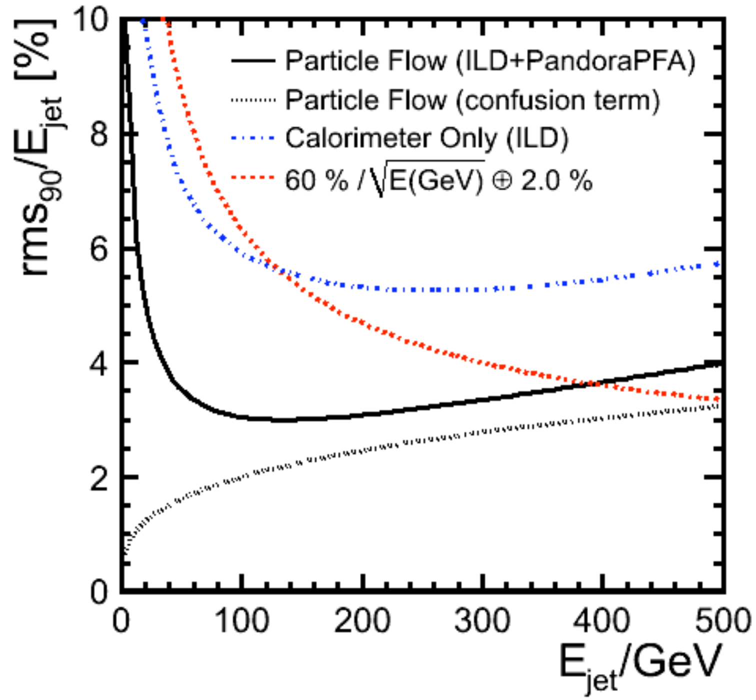
PFA Performance

- Empiric formula for PFA performance

$$\frac{\sigma_E}{E} = \frac{21}{\sqrt{E}} \oplus 0.7 \oplus 0.004E \oplus 2.1\left(\frac{E}{100}\right)^{+0.3} \%$$

Resolution — Tracking — Leakage — Confusion

- Comparing PFA and pure calorimetry:
  - PFA "wins" for $E_{jet} < 400$ GeV
  - There is room for improvement of the algorithm
  - Can chose reconstruction depending on event



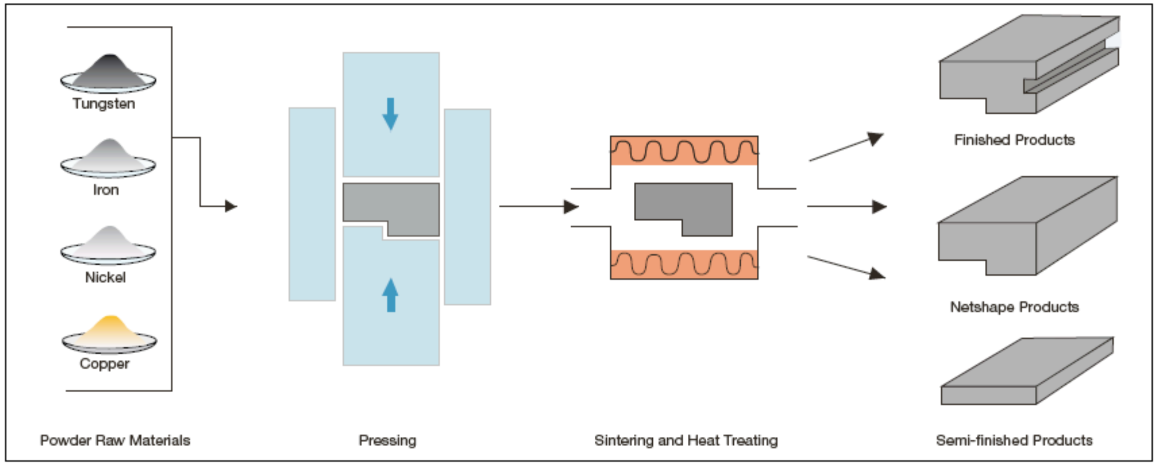
- http://indico.cern.ch/contributionDisplay.py?contribId=268&sessionId=2&confId=30383
- http://indico.cern.ch/materialDisplay.py?contribId=1&materialId=slides&confId=56735

Mark Thomson

Tungsten HCal: Mechanical Issues

Tungsten Production

- Starting from powder, the metal mixture is first pressed and then scintered and finally machined
- Each production step increases the density
- The main limitations are:
  - Plate size – limited by the size of the oven
  - Thin plates – it has to be somehow stable after pressing
  - todays limitations are around 10 x 500 x 800 mm^3
- We are in contact with industry to address these issues



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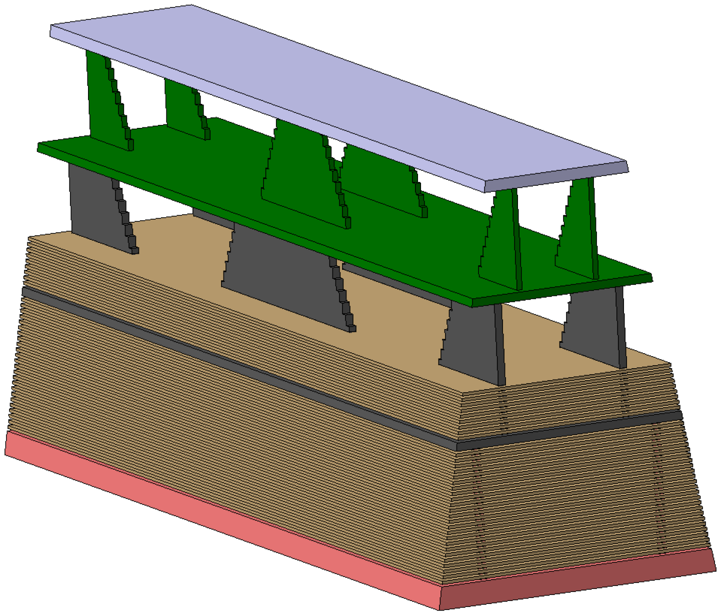
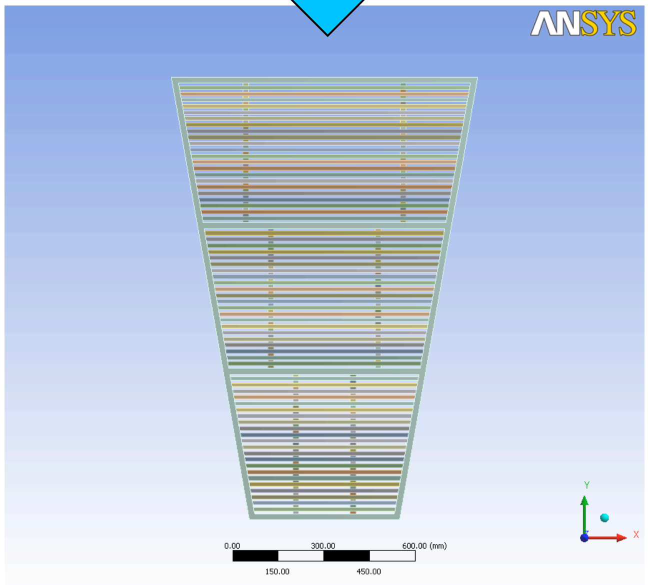
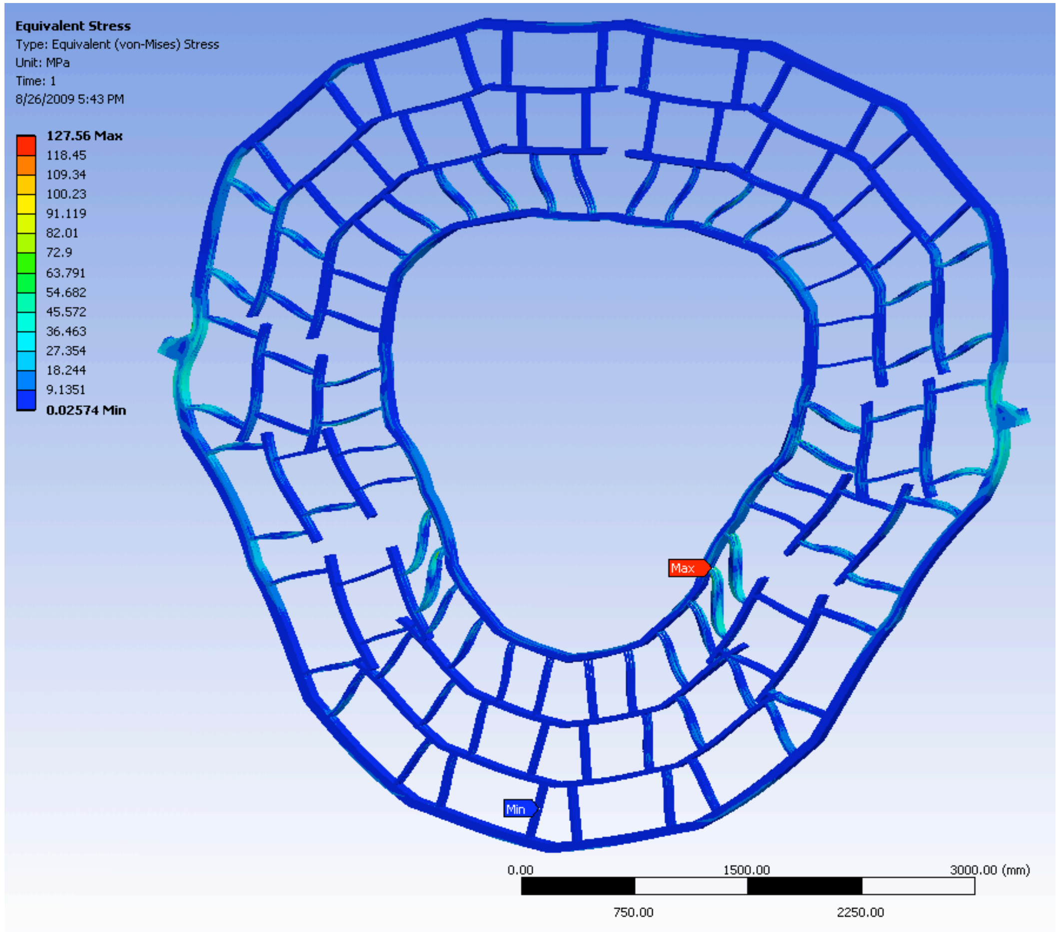
Tungsten HCal Assembly

- Tungsten is not suited to give structural support
- Need steel to provide stability
- 2 possible assemblies studied
  - "Stair" assembly
  - Steel casing with added bolts





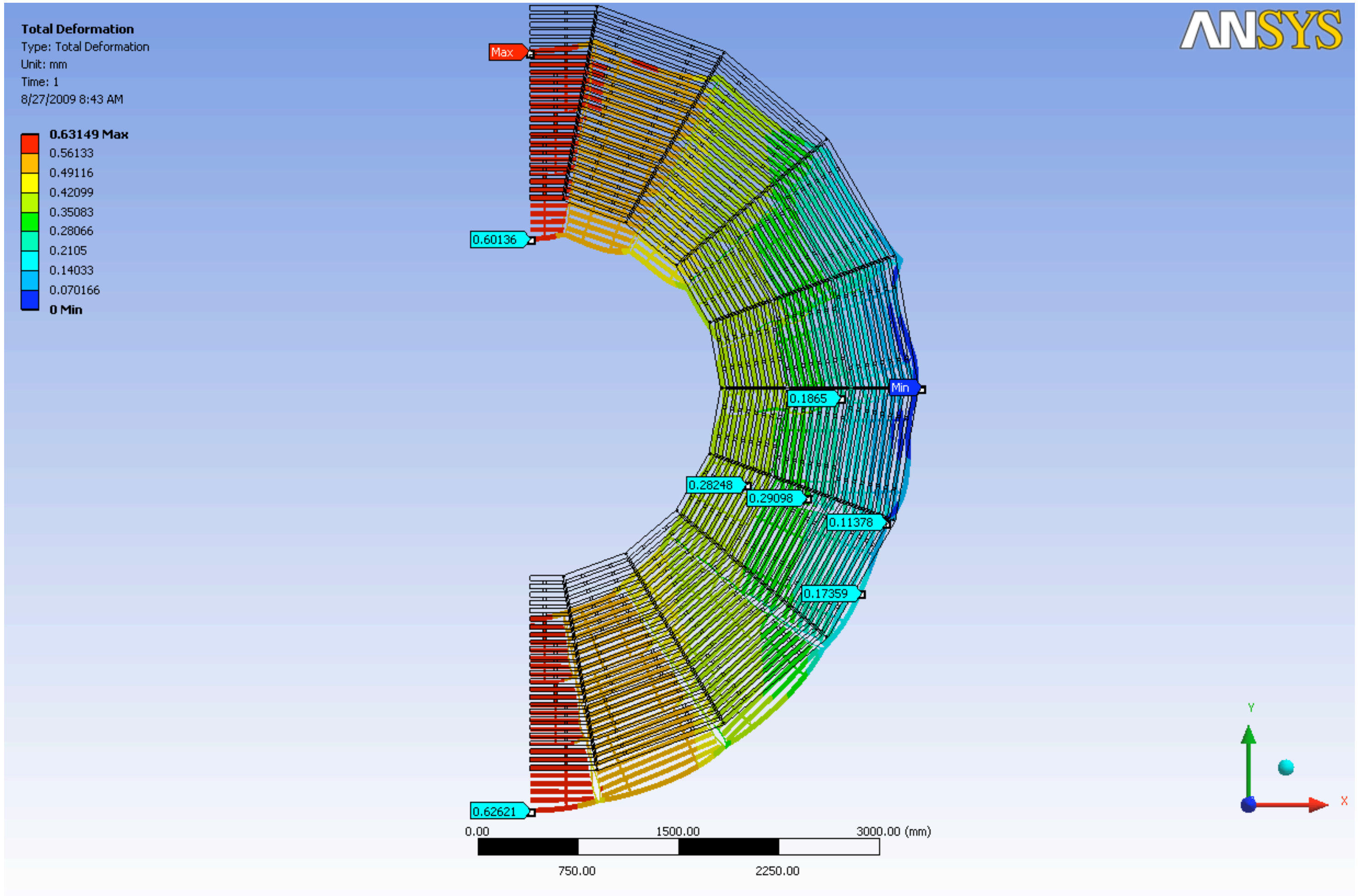
- Stair assembly: max. deformations ~2.00mm
- http://indico.cern.ch/materialDisplay.py?contribId=2&materialId=slides&confId=65785



Niall O Cuilleanain

Full HCal Stability for SiD Flavor

- Steel casing: max. deformations < 1.0 mm
- http://indico.cern.ch/materialDisplay.py?contribId=0&materialId=slides&confId=65785



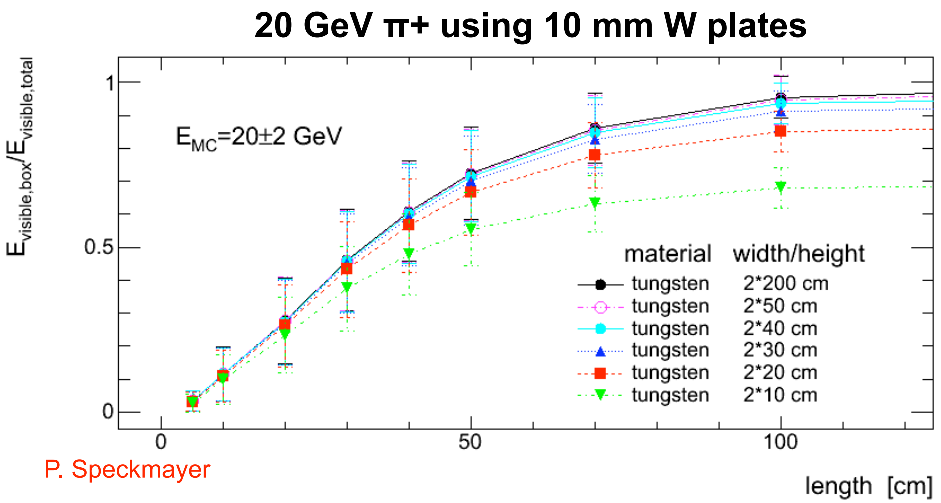
Ronan McGovern

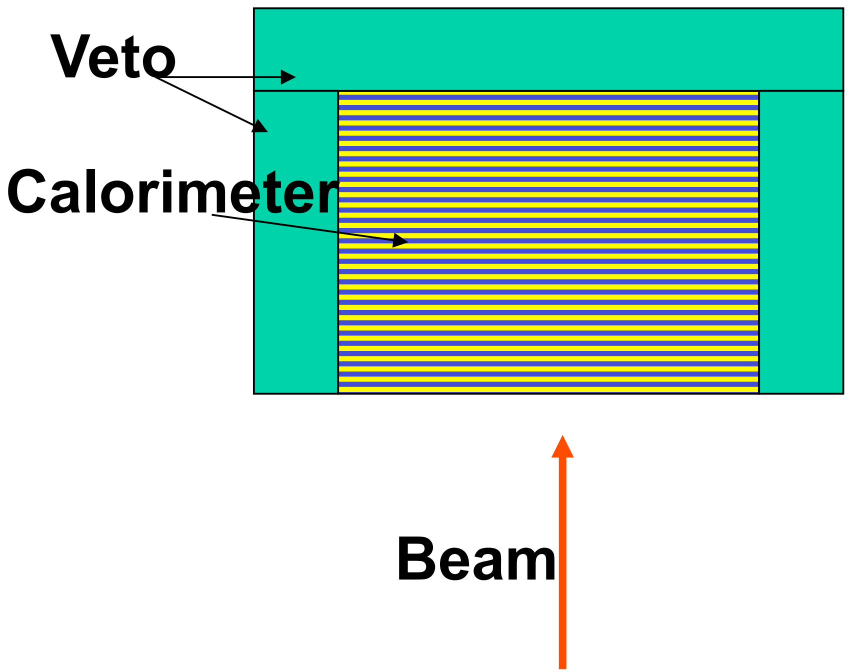
Future Plans

Tungsten HCal Prototype

- Some questions can not be answered by simulations and need a real prototype:
- Physics performance:
  - Verify GEANT4 simulations (resolution, etc.)
  - Include noise terms – do slow neutrons spoil the signal?
  - Test PFA performance with real events
- Tungsten plate production process:
  - Production of large and thin plates
  - Quality of machining? Flatness of plates?
- Mechanical questions:
  - Test assembly in view of a full HCal segment

- If possible use existing CALICE active modules
  - Test Scintillator and RPC together with tungsten
- Start with a smaller prototype (less than 1x1 m^2 plate-size)
- Fill up unused space with Steel plates to have a veto signal and use only fully contained showers





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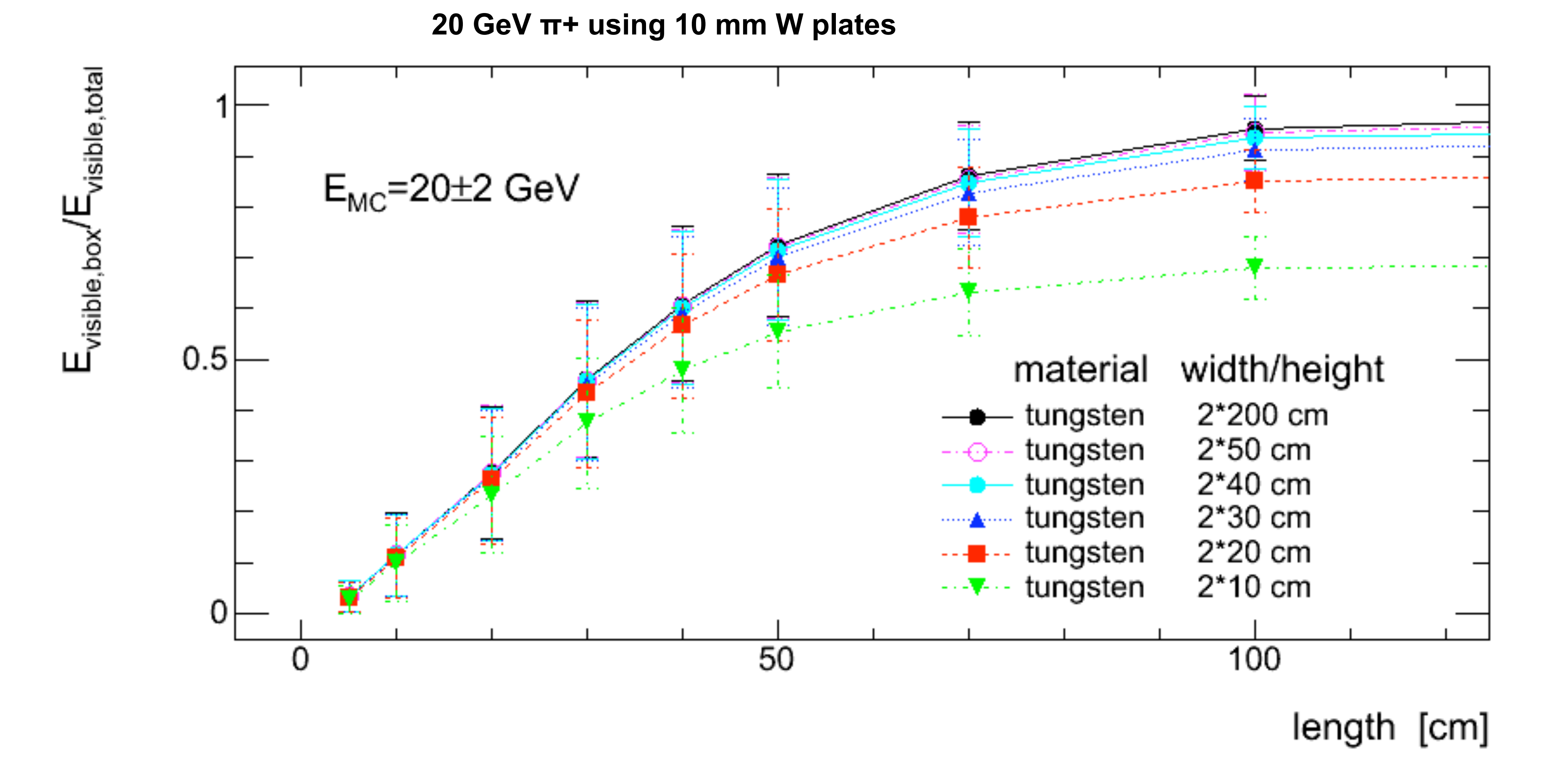


- Cutting on the shower size biases the physics:
- Small showers means high electromagnetic fraction, but we want to investigate hadronic performance!
- Getting the lateral size right is more important than getting the depth right
  - Can select by first interaction without bias on the hadronic part of the shower
  - Easy to add more layers
- Need to understand correlation of shower content and shower size

  → ongoing studies

- Some rough numbers:
  - Minimum plate size seems to be 50x50 cm^2 (low energy tests)
  - Minimum length ~50 cm

Conclusion

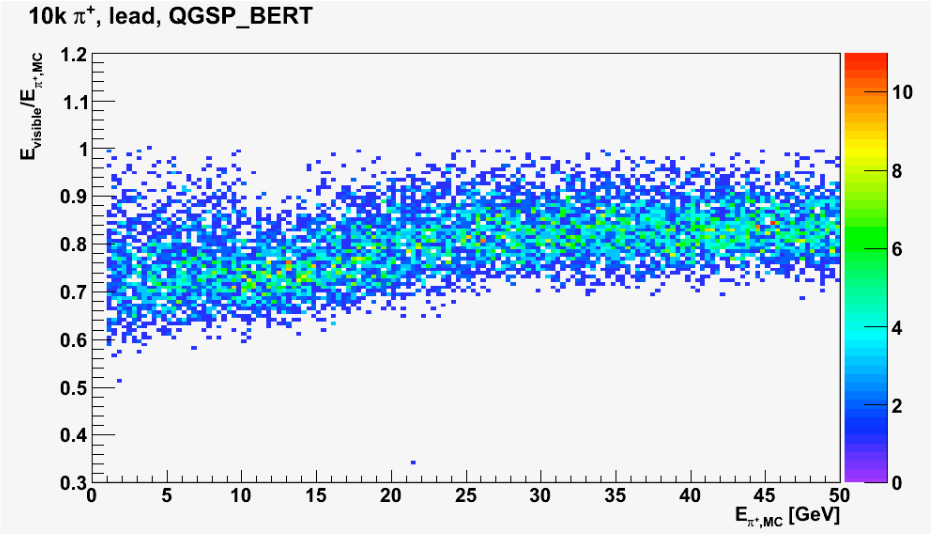
Conclusion

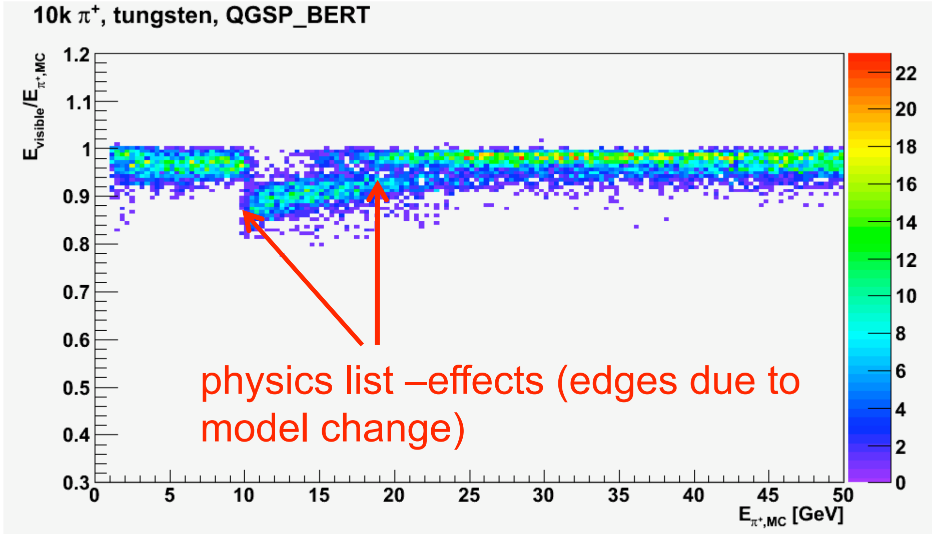
- For CLIC particle flow seems feasible up to jet energies of 1 TeV
- Very forward physics poses much harder problems for PFA and needs to be studied
- Tungsten HCal is a good option to extend the ILC detector concepts to CLIC energies without increasing the coil radius
  - At the moment CLIC baseline is ~60 layers, 1.2 cm W + 0.5 cm Scint HCal
- While tungsten poses some special challenges there is so far no show stopper
- A tungsten HCal prototype is necessary and planned (2010 ?)

Backup Slides

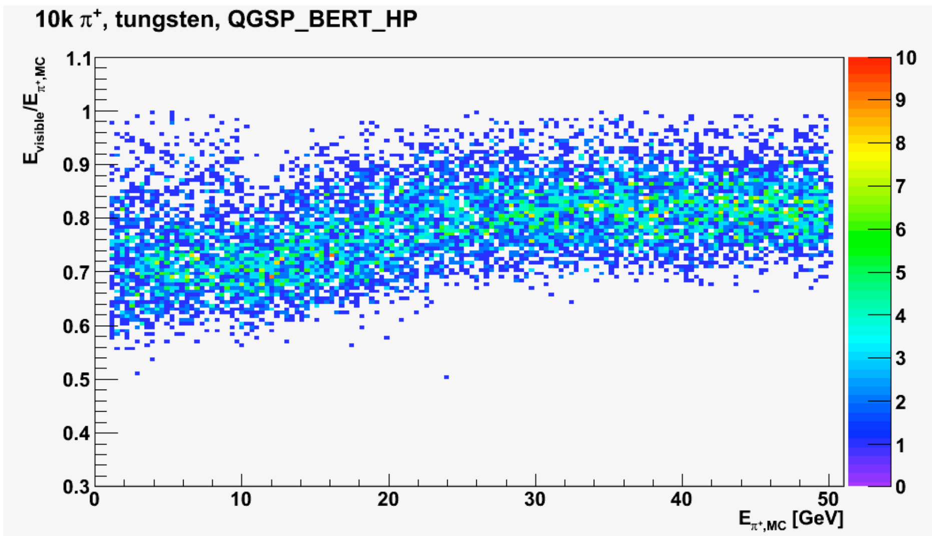
Possible Errors in Simulation

- Recently discovered: error in the GEANT4 treatment of neutrons



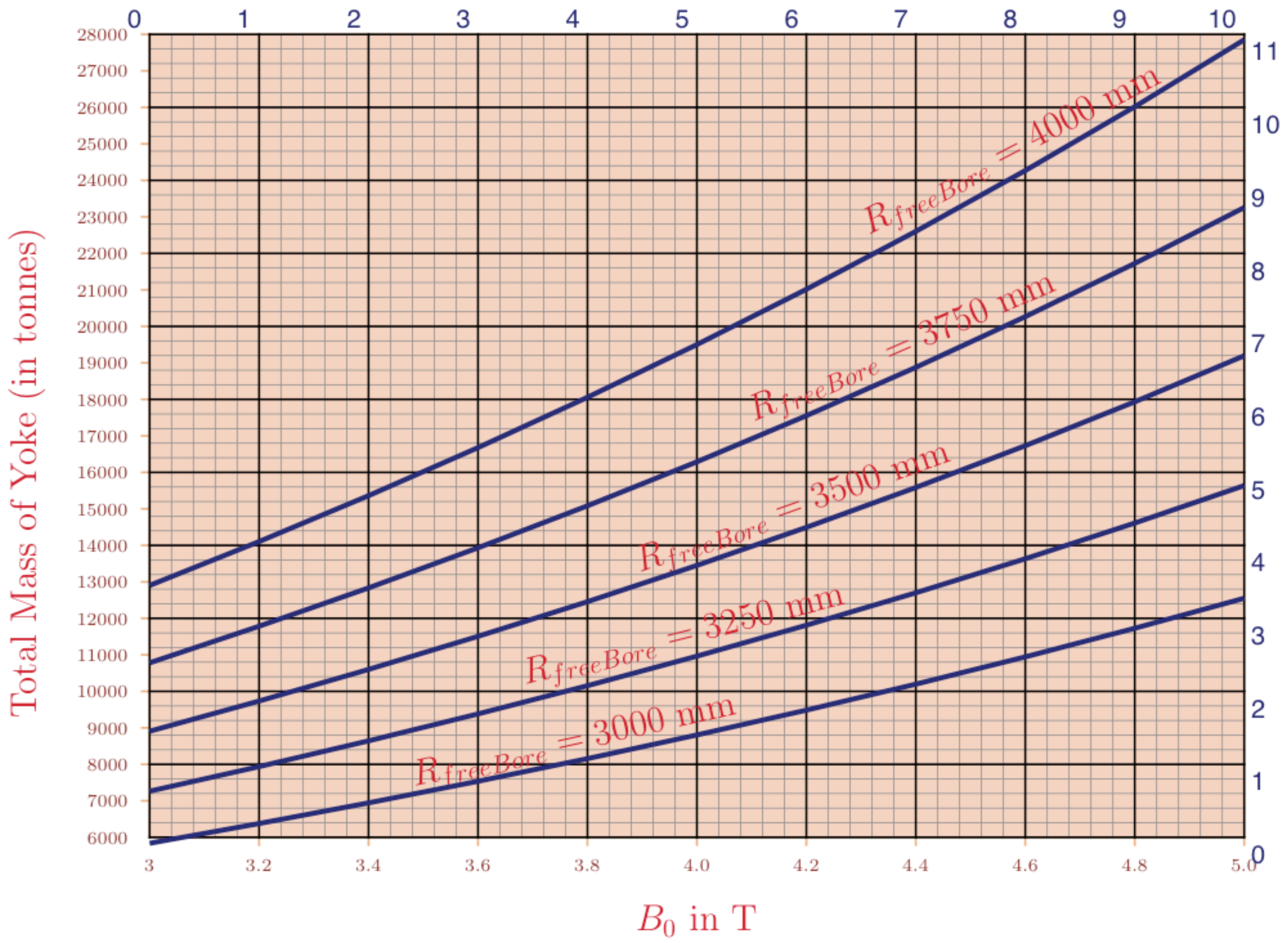


- QGSP_BERT_HP seems to solve the problem
- Need to investigate impact on shower shapes and resolution

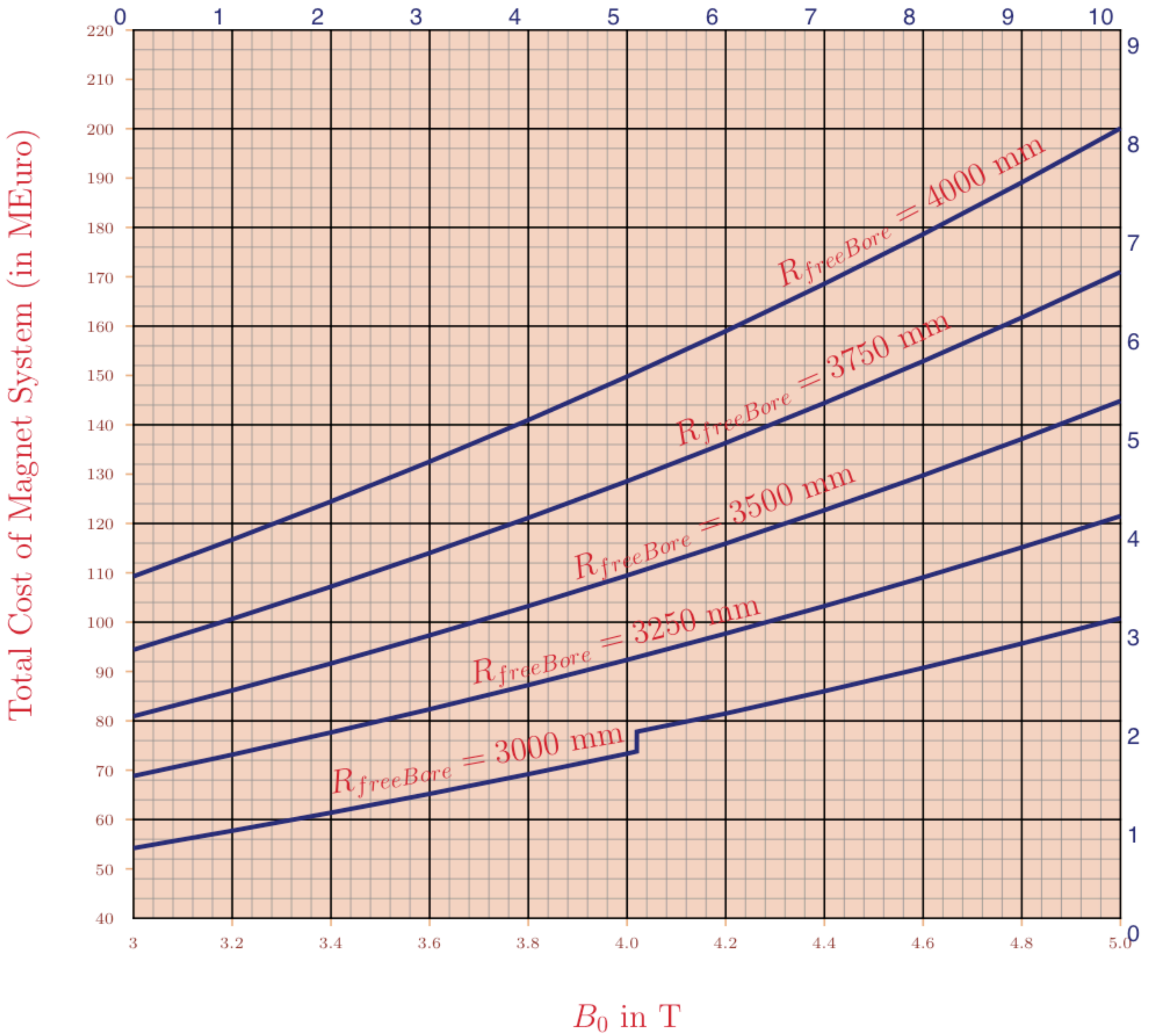


Peter Speckmayer

Coil Parametrization



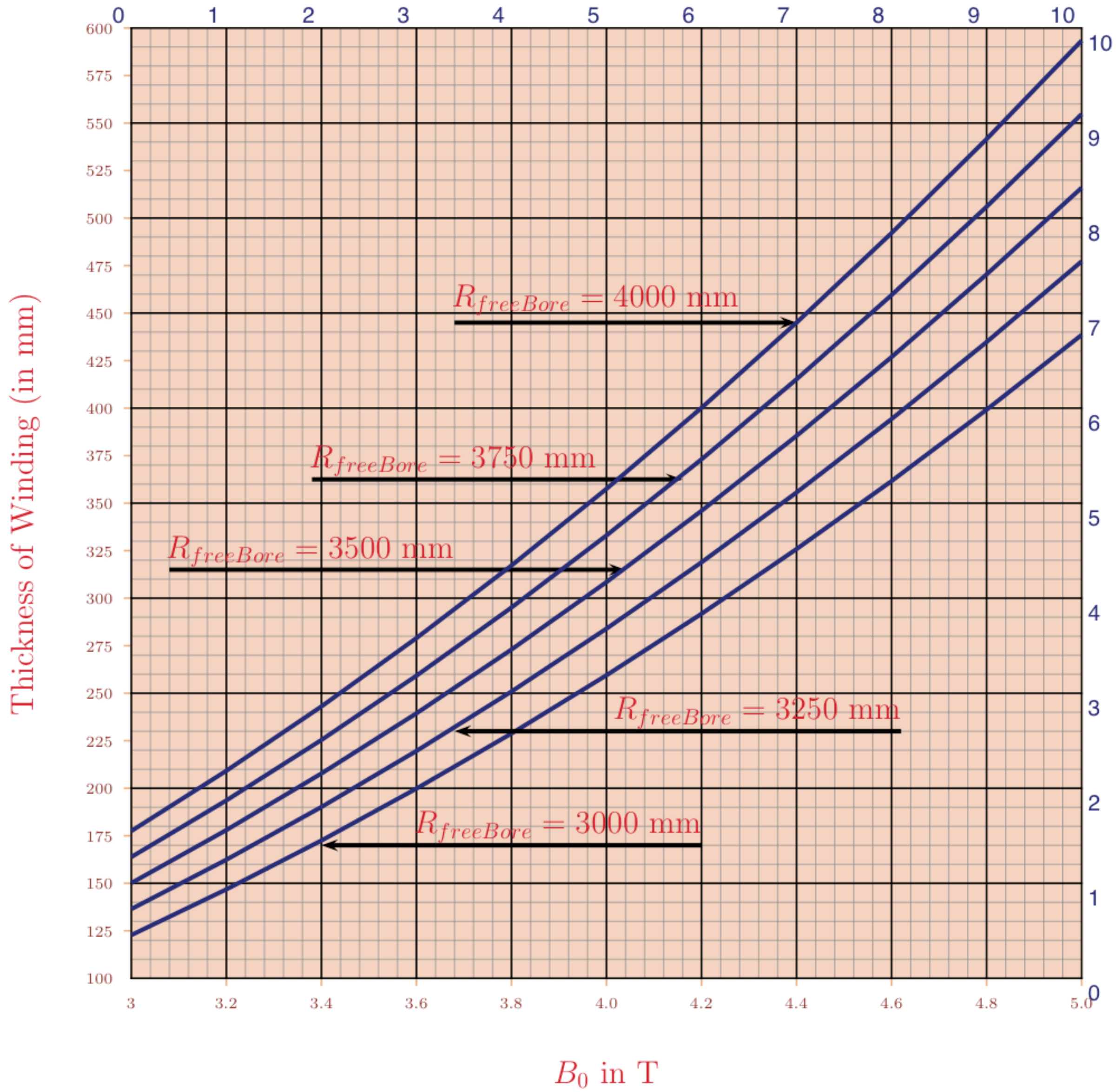
Alain Hervé



Total Cost of Magnet System (in MEuro)
B_0 in T
$R_{freeBore} = 4000$ mm
$R_{freeBore} = 3750$ mm
$R_{freeBore} = 3500$ mm
$R_{freeBore} = 3250$ mm
$R_{freeBore} = 3000$ mm

Alain Hervé

Coil Parametrization



Alain Hervé

Tungsten Properties

- Pure tungsten
  - $\rho = 19.3\ g/cm^3$
  - $\lambda = 9.94$ cm, $X_0 = 0.35$ cm
  - brittle and hard to machine

- Tungsten alloys with W > 90% + Cu / Ni / Fe
  - $\rho = 17 – 19\ g/cm^3$
  - $\lambda \approx 10$ cm, $X_0 \approx 0.4$ cm
  - Well established production procedure
  - Easy to machine
  - Price ~ 70 Euro/kg (without machining)

Tungsten Alloys

- Tungsten is usually used in alloys for better mechanical properties and machinability
- Several ferromagnetic (W,Ni,Fe) or paramagnetic (W,Ni,Cu) alloys are available

Werkstoff Material	Abkürzung Abbreviation	Chemische Zusammensetzung [%] Chemical composition [%] W	 Rest	Nominelle Dichte Nominal density	AMS-T-21014 Class
Schwach ferromagnetisch / Weakly ferromagnetic					
DENSIMET® 170	D170	90,5	Ni, Fe	17,0	1
DENSIMET® 176 / W	D176 / DW	92,5	Ni,Fe	17,6	2
DENSIMET® 180	D180	95	Ni, Fe	18,0	3
DENSIMET® 185	D185	97	Ni, Fe	18,5	4
DENSIMET® 188	D188	98,5	Ni, Fe	18,8	-
DENSIMET® D2M	D2M	90	Ni, Mo, Fe	17,2	-
Paramagnetisch / Paramagnetic					
INERMET® 170	IT170	90,2	Ni, Cu	17,0	1
INERMET® 176	IT176	92,5	Ni, Cu	17,6	2
INERMET® 180	IT180	95	Ni, Cu	18,0	3

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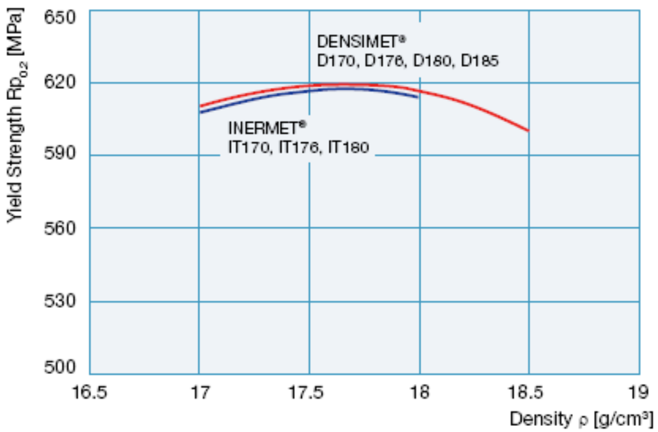
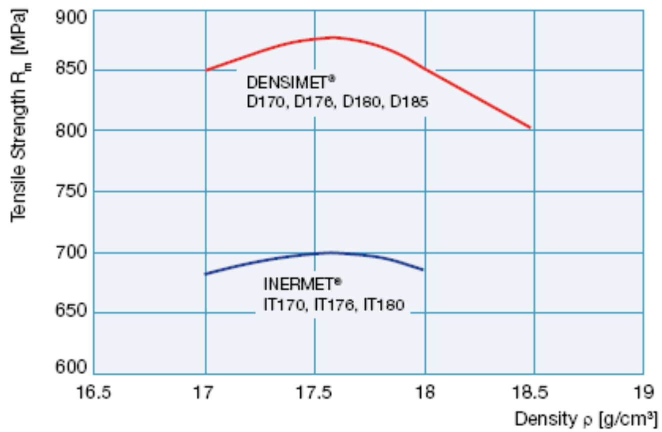
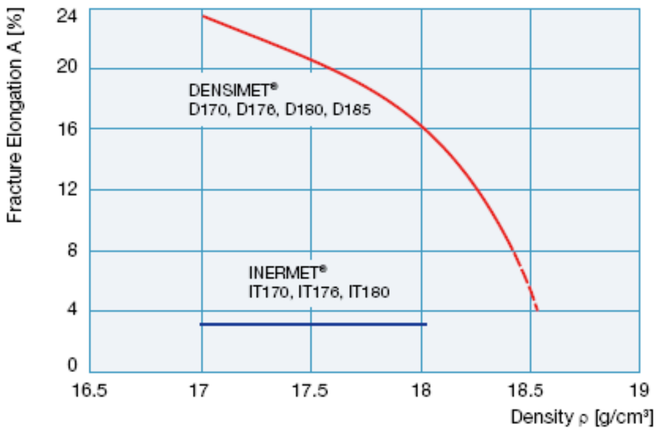
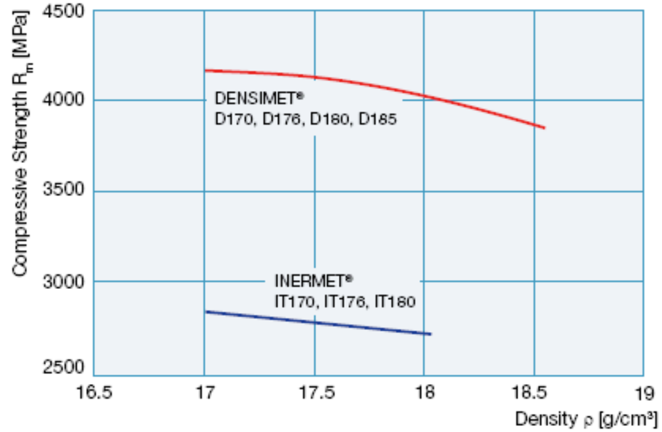
Tungsten Alloys

	D170	IT170	D176 / W	IT176	D180	IT180	D185
Elastizitätsmodul E [GPa] Young's modulus E [GPa]	340	330	360	350	380	360	385
Schubmodul G [GPa] Modulus of rigidity G [GPa]	140	125	145	135	150	140	160









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