Designing and Simulating Wavelength Shifting Geometry for the Active Helium Target

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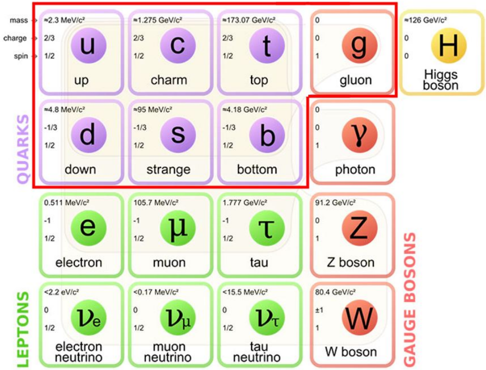
A2 Collaboration

- Nuclear physics research team based in Mainz, Germany
  - Collide real photons with target of protons and neutrons
  - Energy range of 40 MeV to 1.6 GeV
  - Interested in polarization observables - polarizabilities

Quantum Chromodynamics (QCD)

- Theory of quarks and gluons, models strong interaction



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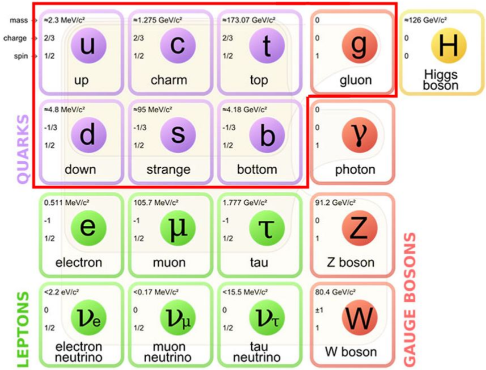

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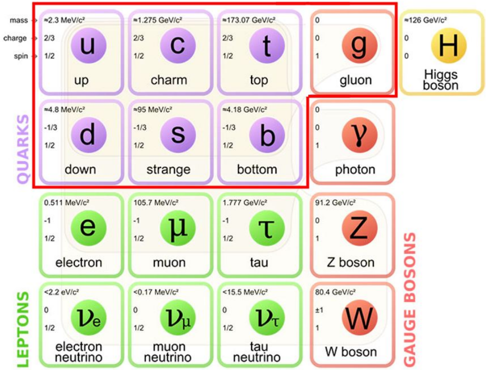
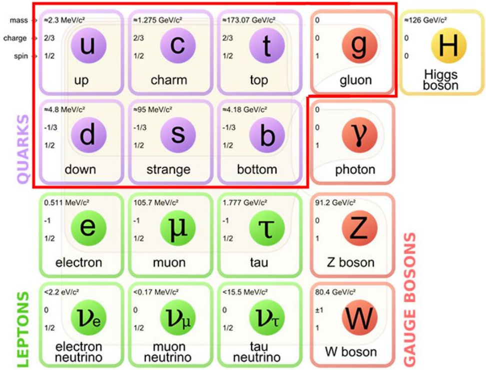


Quantum Chromodynamics (QCD)

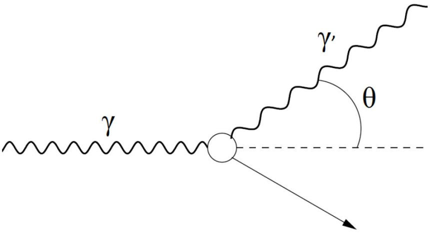
- Theory of quarks and gluons, models strong interaction
- Further exploration needed in the low energy regime (confinement)
- Polarization observables
- The scalar polarizabilities motivate this work



Scalar Polarizabilities

- Fundamental structure constants
- Similar to mass, charge, etc.
- Response of internal structure to applied EM field
- Compton scattering off nucleus

$\rightarrow$ EM field of scattered photon acts as probe



Neutron Polarizability Problem

- Neutron scalar polarizabilities not as well known as proton
- **No free-neutron target** due to short half-life (15 mins)

Nucleon	α_{E1} ($\times 10^{-4}$ fm^3)	β_{M1} ($\times 10^{-4}$ fm^3)
Proton	11.2 ± 0.4	2.5 ± 0.4
Neutron	11.8 ± 1.1	3.7 ± 1.2

[1]

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[1]

Extract neutron scalar polarizabilities via Compton scattering from Helium-3

D.Shulka, A.Nogga, and D. Phillips, NPA 819, 98 (2009)

Active Helium Target (AHeT)

- Target containing pressurized ^{3}He at 20 bar
- Placed within CB directly inline with photon beam

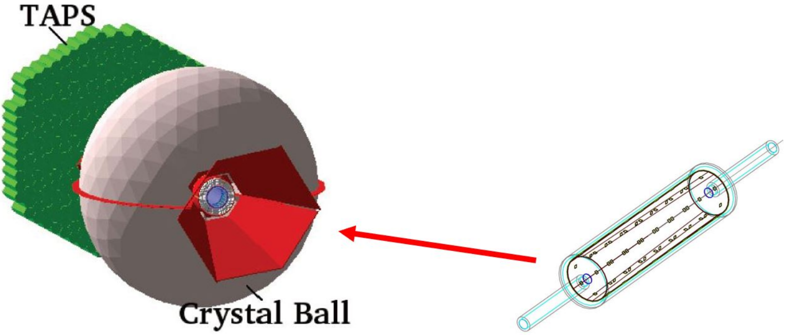
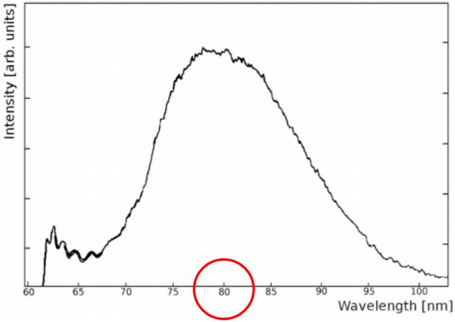


Figure from [2]

Active Component

- $\gamma + {}^{3}\boldsymbol{He} \rightarrow \gamma' + {}^{3}\boldsymbol{He}'$
- ${}^{3}\boldsymbol{He}$ initially at rest
- Ideally: $\boldsymbol{E_{miss} = E_{\gamma} - E_{\gamma'} - E_{He'} = 0}$
- He nucleus recoils and deposits all energy
- Active: gas emits scintillation (peak at 80 nm) [3]
- Light $\rightarrow$ recoil He energy
- 65 photons/1 MeV deposited?



AHeT Dimensions

- 40 cm of active volume + 40 cm extension tubes
- Outer shell of Al alloy, inner diameter: 10.2 cm
- Be windows for low background, mylar windows for beam entry/exit
- Silicon photomultipliers (SiPMs) along inner surface to collect He scintillation
- SiPM detection range 200-900 nm → *blind to scintillation!*
- Nitrogen: wavelength shifter (WLS) [3]

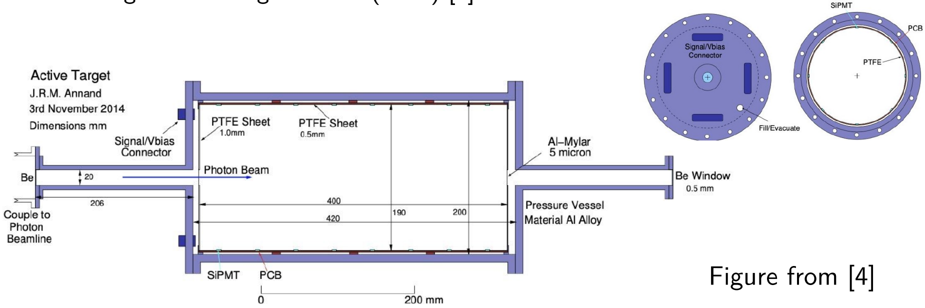


Figure from [4]

Prototype Target

- 8 printed circuit boards (PCBs)
- 18 6×6 mm diodes/PCB
- 144 SiPM diodes in total
- Smaller: 20 cm instead of 40 cm
- Reduced coverage

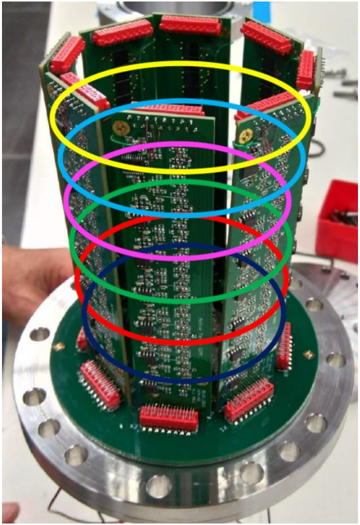


Figure from [5]

Prototype Target

- 8 printed circuit boards (PCBs)
- 18 6×6 mm diodes/PCB
- 144 SiPM diodes in total
- Smaller: 20 cm instead of 40 cm
- Reduced coverage
- Testing with α source and N_2 as WLS (2019)
- Light collection problem!

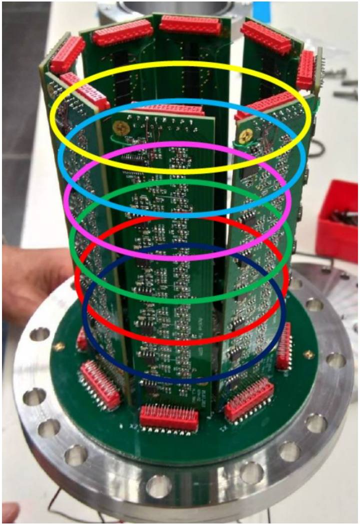
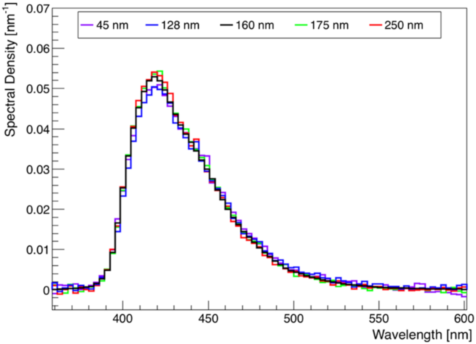


Figure from [5]

Investigating Wavelength Shifting

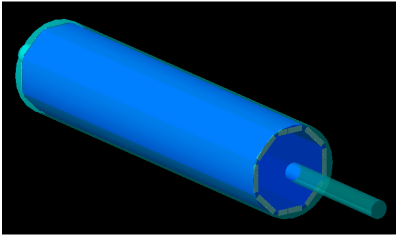
- SiPMs PDE of 420 nm → He scintillates at 80 nm
- N_2 insufficient on its own [5]
- Tetraphenyl Butadeine (TPB)
  - organic compound used as WLS in noble gas experiments
  - Mike Perry, B.Sc. 2020
  - florescent peak at 430 nm
- Coat on material that covers large solid angle
  → less light escapes!



Reemission spectra of a 1.8 μm TPB film for several incident wavelengths. No dependence on incident wavelength was observed [6].

WLS Geometry with TPB - Plates

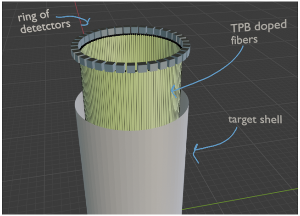
- Coat plates in TPB, run them down cylinder axis
- Plates are bigger than SiPMs, would either need to:
  1. Connect each plate to several SiPMs
  2. Taper down each end so that they are 6x6 mm



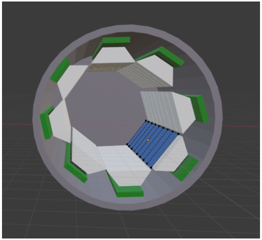
TPB coated plates from Geant4

New WLS Geometry with TPB

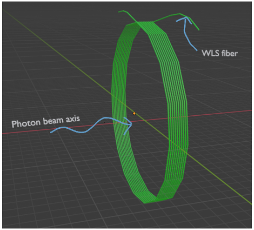
Fiber Barrel
TPB doped fibers



Acrylic Light Guides
coated in TPB



Helix
TPB doped fibers



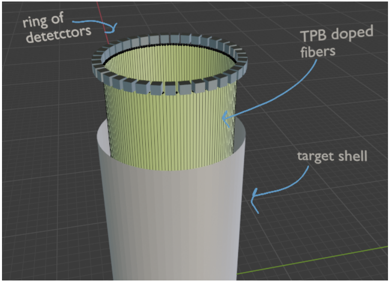
- Custom order TBP doped fibers from St Gobain

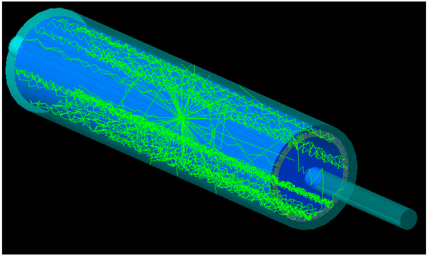
Fiber Barrel Design

- 6 mm TPB doped fibers run down the cylinder axis in a barrel
- Ring of SiPMs at either end
- Each fiber connects to two diodes (6x6 mm each)
- Attenuation:

$$I_z = I_0 e^{\frac{-z}{\lambda}}$$

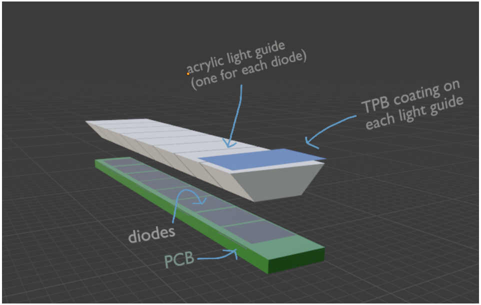
- $\lambda \approx 399$ cm (Kuraray)

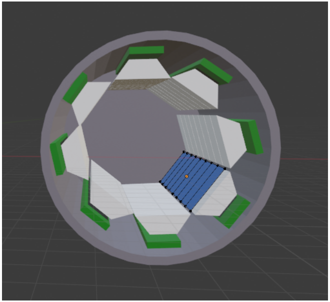




Acrylic Light Guides

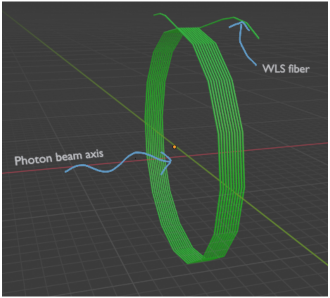
- One acrylic light guide placed on each diode
- Layer of Tetraphenyl butadiene (TPB) on the light guides

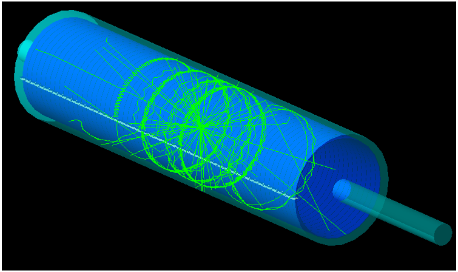




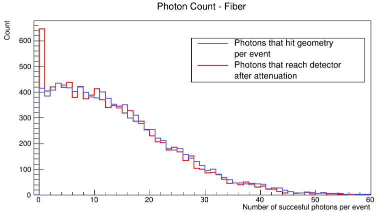
Helix Design

- 0.5 mm TPB doped fibers wrapped 12 times into a spiral (1 mm $\rightarrow$ cracking)
- More wraps = more attenuation
- Each end of helix feeds into a SiPM
  - Geant4 treats each helix like a ring
  - Small cut with each side coupled to SiPM
- Each helix covers a 6 mm section of the z-axis of the target

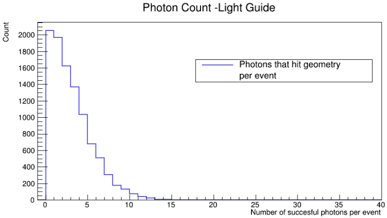


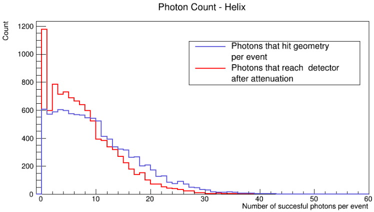


Simulations - Monte Carlo Code Results



- Standalone MC code for preliminary testing
- Sample of each WLS geometry
- Used Event Generator (EvGen) file as input $\rightarrow$ these use Compton at 150 MeV
- Acrylic light guides had low photon yield - throw out this design

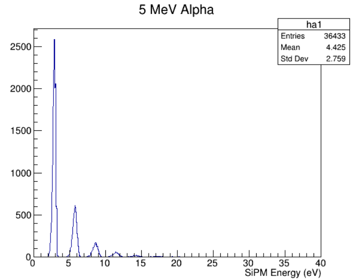


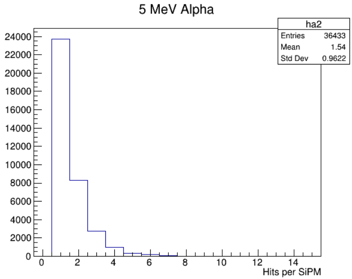


Simulations - A2Geant4

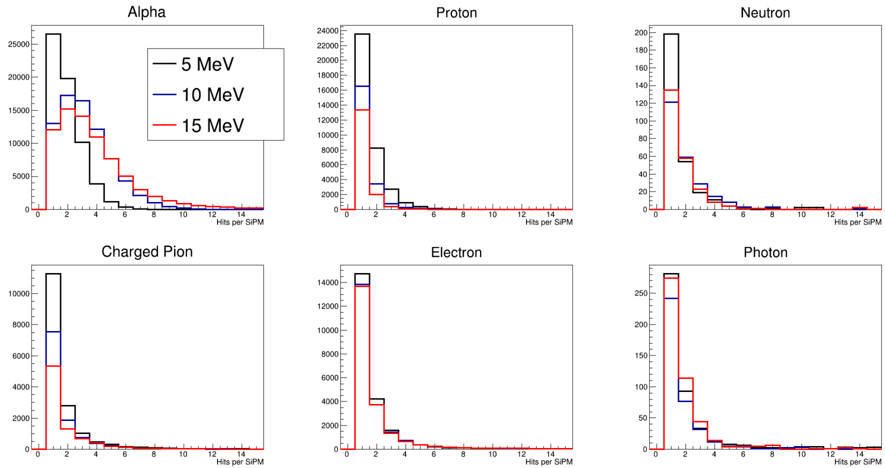
- A2Geant4 simulations
  - more rigorous testing
  - barrel, helix, and plate designs coded in Geant4 by Phil
- Looking at scintillation yield for:

1. simply throwing a particle with certain energy in any direction to see how target reacts
2. using an EvGen file as input





Fiber Barrel - Throwing Particles



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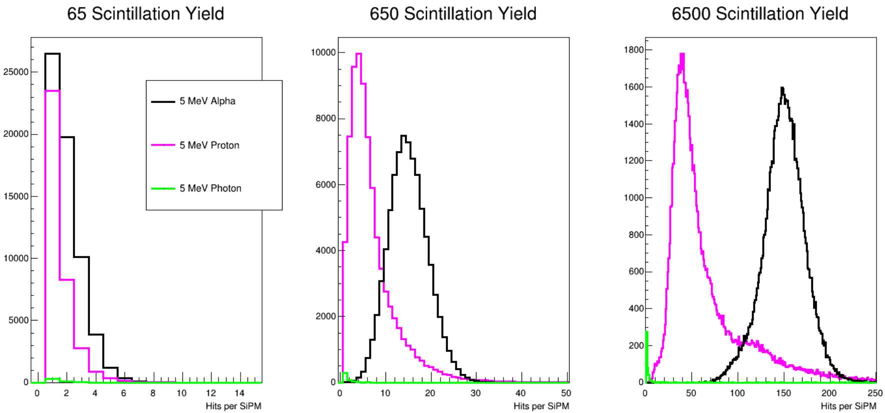
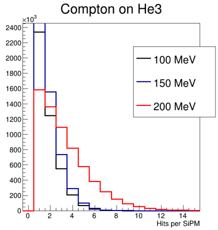
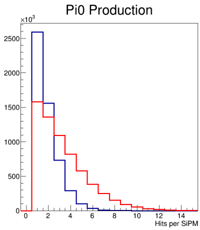
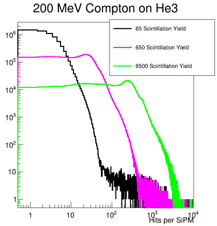


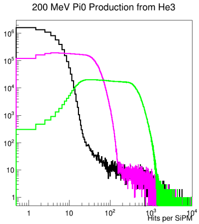
- Vary scintillation yield for alpha and main background particles

Fiber Barrel - EvGen File as Input



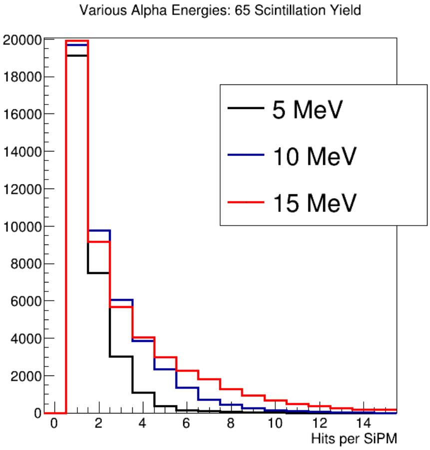


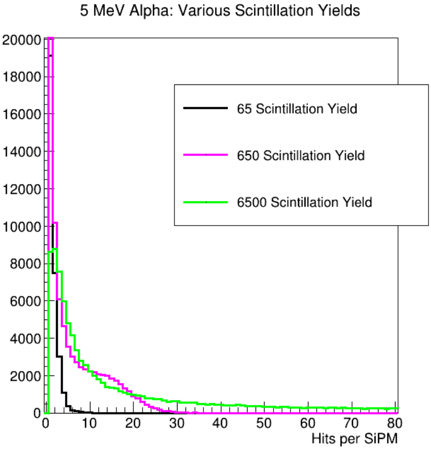




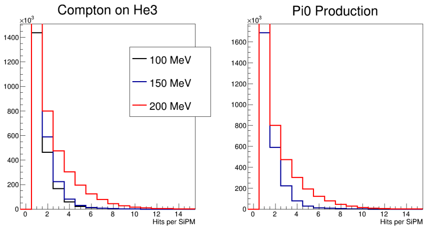
- Keep 65 scintillation yield constant
- Keep 200 MeV photon beam constant

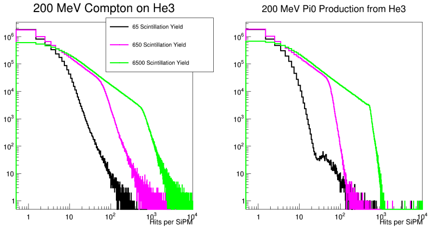
Helix - Throwing Particles





Helix - EvGen File as Input





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Outlook

- Active Helium Target to measure neutron scalar polarizabilities
- Did preliminary tests to get output estimate for each design
- Present: in-depth tests in Geant4 with full geometry
- Promising results $\rightarrow$ different mean hits per SiPM per event for different particles

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- Promising results $\rightarrow$ different mean hits per SiPM per event for different particles
- However:
  - Success of the target is dependent on scintillation yield
  - TPB doped and coated materials are used by many collaborations $\rightarrow$ borrow materials and run physical tests in the target

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- However:
  - Success of the target is dependent on scintillation yield
  - TPB doped and coated materials are used by many collaborations $\rightarrow$ borrow materials and run physical tests in the target
- Decide on WLS geometry based on the results of these simulations

Thank You!

Thanks to...

- Dr. David Hornidge
- Big thank you to Phil at the A2 Collaboration
- NSERC for funding

References

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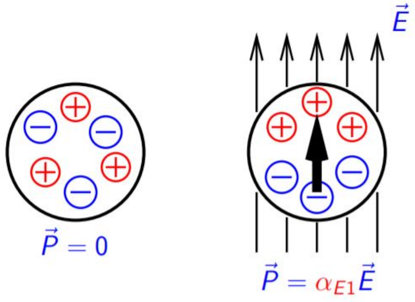
Extra Slides

Electric Polarizability, α

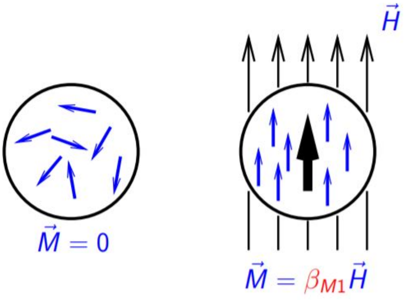
- Particle's response to an external electric field
- $\alpha \rightarrow$ proportionality constant between induced electric dipole moment **p** and applied electric field **E**
  - Electric polarizability $=$ "stretchability"



Separation of internal charge

Magnetic Polarizability, β

- Particle's response to an applied external magnetic field
- $\beta \rightarrow$ proportionality constant between induced magnetic dipole moment **m** and applied magnetic field **B**
  - Magnetic polarizability = "alignability"



Internal magnetic moments align with ***B***

Note: $\beta = \beta_{para} + \beta_{dia}$

Previous Design

- Target from MAX-lab in Lund, Sweden
- Used N_2 as a WLS and PMTs
- Too small for CB, not designed with scattered photon exit in mind

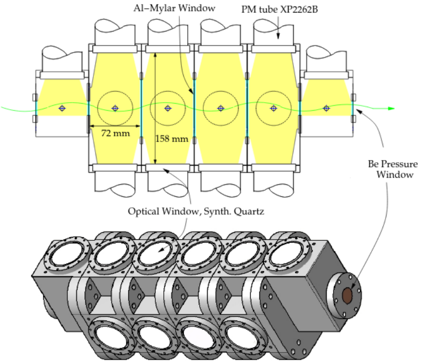
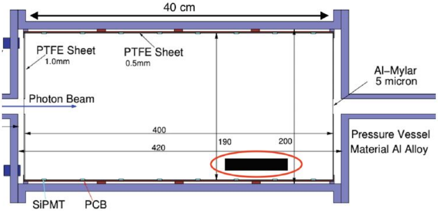


Figure from [3]

AHeT - Nitrogen Tests

- Detected event when α source is placed directly on SiPM
- When placed in middle of volume, detection yield fell greatly [5]
- N_2 is not sufficient on its own



WLS - TPB doped Fibers

- Saint-Gobain - produce a variety of plastic scintillating, wavelength-shifting and light-transmitting fibers
  - BCF-12
  - Peak absorption isn't VUV (only mid 300 nm)
  - Emits blue light (435 nm)
  - SiPMs have detection peak at 420 nm
  - Have to dope them in TPB
- TPB doped fibers used in DUNE experiment (D.L. Adams et al. 2018)
- Have to take attenuation into account

Attenuation Calculation

- Transmission loss, reduction in intensity w.r.t distance travelled (z) in fiber
- Due to reflection and absorption
- Attenuation length (λ) estimate = 399 cm

$$I(z) = I_0 e^{\frac{-z}{\lambda}}$$

- where P_z is final photon output, P_0 is initial photon input, and z is distance travelled in fiber

Possible Design Modifications (Ring and Barrel)

- If low light collection - couple many fibers to each SiPM
- Note: helix is limited by attenuation, not SiPM size

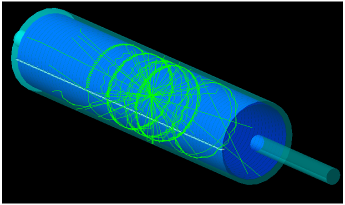
Fiber size	**Fibers per SiPM**	**Effective 'plate'**
6 mm	1	6 mm
3 mm	4	12 mm
2 mm	9	18 mm
1 mm	36	36 mm

Table: Possible fiber to SiPM couplings for the barrel and ring designs.

Barrel vs. Helix

Barrel

- Simple, no cracking
- Insignificant attenuation



Helix

- Risks cracking
- Significant attenuation
- Vertex reconstruction
- Could make '**ring**' of 12 fibers, line of diodes in slice
  - Benefits of helix without complicated winding and attenuation
  - See Geant4 image

Barrel vs. Helix

Pacticle Type	5MeV 65	5MeV 650	5MeV 6500	10MeV 65	10MeV 650	10MeV 6500	15MeV 65	15MeV 65	15MeV 6500
Alpha	1.847	14.771	147.970	2.916	27.879	268.675	3.220	30.592	289.863
Proton	1.113	6.003	56.711	1.005	3.220	29.225	0.903	2.430	21.072
Neutron	0.012	0.042	0.303	0.007	0.031	0.163	0.009	0.022	0.231
Pion	0.752	1.880	14.502	0.430	1.289	6.498	0.276	1.185	4.731
Electron	1.100	1.140	2.001	1.099	1.143	1.983	1.082	1.118	1.996
Photon	0.019	0.023	0.024	0.018	0.025	0.044	0.021	0.027	0.024

Table: Results for different particles thrown in the barrel design.

Particle Type	5MeV 65	5MeV 650	5MeV 6500	10MeV 65	10MeV 650	10MeV 6500	15MeV 65	15MeV 650	15MeV 6500
Alpha	1.114	4.029	14.500	1.839	5.462	27.626	2.089	6.406	40.388
Proton	1.042	2.920	10.085	0.978	2.255	7.825	0.883	1.804	6.354
Neutron	0.010	0.033	0.100	0.006	0.018	0.018	0.006	0.010	0.085
Pion	0.617	1.424	4.811	0.259	1.077	3.212	0.135	1.026	2.660
Electron	1.031	1.094	1.460	1.002	1.032	1.444	0.935	1.080	1.353
Photon	0.003	0.006	0.023	0.001	0.006	0.010	0.016	0.003	0.013

Table: Results for different particles thrown in the helix design.

Factors that Contribute to Signal

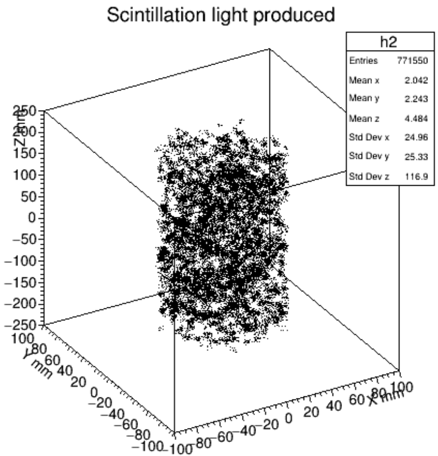
- Beam radius can be changed. This changes solid angle covered by each sample geometry
- Photon beam energy- changes recoil particle energy - changes photon output
- Each end of the fibers need to got to different detectors to discern background from actual events.

Event Generator (EvGen)

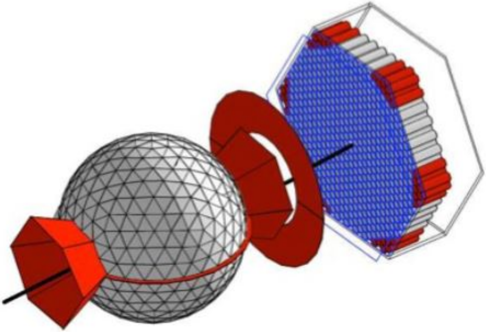
- Written by Dr. David Hornidge
- Event generator for Compton scattering and pion-production
- Currently does H, C, He3, He4 targets
- Valid for $E_\gamma = 0 - 400$ MeV
- Returns scattered photon energy + angle, recoil particle energy + angle, etc.

Monte Carlo Code

- Assumptions:
    1. He recoil nucleus scintillates entirely at the point of interaction
    2. 65 photons per MeV of energy deposited
- Give event position, then use EvGen file to define recoil He energy based on spectrum
- Track trajectory - light output for each sample
- Sample defined as material for one diode

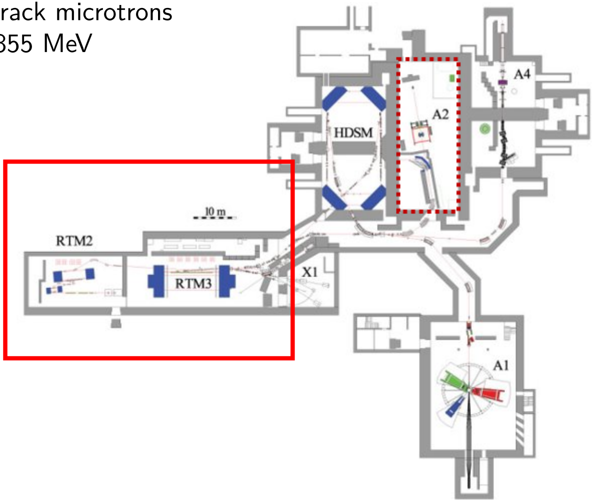


CB TAPS



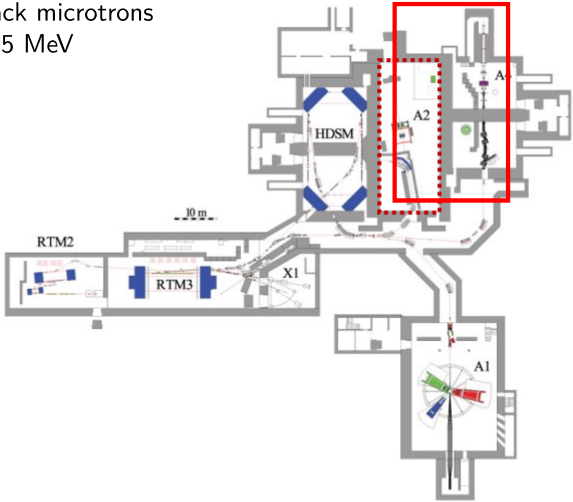
The Mainzer Mikrotron (MAMI)

- 3 Race-track microtrons (RTM) 855 MeV

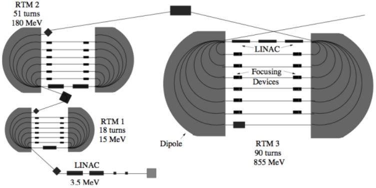


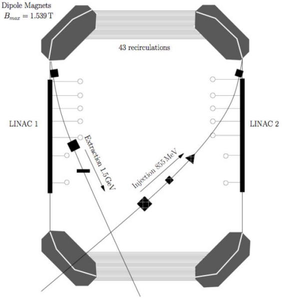
The Mainzer Mikrotron (MAMI)

- 3 Race-track microtrons (RTM) 855 MeV
- A2 hall



MAMI- RTMs and HDSM





- LINACs - alternating voltage to accelerate electrons
- RTM - magnets bend beam 180°, recirculate beam through LINAC multiple times
- As energy ↑, so does beam path
- HDSM - 4 magnets each bend beam 90○

Photon Tagging

- After electrons radiate photon, bent by dipole magnet and hit Tagger
- Landing position depends on energy
- Timing coincidence between electron hit and event
- $E_\gamma = E_{beam} - E_{electron}$