Can we magnetize the DUNE Far Detector?

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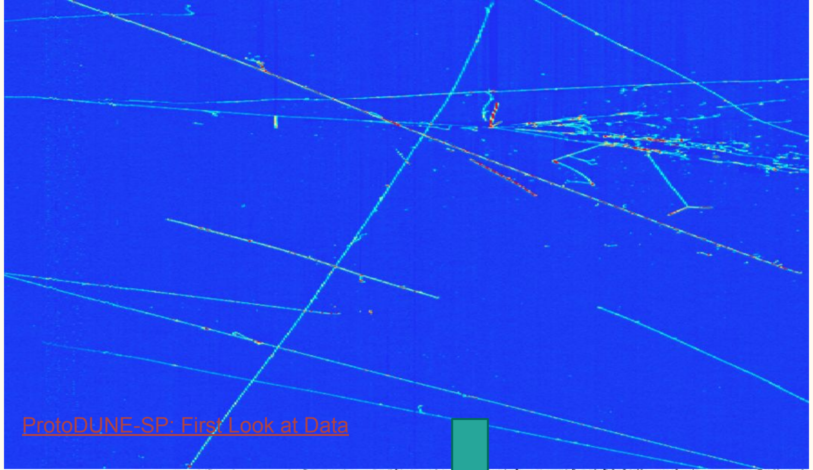
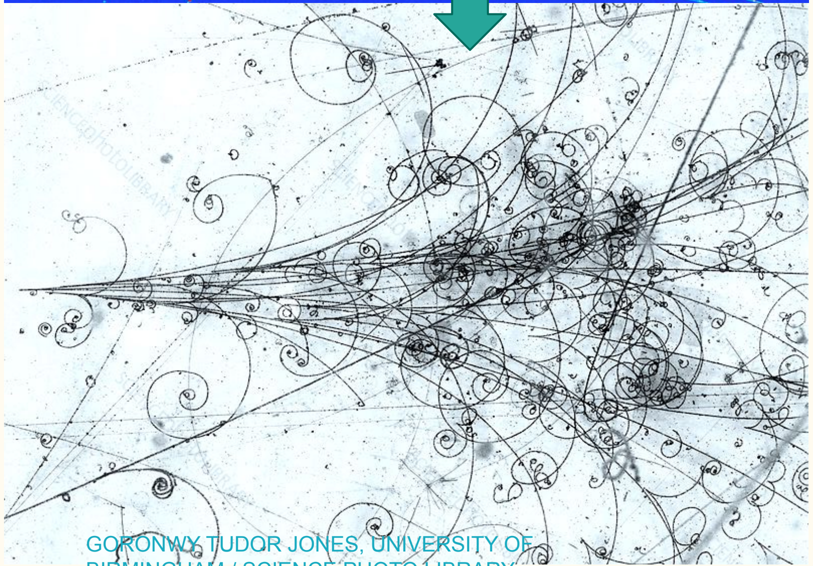
Problem

Suppose you wanted to magnetize the future DUNE detector to allow for 3σ particle-by-particle electron vs. positron separation at 2 GeV. How large a field is required? Compare the energy stored in the field to the total energy used by the residents of Lead, SD in a single day. Suggest how you might construct such a field and estimate the cost of the materials required.



ProtoDUNE-SP: First Look at Data



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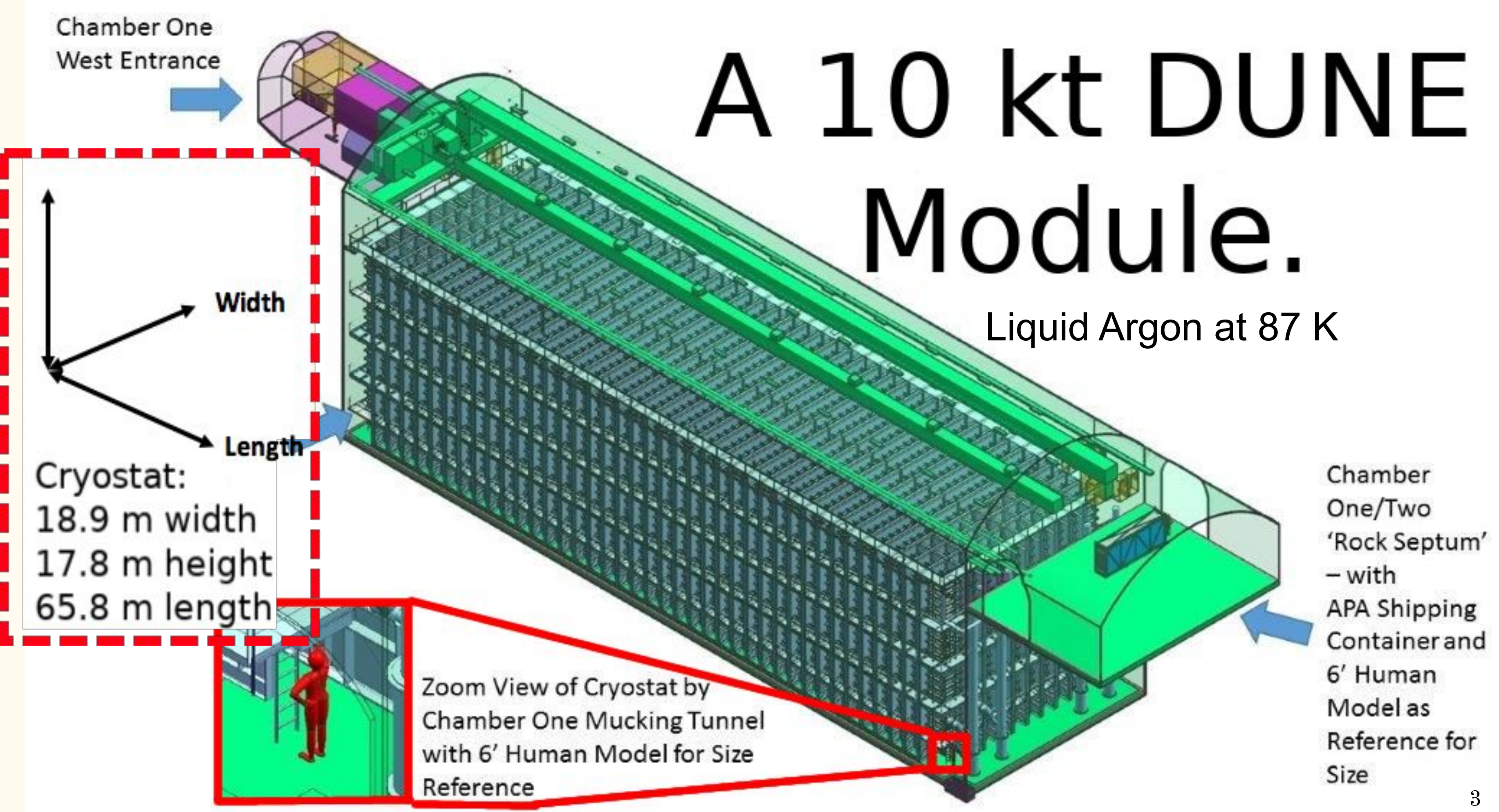
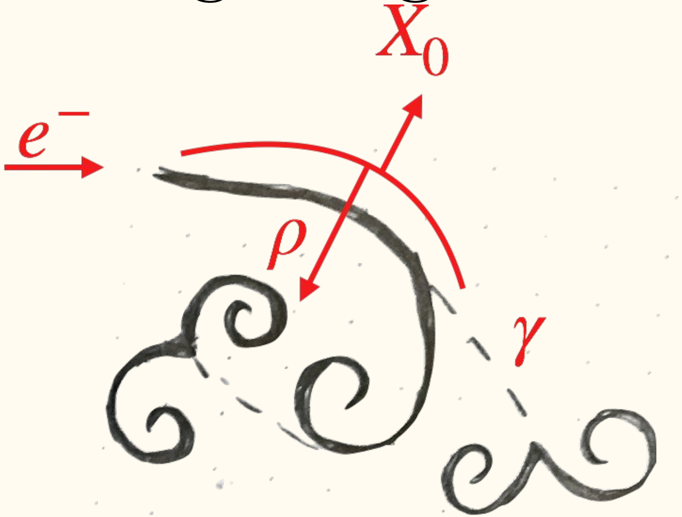
A 10 kt DUNE Module.

Liquid Argon at 87 K



How large magnetic field is required?



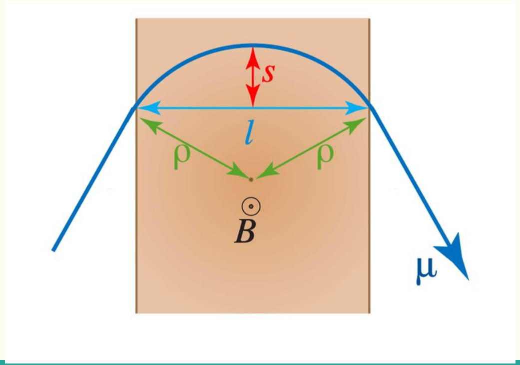
$$\sigma^2_{k,R} = \frac{\epsilon^2}{L^4}\frac{720}{N+5}$$ [1]

$L=X_0$ =14 cm (radiation length)
ϵ = 4.8 mm (uncertainty of position using spacing between anode wires)
$N=X_0/\epsilon$ =29

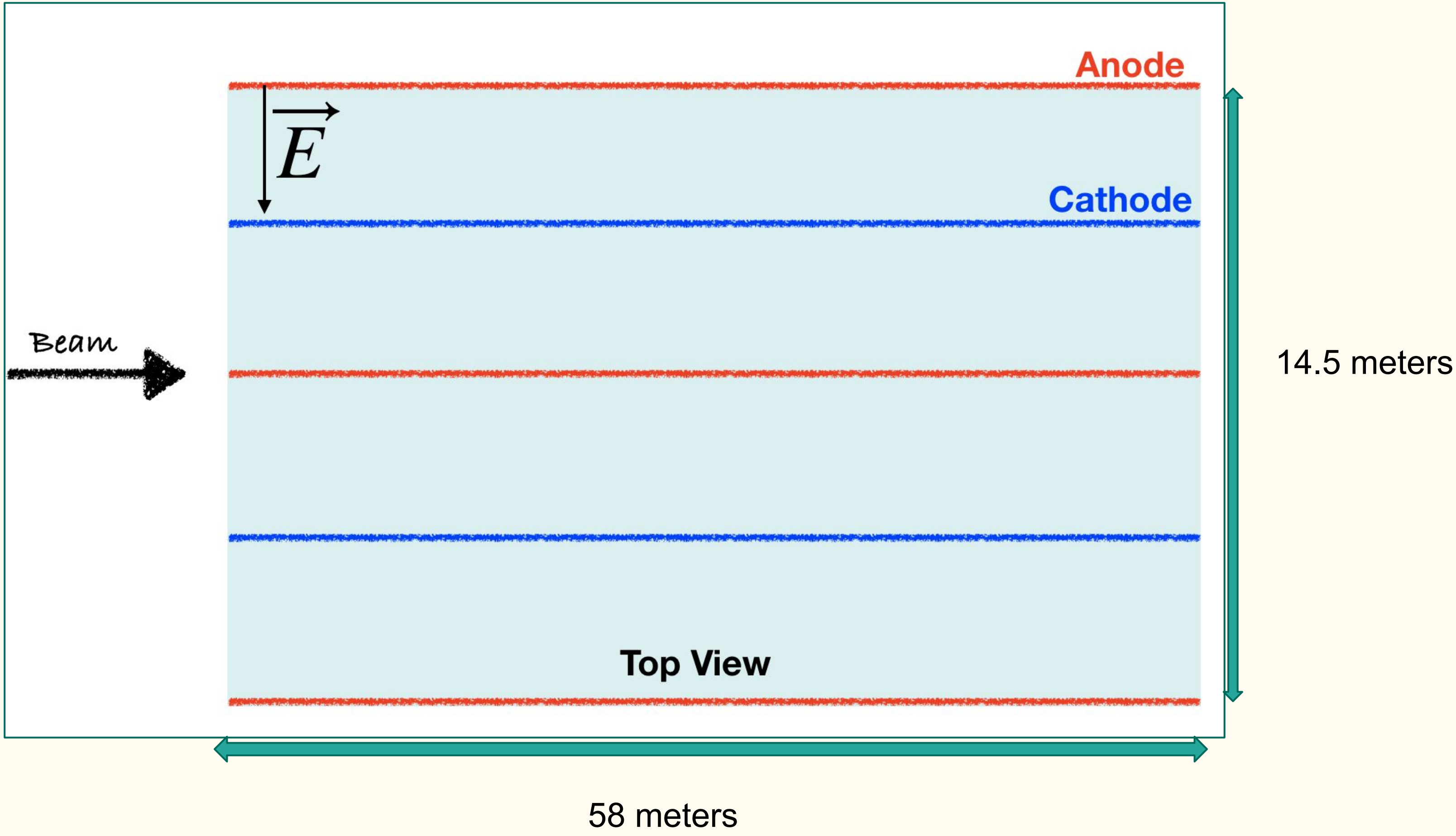
σ^2=1.27e-6 mm^{-2}

p=0.2998Bρ, ρ=1/k -> **B=11T**

To get 3σ we calculated $\chi^2=(k_{th}-k_{obs})^2/\sigma^2=(2k)^2/\sigma^2=3^2$

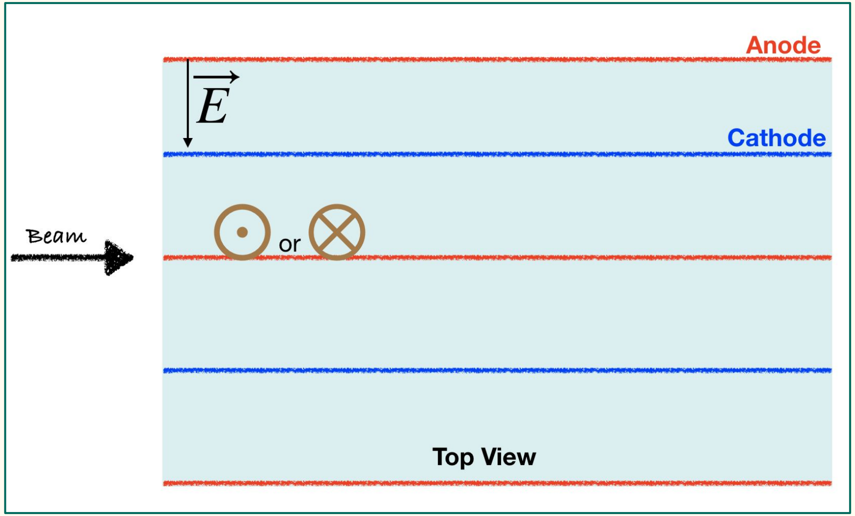


TOP view of the detector



Orientation of the magnetic field

Magnetic field vertical to the electric field is chosen. Both the drifting particle and the beam particles will do circular motion in this magnetic field.



Effect from drifting electron

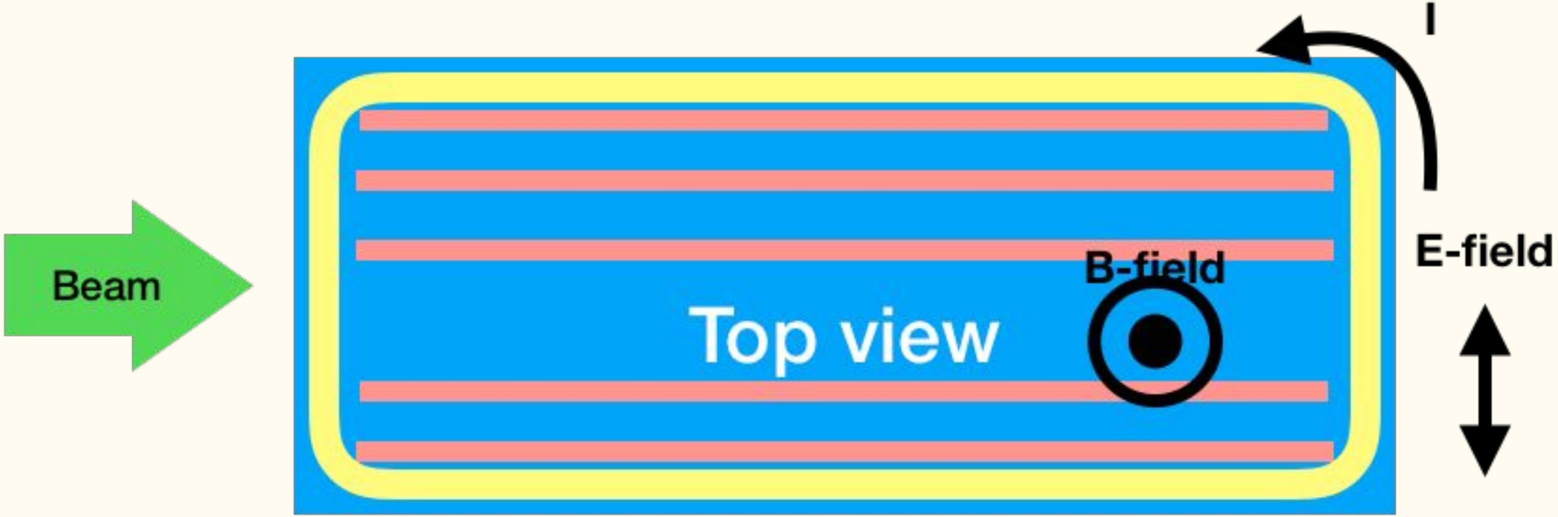
Under $\vec{E} = 500V/cm$, drift velocity is v=1.6mm/μs.
Magnetic force acts as centripetal force:

$$\vec{F} = q\vec{v} \times \vec{B} \qquad evB = \frac{mv^2}{r}$$

The radius of curve is $\approx 1.32 \times 10^{-9}$ neter.
Much smaller than the spatial resolution of detector !

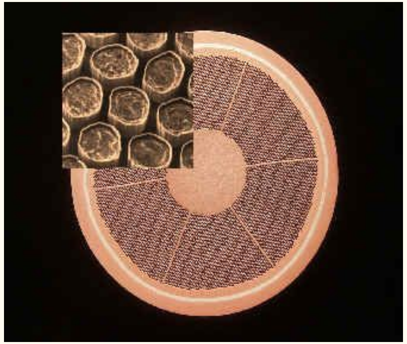
Reasons of choosing this $\overrightarrow{B}$ field

- Coil wrapped parallel to the walls of the detector more feasible
- Alternative loop direction more difficult to construct (weight of detector would be on top of the coil)



Comparison with other solenoids

NbTi superconducting wire
(Tc = 10 K)



	ATLAS	CMS	DUNE
Wire length (km)	9	62	505
Current (kA)	8	19.5	30
Magnetic field (T)	2	3.8	11
Energy stored (GJ)	0.045	2.3	126
Cost ($ million)	**14**	**93**	**760**

[4]

Energy Stored in the Magnetic Field

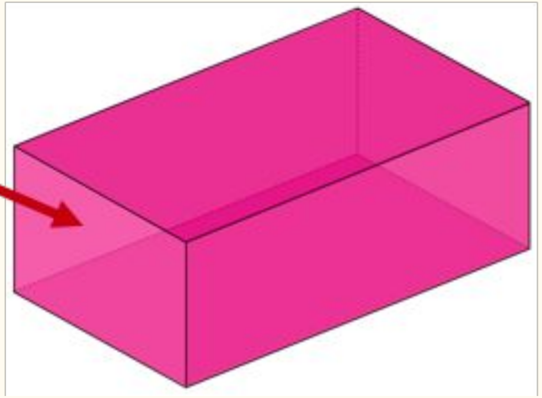
$$E = \frac{B^2}{2 \times \mu_o} \times V$$

V = Active Volume of the DUNE Detector

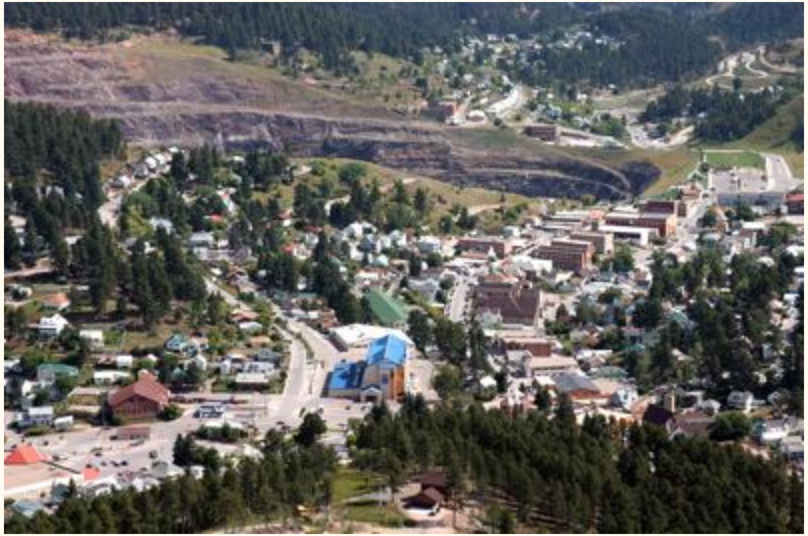
$$V = length \times width \times height$$
$$= 12m \times 14.5m \times 58m$$
$$= 10092.0m^3$$

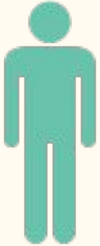
$$E = 1.26 \times 10^{11} Joules$$

Energy due to the B field stored in inside the active volume of the detector.



Comparison with the Energy Usage of Lead, SD





Population of Lead = 2978 [2]

Electric energy usage per person = 10.01 MWH [3]

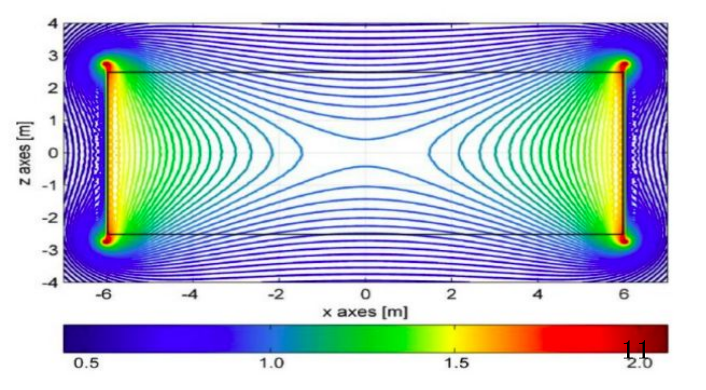
Electricity Used by the City of Lead Residents in 1 Day:

$$7.2 \times 10^{11} Joules$$

Other considerations

- This is assuming electron/positron are moving in the beam direction.
- With the direction of the B-field, the way the tracks bend will also have timing uncertainty
- The weight of the coil might distort the B-field over time.
- Design and cost of the liquid He circulating system.
- Reduced fiducial volume with uniform magnetic field?
- Price of liquid Helium (~$17/liter) needed to keep the wire at ~ 4 K
- Insulator cost

[5]



Conclusion

- ~$760 M (for just the wire!) per cryostat.
    - Keeping wires in superconducting temperature is another cost driving factor that we haven't accounted here.
- DOE recommended range of $1.255 billion to $1.862 billion.
- Multiply by 4 to magnetize all DUNE cryostats ! 🤑
- The factors we didn't take into account could drive up the cost. [9]
- However this is possible (at least to a smaller scale) [10]

References

[1]. Neutrino Detection I, Mark Messier, INSS 2019

[2]. United States Census Bureau, 2017 census

[3]. https://www.eere.energy.gov/sled/#/

[4]. https://www.lhc-closer.es/taking_a_closer_look_at_lhc/0.magnets___detectors_i

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[7]. Long-Baseline Neutrino Facility (LBNF) and Deep Underground Neutrino Experiment (DUNE) Conceptual Design Report, Volume 4 The DUNE Detectors at LBNF, [arXiv:1601.02984]

[8]. https://lhc-machine-outreach.web.cern.ch/lhc-machine-outreach/components/cable.htm

[9].https://web.fnal.gov/organization/OPSS/Projects/LBNFDUNE/LBNF%20APM%20Jul%202015/Review%20Documents/LBNF%20DUNE%20ICR_Final%20Report.pdf

[10]. https://arxiv.org/pdf/physics/0412080.pdf

[11]. https://www.sciencedirect.com/science/article/pii/0011227582901345

Backup

Backup: Approximate Cost of Solenoid

From $B = \mu n I$, taking our current as 30 kA, the number of turns per length is 290.

We need turns all the way up the height of the active volume: 290 turns/m x 12 m = 3,480 turns.

Each turn has length 2 * 14.5 m + 2 * 58 m = 145 m. Multiplying by the number of turns gives a total length: Ltot = 505 km

If the wire has a width of 4 cm and is made of Nb (8.6 g/cm^3), Ti (4.5 g/cm^3) and Cu (9 g/cm^3), we can calculate the total mass

8000 kg/m^3 * 505,000 m * pi * (0.02 m)^2 = 5,075,000 kg

Cost of NbTi wire = $150/kg -> Total Cost: $760 million 😟

NbTi characteristics [11].

Table 1. Small copper/NbTi composite conductors[17]

Conductor	Overall diameter, mm	Copper/NbTi ratio	Number of filaments	Computed diameter of individual filaments, μm
a	0.17	0.7	1	127
b	0.51	2	54	40
c	0.64	1.8	180	28

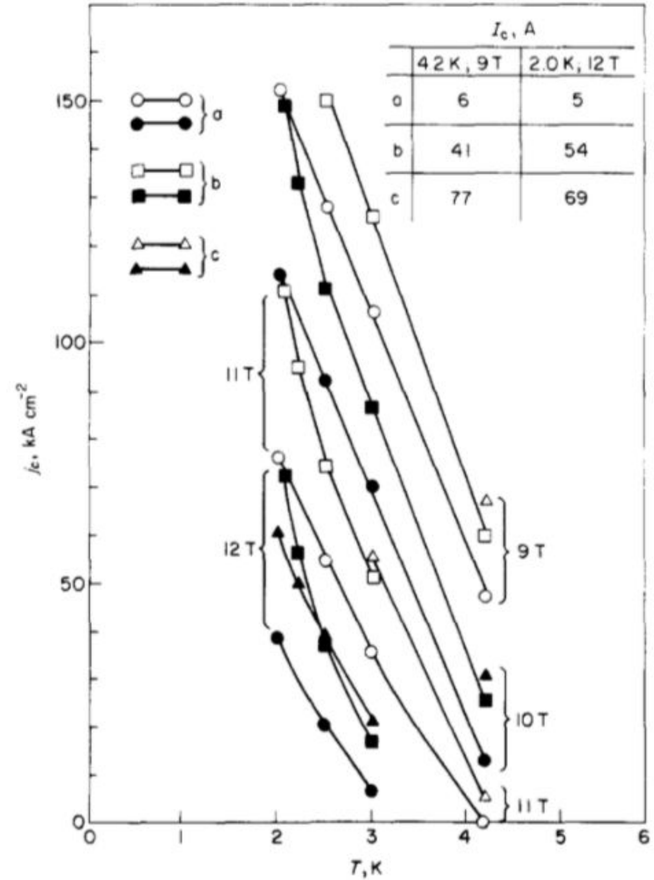
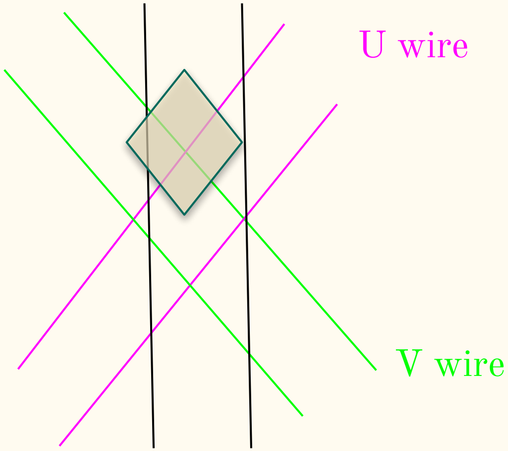


Fig. 1 j_c vs T plots at constant background fields for the three small conductors listed in Table 1

Why is the uncertainty $\epsilon \sim 4.8$mm?



U, V, X wire spacing: 4.8mm

We want to argue that:

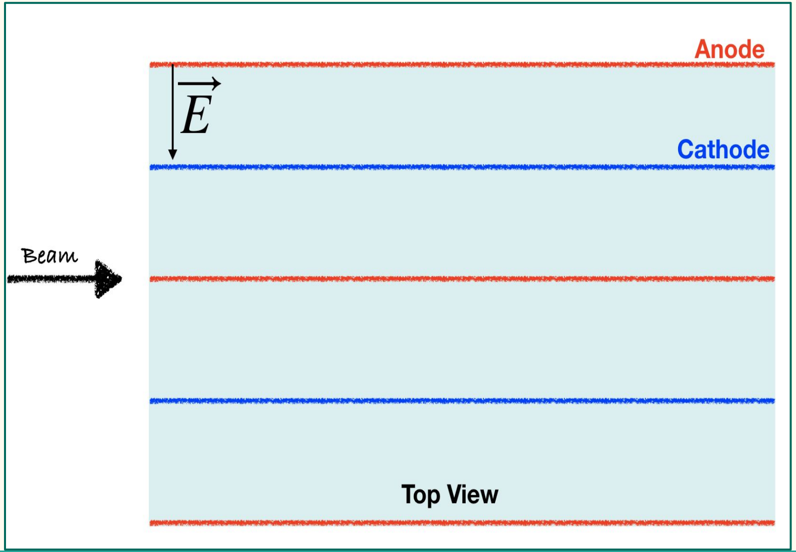
If we only have U,V wires, our resolution would be worse than 4.8 mm (as seen in the gray area)

But if we could get readout from all three wires, the extra X wire will limit our uncertainty to 4.8mm. [7]

Which orientation of magnetic field should we use?

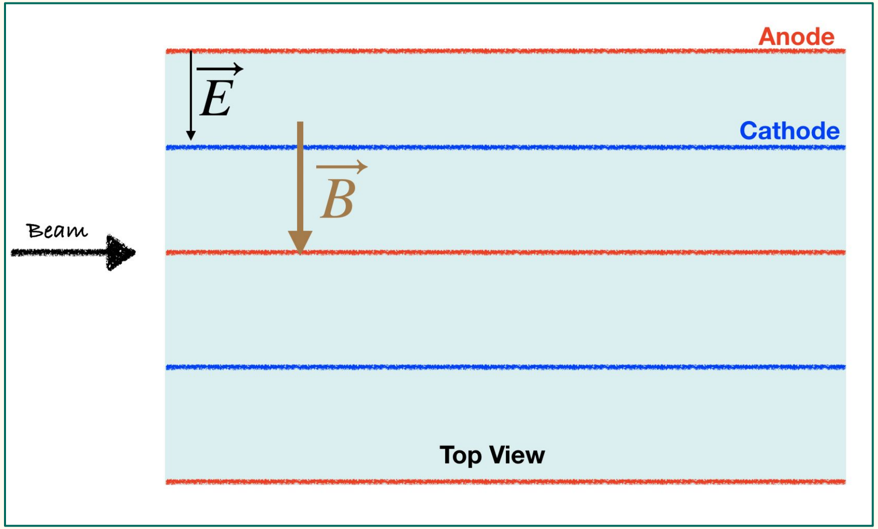
The magnetic field lines have to be perpendicular to the beam direction to curve the track of the charge particle e^{-}/e^{+} We have two options:

1) Magnetic field lines parallel to the drift field line
2) Magnetic field lines perpendicular to the drift field line



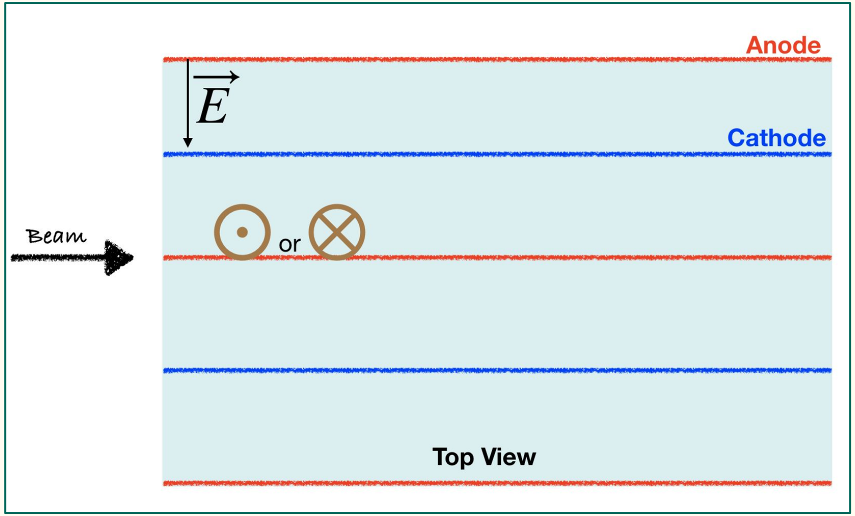
Orientation (1)

1) Magnetic field won't affect the drifting electron, but only the beam particles.
2) Due to the magnetic force $\overrightarrow{F} = q\overrightarrow{v} \times \overrightarrow{B}$, beam particle will move in a circle, which could be seen on APA plane.



Orientation (2)

Magnetic field vertical to the electric field is chosen. Both the drifting particle and the beam particles will do circular motion in this magnetic field.



Uncertainty added by the time resolution

The ADC clock frequency is ~2MHz, with the drift velocity, the uncertainty added by the time resolution is 0.8mm.

The overall spatial uncertainty would be

$$\sqrt{4.8^2 + 0.8^2} \approx 4.866 \text{ mm}$$

Backup: Liquid Helium Flow Rate

Assume 20 cm insulation of k = 0.1 W/(m*K) and our trusty conduction equation:

$$\frac{Q}{t} = \frac{KA(T_2 - T_1)}{d}$$

We find that 144 kW of thermal power will be radiated from the liquid argon to the liquid helium. Assuming that the helium is pumped in at 3 K and pumped out at 4K and has a heat capacity of 1 J / (g*K), this means we need to cycle 144 kg/s of liquid helium to cool the solenoid.