# Progress on dip-coated bars for DUNE

(We can reliably produce Wunderbars again)

Dune light collection meeting
Janet Conrad, MIT, 1/27/2016

*The MIT group: Len Bugel, Janet Conrad, Gabriel Collin, Matt Lindsey, Jarrett Moon, Zander Moss, Taritree Wongjirad*
*And at Fermilab: Matt Toups, Kanika Sachdev.*

New! Welcome to the group!

## We have been working with a new dipping formula,

This is the next step after the "JINST bars" published last march
Initially they produced wonderful results, so we call them "Wunderbars"
However, later bars showed poor attenuation length.
We think we understand the problem and can now
produce repeatable Wunderbars.
We have sent 3 to Stuart for his test starting this week.

## This talk:

1) A quick reminder about the bars
2) Bars made lately, including for Stuart's test
3) Next 6 month plans

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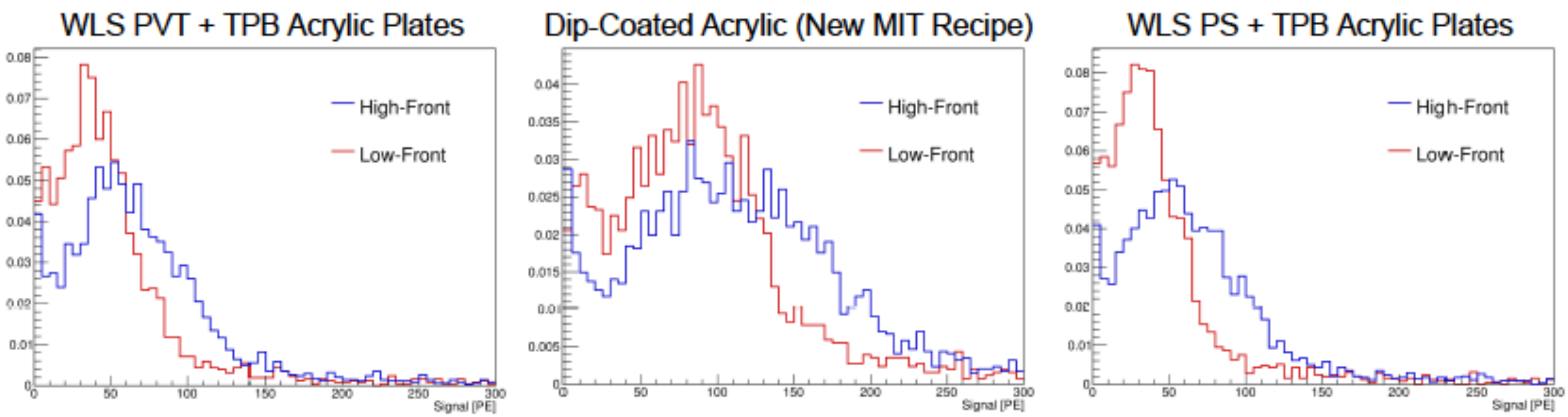
# What is a "Wunderbar"?

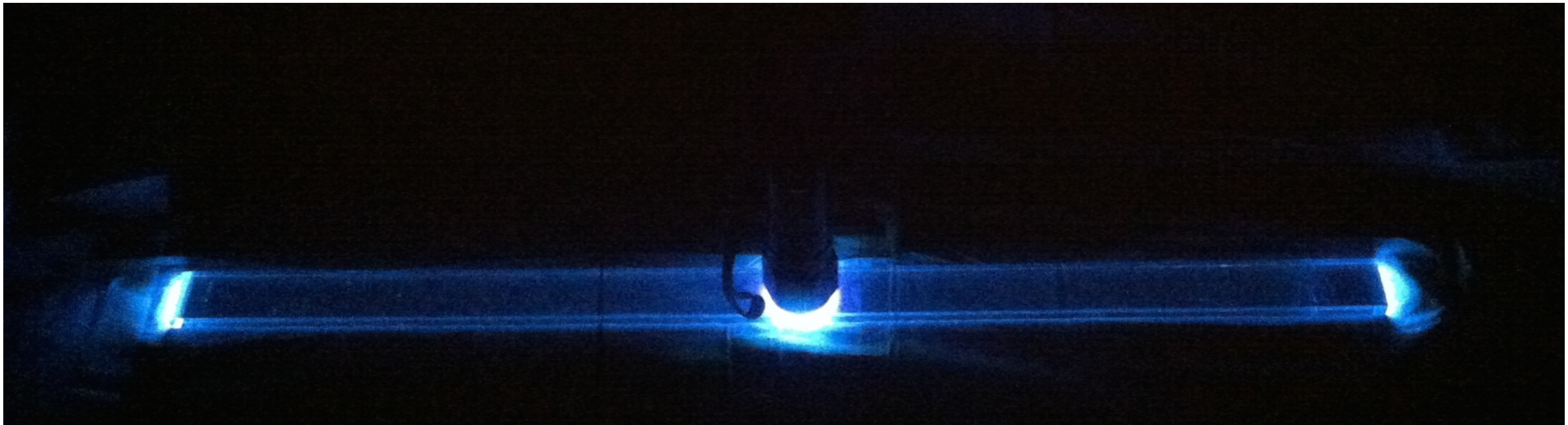



Very bright.
About >2 m attenuation,
Separate testing at Indiana confirmed this attenuation

Three bars (long and short), all made in April 2015, had >2 m attenuation lengths,

# Wunderbars show very little scattering out of bar

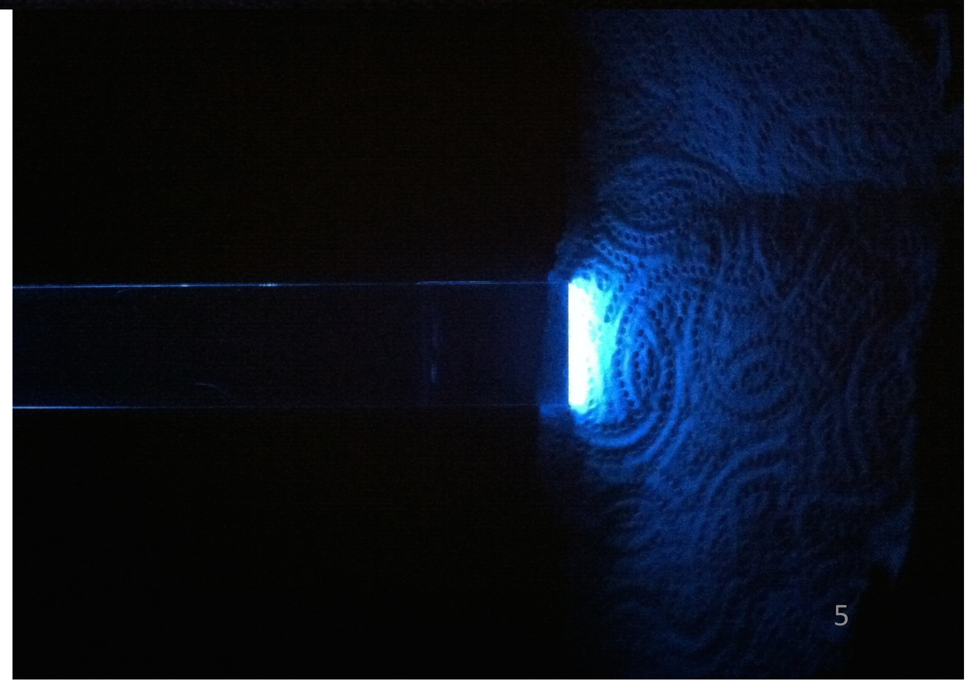
A UV flashlight is at center: ↓



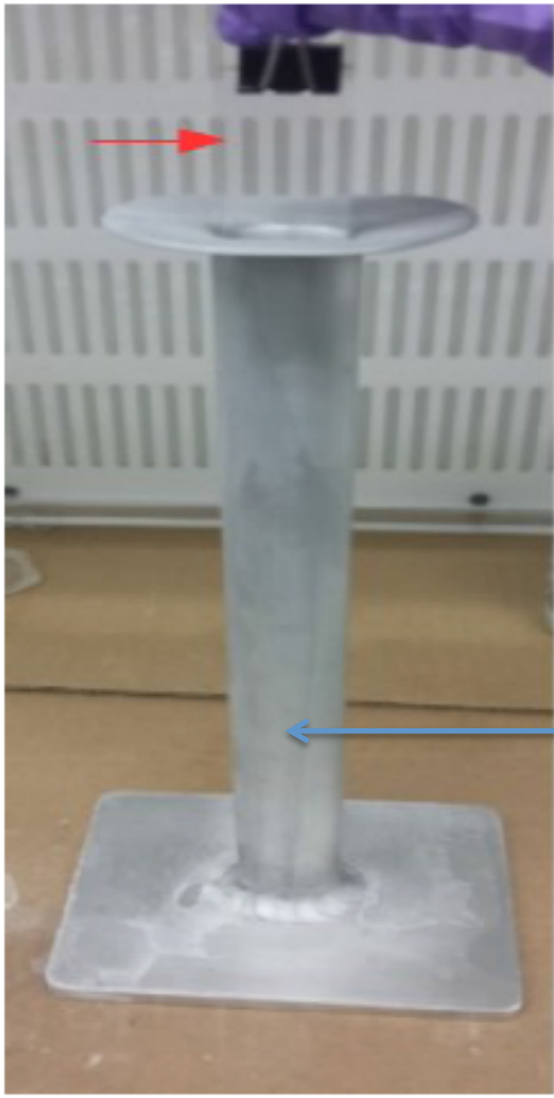
Close-up of end of bar when the flashlight is just upstream (just outside of photo) →

You can't perceive a difference in brightness when you move the flashlight up and down the bar

Almost no light escapes the sides of the Wunderbars!



# The Change in Recipe to Produce Wunderbars:

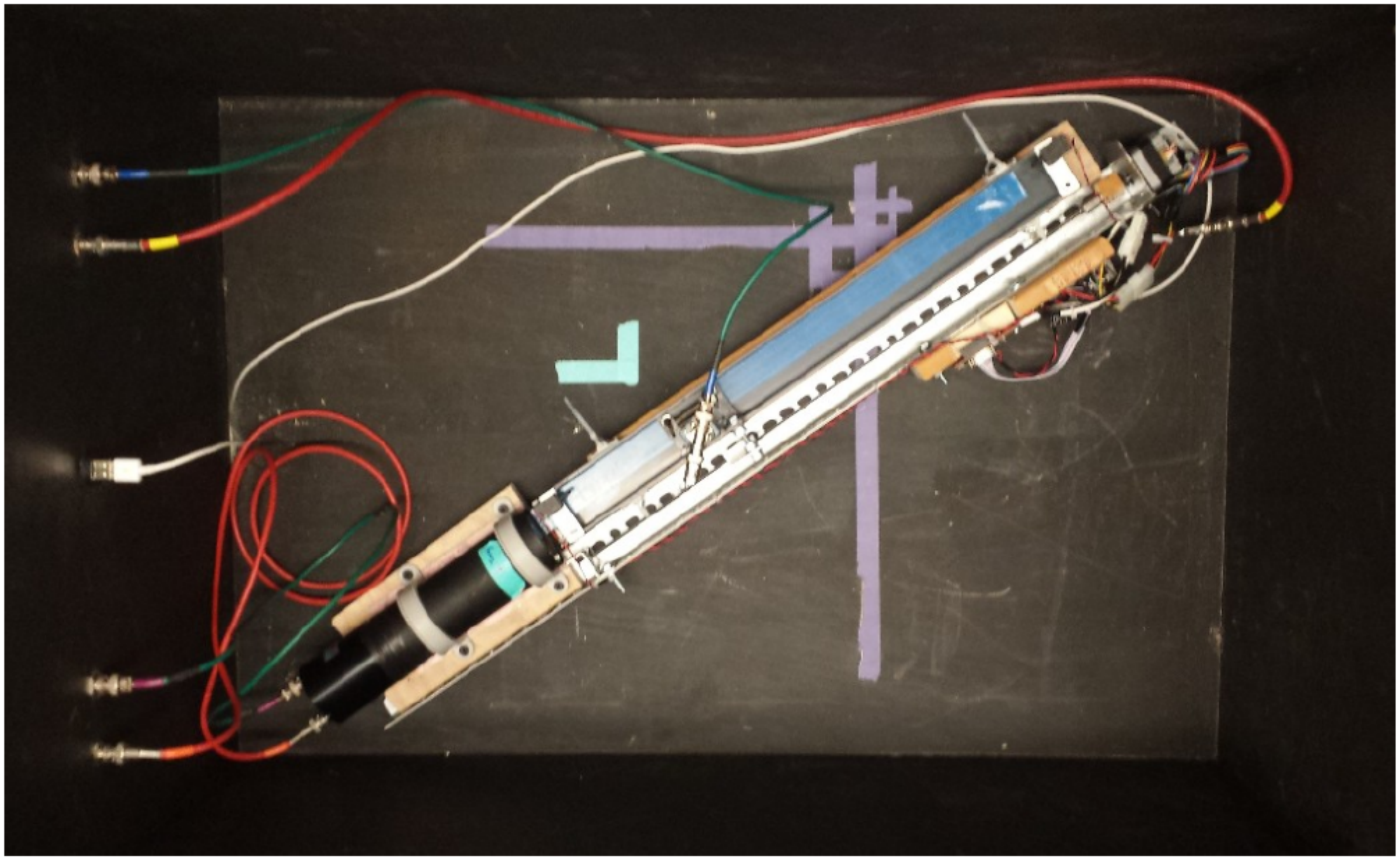


| JINST bars | | Wunderbars |
|---|---|---|
| 0.5 g TPB | → | 0.1 g TPB |
| 50 mL toluene | → | 50 mL toluene |
| 10 mL ethanol | → | 12 mL ethanol |
| 1 g acrylic | → | 0.1 g acrylic |

"Candlestick" is used for dipping.

# How We Measure Attenuation Lengths

We measure attenuation length in air using 20” bars:



We used a set of JINST bars to make a model that connects between the air measurement and the LAr measurement.

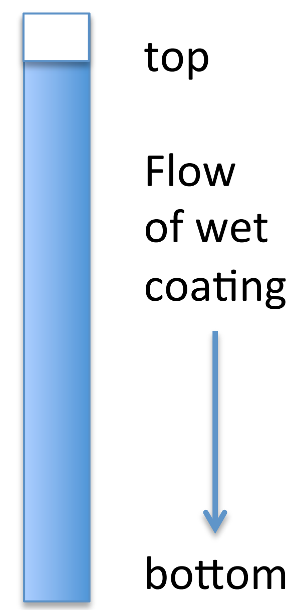
# What is expected in the air test:

Two features affect the light that is detected from any given point ,
when measurement is done in air:

1) The thickness of the coating, since the 286 nm
   light penetrates the coating.

   The coating is thicker at the bottom than the top
   → more light from bottom than top

2) The attenuation of along the bar.




But in liquid argon,
the coating thickness does not matter.
The 128 nm light does not penetrate into the coating.

→ To extract the attenuation length in LAr, we must correct air data for thickness.
→ Also not, even corrected, the light will not look exponential for points near PMT,
because direct light adds in. So we use data 15 cm from the PMT face.

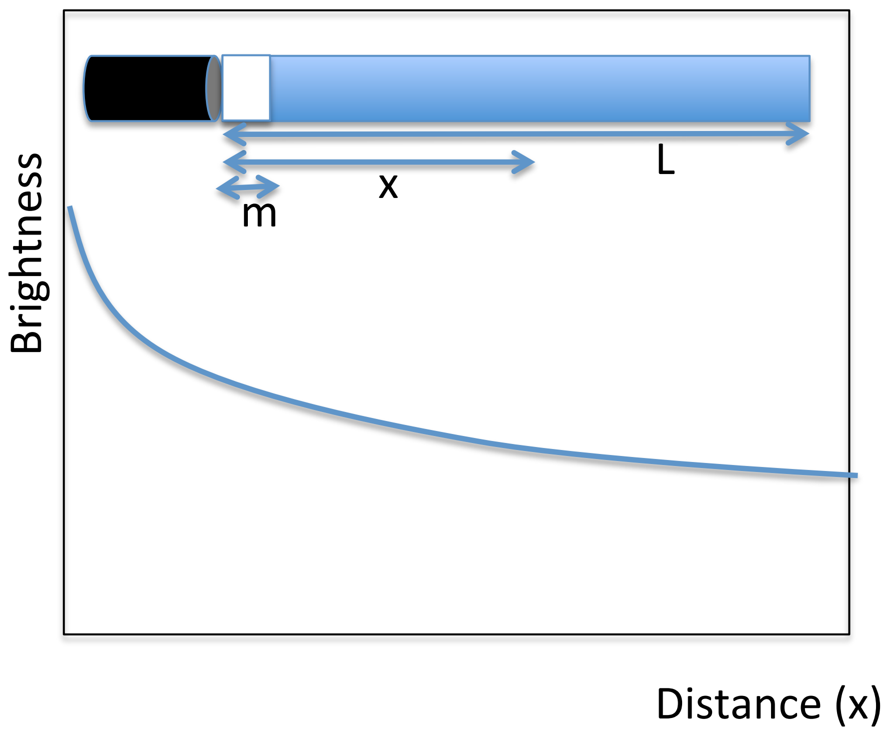
# Correcting data through air measurements in opposite directions

Forward: Air data will look better than in LAr due to thickening

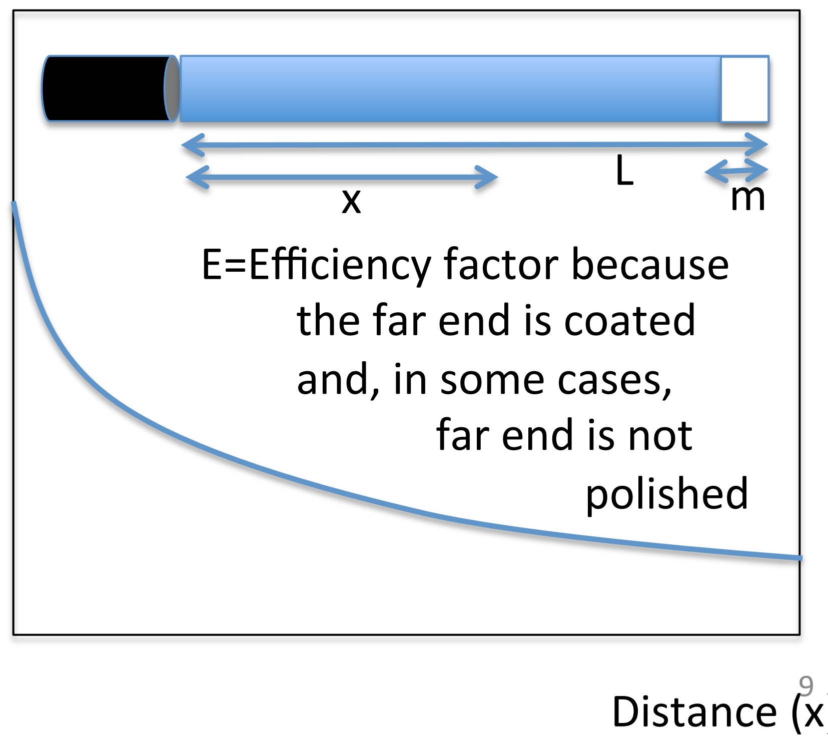
Backward: Air data will look worse than in LAr due to thickening

Assume the change of coating thickness t(x) increases linearly along the bar, fit the data both ways to extract B (the attenuation length)

A*exp(-B*x)*(1+C*(x-m))




E*A*exp(-B*x)*(1+C(L-m-x))

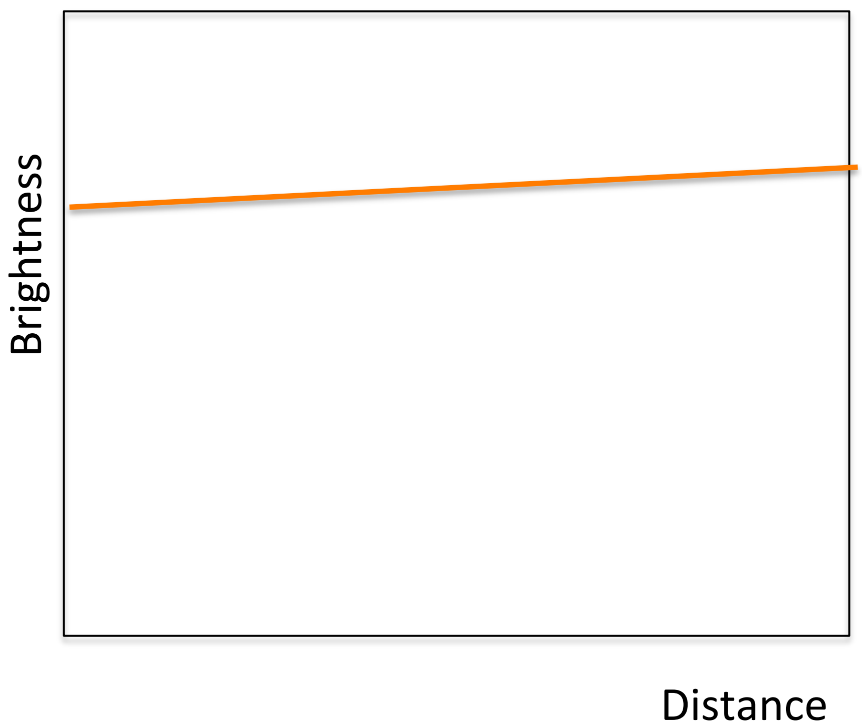


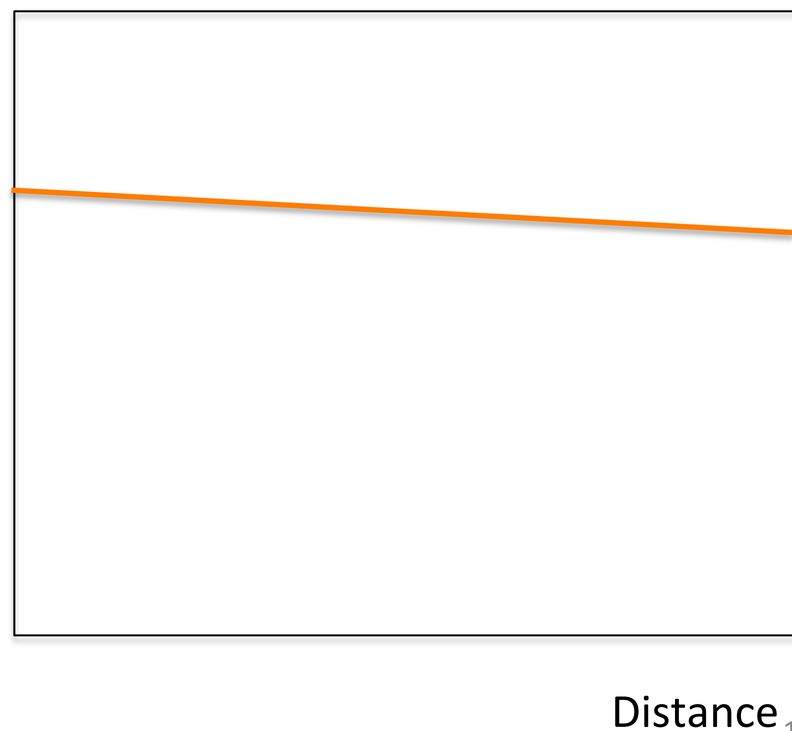
# Correcting data through air measurements in opposite directions

Air data will look better
than in LAr due to thickening

Air data will look worse
than in LAr due to thickening

We find that the latest wunderbars has sufficiently flat attenuation length,
that the coating thickness effect actually causes the forward curve to rise.



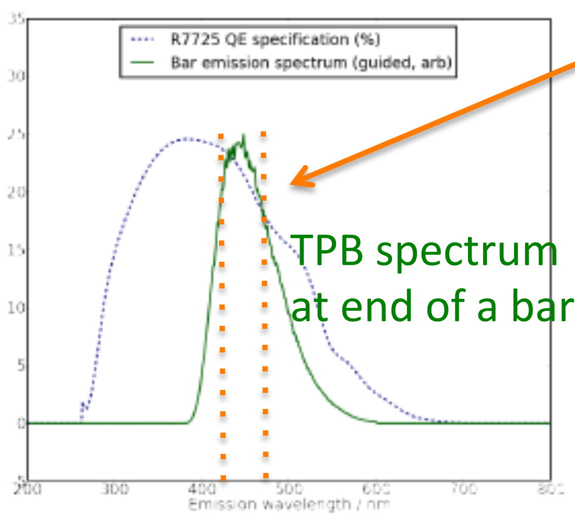



# Bulk Attenuation Length of Our Acrylic

S Mufson and B Baptista,
http://iopscience.iop.org/article/10.1088/1748-0221/8/09/C09006/pdf

**Table 1.** Attenuation Lengths of Acrylics Tested.

| Manufacturer | Acrylic Type | Wavelength Tested (nm) | Attenuation Length (m) |
|---|---|---|---|
| Lucite-UTRAN | Cast UVT | 385 | 1.6 |
| Lucite-UTRAN | Cast UVT | 420 | 2.6 |
| Lucite-UTRAN | Cast UVT | 470 | 2.6 |




Not sure about the variation bar-to-bar

For good Wunderbars,
the measured attenuation length
matches the bulk attenuation length.

# Will the attenuation length we measure in air change in LAr?

I claim not by very much.
The amount of light <u>captured</u> will be different in LAr and than air.
But **if bulk attenuation length dominates, then LAr and air will have similar attenuation**

Reasoning:
If you had a perfect bar, one which is so smooth it always totally internally reflects,
then the attenuation will only depend on the bulk properties of the bar,
not the medium in which it is immersed.

We do not have <u>perfectly</u> smooth bars,
But the lack of light loss from the sides tells you that these bars are <u>very</u> smooth.
(see slide 5) – Light escaping due to defects is very small.

It is the amount of light escaping that changes between LAr and air.
So if this is small, the bulk attenuation effects dominate, and
there should be little difference between attenuation in air and LAr.

In this talk we only present results in air, but expect the LAr results to match these.
We'll see from Stuart's tests and our tests in May.

# We can find acrylic with better bulk attenuation

Measurement of Optical Attenuation in Acrylic Light Guides for a Dark Matter Detector

arXiv:1310.6454v2 [physics.ins-det] 15 Jan 2014

M. Bodmer[a], N. Phan[a], M. Gold[a], D. Loomba[a], J.A.J. Matthews[a] and K. Rielage[a,b*]

Can potentially almost double the light from a 2 meter bar!

| *Sample* | *Wavelength (nm)* | | | | |
|---|---|---|---|---|---|
| | 375 | 405 | 440 | 543 | 632 |
| | *Attenuation Length (m)* | | | | |
| Tecacryl #1 | $0.14 \pm 0.01$ | $0.57 \pm 0.01$ | $7.30 \pm 0.93$ | $11.4 \pm 1.7$ | $36.7 \pm 28.5$ |
| Tecacryl #2 | $0.12 \pm 0.00$ | $0.35 \pm 0.01$ | $1.68 \pm 0.09$ | $10.1 \pm 1.7$ | $10.8 \pm 2.3$ |
| Tecacryl #3 | $1.36 \pm 0.03$ | $4.03 \pm 0.14$ | $5.65 \pm 0.38$ | – | $30.6 \pm 19.6$ |
| Tecacryl #4 | $1.26 \pm 0.04$ | $3.87 \pm 0.22$ | $4.89 \pm 0.30$ | – | $24.9 \pm 19.7$ |
| RPT #1 | $0.30 \pm 0.03$ | $1.52 \pm 0.05$ | $2.50 \pm 0.07$ | $492 \pm 3270$ | $15.6 \pm 6.61$ |
| RPT #2 | $0.31 \pm 0.02$ | $1.56 \pm 0.06$ | $2.51 \pm 0.11$ | $56.2 \pm 39.4$ | $2.9 \pm 3.7$ |
| RPT #3 | $0.29 \pm .03$ | $1.55 \pm 0.07$ | $2.61 \pm 0.11$ | $33.6 \pm 8.80$ | $16.5 \pm 5.6$ |
| RPT #4 | $0.11 \pm 0.00$ | $0.28 \pm 0.01$ | $1.60 \pm 0.05$ | $20.3 \pm 6.1$ | $7.7 \pm 1.1$ |
| Spartech #1 | $0.70 \pm 0.02$ | $1.25 \pm 0.07$ | $1.54 \pm 0.07$ | $17.1 \pm 2.8$ | $22.0 \pm 11.8$ |
| Spartech #2 | $0.56 \pm 0.01$ | $1.19 \pm 0.06$ | $1.53 \pm 0.04$ | $20.1 \pm 4.4$ | $16.5 \pm 6.9$ |
| Spartech #3 (short side) | $0.07 \pm 0.00$ | $0.23 \pm 0.01$ | $2.41 \pm 0.92$ | – | $24.9 \pm 95.0$ |
| Spartech #3 (long side) | $0.05 \pm 0.00$ | $0.26 \pm 0.00$ | $3.01 \pm 0.23$ | – | $11.2 \pm 8.0$ |
| Spartech #4 | $0.15 \pm 0.00$ | $0.28 \pm 0.01$ | $2.74 \pm 0.33$ | $230 \pm 379$ | $27.8 \pm 19.3$ |
| McMaster (Spartech #1 | $0.48 \pm 0.03$ | $1.51 \pm 0.11$ | $1.80 \pm 0.15$ | – | – |
| McMaster (US Cast) #2 | $0.18 \pm 0.00$ | $1.38 \pm 0.03$ | $2.46 \pm 0.25$ | – | – |

**Table 5.** Table of attenuation lengths for all acrylic samples. Entries marked as '–' have a calculated transmittance of 100%. The function used for calculating the attenuation length approaches ∞ as transmittance approaches 100%. Since the attenuation length is independent of the samples dimension this table can be used to compare samples of acrylic with different lengths.

If someone would like to get involved in dipped bars for DUNE finding a better acrylic might be a nice place to start

1) A quick reminder about the bars
2) Bars made lately, including for Stuart’s test
3) Next 6 month plans

# Not Wonderful Wunderbars:

From May through September, we were unable to reproduce the initial Wunderbars.

Attenuation lengths were <1 m

(We actually did not even know we had a problem with these bars until late Sept)

Brainstorming on what could be wrong – 3 ideas:

1. Dip-time – the iniital Wunderbars were all dipped for 10 minutes.
   Then we accidentally switched to 5 minutes for all poor wunderbars.
   Go back to 10 minute dips!

2. Humidity – we know high humidity has clouded past coatings.
   This is why we generally don't work in the summer.
   From April to Sept (and in fact early Dec) the humidity in Boston and the lab was very high.
   If this is the problem, work out an improvement to teststand to send in dry air.

3. Crud in the candlestick
   Due to bars fitting too snuggly in the candlestick and scraping?
   We upgraded the candlestick washing procedure and reduced this to negligible.

# The Path to Wunderbars again:

1) Dipping time:

   Last May we accidentally changed to a 5 minute dip from the original 10 mins, but our dip time tests for the JINST coating mix said >5 is all that is needed. So we did not expect that going to 10 minutes would matter…

   … but it did.
   This change increased the in-air attenuation length from 1 m to ~2 m

   The humidity level in the lab for these bars was still high…

# The Path, cont'd:

2) Low Humidity + 10 minute dip:
   In the week of January 3, the relative humidity in the lab went to <20%
   (the lab is always 70 degrees)

   We produced 4 20" bars all with very long attenuations – up to 3 m.

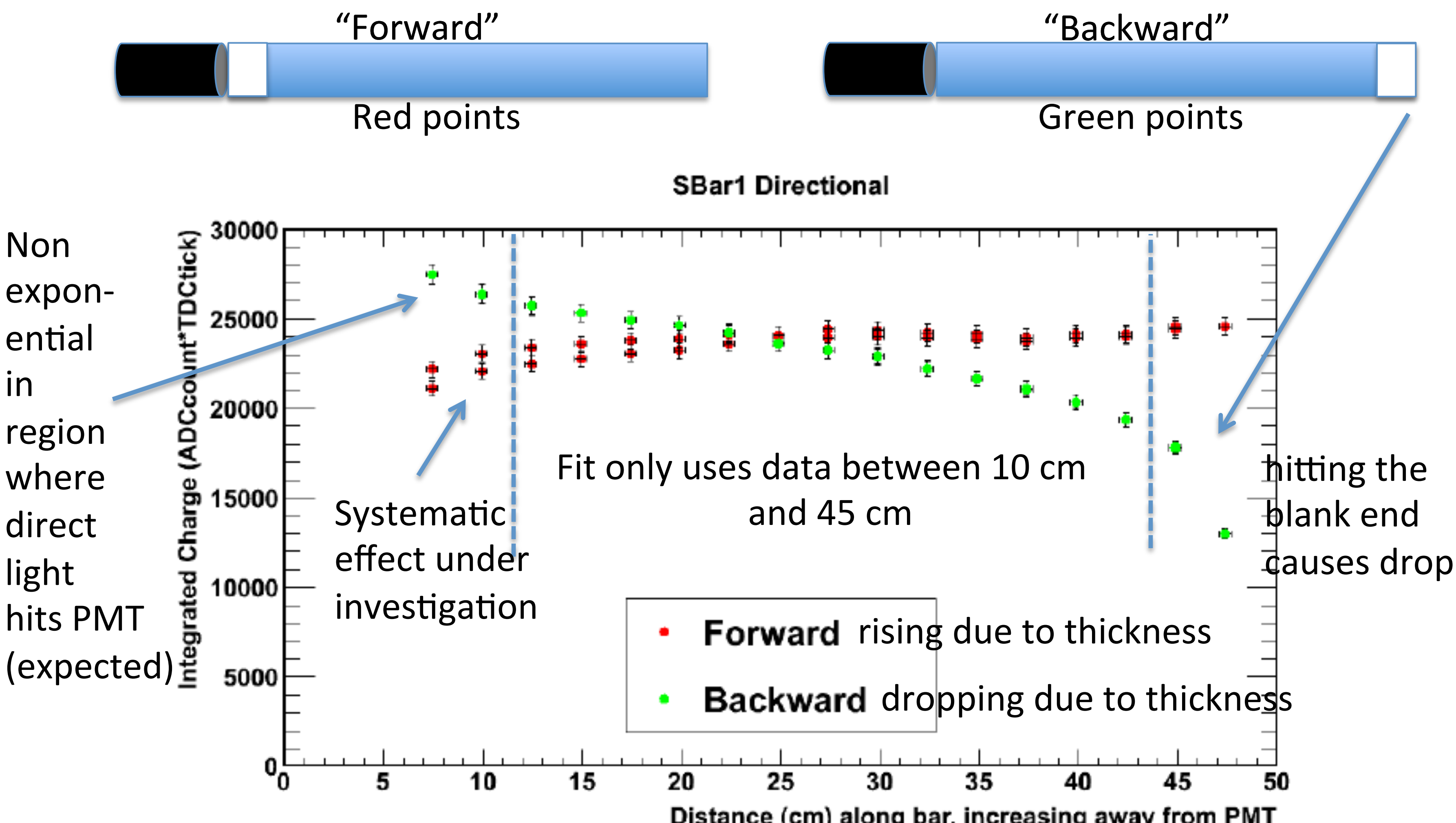
   SUCCESS!

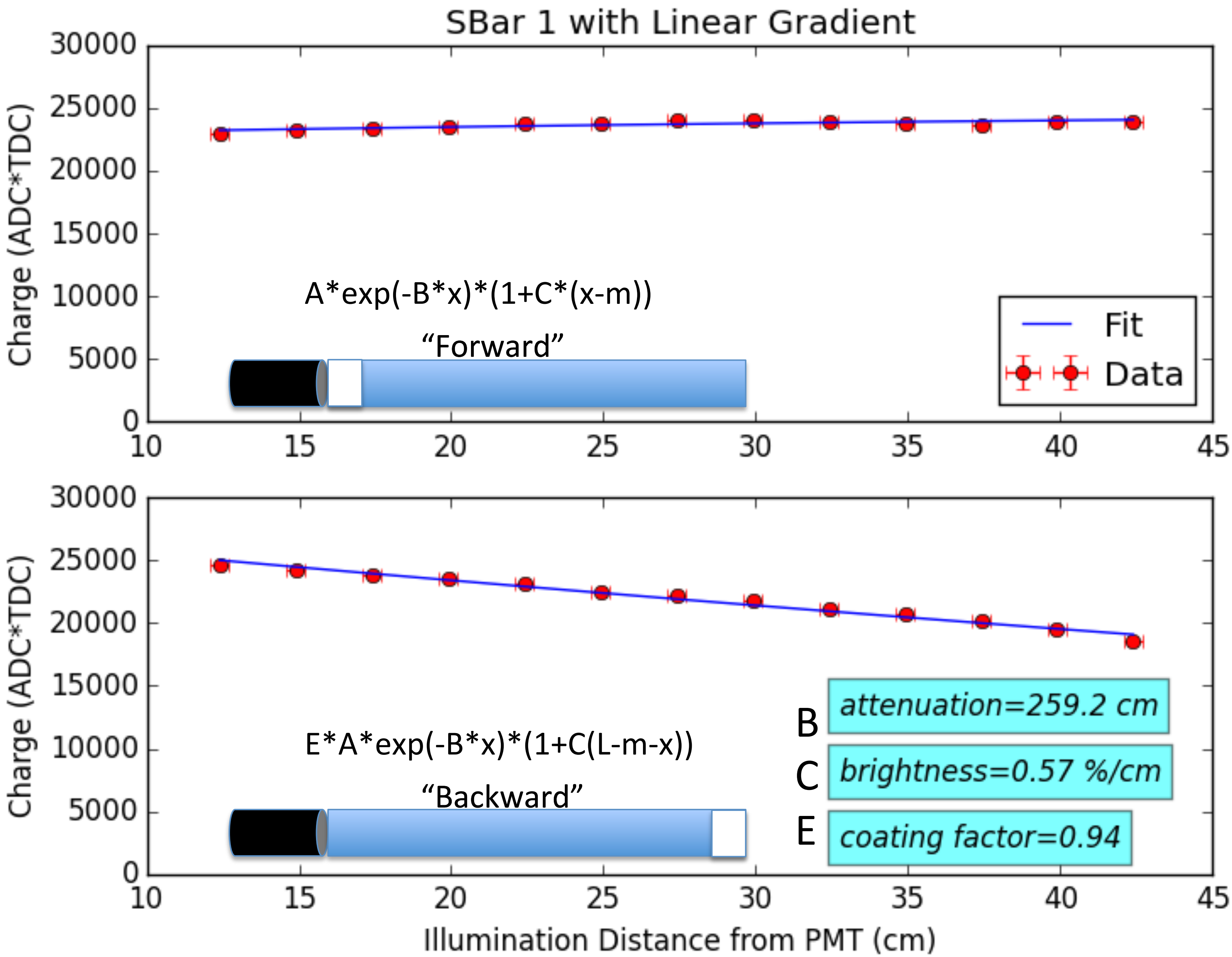
   We also produced 3 long bars for Stuart at this time -- will discuss in a minute.

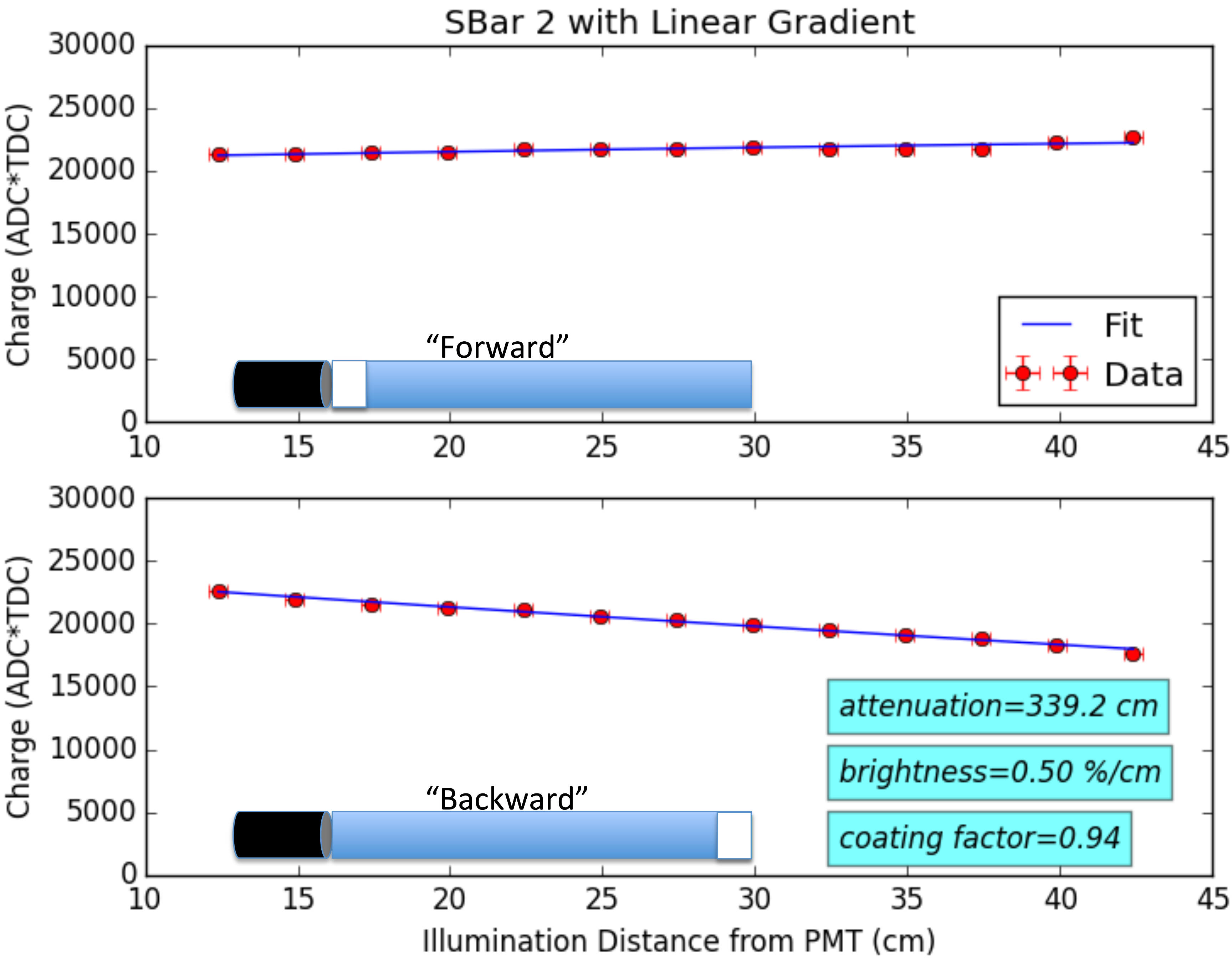
I will now show….

1) Attenuation lengths of 4 short bars
2) A discussion of producing Stuart's 3 long bars
3) Attenuation length of 1 long bar broken into short pieces

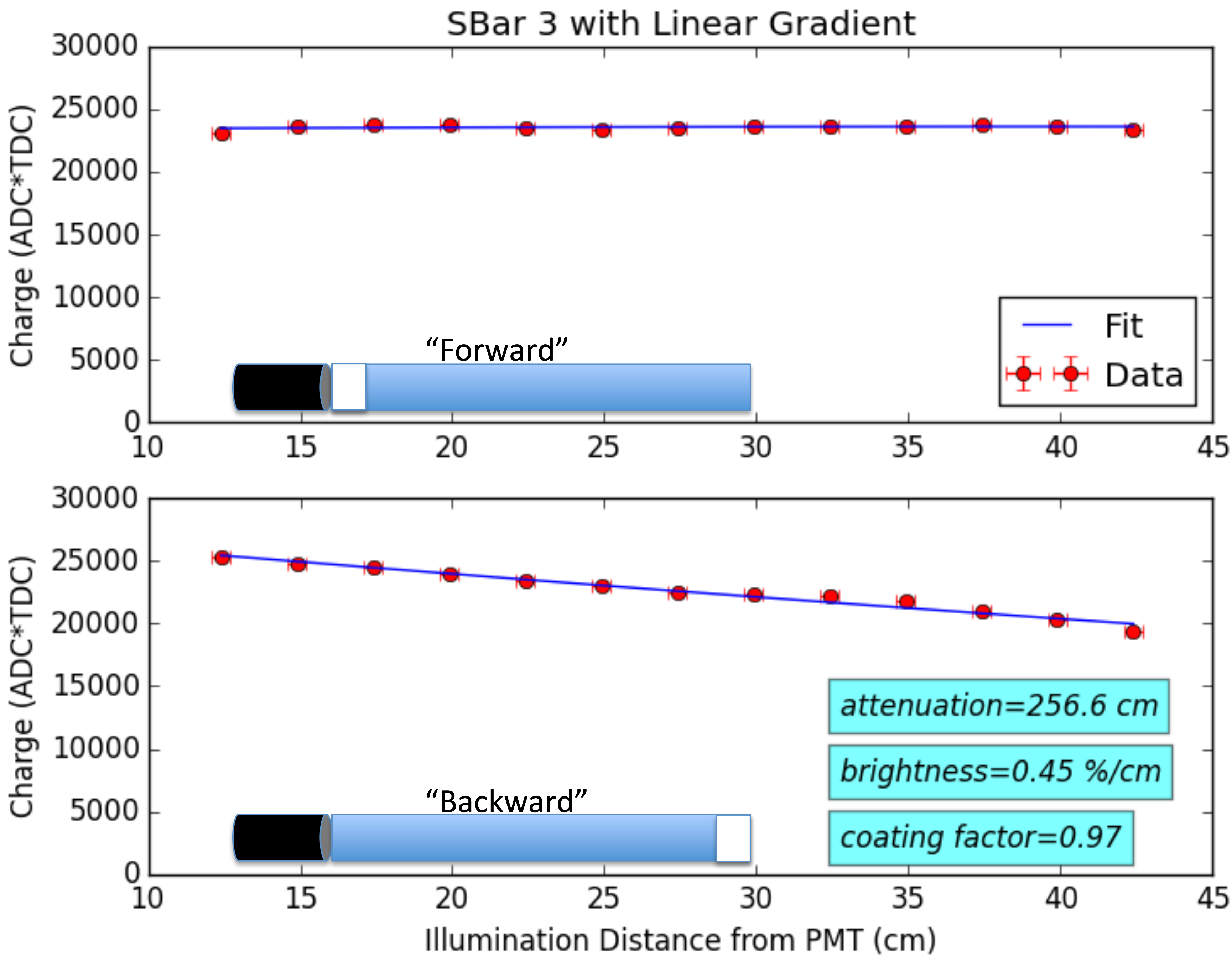
# Some Features (using info from "SBar1")



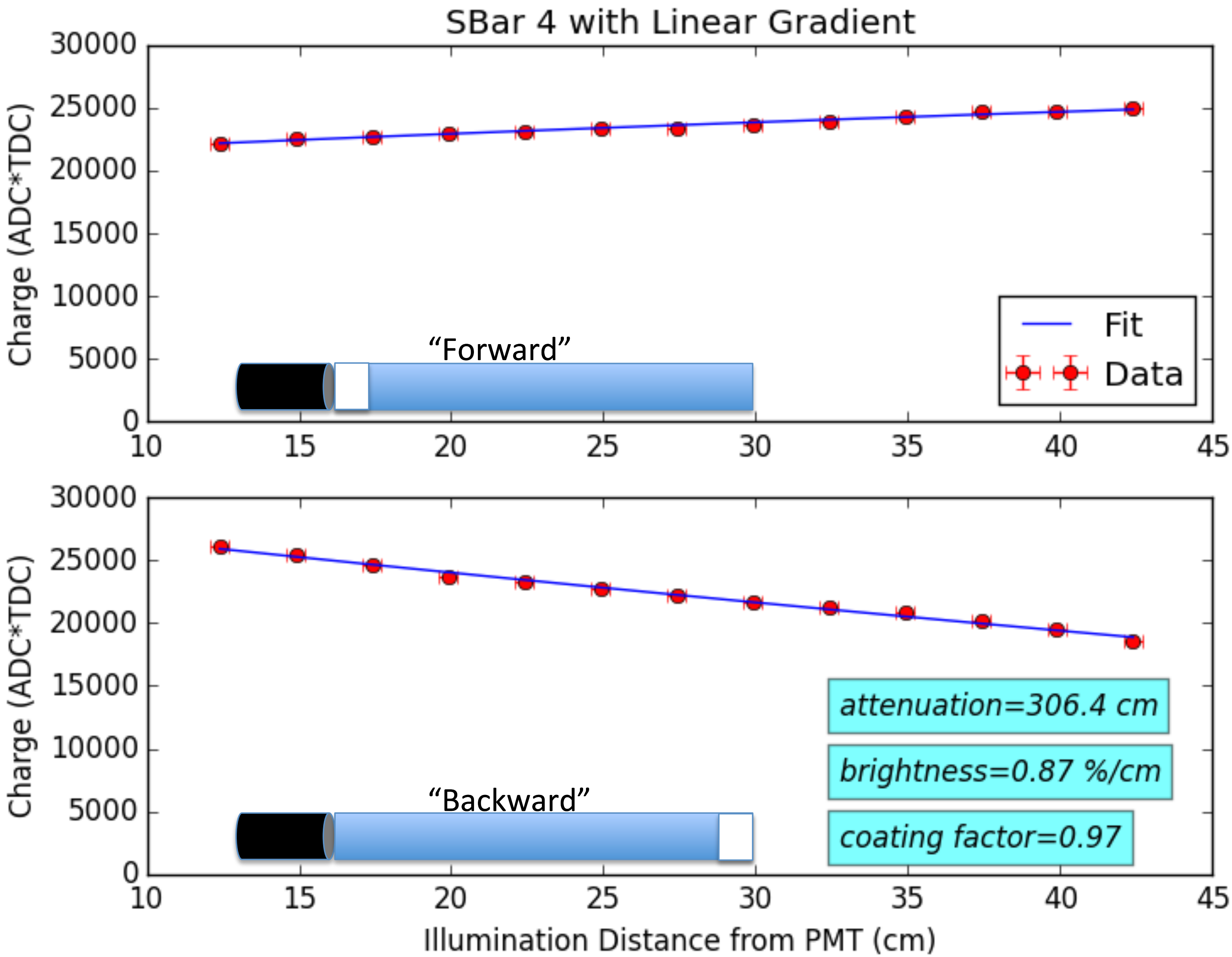

SBar 1 with Linear Gradient
Charge (ADC*TDC)
A*exp(-B*x)*(1+C*(x-m))
“Forward”
Fit
Data
E*A*exp(-B*x)*(1+C(L-m-x))
“Backward”
B
attenuation=259.2 cm
C
brightness=0.57 %/cm
E
coating factor=0.94
Illumination Distance from PMT (cm)



SBar 2 with Linear Gradient
Charge (ADC*TDC)
"Forward"
Fit
Data
"Backward"
attenuation=339.2 cm
brightness=0.50 %/cm
coating factor=0.94
Illumination Distance from PMT (cm)



SBar 3 with Linear Gradient
Charge (ADC*TDC)
30000
25000
20000
15000
10000
5000
0
10
15
20
25
30
35
40
45
Fit
Data
“Forward”
“Backward”
attenuation=256.6 cm
brightness=0.45 %/cm
coating factor=0.97
Illumination Distance from PMT (cm)


SBar 4 with Linear Gradient
Charge (ADC*TDC)
30000
25000
20000
15000
10000
5000
0
10
15
20
25
30
35
40
45
"Forward"
Fit
Data
"Backward"
attenuation=306.4 cm
brightness=0.87 %/cm
coating factor=0.97
Illumination Distance from PMT (cm)

# Bars for Stuart – how will they perform?

Stuart's bars are 60" and when drawn out of the candlestick reach the height of lab.
Drawing out the bars is tricky with our present setup.
(This can be fixed in the future – we are on a learning curve)

Here's the scoop on the bars we sent:
Bar 1 – we accidentally touched on edge as it just came out of the candlestick
(instinctive reaction to swinging)
Bar 2 – had to be touched on edge because the draw-out was not perfectly aligned
(twisting makes it get stuck)
Bar 3 – that went well.

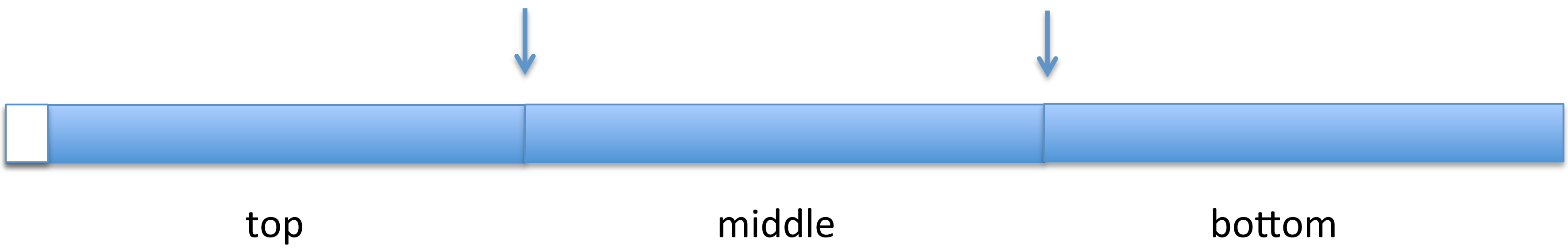
The bars were wet when touched and we think more liquid rolled over the point of contact,
Also, it is only one spot on the edge. But still… disappointing.
We shall see.
At least Bar 3 should be great!

We could not make more long bars because we are now completely out of long bars.

# Breaking Up Long Bar 4 --- a look at what we might expect

We cannot test Stuart's long bars because our tester is too short, but…

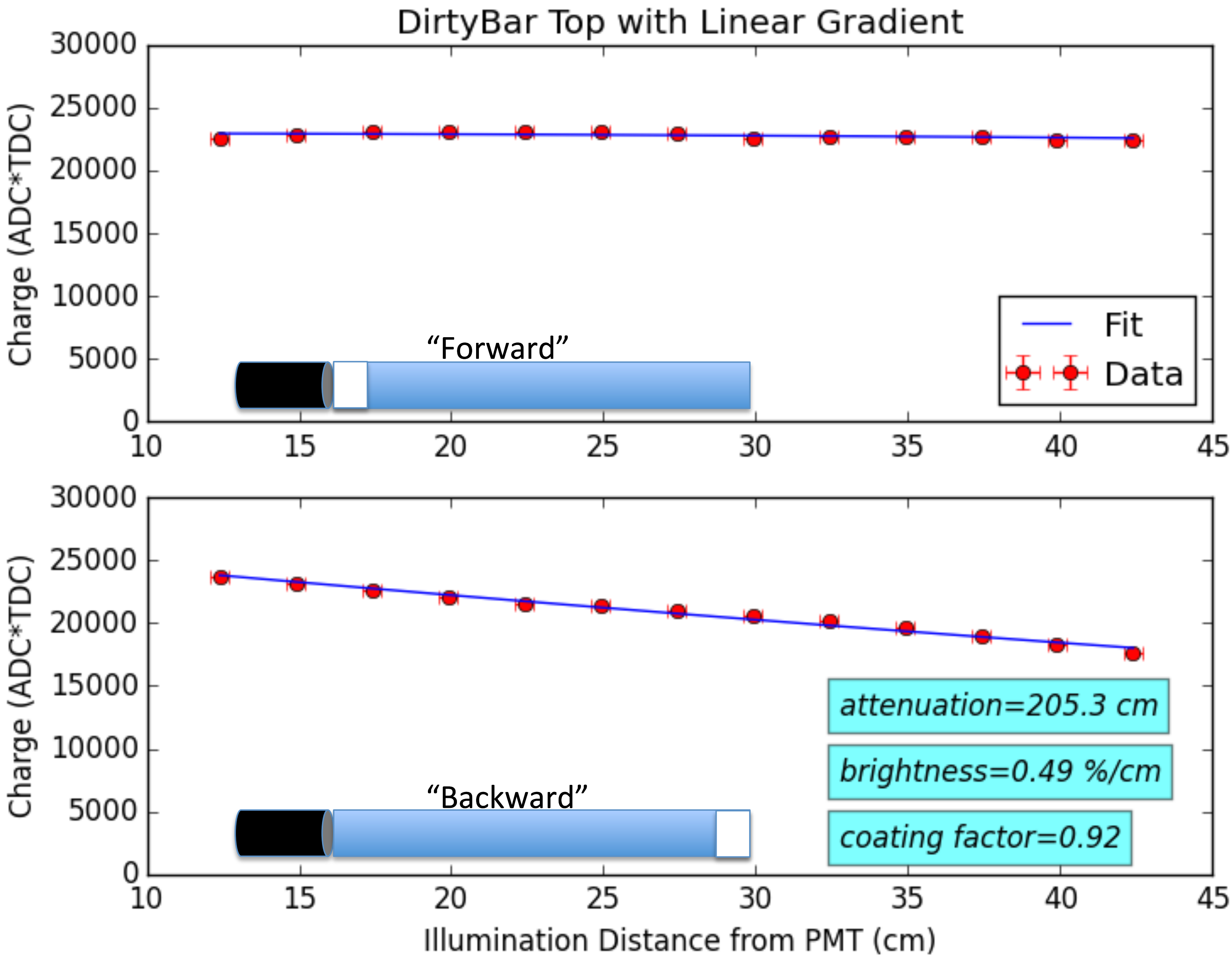
Long bar 4 was dipped in coating that had crud from the candlestick in it, by accident.
However, the crud settles to the bottom.
We were not absolutely sure if this bar would be good.
So instead of sending this to Stuart, we kept it, broke it into 20" segments, and tested.



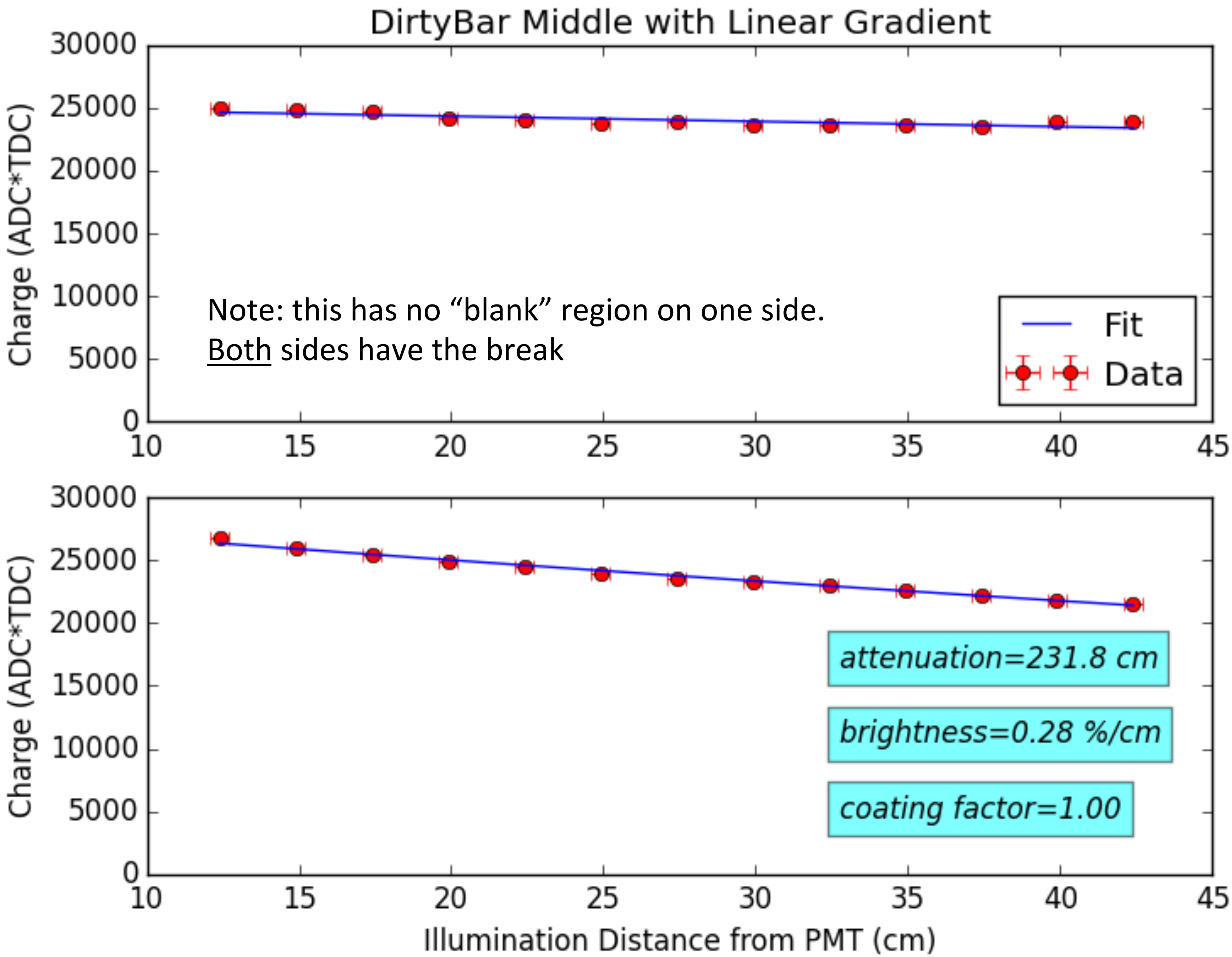

"Dirty Bar" test results follow.
Dirty bar is actually not all that dirty-looking.   It is not bad at all.

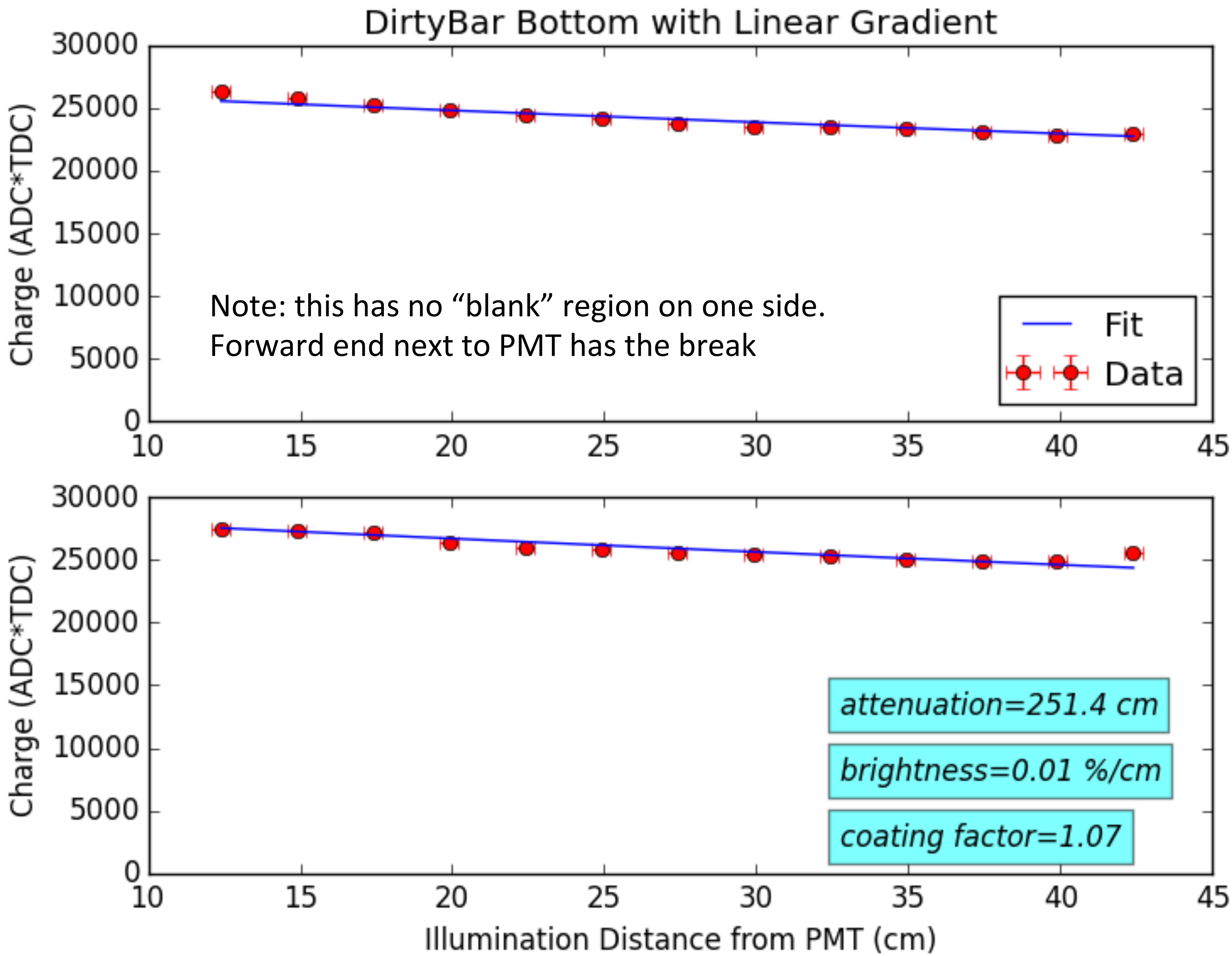
Hold on and I'll explain 2 features of the dirty bar measurements:

1) the observed increasing  efficiency factor (called the coating factor in the plots)
2) the observed increasing attenuation length along the bar.



DirtyBar Top with Linear Gradient
Charge (ADC*TDC)
30000
25000
20000
15000
10000
5000
0
10
15
20
25
30
35
40
45
"Forward"
Fit
Data
Charge (ADC*TDC)
"Backward"
attenuation=205.3 cm
brightness=0.49 %/cm
coating factor=0.92
Illumination Distance from PMT (cm)


DirtyBar Middle with Linear Gradient
Charge (ADC*TDC)
Note: this has no "blank" region on one side.
Both sides have the break
Fit
Data
attenuation=231.8 cm
brightness=0.28 %/cm
coating factor=1.00
Illumination Distance from PMT (cm)


DirtyBar Bottom with Linear Gradient
Charge (ADC*TDC)
Note: this has no “blank” region on one side.
Forward end next to PMT has the break
Fit
Data
attenuation=251.4 cm
brightness=0.01 %/cm
coating factor=1.07
Illumination Distance from PMT (cm)

# Summary of what we learned on attenuation

| | |
|---|---|
| Sbar 1 | 259 cm |
| Sbar 2 | 339 cm |
| Sbar 3 | 257 cm |
| Sbar 4 | 306 cm |
| Dirty Bar Top | 205 cm |
| Dirty Bar Middle | 232 cm |
| Dirty Bar Bottom | 251 cm |

We have had no "not-wonderful" cases since December

1) A quick reminder about the bars
2) Bars made lately, including for Stuart’s test
3) Next 6 month plans

# Dry Air Tube

It looks like the low humidity+10 min soak brought us back to the level of the initial Wunderbars.

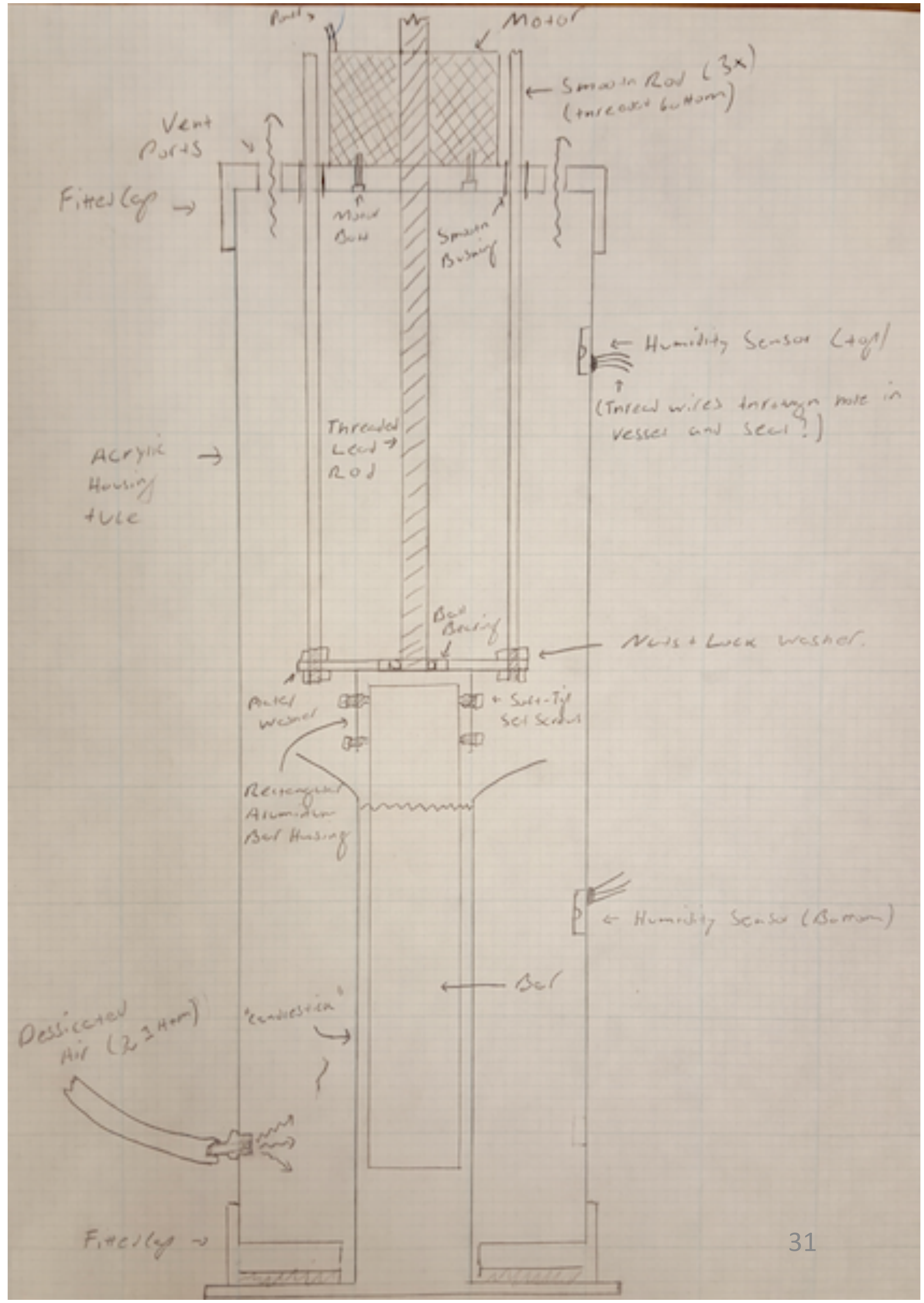
This leads us to want to develop a system where the bars dry in dry air.

Here is a mock-up of the plan:
This is a clear acrylic pipe that extends
 2.2x the candlestick height
The candlestick sits inside
We will add a gas nipple,
 and flow in dry air very slowly.

We are in the process of building this.

Excellent project for an
MIT undergrads (Zander, Matt)
& grad student (Jarrett) for
winter term!

Note that this system should
not twist/swing



# Does “drawing time” matter?

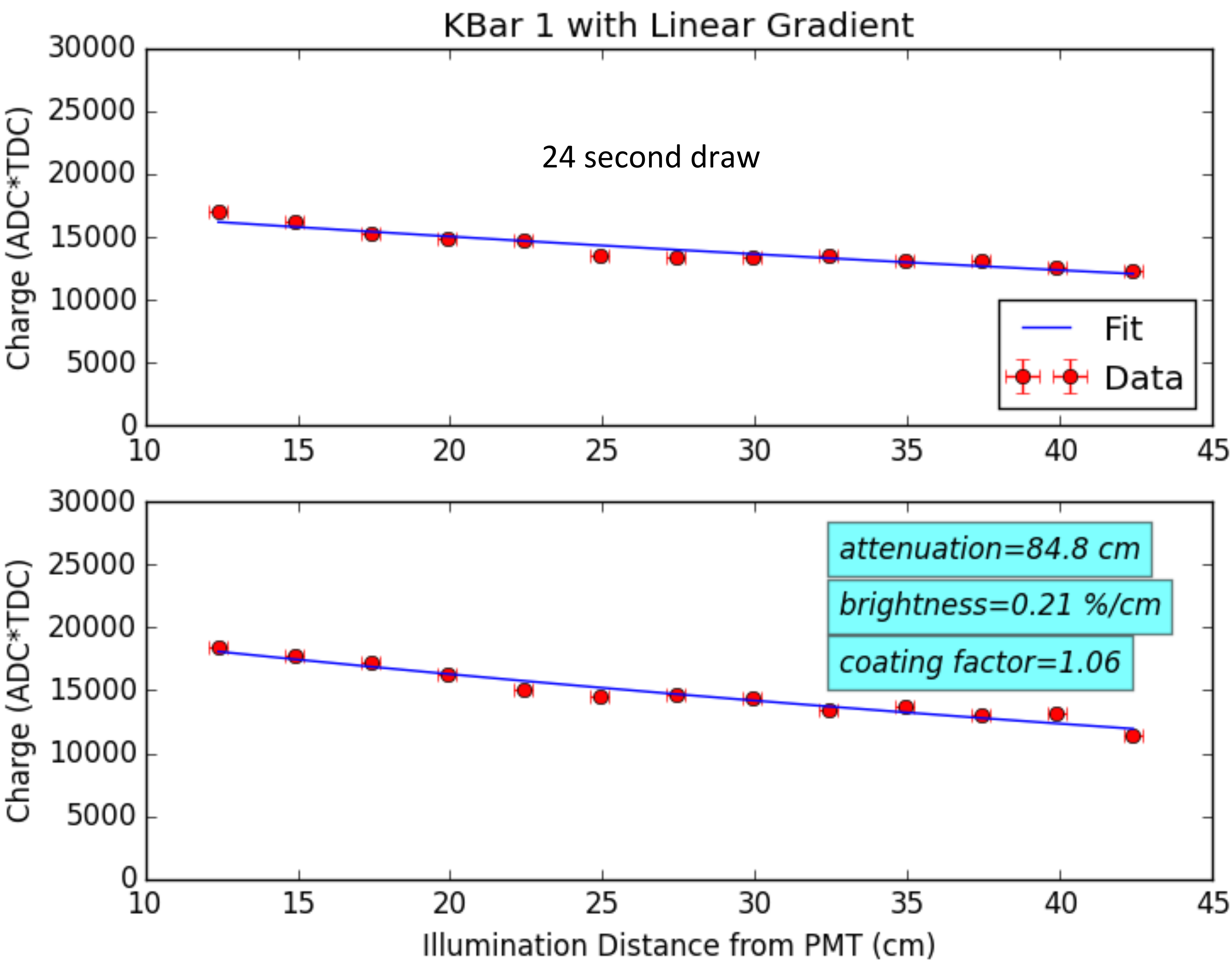
Drawing time = time to pull out the bar.
To date we have not paid a lot of attention. We draw as fast as we can w/o problems.
With mechanized draws, we can set the drawing time.
What is the optimal drawing time?

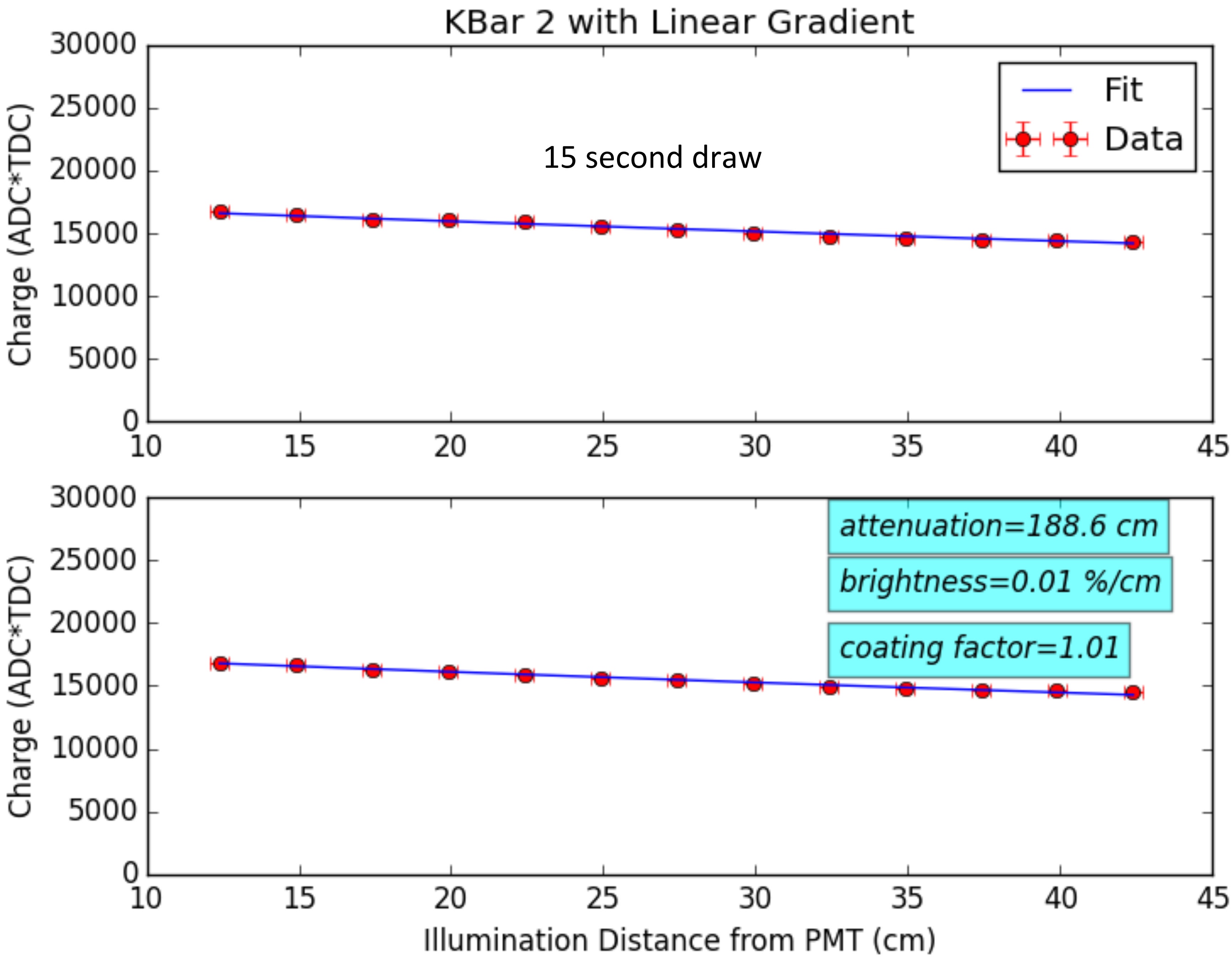
Kanika and Len found a clear dependence on attenuation vs time for 3 bars.
We think drawing slowly past the meniscus produces ripples in the coating.

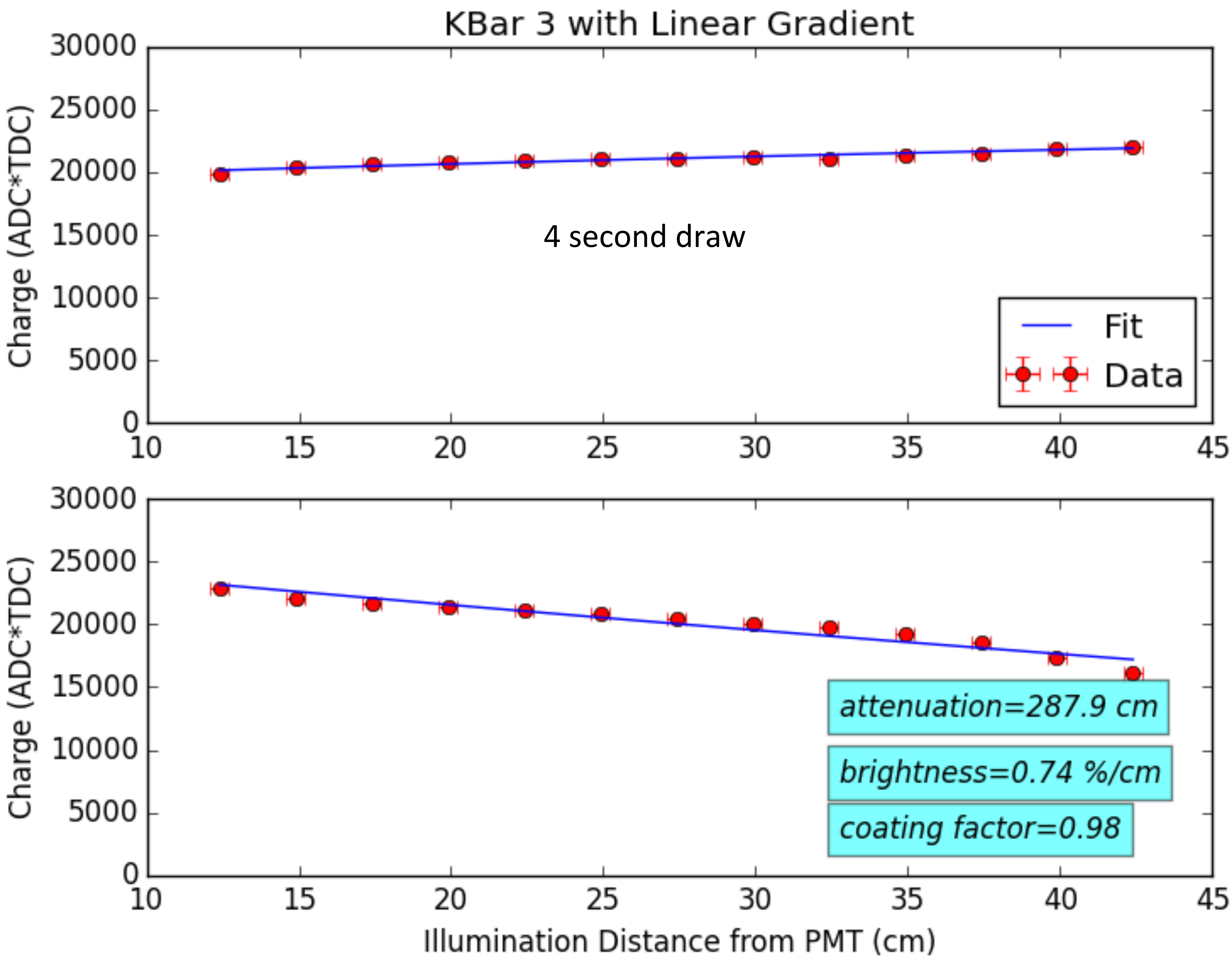
Drawing time is clearly worth examining more closely!

Question: how long did it take us to draw Stuart’s 3 bars?
We don’t really know (didn’t measure) but guess about 10 s/20” section,
except for bar 2 which got stuck and took longer

BUT I think it takes longer at the top of the bar than bottom as I draw the bar,
because I always hesitate at the start to be sure the clip will hold.
So the sequence of attenuation lengths of dirty bar,
where top is worse than bottom, may be due to how fast we draw the bar.


KBar 1 with Linear Gradient
24 second draw
Charge (ADC*TDC)
Fit
Data
attenuation=84.8 cm
brightness=0.21 %/cm
coating factor=1.06
Illumination Distance from PMT (cm)


KBar 2 with Linear Gradient
Fit
Data
15 second draw
Charge (ADC*TDC)
30000
25000
20000
15000
10000
5000
0
10
15
20
25
30
35
40
45
attenuation=188.6 cm
brightness=0.01 %/cm
coating factor=1.01
Illumination Distance from PMT (cm)


KBar 3 with Linear Gradient
4 second draw
Fit
Data
attenuation=287.9 cm
brightness=0.74 %/cm
coating factor=0.98
Charge (ADC*TDC)
Illumination Distance from PMT (cm)

# Immediate plans:

Produce 10 more 20” bars via the dry-air tube to show we can make
Wunderbars consistently.

Think about whether we want to do humidity level tests
(shall we wait to check this?  Lots of other things on the list!)

We want to store 5 bars in a dry environment and leave 5 covered but in the air
to study degradation over a few months due to humidity.
We think this will be fairly small.
This is important to understand if bars or left to sit in ProtoDUNE or DUNE

If all goes well, write a paper on the Wunderbars,
Kanika will make a wiki with all of the latest bar making instructions, step-by-step

And then…

# Move the dipping operation to Fermilab in summer:

artisanal → industrial for SBND
Matt Toups is leading the SBND production effort. Kanika is the key postdoc.

MIT will support this by:
Transferring knowledge
Helping with set up this spring/early summer (Len will come to FNAL)
Providing students for running the 4 factories (annealing, mixing, coating, and testing)

Testing will be performed in an air teststand like the one at MIT but longer.
We will also run tests in LAr in TallBO

This work will be on 1 m bars,
However, all of the info gained from them will directly apply to DUNE 2m bars.

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We also plan to do more work on the anode coupled readout this spring.
In April (or so) I would like to meet with this group to get a list of worries/issues you feel we should address w/r/t anode coupled readout.

# A last thought on lightguides: Officially including us in ProtoDUNE

It is natural for the project to want to limit the number of technologies in ProtoDUNE.
And *you do have a good baseline technology!*

However, we would like to be officially included as an *alternate technology,*
Because…

1) We think these bars will perform well in ProtoDUNE and it is worth considering them.
   The process of making the bars for SBND will teach us some more improvements
   (for example smoother, faster drawing of bars, without mistakes of touching bars)

2) If we are officially included, then I can ask for an NSF supplement
   to cover the cost of making ProtoDUNE bars and the travel to install them.
   On the other hand, if we are not seen as important to ProtoDUNE,
   we will not get this funding and cannot participate. (We know this from experience)

Thanks for considering this!