DEEP UNDERGROUND
NEUTRINO EXPERIMENT

CALCI CI WG meeting
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Temperature requirements for charge attenuation correction

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Introduction

- Jose's slide at CALCI scope review
- The idea is to derive the requirements on temperature measurements to achieve ~1% error on the transport calibration
- For the moment we focus on charge attenuation only

Energy calibration requirements

$$
\begin{aligned}
dE_{hit}(x,y,z)[MeV] = \; & C_{recombination}(x,y,z)[MeV/e]\times \\
& C_{transport}(x,y,z)\times \\
& C_{collection}(wire)\times \\
& C_{electronics}(channel)[e/ADC]\times \quad dQ(channel)[ADC]
\end{aligned}
$$

- The goal of calibration is to determine these correction factors/functions/maps
- The product of recombination, transport, collection and electronics corrections $C_r \times C_t \times C_c \times C_e$ must be known to **2% or better**
- Aim for 0.5% - 1% for each correction factor

Charge attenuation correction

- The charge Q arriving to the anode for a given drift time t and initial deposited charge Q_0:

$$Q(t) = Q_0 \cdot e^{-t/\tau}$$

- where τ is the electron lifetime
- The charge attenuation correction is therefore, assuming τ does not change along the drift path,

$$C = e^{t/\tau}$$

- In practice, τ change along the drift path and therefore one needs to integrate

Electron lifetime prediction

- The electron lifetime is inversely proportional to the impurity concentration
- The electron lifetime at a given position r can be computed using the reference lifetime (τ_0) and the normalized impurities at position r given by CFD simulations, I(r)

$$\tau(\vec{r}) = \frac{\tau_0}{I(\vec{r})}$$

- The reference lifetime (τ_0) is the one measured using cosmics, purity monitors (PrM) and maybe laser tracks.

- Combining those expressions:

$$C = e^{t/\tau}$$

$$\tau(\vec{r}) = \frac{\tau_0}{I(\vec{r})}$$

$$\longrightarrow \quad C = e^{t/\tau} = e^{t \cdot I/\tau_0} = (e^{t/\tau_0})^I = C_0^I$$

- where C_0 is the reference charge attenuation correction (with no CFD extrapolation)

$$C_0 = e^{t/\tau_0}$$

Error on charge att. correction

- The error on charge attenuation correction has several components:
  - Reference electron lifetime error ($\sigma_{\tau 0}$)
  - Error on Normalised impurity prediction from CFD (σ_I)

$$C = e^{t/\tau}$$

$$\tau(\vec{r}) = \frac{\tau_0}{I(\vec{r})}$$

$$\left(\frac{\sigma_C}{C}\right)^2 = \left(\frac{t}{\tau}\right)^2 \left[\left(\frac{\sigma_{\tau_0}}{\tau_0}\right)^2 + \left(\frac{\sigma_I}{I}\right)^2\right]$$

- The higher the e- lifetime the lower the effect of the CFD extrapolation

- Since the PrM measures Q_A/Q_C and not τ let's express the previous equation in terms of Q_A/Q_C, or to be simpler, in terms of C_0

$$C_0 = \frac{Q_C}{Q_A}$$

$$\frac{\sigma_{C_0}}{C_0} = \frac{\sigma_{Q_A/Q_C}}{Q_A/Q_C}$$

- The final expression is:

$$\left(\frac{\sigma_C}{C}\right)^2 = I^2 \left[\left(\frac{\sigma_{C_0}}{C_0}\right)^2 + \left(\frac{t}{\tau_0}\right)^2 \left(\frac{\sigma_I}{I}\right)^2 \right]$$

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Reference charge attenuation correction

$$\left(\frac{\sigma_C}{C}\right)^2 = I^2\left[\boxed{\left(\frac{\sigma_{C_0}}{C_0}\right)}^2 + \left(\frac{t}{\tau_0}\right)^2\left(\frac{\sigma_I}{I}\right)^2\right]$$

PrM lifetime error

from CALCI review answers

- Very small statistical uncertainty due to strong signal strength, low noise and large number of flashes in PrM measurement

RMS=2.0% $\Delta_{stat}(Qa/Qc)=2\%/sqrt(N_{flash})=0.14\%$.

J.Bian

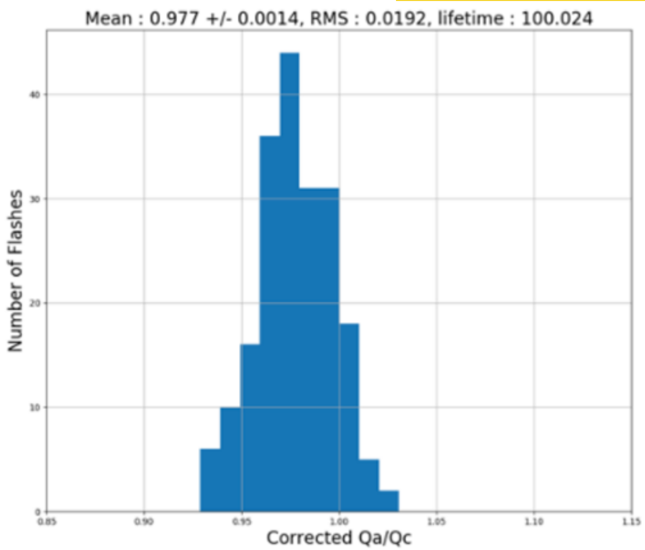


Table I: Summary of statistical and systematic uncertainties

		16 cm drift length (current) (column 1)	47cm drift length (2.9xcurrent) (column 2)	64cm drift length (4xcurrent) (column 3)
1	Statistical uncertainties in PrM Qa/Qc	0.14%	0.14%	0.14%
2	Run to run fluctuations PrM Qa/Qc	0.7%	0.7%	0.7%
3	Systematic uncertainties in PrM Qa/Qc	5.8%	2.1%	1.4%
4	Overall uncertainties in PrM Qa/Qc (drift time 2.3ms)	5.8%	2.2%	1.5%
5	Precision on TPC Qa/Qc at 3ms, 10ms, 100ms lifetimes (0% non-uniformity of impurity concentration)	5.8%	2.2%	1.5%
6	Precision on TPC Qa/Qc at 3ms lifetime (5% non-uniformity of impurity)	6.9%	4.3%	4.0%
7	Precision on TPC charge at 10ms lifetime (5% non-uniformity of impurity)	5.9%	2.5%	1.9%
8	Precision on TPC charge at 100ms lifetime (5% non-uniformity of impurity)	5.8%	2.2%	1.5%

Long purity monitor can control uncertainty in PrM Qa/Qc within 2%

- Uncertainties in TPC Qa/Qc calibrated with PrMs depend on LAr purity and precision of PrM-to-TPC extrapolation
- Under high LAr purity or with good extrapolation technique, uncertainty in TPC Qa/Qc is same as PrM Qa/Qc

Reference lifetime

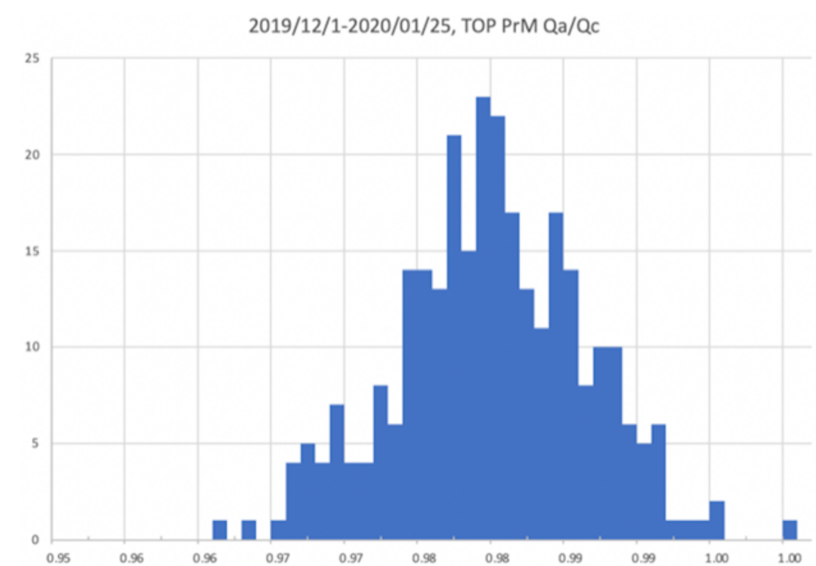
- It seems the PrM absolute Q_A/Q_C measurement error cannot be smaller that 1.5% so we need other ways of estimating the reference correction, as cosmics (and probably laser)
- The PrM measurement will be used to correct for time variations of the reference (absolute) correction (next slides)

$$C_0 = A_{\mathrm{PrM}}(t) \cdot C_0^{abs}$$

- Obviously PrM will be also used for an absolute lifetime measurement when the purity is low or when there are not sufficient cosmics

Time variations

- The attached histogram is Qa/Qc measured by TOP PrM between 2019/Dec/1-2020/Jan/25.
- Each input is one measurement done by averaging 200 flashes within 10 second.
- Standard deviation of these measurements over the two month (lifetime is stable) is 0.64%, to be conservative I use 0.7% as the run-by-run Qa/Qc fluctuation.



Time variations

- In the previous slide 0.7% is the RMS of the Qa/Qc when putting in the same histogram several measurements, so it is most likely due to time variations of the LAr conditions
- If the charge attenuation correction uses a single instantaneous PrM measurement (with 0.14% statistical error) but then it is used over a given period of time (e.g. 1 day) one has to consider as a systematic in the correction the expected time variations of the PrM measurement over a period of 1 day
- Thus, the systematic error on the PrM correction of the reference charge attenuation (A_{PrM}) would be 0.7%. In that case the error on the reference charge attenuation correction cannot be larger that 0.8%, such that the total error is ~1%

$$C_0 = A_{\mathrm{PrM}}(t) \cdot C_0^{abs}$$

Extrapolation using CFD

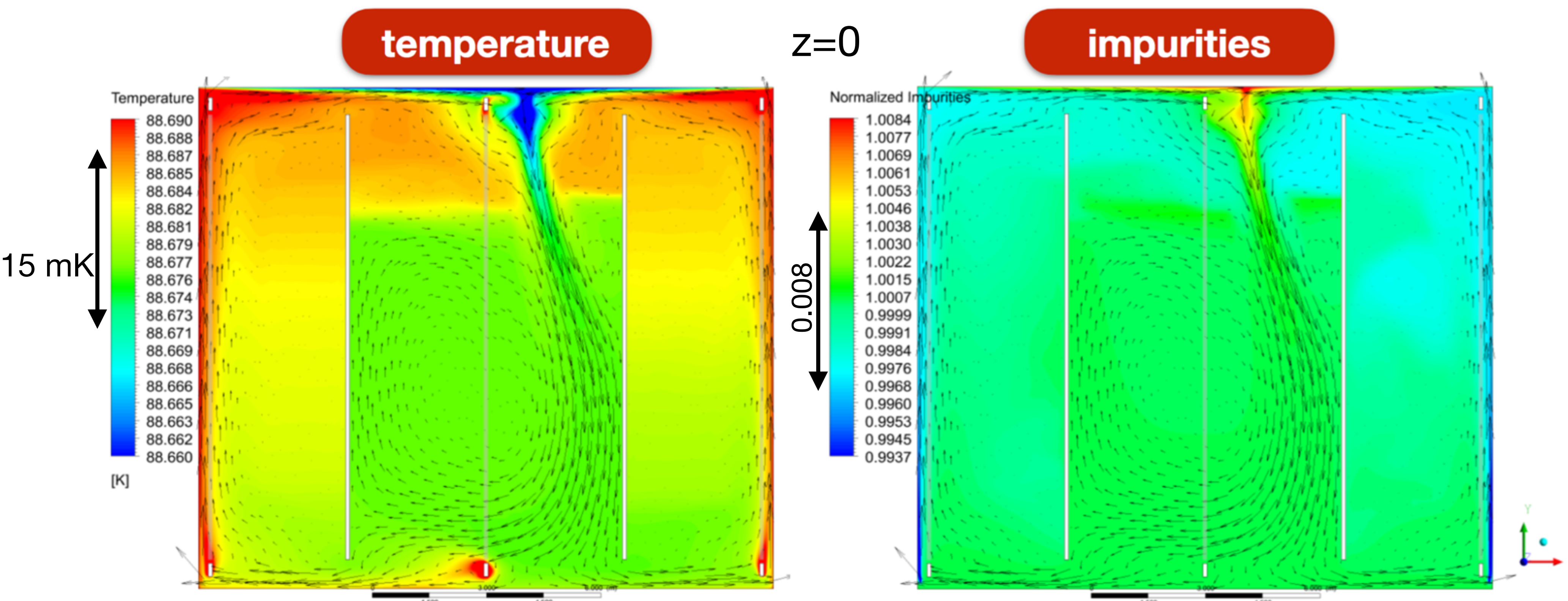
$$\left(\frac{\sigma_C}{C}\right)^2 = I^2\left[\left(\frac{\sigma_{C_0}}{C_0}\right)^2 + \boxed{\left(\frac{t}{\tau_0}\right)^2\left(\frac{\sigma_I}{I}\right)^2}\right]$$

Introduction

- To achieve an energy scale error better that 2% we need ~1% error on charge attenuation correction, what implies <1% error on the reference correction
  - Let's consider 1% error on the reference correction ($\sigma_{C0}/C_0 = 0.01$)
  - And let's aim for a negligible CFD extrapolation error compared to that 1% such that the total error is ~1%

Impurities vs temperature

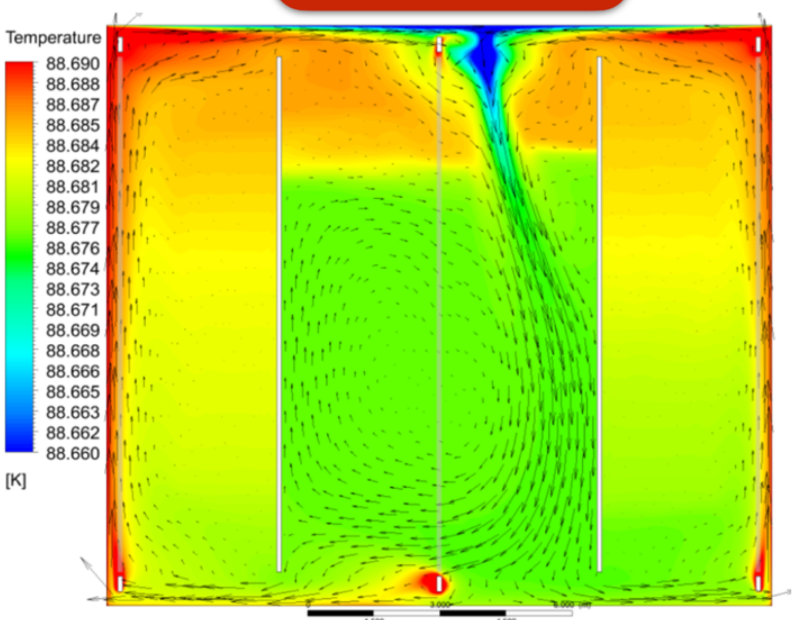
- Using Erik Voirin's CFD simulations (DUNE-doc-1046-v2) an inverse relation between impurities and temperature is observed
  - About 1% variation in normalized impurities for 15 mk variation in temperature
  - Not obvious what the assumptions are. To be investigated



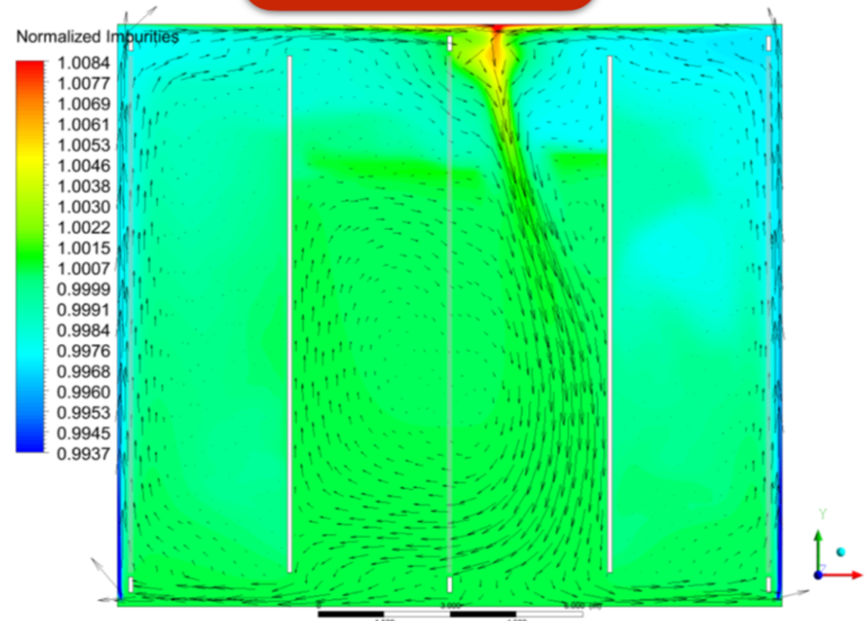
Why the inverse relation ?

- This is probably related to the LAr flow lines. The closer to the inlets (bottom edges) the less impure is the argon because it just came from the purification system. It is also there where it is warmer, as expected, because it is injected warmer in te cryostat
- On the contrary, the longest path is for LAr between the two cathodes, where the impurity is larger. The liquid is cooled down progressively when it enters in contact with the colder LAr in the cryostat, therefore is colder between the two cathodes.

temperature

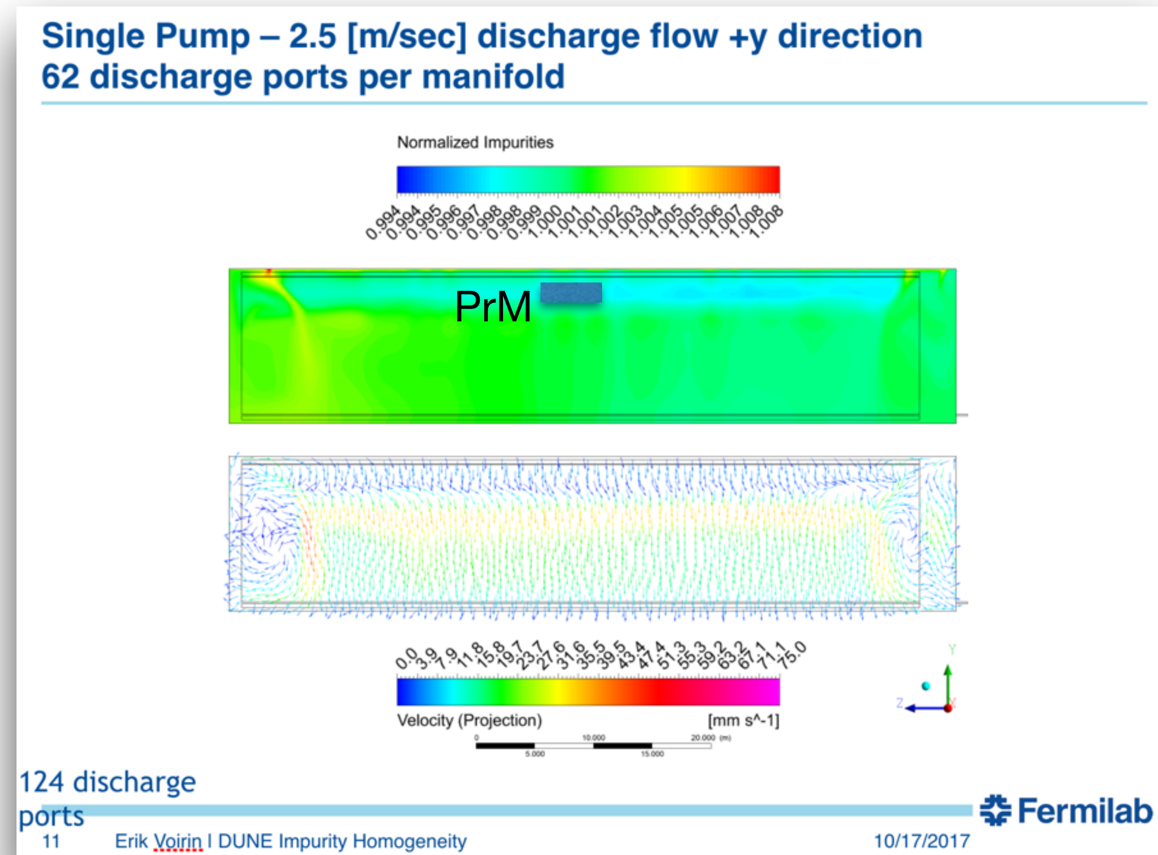


impurities



Impurity range

- Those are simulations, but is there a way of measuring the impurity range ?
- It seems the Purity is larger near the LAr surface, maybe a PrM close to the surface (but not in the corners) could help is measuring the impurity range



CFD simulations

- The function $\mathrm{I}(r)$ will be given by CFD simulations verified/tuned mainly with temperature data
- We don't have yet a clear way of estimating the error on the prediction of normalized impurities but it will depend:
  - On the agreement between measured and predicted temperature maps
  - On the temperature measurement error

Normalised impurities vs T

- We can parametrise it as follows (just a possible parameterization giving an inverse relation):

$$\frac{I - I_0}{I} = \beta \cdot (T - T_0) \longrightarrow I(T) = \frac{I_0}{1 - \beta \cdot (T - T_0)}$$

- Let's assume a worst scenario of 5% decrease in normalised impurities for 15 mk increase in temperature

$$\beta = \frac{(\Delta I / I)}{\Delta T} = \frac{-0.05}{15} = -0.0033\ mK^{-1}$$

- This means that the normalized impurities vary ~0.3% for each mK difference

Error on normalized impurities

- The relative error on the normalized impurities

$$\frac{\sigma_I}{I} = \frac{\beta}{1-\beta\cdot(T-T_0)}\sigma_T$$

- And remember the total error on the charge attenuation correction

$$\left(\frac{\sigma_C}{C}\right)^2 = I^2\left[\left(\frac{\sigma_{C_0}}{C_0}\right)^2 + \left(\frac{t}{\tau_0}\right)^2\left(\frac{\sigma_I}{I}\right)^2\right]$$

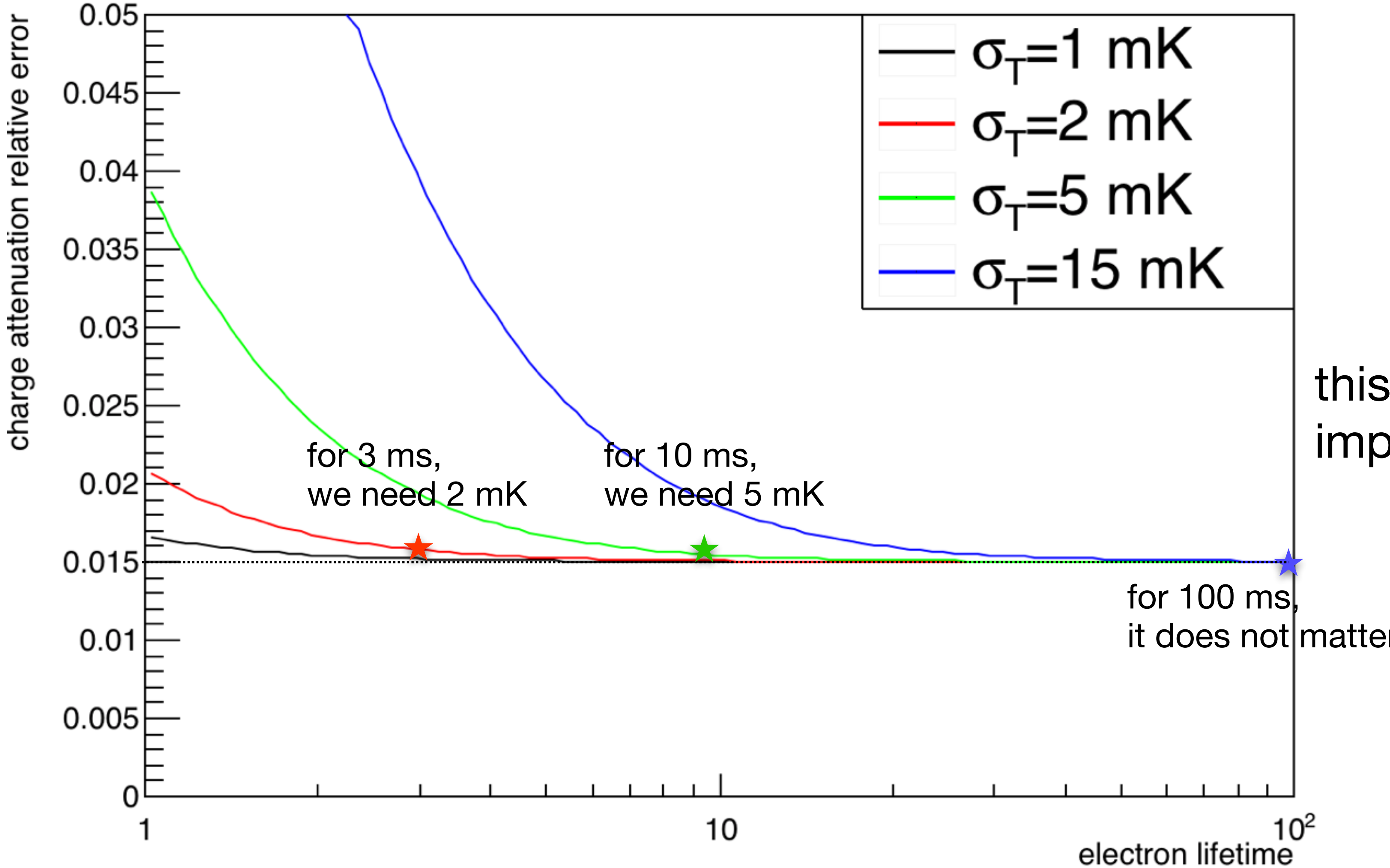
- In DUNE t=2.3 ms for the full drift

Results

$$\left(\frac{\sigma_C}{C}\right)^2 = I^2\left[\left(\frac{\sigma_{C_0}}{C_0}\right)^2 + \left(\frac{t}{\tau_0}\right)^2\left(\frac{\sigma_I}{I}\right)^2\right]$$

1.5% error on Q_A/Q_C

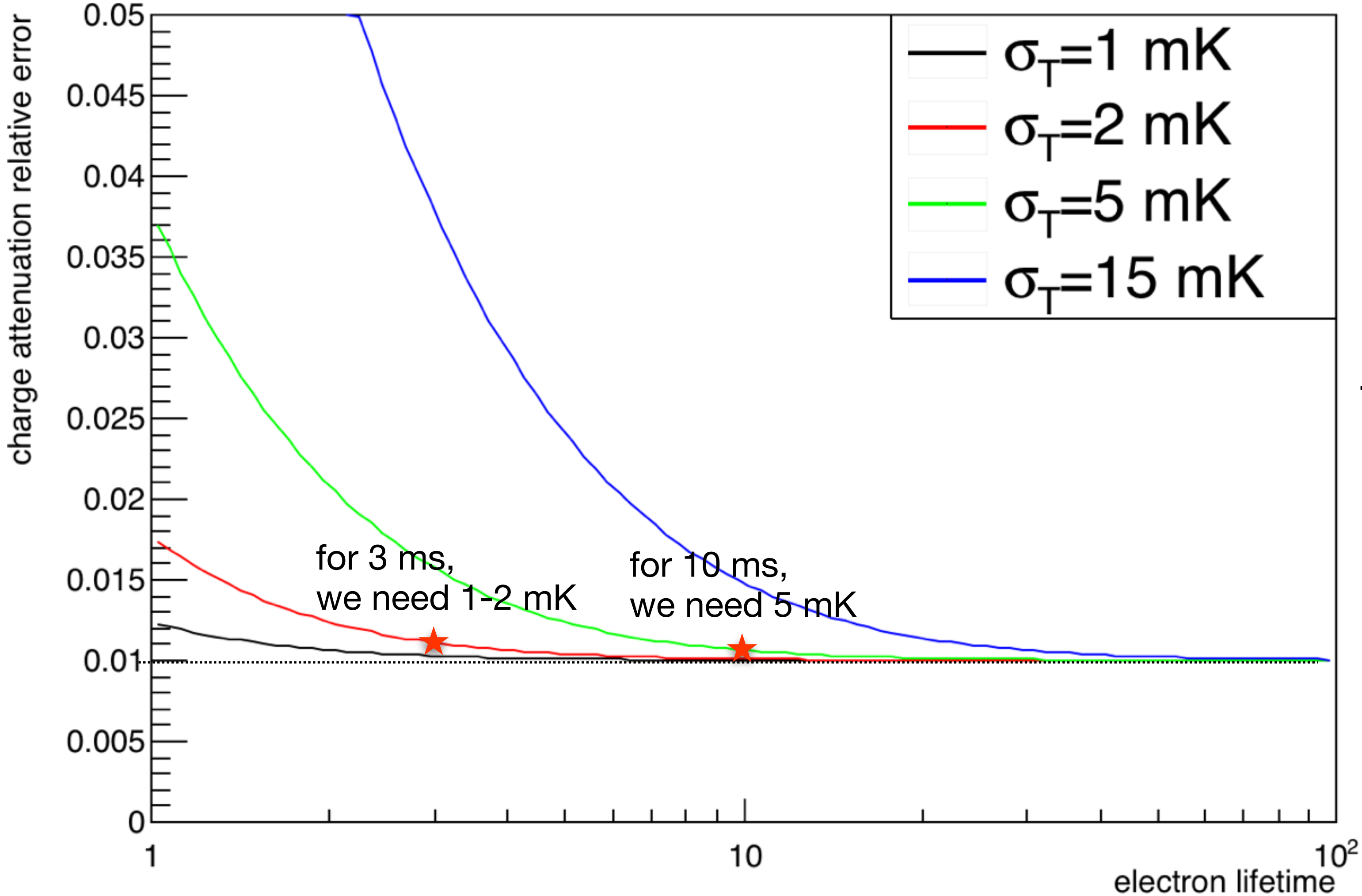
- Aim is to have a small extrapolation error compared to the error on the reference Q_A/Q_C



this is for 5% impurity range

1% reference lifetime error

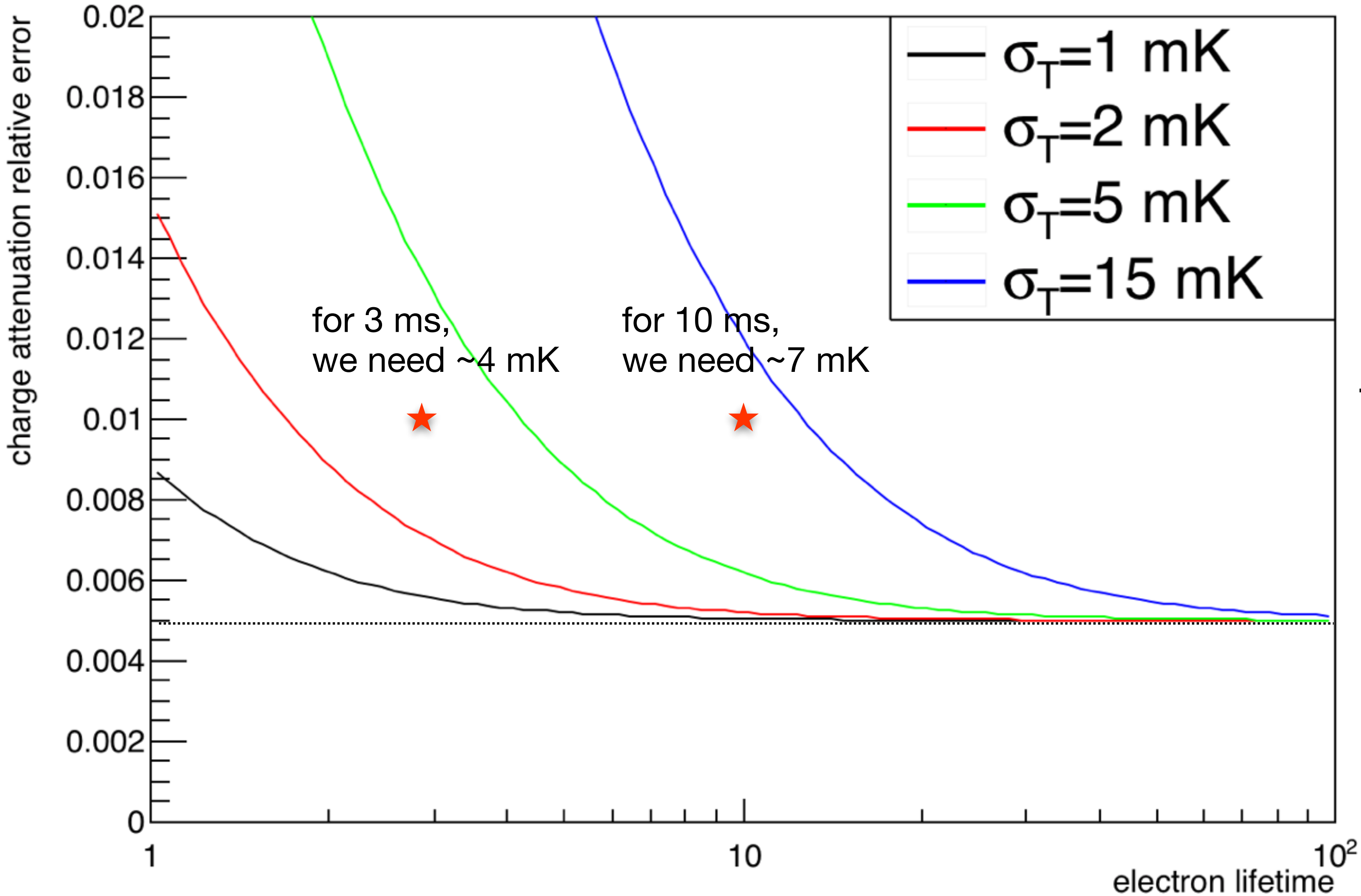
- As mentioned above we need 1% in charge attenuation correction, so let's consider 1% in reference lifetime error



this is for 5% impurity range

0.5% reference lifetime error

- In the case of a better lifetime error, requirements on temperature can be relaxed if we still aim for 1% error on charge attenuation correction



this is for 5% impurity range

Summary

- Requirements for temperature map precision for different values of lifetime and reference lifetime error assuming **5% impurity range**

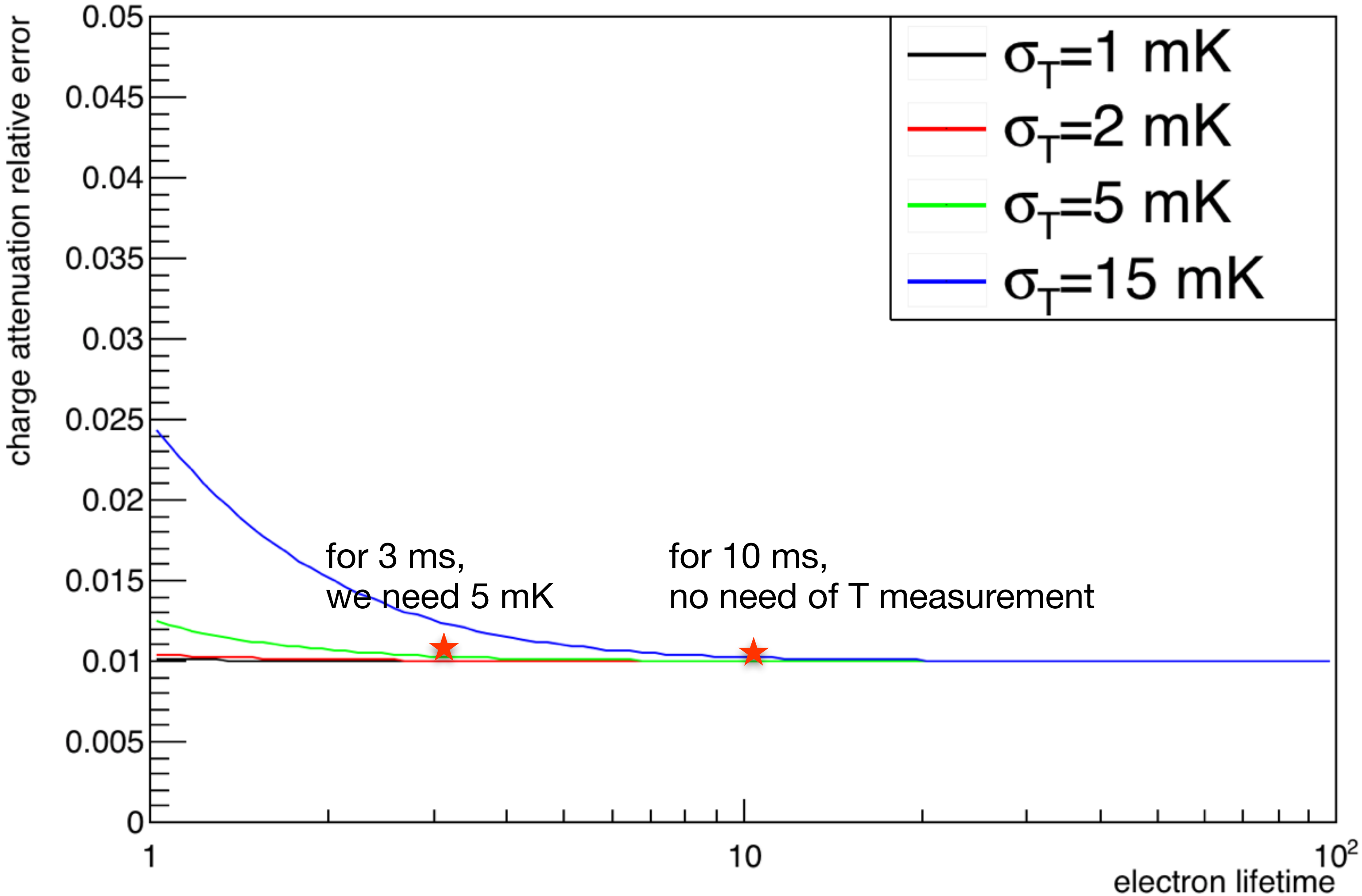
$$I^2\left[\left(\frac{\sigma_{C_0}}{C_0}\right)^2+\left(\frac{t}{\tau_0}\right)^2\left(\frac{\sigma_I}{I}\right)^2\right]=\left(\frac{\sigma_C}{C}\right)^2$$

τ	$(\sigma_C/C)_{\tau 0}$	$(\sigma_C/C)_I$	σ_C/C	required σ_T (mK)
3	0,015	0,0048	0,0158	2,0
10	0,015	0,0051	0,0158	7,0
100	0,015	0,0011	0,0150	15,0
3	0,010	0,0036	0,0106	**1,5**
10	0,010	0,0036	0,0106	**5,0**
100	0,010	0,0011	0,0101	15,0
3	0,005	0,0096	0,0109	4,0
10	0,005	0,0087	0,0100	12,0
100	0,005	0,0011	0,0051	15,0

Results for 1% impurity range

1% reference lifetime error

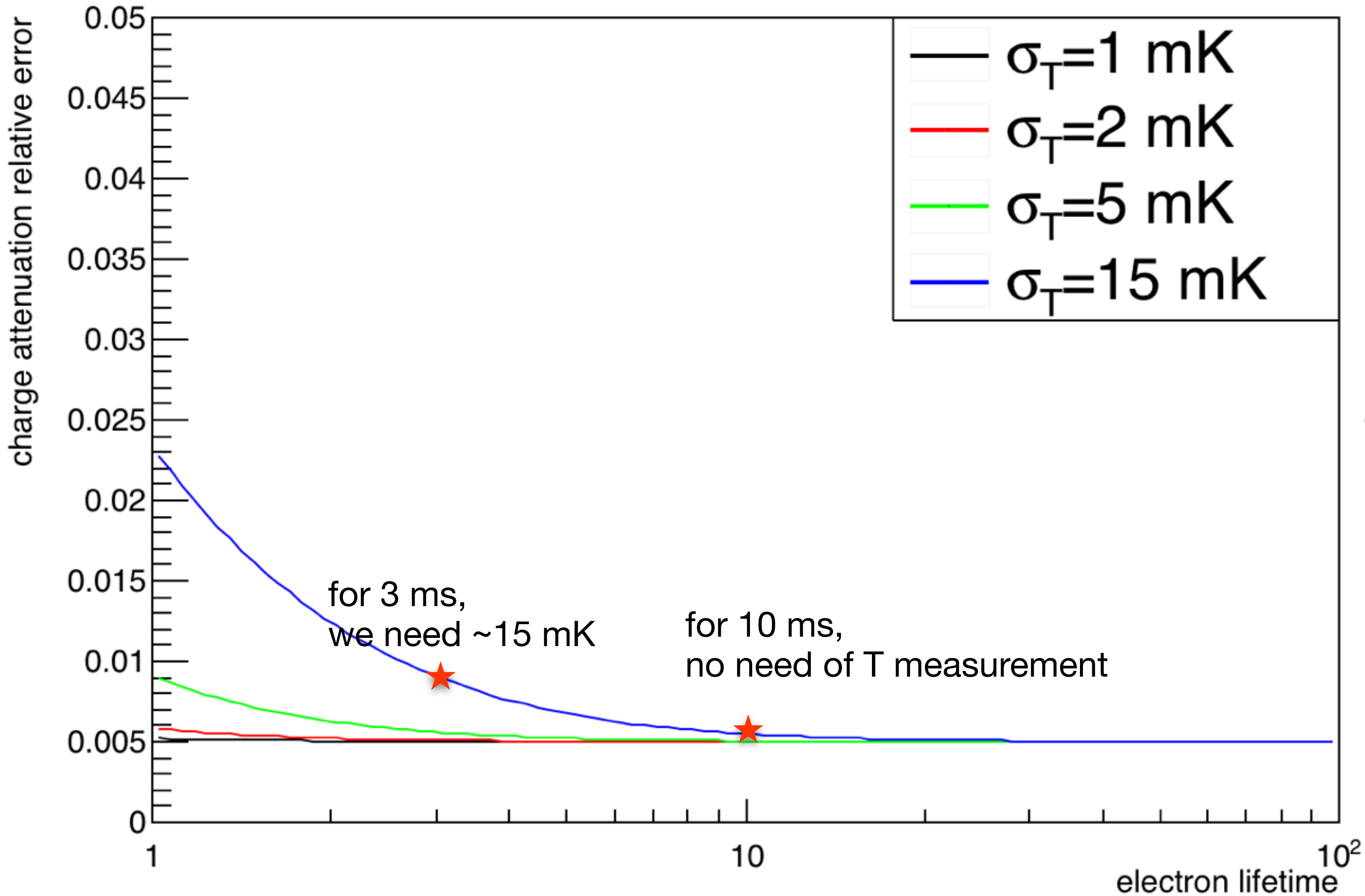
- As mentioned above we need 1% in charge attenuation correction, so let's consider 1% in reference lifetime error



this is for 1% impurity range

0.5% reference lifetime error

- In the case of a better lifetime error, requirements on temperature can be relaxed if we still aim for 1% error on charge attenuation correction



this is for 1% impurity range

Summary II

- Requirements for temperature map precision for different values of lifetime and reference lifetime error assuming **1% impurity range**

$$I^2\left[\left(\frac{\sigma_{C_0}}{C_0}\right)^2+\left(\frac{t}{\tau_0}\right)^2\left(\frac{\sigma_I}{I}\right)^2\right]=\left(\frac{\sigma_C}{C}\right)^2$$

τ	$(\sigma_C/C)_{\tau 0}$	$(\sigma_C/C)_I$	σ_C/C	required σ_T (mK)
3	0,015	0,0025	0,0152	5,0
10	0,015	0,0023	0,0152	15,0
100	0,015	0,0002	0,0150	15,0
3	0,010	0,0025	0,0103	**5,0**
10	0,010	0,0023	0,0103	**15,0**
100	0,010	0,0002	0,0100	15,0
3	0,005	0,0075	0,0090	15,0
10	0,005	0,0023	0,0055	15,0
100	0,005	0,0002	0,0050	15,0

Conclusions

- Required precision on temperature depends on electron lifetime, reference lifetime measurement error and impurity range
- To achieve an energy scale error better that 2% it is assumed we need ~1% error on charge attenuation correction, what implies ~1% error on the reference lifetime measurement (from cosmics, PrM and maybe laser)
- For 5% impurity range:
    - For 1% error on the reference lifetime measurement a local error on the temperature map of **5 mK is sufficient for a lifetime of 10 ms or higher**
    - For the worst scenario of 3 ms lifetime one would need to reduce the error on the temperature map to 1.5 mK
    - The quoted precision is for the temperature map, not for a local temperature measurement (a single sensor)
        - 1.5 mK is perfectly achievable having sufficient number of sensors and a good calibration (3-5 mK), already achieved in PD
- For 1% impurity range, **5 mK** is sufficient in all cases

Conclusions

- But how can we **measure** the impurity range (ΔI_{max}) ? We would need local e-lifetime measurements to cover regions with large expected variations in impurities
    - We could use cosmics but would need long time
    - Can laser do that ?
    - Maybe a PrM in the middle of the cryostat close to the LAr surface, where we ave the maximum variation predicted by CFD (see slide)

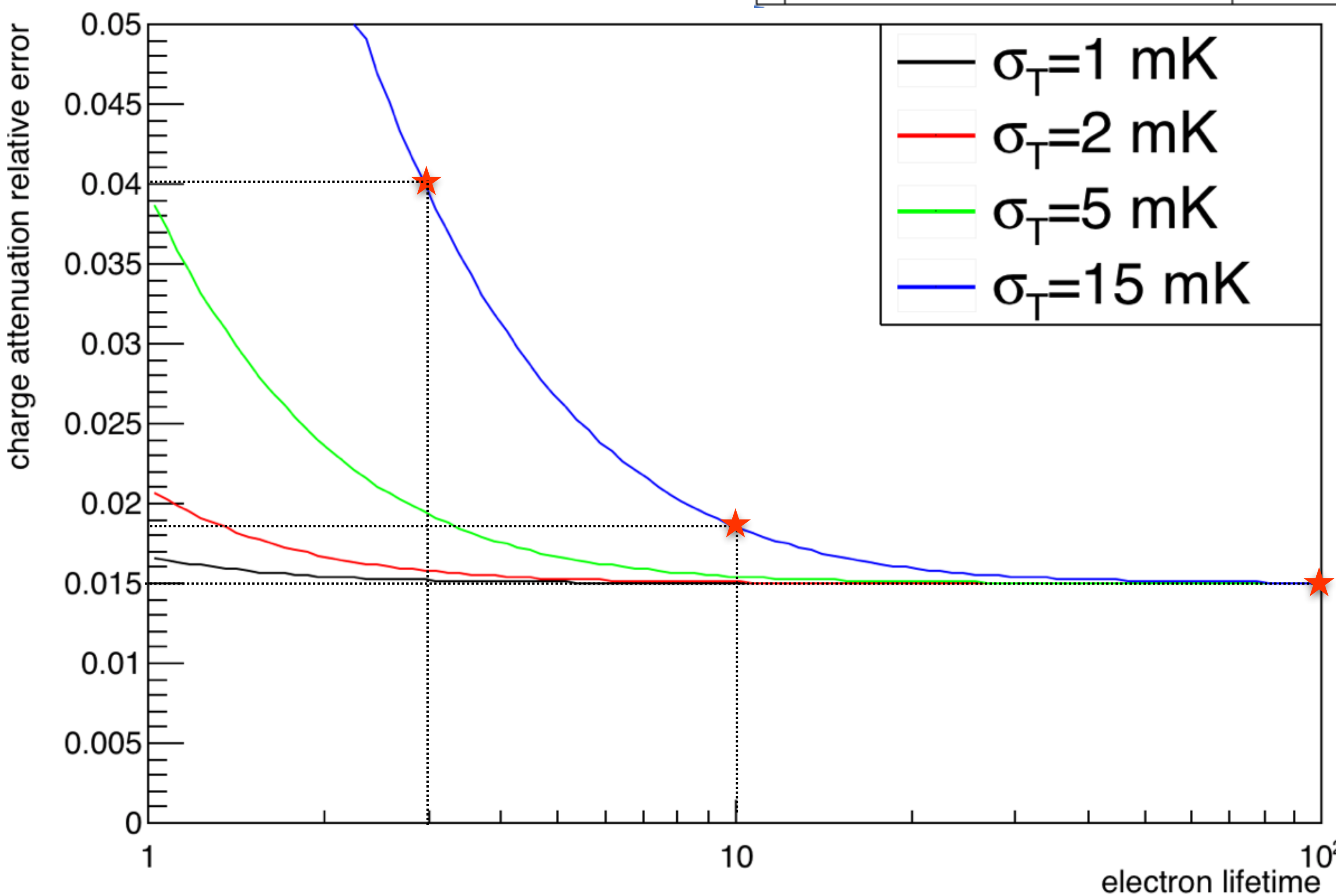
backup

Crosscheck

- For 1.5 % error on lifetime measurement we get agreement with Jianming's numbers

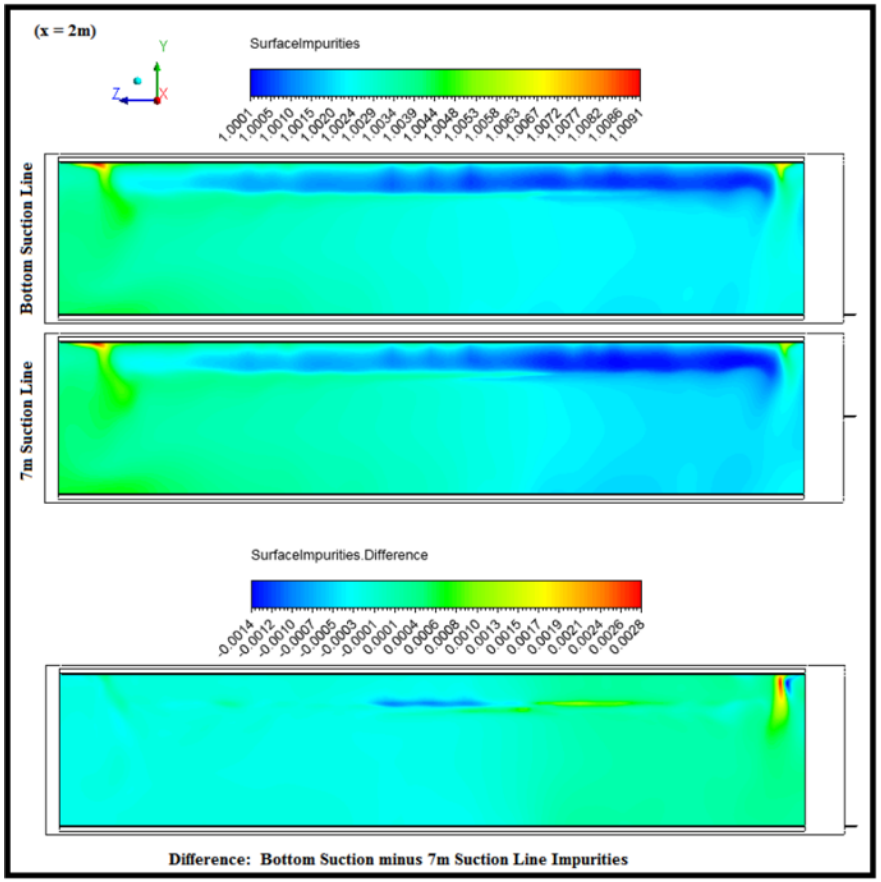
6	Precision on TPC Qa/Qc at 3ms lifetime (5% non-uniformity of impurity)	6.9%	4.3%	4.0%
7	Precision on TPC charge at 10ms lifetime (5% non-uniformity of impurity)	5.9%	2.5%	1.9%
8	Precision on TPC charge at 100ms lifetime (5% non-uniformity of impurity)	5.8%	2.2%	1.5%

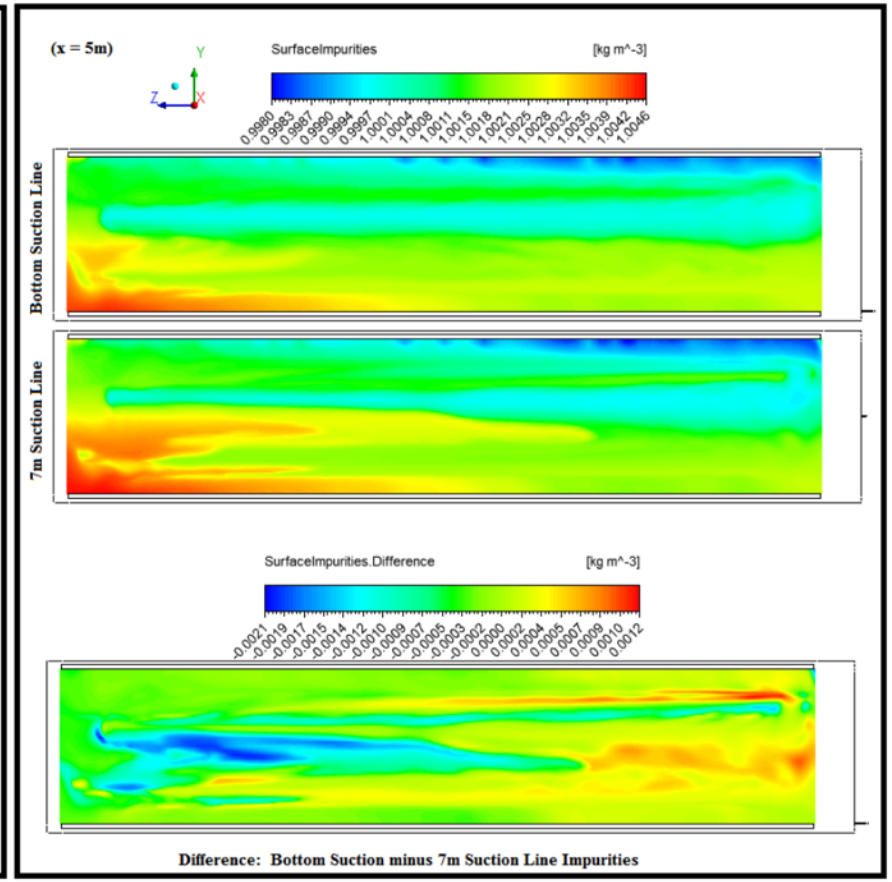
$$\left(\frac{\sigma_C}{C}\right)^2 = \left(\frac{\sigma_{\tau_0}}{\tau_0}\right)^2 + \left(\frac{t}{\tau}\frac{\sigma_I}{I}\right)^2$$



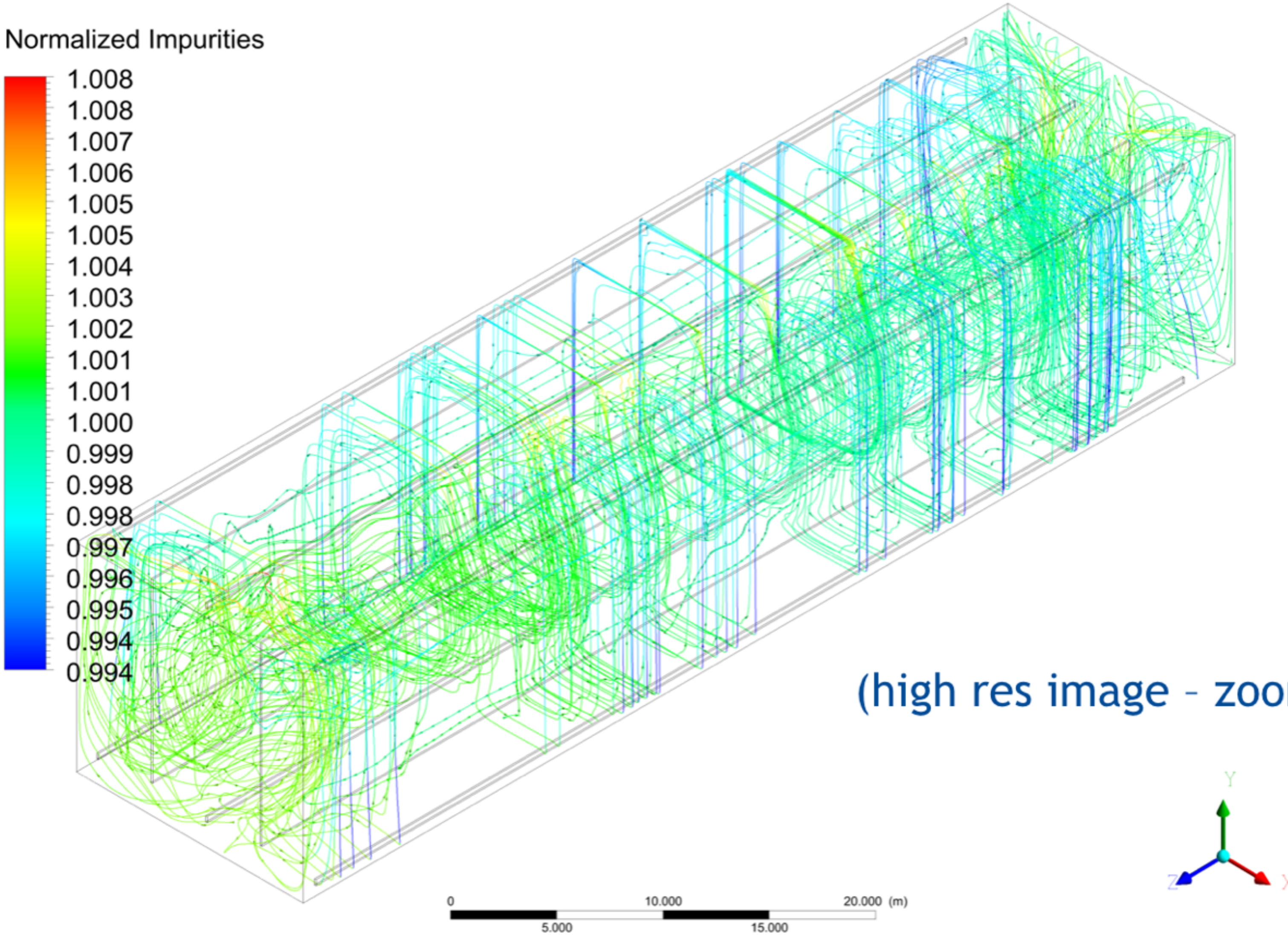
σ_T=15 mK is equivalent to no temperature measurement and thus to a 5% error on impurity concentration. So we use that curve to compare with Jianming's numbers

Case Comparison of Impurities inside Field Cage Volume at several YZ planes: (negligible difference)





Normalized Impurity Streamlines



(high res image – zoom for detail)

124 discharge ports

Fermilab