Impact of Cell Charging on Cryogenic EDM Searches

4^{th} International Workshop on Searches for a Neutron Electric Dipole Moment

Feb 14-19, 2021

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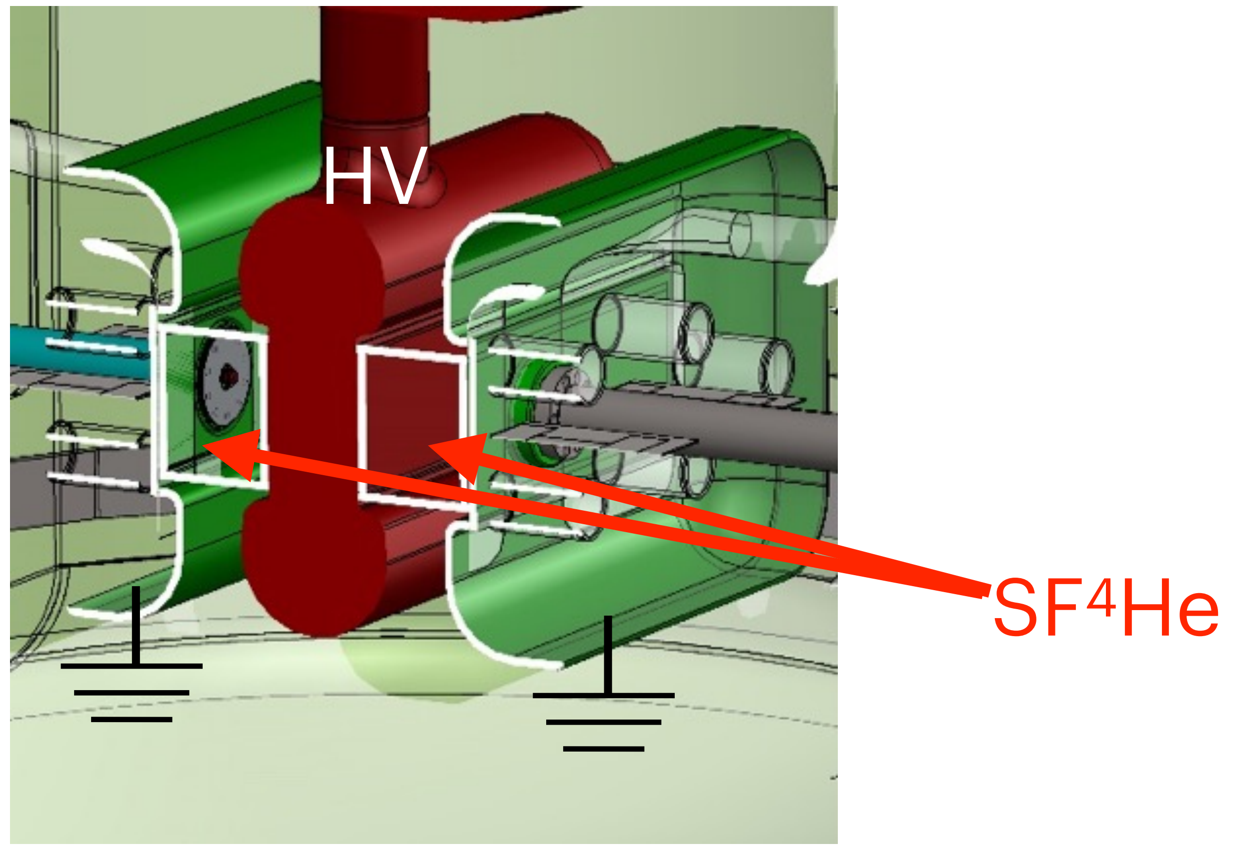
Funding Agencies

Overview

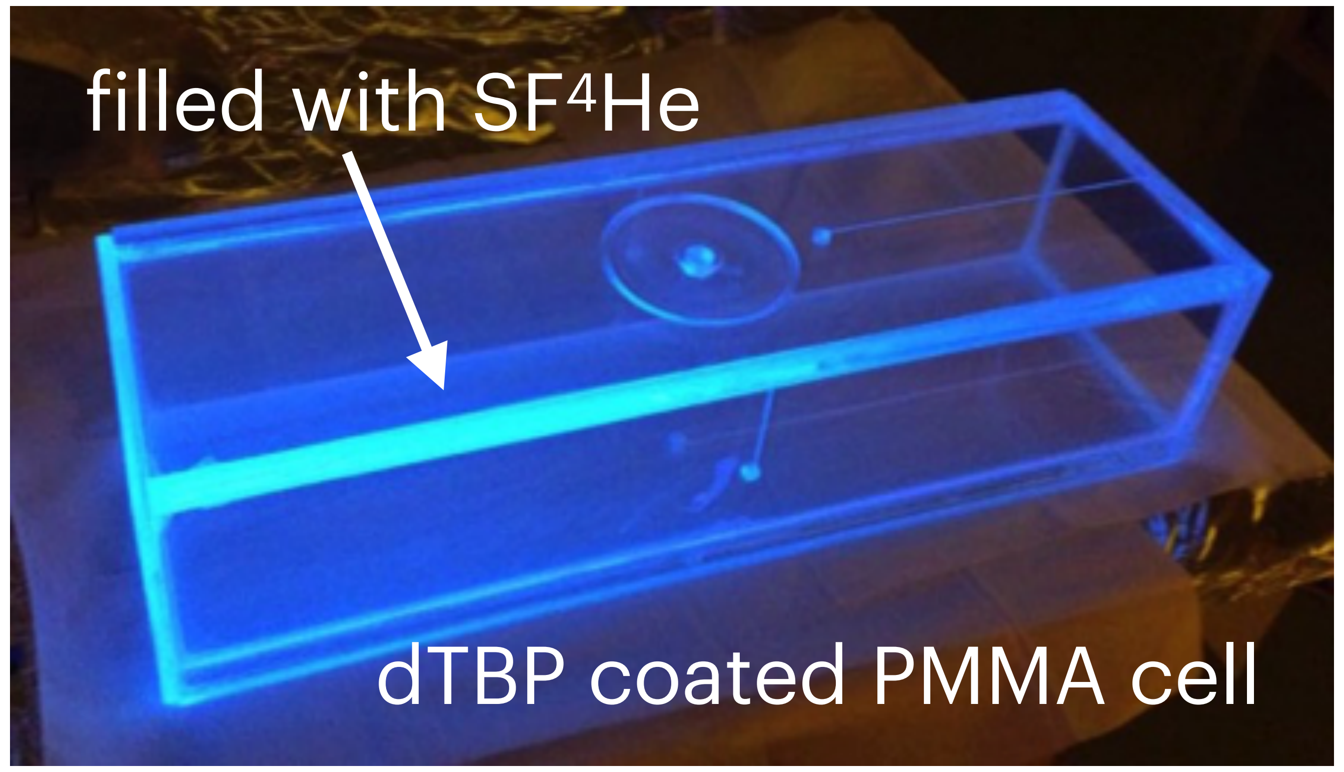
- Motivation for cell charging studies
- Test apparatus at UKy
- Studies of cell charging
- Impact on nEDM@SNS
- Summary

Free Charges in SF^{4}He Cells



During measurement cycle:
- *neutron beta-decay*
- *n + ^{3}He → p + t + 764 keV*
- *other ionizing radiation from ambient materials*

Number of secondaries depends on kind of ionizing radiation (and its energy)
- electrons thermalize via elastic scattering from ^{4}He atoms
- electrons form "bubbles" when thermalized, radius r_e ~1.9 nm
- ions form "snowballs" $M_{snowball}$ ~ (40 - 60) $m_{(4He)}$, r_b ~ 0.7 nm
- if charges are separated, "bubbles" and "snowballs" will drift in presence of external field

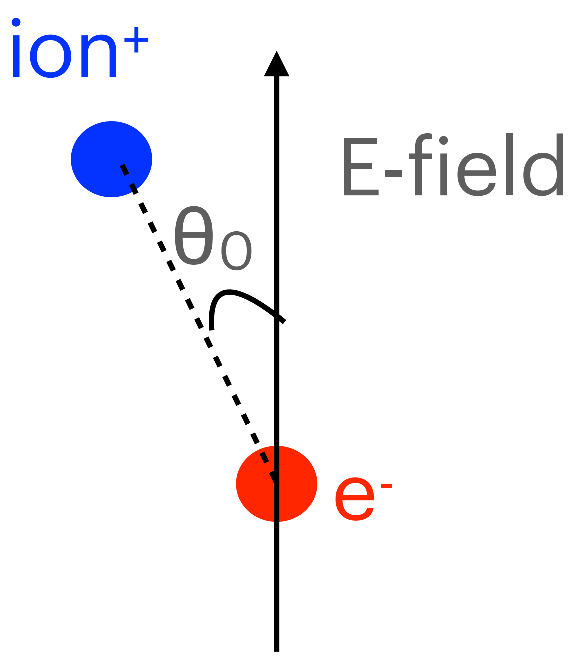


see talk by T. Ito

condition for charge separation (no diffusion):

$$r_0(1 + cos\theta_0) \geq \frac{2e}{4\pi\epsilon_0 \cdot E}$$

r_0: initial separation of charges
E: electric field



Here: E >>10 kV/cm
→ charge separation very likely

G.M. Seidel et al., PRC 89, 025808 (2014)

Free Charges in SF_4He Cells

Effects on E-field stability:

- charges recombine during drift to cell walls (no effect on E-field)
- charges recombine on cell wall (unlikely → insulators)
- charges recombine under E-field reversal
- charges do not recombine but move to opposite wall under E-field reversal

Potential problem for nEDM measurement?

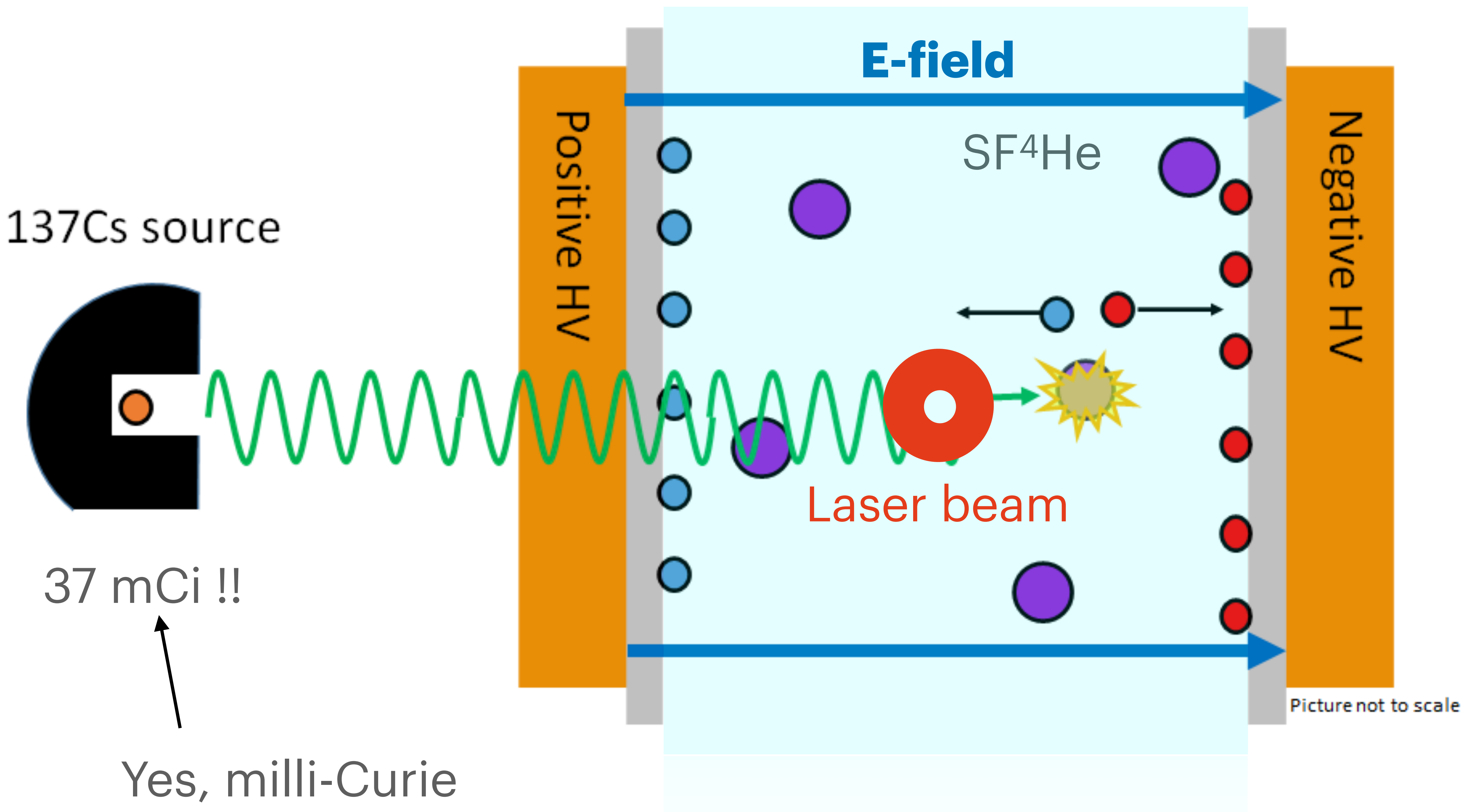
Motional magnetic field: $\overrightarrow{B}_m = \overrightarrow{v}_n \times \overrightarrow{E}$ ⇨ changing E-field causes a changing B-field

nEDM@SNS requirement: ΔB ≲ 0.2 fT → $\dfrac{\Delta E}{E} \leq 1\,\%$ **(per measurement cycle)**

How to measure the effect of cell charging on the stability of the E-field?

Monitor E-field Stability Using the Kerr Effect

Test setup at UKy: no neutrons → ionize SF^{4}He using a strong γ-source (E_γ= 662 keV)



Electro-optical Kerr effect:

Electric field induces an ellipticity in linearly polarized light:

$$\epsilon(t) = \frac{\pi}{\lambda} K E(t)^2 L$$

K = Kerr (material) constant

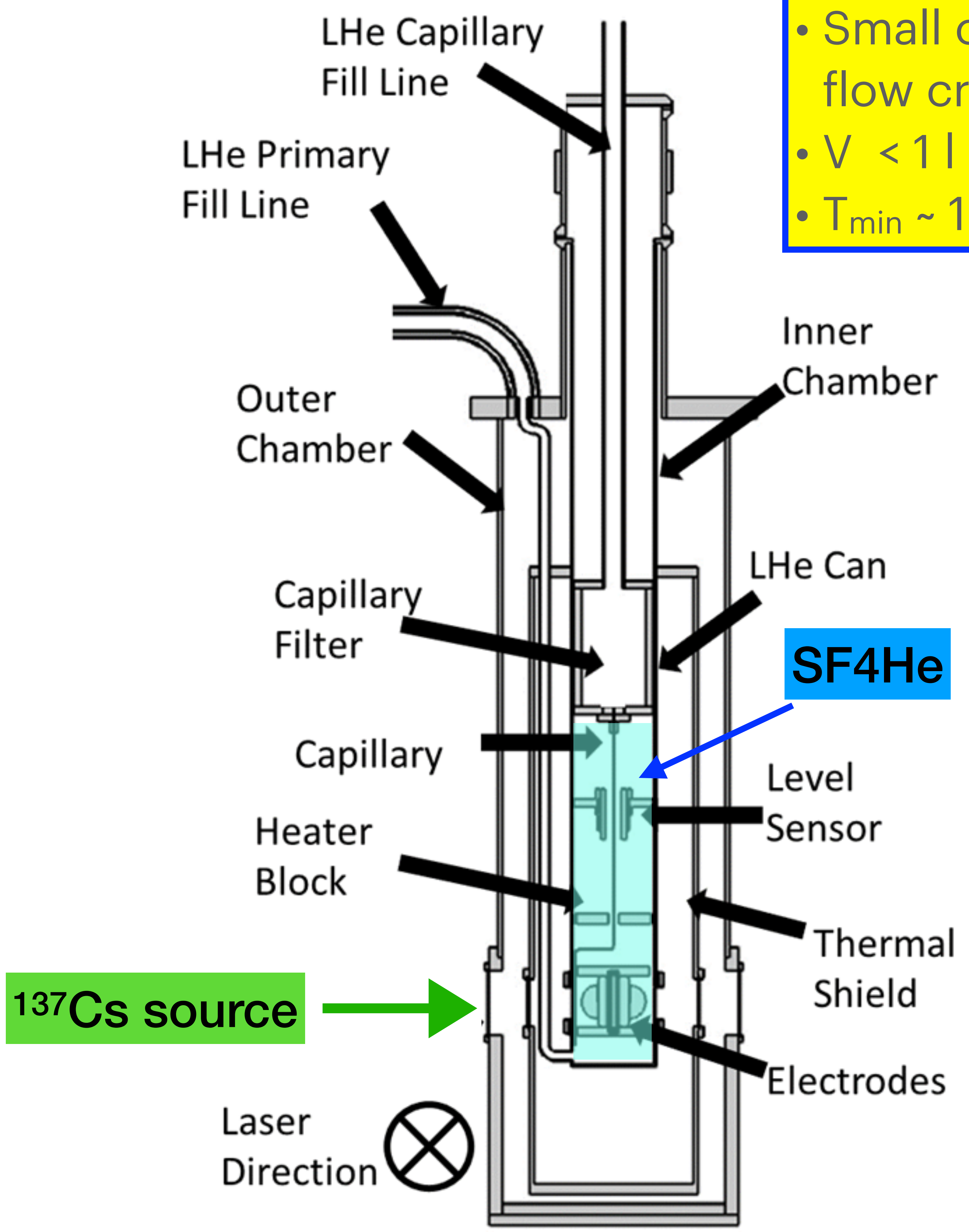
E = electric field → ε ∝ E^2

L = sample length

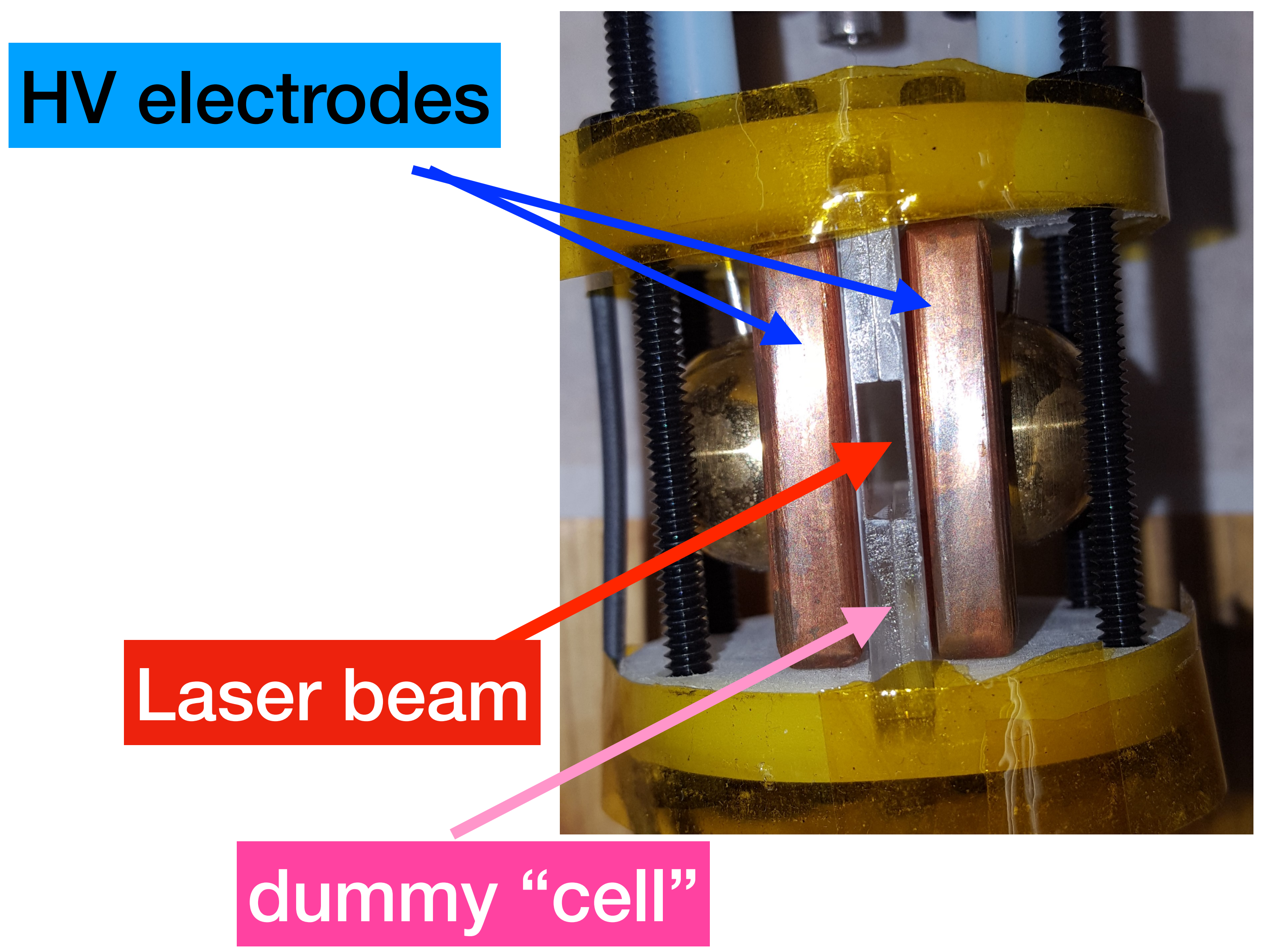
$K_{(SFHe)}$ = $(1.43 \pm 0.02_{stat} \pm 0.04_{sys}) \times 10^{-20} \frac{cm^2}{V^2}$

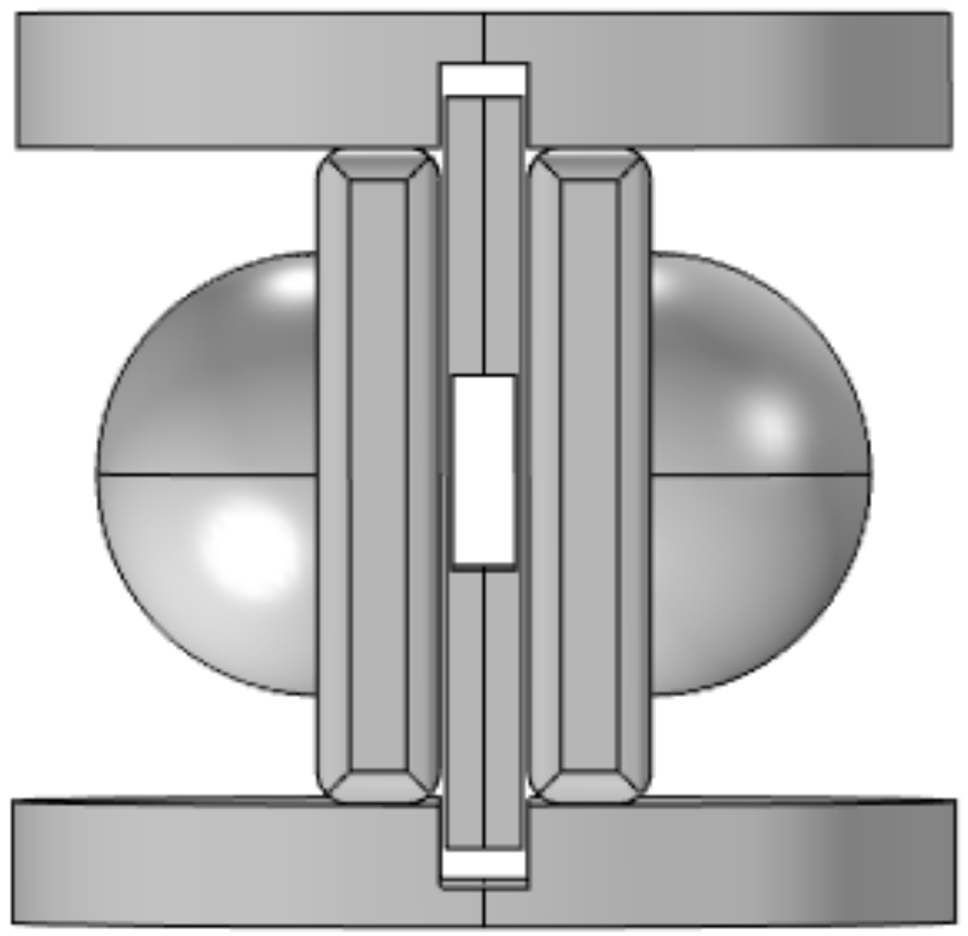
A. Sushkov et al., PRL 93, 153003 (2004)

Cryostat and HV Electrodes

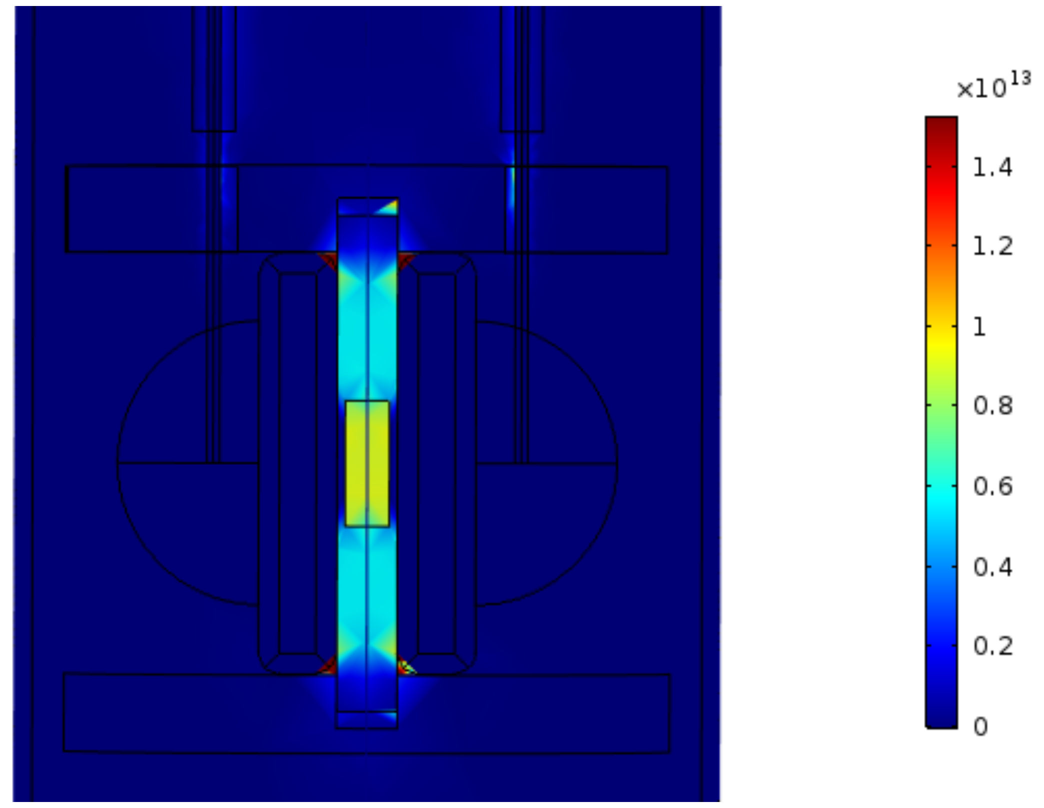


- Small continuous flow cryostat
- V < 1 l
- T_{min} ~ 1.9 K



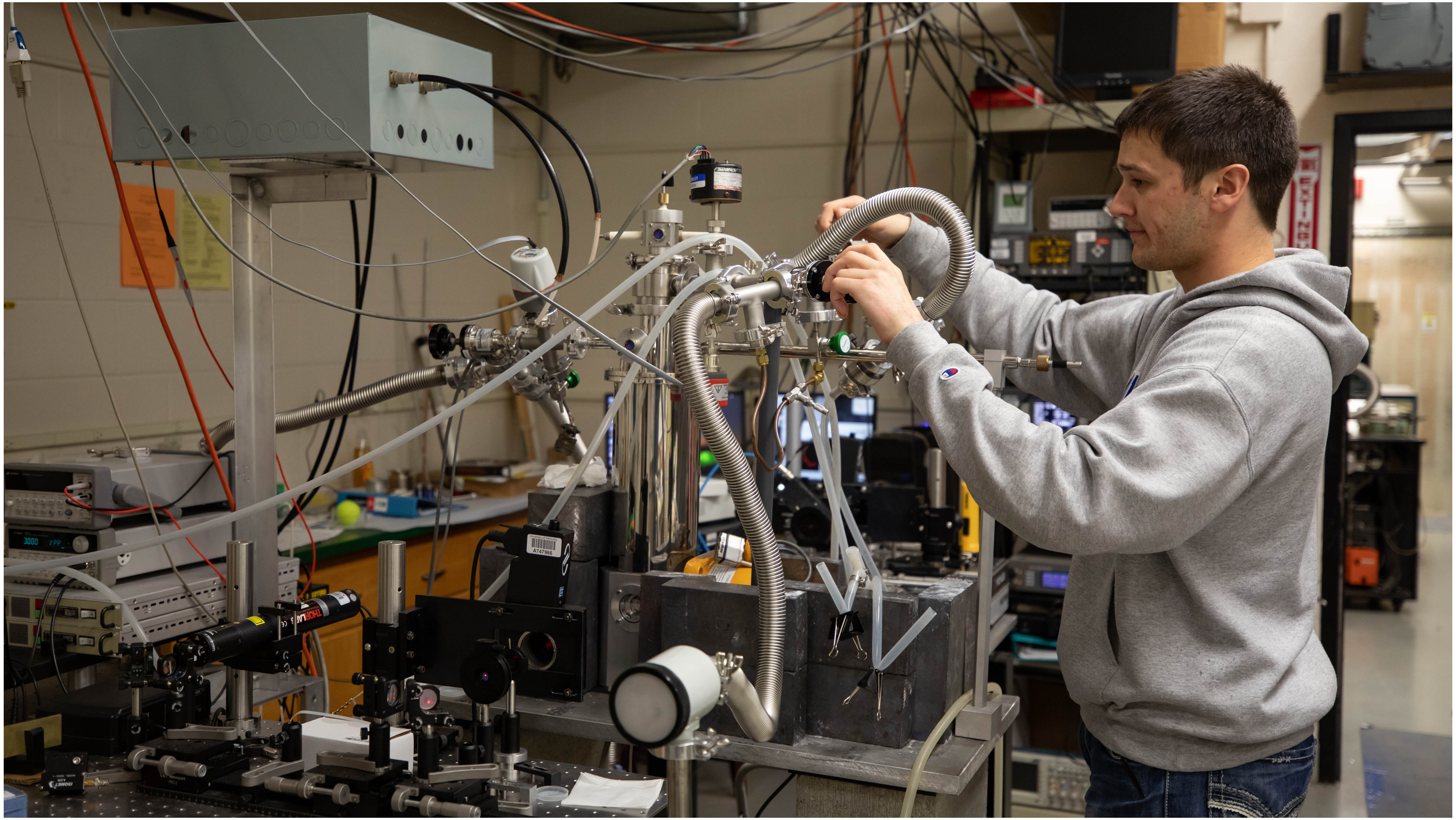


COMSOL Model



Electrodes:
- length L = 3 cm
- gap d = 2.84 mm (between PMMA walls)
- wall thickness t = 0.64 mm

Cell Charging Lab



Ellipticity Monitor

Typical values:
- V_{DC} = 15 kV
- V_{AC} = 7 kV
- E_{peak} ~ 53 kV/cm

expected ellipticity in SF[4]He ~2 μrad (without cell charging)

Extremely small signal!!

Modulate HV so that: $|E| = \dfrac{V_{DC} + V_{AC} \cdot cos(\omega t)}{d}$

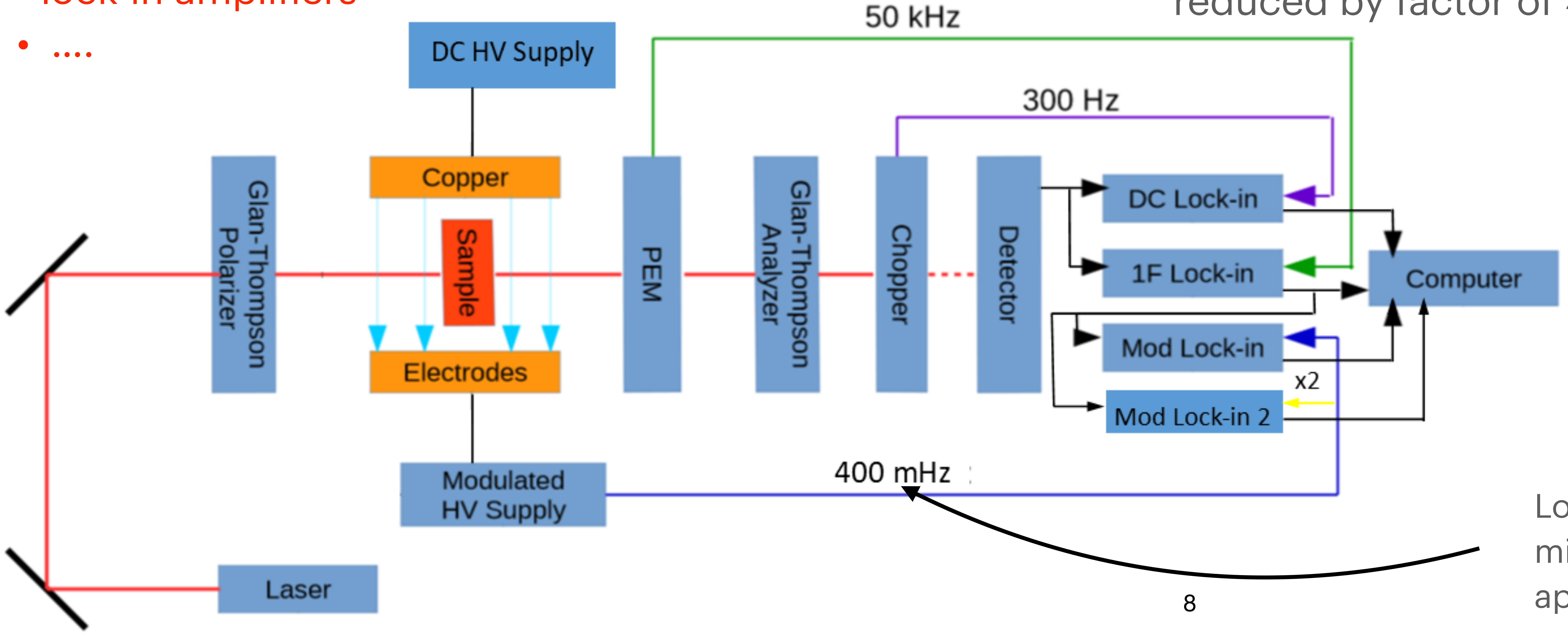
$$E^2 = \frac{V_{DC}^2}{d^2} + \frac{V_{AC}^2}{2d^2} + \frac{2V_{DC}V_{AC}}{d^2}cos(\omega t) + \frac{V_{AC}^2}{2d^2}cos(2\omega t)$$

monitor these two terms using lock-in techniques

$V_{DC} \cdot V_{AC}$ term → sensitive to changes in DC voltage (E-field)

V_{AC}^2 term → monitors stability of AC voltage (E-field), note sensitivity reduced by factor of 4

- triple modulation
- vibration isolation
- avoid frequencies of ambient noise sources
- lock-in amplifiers
- ....

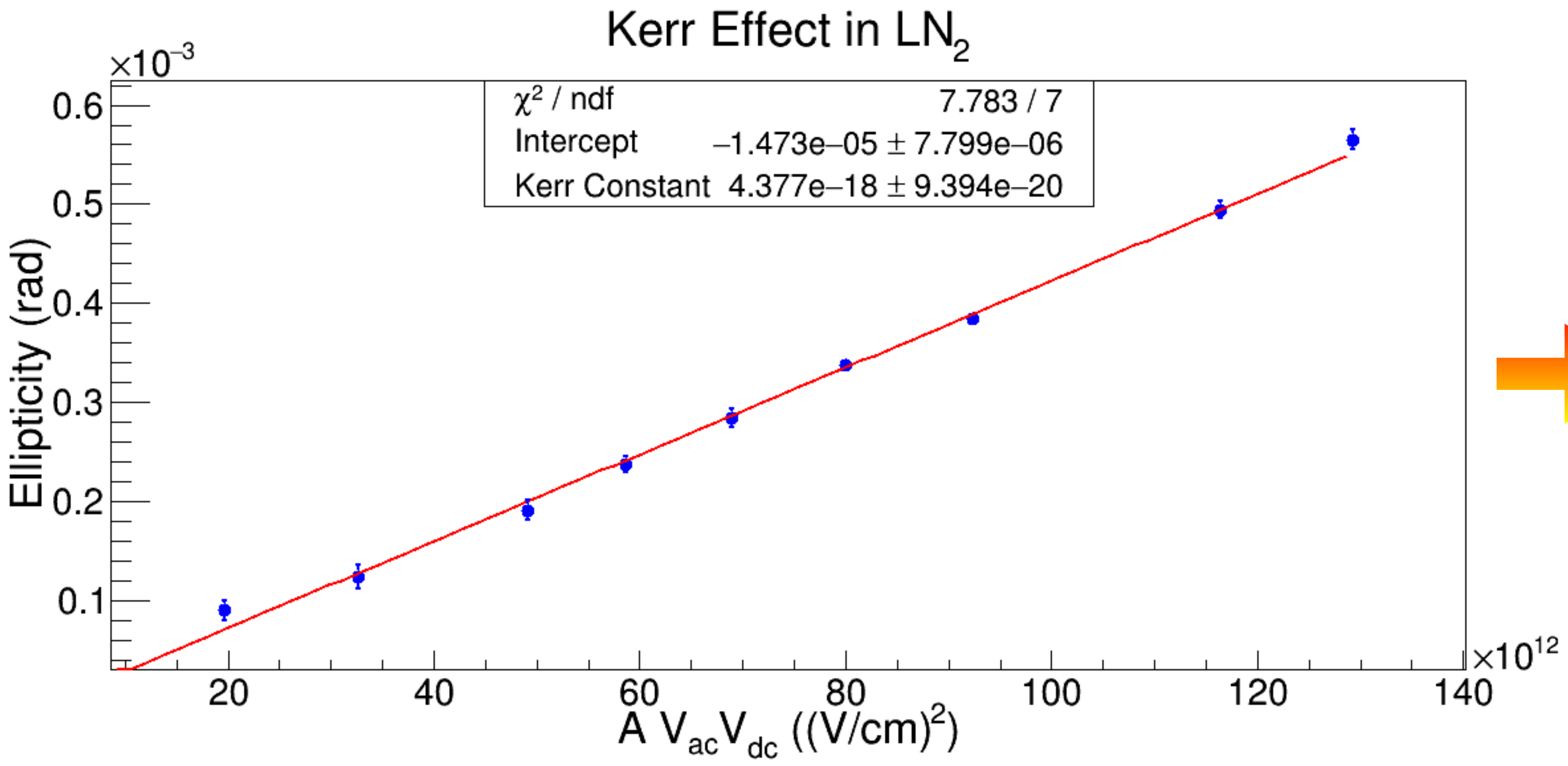


Low frequency E-field modulation to minimize RC distortions (corrections applied)

Calibration of System using LN_2

Kerr constant for LN_2: $K_{(LN2)} = (4.38 \pm 0.15) \times 10^{-18} \frac{cm^2}{V^2}$ factor of 300 higher than K(SF^{4}He)

A. Sushkov et al., PRL 93, 153003 (2004)



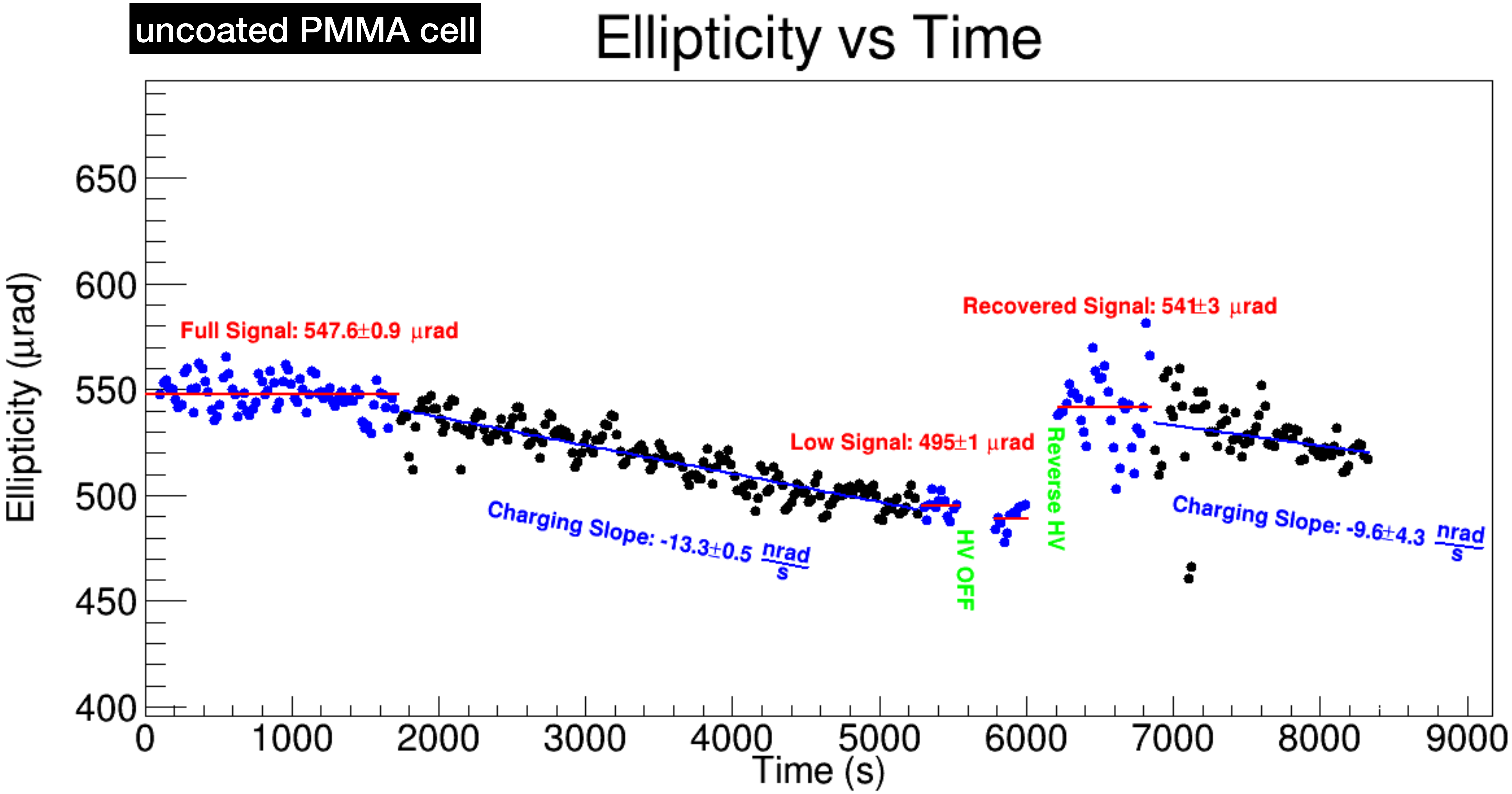
Measured Kerr constant:

$$\boxed{K_{(LN2)} = (4.38 \pm 0.10) \times 10^{-18} \frac{cm^2}{V^2}}$$

Corrections applied:

- electric fringe fields
- signal distortions

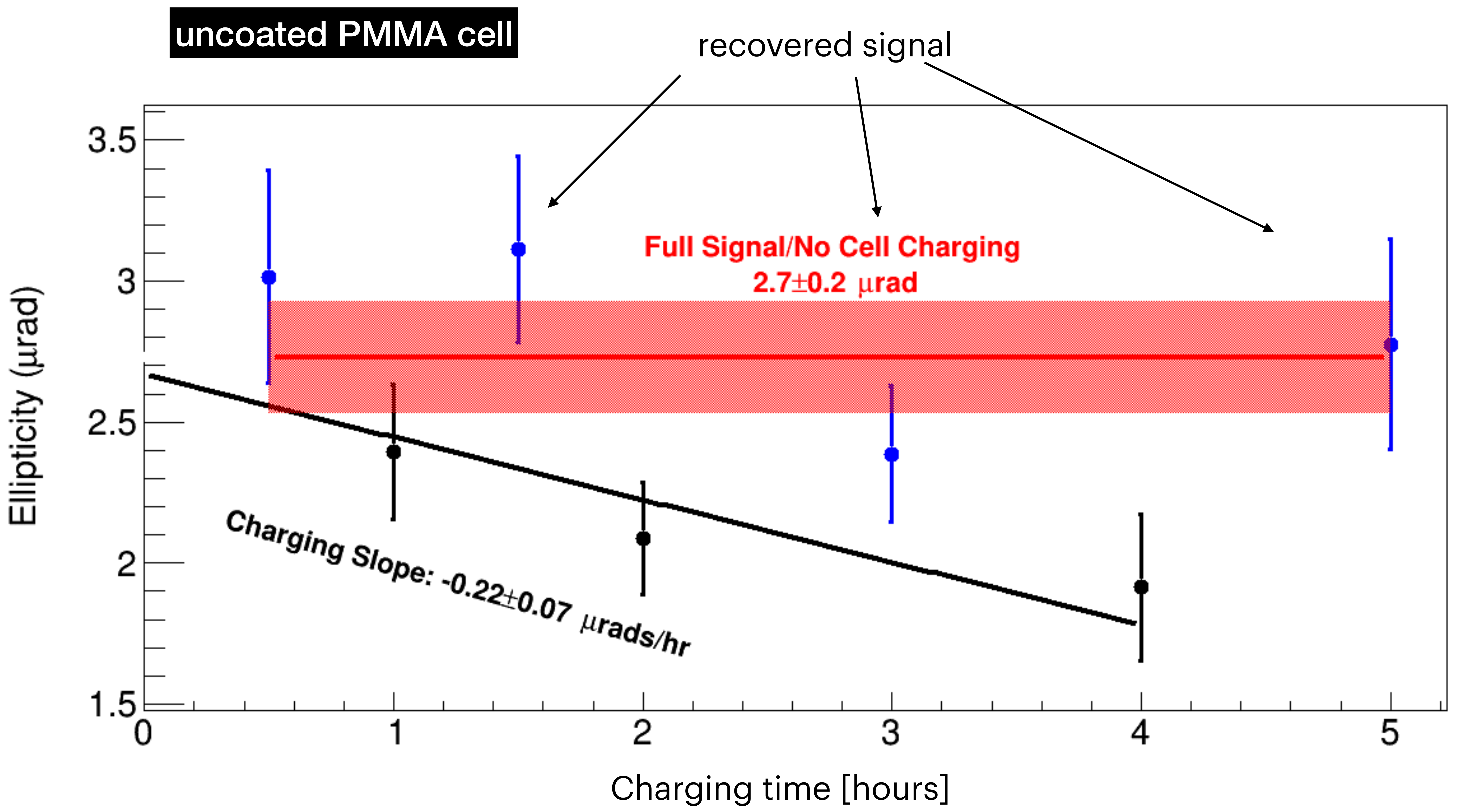
Cell Charging in LN_2



LN_2:

- cell walls charge up
- charges stay on PMMA surface when HV is turned off
- reversing the HV recovers original signal

Cell Charging in SF^4He

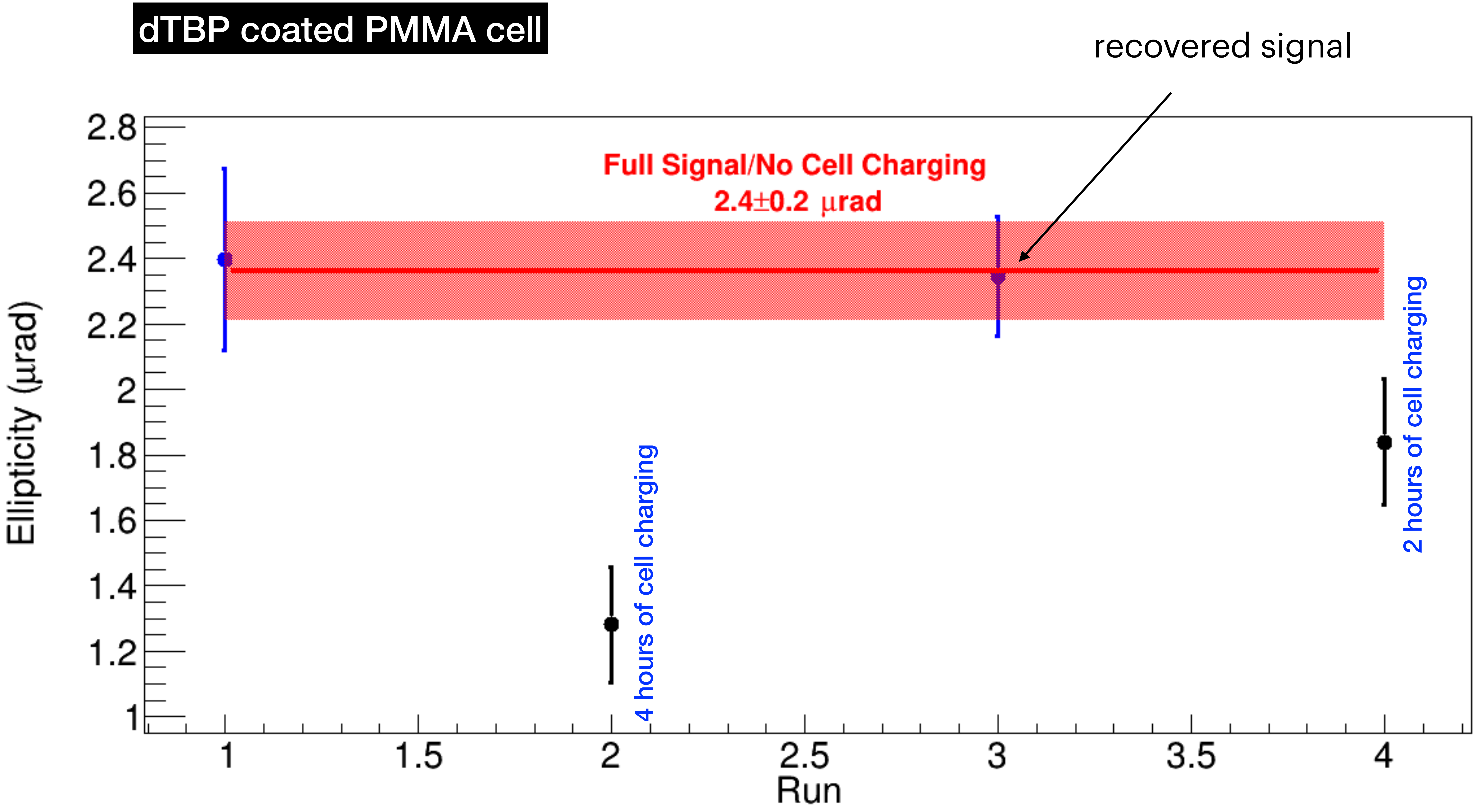


SF^4He:

- cell walls charge up
- charges stay on PMMA surface when HV is turned off
- reversing the HV recovers original signal

sensitivity: few 100 nrad

Cell Charging in SF^4He

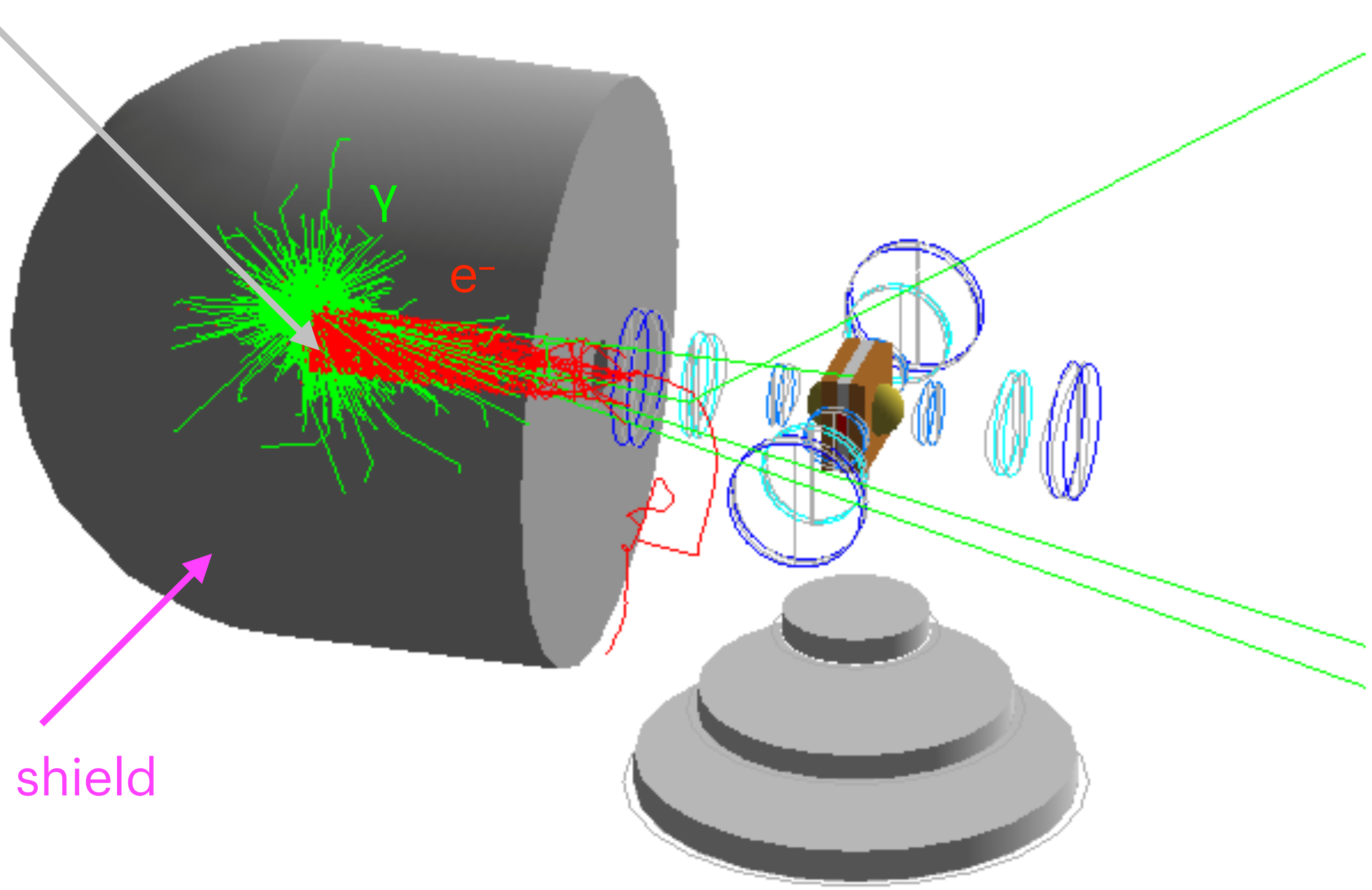


SF^4He:

- No difference to results from uncoated cell (within statistics)

Charge Collection Efficiency

Geant4 model of complete setup → production rate of electron-ion pairs in cell: $\dot{N}_e = 2.88 \times 10^6 \, \frac{e^-}{s}$



charge needed on PMMA surface to cancel external E-field:

$$Q_{E=0} = (6 \pm 1) \times 10^{10} e^- \qquad \kappa_{PMMA} = 1.8^{+0.4}_{-0.3}$$

from this experiment

$$Q_{coll} = \left(1 - \frac{V^{eff}_{charging}}{V^{eff}_{no-charging}}\right) \cdot Q_{E=0}$$

for 100% collection efficiency: $Q_{max}(t) = \dot{N}_e \cdot t_{charge}$

Fractional Charge Collected			
t_{charge} (hrs)	Q_{max} $(10^{10} e^-)$	Q_{coll} $(10^{10} e^-)$	Q_{coll}/Q_{max}
1.06	1.09	0.67 ± 0.45	$60\% \pm 40\%$
2.01	2.08	1.34 ± 0.45	$65\% \pm 22\%$
4.00	4.15	1.79 ± 0.67	$40\% \pm 20\%$

Results consistent with data and theory in Seidel et al.

G.M. Seidel et al., PRC 89, 025808 (2014)

Implications for nEDM@SNS during Measurement Cycle

Cell charging during measurement cycle (mc):

Best estimate so far: Q_{mc} ~ 900 pC

Capacitance of HV electrodes: C ~ 16 pF

- *neutron beta-decay*
- *n + 3He → p + t + 764 keV*
- *other ionizing radiation from ambient materials*

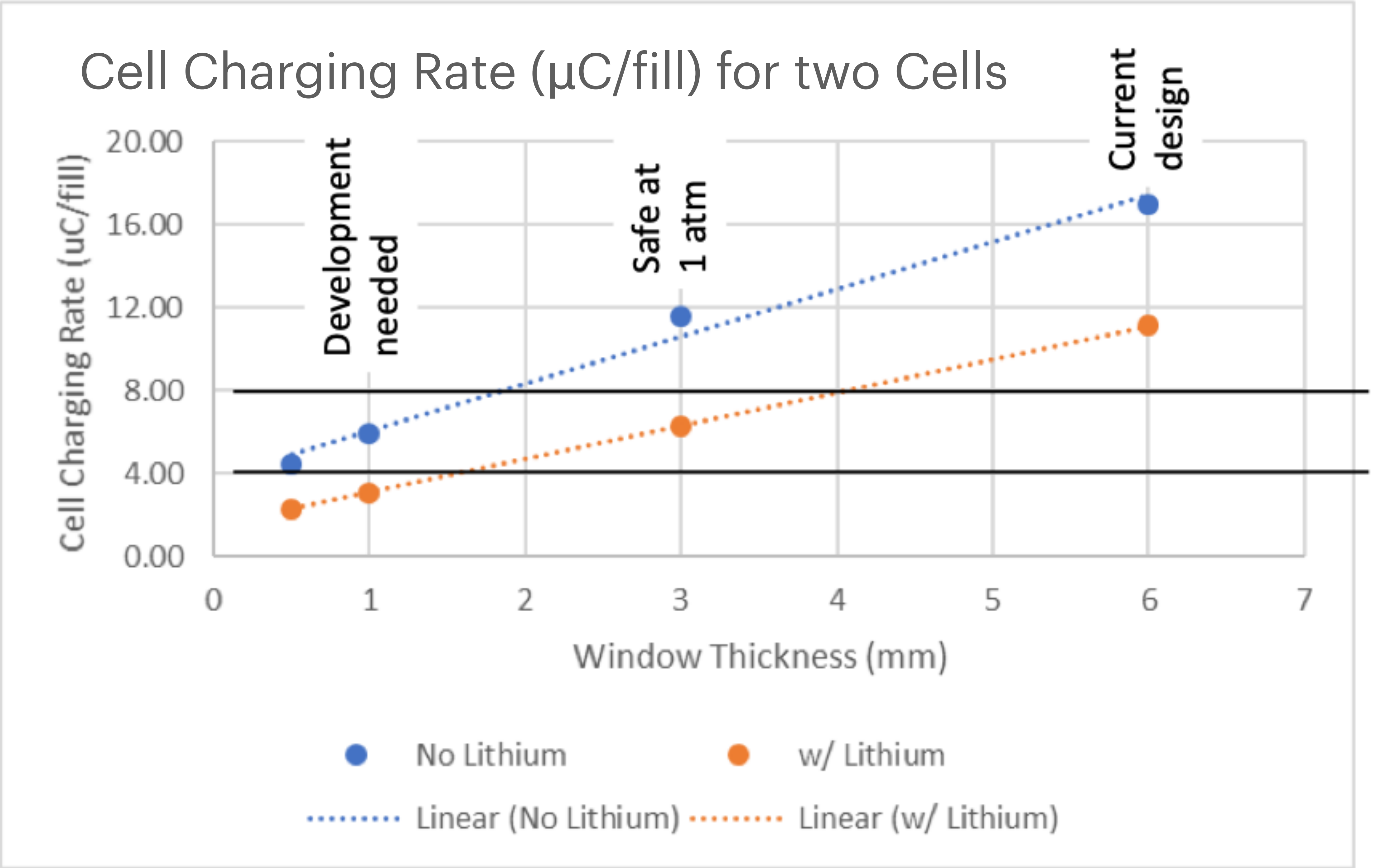
$$\rightarrow \frac{\Delta E}{E} = \frac{\Delta V}{V} = \frac{56V}{635kV} \approx 9 \times 10^{-5} \quad \checkmark$$

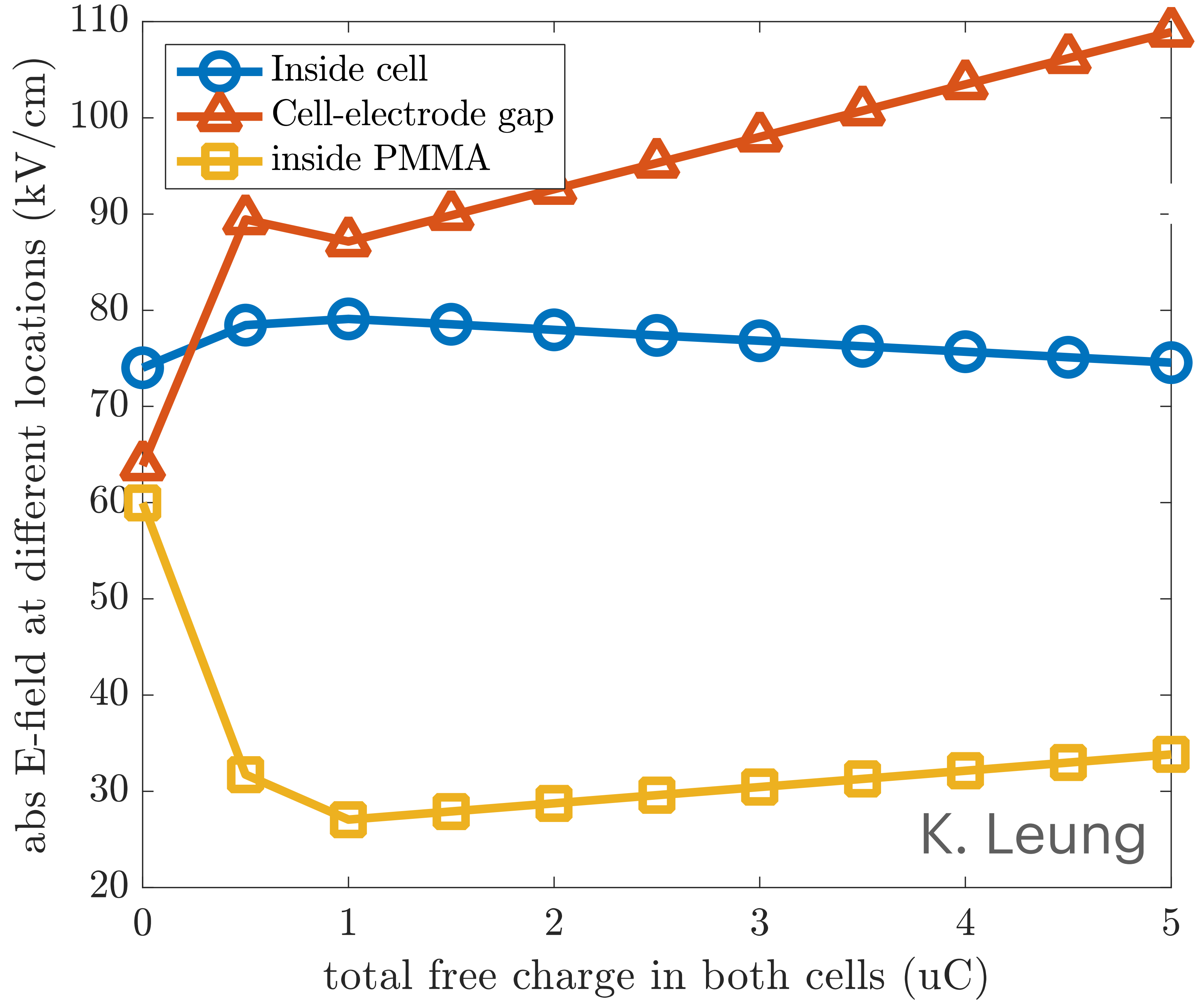
1% E-field stability per measurement cycle: can keep E-field > 100 cycles

Will reverse E-field more frequently for systematic studies

Implications for nEDM@SNS during Filling Cycle

Cell charging during neutron filling of the cells: MCNP, COMSOL simulations for nEDM@SNS





see talk by: D. Loomis

minimize charge build up → Improve
- shielding
- cell material (dPMMA)
- window thickness

→ reverse HV before every measurement cycle ?

Summary

- Cryogenic apparatus with HV electrodes was constructed to study cell charging
- Free charges were produced in cryogenic liquids by means of a strong ^{137}Cs γ-source
- Electro-optical Kerr effect was used to study the stability of E-field
- Cell charging was observed in LN_2 and SF^4He
- Charges were neutralized by E-field reversal
- Charges produced during a measurement cycle of the nEDM experiment are not expected to impact the stability of the E-field significantly
- Frequent E-field reversal is planned to investigate systematic effects
- More systematic studies in progress: “closed cell”, binding energies, …..

Thanks for your attention!