Luminosity Limits for Liquid Argon Calorimetry

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V2.0

At a high $\mathcal{L}$ hadron collider ...

- calorimeter showers produced by copious min-bias events ...
  - flood the liquid argon gaps with ionization
  - This ionization is ...
    - approximately spatially uniform on the scale of the gap (~ 2 mm)
    - approximately uniform in time on the scale of the time it takes for charges to drift across the gap

Ionization in a liquid argon gap

Typical drift velocities

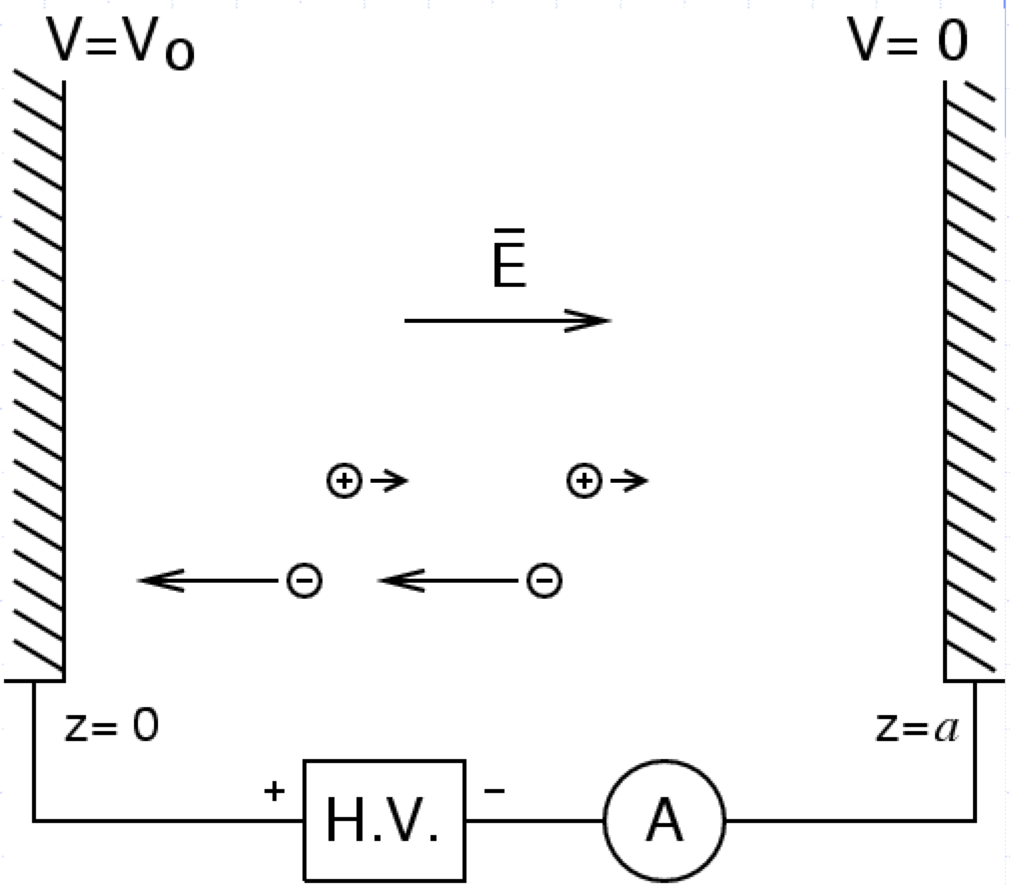
$\upsilon_e = 4.3\times10^6$ mm/s

$\upsilon_{Ar+} = 1\times10^2$ mm/s

at E = 1000 V/mm

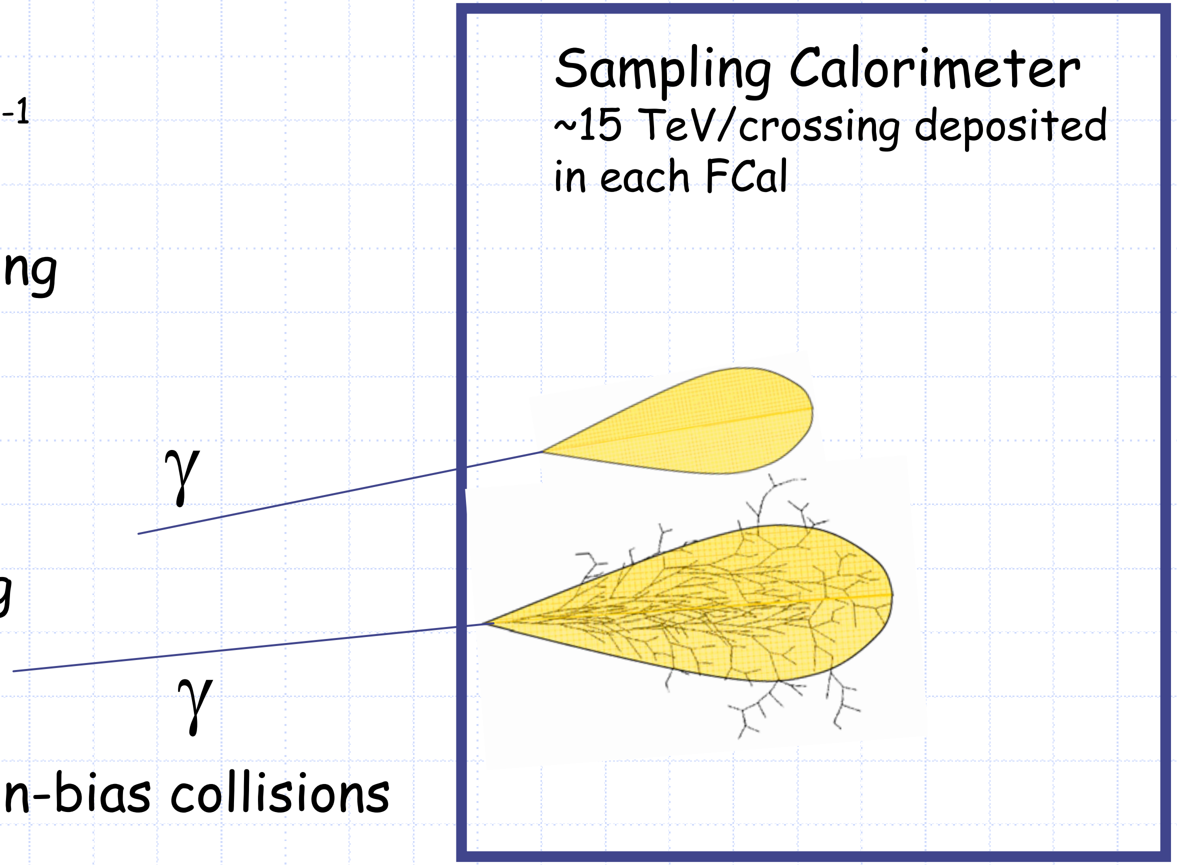
We consider the case where the rate of ionization is constant.

This produces a DC current through the HV supply.



Scale of the problem

At the HL-LHC
at $\mathcal{L} = 5\times10^{34}$ cm^{-2} s^{-1}
at $|\eta|\sim4.7$,
~1 gamma/cm^2/crossing
on face of FCal and
at EM shower max
ionization rate is
~3×10^{11} /mm^3/s   or
~7500 /mm^3/crossing



Particles from min-bias collisions

IP ← 5 m →

Critical ionization rate

Assume Ar^+ ion drift velocity is proportional to Electric field

$$v_+ = \mu_+ E$$

μ_+ is key to space-charge effects

The critical ionization rate is defined in terms of this mobility

$$D_C \equiv \frac{4V_0^{\,2} \varepsilon \mu_+}{ea^4}$$

Finally define relative ionization rate

$$r \equiv \frac{D_i}{D_C}$$

If $D_i > D_C$, then we are in the space-charge limited regime

Value of μ_+ (Ar^+ mobility in LAr)

Measurements of μ_+ reported in the literature vary by about a factor 50 from lowest to highest:

$$0.02 < \mu_+ < 1.0 \text{ mm}^2/\text{Vs}$$

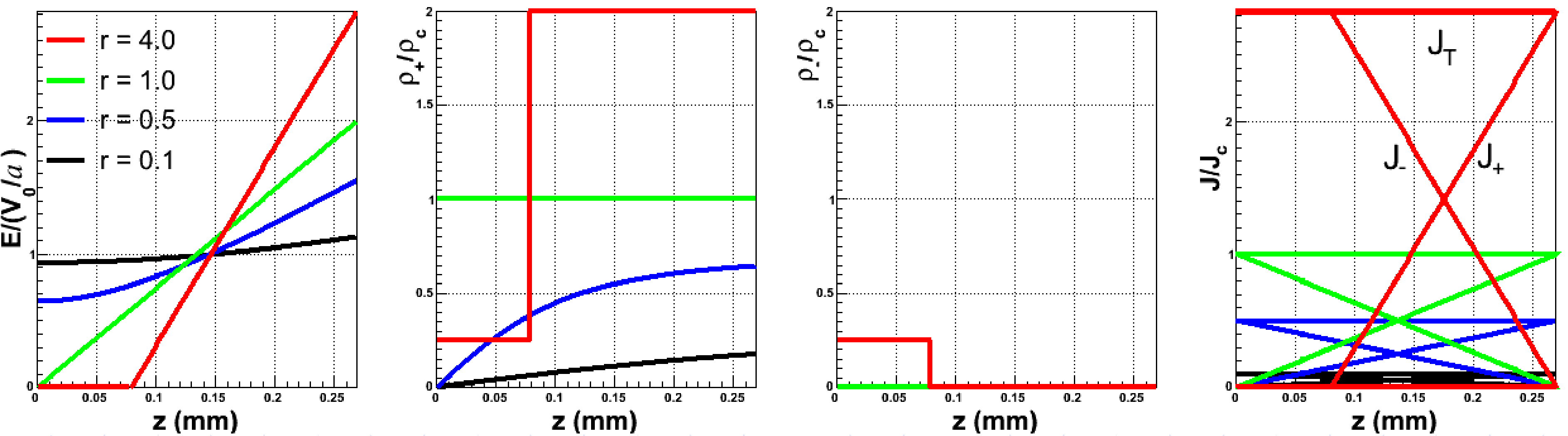
Most recent and best-looking technique – Norman Gee et al., J.Appl.Phys. 57 (1985) 1097, reading off a plot, gives

$$0.15 < \mu_+ < 0.18 \text{ mm}^2/\text{Vs} \pm 3\%$$ Temp dependence

Our preliminary result $\mu_+ = 0.10 \pm 0.02 \text{ mm}^2/\text{Vs}$

Space-charge effects in LAr gaps

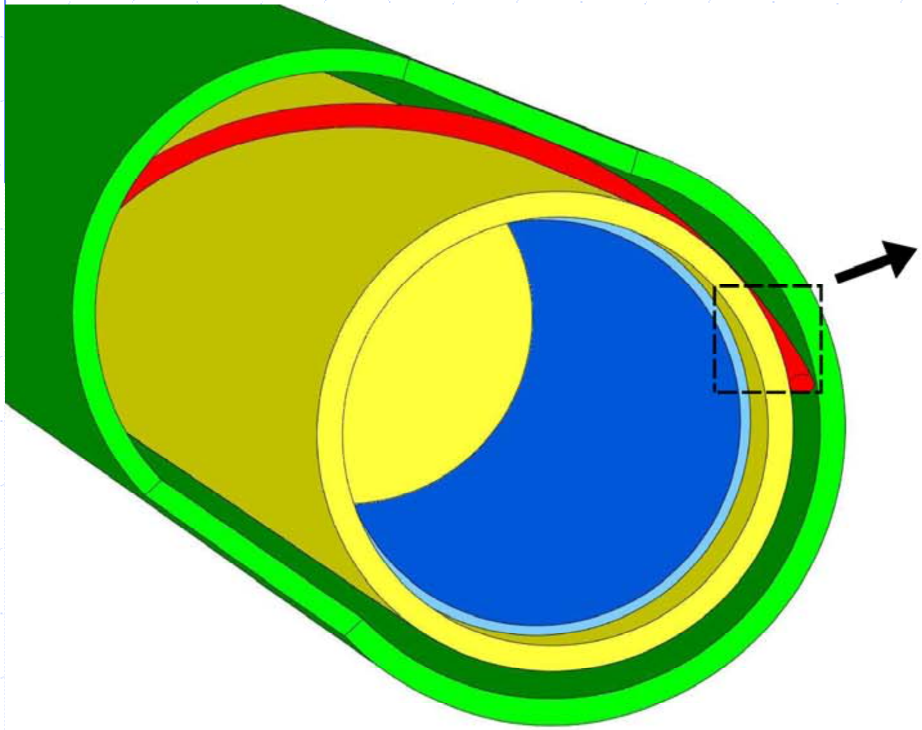
- Our measured observable is the current.
- Simplifications allow an analytic solution

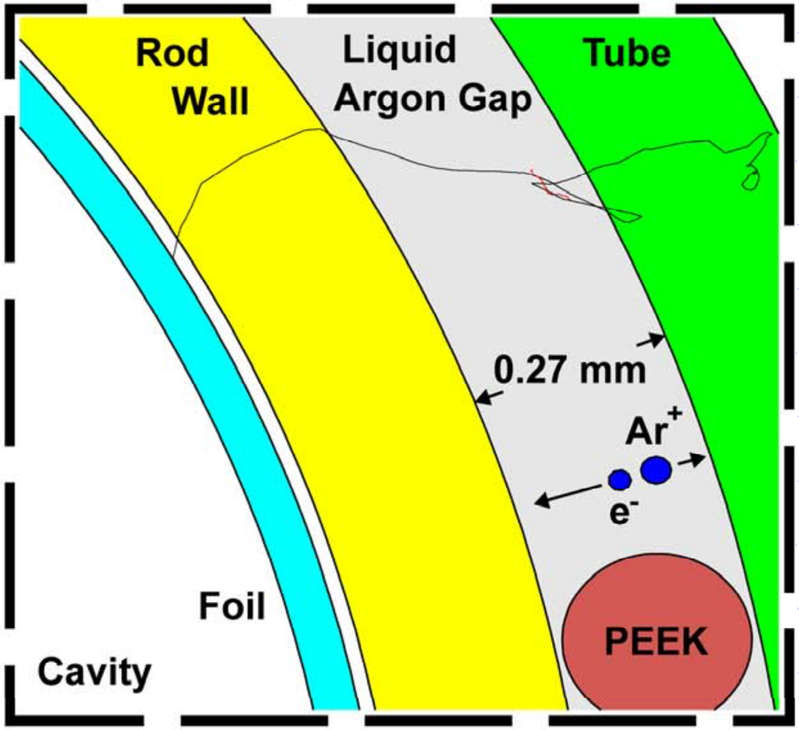


Replicate HL-LHC conditions in the lab

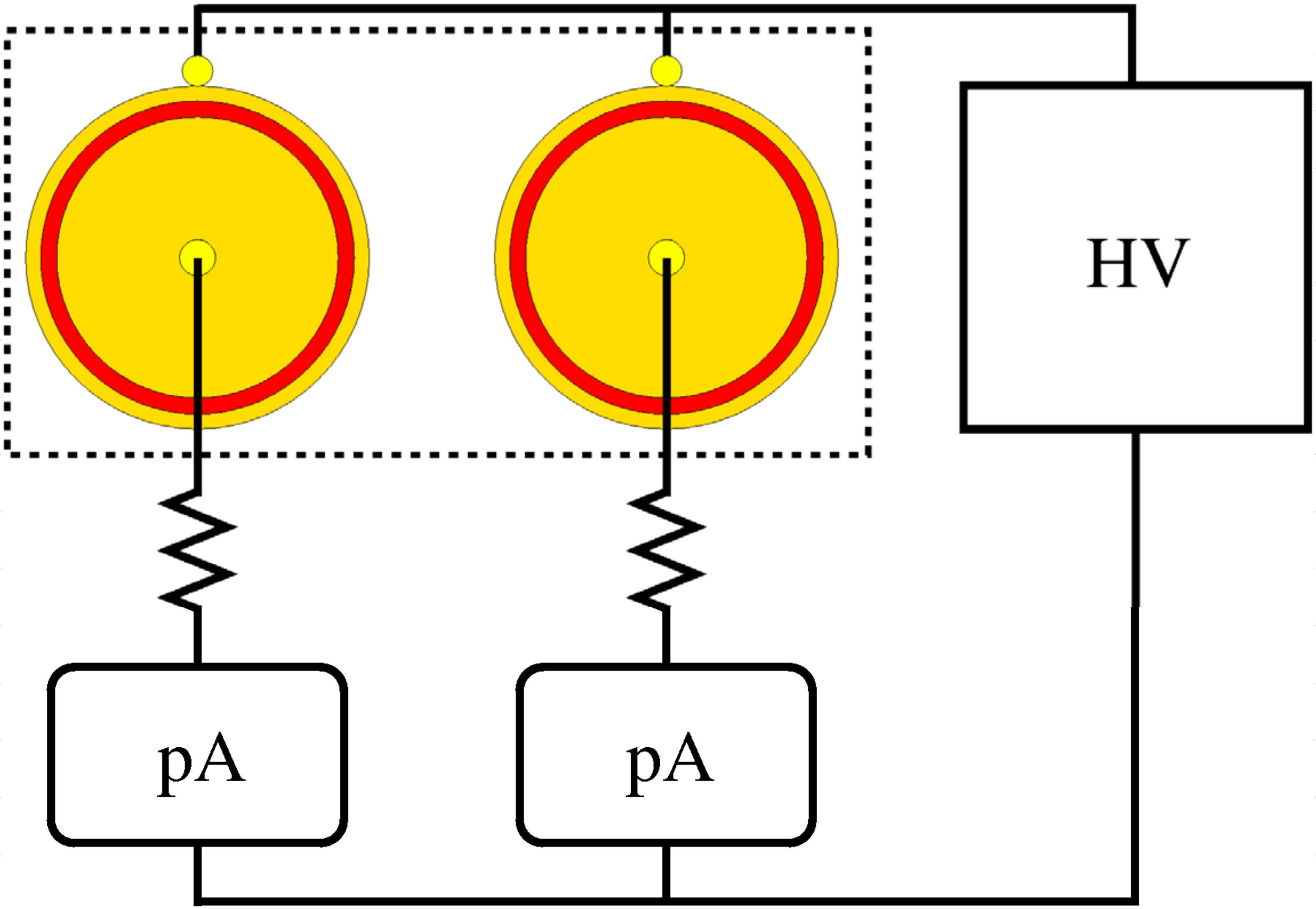
For details on data-taking see NIMA 608 (2009) 238

Hot ^{90}Sr β-source deposited on outer surface of the foil.
$KE_\beta \leq 2.28$ MeV





External wiring



Strategy

- Ideally we would vary the ionization rate and measure the current
- But we have only two ^{90}Sr sources (nominally 50 mCi and 2 mCi)
- So we vary the critical ionization rate by varying the potential across the gap

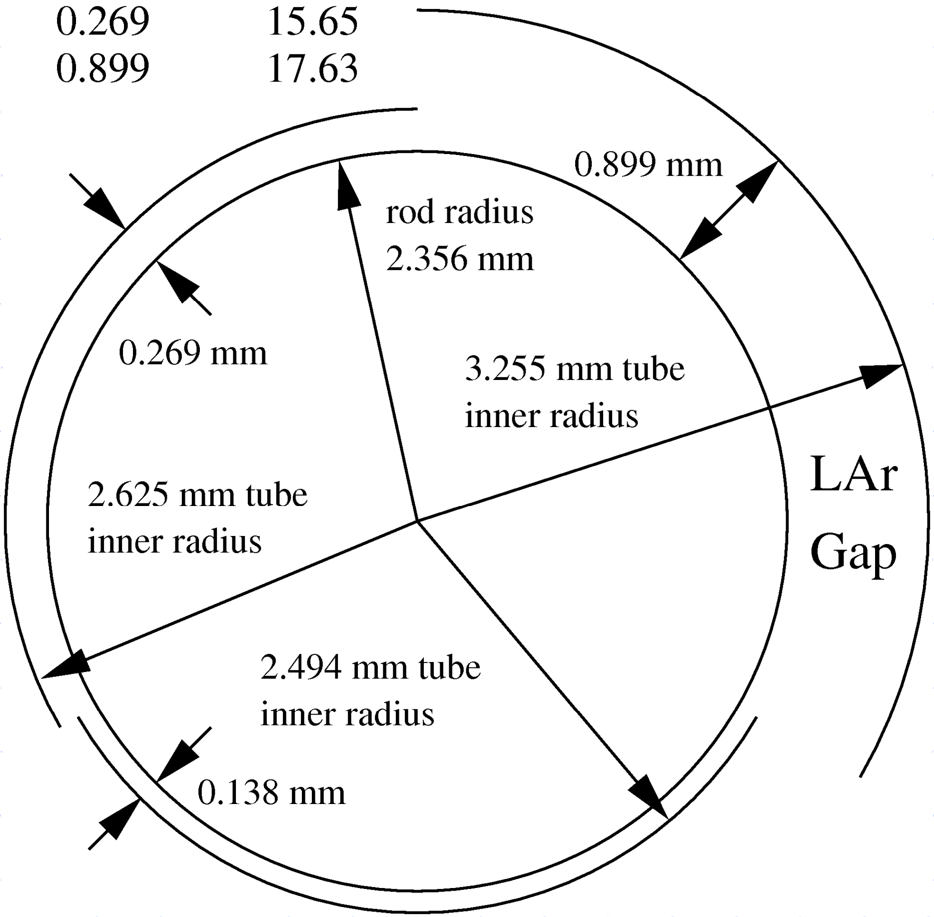
$$r \equiv \frac{D_i}{D_C} \qquad D_C \equiv \frac{4V_0^{\,2}\varepsilon\mu_+}{ea^4}$$

Three different gaps

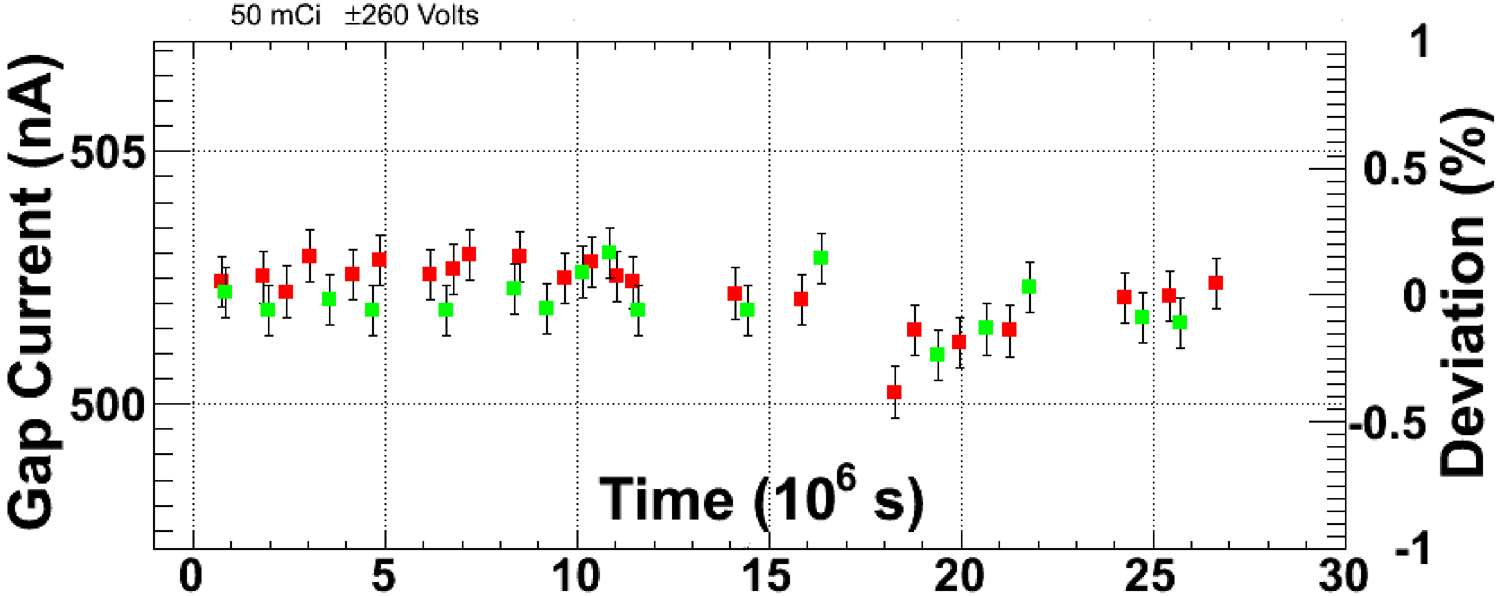
Achieved with different tubes and insulators

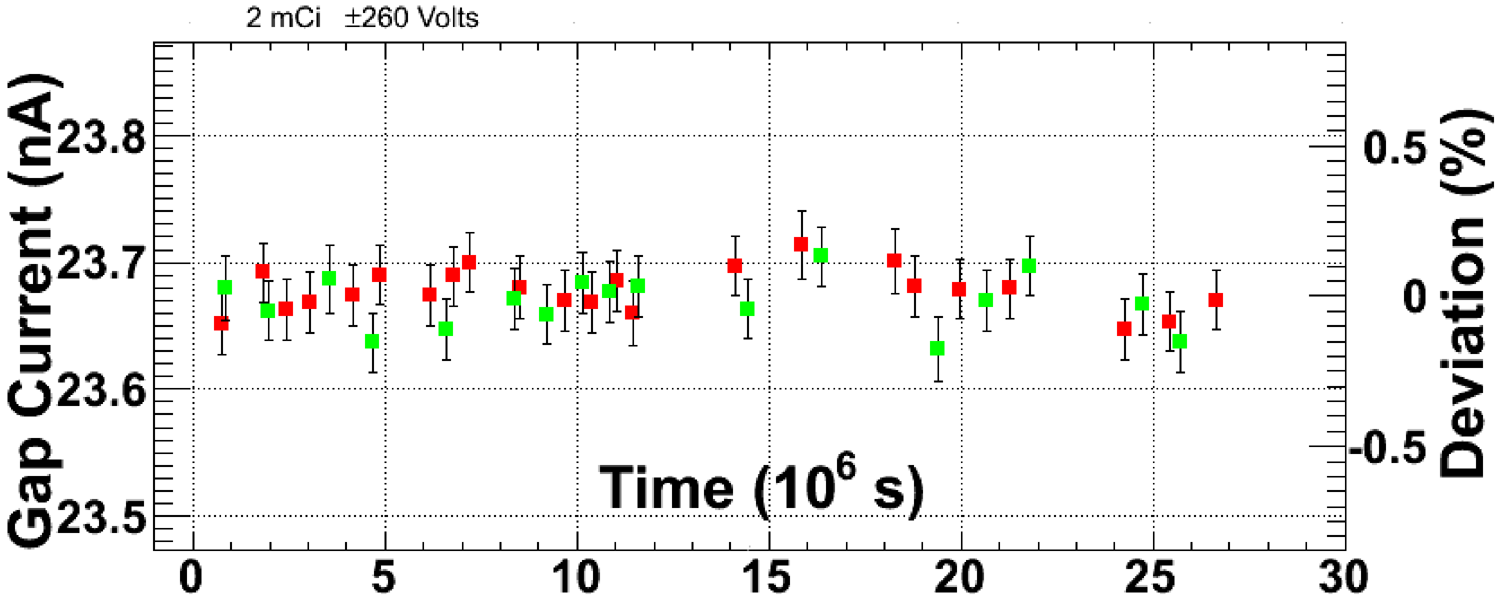
One gap is the same as in the present ATLAS FCal1

Gap (mm)	Circum (mm)
0.138	15.24
0.269	15.65
0.899	17.63

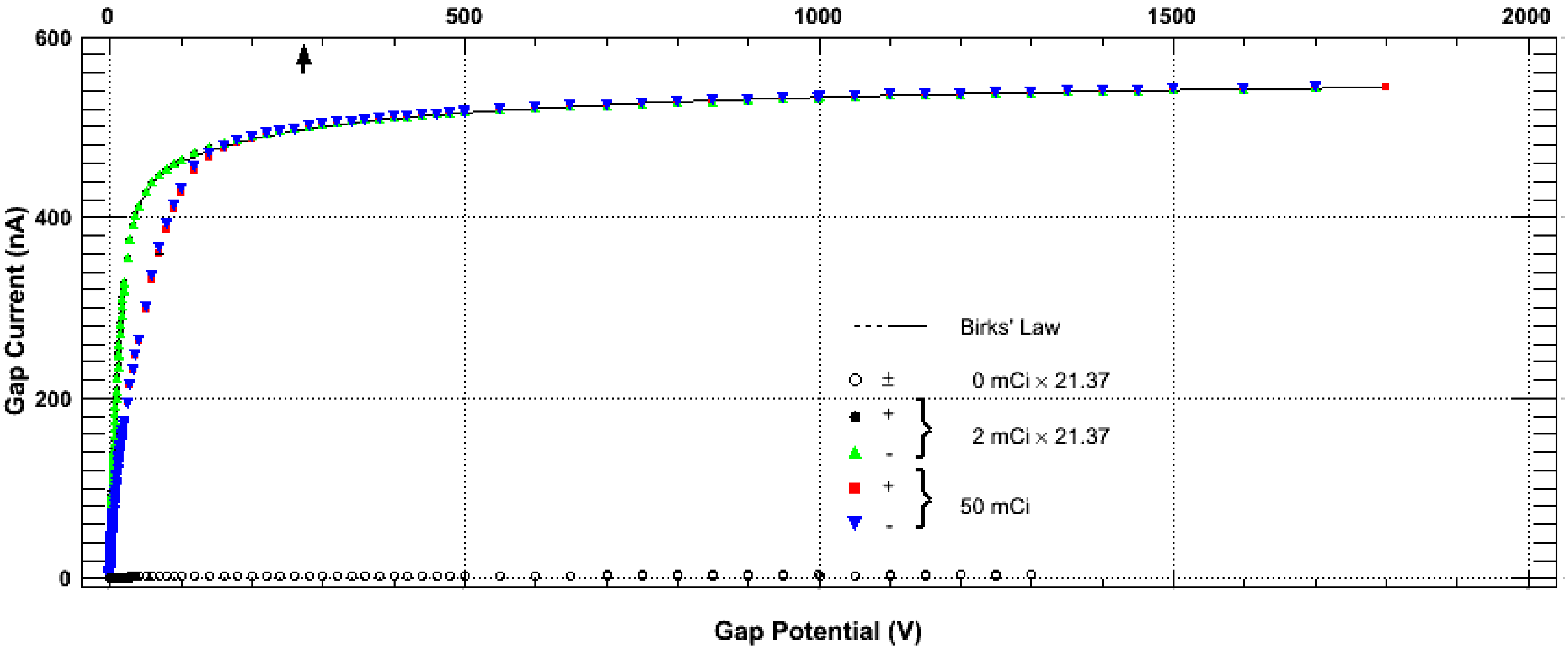


~500 fb^{-1} equivalent running



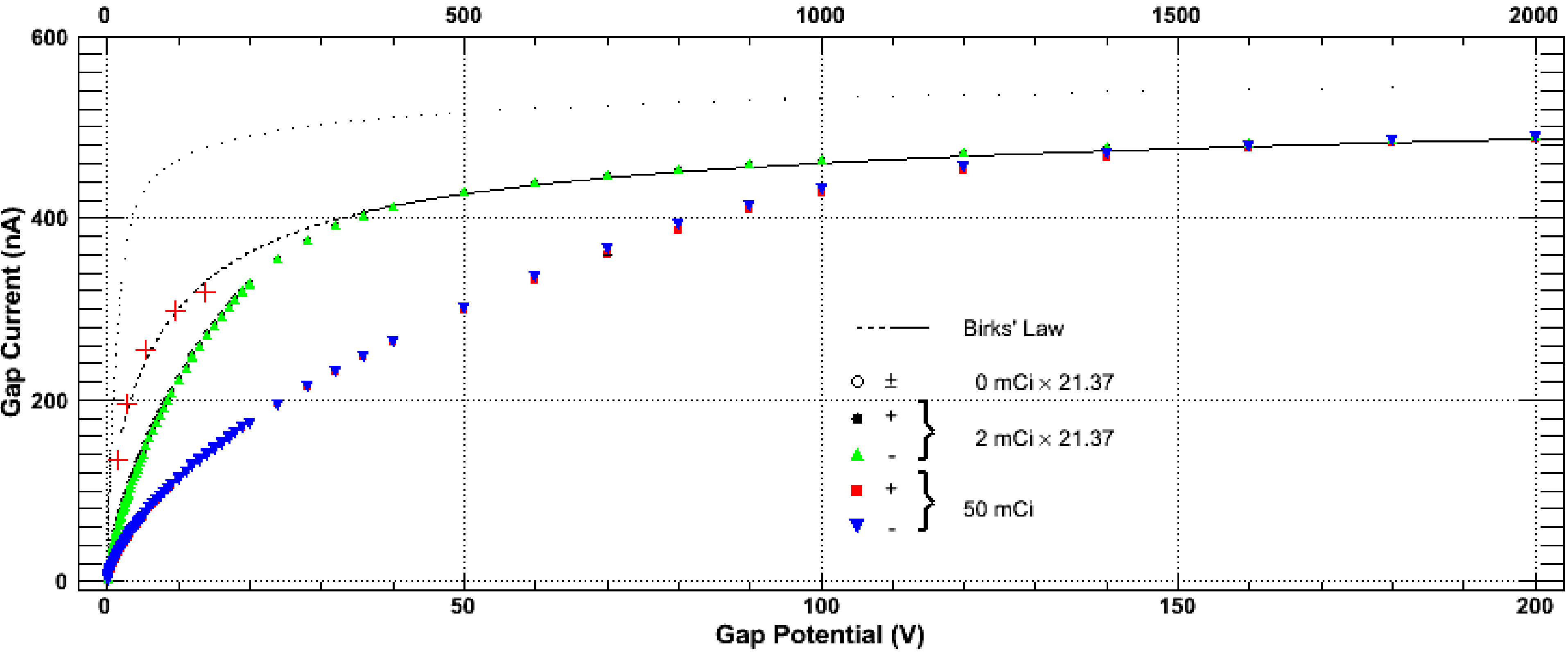


0.268 mm gap

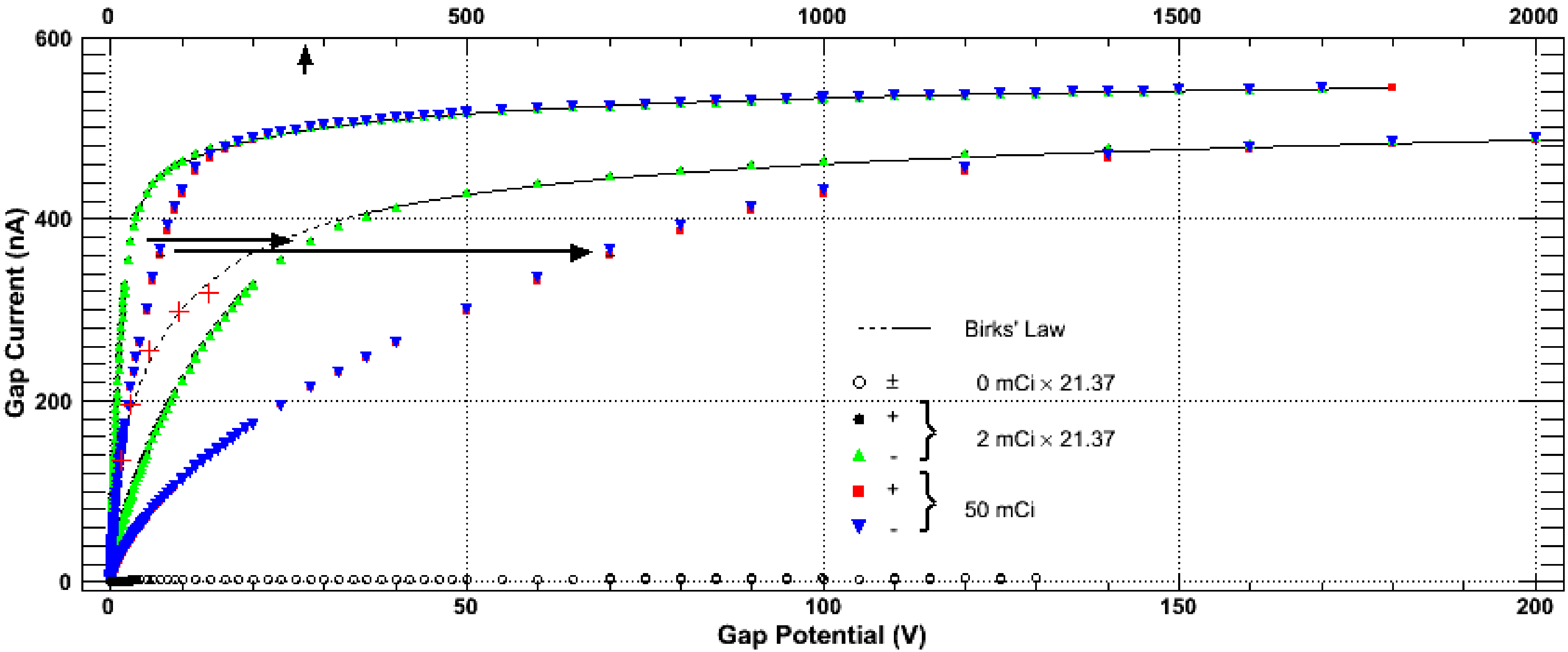


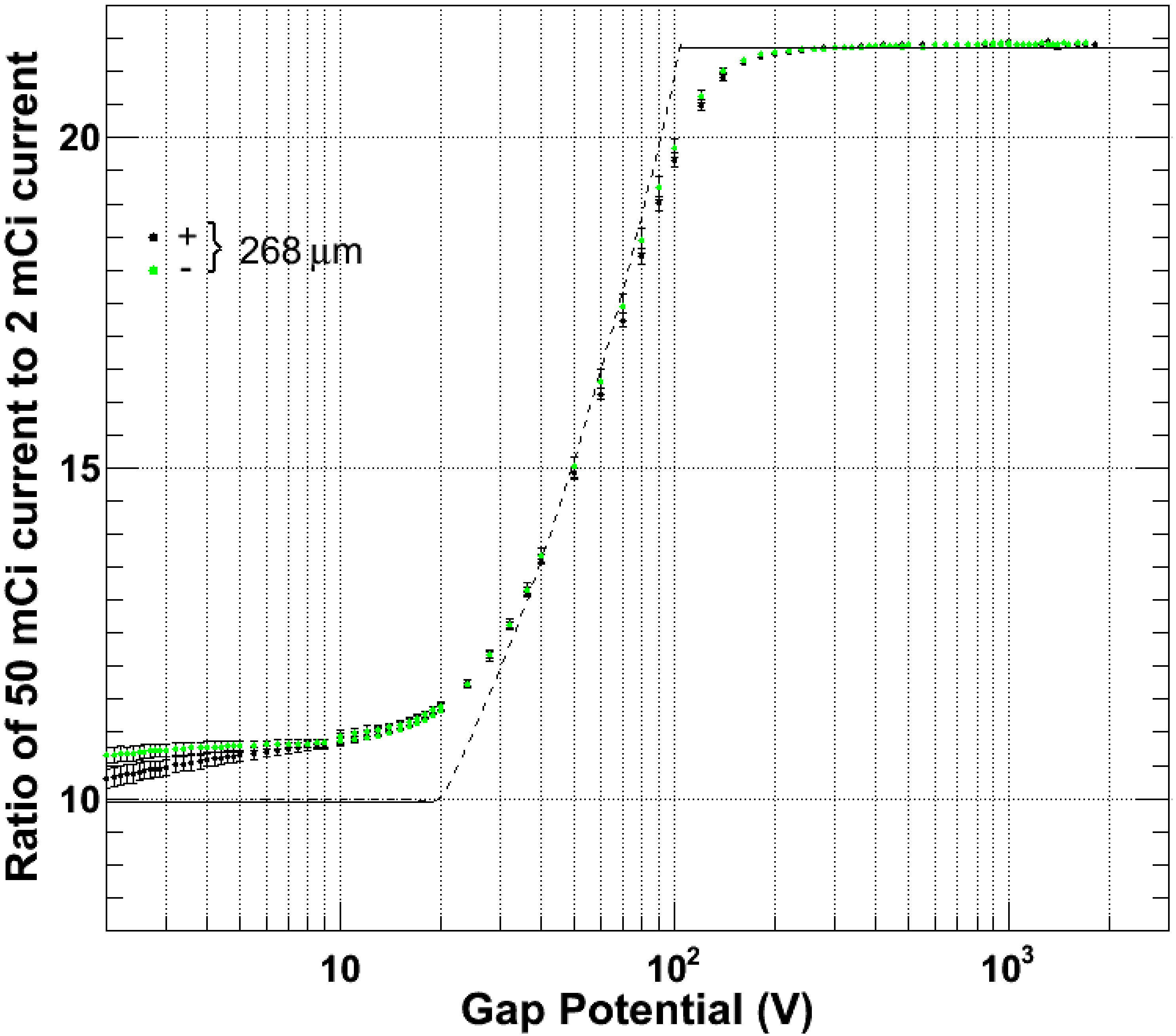
0
500
1000
1500
2000
600
400
200
0
Gap Current (nA)
Gap Potential (V)
Birks' Law
± 0 mCi × 21.37
+
- 2 mCi × 21.37
+
- 50 mCi

Close-up of low potential region

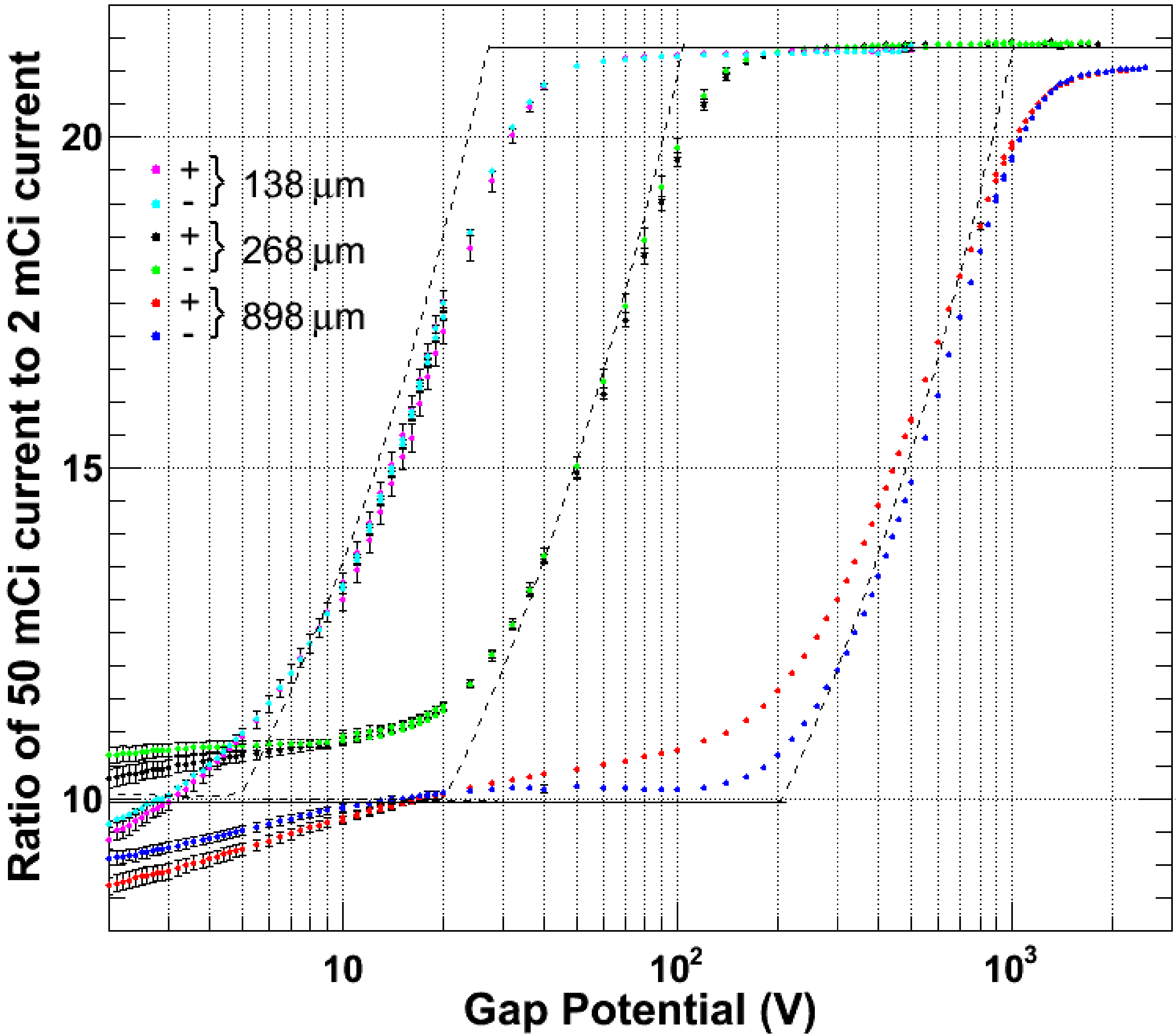


Typical data. This is for 0.268 mm gap



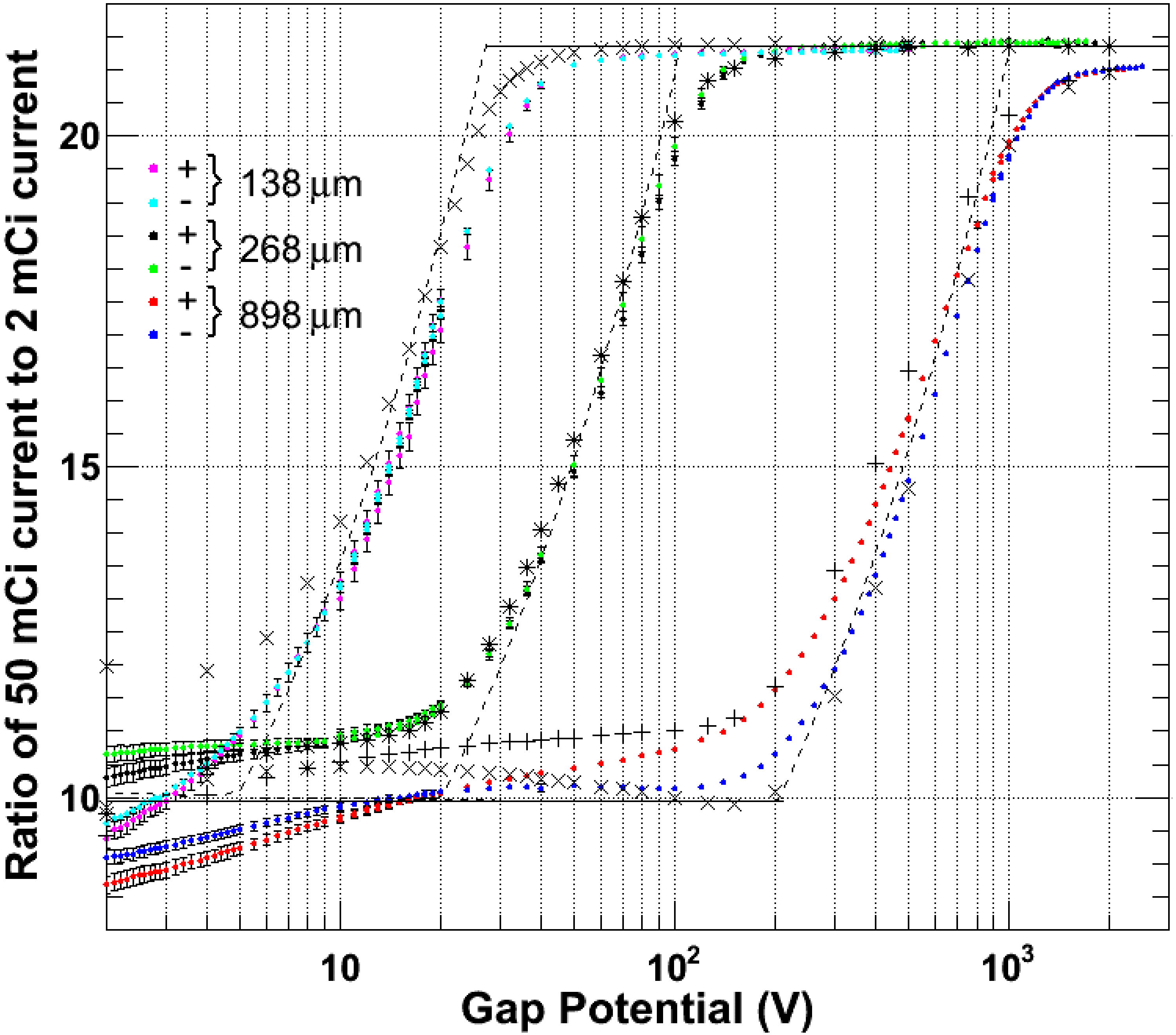


Ratio of 50 mCi current to 2 mCi current
20
15
10
+
-
268 μm
10
10^2
10^3
Gap Potential (V)


Ratio of 50 mCi current to 2 mCi current
Gap Potential (V)
+ - } 138 µm
+ - } 268 µm
+ - } 898 µm
20
15
10
10
10^2
10^3

Simulations

- EGSnrc for energy deposit by ^{90}Sr betas
  - Gives ionization rate
- Custom simulation for
  - Charges drifting in E-field
  - Recombination
  - Diffusion
- A small amount of O_2 (< 1 ppm) makes a big difference in charge density but a small difference in the measured currents.



Ratio of 50 mCi current to 2 mCi current
20
15
10
+
-
} 138 µm
+
-
} 268 µm
+
-
} 898 µm
10
10^2
10^3
Gap Potential (V)

Conclusions

- LAr calorimeter is stable at 0.1% level for 500 fb^{-1} of running
- On-set of space-charge effects is determined by $\mu_+ = 0.10$ mm^2/Vs
- No evidence for minority charge carriers

Backup Slides

Critical values for the on-set of space-charge effects

Charges on the surface of the electrode plates establish the electric field in the LAr gap.

$$|\sigma| = \varepsilon |E| = \frac{\varepsilon V_0}{a}$$

Define critical charge density in the LAr as that which, integrated over the gap, equals the absolute sum of the charges on the plates

$$\rho_C = e n_C = \frac{2|\sigma|}{a} = \frac{2 V_0 \varepsilon}{a^2}$$

Assume Ar^+ ion drift velocity is proportional to Electric field

$$v_+ = \mu_+ E$$

μ_+ is key to space-charge effects

Define characteristic time for Ar^+ ions to drift out of the gap

$$\tau \equiv \frac{a}{2v_+} = \frac{a^2}{2V_0\mu_+}$$

Define D_C as the rate of ion pair creation per unit volume equal to the rate at which the critical density of positive ions is removed from gap

$$D_C \equiv \frac{n_C}{\tau} = \frac{4V_0^{\,2}\varepsilon\mu_+}{ea^4}$$

For ionization rates D_i above the critical value D_C , space-charge effects are important.

Finally define relative ionization rate $$r \equiv \frac{D_i}{D_C}$$