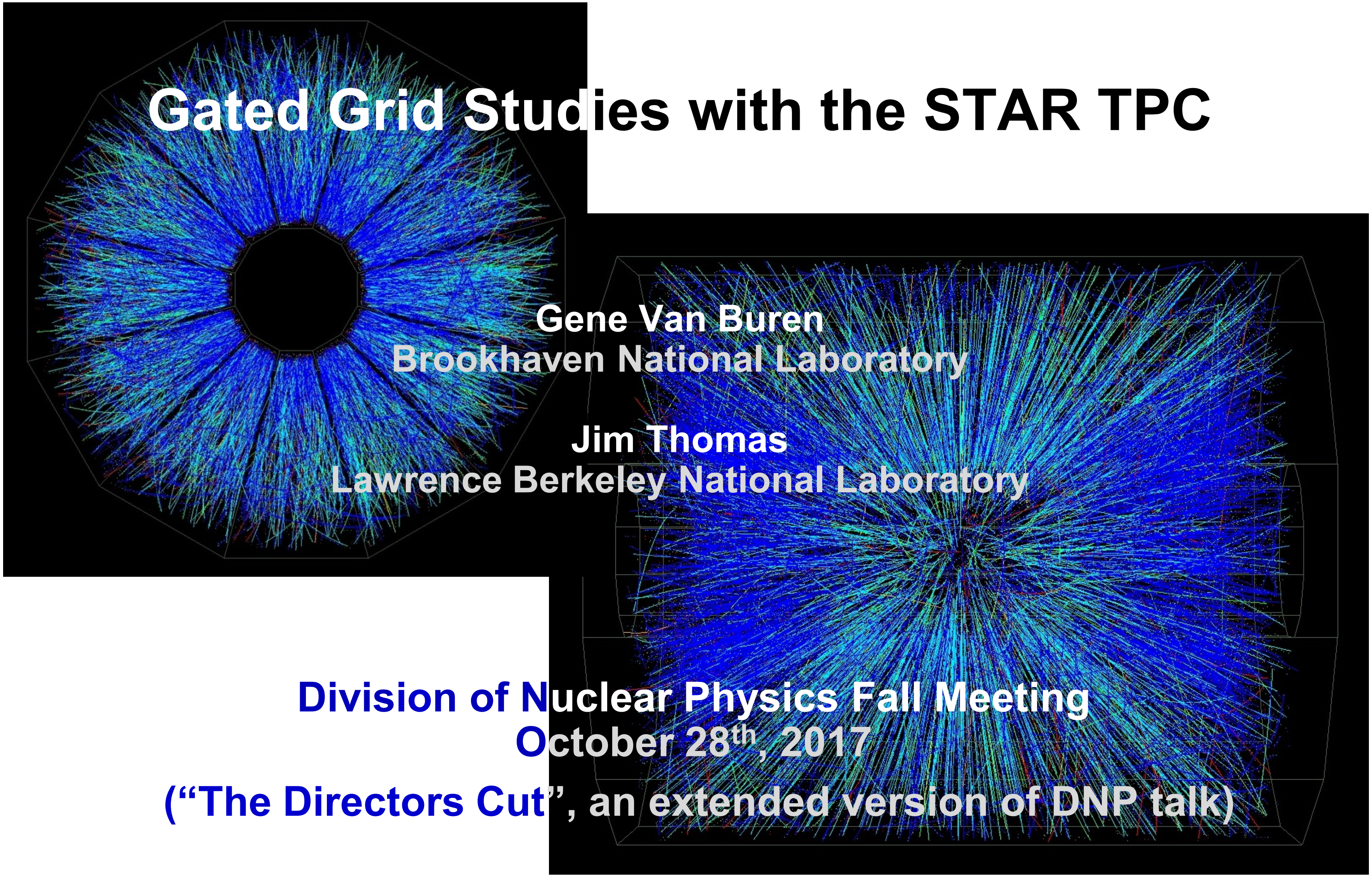


Gated Grid Studies with the STAR TPC

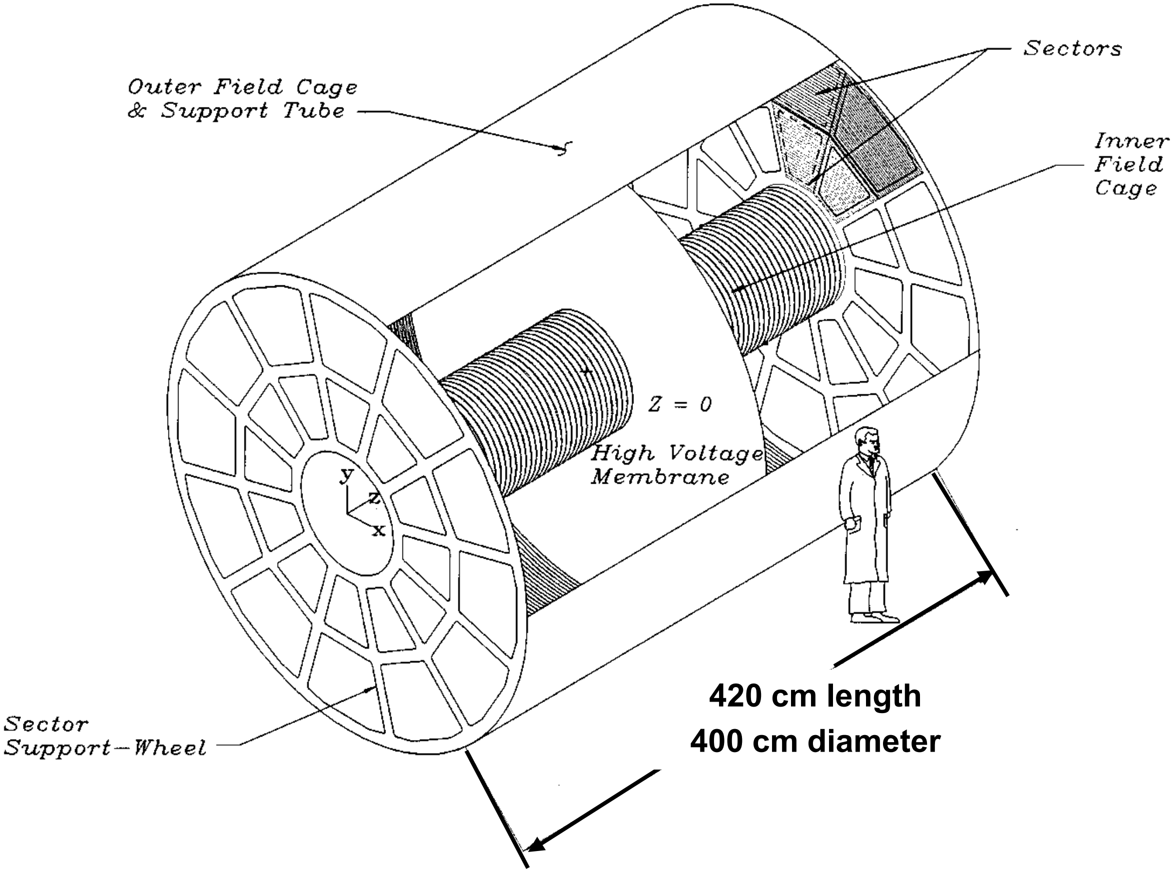
Gene Van Buren
Brookhaven National Laboratory

Jim Thomas
Lawrence Berkeley National Laboratory

Division of Nuclear Physics Fall Meeting
October 28th, 2017

(“The Directors Cut”, an extended version of DNP talk)

Schematic Layout of the STAR TPC

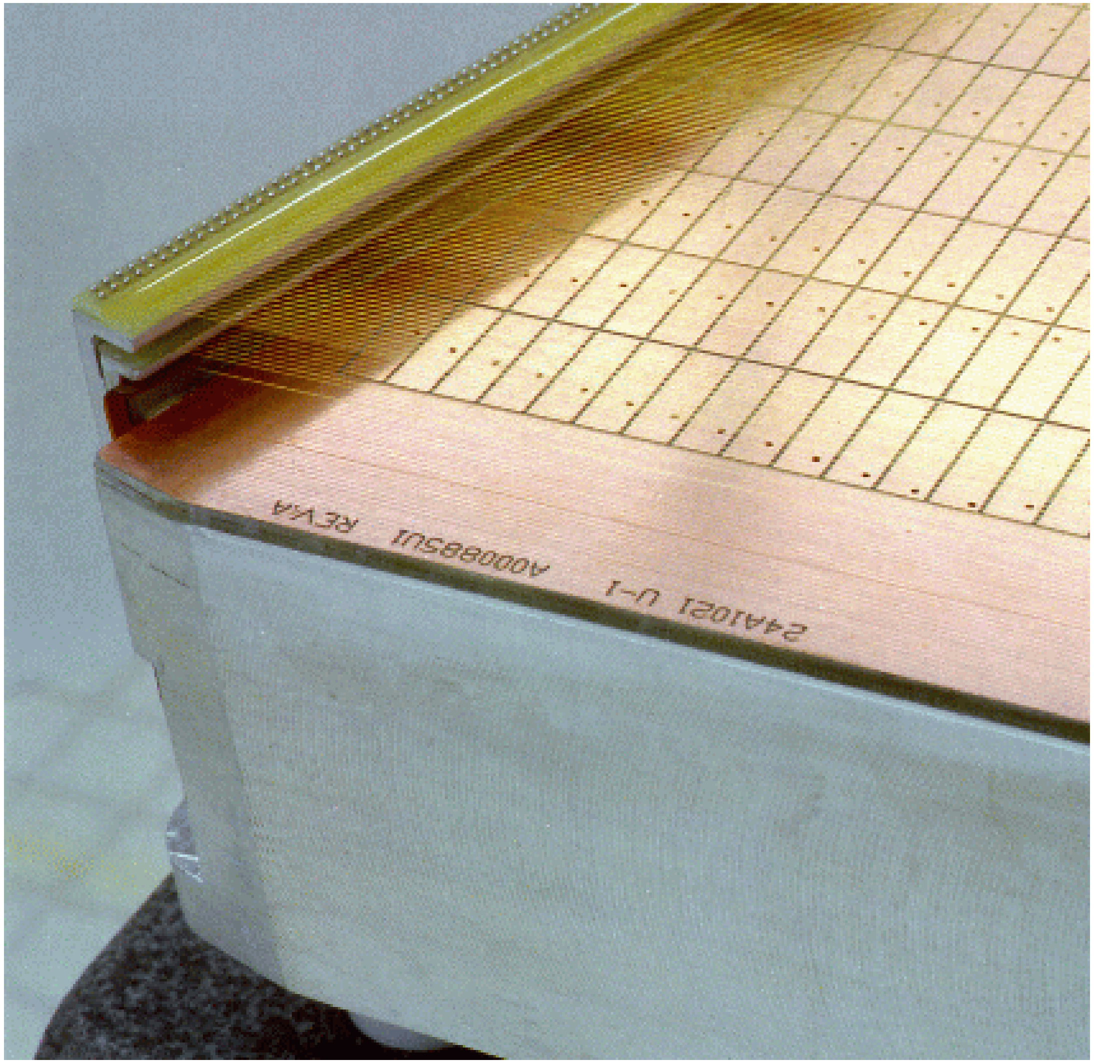


420 cm length
400 cm diameter

- **Voltage :** 28 kV on the central membrane
  135 V/cm over 210 cm drift path

Primary tracks create secondary e^- which drift in Parallel E and B Fields. Pad plane readout on both ends of the TPC. P10 Gas – 90% Ar, 10% CH_4

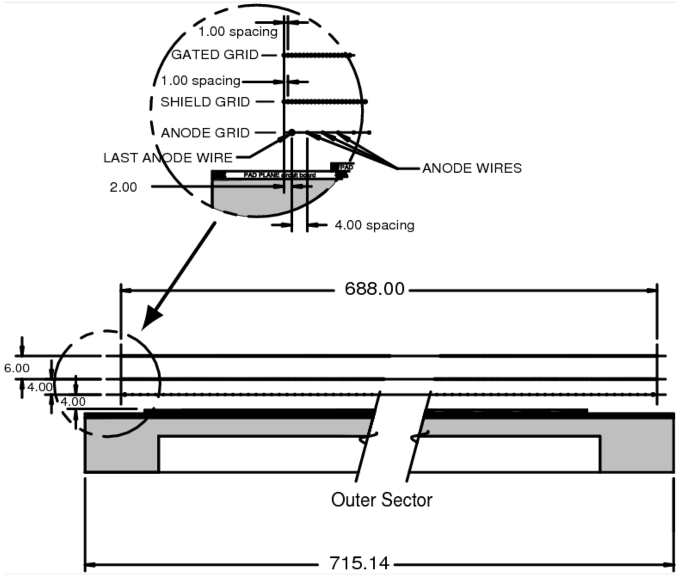
Pad plane readout



- **Gating Grid**
- **Cathode Grid**
- **Anode Wires**
  - **4 mm pitch, no field wires**
- **Pad Plane & Readout**

Sector Operation for 20:1 signal to noise

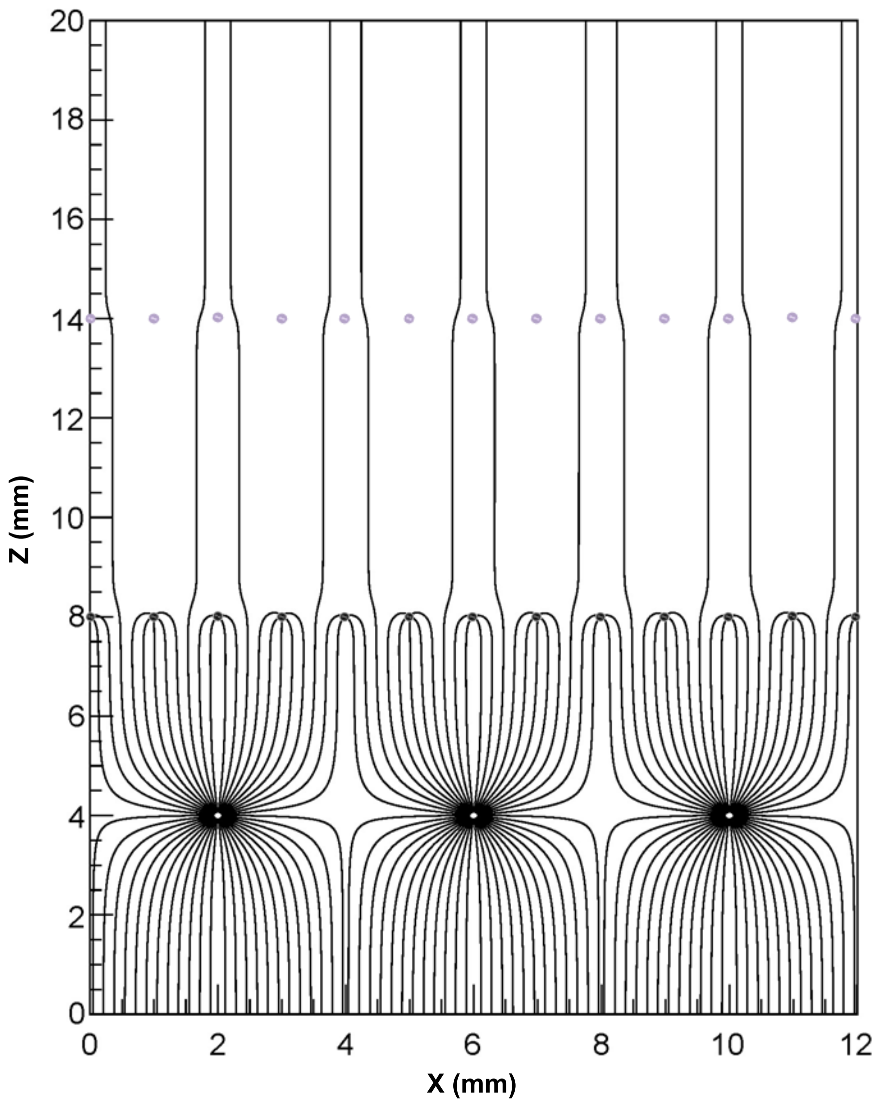
Sector	anode voltage	gas gain
inner	1170	3770 ± 10%
outer	1390	1230 ± 10%



This talk …

- **This talk is about the time required for an electron to drift from the Central Membrane to the readout plane … compared to the time required for an ion to drift into the tracking volume … once an ion is “in” it’s a problem.**
  - **Electrons are born in the tracking volume of the TPC and all must be collected in order to form an image of a track**
    - **Approximately 2000 mm drift**
    - **High velocity**
  - **Ions are born at the anode wires and will drift into the tracking volume (causing problems) if they are not blocked**
  - **So the relevant time for an ion is how long does it take to go from the anode wires to the beginning of the tracking volume**
    - **Approximately 10 mm drift**
    - **Low velocity**

Gated Grid Operation



↑ Central Membrane (-28,000 V) ↑
Z = 2010 mm

-133 V/cm
~750 msec to CM

Bipolar Gated Grid (-115 ± 0 V)

-234 V/cm
~1.25 msec

Cathode Grid (0 V)

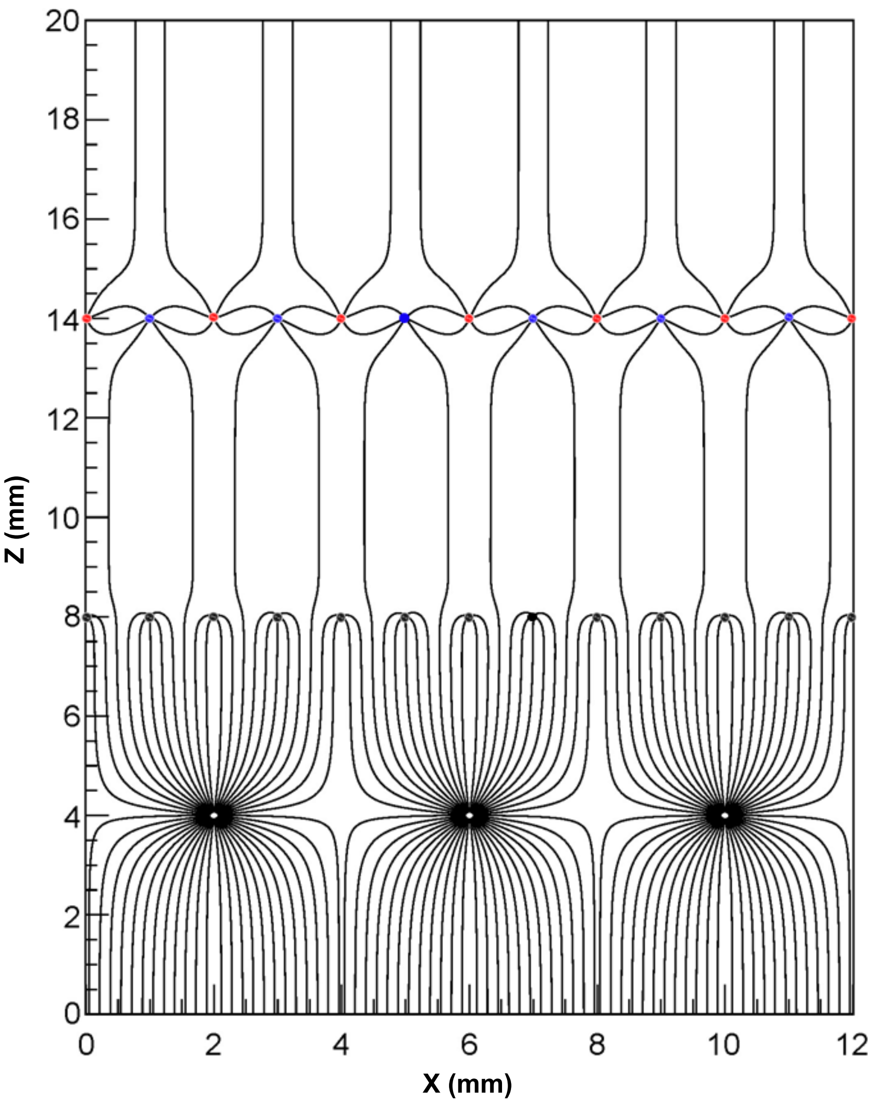
-1500 V/cm
~.125 msec

Anode Wires (+1390 V)

> +1500 V/cm

Pad plane (0 V)

Gated Grid Operation



↑ **Central Membrane (-28,000 V)** ↑
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Cathode Grid (0 V)

-1500 V/cm
~.125 msec

Anode Wires (+1390 V)

> +1500 V/cm

Pad plane (0 V)

Gated Grid Operation – another mode of operation

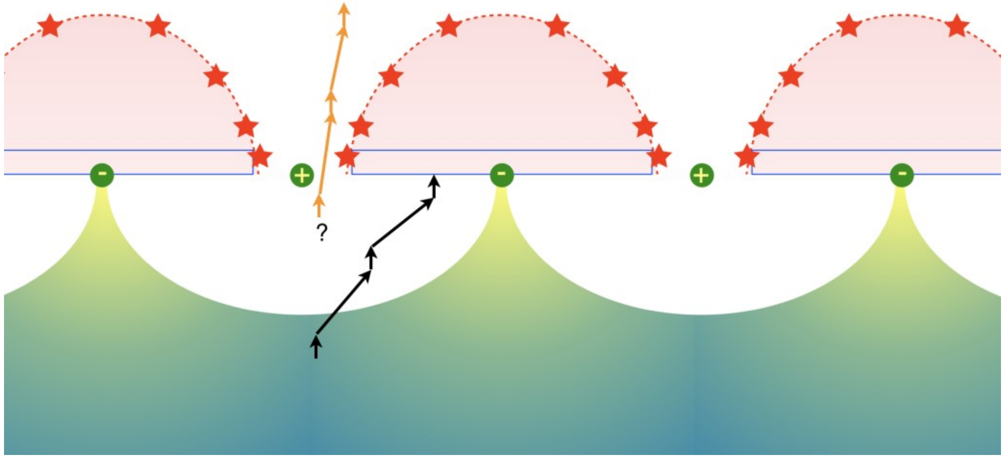
- **Why open and close the gated grid for each event?**
  - Electron drift velocity in TPC 5.4 $\frac{cm}{\mu sec}$
  - Ion drift velocity near GG ~2.08 $\frac{cm^2}{volt\ sec} \cdot 235\ \frac{volt}{cm} = 490\ \frac{cm}{sec}$
- **Opening for each event leads to an upper limit on the trigger rate**
  - Higher rates are possible by holding the gate open for multiple events
- **The ion drift velocity is (more than) 10,000 times slower. So we could (for example) hold the GG open for 1.4 msec then close it for 1.4 msec to clear *all* of the accumulated ions from the past events**
  - 50% open, 50% closed: synchronize to a clock rather than the collisions
  - This collects 50% of all events produced by the accelerator (e.g. 50% of 50 kHz)
    - Multiple GGs would accomplish the same goal more efficiently (HH Wieman, private communication)
  - Does this really work? Do we really understand what we are doing?
    - Yes, we have tested a similar scenario with the STAR TPC & beam
    - But first I have to explain how STAR really works … not the same as ALICE

Gated Grid Operation at STAR

- The STAR Gated Grid is synchronized with the accelerator and the STAR Trigger. It opens once for each Au+Au collision event.

- The Gated Grid is held open for a period of time, then closed until the next event. The open-time is greater than the time required for an e^- to drift from the Central Membrane to the Pad Plane (40 μsec @ 210 cm)

- The GG stops ion backflow through the dynamic operation of the grid
  - GG open < 50 μsec so ions travel < 200 μm past grid (< 3 wire diameters)
  - Ions that pass the GG are pulled back to the grid and quenched



Green circles represent GG wires spaced 1 mm apart

Yellow "-" and "+" symbols indicate wire polarity (± 75 V)

Red stars represent the furthest boundary from which ions can be successfully drawn back to the nearest "-" wire

Blue lines forming a box:

Top is a line at the drift distance (beyond the z of the GG) of an ion during 50 microseconds of GG open time. The top line intersects the oval, at ~±0.75 mm from the "-" wires
Lines down on the sides defines the region where all ions are captured.

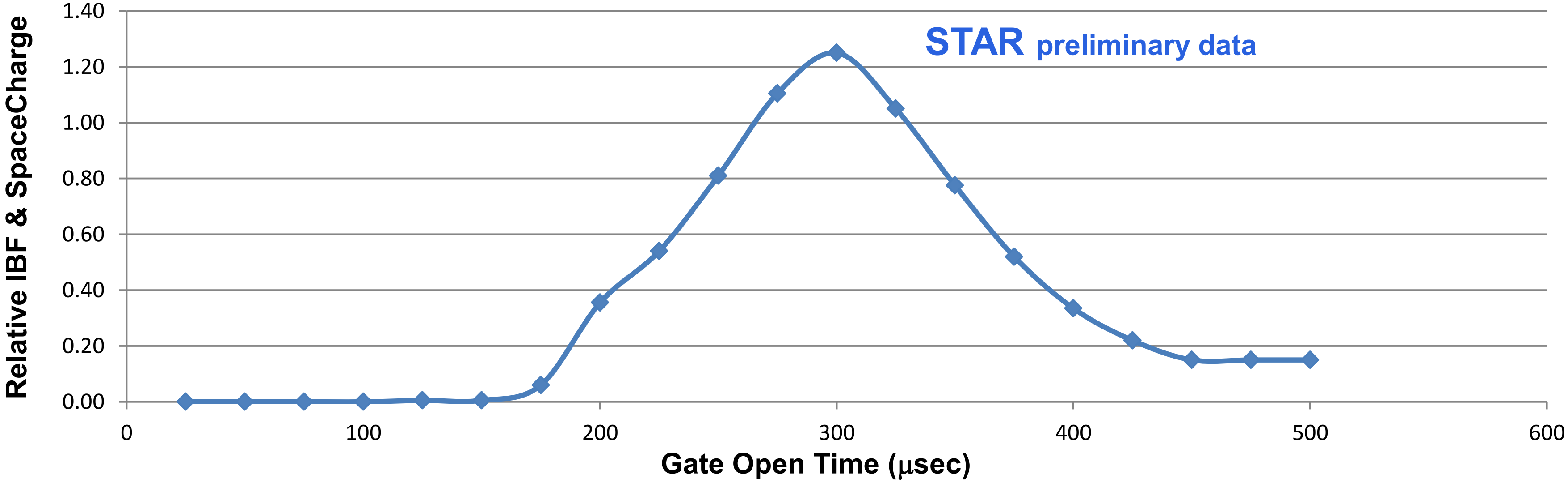
Blue and Yellow region is the zone where ions are confined when the GG is closed.

Black arrows showing a possible path for an ion up to the z of the GG, stepping as the GG opens and closes

Orange arrows showing a potential escape path, but originating from a region which ions very rarely reach

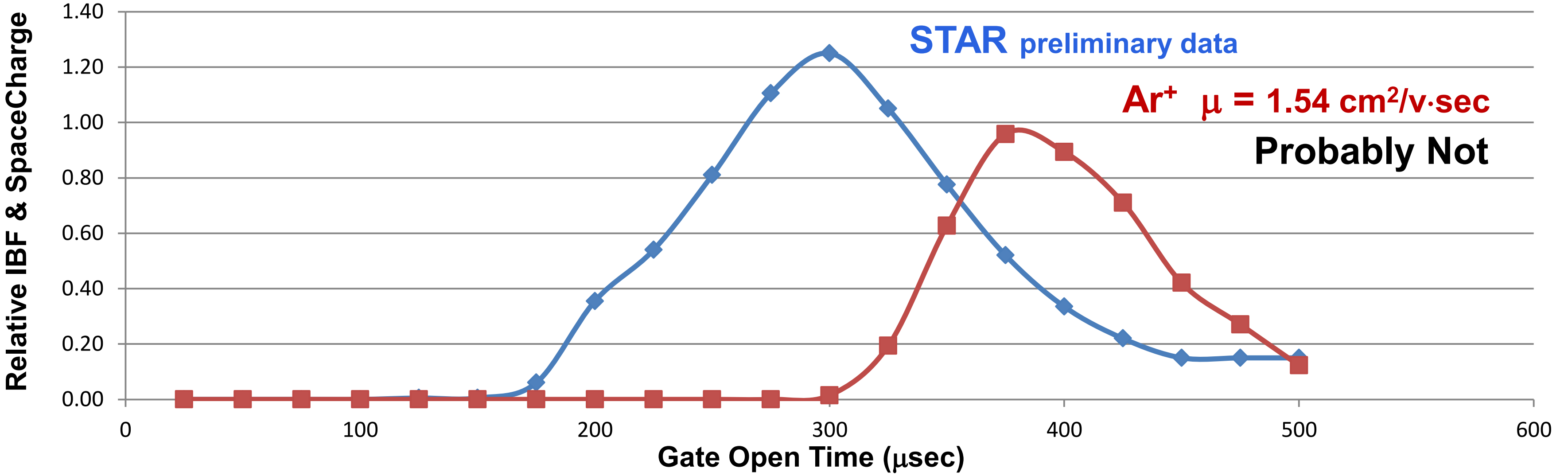
Tests with the STAR TPC

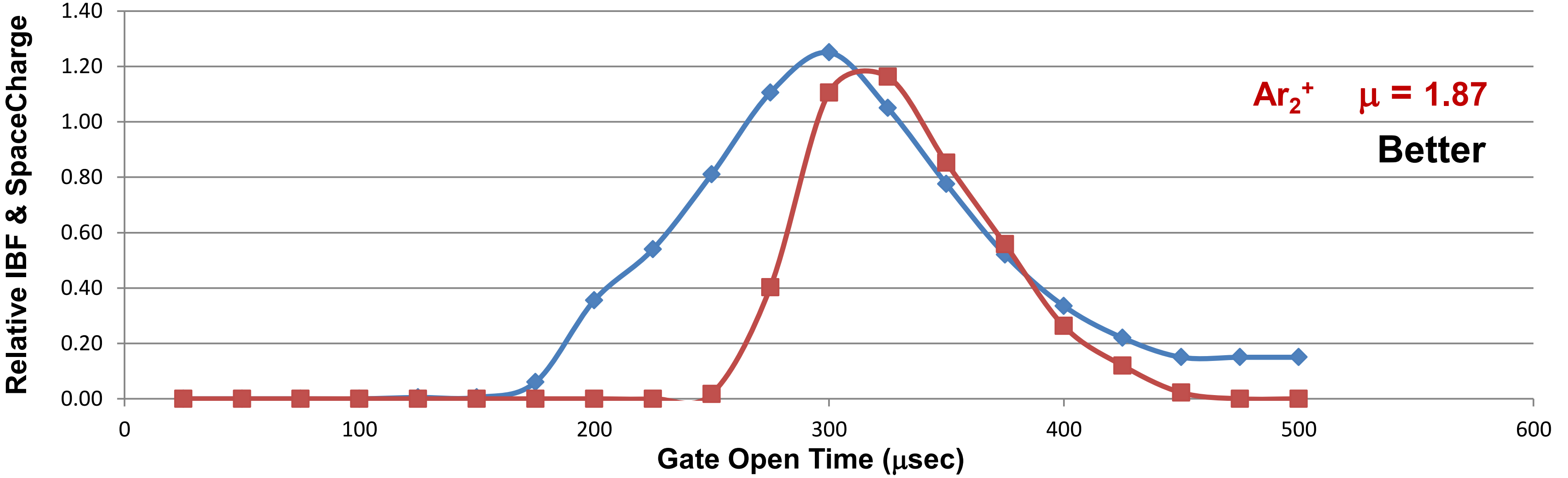
- Due to hardware and trigger constraints the STAR tests were limited to one scenario
  - Fixed length cycle time (Open+Closed adjustable from 700 to 2,650 μsec)
  - Gate Open 20% of the cycle time (range from 140 to 530 μsec)
  - Gate Closed 80% of the cycle time
- Spacecharge due to Ion Back Flow was estimated from the distortion of tracks
  - IBF and spacecharge in the TPC will create a distortion so the majority of tracks do not point at the vertex … magnitude of correction for each experimental setting is noted in the graph, below



Which Ion carries the Charge?

Mobilities from, e.g., Schultz, Charpak and Sauli, Rev. de Phys. App. Vol. 12, 67 (1977)





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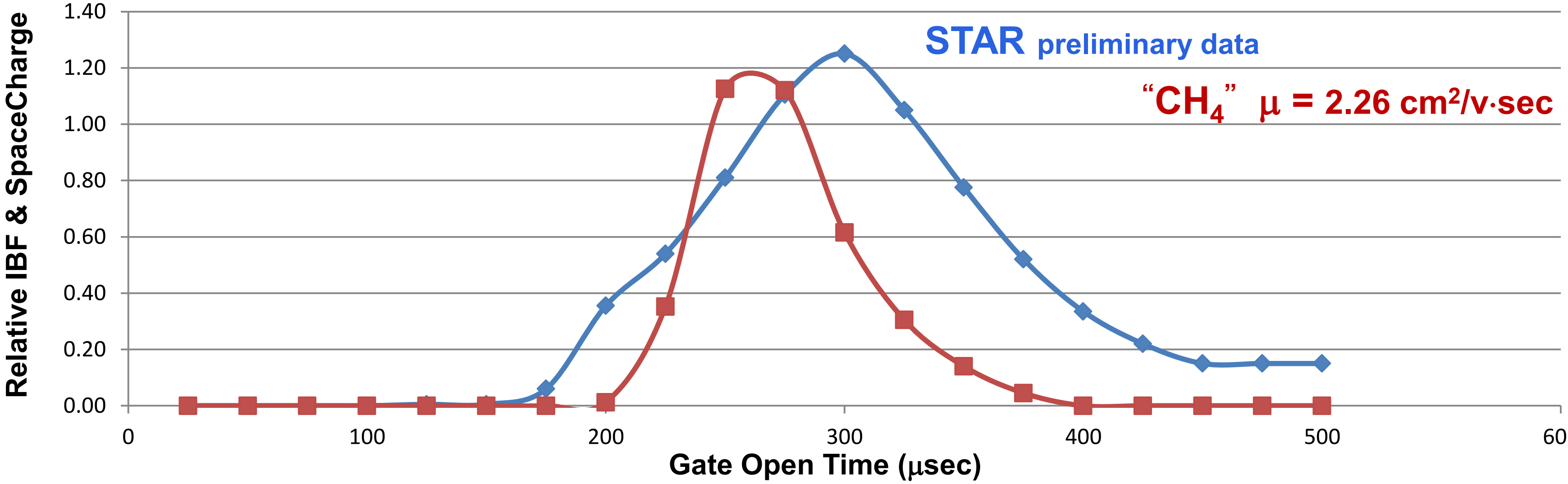
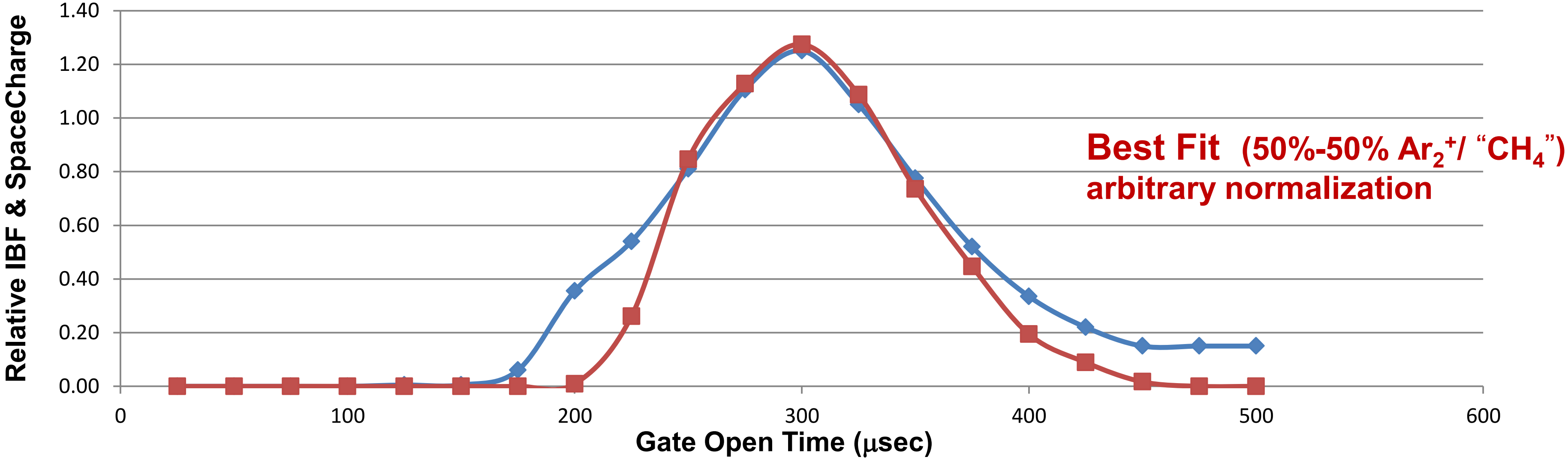
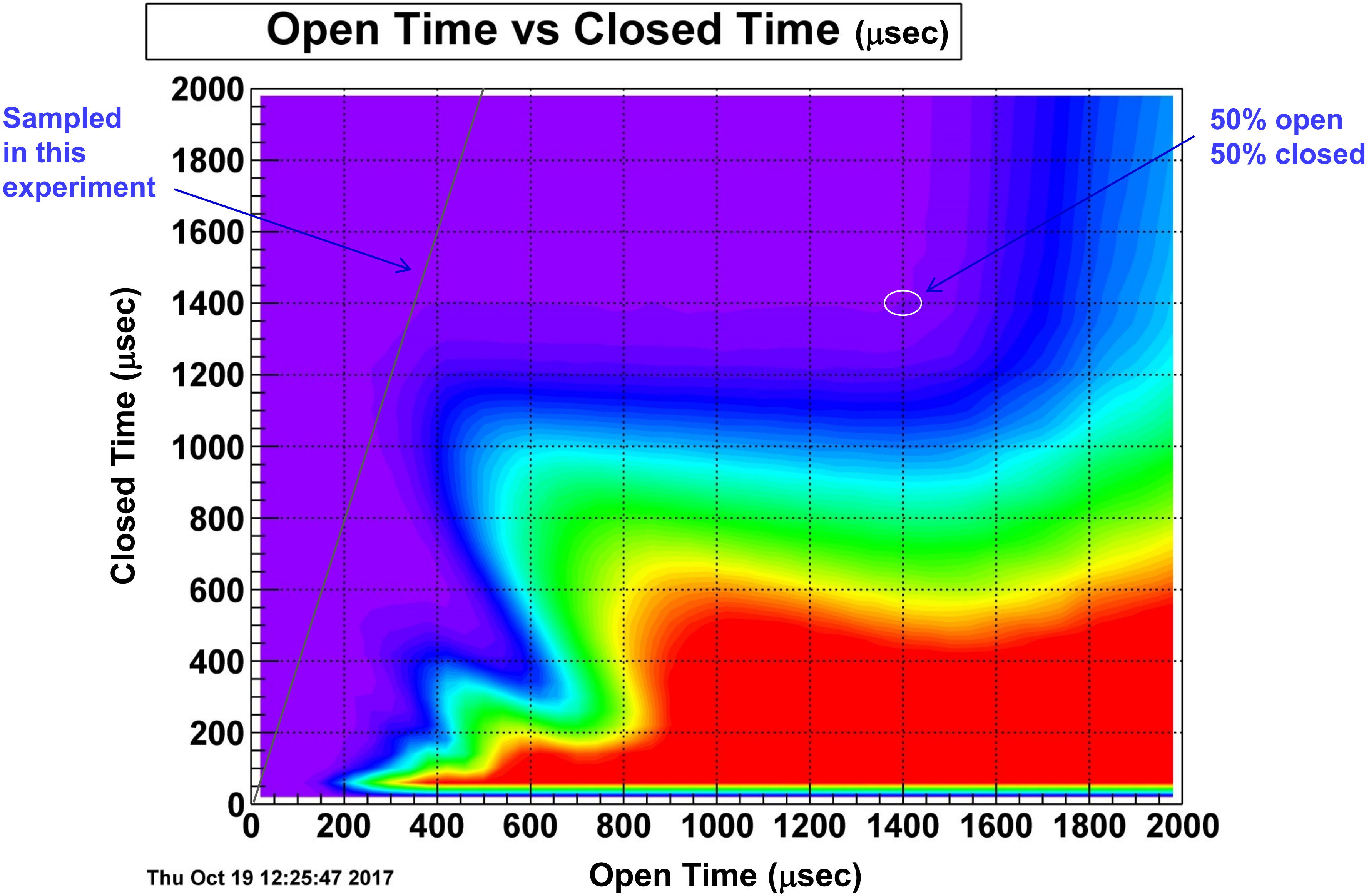




Ideal Case – Outer Sector (only), μ = 2.08 (avg)



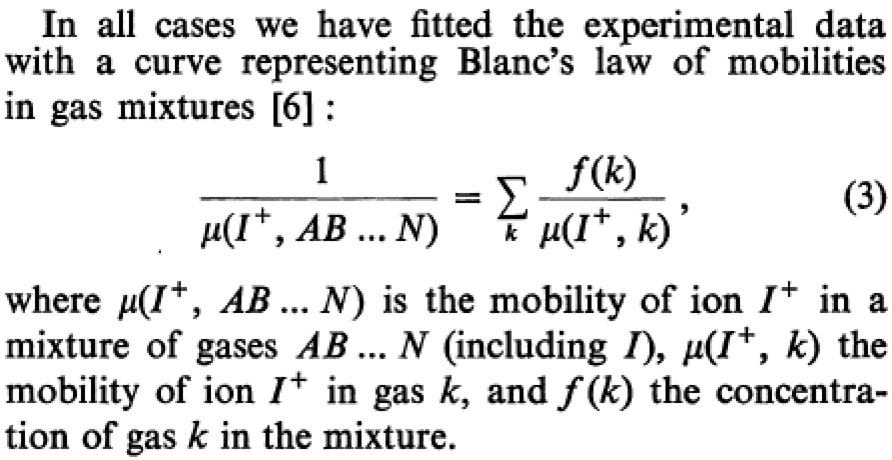
Do we really understand what we are doing?

- **It is possible to trigger a TPC Gated Grid w/o triggering on each event**
  - **50% of all events (e.g. accept >25 kHz min Bias Au beam events at RHIC)**
- **Measured data (mostly) agrees with simple dynamic simulations**
  - **We have additional data with different scan settings which will be analyzed**
- **The unanswered question is "which ion carries the charge in P10 gas"?**
  - **Probably not Ar^+ due to fast charge exchange chemistry**
    - **Rapid charge exchange to Ar_2^+, CH_4^+ and other species (CH_3^+, CH_5^+, etc.)**
    - **Timescale from anode to GG is ~ 1.4 msec**
  - **Better candidates are Ar_2^+ and "CH_4"**
  - **Best Fit is a 50-50 mixture of Ar_2^+ + "CH_4"**
  - **Something faster would be even better**
    - **CH_4 has complex chemistry after the ionization event, which ion?**
    - **The literature contains a range of μ values for Ar ions, which ion?**
- **References**
  - Garfield (2016); Madson & Oskam Phys. Lett. 25A, no 5 (1967); McAfee, Sipler & Edelson Phys. Rev. 160, no 1, (1967); Schultz, Charpak and Sauli, Rev. de Phys. App. Vol. 12, 67 (1977); Trindade et al., JINST 9, P06003 (2014) … more library research required.

Ion Drift Velocities I

- **Schultz, Sauli and Charpak have the best numbers as determined by the fit to our data**
    - They do not identify the ion that is carrying the charge (no mass spec)
    - Their numbers are derived by changing the concentration of Methane in CH_4 + Ar gas mixtures
    - They apply Blanc's law for gas mixtures to identify the drifting ions
    - Thus, they don't know the drifting ion but are deriving "effective" results

Blanc's Law



In all cases we have fitted the experimental data with a curve representing Blanc's law of mobilities in gas mixtures [6] :

$$\frac{1}{\mu(I^+, AB \ldots N)} = \sum_k \frac{f(k)}{\mu(I^+, k)}, \qquad (3)$$

where $\mu(I^+, AB \ldots N)$ is the mobility of ion I^+ in a mixture of gases $AB \ldots N$ (including I), $\mu(I^+, k)$ the mobility of ion I^+ in gas k, and $f(k)$ the concentration of gas k in the mixture.

[3] Schultz, Charpak and Sauli, Rev. de Phys. App. Vol. 12, 67 (1977).

"In most cases, the exact nature of the drifting ions has not been identified directly; therefore, the values indicated might correspond to an average over several species."

[6] F. Sauli, "Gaseous Radiation Detectors", Cambridge Univ. Press, pg. 87 (2014).

- **Blanc's Law can be used to calculate the mobility for a mixture of gases**
- **The "Law" has been extensively verified in the literature**
  - **But, as Sauli says, the exact nature of the drifting ion has not been determined**
- **So when Garfield, or the literature, assigns one value for the mobility of an ion in a mixture of gases … there may actually be multiple ions at work; each with its own characteristic mobility**
- **STAR data supports at least 2 active ions carrying the charge in P10**
- **GEM data with PID seem to agree with this observation, but not necessarily yielding the same list of active charge carriers**

Ion Drift Velocities II

- **More recent studies that do use mass spectrometry do not agree with Schultz, Sauli and Charpak's identification of the ions**
  - **Ar^+ rapidly charge exchanges to become Ar_2^+**
  - **Ar_2^+ is the effective charge carrier in pure Argon (not Ar^+)**
  - **In P10, Ar^+ charge exchanges with CH_4 and starts a complicated cascade of CH_4 based chemical reactions. The end result of these reactions are several hydrocarbon charge carriers such as CH_5^+**
  - **GEM studies at low pressure (7 torr) do not see Argon charge carriers using mass spectrometers to identify the ions. Instead they see CH_5^+, $C_2H_n^+$ and $C_3H_n^+$ ions with CH_5^+ as the most abundant (but not CH_4^+).**
  - **Our data do not agree with the suggestion that hydrocarbon fragments carry all of the positive charge … but these exotics may contribute to the tail at small gate-open times.**
  - **We need many different ions to explain our results**

Argon Ions in Argon Gas or in P10

Neves, Conde and Tavora, The Journal of Chemical Physics **133**, 124316 (2010)

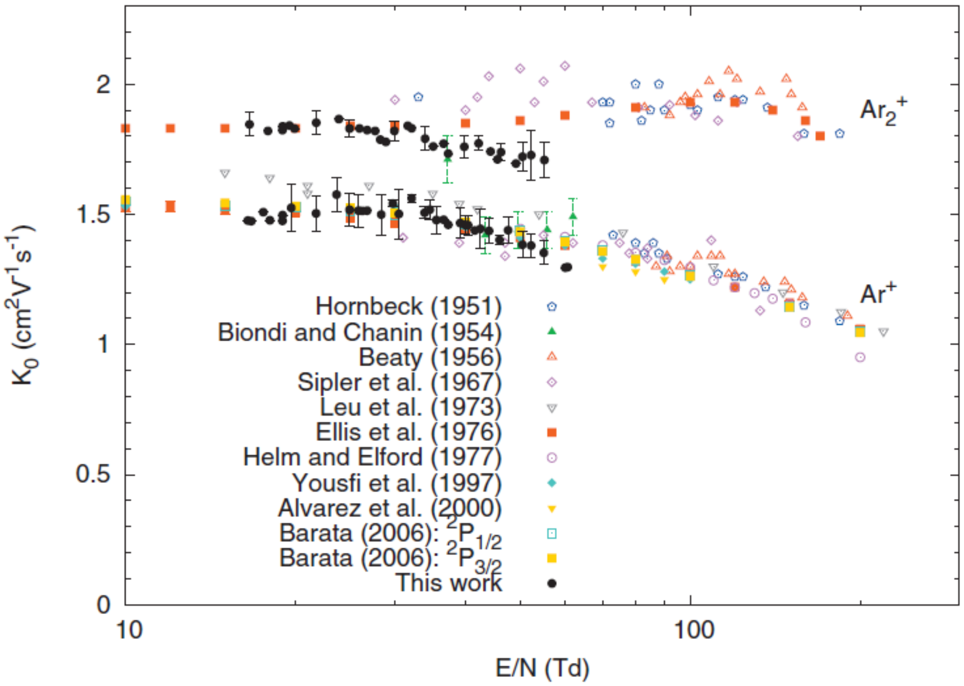


FIG. 4. Experimental reduced mobilities for the Ar^+ and Ar_2^+ ions in Ar. Our results are compared with those of other authors (Refs. 7–16).

$Ar + e^- \rightarrow Ar^+ + 2e^-$

$Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar$

A 2 step process with resonant charge transfer between the Ar^+ and the Ar atoms. The charge transfer slows down the Ar^+ relative to the Ar_2^+ (!)

Extraction to zero field mobility is what is important in the current work

Ar^+ $\mu = 1.54^{1,2(Ar)}$

Ar_2^+ $\mu = 1.83^{1,2(Ar)}$

$\mu = 1.87^{3(P10)}$

Ar^{++} $\mu = 2.60^{2(Ar)}$

$\mu = 2.40^{4(Ar)}$

It is claimed[5] that Ar ions are not seen (none of the above) for GEM foils operating in P10 Gas at 7 torr.

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[1] Neves, Conde and Tavora, The Journal of Chemical Physics **133**, 124316 (2010)

[2] Madson and Oskam, Phys. Lett. Vol. 25A, #5, 407 (1967)

[3] Schultz, Charpak and Sauli, Rev. de Phys. App. Vol. 12, 67 (1977).

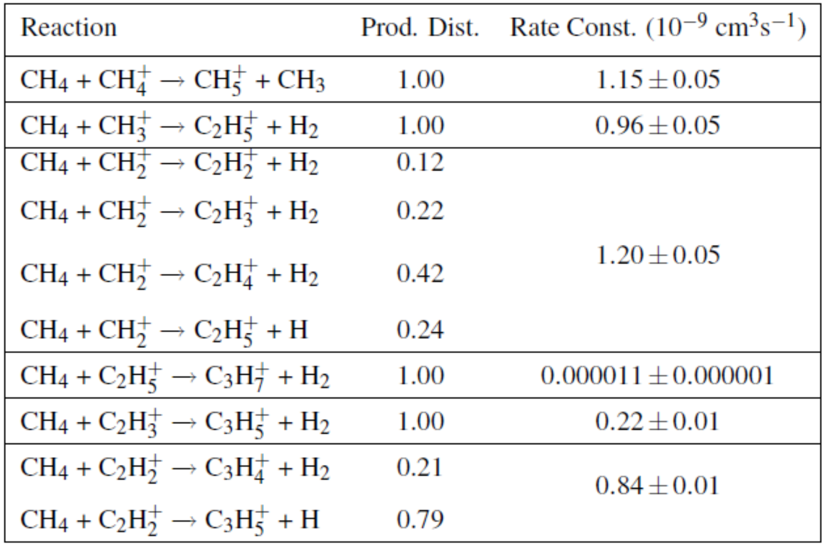
[4] McAfee, Sipler, and Edelson, Phys. Rev. Vol. 160 #1, 130 (1967)

[5] Trindade *et al. JINST* **9** P06003 (2014)

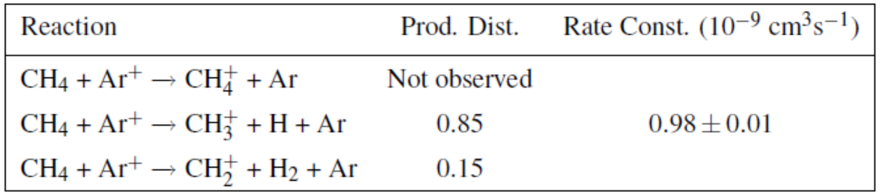
Methane Ions in Argon – complex chemistry!

Ionization products (Table I)[5] and subsequent ionization exchange reactions with CH_4 (Table II)[5] and Ar^+ (Table III)[5]

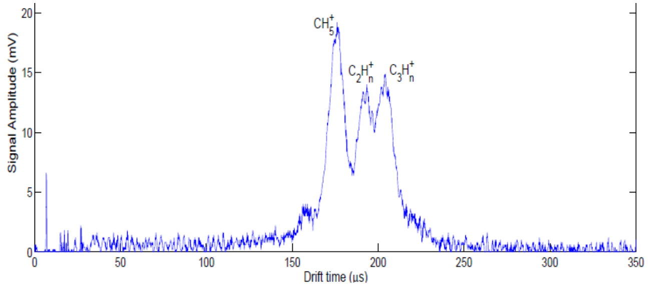
Reaction	Cross Sec. (10^{-16}cm^2)	A. E. (eV)	Prod. Dist.
$CH_4 + e^- \rightarrow CH_4^+ + 2e^-$	0.892	12.7 ± 0.4	56.7 %
$CH_4 + e^- \rightarrow CH_3^+ + H^- + e^-$	0.512	13.7 ± 0.1	32.6 %
$CH_4 + e^- \rightarrow CH_3^+ + H_2 + 2e^-$		14.3 ± 0.1	
$CH_4 + e^- \rightarrow CH_2^+ + H^- + H_2 + e^-$	0.169	15.1 ± 0.1	10.7 %



Reaction	Prod. Dist.	Rate Const. (10^{-9} cm^{3}s^{-1})
$CH_4 + CH_4^+ \rightarrow CH_5^+ + CH_3$	1.00	1.15 ± 0.05
$CH_4 + CH_3^+ \rightarrow C_2H_5^+ + H_2$	1.00	0.96 ± 0.05
$CH_4 + CH_2^+ \rightarrow C_2H_2^+ + H_2$	0.12	1.20 ± 0.05
$CH_4 + CH_2^+ \rightarrow C_2H_3^+ + H_2$	0.22	
$CH_4 + CH_2^+ \rightarrow C_2H_4^+ + H_2$	0.42	
$CH_4 + CH_2^+ \rightarrow C_2H_5^+ + H$	0.24	
$CH_4 + C_2H_5^+ \rightarrow C_3H_7^+ + H_2$	1.00	0.000011 ± 0.000001
$CH_4 + C_2H_3^+ \rightarrow C_3H_5^+ + H_2$	1.00	0.22 ± 0.01
$CH_4 + C_2H_2^+ \rightarrow C_3H_4^+ + H_2$	0.21	0.84 ± 0.01
$CH_4 + C_2H_2^+ \rightarrow C_3H_5^+ + H$	0.79	



Reaction	Prod. Dist.	Rate Const. (10^{-9} cm^{3}s^{-1})
$CH_4 + Ar^+ \rightarrow CH_4^+ + Ar$	Not observed	
$CH_4 + Ar^+ \rightarrow CH_3^+ + H + Ar$	0.85	0.98 ± 0.01
$CH_4 + Ar^+ \rightarrow CH_2^+ + H_2 + Ar$	0.15	



Studies with GEM foils at 7 torr suggest that CH_5^+ is the primary charge carrier in P10 gas. Not CH_4^+ or Ar^+ nor any Ar ion.

Measured mobilities for charge carriers in P10 gas

CH_5^+ $\mu = 2.87$[5(pid)]

$C_2H_n^+$ $\mu = 2.62$[5(pid)]

$C_3H_n^+$ $\mu = 2.45$[5(pid)]

"CH_4" $\mu = 2.26$[3(no-pid)]

"Argon" $\mu = 1.87$[3(no-pid)]

[3] Schultz, Charpak and Sauli, Rev. de Phys. App. Vol. 12, 67 (1977).
[5] Trindade *et al. JINST* **9** P06003 (2014)

The State of the Art

- **State of the Art Measurements – suggest that Argon ions are not involved in the drift of ions from the Anode to Cathode for P10**
  - **What?**
  - **What did Schultz, Sauli and Charpak measure using Blanc's Law?**
  - **Very likely that most of the literature is measuring one thing and publishing it as something else. This would explain why the literature has many different values quoted for the drift velocity of Argon ions in gas mixtures.**

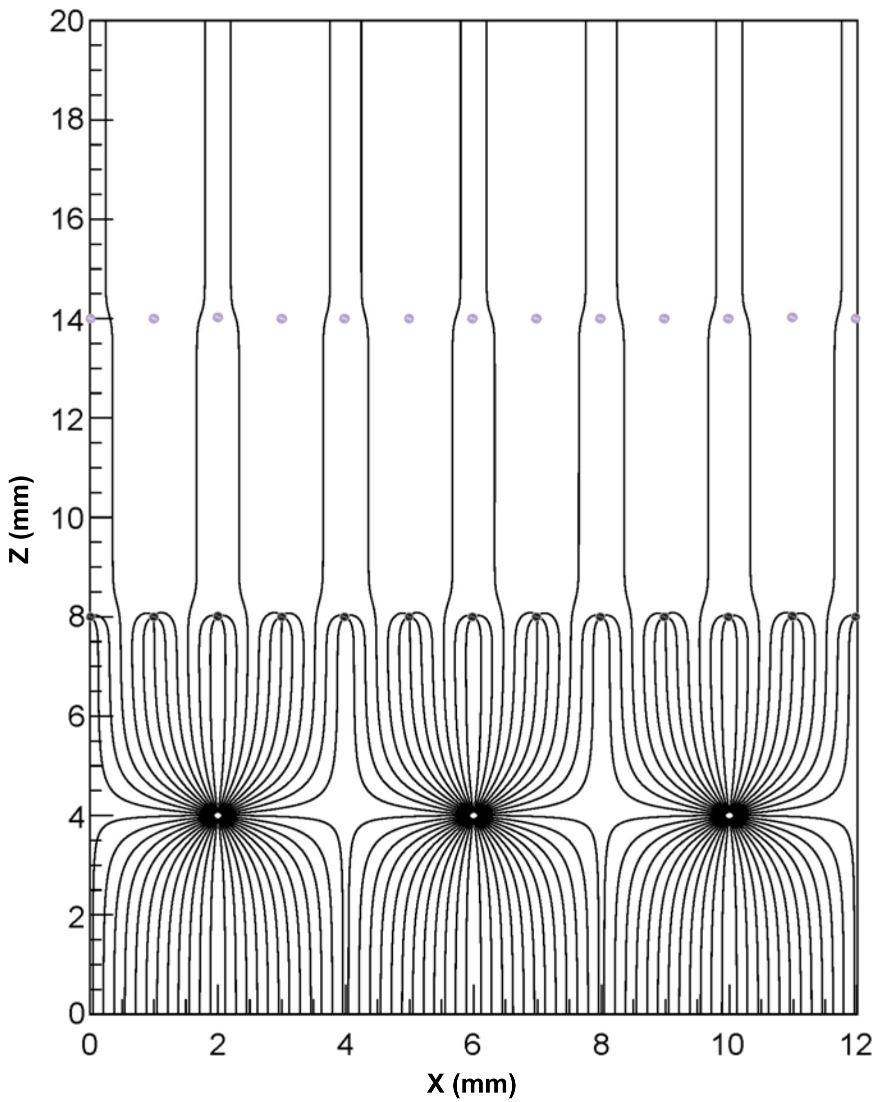
- **State of the Art Measurements – suggest that Methane is doing all of the charge transport when used in combination with Argon**
  - **However, its not CH_4^+**
  - **Something much more complex is going on**

- **Our data – if our data and the analysis are correct (you never know) then we need two ion species drifting from Anode wire to Cathode wire to Gated Grid.**
  - **Probably not Argon ions … but then I cannot explain any of the Blanc's Law measurements from the Literature**

- **We are not out of the woods, yet.**

Now for Something Completely Different

Gated Grid Operation



↑ **Central Membrane (-28,000 V)** ↑

-133 V/cm

Bipolar Gated Grid (-115 ± 0 V)

-234 V/cm

Cathode Grid (0 V)

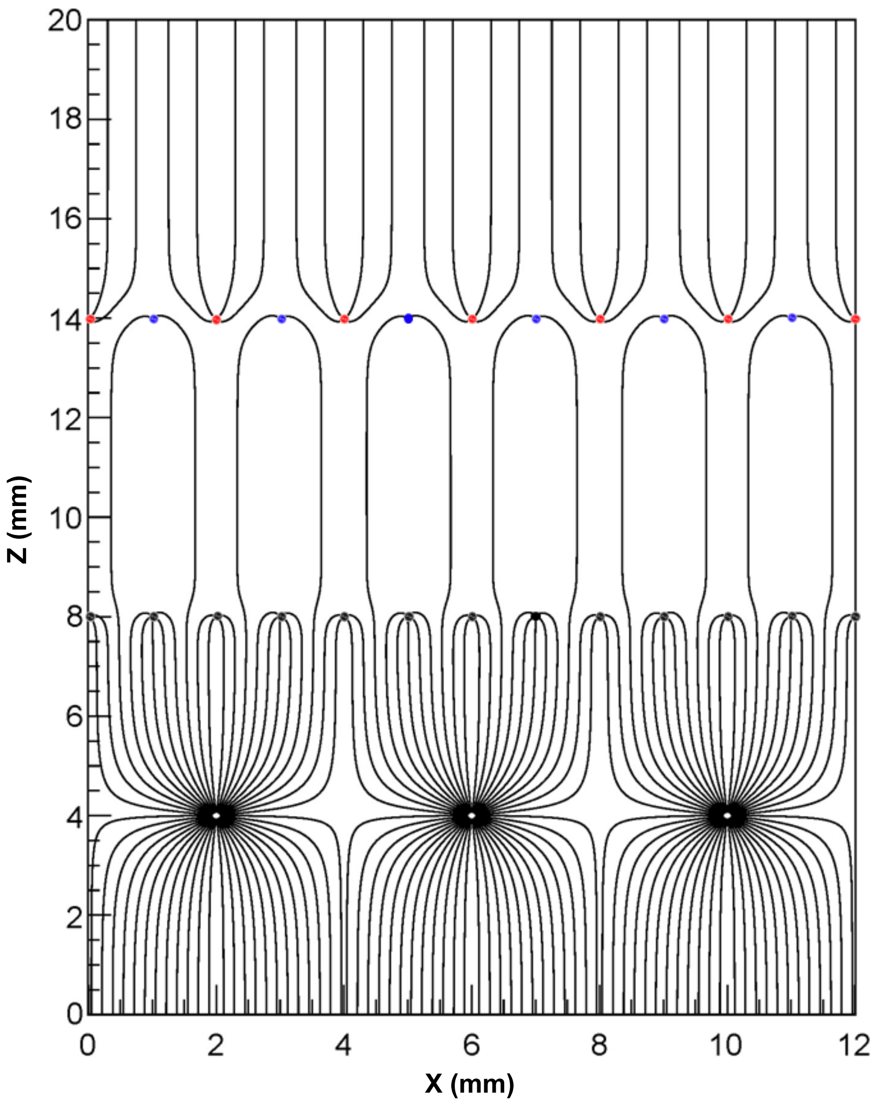
> -1500 V/cm

Anode Wires (+1390 V)

> +1500 V/cm

Pad plane (0 V)

Gated Grid Operation



↑ Central Membrane (-28,000 V) ↑

-133 V/cm

Bipolar Gated Grid (-115 ± 20 V)

-234 V/cm

Cathode Grid (0 V)

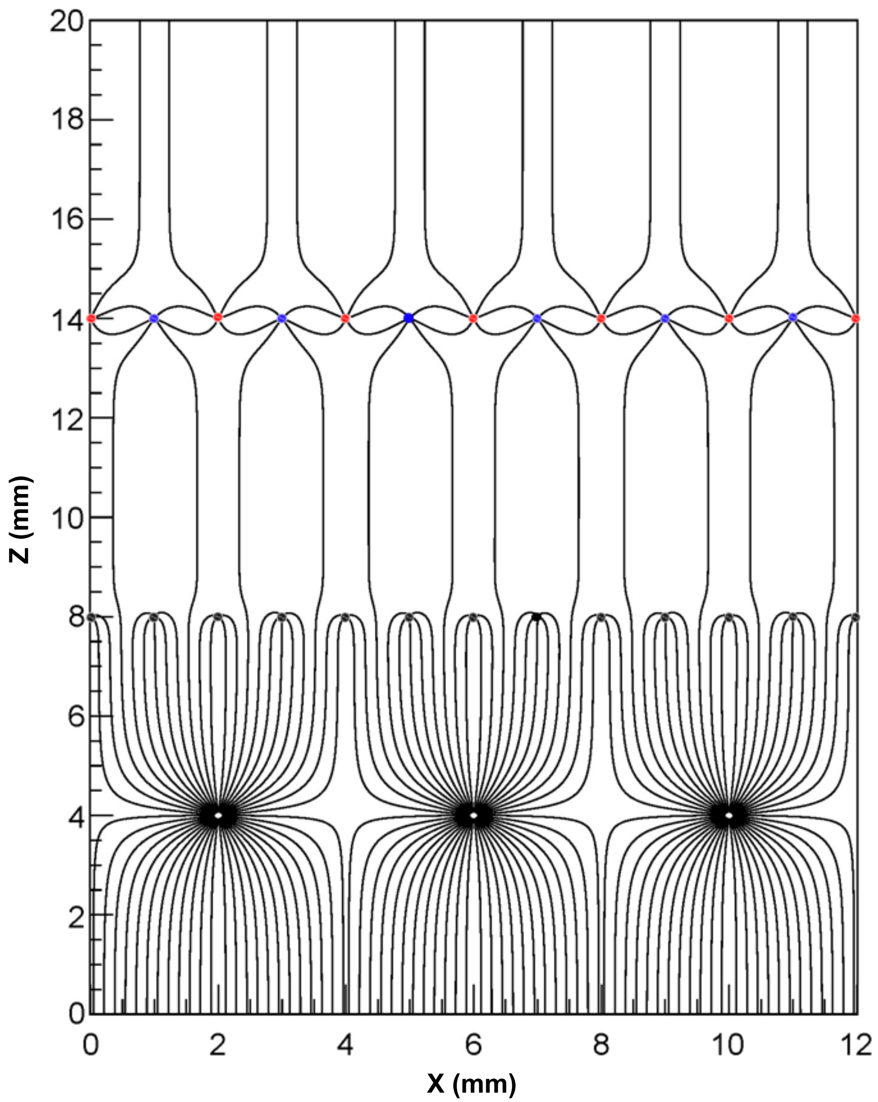
> -1500 V/cm

Anode Wires (+1390 V)

> +1500 V/cm

Pad plane (0 V)

Gated Grid Operation



↑ Central Membrane (-28,000 V) ↑

-133 V/cm

Bipolar Gated Grid (-115 ± 75 V)

-234 V/cm

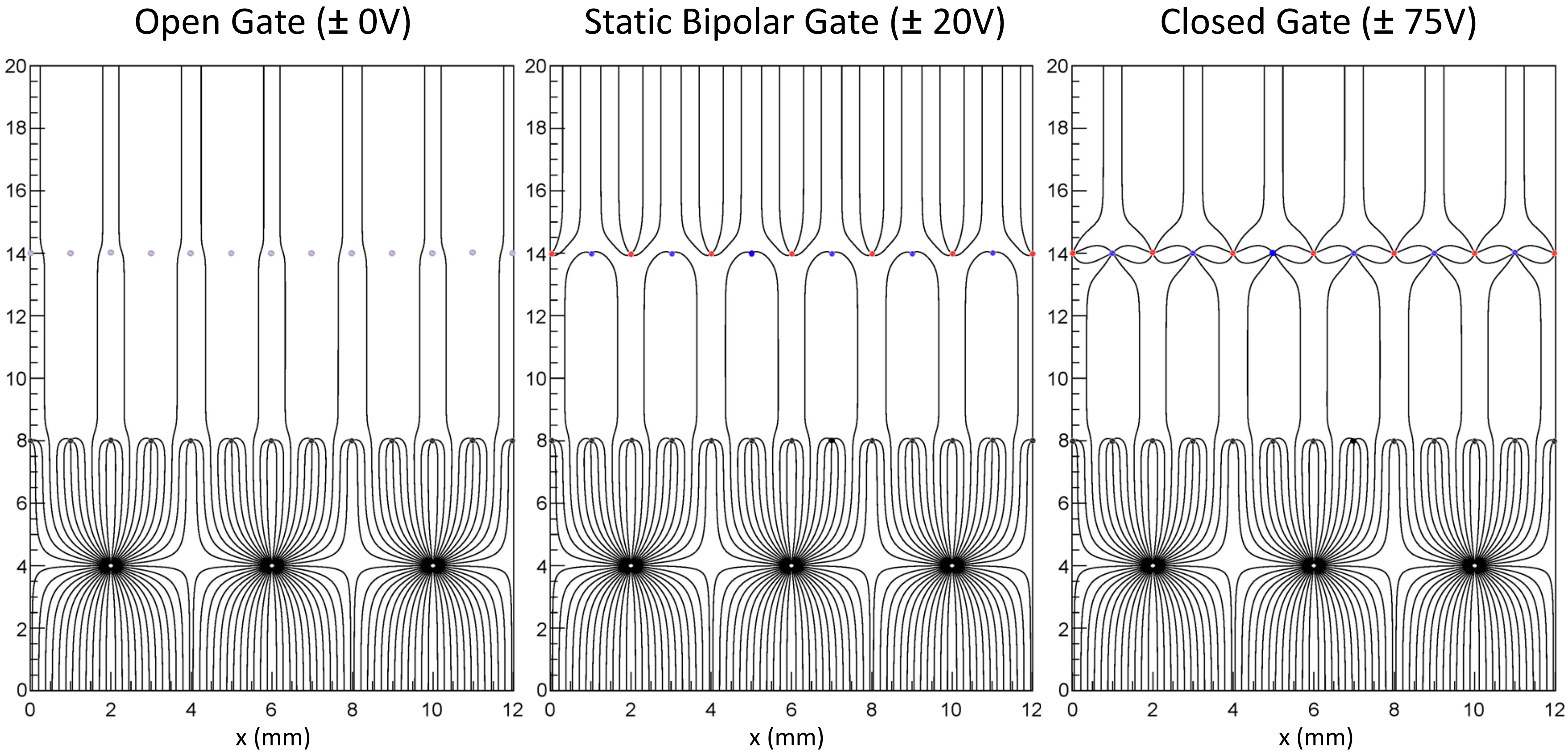
Cathode Grid (0 V)

> -1500 V/cm

Anode Wires (+1390 V)

> +1500 V/cm

Pad plane (0 V)

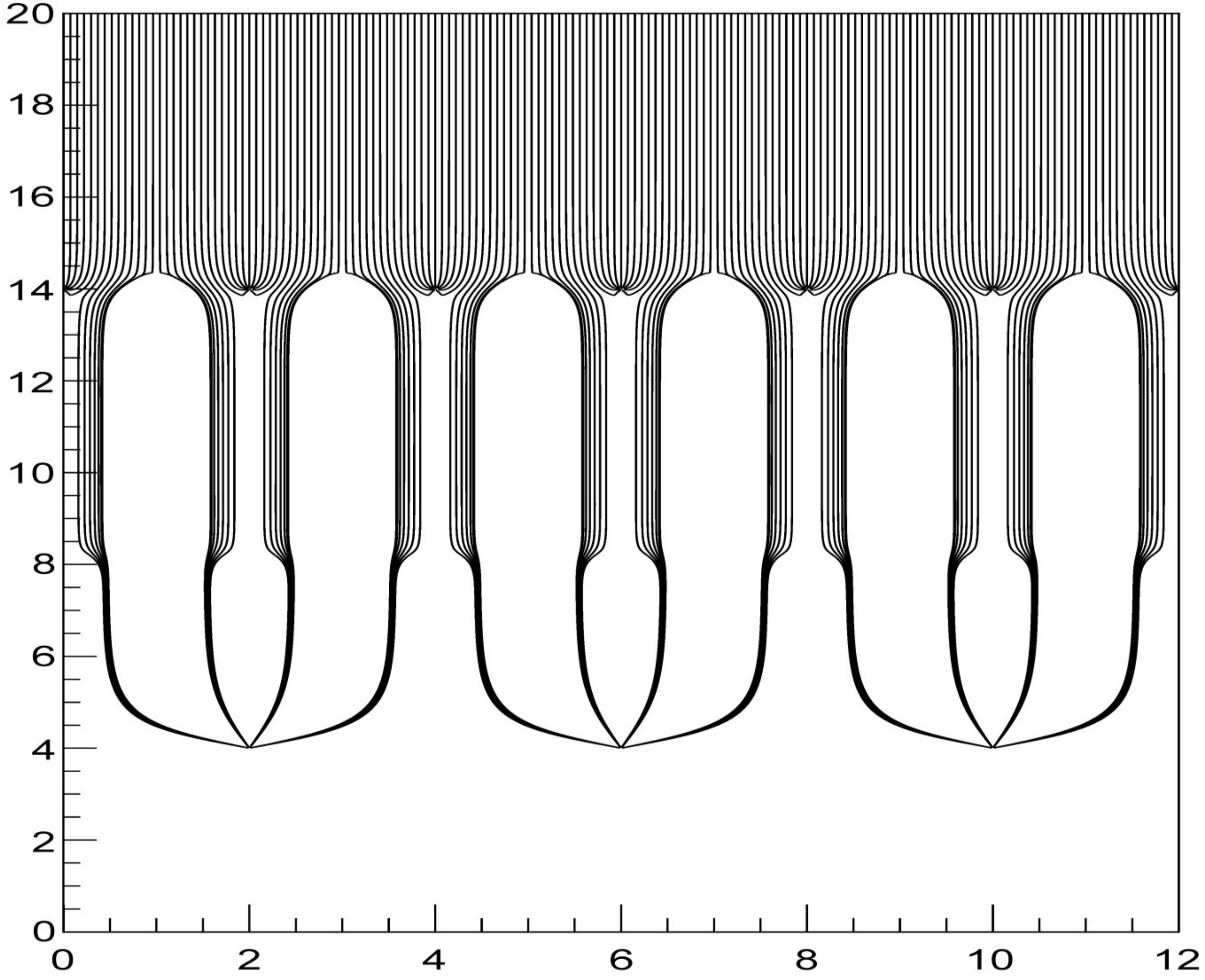


- The SBG is a diode because *ions* follow a path determined by $\delta_x = \int \frac{E_x}{E_z}\, dz$ while the *electrons* follow a less deflected path described by the Langevin Equation

$$\delta_x = \frac{1}{(1+\omega^2\tau^2)} \int \frac{E_x}{E_z}\, dz \quad \text{and} \quad \delta_y = \frac{\omega\tau}{(1+\omega^2\tau^2)} \int \frac{E_x}{E_z}\, dz$$

- For P10 gas, $\omega\tau \approx 2.0$ in a 0.5 Tesla B_z field and 134 V/cm E field. So the coefficients are 0.2 and 0.4, respectively. The z axis is vertical, the x axis goes to the right, and the y axis goes into the page.

electron plot: 50% transmission



Ions follow the field lines, electrons do not

Electron deflection due to field lines is reduced by action of the B field (reduced δ_x but enhanced δ_y, this is the Lorentz effect)

STAR Geometry

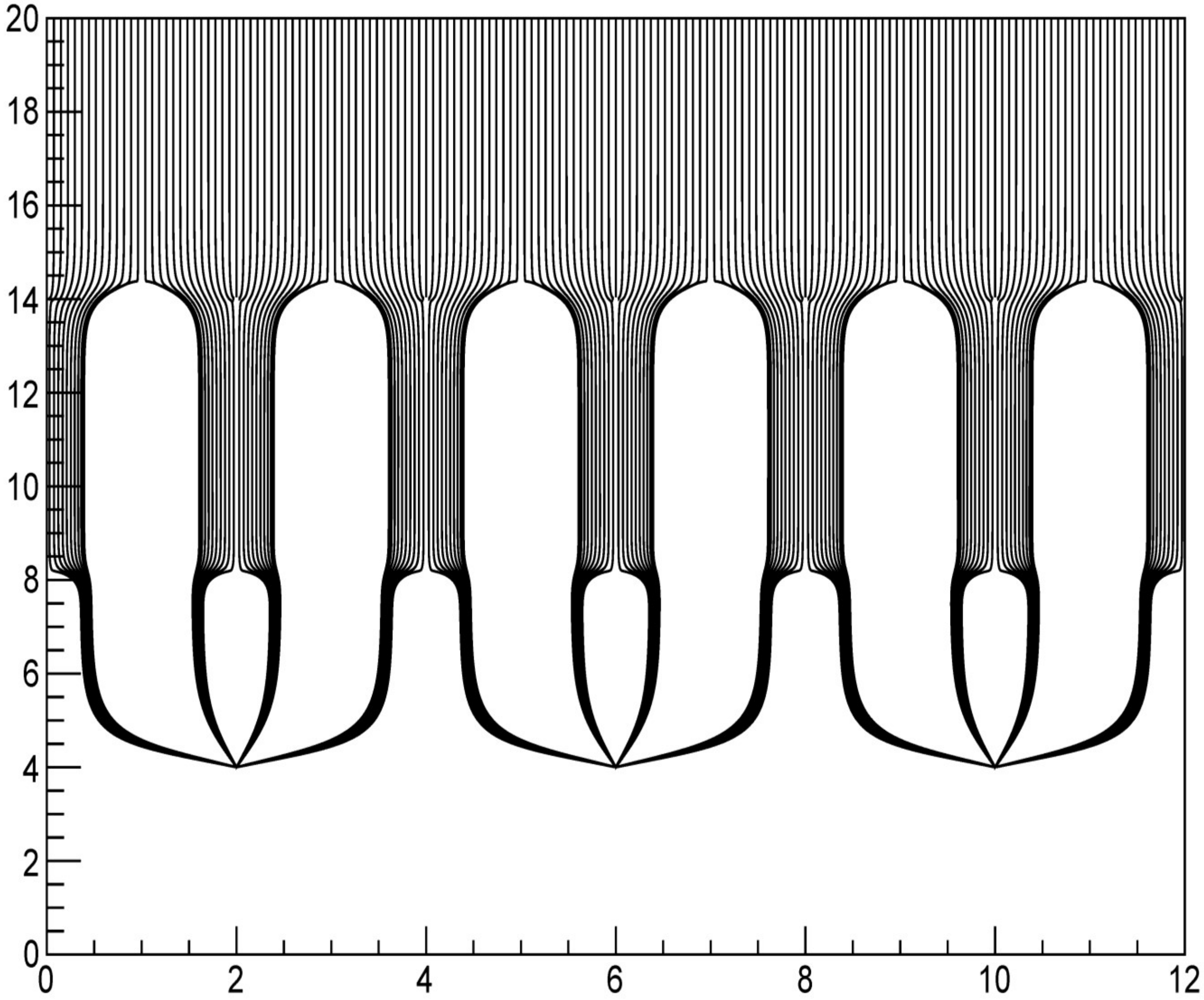
±15 Volts on GG

< 100% ion block

50% electron transmission

Interesting result but not useful

electron plot: 95% transmission



Ions follow the field lines, electrons do not

Improved performance of SBGate if increase E field between Anode and Cathode wires (to 3x Drift field)

STAR Geo Update
+100 V on Cathode
+100 V on Anode

±15 Volts on GG

100% ion block

95% electron transmission

Interesting result
may be useful
not fully optimized

Summary for the Static Bipolar Gate

- **The STAR geometry cannot be used as a Static Bipolar Gate**
  - Because we want > 50% transmission & better than 95% ion block

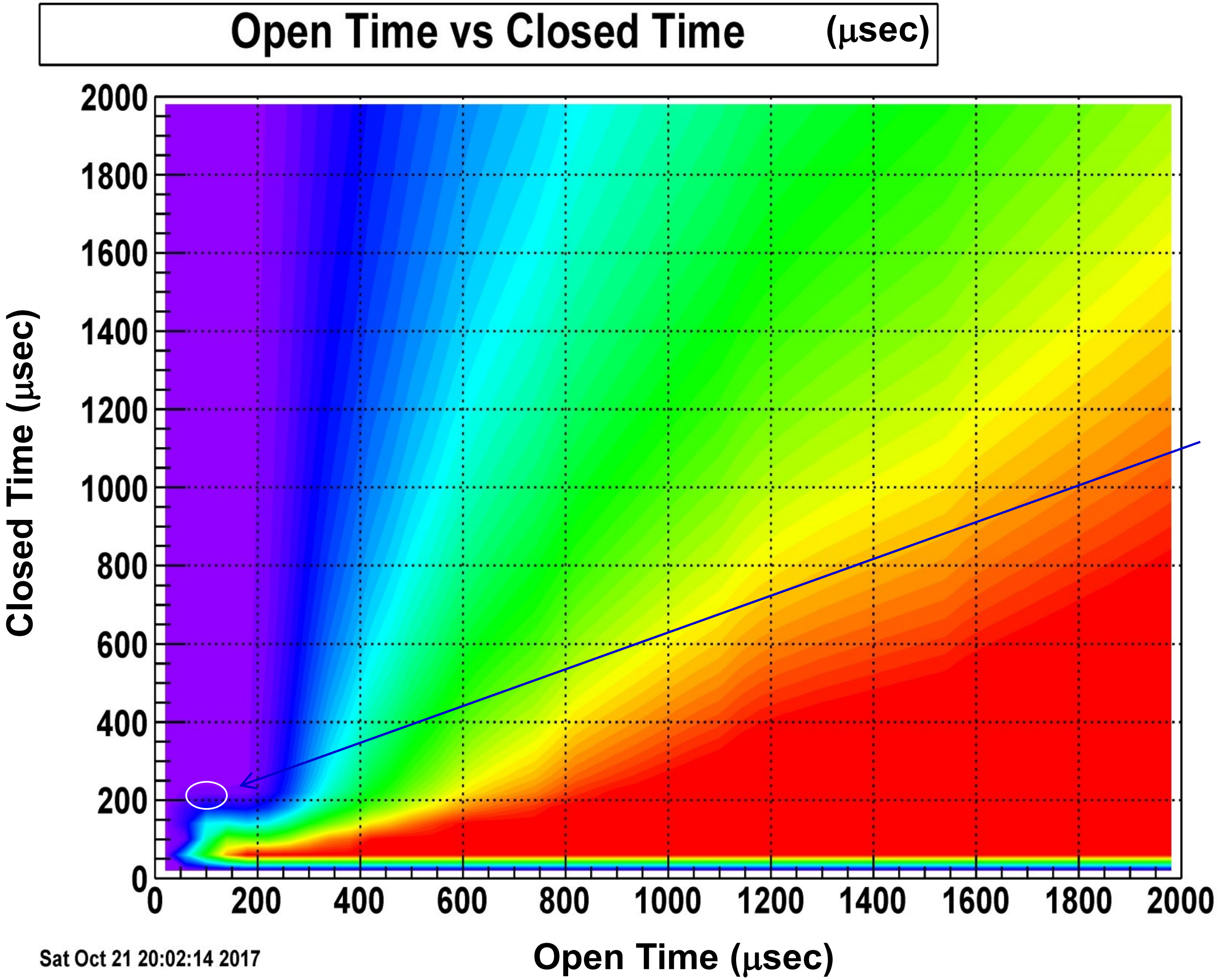
- **However, the performance can be improved if I am allowed to change the electric field between the GG and the Cathode grid**
  - Cannot be done at STAR
  - In STAR, we call the Cathode grid "the Ground grid" because it is grounded … and we cannot change the voltage on the grid

- **If the electric field between the GG and the Cathode grid is 3x the electric field in the drift volume of the TPC then the Static Bipolar Gate works very well, even in the STAR geometry**
  - ~100% transmission for electrons, 100% stoppage of ions

- **Something similar can be done for a GEM in sPHENIX**
  - Need approximately 3x the E field between the GEM foil and the GG as compared to the E field in the drift volume of the TPC
  - Spacing from GEM foil to Grid is not important (propose 5 mm)
    - e.g. Padplane 0 kV, GEM -3 kV, SBGrid -3.6 kV, CM -25 kV (?)

Backup Slides

ALICE Geometry   μ = 2.7



ALICE cannot take multiple events per opening of the GG

100 μsec drift time in TPC so open for 100 μsec

Close for 200 μsec

300 μsec rqr'd for each event, 3 kHz max