Gyrocenter shift of low temperature plasma and retrograde motion of arc discharges

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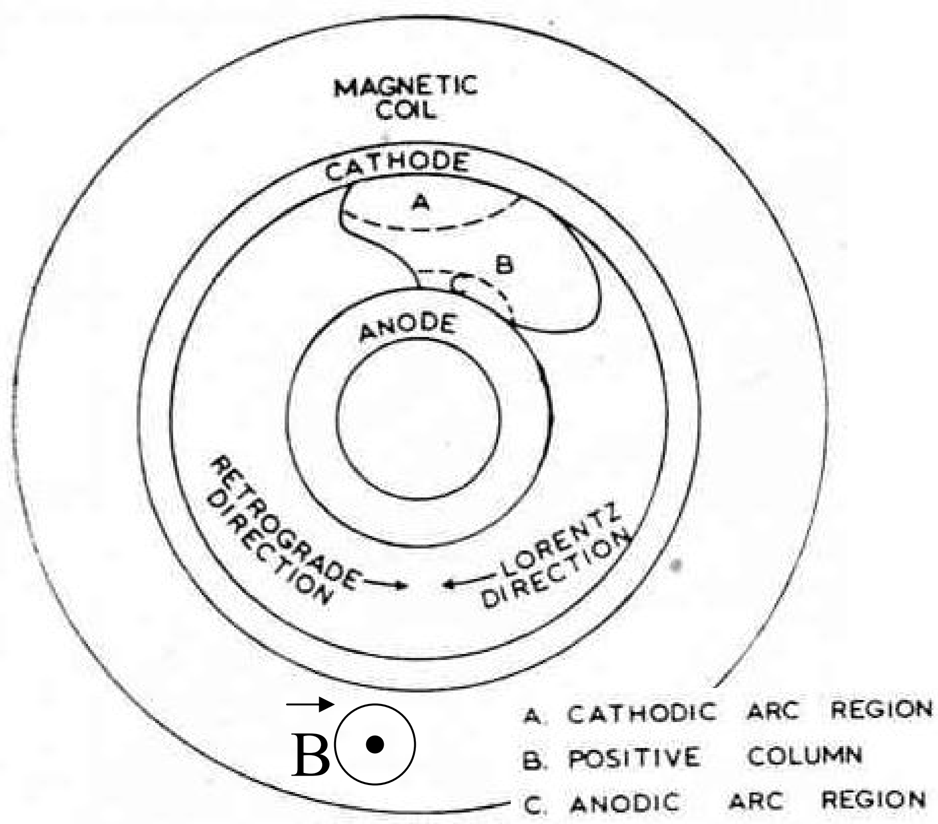
Contents

Retrograde motion of arc cathode

► retrograde motion was noticed by Stark (1903)
► no satisfactory explanation despite numerous attempts.

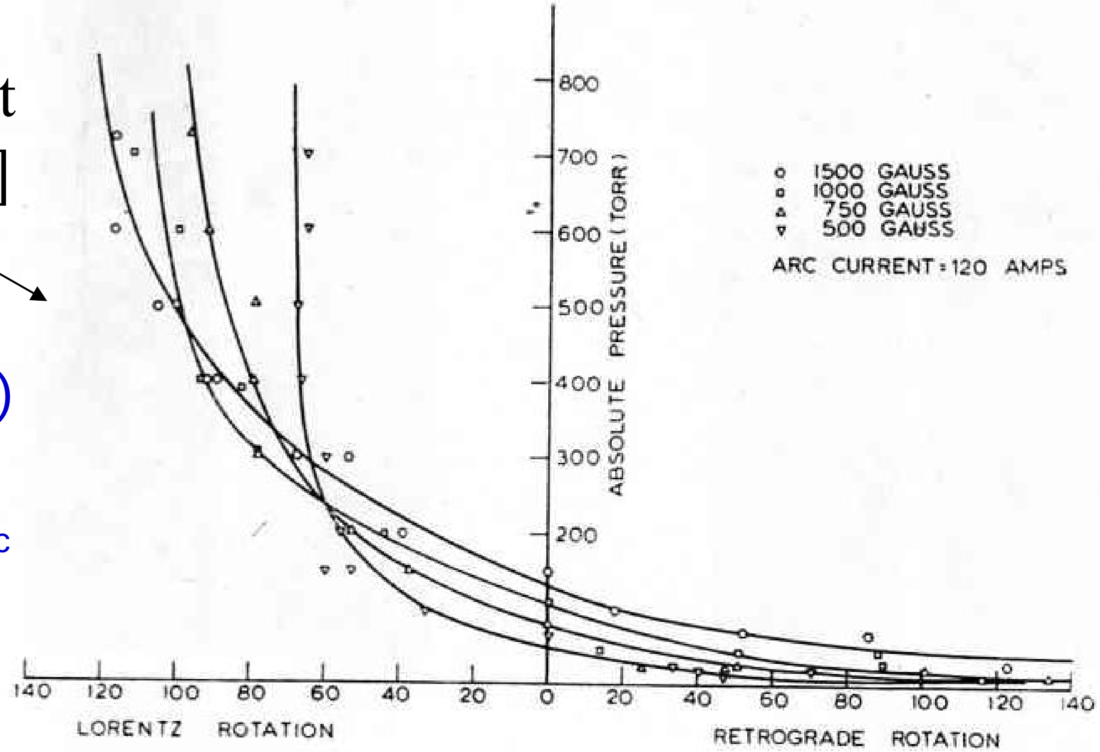


► mysterious cathode spot of arc [Raizer, 1991] (uniquely complex object)

-why do spots split?
-why do they run?
-why such tremendous current density (~10^8 A/cm^2)
-<u>why move opposite direction (retrograde motion) under B-field</u>

100 year old puzzle of the cathode spot

Experimental measurement
[Murphree & Carter, 1969]

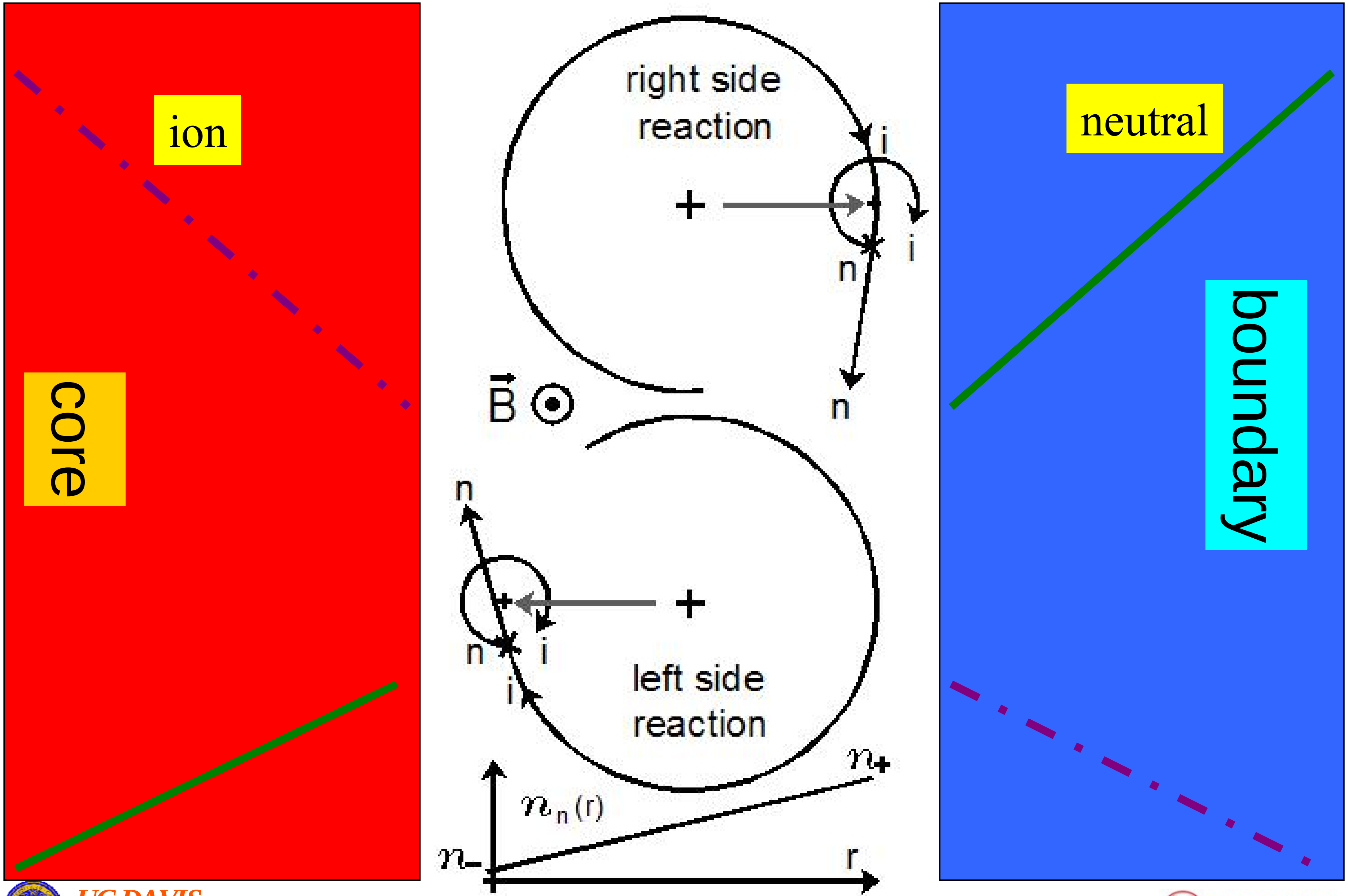


rotation speed (cycles/sec)

- occurring at low pressure (P_c)
- higher B-field → higher P_c
- lower arc current → higher P_c
- smaller gap → higher P_c
- it depends more on gas than cathode material
- no retrograde motion on hot cathode
- no retrograde motion at B-filed > 1 T
- etc. => Most of the list can be explained by "gyrocenter shift"

► recent approaches on retrograde motion
  - Hall electric field => only linear dependency of gas pressure (91')
  - super position of self and external magnetic fields => only when B>1T (02')

Gyrocenter shift by charge exchange



Gyrocenter shift and drift velocity

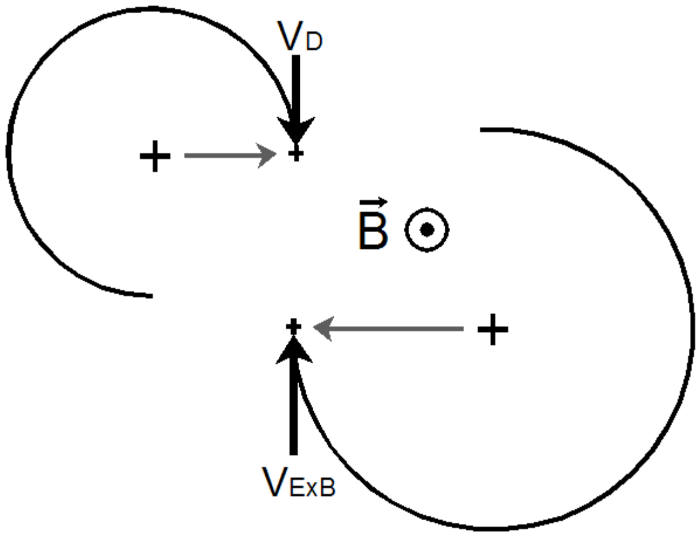
From a fluid equation of motion ; $J \times B = n_i R_{av} S_i^m$

momentum sink by charge exchange

$$J_x^{GCS} = \frac{m_i n_i n_n}{B} < \sigma_{cx} v_i > \left(\frac{E}{B} - \frac{\nabla p}{qBn_i} + \frac{T_i \nabla n_n}{qBn_n}\right)$$

[K.C. Lee, Physics of Plasmas, **13,** 062505 (2006)]

drift velocity

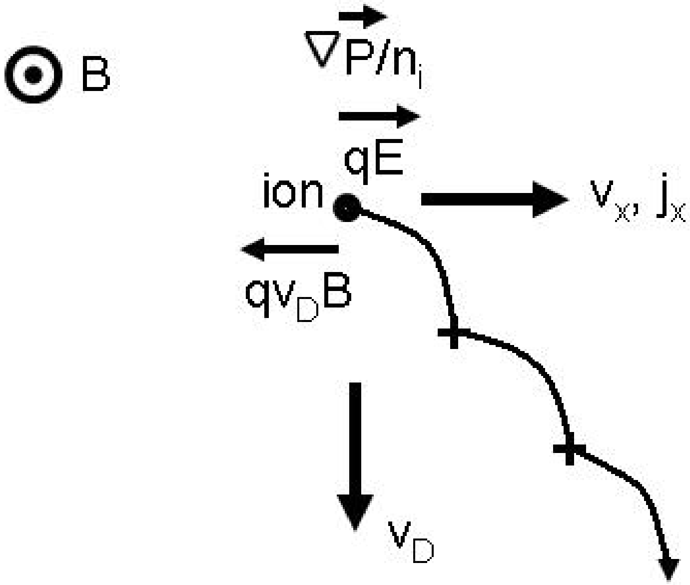


for low temperature / high density

=> high collision rate with neutrals
/ short mean free path

$\Rightarrow$ drift velocity needs modification (generalization) for including high collisional cases

Generalization (I) of drift velocity



$$F_x = qE - qv_D B - \nabla p / n_i$$

(v_D : drift velocity)

$$v_x = \mu(E - v_D B - \nabla p / qn_i)$$

(μ : mobility)

$$F_y = qv_x B$$

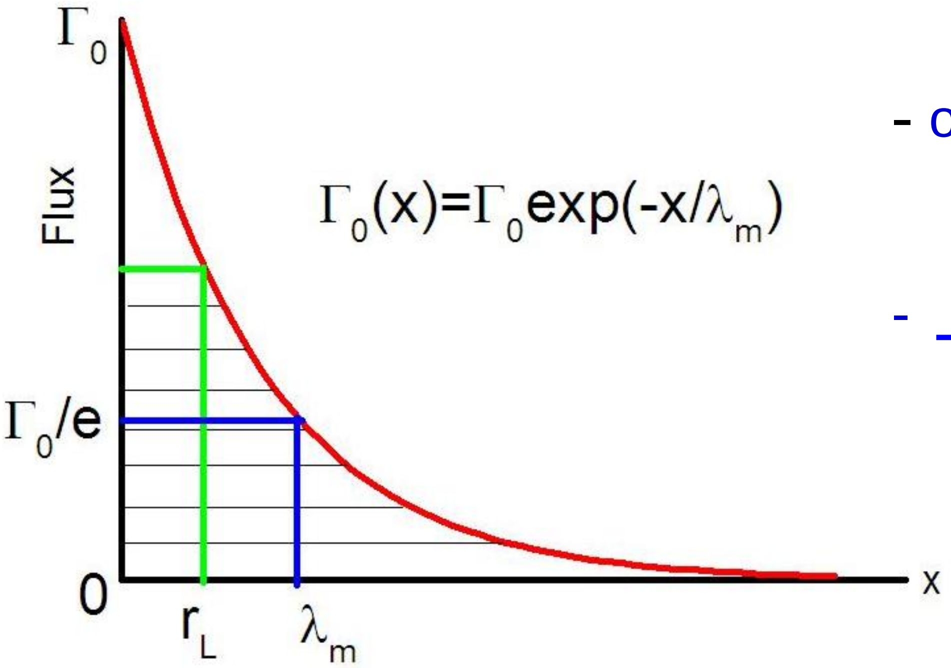
$$v_D = \mu^2 B(E - v_D B - \nabla p / qn_i)$$

$$v_D = \frac{1}{1 + r_L^2 / \lambda_{cx}^2}\left(\frac{E}{B} - \frac{\nabla p}{qBn_i}\right)$$

- only ion-neutral collisions count
- ion-ion collisions are averaged out
- ions are under same influence of E-field & B-field (Lorentz force)
- but collisions with neutrals make new start of accelerations
- new formula is also valid for low collision limit

Generalization (II) of gyrocenter shift

$$J_x^{GCS} = \frac{m_i n_i n_n}{B} < \sigma_{cx} v_i > \left(\frac{E}{B} - \frac{\nabla p}{qBn_i} + \underbrace{\frac{T_i \nabla n_n}{qBn_n}}\right)$$



- only ions have longer λ_{cx} than r_L contribute to gyrocenter shift

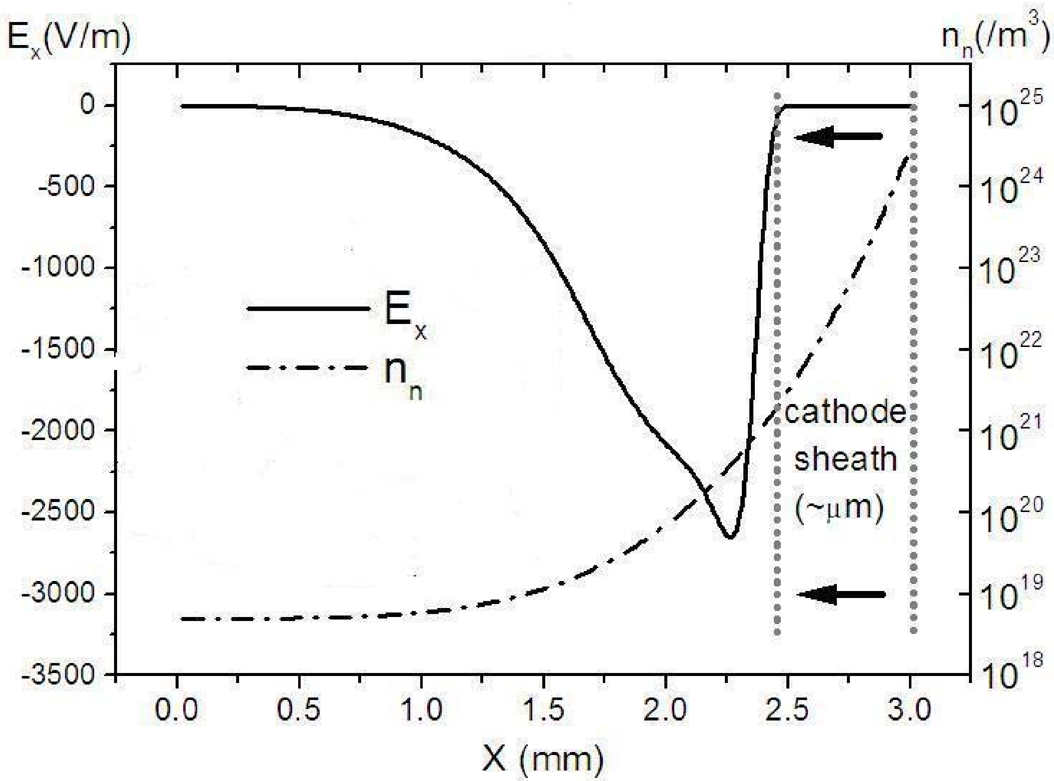
- $\dfrac{\text{number of ions that contribute}}{\text{total number of ions}}$

$$= \quad e^{-r_L / \lambda_{cx}}$$

general formula for the gyrocenter shift

$$J_x^{GCS} = \frac{m_i n_i n_n}{B} < \sigma_{cx} v_i > \left[\frac{1}{1 + r_L^2 / \lambda_{cx}^2}\left(\frac{E}{B} - \frac{\nabla p}{qBn_i}\right) + \frac{T_i \nabla n_n}{qBn_n} e^{-r_L / \lambda_{cx}}\right]$$

Calculation of electric field in arc discharge



- no background E-field
- constant n_i (5×10^{22}/m^3)
- constant T_i (0.5 eV)
- B = 0.1 T
- gas pressure : 100 Torr (Argon)
- gap :16.5 mm
- n_n is an exponential function with its gradient approach zero at middle of the discharge

⇒ reversed electric field is formed

⇒ E_x vanishes when $n_n > \sim 10^{21}$/m^3

► cathode sheath : massive ionizations take place (~μm) where rapid decrease of neutral and increase of ion

► $n_n(0)$ is proportional to the gas pressure

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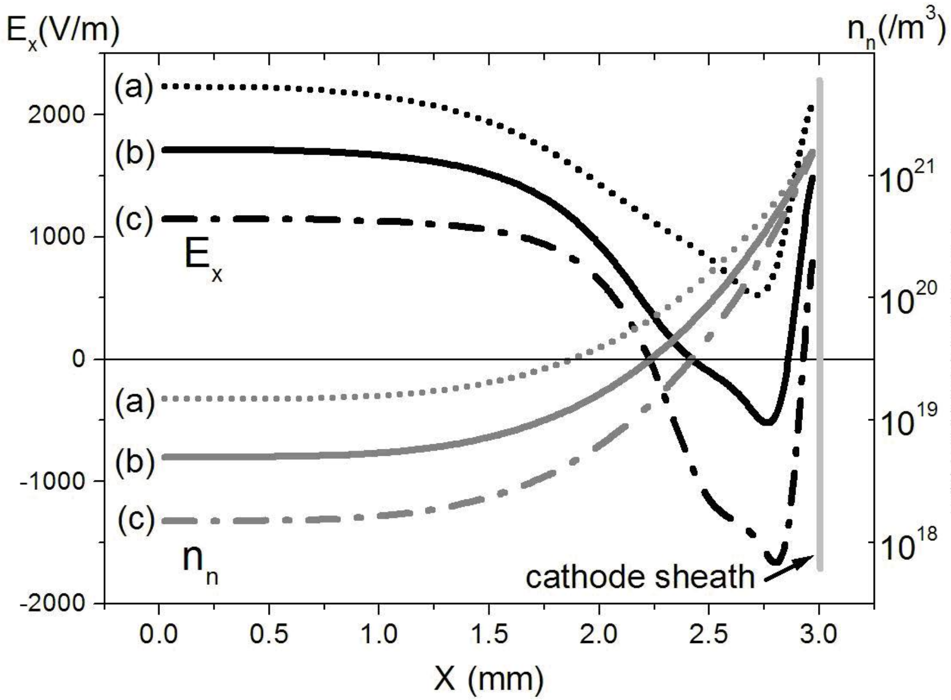
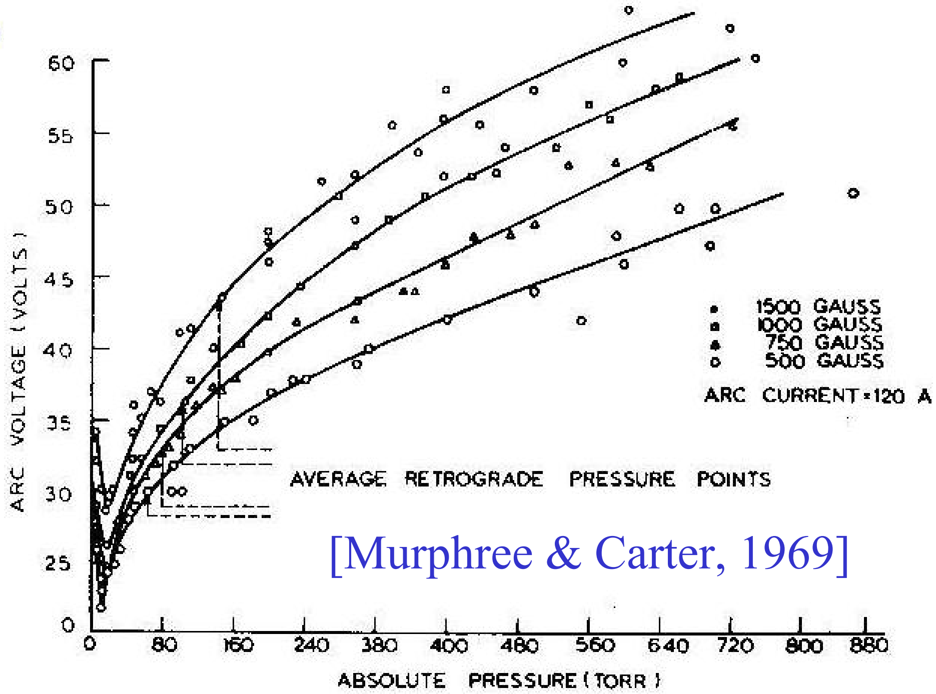
Calculation with arc column electric field



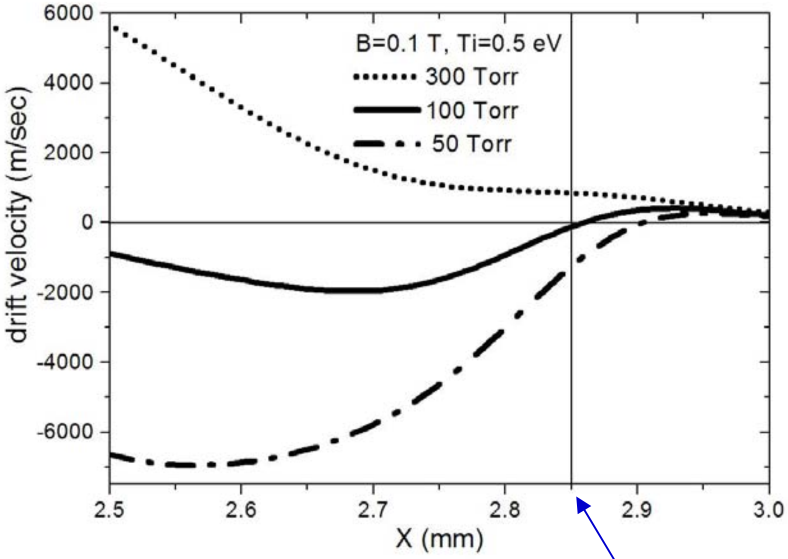


► higher neutral density → higher column electric field (constant current)

⇒ high gas pressure → positive electric field in front of cathode
low gas pressure → negative electric field in front of cathode

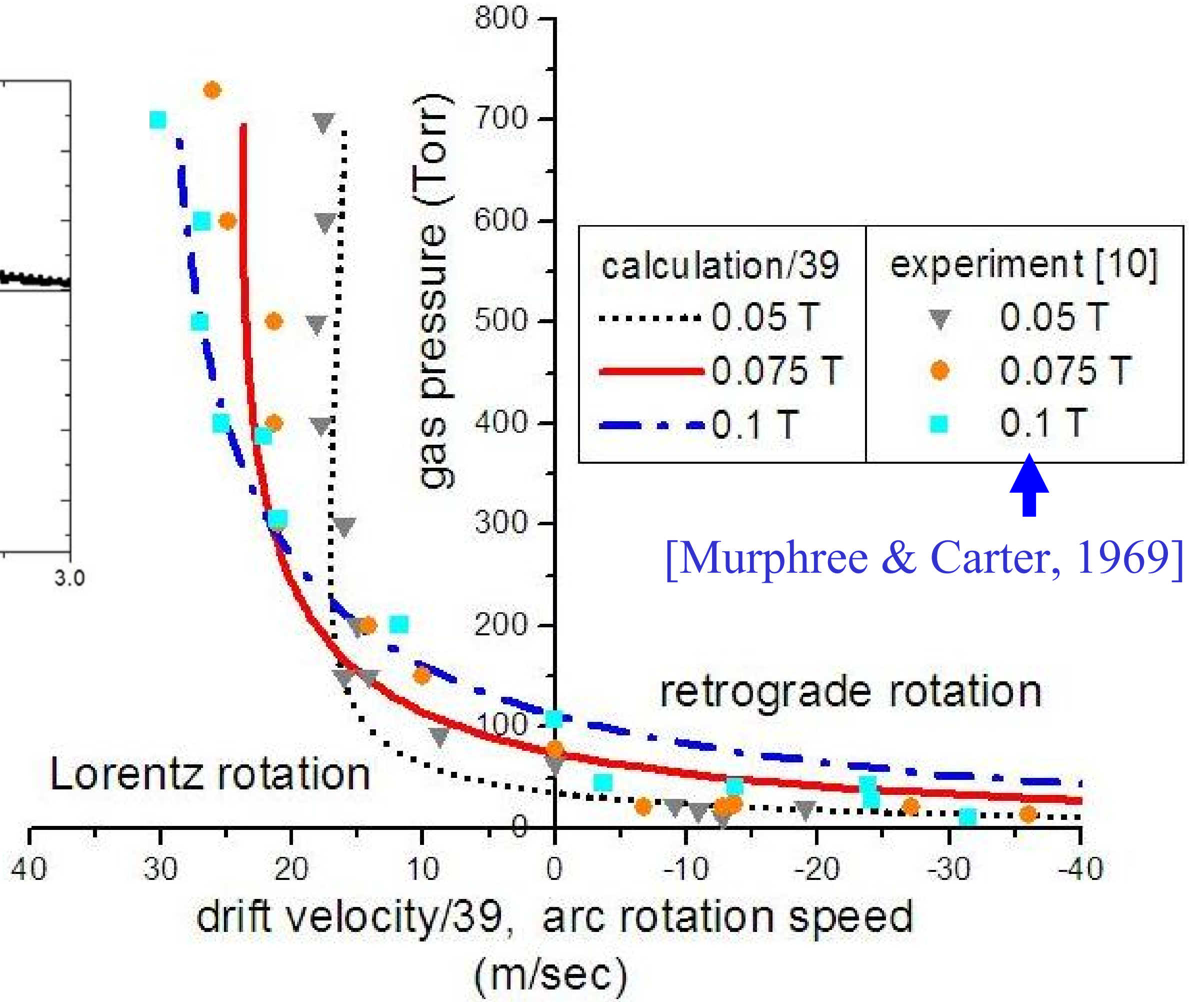
► negative electric field (seems unnatural) : gyrocenter shift is a process of putting ions in a direction which is indepentant of electric force

Comparison of calculation with experiment



1/20 of neutral decay length

$$v_D = \frac{1}{1 + r_L^2 / \lambda_{cx}^2}\left(\frac{E}{B}\right)$$



[Murphree & Carter, 1969]

[K.C. Lee, PRL, Vol 99, 065003 (2007)]

Conclusion

- $$J_x^{GCS} = \frac{m_i n_i n_n}{B} < \sigma_{cx} v_i > [\frac{1}{1 + r_L^2 / \lambda_{cx}^2} (\frac{E}{B} - \frac{\nabla p}{qBn_i}) + \frac{T_i \nabla n_n}{qBn_n} e^{-r_L / \lambda_{cx}}]$$
- retrograde motion of cathode spot is directly related to the ion drift velocity calculated from the generalized equation of gyrocenter shift

Future work of gyrocenter shift

- **coming APS meeting presentations**
- **saturated electric field vs. ambipolar electric field**
  => plasma transport by gyrocenter shift ?

Application to NSTX research

- generalized formula should be used for passing particles (x-point)
- measurement of neutral density profile using existing diagnostics :
  D_β-emission (mid plane) and diverter camera (x-point)
- measurement of neutral density profile using new diagnostics (?) :
  such as Laser Induced Ionization (LII)