An Introduction to the STAR TPC

for the STAR Juniors
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BNL

What does it measure?

- Charge?
- Momentum?
- Rigidity (momentum/charge)?
- Energy?
- Trajectory?
- Species?
- Ionization?
- Energy loss/deposited?
- dN/dx?
- dE/dx?

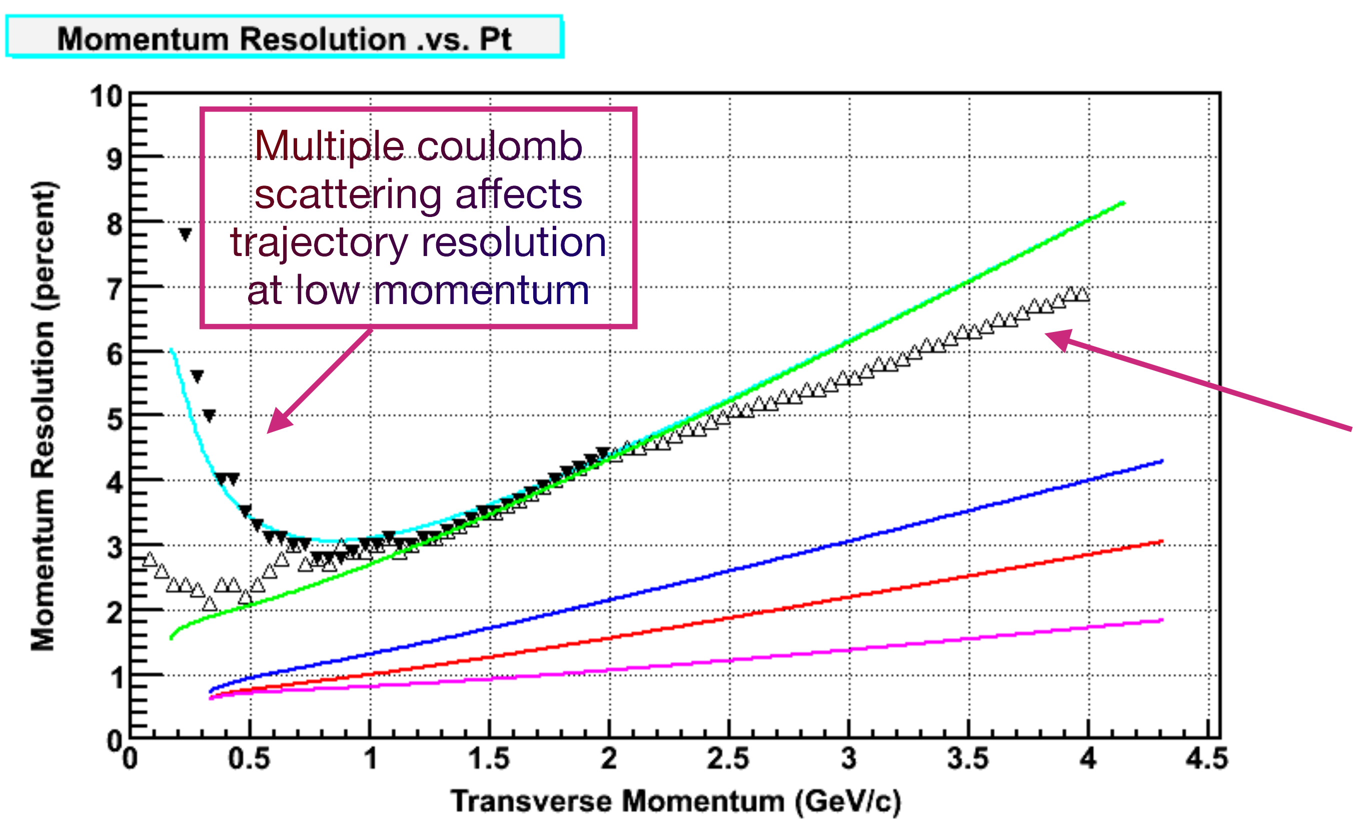
What does it measure?

- Charge? No
- Momentum? No
- Rigidity (momentum/charge)? No
- Energy? No
- Trajectory? Yes : spatial positions
- Species? No
- Ionization? Yes : dN = number of electrons liberated
- Energy loss/deposited?: Yes : dE = function(dN)
- dN/dx? Yes : dx = function(trajectory)
- dE/dx? Yes : see above

Need
measured information
+
B-field
+
models

What does that mean?

- p_T is calculated from curvature of trajectory and B-field, and an assumption of magnitude of charge (e.g. $|Z| = 1$)
  - Error on p_T is dominated by error on trajectory, encapsulated by a fit of the (radius of) curvature using the measured spatial positions
    - Error on positions => error on curvature => error on pT



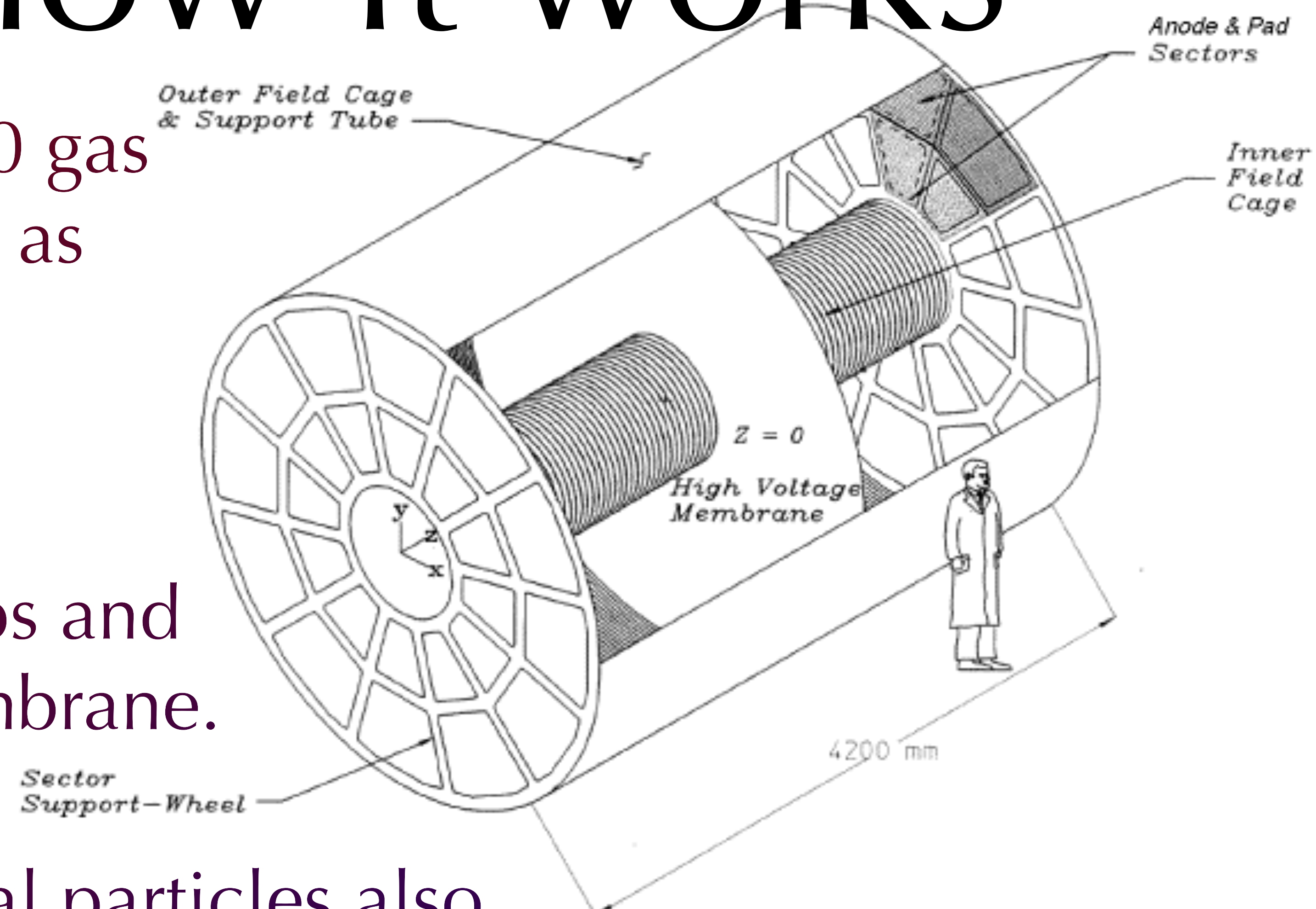
C = curvature

$$p_T \propto 1/C$$

$$\delta(p_T) \propto \delta(1/C) \propto -\delta(C)/C^2 \propto -p_T^2\,\delta(C)$$

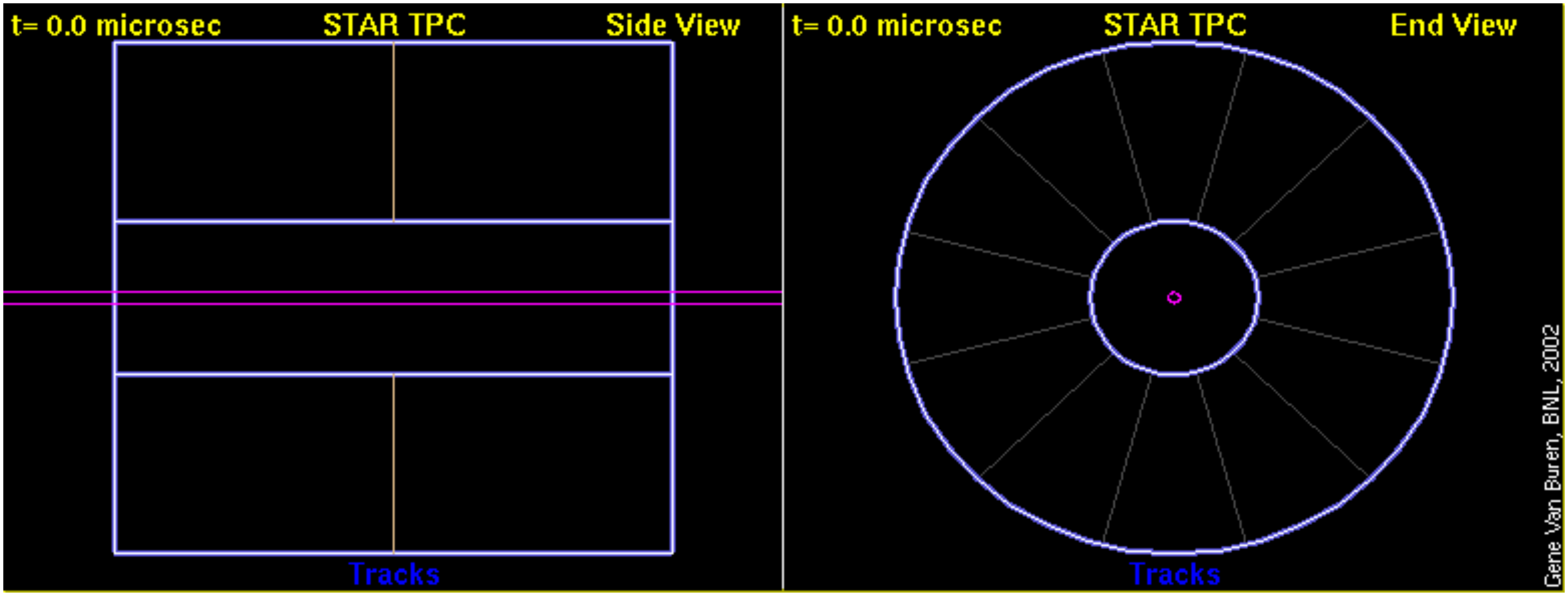
For more details (pre-iTPC), see: https://drupal.star.bnl.gov/STAR/subsys/tpc/perf/tpc-pt-and-dca-resolution

Basics of how it works

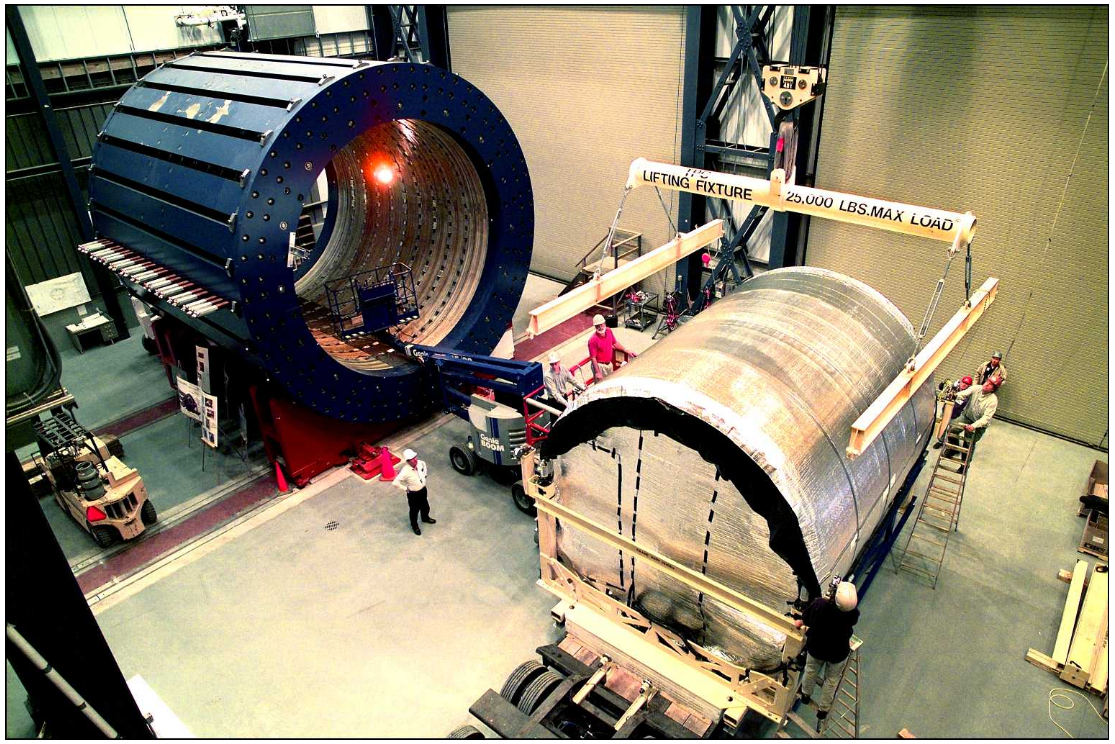


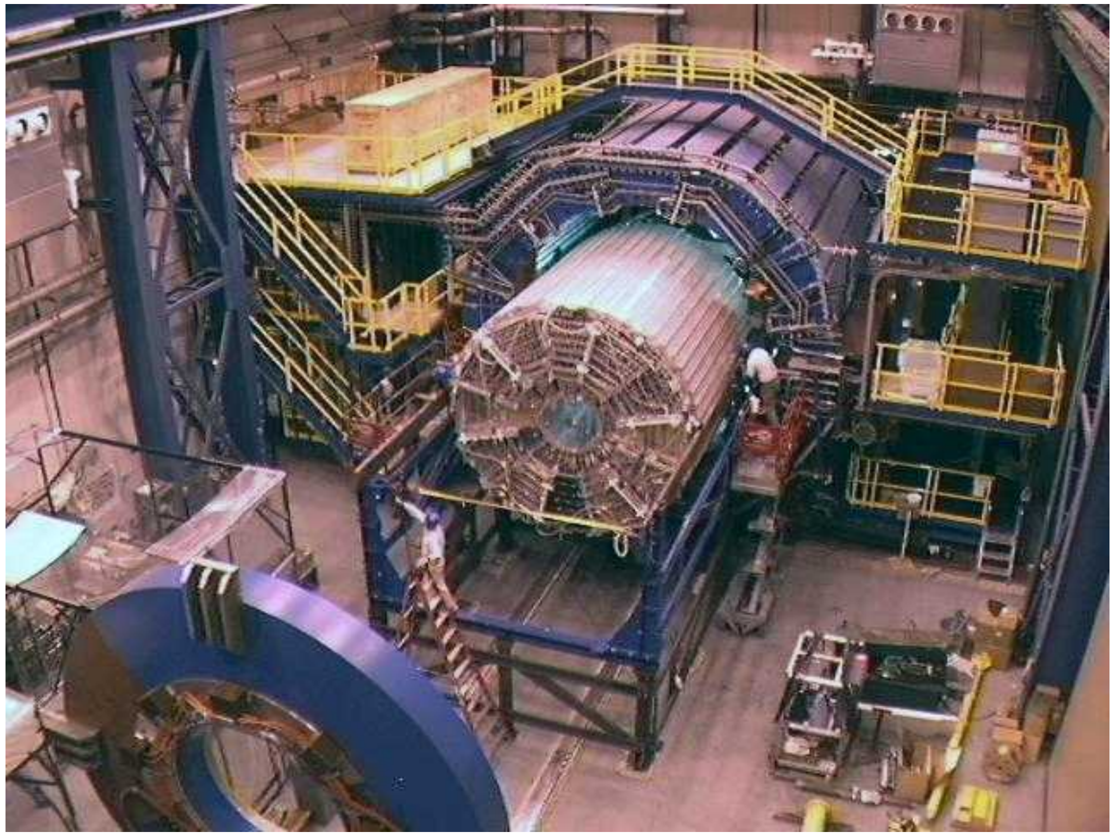
- Charged particles ionize P10 gas (90% Argon, 10% Methane) as they traverse the chamber.
- A modest electric field of ~135 V/cm induces drift: electrons toward the endcaps and ions toward the central membrane.
- A magnetic field that bends the trajectories of the original particles also helps keep the drifting electrons from dispersing as they travel.
- The drifting electrons enter a high electric field region at the endcap (segmented in "sectors") where they avalanche to create significant charge on high voltage wires.
- Copper "pads" just beyond these wires develop mirror charges, which are then read out as the amplitudes of pixel data.

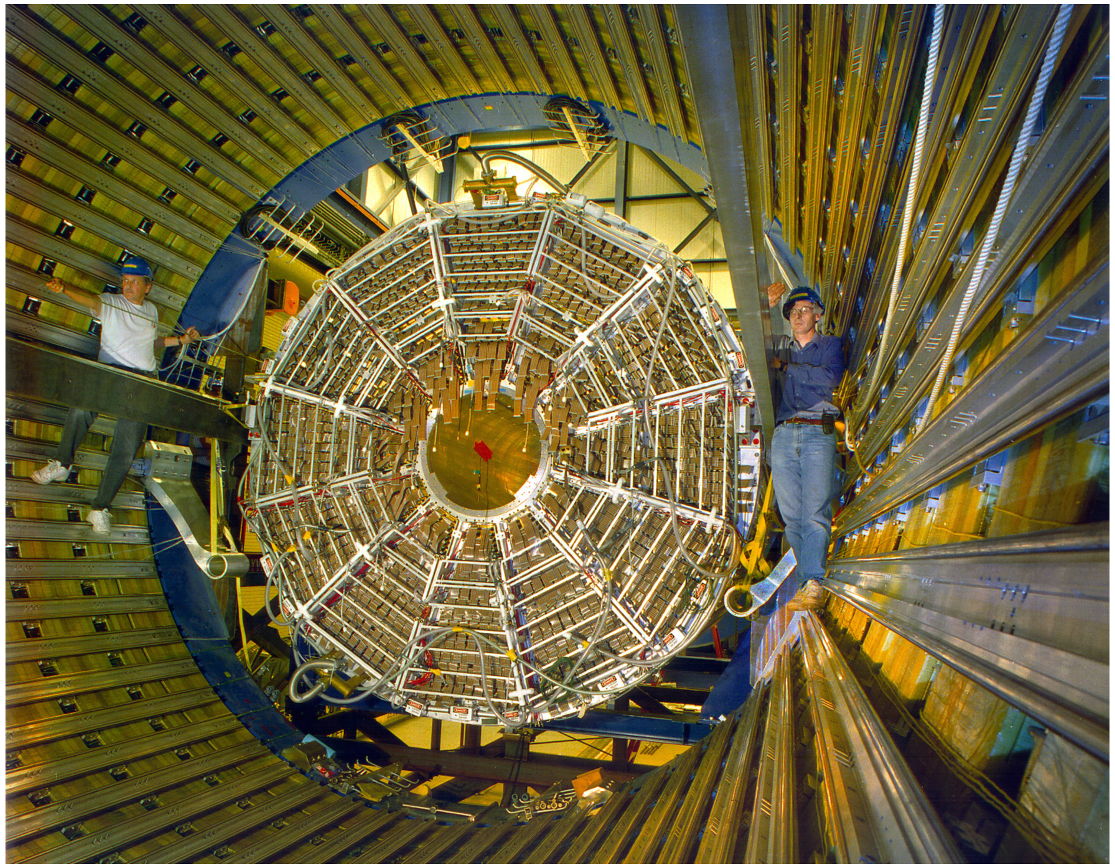
A visualization



Installations

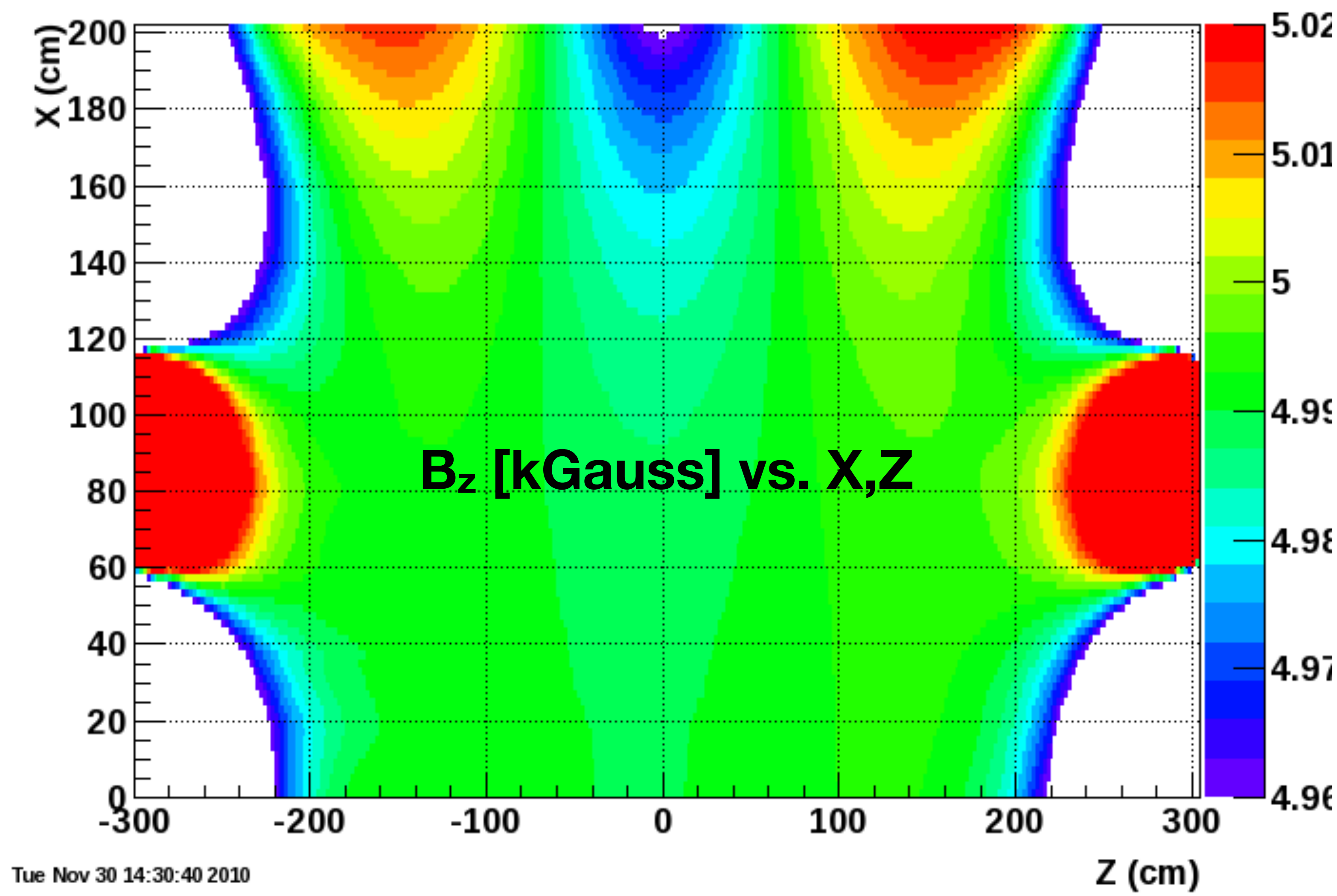






Details: B-field

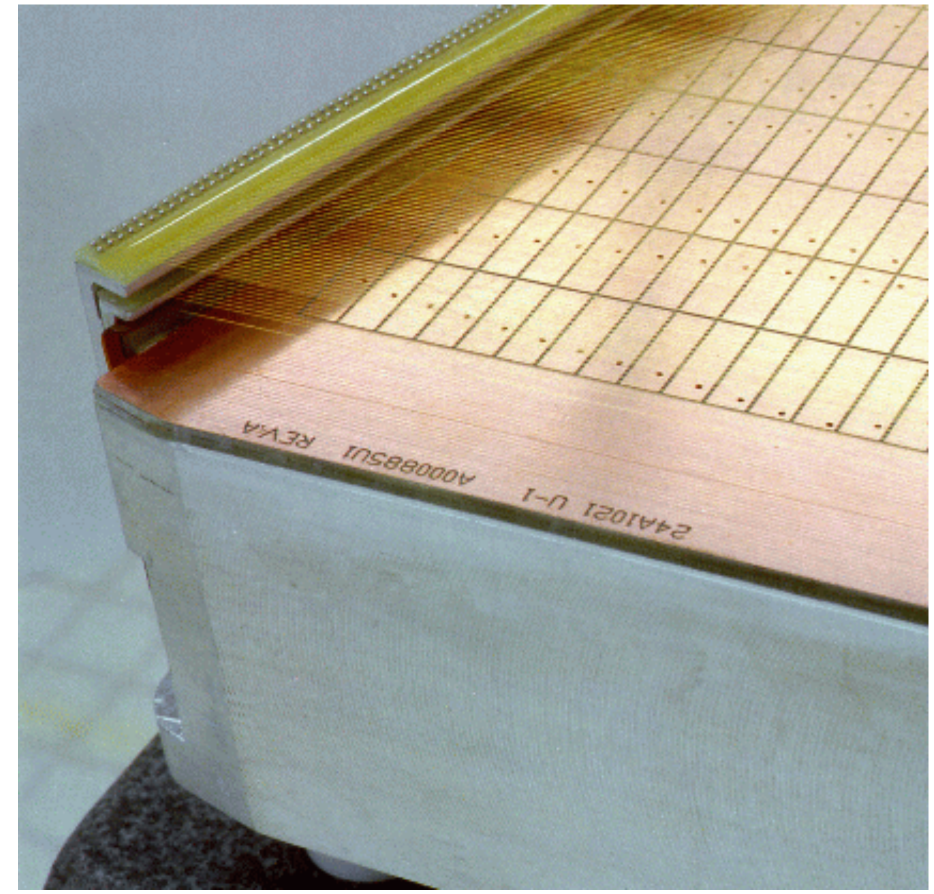
- Not actually a part of the TPC, but clearly important to its operation and utility
- Non-uniformities are important!
  - Everything inside the magnet is designed to be non-magnetic...
  - ...but not everything is perfect, and some things outside the magnet influence the field (e.g. EEMC photomultiplier boxes)

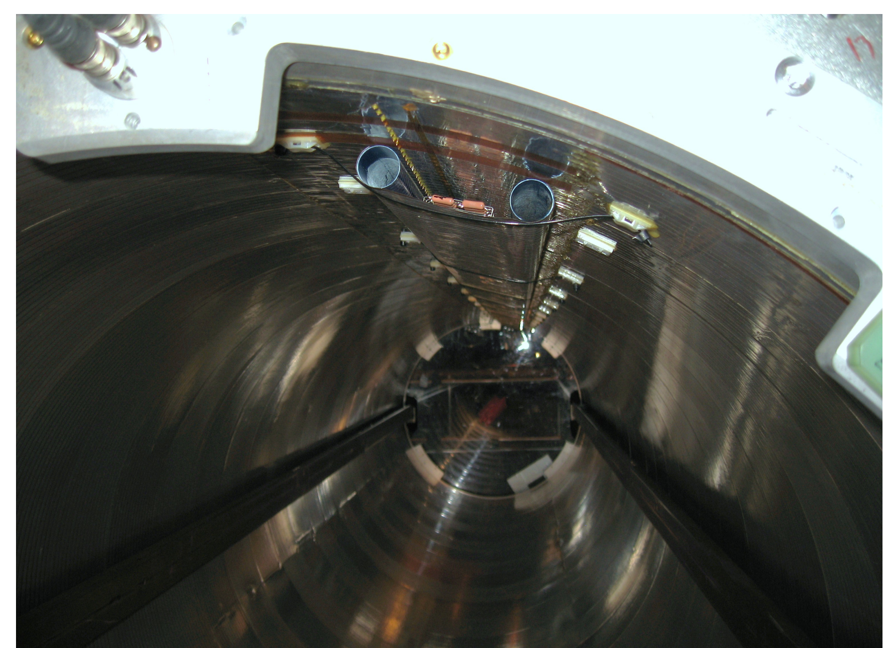


Details: E-field

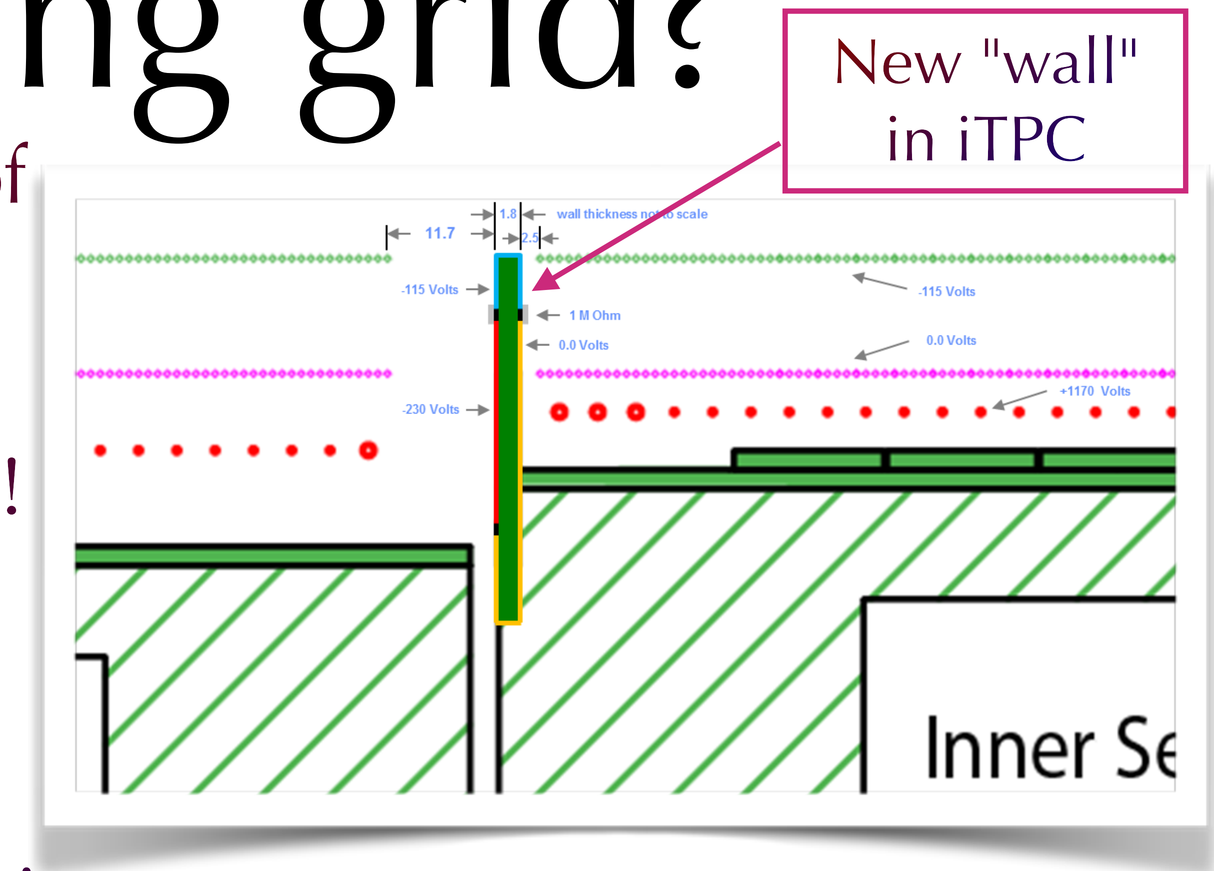
- Voltage on the central membrane is maintained by a single power supply at -27900 V
- Uniformity inside the chamber is carried by "field cages", which are sets of rings that encircle the TPC's gas chamber on both the inside and outside
  - Four of these: (inner + outer) x (east + west)
  - Field cage potentials are maintained by four separate chains of resistors: 2 MOhms between each of 182 rings before reaching ground (there are small currents of ~76 nA flowing through each resistor chain, but these are not flowing through the rings)
- Voltage at the endcaps is expressed by a grid of wires on each sector: the gating grid, positioned where the potential should be -115 V
- Another wire grid called the cathode plane, held at ground potential, begins the high voltage region surrounding the anode wire grid, bounded on the other side by the pad plane at ground potential

E-Field-defining hardware



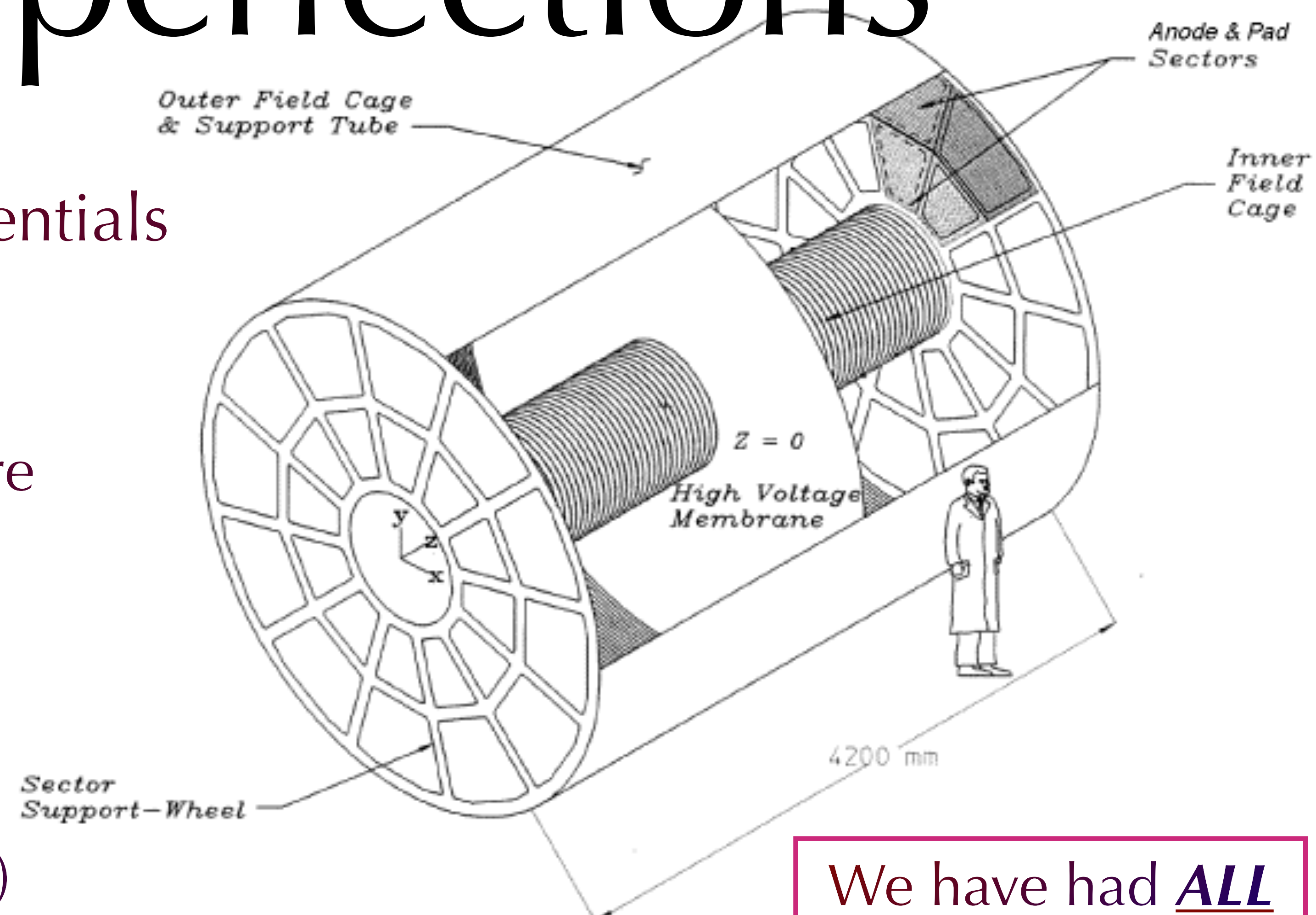


What is a gating grid?



- The high-field anode wire region of the TPC liberates ~3000 electrons per incoming drift electron...
- ...and creates ~3000 ions as well!!!
- The gating grid is designed to act like the shutter of a camera, opening to let the drift electrons in, and closing to keep the avalanche ions in
  - "Close" by creating transverse fields within the plane to attract charges to the wires
  - Also reduces how many of the drift electrons reach the anodes, reducing current, wire aging, and ohmic voltage sag
- sPHENIX and the ALICE upgrade will use GEMs instead of a wire chamber at the endcaps: no gating grid!
  - Also, not a complete block of the back-flowing avalanche ions
  - But they will be able to stream data continuously (no shutter)

E-field Imperfections



- Surfaces:
  - Field cages at the wrong potentials
    - Misaligned with respect to the rest of the TPC
    - Improper resistance anywhere in the resistor chains
    - Electrical charges deposited on the field cage rings
  - Gating grid at the wrong position (mis-aligned sectors)
  - Central membrane at the wrong position (tilts, shifts)
- Volume:
  - TPC (or its halves) not perfectly lined up with axis of magnet
  - Electrical charges in the gas
    - Primary ionization build-up: ions drift quite slowly (SpaceCharge)
    - Ions from the avalanche region entering the main volume (GridLeak)
      - Depends in turn on anode voltages

We have had ***ALL*** of these problems!

Distortions

- A good place to start is the STAR TPC NIM paper: https://www.star.bnl.gov/public/tpc/NimPapers/tpc/tpc_nim.pdf

With the fields known, we correct the hit positions along the pad rows using the distortion equations for nearly parallel electric and magnetic fields[10].

$$\delta_x = \int \frac{-\omega\tau B_y + \omega^2\tau^2 B_x}{(1+\omega^2\tau^2)B_z} dz + \int \frac{E_x + \omega\tau E_y}{(1+\omega^2\tau^2)E_z} dz$$

$$\delta_y = \int \frac{\omega\tau B_x + \omega^2\tau^2 B_y}{(1+\omega^2\tau^2)B_z} dz + \int \frac{E_y - \omega\tau E_x}{(1+\omega^2\tau^2)E_z} dz$$

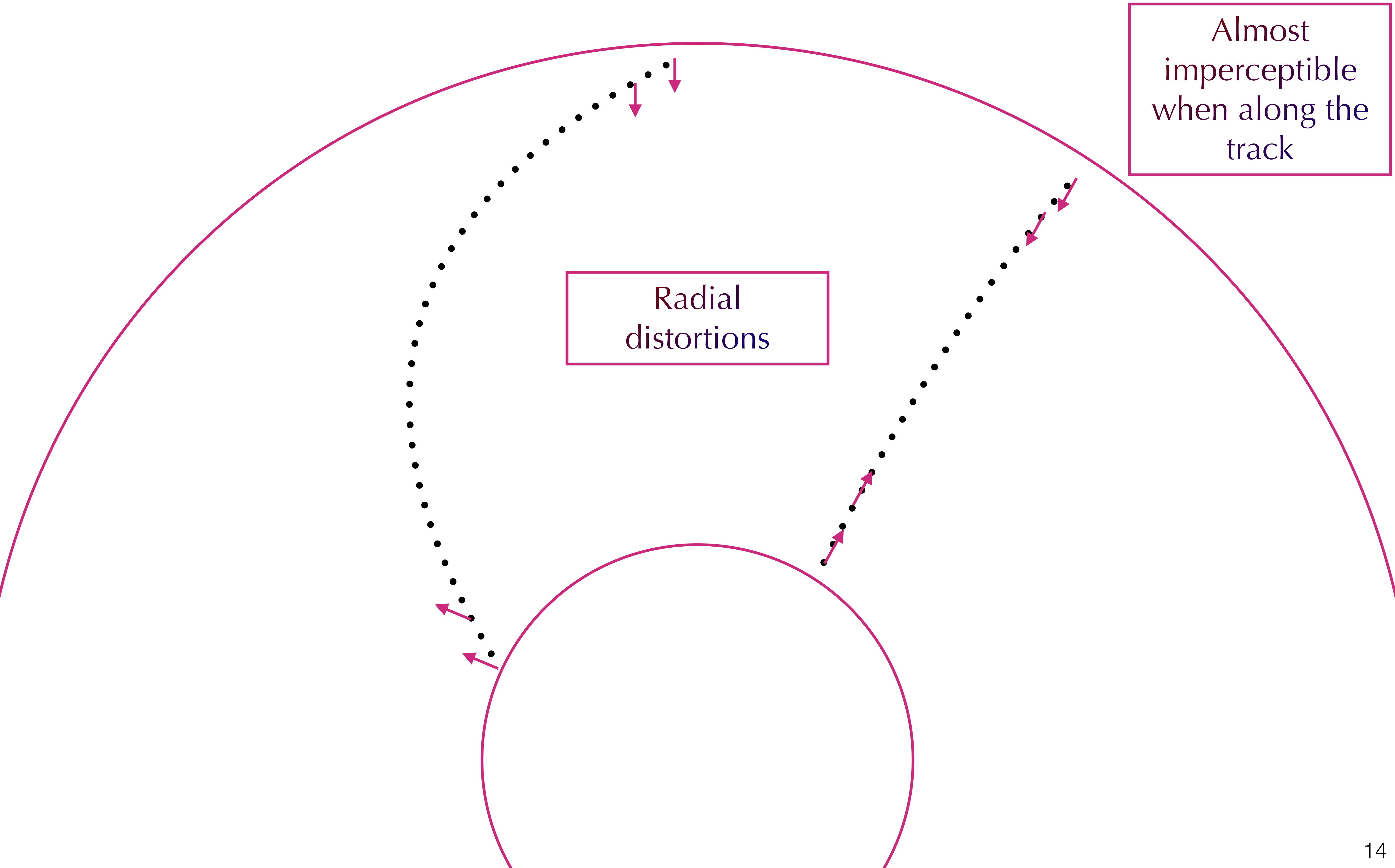
Transverse field components lead to both radial and azimuthal distortions! Radial distortions have much less impact except at very low p_T.

where δ_x is the distortion in the x direction, $\vec{E}$ and $\vec{B}$ are the electric and magnetic fields, ω is the signed cyclotron frequency, and τ is the characteristic time between collisions as the electron diffuses through the gas.

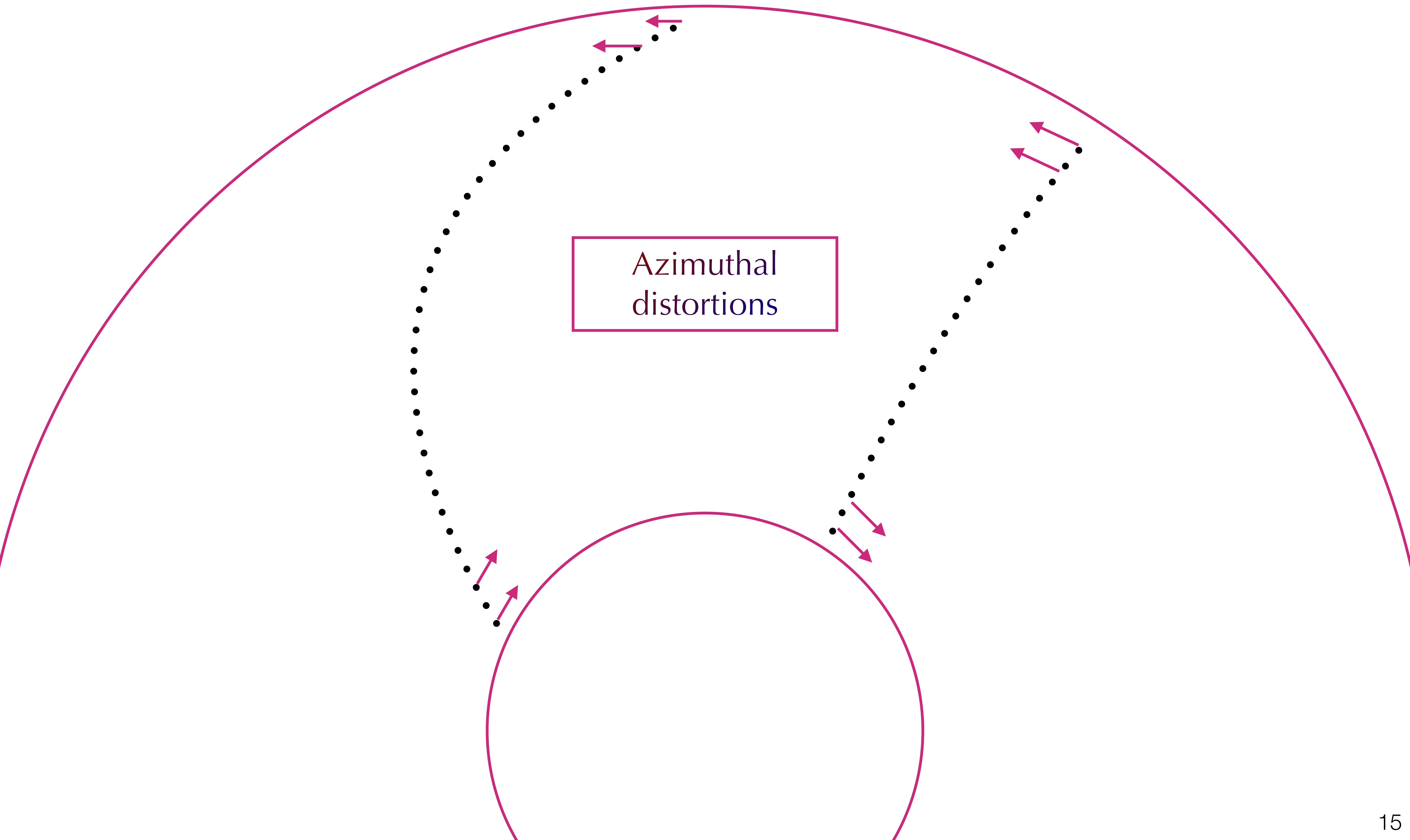
Here, $\omega\tau$ is signed, with the sign depending on the directions of B_z, E_z and the drift velocity u_z where k is a constant.

$$\omega\tau = k \frac{u_z(cm/\mu s)}{E_z(V/cm)} B_z(T)$$

Low and high p_T

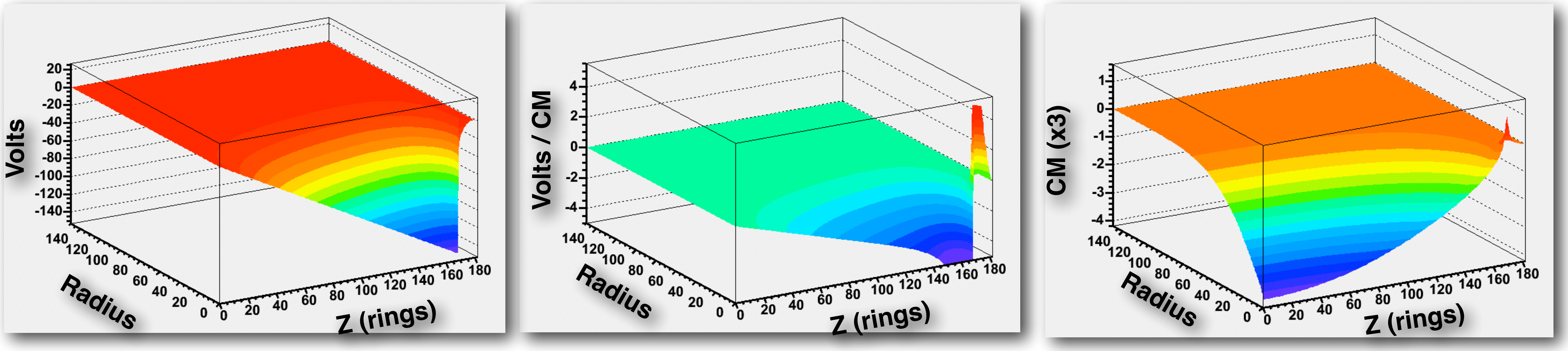


Low and high p_T

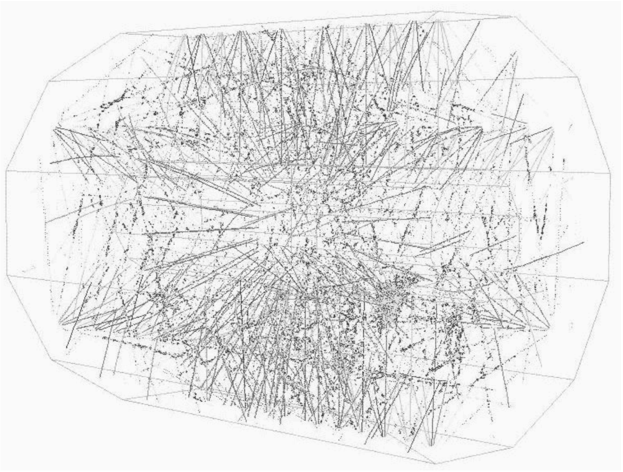


Distortion Maps

- Charges & Potentials -> E-Field distortions -> Displacements
- Example below from an electrical short between two field cage rings
- The many distortions are treated perturbatively: each displacement map is calculated independently and the displacements are summed



Lasers and GMT



- NIM paper for lasers: https://www.star.bnl.gov/public/tpc/NimPapers/laser/laser_nim.pdf
  - Used exhaustively for drift velocities
  - Several attempts to use for distortion measurements, but most attempts failed because of systematics due to tracks appearing continually at the same positions on pads (no gain from randomized statistics)
- GEM Chambers to Monitor the TPC Tracking (GMT)
  - Project initiated in 2007: https://www.star.bnl.gov/protected/future/R-and-D-2008/Proposal-to-Install-GEM-Chambers-GMT.pdf
  - Installed in 2012; Aligned in 2017: https://drupal.star.bnl.gov/STAR/system/files/GmtAlignmentWithCosmics_20170222.pdf
  - Remains almost unused to date because software has been repeatedly orphaned and never made it to peer review!
  - Could do drift velocities better than lasers
  - Would be very valuable to study distortions with a precision space point outside the TPC (STAR has never had this)

I didn't even get into...

- Alignment
  - Getting the hit positions right, and also impacts E-field
- Drift velocity
  - Impacted by gas contents (e.g. trace gasses like oxygen and water vapor) and environment (e.g. pressure)
  - Subsequently impacts any distortions
- dE/dx measurements
  - Impacted by gas contents, anode voltages, distortions altering the pathlength over pads, wire aging, current loads on anode wires (luminosity), ...

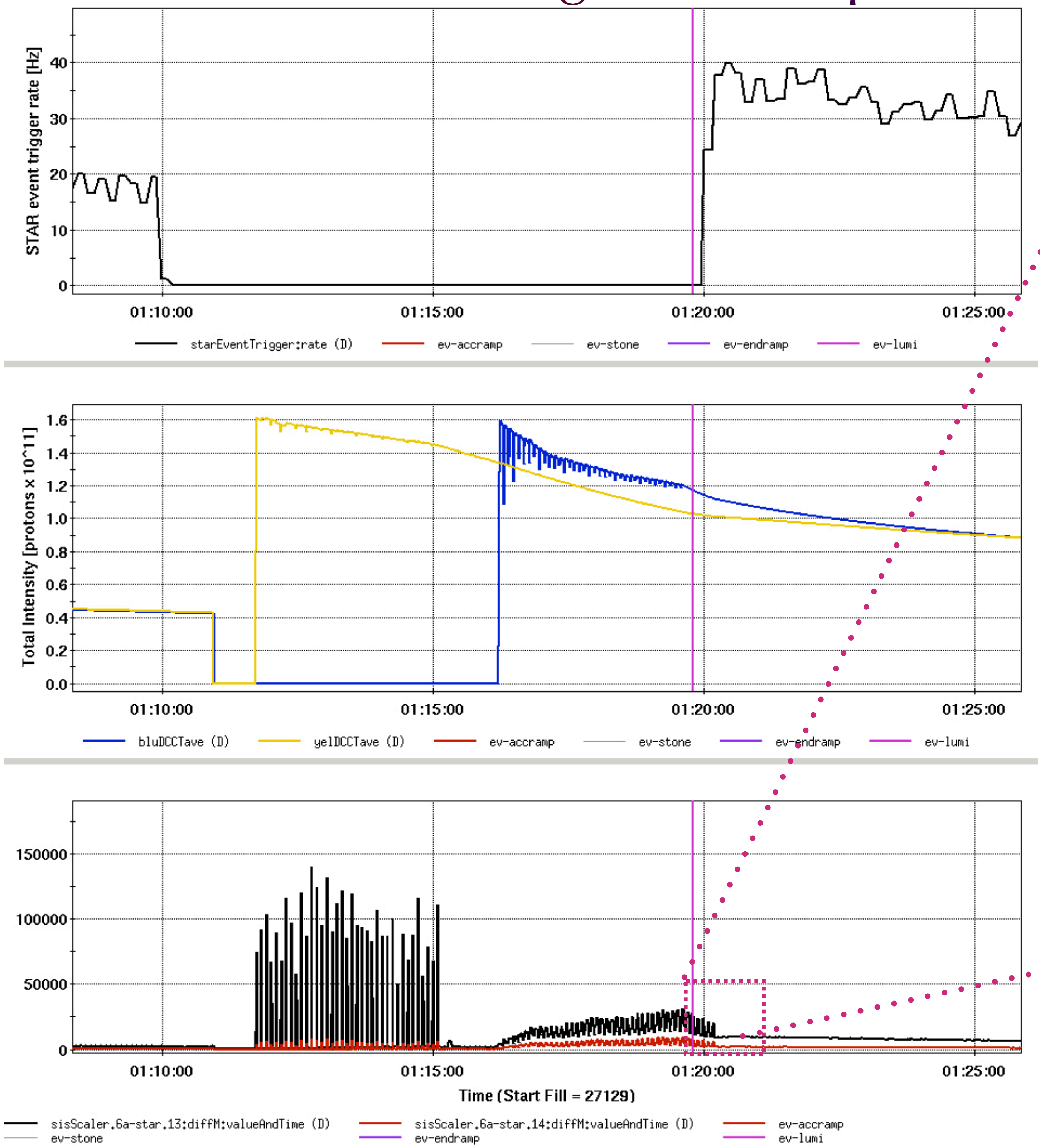
Always something...

- Run 2: SpaceCharge
- Run 4: fluctuating SpaceCharge
- Run 5: GridLeak
- Run 6: field cage shorts, sometimes varying
- Run 7: alignment
- Run 8: asymmetric SpaceCharge; floating gating grid wires
- Run 9: slewing; reduced voltages on some anodes; massive pile-up
- Runs 10-12: alignment again (h^-/h^+)
- Run 13: field cage current losses to ionized air
- Runs 14 & 16: need to account for SpaceCharge uncertainty for HFT
- Run 17: fill-by-fill SpaceCharge
- Run 18: abort gap cleaning; booster main magnet; humidity-induced field-cage conductivity; disconnected gating grid on a sector
- Run 19: GridLeak-mitigating "wall"
- Runs 19 & 20: iTPC alignment, booster main magnet
- Runs 19 & 20 FXT: event-by-event T0s

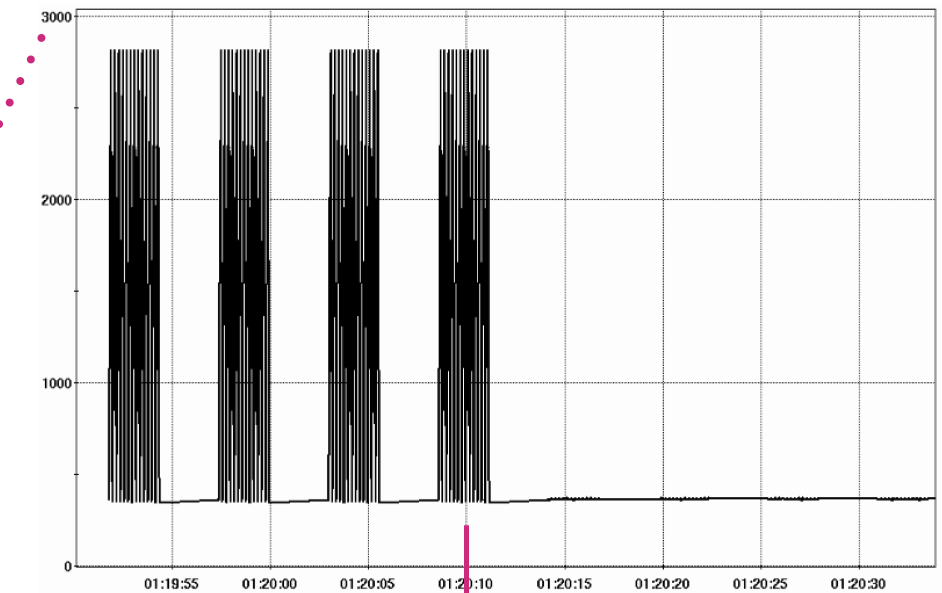
I'm sure I've missed several more things!

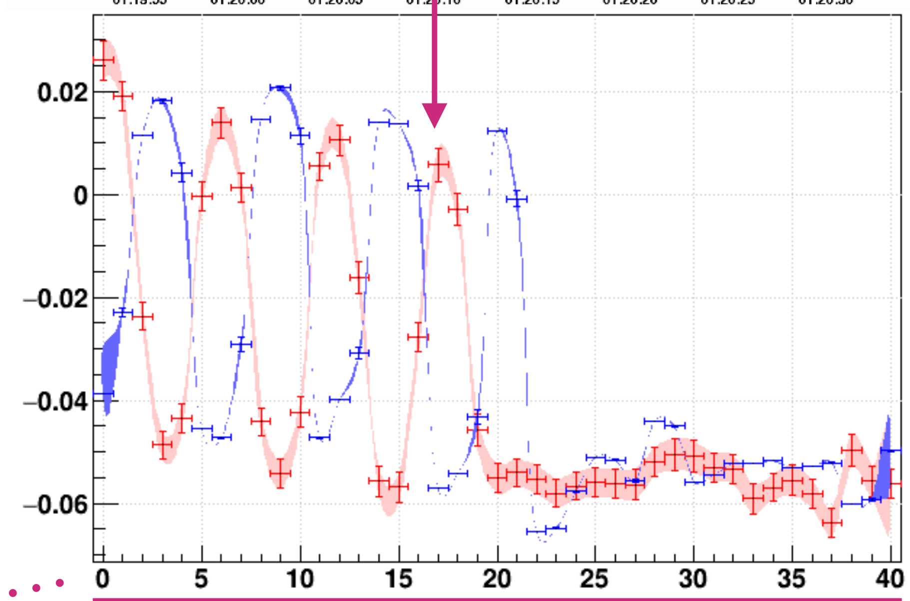
Recent topics in the news

- Booster Main Magnet: example with run 21076004



BMM power supply current





red: signed DCAs
blue: BBC coincidence rate

Recent topics in the news

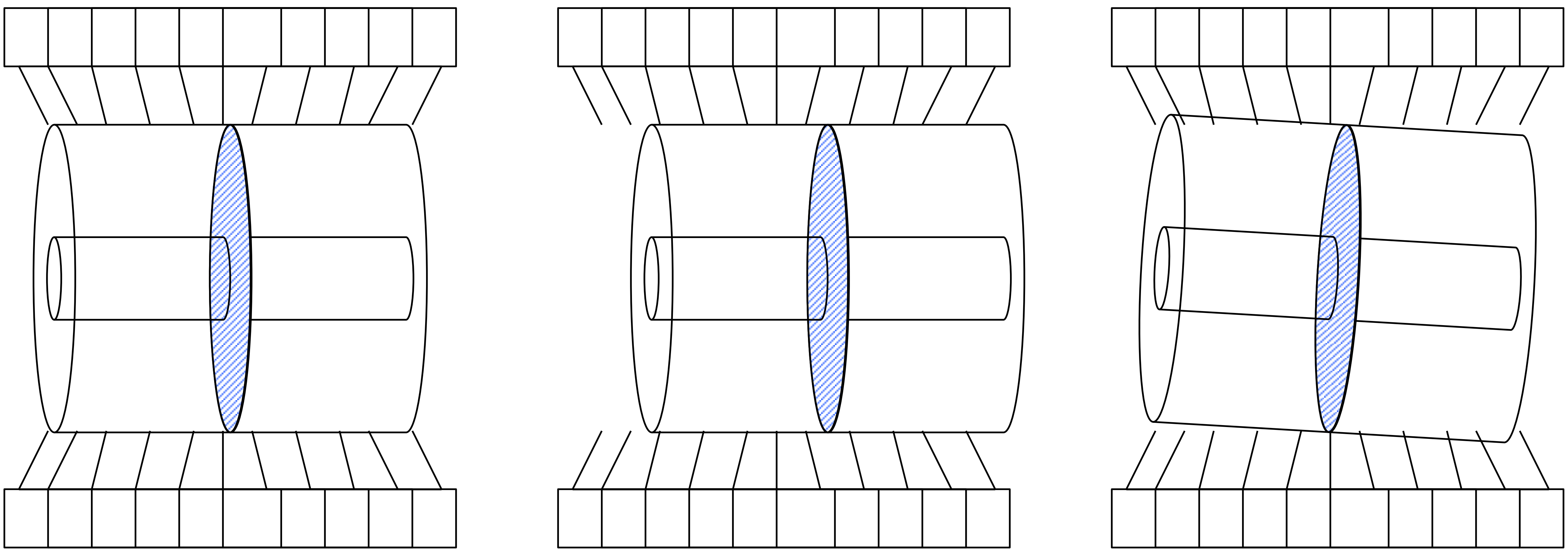
- FXT T0s
  - Elongated beam bunches allow for significant variation between the start time of the event from the pulse of the RHIC clock
    - Where within the bunch passing the target does the collision happen? => When does the collision happen? => Conversion of time to drift distance needs to subtract off the collision time delay
    - Shows up as a displacement between the two TPC halves (visible by reconstructing the primary vertex with each half separately) that varies with collision time (for which the leading EPD time has been useful)

Summary

- After 20 years, and despite all the difficulties, diligent efforts have enabled the STAR TPC to far exceed its original design requirements, even without the iTPC upgrade...which will undoubtedly shine when we produce BES-II data (coming soon!)
- There's always work to do, but it's usually more than turning a crank on a calibration (Next year there will be no issues, right? Each year it's always next year...)
  - It has not been realistic to achieve high quality calibrations on a rapid time scale...ever! (good luck to ALICE and sPHENIX)
  - Notable room for improvement remains in SpaceCharge particularly (e.g. Run 22+; GMT?)
- More materials:
  - Explore the TPC web pages:
    https://www.star.bnl.gov/public/tpc/tpc.html
    https://drupal.star.bnl.gov/STAR/subsys/tpc
  - Read the NIM paper
    https://www.star.bnl.gov/public/tpc/NimPapers/tpc/tpc_nim.pdf

Backup Slides

Global Alignment/Twist



Normal

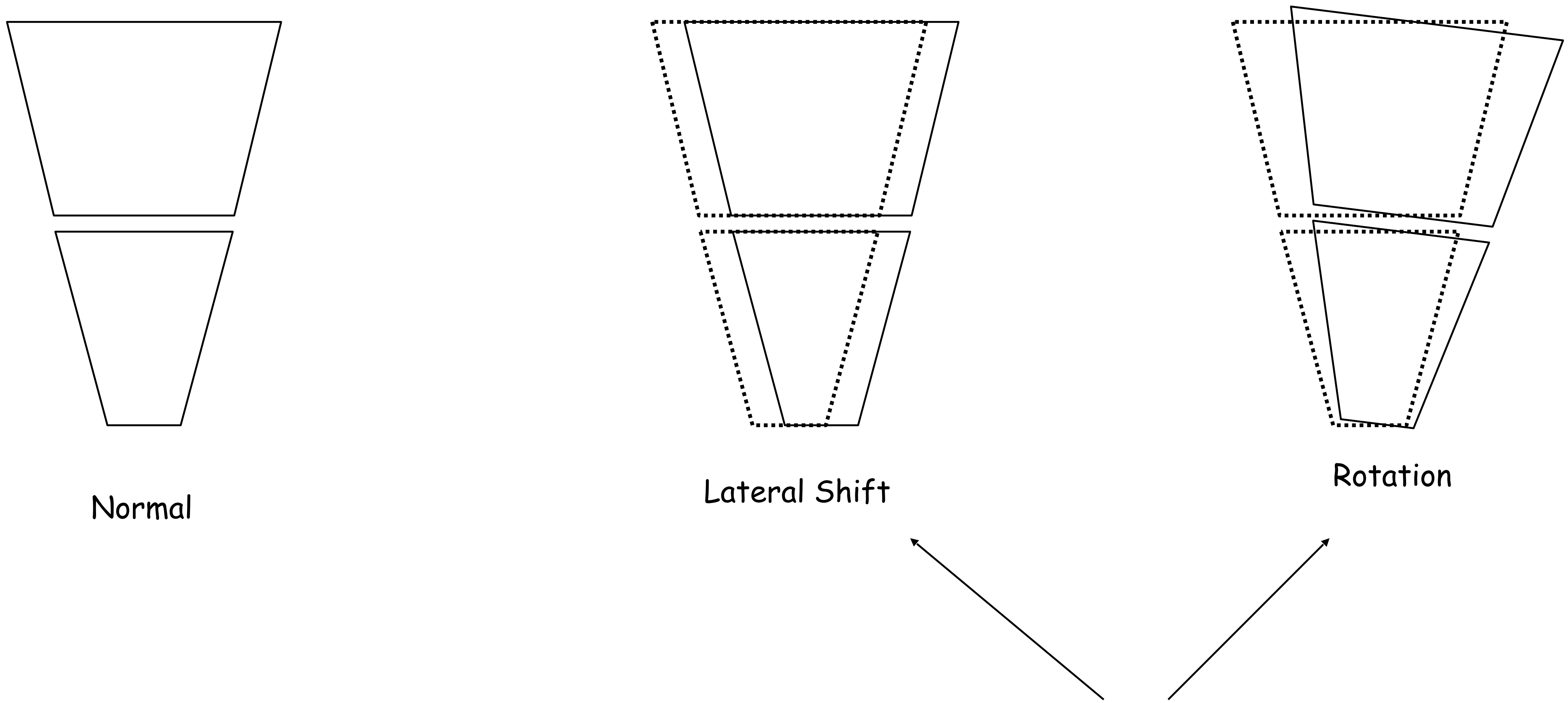
Translation (not ever looked at)

Twist or ExB (done often)

Only really should affect BEMC/TPC alignment

SuperSector Alignment

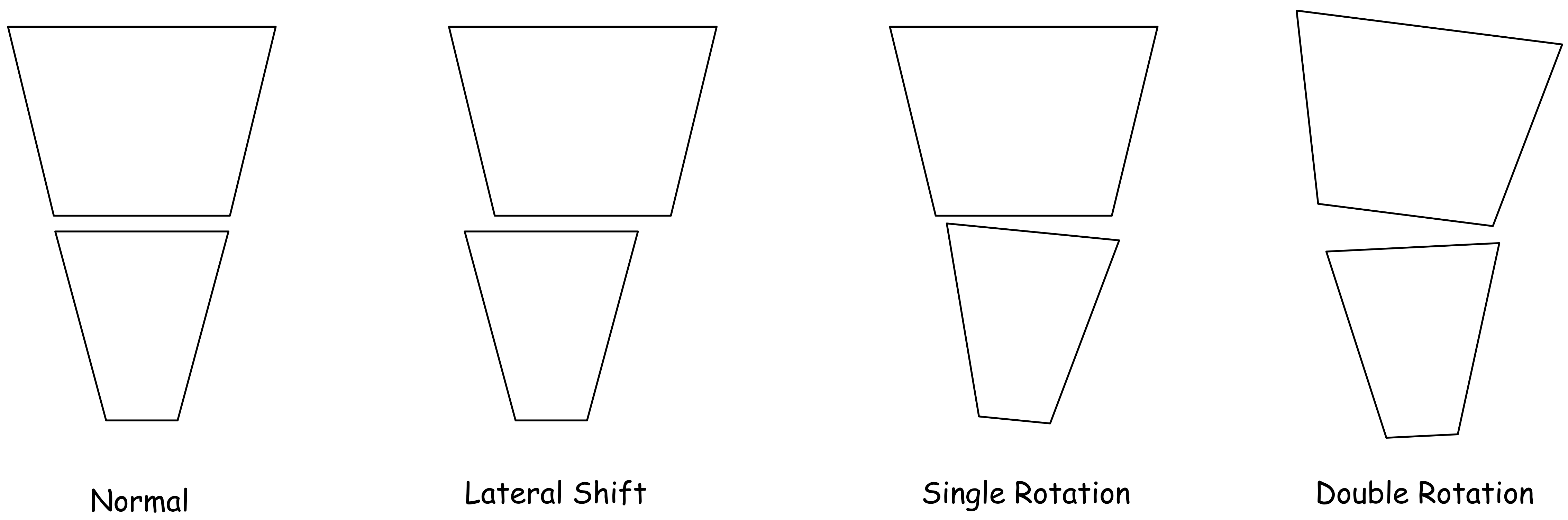
How sure are we about the alignment of the sectors?
Basically, anything you can imagine is possible



With most methods it is hard to distinguish these two (we assume it's rotation)

Fine Alignment of Sectors

How sure are we about the alignment of the inner and outer sectors?
Again, anything you basically imagine is possible



Distortion Equations – (see Bl

Solve:

$$m \frac{d\bar{u}}{dt} = e\bar{E} + e$$

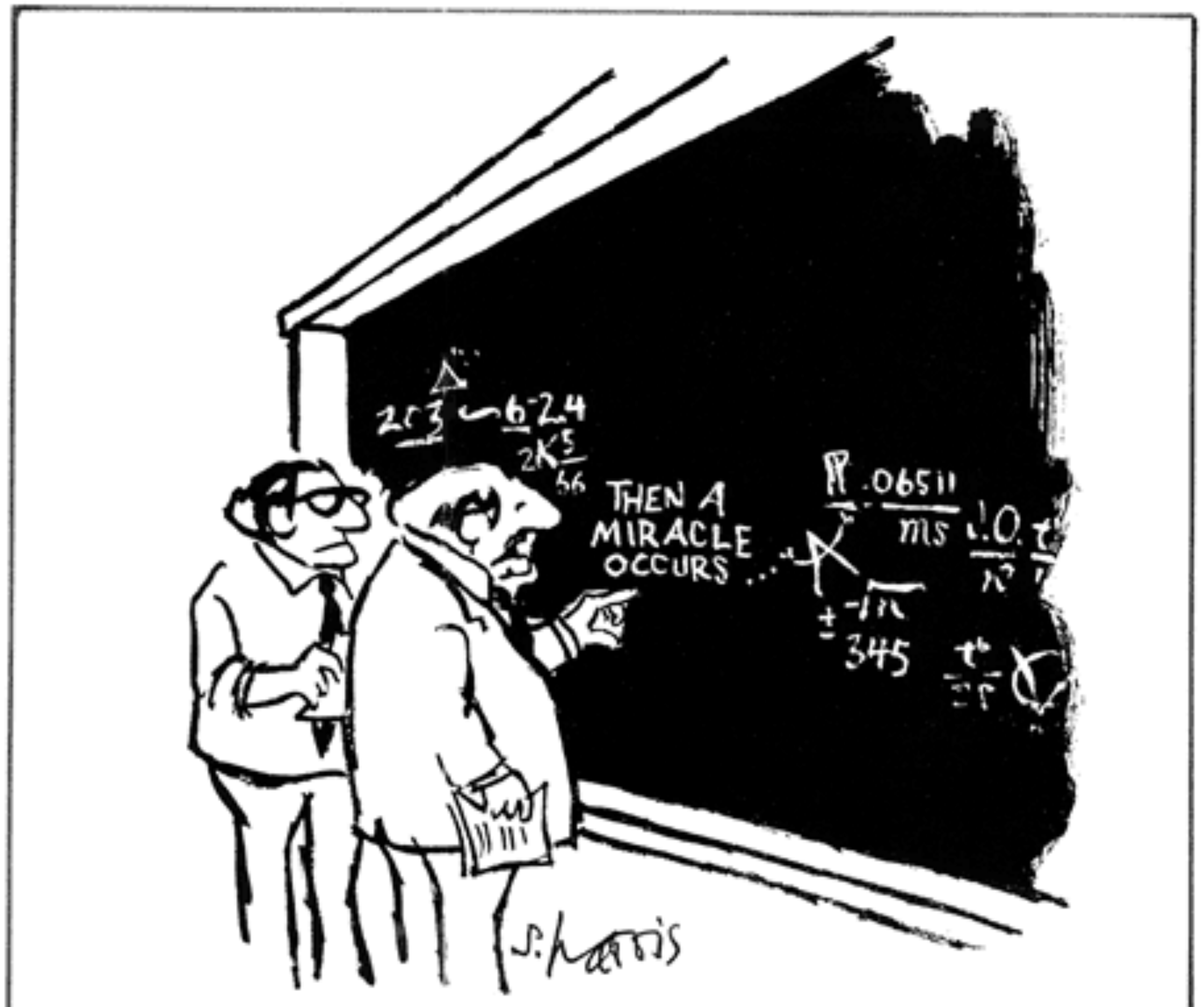
Langev

substituting:

$$\tau = \frac{m}{K}, \quad \omega = \frac{e}{m}|\bar{B}|, \quad \mu =$$

subject to the steady state condition

$$\frac{d\bar{u}}{dt} =$$



"I think you should be more explicit here in step two."

$$\bar{u} = \frac{\mu|\bar{E}|}{(1+\omega^2\tau^2)}\left(\hat{E} + \omega\tau\left[\hat{E}\times\hat{B}\right] + \omega^2\tau^2\left(\hat{E}\bullet\hat{B}\right)\hat{B} \right)$$

where B is a unit vector pointing in the direction of $\bar{B}$.

If you have a well defined model, and good data, then the distortion can be removed with great precision

The Case of E Parallel to B

$$\delta_r = \int \frac{u_r}{u_z}\, dz, \qquad \delta_\phi = \int \frac{u_\phi}{u_z}\, dz$$

Electric field strength cancels out!

$$u_\phi = \frac{\mu \left|\overline{E}\right|}{\left(1+\omega^2\tau^2\right)} \left(\cancel{\hat{E}_\phi} - \omega\tau \left(\hat{E}_r \hat{B}_z - \hat{E}_z \hat{B}_r \right) + \omega^2\tau^2 \cancel{\hat{B}_\phi} \right)$$

etc…so

assuming that $E = E_z$ and $B_z \gg B_r$ or B_ϕ

$$\delta_r = \frac{\omega^2\tau^2}{\left(1+\omega^2\tau^2\right)} \int \frac{\hat{B}_r}{\hat{B}_z}\, dz$$

Simple first order equations

$$\delta_\phi = \frac{\omega\tau}{\left(1+\omega^2\tau^2\right)} \int \frac{\hat{B}_r}{\hat{B}_z}\, dz$$

If you have a well defined model, then the distortion can be removed with great precision