Space Charge and its effects on tracking in a TPC

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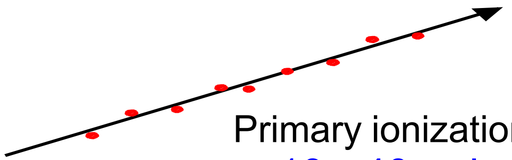
20 - July – 2010

(with many thoughts and ideas due to Stefan Rossegger)

Ionization of gases

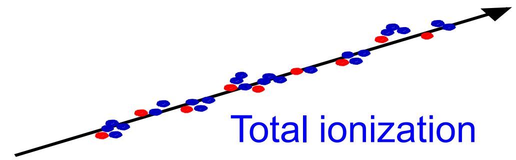
Fast charged particles ionize the gas.



Primary ionization

10 - 40 pairs/cm

ΔE/pair ~ 25 eV



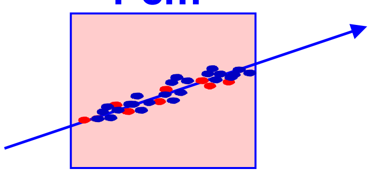
Total ionization

$$n_{total} \approx 3 \ldots 4 \cdot n_{primary}$$

Often the resulting primary electron will have enough kinetic energy to ionize other atoms.

Assume detector, 1 cm thick, filled with Ar gas:

1 cm

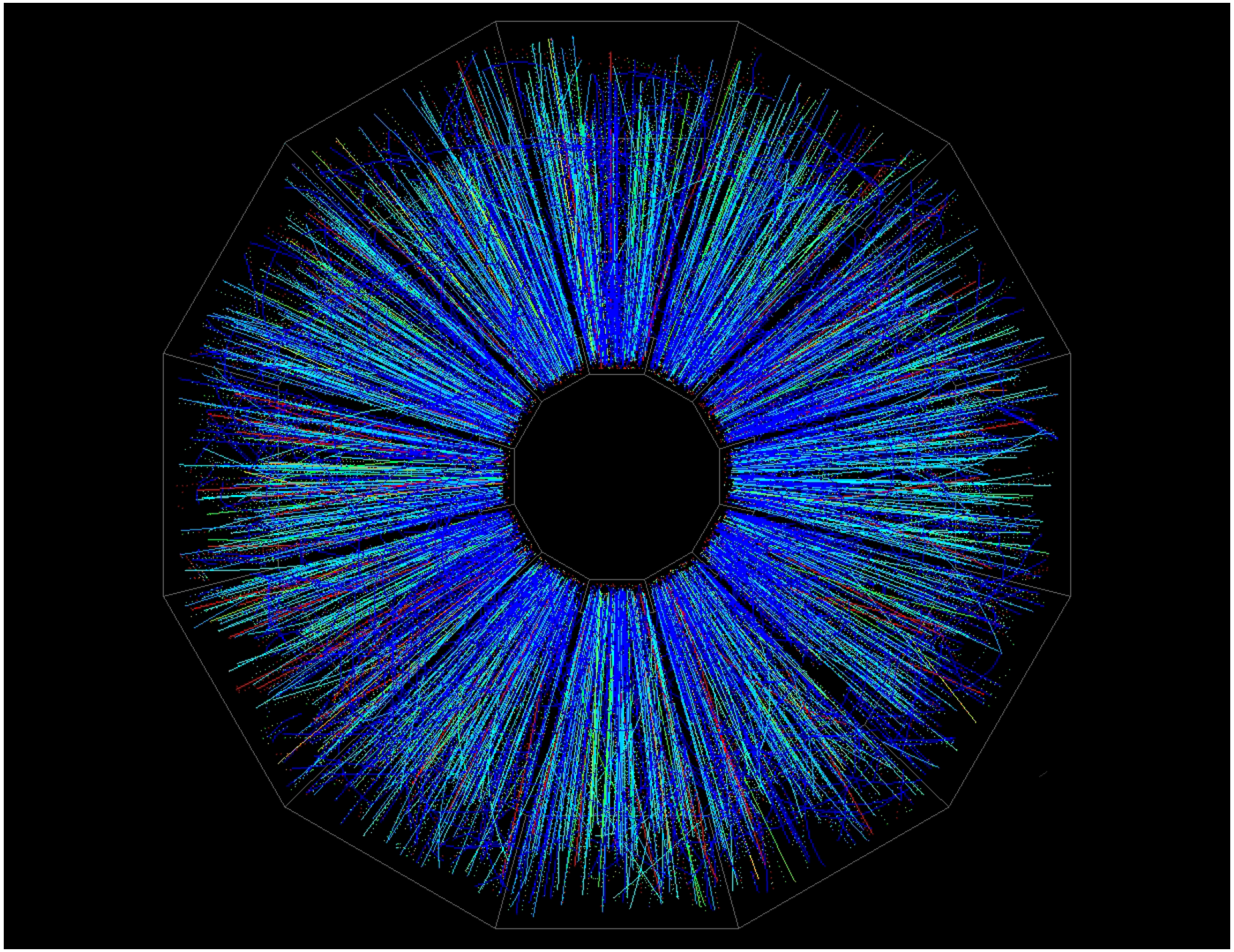


~ 100 e-ion pairs

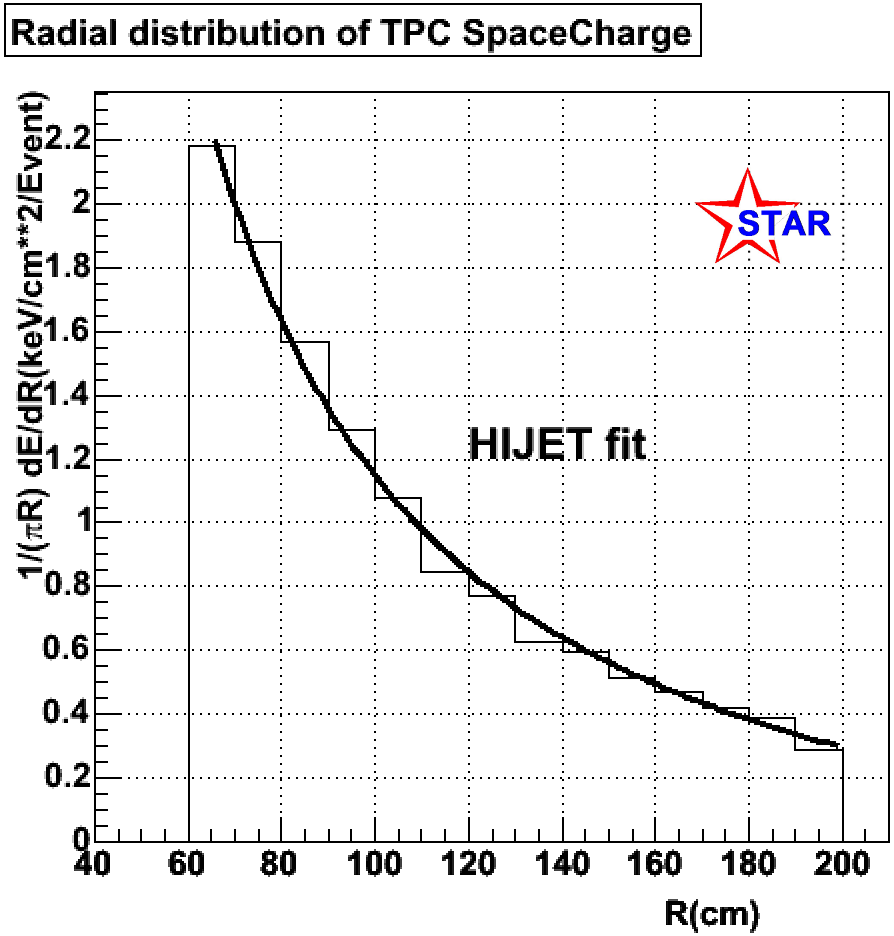
The e^- and ions will drift ⇐ ⇒ under the influence of an E field

- **The electron drift velocity depends on the gas and E field, 2 - 5 cm / μ sec**
- **The ion drift velocity depends on the gas and E field, 200 - 2000 cm / sec**

Physics Events create spacecharge



STAR – SpaceCharge Follows Event Shape



- The radial distribution of charge in the STAR TPC is described by the charge distribution of a Hijet event.
  - $1/r^2$ and independent of z is a very good approximation
  - Strictly speaking, this is the measured distribution of electron charge in the TPC
- STAR experience is that background beam effects are small compared to the charge from the primary event
  - Occasionally, the backgrounds are high but so far they are few enough that we discard these runs.

SpaceCharge

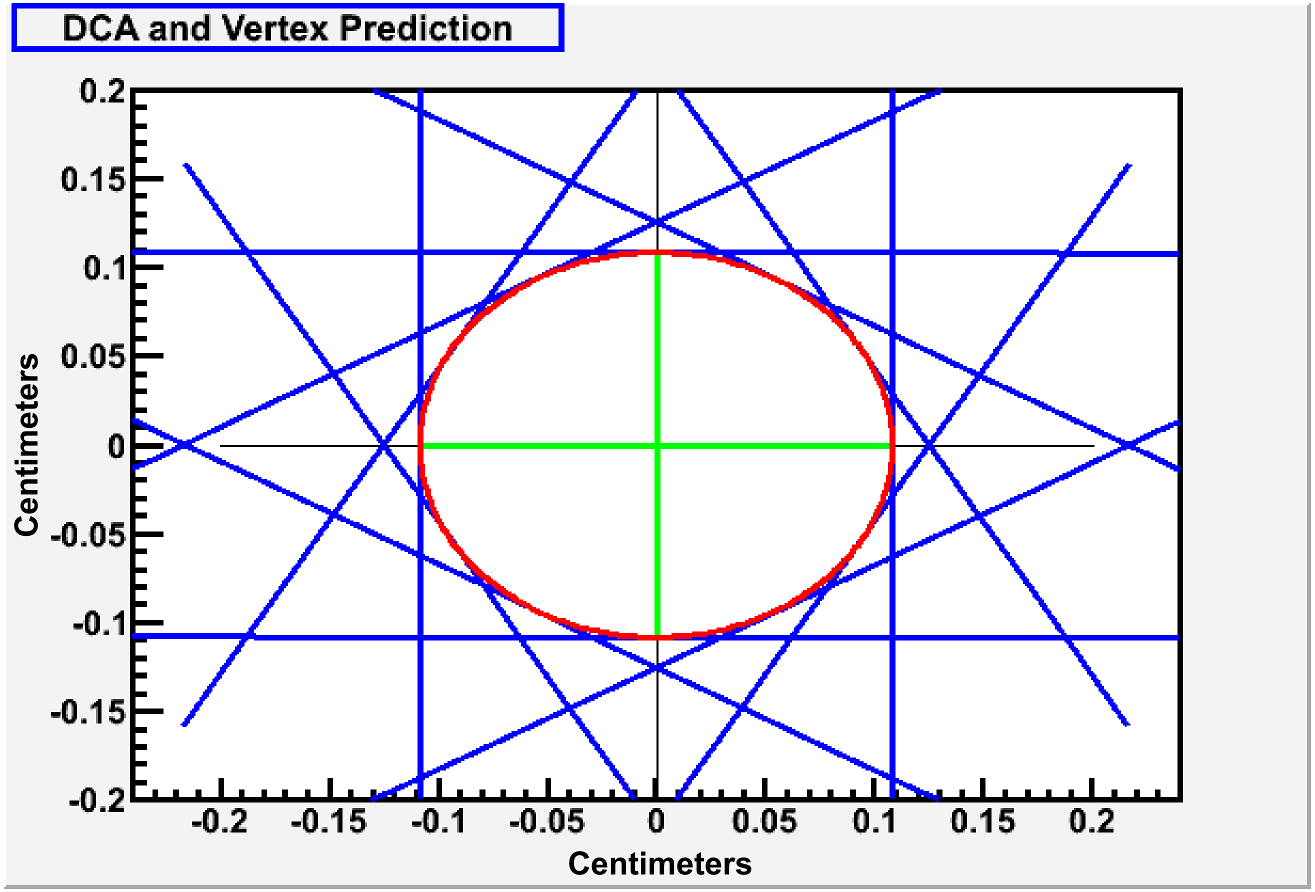
- The electron drift velocity in the ALICE TPC is about 2.73 cm/μsec
  - 92 μsec to drift from the CE to one EndPlate

- The ion drift velocity is much slower … scales ~ by mass
  - An ion drifts from the CE to one EndPlate about as fast as you can bicycle the same distance

- At collision rates of 1k to 10k … a macroscopic amount of positive charge builds up in the TPC
  - Enough positive charge to distort the drift of the electrons

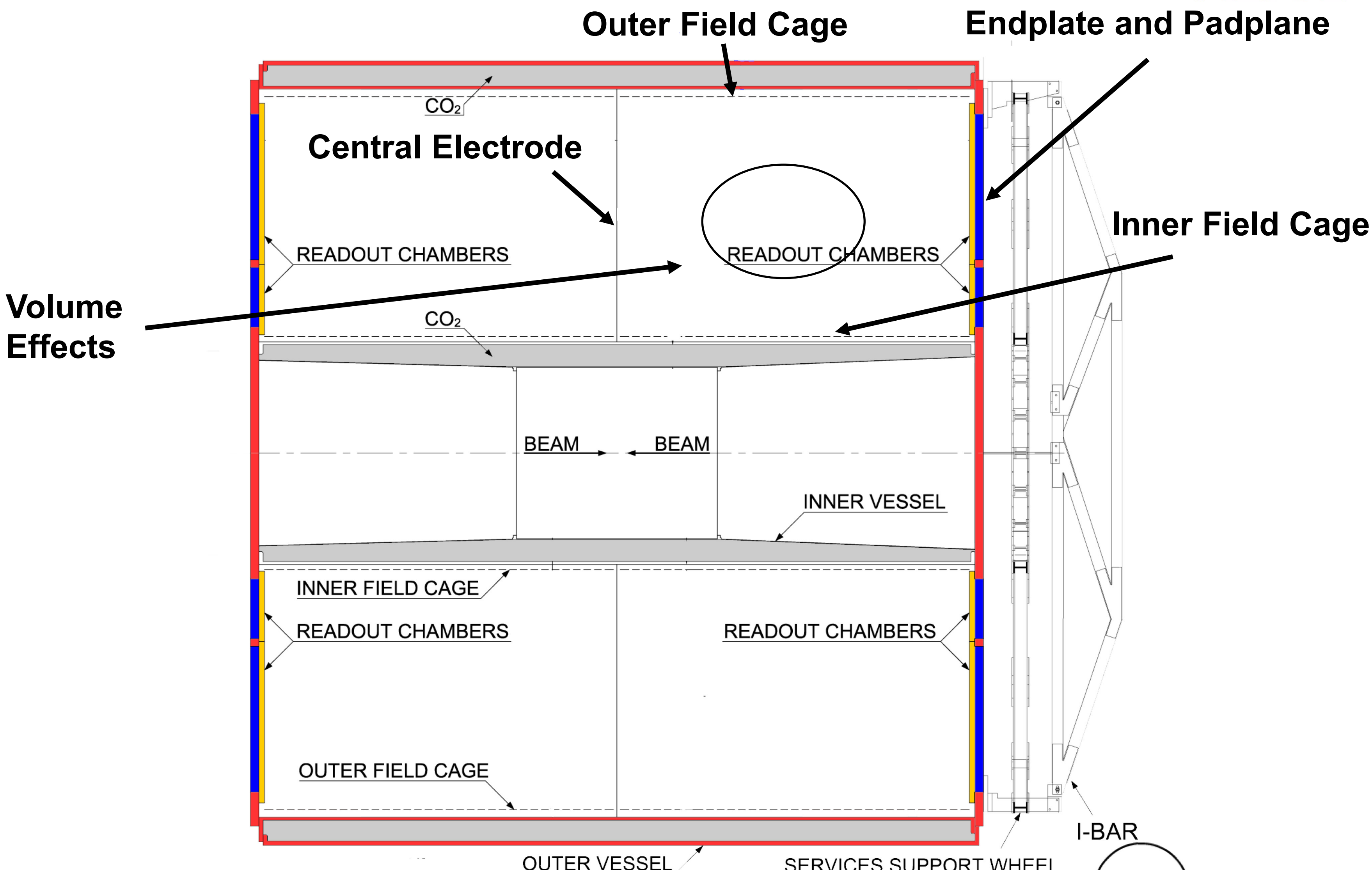
- The projected Distance of Closest Approach (DCA) at the vertex can be several millimeters and depends on luminosity
  - Proton – proton collisions, at full luminosity, will be more challenging than HI because the increased luminosity is more significant than the change in multiplicity per collision.
  - One solution is to voluntarily limit the luminosity of the pp beams

Simulated SpaceCharge Effects in the TPC



8 kHz Collision Rate & 5000 particles per unit rapidity in ALICE

Visual Mnemonic for making a list of distortions, etc.



A List of Distortions and Alignment Issues

The list can be enumerated by surfaces:

- Inner field cage corrections (shorts, shifted rods, and overall displacement)
- Outer field cage corrections (shorts, shifted rods, and overall displacement)
- Central electrode corrections (shape and tilt)
- End-plate and pad-plane corrections (Z location, orientation, and boundaries)
- Rotation and miss-alignment of sectors with respect to each other
- Rotations of TPC end-plates with respect to their ideal locations

and by volume:

- Space Charge corrections due to charge in the volume of the TPC
- Magnetic field corrections due to B fields in the volume of the TPC
- Twist of the TPC with respect to the magnetic field axis
- General coordinate transformations

A few additional items are listed for completeness.

- Gas composition and variations in the drift velocity, Gain variations
- Barometric pressure changes and variations in the drift velocity
- Pressure variations as a function of height in the TPC
- Temperature gradients in the TPC, radial and/or as a function of height

This list is not complete, but the good news is that the list is finite, it is not infinitely long

The Langevin Equation – (see Blum, Riegler and Rolandi)

Solve:

$$m\frac{d\overline{u}}{dt} = e\overline{E} + e\left[\overline{u}\times\overline{B}\right] - K\overline{u}$$

Microscopic Lorentz force with "Friction"

substituting:

$$\tau = \frac{m}{K}\ ,\quad \omega = \frac{e}{m}\left|\overline{B}\right|\ ,\quad \mu = \frac{e}{m}\tau\ ,\quad \text{and}\ \hat{E} = \frac{\overline{E}}{\left|\overline{E}\right|}$$

subject to the steady state condition

$$\frac{d\overline{u}}{dt} = 0$$

yields

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

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

Then a miracle occurs …

Distortion Equations – related to integrals of the fields

ALICE

Distortion in x or y

Integral over distorted field

$$\begin{pmatrix}\delta_x\\ \delta_y\end{pmatrix} = \begin{pmatrix} c_0 & c_1 \\ -c_1 & c_0 \end{pmatrix} \begin{pmatrix} \int \frac{E_x}{E_z}\, dz \\ \int \frac{E_y}{E_z}\, dz \end{pmatrix}$$

$$\begin{pmatrix}\delta_x\\ \delta_y\end{pmatrix} = \begin{pmatrix} c_2 & -c_1 \\ c_1 & c_2 \end{pmatrix} \begin{pmatrix} \int \frac{B_x}{B_z}\, dz \\ \int \frac{B_y}{B_z}\, dz \end{pmatrix}$$

Master Equations
for E or B field distortions
simple linear equations

with $c_0 = \frac{1}{(1+T_2^2\omega^2\tau^2)}$, $c_1 = \frac{T_1\omega\tau}{(1+T_1^2\omega^2\tau^2)}$, and $c_2 = \frac{T_2^2\omega^2\tau^2}{(1+T_2^2\omega^2\tau^2)}$

$$\omega\tau = BField[kGauss] * \frac{-10. \; * \; |Drift\,Velocity[cm/\mu sec]|}{|Electric\,Drift\,Field\,Strength\;[V/cm]|}$$

- **Distortions in the TPC are directly related to integrals of the E and B fields**
- **These solutions of the Langevin Equation are exact to 2nd order**
  - **The matrices are rotations (with a pre-factor) related to the Lorentz angle**
  - **Since rotations commute in 2 dimensions, these matrices commute with other rotations and so these equations are valid in Cylindrical Coordinates, too**

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

EMMI GSI

Calculating the Effects of Space Charge

- Calculating the effects of space charge in the TPC requires a full solution of Poisson's equation.
  - You cannot approximate it because the Coulomb interaction is a very long range interaction. One corner of the TPC affects the opposite corner.
- Cylindrical symmetry is very convenient
  - But not required. In principle, any charge distribution can be simulated … if you know what it is!!
- Knowledge of the shape of the charge distribution is <u>required</u>
  - You can usually assume an event driven charge shape distribution
  - Discard bad runs when this is not true … but other more heroic remedies are possible including measuring the charge shape in each run etc. etc.
- An external measure of beam background is useful
  - A good guide to help eliminate bad runs (usually rare)
- An external measure of the interaction luminosity is useful
  - SC effects will be refined by minimizing the DCAs for tracks however a reliable measure of the luminosity helps to predict the magnitude of the distortion and bootstraps the process of minimizing the DCAs.

Technology

- **Poisson's equation can be solved analytically**
  - **For a uniform charge density in a cylindrical volume it is:**

$$E_r = \frac{-4\,C}{L} \sum_{n=1}^{\infty} -1^{n+1} \frac{I_1(kr)\left[K_0(kb)-K_0(ka)\right]+K_1(kr)\left[I_0(kb)-I_0(ka)\right]}{K_0(kb)\,I_0(ka)-K_0(ka)I_0(kb)}\;\frac{\sin(kL-kz)}{k^2}$$

$$\delta_r = \frac{-4\,C}{L\left|\vec{E}\right|} \sum_{n=1}^{\infty} -1^{n+1} \frac{I_1(kr)\left[K_0(kb)-K_0(ka)\right]+K_1(kr)\left[I_0(kb)-I_0(ka)\right]}{K_0(kb)\,I_0(ka)-K_0(ka)I_0(kb)}\;\frac{1-\cos(kL-kz)}{k^3}$$

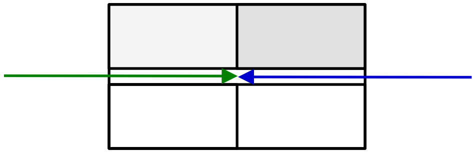
  - **An arbitrary charge density distribution requires a Green's function**
    - **For example, see the work by S. Rossegger, et al., Nucl. Instr. and Meth. A (2009), doi:10.1016/j.nima.2009.06.056, and CERN-OPEN-2009-003.**

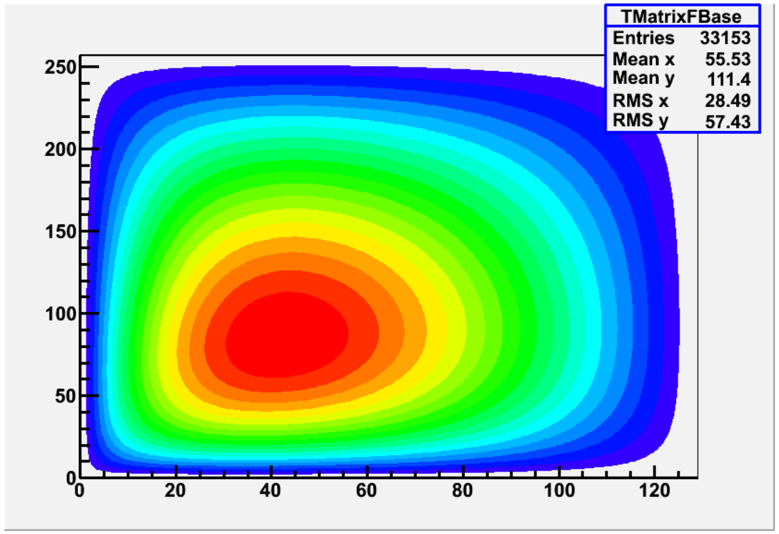
- **For the case of a cylindrically symmetric or nearly cylindrically symmetric charge distribution, the problem can also be solved by numerical relaxation on a grid**
  - **Poisson's equation on a grid can be programmed in 4 lines of code**

    (V(i-1,j) + V(i+1,j) + V(i,j-1) + V(i,j+1) – 4*V(i,j)) = ChargeD(i,j)
  - **Easy to code, easy to debug; but may be slow if you ask for too much detail. Over-relaxation and grid expansion techniques help.**

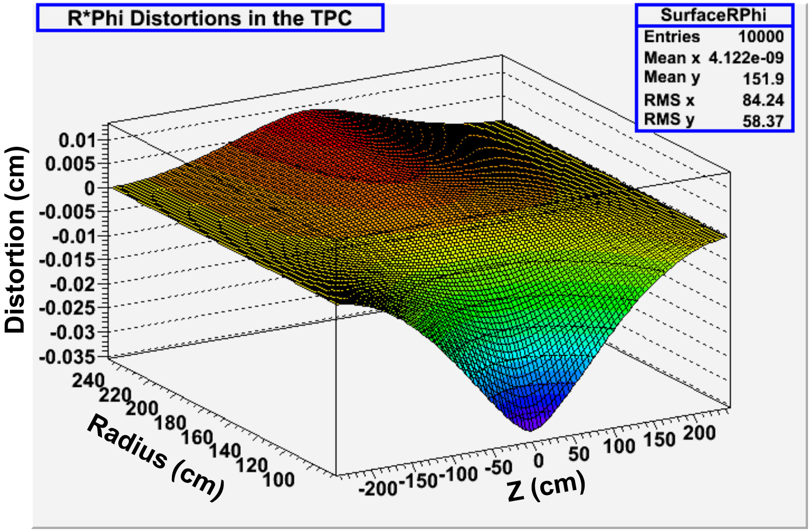
Solutions?

- Distortions in the TPC can be calculated with excellent precision
  - DCAs can be reduced to ~1% of the total distortion (1 cm ⇒ 100 μm)
    - If you know the distribution of charge
    - If you know the luminosity of the beam
    - If you never give up





Voltage inside TPC – arb. Units, one quadrant with cylindrical symmetry, CE to C Endplate



Distortions – all axes are in cm

STAR Experience – Linear with Luminosity

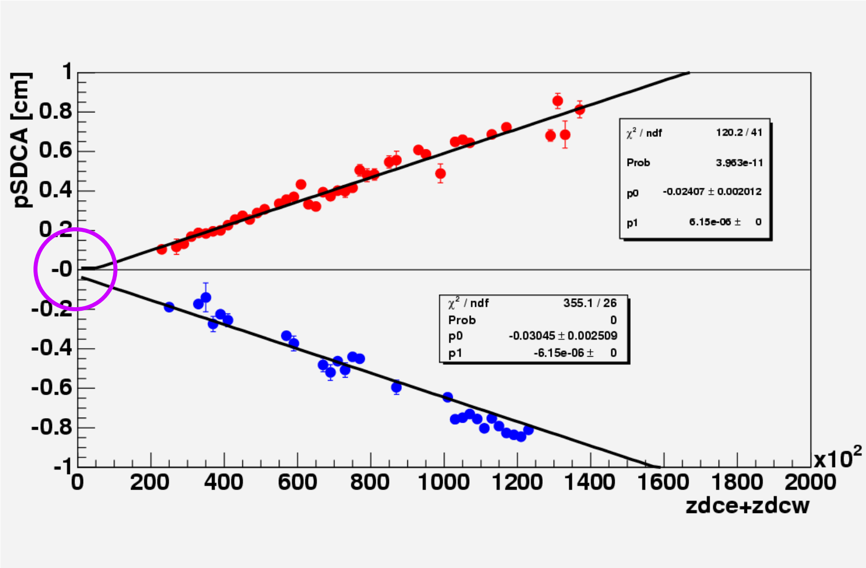


Figure 1: The physical signed DCA versus the Zero Degree Calorimeter count rate. The red and blue data points show the DCAs for Au+Au at 200 GeV for positive and negative full field magnet settings. The purple circle also illustrates that the DCAs extrapolate to small values indicating that the static (non-space charge) distortions are small.

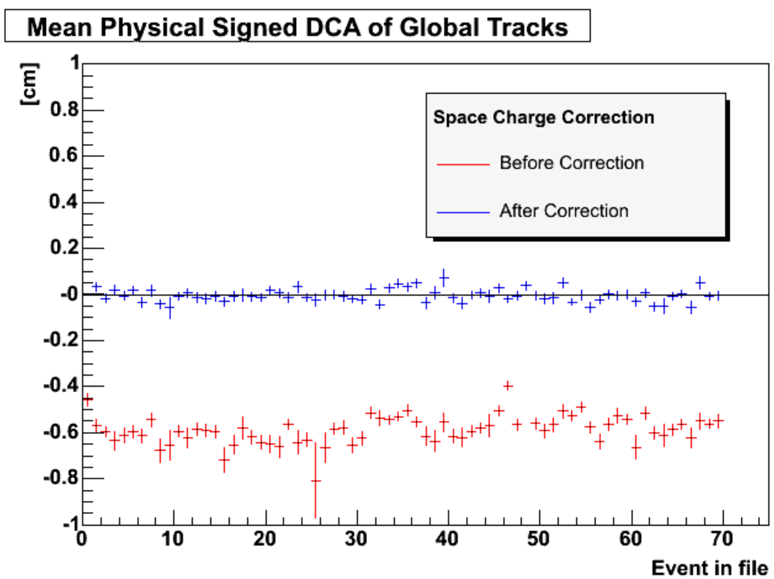
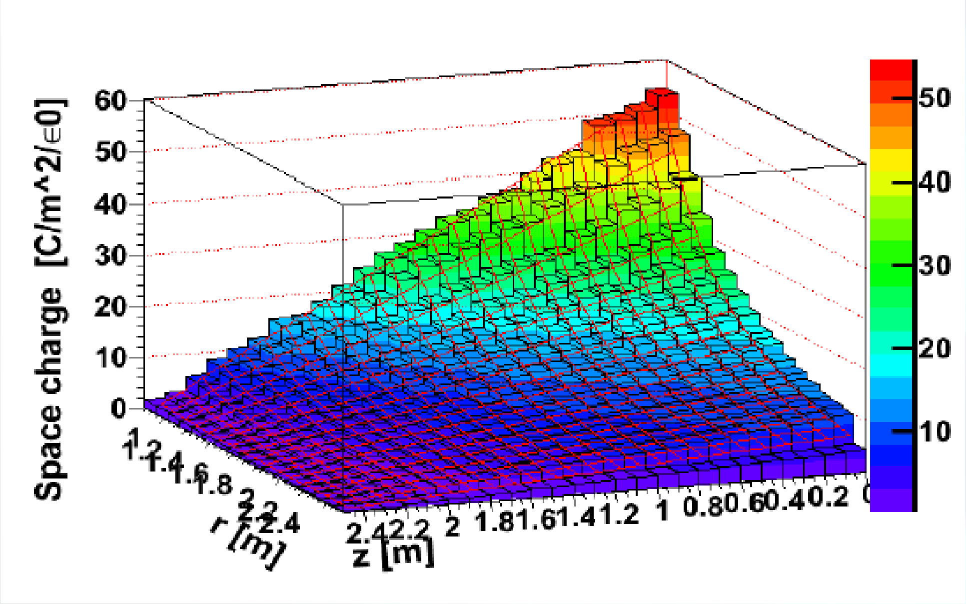


Figure 2: Event by Event space charge corrections are calculated using the average DCA from 1000 tracks in the TPC prior to the current event. The red data points show the raw data. The blue data points show the corrected data. Note that the red events show a small time dependent periodicity that is the result of fluctuating luminosity with a period of a few seconds. It is superimposed upon the mean luminosity of the beams.

Expected space charge densities?

Dominated by Primary Ionization (according to MC simulation)



Simulation settings	
coll.Energy	5.5 TeV
Luminosity	4 10^{26} $1/cm^2s$
event rate	3200 Hz
Ion clear.time (Ne+)	0.156 s
Mult (central 5%)	2300 dN/dη
Mult (min.bias 80%)	950 dN/dη

	A	B
A side	45	-18
C side	39	-16

Fit: $\rho(r,z) = (A + B z)/r^2$

max (at CE and IFC):
~54 to 62 C/m^3/e0

If events are read out:
due to ROC IFB
plus (max.) ~ 20 %

In STAR and ALICE, the ion feedback has ~ the same shape as the primary event ionization. Therefore, they can be lumped together for an effective correction.

How can you avoid SpaceCharge?

- Space Charge is intrinsic to each event
  - so it’s a little hard to avoid unless you have the luxury of being able to reduce the Luminosity of the beam

- But the good news is that a detector builder does have some control over what happens inside his/her detector
  - Appropriate design … such as gated grids
  - Choice of gas & electric field

Most TPCs have a Gated Grid …

Time Projection Chamber → full 3-D track reconstruction

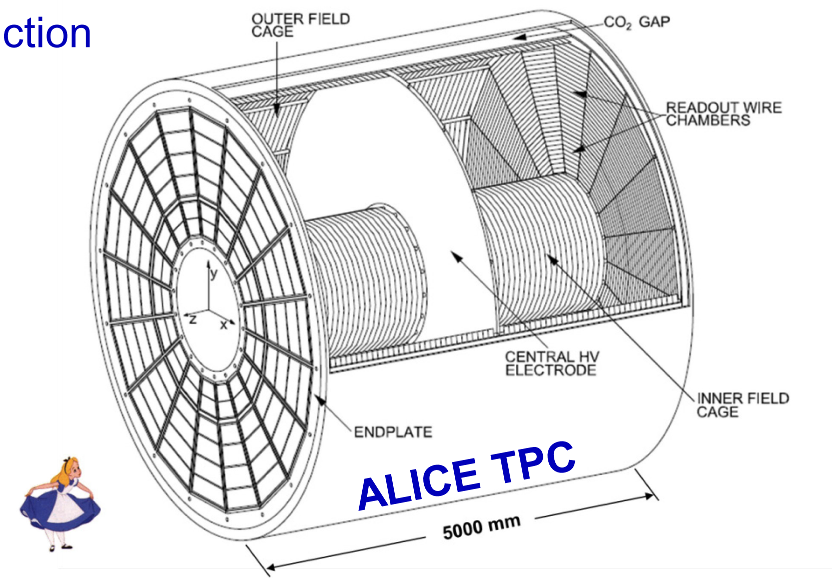
- x-y from wires and segmented cathode of MWPC
- z from drift time
- in addition dE/dx information

Diffusion significantly reduced by B-field.

Requires precise knowledge of v_D →
LASER calibration + p,T corrections

Drift over long distances → very good gas quality required

Space charge problem from positive ions, drifting back to midwall → use a gated grid

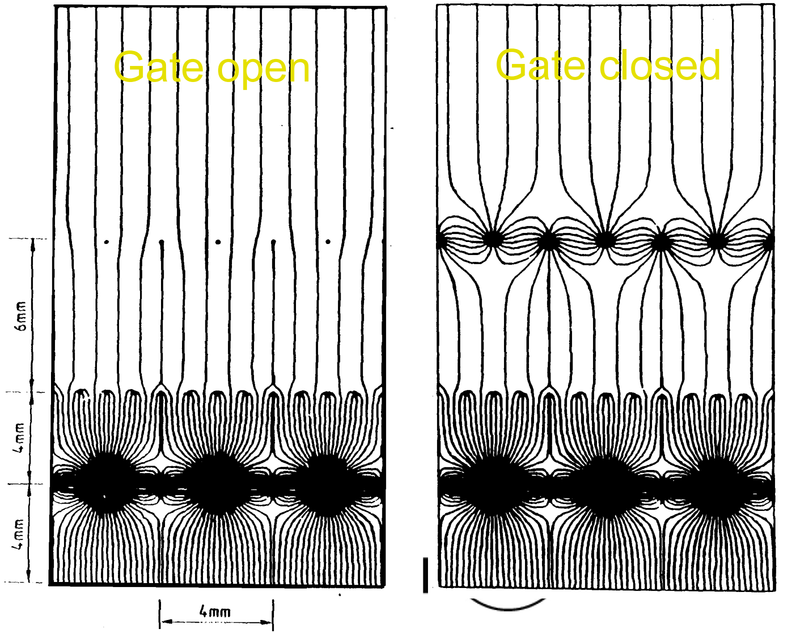


ALEPH TPC
(ALEPH coll., NIM A 294 (1990) 121,
W. Atwood et. Al, NIM A 306 (1991) 446)

$\Delta V_g = 150$ V

Ø 3.6M, L=4.4 m

$\sigma_{R\phi} = 173\ \mu m$
$\sigma_z = 740\ \mu m$
(isolated leptons)



Choice of Gas – pluses and minuses

- **Comparing STAR to ALICE**

Design differences			
	Star (ArCH4)	Alice (NeCO2N2)	Factor
Acceptance	~1	~1	1
Ion - mobility	1.6 cm²/Vs	4 cm²/Vs	
E field	135 V/cm	400 V/cm	
Clearing time	0.96 s	0.156 s	0.16
Energy loss	2.5e-3 MeV/cm	1.4e-3 MeV/cm	0.57
Design scaling factor		Fdesign =	0.0912

- **Alice Electric field is 3x**
- **$Ne-CO_2$ Ion Mobility is 2.5x**
- **Energy Loss is 1.5x less**

- **10x improvement**

- **The price for this handsome reduction is that ALICE operates at 100 KV vs 28 KV in STAR**
  - **This is an engineering consideration**
- **Ne/CO_2 is very temperature sensitive and requires ± 0.1 K control**
  - **P10 operates at the peak of the velocity curve and so not sensitive**

Summary

- **Space Charge is driven by the underlying events as well as by chamber design**
- **Space Charage depends on Luminosity and Multiplicity**
- **The expected charge densities can be estimated in advance**
  - **So can be handled in the original design of a new detector**
- **Space Charge can be reduced by choosing an appropriate Gas and adding design features such as a GG**
  - **Think ahead … there are always compromises to me made when choosing the gas or the drift field**
- **Never give up**

Backup Slides

What about pp collisions?

- max pp luminosity (for Alice): $L = 10^{31}$ $[1/cm^2 s]$
- Inelastic cross-section: ~ 60 mbarn

  ⇒ Interaction rate: 600 kHz

- Charged particle multiplicity (for 14 TeV): ~ 6

⇒ **Max. charge density at CE and IFC: ~ 63 C/m^3/e0** ⇒

max. Δr ~ 0.5 mm (at IFC&CE)
max. $\Delta r\phi$ ~ 0.17 mm (at IFC&CE)
max. Δz ~ 0.15mm (at z~100cm)

THIS IS HALF OF Pb-Pb!

Think about what happens at $L=10^{32}$ or even $L=10^{33}$