Physics and Detector Mini-workshop IAS HEP Program
HKUST, Hongkong, February 12, 2023

TPC R&D and operability at circular colliders

Paul Colas (CEA/Irfu Université Paris Saclay)

Thanks for contribution from LCTPC colleagues. Special thanks to K. Fujii, S. Ganjour, D. Jeans, P. Kluit

Tracking at an EW/Higgs/top factory

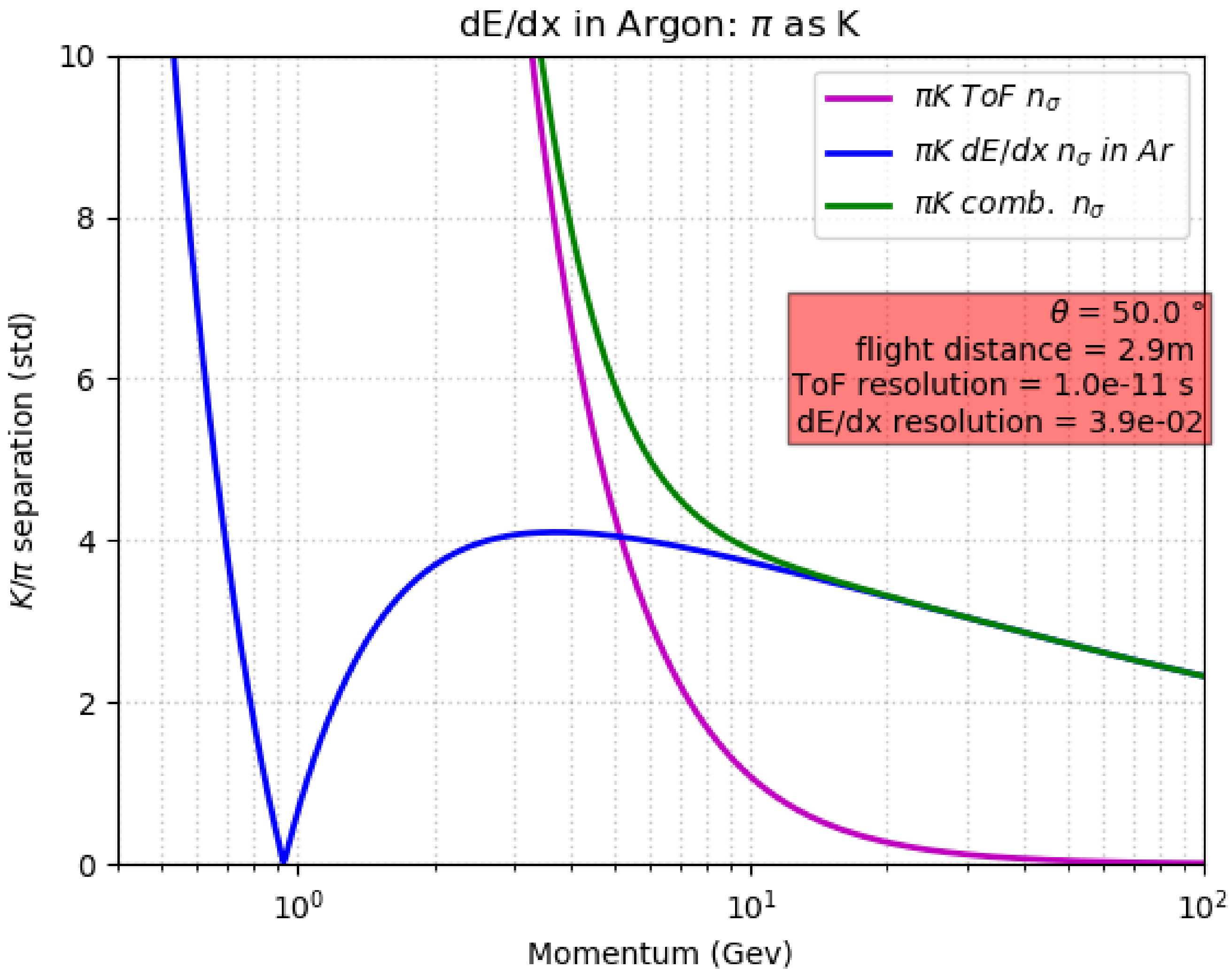
- At the Z pole and beyond, particle ID is an essential ingredient, for tagging and studies of Heavy Flavours (together with an excellent vertex detection)
- A TPC ideally combines dE/dx measurement and low material budget, allowing a continuous measurement of the tracks. A strong magnetic field aligned with the TPC drift field limits diffusion and allows charged track momentum measurement.
- Together with silicon (vertex) detectors, it allows the excellent performance in resolution needed to extract the Z recoil peak to tag Higgses in a model-independent and unbiased way
- TPC is the main tracker for the ILD detector concept. At ILC, it profits from a beam time structure allowing power switching and gating. ILD is considering adapting the concept in case a circular collider is built first.

Particle Identification

SEPARATION POWER

dE/dx and TOF (10 ps) Combined

(see also Manqi Ruan)



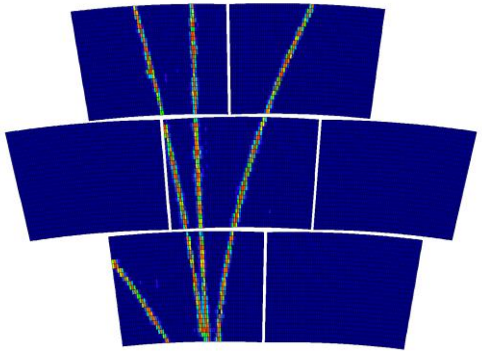
R. Aleksan

TPC R&D

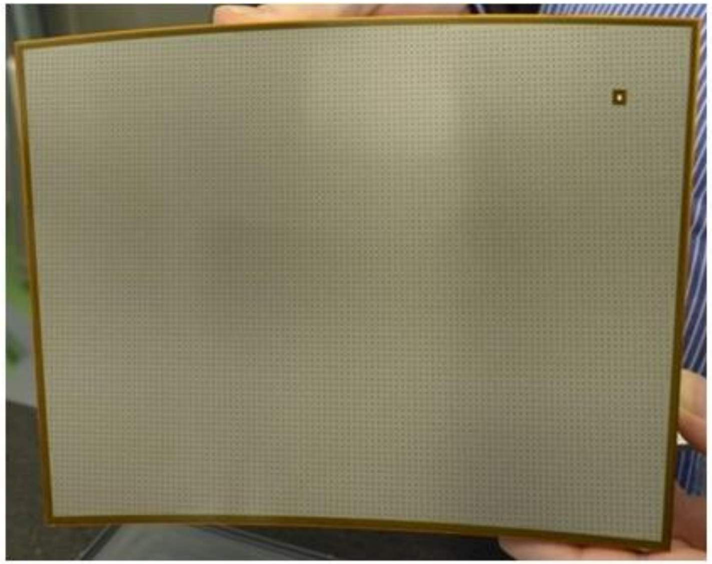
The TPC R&D is carried out within the LCTPC collaboration (spokesperson Jochen Kaminski). There are 3 main options for the readout : Micromegas with a resistive anode (ERAM), GEM, and Gridpix.

Beside this dedicated R&D, lessons are learned from experiments in progress, using TPCs with similar techniques issued from e+e- collider studies : ALICE at LHC (GEMs), T2K/ND280 at J-PARC (resistive Micromegas

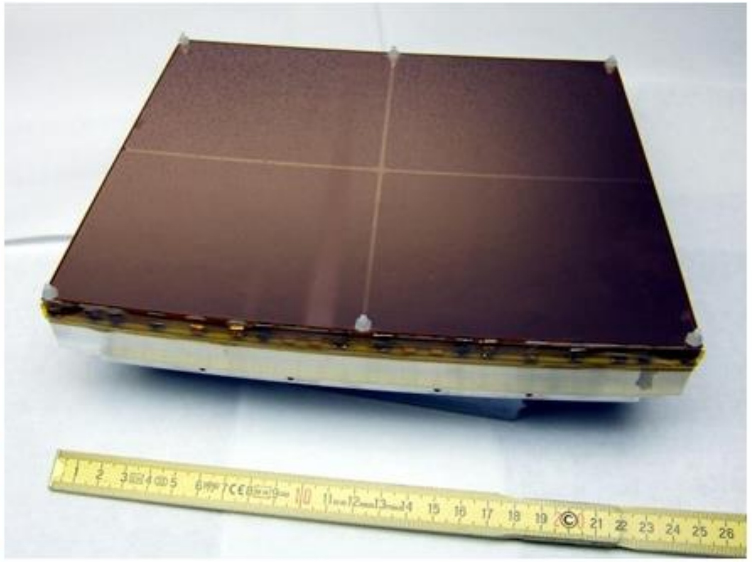
Feasibility and performance has been demonstrated in ILC conditions. New ILD strategic goal is to adapt to conditions at a high lumi circular collider.



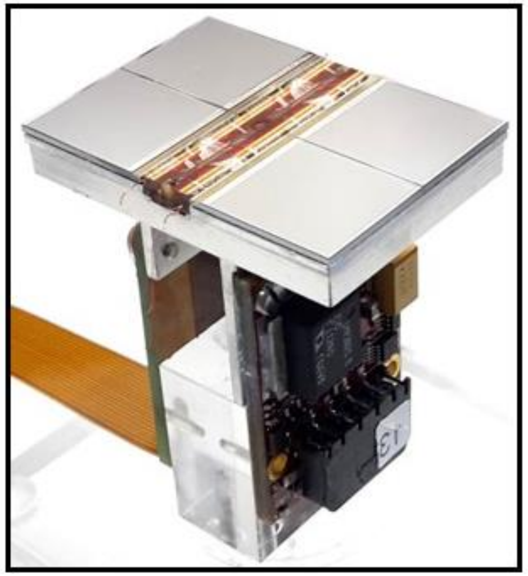
Micromegas



GEM



Gridpix



Gas choice

- Base gas :
  - Ar for largest ionization : 97 e-ion pairs in ~35-40 clusters
  - He for well-separated clusters easing dN/dx (but cannot set field to the maximum drift velocity over 2 m)

- Additional gases
  - Isobutane : quencher, cuts UVs to avoid avalanche propagation
  - CF_4 : increases electron drift velocity and reduces diffusion in magnetic field by a factor of ~10 at 3.5 T and ~5 at 2T.
  - Low e attachment (keep O_2 and H_2O below ~10 ppm to drift over 2m) velocity)

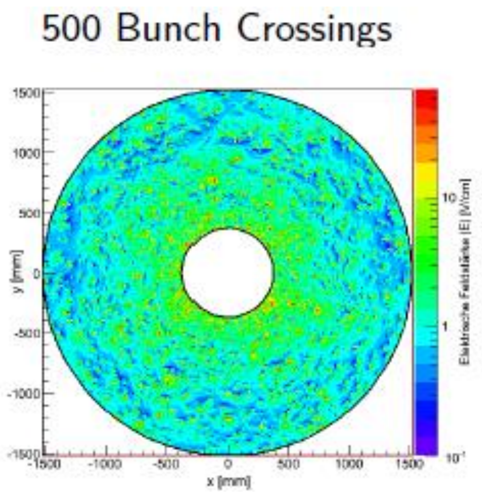
- T2K gas Ar:CF4:Isobutane 95:3:2 satisfies all requirements for a TPC

- Note that the optimal gas is not the same for cluster counting (He) and for space resolution (large $\omega\tau$ for low diffusion: ‘fast gas’)

Distortions from positive ions

- Ions drifting in the gas are very slow (typically a few m/s)
- Primary ions from ionization in the gas (from event tracks of from machine background) or secondary ions created during amplification and back-flowing in the drift region, drift very slowly, producing space charge which distorts the trajectories of the electrons drifting from the tracks by creating a component transverse to the drift field
- This effect is common to all the amplification devices
- Calculated in 2011 by D. Arai and K. Fujii
- 2022-2023 : New calculation in progress, adapt to Z pol

(K. Fujii, D. Jeans, S. Ganjour, Mingrui Zhao…)



Simulation by M. Killenberg (2009)

Calculation of the distortions (K. Fujii)

The ion charge density creates a potential at each point $\boldsymbol{x}$ of the field cage volume :

$$\triangle\phi_{\mathrm{ion}}(\boldsymbol{x}) = -4\pi\,\rho_{\mathrm{ion}}(\boldsymbol{x})$$

From which one derives the transverse field (with I, K modified Bessel functions)

$$\begin{aligned}
E_r(r,z) = -8\pi \sum_{n=1}^{\boxed{\infty}} & \frac{\sin(\beta_n z)}{I_0(\beta_n a)K_0(\beta_n b) - I_0(\beta_n b)K_0(\beta_n a)} \\
& \Big[[K_0(\beta_n b)I_1(\beta r) + I_0(\beta_n b)K_1(\beta_n r)] \int_a^r dr' \, \frac{K_0(\beta_n a)I_0(\beta r') - I_0(\beta_n a)K_0(\beta_n r')}{K_0(\beta_n r')I_1(\beta_n r') + K_1(\beta_n r')I_0(\beta_n r')} \\
& \qquad \boxed{\int_0^L \frac{dz'}{L} \sin(\beta_n z')\rho_{ion}(r',z')} \\
& + [K_0(\beta_n a)I_1(\beta r) + I_0(\beta_n a)K_1(\beta_n r)] \int_r^b dr' \, \frac{K_0(\beta_n b)I_0(\beta r') - I_0(\beta_n b)K_0(\beta_n r')}{K_0(\beta_n r')I_1(\beta_n r') + K_1(\beta_n r')I_0(\beta_n r')} \\
& \qquad \boxed{\int_0^L \frac{dz'}{L} \sin(\beta_n z')\rho_{ion}(r',z')} \Big]
\end{aligned}$$

$$\beta_n = n\pi/L$$

In practice one needs ~n=500 first terms

Calculation of the distortions II (K. Fujii)

The Langevin equation gives the modification of the drift velocity :

$$\langle \boldsymbol{v} \rangle = \left(\frac{\tau}{1+(\omega\tau)^2} \right) \left[1 + (\omega\tau)\hat{\boldsymbol{B}} \times + (\omega\tau)^2 \hat{\boldsymbol{B}}\,\hat{\boldsymbol{B}} \cdot \right] \frac{e}{m} \boldsymbol{E}$$

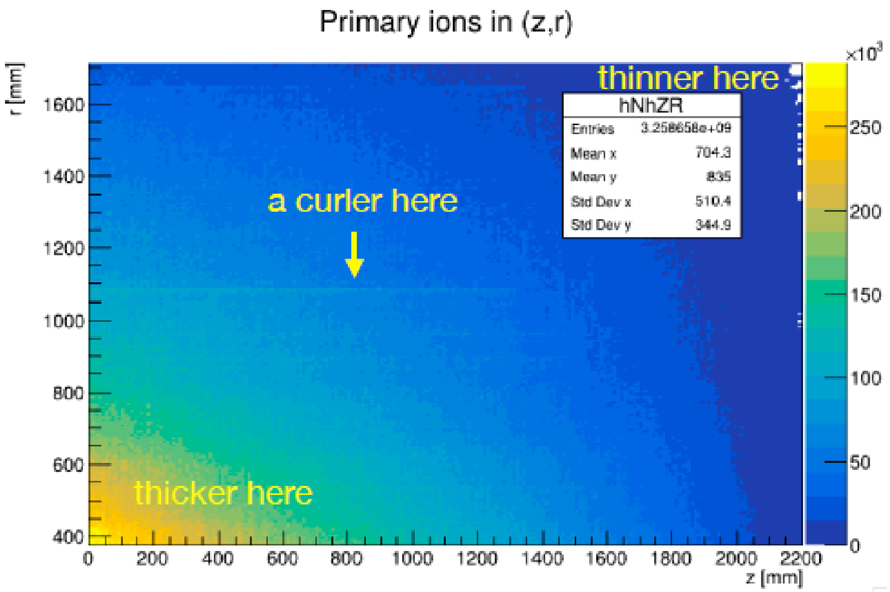
$$\Delta \langle \boldsymbol{v} \rangle = \frac{e}{m} \left(\frac{\tau}{1+(\omega\tau)^2} \right) \left[(1+(\omega\tau)^2) \Delta \boldsymbol{E}_{\parallel} + \boldsymbol{E}_{\perp} - (\omega\tau) \boldsymbol{E}_{\perp} \times \hat{\boldsymbol{B}} \right]$$

$$\boxed{\begin{aligned} \langle \Delta \boldsymbol{x} \rangle &= \sum_{i=1}^{\boxed{n}} \frac{\Delta \langle \boldsymbol{v} \rangle_i}{\langle v_{\parallel} \rangle_i} \delta l_i \\ &\simeq \sum_{i=1}^{\boxed{n}} \delta l_i \left[-\frac{\Delta \boldsymbol{E}_{\parallel i}}{E_0} - \left(\frac{1}{1+(\omega\tau)^2} \right) \frac{\boldsymbol{E}_{\perp i}}{E_0} + \boxed{\left(\frac{\omega\tau}{1+(\omega\tau)^2} \right)} \frac{\boldsymbol{E}_{\perp i} \times \hat{\boldsymbol{B}}}{E_0} \right] \end{aligned}}$$

Positive ion density at the Z peak

- From hadronic Z decays (Toy MC by K.Fujii, full simulation by Daniel Jeans)
- 60 KHz of Z decays : 26 000 ion disks created in the amplification pile-up in the 0.44 s of flushing time of the ions (assuming 5 m/s ion drift velocity)

Primary Ions

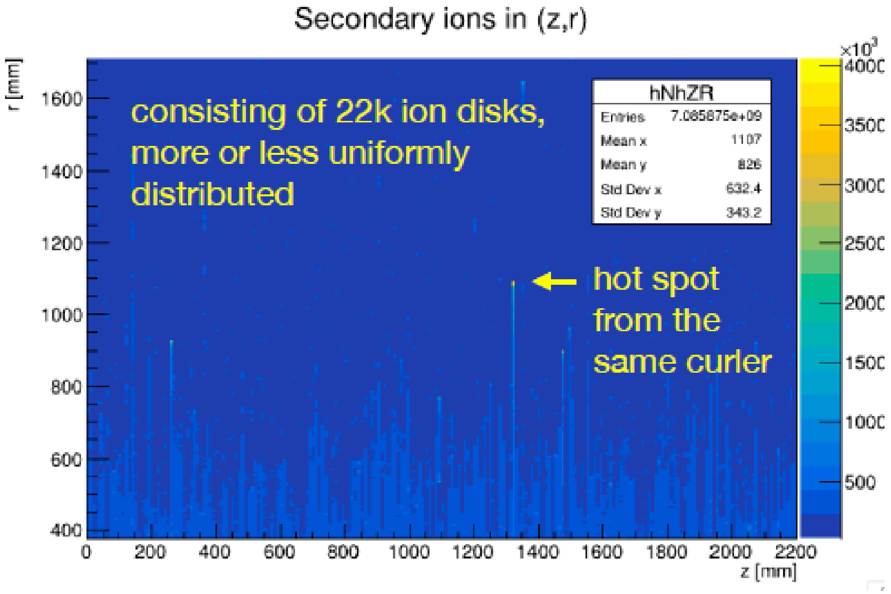


thinner here

a curler here

thicker here

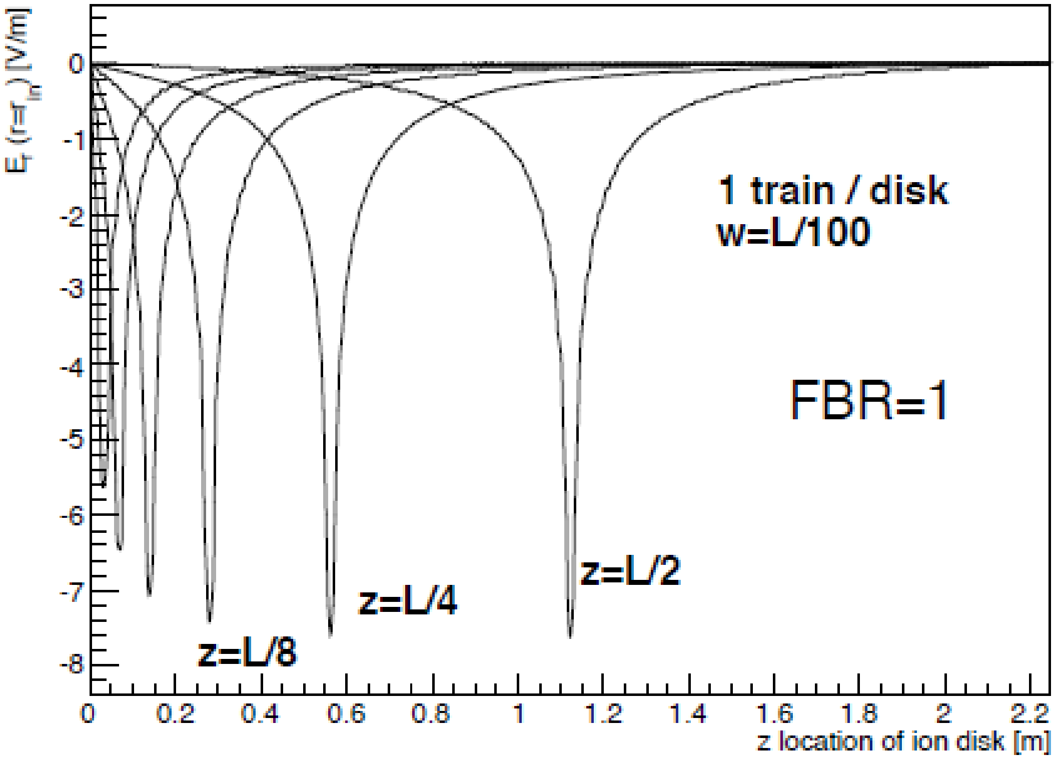
Ion Back Flow



consisting of 22k ion disks, more or less uniformly distributed

hot spot from the same curler

Er(r=rin, z) for different disk locations in “z”



Case of FCC or CEPC at Z pole : almost continuous set of disks.

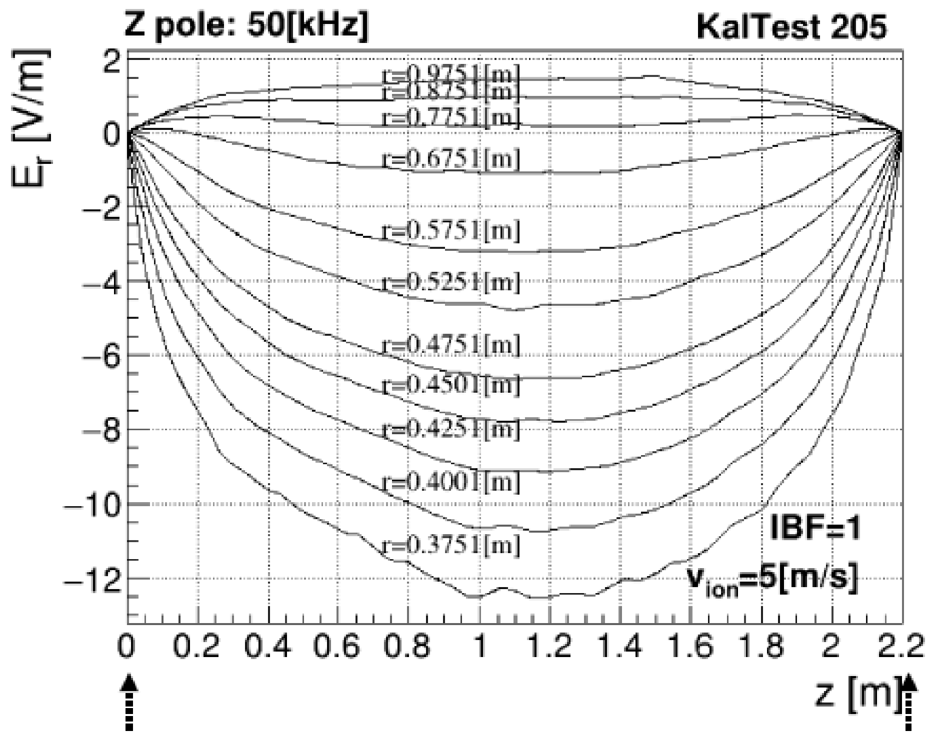
https://agenda.linearcollider.org/event/5504/contributions/24543/attachments/20144/31818/PositiveionEffects-kf.pdf

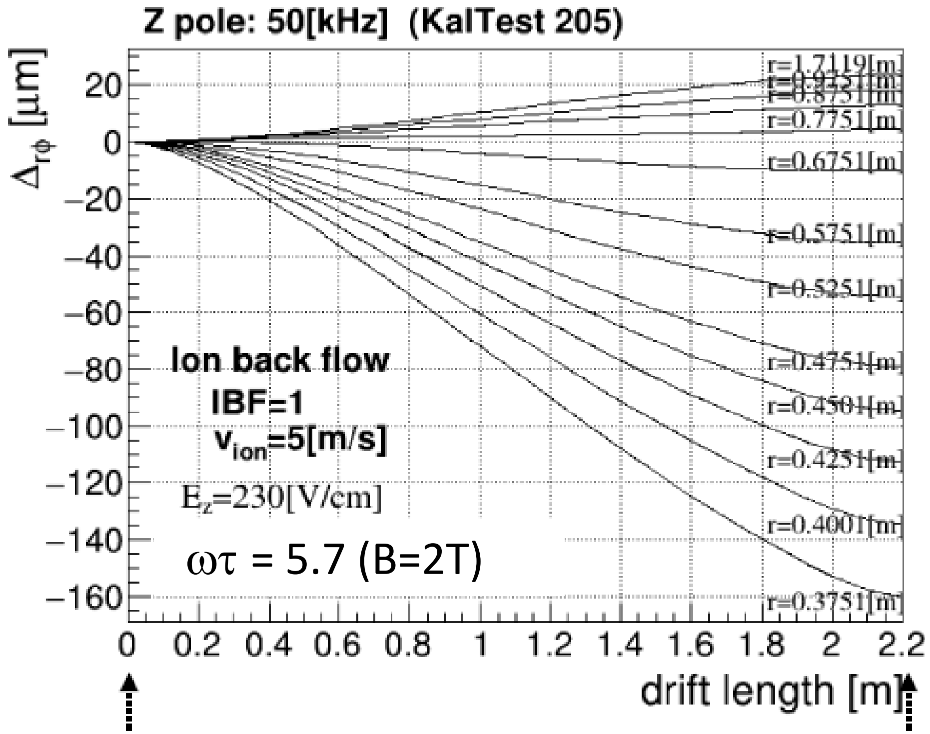
Z pole run: hadronic Z event rate: **50 [kHz]** (toy MC using pythia8)

v_{ion} = 5 [m/s]

IBF*Gain=1

K. Fujii





cathode at z=0

anode at z=2.2[m]

anode

cathode

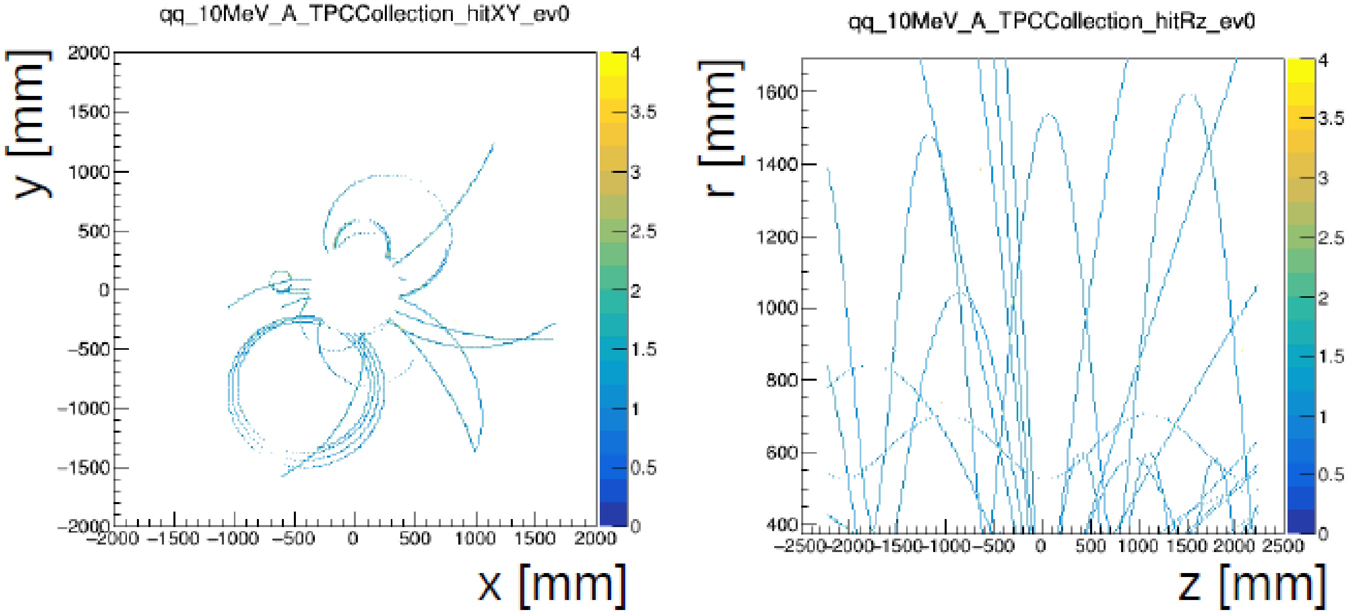
bin size: (Δz, Δr)=(1[cm], 0.5[cm])

Glitches correspond to hot spots in ρ_{ion}, which seem to be averaged out in Δrφ

Maximum distortion ~160 [μm] at the innermost region for hadronic Z rate of 50 [kHz]

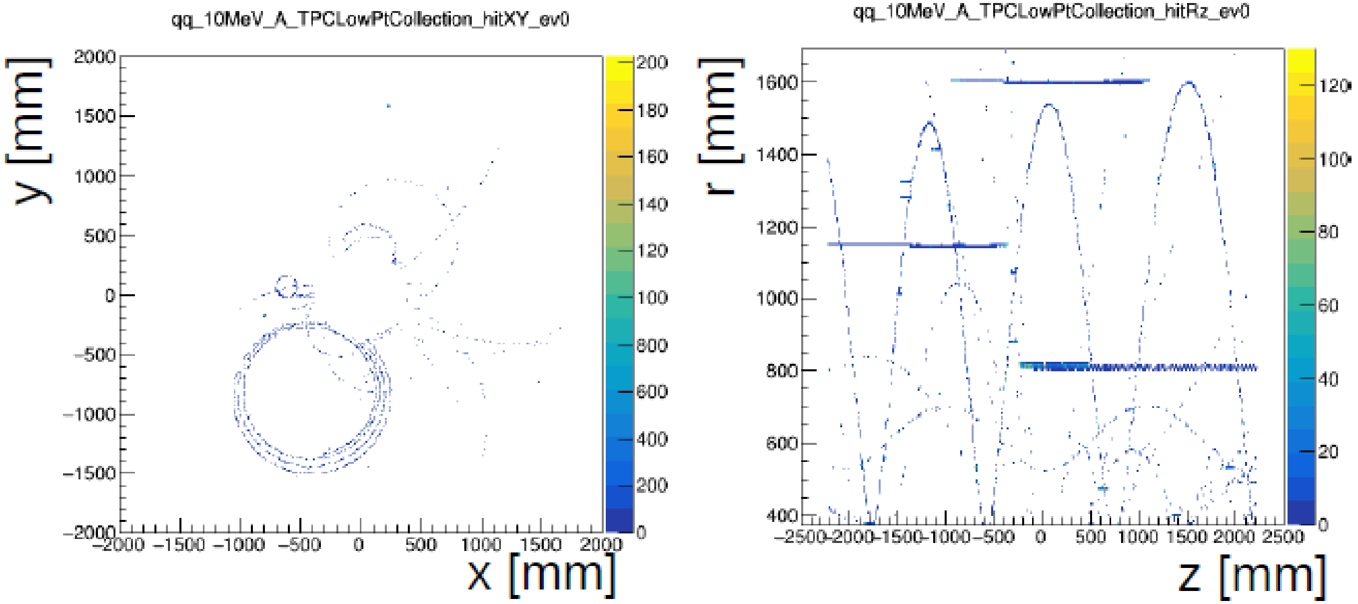
one event

hits associated to track with
pT > 10 MeV
“high pT”



pT < 10 MeV
“low pT”

typically delta-rays along main tracks
some long micro-curlers



D. Jeans

Resulting distortions at Z pole for IBF*gain=5 ~800 µm (preliminary)
(330 µm if IBF can be fully suppressed…)

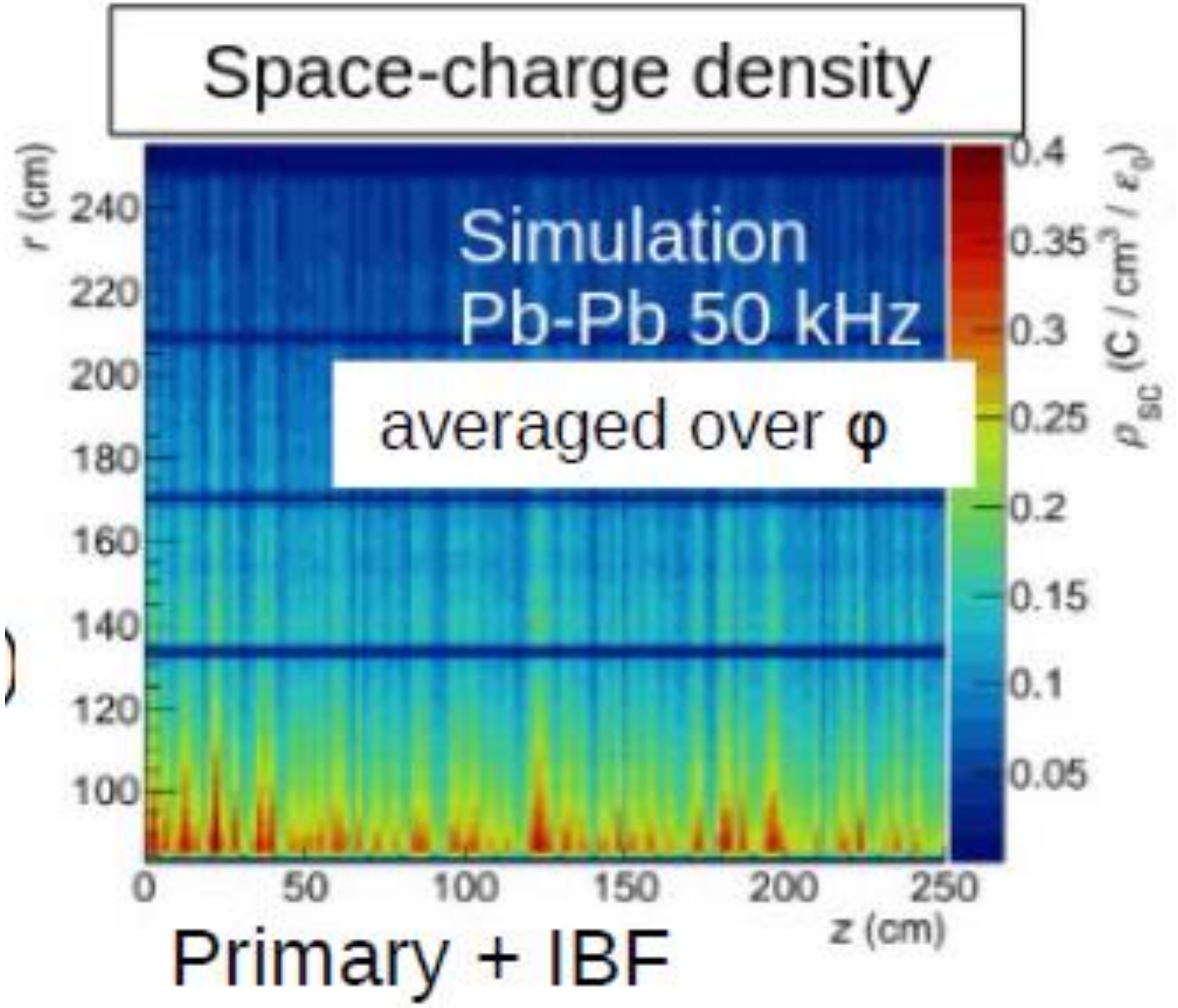
Can it be corrected for?
Only on average, or the charge must be locally measured. This is difficult, as the micro-curlers saturate the amplifiers.

Maybe only way, in Gridpix, using the segmented mesh of the chips : monitor the mesh current of each chip.

Similar situation in ALICE at LHC Run3. IBF~1%, gain=2000.
200 ms ion drift

50 kHz lead-lead collisions.
-> the ions of 10 000 collisions pile-up in a TPC length.

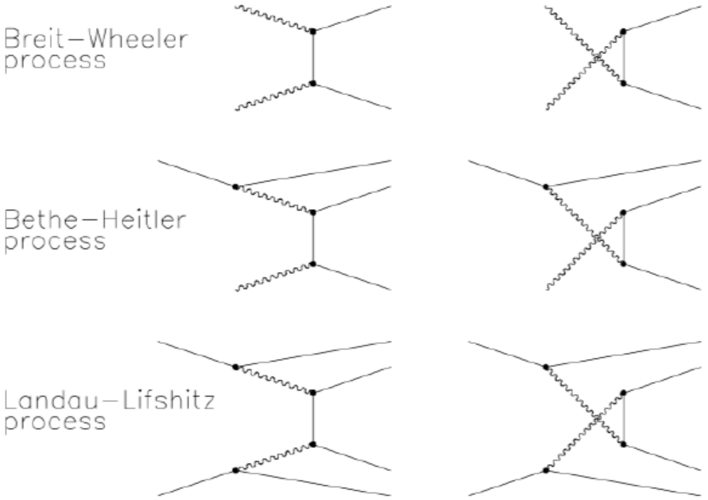
Space-charge density cause distortions up to several cm, varying with instantaneous luminosity and fluctuating. Measurement of the space charge (from integrated currents) necessary.



ALICE, Jens Wiechula, LCTPC collaboration meeting, Jan 18, 2023.

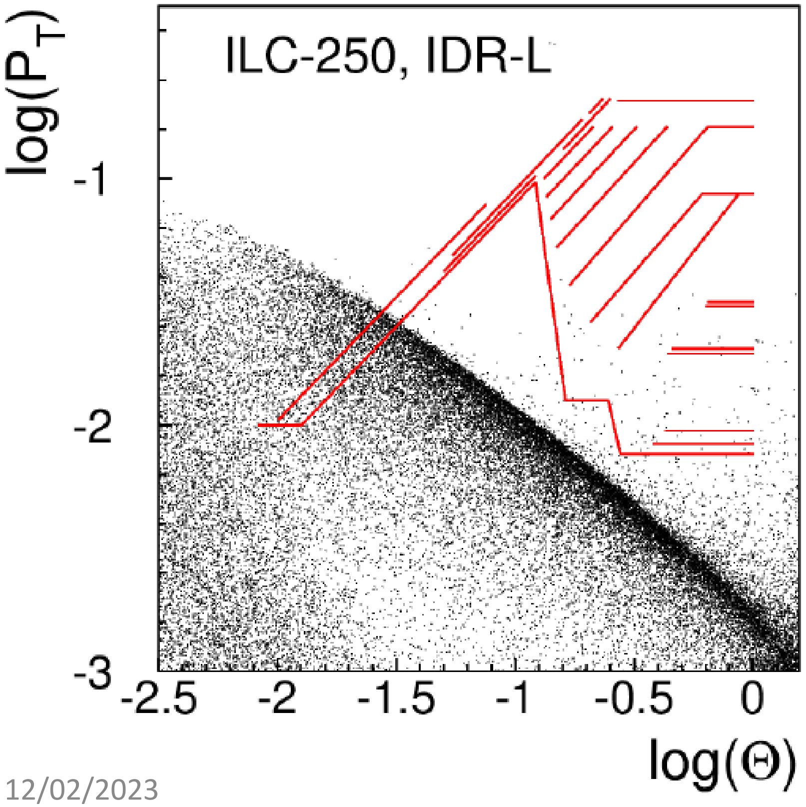
Pair production background

Studied with GUINEA-PIG MC (ILC, D. Schulte 2003, A. Vogel 2007)
and GUINEA PIG++ (FCC, E. Perez 2019, A. Ciarma 2022)

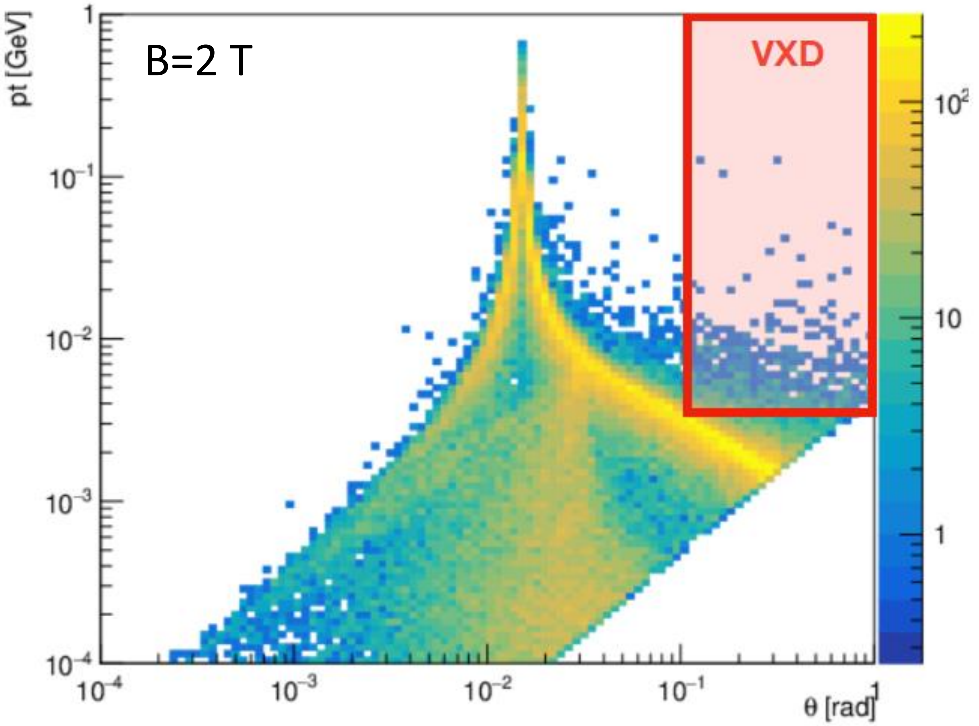


ILC 250 GeV

B=3.5 T



FCC 91.2 GeV

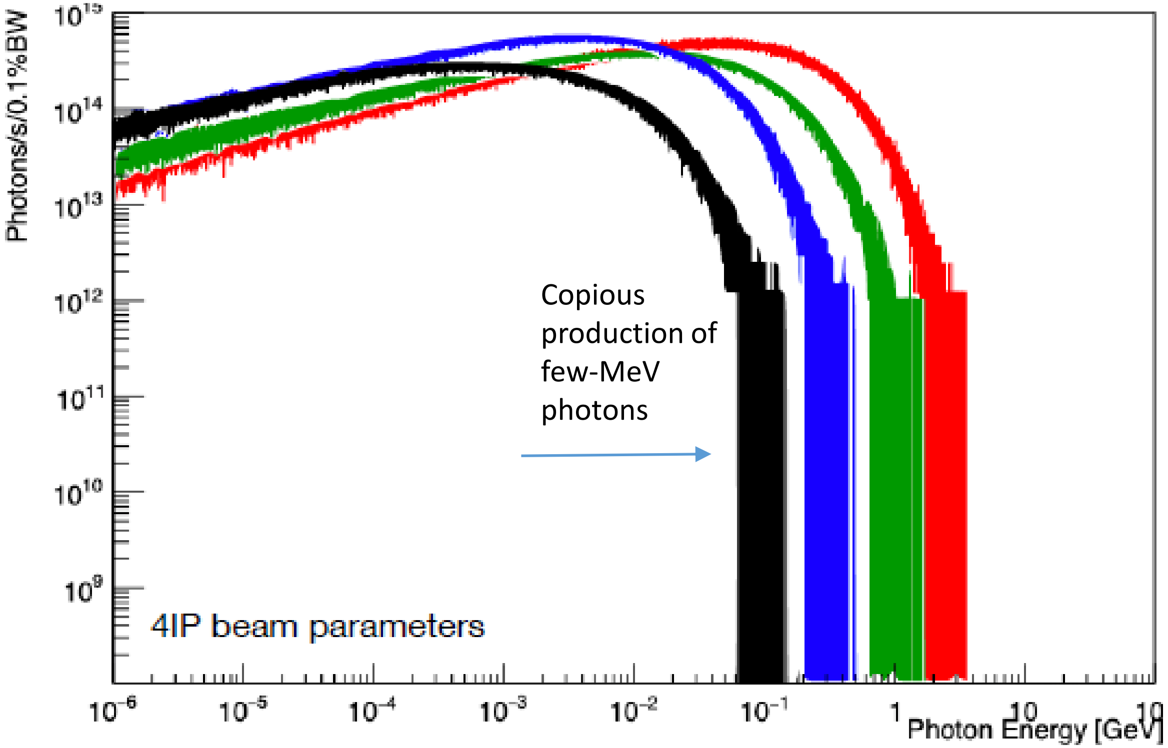


Beamstrahlung photons at FCC

Enormous power radiated and copious photon production with energy of a few MeV: will produce e+e- pairs in the TPC gas if not extracted

Also beam-gas background is being assessed

A. Ciarma



Copious production of few-MeV photons

	Total Power [kW]	Mean Energy [MeV]
Z	370	1.7
WW	236	7.2
ZH	147	22.9
Top	77	62.3

SUMMARY

- Running a TPC @ Z pole @ 2. 10^{36} cm^{-2} s^{-1} is not trivial
- 60 kHz of Z decays means 1 decay every 1.2 mm on average
- The positive ions of 22 000 Zs will accumulate in the TPC volume before drifting out, causing distorsion of several 100 µm at least
- The ion backflow has to be suppressed drastically
- A continuous DAQ and tracking will be necessary, with real-time corrections for space point distortions
- The experience from ALICE at LHC (50 kHz of Pb-Pb collisions) will be crucial
- Control of beam-induced BGs will be crucial, not only at the Z but also at HZ.