Pad TPC towards pixelated TPC technology

Huirong Qi

Institute of High Energy Physics, CAS

March 23 2022

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Motivation of TPC technology

CEPC Accelerator TDR Design

	Higgs	W	Z (3T)	Z (2T)
Number of IPs	2			
Beam energy (GeV)	120	80	45.5	
Circumference (km)	100			
Synchrotron radiation loss/turn (GeV)	1.73	0.34	0.036	
Crossing angle at IP (mrad)	16.5 × 2			
Piwinski angle	3.48	7.0	23.8	
Particles /bunch N_e (10^{10})	15.0	12.0	8.0	
Bunch number	242	1524	12000 (10% gap)	
Bunch spacing (ns)	680	210	25	
Beam current (mA)	17.4	87.9	461.0	
Synch. radiation power (MW)	30	30	16.5	
Bending radius (km)	10.7			
Momentum compaction (10^{-5})	1.11			
β function at IP β_x^*/β_y^* (m)	0.36/0.0015	0.36/0.0015	0.2/0.0015	0.2/0.001
Emittance x/y (nm)	1.21/0.0024	0.54/0.0016	0.18/0.004	0.18/0.0016
Beam size at IP σ_x/σ_y (μm)	20.9/0.06	13.9/0.049	6.0/0.078	6.0/0.04
Beam-beam parameters ξ_x/ξ_y	0.018/0.109	0.013/0.123	0.004/0.06	0.004/0.079
RF voltage V_{RF} (GV)	2.17	0.47	0.10	
RF frequency f_{RF} (MHz)	650			
Harmonic number	216816			
Natural bunch length σ_z (mm)	2.72	2.98		
Bunch length σ_z (mm)	4.4			
Damping time $\tau_x/\tau_y/\tau_E$ (ms)			849.5/849.5/425.0	
Natural Chromaticity			-491/-1161	-513/-1594
Betatron tune	363.10 / 365.22			
Synchrotron tune	0.065	0.040	0.028	
HOM power/cavity (5 cell) (kW)	0.46	0.75	1.94	
Natural energy spread (%)	0.100	0.066	0.038	
Energy spread (%)	0.134	0.098	0.080	
Energy acceptance requirement (%)	1.35	0.90	0.49	
Energy acceptance by RF (%)	2.06	1.47	1.70	
Photon number due to beamstrahlung	0.082	0.050	0.023	
Beamstruhlung lifetime /quantum lifetime† (min)	80/80	>400		
Lifetime (hour)	0.43	1.4	4.6	2.5
F (hour glass)	0.89	0.94	0.99	
Luminosity/IP (10^{34} cm^{-2}s^{-1})	3	10	17	32

† include beam-beam simulation and real lattice

2018 CDR Baseline Design

	ttbar	Higgs	W	Z
Number of Ips	2			
Circumference [km]	100.0			
SR power per beam [MW]	30			
Half crossing angle at IP [mrad]	16.5			
Bending radius [km]	10.7			
Energy [GeV]	180	120	80	45.5
Energy loss per turn [GeV]	9.1	1.8	0.357	0.037
Piwinski angle	1.21	5.94	6.08	24.68
Bunch number	35	249	1297	11951
Bunch population [10^10]	20	14	13.5	14
Beam current [mA]	3.3	16.7	84.1	803.5
Momentum compaction [10^-5]	0.71	0.71	1.43	1.43
Beta functions at IP (bx/by) [m/mm]	1.04/2.7	0.33/1	0.21/1	0.13/0.9
Emittance (ex/ey) [nm/pm]	1.4/4.7	0.64/1.3	0.87/1.7	27/1.4
Beam size at IP (sigx/sigy) [um/nm]	39/113	15/36		35
Bunch length (SR/total) [mm]	2.2/2.9	2.3/		2.5/8.7
Energy spread (SR/total) [%]	0.15/0.20		0.07/0.14	0.04/0.13
Energy acceptance (DA/RF) [%]	2.3	2.2	1.2/2.5	1.3/1.7
Beam-beam parameters (ksix/ksiy)	0.071	0.015/0.11	0.012/0.113	0.004/0.127
RF voltage [GV]	10	2.2	0.7	0.12
RF frequency [MHz]	650	650	650	650
HOM power per cavity (5/2/1cell)[kw]	0.4/0.2/0.1	1/0.4/0.2	-/1.8/0.9	-/-/5.8
Qx/Qy/Qs	0.12/0.22/0.078	0.12/0.22/0.049	0.12/0.22/	0.12/0.22/
Beam lifetime (bb/bs)[min]	81/23	39/18	60/717	80/182202
Beam lifetime [min]	18	12.3	55	80
Hour glass Factor	0.89	0.9	0.9	0.97
Luminosity per IP[1e34/cm^2/s]	0.5	5.0	16	115

2021 Improved Design

67%⇑

259%⇑

Even higher↑

- https://indico.cern.ch/event/1129966/contributions/4747428/attachments/2404058/4112102/ECFAMIniWS-2.pdf
- CEPC Study Group. "CEPC Conceptual Design Report: Volume 2-Physics & Detector." arXiv:1811.10545 (2018).

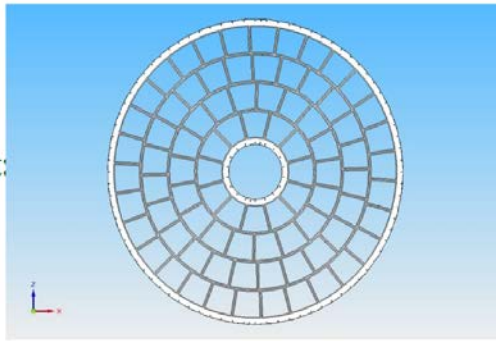
Pad TPC technology

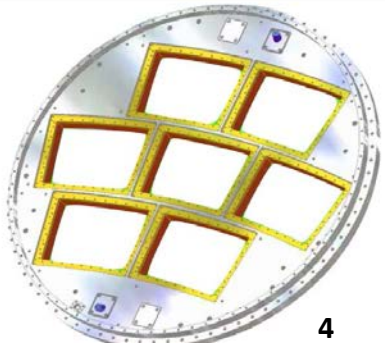
- At a circular collider CEPC there is place for different experiments, one of the detector concept could use a TPC as the main tracker.
- For Higgs, W and top running **no problem** for all TPC read out technologies.
- Laser TPC prototype has been successfully developed **in last 6 years** at IHEP.

- https://agenda.linearcollider.org/event/5504/contributions/24543/attachments/20144/31818/PositiveIonEffects-kf.pdf
- https://indico.fnal.gov/event/46746/contributions/208077/attachments/141125/177798/LCTPC.pdf
- Di Meglio, Alberto, et al. CERN Quantum Technology Initiative Strategy and Roadmap. No. CERN-OPEN-2021-012. 2021
- arXiv:1902.01987 [physics.ins-det, 2019] Yuan, Zhiyang, et al. "Feasibility study of TPC detector at high luminosity Z pole on the circular collider." International Journal of Modern Physics A 36.22 (2021): 2142015.
- Chang, Y., et al. "Performance of the continuous ions suppression TPC prorotype for circular collider." Journal of Instrumentation 15.09 (2020): C09065.

Pad TPC for collider

- Active area: $2\times10m^2$
- One option for endplate readout:
  - GEM or Micromegas
  - 1×6 mm² pads
  - 10^6 Pads
  - 84 modules
  - Module size: $200\times170mm^2$
  - Readout: Super ALTRO
  - CO_2 cooling



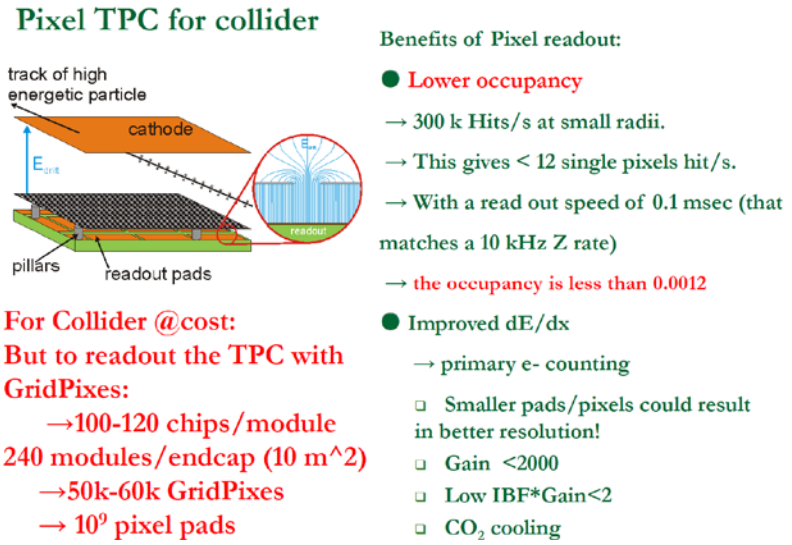


Pixelated TPC technology

- Running at the Z with high luminosities (Lumi.=200 10^34 cm-2 s-1) and high rates is however **problematic** for current pad technologies.
- Tracks will overlap in the read-out plane and the occupancy at low radius will become too high.
- The distortion effect could be significantly reduced (Gain:<2000, even only primary ions, laser calibration) using pixelated TPC, thus it can work at high luminosity.

A pixelated TPC is a realistic option at the CEPC and provides:

- Readout that can deal with high rates
- High precision tracking in the transverse and longitudinal planes
- dE/dx by electron and cluster counting
- Excellent two track resolution



- Ligtenberg, Cornelis. "A GridPix TPC readout for the ILD experiment at the future International Linear Collider." PhD Thesis (2021).
- https://arxiv.org/abs/1902.05519
- https://www.sciencedirect.com/science/article/pii/S0168900216303692

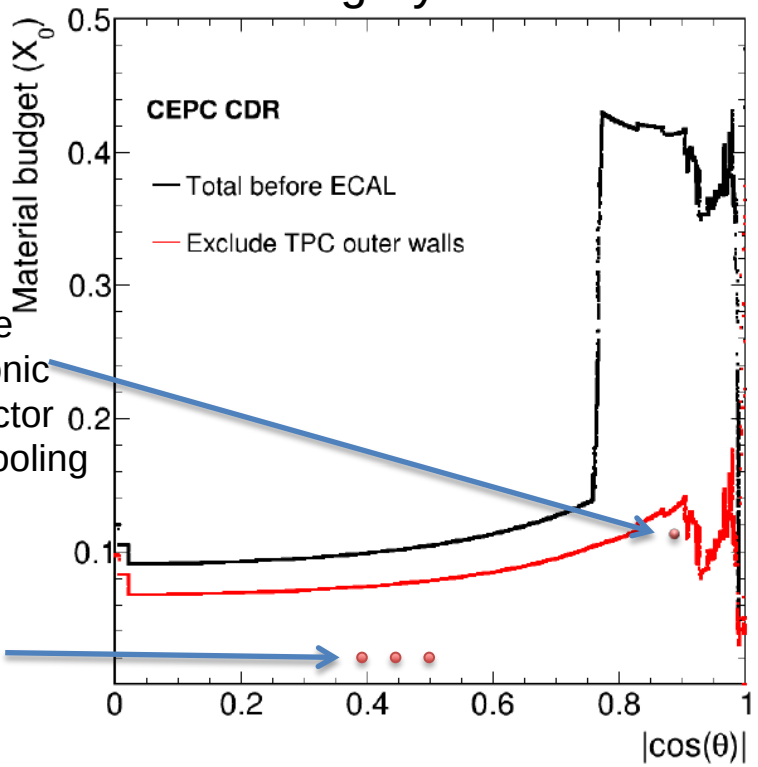
- **Feasibility of pixelated TPC**
  - **Material budget of endplate/chamber**
  - **Ions affect and distortion**
  - **Occupancy**
  - **Channels and power consumption**
  - **Running at 2 Tesla**
  - **Cost estimation**
  - **Improved dE/dx+dN/dx**
  - **Optimization of pad size**

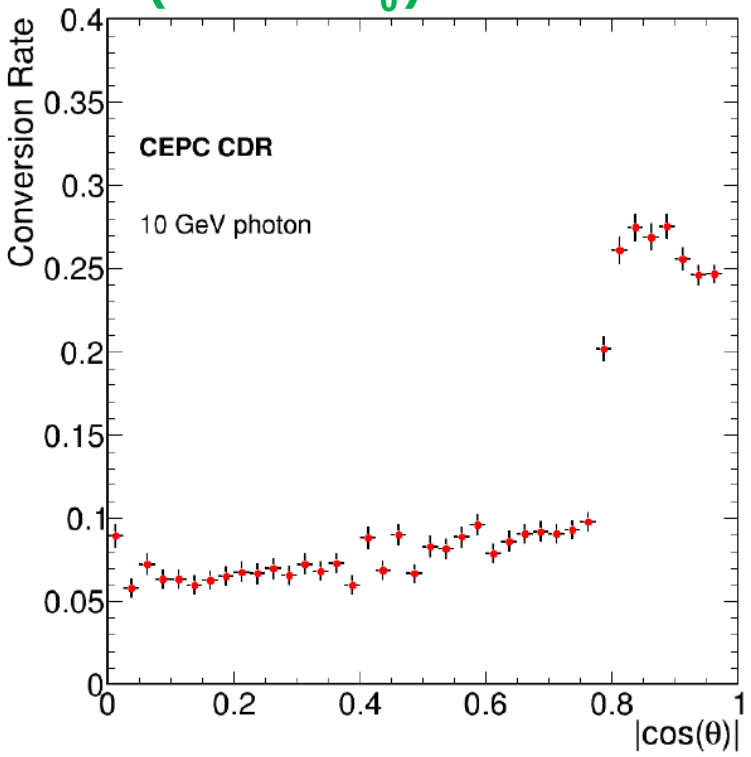
Material budget of endplate/chamber

- The readout Pad TPC and pixelated TPC just is different, all of the structure and material budget is **similar.**
- Material budget of the TPC central region is **very light** filled with gas.
- Material budget of the endplate including the electronic and light structure cooling system **is reasonable (<10 % X_0)**.

TPC endcap structure +electronic +connector +CO_2 cooling

TPC central region





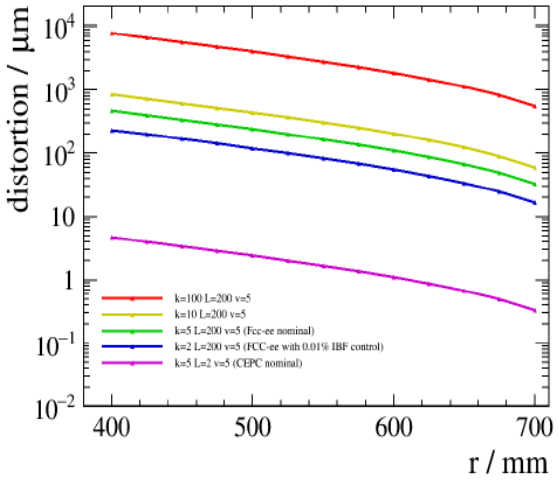
Amount of material in the unit of radiation length inside the tracker

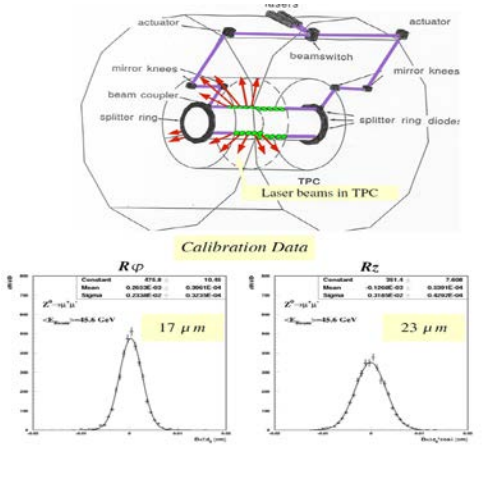
- https://arxiv.org/abs/1811.10545
- https://arxiv.org/abs/1306.6329
- http://flc.desy.de/lcnotes/notes/LC-DET-2014-005.pdf

Ions affect and distortion

- With pixelated TPC, since the intrinsic capacitance is smaller, the noise level is lower, thus the detector can afford **lower gain**.
- Ion back flow of module is measured to IBF*Gain <1+ at gain 2000. The maximum distortion is **no solid evidence** to show unreasonable at high lumi till now. Beam background should be carefully reduced too.
- New strategy of LCTPC raised a task to extend to high lumi .
- Calibration could be fit to data.
  - Muon pairs from Z decays with its kinematic constraints provided a unique reaction to measure residual distributions in the TPC.
  - UV laser system could be as a useful calibration method.

- https://agenda.linearcollider.org/event/9640/contributions/50297/attachments/38019/59677/PositiveIonEffects-kf.pdf
- https://doi.org/10.1088/1748-0221/12/07/P07005
- E. Nappi et al., Alice time projection chamber, Technical Report ALICE-TDR-007 (2000).
- https://www.arxiv-vanity.com/papers/nucl-ex/010
- http://rnc.lbl.gov/~jhthomas/public/ThomasTPCReview.pdf1013/
- https://agenda.linearcollider.org/event/9533/contributions/49842/
- https://indico.cern.ch/event/995633/contributions/4259406/attachments/2210919/3741704/LCWS_TPC_IHEP_20210318_.pdf
- https://arxiv.org/abs/1406.6400
- https://www.nbi.dk/~borge/tpclaser/presentations/Laser-DCS-020927.ppt





IBF and calibration for the pixelated TPC

Rate and occupancy

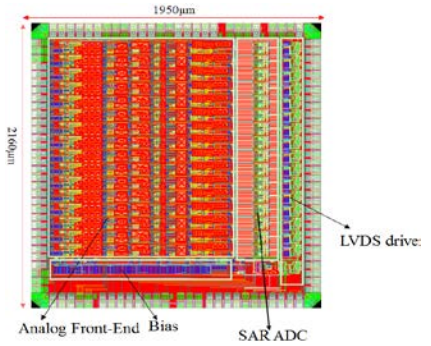
- Ring 100 km -> time one circumference = 333.3 us
- 119521 bunches -> time between crossings = 17 ns (+10% gap)
  - Lumi. = 115 10^34 cm-2 s-1
  - Z0 hadronic cross section = 30.5 nb; average multiplicity ~16
- Using a simulation program the primary Z hit rate in the pixel TPC is calculated as a function of the radius.
- The rate amount to 350 k hits /s at a radius of 40 cm.
- **This is a rate the current quad and read out can easily handle.**
- The test beam showed Timepix can handle up to 2.6M hits/s per chip (1.42x1.42 cm^2). So about a factor 10 higher than what is needed.
- **Occupancies are less than 0.01 at low radii**
- **MPGD as readout could handle the high rate and the occupancy is fine.**

- https://indico.cern.ch/event/1096427/contributions/4671385/attachments/2371853/4051779/HongKong_pixelTPC_2022.pdf (IAS Hong Kong Conference 2022)
- https://agenda.linearcollider.org/event/9533/contributions/49877/attachments/37750/59199/LCTPC_pixelTPC_2022.pdf (LCTPC Collaboration Meeting 2022)

Channels and power consumption

- Pixelated TPC @10^9
  - Power consumption of Gridpix: ~1 A @ 2 V (2W) depending on rate
  - All power: 20kW
  - 1W/cm^2, No optimization
  - **TPX4: <500mW/cm^2 (plan)**
- Pad TPC @ 5×10^5
  - WASA ASIC chip: 2.49 mW/ch@40 MS/s
  - All power：<1.2kW/endplate
  - **300mW/cm^2**
- Optimization pad
  - Pad size will be optimized as 300um×300um
  - **Channels: 10^6 -10^7**
  - All power:<1.8kW/endplate
  - **<400mW/cm^2**
- 2-phase CO_2 Cooling could be selected.

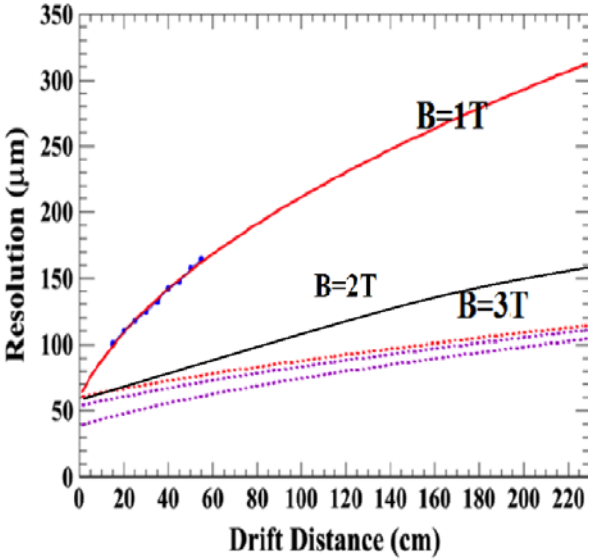
	AGET	PASA+ALTRO	Super-ALTRO	SAMPA
TPC	T2K	ALICE	ILC	ALICE upgrade
Pad尺寸	6.9x9.7 mm²	4x7.5 mm²	1x6 mm²	4x7.5 mm²
通道数	1.25 x 10^5	5.7x 10^5	1-2 x 10^6	5.7 x 10^5
读出结构	MicroMegas	MWPC	GEM/MicroMegas	GEM
增益	0.2-17 mV/fC	12 mV/fC	12-27 mV/fC	20/30 mV/fC
成型方式	CR-(RC)²	CR-(RC)⁴	CR-(RC)⁴	CR-(RC)⁴
达峰时间	50 ns-1us	200 ns	30-120 ns	80/160 ns
ENC	850 e @ 200ns	385 e	520 e	482 e @ 180ns
波形采样方式	SCA	ADC	ADC	ADC
采样率	1-100 MSPS	10 MSPS	40 MSPS	10 MSPS
精度	12 bit(external)	10 bit	10 bit	10 bit
功耗	<10 mW/ch	32 mW/ch	47.3 mW/ch	17 mW/ch
CMOS工艺	350 nm	250 nm	130 nm	130 nm

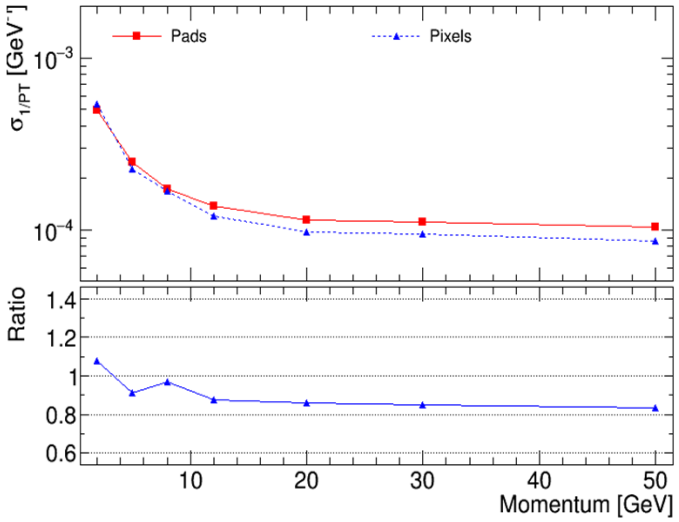


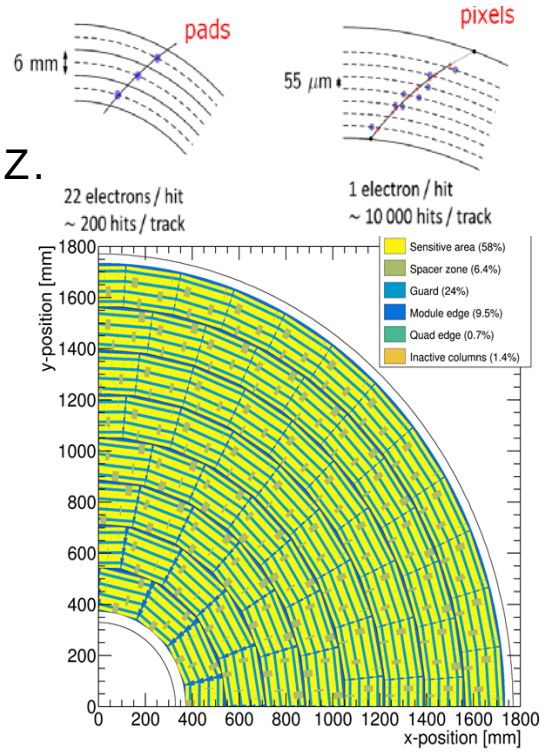
- https://indico.cern.ch/event/850899/contributions/3773052/attachments/2001199/3340572/Xavi_Timepix4.pdf
- https://indico.cern.ch/event/1096427/contributions/4671385/attachments/2371853/4051779/HongKong_pixelTPC_2022.pdf
- https://confluence.desy.de/display/ILD/The+ILD+Design+Report%2C+IDR
- https://www.researchgate.net/publication/341228909_WASA_a_low_power_frontend_ASIC_for_time_projection_chambers_in_65_nm_CMOS
- https://cds.cern.ch/record/2706027/files/ATL-ITK-PROC-2020-001.pdf

Running at 2 Tesla

- TPC can work well at the different magnetic field **without E×B effect**.
- From full simulation the momentum resolution can be determined
- Momentum resolution is **about 15%** better for the pixels with realistic coverage and deltas comparing with same size pad technology.
- TPC geometry could be **optimized and changed** to smaller or larger at 2 Tesla to meet physics requirements at Z.







- https://www.nikhef.nl/pub/services/biblio/theses_pdf/thesis_C_Ligtenberg.pdf
- https://instrumentation2006.lbl.gov/Time_Projection_Chamber_R&D.pdf
- https://www.desy.de/~behnke/LC/tpc.pdf
- CEPC Study Group. "CEPC Conceptual Design Report: Volume 2-Physics & Detector." arXiv:1811.10545 (2018).

Cost estimation

- For the prototype, as know the costs, but they will go down substantially because of prices going down for large numbers. E.g. for 1 module of 100 chips we need 1 wafer 3000 euro plus post processing 3000 euro. (reference from NIKEHF Timpix)
- The total cost of a pad or a pixel readout is **pretty similar**; all readout options need CO2 cooling and electronics and that drives the readout cost.

TPC COST ESTIMATION(unit: *10K RMB)

Total: 180 Millions RMB

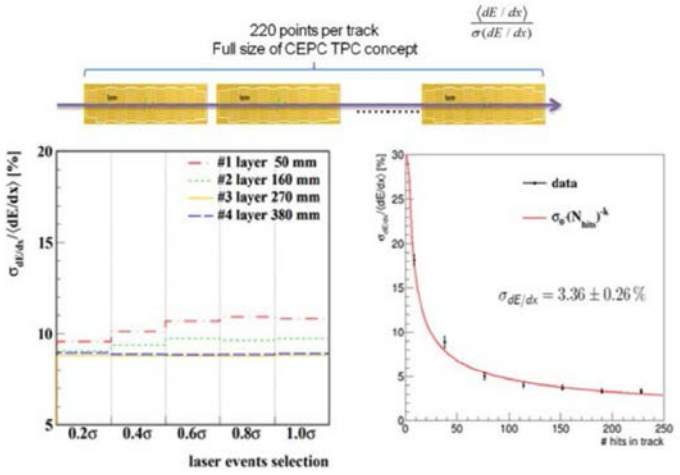
ITEM	DEVICE ITEM	TYPE	UNIT	Quantity	Prive/	Total
3.1	TPC detector (TPC)					18000.00
3.1.1	Chamber					3600.00
3.1.1.1	Fieldcage		set	1	1200.00	1200.00
3.1.1.2	Connector		set	1	800.00	800.00
3.1.1.3	Barrel		set	1	1000.00	1000.00
3.1.1.4	Support device		set	1	600.00	600.00
3.1.2	Readout					2500.00
3.1.2.1	MPGD detector		set	1	800.00	800.00
3.1.2.2	Support board		set	2	600.00	1200.00
3.1.2.3	Readout board		board	200	2.50	500.00
3.1.3	Electronics					10000.00
3.1.3.1	FEE ASIC readout		channel	1200000	0.002	2400.00
3.1.3.2	Cables		set	50000	0.03	1500.00
3.1.3.3	Optical driver		set	50000	0.03	1500.00
3.1.3.4	Optical link, connectors		set	500	1.00	500.00
3.1.3.5	DAQ		set	5000	0.30	1500.00
3.1.3.6	Crate and controller		set	50	20.00	1000.00
3.1.3.7	Cooling sytem		set	1	1600.00	1600.00
3.1.4	Calibration					500.00
3.1.4.1	Calibration system		set	1	500.00	500.00
3.1.5	HV and Gas system					1400.00
3.1.5.1	HV and low power		set	1	800.00	800.00
3.1.5.2	Gas system		set	1	300.00	300.00
3.1.5.3	Monitor system		set	1	300.00	300.00

Including the cooling system

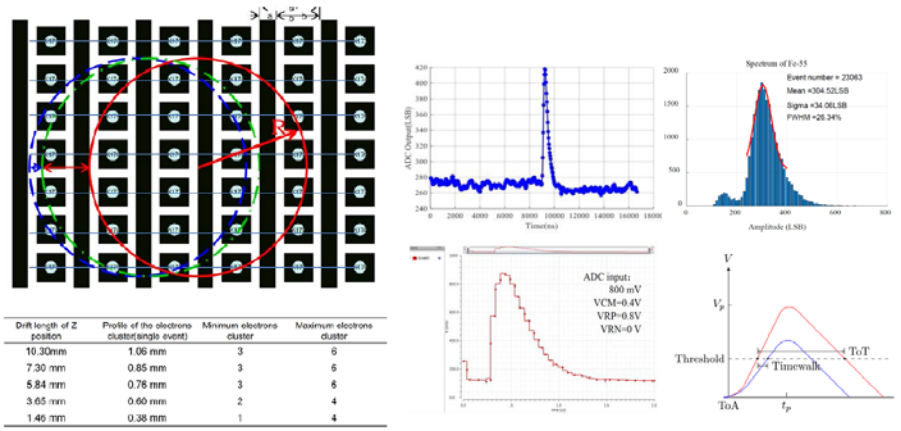
- https://www.semanticscholar.org/paper/International-Large-Detector%3A-Interim-Design-Report-Collaboration/fa917f1bfc07cda27dd3adaa01f466ba1d93a99d/figure/169
- http://ias.ust.hk/program/shared_doc/2018/201801hep/program/exp/HEP_20180119_1145_Manqi_Ruan.pdf
- https://indico.cern.ch/event/777383/contributions/3303091/attachments/1789133/2914027/MB_ACF.pdf

R&D: intermediate solution between pad and pixel

- **R&D plan will mainly focus on making pixelated TPC work**
- **Some key issues R&D**
  - **– improve double hit and double track resolution**
  - **– improved dE/dx to 2% level**
    - Pixel size:(300μm or similar level size)
    - All of channels reduced from 10^9 to 10^7
    - Almost without IBF (Gain< 2000)
    - Micromegas + ASIC Chips (Our option + international collaboration)



Resuls of the laser TPC prototype



Electron cluster profile

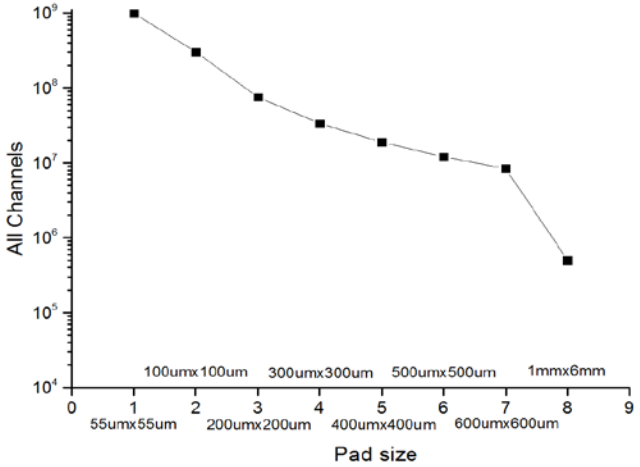
10bit TOT + 12bit TOA

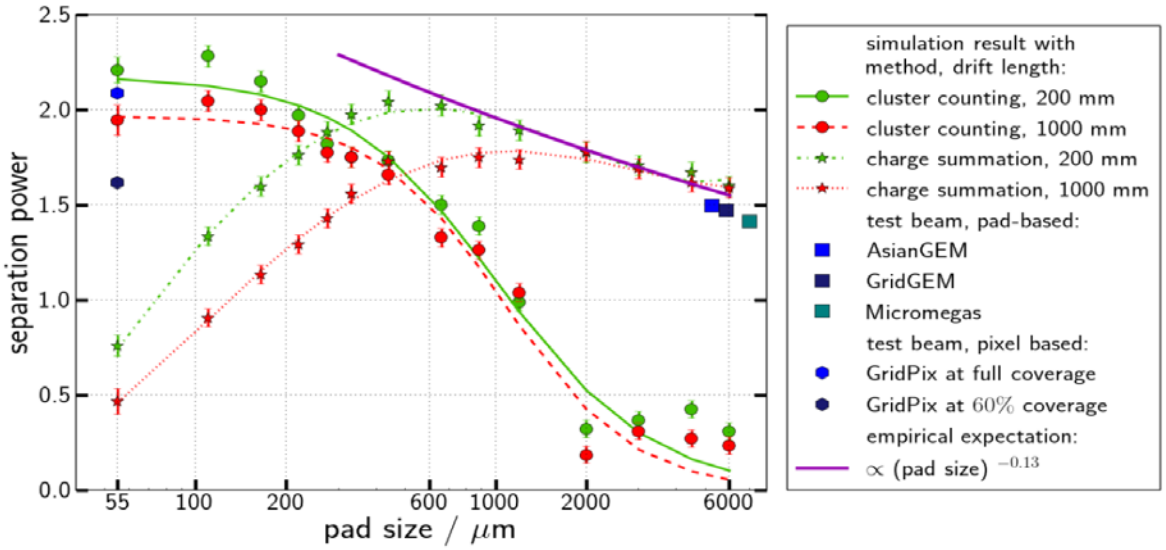
dE/dx along drift length

dE/dx + dN_{cl}/dx

Optimization of pixelated size

- **Pixelated size should be optimized**
  - From 55um×50um to 300um×300um
  - All of channels will be reduced from 10^9 to 10^7
  - Based on the existing Prototype and experimental data results, the pad size could be estimated about 300um×300um or 200um×200um





- https://agenda.linearcollider.org/event/9533/contributions/49862/attachments/37746/59205/2022_01_13%20LCTPC%20Collaboration%20Meeting.pdf
- https://wiki.classe.cornell.edu/pub/ILC/WWS/TrackCornellSim/TPC_Detector_Resp_Sim_LCWS_Paris_19_Apr_2004.pdf
- http://w4.lns.cornell.edu/~dpp/linear_collider/images/talks/20070531-Peterson-LCWS07-SimRecon.pdf

Conclusion

- **Feasibility of pixelated TPC for CEPC**
  - **Material budget of endplate/chamber √**
  - **Occupancy √**
  - **Channels and power consumption √**
  - **Cost estimation √**
  - **Running at 2 Tesla √**
  - **Ions affect and distortion √ (need R&D)**
  - **Improved dE/dx+dN/dx √ (need R&D)**
  - **Optimization of pad size √ (need R&D)**

Many Thanks

Especially thanks to Jianchun, Manqi, Gang, Joao, Xinchou, Zhiyang
Especially thanks to some good inputs from Ron Settle, Peter Kluit, Fujji Keisuke, Paul Colas, Jan Timmermans, Jochen kaminski from LCTPC