Update on Beam Backgrounds at FCCee and CEPC(Tera-Z and Higgs)

Preliminary

Xin She, Huirong Qi, Yue Chang, Jianchun Wang, Manqi Ruan, Mingrui Zhao
Liwen Yu, Jinxian Zhang, Haoyu Shi, Gang Li, Wei Xu

Special thanks to Daniel Jeans/KEK

LCTPC Collaboration Meeting
March 12, 2024

Content

- Motivation and Physics requirements
- Estimation the beam backgrounds of CEPC
- Comparison with FCCee & ILC
- Summary

Phys. requirements on future circular e+e- collider

- Performance & Physics benchmarks: defined
- PFA is essential:
  - BMR < 4% & pursue 3%
  - Highly relevant – and even as the pre-request for excellent JOI & Pid (in jets)
- Phys. Requirements of the track detector
  - TPC can provide hundreds of hits with high spatial resolution compatible with PFA (low X_0)

	Processes @ c.m.s.	Domain	Total Det. Performance	Sub-D
H->ss/cc/sb	vvH @ 240 GeV	Higgs	PFA + JOI (Jet origin id)	All sub-D, especially VTX
Vcb	WW@ 240/160 GeV	Flavor	JOI + Particle (lepton) id	All
W fusion Xsec	vvH @ 360 GeV	Higgs	PFA + JOI	All
α_S	Z->tautau @ 91.2 GeV	QCD	PFA: Tau & Tau final state id	ECAL + Tracker material
B->DK	91.2 GeV	Flavor	PFA + Particle (Kaon) id	All, especially Tracker & ToF
Weak mixing angle	Z	EW	JOI	All
Higgs recoil	llH	Higgs	Leptons id, track dP/P	Tracker, All
H->bb, cc, gg	vvH	Higgs	PFA + JOI	All
	qqH	Higgs	PFA + JOI + Color Singlet id	All
H->inv	qqH	Higgs/NP	PFA	All
H->di muon	qqH	Higgs	PFA, Leptons id	Calo, All
H->di photon	qqH	Higgs	PFA, Photons id	ECAL, All
W mass & Width	WW@160 GeV	EW	Beam energy	NAN
Top mass & Width	ttbar@360 GeV	EW	Beam energy	NAN
Bs->vvPhi	Z	Flavor	Object in jets; MET	All
Bc->tauv	Z	Flavor	-	All
B0->2 pi0	Z	Flavor	Particle/pi-0 in jets	ECAL

Differential Efficiency.
Requirement: Pt threshold ~ o(100) MeV, |cos(theta)| < 0.99
Ref: CDR baseline design

Differential Material Budget.
Requirement: < 10%/50% X0 in Barrel/endcap
Ref: CDR baseline design + BMR & Material Dependence

Differential Resolution of 5 track parameters.
Requirement: In the barrel
δ(D0/Z0) ~ < 3 micro meter at 20 GeV
δ(Pt)/Pt ~ o(0.1%)
Ref: CDR baseline performance

Differential Pid Capability: eff*purity of Kaon id @ Z pole.
Requirement: eff*purity > 90% for all charged Kaon (@ Z pole)
~ relative resolution of dE/dx (or dN/dx) be better than 3%
ToF of 50 ps
Ref: Nuclear Inst. and Methods in Physics Research, A 1047 (2023) 167835

Sep. power: On 3 prong tau decay @ Z pole.
Requirement: efficiency > 99% at 3-prong tau
Ref: CDR baseline performance

Physics requirements (from Manqi Ruan) and requirements on track detectors

CEPC accelerator TDR released in 2023

- CEPC operation stages: **10-years Higgs → 2-years Z pole → 1-year W**
- CEPC phy./det. TDR (**preparation**)
  - Physics and detector concept designed under the principle.
  - **Requirements may be with regard to runs of Higgs and Z-pole separately**.
    - Mandatory requirements MUST be met.
    - Auxiliary requirements, if any, are optional.

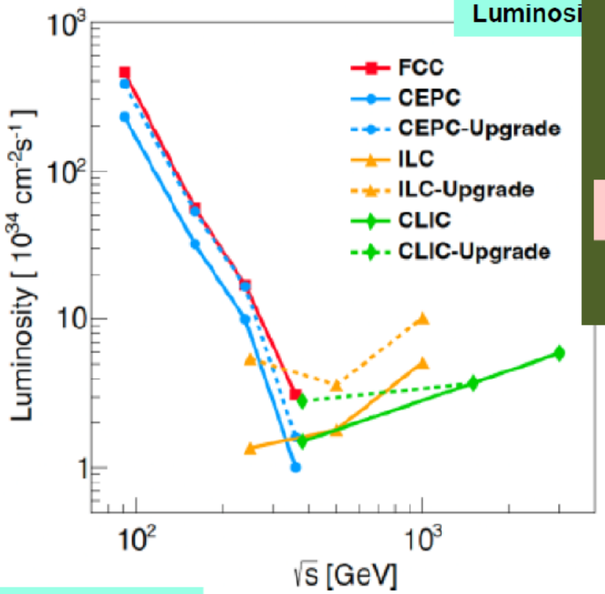
Chapter 3 of this report outlines that the CEPC is planned to be in operation for 8 months annually, totaling 6,000 hours. This operational schedule is used to calculate the cumulative absorbed doses for magnet coil insulations, as illustrated in Figure 4.2.4.16, considering a 10-year Higgs operation, 2-year Z operation, and 1-year W operation. Figure 4.2.4.17 displays the absorbed doses when an additional 5-year $t\bar{t}$ operation is included. These plots also include the upper limit for absorbed dose in epoxy resin, which is measured at 2×10^7 Gy [11].

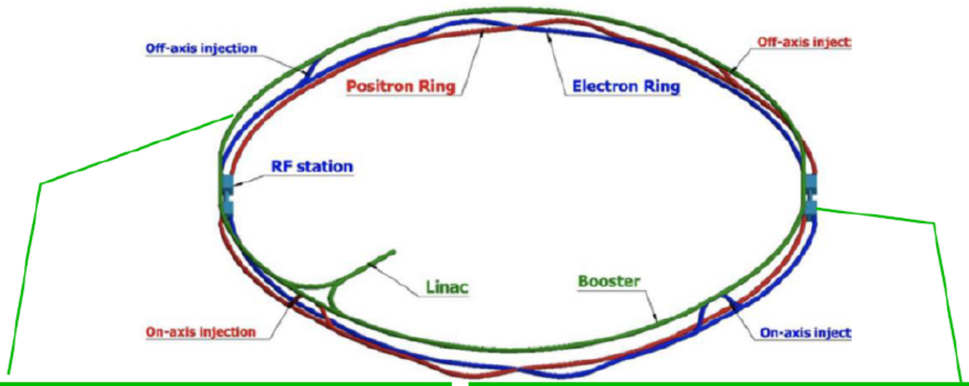
CEPC- TDR p116

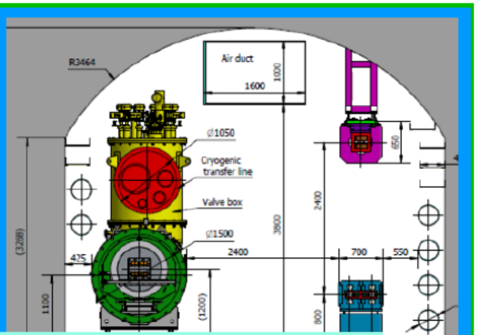
CEPC accelerator TDR design

CEPC TDR design

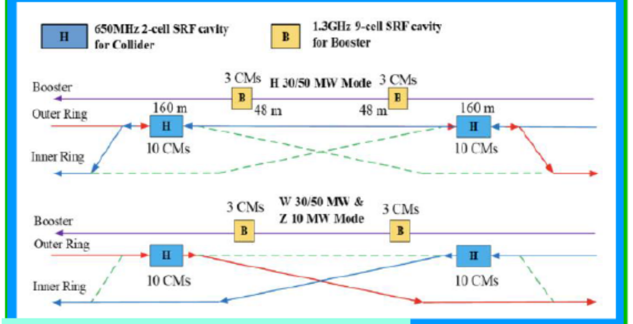
- Circular collider: Higher luminosity than a linear collider
- 100km circumference: Optimum total cost, good also for SppC
- Shared tunnel: Accommodate CEPC booster &collider and SppC
- Switchable operation: Higgs, W/Z, top







Common tunnel for booster/collider & SppC



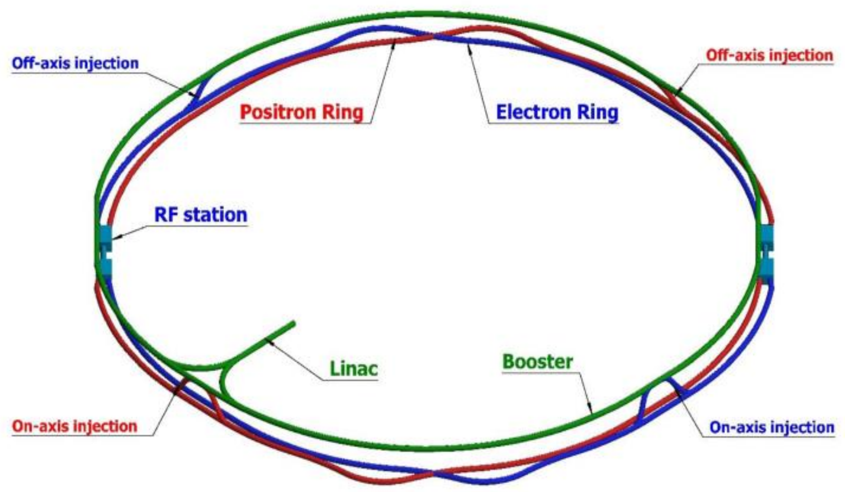
Compatible Operation for Higgs W and Z

Main Parameters: High luminosity as a Higgs Factory

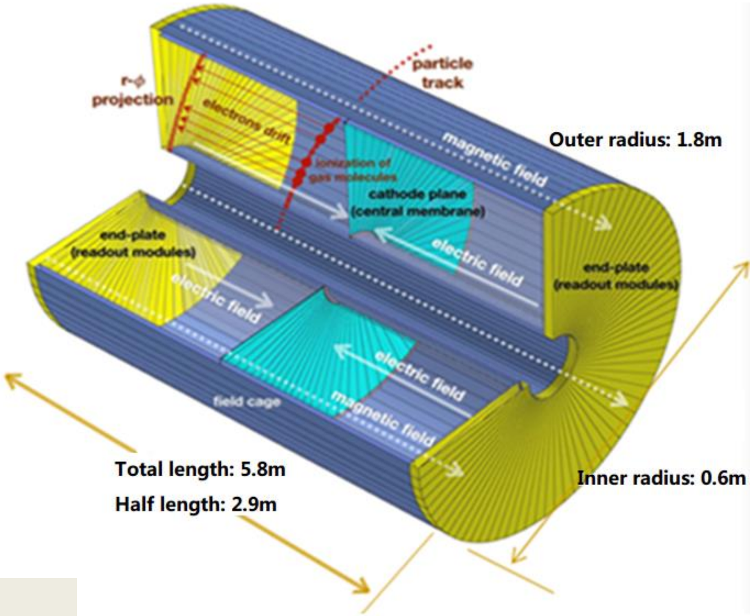
	Higgs	W	Z	ttbar
Number of IPs	2			
Circumference [km]	100.0			
SR power per beam [MW]	**50**			
Energy [GeV]	**120**	**80**	**45.5**	**180**
Bunch number	415	2161	19918	59
Emittance (εx/εy) [nm/pm]	0.64/1.3	0.87/1.7	0.27/1.4	1.4/4.7
Beam size at IP (σx/σy) [um/nm]	15/36	13/42	6/35	39/113
Bunch length (SR/total) [mm]	2.3/3.9	2.5/4.9	2.5/8.7	2.2/2.9
Beam-beam parameters (ξx/ξy)	0.015/0.11	0.012/0.113	0.004/0.127	0.071/0.1
RF frequency [MHz]	650			
Luminosity per IP[10^{34}/cm²/s]	**8.3**	**27**	**192**	**0.83**

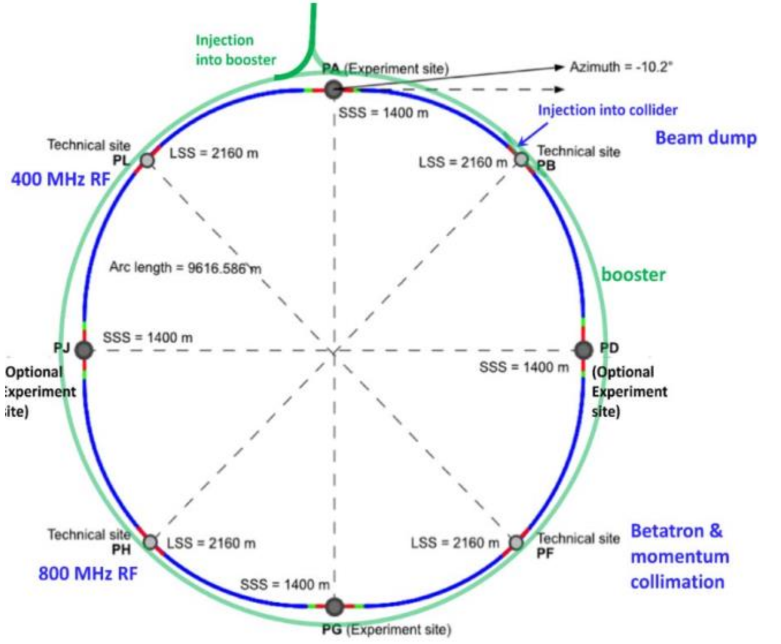
TPC technology for future e+e- collider

- A TPC is the main tracking detector for **some candidate experiments at future e+e- colliders**
    - Baseline detector concept of CEPC and ILD at ILC
    - TPC **selected** as the baseline track detector in CEPC TDR
- Pixelated readout TPC is potential to **improve PID requirements of Flavor Physics** at e+e- collider.
- TPC technology can be of interest for other future colliders (FCC-ee, EIC, KEKb…)



Circular Electron Positron Collider (CEPC)





Future Circular Collider (FCCee)

https://arxiv.org/abs/1811.10545

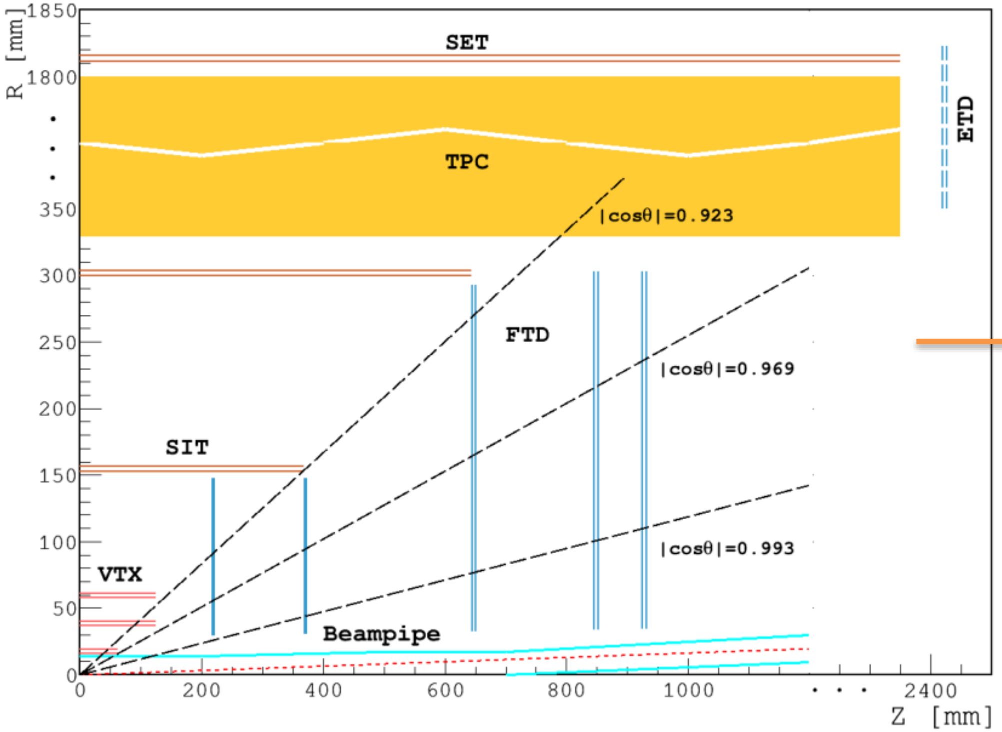
https://arxiv.org/abs/2203.08310

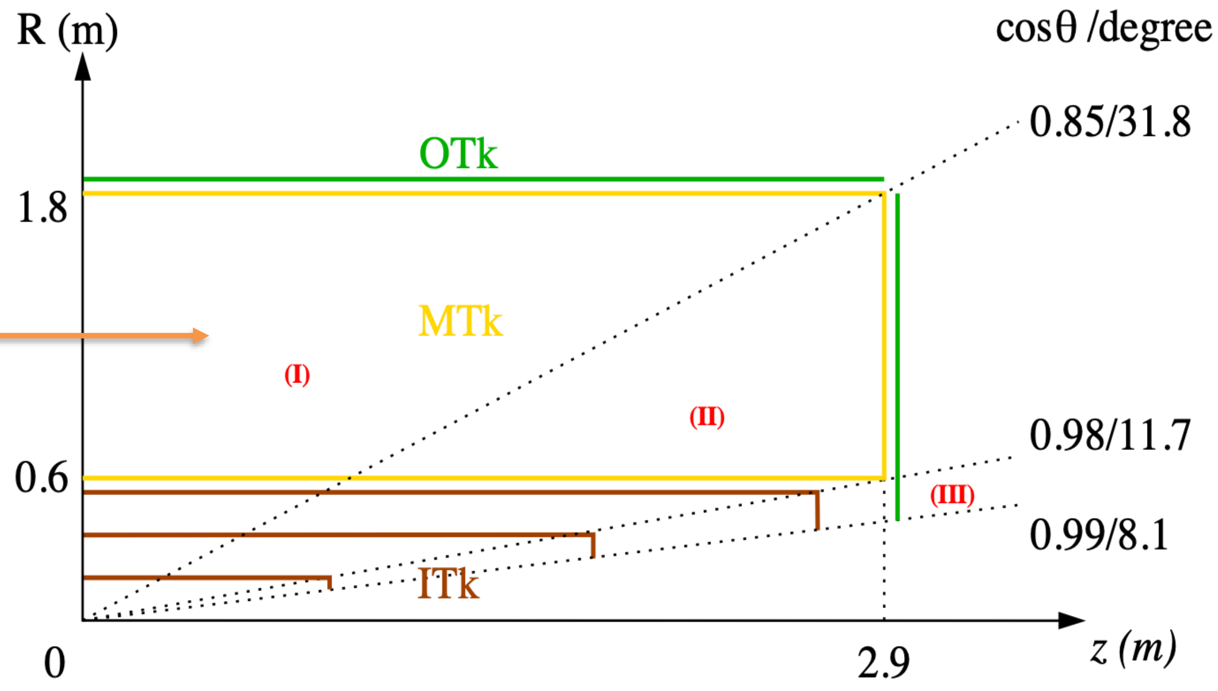
- **Estimation the beam backgrounds of CEPC**

CEPC TPC parameters in TDR

TPC parameters updated in CEPC TDR:

- rMin:0.30m (CDR) → **0.60m (TDR)**
- rMax:1.80m (CDR) → 1.80m (TDR)
- maxDriftLen:2.35m (CDR) → **2.90m (TDR) , cosθ~0.98**

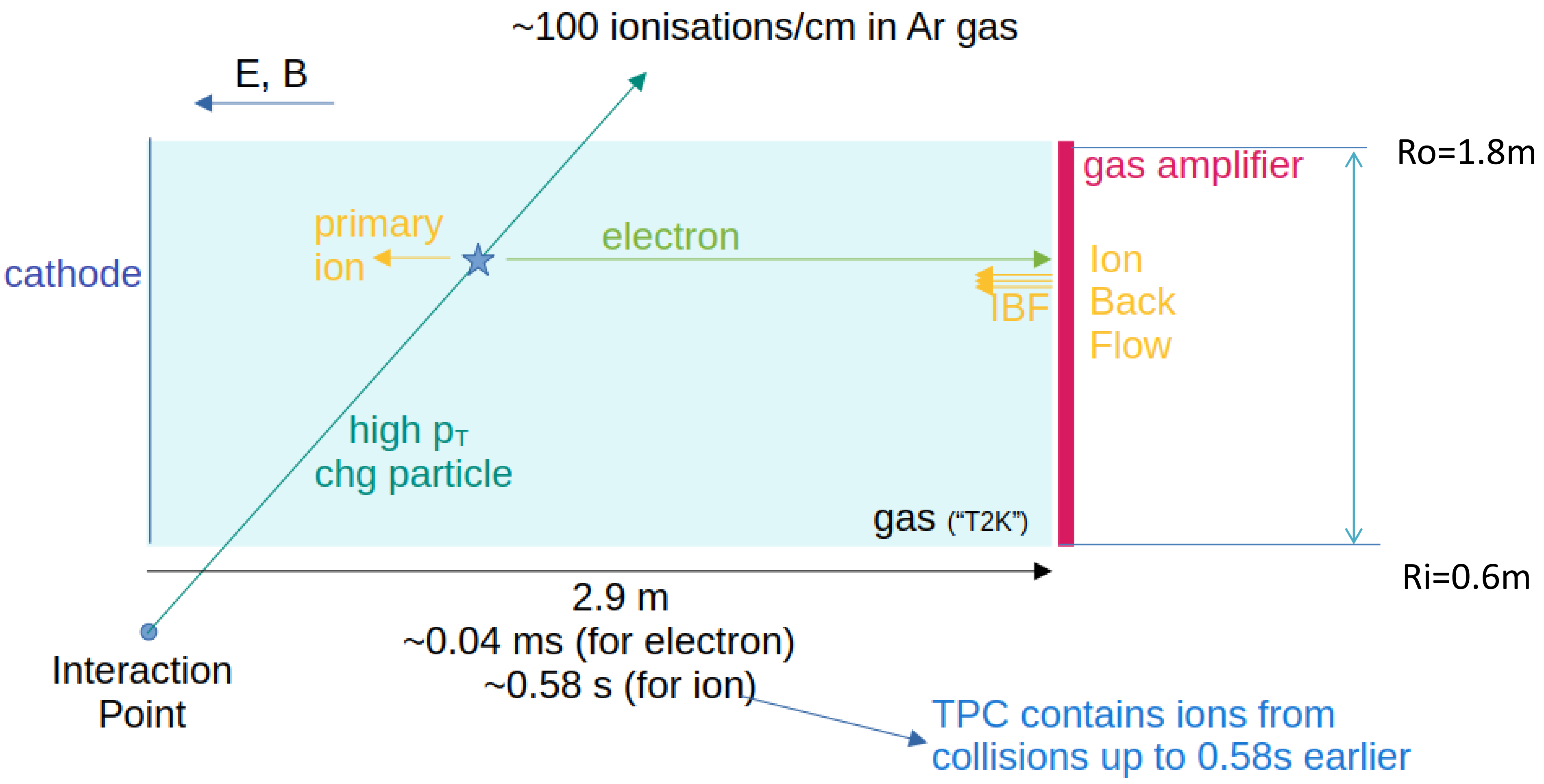




CEPC TPC layout in CDR(left) & CEPC TPC layout in TDR(right)

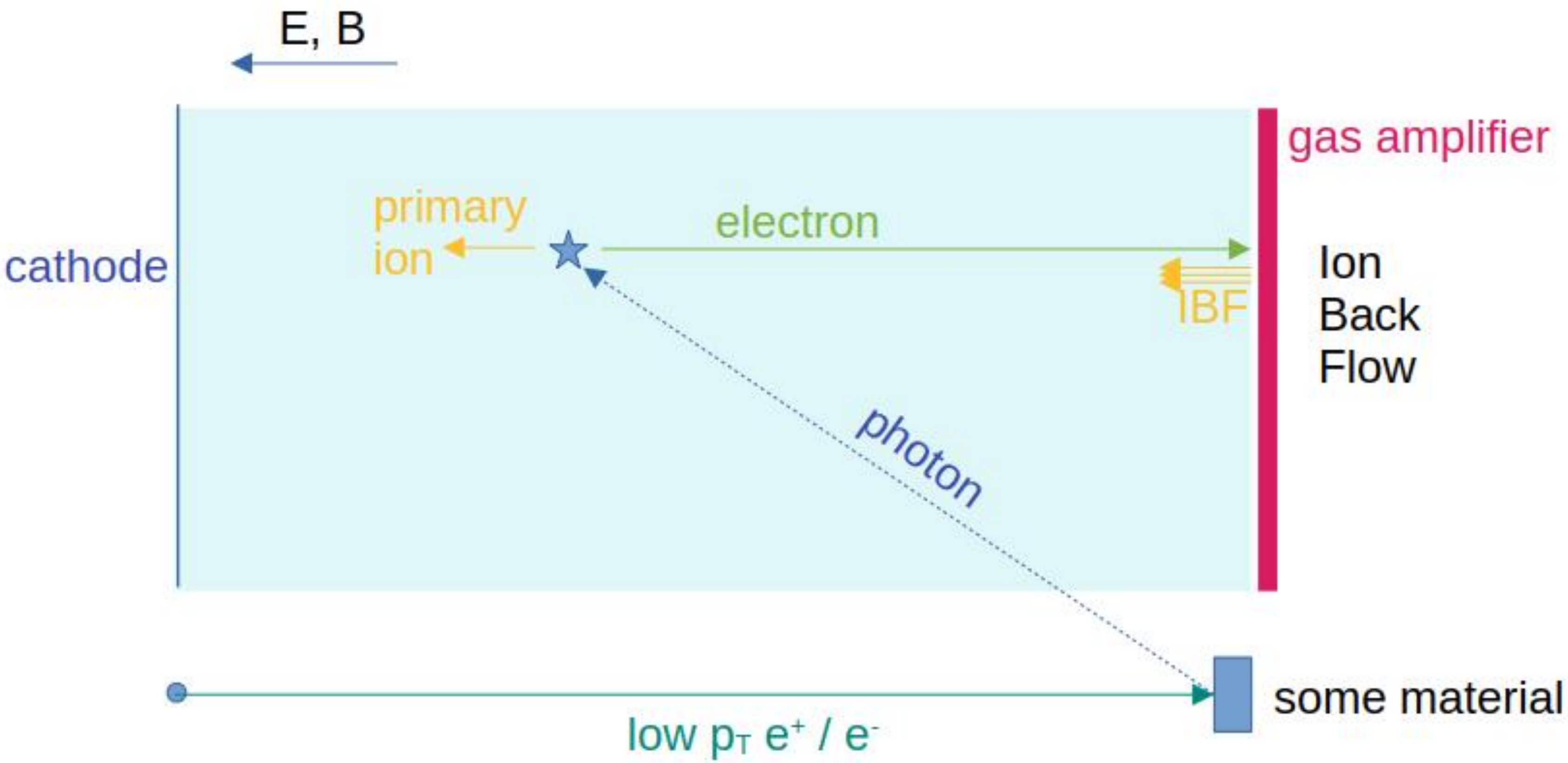
CEPC TPC Beam backgrounds

- **CEPC TPC operation:**



CEPC TPC Beam backgrounds

- **CEPC TPC operation：**
  - Usually small $p_t \rightarrow$ particles do not reach TPC directly

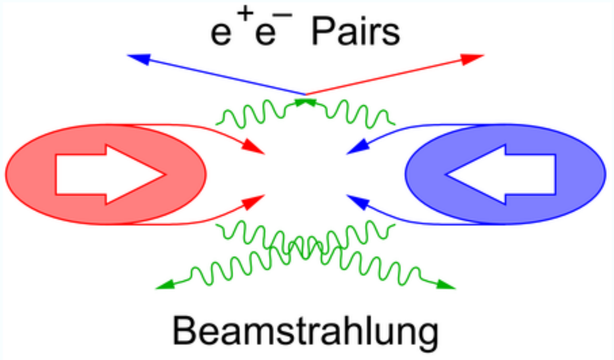


Simulation flow of beam backgrounds

- **GuineaPig** Higgs@240GeV / Z-pole@91GeV
- **Mokka** to correctly track low p_t particles
- Magnetic field： uniform 3T (Higgs run)/2T (Z pole run)
- MDI
  - Optimization of LumiCal position
  - Optimization of the shield

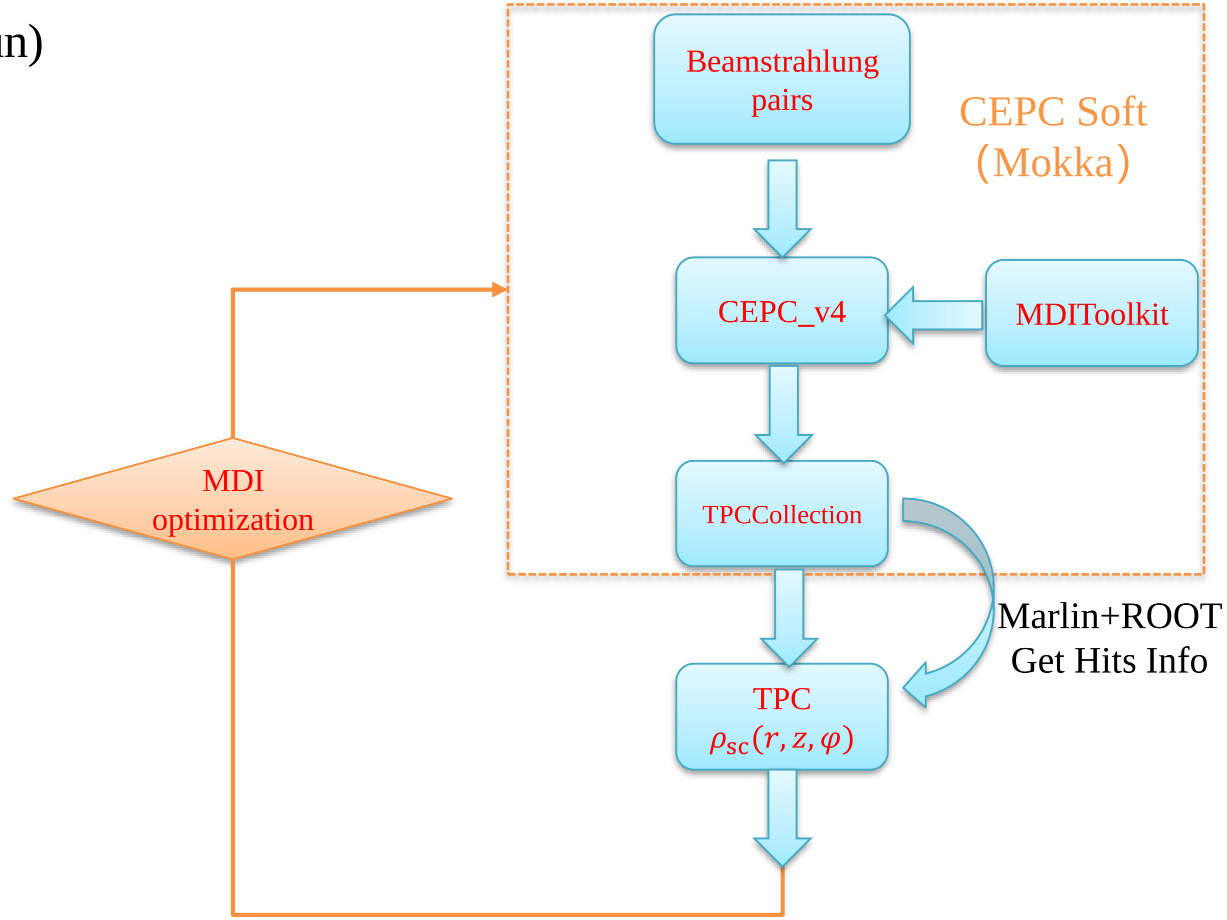
Beamstrahlung

In order to achieve the required luminosity ($1.8\times10^{34}cm^{-2}s^{-1}$) at CEPC, the section size of electron and positron beam will be squeezed to be very small at the interaction point. As a consequence, the trajectories of the electrons/positrons in each bunch will be bent significantly by the electromagnetic field that is formed by the beam particles of the opposite charge inside the crossing bunch. During this process, a particular kind of synchrotron radiation, called "beamstrahlung", will be emitted.



The emitted photons might further interact with each other through pair production and hadronic processes. The pair production was considered to be the dominant backgrounds induced by beamstrahlung.

- **Pair Production**
- **Hadronic Backgrounds**



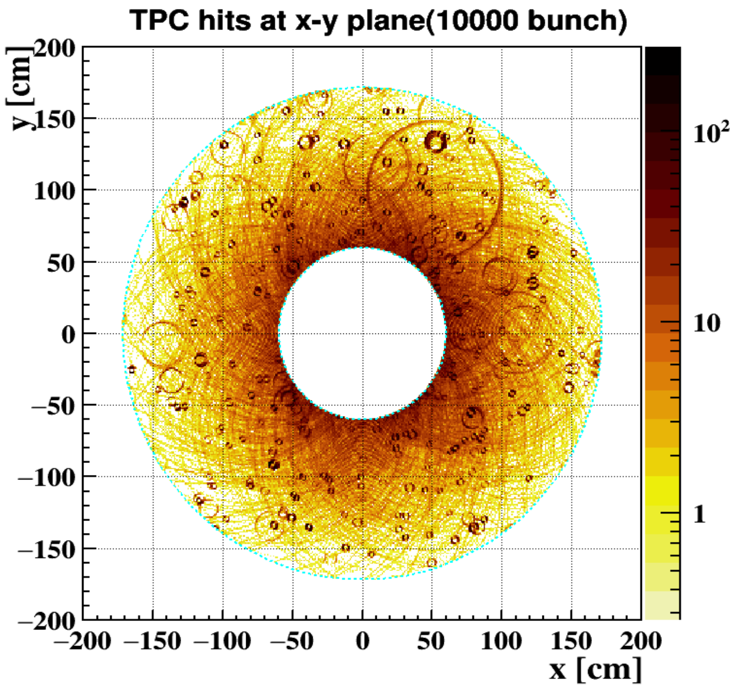
estimate number of **primary ions** produced in the TPC per bunch crossing

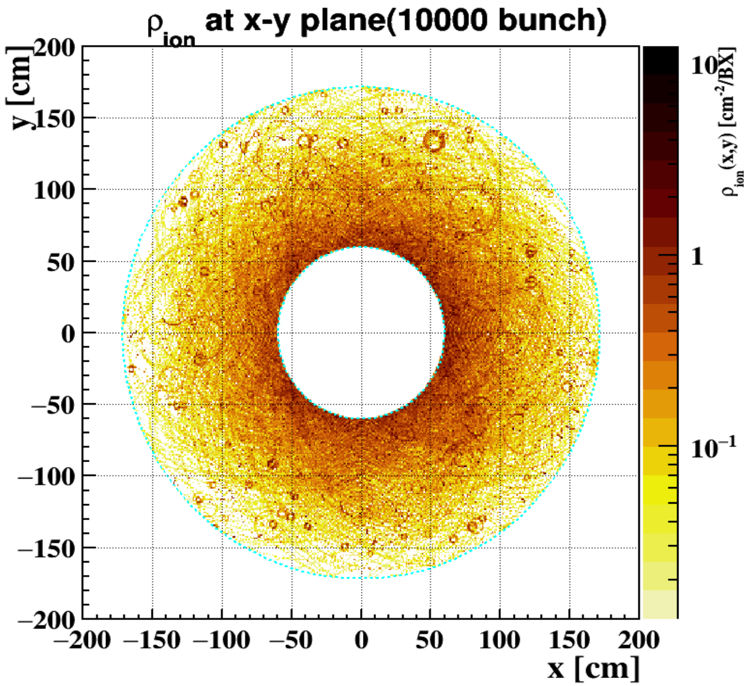
→ geant4 energy deposit / effective ionisation potential of Ar [26 eV]

TPC hits/BX & ion density/BX @Z-pole 2T

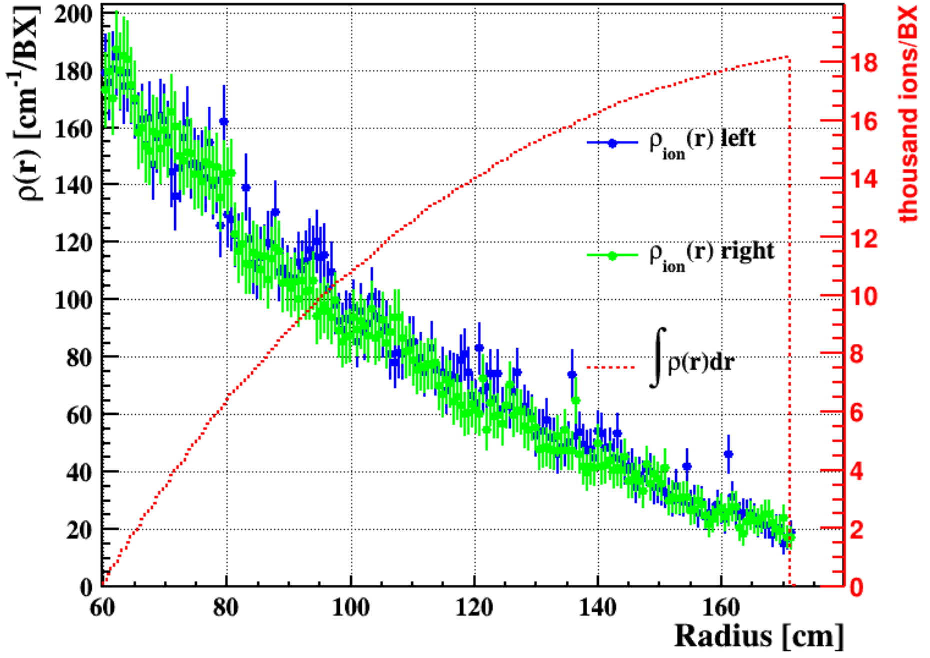
Primary ions per bunch crossing in TPC

- 10000 bunch crossing
- Edep ~4.73GeV in total
- Number of primary ions: BX freq. ~ 1/23ns
  - Edep/effective ionization potential of Ar [26eV] ~18.20k ions/BX





Hits map (left) & Ion density(right) at x-y plane



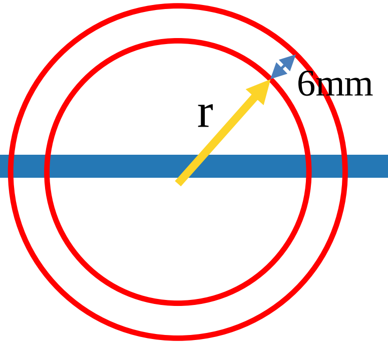
$\rho_{ion}(r)$ distribution

Number of ions at any time @ Z-pole 2T

- CEPC TPC maximum drift length:2.9m Vol_TPC=$52.48 m^3$
- TPC integrates over many collisions; maximum ion drift time ~ 2.9m/(5m/s)=0.58s
- Roughly estimate number of primary ions in the CEPC TPC volume at any time, taking account of different collision rates
  - Number of Ions ~Primary ion/BX · BX $frequency$ · **max drift time** · η · 50%_[ion already reached cathode]
  - BX $frequency$ = 1/23ns ~43.5MHz
  - Primary ions in TPC at any time ~ 2.07×10^{11}
  - Average primary ion charge density ~$0.63 nC/m^3$

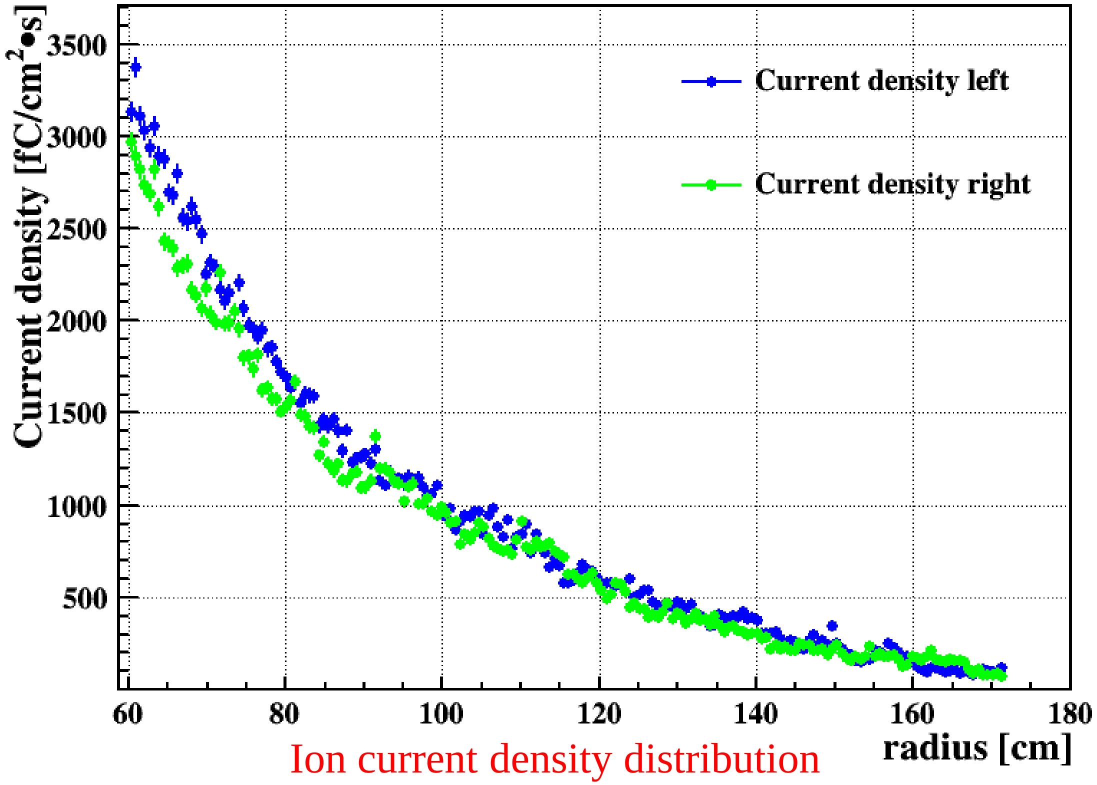
Collider Detector Model	CEPC_v4
Beamstrahlung pairs	CEPC Z-pole(91GeV)
BX freq.	1/23 ns
primary ions/BX	18.20 k
primary ions at any time	2.07×10^{11}
average primary ρ_{ion} [nC/m^3]	0.63

Ion current density in TPC @ Z-pole 2T

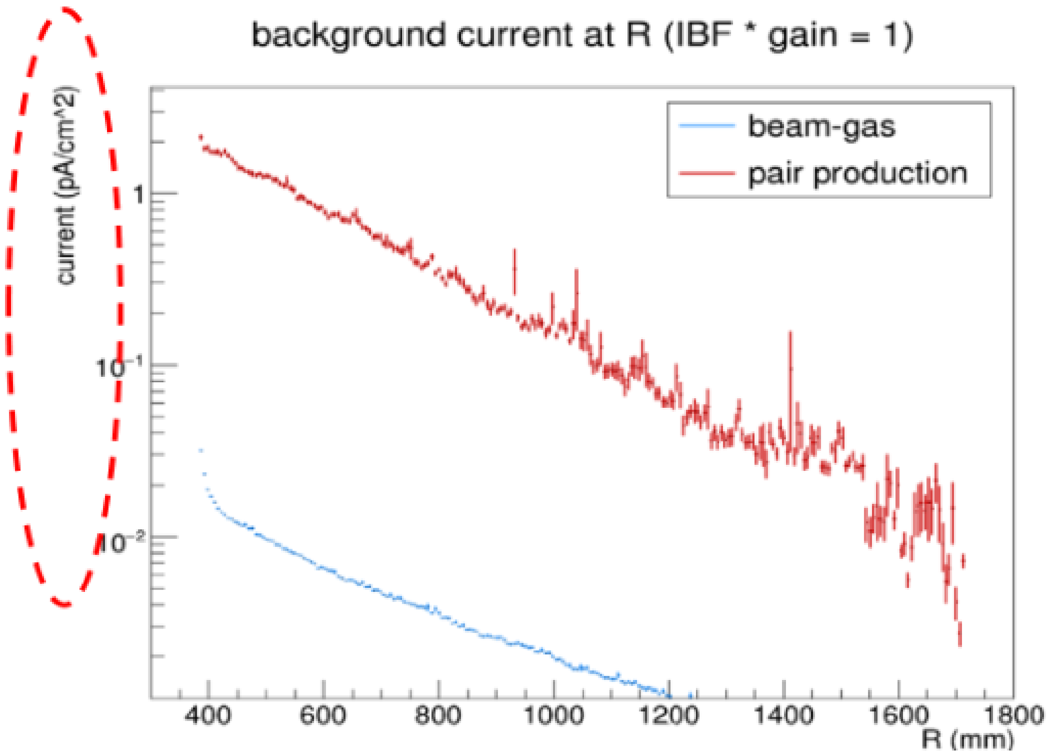


- Primary ions charge density/BX:

- Current density = $\rho_{ion}(r) \cdot 6mm \cdot e \cdot$ BX $frequency$ $\cdot 1015/(2\pi r \cdot$6mm) [fC/cm^2 s]
  - BX $frequency$ = 1/23ns ~43.5MHz
- Max. Current density~3.2 pA/cm^2



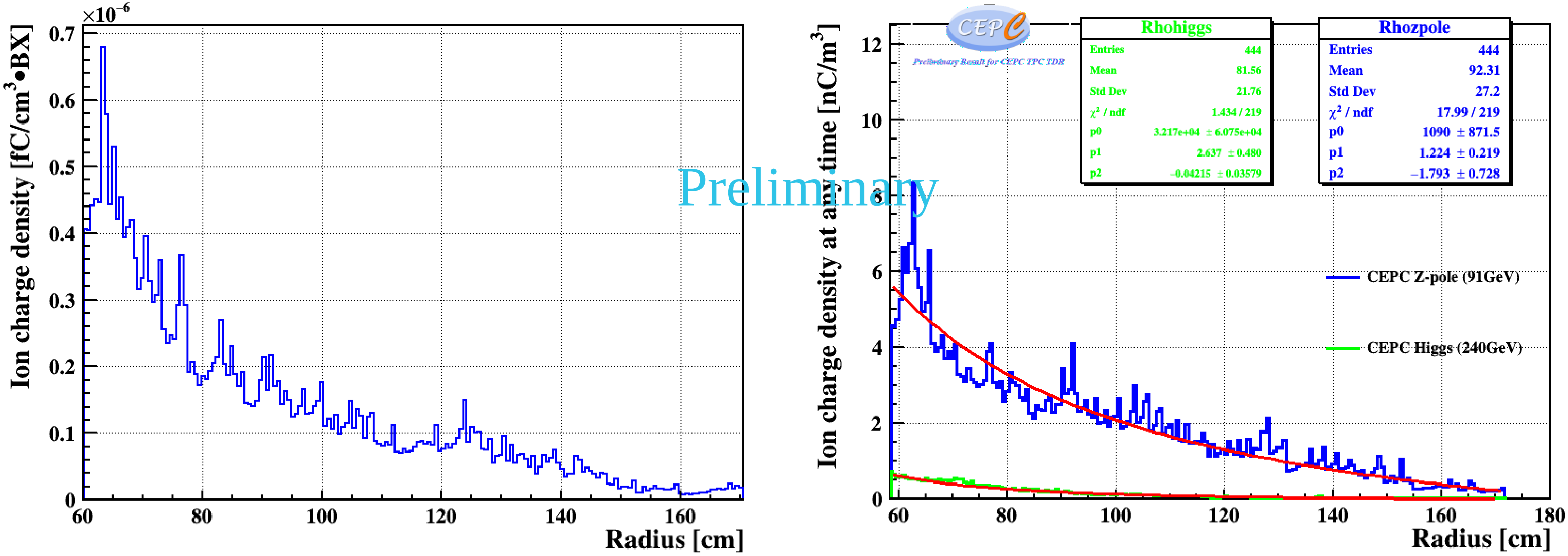
Ion current density distribution



Ion Space Charge density in TPC @Z-pole 2T

- ρ_{sc}(single BX)~ 0.6e-6 nC/m^3/BX
- ρ_{sc}(steady state)~ ρ_{sc}(single BX) × BX freq. × max. drift time × 50% × η = 5.46 nC/m^3 (r=60cm) (Only primary ions)

Ionization efficiency(90%)



$\rho_{sc}(r)$ (single BX) distribution Left & $\rho_{sc}(r)$ (steady state) Right

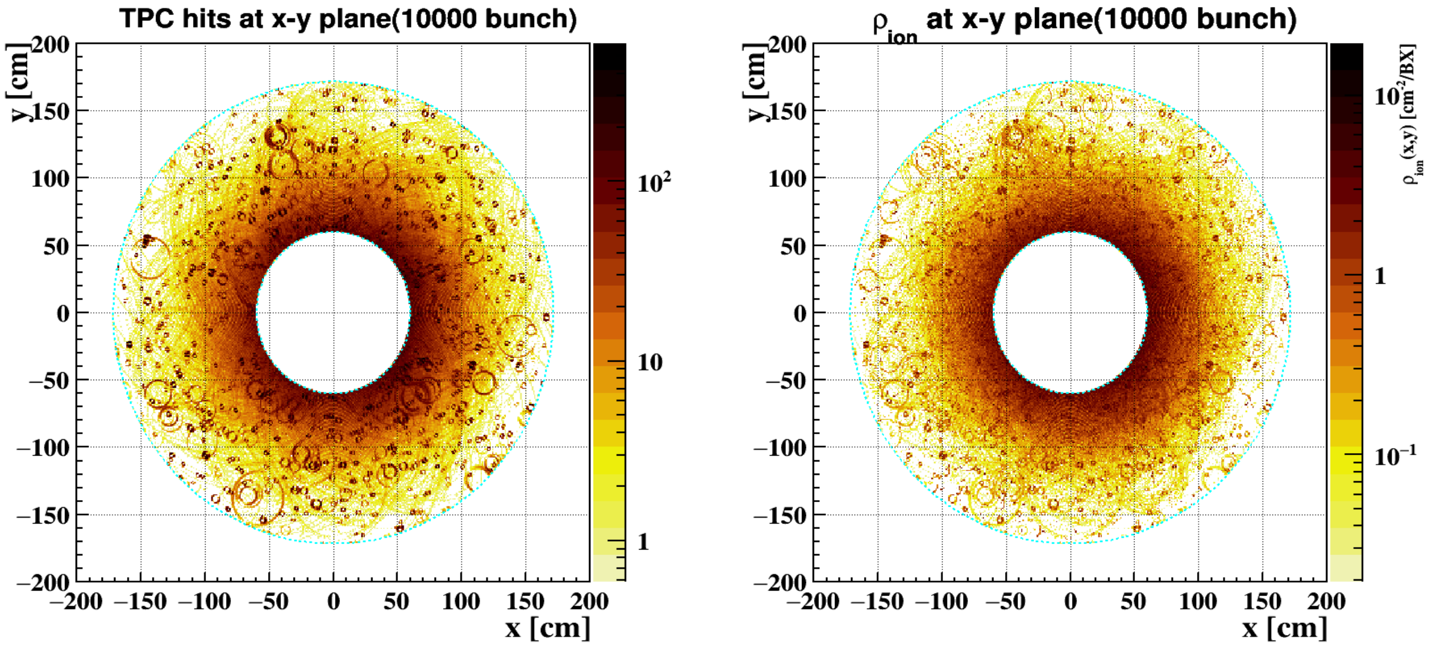
Beam background @ Higgs 3T

Primary ions per bunch crossing in TPC

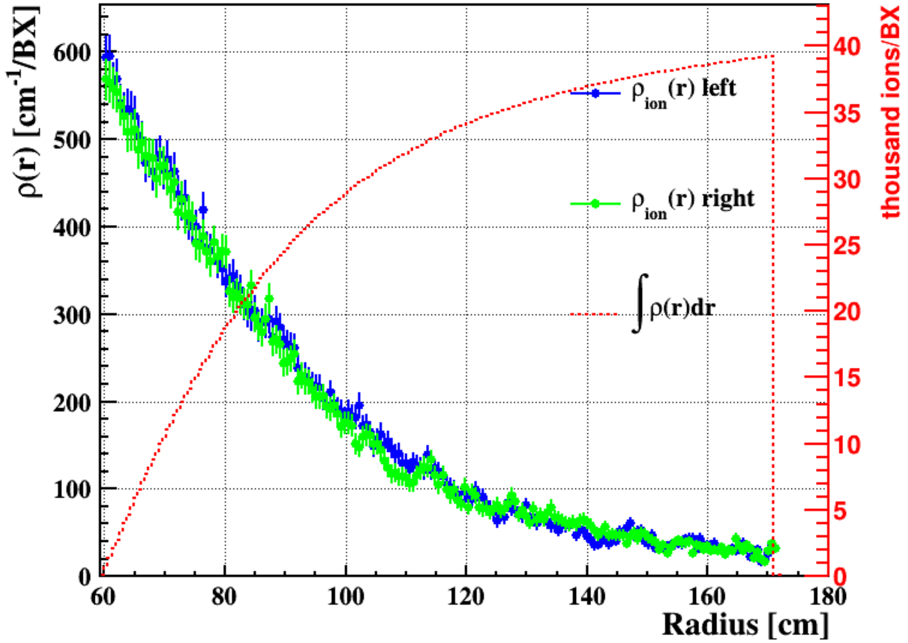
- Edep: 10.21 GeV in total(10000BX)
- Number of primary ions:

BX freq. ~ 1/680ns

  - Edep/effective ionization potential of Ar [26eV] ~39.26k ions/BX
  - Primary ions in TPC at any time ~ 1.5×10^{10}
  - Average primary ion density ~0.05nC/m^3



Hits map (left) & Ion density(right) at x-y plane



$\rho_{ion}(r)$ distribution

Beam background of CEPC TPC Simu. Results

Summary (ionization efficiency $\eta \sim 90\%$)

Collider Detector Model	CEPC_v4	CEPC_v4
Beamstrahlung pairs	CEPC Z-pole(91GeV)	CEPC Higgs(240GeV)
BX freq.	1/23 ns	1/680 ns
primary ions/BX	18.20 k	39.26 k
primary ions at any time	2.07×10^{11}	1.5×10^{10}
average primary ρ_{ion} [nC/m^3]	0.63	0.05
max (single BX) [nC/m^3/BX]	0.6×10^{-6}	1.8×10^{-6}
max (steady state) [nC/m^3]	5.46	0.62

Max (steady state) ~ max(single BX) × BX freq. × max. drift time × 50% × η

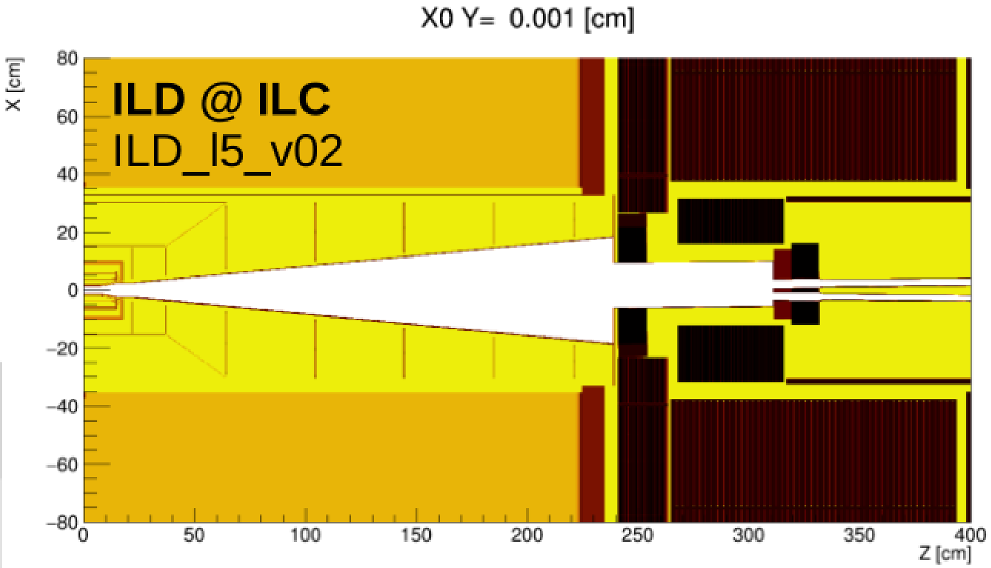
primary ions only

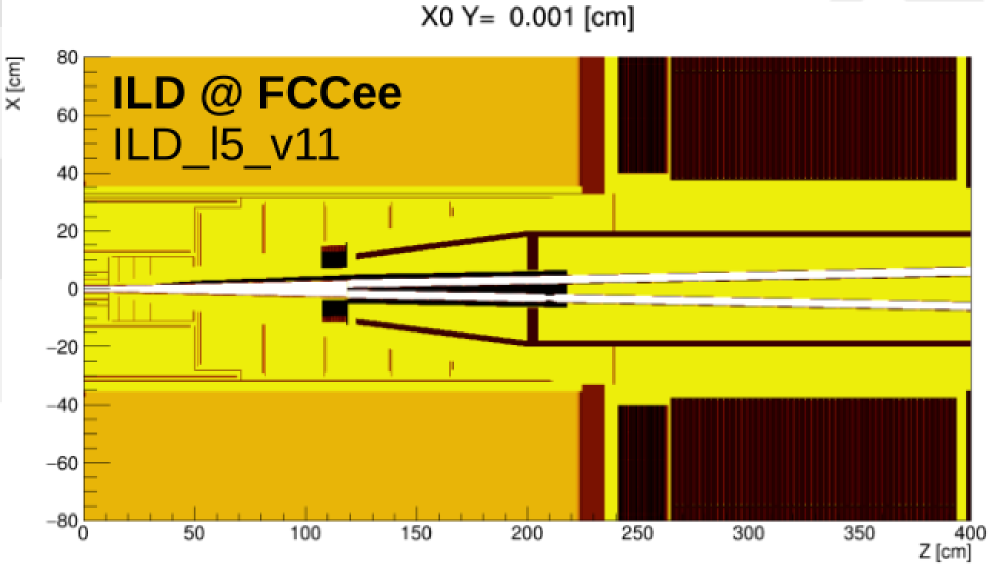
- **Comparison with FCCee & ILC (Slides from Daniel Jeans)**

Comparison with FCCee & ILC

machine-detector interface

	ILC	FCCee
crossing angle	14 mrad	30 mrad
L* [distance from IP to last accel focusing quadupole magnet]	4.1 m	2.0 m
detector solenoid	3.5 T	2.0 T
additional B-fields	anti-DID (?)	- compensating - screening





Comparison with FCCee & ILC

TPC integrates over many collisions; maximum ion drift time ~ 0.44 s

roughly estimate number of primary ions in the TPC volume (~42 m^3) at any time, taking account of different collision rates

number of ions ~ primary ions/BX * BX freq * max drift time * 50% [some ions already reached cathode]

Collider	FCCee-91	FCCee-240	ILC-250
Detector model	ILD_l5_v11γ	ILD_l5_v11γ	ILD_l5_v05
average BX frequency	30 MHz	800 kHz	6.6 kHz
primary ions / BX	270 k	800 k	450 k
primary ions in TPC at any time	1.8×10^{12}	1.4×10^{11}	6.5×10^{8}
average primary ion charge density nC/m^3	6.8	0.54	0.0025

primary ion density in TPC: 2500 times higher at FCCee-91 than ILC-250
200 times higher at FCCee-240 than ILC-250

Comparison with FCCee & ILC

compare to ALICE-TPC

ALICE TPC upgrade TDR: CERN-LHCC-2013-020

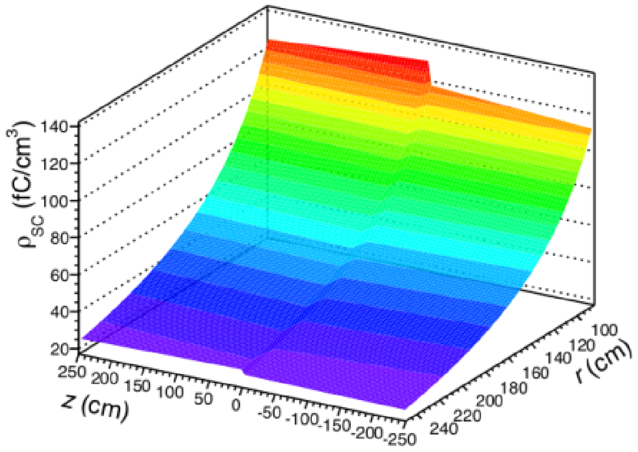
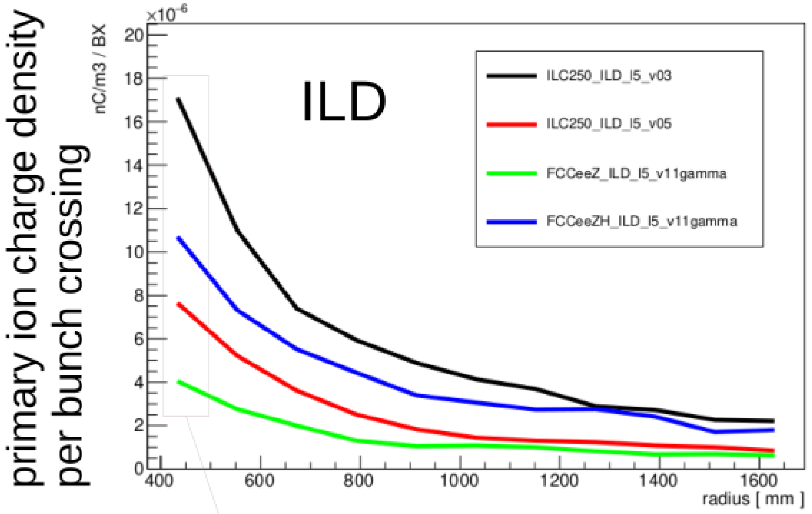


Figure 7.7: Average space charge density for Ne-CO_2-N_2 (90-10-5), R_{int} = 50 kHz and ε = 20.

assumed ion back flow factor ε: 20 secondary ions / primary

20~120 fC/cm^3 → cm-level distortions



maximum steady state space-charge ~
max space-charge/BX * BX freq * max drift time * 50%

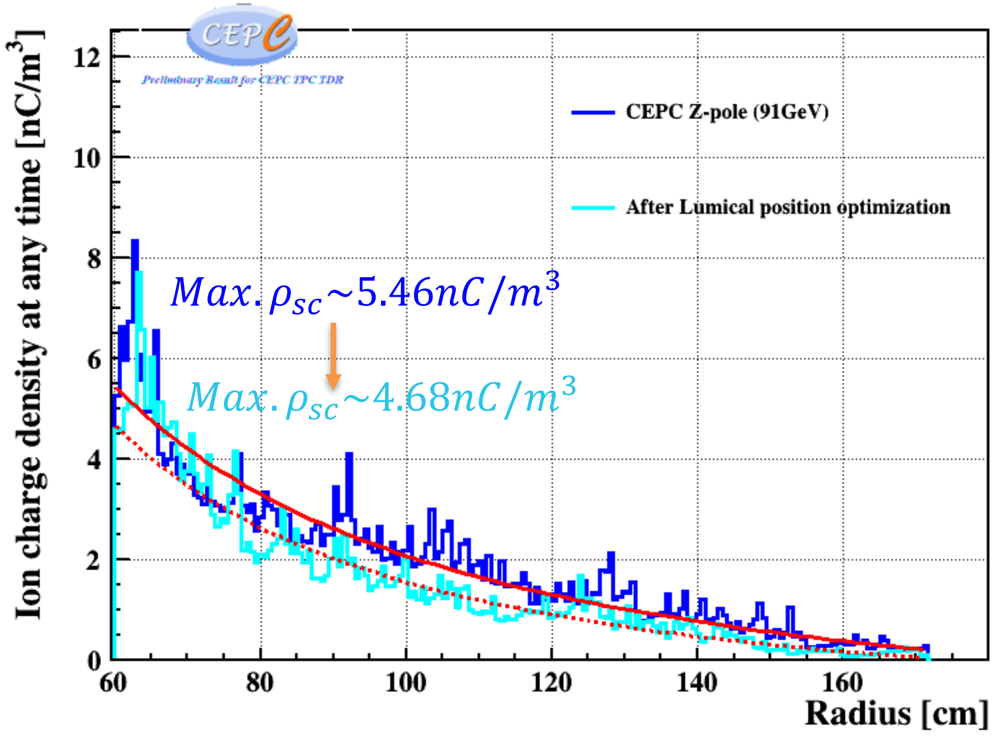
	max (single BX)	BX freq	max (steady state)
FCCee91	4e-6 nC/m^3	30M	26 nC/m^3
FCC240	1e-5 nC/m^3	800k	2 nC/m^3
ILC250 (v5)	8e-6 nC/m^3	6.6k	0.01 nC/m^3
ALICE		50k	120 nC/m^3 with IBF=20

primary ions only: IBF=0

CEPC Zpole	**0.6e-6 nC/m^3**	43MHz	**5.46 nC/m^3 (IBF=0)**

Optimization of MDI design (on going)

- Redesigning MDI can reduce the beam background
  - ρ_{sc}(steady state) ~ 4.68 nC/m^3 after **CEPC Lumical** position optimization ~15% effect
  - After removing **FCCee BeamCal's** graphite layer ~20% effect



model	B-field [T]	MDI	FCCee-91	FCCee-240	ILC-250
			thousand ions / bunch crossing		
ILD_l5_v11β	2.0 (uniform)	FCCee	390	1000	110000
ILD_l5_v11γ	2.0 (map)	FCCee	270	800	100000
ILD_l5_v02	3.5 (uniform)	ILC	6.5	14	960
ILD_l5_v02_2T	2.0 (uniform)	ILC	6.9	15	4700
ILD_l5_v03	3.5 (map)	ILC	5.7	14	1100
ILD_l5_v05	3.5 (map, anti-DID)	ILC	0.6	3.7	450
removing BeamCal's graphite layer					
ILD_l5_v03	3.5 (map)	ILC			1300
ILD_l5_v05	3.5 (map, anti-DID)	ILC			590

~20% effect

Summary

Summary

- A TPC is the main track detector **at future e+e- colliders ,** TPC **selected** as the baseline track detector in CEPC TDR.
- CEPC TPC (larger inner radius) backgrounds from the **beamstrahlung**:
  - Max. ion charge density **(steady state)** is **4-5×** times less than FCCee91 and FCCee240
  - TPC ions from **beamstrahlung** dominate those from ee→qq
- **Optimated MDI design** may further reduce back-scatter and lower the beam backgrounds

Thanks for listening