中国科学技术大学
University of Science and Technology of China

Simulation of beam background on STCF

STCF 2025

2025.7.3 @ 湘潭

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Outline

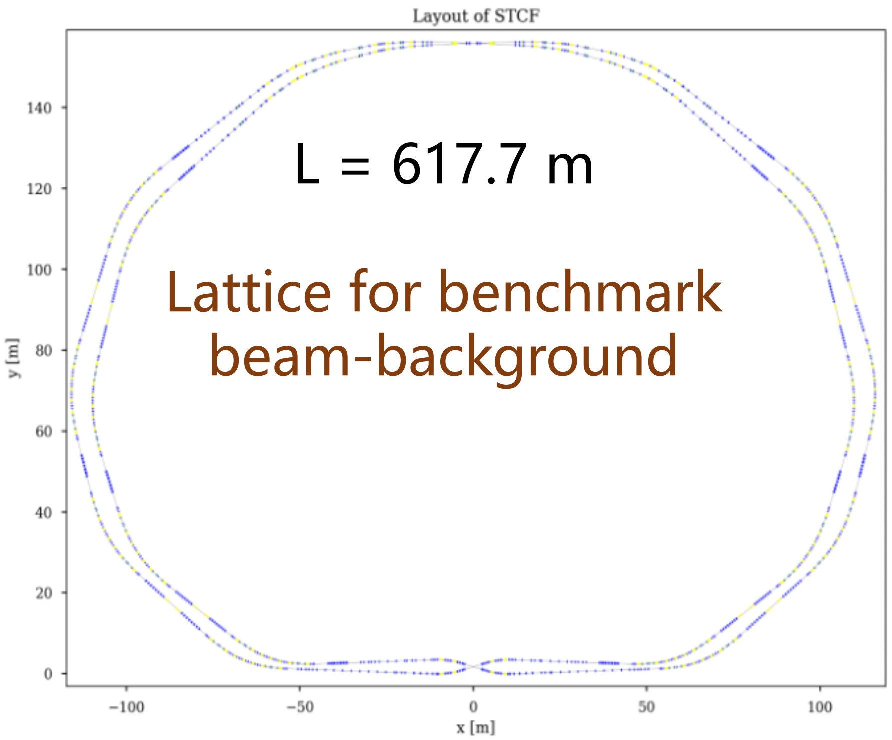
- Lattice and Collimator design.
- Layout of the Machine-Detector-Interface (MDI) on STCF.
- Beam background simulation.
- Deposits on detector evaluation (e.g.: TID, NIEL, Count rate, etc.).
- Summary.

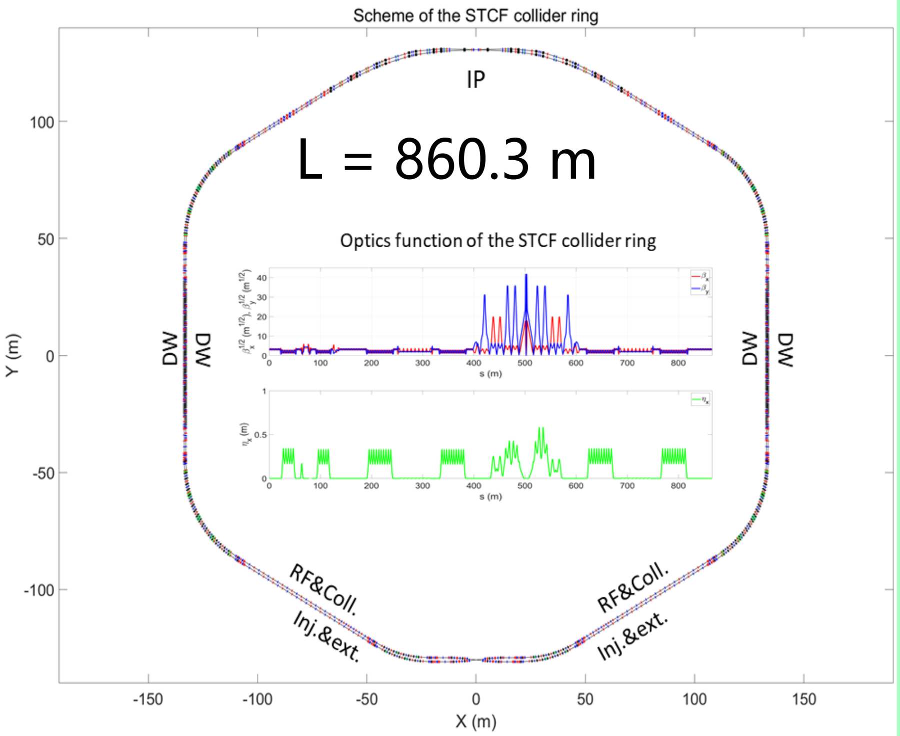
Lattice of the accelerator

Beam current = 2 A; Cross angle at IP = 30 milli-radius

Lattice version	History: v7c3 (@22.10 by Tao)	Current: v12_b (@25.5 by Linhao)

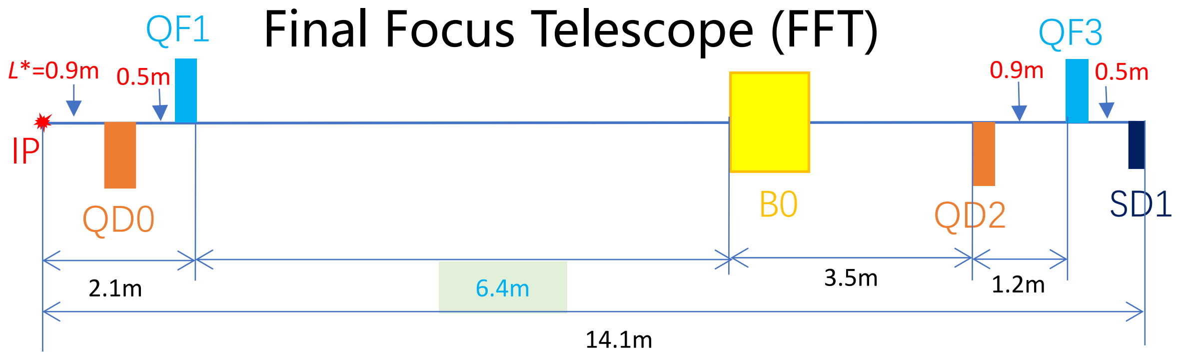
Scheme of the Ring

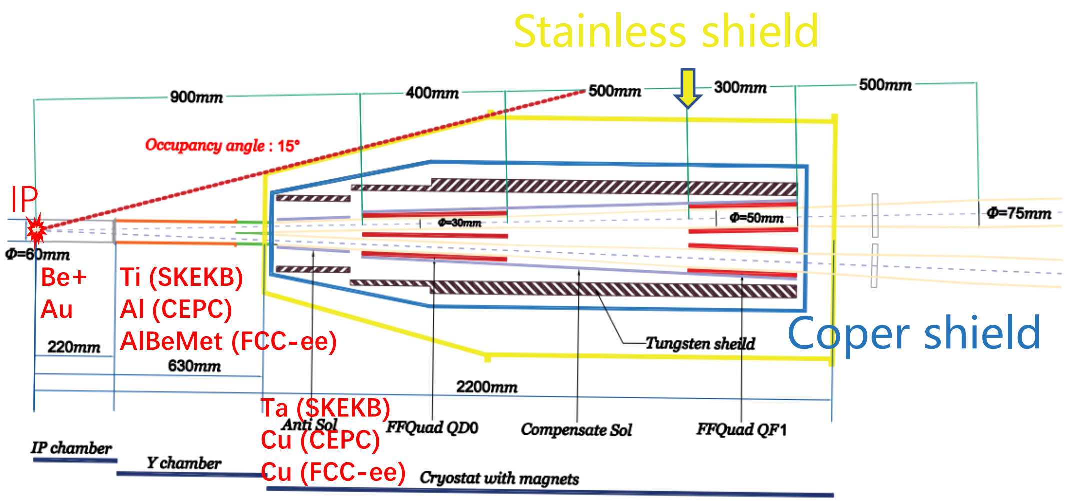




	History: v7c3	Current: v12_b
Emit (m*rad)	$emit_{x(y)} = 5.5 \times 10^{-9}(2.25 \times 10^{-11})$	$emit_{x(y)} = 4.65 \times 10^{-9}(4.65 \times 10^{-11})$
Energy spread	5.16×10^{-4}	7.85×10^{-4}
$\boldsymbol{\beta_{x(y)}^{IP}}$ (m)	0.04 (0.0006) m	0.06 (0.0008) m

Layout of the MDI





- Length of major magnets:
  - ✓ QD0: L=0.4m, k=-1.6298 T/m; (The first SC defocus Quadrupole)
  - ✓ QF1: L=0.3m, k=0.9593 T/m; (The second SC focus Quadrupole)
  - ✓ B0: L=1.0m, θ=1.0°; (Bending dipole, causing unavoidable dispersion, as weak as possible, **adjusting position** to reduce beam background)
  - ✓ QD2: L=0.3m; (defocus quadrupole); QF3: L=0.3m; (focus quadrupole)

Under updating and iterating:

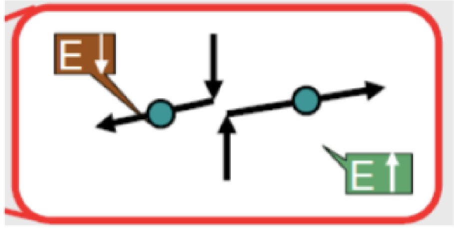
1) Distance between IP and cryostat?
2) Y-chamber mechanic structure?
3) Shield layers, geometry conflict?
4) Compensating solenoid magnet?
5) Location of Luminosity-monitor, ZDD?

...

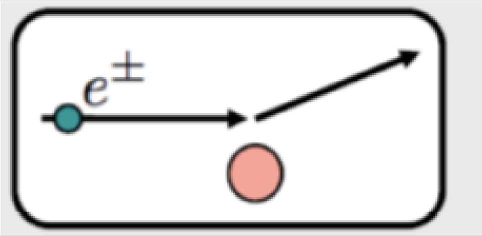
Beam background

- Beam background in MDI
  - ✓Pure beam-related background

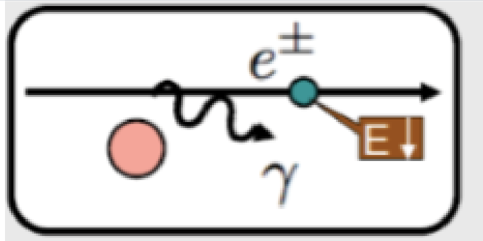
Beam-Gas effect



Touschek



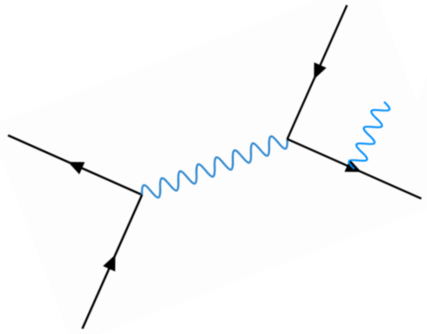
Coulomb

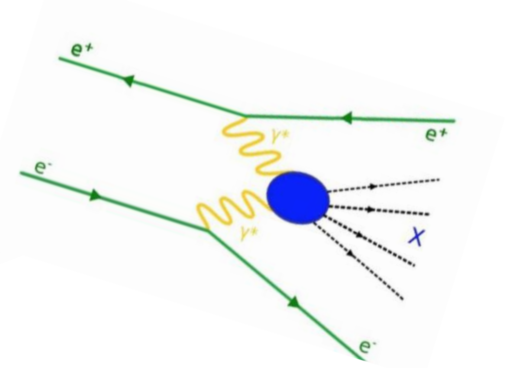


Bremsstrahlung

Pressure: 10^{-7} Pa (MDI: IP±3m); 10^{-8} Pa (out of MDI)

  - ✓Luminosity-related background
    - ◻Radiative Bhabha scattering: $e^+e^- \to e^+e^-(n)\gamma$
    - ◻Two-photon processes: $e^+e^- \to \gamma^*\gamma^* \to e^+e^-X$

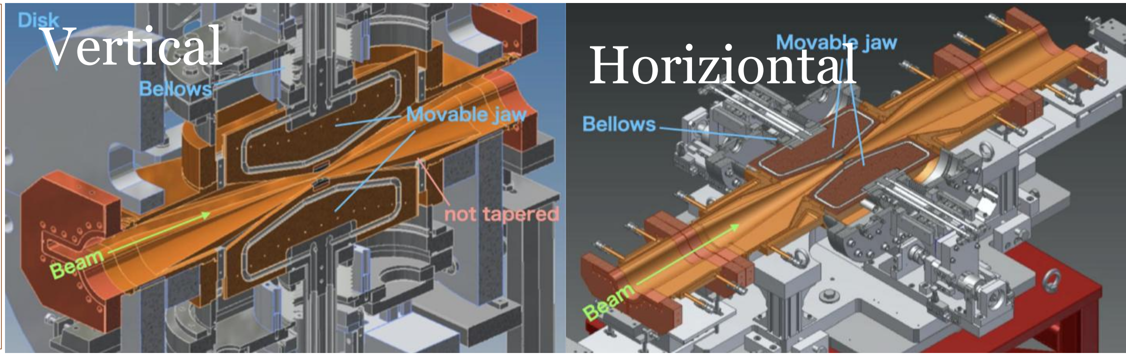




Collimator

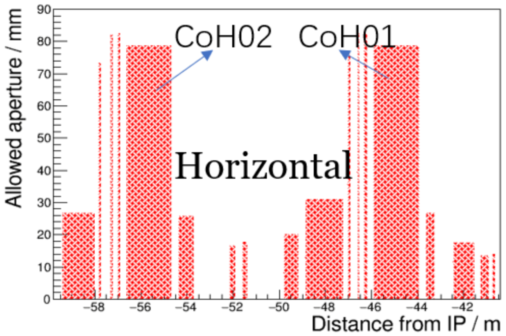
◻About collimator:

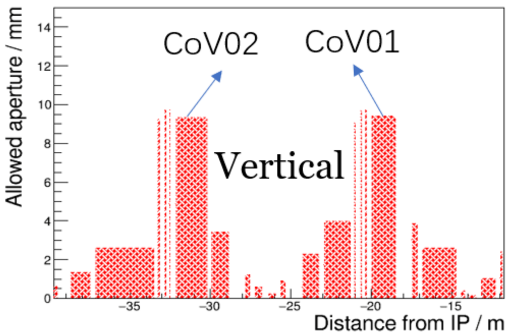
- ✓ Inside beam pipe, scrape off-orbit particles before IR
- ✓ Horizontal(H) and vertical(V)
- ✓ Trapezoid structure to reduce impedance



Collimator designed in v7c3 (H×2, V×2)

Less accelerator details considered



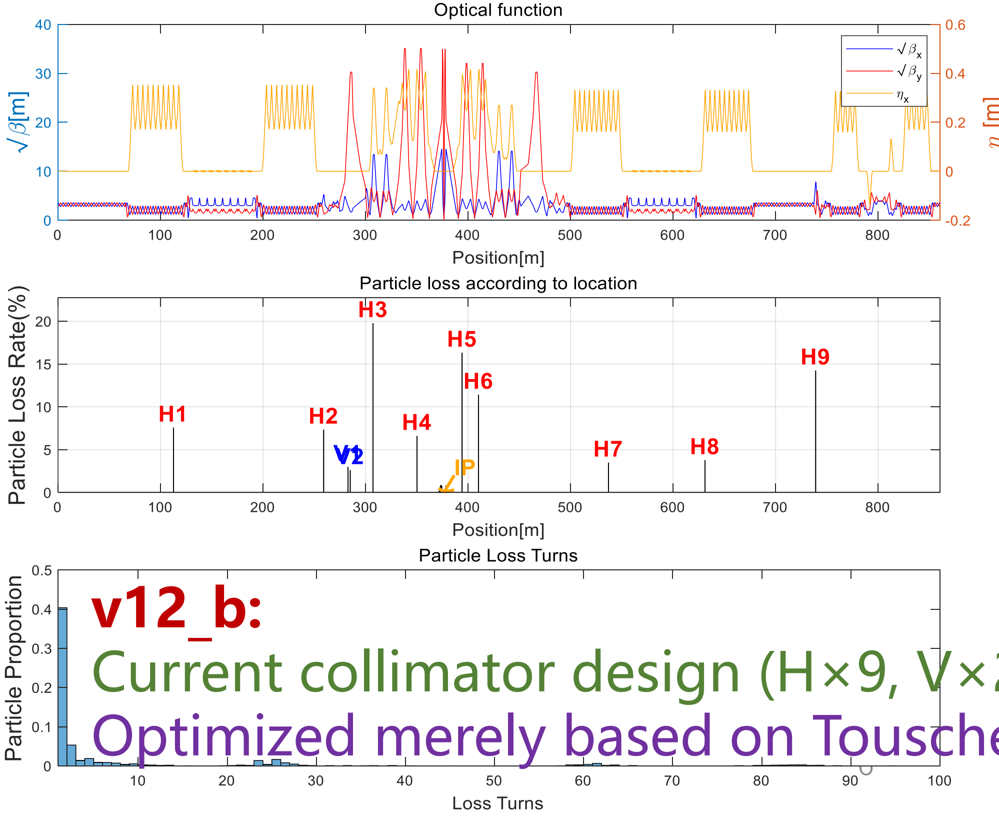


Name	Orientation	Limitation	Design	
		Rmax/mm	Zmid/m	R/mm
CoH01	Hor.	78.63	-45.0	15
CoH02	Hor.	78.70	-56.0	15
CoV01	Ver.	9.40	-19.2	7
CoV02	Ver.	9.32	-31.0	7

Optimized based on Touschek and Beam-Gas

VS

✓ More accelerator details considered



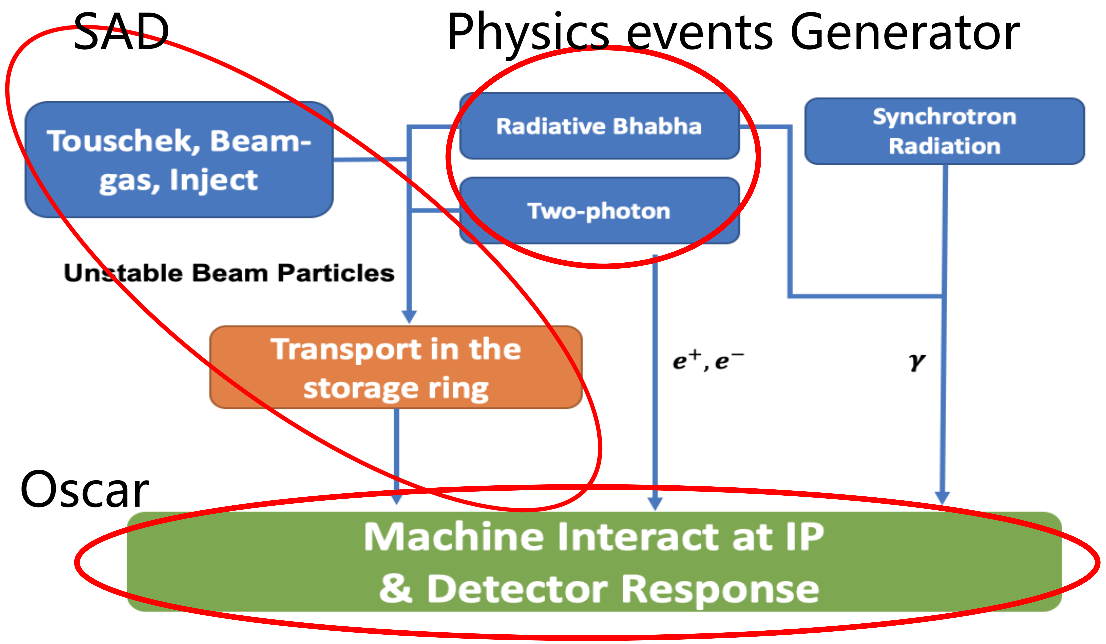
v12_b:

Current collimator design (H×9, V×2)

Optimized merely based on Touschek

Background simulation: overview

- Luminosity background:
  - Available MC generators
- Touschek & Beam-gas background:
  - SAD developed by KEK
  - Sampling with cross section
  - Collimator simply act as narrower sized aperture
- MDI interaction and detector :
  - Geant4 (Under Oscar)



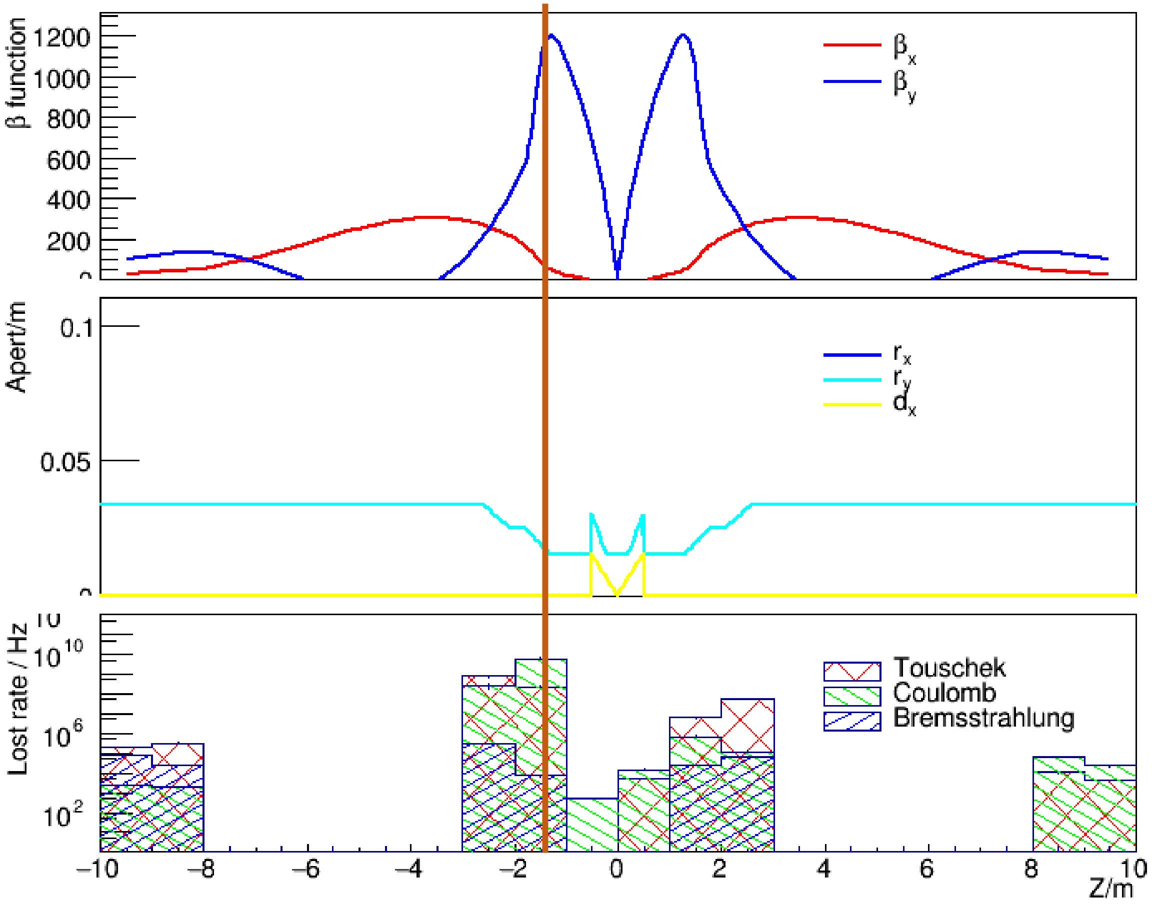
IP ± 10 m

Category	Generator	v7c3 loss rate (MHz)	v12_b loss rate (MHz)
RBB ($\theta_{min} = 4.47\ mrad$)	Babayaga/BBBREM	$e^{\pm}$ (γ): 598 (170)	
Two photon	DIAG36	1030	
Touschek	SAD	2120	1000
Beam-Gas	SAD	Coul: 2.5; Brem: 4.2	Coul: 5700; Brem: 2.6

Promising beam lifetime from v12_b: > 400 s

Distribution of the beam background: v12_b

- Loss rate within IP ± 10m

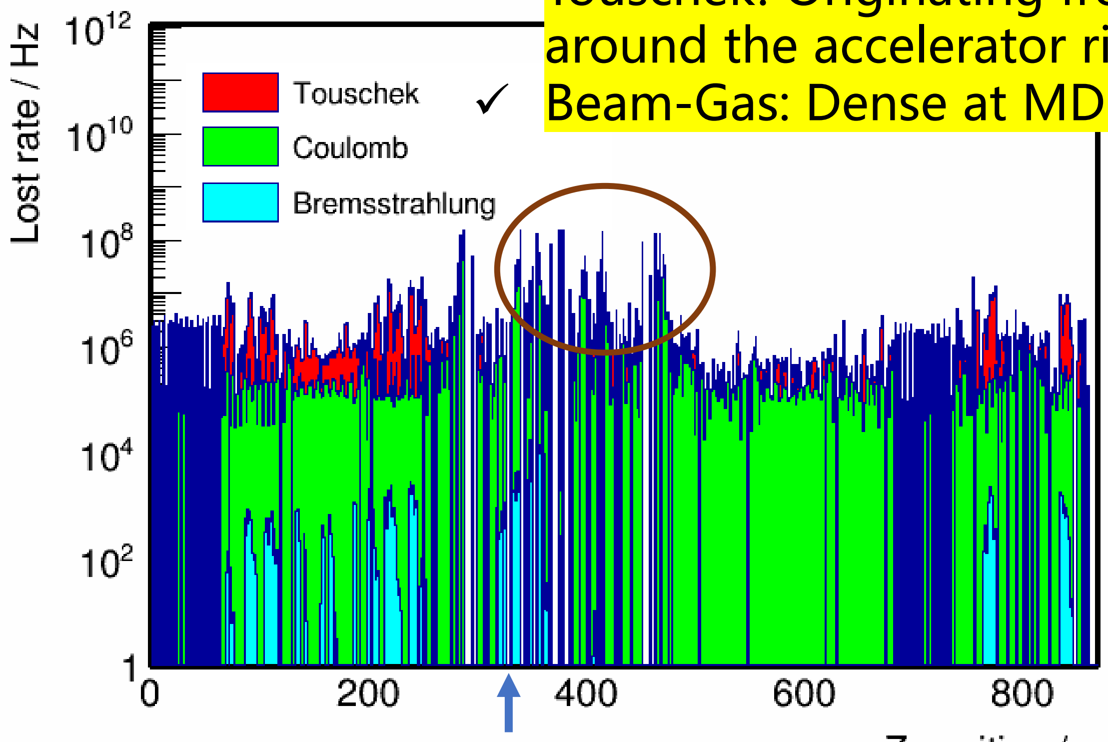


- Originated positrons
  @ 2 GeV beam energy,

✓ The ring is symmetry; thus, the electron distribution is very similar.

✓ Touschek: Originating from all around the accelerator ring

✓ Beam-Gas: Dense at MDI



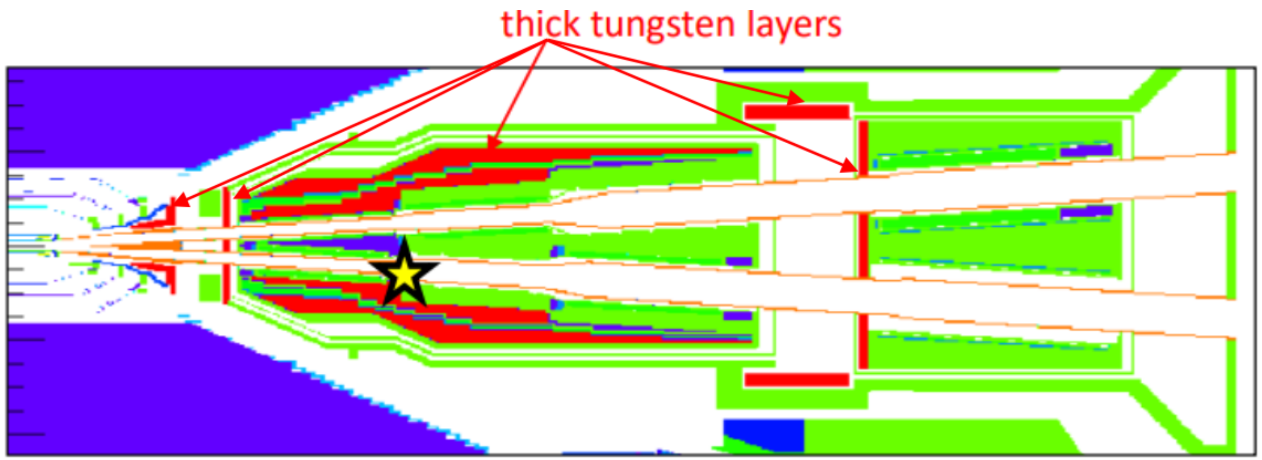
✓ Touschek: mainly lost at min R and max β

✓ Beam-gas: mainly lost at IP ± 3 m (MDI)

External shield design for MDI

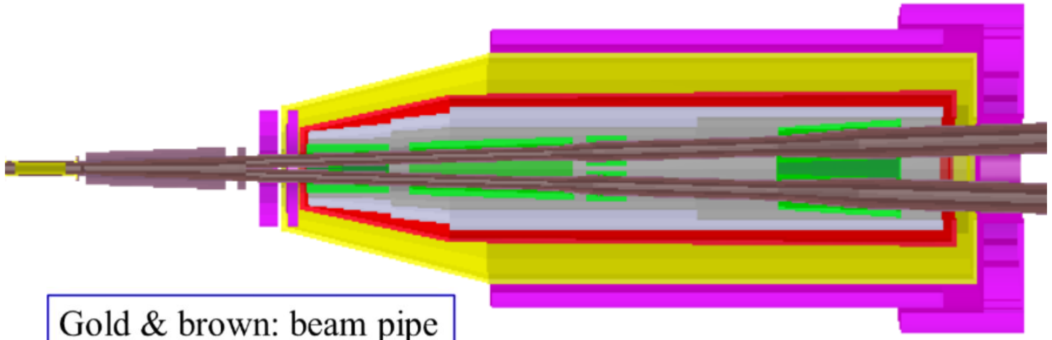
- **Further reduce beam background**
  (Especially for ITK)

- **Experience from Belle II**
  - Tungsten (W) shield layer in MDI



- **Design based on simulation**
  - To reduce background to an order of magnitude
  - Tungsten layer to reduce $e^{\pm},\gamma$
  - (Composites) layer for neutron shielding

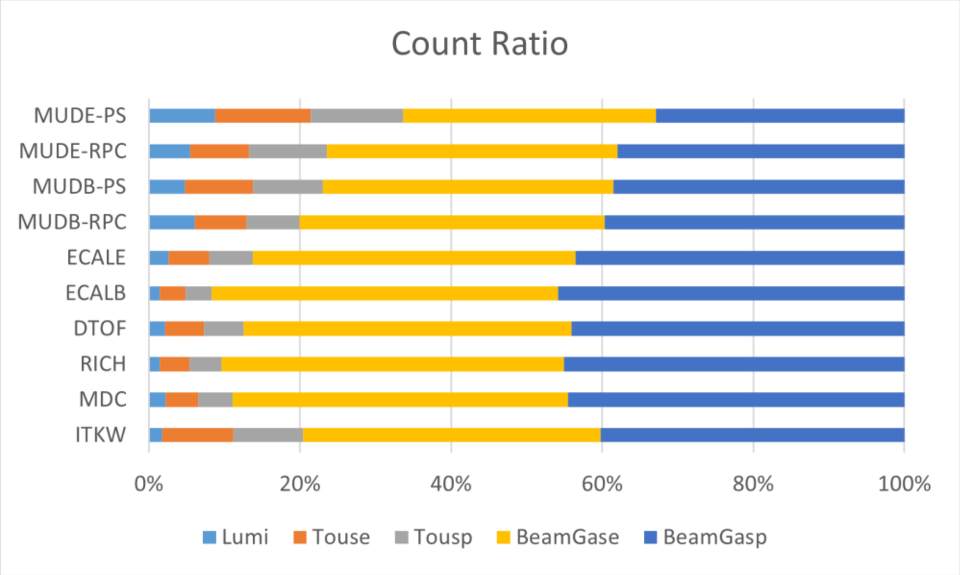
- **Current shield layer design**

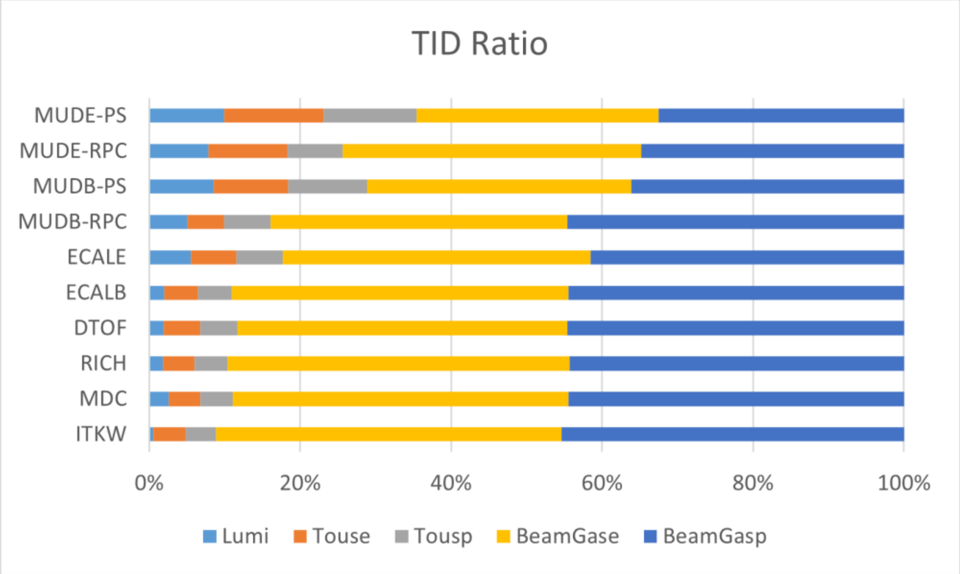


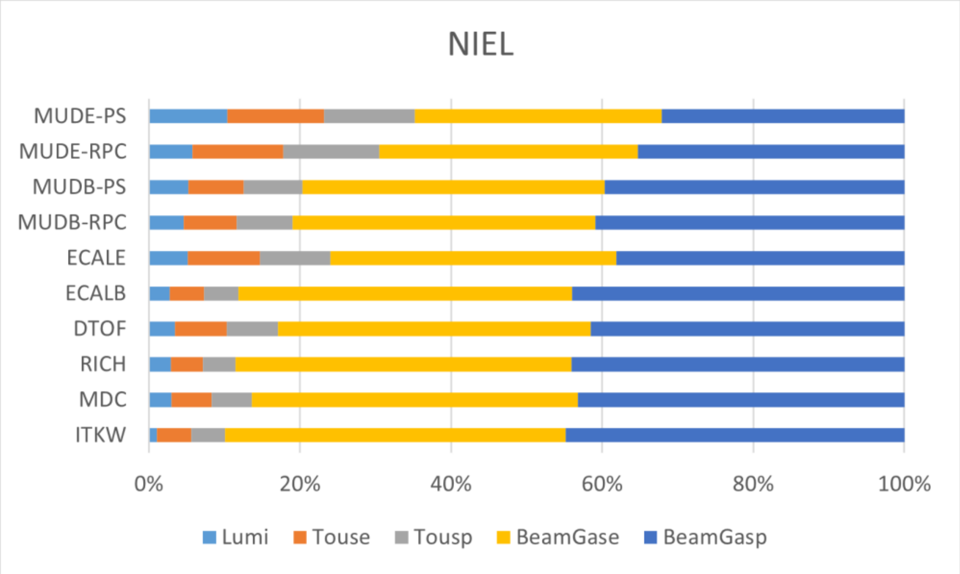
Gold & brown: beam pipe
Pink: tungsten shield
Green: magnets
Yellow & Red: cryostat

Background sources

- Beam-gas effect contributes most of the backgrounds ~75%
- Touschek effect play the sub-dominant role ~20%
- The contributions from electron/positron are almost the same

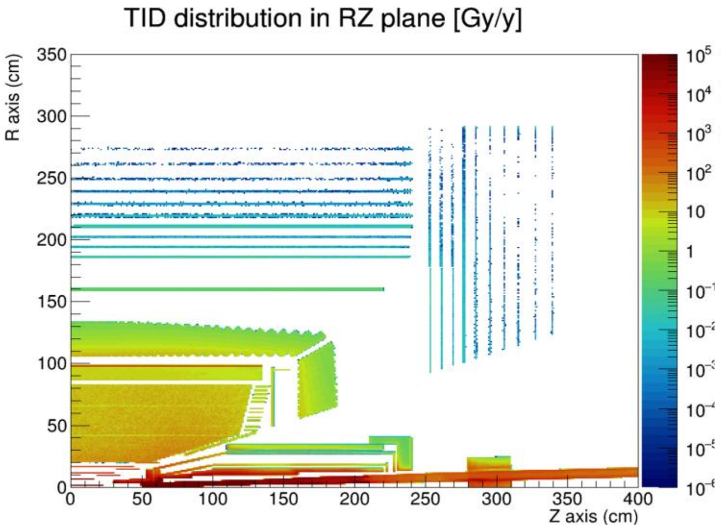




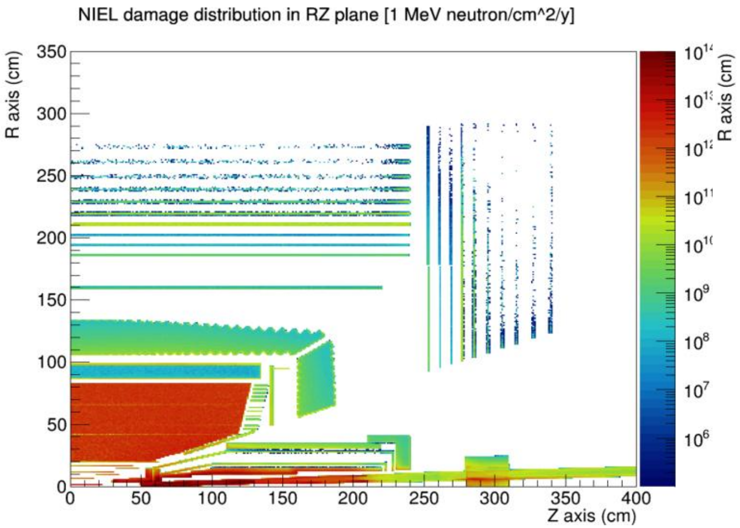


TID, NIEL, Counting rate (Test based on ITKW)

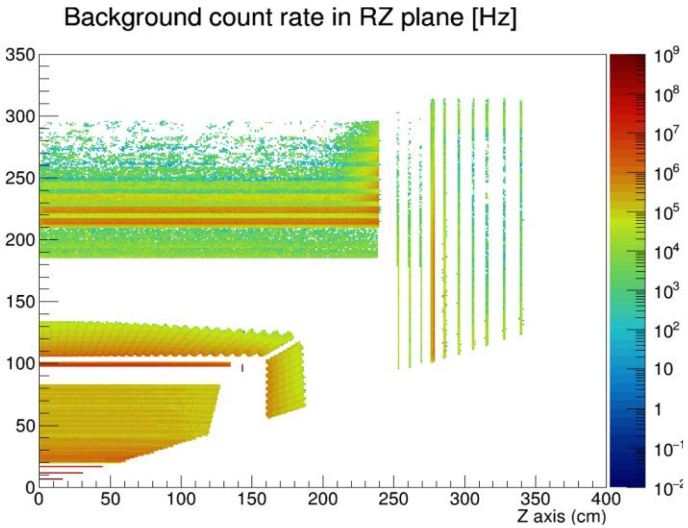
TID v12_b



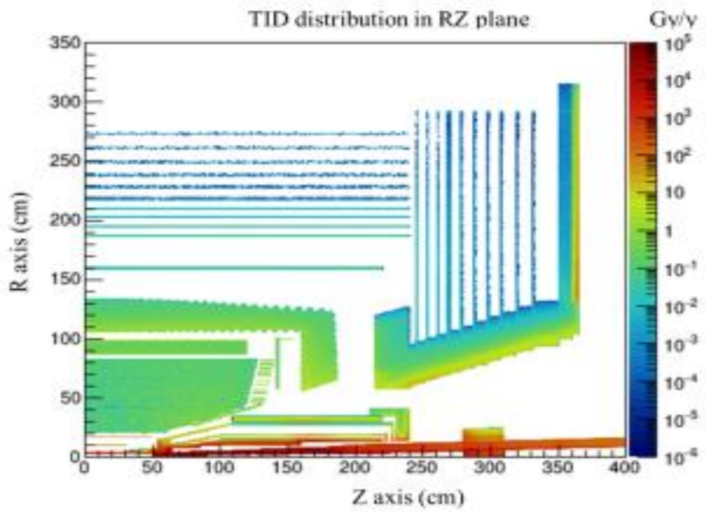
NIEL v12_b



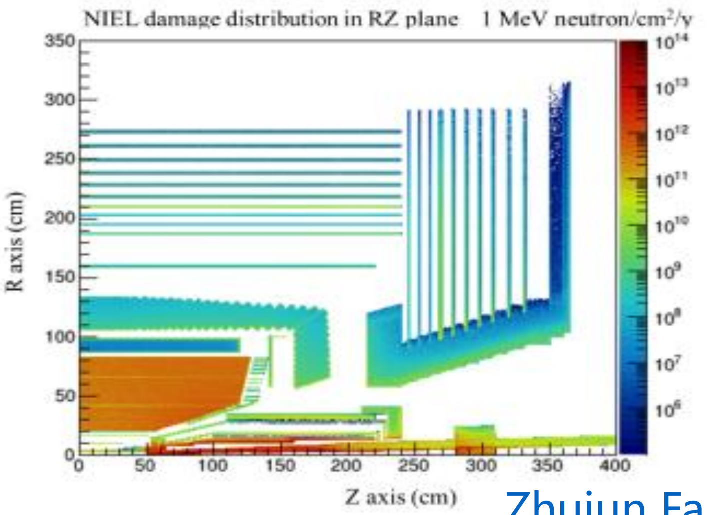
Count rate v12_b



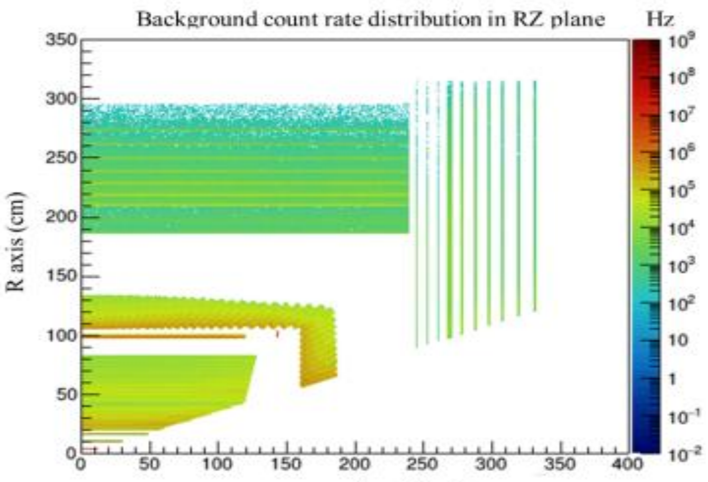
TID v7c3



NIEL v7c3



Count rate v7c3



v12_b much higher than v7c3

[Zhujun Fang et al 2024 JINST 19 P11014]

Beam background deposit in detector

v12_b

DET	TID	NIEL	COUNT
ITKW1	14443.53	5.17E+11	3.93E+09
ITKW2	1273.549	3.58E+11	3.97E+09
ITKW3	501.7721	3.59E+11	2.53E+09
MDC	19.87113	2.03E+14	2.01E+09
RICH	6.737757	7.68E+10	2.37E+09
DTOF	5.891739	5.87E+10	1.61E+09
ECAL-B	3.314257	9.19E+10	1.18E+09
ECAL-E	2.41883	3.19E+10	2.51E+08
MUD-B-RPC	0.014406	3.77E+09	51270400
MUD-B-PS	0.008066	9.12E+10	2.67E+08
MUD-E-RPC	0.004583	7.38E+08	10948000
MUD-E-PS	0.003732	1.11E+10	83901100

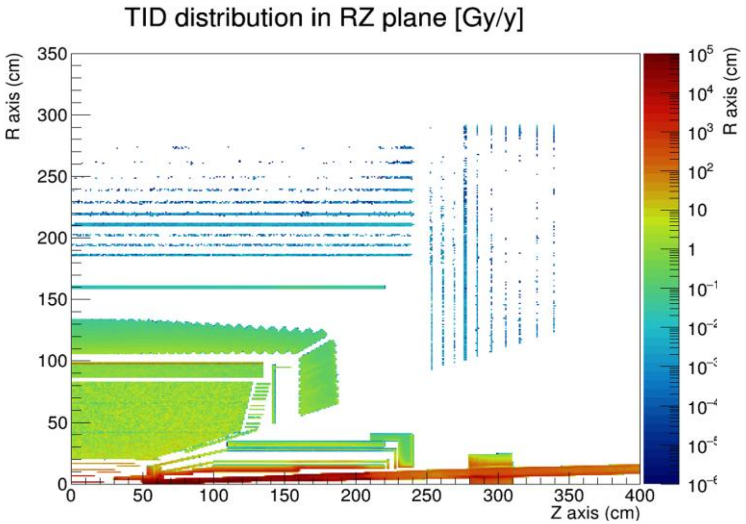
~50 times higher

v7c3

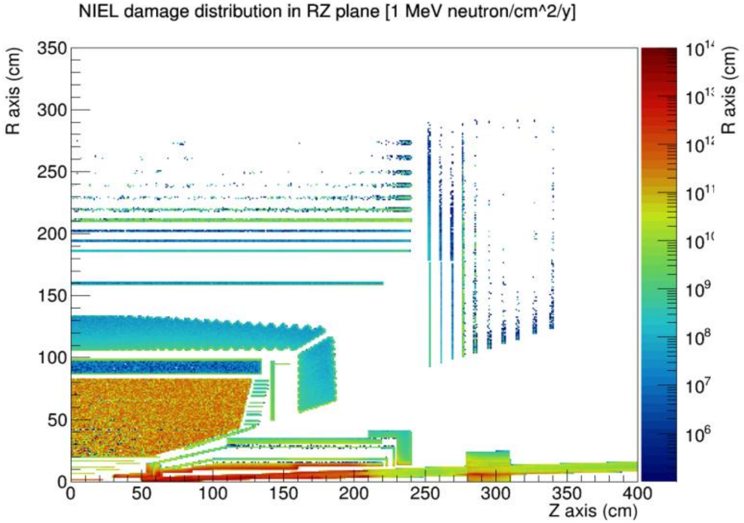
Detector	TID value ($Gy \cdot y^{-1}$)	NIEL damage (1 MeV neutron$\cdot cm^{-2} \cdot y^{-1}$)	Total count rate (Hz)
ITKW-1	260	1.7×10^{10}	3.8×10^{8}
ITKW-2	25	8.3×10^{9}	1.1×10^{8}
ITKW-3	9.0	9.5×10^{9}	7.1×10^{7}
ITKM-1	4700	3.4×10^{10}	2.0×10^{8}
ITKM-2	47	7.9×10^{9}	3.7×10^{7}
ITKM-3	18	1.1×10^{10}	3.3×10^{7}
MDC	0.17	3.6×10^{13}	3.3×10^{8}
PID-Barrel (RICH)	0.33	9.5×10^{9}	2.0×10^{8}
PID-Endcap (DTOF)	1.0	1.6×10^{10}	2.9×10^{8}
ECAL-Barrel	0.36	1.6×10^{10}	6.7×10^{8}
ECAL-Endcap	0.69	1.7×10^{10}	3.5×10^{8}
MUD-Barrel-RPC	0.013	1.8×10^{9}	1.0×10^{7}
MUD-Barrel-Scintillator	0.0036	4.6×10^{10}	6.1×10^{7}
MUD-Endcap-RPC	0.0037	2.8×10^{8}	1.9×10^{6}
MUD-Endcap-Scintillator	0.0023	1.1×10^{10}	7.1×10^{6}

Remove beam-gas contribution

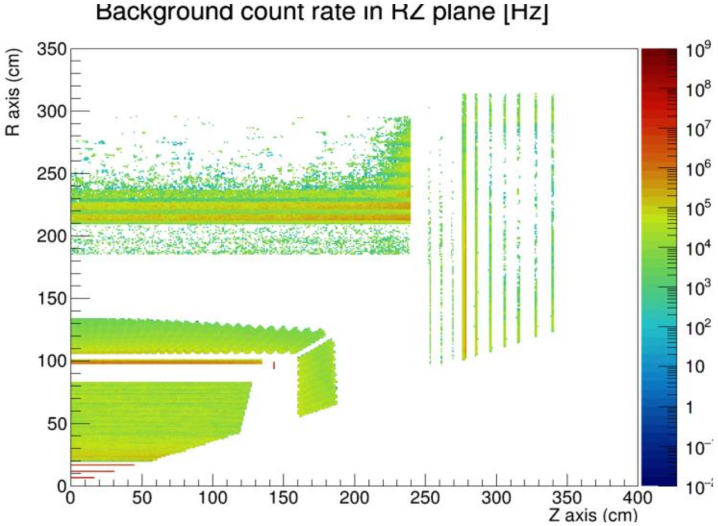
TID v12_b



NIEL v12_b

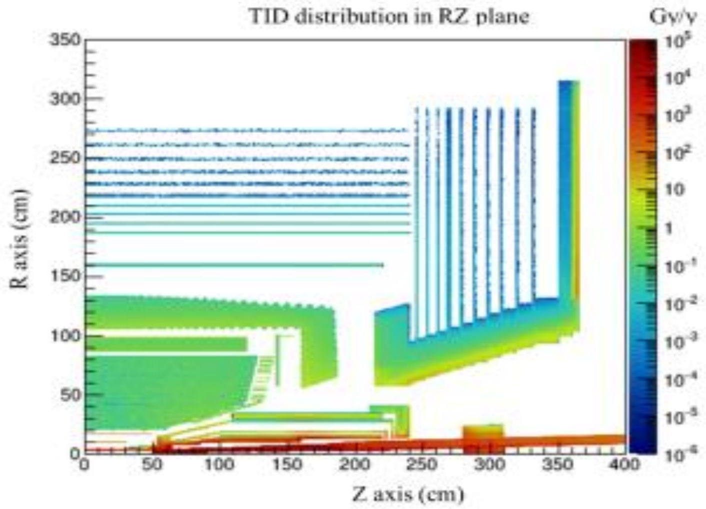


Count rate v12_b

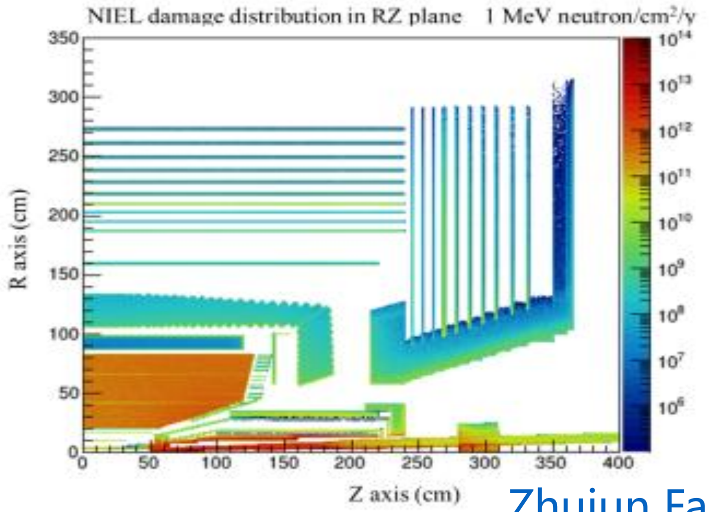


v12_b still higher than v7c3

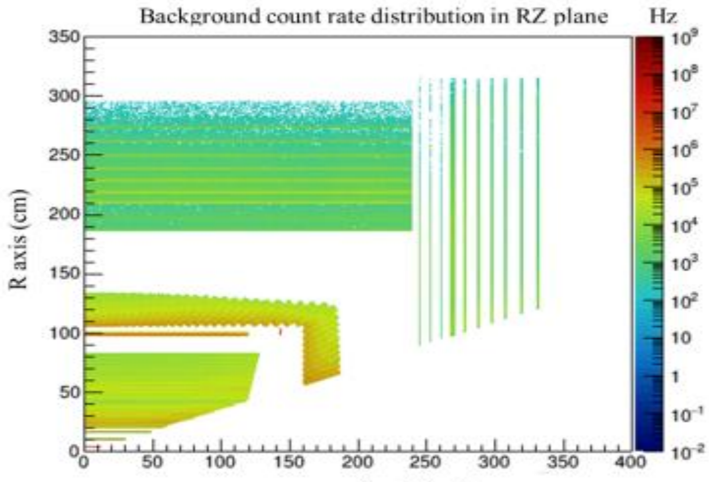
TID v7c3



NIEL v7c3



Count rate v7c3



Zhujun Fang et al 2024 JINST 19 P11014

Remove beam-gas contribution

v12_b

DET	TID	NIEL	COUNT
ITKW1	1247.063	4.66E+10	1.41E+09
ITKW2	112.9324	3.71E+10	4.46E+08
ITKW3	48.54022	3.66E+10	2.69E+08
MDC	2.199967	2.77E+13	2.22E+08
RICH	0.697994	8.82E+09	2.28E+08
DTOF	0.68983	1E+10	2.02E+08
ECAL-B	0.362049	1.09E+10	98363900
ECAL-E	0.428233	7.67E+09	34519000
MUD-B-RPC	0.002322	7.18E+08	10223600
MUD-B-PS	0.002332	1.86E+10	61534100
MUD-E-RPC	0.001177	2.25E+08	2580800
MUD-E-PS	0.001322	3.93E+09	28240000

~5 times higher (Especially ITK)

v7c3

Detector	TID value ($Gy \cdot y^{-1}$)	NIEL damage (1 MeV neutron$\cdot cm^{-2} \cdot y^{-1}$)	Total count rate (Hz)
ITKW-1	260	1.7×10^{10}	3.8×10^{8}
ITKW-2	25	8.3×10^{9}	1.1×10^{8}
ITKW-3	9.0	9.5×10^{9}	7.1×10^{7}
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PID-Barrel (RICH)	0.33	9.5×10^{9}	2.0×10^{8}
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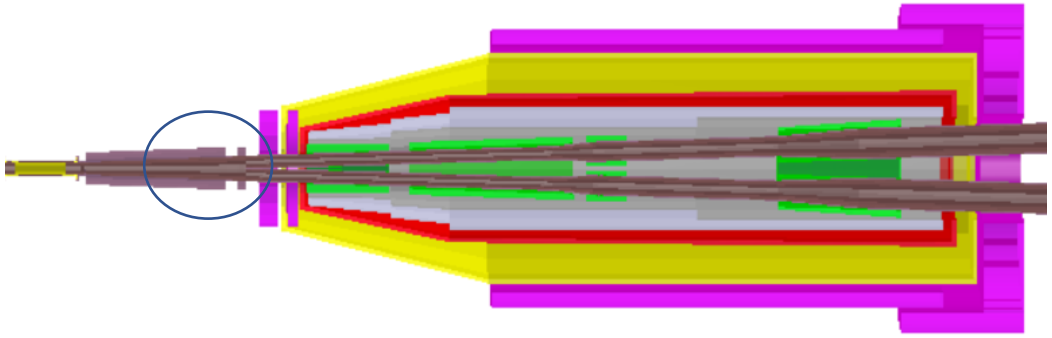
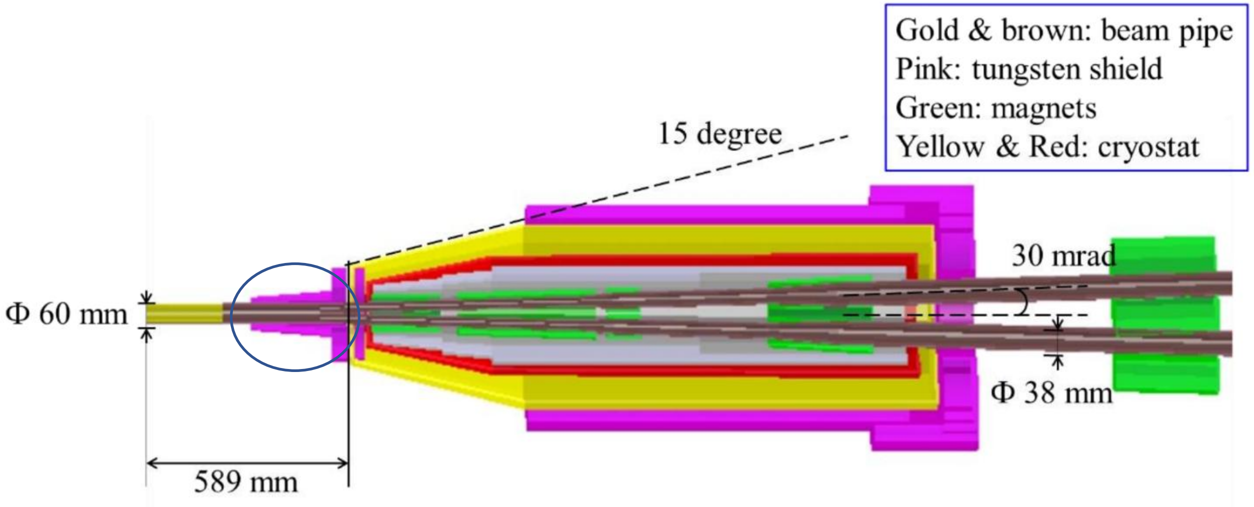
ECAL-Barrel	0.36	1.6×10^{10}	6.7×10^{8}
ECAL-Endcap	0.69	1.7×10^{10}	3.5×10^{8}
MUD-Barrel-RPC	0.013	1.8×10^{9}	1.0×10^{7}
MUD-Barrel-Scintillator	0.0036	4.6×10^{10}	6.1×10^{7}
MUD-Endcap-RPC	0.0037	2.8×10^{8}	1.9×10^{6}
MUD-Endcap-Scintillator	0.0023	1.1×10^{10}	7.1×10^{6}

Reason for higher beam background: shield

Shield for v12_b (MDI Geo v10)



Shield for v7c3 (MDI Geo v7)



- Due to iteration of the beam pipe design, geometry conflict occurs between beam pipe and external shield in version v7c3.
- Much narrower aperture size currently → More beam background generated.
- Thus, no external shield within 0.6 m range currently → More beam background survive.
- Need to place back the hollow cone shield around beam pipe, as pipe geometry fixed.

Summary

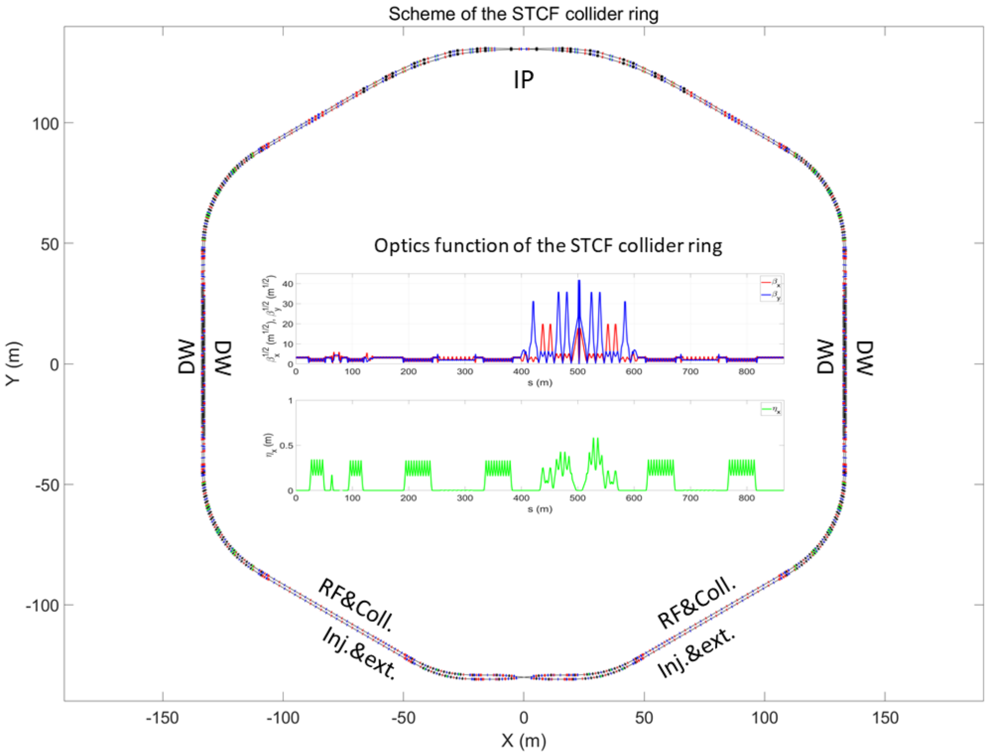
- New design of Lattice and collimator.
- Much higher beam background yield in detector than CDR standard
- Caused by: lack of Beam-gas collimator and inner shield.
- Next step:
  - Collimator iteration.
  - Fix the design of beam pipe (especially the Y-chamber).
  - Place back the hollow cone shield around beam pipe.

Thanks!

Backup

Lattice

stcf_v4.3_2GeV_2A_nux0.543_nuy0.58.sad



Beam Energy	2 GeV
Circumference	860.3 m
Beam Current	2 A
Bunch Number	688
Harmonic number	1434
Emittance in x(y)	4.65e-9 (4.65e-11) mrad
Betax(y) at IP	0.06 (0.0008)
Crossangle	30 mrad
alfap	1.348e-3
energy spread	7.85e-4

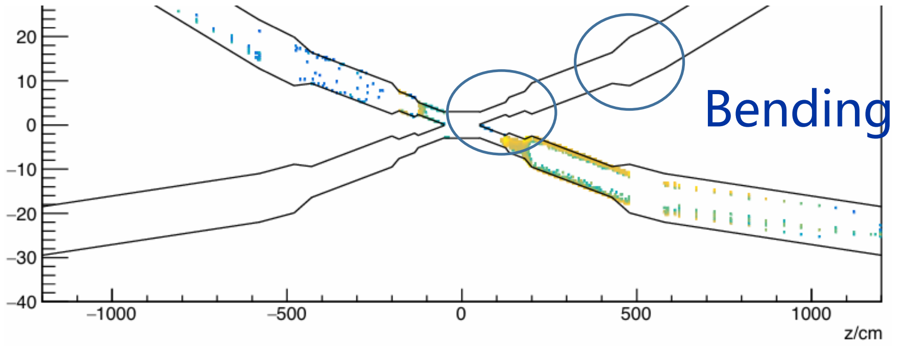
Collimator efficiency

	Total rate (MHz)	**Rate in IP ± 10 m (MHz)**
Touschek	66574.30	1032.03
Coulomb	10.87	0.26
Bremsstrahlung	6089.55	5734.24

Touschek & Beam-gas background

Lattice

➢ Pre-setup
- aperture set
- Slice
- …



Touschek & Beam-gas Generator

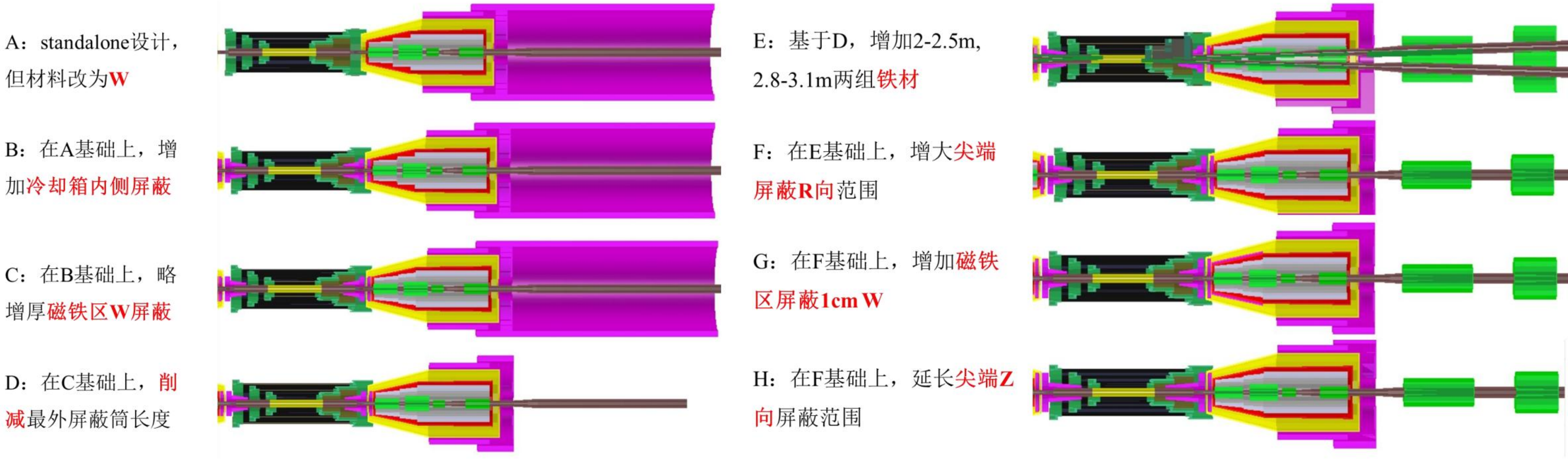
Transport Matrix (Aperture set: $\frac{X^2}{A_X^2}+\frac{Y^2}{A_Y^2}\rightarrow 1$)

Output: position, 4-momentum

Geant4 Simulation

- For G4 simulation, the injection points of particles are projected to the inner wall of beam pipe.
- Coordinates transformation: from accelerator to detector (for both positions and momentums, including rotation & translation).

Iteration for external shield layer design



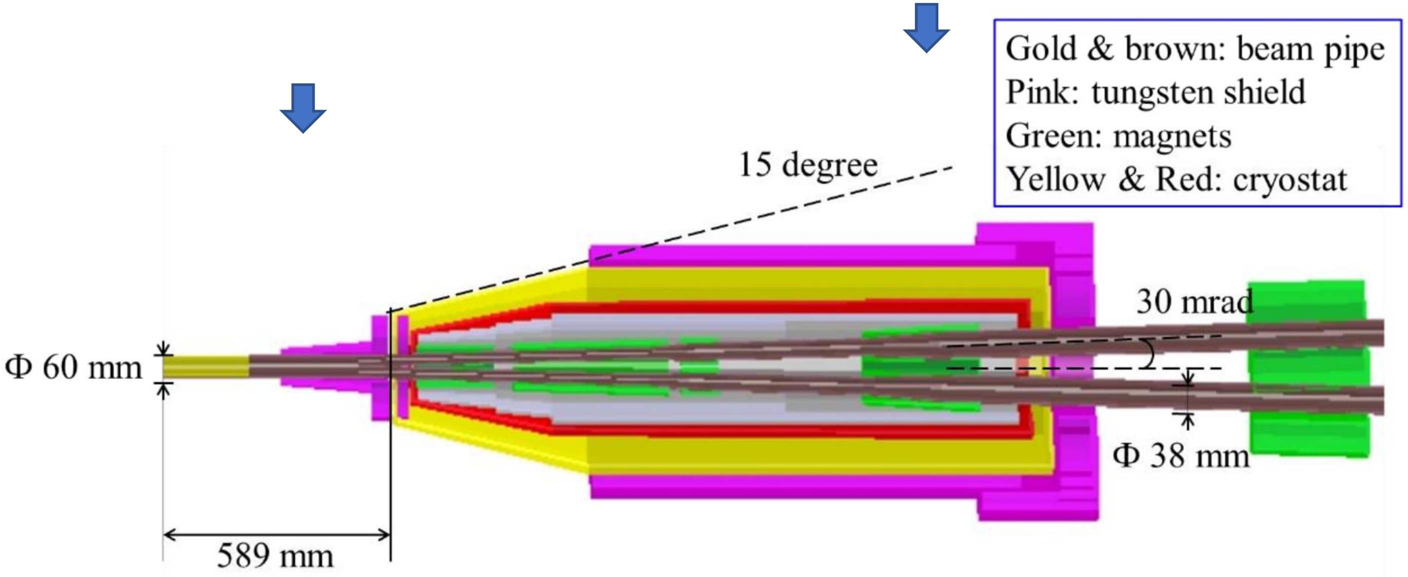
External shield design for MDI – v7c3

ITK Region (W)

- Hollow cone around beam pipe
- Double disc layers

Endcap region (W)

- Envelop surrounding stainless shield (Both barrel & endcap)



Effectively suppress the beam background

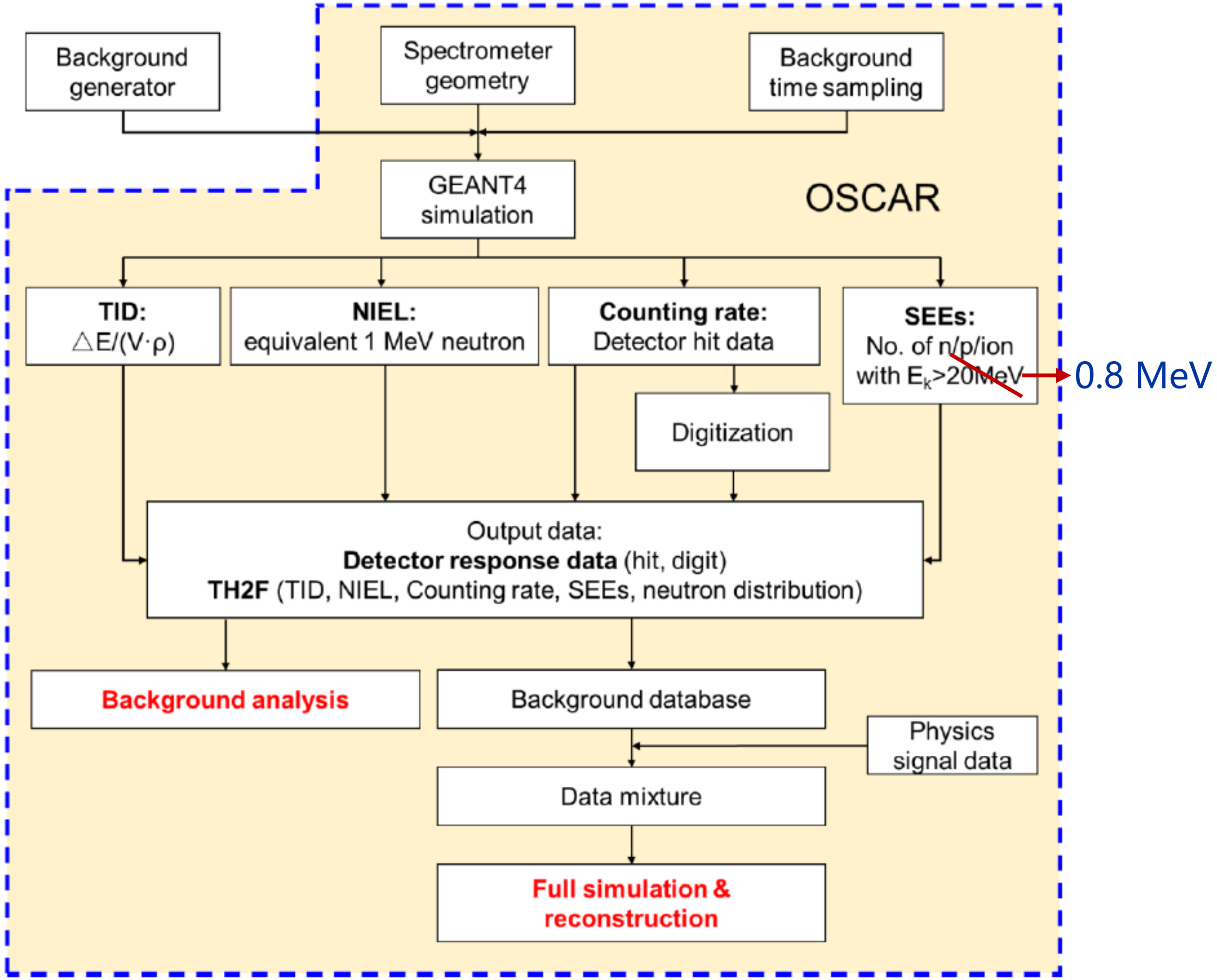
Shield efficiency

Division	With/No shield
ITKW1	29%
ITKW2	9%
ITKW3	4%
MDC	3%
RICH	4%
DTOF	4%
ECAL-B	2%
ECAL-E	13%
MUD-B-RPC	56%
MUD-B-PS	56%
MUD-E-RPC	66%
MUD-E-PS	122%

Beam background deposit in detector

- Major statistics of
  - ✓ Total Ionizing Dose (**TID**)
  - ✓ Non-Ionizing Energy Loss (NIEL)
  - ✓ Counting rate
  - ✓ Single Event Effects (SEE)
  - ✓ Neutron spectrum & distribution
  - ✓ Particle types
  - ✓ …

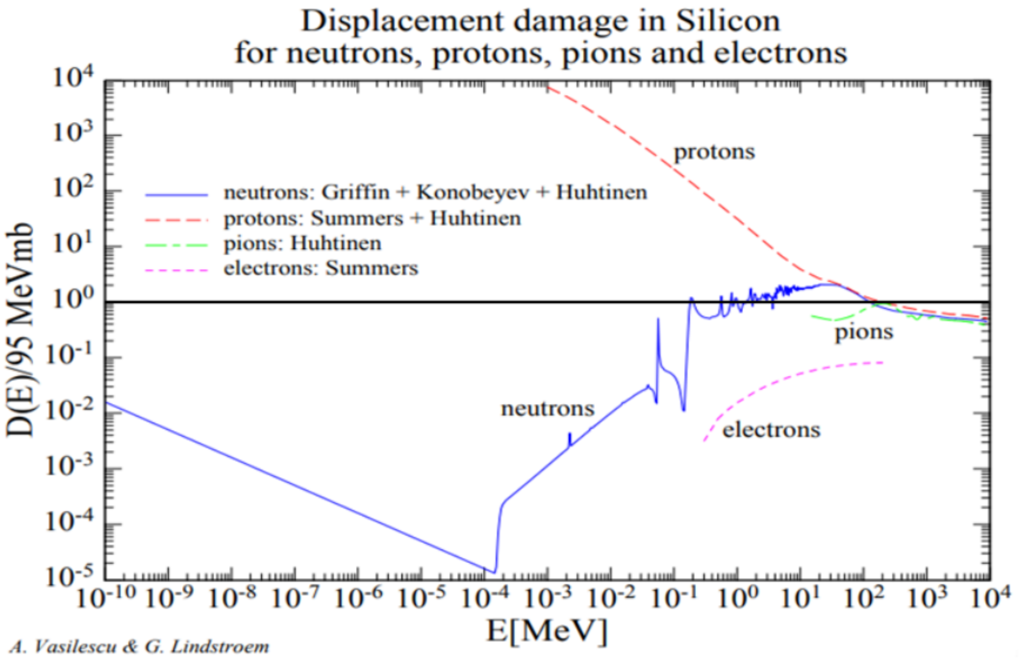
Simulation workflow

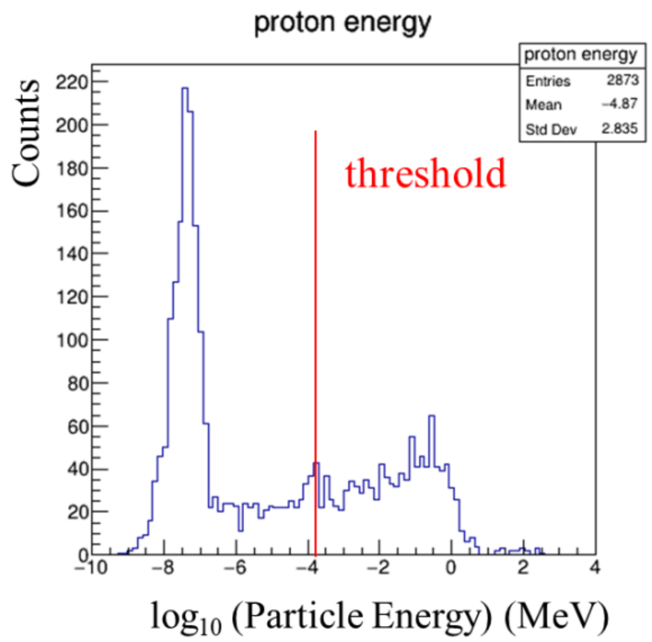


Algorithm for NIEL simulation

Based on Oscar

- Construct Displacement function f(PDG, E)
- Choose dedicated energy region for n, p
- For particles enter sensitive regions, obtain the NIEL via interpolation
- Only consider n, p with energy larger than 158 eV





Last version of lattice (v7c3)

□ 探测器本底水平

Detector	TID value ($Gy \cdot y^{-1}$)	NIEL damage (1 MeV neutron$\cdot cm^{-2} \cdot y^{-1}$)	Total count rate (Hz)
ITKW-1	260	1.7×10^{10}	3.8×10^{8}
ITKW-2	25	8.3×10^{9}	1.1×10^{8}
ITKW-3	9.0	9.5×10^{9}	7.1×10^{7}
ITKM-1	4700	3.4×10^{10}	2.0×10^{8}
ITKM-2	47	7.9×10^{9}	3.7×10^{7}
ITKM-3	18	1.1×10^{10}	3.3×10^{7}
MDC	0.17	3.6×10^{13}	3.3×10^{8}
PID-Barrel (RICH)	0.33	9.5×10^{9}	2.0×10^{8}
PID-Endcap (DTOF)	1.0	1.6×10^{10}	2.9×10^{8}
ECAL-Barrel	0.36	1.6×10^{10}	6.7×10^{8}
ECAL-Endcap	0.69	1.7×10^{10}	3.5×10^{8}
MUD-Barrel-RPC	0.013	1.8×10^{9}	1.0×10^{7}
MUD-Barrel-Scintillator	0.0036	4.6×10^{10}	6.1×10^{7}
MUD-Endcap-RPC	0.0037	2.8×10^{8}	1.9×10^{6}
MUD-Endcap-Scintillator	0.0023	1.1×10^{10}	7.1×10^{6}

□ 电子学芯片本底水平

Electronic system	TID value ($Gy \cdot y^{-1}$)	NIEL damage (1 MeV neutron$\cdot$cm-2$\cdot y^{-1}$)	SEEs ($cm^{-2} \cdot y^{-1}$)
ITKW-1	34	5.4×10^{9}	0
ITKW-2	11	6.3×10^{9}	0
ITKW-3	5.7	1.0×10^{10}	0
ITKM-1	1200	4.5×10^{10}	0
ITKM-2	28	7.3×10^{9}	0
ITKM-3	11	1.0×10^{10}	0
MDC	1.3	6.7×10^{9}	0
PID-Barrel (RICH)	1.7	7.8×10^{9}	0
PID-Endcap (DTOF)	1.1	1.5×10^{9}	0
ECAL-Barrel	0.034	8.5×10^{8}	0
ECAL-Endcap	0.1	1.5×10^{9}	0
MUD	0.2	1.8×10^{9}	0

□ 整体本底水平略低于CDR数据