Investigation on injection-related beam loss at SuperKEKB

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Acknowledgements

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→ Naoko Iida, Yoshihiro Funakoshi, Yukiyoshi Ohnishi, Hiroyuki Nakayama, Hiroshi Kaji, Kenta Uno, Taichiro Koga (KEK Tsukuba)

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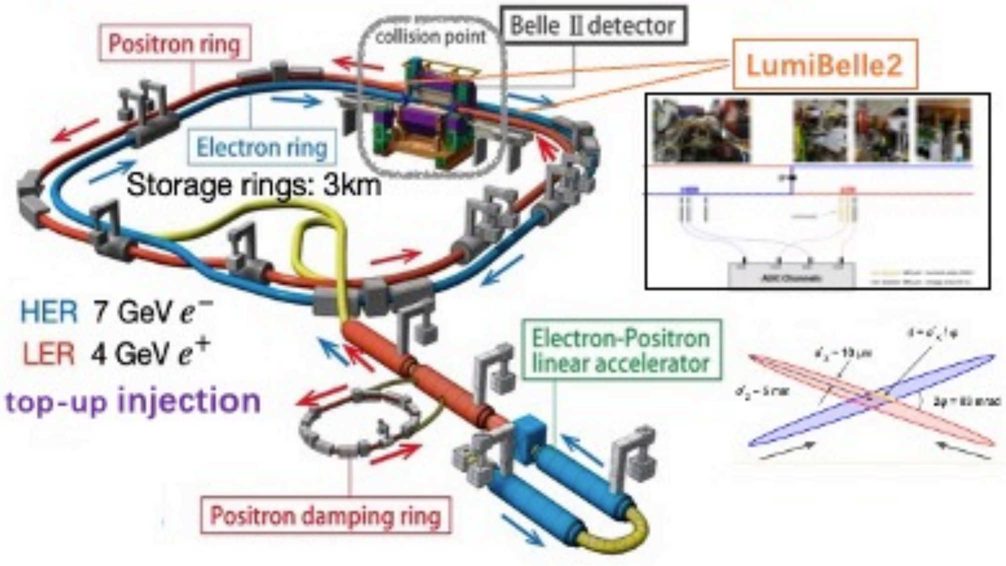
Outline

- ❑ Introduction of injection issues at SuperKEKB
- ❑ Key findings for HER
- ❑ Conclusions and Outlook

SuperKEKB/Belle II project

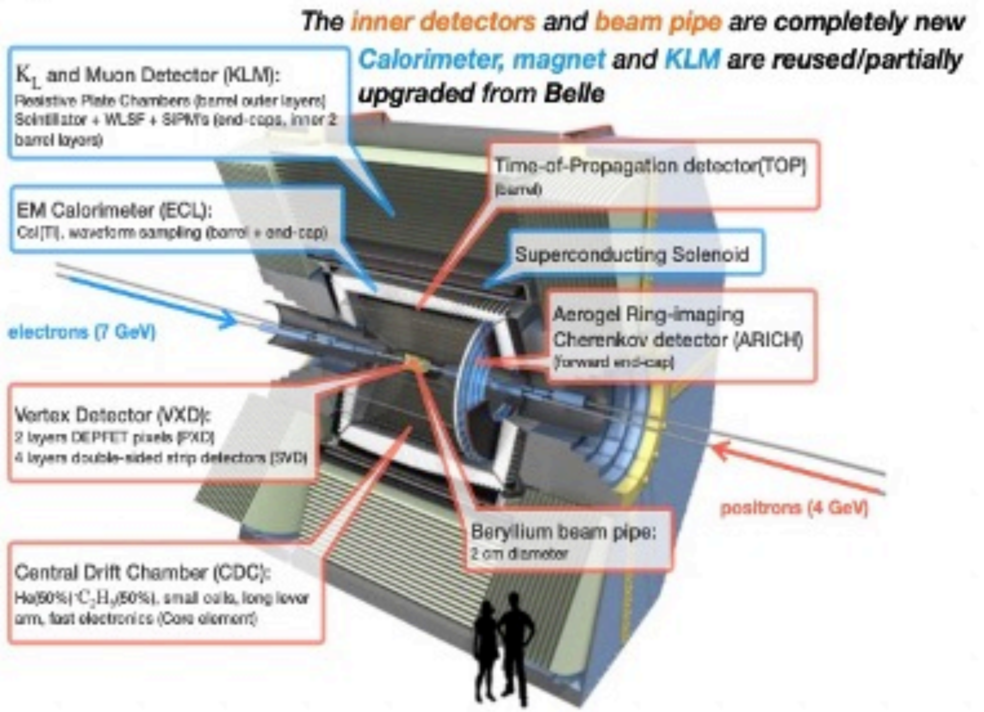
SuperKEKB

- **Asymmetric**-energy e^+e^- collider
- $E_{cm} = M_{\Upsilon(4S)} \approx 10.58$ GeV, B factory
- Goal: $\mathscr{L}_{peak} = 6 \times 10^{35}\,\mathrm{cm^{-2}s^{-1}}$
  - **Nano-beam** scheme and **increased currents**
  - $5.1 \times 10^{34}\,\mathrm{cm^{-2}s^{-1}}$ (**Dec. 2024**, world record)



Belle II

- Target $\mathscr{L}_{int}$: $50\ \mathrm{ab^{-1}}$
  - Physics data taking with full setup in March 2019
  - $575\ \mathrm{fb^{-1}}$ has been recorded by December 2024
- **Upgraded** detectors, trigger and DAQ **vs** Belle



❖ The record luminosity at the end of 2024 was achieved under conditions where the injection was nearly saturated and the beam current could not be further increased.

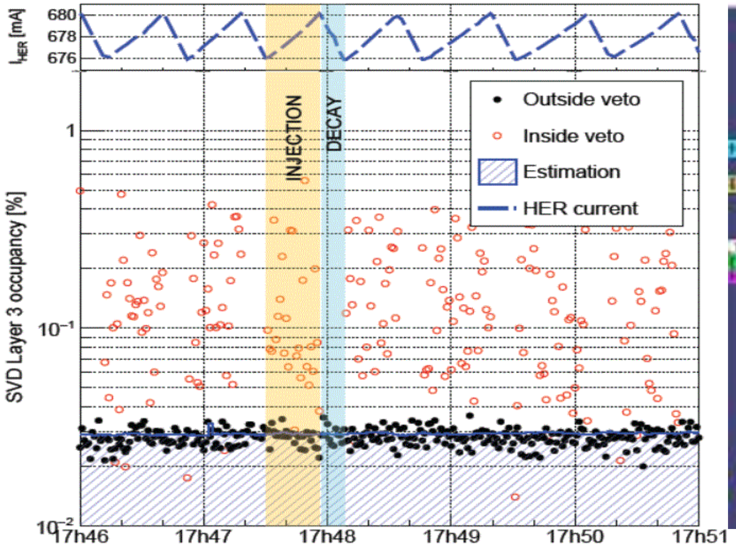
SuperKEKB top-up injection and BelleII DAQ

◻ Injection strongly limit higher luminosity during recent operation

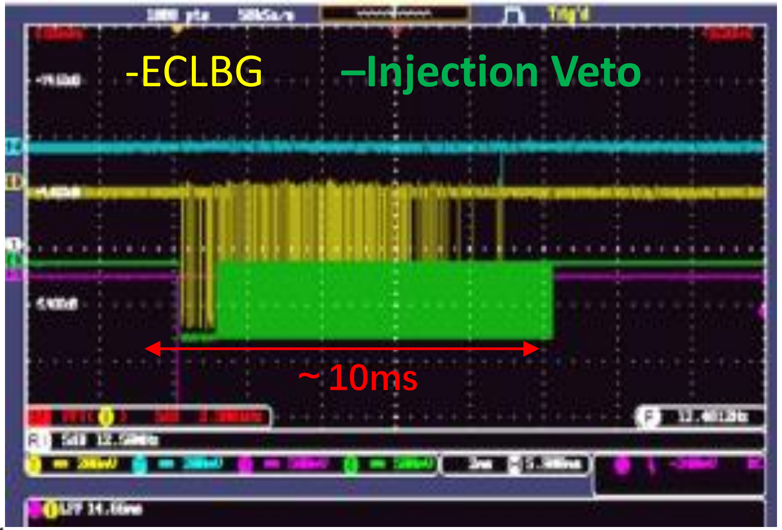
$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{y\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$

- high currents → reduced lifetimes → tried during 2024c run ×
- Small β_y^* → reduced DA → tried 0.8mm during 2022ab run ×

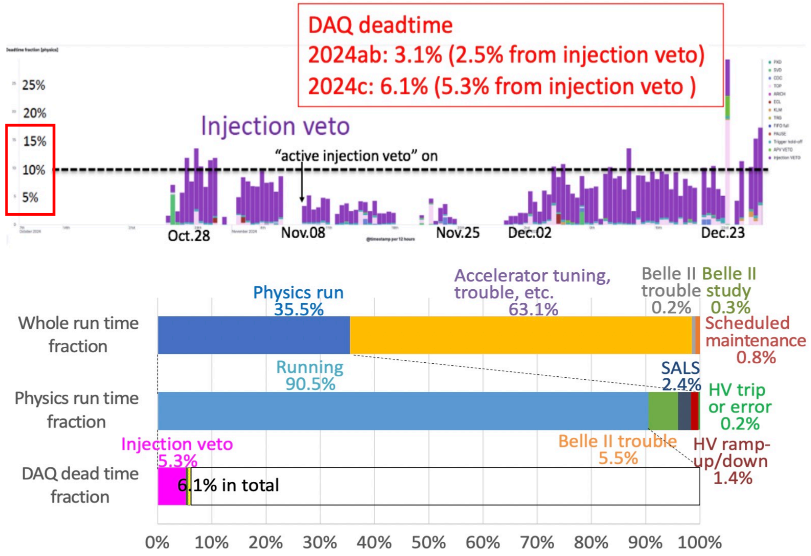
- Achieved injection efficiency during physics run almost lower than half of the required -> limit beam current
- Huge background appear just after beam injection and continues more than 10ms -> limit data taking efficiency
  - -Belle II trigger is vetoed for a while after injection ->large DAQ deadtime of 5~15%
- Injection-related issues are expected to become more severe for higher luminosity -> serious issue for target luminosity
- **Detailed injection-related beam loss and background simulation is essential for improving injection efficiency and BG**



SVD first layer occupancy



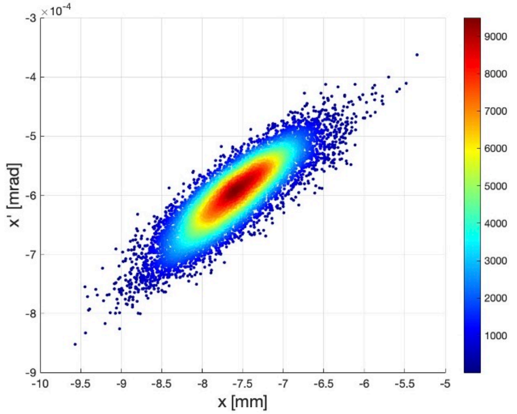
ECLTRG injectionBG duration

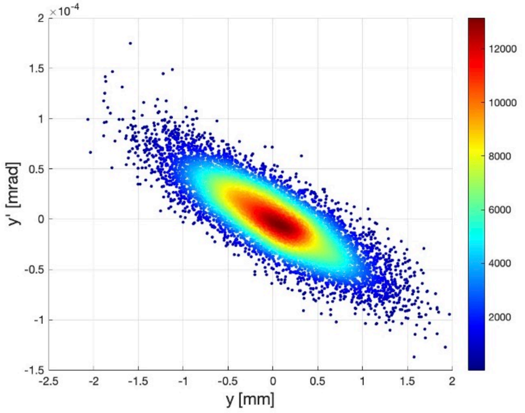


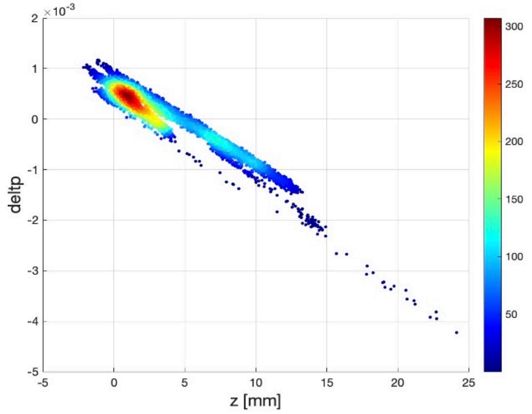
Injection simulation based on realistic operation settings

❖ Detailed HER injection simulations were performed and compared with dedicated experimental measurements.

- **Lattice: HER_CW60_0.9mm-can_rev.sad:** $\beta_x^* = 60mm, \beta_y^* = 0.9mm,$ crab waist=60% (from Ohnishi-san)
- **Injection distribution** (from Yoshimoto-san) + emittance adjustments ($\gamma\varepsilon_x/\gamma\varepsilon_y = 200\mu m/150\mu m$) + injection error ($2J_x = 0.58\mu m$)







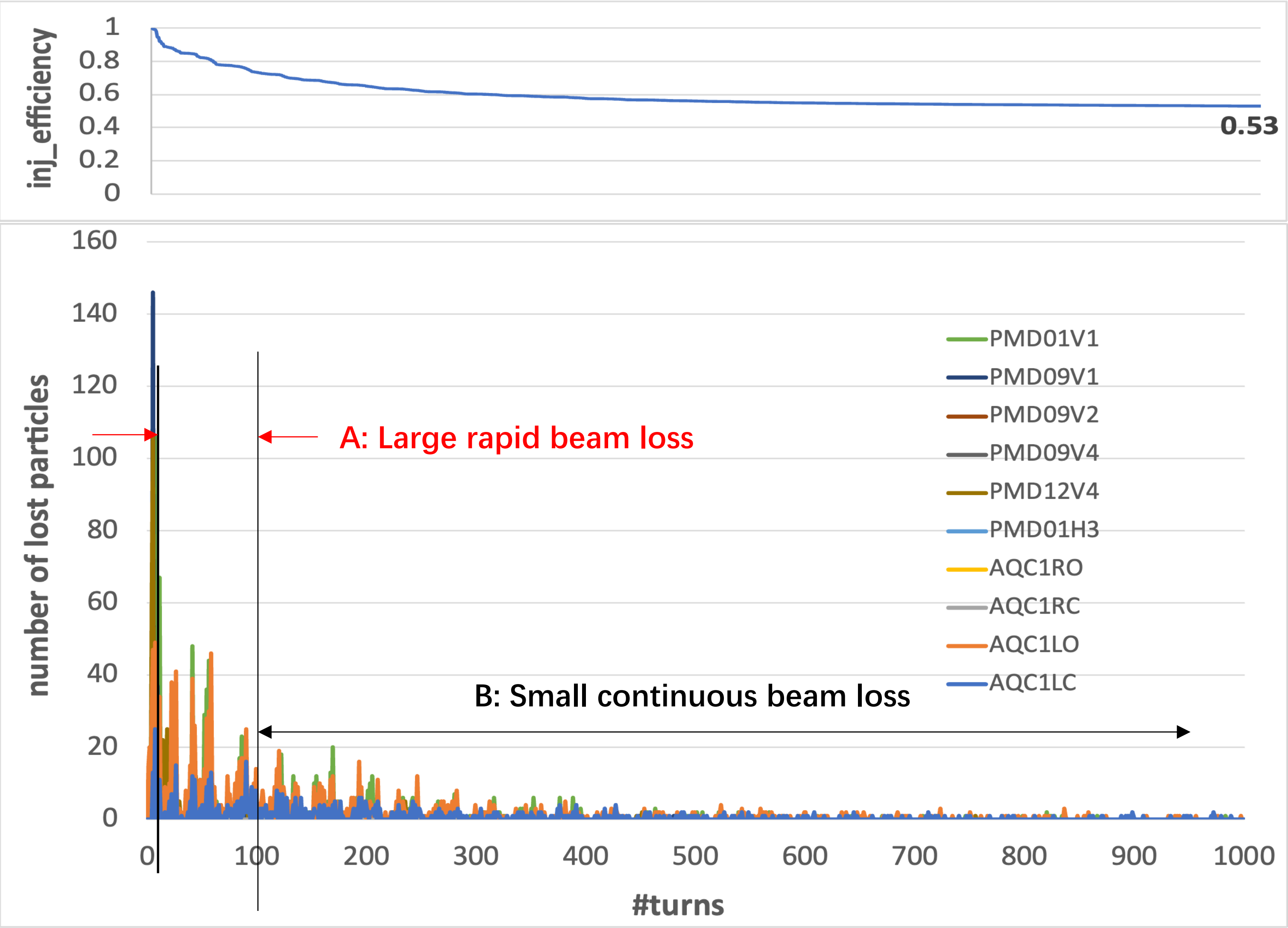
- **Beam-beam(weak-strong model)**

```
BEAMBEAM      FBMBME   =(BX =.08    BY =.0009    XANGLE =.0415   EMITX =1.55e-09   EMITY =26.9e-12   DP =.00075   SIGZ =.006
           SLICE =200 NP =3.3e+10    STURN =10 )
```

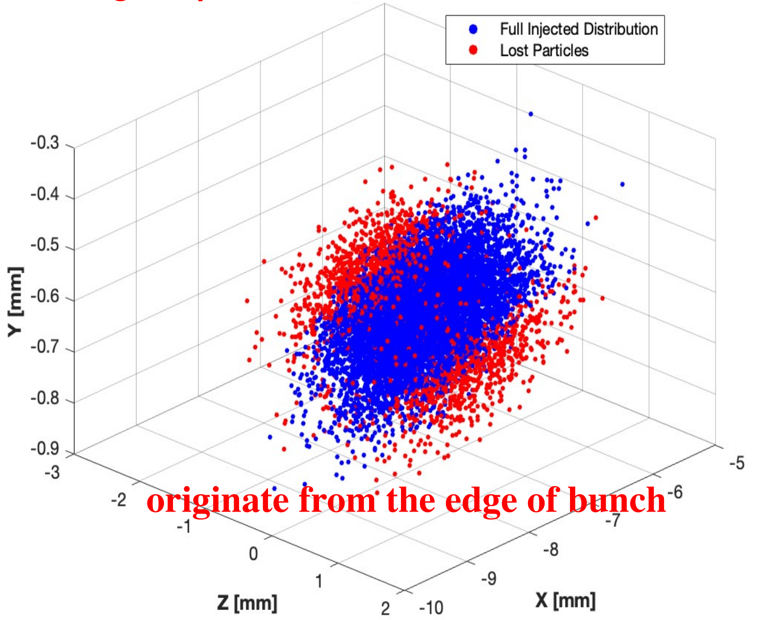
$N_p = 3.31\times10^{10} \rightarrow I_b = 0.5mA \rightarrow \xi_y = 0.017, \xi_x = 0.010$ (based on 2024-6-27 operation emittance and bunch current)

- **Realistic IR beam pipe setting + Collimator** (2024-06-26)
- **Machine error: sextupole vertical mis-alignment** (55μm Gauss random → global coupling: $\varepsilon_y/\varepsilon_x = 0.6\%$)
  manufactory error from cancel coils(correct leakage field from QC1P in the LER)
- **Bunch-by-bunch feedback**(damping time=0.5ms) → Gaussian stored beam also included

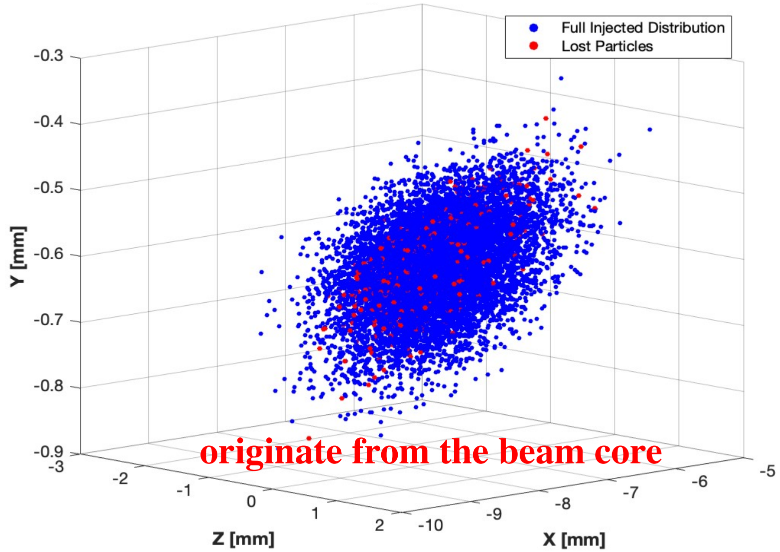
Injection efficiency and beam loss



A: Large rapid beam loss



B: Small continuous beam loss



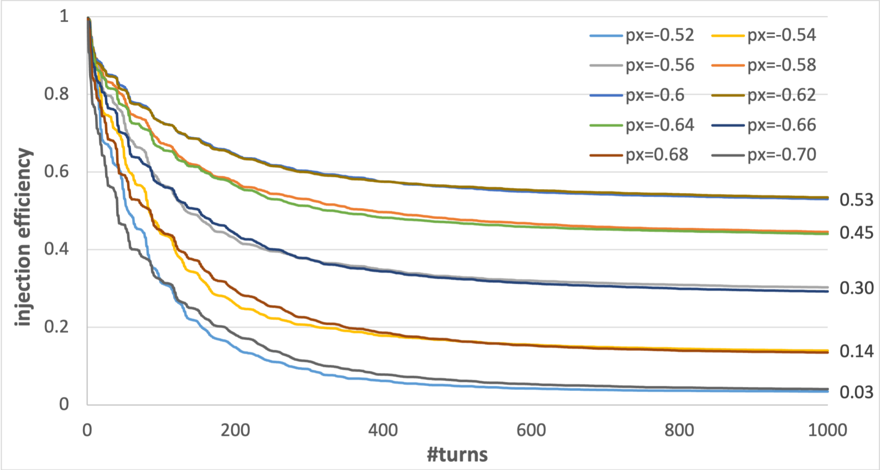
- There are 2 different types of beam loss:

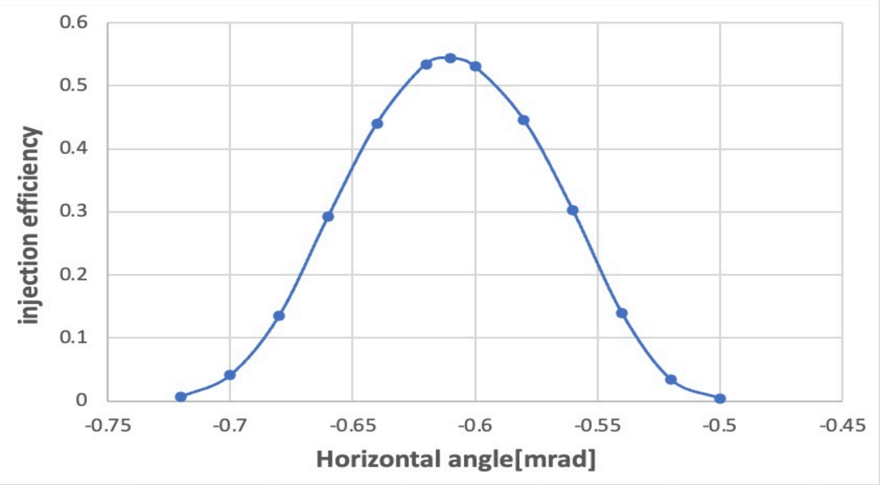
1) large and fast beam loss in the first 100 turns(30%) →injection efficiency

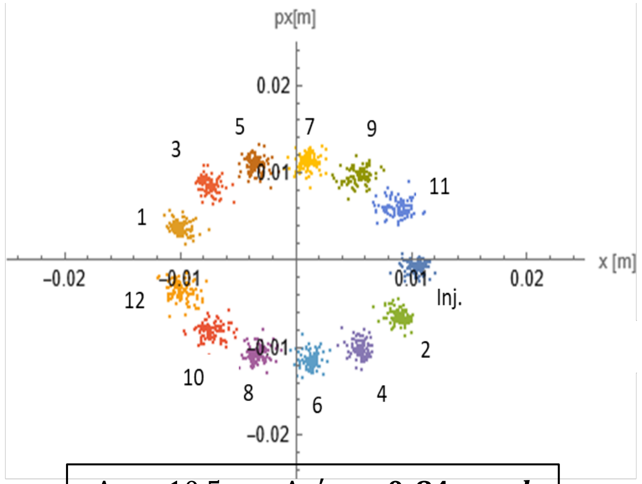
2) small and continuous beam loss until 1000 turns(10%) →injection BG duration

■ Finding1: Injection errors mainly affect injection efficiency

-> injection offset; injection angle; injected emittance; injection phase; x-y coupling

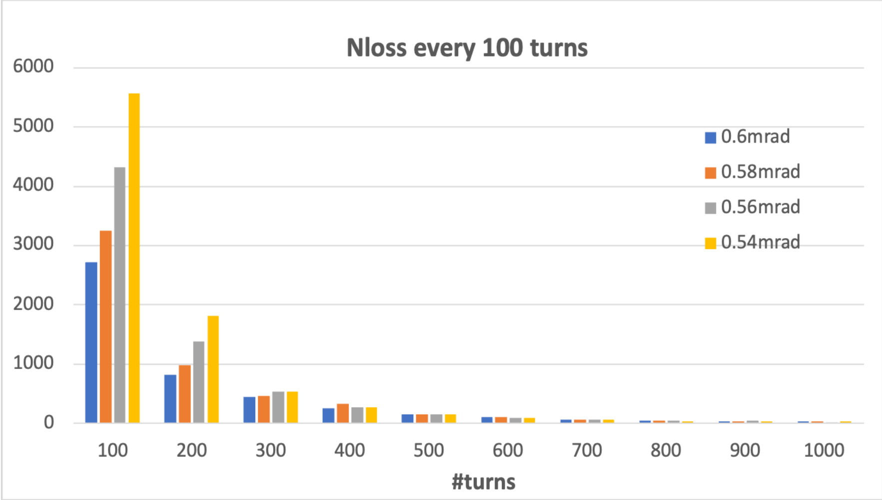


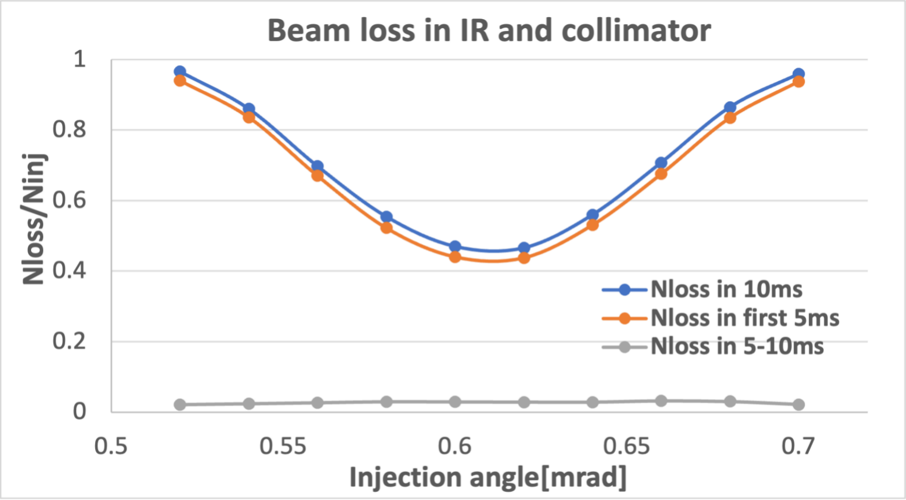


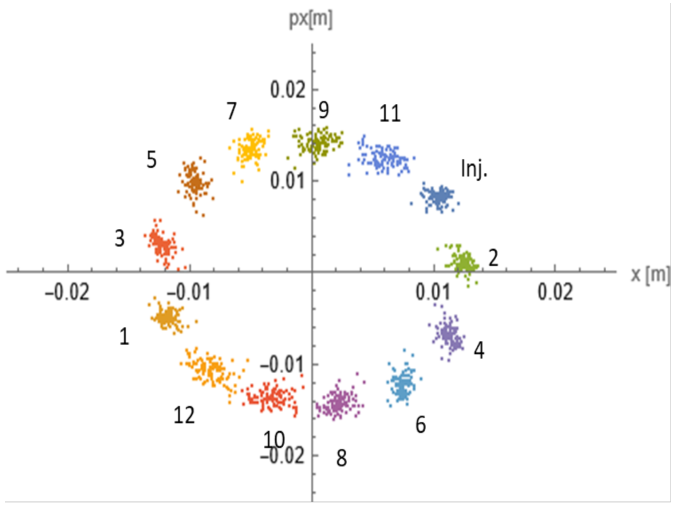


$\Delta x = 10.5mm, \Delta x' = -\mathbf{0.84}\boldsymbol{mrad}$

10.5mm







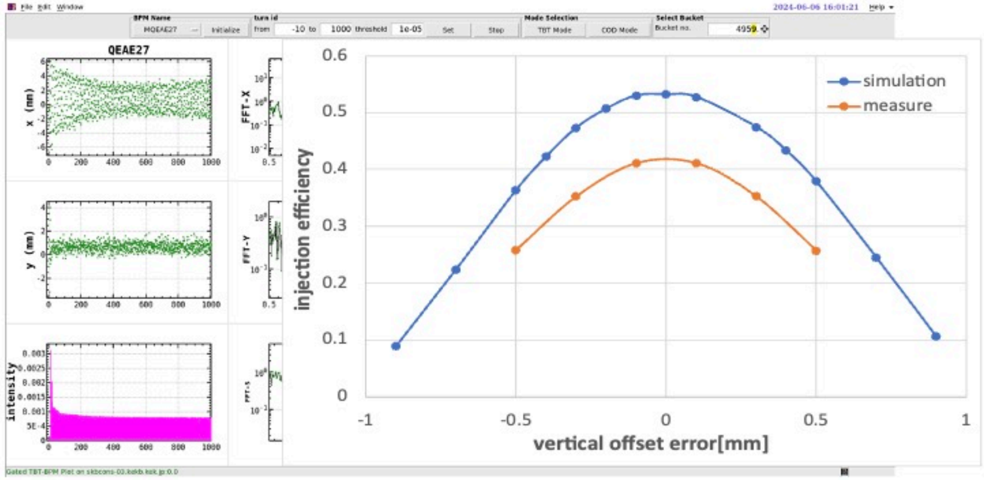
$\Delta x = 10.5mm, \Delta x' = -\mathbf{0.75}\boldsymbol{mrad}$

13.0mm

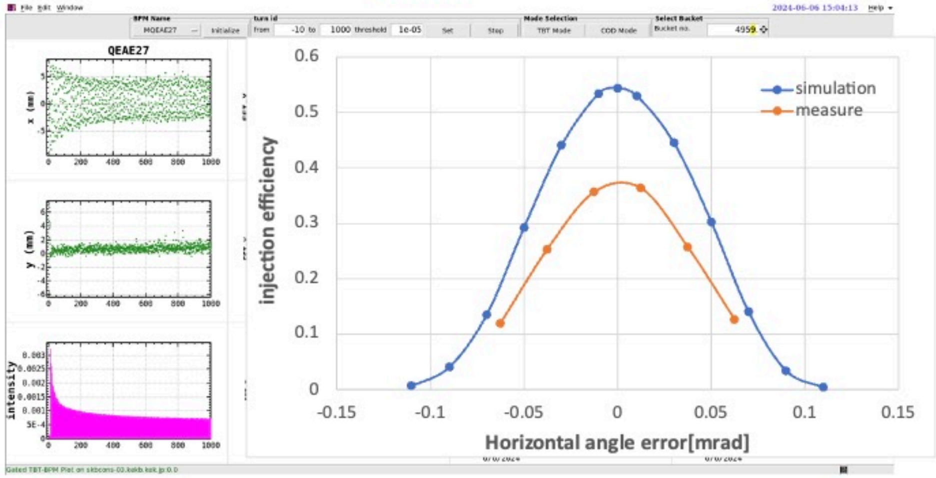
Measurement of Injection Error Effect on Injection(2024-06-06)

(with N. Iida, Y. Ohnishi)

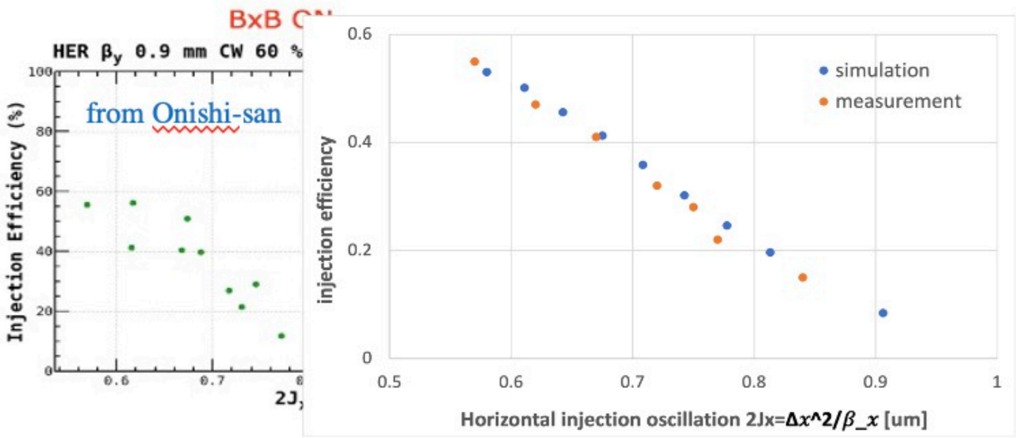
- Vertical Position Scan[mm]: −0.06 → −1.06



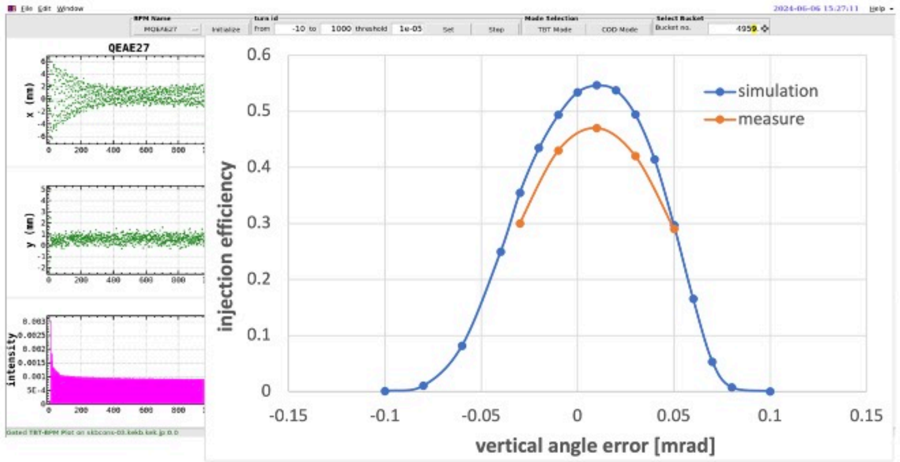
- Septum Angle Scan[mrad]: 2.94 → 3.06



- Septum Position Scan[mm]: 45.1 → 46.1



- Vertical Angle Scan[mrad]: 0.014 → −0.054

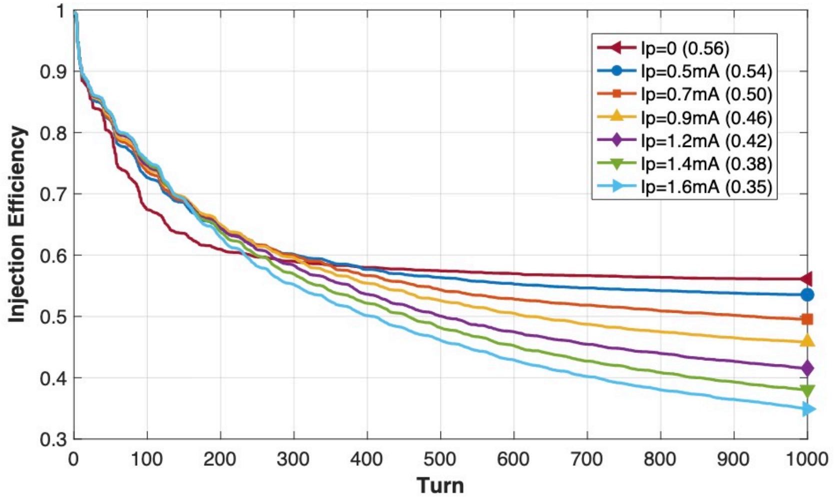


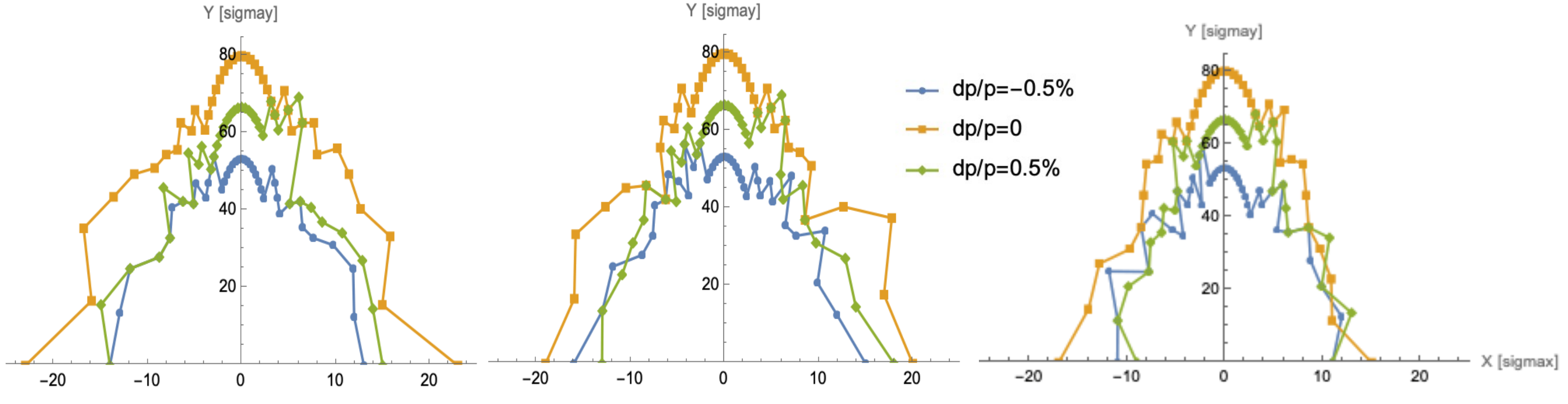
➢ The trend of injection efficiency with respect to the variation in error is consistent.

■ Finding2: Non-linearity in HER lattice affect both efficiency and background

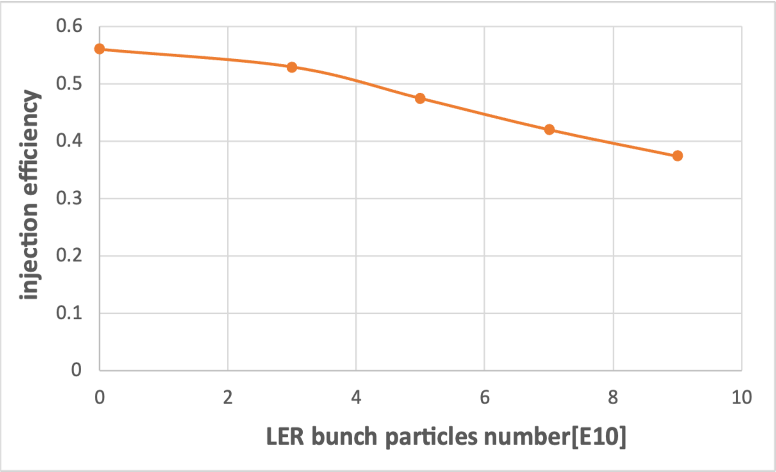
-> Beam-beam effect; cancel coil error; crab waist collision

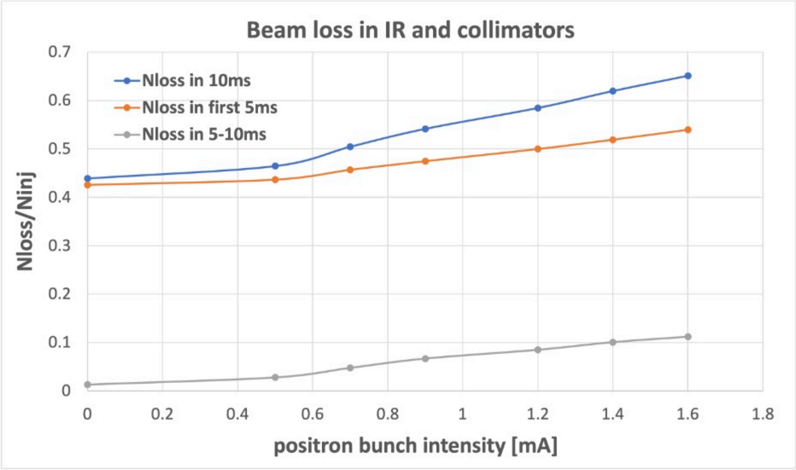
- ❖ Beam-beam interaction can reduce the beam loss rate in the first 100 turns but increase the loss rate after 100 turns.
- ❖ Strengthening the beam-beam interaction decreases DA, lowers injection efficiency, and increases injection background-related beam loss.

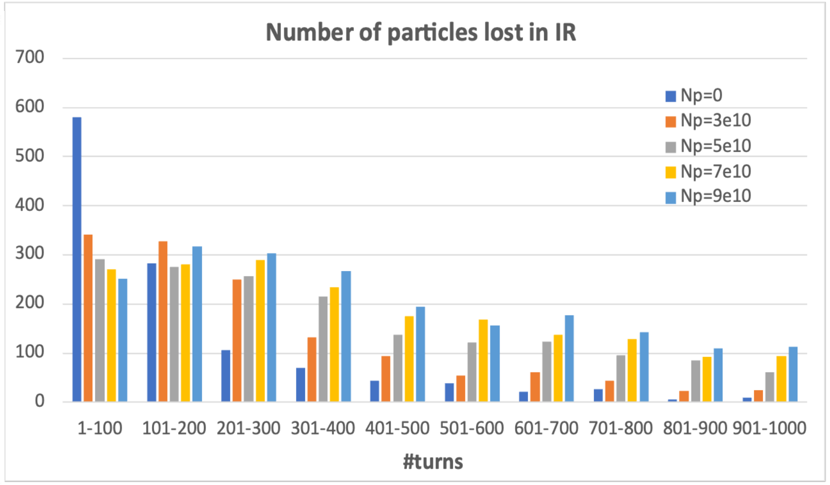




$N_p = 0 \rightarrow \xi_y = 0 \rightarrow \mathbf{23\sigma_x}$ $N_p = 3.3\times10^{10} \rightarrow \xi_y = 0.017 \rightarrow \mathbf{19\sigma_x}$ $N_p = 18\times10^{10} \rightarrow \xi_y = 0.092 \rightarrow \mathbf{15\sigma_x}$

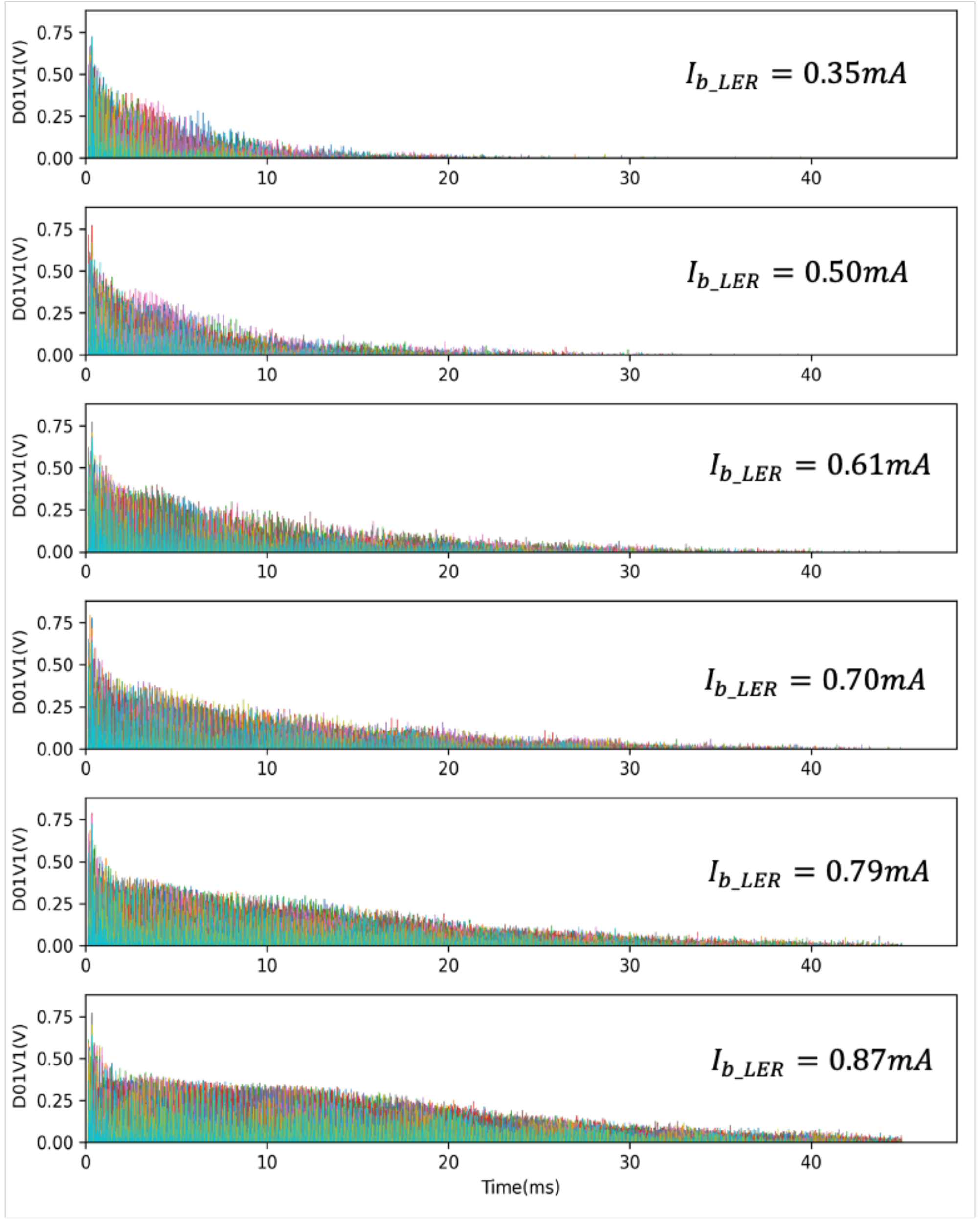


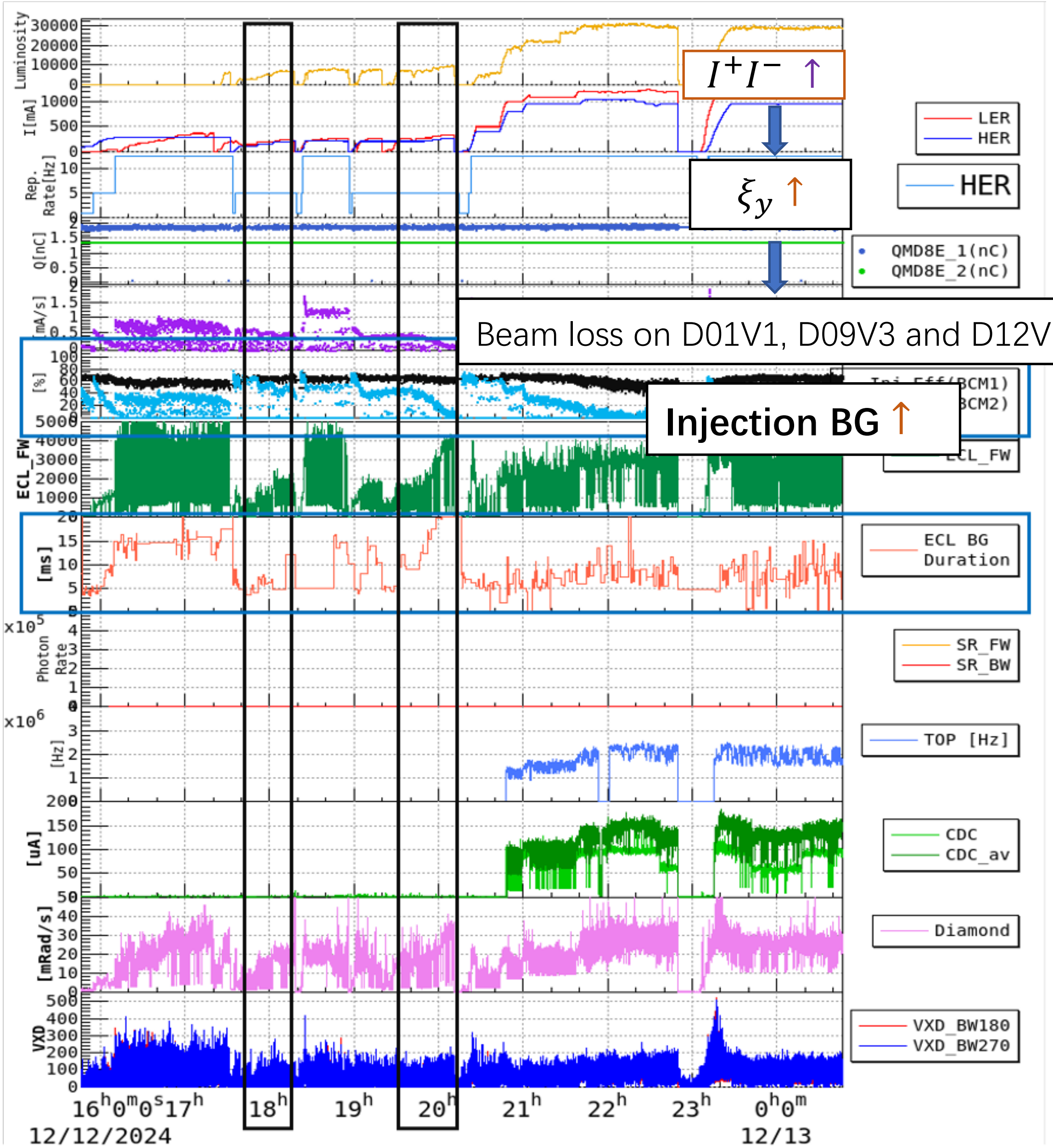




Measurement of Beam-beam effect on injection (2024-12-12)

(with Y. Funakoshi, H. Kaji, T. Koga, U. Bela)



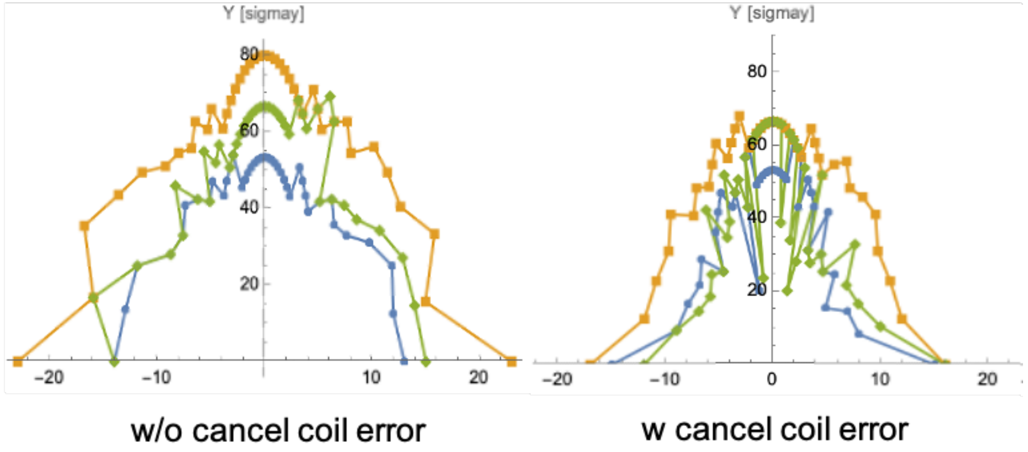


Injection efficiency after 100 turns

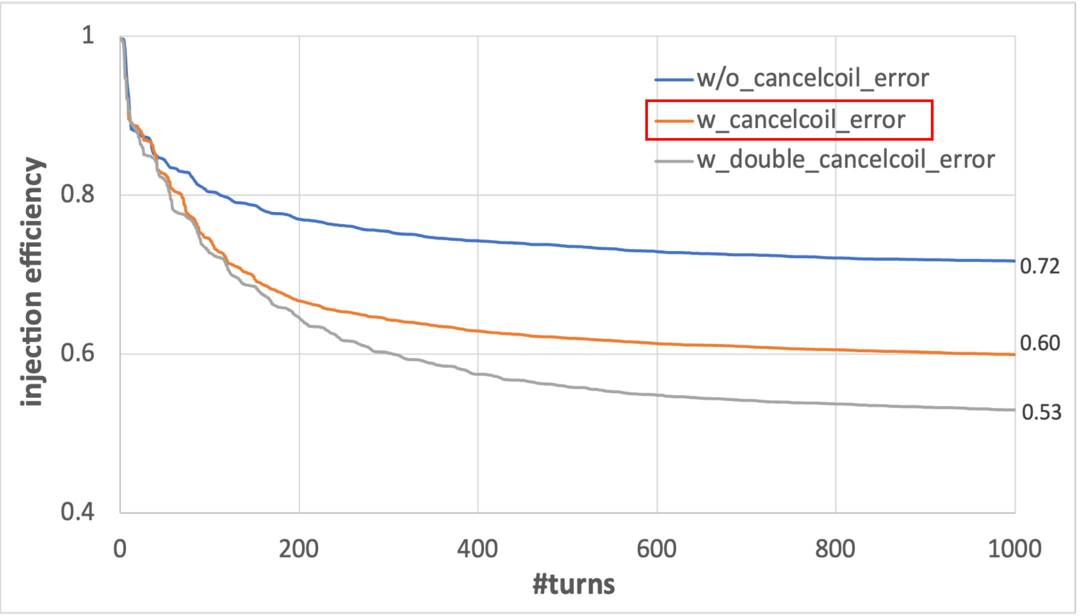
Injection BG duration

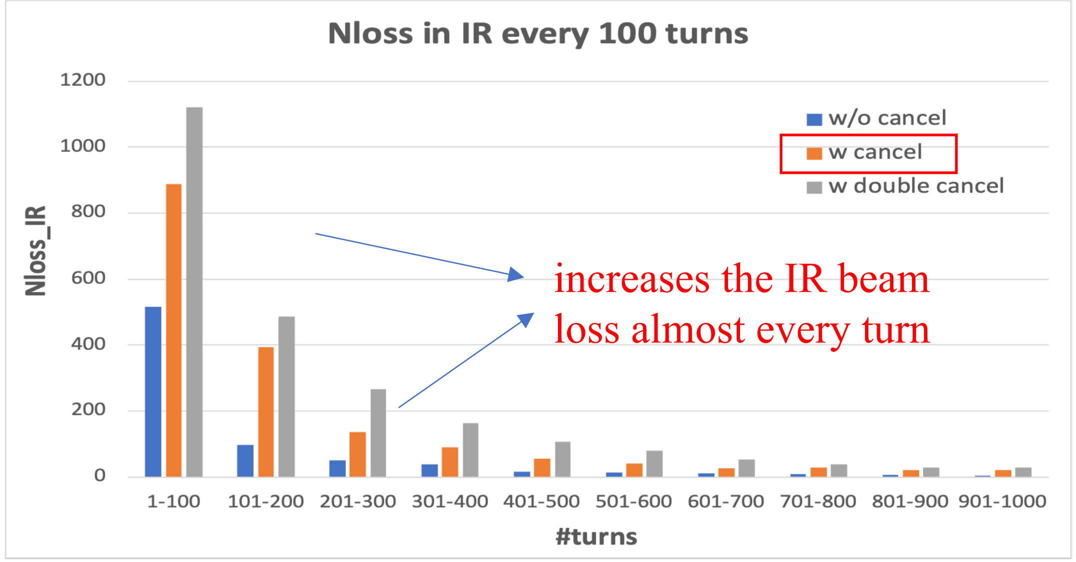
◻ Cancel coil error affect both injection efficiency and background

- Cancel coils in the HER should correct the leakage field from QC1LP and QC1RP in the LER.
- Skew sextupole and skew octupole increase (not cancelled) due to manufacturing mistake.



- Cancel coil error degrades the on-momentum DA: $80\sigma_y \rightarrow 65\sigma_y$, $22\sigma_x \rightarrow 16\sigma_x$
- Decrease the injection efficiency: $72\% \rightarrow 60\%$





☐ Cancel coil error correction— based on 2024c lattice obtained from Ohnishi-san and kosio-san

- **Cancel coil error correction:** H. Kosio

Placed a thin skew sextupole magnet, VSKQC1RE, before VKQC1RE of QC1RE on the beam orbit

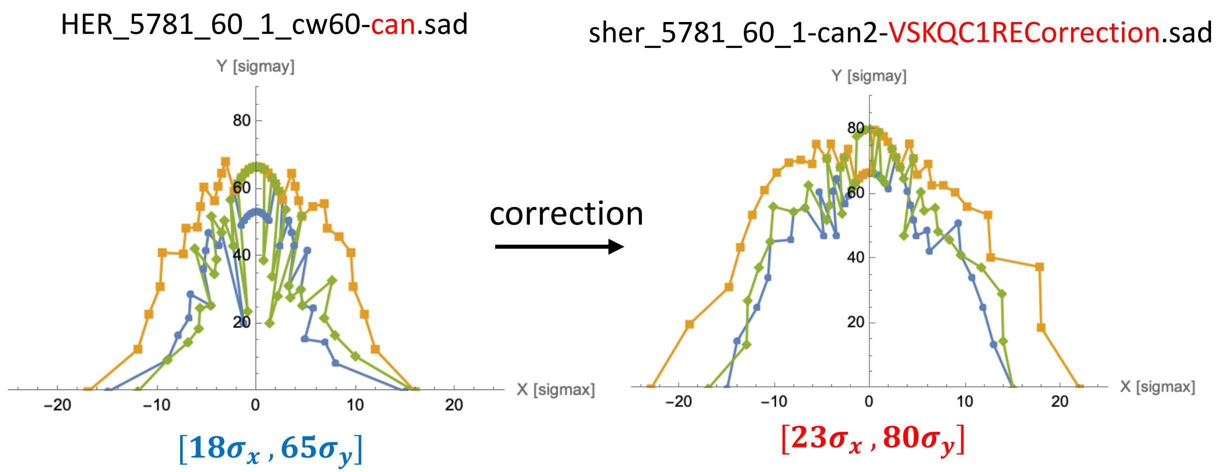
```
VSKQC1RE =(DX =-.0007  SK2=0)
pos=LINE["S", VSKQC1RE]=3014.9047
elm="VSKQC1RE";
Element["DX",elm]=Twiss["DX",elm];
Element["DY",elm]=Twiss["DY",elm];
Element["SK2",elm]=0.04;
CALC;
EMIT;
```

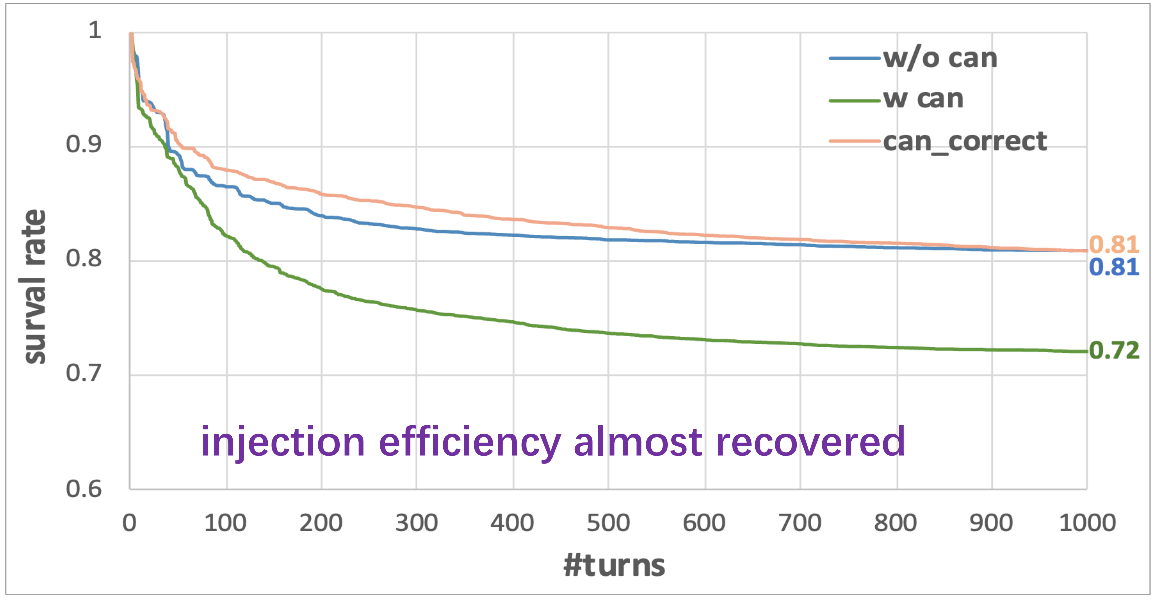
→ does not affect the orbit or linear optics

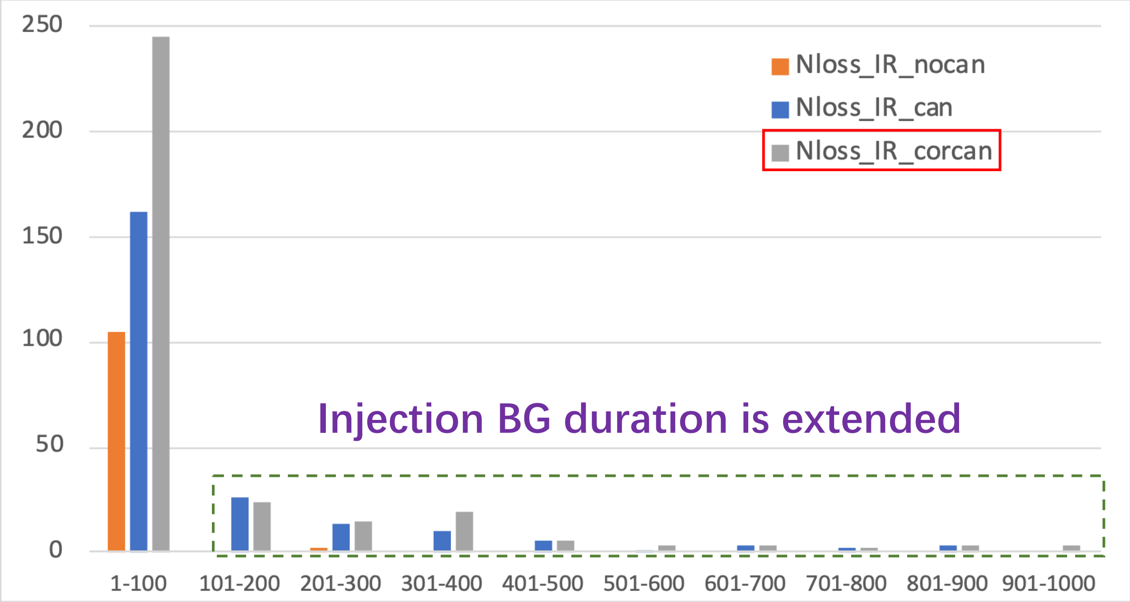
→ L-side ΣSK2 = -0.32853, R-side ΣSK2 = -0.41576 (L-side ΣSK2) - (R-side ΣSK2) ~ -0.0872

→ correcting the SK2 imbalance between the left and right sides of the IP

❖ DA almost recovered after correction





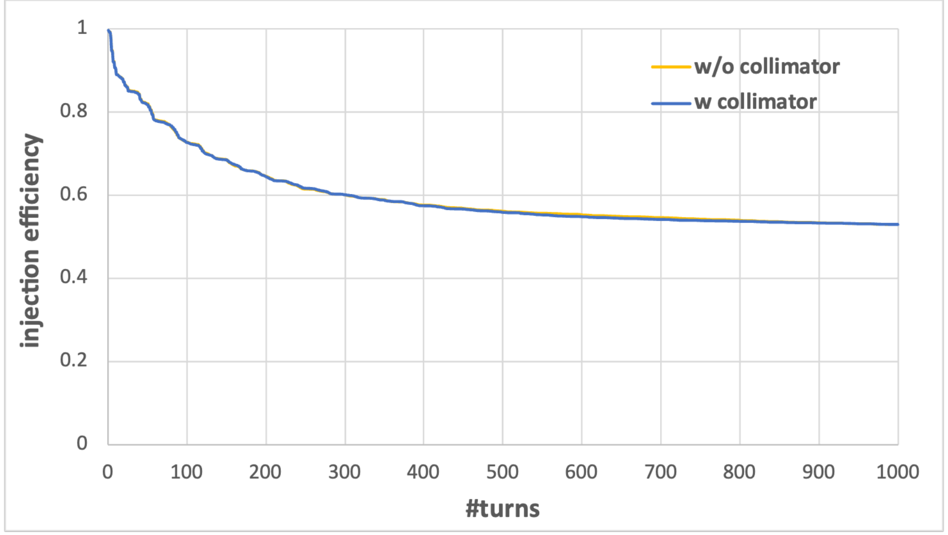


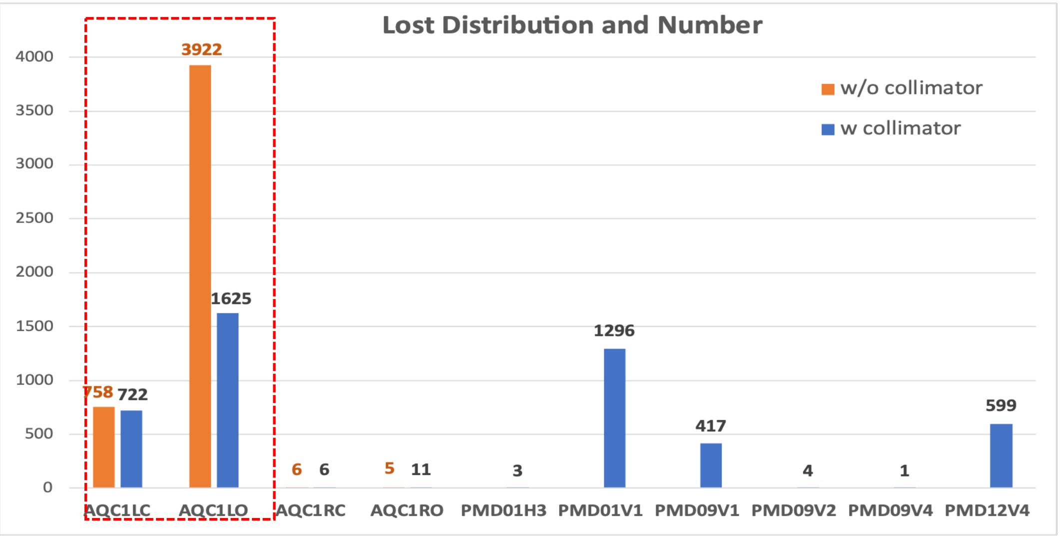
❖ Collimator optimization is required to avoid increase of IR beam loss

❖ Validation experiment will be carried out in 2025c operation

■ Finding3: IR Beam loss can be suppressed by minor collimator aperture adjustment

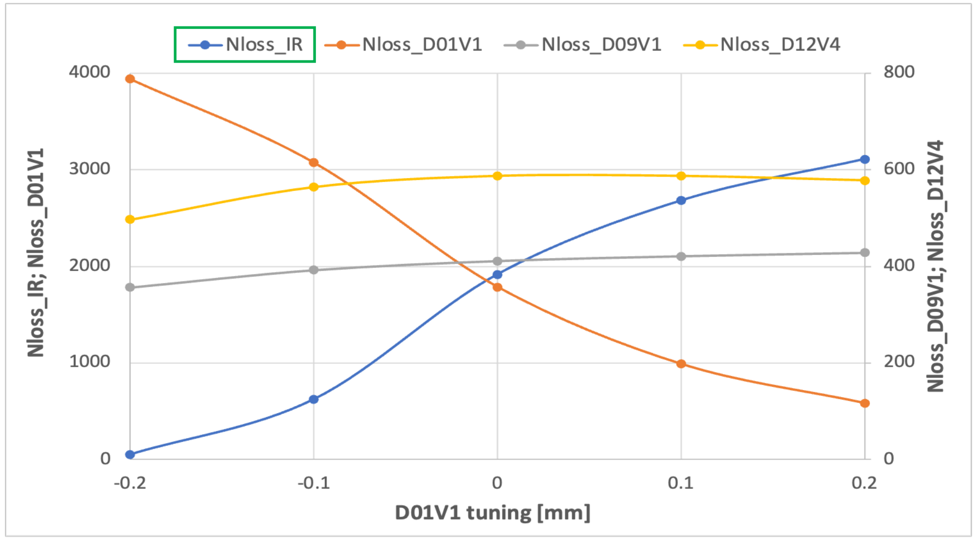
➢ **Current collimator settings are effective in protecting the IR region, but IR losses remain.**

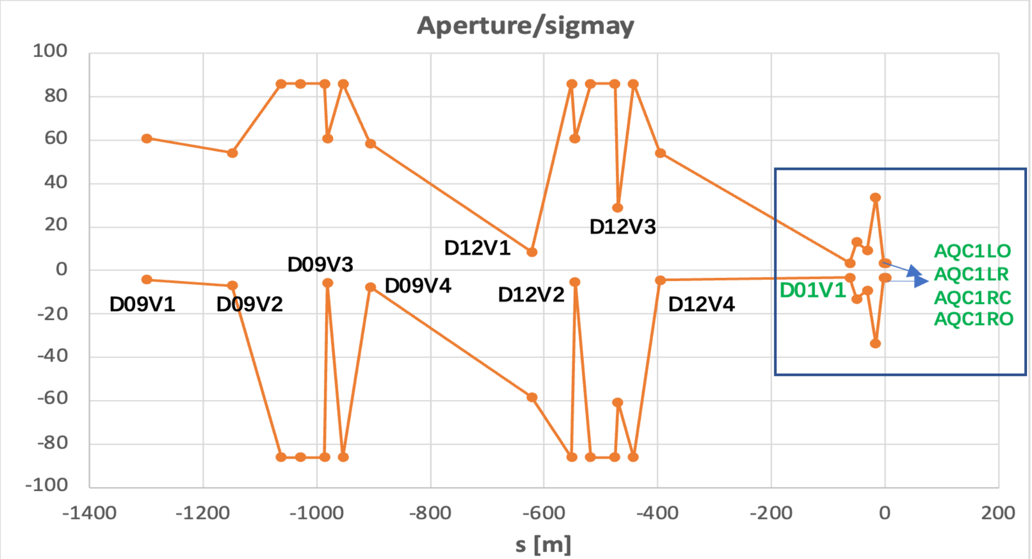




➢ **D01V1 plays a major role in this suppression**

-relative aperture to the injection beam size of D01V1 is almost the same as that of the IR beam pipe





Collimator and beam-beam measurement (2024-12-26)

(with K. Uno, R. Ueki, H. Kaji, T. Koga, U. Bela)

☐ Tuning the collimator D01V1 and recording the injection related beam loss and background

Take data with collimator D01V1 position: original, +-100um, +-200um under two different beam current cases

-> LER:240mA, HER:192mA, 393 bunches (corresponds to 1.4A and 1.1A with 2346 bunches) ->current best operation so condition

-> LER:290mA, HER:230mA, 393 bunches (corresponds to 1.7A and 1.4A with 2346 bunches)-> a little future

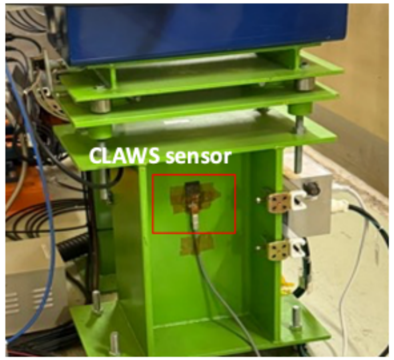
☐ Data recording

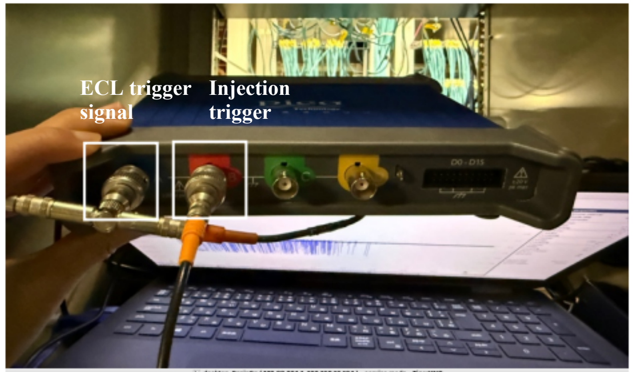
-> injection efficiency -> TbT monitor

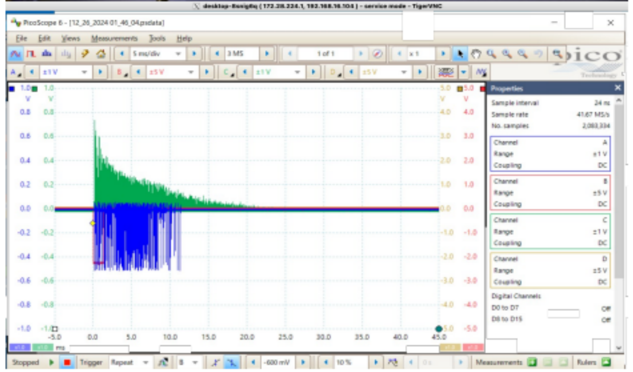
-> beam loss pattern -> CLAWS at D01V1; CsI scintillator + PMT& EMT at D09V3, D12V1

-> injection background duration -> ECLTRG

collision; 393 bucnhes, HER 5Hz, LER 12.5Hz					
HER=192mA(0.49), LER=240mA(0.61)					
No	start time	end time	D01C-V1-TOP[mm]	D01C-V1-BTM[mm]	record waveforms
1	12_26_2024 01:46:04	12_26_2024 01:53:13	2.35	-2.35	37
2	12_26_2024 01:54:42	12_26_2024 02:00:32	2.40	-2.40	-
3	12_26_2024 02:00:34	12_26_2024 02:07:59	2.45	-2.45	34
4	12_26_2024 02:10:23	12_26_2024 02:17:58	2.55	-2.55	29
5	12_26_2024 02:18:00	12_26_2024 02:25:37	2.25	-2.25	43
6	12_26_2024 02:26:16	12_26_2024 02:35:16	2.15	-2.15	45
02:35:02: collimator return to 2.35mm, start to increase current					
HER=230mA(0.57), LER=290mA(0.83)					
No	start time	end time	D01C-V1-TOP[mm]	D01C-V1-BTM[mm]	record waveforms
1	12_26_2024 02:42:40	12_26_2024 02:48:13	2.35	-2.35	35
2	12_26_2024 02:48:47	12_26_2024 02:54:32	2.45	-2.45	34
3	12_26_2024 02:56:24	12_26_2024 03:01:48	2.55	-2.55	34
4	12_26_2024 03:03:01	12_26_2024 03:10:37	2.25	-2.25	39
5	12_26_2024 03:11:57	12_26_2024 03:16:47	2.15	-2.15	37

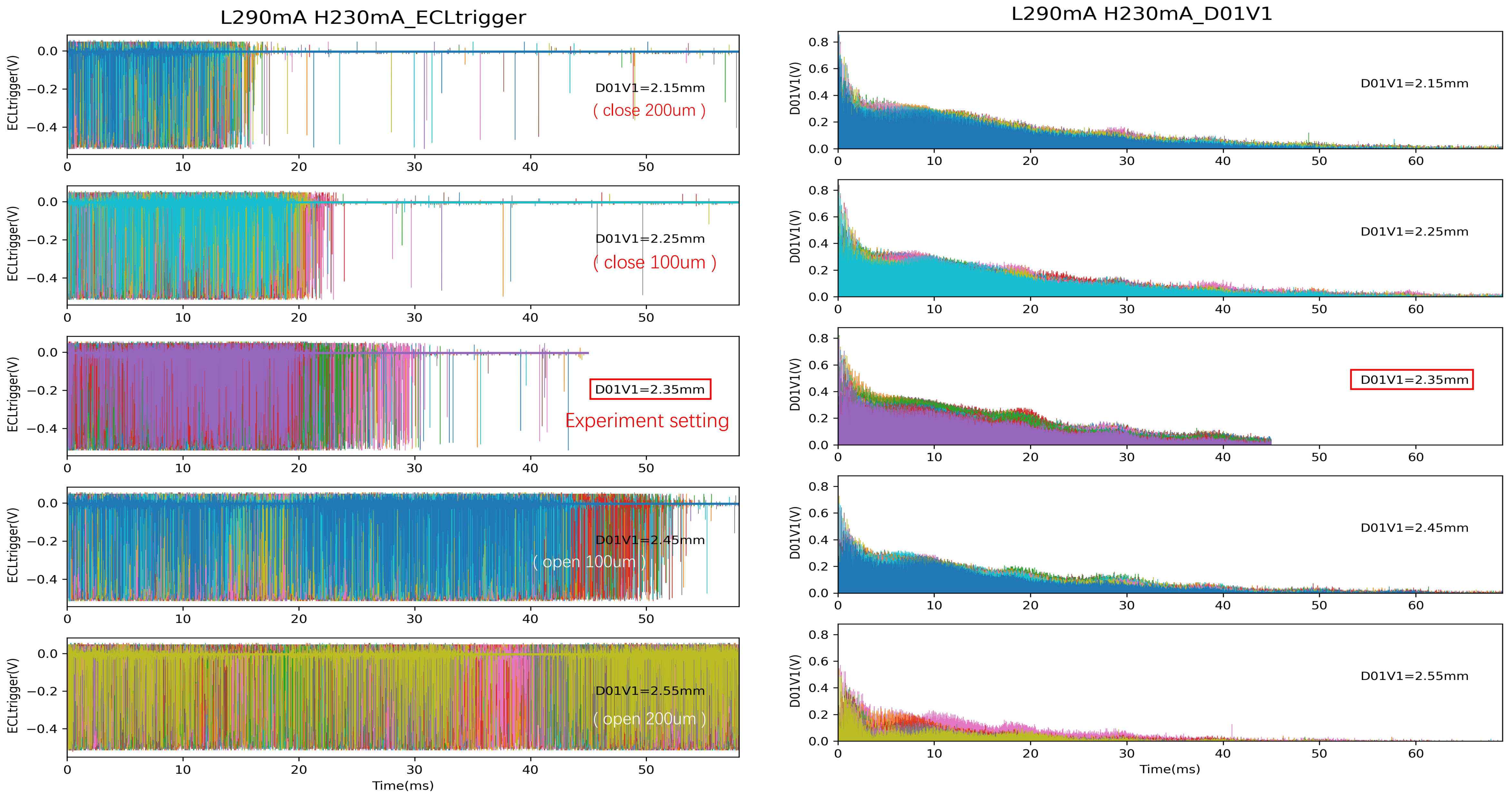






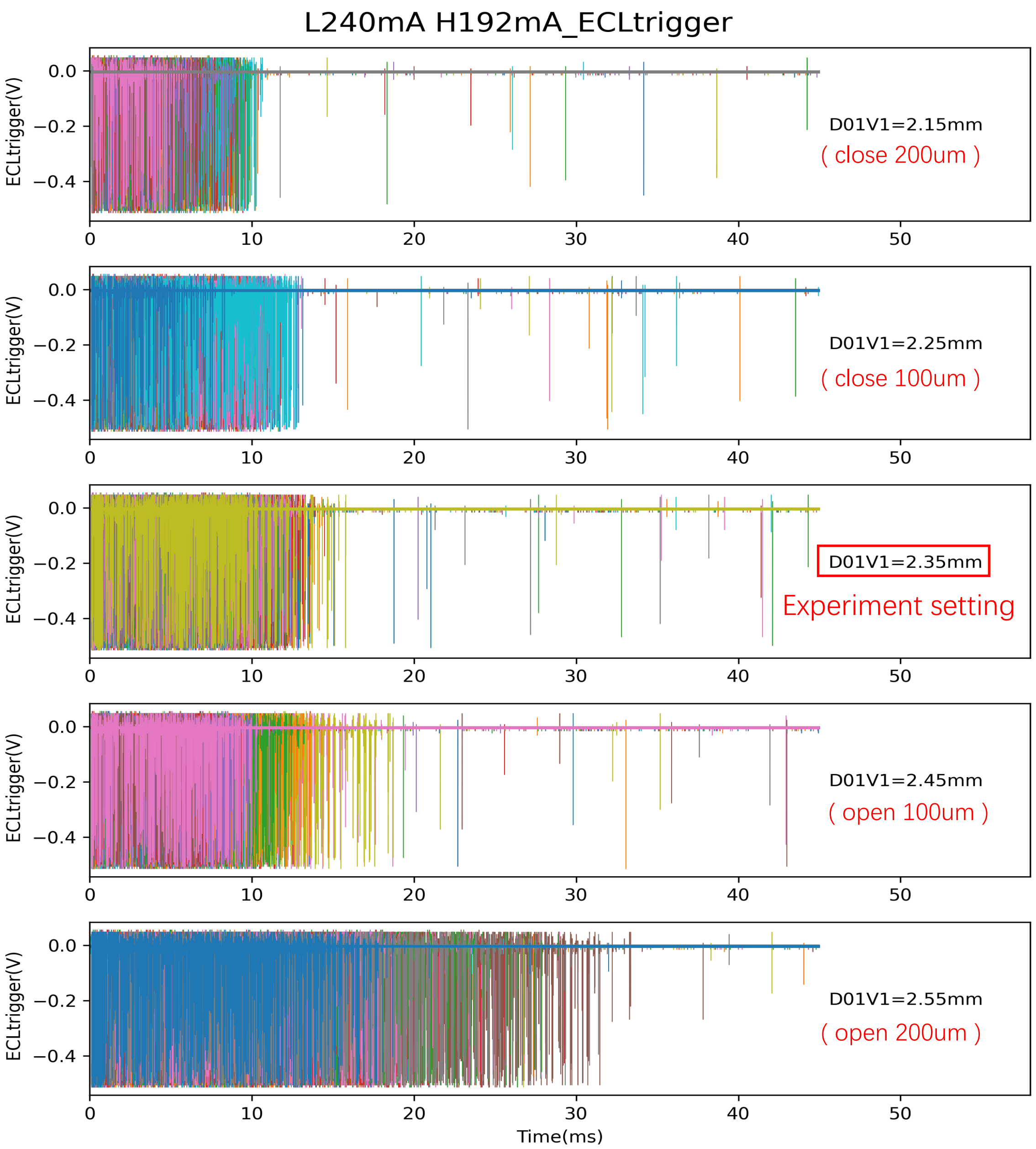
Preliminary analysis

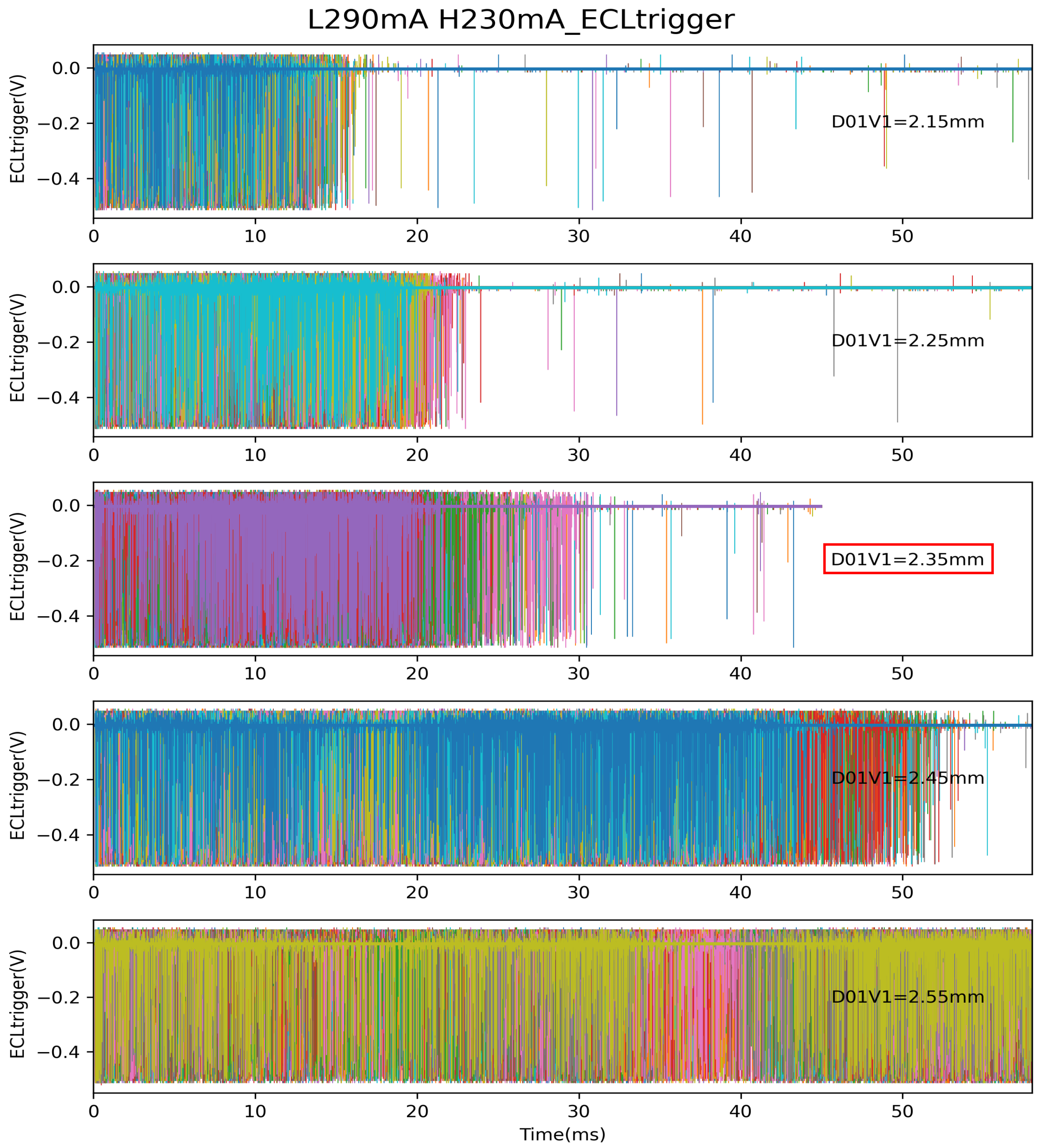
--The injection BG is very sensitive to collimator D01V1 aperture



Preliminary analysis

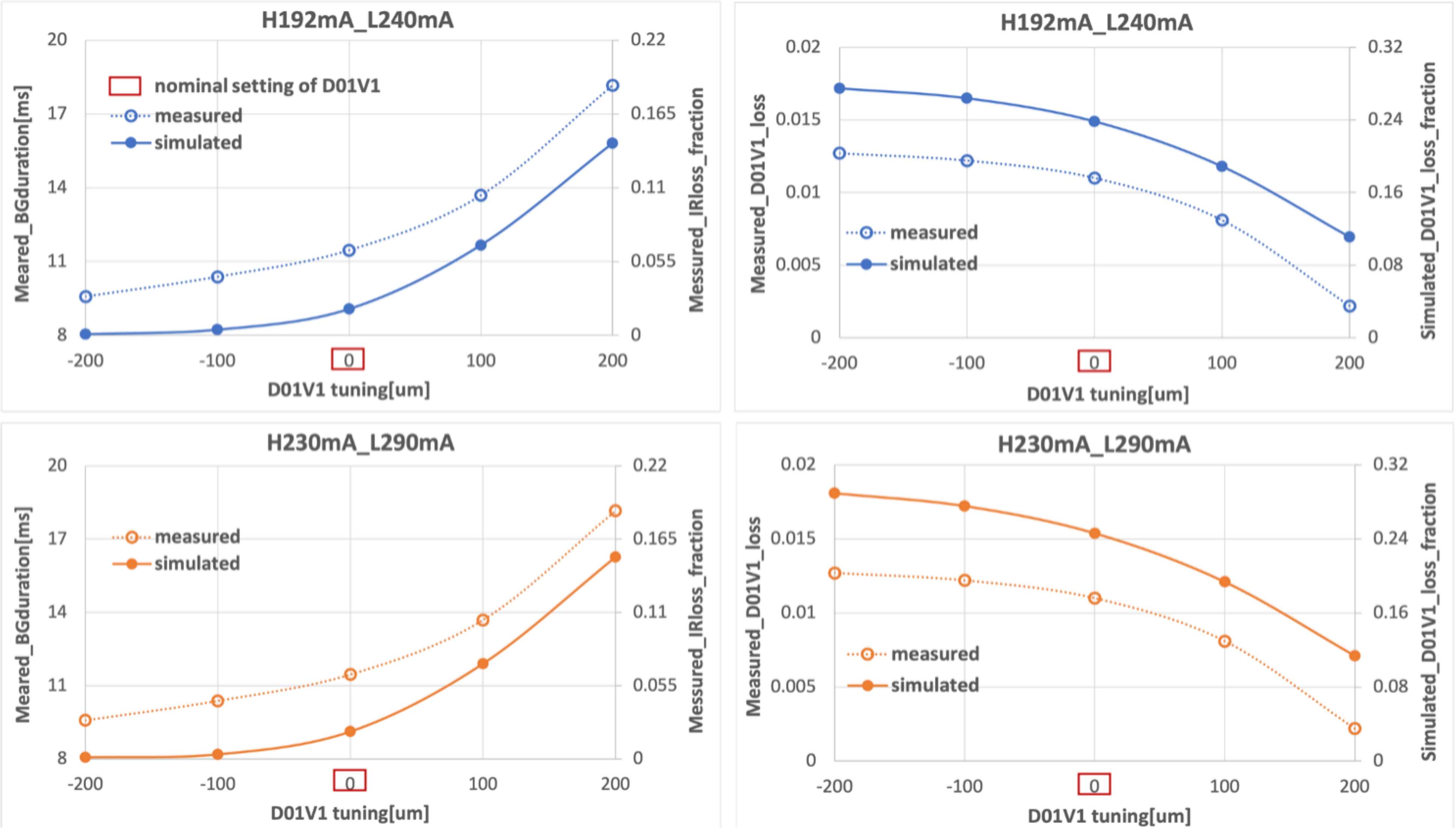
--The injection BG is very sensitive to bunch current(beam-beam strength)





☐ Detailed analysis

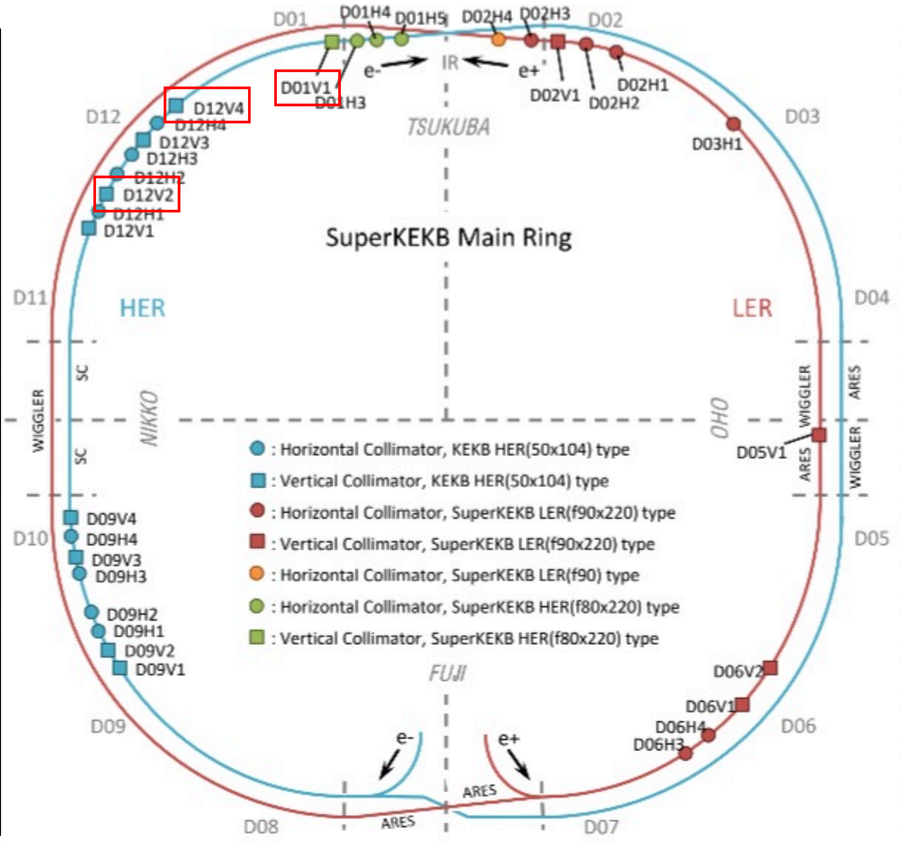
- Local pedestal correction & Integration of D01V1 signals after 5ms → estimate beam loss on D01V1
- Calculate ECLTRG duration automatically →estimate injection BG duration
- Update simulation match to measurement setting



Good qualitative agreement with simulation results

☐ Collimator tuning to share beam loss on D01V1

	Name	PosRel	AbsPos	BX	BY	sigmax	sigmay	dx1	dx2	dy1	dy2	dx1/sigx	dx2/sigx	dy1/sigy	dy2/sigy
D09	PMD09V1	-1299.111	126.345	25.607	15.472	0.000515	0.000392	0.052	-0.052	0.025	-0.00239	100.930	-100.930	63.788	-6.098
	PMD09V2	-1149.053	276.403	31.625	19.438	0.000573	0.000439	0.052	-0.052	0.025	-0.0036	90.820	-90.820	56.910	-8.195
	PMD09H1	-1062.401	363.055	39.731	7.703	0.000642	0.000277	0.052	-0.01304	0.025	-0.025	81.028	-20.319	90.404	-90.404
	PMD09H2	-1029.702	395.754	39.728	7.703	0.000642	0.000277	0.052	-0.01144	0.025	-0.025	81.031	-17.827	90.401	-90.401
	PMD09H3	-986.730	438.726	39.731	7.703	0.000642	0.000277	0.052	-0.01203	0.025	-0.025	81.028	-18.746	90.404	-90.404
	PMD09V3	-981.531	443.925	25.602	15.474	0.000515	0.000392	0.052	-0.052	0.025	-0.00269	100.939	-100.939	63.783	-6.863
	PMD09H4	-954.031	471.425	39.728	7.703	0.000642	0.000277	0.052	-0.01094	0.025	-0.025	81.031	-17.048	90.401	-90.401
	PMD09V4	-905.559	519.898	23.222	16.738	0.000491	0.000408	0.052	-0.052	0.025	-0.00291	105.987	-105.987	61.327	-7.138
D12	PMD12V1	-621.386	804.070	23.217	16.741	0.000491	0.000408	0.052	-0.052	0.00381	-0.025	105.997	-105.997	9.346	-61.323
	PMD12H1	-551.217	874.239	39.731	7.703	0.000642	0.000277	0.052	-0.01159	0.025	-0.025	81.028	-18.060	90.404	-90.404
	PMD12V2	-546.018	879.438	25.607	15.472	0.000515	0.000392	0.052	-0.052	0.025	-0.00179	100.930	-100.930	63.788	-4.567
	PMD12H2	-518.518	906.938	39.728	7.703	0.000642	0.000277	0.052	-0.01144	0.025	-0.025	81.031	-17.827	90.401	-90.401
	PMD12H3	-475.547	949.909	39.731	7.703	0.000642	0.000277	0.052	-0.01151	0.025	-0.025	81.028	-17.935	90.404	-90.404
	PMD12V3	-470.348	955.108	25.607	15.472	0.000515	0.000392	0.052	-0.052	0.01208	-0.025	100.930	-100.930	30.822	-63.788
	PMD12H4	-442.848	982.608	39.728	7.703	0.000642	0.000277	0.052	-0.01162	0.025	-0.025	81.031	-18.107	90.401	-90.401
	PMD12V4	-395.960	1029.496	31.621	19.439	0.000573	0.000439	0.052	-0.052	0.025	-0.0022	90.826	-90.826	56.907	-5.008
D01	PMD01V1	-61.744	1363.712	40.106	46.183	0.000645	0.000677	0.02	-0.02	0.00235	-0.00236	31.018	-31.018	3.471	-3.485
	PMD01H3	-49.604	1375.853	7.055	190.029	0.000270	0.001374	0.005	-0.005	0.02	-0.02	18.489	-18.489	14.561	-14.561
	PMD01H4	-30.901	1394.555	16.700	386.308	0.000416	0.001958	0.00798	-0.00796	0.02	-0.02	19.180	-19.132	10.213	-10.213
	PMD01H5	-16.826	1408.630	30.934	28.651	0.000566	0.000533	0.00981	-0.00978	0.02	-0.02	17.324	-17.271	37.500	-37.500
IR_QCS	AQC2LO	-3.050	1422.406	410.410	456.246	0.002063	0.002128	0.035	-0.035	0.035	-0.035	16.969	-16.969	16.445	-16.445
	AQC2LC	-2.700	1422.756	391.339	528.109	0.002014	0.002290	0.035	-0.035	0.035	-0.035	17.377	-17.377	15.285	-15.285
	AQC1LO	-1.600	1423.856	63.028	1653.443	0.000808	0.004052	0.015	-0.015	0.015	-0.015	18.558	-18.558	3.702	-3.702
	AQC1LC	-1.410	1424.046	37.852	1733.991	0.000626	0.004149	0.015	-0.015	0.015	-0.015	23.946	-23.946	3.615	-3.615
	AQC1RC	1.410	1426.866	37.635	1744.590	0.000625	0.004162	0.015	-0.015	0.015	-0.015	24.015	-24.015	3.604	-3.604
	AQC1RO	1.600	1427.056	61.798	1694.979	0.000800	0.004102	0.015	-0.015	0.015	-0.015	18.741	-18.741	3.657	-3.657
	AQC2RC	2.920	1428.376	478.045	516.408	0.002226	0.002264	0.035	-0.035	0.035	-0.035	15.723	-15.723	15.458	-15.458
	AQC2RO	3.110	1428.566	499.507	472.116	0.002275	0.002165	0.035	-0.035	0.035	-0.035	15.381	-15.381	16.166	-16.166



- **Interaction region(upstream)**
  ReAY: $3.6\ \sigma_{yinj}$
  ReAX: $17.0\ \sigma_{xinj}$

PMD12V2: 1.79mm($4.6\ \sigma_{yinj}$) -> 1.39mm($3.6\ \sigma_{yinj}$) -> 0.99mm($2.6\ \sigma_{yinj}$)

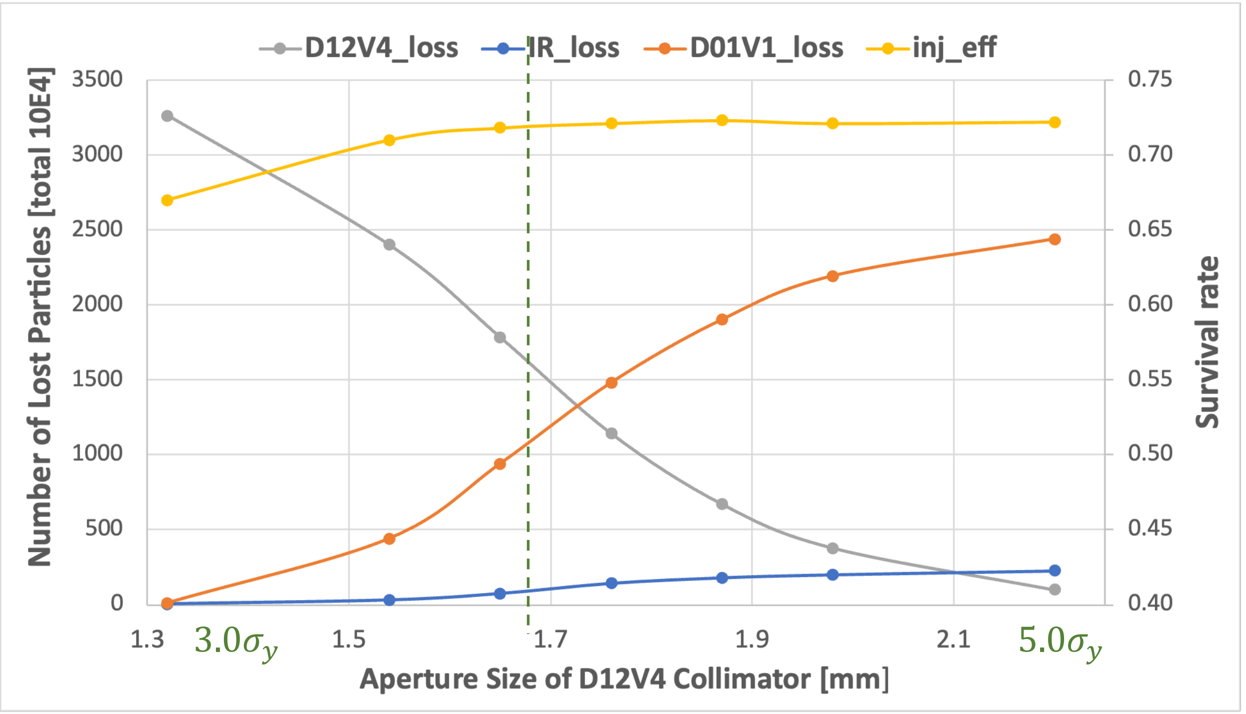
PMD12V4: 2.20mm($5.0\ \sigma_{yinj}$) -> 1.76mm ($4.0\ \sigma_{yinj}$) -> 1.32mm ($3.0\ \sigma_{yinj}$)

PMD01H3: 5.00mm($18.5\ \sigma_{xinj}$) -> 4.46mm($16.5\ \sigma_{xinj}$) -> 3.65mm($13.5\ \sigma_{xinj}$)

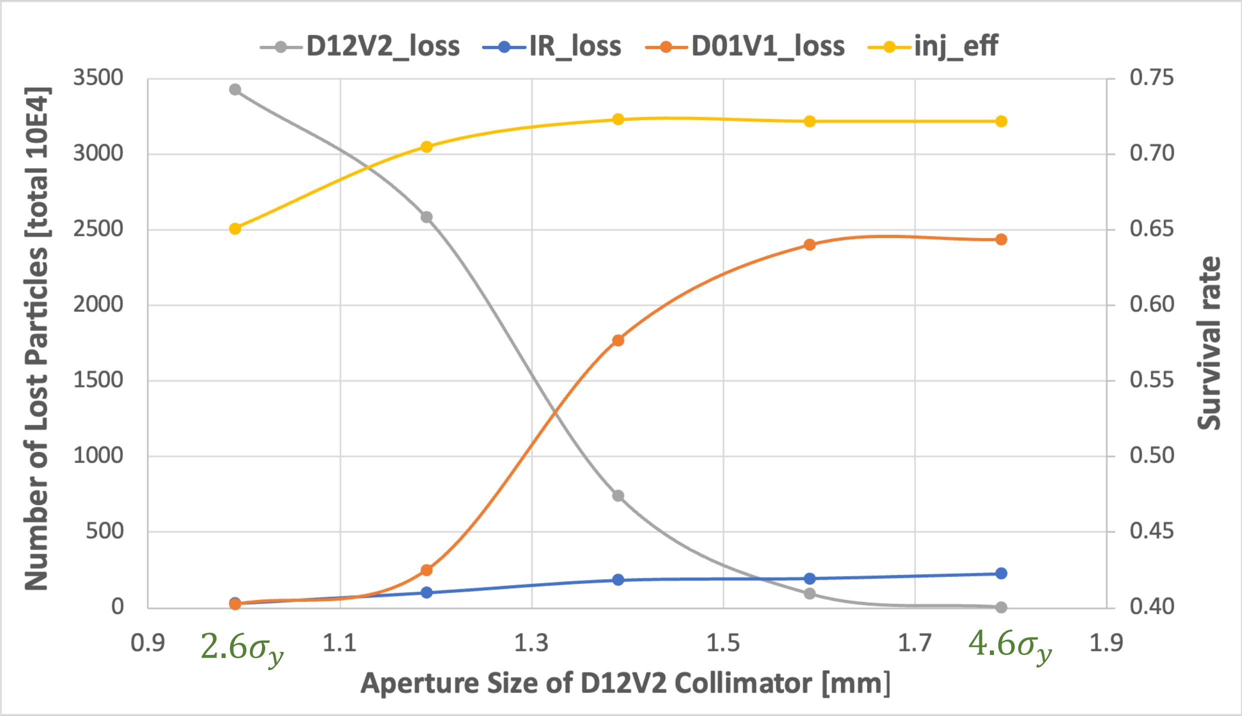
PMD12H1: 11.6mm($18.1\ \sigma_{xinj}$) -> 10.3mm($16.0\ \sigma_{xinj}$) -> 9.0mm($14.0\ \sigma_{xinj}$)

☐Preliminary Vertical Collimator Scan: PMD12V2; PMD12V4

D12V4 Tuning



D12V2 Tuning



- Tightening collimator apertures (D12V2, D12V4) effectively reduces IR beam loss and D01V1 loss.
- However, to suppress the IR beam loss, larger aperture adjustments are required for D12V4 and D12V2 compared with D01V1.
- D12V4 demonstrates higher sensitivity to aperture changes compared to D12V2.

☐Preliminary Horizontal Collimator Scan: PMD01H3

PosRel	ReAX	ReAY	PMD01H3	d=5.00mm	d=4.46mm	d=3.65mm
			d/sigmaxi	18.50	16.50	13.50
1.600	18.74	3.66	AQC1RO	23	22	6
1.410	24.02	3.60	AQC1RC	19	12	5
1.170	21.34	3.70	APIR.517	5	2	1
-1.410	23.95	3.62	AQC1LC	23	10	7
-1.600	18.56	3.70	AQC1LO	157	137	64
			IR_loss	227	183	83
-61.744	31.02	3.47	PMD01V1	2437	2456	2252
-49.604	18.50	14.56	PMD01H3	0	8	359
-395.960	90.83	5.01	PMD12V4	100	111	62
-546.018	100.93	4.57	PMD12V2	5	5	3
-905.559	105.987	7.14	PMD09V4	1	1	1
-1149.053	90.82	8.20	PMD09V2	1	1	1
-1299.1107	100.93	6.10	PMD09V1	5	5	0
sigmax_inj@D01H3 = 0.27mm			Mask_loss	2549	2587	2678
			Total_loss	2776	2770	2761
			INJ_efficiency	0.722	0.722	0.723

Question: What is the minimum achievable collimator aperture?

->Preliminary collimator tuning for individual collimators only.

->still need to optimize several of them together.

- Tightening collimator D01H3 aperture reduces IR beam loss, but the effect was less sensitive compared to vertical collimation.
- Injection efficiency remained stable even with extreme aperture reduction.

Conclusions and outlook

- A more realistic simulation mechanism for injection-related beam loss has been developed
- Verification experiments have been conducted based on its main findings
- Qualitative agreement is observed between simulation and experimental data:
  - comparison includes raw waveform features and further data analysis
  - simulation updated with beam parameters and machine conditions from the measurement day

Further investigation of injection-related beam loss and background

- Detailed tune scan(betatron-synchrotron resonance,…)
- More realistic collimator model including tip-scattering & collimator optimization program integration
- **Connect SAD simulated injection beam loss with Geant4 simulation**
- More validation experiments (CLAWS at D01V1, ECLTRG,…)

Back up

■ Finding2: Non-linear factors affect both injection efficiency and background

➢ Manufacturing error of cancel coil in HER

Cancel coils in the HER should correct the leakage field from QC1LP and QC1RP in the LER.

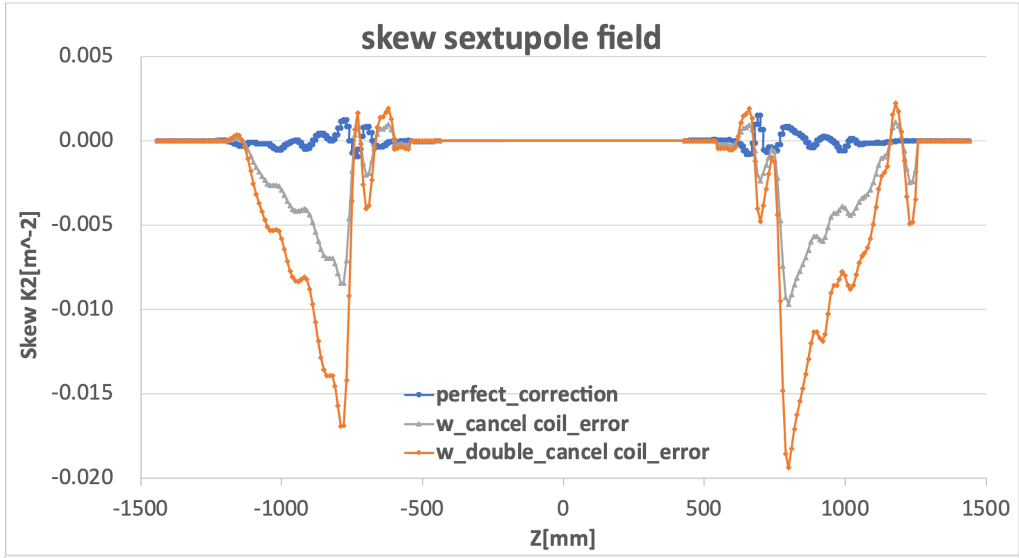
- Normal winding and skew winding coils correct both normal and skew field by using one power supply.

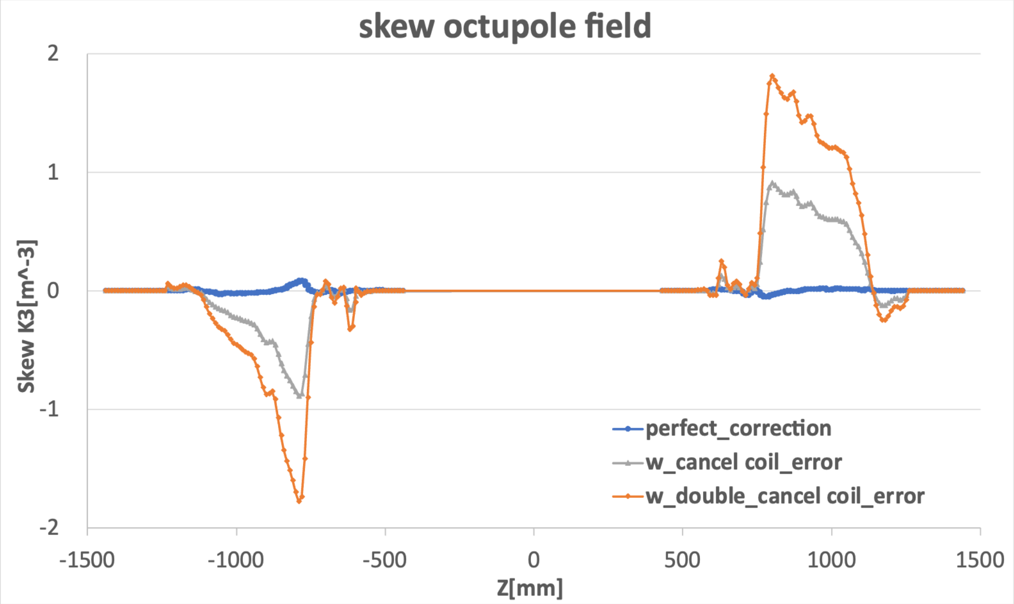
- Skew sextupole and skew octupole increase (not cancelled) due to manufacturing mistake.

Table 24: Measured integral leak fields at R_{ref}=10 mm

Multipole coefficient	QCSL, Tm without cancelling	QCSL, Tm with cancelling	QCSR, Tm without cancelling	QCSR, Tm with cancelling
b_3	3.36×10^{-3}	2.32×10^{-5}	-3.53×10^{-3}	1.27×10^{-5}
b_4	-7.58×10^{-4}	-2.83×10^{-6}	8.02×10^{-4}	4.39×10^{-6}
b_5	1.57×10^{-4}	3.66×10^{-6}	-1.67×10^{-4}	-3.73×10^{-6}
b_6	-2.98×10^{-5}	7.8×10^{-7}	3.24×10^{-5}	2.35×10^{-6}
a_3	-2.42×10^{-4}	-3.88×10^{-4}	-2.52×10^{-4}	-4.93×10^{-4}
a_4	-5.88×10^{-5}	-1.16×10^{-4}	4.94×10^{-5}	1.71×10^{-4}
a_5	-1.48×10^{-5}	-1.48×10^{-5}	6.26×10^{-6}	-8.31×10^{-6}
a_6	1.88×10^{-5}	1.48×10^{-5}	-4.31×10^{-6}	-1.09×10^{-6}

Y. Ohnishi





Preliminary Vertical Collimator Scan: PMD12V2; PMD12V4

PosRel	ReAX	ReAY	PMD12V2	d=1.79mm	d=1.39mm	d=0.99mm	PMD12V4	d=2.20mm	d=1.76mm	d=1.32mm
			d/sigmaxi	4.57	3.57	2.57	d/sigmaxi	5.00	4.00	3.00
1.600	18.74	3.66	AQC1RO	23	29	7	AQC1RO	23	15	4
1.410	24.02	3.60	AQC1RC	19	15	2	AQC1RC	19	20	0
1.170	21.34	3.70	APIR.517	5	1	0	APIR.517	5	1	0
-1.410	23.95	3.62	AQC1LC	23	12	1	AQC1LC	23	9	1
-1.600	18.56	3.70	AQC1LO	157	139	20	AQC1LO	157	99	2
			IR_loss	227	196	30	IR_loss	227	144	7
-61.744	31.02	3.47	PMD01V1	2437	1770	22	PMD01V1	2437	1480	14
-395.960	90.83	5.00	PMD12V4	100	41	0	PMD12V4	100	1143	3262
-546.018	100.93	4.57	PMD12V2	5	744	3428	PMD12V2	5	6	0
-905.559	105.987	7.14	PMD09V4	1	1	0	PMD09V4	1	0	0
-1149.053	90.82	8.20	PMD09V2	1	1	0	PMD09V2	1	1	1
-1299.1107	100.93	6.10	PMD09V1	5	5	0	PMD09V1	5	4	1
sigmax_inj@D12V2 = 0.40mm			Mask_loss	2549	2562	3450	Mask_loss	2549	2634	3278
sigmax_inj@D12V4 = 0.44mm			Total_loss	2776	2758	3480	Total_loss	2776	2778	3285
			INJ_efficiency	0.722	0.723	0.651	INJ_efficiency	0.722	0.721	0.671

- Tightening collimator apertures (D12V2, D12V4) effectively reduces IR beam loss.
- D12V4 demonstrates higher sensitivity to aperture changes compared to D12V2.