Accelerator operation plan

Gaku Mitsuka (KEK, Accelerator Laboratory)
on behalf of the SuperKEKB commissioning group

Joint review focusing on the operation plan, 18-19 Dec. 2025

Agenda

- How to achieve 1 ab^{-1} and $1x10^{35}$ $cm^{-2}s^{-1}$
  - How to reach LER > 2.0 A and HER > 1.4 A, issues to be addressed to reach it, and how to address it.
  - How to keep 80% of physics run time and how to improve the accelerator operation efficiency
- Machine studies
- Plan ahead for possible issues and contingencies

2026ab operation target plan

Target

Peak luminosity = 1×10^{35} cm^{-2}s^{-1}

Integrated luminosity > 425 fb^{-1}

Key parameters

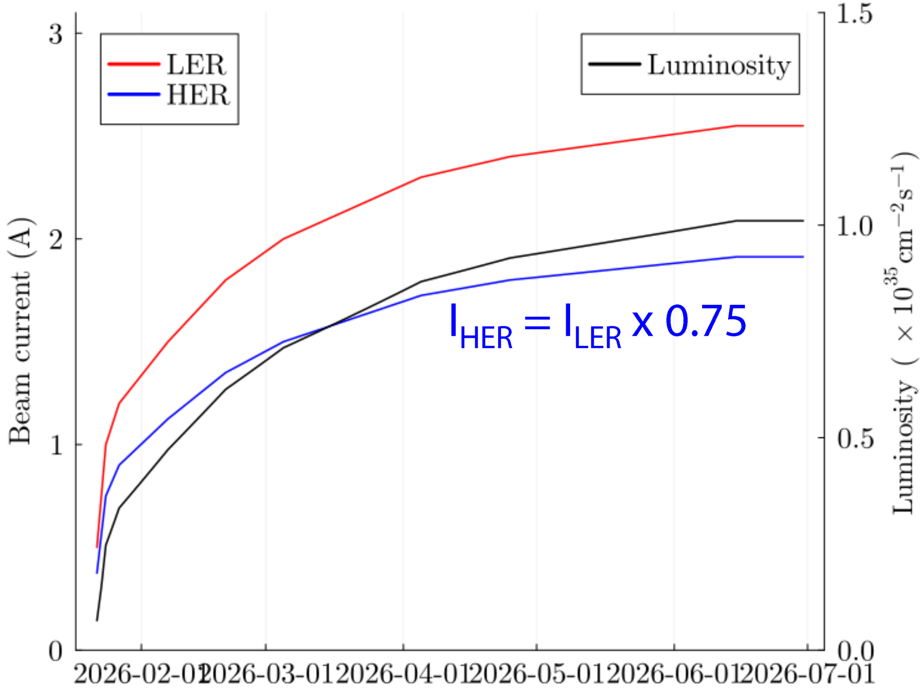
Specific luminosity = 4.9×10^{31} cm^{-2}s^{-1}mA^{-2} at 0.88 mA^2

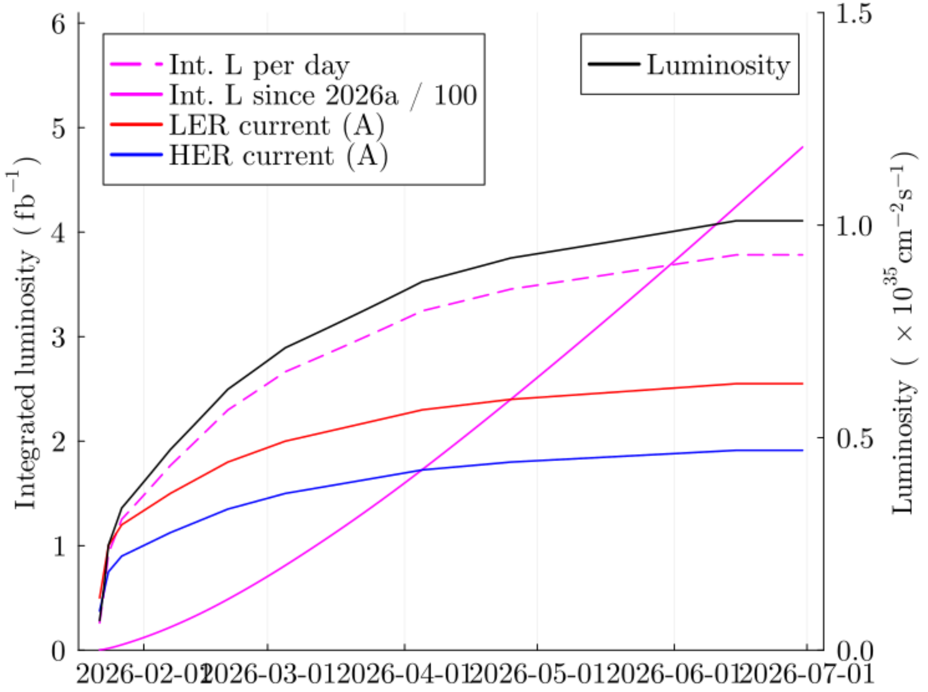
Operation performance score (defined later) ≥ 65%

Requirements

2-bunch injection in HER and LER, β_y^* squeezing to 0.9 mm, Mitigation of beam-beam effects

We must limit machine tuning time (incl. Liq. He work) to 35% of the total operating time.





Target parameter values

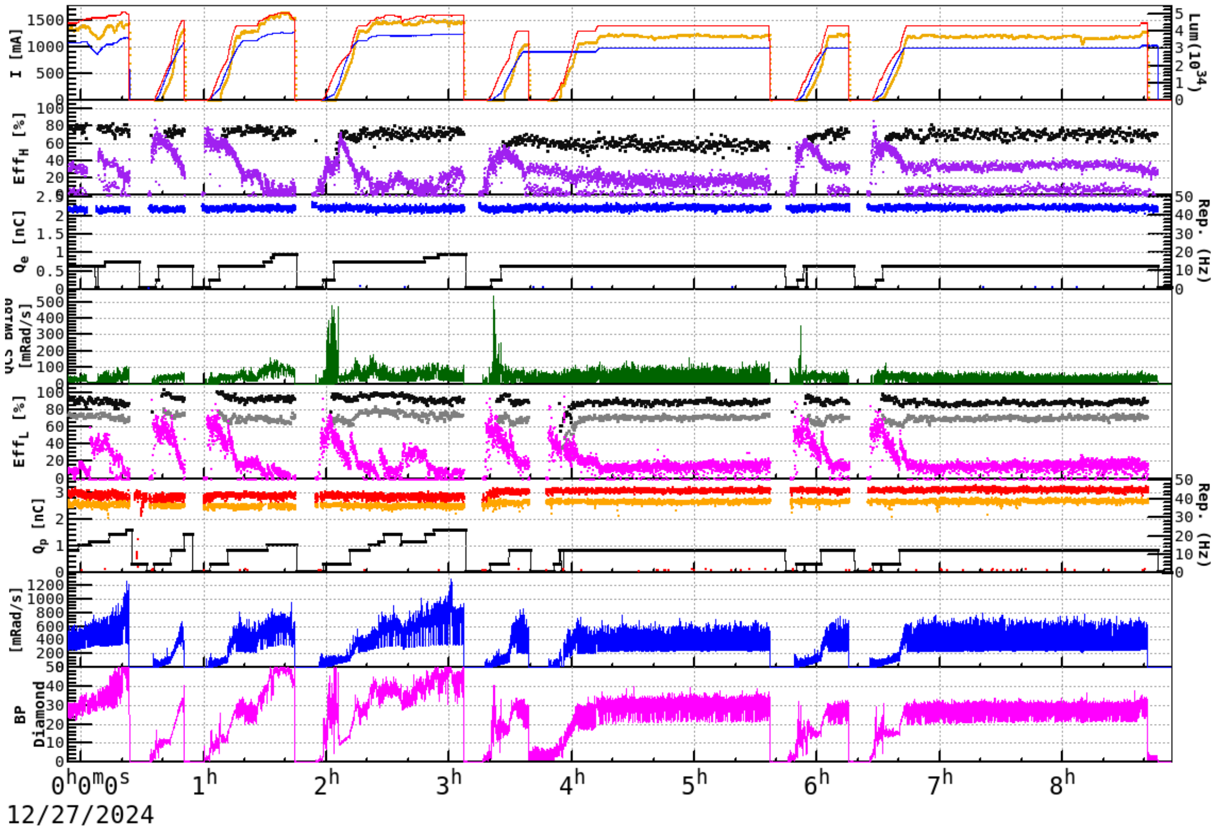
Parameters	Target values	Comments
Peak luminosity ($cm^{-2}s^{-1}$)	$1x10^{35}$	
HER beam current (A)	1.9 A	LER current x 0.75
HER bunch current (mA)	0.8 mA	for 2346 bunches
LER beam current (A)	2.6 A	
LER bunch current (mA)	1.1 mA	for 2346 bunches
Specific luminosity ($cm^{-2}s^{-1}mA^{-2}$)	4.9×10^{31}	
Operation efficiency (%)	> 65%	
Physics run period (days)	85 (physics) + 45 (others)	

Includes machine trouble & maintenance time, e.g.

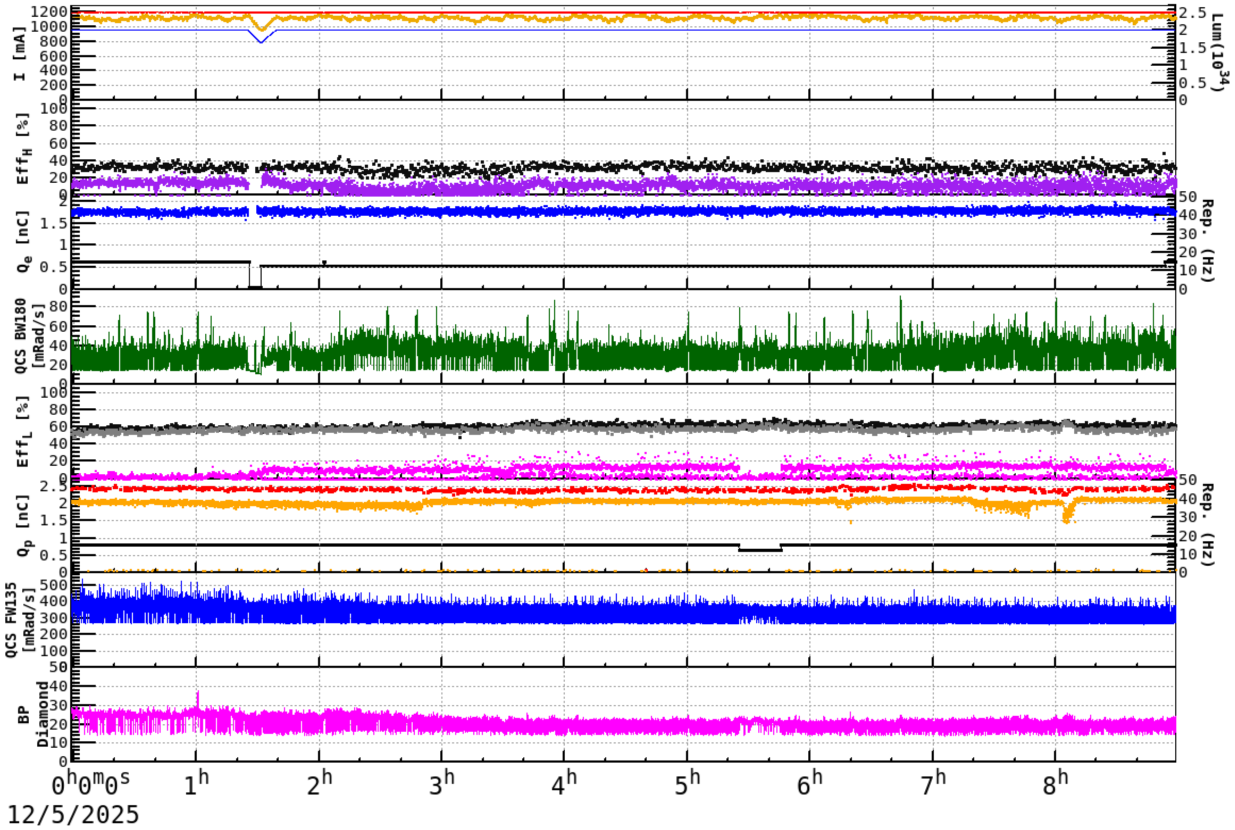
- Hardware trouble ~15% (average over 2022-2025)
  - + Liquid He work ~10%, i.e., 2 shifts every week
- Monthly maintenance day ~3%

Injection comparison 2024c vs. 2025c

27 Dec. 2024 (achieved 5.11e+34/cm²/s)



5 Dec. 2025



HER in 2025c: Poor injection efficiency <50%. With 3 nC of charge immediately after the RF gun, the vertical emittance increases, so we limit the charge to 2 nC.

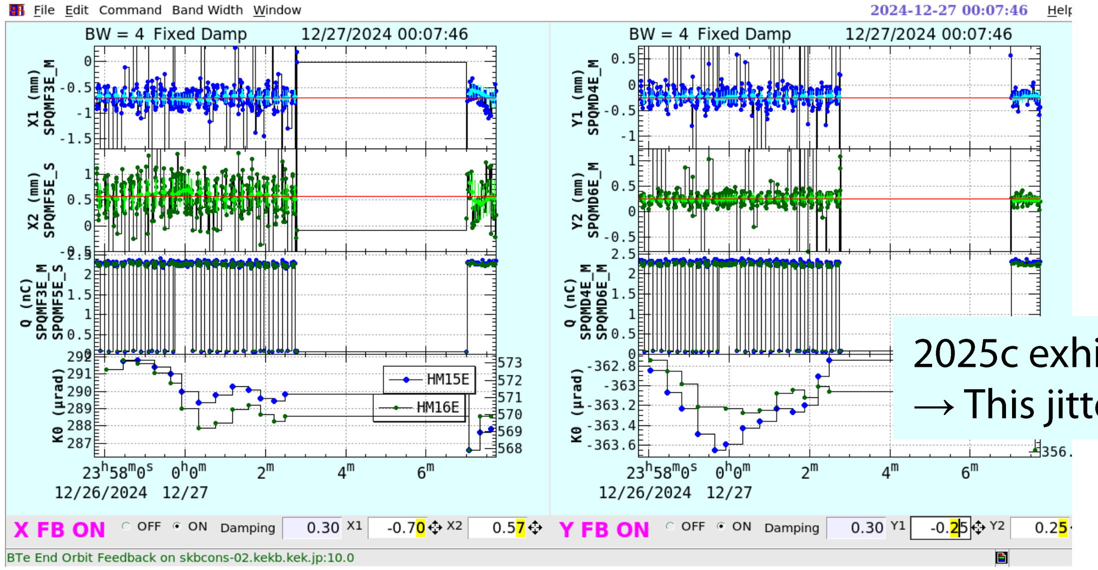
LER in 2025c: By adding an orbit-correction kicker and adjusting the beam energy equivalent between two bunches, we maintain the same injection efficiency for the 1st and 2nd bunches. The efficiency of ~60% is likely due to insufficient tuning (was 70% under good conditions). Able to achieve a similar level to 2024c.

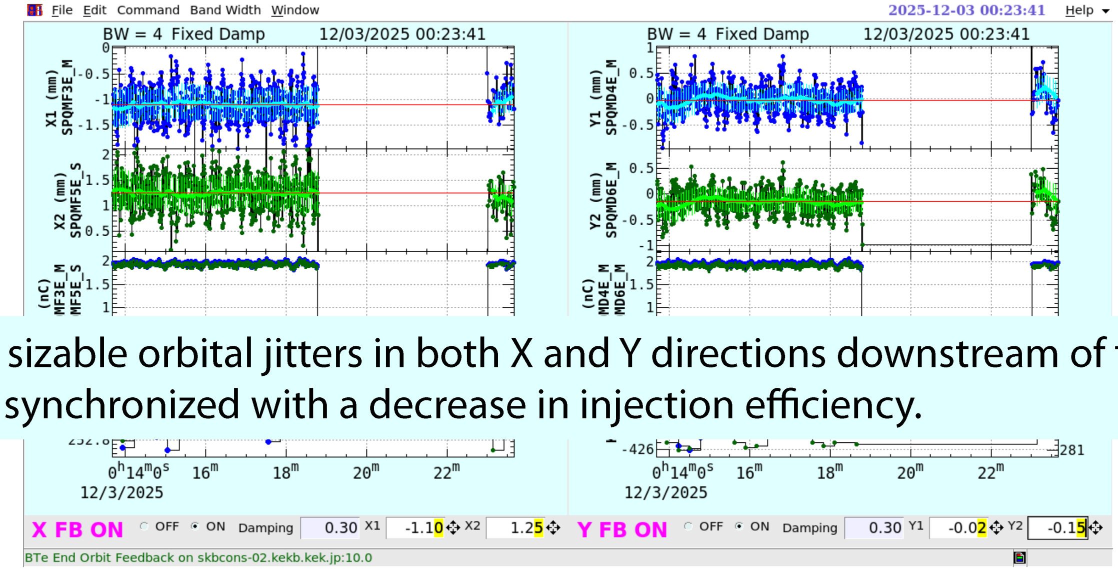
Injection comparison 2024c vs. 2025c

Dec. 2024

Dec. 2025

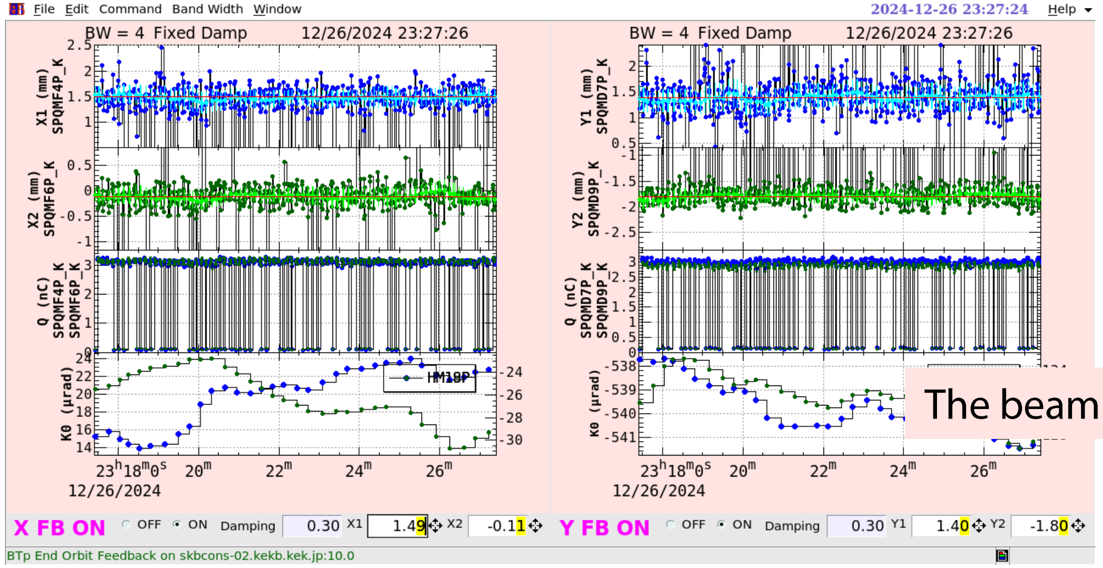
HER

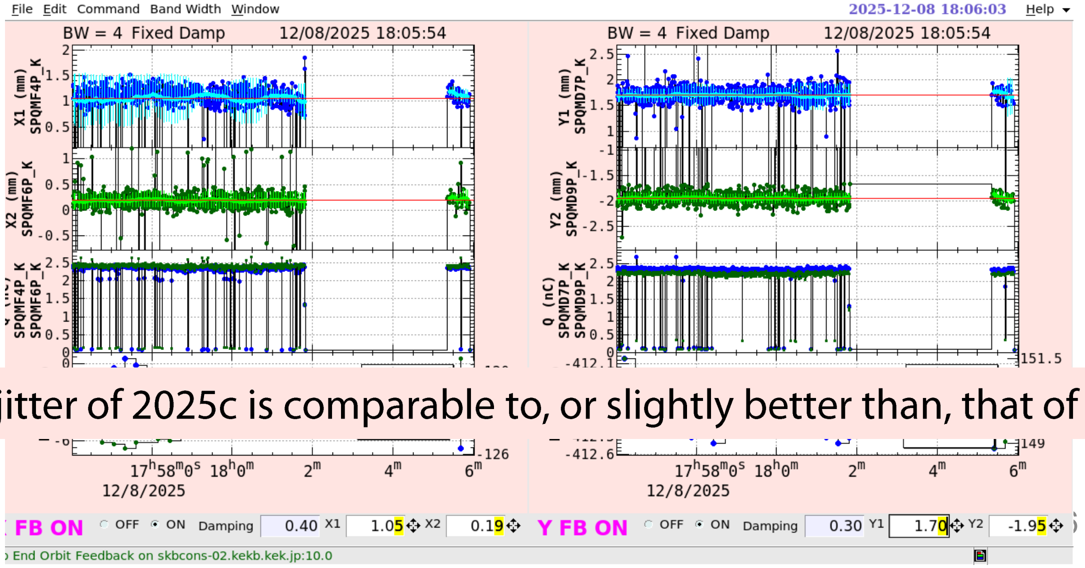




2025c exhibits sizable orbital jitters in both X and Y directions downstream of the BT.
→ This jitter is synchronized with a decrease in injection efficiency.

LER





The beam orbit jitter of 2025c is comparable to, or slightly better than, that of 2024c.

Injection: Issues and workflow

Issues to be solved before the main ring operation

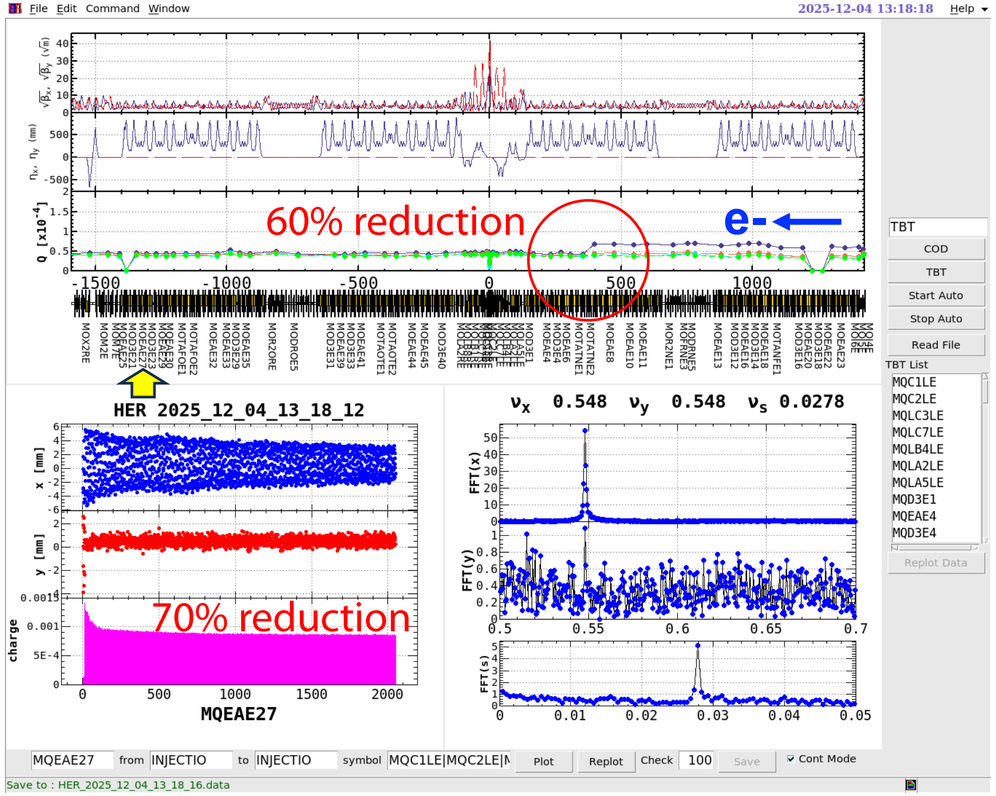
- Beam orbit jitter downstream of BT → Injection efficiency drastically reduced
  - Orbit jitter combined with large emittance (at BT end) has been negatively impacting injection efficiency.
  - Large Y-direction orbit jitter from the RF gun onwards needs to be mitigated with the 2024c level.
- The two-bunch operation in HER was difficult with the new RF gun.
  - Tuning time was insufficient this season. We are currently tuning the vertical orbit at Linac.
- Maintenance of the BT beam diagnostics
  - Non-invasive synchrotron radiation monitor should come back to normal (not usable in 2025c)
  - Stable measurements for both 1st and 2nd bunches are desirable for all BT BPMs.
- Linac and BT studies for 10 days or more are preferred prior to the MR operation.

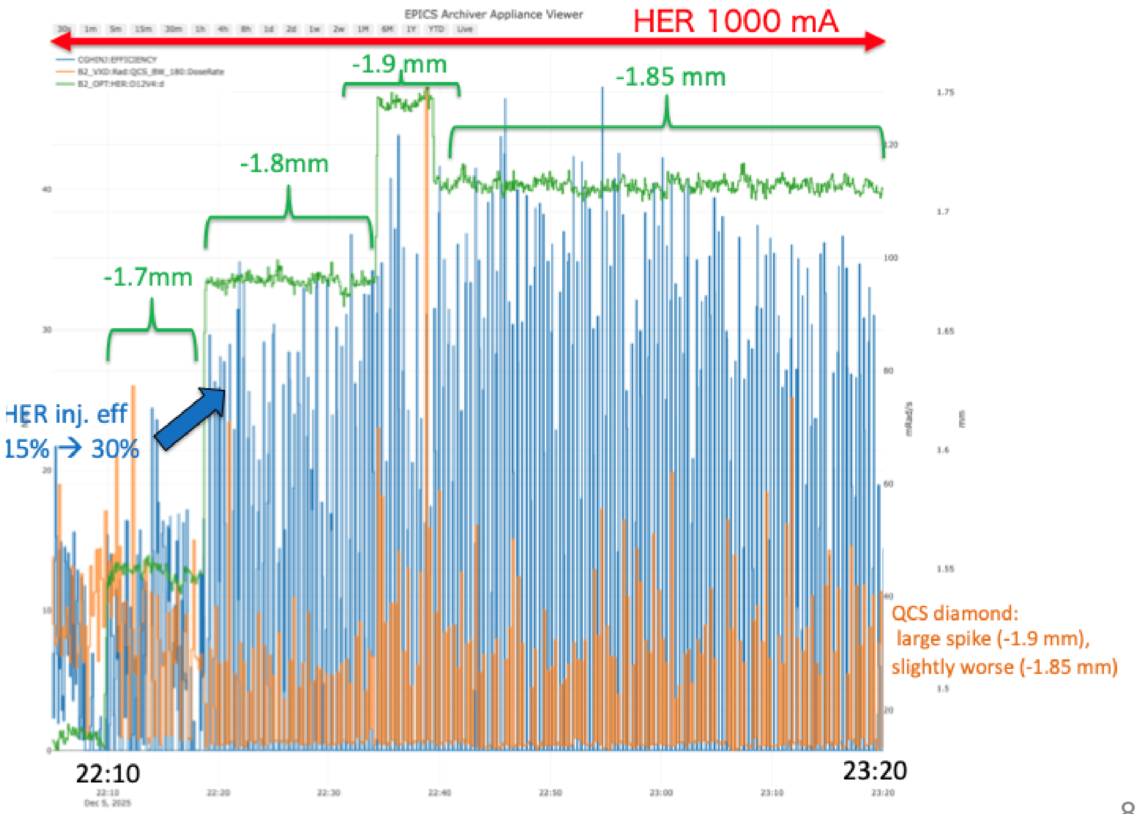
Issues can be solved during the main ring operation

- Long-term stability and non-invasive beam tuning are mandatory not to interrupt physics run.

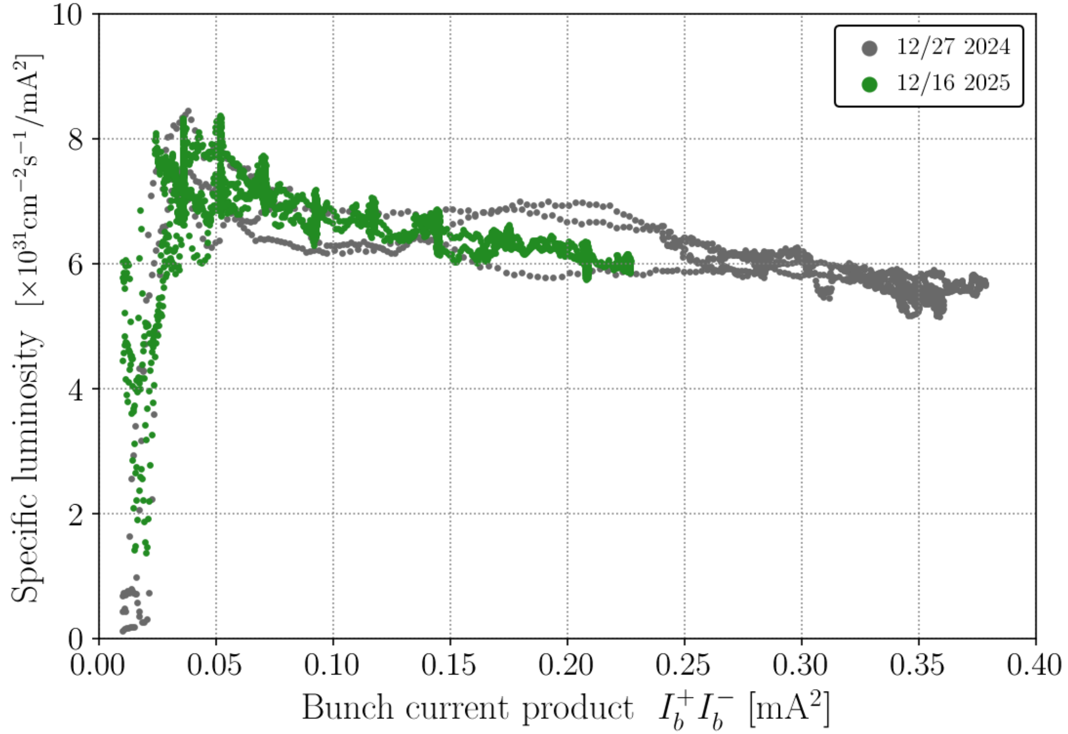
Injection: Issues and workflow

- Injection efficiency reduced to ~60% within the first turn with the D12V4 collimator.
  - To protect the damaged D01V1 collimator and suppress inj. BGs, the D12V4 collimator is kept closed.
- Due to large vertical emittance, many injected particles are likely being lost (~70%).
  - 60% x 70% ~42% injection efficiency.
  - The solution is to replace the damaged D01V1 (scheduled in Jan. 2026) and reduce vertical emittance.





Specific luminosity comparison 2024c vs. 2025c

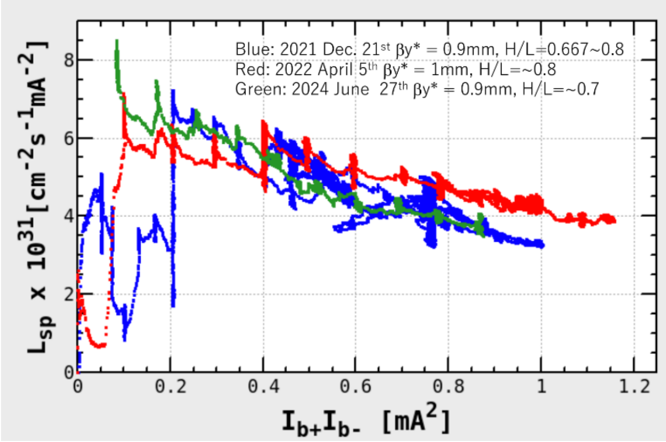


5.9×10^31 cm^-2s^-1mA^-2

4.9×10^31 cm^-2s^-1mA^-2

0.44 mA^2 (6e+34 cm^-2s^-1)

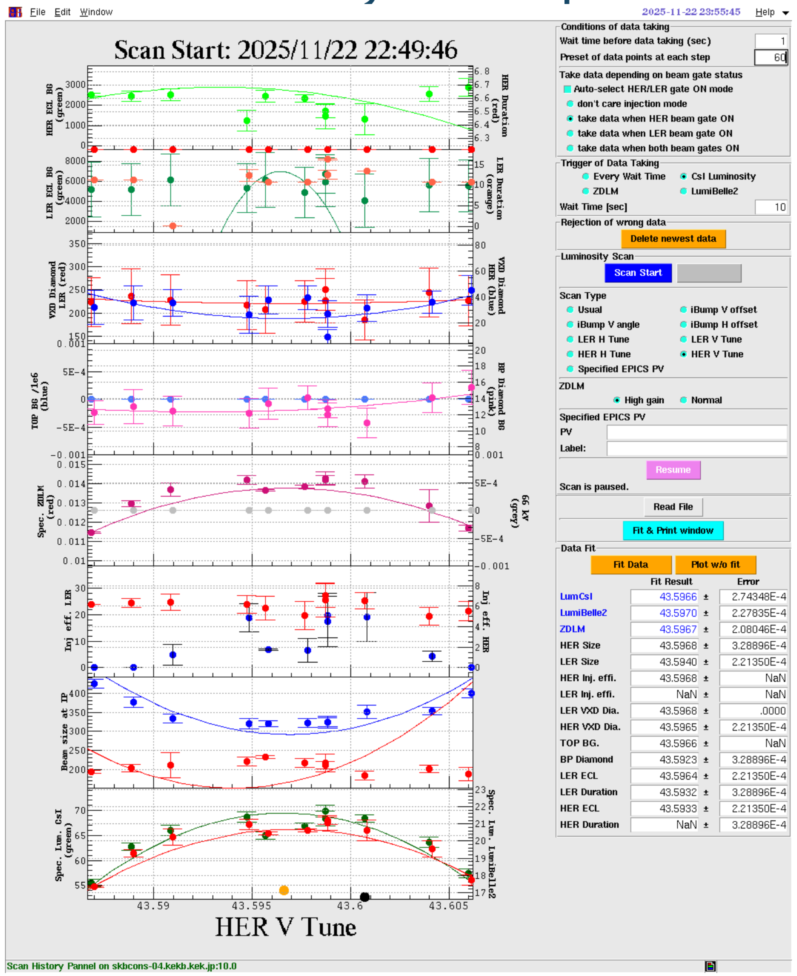
0.88 mA^2 (1e+35 cm^-2s^-1)



- Approached the best levels in 2024c (thanks to coupling near the IP, vertical angle, and HER tunes). The key is whether we can increase the current while maintaining the specific luminosity.
- High specific luminosity could be demonstrated for a small number of bunches, e.g., 393 bunches.

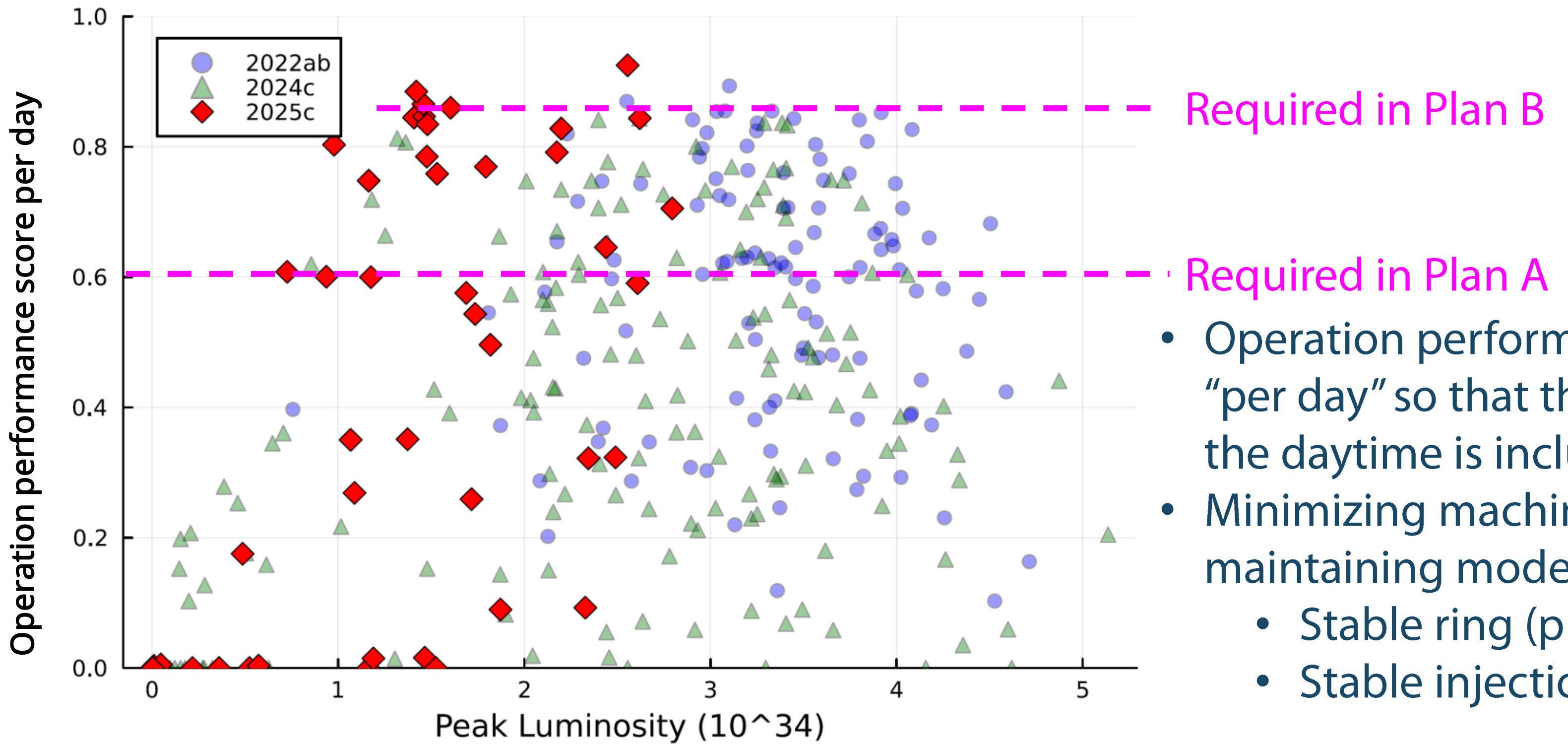
Collision: Issues and workflow

1. Scan horizontal and vertical tunes to balance injection and specific luminosity, i.e. “tune scan”
   1. Has performed in HER several times in 2025c
2. Test multiple sextupole configurations to extend lifetime and increase dynamic aperture
3. Achieve the peak luminosity of 5e+34 $cm^{-2}s^{-1}$
4. Adjust chromatic coupling using the rotating sextupoles in LER to optimize luminosity
5. Increase the beam current to the target values
6. β_x* squeezing to 50 mm or more
7. β_y* squeezing to 0.9 mm
8. Challenging to realize high specific luminosity for 2346 bunches at > 0.5 mA^2 due to injection power, chamber-heating induced optics deformation, possibly beam instability, etc.



Accelerator operation performance score

- A measured quantity of how constantly we can acquire the integrated luminosity while keeping the peak luminosity
- Operation performance score is defined as $\varepsilon_{\mathrm{acc}} \equiv \dfrac{\text{Integrated luminosity}}{\int^{24\text{ hours}} L_{\mathrm{peak}} dt}$
- Cause of low performance score: beam aborts, machine tuning inserted in physics run, unstable injection, etc.



- Operation performance score in the left figure is defined as "per day" so that the inefficiency due to machine tuning in the daytime is included.
- Minimizing machine tuning time as much as possible while maintaining modest luminosity yields high efficiency.
  - Stable ring (pressure, RF, magnet, FB, software)
  - Stable injection (orbit jitter, energy jitter, gun)

Beam abort statistics

Beam loss events in 2024c (79 days)

ring	SBL	BeamLoss
TOTAL	100	308
Both(LER)	70	46
Both(HER)	18	64
Both(Both)	-	-
Both	-	-
LER	12	146
HER	-	52

Beam loss events in 2025c (42 days)

ring	SBL	BeamLoss
TOTAL	10	32
Both(LER)	9	4
Both(HER)	1	24
Both(Both)	-	-
Both	-	-
LER	-	1
HER	-	3

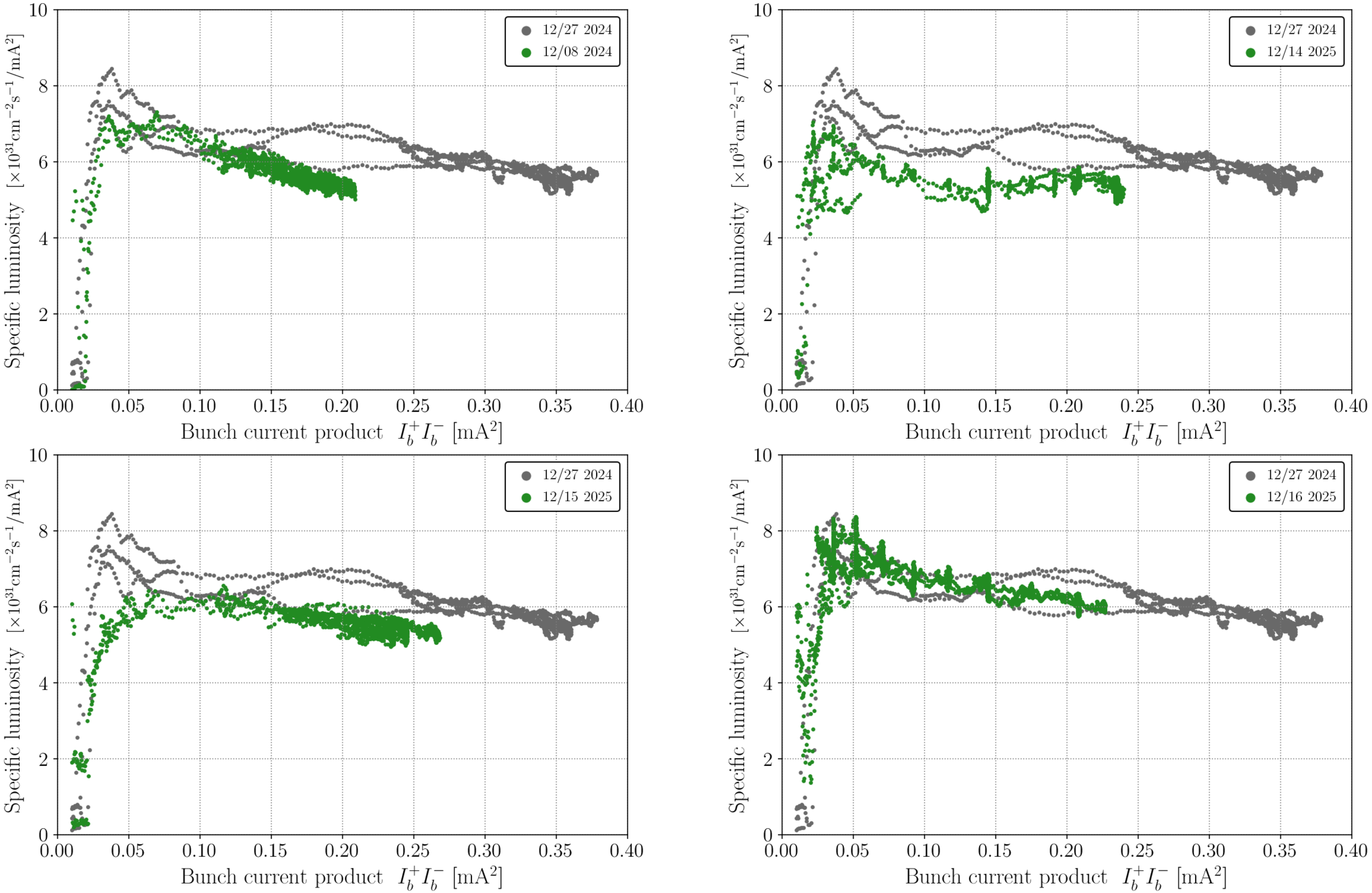
- Very reduced beam aborts in 2025c compared with 100 SBLs and 308 other beam-loss events in 2024c
- One HER-induced SBL in 2025c
- Normalized by only run period, beam aborts are reduced to 1/5.

Summary

- Injection
  - Beam orbit jitter downstream of BT must be solved for increasing injection efficiency.
  - The new RF gun needs more tuning for the 2-bunch operation and jitter reduction.
  - Stable beam diagnostics at BT is desirable for injection beam tuning.
  - Long-term stability and non-invasive beam tuning are mandatory not to interrupt physics run.
- Collision
  - Adjust chromatic coupling using the rotating sextupoles in LER to optimize luminosity
  - Test multiple sextupole configurations to extend lifetime and increase dynamic aperture
  - β_x^* and β_y^* will be squeezed as much as we can maintain lifetime and dynamic aperture.
- Machine safety
  - Though SBL events has been reduced, sizable number of beam loss aborts has occurred.

Backup

Specific luminosity comparison

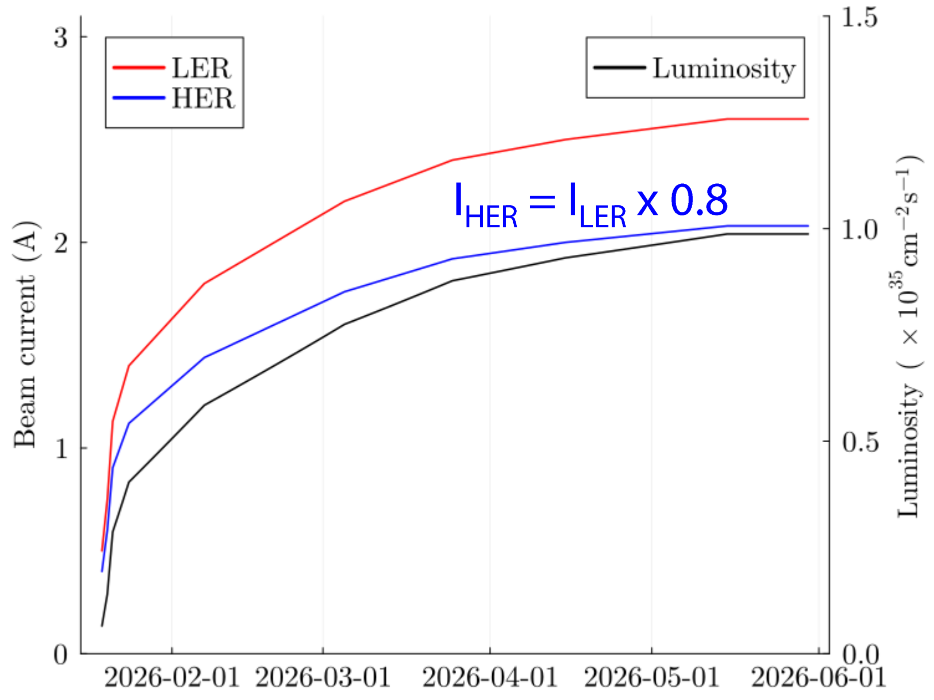


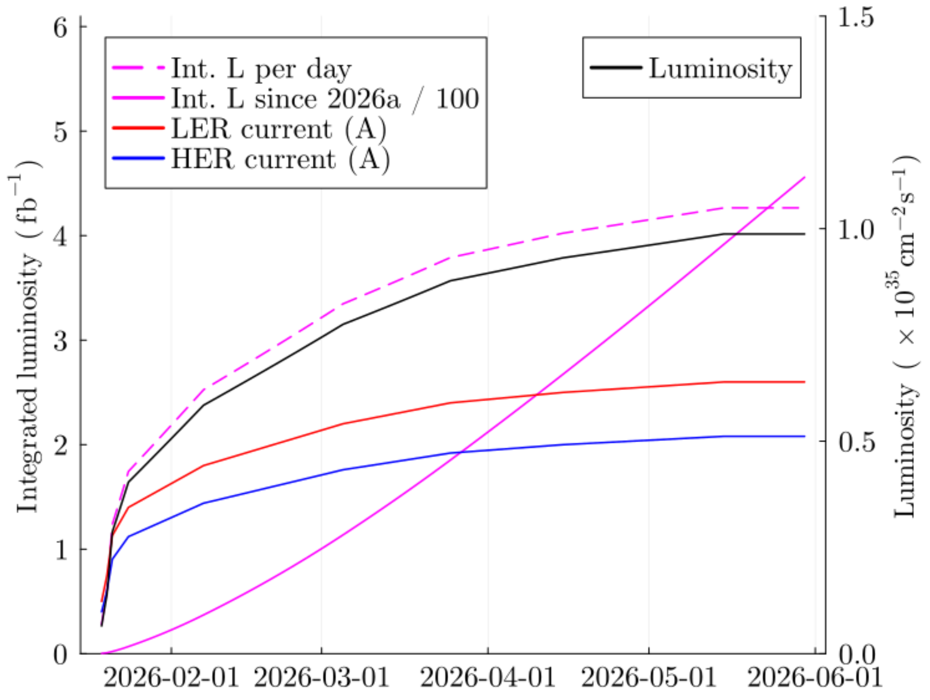
2026ab operation scenario (Plan C)

Target
Peak luminosity = $\underline{1 \times 10^{35}\ cm^{-2}s^{-1}}$
Integrated luminosity > 425 fb^{-1}

Key parameters
Specific luminosity = $5.0 \times 10^{31}\ cm^{-2}s^{-1}mA^{-2}$ at 0.86 mA^2
Operation efficiency $\underline{\geq 75\%}$

Requirements
2-bunch injection in HER and LER, β_y^* squeezing to 0.9 mm, Mitigation of beam-beam effects
We must limit machine tuning time (incl. Liq. He work) to 30% of the total operating time.





Machine parameter comparisons

	Plan C	
Peak luminosity	1×10^{35} $cm^{-2}s^{-1}$	
HER beam current	2.1 A ← limited to 2.0 A	LER current x 0.8
HER bunch current	0.9 mA	for 2346 bunches
LER beam current	2.6 A	
LER bunch current	1.1 mA	for 2346 bunches
Specific luminosity	4.8×10^{31} $cm^{-2}s^{-1}mA^{-2}$	
Operation efficiency	> 75%	
Physics run period	100 days	

Plan A for achieving 1 ab^{-1} and $1x10^{35}$ $cm^{-2}s^{-1}$

Target

Peak luminosity = 1×10^{35} $cm^{-2}s^{-1}$

Integrated luminosity > 425 fb^{-1}

Key parameters

Specific luminosity = 5.0×10^{31} $cm^{-2}s^{-1}mA^{-2}$ at 0.86 mA^2

Average operation efficiency > 60%

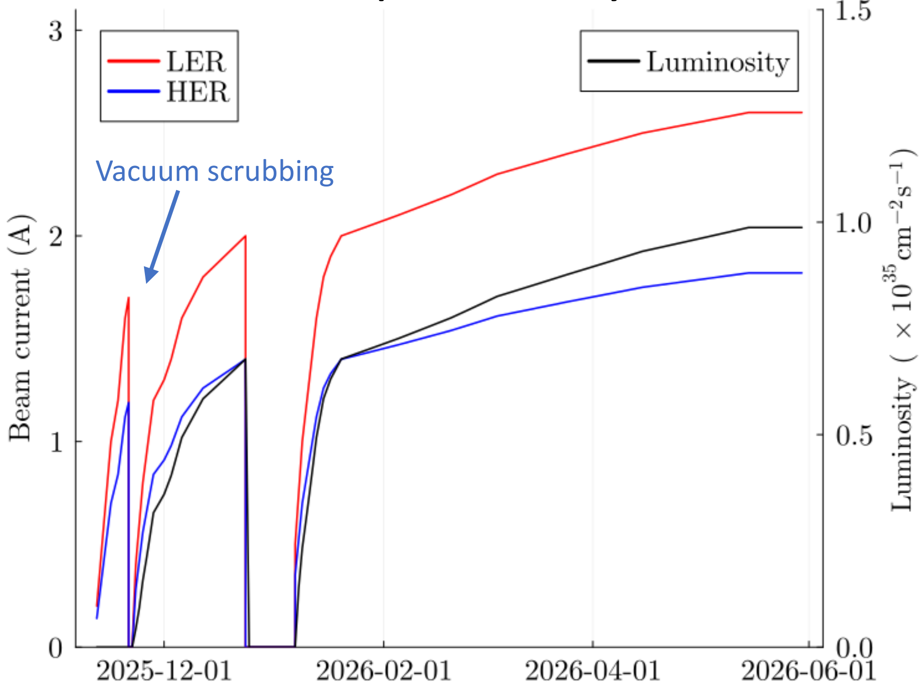
(N.B., ~67% at 1.7 A & 1.3A in 2024c)

Requirements

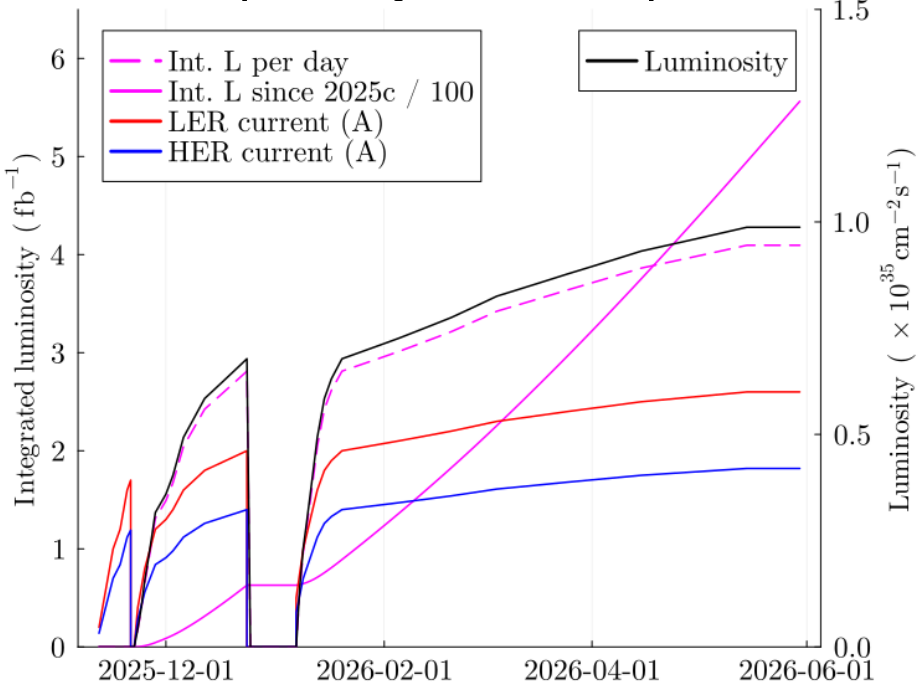
2-bunch injection in HER and LER, β_y^* squeezing to 0.9 mm (plus, possibly β_x^* squeezing)

Mitigation of beam-beam effects

Beam current and peak luminosity



Luminosity and integrated luminosity



Plan B for achieving 1 ab^{-1} with $6x10^{34}$ $cm^{-2}s^{-1}$

Target

Peak luminosity = $\underline{6 \times 10^{34}\ cm^{-2}s^{-1}}$

Integrated luminosity > 425 fb^{-1}

Key parameters

Specific luminosity = 5.9×10^{31} $cm^{-2}s^{-1}mA^{-2}$ at 0.44 mA^2

Average operation efficiency $\underline{\geq 85\%}$

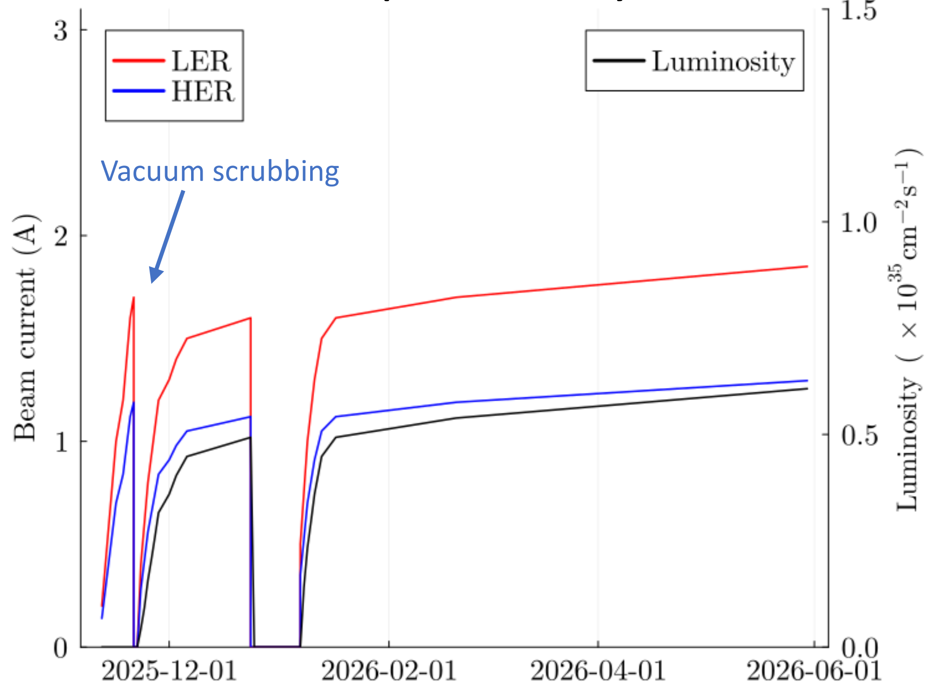
(N.B., highest record~88% in 2022c)

Requirements

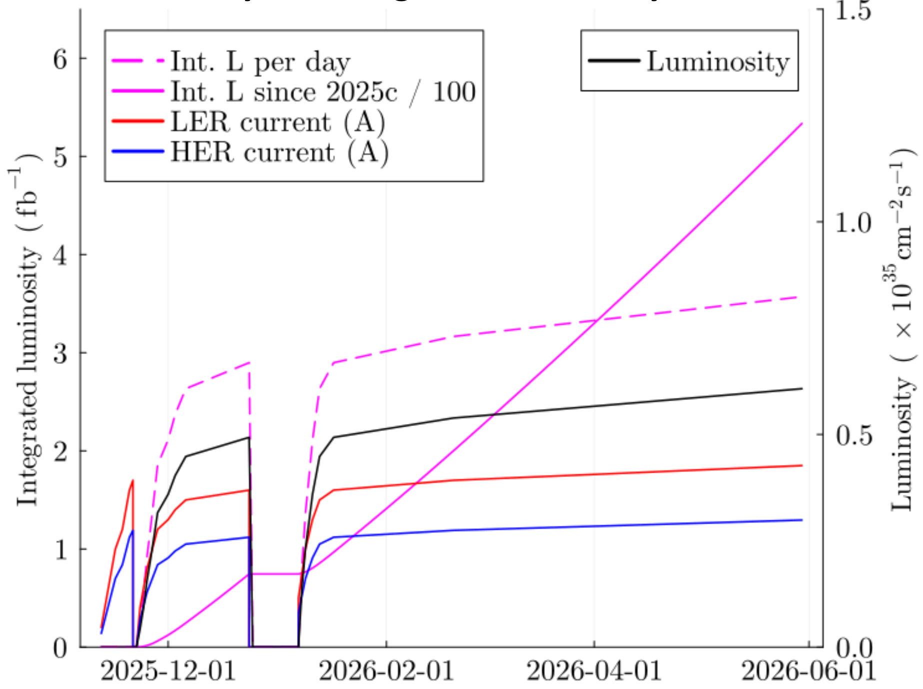
Stable operation (less SBL, less QCS quench, less machine/detector trouble)

2-bunch injection in LER, Relaxing beam-beam effects

Beam current and peak luminosity



Luminosity and integrated luminosity



Machine parameter comparisons

	Plan A	Plan B	
Peak luminosity ($cm^{-2}s^{-1}$)	$1x10^{35}$	$6x10^{34}$	
HER beam current (A)	1.8	1.3 A	LER current x 0.7
HER bunch current (mA)	0.8	0.6	for 2346 bunches
LER beam current (A)	2.6	1.9	
LER bunch current (mA)	1.1	0.8	for 2346 bunches
Specific luminosity ($cm^{-2}s^{-1}mA^{-2}$)	5.0×10^{31}	5.9×10^{31}	
Average operation eff. (%)	> 60%	> 85%	
Run period (days)	120 (physics) + 60 (others)	150 (physics) + 30 (others)	

Plan A: basic plan

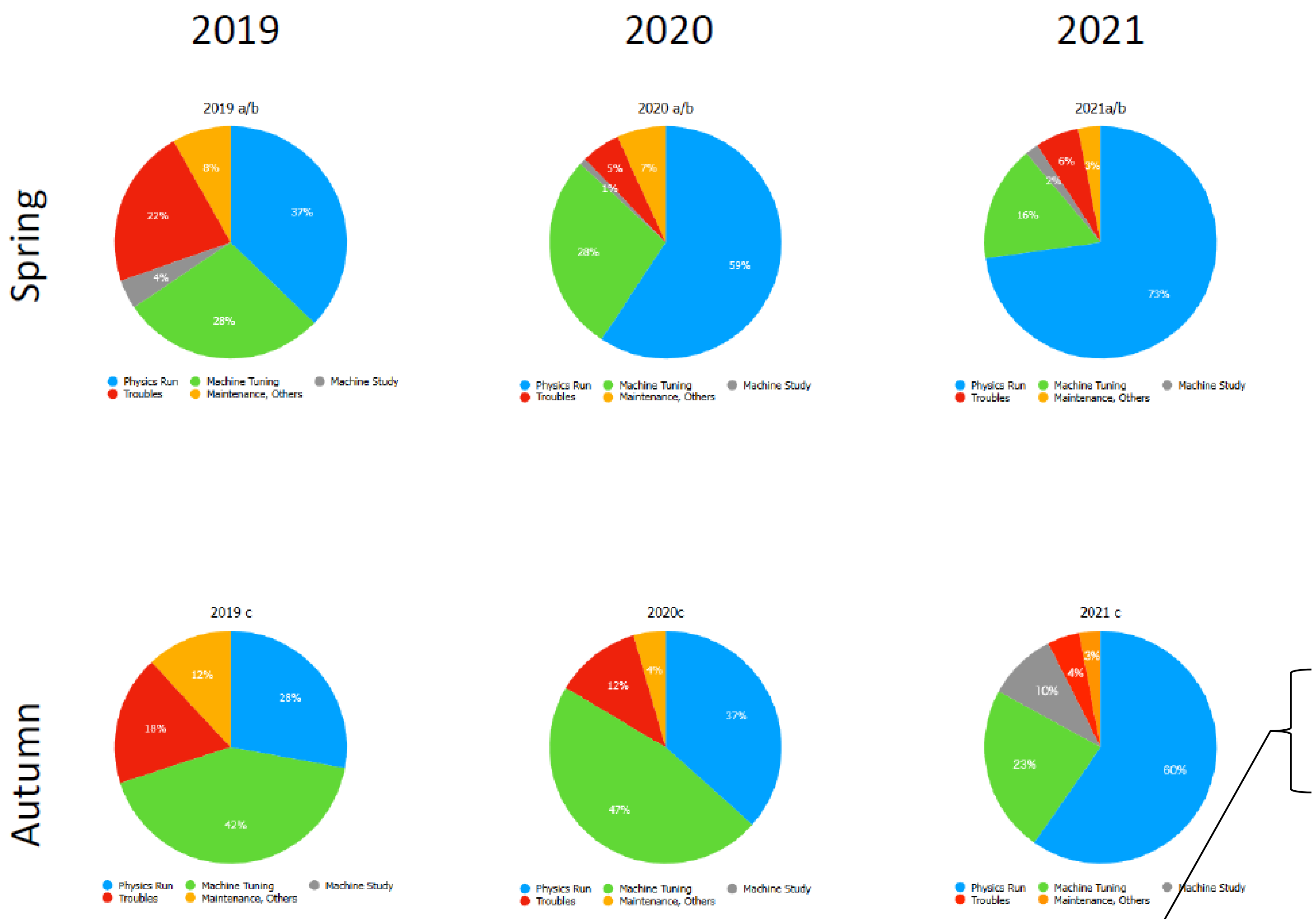
Detailed explanation

- **Peak luminosity = 5.0×10^{31} $cm^{-2}s^{-1}mA^{-2}$ x 0.86 mA^2 x 2346 bunches = 1.0×10^{35} $cm^{-2}s^{-1}$**
- **Challenge 1: specific luminosity 5.0×10^{31} $cm^{-2}s^{-1}mA^{-2}$** (see p8)
  - Needs to solve the emittance blowup that occurred in HER 2024c
  - Needs squeeze β_y^* to 0.9 mm to lower the beam size at IP
- **Challenge 2: high bunch current 0.86 mA^2 for 2346 bunches** (see p9-11)
  - Corresponds to 1.8 A in HER and 2.6 A in LER
  - Needs to realize 2-bunch injection in LER and HER
  - Needs to mitigate beam-beam effects
  - β_x^* squeezing to 50 mm or lower is planned to avoid σ_x^* blowup harming beam injection.
- **An even relaxed requirement on machine tuning time** (see p12, 13)
  - Accelerator efficiency > 60% is tolerable (N.B., ~67% at 1.6 A & 1.3A in 2024ab.)
  - Namely, machine tuning in the daytime and physics run in the evening and midnight are allowed.

Plan B: optional plan

Detailed explanation

- **Peak luminosity = 5.9 × 10^{31} $cm^{-2}s^{-1}mA^{-2}$ x 0.44 mA^2 x 2346 bunches = 6.0 × 10^{35} $cm^{-2}s^{-1}$**
- **Challenge 1: very stable physics run, minimizing machine tuning time** (see p12, 13)
  - Needs to avoid beam abort, QCS quench, and machine/detector troubles as low as possible
  - Needs to minimize machine tuning time as much as possible while securing modest luminosity
- **An even relaxed requirement on the high current operation** (see p11)
  - Target current is 1.3 A in HER, 1.9 A in LER with 2346 bunches.
  - Could achieve 1.3 A in HER even with 1-bunch injection since the end of Nov. 2024



Physics run

Machine tuning

Machine study

Troubles

Maintenance, others

Y. Ohnishi

11-17% in 2020-2022

80% of physics run time means no contingency.

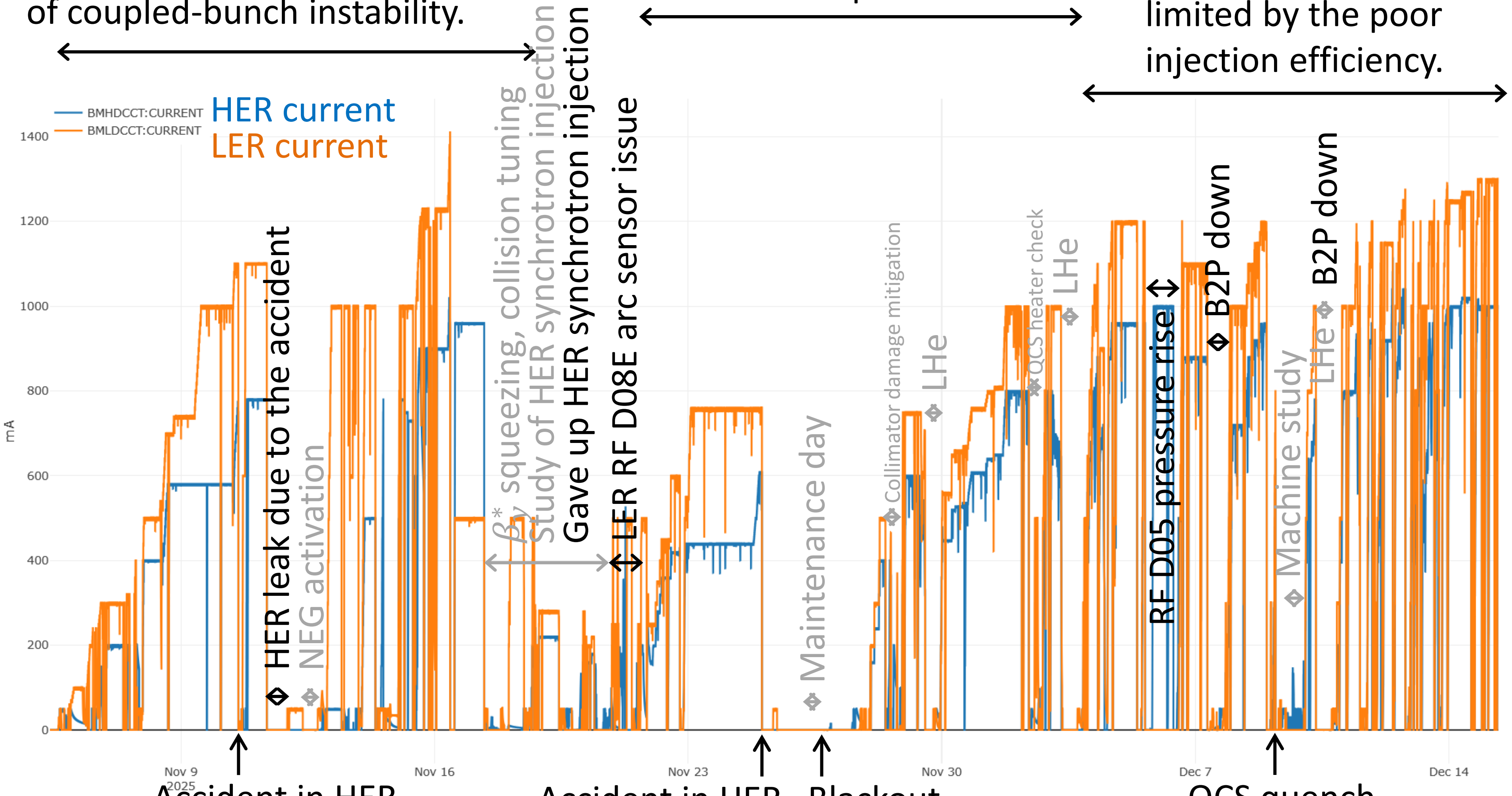
Black: troubles, issues
Gray: work, tuning

HER current is limited by the poor injection efficiency.

HER current was limited by +1 mode of coupled-bunch instability.

LER current was limited by bellows temperature.

LER current is limited by the poor injection efficiency.



Accident in HER (Room phase)

Accident in HER (Abort kicker)

Blackout

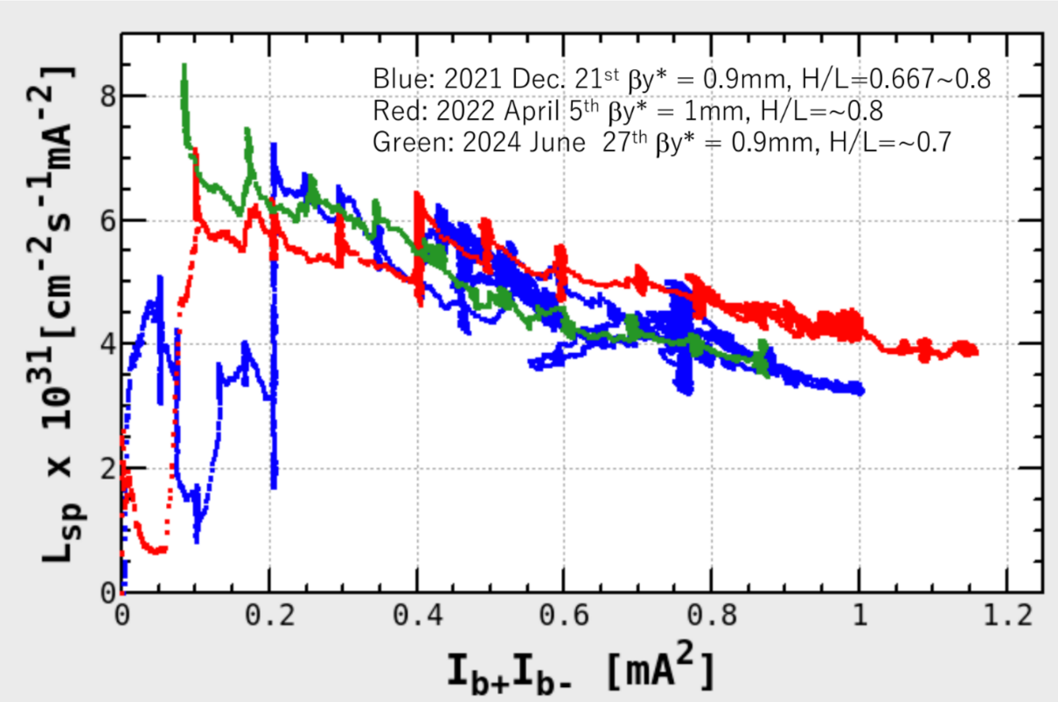
QCS quench

Physics run time: 45% (11/19-12/15)

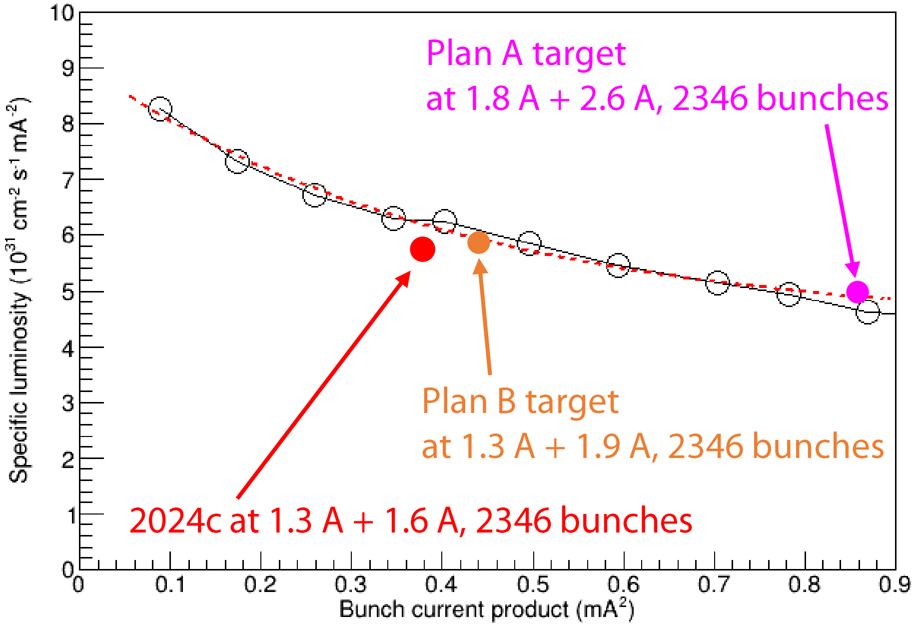
Lost time due to the abort kicker issue: 12% (73 h)

Lost time due to the other troubles: 12% (73 h)

Specific luminosity



Combined data (red and green in the left panel)

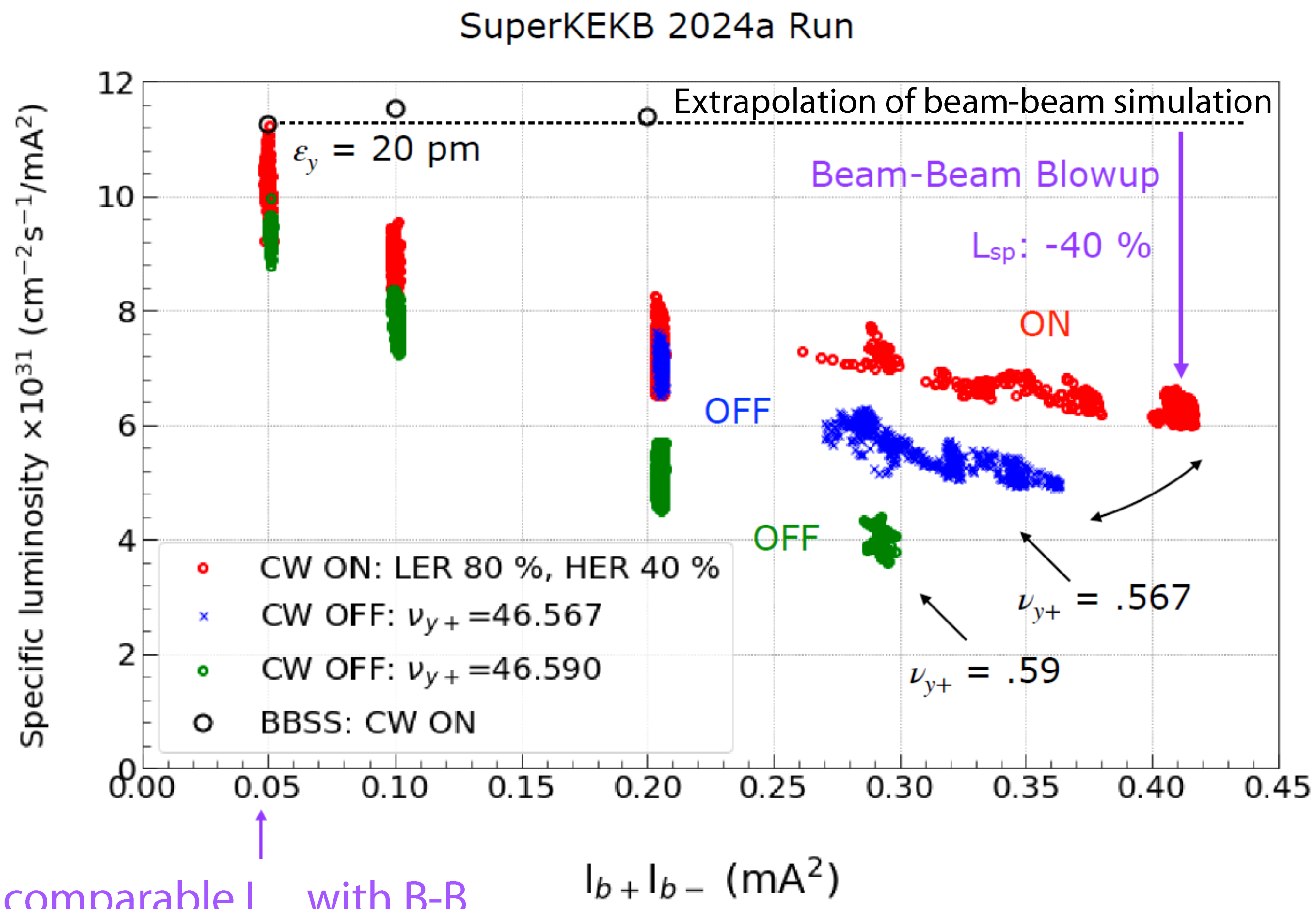


- High specific luminosity could be realized for a small number of bunches, e.g., 393 bunches.
- Challenging to realize it for 2346 bunches due to injection power, chamber-heating induced optics deformation, possibly beam instability, etc.

- Specific luminosity lying on the red dashed curve could be realized if HER emittance blowup in 2024c was solved (though not solved.)
- Optics study is planned for early 2025c to address emittance blowup if it reappears.

Beam-beam effects

(Y. Ohnishi, eeFACT2025)

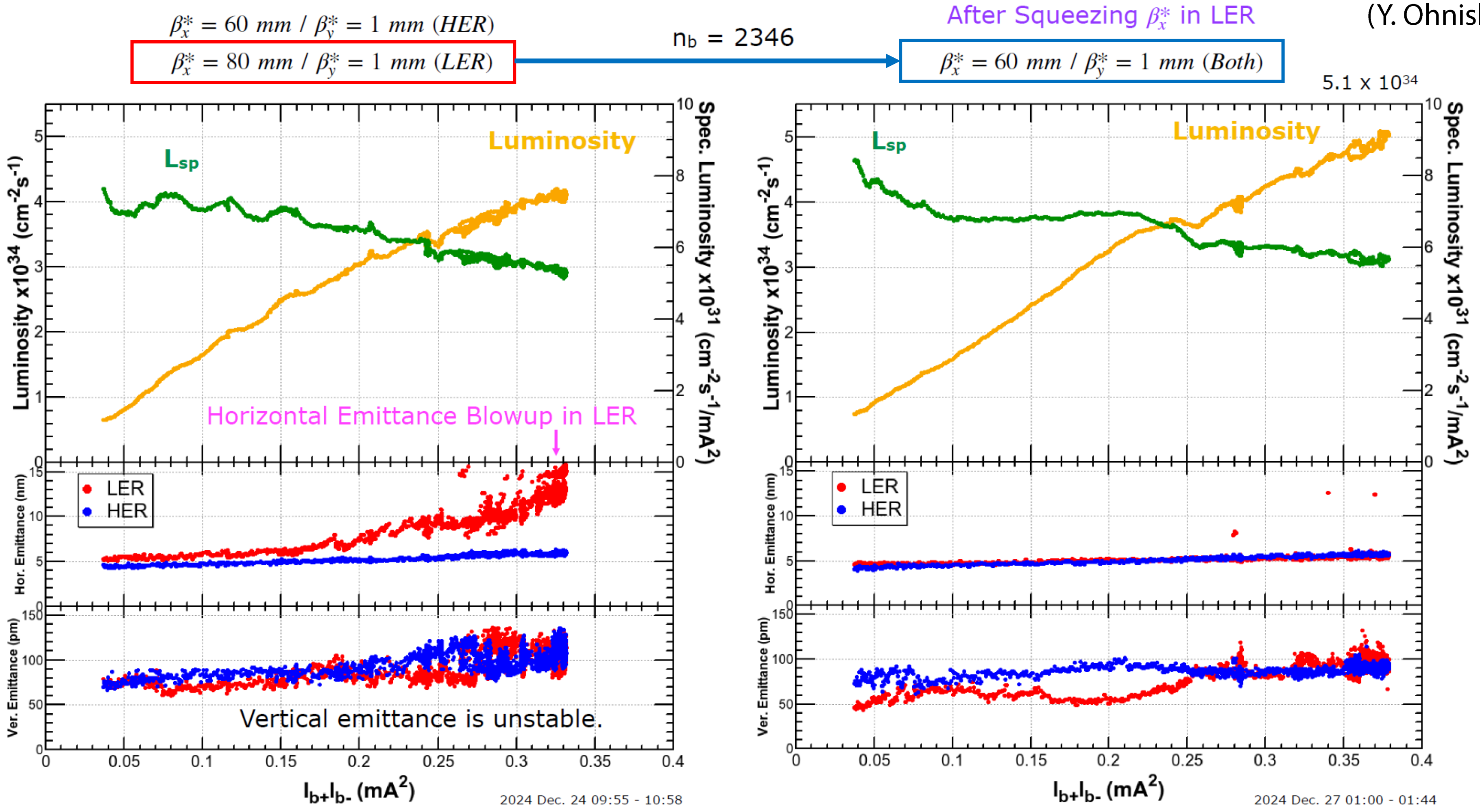


Obtained comparable L_{sp} with B-B simulation at low bunch current

- International collaboration is formed to tackle the beam-beam blowup issue (https://kds.kek.jp/category/1840/).
- Feedback will be applied to machine operation and studies in 2025c.

β_x* squeezing

(Y. Ohnishi, eeFACT2025)



- β_x* squeezing to 60 mm in LER was successful in mitigating σ_x* blowup, then achieving 1.7 A in LER.
- β_x* squeezing to 50 mm or lower is considered to avoid σ_x* blowup harming beam injection.

2-bunch injection

- We could achieve 1.3 A in HER (1-bunch) and 1.7 A in LER (2-bunch) with 2346 bunches in 2024c.
- HER injection started with a 2-bunch scheme. It came to a 1-bunch injection due to the discharge of the RF e- gun.
- Before 2025c, RF e- gun will be replaced with a new type of gun or fixed using a spare cathode plug.
- 2-bunch injection is essential for 1.8 A in HER and 2.6 A in LER in Plan A.

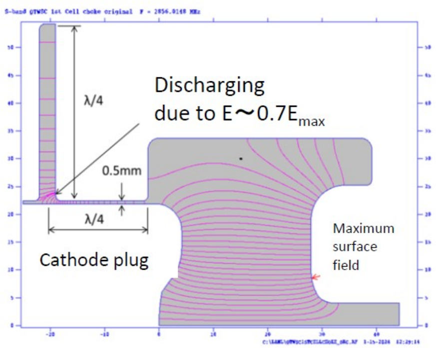
Status of RF Gun (Linac) – Updated QTWSC RF Gun

[M. Yoshida *et al.*]

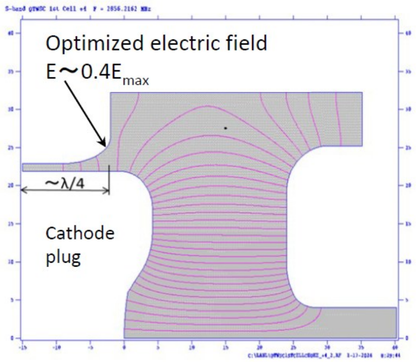
(T. Ishibashi, B2GM, June 2025)

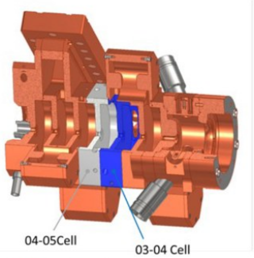
- The current RF gun cathode cell includes a choke structure for thermal cleaning of the cathode.
- The updated cathode cell is designed with:
  - Optimized surface field
  - Additional vacuum pumping
  - A new triplet downstream of the gun
- During brazing, the wrong cavity cell was assembled, resulting in a 10 MHz frequency offset (No tuning required for cathode side cavity chain).
- Tuning of the RF cavity is scheduled this week. RF conditioning will be performed until July.

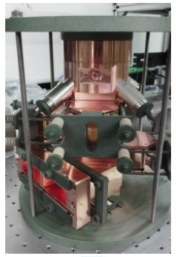
Current



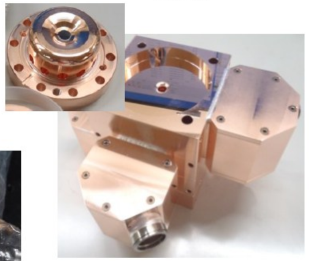
Updated

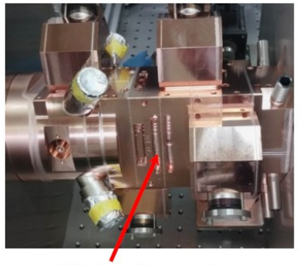






Brazing assembly





Additional machining for tuning

- If tuning cannot sufficiently correct the frequency offset and the schedule is delayed, a new IrCe cathode plug will be installed in the current RF gun.

New IrCe Cathode Plug

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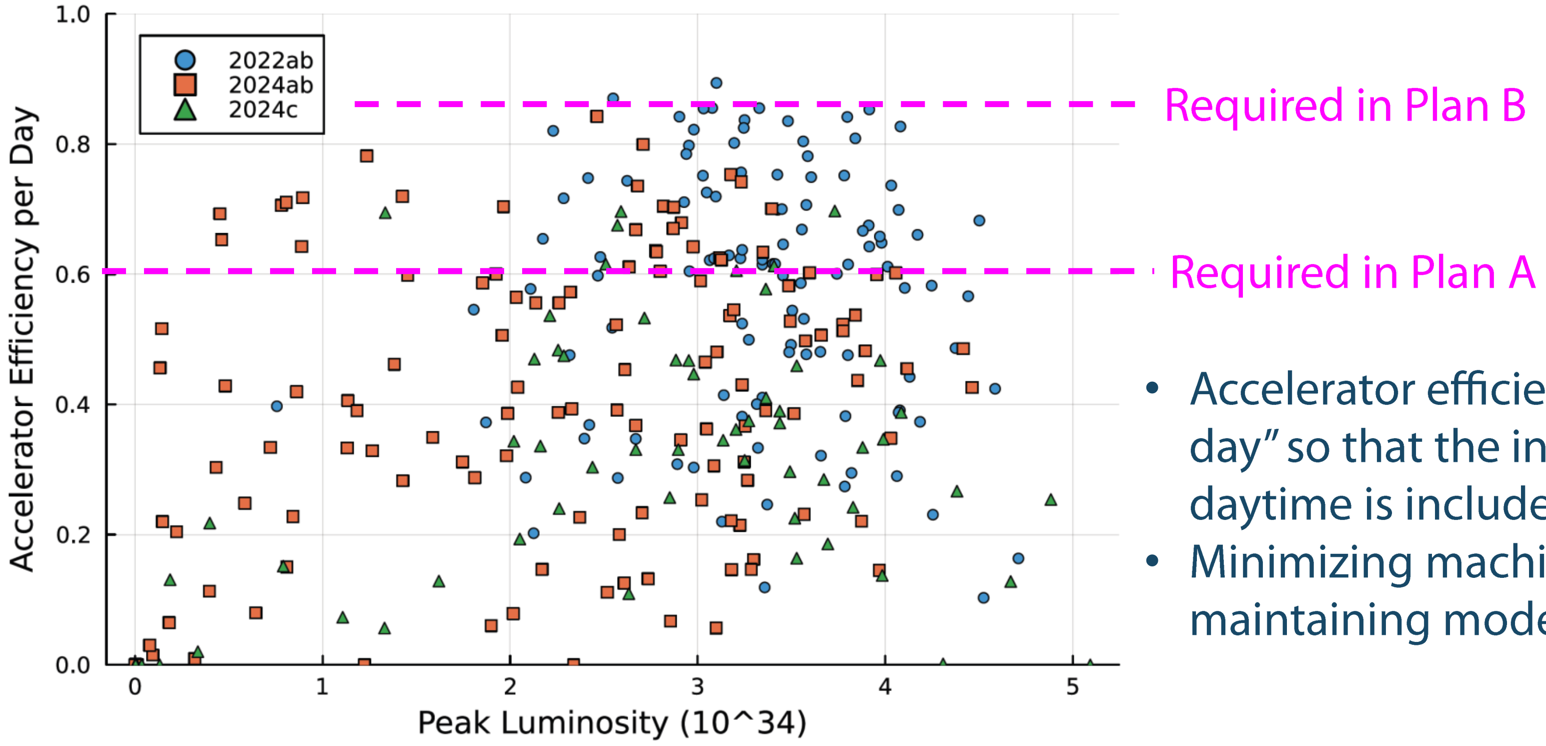
Accelerator efficiency

- A measured quantity of how constantly we can acquire the integrated luminosity while keeping the peak luminosity
- Accelerator efficiency is defined as $\varepsilon_{\mathrm{acc}} \equiv \dfrac{\text{Integrated luminosity}}{\int^{24\text{ hours}} L_{\mathrm{peak}} dt}$
- Cause of low accelerator efficiency: beam aborts, machine tuning inserted in physics run, unstable luminosity, etc.



- Accelerator efficiency in the left figure is defined as "per day" so that the inefficiency due to machine tuning in the daytime is included.
- Minimizing machine tuning time as much as possible while maintaining modest luminosity yields high efficiency.

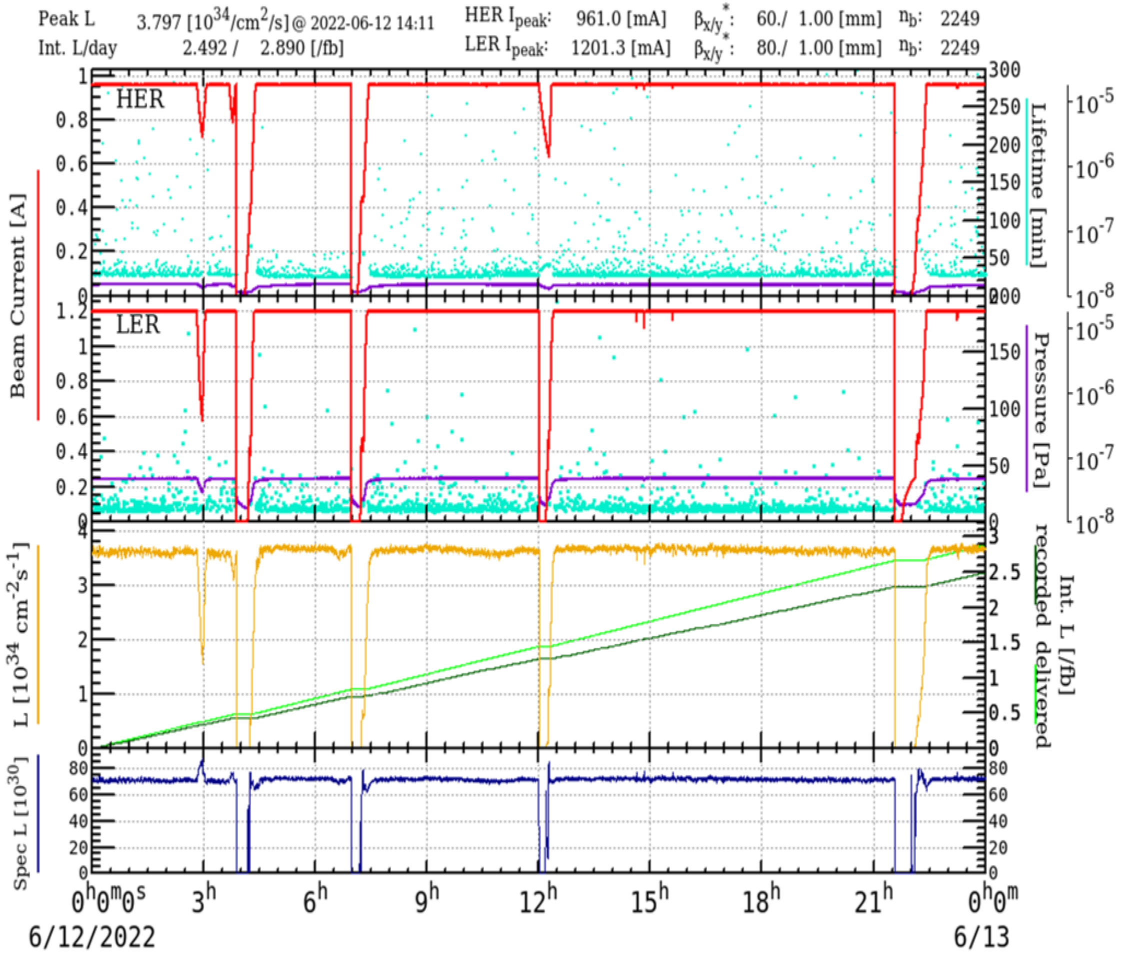
Accelerator efficiency on 12 June 2022

Example of high integrated luminosity/day

- Date: 2022-06-12, with β_y^*=1 mm
- Beam currents: I_{LER}=1.2 A, I_{HER}=0.96 A (2249 bunches)
- Peak luminosity: 3.8×10^{34} $cm^{-2}s^{-1}$
- Integrated luminosity (delivered): 2.89 fb^{-1} (2.49 fb^{-1} recorded with the DAQ efficiency: ~86%)

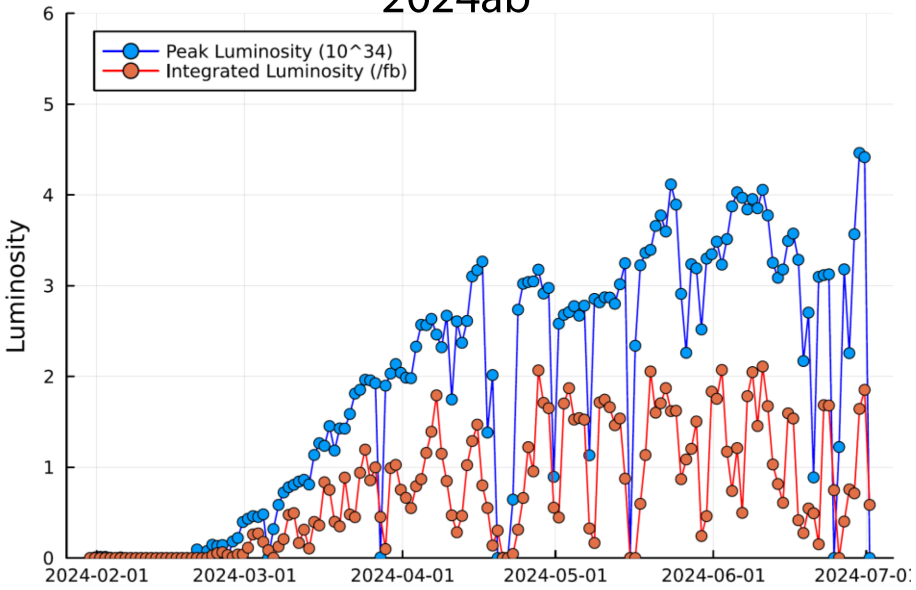
If operated at this luminosity for 24 hours:

- Delivered integrated luminosity = 3.28 fb^{-1}/day
- Accelerator efficiency: (2.89/3.28) × 100 ≈ 88%

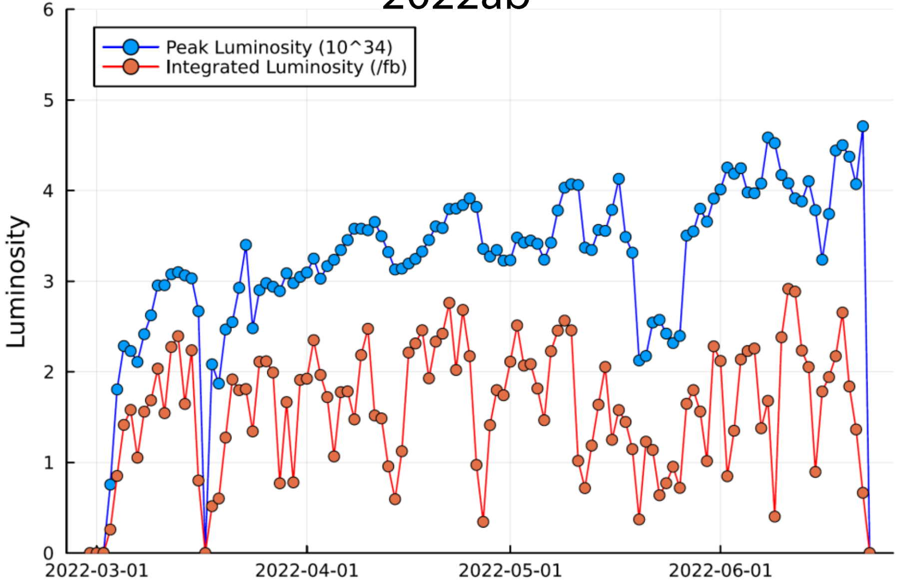


Luminosity history

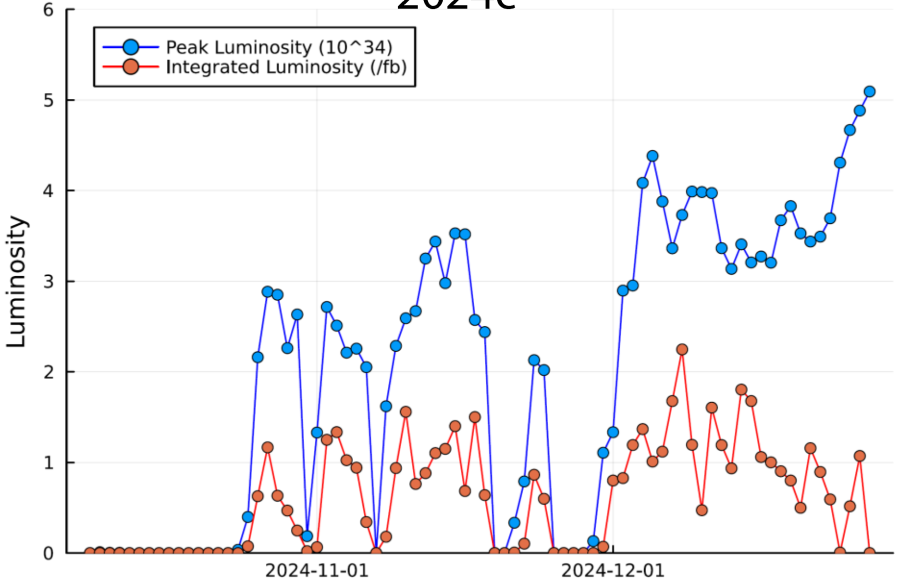
2024ab



2022ab



2024c



Towards high luminosity

- **Beam current (bunch current)**
  - Single beam: beam lifetime (pressure rising), injection (2-bunch operation)
  - Beam collision: beam-beam effect → narrow dynamic aperture

Obvious at <1.7 A in 2024c

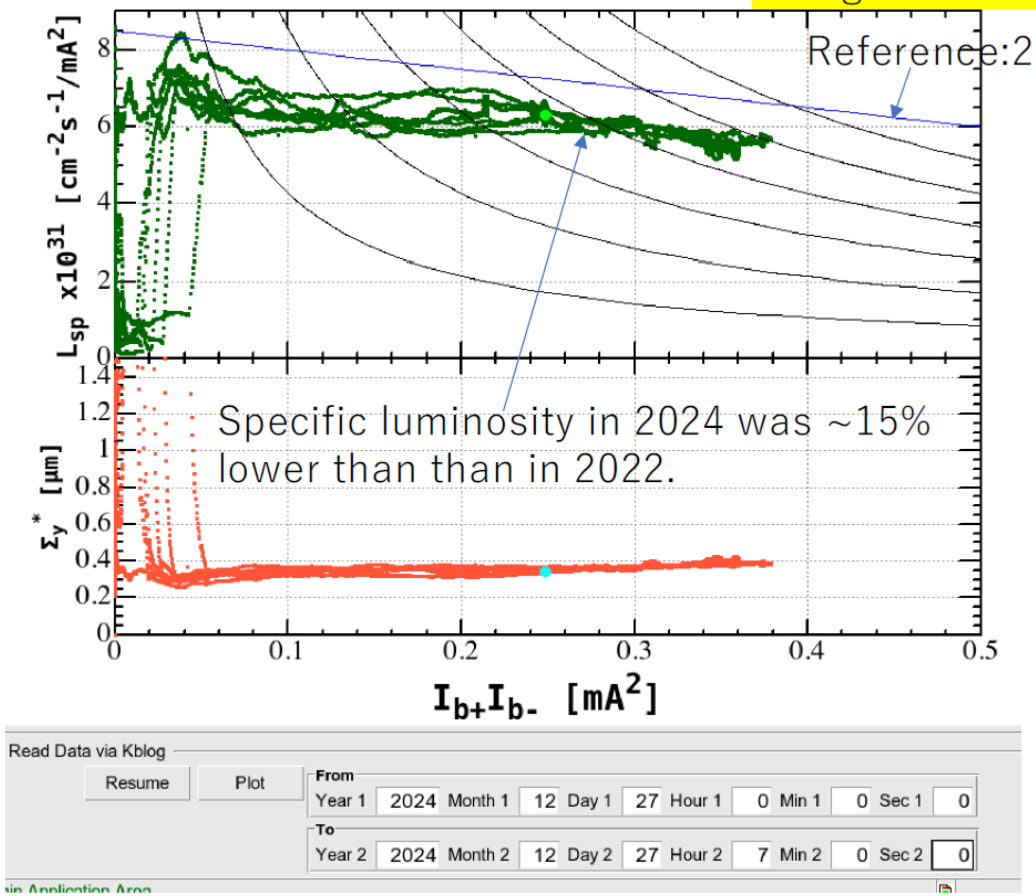
- **Emittance**
  - Single beam
    - Vertical: emittance blowup in HER
    - Horizontal: no problem?
  - Beam collision
    - Vertical: emittance blowup owing to beam-beam effects
    - Horizontal: emittance blowup owing to beam-beam effects → solved by lowering β_x^*

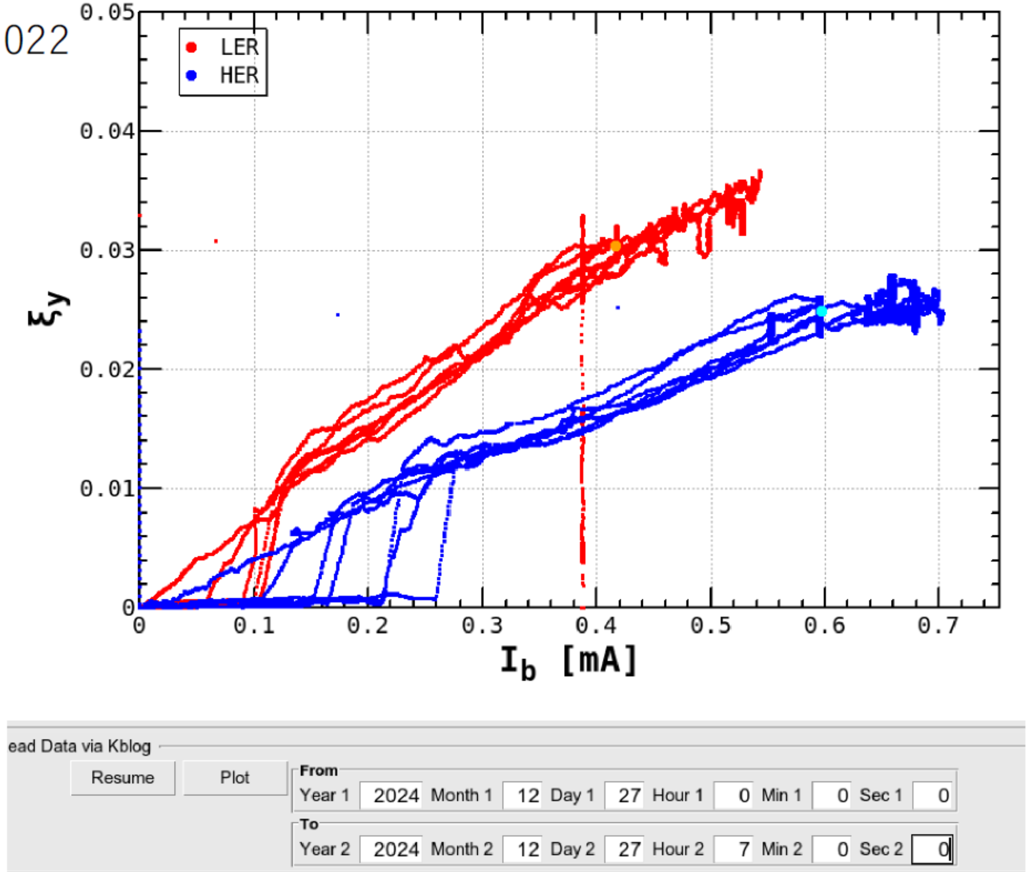
Plan for machine study

- Beam collision with corrects of HER cancel coil errors (1 shift?)
  - 393 bunches /beam
  - Up to higher bunch currents
- Beam collision up to high bunch currents with 393 bunches / beam
  - Reference measurement with good collision performace (1 shift)
  - With collimators open if possible (less transeverse impedance) (1 shift)
- Collision w/ and w/o bunch-by-bunch feedback
  - 31 bunches /beam (1 shift)
- Collision with higher βy^* such as 3 mm (less lattice nonlinearity)(3 days?)
  - We need luminosity tuning.
- Measurement on lattice nonlinearity and impedance (1 shift)
  - Decoherence of dipole oscillation, bunch charge dependence
  - Others?

Specific luminosity and beam-beam parameter

At highest luminosity: Dec.27th 2024





(Courtesy of Y. Ohnishi)

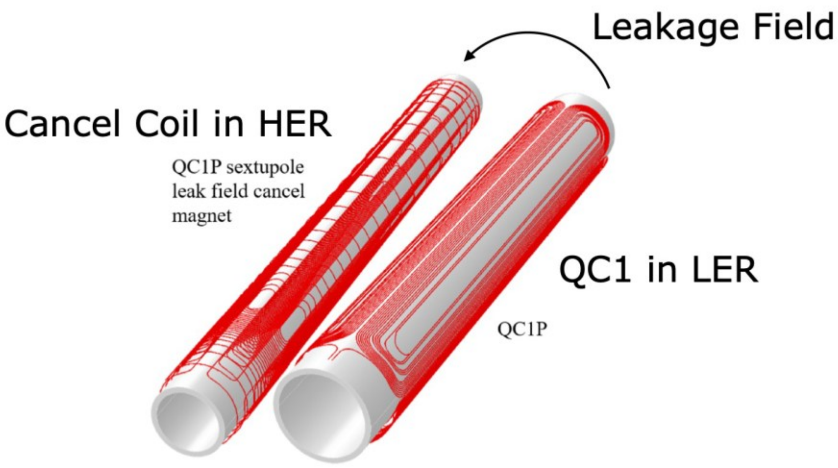
Manufacturing Failure of Cancel Coil in HER

Skew sextupole and skew octupole increase (Not cancelled).

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

	QCSL, Tm		QCSR, Tm	
Multipole coefficient	without cancelling	with cancelling	without cancelling	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}

Definition of the coordinate system seems to be wrong.



N. Ohuchi, Y. Arimoto

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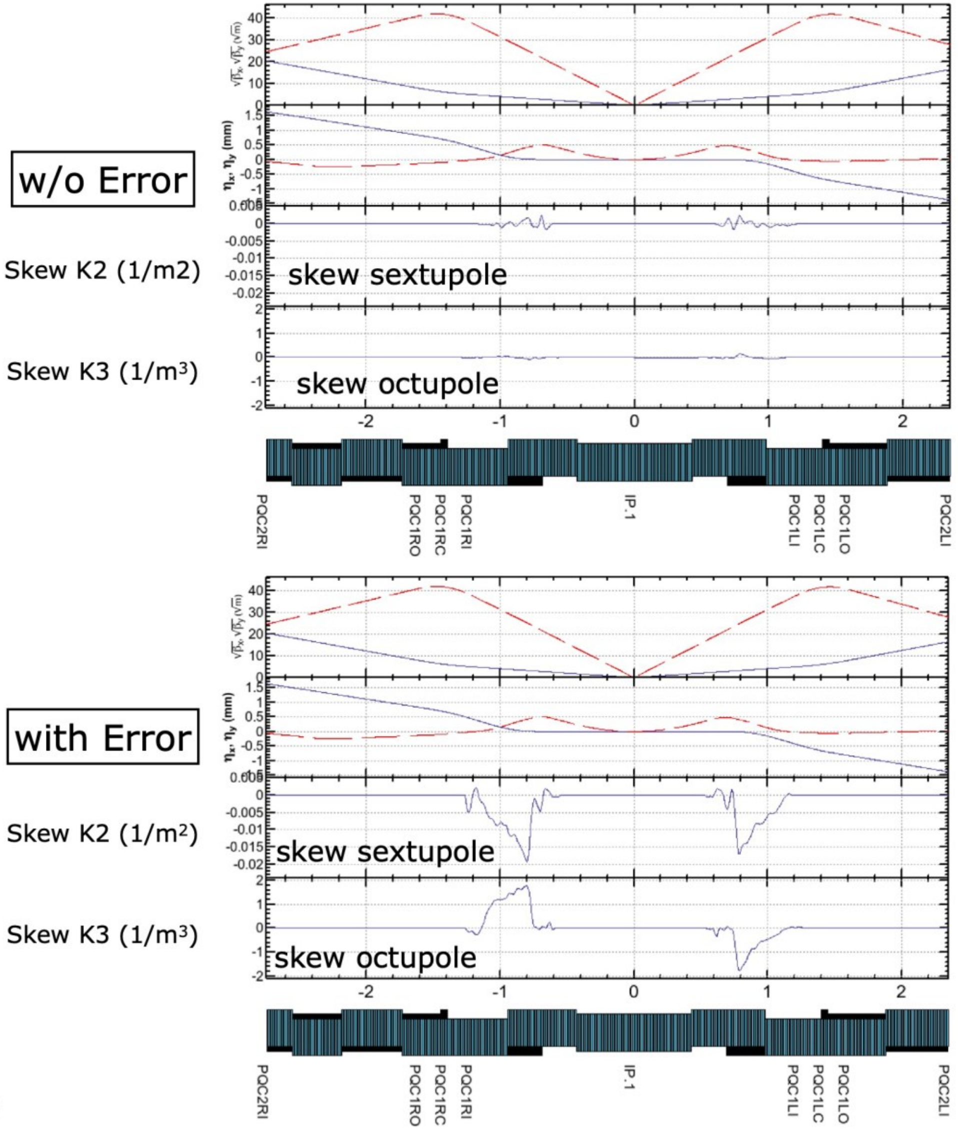
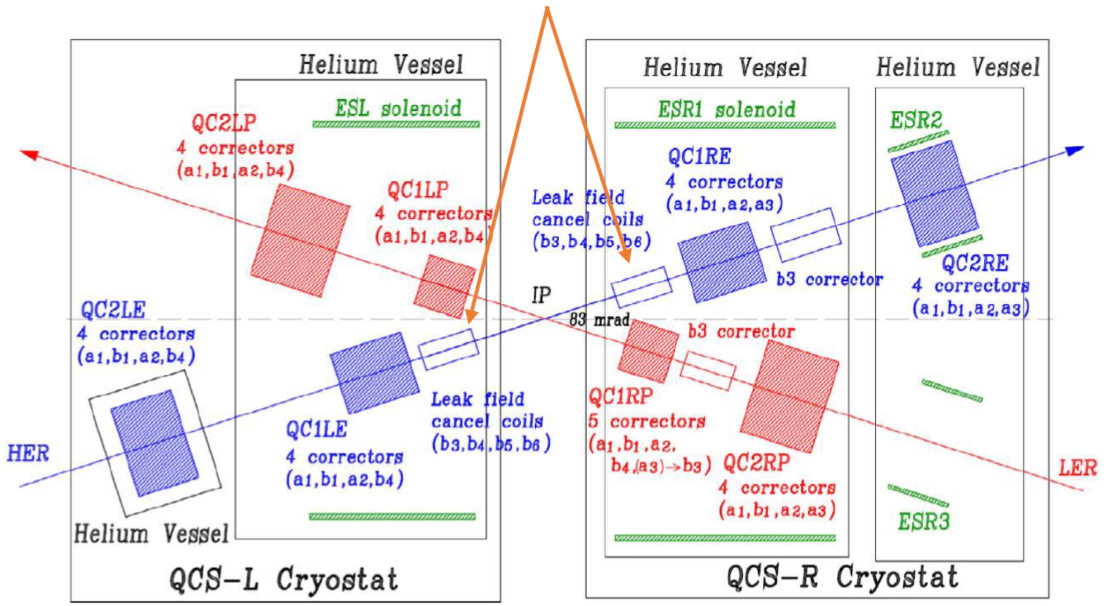


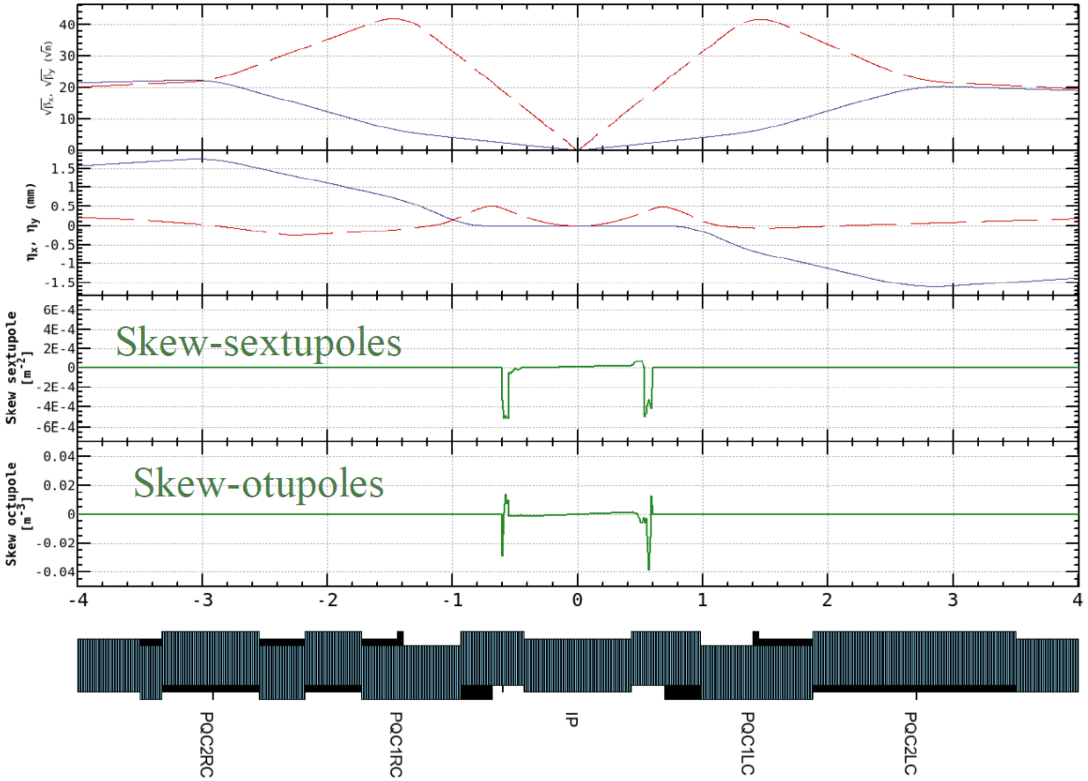
Manufacturing Errors in Leak-Field Cancellation Coils in HER

- The cancellation coils used to compensate the QC1P leakage field in the HER beamline have manufacturing errors.
- These errors introduce additional skew-sextupole and skew-octupole field components into the HER beamline.

Leak Field Cancellation Coils

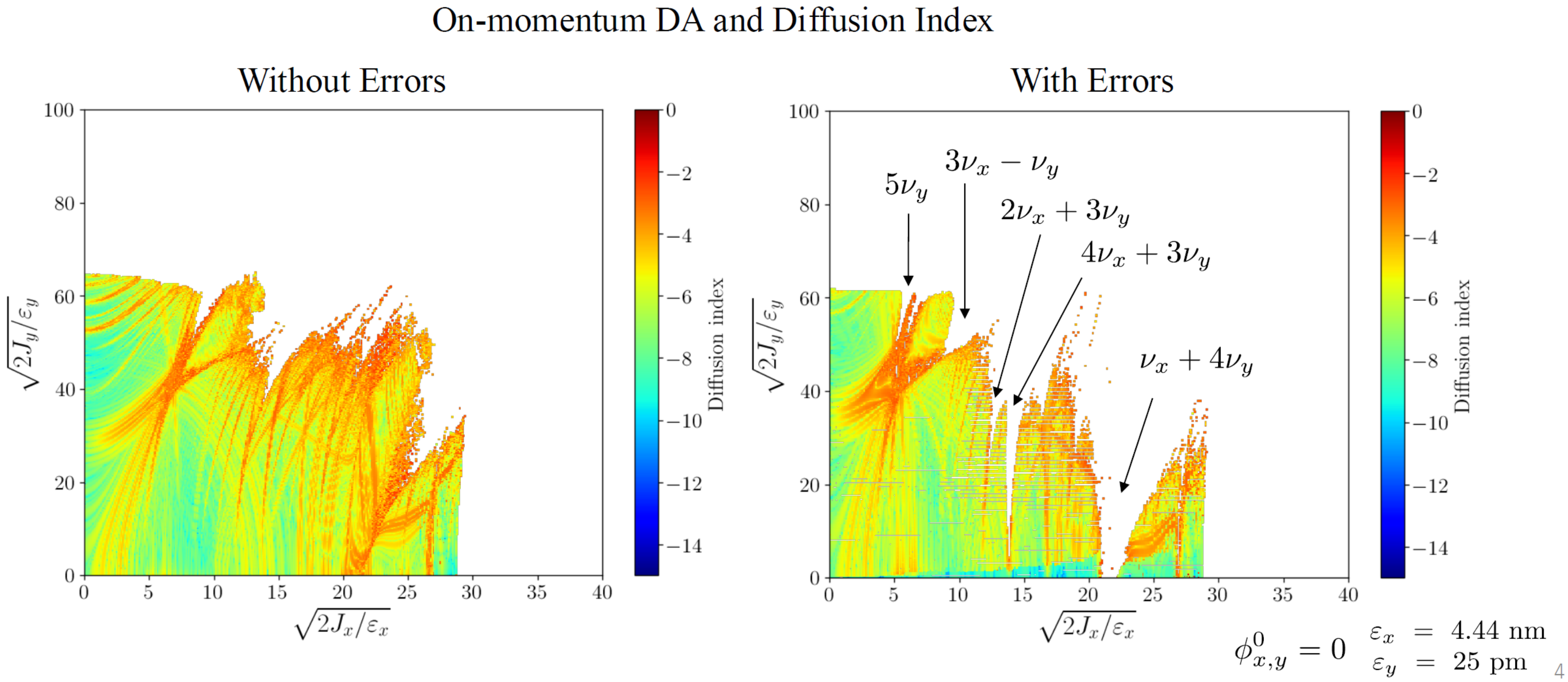


Skew-sextupoles & Skew-octupoles due to Manufacturing Errors



Impact on Dynamic Aperture (DA)

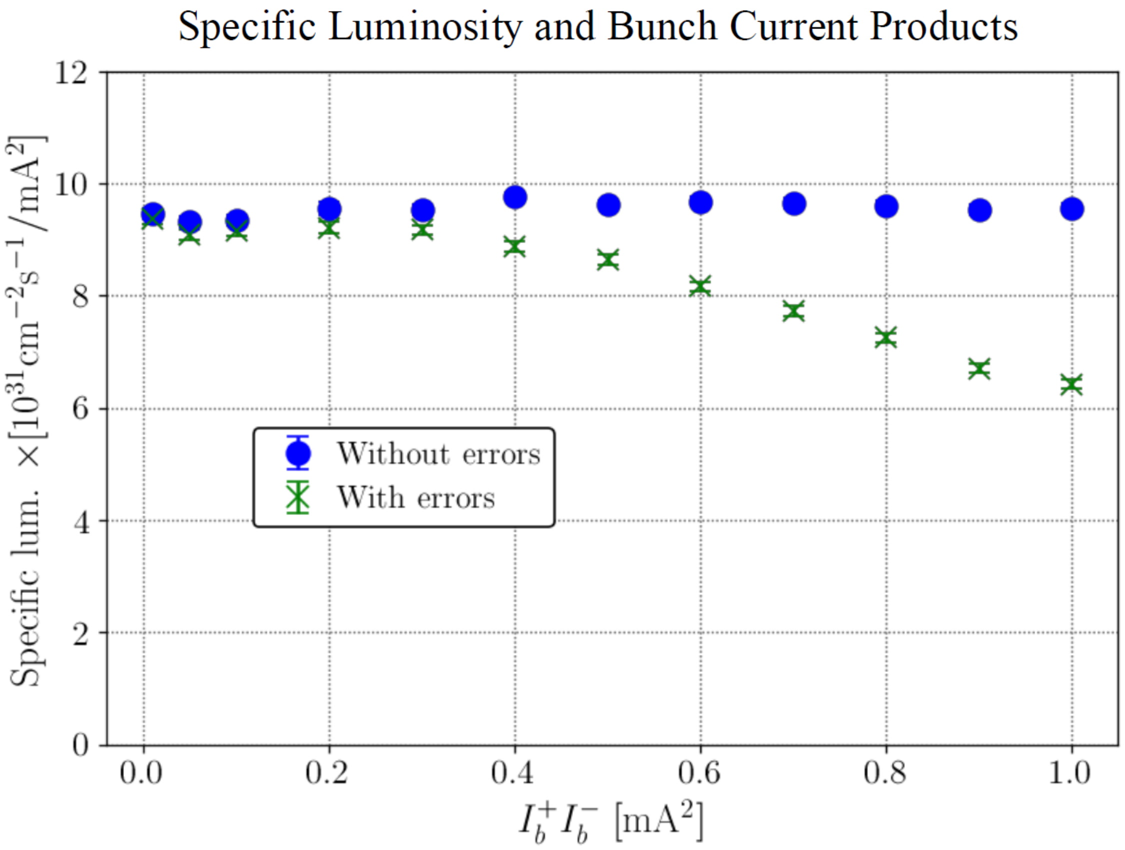
- Frequency-map analysis indicates that these errors intensify nonlinear lattice resonances.
- As a result, particles at large amplitudes exhibit chaotic, unstable motion.



4

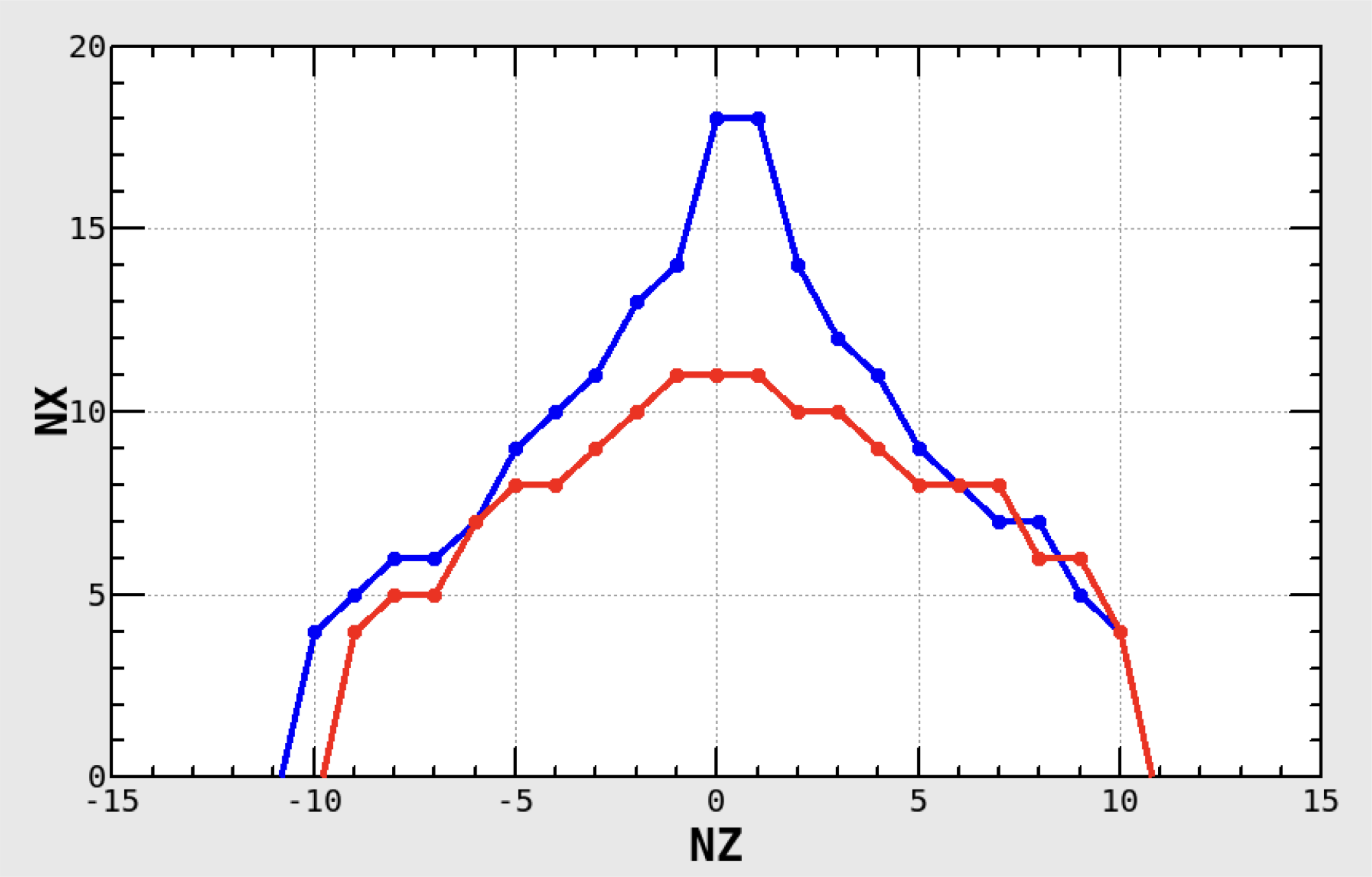
Impact on Luminosity (SAD, Weak-Strong, No wake)

- When cancellation-coil errors are included, vertical beam size increases with beam current.
- The vertical beam blowup arises from the interplay between beam–beam interactions and lattice nonlinearities.
- This report examines the nonlinear terms responsible for luminosity degradation.



(Courtesy of H. Koiso)

キャンセルコイルのエラー有無による力学口径の違い



キャンセルコイルのエラー有無による力学口径の違い

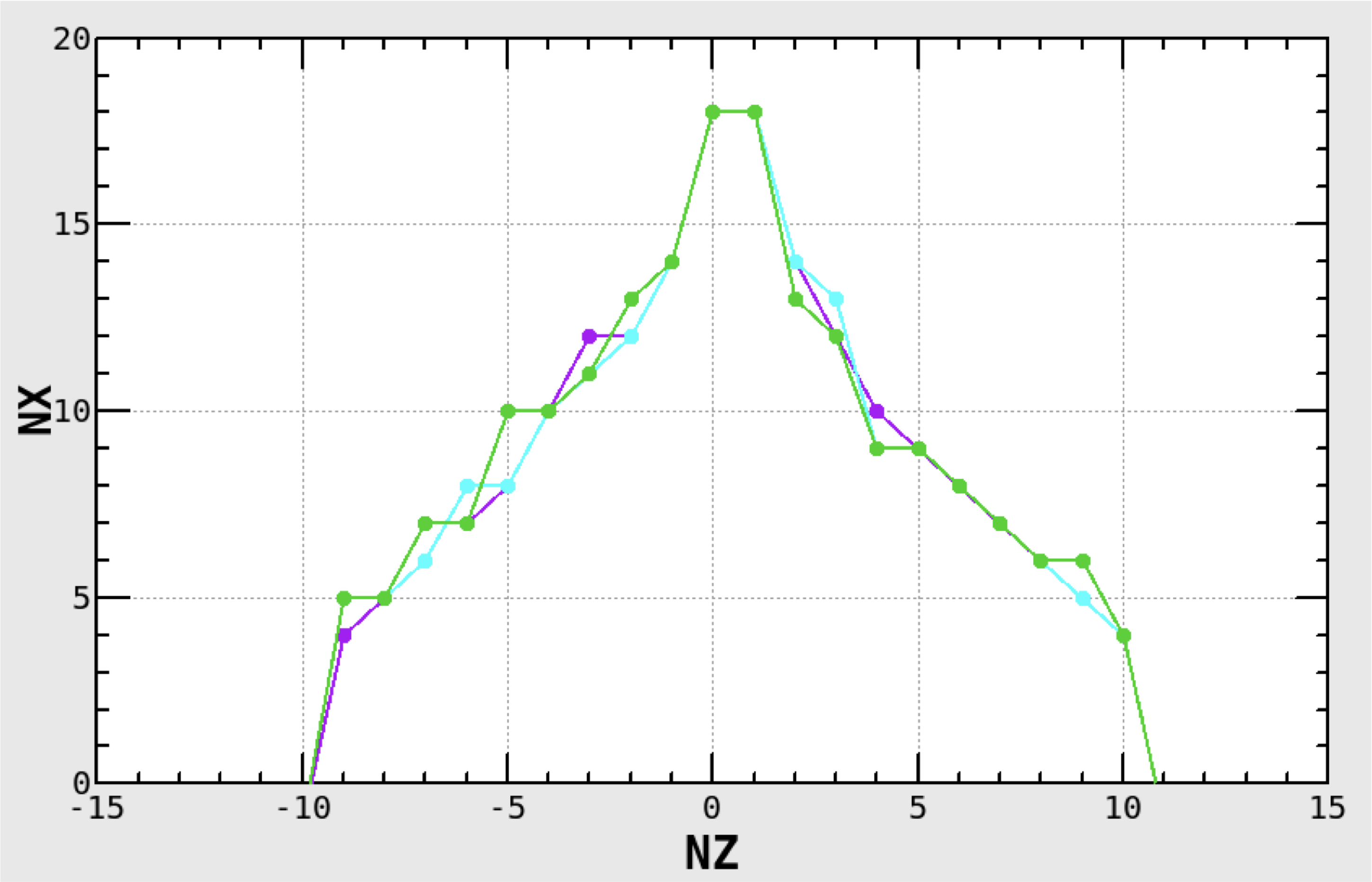
エラーなし
In[8]:= Plus@@LINE["SK2"]
Out[8]:= -.009067889596233848
sher_5781_60_1-YO20250213.sad

エラーあり
In[26]:= Plus@@LINE["SK2"]
Out[26]:= -.7442901095589288
sher_5781_60_1-can2-VSKQC1RE.sad
(VSKQC1RE SK2=0)

EMITY/EMITX
= 25 E-12 / 4.44 E-9
= 0.00563
2/27(木)杉本さんのスライドp.2
と同じ垂直エミッタンス

(Courtesy of H. Koiso)

キャンセルコイルのエラー補正



キャンセルコイルのエラー補正

VKQC1REの直前に thin element
VSKQC1REを置きSK2を調整する。
sher_5781_60_1-can2-VSKQC1RE.sad

VSKQC1REは軌道上に配置する。
SK2を変えても線形オプティクス
は変化しない。

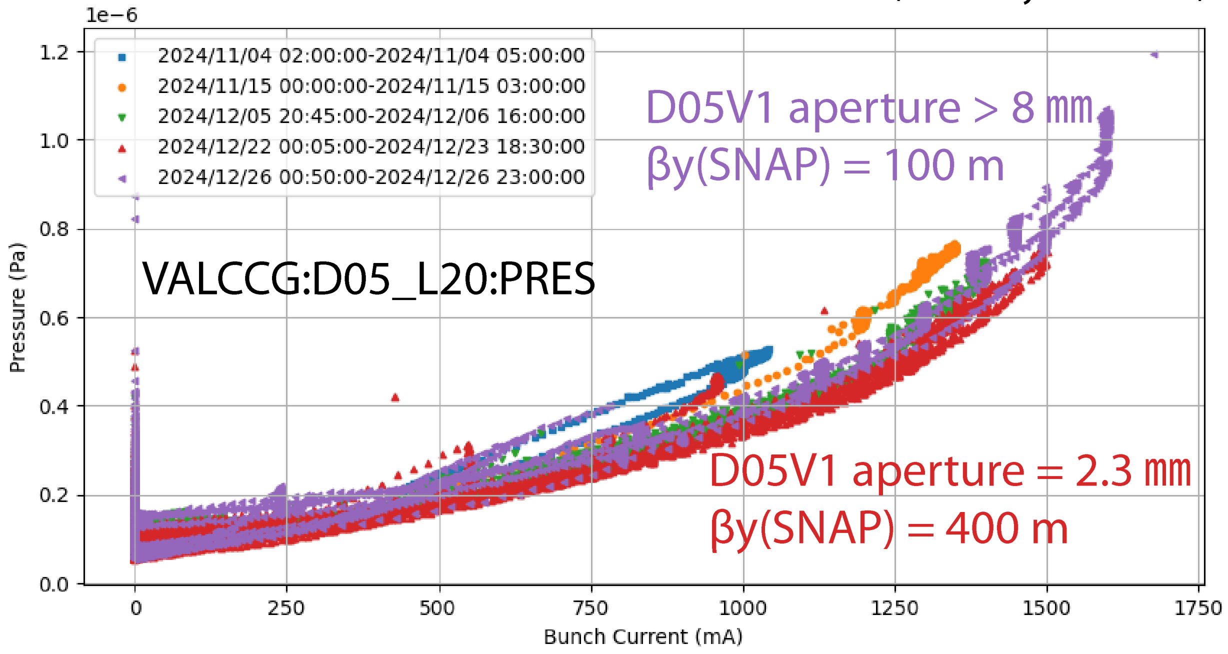
VSKQC1RE SK2 に
+0.03、+0.04、+0.05
を与えた場合、NZ = -5 ~ +5
あたりの力学口径はほぼ回復する。
これは予想通り IP左右のSK2の
アンバランスを補正する方向。

NLC

NLC aperture

- Open — Inj. amplitude of 2nd bunch — Injection BG increases
- Close — Lifetime shortens

(Courtesy of S. Terui)



- Pressure rising independently of the D05V1 aperture and βy(SNAP)