Preliminary and unofficial

Crab waist at SuperKEKB

May 25, 2020 @ FCC-ee MDI Meeting

K. Oide

Many thanks to the SuperKEKB Team, esp.:
Design/optics/commissioning: Y. Funakoshi, H. Koiso, A. Morita, Y. Ohnishi, K. Ohmi, H. Sugimoto, D. Zhou, and all SuperKCG members
Crab waist sextupole setup: M. Masuzawa, T. Oki, S. Nakamura, and the magnet group
Linac, injector: K. Furukawa, N. Iida, T. Kamitani, and the linac and BT groups
Belle-II: I. Adachi, S. Tanaka

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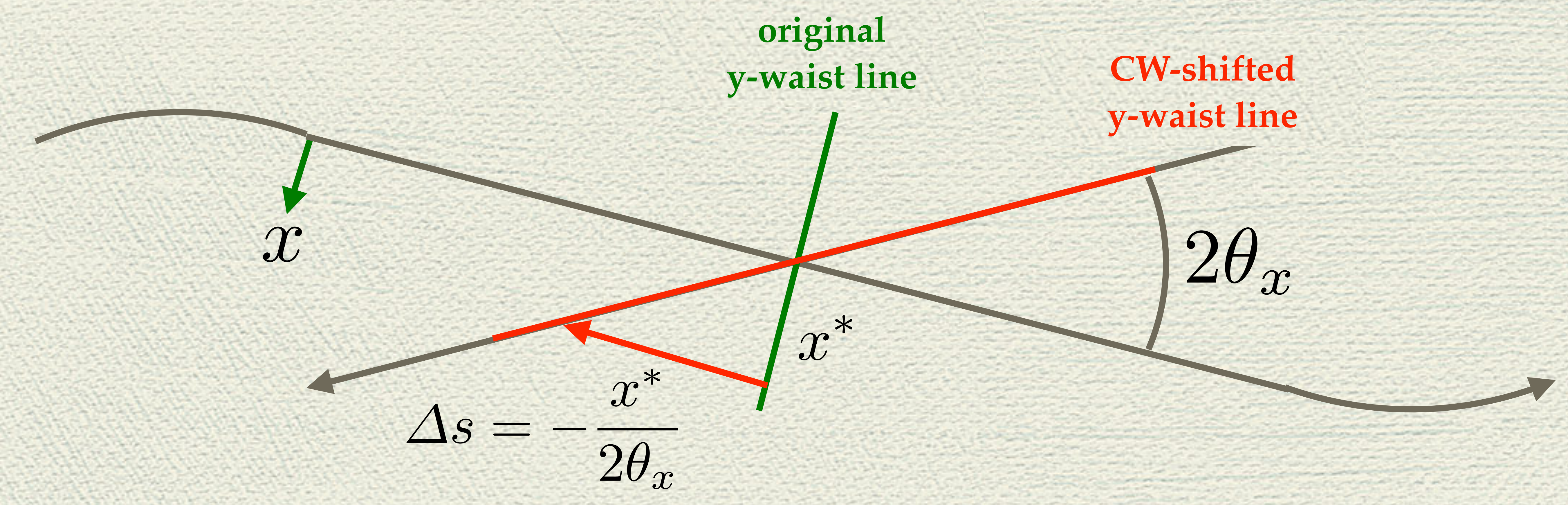
Principle of Crab Waist



The crab waist scheme shifts the vertical waist of a beam by

$$\Delta s = -\frac{x^*}{2\theta_x} \ . \tag{1}$$

Thus the associated transformation is

$$y^* \to y^* - p_y^* \Delta s = y^* + \frac{p_y^* x^*}{2\theta_x} \ , \tag{2}$$

which is performed by a Hamiltonian at the IP:

$$H^* = \frac{x^* p_y^{*2}}{4\theta_x} \ . \tag{3}$$

If there are the phase relations between the IP and the sextupoles:

$$\Delta\psi_x = 2\pi \ \text{ and } \ \Delta\psi_y = 2.5\pi, \tag{4}$$

then the variables at the IP (x^*, p_y^*) are expressed in those at the sext (x, y):

$$x^* = \sqrt{\frac{\beta_x^*}{\beta_x}} x, \quad p_y^* = -\frac{y}{\sqrt{\beta_y^* \beta_y}} \ . \tag{5}$$

Thus the Hamitonian at the IP is equivalent to a Hamiltonian at the sext:

$$H = \frac{x y^2}{4\theta_x \beta_y^* \beta_y} \sqrt{\frac{\beta_x^*}{\beta_x}} \ , \tag{6}$$

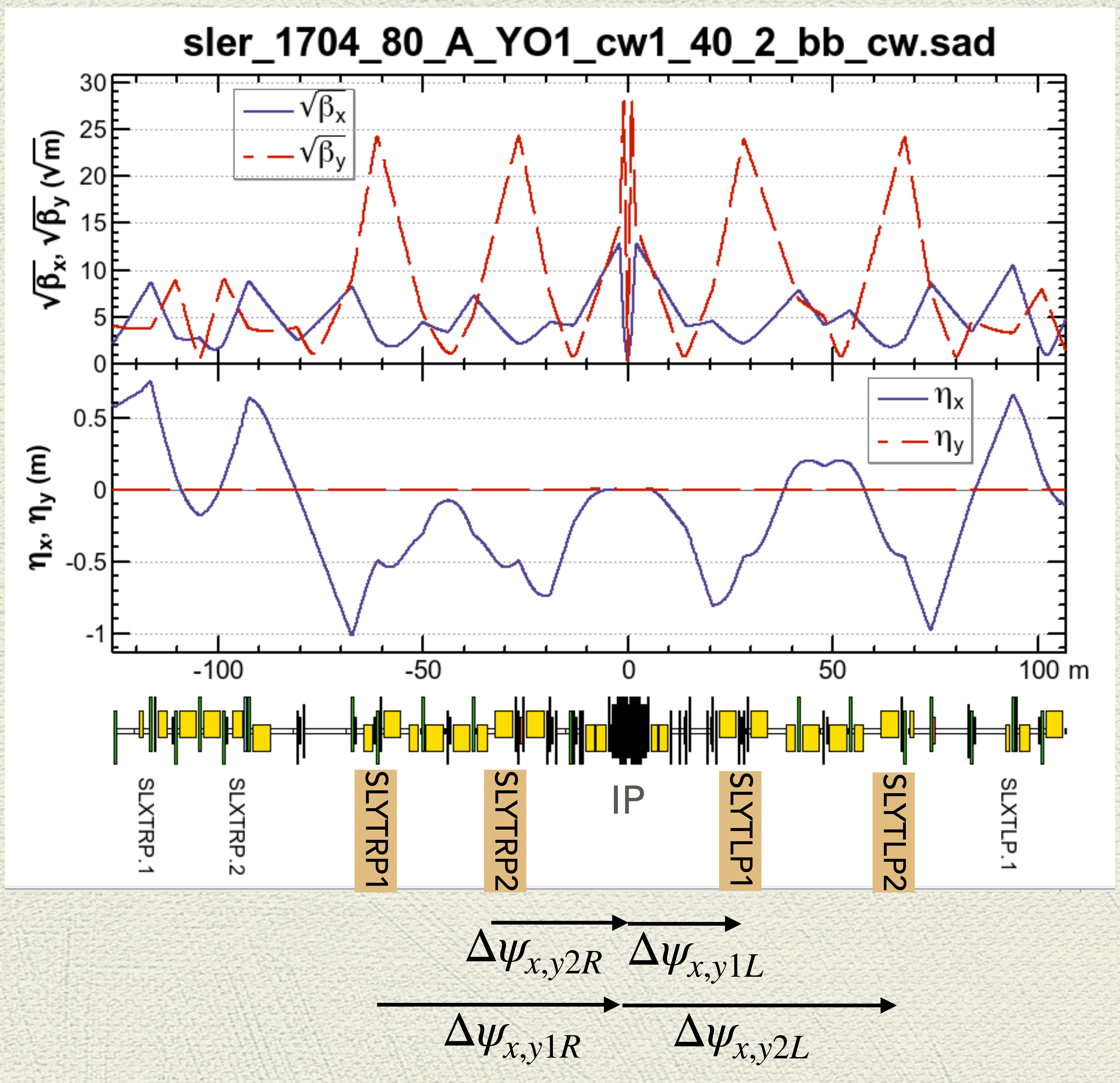
which can be approximated by a Hamiltonian of a sextupole:

$$H_s = \frac{k_2}{6} \left(x^3 - 3xy^2 \right) \ , \tag{7}$$

with

$$k_2 = -\frac{1}{2\theta_x \beta_y^* \beta_y} \sqrt{\frac{\beta_x^*}{\beta_x}} \ . \tag{8}$$

SuperKEKB(LER, e+) IR optics ($\beta^*_{x/y} = 80/1$ mm)



Base optics: sler_1704_80_A_YO1 (Y. Ohnishi)

- *K. Ohmi has noticed that the phase advances between CCY sexts (SLY*) and IP are close to the crab-waist condition (SuperKEKB Beam Dynamics Workshop, Sept. 2019):*

	$\Delta\psi_x/2\pi$	$\Delta\psi_y/2\pi$
SLY1R	**1.005**	**1.250**
SLY2R	**0.505**	**0.750**
SLY1L	**0.495**	**0.750**
SLY2L	**0.995**	**1.250**

- *Thus these sextupoles can be usable for crab sexts. The effects due to the small differences in the phase advances are tiny (K. Ohmi).*

Parameters (if there is no blowup...)

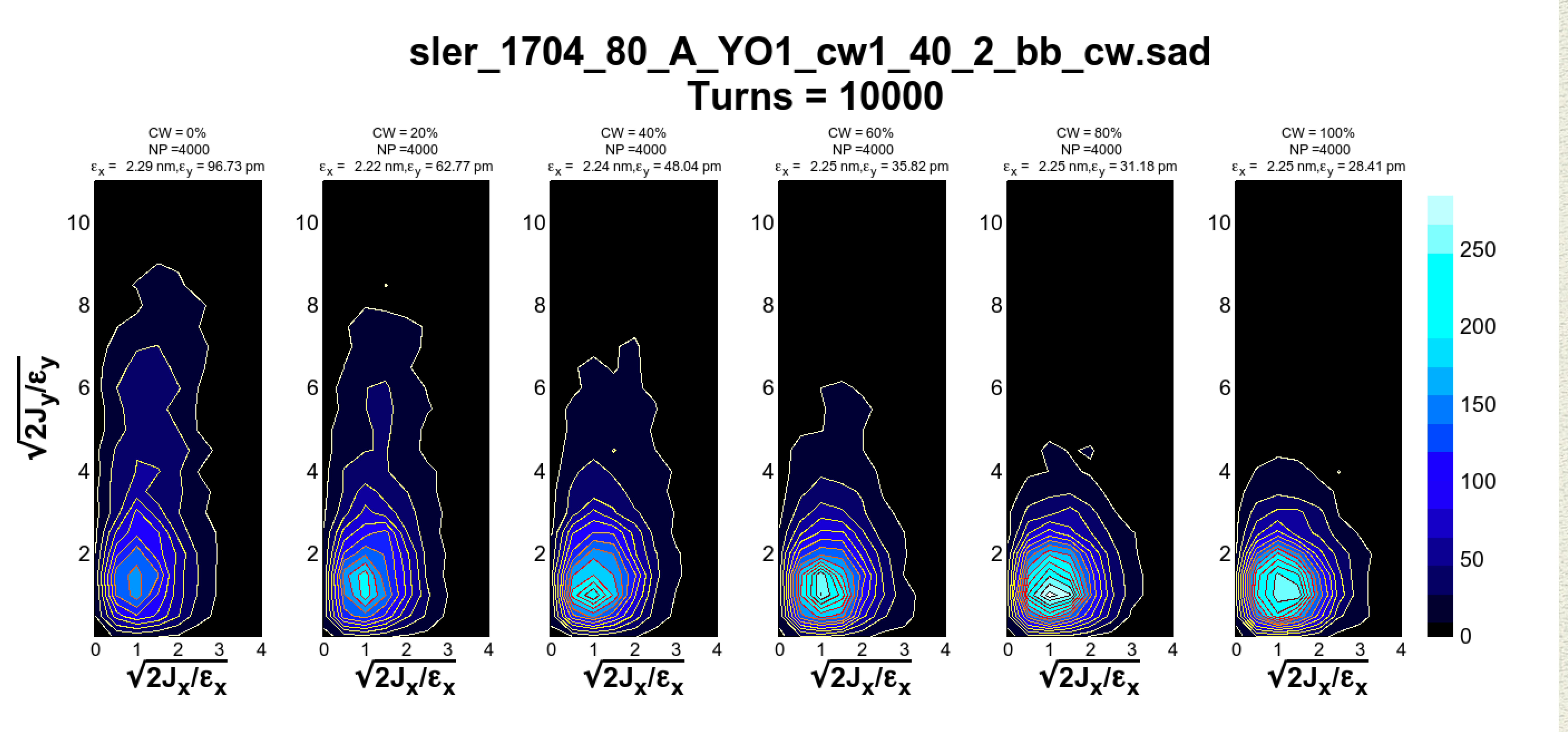
Lattices (Y. Ohnishi, provided via H. Koiso):
LER 4 nm: sler_1705_80_1_20200522180706.sad
LER 2 nm:sler_200310_170033989.sad
HER: sher_5780_60_1_20200426082304.sad

Parameters		LER (4 nm)	LER (2 nm)	HER
Beam energy	GeV	4		7
Particles / bunch	10^{10}	4		4
Emittance x (lattice/IBS)	nm	4.03 / 4.32	1.64 / 2.17	4.48 / 4.51
Emittance y (lattice/IBS)	pm	0.48 / 22.9	0.48 / 21.7	0.58 / 21.7
Bunch length (lattice/IBS)	mm	4.7 / 4.8		5.04 / 5.06
Mom. spread (lattice/IBS)	10^{-4}	7.5 / 7.7		6.3 / 6.3
$\beta^*_{x/y}$	mm	80 / 1		60 / 1
$\sigma^*_{x/y}$	μm	18.6 / 0.151	13.2 / 0.147	16.5 / 0.147
Tunes		44.525/46.586/ – 0.0235		45.531/43.581/ – 0.0272
Long. damping	turns	2270		2880
Beam-beam $\xi_{x/y}{}^a$		0.0041/0.076	0.0041/0.075	0.0020/0.045
Beam current	A	0.5		0.5
Bunches/ring		783		
Half crossing angle	mrad	41.5		
Luminosity	nb/s	31.6	31.3	

[a] incl. hour glass

Beam distribution for various CW ratios ($\beta_y^* = 1$ mm)

LER

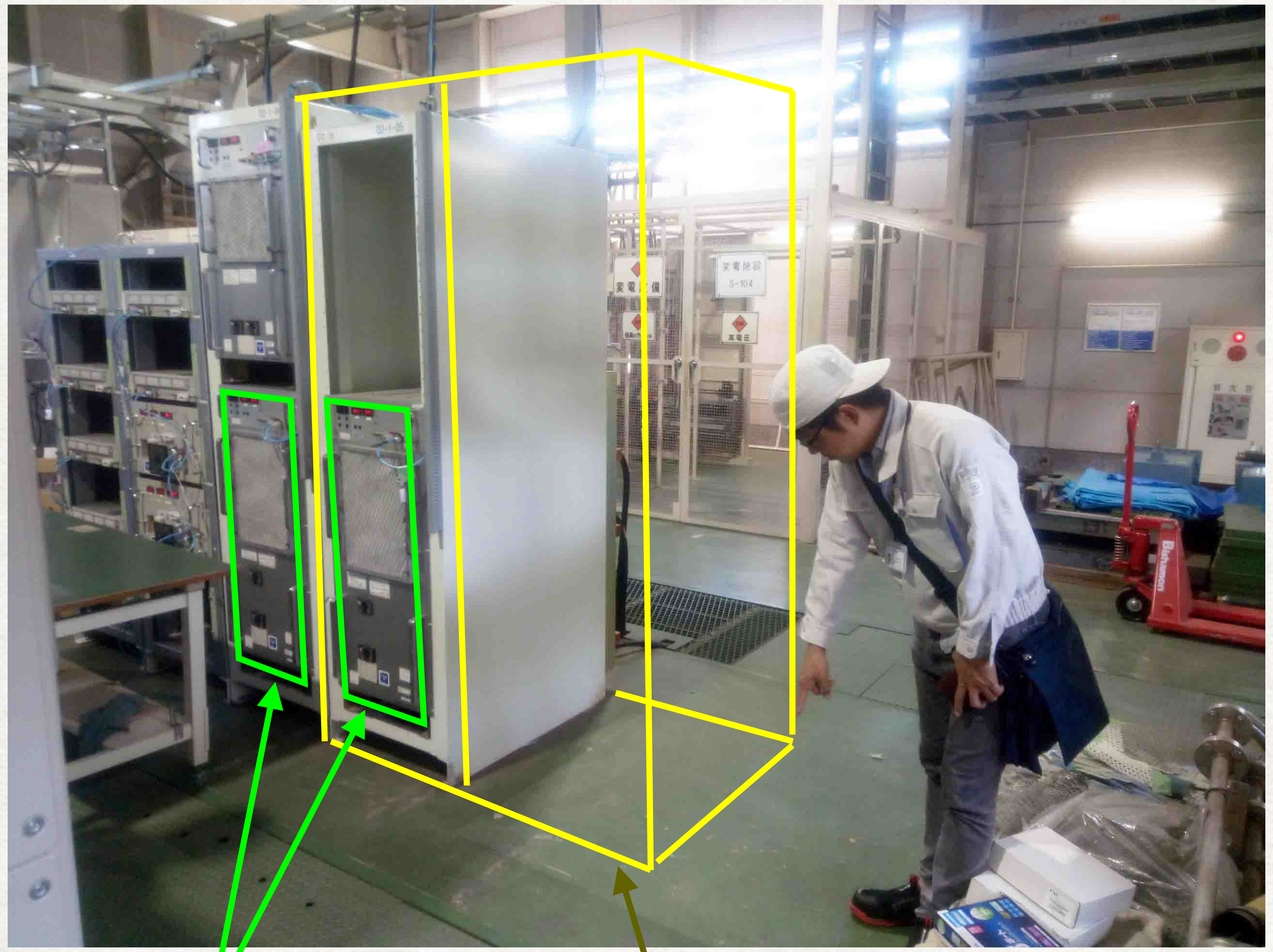


- Same contours for all CW ratios.
- Suppression of the tail as well as higher density of the core are visible, even for CW = 20%.
- Simulation: BBWS(K. Ohmi) + lattice, by SAD

Works for crab sextupoles, cables, power converters

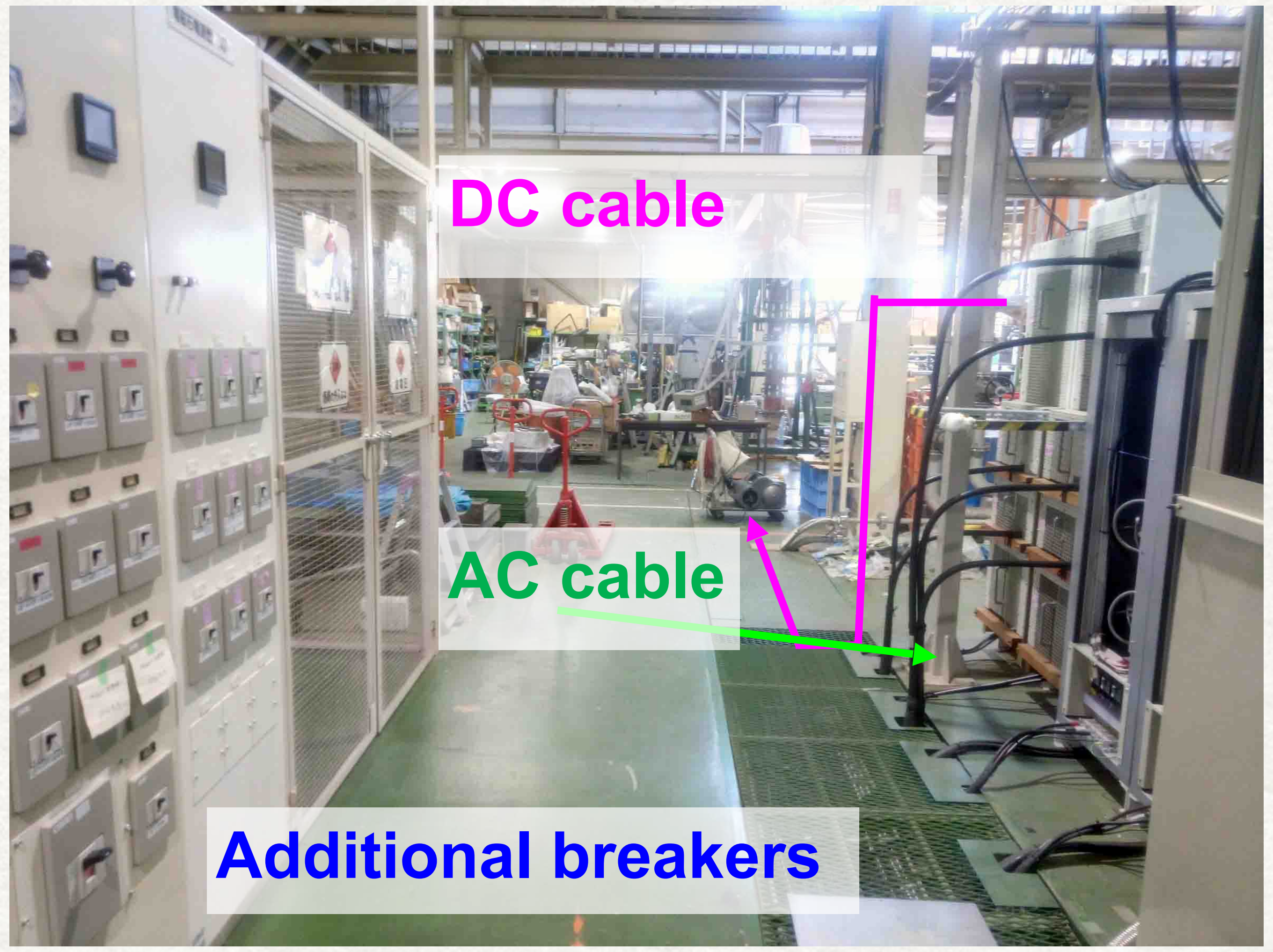
during the winter shutdown

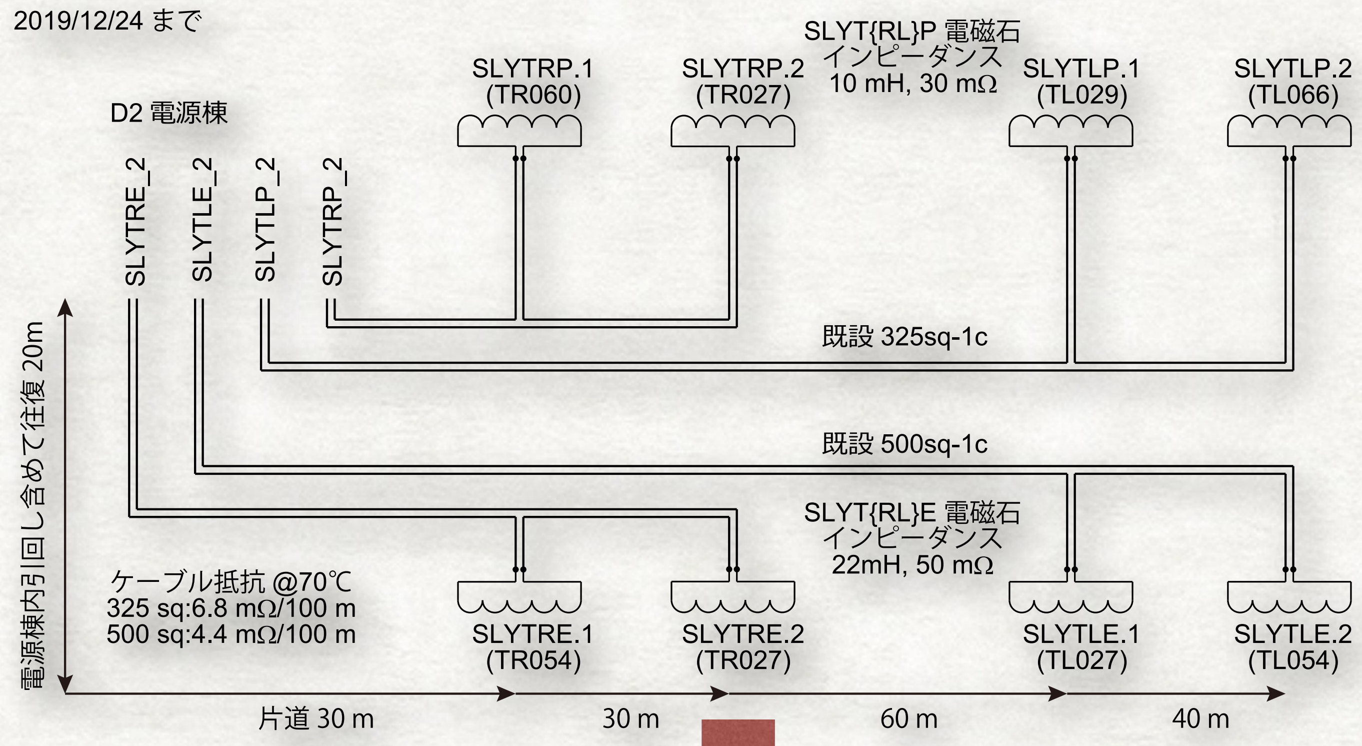
M. Masuzawa, T. Oki, S. Namamura, magnet group

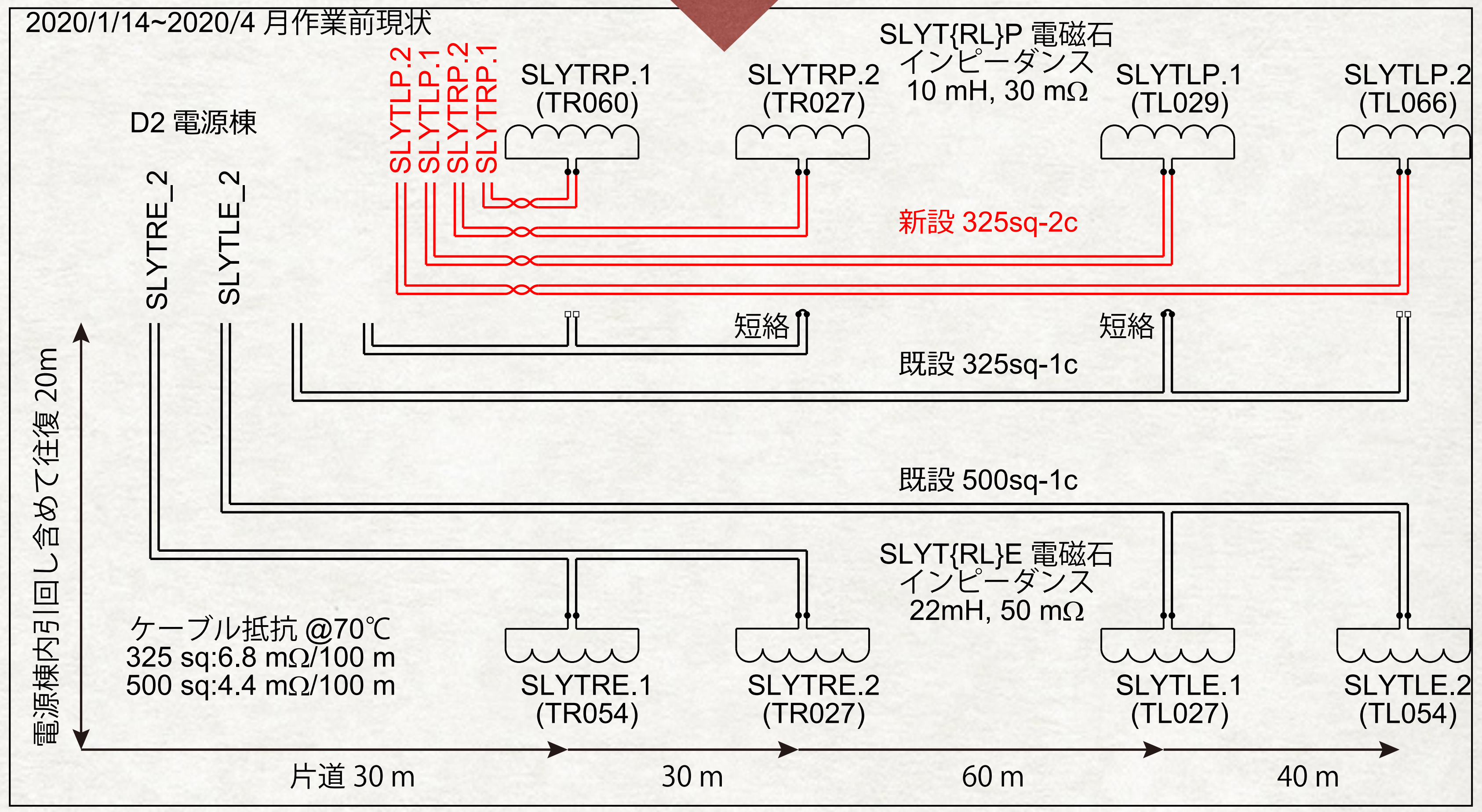


Existing converter for sextupoles

Spaces for 4 converters





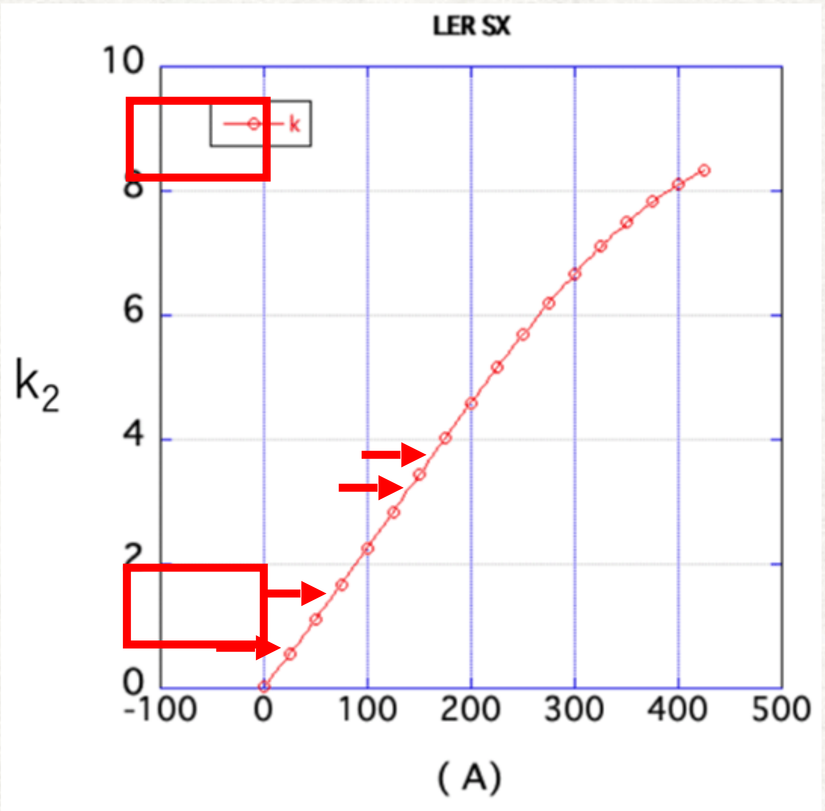


- Left

	$K_2 (m^{-2})$	xp_y^2	
SLYTLP.1	1.4503	3.1772	<100A
SLYTLP.2	3.7325	−8.1772	<200A
SLXTLP.1	0.6718	−0.0148	
SLXTLP.2	0.6718	0.0148	
sum		−5	

- Right

	$K_2 (m^{-2})$	xp_y^2	
SLXTRP.1	0.3335	−0.0061	
SLXTRP.2	0.3335	0.0061	
SLYTRP.1	0.8757	−1.8729	<100A
SLYTRP.2	3.2135	6.8729	<200A
sum		5	



- Relatively small power converters up to 200 A, and thin cables (325 sq) are OK to drive four crab + chromatic sextupoles, up to 100% crab waist.

LER SLY crab waist sextupoles: cablings & tests

- Power converters: tested by Jan. 23.



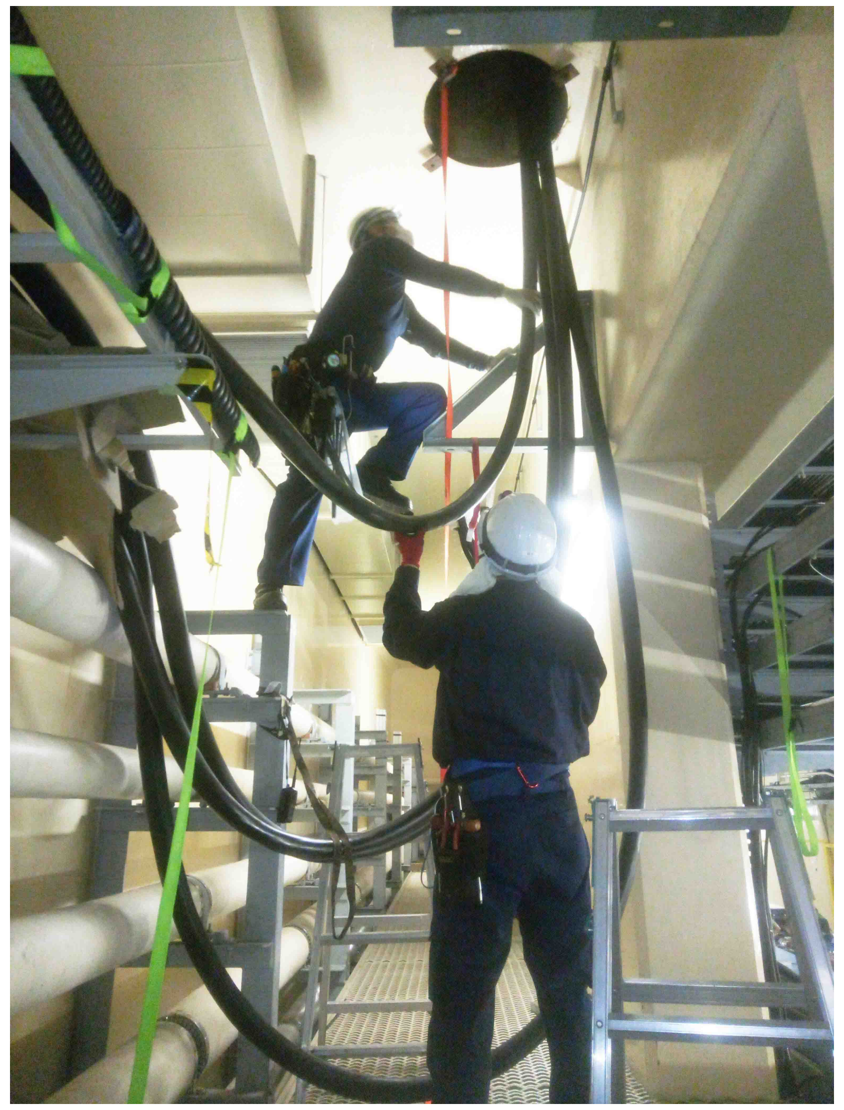
Polarity check by clamp meter & hole probe.


Installed new circuit breakers, on Jan. 7.

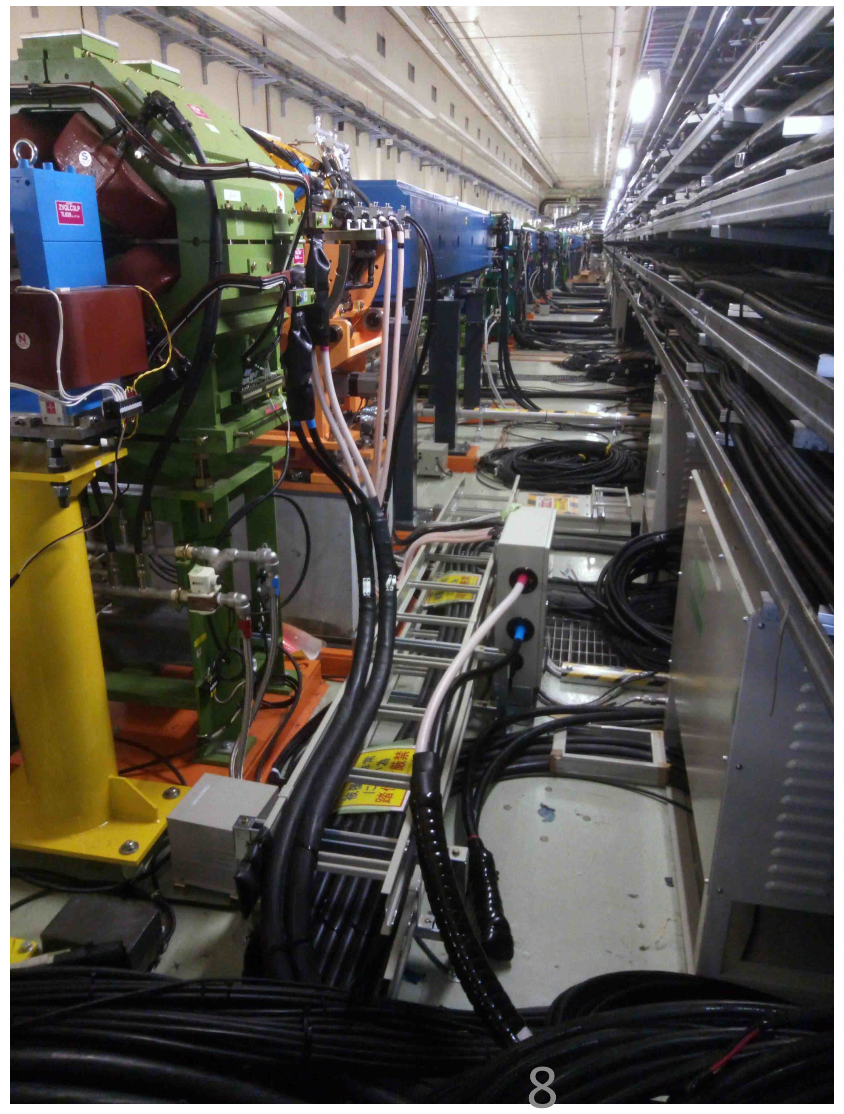
via T. Oki

LER SLY crab waist sextupoles: cablings & tests

- 325sq-2c 4 cables laid from Dec. 23 through Jan. 10. Scaffolds removed Jan. 15.

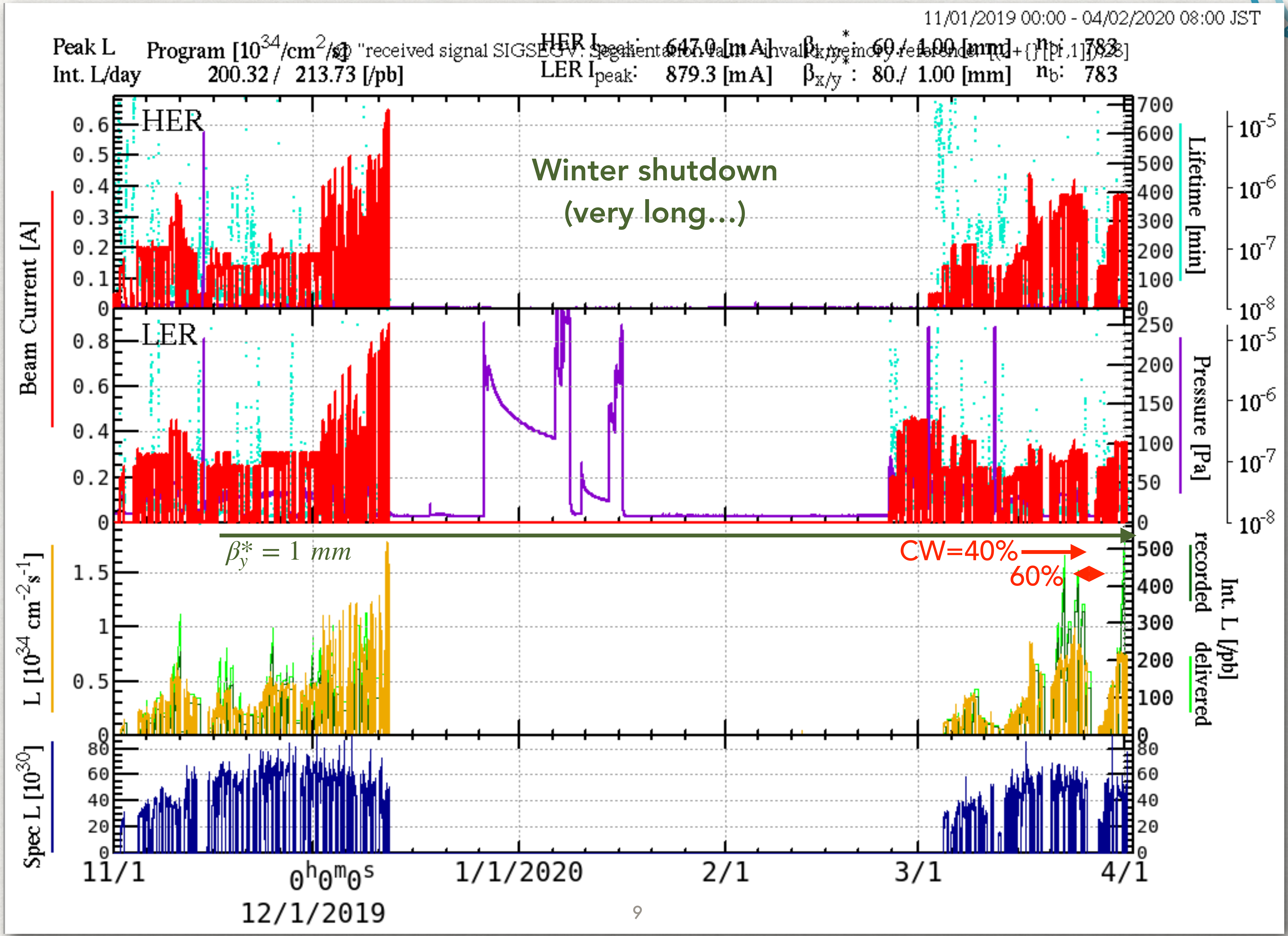





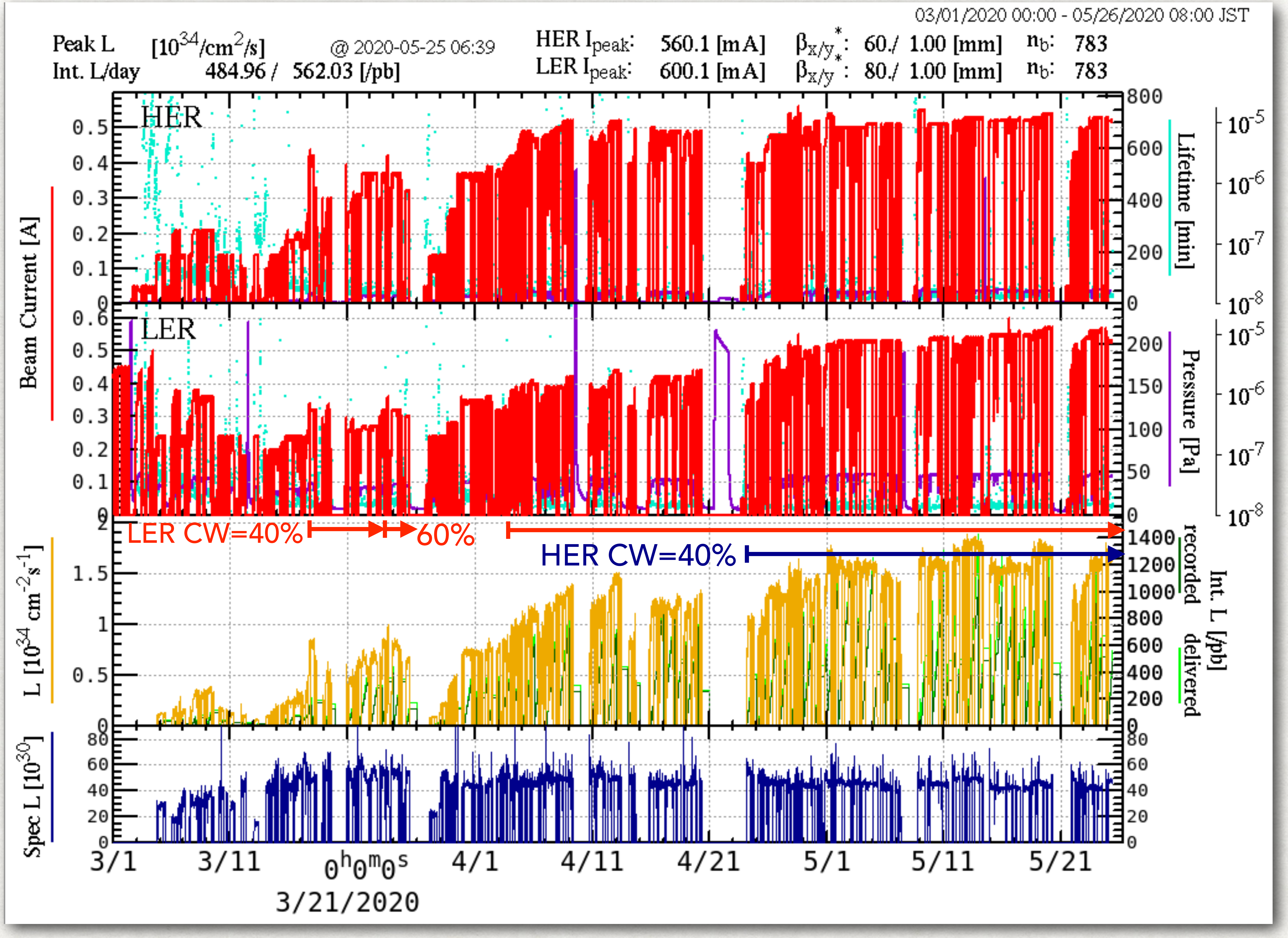



via T. Oki

SuperKEKB since Nov. 1, 2019 - Apr. 1, 2020



SuperKEKB since Mar. 1, 2020



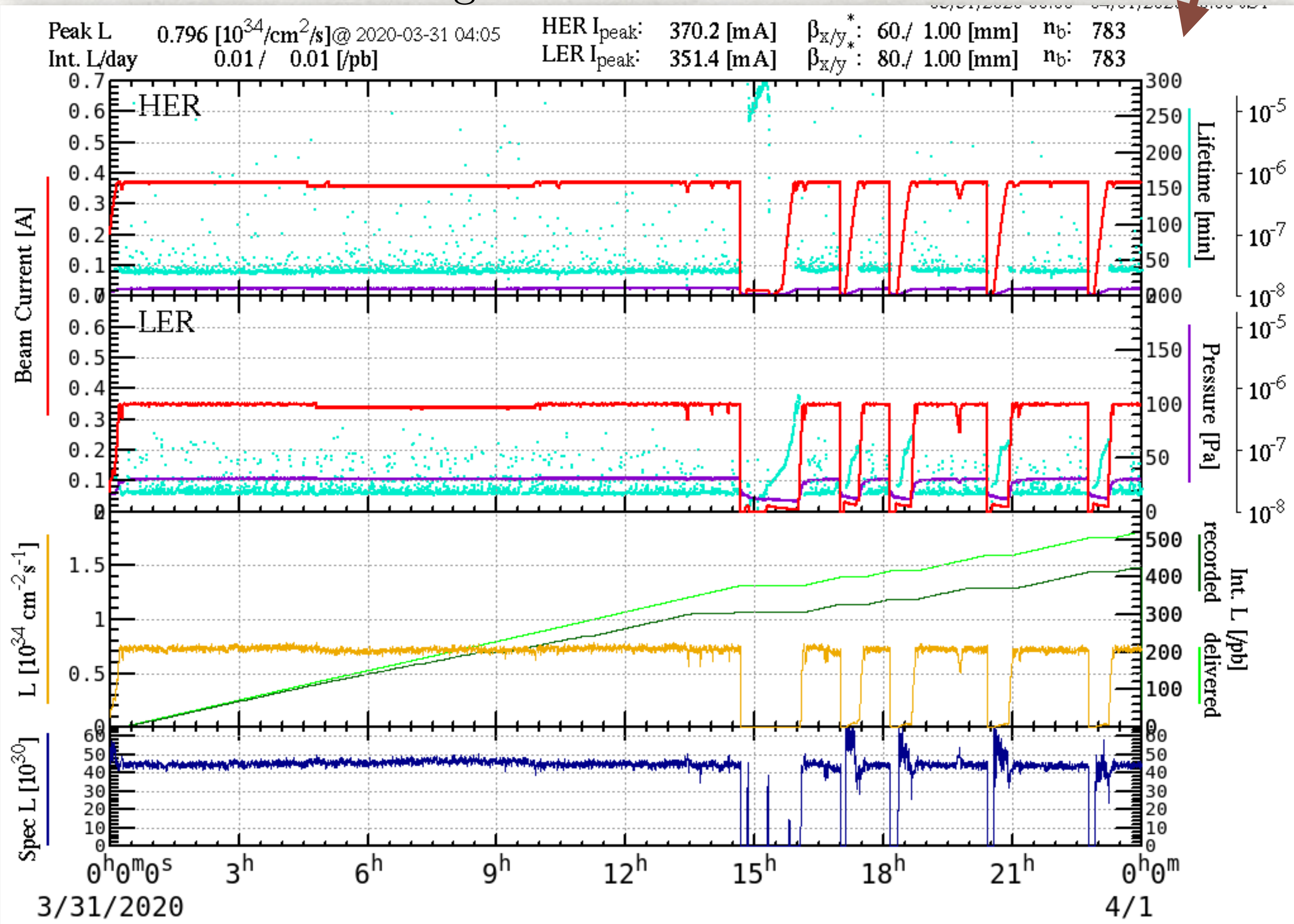
- Crab waist of one ring has made it possible to increase the beam current of *another ring*.

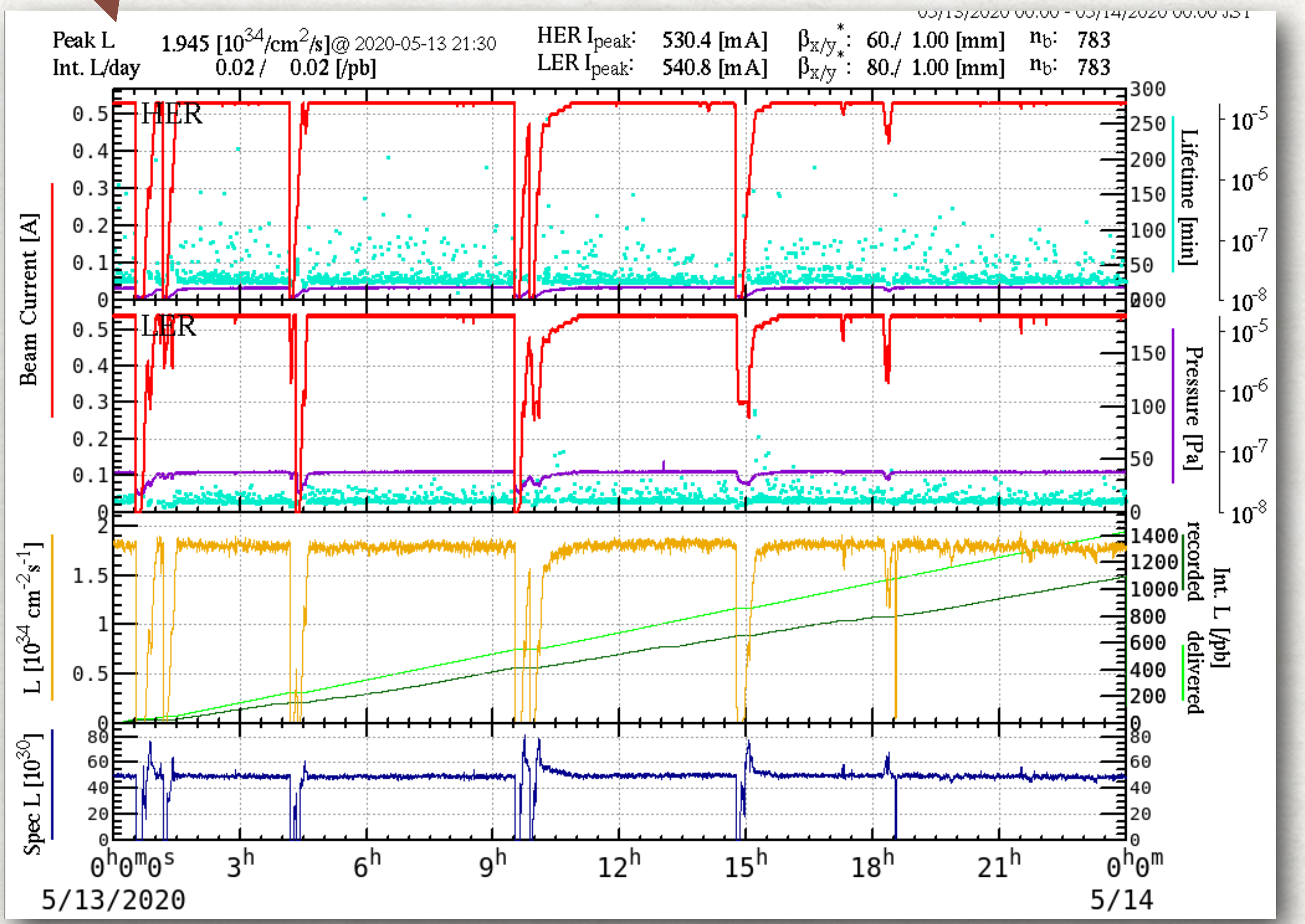
Luminosity performance by the Crab Waist

Date		Mar. 31, 2020 LER	Mar. 31, 2020 HER	May 13, 2020 LER	May 13, 2020 HER
Beam energy	GeV	4	7	4	7
Current/beam	A	0.35	0.37	0.54	0.53
Particles/bunch	10^{10}	2.2	2.3	3.4	3.3
β_x^*	mm	80	60	80	60
β_y^*	mm	1	1	1	1
σ_x^*	μm	13.0	16.6	13.0	16.6
σ_y^* single/colli.	μm	0.12/0.27	0.15/0.24	0.12/0.24	0.13/0.23
ξ_x		0.0028	0.0014	0.0043	0.0021
ξ_y [a]		0.0262	0.0165	0.0413	0.0254
Bunches/ring		783			
Half crossing angle	mrad	41.5			
Crab waist LER/HER	%	0	0	60	40
Luminosity	nb/s	8.0		19.2	

[a] incl. hour glass

- The 60%/40% crab waists in the LER/HER has made possible to increase the stored current by 50% in both rings.
- ξ_y has been increased by 60% by the crab waist, in both rings.
- Luminosity was more than doubled.

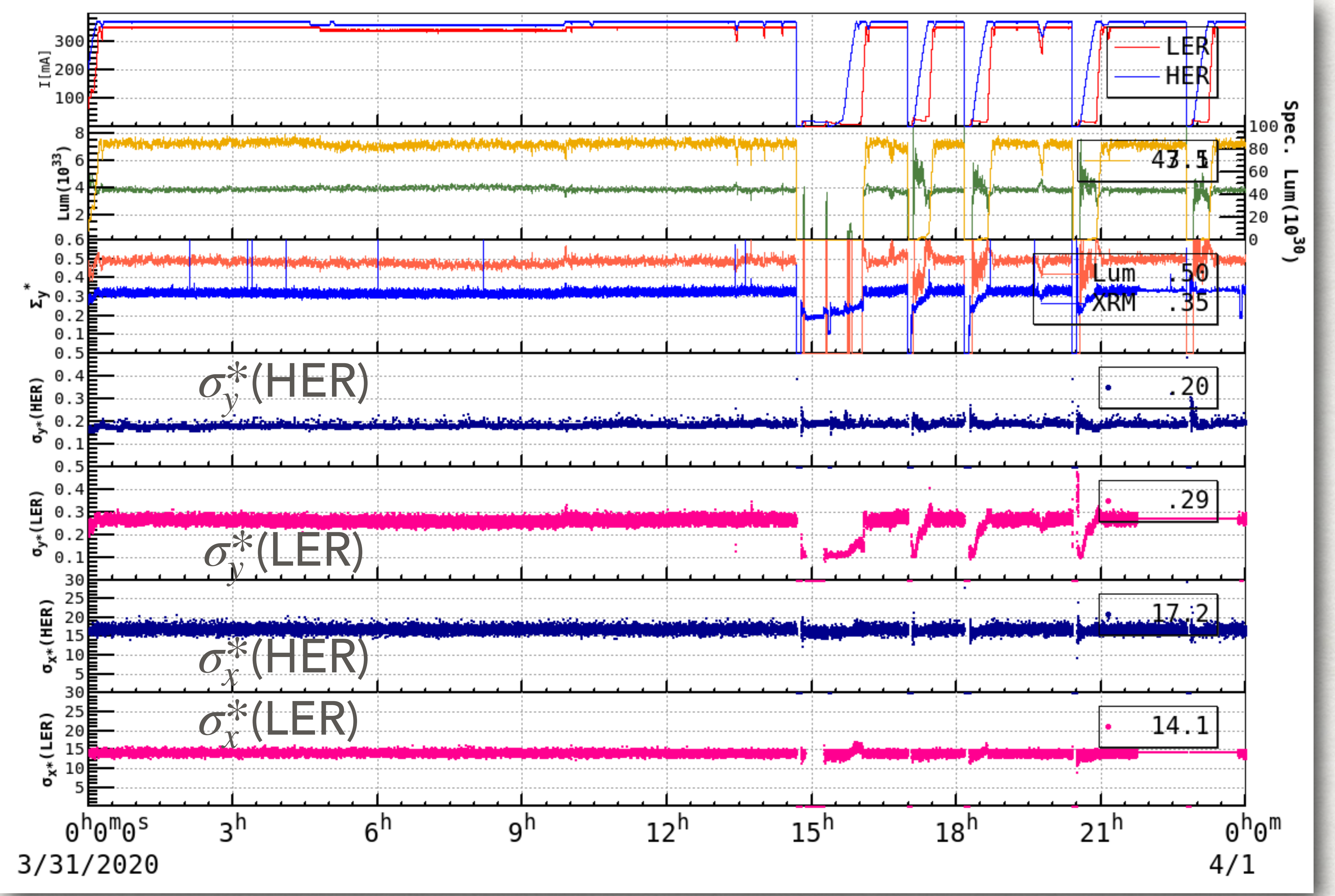




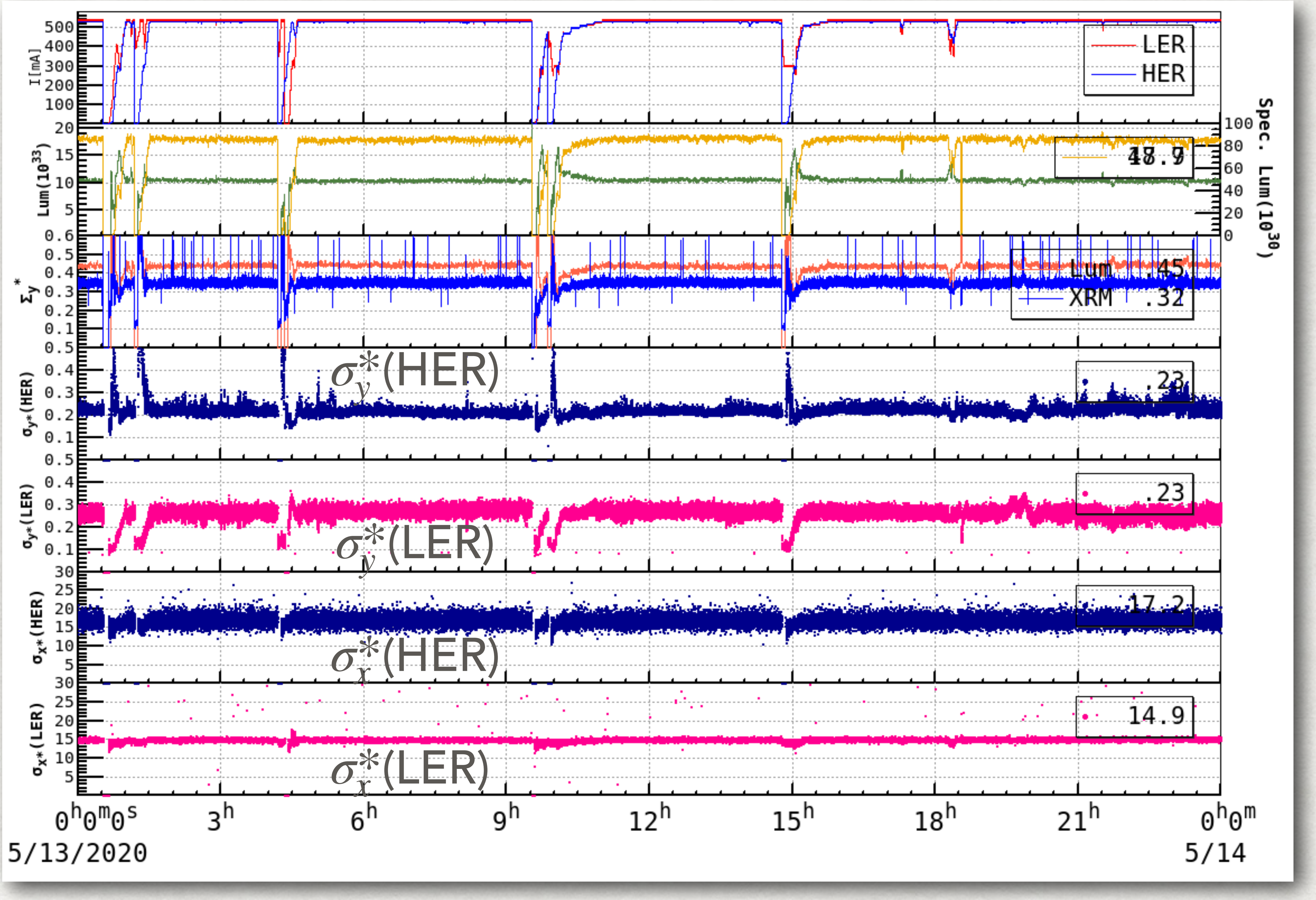
May 25, K. Oide

Beam sizes

CW = 0%/0%

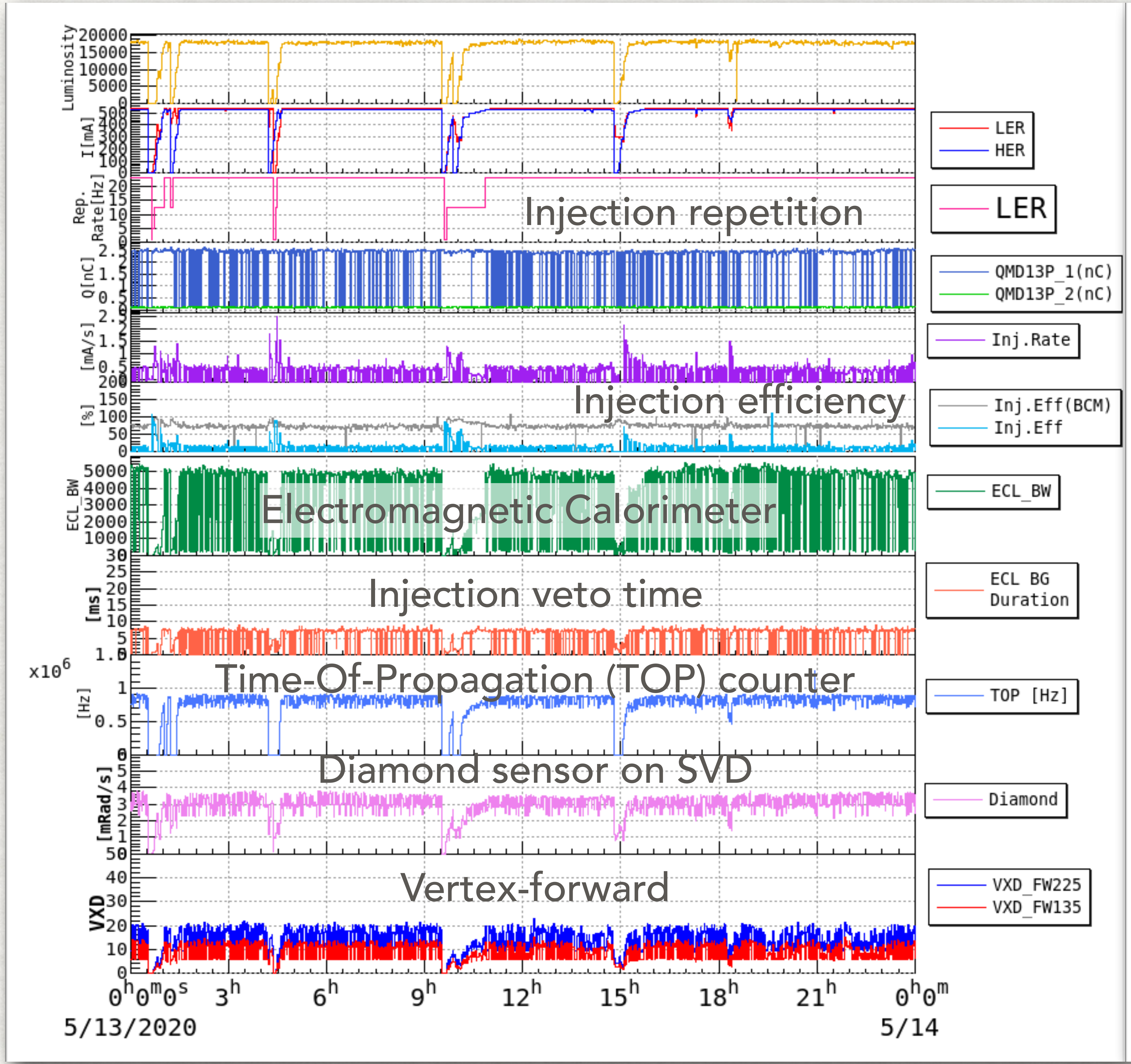


CW = 60%/40%

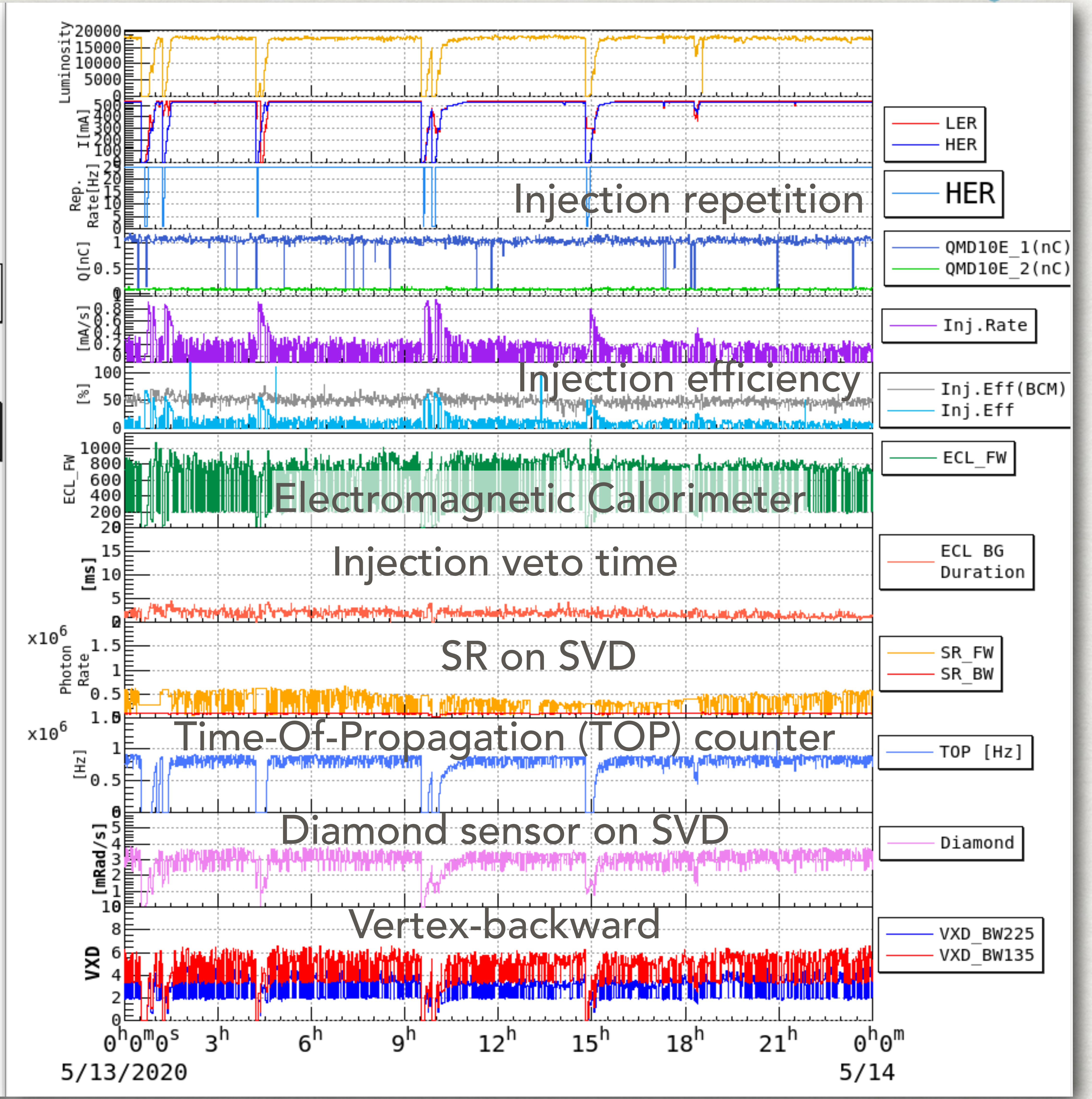


Belle II Backgrounds on the best day

LER



HER



Issues & further improvements

- For this period of machine operation, the highest priority is put on accumulation of the luminosity of Belle II.
  - No drastic change of parameters, such as tune scan across resonance lines, are allowed. All tunings must be adiabatic.
- Belle-II backgrounds set limitations on beam current, collimation aperture, synchrotron radiation, etc.
  - Both stored beam (vacuum, Touschek) and injected beam (beam loss, SR) contribute to the background.

- To be tried in the near future:
  - Higher CW ratios.
  - Chromatic x-y coupling correction (ChCC) in the both rings.
    - By skew or rotating sextupoles (HER/LER).
  - Synchrotron injection in the HER.
  - Smaller β_y^*.

$\varepsilon_{y0}/\varepsilon_y$ LER tune servey with misalignment of sextupoles

SuperKEKB

CW = 0%

$2\nu_x + 2\nu_z = N$ $2\nu_x + 3\nu_z = N$ "Ohnishi" resonance

CW = 40%

LER tune survey with misalignment of sextupoles

- Method:
  - Randomly put skew quads on SD* sextupoles in the arc, to achieve $\varepsilon_y/\varepsilon_x = 1\,\%$ at each tune.
  - The couplings and dispersions are kept zero at the IP and the Fuji straight section.
  - Weak-strong beam-beam simulation with lattice (BBWS/SAD).
  - Synchrotron radiation is emitted at each element with realistic spectra.
  - Tested for 8 random number seeds for misalignment.

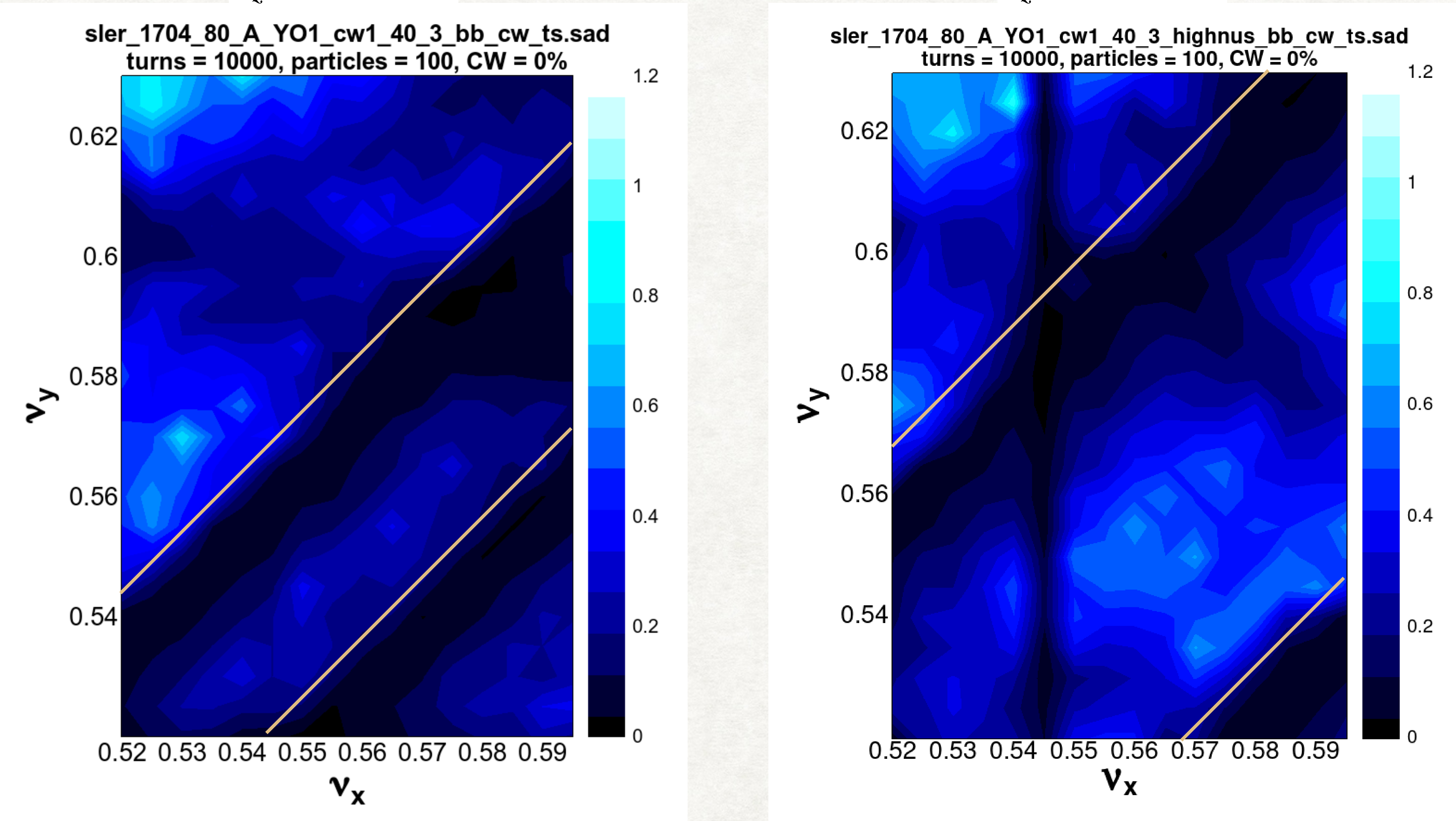
- Results:
  - The blowup of the vertical emittance strongly depends on the random number for misalignment.
  - Crab waist is always positive even at 40%.
  - Some resonance lines such as "Ohnishi" $2\nu_x + 3\nu_z = N$ become visible by the misalignments.
  - It is difficult to predict the blowup in the SuperKEKB exactly, unless we know the actual machine errors.

Synchrotron sidebands of the main coupling resonance:

$$\nu_x - \nu_y \pm \nu_z = N$$

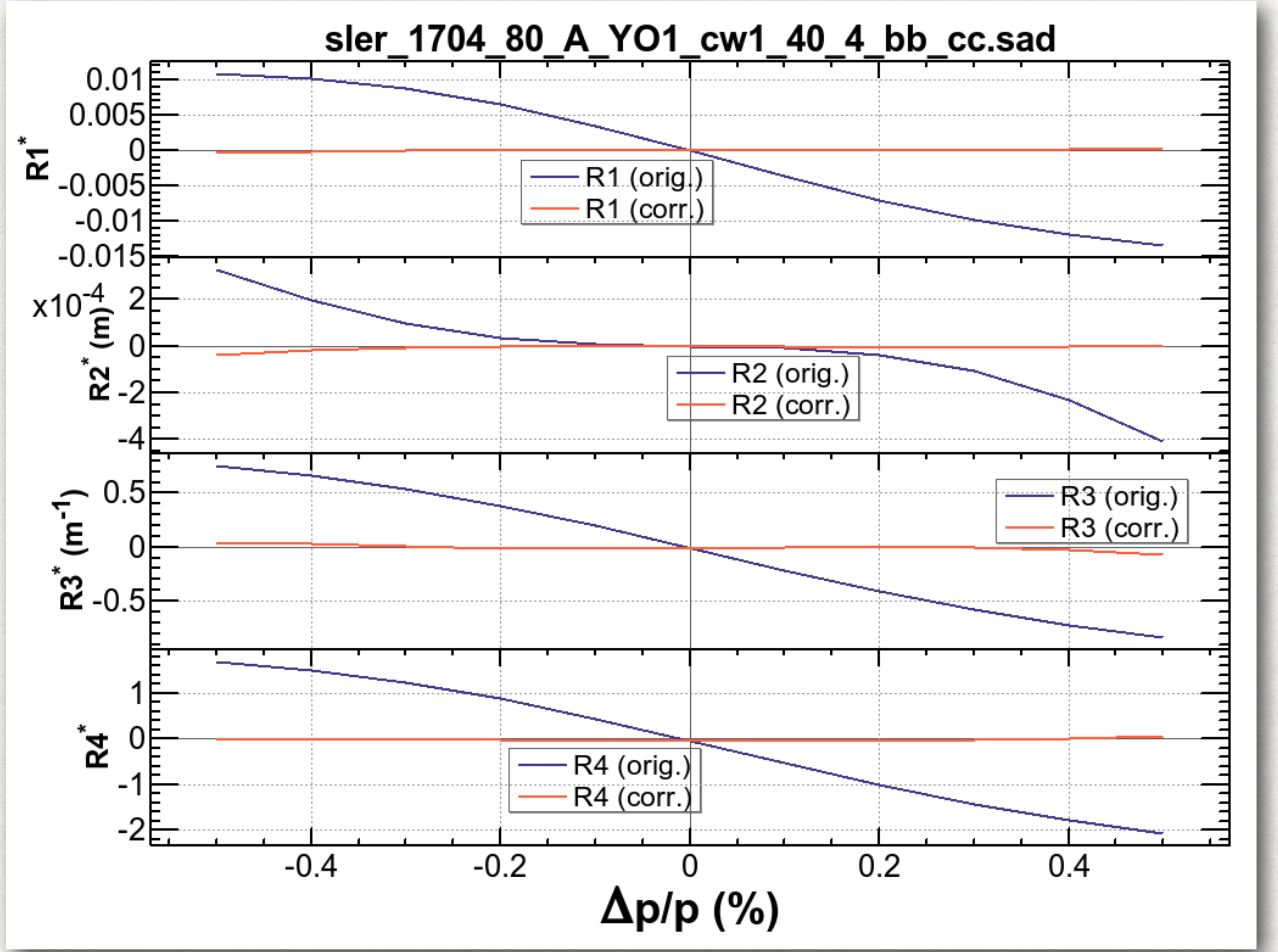
$\varepsilon_{y0}/\varepsilon_y$

$\nu_z = -0.0235$ $\nu_z = -0.0470$



- The dark area is right below the synchrotron sidebands $\nu_x - \nu_y \pm \nu_z = N$: They separate to each other by doubling the synchrotron tune.
- Thus the source of the resonance is the chromatic x-y coupling, which is completely removed by separated compensation solenoids at the IP.

LER chromatic x-y coupling correction (CC)



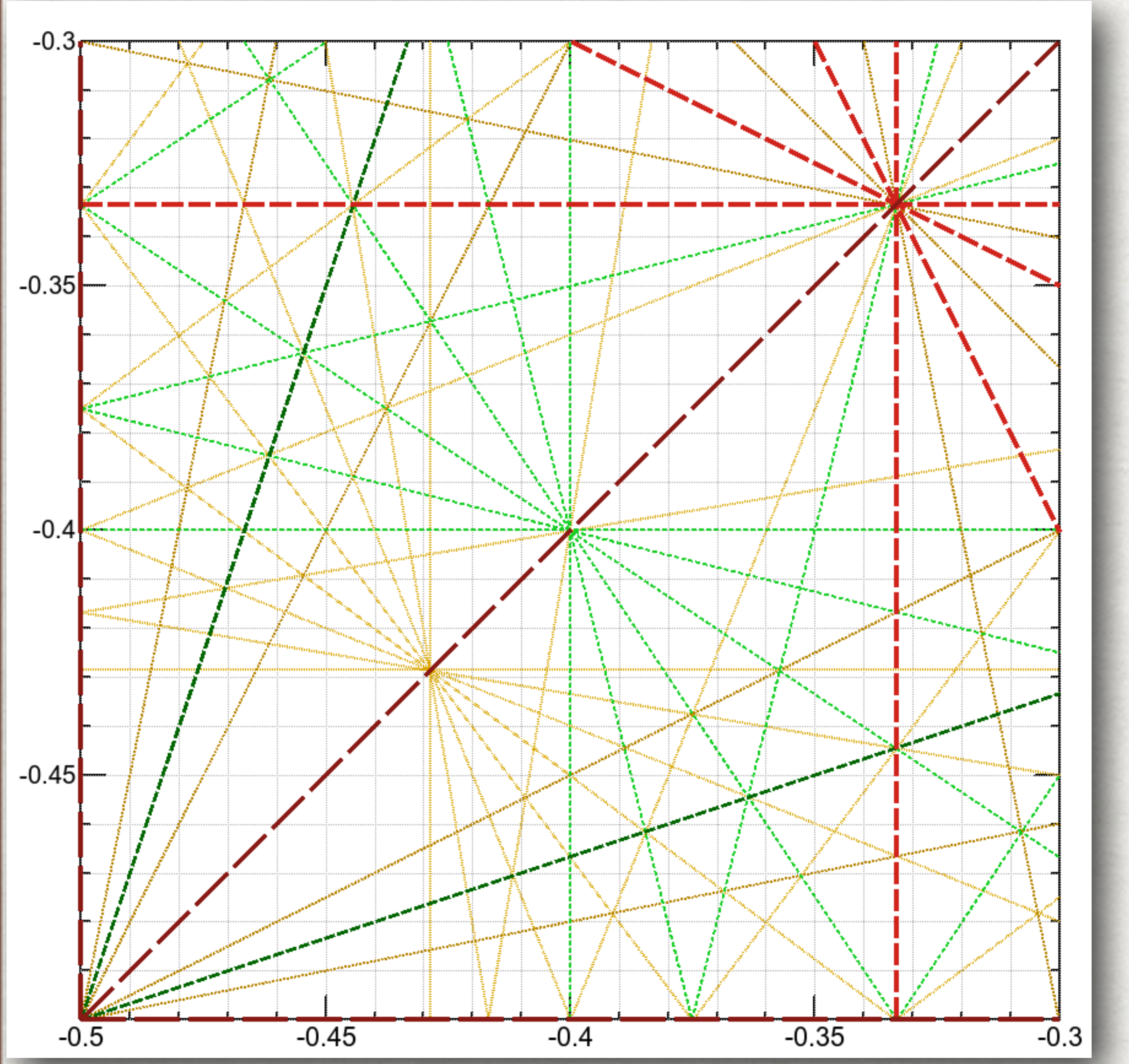
Sext	K2(m^-2)	SK2(m^-2)	ROTATE(deg)
SF6TRP	1.8170	-.7684	-7.6408
SD5TRP	-4.0138	-.2411	1.1460
SF4TRP	.9778	.1747	3.3772
SD3TRP	-.9209	-.2147	4.3757
SLXTRP	.2454	.3231	17.5948
SLYTRP2	2.1737	-.2574	-2.2511
SLYTRP1	2.1737	-.2574	-2.2511
SLYTLP1	2.4909	.1041	.7978
SLYTLP2	2.4909	.1041	.7978
SLXTLP	.6553	.1089	3.1459
SD3TLP	-.2219	.0616	-5.1710
SF4TLP	2.6047	.1633	1.1960
SD5TLP	-4.9820	.3716	-1.4220
SF6TLP	1.2915	-.1921	-2.8198

- The x-y coupling coefficients R1-R4 are fit to zero at the IP and Fuji, within ±0.3%.
- All rotating sextupoles around the IR are used.

LER tune survey

$\varepsilon_{y0}/\varepsilon_y$

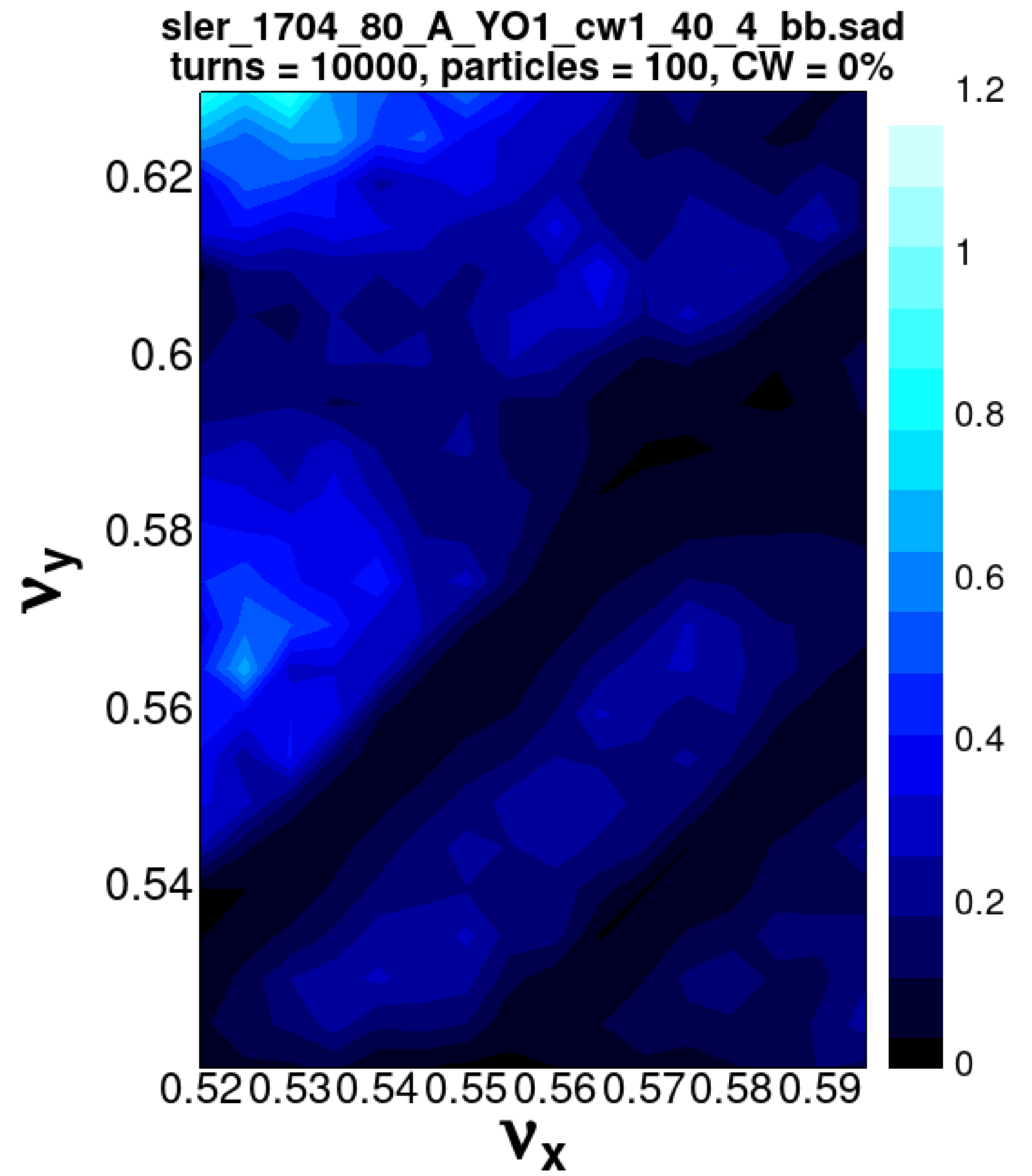
CW = 0%

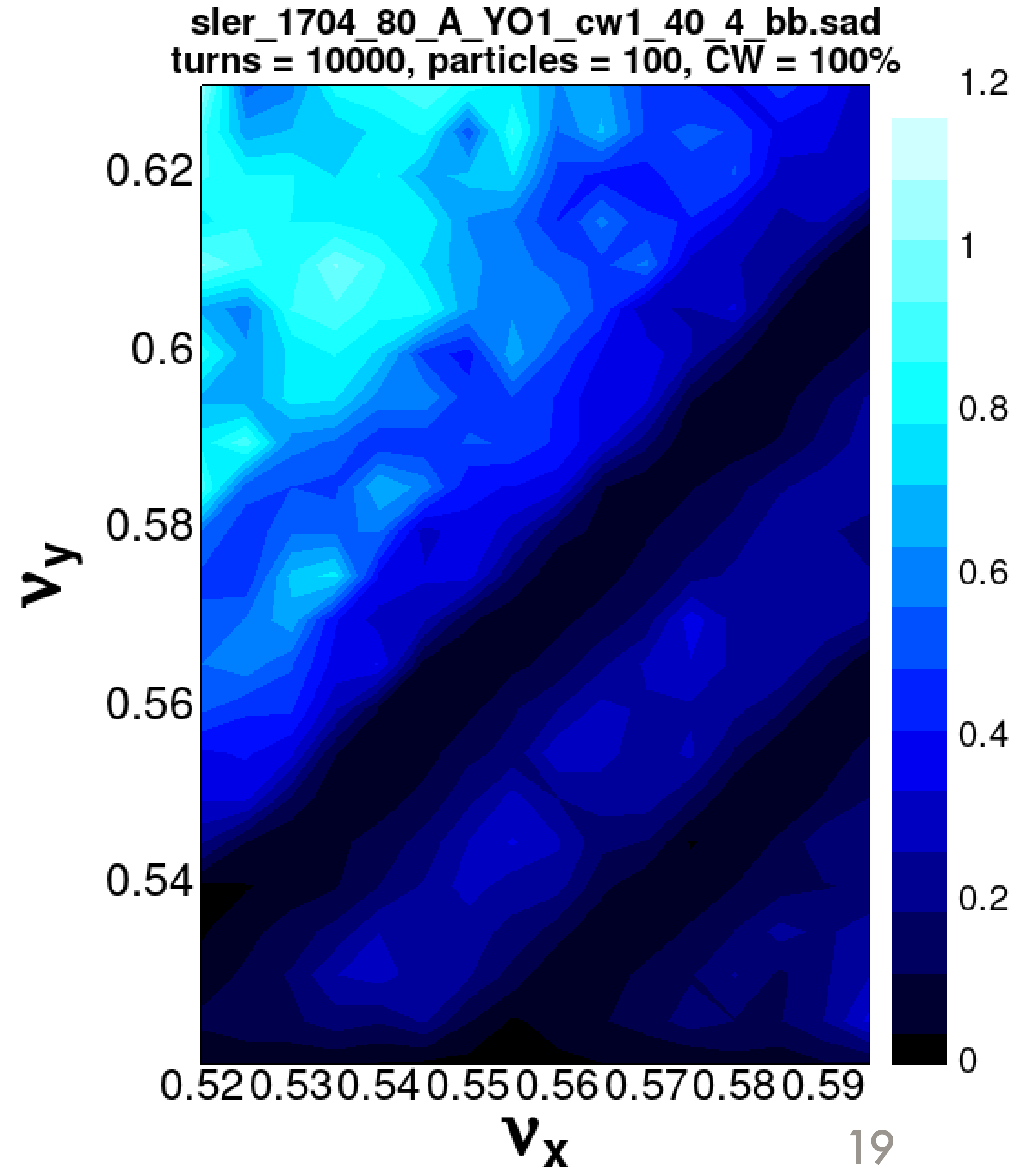


CW = 100%

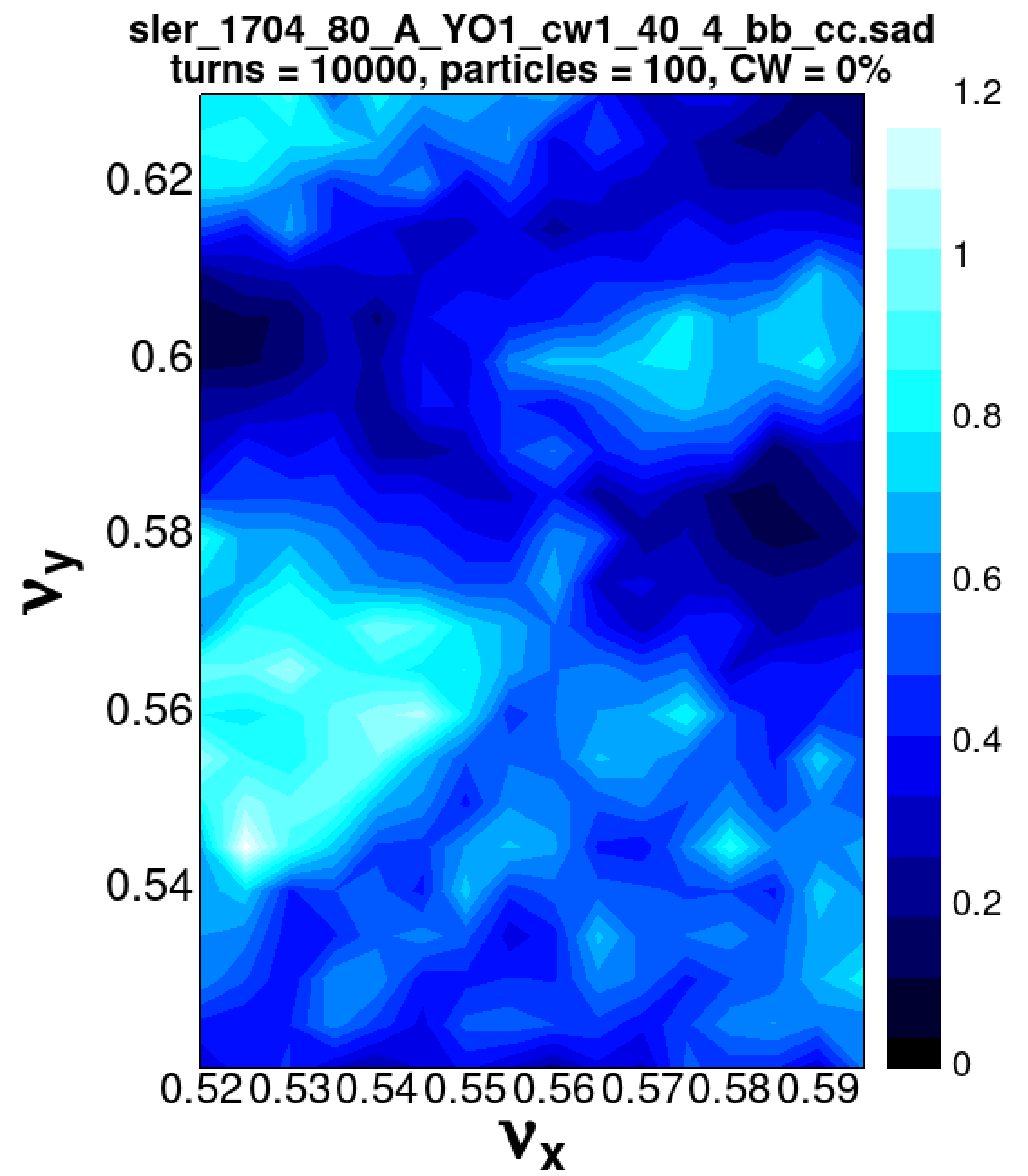
- Sextupoles are not re-optimized at each point.

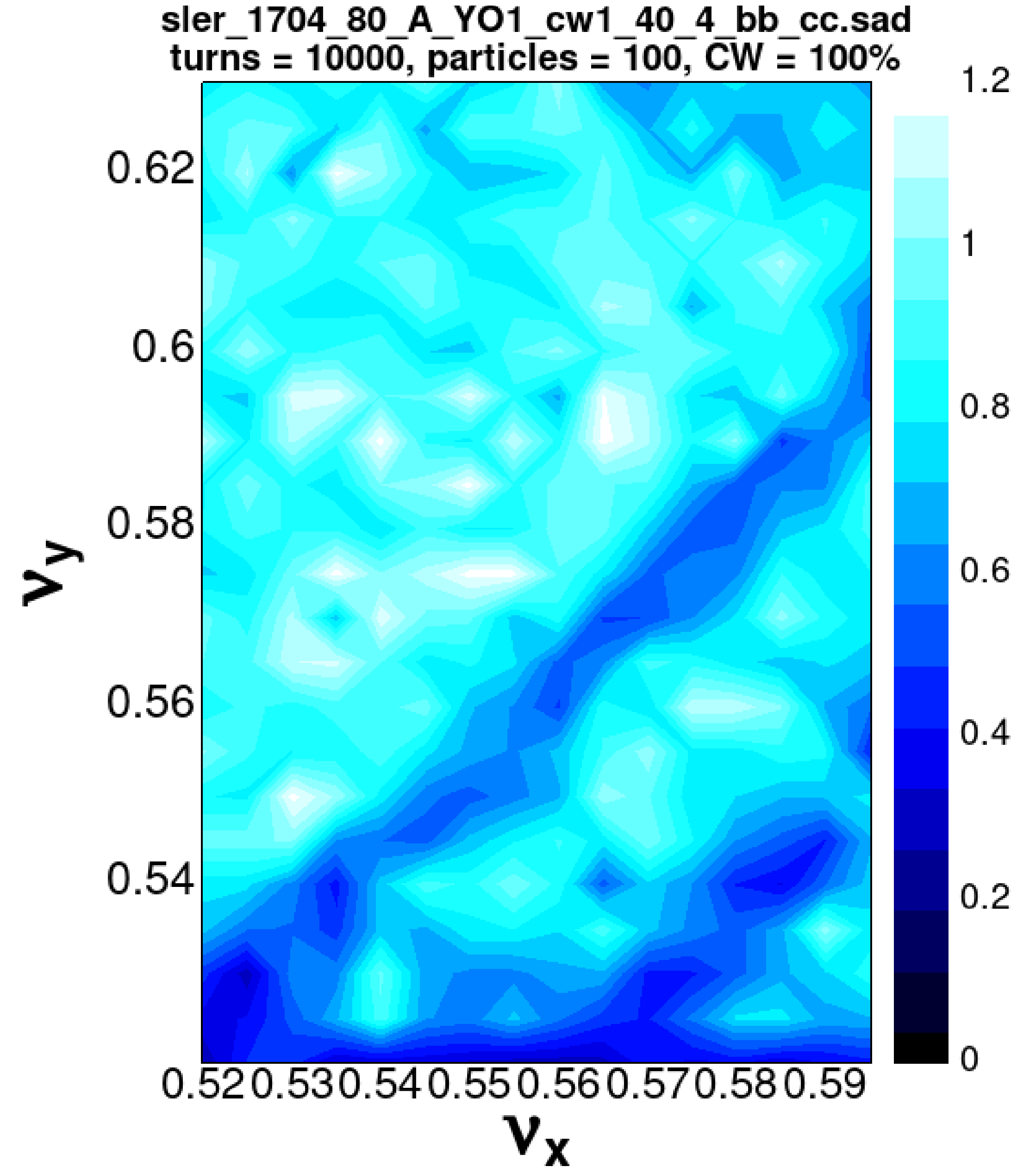
Original (SK2=0)



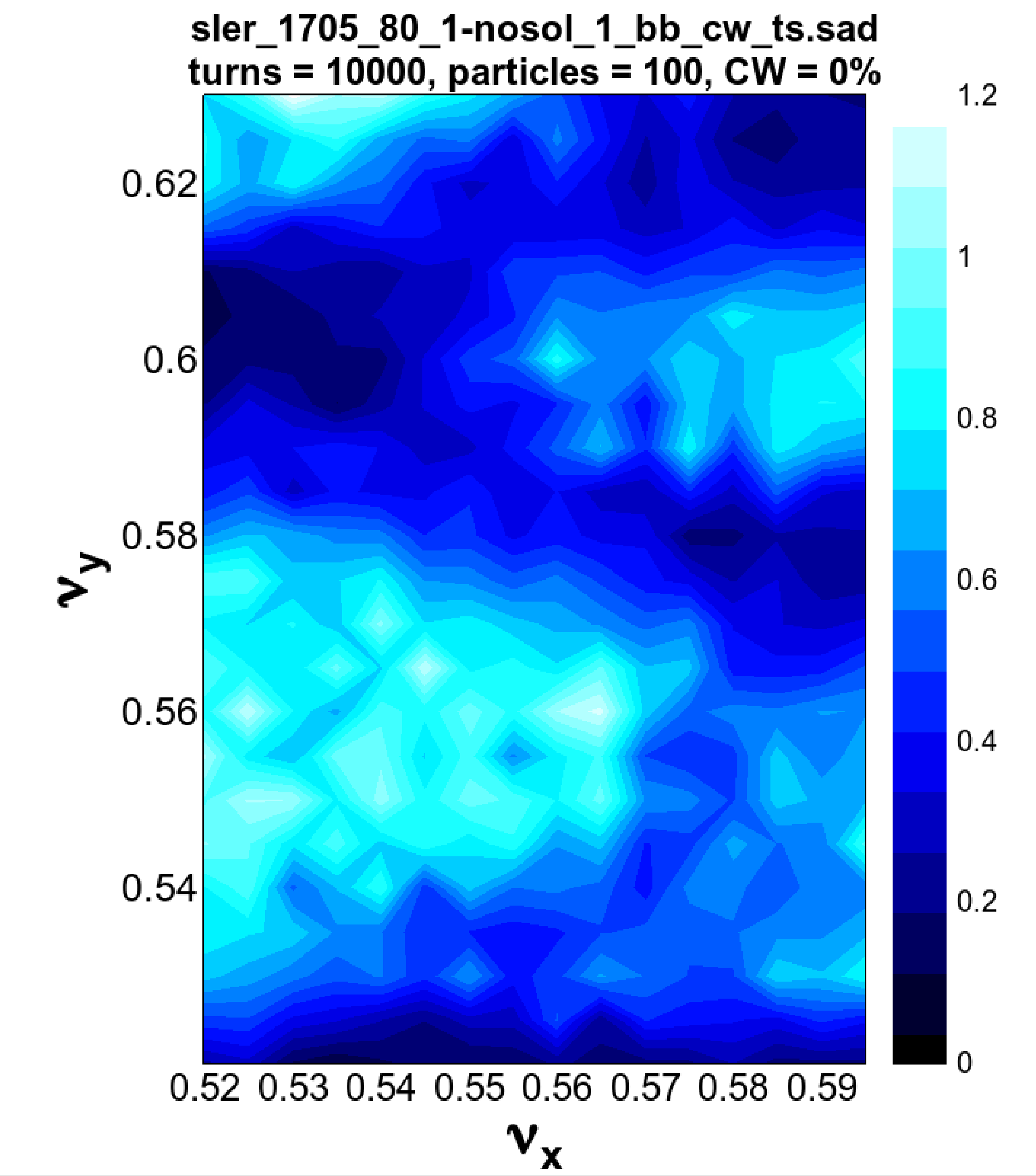


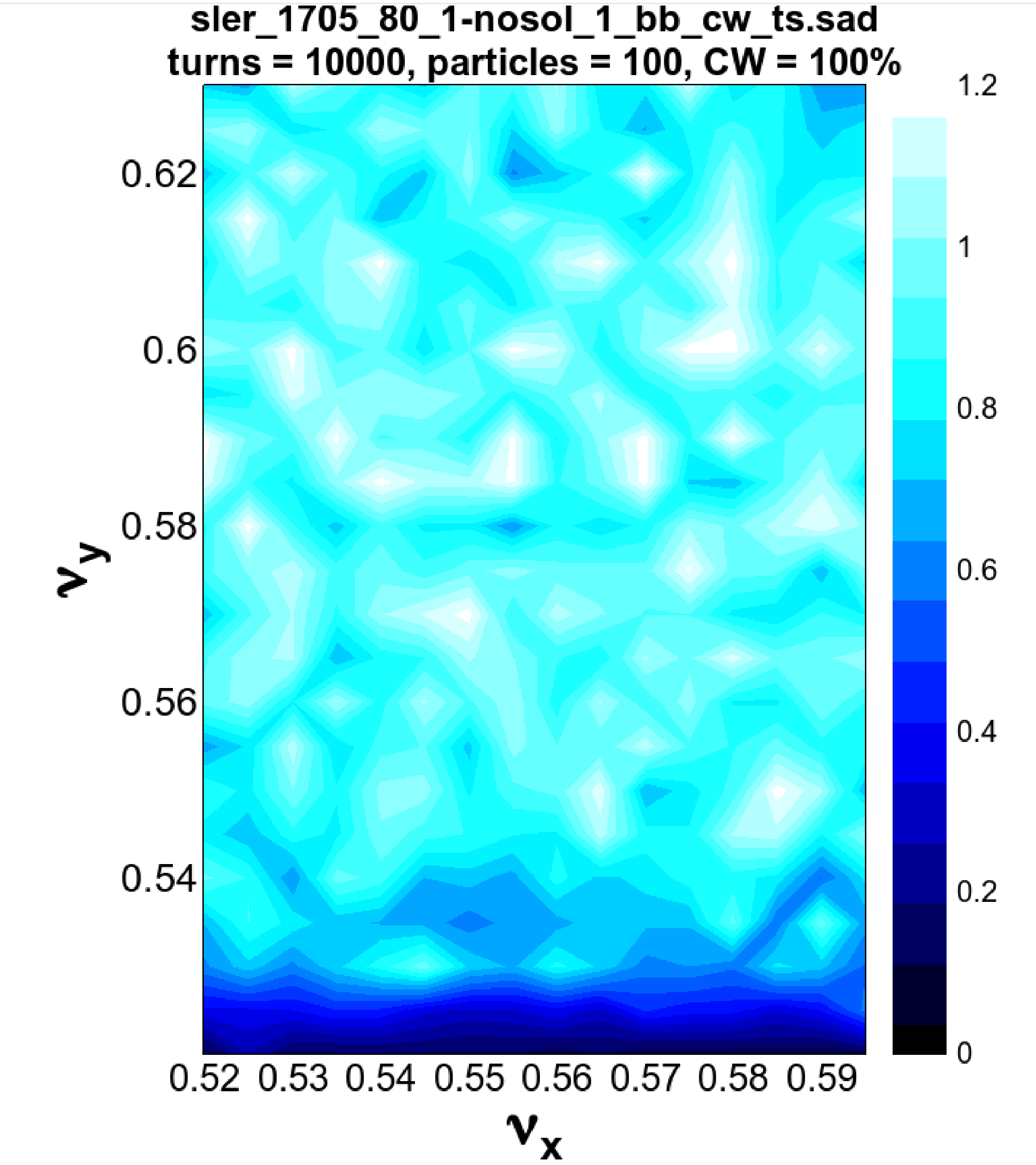
Chromatic coupling corr.





No solenoid lattice





Crab waist & chromatic coupling

- Both crab-waist and chromatic x-y coupling correction are effective to suppress the beam blowup. They work differently, depending on the tune working point.

- Both crab-waist and the chromatic coupling correction should be tried in this run (ASAP). They will open the space up to 10^{35} with the parameters presented here.

- Many things will be learnt by two beam studies to determine the future direction.

- Simulations with future parameters, ie.,smaller β^* and higher bunch charge, will be tried to access the design luminosity.

$\varepsilon_{y0}/\varepsilon_y$

HER tune survey with crab waist

CW = 0% | CW = 20% | CW = 40% | CW = 60% | CW = 80% | CW = 100%

- Base optics: sher_5780_60_1_A_YO3 (via Y. Ohnishi).
- $\beta^*_{x,y} = (60,1)$ mm. $\sigma^*_y = 170$ nm, which is close to the single beam one in these runs.
- Sextpoles are optimized at (0.535,0.585) (★), and kept nearly unchanged for each tune.
- Beam-beam + lattice (BBWS/SAD), no errors. SR is emitted turn by turn.
- **Crab waist looks also very effective for the HER.**

Thank you!