Phase I commissioning of the SuperKEKB rings

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On behalf of SuperKEKB Commissioning Group

General seminar, LNF INFN, Frascati, Italy

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Outline

- Introduction
- Phase I commissioning
  - Vacuum scrubbing
  - Low emittance tuning
  - Beam background
  - Electron cloud
  - Impedance
- Plan for Phase II and III commissioning
- Summary

Outline

- ➤ **Introduction**
- ➤ Phase I commissioning
  - Vacuum scrubbing
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  - Beam background
  - Electron cloud effects
  - Impedance
- ➤ Plan for Phase II and III commissioning
- ➤ Summary

1. Introduction

➤ Nano-beam scheme

- E (LER/HER): 3.5/8 ➟ 4/7 GeV
- β_y^* (LER/HER): 5.9/5.9 ➟ 0.27/0.3 mm
- I_{beam} (LER/HER): 1.7/1.4 ➟ 3.6/2.6 A
- ξ_y: 0.09 ➟ 0.09
- Crab waist: optional
- $\mathcal{L}$: 2.1 ➟ 80 $\times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

➤ Phase I

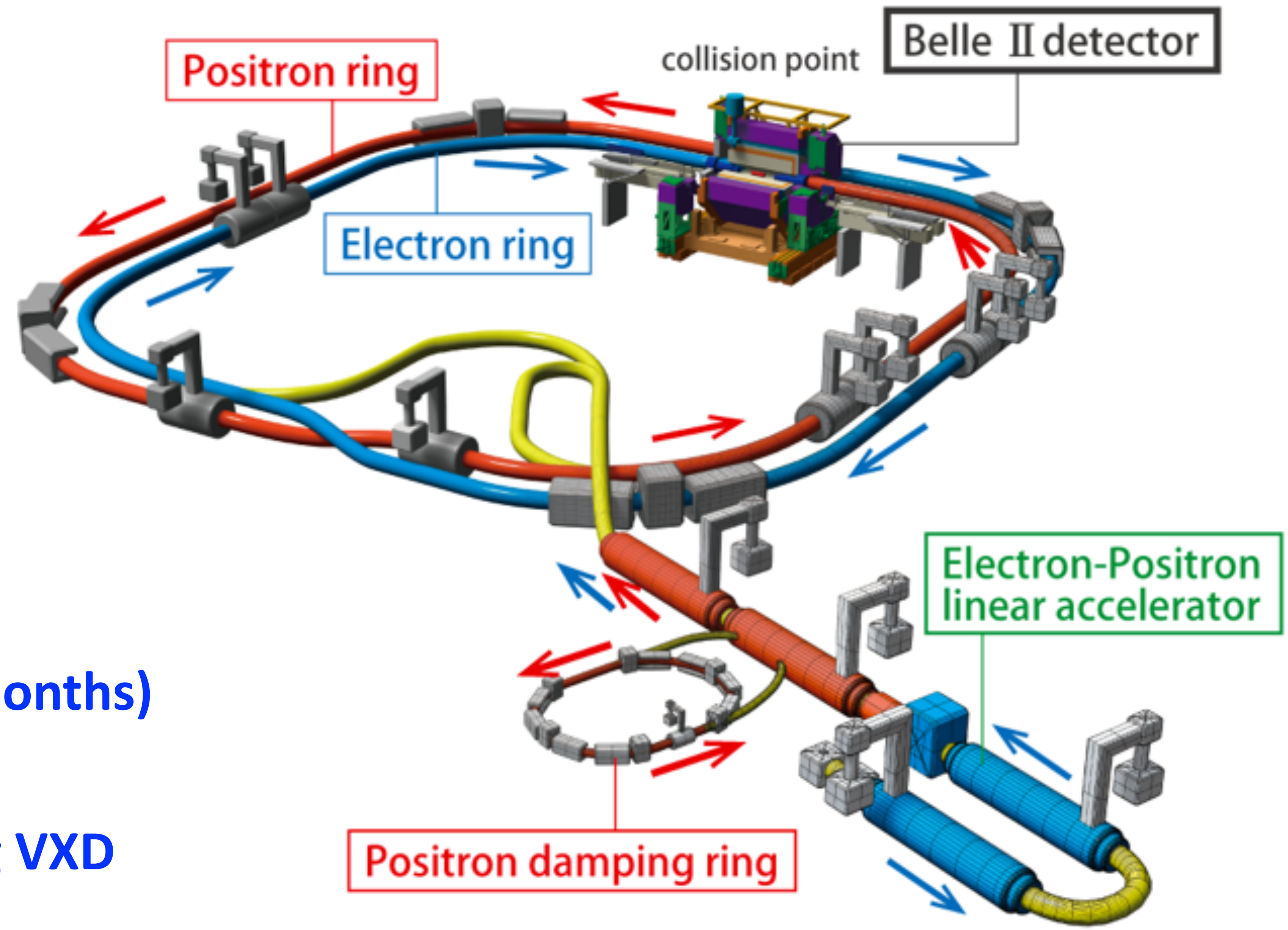
- w/o QCS and Belle-II
- Feb. - Jun., 2016

➤ Phase II

- w/ QCS and Belle-II
- w/o Vertex detector
- Around Nov. 2017 (~5 months)

➤ Phase III

- w/ Full Belle-II including VXD
- After summer of 2018



1. Introduction

➤ Machine parameters

Phase III (w/ IBS)

	LER	HER	Unit
E	4.000	7.007	GeV
I	3.6	2.6	A
n_b	2500		
C	3016.315		m
ε_x	3.2	4.6	nm
ε_y	8.64	12.9	pm
β_x^*	32	25	mm
β_y^*	270	300	μm
$2\phi_x$	83		mrad
α_p	3.19×10^{-4}	4.53×10^{-4}	
σ_δ	7.92×10^{-4}	6.37×10^{-4}	
V_{RF}	9.4	15.0	MV
σ_z	6	5	mm
ν_s	-0.0245	-0.0280	
ν_x	44.53	45.53	
ν_y	46.57	43.57	
U_0	1.76	2.43	MeV
τ_x	45.6	58.0	msec
ξ_x	0.0028	0.0012	
ξ_y	0.0881	0.0807	
L	8×10^{35}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Phase I (w/o IBS)

	LER	HER	Unit
E	4.000	7.007	GeV
I	1.01	0.87	A
n_b	1576		
ε_x	1.8	4.6	nm
α_p	2.45×10^{-4}	4.44×10^{-4}	
σ_δ	7.52×10^{-4}	6.30×10^{-4}	
V_{RF}	7.56	12.61	MV
σ_z	4.6	5.3	mm
ν_s	-0.0192	-0.0253	
ν_x	44.53	45.53	
ν_y	46.57	43.57	
U_0	1.76	2.43	MeV
τ_x	46	58	msec

Courtesy of Y. Ohnishi, NAPAC16

1. Introduction

➤ Tasks for Phase I commissioning

- Preparations
  - ➢ Hardware tunings with beam
  - ➢ Operation software tests with beam
- Vacuum scrubbing
- Low emittance tuning
  - ➢ Machine imperfections and countermeasures
  - ➢ Target: vertical emittance <10 pm
- Studies on intensity-dependent phenomena
  - ➢ Beam background measurement with Beast detector
  - ➢ Electron cloud effects
  - ➢ Impedance measurements
  - ➢ … …

➤ Experiences of KEKB benefit SuperKEKB

- Reuse/upgrade of KEKB hardwares and softwares
- Well developed commissioning strategy

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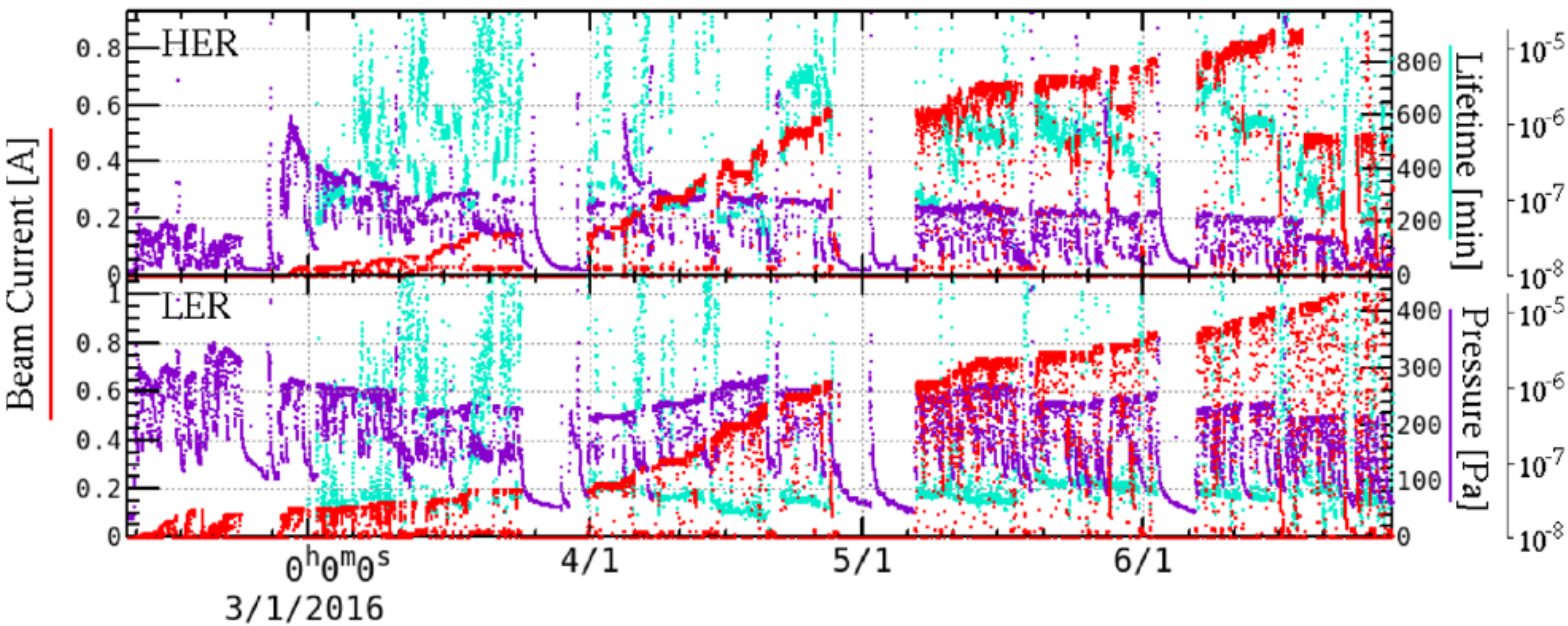
2. Vacuum scrubbing

➤ Early milestones

- Feb.1: Beam transport to BT => BT tuning
- Feb.8: Beam delivered to LER
- Feb.10: Beam stored in LER => LER tuning
- Feb.22: Beam delivered to HER
- Feb.26: Beam stored in HER => HER tuning

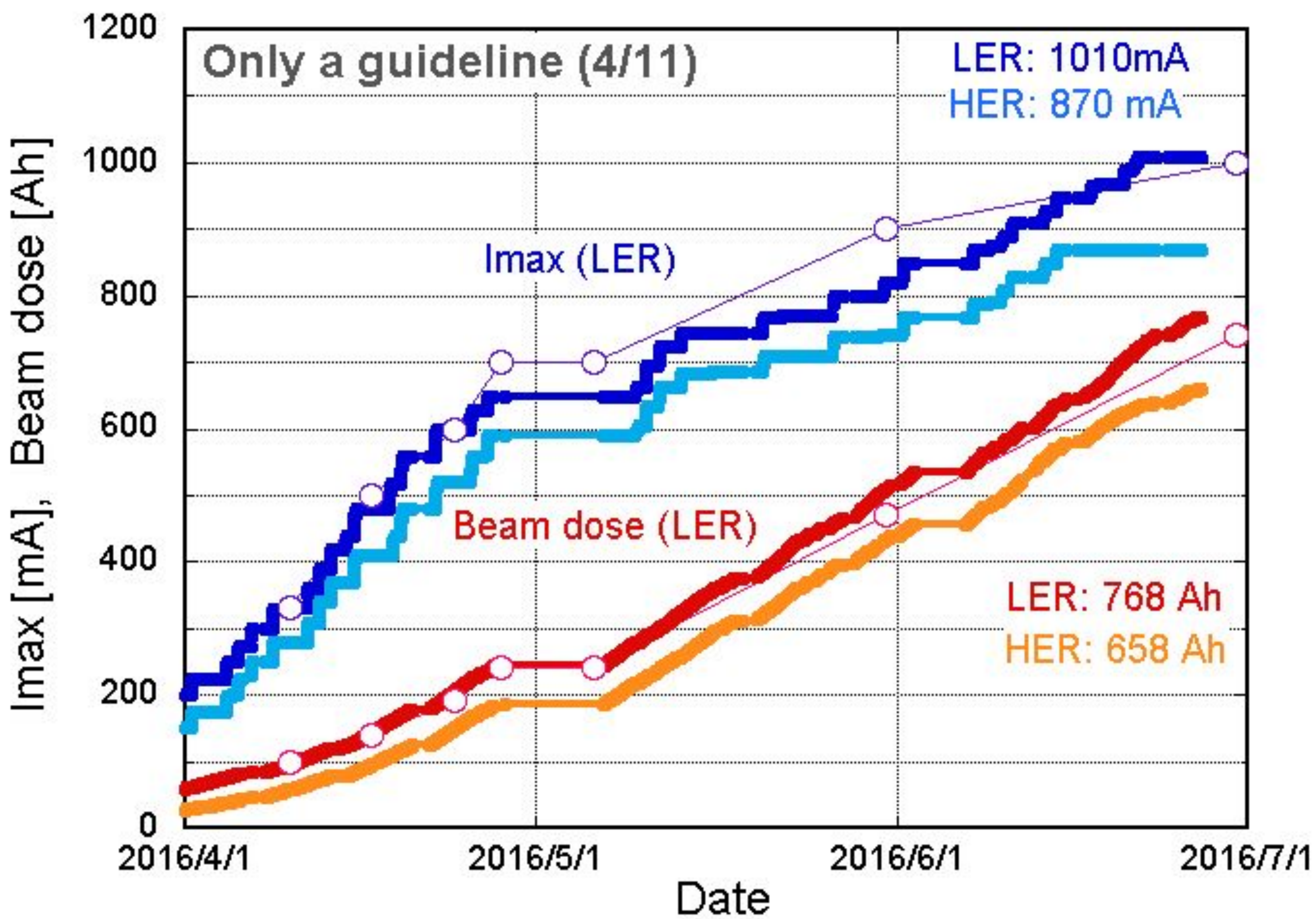


Courtesy of Y. Ohnishi, NAPAC16

2. Vacuum scrubbing

➤ After 3 months from start

- KEKB (LER/HER): ~300/~200 mA
- SuperKEKB (LER/HER): ~650/~590 mA
- KEKB experiences => Efficient commissioning, less hardware failures, …



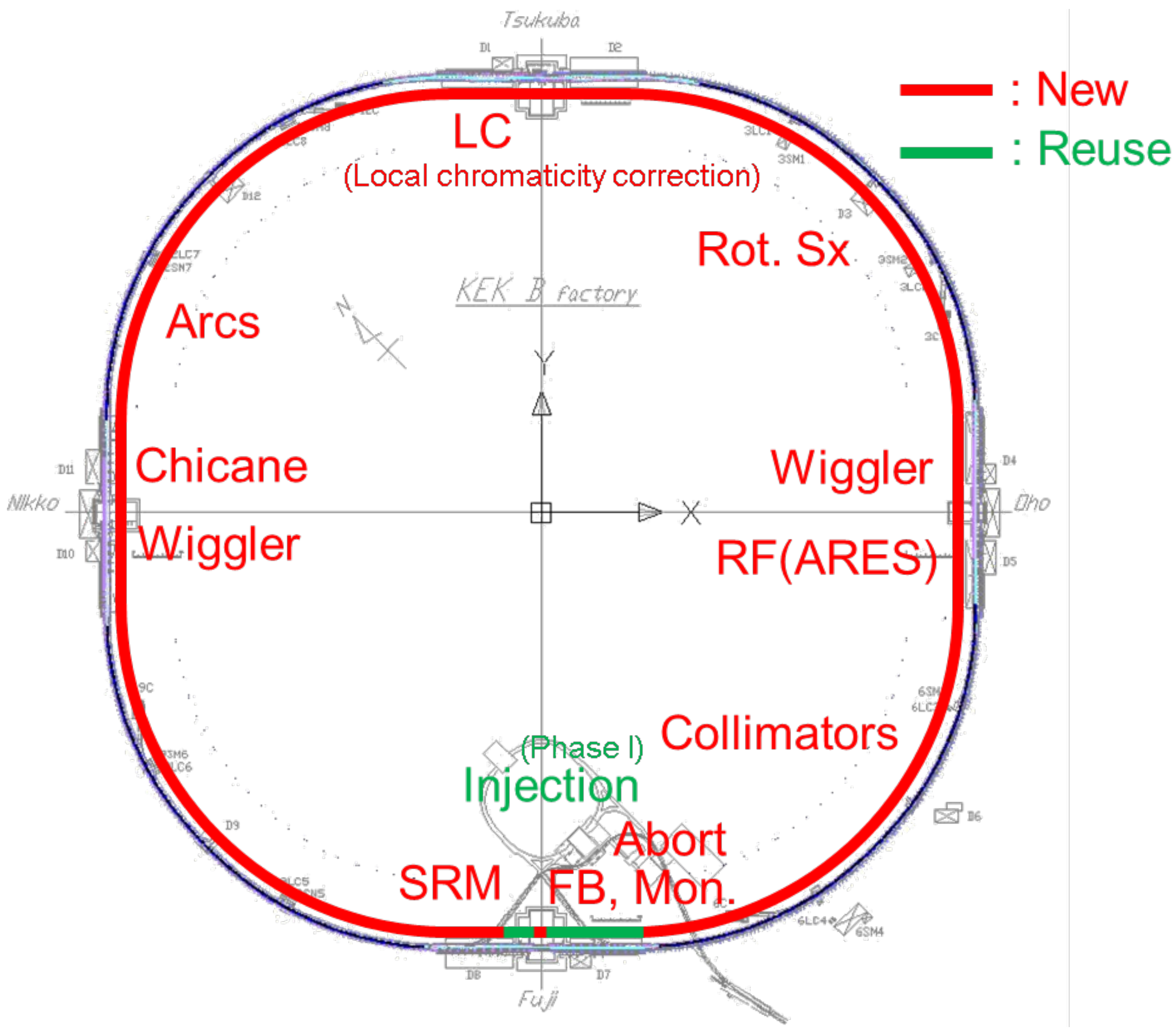
Courtesy of Y. Funakoshi

2. Vacuum scrubbing

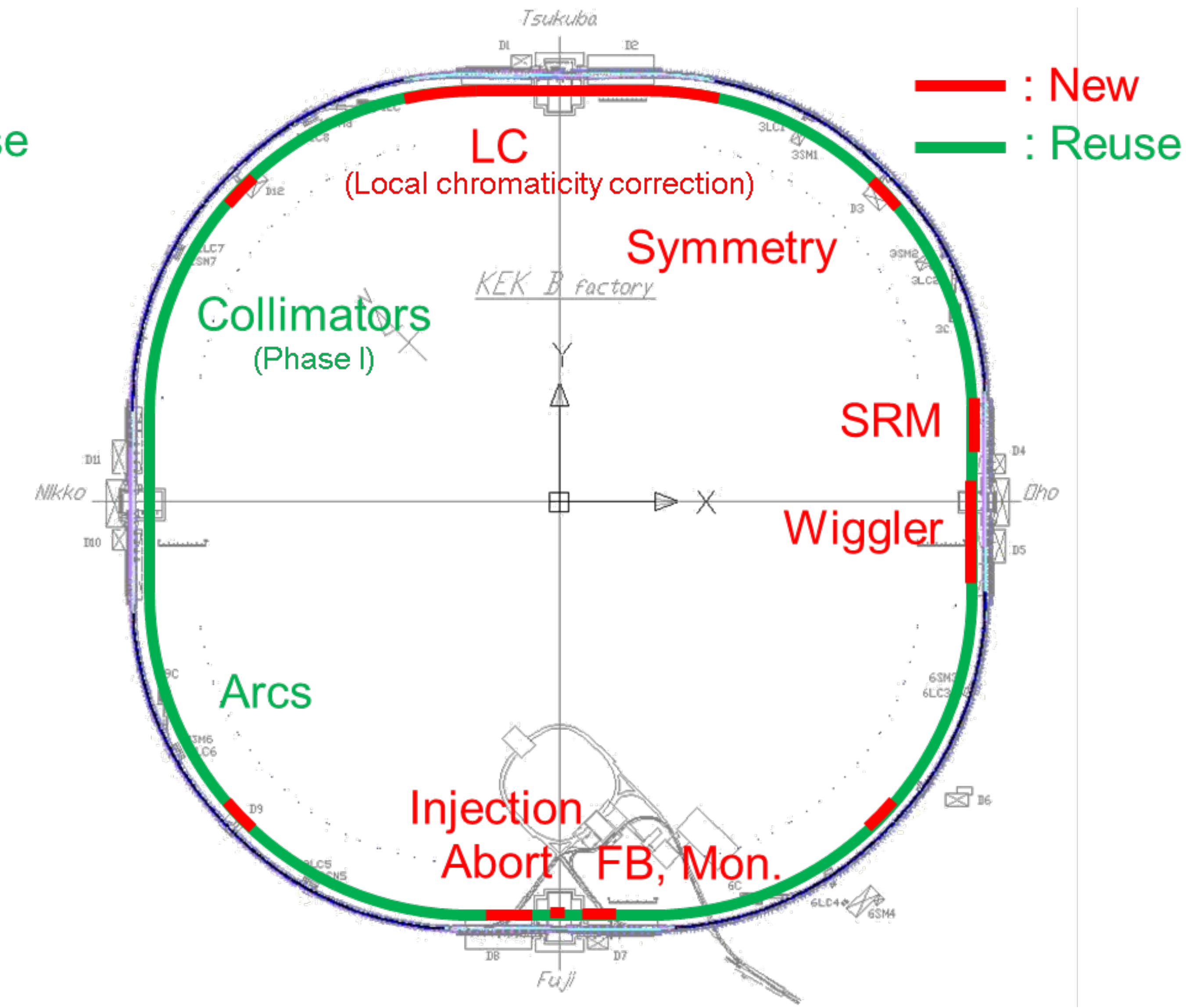
➤ Vacuum chambers

- **LER: ~93% renewed**
- **HER: ~82% reused**

LER



HER

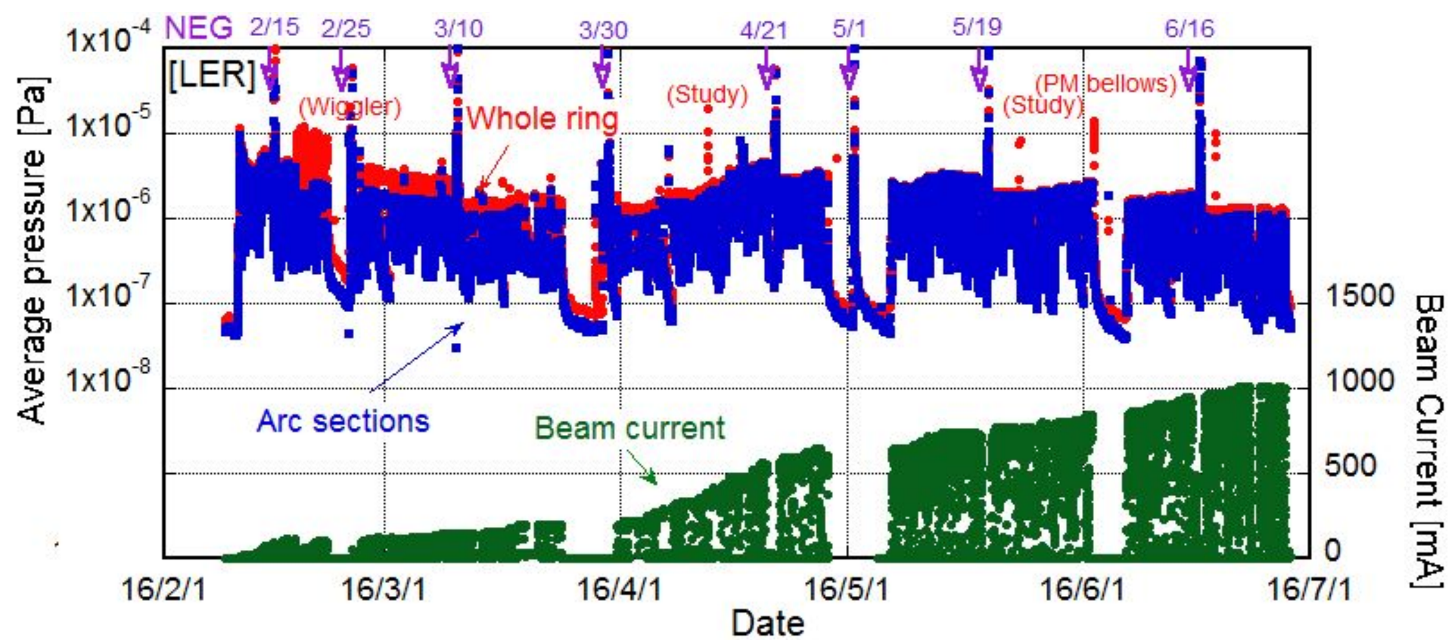


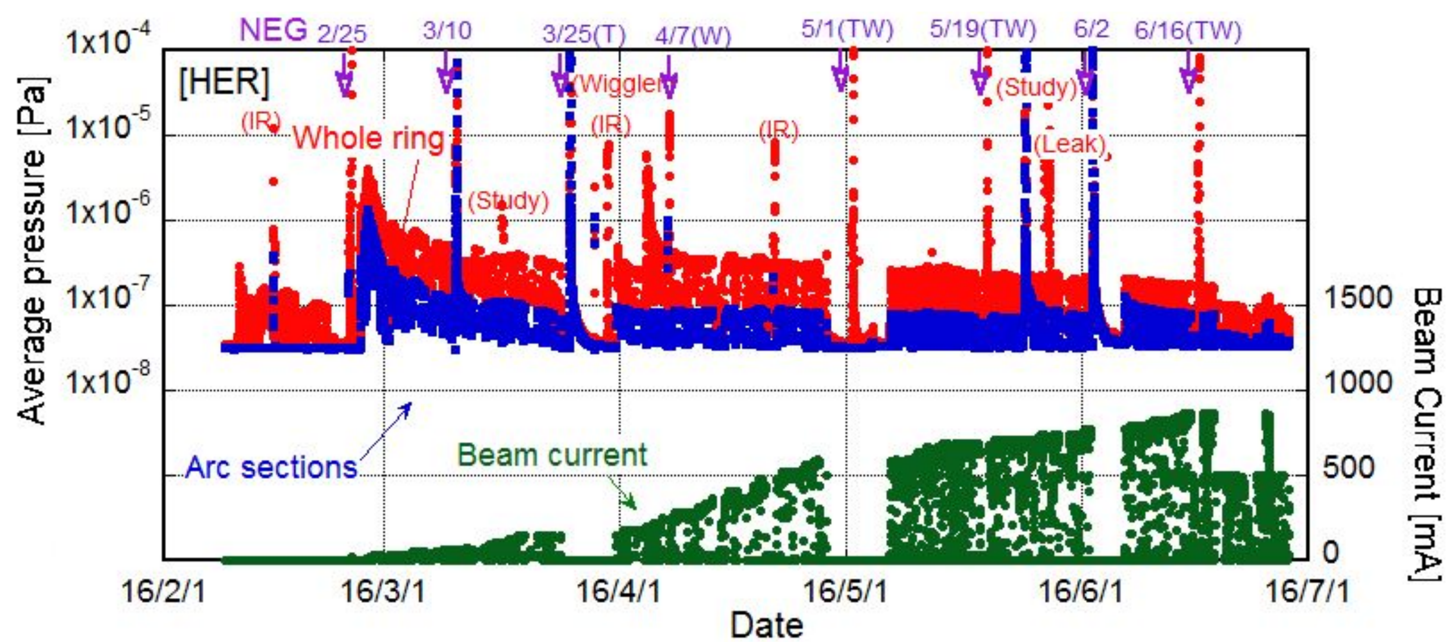
Courtesy of Y. Suetsugu

2. Vacuum scrubbing

➤ **Achieved**

- **LER**
  - ➢ Base pressure: ~5×10^{-8} Pa
  - ➢ Ave. pressure: ~1×10^{-6} Pa
  - ➢ I_{beam}: ~1.01 A
  - ➢ τ_{beam}: ~70 min
- **HER**
  - ➢ Base pressure: ~3×10^{-8} Pa
  - ➢ Ave. pressure: ~1×10^{-7} Pa
  - ➢ I_{beam}: ~0.87 A
  - ➢ τ_{beam}: ~400 min

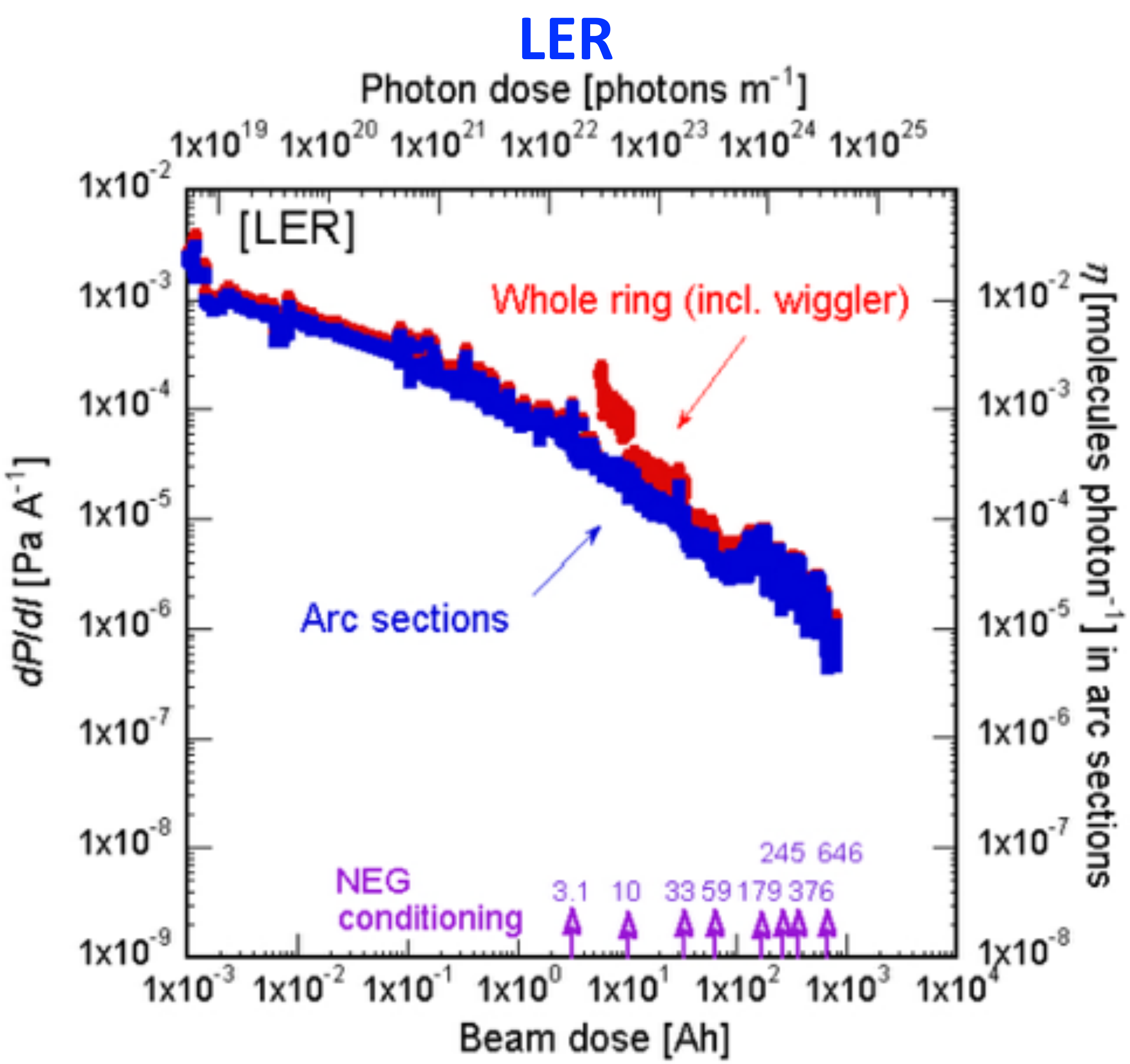


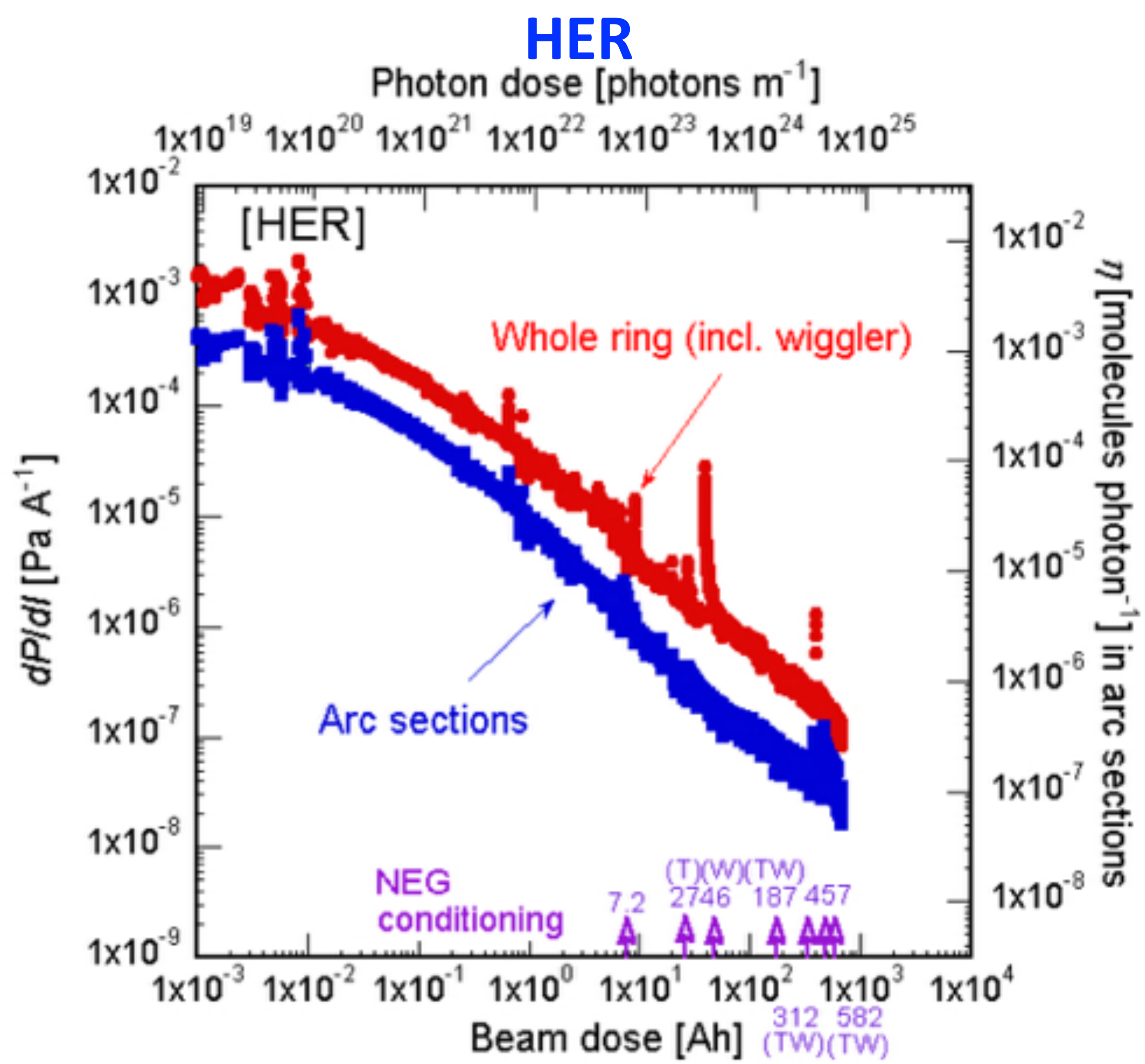


Courtesy of Y. Suetsugu

2. Vacuum scrubbing

➤ Pressure rise and expected photon stimulated gas desorption rate





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3. Low emittance tuning

➤ Tools for optics correction

- Optics and orbit servers
- Continuous Closed orbit Correction (CCC)
- Tune changer
- Optics measurement and correction
- Local bump control
- … …

➤ Preparations before fine low emittance tuning

- Check polarity of magnets with beam
- Check BPM system (cabling, resolution, stability, …)
- Beam Based Alignment (BBA)
- … …

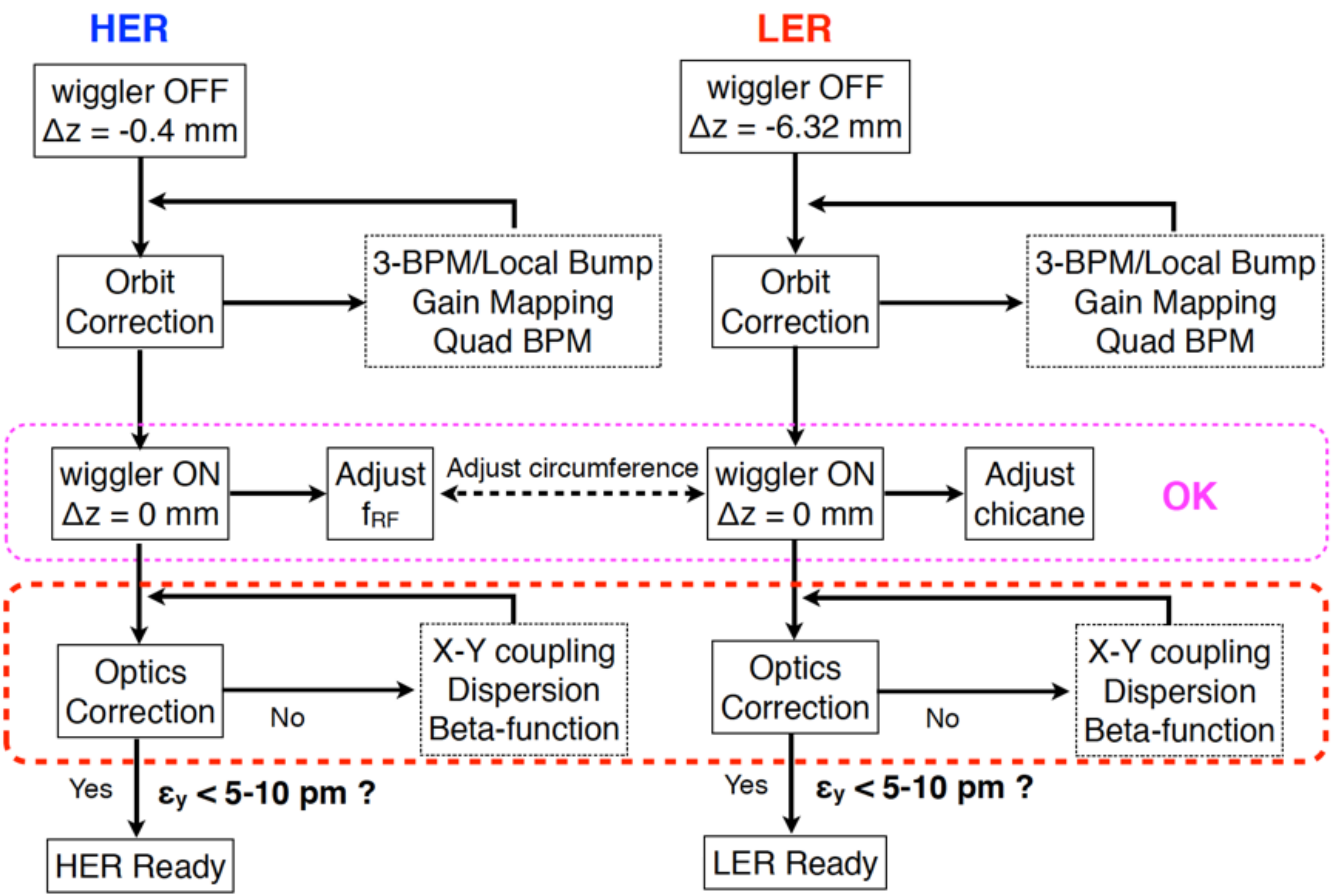
➤ Optics measurements based on orbit response

- X-Y coupling: Measure leakages in vert. orbits by hor. kicks
- Dispersion: Measure response by changing RF frequency
- Beta function: Measure orbit response by steering kicks

Courtesy of H. Sugimoto

3. Low emittance tuning

➤ Strategy for optics tuning

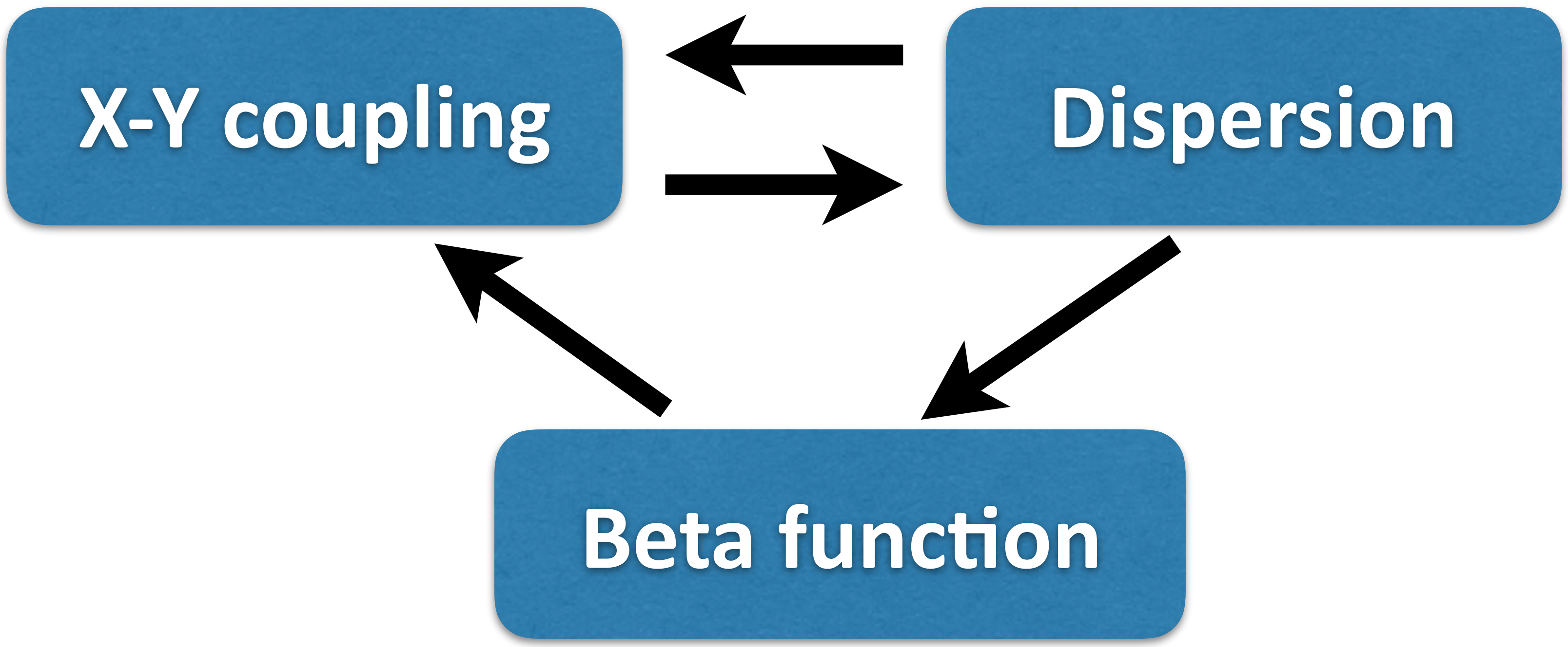


Courtesy of Y. Ohnishi

3. Low emittance tuning

➤ Fine low emittance tuning

- Use iteration instead of full response matrix method



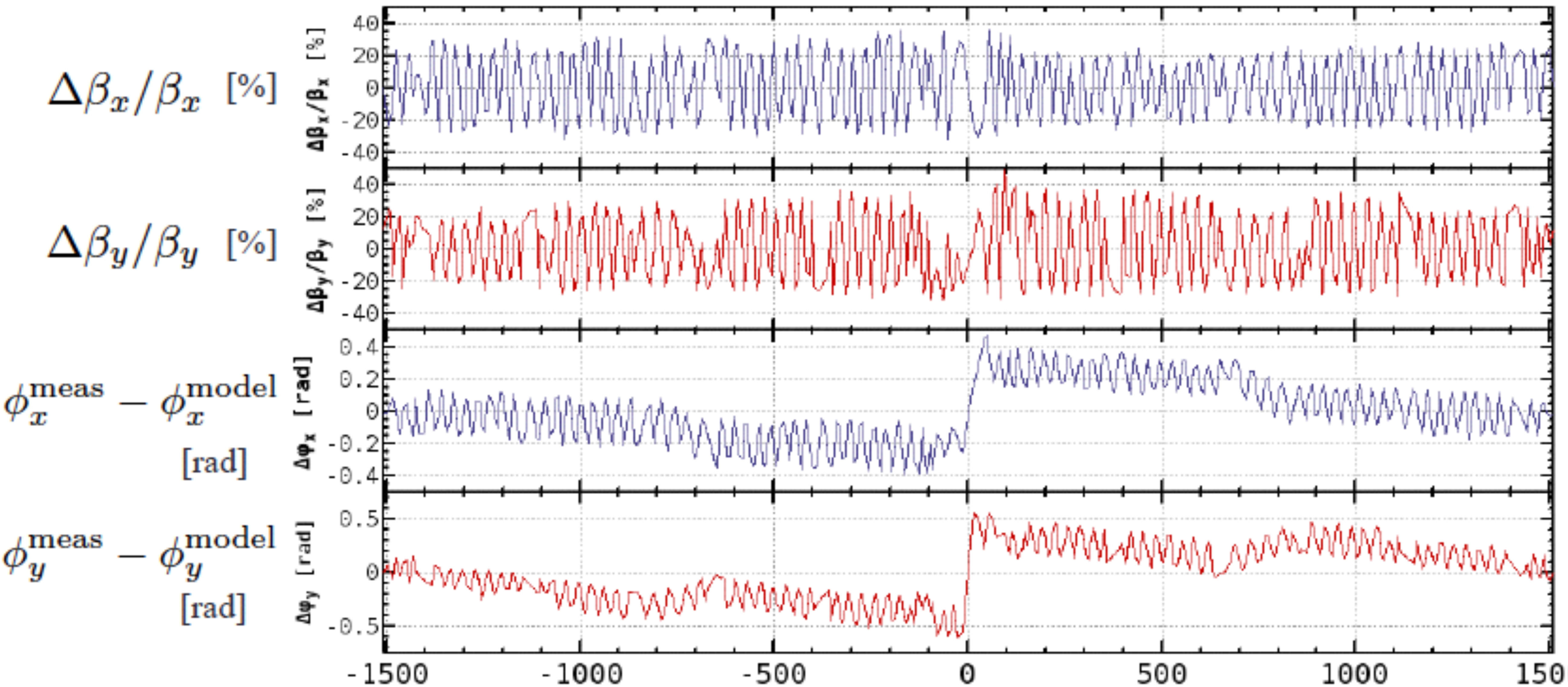
$$\begin{pmatrix} XX & XY & XZ \\ XY & YY & YZ \\ XZ & YZ & ZZ \end{pmatrix}$$

- The 3 corrections are correlated with each other, but interference assumed to be small since the diagonal parts of transfer matrix dominate
- For one ring, the iteration (loop of corrections in X-Y coupling, dispersion and beta function) converges typically in 30-60 min

3. Low emittance tuning

➤ Beta function correction: LER

- **Before correction**



$$(\Delta\beta_x/\beta_x)_{\rm rms} \sim 19.5\ \% \qquad \Delta\nu_x \sim -0.074$$

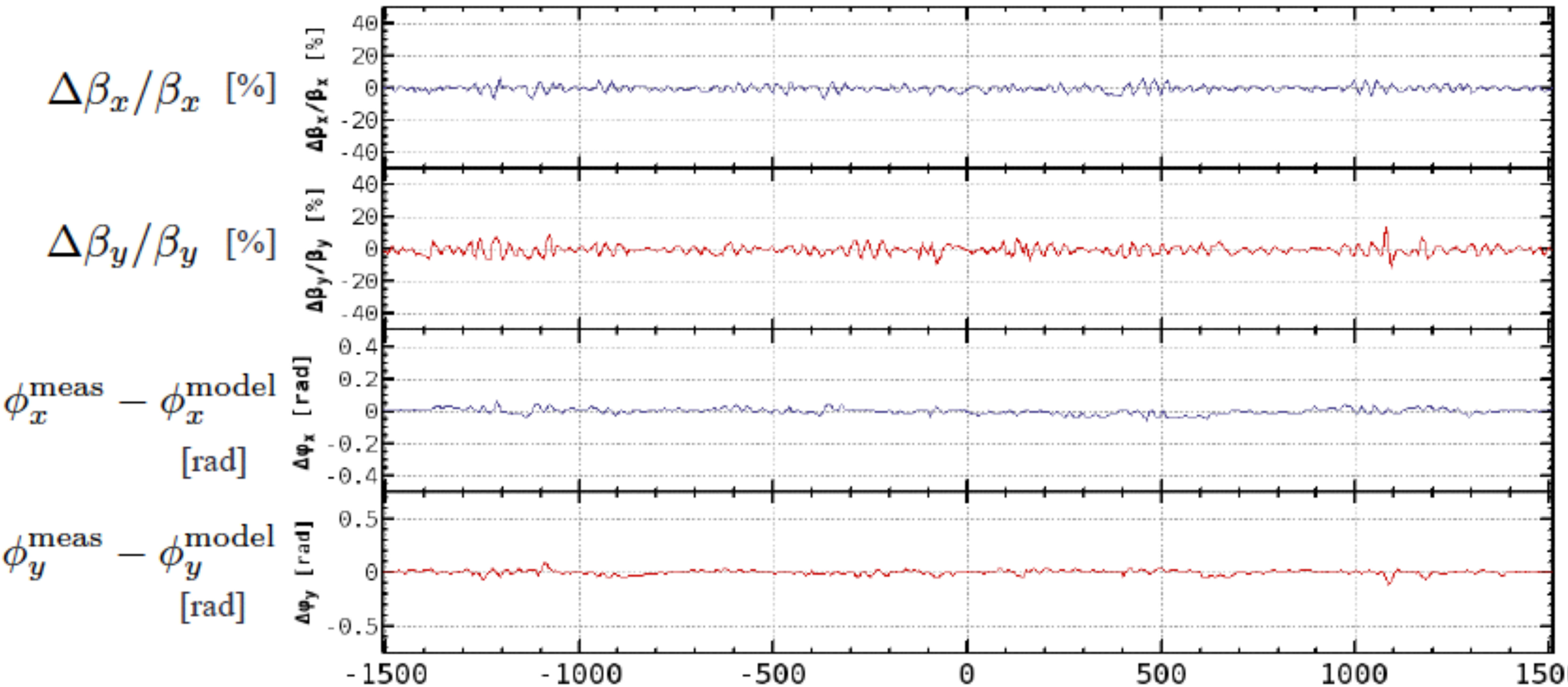
$$(\Delta\beta_y/\beta_y)_{\rm rms} \sim 20.5\ \% \qquad \Delta\nu_y \sim -0.141$$

Courtesy of H. Sugimoto

3. Low emittance tuning

➤ Beta function correction: LER

- **After correction**



$$(\Delta\beta_x/\beta_x)_{\mathrm{rms}} \sim 2.0\ \% \qquad \Delta\nu_x \sim 0.004$$

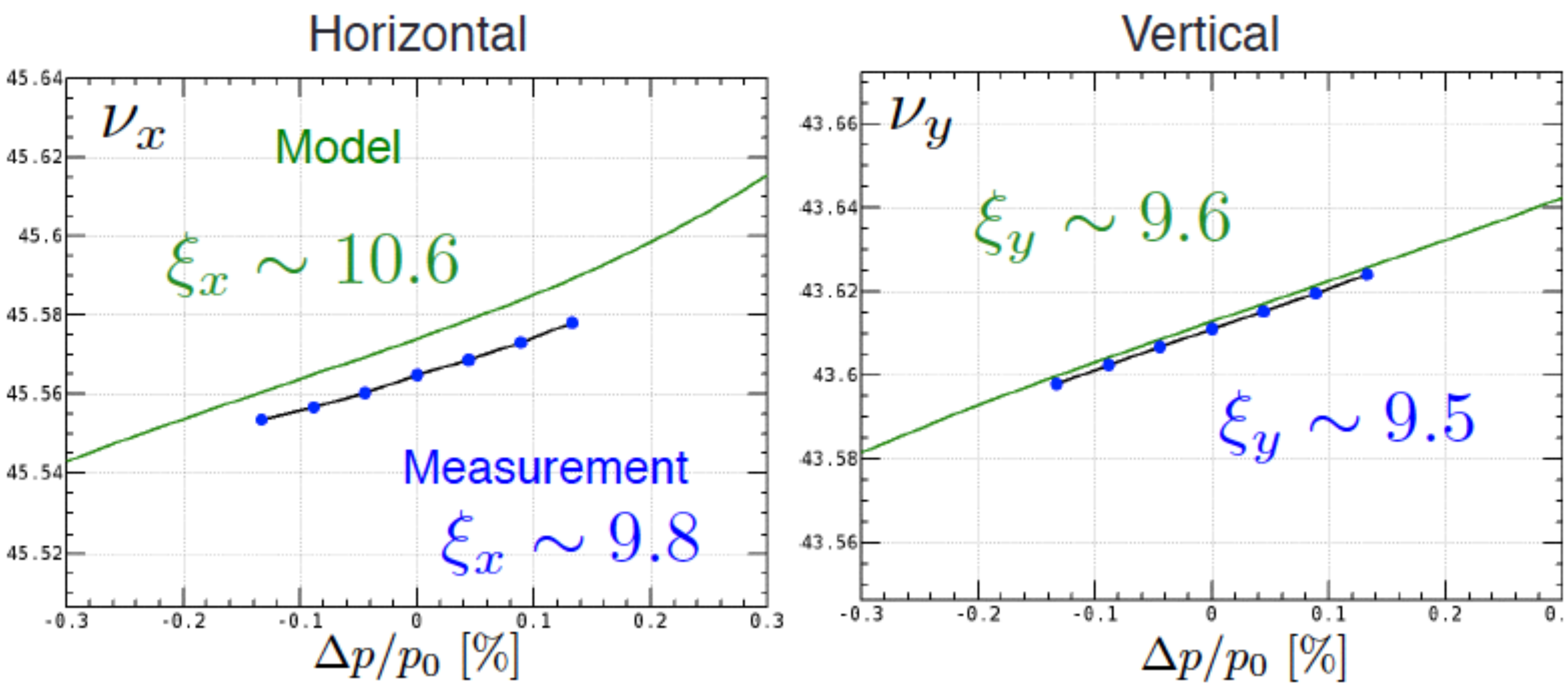
$$(\Delta\beta_y/\beta_y)_{\mathrm{rms}} \sim 2.9\ \% \qquad \Delta\nu_y \sim 0.001$$

Courtesy of H. Sugimoto

3. Low emittance tuning

➤ **Tune chromaticity measurement: HER**

- **Good agreement with optics model**



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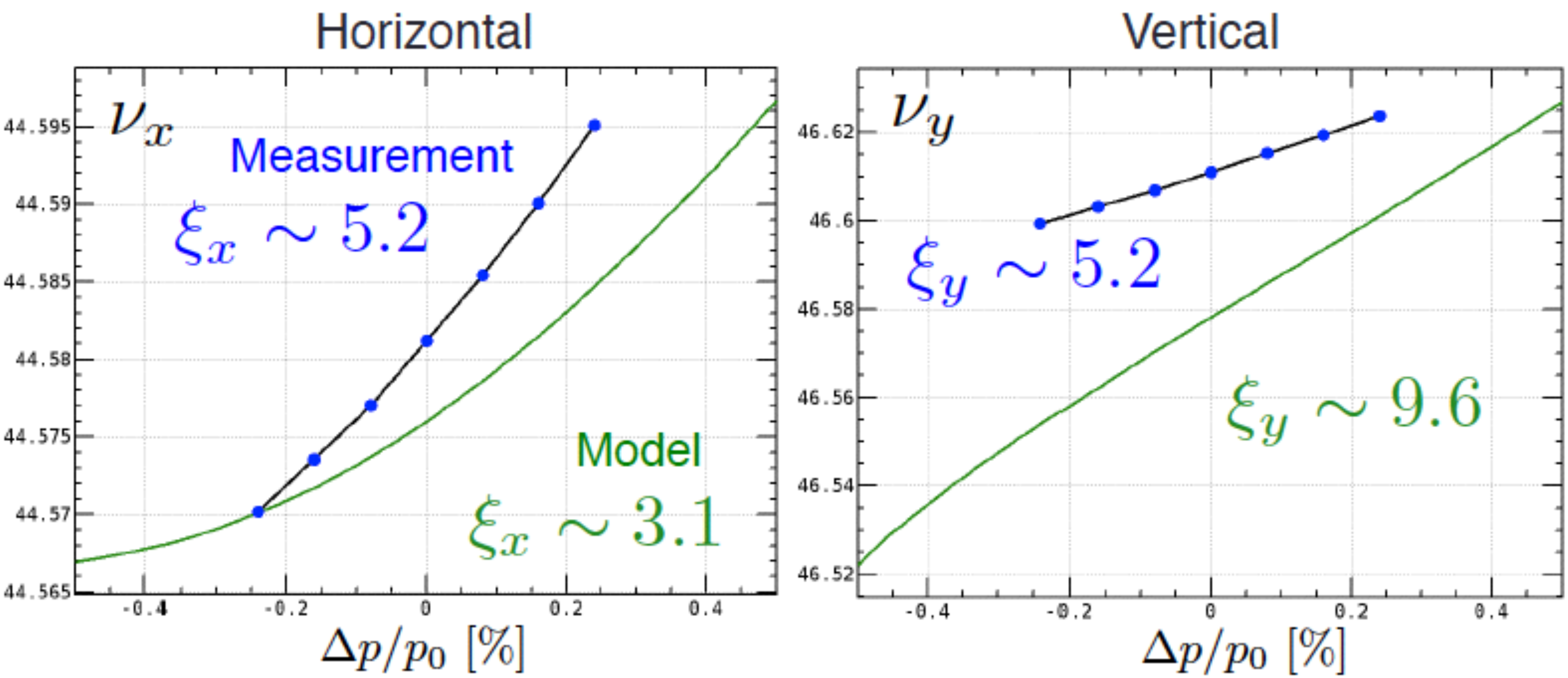
3. Low emittance tuning

➤ **Tune chromaticity measurement: LER**

- **Remarkable discrepancy against optics model**

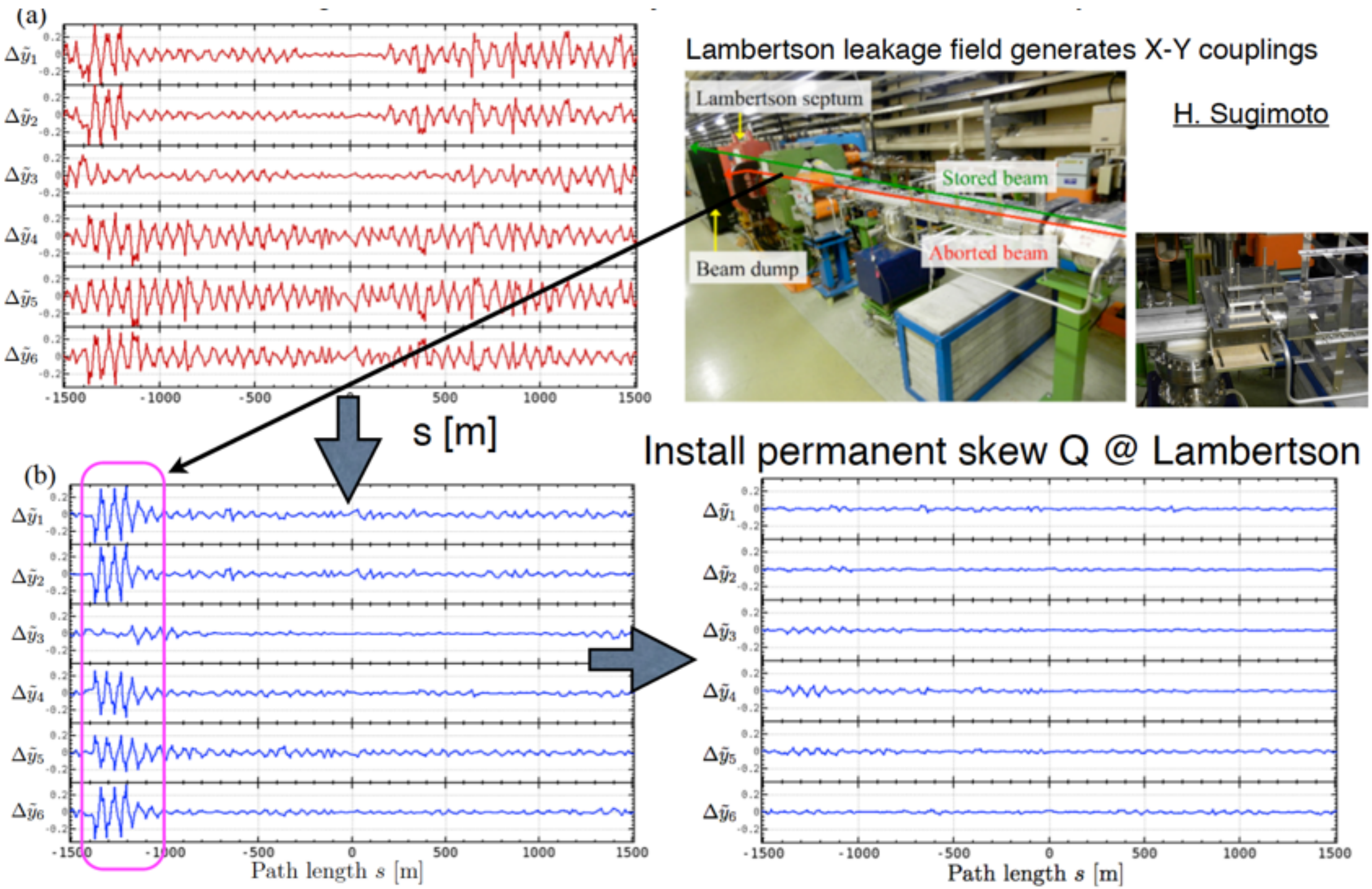


Courtesy of H. Sugimoto

3. Low emittance tuning

➤ X-Y coupling correction: LER

- **Leakages in vert. orbits induced by 6 kinds of horizontal dipole correctors**



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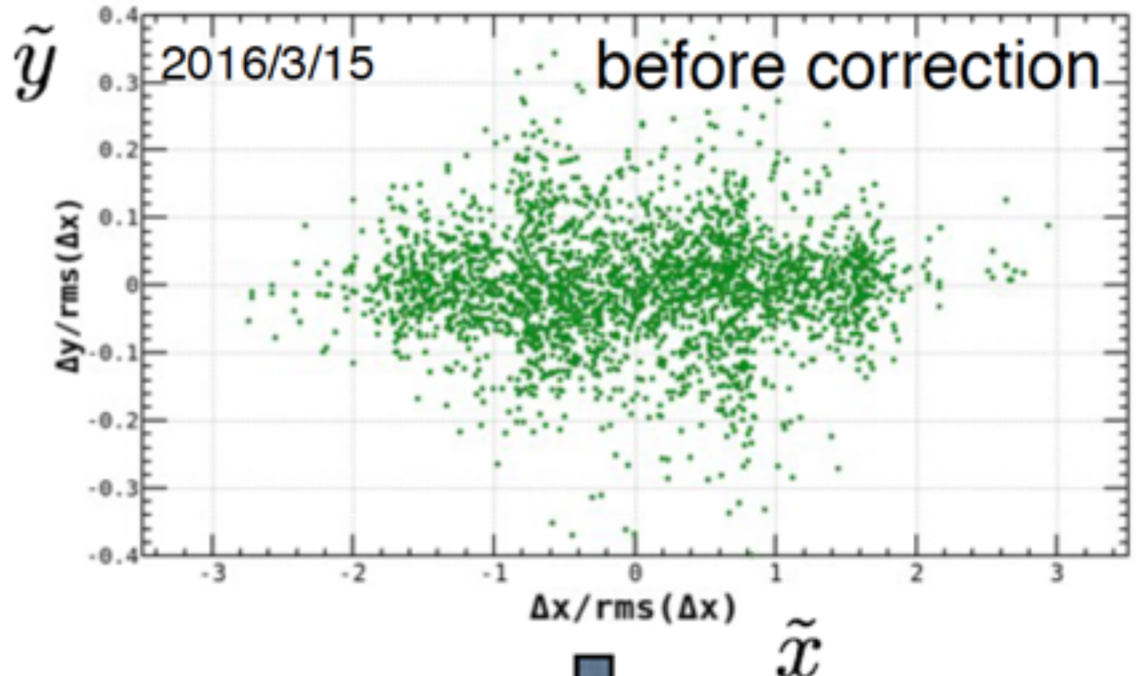
3. Low emittance tuning

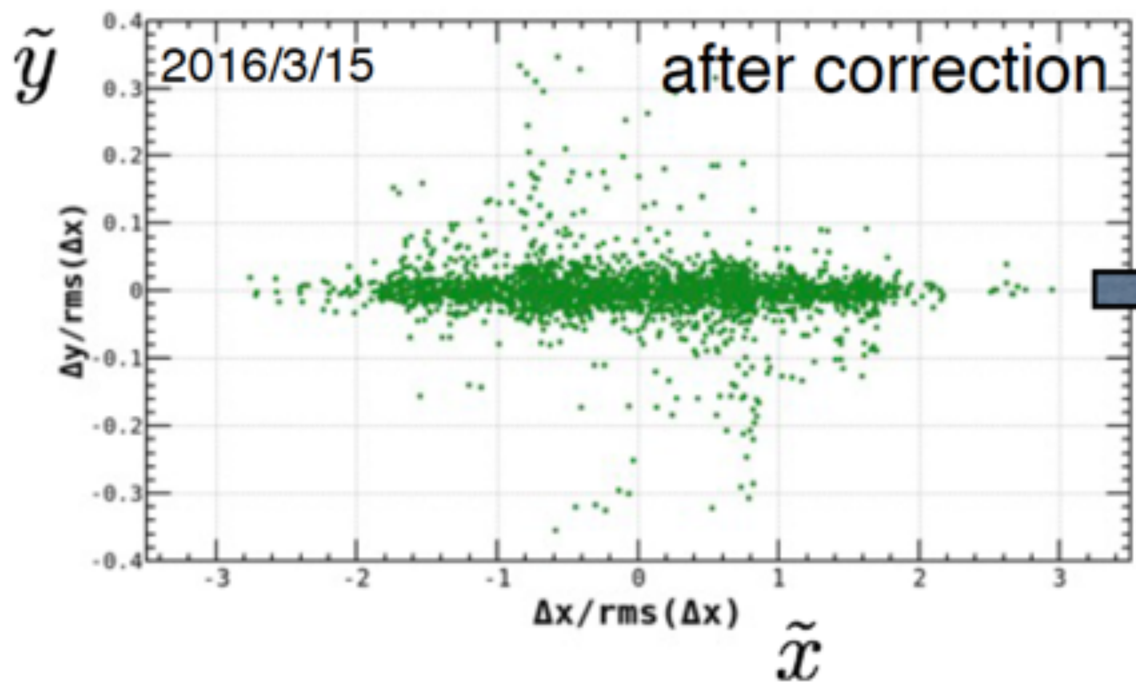
➤ **X-Y coupling correction: LER**

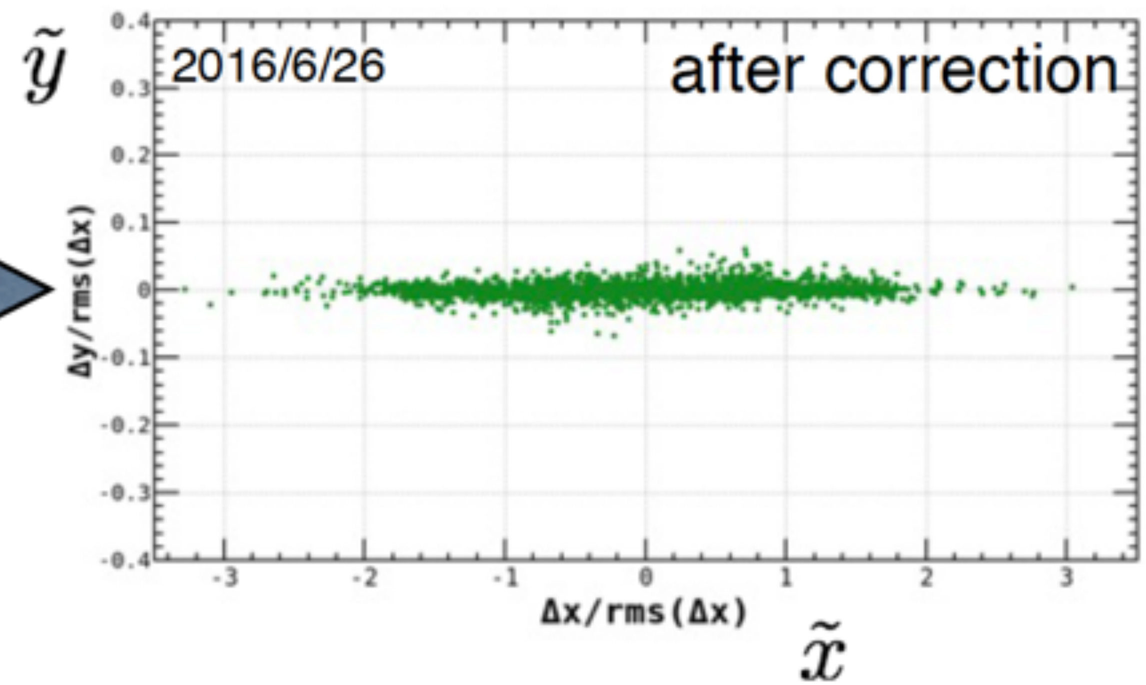


$$\tilde{x} = \frac{\Delta x_i}{rms(\Delta x_i)} \qquad \tilde{y} = \frac{\Delta y_i}{rms(\Delta x_i)}$$

Plot includes 6 orbits.

Install permanent skew Q @ Lambertson

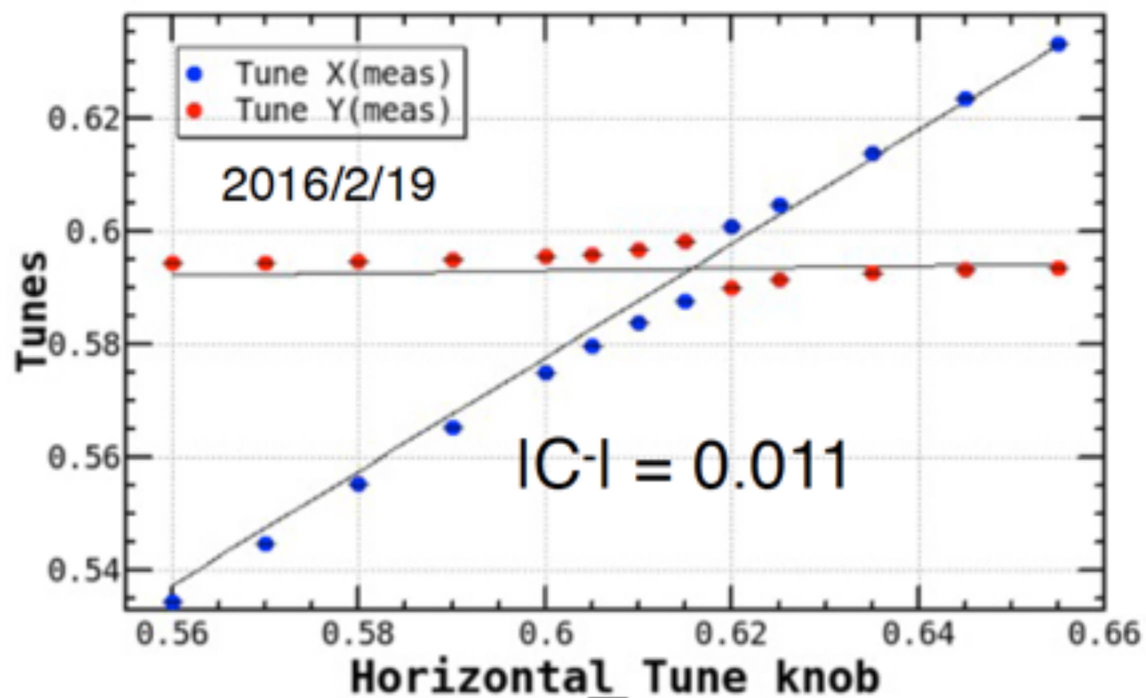


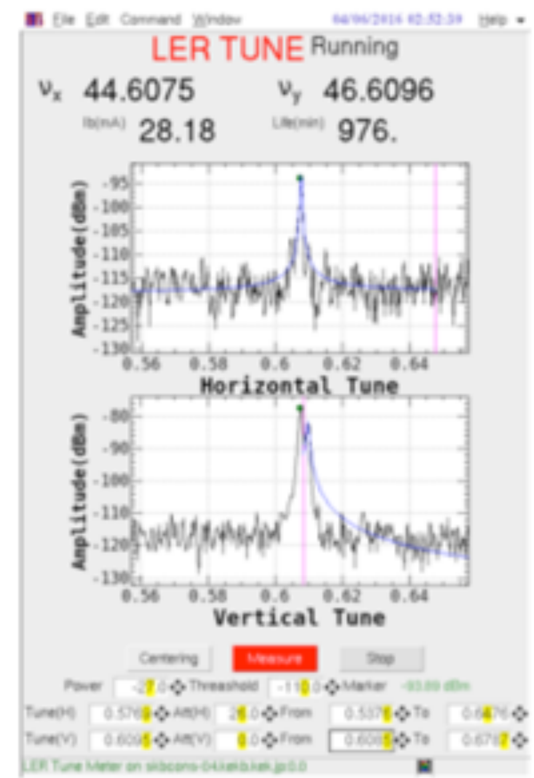


Courtesy of Y. Ohnishi

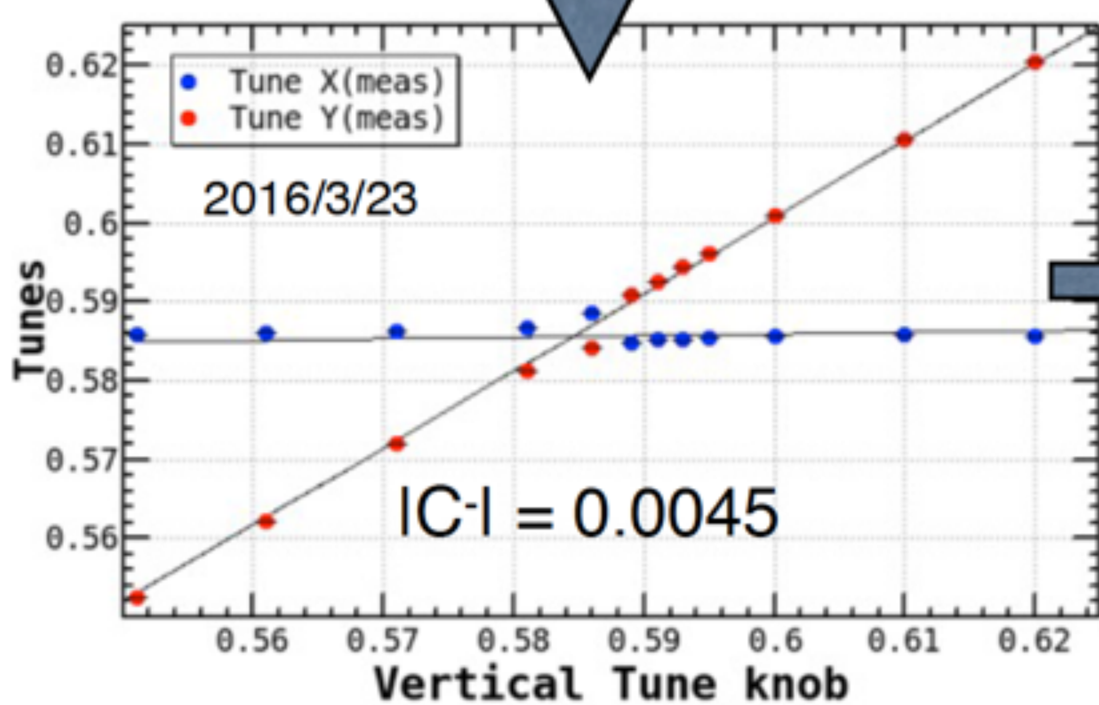
3. Low emittance tuning

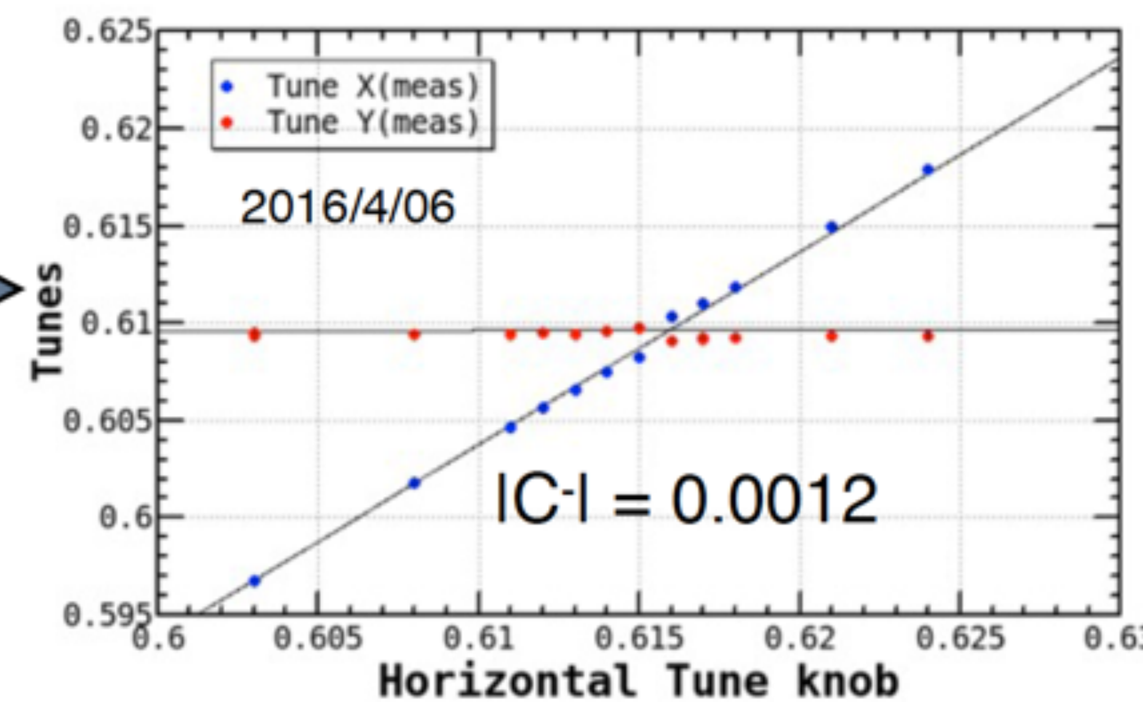
➤ X-Y coupling correction: LER





$$\frac{|C^-|^2}{2\Delta^2 + |C^-|^2} = 0.00045$$



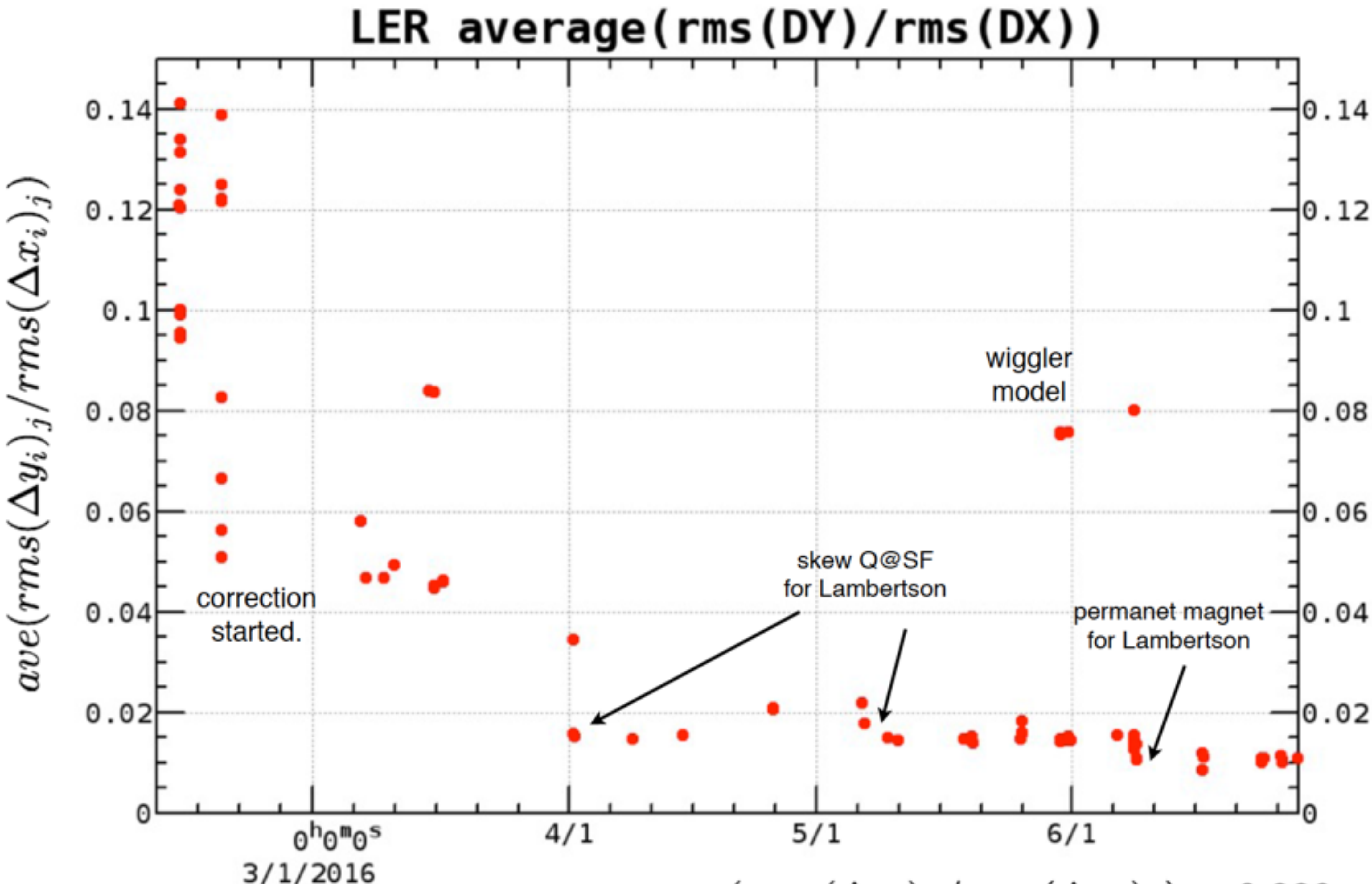


Courtesy of Y. Ohnishi

3. Low emittance tuning

➤ X-Y coupling correction: LER

- **History of global X-Y coupling**



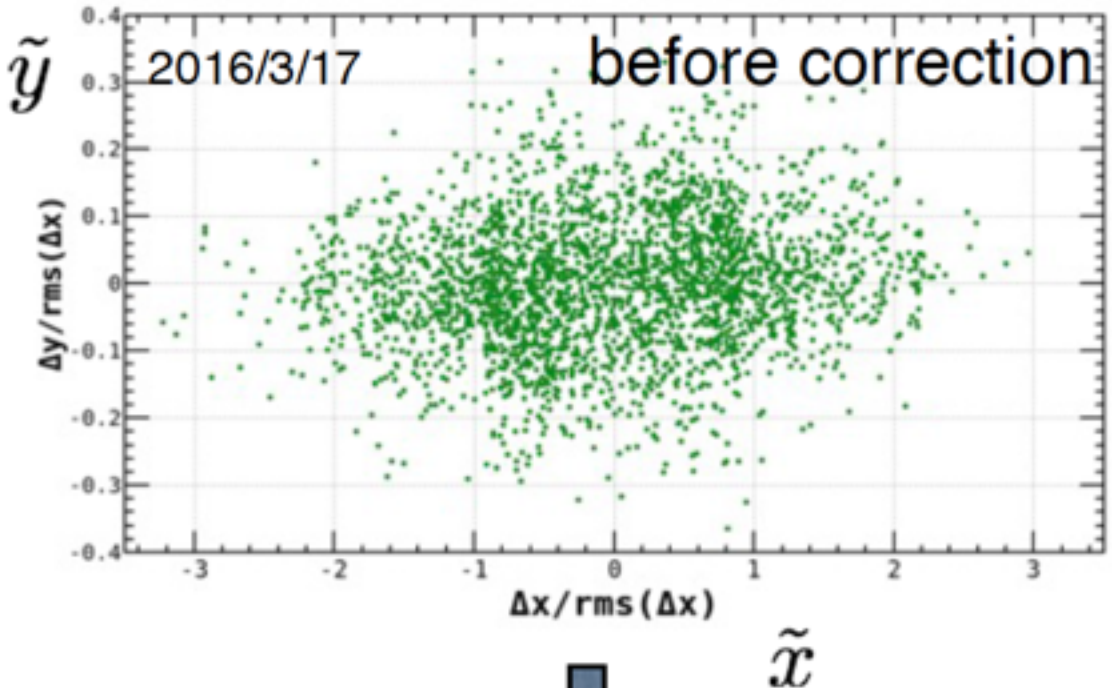
$ave(rms(\Delta y_i)_j/rms(\Delta x_i)_j) = 0.009$

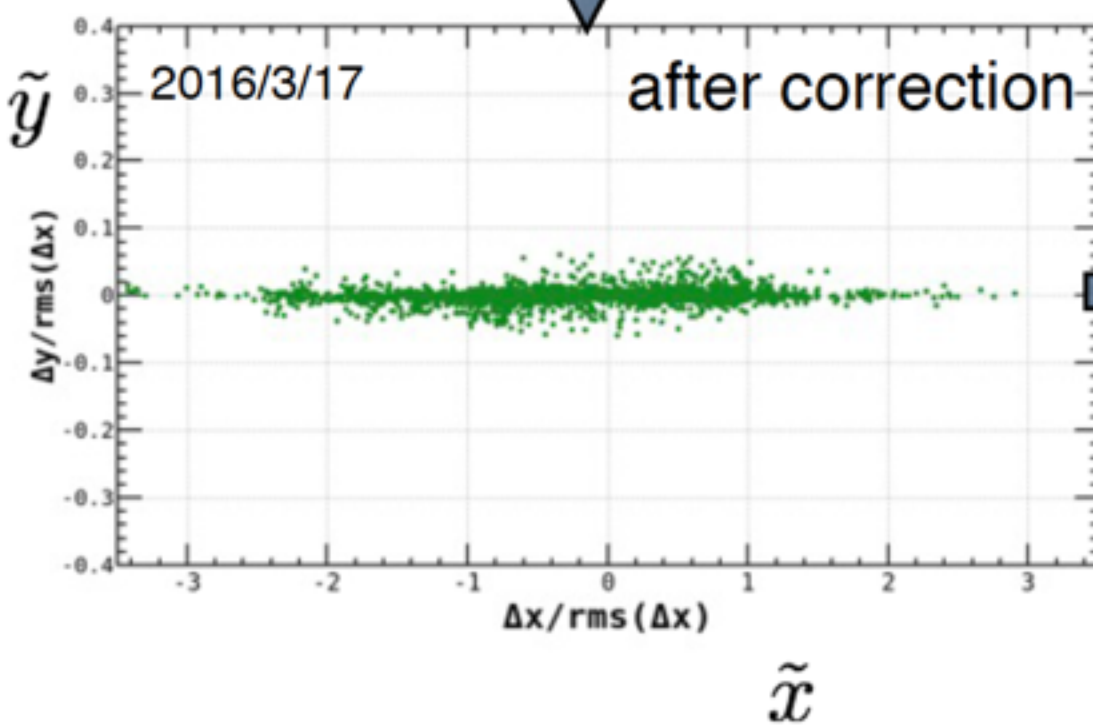
Courtesy of Y. Ohnishi

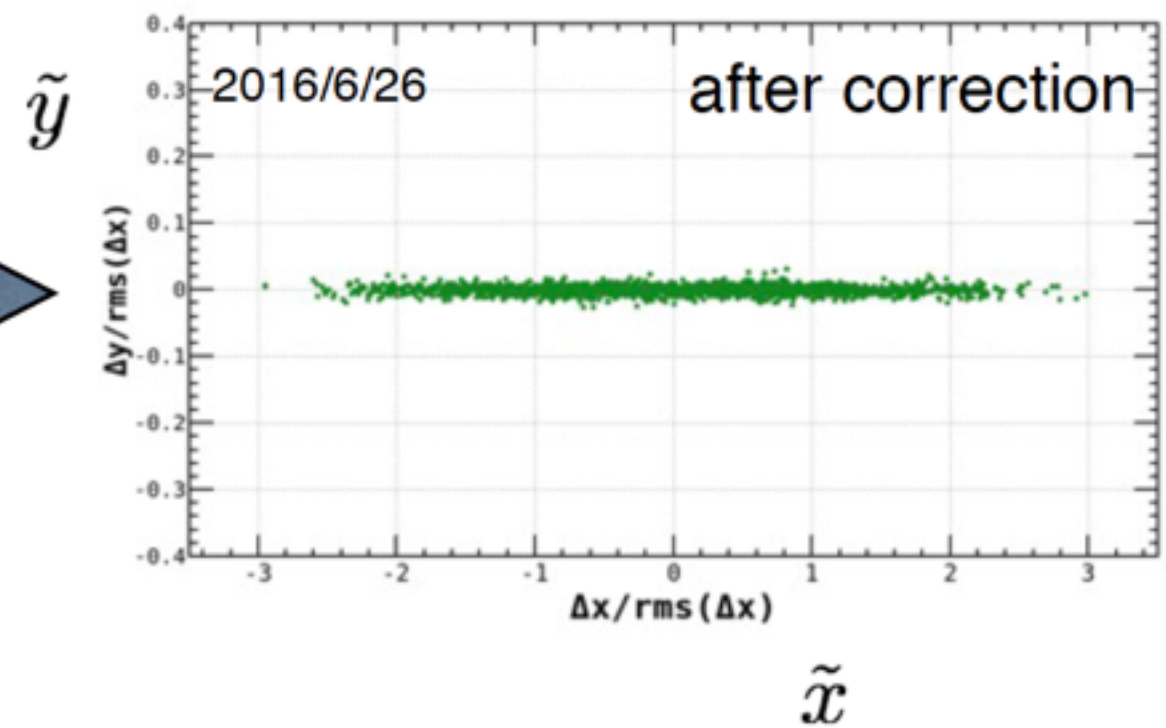
3. Low emittance tuning

➤ X-Y coupling correction: HER

$$\tilde{x} = \frac{\Delta x_i}{rms(\Delta x_i)} \qquad \tilde{y} = \frac{\Delta y_i}{rms(\Delta x_i)}$$



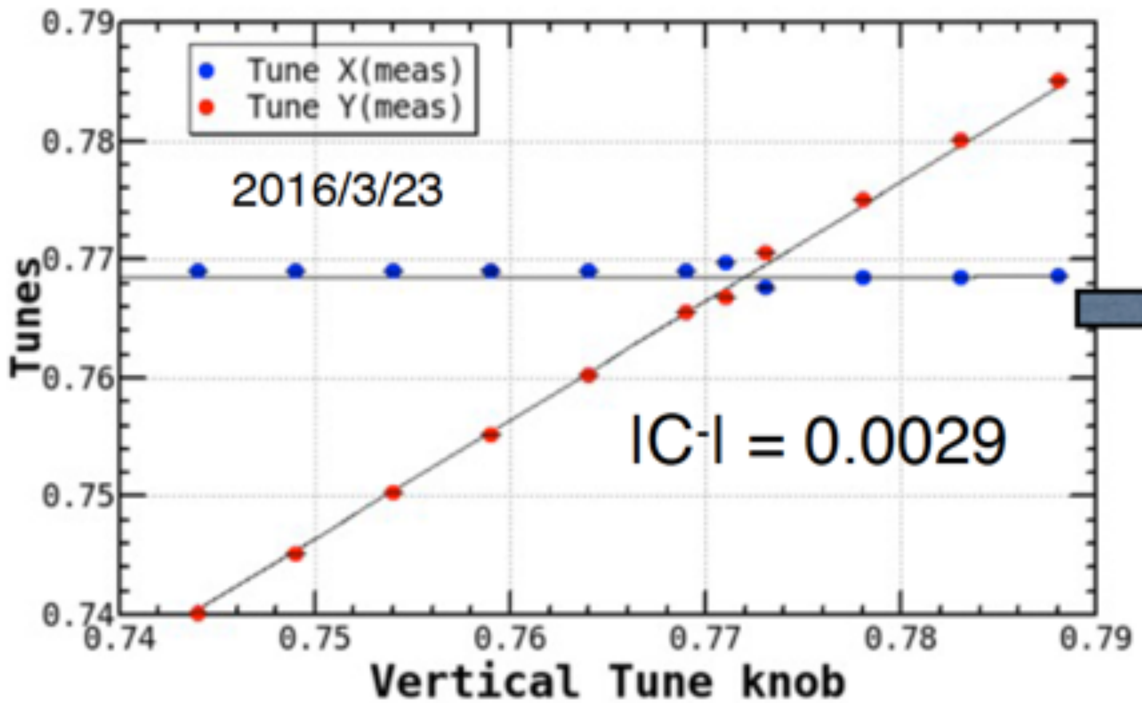


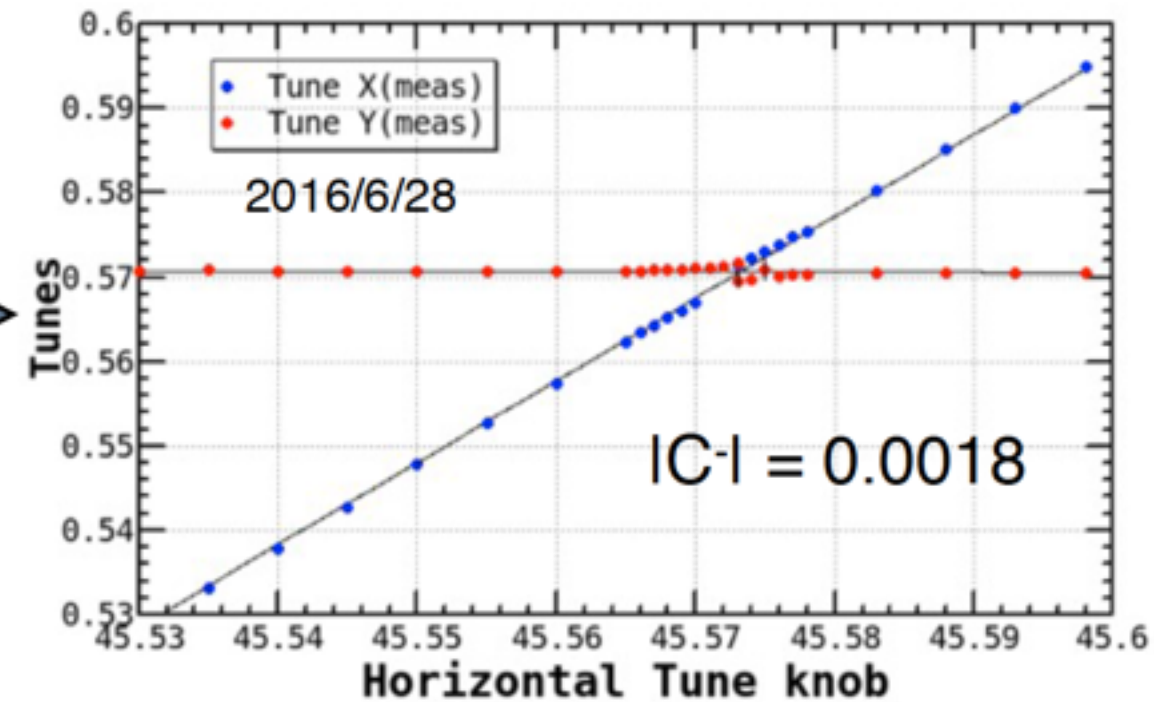


Courtesy of Y. Ohnishi

3. Low emittance tuning

➤ X-Y coupling correction: HER



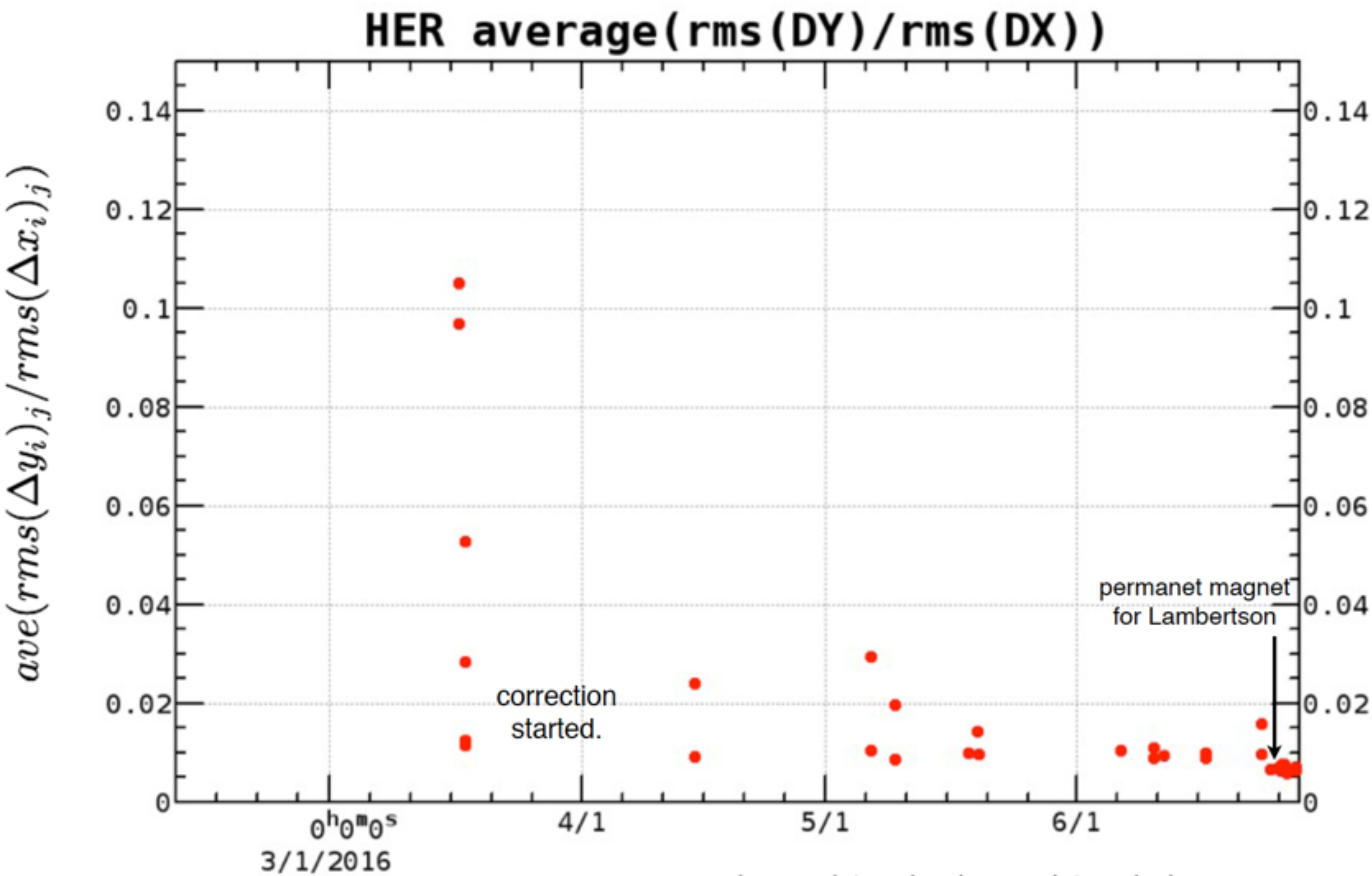


Courtesy of Y. Ohnishi

3. Low emittance tuning

➤ X-Y coupling correction: HER

- **History of global X-Y coupling**



$$ave(rms(\Delta y_i)_j/rms(\Delta x_i)_j) = 0.006$$

Courtesy of Y. Ohnishi

3. Low emittance tuning

➤ Performance of optics correction

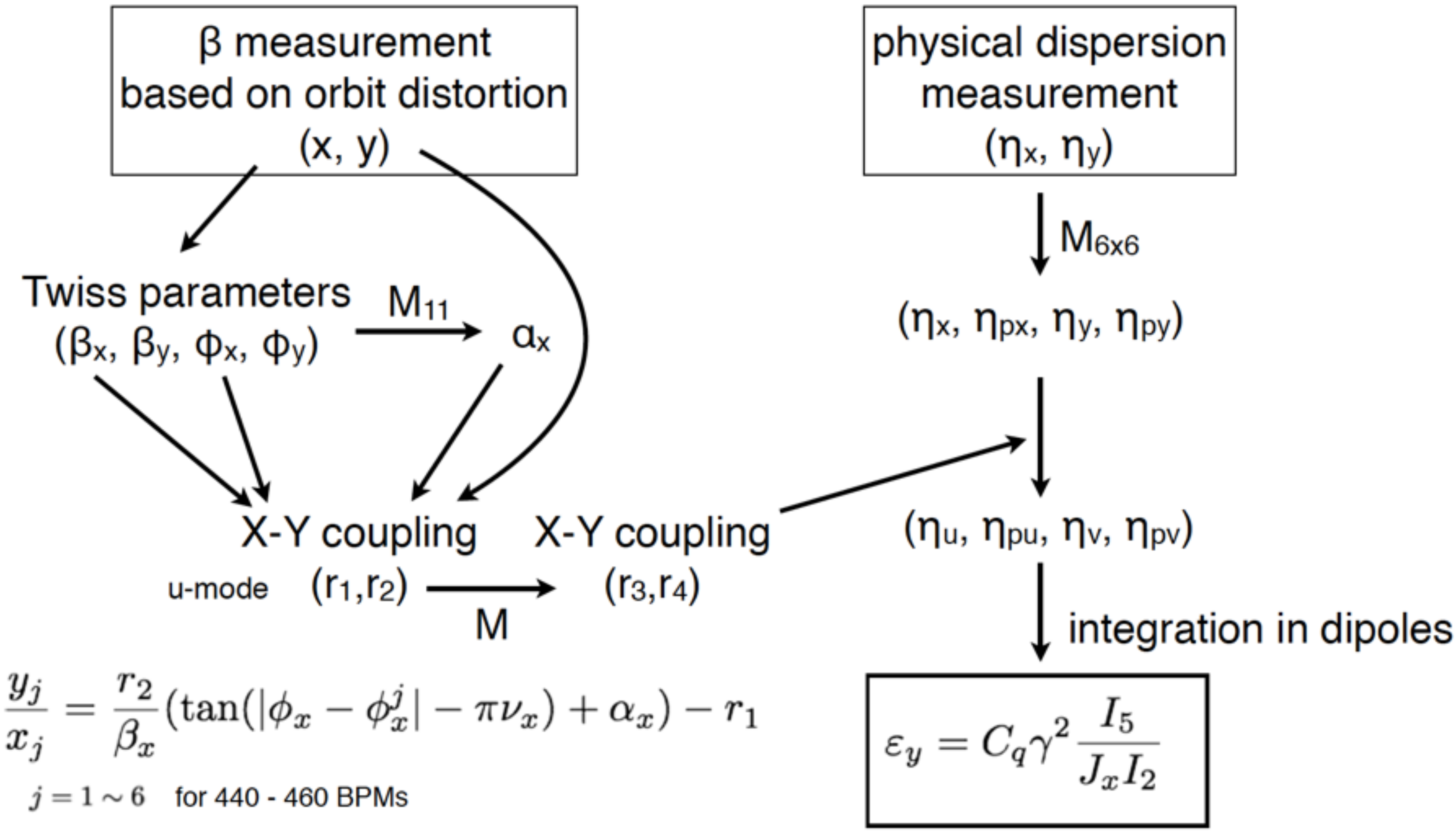
- **Achieved in the end of Phase I**

Items	Symbol	LER	HER
Global coupling	$\mid C^{-} \mid (\times 10^{-3})$	1.2	2.0
X-Y coupling*	$\mathrm{rms}(\Delta y)/\mathrm{rms}(\Delta x)$	0.9 %	0.6 %
Hor. dispersion	$\mathrm{rms}(\Delta \eta_x)$	8 mm	11 mm
Ver. dispersion	$\mathrm{rms}(\Delta \eta_y)$	2 mm	2 mm
Hor. beta func.	$\mathrm{rms}(\Delta \beta_x / \beta_x)$	3 %	3 %
Ver. beta func.	$\mathrm{rms}(\Delta \beta_y / \beta_y)$	3 %	3 %
Hor. tune	$\Delta \nu_x\ (\times 10^{-4})$	2	5
Ver. tune	$\Delta \nu_y\ (\times 10^{-4})$	5	1

Courtesy of Y. Ohnishi, NAPAC16

3. Low emittance tuning

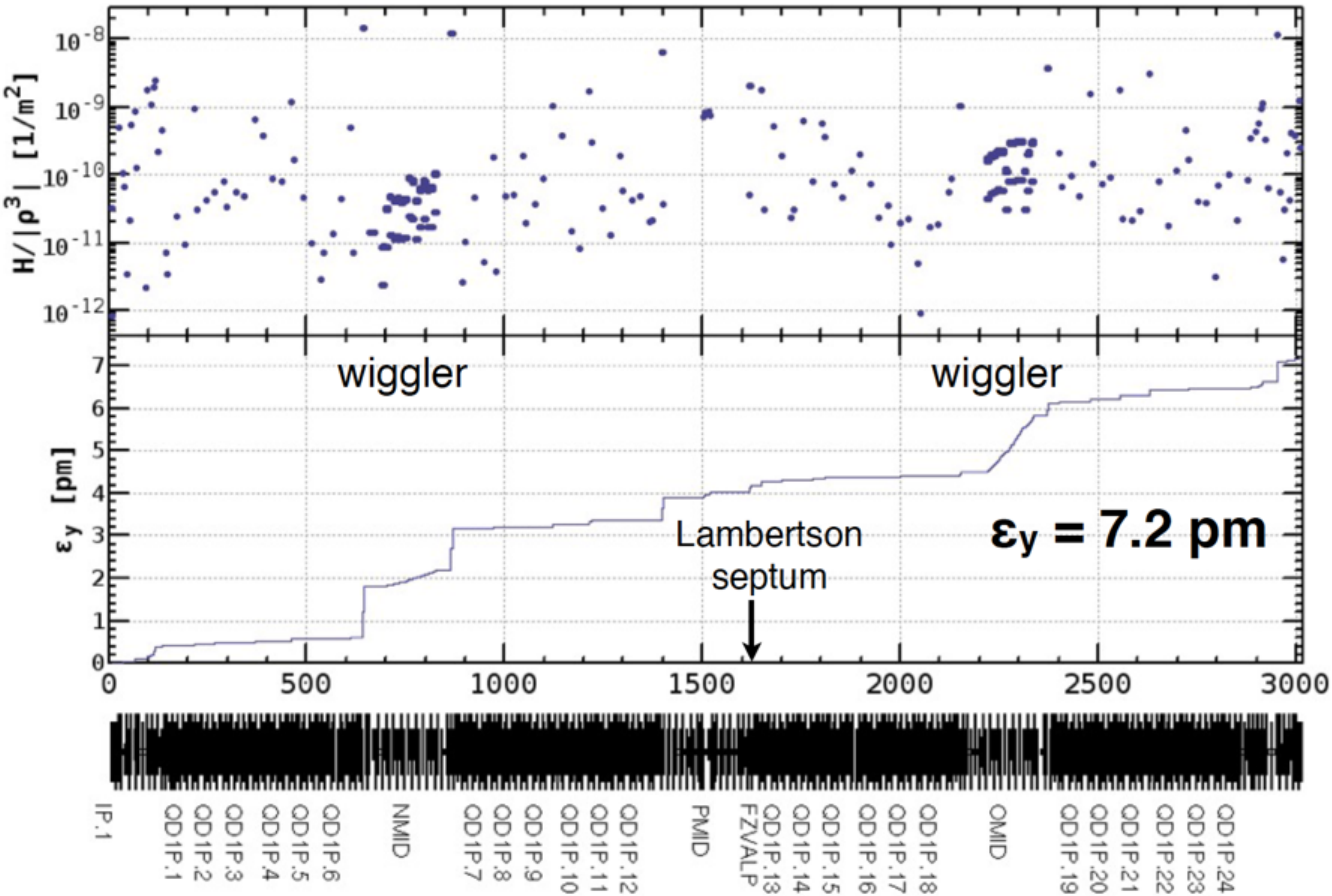
➤ **Estimate of vert. emittance**



Courtesy of Y. Ohnishi

3. Low emittance tuning

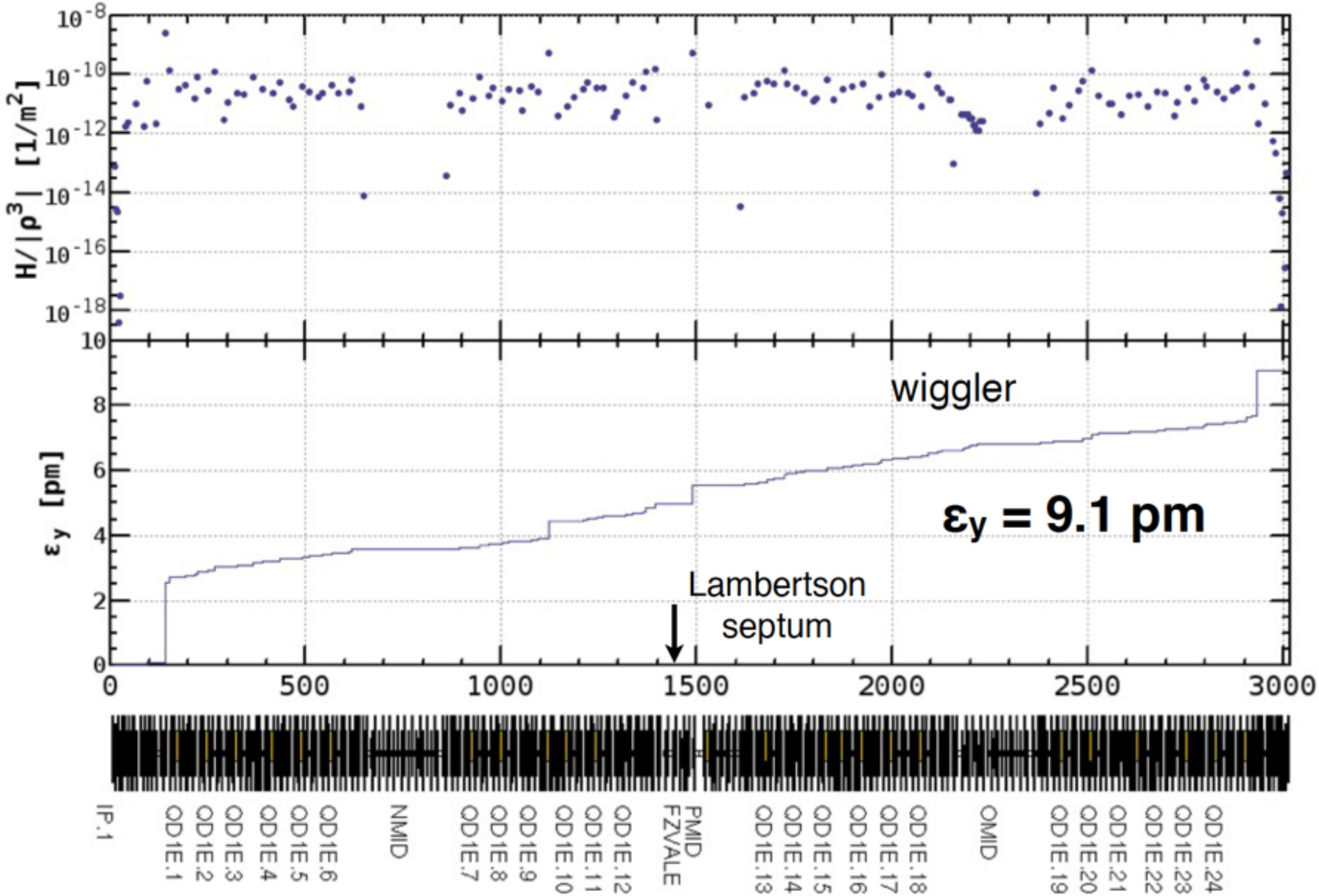
➤ **Estimate of vert. emittance: LER**



Courtesy of Y. Ohnishi

3. Low emittance tuning

➤ **Estimate of vert. emittance: HER**

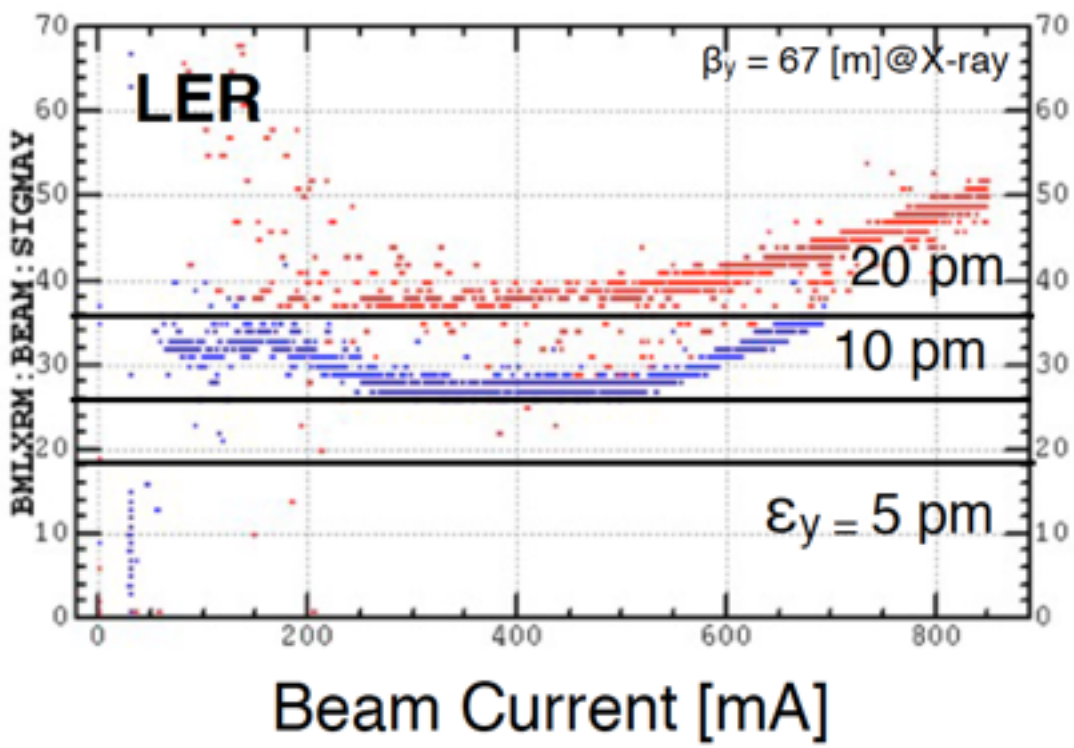


Courtesy of Y. Ohnishi

3. Low emittance tuning

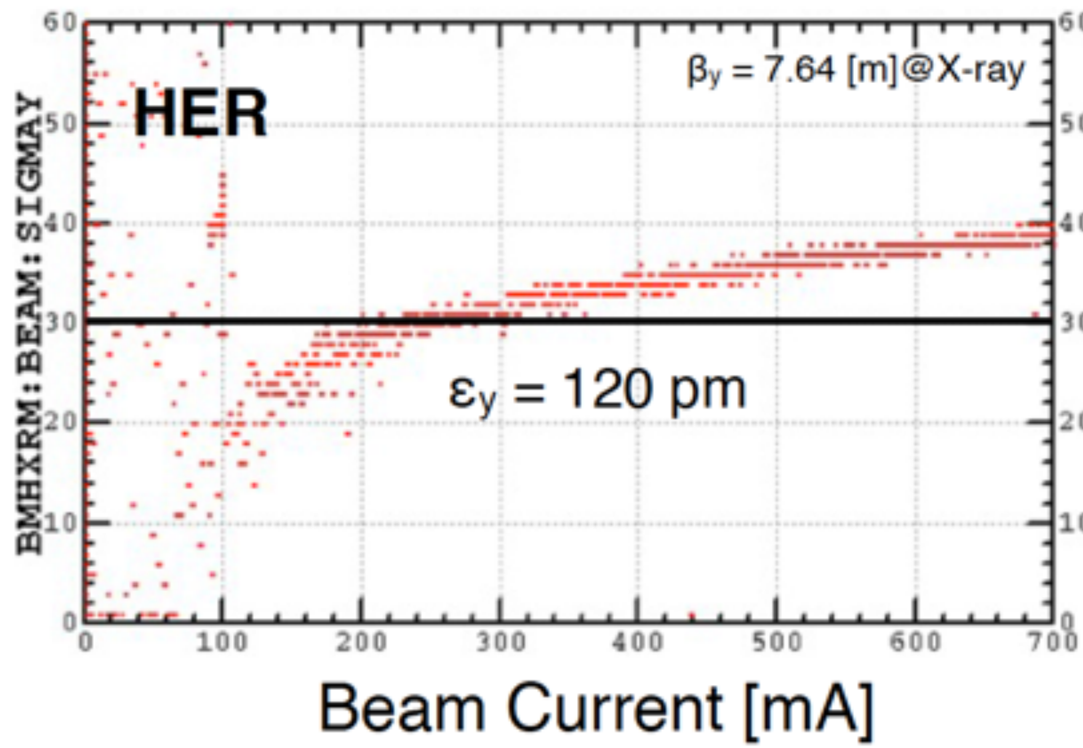
➤ **Compare with estimate from X-ray beam size monitor**

- **LER: Almost agree**
- **HER: Huge discrepancy (to be understood)**



Red: before installing permanent skew quad to correct leakage skew quad. field from Lambertson.

Blue: after installing permanent skew quad



ε_x = 4.6 nm

↓

$\varepsilon_y/\varepsilon_x$ = 2.6 % ?

Is ε_y relally big in HER ?

Courtesy of Y. Ohnishi

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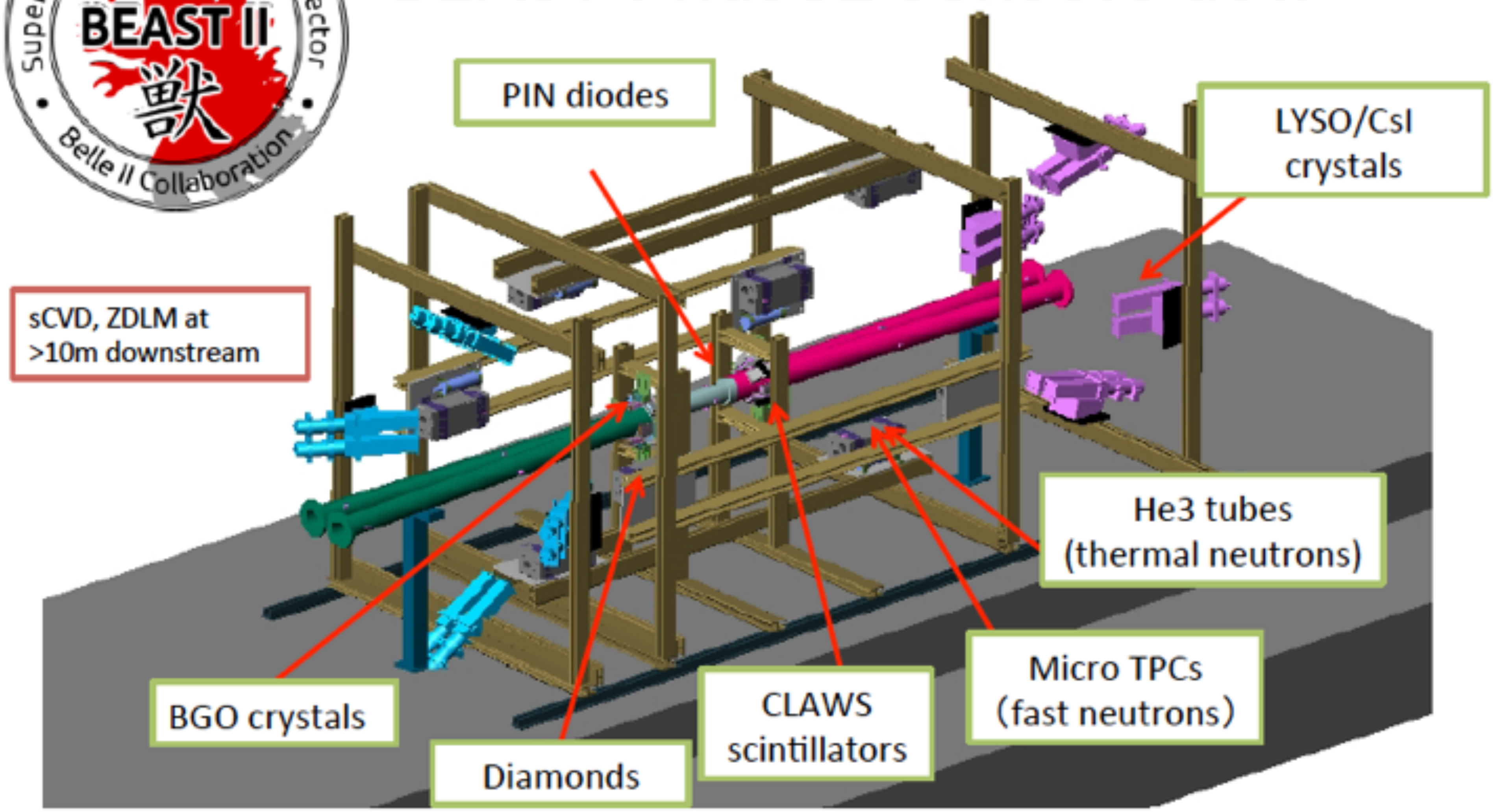
4. Beam background

➤ Items to be studied

- **Touschek, vacuum and injection backgrounds**
- **Collimators for reducing background**

BEAST Phase1 sensors at IP

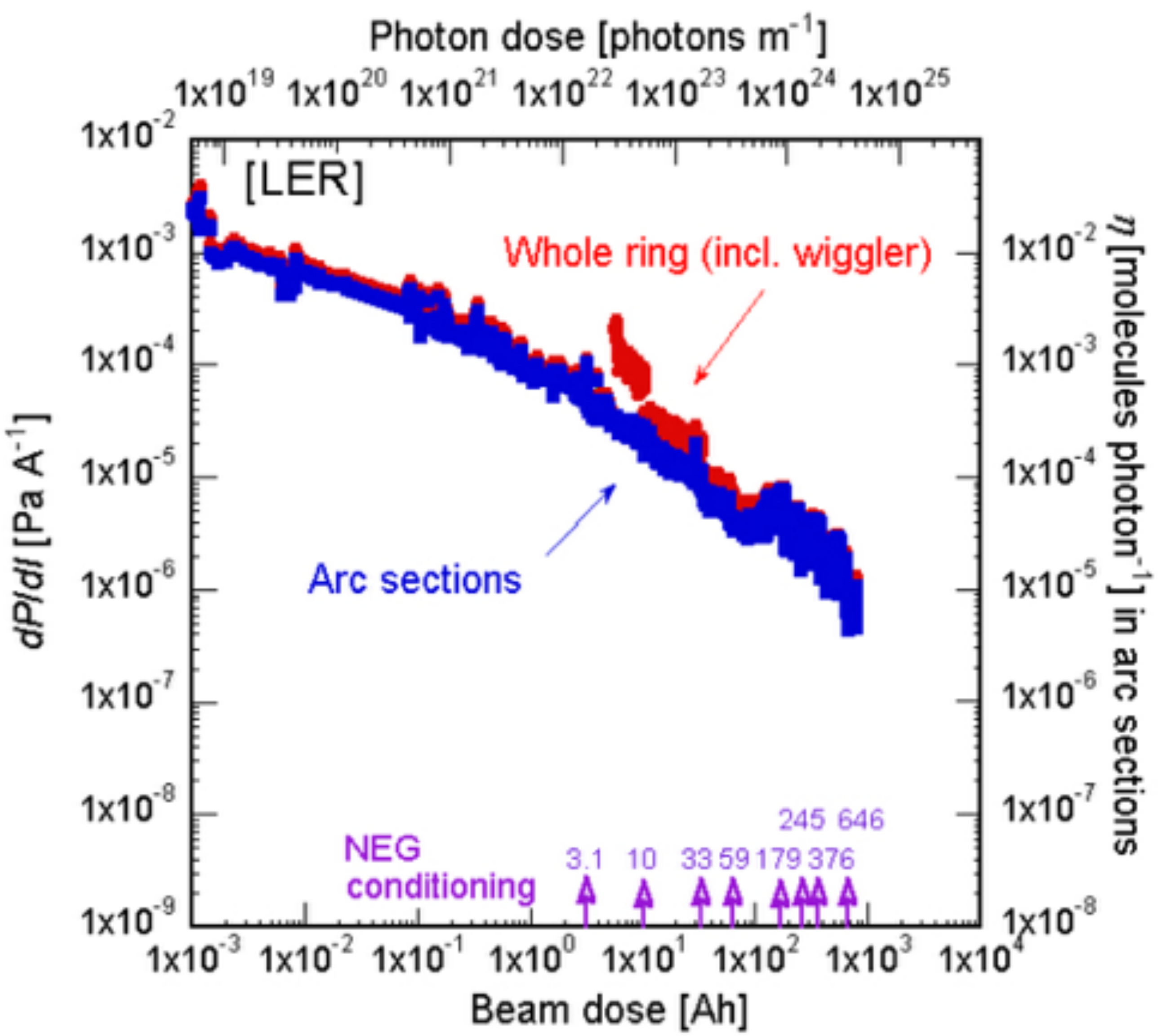


Various measurements (fast charged particle, high-energy photons, thermal/ MeV neutron, dosimetry, etc..) to **validate beam loss simulation**

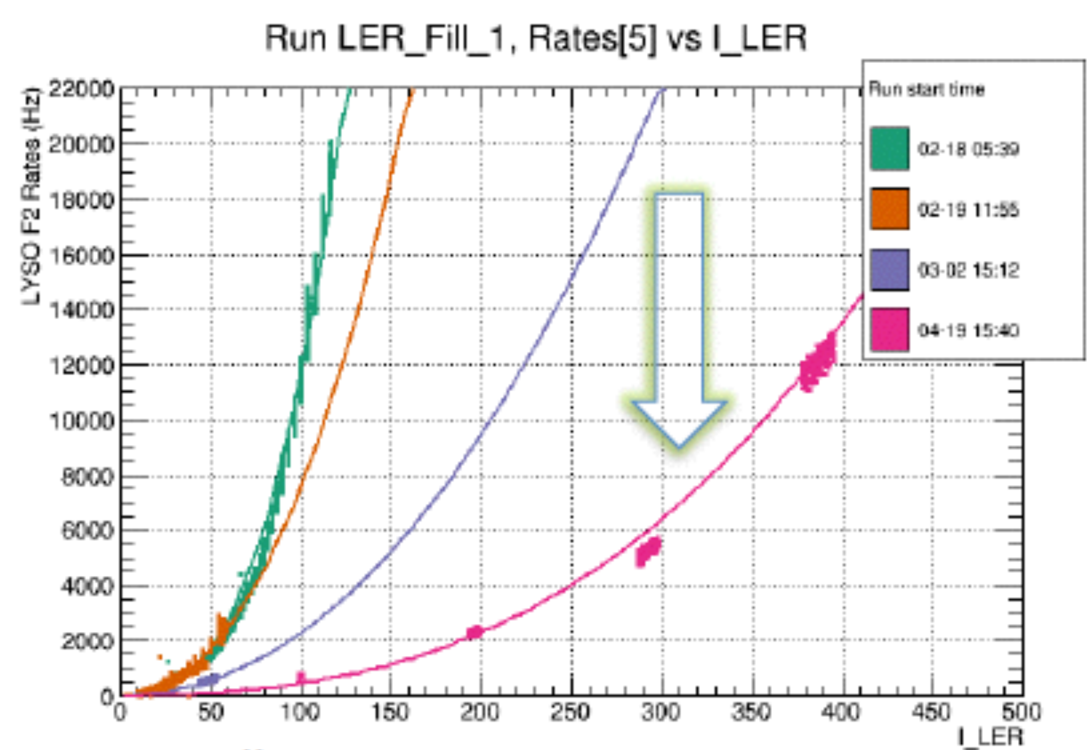
Courtesy of H. Nakayama

4. Beam background

➤ Beam gas backgrounds reduce with vacuum scrubbing



BEAST background in the LER vs time



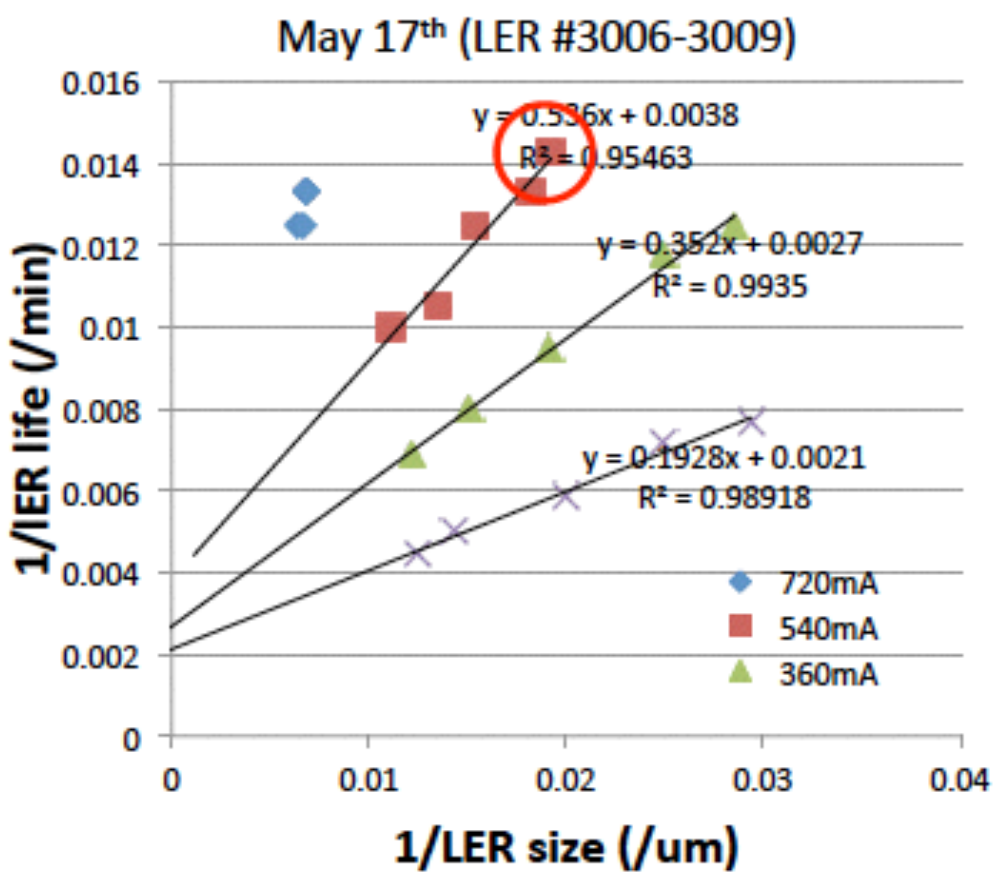
A. Beaulieu

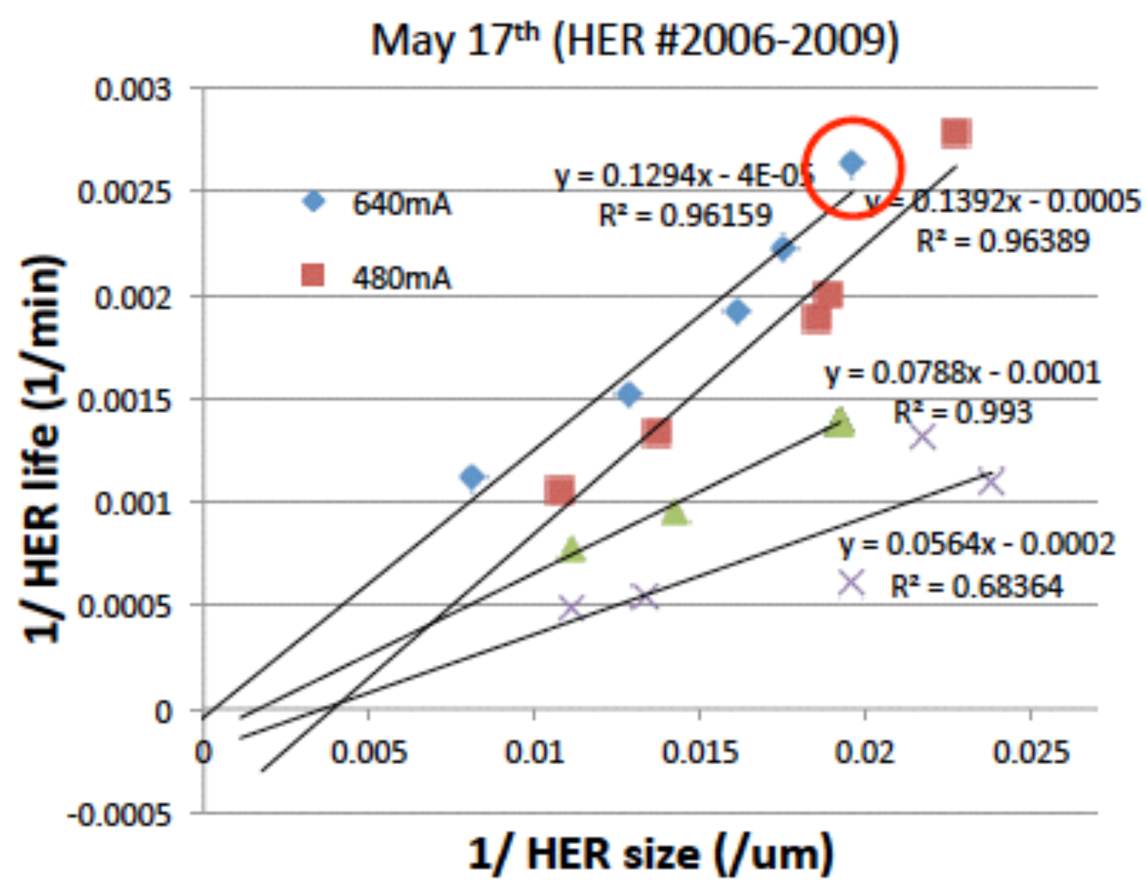
BEAST data shows the LER backgrounds decreasing as vacuum scrubbing proceeds.

Courtesy of H. Nakayama

4. Beam background

➤ Measured Touschek lifetime





	Measured Touschek life	Measured Touschek rate	Simulation (scaled to study condition)
LER (I_b=0.34mA, I=540mA, σ_y=56um)	~100 min	5.9GHz (ring total)	3.6~5.0 GHz
HER(I_b=0.41mA,I=640mA,σ_y=62um)	~400 min	1.7GHz (ring total)	0.6~0.9 GHz

LER loss rate seems consistent. HER might be also consistent if HER X-ray monitor overestimates beam size by factor of 2~3.

Courtesy of H. Nakayama

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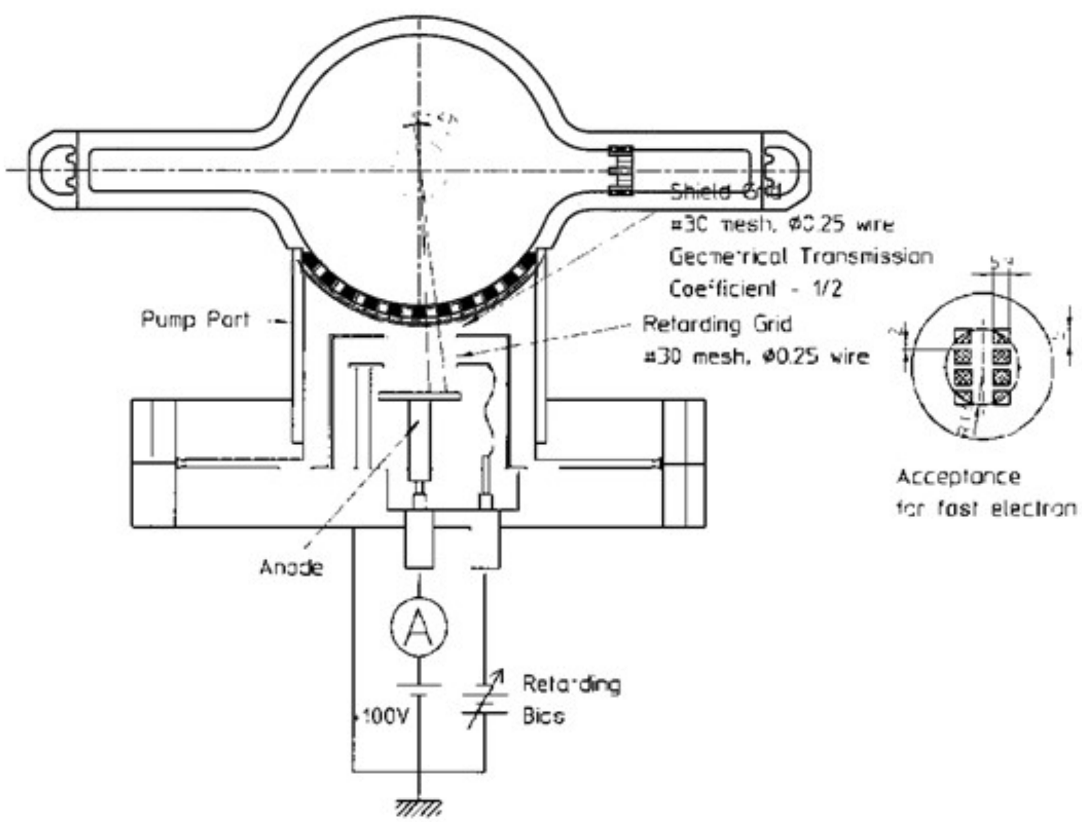
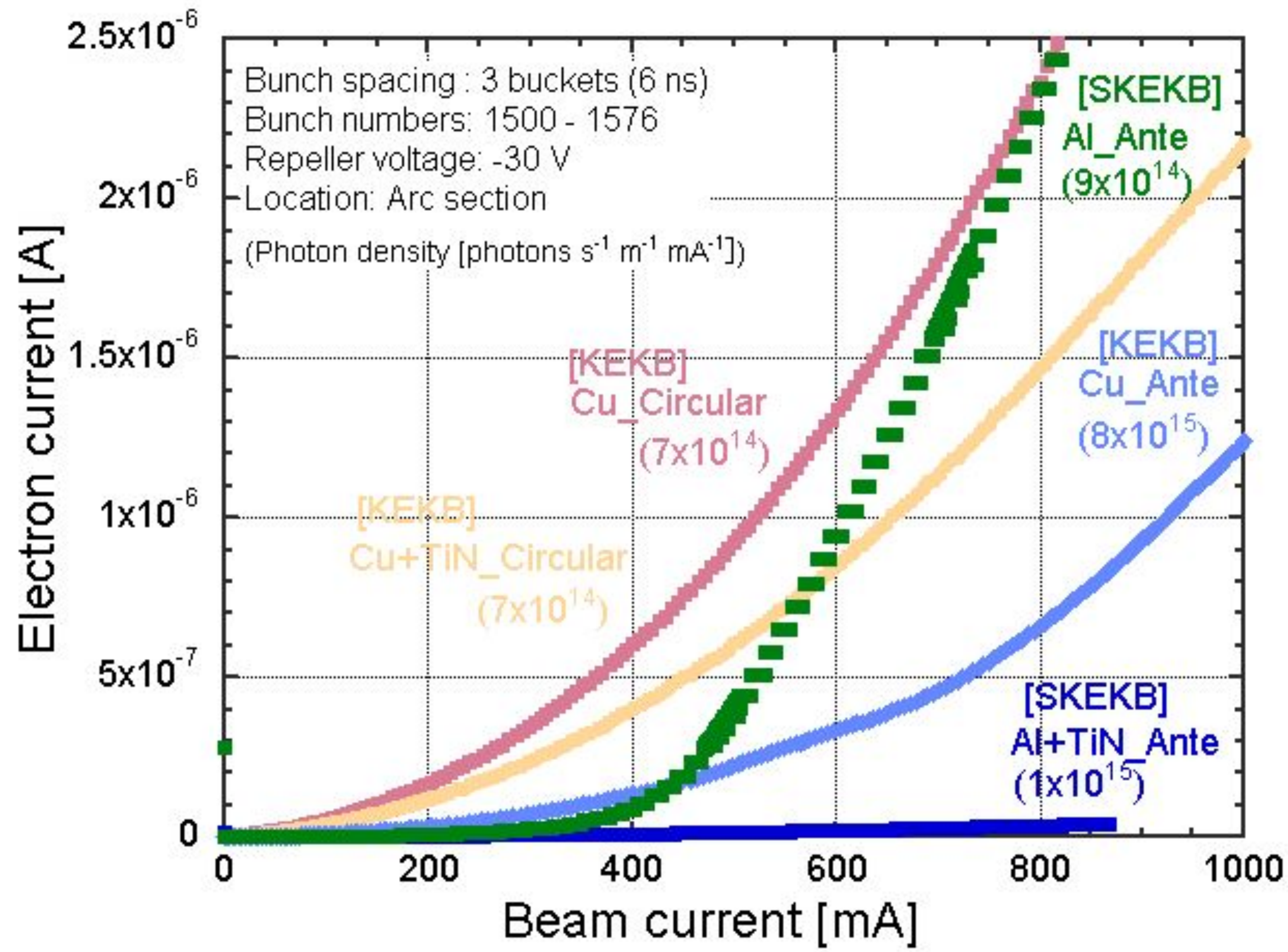
5. Electron cloud

➤ Effect of antechamber and TiN coating in LER

- Use electron current monitor to detect e-cloud
- Compared with KEKB
- When I_{beam}<400mA, e-cloud well suppressed
- When I_{beam}>500mA, e-clould build up w/o TiN coating



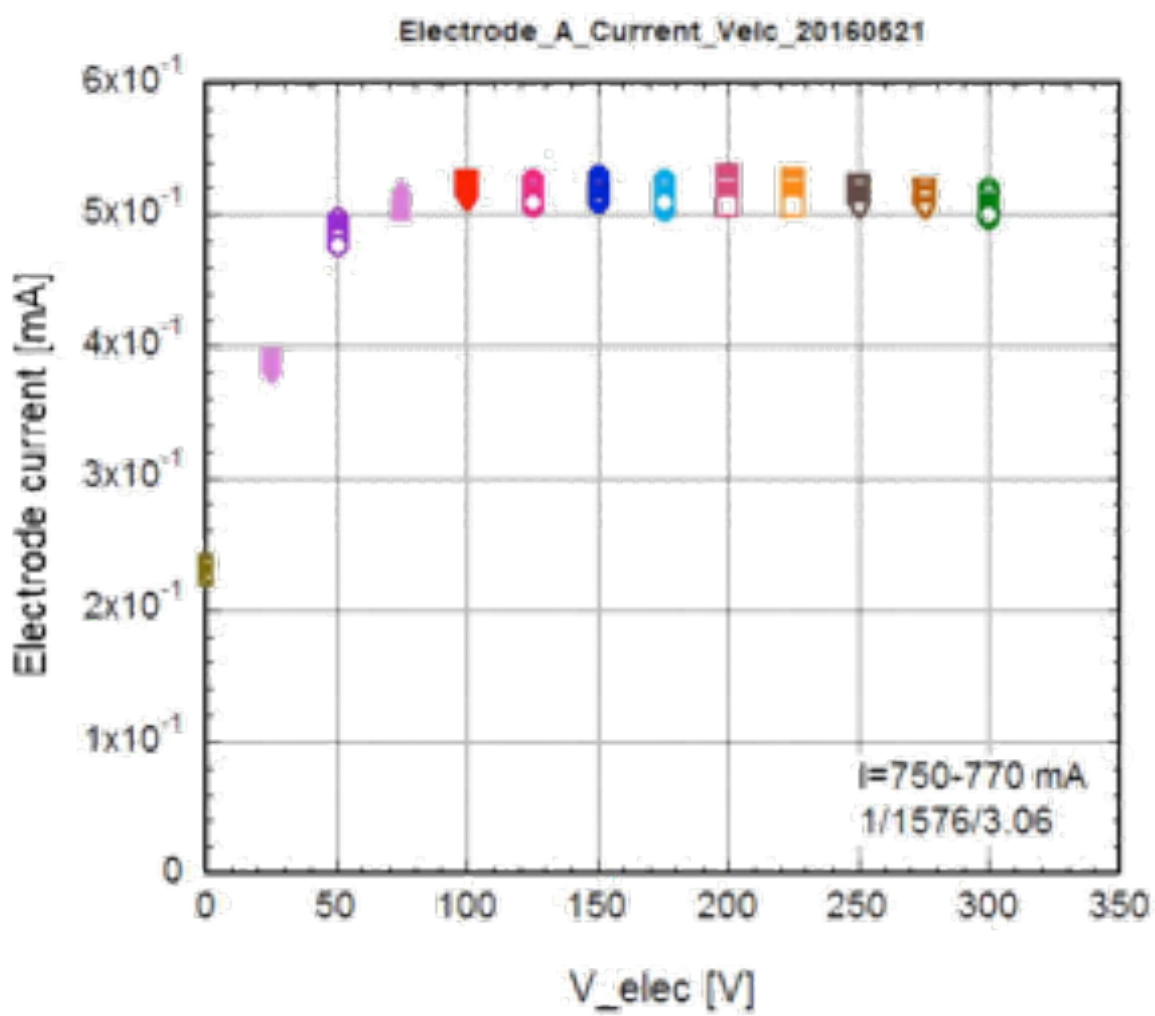


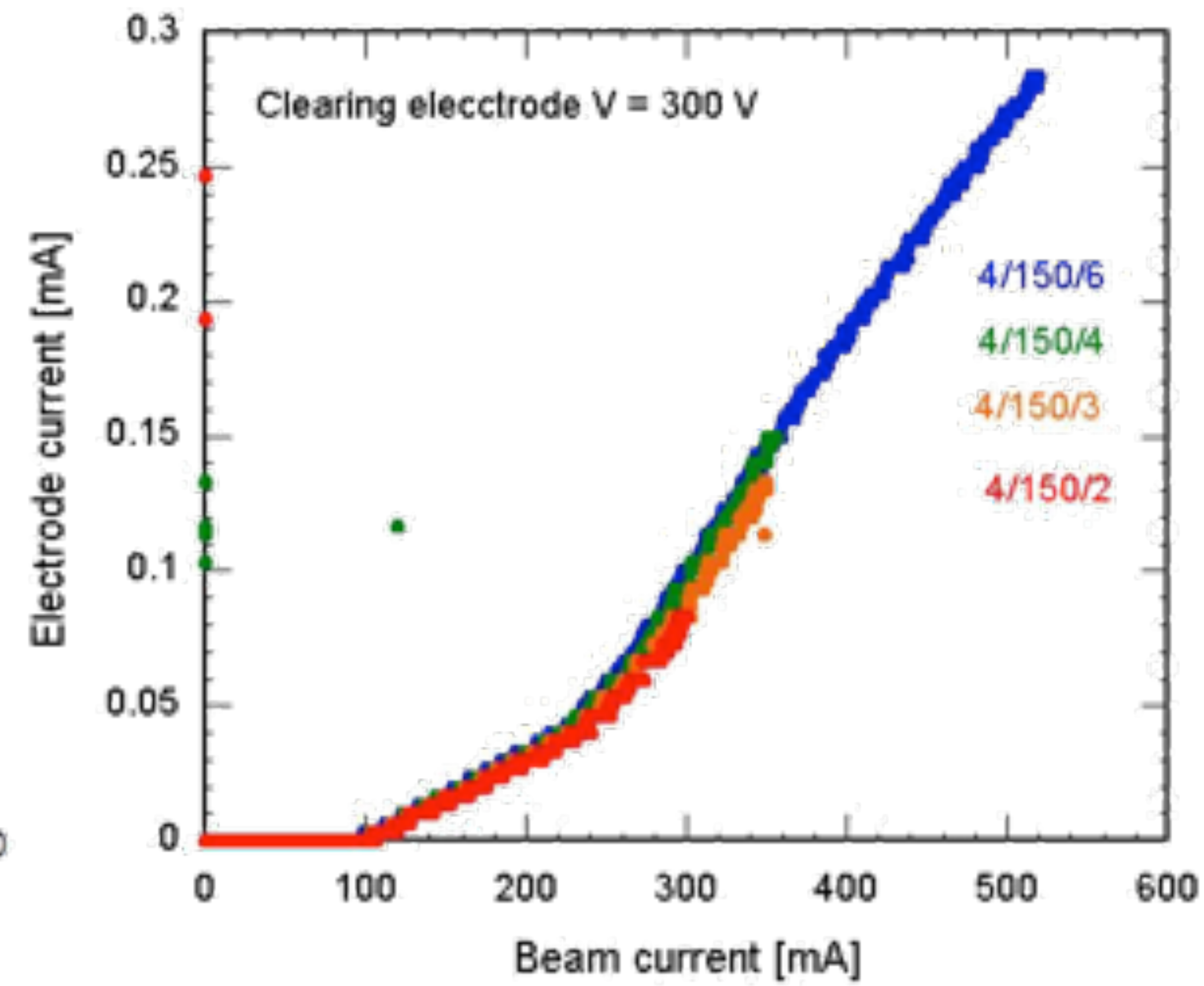
Courtesy of Y. Suetsugu

5. Electron cloud

➤ Effect of clearing electrodes in LER

- Clearing electrodes installed in the wiggler sections
- Use electron current monitor to detect e-cloud
- Fixed beam current: Electron current saturates at ~100 V
- Fixed DC 300 V: Electron current independent of filling pattern => Likely evidence of secondary photoelectron





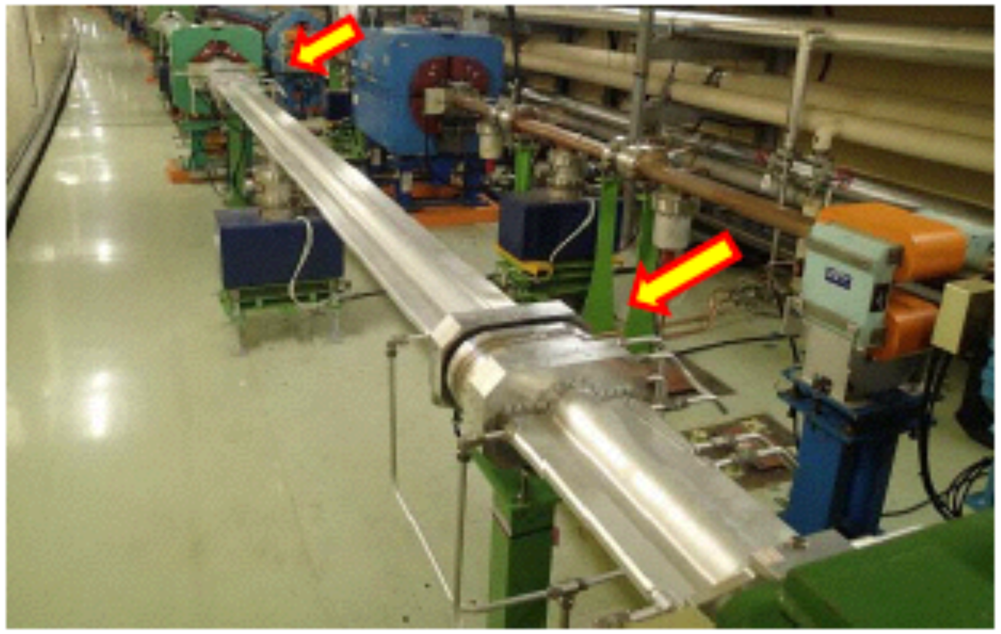
Courtesy of Y. Suetsugu

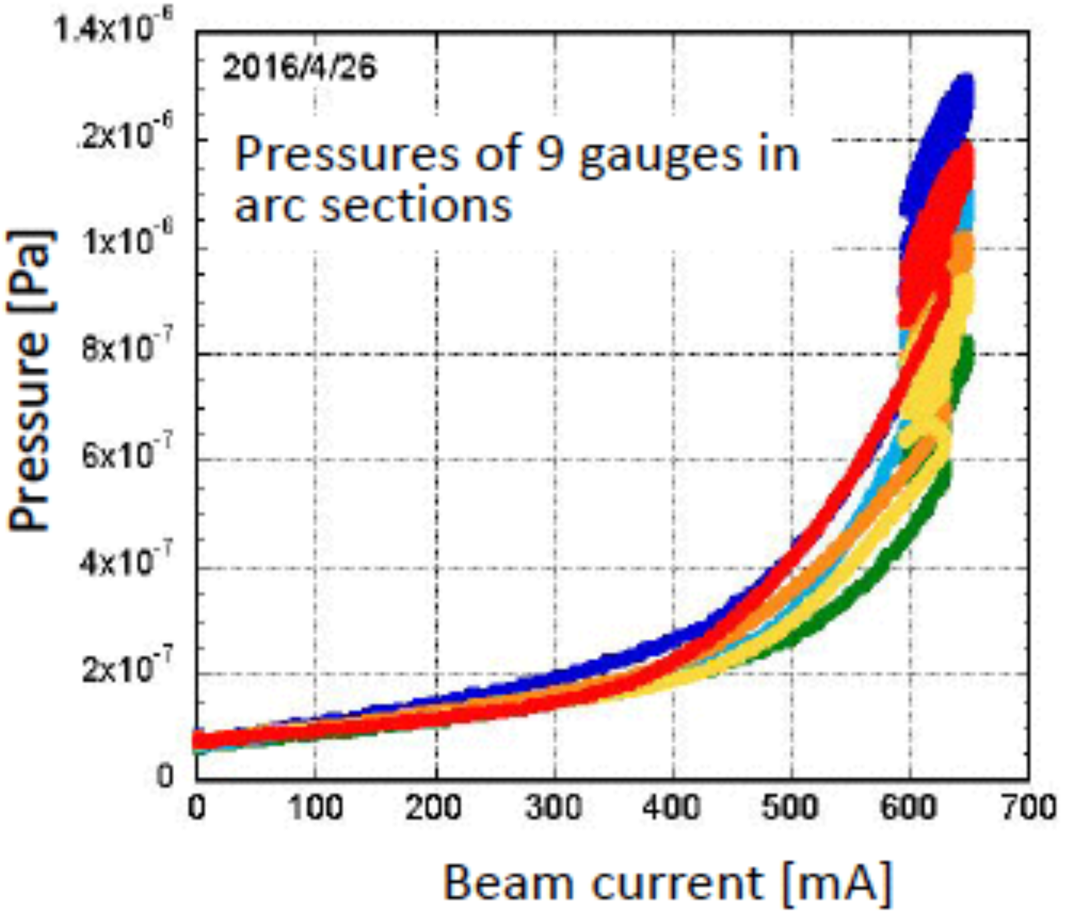
5. Electron cloud

➤ Nonlinear pressure rise caused by aluminium bellows

- **Bellows fabricated w/o TiN coating**

- Non-linear pressure rise against the beam current in LER
- The behavior is quite similar to that of electron currents measured at aluminum parts without TiN coating.
- Actually, we have aluminum bellows chambers without TiN coating along the ring. The bellows chamber has a length of 0.2 m and located every 3 m on average. ~5 % in the ring.





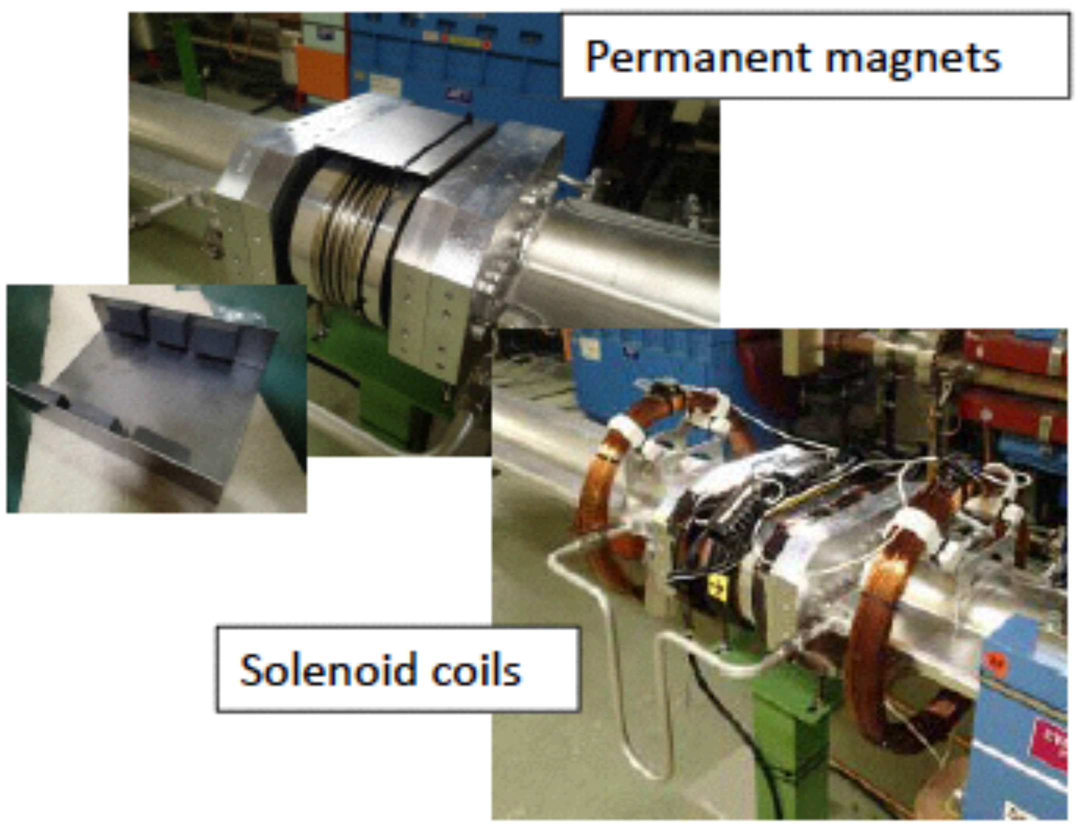
Courtesy of Y. Suetsugu

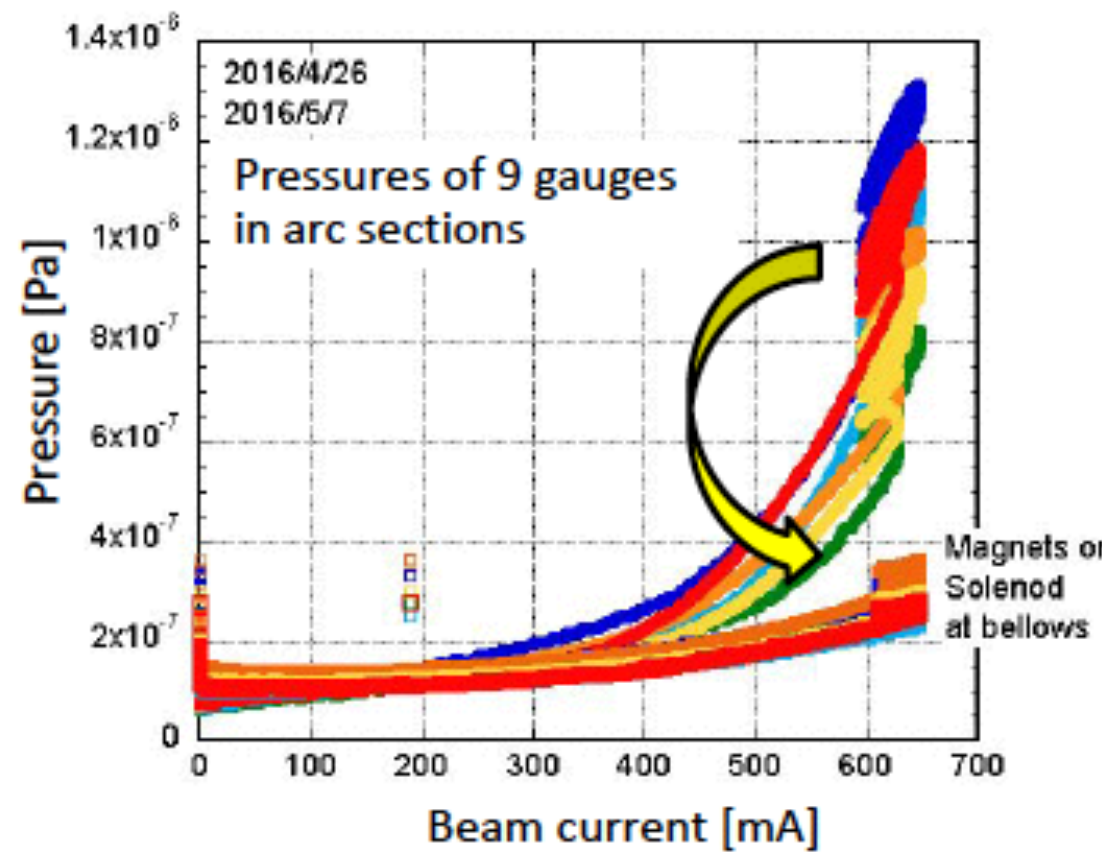
5. Electron cloud

➤ Nonlinear pressure rise caused by aluminium bellows

- Countermeasures: permanent magnets or solenoid windings

- Non-linear pressure rise against the beam current in LER
- As a test, we applied a magnetic field of axial direction by solenoids or permanent magnets at nine aluminum bellows chambers (~30 m section). The strength is 40 ~ 100 G near the inner wall at the center of bellows.
- As a result, the rate of pressure rise at this section relaxed!



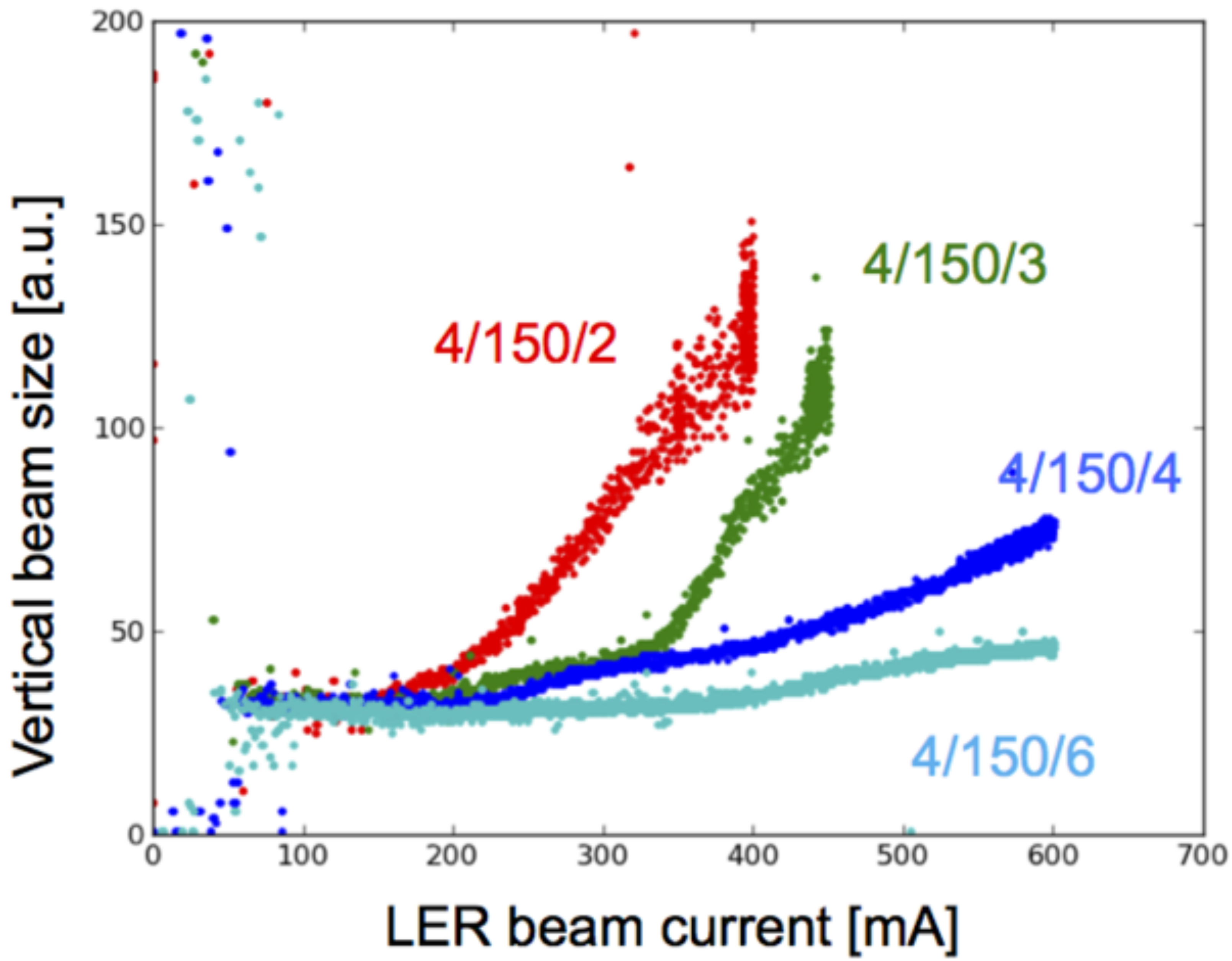


Courtesy of Y. Suetsugu

5. Electron cloud

➤ Vert. beam-size blowup (from XRM) in LER

- Threshold: depend on filling pattern and increase with vacuum scrubbing
- Varied conditions: # of trains, # of bunches in each train, # of buckets for bunch spacing



Courtesy of Y. Suetsugu

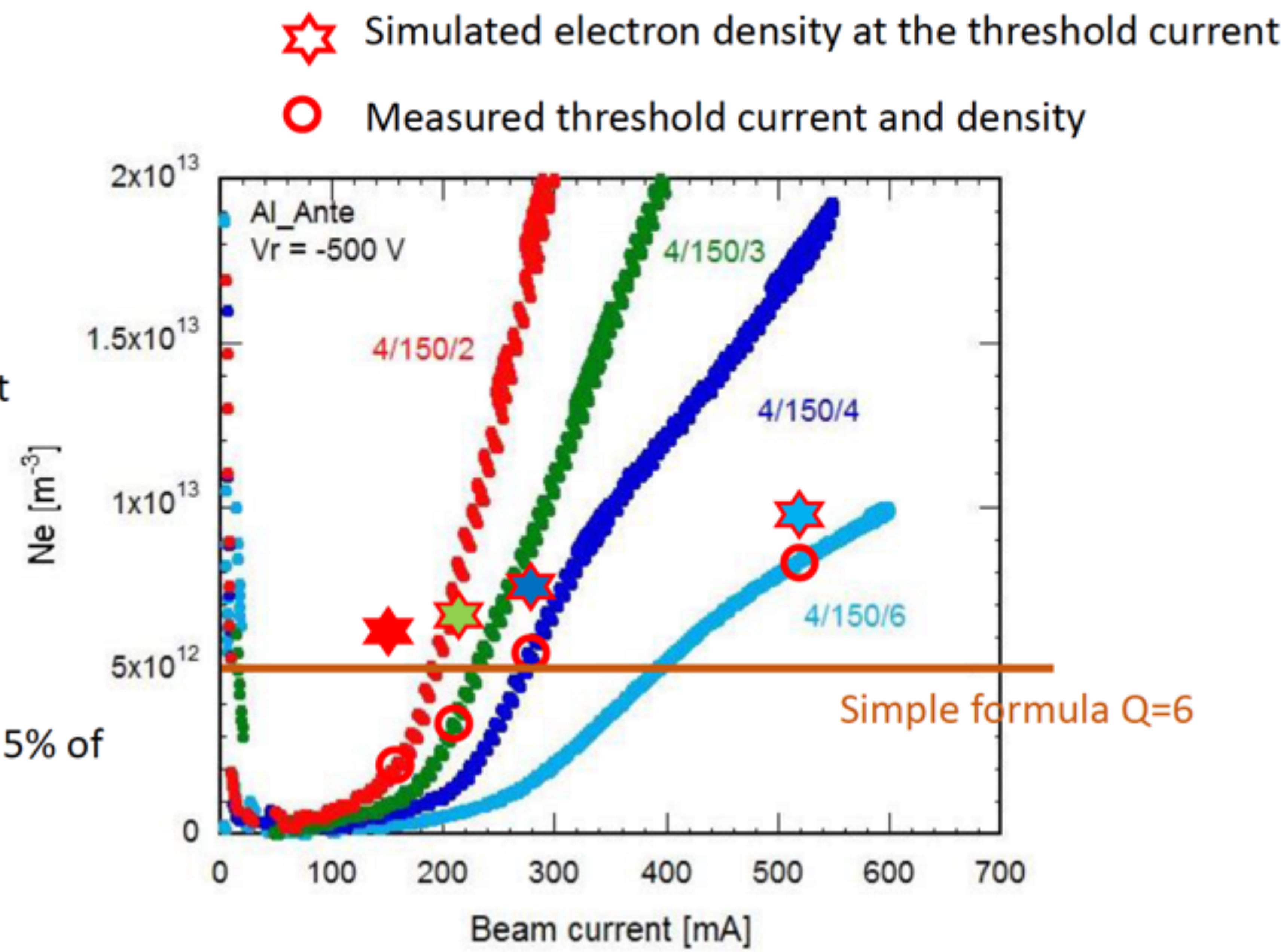
5. Electron cloud

➤ Electron cloud density at the blowup threshold

- Before installation of permanent solenoid at bellows
- Varied conditions: # of trains, # of bunches in each train, # of buckets for bunch spacing

Only Al part

Bellows occupy 5% of total circumf.

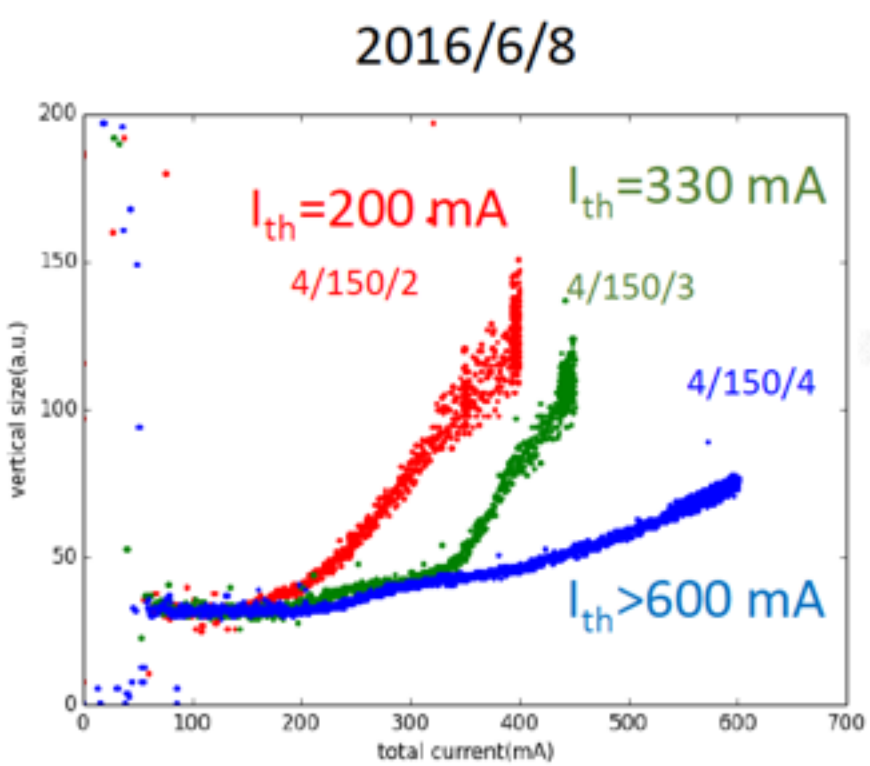


Courtesy of K. Ohmi

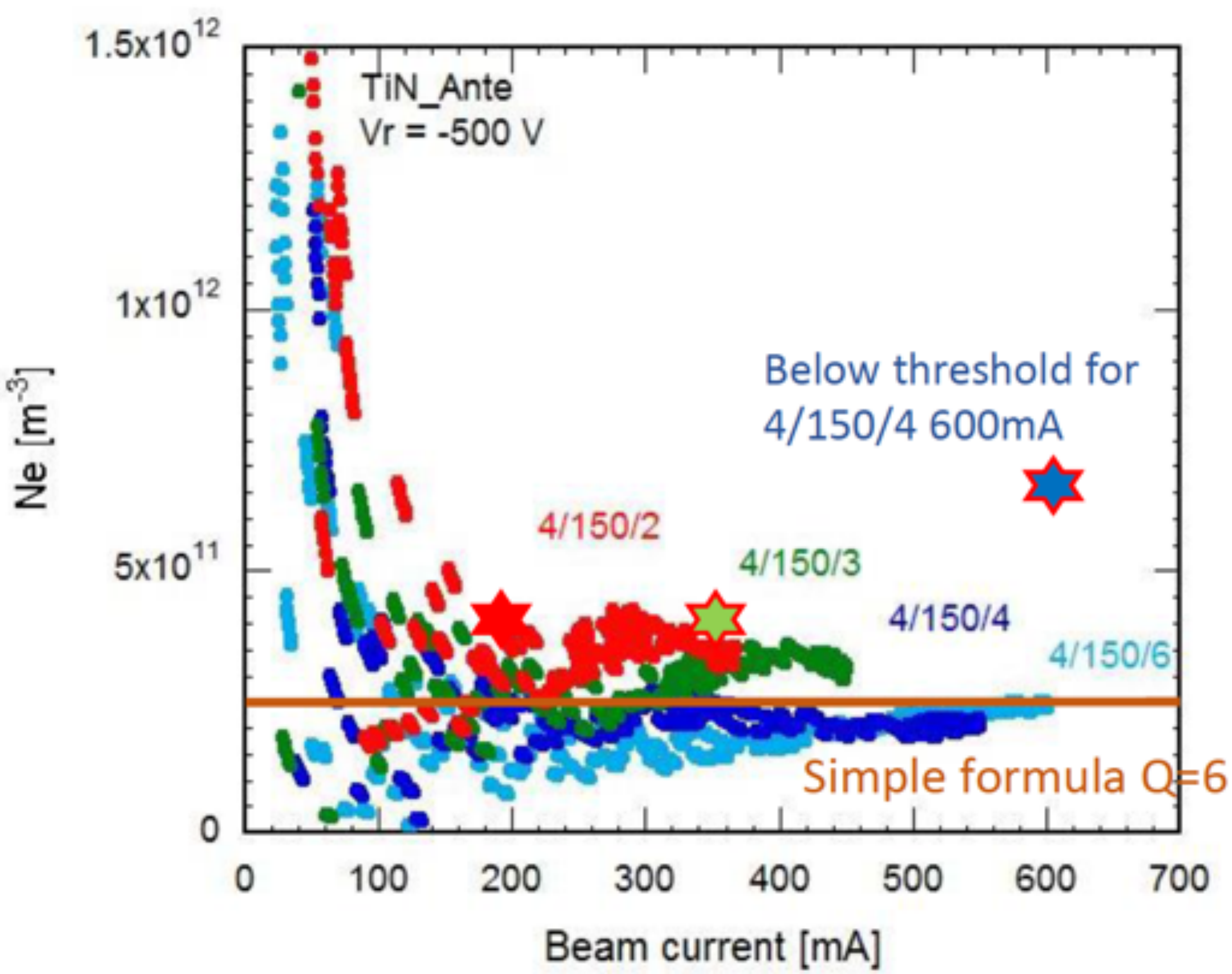
5. Electron cloud

➤ Electron cloud density at the blowup threshold

- After installation of permanent solenoid at bellows
- Varied conditions: # of trains, # of bunches in each train, # of buckets for bunch spacing



Simulated electron density at the threshold current



Courtesy of K. Ohmi

Outline

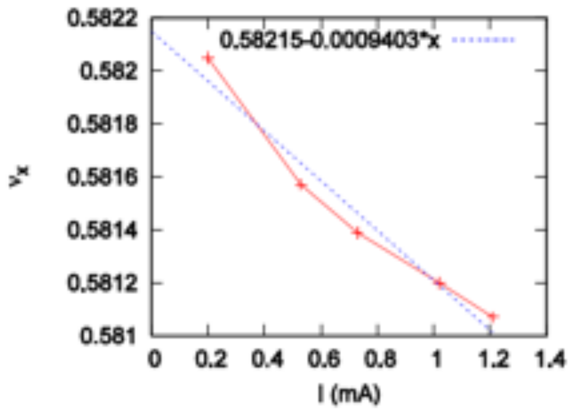
- Introduction
- Phase I commissioning
  - Vacuum scrubbing
  - Low emittance tuning
  - Beam background
  - Electron cloud
  - Impedance
- Plan for Phase II and III commissioning
- Summary

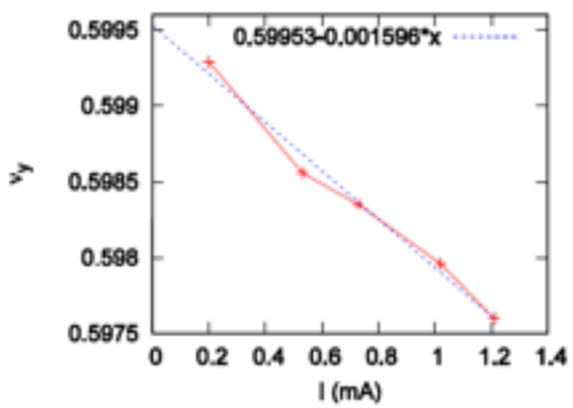
6. Impedance

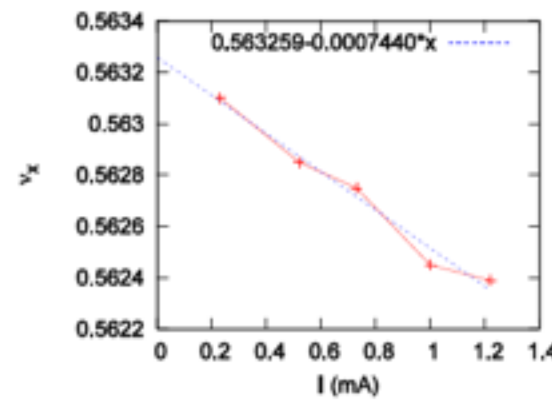
➤ Transverse impedance

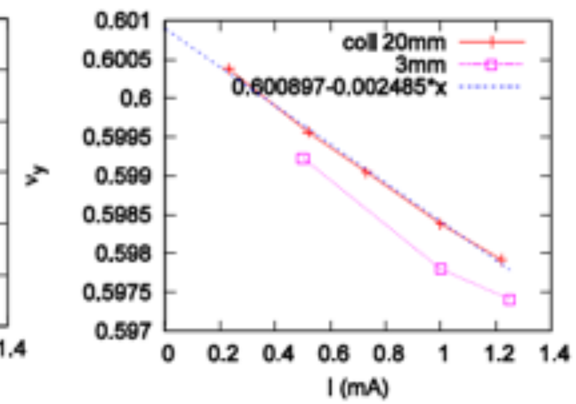
- **Tune shift as function of bunch current**

$$\Delta\nu_x = \frac{1}{4\pi^{3/2}}\frac{Nr_e}{\gamma}\frac{L}{\nu_x\sigma_z}\frac{iZ_{eff}}{Z_0} \qquad iZ_{eff}(k\Omega) = 33.3\frac{\Delta\nu_x}{I(mA)} \text{ LER} \qquad = 58.2\frac{\Delta\nu_x}{I(mA)} \text{ HER}$$



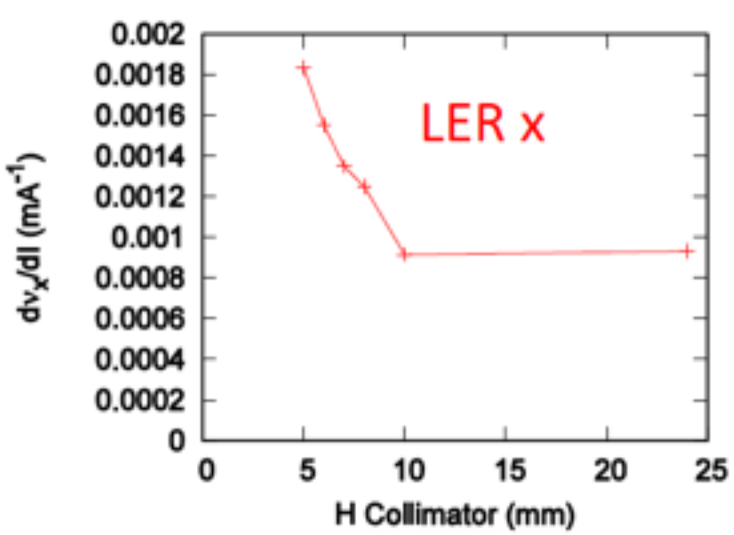


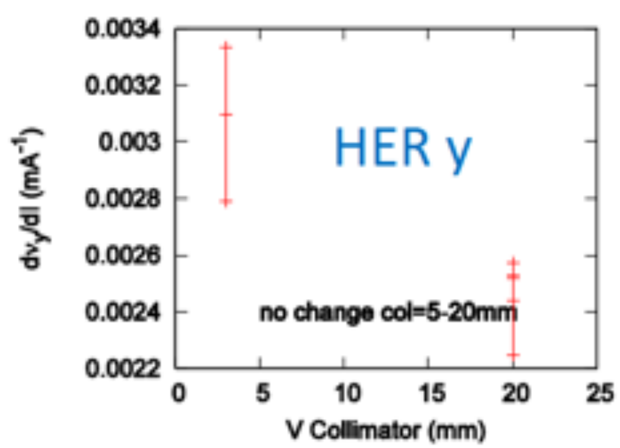




$iZ_{eff} = 31\ (x) \quad 53\ (y)\ \ k\Omega/m$

$iZ_{eff} = 43\ (x) \quad 145\ (y)\ \ k\Omega/m$





Collimator dependence

KEKB-LER: -0.0034mA^{-1}, 81kΩ/m

coll. open 33-46 kΩ/m T. Ieiri, EPAC00

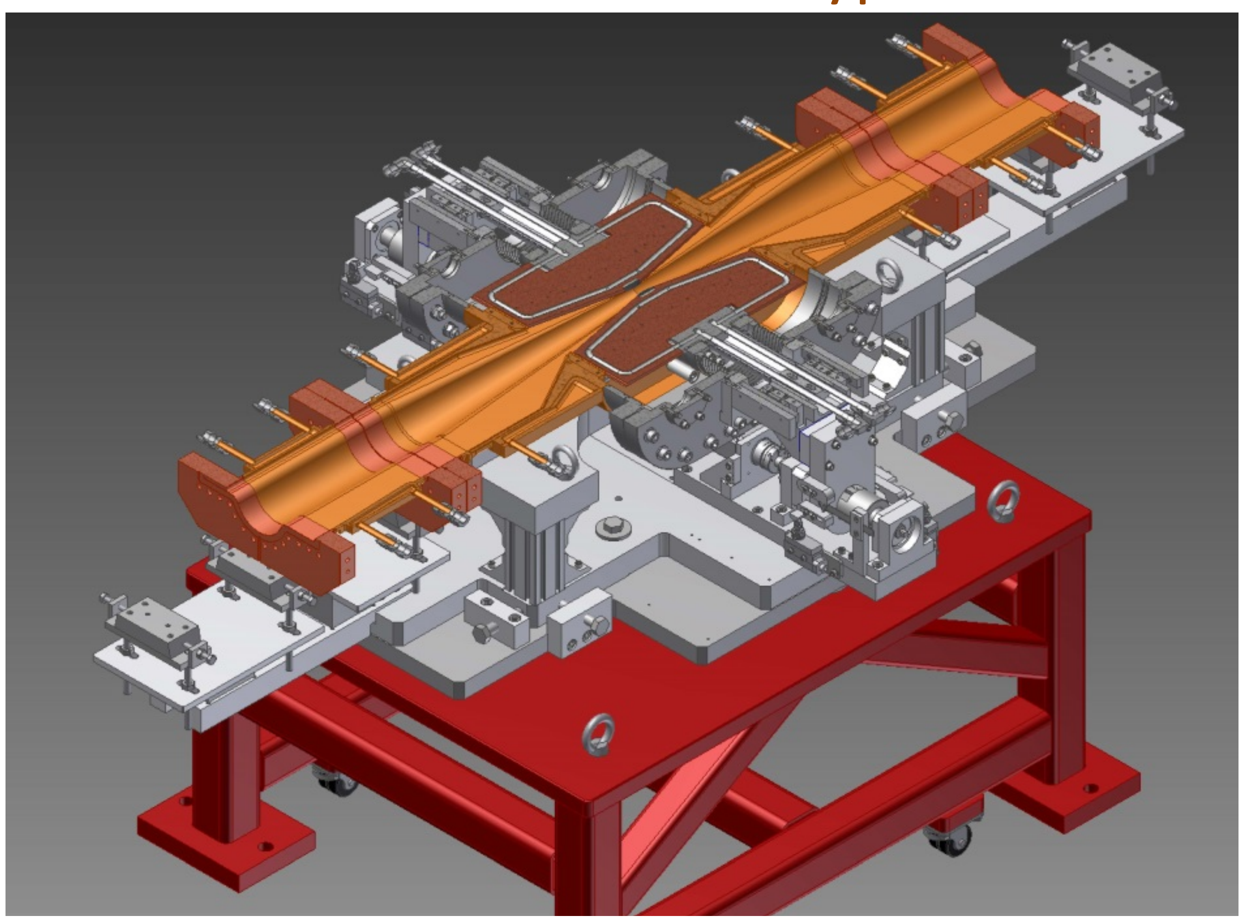
Courtesy of K. Ohmi

6. Impedance

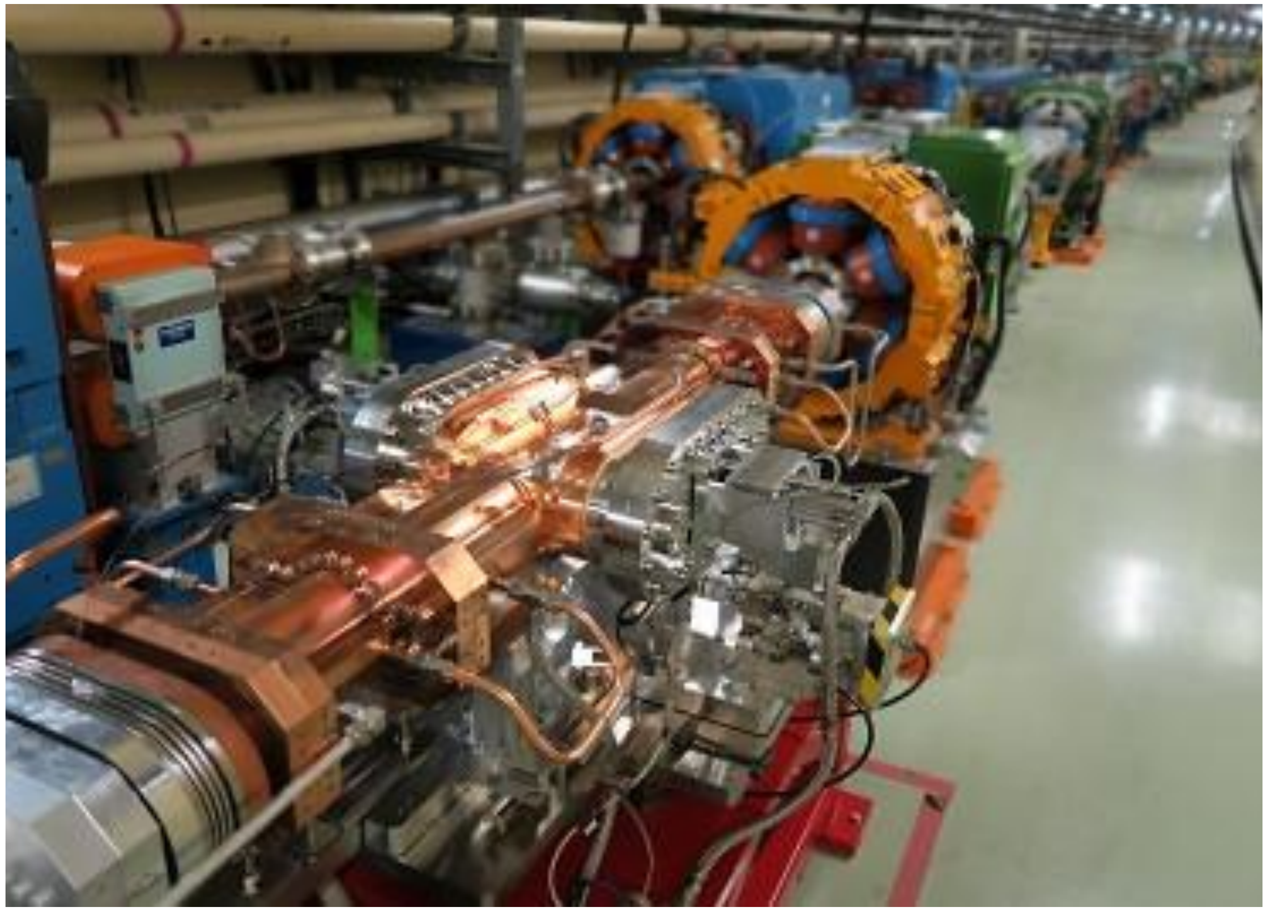
➤ Collimator

- Two PEP-II type collimators fabricated and installed to LER
- Tested with beam => Worked well and no excess heating at bellows behind
- Transverse impedance simulated and compared with measurement in tune shift => Good agreement

Schematic of a horizontal-type collimator



Collimator installed in the tunnel



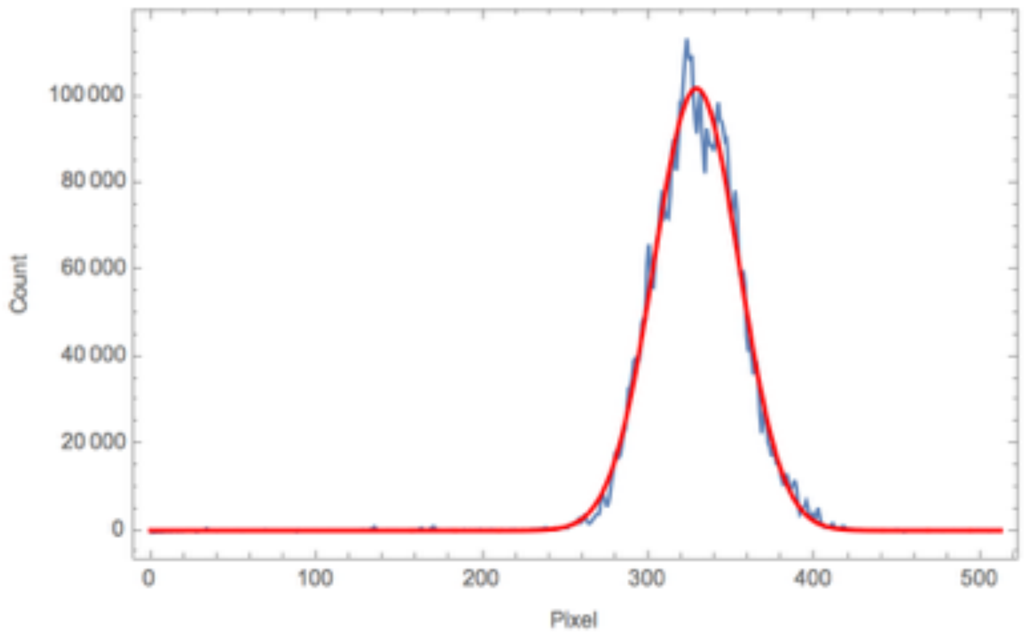
Courtesy of Y. Suetsugu

6. Impedance

➤ Longitudinal impedance

- Measure bunch lengthening using streak camera
- Asymmetric Gauss fitting (Mathematica)
- Compare with MWI simulations

$$\psi(z) = I_0 * e^{-\frac{(z-\bar{z})^2}{2[1+\text{sign}(z-\bar{z})A]^2\sigma^2}} + I_1$$



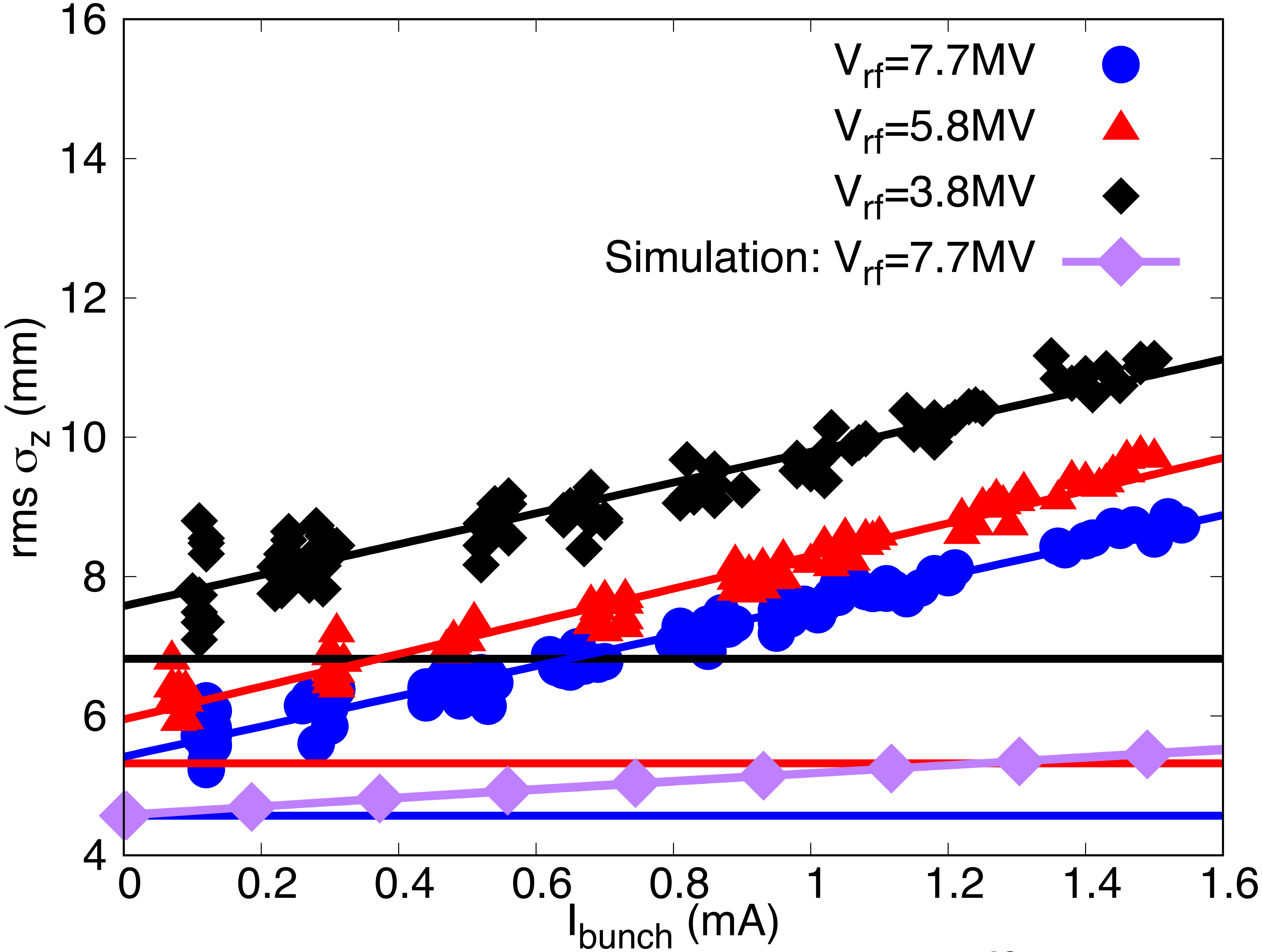
➤ RF tuning

- RF voltages are measured via power meter. The uncertainty of RF voltage for each cavity is ~±5%
- The RF phase for each cavity is tuned to maximise the measured synchrotron tune
- The RF phase is automatically determined by the balance between RF acceleration and SR+HOM loss.
- After RF phase optimization, measured synch. tune is compared with analytic formula => Good agreement at low bunch current

6. Impedance

➤ Longitudinal impedance: LER

- Fitting model: $f(I_b)=a*I_b+b$
- σ_z from SAD simulation: 4.6, 5.3, 6.8mm at zero current
- Large discrepancy in zero-current bunch length between SAD simulation and measurements



$f_1(I_b)=5.41+2.17I_b$

$f_2(I_b)=5.95+2.35I_b$

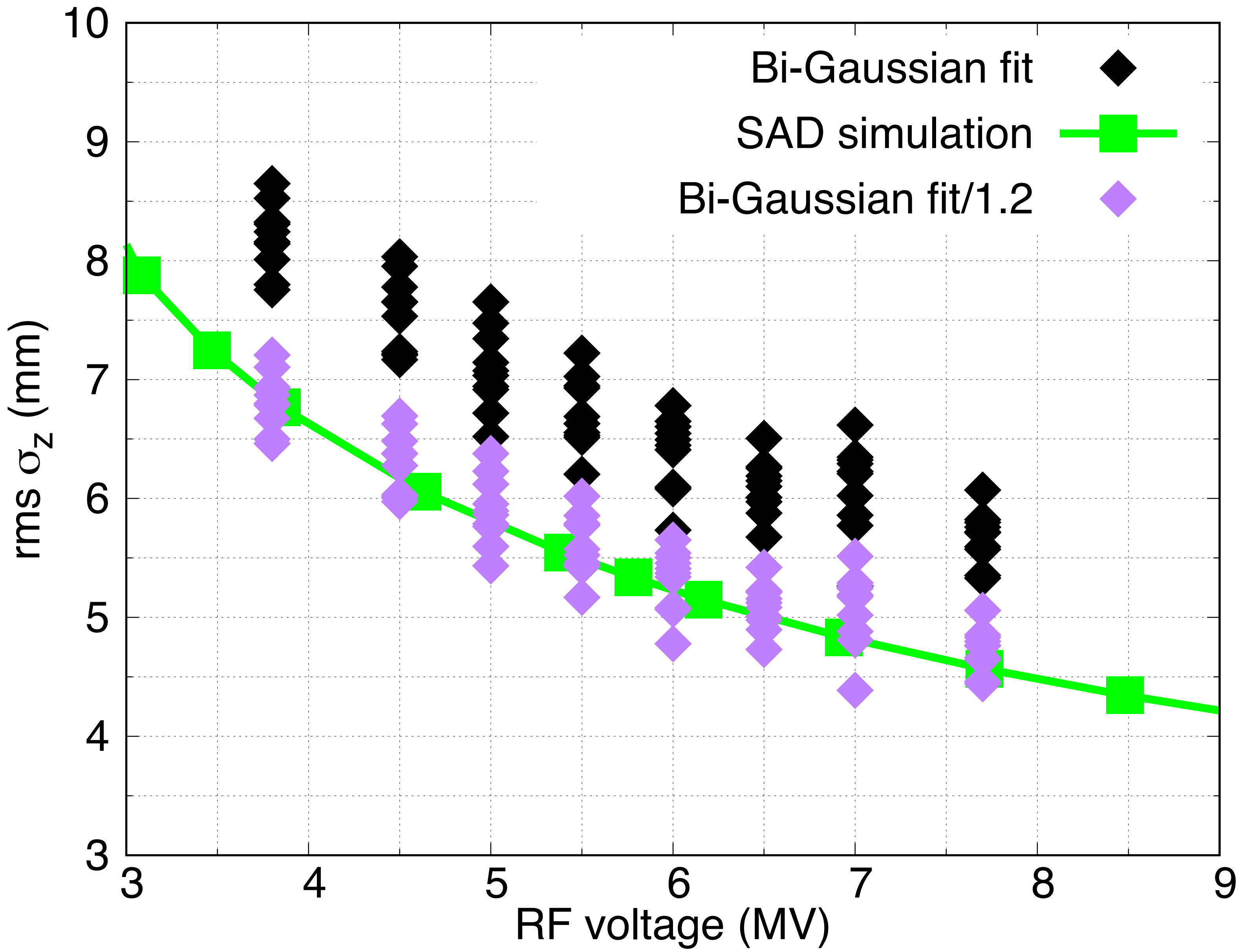
$f_3(I_b)=7.58+2.21I_b$

$f_4(I_b)=4.58+0.59I_b$

6. Impedance

➤ Longitudinal impedance: LER

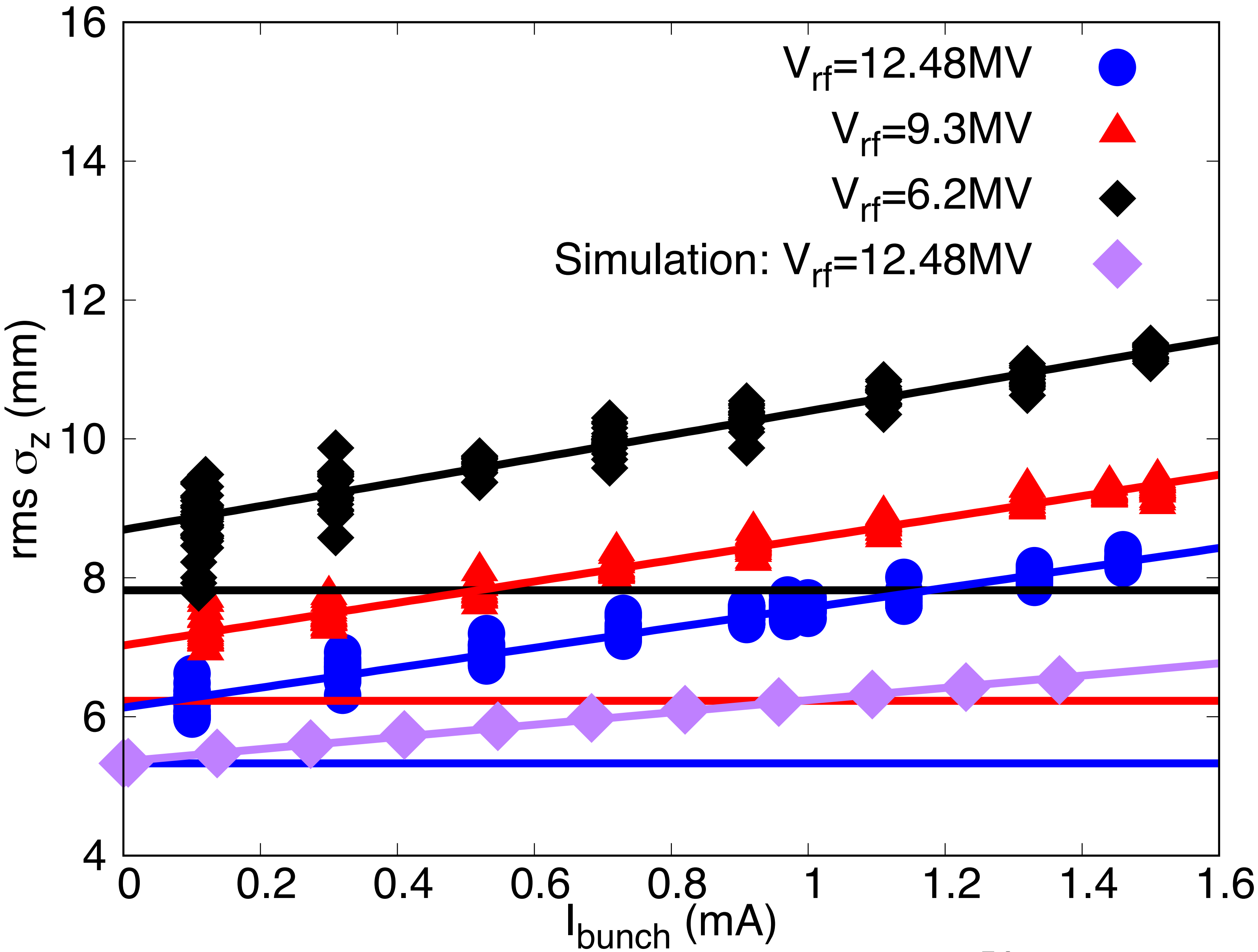
- Bunch length as function of RF voltage
- Bunch current 0.25->0.11mA (V_{rf}=3.8->7.7MV)
- Measured bunch length ~20% larger than model => Systematic error in stream camera system?



6. Impedance

➤ Longitudinal impedance: HER

- **Fitting model: $f(I_b)=a*I_b+b$**
- **σ_z from SAD simulation: 5.3, 6.2, 7.8mm at zero current**
- **Large discrepancy in zero-current bunch length between SAD simulation and measurements**



$f_1(I_b)=6.13+1.44I_b$

$f_2(I_b)=7.03+1.54I_b$

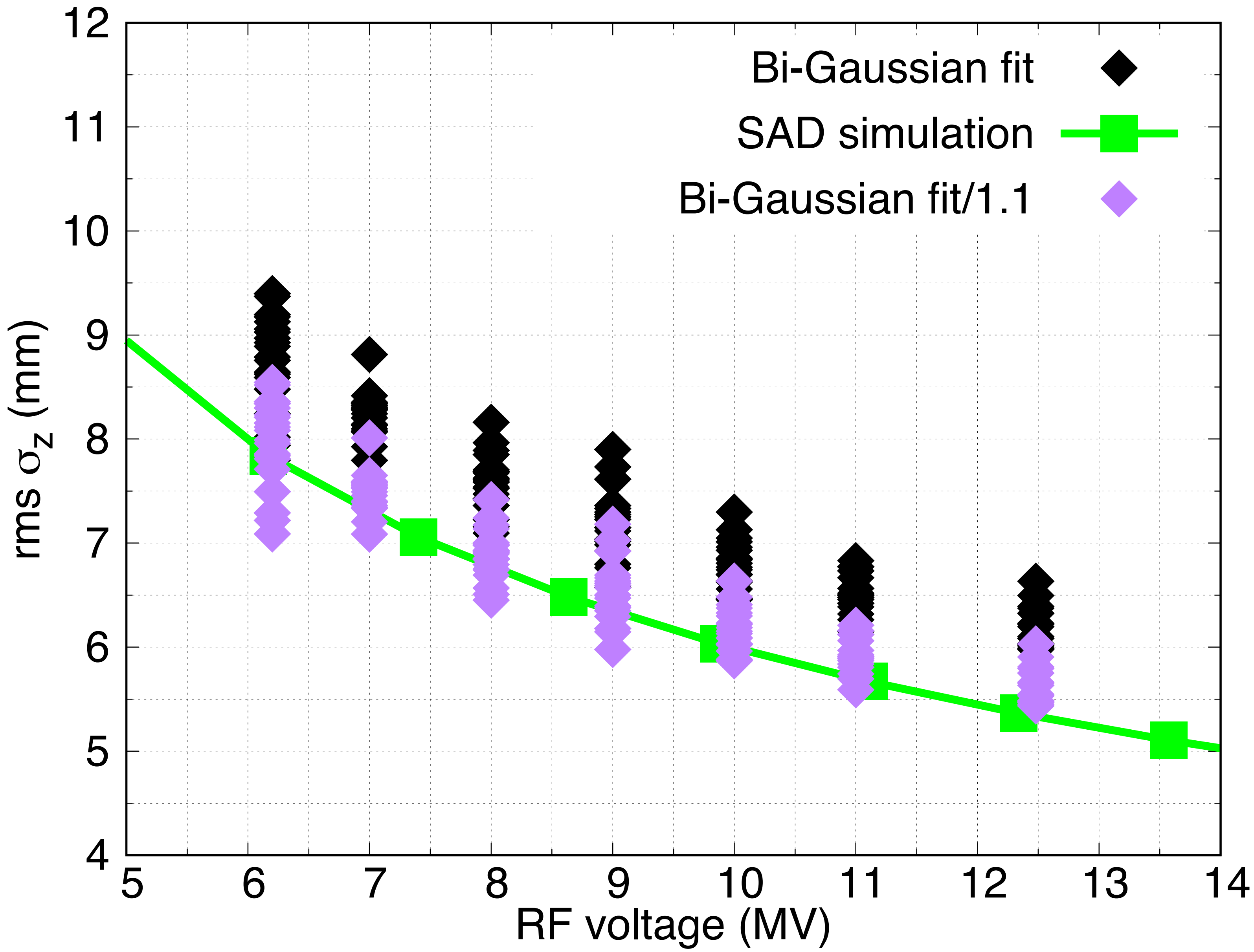
$f_3(I_b)=8.69+1.71I_b$

$f_4(I_b)=5.34+0.88I_b$

6. Impedance

➤ Longitudinal impedance: HER

- **Bunch length as function of RF voltage**
- **Bunch current 0.11->0.1mA (V_{rf}=6.2->12.48MV)**
- **Measured bunch length ~10% larger than model => Systematic error in stream camera system?**



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7. Plan for Phase II and III commissioning

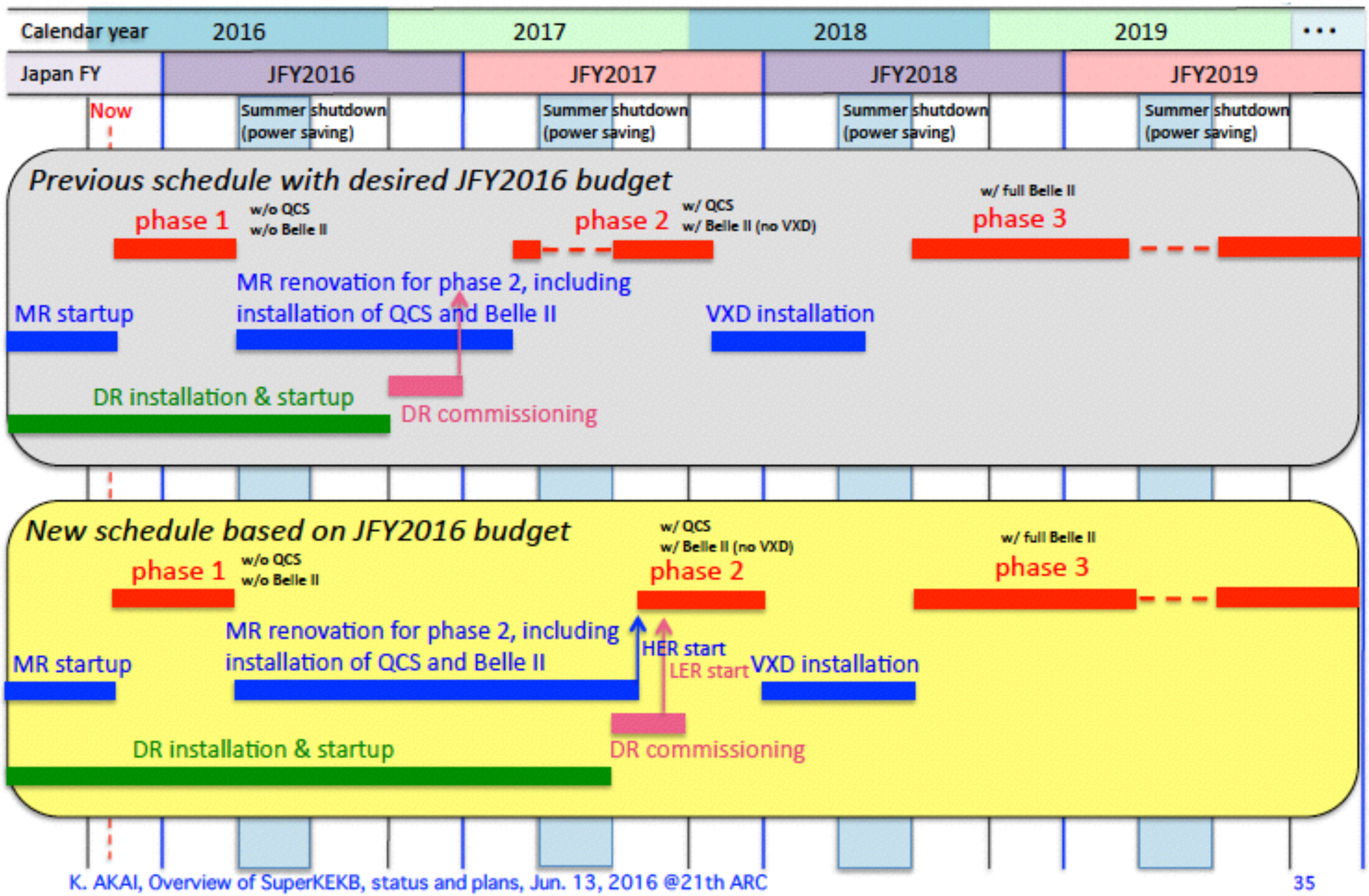
➤ From Phase I to Phase II

- After phase 1 operation ends, renovation of MR from phase 1 to phase 2 will be conducted, which starts in July 2016.
  - QCS and Belle II installation and related works
    - Installation of QCS, cabling, piping, cool down, refrigerator test, and field measurements
    - Belle II roll-in
  - Related work to change IR configuration
    - Floor leveling, change concrete shields, remove/set normal-conducting magnets, etc.
  - More collimators
    - Two collimators are used in LER for phase 1. Six collimators will be added for phase 2.
    - Furthermore, after phase 2, more collimators are planned to be added.
  - Change injection part of LER
    - Septums and some vacuum components need to be changed to adopt low-emittance beam from DR and to match to smaller aperture at the IR.
  - Other improvements in LER and HER.
    - More turn-by-turn BPM detectors
    - Solenoid windings for electron-cloud, etc.
- Installation and startup of accelerator components for DR continues to start DR commissioning prior to (or during) phase 2.

Courtesy of K. Akai, KEKB MAC 2016

7. Plan for Phase II and III commissioning

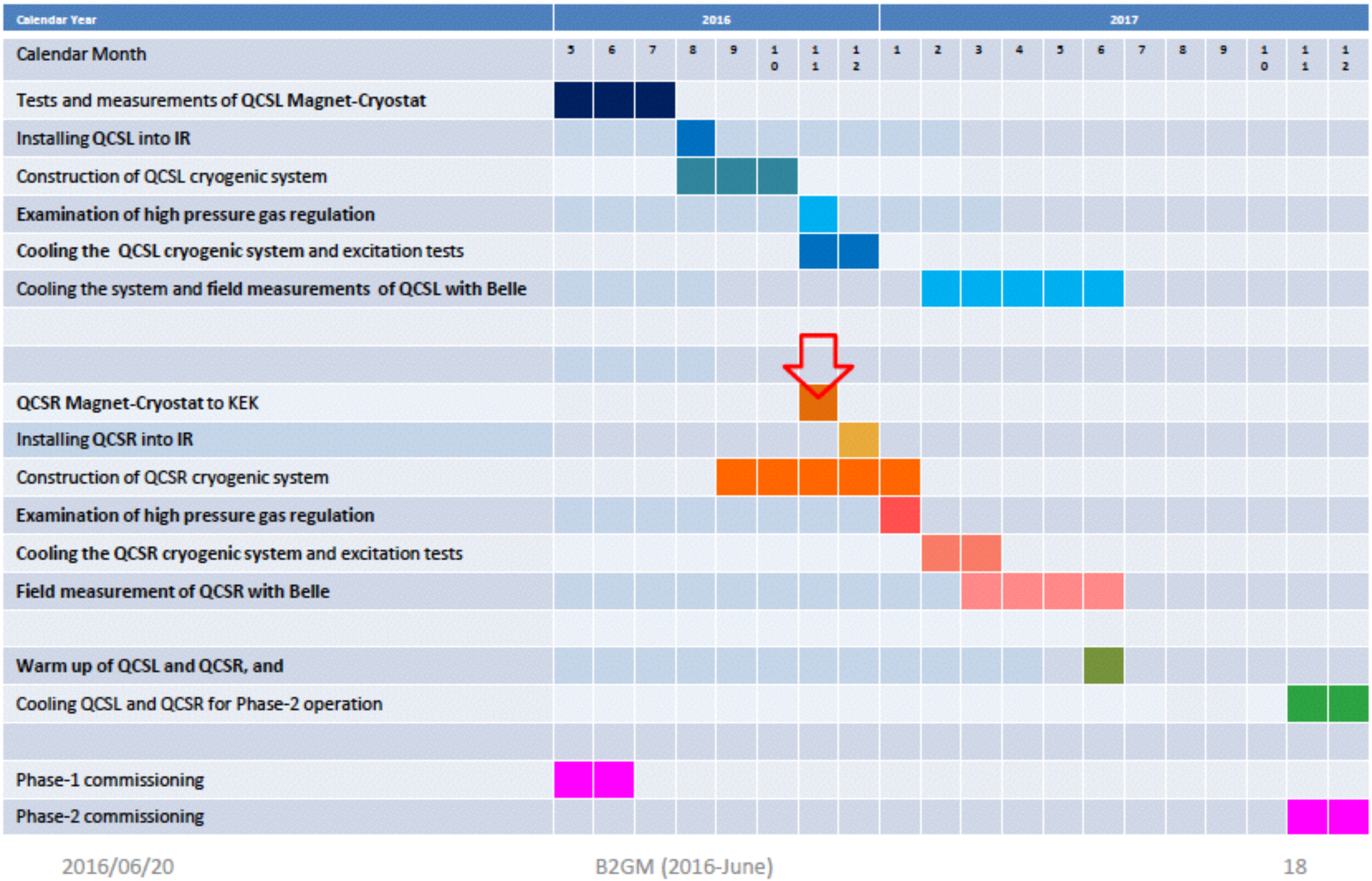
➤ Operation schedule



Courtesy of K. Akai, KEKB MAC 2016

7. Plan for Phase II and III commissioning

➤ Schedule for IR construction



 Courtesy of N. Ohuchi, 24th B2GM, Jun. 2016

7. Plan for Phase II and III commissioning

➤ Machine parameters

- **Phase II target: 1×10^{34} cm^{-2}s^{-1}**

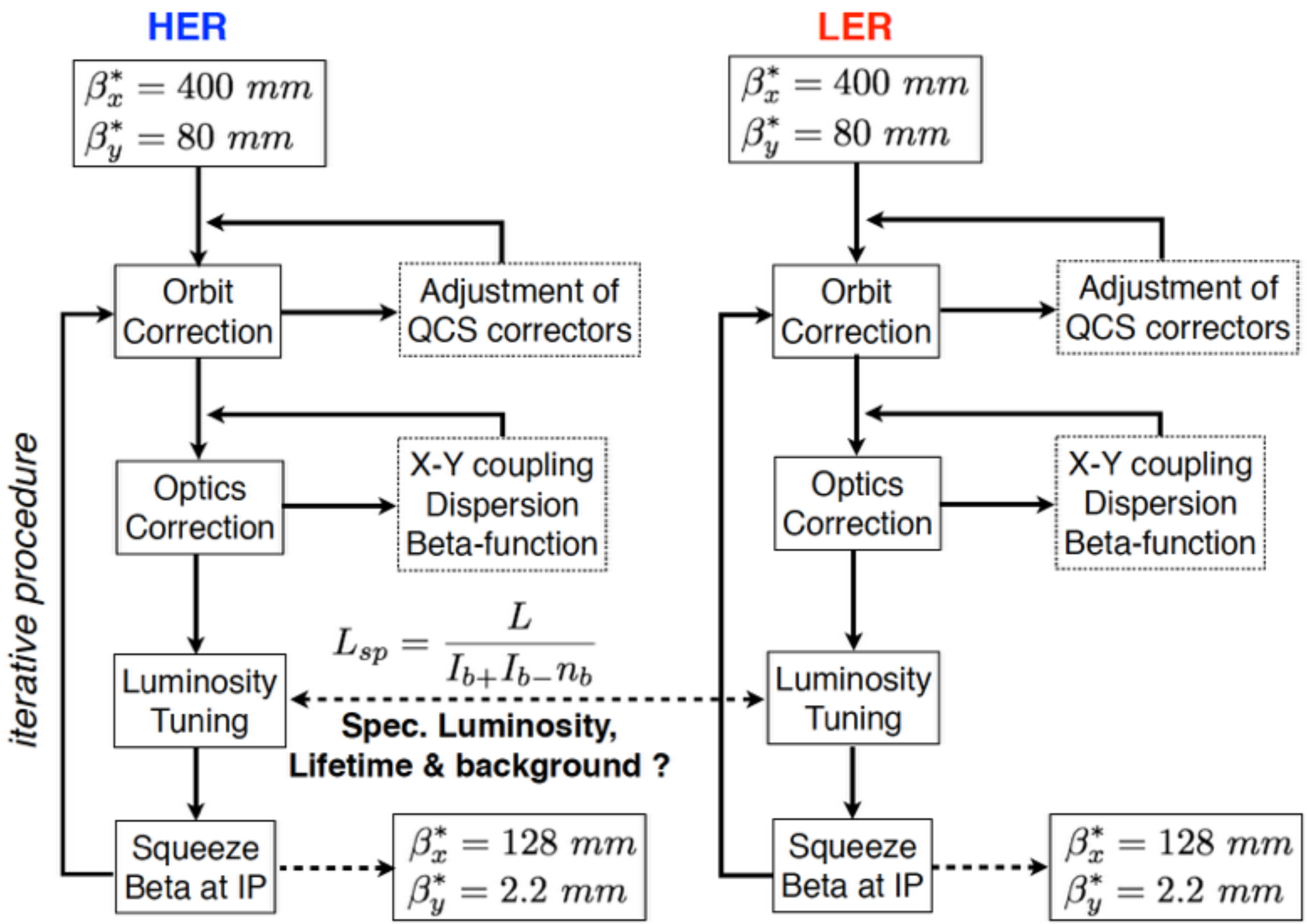
Parameters	symbol	Phase 2.x		Phase 3.x		unit
		LER	HER	LER	HER	
Energy	E	4	7.007	4	7.007	GeV
#Bunches	n_b	1576		2500		
Emittance	ε_x	2.0	4.6	3.2	4.6	nm
Coupling	$\varepsilon_y/\varepsilon_x$	5	5	0.27	0.28	%
Hor. beta at IP	β_x^*	128	128	32	25	mm
Ver. beta at IP	β_y^*	2.2	2.2	0.27	0.30	mm
Beam current	I_b	1.0	0.8	3.6	2.6	A
Beam-beam	ξ_y	0.0228	0.0246	0.088	0.081	
Hor. beam size	σ_x^*	16	24	10	11	μm
Ver. beam size	σ_y^*	470	711	48	62	nm
Luminosity	L	1×10^{34}		8×10^{35}		cm^{-2}s^{-1}

Courtesy of Y. Ohnishi, 24th B2GM, Jun. 2016

7. Plan for Phase II and III commissioning

➤ Optics tuning strategy for Phase II

- **Step-by-step squeezing $\beta_{x,y}^*$**

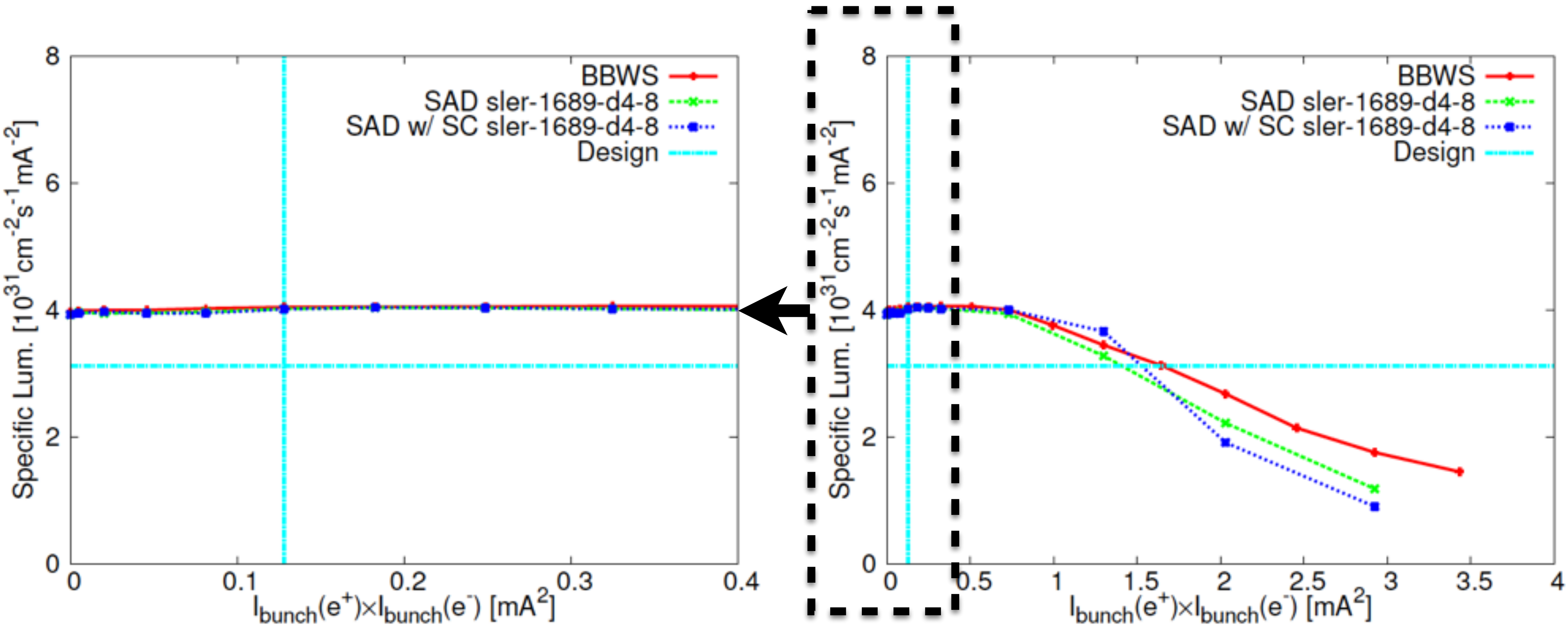


 Courtesy of Y. Ohnishi, 24th B2GM, Jun. 2016

7. Plan for Phase II and III commissioning

➤ **Very optimistic from beam-beam simulations**

- Assume emittance coupling = 2%
- Space-charge effect is not important
- Lattice nonlinearity is not very important
- $L=1\times10^{34}$ $cm^{-2}s^{-1}$ is promising
- Even $L=10\times10^{34}$ $cm^{-2}s^{-1}$ is possible



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8. Summary

➤ **With KEKB experiences, the Phase I commissioning of SuperKEKB went smoothly**

- Hardware tuning
- Vacuum scrubbing
- Beam background

➤ **Low emittance tuning**

- Optics correction well done
- Leakage fields of Lambtrson magnet set an obstacle but not serious
- Vert. emittance <10pm almost achieved
- E-cloud effects unexpected but well understood from simulations

➤ **Some issues to be understood**

- Tune chromaticity in LER
- X-ray monitor measurement in HER
- Streak camera measurement and bunch lengthening
- … …

9. Acknowledgements and References

➤ **Acknowledgements**

- The SuperKEKB commissioning team
- The Belle-II team
- INFN: M. Biagini, S. Guiducci, M. Boscolo, M. Zobov, et al.

➤ **For more details, refer to:**

- Talks given by K. Akai, Y. Funakoshi, H. Nakayama, K. Ohmi, N. Ohuchi, H. Sugimoto, Y. Suetsugu, et al. at the 21st KEKB Accelerator Review Committee meeting:
  http://www-kekb.kek.jp/MAC/2016/
- The 24th B2GM meeting for Belle-II:
  https://kds.kek.jp/indico/event/21740/
- Y. Ohnishi, paper and talk at NAPAC 2016

Thanks for your attention!