β^* Measurements in SuperKEKB to Demonstrate CLIC-like FFS

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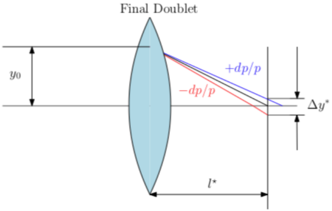
Outline

- Motivation for doing CLIC FFS tests in SuperKEKB
- Measuring β^* in SuperKEKB using K modulation.

FFS Chromaticity Correction

- To achieve the required high luminosity, the CLIC FFS must focus the beam to extremely small sizes at the IP.
- This requires strong focusing quadrupoles with large chromatic aberrations that must be corrected.
- Large β in the IR increases effects from misalignments, nonlinearities etc.



$$\sigma_y^* \approx \sigma_{0y}^* \sqrt{1 + \xi_y^2 \sigma_\delta^2}$$

$$\beta(s) = \beta^* + \frac{s^2}{\beta^*}$$

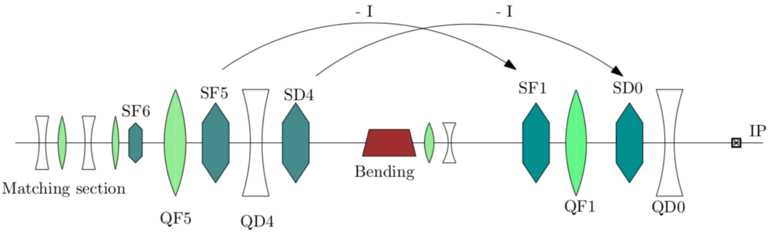
H. Garcia, R. Tomás and Y. Kubyshin. "Comparative study of Final Focus Systems for CLIC and other luminosity ehancement studies for future linear colliders", CERN-THESIS-2014-230.

FFS chromaticity comparison

	L^*[m]	β_y^*[μm]	$\xi_y \sim (L^*/\beta_y^*)$
CLIC	3.5	70	50 000
ILC	3.5 /4.1	410	8540 /10 000
ATF2	1	100	10 000
FFTB	0.4	100	4000
SuperKEKB LER	0.74	270	2740
SuperKEKB HER	1.22	300	4070

- Nominal SuperKEKB will demonstrate chromaticity correction on same scale as FFTB.
- A factor 3 reduction of β_y^* in SuperKEKB would be on scale with ATF2 and ILC.

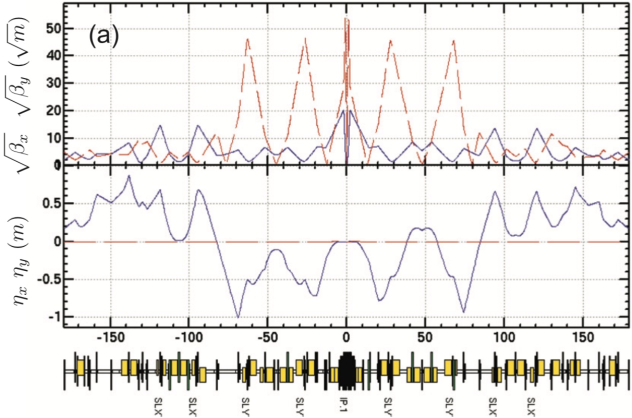
ATF2



- Uses two pairs of sextupoles interleaved with the final doublet to correct chromaticity.
- Similar to baseline CLIC design.

H. Garcia, R. Tomás and Y. Kubyshin. "Comparative study of Final Focus Systems for CLIC and other luminosity ehancement studies for future linear colliders", CERN-THESIS-2014-230.

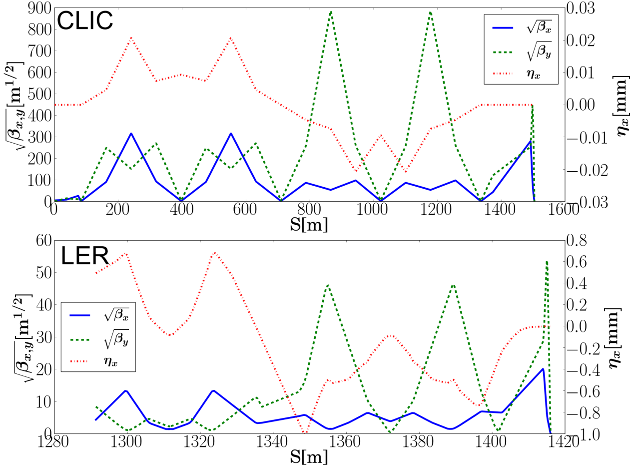
FFS of SuperKEKB



- Two sections with sextupoles for correcting the vertical and horizontal chromaticity separately. Likewise downstream.

Y. Onishi et. al. "Accelerator design at SuperKEKB", Prog. Theor. Exp. Phys. 2013.

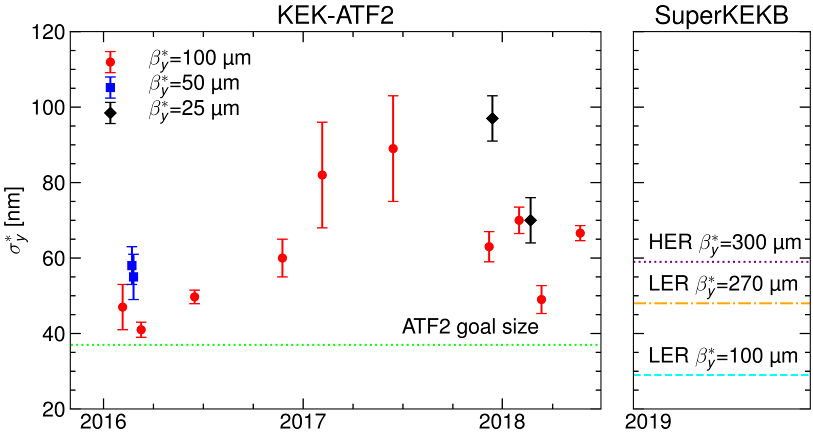
FFS of SuperKEKB Compared to CLIC



- CLIC has second proposed FFS similar to SuperKEKB.

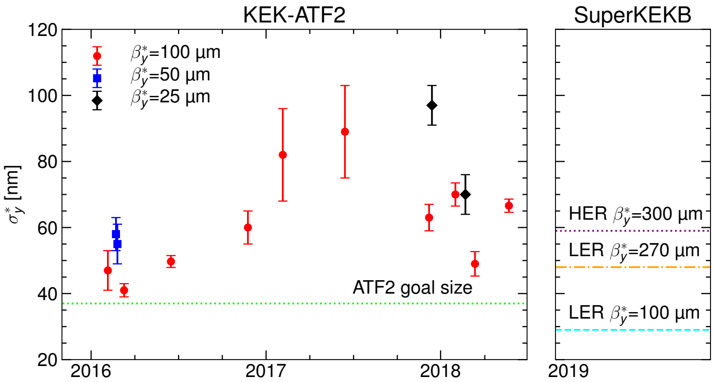
P. Thrane et. al. "Probing LINEAR Collider Final Focus Systems in SuperKEKB", CERN-ACC-2017-0052. CLIC-Note-1077, 2017.

Beam Size Measurements in ATF2



Plot by Renjun Yang, data from ATF2 logbook and Fabien Plassard: Optics optimization of Longer L* Beam Delivery System Designs for CLIC and Tuning of the ATF2 Final Focus System at Ultra-low β^* Using Octupoles. HEP-EX. Université Paris-Saclay, 2018.

Reducing β^* in SuperKEKB



- Introductory studies have been made into the possibility of pushing down β^*_y further at SuperKEKB LER.
- A reduction up to a factor 3 might be possible, giving a β^*_y of 90 μm.[a]

[a] P. Thrane et. al. "Probing LINEAR Collider Final Focus Systems in SuperKEKB", CERN-ACC-2017-0052. CLIC-Note-1077, 2017.

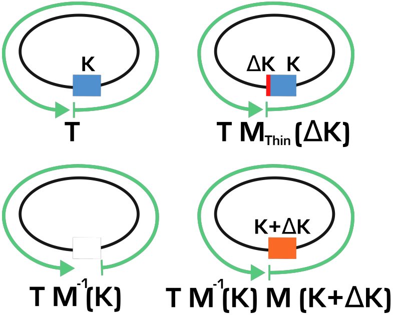
Measuring β_y^* in SuperKEKB

- A precise measurement of β_y^* is important for both nominal SuperKEKB operation and potential dedicated FFS studies.
- Current β function measurements done globally using an orbit response matrix method.

Tune Shift from Quadrupole Modulation

$$\begin{bmatrix} \cos(2\pi Q) + \alpha_0 \sin(2\pi Q) & \beta_0 \sin(2\pi Q) \\ -\gamma_0 \sin(2\pi Q) & \cos(2\pi Q) - \alpha_0 \sin(2\pi Q) \end{bmatrix}$$

- Usual derivation uses a thin quadrupole perturbation.
- Simple reformulation takes into account magnet length and higher orders. Perfect match with thin lens method to first order.



Details found in: P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

K Modulation

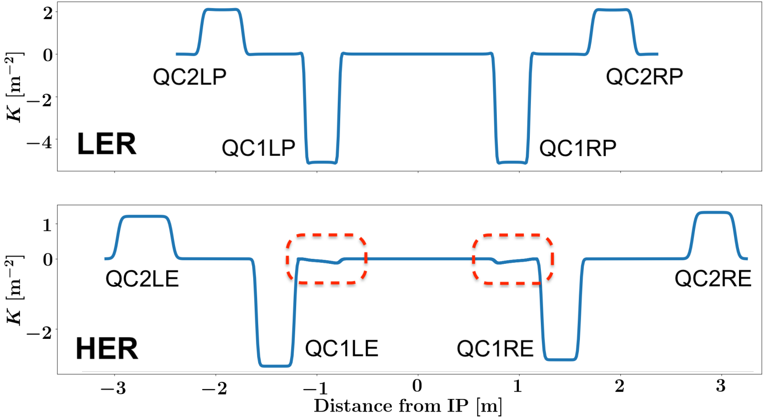
- By modulating the strength of a quadrupole and measuring the resulting tune shift, the average of the β function in the modulated quadrupole is found.

$$\beta_{average,x,y} = \pm\frac{2}{\Delta KL}\left(\frac{1-\cos(2\pi\Delta Q_{x,y})}{\tan(2\pi Q_{x,y})}+\sin(2\pi\Delta Q_{x,y})\right)$$
$$\approx \pm 4\pi\frac{\Delta Q_{x,y}}{\Delta KL}$$

- The average value of quadrupoles near the IP can then be used to find β^* as well as any longitudinal shift in the waist away from the IP.[a]

[a] F. Carlier and R. Tomás. "Accuracy and feasibility of the β^* measurement for LHC and High Luminosity LHC using k modulation", Physical Review Accelerators and Beams, 2017.

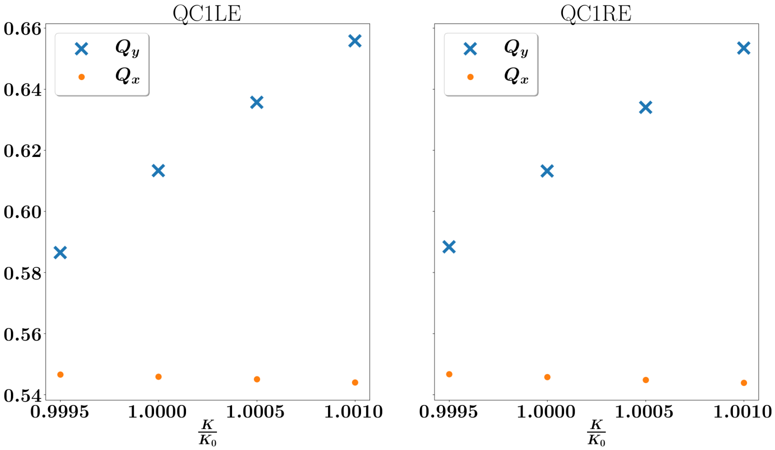
Modifying K Modulation



- General transfer matrices included in formulation of K modulation to account for fields in HER from LER magnets.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

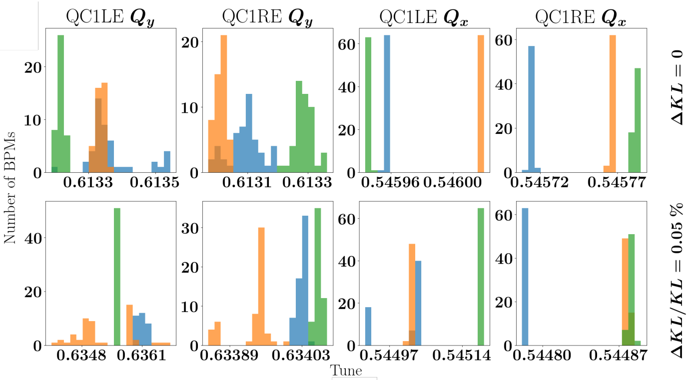
Tune Measurements

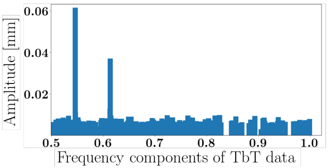


- Shift in tune from changing strength of the two quadrupoles in SuperKEKB HER closest to the IP.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

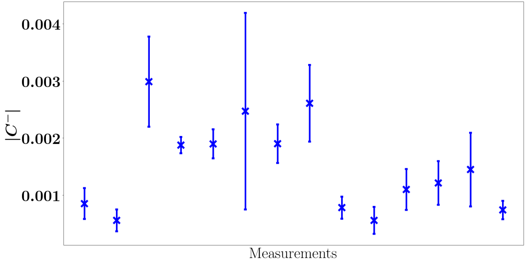
Turn by Turn Data





P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

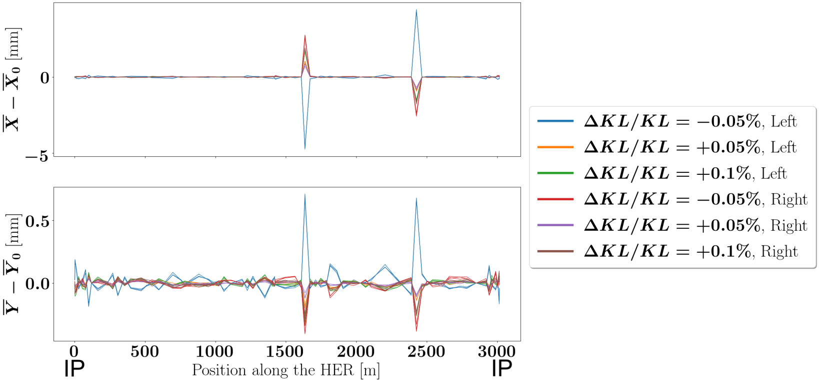
Coupling



- Coupling estimated from turn by turn data
  - A. Franchi, R. Tomás, and G. Vanbavinkhove, "Computation of the Coupling Resonance Driving term f1001 and the Coupling Coefficient C from turn by turn single BPM Data" May 2010. http://cds.cern.ch/record/1264111
- Coupling a factor 20 smaller than the smallest tune separation during measurements.
- Effect of coupling can be minimized by modulating such that tune separation becomes larger.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

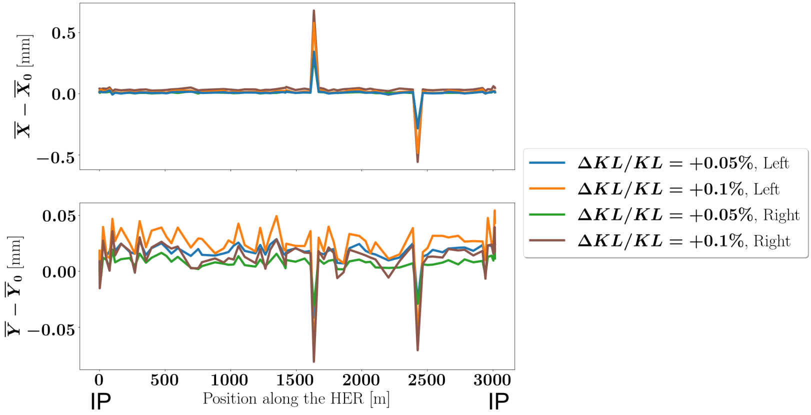
Orbit shift



- Orbit changes slightly when modulating quadrupoles.
- Spikes are thought to be due to faulty BPMs, this is under investigation.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

Orbit shift

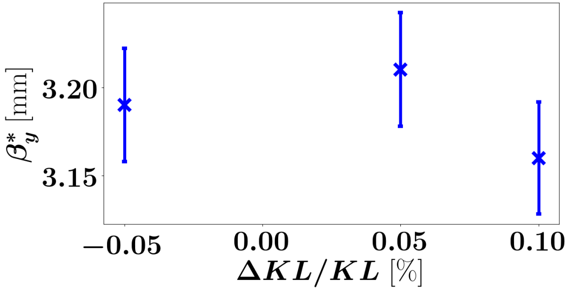


- Orbit displacement in a sextupole gives a tune shifts

$$\Delta Q_s \approx \pm \frac{\beta_s K_2 L_s}{4\pi} \delta x.$$

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

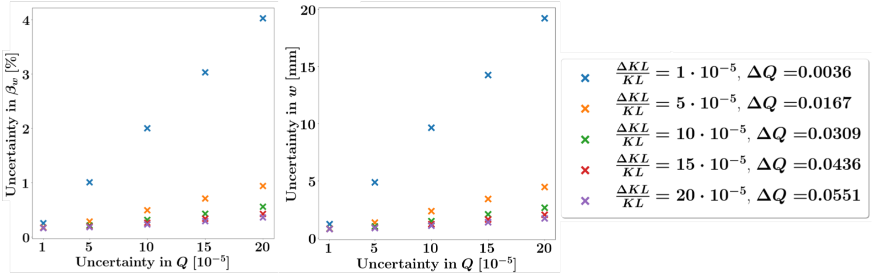
Measured β_y^*



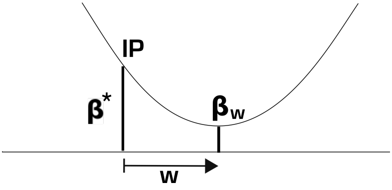
- No significant changes in measured β_y^* for different modulations.
- Uncertainties estimated using simulations without taking into account orbit shifts.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

Uncertainties



- Simulated uncertainties show K modulation is suited for measuring β at the waist, but not for finding the displacement of the waist away from the IP.
- $\beta_y^* = \beta_w + \frac{w^2}{\beta_w}$



P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

Conclusions and Further Work

- The tuning of SuperKEKB to achieve nominal machine parameters faces many of the same challenges as the CLIC FFS.
- A dedicated FFS study could be possible, if planned thoroughly.
- Accurate β^* measurements are needed. Good results have been shown during phase 2 of commissioning.
  - $\beta^*_y = 3.2$ mm was measured with goal 3 mm during the measurements, indicating 7% β beating.
  - K modulation is shown to be good for measuring β_w, but not accurate enough for finding waist shift away from IP.
  - Further testing should be done for smaller β^*_y, when tunes will be closer to half integer.
- Further work also includes comparing the K modulation measurements with other techniques like β from amplitude and from phase.

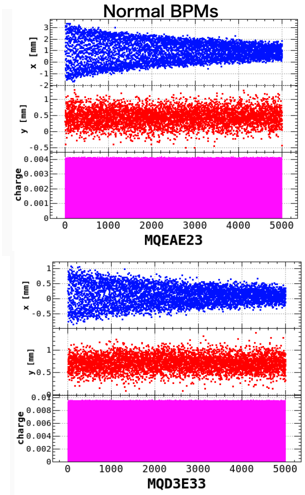
Backup Slides.

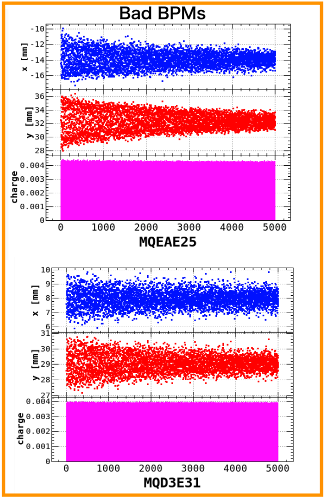
SuperKEKB Nominal Machine Parameters

		LER (e^+)	HER (e^-)	Unit
Energy	E	4.000	7.007	GeV
Current	I	3.6	2.6	A
Number of bunches		2 500		
Bunch current		1.44	1.04	mA
Circumference	C	3 016.315		m
Emittance	ϵ_x/ϵ_y	3.2/8.64	4.6/12.9	nm/pm
Coupling		0.27	0.28	%
β function at IP	β_x^*/β_y^*	32/0.27	25/0.30	mm
Transverse beam size at IP	σ_x^*/σ_y^*	10.1/48	10.7/62	μm/nm
Crossing angle		83		mrad
Momentum compaction	α_p	3.20	4.55	10^{-4}
Energy spread	σ_δ	7.92	6.37	10^{-4}
Total cavity voltage	V_c	9.4	15.0	MV
Bunch length	σ_z	6.0	5.0	mm
Synchrotron tune	ν_s	-0.0245	-0.0280	
Betatron tune	Q_x/Q_y	44.53/46.57	45.53/43.57	
Energy loss per turn	U_0	1.76	2.43	MeV
Damping time	$\tau_{x,y}/\tau_z$	43.2/22.8	58.0/29.0	msec
Beam-beam parameter	ξ_x/ξ_y	0.0028/0.0881	0.0012/0.807	
Luminosity	L	8×10^{35}		$\mathrm{cm}^{-2}\mathrm{s}^{-1}$

http://www-superkekb.kek.jp

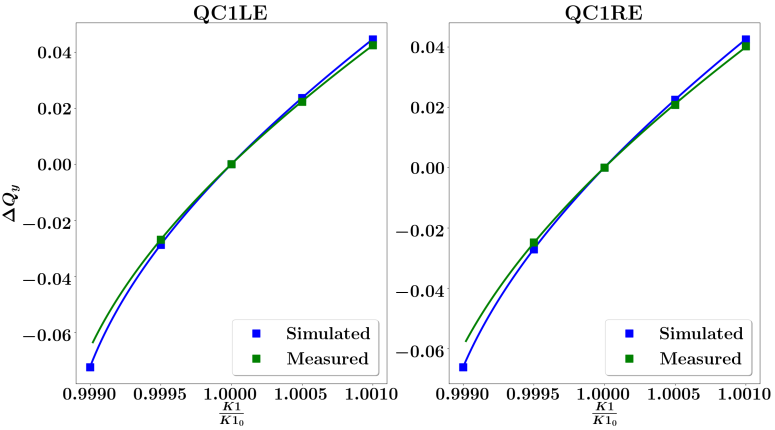
Bad BPMs





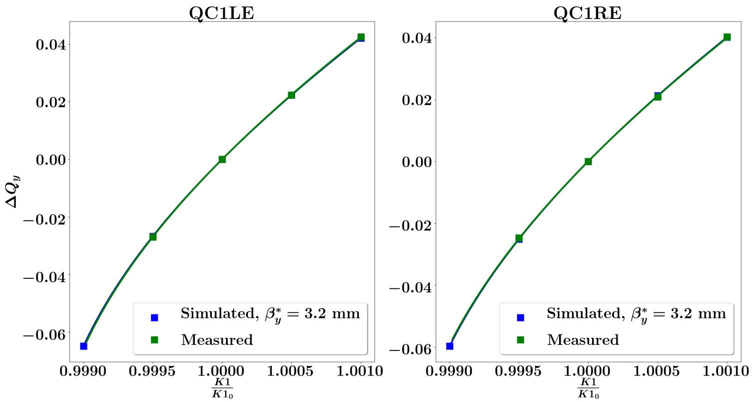
Thanks to Yukiyoshi Onishi

Tune Shift



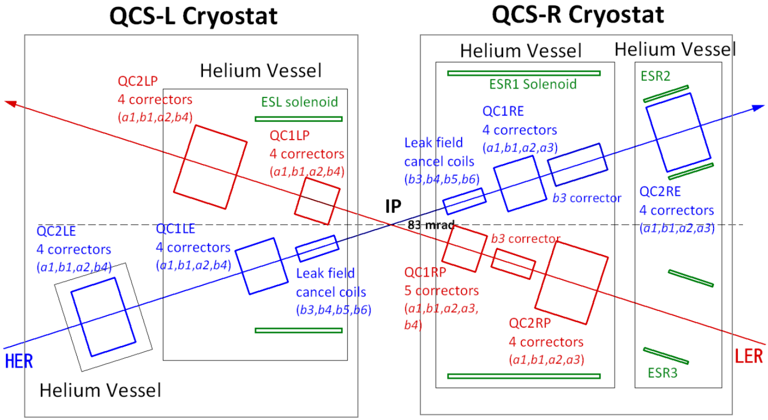
- Shift in vertical tune from changing strength of the two quadrupoles in SuperKEKB HER closest to the IP. Measured and simulated values. Lines are made by fitting $\beta_{average}$.

Tune Shift



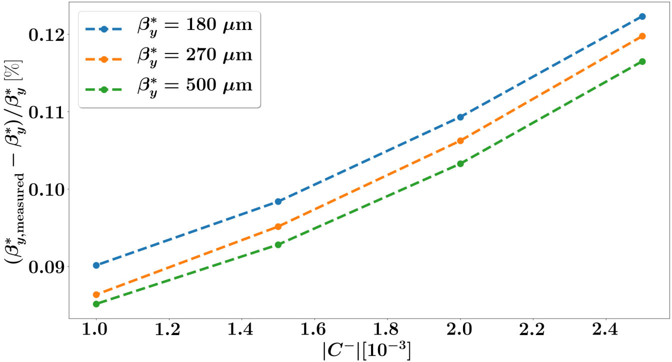
- Design $\beta_y^* = 3.0$ mm
- Measured $\beta_y^* = 3.2$ mm

SuperKEKB IR



Y. Funakoshi, Overview of SuperKEKB, issues and Commissioning Plan. Presentation at KEK 11. November 2013.

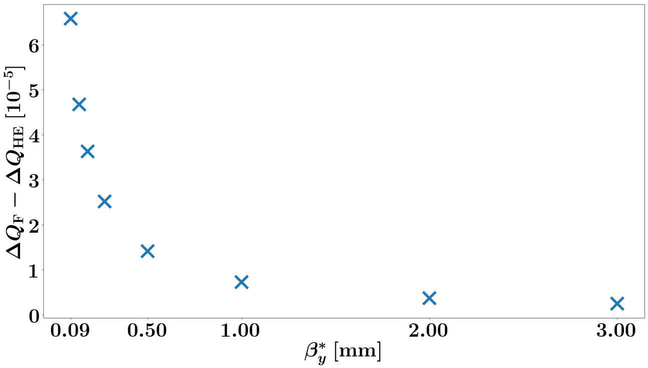
Simulations, Coupling



- Error in measurements for different coupling values.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

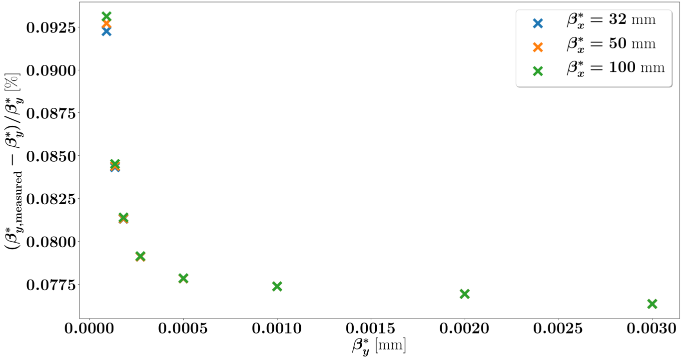
Simulations, Fringes



- Difference in tune shift from hard edge quadrupole and quadrupole with fringes
- Very dependent on range of fringes.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

Simulations, β^*



- Error in measurements due to different β^*_y and β^*_x.

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

Simulations, Uncertainties

- Uncertainties used for estimating error of β^* measurements

Parameter	Uncertainty
L^* [mm]	1
h [mm]	1
Q	$2 \cdot 10^{-4}$
K [relative]	$1 \cdot 10^{-3}$
$K^\dagger$ [relative]	$1 \cdot 10^{-2}$

P. Thrane "Measuring β^* in SuperKEKB with K Modulation", CERN-THESIS-2018-300. http://cds.cern.ch/record/2652855, 2018.

ATF2 Beam Size Measurements

Optics	run date	Minimum σ_y^* [nm]	Comments
$10\ \beta_x^* \times 1\ \beta_y^*$	16/02/05	47±6	-
$10\ \beta_x^* \times 0.5\ \beta_y^*$	16/02/22	58±5	-
$25\ \beta_x^* \times 0.5\ \beta_y^*$	16/02/25	55±6	-
$10\ \beta_x^* \times 1\ \beta_y^*$	16/03/10	41±2	2 bunch mode
$10\ \beta_x^* \times 1\ \beta_y^*$	16/05/20	75±10	-
$10\ \beta_x^* \times 1\ \beta_y^*$	16/06/16	69±5	-
$10\ \beta_x^* \times 1\ \beta_y^*$	16/11/24	60±5	-
$10\ \beta_x^* \times 1\ \beta_y^*$	16/12/01	74±9	-
$10\ \beta_x^* \times 1\ \beta_y^*$	17/02/15	82±14	-
$10\ \beta_x^* \times 1\ \beta_y^*$	17/06/15	89±14	mOTR non-operational
$10\ \beta_x^* \times 1\ \beta_y^*$	17/12/08	63±4	mOTR non-operational + correction of the matching optics
$25\ \beta_x^* \times 0.25\ \beta_y^*$	17/12/14	97±6	mOTR non-operational + bad optics matching
$25\ \beta_x^* \times 0.25\ \beta_y^*$	18/02/22	70±6	mOTR non-operational + correction of the matching optics w/o 2$^{\text{nd}}$ order knobs and octupoles

Fabien Plassard. Optics optimization of Longer L* Beam Delivery System Designs for CLIC and Tuning of the ATF2 Final Focus System at Ultra-low β^* Using Octupoles. HEP-EX. Université Paris-Saclay, 2018.