FUTURE CIRCULAR COLLIDER

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Experience at SuperKEKB

JACQUELINE KEINTZEL

TU WIEN, VIENNA, AUSTRIA

CERN, GENEVA, SWITZERLAND

FCC Week

29th June 2021

Acknowledgements:

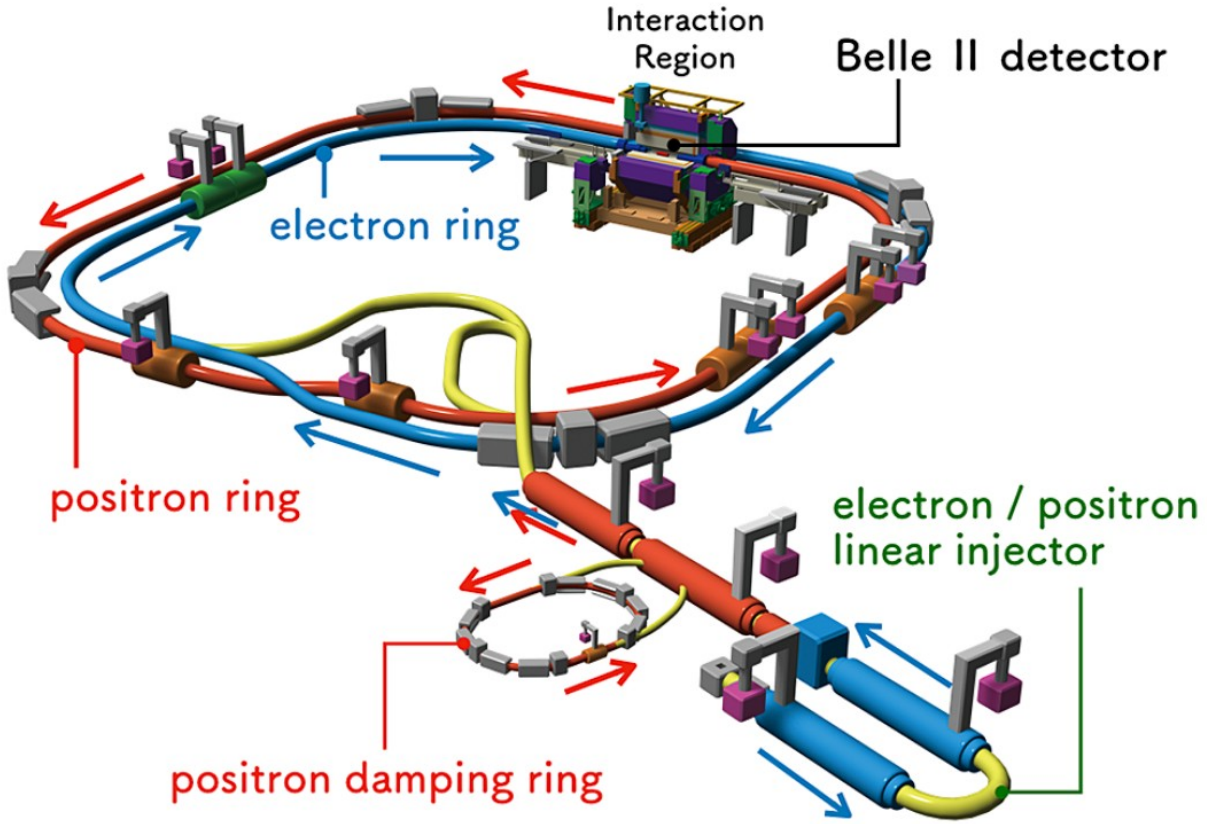
Michael Benedikt, Helmut Burkhardt, Yoshihiro Funakoshi, Kazuro Furukawa, Naoko Iida, Haruyo Koiso, Marian Lückhof, Toshi Mitsuhashi, Gaku Mitsuka, Akio Morita, Hiroyuki Nakayama, Yukiyoshi Ohnishi, Kazuhito Ohmi, Katsunobu Oide, Makoto Tobiyama, Hiroshi Sugimoto, Rogelio Tomás, Renjun Yang, Frank Zimmermann

FCCIS – The Future Circular Collider Innovation Study. This INFRADEV Research and Innovation Action project receives funding from the European Union's H2020 Framework Programme under grant agreement no. 951754.

Introduction SuperKEKB

Ref: [1,2,3]

- Injection linac (electrons and positrons)
- Positron damping ring
- High energy ring: electrons, 7 GeV
- Low energy ring: positrons, 4 GeV
- 2 beam crossings
- 1 interaction point (Belle II)
- Crab waist collision scheme
- Record luminosity of above 3 x 10^{34} $cm^{-2}s^{-1}$



SuperKEKB and FCC-ee

Ref: [1,2,4-8]

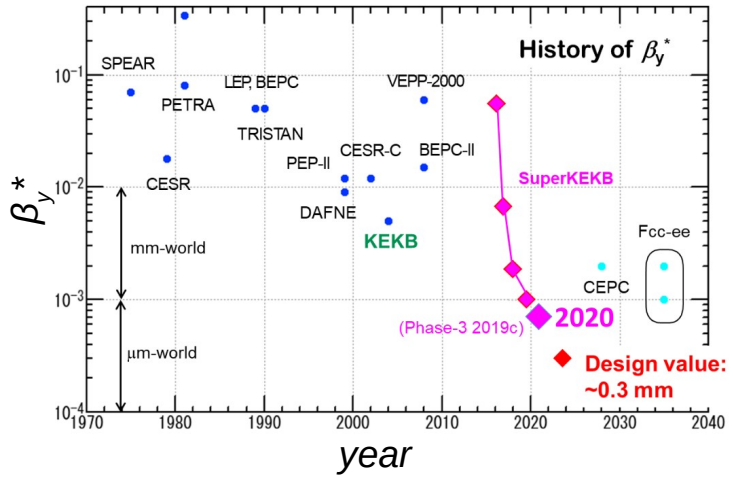
Parameter	FCC-ee				SuperKEKB	
	Z	WW	ZH	tt	LER	HER
Circumference [km]	97.756				3.016	
Beam Energy [GeV]	45.6	80	120	182.5	4	7
Hor. Emittance [nm]	0.27	0.84	0.63	1.46	1.9	4.4
Ver. Emittance [pm]	1.0	1.7	1.3	2.9	2.8	1.5
βx* [cm]	15	20	30	100	3.2	2.5
βy* [mm]	0.8*	1.0	1.0	1.6	0.27	0.30
Bunch Length with SR/BS [mm]	3.5/12.1	3.0/6.0	3.3/5.3	2.0/2.5	4.7	4.9

** Achieved during spring run 2020 in SuperKEKB*

- Electron-positron circular collider
- Comparable beam parameters

Talk: K. Oide

Talk: D. Shatilov



Design βy = 0.3 mm in SuperKEKB Smallest βy* for FCC already reached in 2020*

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** Achieved during spring run 2020 in SuperKEKB*

- Electron-positron circular collider
- Comparable beam parameters
- Crab-waist collision scheme
- -I transformation between sextupoles

- Similar beam instrumention
- Top-up injection **Talk: M. Aiba**

→ *SuperKEKB is a small FCC-ee!*

Crab-Waist Collision Scheme

Ref: [9-11]

- Large Piwinksi-Angle (>1)
  - Large crossing angle
  - Small beam sizes
  - Higher luminosity
  - Fewer beam-beam effects

$$\varphi_{\mathrm{piw}} = (\theta/2)\,(\sigma_s/\sigma_x)$$

Luminosity defined by revolution frequency (f_{rev}), number of particles (N_1,N_2) and transverse beam sizes (σ_x,σ_y)

$$\mathcal{L} = \frac{f_{\mathrm{rev}} N_1 N_2}{4\pi\sigma_x\sigma_y} S$$

Luminosity reduction factor for Gaussian beams with crossing angle θ and bunch length σ_s

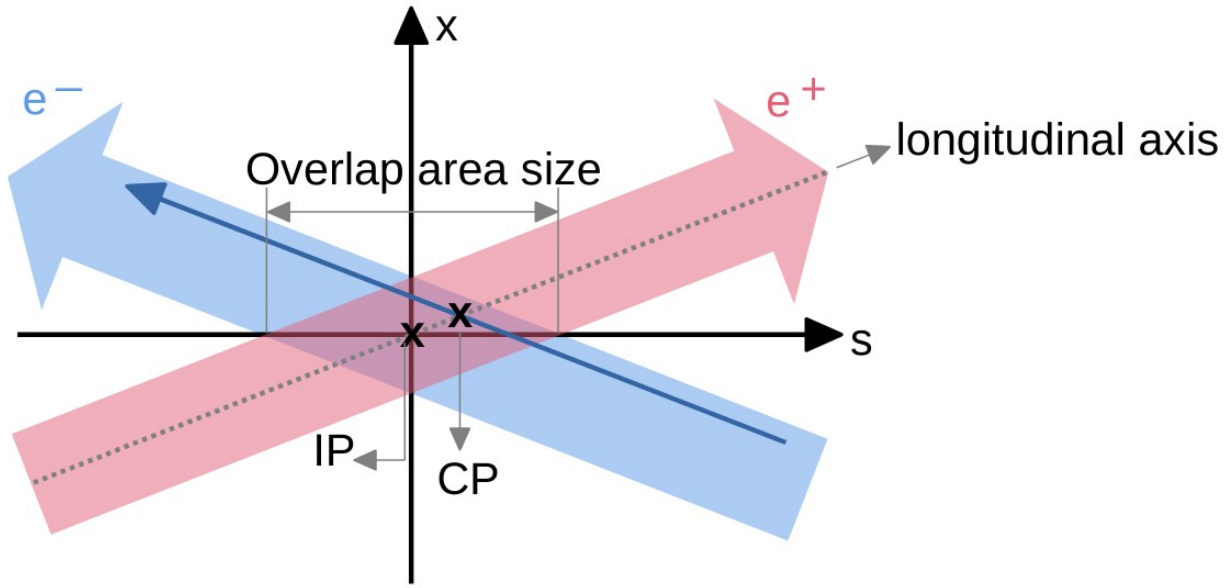
$$S \approx \frac{1}{\sqrt{1 + \left(\frac{\theta}{2}\frac{\sigma_s}{\sigma_x}\right)^2}}$$

Crab-Waist Collision Scheme

Ref: [9-11]

- Large Piwinksi-Angle (>1)
  - Large crossing angle
  - Small beam sizes
  - Higher luminosity
  - Fewer beam-beam effects
- β_y^* ~ overlap area size
  - Luminosity further increased
  - Suppression of
    - Beam-beam tune shift
    - Synchro-betatron resonances from beam-beam
  - Introduction of new resonances → suppressed by crab-waist transformation

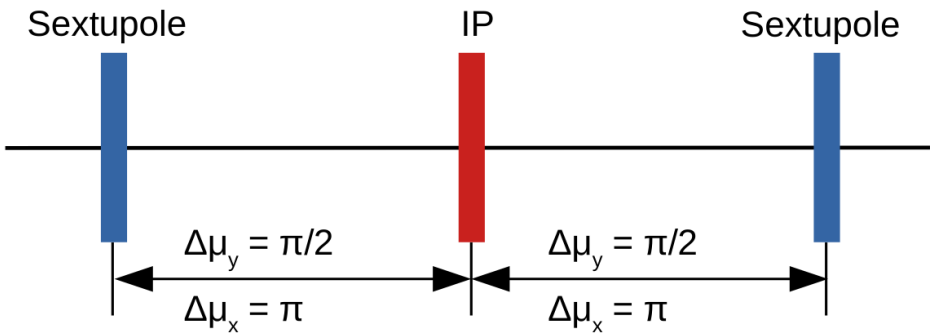
$$\beta_y^* \approx \frac{\sigma_x}{\theta} \ll \sigma_s$$

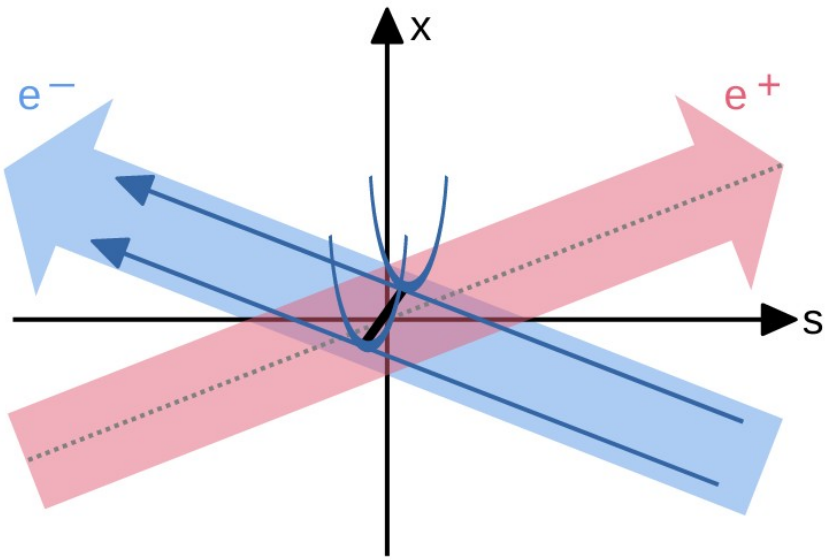


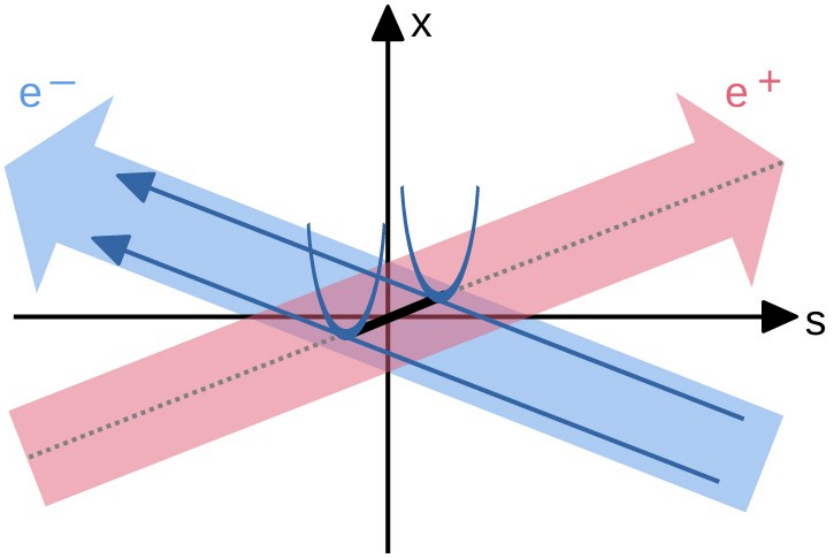
Crab-Waist Collision Scheme

Ref: [9-11]

- Crab-waist transformation
  - Phase advance controlled with sextupoles
  - $\mu_y=\pi/2$ between IP and sextupole
  - Waists aligned along trajectory of other beam







Recent Parameters

Ref: [12]

Parameter	SuperKEKB July 2020		SuperKEKB June 2021		Final Design	
Ring	LER	HER	LER	HER	LER	HER
Beam current [mA]	536	530	790.3	686.6	3600	2600
Number of bunches	978		1174		2500	
Horizontal beam size [μm]	15.5	16.6	24	22	10.1	10.7
Vertical beam size [μm]	0.224	0.224	0.26	0.23	0.048	0.062
βx*/βy* [mm]	60/0.8	60/0.8	80/1	60/1	32/0.27	25/0.30
Vertical beam beam parameter	0.0345	0.0199	0.0529	0.0264	0.0881	0.0807
Luminosity [$cm^{-2}s^{-1}$]	2.00×10^{34}		3.12×10^{34}		$\sim 6 \times 10^{35}$	
Remarks	Crab waist		Crab waist		-	

Recently new record luminosity of 3.12×10^{34}

Powering of crab-waist sextupole
LER: 80%
HER: 40%

Record Luminosity

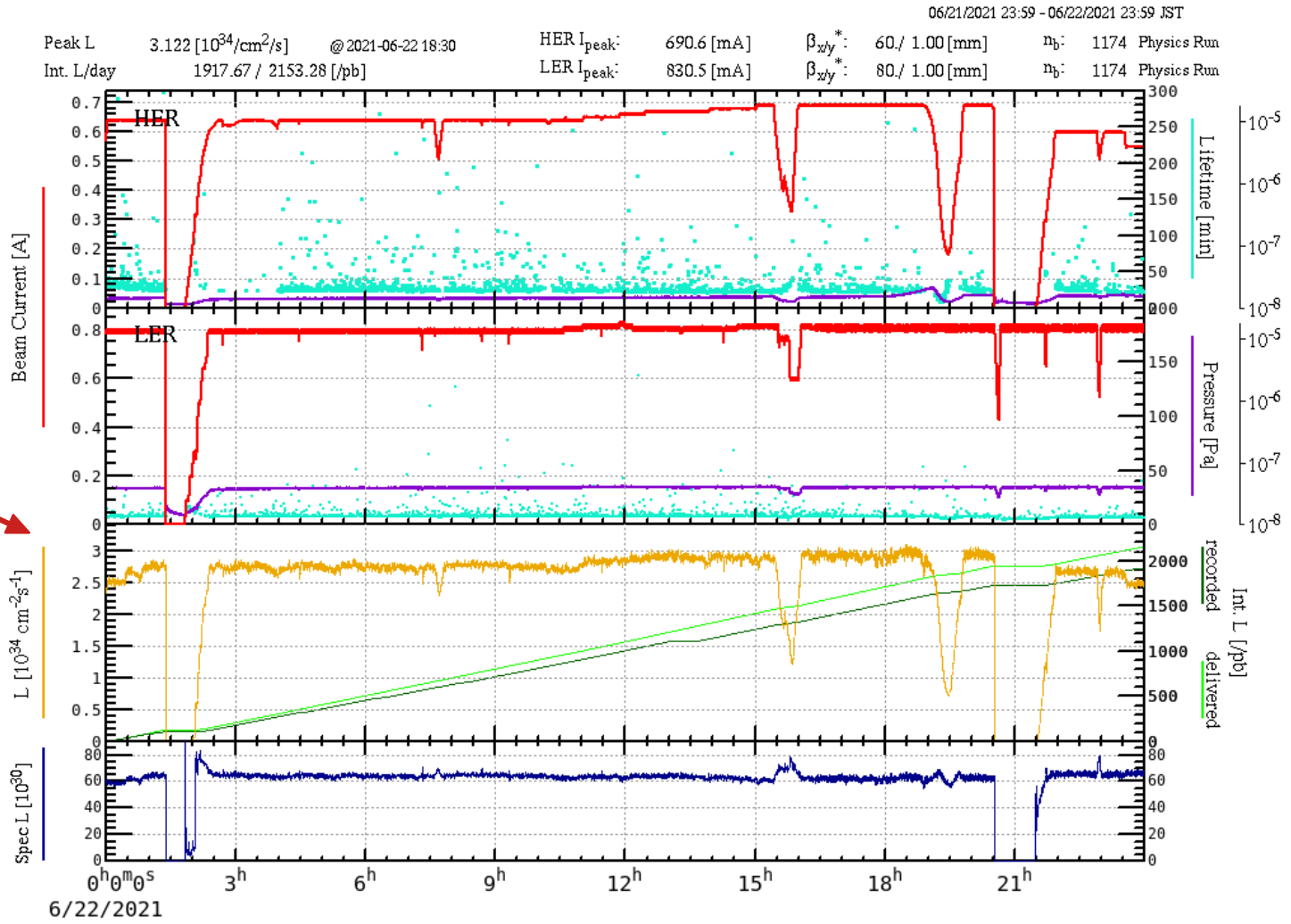
Ref: [12]

- LER: 80/1 mm with 80% CW
- HER: 60/1 mm with 40% CW

- Record luminosity in June 2021
- About **3.1 x 10^{34} $cm^{-2}s^{-1}$**

- Specific luminosity defined as

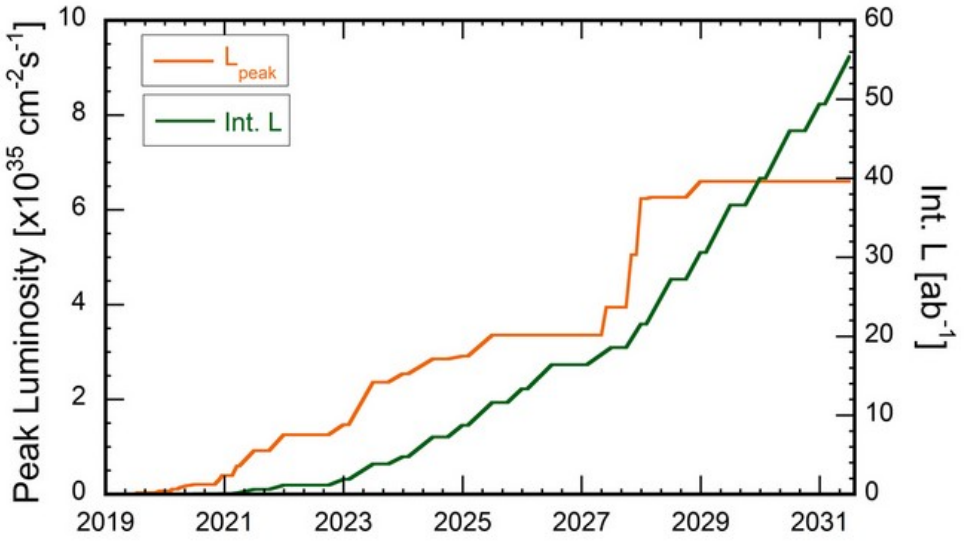
$$L_{SP} = \frac{L}{n_b I_+ I_-}$$

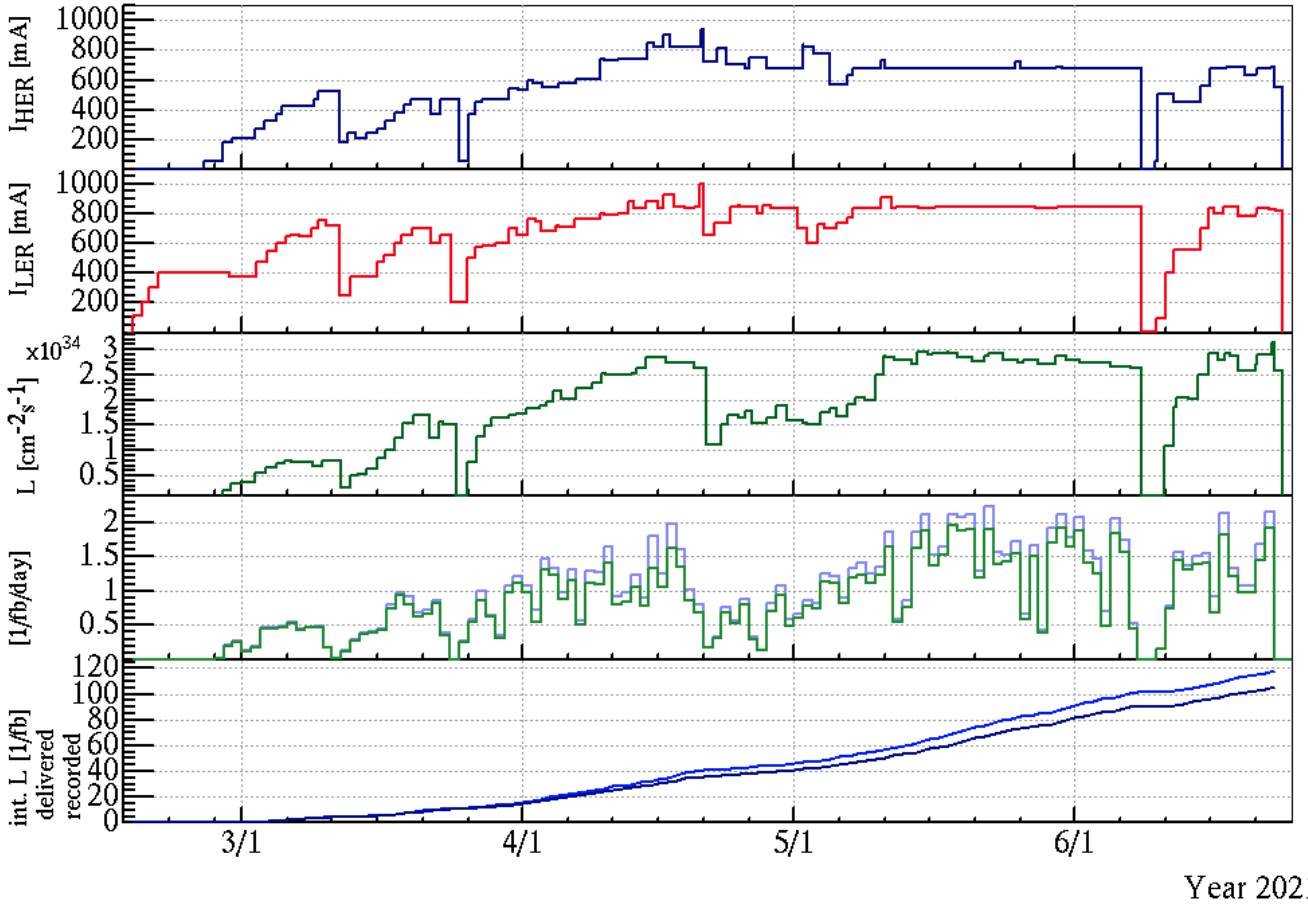


Luminosity Plan

Ref: [12]

- Ultimate goal of about 6 x 10^{35} $cm^{-2}s^{-1}$ planned to be achieved around 2028
  - Higher bunch currents
  - Lower β* for both rings
- Optics corrections in each squeezing step



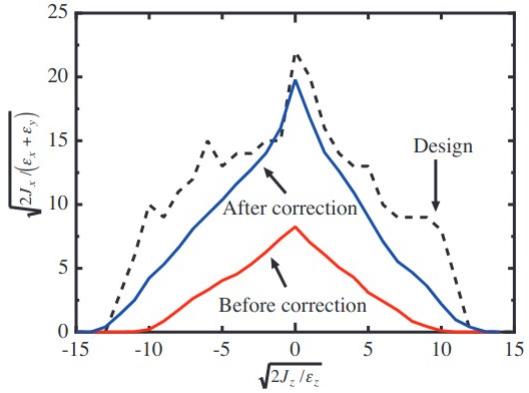


Performance Optimisation

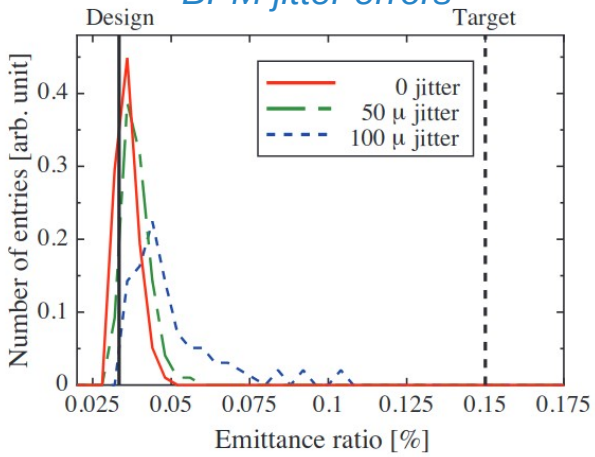
Ref: [12,13]

- iBump: vertical orbit bump at the IP to increase luminosity
  - Feedback system based on beam-beam deflection
  - Correct strengths improve luminosity
- Optics correction in simulations
  - Increased dynamic aperture
  - Acceptable emittance ratio

Dynamic aperture increases after correction

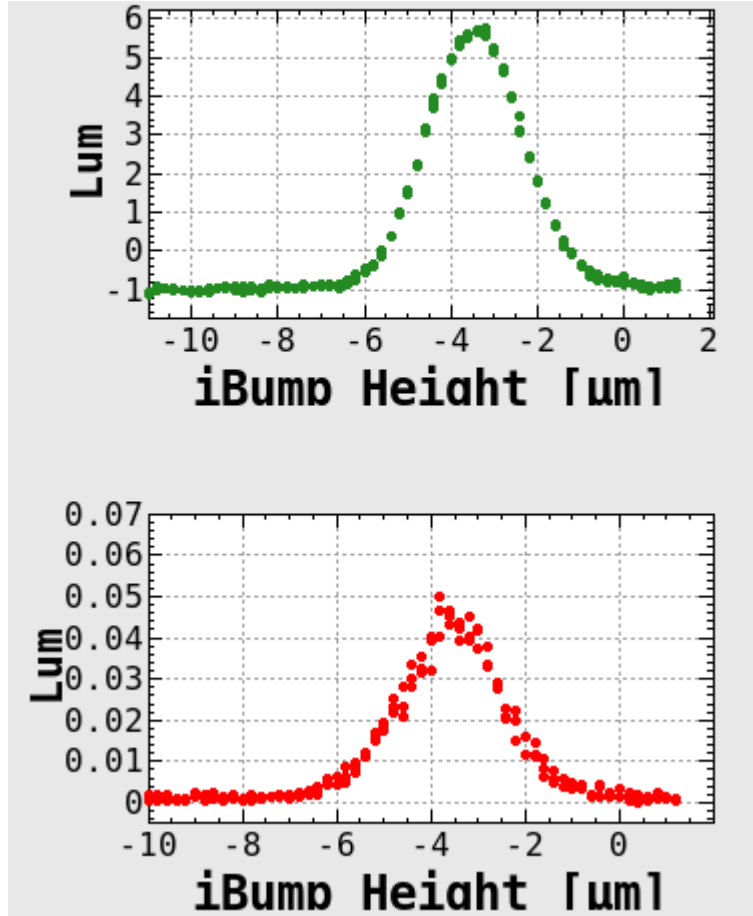


BPM jitter errors



Design: includes fringe field of solenoid, beam-beam interaction, intra-beam scat-tering and some machine errorr
Target: tentative target including other machine errors (misalignments, rotation,...)

Measurements 26th February 2021
Green: Luminosity monitor
Red: Belle measurement

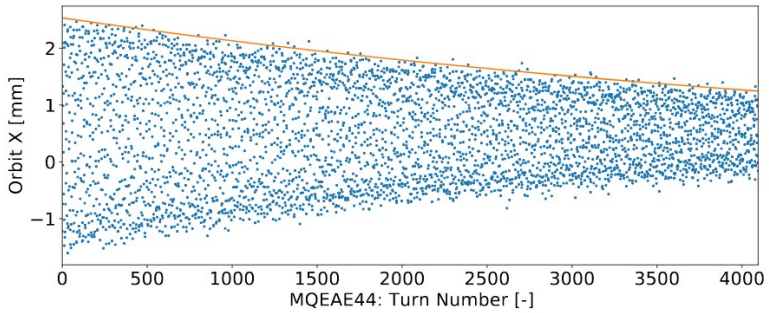


Optics Measurements

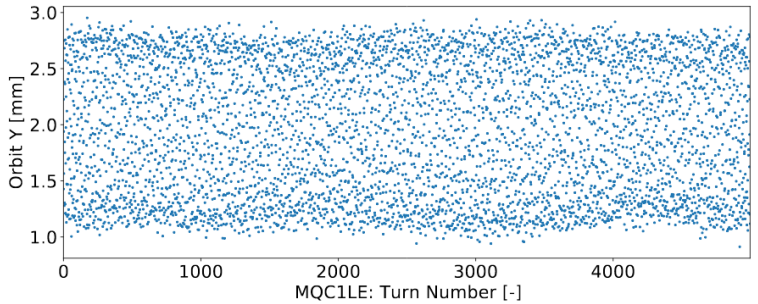
Ref: [14]

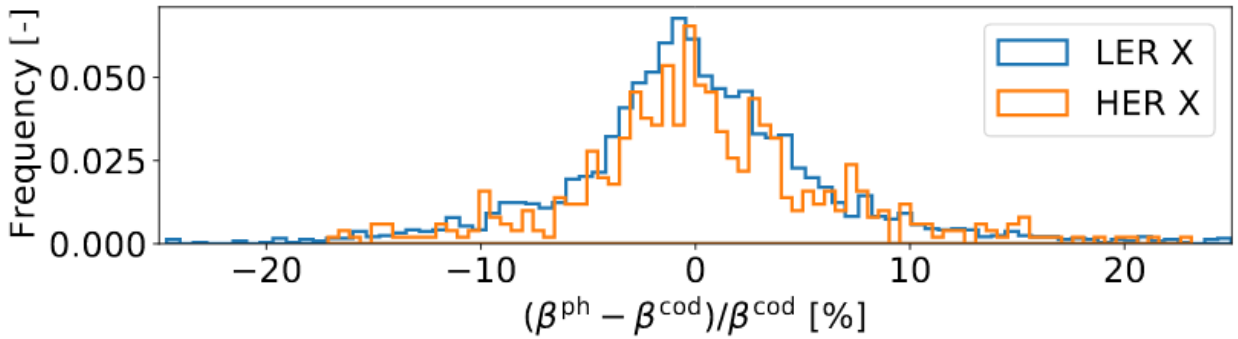
- Closed Orbit Distortion (COD) or Turn-by-Turn (TbT) measurements performed
  - Single kicks or driven motion with TbT
  - In general good agreement

HER single kick in x-plane

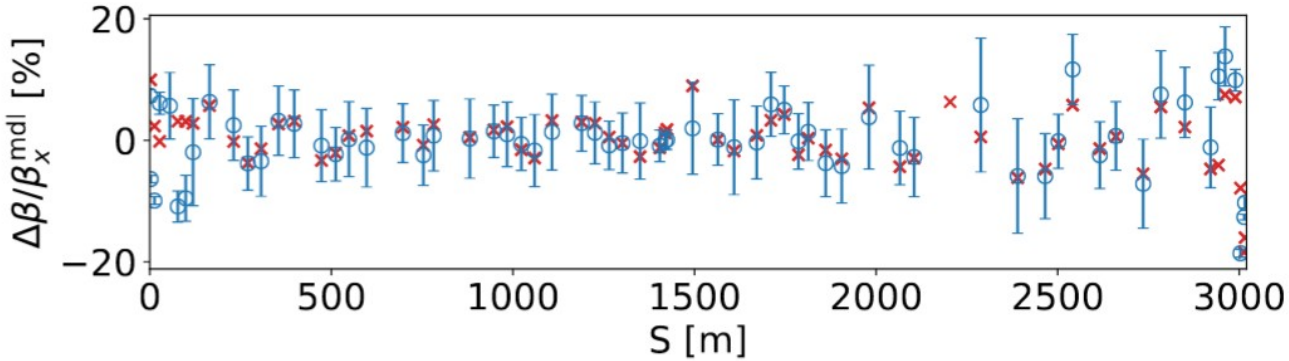


HER driven motion in y-plane





HER with 80/2 mm optics
rms beta-beating between COD and TbT with single kicks 6 %



HER with 80/2 mm optics
rms beta-beating w.r.t. model about 5 %

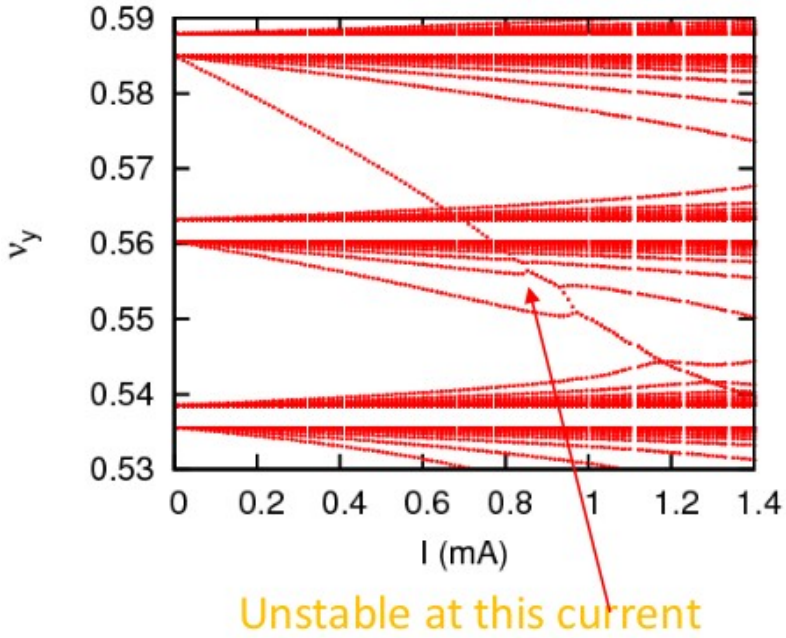
Impedance and Collimation

Ref: [15,16]

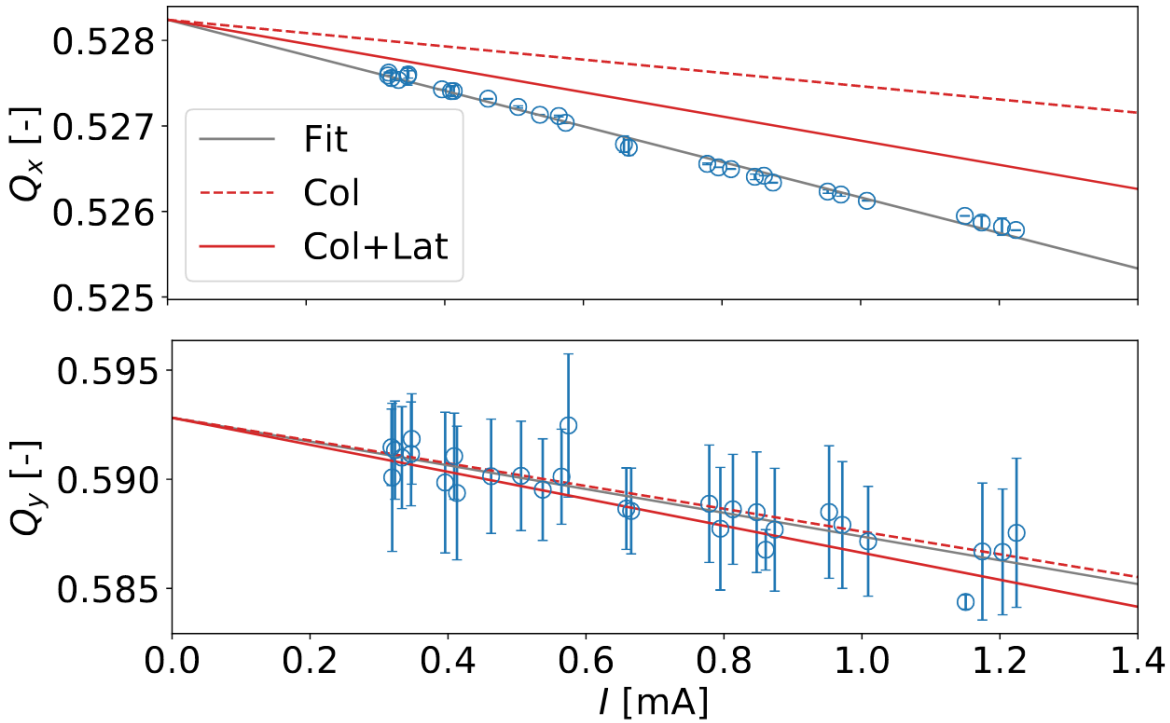
- Design bunch current not yet reached
  - Tunes decrease with higher bunch current
  - Impedance from collimators

Talk: T. Ishibashi

Example for TMCI threshold simulations for vertical tunes from 0.53 - 0.59 → unstable around 0.9 mA bunch current → different working point used in SuperKEKB



LER with 80/2 mm, working point at 0 mA of (0.528, 0.593)
Col: Tune shift due to collimator impedance
Col+Lat: Tune shift due to collimators and known lattice impedance
Known impedance sources can explain only about 80% of tune horizontal tune shift → probably unkown impedance sources

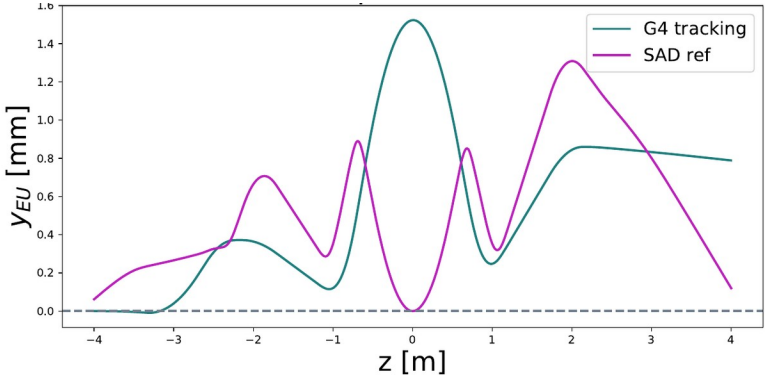


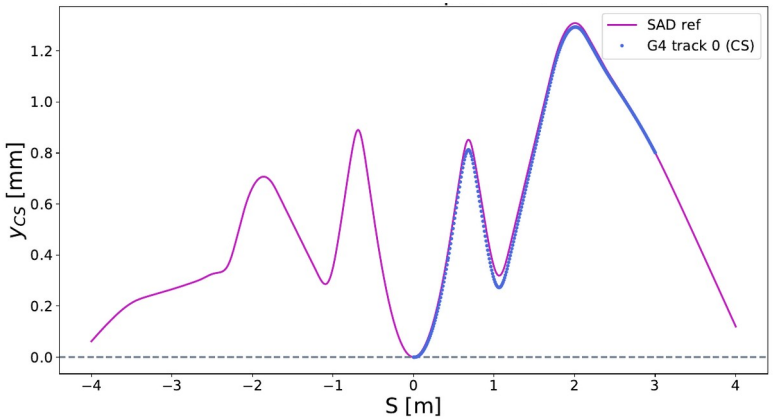
MDI and Background

Ref: [17-21]

- Rebuild SuperKEKB interaction region based on SAD in MDISim
  - MDISim comparable to SAD model
  - Aim at measuring orbit using e.g. beam gas vertex
- Vacuum system crucial for performance

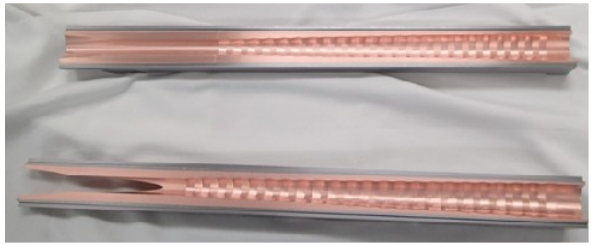
Vertical closed orbit before and after correct implementation in MDISim for SuperKEKB interaction region



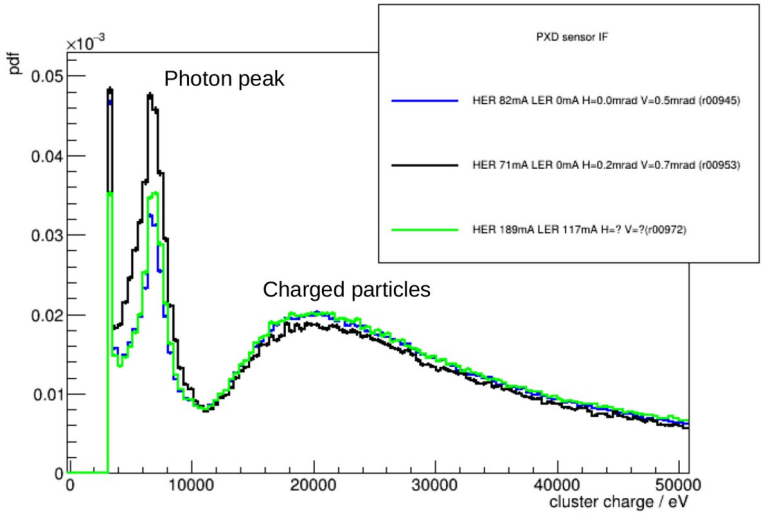


Talk: Y. Suetsugu

Strong 10 keV photon line in synchrotron radiation background



Beam pipe next to interaction point



Summary

- SuperKEKB holds the present luminosity record of about 3.1 x 10^{34} $cm^{-2}s^{-1}$
- Reaching design goal demands optics measurements and control in all squeezing steps
- Commissioning of SuperKEKB demonstrates key concepts for FCC-ee
  - Crab-waist collision scheme (small β_y*, phase advance), independent -I sextupoles for DA optimization, hardware requirements, positron source…

- Future studies could be performed to help understanding FCC-ee challenges
  - Optics and corrections
  - Electron cloud
  - Wake fields and impedance studies
  - Collective effects
  - Extensive crab-waist studies
  - Code benchmarking
  - ...

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Other Parameters

Ref: [12]

Powering of crab-waist sextupole
LER: 80%
HER: 40%

	KEKB : June 17, 2009		SuperKEKB : May 17, 2021		SuperKEKB : July 1, 2020		SuperKEKB : final design		Unit
Ring	LER	HER	LER	HER	LER	HER	LER	HER	
Emittance	18	24	4.0	4.6	4.0	4.6	3.2	4.6	nm
Beam Current	1637	1188	837	676	536	530	3600	2600	mA
Number of bunches	1585		1174		978		2500		
Bunch current	1.03	0.750	0.713	0.576	0.548	0.542	1.44	1.04	mA
Horizontal size σ_x^*	147	170	17.9	16.6	15.5	16.6	10.1	10.7	μm
Vertical cap sigma Σ_y^*	1.33		0.357		0.317		0.079		μm
Vertical size σ_y^*	0.940		0.253		0.224		0.048	0.062	μm
Betatron tunes ν_x / ν_y	45.506 / 43.561	44.511 / 41.585	44.524 / 46.596	45.531 / 43.581	44.525 / 46.581	45.531 / 43.574	44.53 / 46.57	45.53 / 43.57	
β_x^* / β_y^*	1200 / 5.9	1200 / 5.9	80 / 1.0	60 / 1.0	60 / 0.8	60 / 0.8	32 / 0.27	25 / 0.30	mm
Piwinski angle	0	0	10.7	12.7	12.3	12.7	19.3	19.0	
Beam-Beam parameter ξ_y	0.129	0.090	0.0407	0.0288	0.0345	0.0199	0.0881	0.0807	
Specific luminosity	1.71×10^{31}		6.13×10^{31}		6.90×10^{31}		2.14×10^{32}		$cm^{-2}s^{-1}/mA^2$
Luminosity	2.11×10^{34}		2.96×10^{34}		2.00×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$
Remarks	Crab crossing		Crab waist		Crab waist		-		