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REPORT ON SuperKEKB PHASE 2 COMMISSIONING

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Abstract

The SuperKEKB electron-positron collider is being commissioned at KEK in three phases. The first phase was successfully completed in 2016, focusing on vacuum scrubbing and single beam studies without final focus optics. The second phase has started in March 2018 and until mid of July 2018. It is dedicated to achieve the target specific luminosity larger than 4x10^{31} $cm^{-2}s^{-1}/mA^2$, using the novel "nano-beam" collision scheme. The final focus optics was installed, as well as the Belle II detector, but without the vertex detector. The commissioning in the second phase will also serve to assess and learn to control beam backgrounds expected to be larger than at KEKB in the past, as a result of the much lower beta functions at the interaction point. This is important before installing the vertex detector for the final phase of commissioning, due to start at the beginning of 2019, when high luminosity needed for data taking with the Belle II detector. We present the recent progress and performance of SuperKEKB that is enabled by these upgrades.

INTRODUCTION

SuperKEKB is an electron-positron collider [1] and the Belle II detector [2] built to explore new phenomena in particle physics. The physics program of the next B-factory delivering ultra high statistics is almost independent of, and complementary to, the high energy experiments at the LHC. The target luminosity is 8×10^{35} $cm^{-2}s^{-1}$, which is 40 times the performance of the predecessor, KEKB [5], which has been operated for 11 years until 2010. The strategy for the luminosity upgrade is a nano-beam scheme. The nano-beam scheme was first proposed by P. Raimondi in Italy [3]. The collision of low emittance beams under a large crossing angle allows squeezing the beta functions at the IP to value much smaller than the bunch length. Consequently, extremely higher luminosity can be expected with only twice the beam current of KEKB.

The SuperKEKB operation is divided by 3 stages, Phase 1, Phase 2, and Phase 3. The upgrade work was started after the shutdown of KEKB, and it took 6 years to make the Phase 1 commissioning ready. The final focus system and Belle II detector were not installed in Phase 1 [4] since the subjects were vacuum scrubbing for new vacuum system replaced with ante-chambers, low emittance tuning for new arc lattice to realize low emittance, and beam background study prepare for the installation of Belle II detector before Phase 2. Prior to the main ring operation, the commissioning of the positron damping ring started on 8th February 2018 almost in 2 years after the Phase 1 commissioning. The Phase 2 commissioning started on 19th March 2018. The final focus system and Belle II detector were installed between Phase 1 and Phase 2. The commissioning in Phase 2 will continue until 17th July 2018 for about 4 months in total.

The Phase 3 operation will start in the early 2019, which is a full-scale collider experiment after installation of the pixel vertex detector(PXD) to Belle II.

NANO-BEAM SCHEME

The luminosity for the nano-beam scheme is also written by

$$L = \frac{N_+ N_- n_b f_0}{4\pi \tilde{\sigma}_x^* \sigma_y^*} R_L = \frac{N_+ N_- n_b f_0}{4\pi(\sigma_z \phi_x)\sqrt{\varepsilon_y \beta_y^*}} R_L, \qquad (1)$$

where the effective beam size at the IP in the horizontal direction is indicated by the bunch length σ_z multiplies the half crossing angle ϕ_x as the following

$$\tilde{\sigma}_x^* = \sigma_z \phi_x. \qquad (2)$$

The particle population in a bunch is $N_\pm$, n_b is the number of bunches, f_0 is the revolution frequency, β_y^* is the vertical beta function at the IP, ε_y is the vertical emittance, and R_L is the luminosity reduction factor.

The beam-beam parameters which express the luminosity performance are written in the nano-beam scheme by

$$\xi_{y\pm} \propto \frac{N_\mp}{\sigma_z \phi_x}\sqrt{\frac{\beta_y^*}{\varepsilon_y}} \qquad (3)$$

$$\xi_{x\pm} \propto \frac{N_\mp \beta_x^*}{(\sigma_z \phi_x)^2}. \qquad (4)$$

These formulas shown in Eq. (1) and Eq. (3) imply that higher luminosity can be achieved with keeping the ratio of the vertical beta function at the IP to the vertical emittance constant, namely constant beam-beam parameter in the vertical direction even though both of them can be small.

The Piwinski angle implies how much we can squeeze the vertical beta function at the IP. In order to reduce hourglass effect, the vertical beta function at the IP should be larger than the effective bunch length;

$$\beta_y^* > \tilde{\sigma}_z = \frac{\sigma_x^*}{\phi_x} = \frac{\sigma_z}{\Phi}, \qquad (5)$$

where Φ is the Piwinski angle. In order to make a larger Piwinski angle, smaller horizontal beta function at the IP and lower horizontal emittance is necessary. The horizontal beam-beam parameter is independent of the horizontal emittance and it becomes small as squeezing the horizontal beta function. Consequently, the horizontal beam-beam

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parameter is very small in the case of nano-beam scheme. Therefore, we expect that there is no aperture problem due to the dynamic beta and dynamic emittance in the horizontal direction. SuperKEKB realizes the large Piwinski angle to be more than 10-20 with the bunch length about 6 mm.

SuperKEKB FACILITY

The SuperKEKB collider is an asymmetric-energy and double-ring consists of the High Energy Ring (HER), the Low Energy Ring (LER), and the injector linac [6] with the positron damping ring (DR) [7]. The energy of the HER is 7 GeV for electron beams and 4 GeV positron beams in the LER, respectively (Table 1). The circumference of the main ring is about 3 km and the collision point is one where the Belle II detector is located. The crossing angle is 83 mrad for the separation of two colliding beams. The configuration of normal magnets is the same as those of Phase 1. The detailed description of SuperKEKB is found elsewhere.

Table 1: Machine Parameters Related to the RF in Phase 2. The intra-beam scattering and other collective effects are not considered.

	LER	HER	Unit
E	4	7	GeV
C	3016.3		m
Harmonic no., h	5120		
RF voltage, V_c	8	12.4	MV
α_p	2.88×10^{-4}	4.50×10^{-4}	
σ_z	4.8	5.4	mm
σ_δ	7.53×10^{-4}	6.3×10^{-4}	
U_0	1.76	2.43	MV
ν_s	-0.021	-0.025	

Final Focus

The final focus system consists of the superconducting Quadrupole magnets and Compensation Solenoids (QCS) [8]. The number of magnet coils is 55 in total. They are categorized by three types; main quadrupoles, correctors, and compensation solenoids. The compensation solenoids are utilized to compensate the Belle II detector solenoid as much as possible, the magnetic field is 1.5 T at the maximum. Since the most closest quadrupoles to the IP have no iron shield in the LER, the leakage filed from them affect the beam orbit and optics in the HER. The leakage dipole and quadrupole field are utilized in the optics design, however, higher multipole fields are almost cancelled by cancel coils installed in front of the main coils in the HER.

STRATEGY OF COMMISSIONING

One of the targets of the Phase 2 commissioning is a verification of the nano-beam scheme and the other is a study of the beam background for the Belle II detector. Reduction and understanding of the beam background are very important to install the pixel vertex detector (PXD) in Phase 3.

The specific luminosity can be dined by

$$L_{sp} = \frac{L}{n_b I_+ I_-} = \frac{1}{4\pi e^2 f_0} \frac{R_L}{(\sigma_z \phi_x)\sigma_y^*}, \tag{6}$$

where $I_\pm$ is the bunch current. The specific luminosity is expected to be larger than 4×10^{31} cm^{-2}s^{-1}/mA^2 with the beam-beam parameter of about 0.05.

There several sub phases in Phase 2. We started very big beta function at IP, for instance, about 50-80 mm in the vertical direction in the early stage to find a closed orbit with the final focus system (QCS). The horizontal beta is 400 mm at the IP for the detuned optics. This sub phase is called Phase 2.0. The hardware devices and software were checked in this phase. The measurements and corrections of the optics were also performed. In Phase 2.1, the beta functions at IP are squeezed down to be 200 mm in the horizontal direction and 8 mm in the vertical direction, respectively. The first collision that means a measurement of beam-beam deflection will be performed during this phase. Further beta squeezing will be performed in Phase 2.2 to Phase 2.4. The target of vertical beta function at the IP is about 2 mm in Phase 2.2 and Phase 2.3, and about 1mm in Phase 2.4.

The specific luminosity as the function of the number of bunches multiplies the bunch current products is shown in Fig. 1. We start small beam current with small number of bunches to keep bunch currents as much as possible for the collision tuning. The nominal bunch current is 0.6 mA in the LER and 0.5 mA in the HER, respectively. When we will achieve the specific luminosity of 2×10^{31} cm^{-2}s^{-1}/mA^2, we will increase the number of bunches up to 1576 that corresponds to 3-bucket spacing. The total beam currents become 1 A in the LER and 0.8 A in the HER, then the total luminosity of 10^{34} cm^{-2}s^{-1} can be achieved with assuming 5 % emittance ratio. If we can improve the emittance ratio down to 1.4 %, the specific luminosity reaches approximately 4 $\times10^{31}$ cm^{-2}s^{-1}/mA^2 and 2×10^{34} cm^{-2}s^{-1} of luminosity which is almost the same as the highest luminosity at KEKB. Machine parameters are shown in Table 2.

The dynamic aperture of the LER and HER are considered in Phase 2 with particle tracking simulations. In the case of Phase 2.3, Touschek lifetime is expected to be 60 minutes in the LER and 190 minuets in the HER without machine error and beam-beam interactions. The machine error reduces the dynamic aperture about 10-20 % and the effect of the beam-beam interaction is expected to be less than 10 %. Consequently, we assume that the total lifetime in the LER is 40 minuets and 150 minuets in the HER during Phase 2.

COMMISSIONING HISTORY AND RESULTS

History of the beam currents and beam dose are shown in Fig. 2. The target of beam dose is 100 Ah before the official physics run. The vacuum scrubbing is on going and we have achieved almost half of the target beam dose until the early

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Table 2: Machine Parameters in Phase 2. The left column is values in the LER and those of the HER in the right. The KEKB machine parameters refer the operation performed in 2006. The parameters in Phase 3 is the final design of SuperKEKB. The unit of specific luminosity and luminosity are $cm^{-2}s^{-1}/mA^2$ and $cm^{-2}s^{-1}$, respectively.

LER / HER	KEKB*	Phase 2.0	Phase 2.1	Phase 2.2	Phase 2.3	Phase 2.4	Phase 3
β_x^* mm	590 / 560	384 / 400	200 / 200	256 / 200	128 / 100	128 / 100	32 / 25
β_y^* mm	6.5 / 5.0	48.6 / 81	8 / 8	2.2 / 2.4	2.2 / 2.4	1.1 / 1.2	0.27 / 0.30
ε_x nm	18 / 24			2.1 / 4.6			3.2 / 4.6
$\varepsilon_y/\varepsilon_x$ %	3 / 2.5	5	10	5	1.4	0.7	0.27
σ_z mm	7			6			
$2\phi_x$ mrad	22			83			
Φ	0.75 / 0.66	8.8 / 5.8	12.2 / 8.2	10.7 / 8.2	15.2 / 11.6		24.6 / 23.2
I_{tot} (A)	1.66 / 1.34	0.25 / 0.17	0.25 / 0.22		1.0 / 0.8		3.6 / 2.6
n_b	1388	1576	400		1576		2500
ξ_x	0.117 / 0.070	-	0.006 / 0.004		0.005 / 0.002		0.003 / 0.001
ξ_x	0.105 / 0.056	-	0.03 / 0.03	0.026 / 0.026	0.05 / 0.05	0.05 / 0.05	0.088 / 0.081
L_{sp} $\times 10^{31}$	1.06	-	0.7	1.97	3.94	7.88	21.4
L $\times 10^{34}$	1.7	-	0.1	1	2	4	80

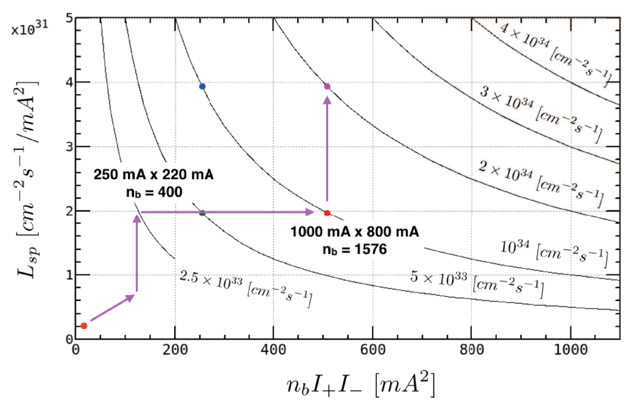

Figure 1: Specific luminosity as a function of bunch current products multiplies number of bunches. Lines indicate total luminosity.

May. We will increase the beam current up to 1 A in the LER and 0.8 A in the HER, respectively. Those beam currents correspond to about 30 % of the design values.

The detuned lattice was used in Phase 2.0. This lattice is a temporary lattice and the large beta functions at the IP to store beams first and to correct closed orbit distortions. First of all, we turned off all RF cavities and injected electron beams to the HER. We checked the beam intensity along the beam line by using Turn-by-Turn BPMs. Assuming that the momentum acceptance is 2 %, the maximum turns can be estimated to be about 20-30 turns from the energy loss per turn, U_0. Then, we turned on the RF cavities, station by station with adjustment of the RF phase to maximize number of turns. After storage beams and the beam injection was established, the orbit responses of the QCS correctors were measured by using a single-kick method. The start of LER is similar to the HER commissioning. During the hardware inspections, we figured out wiring mistake between the skew dipole and skew quadrupole corrector coil in the LER. The beams could be stored and the closed orbit distortion was corrected with a peculiar way even though the mistake. However, we had several QCS quench events during beam injections due to hitting of the particles. We estimate that 8000 particles can make a QCS quench by a simple calculation. After correction of the wiring mistake, the injection and closed orbit became normal and consistent. The QCS system has been operated successfully with the beam commissioning after fixing these issues.

The movable collimators are necessary not only to reduce beam backgrounds for the Belle II detector but also to avoid QCS quench. The collimators were loose setting during we got several experiences of QCS quench. There is no QCS quench due to injected beams after maintaining the collimators so as to be smaller apertures than those of QCS.

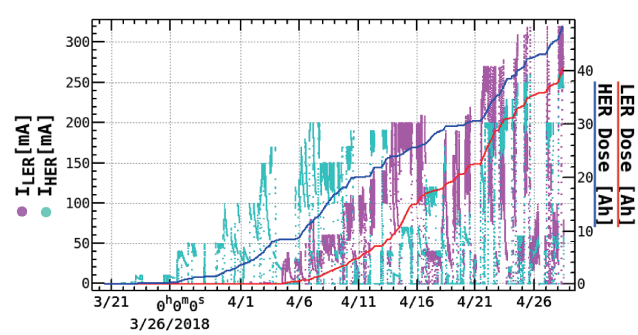

Figure 2: Beam dose and beam currents in the LER and HER, respectively.

Once we can realize Phase 2.1 or later successfully, we can squeeze the beta functions at the IP adiabatically. In order to squeeze the beta functions at the IP, several quadrupole magnets located in the matching section near the arc sections can be used without any modifications of the final focus magnets as well as the local chromaticity corrections. The Phase 2.1 lattice is for a collision optics, the horizontal beta function at

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the IP is 200 mm and 8 mm in the vertical direction, respectively. The lattice includes the local chromaticity corrections in both of the x and y direction. The optics measurements and corrections have been performed during both Phase 2.0 and Phase 2.1. The results of the optics corrections for Phase 2.1 lattice is shown in Table 3. The measurements of the optical functions are based on closed orbit responses which are compared with the model lattice. The skew quadrupole correctors are installed at each sextupole magnet, which are two identical sextupoles connected by $-I'$ transfer matrix. Therefore, these correctors can correct X-Y couplings and vertical dispersion independently for on-momentum optics. The beta corrections are done by adjustment of quadrupole field to reproduce the model lattice for the real machine. The optics corrections are under way, especially the X-Y couplings and beta-beat in the HER are large values.

Table 3: Status of the Optics Measurements and Corrections in Phase 2.1. X-Y couplings, dispersions, beta-beat, and emittance ratio. The emittance ratio is obtained from X-ray beam size measurement with assuming the beta functions.

Item	LER	HER	Unit
$(\Delta y)_{rms}/(\Delta x)_{rms}$	0.024	0.077	
$(\Delta\eta_x)_{rms}, (\Delta\eta_y)_{rms}$	20, 5	16, 19	mm
$(\Delta\beta_x/\beta_x)_{rms}$	4	18	%
$(\Delta\beta_y/\beta_y)_{rms}$	8	13	%
$\varepsilon_y/\varepsilon_x$	3.4	10	%

The lifetime is 500 min in the HER at 250 mA, on the other hand, the lifetime in the LER is 90 min at 300 mA with 1576 bunches. The Touschek lifetime in the LER is shorter than what we expected, therefore it is necessary to optimize the dynamic aperture to make Touschek lifetime longer.

For the injection of the electron beams, the RF gun was tested. It provides low emittance beams to the HER. Both of the RF gun and thermionic gun are available in Phase 2. The emittance of the thermionic gun does not restrict the injection in the HER so far. The injection efficiency is typically 50 to 70 % which is caused by the X-Y couplings not yet corrected well. However, the low emittance beams from the RF gun will only able to be injected when the beta functions at the IP will be further squeezed, consequently, the dynamic aperture will become small. The advantage of thermionic gun is applicable for "simultaneous injection" to the HER and LER. The thermionic gun can provide beams for different rings; not only the LER and HER but also two photon factories, which are different energies. To make this possible, pulsed magnets such as dipoles and quadrupoles are installed in the downstream and half of the linac. The thermionic gun also provide large charge to produce positron beams with the flux concentrator. The damping ring has been working well to provide low emittance positrons and inject to the LER. The injection efficiency is typically 90 to 100 % in the LER.

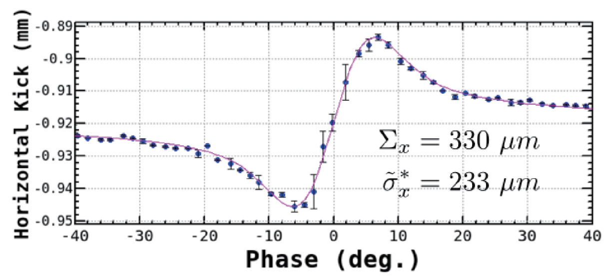
Beam-Beam Deflections

The horizontal offset can be calculated by the translation of RF phase as the following:

$$\Delta x = \Delta z\, \phi_x \tag{7}$$

$$\Delta z = \frac{\varphi - \varphi_0}{360^\circ}\left(\frac{C}{h}\right), \tag{8}$$

where $\varphi - \varphi_0$ is the shift of RF phase, C is the circumference, and h is the harmonics number. The first measurement of beam-beam deflection was tried on 20th April 2018. However, it took a few days to find the beam-beam deflection since the collision timing was ambiguous due to the double-ring collider. Finally, the horizontal beam-beam deflection was observed on 25th April with multi-bunch collisions. Figure 3 shows the clear signal of the horizontal beam-beam deflection together with the luminosity measurement. The effective beam size in the horizontal direction can be estimated to be 233 μm from the beam-beam deflection. On the other hand, the beam size is also estimated from the specific luminosity(arbitrary unit) and it is 224 μm. Those values are consistent with the effective horizontal beam size calculated from $\tilde{\sigma}_x^* = \sigma_z\, \phi_x$.



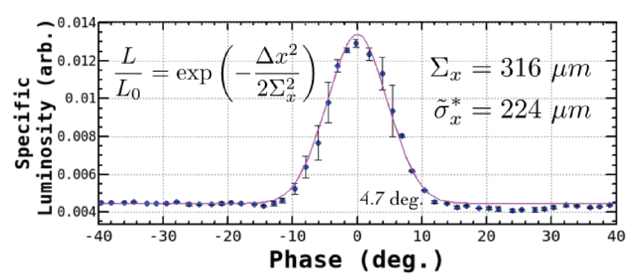


Figure 3: Horizontal beam-beam scan by using RF phase in the LER.

As the next step, we tried the vertical scan by using the local-bump orbit in the vicinity of the IP. The vertical beam-beam deflection was observed on 26th April. Figure 4 shows the beam-beam deflection in the vertical direction. The vertical beam size was estimated to be 4 μm from the vertical beam-beam deflection. It is found that the luminosity becomes a shape of the double peak. This behaviour is caused by the vertical angle of orbit in the HER since the double-peak is disappeared by changing the vertical angle with the local-bump orbit. The vertical beam size is still large because the X-Y couplings in the HER have not yet been corrected

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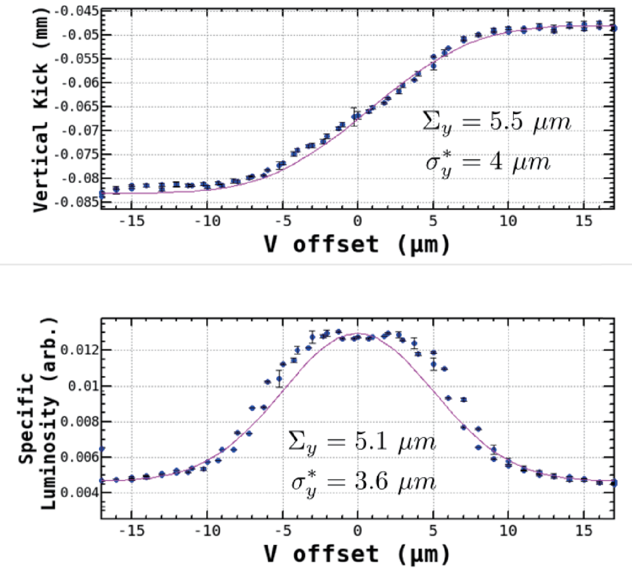

Figure 4: Vertical beam-beam scan by changing the vertical local-bump offset with dipole correctors in the HER.

well. We have observed a beam-beam kick affects the lifetime decreased in the HER and the beam-beam blowup is suspected.

CONCLUSIONS

We have just started the Phase 2 commissioning since 19th March 2018. The beam currents are stored up to 200 - 300 mA under the stable condition. The vacuum scrubbing has been continued and almost 50 Ah beam dose has been achieved, while the target value is 100 Ah. We could jump from Phase 2.0 non-collision optics to Phase 2.1 collision optics which is completely different lattice. The beta functions at the IP is 200 mm in the horizontal and 8 mm in the vertical direction for the collision optics in Phase 2.1. In the lattice in Phase 2.1 or later, the beta functions at the IP can be squeezed adiabatically.

The beam-beam deflections have been observed in Phase 2.1 and also the first physics event on 26th April 2018. Figure 5 shows the first hadronic event observed by the Belle II detector. The machine parameters achieved under the collisions are shown in Table 4. The luminosity is estimated from the observed beam size by beam-beam scans with assuming the electron and positron beam are the same. The remaining issues are the X-Y couplings and beta-beat in the HER, preparation of the IP knobs such as the coupling and vertical dispersions at the IP, and waist knobs. The scan of the vertical angle is also important. Fast orbit feedback with local-bump to keep optimized collisions will be prepared, and dithering system has been tested recently, the dithering feedback with the luminosity monitor will be available soon. We will try to squeeze further beta function down to 2 mm at the IP in the vertical direction in Phase 2.

The verification of the nano-beam scheme and understanding of beam backgrounds are ongoing.

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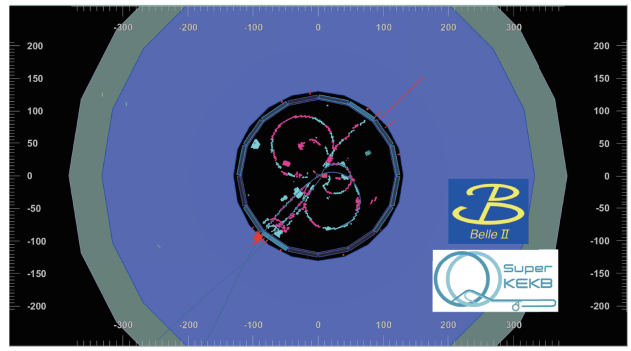

Figure 5: Hadronic event in the Belle II detector at the first time.

Table 4: Machine Parameters Achieved in the Collisions and Comparison with the Tentative Target in Phase 2.1. The horizontal beam size at the IP is the effective value.

Item	**Phase 2.1** Achieved		**Phase 2.1** Target		Unit
	LER	HER	LER	HER	
I	77	59	250	220	mA
n_b	300		400		
β_x^*	200	200	200	200	mm
β_y^*	8	8	8	8	mm
$\tilde{\sigma}_x^*$	224		250		μm
σ_y^*	4		1.6		μm
I_{bunch}	0.26	0.20	0.625	0.55	mA
L_{Sp}	2.1×10^{30}		$7{\times}10^{30}$		$cm^{-2}s^{-1}/mA^2$
L	3.2×10^{31}		$1{\times}10^{32}$		$cm^{-2}s^{-1}$

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