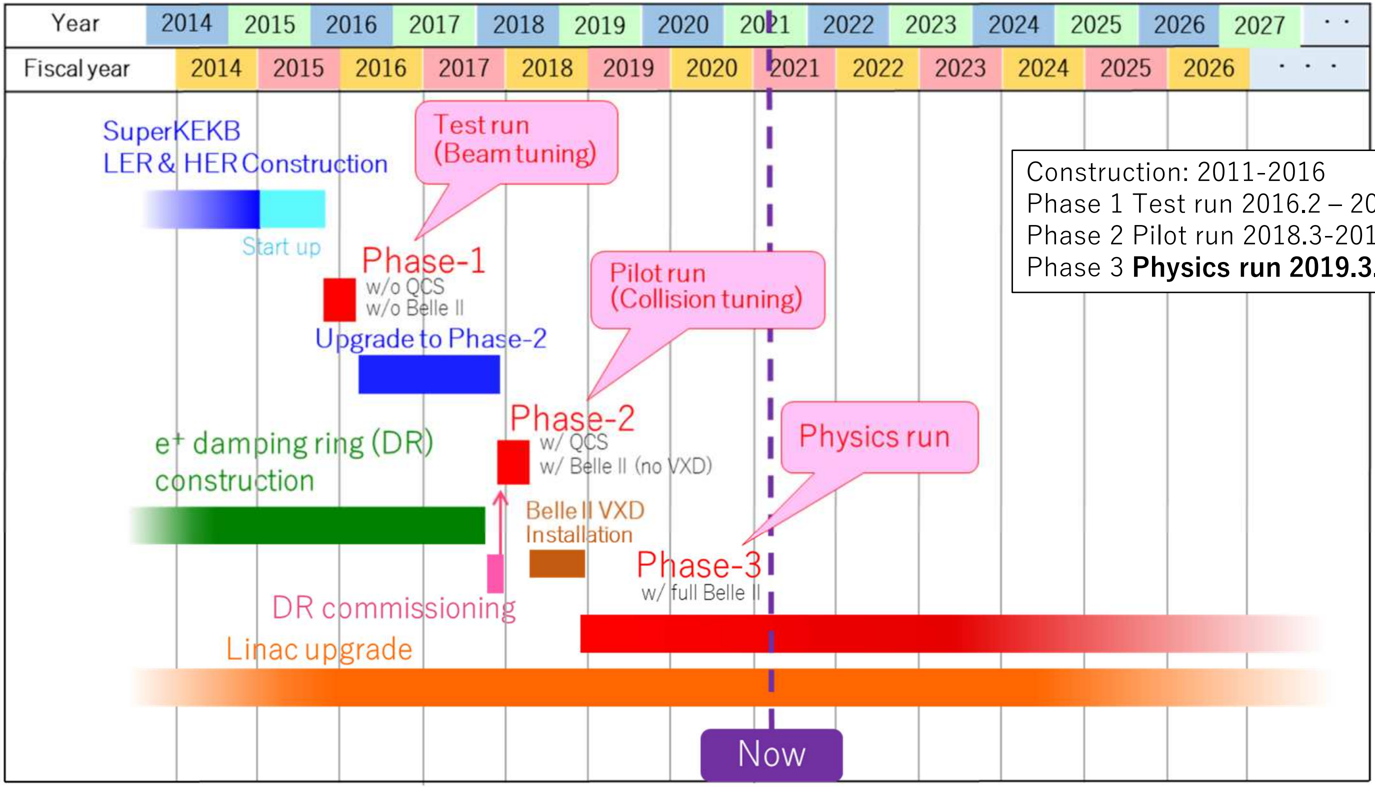
Long-term SuperKEKB operation and upgrade plan

Y. Suetsugu, M. Tobiyama and K. Furukawa, KEK

B2GM plenary

2021/6/21

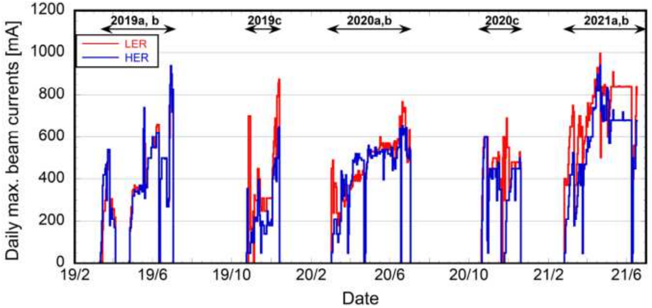
SuperKEKB project timeline



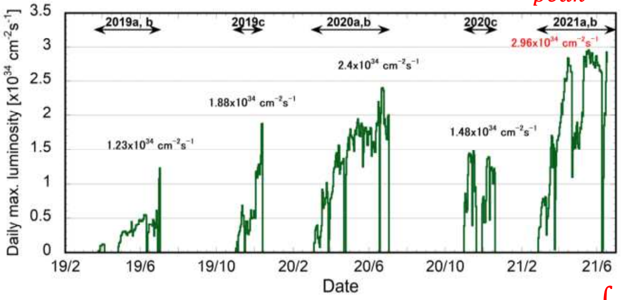
Construction: 2011-2016
Phase 1 Test run 2016.2 – 2016.6
Phase 2 Pilot run 2018.3-2018.7
Phase 3 **Physics run 2019.3.11-present**

SuperKEKB achievements to date

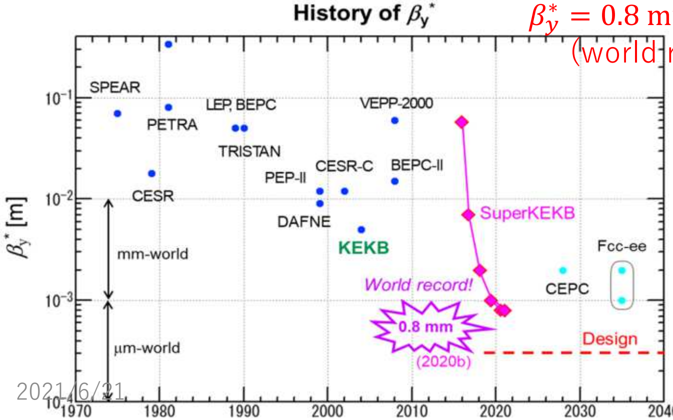
- SuperKEKB is already exploring uncharted territory!
- It is very challenging to improve the machine further to achieve the design goal.



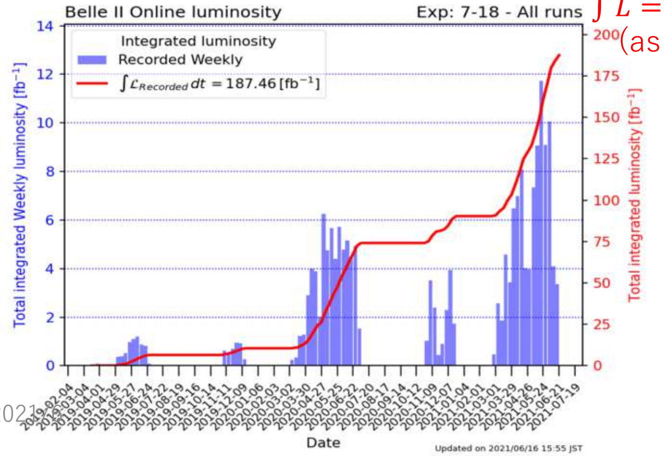
$L_{peak} = 2.96 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$
(world record)



$\beta_y^* = 0.8$ mm
(world record)

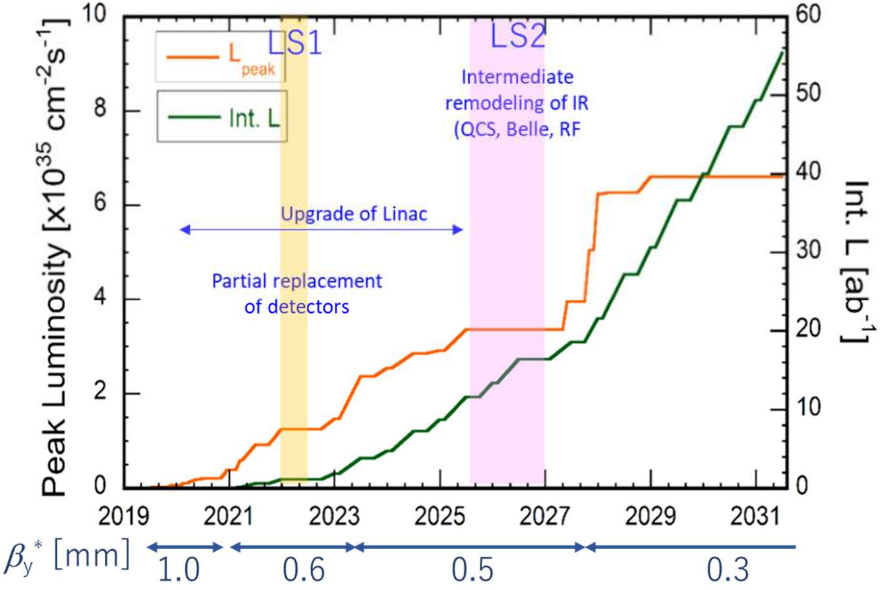


$\int L = 187 \mathrm{fb}^{-1}$
(as of May, 2021)



Long-term luminosity profile

Current profile = MEXT Roadmap 2020



- The current goal is to achieve
  $L \sim 6 \times 10^{35} cm^{-2} s^{-1}$ and
  $\int L = 50\text{ab}^{-1}$ by around 2031,
  which requires an intermediate machine upgrade around 2026 that improves the luminosity by a factor of 2-3.
- The plan and profiles were assessed by the external review committees (BPAC (2020/6, 2021/3) and Accelerator Review Committee (ARC, 2020/7)).
- A variety of ideas to realize the plan have been proposed and discussed not only in the Long-term operation plan meeting but also other meetings, such as MDI meeting and IR technical meeting.

Limitations found so far

- While we have been confronting various difficulties during operation, the underlying issues became evident in 2020c. Identified challenges are as follows:
    - Shorter beam lifetime than expected
        - As a result, the maximum bunch currents are limited by the balance between the lifetime and the injection power.
    - Lower bunch-current limit due to TMCI than expected
        - Due to higher impedance of beam collimators, in which the apertures are smaller than the design values to suppress high background.
    - Beam-beam effect (vertical beam size blow-up)
        - Relaxed by the crab-waist collision scheme, but still remains.
    - Low operation efficiency
        - Operation efficiency during 2021a, b is almost 0.5, lower than expected one, 0.65.
        - Machine tunings, machine troubles, maintenance, etc.
    - Aging of hardware and facilities, and so on.
- Various measures to solve these challenges have been also discussed at the same time.

Planned countermeasures

	Aim	Possible countermeasures
(1)	Increase injection power (efficiency)	Linac upgrade to designed specification
		Large physical aperture at electron injection point (HER)
		Linac upgrade beyond designed specification
(2)	Improve dynamic aperture	Rotatable sextuplole magnets
		Perfect matching
		QCS modification (Option#1): Move QC1RP to far side of IP
		Large scale QCS modification (Option #8)
(3)	Lower BG Improve physical aperture	QCS cryostat front panel modification and additional shield to IP bellows
		Optimization of collimator location
		QCSR beam pipe enlargement (Option#3)
(4)	Relax TMCI limit	Non-linear collimator
(5)	Improve stability	Robust collimator
		Upgrade of beam abort system and loss monitor system
(6)	Anti-aging measures	Preparation of standby machines and spares, repair of facilities, etc.

Planned countermeasures

- High-priority countermeasures before LS2

Aim	Possible countermeasures	Expected improvement	Ready status	LS1 LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Increase injection power (efficiency)	Linac upgrade to designed specification	**Full spec injection**	On going sequentially.	
Improve dynamic aperture	Rotatable sextupole Magnets	Beam-beam parameter (emittance), beam lifetime	Ready. Preparation of tuning knob.	
Improve stability	Robust collimator	Sustainability	Need R&D and beam test	
Improve stability	Beam abort system and loss monitor system	Operation stability	On going sequentially.	
Anti-aging measures	Anti-aging measures	Operation efficiency (standby machine, repair of facilities)	On going sequentially. Especially for long shut down periods	

- Essential to achieve $\sim 2 \times 10^{35}$ $cm^{-2}s^{-1}$ before LS2.

Planned countermeasures

- Possible countermeasures in LS1

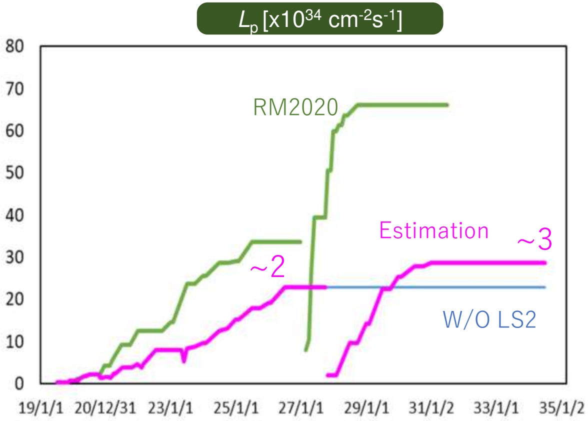
Aim	Possible countermeasures	Expected improvement	Ready status	LS1 LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Increase injection power (efficiency)	Large physical aperture at electron injection point (HER)	HER Injection rate x #?	Need further estimation, design of pipes	
Improve dynamic aperture	Perfect matching	**LER beam lifetime x ~1.5.**	Need further simulation, design, manufacturing of magnets and pipes	
Improve physical aperture Lower BG	QCS cryostat front panel modification and additional shield to IP bellows	Background, Physical aperture, **TMCI limit x ~1.2**	Will be ready by 2022.	
Improve physical aperture Lower BG	Optimization of collimator location	**Background x ~1/2 (Storage beam)**	Need further simulation, manufacturing of pipes	
Relax TMCI limit	Non-linear collimator	**Background x ~3/5 (Storage beam)**	Need further simulation, design, manufacturing of magnets and pipes	

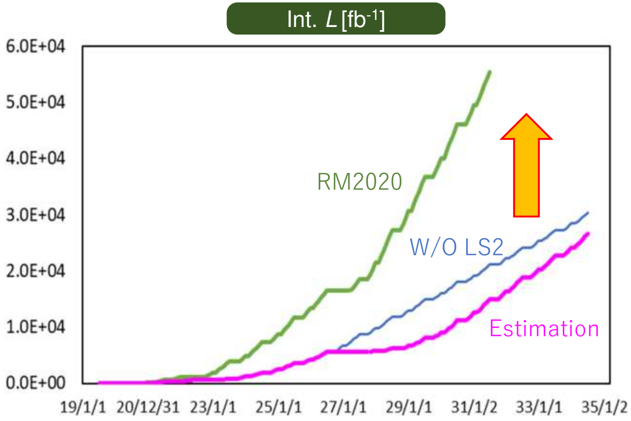
- Possible countermeasures in LS2

Aim	Possible countermeasures	Expected improvement	Ready status	LS1 LS2 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Improve dynamic aperture	QCS modification (Option#1): Move QC1RP to far side of IP	Found to be no effect.	Will be not adopted	
Improve physical aperture Lower BG	QCSR beam pipe enlargement (Option#3)	13.5 mm -> 15 or 18 mm, β_y^*=0.3 will be possible, no effect on dynamic aperture, **TMCI limit x ~1.5.**	Need design, manufacturing of correction magnets and pipes	

Preliminary luminosity estimation

- Estimated luminosity with these countermeasures





- The luminosity will be lower than expected considering various limitations.
- The ideas of the intermediate upgrade of IR around 2026 we have planed so far are not satisfactory from the viewpoint of int. luminosity as given in RM2020, and therefore we are continuing the effort to find more effective measures(x2~3), not limited to the IR but also to other parts of the MR and Linac.
- Ideas of a more revolutionary upgrade including some modification of Belle II should be considered to reach even higher luminosity; this may require a longer time for R&D (~203x).

Plan

- We continue to find more effective measures, not only limited to the IR but also including the MR, other parts and Linac to maintain the target luminosity profile.
- Inaugurate an international taskforce under the management of the KEK Accelerator Lab. to pursue effective measures for recovering the luminosity profile and reaching target luminosity.

- The results of ongoing studies will be reported at the next ARC, scheduled in September.
- Some practical conclusion should be obtained before LS1 on the feasibility and contents of the upgrade around 2026.
- The actual long-term plan will be revised based on the progress of the ongoing luminosity improvement.

We greatly appreciate your continued support!

Back up

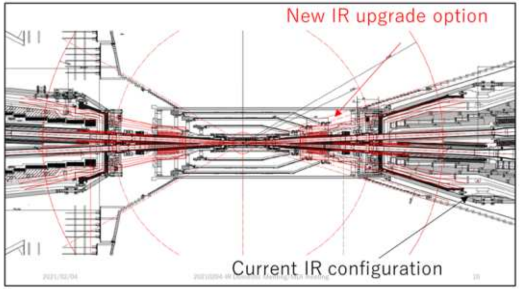
Planned countermeasures

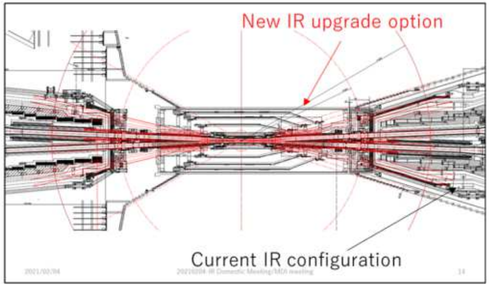
- For reference, proposed countermeasures **after LS2** (~2031?)
  - Still preliminary discussion

Aim	Possible countermeasures	Expected improvement	Ready status	**LS1** **LS2** 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031~
Improve dynamic aperture	Large scale QCS **and also Belle II** modification (Option #8)	**LER beam lifetime x ~2.2**	Need further simulation	
Increase injection power (efficiency)	Linac upgrade **beyond designed specification**	**Injectin power x ~2?**	Need further invesitgation	

- With these countermeasures
  - **L = ~2×10^{35} $cm^{-2}s^{-1}$ -> ~4×10^{35} $cm^{-2}s^{-1}$**

IR modification (option #8) including Belle II (SVD etc.)



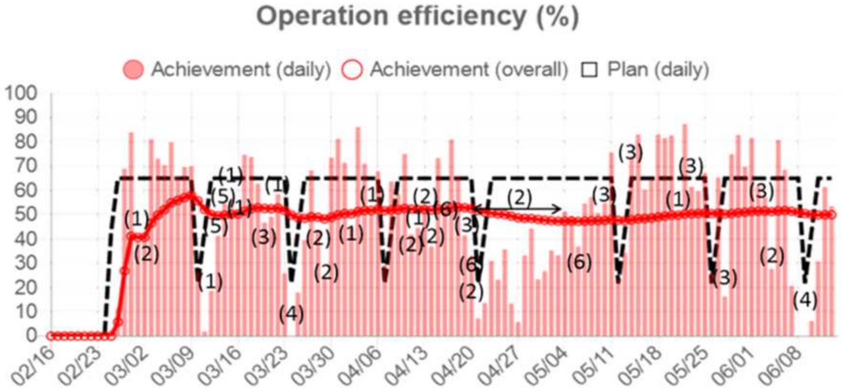


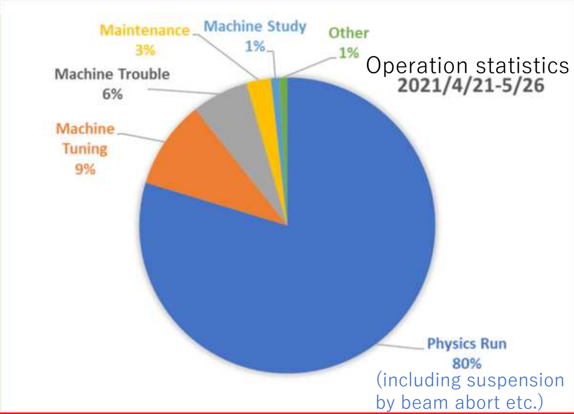
Limitations found so far

(3) Low operation efficiency

- Operation efficiency during 2021a, b is almost 0.5, lower than expected one, 0.65.
- Main reasons (analyzed by K. Matsuoka):

(1) Accelerator/collimator study/tuning
(2) Accelerator troubles
(3) QCS quench
(4) Collimator replacement
(5) Slow recovery after the maintenance
(6) Baking run





- Note that the efficiency was ~66% during 5/11~5/25, where the beam currents were kept constant, and the operation was dedicated to physics run.
  - A key point is how to keep the stability of machine.
- Hardware trouble due to aging can be avoided by planned and prepared updating or replacing old hardware.
  - Preparation of standby machines and spares, and anti-aging measure for facilities and old hardware are urgent matters.

Luminosities expected under these limitations

- These challenges add new bunch current limits in the operation, and will limit the luminosity.
  - Lifetime (injection power) limit based on the formula presented by K. Oide.

$$i_{b+}^{inj} = \sqrt{\epsilon_+ I_+^{inj} f_0 \frac{C_+^i \beta_y^* \sqrt{\varepsilon_y}}{N_b}} \qquad i_{b-}^{inj} = \sqrt{\epsilon_- I_-^{inj} f_0 \frac{C_-^i \beta_y^* \sqrt{\varepsilon_y}}{N_b}}$$

  - TMCI limit $\quad i_{b+}^{tmci} = 1.4\ mA \quad i_{b-}^{tmci} = 1.5\ mA$
  - RF power limit $\quad i_{b+}^{RF} = \frac{I_+^{max}}{N_b} \quad i_{b-}^{RF} = \frac{I_-^{max}}{N_b}$

    I_+^{max}=2.59 A, I_-^{max} = 1.87 A before LS2

    I_+^{max}=2.82 A, I_-^{max} = 2.04 A after LS2
  - Hardware limit (for example by BPM)

$$i_{b+}^{hard} = 2\ mA \qquad i_{b-}^{hard} = 2\ mA$$

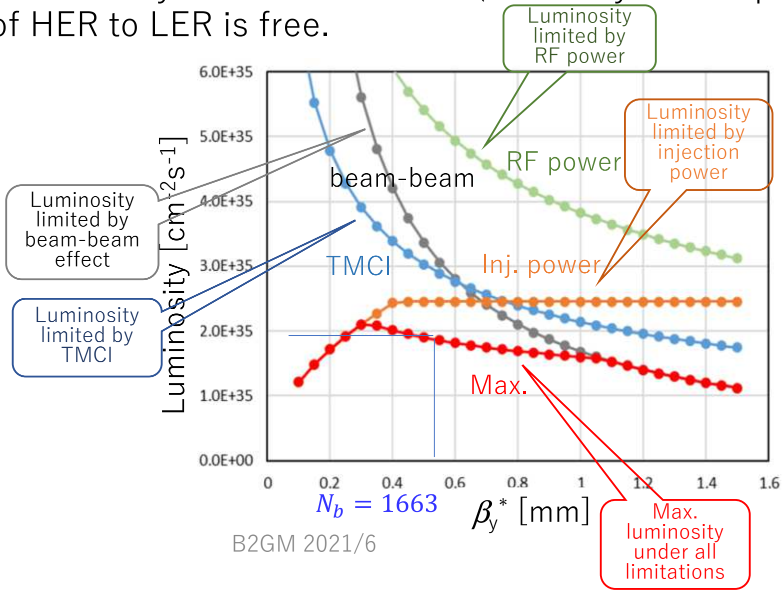
- Luminosity formula

$$L = \frac{1}{4\pi e^2 f_0 \sin\phi_c \sigma_z} \frac{N_b i_{b+} i_{b-}}{\sqrt{\beta_y^* \varepsilon_y}}$$

$$L_\xi = \frac{\gamma_\pm}{2 e r_e}\left(1 + \frac{\sigma_{y\mp}^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*} \sim \frac{\gamma_\pm}{2 e r_e}\frac{I_\pm \xi_{y\pm}}{\beta_{y\pm}^*}$$ (when limited by beam-beam parameter, ξ_y)

Luminosities expected under these limitations

- The luminosities under these bunch current limitations were estimated by H. Nakayama and K. Nakamura.
  - Reported in MDI meeting, IR technical meeting, and LTOP meeting.
  - Here, the maximum luminosity was searched by scanning N_b (500~2500) for each β_y^*.
  - Assumptions:
    - Background does not matter.
    - Beam-beam parameter (ξ_y) and emittance (ε_y) are constant (no dependence on β_y^*).
    - Beam lifetime is determined by Touschek lifetime (due to dynamic aperture).
    - Beam current ratio of HER to LER is free.
- The calculation is not a strict simulation, but will give some guideline of achievable luminosities under these limitations.



$I_+^{max} = 2.59$ A, $I_-^{max} = 1.87$ A — Max. beam currents

$\sigma_z = 6.5$ mm — Bunch length

$N_b^{max} = 2500$ — Max. number of bunches

$\varepsilon_y = 20$ pm — Vertical emittance

$\xi_{y+}^{max} = 0.075$ — LER ver. beam-beam parameter

$C_+^i = 3.6 \times 10^7$, $C_-^i = 1.2 \times 10^8$ — Lifetime parameter

$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$ — Inj. efficiency

$q_+^{inj} = q_-^{inj} = 4$ nC — Inj. bunch charge

$N_{b+}^{inj} = N_{b-}^{inj} = 2$ — Inj. number of bunches

$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz — Inj. repetition rate

$i_+^{hard} = 2$ mA, $i_-^{hard} = 2$ mA — Hardware limit

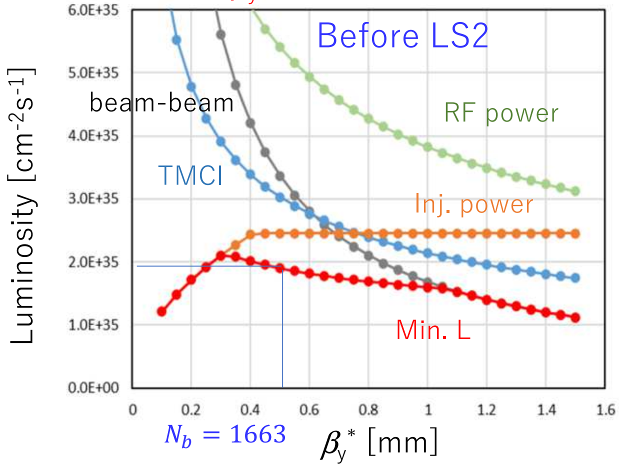
$i_+^{tmci} = 1.4$ mA, $i_-^{tmci} = 1.5$ mA — TMCI limit

Luminosities expected under these limitations

- The maximum luminosities before and after LS2 were calculated using possible parameters basically following their methods.
  - Note here, we assumed the full-power injection, that is, 4 nc/bunch, 2 bunches, 25 Hz injection with an efficiency of 80%.

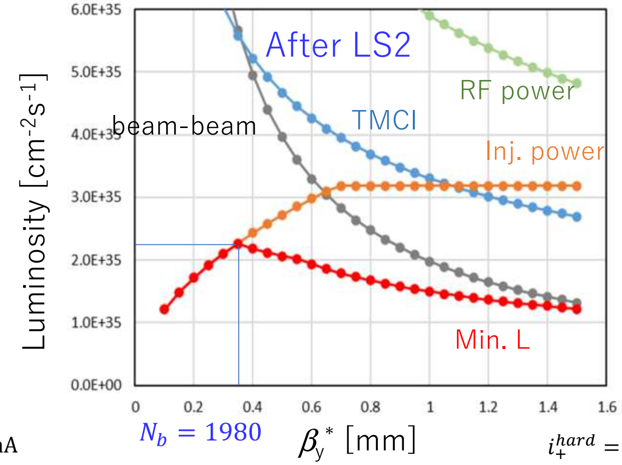
- Preliminary results;

- **Before LS2**($\beta_y^* \geq 0.5$ mm), **L = 1.9x10^35** [$cm^{-2}s^{-1}$]



$I_+^{max} = 2.59$ A
$I_-^{max} = 1.87$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 20$ pm
$\xi_{y+}^{max} = 0.075$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA

- **After LS2**($\beta_y^* \geq 0.3$ mm), **L = 2.3x10^35** [$cm^{-2}s^{-1}$]



$I_+^{max} = 2.82$ A
$I_-^{max} = 2.04$ A
$\sigma_z = 6.5$ mm
$N_b^{max} = 2500$
$\varepsilon_y = 10$ pm
$\xi_{y+}^{max} = 0.081$
$C_+^i = 3.6 \times 10^7$
$C_-^i = 1.2 \times 10^8$
$\epsilon_+^{inj} = \epsilon_-^{inj} = 0.8$
$q_+^{inj} = q_-^{inj} = 4$ nC
$N_{b+}^{inj} = N_{b-}^{inj} = 2$
$f_{r+}^{inj} = f_{r-}^{inj} = 25$ Hz
$i_+^{hard} = 2$ mA $\quad i_-^{hard} = 2$ mA
$i_+^{tmci} = 1.4$ mA $\quad i_-^{tmci} = 1.5$ mA

Luminosities expected under these limitations

- Re-estimated luminosities was much lower than that presented in RM2020.
- Operation efficiency should be also improved to accumulate the expected luminosity.

- To improve luminosity
  - Increase injection power (injection efficiency, bunch charge) or improve beam lifetime (dynamic aperture and also physical aperture)
  - Lower background -> Wide collimator aperture (physical aperture) -> Long beam lifetime, Low impedance -> Relax TMCI limit
  - Relax TMCI limit (important if emittance is still large).
  - Improve beam-beam parameter (low emittance,)

- To improve operation efficiency (Integrated luminosity)
  - Increase efficiency of beam tuning (improvement tuning knobs)
  - Improve stability of machines
  - Prepare standby machine and spares
  - Execute anti-aging plans for facilities