Overview of SuperKEKB Vacuum System

Contents

- SuperKEKB vacuum system
- Present status
  - Status of components, Vacuum scrubbing, Electron cloud effect, Pressure bursts, etc.

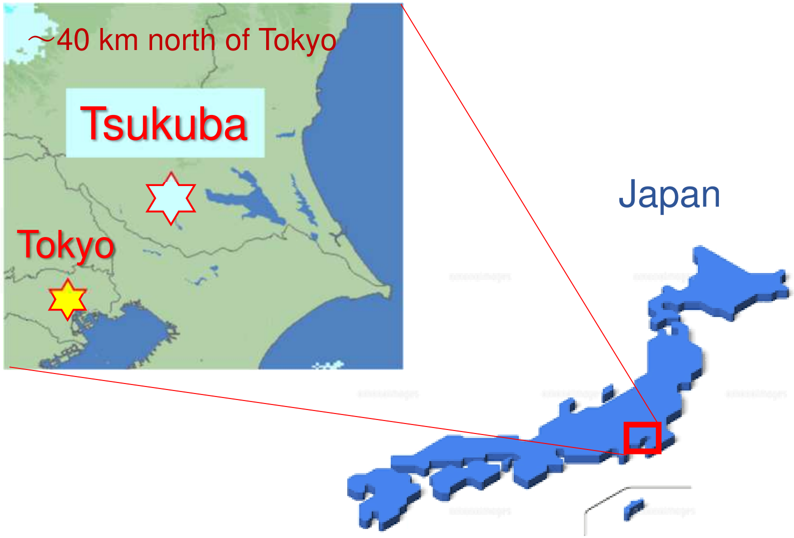
Y. Suetsugu, KEKB Vacuum group
Accelerator Laboratory, KEK

Note:
The vacuum system at interaction region (IR) will be covered by Shibata-san in the next talk.
My talk is focused on other vacuum system.

SuperKEKB

- An electron – positron collider with asymmetric energies.
  - Located at KEK Tsukuba campus
- Upgrade project of KEKB B-factory, which had been successfully in operation during 1998~2010.
- Mission: Quest new theories beyond the standard model at B-meson regime.

SuperKEKB in KEK Tsukuba campus

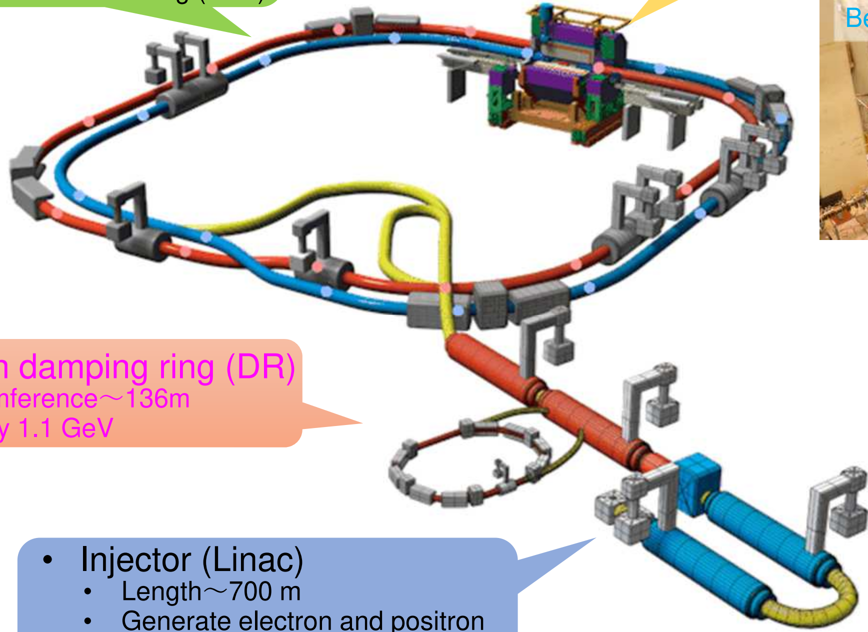


Configuration

- Main ring (MR)
  - Circumference～3016 m
  - 7 GeV Electron ring (HER)
  - 4 GeV Positron ring (LER)

Belle II Detector

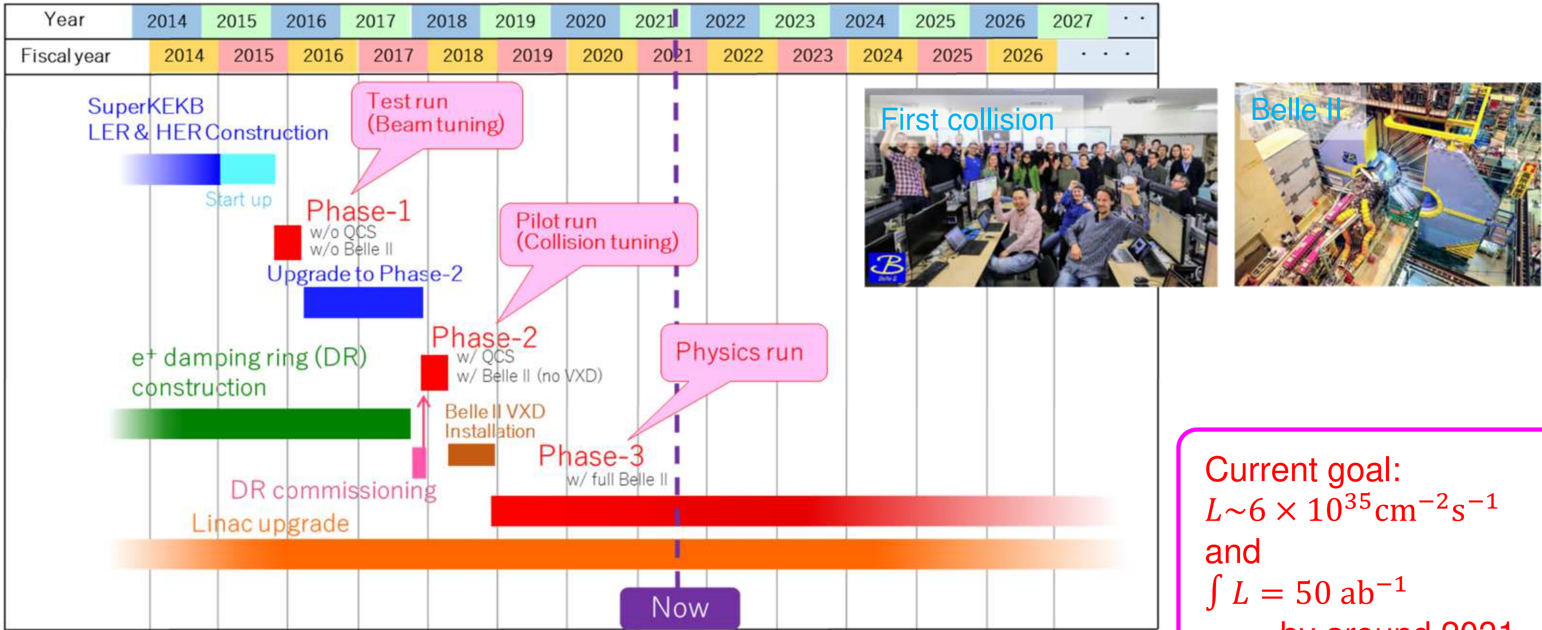
Collision point



- Positron damping ring (DR)
  - Circumference～136m
  - Energy 1.1 GeV

- Injector (Linac)
  - Length～700 m
  - Generate electron and positron
  - Accelerate up to final energy

Project timeline

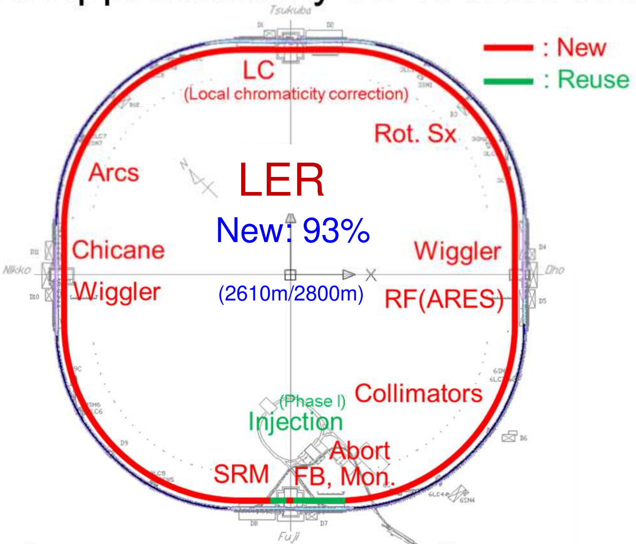


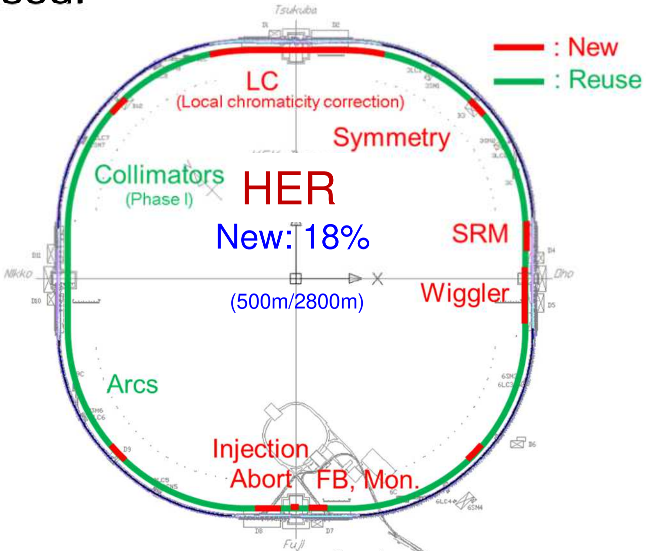
Current goal:
$L \sim 6 \times 10^{35} \mathrm{cm}^{-2} \mathrm{s}^{-1}$
and
$\int L = 50\ \mathrm{ab}^{-1}$
by around 2031

- 2010～2016 Construction (Upgrade work from KEKB)
- 2016/2～6 Phase-1: Test operation (Beam tuning)
- 2018/3～7 Phase-2 : Commissioning operation (Collision tuning)
  (with final focusing SC magnets and Belle II Detector)
- 2019/3～ Phase-3 : Physics operation

New vacuum system

- The vacuum system was a key upgrade point.
- LER: Approximately 93% of beam pipes and bellows chambers in length were renewed.
- HER: Approximately 82 % were reused.





- Sub systems, such as cooling water system, compressed air system, were basically reutilized, with necessary upgrades.
- Control system is also reused, but the antique components were updated.

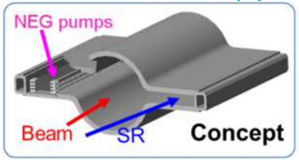
Requirements to vacuum system

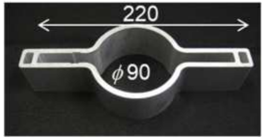
- Ultra-high vacuum to ensure long beam lifetime, keep small beam emittance, reduce background noise to detector, and avoid ion instability (HER)
  - Target pressure : ~ 10^{-7} Pa with beams
- High tolerance against high current beams for stable operation
  - New RF shields for bellows chambers and gate valves
- Suppression of electron cloud effect (ECE) to avoid emittance growth and beam size blow up in LER
  - Beam pipe with antechamber, solenoid field, coating of TiN film, clearing electrodes, groove structure, and external magnetic field
- Low beam impedance to keep small beam emittance and short bunch length, and to avoid beam instabilities
  - Beam pipe with antechamber, step-less connection flange, new collimators with low impedance
- Reliable and stable system
  - Large scale vacuum system: Several thousands control points.
  - Cost performance

Main components -1

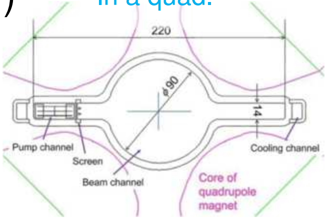
- New beam pipes with antechambers.
  - Realize low beam impedance by putting SR masks and pump ports in antechambers
  - Effective to reduce photo electron effect
  - LER arcs: Aluminum alloy (A6063)
  - HER and Wigglers: OFC (C1011)

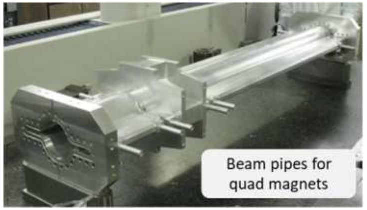
Beam pipe with antechambers



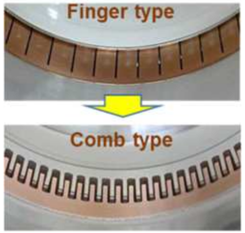


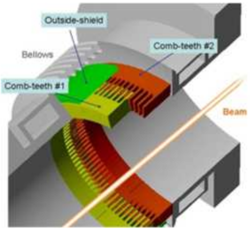
In a quad.





- New bellows chambers and gate valves with comb-type RF shield
  - High thermal strength
    - No thin fingers on the inner wall.
  - Applicable to cross sections with antechambers





Inside view

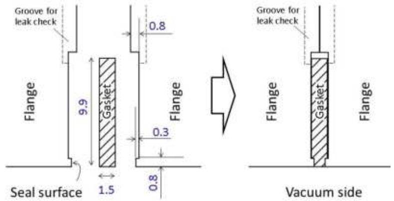
Bellows chamber

Gate valve

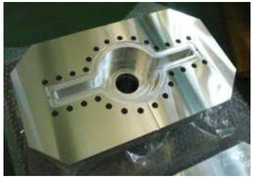
Main components -2

- Step-less connection flange: MO-type flanges
  - Little step inside and low beam impedance
  - Adaptable to various types of cross sections
    - No RF-shielding between flanges.
  - Various types of copper (C18200) and aluminum-alloy (A2219) flanges were developed.

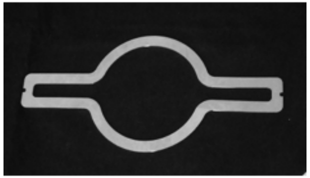
Cross section



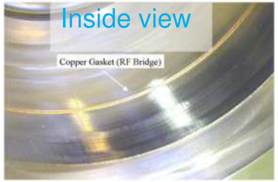
Al flange (test model)



Al gasket

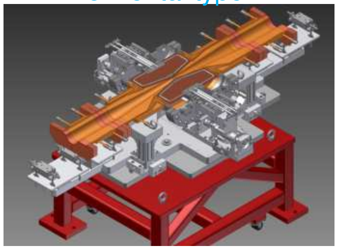


Inside view



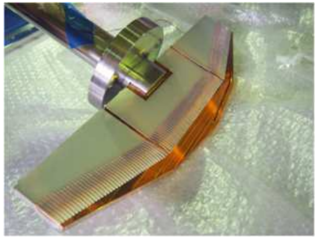
- Beam collimator
  - Key component to suppress beam background of Belle II.
  - New type collimators, which have low impedances and fit antechamber scheme, were developed.
    - The concept is based on that in PEP II

Horizontal type

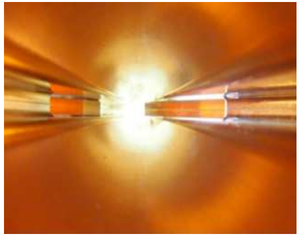


Horizontal type in tunnel

Collimator head (jaw)



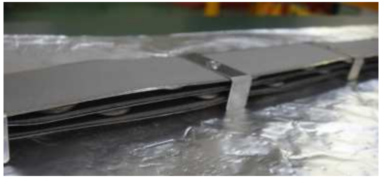
Inside view



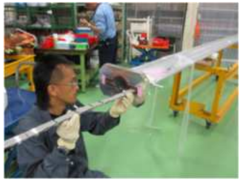
Main components -3

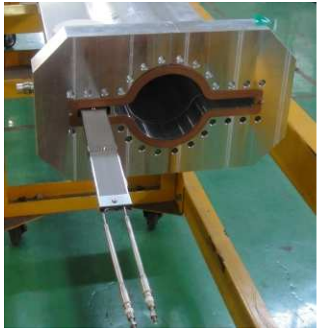
- Main pump: Three layers of NEG strips ST707 (arc)
  - Installed into an antechamber: provide effective pumping system
  - Activation by micro-heaters (sheath heaters) inserted between strips
  - Screens between pump and beam
  - Average pumping speed of 0.14 $m^3s^{-1}m^{-1}$ for CO
- Auxiliary pump: Sputter ion pumps
  - Almost every 10 m, RF shield on the port
  - Official pumping speed of 0.4 m^3s^{-1}.

Three-layer NEG strips



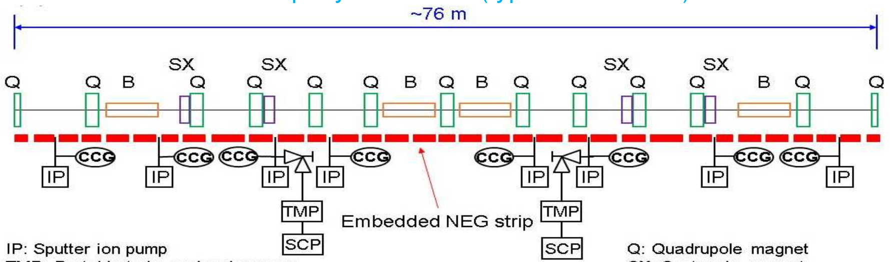
Installation

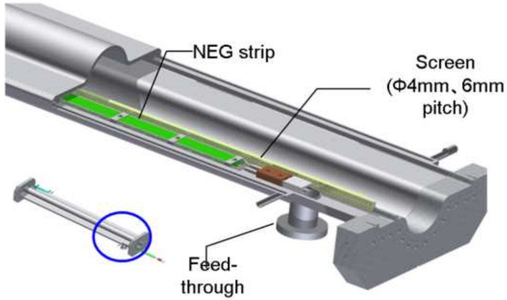




NEG pump in an antechamber (inside of ring)

Pump layout of LER (typical cell in arc)

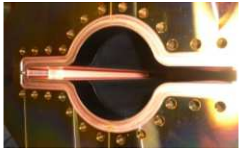




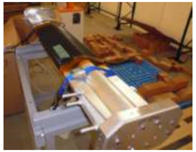
- Countermeasures against electron cloud effect (ECE)
  - ECE: A critical issue for the SuperKEKB positron ring (LER)
  - Based on various R&D results in KEKB and other institutes, various countermeasures were prepared.

Antechamber

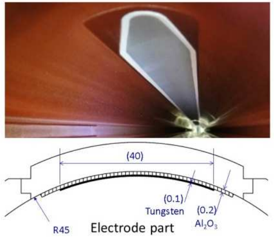
TiN coating



Magnetic field (solenoid)



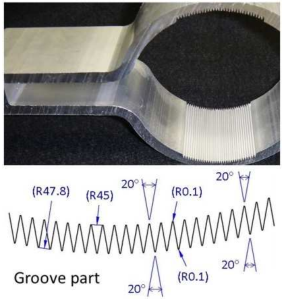
Clearing electrode



Summary of countermeasures for LER

Sections	L [m]	L [%]	Countermeasure	Material
Drift space (arc)	1629	54	TiN coating + Mag. field	Al (arc)
Steering mag.	316	10	TiN coating + Mag. field	Al
Bending mag.	519	17	TiN coating + Grooved surface	Al
Wiggler mag.	154	5	Clearing Electrode	Cu
Q & SX mag.	254	9	TiN coating	Al (arc)
RF section	124	4	(TiN coating +) Mag. Field	Cu
IR section	20	0.7	(TiN coating +) Mag. field	Cu
Total	3016	100		

Grooved surface

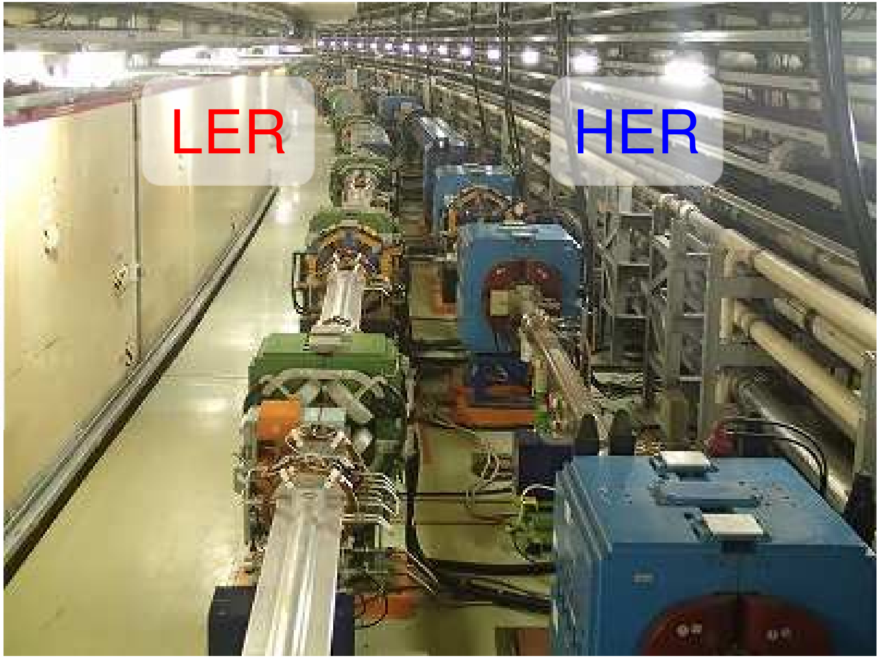


- Expected average e⁻ density ~ 2×10^{10} $e^- m^{-3}$
- Less than the threshold estimated by simulations.

Upgrade work

- Upgrade to SuperKEKB finished in 2016.
  - It took approximately 6 yeas, including the removal of KEKB components

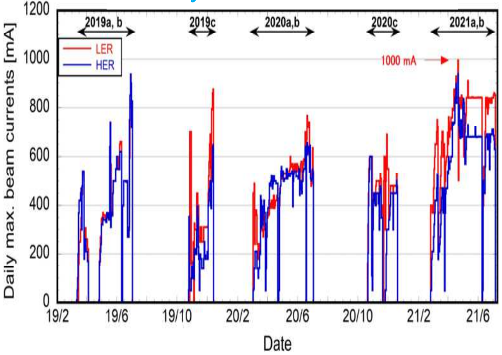
Present status in the SuperKEKB tunnel (arc section)



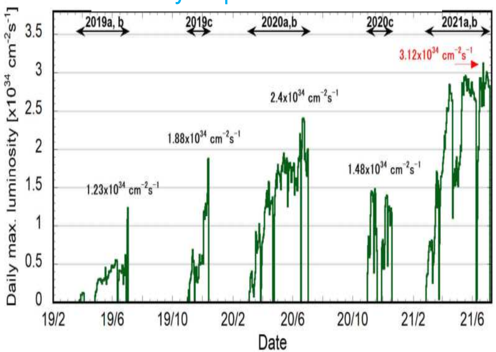
Present operation status

- Phase-3 operation (Physics run)
  - Collision experiment is continuing steadily.
  - No break even with COVID-19!

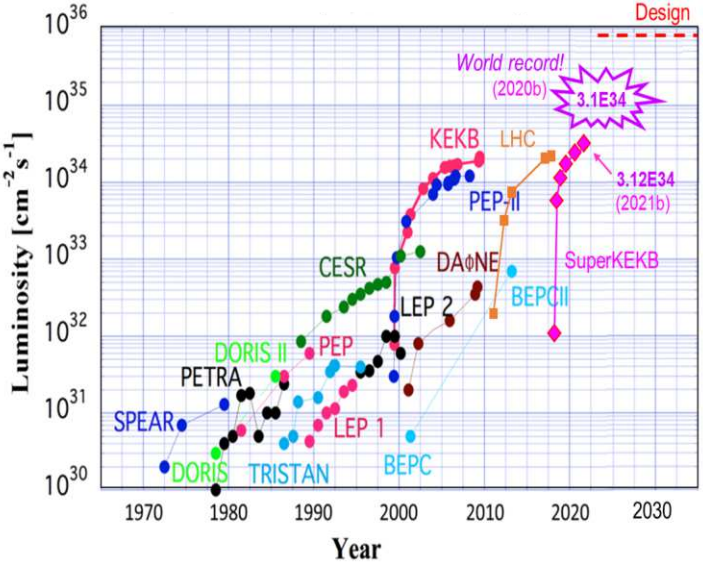
History of beam currents



History of peak luminosities



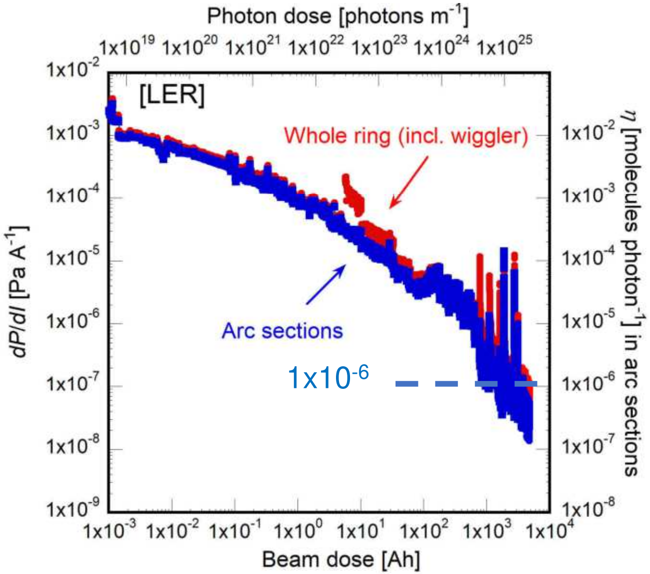
History of peak luminosities so far in colliders around the world

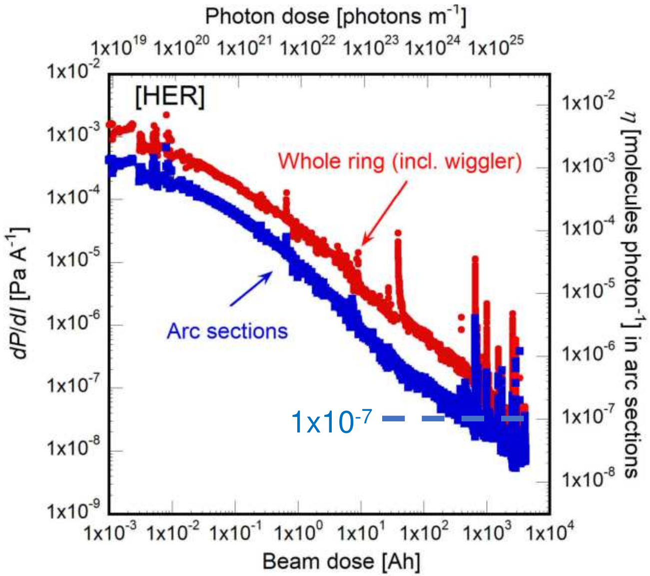


- We are now exploring uncharted territory!
  - β_y^* (ver. β function at IP) = 1 mm (Min. 0.8 mm)
  - Max. luminosity = 3.12×10^{34} $cm^{-2}s^{-1}$
- We are working diligently to improve machine performance to achieve the goal luminosity, although it is very challenging.

Vacuum scrubbing

- Vacuum scrubbing (d*P*/d*I* vs beam dose, η vs photon dose)
  - LER: η decreased to less than 1×10^{-6} molecules photon^{-1}, at a photon dose of 2.5×10^{25} photons m^{-1}, here the pumping speed of 0.06 m^{3}s^{-1}m^{-1} is assumed.
  - HER: η is lower than that in LER. For arc section, where the beam pipes was reused, h decreased to less than 1×10^{-7} molecules photon^{-1}, at a photon dose of 3.7×10^{25} photons m^{-1}. → Memory effect

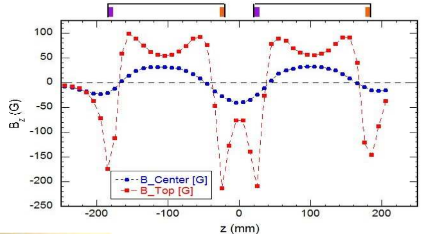




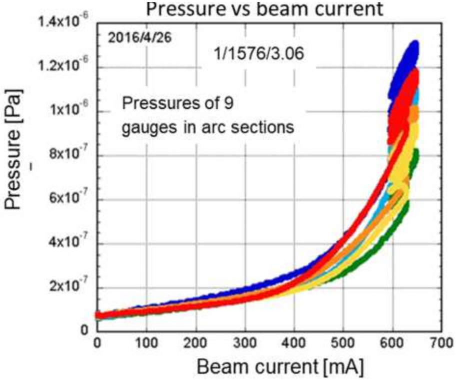
Electron cloud effect (ECE)-1

- Non-linear behavior of pressure against beam current due to ECE was observed at a beam current of ~900 mA during Phase-1 (w/o magnetic fields).
  - EC → Electron multipactoring → Non-linear behavior of pressure
- TiN-coated beam pipes with antechambers at drift spaces were the source of EC.
  - Measured electron density is near to the threshold of the instability, ~3×10^{11} $e^- m^{-3}$.
- This ECE was cured by permanent magnets around beam pipes after Phase-2.
  - Magnetic field of ~50 G in the beam direction.
  - At present, any obvious signs of EC are not observed.

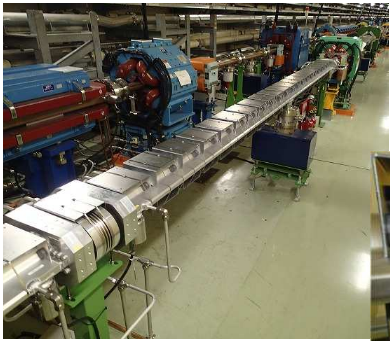
Magnetic fields inside of magnet units

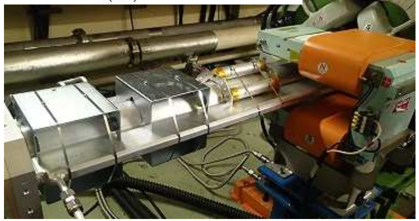


Pressure vs beam current



Magnet units attached to beam pipes



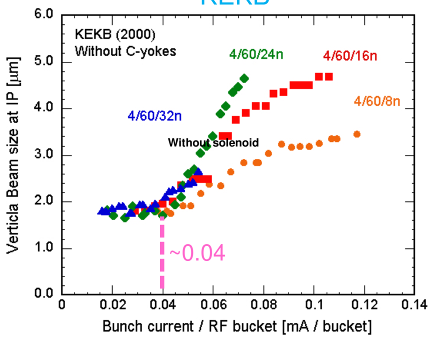


Electron cloud effect (ECE)-2

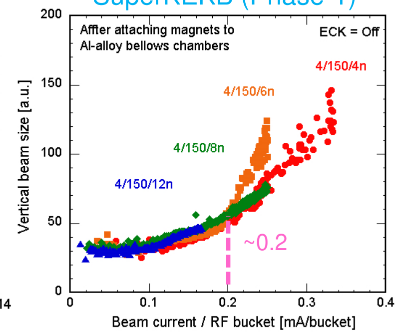
- The ECE (vertical beam size blowup) was not observed until a line charge density of 0.4 mA bunch^{-1} RF bucket^{-1} with magnetic fields.
  - Beam pipes with antechamber and TiN coating were found to be effective to suppress EC compared to a round Cu beam pipe (KEKB type). [Line charge density of 0.04 → 0.2 mA bunch^{-1} RF bucket^{-1}]
- However, the threshold of ECE w/o magnetic fields was lower than expected, although the δ_{max} of TiN coating seems low (1.2～1.0).
- The most plausible reason is that the irradiation of photons in the beam channel is stronger than expected due to the vertical spread or scattering of SR.
  - Photoelectrons is very important for the ECE in the real machine.

Please check “Y. Suetsugu et al., PRST-AB, 22, 023201 (2019)” for detail.

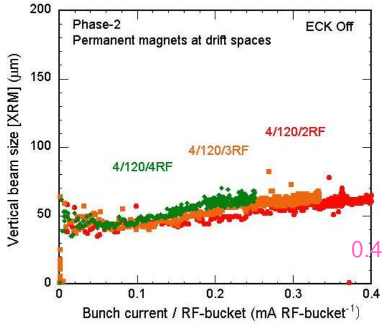
KEKB



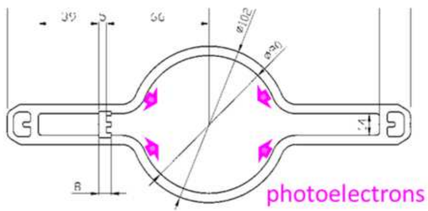
SuperKEKB (Phase-1)



SuperKEKB (Phase-2) with magnets



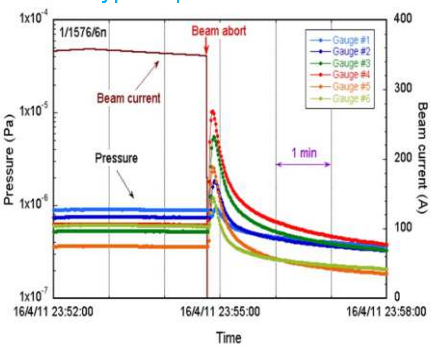
Possible source of photo-electrons



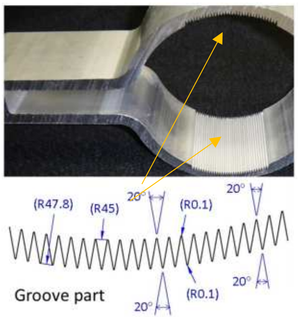
Beam losses accompanied by pressure bursts

- Beam aborts (losses) accompanied by local pressure bursts was frequently observed in especially LER during Phase-1.
  - In most cases, the bursts were observed near aluminum beam pipes in dipole magnets, with groove structure (a measure against ECE).
- A possible cause: Collision of "dusts" with circulating beams.
  - A "knocker" was set at a beam pipe in a bending magnet, where the burst had been observed frequently, and we could reproduce the phenomena by knocking it.
- As a countermeasure, we knocked most of beam pipes in bending magnets (with groove) around the ring before Phase-2.
  - The reduction of the frequency of bursts was observed after Phase-2.

Typical pressure burst

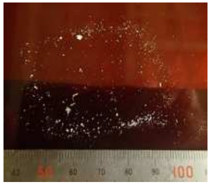


Groove in the beam pipe

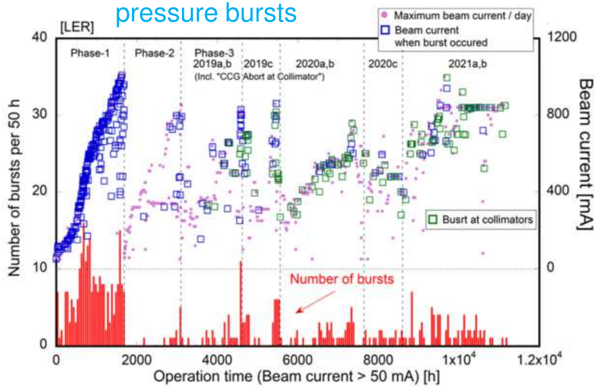


Knocker

Dusts collected



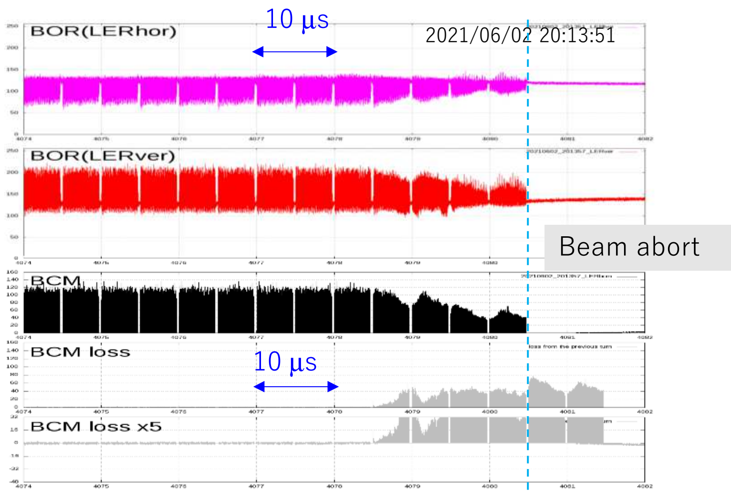
History of beam aborts accompanied by pressure bursts



Rapid heavy beam loss

- Recently, rapid (in 20~30 μs = 2 ~ 3 turns) heavy beam losses have been observed in (mostly) LER and HER.
  - Sometimes, it resulted in damage of collimator head and QCS (SCC final focus magnets) quench, and also damage of detectors.
  - No clear transvers oscillation has not been observed by BOR (Bunch Oscillation monitor)
- The cause has not been clarified yet.
  - Possible causes will be “dust event” and/or beam instability.
  - However, the beam loss is so fast, and simulations so far have not been able to explain the phenomena.
  - Preparation of more loss monitors around ring is planned to identify the origin points of these losses.
- An urgent issue to be solved to increase beam current further.

Typical records of BOR (Beam Oscillation Recorder)



Summaries

- The SuperKEKB vacuum system has been working mostly well.
  - No abnormal temperature increase or vacuum pressure was observed for the new vacuum components up to beam currents around 1 A.
  - Vacuum scrubbing progressed steadily.
  - The effects of the antechambers and TiN coating against ECE were confirmed.
  - No clear indication of ECE has not been observed with permanent magnets.
    - Effect of photons hitting in the beam channel seems larger than expected.
  - Beam aborts (losses) accompanied by local pressure bursts have been frequently observed in the LER during Phase-1.
    - Knocking of beam pipes seems working to some extent after Phase-2.
  - Very rapid heavy beam losses are now frequently observed.
    - The analysis is ongoing.
  - Beam collimator has been working well for suppressing background.
    - Damage of head is now a serious problem. → See Ishibashi’s talk.
- We will continue the operation aiming at further higher luminosity by increasing beam currents and squeezing β_y^*. It is very challenging and exciting.
- The vacuum system must be monitored closely and carefully.

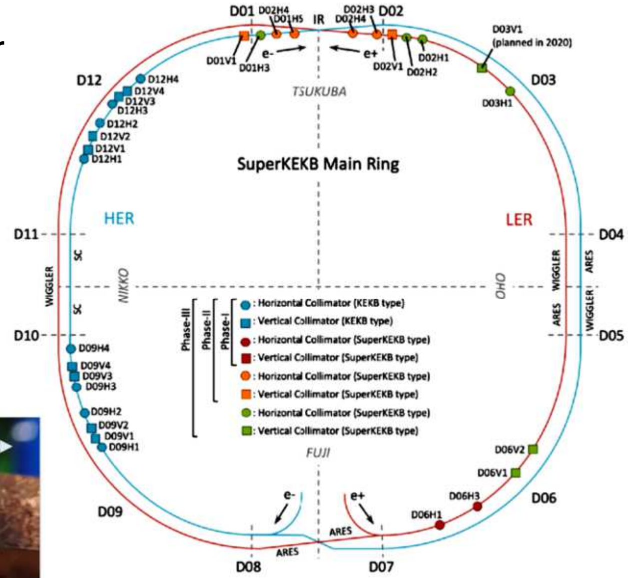
Thank you for your attention.

Backup

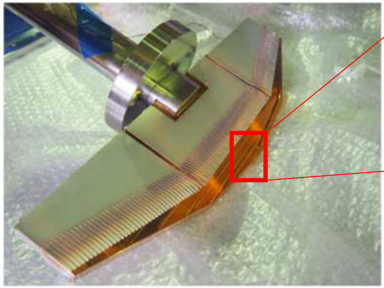
Beam collimator

- New collimators of 3 horizontal and 1 vertical type, and 7 horizontal and 3 vertical type have been installed in HER and LER, respectively.
  - 16 KEKB-type collimators have been installed in HER.
- These collimator is working well so far to suppress the background.
- Problems
  - Excitation of transvers mode coupling instability (TMCI) due to their high-beam impedance. (Narrower aperture than expected in the design phase.)
  - Damage of collimator head due to beam hitting.
- Details will be reported by T. Ishibashi (KEK) in other session.

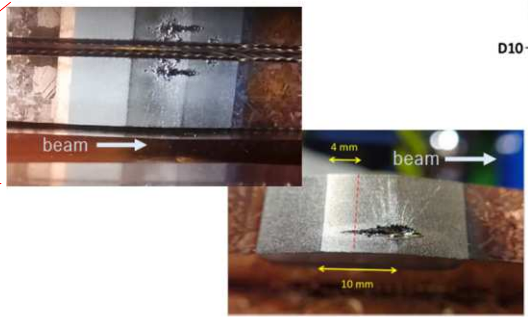
Layout of collimators in MR



Collimator jaw

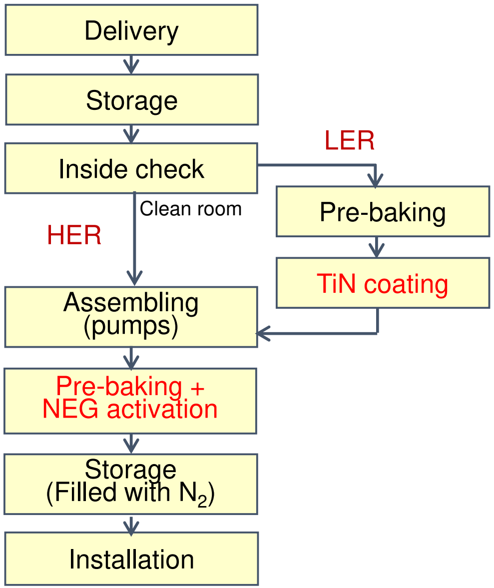


Examples of damages (Ta head)



Installation procedure

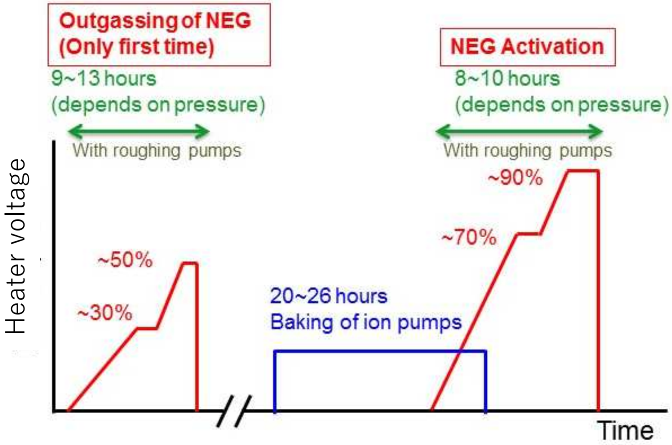
- Basically, all beam pies are baked at 150°C for ~24 hours including NEG activation before installing them into the tunnel.
- Inside of LER beam pipes are coated with thin TiN to mitigate ECE.



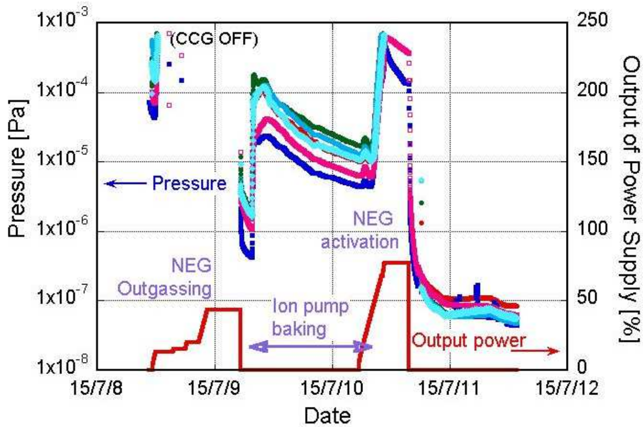
NEG activation procedure

- NEG activation in the tunnel
  - Regions between gate valves in the tunnel were evacuated in series after installing beam pipes and bellows chambers
  - After rough pumping and He leak check, ion pumps were baked and NEG pumps are finally activated.
  - No baking of beam pipes in the tunnel
  - After NEG activation, average pressures of less than 1×10^{-7} Pa were obtained for most cases.

NEG activation pattern



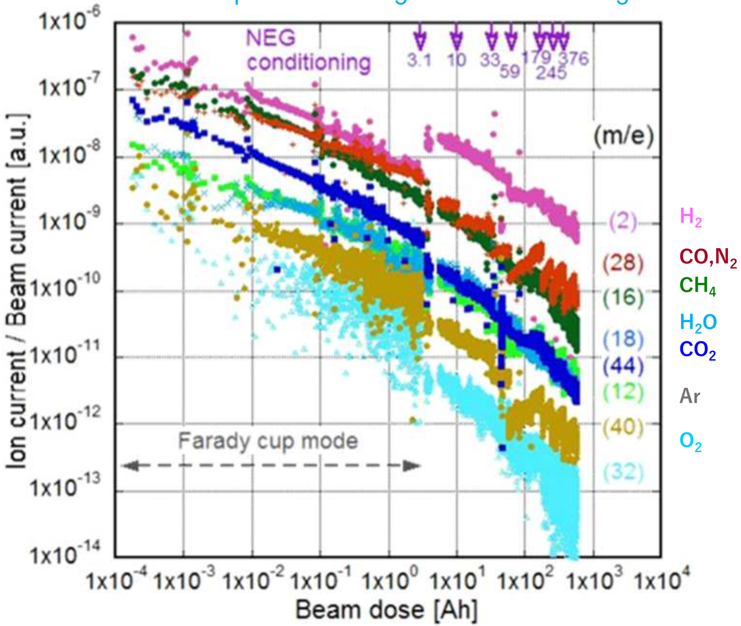
A typical trend of pressures during activation



Residual gases

- Residual gases during the beam operation have been monitored with a quadrupole mass analyzer (QMA) at an arc section.
- The QMA is located just above a sputter ion pump.
  - The main gases are hydrogen (m/e = 2), carbon monoxide (m/e = 28), methane (m/e = 16), water (m/e = 18), and carbon dioxide (m/e = 44).
    - The high partial pressure of methane should be due to the pumping system using NEG as a main pump.
    - Because the beam pipes were not baked in the tunnel, water vapor still remains in the beam pipe.

Gas components during vacuum scrubbing



Main machine design parameters

- The main ring consists of 4.0 GeV positron ring (Low energy ring, LER) and 7.0 GeV electron ring (High energy ring, HER).

	LER (positron)	HER (electron)	Unit
Beam energy	4.0	7.0	GeV
Beam current	3.6	2.6	A
Circumference	3016		m
Number of bunches	2500 (Bunch interval = 1.2m)		
Bunch current	1.44	1.06	mA
Bunch length	6.0	5.0	mm
$\varepsilon_x/\varepsilon_y$	3.2/8.64	4.6/11.5	nm/pm
β_x^*/β_y^*	32/0.27	25/0.3	mm
Crossing angle	83		mrad
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$
Bending radius (Arc)	74.68 (arc)	105.98 (arc)	m

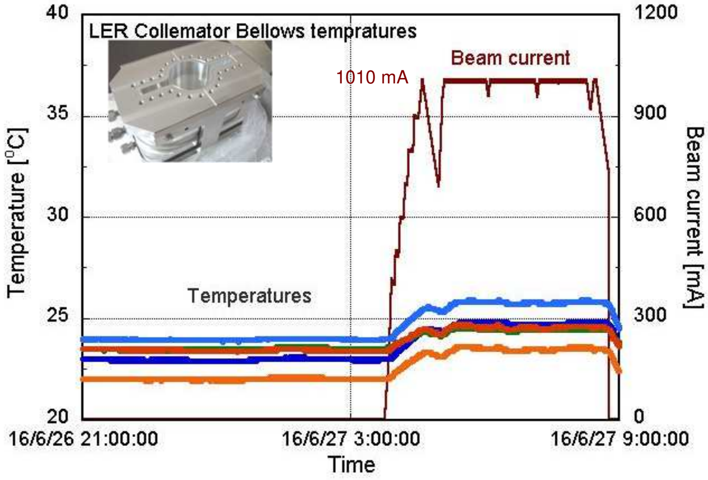
Main parameters (vacuum)

	LER (positron)	HER (electron)	Unit
Material of new beam pipe	Al-alloy (arc) OFC (wiggler)	OFC (arc), OFC (wiggler)	
Cross section of new beam pipe	f90 + Antechambers	Racetrack (50×104) f50 + Antechambers	
Main pumps	NEG (strip)	NEG (strip + cartridge)	
Total Power of SR	1.1 (arc:2200 m) 6.3 (wiggler:300 m)	5.2 (arc: 2200 m) 1.1 (wiggler:100 m)	MW
Critical Energy of SR	1.9 (arc) 9.2 (wiggler)	7.2 (arc) 17 (wiggler)	keV
Max. SR power line density	2.6 (arc) 13 (wiggler)	7.7 (arc) 9 (wiggler)	kW m^{-1}
Avg. photon flux line density	~5.5×10^{18}(arc) ~4.7×10^{19}(wiggler)	~6.8×10^{18}(arc) ~1.3×10^{19}(wiggler)	photons s^{-1} m^{-1}
Linear pumping speed	~0.1 (arc)	~0.06 (arc)	m^3 s^{-1} m^{-1}
Ave. pressure with beam	~10^{-7}		Pa
Ave. base pressure	~10^{-8}		Pa

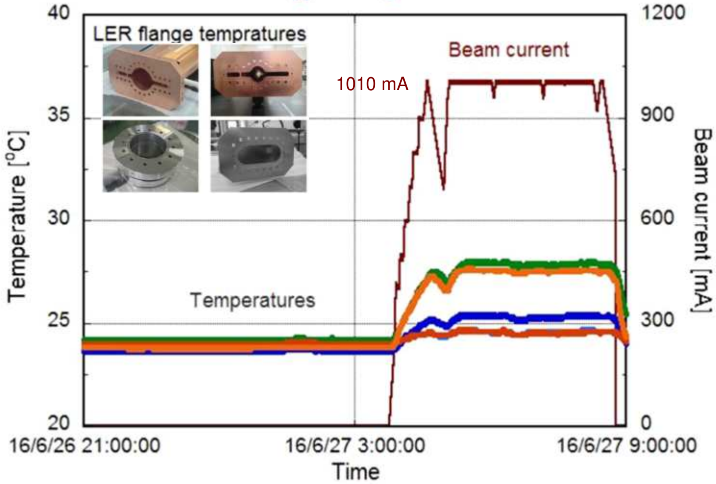
Temperatures of new components

- Status of new vacuum components
  - Confirming the stability of the new vacuum components was a major subject for the Phase-1 beam commissioning.
  - No extra heating or abnormal pressure rise in these components was observed.
  - The temperature rises in the bellows chambers, gate valves and flanges are 2~4 °C at 1010 mA, for example.

Bellows chambers



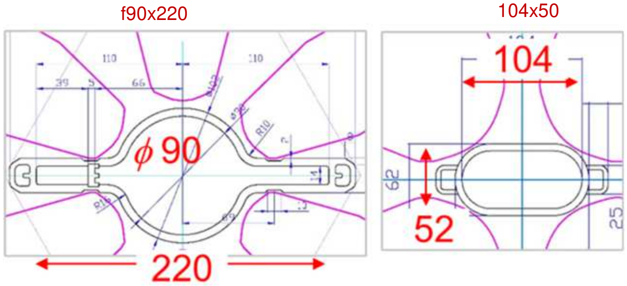
MO-type flanges



Types and numbers of main new components

Types of beam pipes

Type	HER	LER	Total
Q-type	86	421	507
B-type	24	152	176
S-type	100	415	515
T-type	19	14	33
Total	229	1002	1231



Types of NEG pumps

Type	Length[mm]	LER	HER	Total
Type-1	700	21	9	30
Type-2	1000	53	12	65
Type-3	1300	60	18	78
Type-4	1600	227	19	246
Type-5	1900	163	32	195
Type-6	2200	389	30	419
Type-7	2500	66	2	68
Type-8	2800	6	2	8
Type-9	3100	0	17	17
Total		985	141	1126

Types of bellows chambers

Type	Material	Total
Bell_104x50-Cu	Cu	42
Bell_122x50-Al	Al	4
Bell_60x40	Al, Cu	19
Bell_f50x190-Ar	Cu	35
Bell_f80-Cu	Cu	31
Bell_f80x220-Ar	Cu	84
Bell_f90	Al, Cu, Al-Cu	19
Bell_f90x220	Al, Cu, Al-Cu	991
Bell_f90x220H24-Al_E	Al	16
Total		1241