Operation of SuperKEKB in Phase 2

Y. Funakoshi for the SuperKEKB commissioning team

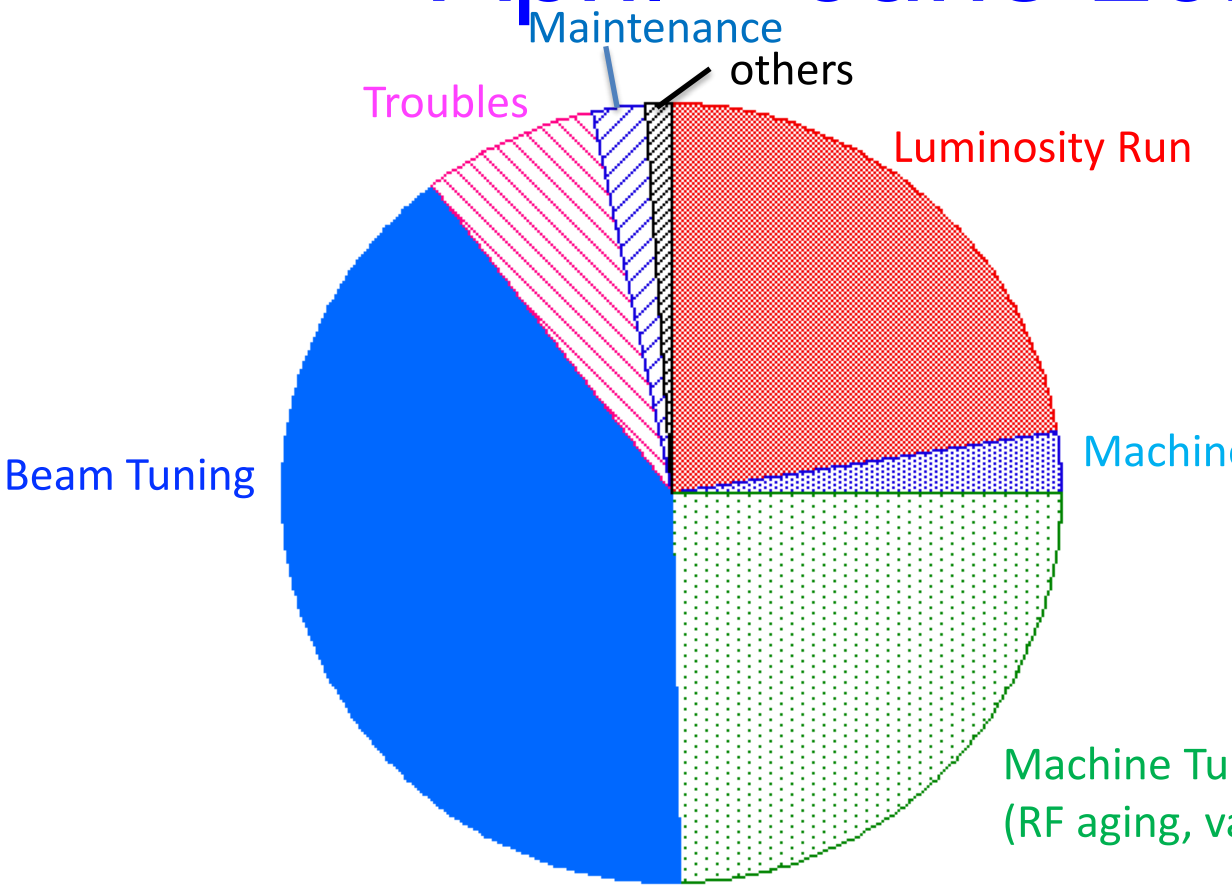
Accelerator Laboratory, KEK

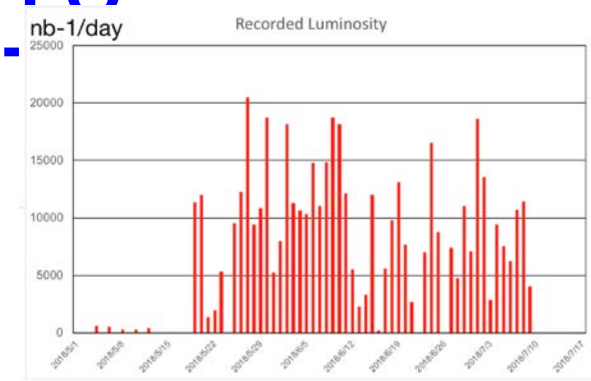
2018.09.26@eeFACT 2018

Contents

- Operation statistics
- QCS quench issue
- Phase 3 operation

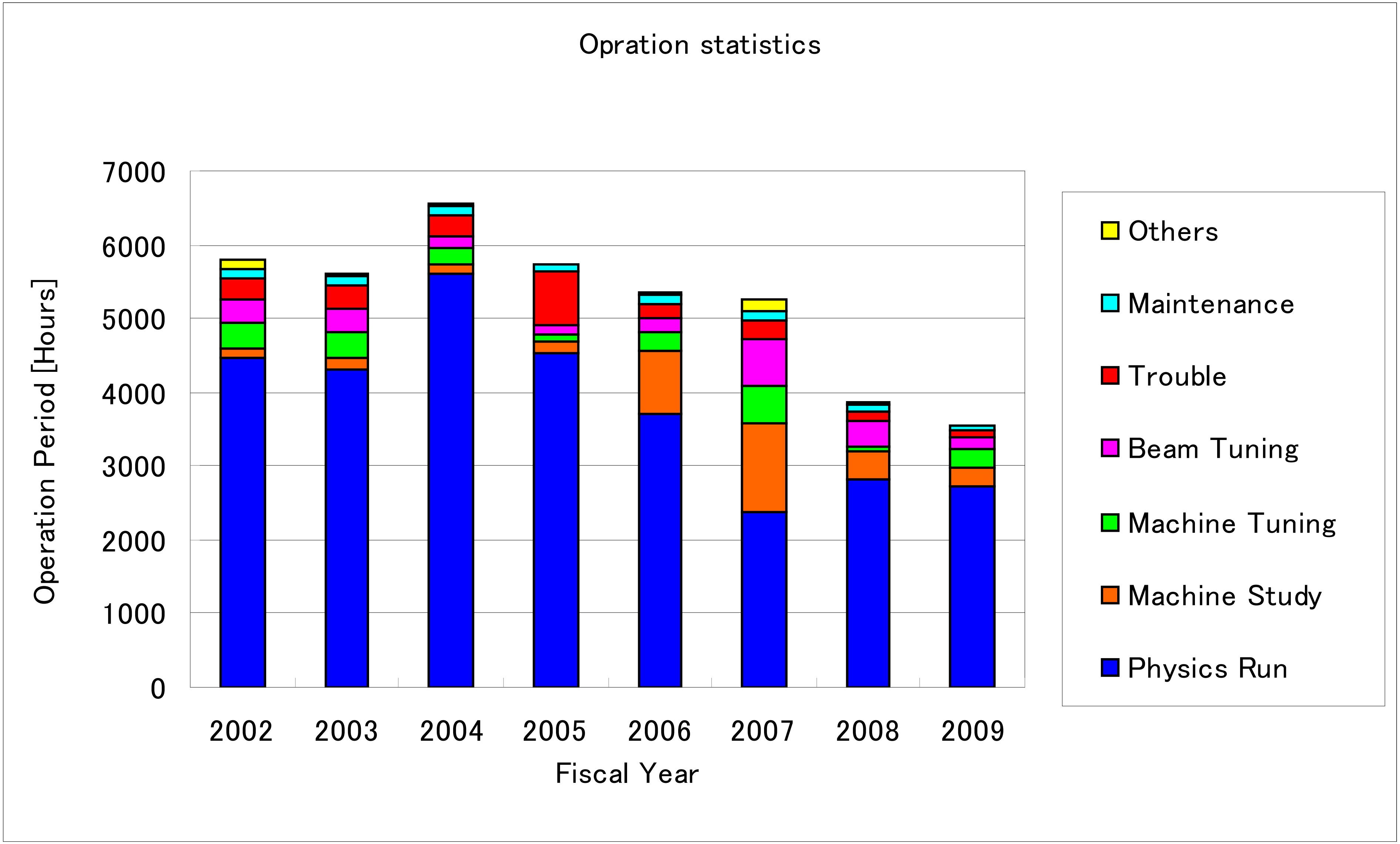
Operation of SuperKEKB (Phase 2) April ~ June 2018



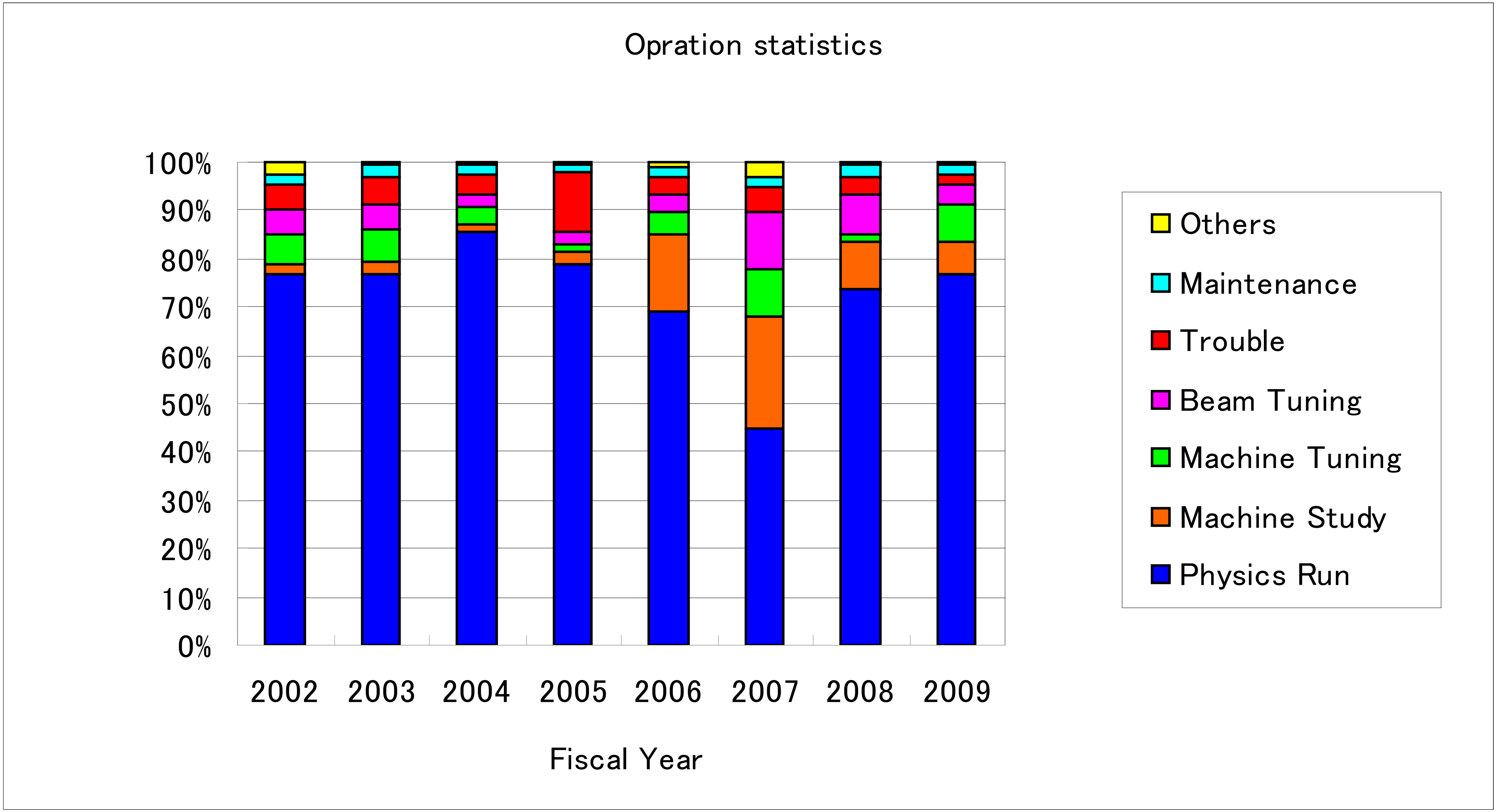


L~ 500/pb

KEKB operation statistics



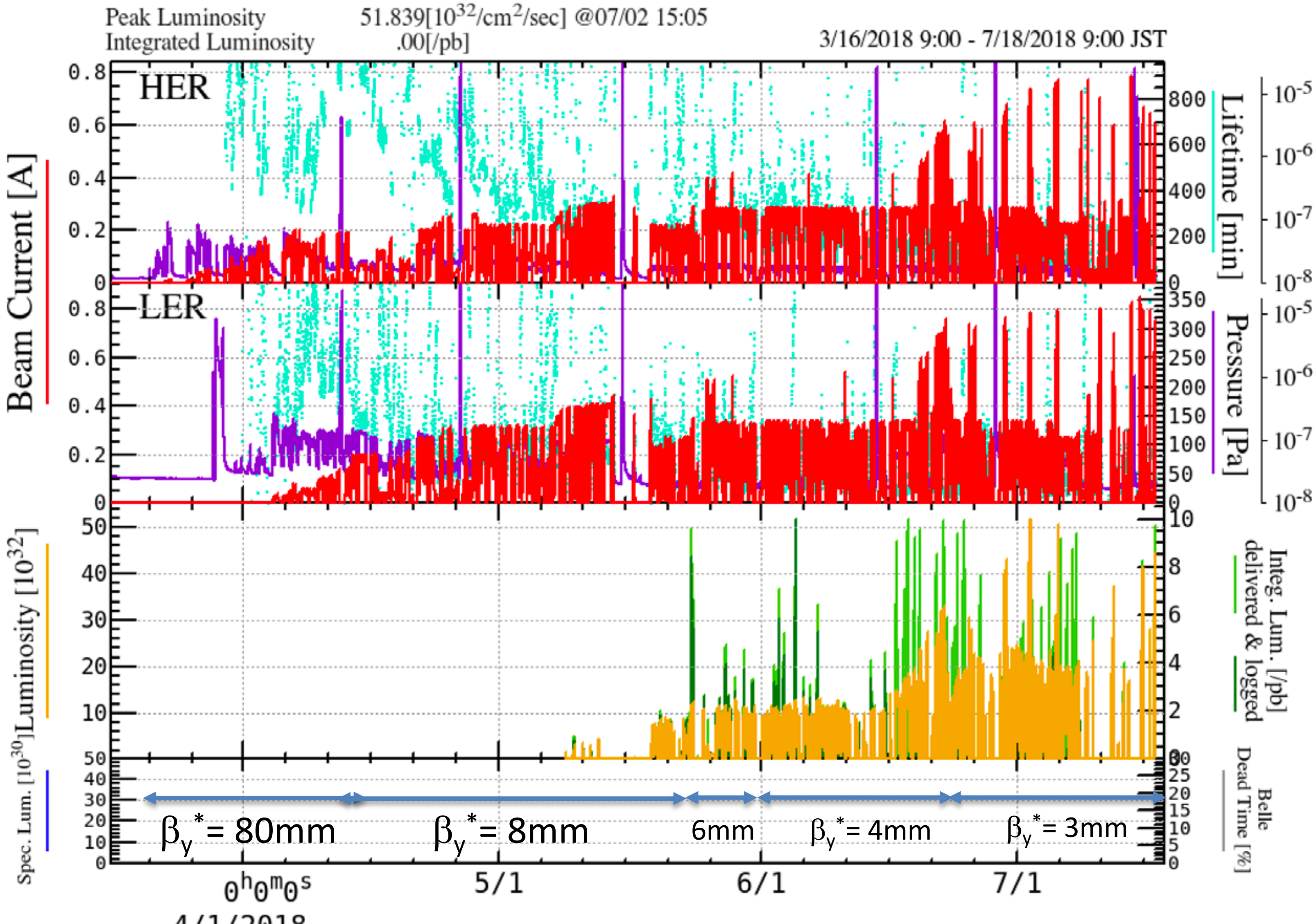
KEKB operation statistics (2)



[1] Luminosity of 1 x 10^{34} cm^{-2} s^{-1}

- Simple scaling
  - 5/9
    - Luminosity: 4.7 x 10^{32}
    - Beam currents: 250mA, 220mA
    - β_y^* = 8mm
    - Beam-beam parameter: ~0.014
    - Number of bunches: 600
  - Possible parameter set
    - Beam currents: 1A, 0.88A (x 4)
    - β_y^* = 3mm (x 8/3)
    - Beam-beam parameters: ~0.03 (x 2)
    - Luminosity = (4.7 x 10^{32}) x 4 x 8/3 x 2 = 1.0 x 10^{34}
    - Number of bunches: 1576 (for example)
- We need
  - Squeezing β_y^*
  - Increasing beam currents
  - Luminosity tuning to raise the beam-beam parameters

History of SuperKEKB Phase 2



5.55 x 10^{33}/cm^2/s (βy*3mm, LER: 800mA, HER: 780mA, 1576 bunches/beam July 5th)
2.29 x 10^{33}/cm^2/s (βy*3mm, LER: 270mA, HER: 225mA, 394 bunches/beam July 3rd)

Missions of Phase 2

- Peak luminosity 1 x 10^{34} cm^{-2} s^{-1} (Validation of "nano beam scheme")
  - Squeezing β_y^*
    - Optics setting and corrections : 2mm (LER, HER) was already achieved with small current.
    - In QCS quench study, we squeezed β_y^* down to
  - Specific luminosity (beam-beam parameter)
    - The problem that the luminosity is not increase with squeezing β_y^* =6 to 4mm has been solved by tuning the IP local coupling. We squeezed β_y^* down to 3mm in luminosity tuning.
  - Increasing beam currents
    - We intended to increase beam currents up to 1A in LER. But we couldn't. The cause of the beam current limitation was a coupled bunch instability in the longitudinal direction.
    - HER vacuum leak: downstream of IP (SR from QCS)
- Beam background issues
  - Discussions are going to in the Background Task force.
  - How should we consider the problem that Belle2 cannot run without decreasing the beam currents with β_y^* =3mm?
  - We conducted dedicated machine studies at the end of Phase 2.
- QCS quench issue
  - Beam loss scenario is under investigation. (Effectiveness of additional W shields)
    - A simulation of particles with large energy deviation will be done.
  - We conducted a study on the QCS quench with even smaller β_y^*. (No QCS quench)
    - β_y^*=1.5mm: optics corrections, β_y^*=1.2mm: single bunch injection OK, β_y^*=1.0mm: trial
  - We haven't understood the cause of QCS quench on June 25th
- Study of Injector Linac
  - Linac study has been done on Wednesday every week.
    - At the end of Phase 2, an overload test of Flux Concentrator was done.

Machine Parameters of SuperKEKB Phase 2 (July 5th 2018)

	LER	HER	
Horizontal Emittance	1.64	4.54	nm
Beam current @Maximum Luminosity	788	778	mA
Maximum Beam current in Phase2	860	800	mA
Number of bunches	1576		
Averaged bunch spacing	1.80		m
Total RF voltage V_c	8.8	12.8	MV
Synchrotron tune ν_s	-0.0226	-0.0258	
Calculated bunch length σ_z @zero current	4.64	5.33	mm
Betatron tune ν_x / ν_y	44.562/46.614	45.545/43.612	
Beta function at IP β_x^* / β_y^*	200/3	100/3	mm
Measured vertical beam size (XRM) @IP σ_y^*	1.48	0.610	μm
Vertical beam-beam parameters ξ_y	0.050	0.010	
Beam lifetime	40	65	min.
Luminosity (Belle 2 CsI)	5.55		10^{33} cm^{-2} s^{-1}

List of QCS quenches (from QCS group)

38coils quenches, 26 events

Date	Time	Quenched Magnet	Beam Line		Causes	Injection/strorage
2018/4/1	20:55	QC1LP	LER		Injection Kicer K1, K2 balance	Injection
2018/4/2	19:29	QC1LP	LER		Injection Kicer K1, K2 balance (EVR module)	Injection
2018/4/9	17:31	QC1LE-a1	HER		Trial of βy*=2.4mm	Injection
2018/4/9	20:06	QC1LE-a1	HER		Trial of βy*=2.4mm	Injection
2018/4/9	20:53	QC1LE-a1	HER		Trial of βy*=2.4mm	Injection
2018/4/9	21:40	QC1LE-a1	HER		Trial of βy*=2.4mm	Injection
2018/4/10	17:44	QC1LE-a1	HER		Trial of βy*=2.4mm (BT V steering tuning中)	Injection
2018/4/10	21:56	QC1RE-b1	HER		Trial of βy*=8mm	Injection
2018/4/11	14:21	QC1RE-b1	HER		Trial of βy*=8mm	Injection
2018/4/11	15:25	Cancel-Mag-b3	HER		Trial of βy*=8mm	Injection
2018/4/11	18:45	QC1RE-b1	HER		Trial of βy*=8mm tune changer	Storage? (10mA)
2018/4/11	20:23	QC1RE-b1	HER		Trial of βy*=8mm local bump in downstream of IP	Storage (5mA)
2018/4/11	21:15	QC1RE-b1	HER		Trial of βy*=8mm local bump in downstream of IP	Storage (10mA)
2018/4/20	14:33	QC1RP	LER	Single event	RF Phase scan Mis-operation (big Phase jump)	Storage (48mA)
	14:33	QC1LP	LER			
	14:33	QC1RP-b1	LER			
2018/4/21	0:21:49	QC1LP	LER	single event	unknown (after end of RF phase scan)	Storage (18mA)
	0:21:51	QC1RP	LER			
	0:22:13	QC1RP-b1	LER			
2018/5/6	11:28	QC1LE-b1	HER		Waist knob test (locally large orbit or beta-beat)	Storage (35mA)
2018/5/13	2:45	QC1RP-b1	LER		Beam injection with ECK=-2	Injection
2018/5/17	2:09	QC1RP-b1	LER		βy*=6mm K2-3 malfunction?	Injection
2018/5/17	4:06	QC1RP-b1	LER		βy*=6mm K2-3 malfunction?	Injection
2018/5/24	17:17	QCSL-Can-b3	HER		Trial of βy*=4mm, v-collimators not enough	Injection

Narrower collimator setting to prevent QCS quench

May 28th Belle abort using diamond sensor was introduced.

Belle 2 beam abort based on diamond sensors

Summary

We would like to propose a new set of thresholds for the diamond abort system:

- "fast" = **10 Rad/s** (average dose rate) in **1 ms** => integral = **10 mRad**
- "slow" = **200 mRad/s** (average dose rate) in **1 second** => integral = **200 mRad**

With these settings 15 out of 19 QCS quenches would have been avoided.

These new settings will help in preventing QCS quenches, hopefully, without interfering with accelerator tuning. Iterations and adjustments might be needed to tune the system in a better way.

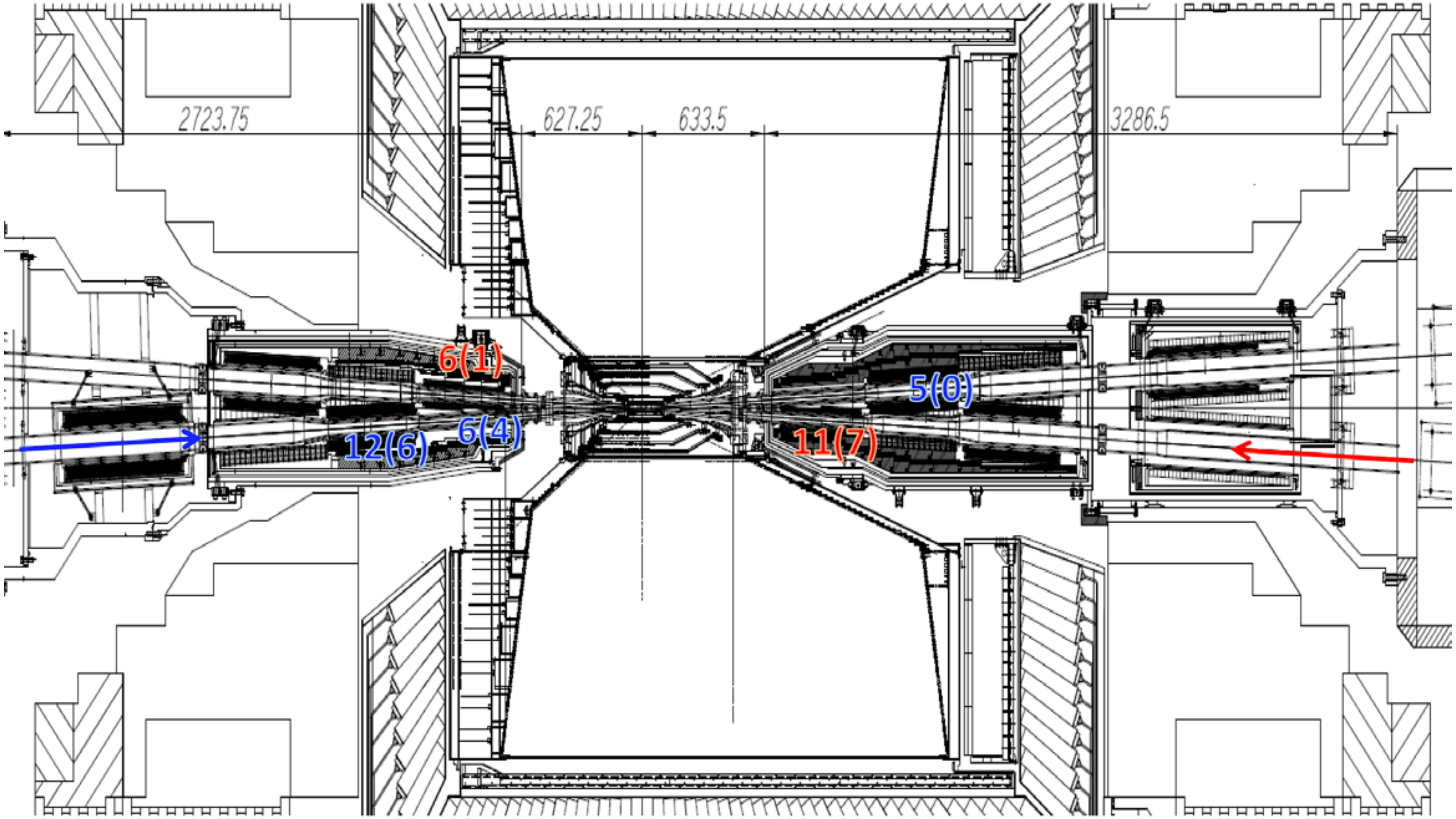
List of QCS quenches (from QCS group)

38coils quenches, 26 events

Date	Time	Quenched Magnet	Beam Line		Causes	Injection/storage
2018/6/25	11:20	QC1RP	LER		D02V1 collimator was damaged. At this moment, a big beam loss (~100mA) was induced. A vacuum burst was observed.	Storage (728mA)
		QC1RP-b1				
		QC1LP				
2018/7/3	5:14	QC1RP-b1	LER		Continuous bad injection?	Injection
2018/7/9	11:20	QC1LE	HER		D01V1 collimator was damaged. At this moment, a big beam loss (~100mA) was induced. A vacuum burst was observed.	Storage(766mA)
		QC1LE-b1				
		QCSL Cancel				
2018/7/15	22:32	QC1RP	LER		LER QCS quench happened first due to longitudinal instability. A vacuum burst was observed. LER QCS quench induced HER beam loss and HER QCS quench.	Storage (LER: 793mA)
		QC1LE	HER			
		QC1LE-b1				
		QCSL Cancel				
2018/7/16	17:53	QC1LE-b1	HER		A vacuum burst at D02H collimator was observed.	Storage (HER: 670mA)
		QCS Cancel				

- 5 quenches happened after June 25th.
  - 4 of them were induced stored beam accompanied with vacuum burst.
  - In 2 cases, beam hit vertical collimators and gave some damages.
    - The reason why beams hit collimators has not been understood.
      - No beam orbit change, no beam oscillation.
      - We suspect the dust trapping effect.

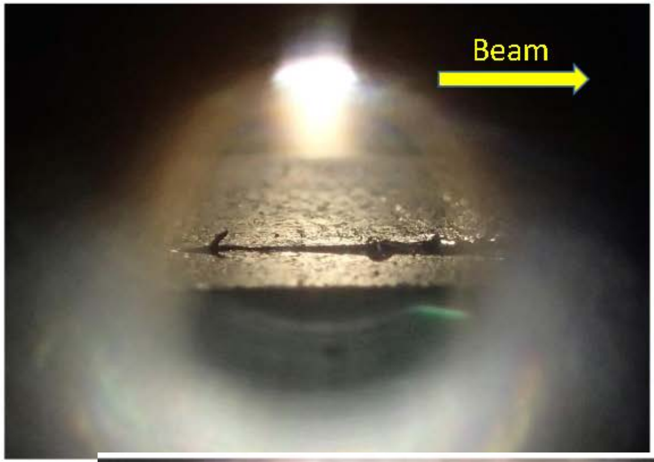
Locations of QCS quenches

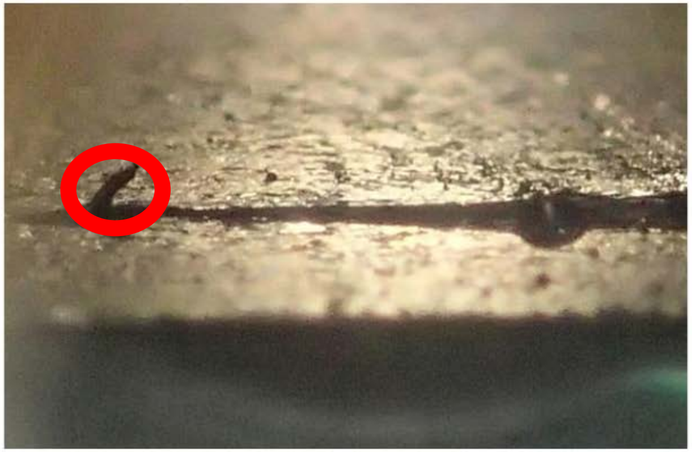


( )内値は、4月23日コリメータ調整後

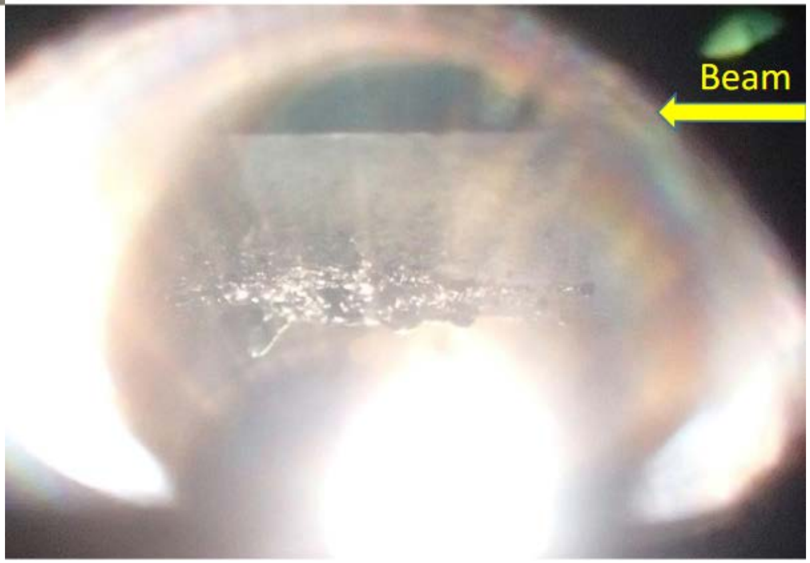
Damage of collimator (LER D02V1)

Bottom





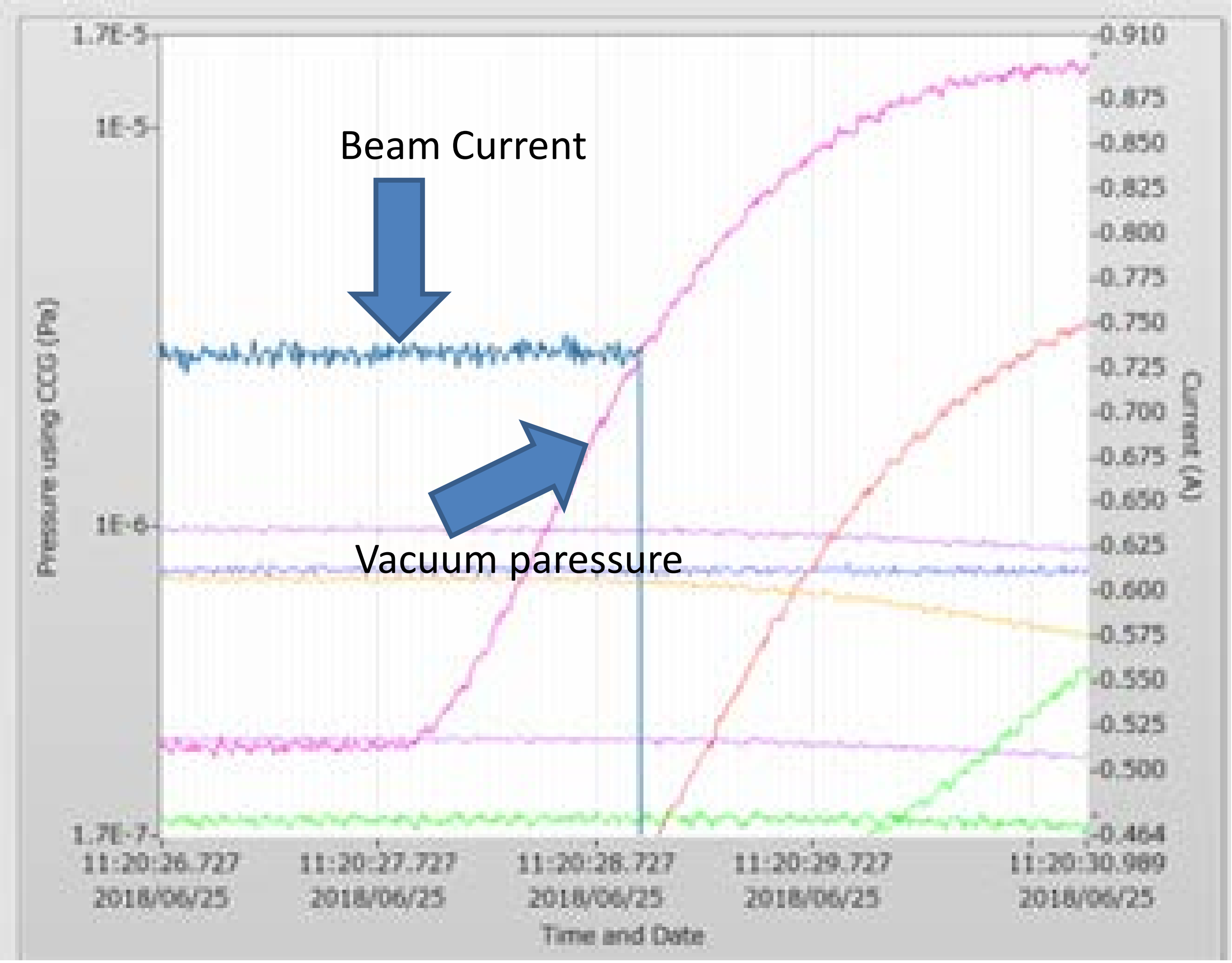
Top



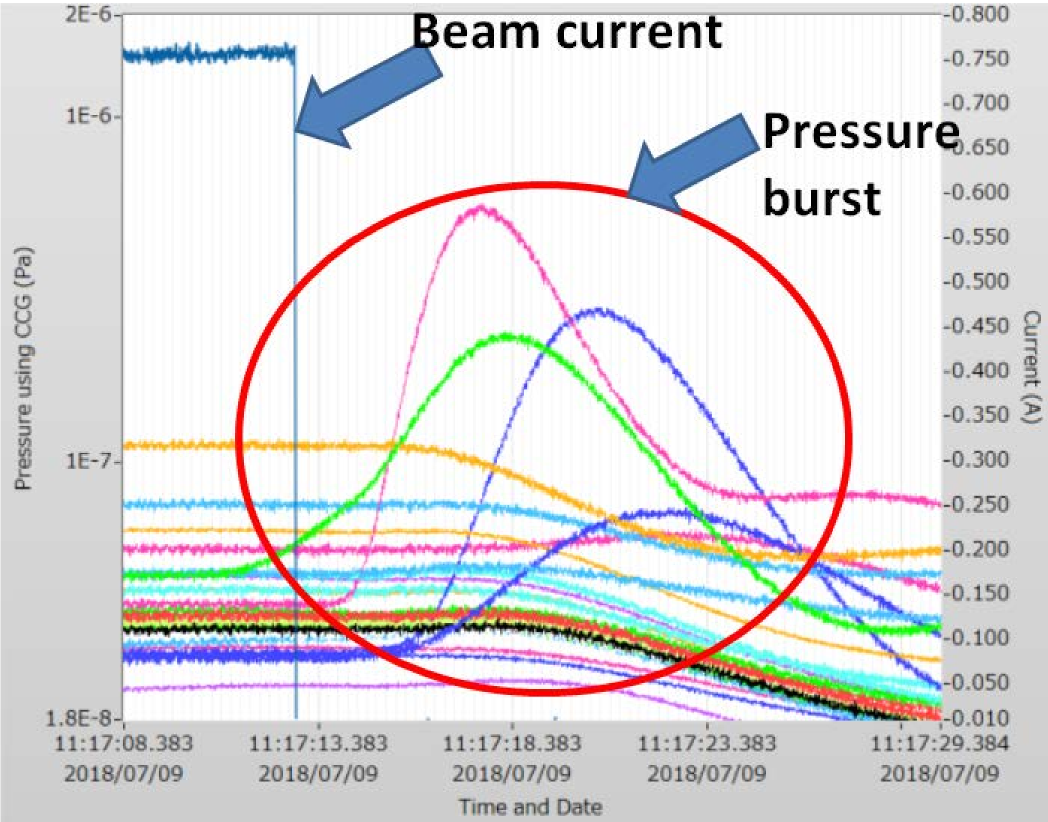
Beam hit bottom of collimator.
Sputtered material (W) stuck to top?

S. Terui

Vacuum burst when collimator was damaged



Damage of collimator (HER D01V1)

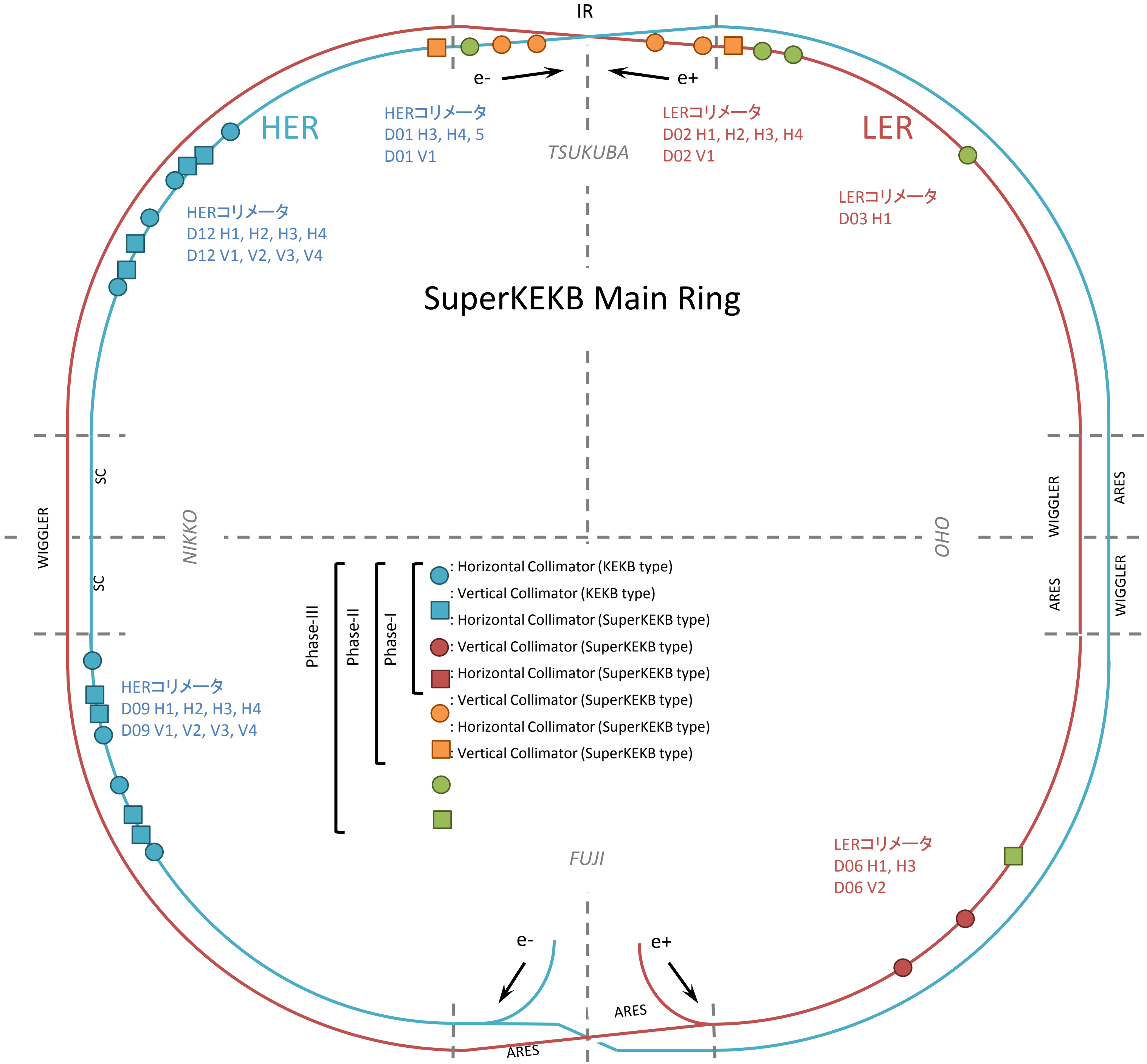


Summary of QCS quench in Phase 2

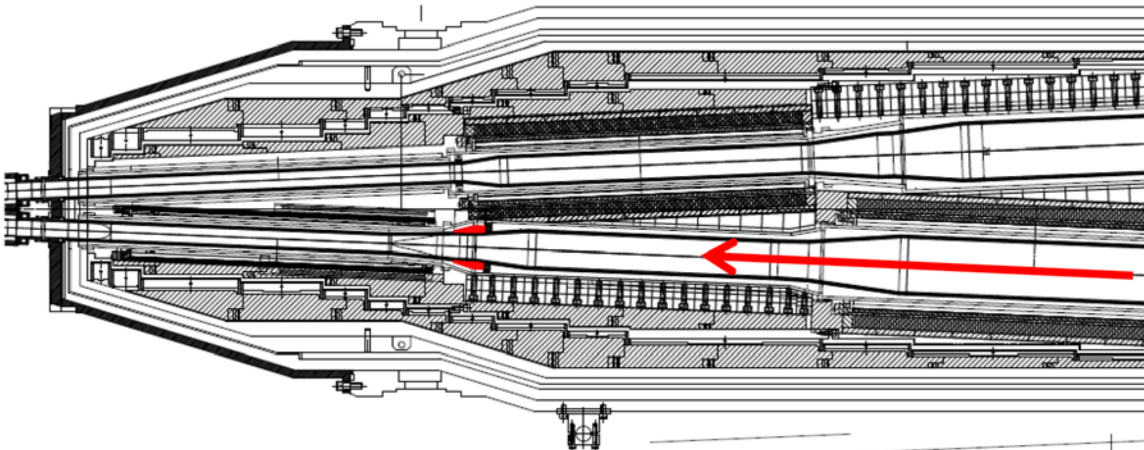
- During Phase 2, QCS quenches happened 26 times. Once QCS quench happens, it takes about 1.5~2 hours for recovery.
- Initial quenches in Phase 2 were mainly induced by injecting beams.
  - The quenches were almost prevented by setting movable collimators properly and introducing the Belle 2 abort using diamond sensors.
  - We felt that we had overcome the quenches, since we had no quenches for about a month after the quench on May 24th.
- However, on June 25th, the quench happened again by a stored LER beam and 4 quenches followed in July.
  - The reasons for the QCS quenches have not been understood well. I suspect the dust events may have something to do with the quenches.

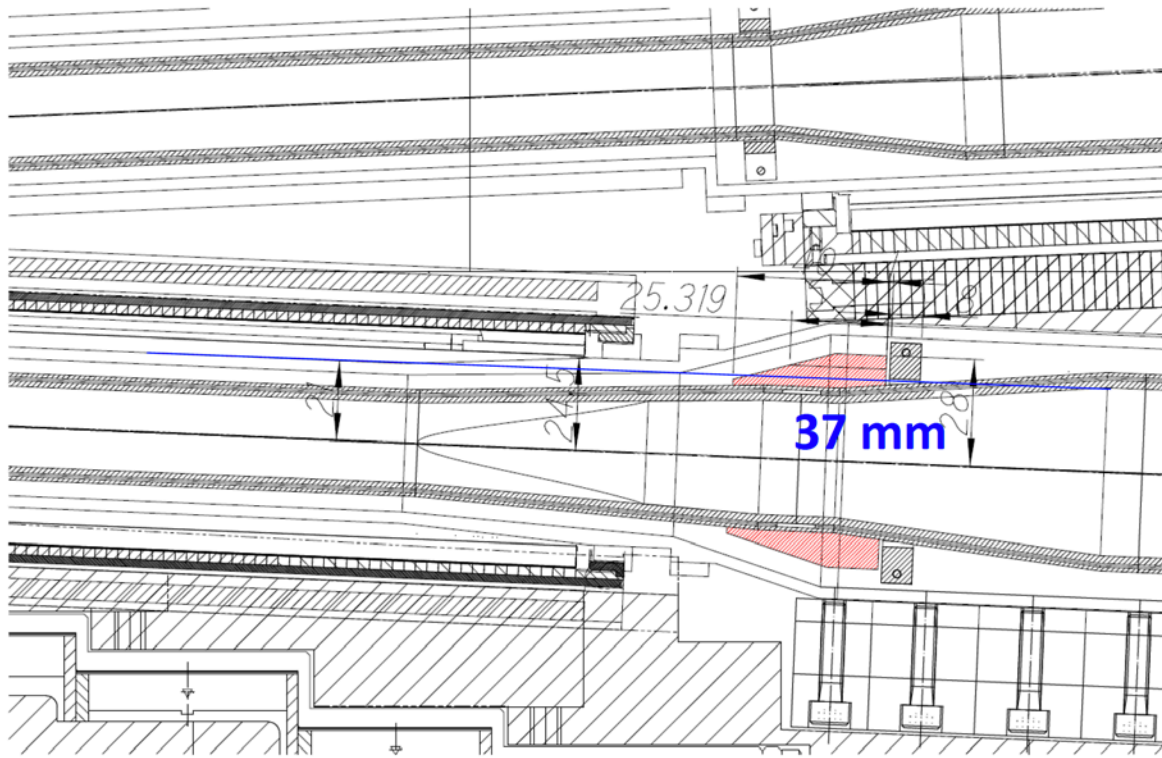
To do list for QCS quench

- Install more collimators before Phase 3
  - 1 vertical collimator (LER)
  - 3 horizontal collimators (LER), 1 horizontal collimator (HER)
- Understanding of mechanism of QCS quench
  - Ohuchi-san's simple calculation: If ~8000 electrons (7GeV) lose their entire energy at a small part of a coil, QCS quench can happen.
  - Simulation on the more precise locations of particle loss near QCS.
    - Collimator chip scattering, dust trapping…
  - Simulation on the effect of continuous particle loss due to some processes (ex. Radiative Bhabha process).
  - More experiences in early stage of Phase 3
- W shields near QCS? (2019?)
  - Simulation works are in progress.
- Modification of QCS magnet system?

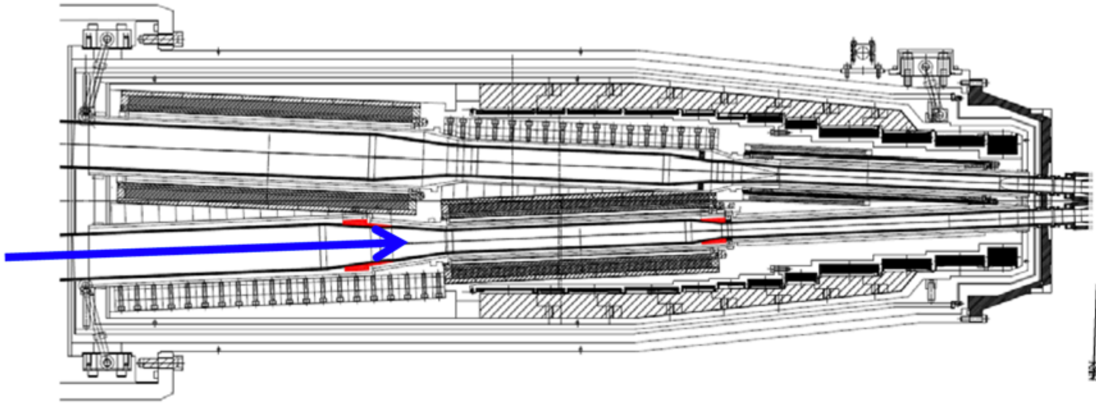

SuperKEKB Main Ring
IR
e-
e+
HER
LER
TSUKUBA
NIKKO
OHO
FUJI
HERコリメータ
D01 H3, H4, 5
D01 V1
LERコリメータ
D02 H1, H2, H3, H4
D02 V1
LERコリメータ
D03 H1
HERコリメータ
D12 H1, H2, H3, H4
D12 V1, V2, V3, V4
HERコリメータ
D09 H1, H2, H3, H4
D09 V1, V2, V3, V4
LERコリメータ
D06 H1, H3
D06 V2
WIGGLER
SC
ARES
Phase-III
Phase-II
Phase-I
: Horizontal Collimator (KEKB type)
: Vertical Collimator (KEKB type)
: Horizontal Collimator (SuperKEKB type)
: Vertical Collimator (SuperKEKB type)
: Horizontal Collimator (SuperKEKB type)
: Vertical Collimator (SuperKEKB type)
: Horizontal Collimator (SuperKEKB type)
: Vertical Collimator (SuperKEKB type)

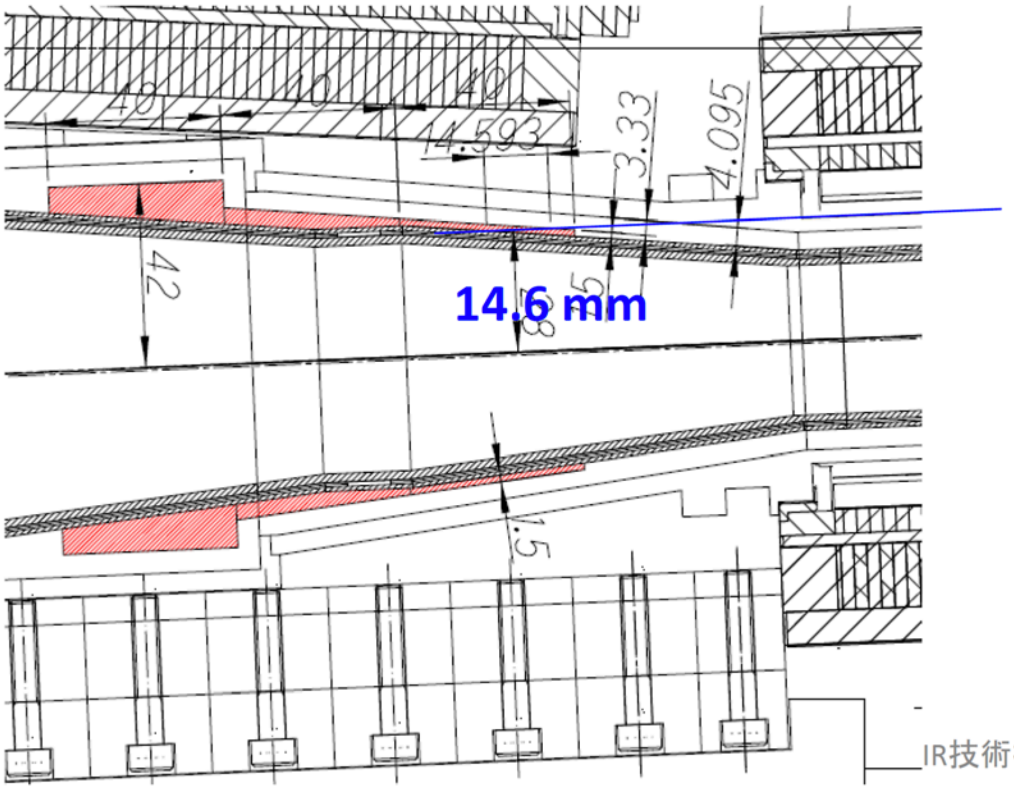
Additional tungsten(W) shield?

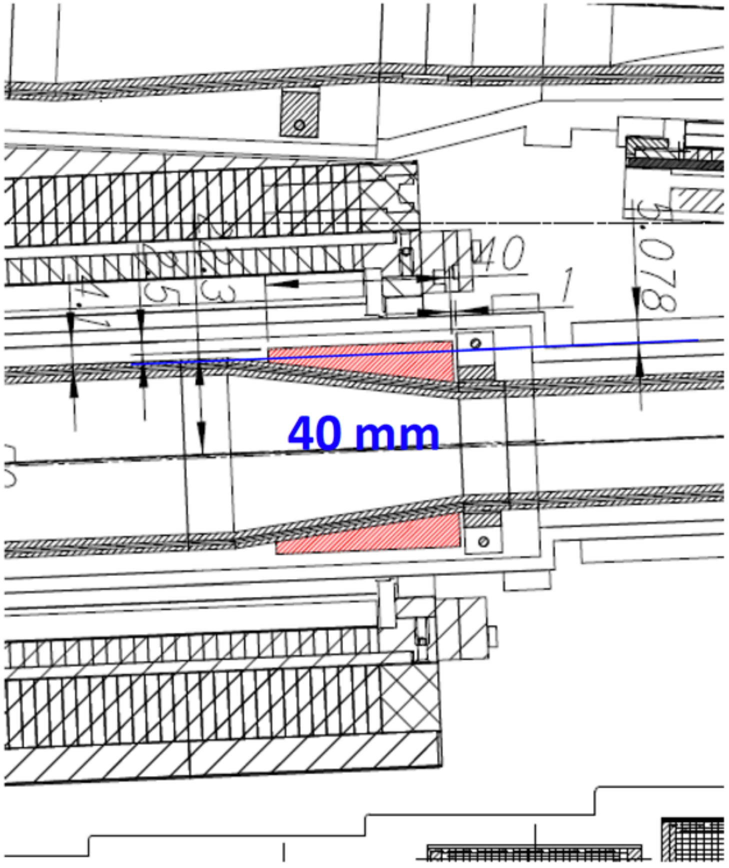




Additional tungsten(W) shield?



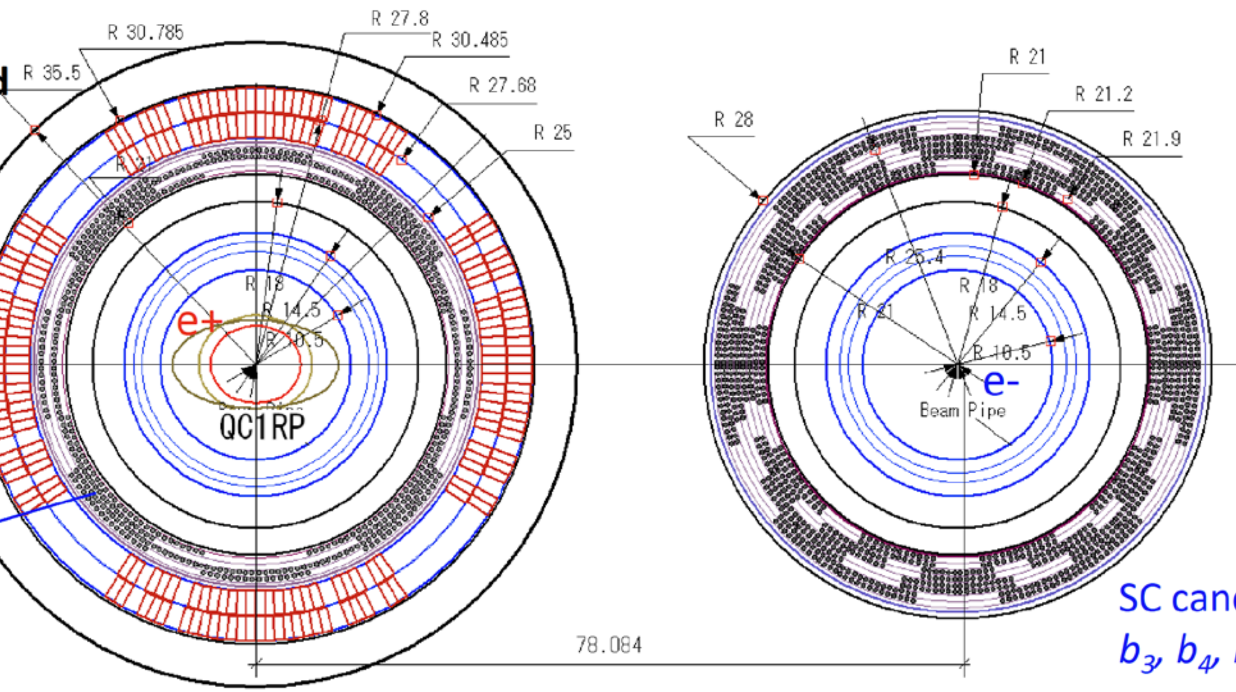




QC1P (No iron yoke)

Original design
Need to be modified

QC1P



SC correctors
a_2, b_1, a_1, b_4

SC cancel correctors
b_3, b_4, b_5, b_6

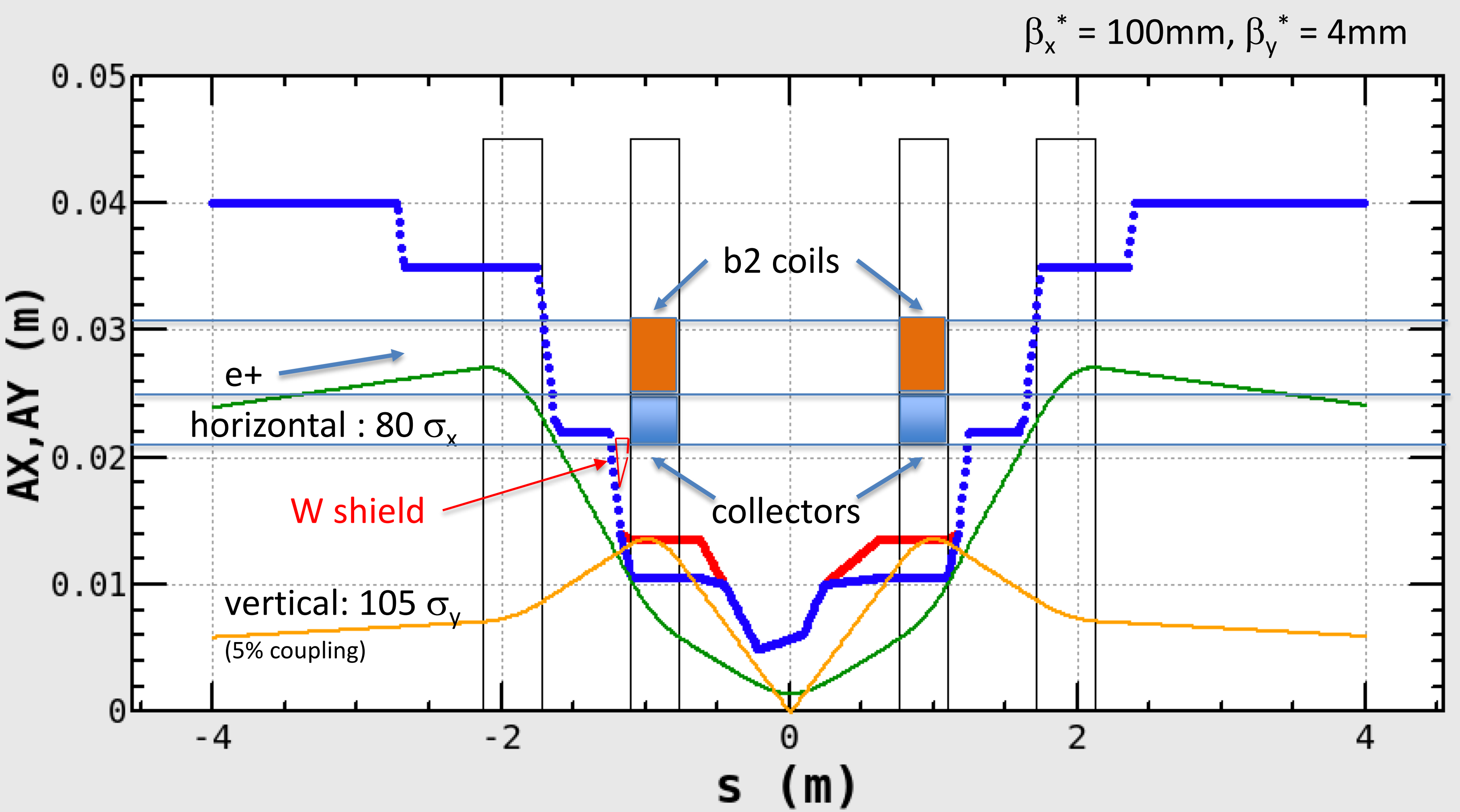
QC1P magnet design (QC1RP, QC1LP)

- Same design for QC1RP and QC1LP
- 2 layer coils [double pancake]
- **SC correctors [design changed by the discussion with BNL]**
  - **a_2, b_1 and a_1 inside of the magnet bore**
  - **b_4 outside of the magnet collar**
- Cryostat inner bore radius=18.0 mm
- Beam pipe (warm tube)
  - inner radius=10.5 mm, outer radius=14.5 mm

SC cancel coils against the leak field from QC1P

- b_5, b_6, b_4 , b_3 from the inside
- Cryostat inner bore radius=18.0 mm
- Beam pipe(warm tube)
  - inner radius=10.5 mm, outer radius=14.5 mm

LER beam envelop

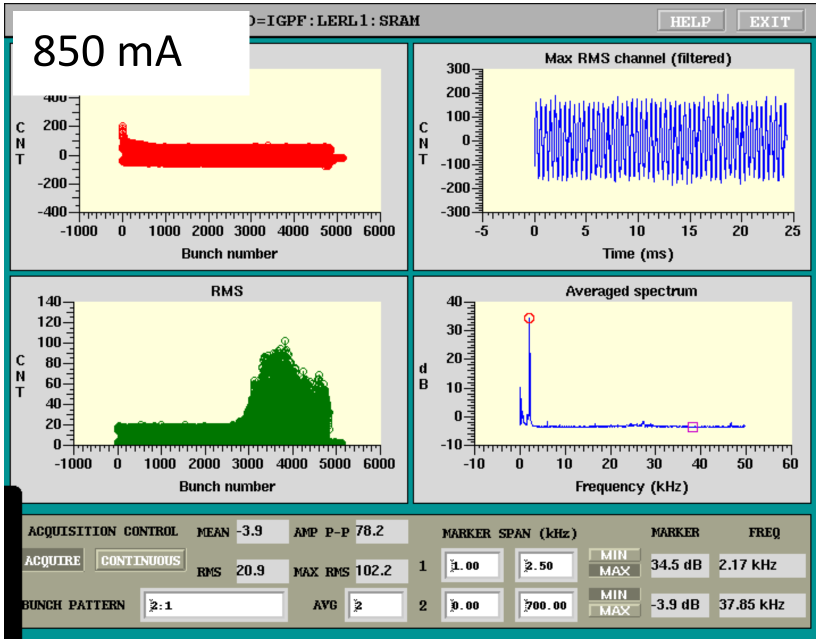


Quenches of downstream of IP: induced by horizontal oscillation?
Quenches of upstream of IP: induced by vertical oscillation?

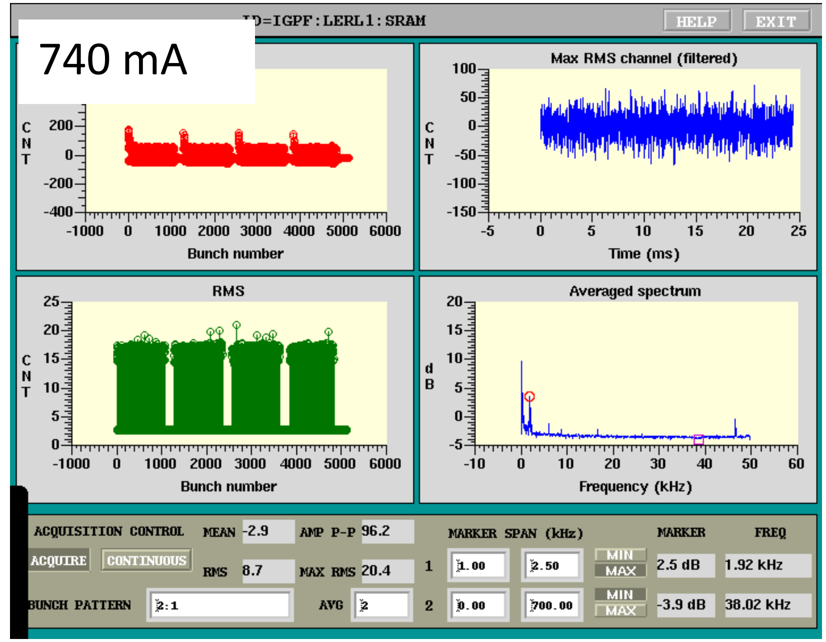
Coupled bunch instability in LER

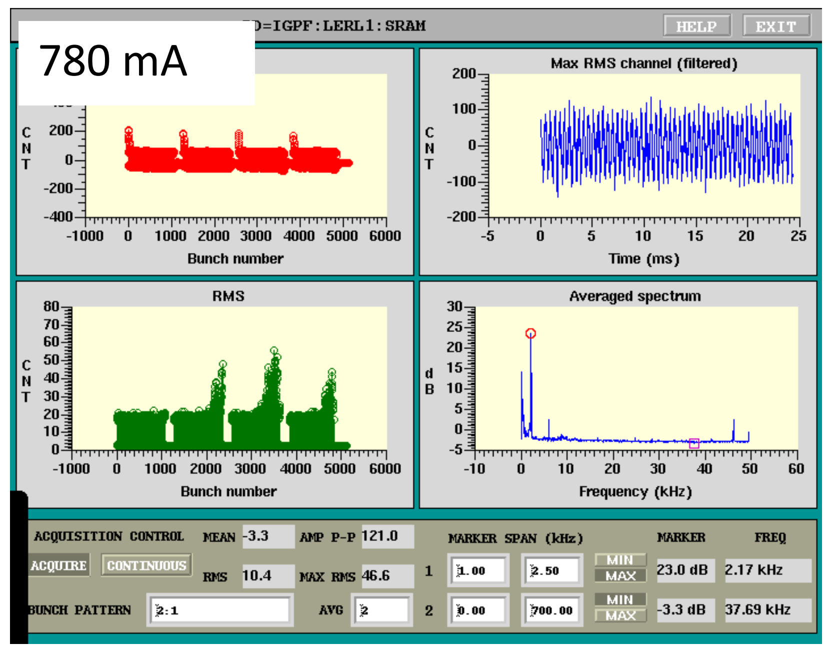
- The LER beam current was limited by the longitudinal coupled bunch instability.
  - It turned out that the source of the instability was not RF cavities.
  - It seemed that the one of the collimator was related to the instability.
  - The nature of the instability should be investigated in more details in Phase 3.
  - In LER, we have a feedback system to suppress the instability. But we didn't have a time to tune the feedback system.

1576 bunch



1372 bunch



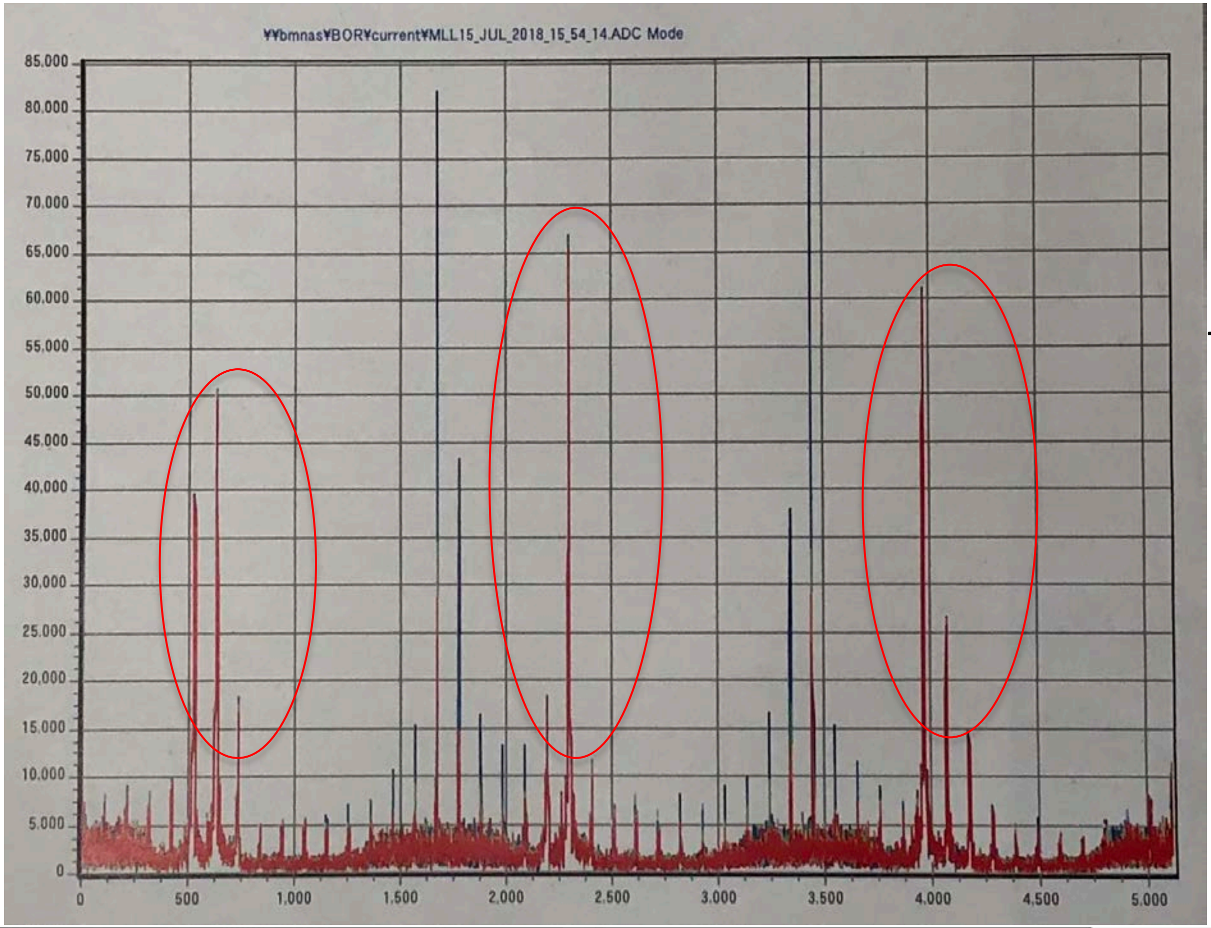


When LER beam current exceeded 830mA, a longitudinal coupled bunch instability started to be observed.

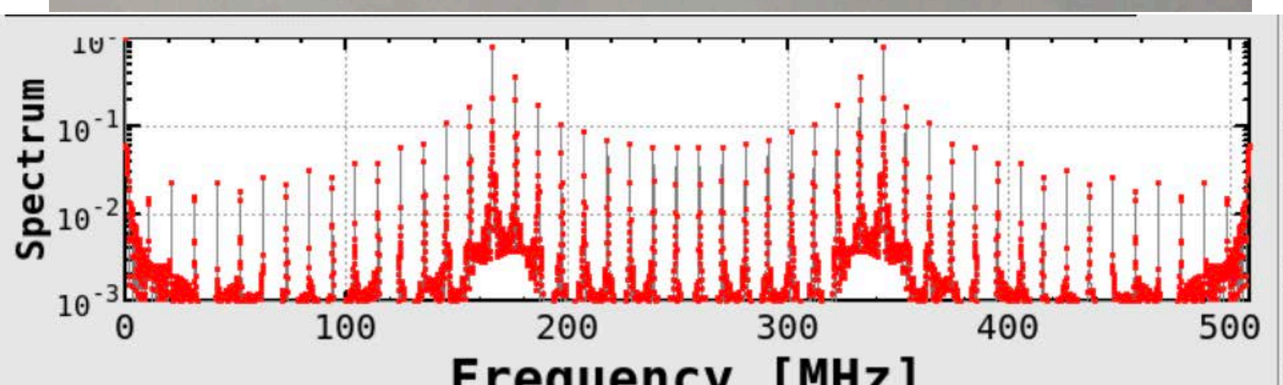
With 4trains the instability was not observed with the same bunch current. But with a higher (total) beam current, the instability is induced again.

With changing D2H4 collimator setting, the instability became stronger.

Spectrum when longitudinal instability occurred



Mode number = ~ 2300
This is not due to RF cavity.



Task forces

- Several task forces have been established or are being planned.
  - Detector beam background issues
  - Linac BT emittance preservation issues
  - QCS quench issues
  - (High beam current issues)
  - (Beam-beam issues)

Comparison of machine parameters between design and Phase2

parameters	Design	Phase 2	units	factor
I_{beam} (LER/HER)	3.6/2.6	0.8/0.78 (0.27/0.225)	A	0.22/0.3
ξ_y (LER/HER)	0.0881/0.0807	0.03/0.02		0.34/0.25
β_y^*	0.27/0.30	3/3 (2/2)	mm	0.09/0.1
# of bunches	2500	1576 (394)		
I_{bunch} (LER/HER)	1.44/1.04	0.508/0.495 0.685/0.571	mA	0.35/0.48 0.48/0.55
Luminosity	8×10^{35}	5.55×10^{33}	$cm^{-2}\ s^{-1}$	0.0069

Phase 3 (2019 March – June)

- Identify what limits the luminosity or machine operation.
  - What happens with squeezing β_y^*?
    - Lifetime decrease?, bad injection efficiency?, QCS quench?
  - What limits beam-beam parameter?
    - IP Chromatics coupling…?
  - What limits beam current?
    - Longitudinal coupled bunch instability…
    - Effects of electron cloud…
  - Understanding Belle 2 beam background and how to suppress it?
    - With SVD, Pixel detector
    - Establishment of continuous injection
    - Collimator tuning
    - Injector and injection tuning
  - QCS quench
    - Mechanism of QCS quench
    - LER vertical collimator tuning
- Physics Run
  - Next week we will discuss with Belle 2 group a guide line of physics run (how much luminosity the accelerator group assure to them) in the first year of Phase 3.
- We need to set target parameters
  - Beam current : ex.1.5A (LER), 1.2A (HER)
  - Luminosity: ex. 2 x 10^{34} cm^{-2} s^{-1}

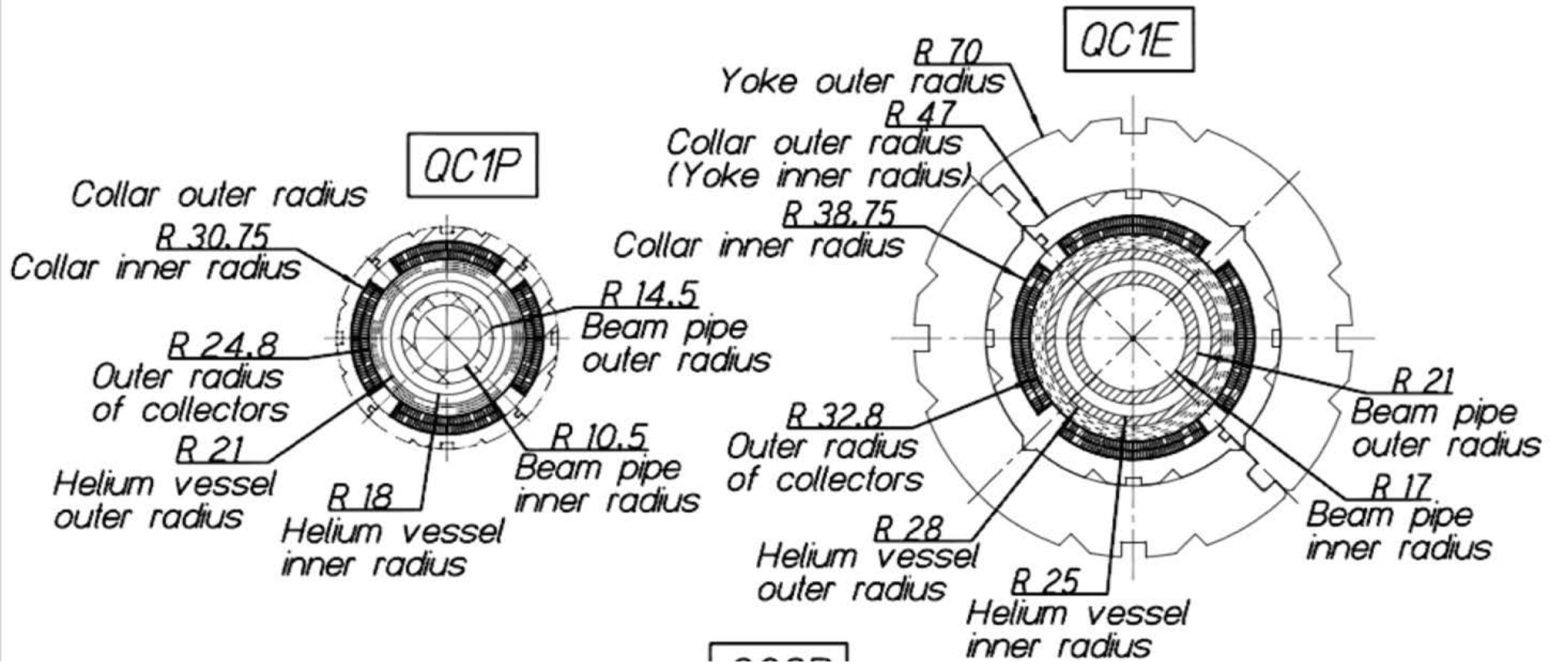
Spare slides

Efforts to prevent QCS quench

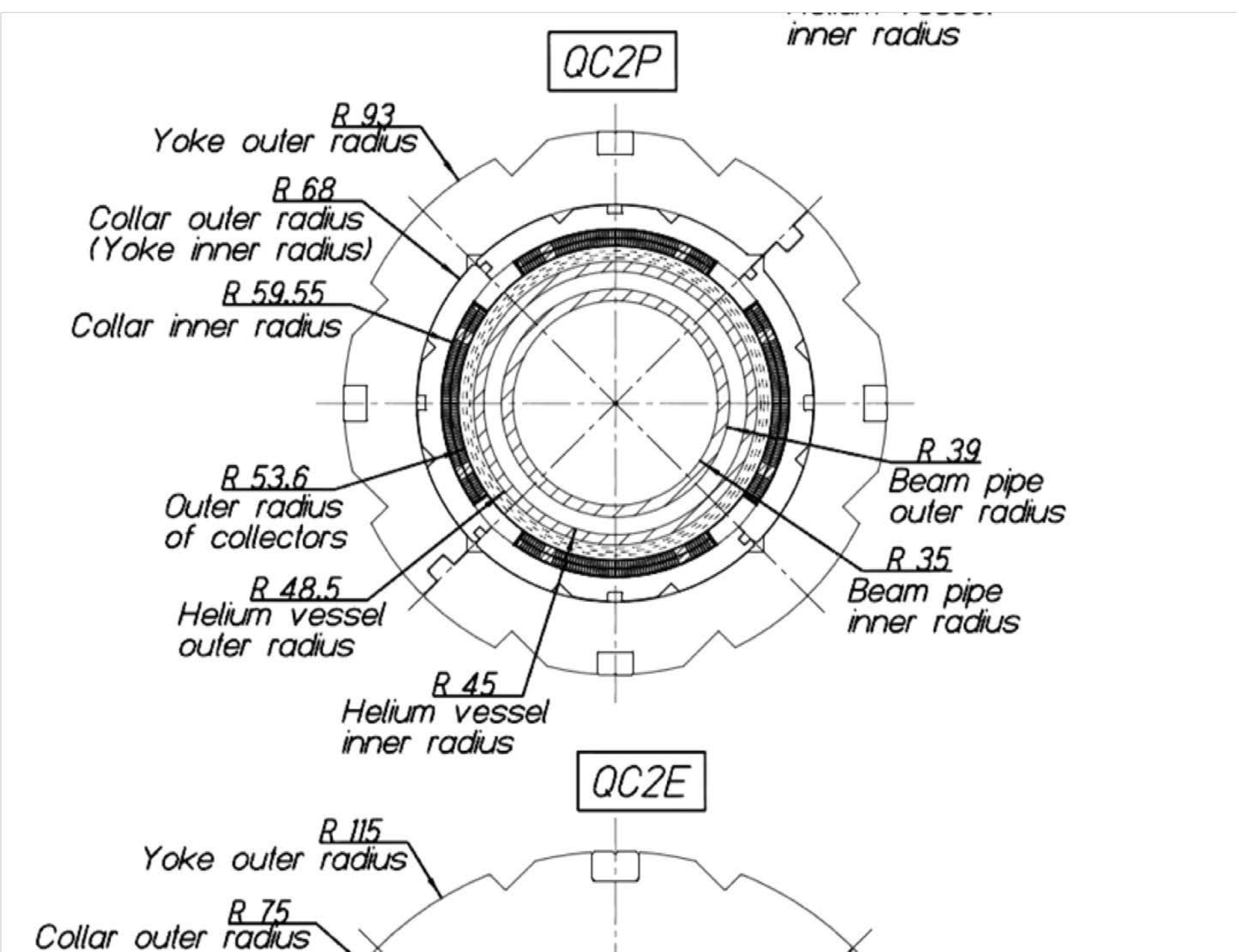
- Countermeasure meetings were held several times.
- Narrower collimator setting from the viewpoint of QCS quench protection (April 11th)
  - Our feeling is that HER QCS is well protected by collimators but we need more vertical collimators in LER. Vertical collimator setting was not enough, when the quench occurred on May 24th in HER.
- Belle 2 diamond sensor beam abort was introduced (May 28th).
  - Our feeling is that this abort system helps to prevent QCS quenches.
- Continuous efforts to improve beam injection (to reduce Belle 2 BG)
- Others
  - Move loss monitors to the place where the betatron phase is same as QC1s and the beta function is large.
  - A fiber loss monitor was installed in upstream of QCSL in LER.
  - I ask Belle 2 group that the 40 scintillators on QCS are available for monitoring beam loss at QC1s.
  - More steps in setting local orbit bumps or luminosity tuning knobs
    - Synchronized magnet setting system will be introduced shortly.
  - Careful operation in RF phase scan

Further countermeasures for QCS quench

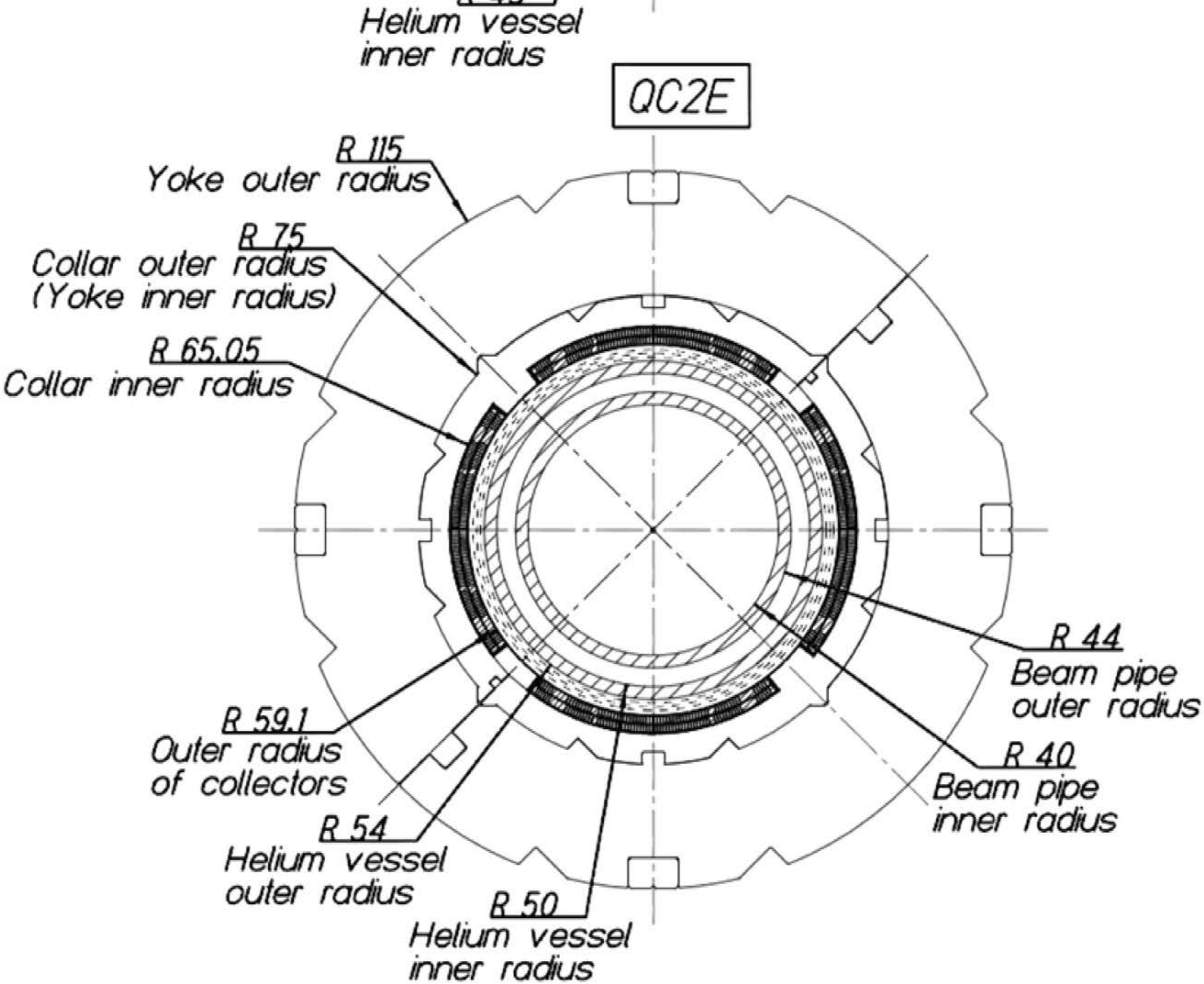
- New collimators before Phase 3
  - LER: 1 new vertical collimator, 3 new horizontal collimators
  - HER: 1 new horizontal collimator
- Installation of heavy metal (W) shields was proposed by Ohuchi-san.
  - We are estimating their effectiveness. More realistic beam loss scenario is needed. If needed, we will perform some machine study in Phase 2.
- More simulations are needed to simulate effects of ``chip scattering" of collimators.
- Are there any alternatives of QC1 dipole corrector coils?
  - It seems that luminosity performance is degraded, if we use other correctors instead of QC1 dipoles.
- Remodeling QC1 magnets?
  - We should consider it as a part of a long-term upgrade plan of SuperKEKB.
- QCS quench due to continuous beam loss?
  - We started estimation.



QC1P
Collar outer radius
R 30.75
Collar inner radius
R 14.5
Beam pipe
outer radius
R 24.8
Outer radius
of collectors
R 21
Helium vessel
outer radius
R 18
Helium vessel
inner radius
R 10.5
Beam pipe
inner radius
QC1E
R 70
Yoke outer radius
R 47
Collar outer radius
(Yoke inner radius)
R 38.75
Collar inner radius
R 32.8
Outer radius
of collectors
R 28
Helium vessel
outer radius
R 25
Helium vessel
inner radius
R 21
Beam pipe
outer radius
R 17
Beam pipe
inner radius

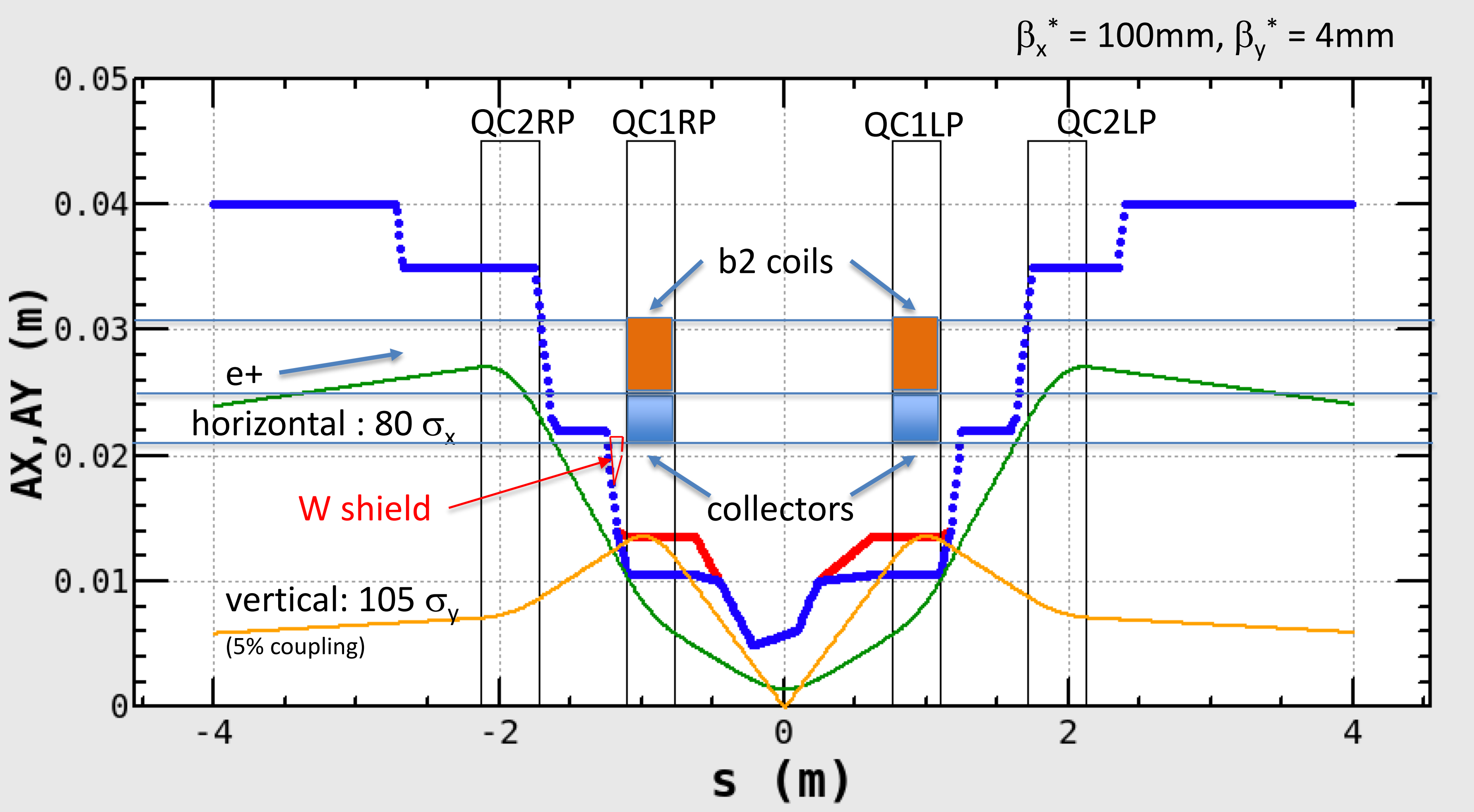


inner radius
QC2P
R 93
Yoke outer radius
R 68
Collar outer radius
(Yoke inner radius)
R 59.55
Collar inner radius
R 53.6
Outer radius
of collectors
R 48.5
Helium vessel
outer radius
R 45
Helium vessel
inner radius
R 39
Beam pipe
outer radius
R 35
Beam pipe
inner radius
QC2E
R 115
Yoke outer radius
R 75
Collar outer radius



Helium vessel
inner radius
QC2E
R 115
Yoke outer radius
R 75
Collar outer radius
(Yoke inner radius)
R 65.05
Collar inner radius
R 44
Beam pipe
outer radius
R 40
Beam pipe
inner radius
R 59.1
Outer radius
of collectors
R 54
Helium vessel
outer radius
R 50
Helium vessel
inner radius

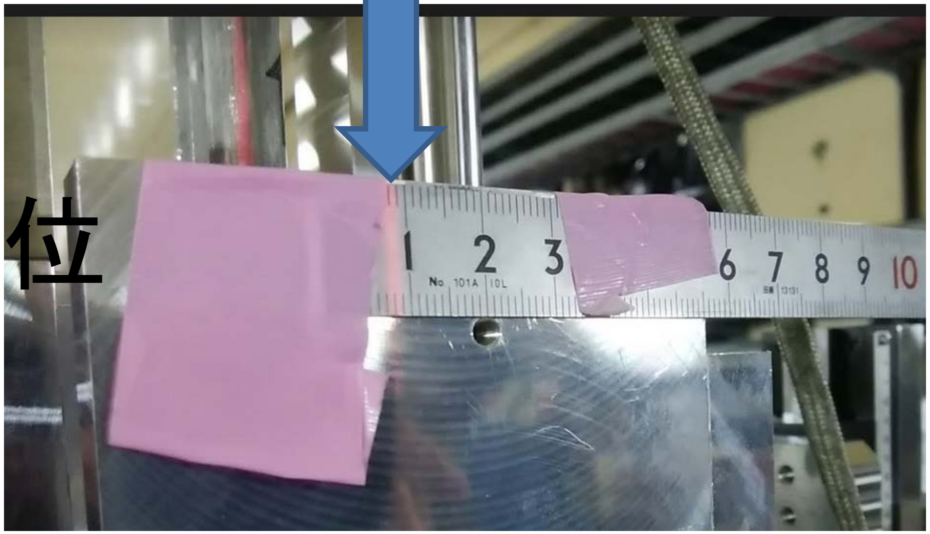
LER beam envelop

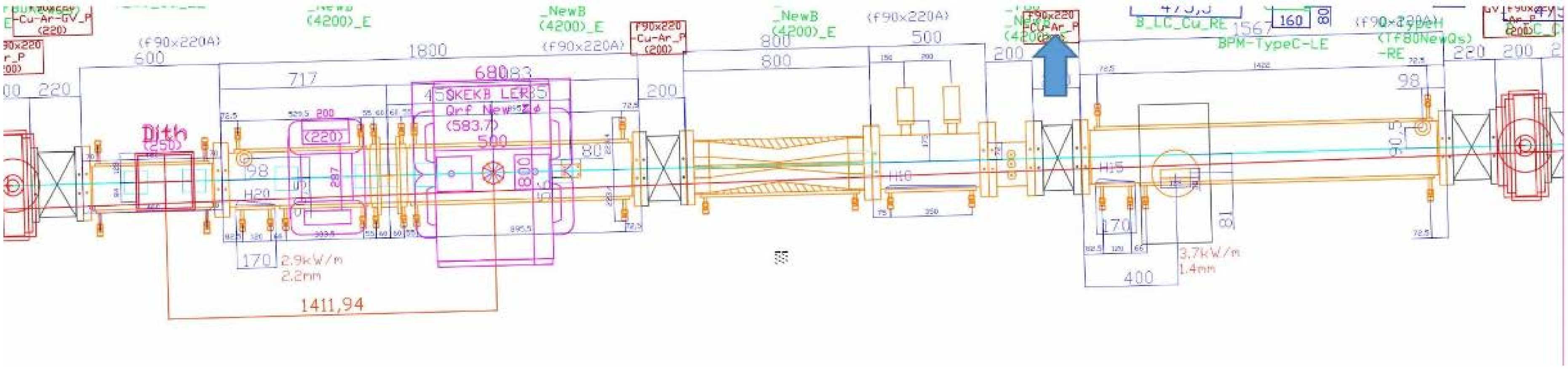


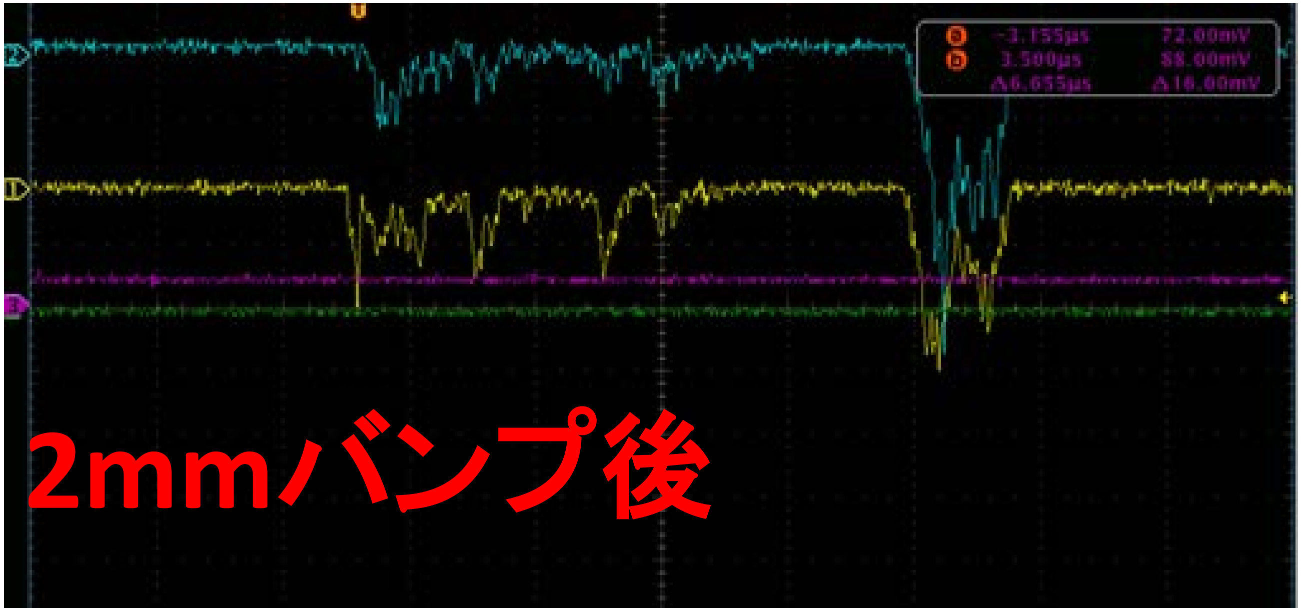
コリメータヘッドが損傷(LER)したためBGが増えた。

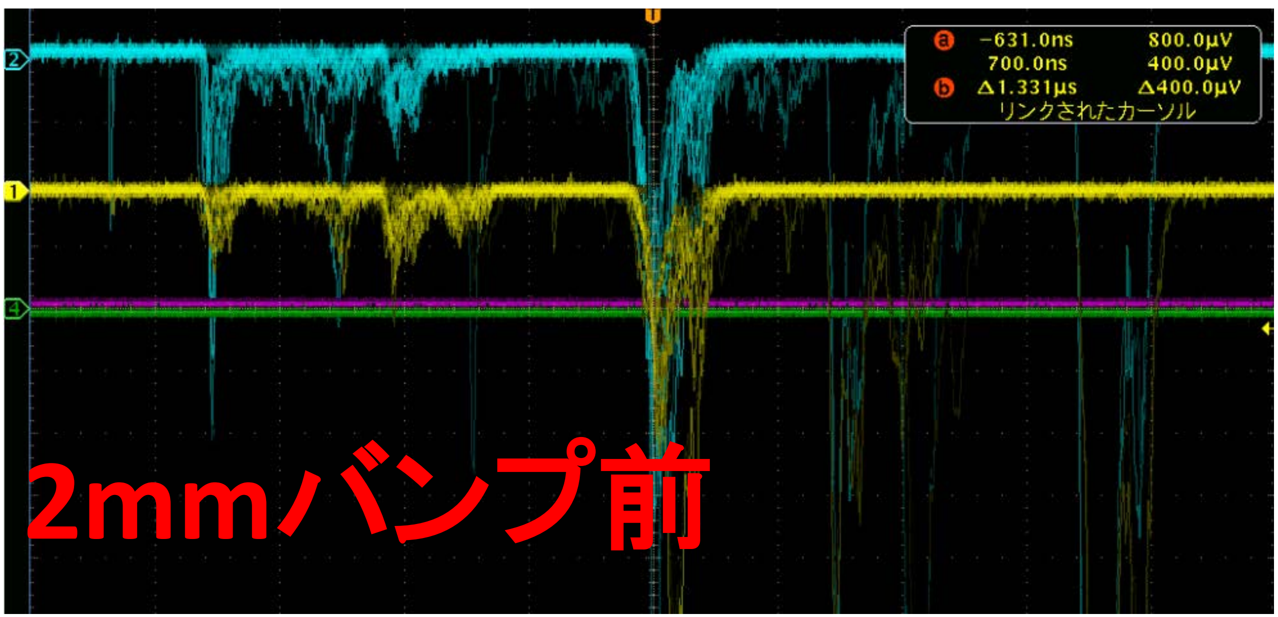
リング外側に2mm位コリメータを移動

レーザーの位置
最初は1cmの位置
2mm位動かした。









光ファイバーロスモニターでの信号。
矢野さんの協力でQCSの近くに設置

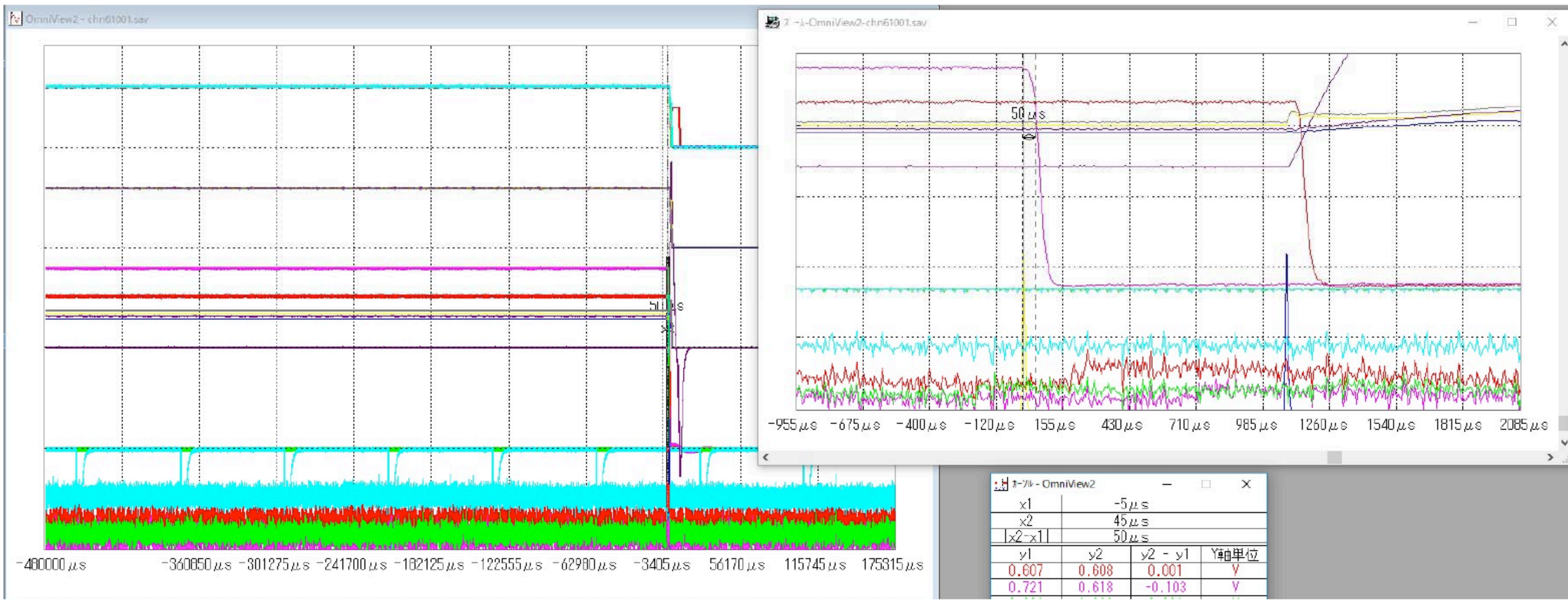
Finally two crab cavities were installed in KEKB, one for each ring in January 2007

HER (e-, 8 GeV)

LER (e+, 3.5 GeV)

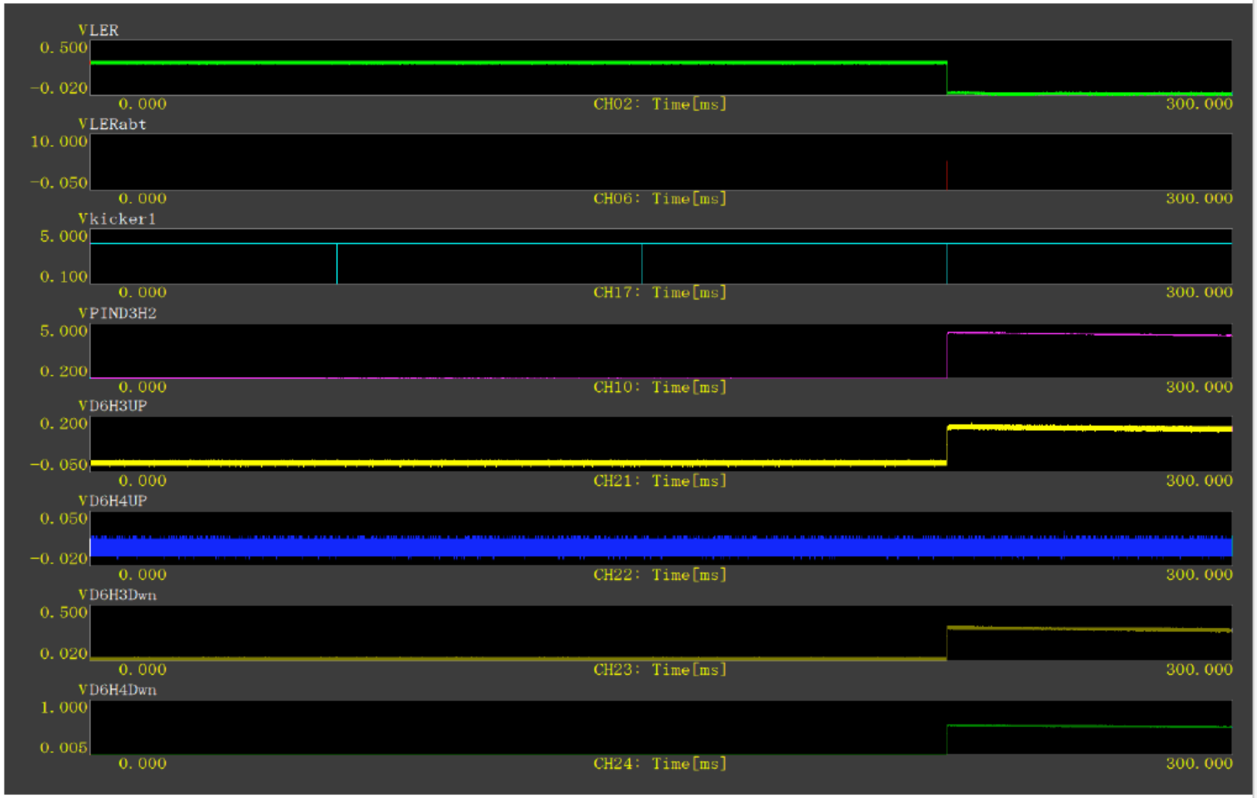
.....after 13 years' R&D from 1994

- 6/25（D2 collimator LM Abort）
  大きなbeam loss（～100mA）があって，一瞬でD2直線部にbeamをばらまいた。
  その時に，LMやQCSに同時にbeamが入って、abort&クエンチを引き起こした。
  Abort時に急に信号が出ていて、その前後で特に高くなっていた様子はない.
  入射タイミングとは非同期

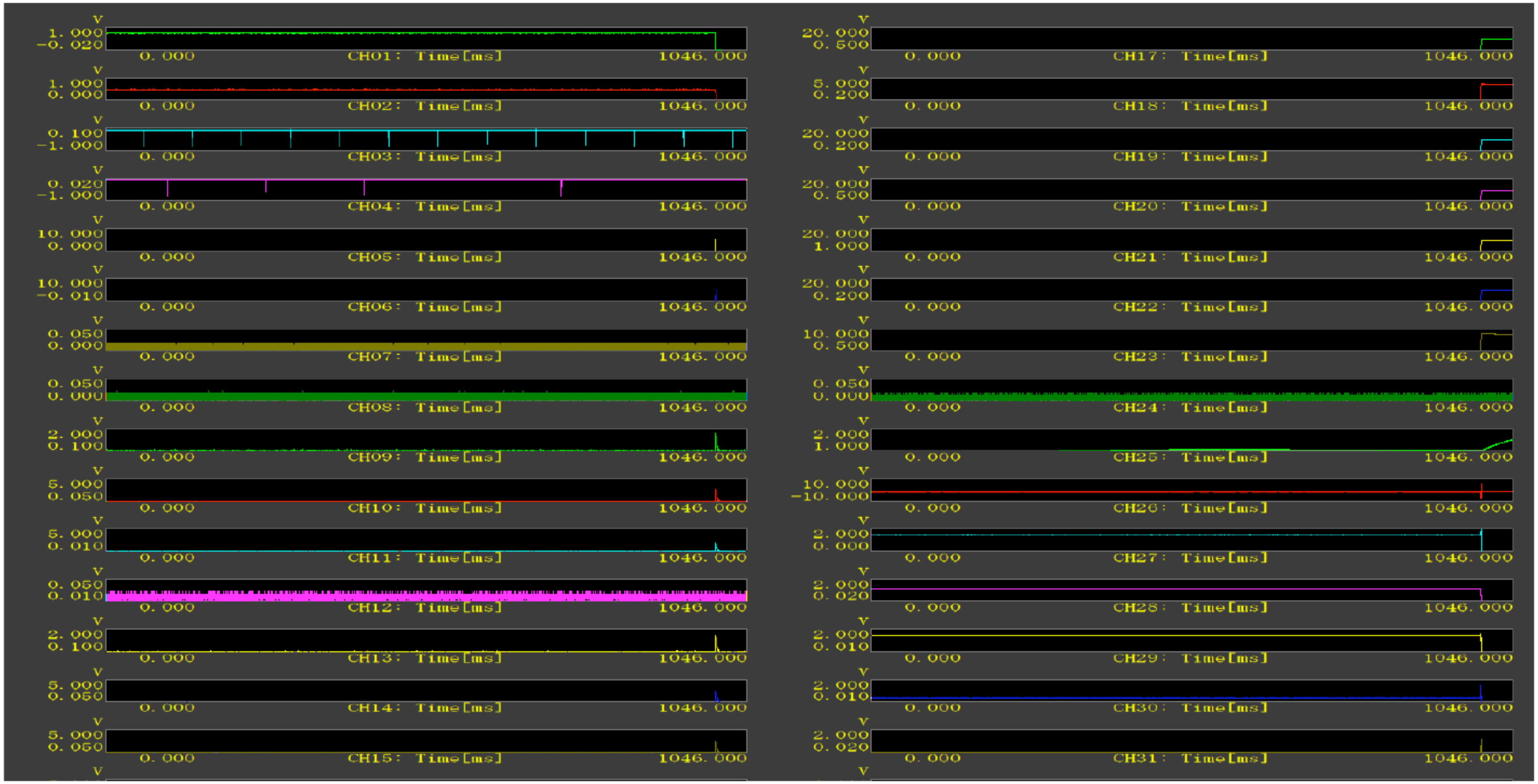


7/3(D2V1collimator LM Abort)

- 大きなbeam lossは見られない.
- LM信号が数秒前から上昇、~1s前からQCS coil voltage 変動.
- Abort は入射信号に同期.
- 入射ビームがQCS, collimatorに違うタイミングでぶつかった

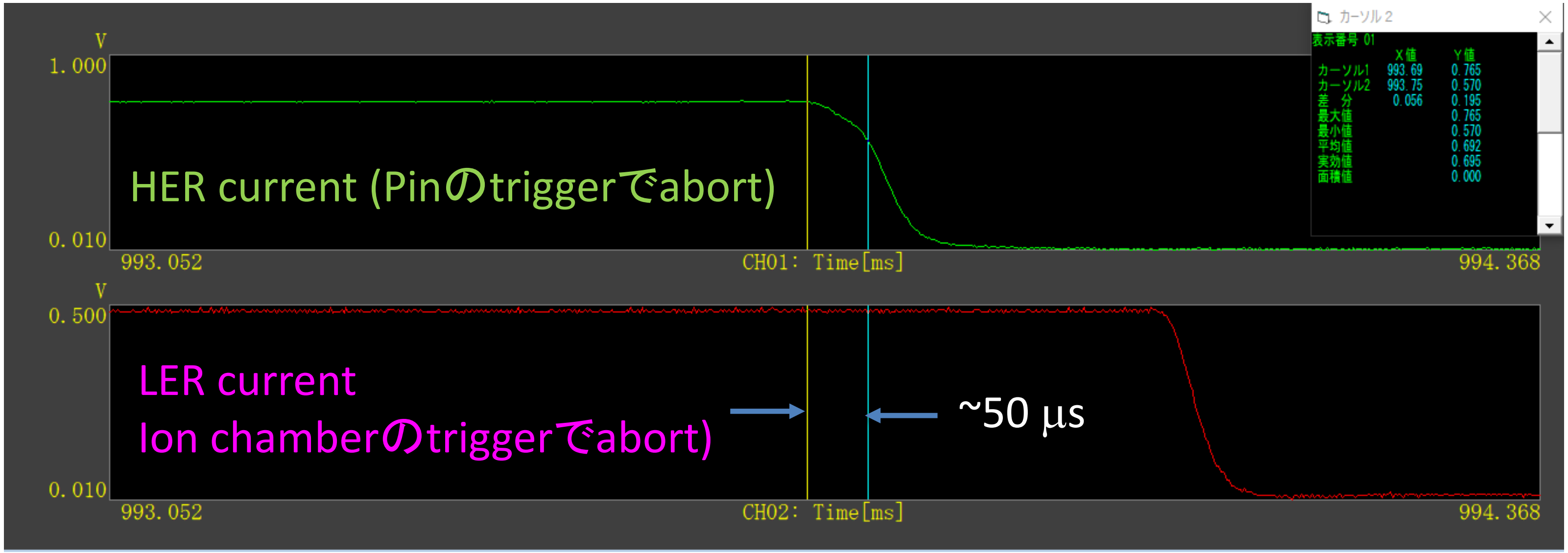


7/9
　D12 collimator,D1 collimator, D1V1 collimator 下流のケーブルラックに付いたICの順でAbort trigger発報、両リングAbort
大きなbeam loss（～100ｍA）があって，一瞬でD１直線部にbeamをばらまいた。
その時に，LMやQCSに同時にbeamが入って、abort&クエンチを引き起こした。



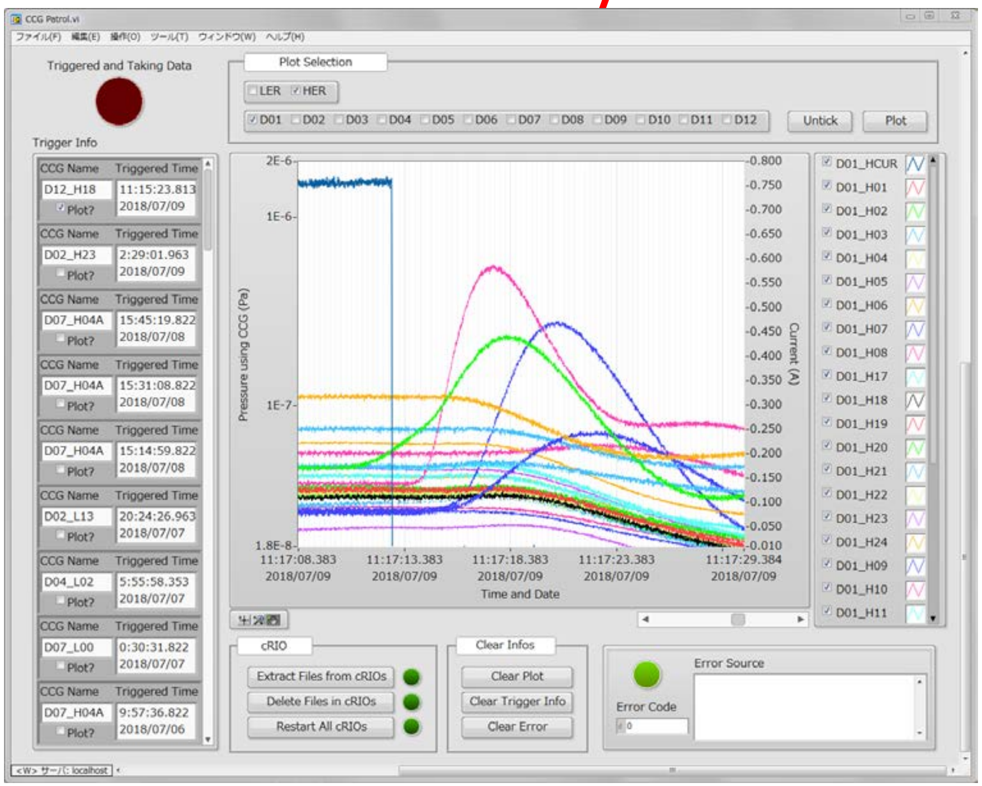
Troubles

- 11:17:19 HER/LER Abort (766 mA/487 mA)
  - ビームロスは見えるが数ターンでロスしている。(池田氏)
  - BORでは振動は見えていない。



Troubles

- 11:17:19 HER/LER Abort (766 mA/487 mA)



- D01_V1コリメータ部で圧力のバースト(～1E-6 Pa)
- 下流のD01_H4コリメータ付近のイオンチェンバーも反応している。
- ヘッドにビームが衝突したか。

Troubles

- 11:17:19 HER/LER Abort (766 mA/487 mA)
  - QCS復帰後、同じヘッド位置で入射は可能だった。効率が少し悪い？
  - BTの軌道が少し乱れていた。⇒ダンプモードで調整。

  - 原因は不明。
  - 6/25 のアボート+QCSクエンチ時の状況と似ている。。。

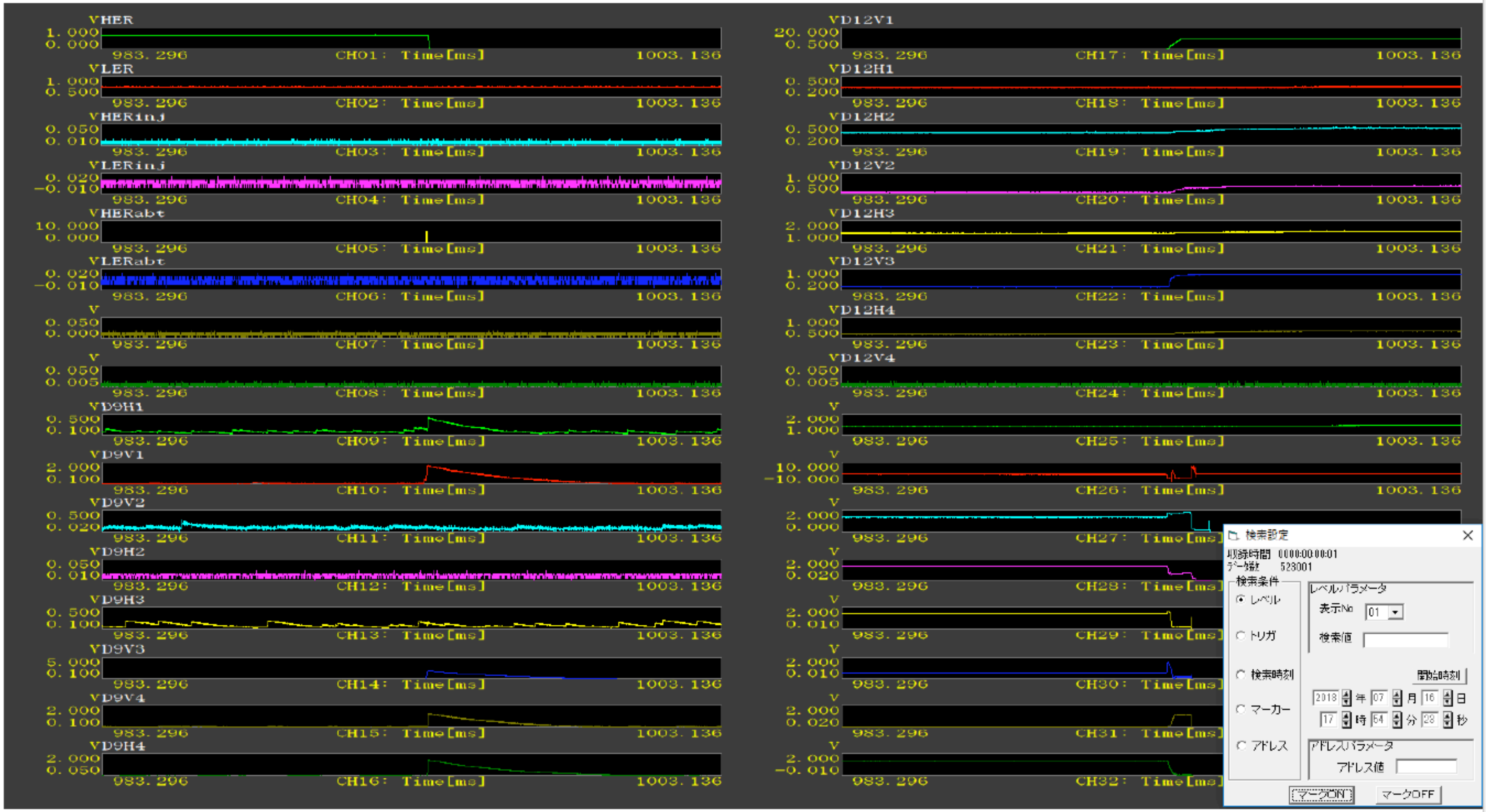
  - 参考情報
    - 6/25は月曜日、11:20:30頃
    - 気温が高く、Linac A3ギャラリーの温度が上昇しているタイミング？？(飯田氏)
    - ただし、入射のタイミングではない。また、前回はLER

7/16

D1 collimator(HER) D12 collimator(HER)の順に発報。D9コリメータ部PINも鳴っている。

入射中ではない。

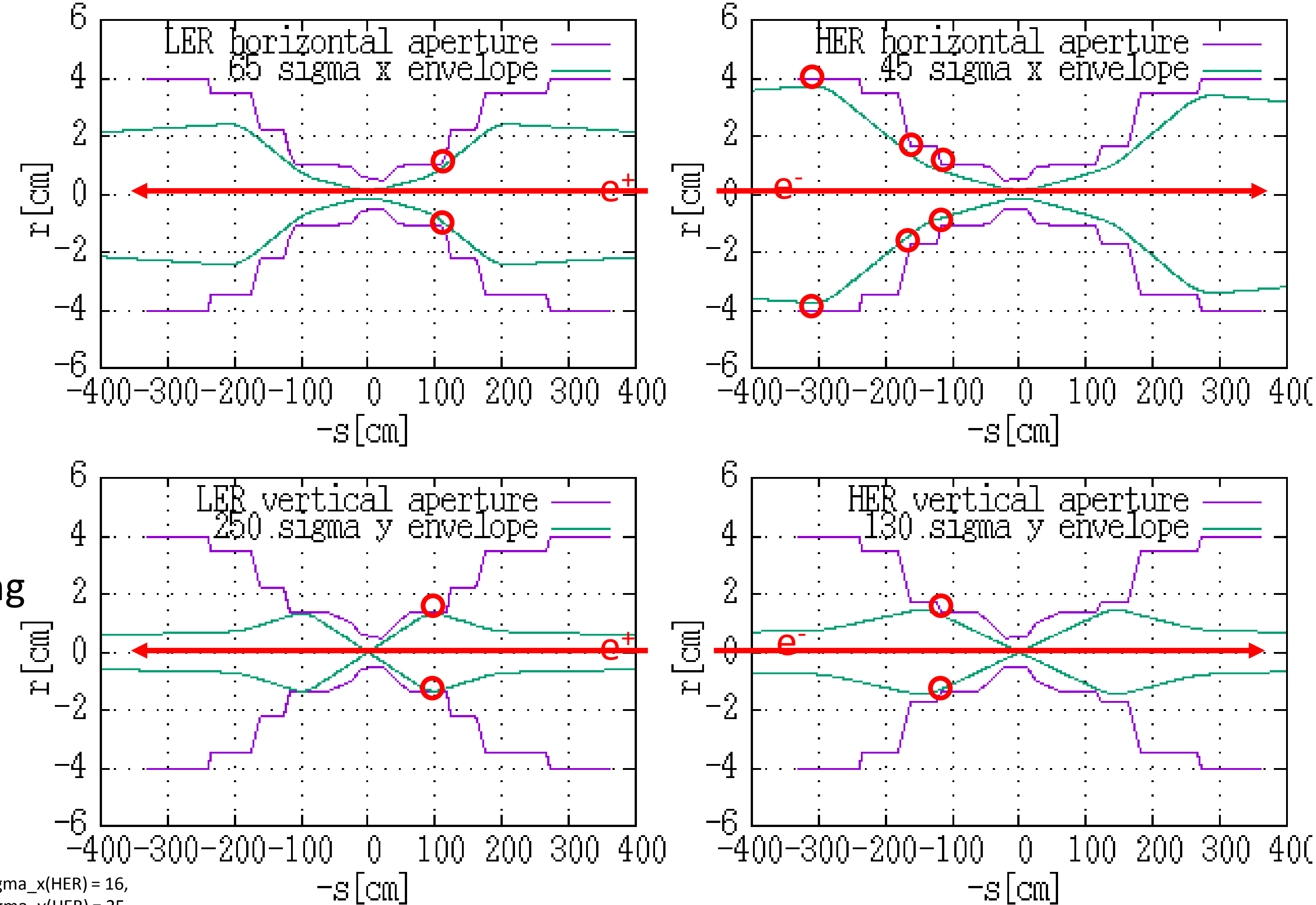
大きなビームロス無し。



H. Nakayama

Phase2.1

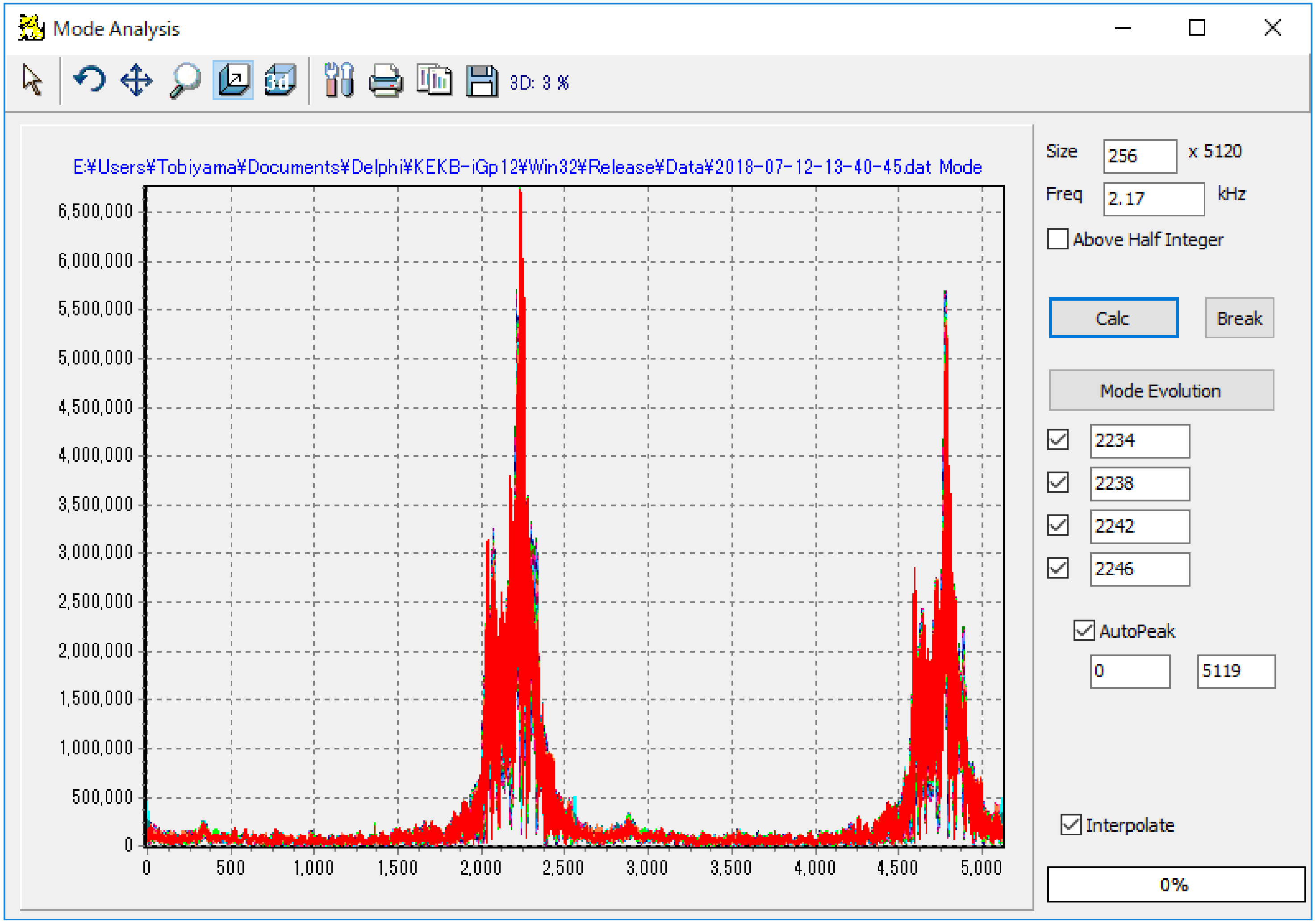
105σ_y w/
5% coupling
βy^*=4mm



For phase3,
nsigma_x(LER) = 25, nsigma_x(HER) = 16,
nsigma_y(LER) = 45, nsigma_y(HER) = 25,

In case of LER vertical, aperture at QC1 is narrowest.
In other cases, edges of vacuum chambers are narrowest.

By 2でのLongitudinal Mode



Ohuchi-san’s estimation

- 皆様、
-
- QCS補正磁石をクエンチさせるのに必要な7 GeV電子の個数を計算しましたので連絡します。
- この計算を行った時の条件は以下の様になります。
- 補正磁石の超伝導線パラメータ:
- 外径:0.35�弍∩叛�比Cu:Nb:Ti＝0.5:0.25:0.25
- 長さ10mmの超伝導線に電子が衝突して電子のエネルギー7GeVが断熱的に超伝導線に与えられるとします。
-
- SCワイヤーの体積＝0.962mm^3、SCワイヤー中のCuの重量＝4.31 X 10^{-3} g、NbTiの重量＝3.16 X 10^{-3} g
- Cuの比熱＝0.1 J/kg･K、NbTiの比熱＝0.87 J/kg･K　@4K
-
- 以上より、超伝導線の熱容量＝3.18 X 10^{-6} J/K
-
- 電子1個のエネルギー7GeV＝7 X 10^9 X 1.6 X 10^{-19} Jouleより温度を1度上昇させるのに必要な電子の個数は2696個となります。
- 実運転では、3度の温度上昇でクエンチすると考えるとその個数は3倍となり8087個です。
-