Development of Pulse Magnets for Injection and Abort Systems

T. Mori (KEK)

SuperKEKB Review

Mar. 4, 2014

Construction Schedule

- **Phase 1**
  - The new HER injection/abort system is installed
    - This is urgent issue & main topic of this talk
  - The KEKB LER injection/abort system is preserved
    - DR is not ready at the beginning of Phase 1
      - Emittance is large; new LER system doesn't work well for Phase 1
    - The LER current must be low to protect the abort window (< 500mA)
- **Phase 2**
  - The new LER injection/abort system is installed
    - DR is ON
    - New LER chambers have smaller apertures than those of KEKB
      - They should be installed at the same time not to make cavity structures
      - New injection channel can't be used for large emittance beam of Phase 1

List of BT Pulsed Magnets

	MR-BT				DR-BT	
	Injection		Abort		Injection	Extraction
	HER	LER	HER	LER		
H-kicker	6(3+3)	6(3+3)	4	1	2(1+1)	1
V-kicker	-	-	1	1	-	-
Septum	4	2	-	-	1	1
Quad	-	-	-	2	-	-

- 5 horizontal kickers for HER abort considered
  - Pulse uniformity problem (shown in later slides)

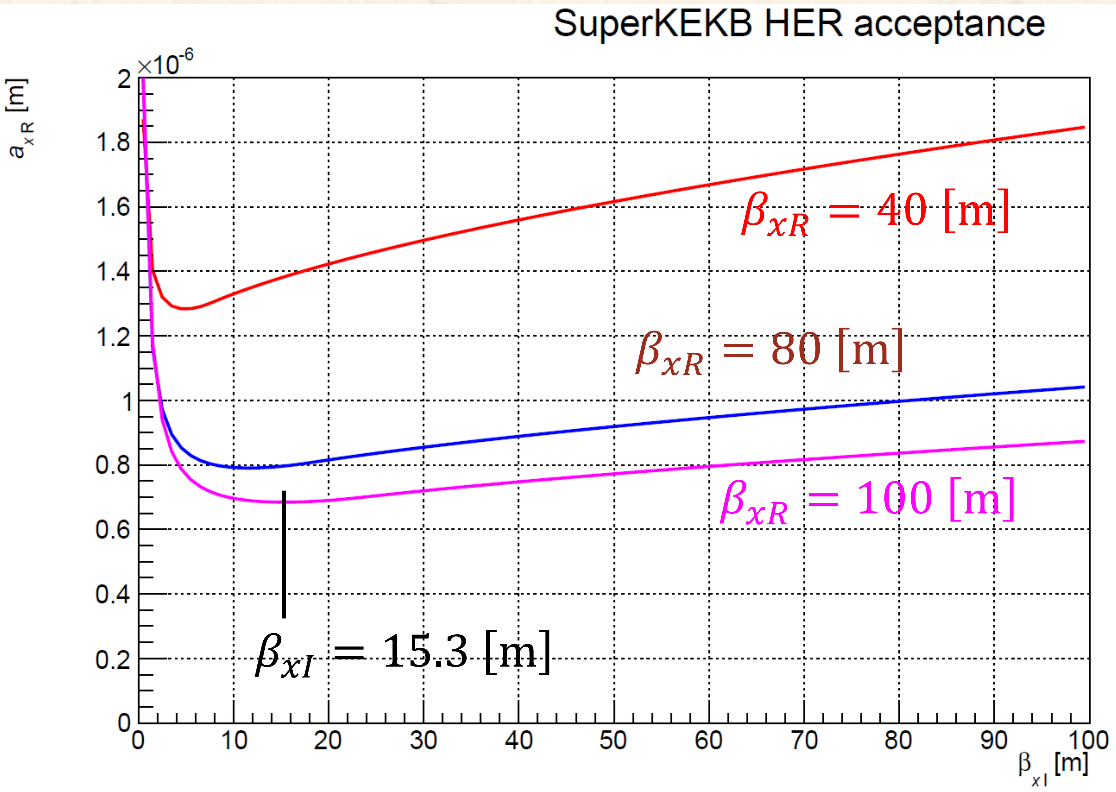
MR INJECTION

Method & Parameters

- 2 candidates for HER
  - Baseline: betatron injection; same as KEKB
  - Backup: synchrotron injection
- Injection system:
  - 2 kicker systems to make injection bump (π phase advance)
  - Kicker pulse: 2μs
  - kicker pulse height fluctuation affecting the height of the bump: 1mm
  - Effective septum width: 3.5mm (KEKB: 5mm)
    - Including non-uniform field region
  - Totally 4.5mm gap required by hardware
- Injection parameters are determined according to ring & Linac parameters

Parameters for Betatron Injection

- Required ring aperture for beam($2.5\sigma_{xI}$) injection is calculated as function of β_{xI}
  - $\alpha_{xR} = 0$ is assumed
  - β_{xI} is determined at minimum ring aperture



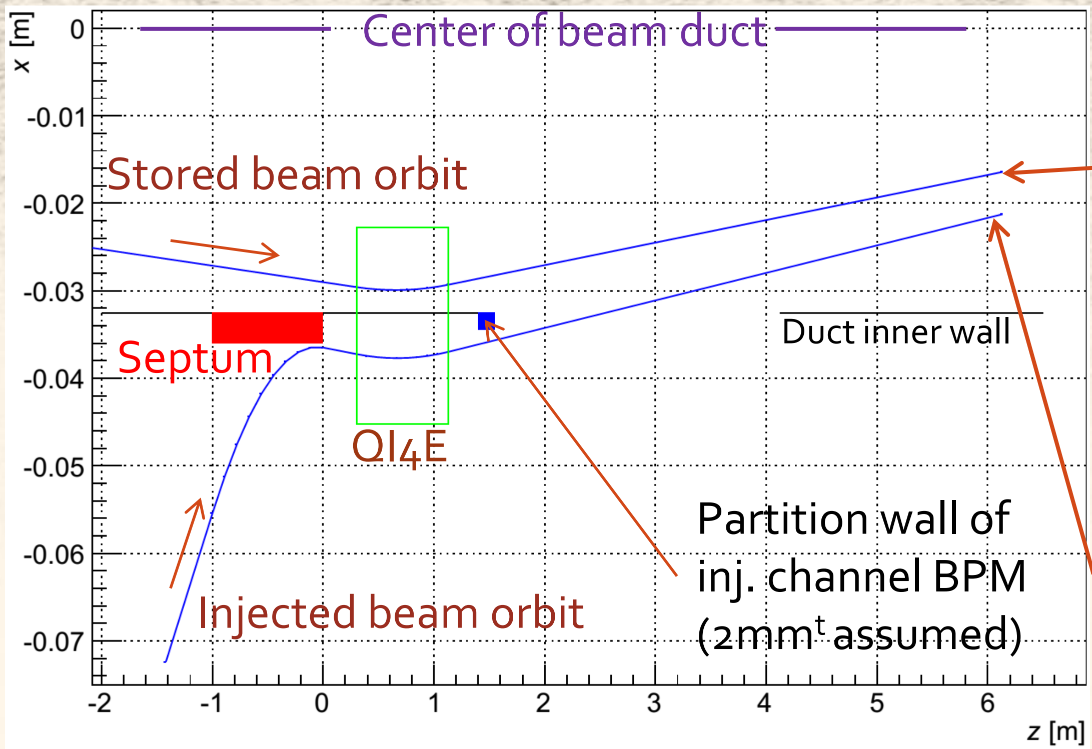
Ring parameters

Parameter	Value
α_{xR}	7.93
β_{xR}	100m
ε_{xR}	4.6×10^{-9}m
ε_{xI}	1.46×10^{-9}m

Injection parameters

Parameter	Value
Δx	7.8mm
$\Delta x'$	-0.62mrad

Betatron Injection Orbit



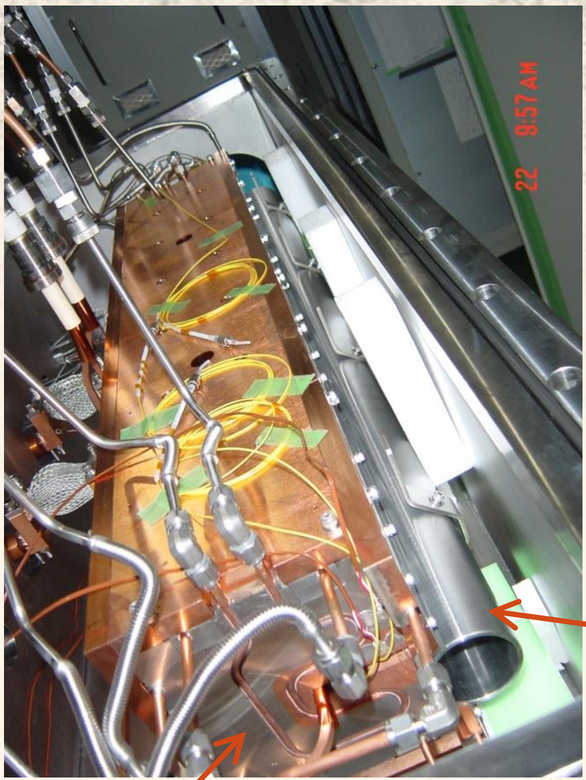
Injection param.	Value
Kicker height	28.5mm
Slope angle	-1.88mrad
K_1(QI4E)	0.1498
Height at QI4E	29.5mm
$3\sigma_{xR}$	2.0mm
Δx	7.8mm
$\Delta x'$	-0.62mrad
$2.5\sigma_{xI}$	0.37mm

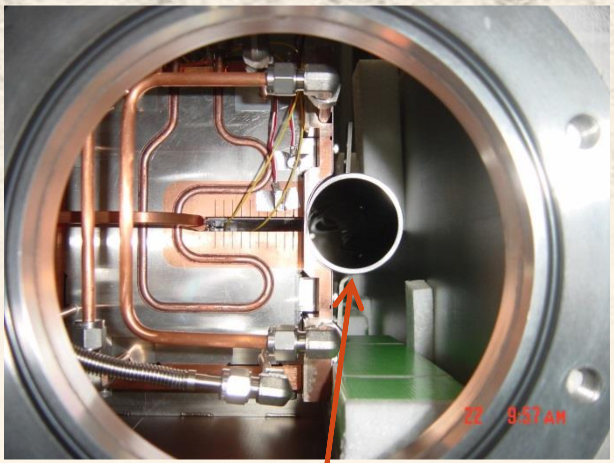
- We plan to install BPM on injection channel
- Increase of K_1(QI4E) increases the risk of wall hit

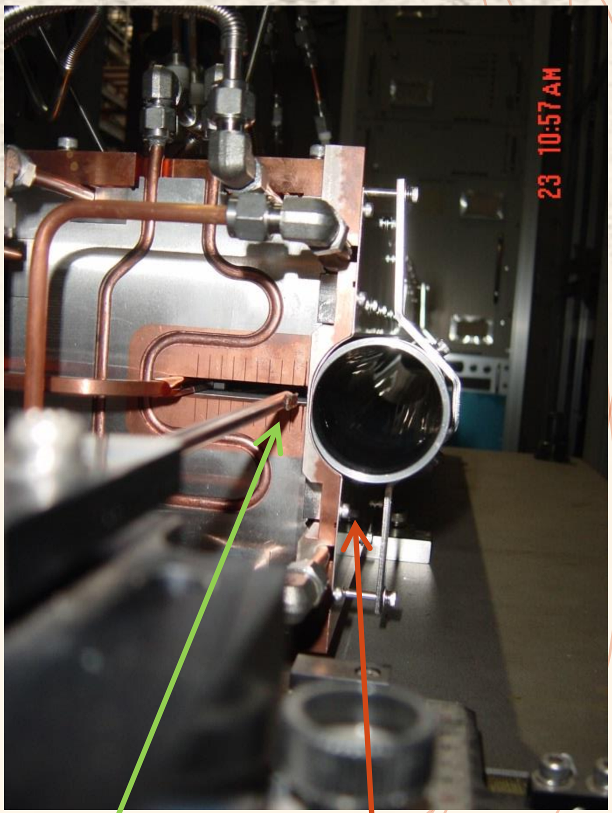
Betatron injection orbit can be designed with current HER optics & hardware designable

- Synchrotron injection orbit also designed; almost same as betatron injection

Septum Magnet Prototype







MR beam duct mockup (SUS430)

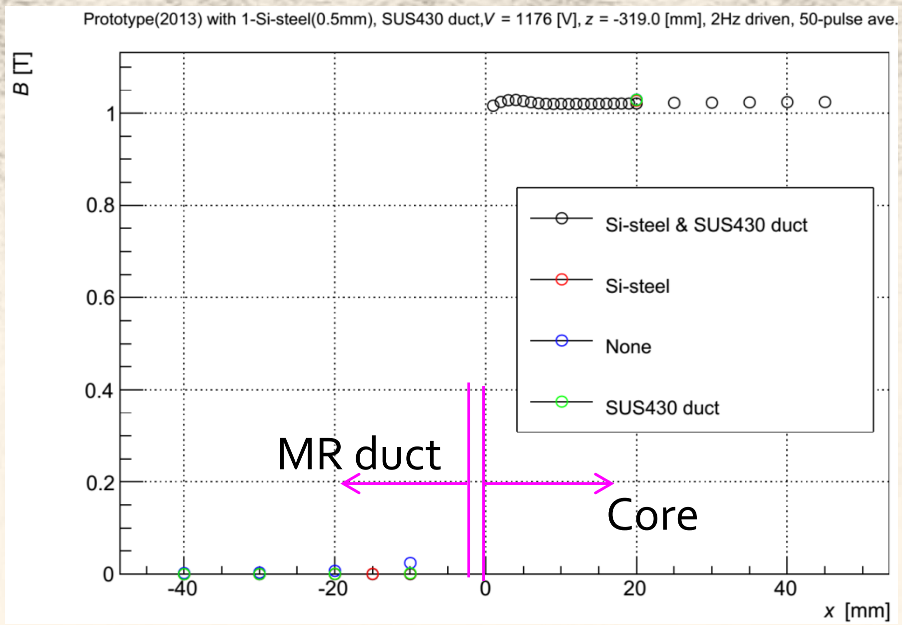
Magnet

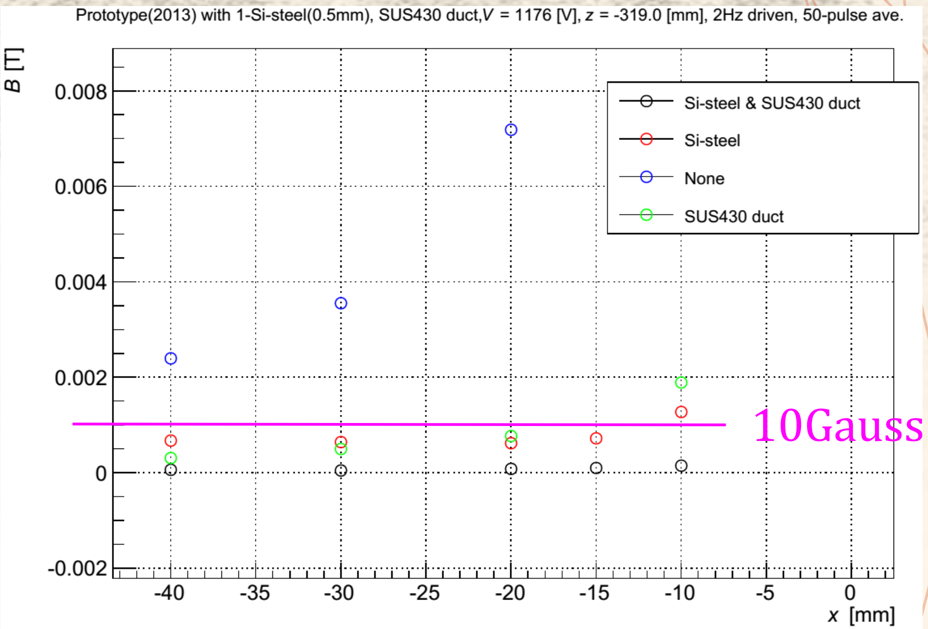
Pickup coil

0.5mm Si-steel sheet

	HER	LER
Septum conductor width	1mm	
Effective septum width	3.5mm	
Gap	8mm	
Core length	1m	790mm

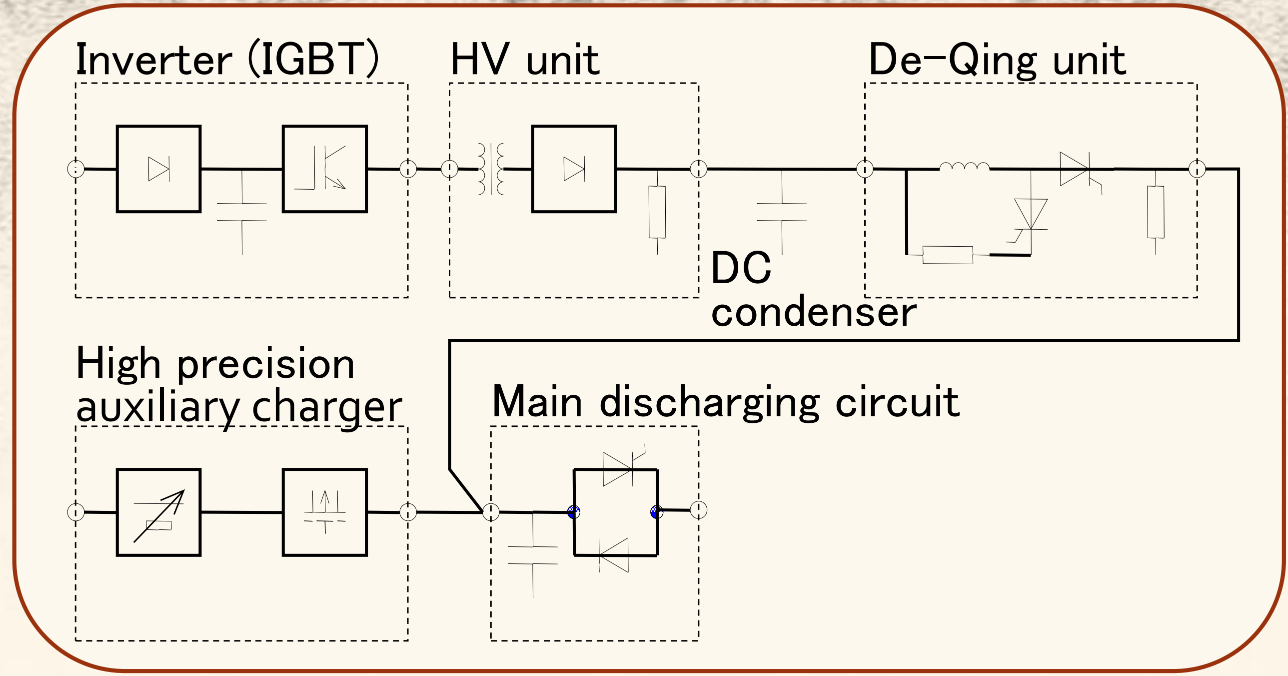
Field Measurement





- Field profile with SUS430 duct is fine
  - Leakage field sufficiently suppressed
  - Necessary and sufficient design
- Simulation study for shim shape on going

Power Supply for Septum



- Upgrade for SuperKEKB
  - Thyristor ➔ Inverter (IGBT)
  - Transistor ➔ De-Qing unit
    - Controlled charge timing; double trigger driven
  - High precision auxiliary charger introduced
- Current R&D issue
  - Pulse stability is not perfect:
    - fluctuation $> 1 \times 10^{-3}$ seen in beginning 1-2 seconds
    - De-Qing drift?

Kickers for MR Injection

- Magnets and power supplies will be reused
- Issues
  - Thyratrons (1 thyratron/kicker)
    - KEKB type(EEV CX1154C) is expected to be exchanged every year with 25Hz injection
      ➔ Long lifetime type(EEV CX1826A) (is already installed in HER for test)
        - 6-year achieved in KEKB, CX1154C lifetime in KEKB: 3-year with 5 – 10Hz continuous inj.
        - Demerit: price × 2
      - Another candidates
        - Replaced by semiconductor device
          (Si thyristor, solid state thyratron, etc?)
        - Pulse compression circuit (Rise time 5μs → 1μs)
          (Standard thylistors + saturable inductance)
  - Beam chambers
    - No upgrade planned for Phase 1
    - HER
      - Heat generation on fringe part is possible
        → Cu or Cu-coated kovar fringe is considered
    - LER
      - 3 chambers are planned to be exchanged for Phase 2
  - Waveform shaping circuit
    - Radiation tolerance unknown
    - Placed under the kicker magnet

Spec. of MR injection kickers	
Type	Window frame
Core	Ferrite
Max voltage	32kV
Max current	2kA
Pulse shape	Half sine
Pulse width	~2μs

T. Mimashi

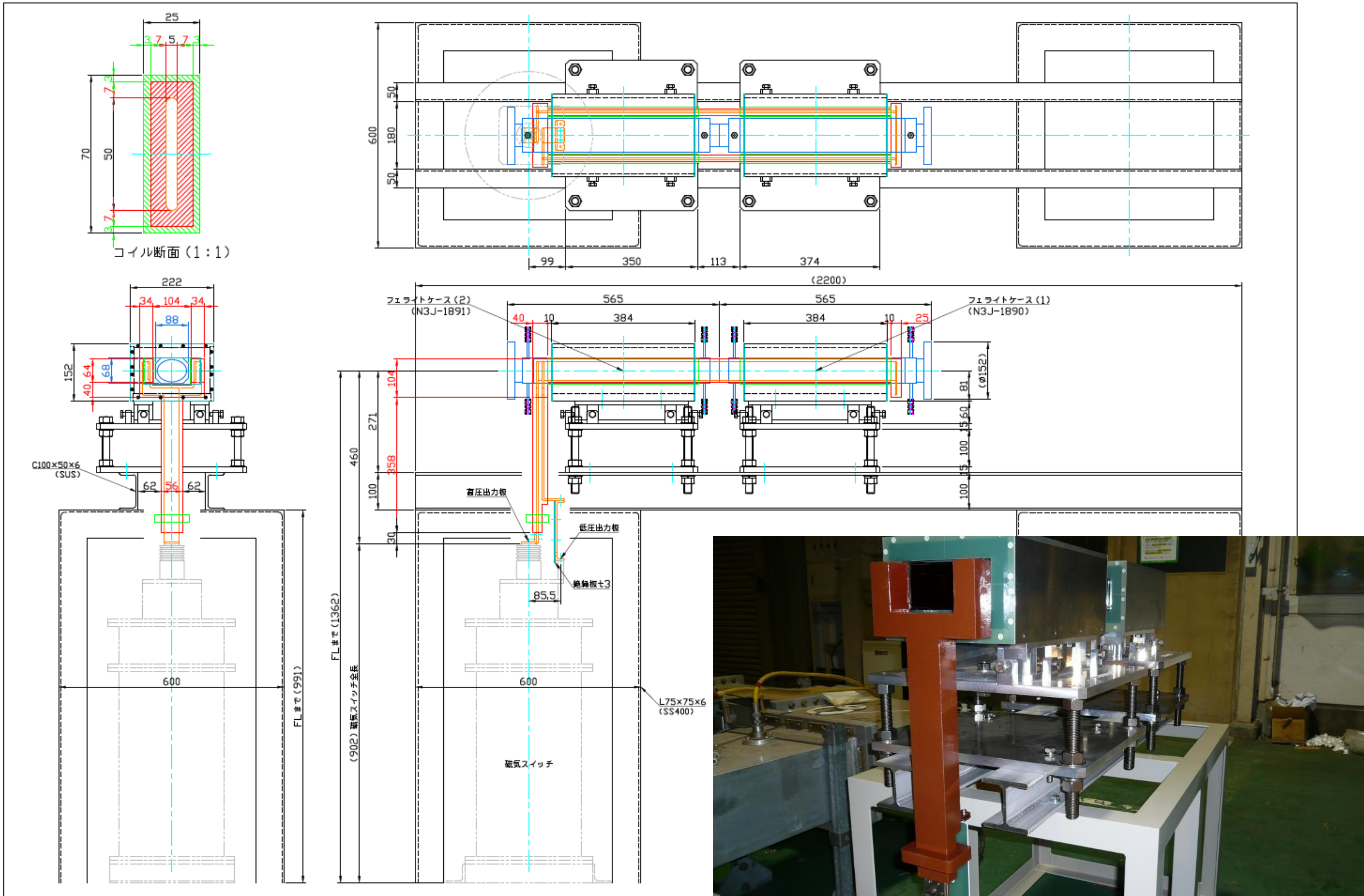
MR ABORT

Abort Kickers

- Magnet
  - Newly designed & constructed
- Ceramic beam camber
  - HER
    - Single ceramic (hollow type ceramic for water channel)
    - Sleeve: kovar + 100μm Cu coat
    - Problem: Ti wire evaporation coating failed
      ➔ Sputtering system constructed for 5μm Ti coat
  - LER
    - Double ceramic tube
    - Sleeve: Cu
    - Problem: many vacuum leaks during fabrication
      ➔ Sleeve structure changed
  - Entire Ti coated inner wall surface
    - Selected by the achievement on KEKB
    - Stripped coat with high current beam is not trivial
- Power supply
  - Pulse shaping issue
  - Radiation hardness of pulse transformer

Kicker Magnet Construction

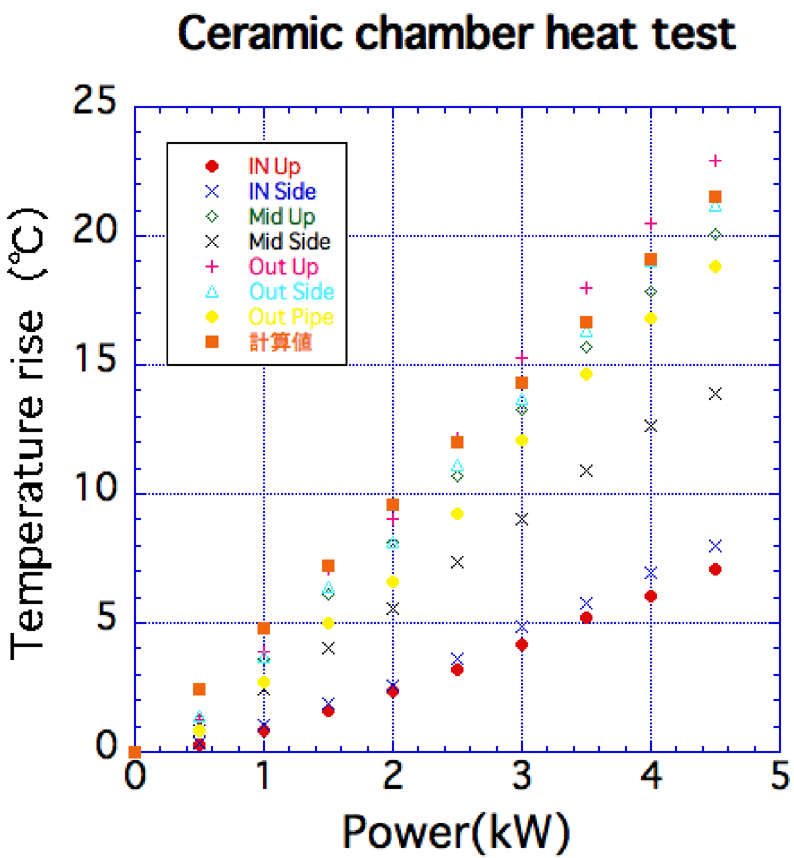
T. Mimashi

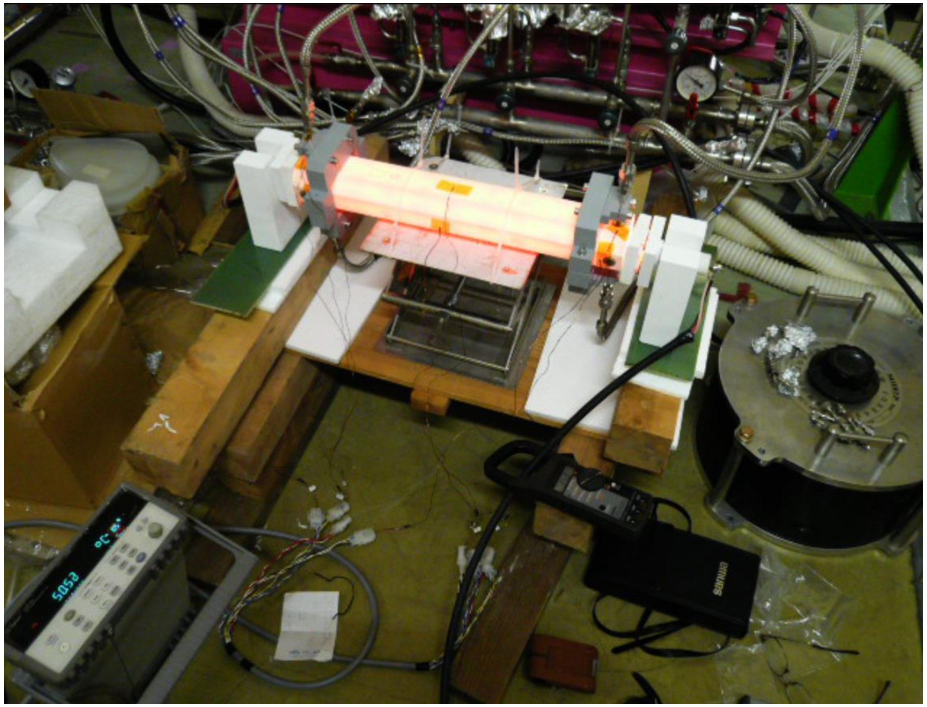


Ceramic Chamber

T. Mimashi

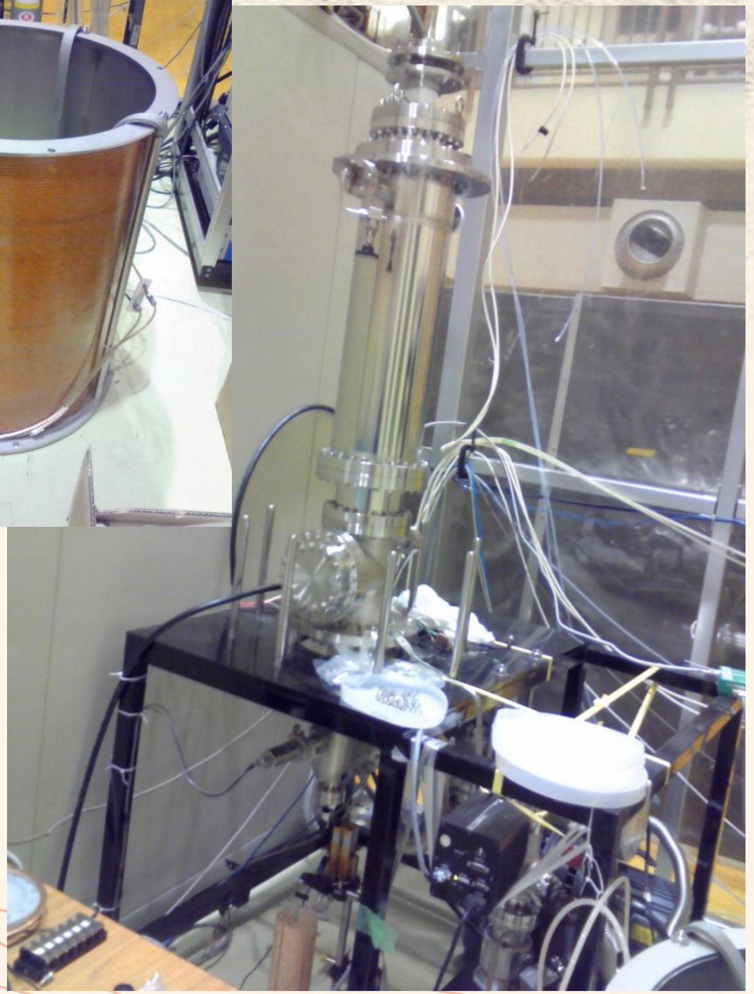
	HER	LER
KEKB	0.29kW	0.56kW
SuperKEKB	1.8kW	2.7kW

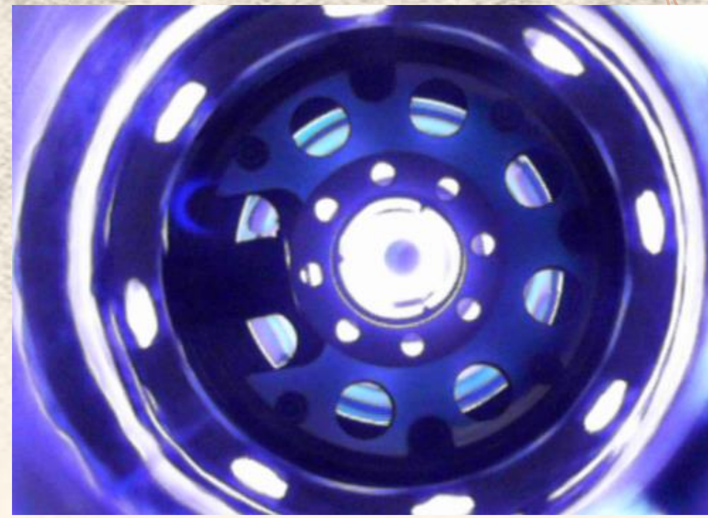




No local heating observed

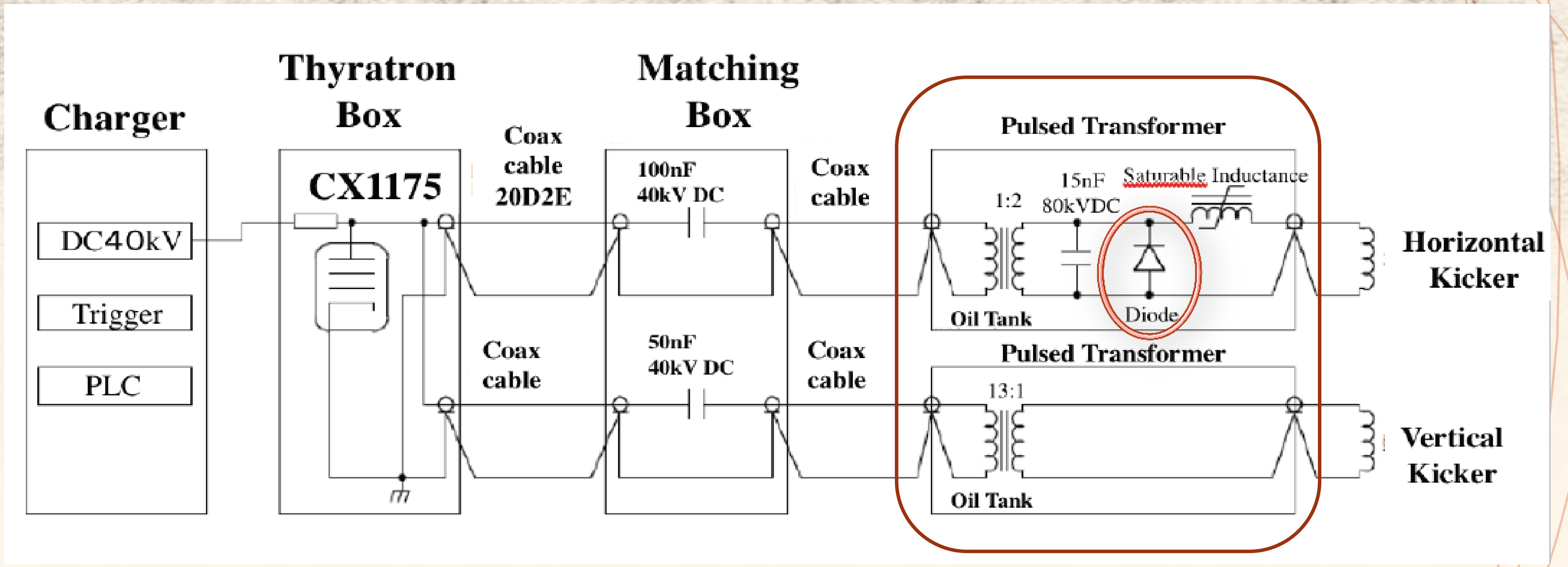
Sputtering System





- Parameter tuning
  - Current rate 60hours/chamber
  - $B = 160\text{Gauss}$
  - $V \cong 300\text{V}$
  - $I = 300\text{mA}$

Power Supply Circuit

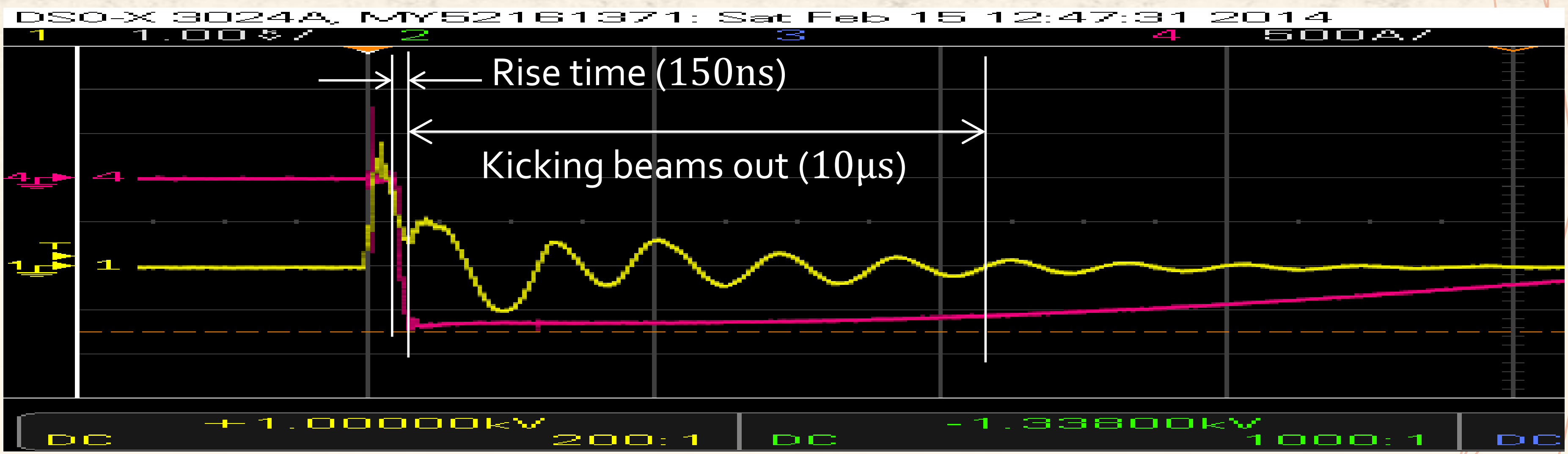


Placed under kicker magnet

- Issue
  - Radiation hardness problem
    ➔ 200mm polyethylene for neutron reduction
    ➔ 7mm Pb shield

Output Current of Power Supply

Inductance 4.5μH/165Ω+940pF
Voltage 39.3kV
(W/ additional inductance)



Peak 1750Ap(103%)
Flat 1700A(100%)

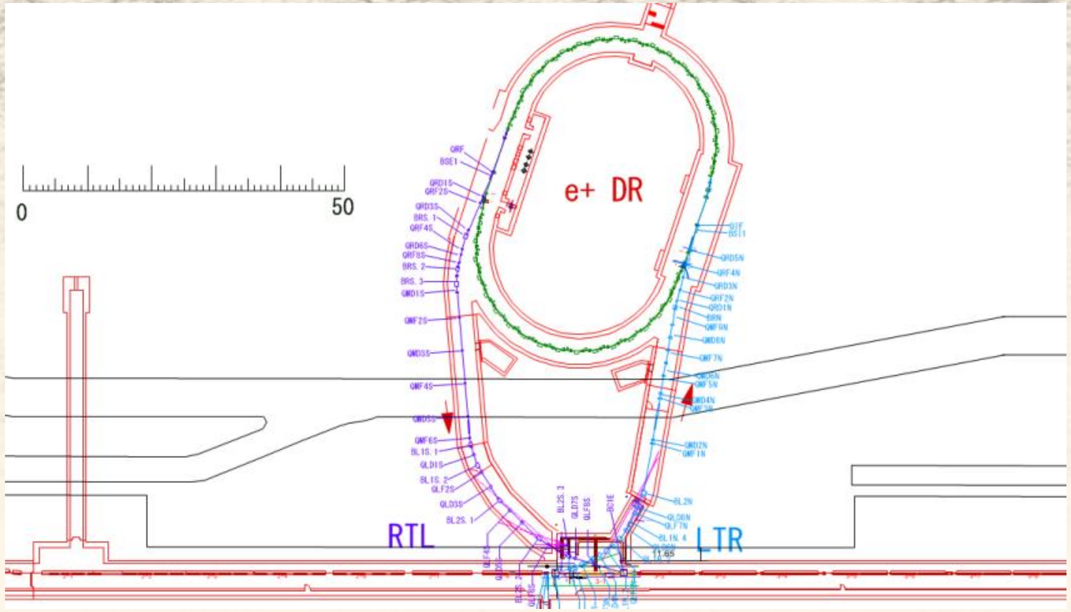
(500A/div,5μs/div)

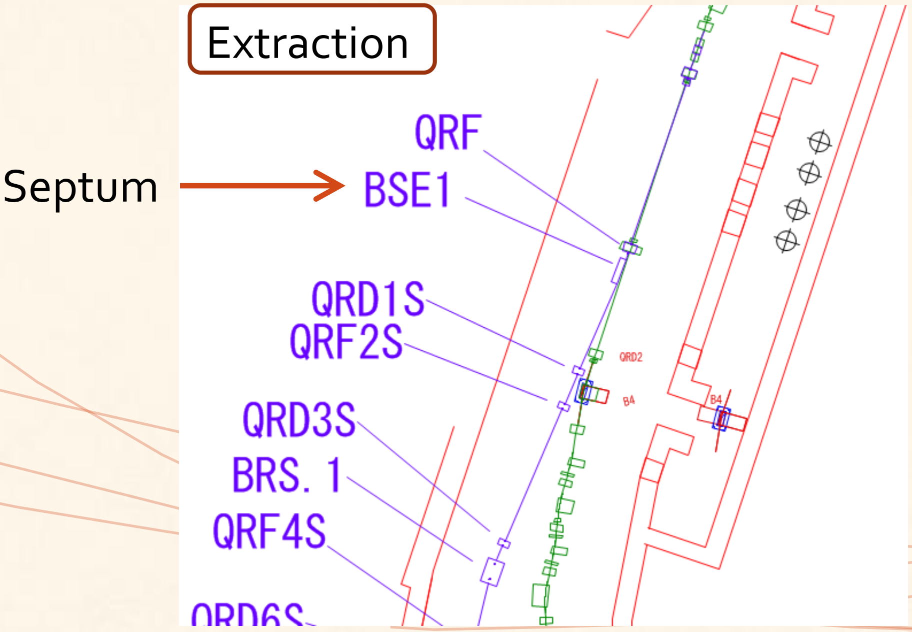
Rise time (2%-90%): 150ns
➔ Sufficient

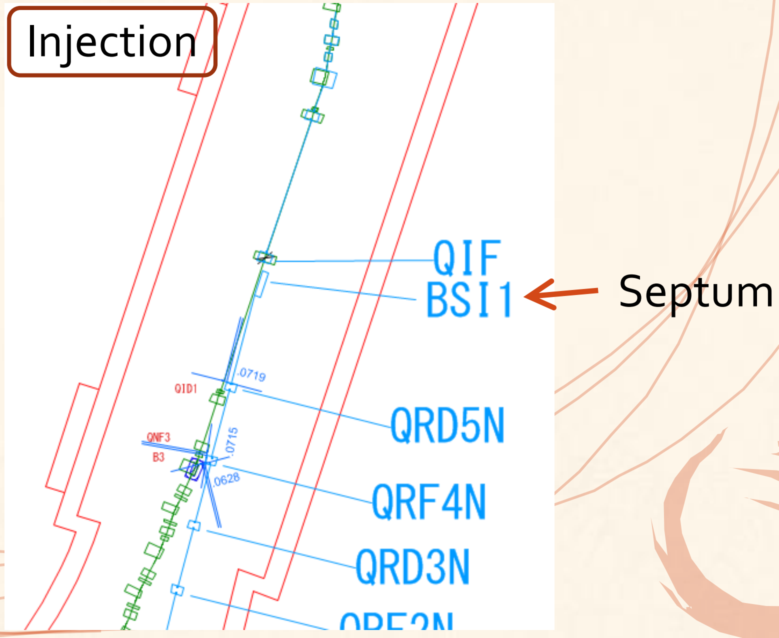
10μs-flat: 8.8% Drop (it is not fatal)
➔ 1 – 2mm shift on abort window
➔ Target: <5%

DR INJECTION & EXTRACTION

DR Injection & Extraction Arrangements

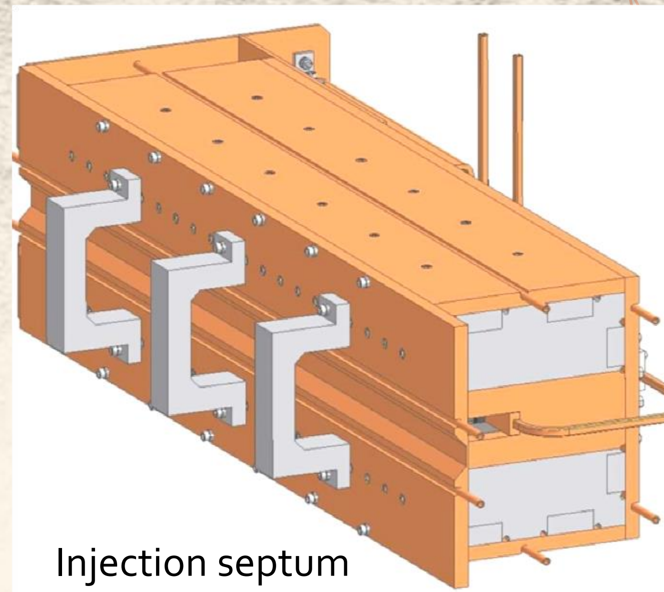




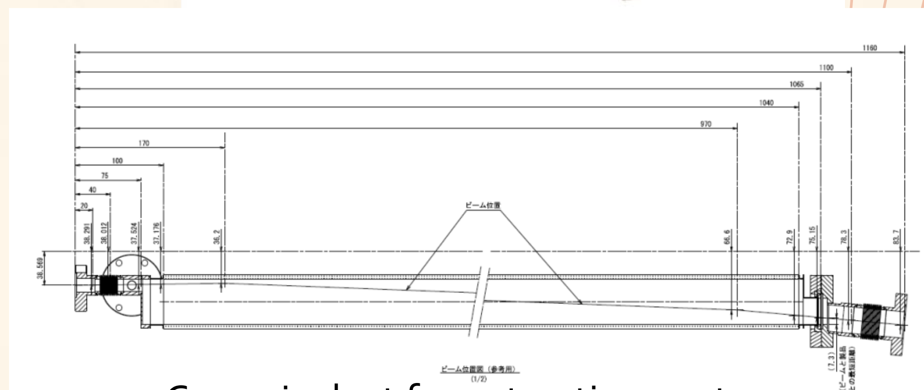


DR Injection & Extraction Septa

	Injection	Extraction
Deflection angle (mrad)	80	103
No. of magnet	1	1
Field strength (T)	0.36	0.47
Type	Eddy-current	Eddy-current
Aperture (mm)	70(H)x24(V)	98(H)x30(V)
Core length (mm)	800	800
Coil turns	1	2
Septum thickness (mm)	2.5	2.5
Waveform	Full-sine	Full-sine
Pulse width (μs)	300	300
Peak Current (A)	8000	5700
Max repetition rate (Hz)	50	50
Stability	<1E-3	<1E-4
	In-vacuum	Out-vacuum w/ ceramic duct



Injection septum



Ceramic duct for extraction septum

- RF system near Ext. septum requires pressure $< 10^{-7}\mathrm{Pa}$
  ➔ Out vacuum septum for extraction
- Power supplies are same type as MR septa

M. Tawada

Summary of Remaining R&D Issues

- MR injection
  - Septum
    - Stability of power supply
    - Shim shape study
  - Kicker
    - Thyratron lifetime issue: long life type is planned to be used
    - Radiation tolerance for pulse shaping circuit
- MR abort
  - Ceramic chamber: Ti sputtering
  - Power supply: pulse shaping & radiation hardness
- DR injection/extraction
  - Septum
    - Design
  - Kicker
    - Power supply R&D

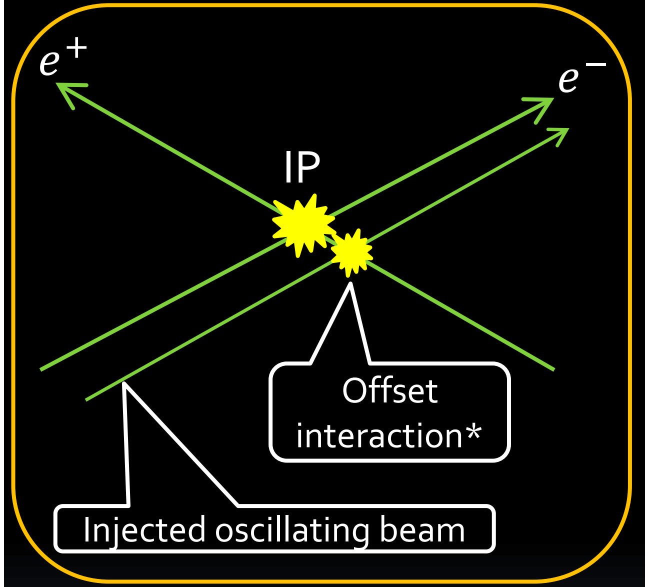
Thank you for your attention.

BACKUP

MR INJECTION

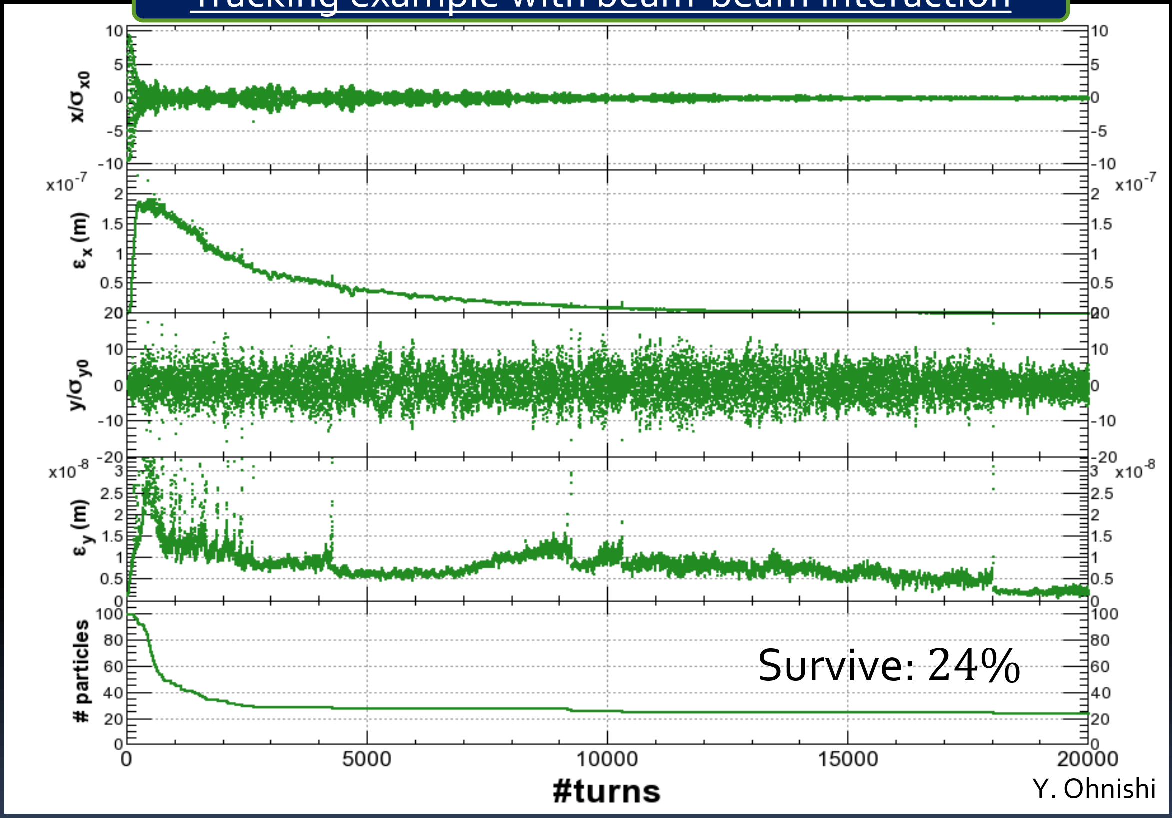
Need for synchrotron injection

- Very low survival rate with betatron injection into HER is expected
  - If offset Δx from IP for betatron oscillation,
  - Kicked vertically by beam-beam force from the colliding beam



* Finite y-amplitude
⟹ Large beam-beam kick
∵ Hour-glass effect

Tracking example with beam-beam interaction

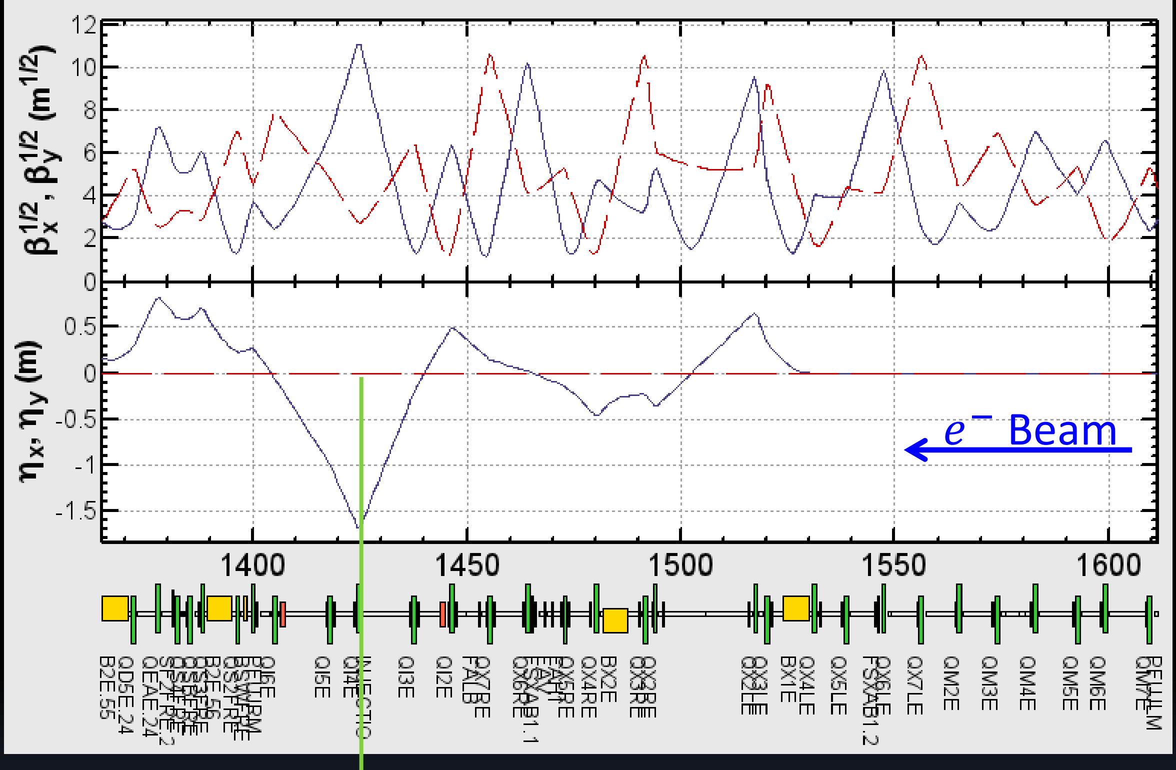


- Synchrotron oscillation ⇒ no offset Δx ($\because \eta^* = 0$)

⇒ **Synchrotron injection** (as a backup option of betatron inj.)

Dispersion & Momentum spread

- Dispersion by matching
  - $\eta = -1.6$ [m]
  - $\varepsilon_x = 4.6$ [nm]

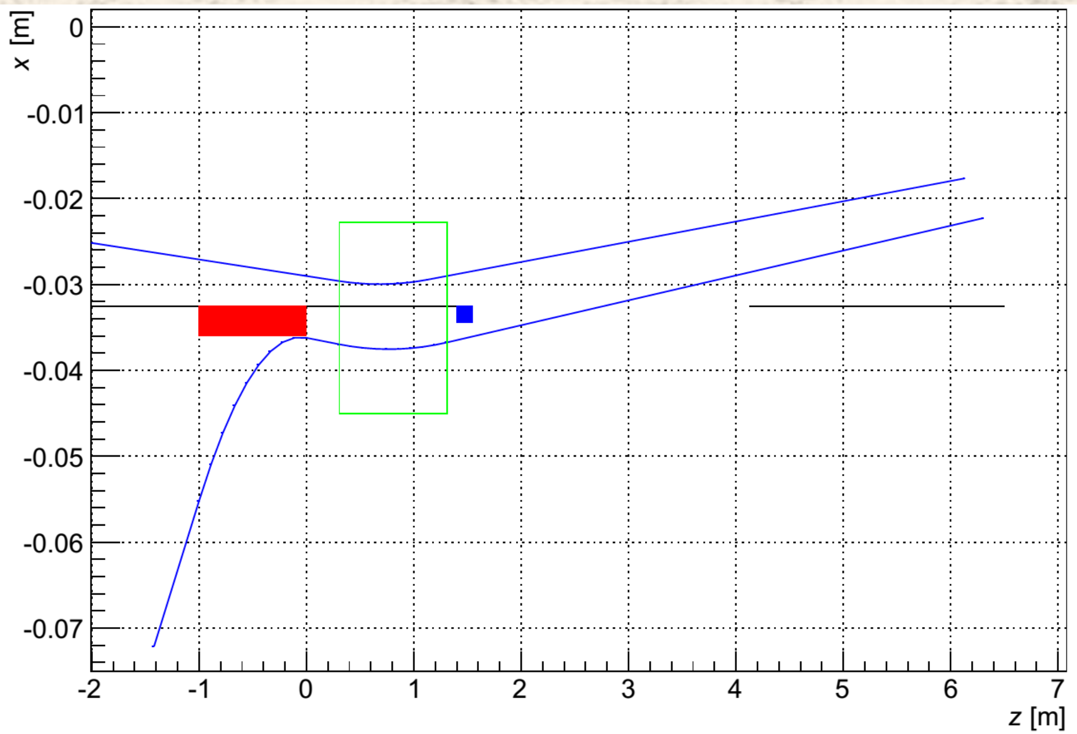


Injection point

- Momentum spread
  - $\sigma_{\delta \mathrm{I}} = 0.1$ [%] is assumed

Synchrotron injection orbit

- Almost same as betatron injection case, only slightly tighter



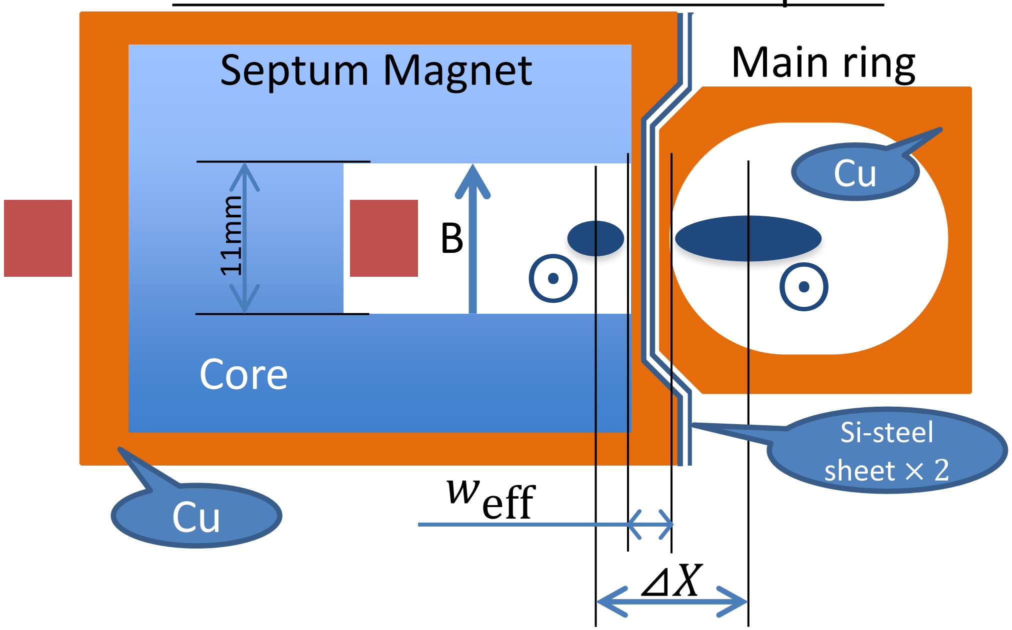
Injection param.	Value
Kicker height	29mm
Slope angle	$-1.89\mathrm{mrad}$
K_1(QI4E)	0.1437
Height at QI4E	30mm
$3\sigma_{xR}$	1.5mm
Δx	7.2mm
$\Delta x'$	$-0.52\mathrm{mrad}$

Synchrotron injection orbit can also be designed

Acceptance for Synchrotron Injection

☆Synchrotron injection is intended to avoid stored beam blow up by injection beam

Schematic view of KEKB HER septum



- $w_{\mathrm{eff}} \sim 5[\mathrm{mm}]$(KEKB)

SuperKEKB parameters

- $\beta_R = 60[\mathrm{m}]$
- $\varepsilon_R = 4.6[\mathrm{nm}]$
- $\sigma_{\delta R} = 0.059[\%]$
- $n_R = 3.0$
- $\beta_I = 20[\mathrm{m}]$
- $\varepsilon_I = 1.46[\mathrm{nm}]$
- $\sigma_{\delta I} = 0.1[\%]$
- $n_I = 2.5$

- $\Delta X = \eta\delta_0 = n_I\sqrt{\beta_I\varepsilon_I + (\eta_I\sigma_{\delta I})^2} + w_{\mathrm{eff}} + n_R\sqrt{\beta_R\varepsilon_R + (\eta\sigma_{\delta R})^2}$
- $\delta_0 = (p_I - p_R)/p_R$
- $\delta_0 + 2\sigma_{\delta I} = 0.65[\%]$ (by Y. Ohnishi)
- $\eta = -1.6[\mathrm{m}]$ (Achieved, so far)

Injection Kicker magnet

(Total 12 thyratrons are used)

- KEKB continuous injection (5～10Hz)
  - > SKEKB 25Hz injection
  - KEKB: life time of thyratron (CX1154C) ->3 years

-SuperKEKB : life time of thyratron : 1 year?

three possibilities

(1) Use long life thyratron (CX1826A)

(2) Replace thyratron to semiconductor device

- (SI thyristor? or commercial available Solid State Thyratron Replacement ?)

(3) Standard Thyristors + Saturable inductance(Pulse compress circuit) 5μsec -> 1μsec

We chose (1) Long Life thyratron for HER (CX1826A has been used for 6 years in KEKB)

MR ABORT

K. Oide

Abort optics with DC sextupole

- Instead of pulsed quadrupoles, a DC sextupole is used for enlarging the horizontal beam size.
- A DC sextupole is installed between the abort kickers and the abort window. The deflected beam feels an additional quadrupole kick effectively.
- Another DC sextupole is needed to make a pair of sextupoles for cancellation of the geometrical nonlinearity.
  The pair of Sextupoles is connected by *I* or - *I* transformation.

Abort system of KEKB

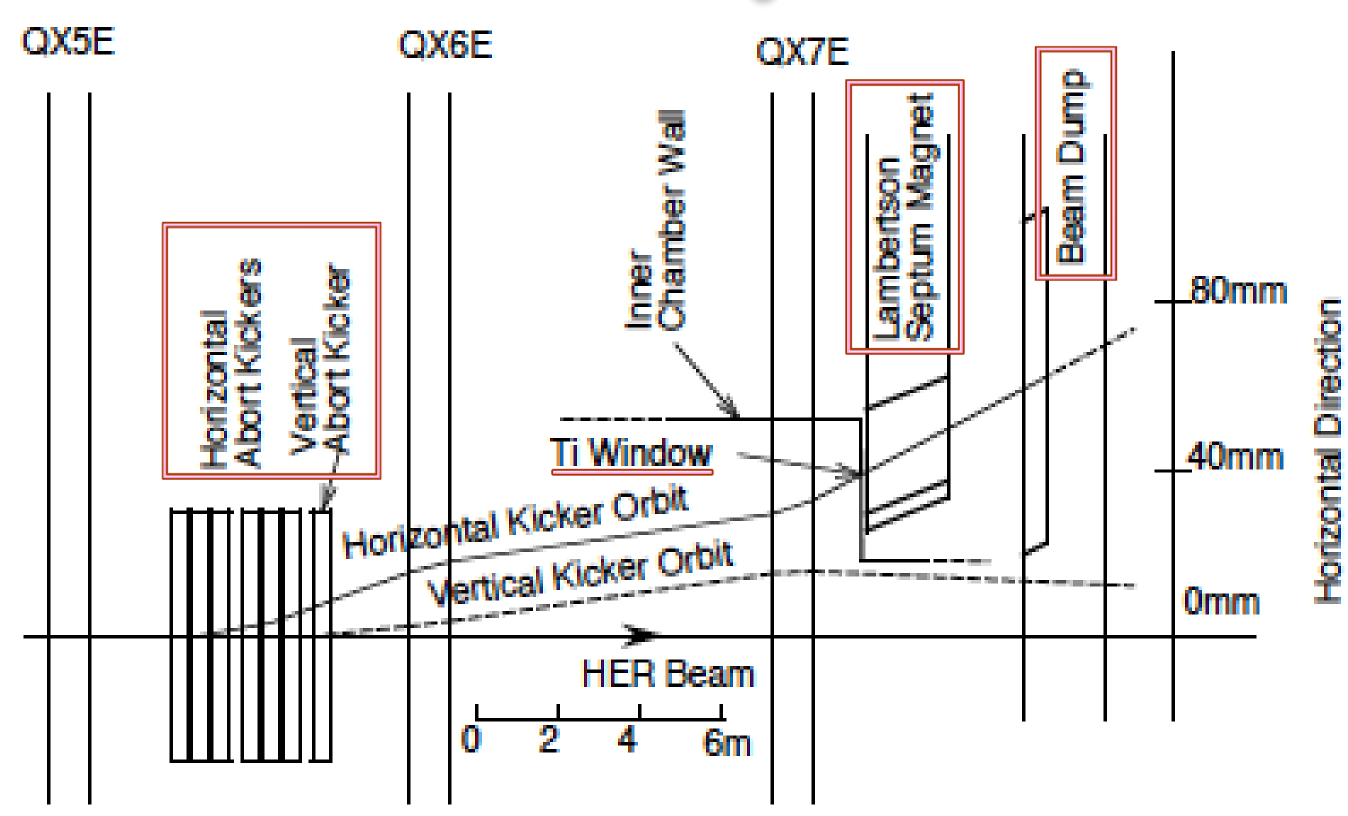


Fig. 16. Schematic layout of the abort system of HER.

K. Satoh

Abort fail-safe system

DCCT detects current

Weak bend shut down

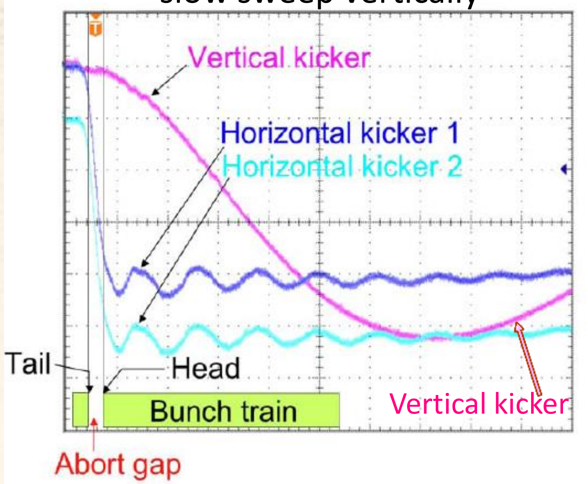
Beam scatters all around

- Horizontal abort kickers kick the stored beam out of vacuum chamber (Rise time～500ns)
  Beam is extracted through Ti window to the atmosphere before entering Lambertson magnet
- Vertical kicker sweeps beam vertically: energy deposit on Ti window is diffused
- The beam is bent downward by Lambertson and leads to Dump

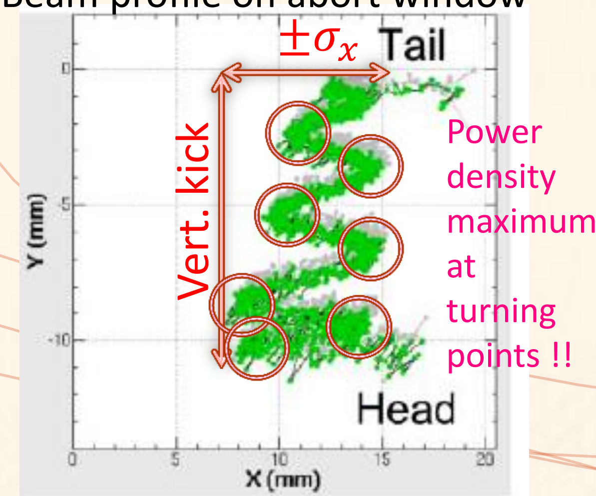
Abort system of SuperKEKB

KEKB

Horizontal kicker :
fast kick to abort window
Vertical kicker :
slow sweep vertically



Beam profile on abort window



SuperKEKB

- Low emittance beam has higher possibility of destroying abort window than KEKB beam
- Enlarging horizontal beam size required additionally

LER

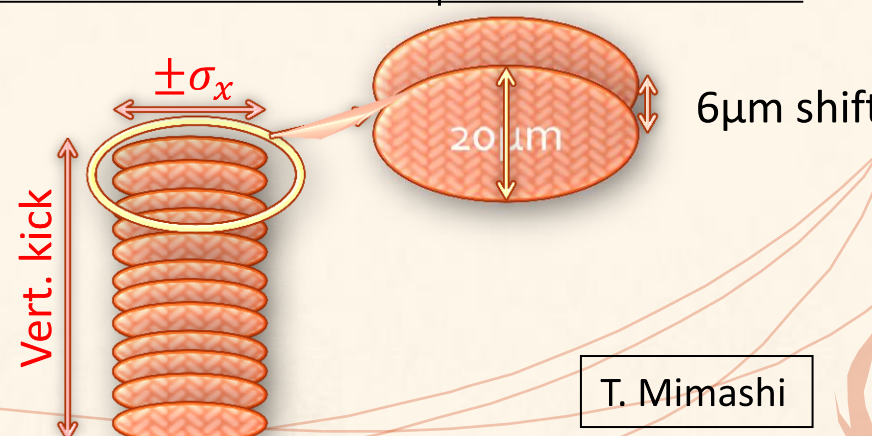
Horizontal kicker :
fast kick to the Abort window
Vertical kicker :
slow sweep vertically
PULSED quadrupole :
enlarge the horizontal beam size

HER

Horizontal kicker :
fast kick to the Abort window
Vertical kicker :
slow sweep vertically
DC sextupole :
enlarge the horizontal beam size

Abort fail-safe system like KEK is also designed

Schematic view of new beam profile on abort window

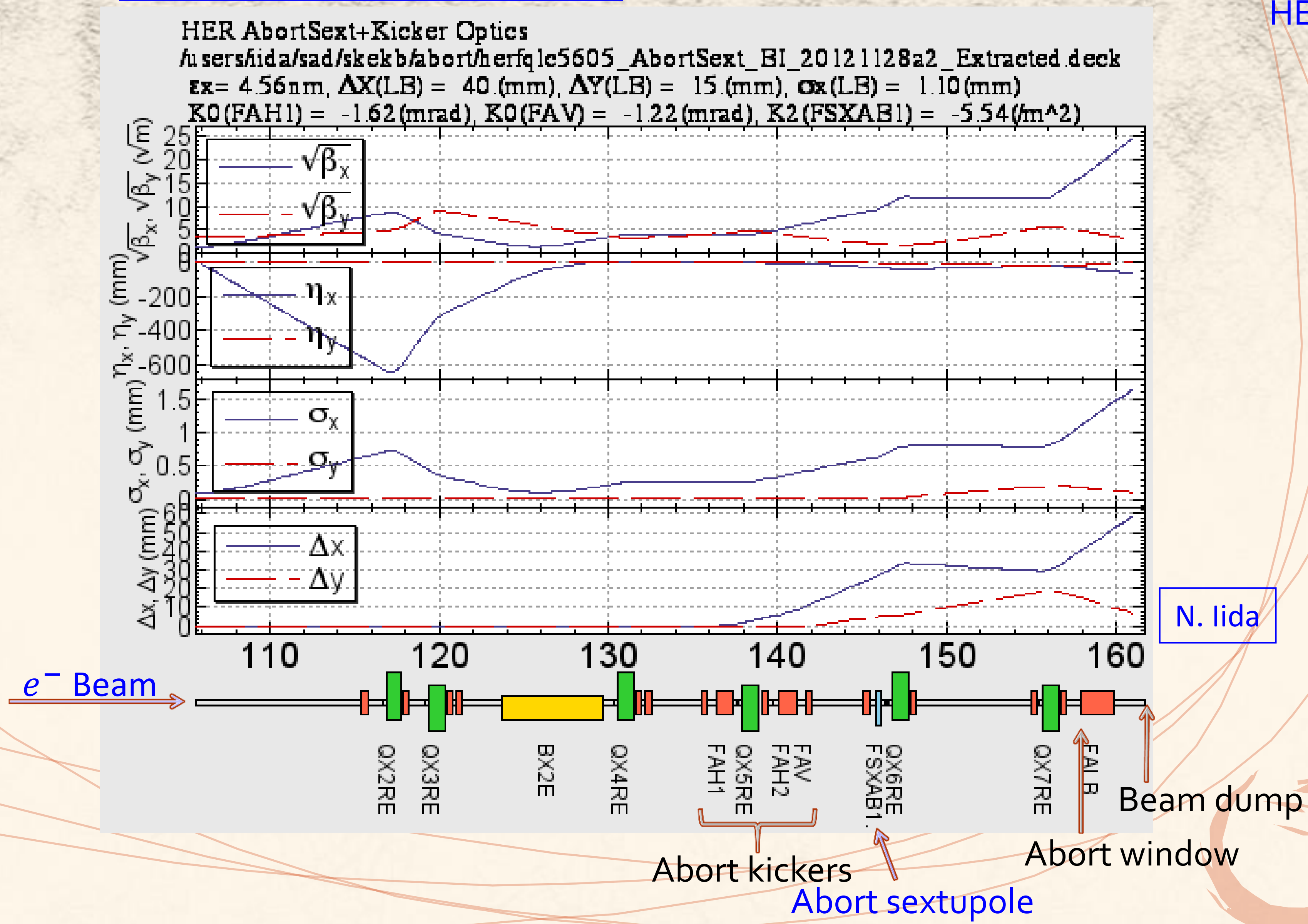


T. Mimashi

Abort Beam Optics with Betatron Injection

herfqlc5605_AbortSext_BI_20121128a2_Extracted.deck

HER



N. Iida

HER Optics for Betatron Injection

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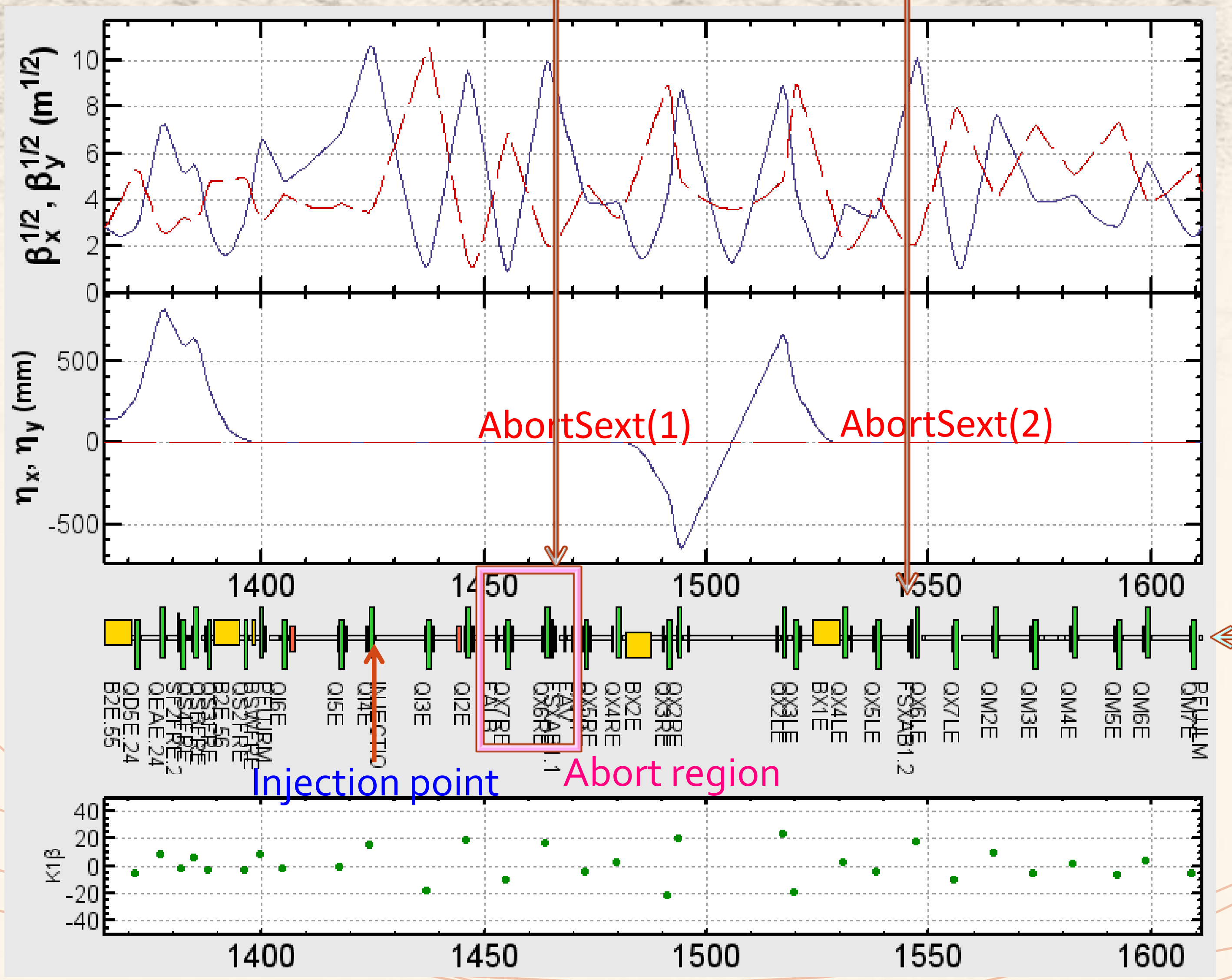


Matching :

$\beta x_1 = \beta x_2$

$\beta y_1 = \beta y_2$

$\nu_{x1} - \nu_{x2} = 1.5$

$\nu_{y1} - \nu_{y2} = 1.0$

1: AbortSext(1)

2: AbortSext(2)

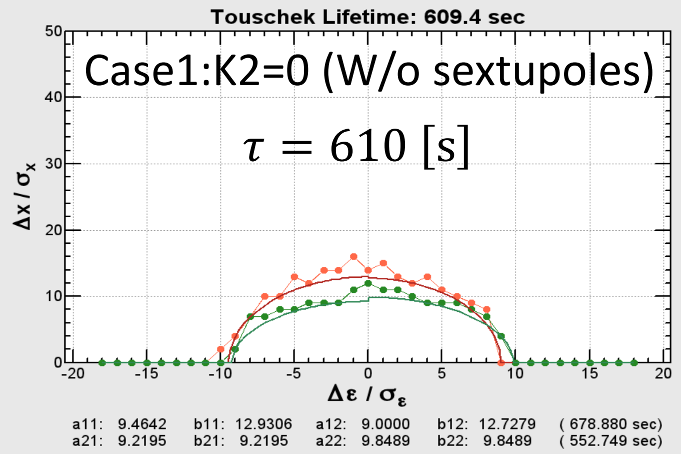
$\eta x = 0$ at the center of the sexts.

$\varepsilon x = 4.511$nm

$\varepsilon y = 11.28$pm

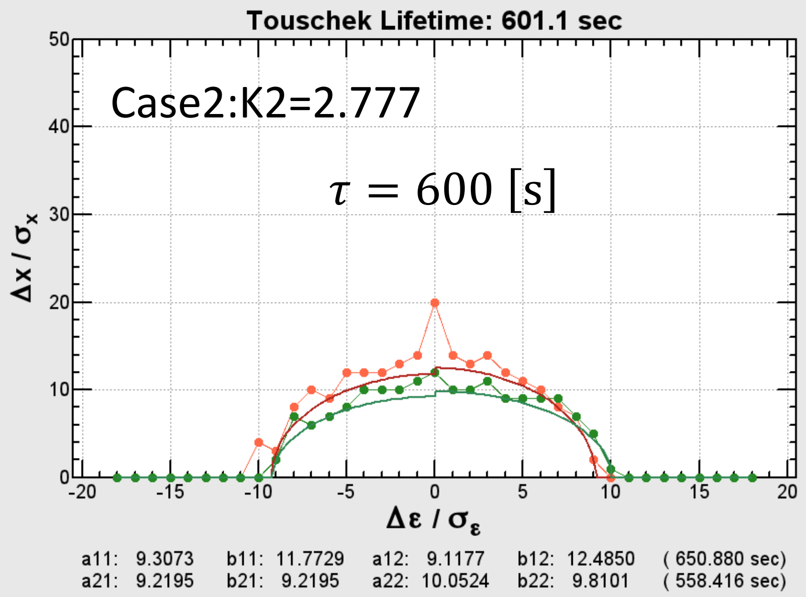
Emittance change is negligible.

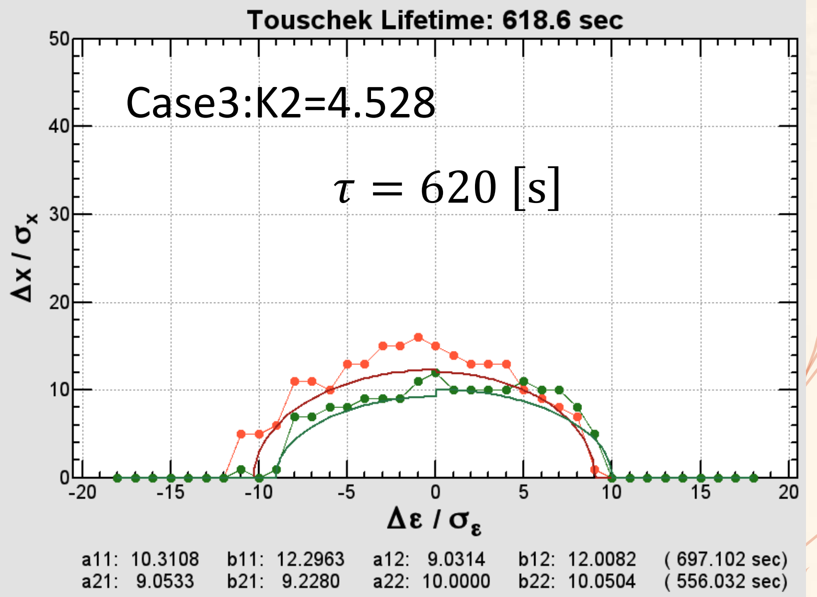
Dynamic aperture



Dynamic apertures & Touschek lifetimes are tested with insertion of a pair of sextupoles.

The life time is optimized for each sextupoles.
Case1: SEXT FSXAB1 =(L =.334 K2 =0) -> 610 sec Case2: SEXT FSXAB1 =(L =.334 K2 =2.777278350689298) -> 600 sec Case3: SEXT FSXAB1 =(L =.334 K2 =4.528207642946944) -> 620 sec





Y. Ohnishi

No performance drop found.

Abort Beam Optics for Synchrotron injection

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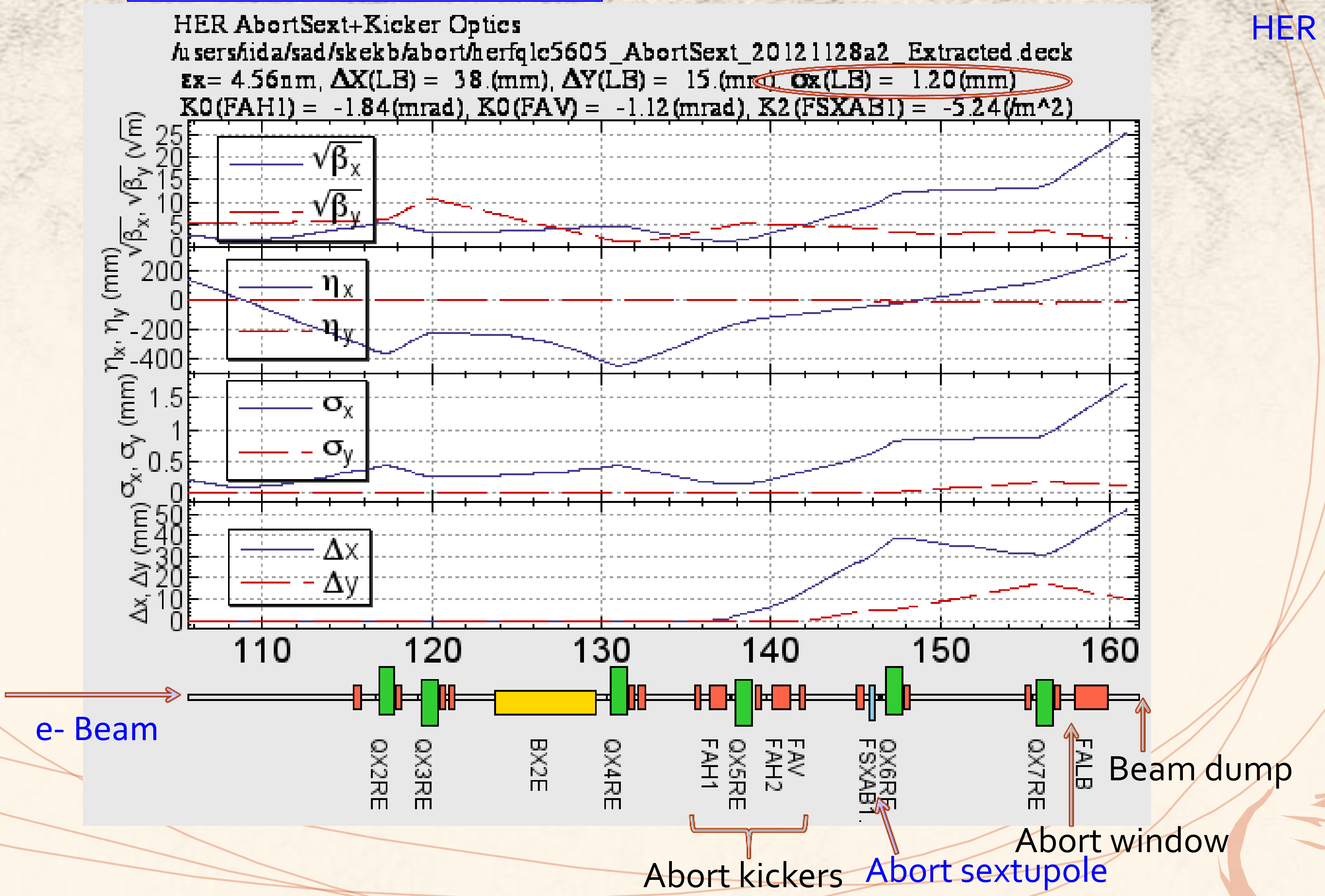

HER Optics for Synchrotron injection

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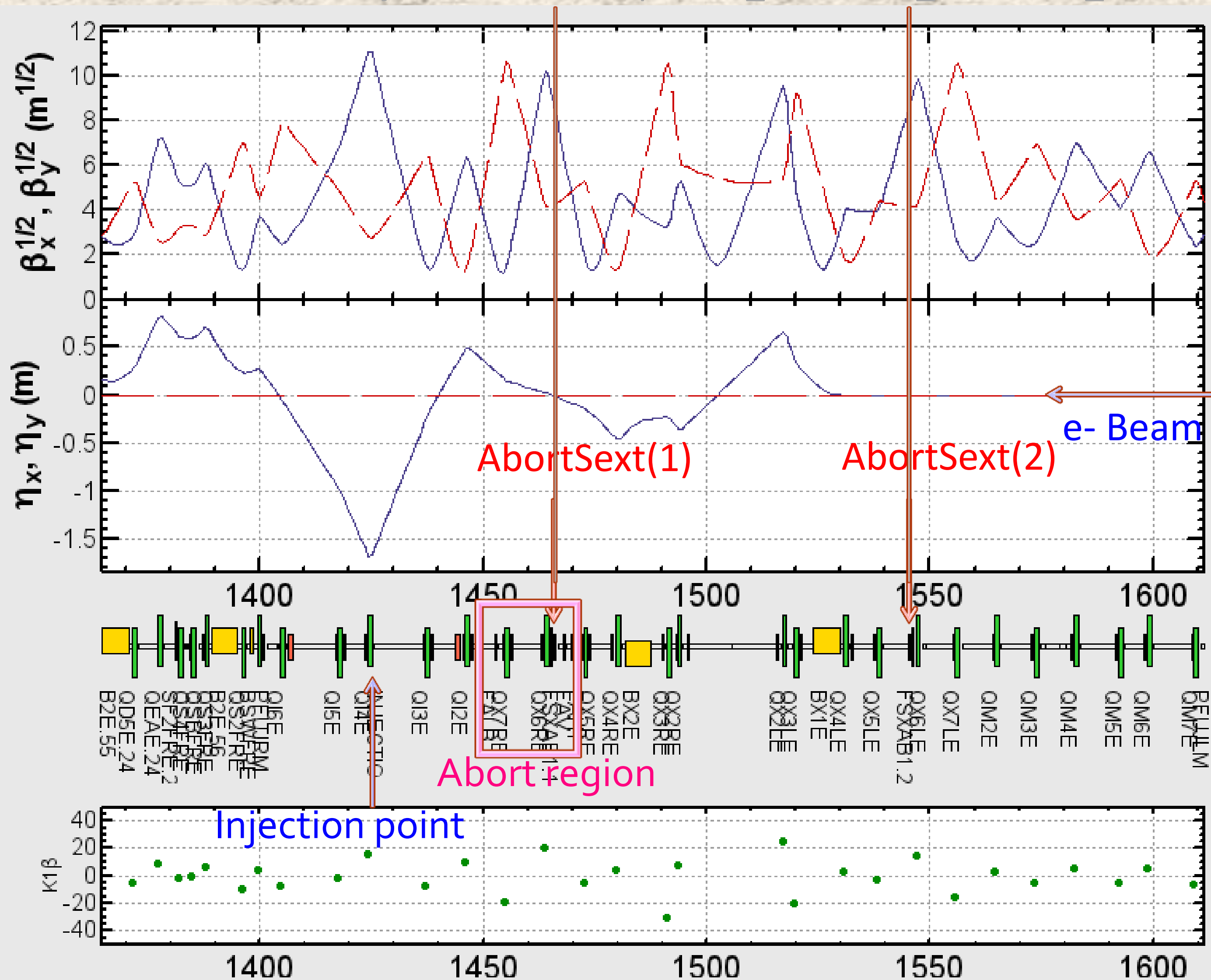

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2: AbortSext(2)

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$\varepsilon x = 4.646$nm

$\varepsilon y = 11.62$pm

Emittance changes are negligible.

Protection from Coherent Oscillation

- Avoiding abort beams hit outside of abort window
- Vertical
  - Acceptance determined by vertical mask
  - Coherent oscillation amplitudes:
    - LER: 4.7×10^{-8} m
    - HER: 3.8×10^{-8} m
  - Amplitudes small enough: no protection applied
- Horizontal
  - Max. displacement at abort window calculated
    - (orbit) $+3.5\sigma_x + \eta\delta$ (1%) + (coherent oscillation)
    - HER : 50mm
    - LER : 47.6mm
  - Coherent oscillation amplitudes
    - HER: 6.8 mm ($6\sigma_x$)
    - LER: 6.8 mm ($5\sigma_x$)
  - 5 or $6\sigma_x$ coherent oscillation amplitudes make interlock BPM trigger abort signal

Protection from Coherent Oscillation

- Abort beam may hit outside of abort window
- Vertical oscillation
  - Vertical acceptance determined by vertical mask
  - Vertical amplitudes:
    - LER: 4.7×10^{-8} m
    - HER: 3.8×10^{-8} m
  - Amplitudes small enough: no protection
- Horizontal oscillation
  - (orbit) $+3.5\sigma_x + \eta\delta$ (1%) + (coherent oscillation)
  - Max. amplitudes at abort window
    - HER : 50mm
      - Synchrotron入射：Coherent振動＝6.8mm＝5.7σx
      - Betatron入射：Coherent振動＝6.8mm＝6.2σx
    - LER : 47.6mm
      - Coherent振動＝6.5mm＝5.4σx
  - Coherent oscillation amplitudes
    - HER: 6.8 mm ($6\sigma_x$)
    - LER: 6.5 mm ($5\sigma_x$)
  - $5-6\sigma_x$ coherent oscillation amplitudes trigger abort signal

Power Supply

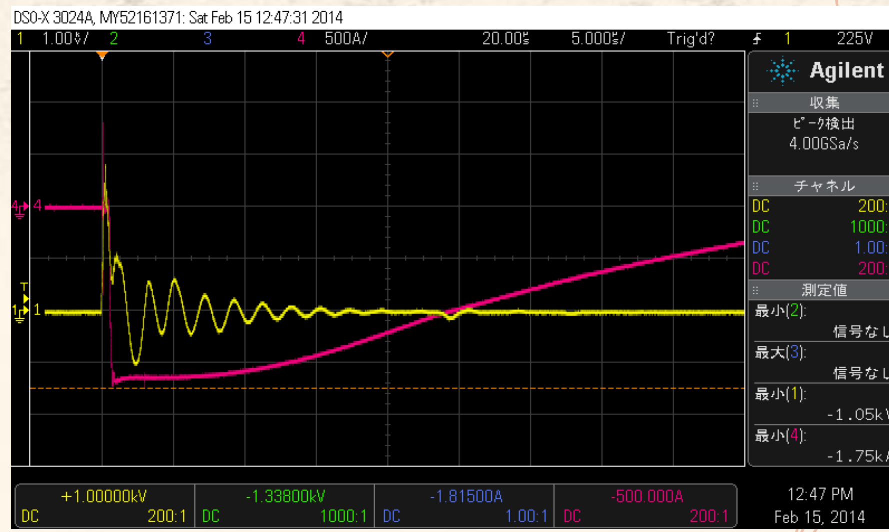
- Issues
  - Pulse compress circuit
    - We could get enough rise time (< 200nsec), but 10μsec flatness is not enough.
    - Add dummy inductance to the coil
      - Flatness is improved from 14.6% -> 8.8% (or better)

Power Supply 3

	LER	HER
Operation Current (Horizontal kicker)	1.4kA (4GeV) 1.46kA(4.16GeV)	1.26kA (7GeV) 1.55kA (8.6GeV)
Maximum current of Power supply	1.7kA	
Current drop	8.8%	
# of kicker magnets	Horizontal 1 Vertical 1 Pulsed quad 2	Horizontal 4 Vertical 1

Output Current of Power Supply

Inductance 4.5μH/165Ω+940pF
Voltage 39.3kV
(W/ additional inductance)



(500A/div,500ns/div)
Peak 1750Ap(103%)
Flat 1700A(100%)

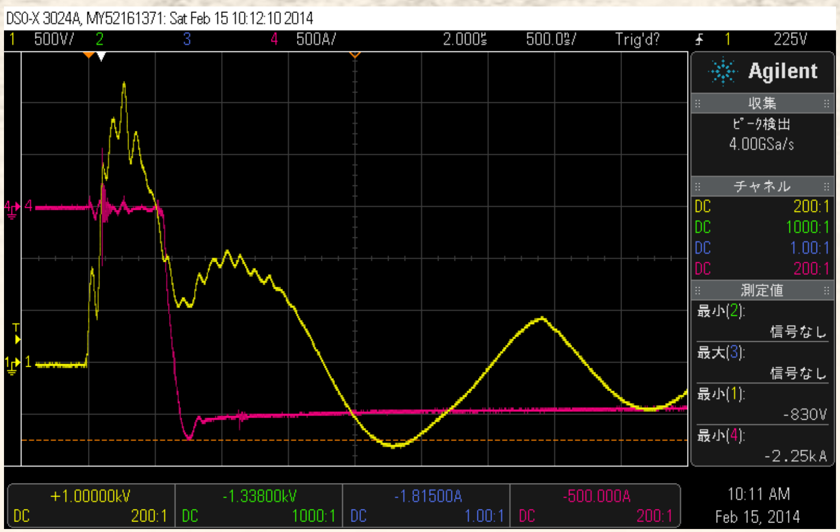
Rise time (2%-90%) 150ns
➔ Sufficient

Whole pulse

(500A/div,5μs/div)
10μs 8.8% Drop

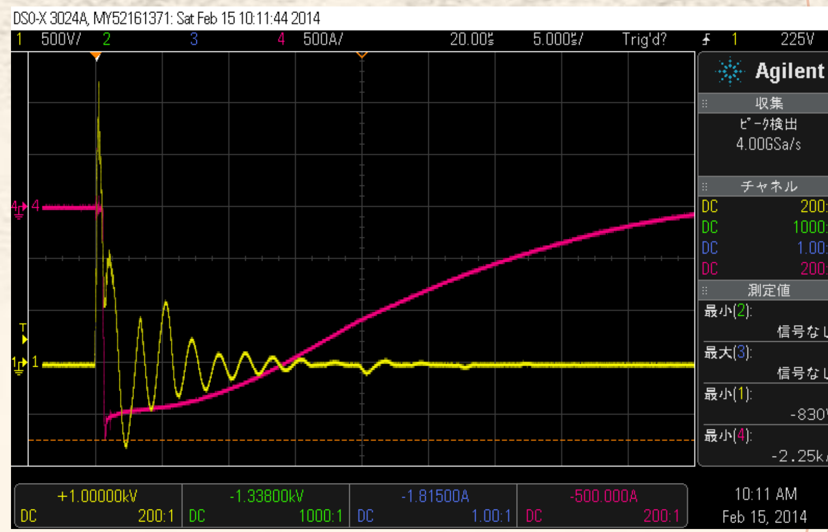
Output Current

Inductance 2.2μH//165Ω+940pF
Voltage 37.0kV



(500A/div,500ns/div)
Peak 2250Ap(110%)
Flat 2050A(100%)

Rise Time(2%-90%) 150ns



Whole Pulse

(500A/div,5μs/div)
10μs Drop 14.6%

DR INJECTION/EXTRACTION

Kickers for DR Injection/Extraction

- Power supply study on going
  - Both rising & falling times should be fast for other bunches

Machine Parameters

2013/July/29	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.18\text{x}10^{-4}$	$4.53\text{x}10^{-4}$		
σ_δ	$8.10(7.73)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	-0.0244	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.86	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.2/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	