ルミノシティ調整

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2017.9.8@SuperKEKB国内レビュー

Contents

- Phase 2 commissioning
- 衝突調整
  - Dithering system（水平方向の衝突調整用システム）の最近の進展と立ち上げ
  - 垂直方向の衝突調整
- ルミノシティ調整

SuperKEKB commissioning phases

Feb. 2016 ~ June 2016

Phase 1
w/o QCS and Belle II

vacuum scrubbing
basic machine tuning

No beam collision

Already done!

Feb. 2018 ~ July 2018

Phase 2
w/QCS and Belle II
w/o Vertex detector

BKG study
Luminosity tuning
Target luminosity:
$1\sim2 \times 10^{34}\ cm^{-2}\ s^{-1}$

~ autumn 2018

Phase 3
Physics Run

Luminosity tuning

Damping ring commissioning: ~ Dec. 2017

Tasks in Phase 2

- Basic tuning
  - Beam injection of the beam from DR, vacuum scrubbing…
- Performance check of QCS magnets
- Squeezing IP beta functions at IP
  - Optics corrections
- Beam collision tuning with “Nano beam scheme”
- Belle II beam BG study and tuning
- Other studies: electron clouds, other instabilities…
- Luminosity tuning
- Physics Run

衝突調整

- 衝突状態のサーチ
- ビーム衝突フィードバック（軌道フィードバック）システムの立ち上げ
- ビームアボート後の衝突の確立の手法

ビーム衝突のサーチ

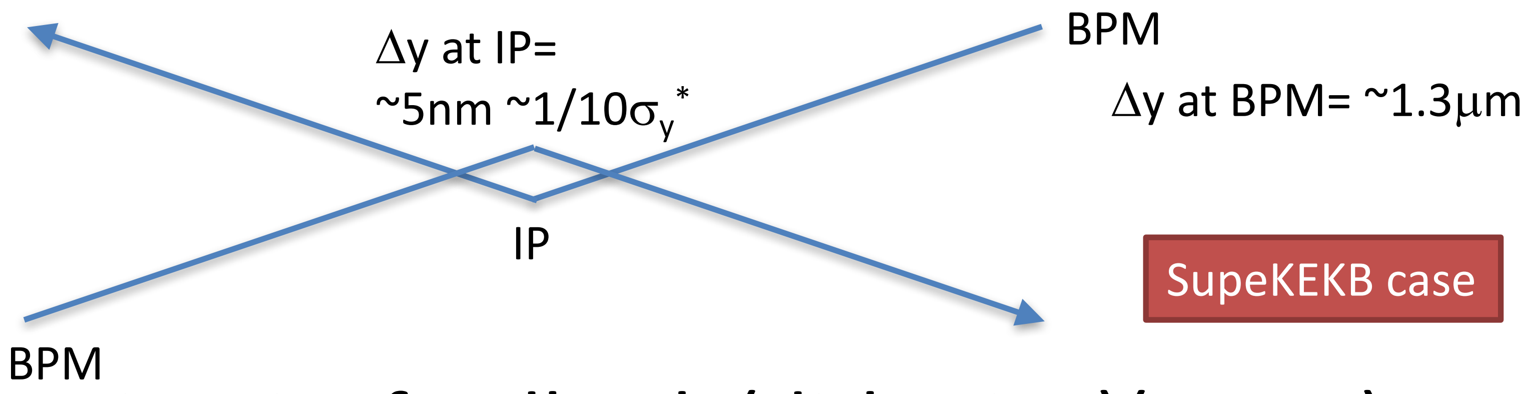
- Closed orbit correction of each beam
- Bunch timing adjustment
  - Rough adjustment: search for collision bucket
    - BPM measurement, luminosity monitor?
  - Fine adjustment: RF phase scan
    - Observer horizontal beam-beam deflection
- Orbit adjustment
  - Scan orbits
    - beam-beam deflections
    - Luminosity
    - beam lifetime

軌道フィードバックシステム

- アルゴリズム
  - Vertical
    - Beam-beam deflection (like KEKB)
    - Based on COD measurements using BPMs
  - Horizontal
    - Dithering system (like PEP-II)

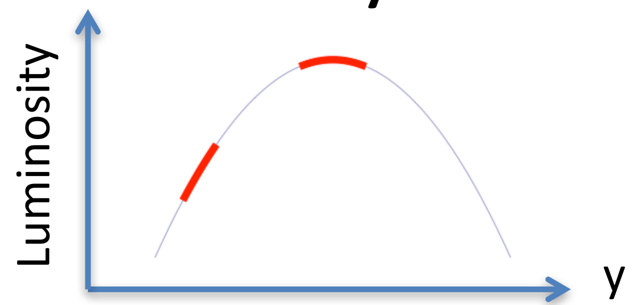
Orbit feedback at IP :Algorism

- Beam-beam deflection (SLC, KEKB vertical)



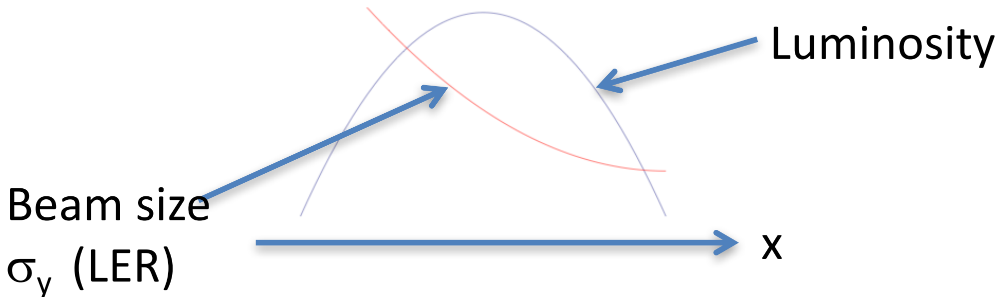
SupeKEKB case

- Luminosity feedback (dithering)(PEP-II)



When we shake the beam at around the peak of the luminosity (dithering), the dithering frequency in the luminosity is minimized and there appears twice of the the dithering frequency.

- Beam size feedback (KEKB horizontal)



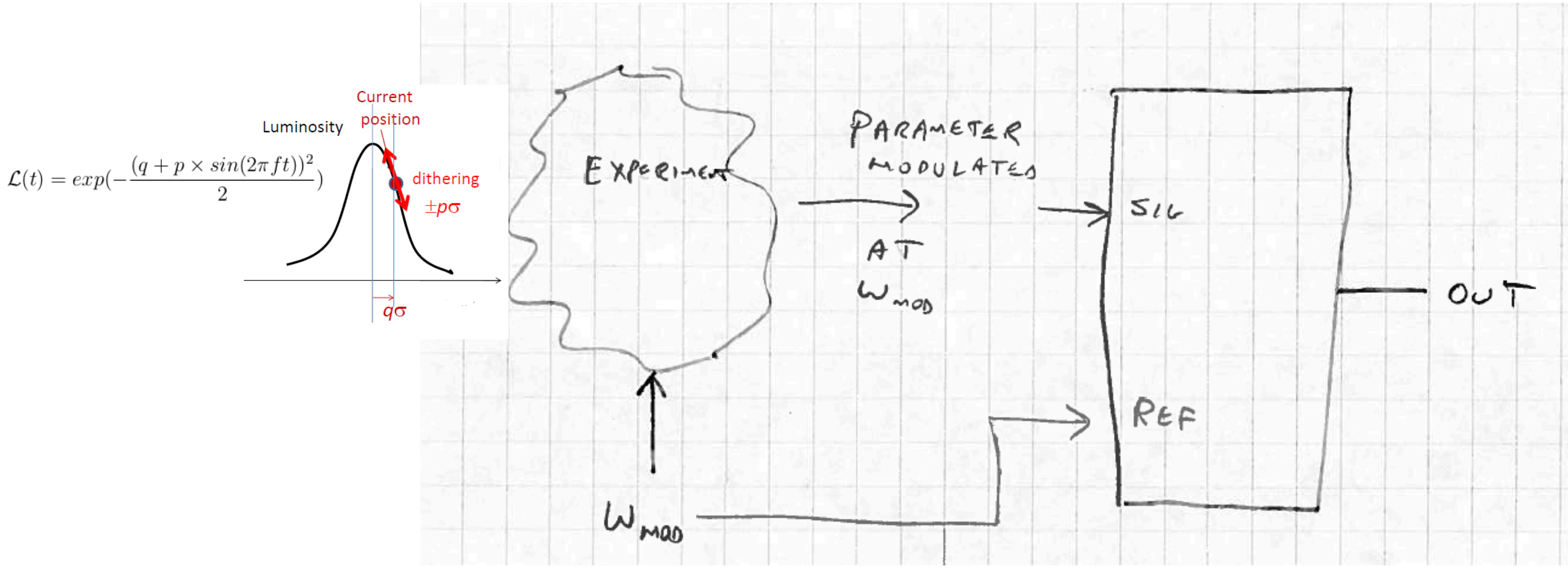
At KEKB before installation of crab cavities, the vertical beam of LER was used for the horizontal orbit feedback at IP.

Horizontal orbit feedback

- Difficulty to develop based on the beam-beam defection like the vertical case
  - Small ξx
    - ξx ~ 0.0028(e+), 0.0017(e-)
  - Two sources of horizontal beam-beam kick
    - Horizontal offset and shift of collision timing
- We need a different method for the Hor. feedback.
  - Luminosity feedback (dithering) (like PEP-II)
  - Beam size feedback (like KEKB Hor. feedback before crab)
- Effect of horizontal offset
  - Due to Hor. offset, the two beams collide at the position which is shifted from the waist point.
  - The crab waist seems to compensate this shift of waist.
  - However, actually the situation becomes worse with the crab waist, since we have to keep the both beams at the design collision point with this scheme.
- Feedback speed
  - Fast vibration of IR quads is tolerable. We do not need very fast feedback (slower than ~ 1 Hz).

Synchronous Modulation

- Modulate your desired signal at a known frequency ω_{mod}
  - could be - chopping optical signals
  - directly modulating electronic signals
  - mechanically modulating signals (rocking antenna)
  - modulation - is multiplication by known modulating signal
  - Purpose - move signal of interest to a known frequency with specific phase relationship

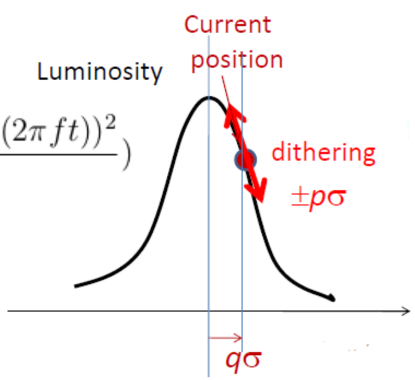


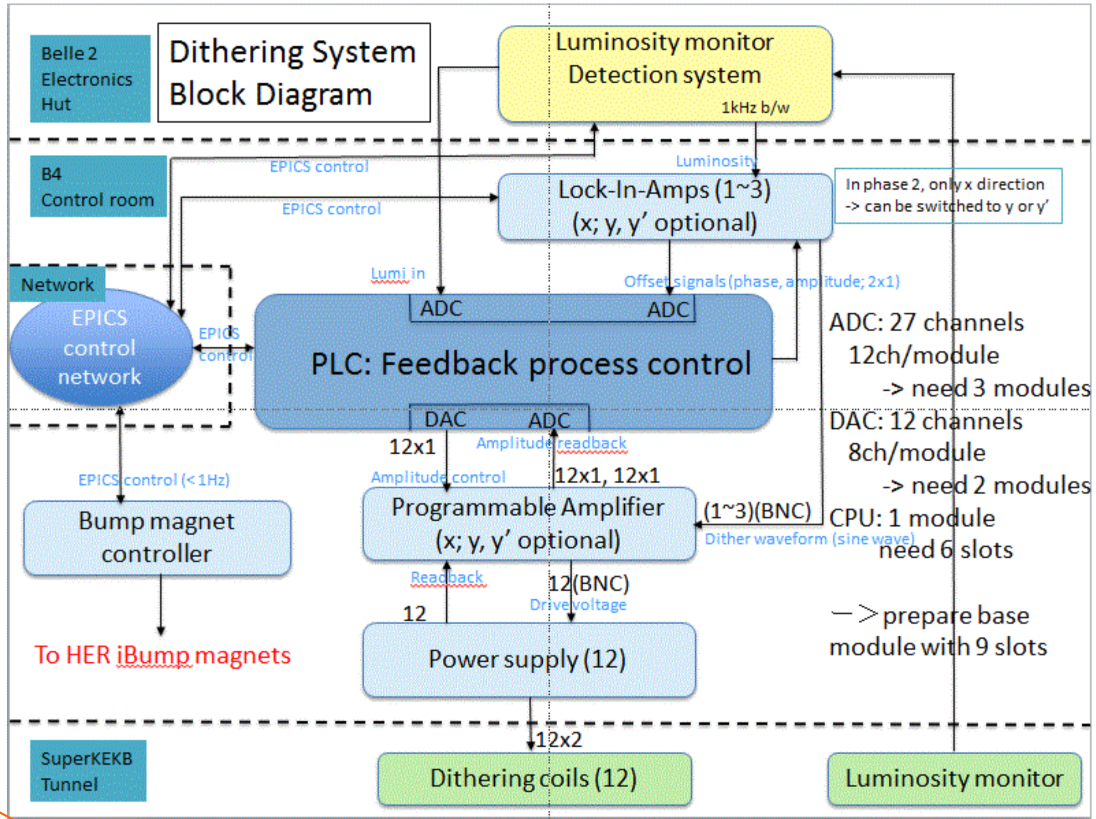
Fast luminosity monitoring - Plan for 2018 (and beyond...) (1)

01/2018-06/2018: tests during phase II of SuperKEKB commissioning

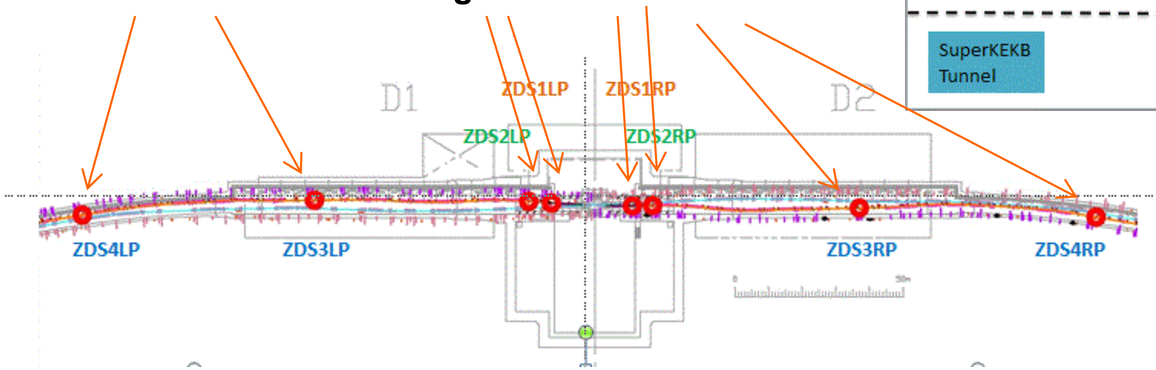
- Bhabha acquisition and first luminosity measurement tests
- Single beam background characterization
- Luminosity DAQ output provided to the SuperKEKB monitoring system and **dithering system tests**:

$$\mathcal{L}(t) = exp(-\frac{(q + p \times sin(2\pi f t))^2}{2})$$

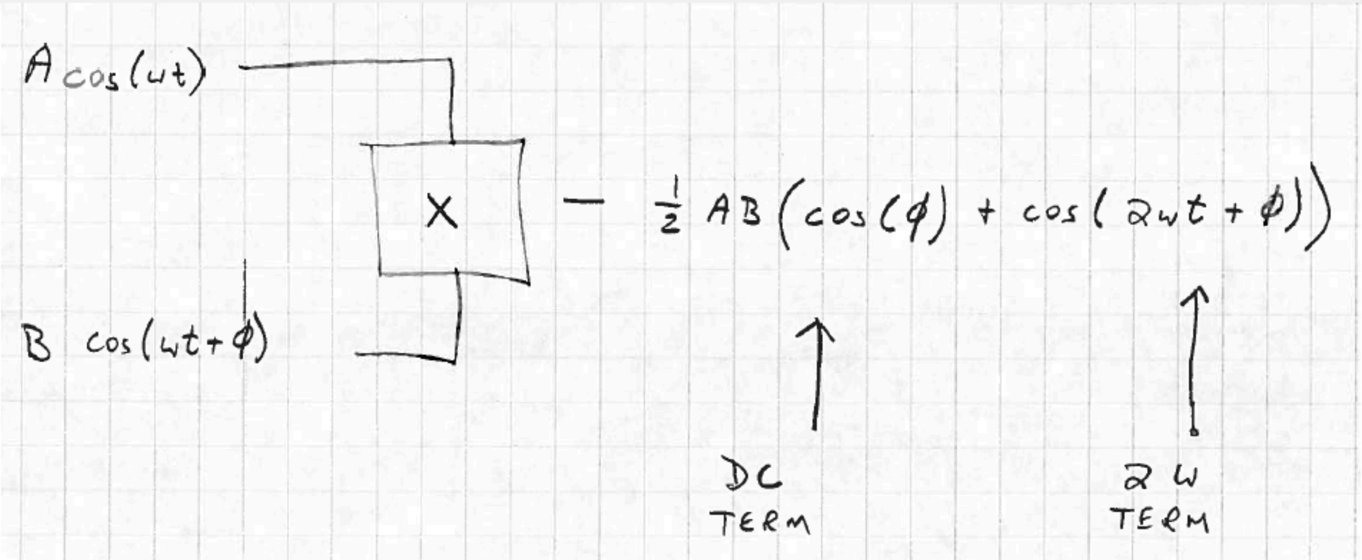




8 locations for the dithering coils in LER around IP.



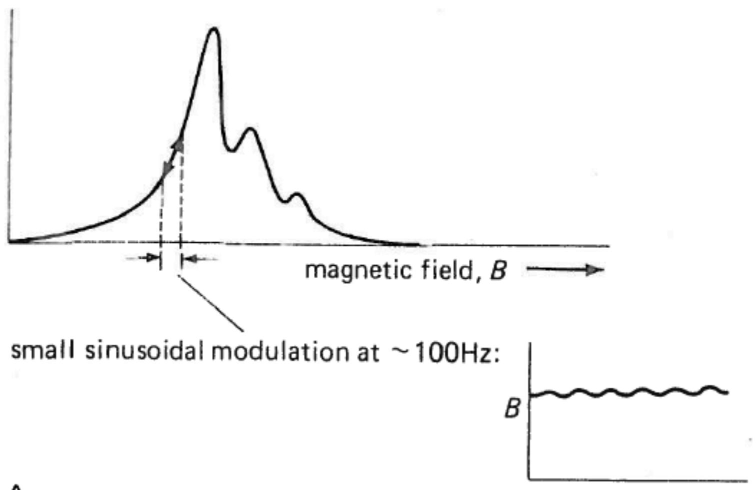
Multiplier as a Phase Detector



- Output contains sum and difference terms
  - filter output with low pass filter
  - only difference term (DC term) remains
  - $V_{output} = (AB)/2 \cos\phi$
  - if amplitude AB constant, output is phase detected
  - if phase constant, output is amplitude detected
- Suppose B is a square wave ω_{mod}
  - Output contains harmonics at $(2n+1)\omega_{mod}$ frequencies
  - DC term as before (plus $2/\pi$ normalization)

Using Synchronous Demodulation for a feedback signal

- Modulation (dithering) of signal of interest with reference function
- Recover signal via amplification, demodulation, bandwidth reduction
- Use derivative of signal as feedback error discriminant



A

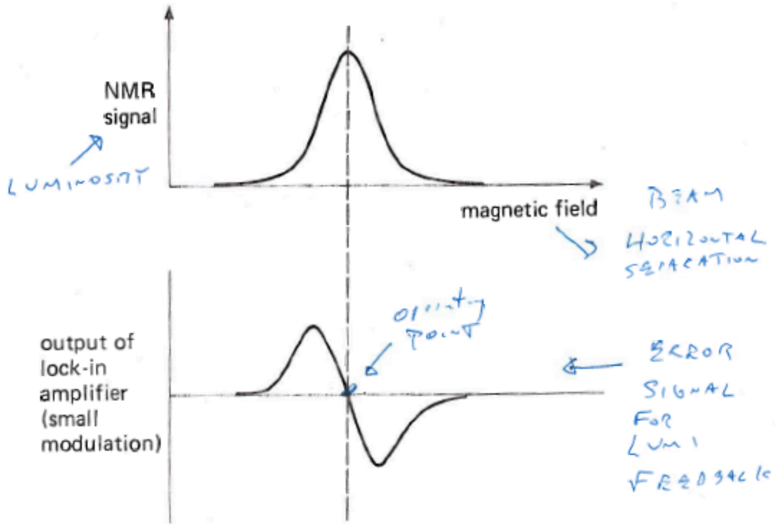
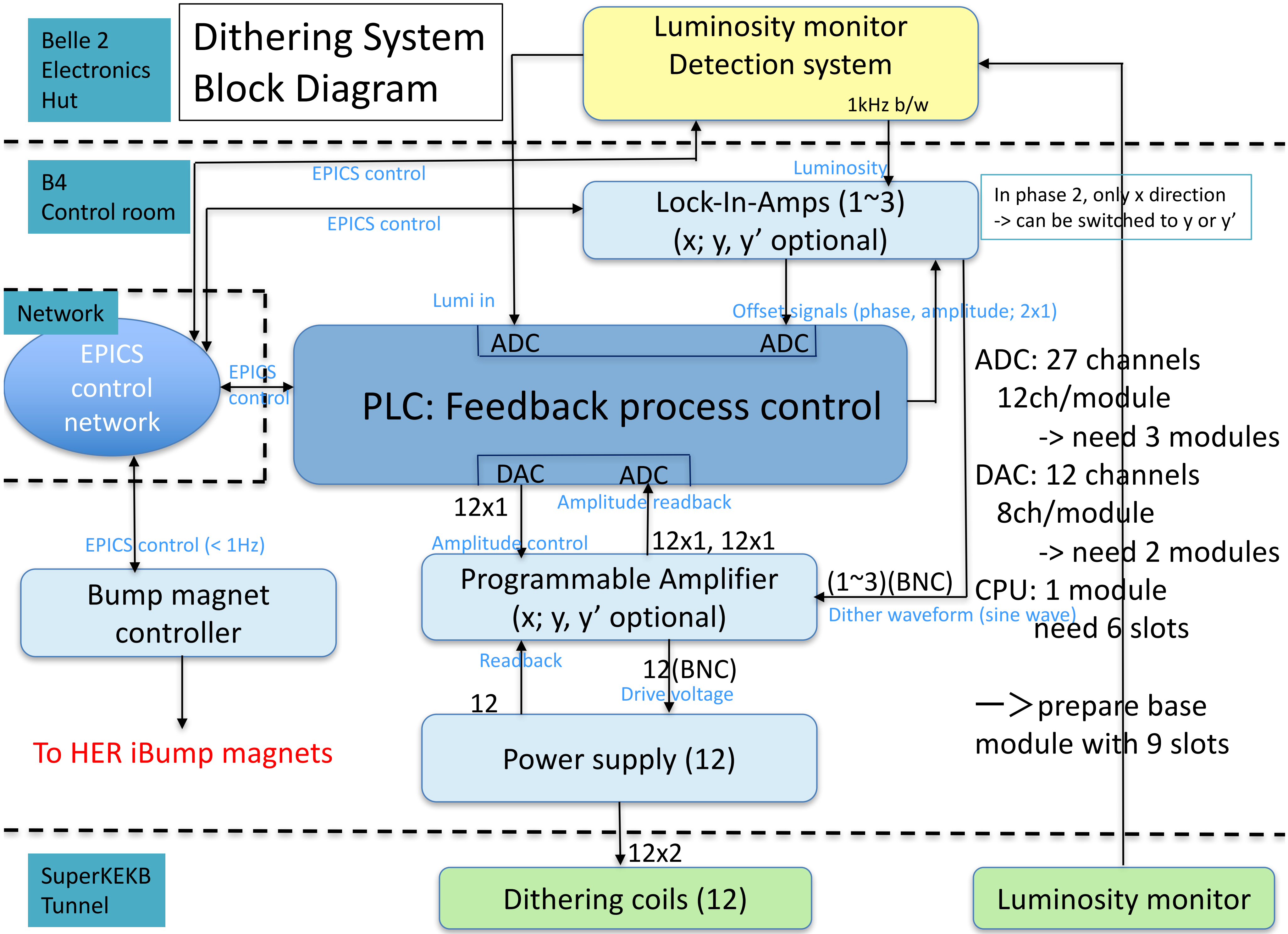


Figure 15.40. Line shape differentiation resulting from lock-in detection.

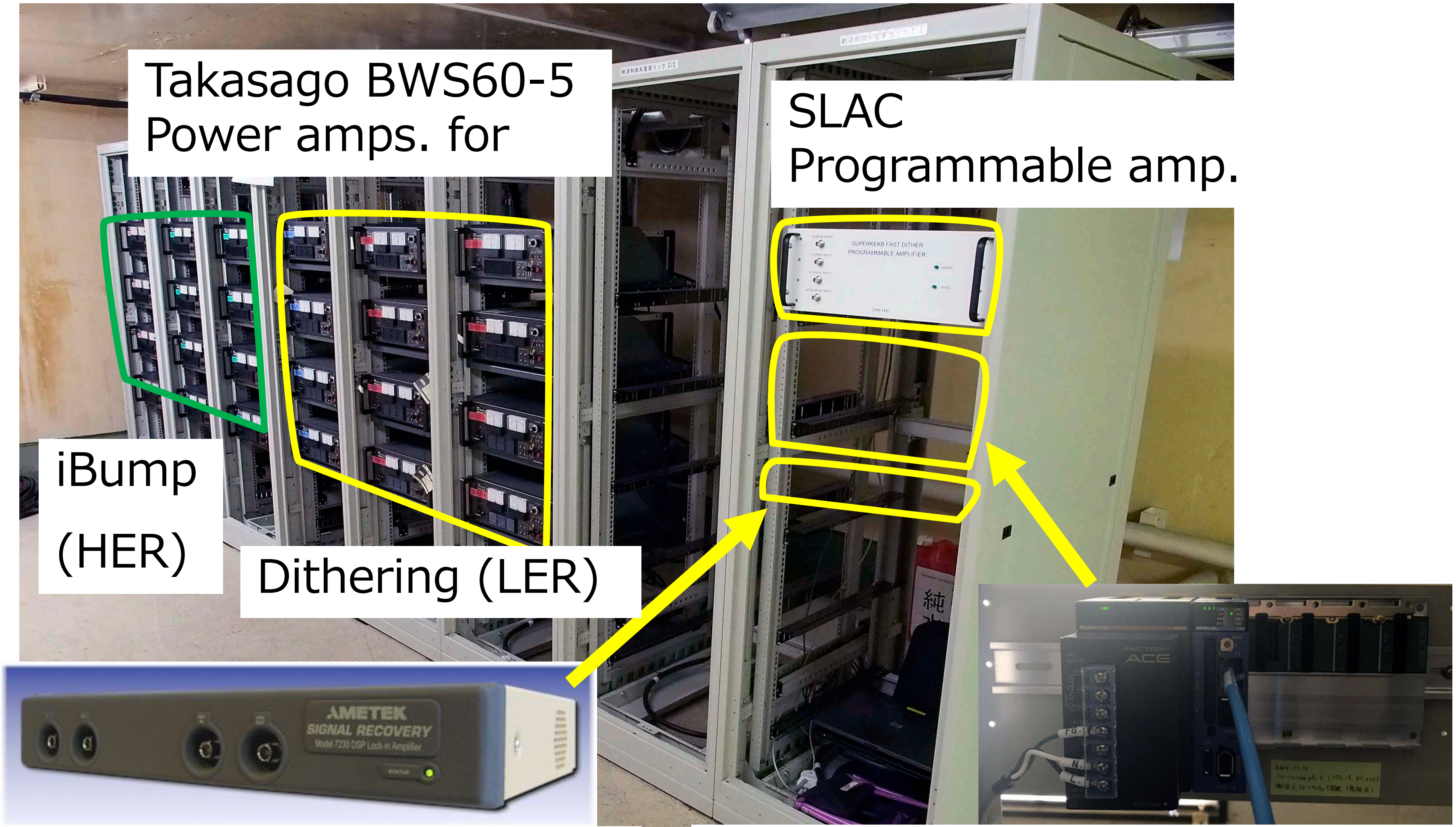

Belle 2 Electronics Hut
Dithering System Block Diagram
Luminosity monitor Detection system
1kHz b/w
B4 Control room
EPICS control
Luminosity
EPICS control
Lock-In-Amps (1~3) (x; y, y' optional)
In phase 2, only x direction -> can be switched to y or y'
Network
EPICS control network
Lumi in
Offset signals (phase, amplitude; 2x1)
ADC
ADC
EPICS control
PLC: Feedback process control
ADC: 27 channels 12ch/module -> need 3 modules
DAC: 12 channels 8ch/module -> need 2 modules
CPU: 1 module
need 6 slots
—> prepare base module with 9 slots
DAC
ADC
12x1
Amplitude readback
12x1, 12x1
EPICS control (< 1Hz)
Amplitude control
Bump magnet controller
Programmable Amplifier (x; y, y' optional)
(1~3)(BNC)
Dither waveform (sine wave)
Readback
12(BNC)
Drive voltage
12
To HER iBump magnets
Power supply (12)
12x2
SuperKEKB Tunnel
Dithering coils (12)
Luminosity monitor

Orbit Feedback collaborators

- Horizontal orbit feedback system
  - Organizer
    - M. Masuzawa, Y. Funakoshi
  - Dithering coils, programmable amp (designed and fabricated at SLAC)
    - U. Wienands, A. Fisher and others (SLAC)
  - Fast luminosity monitor
    - S. Uehara (Belle-II group)
    - P. Bambade, C. Rimbault, D. EL Khechen, D. Jehanno, S. D. Carlo, C. Pang (LAL Group)
  - Other hardware preparation (Lock-in Amp, Power supplies, PLC, DAC,cabling…)
    - T. Oki, S. Nakamura, T. Kawamoto (Magnet Group) + Control group
  - Software, Simulations
    - U. Wienands, T. Oki, T. Kawamoto, Y. Funakoshi + Control group
- Vertical orbit feedback system
  - H. Fukuma and beam monitor group
    - BPMs, feedback circuits….
  - N. Ohuchi, H. Yamaoka (QCS group)
    - QCS supports and vibration measurement, Simulation on QCS vibrations

Dithering system components (TB4 control room, old)

- ✓ Components for the dithering system has been installed.



Signal Recovery Model 7230
DSP Lock-in amp.

Yokogawa FA-M3
Programmable logic controller

Tsukuba B4 control room (new)

PLC, DAC, ADC

Lock-in Amp

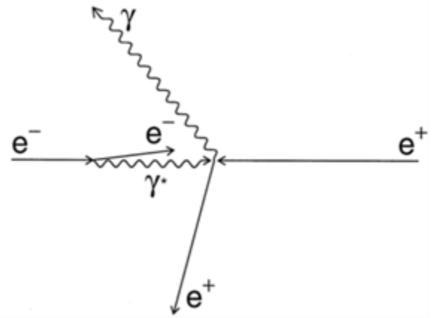
Programmable Amp

Fast Luminosity Monitoring at LAL ↔ KEK

C. Rimbault

- **Goal: Realization of a fast luminosity monitor based on radiative Bhabha scattering measurements for SuperKEKB luminosity feedback, tuning and backgrounds studies (BEAST).**
  - **Aimed precision for Train Integrated Luminosity (TIL):** $\delta L/L \sim 10^{-2}$ **to** 10^{-3} **in 1 to 10ms**
  - **Fast signal from each bunch crossing for Bunch Integrated Luminosity (BIL),**

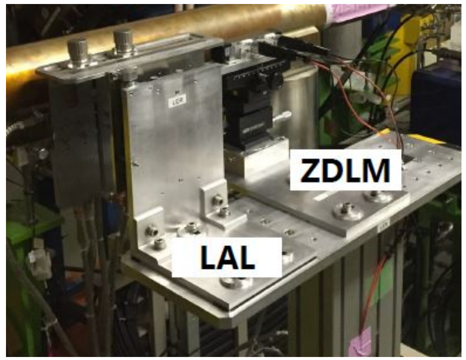
    2500 bunches/train, collisions every 4 ns



- **Measure the radiative Bhabha process at vanishing photon scattering angle**
  - **Rate proportional to Luminosity**
  - **Large cross section ~ 0.2 barn**

- **Two complementary techniques developed at LAL and KEK:**
  - ➢ **~ 5x5x0.5 mm³ single crystal CVD diamond sensors (CVD DS) pairs coupled to fast charge / current amplifiers (LAL)**
  - ➢ **Cerenkov detector + scintillator (ZDLM group @ KEK)**

  positioned together outside of the beam pipe

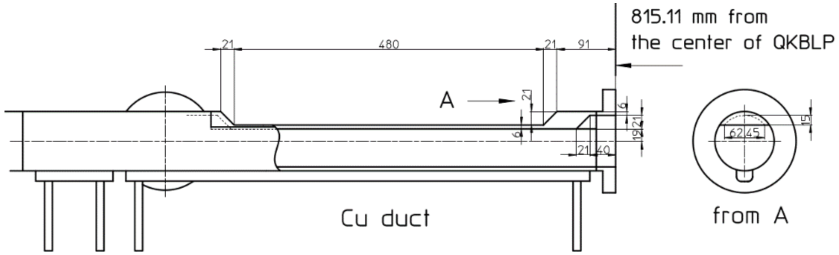


- **Two optimized locations fixed in 2014 and 2015:**

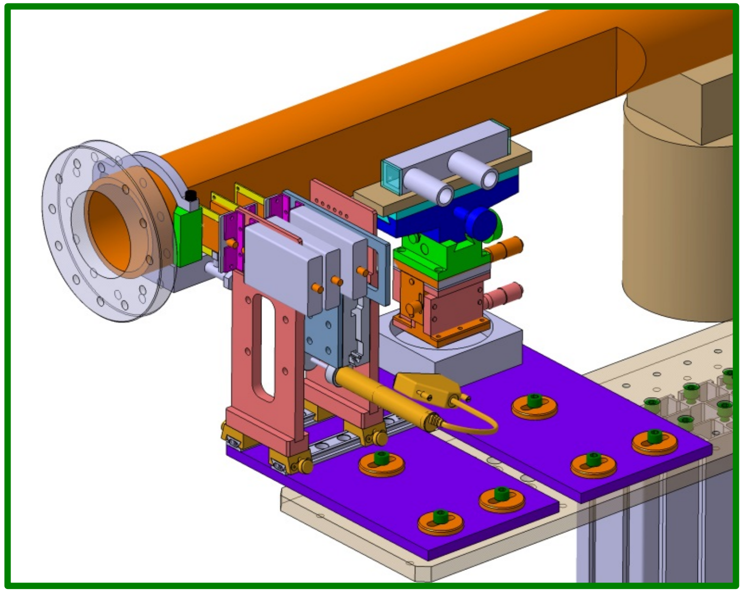
- In High Energy Electron Ring : 30m downstream the Interaction Point for Bhabha photon detection

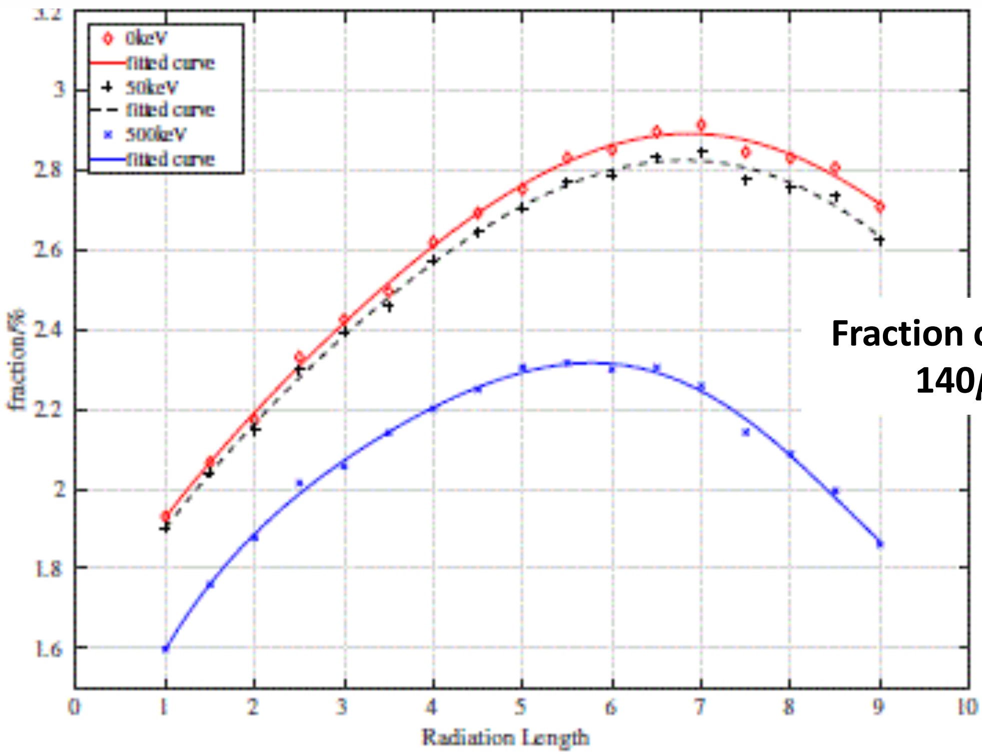
- In Low Energy Positron Ring : 11.9m from IP for Bhabha scattered positron detection

July 2016 → December 2017 : Prepare phase 2 commissioning (1)



- **Development of FPGA based DAQ for the phase II :**
  - **➔Luminosity firmware development:**
    signal pulse reconstruction algorithm: A1-A4
  - **➔test on Train Integrated Lumi (TIL) & Bunch**
    Integrated Lumi (BIL) reconstruction: almost validated
- **Installation of a window in LER (confirmed for spring 2017)**
  - **➔ Adaptation of existing pillar for phase 2**
  - **➔ radiator design study: trapezoid shape Tungsten radiator with thickness of 6*RL will be used.**



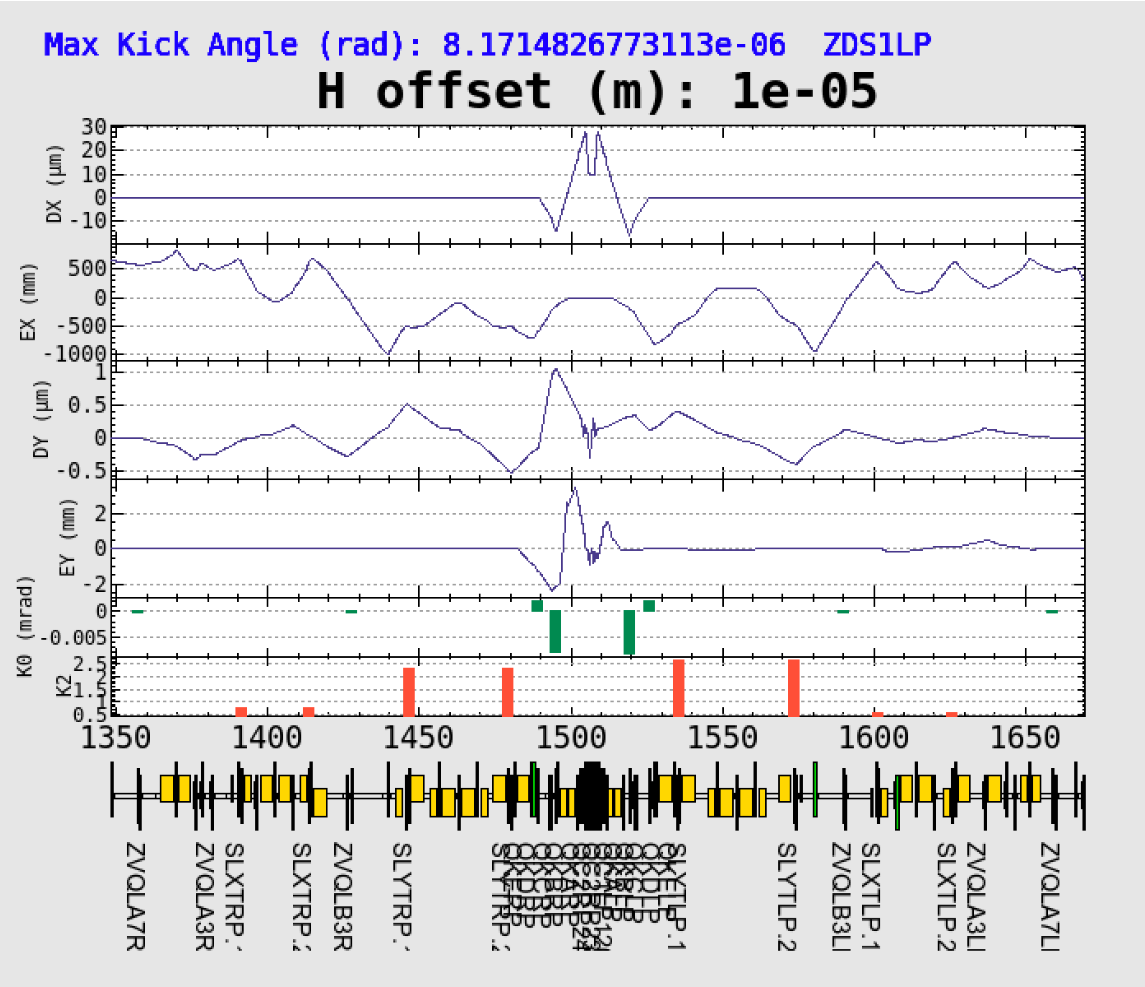


Fraction of detected Bhabha which can be achieved in 140μm DS with different thickness radiator

Recent progress in preparation of the dithering system

- Hardware
  - Network connection in TB4 control room: done
  - Cabling among devices: almost done
  - Installation and setup of PLC in TB4 control room: done
  - Fast luminosity monitor: to be ready by the start of Phase 2
- Software
  - Soft IOC on PLC: setup done
  - EPICS records for Lock-in-am, DAC, ADC: prepared
  - Feedback control software written in Maple (U. Wienands)
    - Transferring to SAD script is going on. Simulation will be done on SAD.
    - In the actual operation, it will work in soft IOC on PLC in the present plan.
- System tests in TB4 control room
  - System test of Lock-in Amp was done.
  - System test of programmable amp was done.
    - U. Wienands stayed at KEK for a week for the test at the end of August.

iBump LER (Phase 3)



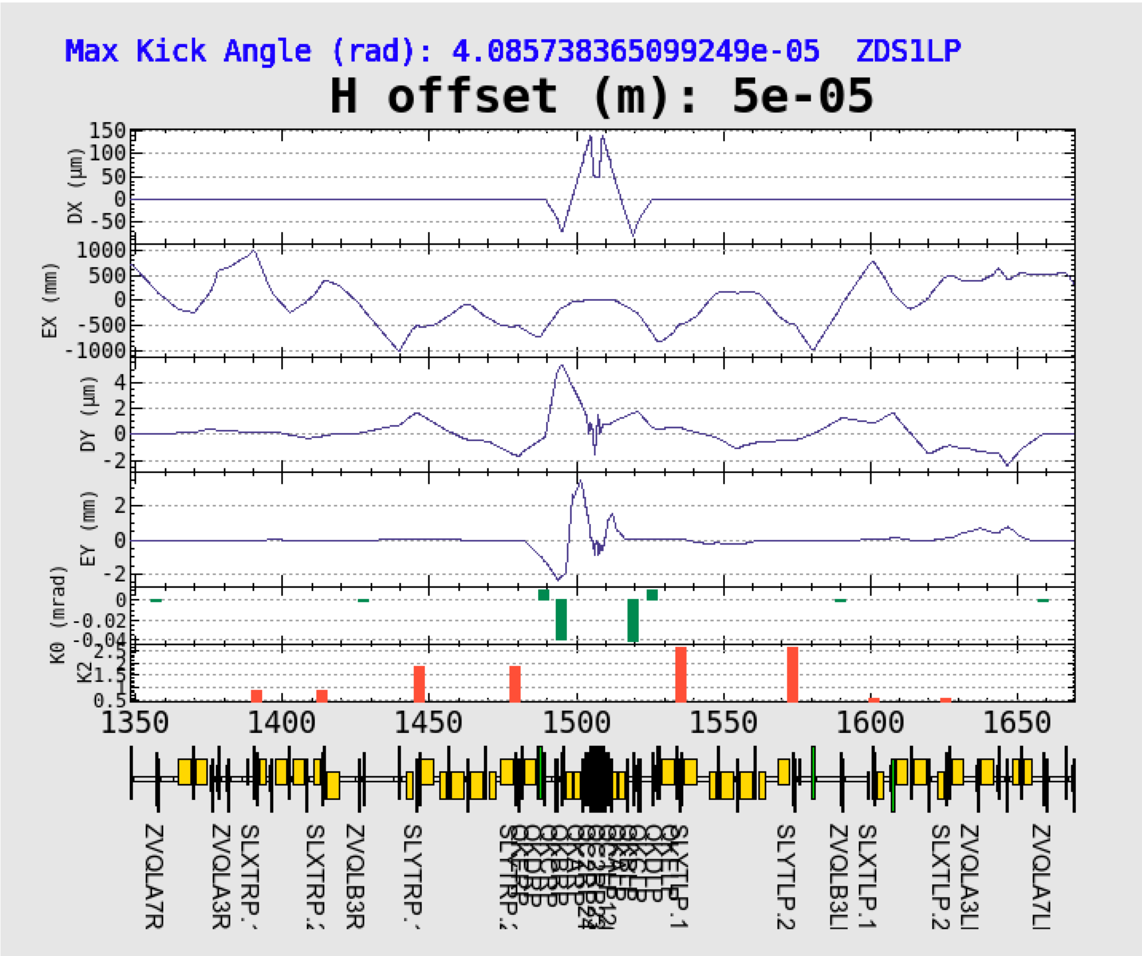
!Variable	Keyword	Now	!
ZDS4RP	SK0	-1.05481473E-8	!
ZDS3RP	SK0	-1.80964401E-8	!
ZDS2RP	SK0	2.322769393E-7	!
ZDS2RP	K0	1.998205872E-6	!
ZDS1RP	SK0	-1.81953828E-7	!
ZDS1RP	K0	-7.96463233E-6	!
ZDS1LP	SK0	-1.45438367E-9	!
ZDS1LP	K0	-8.17148268E-6	!
ZDS2LP	SK0	6.673170924E-8	!
ZDS2LP	K0	2.008672094E-6	!
ZDS3LP	SK0	1.690789732E-9	!
ZDS4LP	SK0	3.600758858E-9	!

Bump Height: 10 μm

Bumpがない時 : 8.18E-13 m

Emittance X	= 1.90736E-9 m	Emittance Y	= 8.2379E-13 m
Emittance Z	= 3.53502E-6 m	Energy spread	= 7.51396E-4
Bunch Length	= 4.70496494 mm	Beam tilt	= -.00159327 rad
Beam size xi	= .16905538 mm	Beam size eta	= .03019979 mm

iBump LER (Phase 2 4x8)



!Variable	Keyword	Now
ZDS4RP	SK0	1.500702337E-8
ZDS3RP	SK0	5.583882830E-8
ZDS2RP	SK0	1.059905106E-6
ZDS2RP	K0	9.989463062E-6
ZDS1RP	SK0	-7.84669988E-7
ZDS1RP	K0	-3.98219947E-5
ZDS1LP	SK0	-2.43806864E-8
ZDS1LP	K0	-4.08573837E-5
ZDS2LP	SK0	2.132436803E-7
ZDS2LP	K0	1.004362402E-5
ZDS3LP	SK0	1.018543756E-7
ZDS4LP	SK0	-1.45019037E-7

Horizontal kick < 44.4μrad

Bumpがない時：1.96E-13 m

Emittance X	= 1.58169E-9 m	Emittance Y	= 2.0131E-13 m
Emittance Z	= 3.38415E-6 m	Energy spread	= 7.51449E-4
Bunch Length	= 4.50375739 mm	Beam tilt	= -8.3801E-4 rad
Beam size xi	= .15410414 mm	Beam size eta	= .03009962 mm

Parameters for dither simulation

	initial		nominal		ultimate	
Luminosity	**1×10^{34} cm^{-2} s^{-1}**		**1×10^{35} cm^{-2} s^{-1}**		**8×10^{35} cm^{-2} s^{-1}**	
	LER	HER	LER	HER	LER	HER
I_{beam} [A]	1.0	0.8	2.7	1.95	3.6	2.6
# of bunches	2500		2500		2500	
$\varepsilon_x/\varepsilon_y$ (nm/pm)	2.2/44	5.2/104	3.2/51.84	4.6/77.28	3.2/8.64	4.6/12.88
β_x^*/β_y^* (mm)	128/2.16	100/2.4	128/1.08	100/1.2	32/0.27	25/0.30
σ_x^*/σ_y^* (μm/nm)	16.8/308	22.8/500	20.2/237	21.4/305	10.1/48	10.7/59
$\sigma_{x\ eff}^*$ (μm)	249	208	249	208	249	208
ξ_x/ξ_y	0.0033/0.024	0.0013/0.0257	0.0083/0.049	0.0052/0.046	0.0028/0.0881	0.0012/0.0807
Δx (lumi:20% drop)	~110μm		~55μm		~10μm	
Lumi. meas.	1kHz		1kHz		1kHz	
accuracy	~5 x 10^{-3} (w/ radiator)		1.3 x 10^{-3}(w/o radiator)		< 1 x 10^{-3}	

$\sigma_{x\ eff}^* = \sigma_z \sin\phi$

Field measurements and programmable amp calibration data

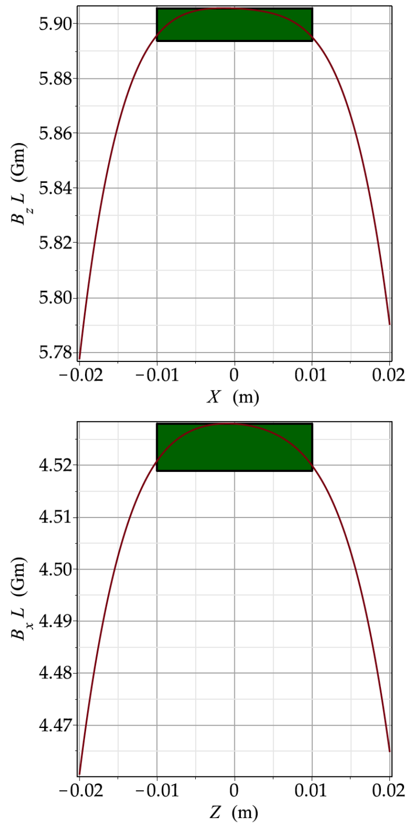
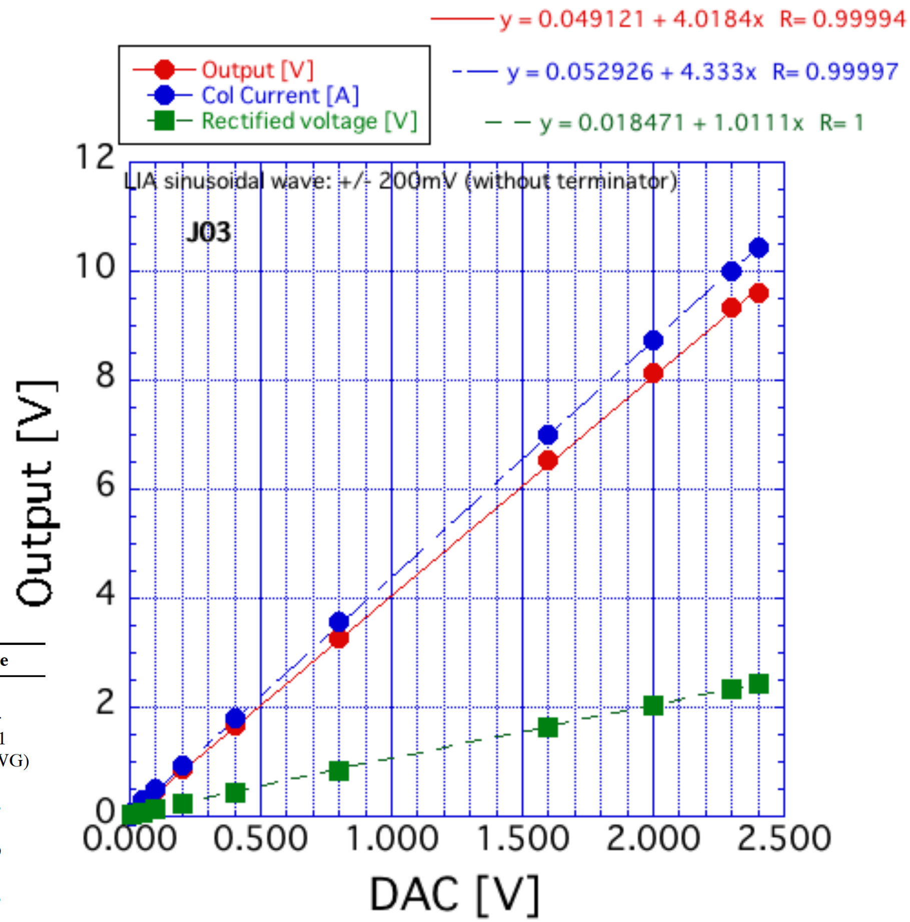


Figure 4: Top frame: Vertical field *vs.* horizontal coordinate. Bottom frame: Horizontal field *vs.* vertical coordinate. The box represents ±0.1% tolerance over ±1 cm

Table 1: Parameters of the coils

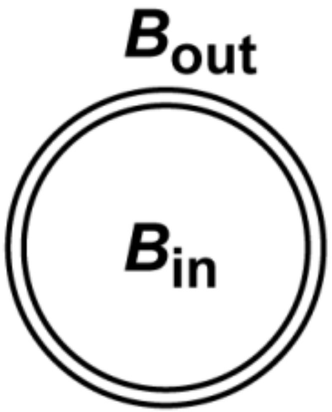
Parameter	Unit	Value
Overall Length	cm	25
Aperture radius	cm	5.24
Wire diameter	mm	1.291 (#16 AWG)
# of turns per coil		39
Resistance/coil (vert. field, 20°C)	Ω	0.33
Resistance/coil (horiz. field, small, 20°C)	Ω	0.39
Coil resistance (horiz. field, large, 20°C)	Ω	0.53
Coil inductance (approx.)	mH	1
Field integral (horizontal)	Tm	4.51×10^{-4}
Field integral (vertical)	Tm	5.92×10^{-4}
Good-field region	cm	1
Field uniformity	1	1×10^{-3}



Measured on Aug. 31st 2017

T. Oki

Damping and phase delay of a magnetic field



$$B_{out} = B_0 \sin(\omega t)$$

$$B_{in} = \frac{1}{\sqrt{1+(\omega\tau)^2}} B_0 \sin\left[\omega t - \arctan(\omega\tau)\right]$$

Damping ratio — Phase delay

where,

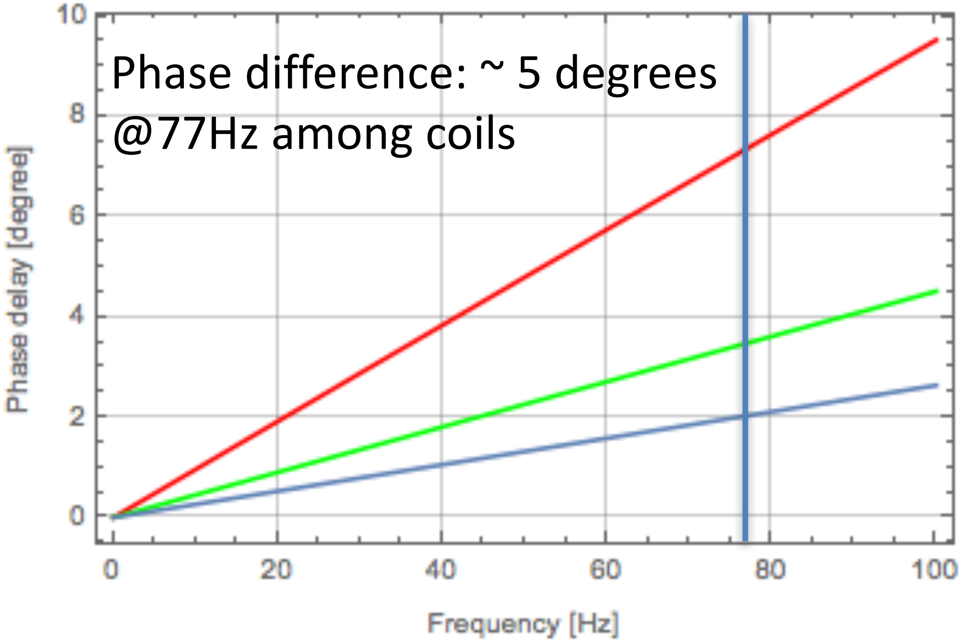
$$\tau = \frac{\mu_0}{2}\frac{bt}{\rho}$$

: ramping time for step response,

b: outer radius (m),

t: thickness (m),

ρ: resistivity ($\Omega \cdot$m)



Red: outer radius = 51mm, thickness = 6mm
Green: outer radius = 48mm, thickness = 3mm
Blue: outer radius = 42mm, thickness = 2mm

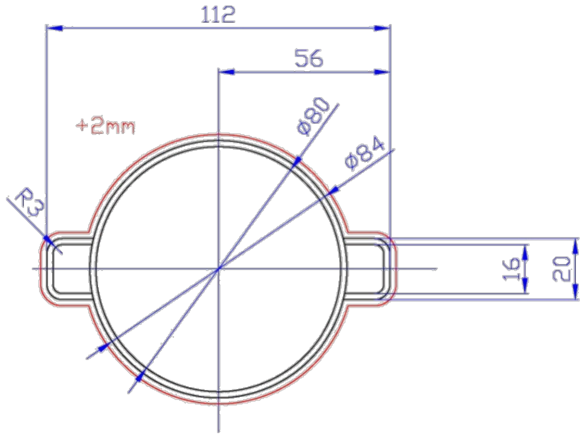
A.W. Chao and M. Tigner, Editors, Handbook of Accelerator Physics and Engineering, World Scientific, Singapore (1999), p. 268

Conceptual drawing for 3 type of beam pipes

ZDS1{L, R}P

Inner diameter: 80 mm

Thickness: 2 mm

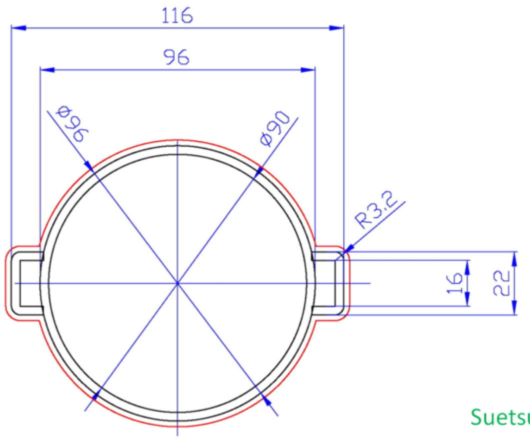


ZDS2{L, R}P

Inner diameter: 90 mm

Thickness: 3 mm

10 μm Cu coating inside.

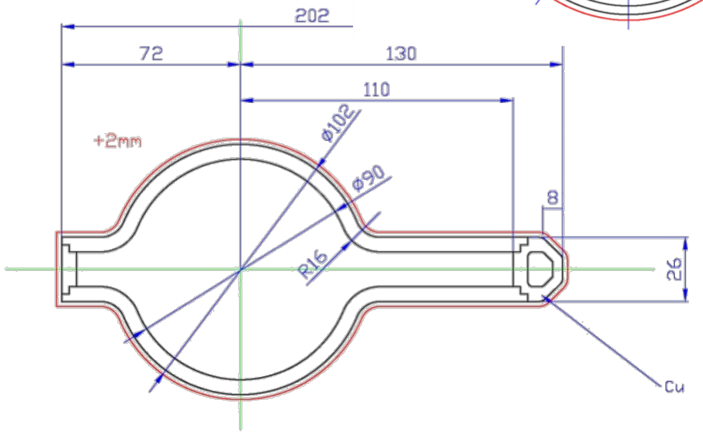


ZDS{3, 4}{L, R}P

Inner diameter: 90 mm

Thickness: 6 mm

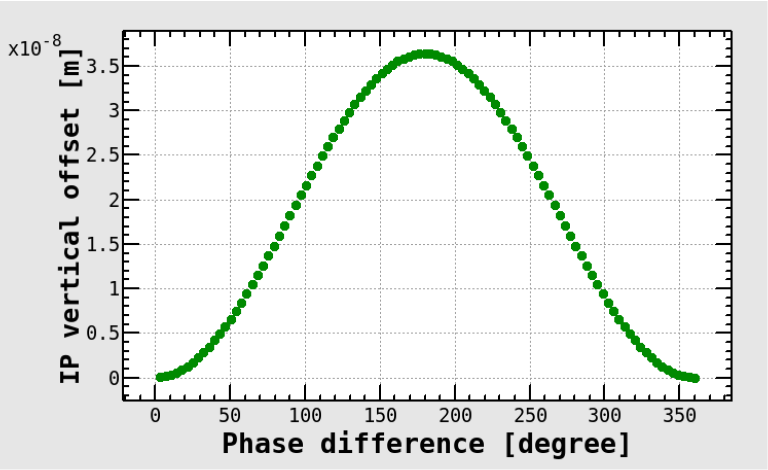
10 μm Cu coating inside.

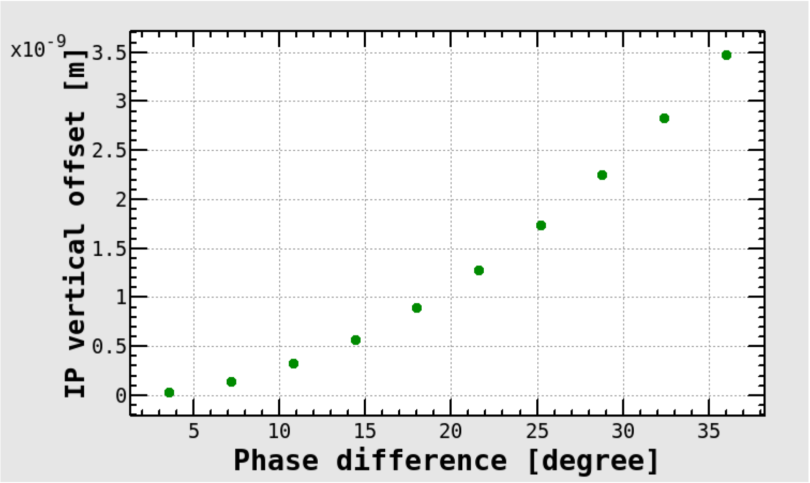


All pipes are made of SS316L.

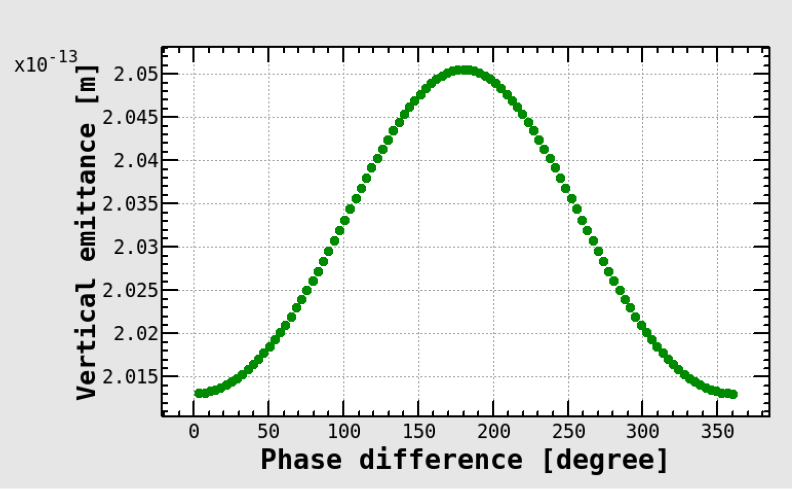
Y. Suetsugu

Effect of phase difference among coils





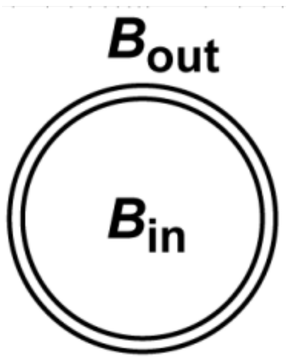
Phase 2 4x8



T. Oki

Damping of magnetic field due to eddy current

Damping ratio



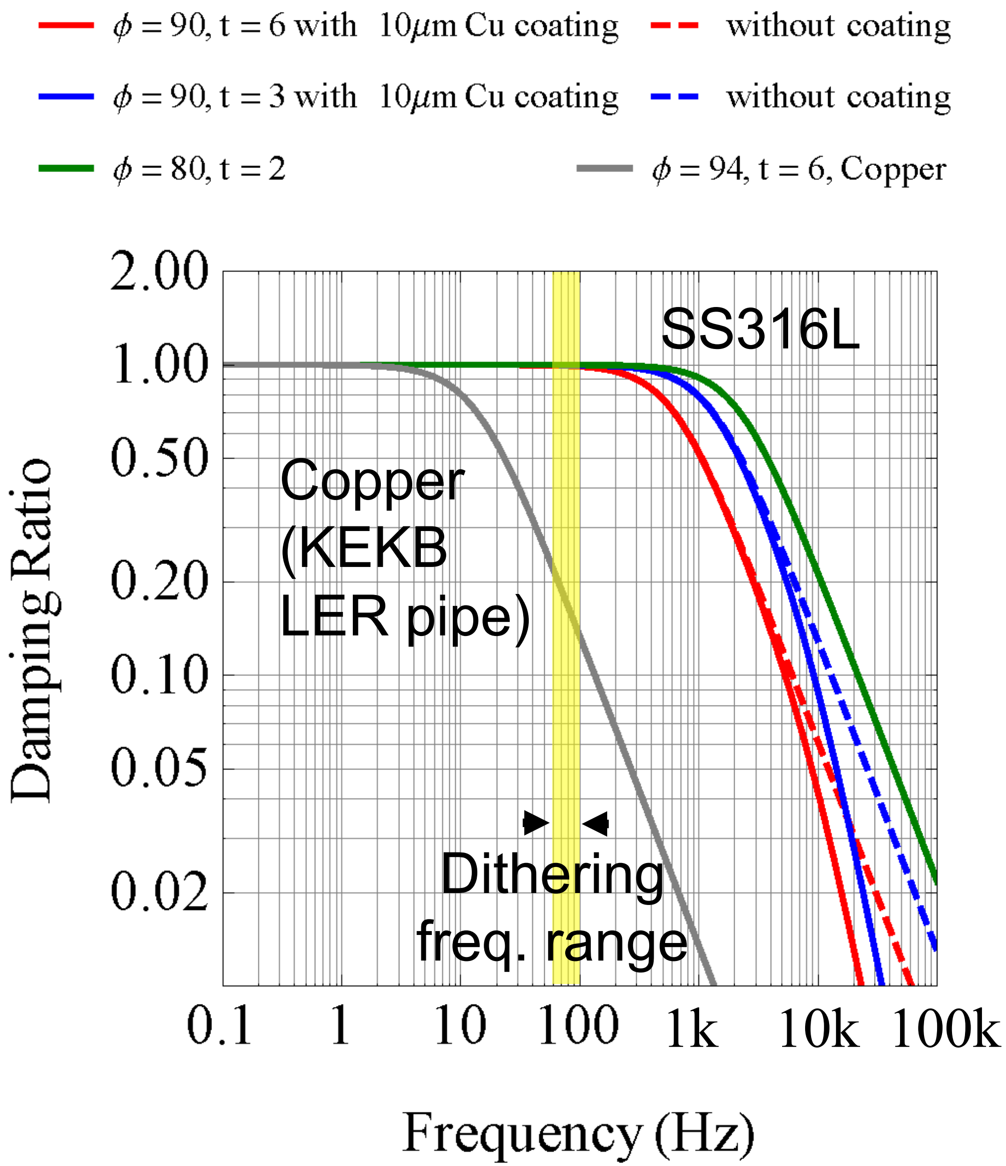
$$\frac{B_{in}}{B_{out}} = \frac{1}{\sqrt{1+(\omega\tau)^2}}$$

where: $\tau = \frac{\mu_0}{2}\frac{bt}{\rho}$,

b: outer radius (m),

t: thickness (m),

ρ: resistivity ($\Omega \cdot$m)



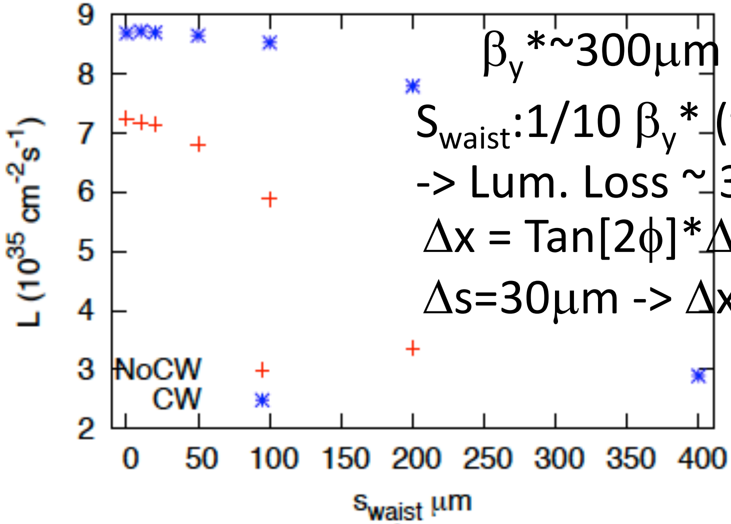
A.W. Chao and M. Tigner, Editors,
Handbook of
Accelerator Physics and Engineering,
World Scientific, Singapore (1999), p. 268

Resistive and thinner pipe suppresses the damping effect.

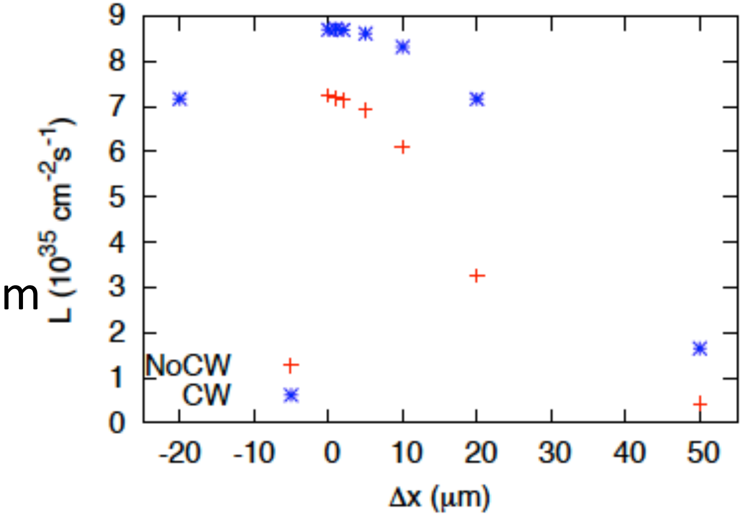
K. Ohmi

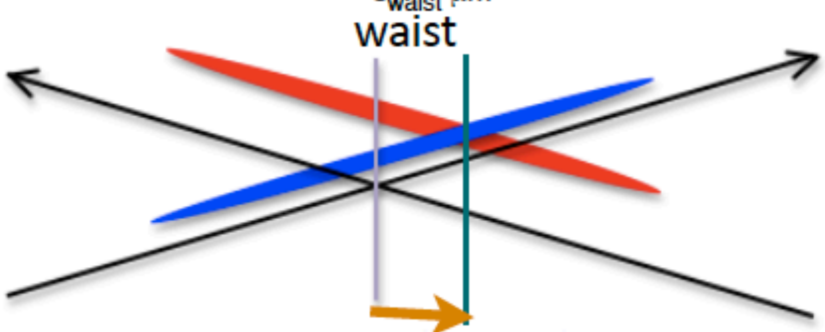
Tolerance of collision condition
Horizontal collision offset and waist

- Horizontal offset and waist are related to each other.
- The cross point of the waist is only one in x-z plane for the crab waist scheme.

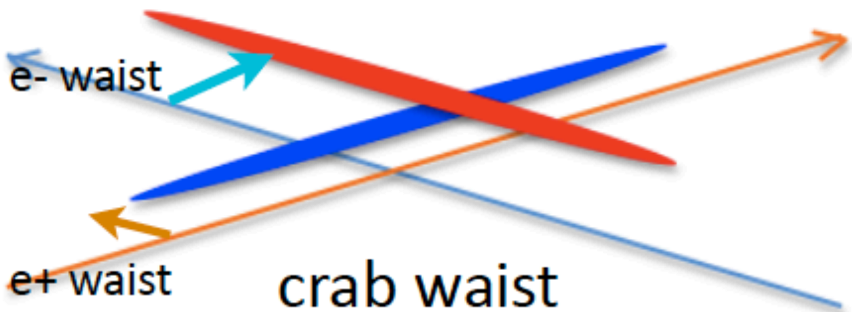


β_y*~300μm
S_{waist}:1/10 β_y* (~30μm)
-> Lum. Loss ~ 3.5%
$\Delta x = \mathrm{Tan}[2\phi]^*\Delta s$
Δs=30μm -> Δx = =2.5μm



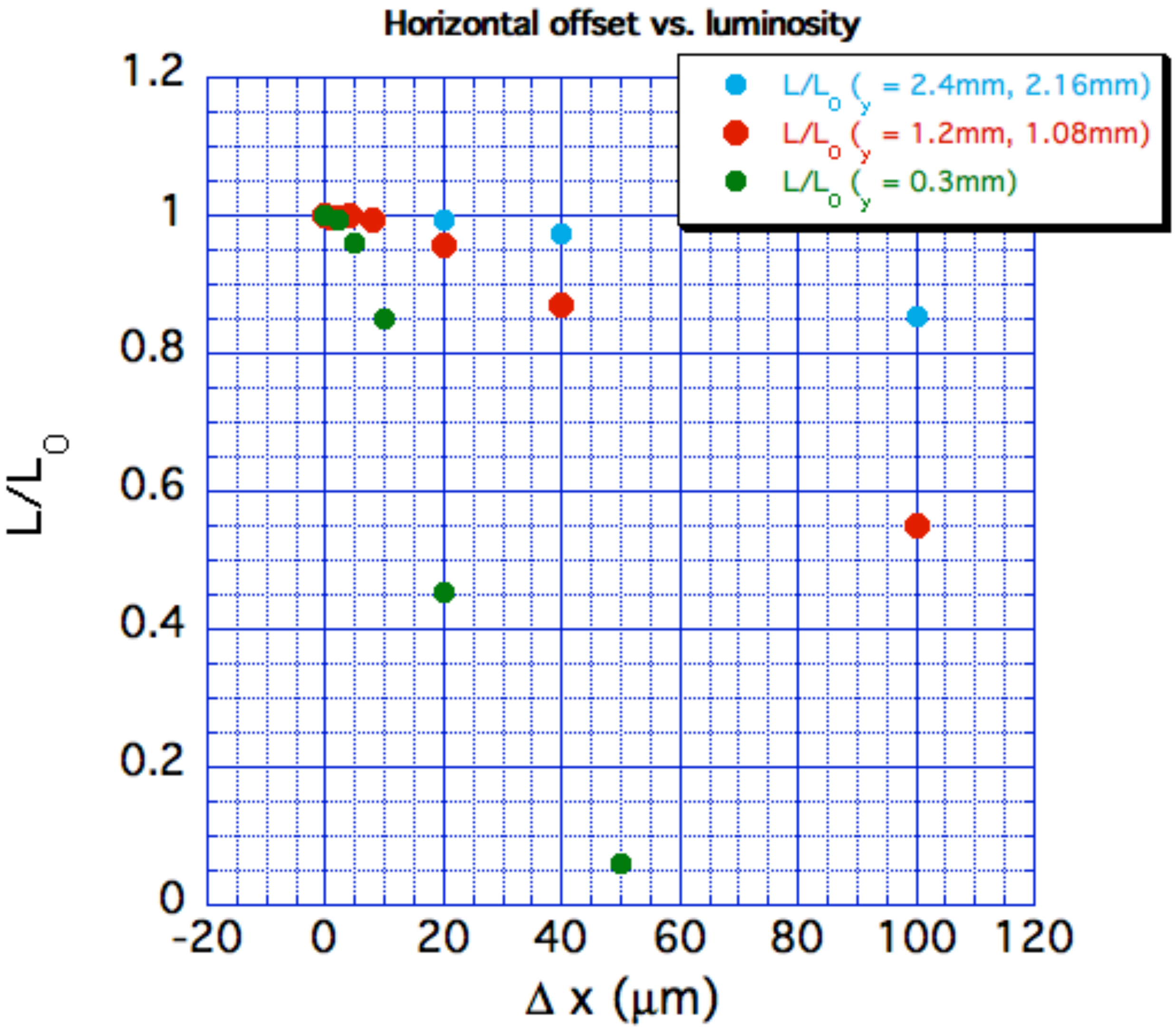


No crab waist



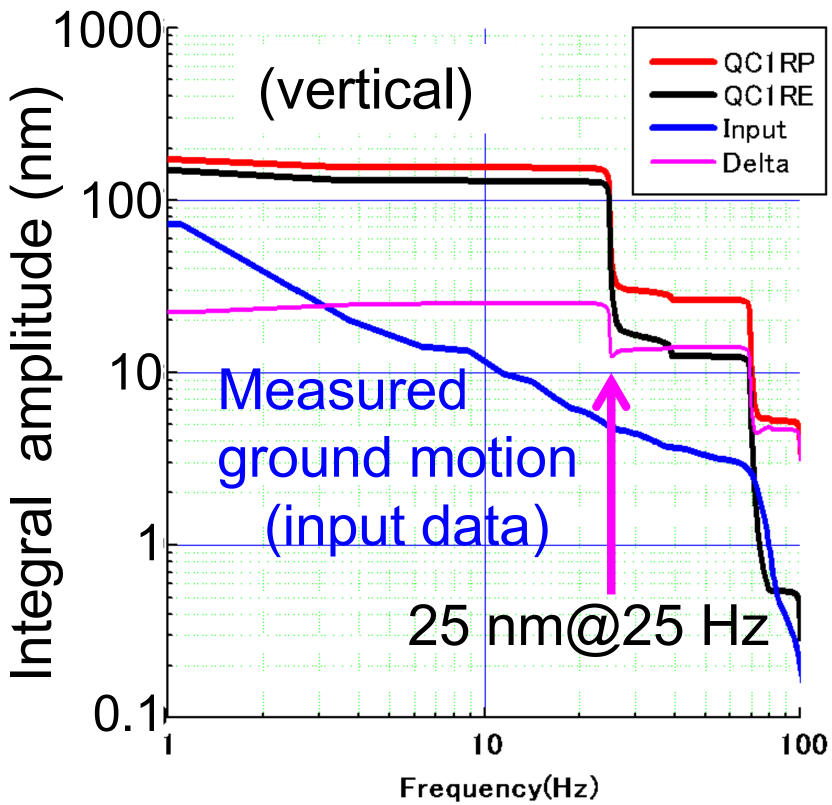
crab waist

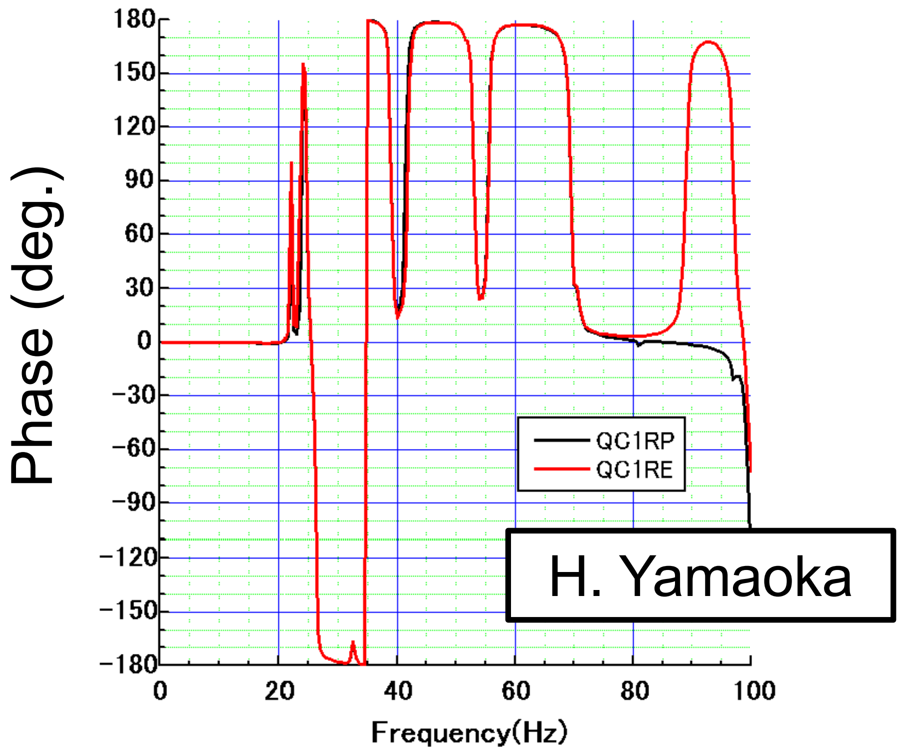
Luminosity degradation due to horizontal orbit shift at IP



β_y^*
8
4
1

Estimation of QCS vibration and luminosity degradation





QC1RP and QC1RE vibrate with same phase,

Phase 3

but the amplitude difference still arises: 25 nm at 25 Hz…

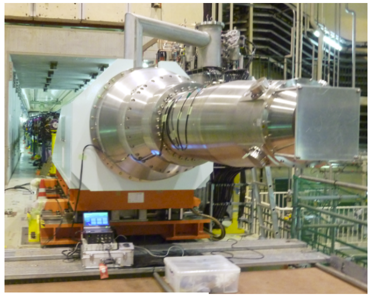
Luminosity degradation (based on beam-beam simulation by K. Ohmi)

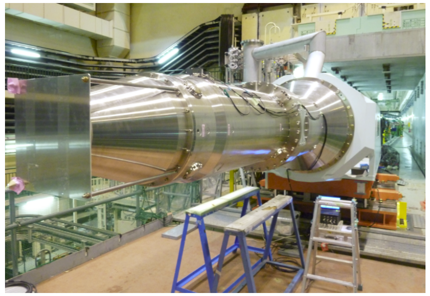
Frequency (Hz)	24.85	38.93	69.34	99.60	15 (recent meas.)
Δy_{IP*}^{rms} (nm)	18.63	1.72	8.29	3.14	40
$L/L_0^{average}$ (%)	95.4	99.8	99.7	99.7	84

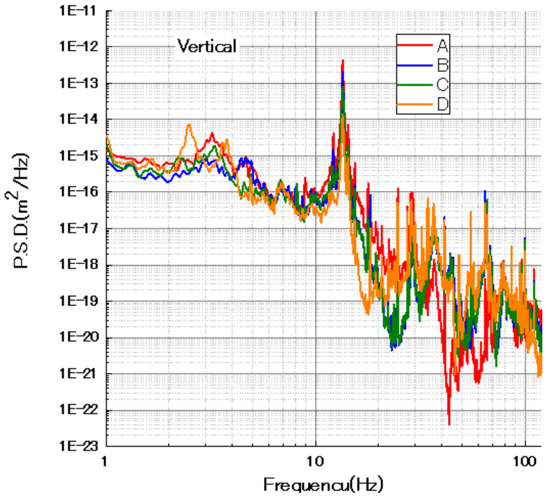
Feedback rejection gain -16.7dB (19 nm -> 2.8 nm) -23dB (40nm -> 2.8 nm)

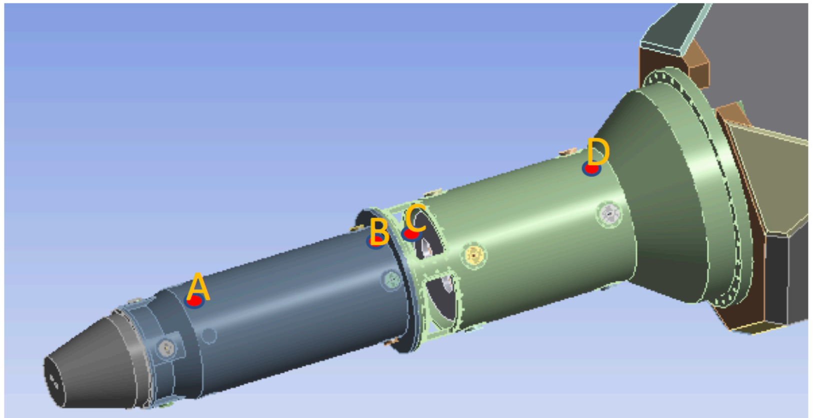
QCSLとQCSRクライオスタットの振動測定（山岡さん）

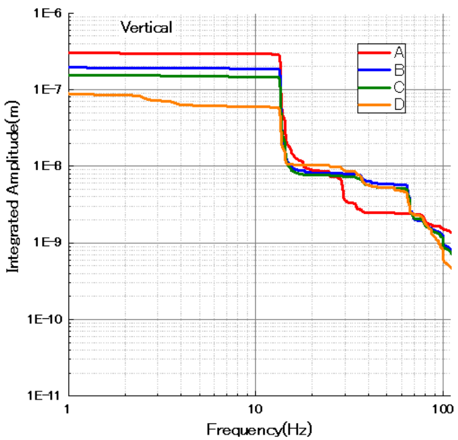
・2017/3/6の電磁石打合せの資料より…。









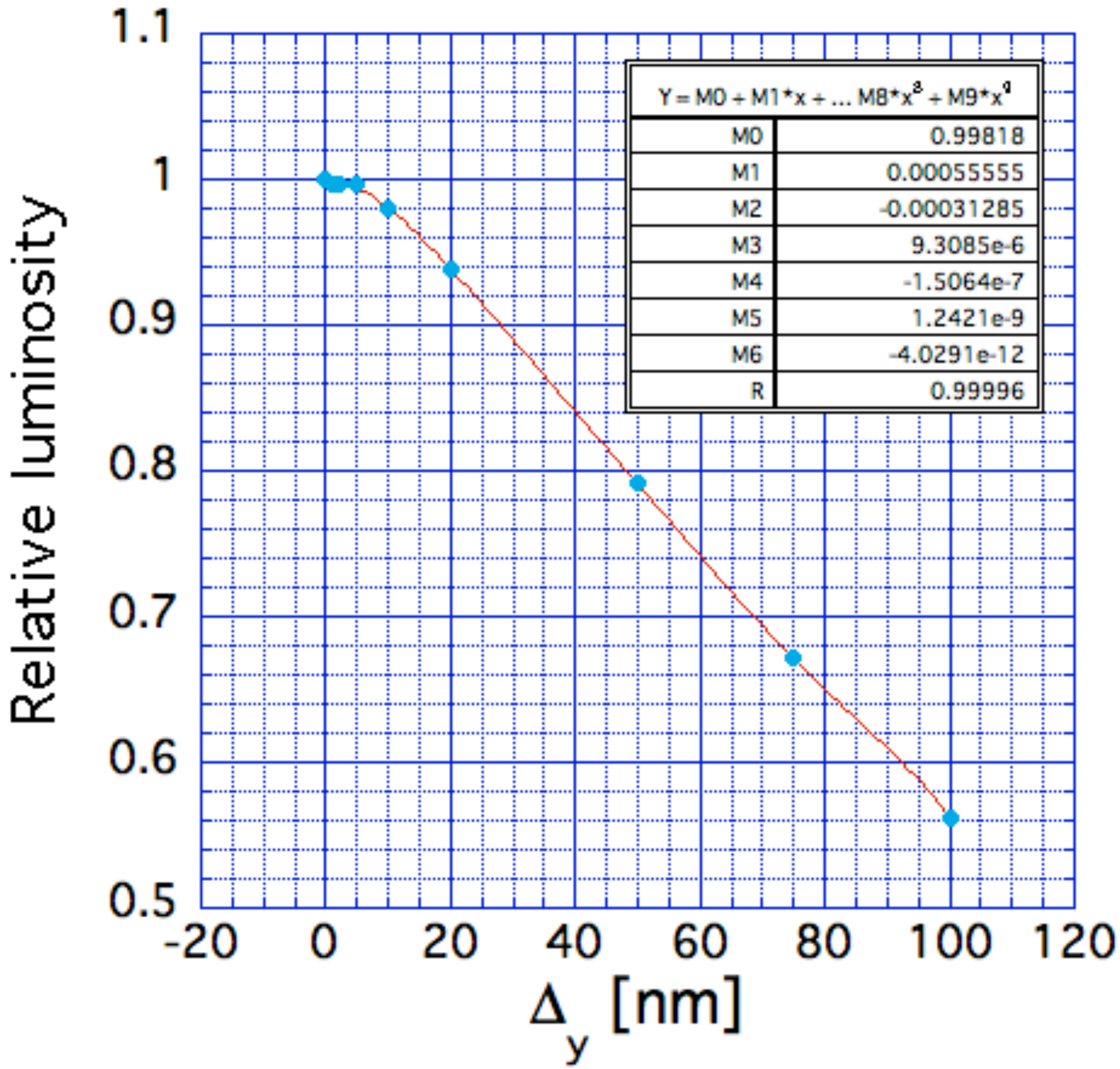


鉛直方向
QCSL: 45nm@20Hz
QCSR: 300nm@15Hz

注意：前頁のはコイルの振動で、こっちはクライオスタット

Beam-Beam simulation results

K. Ohmi



Just 20 nm offset leads to 6 % degradation of luminosity.

Commissioning of orbit feedback systems

- Tuning of iBump orbit
  - iBump in HER: COD measurements -> correction so that the bumps are closed.
  - iBump in LER (dither orbit):
    - Response of bpm signal (phase) to coil excitation by using LIM
    - observe the 77 Hz component at two BPMs outside of the bump with 90 degree phase difference in each horizontal and vertical directions -> correction so that the 77 Hz components are minimized
    - correction using turn-by-turn BPMs?
    - Prior to those corrections, should we do corrections by using a DC bump?
- Setup the orbit feedbacks
  - Vertical feedback
  - Horizontal feedback (dithering)
    - A. Fisher (SLAC) will stay at KEK in the commissioning of dithering system
    - U. Wienands will stay at KEK for about 1 month in the commissioning of dithering system.

ビームアボート後の衝突の確立の手法

- KEKBでは、二つのビームを衝突状態に持っていく途中（過渡現象）でビームロスするなどの現象が見られ、苦労する場合があった。
  - Nano beam 衝突はでどうか？
    - 実際にやって見ないとわからないことも多いが、予めシミュレーションをやっておきたい

ルミノシティ調整

- 基本的なマシンパラメータの確立
  - IP beta functions
  - Betatron tunes
  - Beam currents, Number of bunches
- Tuning items
  - Tuning knobs
    - X-Y coupling
    - waist points
    - IP dispersions
    - Target values of orbit feedback
    - Betatron tunes
  - Method of parameter search
    - Scan, scan, scan,,,,,

Strategy of Beta Squeezing in Phase-2

We hope to squeeze the IP beta functions down to 4 x 8 in Phase 2.
If possible, 4 x 4 is desirable.

Phase	LER			HER			
	β_x* [mm]	β_y* [mm]	scale	β_x* [mm]	β_y* [mm]	scale	
2.0*	384	81	12 x 300	400	81	16 x 270	
2.1	384	5.4	12 x 20	400	6	16 x 20	$\simeq \sigma_z$
2.2	256	2.16	8 x 8	200	2.4	8 x 8	adiabatic squeezing ↓
2.3	128	2.16	4 x 8	100	2.4	4 x 8	
2.4	128	1.08	4 x 4	100	1.2	4 x 4	
3.x	32	0.27	1 x 1	25	0.30	1 x 1	

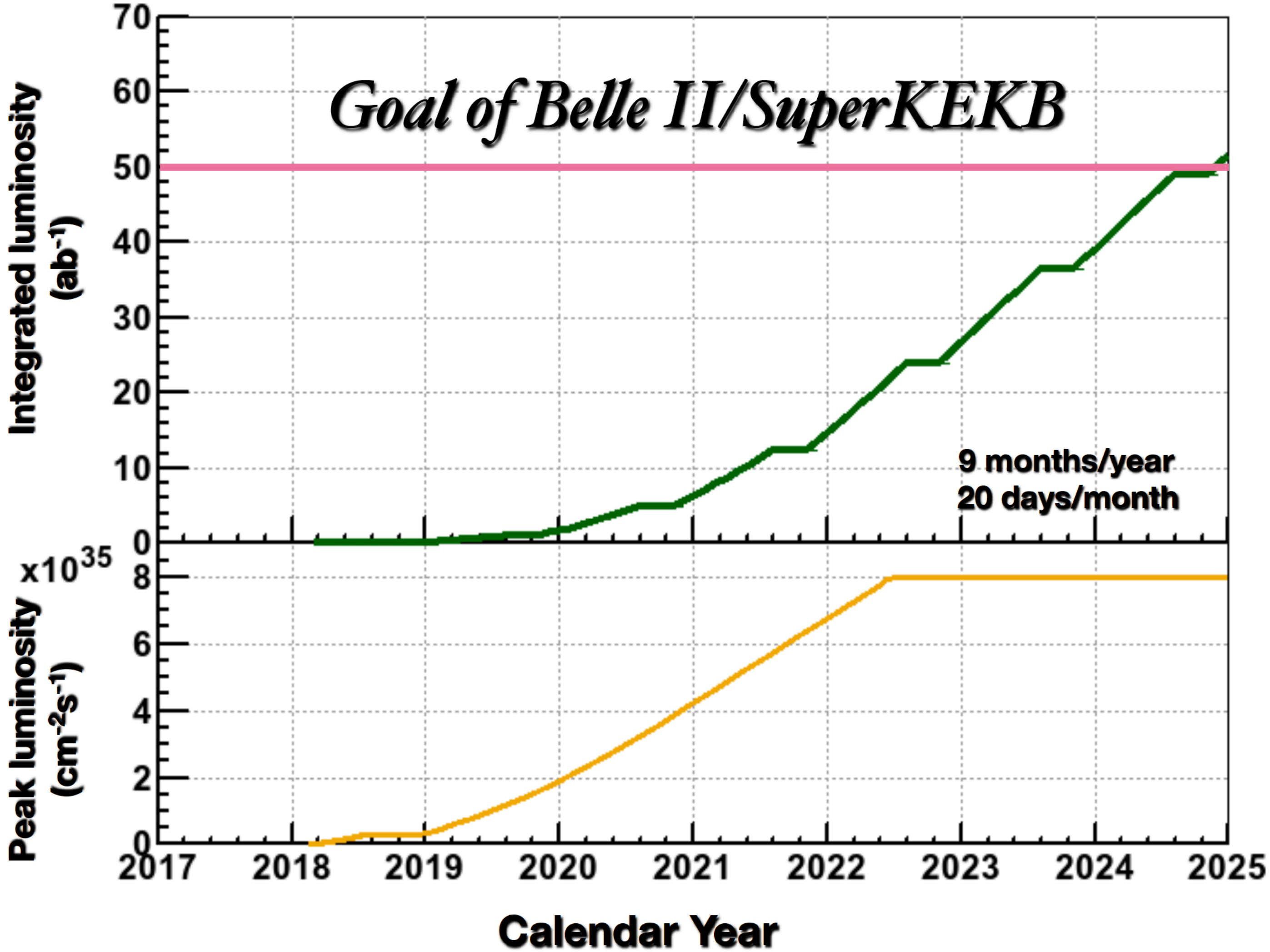
Y. Ohnishi

Issues

- IR design and dynamic aperture
- Optics corrections & Low emittance tuning
- Beam-beam related issues
- IP orbit control to maintain beam collision
- Beam loss and beam injection
- Electron clouds
- Injector upgrade for low emittance & high intensity beams
- Detector beam background

The items in red were partially studied in Phase 1.

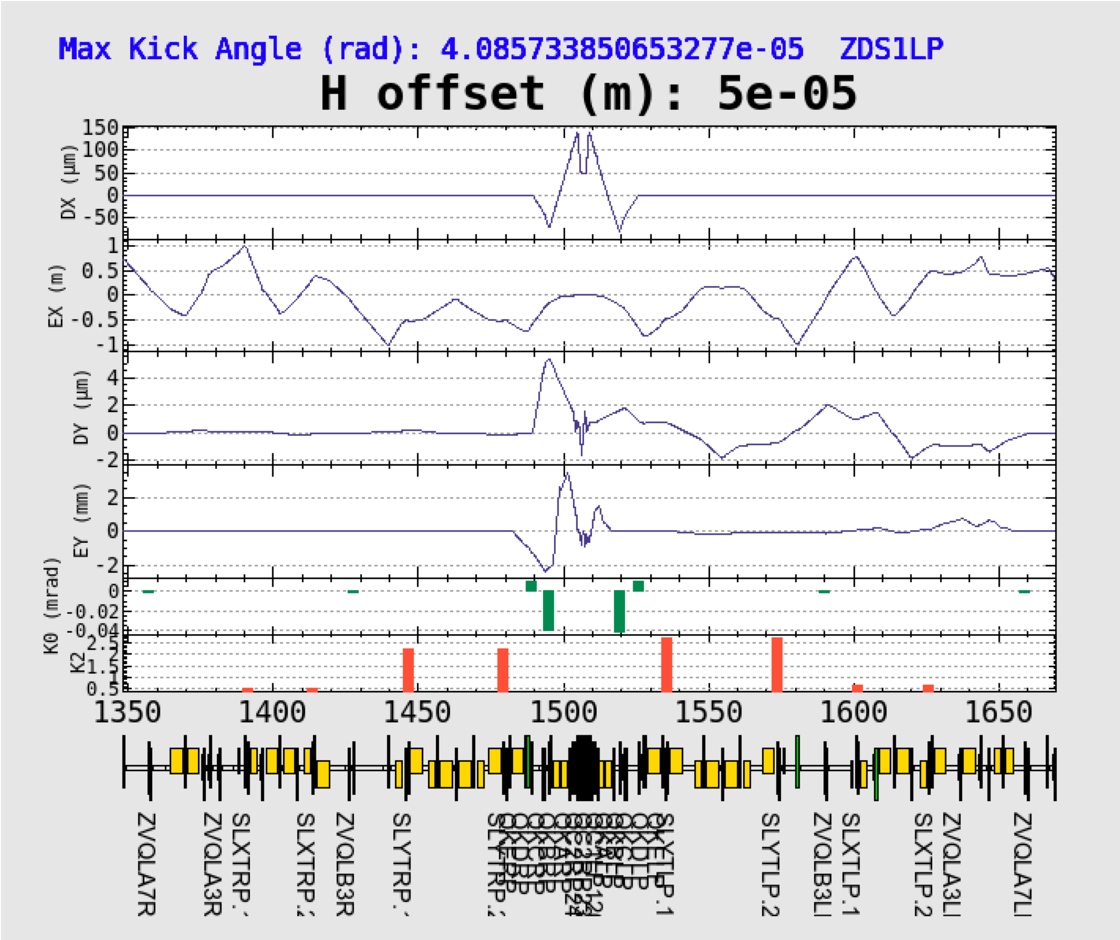
SuperKEKB Luminosity Projection



A lot of difficult works should be done in Phase 2 and 3.

Spare slides

iBump LER (Phase 2 8x8)



!Variable	Keyword	Now
ZDS4RP	SK0	5.909167180E-9
ZDS3RP	SK0	1.44962952E-10
ZDS2RP	SK0	1.131717341E-6
ZDS2RP	K0	9.987509252E-6
ZDS1RP	SK0	-7.36886574E-7
ZDS1RP	K0	-3.98208052E-5
ZDS1LP	SK0	3.740126597E-8
ZDS1LP	K0	-4.08573385E-5
ZDS2LP	SK0	1.381800531E-7
ZDS2LP	K0	1.004344799E-5
ZDS3LP	SK0	1.384802776E-7
ZDS4LP	SK0	-9.90627157E-8

Bump Height: 10 μm

Bumpがない時 : 1.96E-13 m

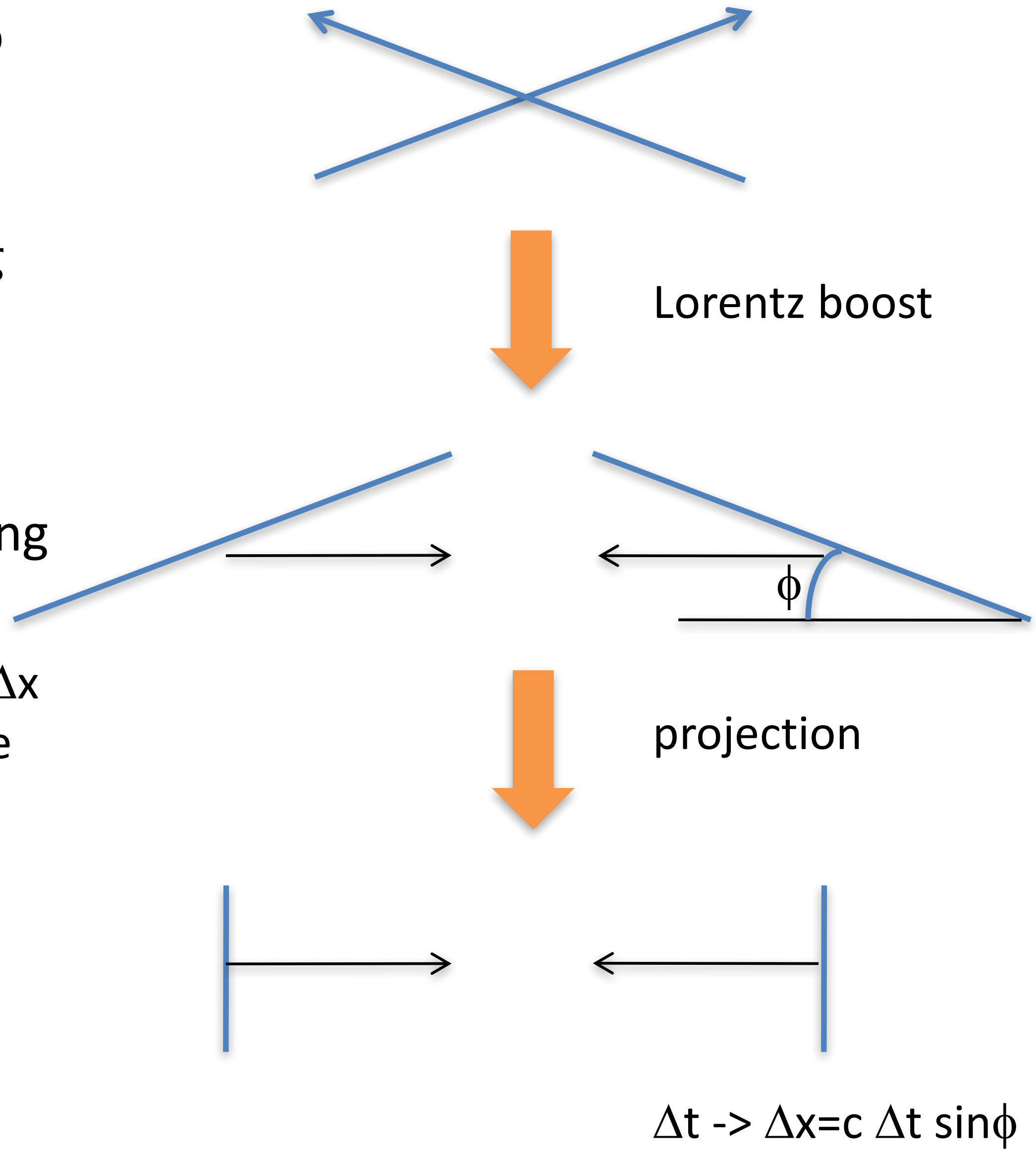
Emittance X	= 1.85573E-9 m	Emittance Y	= 1.9883E-13 m
Emittance Z	= 3.31853E-6 m	Energy spread	= 7.51475E-4
Bunch Length	= 4.41622411 mm	Beam tilt	= -5.7885E-4 rad
Beam size xi	= .16695389 mm	Beam size eta	= .03006460 mm

iBump steering kick angle

iBump FB	積分磁場（Tm）	kick angle(mrad) @7GeV @5A	Commemnt
垂直ステアリング	0.00335	0.143571429	江川・植木さんの磁場測定結果
水平ステアリング	0.00611	0.261857143	江川・植木さんの磁場測定結果
Dithering	積分磁場（Tm）	kick angle(microrad) @4GeV @5A	
Horizontal	0.000451	33.825	UliさんのIPAC論文
Vertical	0.000592	44.4	UliさんのIPAC論文

Shift of collision timing makes a horizontal kick

- With the drift of collision timing ->no shift of collision point ->no waist problem
- However, the drift of collision timing makes a beam-beam defection and interferes with the detection of the true hor. offset.
- Hor. offset from shift of collision timing
  - offset : $\Delta x = c\ \Delta t \sin\phi$
  - Tolerance for true horizontal offset: Δx corresponding Δt =0.20ps ->RF phase of 0.07°



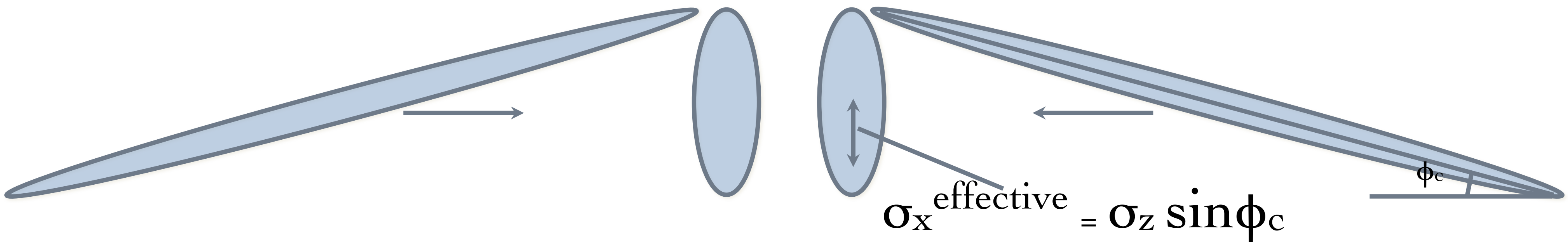
Luminosity and beam-beam parameter with superbunch collision

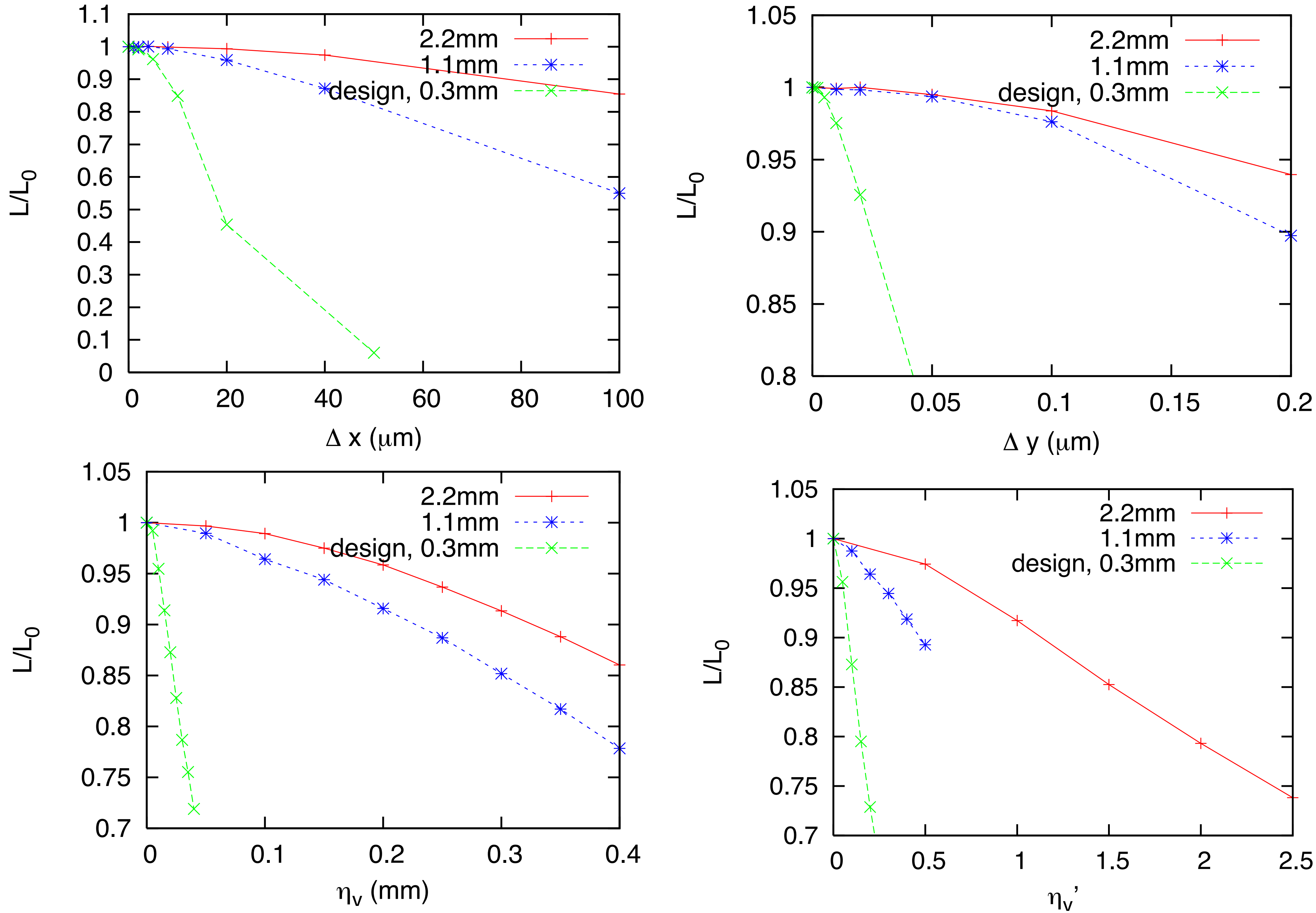
- Luminosity

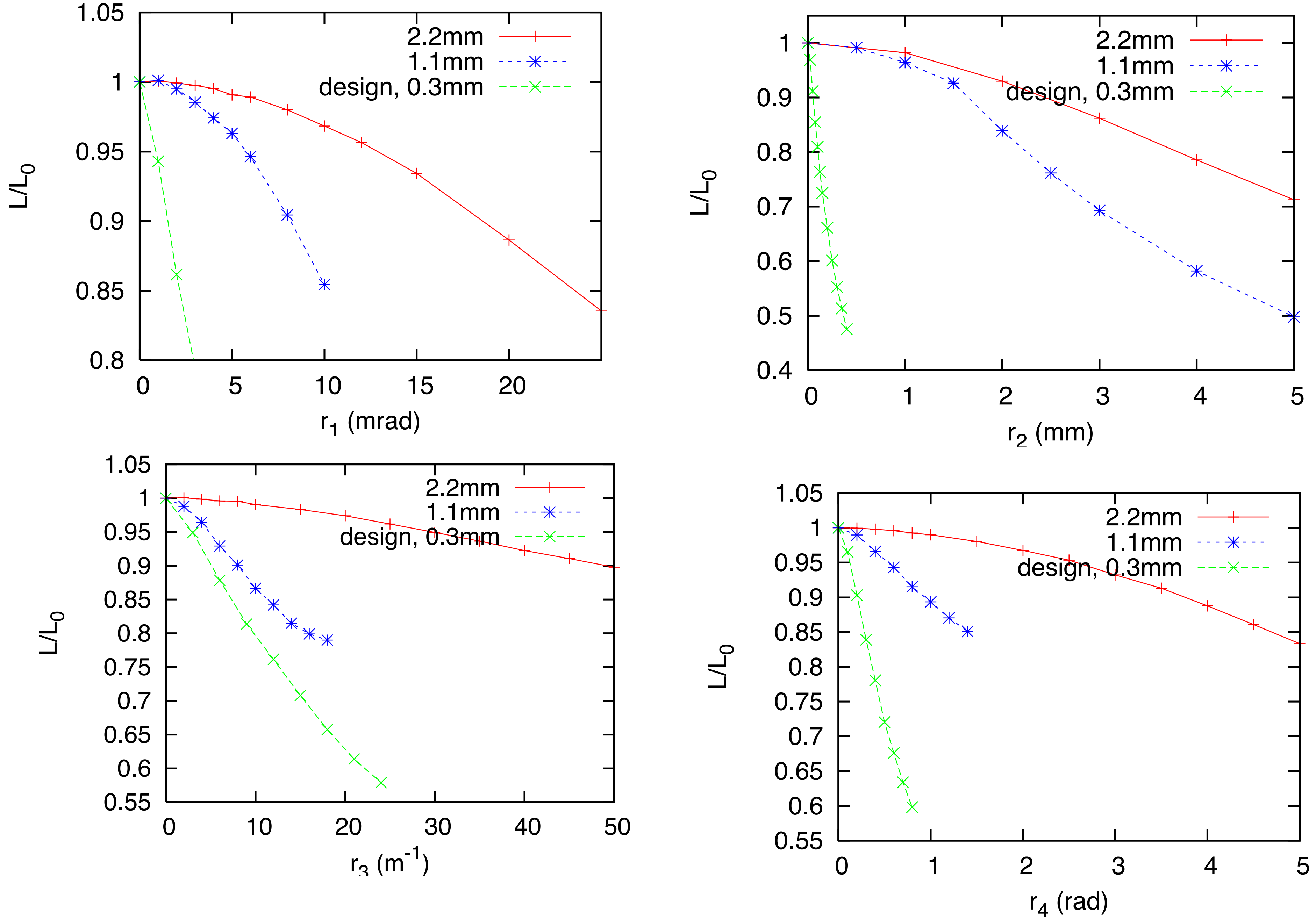
$$L = \frac{1}{2\sqrt{2}p} \frac{N_p N_e}{s_z f_c \sqrt{s_{ye}^2 + s_{yp}^2}} f_{col}$$

- Beam-beam parameter

$$x_{yp} = \frac{r_e}{2pg_p} \frac{b_{yp}^* N_e}{s_z f_c s_{ye}} \qquad x_{ye} = \frac{r_e}{2pg_e} \frac{b_{ye}^* N_p}{s_z f_c s_{yp}}$$

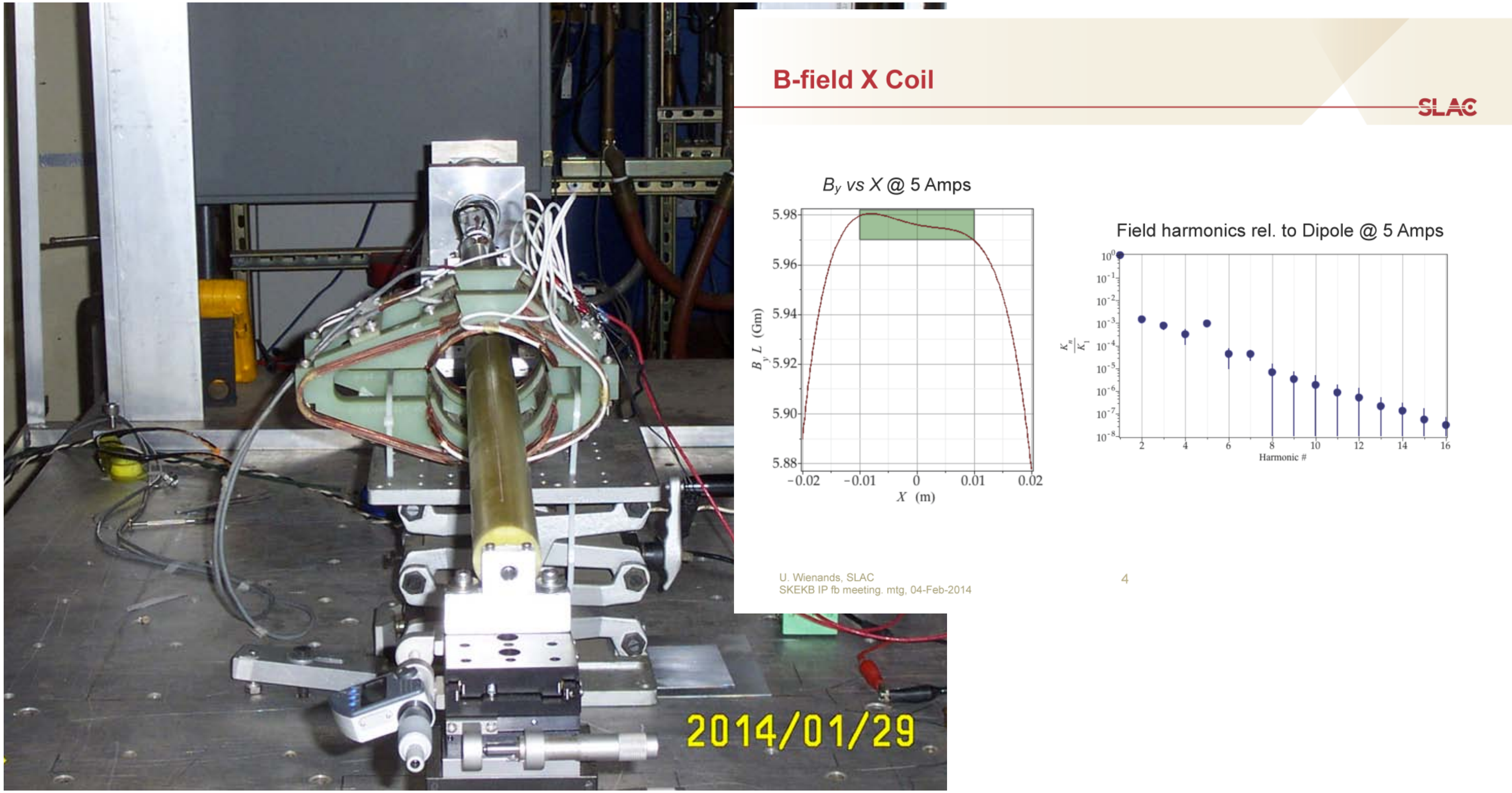



2.2mm
1.1mm
design, 0.3mm
L/L0
Δ x (μm)
Δ y (μm)
ηv (mm)
ηv'



2.2mm
1.1mm
design, 0.3mm
L/L0
r1 (mrad)
r2 (mm)
r3 (m-1)
r4 (rad)

Fabrication and field measurement



Fabrication and measurement of coils will be finished by this March.

U. Wienands, S.D. Anderson, MFD Metrology, SLAC