SuperKEKB e-cloud mitigation and instrumentation

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CesrTA Program Advisory Committee Mtg.

2012.9.11

Outline

- SuperKEKB introduction
- Collaborative efforts at CesrTA:
  - E-cloud dynamics studies
  - E-cloud mitigation studies
  - X-ray beam-size monitor development

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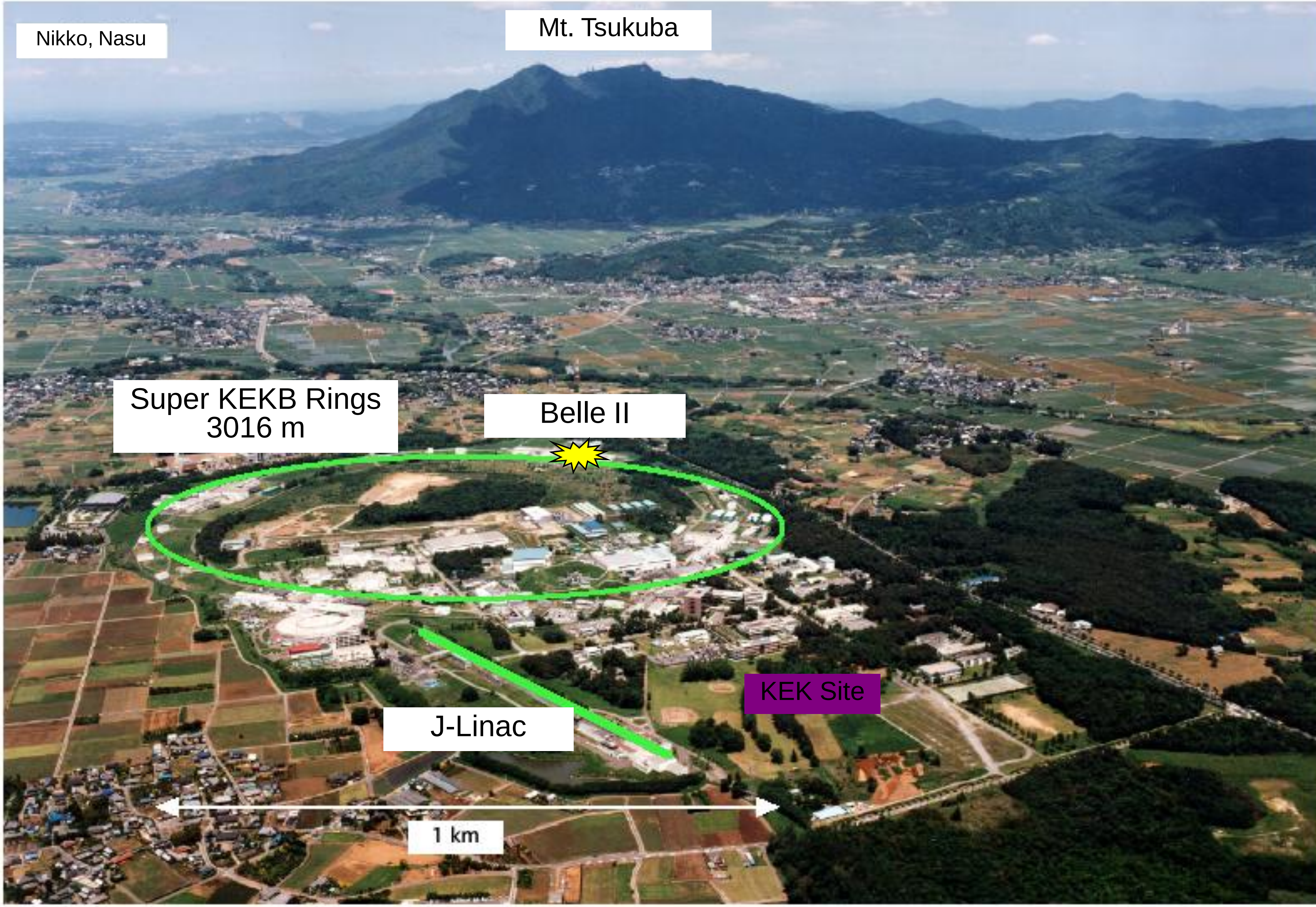
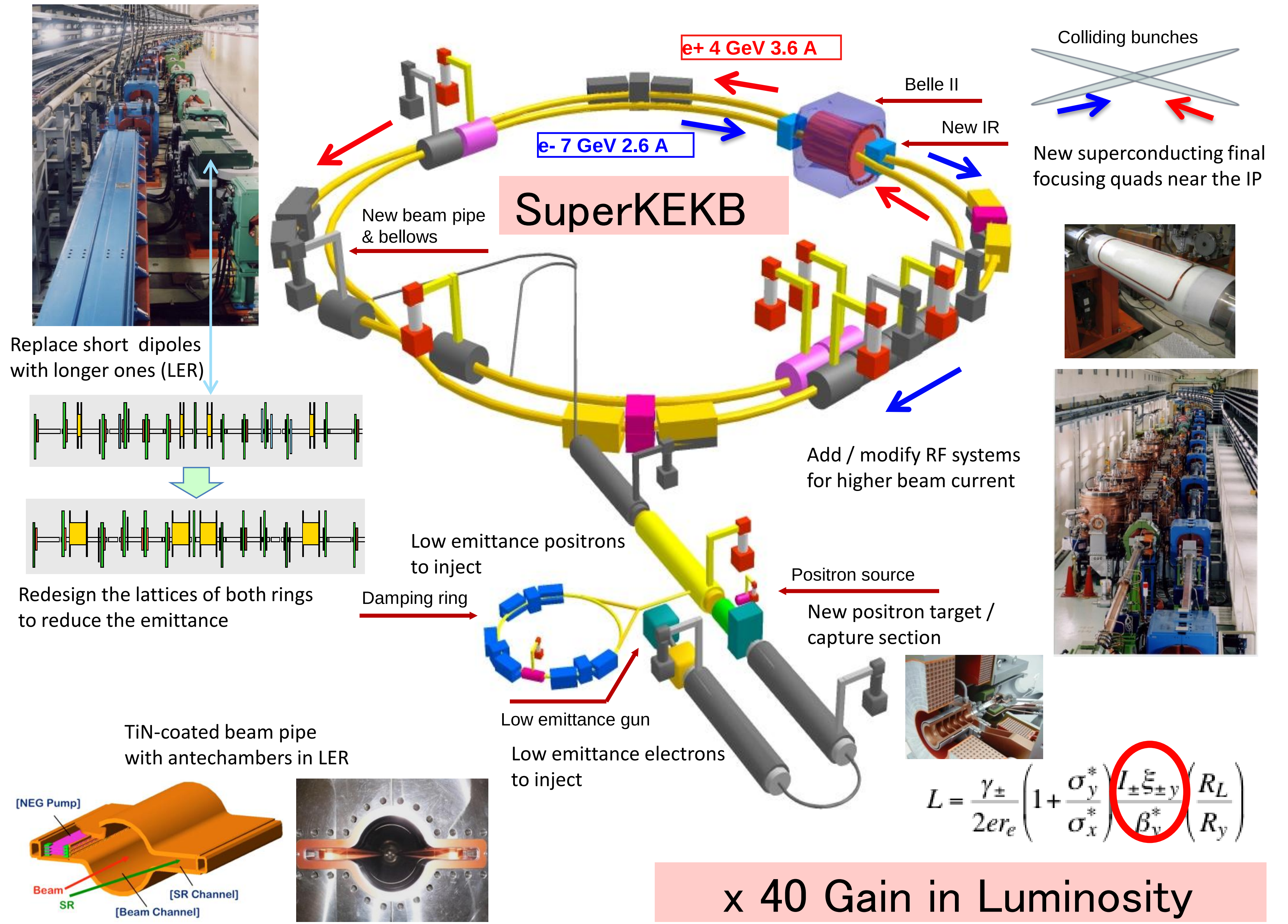
SuperKEKB



Nikko, Nasu
Mt. Tsukuba
Super KEKB Rings
3016 m
Belle II
KEK Site
J-Linac
1 km



$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right)$$

Design Concept of SuperKEKB

- Increase the luminosity by 40 times based on "Nano-Beam" scheme, which was first proposed for SuperB by P. Raimondi.

Luminosity Gain

- Vertical β function at IP: 5.9 → 0.27/0.30 mm (× 20)
- Beam current: 1.7/1.4 → 3.6/2.6 A (× 2)
- Beam-beam parameter: .09 → .09 (× 1)

$$L = \frac{\gamma_{\pm}}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{\pm}\xi_{\pm y}}{\beta_y^*}\right)\left(\frac{R_L}{R_y}\right) = 8 \times 10^{35}\ \mathrm{cm^{-2}s^{-1}}$$

- Beam energy: 3.5/8.0 → 4.0/7.0 GeV

  LER : Longer Touschek lifetime and mitigation of emittance growth due to the intra-beam scattering
  HER : Lower emittance and lower SR power

Comparison of Parameters

	KEKB Design	KEKB Achieved : with crab	SuperKEKB Nano-Beam
Energy (GeV) (LER/HER)	3.5/8.0	3.5/8.0	4.0/7.0
β_y^* (mm)	10/10	5.9/5.9	0.27/0.30
β_x^* (mm)	330/330	1200/1200	32/25
ε_x (nm)	18/18	18/24	3.2/5.3
$\varepsilon_y/\varepsilon_x$ (%)	1	0.85/0.64	0.27/0.24
σ_y(μm)	1.9	0.94	0.048/0.062
ξ_y	0.052	0.129/0.090	0.09/0.081
σ_z (mm)	4	6 - 7	6/5
I_{beam} (A)	2.6/1.1	1.64/1.19	3.6/2.6
$N_{bunches}$	5000	1584	2500
Luminosity (10^{34} cm^{-2} s^{-1})	1	2.11	80

Y. Ohnishi et al.

SuperKEKB

- Higher beam currents, lower emittance than KEKB mean electron clouds a big issue.
- Need to understand:
  - Electron cloud blow-up threshold (dynamics studies).
  - Electron cloud mitigation methods
  - Electron cloud and low-emittance beam diagnostics.
- ➔*Studies at CesrTA*

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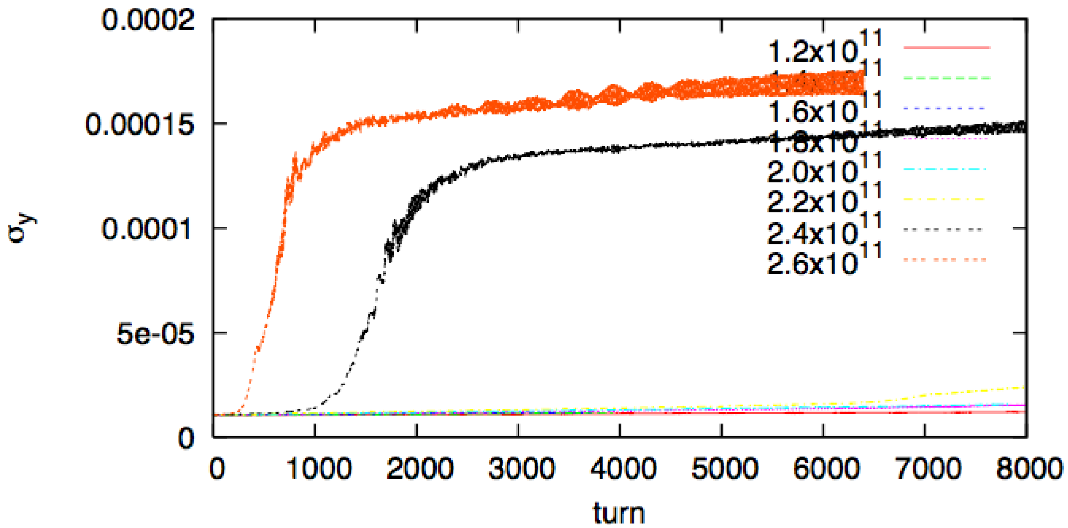
Electron cloud instability

- Single bunch instability
- Coupled bunch instability

K. Ohmi

Head-tail blow-up at SuperKEKB

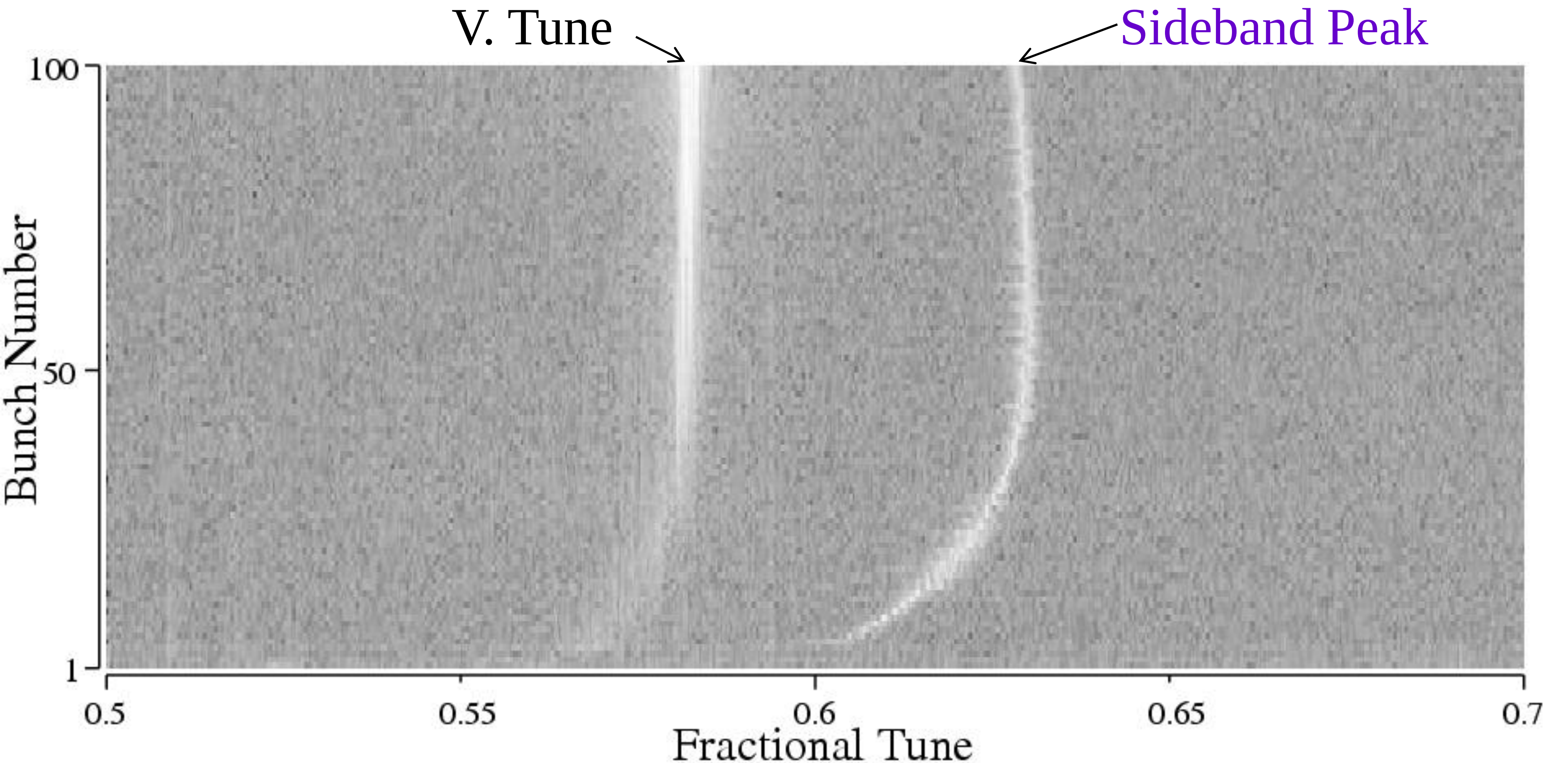


- Simulation ρ_{th}=2.2x10^{11} m^{-3}.(ν_s=0.012)
- Analytic ρ_{th}=2.7x10^{11} m^{-3}.
- Target ρ_e~1x10^{11} m^{-3}
- Take care of high β section. Effects are enhanced.

$$\oint \rho_e \beta_y ds/L = 10^{11} \times 10 \ \mathrm{m}^{-2}$$

K. Ohmi

Fourier power spectrum of BPM data



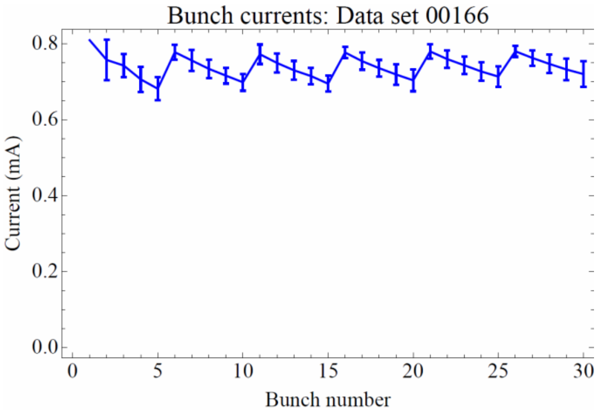
- LER single beam, 4 trains, 100 bunches per train, 4 rf bucket spacing
- Solenoids off: beam size increased from 60 μm ->283 μm at 400 mA
- Vertical feedback gain lowered
  - This brings out the vertical tune without external excitation

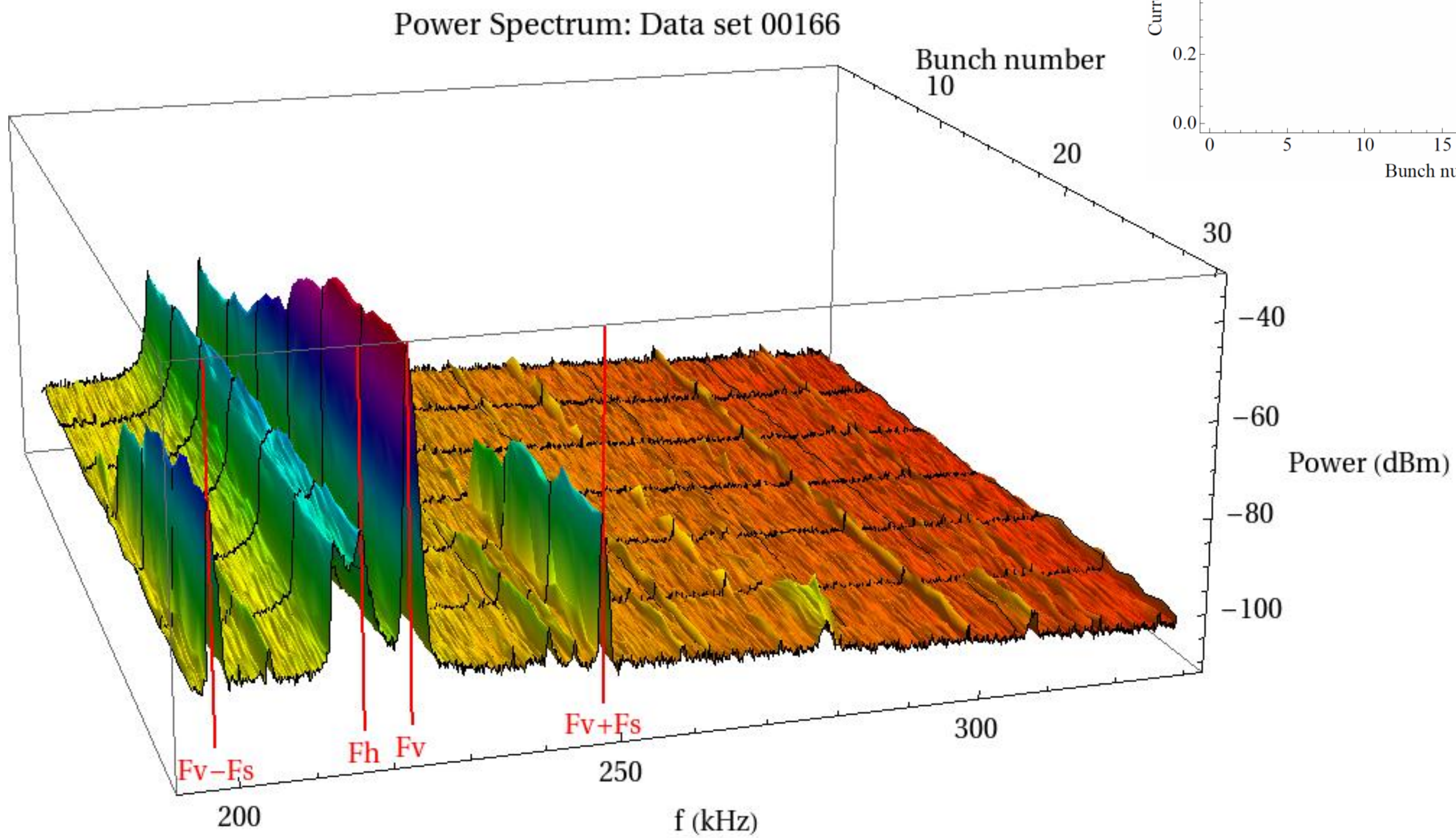
30 bunch train: bunch by bunch spectra

Beam parameters:

- 2.1 GeV;
- H (V) emittance: 2.6 nm (20 pm);
- bunch length 10.8 mm;
- tunes (H, V, S): (14.57,9.6, 0.065)

- momentum compaction 6.8×10^{-3}
- (H,V) chrom = (1.33,1.155)
- Avg current/bunch = 0.74 mA.
- L-FBK off; H-, V-FBK at 20%





Parameters

Table 1: Basic parameters of the positron rings

Lattice		KEKB	Cesr-TA	PETRA-III	SuperKEKB	Super B
Circumference	L (m)	3,016	768	2304	3016	1260
Energy	E (GeV)	3.5	2-5	6	4.0	6.7
Bunch population	$N_+(10^{10})$	8	2	0.5	9	5
Beam current	I_+ (A)	1.7	-	0.1	3.6	1.9
Emittance	ε_x(nm)	18	2.3	1	3.2	2
	ε_y(nm)	0.18	0.023	0.01	0.01	0.005
Momentum compaction	$\alpha(10^{-4})$	3.4	68	12.2	3.5	
Bunch length	σ_z(mm)	6	6.8	12	6	5
RMS energy spread	$\sigma_E/E(10^{-3})$	0.73	0.8		0.8	0.64
Synchrotron tune	ν_s	0.025	0.067	0.049	0.0256	0.0126
Damping time	τ_x(ms)	40	56.4	16	43	26

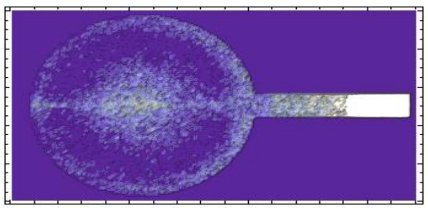
Table 2: Threshold of the B factories positron rings and others

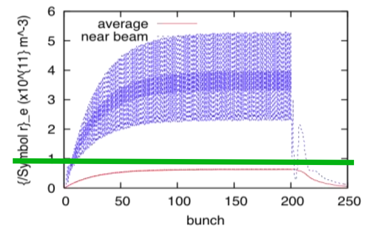
		KEKB (no sol.)	KEKB (50 G sol.)	Cesr-TA	PETRA-III	SuperKEKB	SuperB
Bunch population	$N_+(10^{10})$	3	8	2		8	5
Beam current	I_+ (A)	0.5	1.7	-	0.1	3.6	1.9
Bunch spacing	ℓ_{sp}(ns)	8	7	4-14	8	4	4
Electron frequency	$\omega_e/2\pi$(GHz)	28	40	43	35	150	175
Phase angle	$\omega_e\sigma_z/c$	3.6	5.9	11.0	8.8	18.8	18.3
Threshold	ρ_e (10^{12} m^{-3})	0.63	0.38	1.7	1.2	0.27	0.54

K. Ohmi

Estimation of cloud density and coupled bunch instability

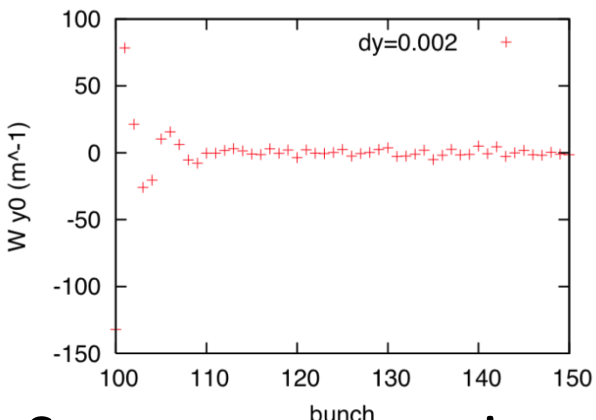
- Ante-chamber, $\delta_{2,max}$=1.2 without special structure like groove

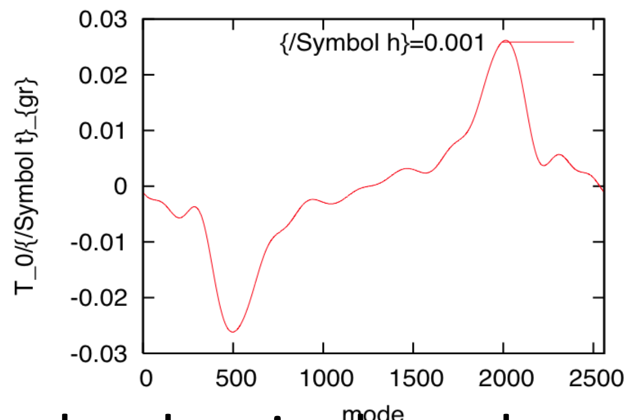




$\rho_e = 2.2\times10^{11}\ m^{-3}$

- Wake field and growth rate of the couplied bunch instability.





Growth time is 40 turns. It should be suppressed at $\rho_e = 1\times10^{11}\ m^{-3}$.

- Suetsugu-san estimates the density based on measurements and is designing the chamber to achieve required density.

K. Ohmi

Summary

- Threshold of the fast head-tail instability: Theory and simulation agree with measurements at CesrTA and KEKB.
- SuperKEKB prediction should be reliable.
- Head-tail spectrum at KEKB has an upper sideband, with separation >= ν_s. The head-tail spectrum of Cesr-TA is different from that of KEKB, with a lower sideband at $-\nu_s$.
- Understanding of the head-tail mode is next step.

K. Ohmi

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Clearing electrode collaboration at CesrTA

- Beam tests of a clearing electrode as a method to mitigate the electron cloud effect was proposed in 2008.
- The clearing electrode suggested is a thin electrode formed by a thermal-spray method, which had been also tested at KEKB.
- The electrode was prepared at KEK and assembled (welded) at LBL.
- Two beam pipes with electrodes for a preliminary test were produced in 2009, and the basic properties, such as the electrical insulation, were investigated at KEK, LBL and Cornell University.

Y. Suetsugu

Preliminary test

- Test beam pipes with electrodes

Y. Suetsugu

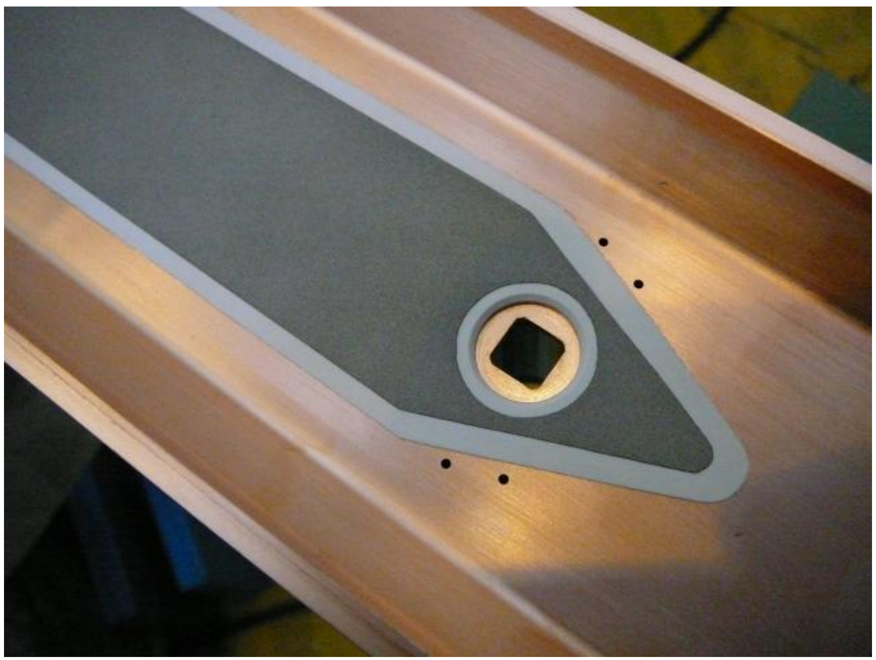
Installation

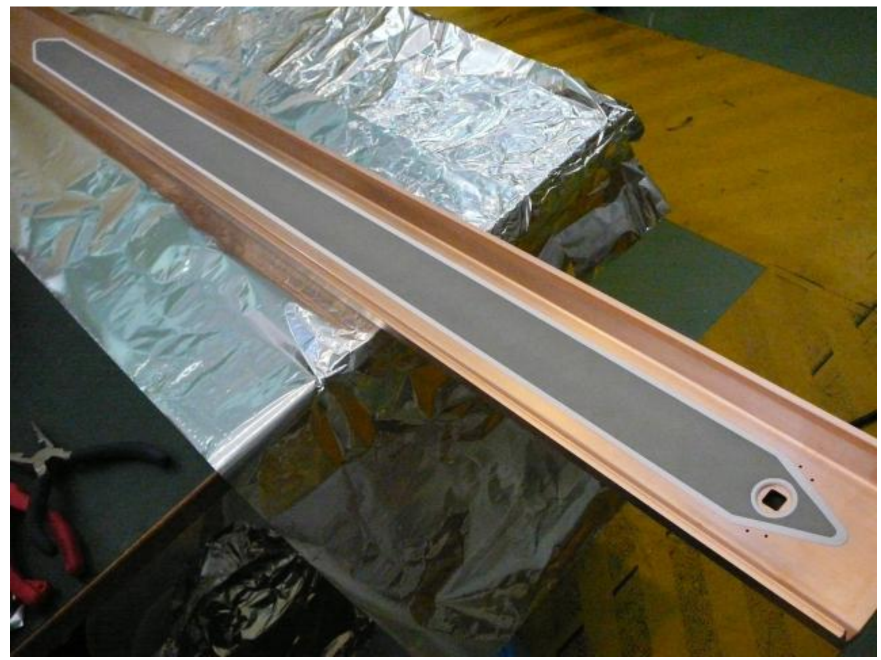
- A beam pipe with electrode for actual beam test was produced in 2010.
- The beam pipe was installed in a SC wiggler magnet (L0) at CesrTA in April, 2010.
- The beam pipe has an electron monitor (RFA, Retarding Field Analyzer) at the opposite side from the electrode, and the electron population in the beam pipe can be measured just above the electrode.

Y. Suetsugu

KEK

- Thermal spray of electrode (Al_2O_3 and tungsten) on to a half-cut beam pipe

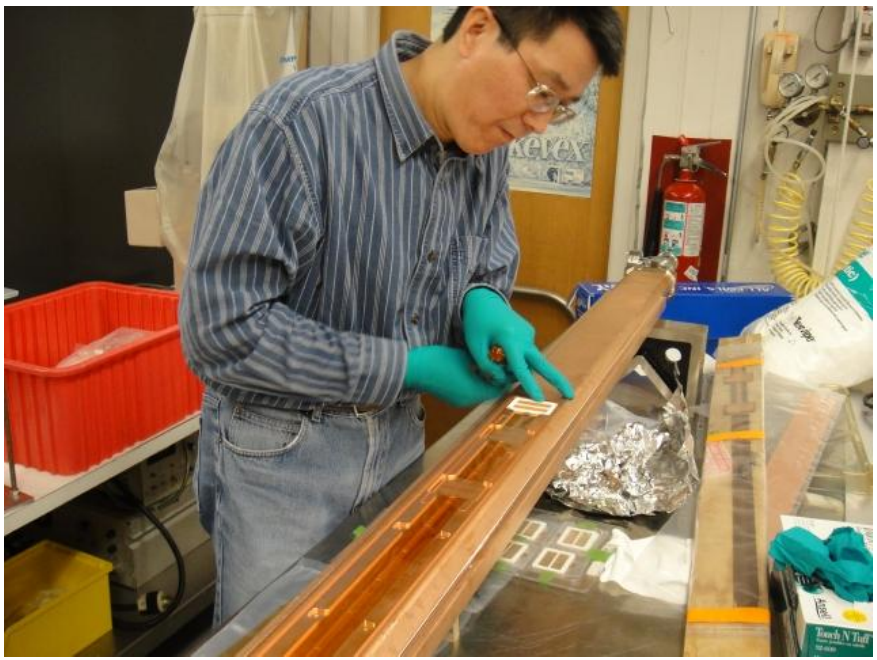


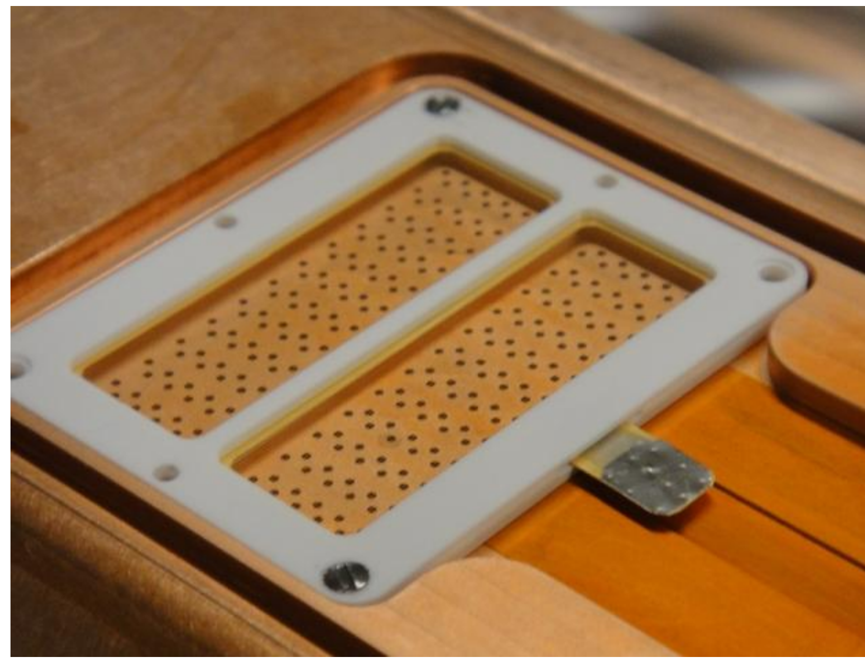


Y. Suetsugu

Cornell University

- Assembling of RFA at Cornell





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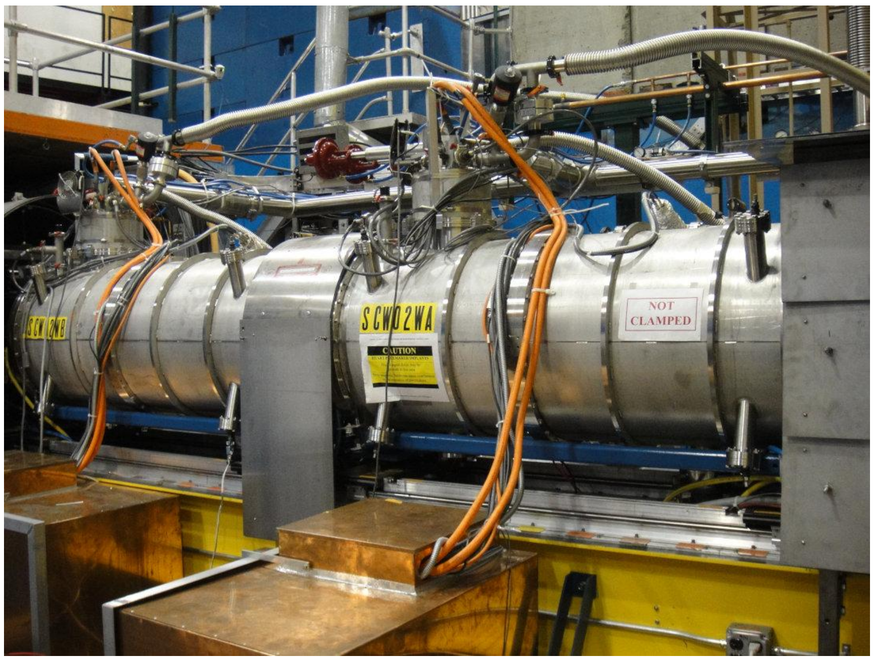
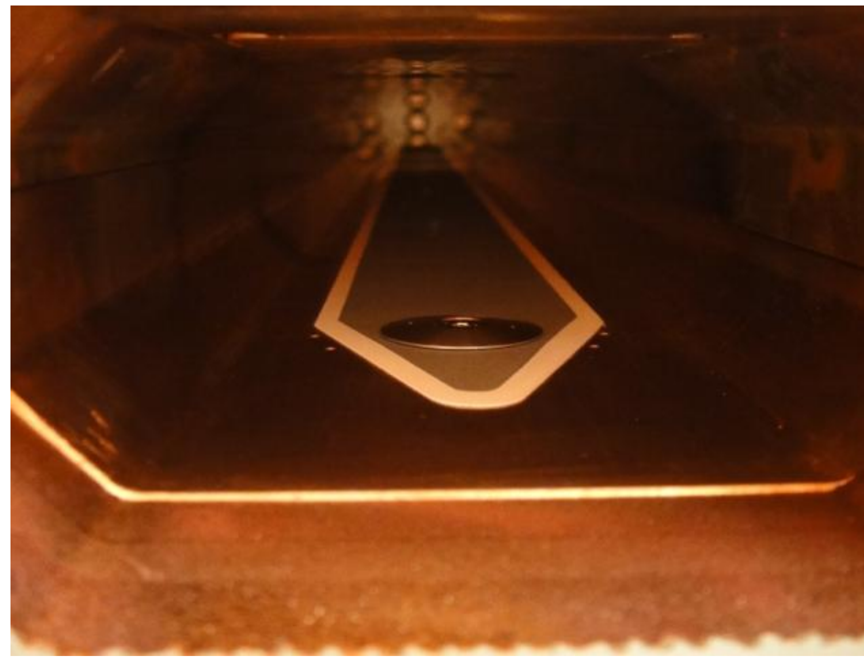
Cornell University

- Wiggler magnet and beam pipe for wiggler magnet (inside view) before experiment



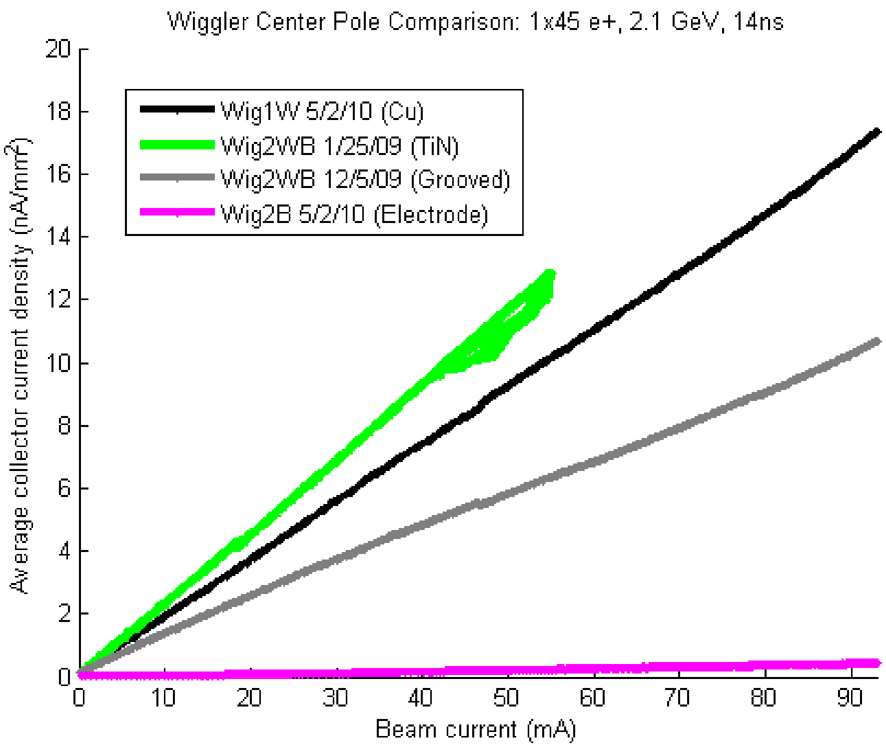


Experiment

- The experiment was performed in Run #7, 2010.
- The effectiveness of the electrode was compared with that of other mitigation techniques, such as bare copper, TiN coated copper, and grooved copper, under the same beam conditions.
- A significant reduction in electron density by using the electrode was confirmed.

Experimental Result

- The plot shows average collector current density vs beam current.(1x45 e+, 2.1 GeV, 14ns)
- TiN, Grooved, Electrode chamber all in same location at different times.
- Cu, TiN, and grooved chambers all within a factor of two.
- Electrode chamber does significantly better.

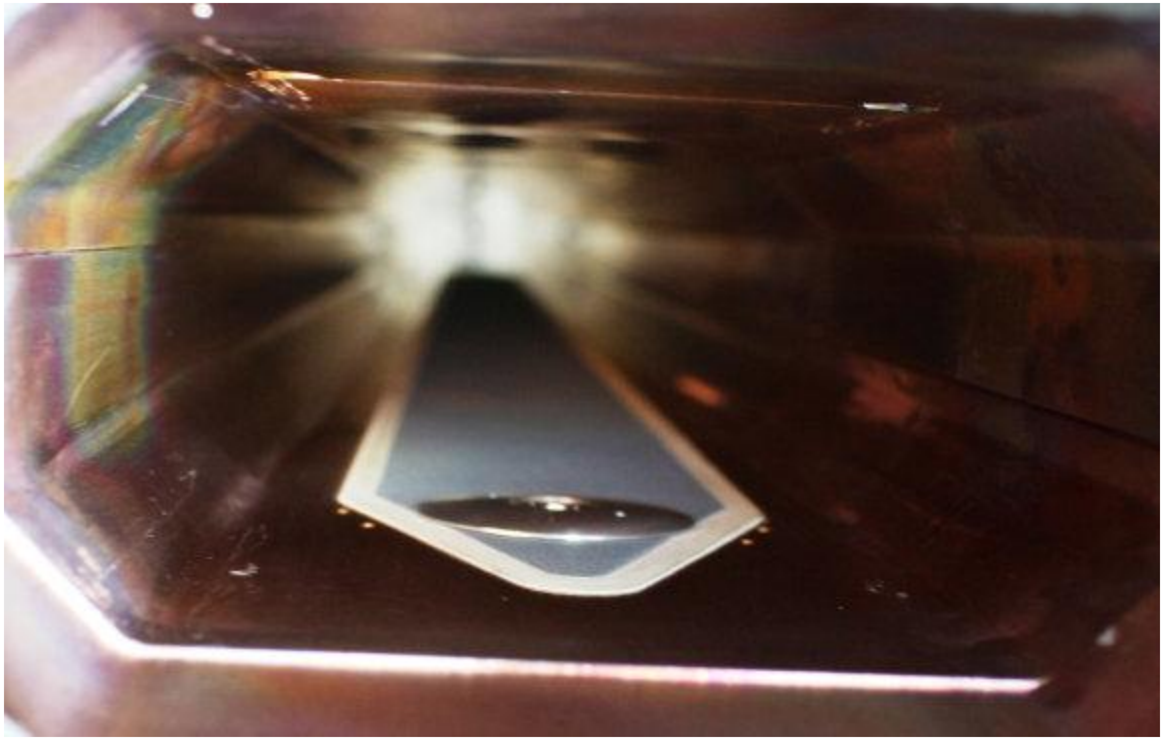


Joseph Calvey
8/9/2010
at ECLOUD10

Y. Suetsugu

After experiment

- The thermal sprayed electrode was visually inspected in January, 2011. (By Yulin Li)
- The electrode is in excellent condition.



Y. Suetsugu

Results

- Based on the experiment at KEKB and CesrTA:
  - Wiggler chambers for SuperKEKB will use clearing electrodes to suppress electron cloud build-up.
  - In the report of “Recommendation for Mitigations of the Electron Cloud Effect in the ILC Damping Ring” (ECLOUD10), clearing electrodes deposited via thermal spray on copper chambers was recommended for wiggler regions.

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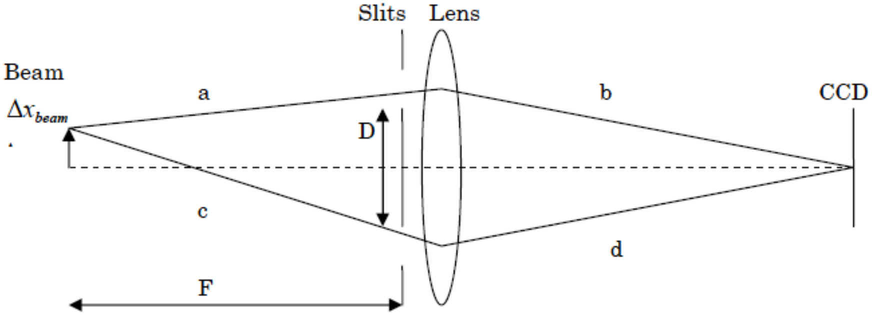
Beam size measurement at SuperKEKB

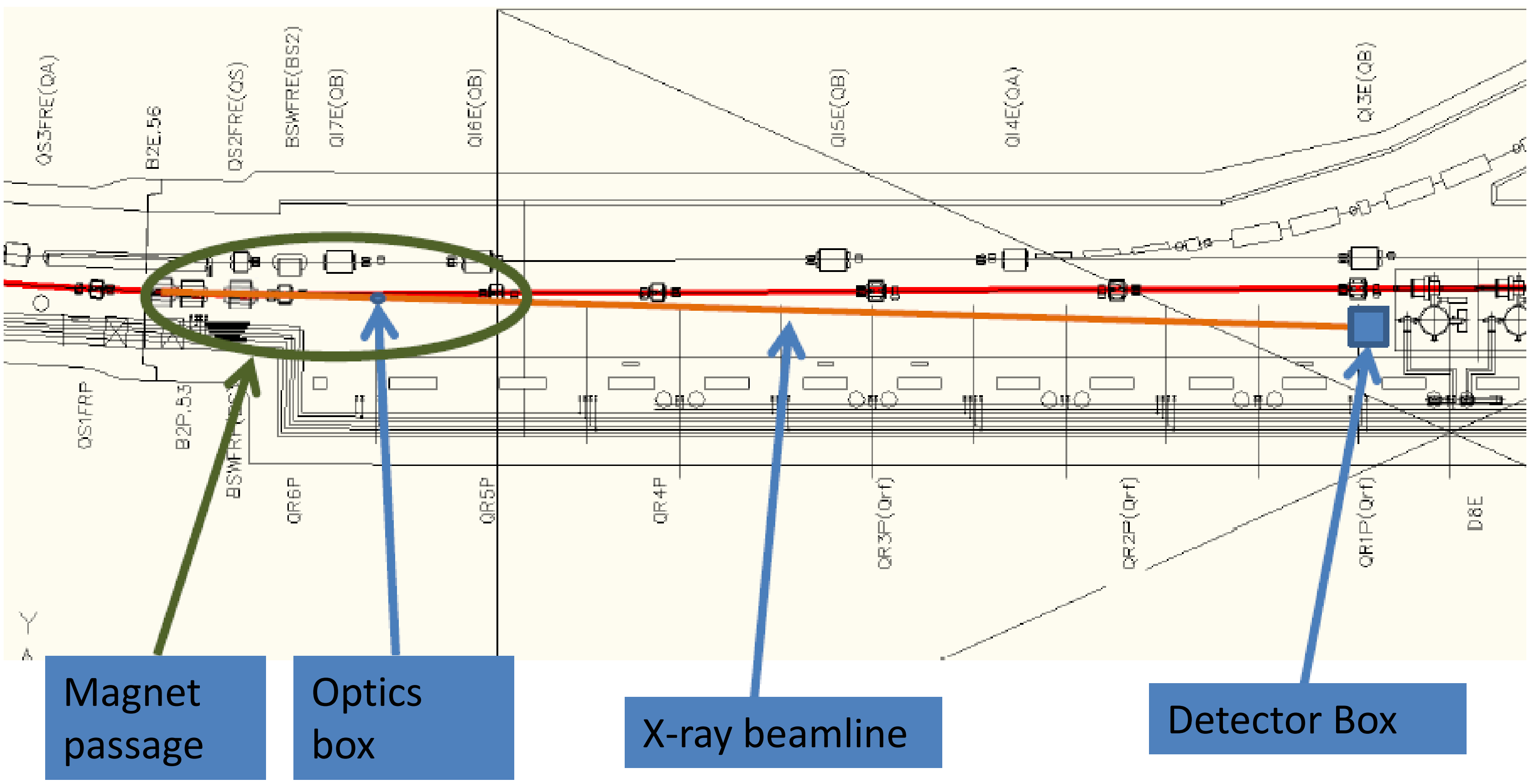
SR Source Bend Parameter	S-LER1 (BSWFRP)	S-HER (BSWOLE)	Units
ε_x	3.20E-09	4.60E-09	m
κ	0.27%	0.24%	
ε_y	8.64E-12	1.10E-11	m
β_y	29.98	32.49	m
σ_y	16.1	18.9	μm
Beam Energy	4	7	GeV
Bend effective length	0.89	2.90	m
Bend angle	5.04	5.00	mrad
Bend radius ρ	179.0	580.0	m
Observation wavelength λ	4.00E-07	4.00E-07	m
SR Opening angle θ_c (λ)	1.0	0.7	mrad
Slits opening angle D/F	1.2	1.1	mrad
Max. Visibility (fringe depth) γ_{max}	95%	95%	
Min. measurable beam size $\sigma_{y\ min}$	17.3	18.4	μm

- Resolution fundamentally limited by measurement wavelength and opening angle between slits from beam (D/F).
- Max. slit separation determined by beam spread and mechanical considerations.

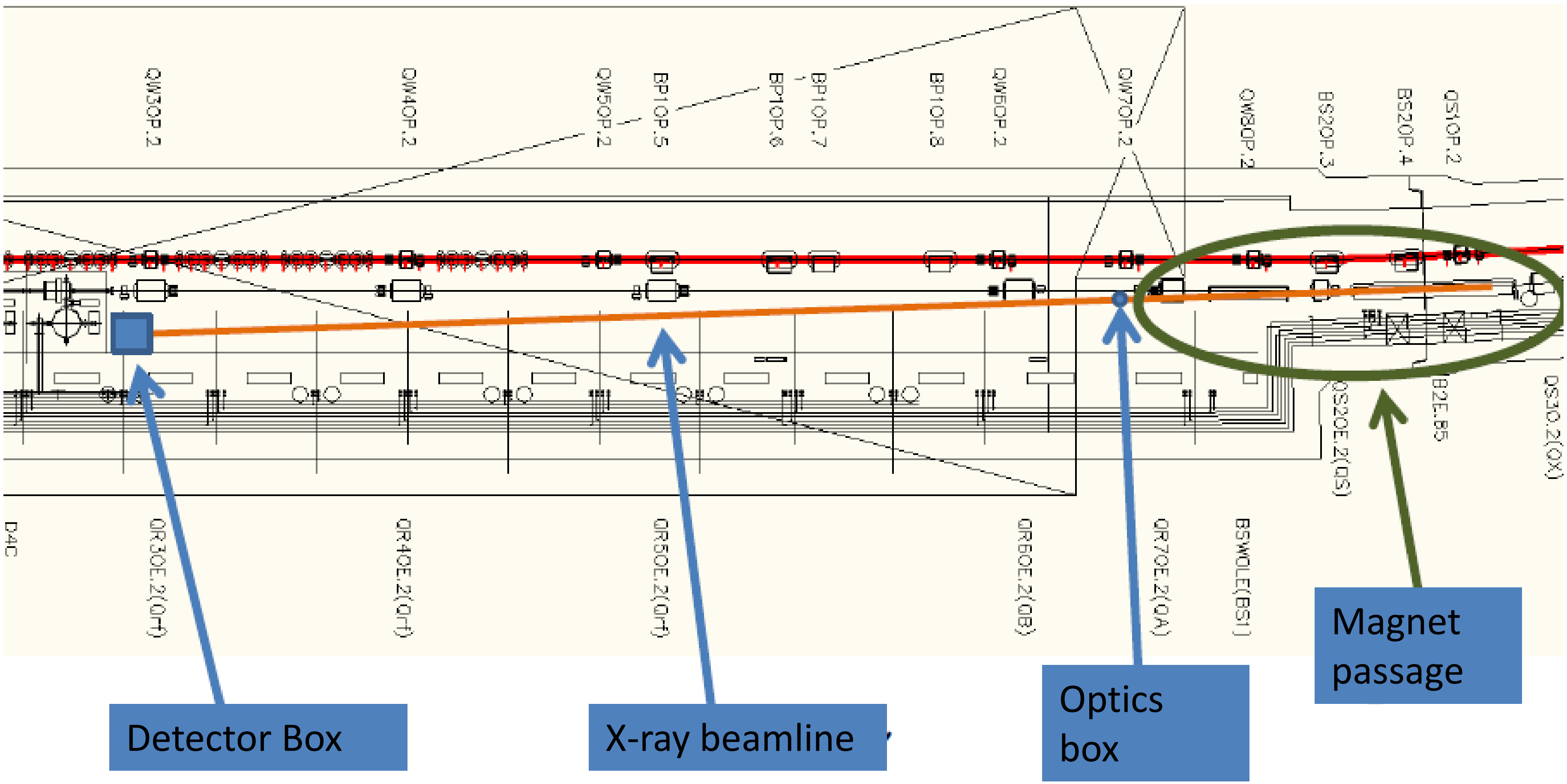


- Vertical beam size measurement is possible with interferometers, though is near the limit of the interferometer resolution.
- Interferometer is also not capable of bunch-by-bunch, turn-by-turn measurements.
- ➔Use x-ray beam size monitors

XRM: LER X-ray beamline (Fuji D8)



XRM: HER X-ray monitor beamline (Oho D4)



XRM: Coded Aperture Imaging

Technique developed by x-ray astronomers using a mask to modulate incoming light. Resulting image must be deconvolved through mask response (including diffraction and spectral width) to reconstruct object. Open aperture of 50% gives high flux throughput for bunch-by-bunch measurements. Heat-sensitive and flux-limiting monochromator not needed.

We need such a wide aperture, wide spectrum technique for shot-by-shot (single bunch, single turn) measurements.

Source distribution:

$$\begin{bmatrix} A_\sigma \\ A_\pi \end{bmatrix} = \frac{\sqrt{3}}{2\pi}\gamma\frac{\omega}{\omega_c}\left(1+X^2\right)(-i)\begin{bmatrix} K_{2/3}(\eta) \\ \frac{iX}{\sqrt{1+X^2}}K_{1/3}(\eta) \end{bmatrix},$$

where

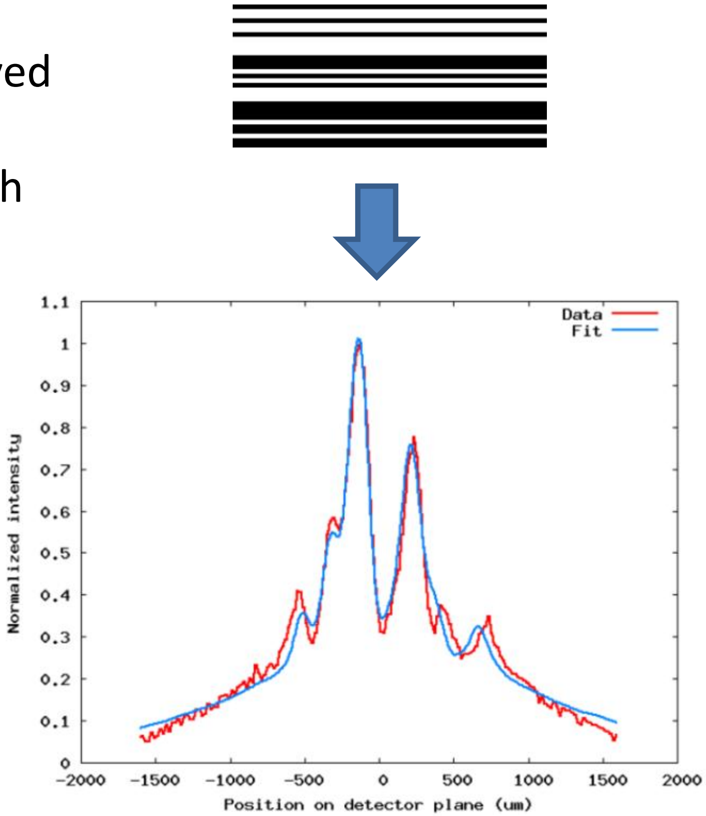
$$X = \gamma\psi,$$

+

$$\eta = \frac{1}{2}\frac{\omega}{\omega_c}\left(1+X^2\right)^{3/2},$$

Kirchhoff integral over mask
(+ detector response)
→ Detected pattern:

$$A_{\sigma,\pi}(y_d) = \frac{iA_{\sigma,\pi}(\text{source})}{\lambda}\int_{\text{mask}}\frac{t(y_m)}{r_1 r_2}e^{i\frac{2\pi}{\lambda}(r_1+r_2)} \times\left(\frac{\cos\theta_1+\cos\theta_2}{2}\right)\mathrm{d}y_m,$$



Measured slow-scan detector image (red) at CesrTA, used to validate simulation (blue)

XRM: Single-shot resolution estimation

- Want to know, what is chance that a beam of a certain size is misfit as one of a different size?
- Tend to be photon statistics limited. (Thus coded aperture.)
- So:
  - Calculate simulated detector images for beams of different sizes
  - "Fit" images pairwise against each other:
    - One image represents true beam size, one the measured beam size
    - Calculate χ^2/ν residuals differences between images:

N = # pixels/channels
n = # fit parameters (=1, normalization)
S_i = expected number of photons in channel i

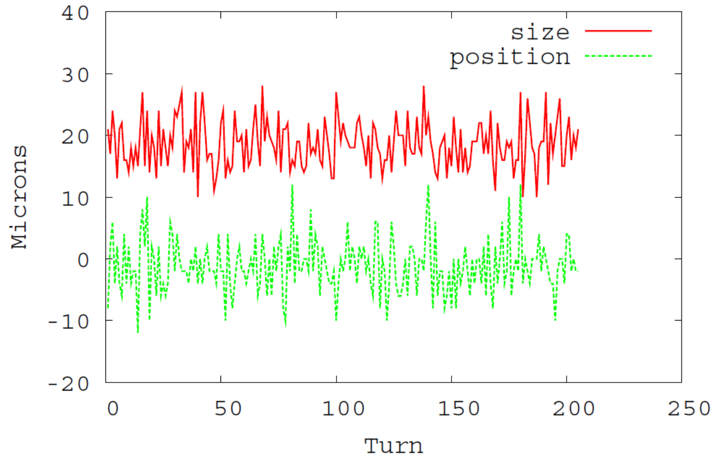
$$\frac{\chi^2}{\upsilon} = \frac{1}{N-n-1}\sum_{i=1}^{N}\frac{[s_i' - s_i]^2}{\sigma_i^2},$$

    - Weighting function for channel i:

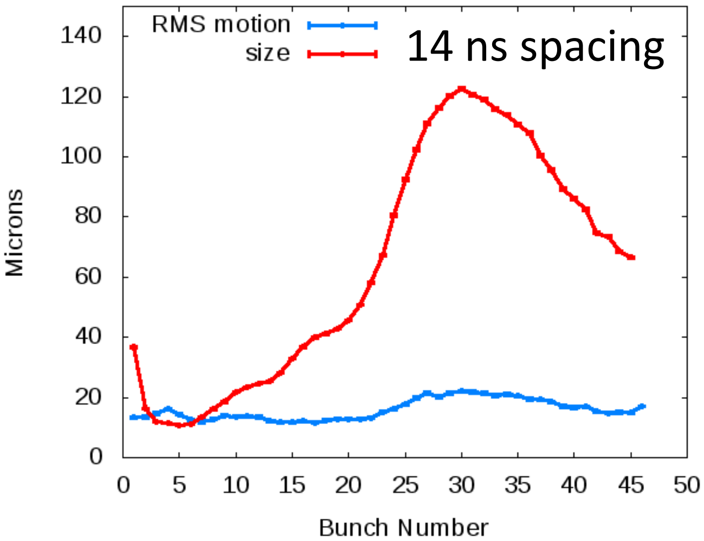
$$\sigma_i = \sqrt{s_i}\,.$$

  - Value of χ^2/ν that corresponds to a confidence interval of 68% is chosen to represent the 1-s confidence interval

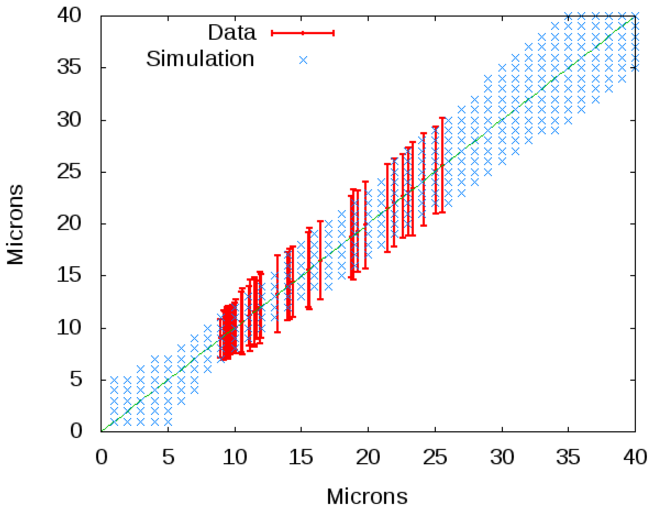
XRM: Coded Aperture tests at CesrTA



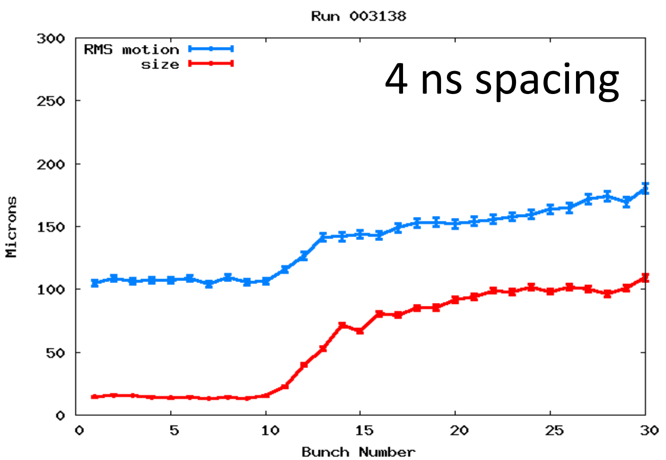
Example of turn-by-turn size and position data (one bunch out of train)



Examples of bunch-by-bunch data (electron-cloud blow-up study data)
Single-shot data average for each bunch



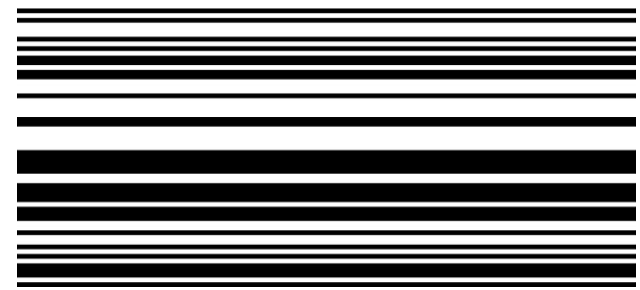
Single-shot resolution (simulation + measured spread)



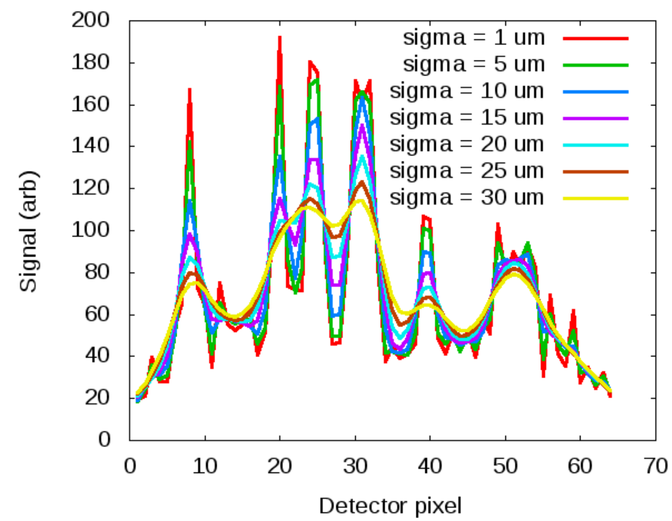
XRM: SuperKEKB x-ray monitor

Xray Source Bend Par.	S-LER (BS2FRP.1)	S-HER (BS2E.82)	Units
ε_x	3.20E-09	4.60E-09	m
κ	0.27%	0.24%	
ε_y	8.64E-12	1.10E-11	m
β_y	50.0	11.5	m
σ_y	20.8	11.3	μm
Beam Energy	4	7	GeV
Effective length	0.89	5.9	m
Bend angle	28.0	55.7	mrad
ρ	31.7	105.9	m
Critical Energy	4.4	7.1	keV

- Mask:
  - 59-element, 10 μm/element URA
  - High-power design
    - 10 μm Au mask
    - 625 μm Si substrate
    - Test at CesrTA
  - Other patterns, materials under study
- Detector:
  - 64-channel, 50 μm
  - More channels desirable, for background subtraction and to accommodate beam deviations.



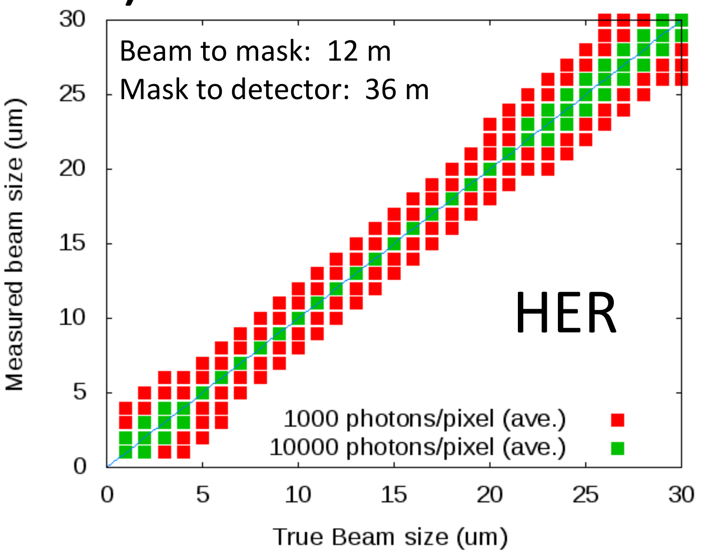
Uniformly Redundant Array (URA) for x-ray imaging to be used at SuperKEKB

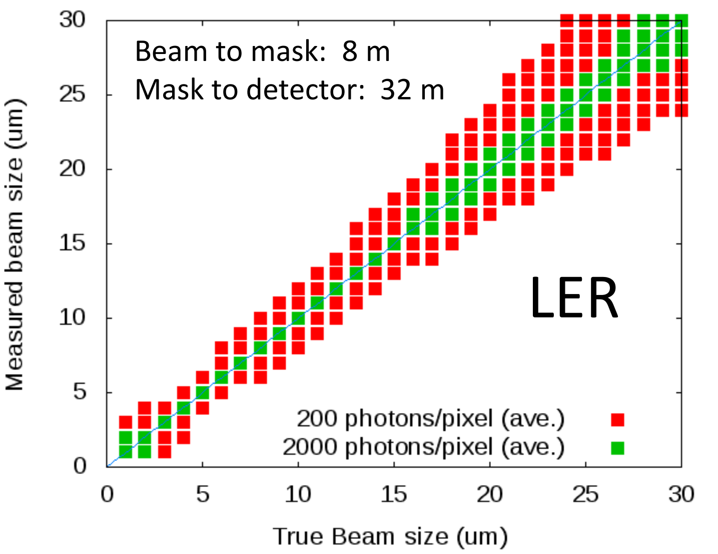


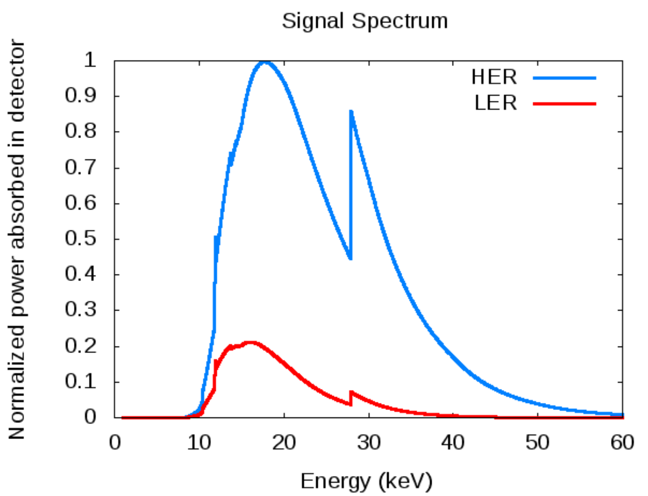
Simulated detector response for various beam sizes at SuperKEKB LER

XRM: SuperKEKB estimated single-shot resolutions (SuperKEKB full current)

- Red points: using 64-pixel detector of same type as at CesrTA (Fermionics)
- Green points: using detector with improved photon detection efficiency at higher x-ray energies (to be developed)



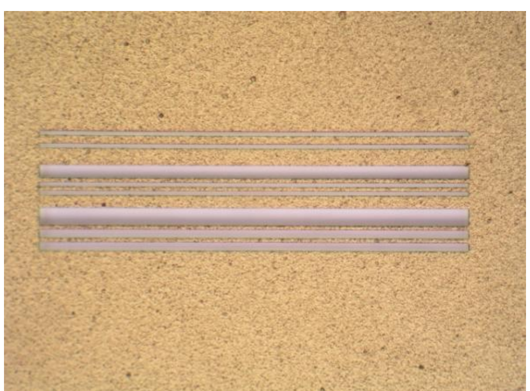




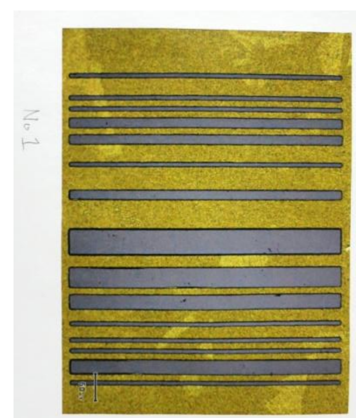
Detected spectrum (Fermionics detector)

XRM: Mask

- Tests at CesrTA show URA mask gives predicted single-shot resolution.
- High-power mask testing started in Fall, 2011
  - Thick Si mask installed at CesrTA for high-power testing.
    - CesrTA at 5.3 GeV can duplicate power load expected at SuperKEKB
    - SuperKEKB full current power load test successful!
      - Big thanks to folks at Cornell for their assistance and efforts.
    - Plan to test at ~20% higher power load
  - Diamond substrate mask also fabricated and installed at CesrTA, and ready to be tested.



Si+Au mask



Diamond+Au mask

Summary

- Collaborative studies done at CesrTA have been *very helpful* in the design of SuperKEKB.
  - Electron cloud blow-up threshold studies
  - Cloud mitigation methods
  - Low-emittance beam diagnostics
- Further studies will still be valuable:
  - Understanding better the electron-cloud blow-up mechanism (dominant instability mode under different conditions).
    - Dec?
  - X-ray beam size monitor development (high-power component testing, in particular).
    - This Fall for Si, plus future for diamond?
    - Low-emittance high-energy studies?
- **CesrTA has proven to be a very useful test bed for effective collaborative studies.**

Spares

Synrad 3D?

Machine Parameters

2011/July/20	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)/11.5(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	3.25×10^{-4}	4.55×10^{-4}		
σ_δ	$8.08(7.73)\times10^{-4}$	$6.37(6.31)\times10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6.0(5.0)	5(4.9)	mm	():zero current
ν_s	−0.0247	−0.0280		
ν_x/ν_y	44.53/44.57	45.53/43.57		
U_0	1.87	2.43	MeV	
$\tau_{x,y}/\tau_s$	43.1/21.6	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	8×10^{35}		$cm^{-2}s^{-1}$	

SuperKEKB luminosity projection