SuperKEKB Photon Monitors (SRM/XRM/LABM)

J.W. Flanagan, H. Ikeda, M. Arinaga, H. Fukuma, KEK
G.S. Varner, U. Hawaii
G. Bonvicini, Wayne State U.

SuperKEKB MAC
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Photon Monitors

- SRM: Synchrotron Radiation Monitor
  - Visible light monitor. Interferometer, streak, etc.
  - σ_z, σ_x (σ_y)
- XRM: X-ray Monitor
  - Pinhole, URA mask, etc.
  - σ_y (σ_x)
- LABM: Large Angle Beamstrahlung Monitor
  - SR-like radiation from interaction point (~300-600 nm)
  - Can measure relative offsets and size ratios at collision point.

- (Damping Ring monitors will be discussed by H. Ikeda.)

SRM: Extraction mirrors

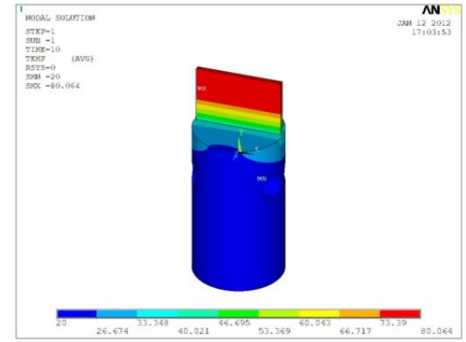
- Large incident power a source of heat-load induced deformations
- SuperKEKB LER source bend is recycled arc bend, with bending radius twice that of KEKB source bend.
    - Incident power becomes less than that of the KEKB HER, though more than that of the KEKB LER.
- HER bend does not change, and incident power becomes a bit higher than that of the KEKB HER.

	LER (BSWFRP)		HER (BSWOLE)	
	SuperKEKB	KEKB	SuperKEKB	KEKB
Energy(GeV)	4	3.5	7	8
Current(A)	3.6	2	2.6	1.4
Bending radius(m)	177.4	85.7	580	580
Power(W/mrad)	72	48	149	136
Distance to mirror (m)	11	11	13	13
Be Mirror width (mm)	35	35	35	35
Total incident power(W)	161	109	283	260

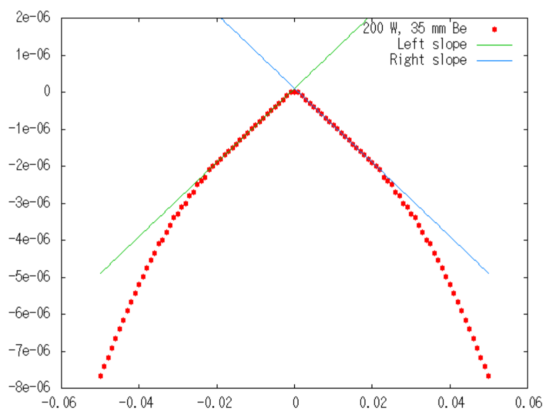
The heat deformation was already a great problem at KEKB, so would like to have a mirror that does not deform as much under the same heat load: diamond mirrors.

SRM: Diamond Mirrors

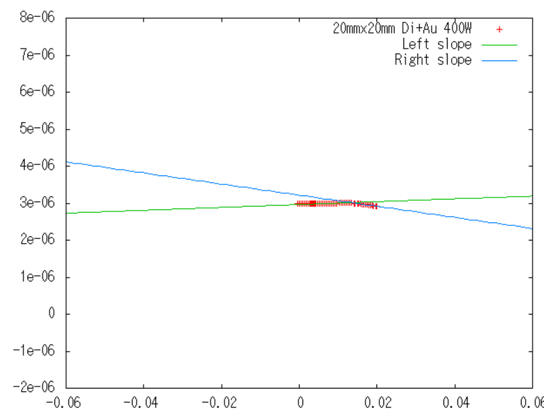
- Monocrystalline diamond:
  - Being developed by Seki Technotron
    - 10 mm x 20 mm x 0.5 mm prototype completed.
    - 20 mm x 20 mm x 1 mm prototype in fabrication
  - Surface: 3 μm Au, with thin Cr layer below that.
  - Diamond surface is (nearly) a single crystal, so good surface flatness expected (Ra ~ 2 nm, <~λ/50)
  - Very good heat conductance and low thermal expansion coefficient makes apparent change in magnification smaller than that of Be mirrors used at KEKB:
    - Beryllium: δmagnification = 43% @ HER full current
    - Diamond: δmagnification = 3% @ HER full current



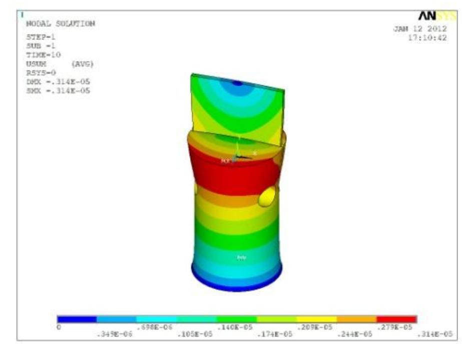
Diamond mirror temperature distribution due to 400W of SR power



Mirror surface distortion due to 200W of SR power at center of Be mirror



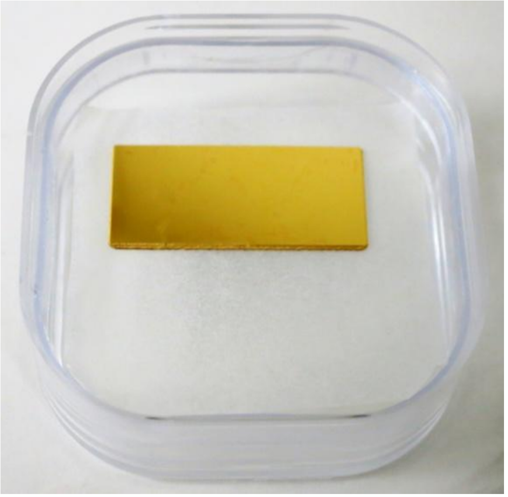
Mirror surface distortion due to 400W of SR power at center of Au+Dia mirror



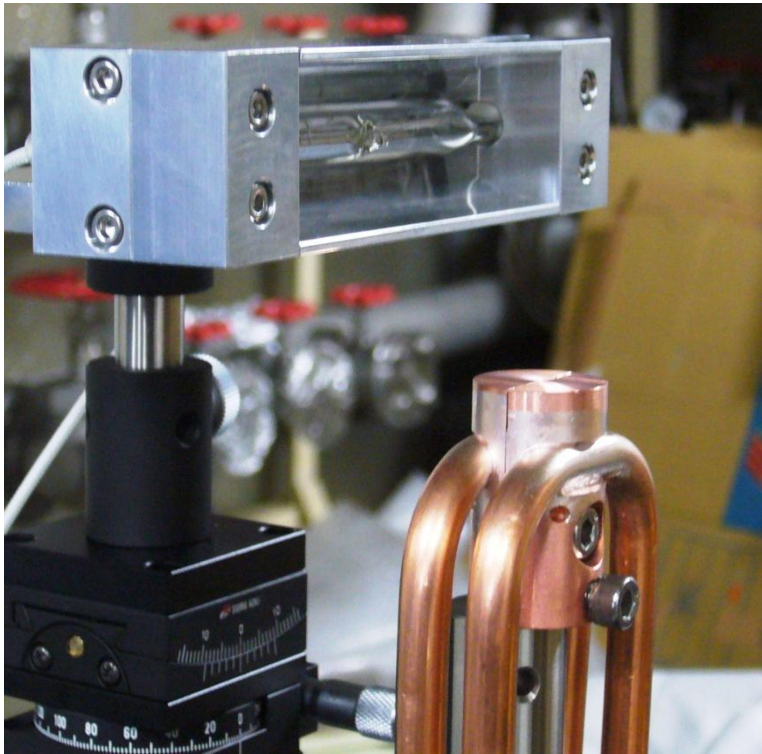
Diamond mirror surface distortion due to 400W of SR power

ANSYS simulations: M. Arinaga

SRM: Diamond Mirror & Holder



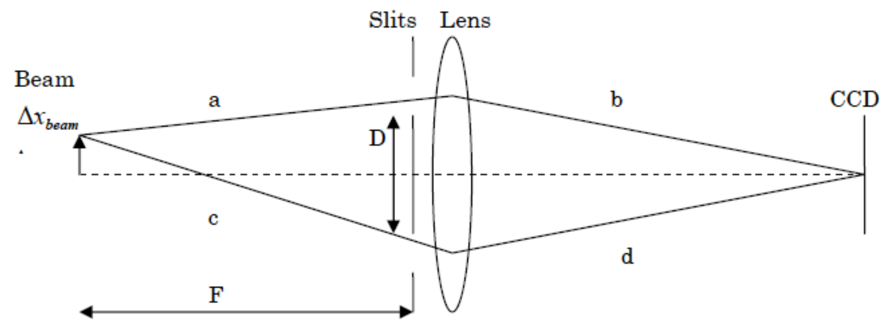
- Mirror:
  - 10 mm x 20 mm x 0.5 mm prototype made
  - 20 mm x 20 mm x 1 mm prototype in fabrication
- Holder:
  - Vertically split soft copper cylinder



SRM: Interferometers

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	0.7	0.7	mrad
Max. Visibility (fringe depth) γ_{max}	99%	99%	
Min. measurable beam size $\sigma_{y\ min}$	12.8	13.5	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.



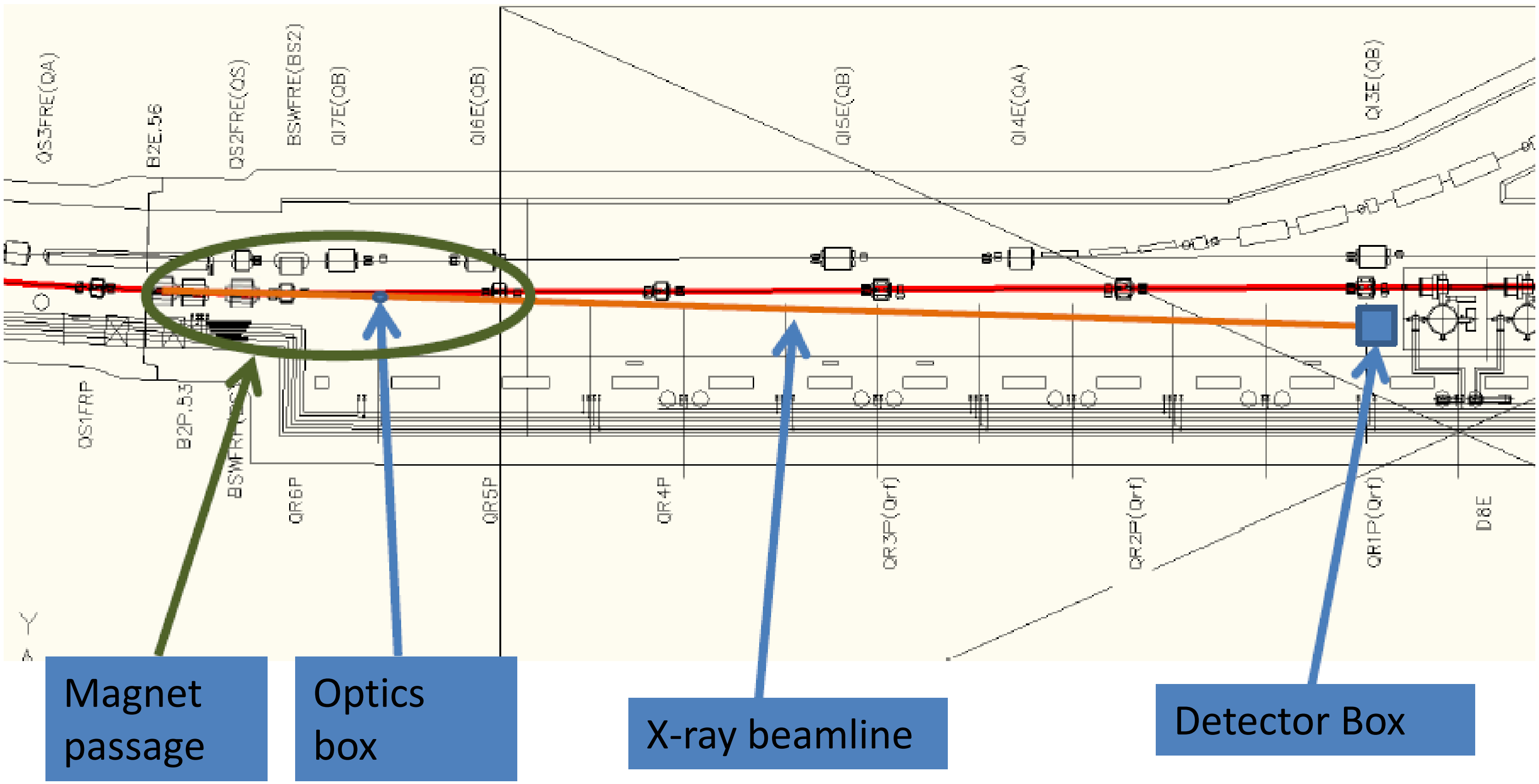
- Vertical beam size measurement is possible with interferometers, though is near the limit of the interferometer resolution.
- Measurement wavelength needs to be lowered to fit beam size into dynamic range.

  Also need to be able to measure 99% visibility. (Very difficult!)
- Limitation on slit separation is due to antechamber height (14 mm).
  - ◊Extraction mirror will be in antechamber for reduced impedance.
  - ◊If we could increase antechamber height by factor of two for 2 m (LER) or 4 m (HER) in front of extraction mirror, we could correspondingly reduce minimum measurable beam size by factor of two. Appears difficult due to presence of upstream quads (both HER and LER).

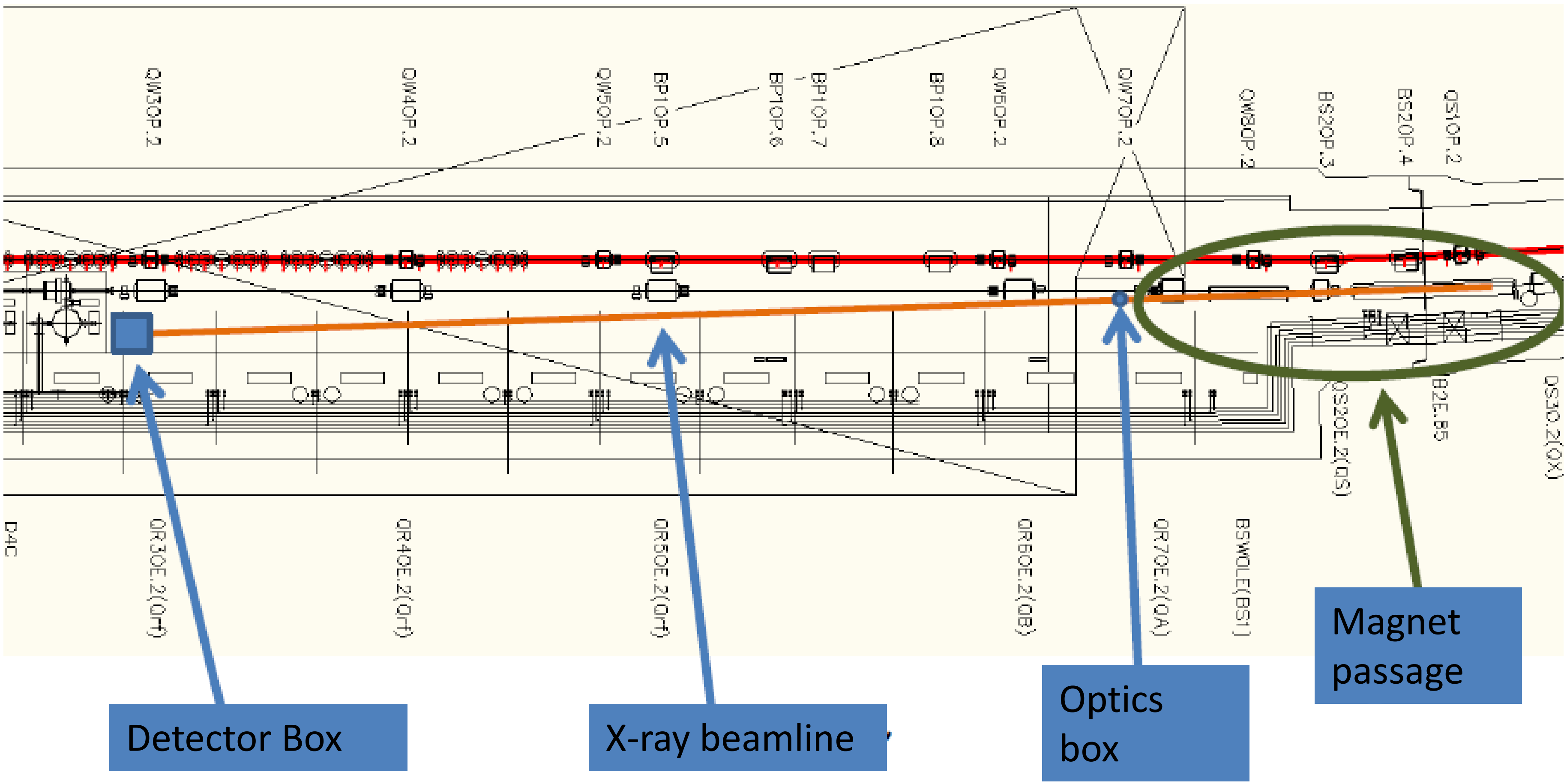
SRM: Summary

- Reuse present source bend locations
  - LER bend becomes longer, to reduce heat load
  - HER remains the same
- Would like to move downstream ~few meters
  - Put mirror in antechamber for reduced impedance
  - More effort in HER, since no antechamber already existing
- Bases under above-ground tunnel components will be reinforced/ to reduce vibrations
- Transfer lines will be rebuilt to be better sealed against air flow
- σ_z: Streak Camera
  - OK
- σ_x: Interferometer
  - OK (not single-shot, though)
- σ_y: Interferometer
  - Will be difficult to get required resolution
  - Not possible to get single-shot (single bunch, single turn) measurements, which may probably be needed for low-emittance tuning, based on experience at CesrTA.
  - However, should be useful for cross-checking with x-ray monitor at larger beam sizes.

XRM: LER X-ray beamline (Fuji D8)

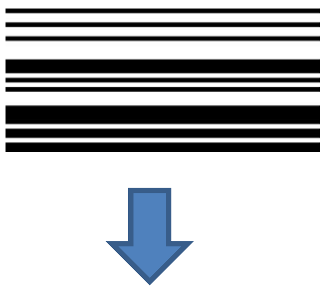


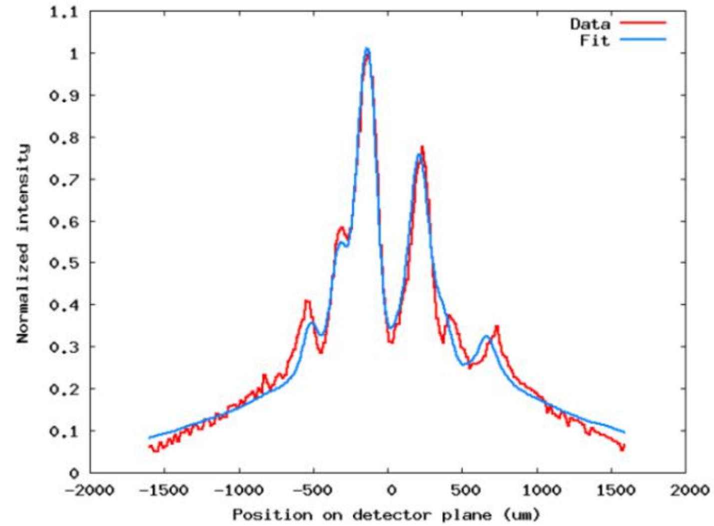
XRM: HER X-ray monitor beamline (Oho D4)



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.





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

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:

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

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*

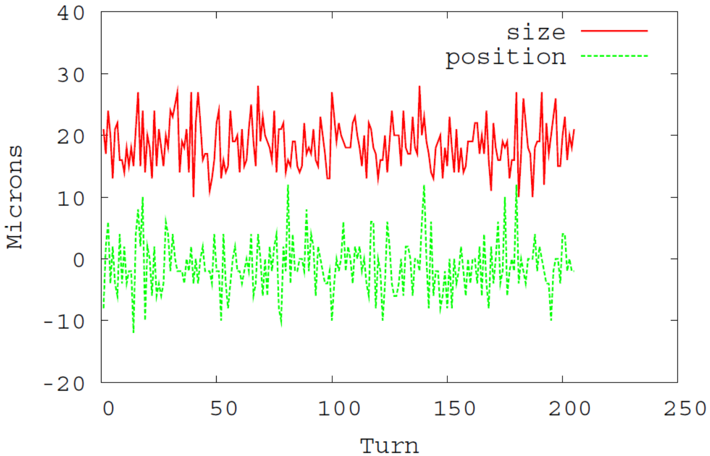
$$\frac{\chi^2}{\upsilon} = \frac{1}{N-n-1}\sum_{i=1}^{N}\frac{[s_i' - s_i]^2}{\sigma_i^2},$$

    - Weighting function for channel i:

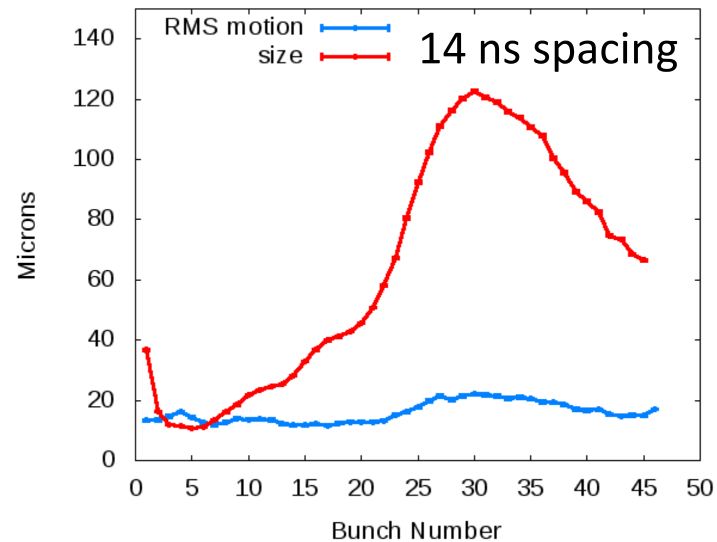
$$\sigma_i = \sqrt{s_i}\,.$$

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

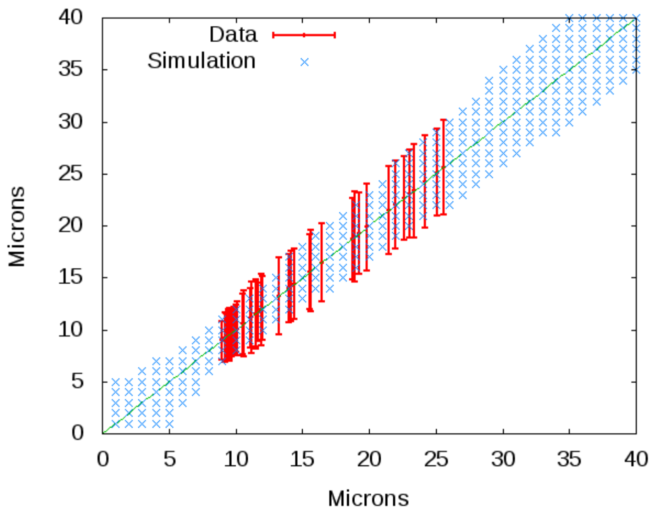
XRM: Coded Aperture tests at CesrTA



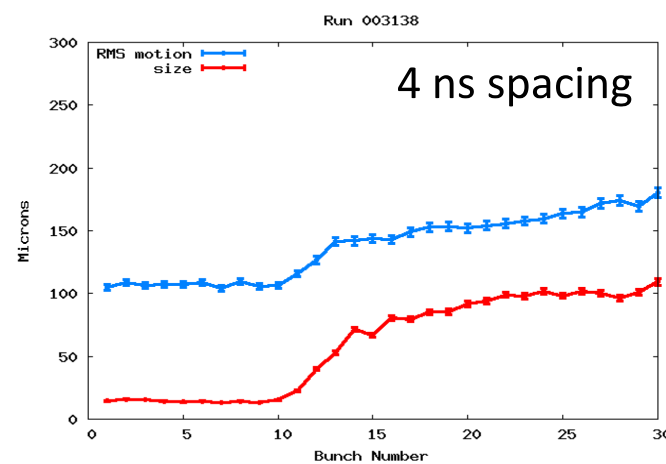
Example of turn-by-turn size and position data (one bunch out of train)



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



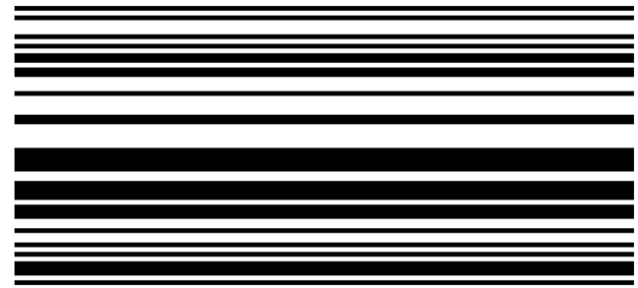
Single-shot resolution (simulation + measured spread)



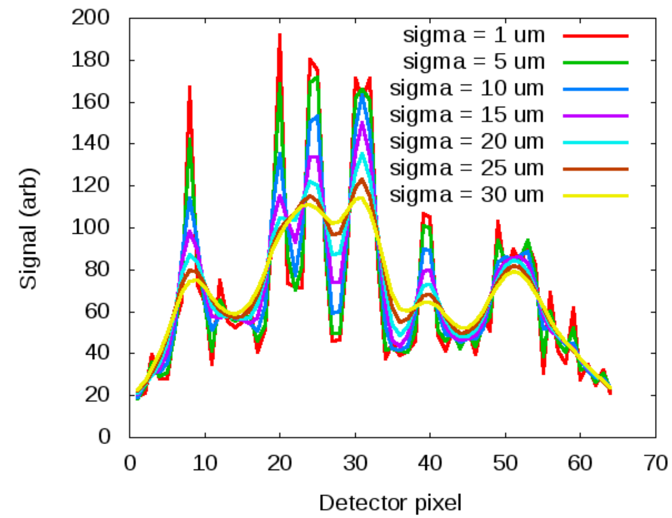
XRM: SuperKEKB x-ray monitor

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.



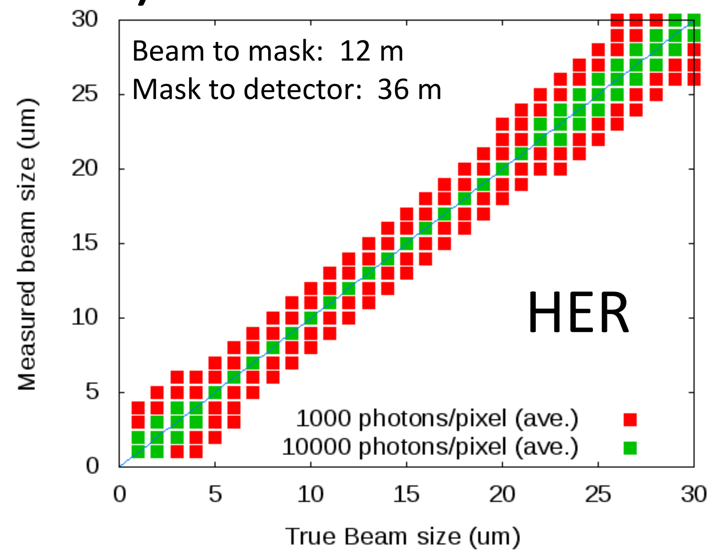
Uniformly Redundant Array (URA) for x-ray imaging to be used at SuperKEKB

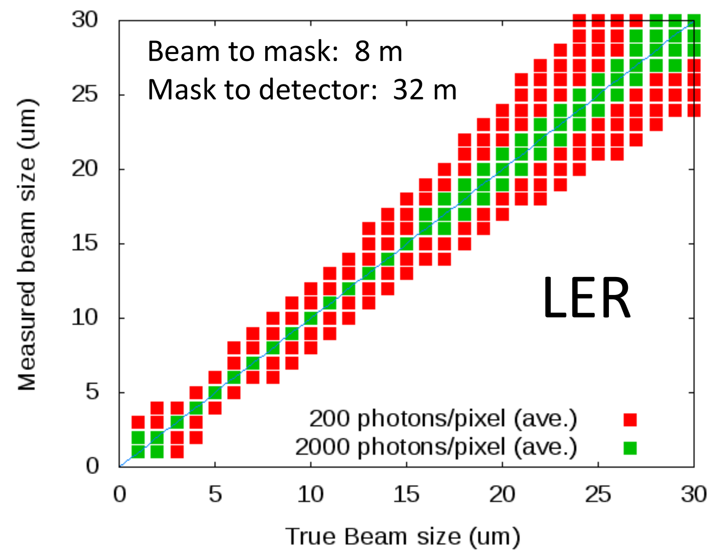


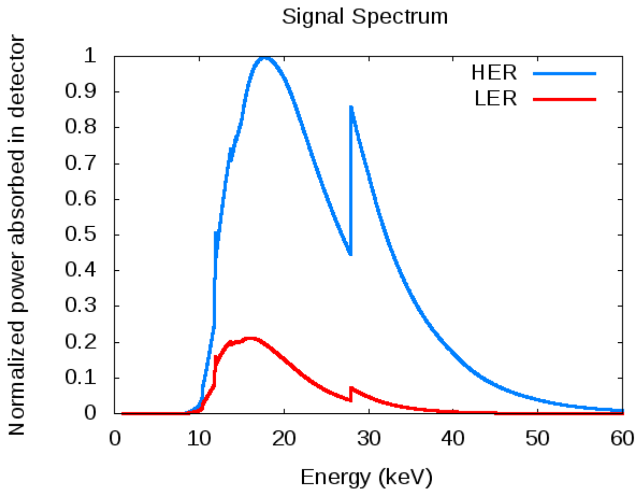
Simulated detector response for various beam sizes at SuperKEKB LER

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)



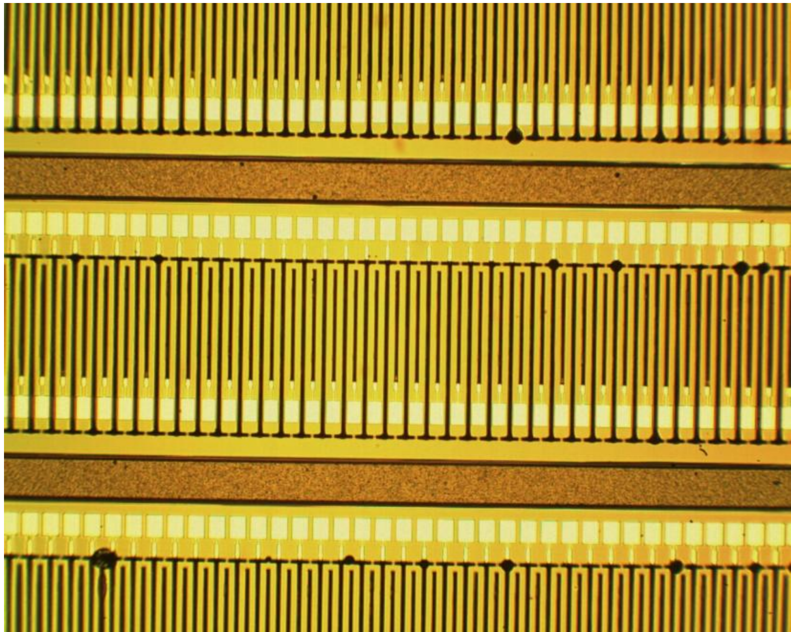




Detected spectrum (Fermionics detector)

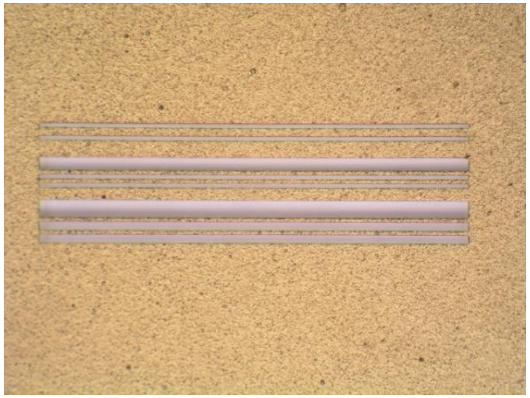
XRM: Detector

- Tests with Fermionics detector at Photon Factory showed that detection efficiency at high energies is very low
  - Active pixel depth is only 3.5 microns.
- Detector development needed for the future
  - Higher efficiency at hard x-ray spectrum seen at SuperKEKB
  - Faster response for being able to directly diagnose head-tail instabilities at SuperKEKB.
  - Trench diode design being pursued:
    - Deep but narrow pixels
    - First prototype fabricated (SLAC/UH)



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

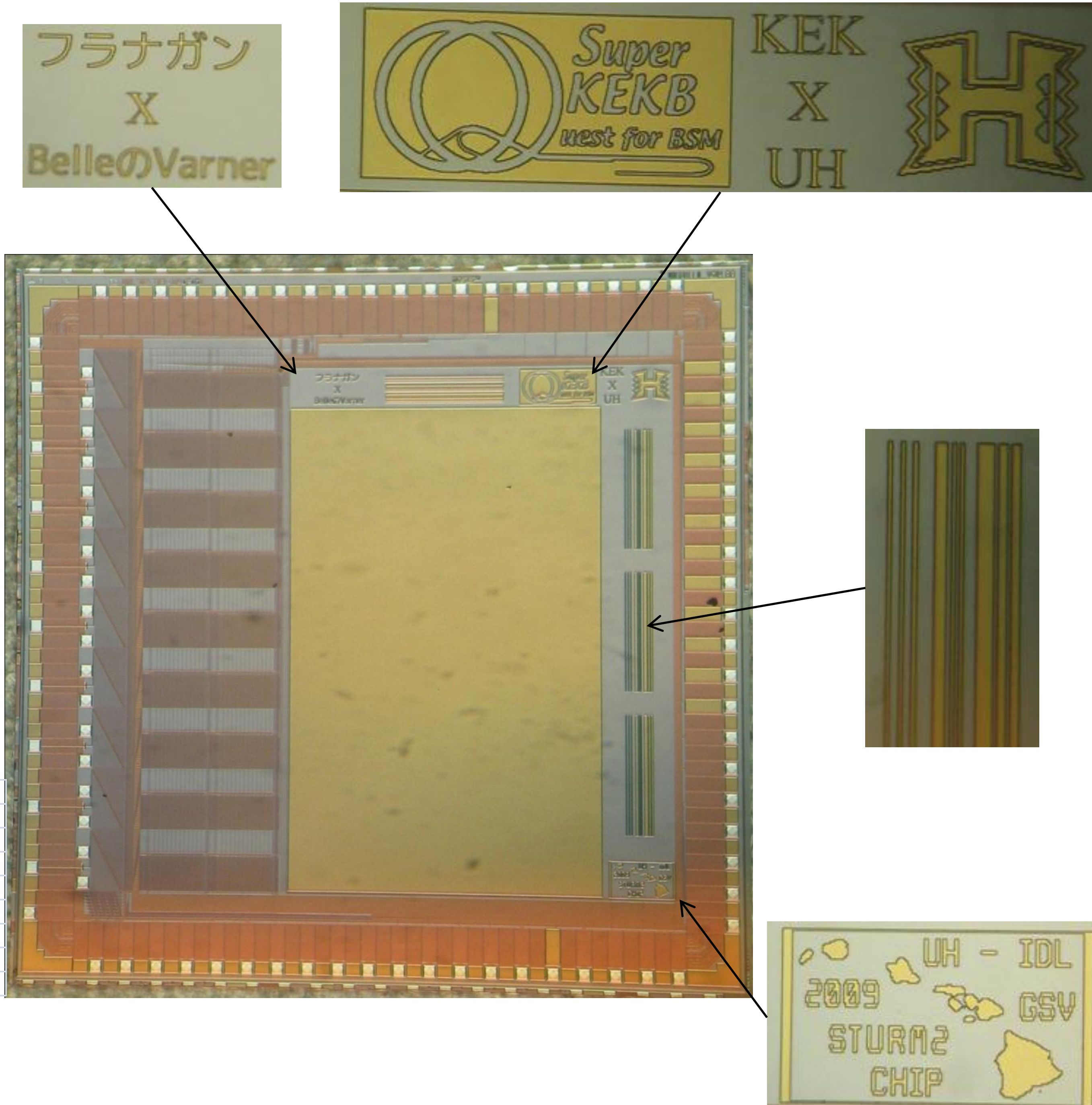
Diamond+Au mask

XRM: Digitizer

STURM2 ASIC

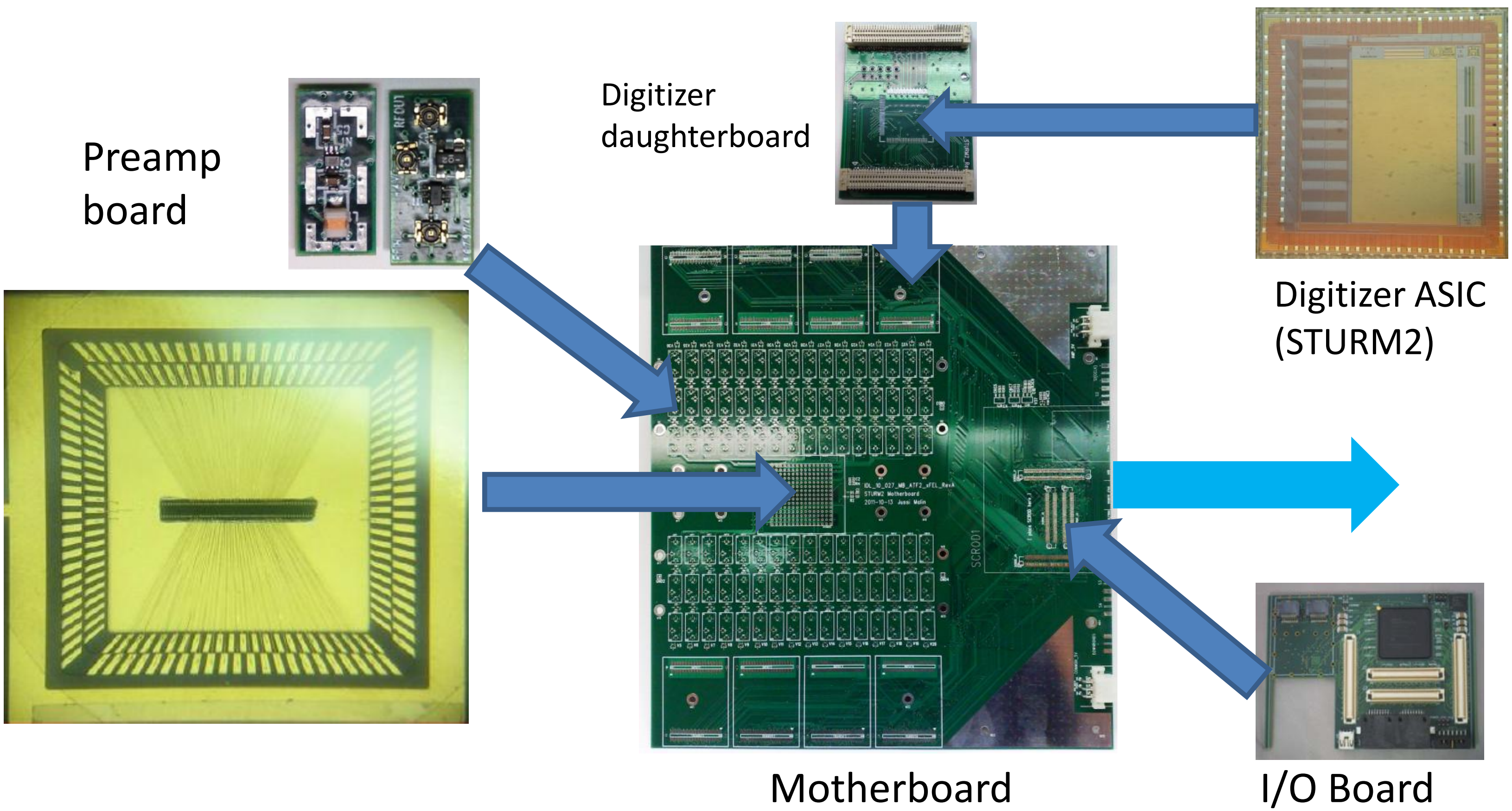
STURM ASIC for high-speed readout (G. Varner).
Ver. 1 tested at KEK PF, March 2009.
Ver. 2 fabricated.
Ver. 2 specs:

8	channels/STURM sampling
1	monitor channel
4	TSA sample buffers
8	samples/TSA buffer (32x channel)
288	Wilkinson conversion cells
1-200	GSa/s effective (5ps - 1ns Tstep)
1	word (RAM) sample readout
1+n*0.02	us to read n samples
100	kHz sustained readout (orbit)



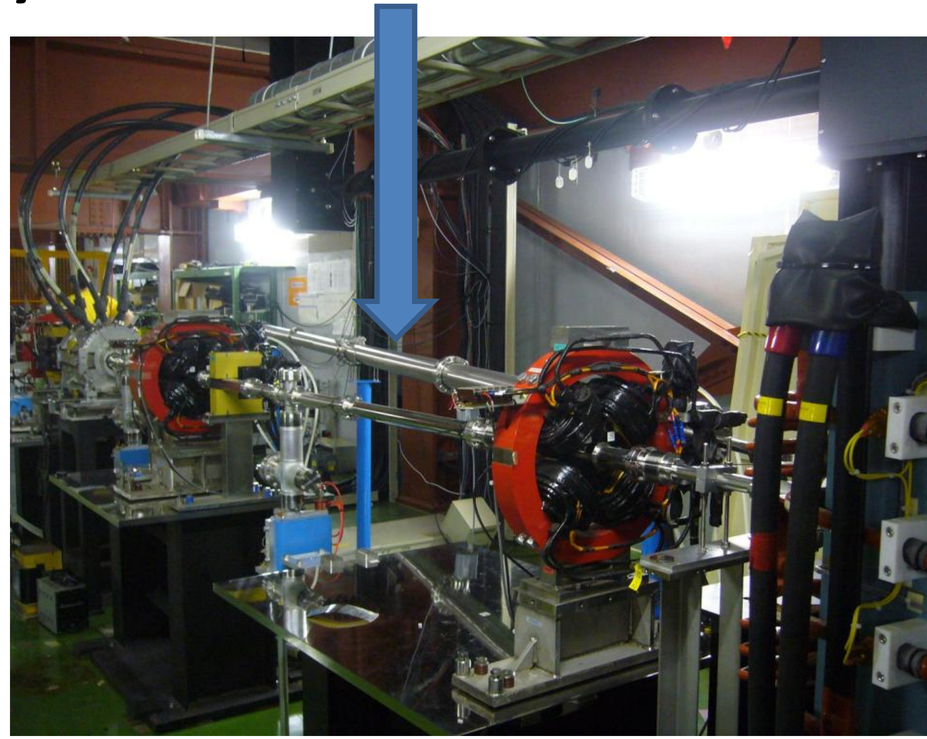
XRM: 64-channel system

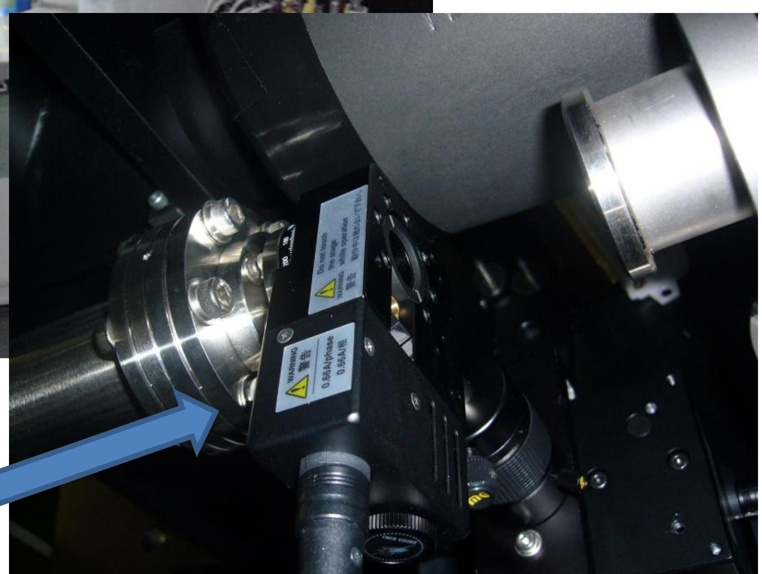
- 64-channel system for testing at ATF2
  - Using Fermionics (low-energy) detector.



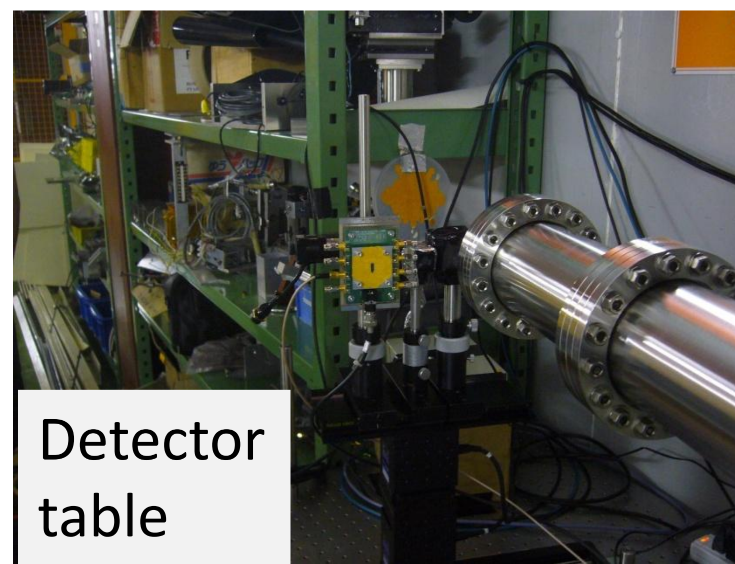
ATF2 x-ray beamline

During construction





Rotating mask holder



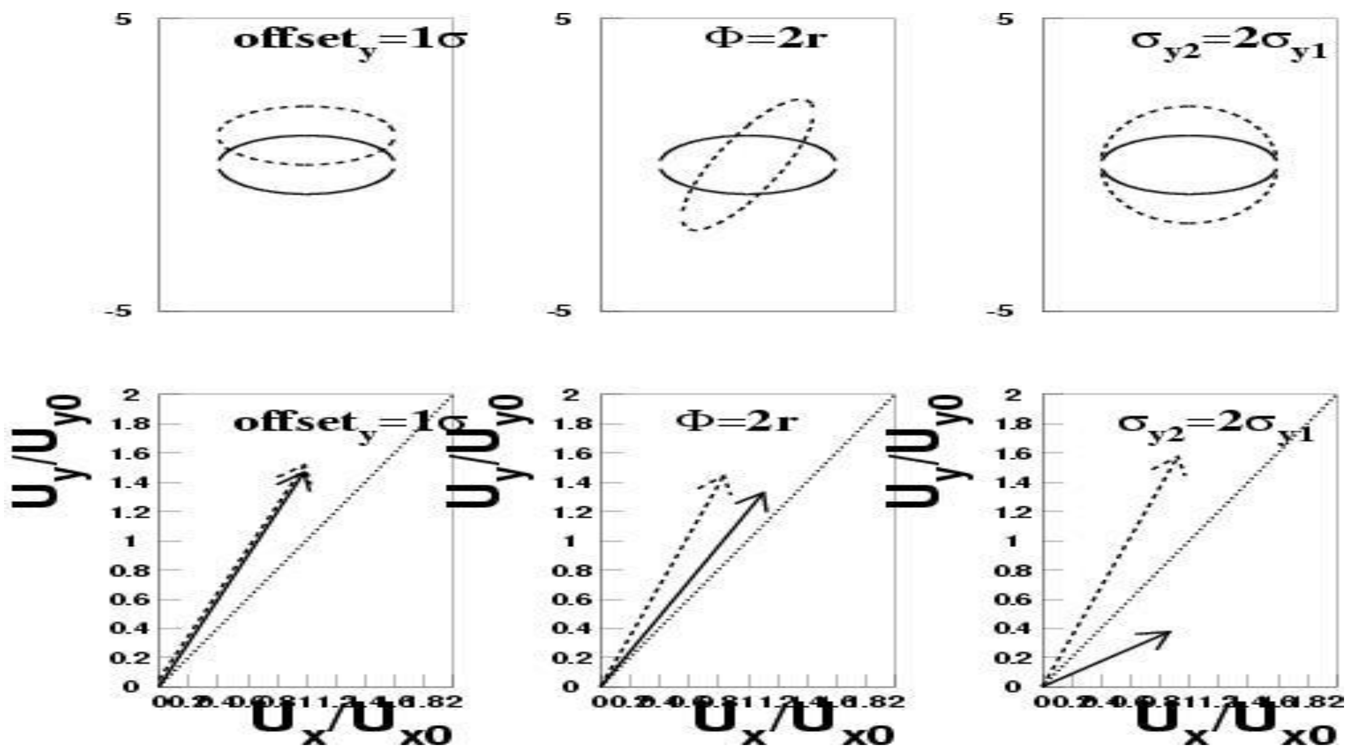
Detector table

XRM: Summary

- Source bends upstream of SRM source bends
  - LER bend is reused KEKB LER bend magnet (at half strength)
  - HER uses same current arc bend magnet
- σ_y: Coded Aperture Mask
  - Single-shot (single-bunch, single turn) resolution expected to be sufficient.
  - Single-shot mode probably be needed for low-emittance tuning, based on experience at CesrTA.
- σ_x: Possible, if single-shot measurements are needed
  - SRM should work for this in slow integration mode
- Being developed in collaboration with Cornell U. and U. Hawaii.
  - Testing different components at CesrTA and ATF2
- Development work continuing on detector and readout

LABM: Large Angle Beamstrahlung Monitor

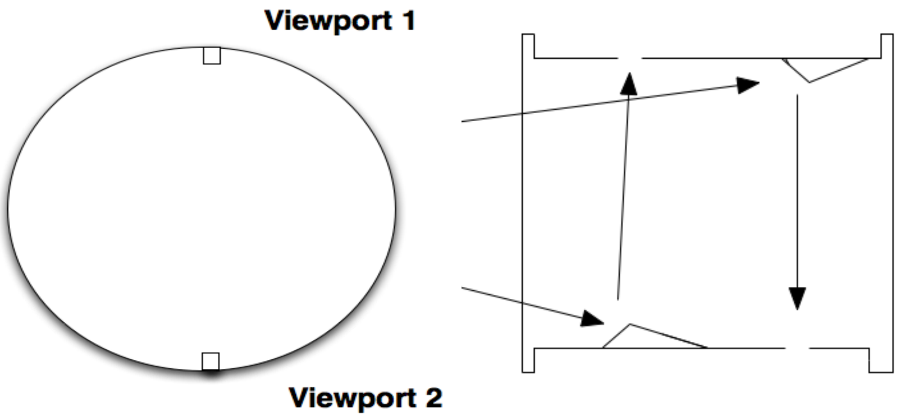
- The radiation of the particles of one beam due to the bending force of the EM field of the other beam
- Beamstrahlung POLARIZATION at specific azimuthal points provides unique information about the beam-beam geometry.

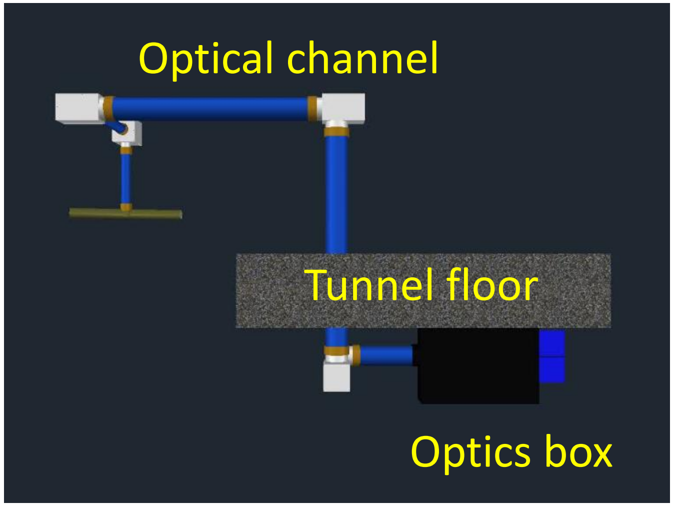


G. Bonvicini

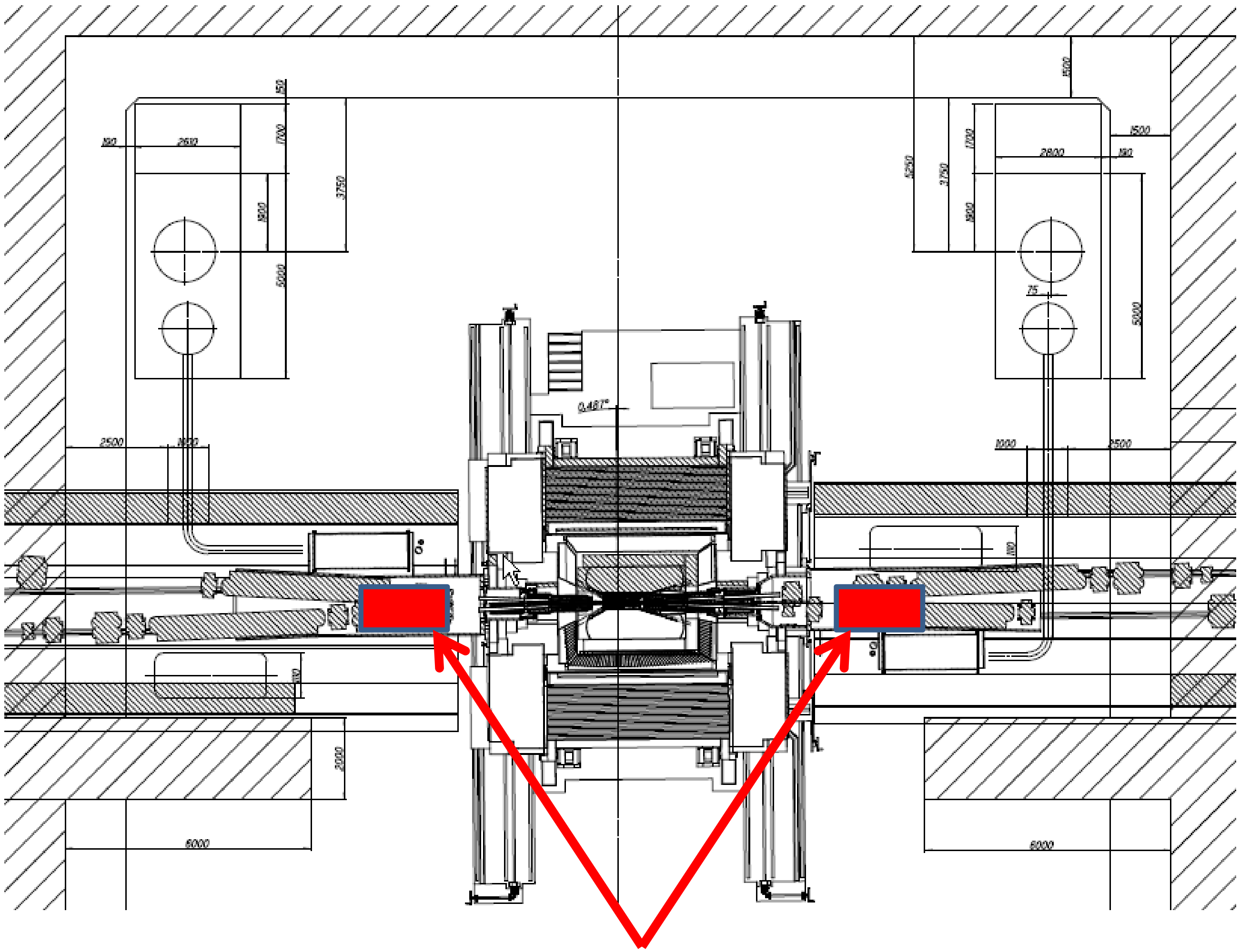
LABM: Layout

- 4 viewports and associated 4mm^2 mirrors on Beam Pipe (KEK), at 7-8 mrad w.r.t beam axis
- 4 narrow acceptance telescopes, which count photons in two polarizations and 4 bands (32 channels total, WSU)
- Build flexible electronics for a variety of beam measurements (Hawaii, Tabuk, WSU)
- Interface with EPICS (Luther)
- Discussions begun with company to make Be extraction mirrors (2 mm x 2.8 mm). (KEK)





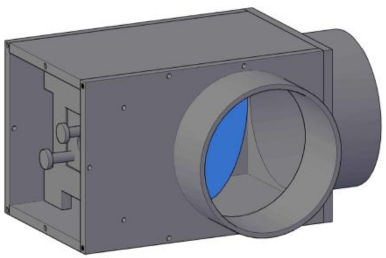
LABM: Optical box locations



Tsukuba B4 (below accelerator floor level)

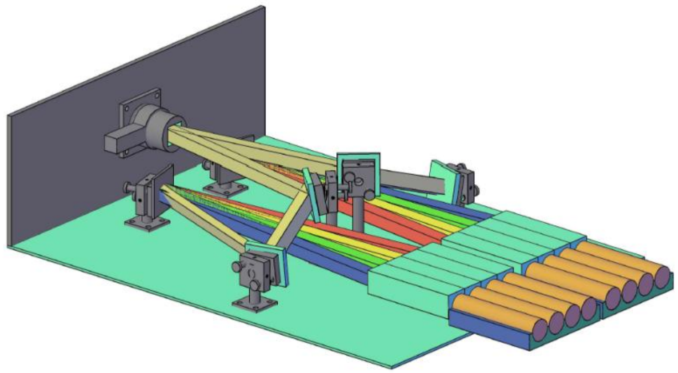
LABM: Optical channel

- Designed optical channel. Built first elbow and two test pipes. (Wane)

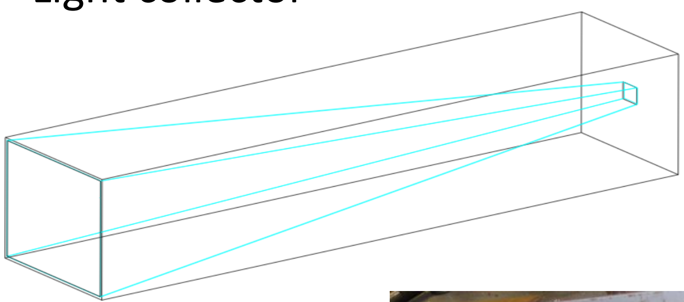


LABM: Optics box

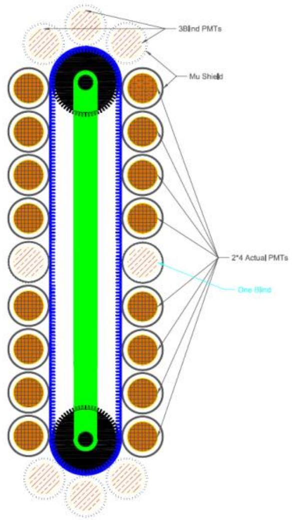
- Optics Box

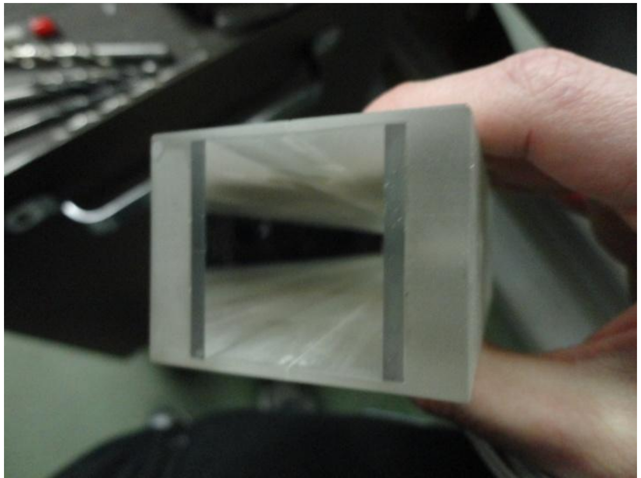


Light collector



PMT conveyor
Belt for relative
calibration





Summary

- Optical Channel prototype designed and built
- Optics Box designed. Production has started
- Work on electronics has started.
- Consulting with company on extraction mirror design.

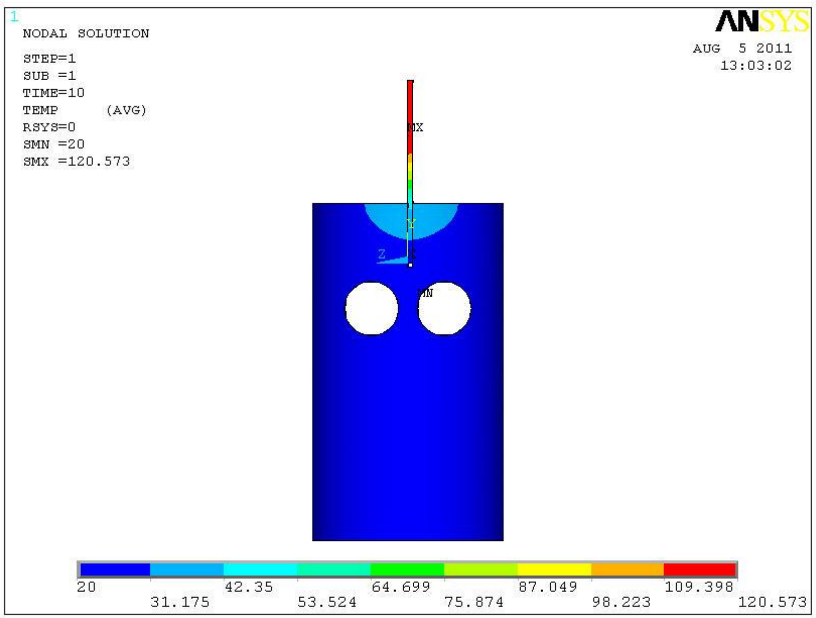
Photon Monitors Schedule

- 2012:
  - SRM
    - Mirror + holder heat distortion test
    - Extraction chamber design
  - XRM
    - Continue heat and imaging tests with high-power optics at CesrTA
    - Continue Electronics and detector development
    - Design beamline, determine magnet apertures required. Start fabrication of downstream beamline components.
  - LABM
    - Construction of optics box and PMT calibration conveyor
    - Start electronics readout development
    - Preparation for possible Frascati beam test in 2013
- At SuperKEKB turn-on:
  - SRM & XRM commissioning
- Sometime soon after (real, non-bakeout) turn-on:
  - LABM comissioning

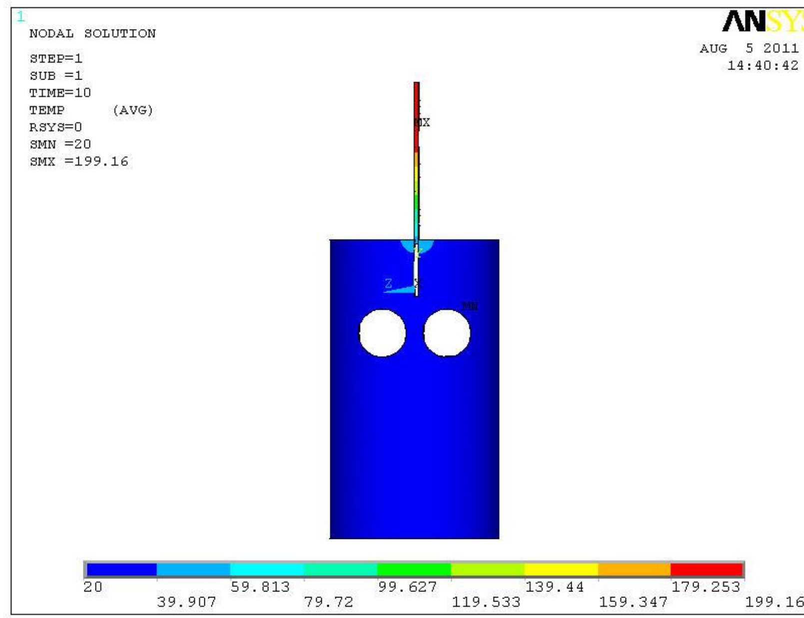
Spares

Effect of amount of contact surface between mirror and holder

6 mm of contact surface (contact equivalent to brazing)



0.5 mm of contact surface



Reducing effective contact surface to 1/10 of ideal raises maximum temperature by about a factor of 2.
(Distortion ~ linear with temperature.)

Examples of no-good holder designs