X-ray Monitor R&D at ATF2 Extraction Line

J.W. Flanagan, T. Mitsuhashi, H. Ikeda, H. Fukuma, M. Arinaga (KEK)

G.S. Varner, J. Anderson, M. Andrew, S. Negrashov, K. Nishimura, L. Ridley (U. Hawaii)

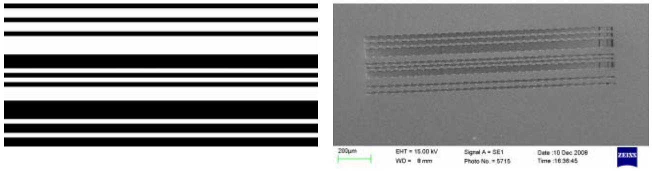
Introduction

- Coded aperture x-ray monitor:
  - Overview, motivation
- Results so far of ongoing studies at CesrTA
- Detector and digitizer development
- Goals for ATF2 beam line
- Resolution calculation
- Beam line layout and study schedule

X-ray Monitor Development

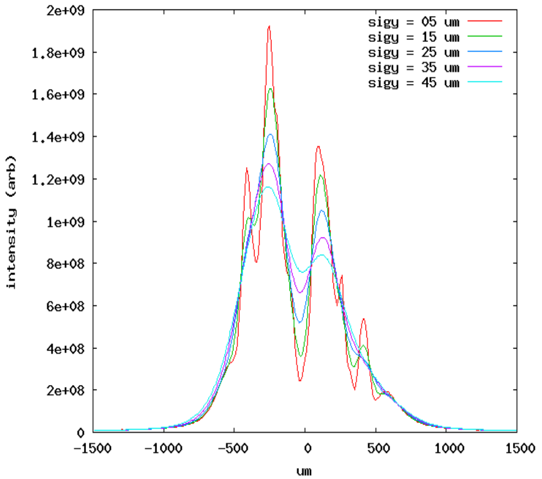
- Purpose: Provide high-resolution bunch-by-bunch measurement capability, with low beam current dependence (low distortion).
- Currently investigating and developing (in collaboration with Cornell U. and U. Hawaii) an x-ray monitor system featuring:
  - Coded Aperture Imaging
    - Being tested in collaboration with CesrTA at Cornell
    - Test beam line being set up at ATF2
  - High-speed detector and readout
    - STURM readout being developed at UH (Gary Varner)
    - Detector options being studied, including 3-D pixel detector (SLAC/UH)

Xray Beam Size Monitors



Uniformly Redundant Array (URA) for x-ray imaging being tested at CesrTA

- 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 monochromator not needed.



Simulated detector response for various beam sizes at CesrTA

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

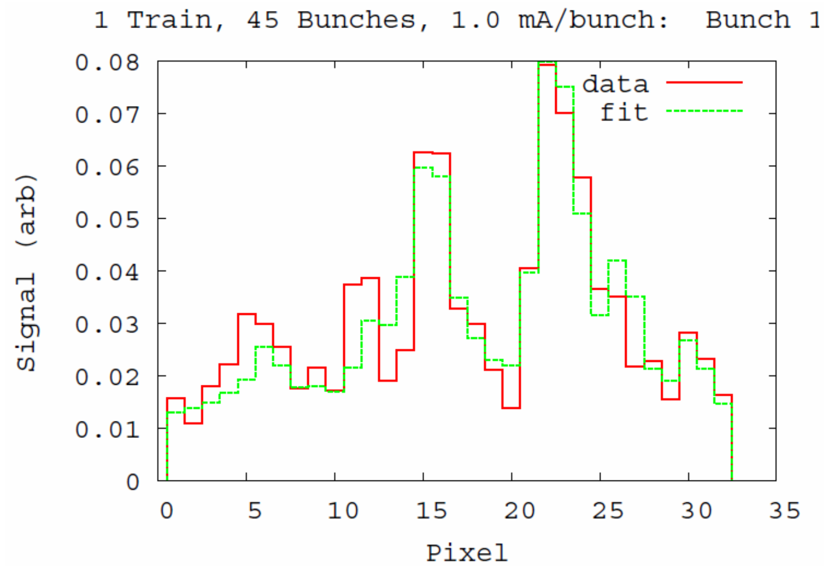
(+ detector response)

→ Detected pattern:

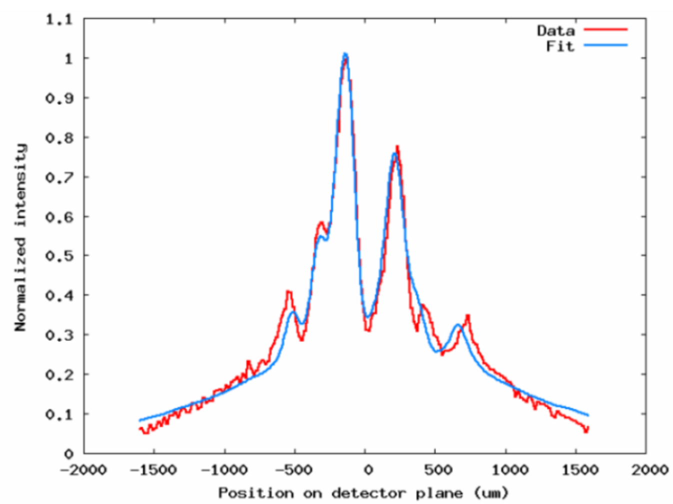
$$A_{\sigma,\pi}(y_d) = \frac{iA_{\sigma,\pi}(\text{source})}{\lambda}\int_{\text{mask}}\frac{t(y_m)}{r_1 r_2}e^{i\frac{2\pi}{\lambda}(r_1+r_2)} \times \left(\frac{\cos\theta_1+\cos\theta_2}{2}\right)\mathrm{d}y_m,$$

Data Analysis

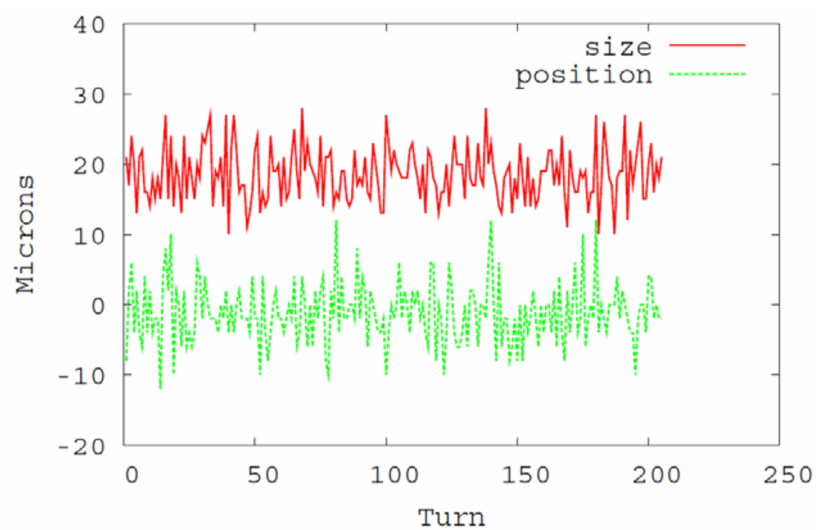
- 1) Simulate point response functions (PRFs) from various source positions to detector, taking into account beam spectrum, attenuations and phase shifts of mask and beamline materials, and detector response.
- 2) Add PRFs, weighted to possible proposed beam distributions.
- 3) Find best fit to detector data.



Example of single-shot data (single-bunch, single-turn)

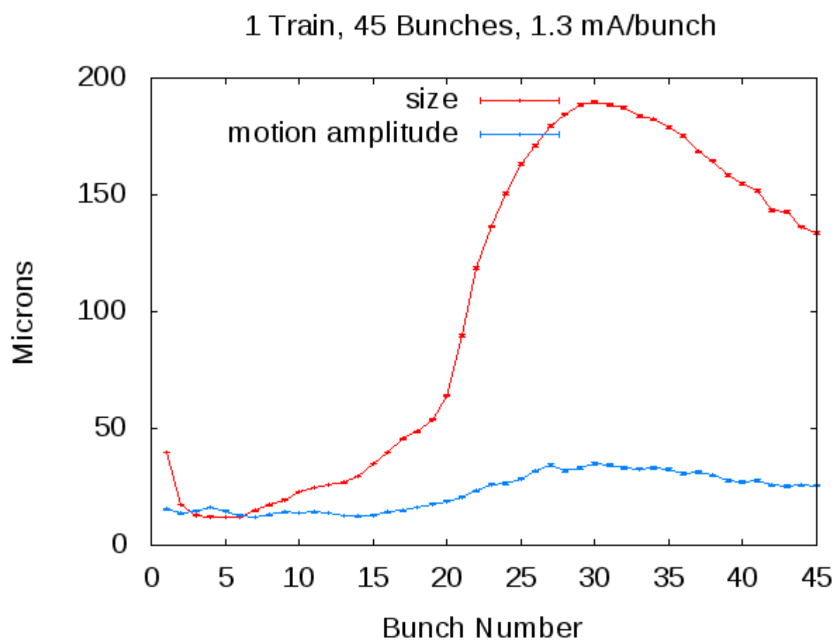


Measured slow-scan detector image (red) at CesrTA, used to validate simulation (blue)



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

Example of electron-cloud study data taken at CesrTA

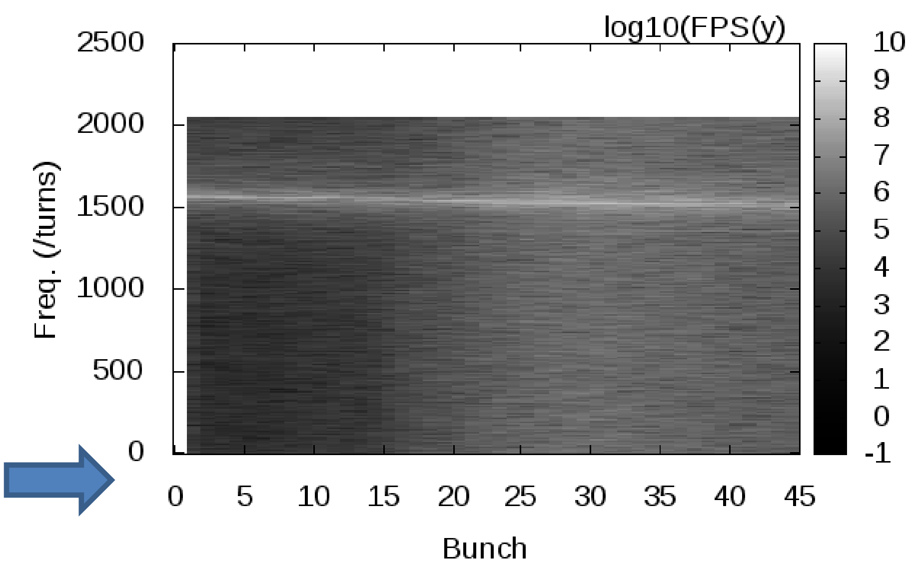


Progress so far at CesrTA:

- Validated simulation code with real beam.
- Demonstrated measurement of beam sizes down to ~10 μm (preliminary) .
- Demonstrated bunch-by-bunch, turn-by-turn size measurements.

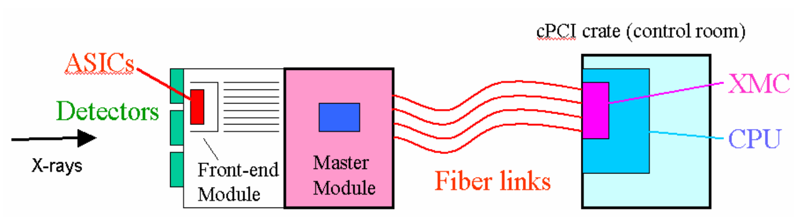
Bunch-by-bunch size and centroid RMS motion.
4096 turns, fitted separately then averaged for each bunch.
(Error bars statistical.)

Fourier power spectrum of fitted beam position



X-ray detectors and readout

- Fermionics InGaAs sensor array in use at CesrTA
- Have also done some tests at KEK PF
  - Determined that Fermionics detector efficiency too low at high x-ray energies (such as will be seen at SuperKEKB and ILC).
  - →Need new detector. Studying new detector technologies:
    - Geiger-mode array of small photon-counting elements (various companies and labs)
    - 3D (deep but thin) silicon detector (SLAC/UH) (calorimeter style detector)
- Compact-PCI based DAQ being developed.



Signal flow diagram for x-ray monitor system

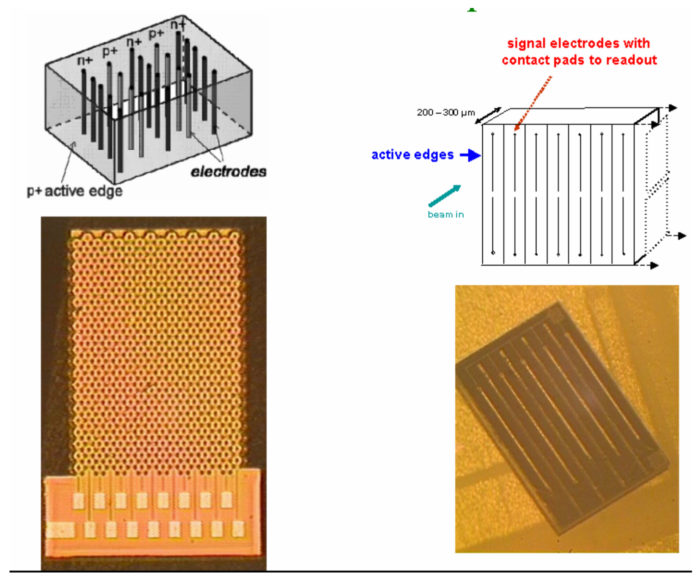
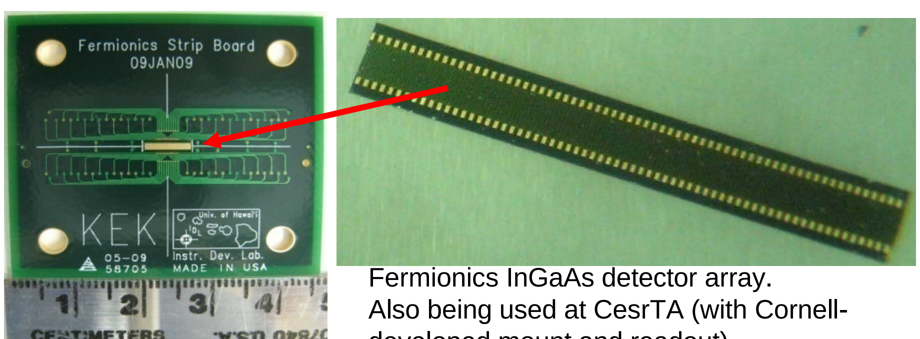


Illustration of two of the detector concepts to be explored in next phase of x-ray detector development. At left, a regular pattern of n and p electrodes, at right, a trench structure, which provides a more uniform drift volume.

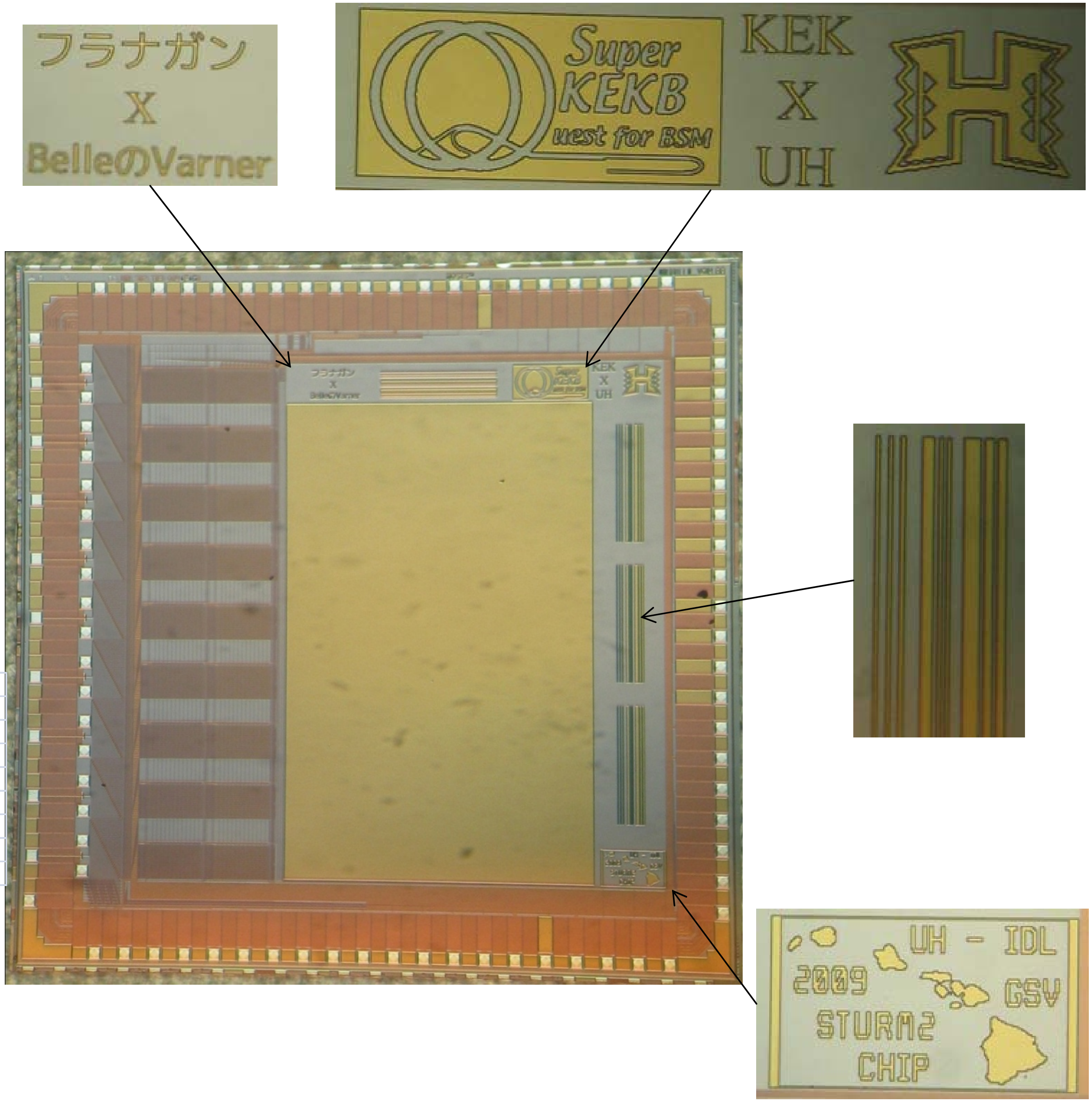


Fermionics InGaAs detector array.
Also being used at CesrTA (with Cornell-developed mount and readout).

STURM2 Digitizer

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)



Goals at ATF2

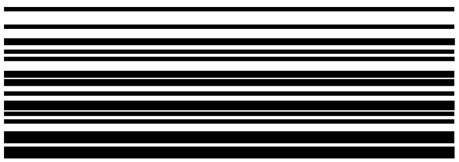
- 1) Push demonstrated resolution limits of coded aperture imaging below 10 μm.
  - Funded in part by Kakenhi
- 2) Test new fast detector and readout systems.
  - Funded in part by Nichibei

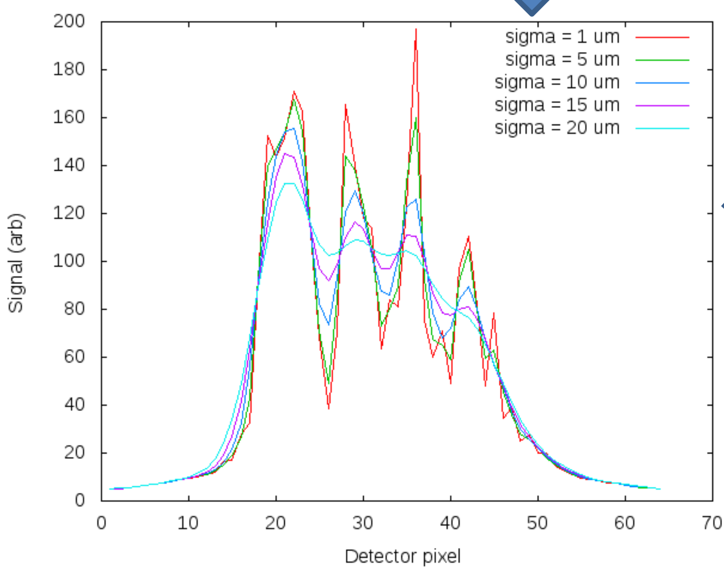
Resolution Estimate @ ATF2

- **Beamline:** 1.5 m from source to CA mask, 9 m from mask to detector
- **Mask:** 5 μm 47-pixel mask (example)
  - 4 um Ta on ~2 um Ru/SiN/SiC membrane (NTT-AT) (In hand)
- **Detector:** Fermionics (50 μm pitch) (same type used at CesrTA), 64 pixels
  - Expect ~250 photons/pixel/nC/bunch on average.
- **Procedure:**
  - Detector images calculated for beams of σ_y=1-20 μm.
  - Images fitted against each other. Chi-squared is calculated for cross-fits:
    - Chisq/nu = (1/(N-n-1))*SUM[(y_i-y(x_i))^2 / sigma_i2^]
    - E.g., 5 um pattern is checked for fit against 1-, 2-, 3-, … um patterns.
    - Bin weights are assumed to be statistical (sigma_i = sqrt(y(x_i))), assuming average bin height represents 200 photons
    - Chi-sq 70% exclusion values are taken to represent the resolution contours
      - Should approximate something like 1-sigma contours.
- **Note that these are *single-shot* resolutions.**
    - **Detector noise is not included, only photon statistics.**

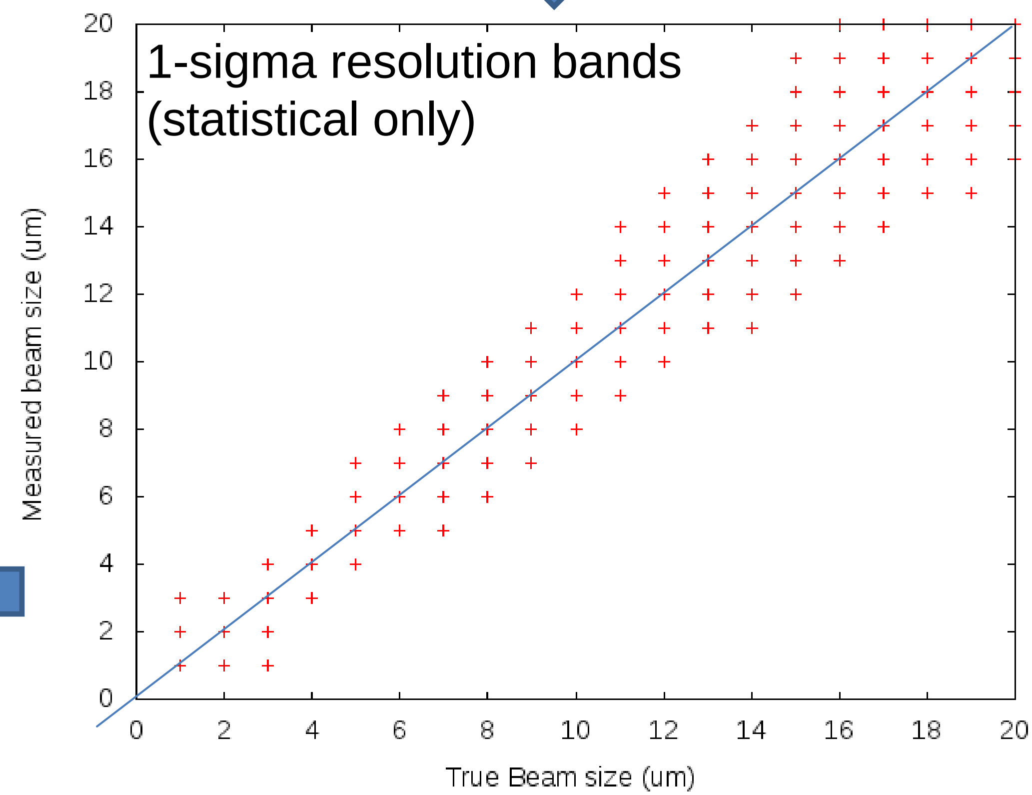
5 μm, 47-element mask @ ATF2

Generate detector images for various beam sizes:





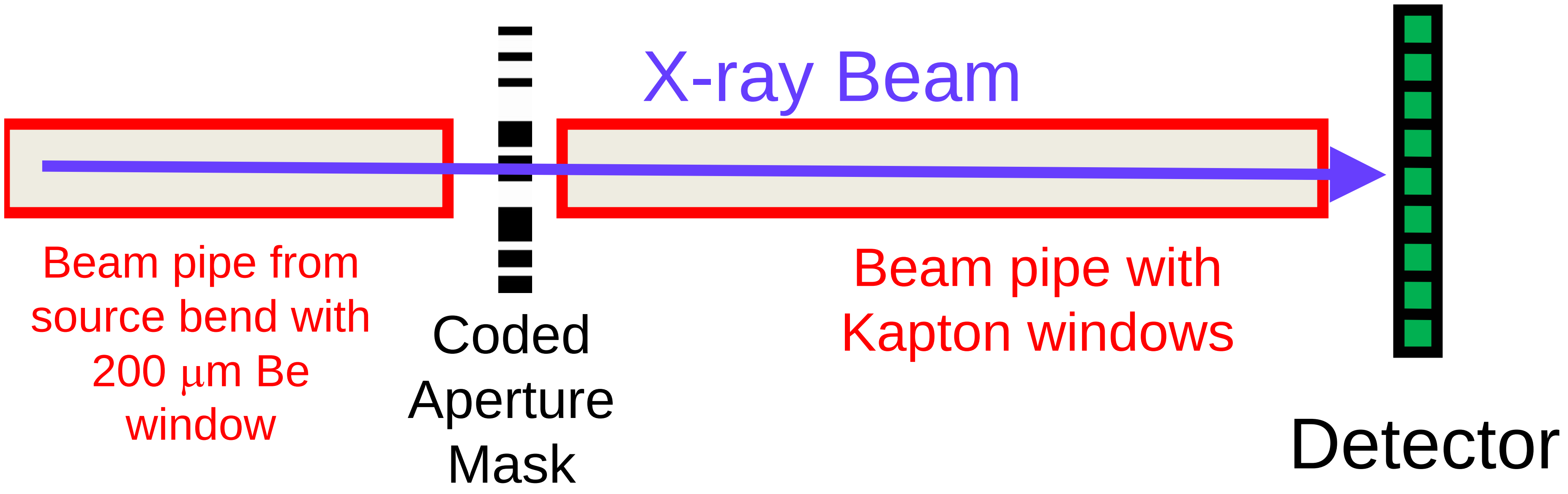
Cross-correlate between beam sizes.
Plot 1-sigma statistical confidence regions,
Assuming 200 photons/pixel (average):



Statistical single-shot resolution at 5 μm beam size = +/- ~1.5 μm
(Assuming ideal detector.)

Beamline construction

- Extract x-rays from BH3X bend
  - Energy 1.3 Gev, bending radius 4.3 m
  - Critical energy: 1.12 keV
  - Predicted flux at detector: ~250 photons/nC/bunch/50-um pixel (Fermionics detector)

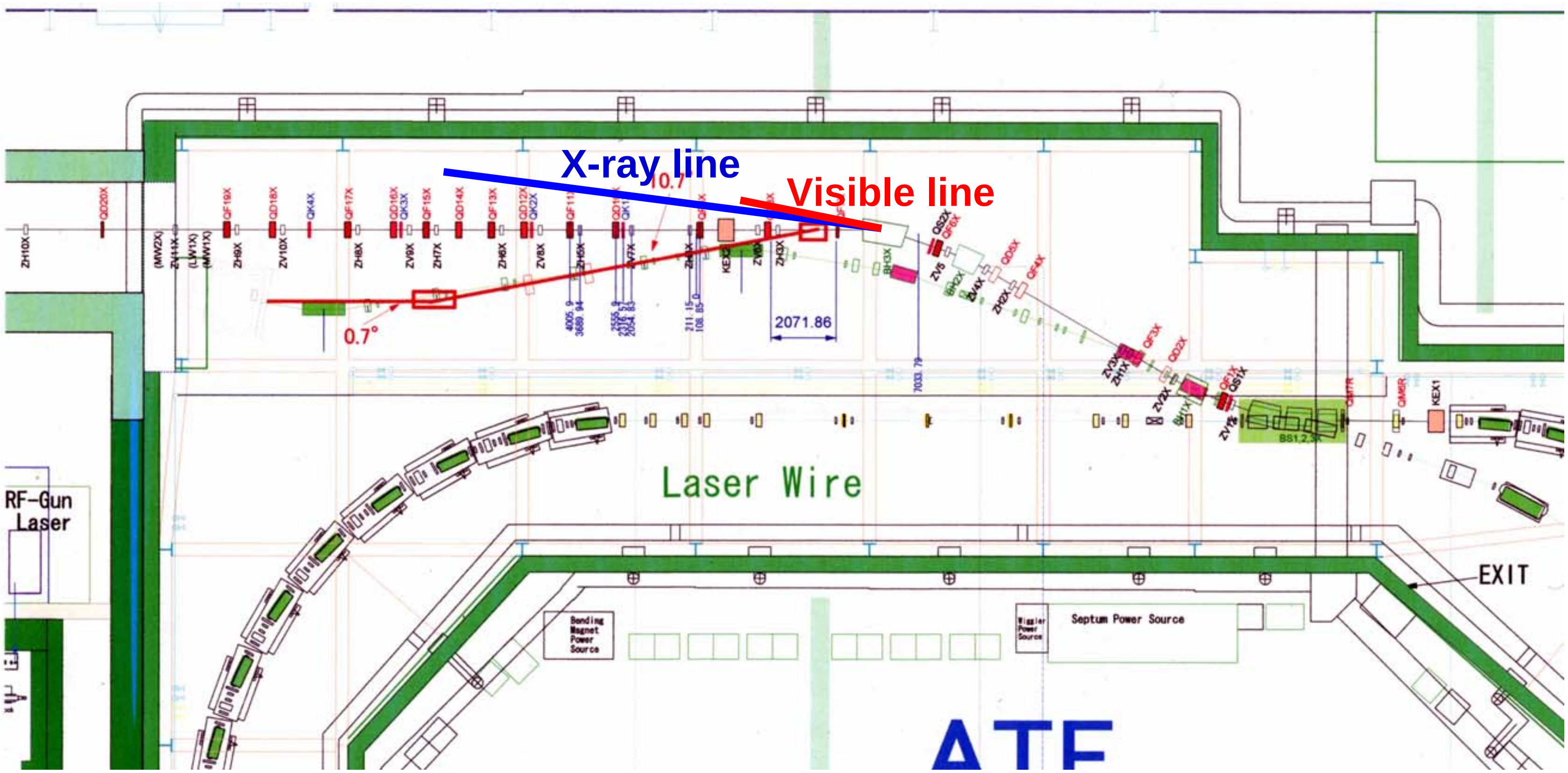


Layout

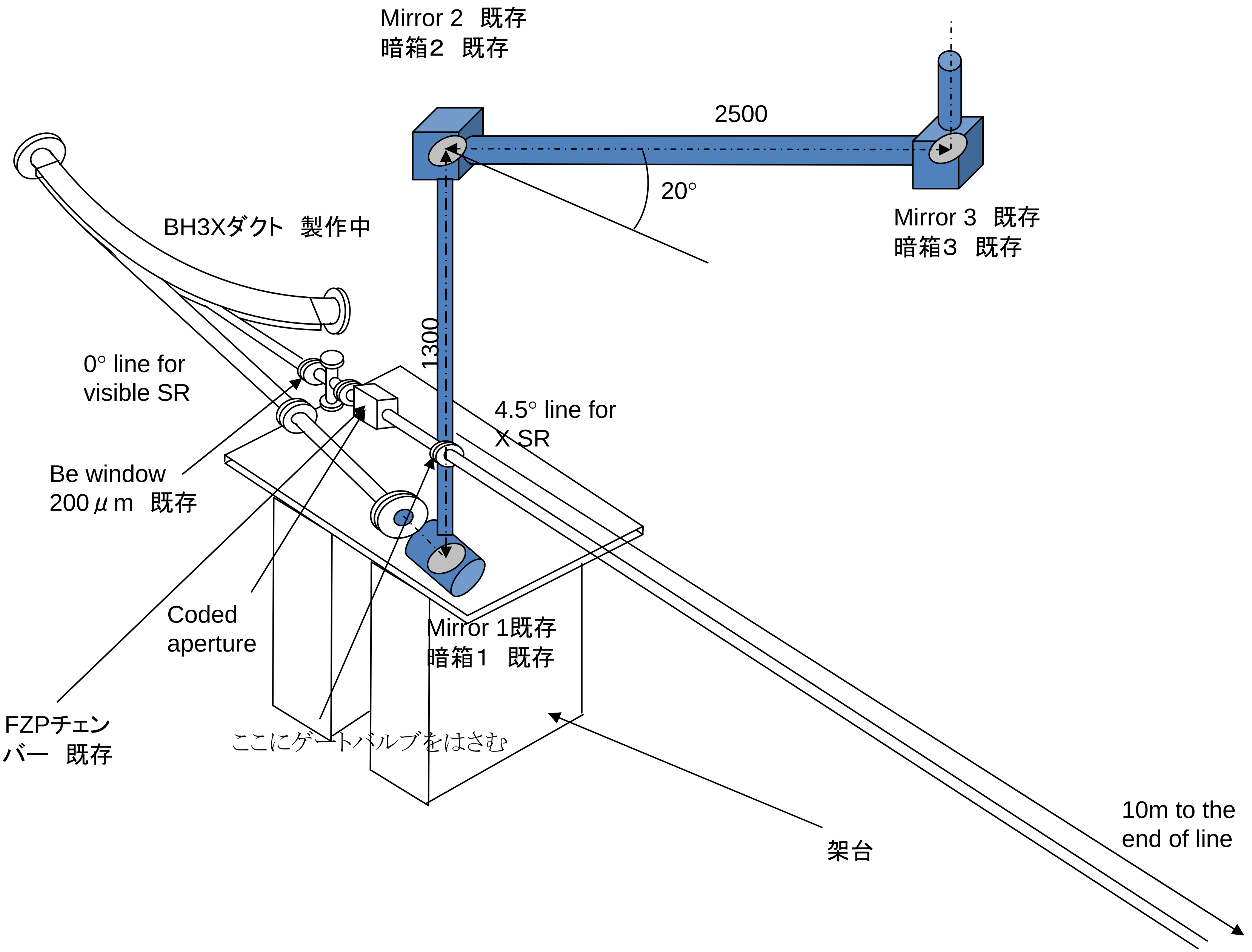
Location

Source of SR:

BH3X



T. Mitsuhashi

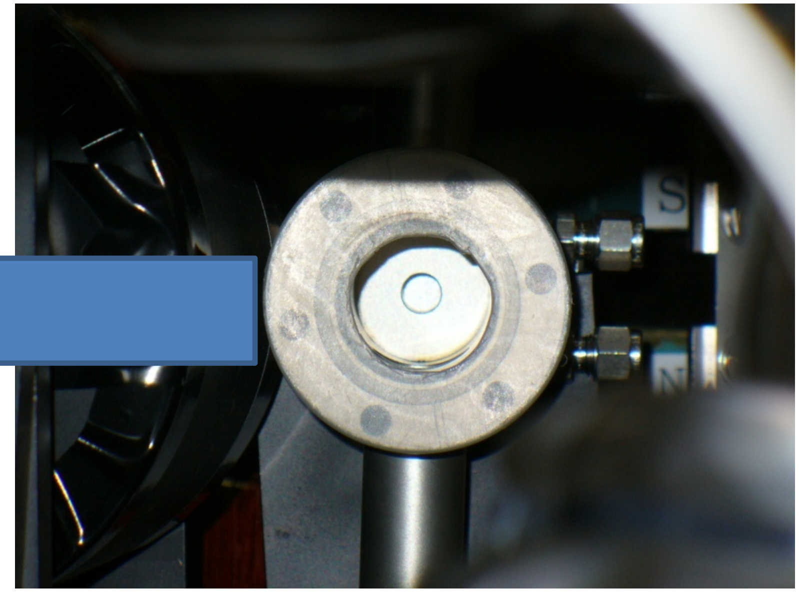


T. Mitsuhashi

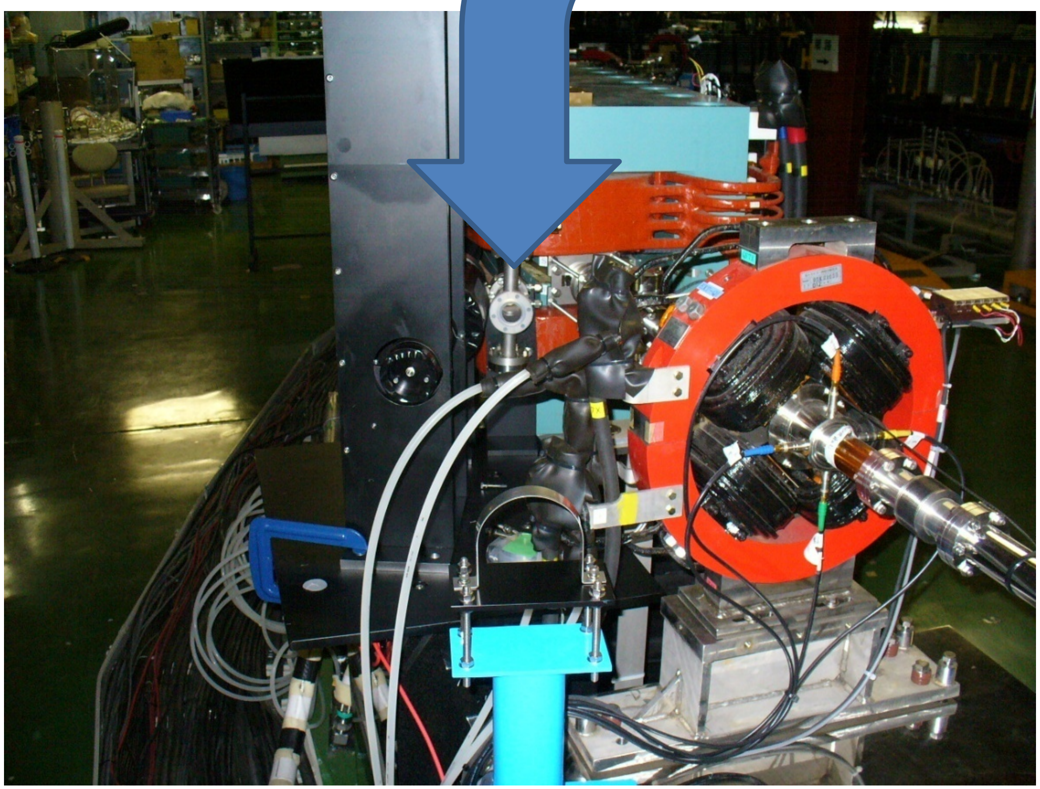
View down proposed beamline

Optical table for detector

Source bend



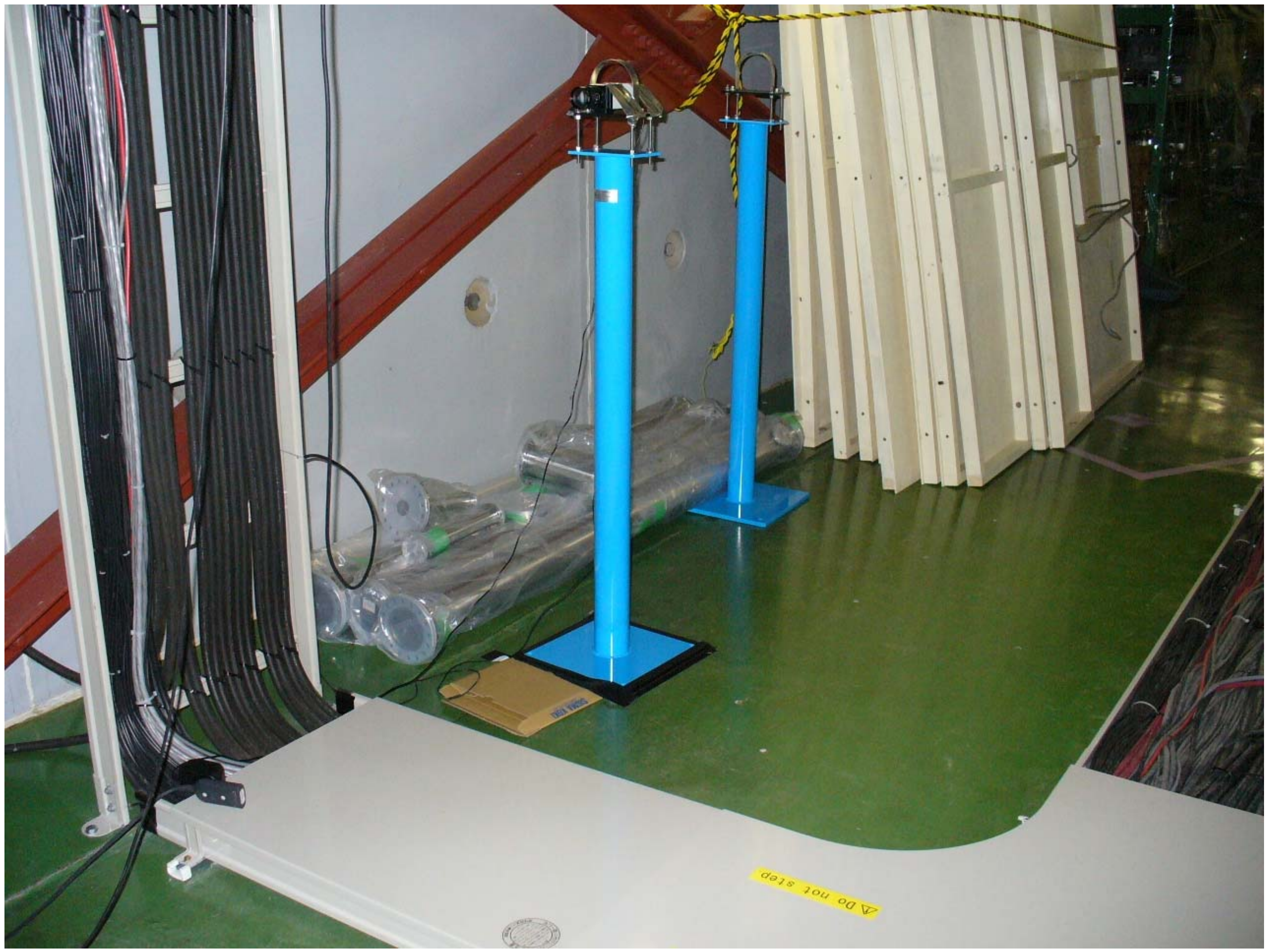
Be window



Beam pipes and stands

Free standing, not connected to ATF2 beam pipe.

Can be temporarily removed after installation if needed for access



Construction and Study Schedule

- The extraction chamber is already in place. An optical table has been set up downstream, and movable stages and beampipe purchased.
- This summer: set up beam pipe between extraction window and optical table. Beam pipe will have Kapton windows, and pumped down to a rough vacuum. (Possibly use He at first.) Readout and control in the dark room upstairs.
- This fall: Find and align beam with Ce:YAG targets. Test present and possibly new masks with current detector and STURM2-based readout system. Towards end of fall run, hope to **request tuned beam with sub-10 μm vertical beam sizes**.
- Next year: Continue with new mask, detector and readout prototypes.

宜しくお願い致します