Optics Activities at Argonne

For FNAL meeting on Optical Data Transmission, Aug. 19, 2010

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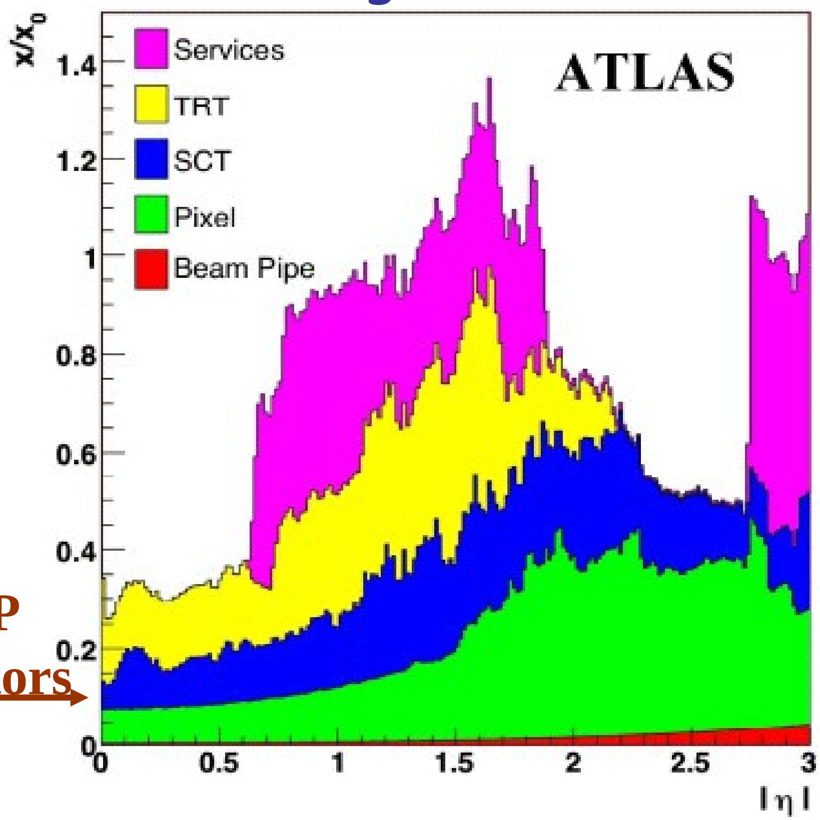
D. Lopez Center Nanoscale Materials, Argonne

ATLAS/CMS: from design to reality

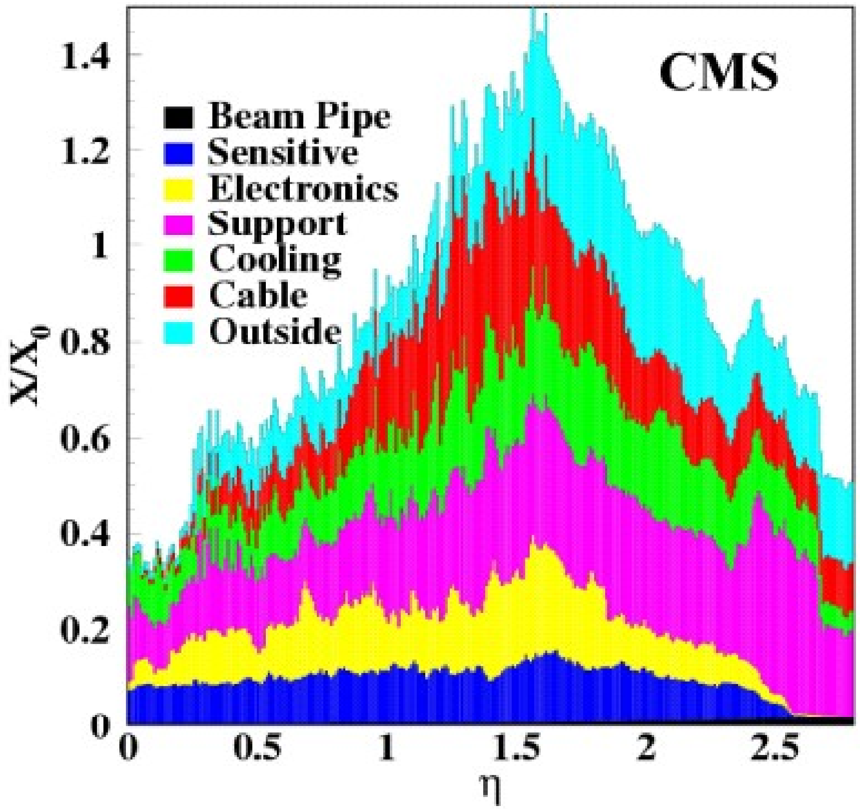
Amount of material in ATLAS and CMS inner trackers

Weight: 4.5 tons



LEP detectors

Weight: 3.7 tons



- Active sensors and mechanics account each only for ~ 10% of material budget
- Need to bring 70 kW power into tracker and to remove similar amount of heat
- Very distributed set of heat sources and power-hungry electronics inside volume: this has led to complex layout of services, most of which were not at all understood at the time of the TDRs

We are Interested in Several Aspects of Optical data Transmission

- 1) Get the lasers out of tracking
  issues: power, heat, reliability,
  driver power=mass…
  Promote Light modulators as solution
- 2) Links in air between tracking layers for trigger
- 3) Links in air for data readout
  reduce mass, (connectors, fibers, etc)
  reduce fiber routing problems
- 4) General problems such as long distance in air, analog vs digital signals, etc

More interest in reliability since ATLAS tracking has lost 100 of 300 VCSEL

Reasons for Optical Modulators:

Very little electric power : laser is outside tracking volume
Integrated into CMOS , e.g. GBT-like, multiplexers
Communicate between chips with no copper
(MIT, IBM, Intel, … are developing devices for beams between chips)

Reasons for Beams in air :

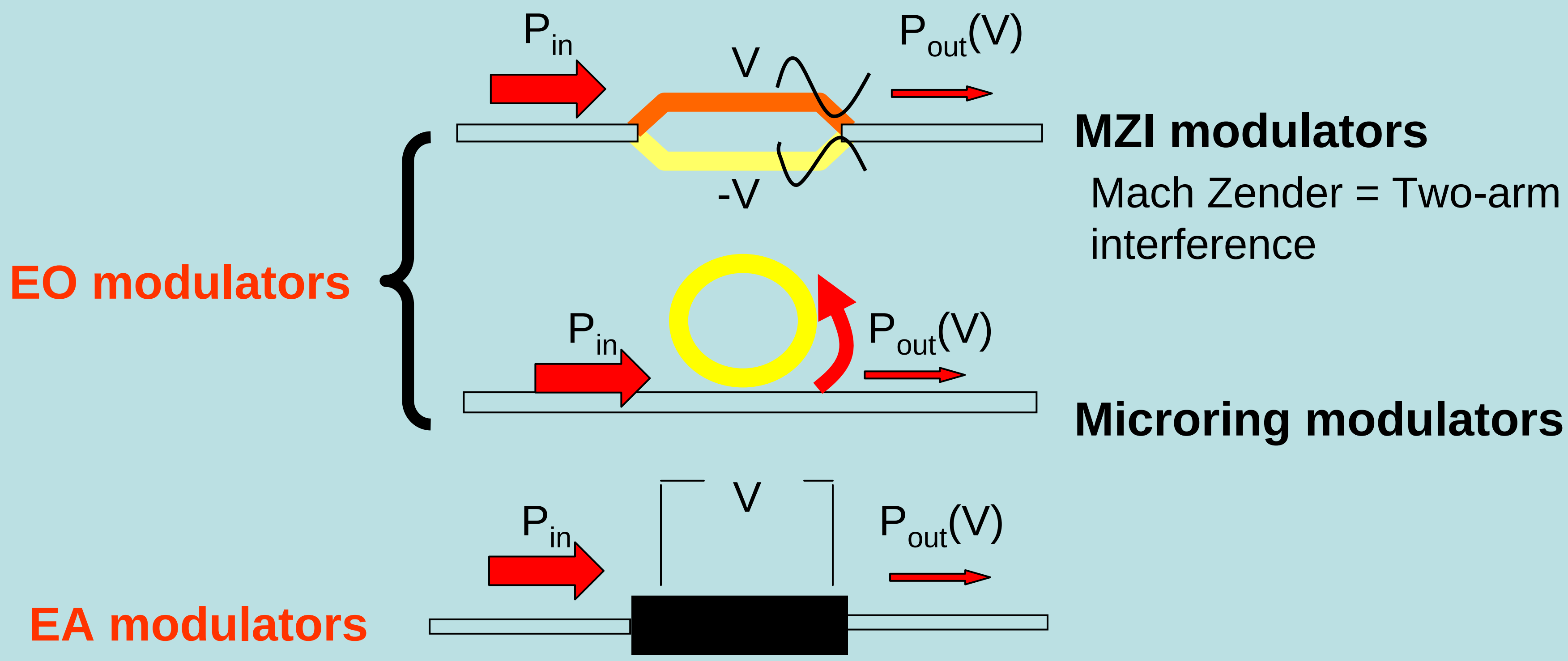
Size of connections between Detector layers
Small Lenses and Mirrors - No fiber connectors
Replace fibers
No fiber mass
No fiber plant / fiber routing

Possibly more rad. hard – needs more study
Claimed to be cheaper (Harvard Broadband Lab and LBL…)

Tracking Trigger utilizing combined Beams and Modulators
Low-mass, broadband link between tracking layers

Separate issue is getting data out using beams with MEMS mirrors

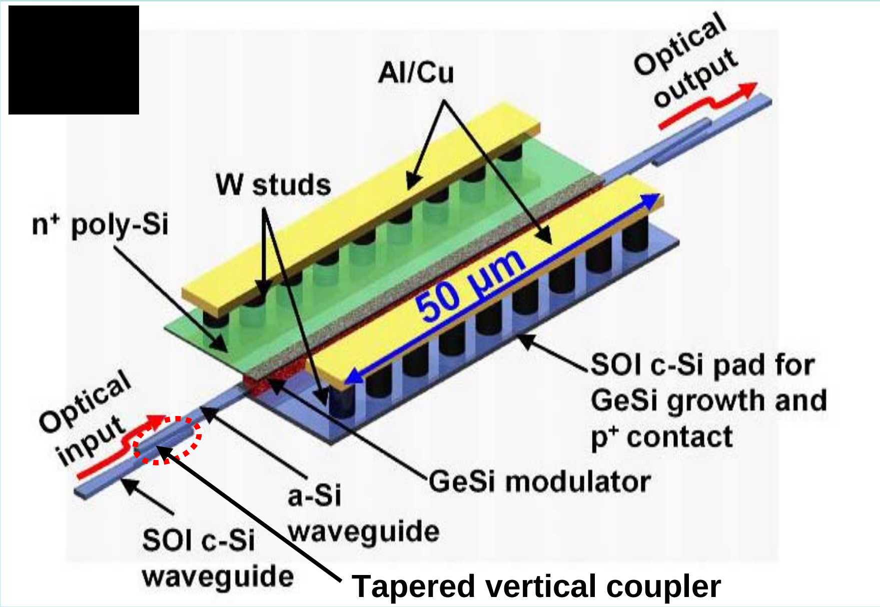
Electro-Optical vs. Electro-Absorption Modulators

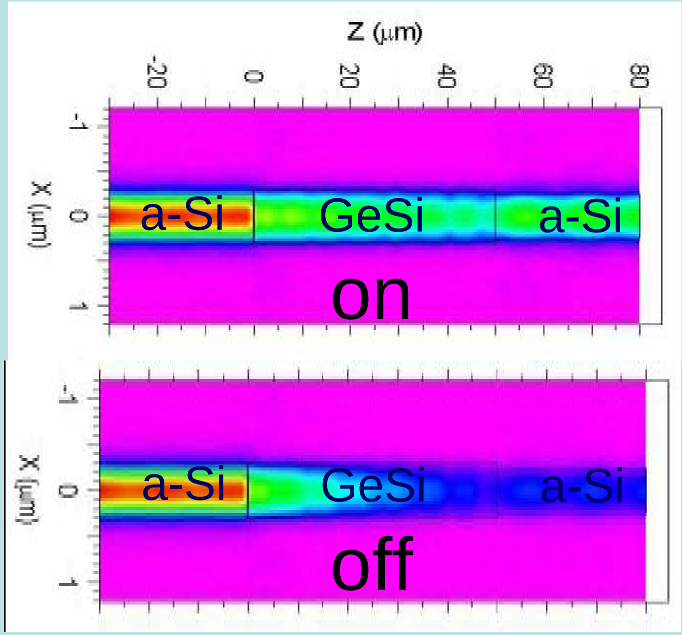


- EO modulators are based on the index change (Δn) .
  - MZIs typically large (mm in length) and power hungry
  - Mirocrorings very compact yet with limited operation spectrum range (~1 nm)
- EA modulators are based on field-induced absorption change (Δα).
  - Compact (<100 µm), low power consumption, ultrafast intrinsic response (<1 ps)
  - ~20 nm operation spectrum width

EAM are Ideal for integration!

MIT Design of GeSi EAM Device Structure



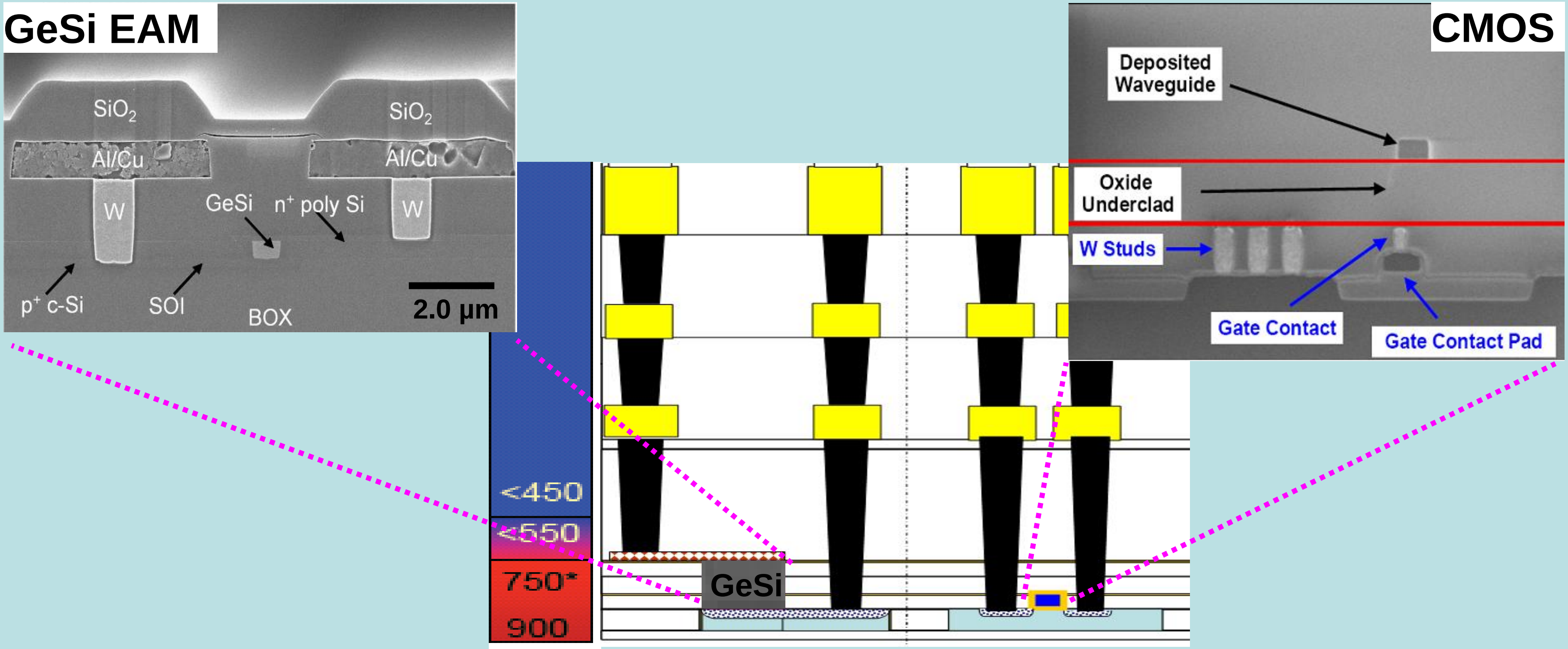


- **Fabricated with 180 nm CMOS technology**
- **Small footprint (30 µm^2)**
- **Extinction ratio: 11 dB @ 1536 nm; 8 dB at 1550 nm**
- **Operation spectrum range 1539-1553 nm (half of the C-band)**
- **Ultra-low energy consumption (50 fJ/bit, or 50 µW at 1Gb/s)**
- **GHz bandwidth**
- **3V p-p AC, 6 V bias**
- **Same process used to make a photodetector**

Liu et al, Opt. Express. 15, 623-628 (2007)

the MicrophotonicsCenter @MIT

Integration of GeSi EAMs into CMOS Process



- **GeSi grown between front and backend of CMOS process for electronic-photonic integration.**
- **Two-step UHVCVD GeSi selective growth:**

(1) a 30-60nm GeSi buffer at 360C; (2) rest of the growth at 600-700C
Annealing at 800-850C decreases dislocation density to ~10^7/cm^2
CMP to remove top facets

M. Beals et al, Proc. SPIE. 6898, 689804 (2008)

Comments to HEP from Modulator designers

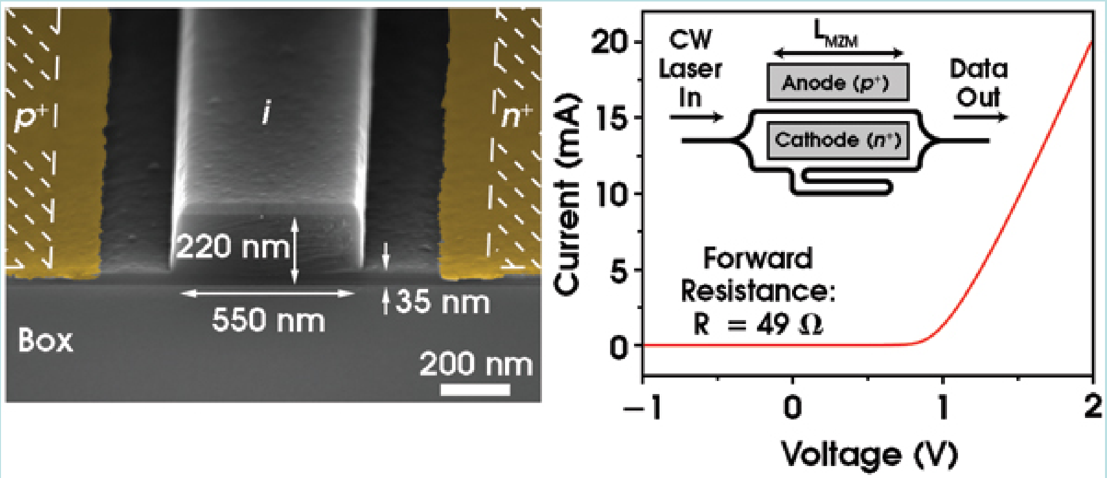
- 1. 3D usually refers to chip-stacking, and the modulator is not 3D but fabricated as monolithic in a standard CMOS process flow.
- What you see was produced with the standard IBM 150nm process flow using layer-by-layer processing.

- We have worked out all of the engineering issues to insert Ge in the process.

- 2. BAE made the structure, but any fab can do it.
- I estimate that two engineering runs would be needed to qualify the fab for reasonable yield.
- If our Ge is required, a six-inch wafer size or smaller would be best; and protocols for contamination control would need to be established.

- 3. I am not sure what the number of devices you need is and whether drive electronics are already available.
- A few wafers would likely represent all of the modulators that you would need.

- The one issue that may limit deployment is packaging, and we should probably discuss your needs.



41 mW at 5 Gb/sec

100 u long x 10 u wide

Thin,   order u

Broad spectrum   7.3 nm at 1550

80 u long delay line internal

1V p-p AC, 1.6V bias

Ultra-compact, low RF power, 10 Gb/s silicon Mach-Zehnder modulator

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http://www.research.ibm.com/photonics

Abstract: Silicon p^+-i-n^+ diode Mach-Zehnder electrooptic modulators having an ultra-compact length of 100 to 200 μm are presented. These devices exhibit high modulation efficiency, with a $V_\pi \cdot L$ figure of merit of 0.36 V-mm. Optical modulation at data rates up to 10 Gb/s is demonstrated with low RF power consumption of only 5 pJ/bit.

Modulating Lasers is inefficient compared to modulating light.
Also, much of the power can be moved out of the tracker

Power for Electro-Absorption Light Modulator :

MIT 50 uW at 1 Ghz, scales with F, 500 uW at 10 GHz ?

Drivers – not known, but driving low power devices

Power of Laser and Driver:

* **Lasermate VCSEL 850 nm**

  10 ma, 1.6 V = 16 mW for approx 300 u W light

* **A 10 Gb driver for VCSEL is claimed to be very efficient at 45 mW**

Radiation Hardness of SiGe

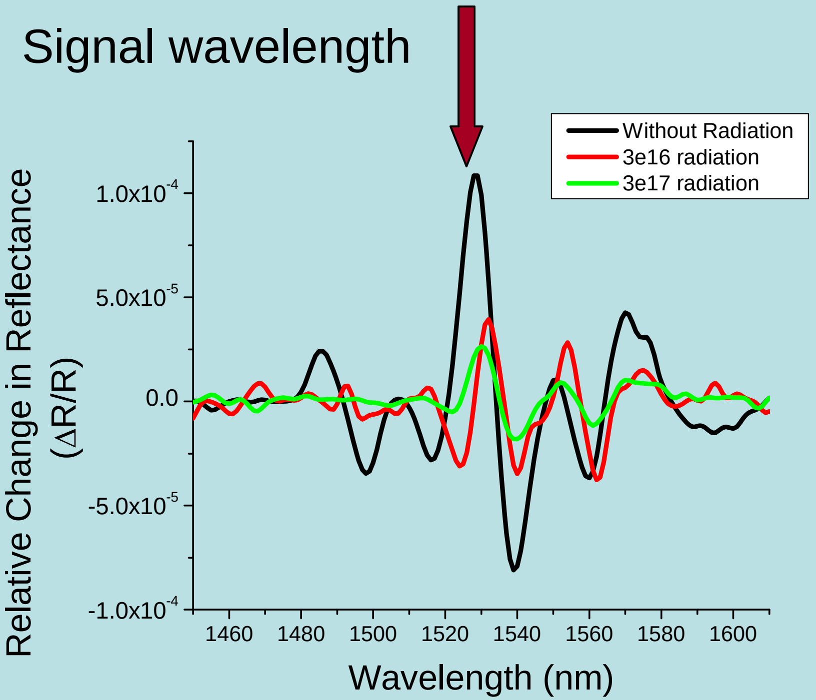
We irradiated the MIT SiGe modulator material at the Argonne 1 MeV Van de Graaf

Two exposures:

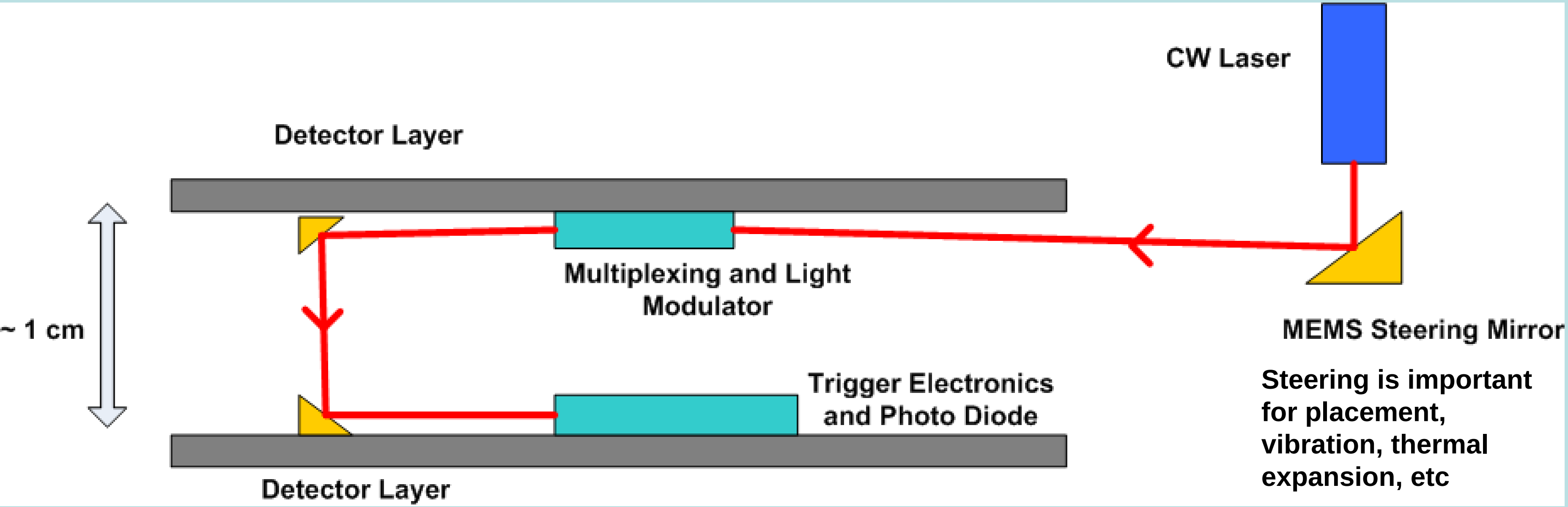
3e16 and 3e17 / cm^2

After 3e17 electrons/cm^2 radiation the carrier lifetime is decreased by ~4x due to radiation defects.

- As a result, it is very likely that the modulator is still operational but the dark current is increased.



Basic Triggering Data Flow



This is a way to get data from one layer to another

distances from ~ 3 mm up to cm

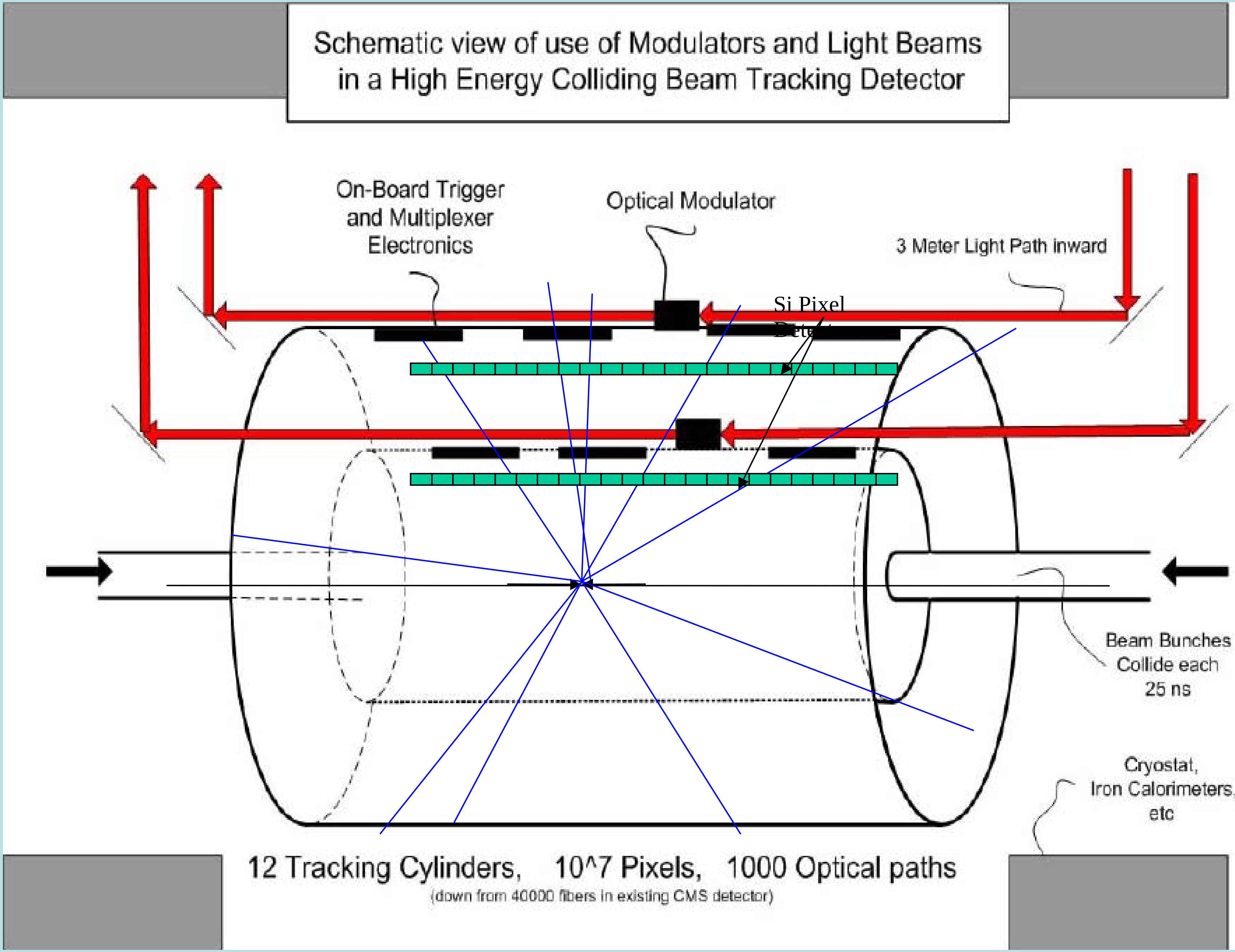
bandwidths per channel of 1 to 5 Gb.

There could be many of these per pair of Staves

Data can be taken off detector in the same way (Not Shown Here)

Data Path for

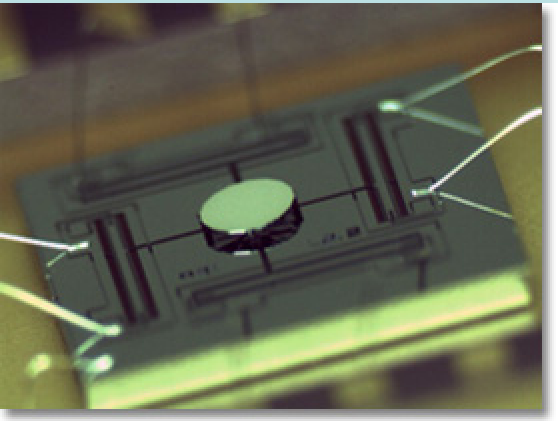
On-Board Trigger



What is shown here is readout of data from tracker

MEMS Mirrors and Lenses

A commercially available MEMS mirror (Developed at ARI, Berkeley)



The Lucent LambdaRouter: MEMS Technology of the Future Here Today

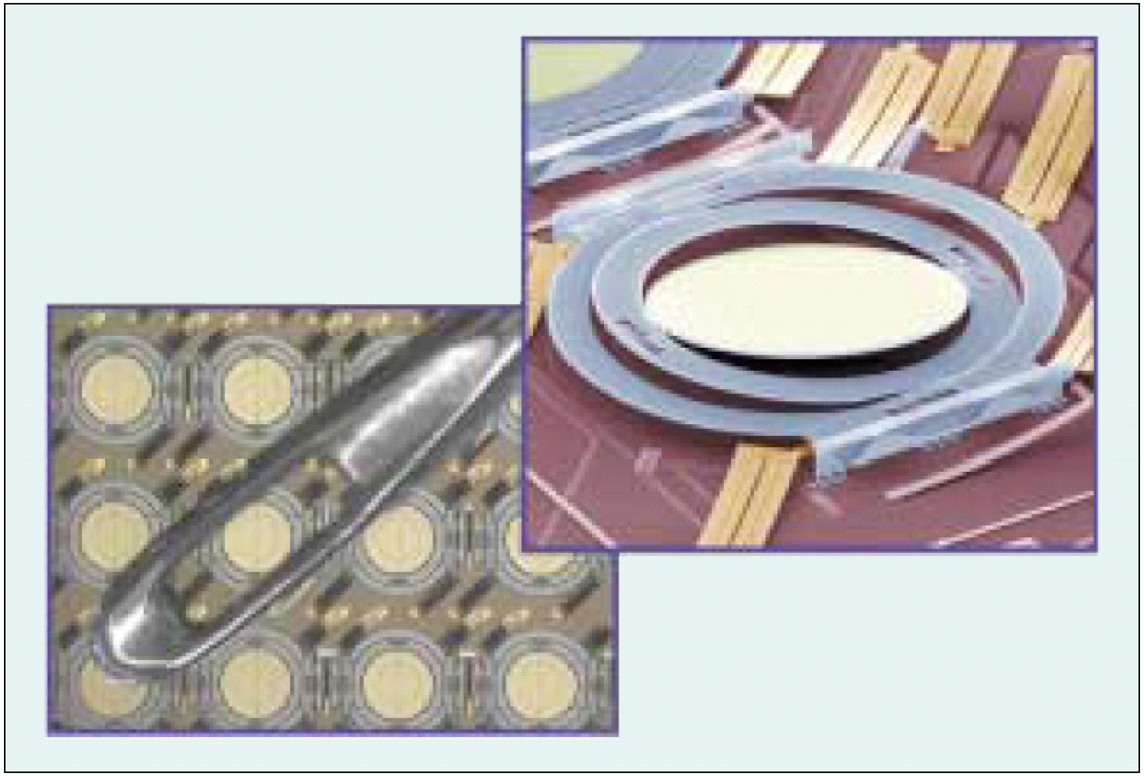


Figure 4. *Two images of MEMS-based OXC mirrors used in the Lucent LambdaRouter. The image in the upper right is a single mirror, and an array of mirrors is shown in the lower left. An eye of a needle is shown for comparison on the array.*

Coupling

- Between Tracking Layers –

  ..Short distances between layers and relative stability allows use of simple mirrors (gold plated silicon)

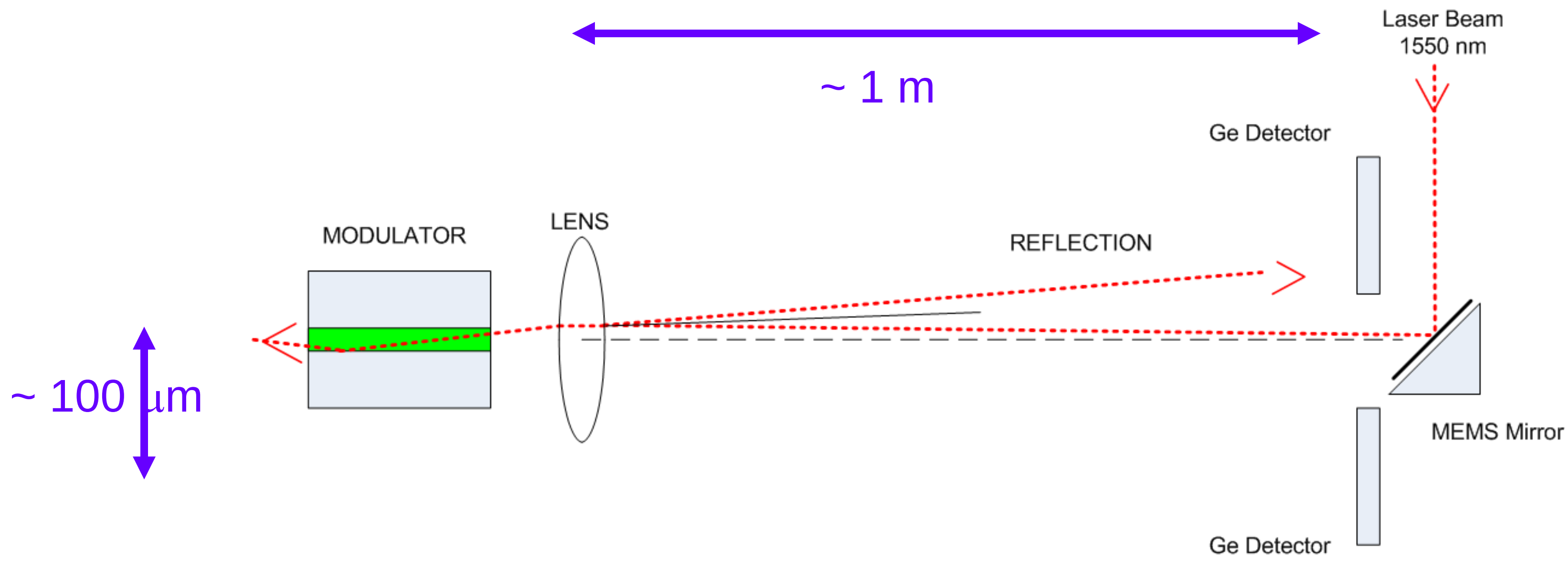
- Some kind of focusing is needed in and out of modulator and photodetector if these are small, integrated into CMOS
- Size of features in Silicon is < wavelength of light in air.
- There is ongoing work on these issues:

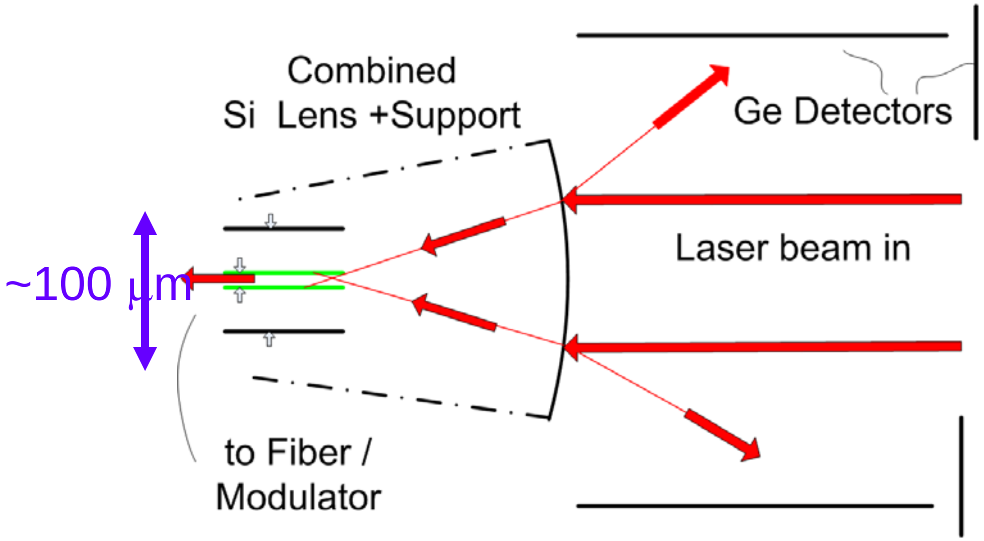
  .. Silicon, SiO2 light pipes,

  .. Radar-horn like with index gradient

  .. Holographic lenses

Our ideas for the link to test in MC and in Hardware





A Basic Issue is the data path for the Feedback loop.

We Are trying to integrate the optical coupling with the Feedback.

LBL-HP Approach

MEMS Lenses

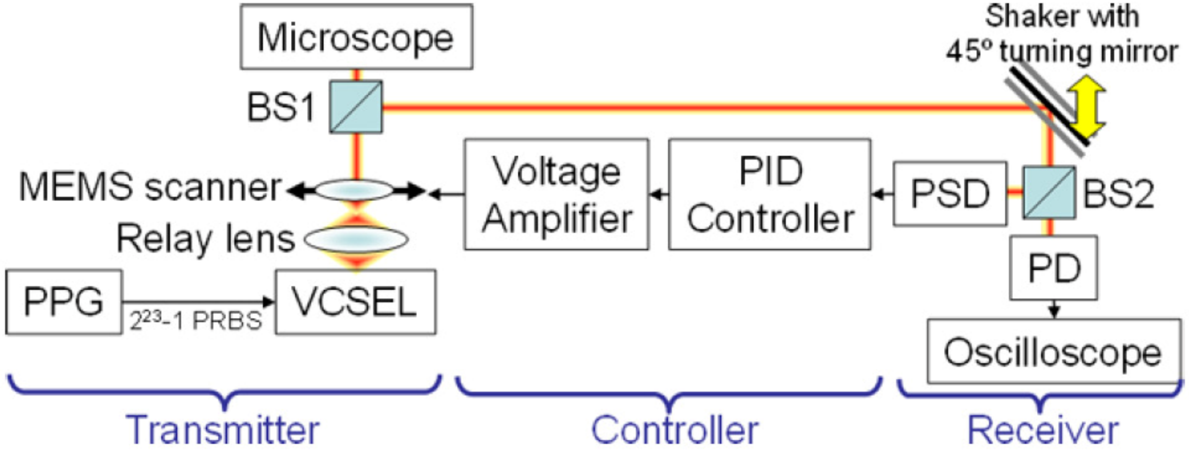
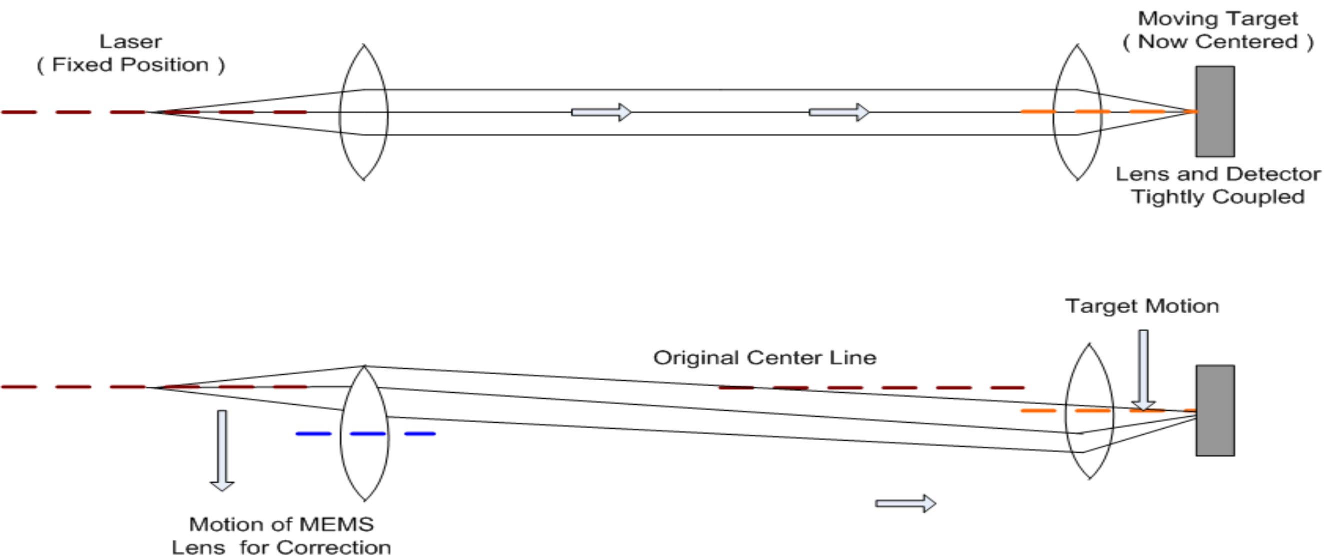
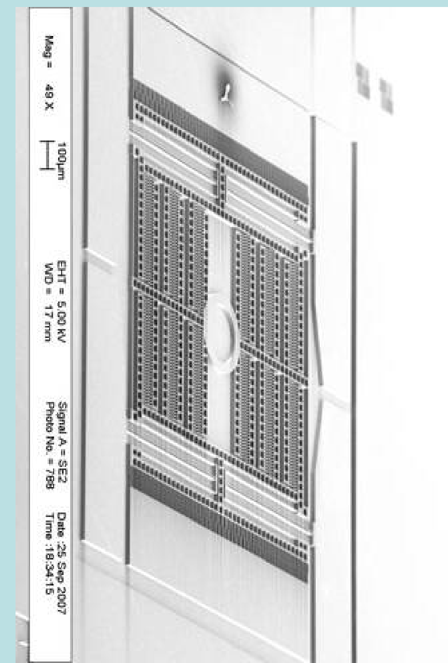


Fig. 11 Schematic diagram of our experiment setup with a mechanical shaker for real beam displacement. BS: Beam splitter. PPG: Pulse pattern generator at 1 Gbits/s. PD: high-speed photodetector with 1 GHz 3-dB bandwidth

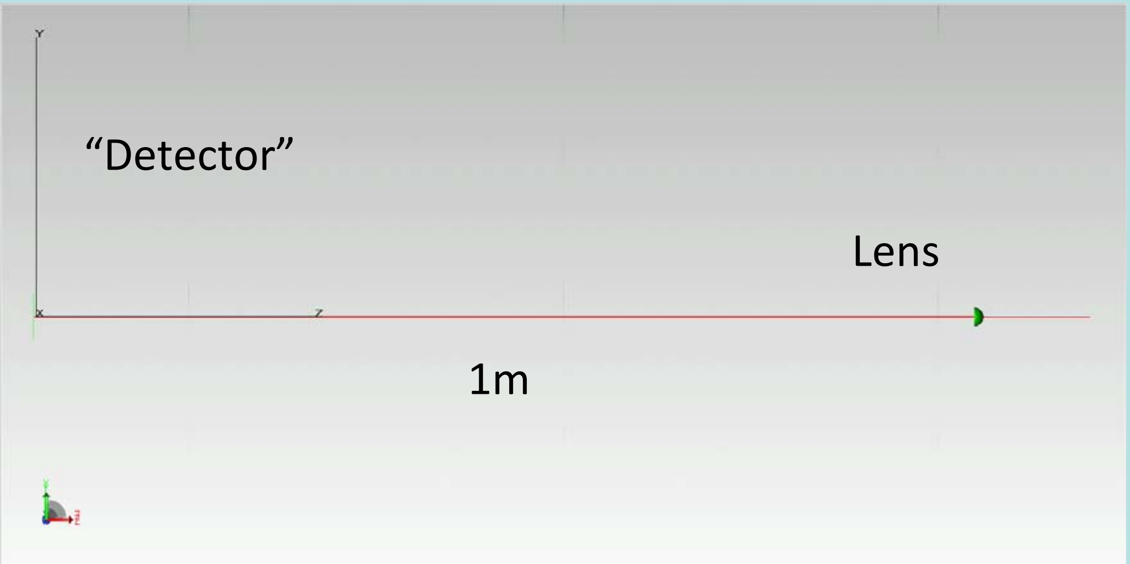
Schematic of LBL MEMS Lens Steering
(Very schematic)

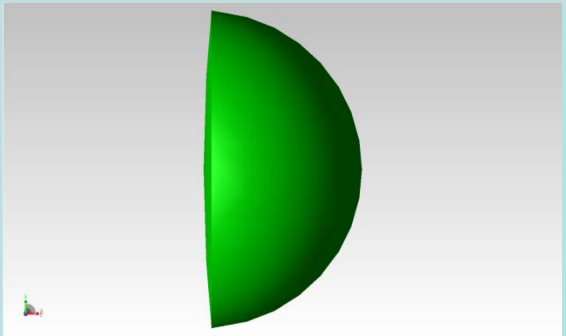




Results from a commercial ray-tracing program.

We also have ray-tracing we wrote to run in CERN root.

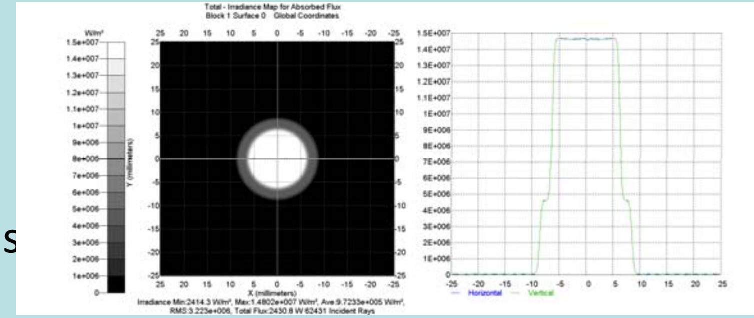


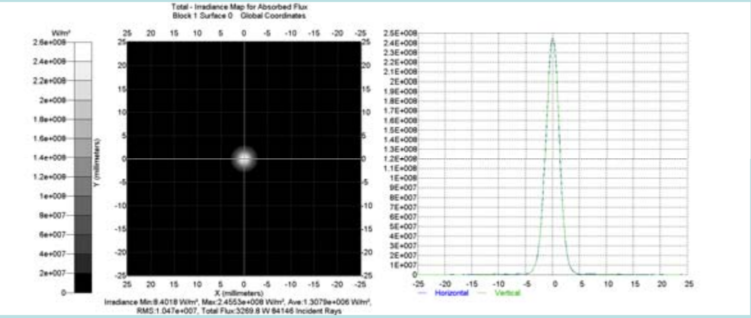


Uniform Beam

Gaussian Beam

Lens
50 mm
surface radius

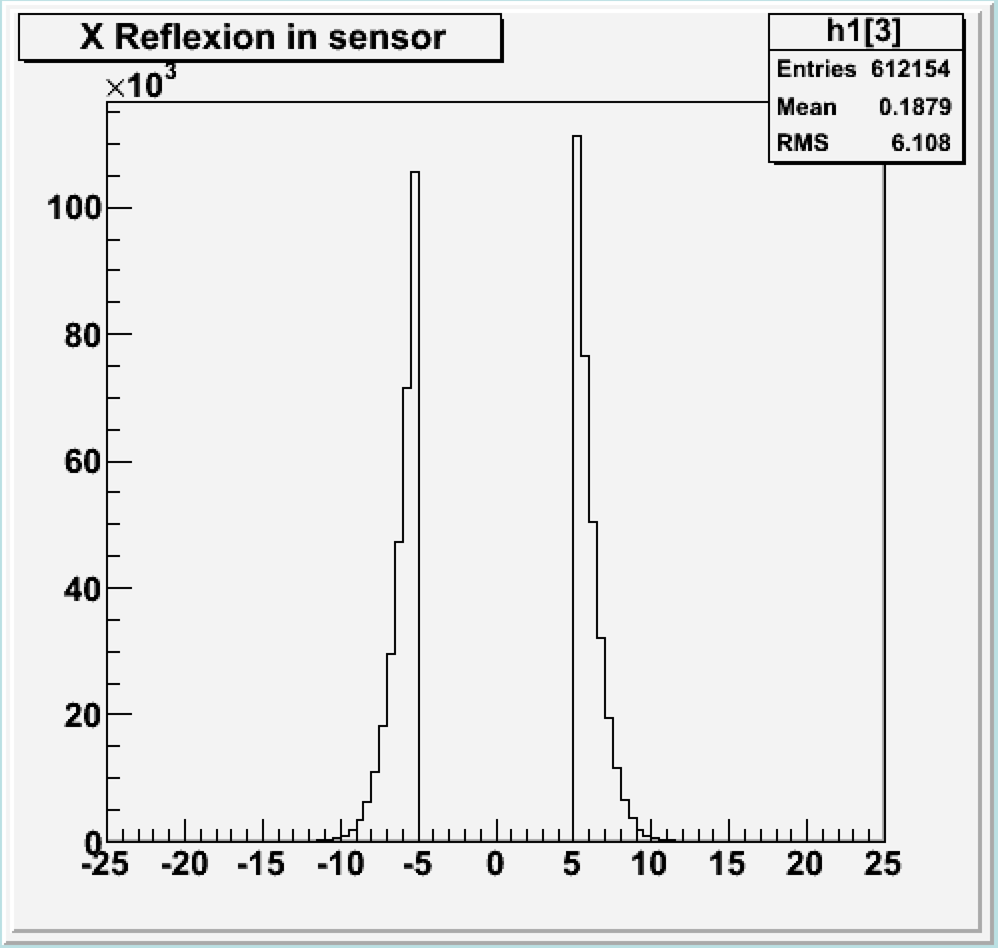




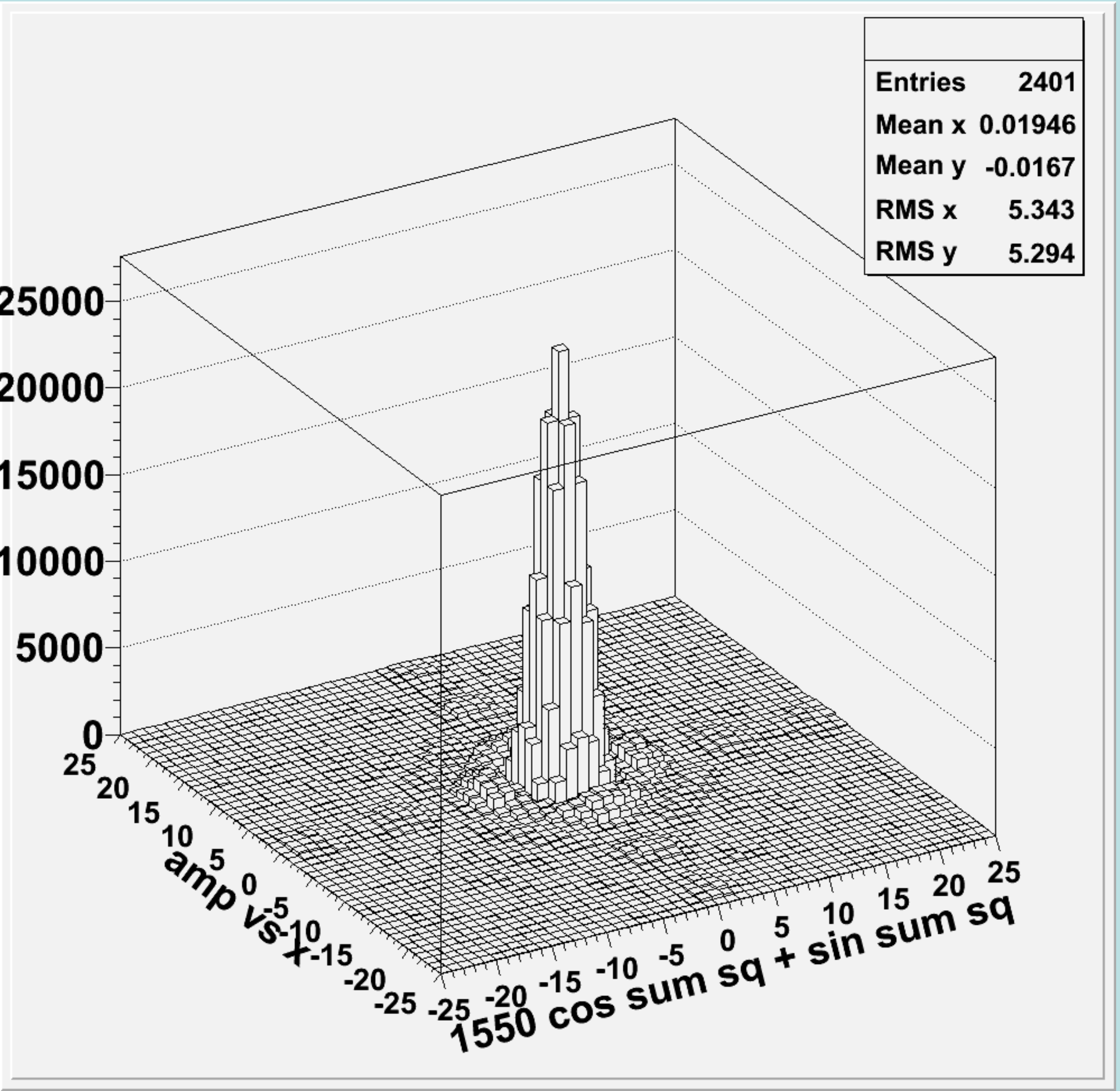
MC of reflection from lens at detectors around MEMS mirror

Plot of photon hits at sensor plane, cut on sensor edges at 5, 25 mm

500 mm lens to sensors, 300 mm lens radius, 1 mm beam sigma (parallel)



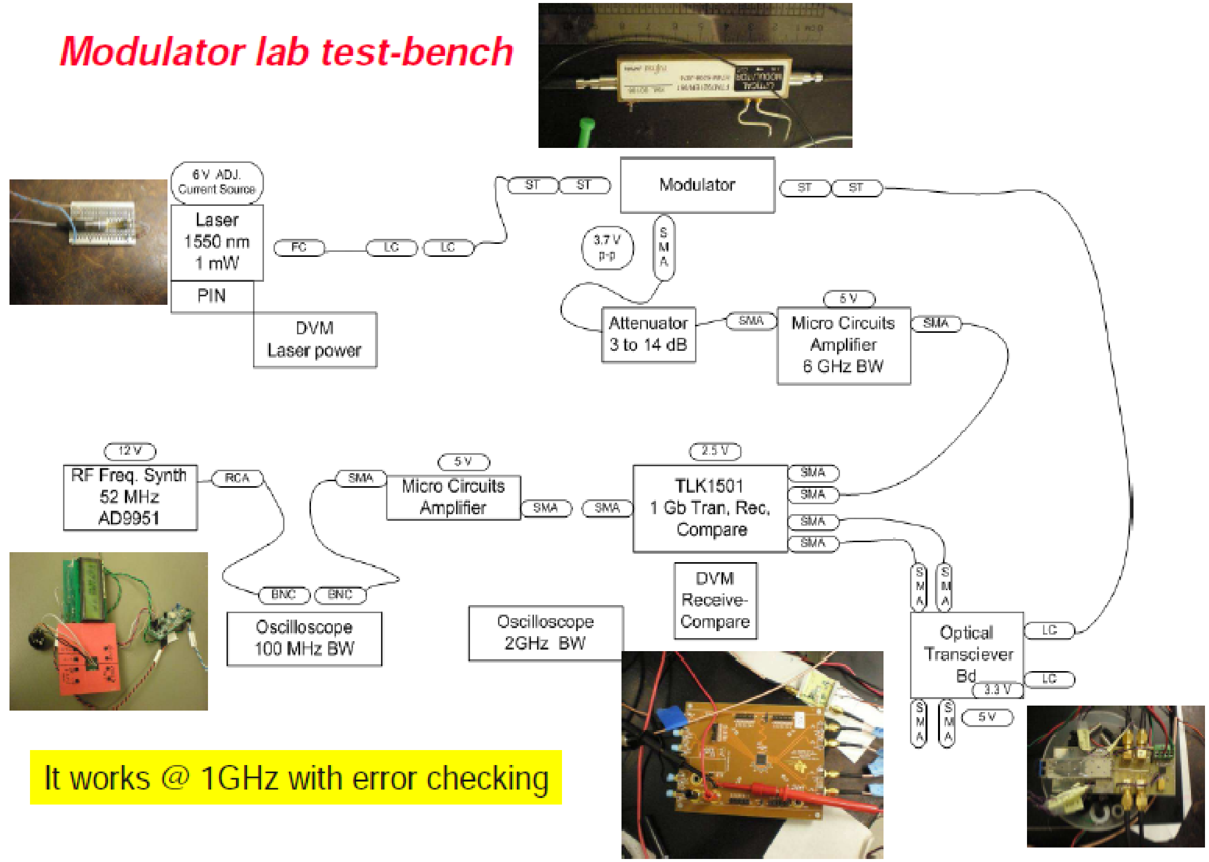
Monte-Carlo Using Phase, Not Rays



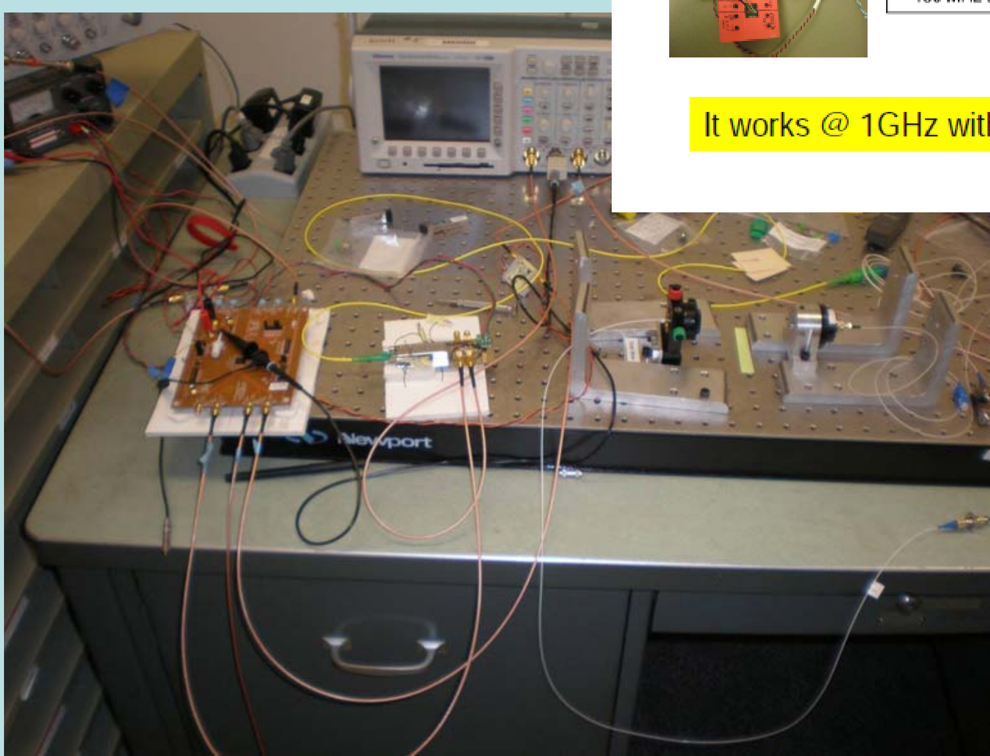
Focus found by using 1550 nm light with a mirror of 5 mm focal length and 2 mm diameter. The peak is wider than at 650, and the diffraction rings are more visible.

Diffraction pattern modified by having 4 support vanes in front of the 2 mm mirror, and a hole in the middle of the mirror. The vanes are 125 u wide and the hole is 125 u square.

Modulator lab test-bench



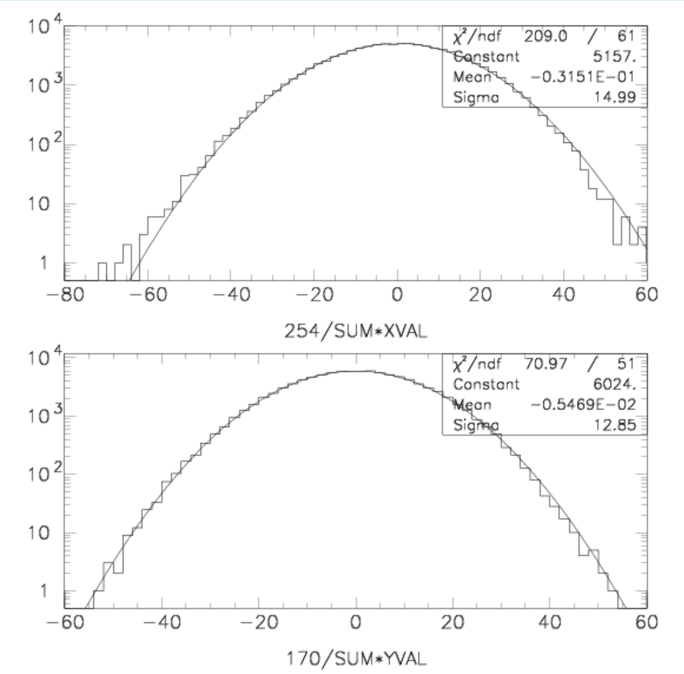
It works @ 1GHz with error checking



Learning to cope with resonance in commercial MEMS mirror in feedback loop.

This is work in progress.

Graph is system noise in feedback loop with non-moving target.



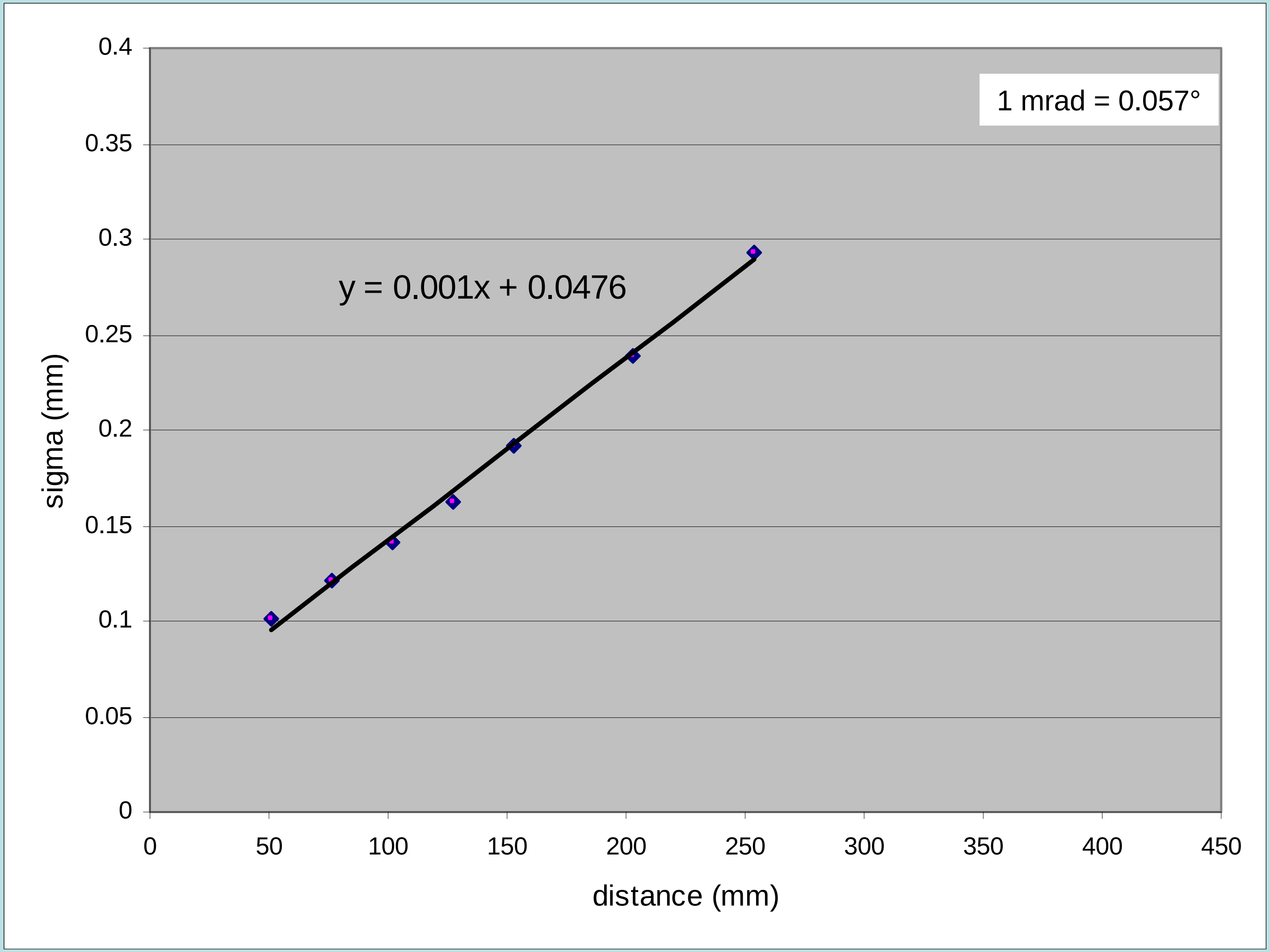
System noise gives about 15 microns position noise at 2 meters.

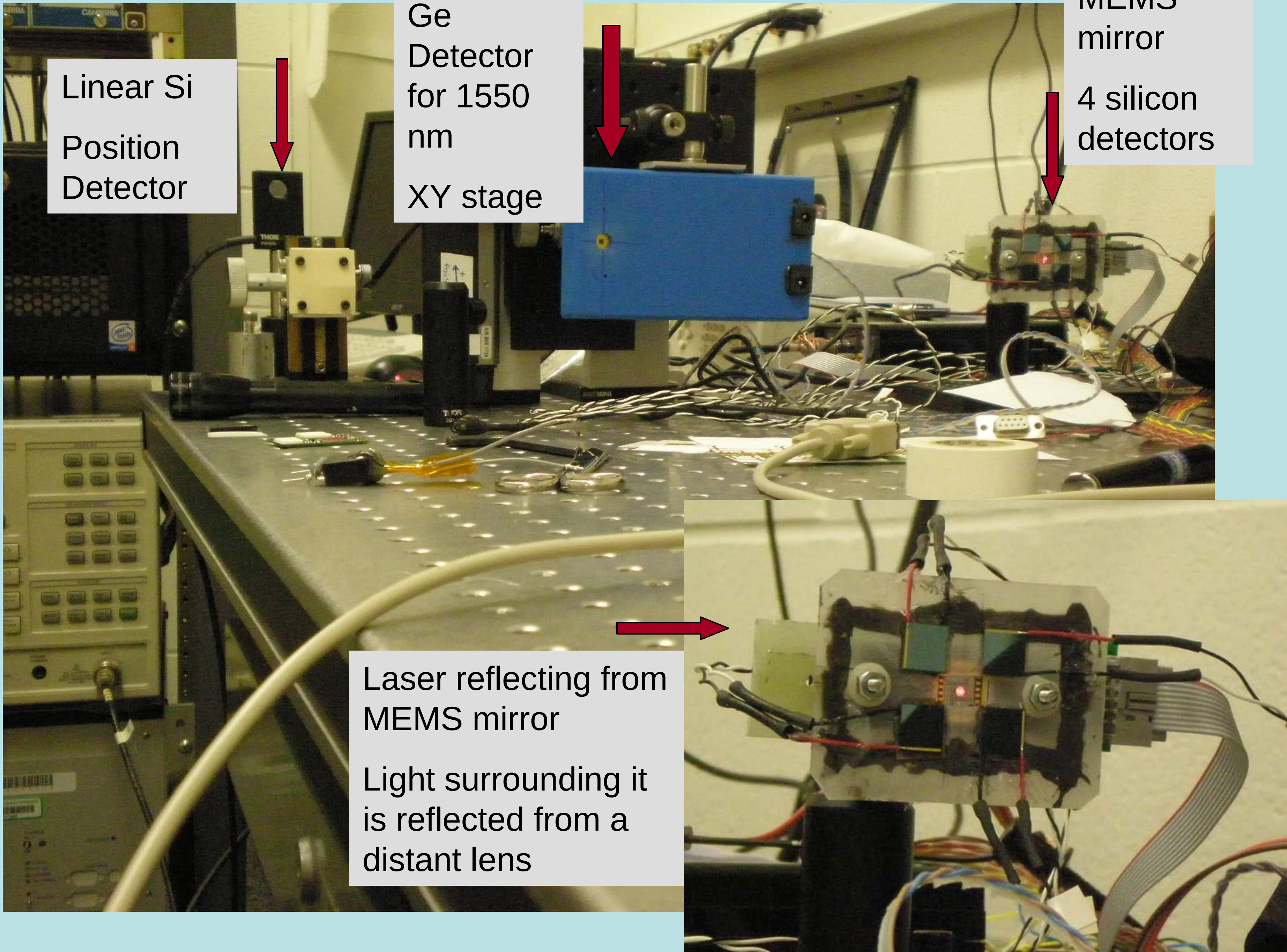
New Commercial mirrors will have higher resonance frequency (this one is 1 KHz for 2 mm mirror)

Mirrors from Argonne CNM will have a different suspension system, gimbals similar to Bell Labs mirror.

Example of work by our summer student, John Abrahams, who measured beam profiles vs distance for several visible and IR lasers, some with GRIN lenses.

1550nm laser coupled into SingleMode fiber, tipped with grin lens





Linear Si

Position Detector

Integrating Ge Detector for 1550 nm

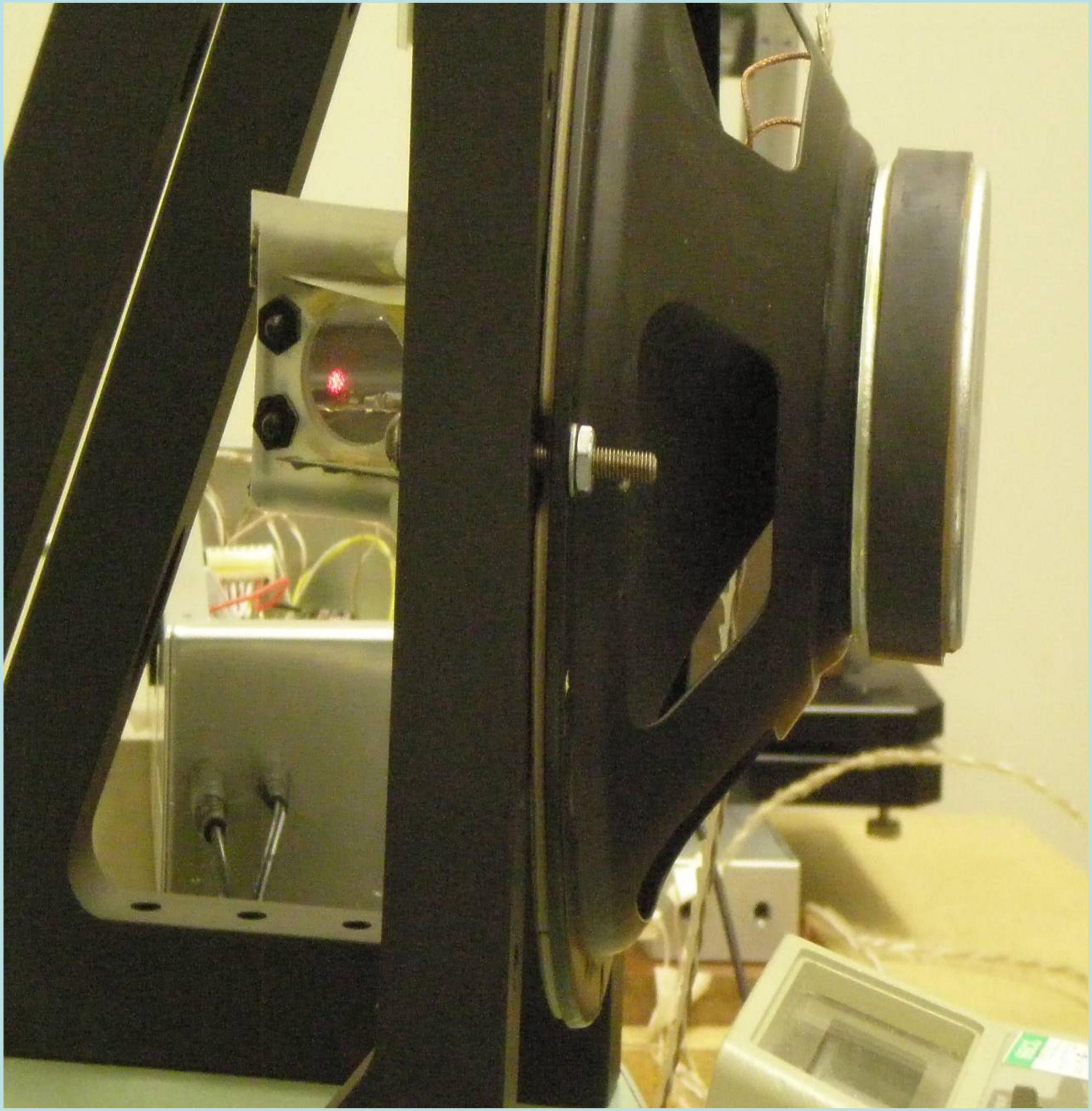
XY stage

MEMS mirror

4 silicon detectors

Laser reflecting from MEMS mirror

Light surrounding it is reflected from a distant lens



Conclusions

- Optical Technologies now being developed could provide a lot more flexibility in HEP detectors for -

  Reliability

  Choice in where mass is placed

  Onboard tracking trigger

  Reduction of fiber routing

  More bandwidth

REFERENCES

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The IBM Mach-Zender:

Paper by Green, et al in Optics Express Vol 5, No 25, December 2007
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THE MIT DEVICE:
Paper by Liu, et al. as described in Nature Photonics, December, 2008
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MEMS mirrors:
"Monolithic MEMS optical switch with amplified out-of-plane angular motion",D. Lopez, et al, IEEE Xplore 0-7803-7595-5/02/
"The Lucent LambdaRouter", D.J.Bishop, et al, IEEE Communications Magazine, 0163-6804/02/

Robust free space board-to-board optical interconnect with closed loop MEMS tracking

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Free-space optical links for board-to-board interconnects

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(1) HP Labs, Hewlett Packard, 1501 Page Mill Road, Palo Alto, CA 94304, USA,
Applied Physics A: Materials Science & Processing, V 95, #4, (June 2009)

Radiation hardness references

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