Alignment of Silicon tracking systems: R&D, toward first prototype

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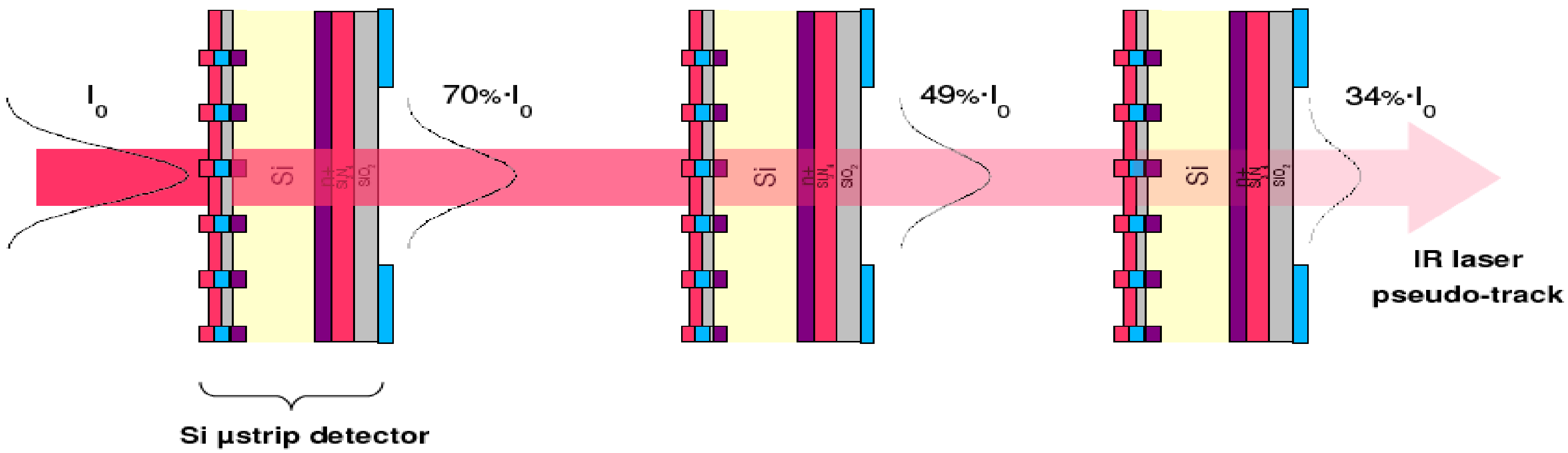
Laser alignment

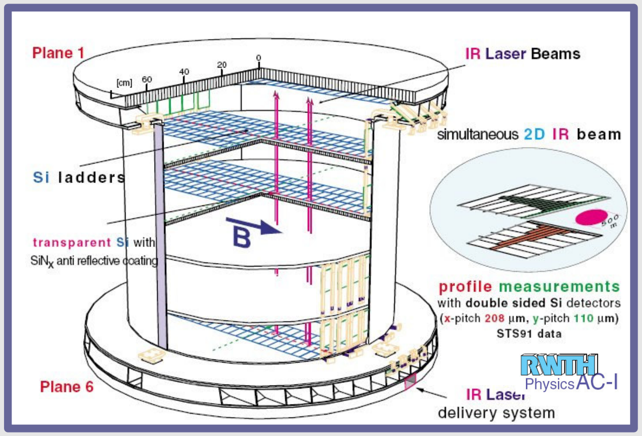
Proposed alignment method for Si microstrips is a track alignment where particle tracks are replaced by laser tracks. Laser gaussian beam is spatially reconstructed.

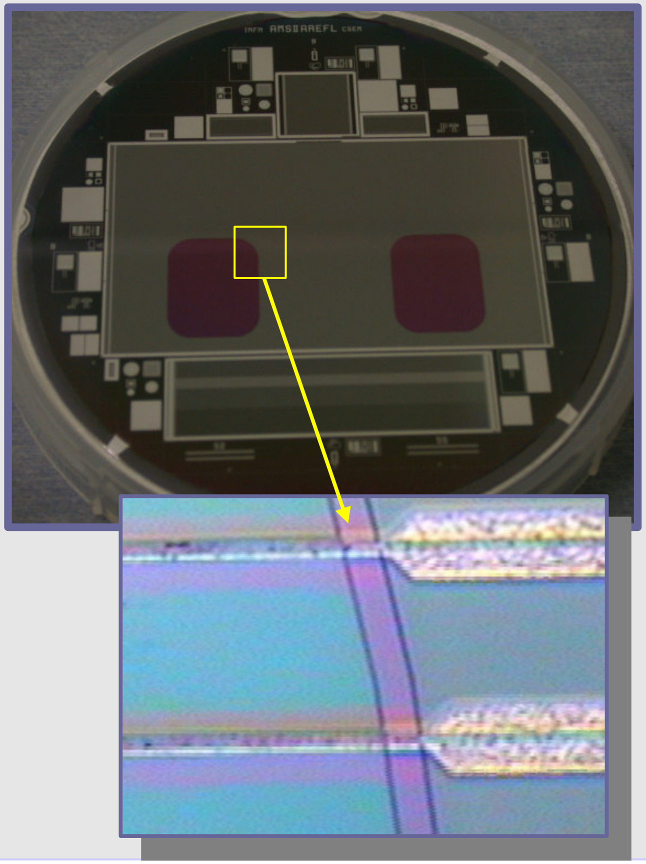


- This is possible because...
  - IR light is partially absorbed by Si.
  - Back electrode (opaque material) removed only in the window where the laser goes through (Al free line of sight through layers of Si)

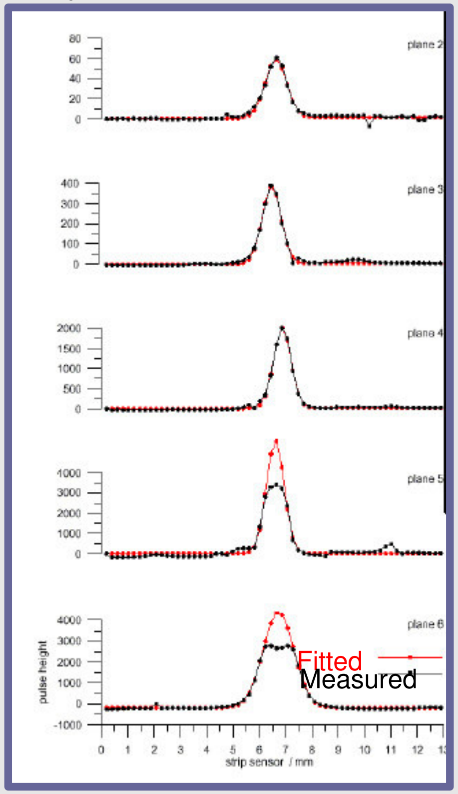
- Advantages
  - Laser~200 MIPS → sharing same DAQ as Si detector
  - Silicon modules are directly monitored, no external fiducial marks
  - No extra material added
  - System can be easily accommodated to any tracker design

An idea that works ...





Up to 4 ladders traversed



AMS-01 innovation (W. Wallraff)

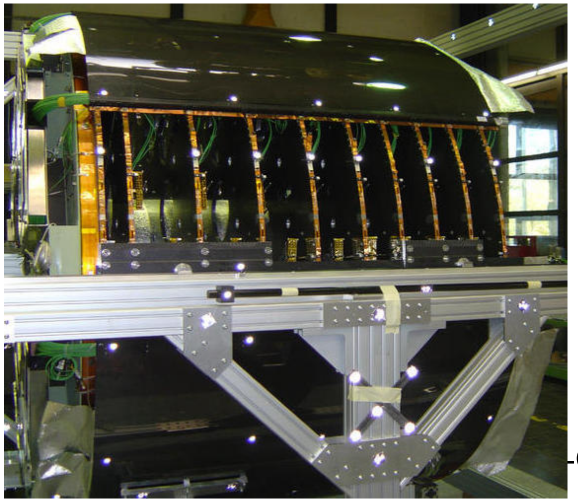
λ = 1082 nm

IR "pseudotracks"

1-2 µm accuracy obtained

Transmittance~ 50%

CMS
TEC



λ = 1075 nm

• Optimization of sensors not included from beginning of sensor design → **lower transmittance** achieved~20%

• 180 deg **beam splitters** in the middle of the tracker produce back to back beams measured by modules

• Laser spot reconstructed with **10 µm resolution** (1st sensor)

9 TEC disks (18 petals) reconstructed using 2 beams with 50 µm accuracy (100 µm required in CMS)

SiLC: 2-fold approach

R&D on transparent Silicon μstrip sensors:

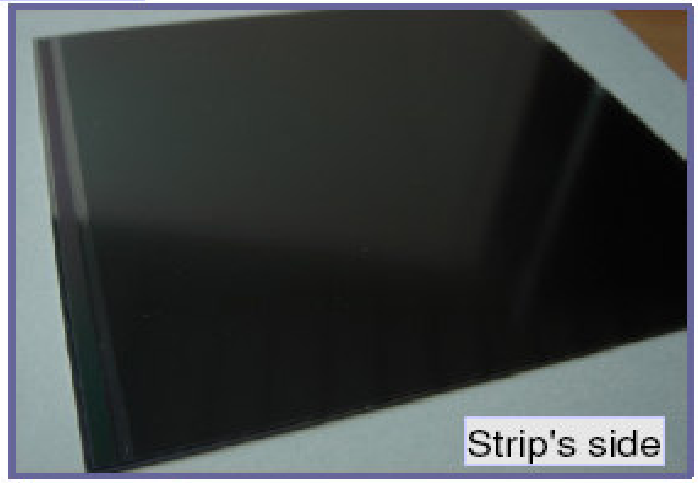
• Together with **IMB-CNM (Barcelona)** design, build and test new IR-transparent Silicon microstrip detectors.
• Consider option of aluminum electrodes or transparent electrodes

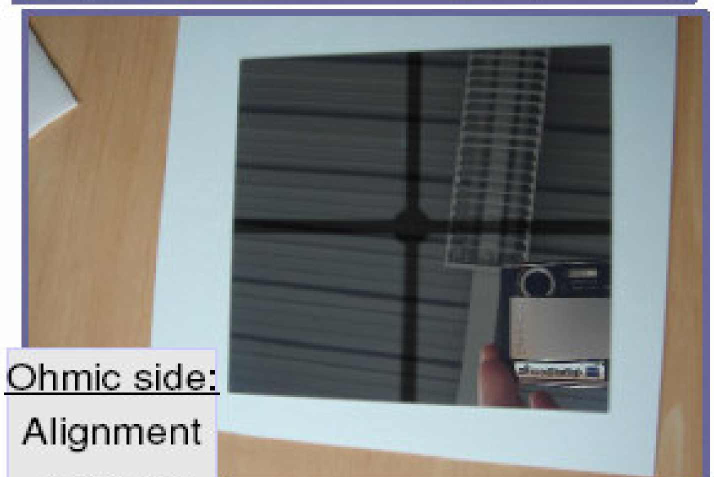
AMS-like approach:

Baseline version: Minimum set of changes for any SiLC sensors. For instance, for the new HPK sensors

Implemented:
- ∅~10 mm window where Al back-metalization has been removed

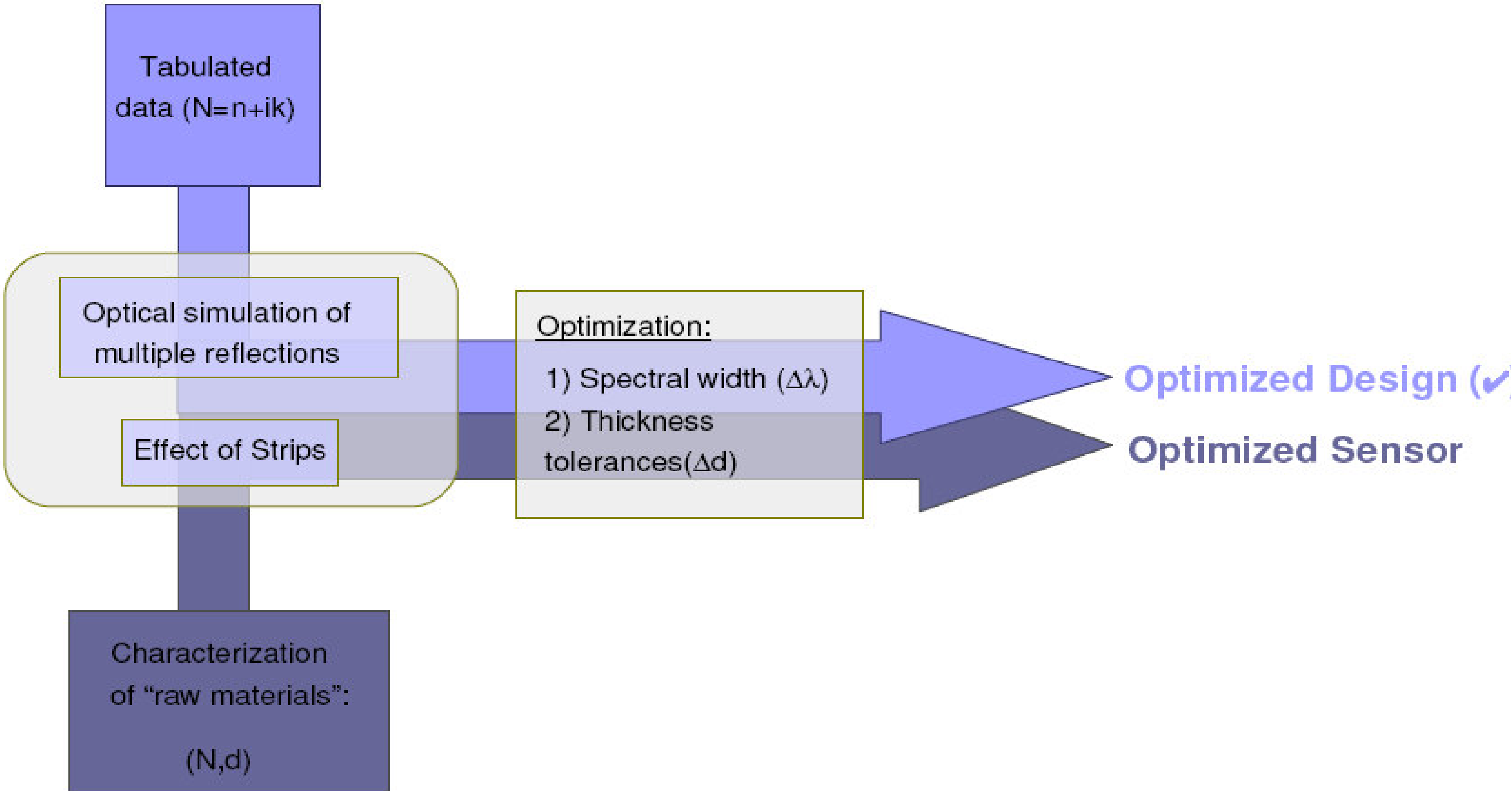
Suggested (not cost effective for small batches):
- Strip width reduction (in alignment window)
- Alternate strip removal (in alignment window)


Strip's side


Ohmic side: Alignment passage

…

Transparent sensors HOWTO



R&D on IR transparent µstrips

• Parallel R&D line that we initiated **together with CNM-Barcelona**

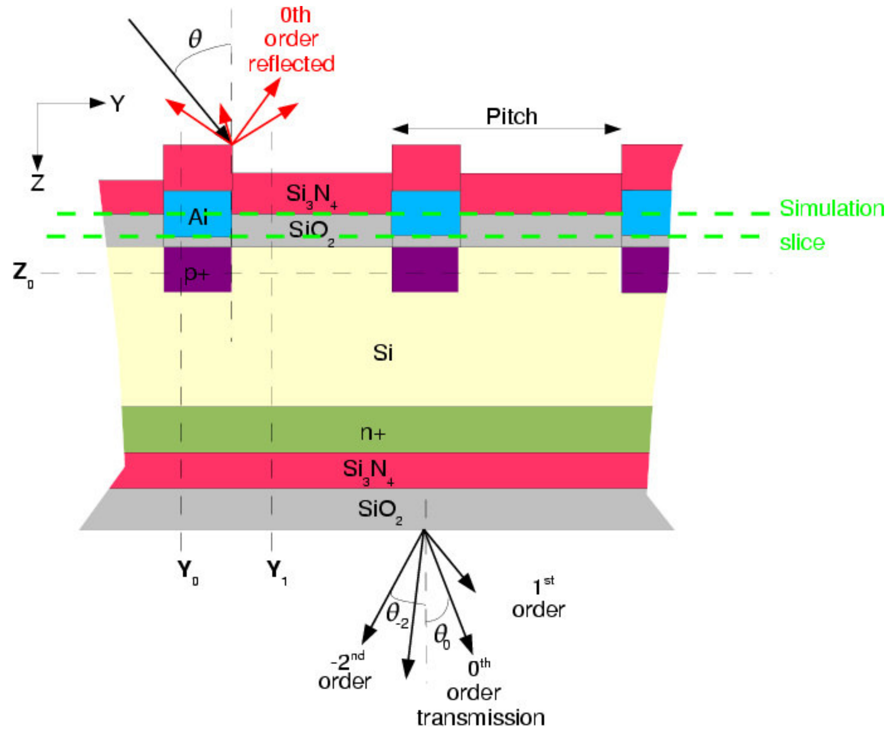
• The goal is to increase the optical transmittance of Silicon microstrips detectors to IR light, without making fundamental changes to the sensor.

How?

We have developed a **realistic simulation** of the passage of light through a detector, **including interferential** effects due to multiple reflections at the interfaces **and diffraction** due to the patterned strips. Not such level of detail found in AMS or CMS works before.

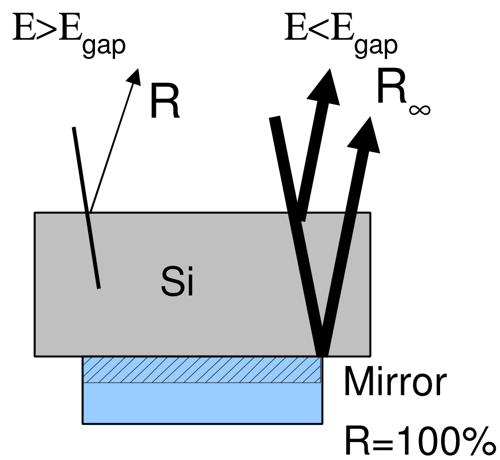
Identified **key parameters** contributing to the %T of the detector

Stack of materials is then **optimized** for maximum and robust %T



Calculating n

- The real part of the refractive index can be calculated easily. Due to Si high absorption for $E>E_{gap}$ and due to the thickness of the wafer, the photons do not reach the bottom surface
- Checked with a **mirror** on the Si wafer



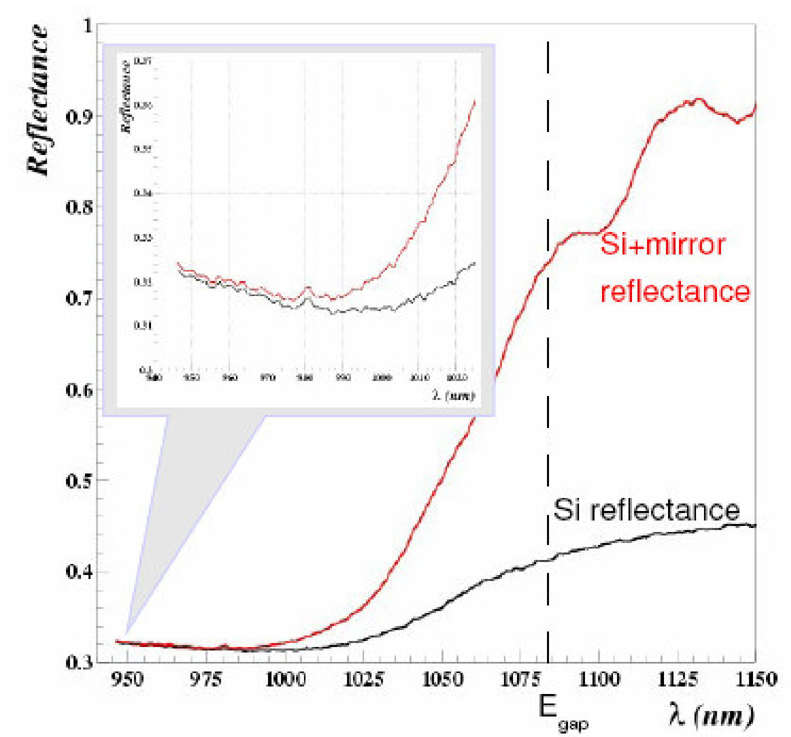
n(R) can be calculated using above formula:

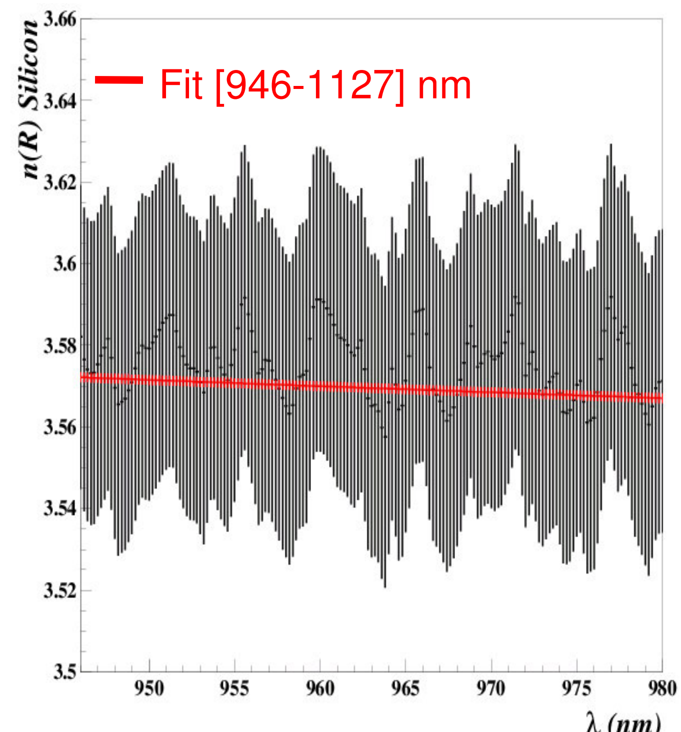
$$R=\frac{(n-1)^2+k^2}{(n+1)^2+k^2}\approx\frac{(n-1)^2}{(n+1)^2}$$

($n \sim 3.5, k \sim 10^{-3}$)

Independent of thickness and k

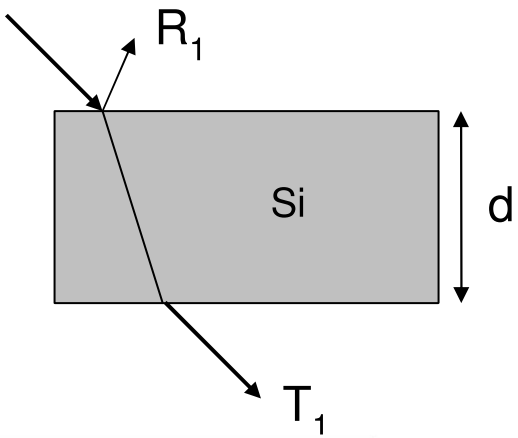
$$\sigma_n=\frac{\sigma_R}{\frac{\delta R}{\delta n}}=\sigma_R\frac{(n+1)^3}{4(n-1)}\approx 10\,\sigma_R$$



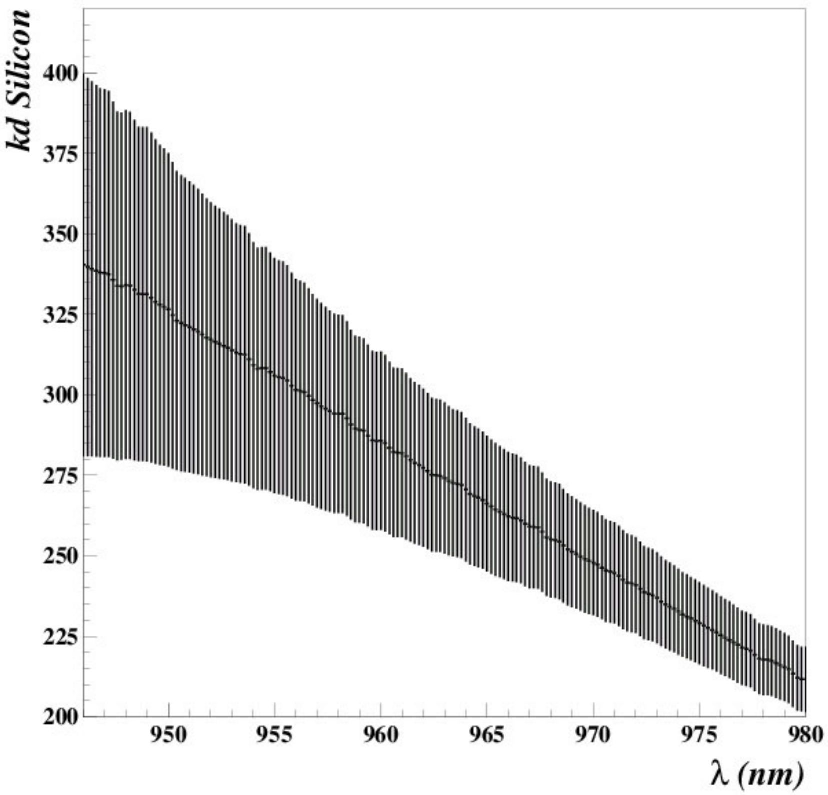


Calculating kd

- We can find kd analytically from the 1st transmitted beam (T_1), as a function of λ and R_1 (calculated before)



$$kd = \frac{\lambda}{4\pi} \ln\left(\frac{(1-R_1)^2}{T_1}\right)$$



Example of kd calculated from λ<980 nm

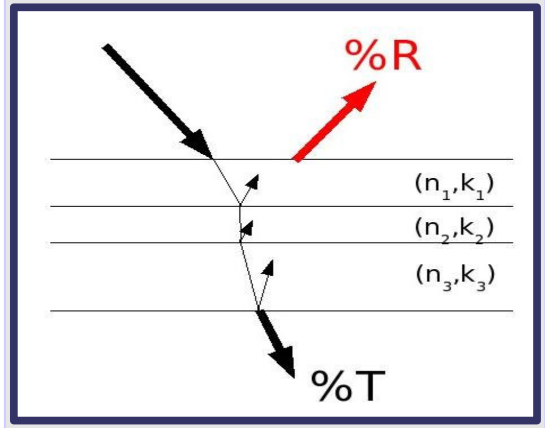
After multiple beams are reflected kd cannot be easily computed.

"k" always appears multiplied by "d". Correlation=1

Best is to measure "$d \pm \sigma_d$" independently and use this information in the global fit as a constraint

Cont. layers, sensor simulation

- The sensor is modeled as a multilayer media. Simulation features:
  - Interferential effects due to multiple reflections are considered
  - Absorption effects are included
  - Refraction index (n,k) is a function of λ
  - Typical deposition thicknesses considered
  - Deposition tolerances are included $\Rightarrow$ We simulate realistic designs
  - Laser spectral width is assumed (±2.5 x 2 nm)



T+R+A = 1

- Simulation particularities:
  - Multilayers are left/right borderless
  - Effect of aluminum electrodes is not included yet
  - Energy going to secondary and higher order maxima (grid effect) is included

Transmittance	90%	80%	70%	60%	50%	40%
Traversed	30	15	10	7	5	4

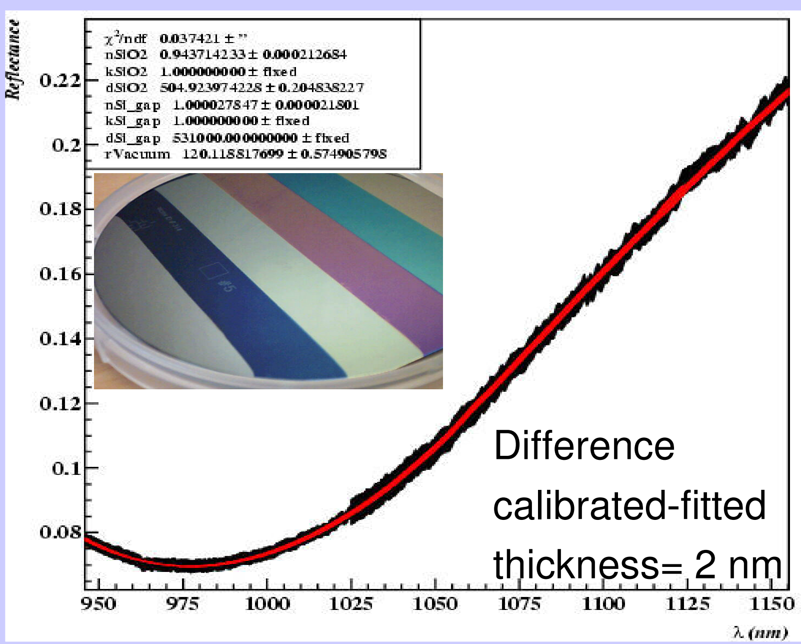
- Aim is to achieve a transmittance as high as possible with moderate absorption (>3%)

Validation of simulation

— Different wafers have different doping levels
— Wafers divided into quadrants.
— In each quadrant only one new material has been deposited.

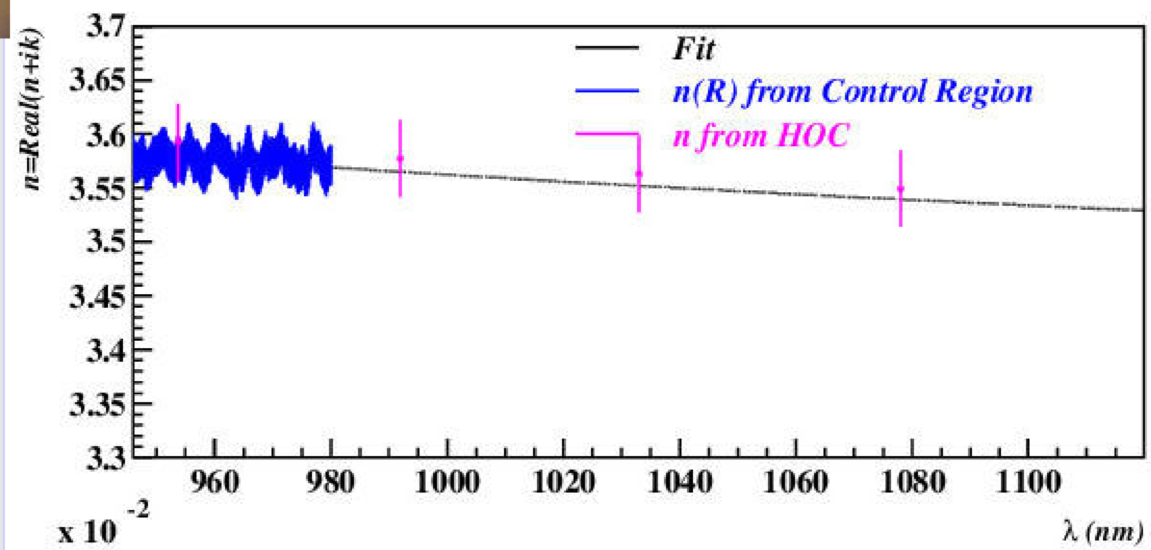
Firstly, continuous layers [no strips=easier] have been reproduced

This part of the simulation has been validated using a calibrated reference wafer



Another example:

Calculated refraction index of a Si wafer compared against tabulated Si data

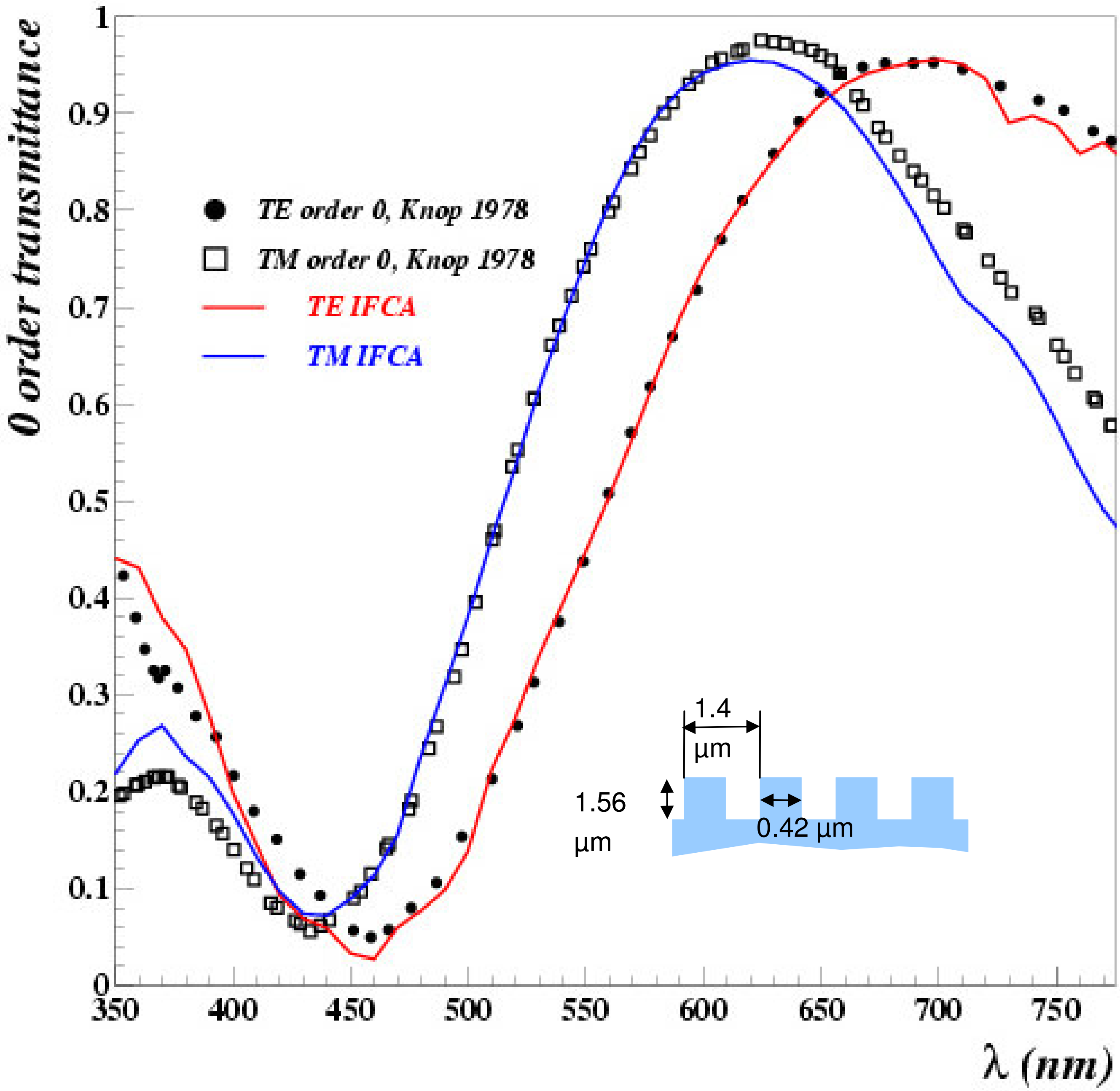


Si wafer + sample materials provided by CNM

Material **refraction indexes** are the input needed for the simulation of the full sensor stack.

Next, strips simulation validation

0th order transmittance



K. Knop, J. Opt. Soc. Am., Vol. 68, No. 9, September 1978

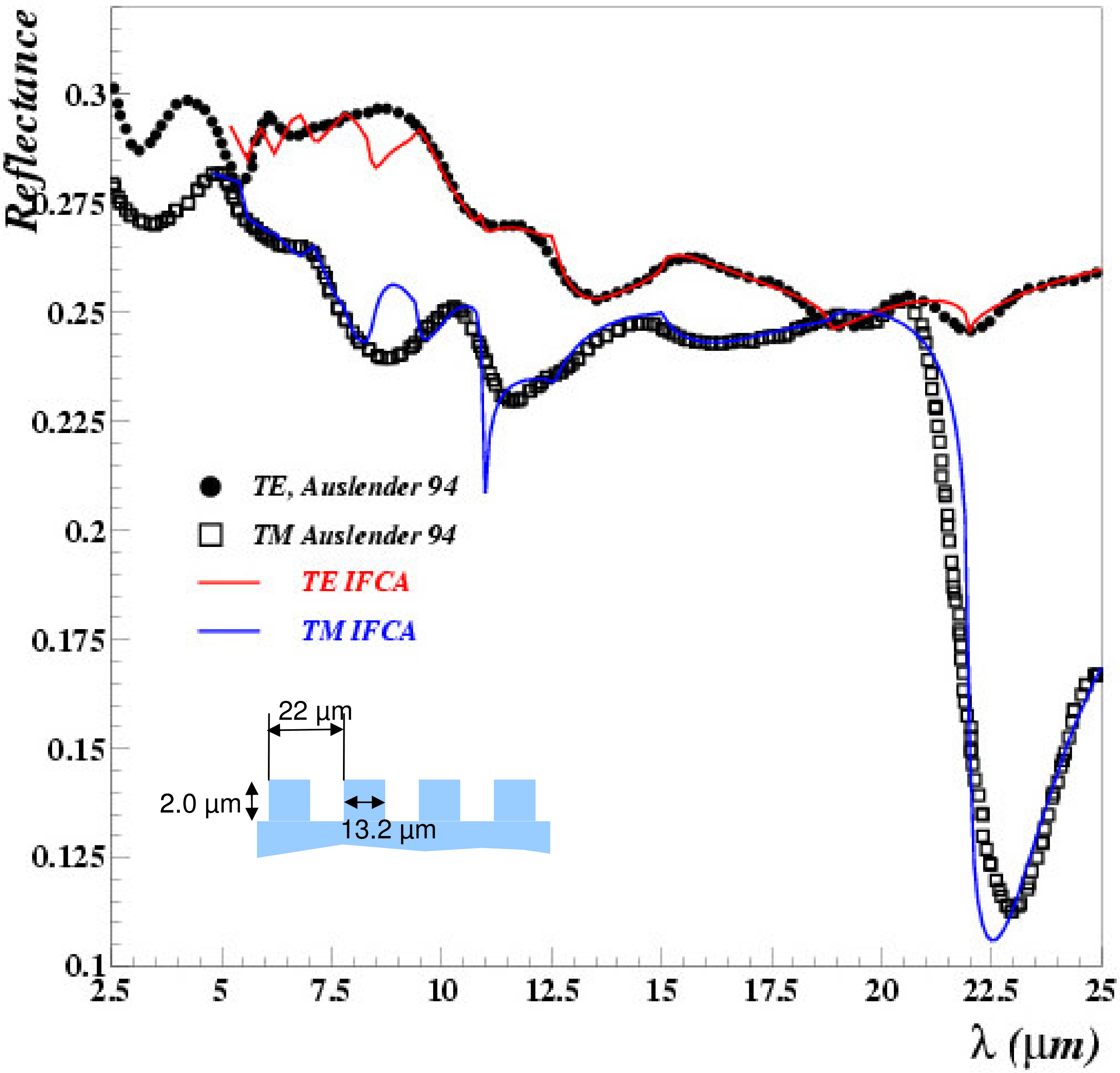
Markers are different simulations from other author

Lines are our simulation

Only 0th order (directly transmitted)

Studied for both TE and TM polarizations

Reflectance



M. Auslender, Appl. Optics, Vol 33, No 21, 20 July 1994

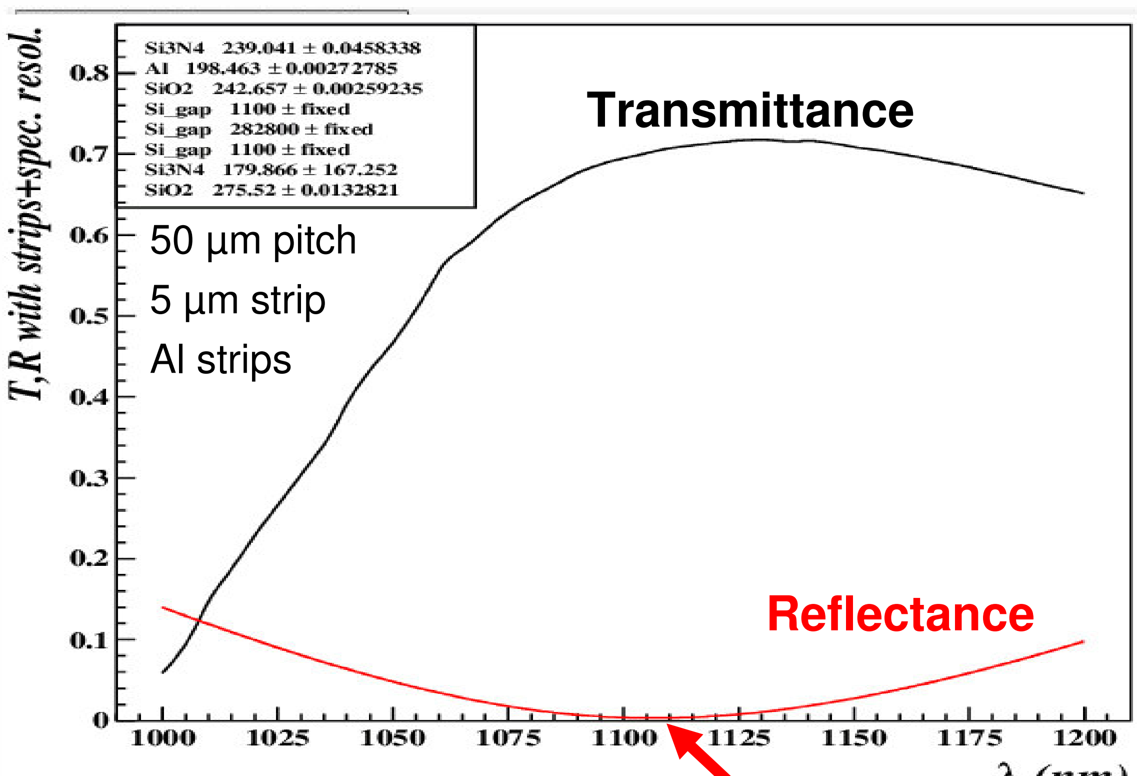
(Total) reflectance is the sum of all reflected diffraction orders

TE and TM polarizations

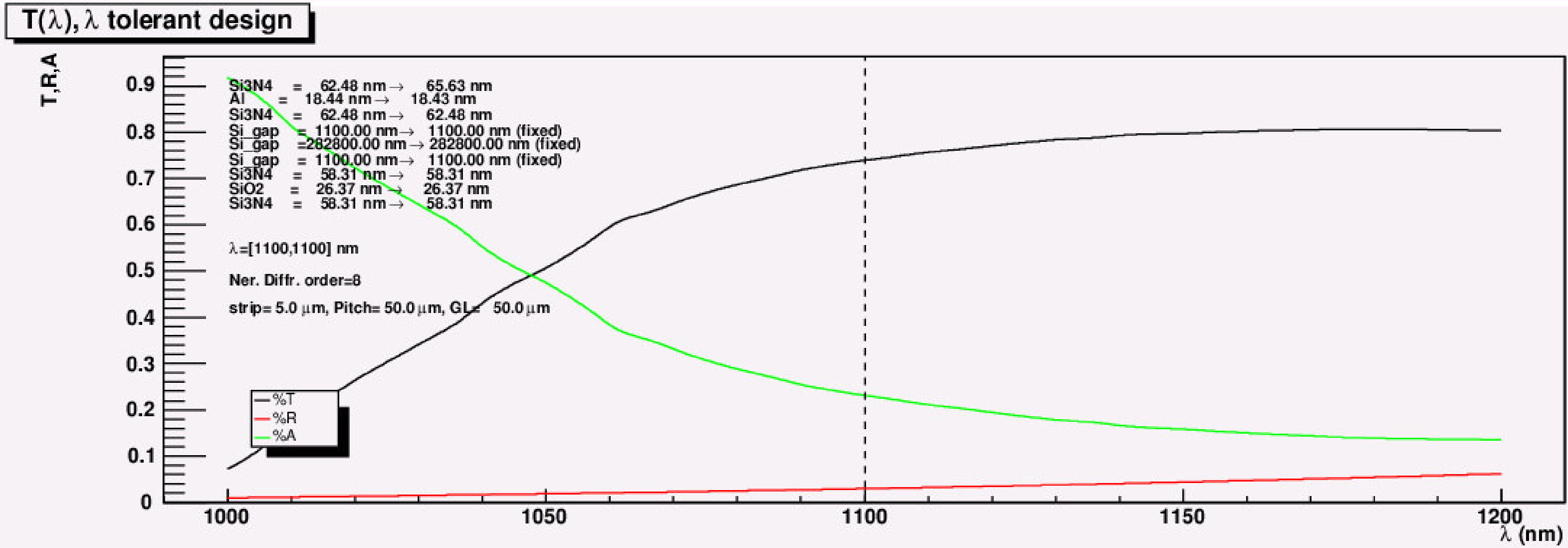
Design optimization

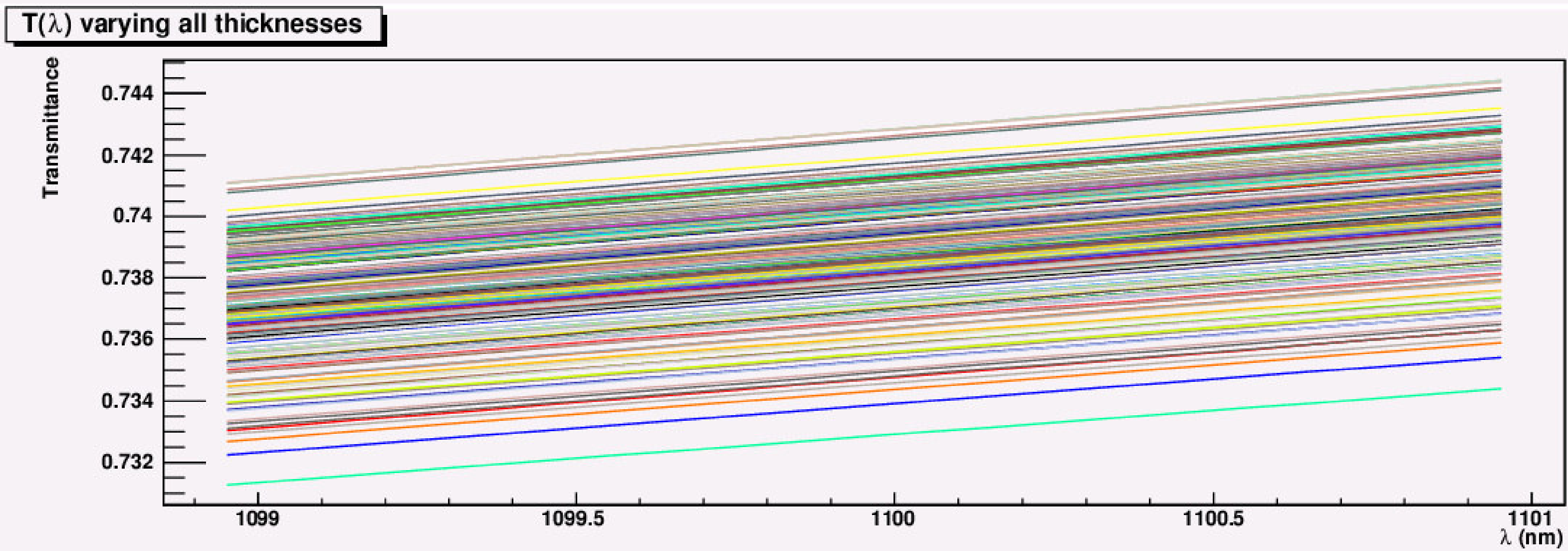
- Once strip_width/pitch is optimum, we modify material thicknesses to get maximum transmittance **(constructive interference)** using the following χ^2:

$$\chi^2 = \underbrace{\sum_{\lambda=1098}^{1102} \left[(T(N,d) - T_{MAX})^2 + R^2 + \underbrace{\sum (T_{MC} - T_{MAX})^2}_{\text{Thickness Tolerance: MonteCarlo}} \right]}_{\text{Laser spectral width}}$$



- ✓ Al strips
- ✓ Pitch=50 µm
- ✓ Strip Width=5 µm
- ✓ p,n implants 7×10^{16} cm^{-3}
- ✓ Spectral width included
- ✓ Using tabulated N=n+ik


T(λ), λ tolerant design
T,R,A
Si3N4 = 62.48 nm → 65.63 nm
Al = 18.44 nm → 18.43 nm
Si3N4 = 62.48 nm → 62.48 nm
Si_gap = 1100.00 nm → 1100.00 nm (fixed)
Si_gap =282800.00 nm → 282800.00 nm (fixed)
Si_gap = 1100.00 nm → 1100.00 nm (fixed)
Si3N4 = 58.31 nm → 58.31 nm
SiO2 = 26.37 nm → 26.37 nm
Si3N4 = 58.31 nm → 58.31 nm
λ=[1100,1100] nm
Ner. Diffr. order=8
strip= 5.0 μm, Pitch= 50.0 μm, GL= 50.0 μm
%T
%R
%A
λ (nm)


T(λ) varying all thicknesses
Transmittance
λ (nm)

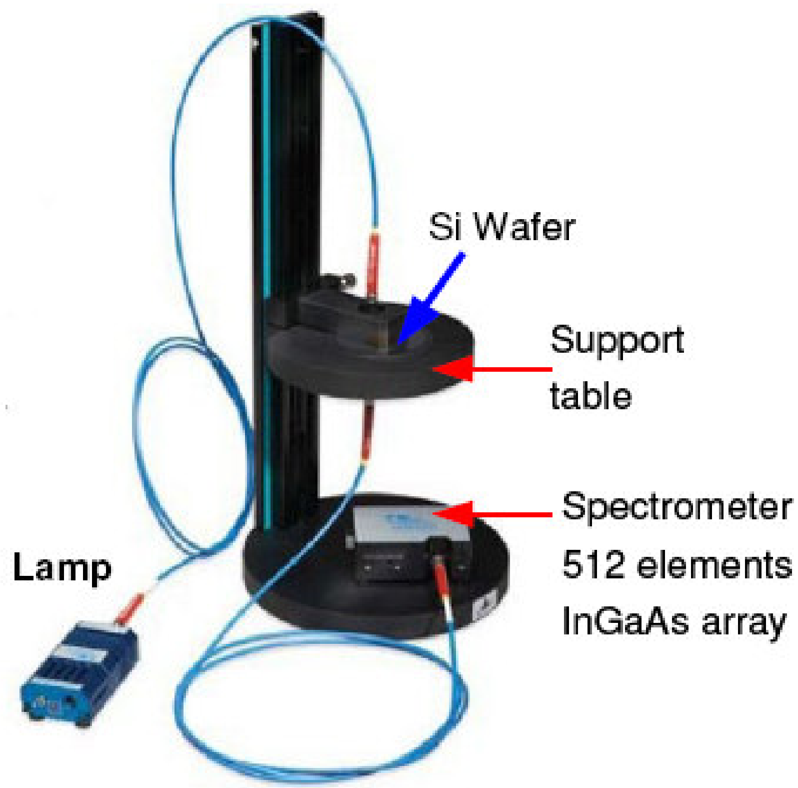
Measuring %T and %R

- A spectro(photo)meter provides Transmittance (T) and Reflectance (R) as a function of wavelength (λ).

- Jan 08: Custom designed grating in a spectrometer (SPM): λ=[950,1150] nm ; σ_λ=1.2 nm spectral resolution %T and %R accessories

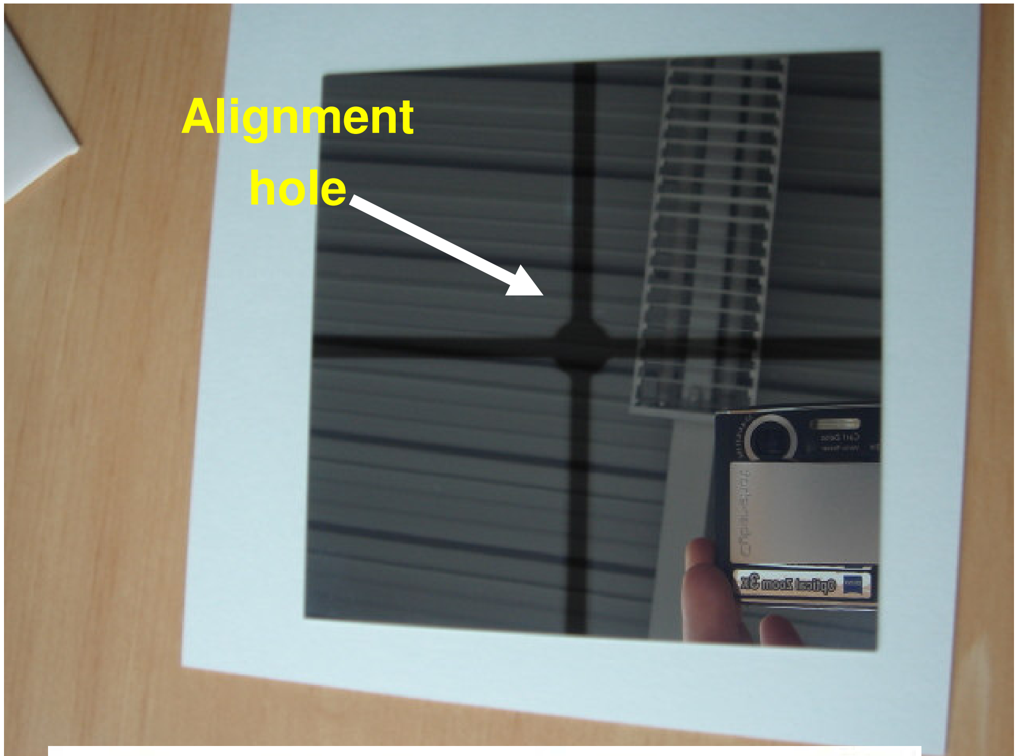
- Measurements of T and R can be used to characterize the materials optically: find the refraction indexes that produced the measured (T,R).

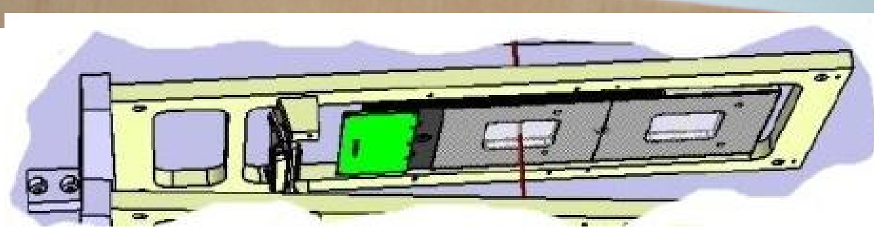
$$\left.\begin{array}{l} T[n(\lambda), k(\lambda), d] \\ R[n(\lambda), k(\lambda), d] \end{array}\right\} \Rightarrow n(\lambda), k(\lambda), d$$

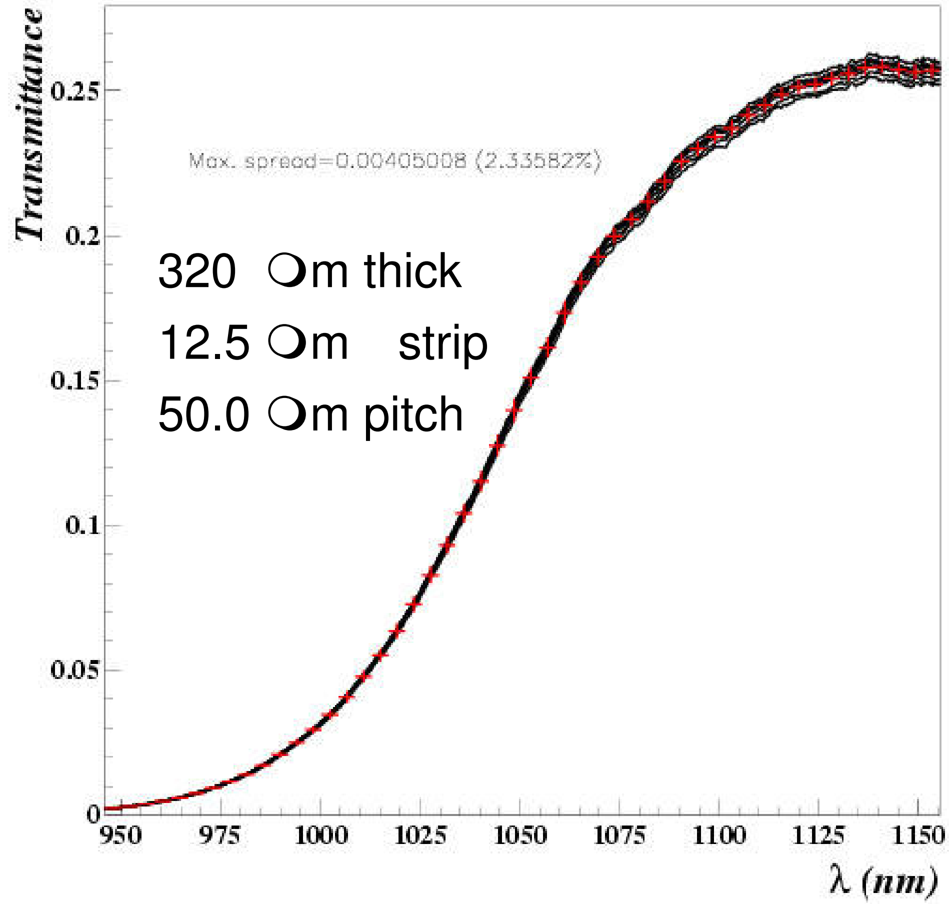


- We compared the output of our SPM with a high end SPM: both agree at 2% level

Sensor optical characterization







Measuring transmittance and reflectance to IR light using a spectrometer: T[λ=1060 nm] ~ 16%

Low transmittance of the sensors was expected. We did not ask for any modification to HPK sensors. This value agrees with CMS measured values of uncoated sensors.

Further optical tests of the sensors will be done at alignment lab in IFCA-Santander, after completion of the test beam...

Optical characterization at IFCA

Linearity (comparison of reconstructed position of a fixed laser spot scanned over the sensor vs displacement of motors) will be studied using a 3D motion table.

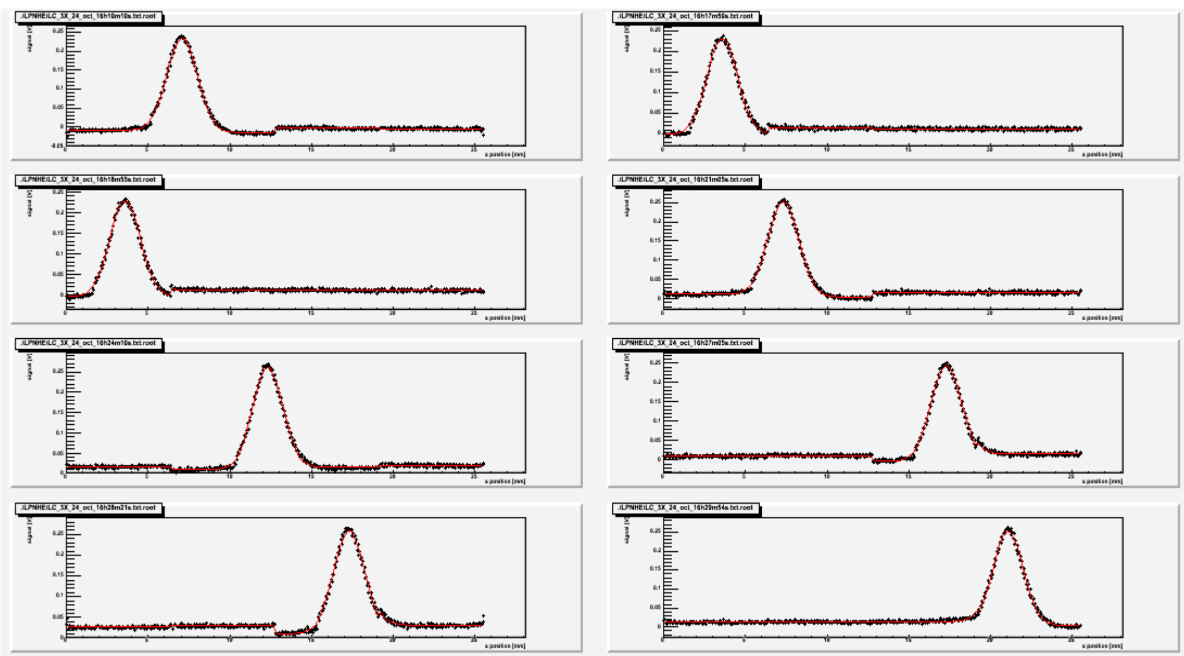
The table is in turn calibrated using an interferometer giving accuracy of ~1 μm

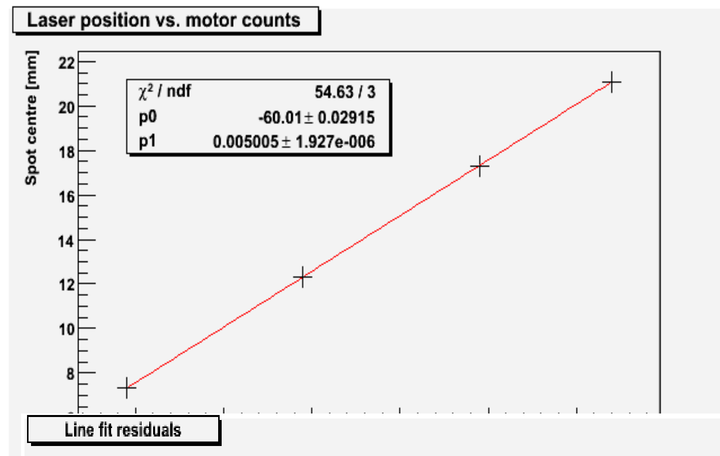
Deflection (=deviation wrt incident direction) of the beam after traversing one module can be measured using a long granite bench and a laser.

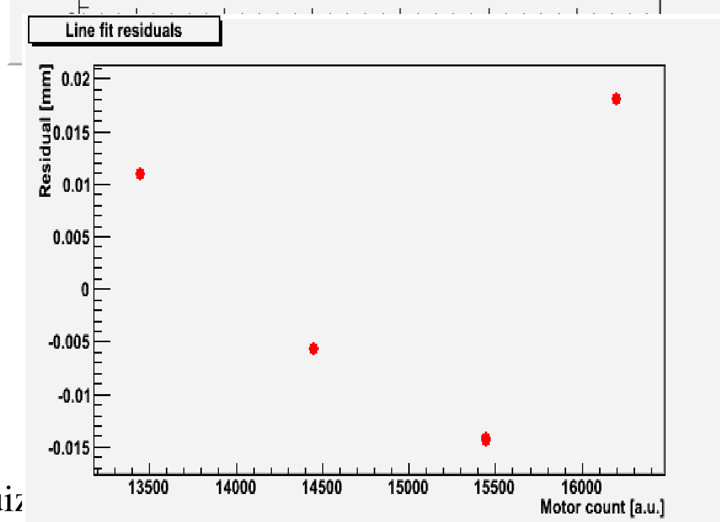
Fit results

- The position of laser spot on an HPK sensor (50 µm pitch) with 4VA1 readout was calculated by a Gaussian fit to the observed detector signal profile.
- No CMN correction was used
- The pedestal signals were modelled by 4 constant levels corresponding to 4 sensor regions read out by individual VA1s.
- Profiles from 8 runs with different laser positions were analysed.

mean	RMS error
7.0785+/-0.0044	0.9322+/-0.0044
3.5684+/-0.0042	0.9241+/-0.0059
3.5720+/-0.0040	0.9273+/-0.0057
7.3183+/-0.0042	0.9315+/-0.0044
12.3065+/-0.0048	0.9212+/-0.0046
17.3028+/-0.0041	0.9391+/-0.0049
17.3027+/-0.0043	0.9443+/-0.0054
21.0888+/-0.0038	0.9190+/-0.0046







Conclusions

• Proposed alignment strategy is based in already existing CMS and AMS systems: IR laser tracks shot across layers

• A prototype following these guidelines is currently being built. Beam test will take place soon

• Typical microstrip sensor transmittance to IR light is below 20%.

The higher transmittance → the more detectors can be aligned with a single beam

• We proposed a second R&D line with the goal of reaching high transmittance values of ≥70%. With a good choice of thicknesses, a simple reduction of the strip witdth to 10% of the pitch provides a dramatic increase of %T.

• Optimization of the current design is done in 2 steps:

1) a simulation of continuous planeparallel layers is used to extract the refraction indexes of the materials. This simulation has been validated

2) The refraction indexes are fed into a more complex simulation which takes into account diffraction by the strips. The simulation is being validated, first results are optimist

• A robust sensor design will be settled by the end of this month and production of a 1st version will take place at CNM before the end of this year

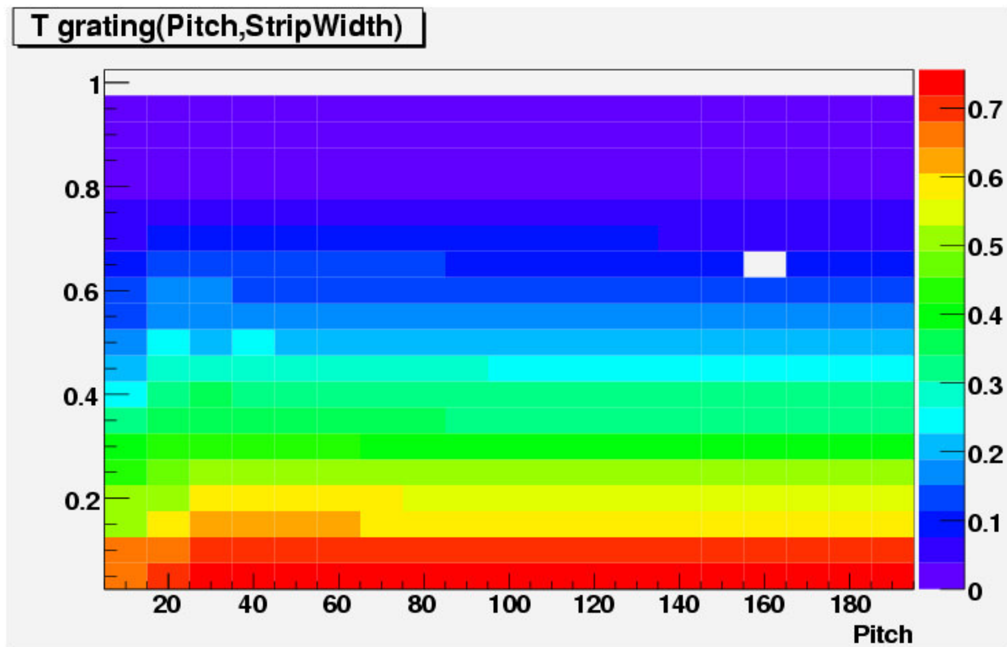
B A C K U P

Maximization of transmittance

• We found that most critical parameter is the width/pitch ratio. Intuitively, the less Al, the more transmittance. Good compromise: **strip_width = 10% · Pitch**

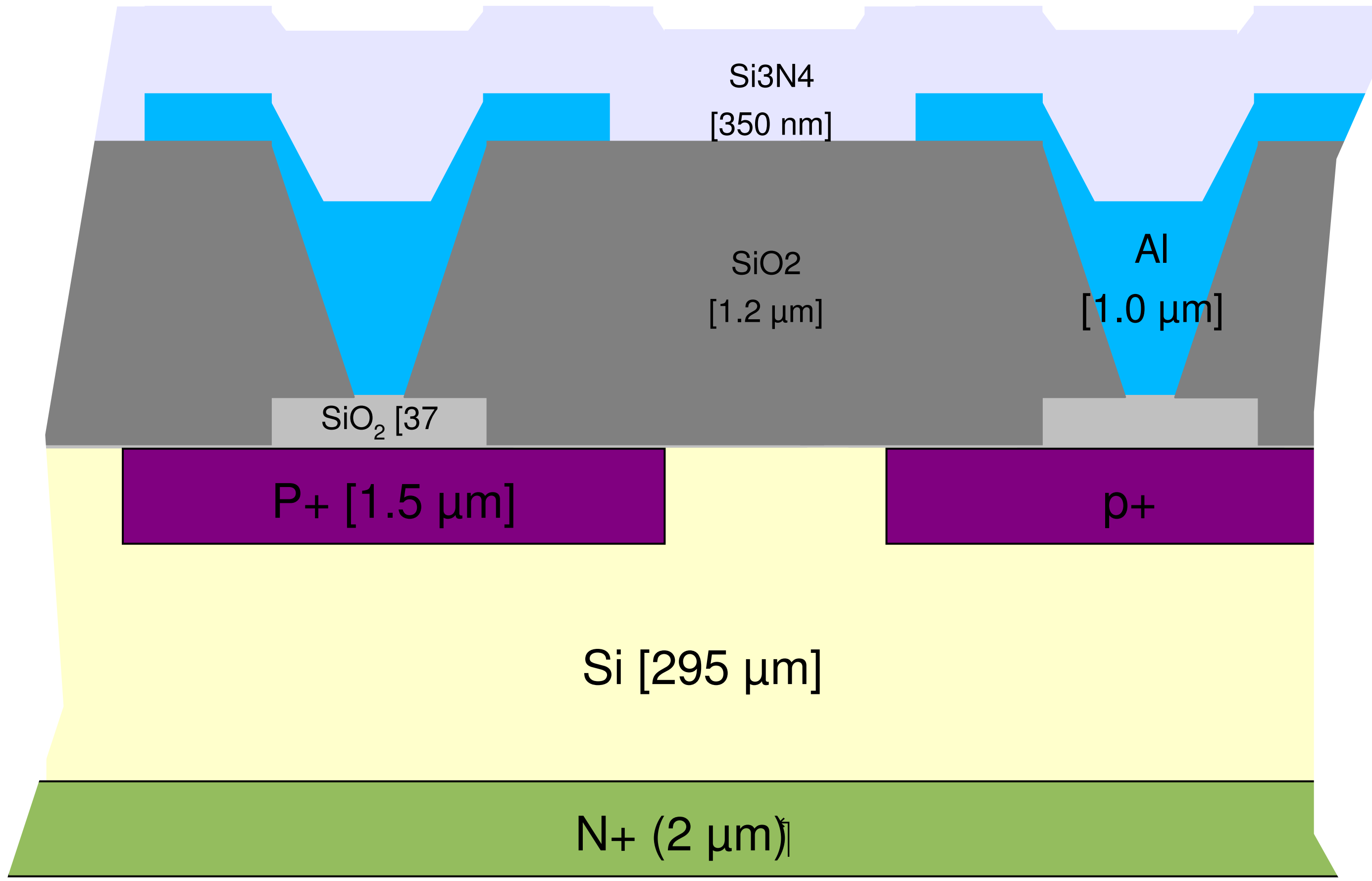
• T(pitch,strip_width), with strip_width expressed as percentage of the pitch

Using Al strips:



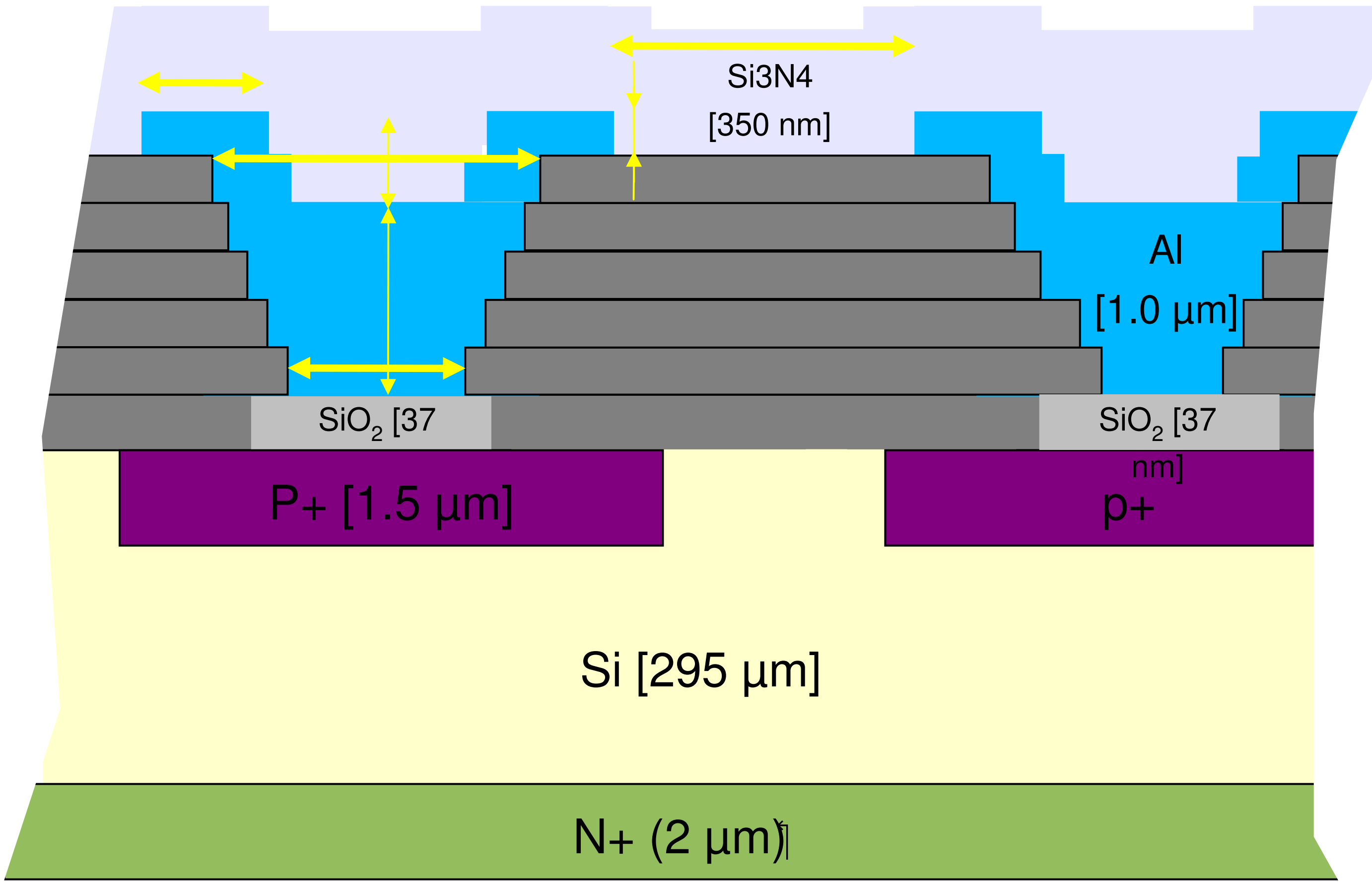
• A further thickness optimization of the multilayer leads to few % increase of transmittance However, %T has to be maximized such that it is robust against small changes of layer thickness (fabrication tolerance).

Next step: more realistic layout of the sensor ?



I need input for this

Next step: more realistic layout of the sensor ?



Integrated alignment prototype

Standard module

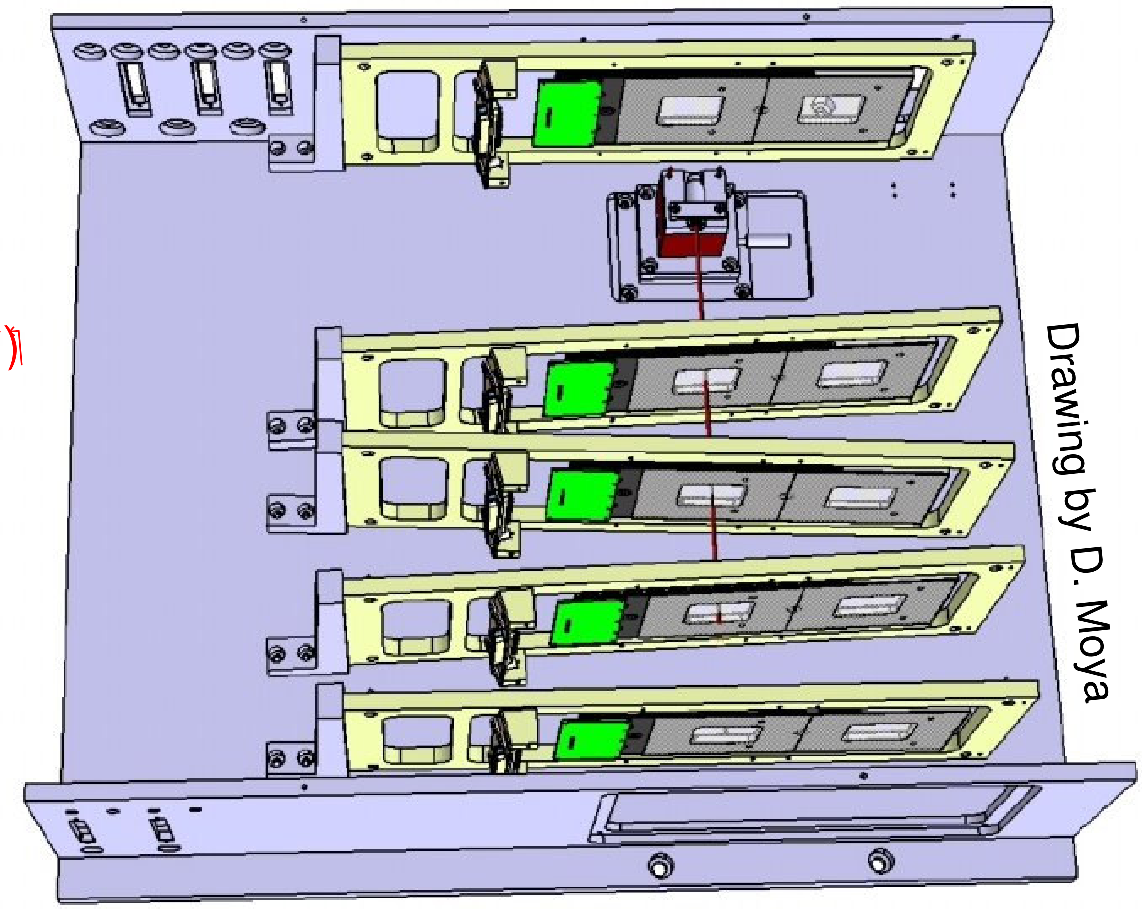
Laser colimator

Alignment module(*)

Alignment module

Alignment module

Standard module

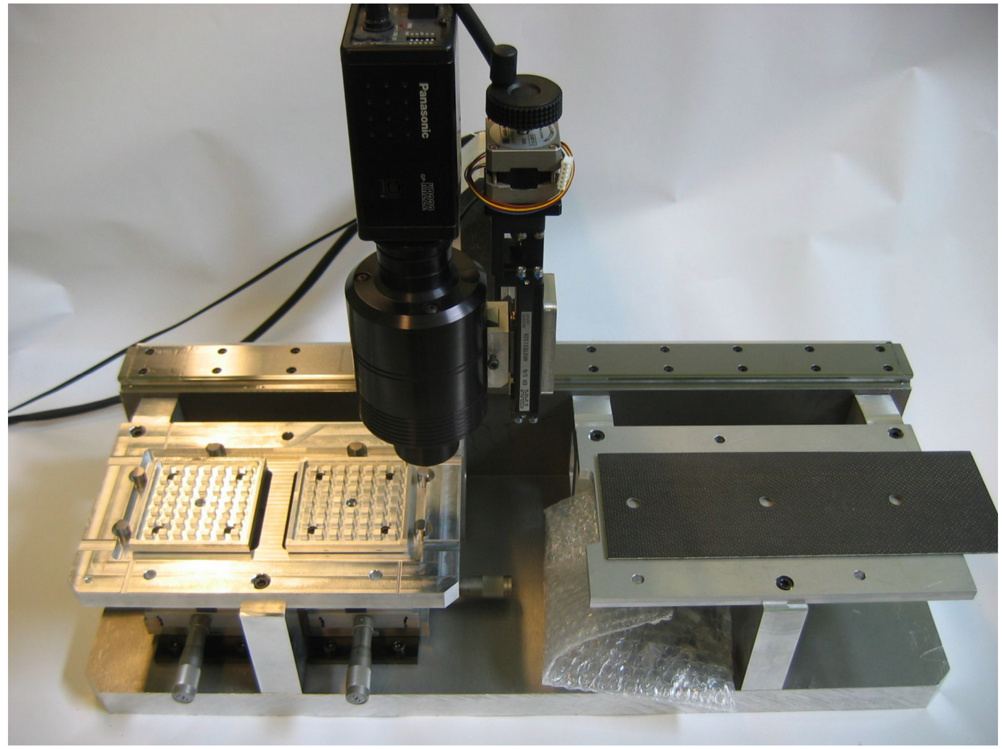


Goal:

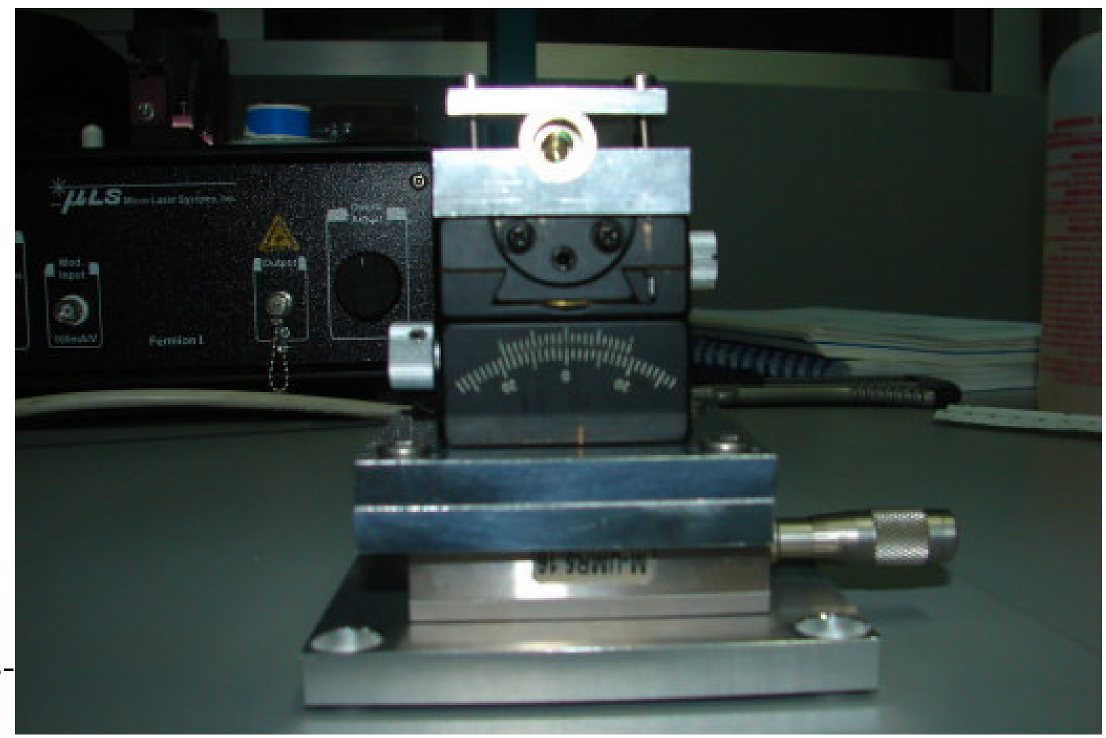
3 inner modules can be aligned with particle tracks or with laser tracks → proof of principle

Inner module can be slightly “pushed/pulled”, comparison of reconstruction accuracy

(*) P.S. Alignment modules are rotated to avoid backward reflected beam traveling beam (avoids interferences beam-beam)



Panasonic



Fermion 1

Alignment bench for beam deflection measurements. Deflections of order μrad can be measured as displacements of μm in meters