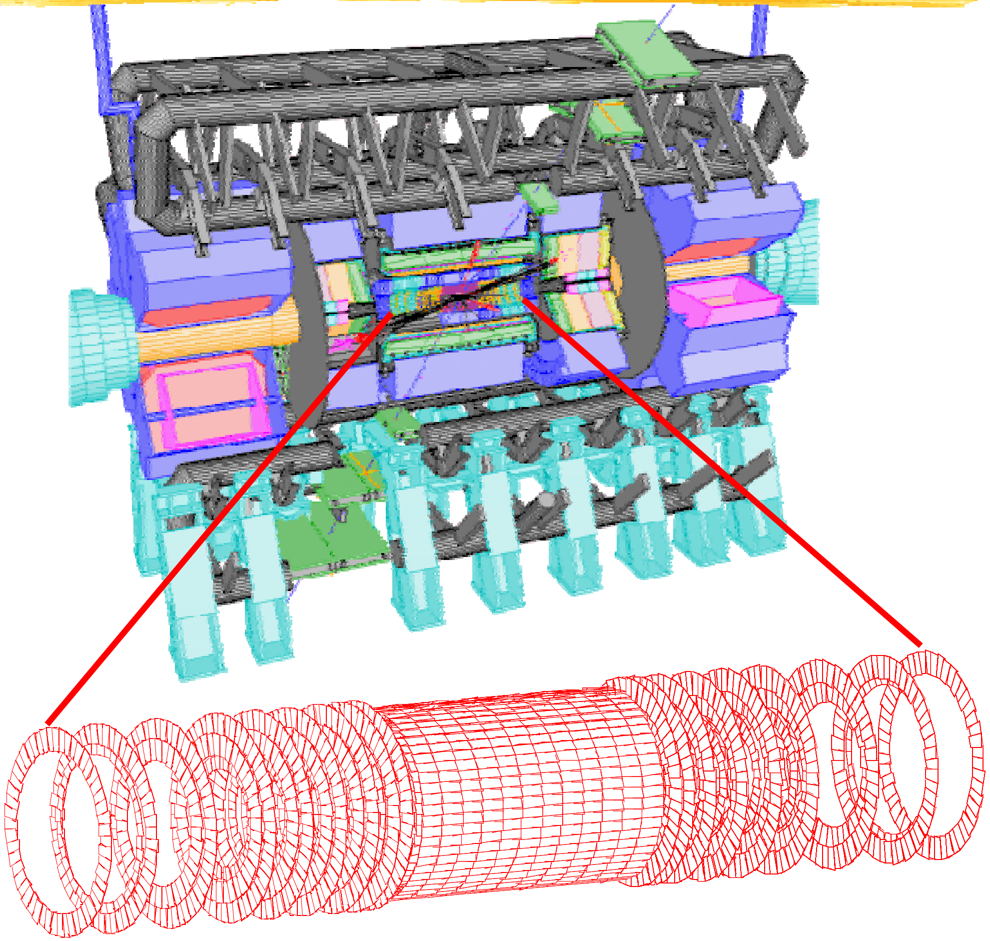
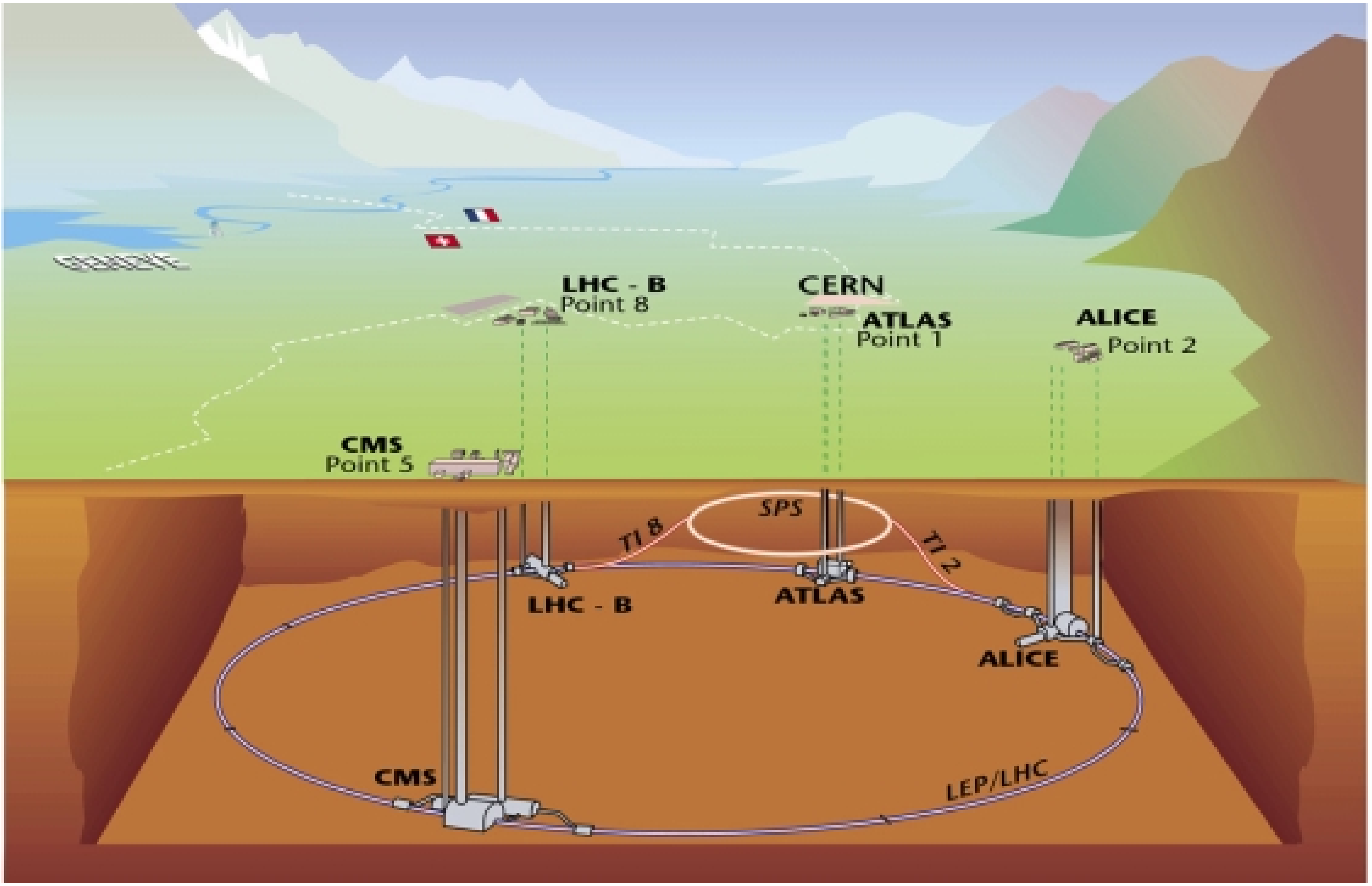
The ATLAS Silicon Microstrip Tracker

Lutz Feld
Freiburg University

- introduction
- system design
- module design
- sensors
- electronics
- hybrids
- module assembly

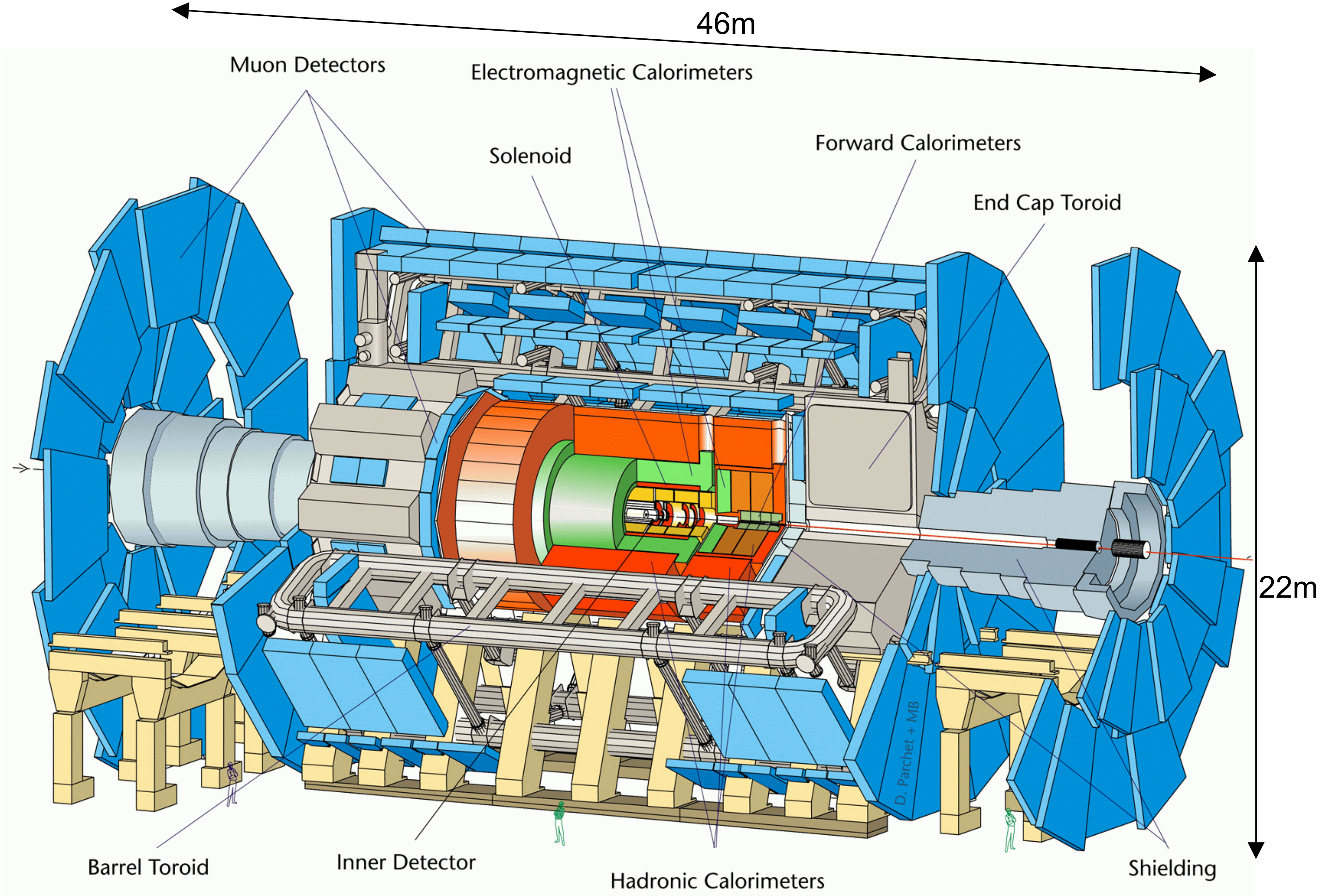


Large Hadron Collider at CERN

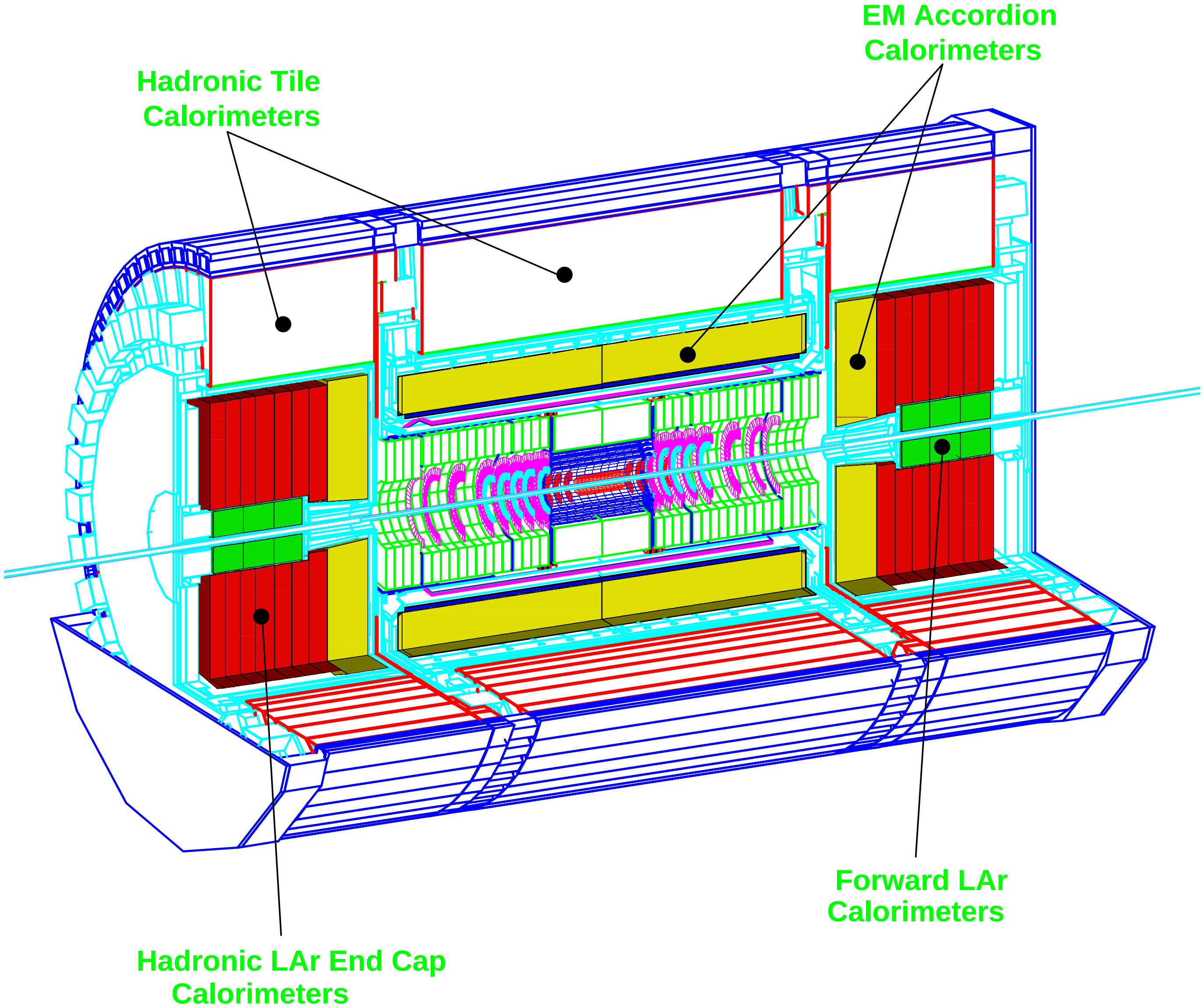


- pp collisions at 14 TeV centre of mass energy
- two multi purpose experiments: ATLAS and CMS
- two specialised experiments: ALICE (heavy ions) and LHC-B (b physics and CP)
- first beam in 2005

ATLAS-Detector



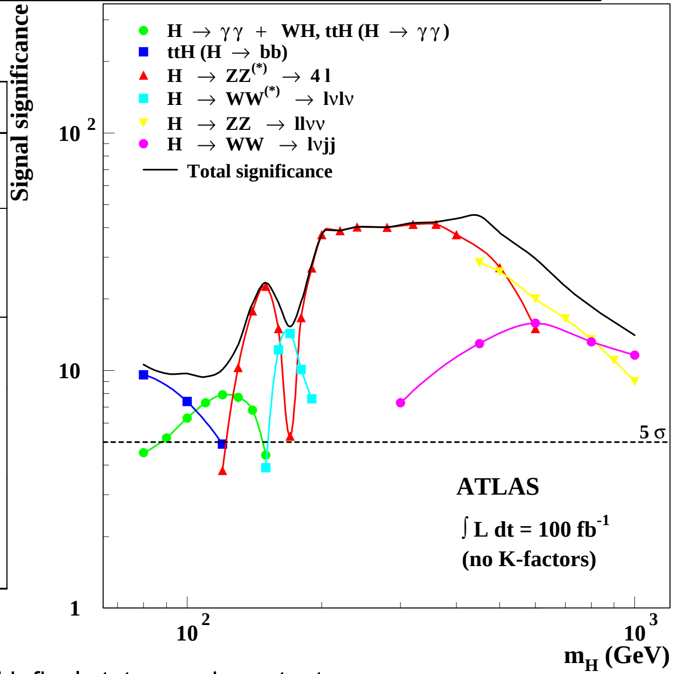
ATLAS without Muon Spectrometer



LHC Physics and its Requirements on the Tracker Performance

- **SM Higgs H^0**

higgs mass	explorable decays	tasks for the tracker
<110 GeV	$H^0 \to bb$	• **secondary vertex tag**
80 GeV-150 GeV	$H^0 \to \gamma\gamma$	• **isolation** of photon candidates • **calibration** of ECAL • **low mass**
110 GeV-700 GeV	$H^0 \to Z Z^{(*)} \to 2l^+ 2l^-$	• measurement of high momentum **electrons** and **muons** • **lepton isolation** • measurement of high energy **jets**
150 GeV-200 GeV	$H^0 \to W^+ W^- \to l^{+/-} \nu\, l^{+/-} \nu$	
300 GeV-1 TeV	$H^0 \to Z Z \to l^+ l^- \nu \nu$ $H^0 \to Z Z \to l^+ l^- j j$ $H^0 \to W^+ W^- \to l^{+/-} \nu j j$	



- **MSSM Higgs $H^{+/-}$, h, H, A:**
  - Many decays give signatures similar to the SM higgs decays, but in addition t and b final states are important,
  - therefore **impact parameter resolution**, recognition of **secondary vertices** in high energy jets and **track isolation** are important.

- **Supersymmetric Particles:**
  - Depending on SUSY parameters decays to final states with many b's or many μ's are expected.

- **b-Physics (CP Violation, Oscillations, B_c, ...):**
  - Obviously **impact parameter resolution** (2D and 3D) and **secondary vertexing efficiency and purity** are important.

Silicon Tracking is very powerful at hadron colliders: top quark discovery as seen by CDF

e + 4 jet event

40758_44414

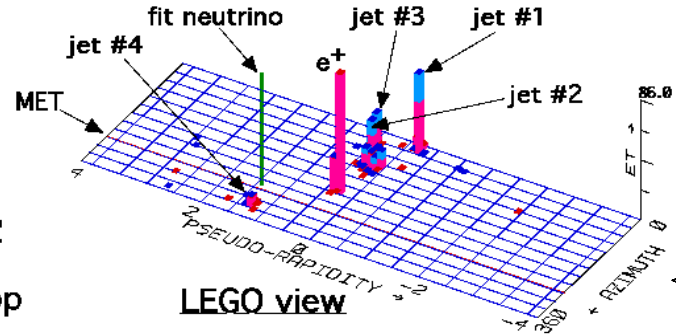
24-September, 1992

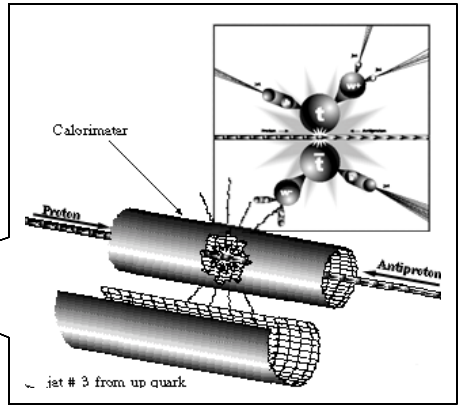
TWO jets tagged by SVX

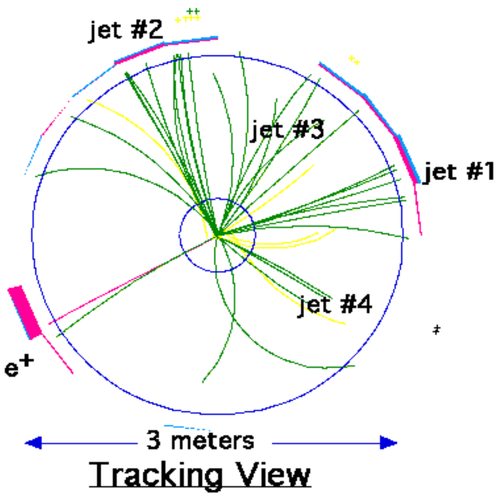
fit top mass is 175±10 GeV/c^2

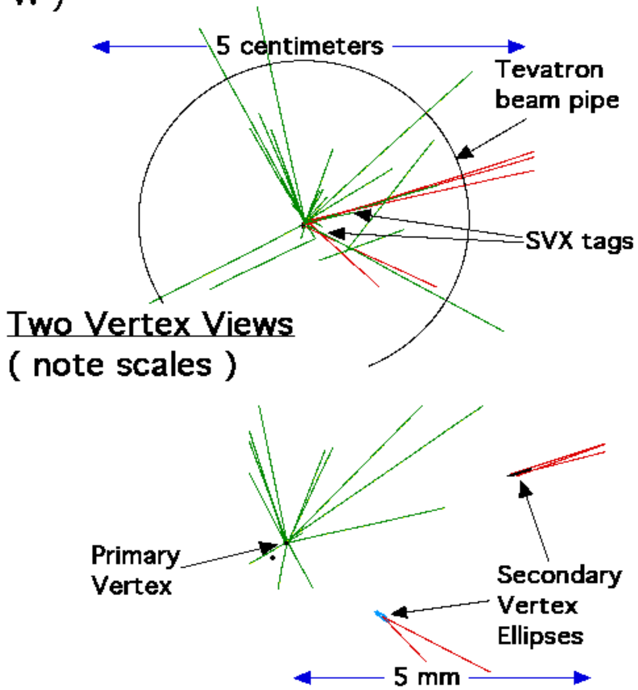
e^+, Missing E_t, jet #4 from top

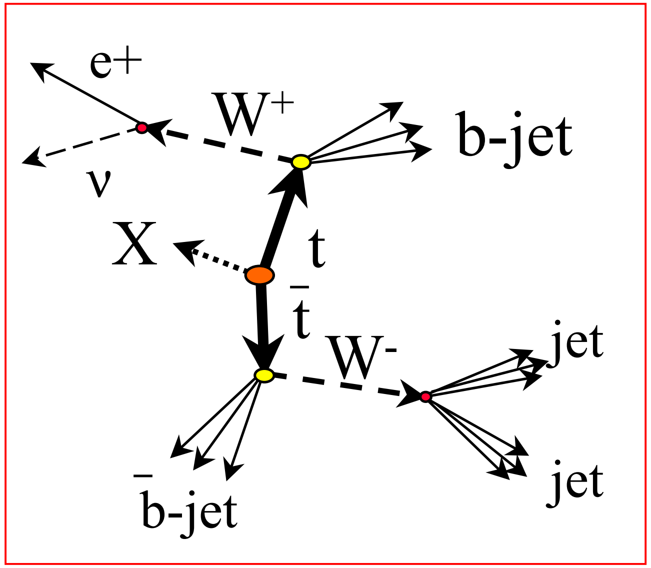
jets 1,2,3 from top (2&3 from W)









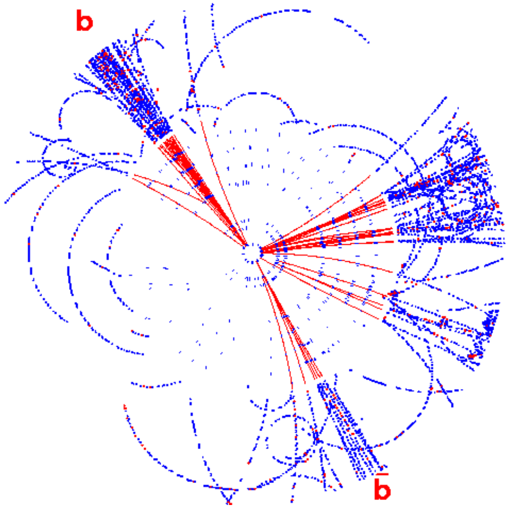


LHC means high rate and high multiplicity

at full luminosity $L=10^{34}\ cm^{-2}\ s^{-1}$:

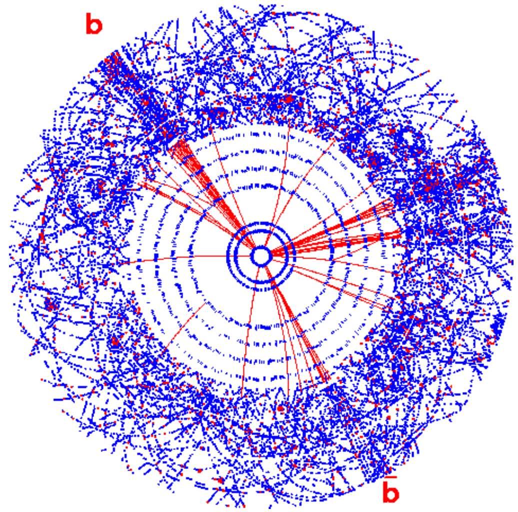
- ~23 overlapping interactions in each bunch crossing (every 25 ns)
- event rate of ~1GHz needs to be reduced to ~100Hz written to tape => reduction of 10^7
- ~6.5 charged particles per unit of rapidity in average collision
- => inside tracker acceptance ($|\eta|<2.5$) 750 charged tracks (plus ~375 neutrals) per bunch crossing
- per year: ~5×10^{14} bb; ~10^{14} tt; ~20,000 higgs; ~10^{16} inelastic collisions

a H->bb event

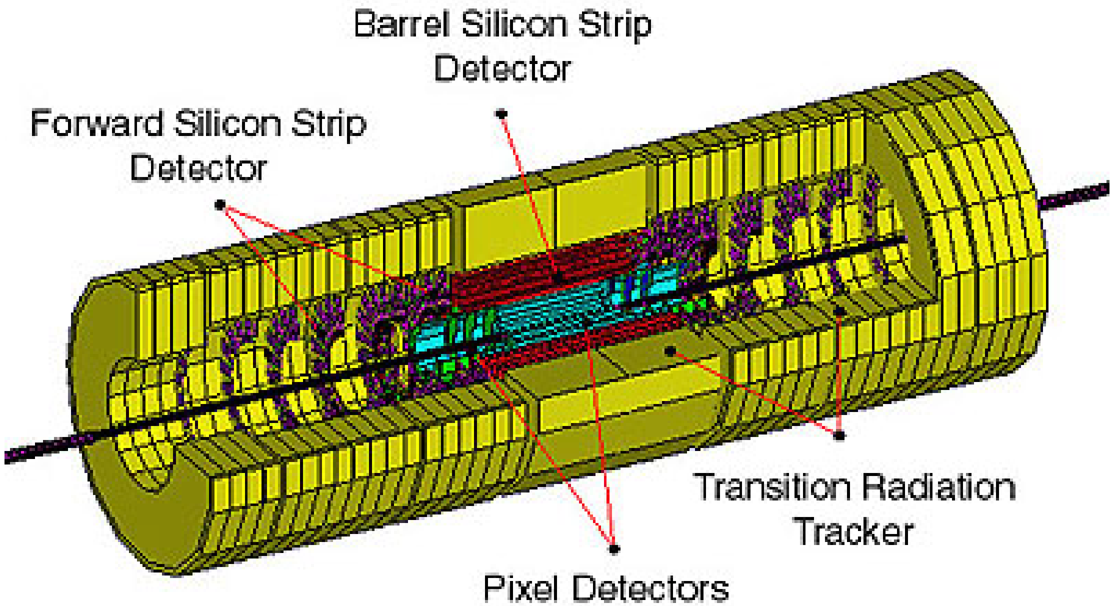


plus 22 minimum bias interactions

a H->bb event as observed at high luminosity



ATLAS Inner Tracker



system		area (m^2)	resolution (μm)	channels (10^6)	|h| coverage
pixel	1 b layer	0.2	RF =12, z=66	16	2.5
	2 barrels	1.4	RF =12, z=66	81	1.7
	2x5 disks	0.7	zF =12, R=77	43	1.7-2.5
	total	**2.3**		**140**	**2.5**
SCT	4barrels	34.4	RF =16, z=580	3.2	1.4
	2x9 disks	26.7	zF =12, R=580	3.0	1.4-2.5
	total	**61.1**		**6.2**	**2.5**
TRT	barrel (36)		170 per staw	0.1	0.7
	end-caps		170 per straw	0.32	0.7-2.5
	total			**0.42**	**2.5**

High flux environment:
at $L=10^{34} cm^{-2} s^{-1}$ ~1000 particles per 25 ns inside the acceptance of the tracker from about 20 proton proton collisions.

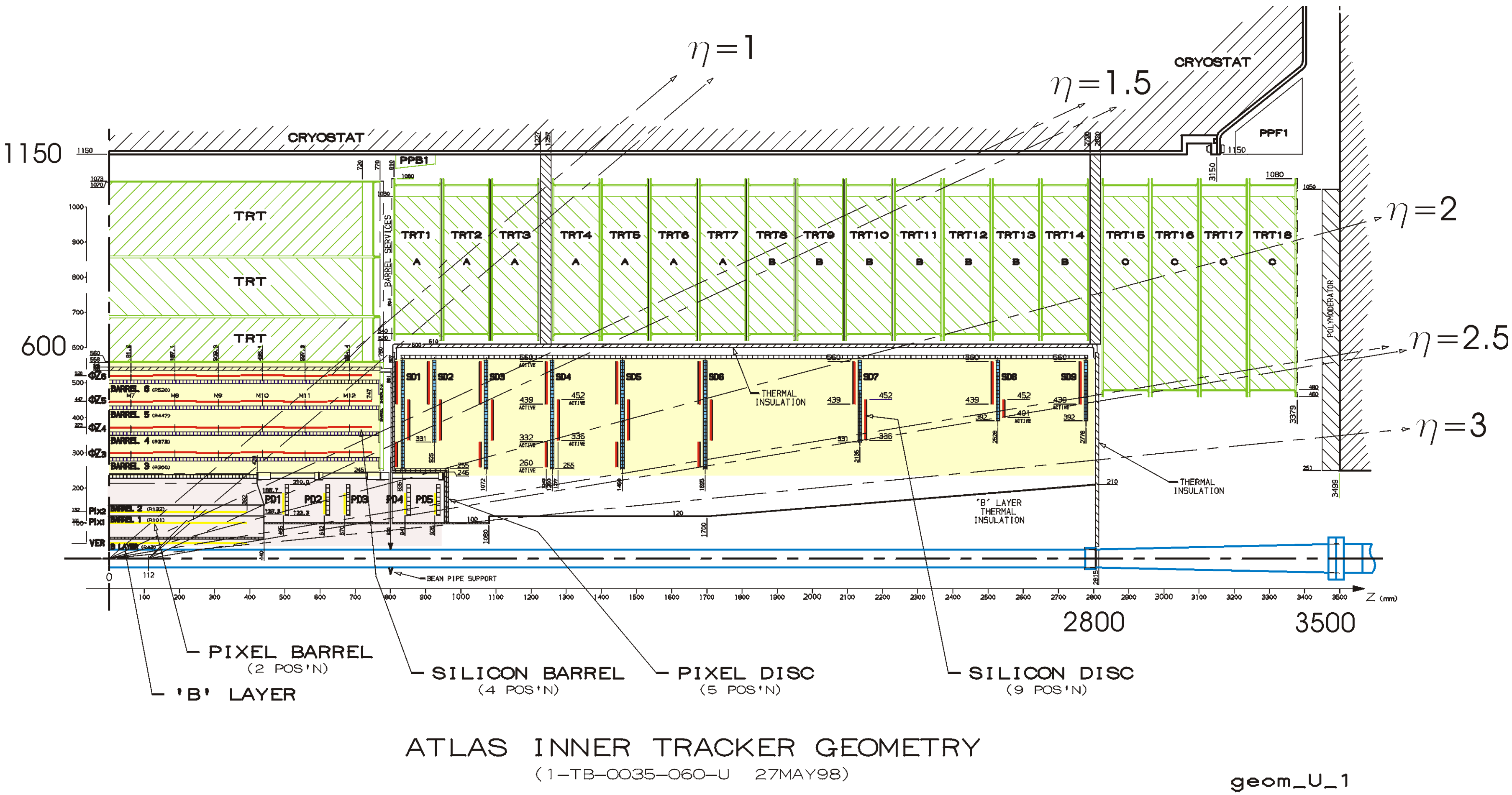
Requires detector techniques which ensure
- low occupancy -> high granularity
- read-out speed -> fast detectors
- radiation tolerance -> radiation hardness

this has to balanced with the cost for large sensor areas.

Performance:

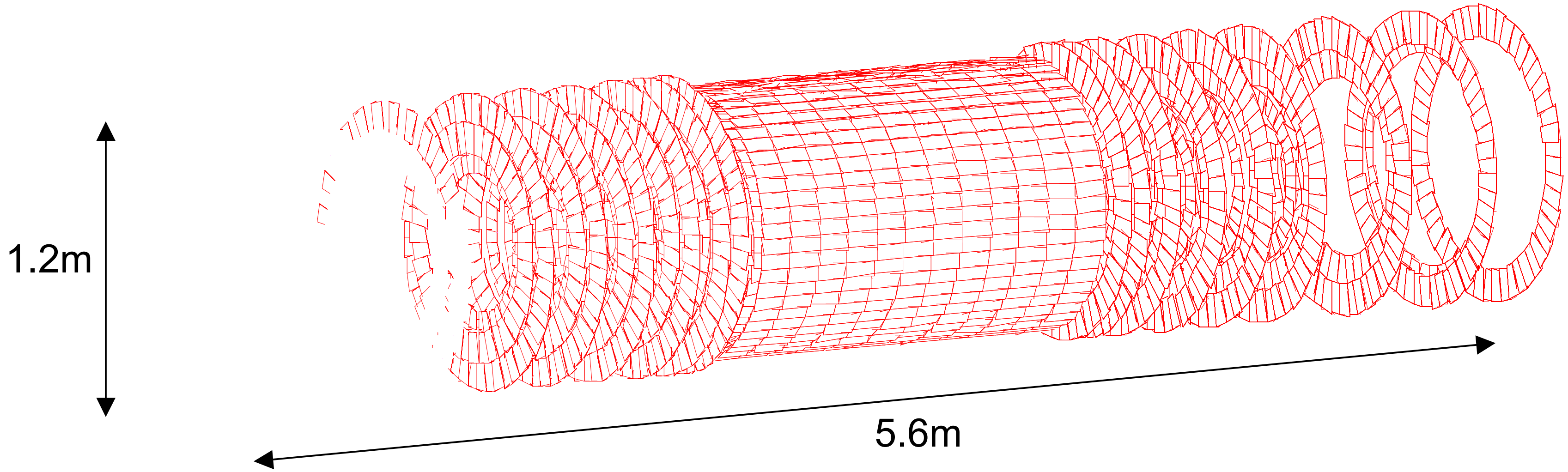
- rapidity coverage: $|\eta| < 2.5$
- momentum resolution for isolated leptons: $\Delta p_T / p_T \sim 0.1\, p_T$ (TeV)
- track reconstruction efficiency (high-p_T)
  - for isolated tracks $\varepsilon > 95\%$, within jests $\varepsilon > 90\%$,
  - ghost tracks < 1% (for isolated tracks)
- impact parameter resolution at high-p_T $\sigma_{r\text{-}\phi} < 20$ μm, $\sigma_z < 100$ μm
- low material budget for tracker and ECAL performances
- lifetime > 10 LHC years

ATLAS Inner Tracker

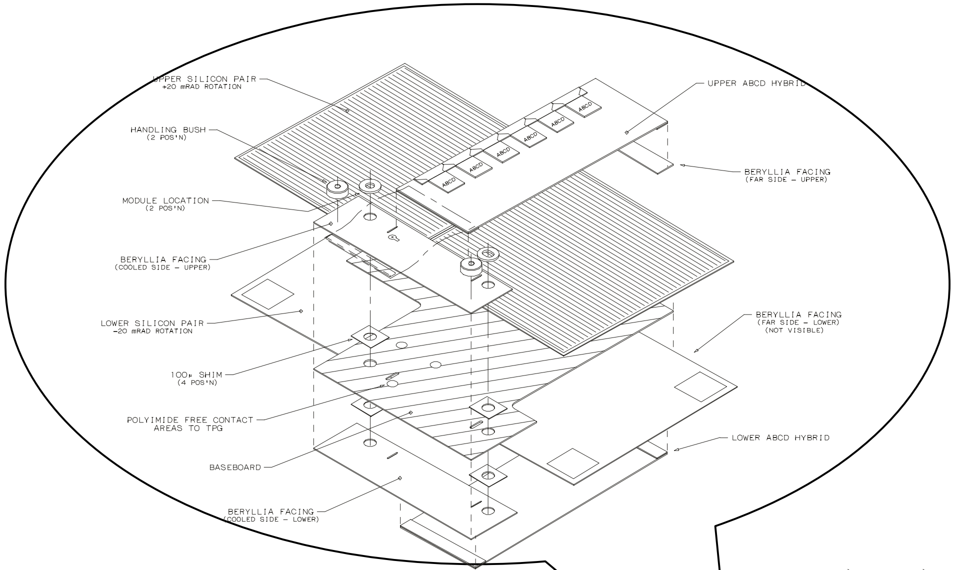


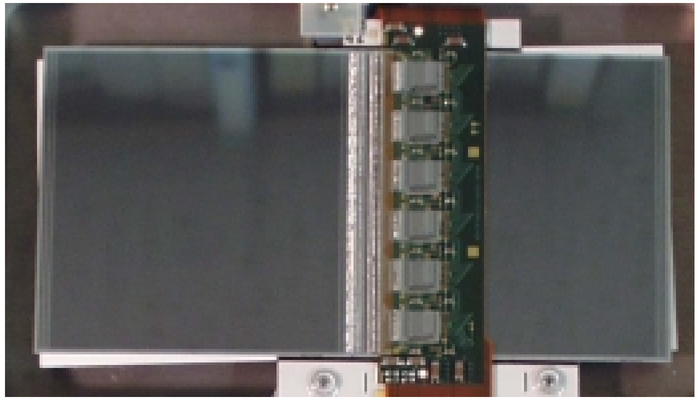
ATLAS Silicon Microstrip Tracker SCT

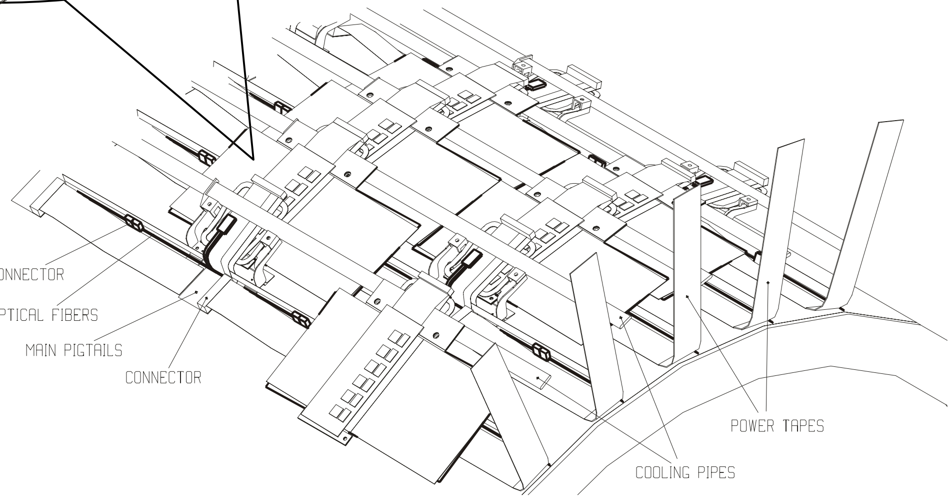
- 4 barrel layers
  - barrel radii: 300, 371, 443 and 514 mm; length 1600 mm
  - in total 2112 modules
- 2 x 9 forward disks
  - disk distance from z = 0: 835 - 2788 mm, radii: 259-560 mm
  - in total 1976 modules (3 rings: 40, 40, 52 modules each)
- all 4088 modules double side
- 15,392 sensors of total 61.1m²
- total length of diode: 716 km
- 49,056 front-end chips of total 6.3 Mio. channels



Barrel Modules

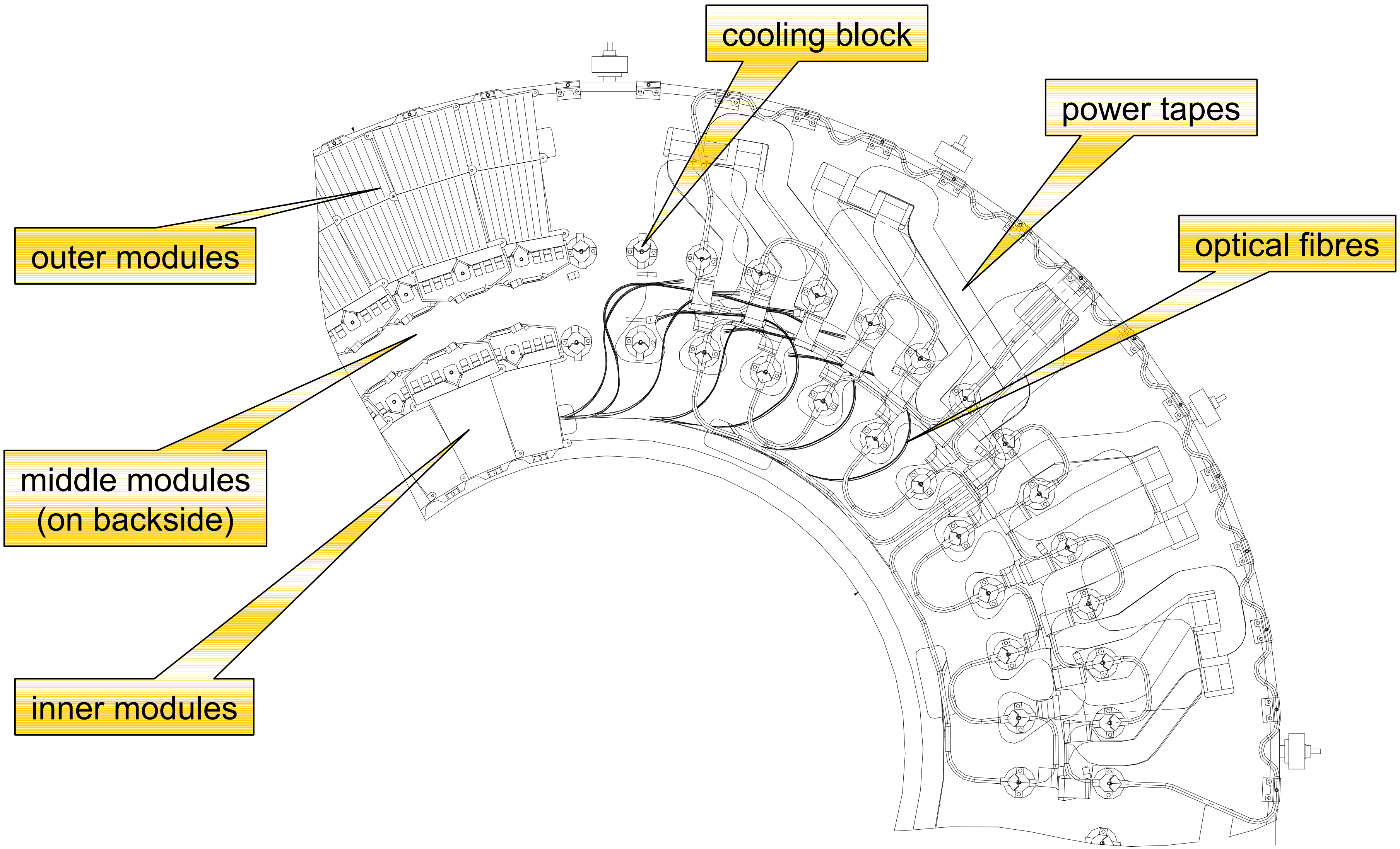




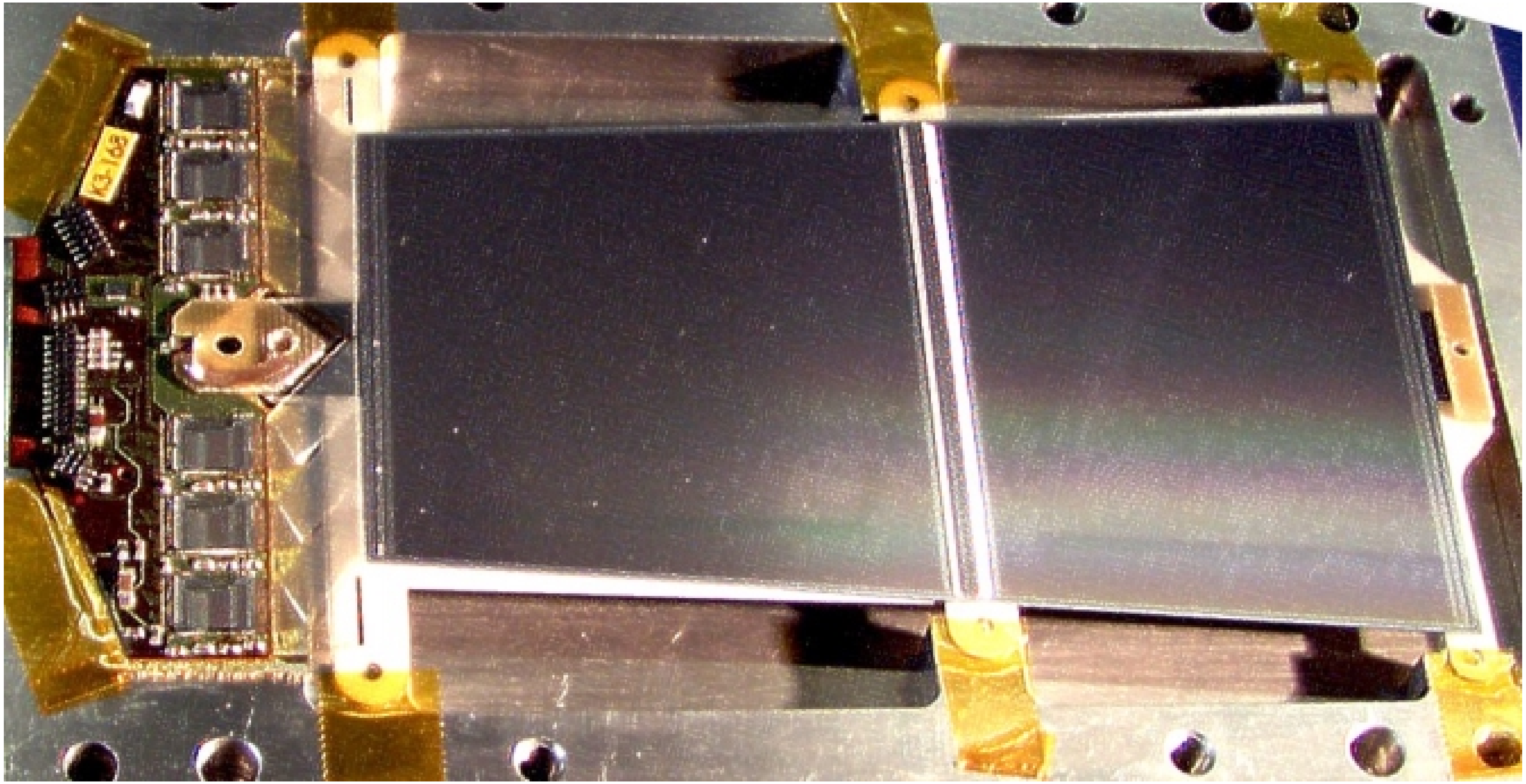


- double sided module as back-to-back build-up of 2 pairs of rectangular sensors
- 40 mrad stereo angle to measure second co-ordinate
- centre-tapped electronics hybrid

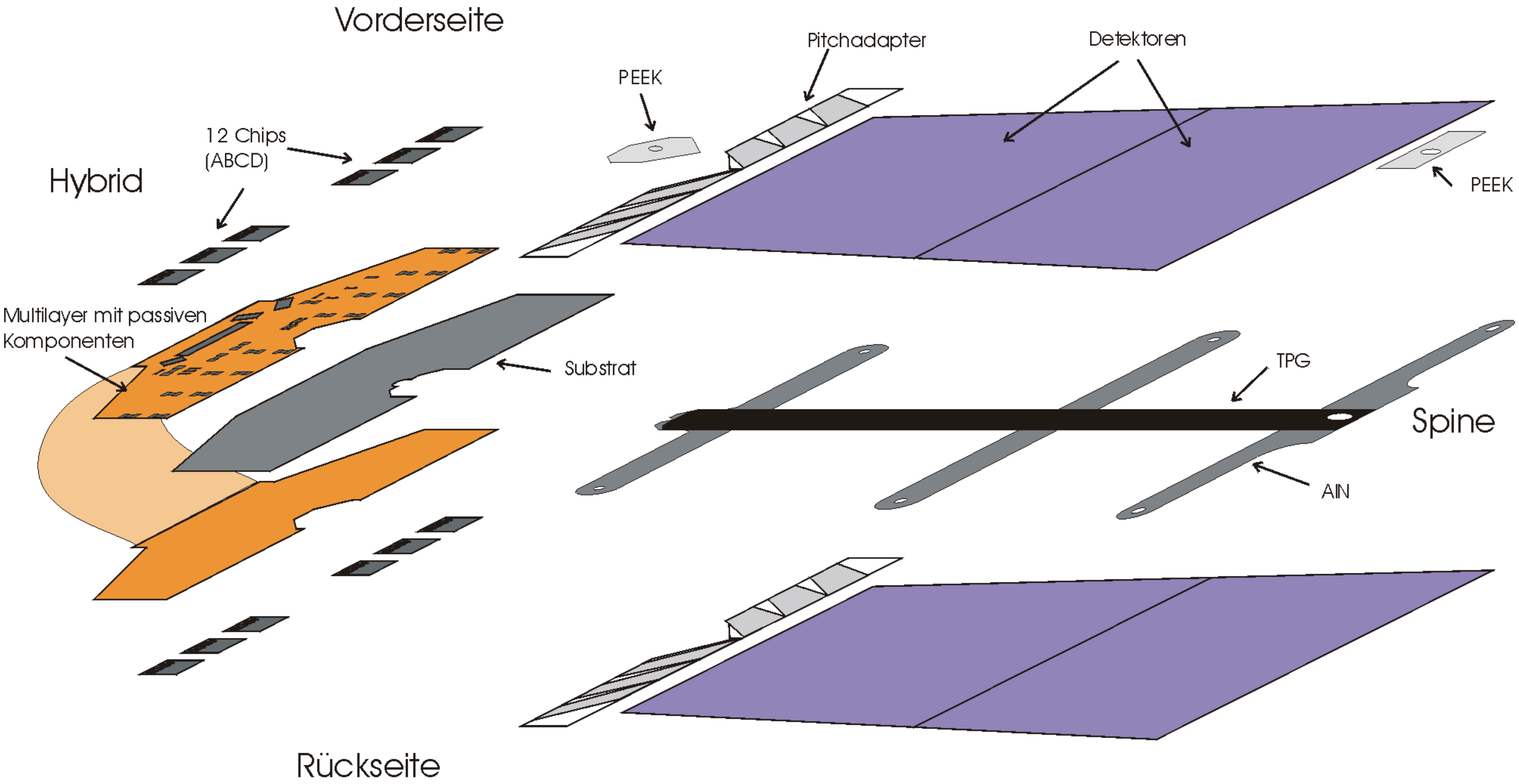
SCT Forward Disk



Forward Module in Transport Frame



Forward Module



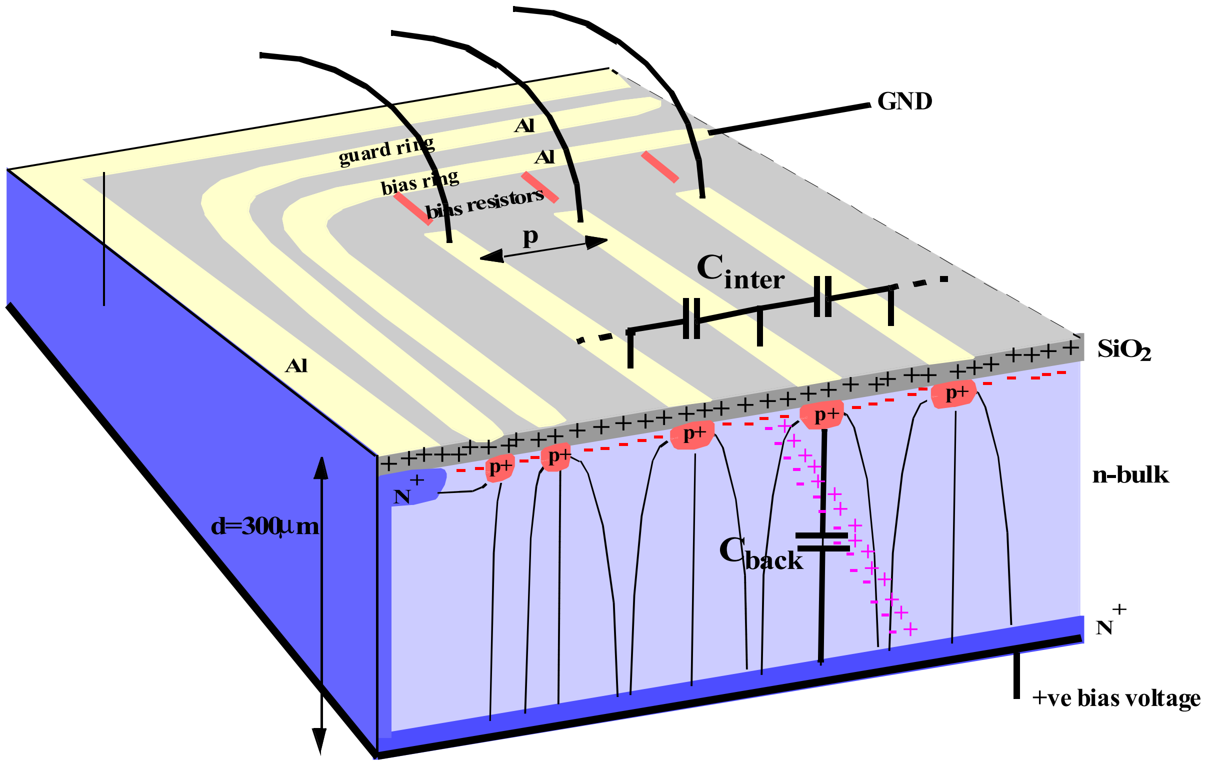
- **double sided module as back-to-back build-up of 2 pairs of wedge shaped sensors**
- **40 mrad stereo angle to measure second co-ordinate**
- **double sided, end-tapped electronics hybrid**
- **alignment: 4µm sensor-to-sensor on each side, 8µm front-to-back**

Silicon Microstrip Detector

- **principle:** collection of charge released in the depleted volume of a reverse biased diode
- spatial resolution through segmentation of diode
- p strips on n substrate
- AC coupling to keep leakage current away from read-out electronics
- biasing through polysilicon or implanted resistors

properties

- leakage current
- depletion voltage and substrate resistivity
- high voltage stability
- interstrip capacitance
- backplane capacitance
- crystal orientation
- charge collection
- signal to noise



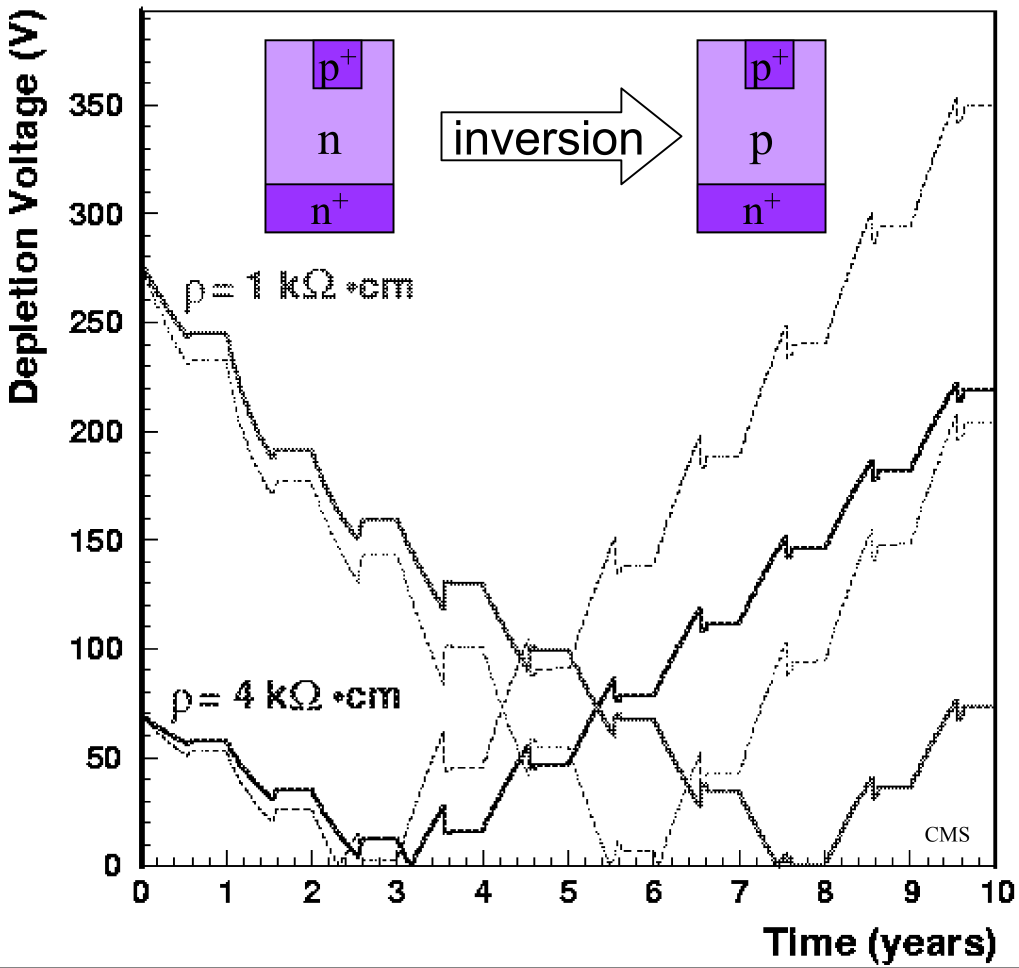
Radiation Environment

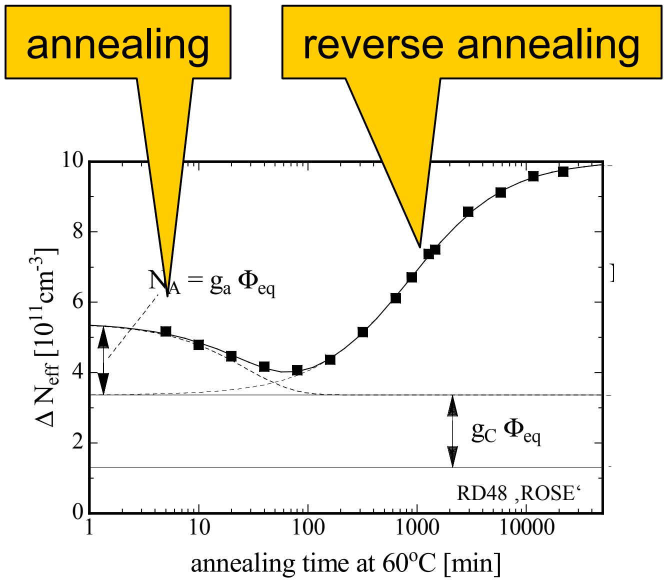
- tracking detectors at the LHC are subject to a significant amount of irradiation by charged particles and neutrons
- in SCT volume up to **1.2×10^{14} 1-MeV-n/cm² for 10 years** of LHC running
- **major challenge for the system design**
- **damage to sensors**
  - **bulk damage:** displacement of Si atoms from lattice sites
    - creation of energy levels in the band gap: **increases leakage current** I_{leak}~fluence
    - deep levels act as acceptors: **inversion from n-type to p-type and depletion voltage changes**
    - radiation induced energy levels act as traps: **deterioration of charge collection**
  - **surface damage:** creation of charge carriers in silicon oxide
    - modification of electron accumulation layer and change of interstrip capacitance
- **damage to electronics**
  - modification of oxide charge changes threshold voltages of MOS transistors
  - parasitic currents
  - single event upset
- **damage to other material**
  - deterioration of mechanical properties
  - creation of radicals
  - induced radioactivity

Depletion Voltage

Depletion Voltage V_{dep} and Substrate Resistivity ρ

$V_{dep} = (e\, d^2 N_{eff}) / (2\, \varepsilon_0 \varepsilon_{Si})$ $N_{eff} = 1/(q_e\, m_e\, \rho)$

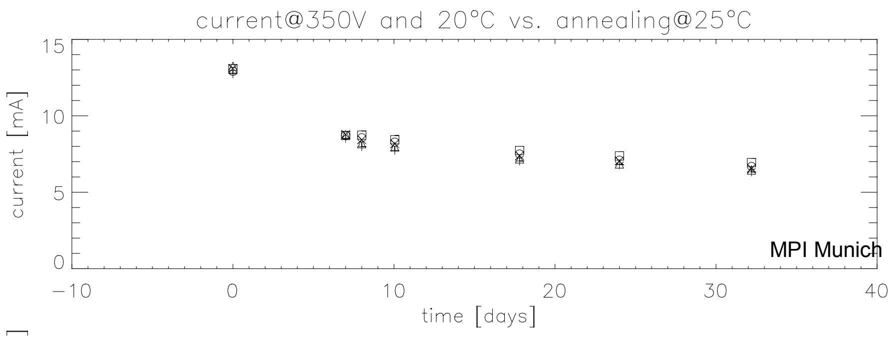




- annealing rate is strongly temperature dependent
- reverse annealing is supressed at T<0°C

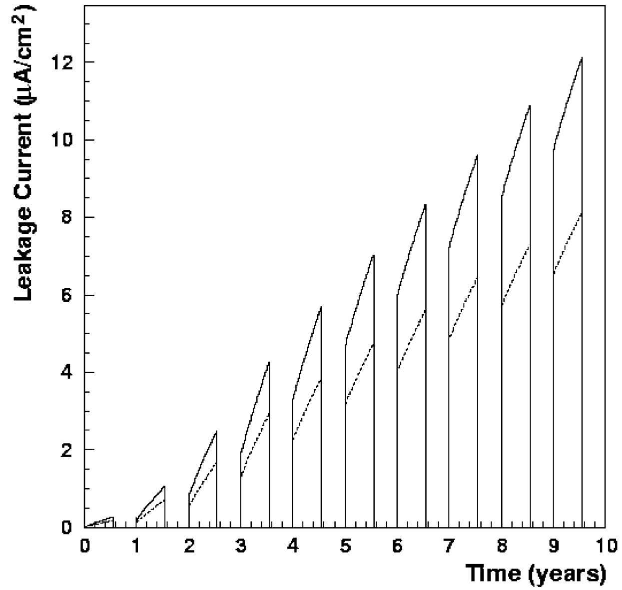
Leakage Current

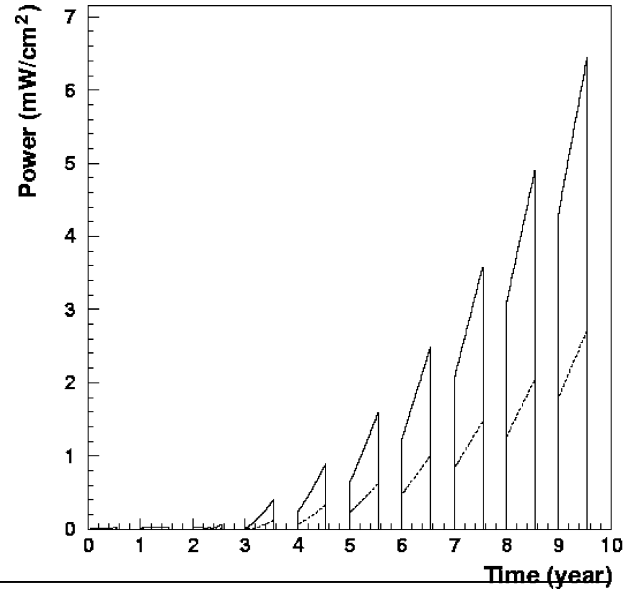
- $I_{leak} = \alpha_\infty$ **x volume x fluence**
  - $\alpha_\infty \approx 3\times10^{-17}$ A/cm at 20 °C, fluence in 1MeV equiv.
  - independent of material or radiation type
- beneficial annealing has a significant effect



- after 10 years of LHC running:
  - a 12 cm long strip at 100 mm pitch draws ~1 μA,
  - a detector module (160 cm²) draws ~2mA,
  - both at -10 °C.
- given the high bias voltage this leads to a significant power dissipation of the silicon itself

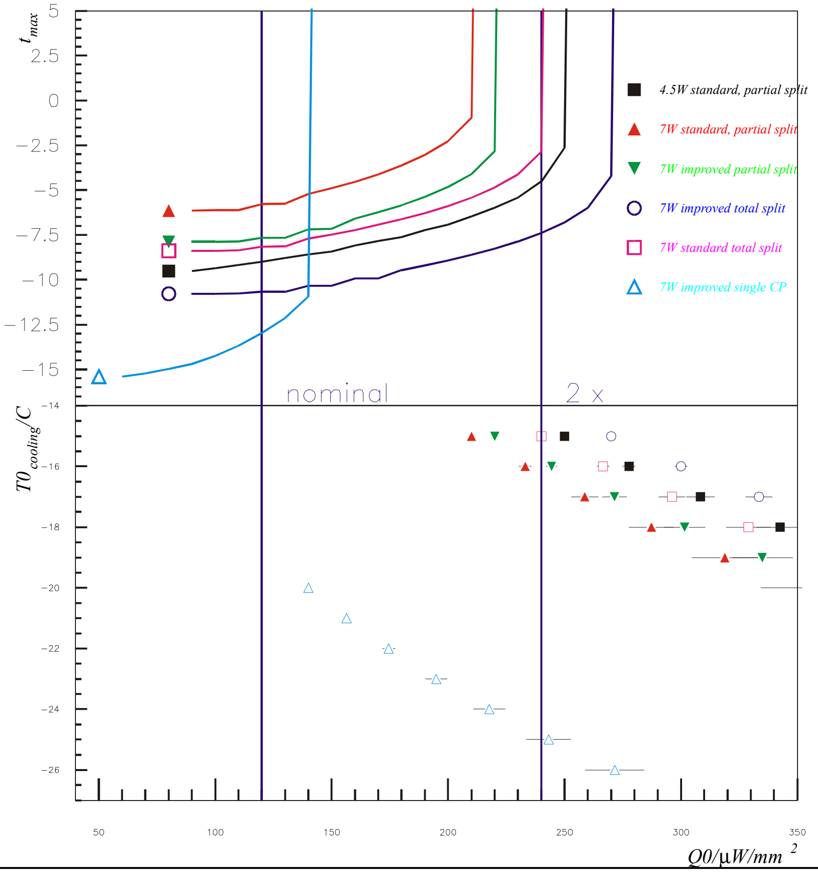
-> need efficient cooling to avoid **thermal runaway**

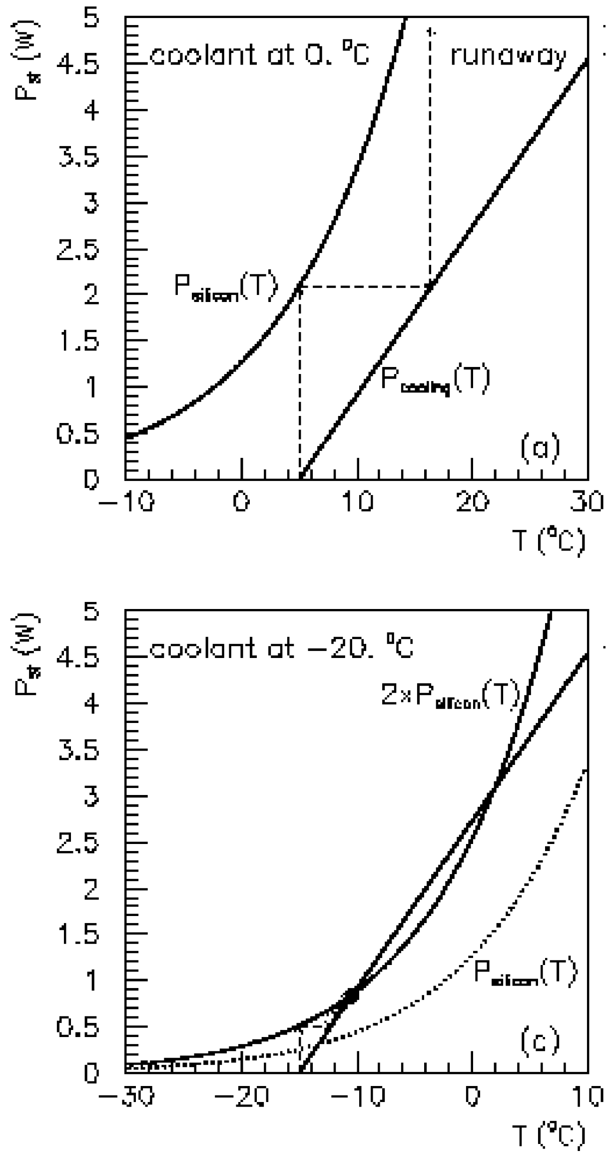




Thermal Runaway

- leakage current strongly temperature dependent
  - $I = I_0 \, T^2 \exp(-E_g/kT)$
  - current doubles every 7°C.
- large depletion voltages (>350 V)
- after 3×10^{14} p/cm^2: 120 µW/mm^2 at 0 C
- design requirement: stable operation up to 240 µW/mm^2

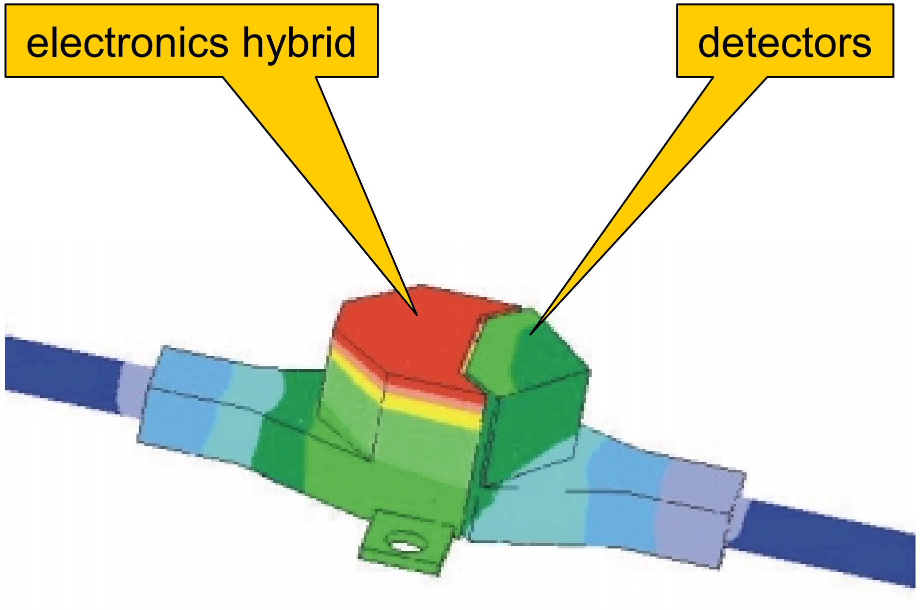




Lutz Feld, Uni Freiburg

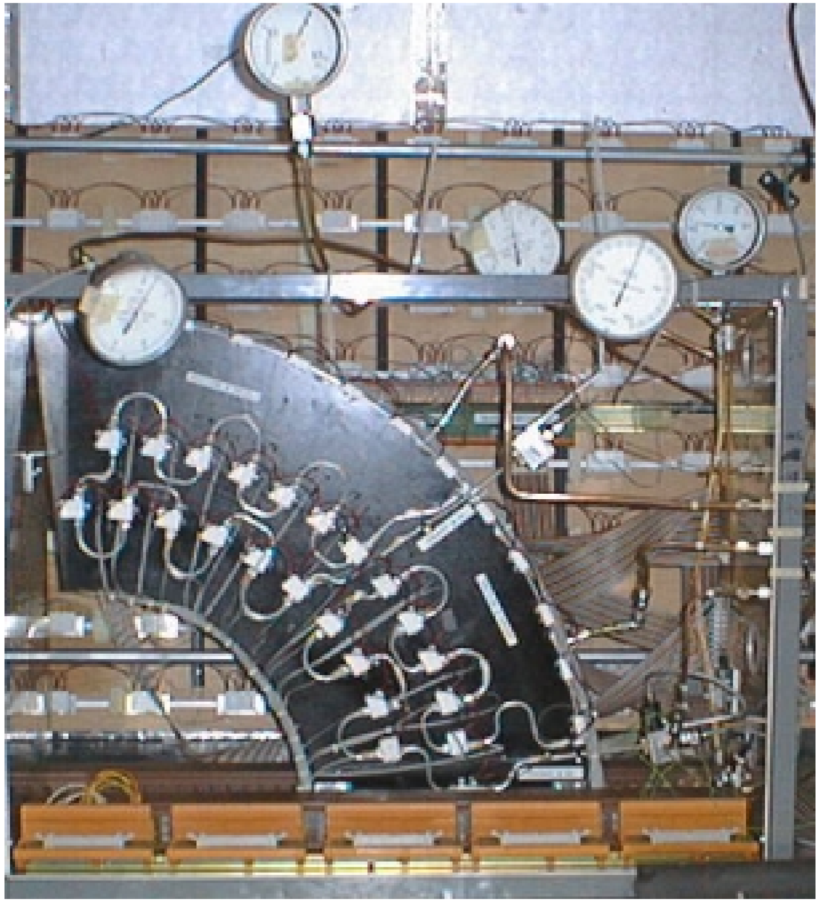
Thermal Split

- modules and cooling blocks designed to separate electronics power dissipation from silicon
- power dissipation of electronics hybrid ~7.5 W
- power dissipation of detectors after 10 years running ~1 W

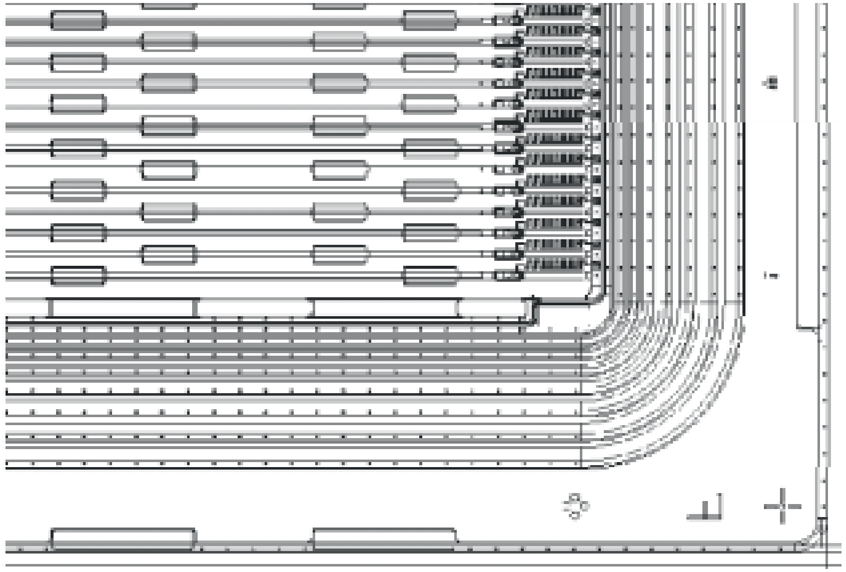


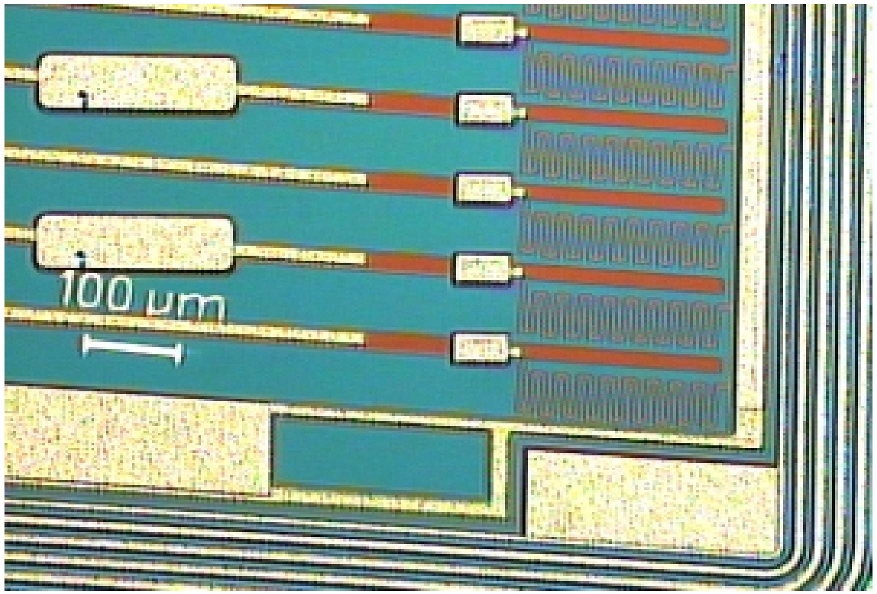
Cooling System

- C_3F_8 evaporative cooling system
- better heat removal per unit mass flow compared to monophase system (use evaporation) ->use fewer and smaller diameter pipes, warm input pipe
- input pressure ~8bar, in cooling manifold ~1.5 bar
- operating temperature ~-20°C
- cooling system tested ok on several test structures (picture)
- measurements on modules agree with thermal simulations



ATLAS SCT Sensors

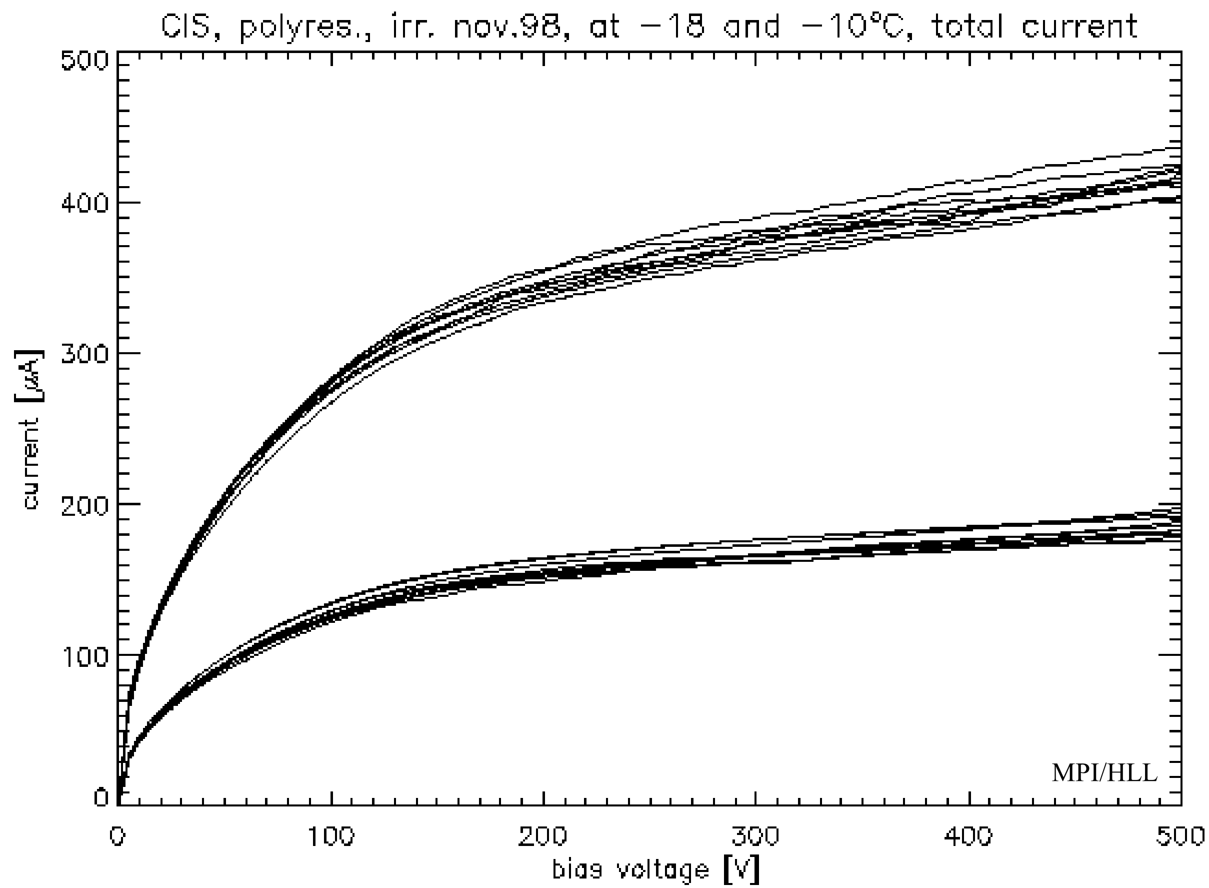




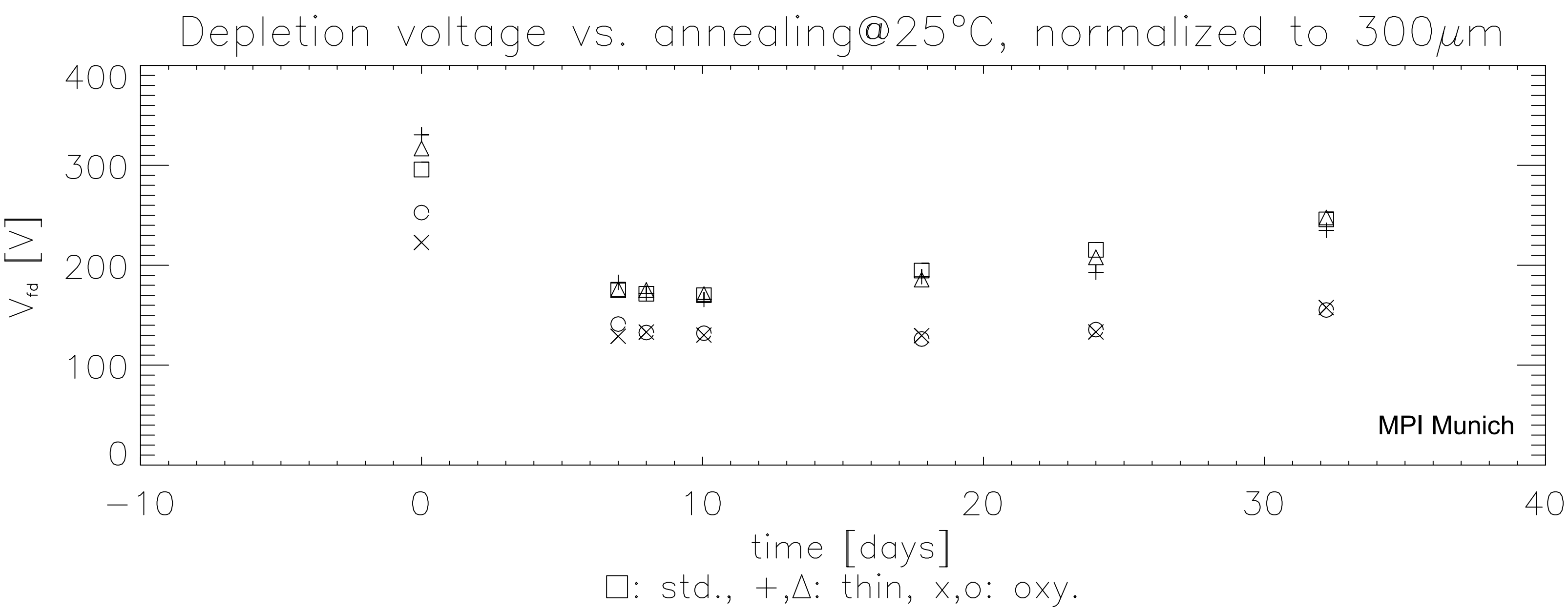
- p-on-n single sided detectors
- 285µm thick
- 2-8 kΩ.cm
- 4“ substrate
- barrel
  - 64x64mm²
  - 80µm pitch
- forward
  - 5 different wedge shaped sensors
  - radial strips
  - 50...90µm pitch
- 768 read-out strips
- AC coupled to read-out
- polysilicon or implanted resistors
- multiguard structure for HV stability
- ~20000 sensors needed
- ordered from Hamatsu, CIS and Sintef

IV after Irradiation

- **IV curves for CiS wedge detectors after 3x10^{14} p/cm^{2} (7 days annealing at 25°C)**
- **Spec: <250 mA @ 450V @-18 C**



Depletion Voltage after Irradiation



- **beneficial annealing: few days at room temperature decreases depletion voltage**
- **reverse annealing: longer time at temperatures >0°C increases depletion voltage**
- **-> need to keep irradiated silicon cold (<0°C)**

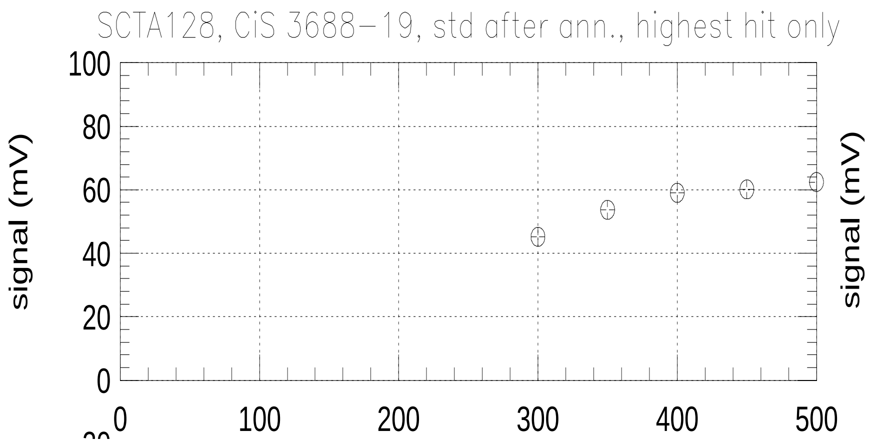
- **oxigenated detectors: less damage and slower reverse annealing**

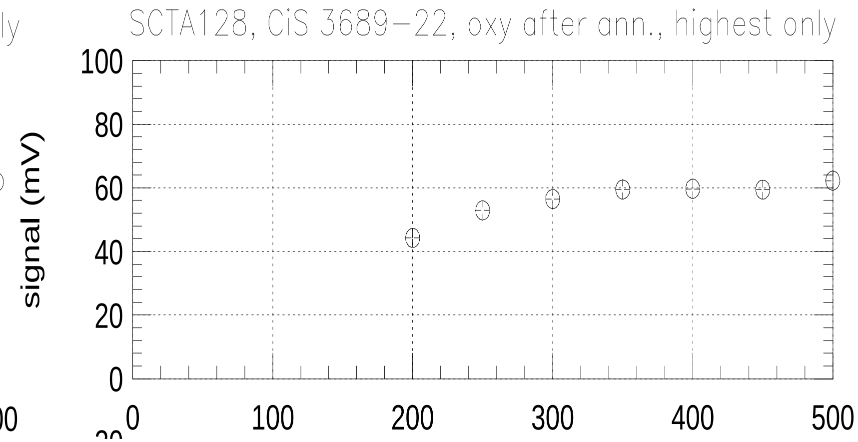
Charge Collection Efficiency

sensors irradiated to $3x10^{14}$ 24GeV-p/cm^2

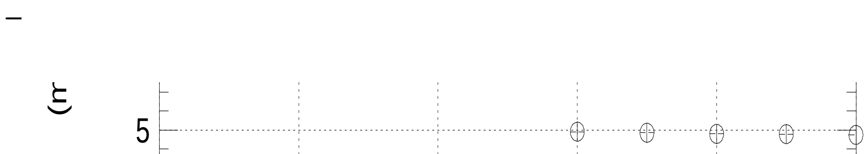
standard material

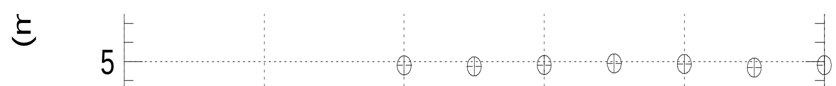
oxygenated material





signal seen on single strip with ~20ns shaping after 32 days annealing at 25°C *(MPI Munich)*





ATLAS Trigger Concept

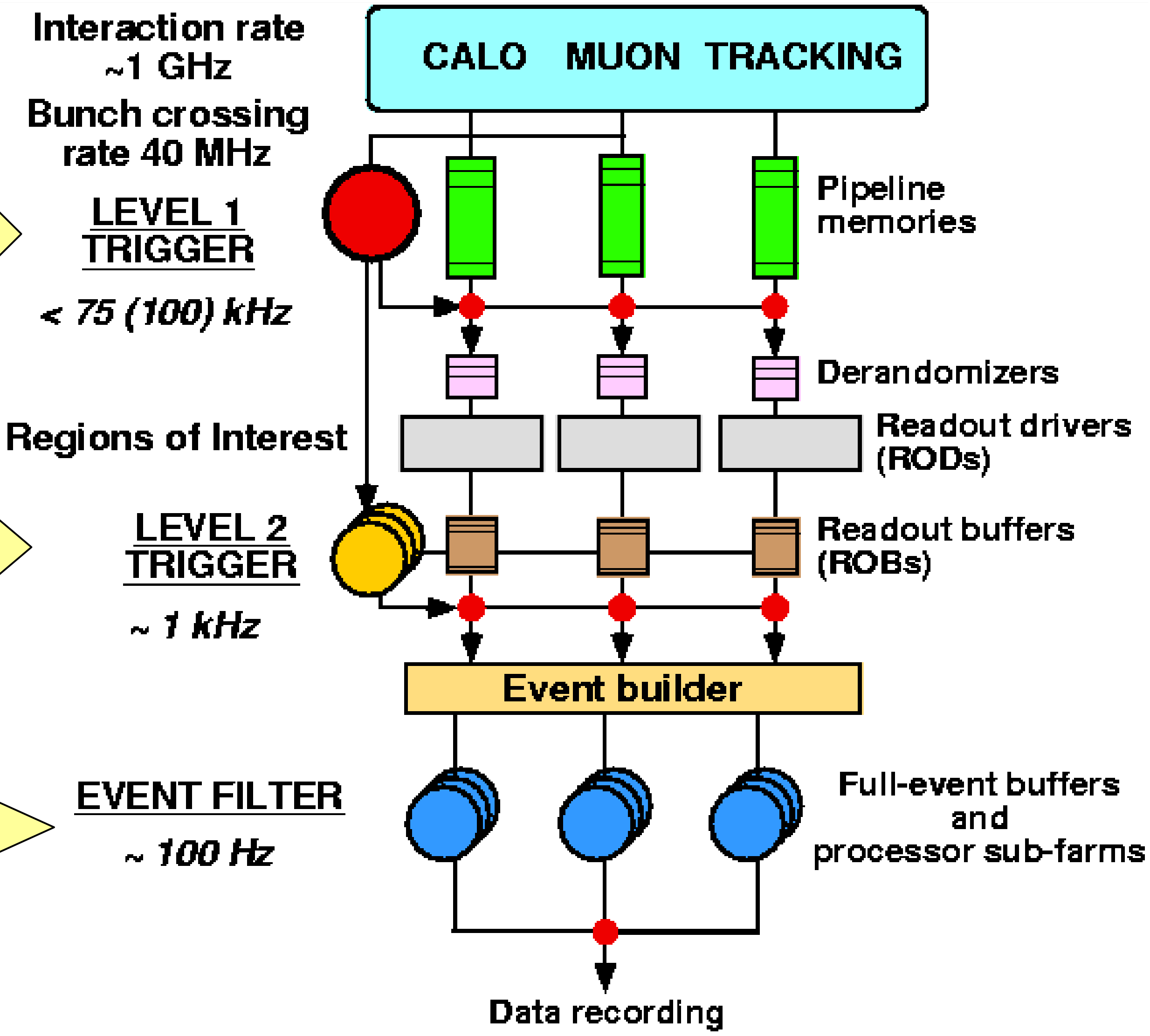
reduced granularity info from:
- muon chambers (high p_t muons)
- EM calorimeters (high E_t e/γ)
- all calorimeters (high E_t hadrons, jets, $E.E_t$, $E_{tmiss,\ isolation}$)

latency 2.0μs
purpose built hardware proc.

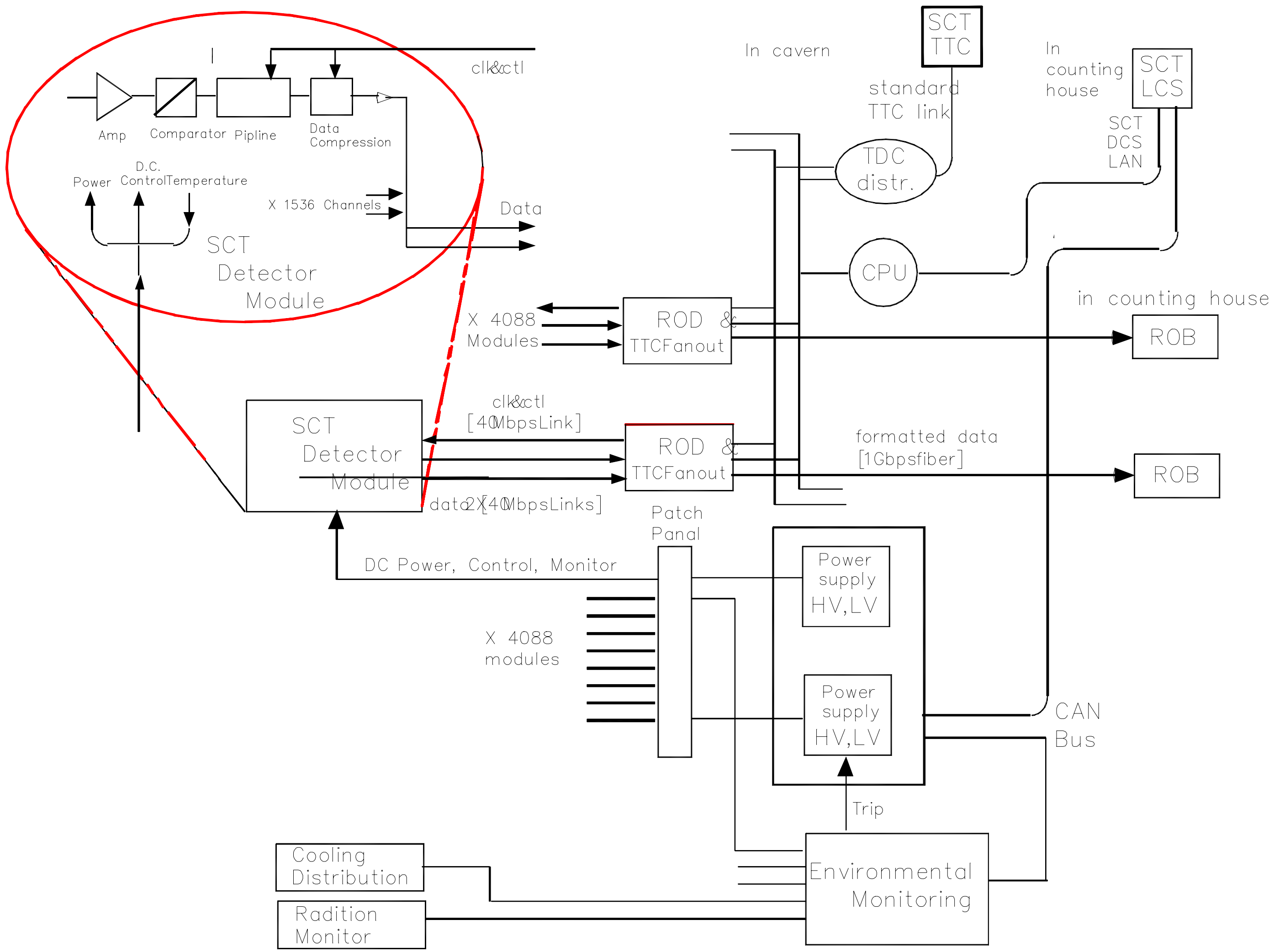
refine decision based on L1 RoI:
- full muon and ID info
- full granularity calorimeter info
- track-cal matching
- b-tagging (?)

programmable trigger menues

- offline algorithms and methods
- full calibration, magnetic field map
- output: ~100 MB/s

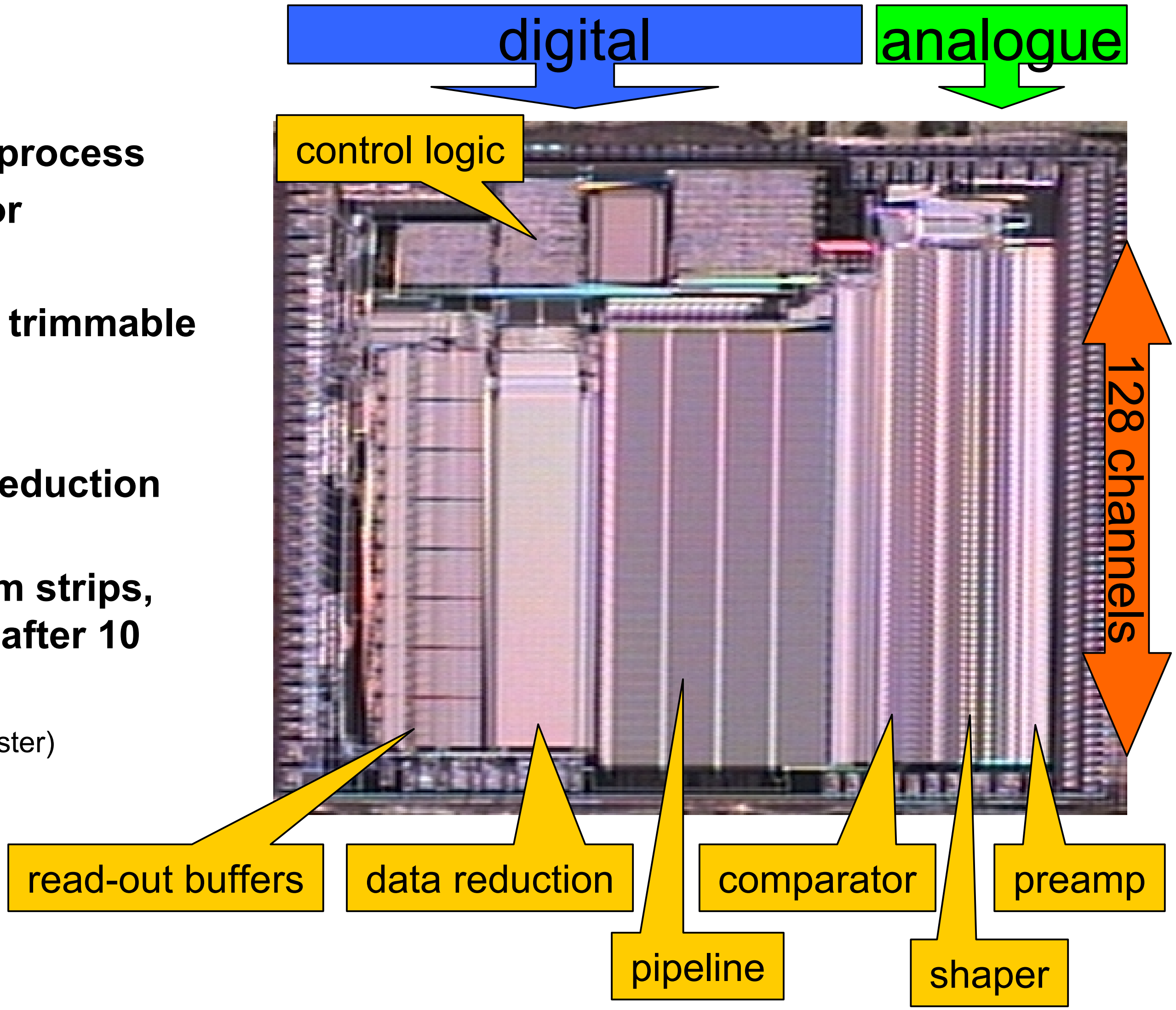


Read-Out Concept



Front-End ASIC ABCD3T

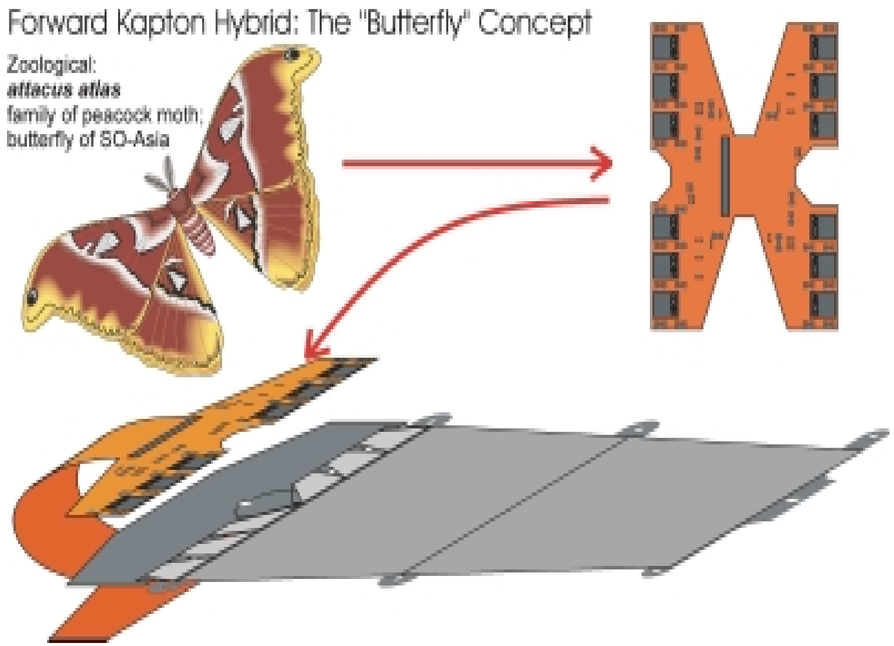
- **binary read-out**
- **128 channels**
- **DMILL radiation hard process**
- **bipolar input transistor**
- **shaping time ~20ns**
- **comparator threshold trimmable for each channel**
- **132 cell pipeline**
- **edge detection, data reduction and multiplexing**
- **ENC ~ 1500 e for 12 cm strips, increasing to ~1800 e after 10 years of irradiation**
- 3 mW/channel (3.5 for master)



Forward Electronics Hybrid *developed at Freiburg University*

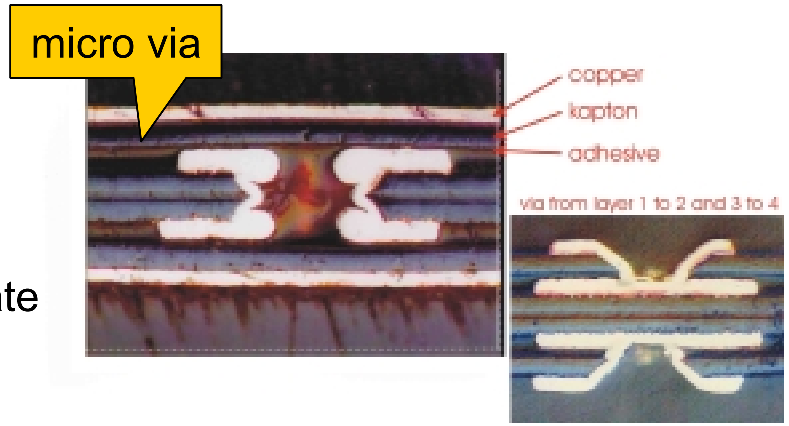
requirements:

- double sided
- distribute and filter
 analogue and digital currents (4V, 1.8A)
- route/filter detector bias (500V)
- filter/shield noise/pick-up
- route commands and data
- full redundancy
- provide electrical/optical connectivity
- remove heat (7.2W)
- low mass

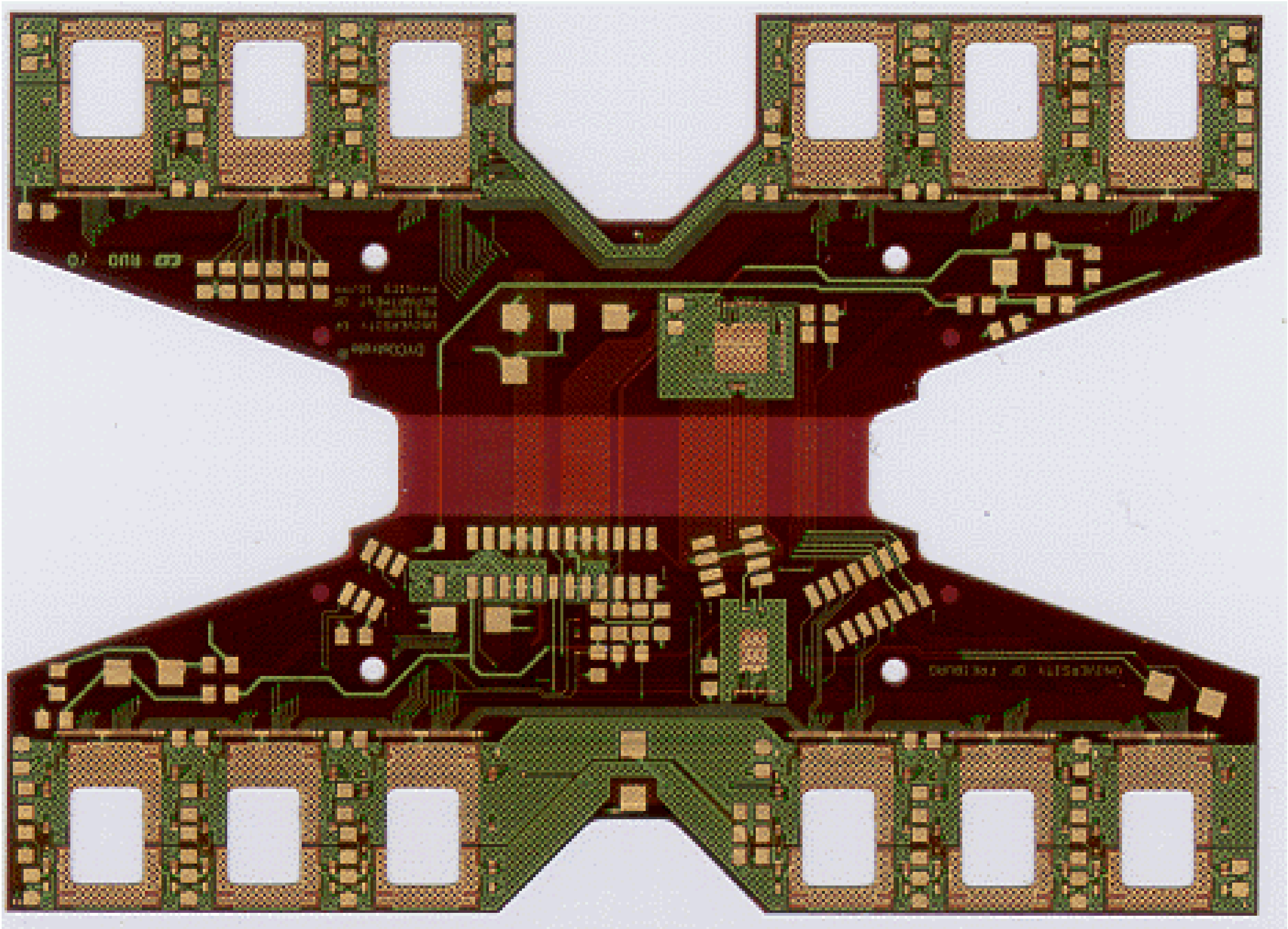


implementation:

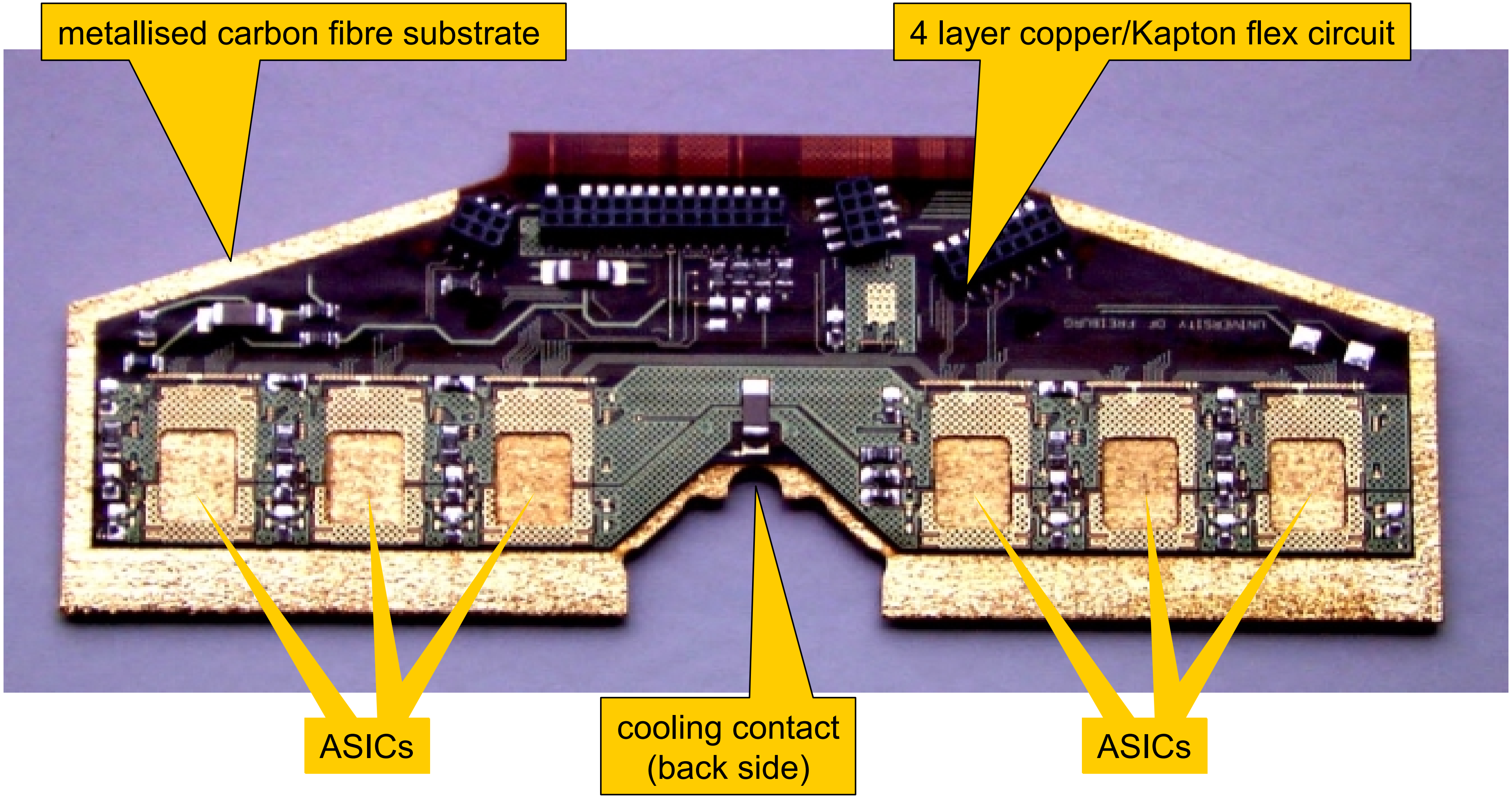
- 4 layers of copper traces in Kapton flex
- trace width/gap ~75μm
- layer thickness ~15μm
- ~3000 micro vias for connections between planes
- produced at DYCONEX AG
- flex folded around a metallised carbon fibre substrate



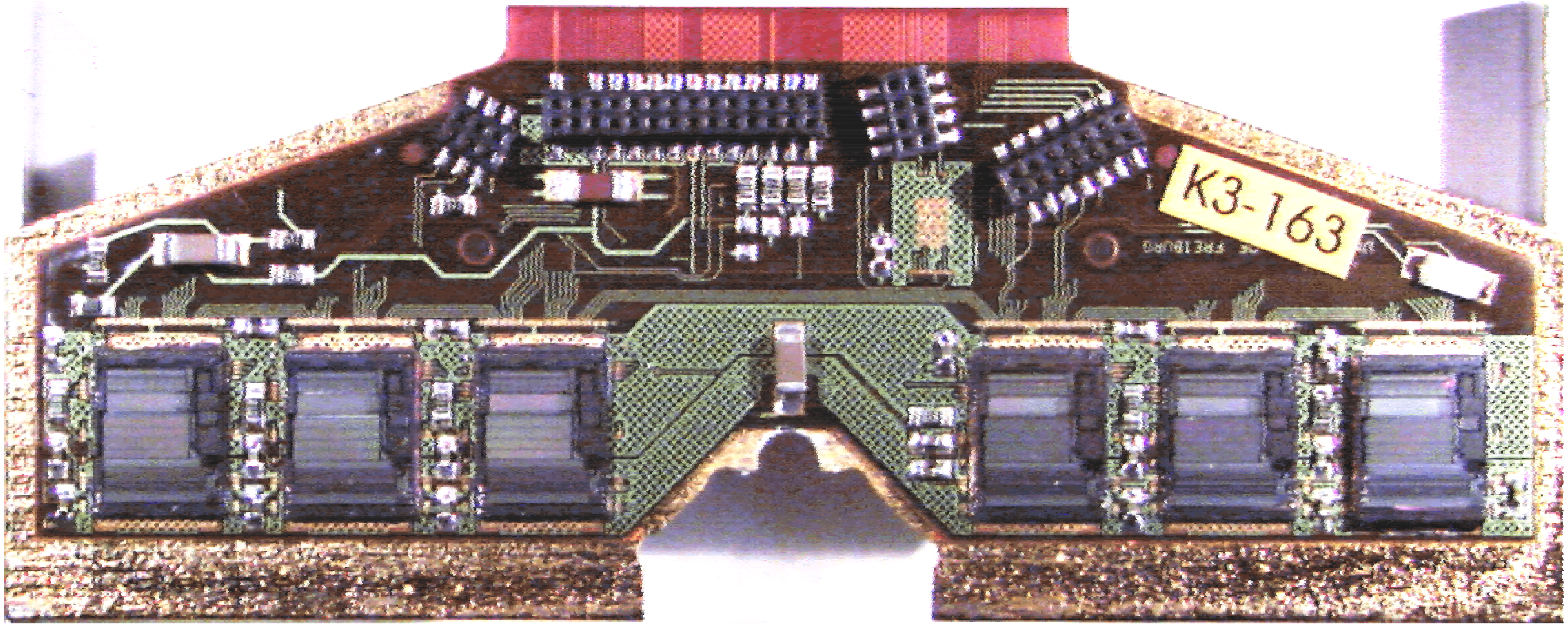
Hybrid Flex Circuit



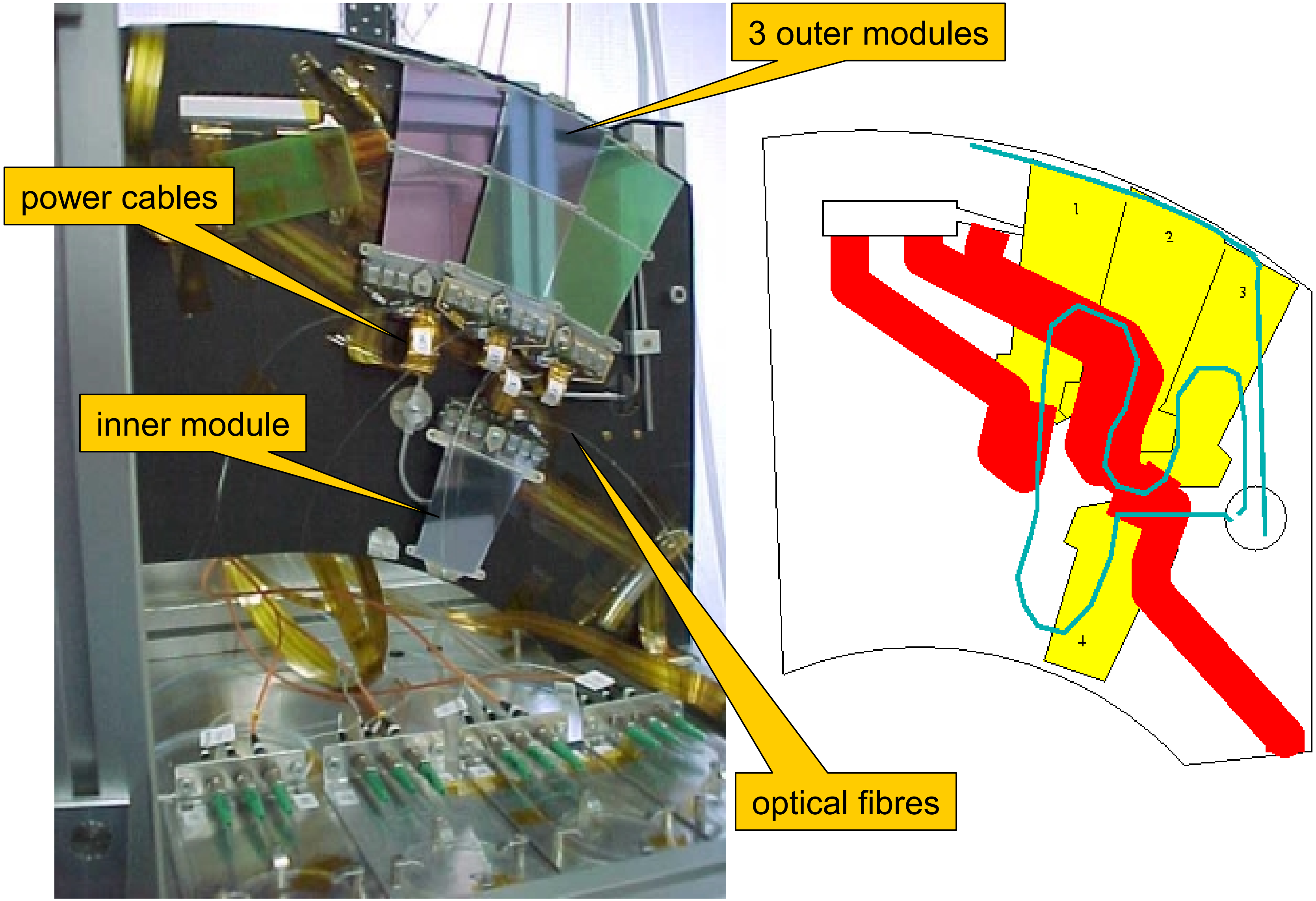
Double Sided Electronics Hybrid (Forward)



Forward Hybrid with ABCD3T Chips



System Test: Forward Mini-Sector



K3-152: Noise on Sector vs. Noise on Bench

I_{preamp}=267uA, I_{shaper}=30uA,V_{det}=100V, $T_{coolant}$=15°C
Compression 01X, Edge Detect On, chips trimmed at 2 fC

Bench:

Run 1786.1,
SCTLV2,
no choke,
conventional cable used.
"Output noise" ~ 12-14 mV

Chip	M0	S1	S2	S2	S4	E5
Gain (mV/fC)	58	57	56	57	55	53
Noise (ENC)	1500	1500	1484	1464	1460	1530

Chip	M8	S9	S10	S11	S12	E13
Gain (mV/fC)	54	52	56	55	56	58
Noise (ENC)	1545	1455	1483	1517	1477	1495

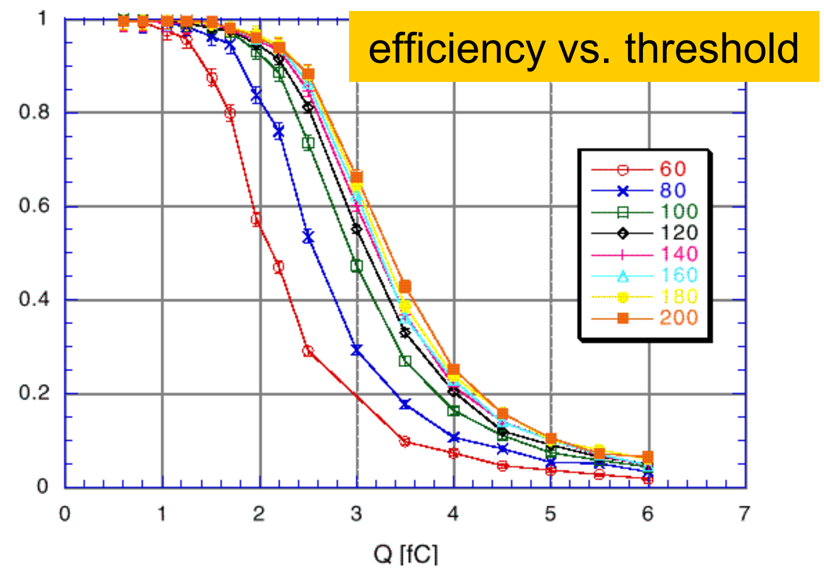
Sector:

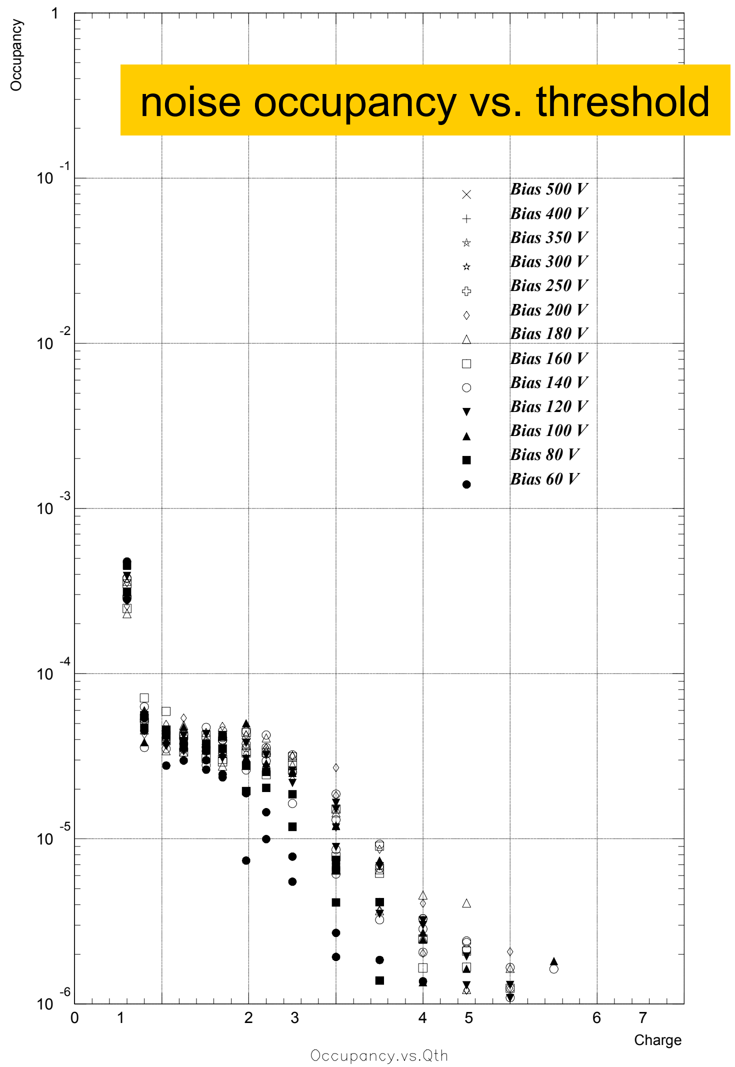
Run 825.1,
choke at SCTLV2,
all PPF1 connections made,
module in position 3.
"Output noise" ~ 13-15 mV

Chip	M0	S1	S2	S2	S4	E5
Gain (mV/fC)	62	60	59	62	63	59
Noise (ENC)	1525	1505	1451	1409	1415	1525

Chip	M8	S9	S10	S11	S12	E13
Gain (mV/fC)	62	59	62	59	60	63
Noise (ENC)	1489	1419	1436	1493	1435	1469

Testbeam Results

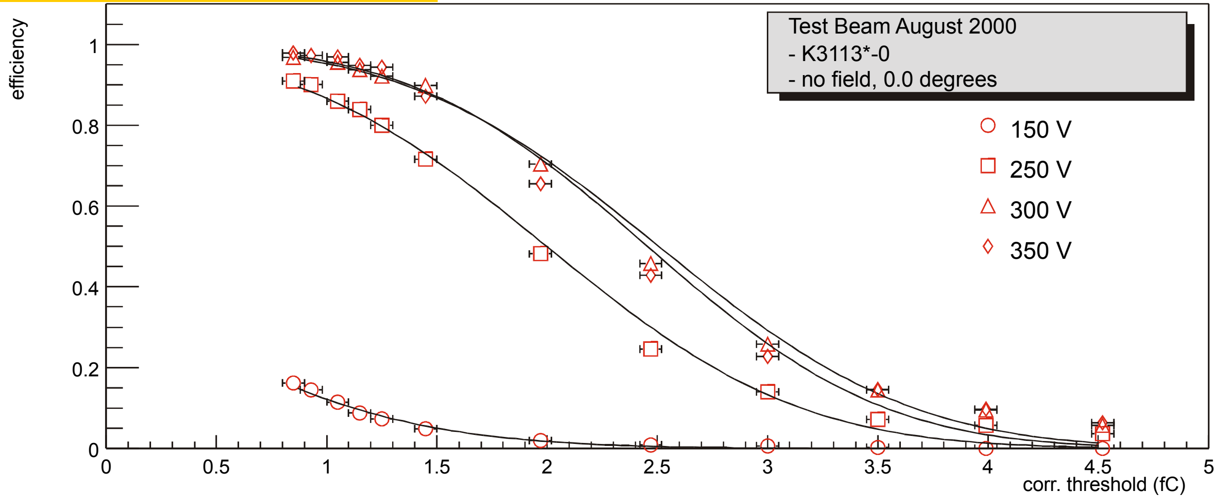




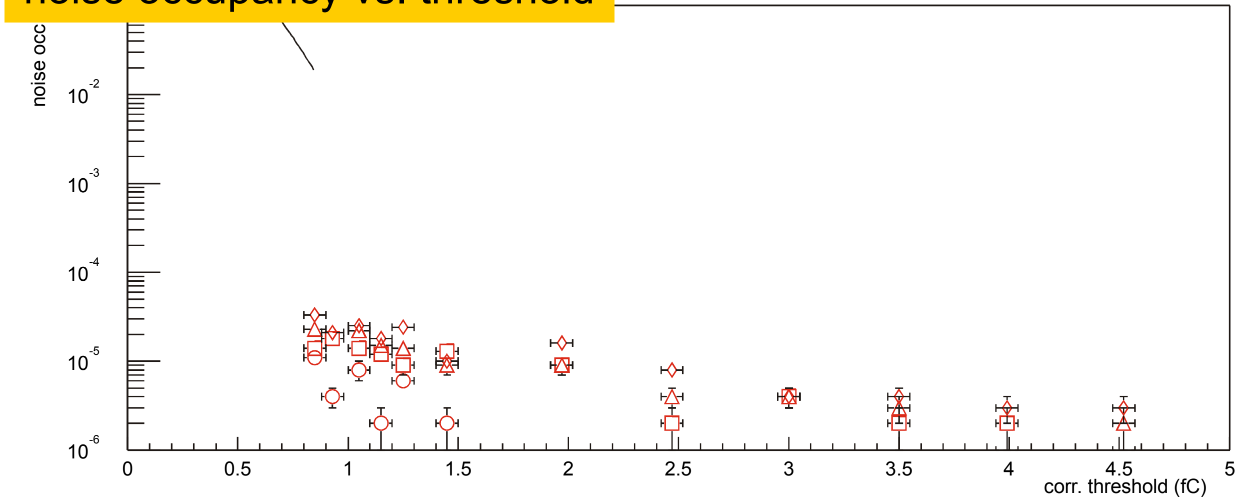
analysis: N. Unno
PRELIMINARY

Testbeam Results on Irradiated Detectors

efficiency vs. threshold

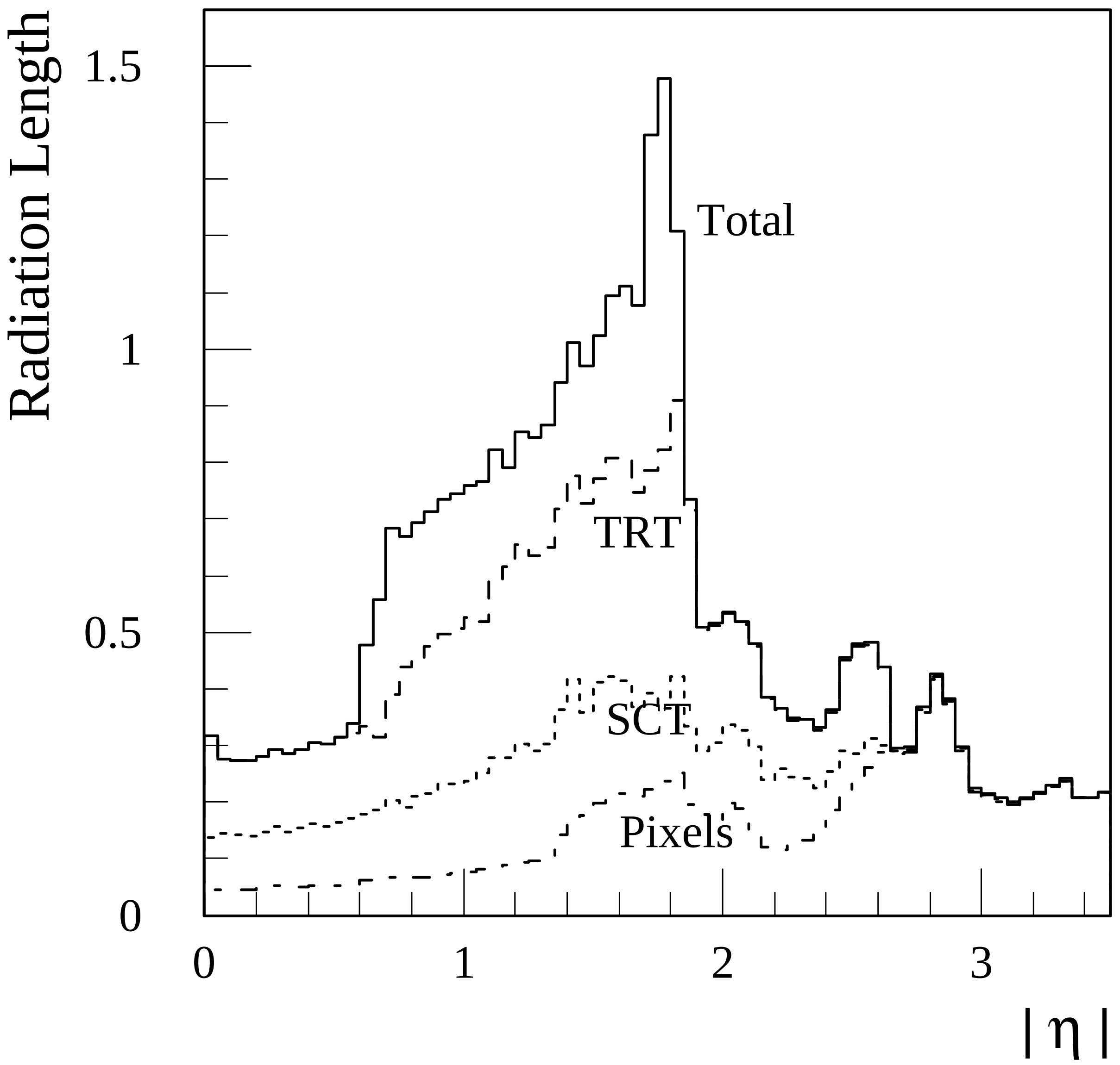


noise occupancy vs. threshold

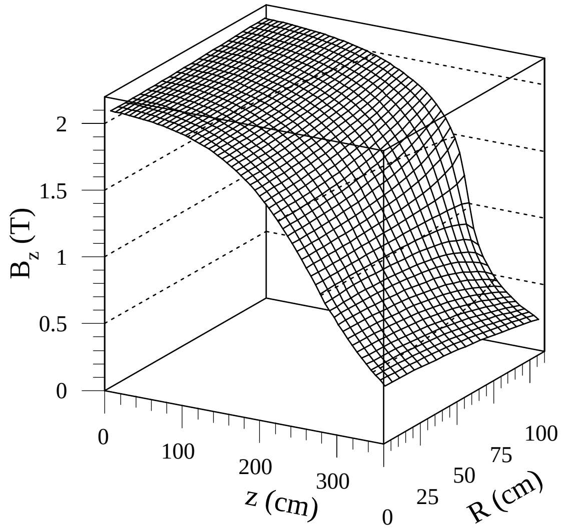


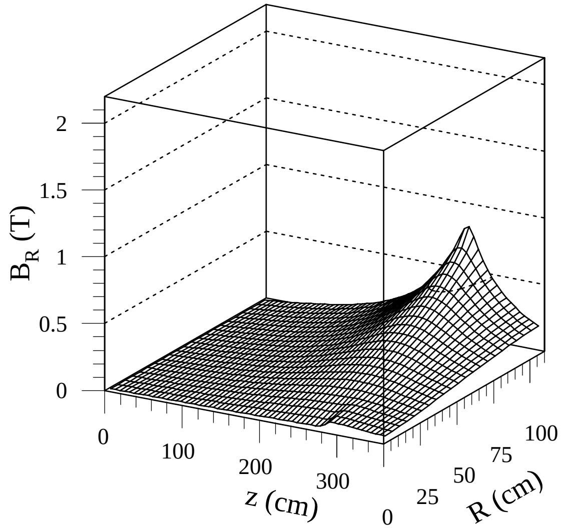
analysis: M. Vos
PRELIMINARY

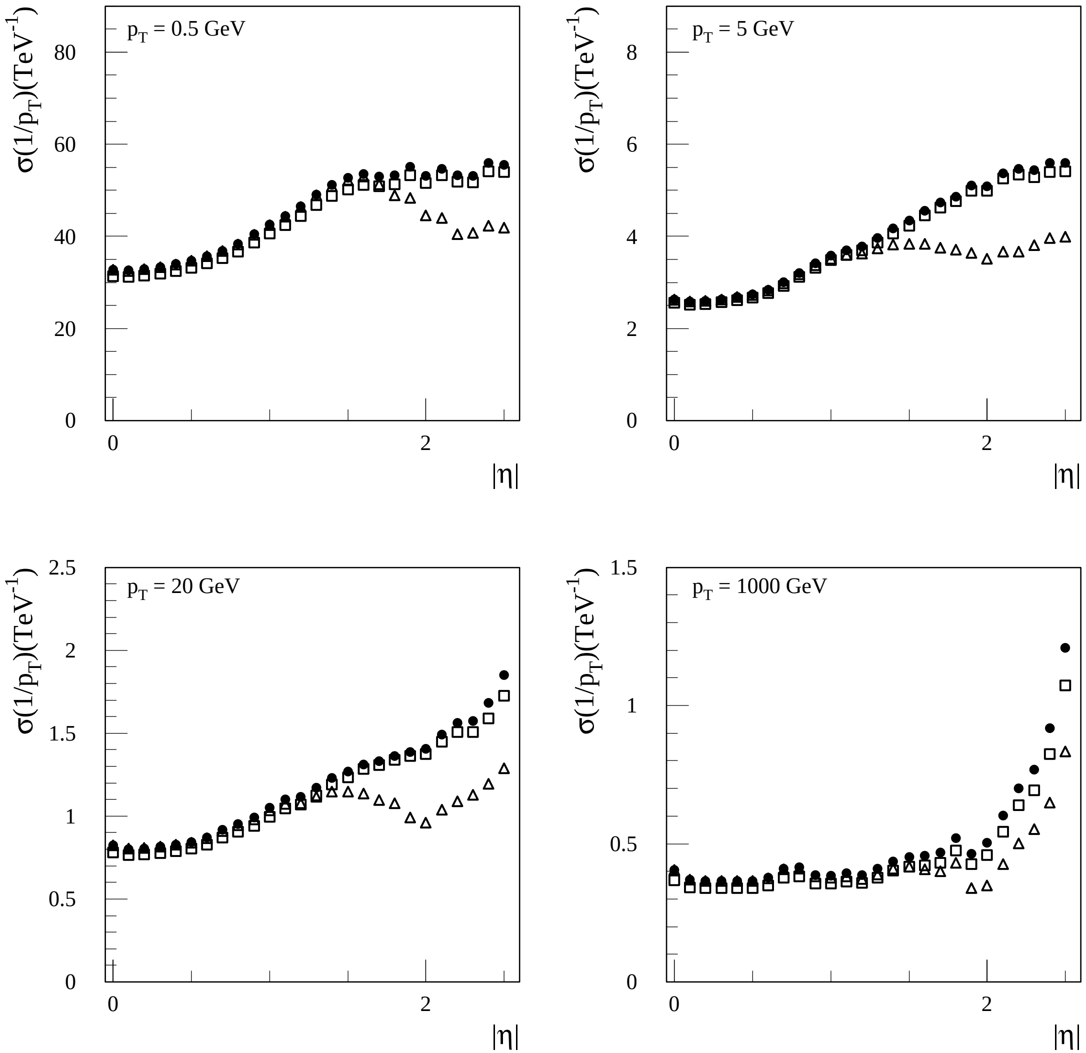
SCT Material Budget



Magnetic Field and p_t Resolution

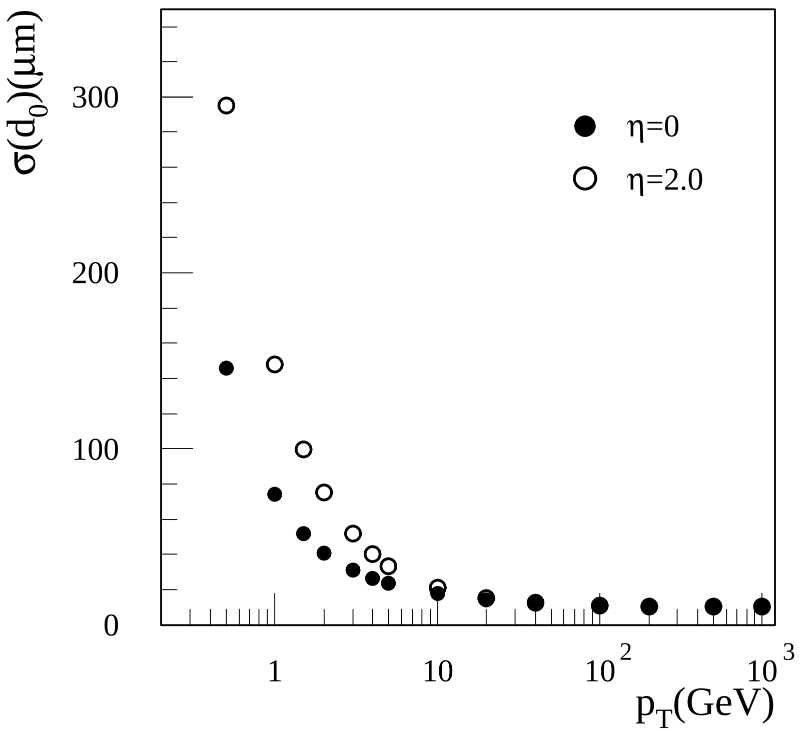


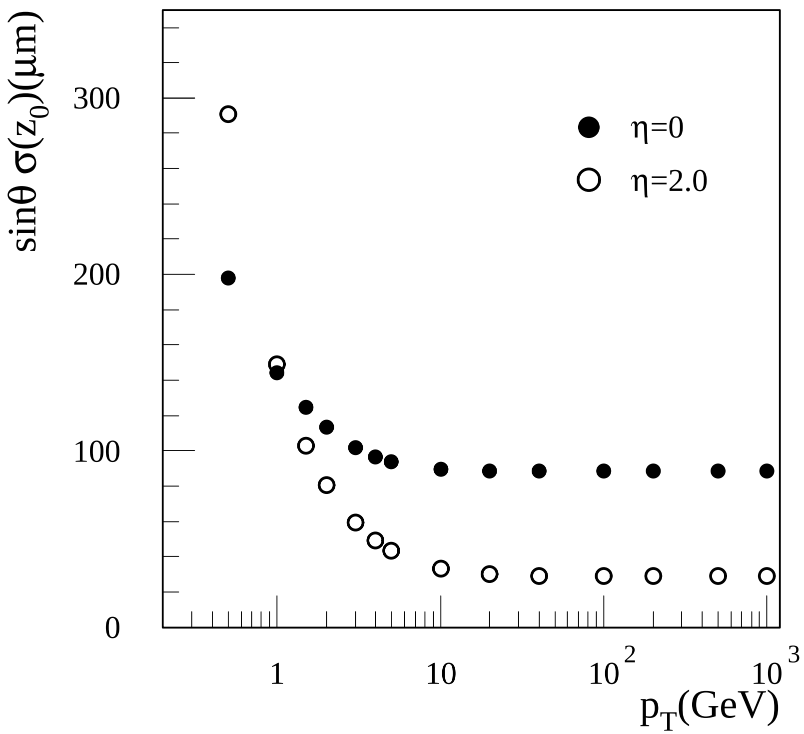




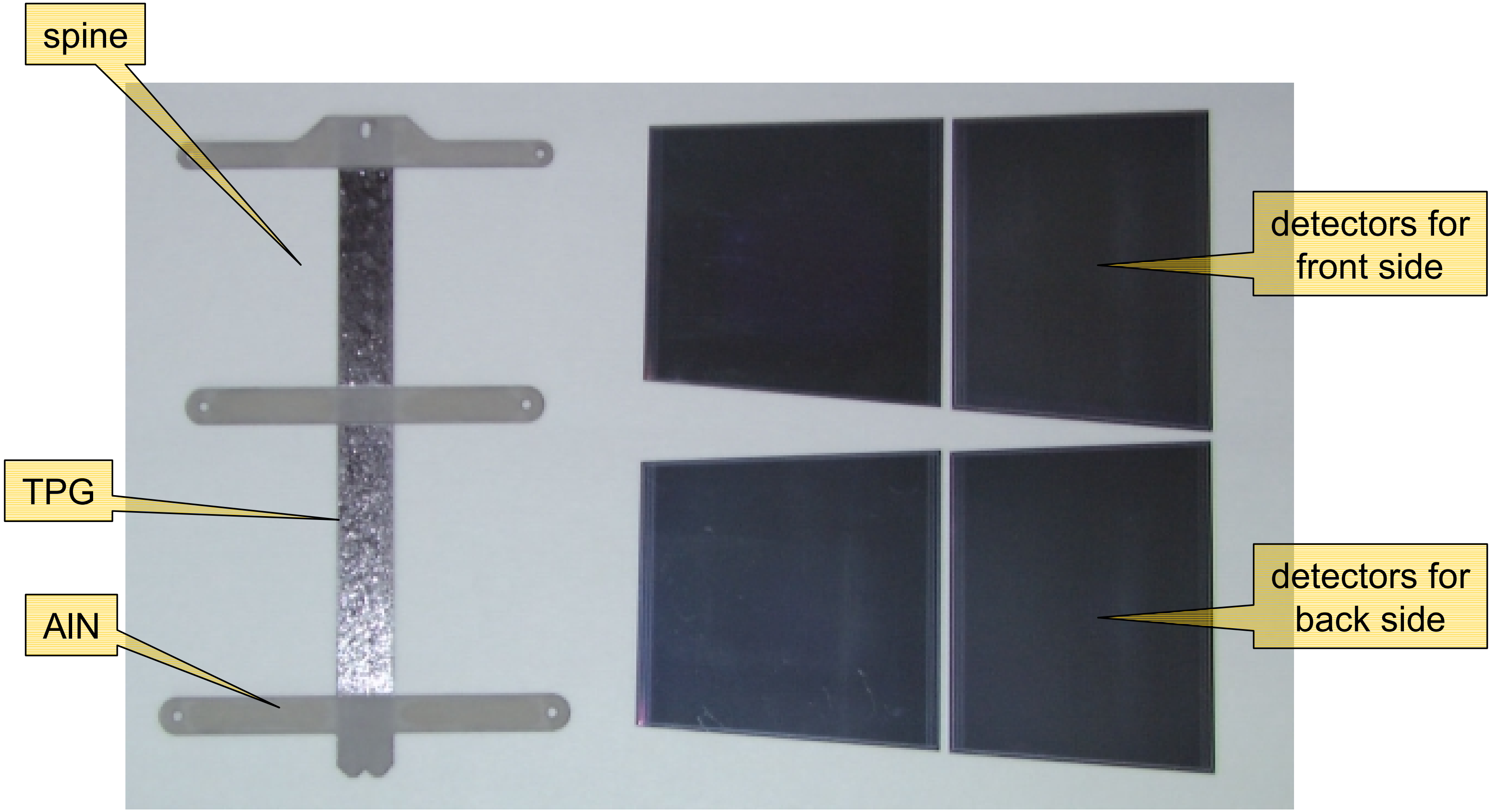
- p_t resolution as a function of $|\eta|$ for muons of various momenta
- circles and squares show simulation for ATLAS solenoidal field, triangles for uniform field

Impact Parameter Resolution

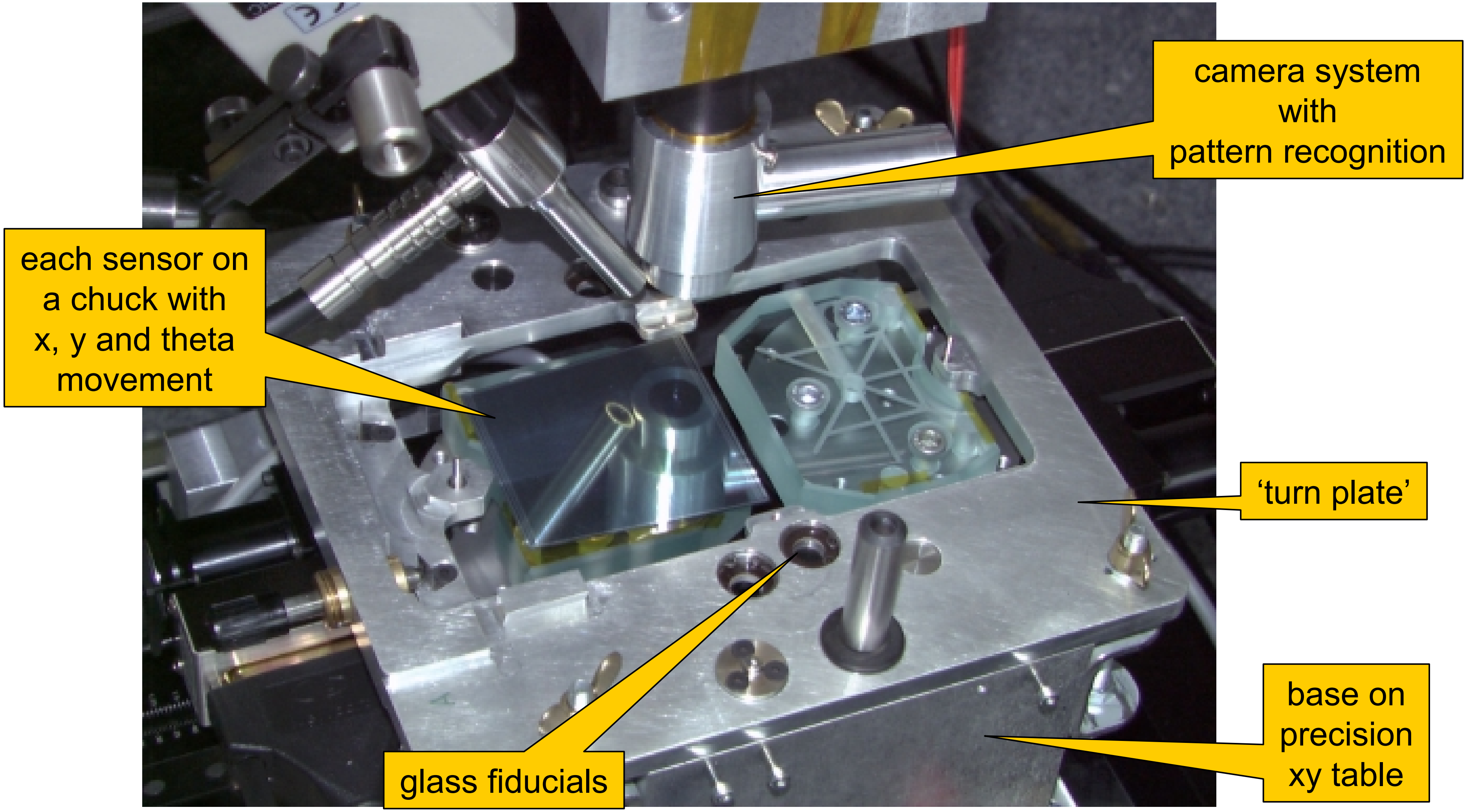




Components for a Detector Module

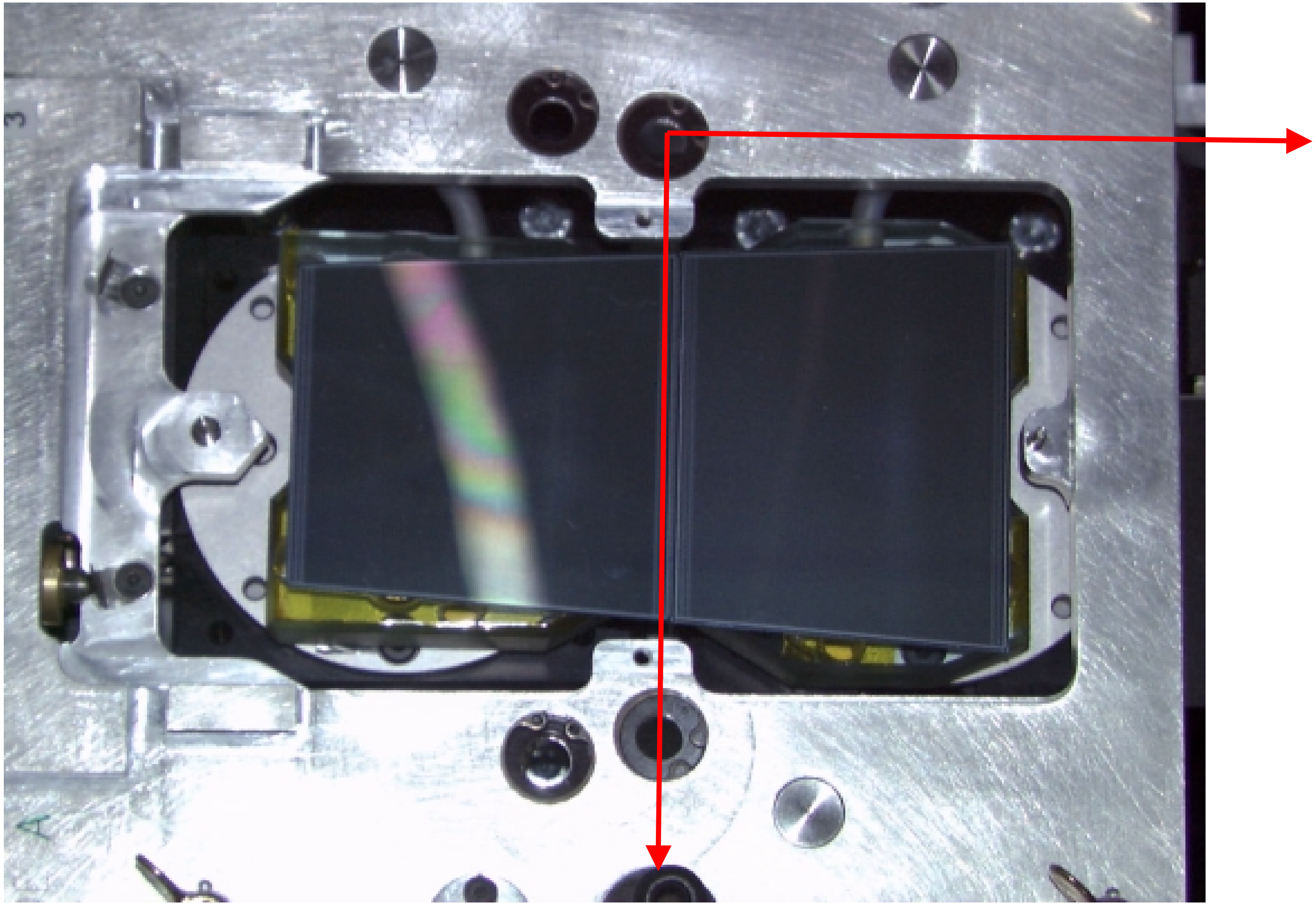


Semi-Automatic Module Assembly

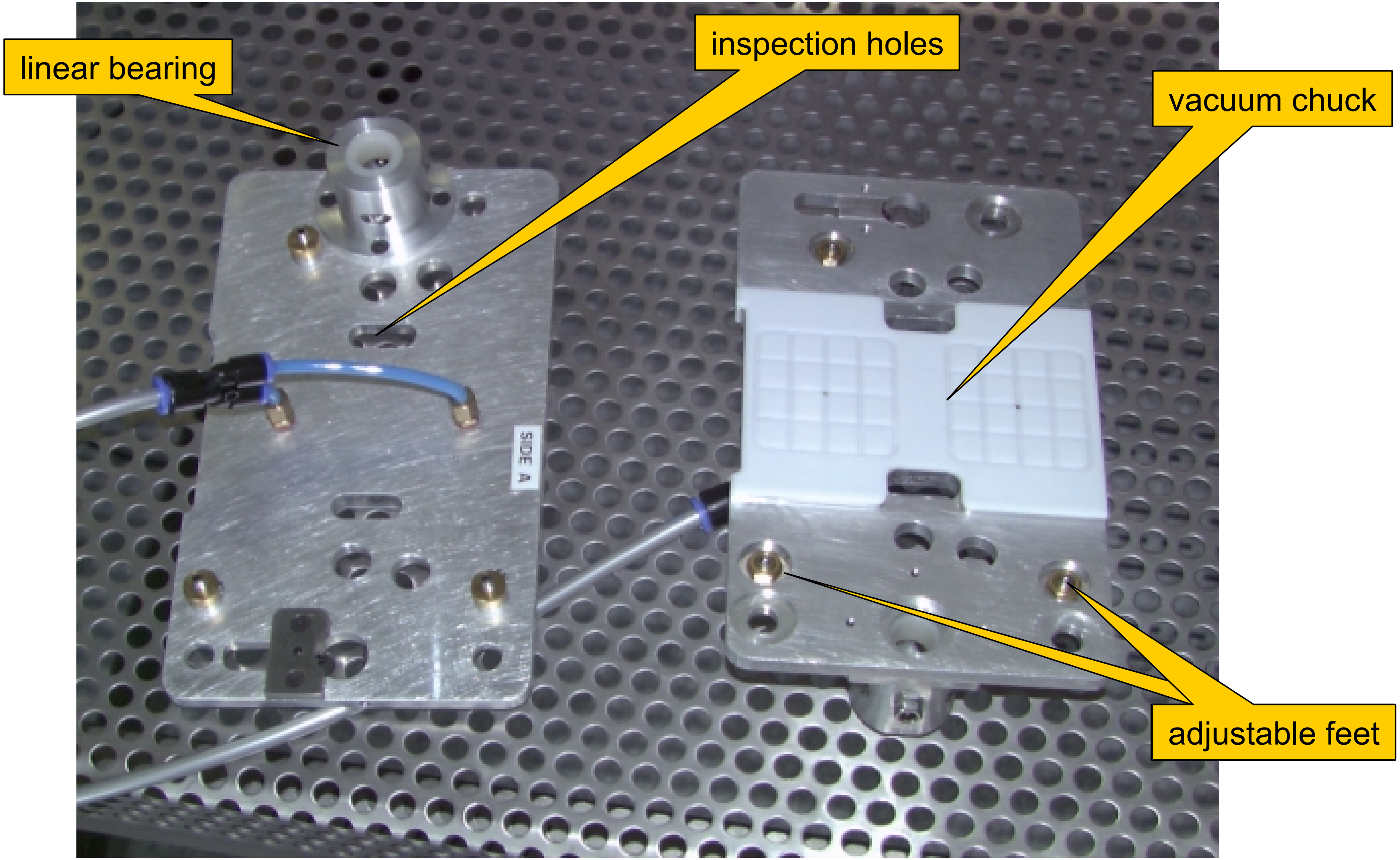


all stages computer controlled (LabVIEW)

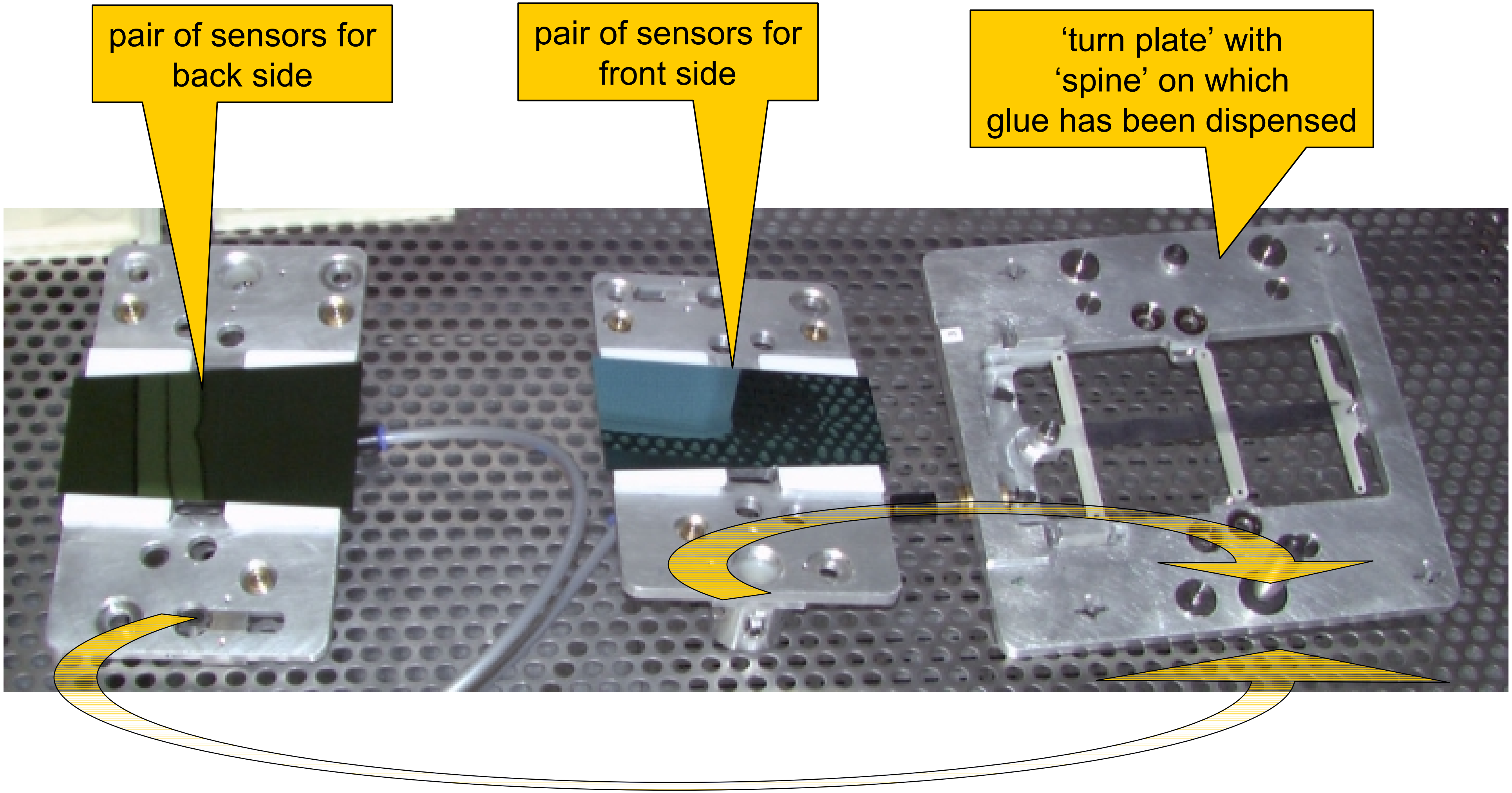
Aligned Sensors in ‘Turn Plate’



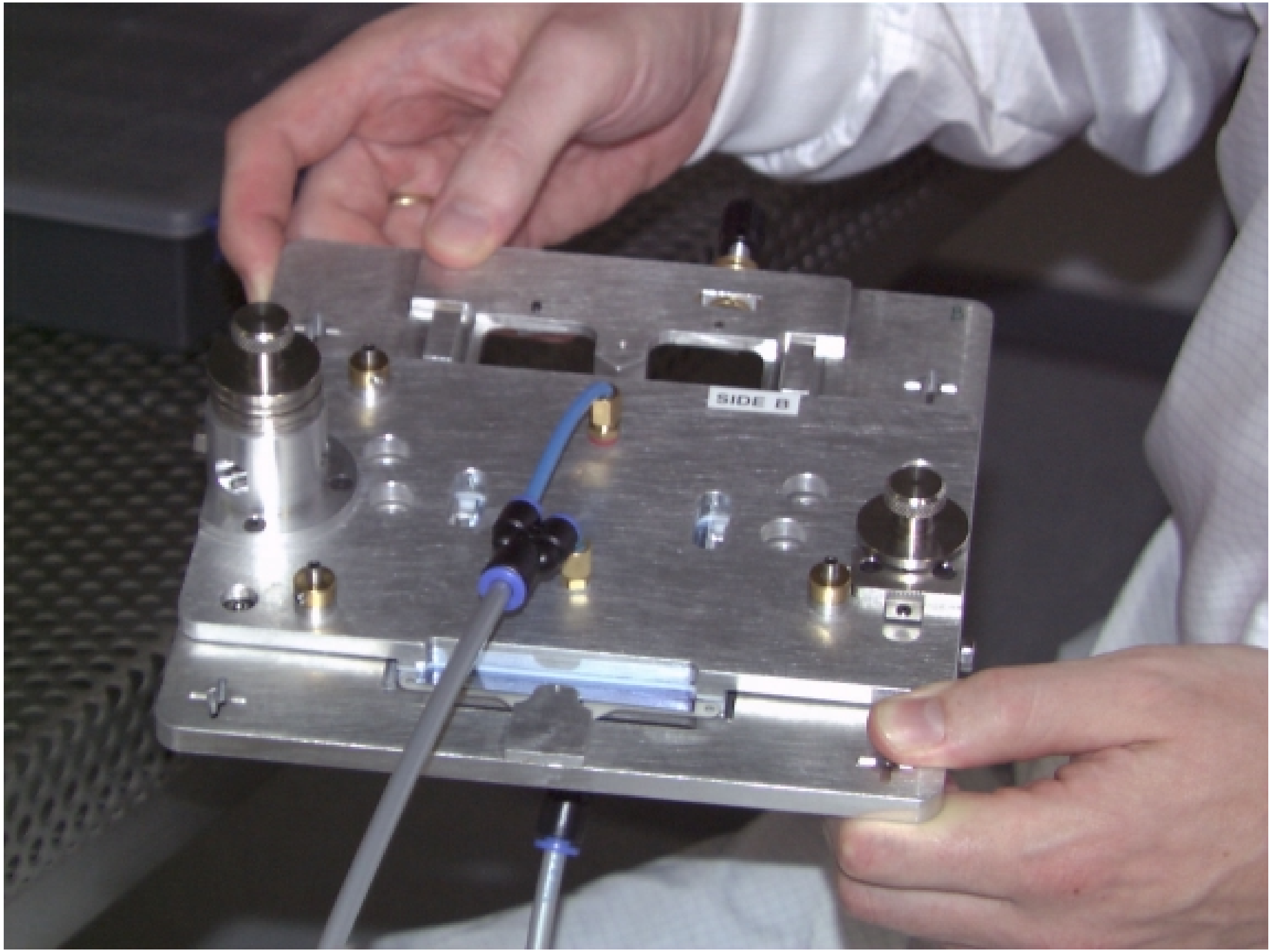
Transfer Plates



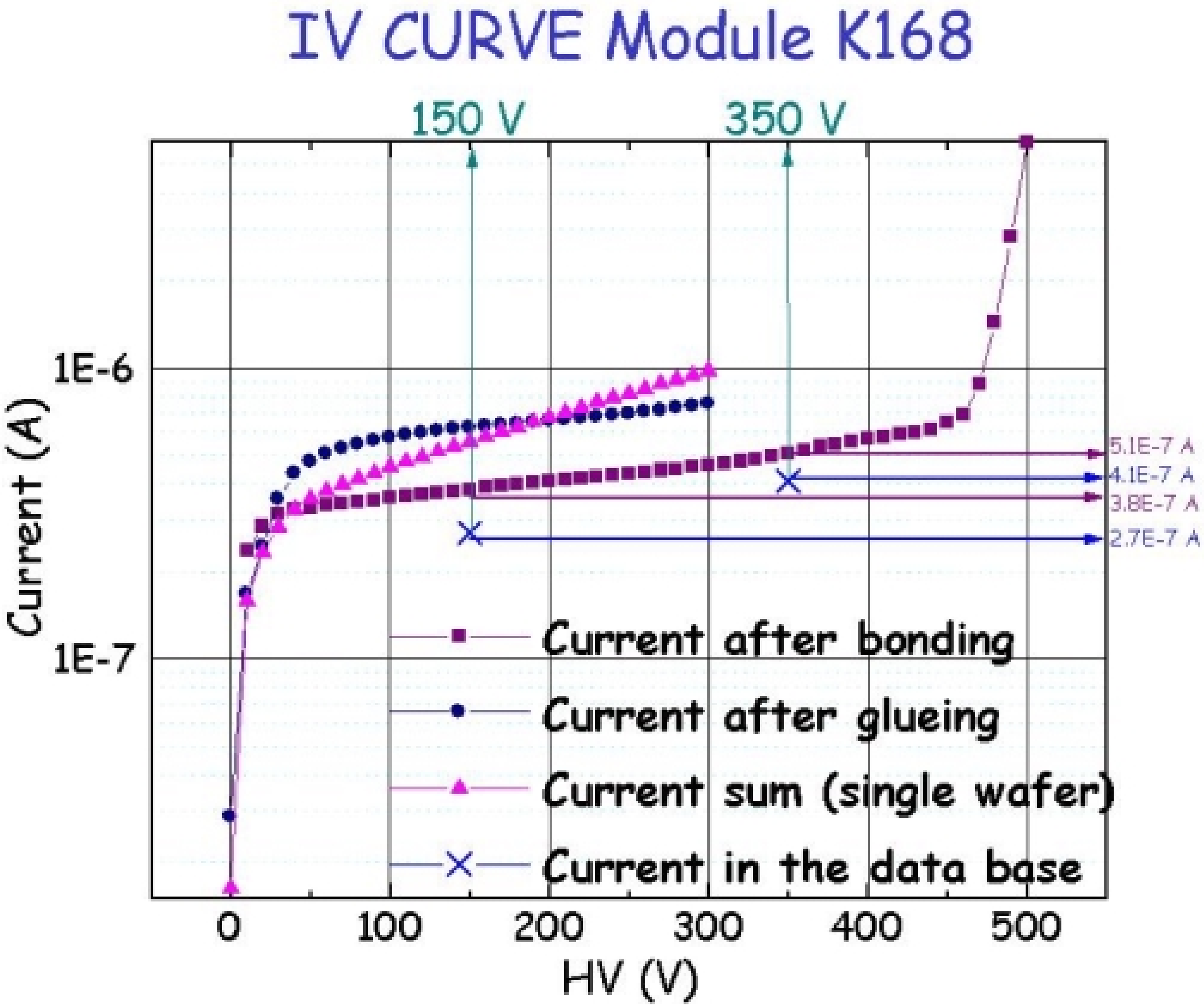
Aligned Pieces ready for Assembly



Assembly is finished



Leakage Current before and after Assembly

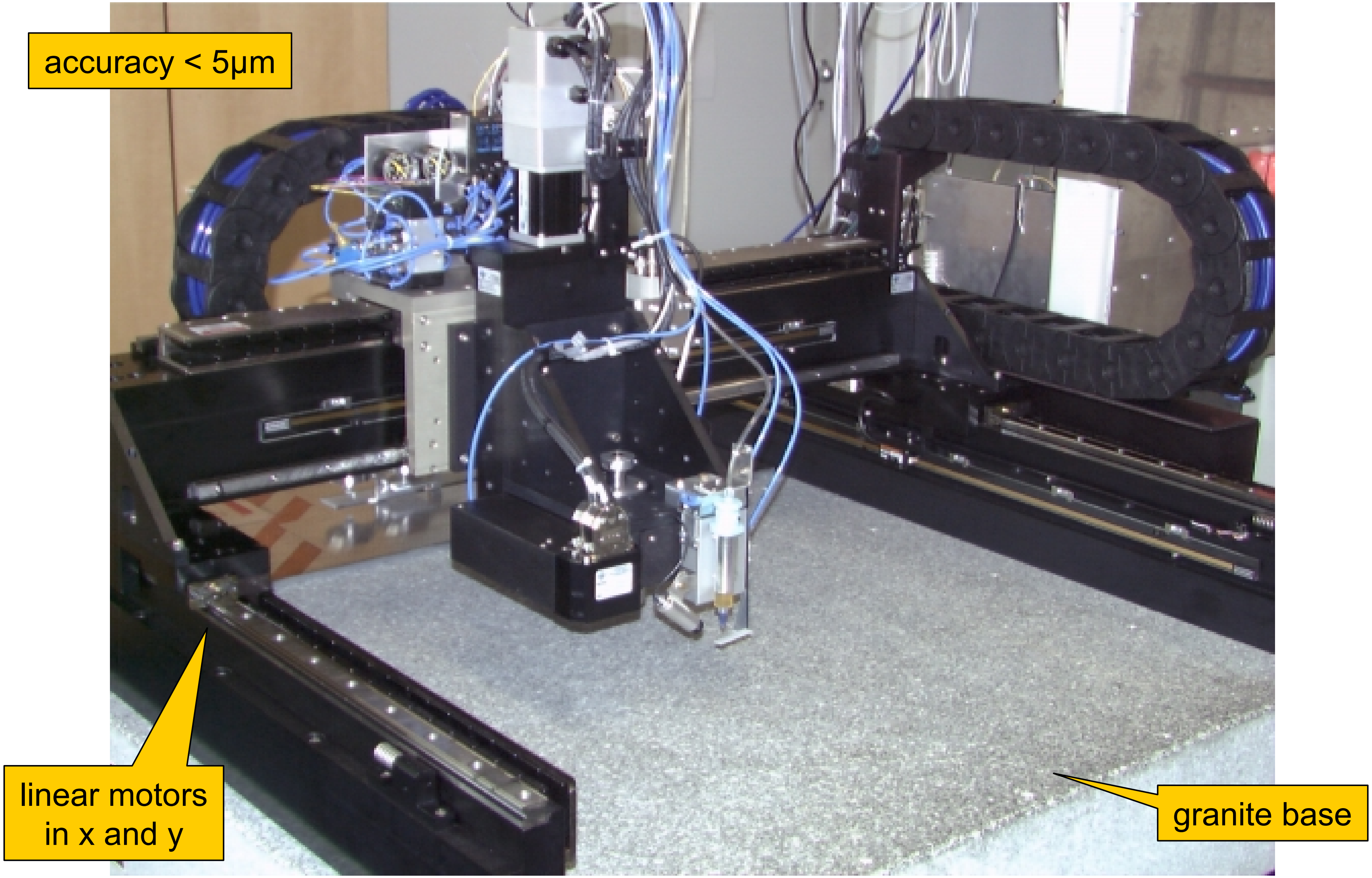


Metrology: Measurement Microscope

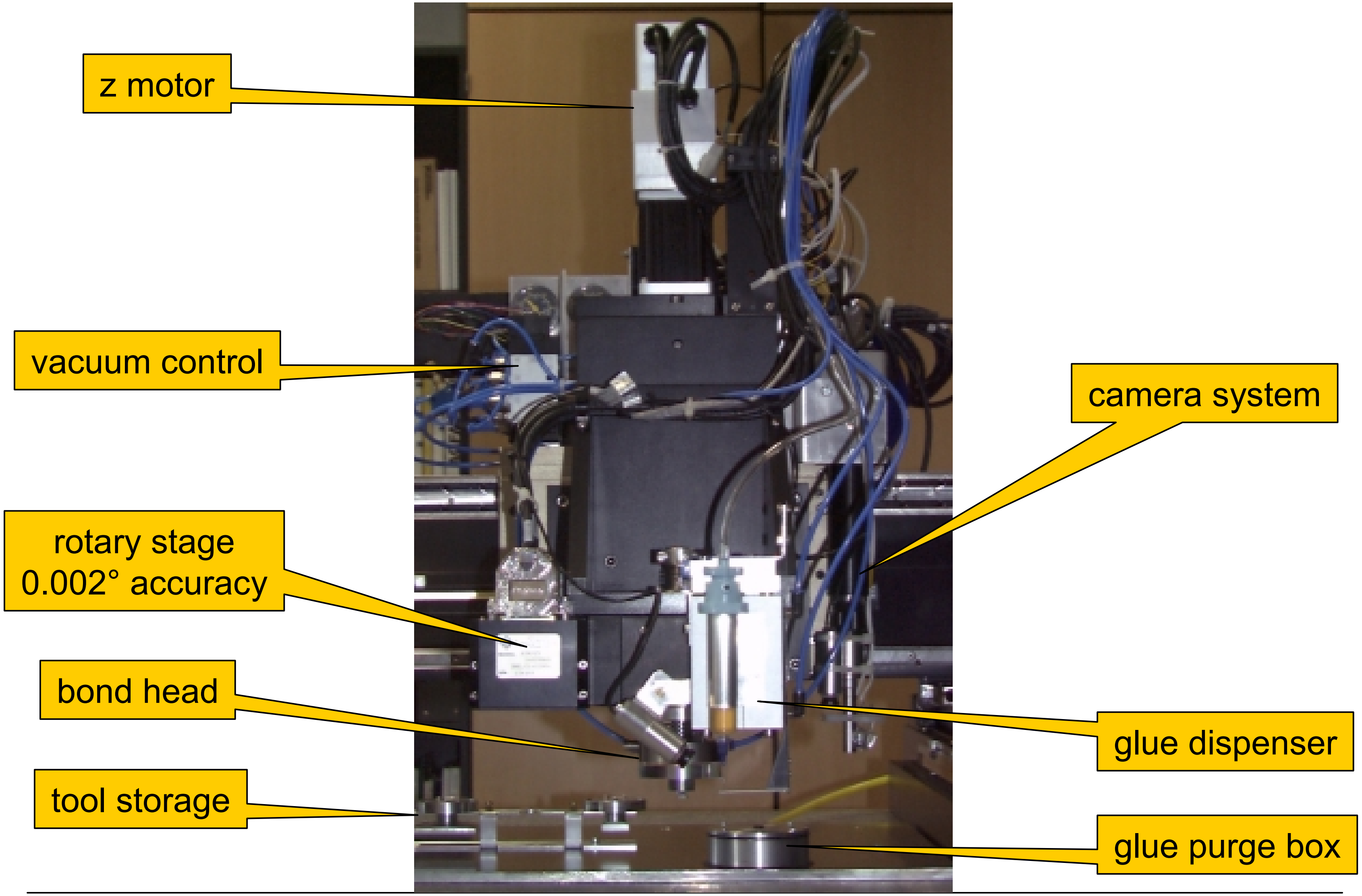
LEICA VMM200
2µm accuracy
in x,y,z

computer controlled
metrology using
pattern recognition

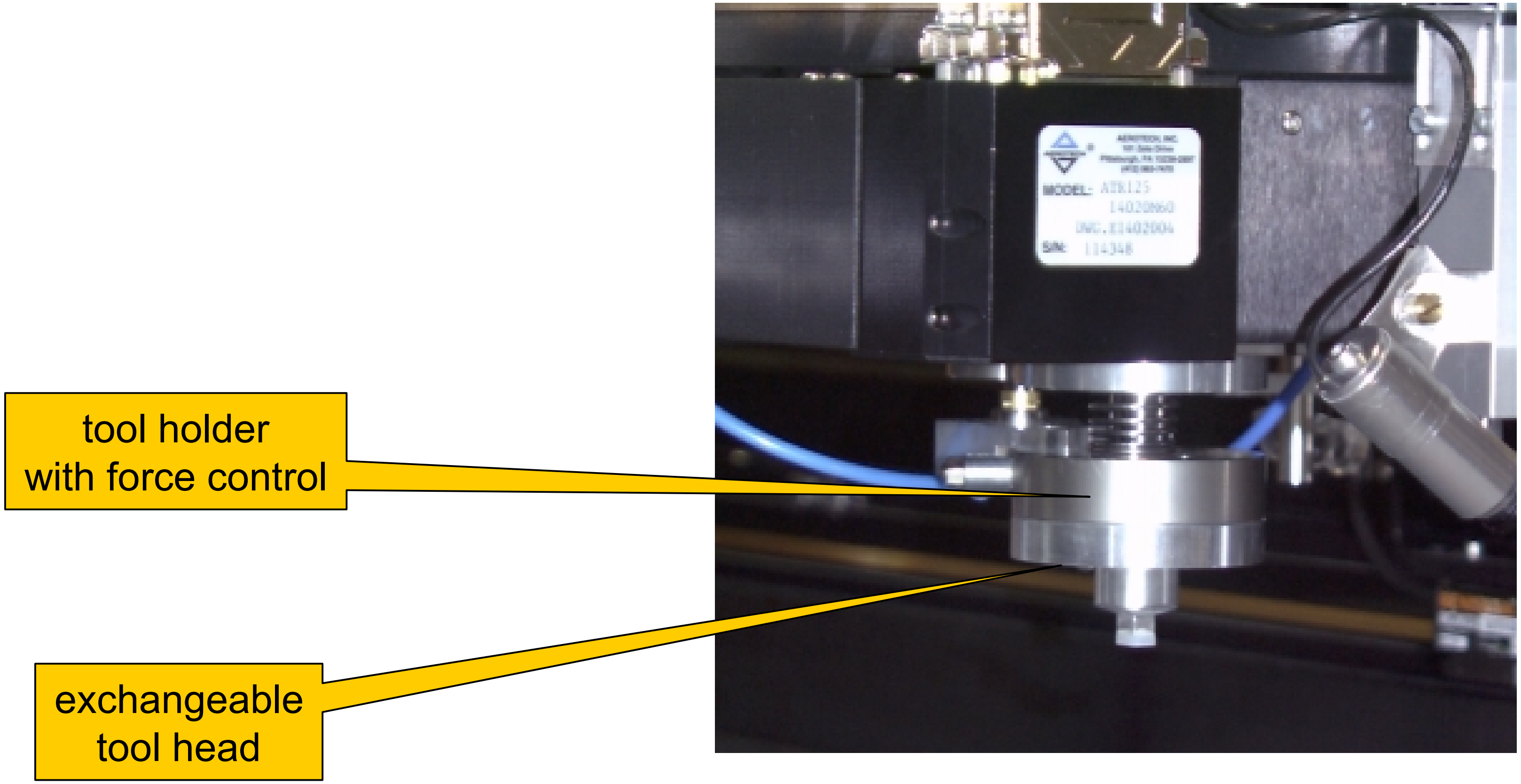
Automatic Assembly Robot



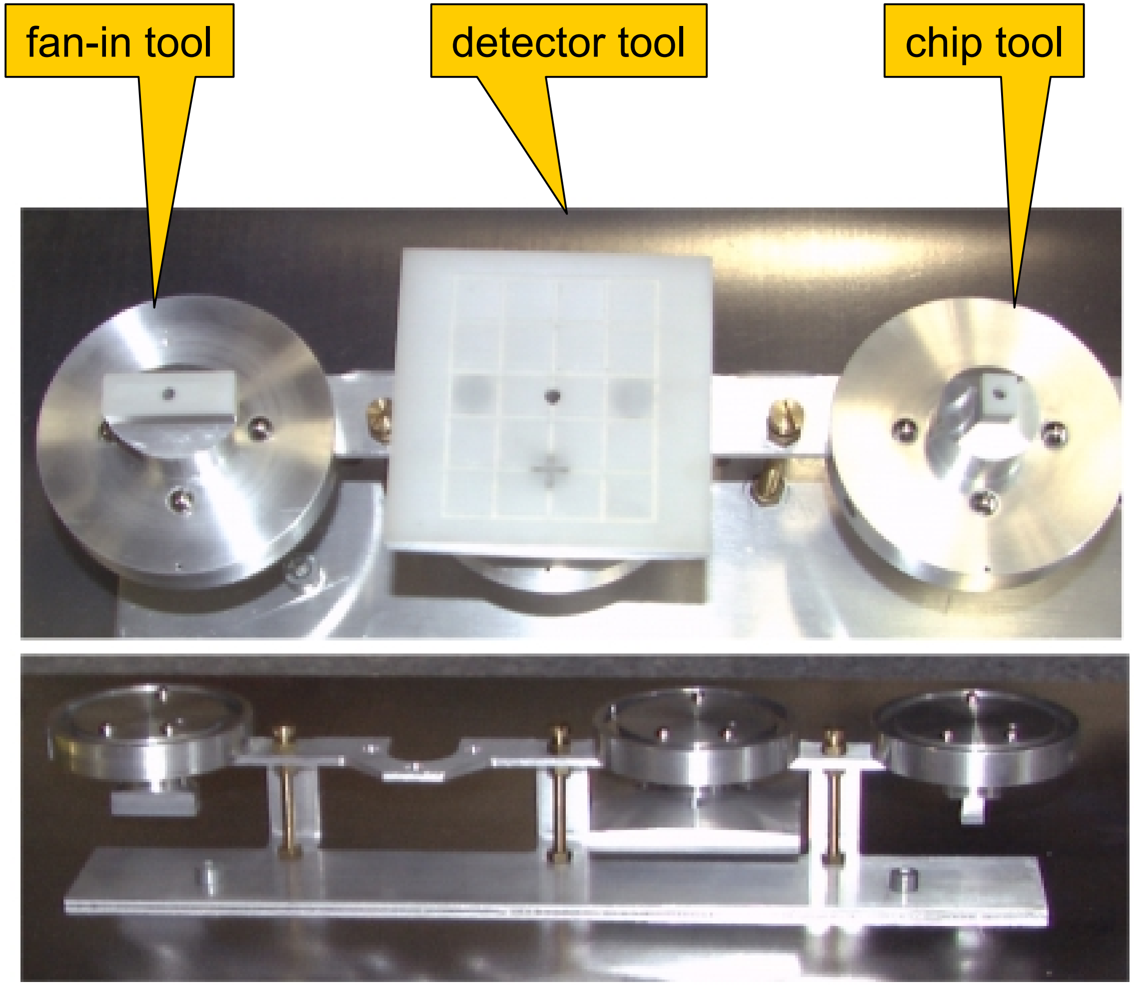
Assembly Head



Bond Head

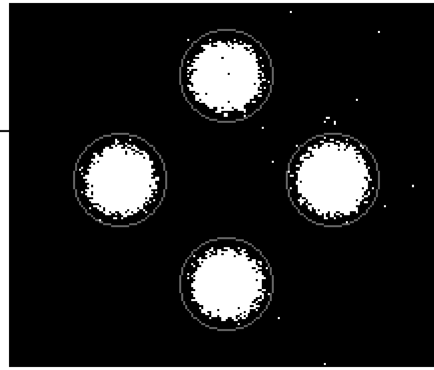


Tool Heads



Repeatability

fiducial



measurement in xy:

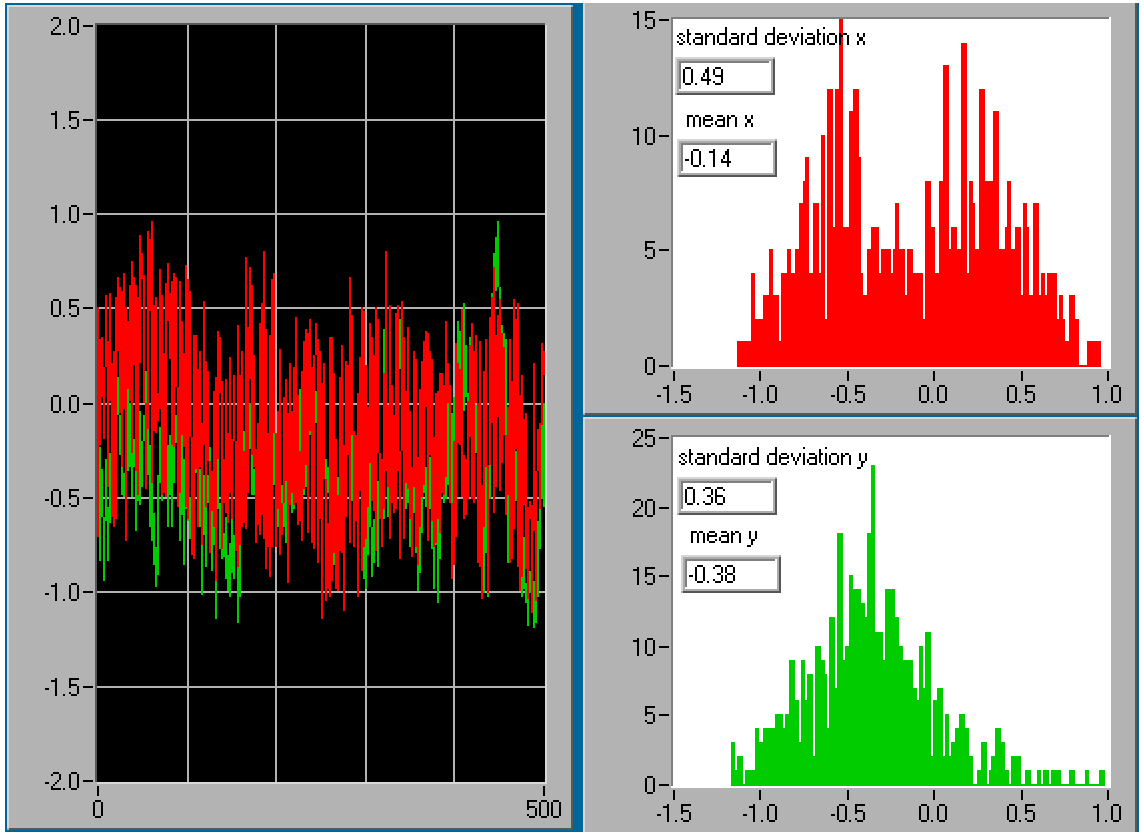
random run with 20 cm diameter and a speed of 5 m/min

->repeatability in x,y<1μm

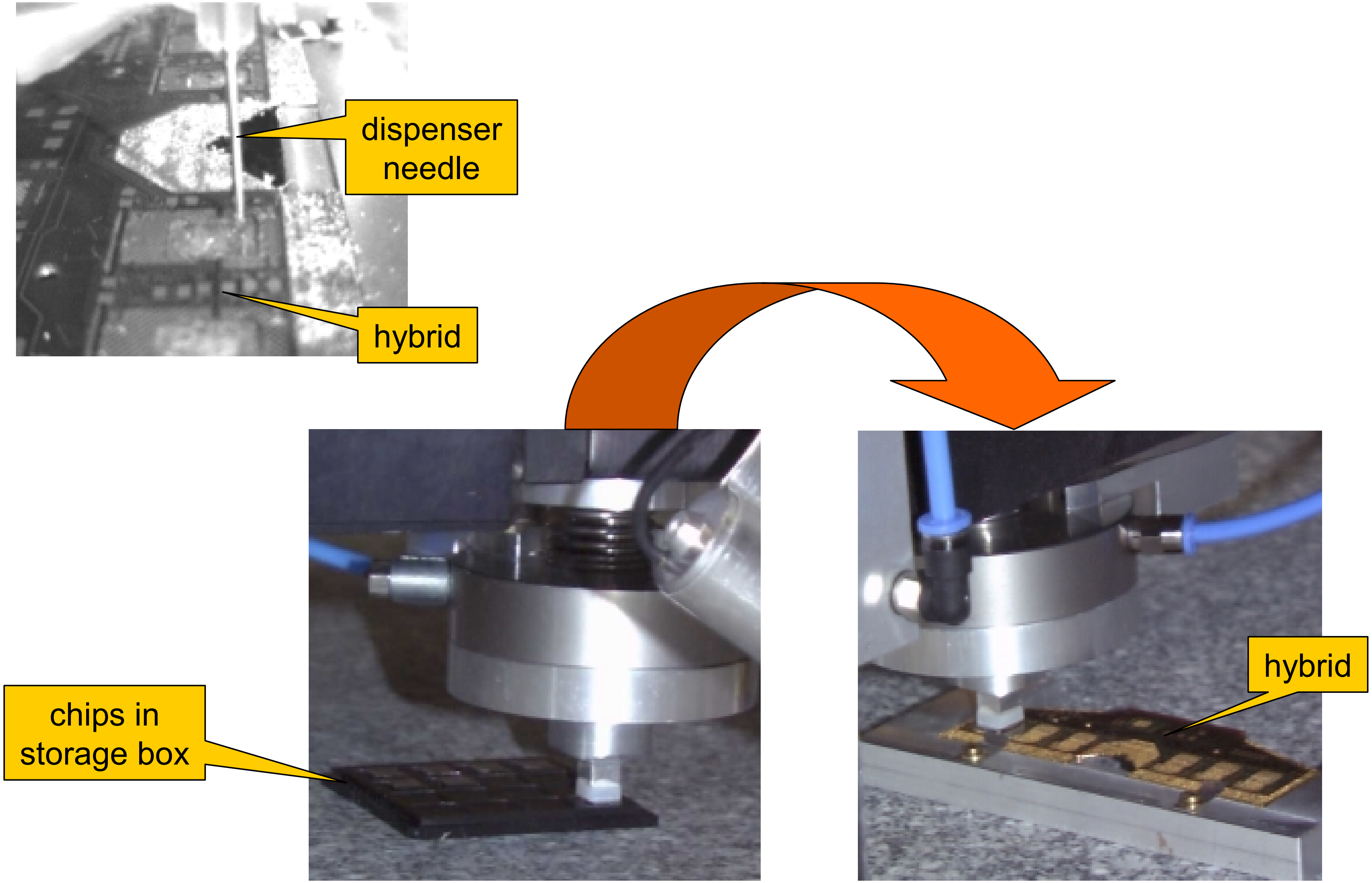
rotation:

using laser setup

->repeatability 0.002°



Glue Dispensing and Placement of Chips on a Hybrid



Summary and Current Status

- the ATLAS SCT is now preparing the production phase
- sensors are under fabrication
- front-end electronics chosen and starting pre-production
- electronics hybrids close to final design review
- module design close to final design review
- several close-to-final modules built and tested (incl. irradiation)
- module assembly procedure defined and production centres in qualification step
- off-detector electronics and services in prototyping
- cooling tested on prototypes
- barrel support structure under construction
- forward support structure in prototyping